The Einstein Telescope: Scientific Reach and Technological Challenges of a Third-Generation Gravitational-Wave Observatory

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on behalf of ET collaboration

Gran Sasso Science Institute

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Brief personal intro

Research focus

- AI/ML and control systems for gravitational-wave detectors
- Seismic isolation, vibration control, and low-frequency noise mitigation
- Digital twins and reinforcement-learning control for LIGO, Virgo, GEO600, and ET-relevant systems

Collaboration roles

- Co-coordinator, AI-for-ET Division
- Co-chair, LVK/IGWN Machine Learning Algorithms Working Group
- Co-chair, ET Inter-Platform Motion Working Package

Relevant experience

- Developed and tested advanced control strategies with teams at LIGO Livingston, GEO600, Caltech 40m, KAGRA, and Virgo
- Core contributor to the LIGO–Caltech–Google DeepMind “Deep Loop Shaping” result, published in Science, demonstrating reinforcement-learning control on a gravitational-wave detector.

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GS SI

Why This Topic Matters

The Birth of a New Astronomy

- Gravitational waves are ripples in spacetime caused by massive, violent cosmic events like black hole collisions or neutron star mergers
- First direct detection in 2015 (GW150914) confirmed a 100-year-old prediction from Einstein's theory
- Led to the 2017 Nobel Prize in Physics for the founders of LIGO

Opened an entirely new window on the cosmos

- Revealed a population of invisible black holes, neutron star collisions, and more
- Enables multi-messenger astronomy: combining light + gravitational waves to understand cosmic events

Why the Technology Behind It Is So Impressive

- Measuring spacetime distortions as small as 1 part in 10^{21}
- Requires some of the most advanced engineering in optics, control systems, vacuum technology, and noise suppression
- Constant upgrades and innovations — including the work I contribute to — are what make new discoveries possible

LIGO VIRGO KAGRA

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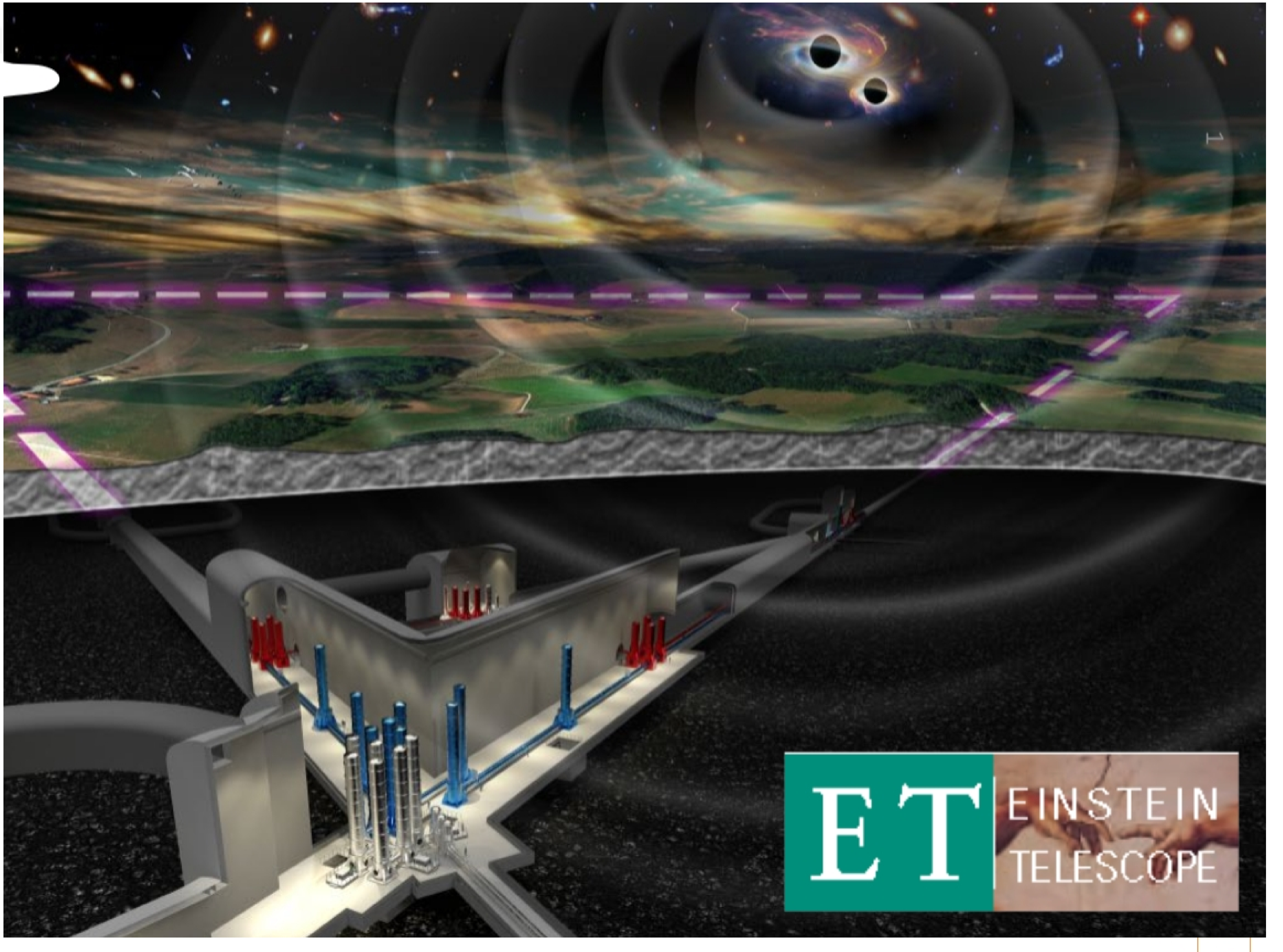
GSSI

Talk roadmap

1. Introduction
2. ET design concept & Scientific reach
3. Technological challenges
4. Project status and roadmap



GS
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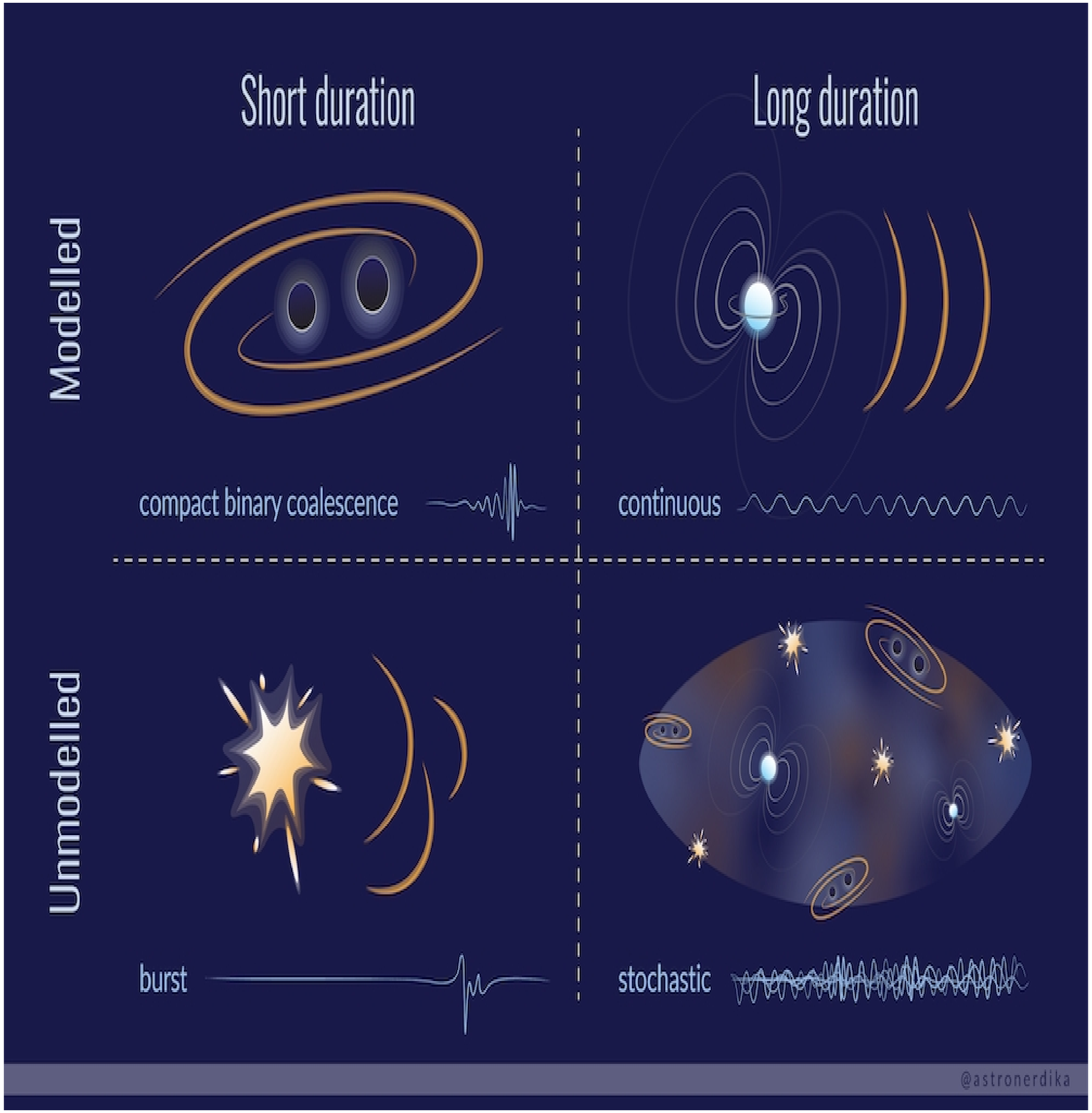
PART 1:
INTRODUCTION,MOST RELEVANT EVENTS, LVK, WHY DO WE NEED *ET?*

GSSI

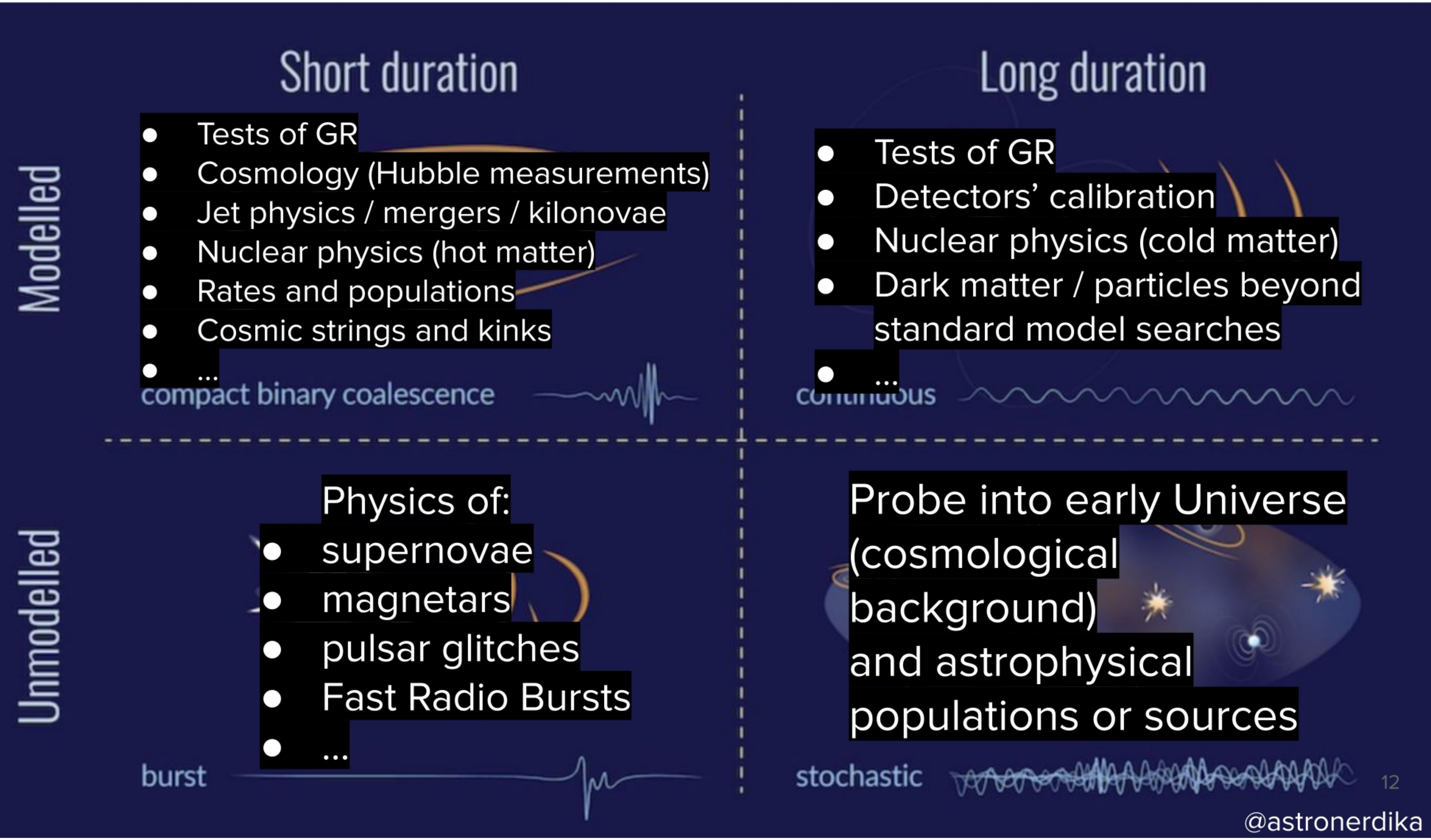
Where Do GWs Come From?



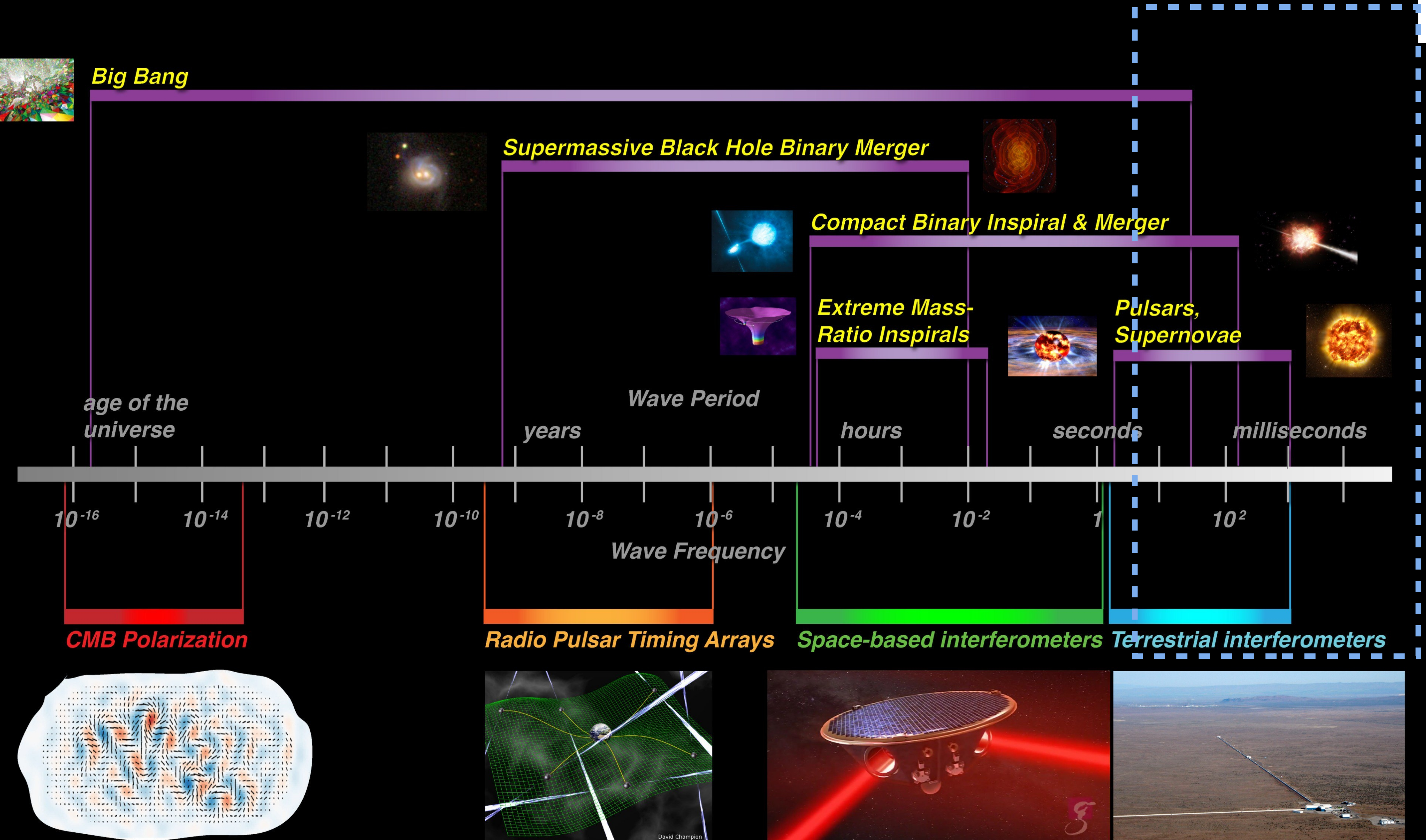
Credits: Shanika Galaudage

- Compact Binary Coalescence (CBC):
  - Binary black holes
  - Binary neutron stars
  - Inspiral → merger → ringdown
- Continuous Waves:
  - Rotating neutron stars
  - Long-duration nearly monochromatic signals
- Bursts:
  - Poorly modeled transients
  - Supernovae / unexpected sources
- Stochastic Background:
  - Cosmological or astrophysical background
  - Statistical detection

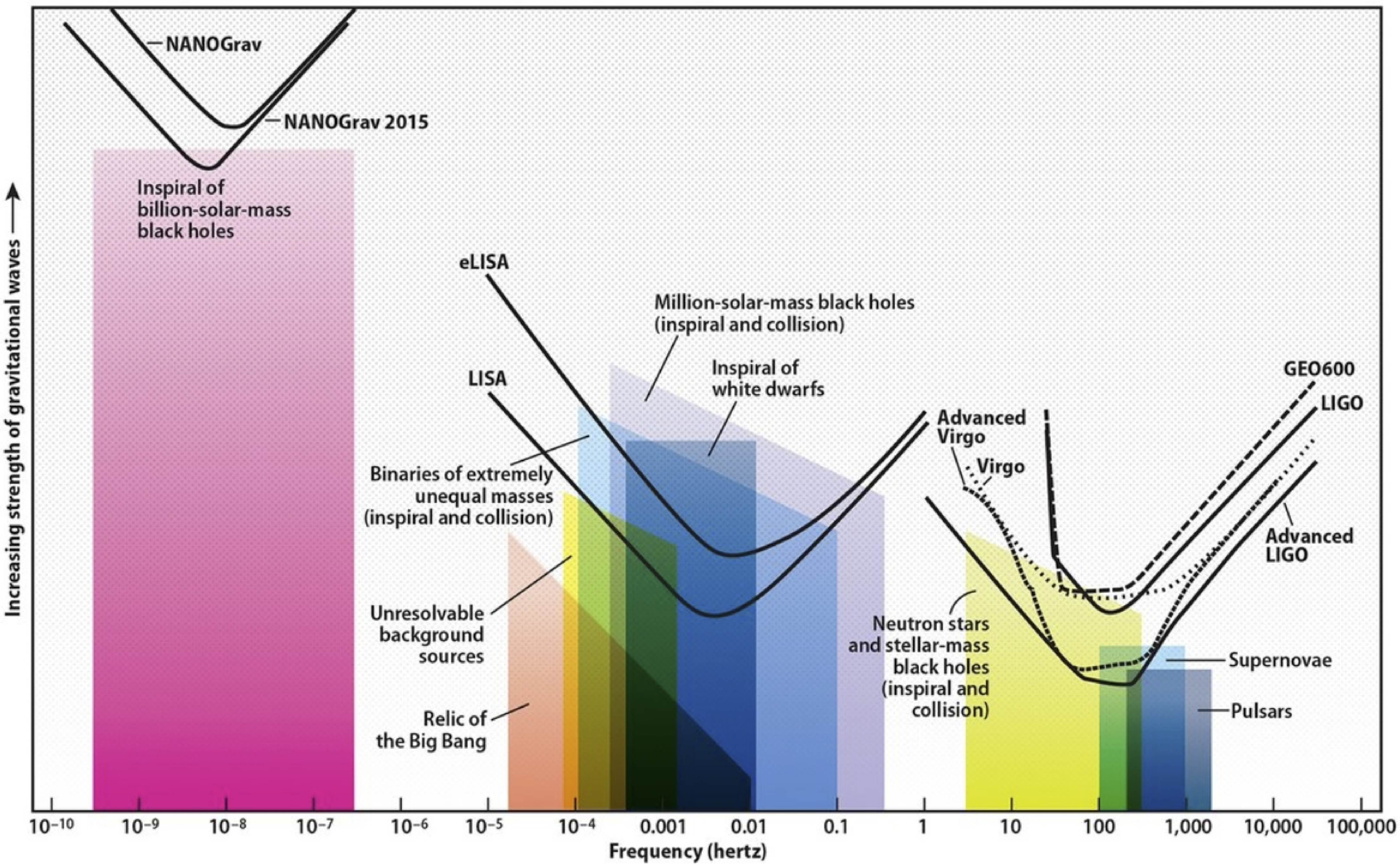
Where Do GWs Come From?



Tens of Hz-kHz GW band



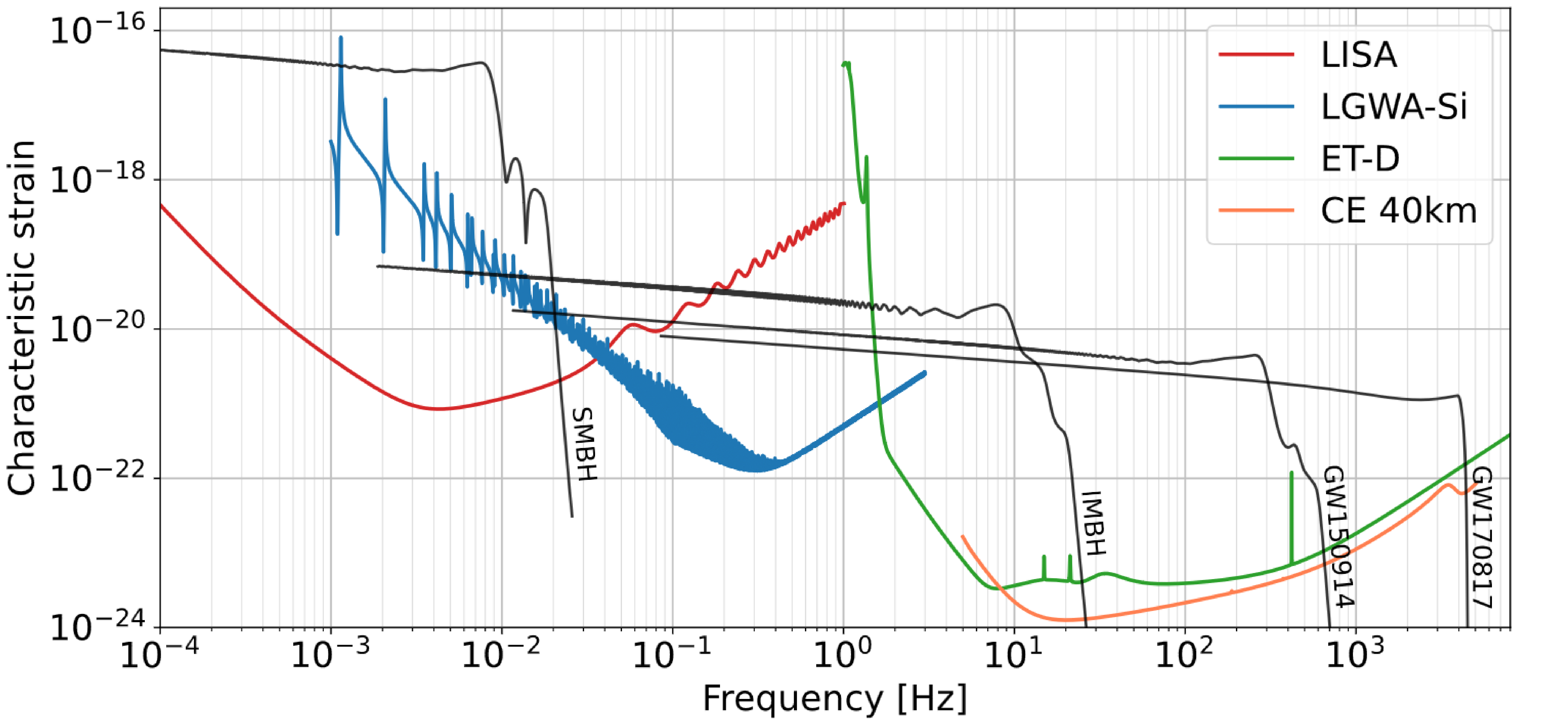
Sensitivity



Sensitivity

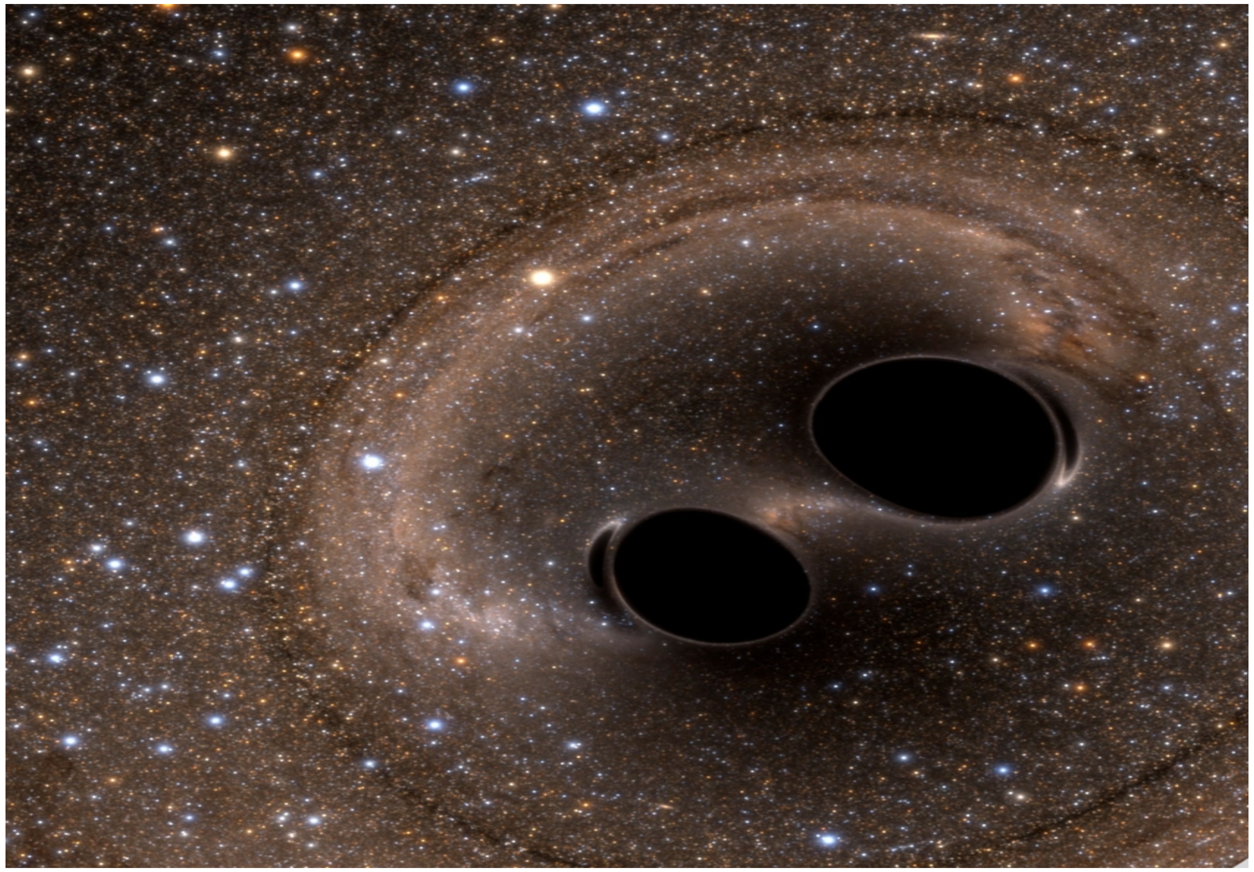
Multibanding: LISA detects a massive BBH inspiral years before merger → sends precise sky position and merger time to ET → ET observes the final plunge at high SNR with zero search cost — a completely new mode of GW astronomy

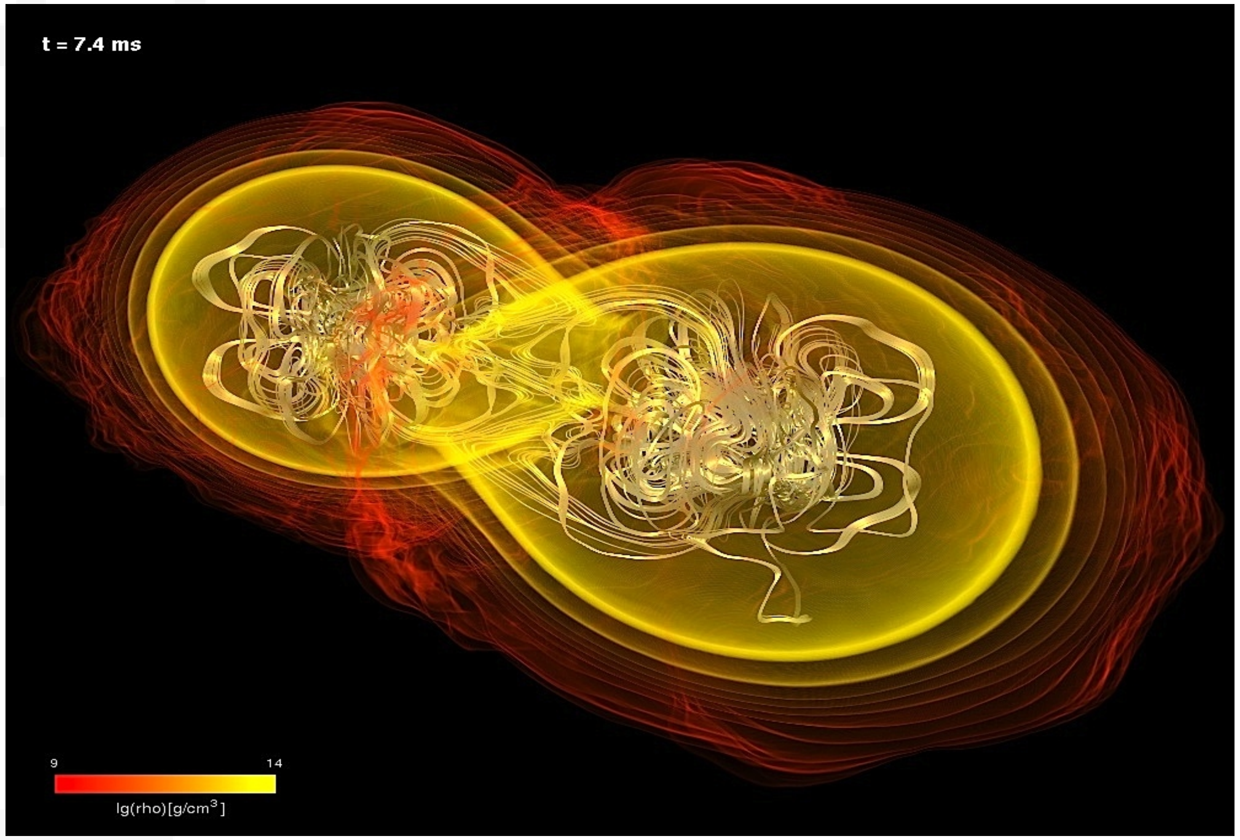
Multibanding with LISA + LGWA + ET



Gravitational-Wave Astronomy

- GW150914: first BBH detection
- GW170817: first multi-messenger BNS
- GW190521: massive merger / IMBH candidate

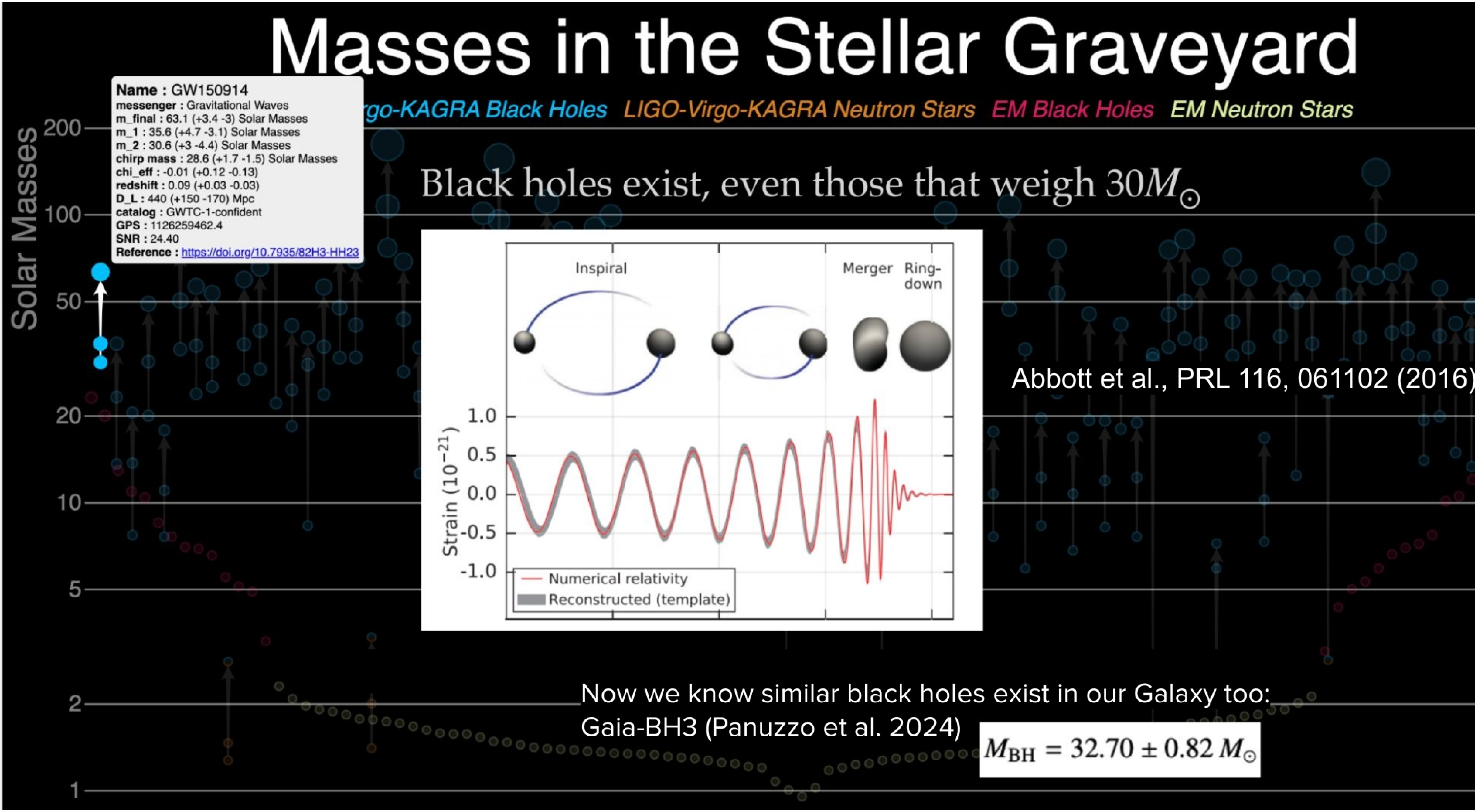




First Detection

GW150914 provided the first direct observation of a binary black-hole merger and of the strong-field dynamical regime of General Relativity, while revealing a population of unexpectedly massive stellar-origin black holes (~30 M☉).

The observed waveform was in remarkable agreement with numerical relativity predictions, providing the first direct observation of the inspiral, merger, and ringdown of a binary black-hole system and enabling precision tests of gravity in the highly dynamical, strong-field regime.



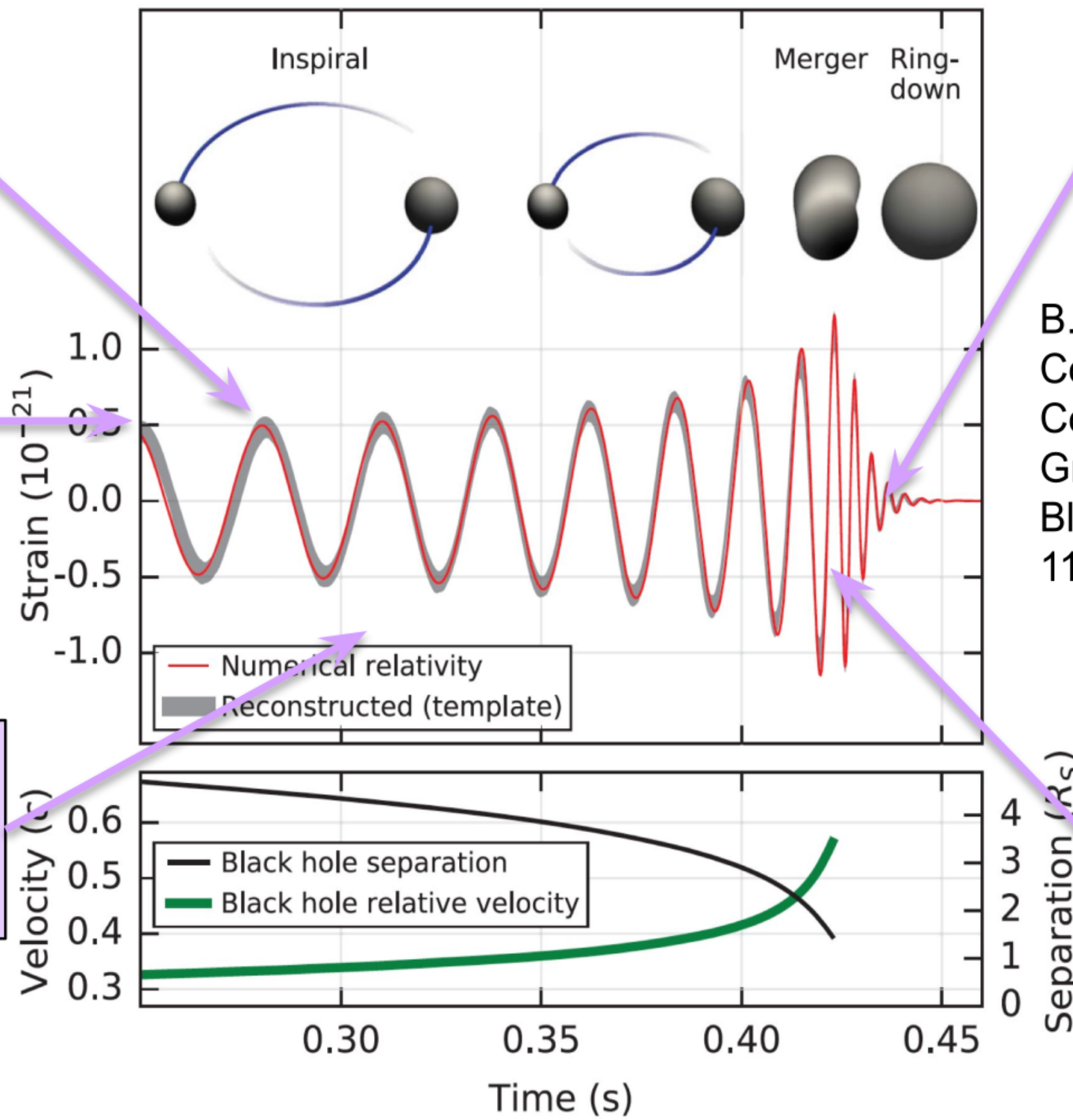
Slide adapted from M. Bejger (LIGO-Virgo-KAGRA gravitational-wave sources and observational results)

First Detection

Phase evolution gives chirp mass and aligned components of spin

Amplitude scale factor gives luminosity distance (standard siren)

Modulation of amplitude gives nonaligned spin components



Ringdown frequency and Q give mass and spin of final black hole.

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Observation of Gravitational Waves from a Binary Black Hole Merger, Phys. Rev. Lett. 116, 061102 (2016)

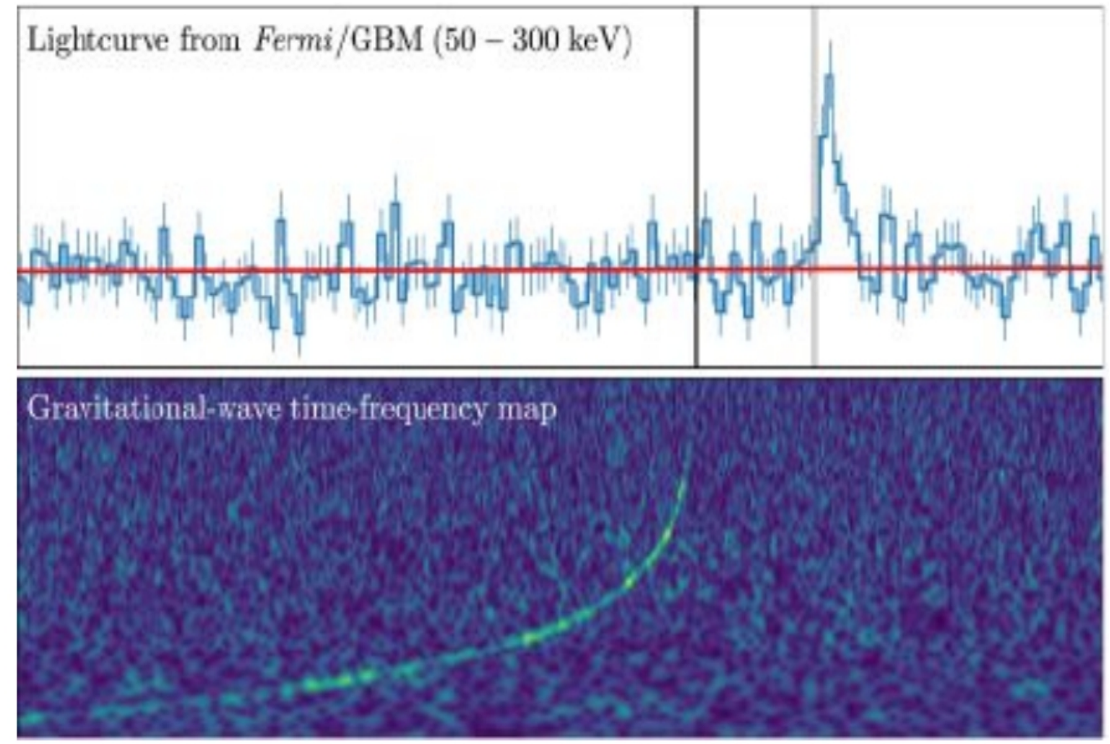
Highest frequency gives sizes of objects just before merger.

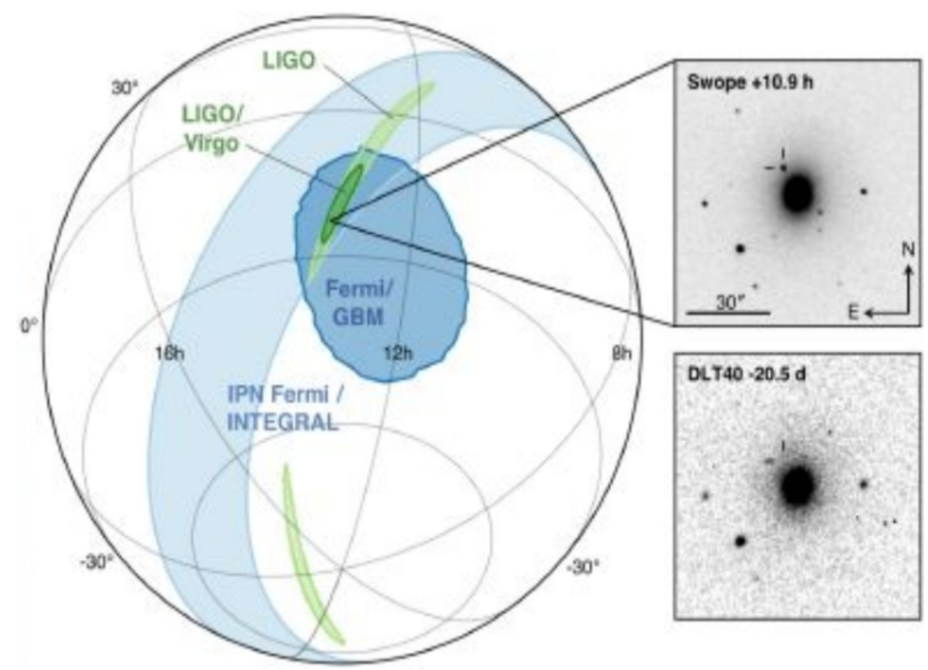
Slide adapted from F. Sorrentino (LVK detectors status and future plans)

The golden event: GW170817

LIGO-Virgo detection and GRB coincidence

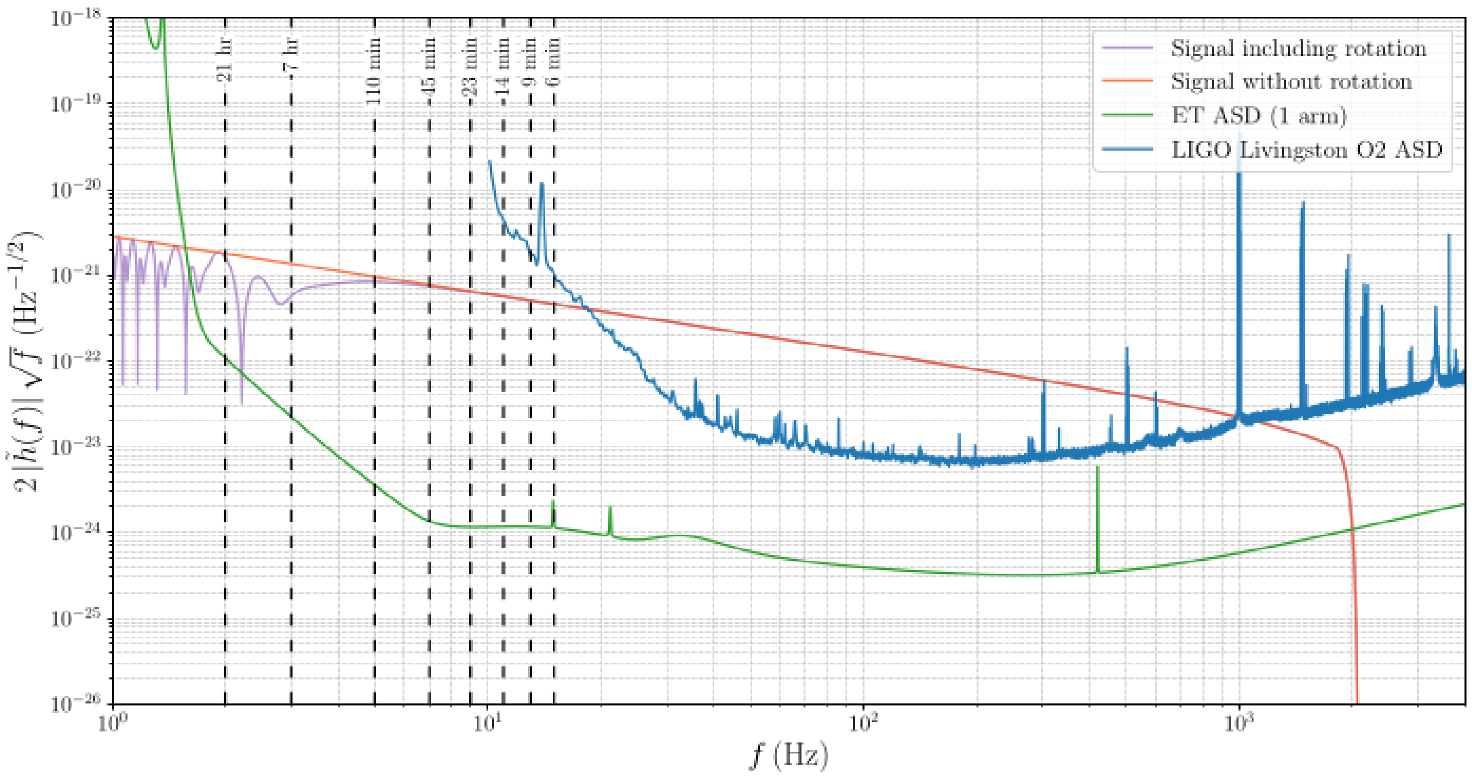
- first multimessanger event!
- first “standard siren” measurement of the Hubble constant (see slide 13)
- speed of gravity ≈ speed of light
- constraints on tidal deformability: neutron star maximum mass, equation of state of nuclear matter at extreme densities
- BNS mergers as prime source of heavy elements in the Universe





Slide adapted from L. D’Onofrio (An overview of the LVK observational science and results)

GW170817 at LVC-O2 and at ET



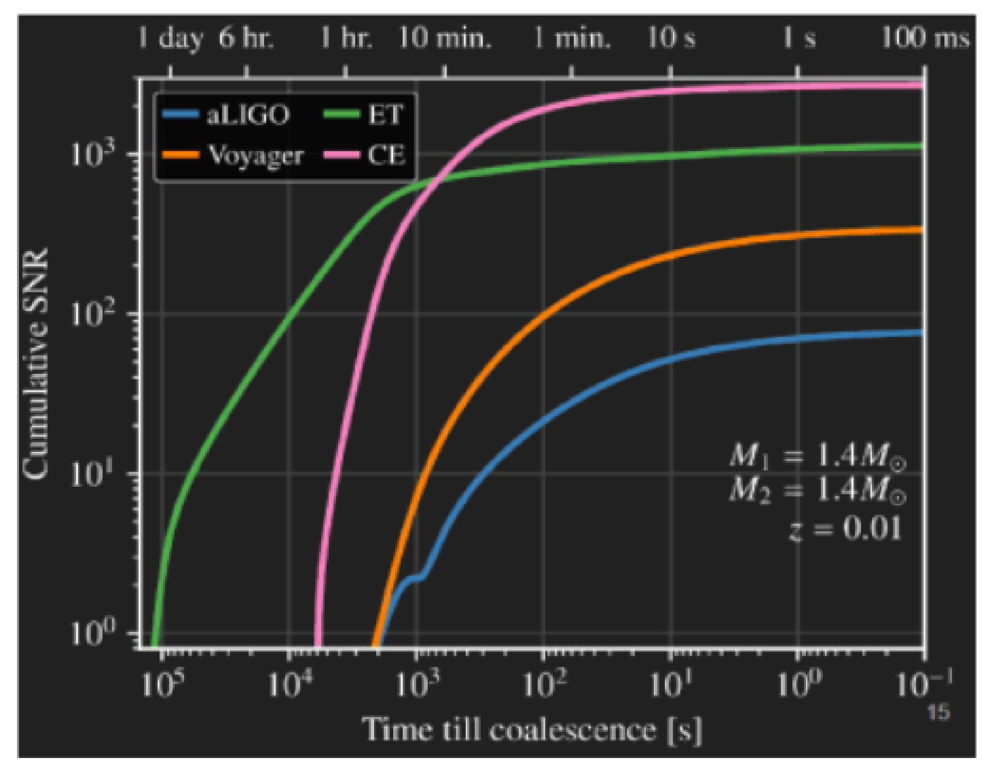
Current detectors observe mainly the final seconds before merger

ET sensitivity down to a few Hz enables detection hours earlier

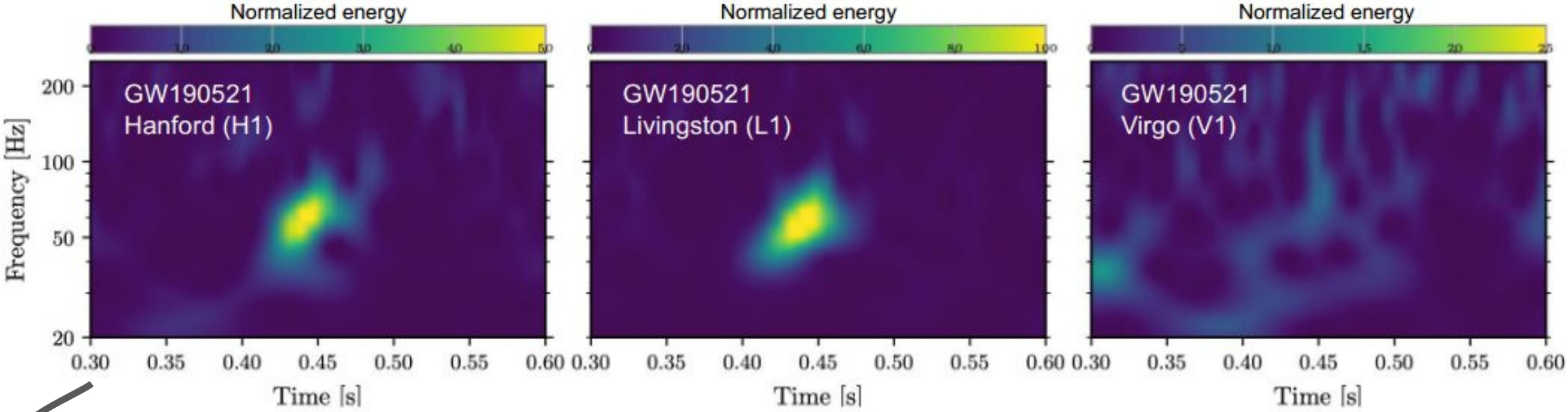
Low-frequency sensitivity enables predictive multimessenger astronomy

we can trigger e.m. observations before the emission of photons

Keyword: low frequency sensitivity!

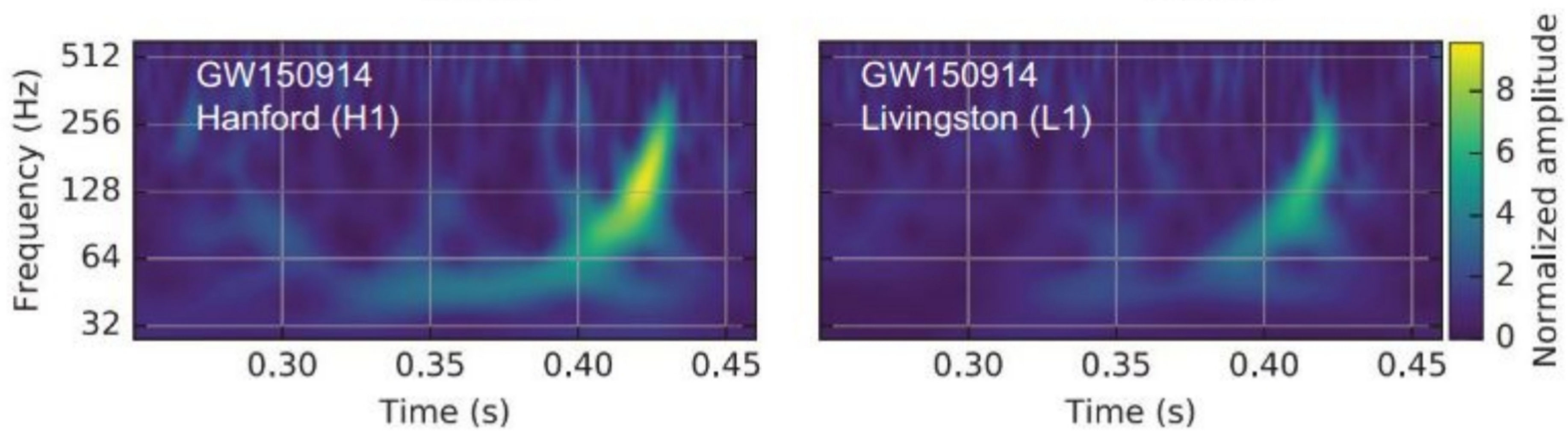


The “massive” event: GW190521



85 and 66 $M_\odot$ →144 $M_\odot$

Compared to the first event (36 and 29 $M_\odot$)



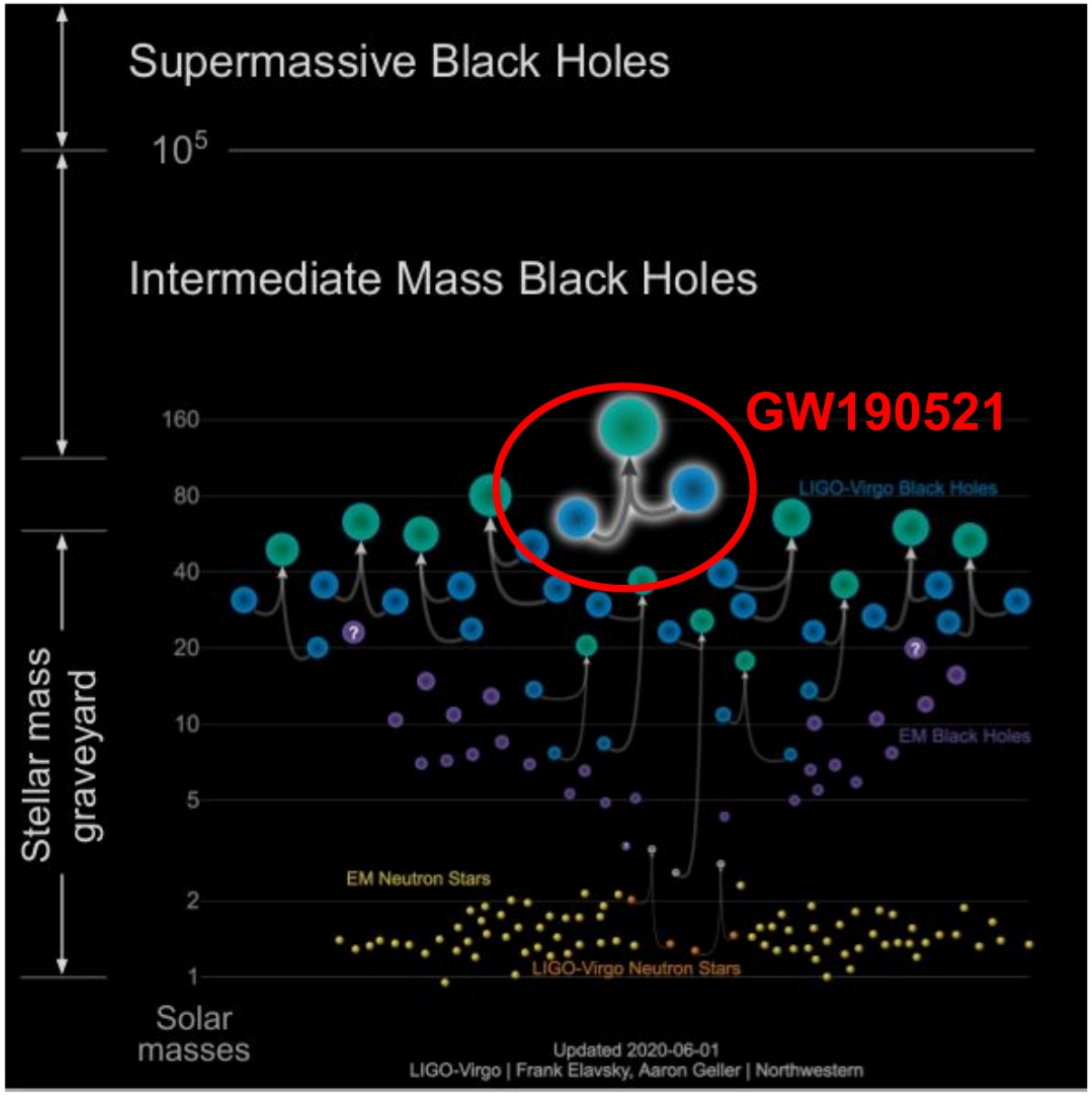
10

Spectrogram heat map computed using Q transform (Class.Quant.Grav. 21,S1809-S1818 (2004))

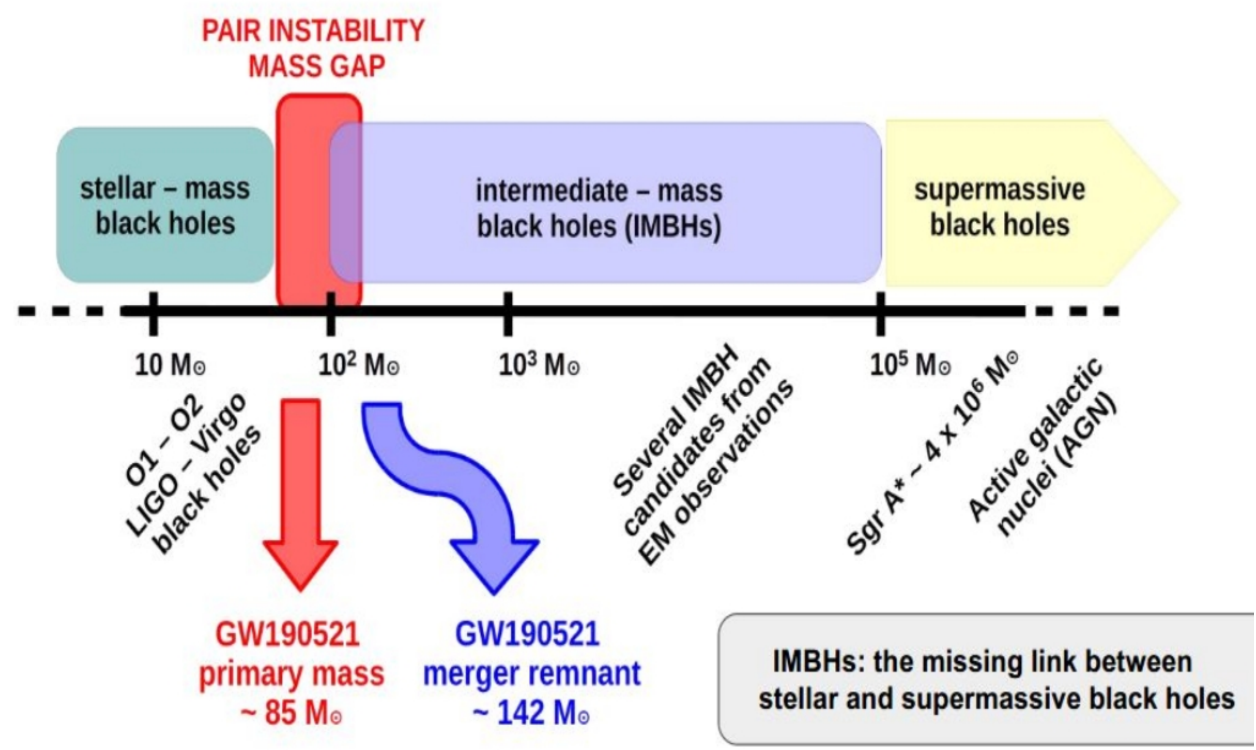
GW190521: very massive system, with component masses around 66 M☉ and 85 M☉, forming a remnant of about 142 M☉. The total mass is so large that the entire inspiral occurs below the sensitive band of current detectors — only the merger is visible, appearing as a single short burst with no chirp. ET's low-frequency sensitivity would track the full inspiral for minutes beforehand.

Slide adapted from L. D’Onofrio (An overview of the LVK observational science and results)

The “massive” event: GW190521



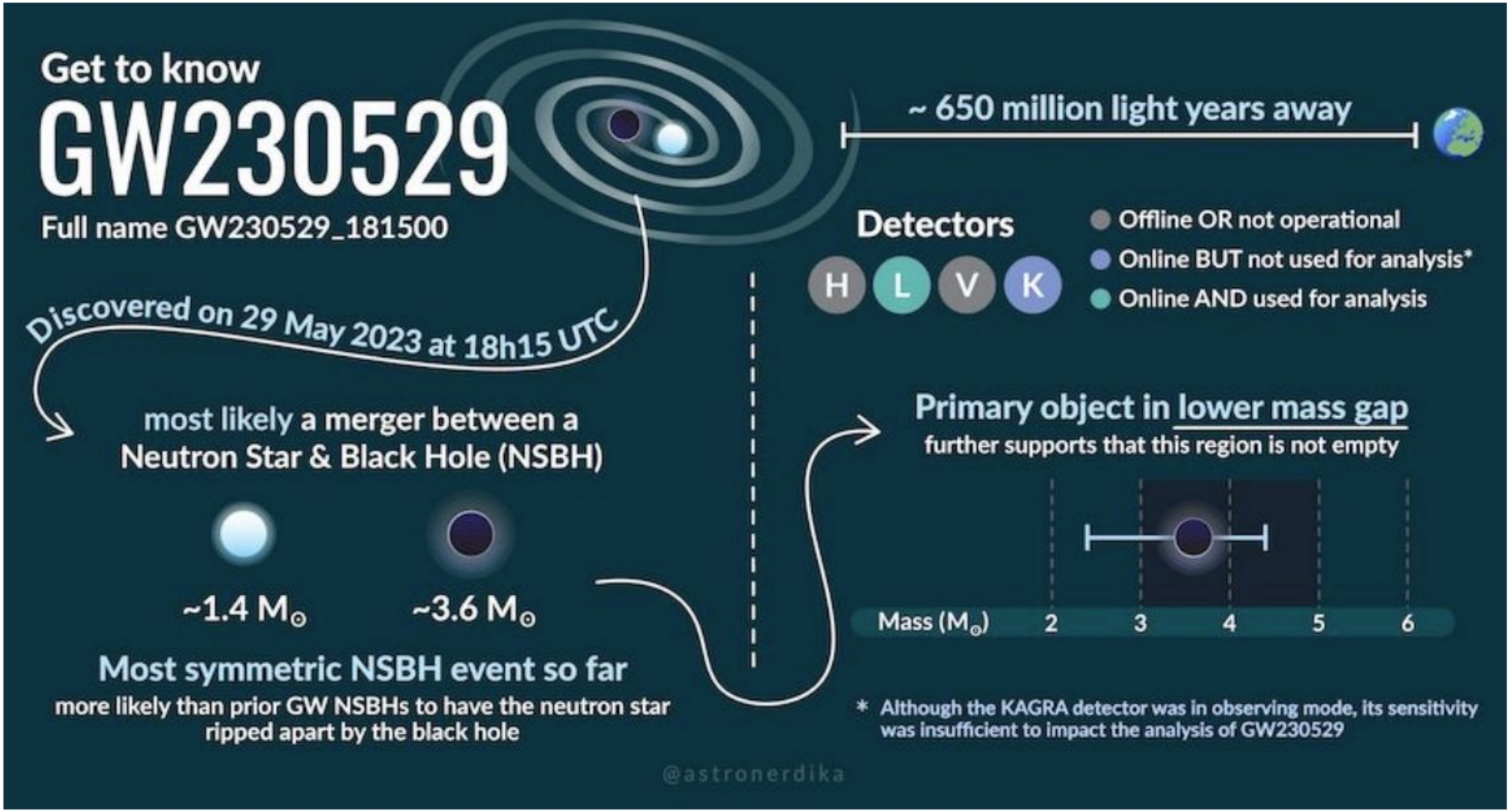
- First confident inference of an intermediate mass BH
- The primary mass falls in the Pair Instability mass gap → Challenges for stellar evolution



GW190521: the primary mass lies in the pair-instability mass-gap region, where standard stellar-evolution models predict strongly suppressed black-hole formation. The ∼142M⊙ remnant provided the first strong GW evidence for an intermediate-mass black-hole remnant. This motivates formation scenarios such as hierarchical mergers, dense stellar environments, very low metallicity evolution, or other channels.

Slide adapted from L. D’Onofrio (An overview of the LVK observational science and results)

First O4 result: GW230529



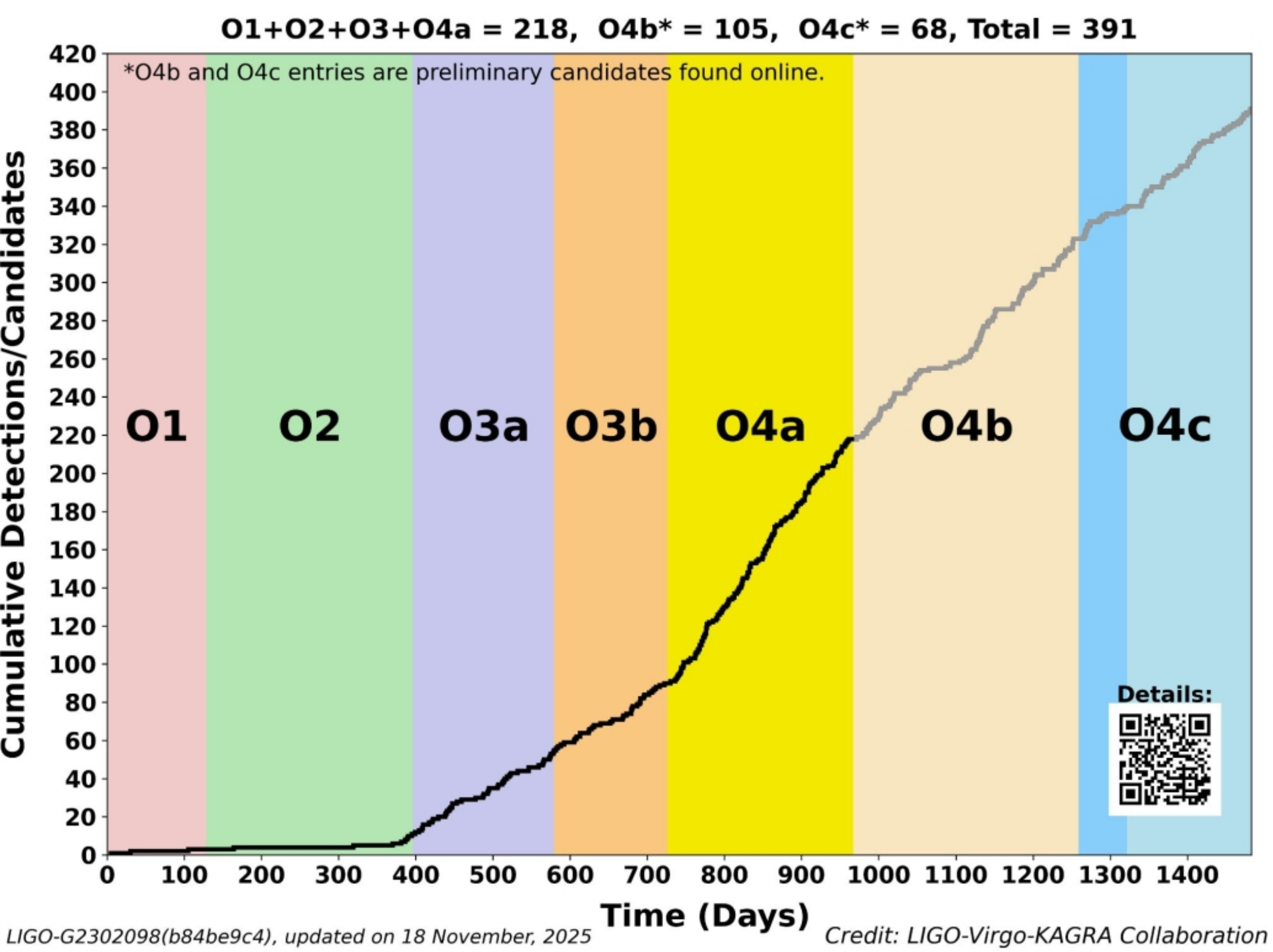
GW230529: likely neutron-star–black-hole merger with a compact object of ∼3.6M⊙, lying in the so-called lower mass gap between typical neutron-star and black-hole populations.

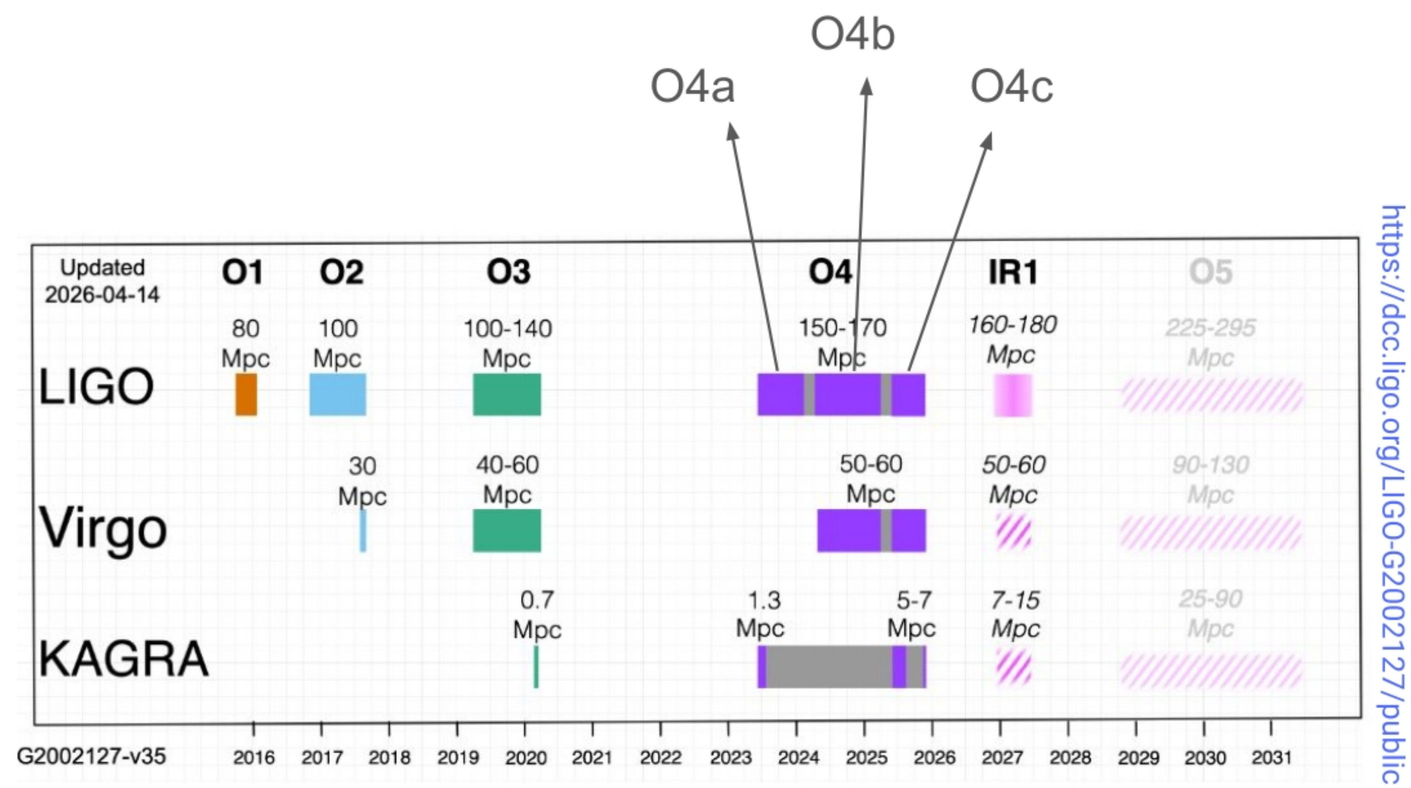
This event suggests that the lower mass gap may not be empty and highlights the importance of future observations for understanding compact-object formation and dense-matter physics.

The relatively symmetric masses also increase the possibility of tidal disruption and electromagnetic emission, making such systems especially interesting for multimessenger astronomy.

Slide adapted from L. D’Onofrio (An overview of the LVK observational science and results)

Runs and Detections

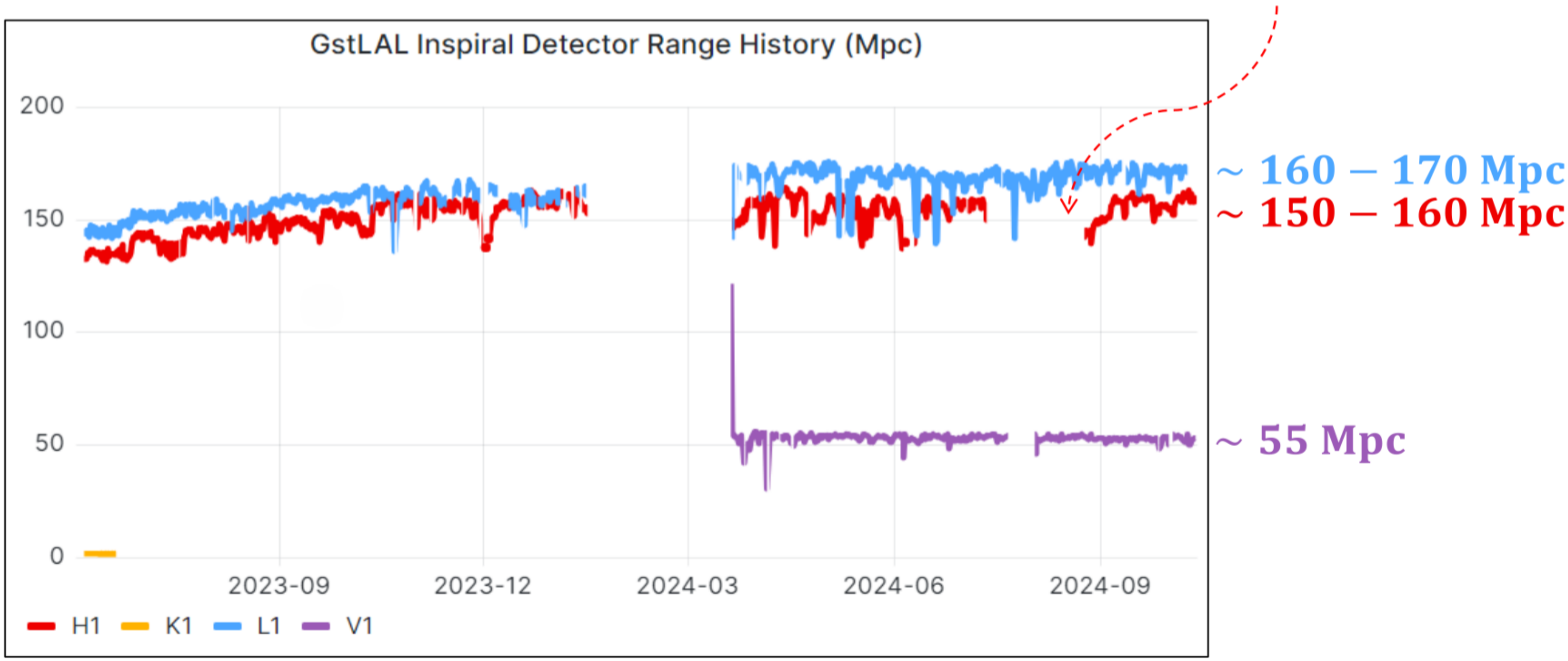




O4 run

First part (O4a) from May 2023 to Jan 2024
- Joint observation of LIGO H + L (+ KAGRA the first 4 weeks) → 53% HL uptime

Second part (O4b) from Apr 2024 to Jun 2025
- Virgo joined the run (+ KAGRA at the end) → 45% HLV uptime (excluding breaks)



Slide adapted from L. Pierini (The Virgo experiment and the hunt for gravitational waves: status, recent results and prospects)

O4 run

Observing Run 4 (O4):

- Started on 24th May 2023
- Maintenance/commissioning break from 1st April - 11th June 2025
- Ending on 18th November 2025

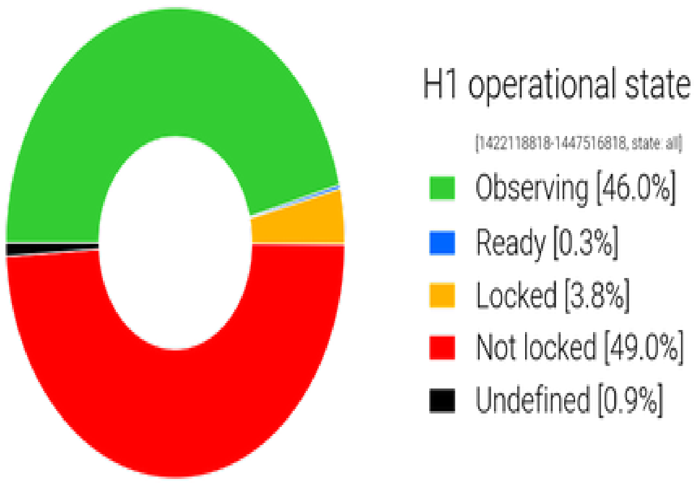
Run	Date range	Time span
O4a	2023-05-24 2024-01-16	7.7 months
O4b	2024-04-10 2025-01-28	9.5 months
O4c	2025-01-28 2025-11-18	9.5 months

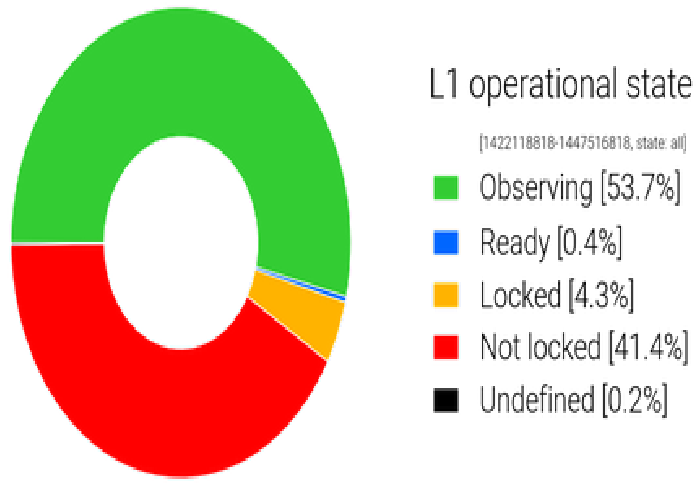
- Binary Neutron Stars (BNS) range: the farthest distance at which the detector would have an SNR of 8 for BNS

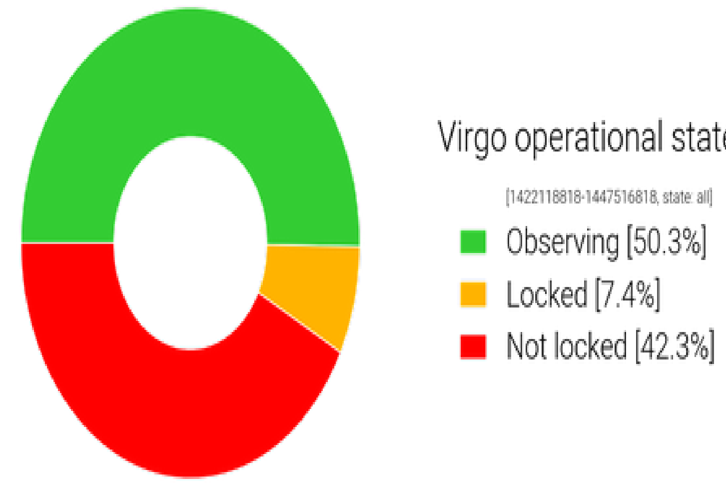
https://observing.docs.ligo.org/plan/

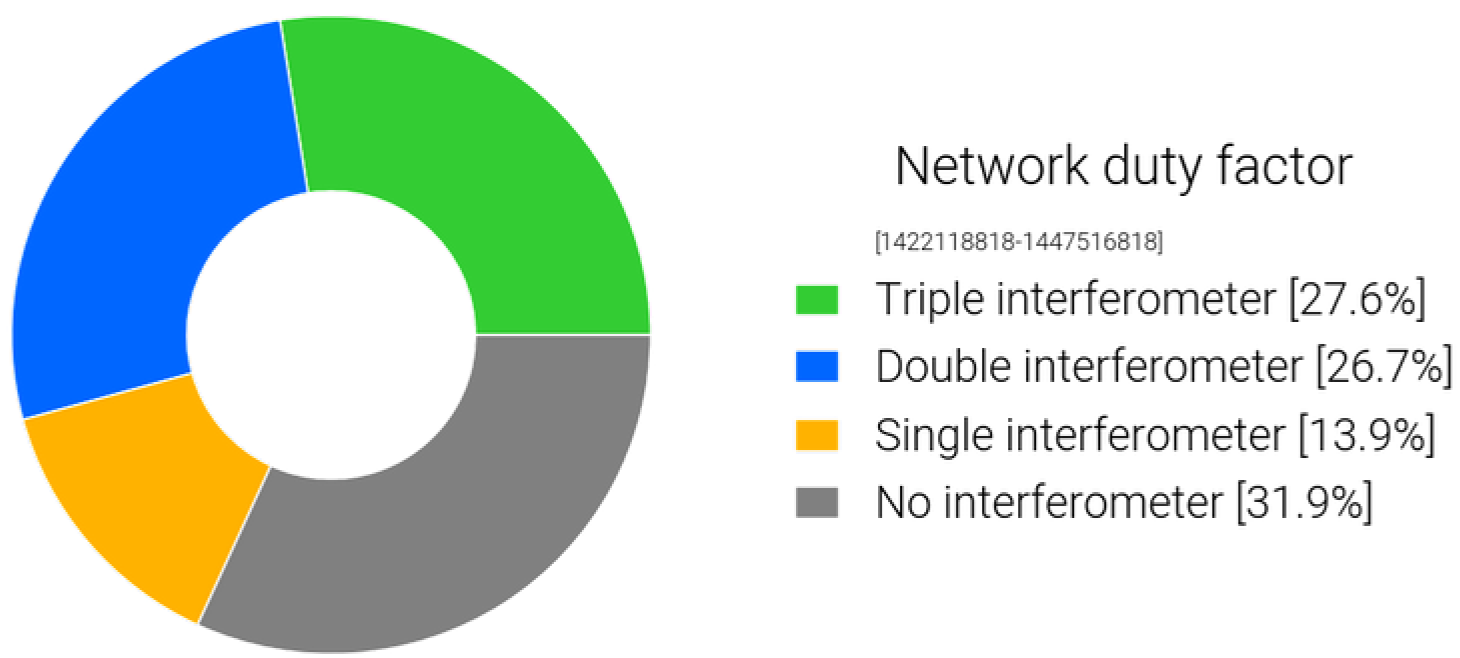
Slide adapted from M. Di Cesare (Status of the O4 run and latest non-CBC results)

Status of the O4c run



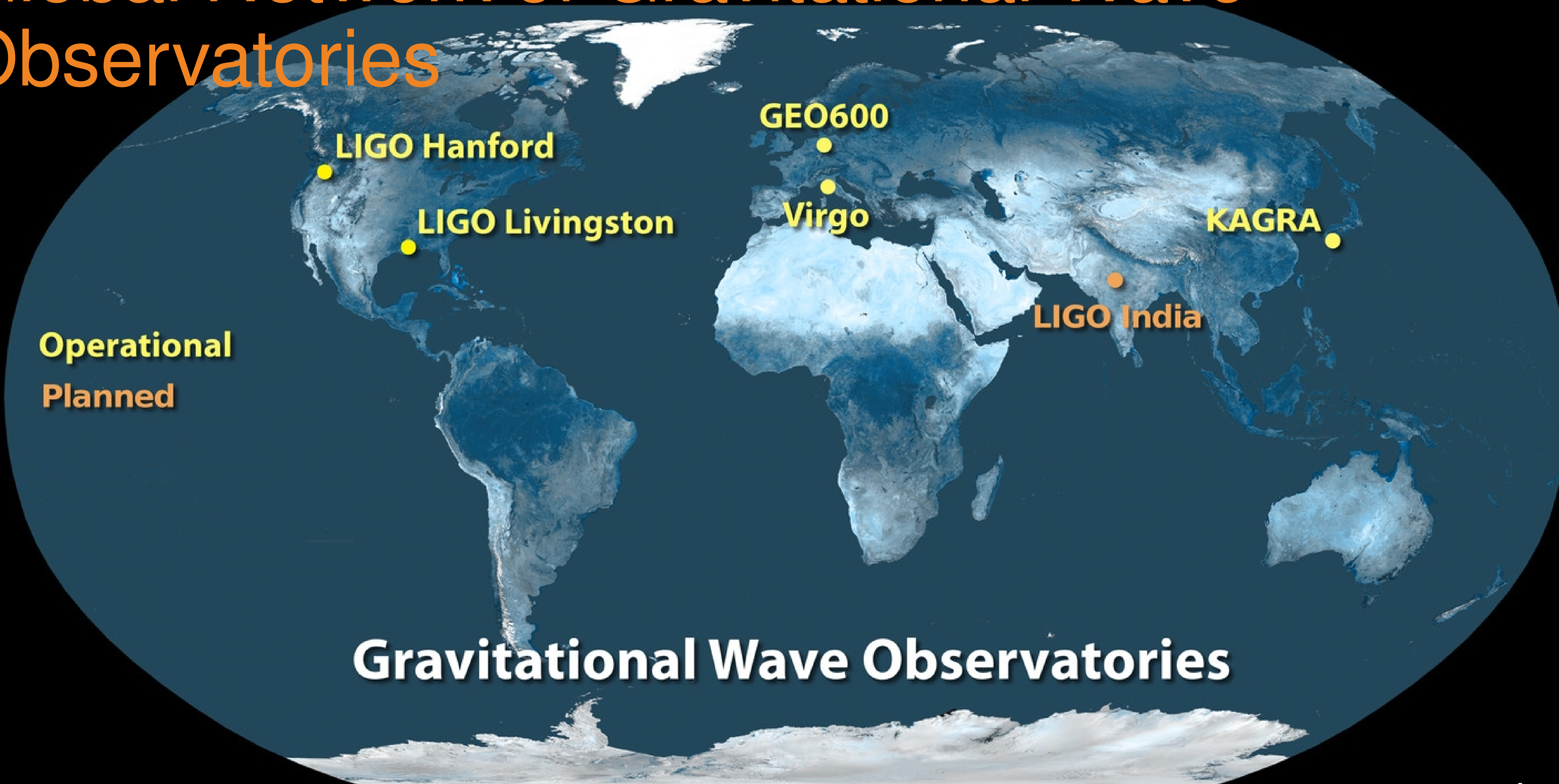






https://gwosc.org/detector_status/O4c/

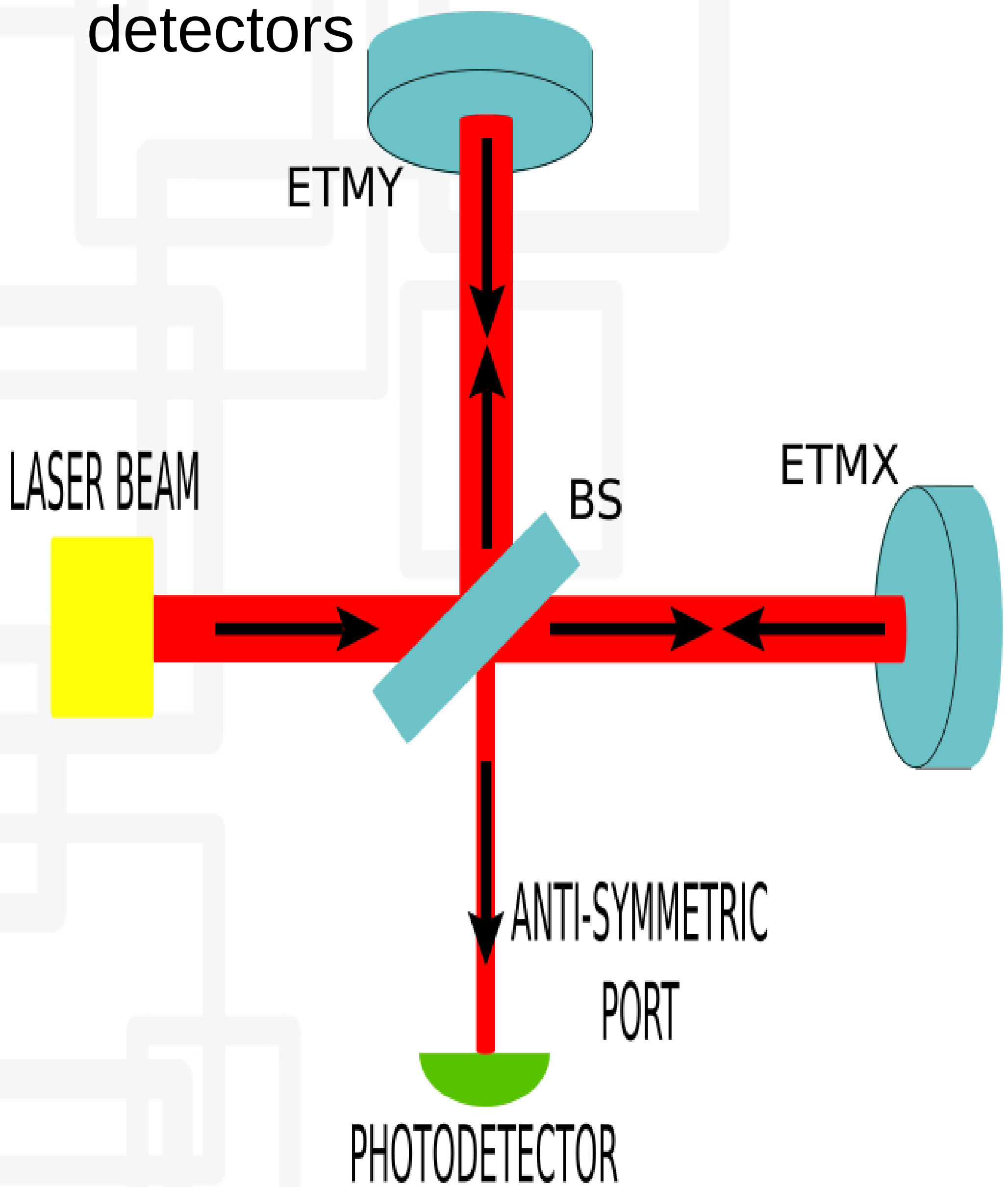
Global Network of Gravitational Wave Observatories

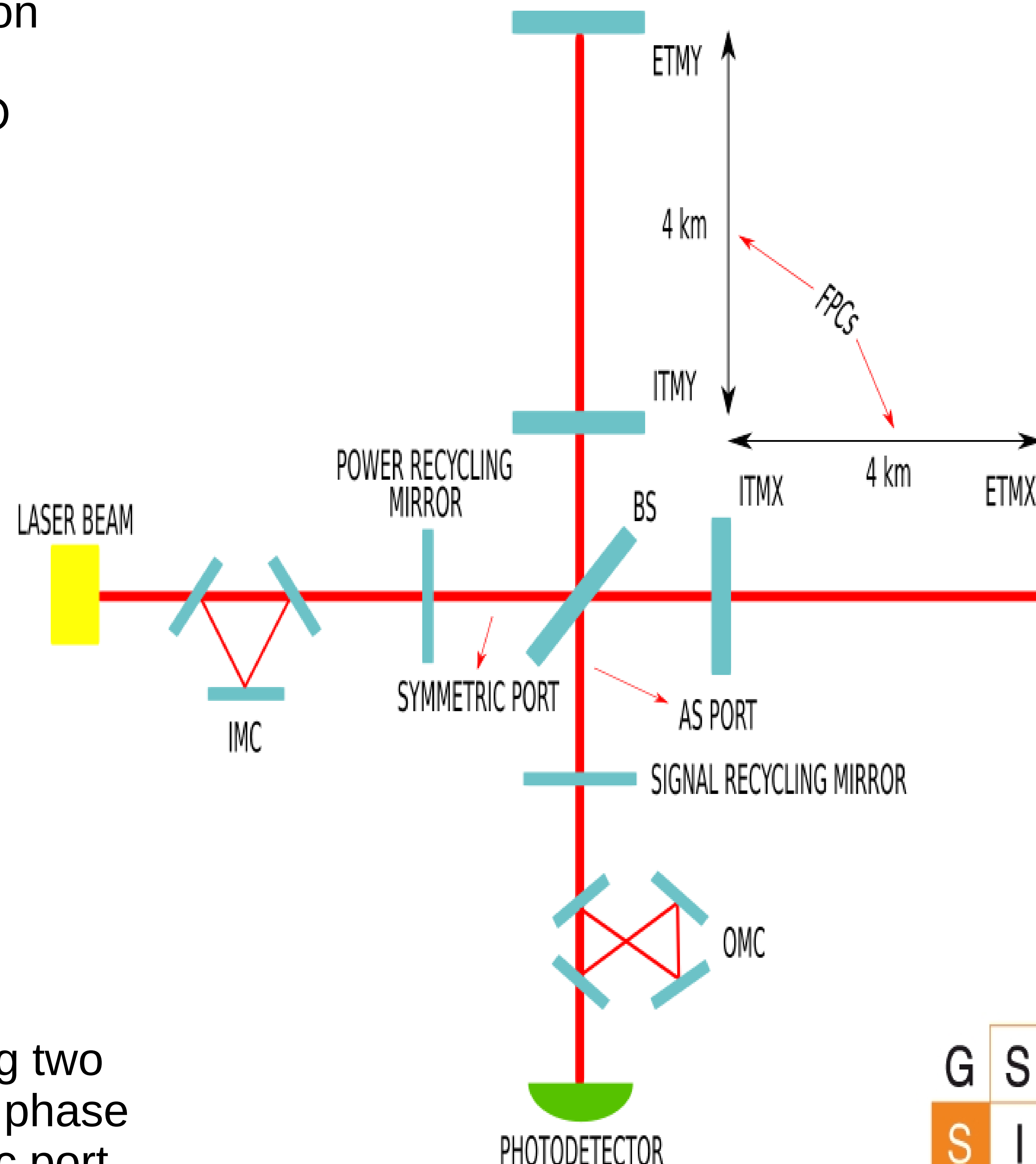


>2600 members!!

Gravitational Wave Detectors

- Dual-recycled Fabry-Perot-Michelson interferometer
- Simplified optical layout of the LIGO detectors



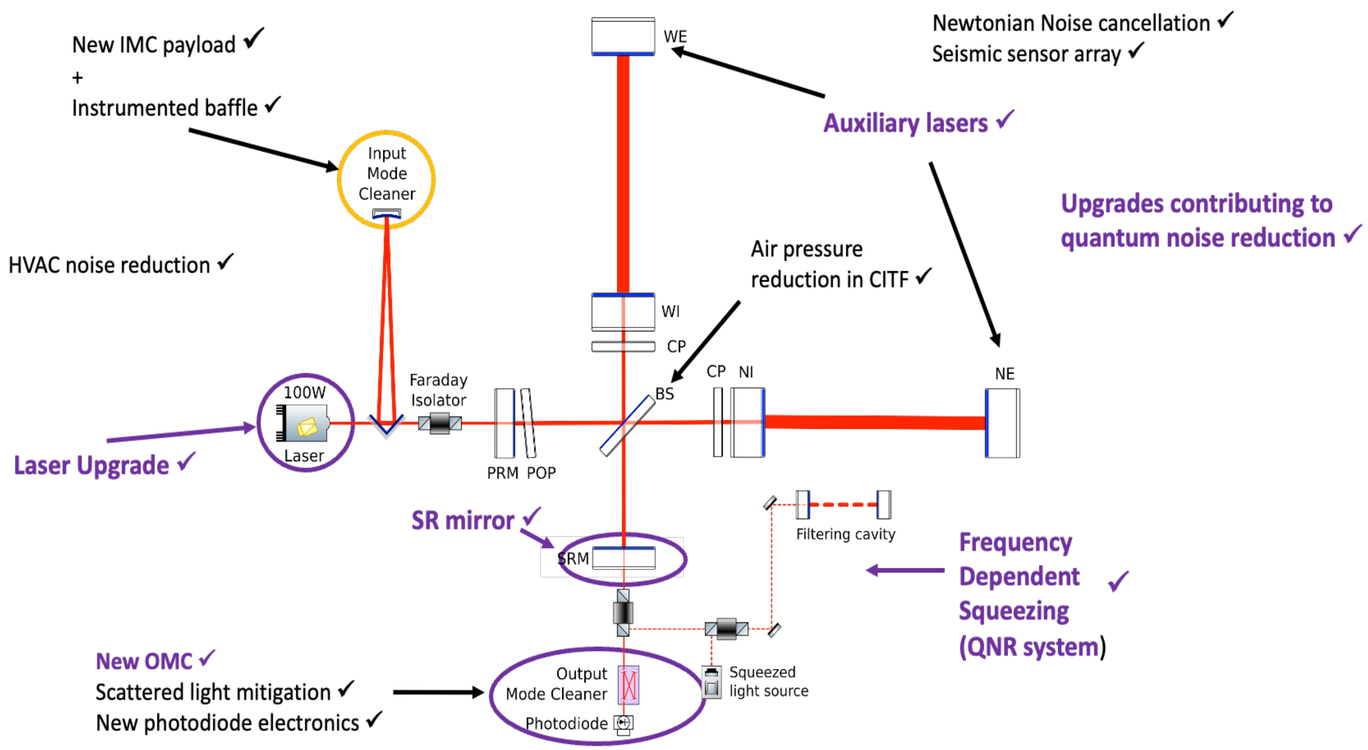


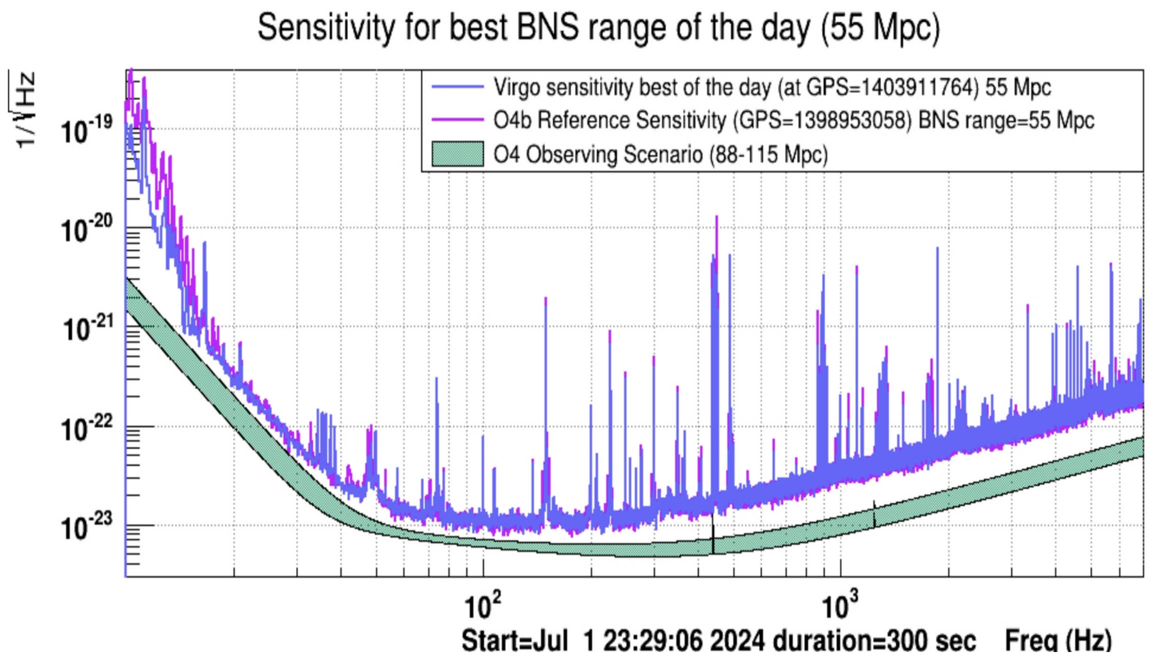
- Two coherent light beams travel along two perpendicular arms, then the relative phase shift is measured at the antisymmetric port

Virgo

https://www.virgo-gw.eu/about/scientific-collaboration/.

- Collaboration Size: The Virgo Collaboration consists of approximately 880 members from about 152 institutions in 17 different (mainly European) countries. This number can fluctuate slightly, but your figures are broadly correct.
- Detector Host & Location: The Virgo detector is a 3-km arm-length interferometer hosted by the European Gravitational Observatory (EGO) located in Cascina, near Pisa, Italy.
- The Advanced Virgo+ Phase I upgrade focuses on reducing quantum noise and increasing the laser power; Phase II aims to further enhance sensitivity, particularly at lower frequencies, by tackling coating thermal noise and other limitations



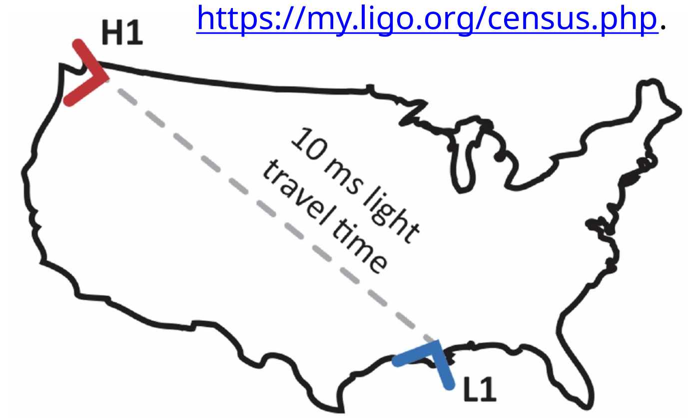


- Virgo didn't join O4a: continued commissioning activities; joined O4b later
- Stable and reproducible control of interferometer mostly achieved in fall 2022: Lowering input power from nominal 40 W to 18 W (currently), new thermal actuator to correct power-recycling mirror curvature, deal with signal-recycling cavity with resonating higher-order modes….
- Recycling cavities are in marginally stable configuration, making the detector very sensitive to aberrations and thermal effects. This negatively impacts controllability of the instrument, and thus commissioning complexity and schedule

Slide adapted from L. Seglar-Arroyo (Status of the gravitational-wave interferometers LIGO-Virgo-KAGRA)

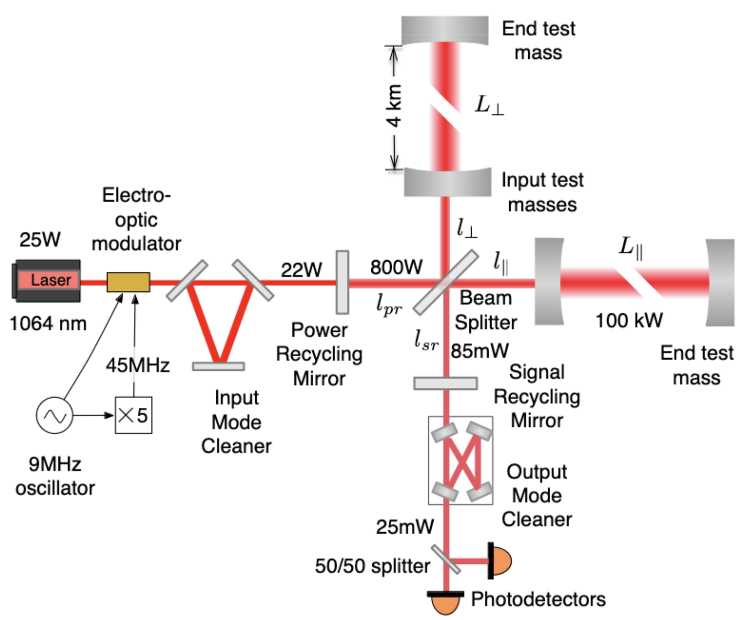
LSC LIGO Scientific Collaboration

LIGO

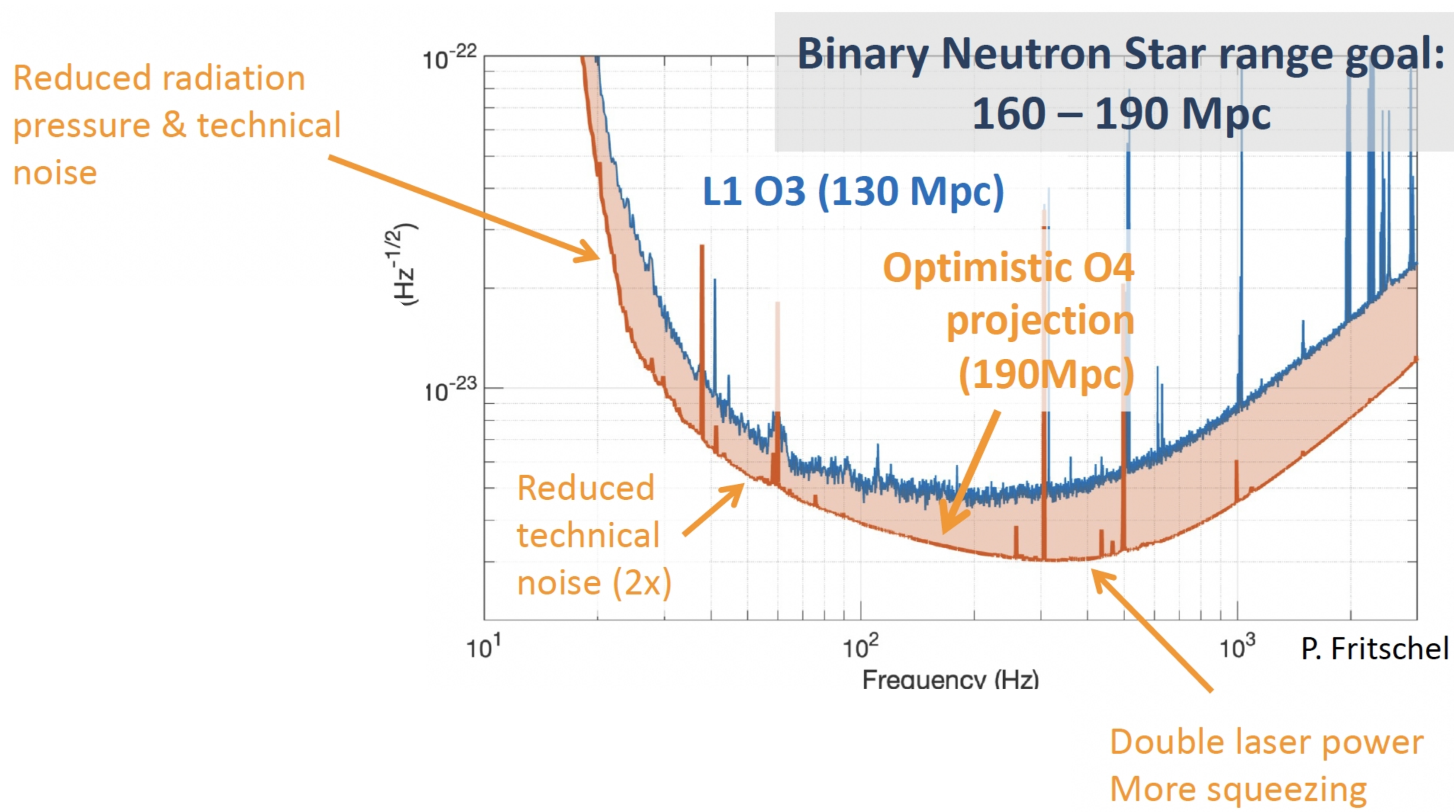


- Two 4-km interferometric gravitational wave detectors in USA
- Funded by US NSF, operated by Caltech and MIT, with contributions from Germany, UK and Australia
- More than 1,600 scientists from around the world participate in the effort through the LIGO Scientific Collaboration, which includes the GEO Collaboration.
- Some of the goals for O4:
  - 400 kW circulating arm power (Compare to 200 kW in O3)
  - Squeezed light efficacy: cca 5.5-6 dB (2-3 dB in O3)
  - 300 m filter cavity for frequency dependent squeezing
  - Low frequency technical noise reduction (below 100 Hz): Scattered light, control, electronics

From G. Vajente



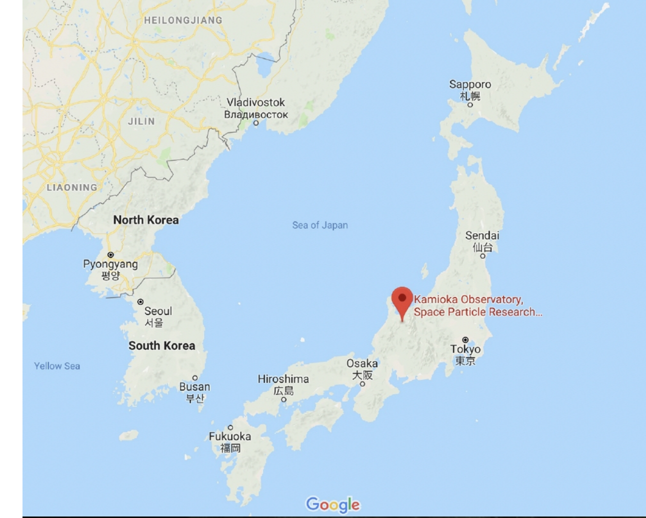
Phys. Rev. D 93, 112004

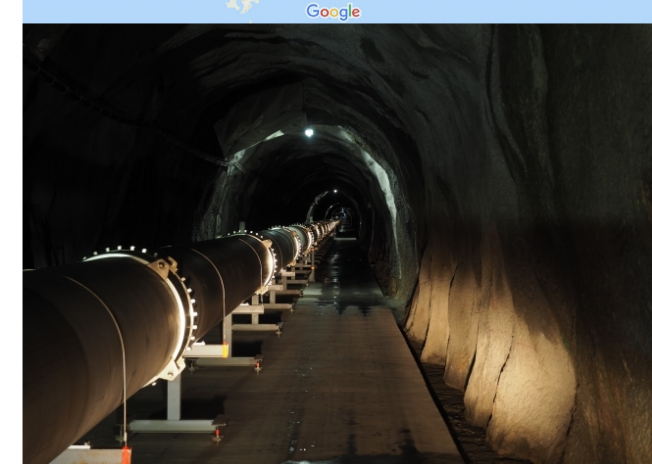


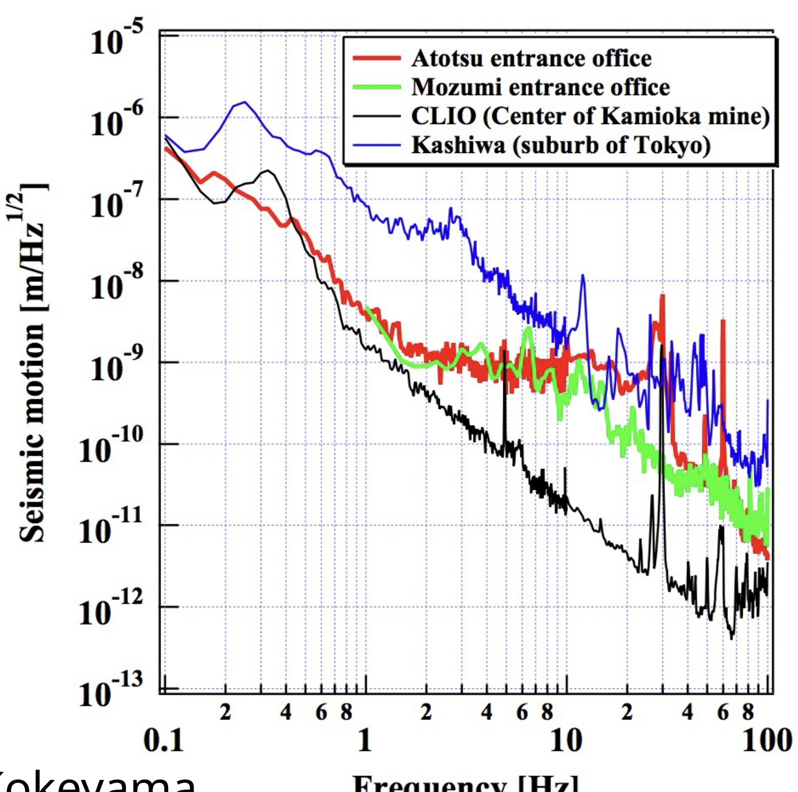
Slide adapted from L. Seglar-Arroyo (Status of the gravitational-wave interferometers LIGO-Virgo-KAGRA)

KAGRA

- 3 km arm-length interferometer, placed deep under the Kamioka mines : underground to reduction seismic motion
- Host institute is ICRR, co-hosted by NAOJ and KEK
- The KAGRA Scientific Collaboration (KSC) is a large international group. As of early 2025, the numbers are typically cited as over 480 active members from more than 150 institutions in 18 countries/regions
- Test masses: Sapphire at~20K. Fused silica for room temperature auxiliary mirrors.
- Some of the goals for O4: Suspension sensing and control, suppressing scattered light with baffles, SRM replacement, improve low-frequency region
- Joined O4a for a month before going back to commissioning.
- Rejoined O4b in late 2024







From K. Kokeyama

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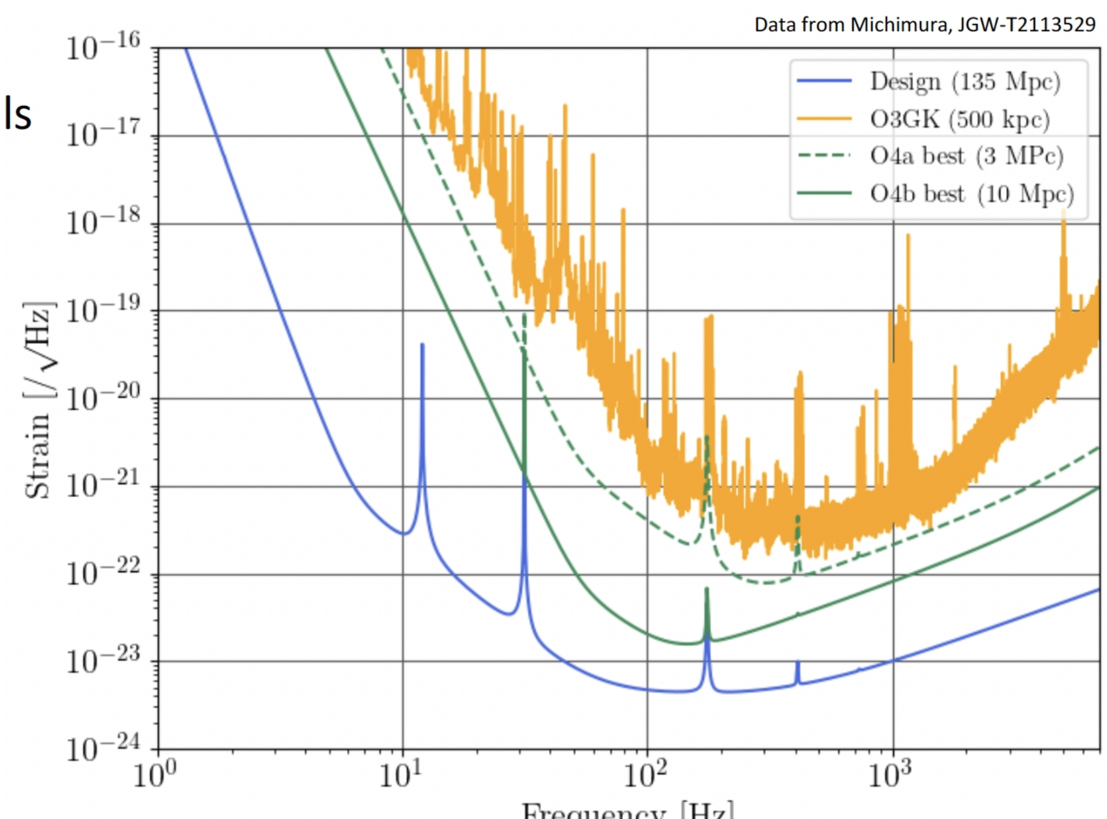
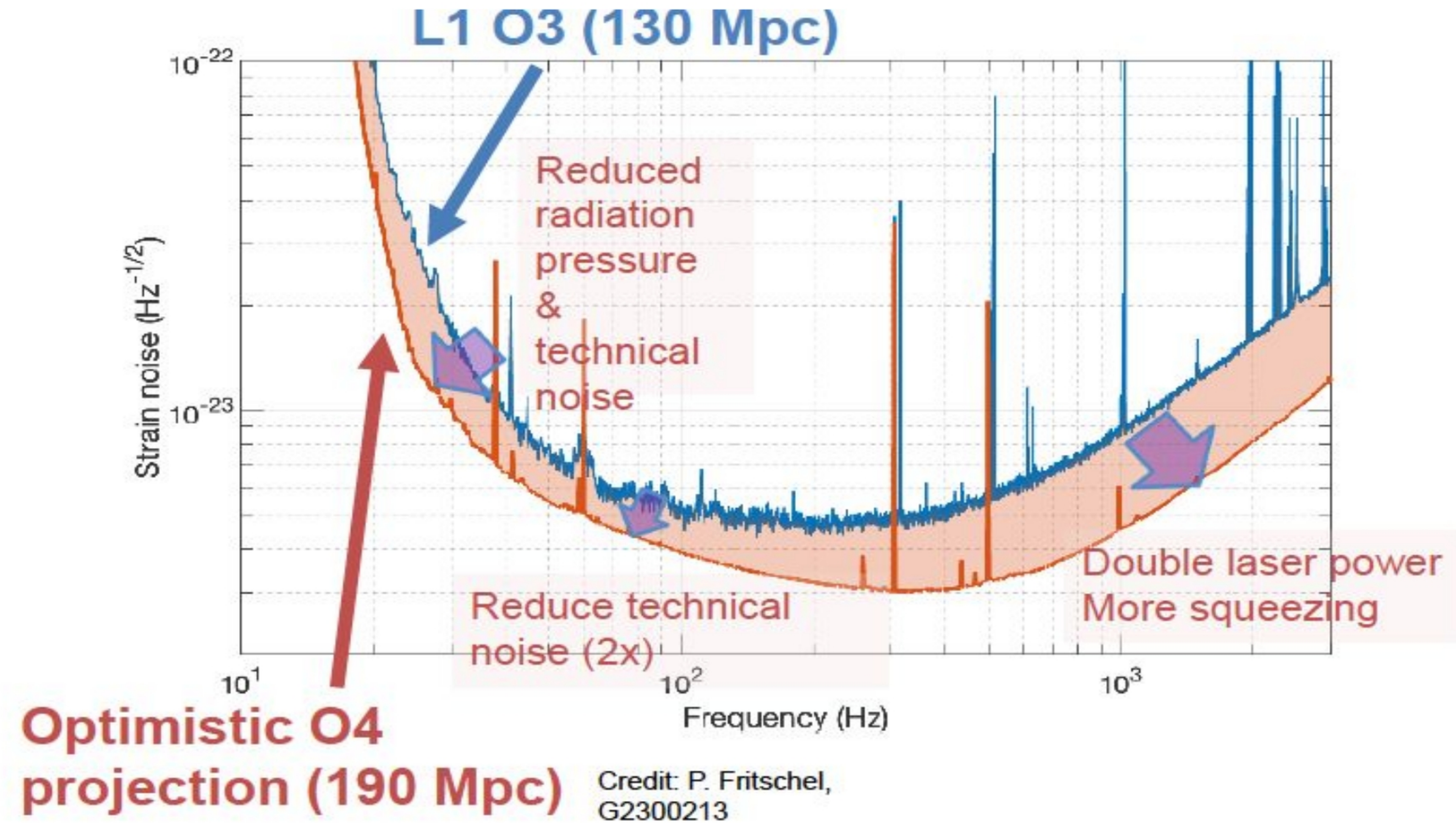


Slide adapted from L. Seglar-Arroyo (Status of the gravitational-wave interferometers LIGO-Virgo-KAGRA)

Upgrades for O4 & O5: ALIGO+



Slide taken from F. Sorrentino (LVK detectors status and future plans)

The new plans for O5

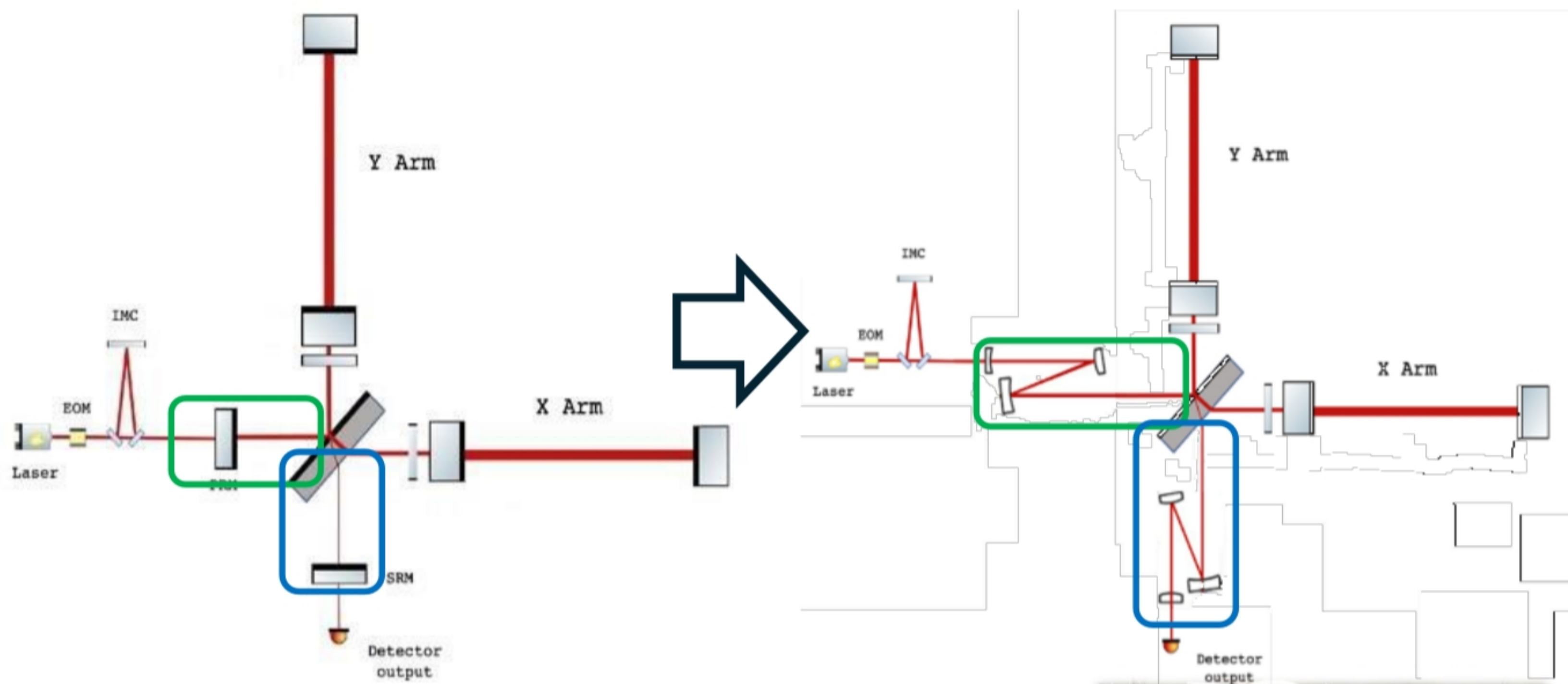
Original plans:

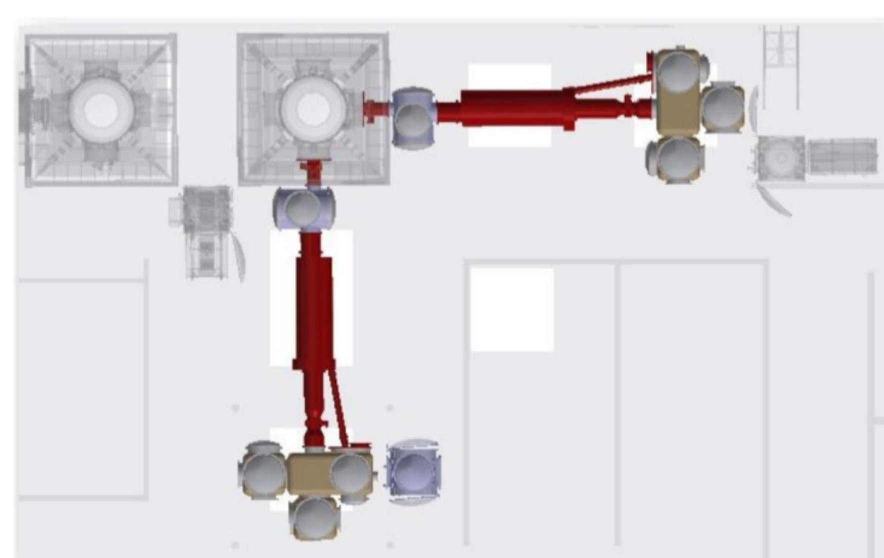
- Install heavier end test mirrors, enlarge the beam size.
- Better coatings.
- Increase input power up to 80W.

  ↳ Hard/impossible with marginally stable cavities!

Current plan:

- PRIORITY: Install stable (folded) cavities, at the cost of a later start of O5. It implies the removal and substitution of some big vacuum chambers.
- Postpone the installation of heavier test mirrors at post-O5.





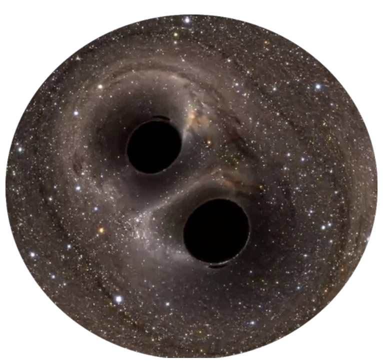
Slide adapted from L. Pierini (The Virgo experiment and the hunt for gravitational waves: status, recent results and prospects)

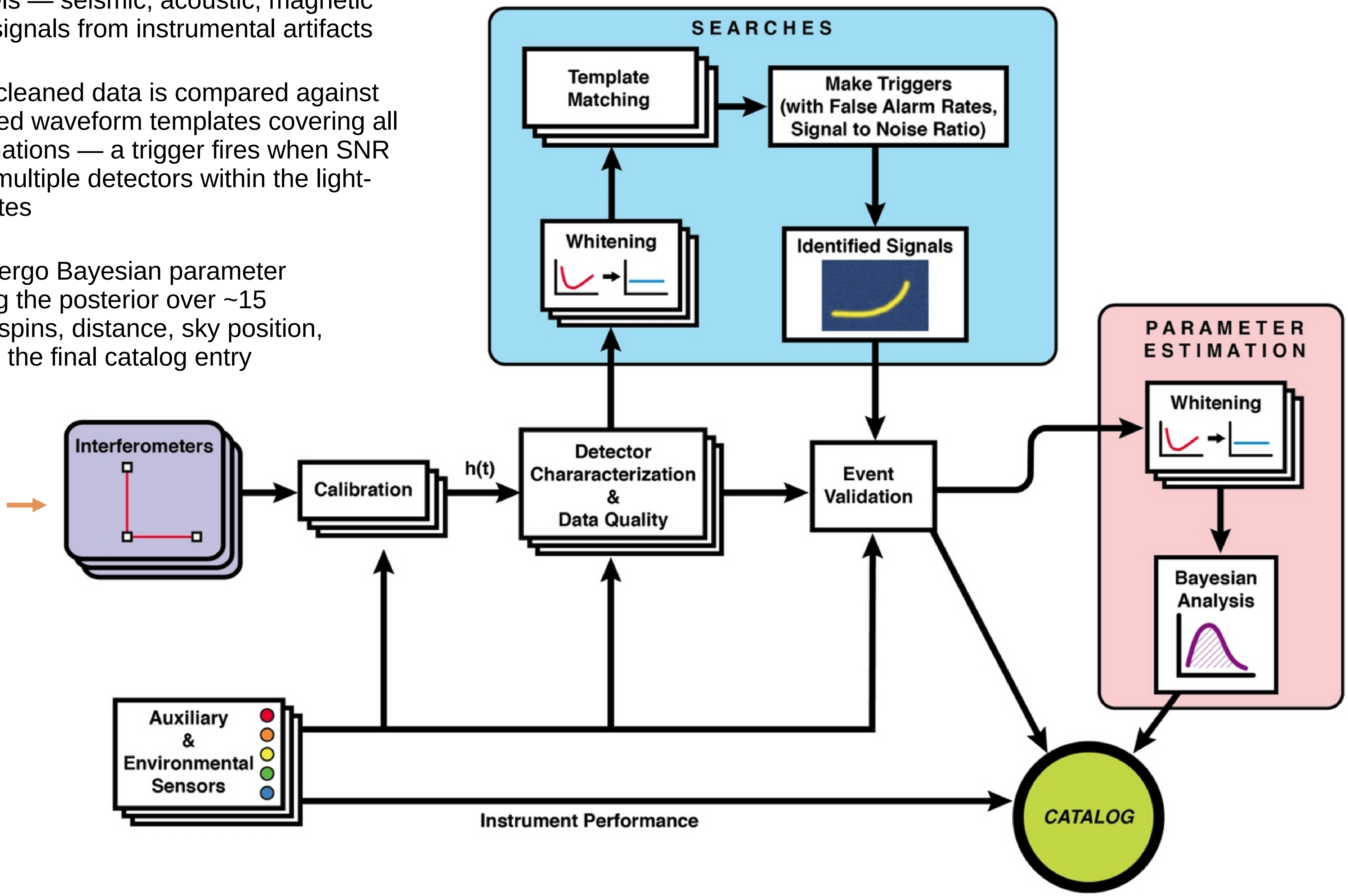
LVK framework

Raw detector output h(t) is whitened and cleaned using auxiliary sensors that monitor thousands of environmental channels — seismic, acoustic, magnetic — to distinguish GW signals from instrumental artifacts

Matched filtering: the cleaned data is compared against ~1 million pre-computed waveform templates covering all possible mass combinations — a trigger fires when SNR exceeds threshold in multiple detectors within the light-travel time between sites

Surviving triggers undergo Bayesian parameter estimation — sampling the posterior over ~15 parameters (masses, spins, distance, sky position, inclination) to produce the final catalog entry

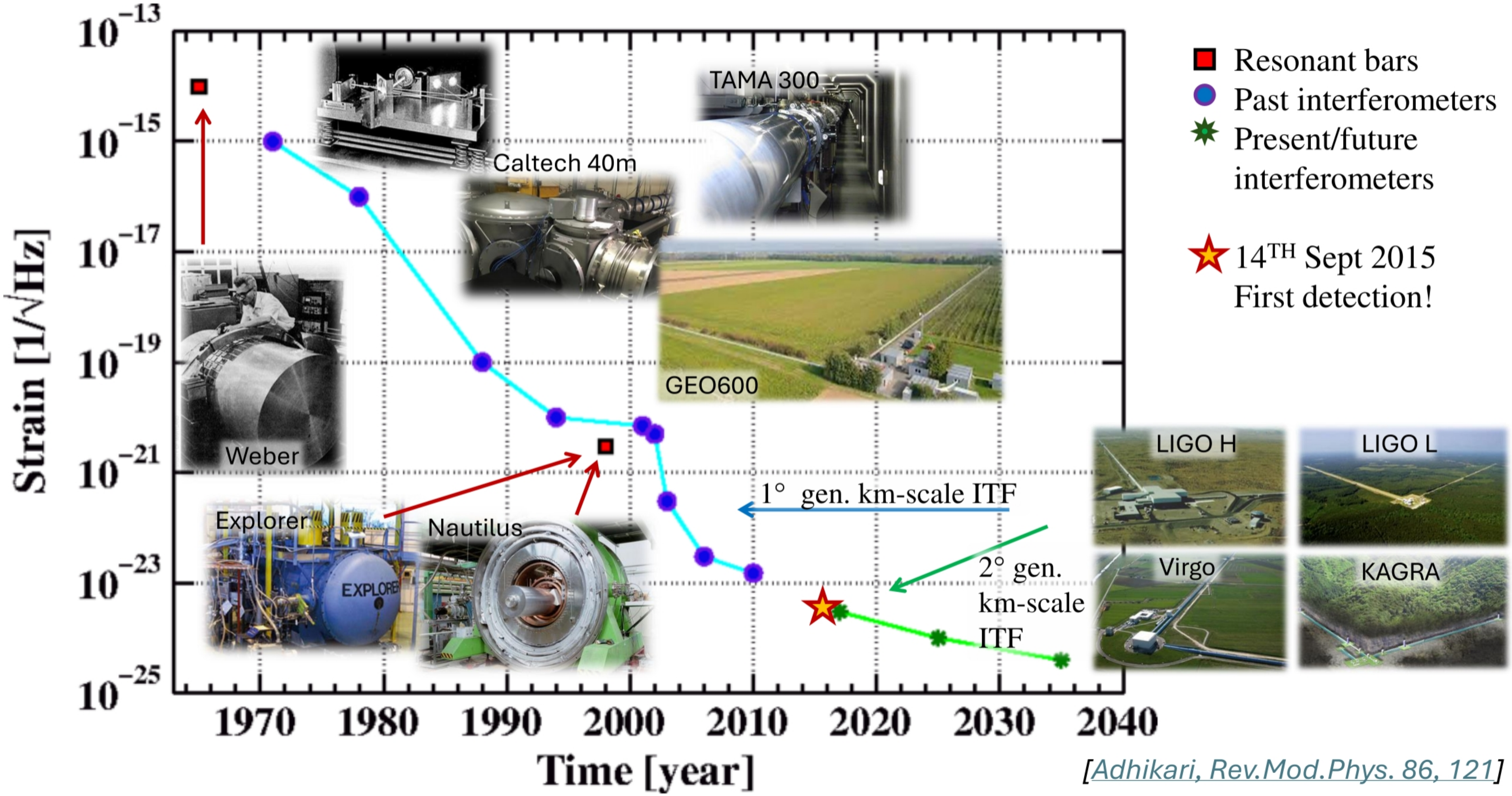




Modified from Davis, D.; Walker, M., *Galaxies* **2022**, *10*, 12.

Slide adapted from L. Seglar-Arroyo (Status of the gravitational-wave interferometers LIGO-Virgo-KAGRA)

The long journey of the hunt for gravitational waves



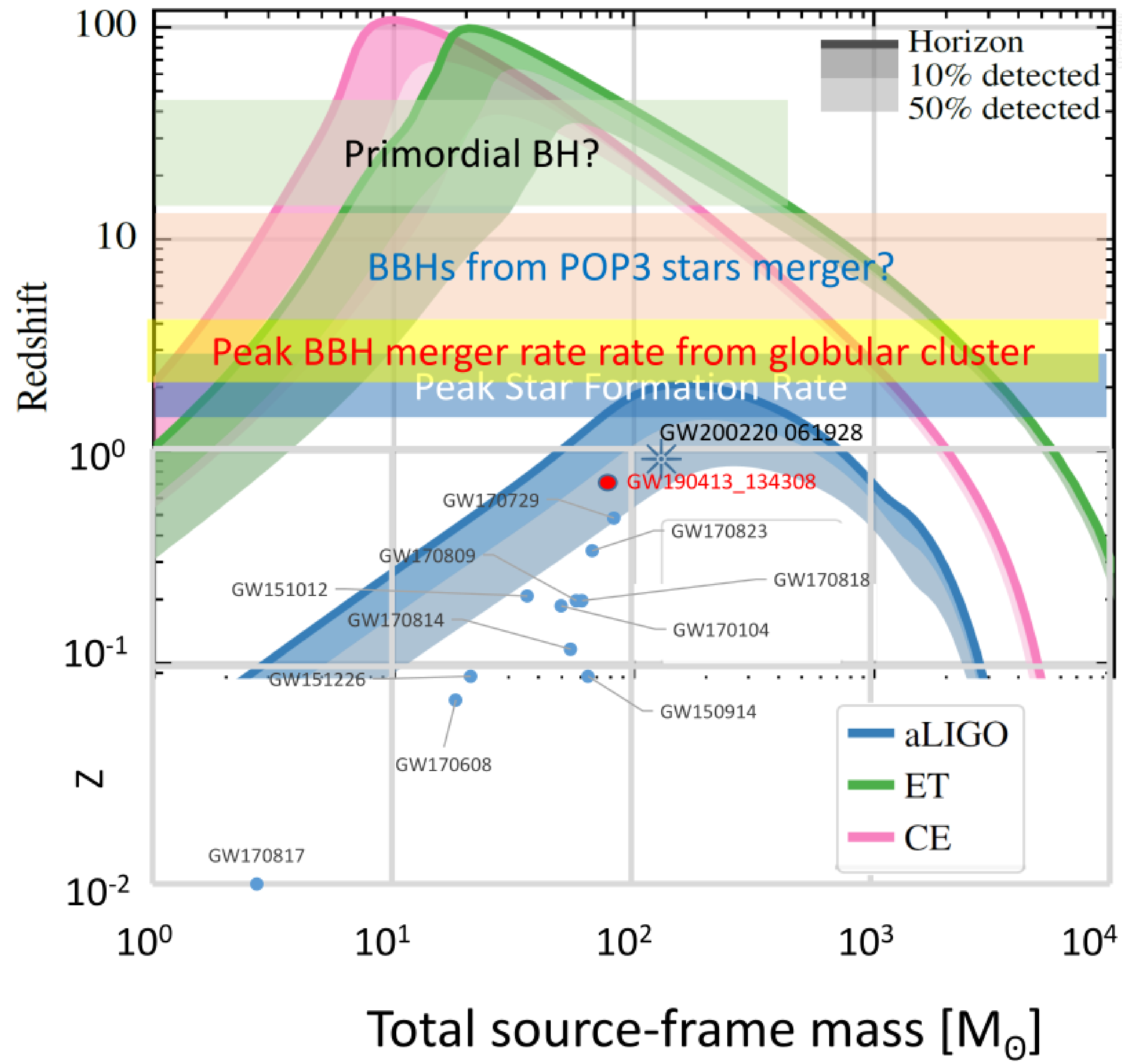
[Adhikari, Rev.Mod.Phys. 86, 121]

ISB’s main goal:
Set this new sensitivity record

Slide adapted from L. Pierini (The Virgo experiment and the hunt for gravitational waves: status, recent results and prospects)

Why Current Detectors Are Not Enough

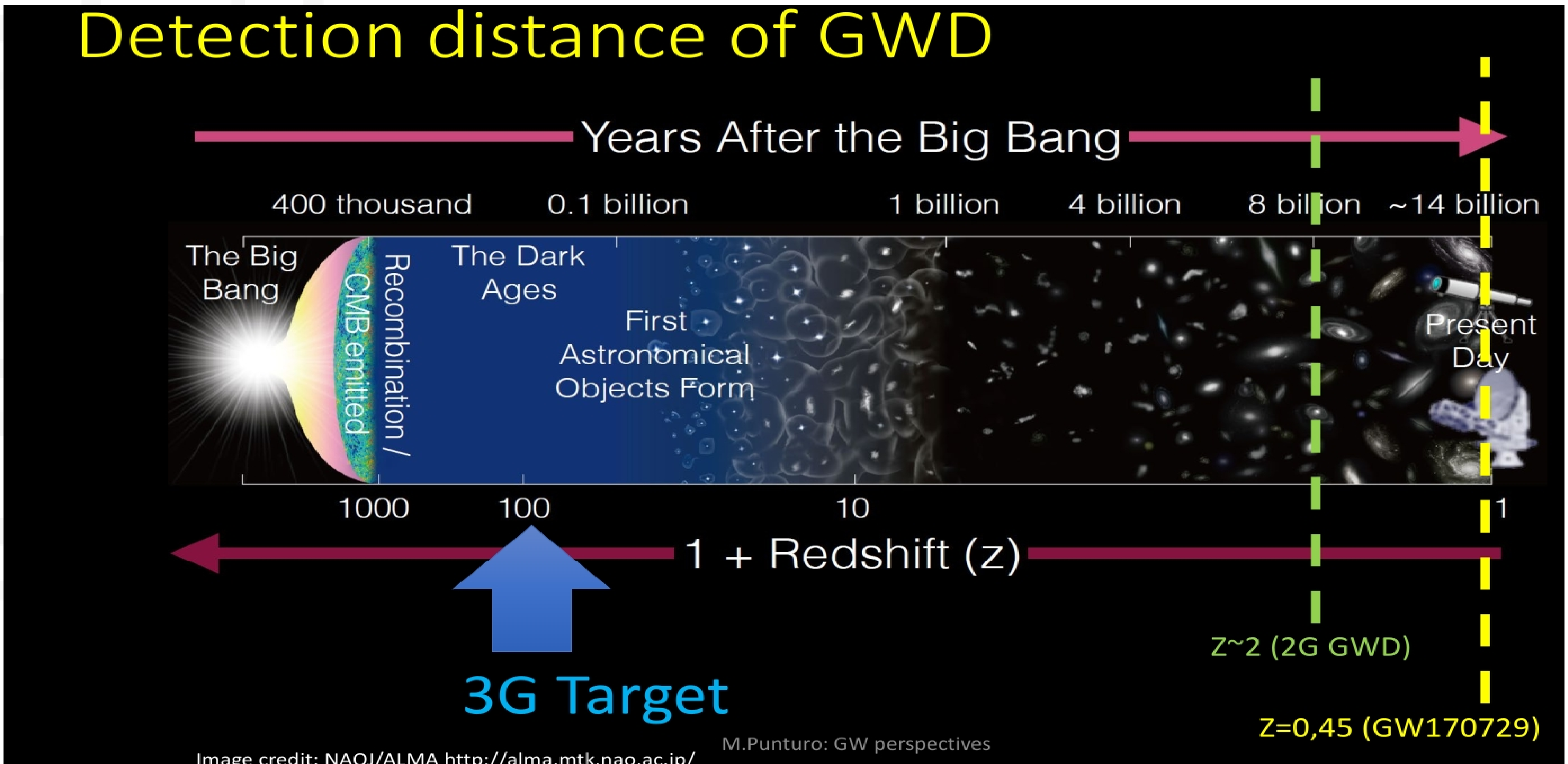
- 2G detectors mainly probe the nearby Universe: BNS systems to z∼0.1, and stellar-mass BBHs to moderate redshift
- ET extends GW observations deep into cosmic history, reaching z≳20 for favorable BBH populations
- Colored regions indicate key science targets that become accessible primarily with 3G detectors
- The peak star-formation epoch (z∼2) is only partially accessible to current detectors
- Population III black-hole remnants may become observable only with 3G detectors
- Very high-redshift mergers could provide evidence for primordial black-hole populations
- A factor of 10 in strain sensitivity corresponds to roughly a factor of 1000 in surveyed volume
- Current detectors are approaching infrastructure and environmental limits — ET is not simply an upgrade, but a new observatory



Adapted from M. Punturo (Einstein Telescope and the 3rd Generation GW Observatories: Science, Technologies and Perspectives)

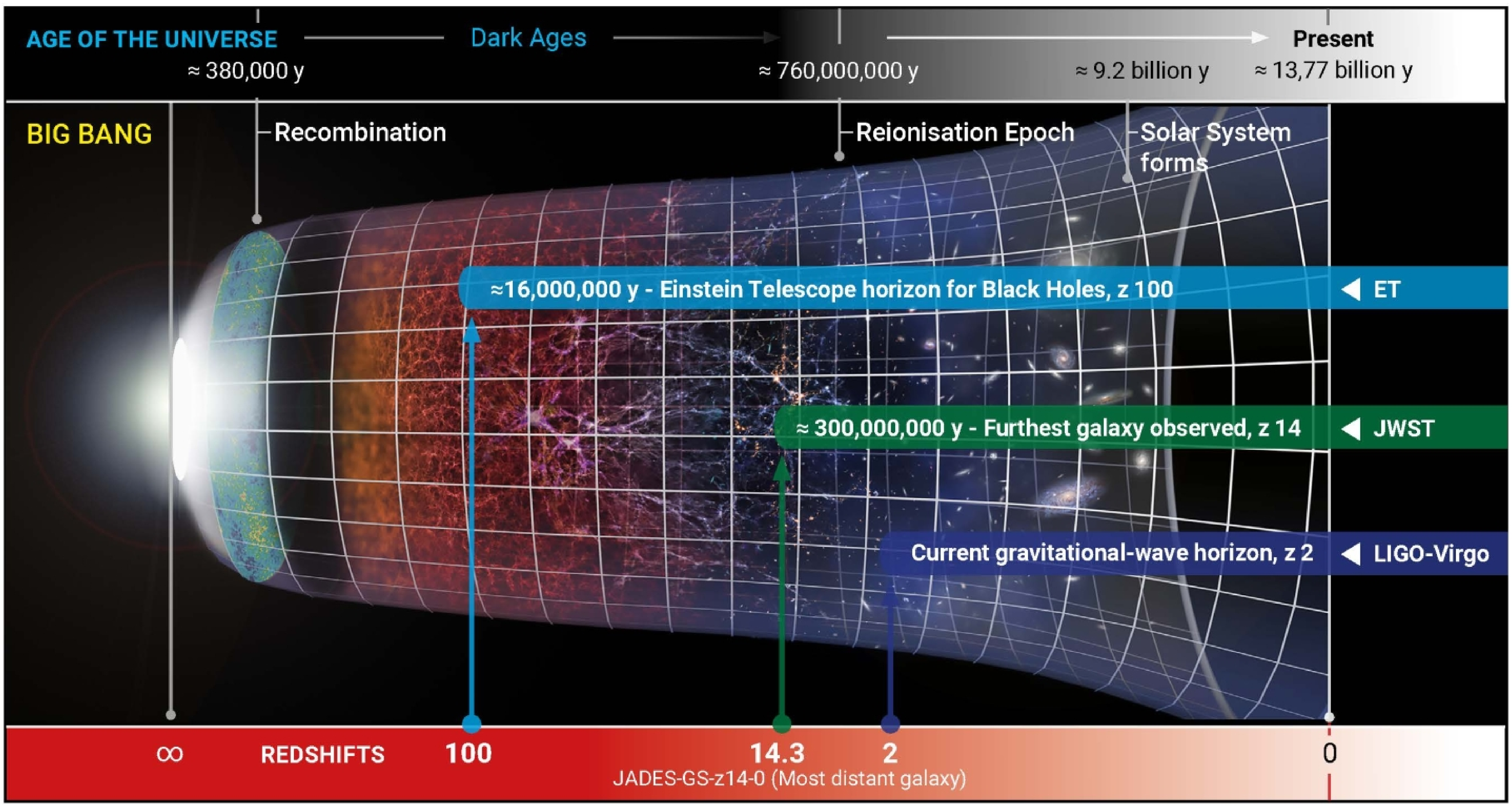
The Third-Generation Goal

- Current 2G detectors mainly probe the nearby and intermediate-redshift Universe
- 3G detectors aim to observe compact binaries across nearly the entire history of cosmic structure formation
- Gravitational waves provide access to epochs and environments inaccessible to traditional electromagnetic astronomy
- ET is not simply an upgrade in sensitivity — it transforms gravitational-wave astronomy into a cosmological probe

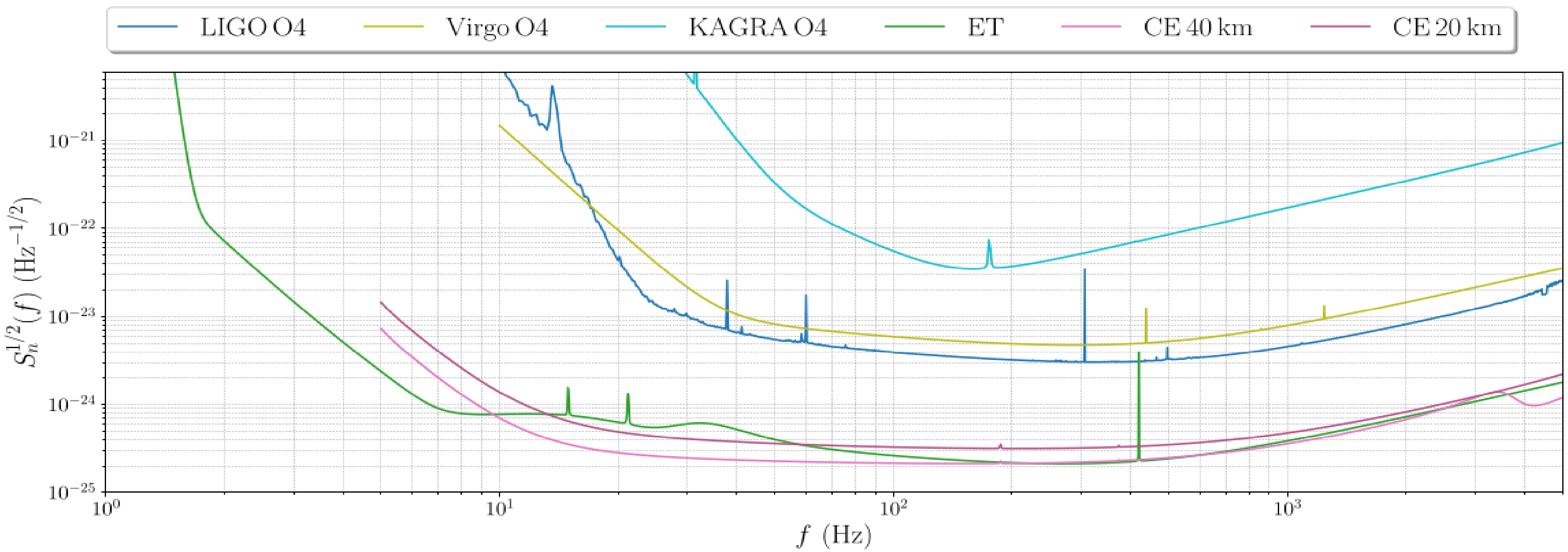


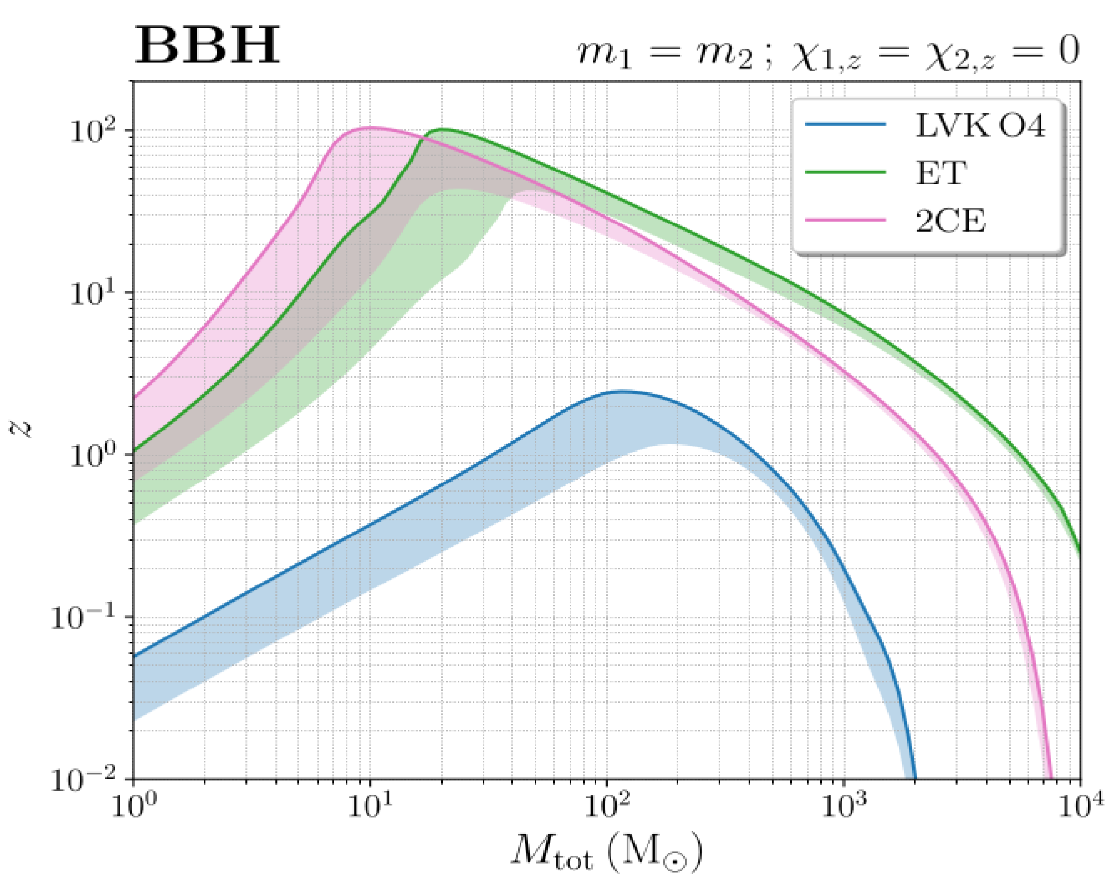
The Third-Generation Goal

- Current GW detectors mainly probe compact binaries at low-to-moderate cosmological redshift
- JWST has pushed electromagnetic observations to z∼14, revealing the earliest known galaxies
- For favorable massive systems, ET horizons may extend to extremely high redshift (z∼100)
- Very high-redshift mergers may provide insight into early-Universe compact-object formation, including Population III remnants and primordial-black-hole scenarios



Why Low-frequencies matter





BBH up to z=O(50-100) !!

BNS up to z ~ 3

Current detectors rapidly lose sensitivity below ~20 Hz, while ET is designed to operate down to a few hertz

The low-frequency extension is one of the key scientific differences between 2G and 3G detectors

Massive black-hole binaries emit strongly at low frequencies; improved low-frequency sensitivity dramatically increases redshift reach

ET may probe favorable massive BBH systems to extremely high redshift (z~50–100)

Binary neutron-star systems may become observable to cosmological redshift (z~2–3)

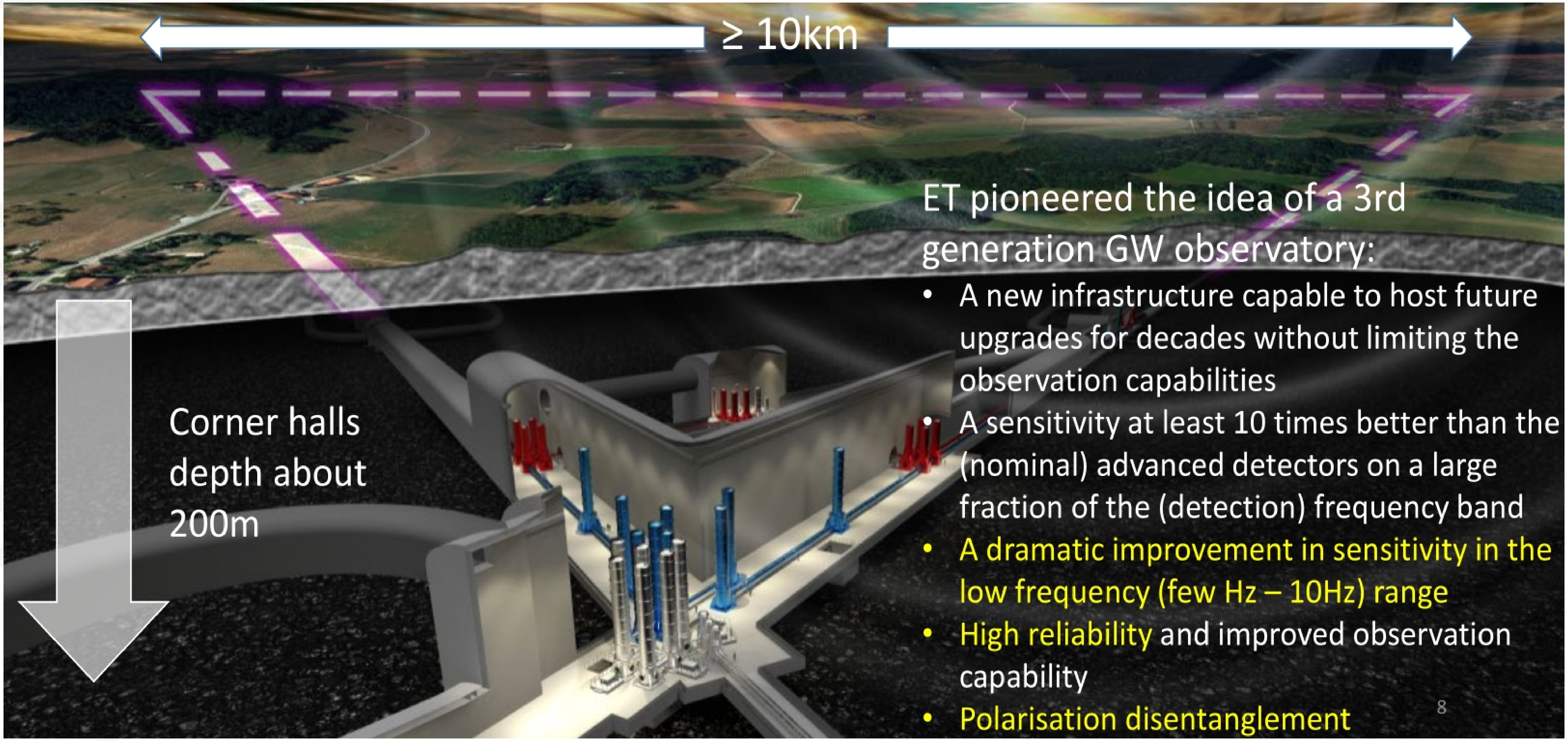
Low-frequency sensitivity allows much longer inspiral tracking, earlier detection, and significantly larger accumulated signal-to-noise ratio

PART 2: ET OBSERVATORY CONCEPT AND SCIENTIFIC REACH

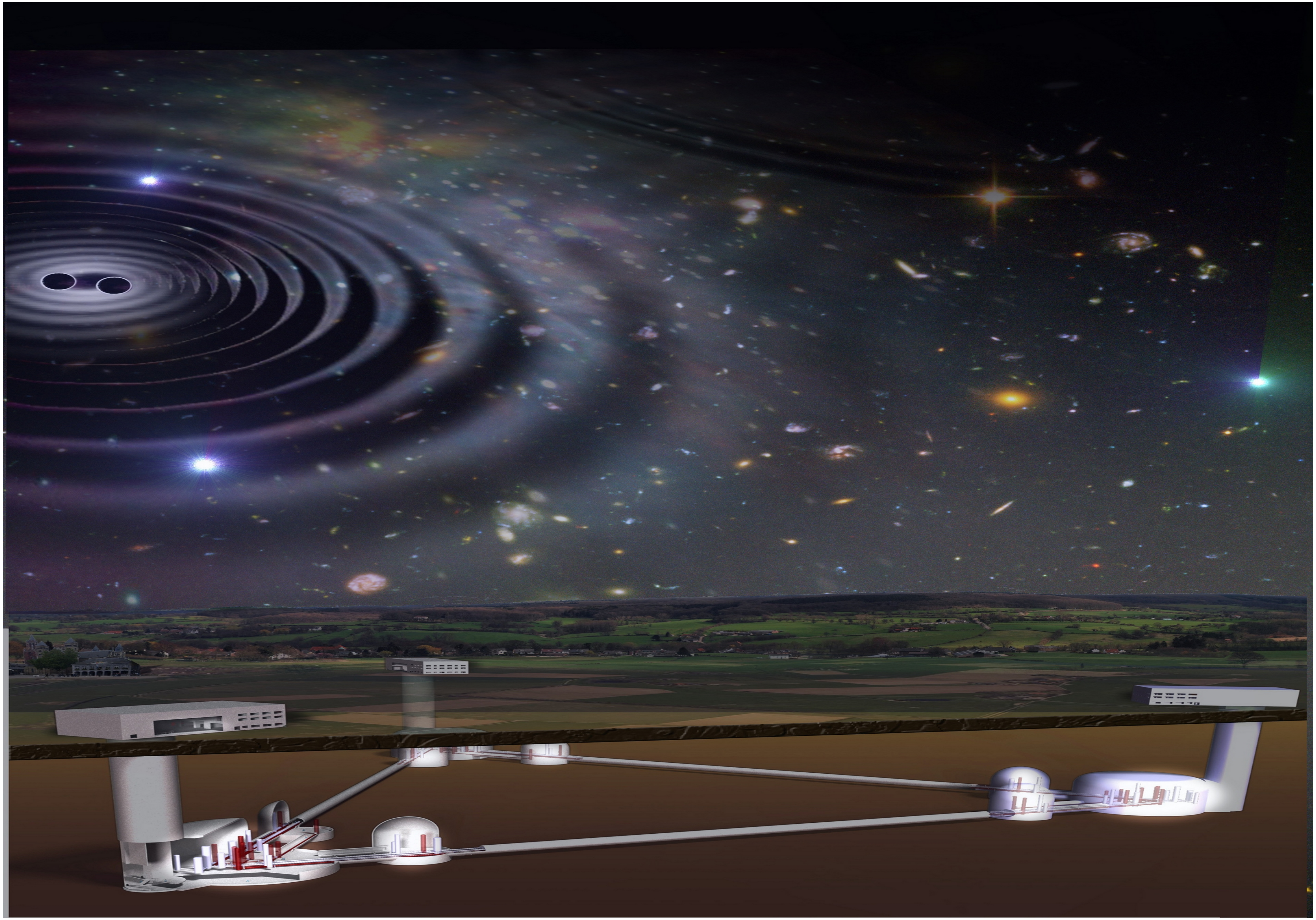
Einstein Telescope

European 3rd-generation GW observatory — target operations mid-2030s/early 2040s

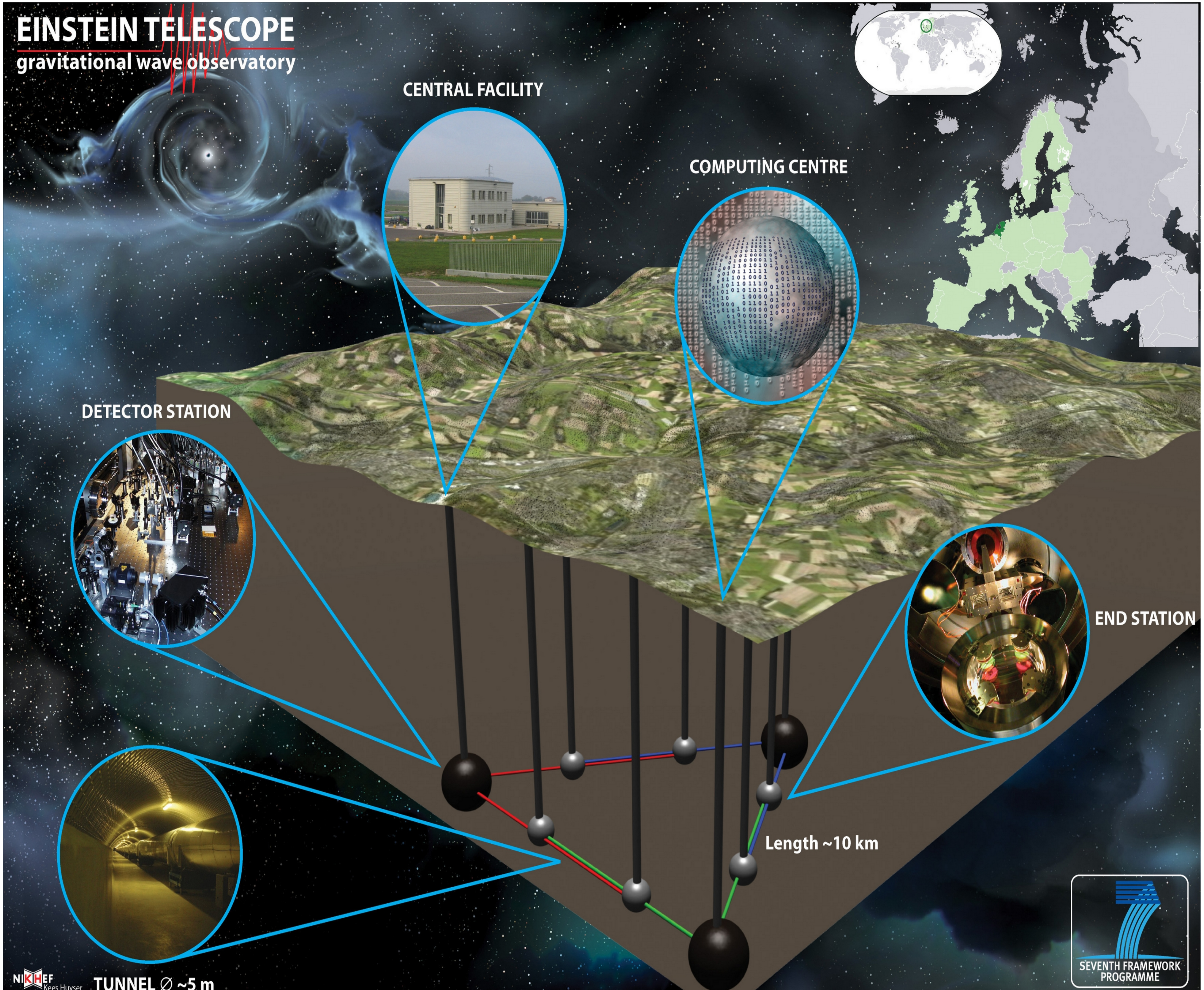
- Underground at 200m depth — eliminates seismic and Newtonian noise that fundamentally limits surface detectors below 20 Hz
- Arms ≥10 km — factor 2.5 longer than LIGO — direct sensitivity gain at all frequencies
- Sensitivity 10× better than Advanced LIGO across the band, qualitatively better below 20 Hz — not an upgrade, a new infrastructure
- Designed for decades of detector upgrades without rebuilding the tunnel infrastructure — the tubes last 50+ years, the instruments inside evolve



Einstein Telescope



Einstein Telescope

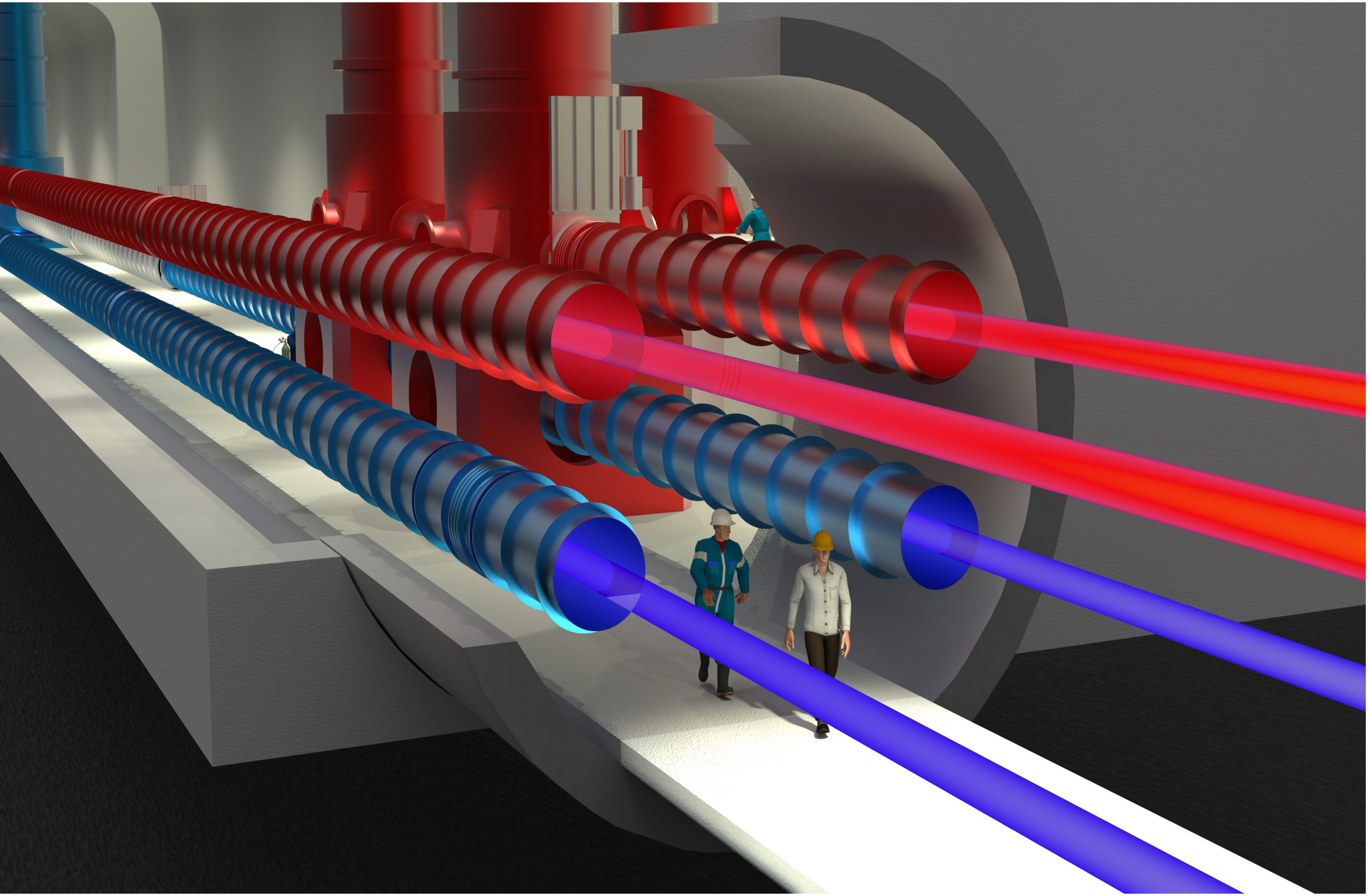


Three detector stations connected by tunnels ~10 km long, diameter ~5m — excavated 200m underground

Each corner hosts a full interferometer station — vacuum tubes, suspended mirrors, laser injection and detection equipment

Surface infrastructure: central facility for operations, distributed computing centre for the ~10^5 events/year data pipeline

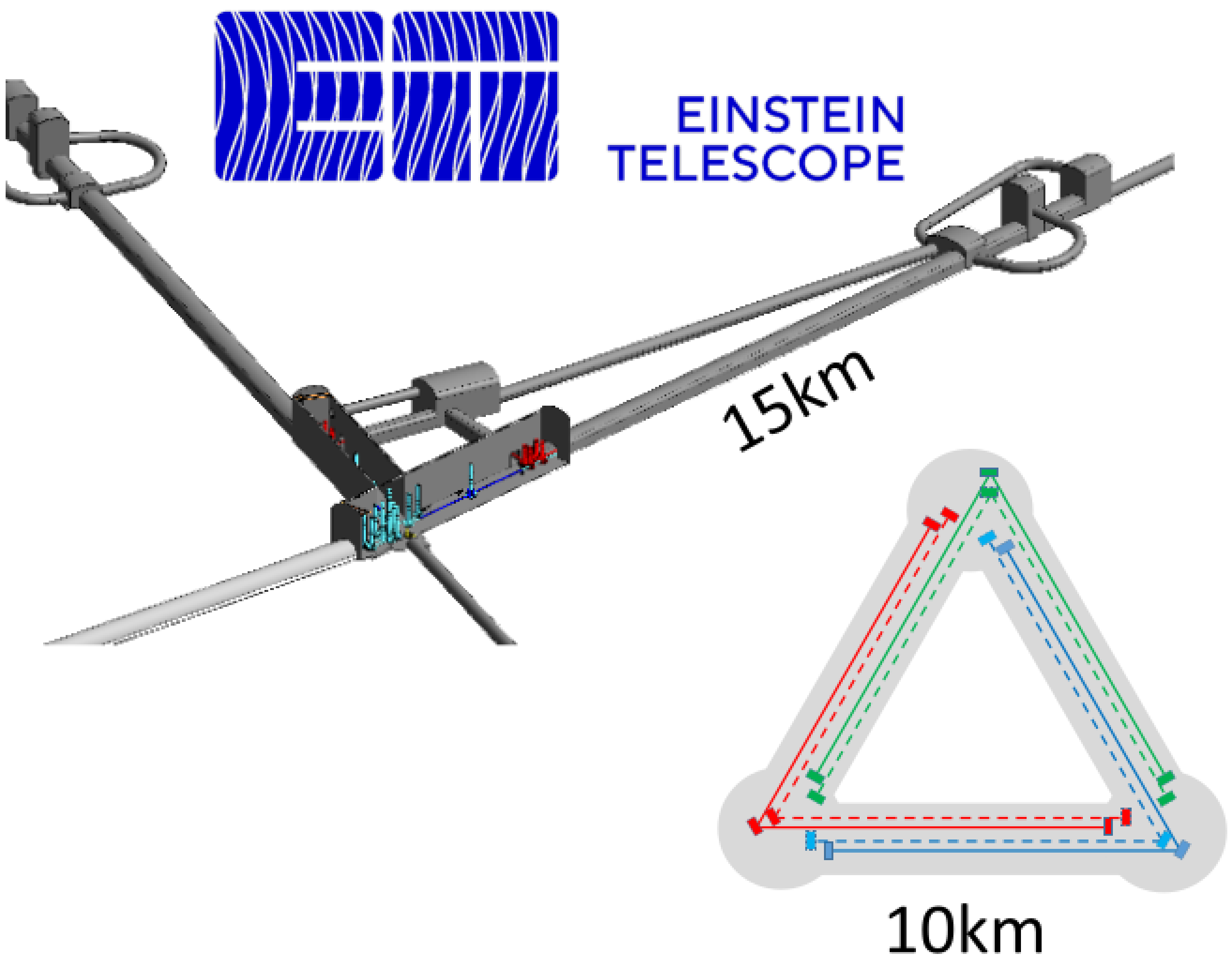
Einstein Telescope



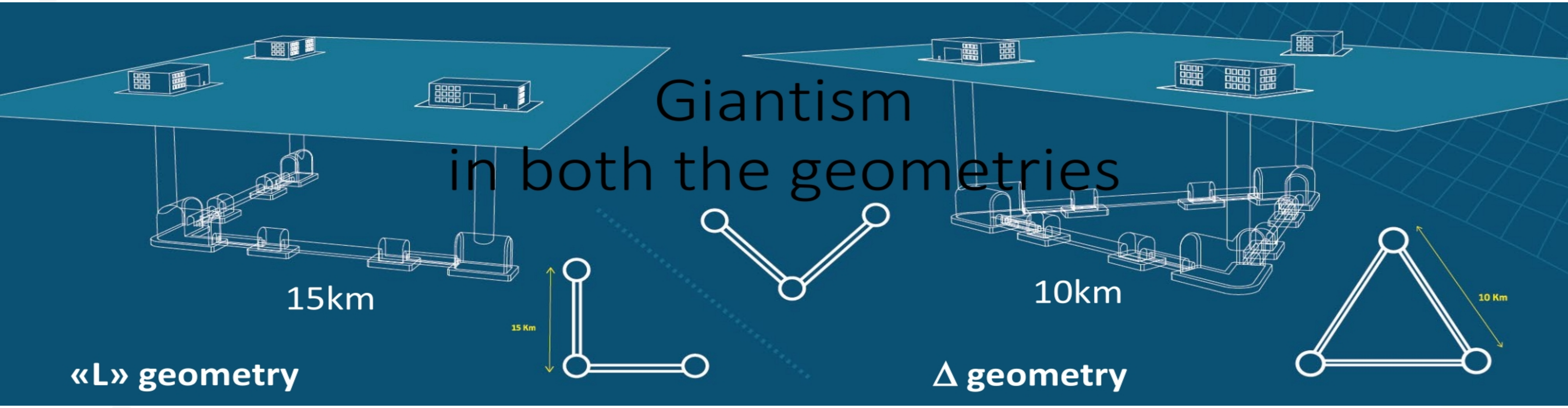
Red beam = ET-HF (high frequency, room temperature) and blue beam = ET-LF (low frequency, cryogenic ~10K) — two completely separate interferometers sharing one tunnel — the xylophone design

ET Observatory Concept

- Triangle, 10 km
  - One underground site
  - Three nested detectors / xylophone interferometers
  - Strong polarization reconstruction and null-stream capability
  - Compact single-site infrastructure
- 2L, 15 km-scale
  - Two geographically separated L-shaped detectors
  - Longer arms and wider baseline
  - Strong network localization potential
  - More complex site/infrastructure coordination
- Both options remain part of the ET optimization and design process



Adapted from M. Punturo (The Einstein Telescope Status and Roadmap)



ET Observatory Concept: Triangle vs 2L

Aspect	Triangle (Δ, 10 km)	2L (2×15 km)
Null stream / glitch rejection	Strong intrinsic capability	No intrinsic null stream
Polarization & GR tests	Intrinsic polarization reconstruction	Improved with global network
Sky localization	Good	Generally improved
Correlated noise	Same-site concern	Strongly reduced
Stochastic background	Requires careful noise mitigation	Generally favored
Detection reach	Baseline	Enhanced for many source classes

Both configurations achieve transformative science. Final decision involves science, cost, site, and organization.

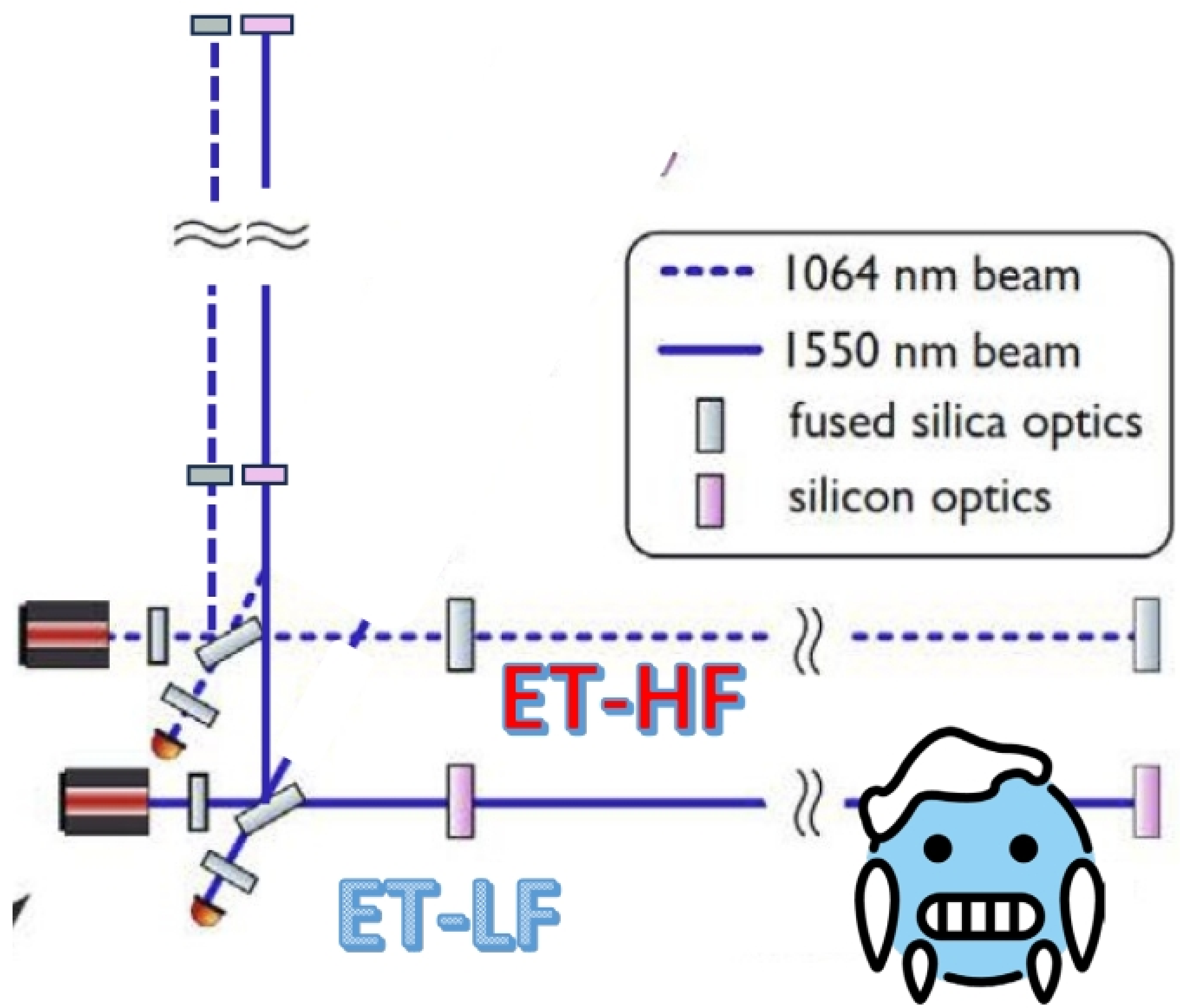
Xylophone Design

ET-LF

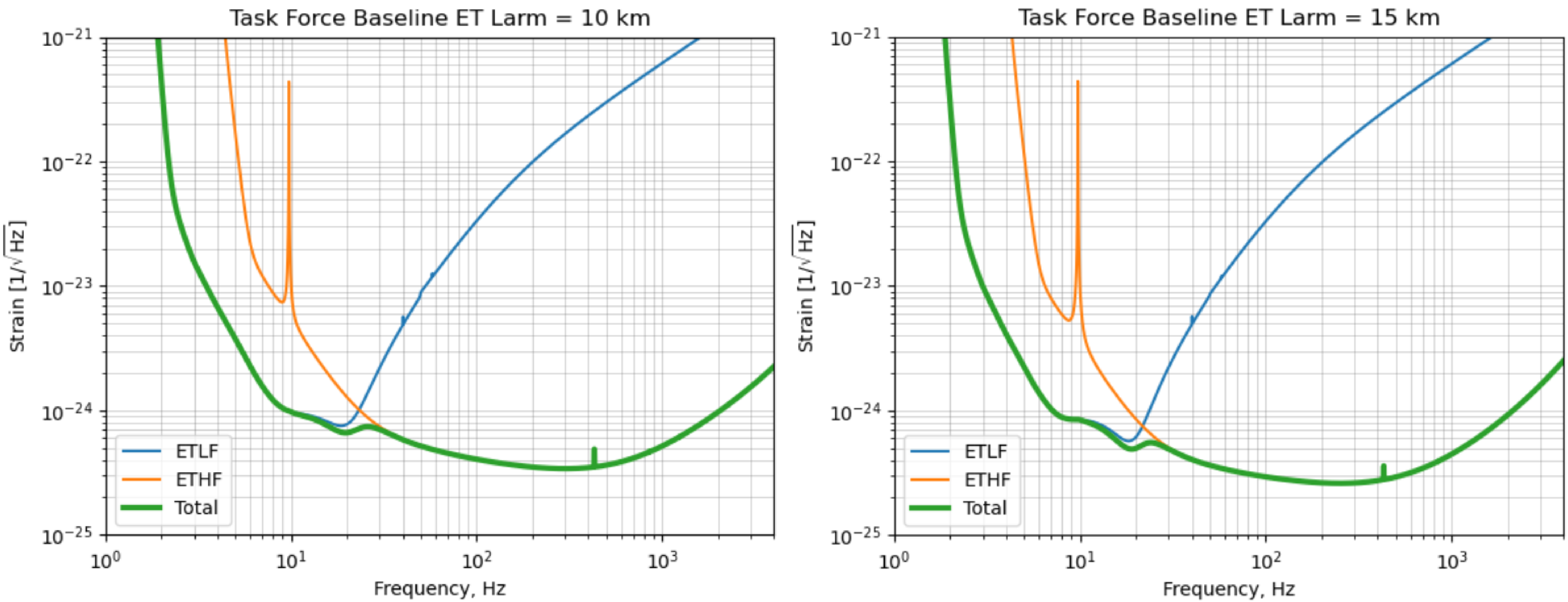
- Cryogenic at 10–20 Kelvin — suppresses thermal noise dominating below 30 Hz
- Silicon mirrors — fused silica absorbs 1064 nm at low temperature; silicon is transparent at 1550 nm — forces the wavelength change
- Low circulating power (18 kW) — minimises radiation pressure noise which dominates at low frequency

ET-HF

- Room temperature 290 K — no cryogenics needed above 30 Hz
- Fused silica mirrors — standard material, well understood, low mechanical loss at room temperature
- High circulating power (3 MW) — suppresses shot noise which dominates at high frequency



ET Observatory Concept



Blue = ET-LF: low-frequency cryogenic instrument — sensitive from ~1–3 Hz to ~30 Hz

Orange = ET-HF: high-frequency room-temperature instrument — sensitive from ~20 Hz to ~10 kHz

The two instruments are nested in the same tunnel — this is the xylophone design

Right plot (15km): deeper sensitivity minimum — longer arms = better strain sensitivity

ET Observatory Concept

Going 10 km → 15 km: how do noises scale?

	Scaling with length	Improvement factor
Shot noise	$\sqrt{L}$	1.2
Radiation-pressure	$\sqrt{L^3}$	1.8
Coating thermal	L	1.5
Suspension thermal	L	1.5
Residual gas	$\sqrt{L}$	1.2
Seismic		complicated

Core principle: GW signal = phase accumulated over arm length — longer arms → larger phase shift → stronger signal for the same gravitational wave

Thermal noises (coating, suspension) are fixed mirror displacement noises — signal grows with L but noise stays fixed → full 1.5× gain

Quantum noises (shot, radiation pressure) depend on circulating power and optical design — gain is partial (1.2–1.8×) depending on whether finesse is re-optimised for the longer cavity

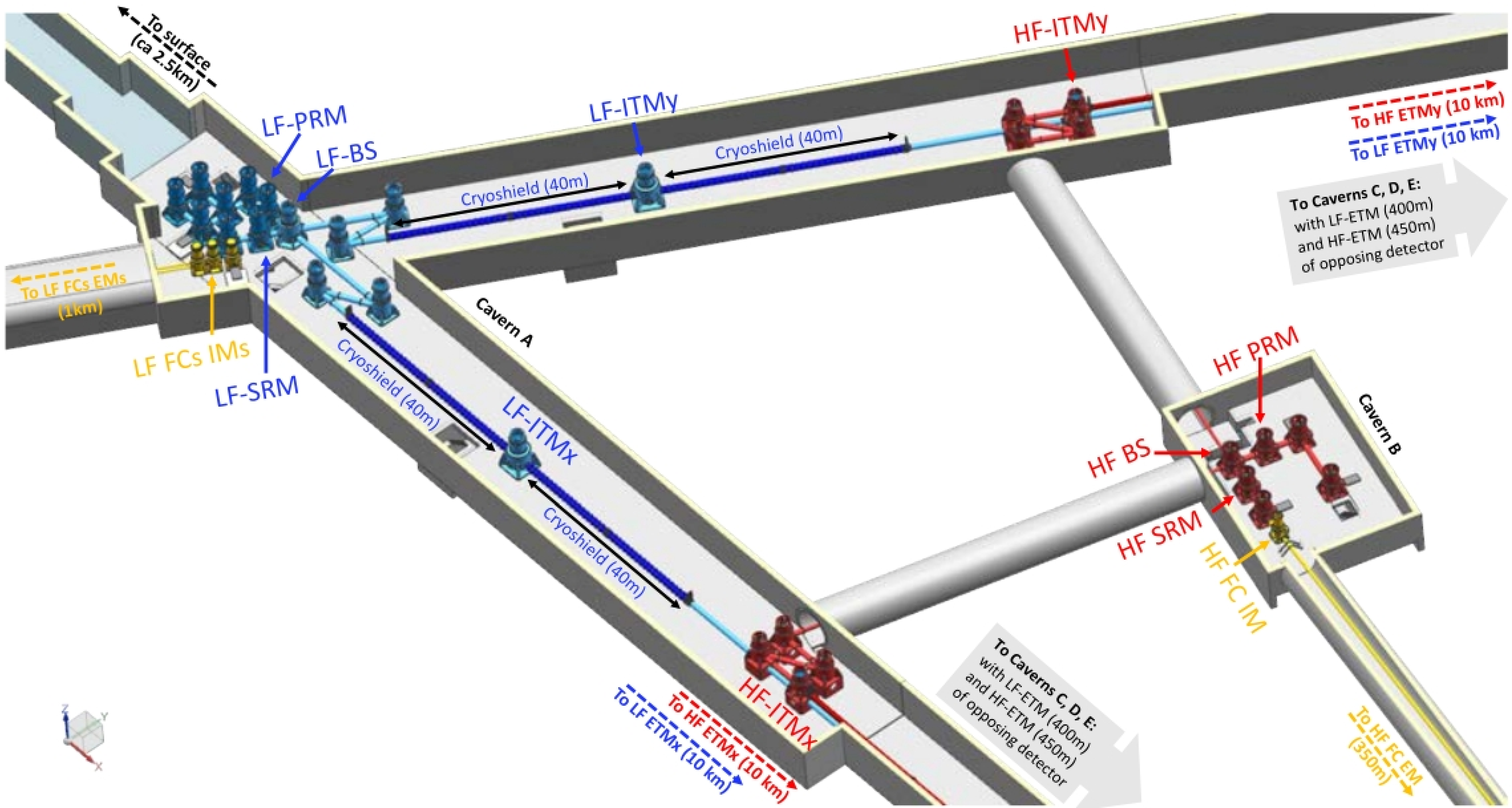
ET Parameters

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\ \mathrm{m}/f^2$	$5 \cdot 10^{-10}\ \mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few

Table 6.1: Summary of the most important parameters of the ET high and low frequency interferometers. SA = super attenuator, freq. dep. squeez. = squeezing with frequency dependent angle.

G S
S I

ET Corner caverns



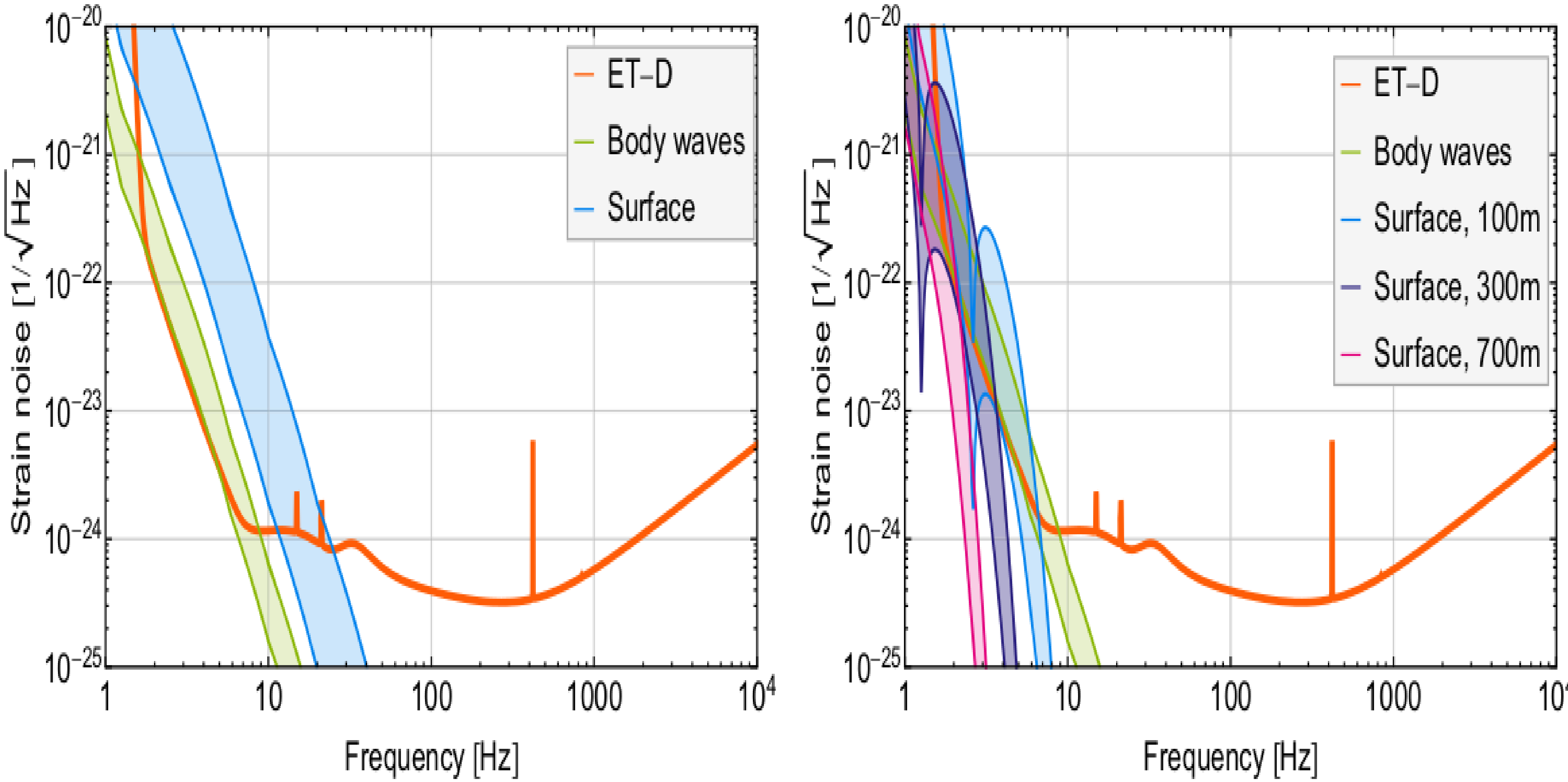
One ET corner station houses both LF and HF interferometers simultaneously — blue = LF cryogenic, red = HF room temperature — completely separate optical paths sharing the same cavern

Cryoshields (40m long) visible in blue — these are the cryogenic enclosures around the LF input mirrors and beam splitter — maintaining 10K inside while room temperature surrounds them

The cavern splits into two tunnel directions — each carrying both an LF and HF beam tube toward the next corner station 10 km away

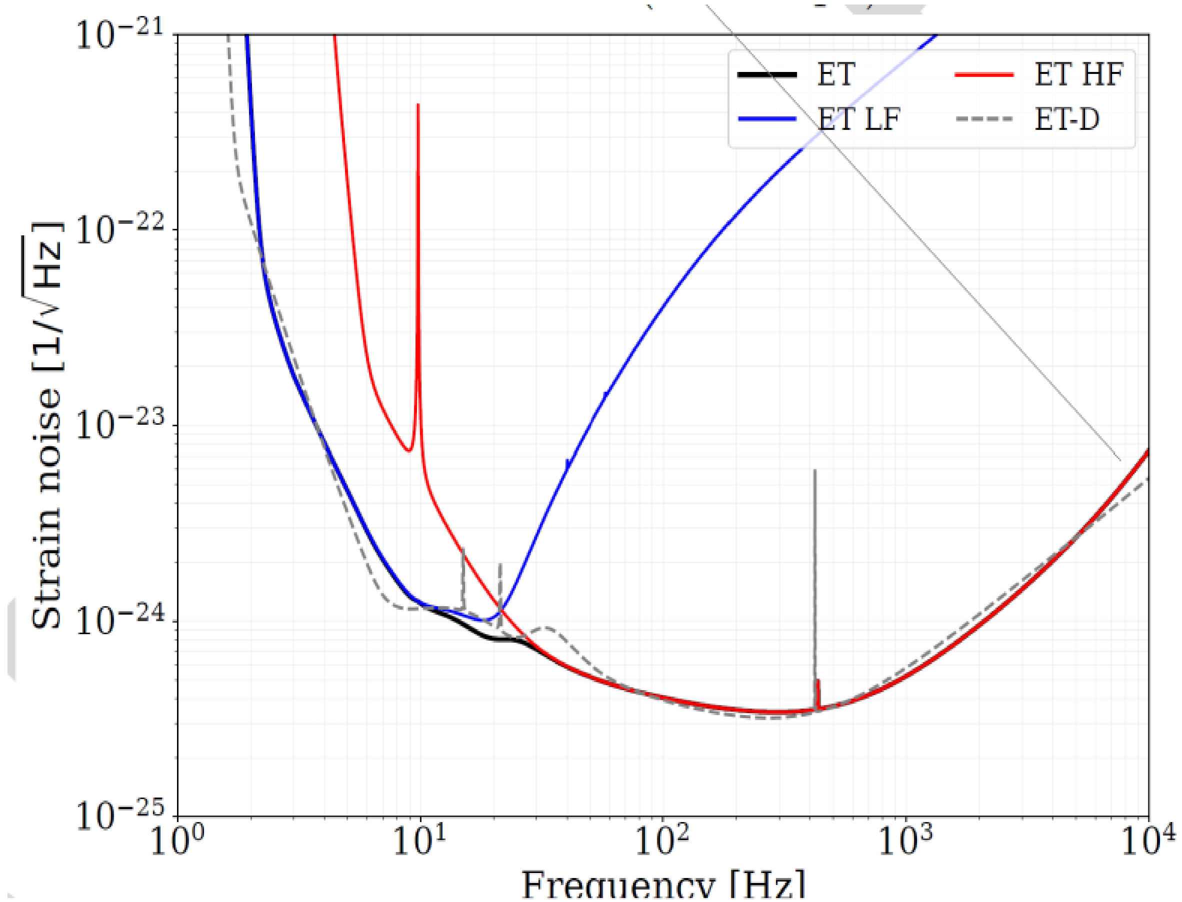
Why underground

- Suppression of seismic noise
- Reduction of Newtonian noise
- Environmental stability
- Reduced anthropogenic disturbances



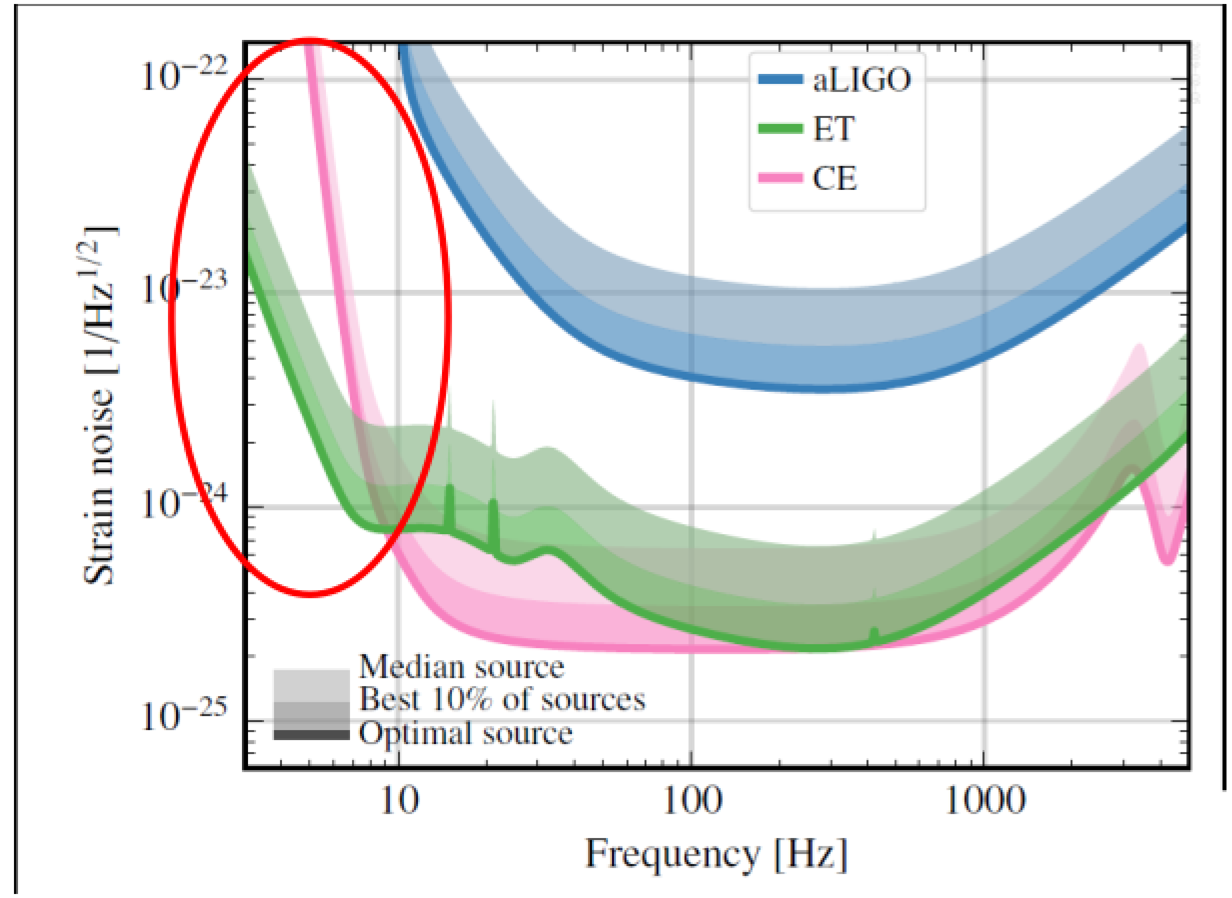
Low frequency is the ET science driver

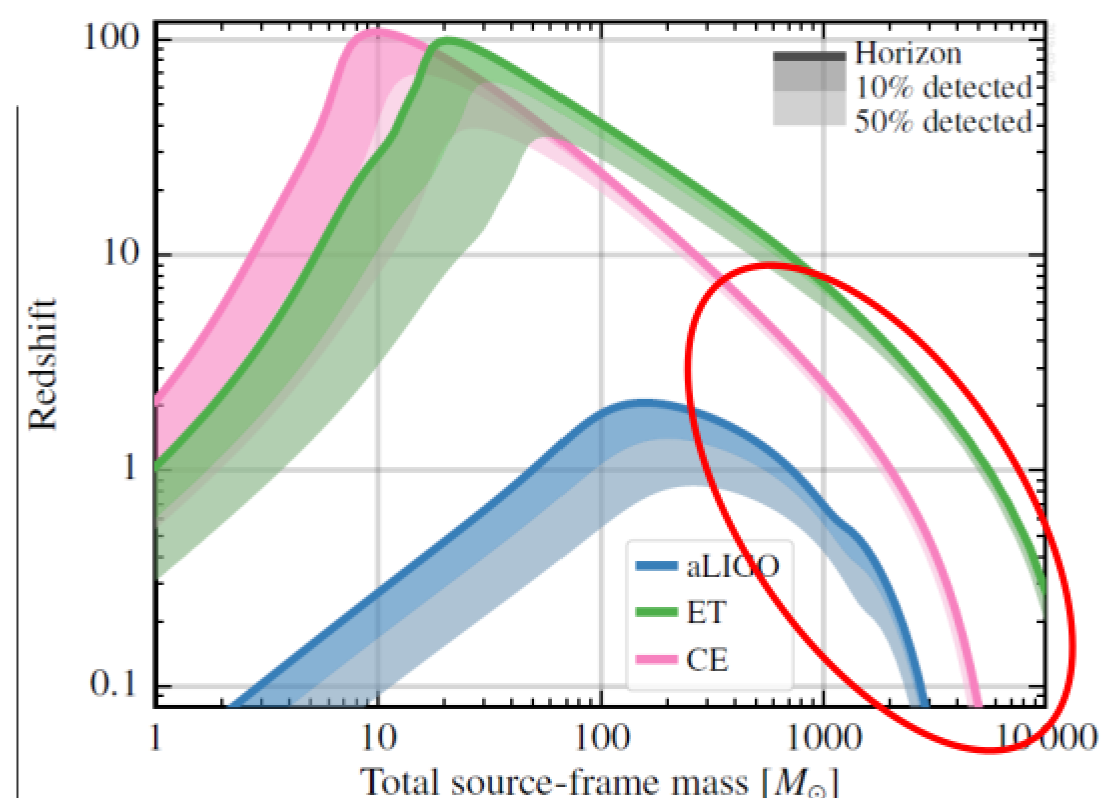
- ET wants to achieve a detection sensitivity about one order of magnitude better than the current GW detectors
- But the primary science targets of ET is to access the 1-10Hz frequency range
  - Cosmology
    - high red-shift → low frequency
    - Primordial BH and the Dark Matter quest
  - Intermediate mass black holes
    - Fill the gap between the stellar mass black holes (à la LIGO/Virgo) and the supermassive black holes (à la LISA)
  - Early warning in multimessenger astronomy with GW emitted by BNS



ET Sensitivity

- ~10× strain sensitivity improvement
- Extension to few-Hz regime
- Massive increase in observable volume



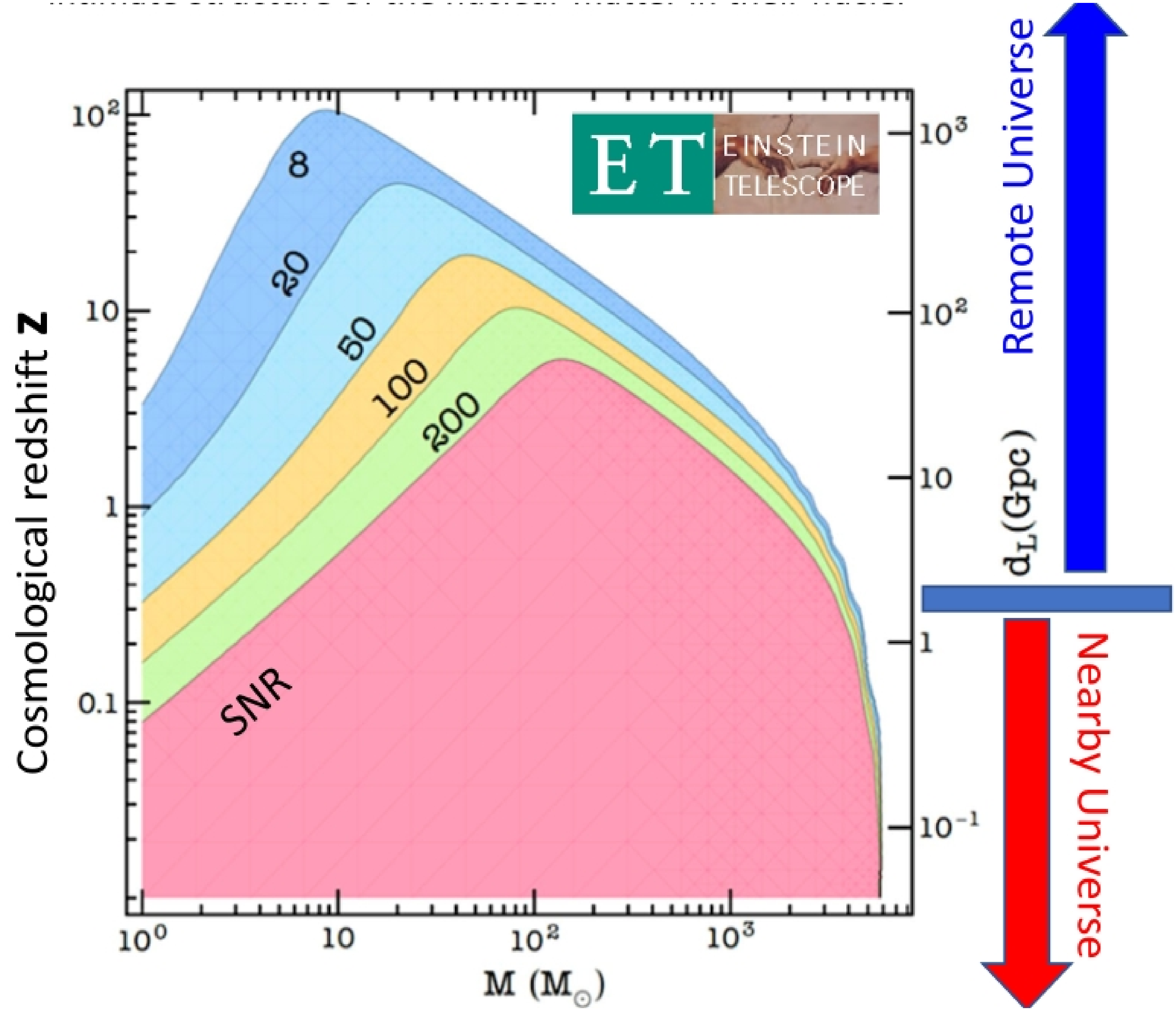


- The red circle highlights the high-mass regime — massive black holes above 100 solar masses that LIGO can barely see at z~1, ET detects out to z~20 or beyond
- This is the entire cosmic history of star formation opened up. ET detects massive BH mergers across the entire observable universe

Science Landscape

- Compact binaries
- Cosmology
- Fundamental physics
- Neutron star physics
- Multi-messenger astronomy

- Full detectable region bounded by outermost SNR=8 contour
- Peak sensitivity around 5–30 M☉: ET reaches z ~ 50–100 — deepest look into the universe
- BNS (~1.4 M☉): horizon z ~ 2–3
- IMBHs (~1000 M☉): horizon z ~ 5 or less, rolling off steeply

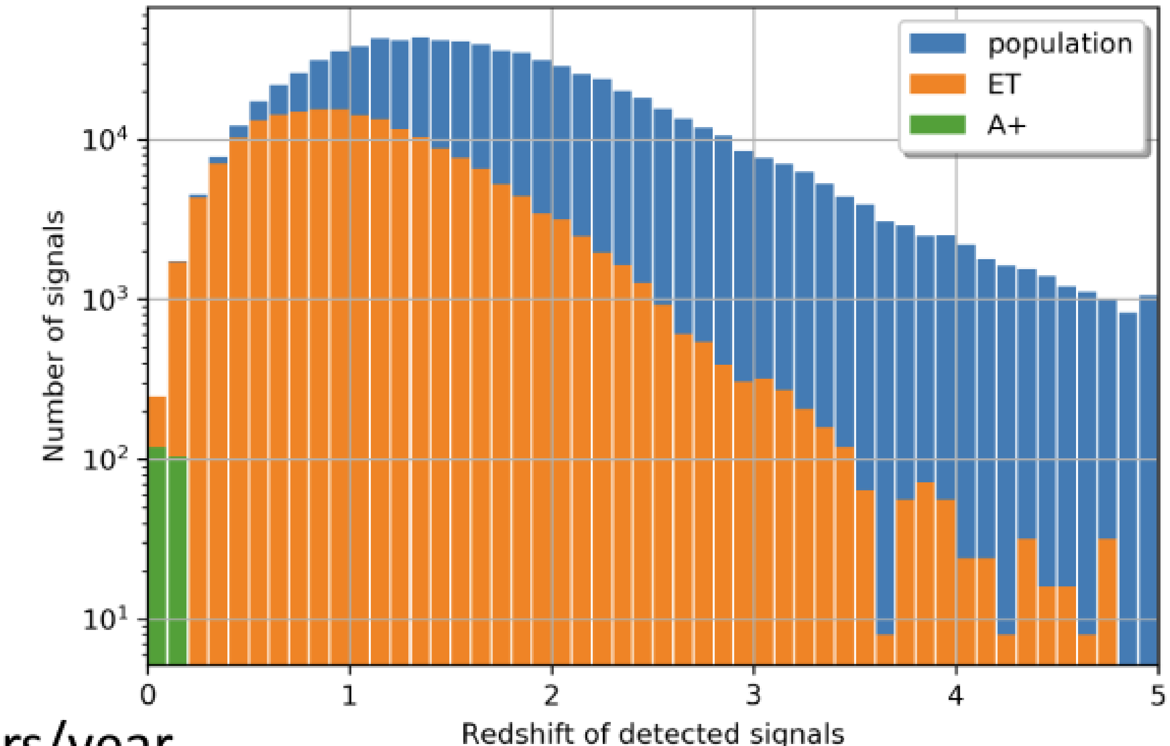


Compact Binaries Across Cosmic History

- ET recovers a large fraction of the BBH population out to high cosmological redshift
- For BNS, ET maintains high detection efficiency out to z∼2–3
- Current-generation detectors remain primarily sensitive to nearby populations
- ET is expected to detect O(10^5) compact-binary mergers per year
- This enables precision studies of merger rates, masses, spins, and formation channels across cosmic history
- With this statistics ET maps merger rate, mass distribution, spin distribution, and formation channels across the entire cosmic history — completely inaccessible to current detectors

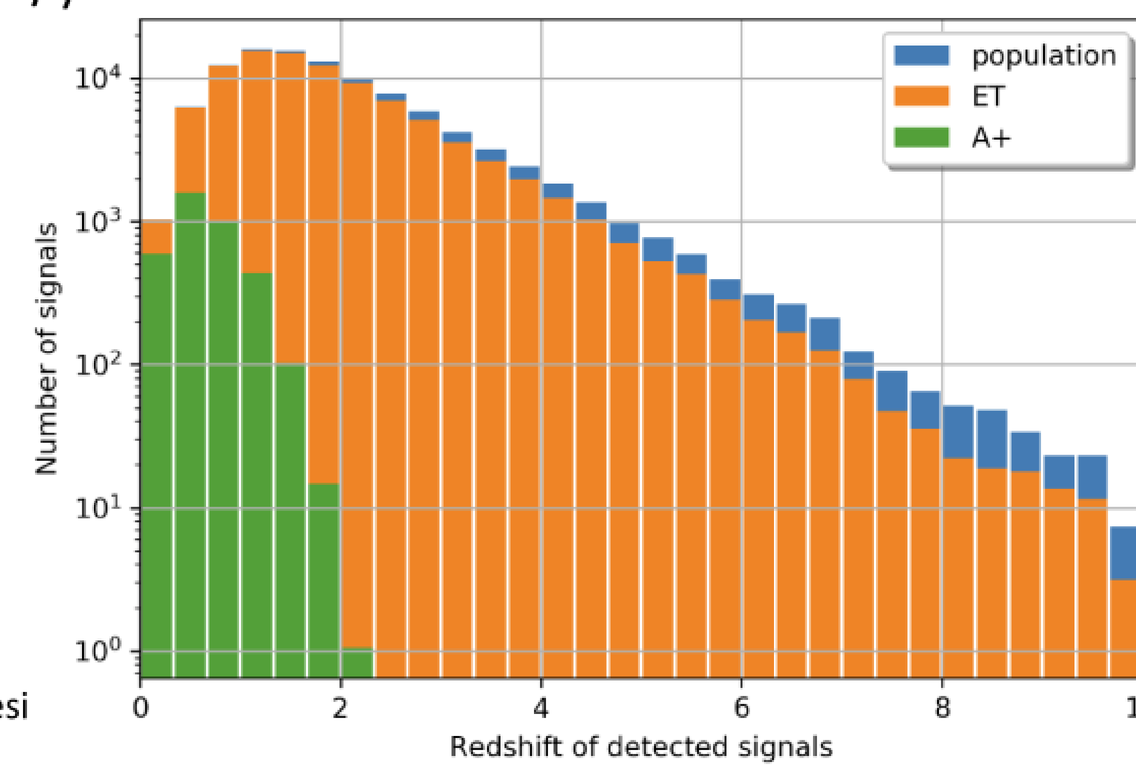
Compact Object Binary Populations

BNS mergers



O(10^5) mergers/year

BBH mergers



Credit: M.Branchesi

Intermediate-Mass Black Holes

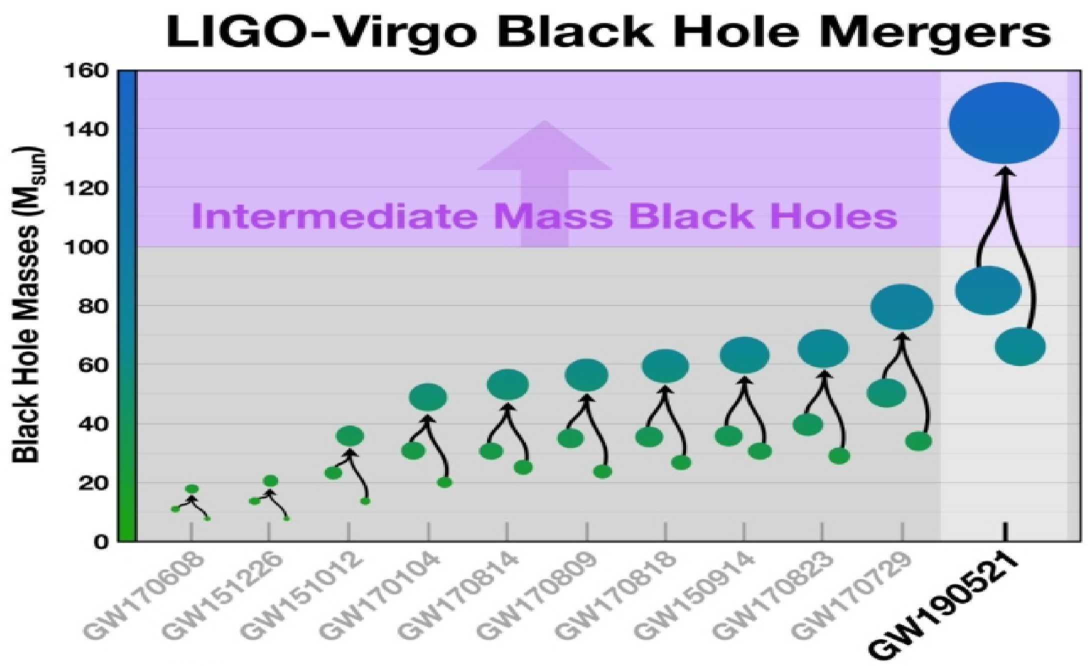
- ET opens the intermediate-mass black hole regime (100–10^4 M☉) — almost completely invisible to current detectors
- Current detectors hit a seismic wall at ~20 Hz — high-mass systems merge below this, entering the band only at the very last moment with no inspiral visible
- GW190521 is a perfect example: the signal was extremely short and merger-dominated, with very little inspiral visible in band
- ET's low-frequency sensitivity (~3–5 Hz) means high-mass systems are tracked through their inspiral — not just caught at the final plunge
- M_1 = 85 M☉ in GW190521 should not exist from a single star — pair-instability supernovae destroy stars in this mass range completely — points to hierarchical mergers
- The 142 M☉ remnant is the first IMBH ever directly observed — ET will detect hundreds of such systems per year
- IMBHs are the suspected missing link between stellar-mass and supermassive black holes — detecting them with ET would directly constrain how the first galaxies and their central black holes formed and grew.

Why low frequency focus?

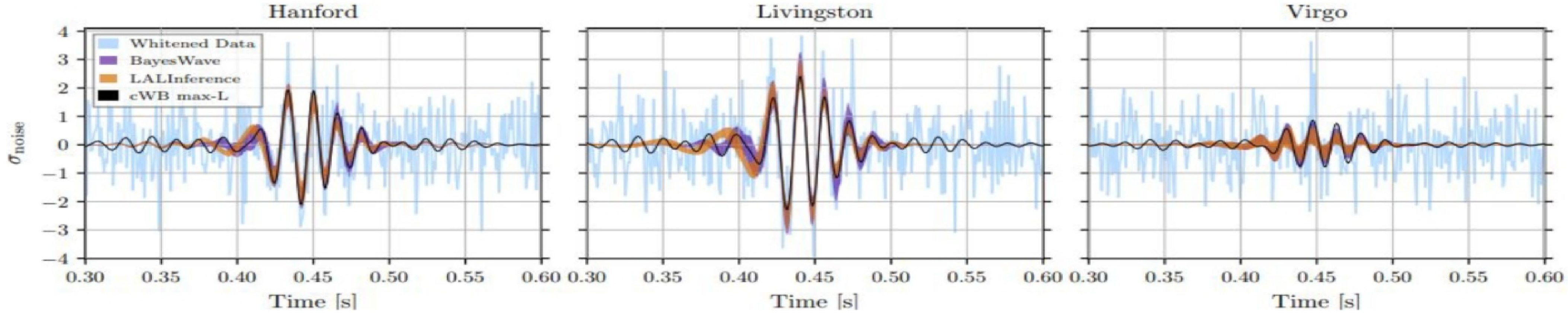
GW190521

$M_1 = 85^{+21}_{-14} M_\odot$, $M_2 = 66^{+17}_{-18} M_\odot$
at $z \sim 0.82$ (5.3Gpc)
Remnant $M_f = 142^{+28}_{-16} M_\odot$

- Very special event:
  - M_1, a black hole that should not exist
  - M_f, the first IMBH ever seen



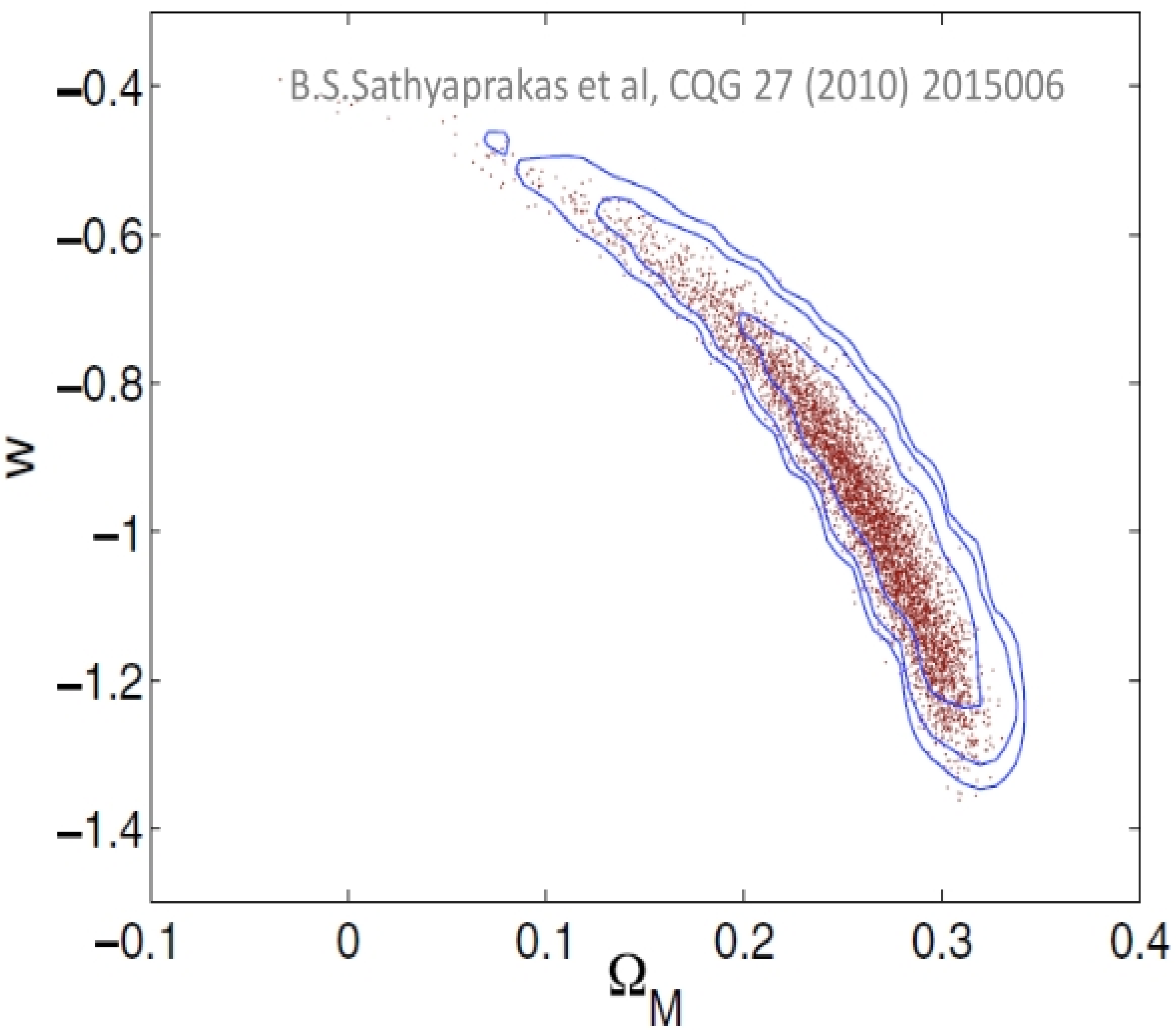
Phys. Rev. Lett. 125, 101102 (2020)
Astrophys. J. Lett. 900, L13 (2020)



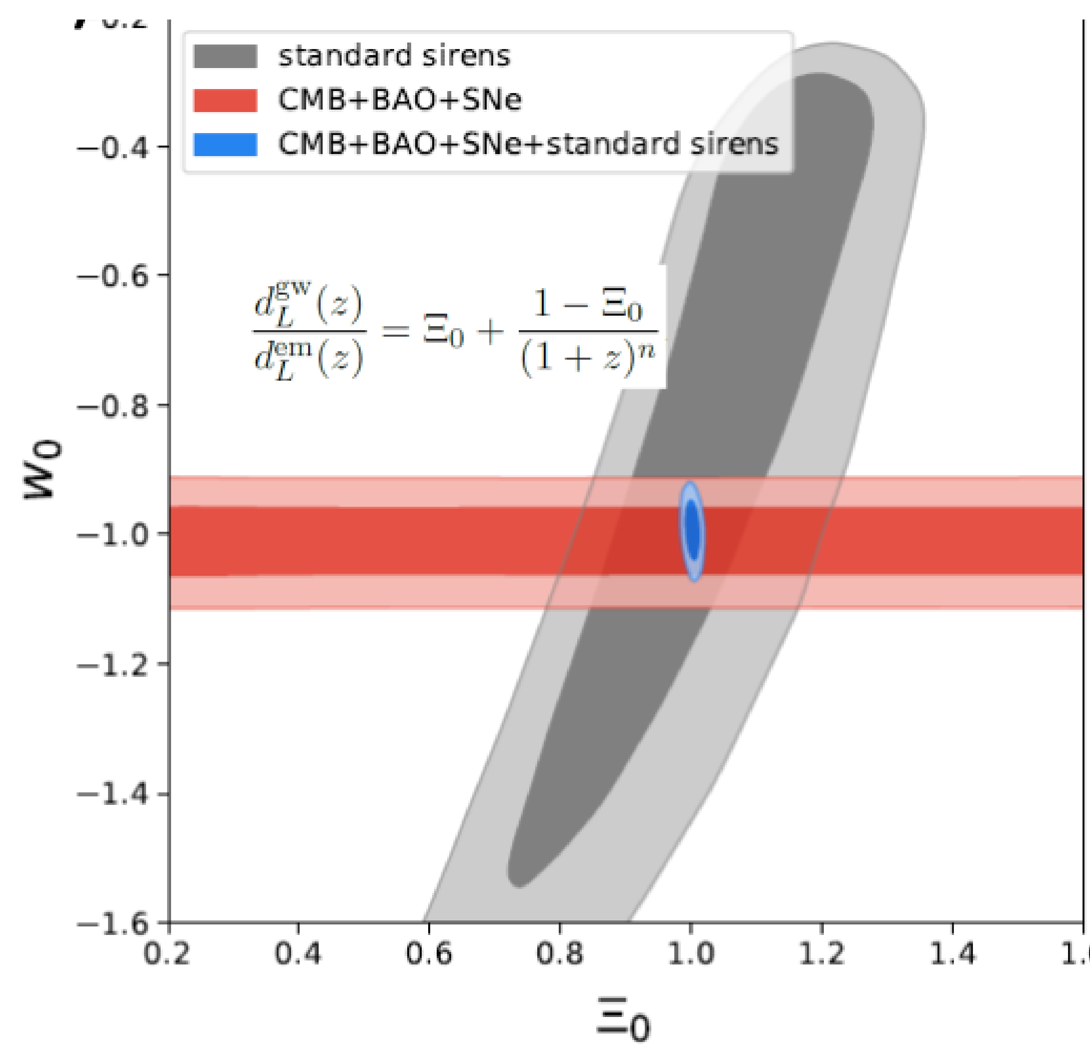
Where is the chirp?

Cosmology with standard sirens

- GW waveform directly measures luminosity distance — no distance ladder, fully independent
- Pair with redshift from EM counterpart or galaxy catalogs → standard sirens
- ET detects $O(10^5)$ compact binaries per year — transforms this from proof of concept to precision cosmology
- Left plot: dark energy parameter space — w vs Ω_m — smaller contours mean better constraints — GW170817 alone already competitive
- Right plot: tests whether GWs propagate exactly like light — GR predicts ratio = 1 — ET reaches percent-level precision



Enis Belgacem et al JCAP08(2019)015

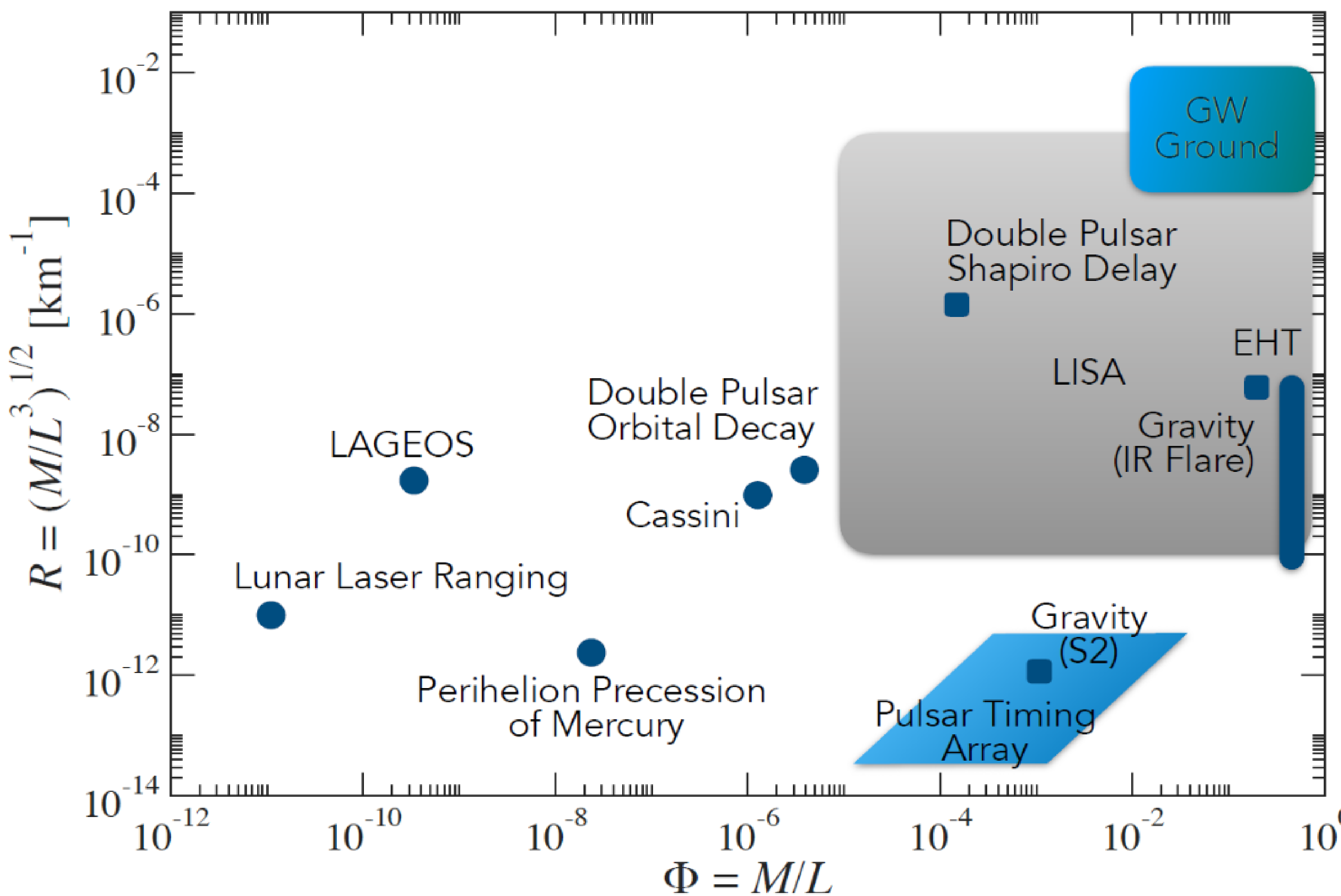


Fundamental Physics

- This plot maps every GR test ever done onto compactness vs curvature — right and up means more extreme gravity
- Solar system tests bottom left, binary pulsars middle — GW detectors uniquely top right
- BBH mergers probe simultaneously maximum compactness AND maximum dynamical strong-field gravity — no other experiment reaches there
- ET does not access a different gravity regime than LIGO — same sources, but orders of magnitude better SNR and statistics
- This turns strong-field GR tests into precision measurements

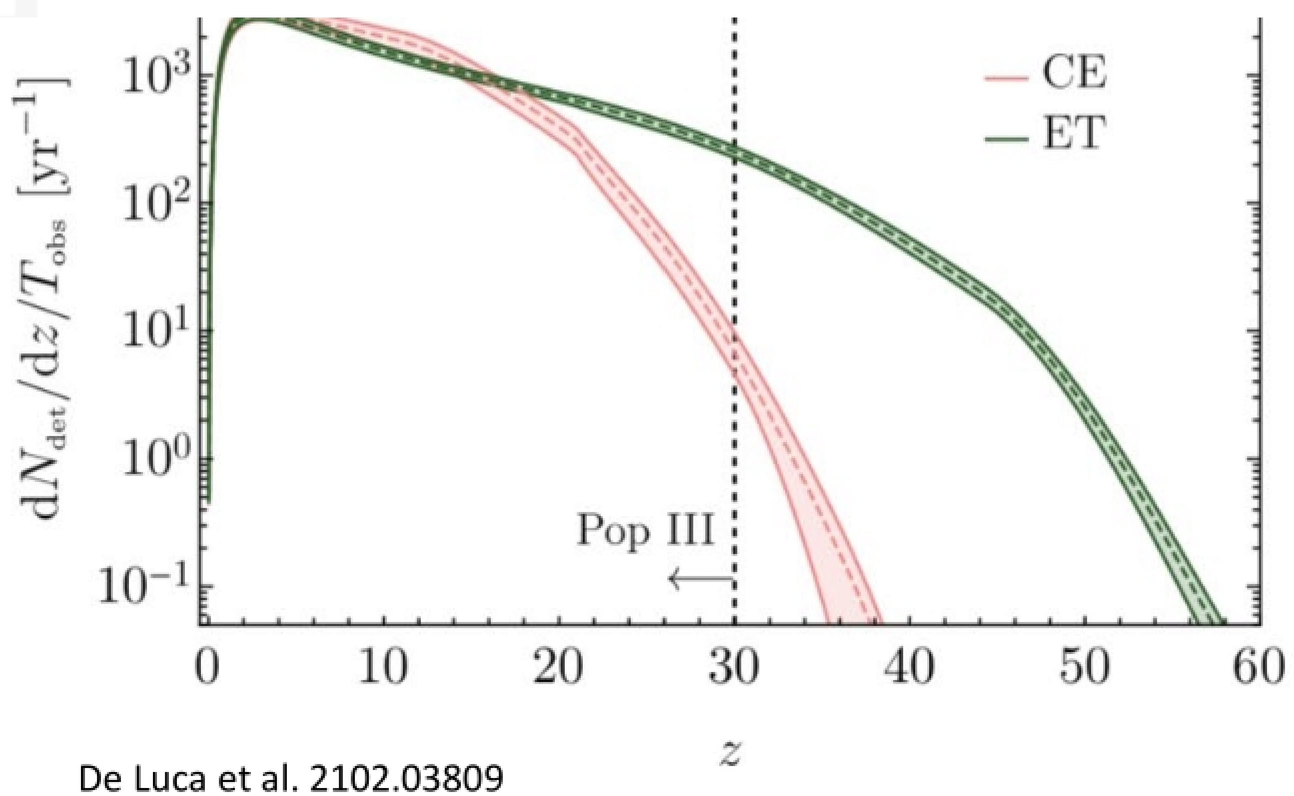
- BBH coalescences allow to test GR in strong field conditions

Yunes N. et al.
Phys. Rev. D 94, 084002 (2016)
Edited by ET science case team



Primordial Black Holes

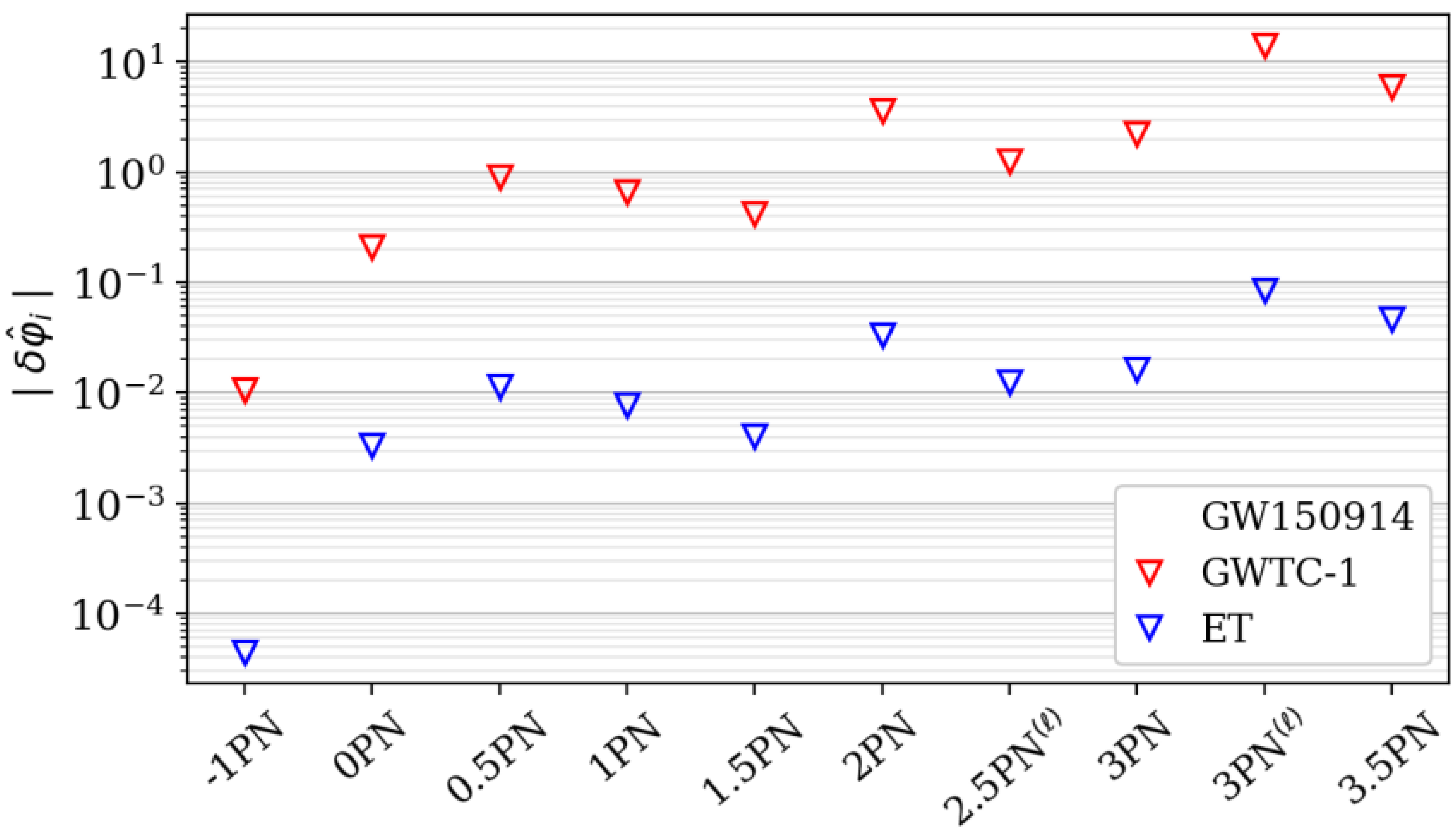
- Stellar-origin BBH merger histories broadly follow cosmic star-formation evolution
- Primordial-black-hole scenarios may extend to much higher redshift than standard stellar populations
- ET can detect BBH mergers deep into the high-redshift Universe, probing epochs inaccessible to current detectors
- Comparing merger-rate evolution with cosmic star-formation history may help distinguish astrophysical and primordial formation channels
- BBH mergers detected at extremely high redshift (z≳30) would strongly favor exotic early-universe formation scenarios



De Luca et al. 2102.03809

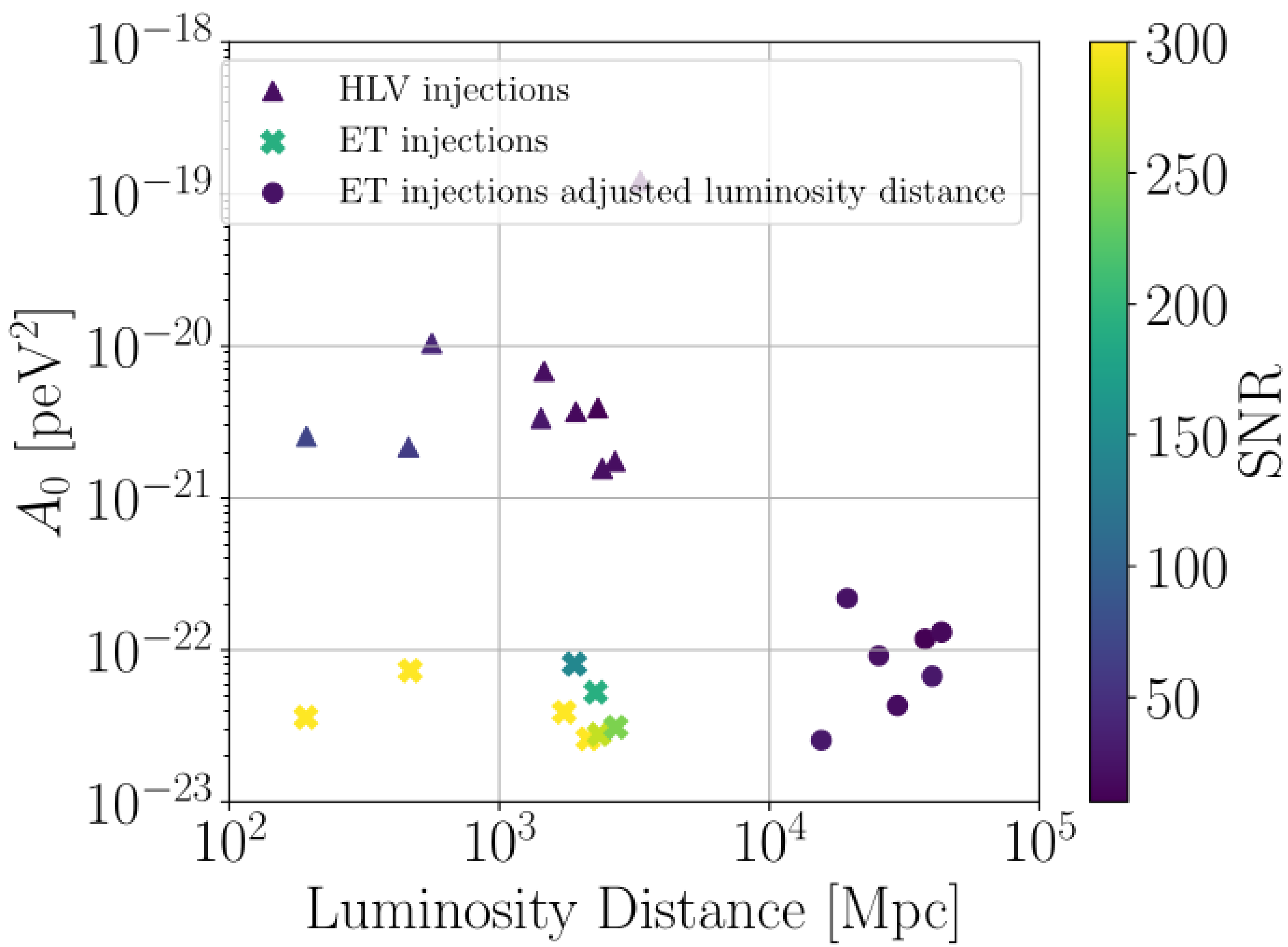
Testing GR in the Inspiral — Post-Newtonian Tests

- GW inspiral phase = post-Newtonian series in orbital velocity — GR predicts every coefficient exactly
- Any deviation = new physics — modified gravity, dipole radiation, extra dimensions
- Red = current LVK, Blue = ET — two orders of magnitude better across every single coefficient
- With $O(10^5)$ detections combined, bounds scale as $1/\sqrt{N}$ — ET either confirms GR below 1% or reveals a violation of that size



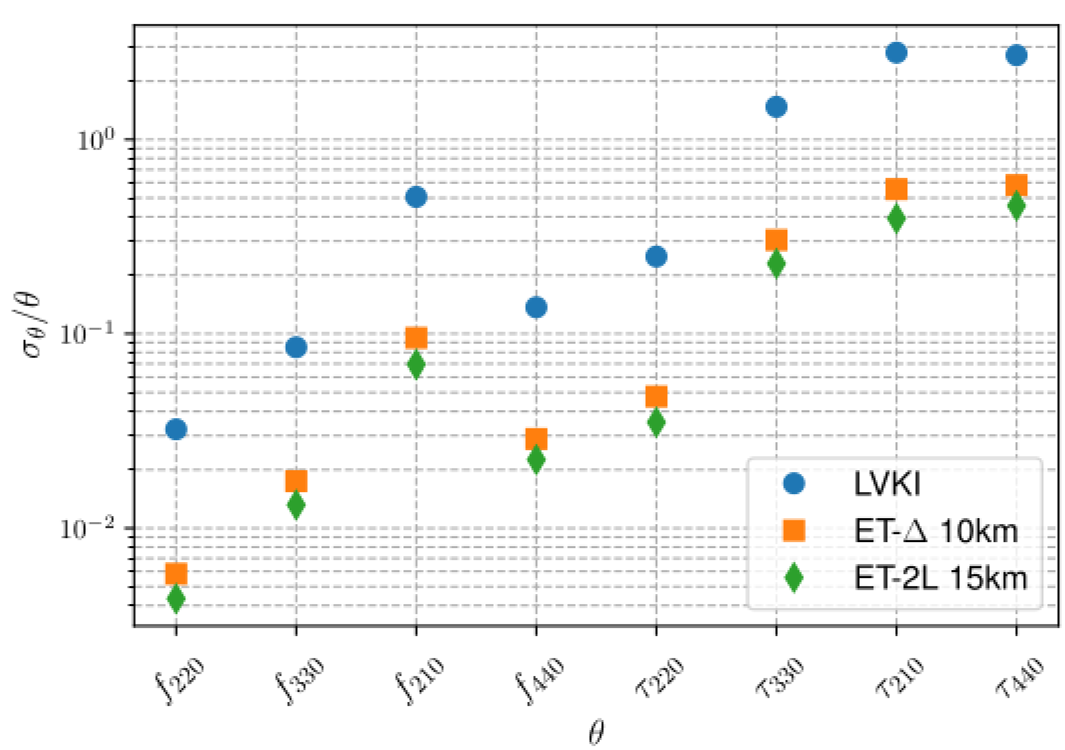
Massive Graviton and Lorentz Violation

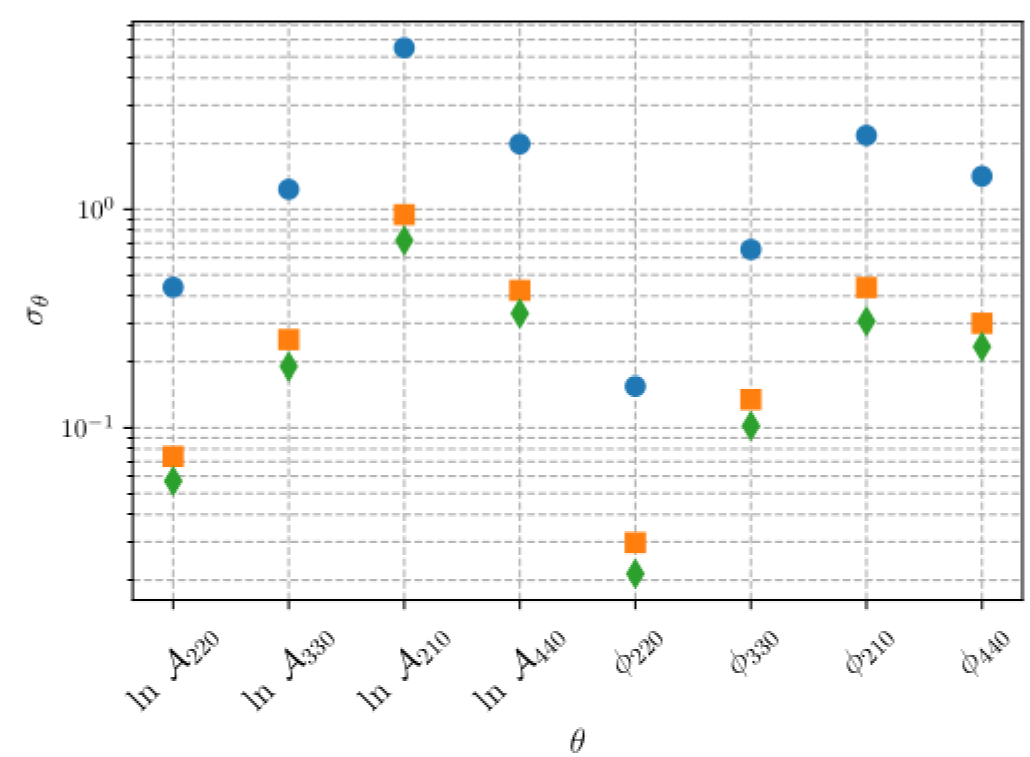
- In GR gravitational waves are nondispersive — travel at exactly c
- Massive graviton or Lorentz violation modifies propagation — accumulated phase shift grows with distance
- Triangles = current LVK, crosses = ET at same distances, circles = ET at larger distances — lower = tighter graviton mass bound — color = SNR
- ET wins two ways: higher SNR at any distance and access to sources at 10^4–10^5 Mpc completely invisible to current detectors
- Effects accumulate over cosmological distance — distant sources give tightest bounds, only ET can reach them
- Result: ~2 orders of magnitude improvement on graviton mass bounds over current detectors



Black Hole Spectroscopy and the No-Hair Theorem

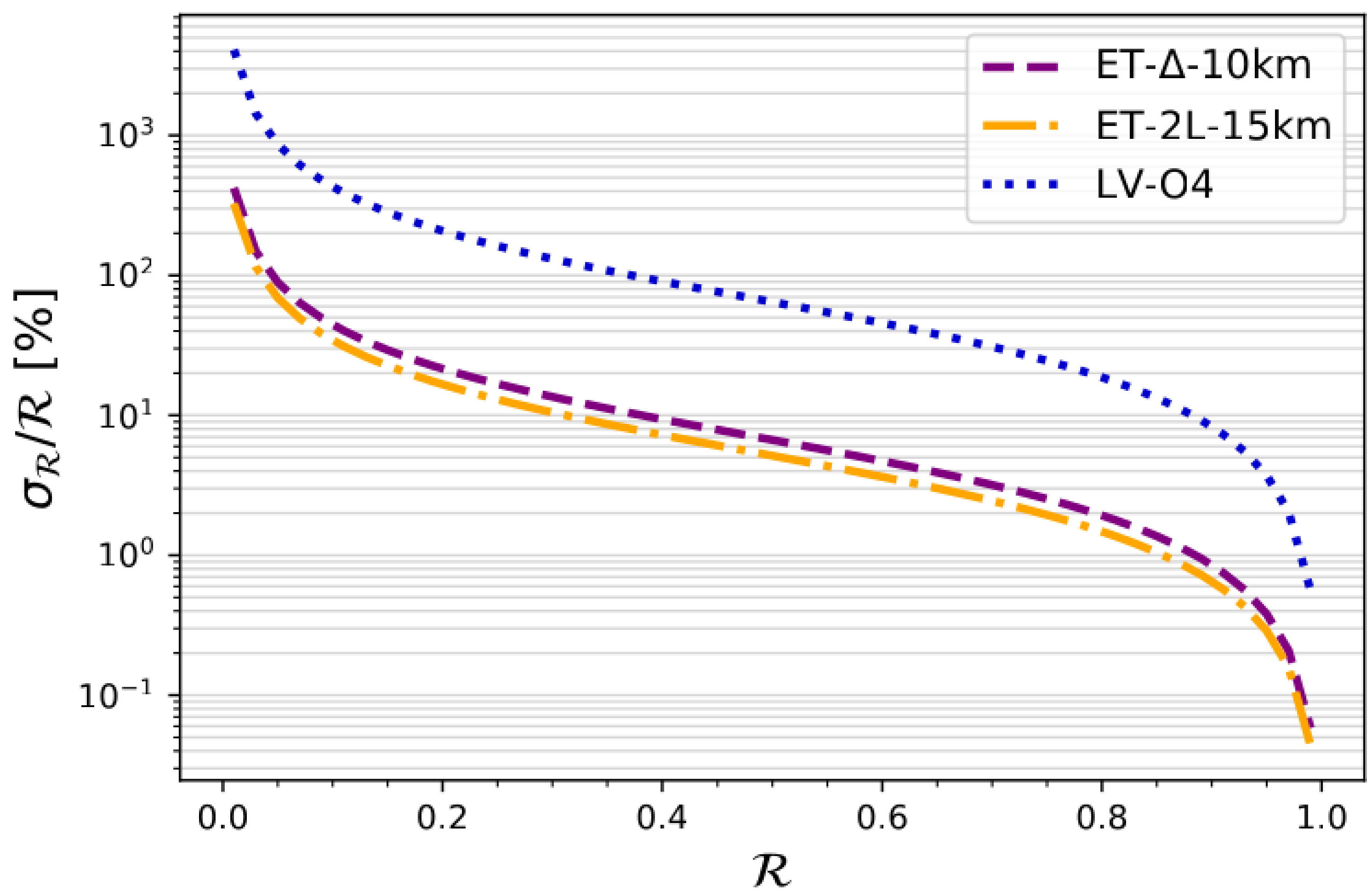
- In GR a black hole is fully described by mass M and spin χ alone — the no-hair theorem
- After merger remnant emits quasi-normal modes — frequencies and damping times uniquely predicted by Kerr
- Measure two independent modes → consistency test — inconsistency signals new physics or exotic compact object
- Left plot: precision on ringdown frequencies f and damping times τ for each mode — right plot: same for amplitudes A and phases φ — blue = LVKI, orange/green = ET — lower = better
- Both plots show ET roughly one order of magnitude better than LVKI — triangle and 2L perform similarly
- ET expects O(10³) ringdowns/year at >10% precision, O(10)/year at 1% — true black hole spectroscopy





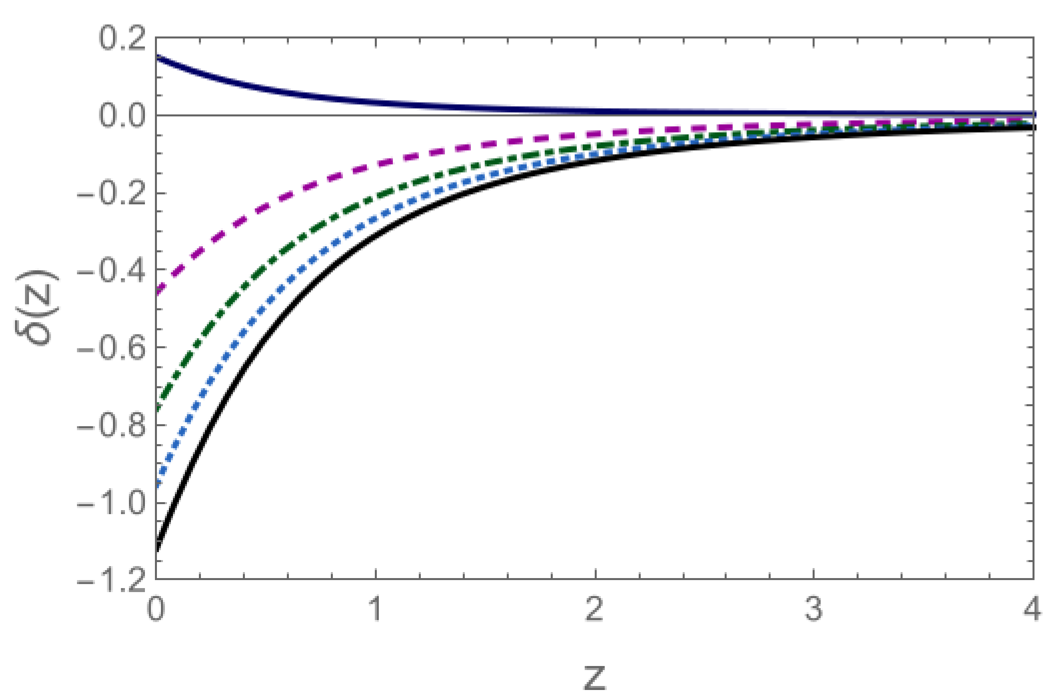
Echoes and Exotic Compact Objects

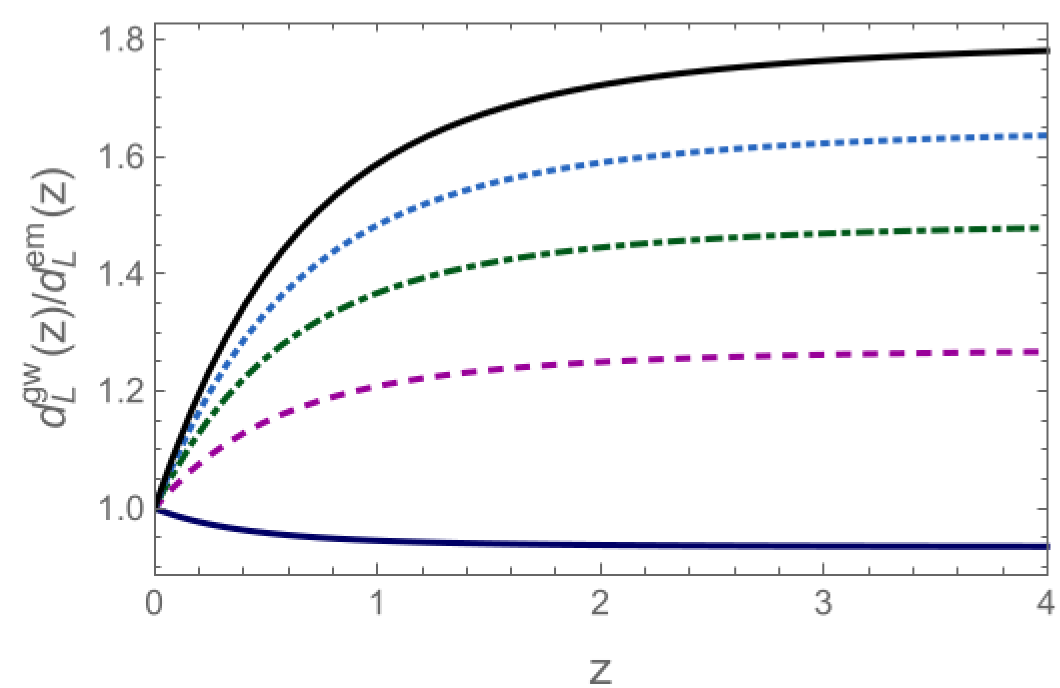
- GR predicts black holes have event horizons — quantum gravity models suggest they may not
- Horizon-less exotic compact objects would produce GW echoes after ringdown — repeated pulses of trapped GWs leaking out — amplitude ∝ surface reflectivity R
- R = surface reflectivity — R=0 is a real black hole, R=1 is a perfect mirror
- Y-axis = fractional measurement error on R — lower = more precisely we can measure it — blue dotted = current detectors, purple/orange = ET
- Current detectors only useful near R=1 — physically trivial — ET probes down to a few percent — where real ECO models live
- Requires ringdown SNR ≥ 100 — ET expects ~5 such golden events per year



Extra GW Polarizations & Modified GW Propagation

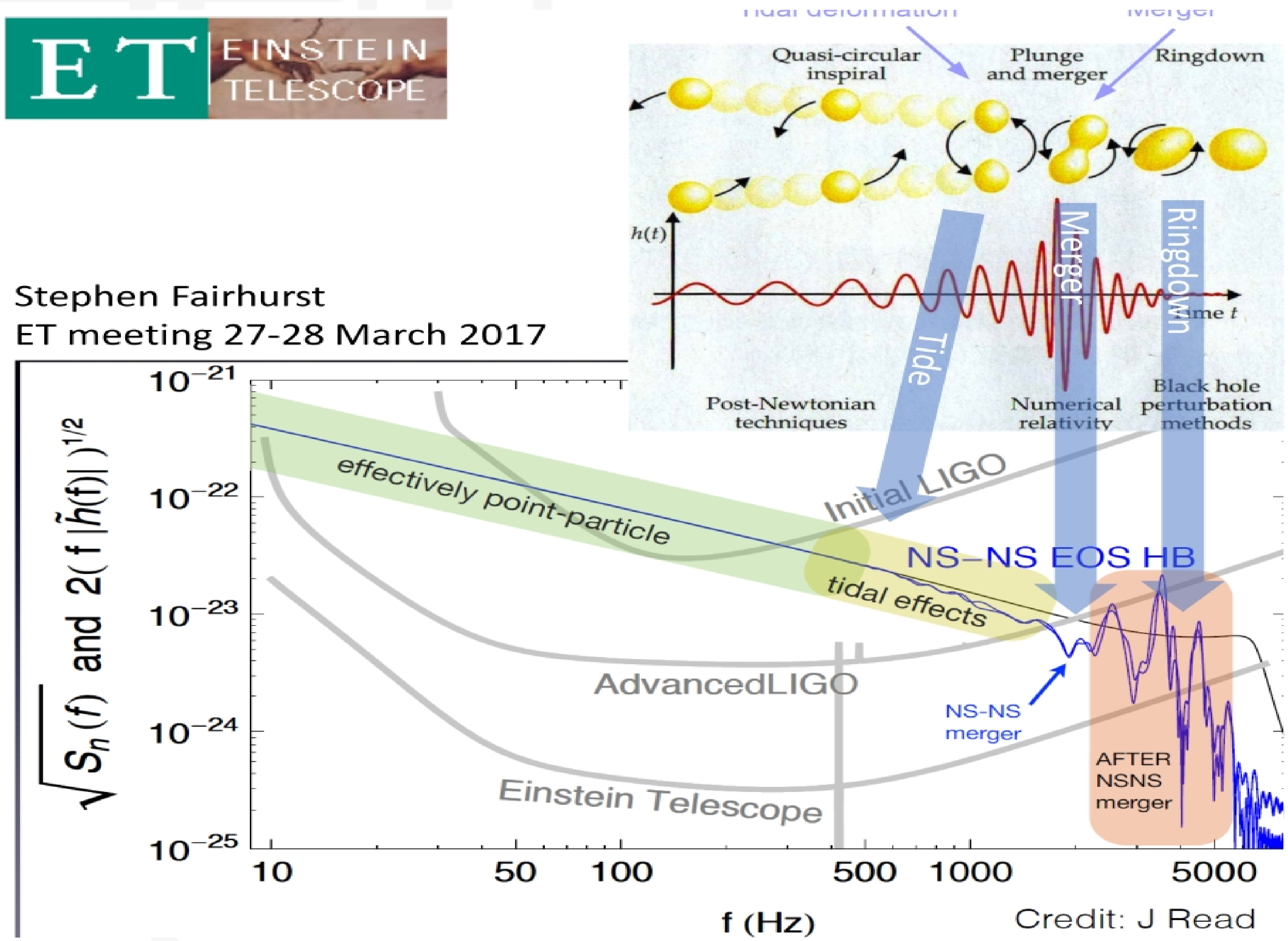
- GR predicts exactly 2 tensor GW polarization modes — many beyond-GR theories allow additional scalar or vector modes, up to 6 in the most general metric theories
- A single L-shaped detector cannot fully reconstruct polarization content — ET triangle with 3 non-coaligned interferometers strongly improves polarization reconstruction — unique geometric advantage of the triangular configuration
- In some modified gravity theories GWs propagate differently from light on cosmological scales — left plot: δ(z) parametrizes this — GR predicts δ=0 flat line, colored curves are example beyond-GR models
- Right plot: modified propagation makes GW luminosity distance differ from EM luminosity distance — GR predicts ratio=1 — deviations grow with redshift — ET's high-redshift sources are especially powerful here
- GW observations provide complementary tests of gravity difficult or impossible to access with electromagnetic observations alone

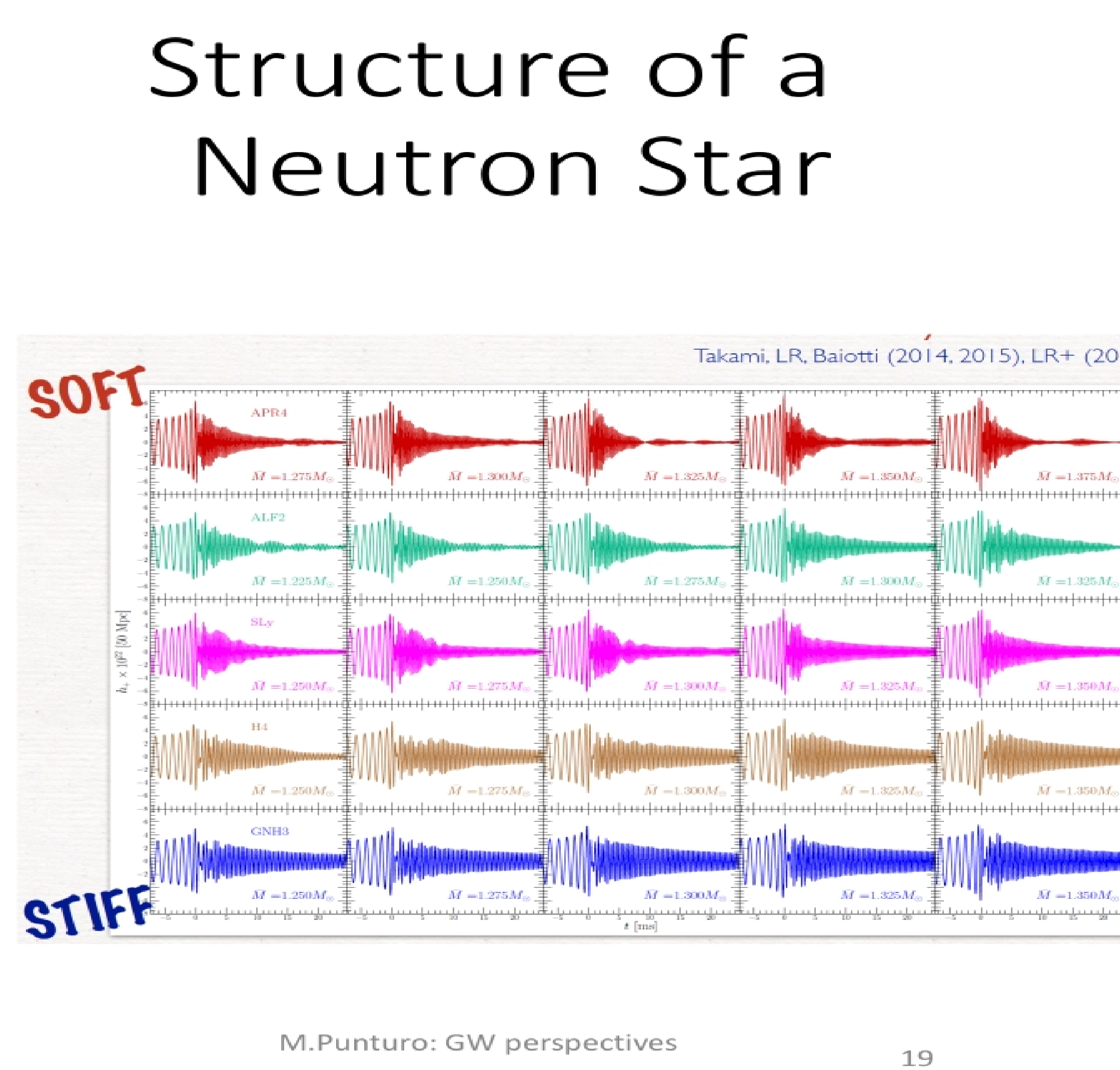




Neutron-Star Physics

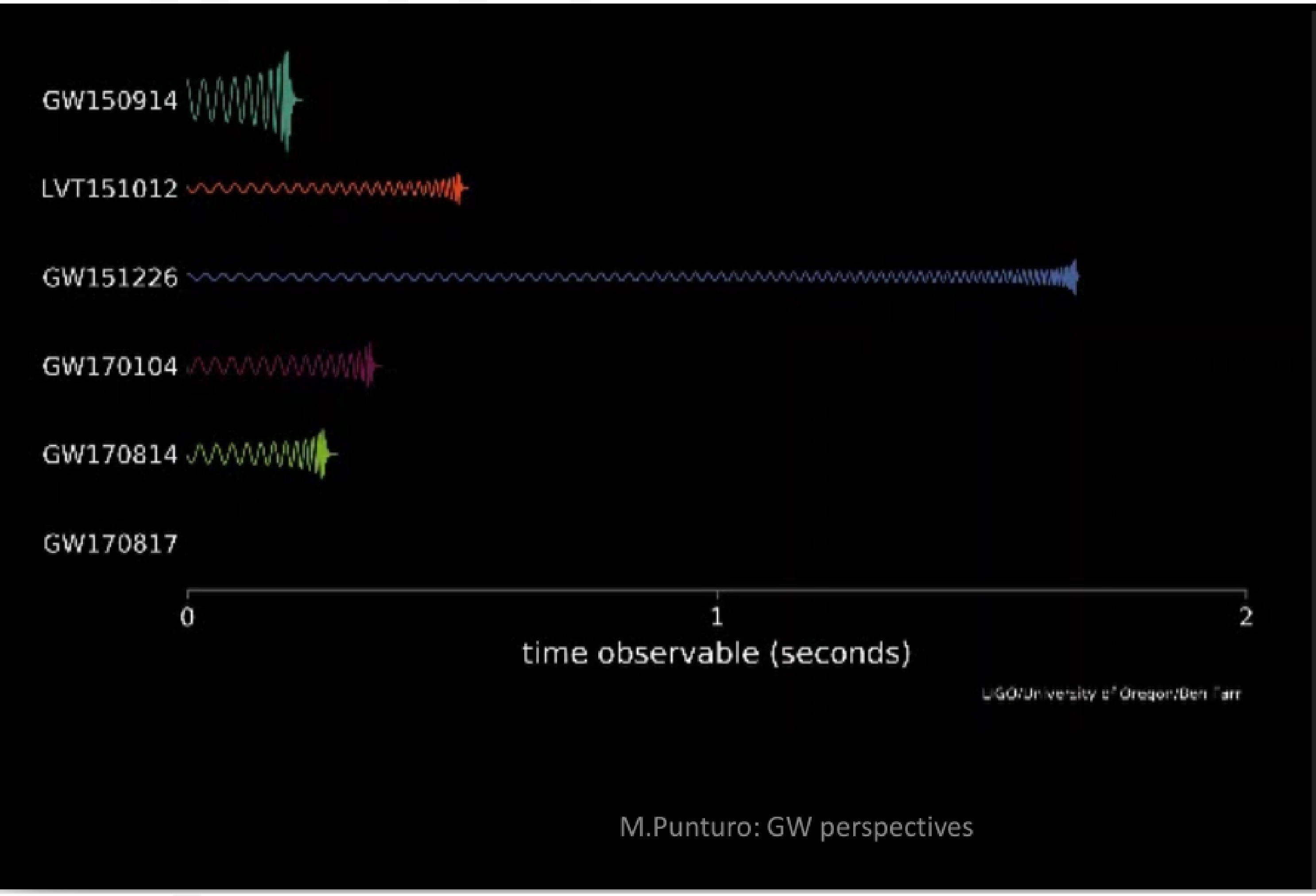
- Neutron stars contain matter at 5–10× nuclear saturation density — no laboratory on Earth can reach this
- Tidal deformability during inspiral probes the EOS at 1–2× saturation density — how much the NS deforms depends on how compressible the matter is
- Post-merger oscillation frequency probes EOS at 2–3× saturation density — the merged remnant oscillates at a frequency set by the internal pressure — no lab can reach this regime
- Left figure: ET sensitivity curve covers both the tidal frequency band (~100–500 Hz) and post-merger band (~2000–5000 Hz) — current detectors miss both completely
- Right figure: each row is a different EOS from soft to stiff — ET distinguishes them cleanly from the post-merger frequency alone
- With O(10^4–10^5) BNS detections per year — statistical EOS constraints at percent level, mapping the full neutron star interior structure

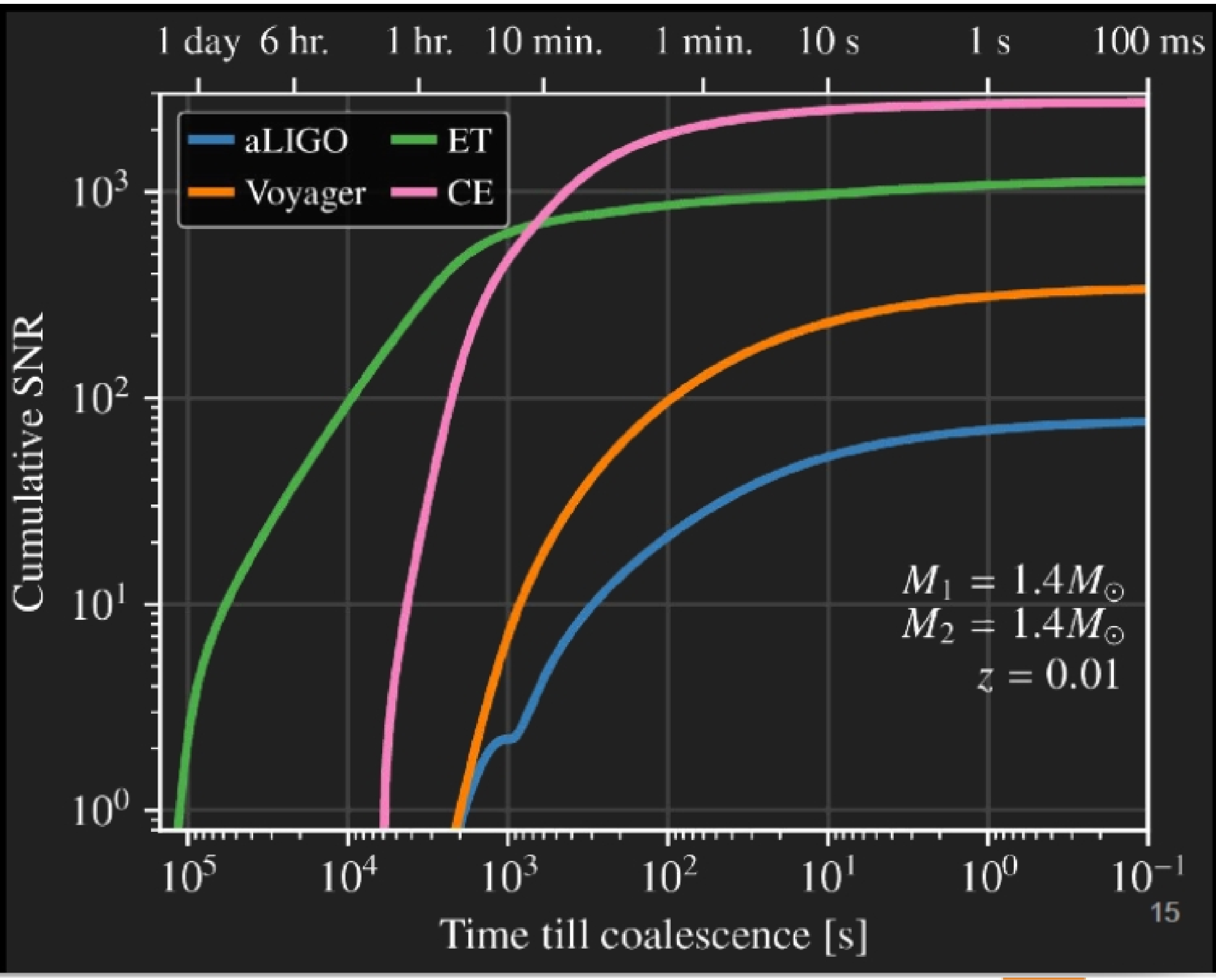




Multi-Messenger Astronomy

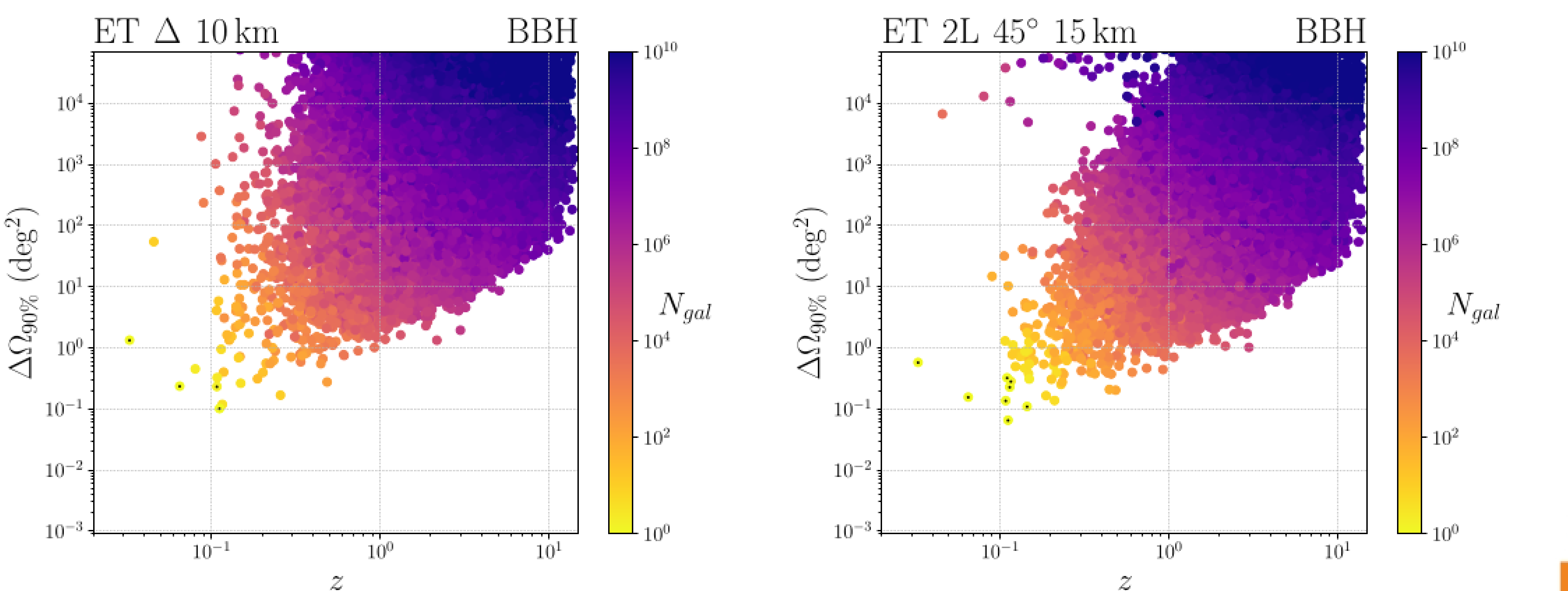
- Current detectors see BNS mergers for only seconds in their sensitive band — left panel shows all O1/O2 signals lasted less than 2 seconds — no time to alert telescopes
- ET's low-frequency sensitivity (~3 Hz) means a BNS system is audible for hours to days before merger
- Right panel: ET (green) accumulates SNR=10 detection threshold more than a day before coalescence — aLIGO (blue) only reaches this in the last few seconds
- This enables early warning alerts — telescopes can be pointed at the source before the first photon is emitted
- Kilonovae, gamma-ray bursts, neutrinos — all arrive after merger — ET sees the system coming and pre-positions every telescope on Earth
- This is only possible because of low-frequency sensitivity — the keyword of ET design





Localization and global 3G network

- X-axis = redshift z, Y-axis = sky localization area — lower means smaller patch of sky, more precise
- Color = number of galaxies in localization volume — yellow = few galaxies, purple = millions — black dots = localized to single galaxy
- ET triangle alone localizes several BBH per year to a single galaxy — host identification and cosmology without any EM counterpart
- ET-2L slightly better — more black dots — both configurations transformative vs current detectors which localize to hundreds to thousands of deg²
- Adding CE improves localization by orders of magnitude — thousands of events per year to <10 deg² — essential for EM follow-up, H0, and multimessenger GR tests



Cosmic Explorer

Overview

- ***Cosmic Explorer (CE) is the planned third-generation GW detector in the United States***
- ***Will be ~40 km long, 10× longer than LIGO arms; Designed to be ~10× more sensitive than current detectors like Advanced LIGO***

Scientific Goals

- ***Detect binary black hole mergers throughout the observable universe; Access early inspirals of neutron stars and black holes down to 1–2 Hz***
- ***Enable precise tests of General Relativity, nuclear physics, and cosmology***

Design and Technologies

- ***Two-phase plan: CE1: based on upgraded Advanced LIGO tech (~2035); CE2: cryogenic mirrors, silicon optics, 1550 nm laser (~2040+)***
- ***Requires new facility in a seismically quiet U.S. location***
- ***Complement to Einstein Telescope***
- ***CE + ET = global 3G network***
- ***Triangulation, sky localization, and early warning for EM follow-up; Jointly open the era of precision GW astronomy***

PART 4: TECHNOLOGICAL CHALLENGES

Technological Challenges Overview

- Underground infrastructure and site noise
- Seismic isolation and Newtonian noise
- Cryogenic payloads
- Optics, coatings, and materials
- Quantum noise reduction
- Controls, computing, and AI
- Most of the challenges listed here has no existing solution at ET scale — this is frontier technology development, not engineering known problems

ET key elements

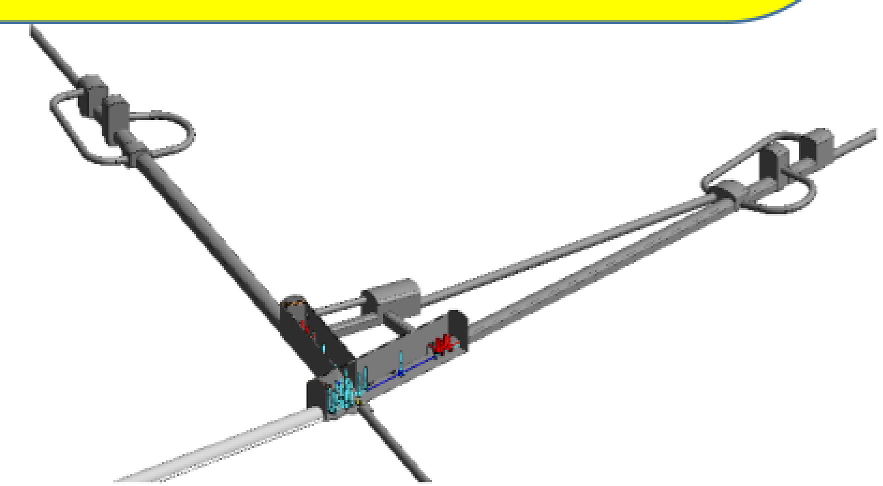
Requirements

- Wide frequency range
- Massive black holes (LF focus)
- Localisation capability
- (more) Uniform sky coverage
- Polarisation disentanglement
- High Reliability (high duty cycle)
- High SNR

Design Specifications

- Xylophone (multi-interferometer) Design
- Underground
- Cryogenic
- Triangular shape
- Multi-detector design
- Longer arms

ET EINSTEIN TELESCOPE

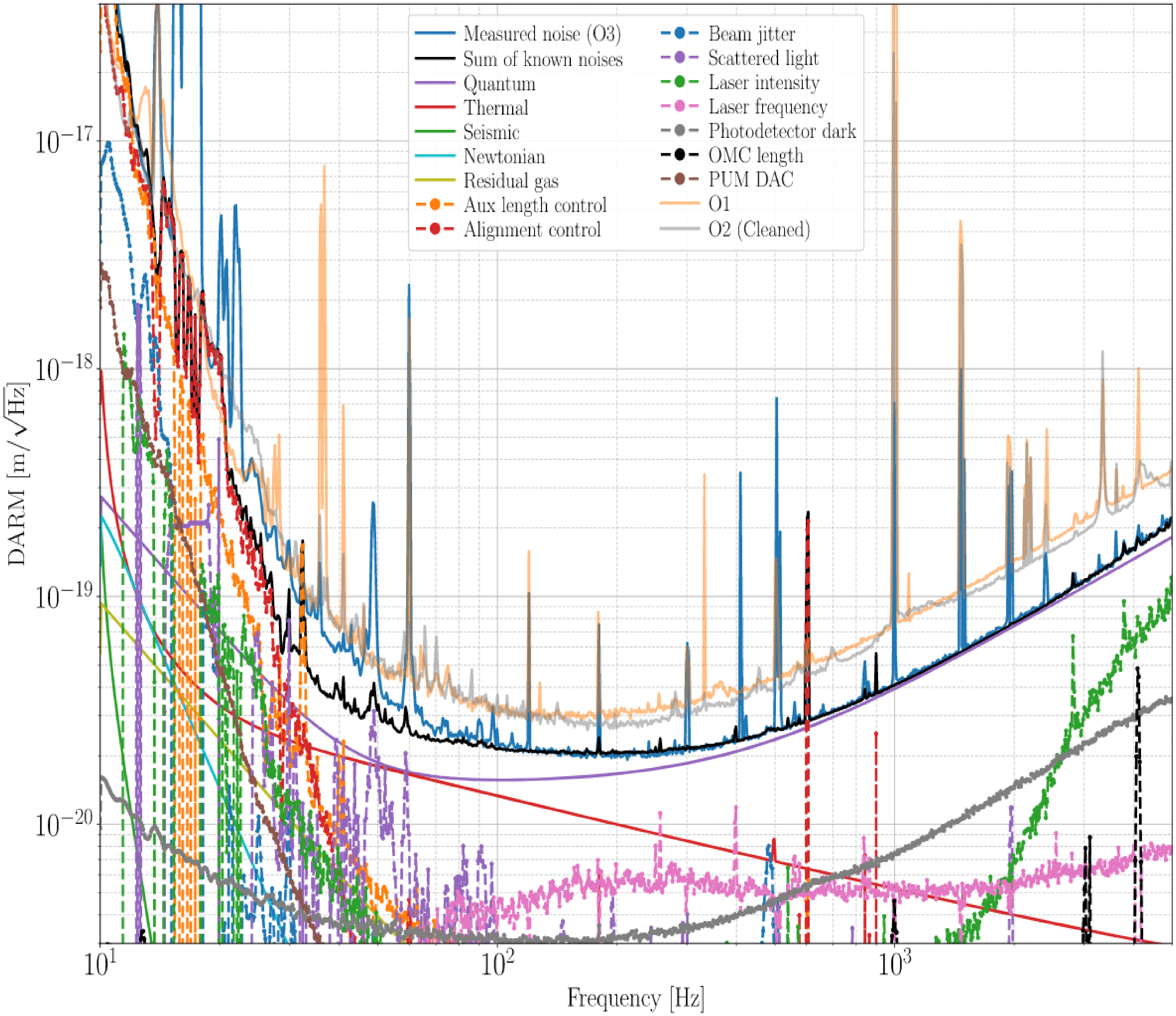


Underground Infrastructure Challenges

- **~30km of underground tunnels**
  - Safety (fire, cryogenic gasses, escape lanes, heat handling during the vacuum pipe backing)
  - Noise (creeping, acoustic noise, seismic noise, Newtonian noise)
  - Minimisation of the volumes, but preservation of future potential)
  - Water handling, hydro-geology and tunnels inclination
  - Cost
- **Large caverns**
  - In addition to the previous points:
  - Stability
  - Cleanliness
  - Thermal stability
  - Ventilation and acoustic noise

Noises

- $\Delta L = 10^{-19}$ m
- Displacement (thermal, seismic, controls) and sensing (shot, frequency, PD dark) noises
- Fundamental (suspension thermal, coating Brownian, quantum) and technical (electronics, from controls loops, scattered light) noises



- Noise budget at LIGO Hanford observatory during O3 science run. Figure taken from https://ccahilla.github.io/lho_noisebudget.svg

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Instrumental Noise

Environmental noise
- Seismic
- Atmospheric
- Electromagnetic

Mitigation
- Isolation
- Noise cancellation
- Control

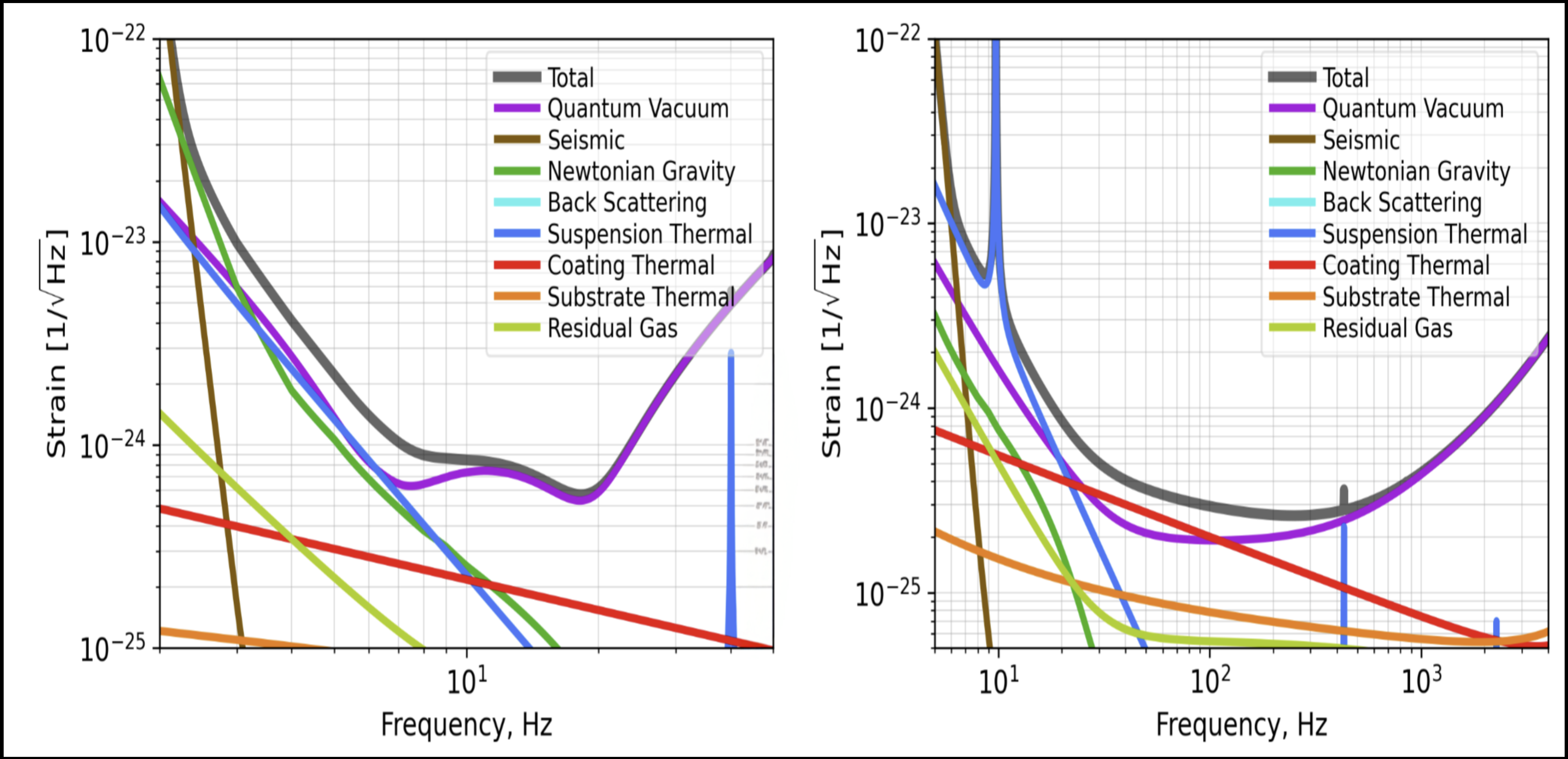
Intrinsic noise
- Thermal
- Sensing and control

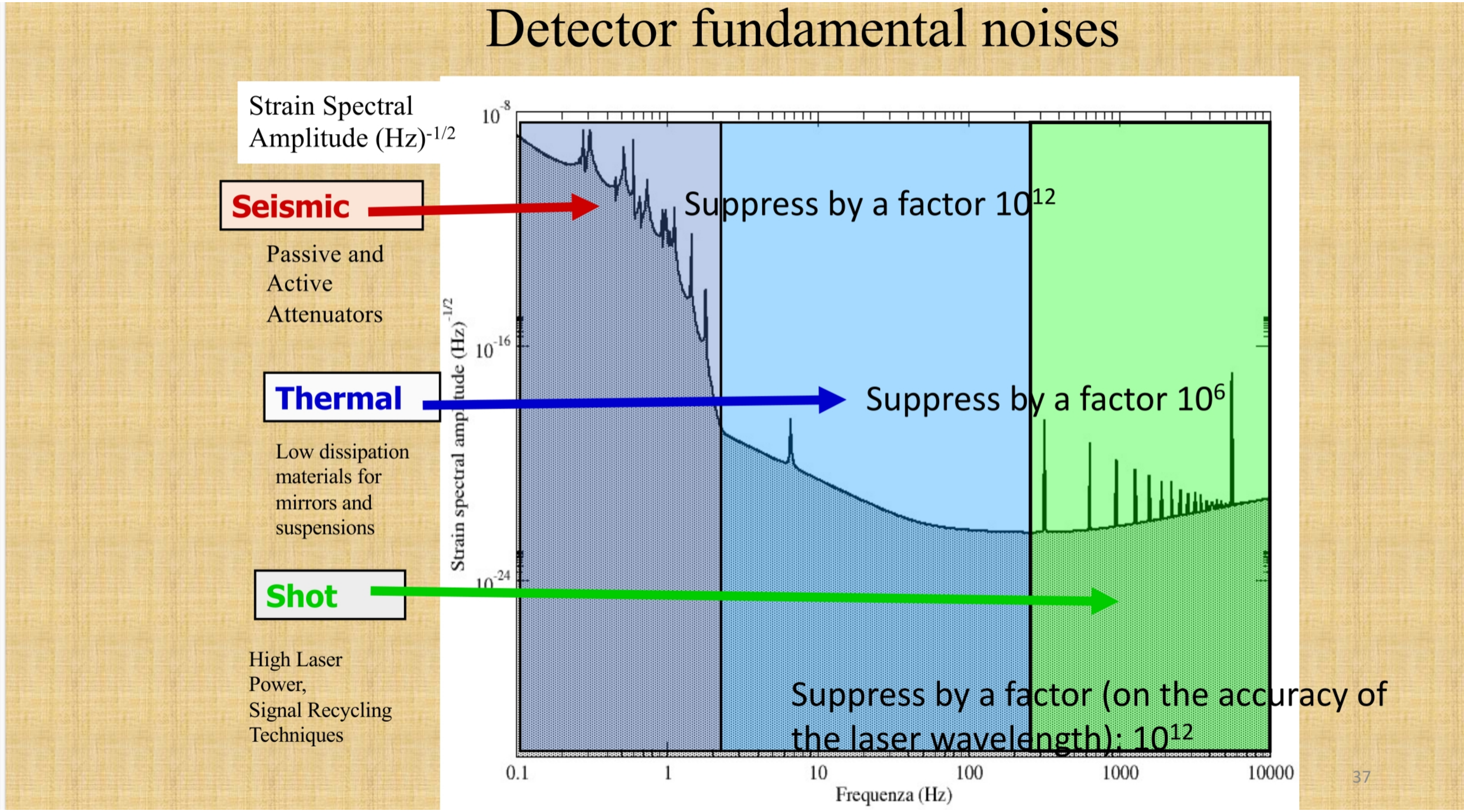
Mitigation
- Lower temperature
- Increase material quality
- Improve sensors
- Optimize control

Quantum noise
- Vacuum fluctuations
- Back action

Mitigation
- Quantum-non-demolition
- Reduce decoherence
- Manipulate quantum state

ET Noise Bugdet





Slide taken from C. Palomba (Neutron star physics with gravitational waves)

Major Technological Challenges

ET-HF

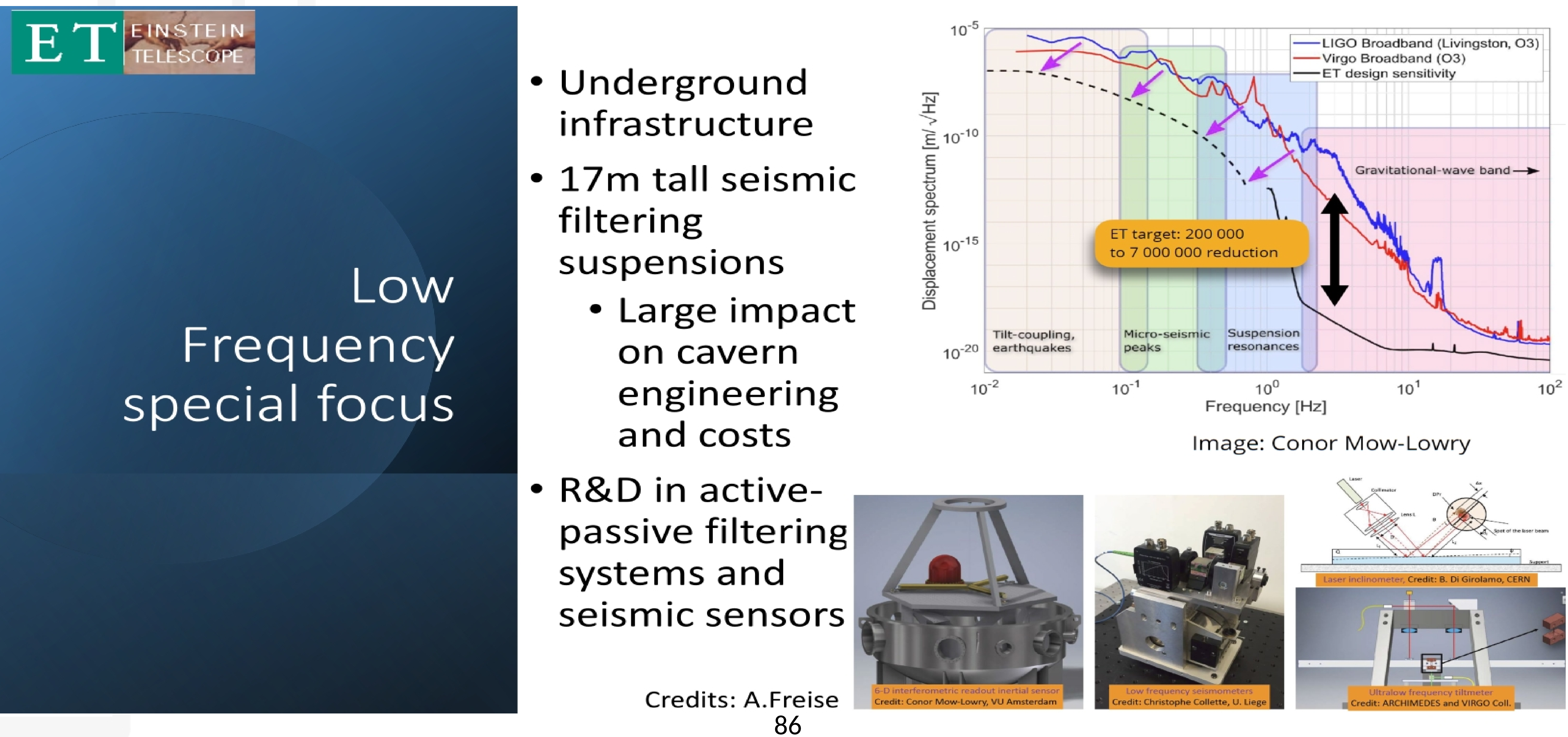
- High-power laser and laser stabilization
- Thermal compensation system
- High-levels of effective squeezing

ET-LF

- Low-noise cooling of the payload
- Low-noise interferometer control
- Fabrication of test masses and suspensions
- Modeling the environment and mitigating its effects

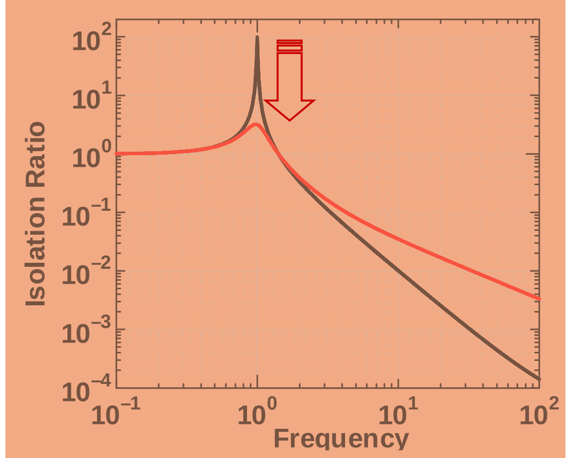
Seismic Isolation and Low-Frequency Noise

- Underground reduces seismic by ~factor 100–1000 vs surface at 1–10 Hz — but alone not sufficient — ET needs 200,000 to 7,000,000× seismic reduction
- 17m tall super-attenuator — cascaded pendulum system, 6 stages, each stage filters seismic above its resonance frequency — the taller the chain, the lower the resonance, the better the isolation at low frequency
- The super-attenuator is so tall it drives the cavern height — this is why corner caverns must be large underground halls, not just tunnels — direct cost impact
- Newtonian noise — cannot be filtered mechanically, only subtracted using seismometer arrays around the detector
- Active-passive hybrid systems + new low-frequency seismometers currently under R&D — essential to reach ET's 2–3 Hz target



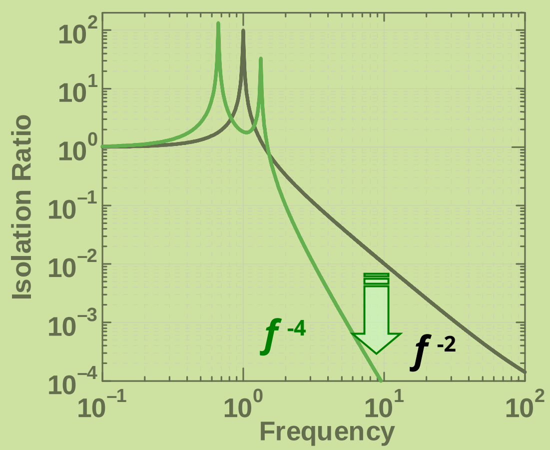
Seismic Isolation

Damping
Lower peak height



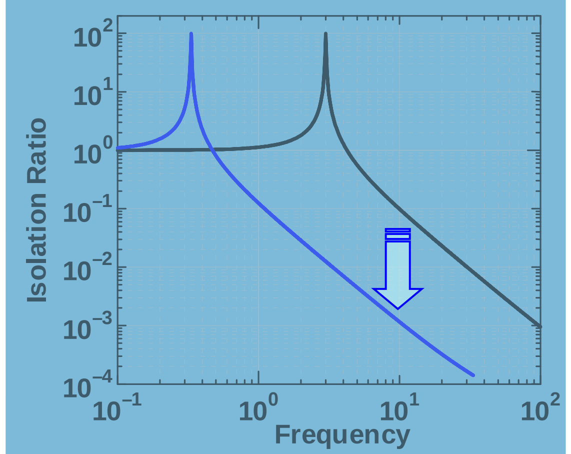
Less isolation

Cascaded
Steeper isolation curve



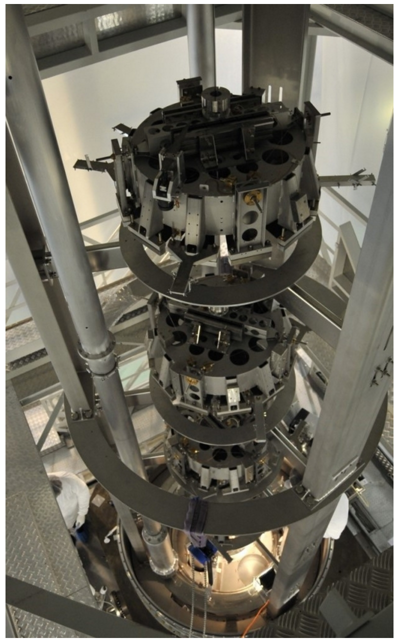
More peaks

Larger structure
Lower resonance frequency



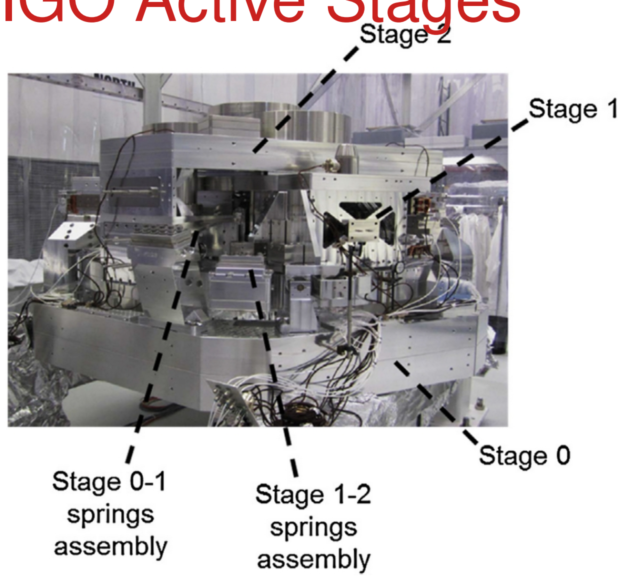
Difficult to realize

Virgo Superattenuator



In pratice: use combination of these methods and enhance the performance with active isolation (create the best combination of the Virgo/LIGO isolation concepts)

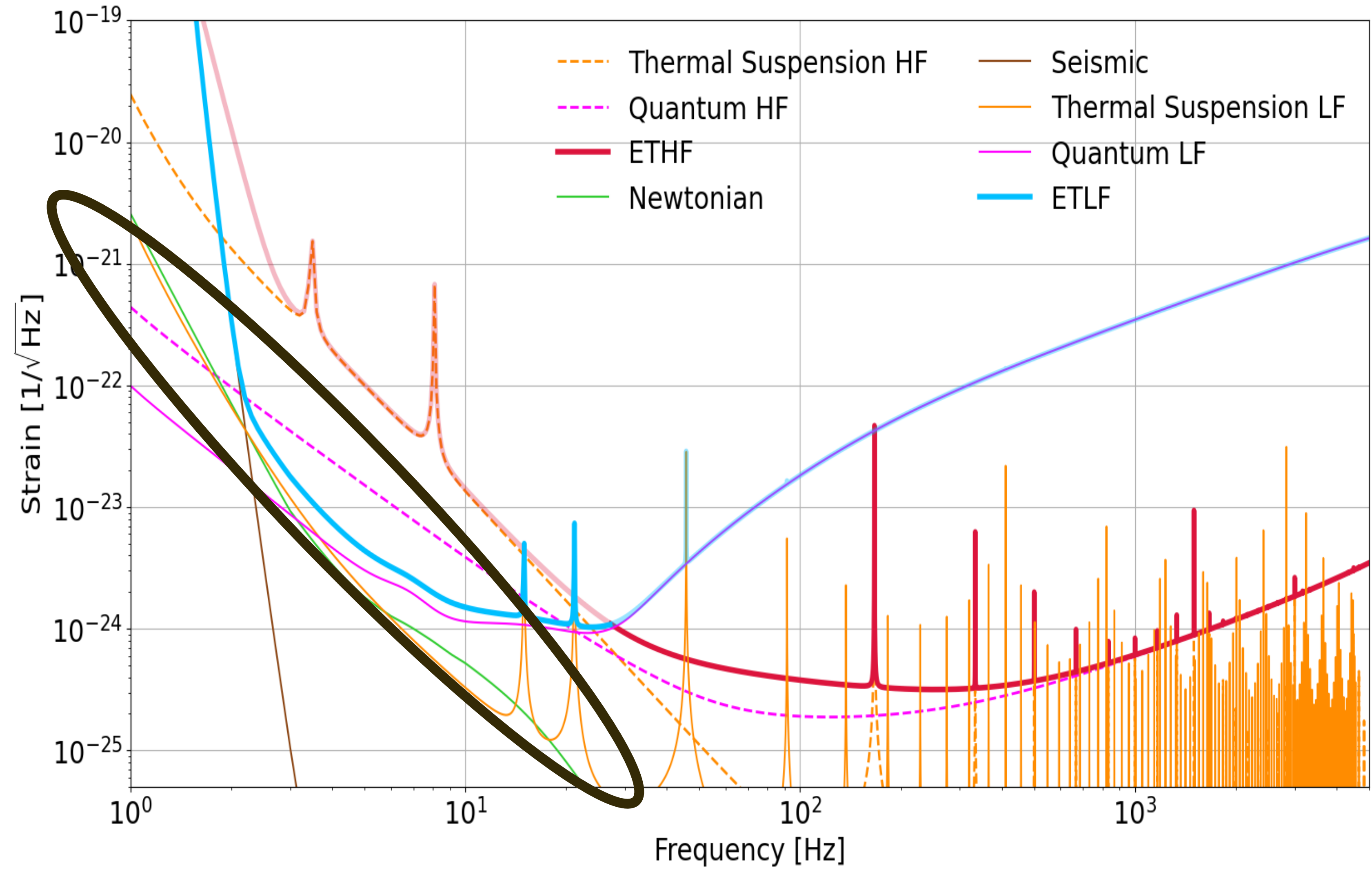
LIGO Active Stages

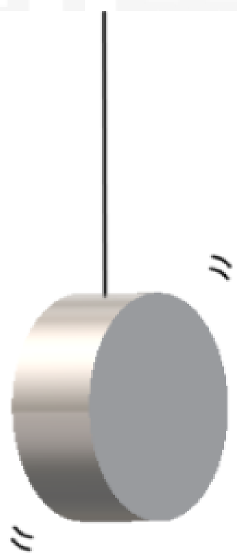


- **Single pendulum** isolates above resonance as f^{-2} — but resonance peak causes large mirror motion — damping reduces peak but does not improve isolation
- **Cascaded pendulums** (Virgo superattenuator concept): N stages → isolation scales as f^{-2N} — 6 stages gives f^{-12} — dramatically steeper but introduces multiple resonance peaks requiring active damping
- **Longer pendulum** → lower resonance frequency → isolation starts at lower frequency — ET needs resonance below 0.1 Hz → requires **17m tall suspension chains**
- **ET solution**: combine both concepts — passive cascaded chain (Virgo-style) for steep isolation + active seismic pre-isolation platform (LIGO-style) to damp resonance peaks — **best of both worlds**
- Active platform uses **inertial sensors and actuators** to measure and cancel low-frequency motion before it enters the passive chain — extends effective isolation down to ~0.01 Hz

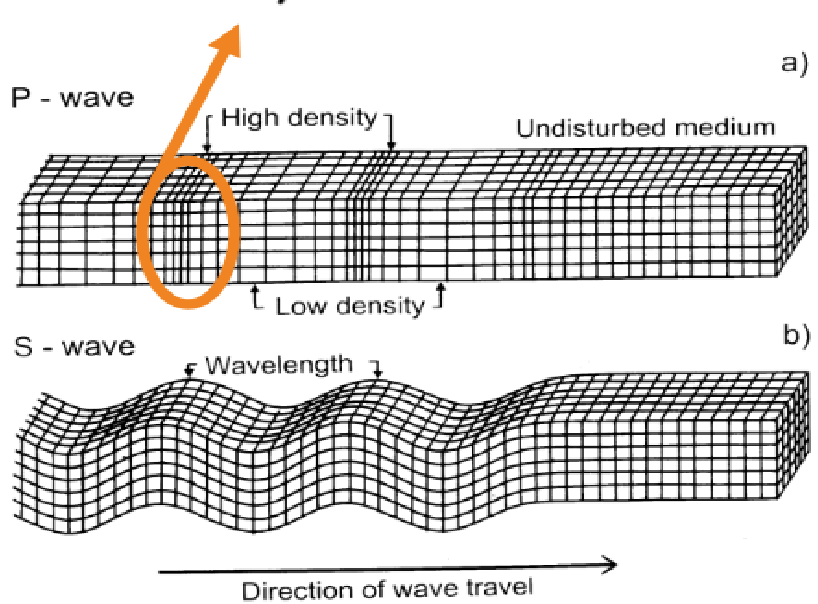
Seismic and Newtonian Noise

- Seismic Newtonian noise:
  1. Seismic surface displacement
  2. (De)compression of rock
  3. Displacement of underground cavern walls

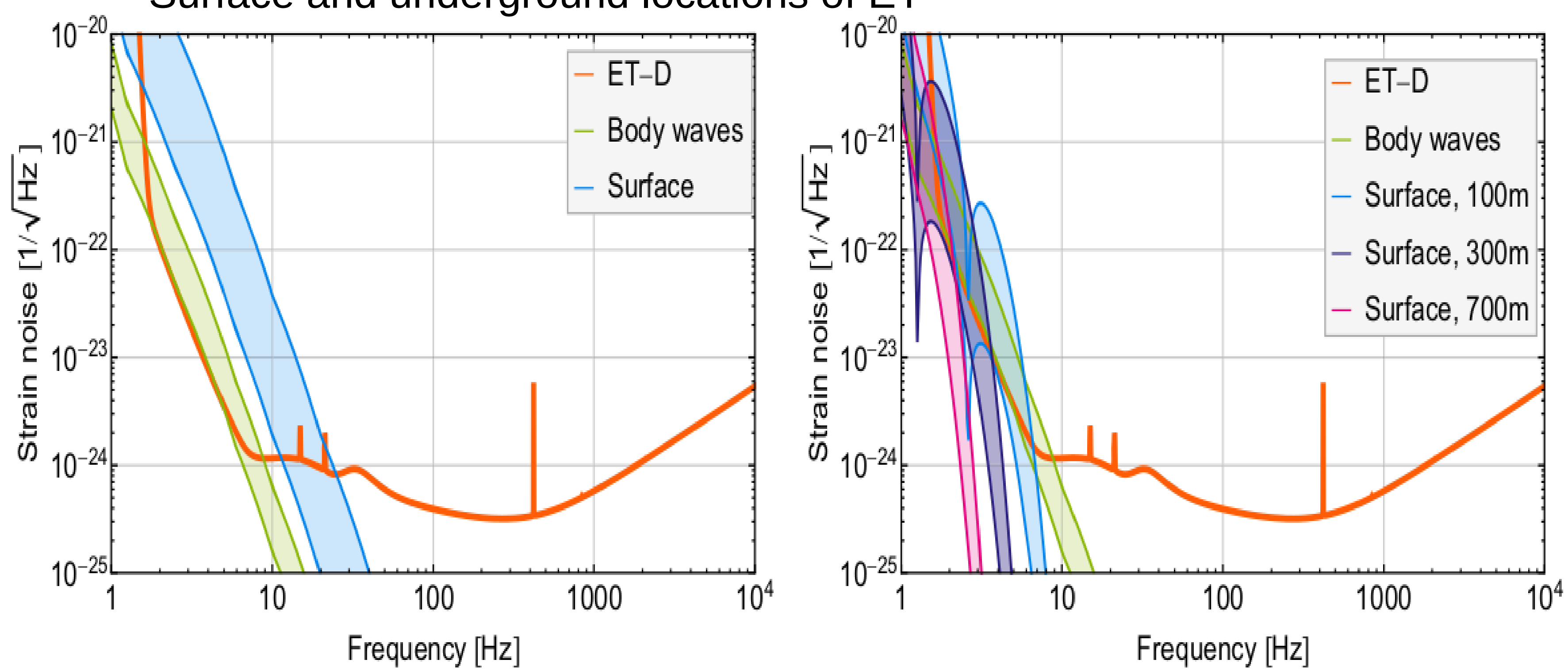




$$\delta\rho \rightarrow NN$$



- Surface and underground locations of ET



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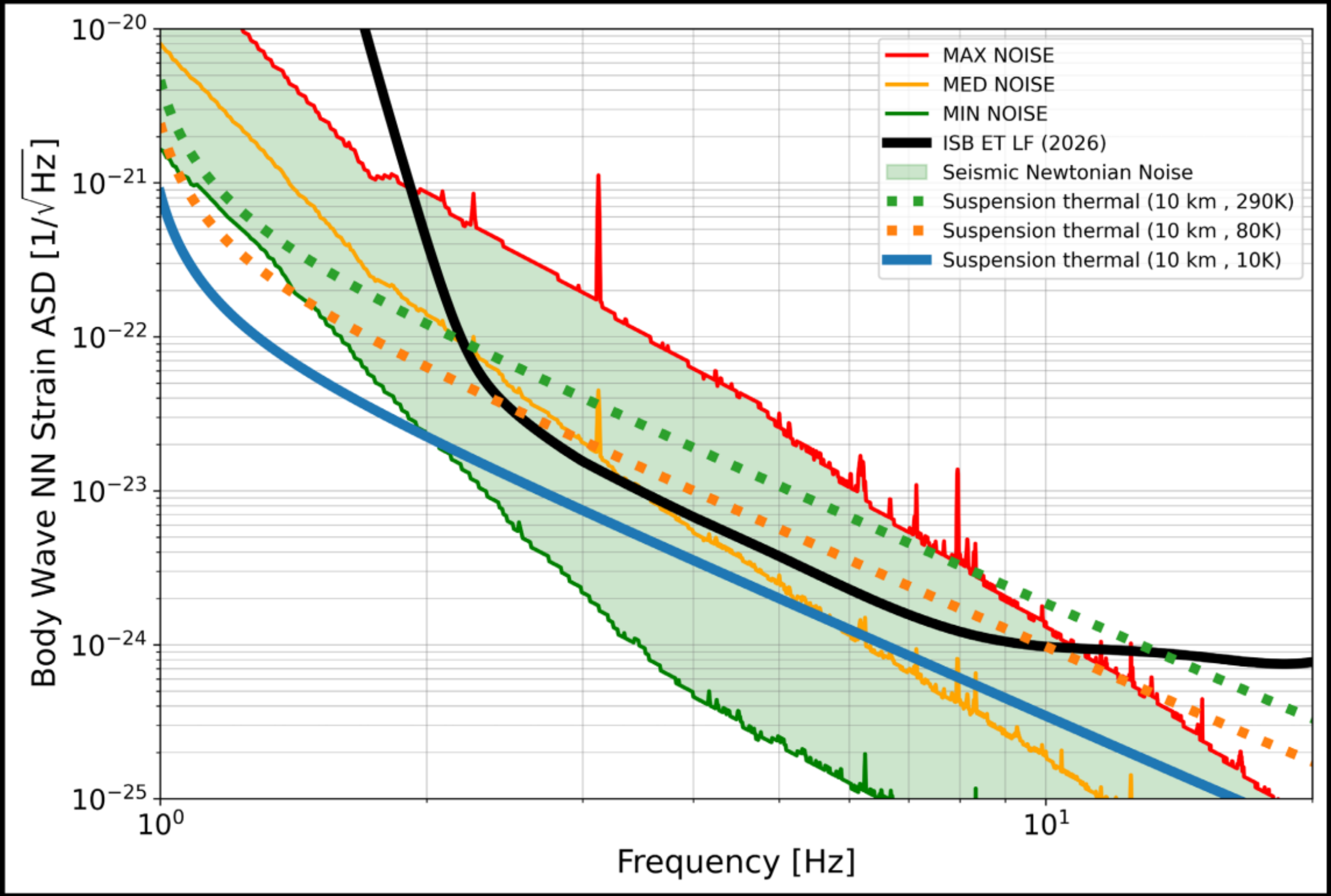
Seismic and Newtonian Noise

G S S I

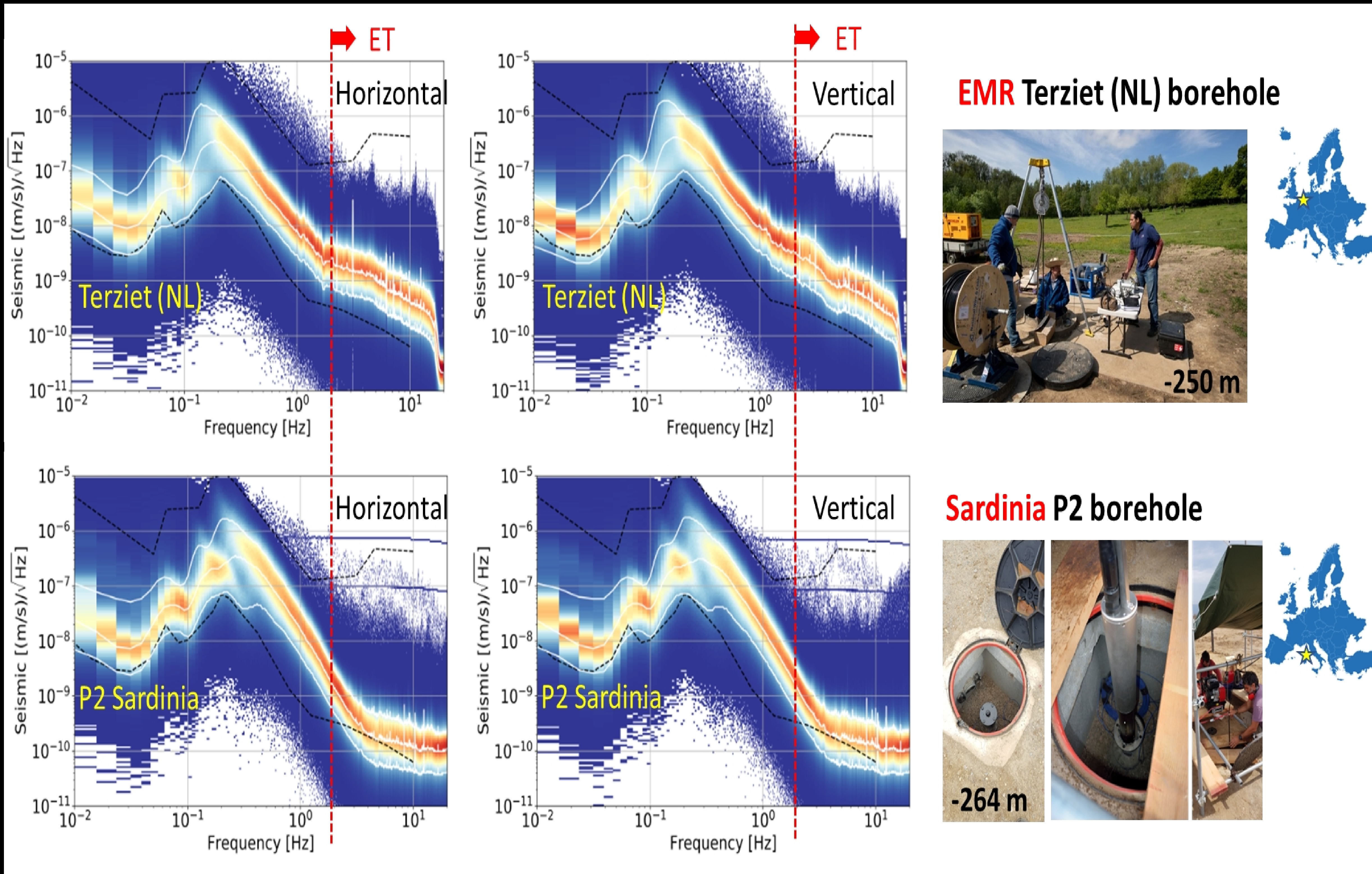
The importance of site selection for the ET design

INFN

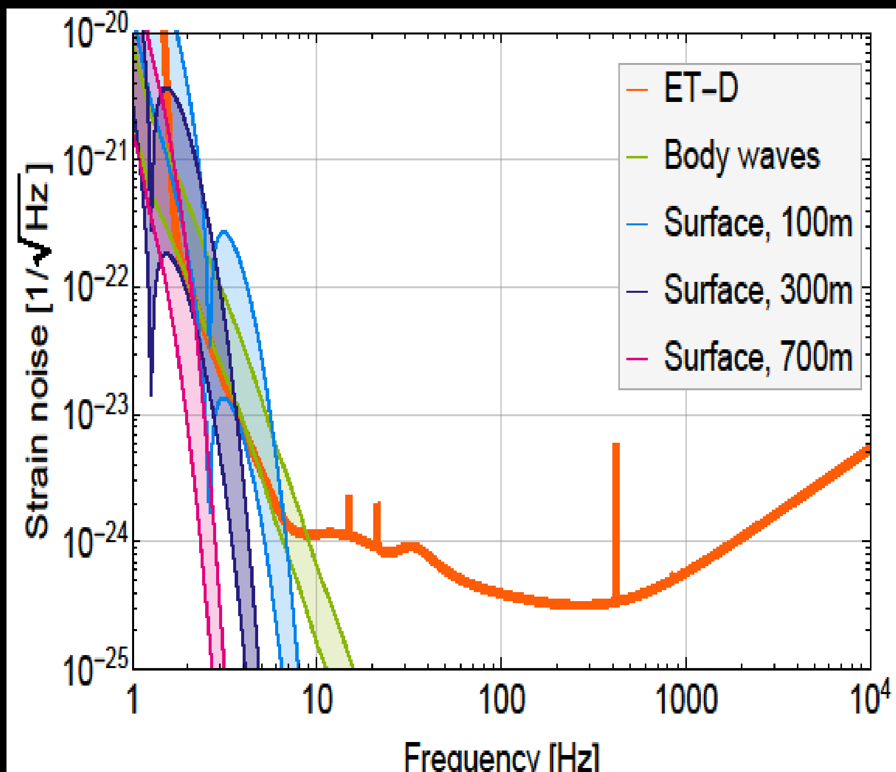


- The range of seismic noise in boreholes across sites is about a factor 100 (10^{th} perc at quietest site to 90^{th} perc at loudest site)
- ET-LF design depends on site quality

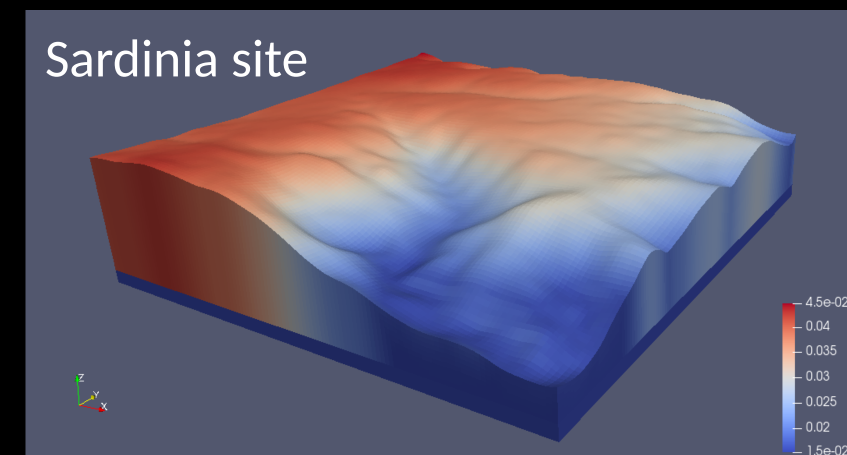
Seismic Ground Motion

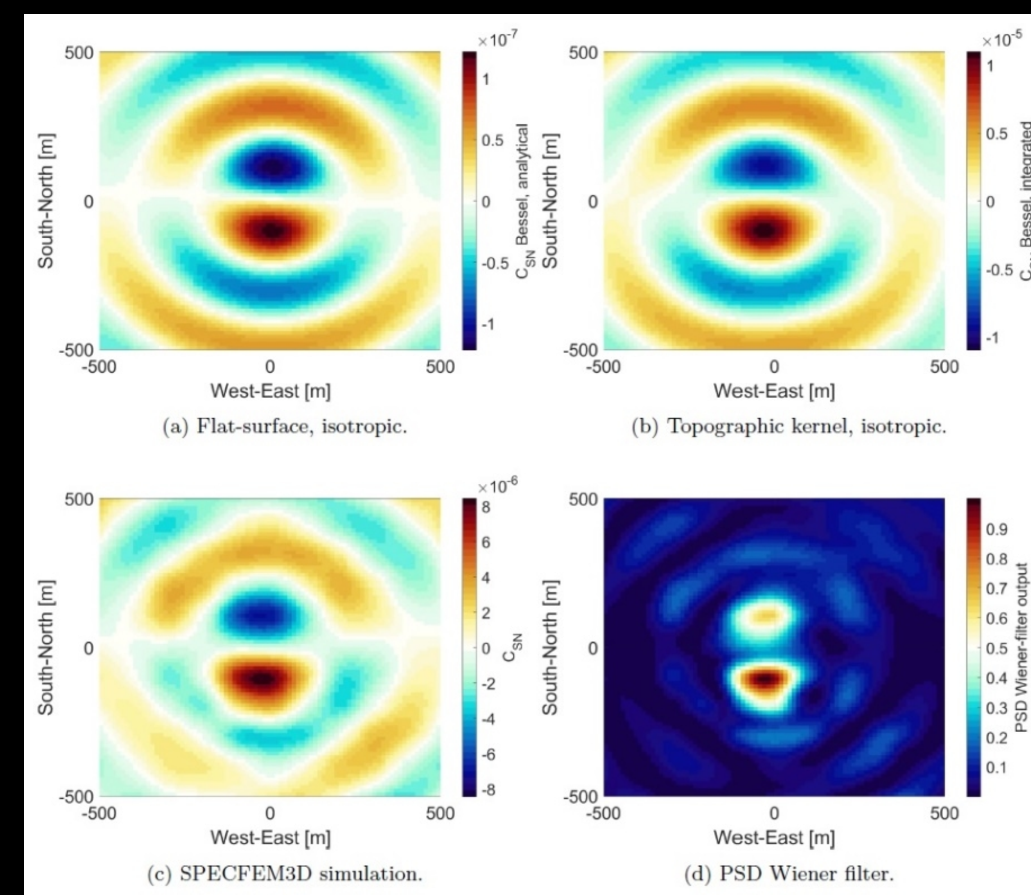


Newtonian-noise Mitigation



Simulations + data for array optimization

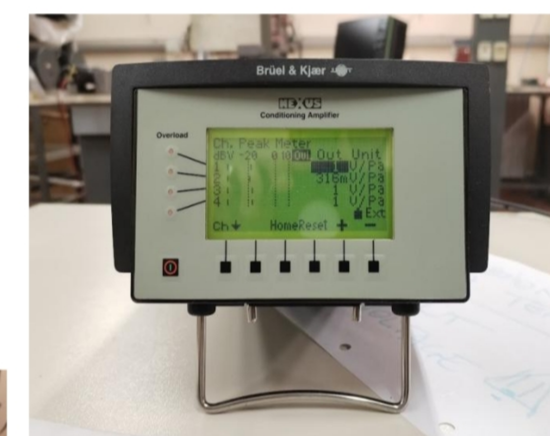




- Hundreds of borehole seismometers
- Probably one can only deploy one seismometer per borehole
- High cost, complexity, risk…

Atmospheric Newtonian Noise

- **Atmospheric NN has three mechanisms**: infrasound pressure waves, advected temperature/humidity fields carried by wind, and turbulent pressure fluctuations (Lighthill process) — each with different frequency dependence
- **Infrasound NN** — dominant above ~1 Hz at surface — suppressed **exponentially with depth** as $e^{(-\omega z/c_{sound})}$ — at 200m underground and 10 Hz, essentially eliminated — **strongest physical argument for underground construction**
- **Advected temperature fields** — wind carries density inhomogeneities past detector — very steep spectrum ($\omega^{-(p+7)}$, $p \approx 2/3$) — potentially dominant below ~1 Hz — suppression with depth **poorly understood, active research area**
- **Residual concern**: internal cavern air flow — ventilation systems, pumps, thermal convection inside the tunnels — must be carefully controlled since external suppression does not help with internal sources
- **Mitigation strategy**: dense arrays of microphones + seismometers around detector measure the field → coherent cancellation (NNC) — wind shields on microphones reduce turbulence contamination of the sensor signal — interferometric seismometers (van Heijningen, Collette) provide sensitivity beyond commercial standards needed for effective subtraction



Magnetic Noise

What it is

- Ambient EM fields couple to the detector via magnetized components and electronics/cabling
- Relevant from ~1–100 Hz, potentially limiting for ET-LF

Why it matters for ET

- Below a few ×10 Hz, dominant couplings act on coil-magnet actuators / suspension hardware / benches
- At higher f, coupling shifts toward cables, electronics and grounding

Main risk

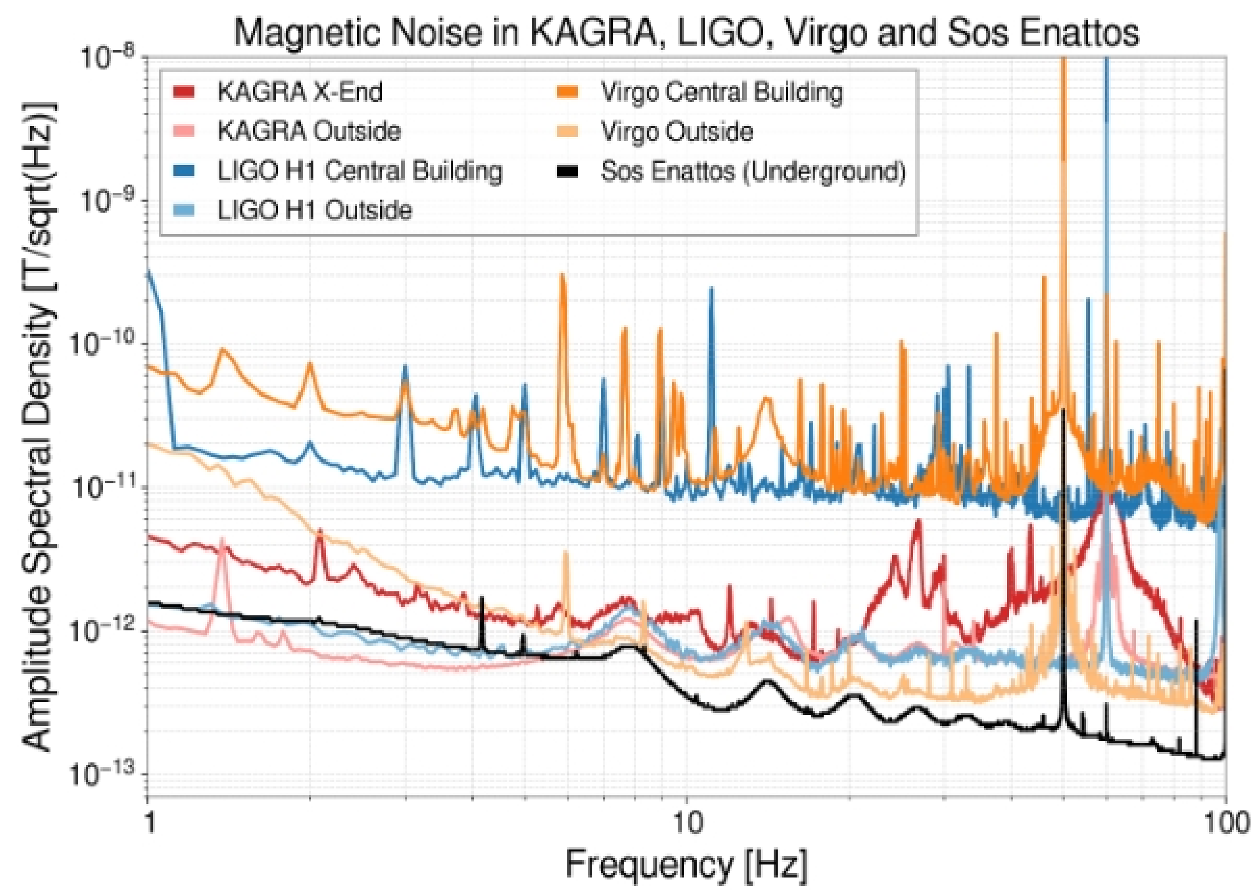
- “Self-inflicted” infrastructure noise can dominate → mitigation must be designed-in (power distribution, routing, EMC discipline, zoning)

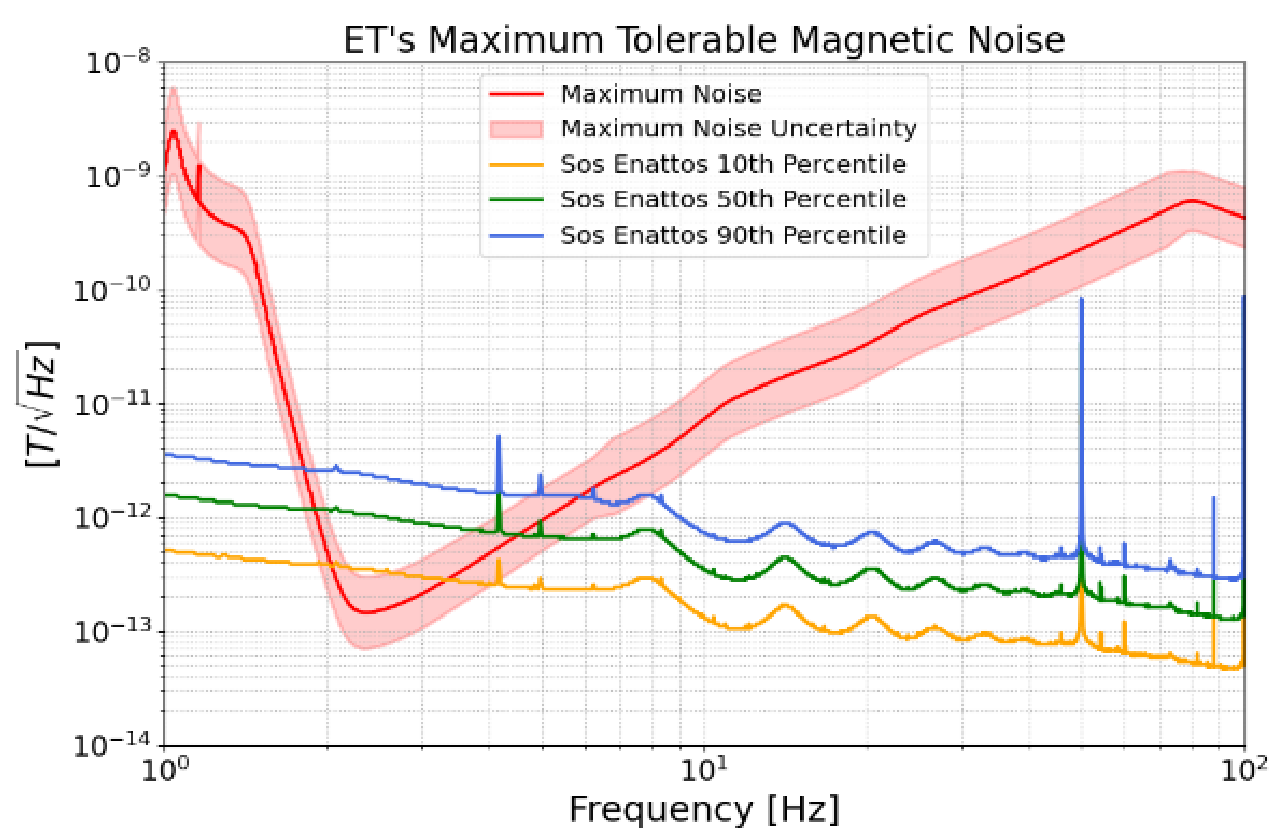
Design target

- ET requires ambient magnetic noise near geomagnetic background + reduced coupling (low magnetic moment, screening, shielding where needed)

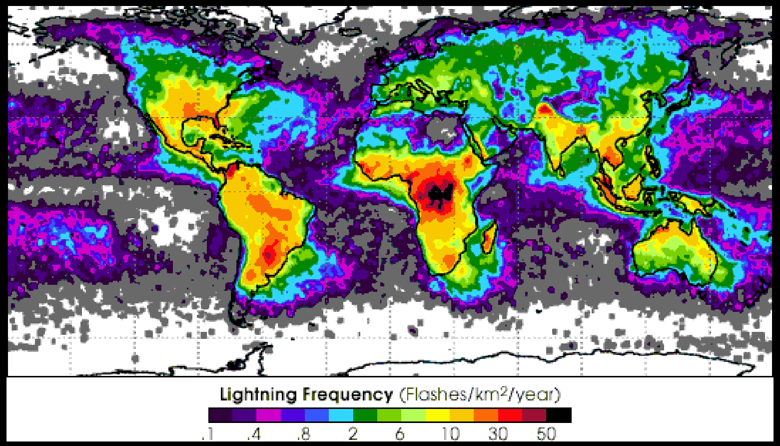
What must be delivered (next years)

- Site qualification + infrastructure rules and a validated coupling/mitigation budget (requirements → design choices)





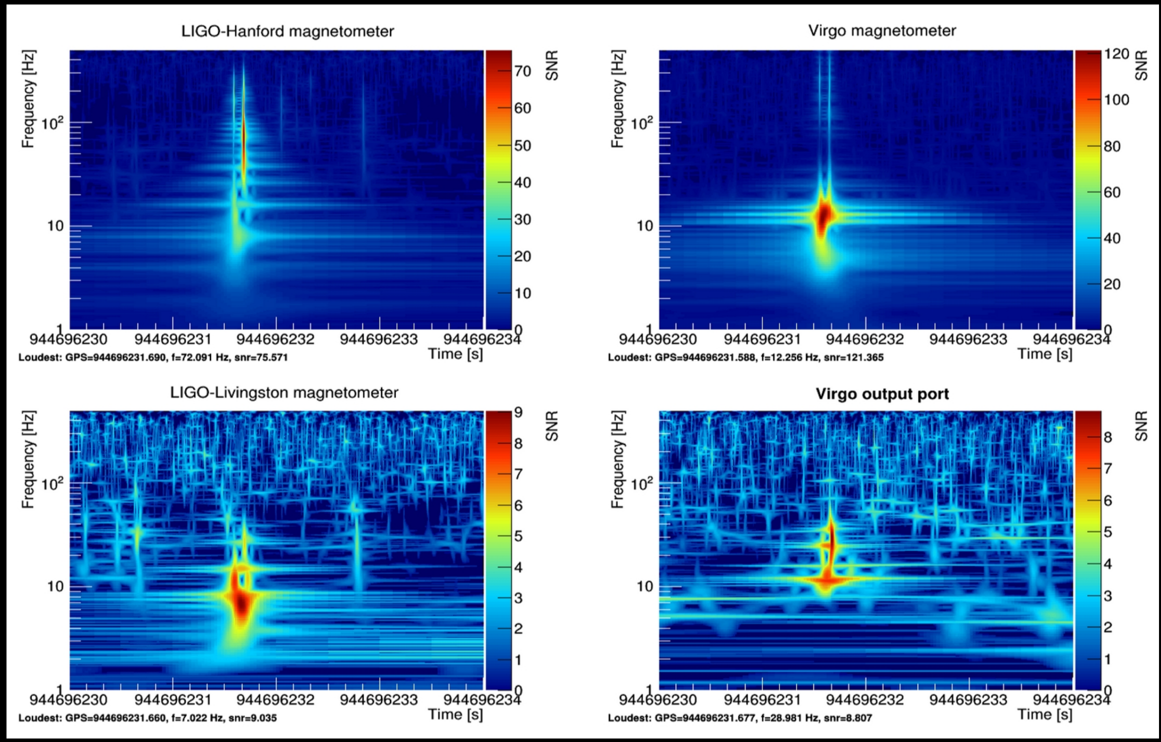
Magnetic Fluctuations



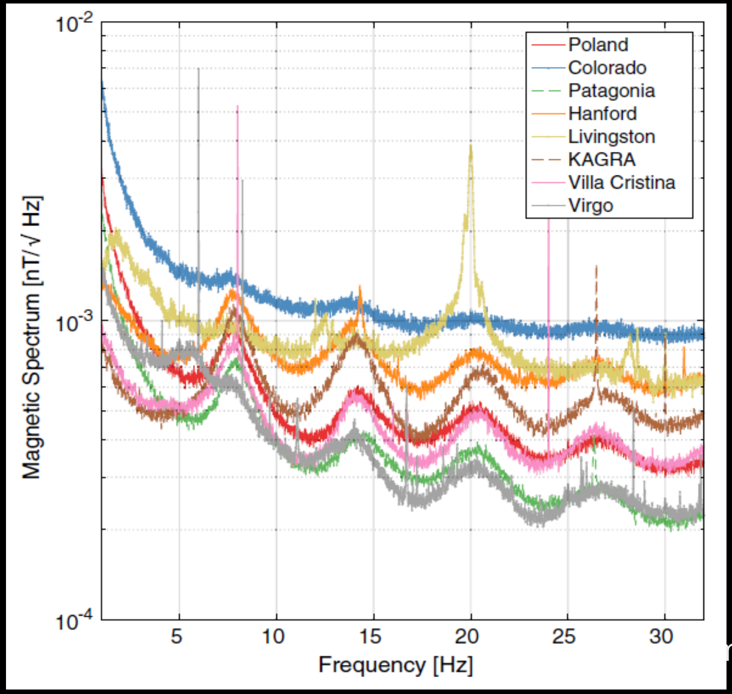
Magnetic disturbances can appear coherently in a global detector network.

Lightning transient can be coincident

Schumann resonances



Globally coherent disturbances and noise



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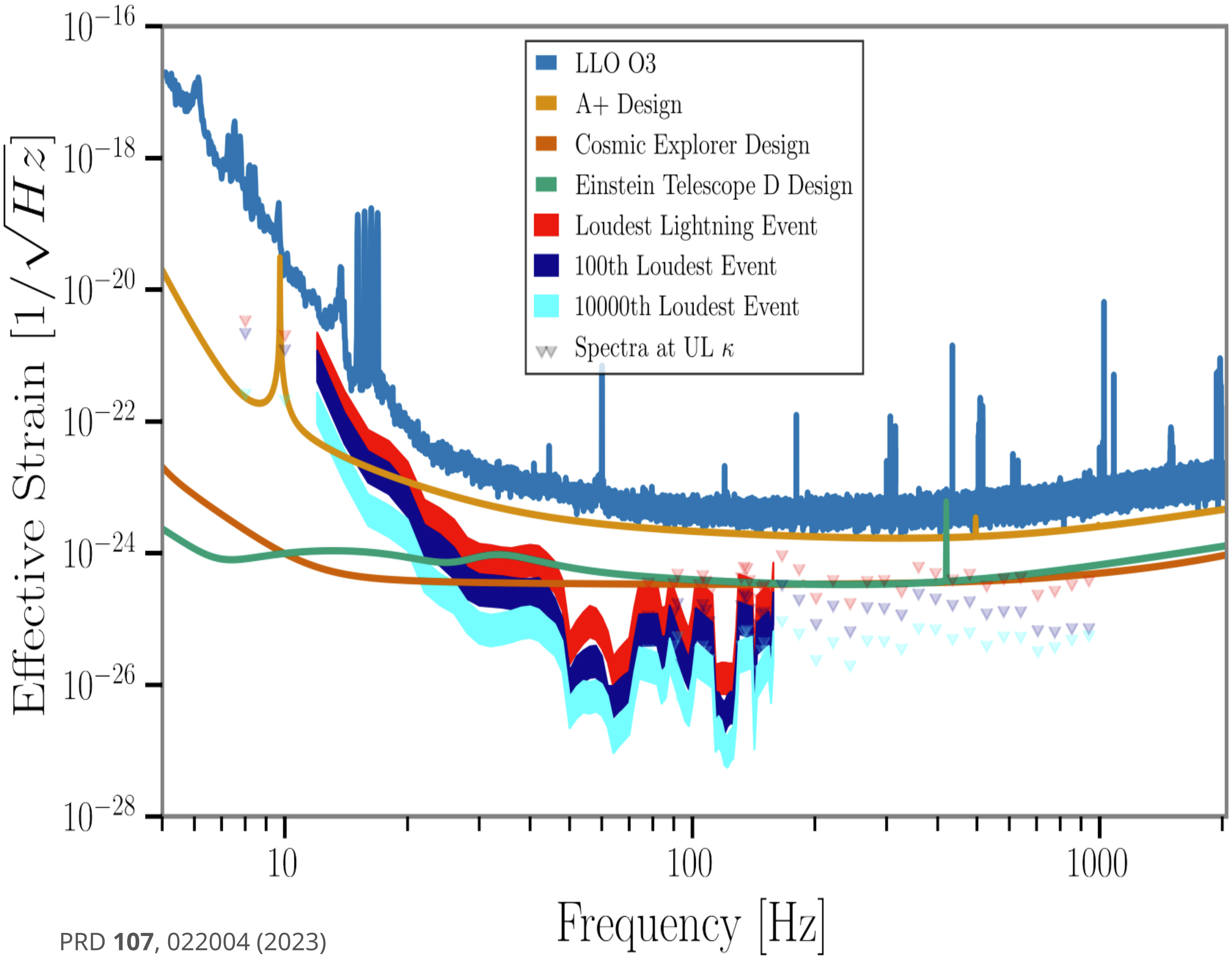
Schumann resonances — lightning strikes excite standing electromagnetic waves in the Earth-ionosphere cavity at 7.8, 14.3, 20.8 Hz... — visible as peaks in the magnetometer spectrum (center plot) — these frequencies sit directly in ET's science band

Global coherence — the same lightning strike appears simultaneously in magnetometers at LIGO Hanford, LIGO Livingston, Virgo, and KAGRA — a magnetic transient that looks like a coincident GW signal across the entire global network — cannot be vetoed by requiring multi-detector coincidence

Coupling mechanism: magnetic fields exert forces on magnets used in mirror actuators and on any magnetic components in the suspension — underground reduces but does not eliminate this coupling — requires non-magnetic actuation systems and magnetometer-based noise subtraction

Magnetic Noise



PRD **107**, 022004 (2023)

Magnetic noise needs to be mitigated by a few orders of magnitude.

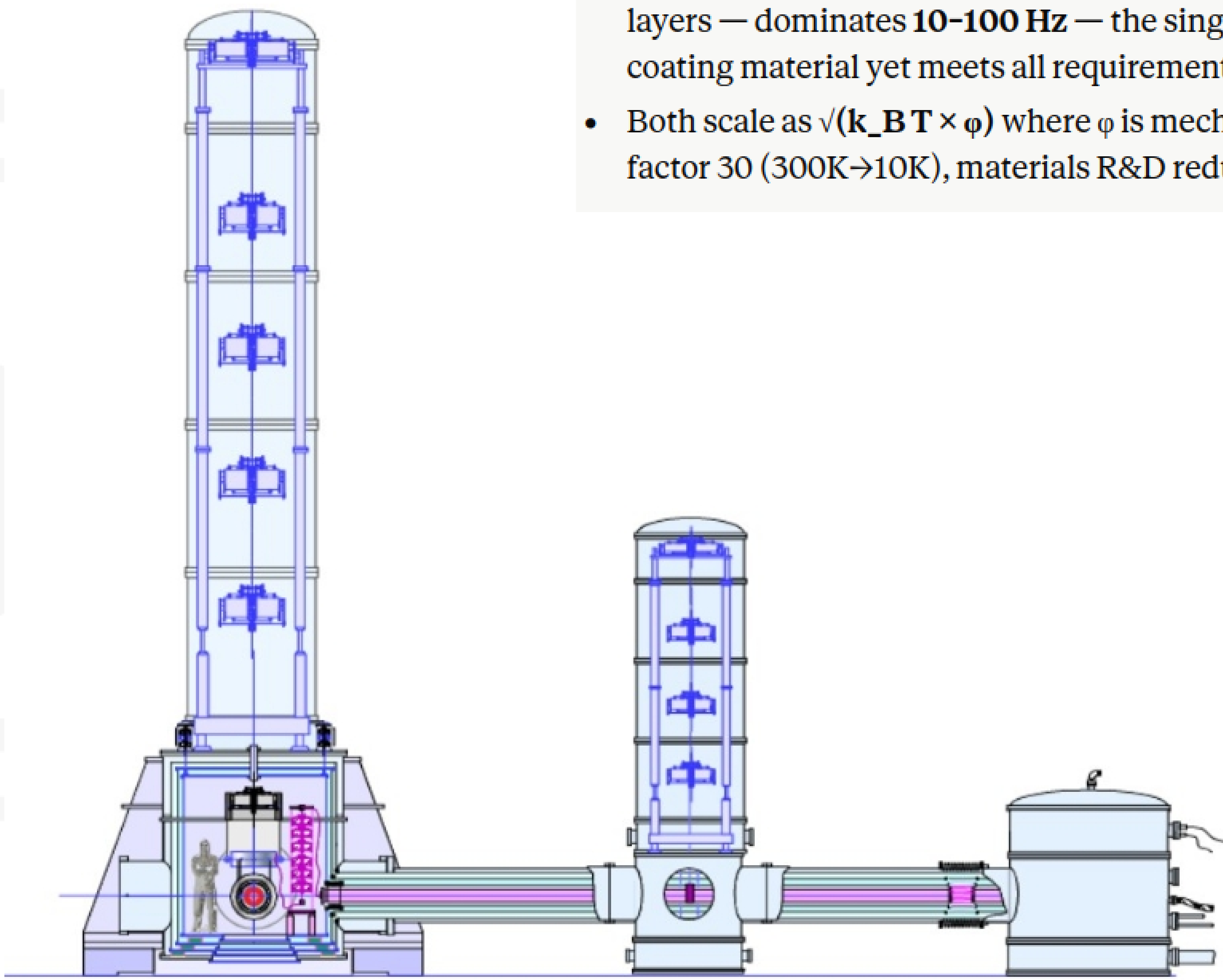
Red/blue/cyan bands = strain noise from individual lightning strikes projected into the GW channel — ranked by amplitude: loudest event (red), 100th loudest (blue), 10,000th loudest (cyan)

Critical problem: the loudest lightning events sit above ET sensitivity (green line) at 5–50 Hz — meaning individual lightning strikes would appear as false GW signals in ET without mitigation

Required mitigation: magnetic coupling must be reduced by several orders of magnitude from current LIGO levels — achieved by eliminating actuation magnets from mirror suspensions, separating cables from beam tubes, and real-time magnetometer-based subtraction

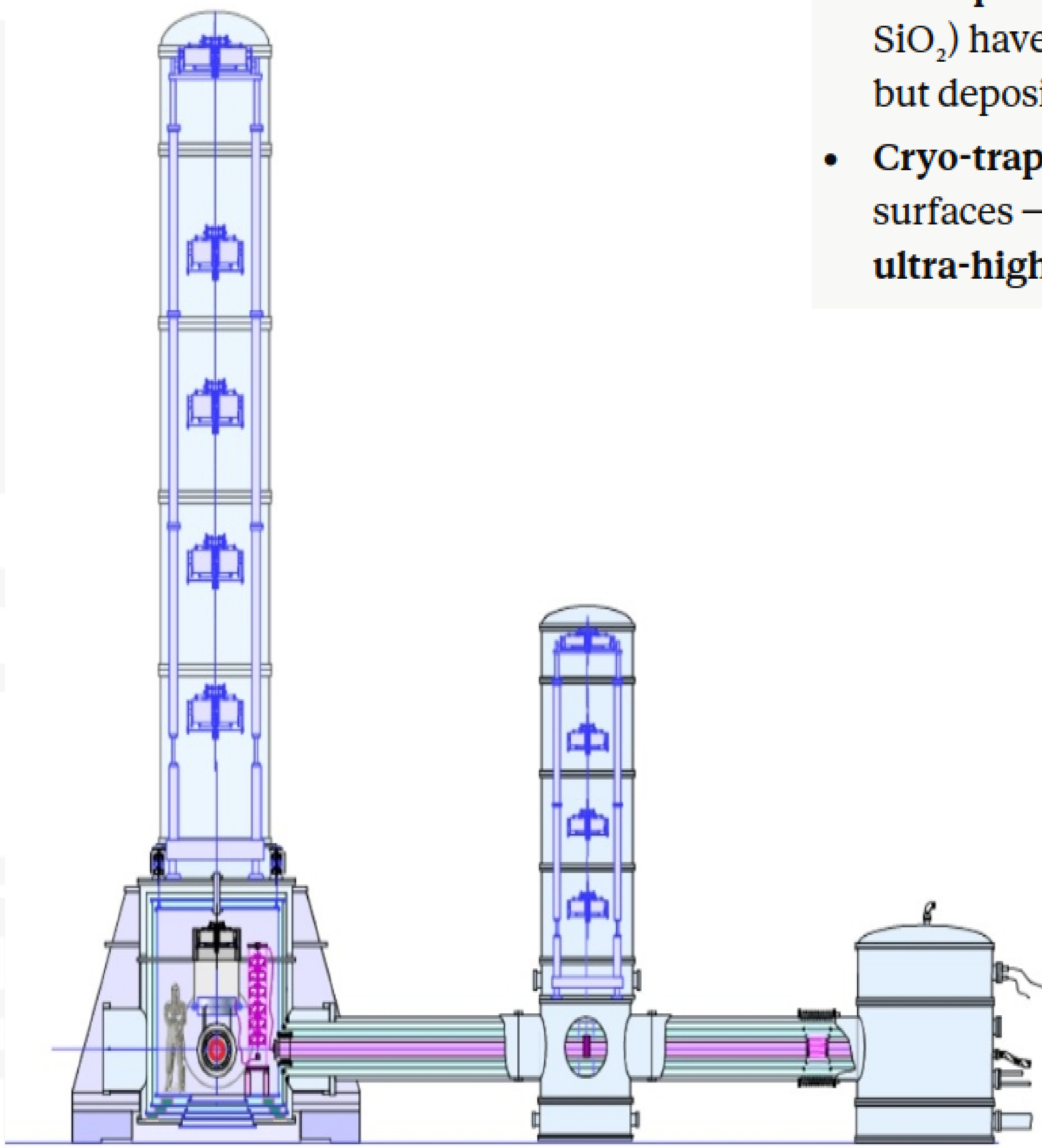
Thermal Noise

- **Suspension thermal noise:** Brownian motion in the fiber suspensions — dominates **1-10 Hz** — reduced by cooling fibers to 10K and using silicon fibers (very low mechanical loss at cryogenic temperature)
- **Coating thermal noise:** random thermal fluctuations of atoms in the mirror coating layers — dominates **10-100 Hz** — the single hardest materials problem in ET — no coating material yet meets all requirements simultaneously
- Both scale as **$\sqrt{k_B T \times \varphi}$** where φ is mechanical loss angle — cryogenics reduces T by factor 30 (300K→10K), materials R&D reduces φ — **need both**



Thermal Noise

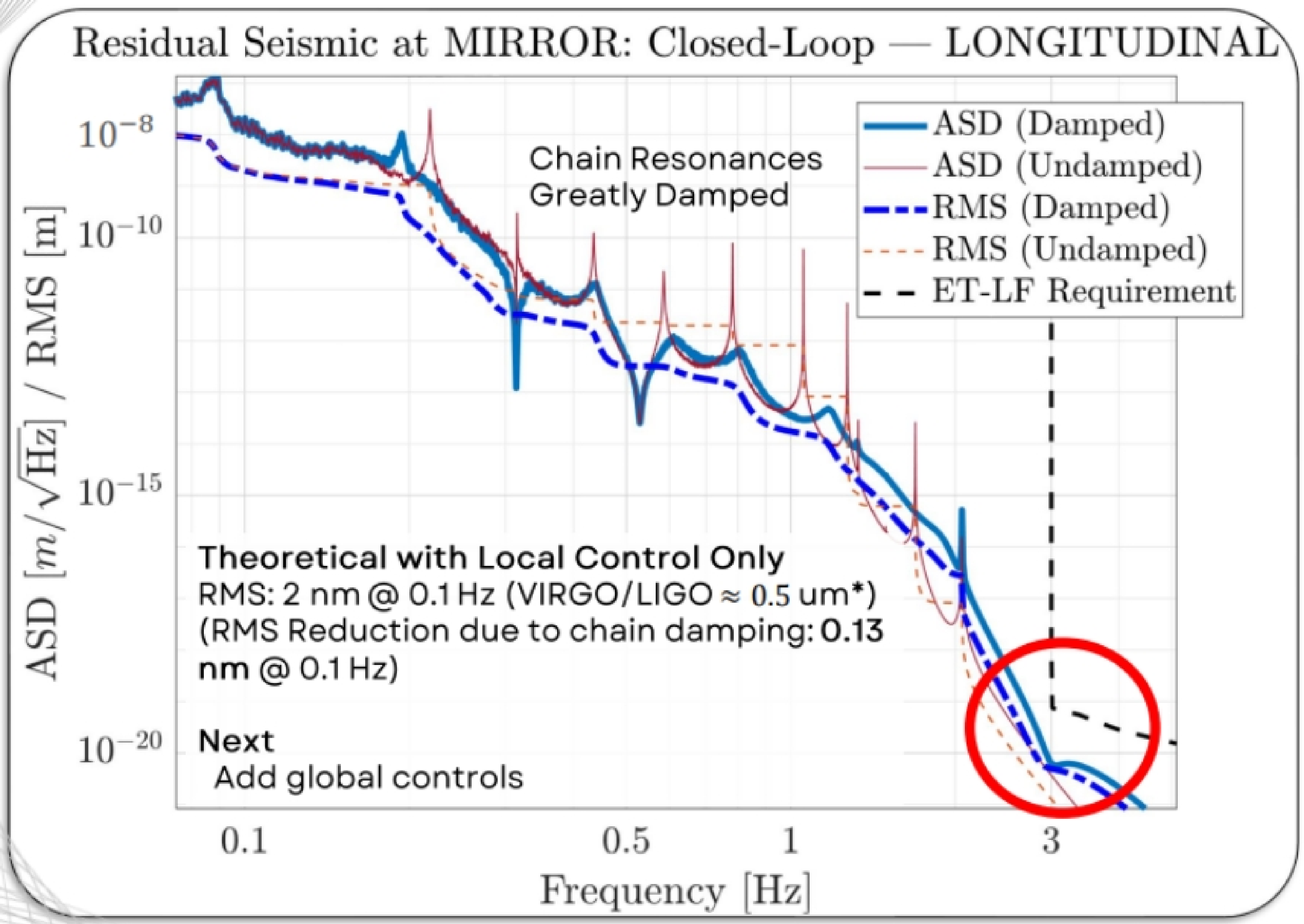
- **The fundamental conflict**: coating must have **high reflectivity** (optical requirement) AND **low mechanical loss** (noise requirement) — these are competing material properties — no existing material satisfies both at cryogenic temperature
- **Amorphous vs crystalline coatings**: amorphous coatings (current standard — Ta_2O_5/SiO_2) have high loss at low temperature — crystalline AlGaAs coatings have lower loss but deposition at 10km mirror scale is **not yet demonstrated**
- **Cryo-trapping**: cooling to 10K causes residual gas molecules to freeze onto mirror surfaces — contaminating the coating and changing optical properties — **requires ultra-high vacuum AND cryogenics simultaneously**

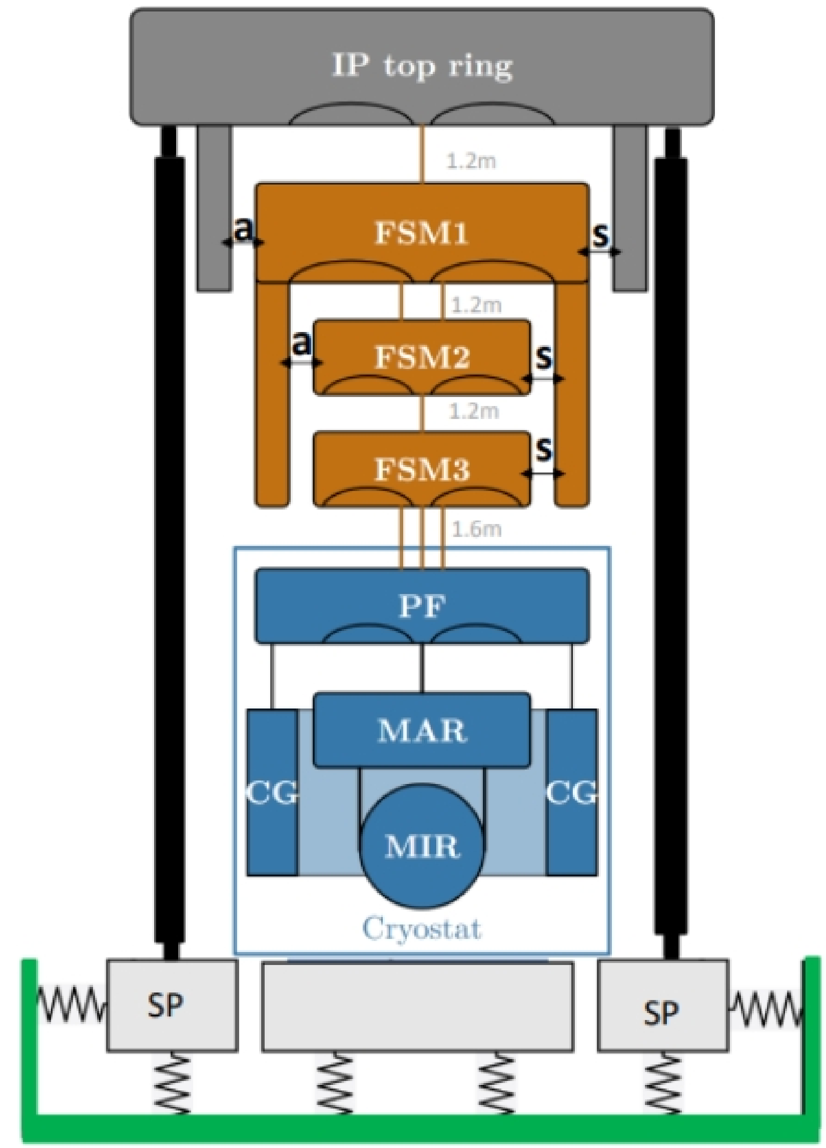


Cryogenic Payload Seismic Performance

Blue = closed-loop (damped), red = undamped — active damping suppresses chain resonances by orders of magnitude

Current result with local control only just meets ET-LF requirement at 3 Hz (red circle) — adding global controls will push compliance to lower frequencies





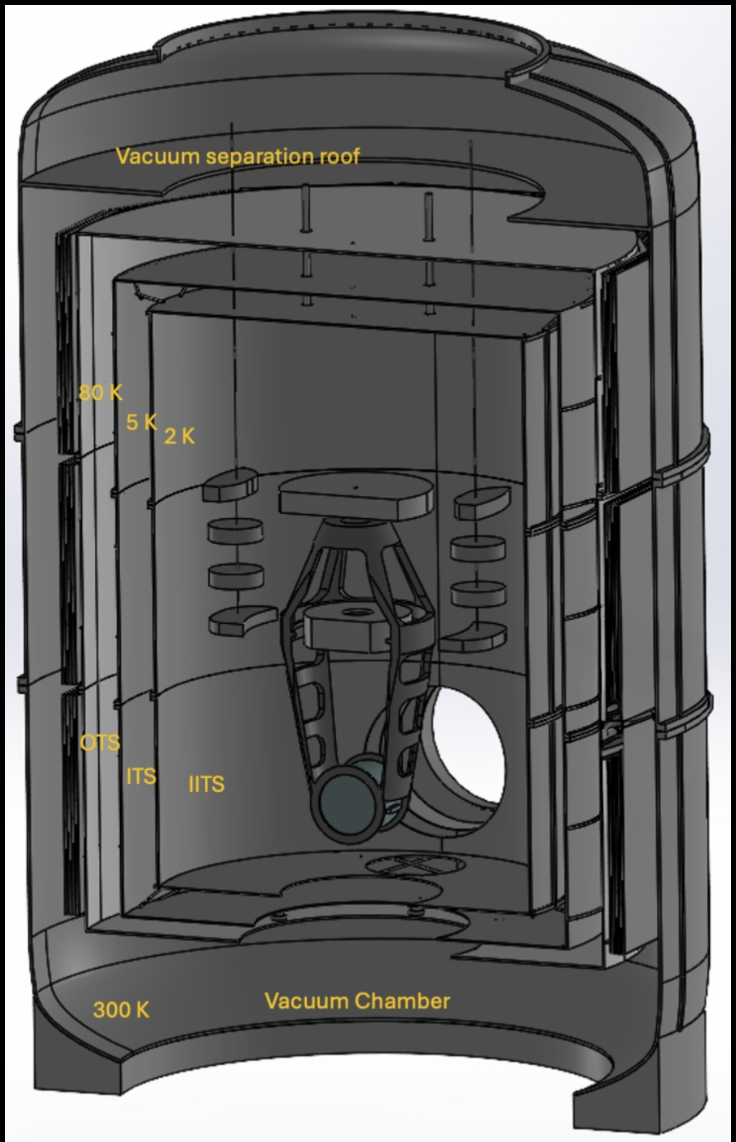
*Inertial Control of the VIRGO Superattenuator Giovanni Losurdo

Seismic Platform: SP (6D) → T360 + BRS w/ HOQI

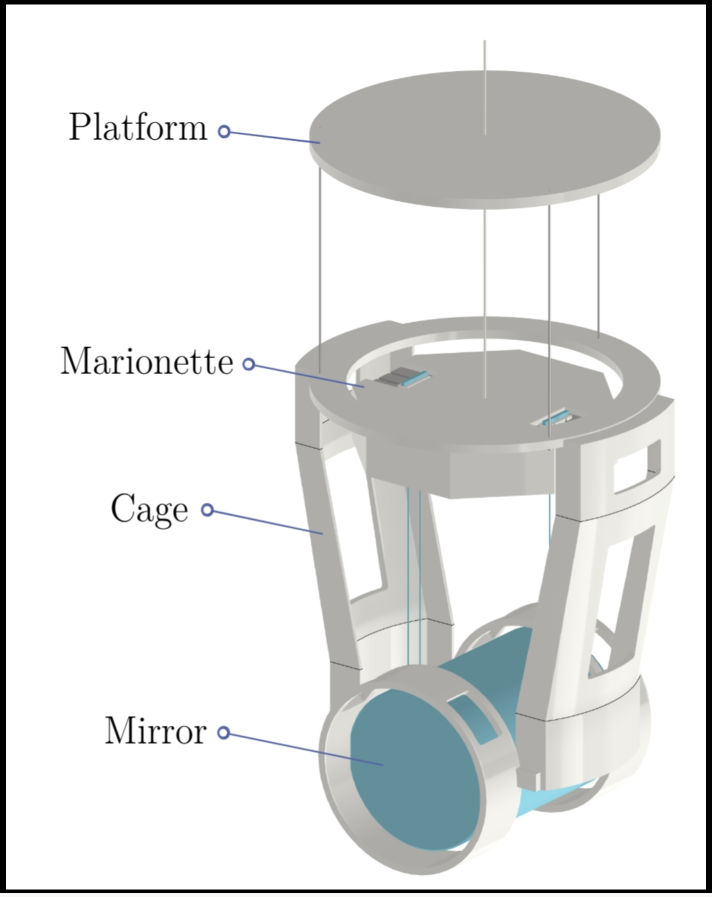
s = HOQI sensor
a = voice coil actuator

Schematic overview of the payload suspension and compact cryostat for ET (right). Both the suspension and cryostat rest on active platforms suspended from the ground and decoupled from the frame of the vacuum vessel. For this suspension, open and close loop noise transfer functions have been calculated (left); a compact suspension can meet the ET sensitivity requirements.

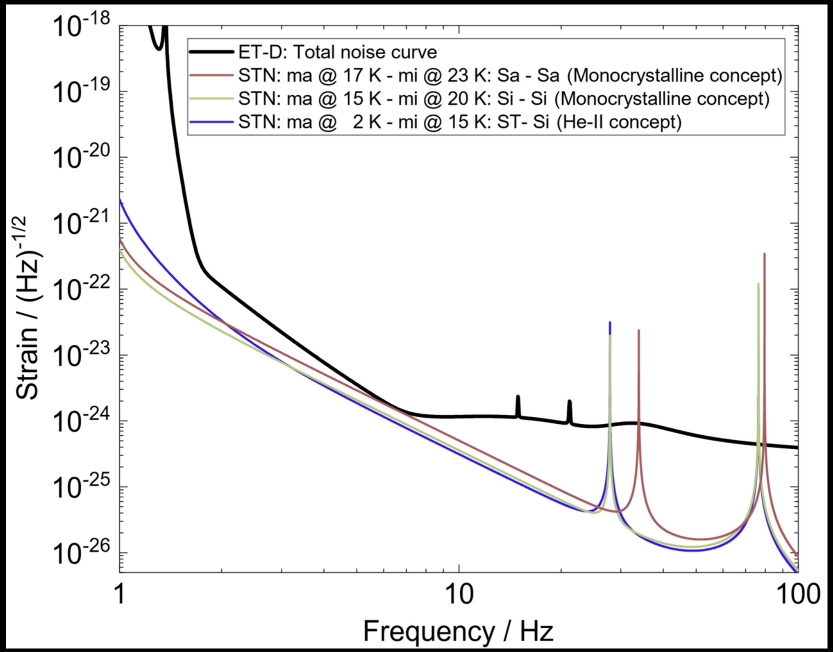
Cryogenics and the ET-LF Payload



Cooling to 10-20K is the most delicate problem to solve for ET



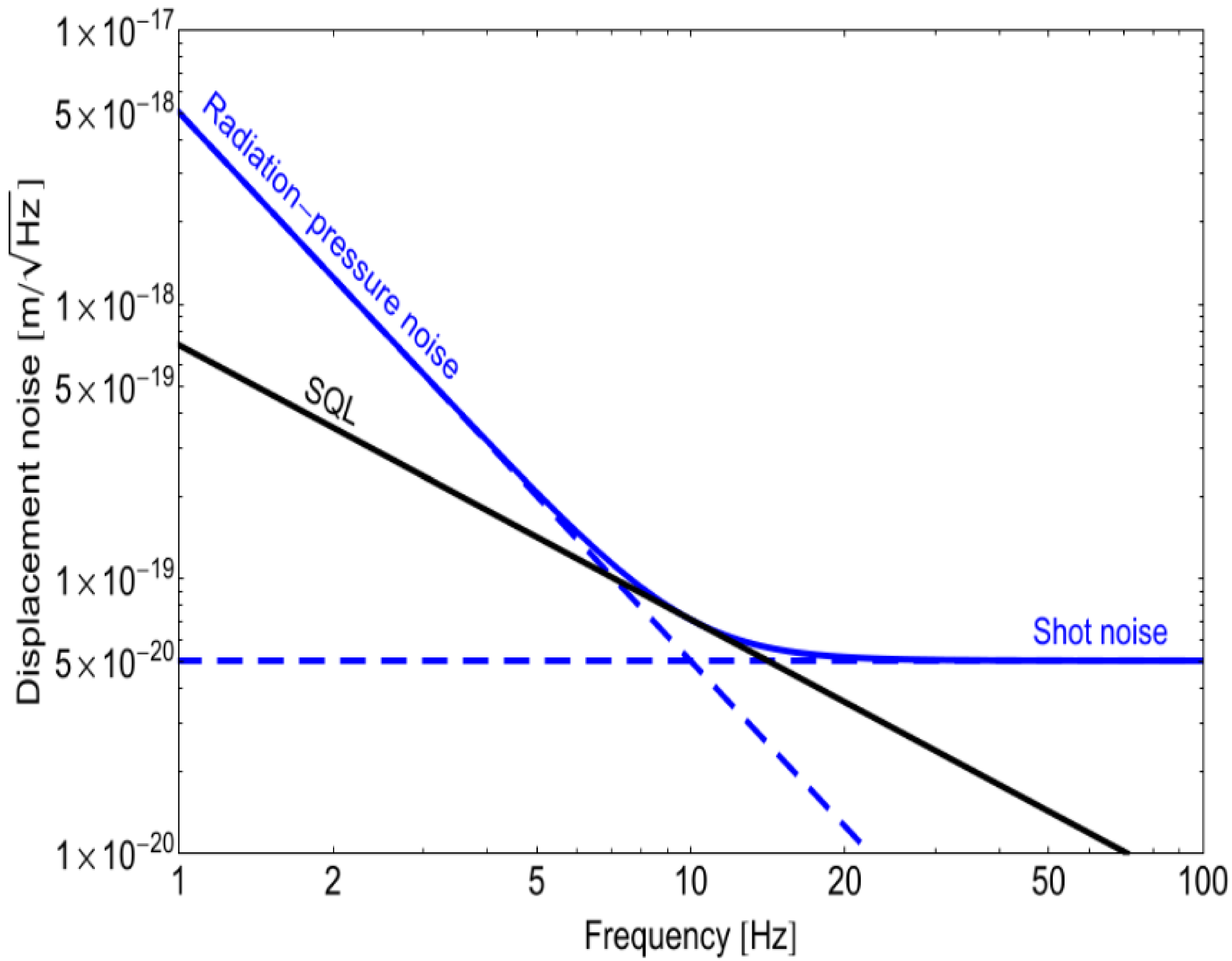
We have a conceptual solution, but it requires a payload of unprecedented quality and a yet unproven heat-extraction mechanism



- **Left**: nested cryostat — outer vacuum vessel at 300K, inner shields at 77K and 4K, mirror at **10-20K** — thermal radiation from room-temperature walls must be blocked at every stage
- **Center**: the payload chain — Platform → Marionette → Cage → Mirror — each stage thermally connected to extract heat while mechanically isolated to avoid vibration coupling — **extracting laser-deposited heat without transmitting mechanical noise is the central unsolved problem**
- **Right plot**: thermal noise curves for different material/temperature combinations — monocrystalline silicon at 15K (blue) sits below ET-D noise curve (black) — **silicon at 15K is the target but requires He-II cooling which has never been done at this scale**

Quantum Noise

- Shot Noise and Quantum Radiation Pressure
- Shot noise: uncertainty in photon arrival time → dominates at high frequency
- Radiation pressure: quantum back-action on mirrors → low-frequency effect
- Together they form the standard quantum limit
- Mitigated by increasing power, squeezing, and filter cavities



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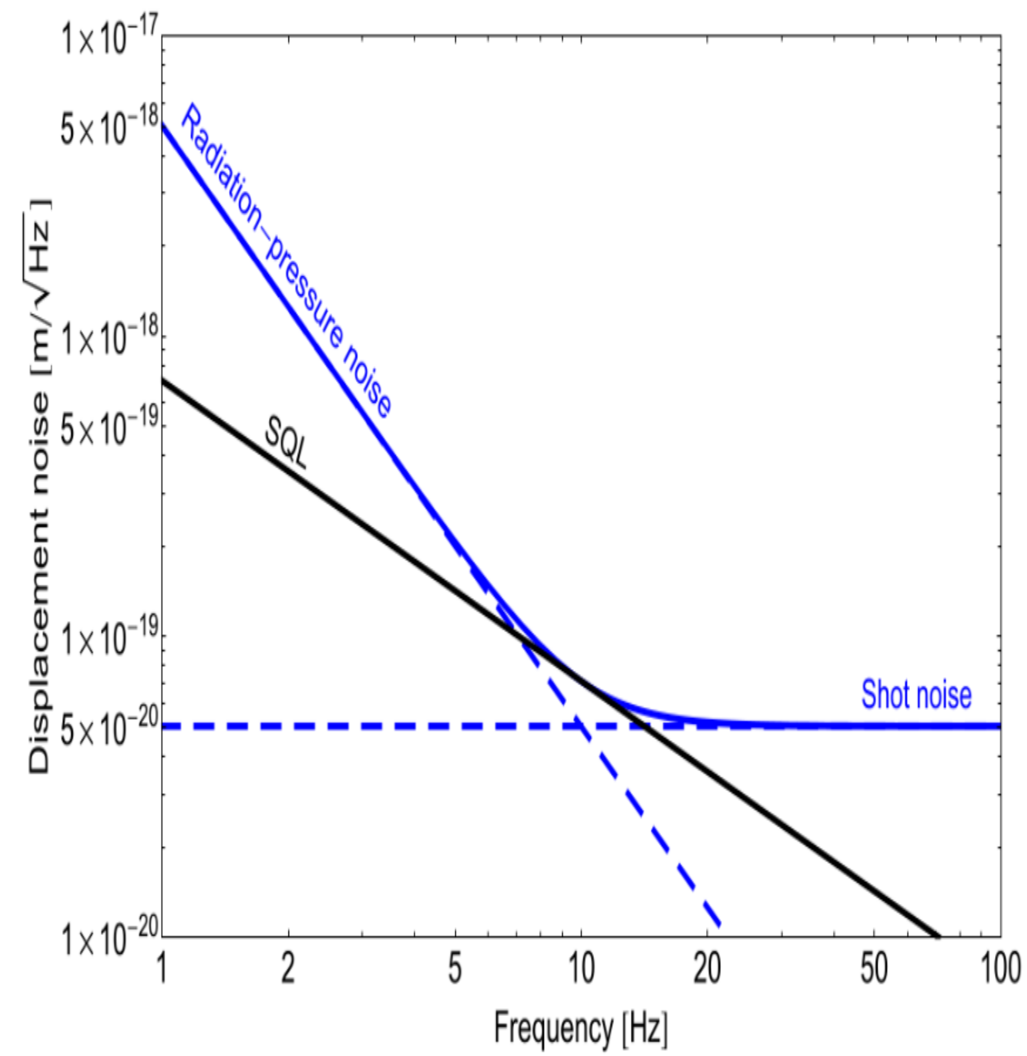
Quantum Noise

Dominant at High Frequencies, Increasingly at Mid-Frequencies:

- Challenge: Heisenberg's Uncertainty Principle creates a fundamental limit: shot noise (photon counting uncertainty) and radiation pressure noise (photons imparting momentum to mirrors).

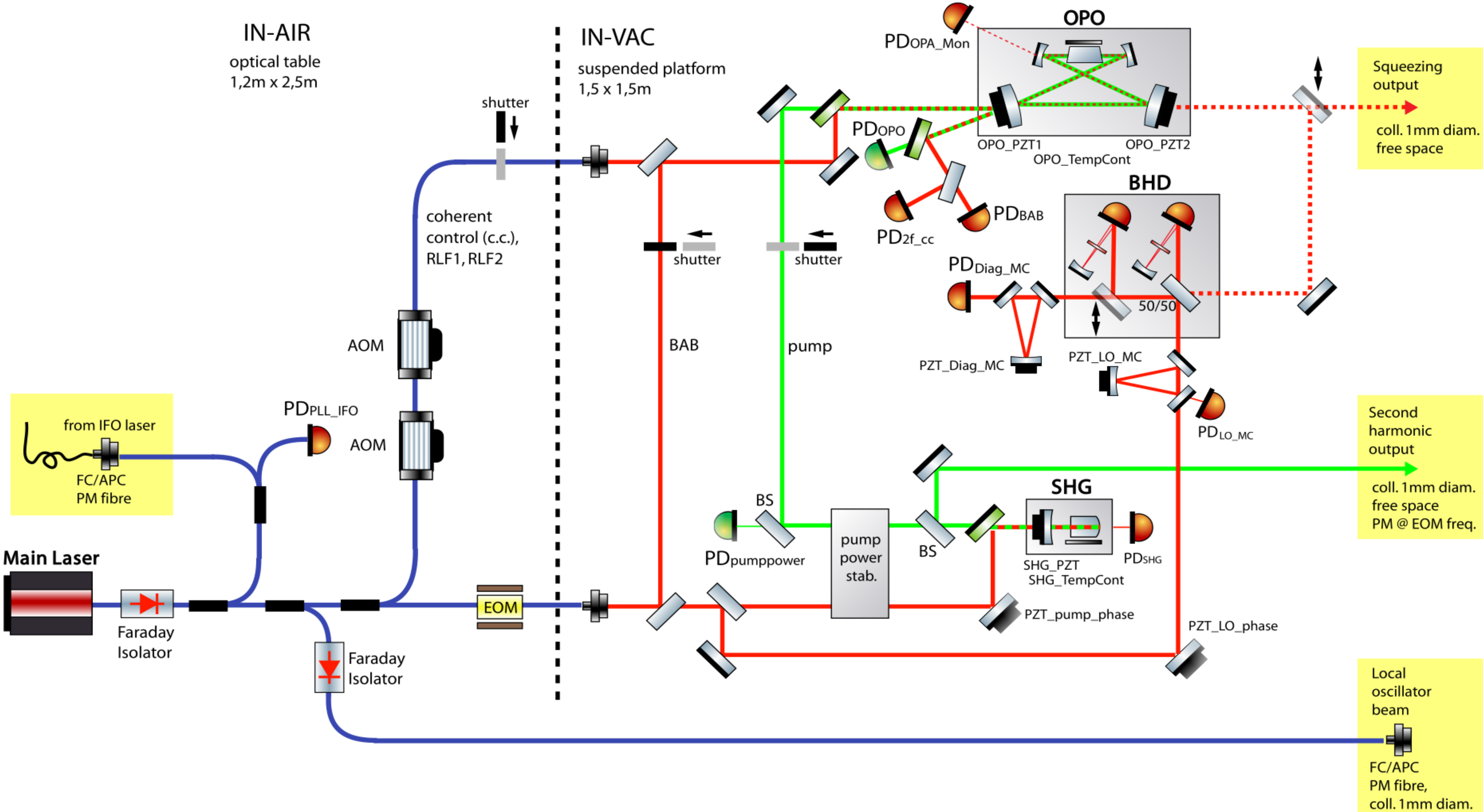
Current/Ongoing Solutions & Challenges:

- Frequency-Dependent Squeezing: Implementing and optimizing squeezed light sources that change their squeezing ellipse orientation to reduce noise differently across the detection band. This is complex to maintain stably
- Improving Squeezing Levels: Generating higher levels of squeezing and, crucially, reducing optical losses that degrade injected squeezing
- Future: Filter Cavities: Developing and commissioning longer filter cavities to rotate the squeezing ellipse effectively over a broader band remains a significant engineering challenge



GSSI

Quantum Noise

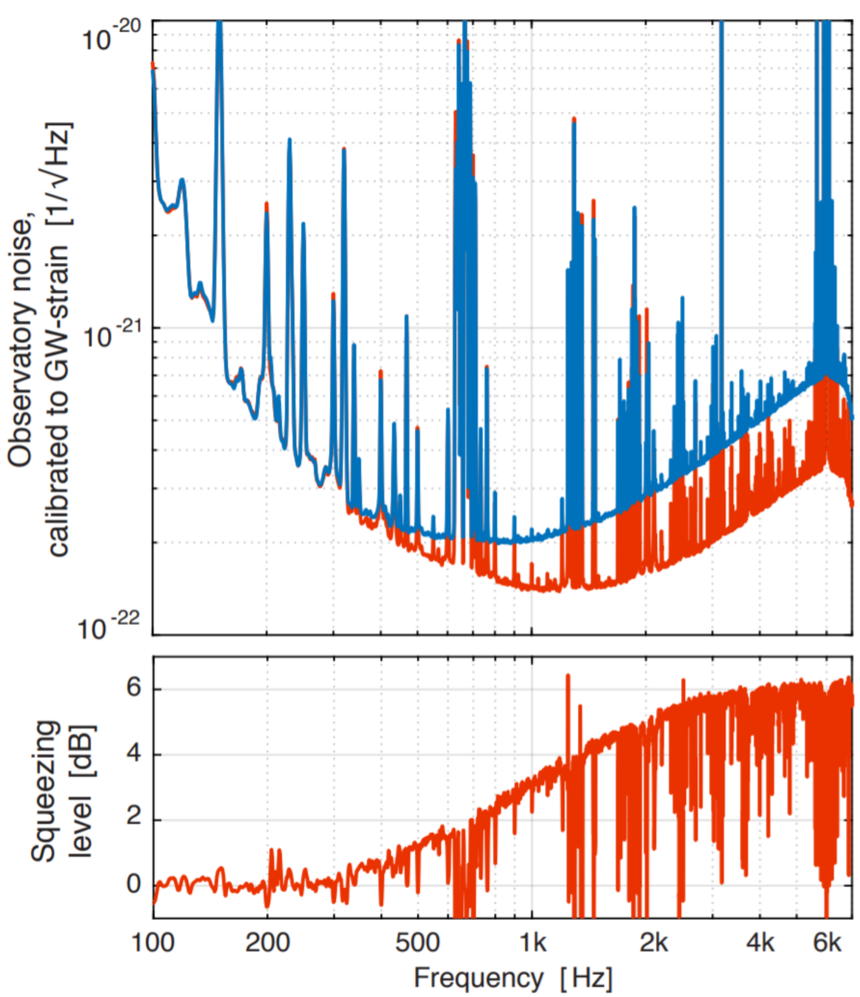


Schematic of the Squeezed Light Source (SLS) subsystem of ET-LF. The generation of squeezed states of light is realised by utilizing a Main laser source phase locked to the interferometer laser carrier. A pick-off of this Main laser is frequency shifted using two Acousto-Optics Modulators (AOMs) to generate a Coherent Control (CC) field used for the coherent control of the squeezing source and a Resonant Locking Fields (RLF1 and RLF2) used for the control of the filter cavities

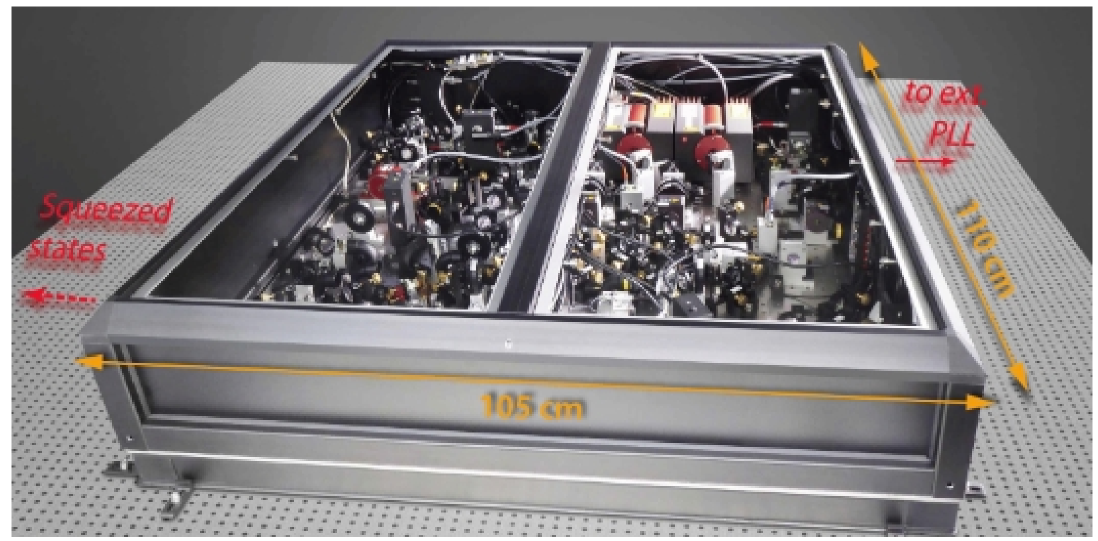
Squeezed-light source (from 1064 to 1550nm)

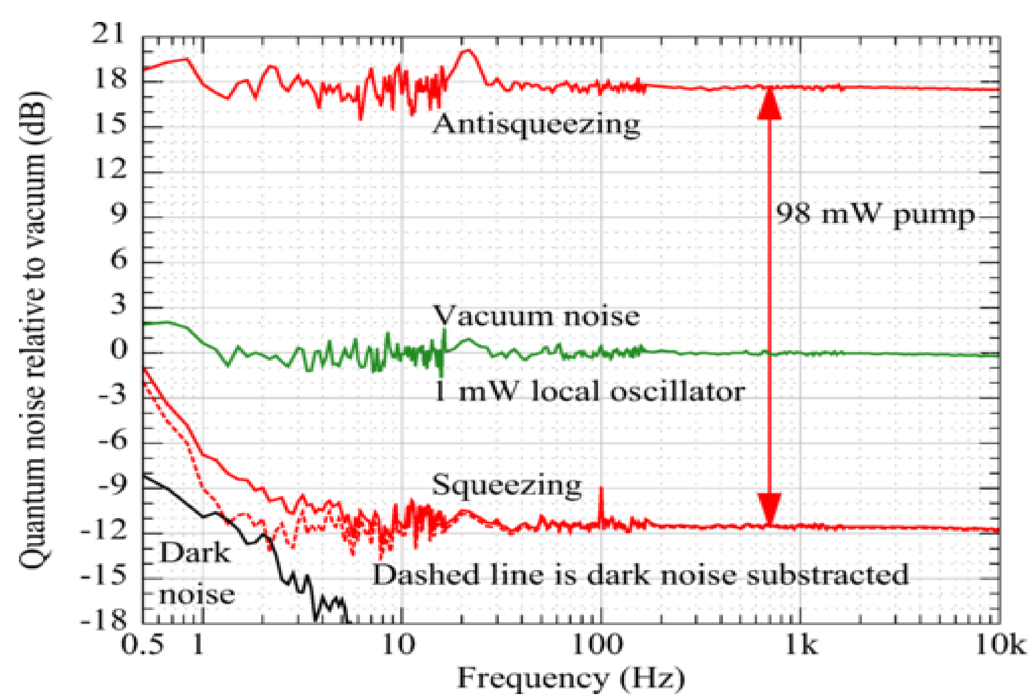
Virgo squeezer: the physical hardware — 105cm bench hosting the OPO, laser, and homodyne detection — entire squeezing system fits on one optical bench

Reduced quantum noise at GEO600



Lough et al 2020





squeezing (red, ~12 dB below vacuum) vs antisqueezing (18 dB above) — vacuum noise (green) is the reference — demonstrates 12 dB squeezing at 1550 nm already achieved

PRL 129, 121103 (2022)

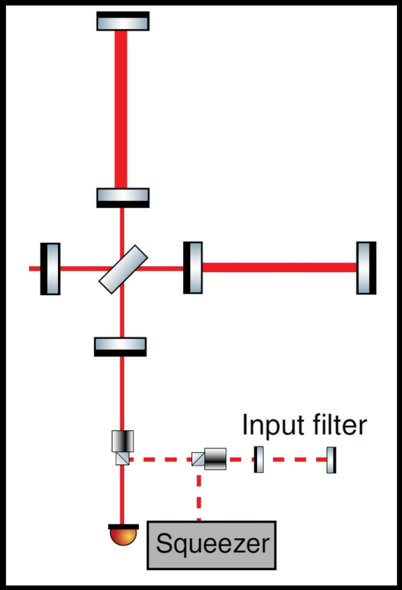
Filter Cavities

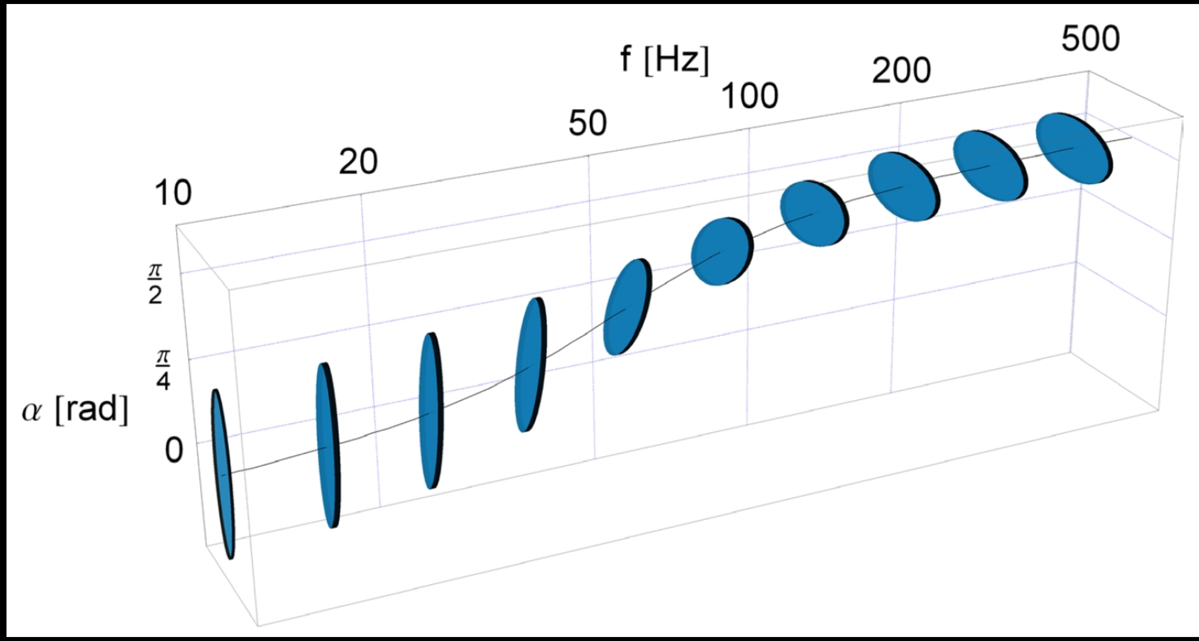
Virgo filter cavity

300m long, installed in one of the Virgo arms — proof of concept for ET

Frequency-dependent quantum noise reduction

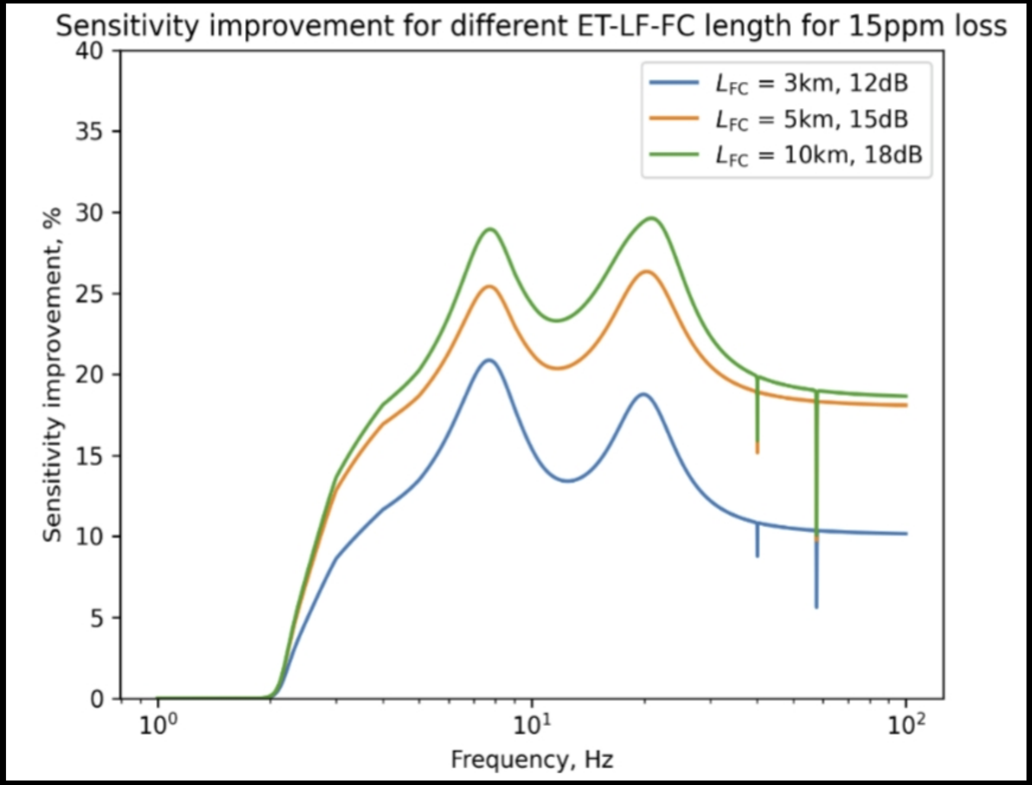
interferometer with filter cavity injected at dark port — squeezer feeds into filter cavity before entering IFO





the squeezing ellipse rotates as a function of frequency — at low frequency it needs to be rotated to suppress radiation pressure noise, at high frequency to suppress shot noise — filter cavity performs this frequency-dependent rotation

Very low optical loss is key



sensitivity improvement vs frequency for different filter cavity lengths at 15 ppm loss — 5 km gives ~25–30% improvement, 10 km gives ~35% — longer cavity = lower required finesse = fewer round trips = less loss

Control and Technical Noises

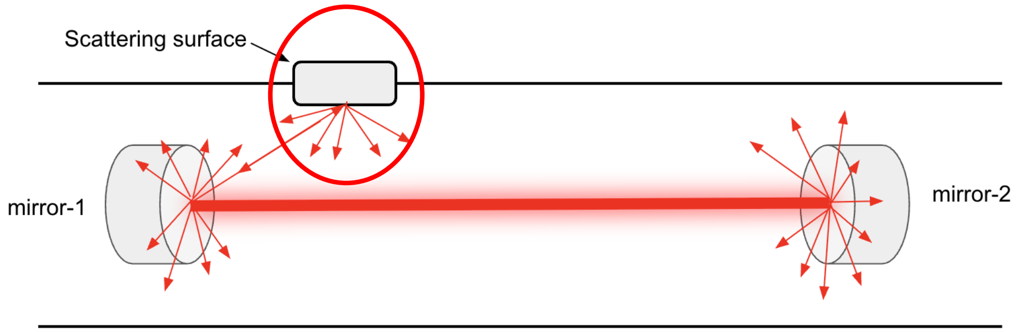
- Control Systems and Technical Sources
- Noise from length and alignment control loops
- Includes DAC noise, sensor noise, electronics, and residual actuation coupling
- Also includes beam jitter, photodetector dark noise, and laser frequency noise

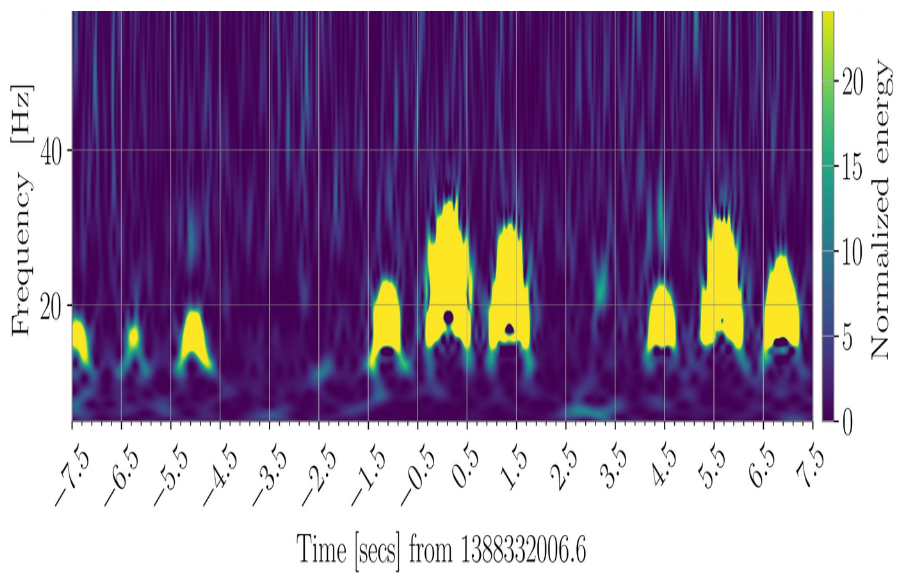
Scattered Light and Environmental Couplings

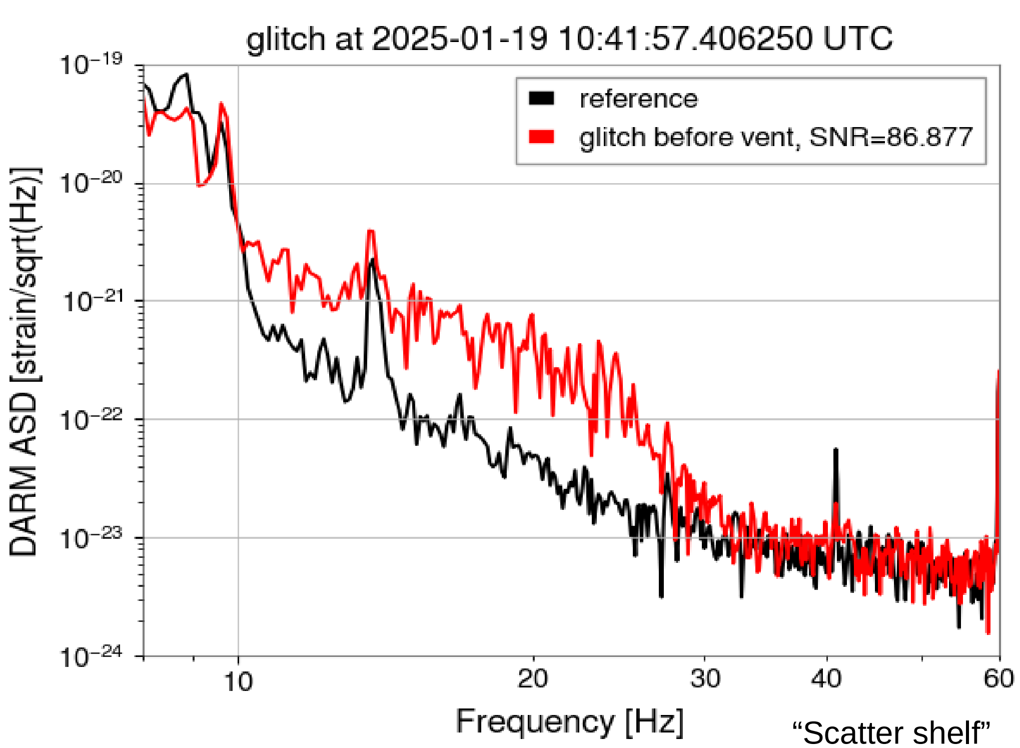
- Scattered Light and Coupling Paths
- Light scattering off surfaces or inside vacuum baffles → recombines with main beam with noise
- Sensitive to vibrations, acoustic noise, and alignment errors
- Tricky to model → often found via witness sensors or coherence

GSSI

Scattered light noise







Mechanism:

- Scattered light reflects off a moving surface and recombines with the main beam → spurious phase shift
- Coupling is strongest via surfaces not seismically isolated (move relative to the test masses)

Arch patterns in spectrogram:

- Arch shape directly traces the velocity profile of the scattering surface over time
- Glitches fall in 10–120 Hz — overlapping exactly with the inspiral/merger detection band

Scatter shelf (ASD):

- Broadband noise floor rise = continuous low-amplitude scattering, not individual glitches
- ~32% of all LIGO O3 glitches were scattered light — the single most common class

Scattered light noise

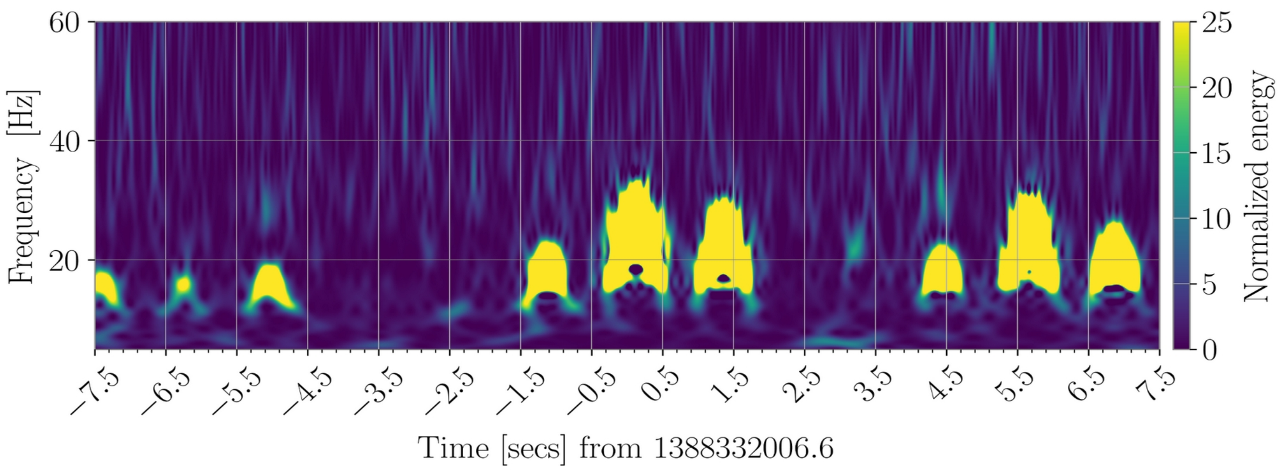
$$\delta x_{sc}(t) = X_0 \sin(\omega_{sc} t)$$

$$\delta\phi_{sc}(t) = 2k\delta x_{sc} = 4\pi \frac{X_0}{\lambda} \sin(\omega_{sc} t)$$

$$h_{sc}(t) = A\frac{\lambda}{8\pi L} \sin(\delta\phi_{sc}(t))$$

$$\tilde{h}_{sc}(f) = \mathcal{F}[h(t)] = A\frac{\lambda}{8\pi L}\mathcal{F}\left[\sin\left(\frac{4\pi}{\lambda}\delta x_{sc}(t)\right)\right]$$

$$\tilde{h}_{sc}(f) = |\tilde{h}_{sc}(f)|e^{i\Phi(f)}$$



λ → Wavelength of laser, 1064 nm in LIGO
A → Light amplitude in the scattered beam, expressed as a fraction of the main beam
L → arm length, 4 km in LIGO

$$f_{\text{fringe}}(t) = \left|\frac{2nv_{sc}(t)}{\lambda}\right|$$

Low frequency motion gets upconverted to create noise at higher frequency

Fringe frequency: faster surface motion → noise at higher frequency

Nonlinearity means even pure low-frequency motion creates broadband harmonic content

Below ~0.45 Hz pendulum resonance, seismic isolation fails → ground motion directly drives scattering

Mitigation: damping the Arm Cavity Baffles reduced transient rate by ~50× for similar seismic conditions

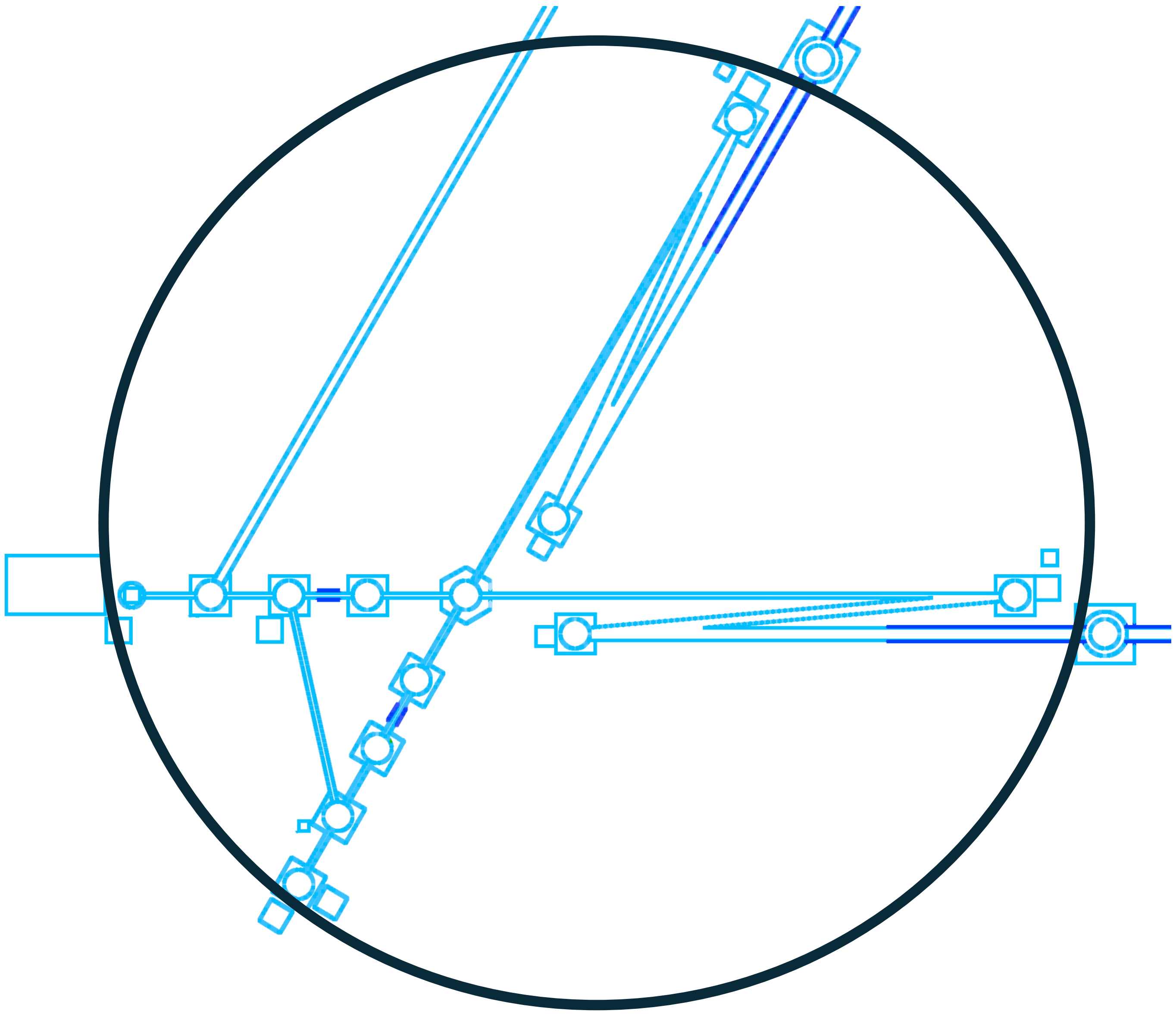
What baffles do:

- Physically intercept stray photons before they can reach the vacuum tube walls and scatter back toward the main beam
- Metal surfaces with a central aperture: block stray light, pass the intended beam — placed at the input, output, and along each arm
- Arm Cavity Baffles (ACBs) are suspended close to the test masses, so they move with the seismically isolated platform, reducing relative motion with the main optics

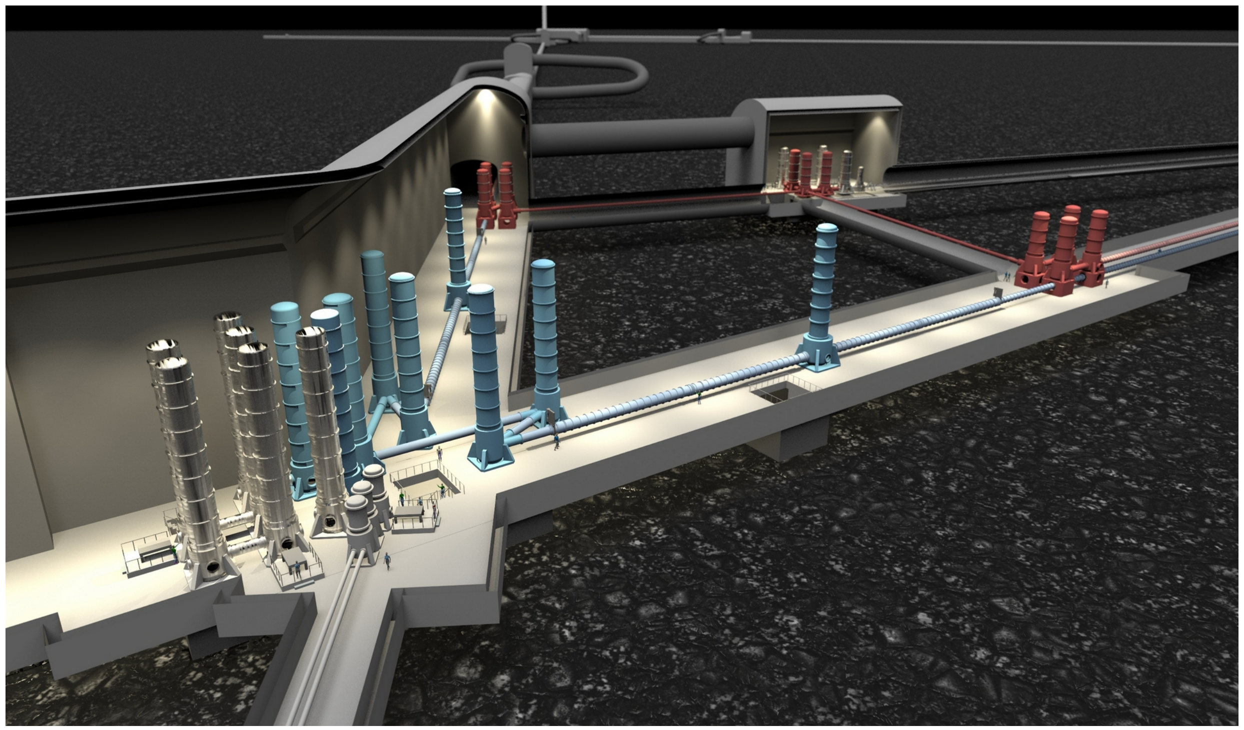
Other mitigation strategies:

- Damping the baffles themselves reduces their resonant motion — cutting transient scatter rates by ~50× for similar seismic conditions
- Installing additional seismic isolation under the scattering surface can eliminate entire glitch populations
- Witness sensors on suspected scattering surfaces allow offline subtraction or flagging of contaminated data segments

Inter-platform Sensing and Control



Lock all suspension platforms into a common motion across the full central vertex of an interferometer
Refer this optically rigid body to the two input masses



Inter-Platform Motion

What it is (0.01–3 Hz)

- ET vertex optics/sensors live on multiple platforms → relative motion is not common-mode rejected

Why it matters (root cause)

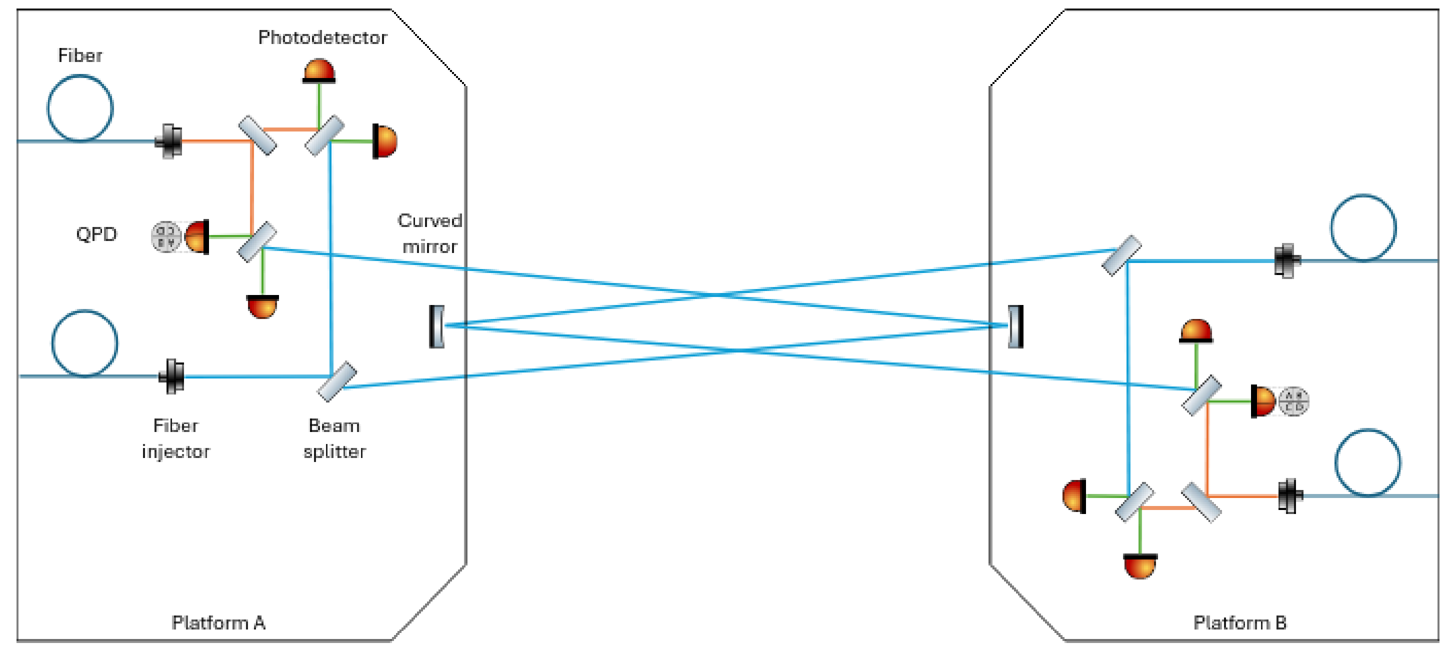
- Differential platform motion drives auxiliary length loops (PRC/SRC/MICH) → reinjection of motion + sensing noise
- It increases risk of scattered-light upconversion during slow drifts / microseism
- It couples alignment ↔ length (geometry), reducing robustness and commissioning margin

Mitigation concept

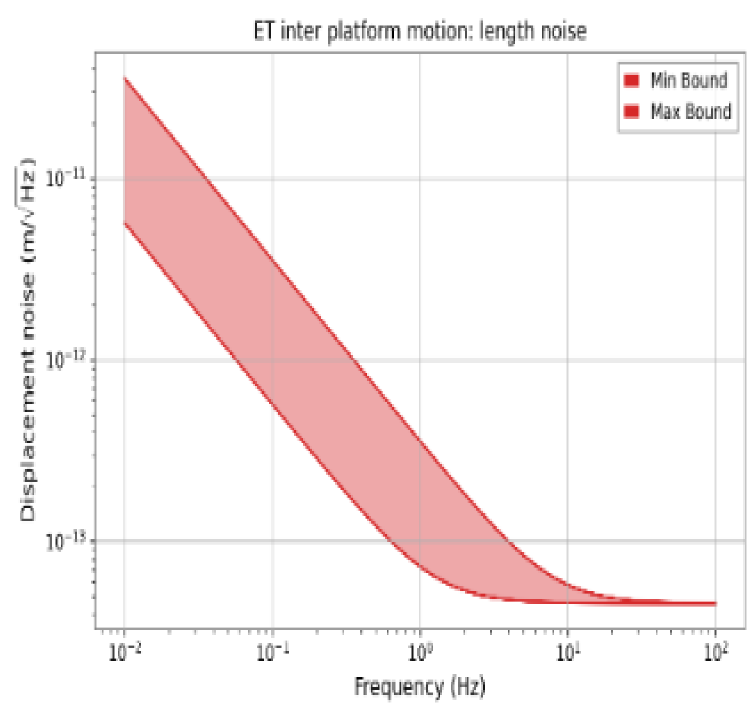
- Use an interferometric laser link (SPI at platform level) to measure differential motion and actively suppress it
- Unlike inertial isolation, SPI has no low-frequency cut-off → targets exactly the sub-Hz problem band

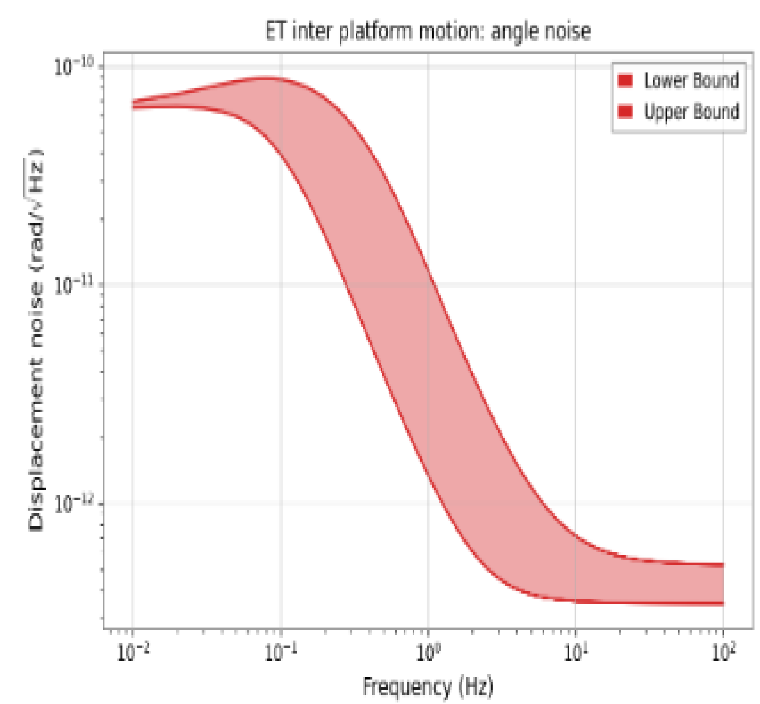
Design target (what success looks like)

- Reduce differential motion until limited by SPI readout noise (quasi-rigid body behaviour)



a) Simplified schematic of an interferometric link between two platforms, based on heterodyne Mach Zehnder interferometers with reflected laser beams.

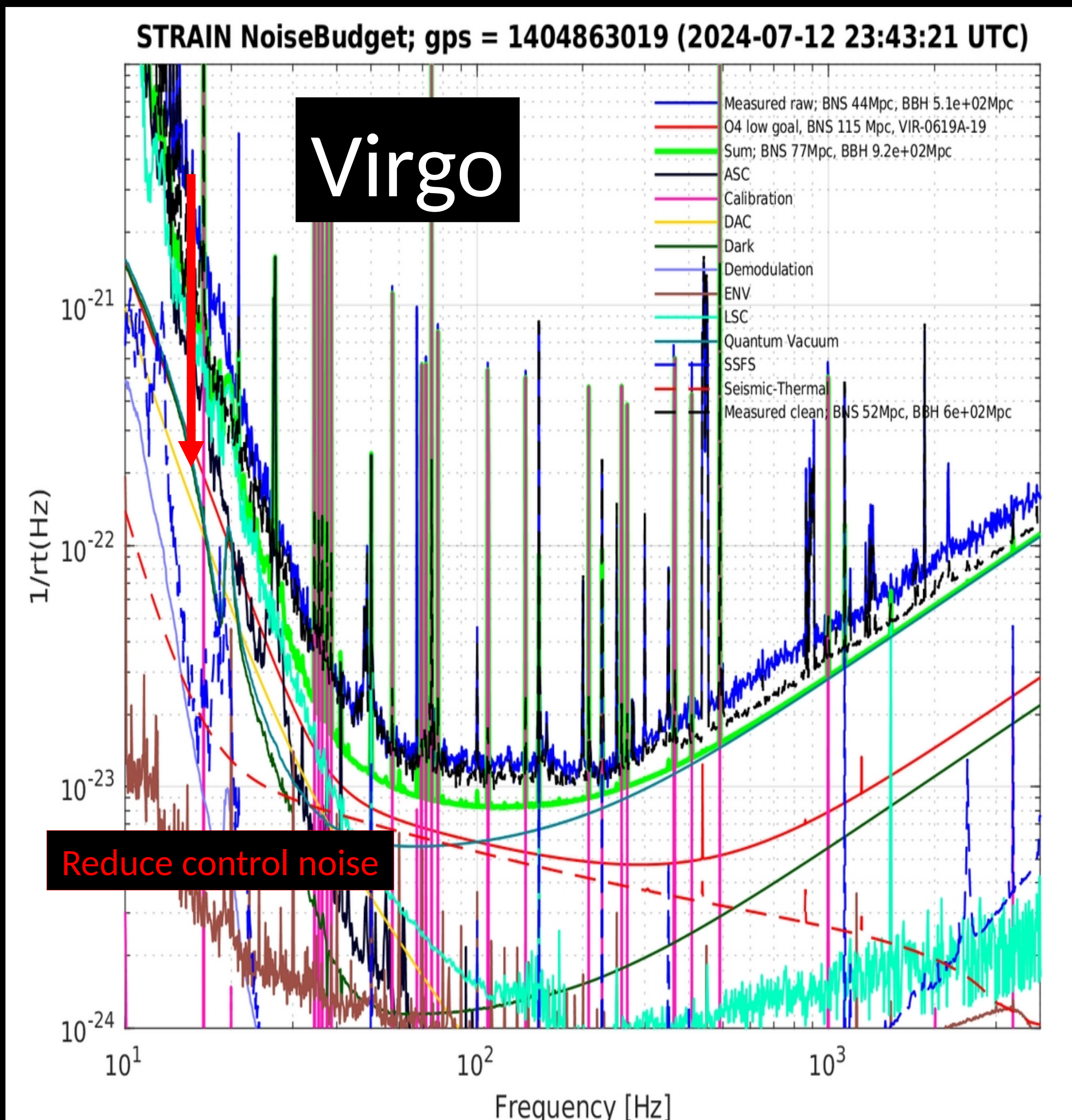




b) Expected performance of the IPM system for the differential length sensing between platforms.

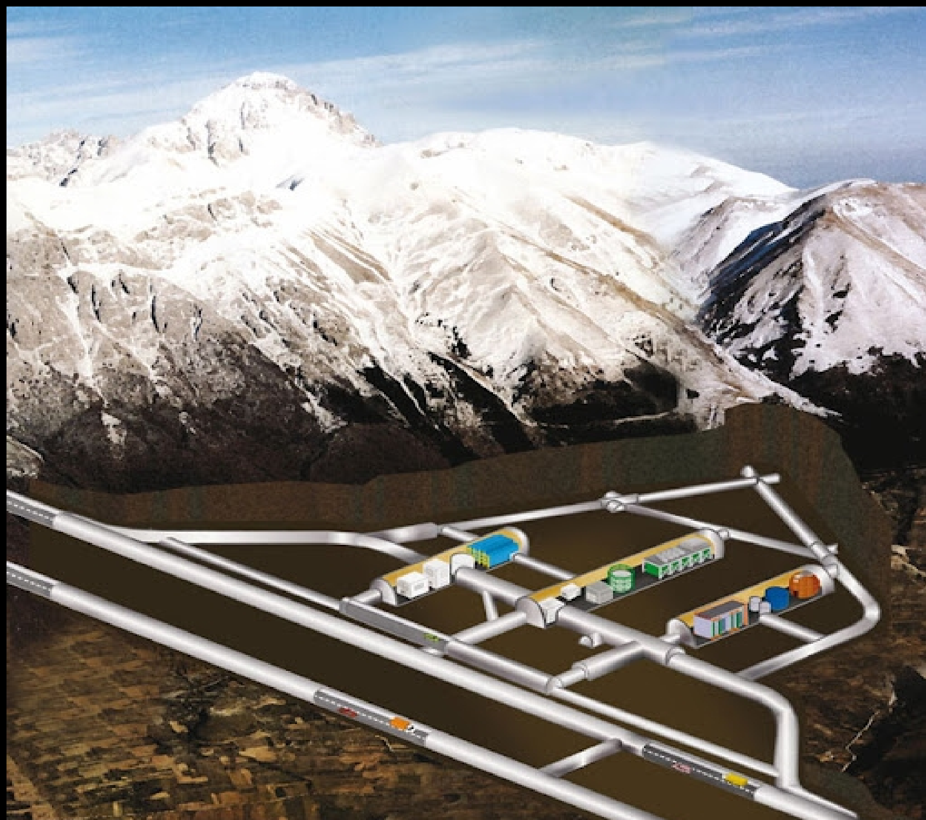
c) Expected performance of the IPM system for inertial rotation of an individual platform in pitch and yaw.

Scientific Goal 1: ET

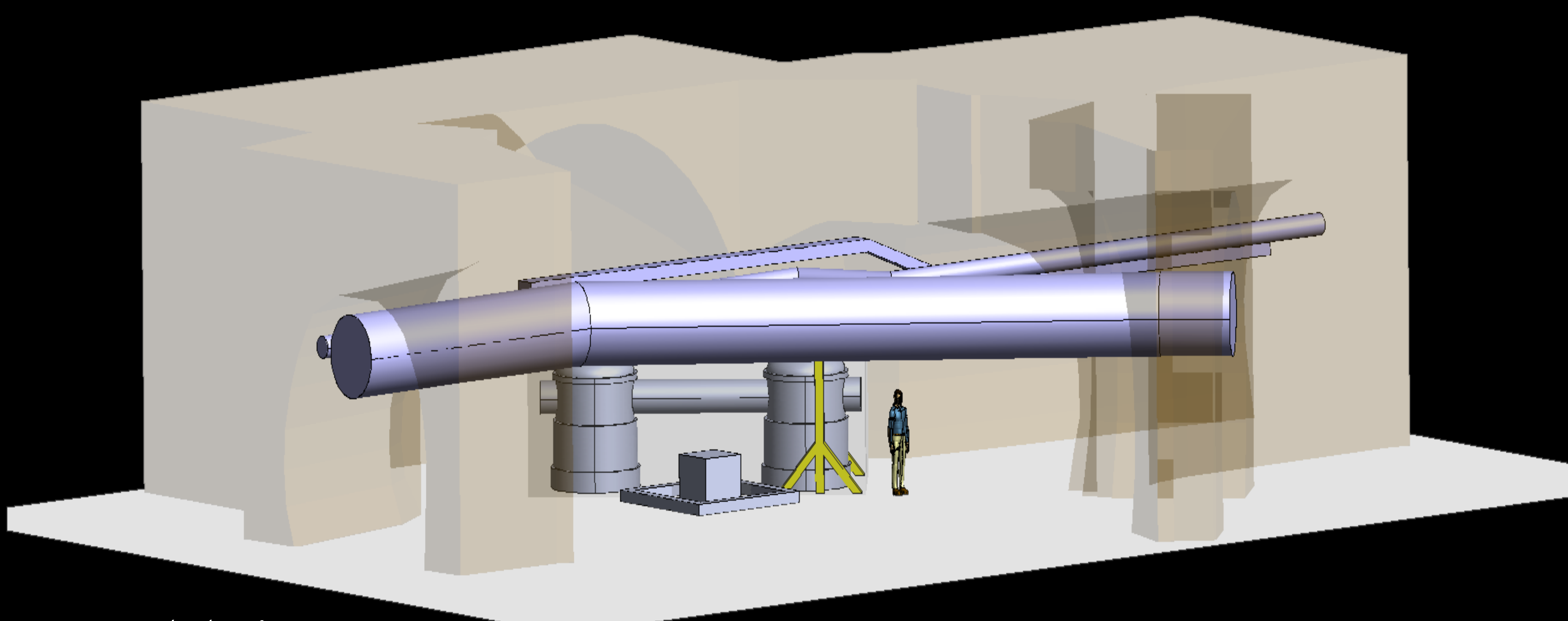


- At low frequencies, control noise from auxiliary DOFs (length and alignment) can limit the sensitivity of ET
- GEMINI develops an inter-platform motion control system to suppress differential motion across large suspended platforms
- Lock all suspension platforms into a common motion across the full central vertex of an interferometer

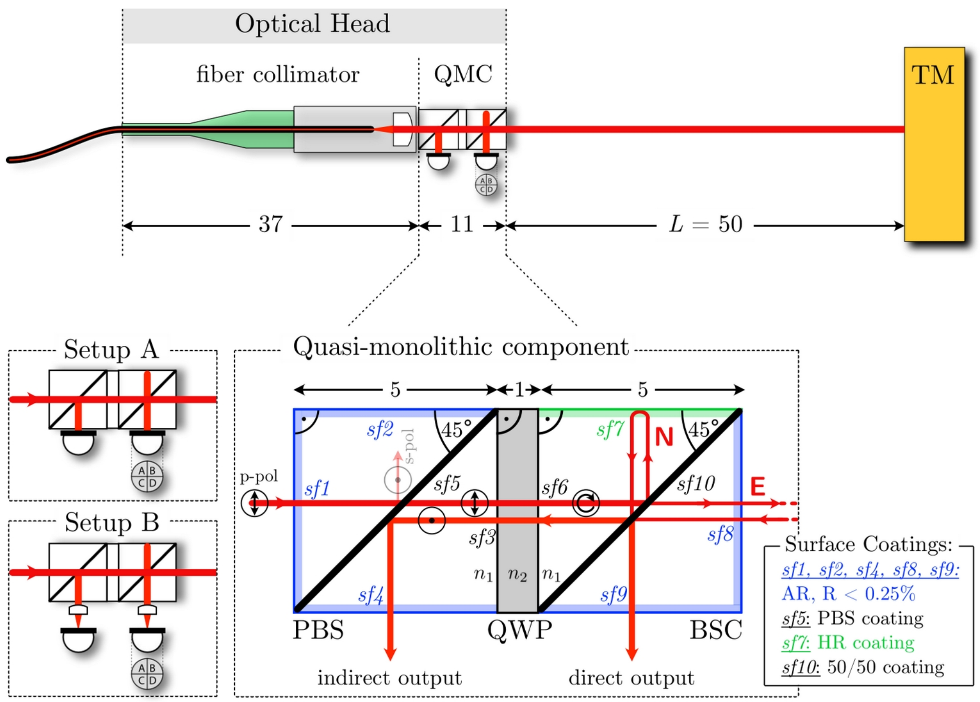
Underground Laboratory



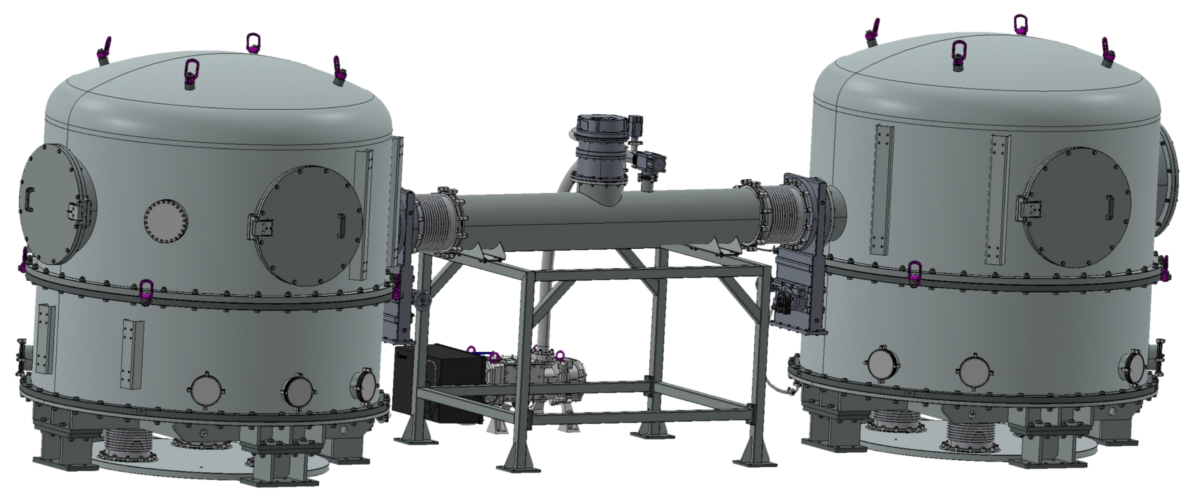
- Floor treatment
- Laminar-flow enclosures
- Lifting device for platforms and chamber segments
- Access to cooling water for cryocooler
- Timing signal from surface
- Low-latency data transfer to server at the surface

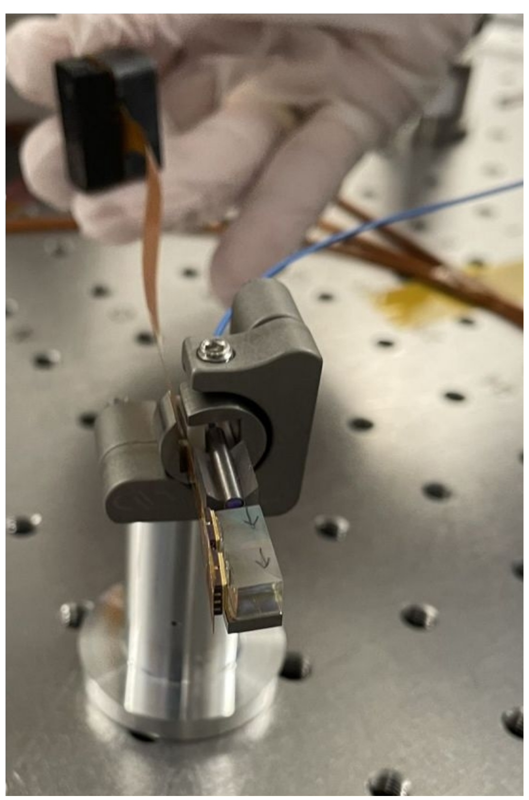


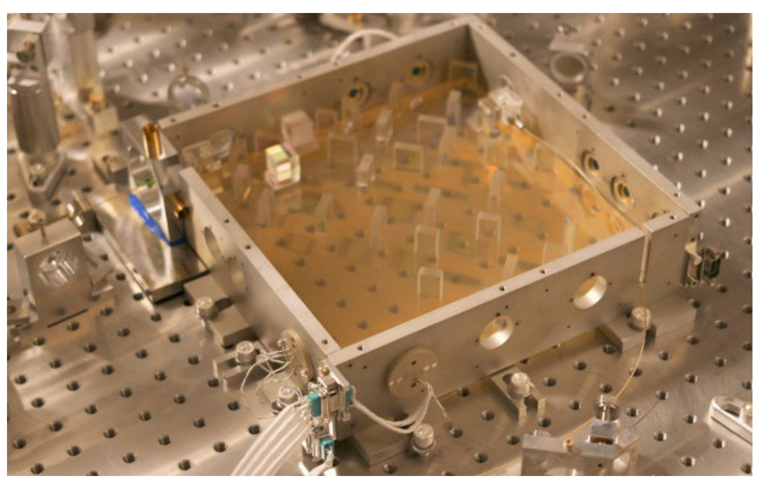
GEMINI at LNGS

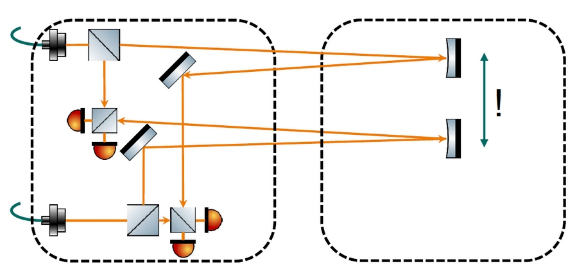


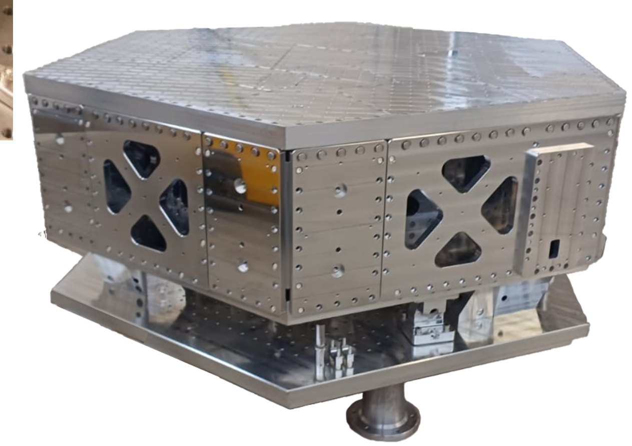
High-precision laser interferometry to put the two suspended platforms into a common motion





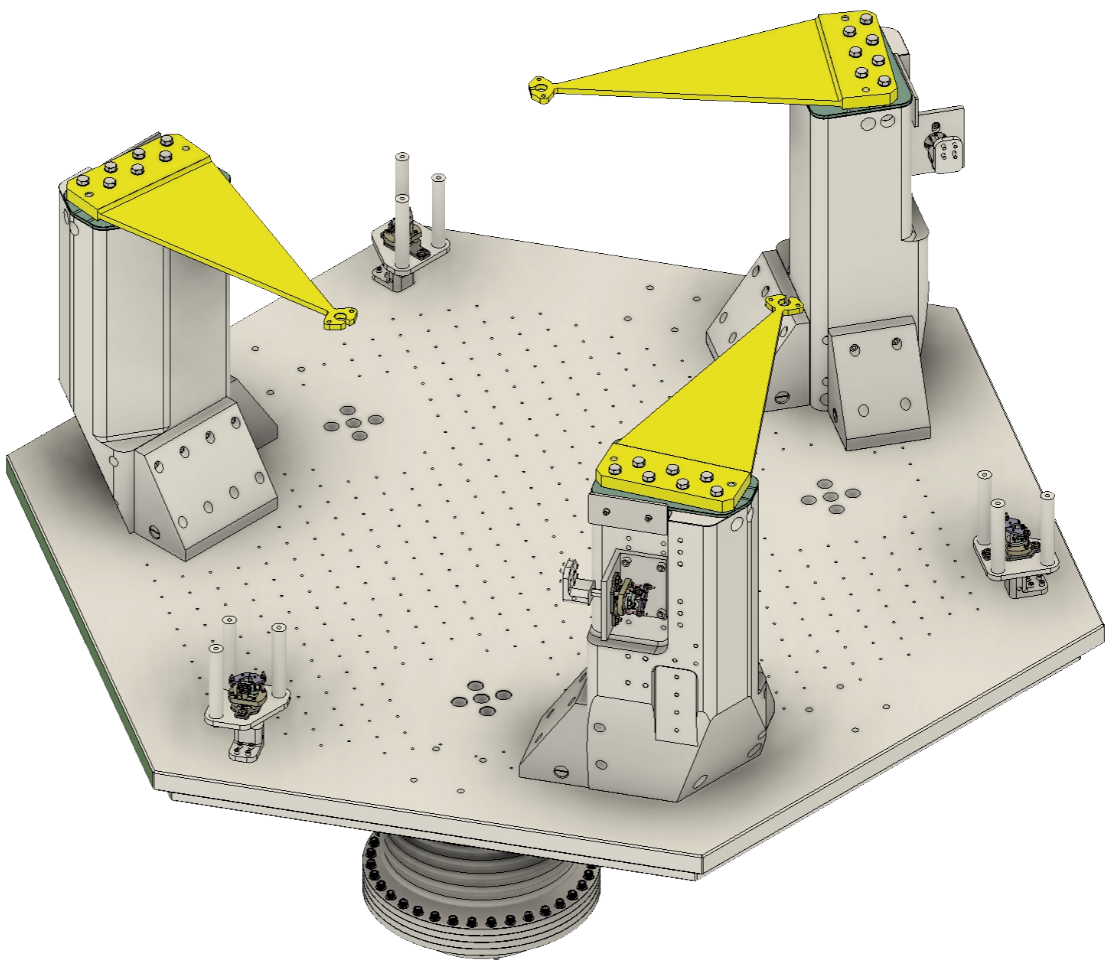


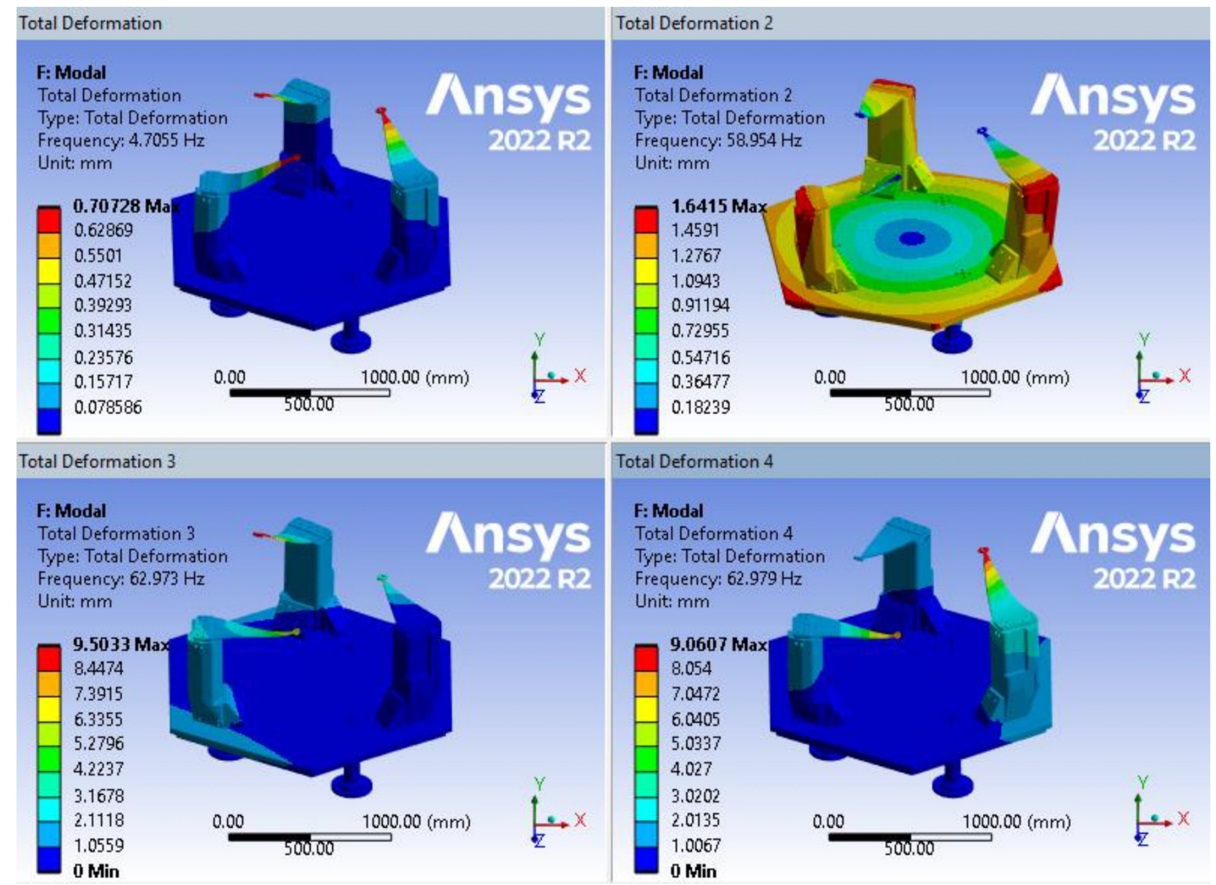




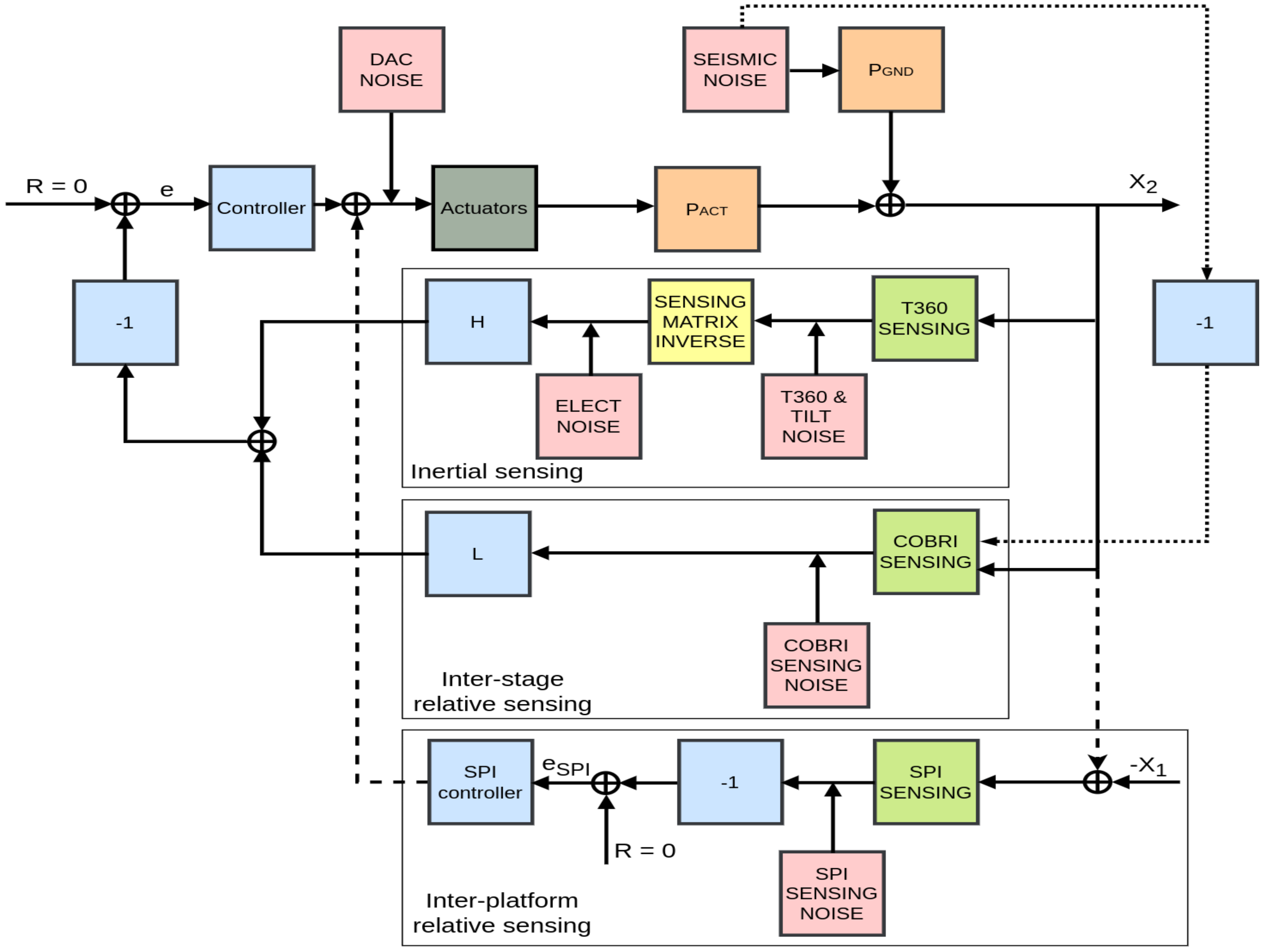
GEM-VCP: Stage 0

100Hz HAM-ISI (unconstrained)
70Hz GEM-VCP (under load)





Simulations



Low-Frequency Control Noise (WP 5)

Why it matters (ET-LF band)

- At low f, sensitivity and robustness are often limited by technical noise from control loops, not by quantum noise
- Dominant contributor is frequently angular sensing & control (ASC), with interfaces to LSC, suspensions, and optics

Core mechanism (coupling story)

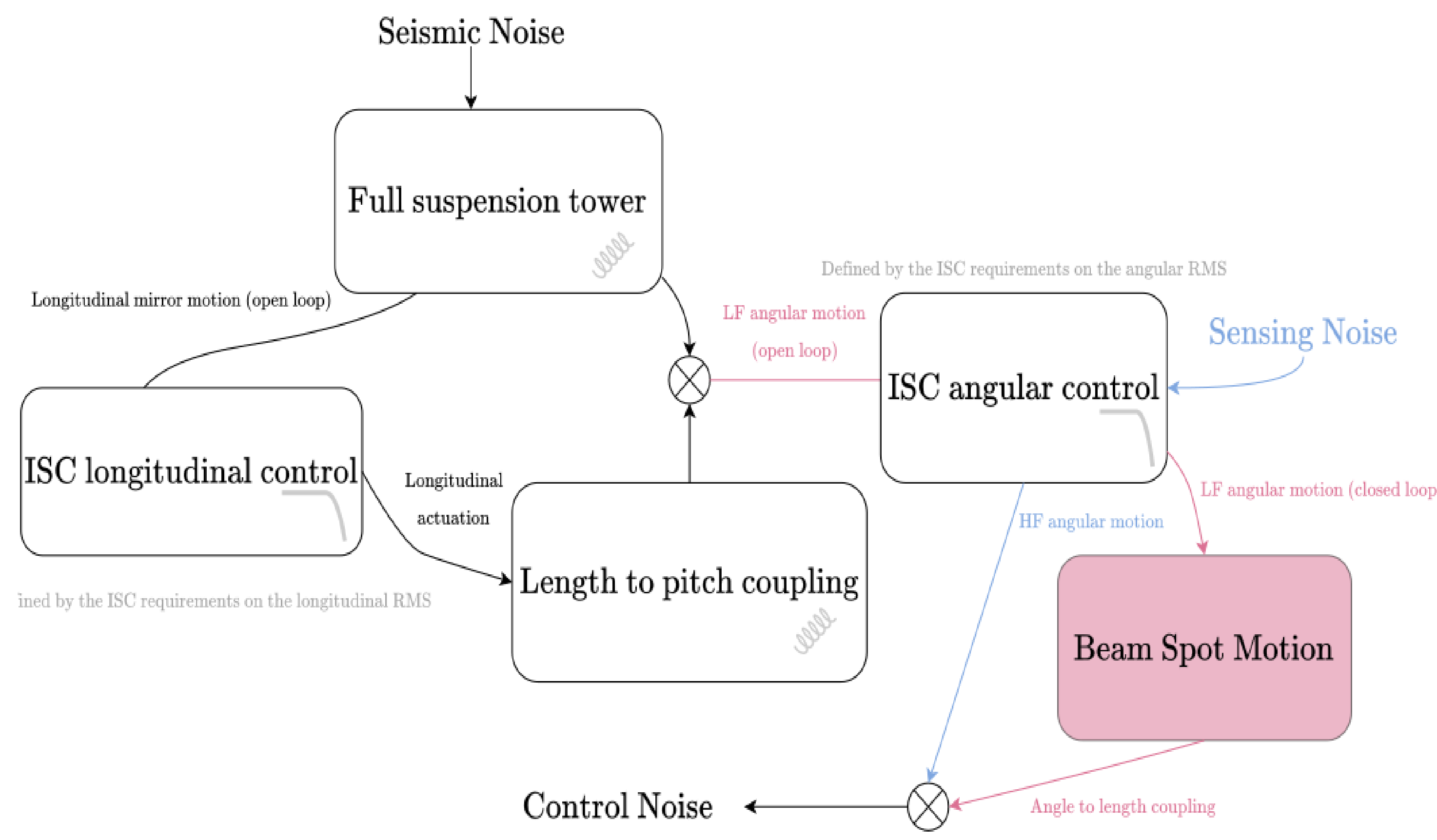
- Low-frequency residual motion + alignment control → beam-spot motion and angle-to-length coupling
- This can upconvert noise and create non-stationary behaviour (drifts, microseism, scattered-light triggering)

Design implication

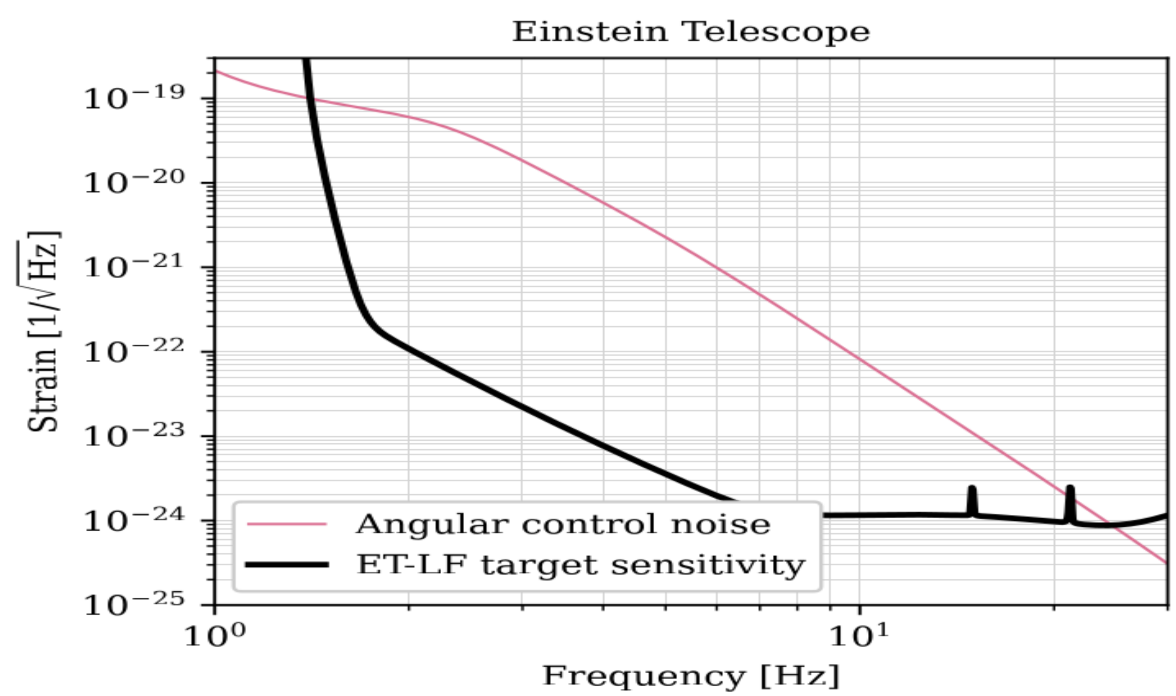
- Control noise is set by architecture (sensing geometry, actuation, dynamic range, cross-couplings)
- So requirements must be self-consistent across subsystems, not “one magic number”

What WP V.5 delivers

- A requirements & verification matrix linking residual motion → sensing noise → control injection → strain impact



Basalaev et al, Iterative approach to derive requirements on control noise for the ET-LF

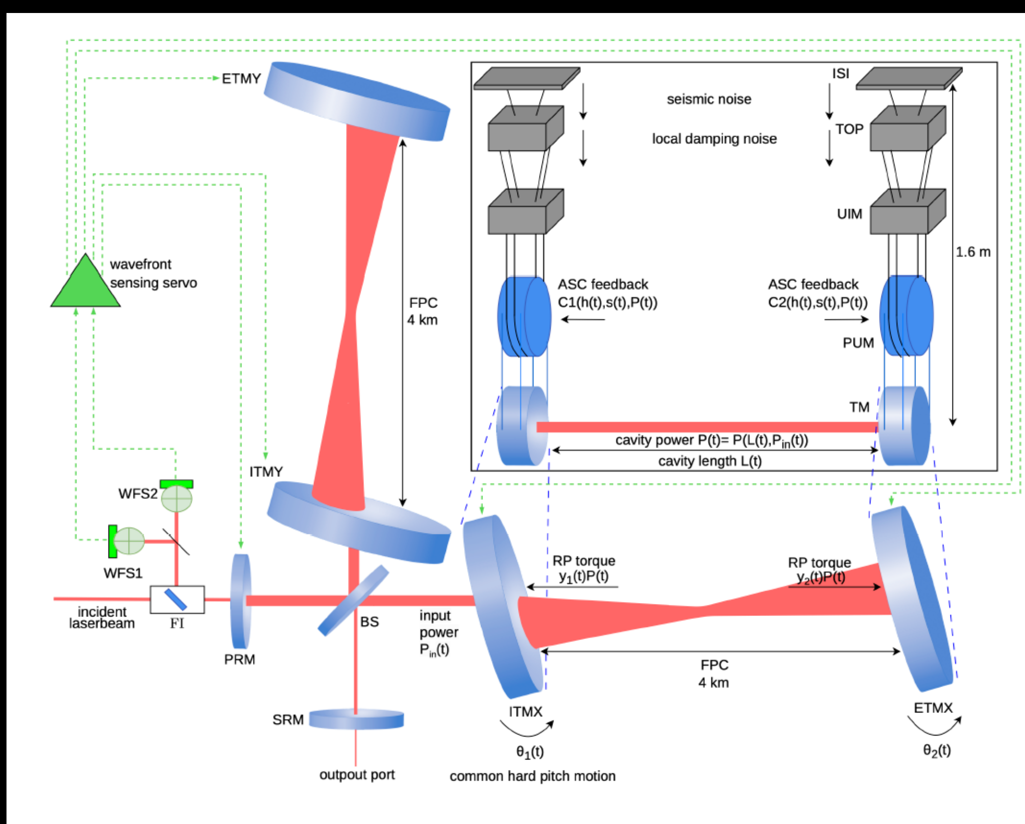


Maggiore et al, Angular control noise in Advanced Virgo and implications for the Einstein Telescope

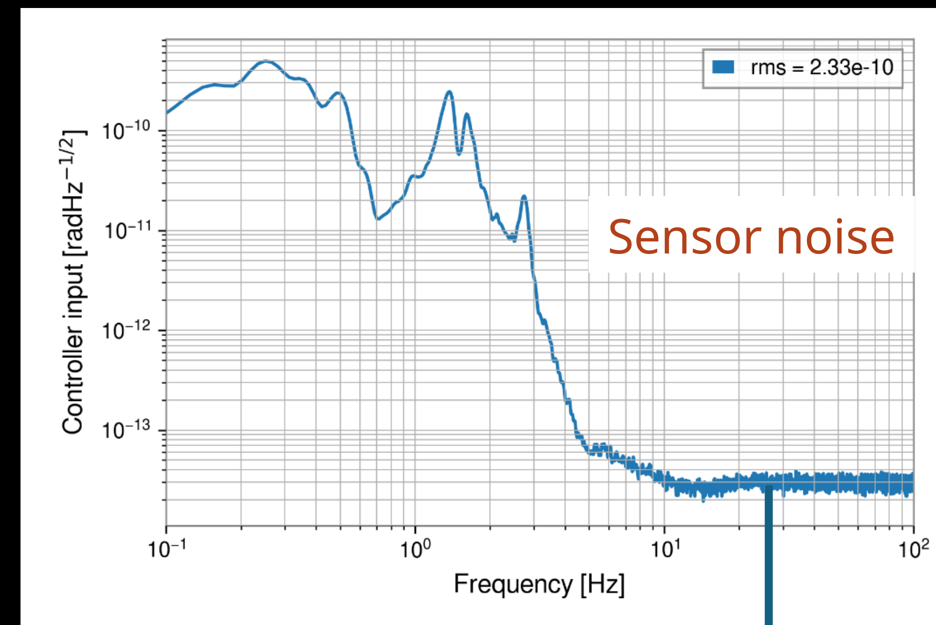
Control of Auxiliary Degrees of Freedom

We need to align and control the relative positions between many suspended optics. The control introduces noise.

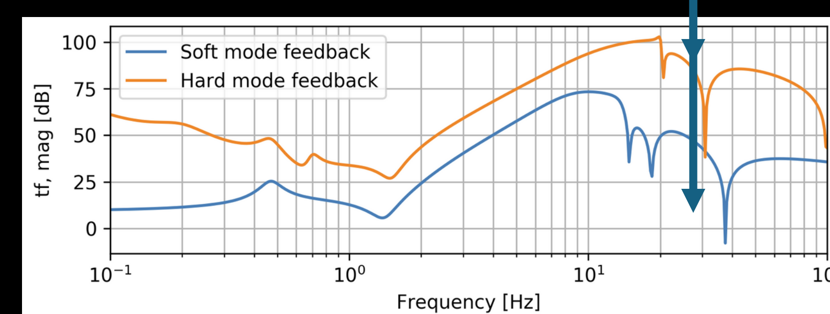
Global angular control



Error signal: observed misalignment



Feedback filter

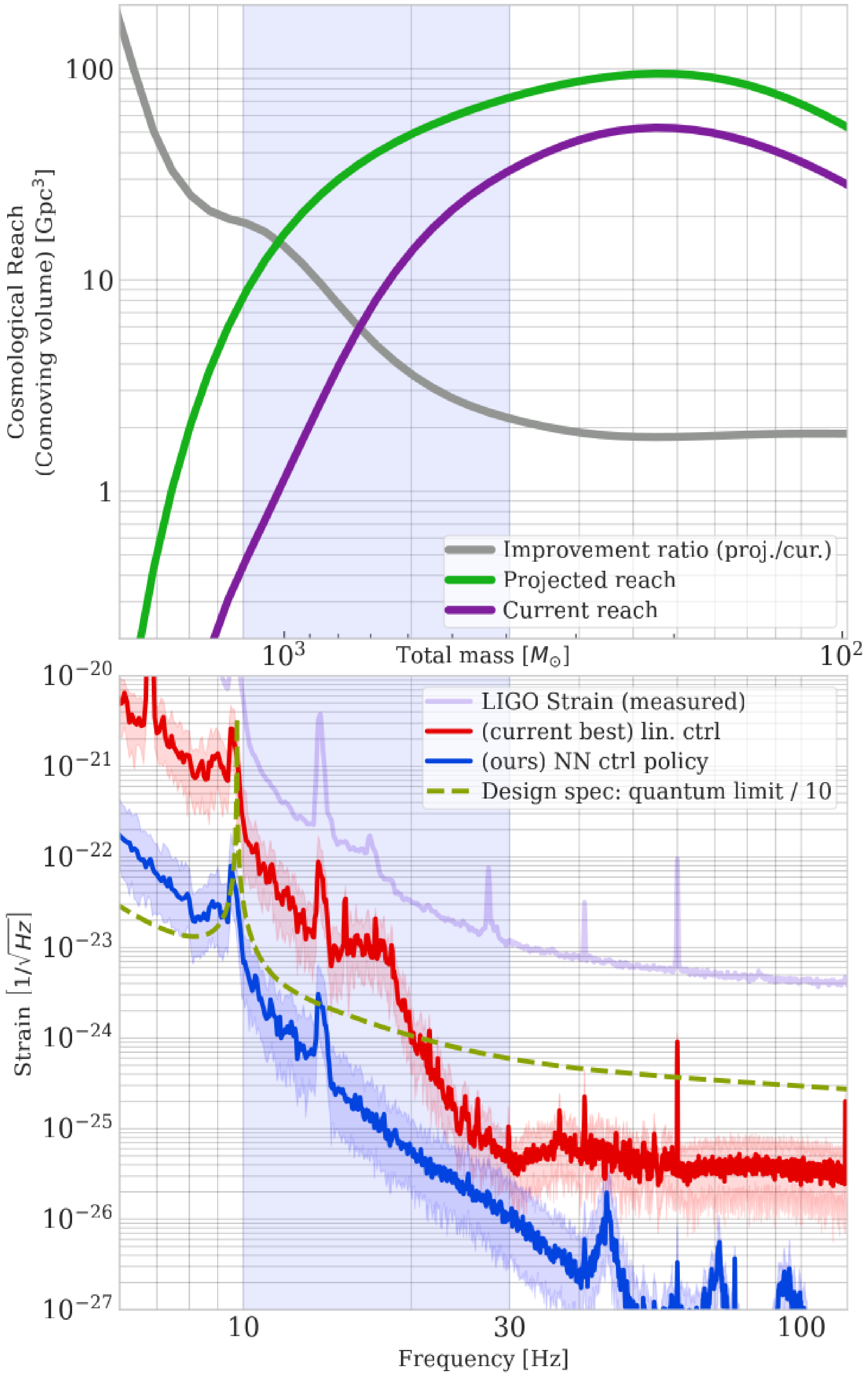


Back to suspensions and test masses

Key result: RL policy reduces noise up to 100x

Main Results:

1. Very good performance with linearized simulations
2. Good performance at LLO
3. Mostly short ~15 min tests.
4. Longer runs - no issues.



Overview: use neural networks for better feedback control

- Shimmer Project started ~2020.
- Main aim was to have a stable HARD ASC loop with less noise injection > 10 Hz.
- Time domain simulation: Tomislav Andric, Jan Harms -> LightSaber.
- Linearized time-domain simulation: Chris Wipf - RT SimPlant
- Neural Network training: DeepMind / Caltech

Setup

- A GW detector is a system of optomechanical degrees of freedom (e.g., mechanical suspensions, beam phase/alignment/shape, laser amplitude and frequency)
- Something like 100 degrees of freedom need to be controlled, and there is an important coupling between most of them

Goals

- Laser interferometer must be operated as close as possible to its ideal state
- Low-frequency motion must be strongly reduced
- System must remain stable
- Noise injected by the controller must be minimized

Science

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RESEARCH ARTICLE | ASTROPHYSICS

Improving cosmological reach of a gravitational wave observatory using Deep Loop Shaping

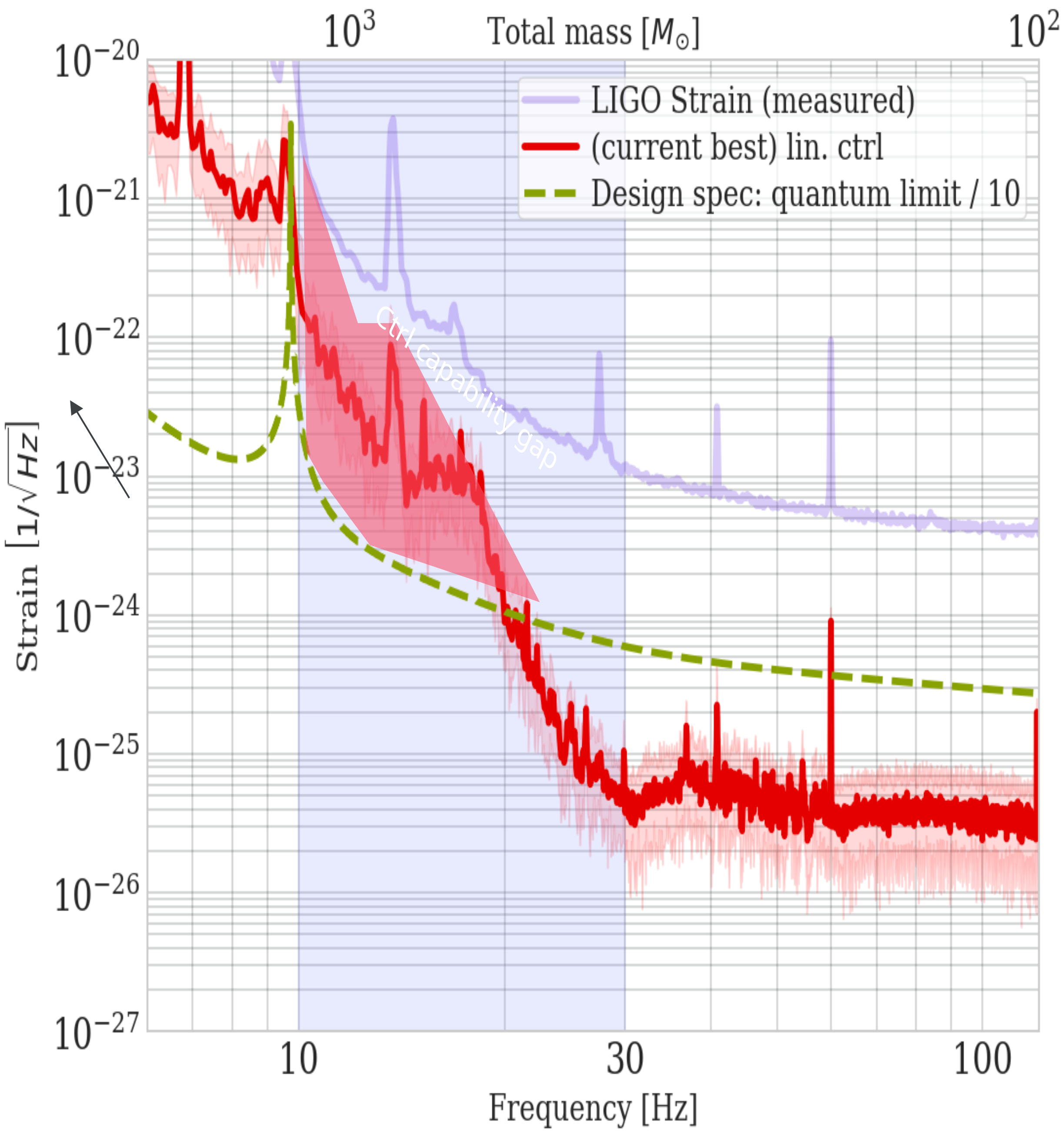
JONAS BUCHLI, BRENDAN TRACEY, TOMISLAV ANDRIC, CHRISTOPHER WIPF, YU HIM JUSTIN CHIU, MATTHIAS LOCHBRUNNER, CRAIG DONNER, RANA X. ADHIKARI, JAN HARMS, [...], AND THE LIGO INSTRUMENT TEAM +21 authors Authors Info & Affiliations

SCIENCE • 4 Sep 2025 • Vol 389, Issue 6764 • pp. 1012-1015 • DOI: 10.1126/science.adw1291

Editor's summary

Gravitational wave detectors have revolutionized astrophysics by detecting black holes and neutron stars. Most signals are captured in the 30- to 2000-Hz range, and the lower 10- to 30-Hz band remains largely unexplored because of persistent low-frequency control noise that limits sensitivity. Enhancing this sensitivity could increase cosmological reach. Using nonlinear optimal control through reinforcement learning with a frequency-domain reward, Buchli *et al.* developed a method that effectively reduces control noise in the low-frequency band. This method was successfully implemented at the Laser Interferometer Gravitational-Wave Observatory (LIGO) in Livingston and the Caltech 40 Meter Prototype, achieving control noise levels on LIGO's most demanding feedback control loop below the quantum noise, thus removing a critical obstacle to increased detector sensitivity. —Yury Suleymanov

Current control is significant source of noise



The angular control noise is now one of main remaining blocker for increased low frequency sensitivity of LIGO!

Any reduction of the control noise will have a huge scientific impact.

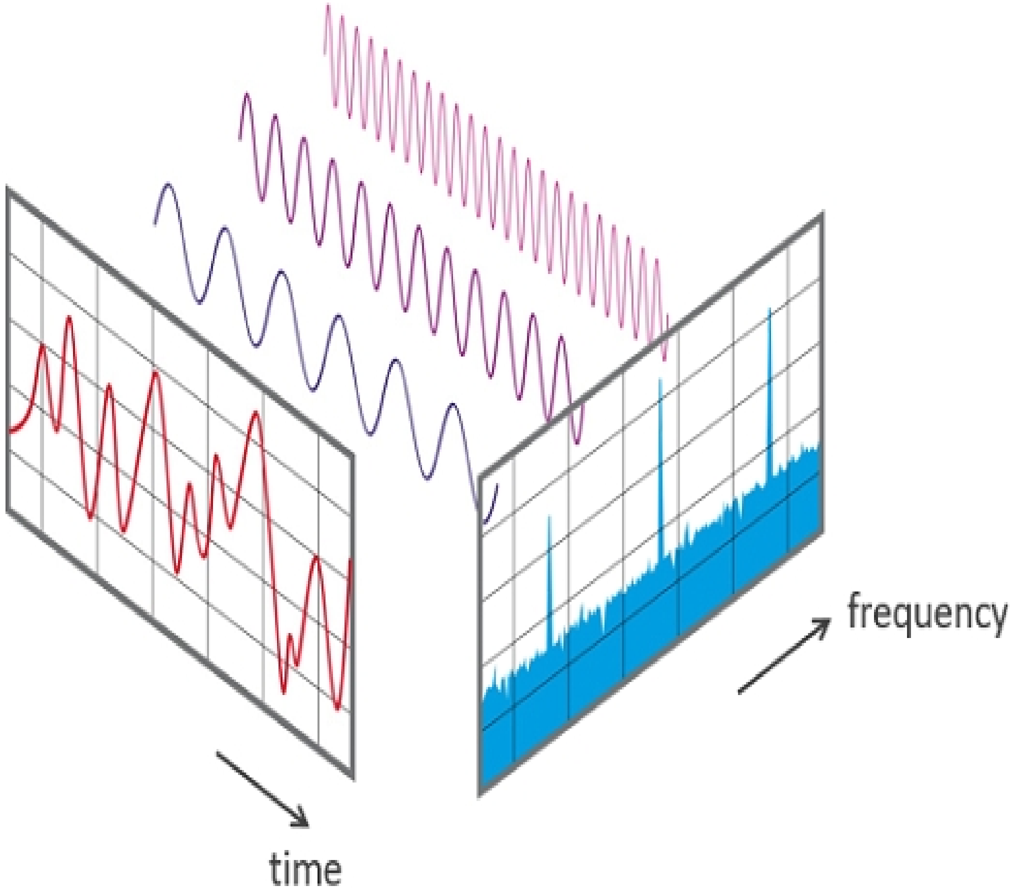
Big question: How can we improve the controller satisfying both stability and observation band performance?

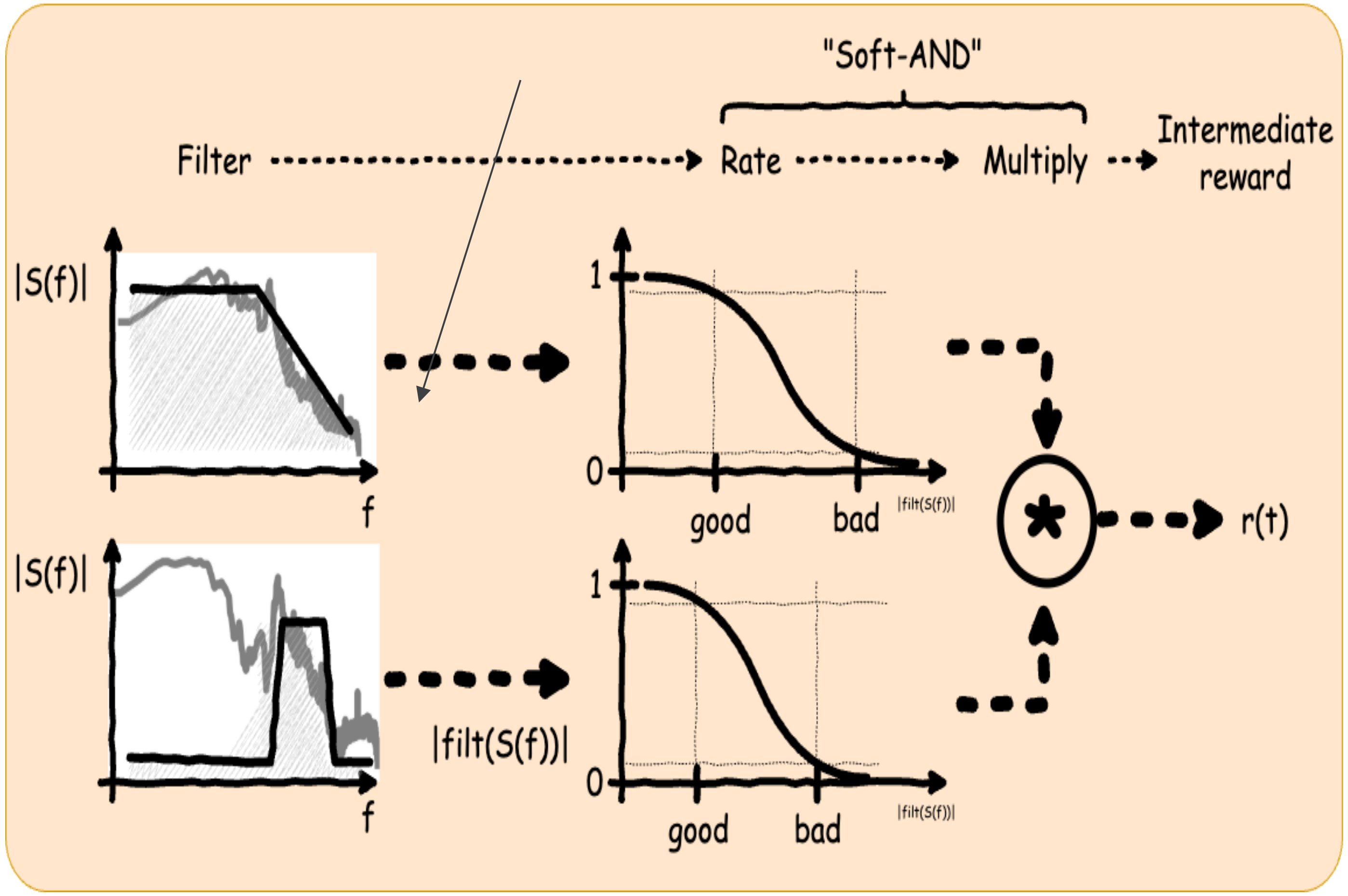
Success criteria:

Improve the noise floor in the frequency range 10-30Hz for the LIGO system by at least one order of magnitude when compared to the currently used controllers.

Logarithmic scale!

Frequency domain rewards closed loop control design:
Deep Loop Shaping

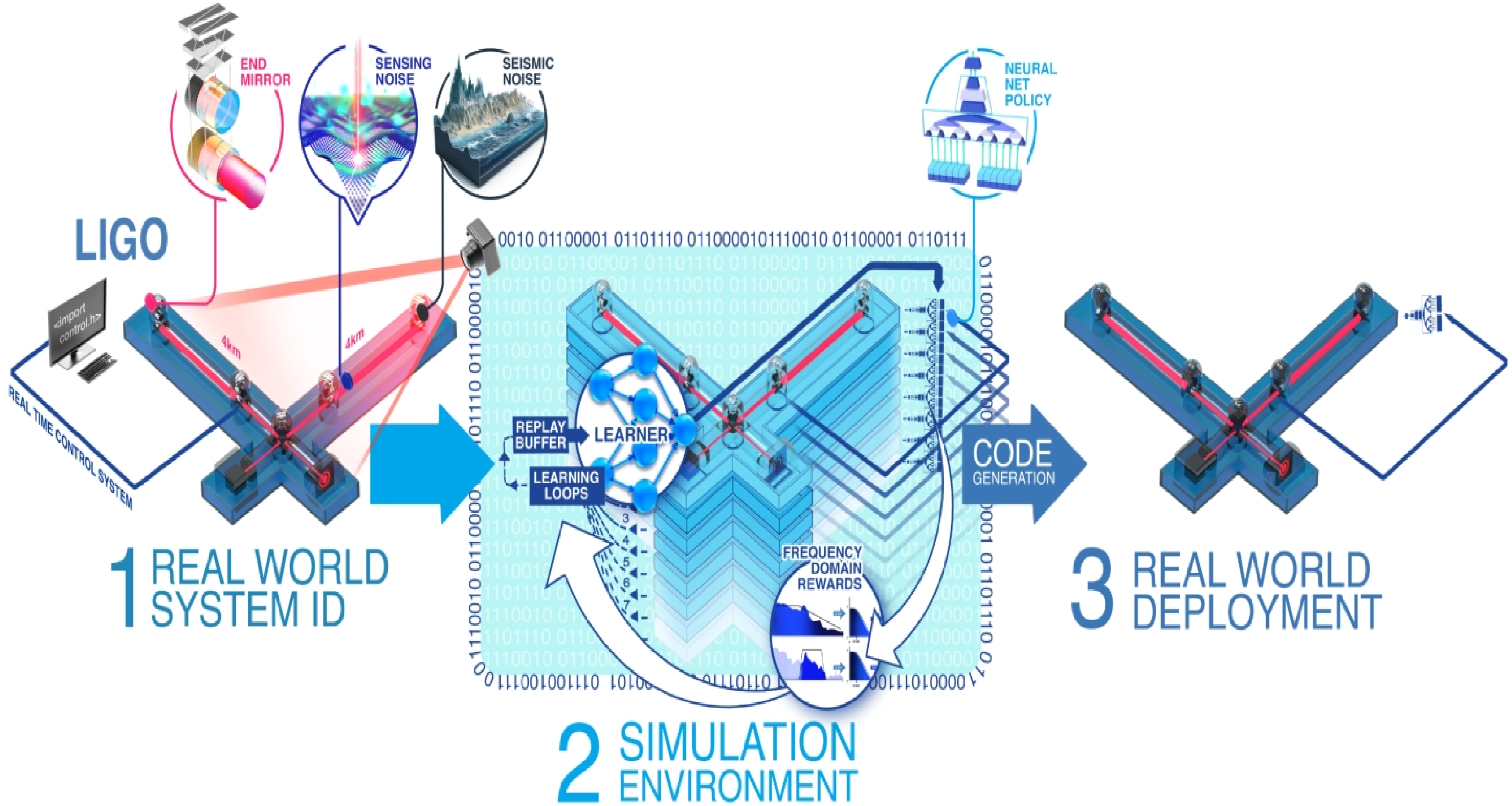


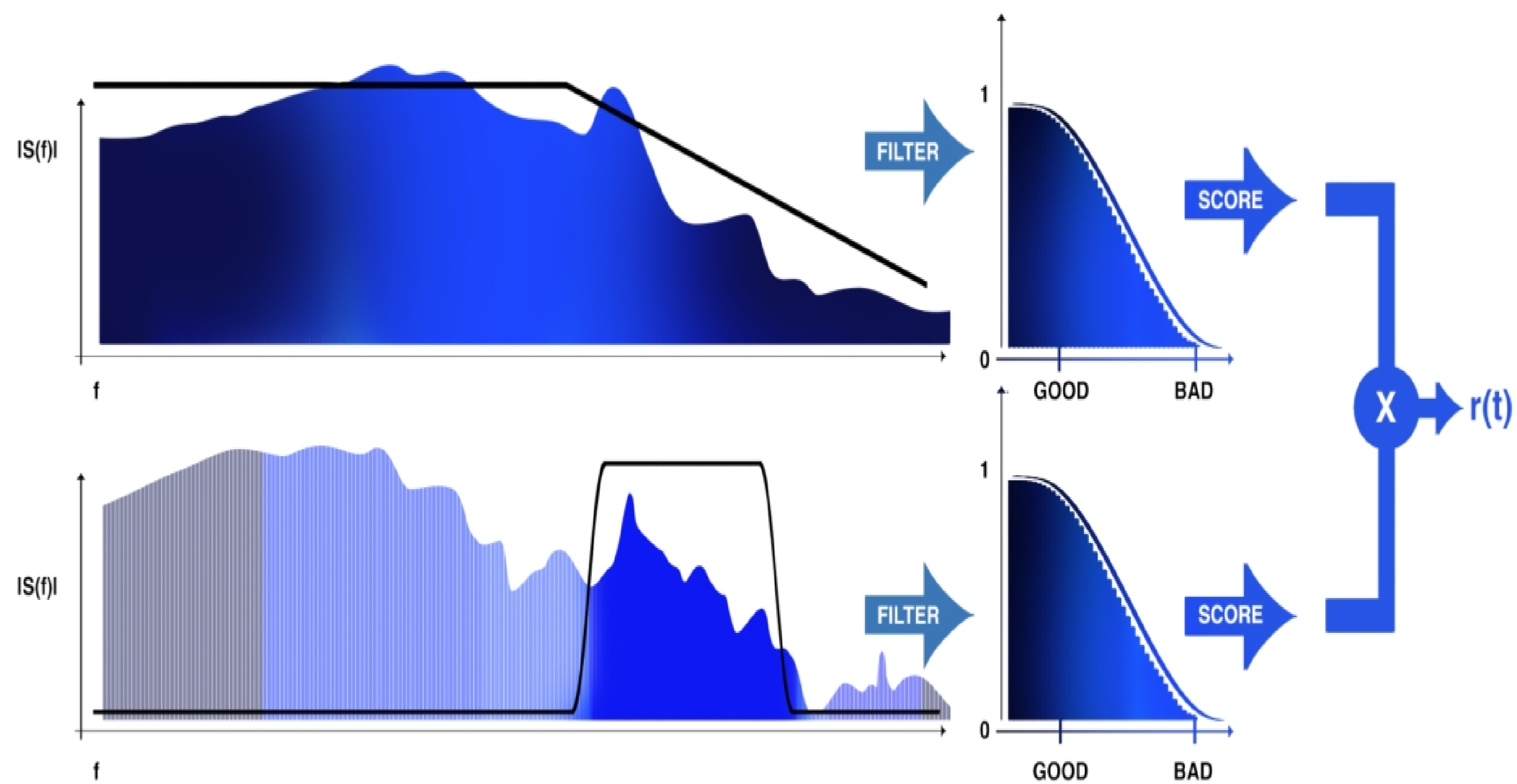


Deep Loop Shaping is a general RL/control design method!

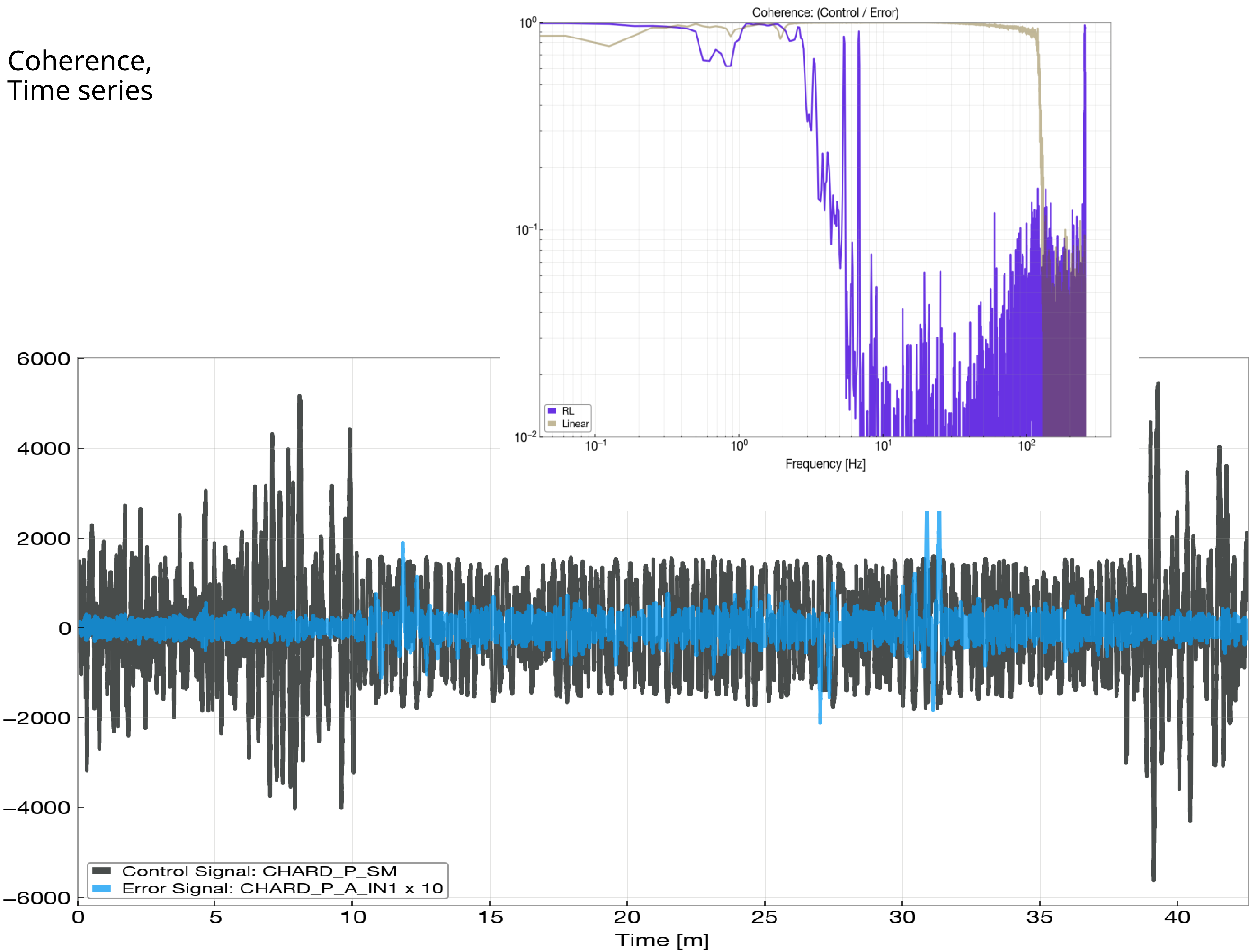
$$\pi^* = \underset{a \sim \pi}{\arg\max}\, J = \mathbb{E}_\pi \left[\sum_{t=0}^{\infty} \gamma^t r(s_t, a_t, s_{t+1}) \right]$$

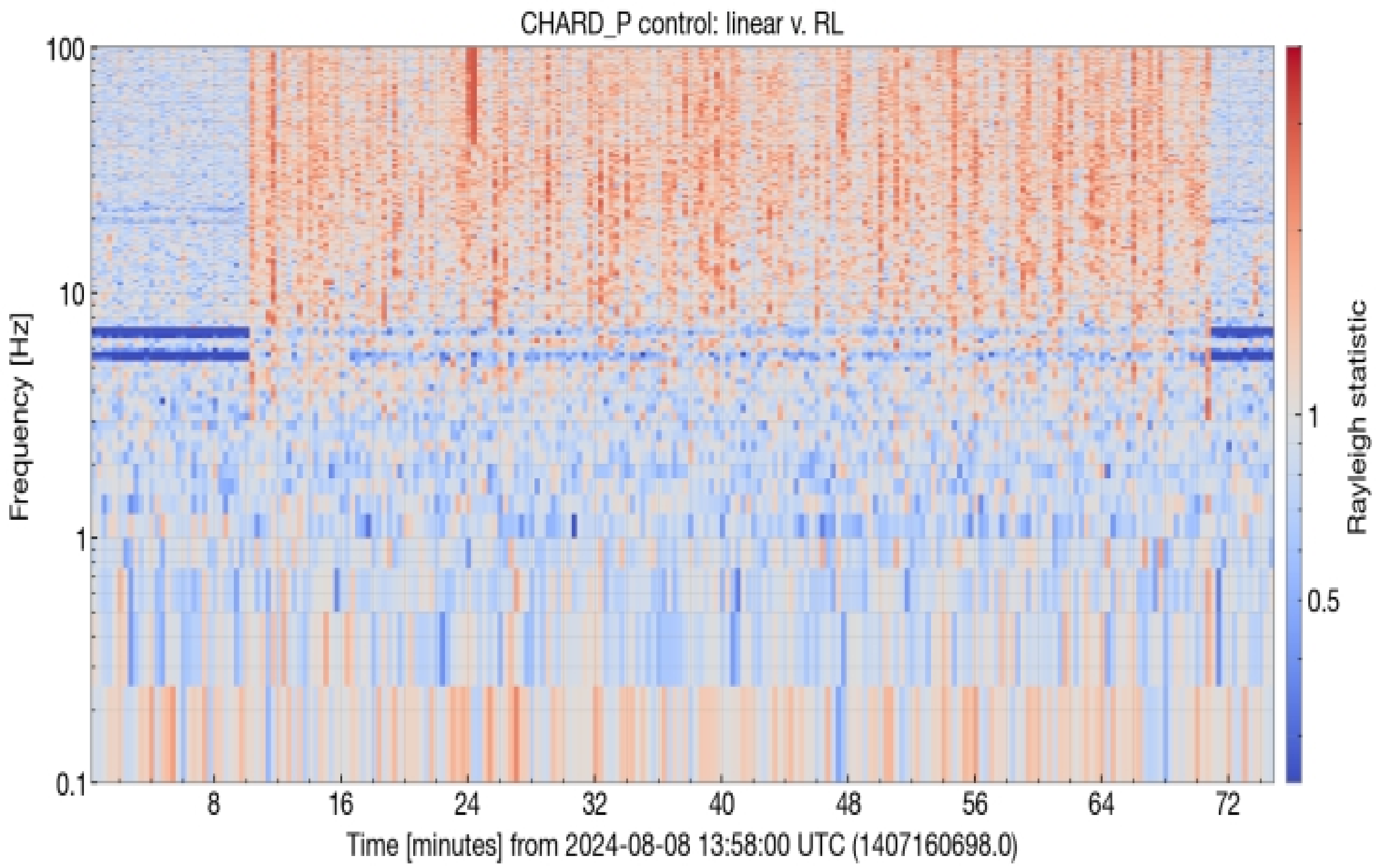
Illustration of method

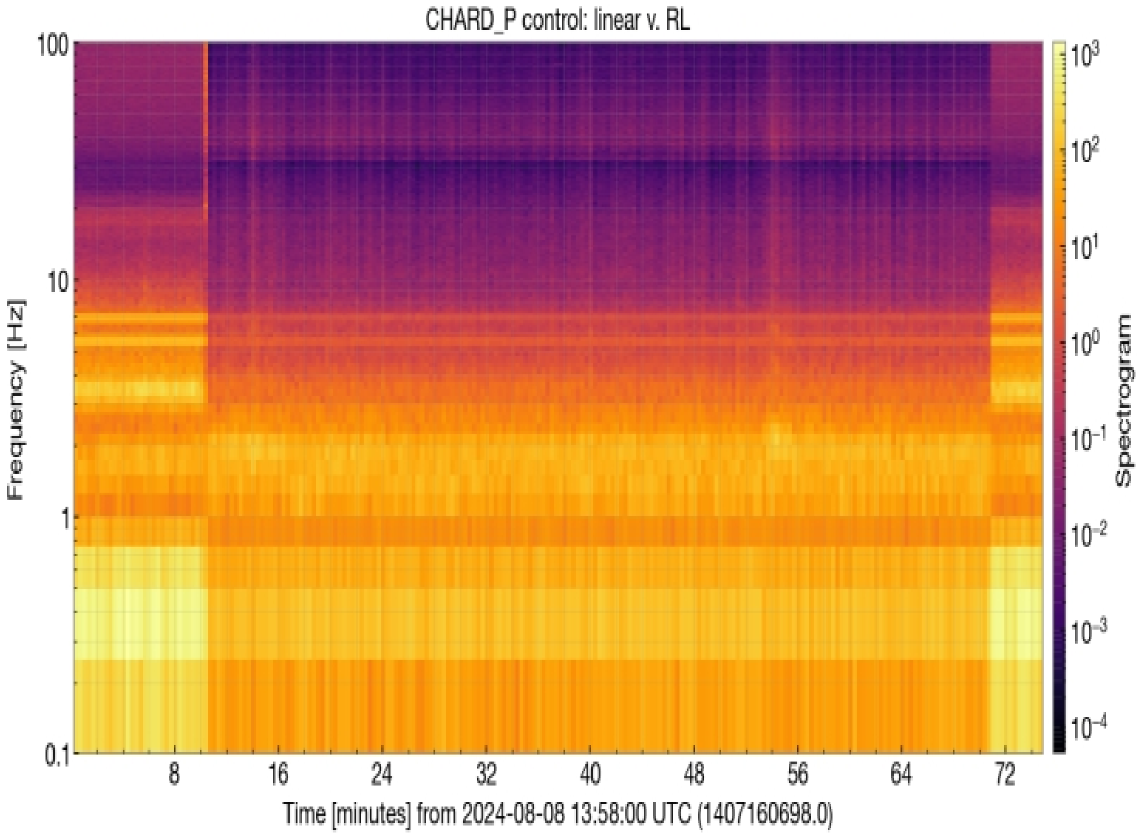




Coherence,
Time series







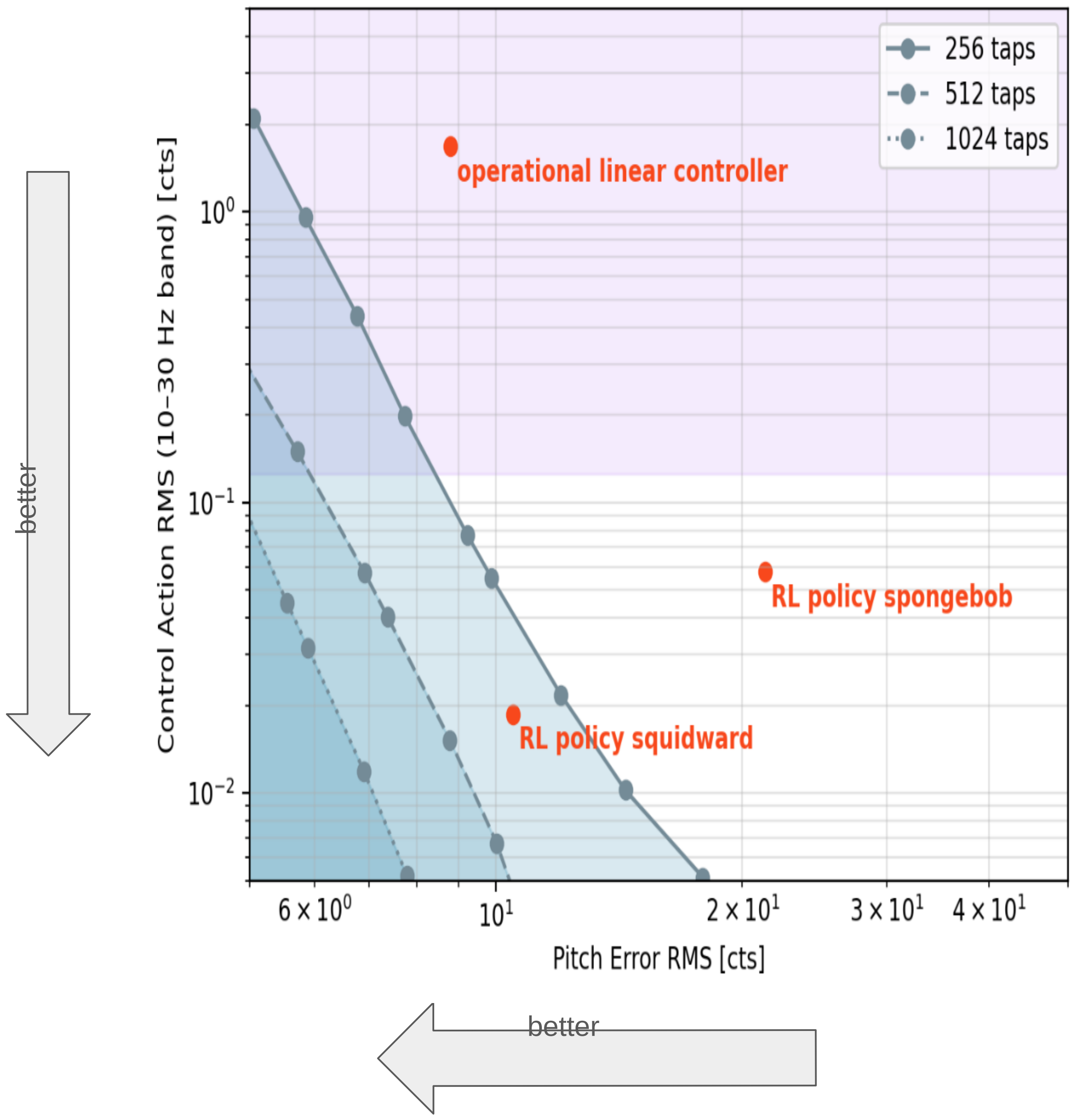
LIGO

RayleighMonitor Algorithm

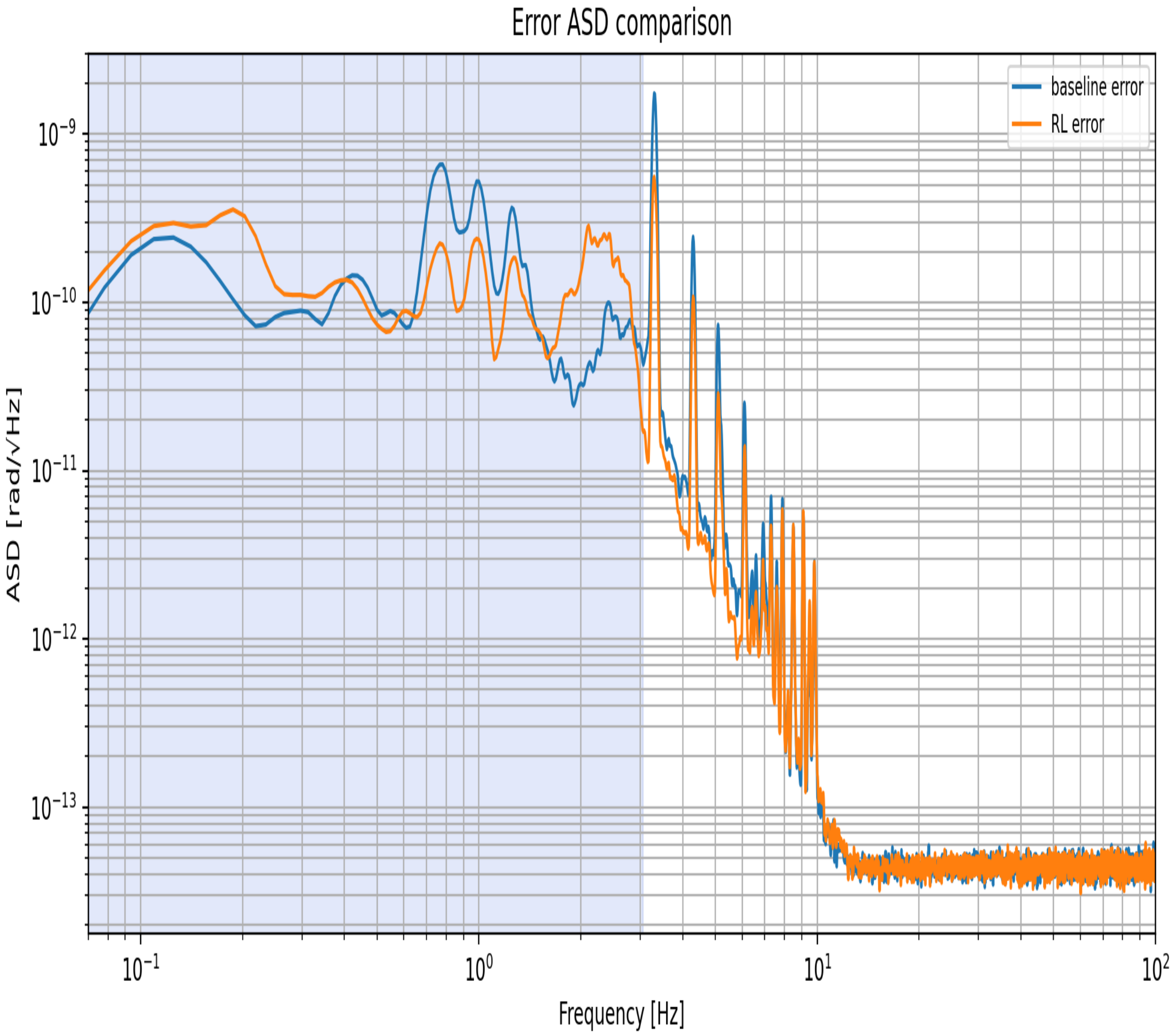
- Makes a set of short-time power spectra.
- Calculates the mean μ and the standard deviation σ of the power spectrum in each frequency bin.
- Ratio $R := \sigma/\mu$ is an interesting statistic:
  - » $R = 1$ is what you expect for Gaussian noise.
  - » $R < 1$ indicates coherent variation.
  - » $R > 1$ indicates glitchy/ratty data.
- RayleighMonitor plots scrolling spectrograms (μ) and "Rayleighgrams" (R) for visual inspection of data characteristics.

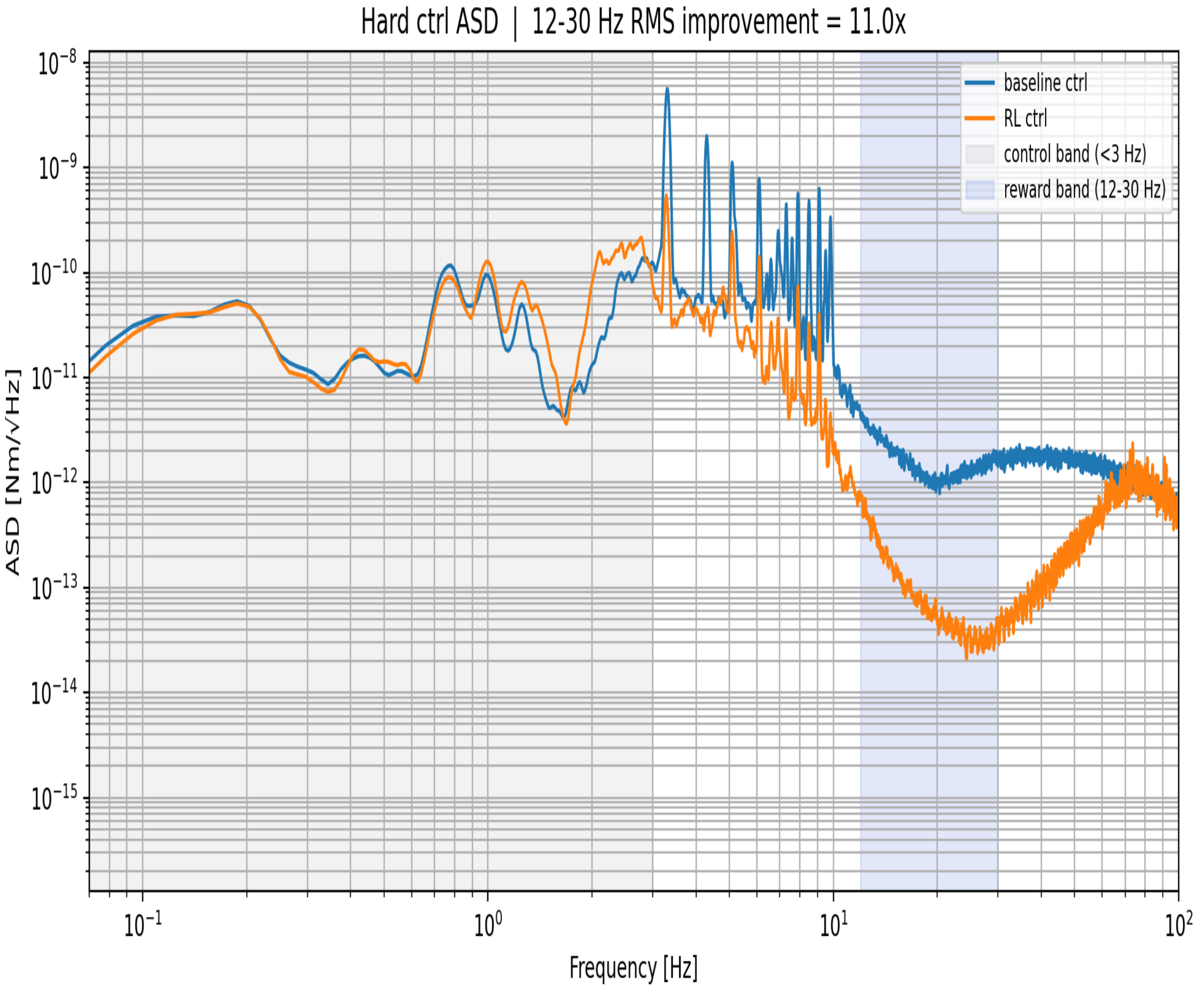
Optimized Linear Controllers

- Since the 1980s, convex optimization was recognized as a powerful tool for optimizing linear control loops
- This method lets us map out a "[Pareto frontier]" of high-performance linear CHARD_P controllers. These can provide a baseline of comparison for the nonlinear policies
- Optimization performed over: FIR filters with varying tap length (i.e., history window size)
- RL policies operate without an auxiliary stabilizer, yet outperform convex-optimized controllers that require one
- Not yet fit for deployment (not robust under plant variation)



Virgo Results

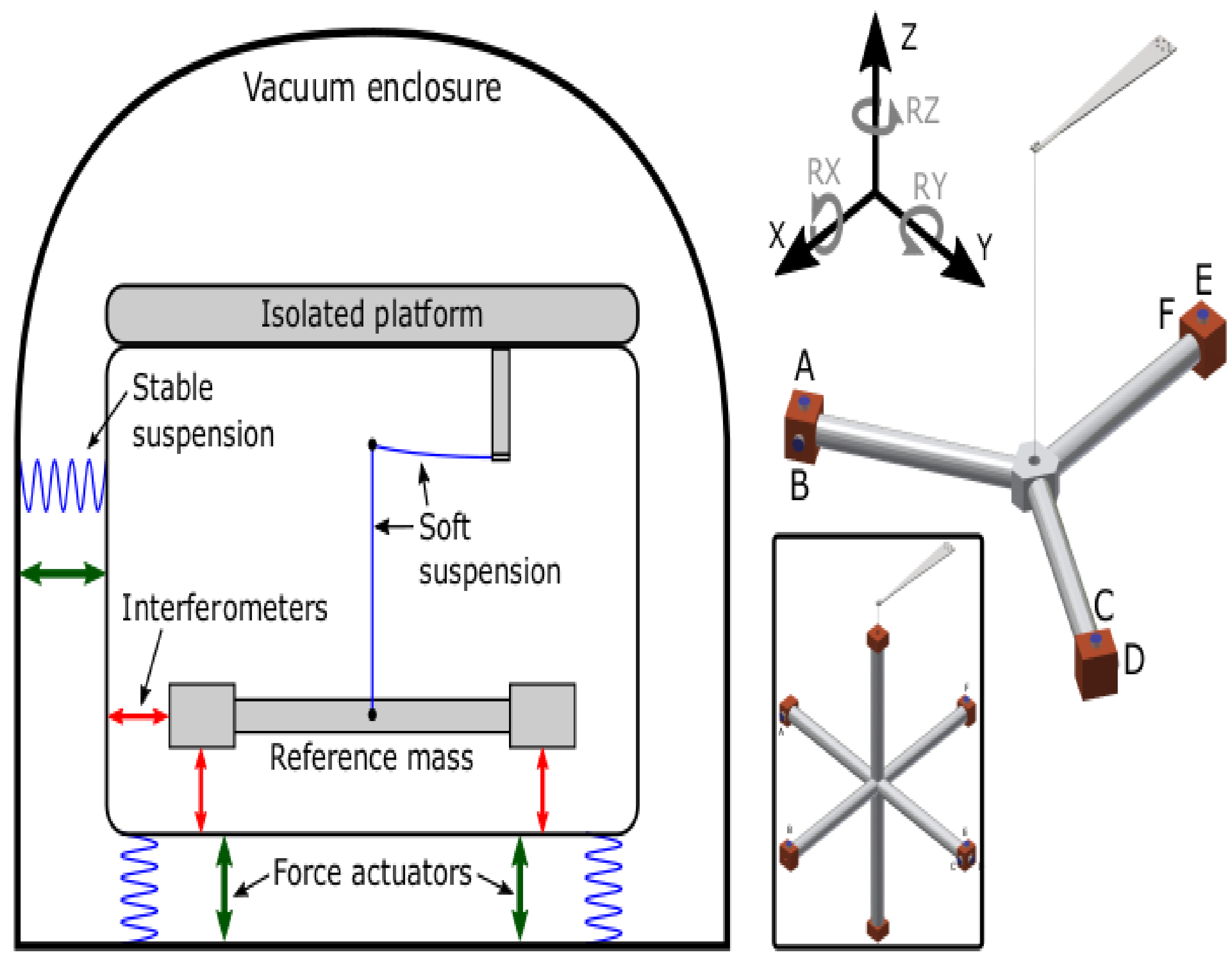




ASC for ET-LF

- ET – issue needs to be addressed already with its design
- RMS not filtered with mechanical suspension
- Sensors will not become better
- Natural resonant frequency ~0.05 Hz in pitch and ~0.2 Hz in yaw
- Resonant frequencies for ET-LF are:
  - soft mode pitch: 0.0218 Hz
  - hard mode pitch: 0.1413 Hz
  - soft mode yaw: 0.1949 Hz
  - hard mode yaw: 0.2397 Hz
- **Need for RL for improvements**
- **Work in progress – ET-LF-Lightsaber**

- Omnisens



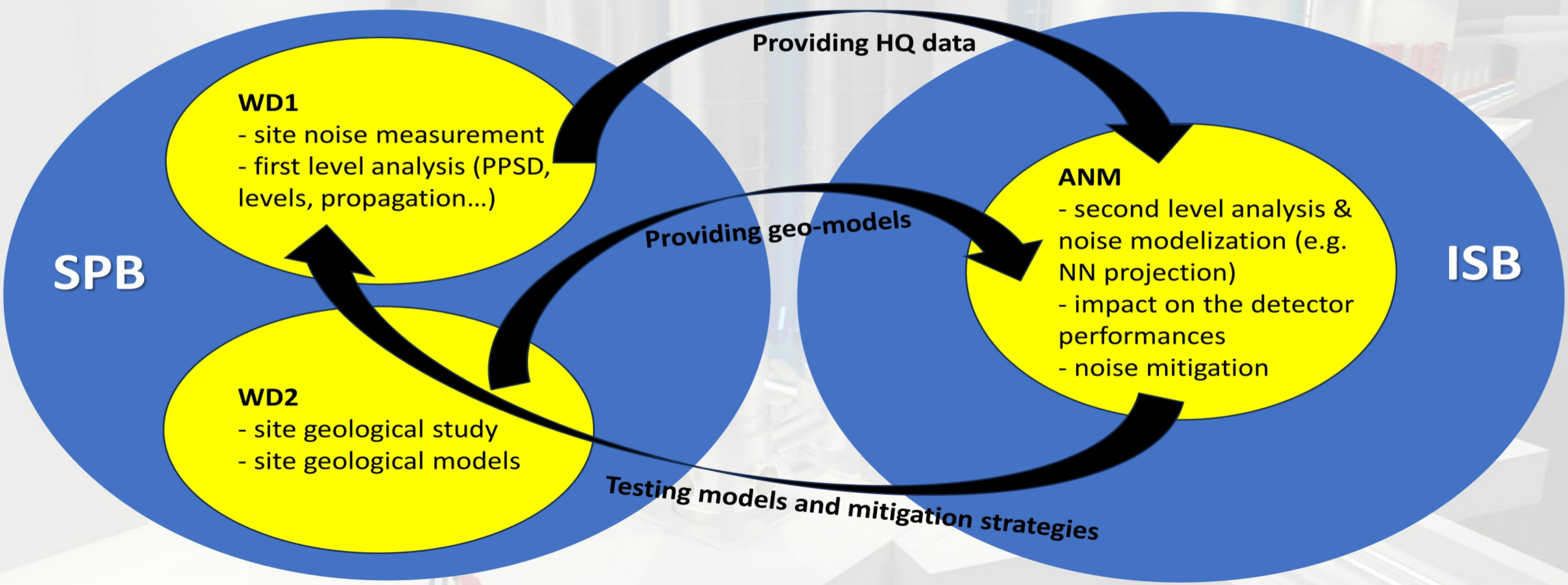
C M Mow-Lowry and D Martynov 2019 Class. Quantum Grav. 36 245006

ANM as a Cross-Divisional Interface

ANM does not live in isolation.

- It interfaces with:
  - Suspensions – sensors, actuation, tilt–translation coupling
  - Optics & Interferometer – ASC/LSC, scattered light, auxiliary DOFs
  - Vacuum & Cryogenics – cryostat motion, cooling-induced vibration
  - Site Characterization Board (SCB) – seismic, magnetic, acoustic boundary conditions

ANM is where environment, mechanics, optics, and control meet.



L. Naticchioni, ISB/ANM PBS Review, Apr.2024, Rome

Some ET R&D and Integration Facilities

CAOS

Amaldi Research Center

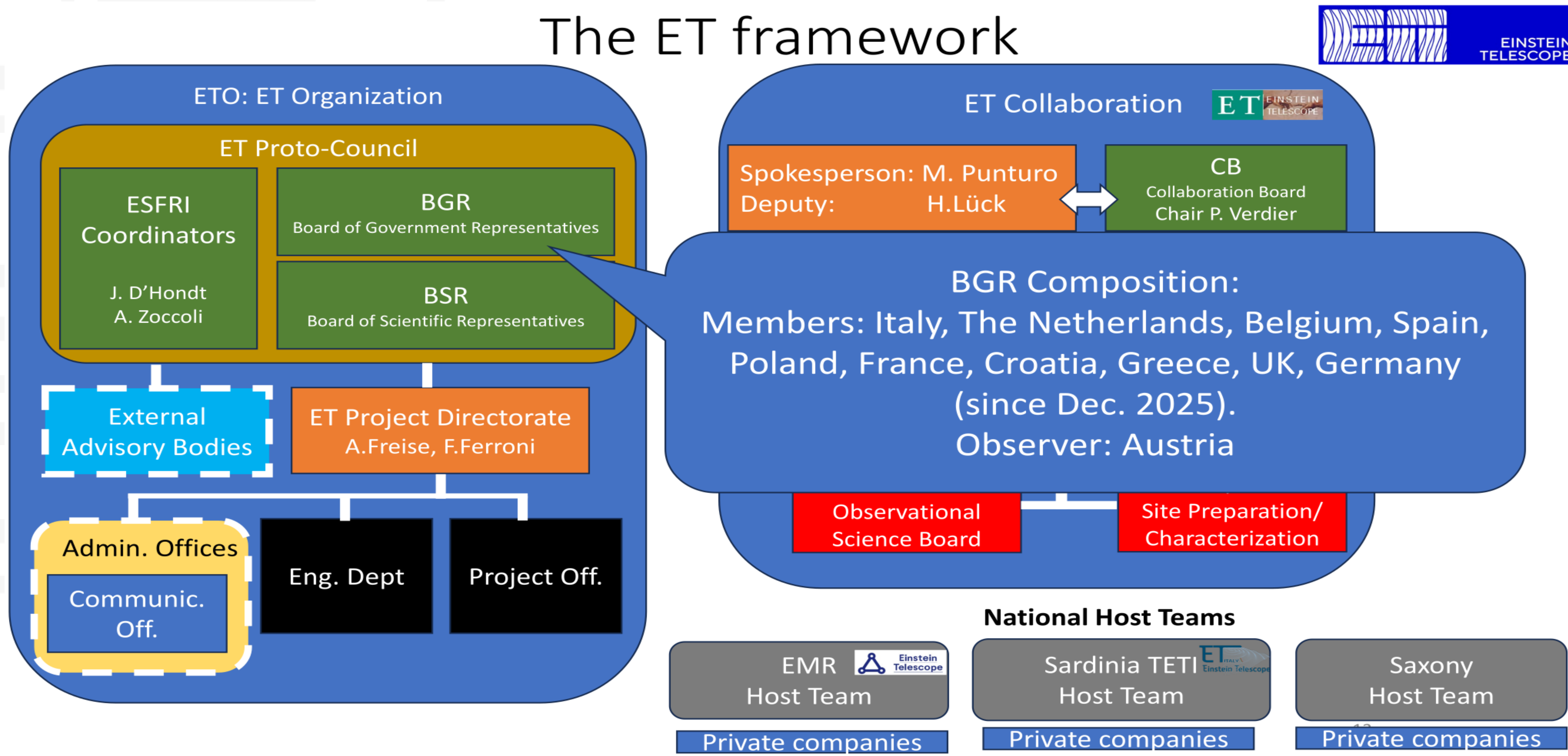
ETpathfinder

PART 5: STATUS / ROADMAP

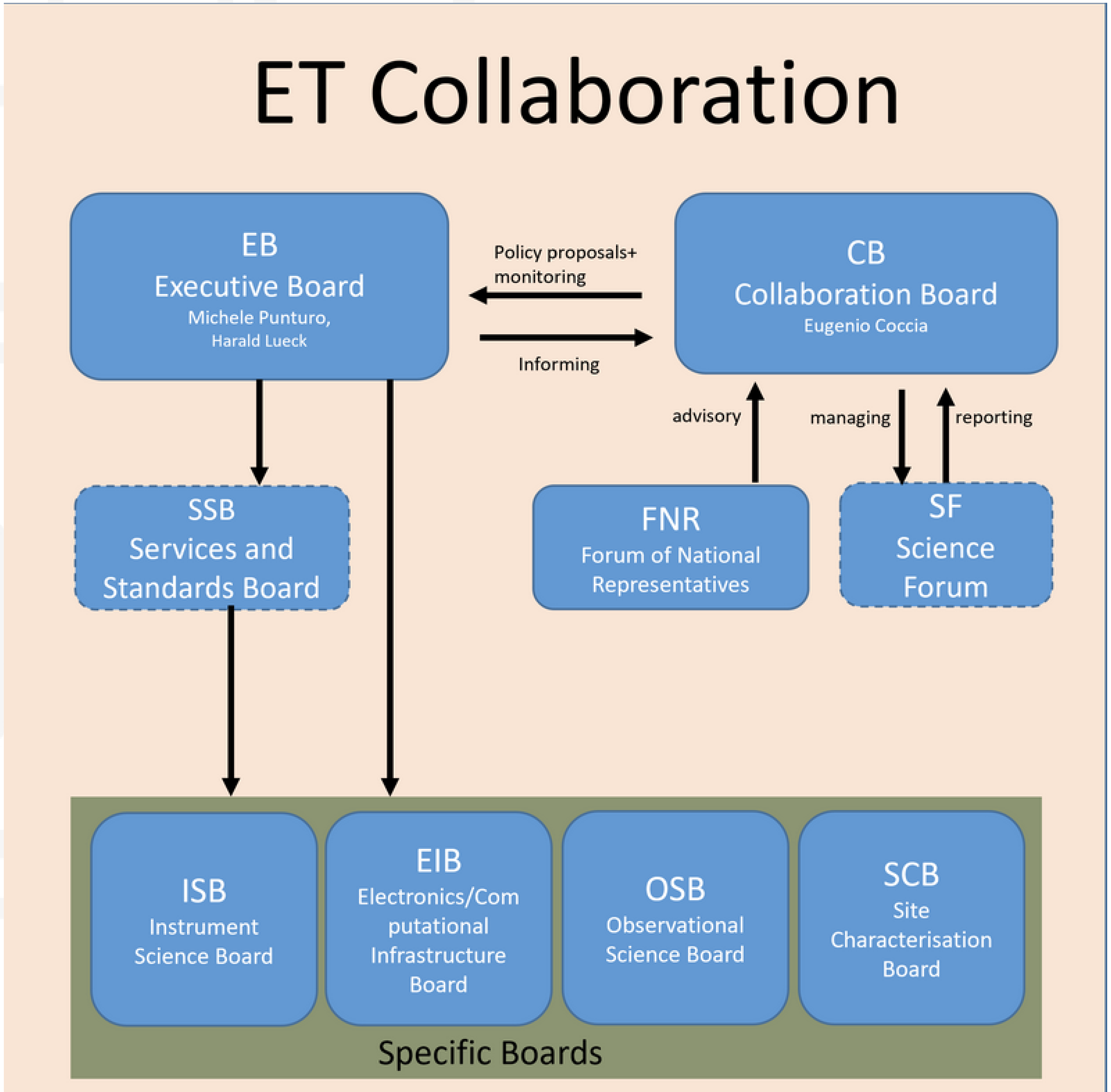
GSSI

ET Collaboration and Governance

- ET is on the ESFRI roadmap — European Strategy Forum on Research Infrastructures — meaning it has formal EU-level recognition as priority infrastructure
- ~1500 scientists, ~250 institutions across Europe organised in the ET Collaboration under spokesperson Michele Punturo
- Three candidate sites under parallel study: EMR (Belgium/Netherlands/Germany), Sardinia (Italy), Saxony (Germany) — final decision pending
- 9 member countries in the Board of Government Representatives: Italy, Netherlands, Belgium, Spain, Poland, France, Croatia, Greece, UK, Germany — a genuinely pan-European project



ET Collaboration and Governance



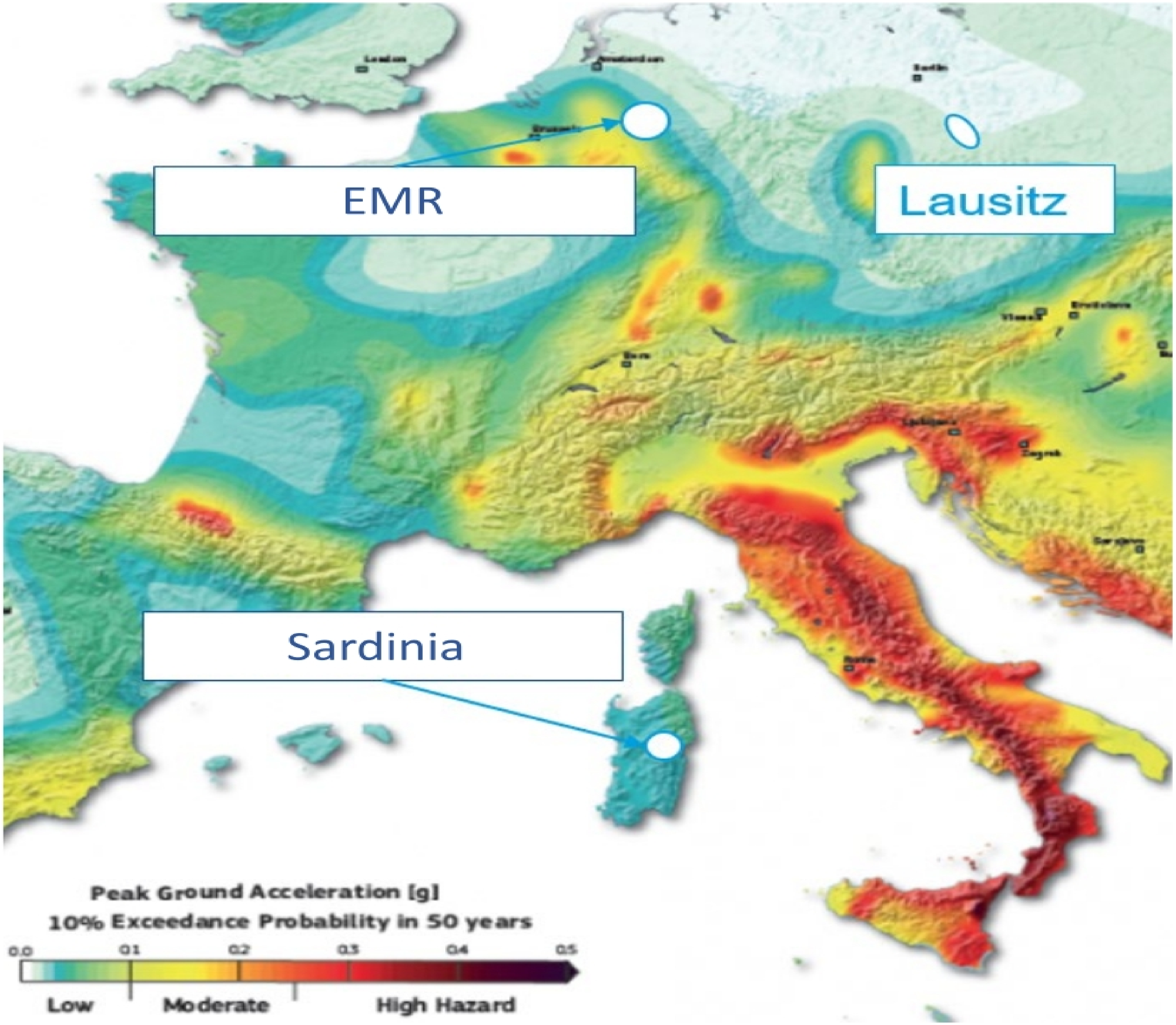
ET is a European collaboration of ~1500 scientists across ~250 institutions — organised through an Executive Board, Collaboration Board, and four specific science/technical boards

ISB (Instrument Science Board) — detector design and noise; OSB (Observational Science Board) — science case and data analysis; EIB — computing infrastructure; SCB — site characterisation at candidate locations

Currently two candidate sites under parallel study: Sardinia (Italy) and the Meuse-Rhine Euroregion (Belgium/Netherlands/Germany) — final site decision expected in the coming years

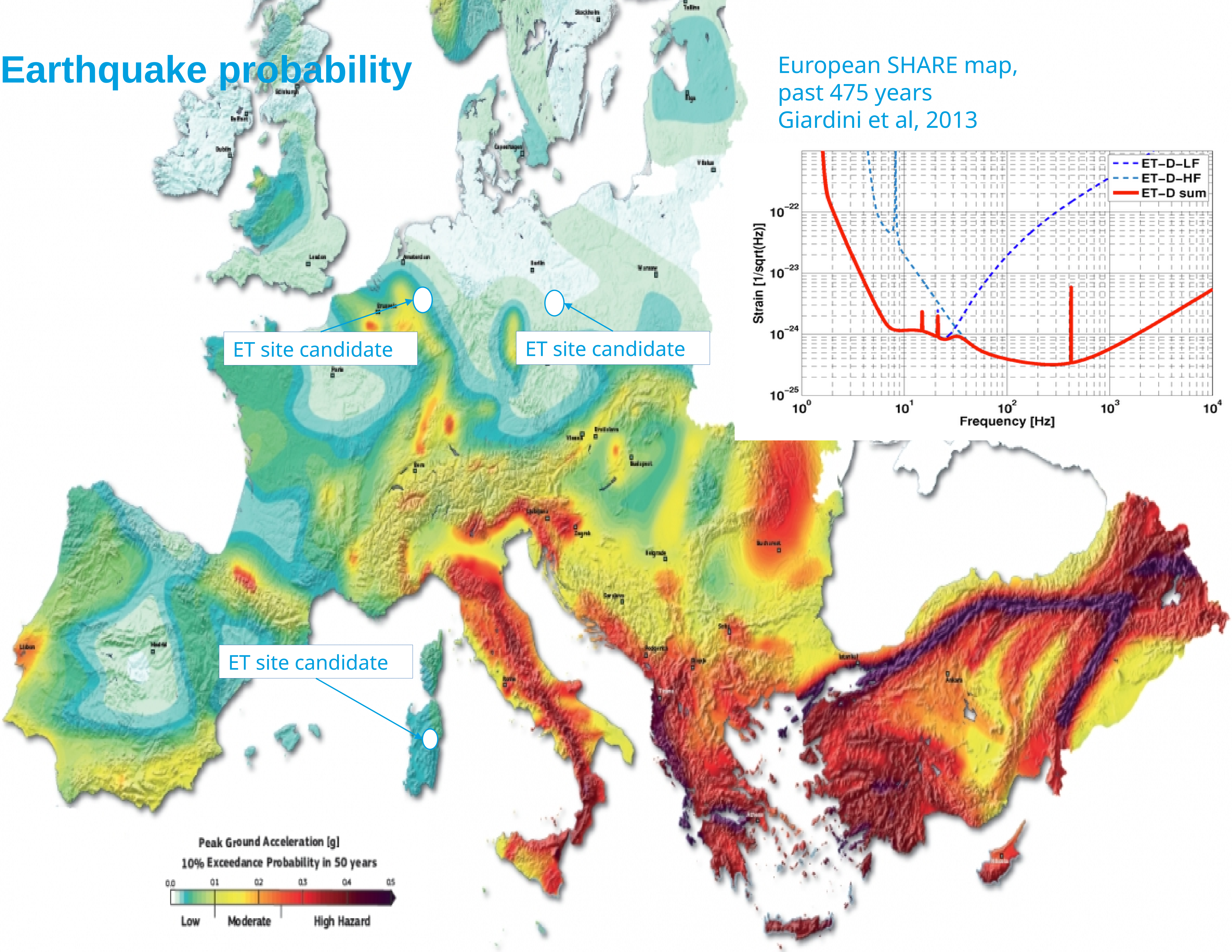
Candidate Sites

- EMR
- Sardinia
- Saxony
- Site characterization ongoing



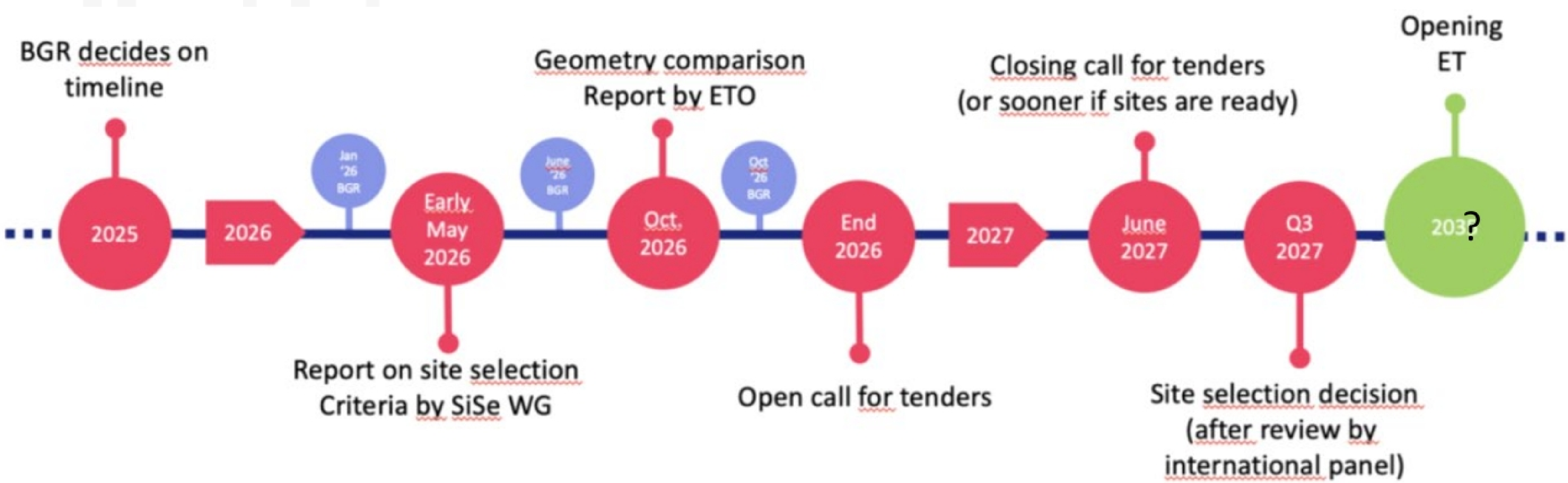
Earthquake probability

European SHARE map,
past 475 years
Giardini et al, 2013



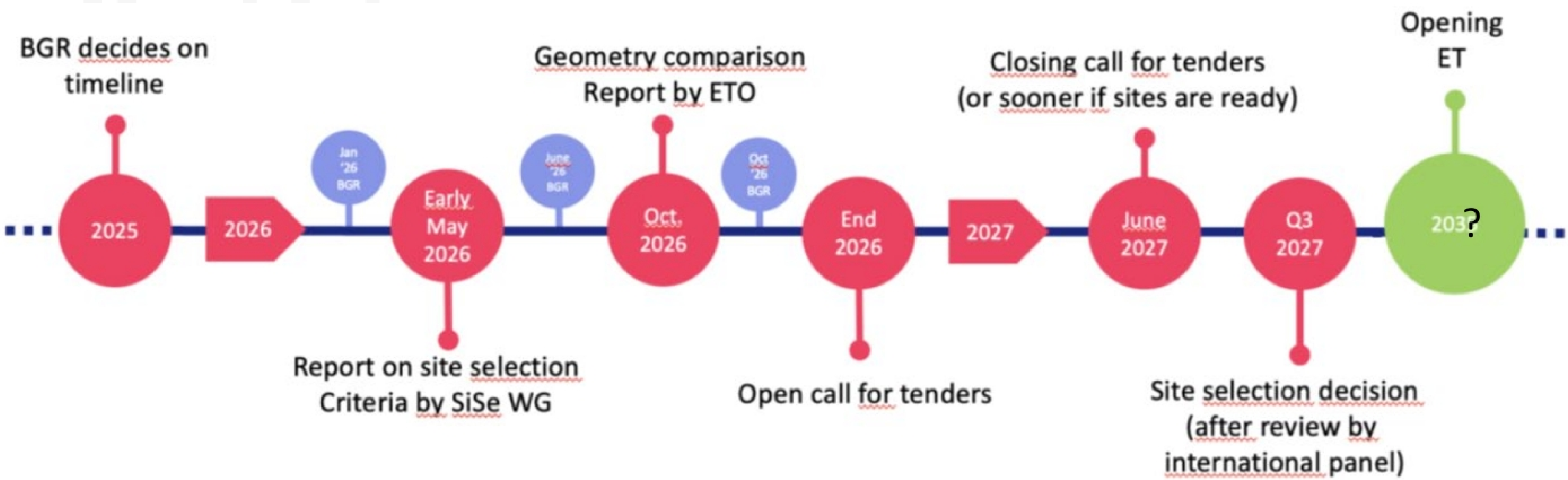
From science case to technical design

- ET science case / Blue Book defines science priorities
- Detector baseline layout under optimization
- PBS/WBS and requirements work ongoing
- Pre-TDR / technical design activities advancing
- R&D testbeds are reducing technology risk



Funding and Timeline

- Preparatory phase and technical design ongoing
- Geometry and site-selection processes active
- Large national investments from candidate host regions
- Timeline under review
- Opening date remains tentative



TDR & Blue Book

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Received: *March 18, 2025*
Revised: *July 19, 2025*
Accepted: *August 28, 2025*
Published: *March 26, 2026*

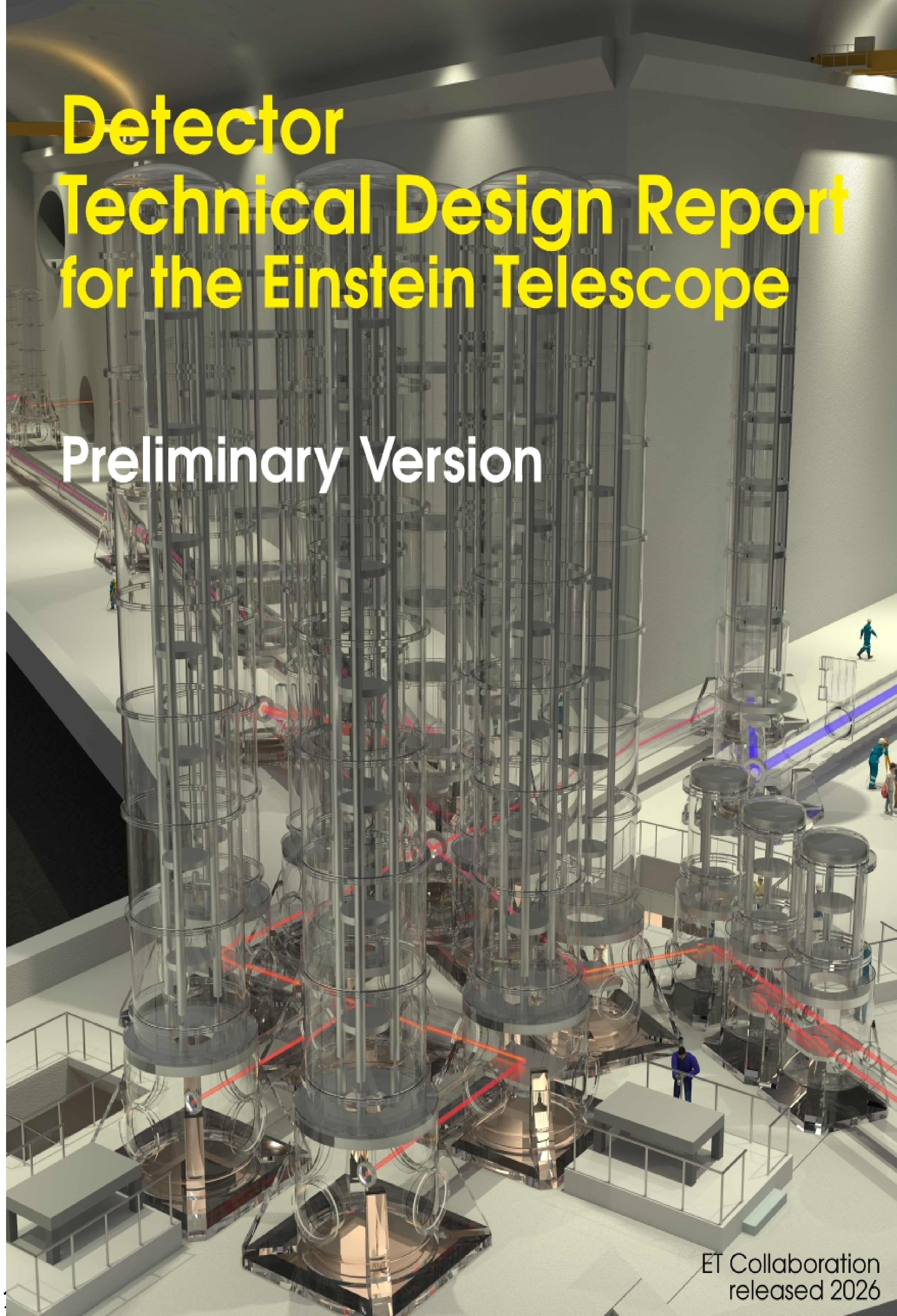
The Science of the Einstein Telescope

The Einstein Telescope collaboration

Full author list at the end of the paper

E-mail: marica.branchesi@gssi.it, archisman.ghosh@ugent.be, michele.maggiore@unige.ch

Abstract: Einstein Telescope (ET) is the European project for a gravitational-wave (GW) observatory of third-generation. In this paper we present a comprehensive discussion of its science objectives, providing state-of-the-art predictions for the capabilities of ET in both geometries currently under consideration, a single-site triangular configuration or two L-shaped detectors. We discuss the impact that ET will have on domains as broad and diverse as fundamental physics, cosmology, early Universe, astrophysics of compact objects, physics of matter in extreme conditions, and dynamics of stellar collapse. We discuss how the study of extreme astrophysical events will be enhanced by multi-messenger observations. We highlight the ET synergies with ground-based and space-borne GW observatories, including multi-band investigations of the same sources, improved parameter estimation, and complementary information on astrophysical or cosmological mechanisms obtained combining observations from different frequency bands. We present advancements in waveform modeling dedicated to third-generation observatories, along with open tools developed within the ET Collaboration for assessing the scientific potentials of different detector configurations. We finally discuss the data analysis challenges posed by third-generation observatories, which will enable access to large populations of sources and provide unprecedented precision.



Conclusions

Scientific Impact

- ET will transform gravitational-wave astronomy from nearby detections to a probe of the **entire cosmic history**
- Low-frequency sensitivity is the key enabling technology: high-redshift sources, intermediate-mass black holes, early-warning multimessenger astronomy, precision strong-field gravity tests
- ET will enable precision cosmology, nuclear physics, and tests of GR with **unprecedented statistics and signal quality**

Technological Challenge

- Achieving ET sensitivity requires frontier technologies: underground infrastructure, seismic and Newtonian noise mitigation, cryogenics, quantum noise reduction, ultra-low-noise control systems
- Many of these challenges are **active frontiers of experimental physics** — ET is driving cutting-edge technology development

Final Message

- ET is **not simply a more sensitive LIGO**
- It is a new observatory designed to explore the gravitational-wave universe **across cosmic time**
- Together with Cosmic Explorer, ET will define the **global third-generation gravitational-wave network**

The Einstein Telescope — if we build it right — will answer questions we have not yet thought to ask.

GS
SI

GRAN SASSO SCIENCE INSTITUTE

Thank you for your attention

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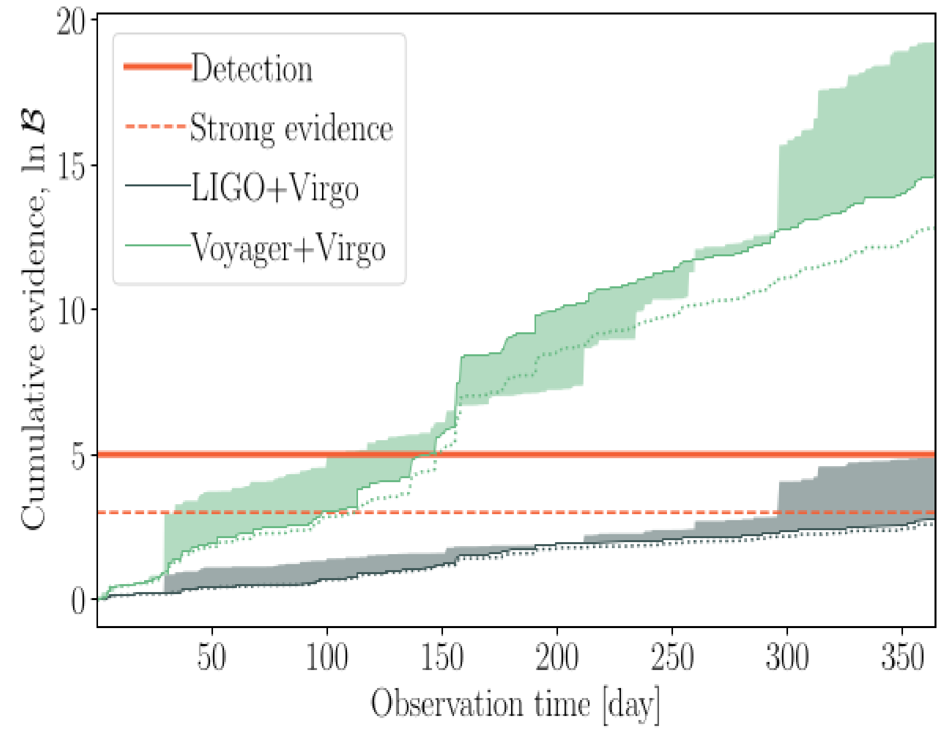
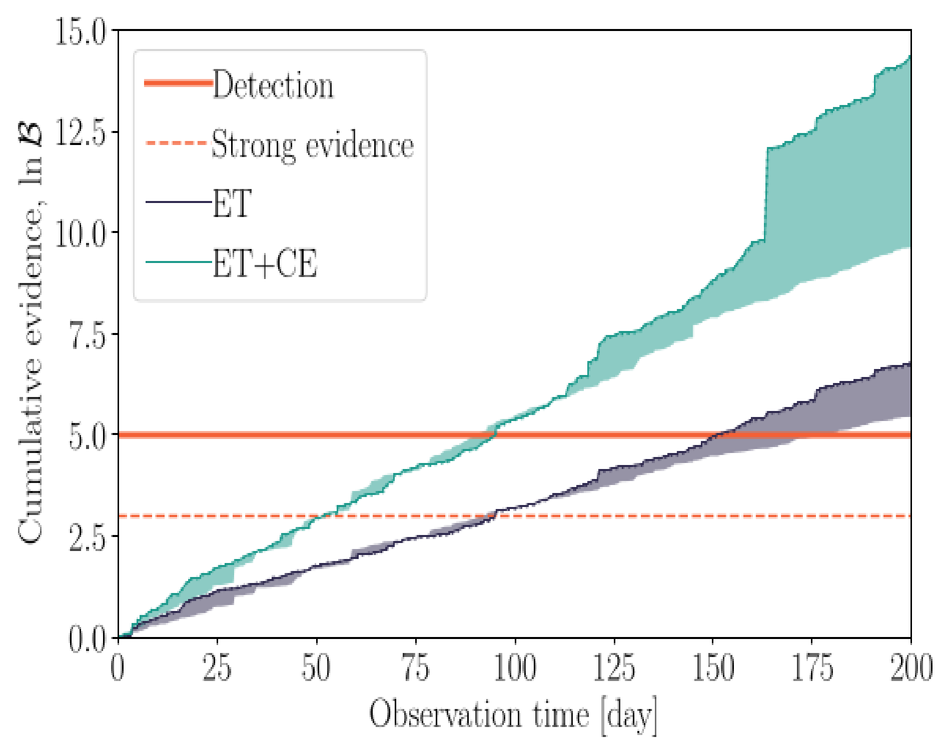
BACKUP

Gravitational Wave Memory and Asymptotic Symmetries

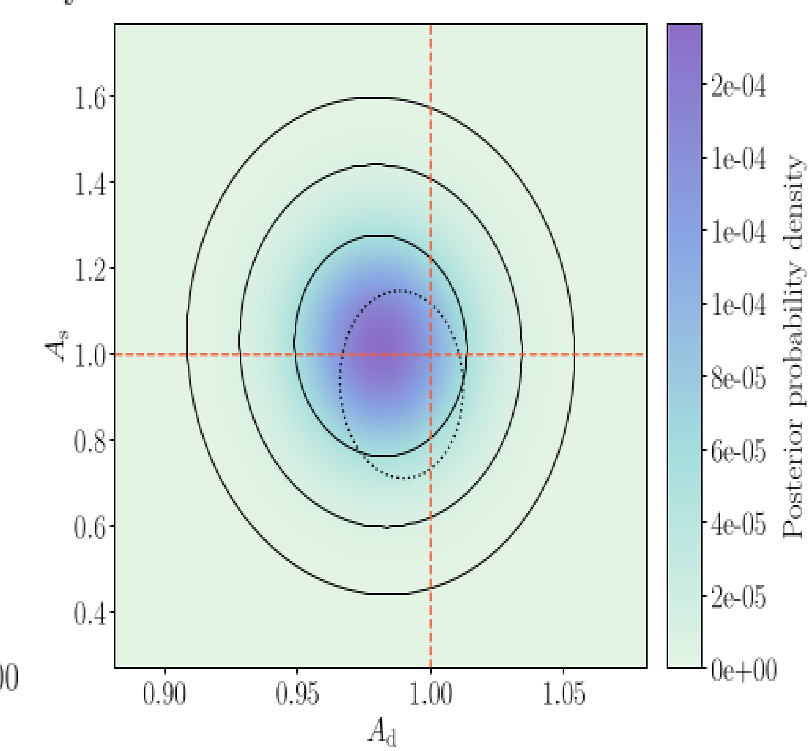
- After a GW passes spacetime retains a permanent offset — test particles never return to original separation — gravitational wave memory
- Deeply connected to BMS symmetry group of asymptotically flat spacetimes and Weinberg's soft graviton theorem — a fundamental prediction of GR
- Panel (a): LIGO+Virgo and Voyager never cross detection threshold — ET crosses it with just a handful of BBH events
- Panel (b): spin memory — even subtler effect related to angular momentum — ET+CE network detectable within ~150 days
- Panel (c): ET simultaneously recovers both memory amplitudes with good precision from 1000 BBH events
- First ever precision probe of asymptotic symmetry structure of GR — current detectors marginally sensitive, ET transforms this into a real measurement



(a) Displacement memory detection.



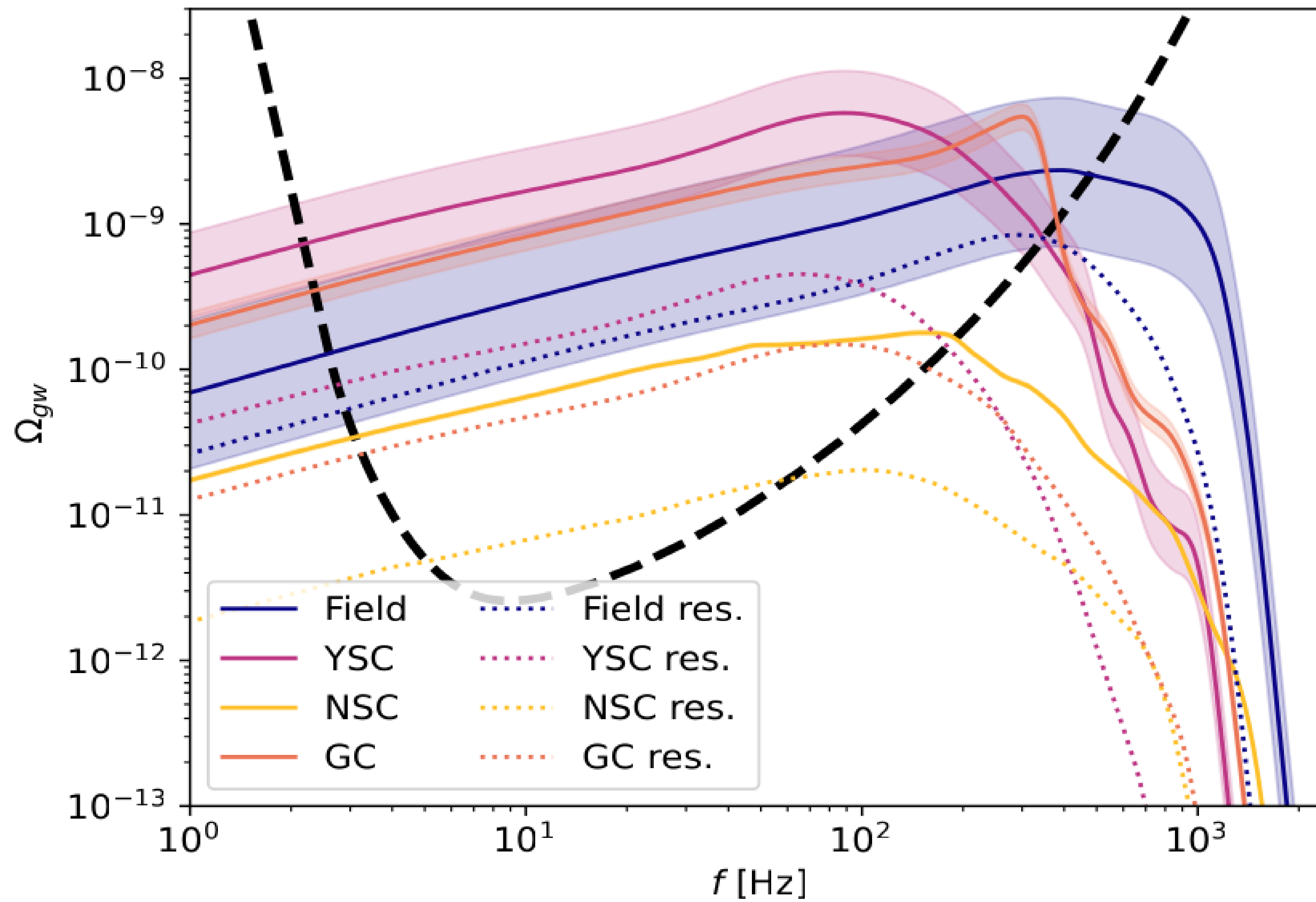
(b) Spin memory detection.



(c) Parameter estimation.

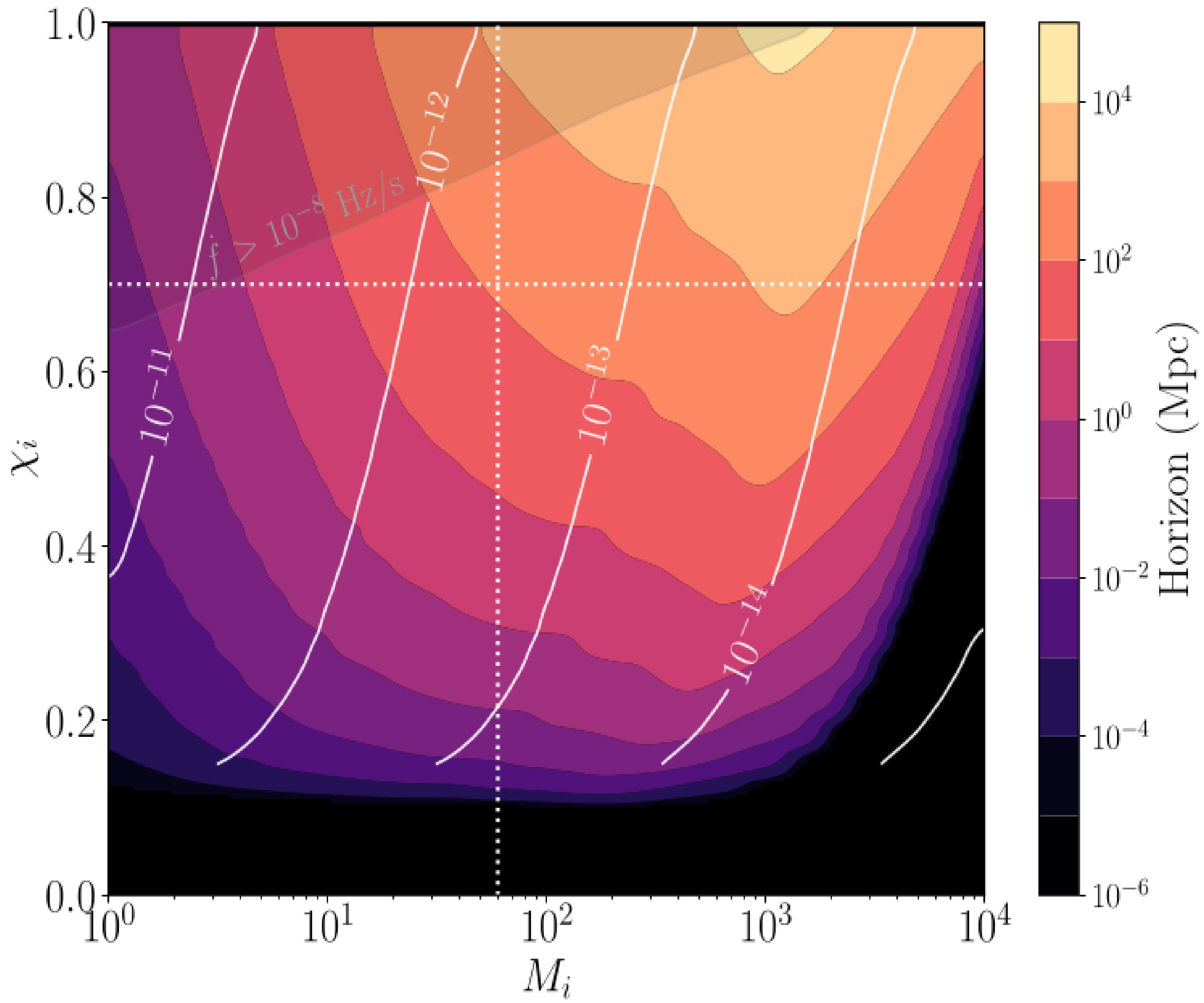
Stochastic Gravitational Wave Background

- SGWB = permanent hum from all unresolved GW sources — astrophysical and cosmological
- Solid lines = total background from four BBH formation channels, dotted = residual after ET removes individually detected mergers — the gap is ET's resolving power
- Each formation channel leaves a distinct spectral shape — ET reads the background like a fingerprint of cosmic binary evolution

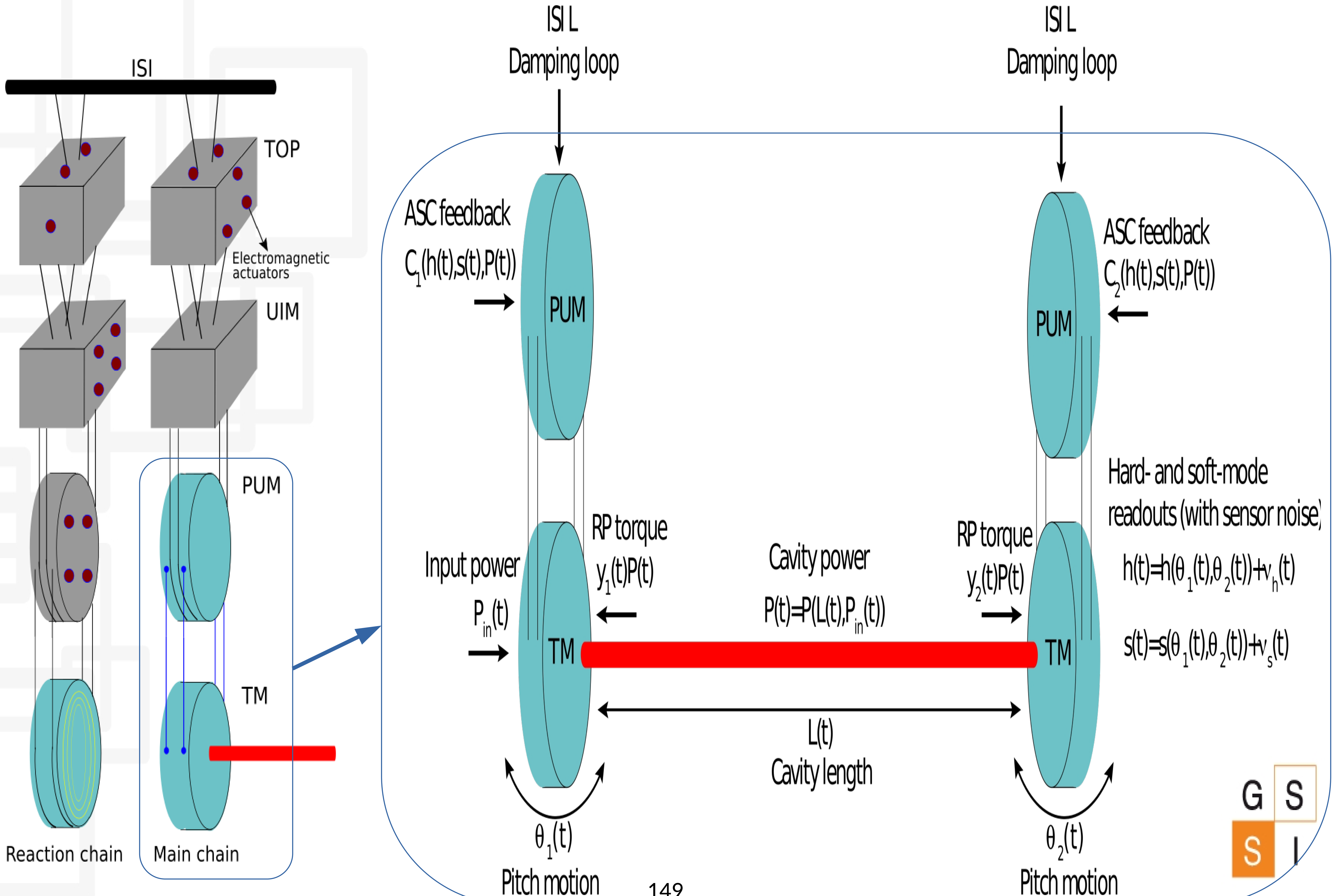


Boson Clouds and Ultralight Dark Matter

- Ultralight bosons with mass ~10^{-21}–10^{-11} eV have Compton wavelengths matching BH sizes — completely inaccessible to any particle collider
- Spinning BH spontaneously transfers rotational energy to boson field via superradiant instability — a macroscopic boson cloud grows around the BH
- Cloud emits quasi-monochromatic continuous GWs at frequency f_gw ≈ 483 Hz (m_b/10^{-12} eV) — a persistent nearly-sinusoidal signal lasting years
- Plot: x-axis = BH mass, y-axis = BH spin, color = ET detection horizon in Mpc — yellow = detectable to thousands of Mpc, black bottom-left = no superradiance possible
- White contour lines = specific boson masses in eV — dashed white = GW150914-like remnant, sitting in bright region — ET sensitive to boson masses ~10^{-13} eV around such systems
- ET probes boson masses 10^{-14}–10^{-11} eV — direct connection to axion dark matter and string theory landscape
- Non-detection equally powerful — excludes boson masses across a wide range, directly constraining dark matter models



LIGO seismic isolation



G S S I

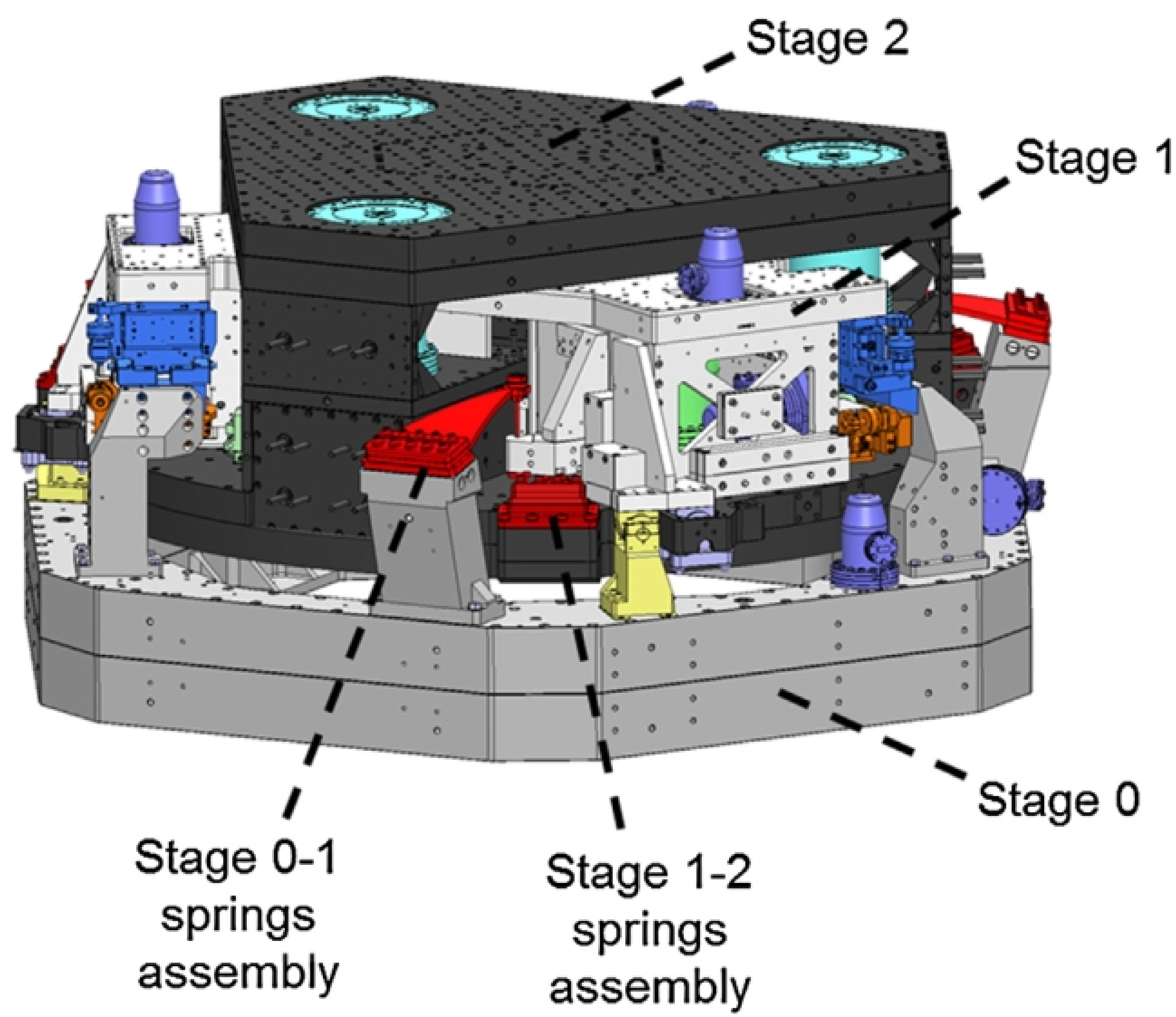
LIGO seismic isolation

What is BSC-ISI?

- The BSC-ISI is a two-stage, 12-DOF active seismic isolation platform housed in the Basic Symmetric Chambers of LIGO. It isolates core optics from ground motion using a combination of springs, sensors, and feedback actuators.

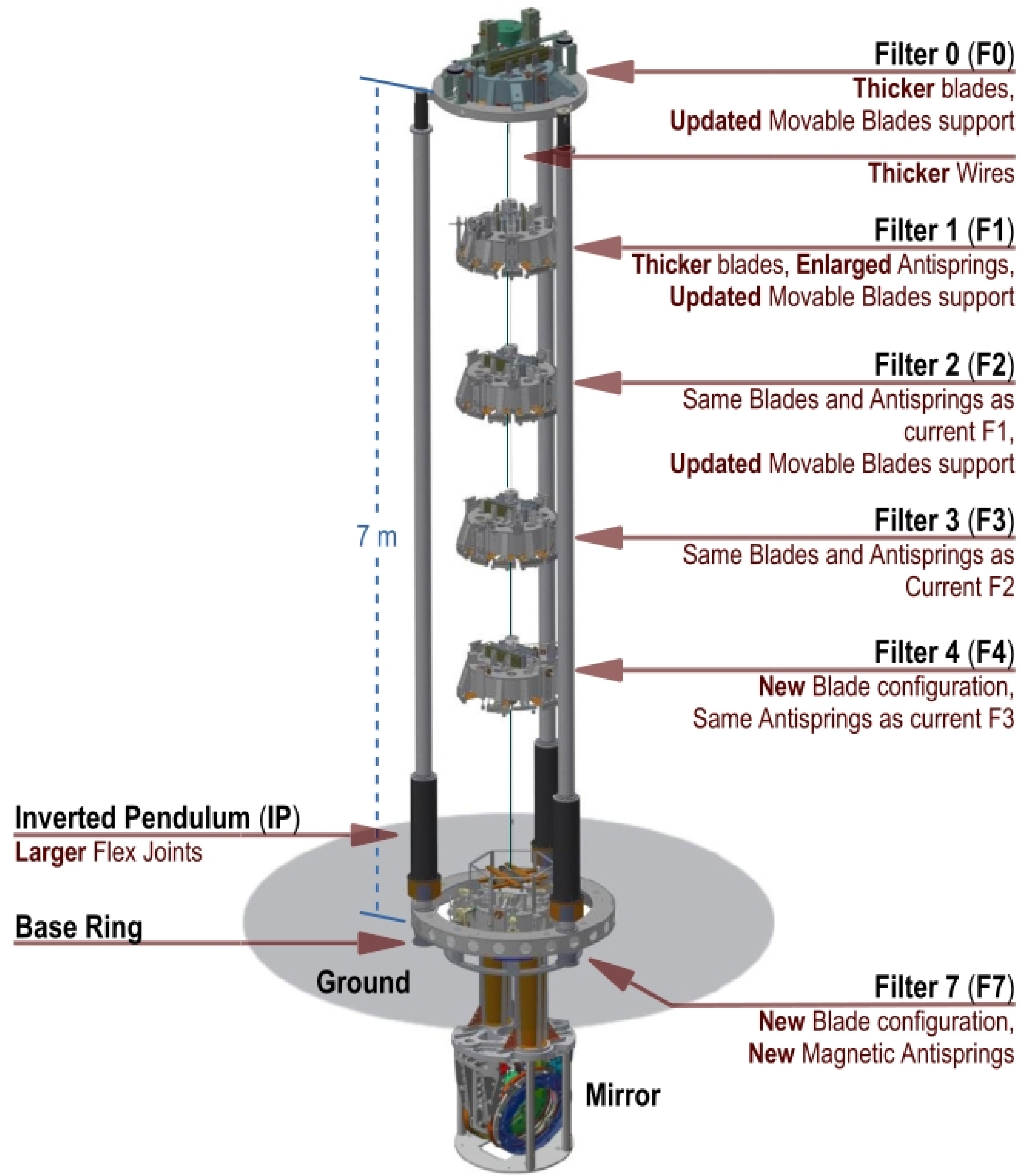
How It Works:

- Stage 1: Provides inertial isolation using seismometers, geophones, and actuators
- Stage 2: Nested platform for additional passive and active isolation
- Uses capacitive position sensors, coil-magnet actuators, and rigid structural elements for control



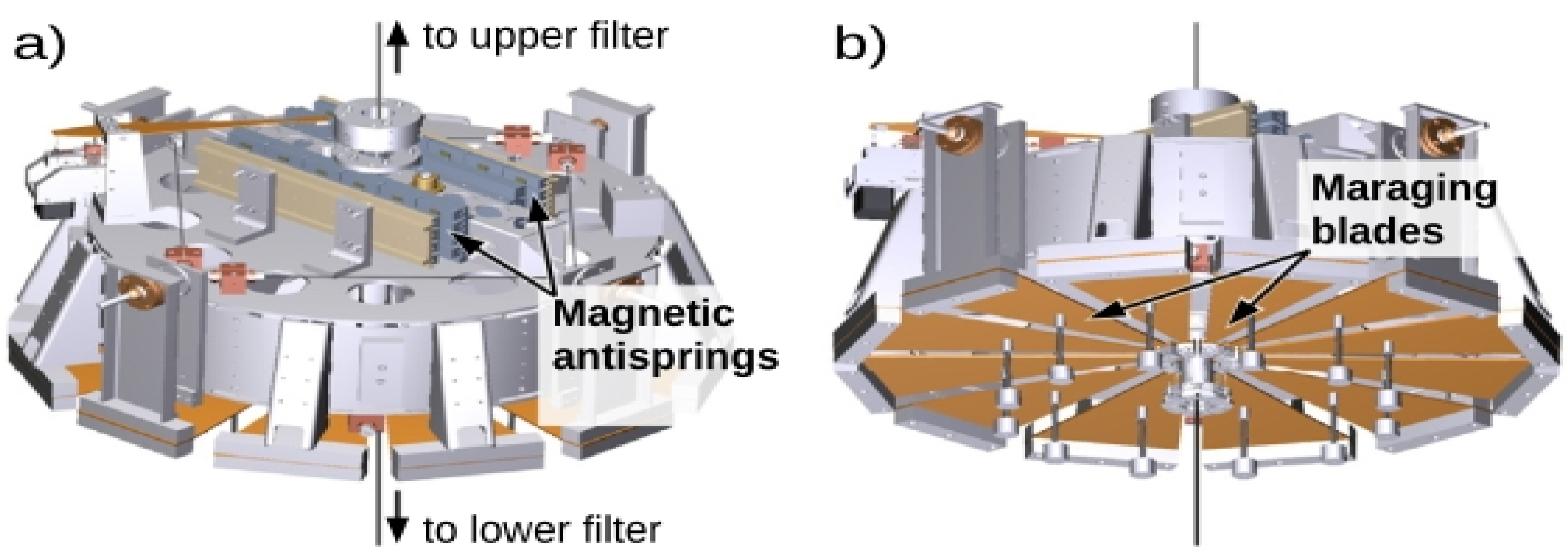
VIRGO seismic isolation

- Core of Virgo's seismic isolation system: the Superattenuator (SA)
- Designed to suppress seismic noise by $>10^{-12}$ in all 6 degrees of freedom above 10 Hz
- SA consists of:
- An Inverted Pendulum (IP) for horizontal attenuation
- A chain of 7 vertical filters (F0–F7) acting as pendulums and vertical springs
- The final filter (F7) supports the payload: marionette, actuation cage, and mirror
- Each filter uses maraging blades and magnetic antisprings to achieve sub-Hz resonances

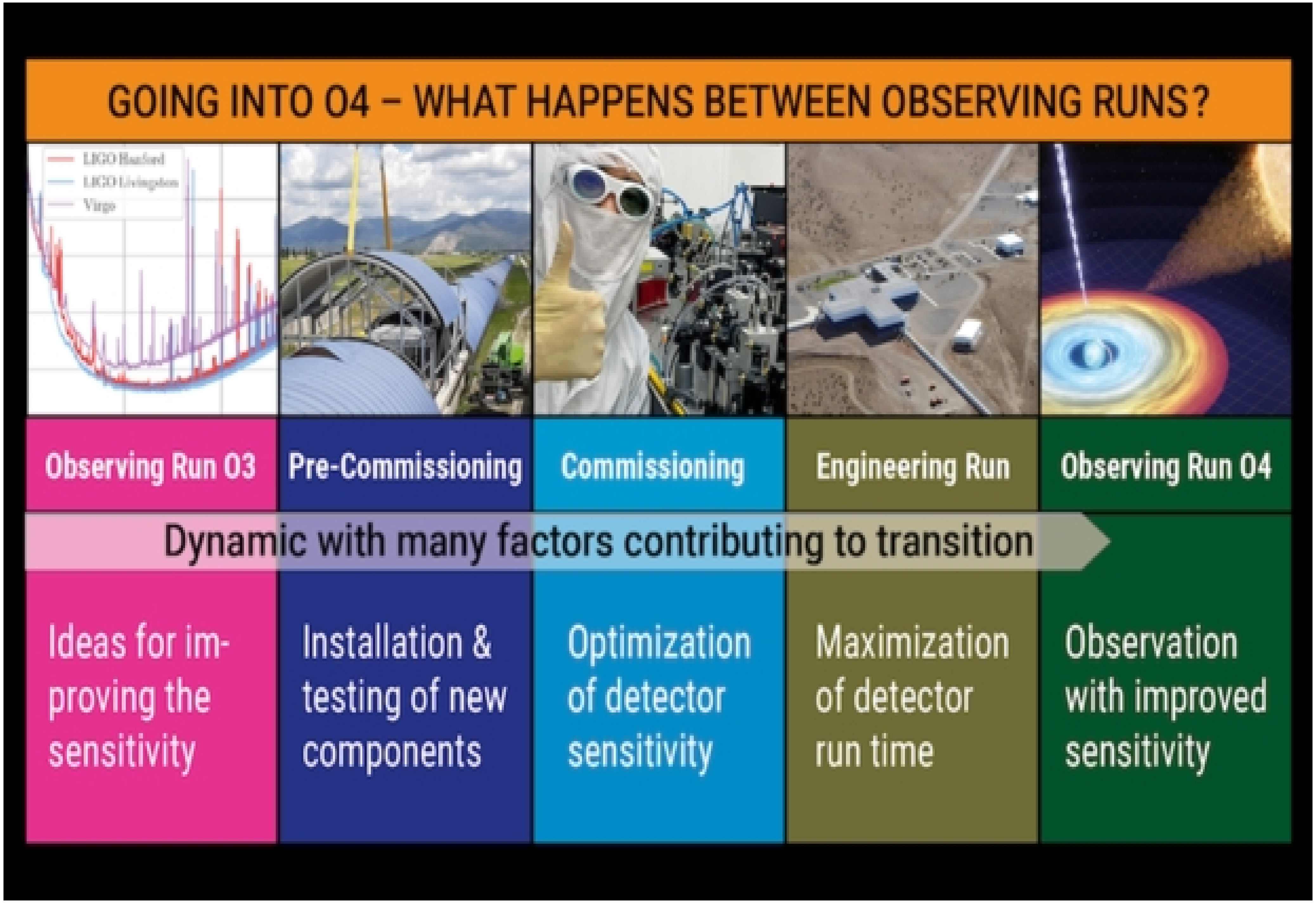


VIRGO seismic isolation

- AdV+ Phase II increases mirror mass from 42 kg → 104 kg
- Total suspended load under F7: 146 kg → 285 kg
- To preserve sub-Hz resonances, Virgo upgraded:
- Maraging blades (increased thickness for load-bearing)
- Magnetic antisprings (stronger and more linear)
- F7 filter redesigned to host more G-type blades (from 4 → 6)
- Finite element simulations and prototypes validated new designs

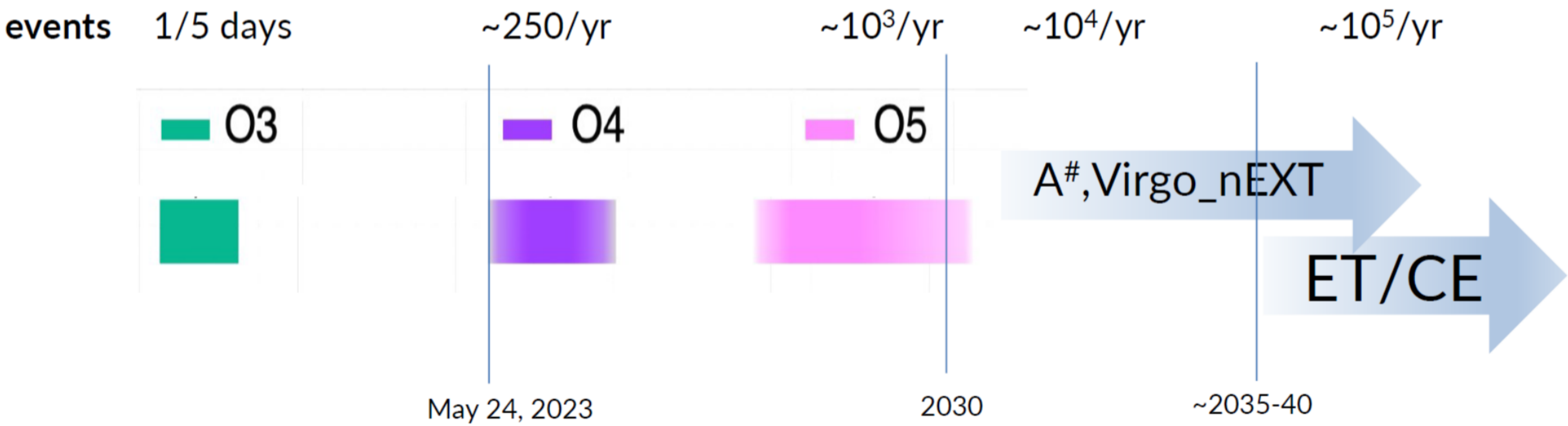


O4 Commissioning and O4 observing run



… but the future is far!

- 3G detector will not produce observational science before 2040.
- Many technological/engineering challenges must be overcome to move from 2G to 3G. The technological gap between 2G and 3G is highly risky!
- Need to extend the LIGO/Virgo/KAGRA scientific program until the advent of 3G.
- Keep the community together, allowing to form a new generation of experts.
  - Projects: A#, Virgo_nEXT.



Slide taken from L. Pierini (The Virgo experiment and the hunt for gravitational waves:
status, recent results and prospects)

Virgo_nEXT

- "Post-O5 study" committee set up in 01/21.
- Virgo_nEXT concept study released in 02/23.

- All design choices made within a Virgo-compatible framework: same infrastructure, same laser wavelength, room temperature mirrors.

Some foreseen upgrades:
- O(MW) intracavity power
- Enhanced squeezing
- Large test masses, better coatings
- NN subtraction
- Improved LF sensitivity

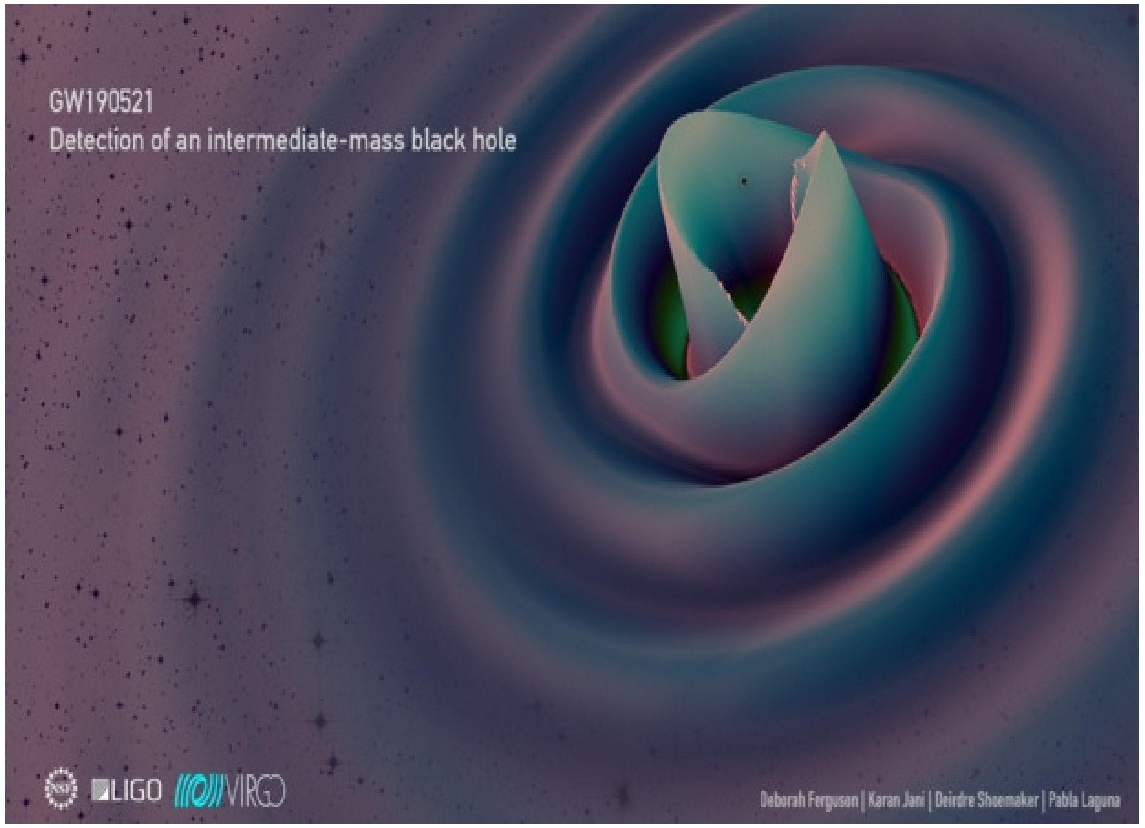
Baseline Design Report by June 2025.

	AdV+ best	V_nEXT best	ET HF
Power injected	125 W	277 W	500 W
Arm power	390 kW	1.5 MW	3 MW
FDS detected	6 dB	10 dB	10 dB
Mirror mass	42/105 kg	105 kg	200 kg
Beam radius	49/91 mm	91 mm	120 mm
Coating losses	5.4e-5	6e-6	1.25e-5
NN reduction	1/5	1/5	0-1/3

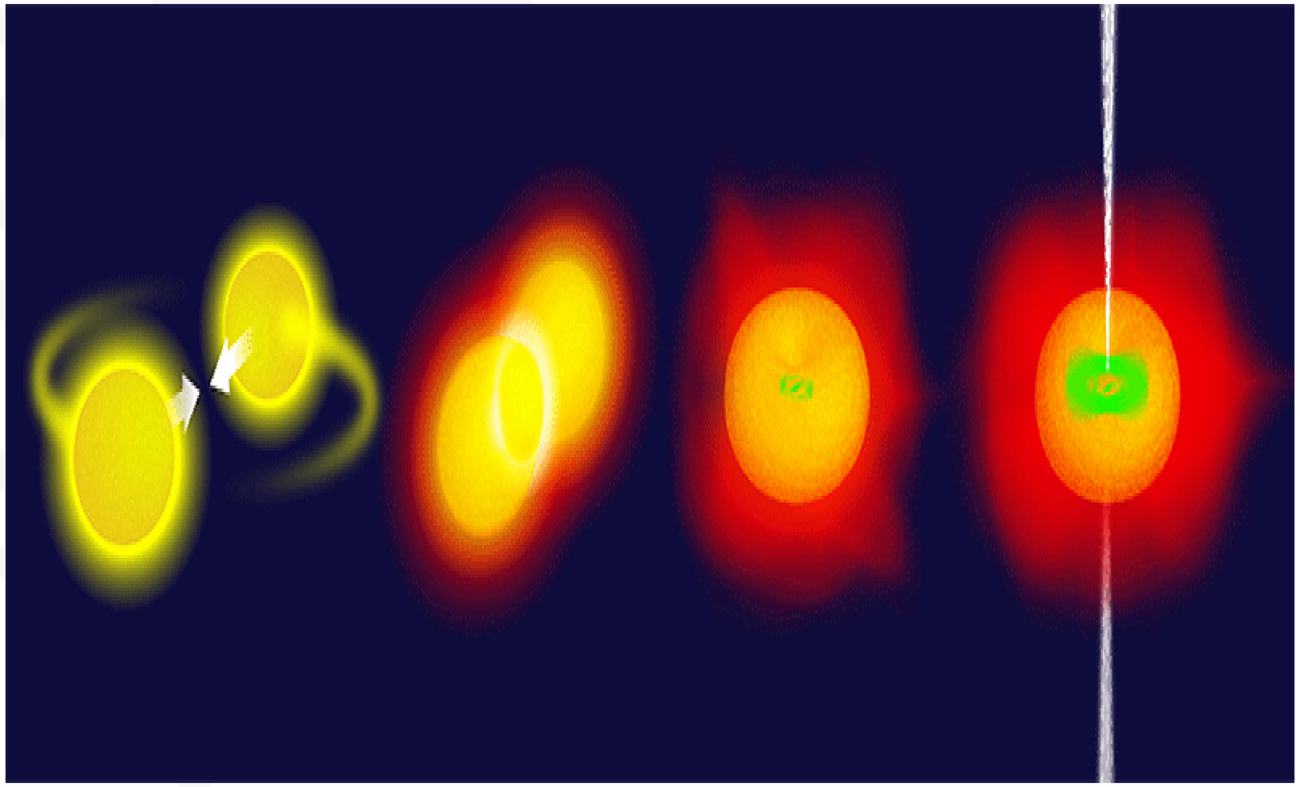
Slide taken from L. Pierini (The Virgo experiment and the hunt for gravitational waves: status, recent results and prospects)

Motivation

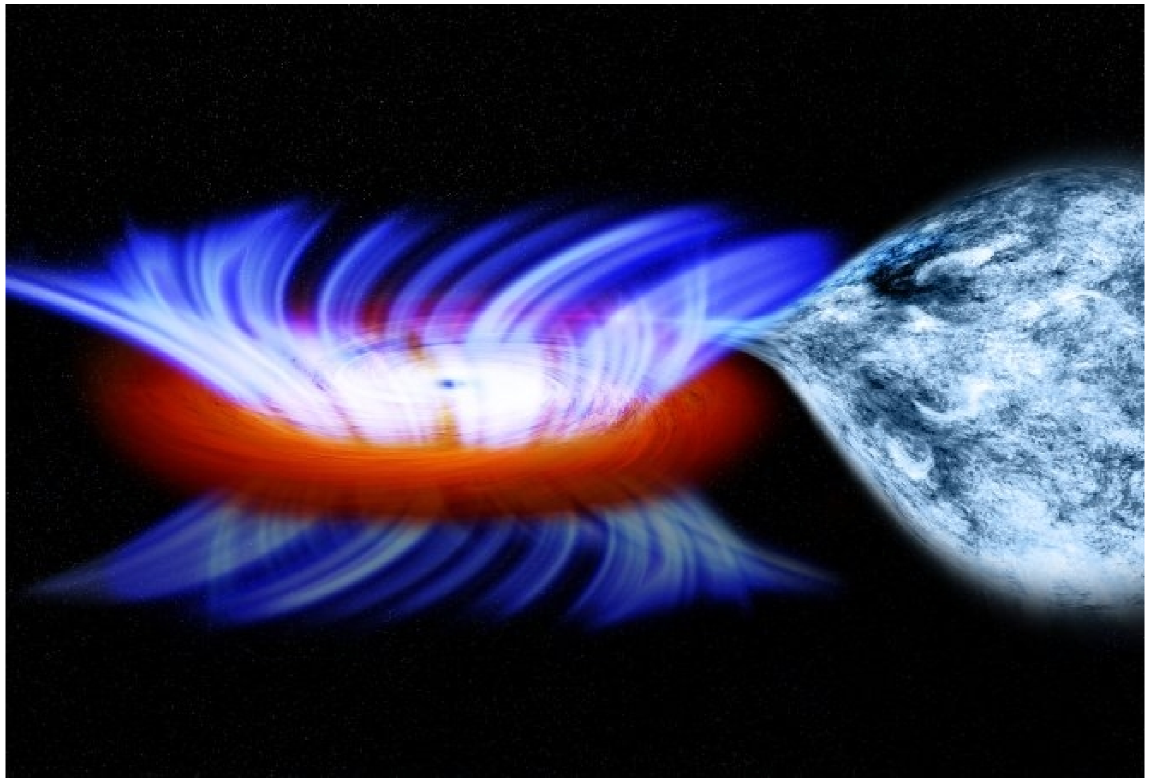
- Observing black-hole binaries with masses beyond the currently accessible mass range
- Enabling the deepest multi-messenger studies of binary neutron-star mergers
- Studying the properties of GWs sources with unprecedented precision



Fom a numerical relativity simulation for GW190521 (https://www.ligo.caltech.edu/image/ligo20200902f)



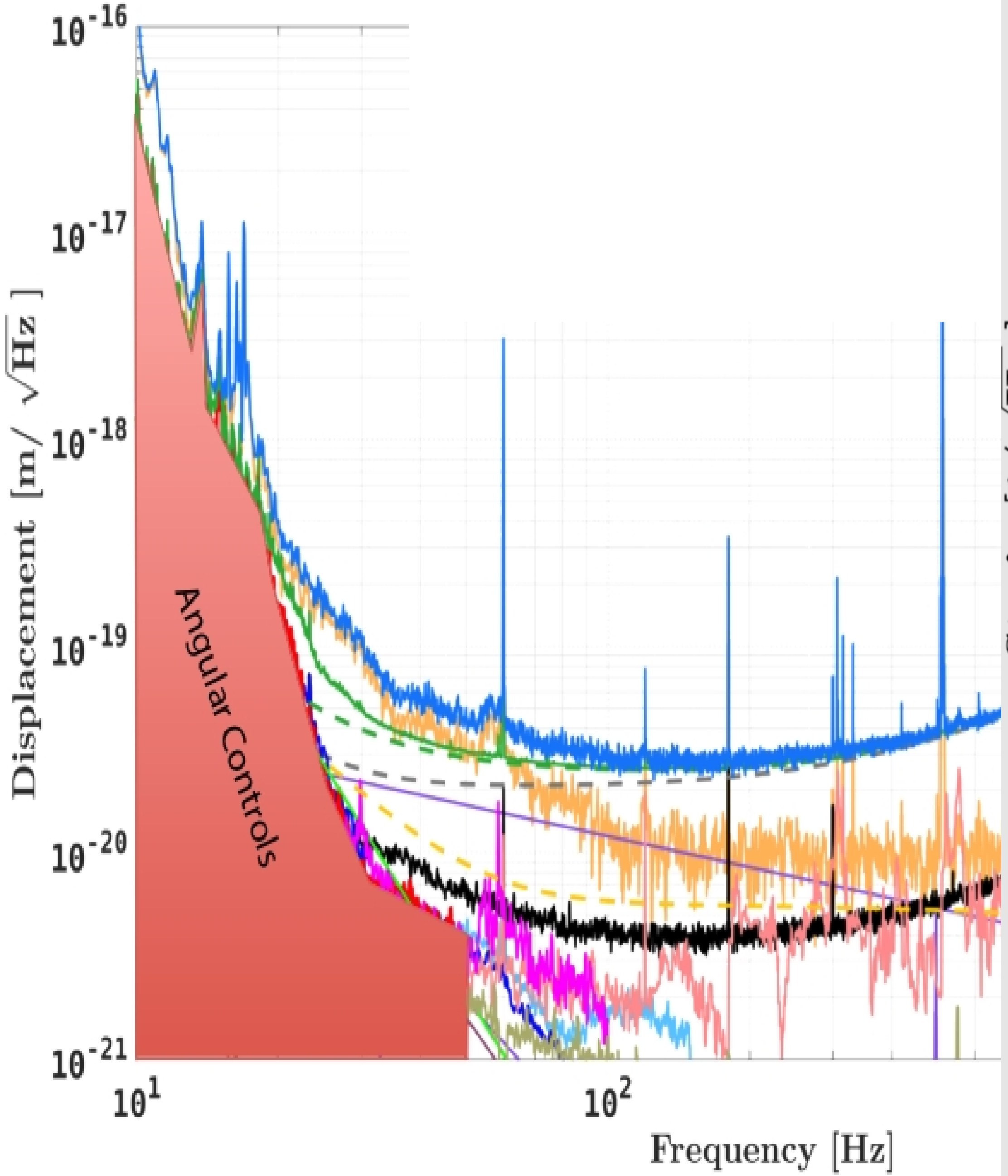
APS/Alan Stonebraker, adapted from simulations by NASA/AEI/ZIB/M. Koppitz and L. Rezzolla (https://physics.aps.org/articles/v10/114)



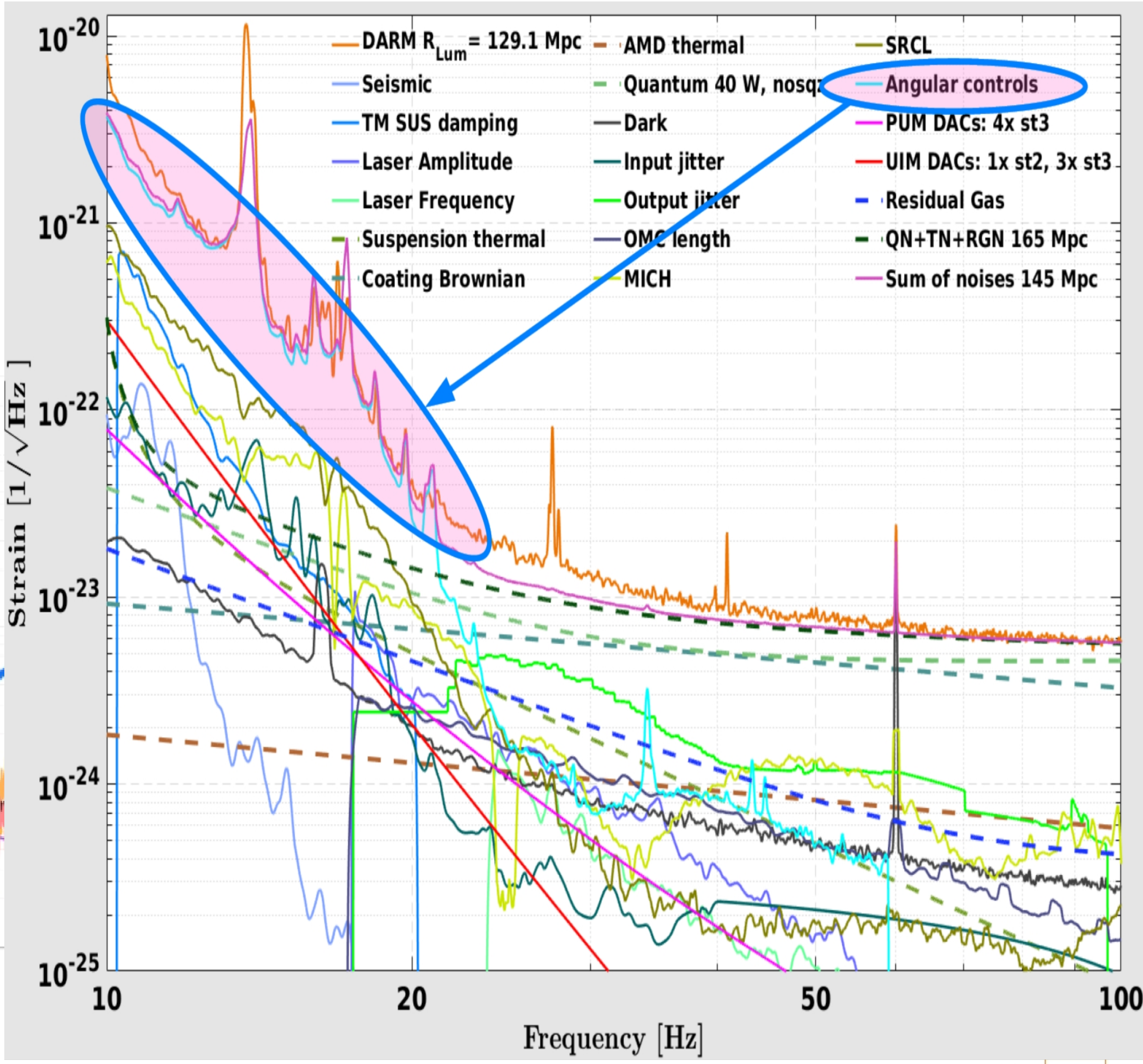
Artist's impression shows a binary system containing a stellar-mass black hole called IGR J17091-3624 (https://www.nasa.gov/mission_pages/chandra/multimedia/igr.html)

Motivation

- LIGO – limited by ASC noise
- No straight-forward solution



Seymour et al, 2017. For the LIGO Livingston Detector.



LIGO Livingston Detector noise budget.

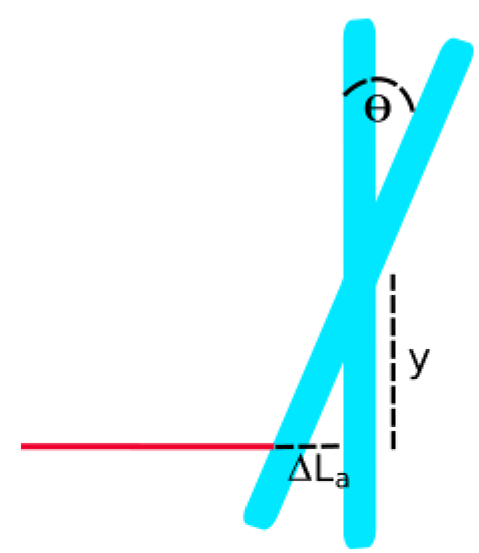
Nonlinearities

- Most input noises are simulated by spectral methods
- SOS – Second-Order Sections
- Nonlinear optomechanical couplings are included explicitly through equations of motion
- Nonlinear optomechanical couplings:
  1) Fluctuations of arm-cavity power
  2) Radiation-pressure torque
  3) Strain noise

$$P(t) = \frac{\tau^2 P_i(t)}{\left|1 - \rho \exp\left(2\pi j \frac{\Delta L(t)}{\lambda}\right)\right|^2}$$

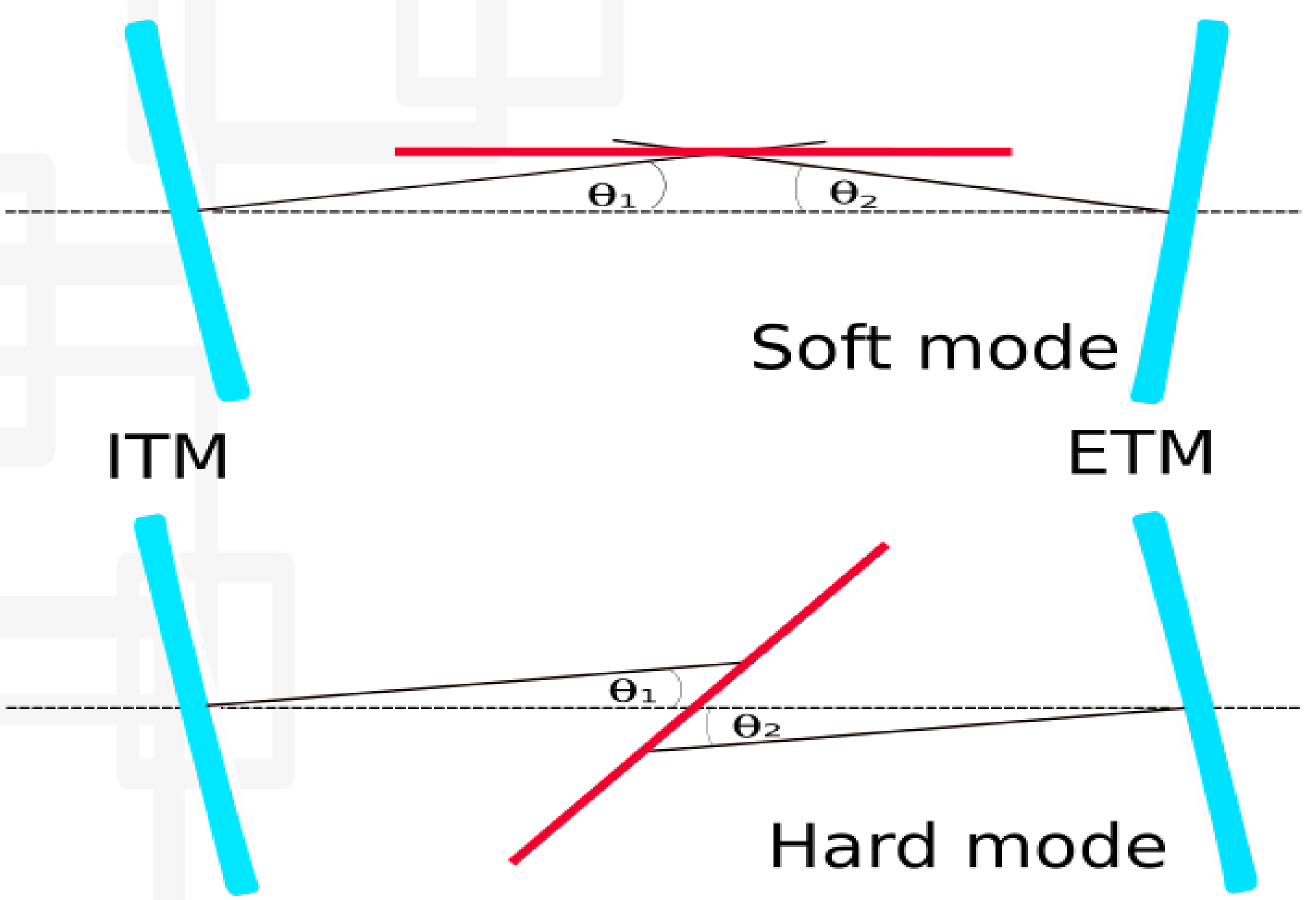
$$\tau_{\mathrm{RP}}(t) = \frac{2P(t)}{c} y(t)$$

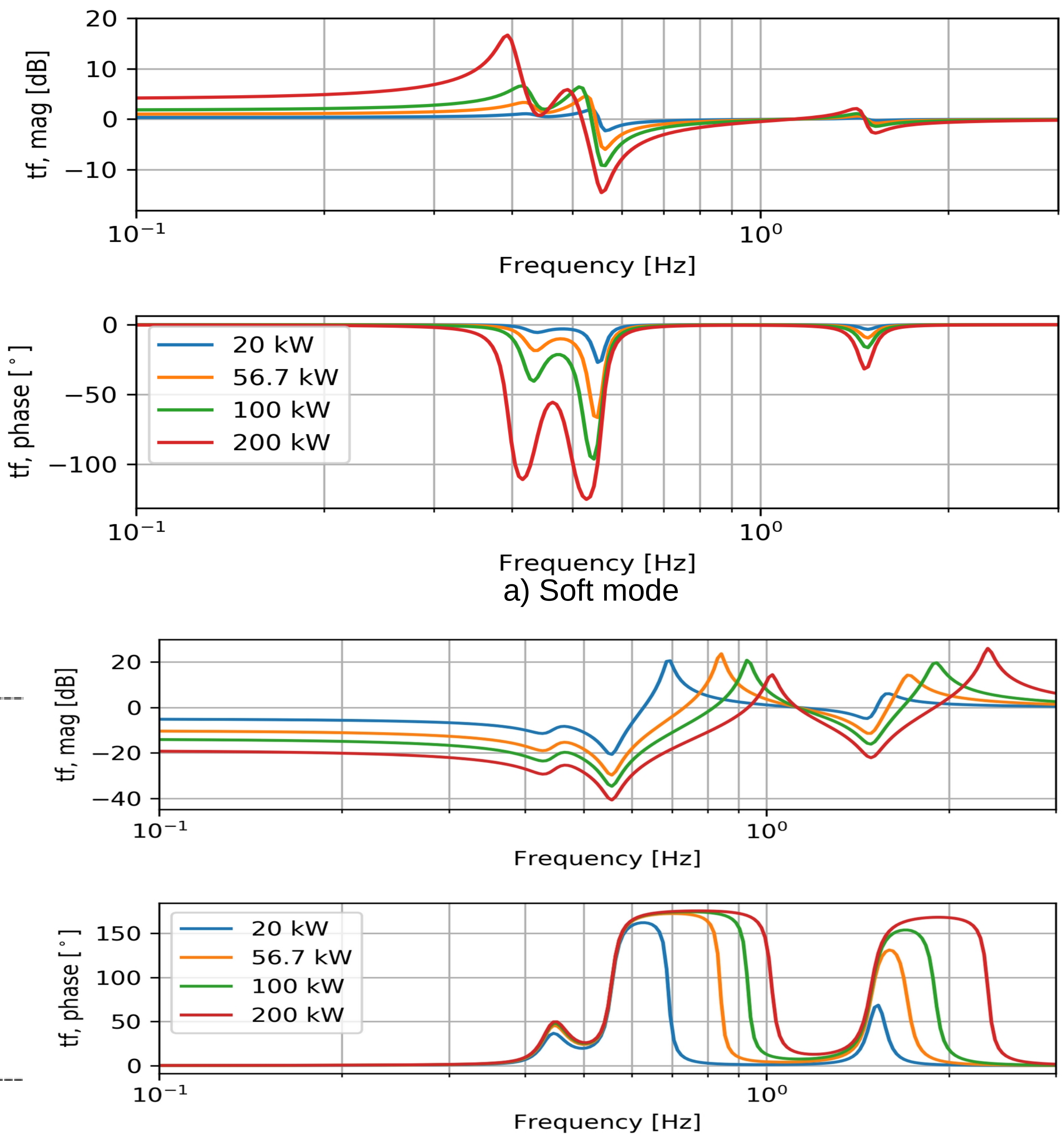
$$\Delta L(t) = y(t) \times \theta(t)$$



Optomechanical system

- Radiation pressure exerts a torque on the suspended mirrors, adding to the fixed restoring torque of the suspension
- ASC allows us to operate IFO with angular mechanics dominated by RP
- Normal mode basis which decouples the effects of RP in 2 independent modes
- Bode plots of Sidles-Sigg feedback transfer function changing the arm cavity power

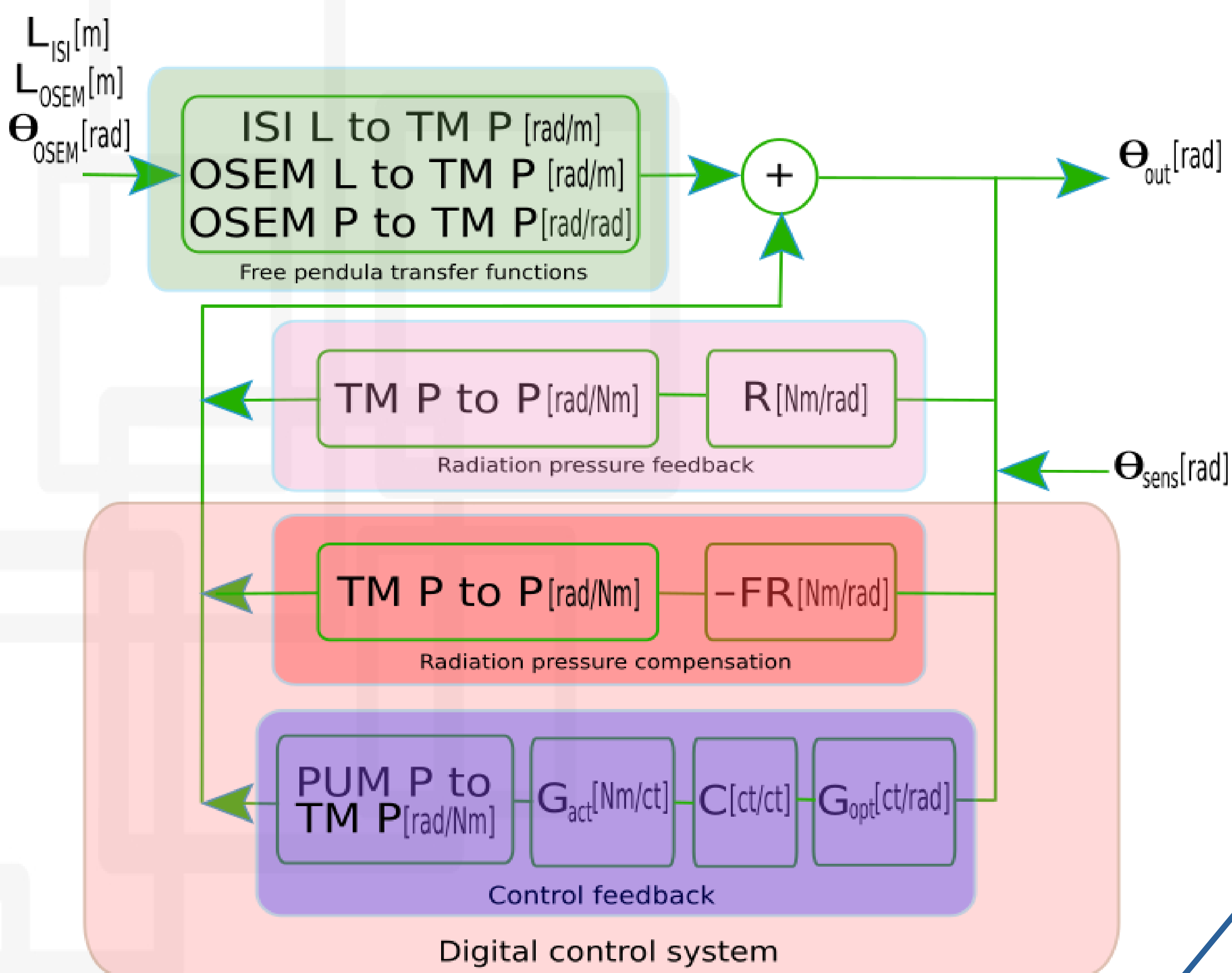




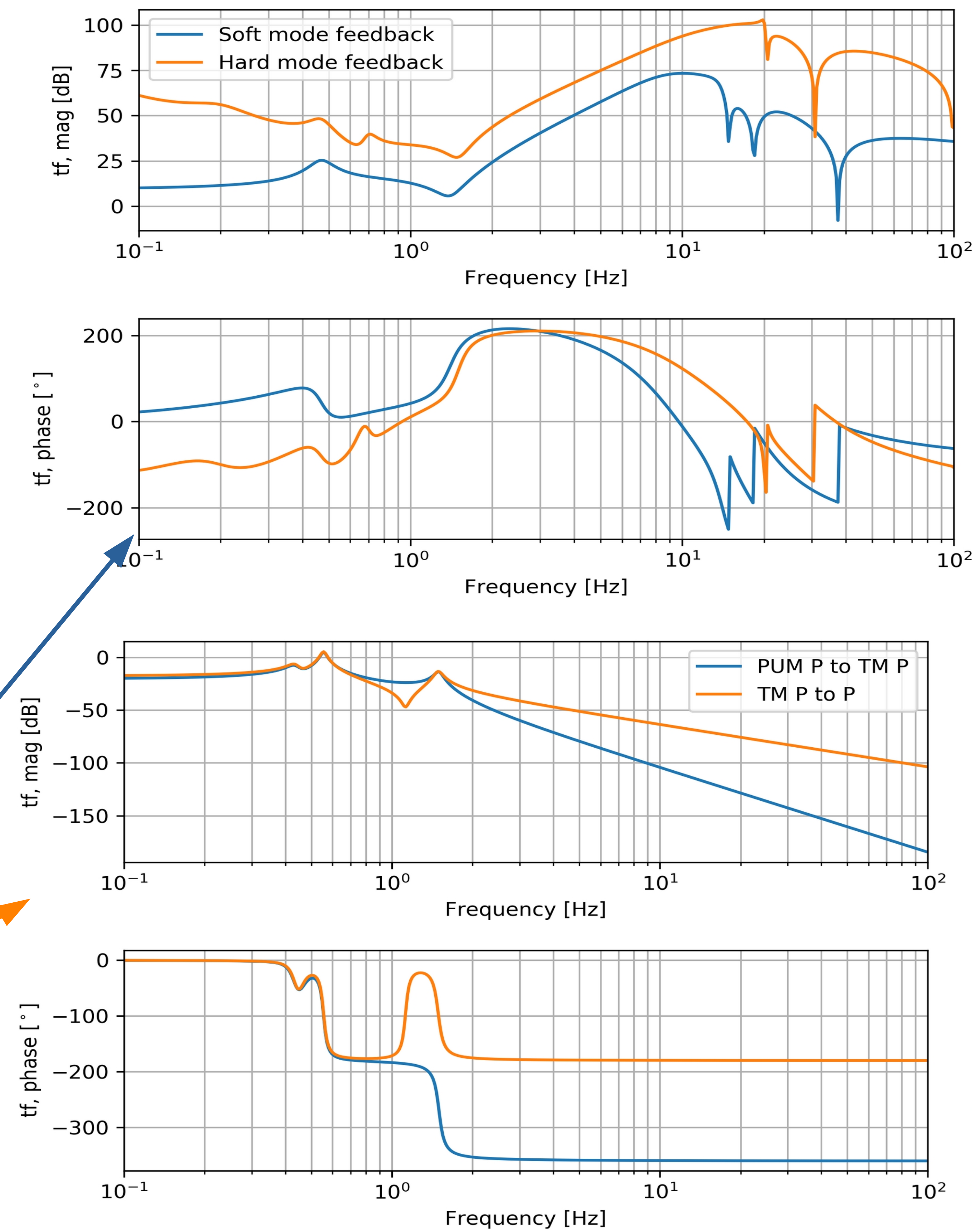
a) Soft mode

b) Hard mode

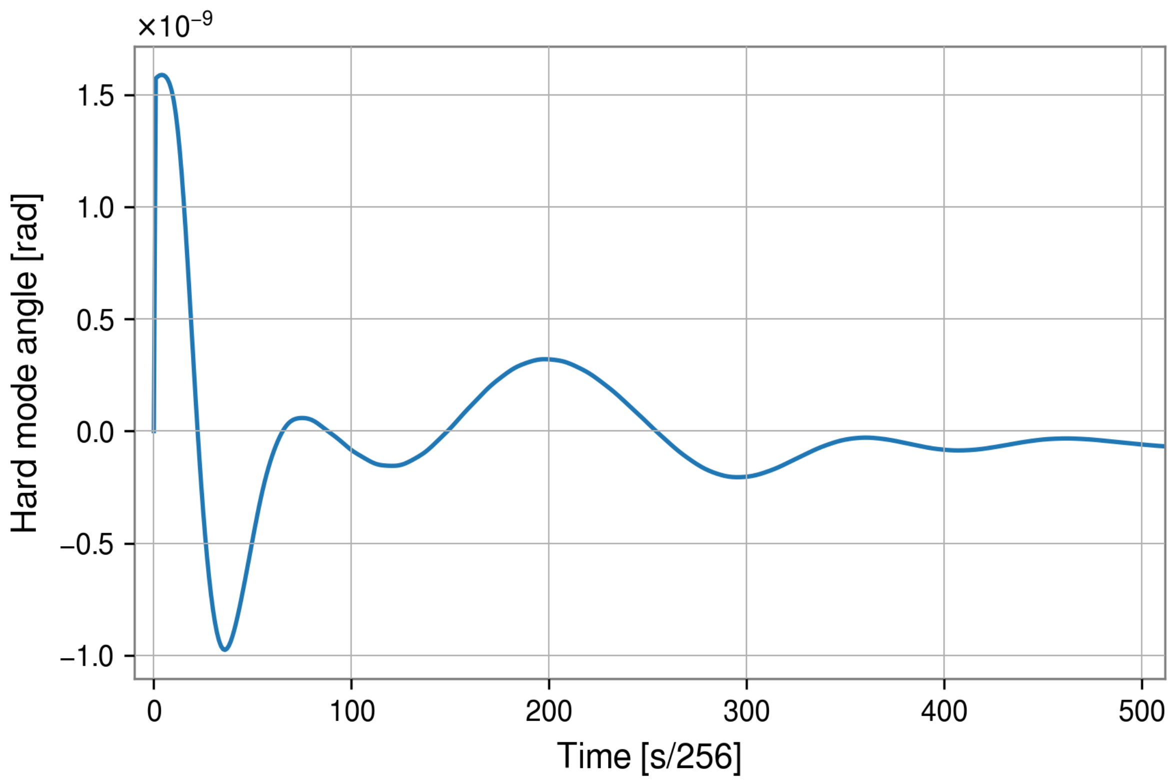
Diagram and Bode plots



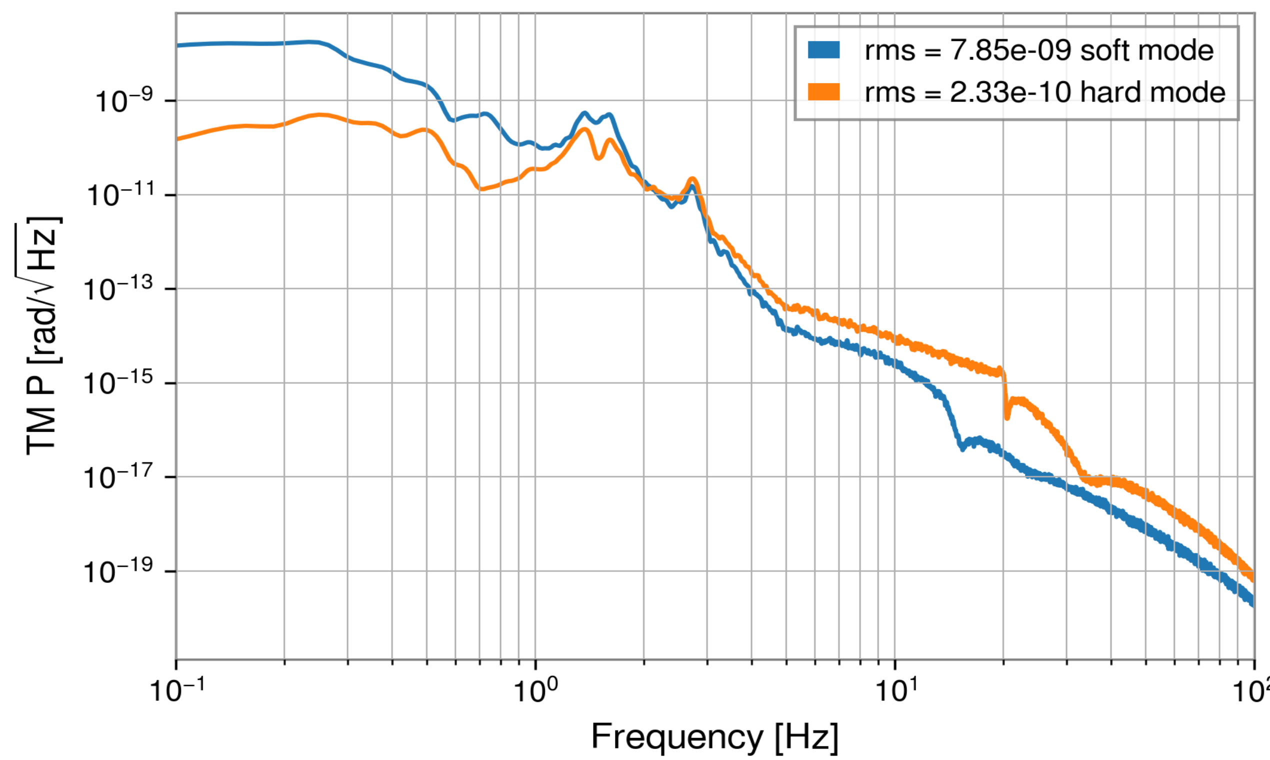
- The linear couplings of the simulation are based on SOS models, which means that also the ZPK specifications of control filters are internally converted into SOS models
- This part of the suspension system needs to be included in the dynamics of the time-domain simulation, it is represented as a SOS model



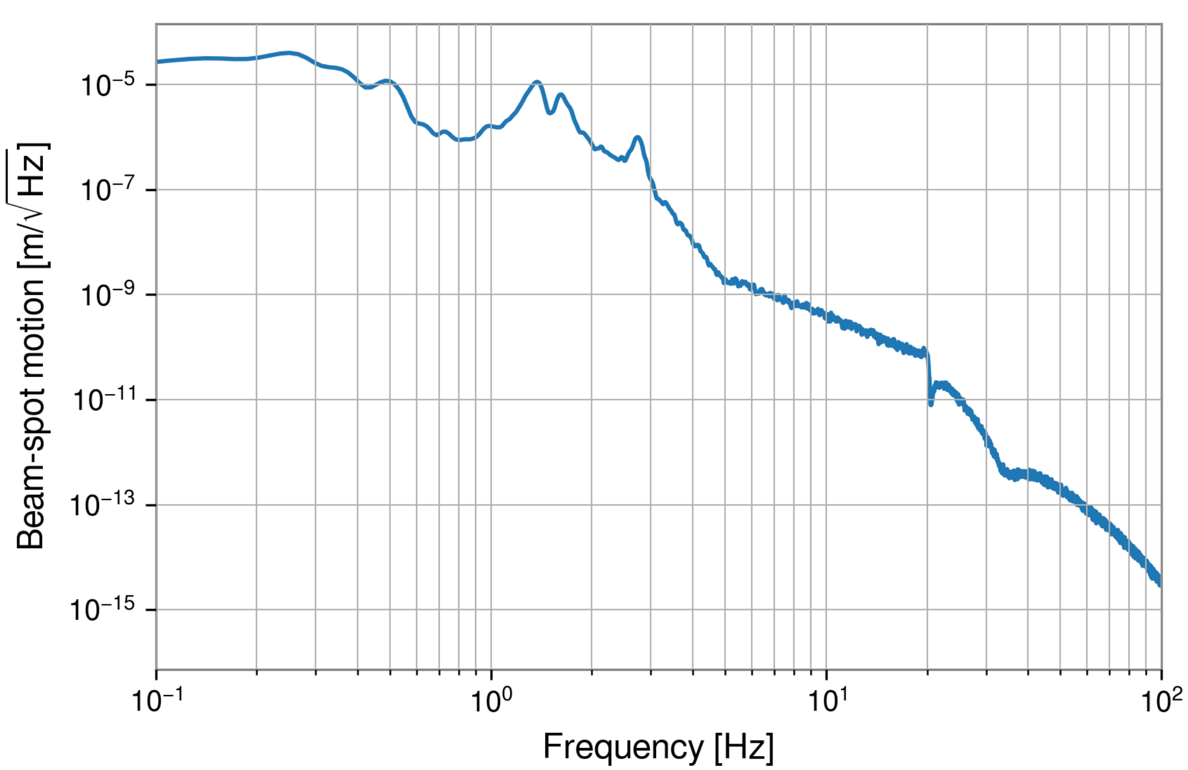
Results



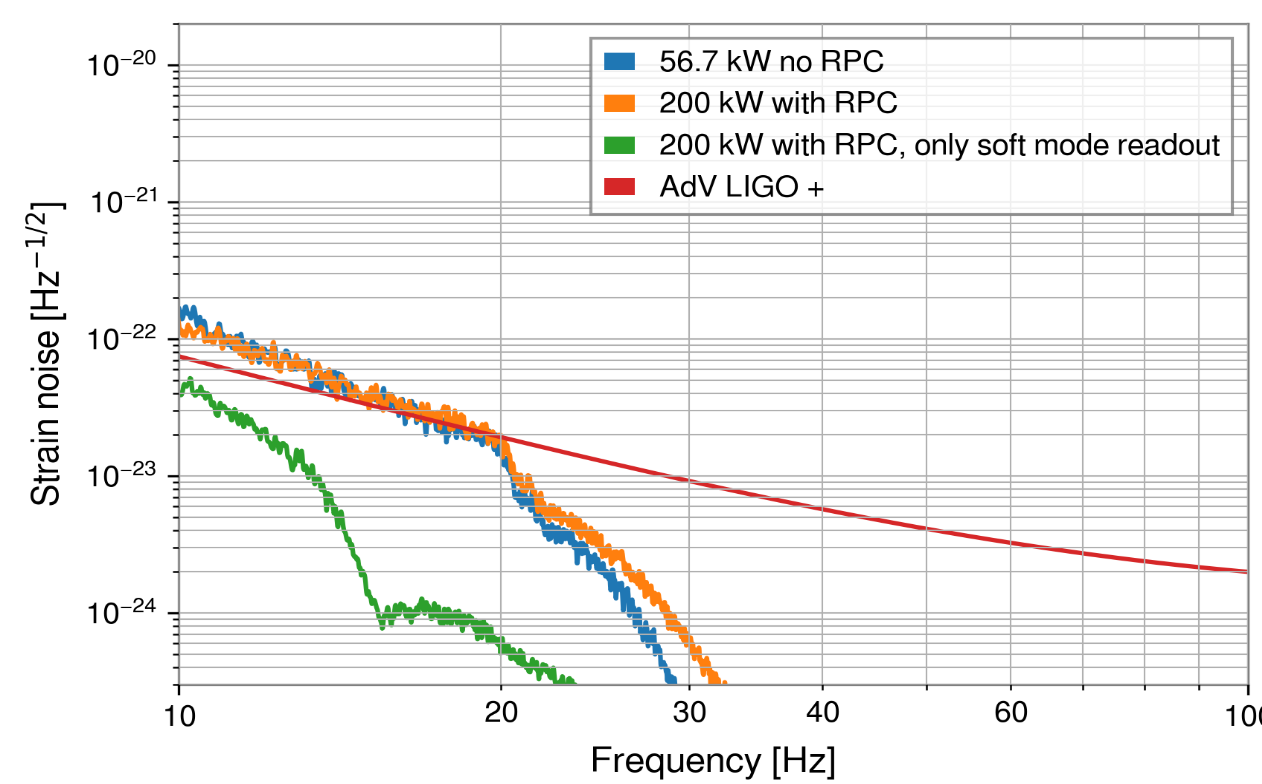
a) Controls engagement demonstration



b) Test mass pitch motion



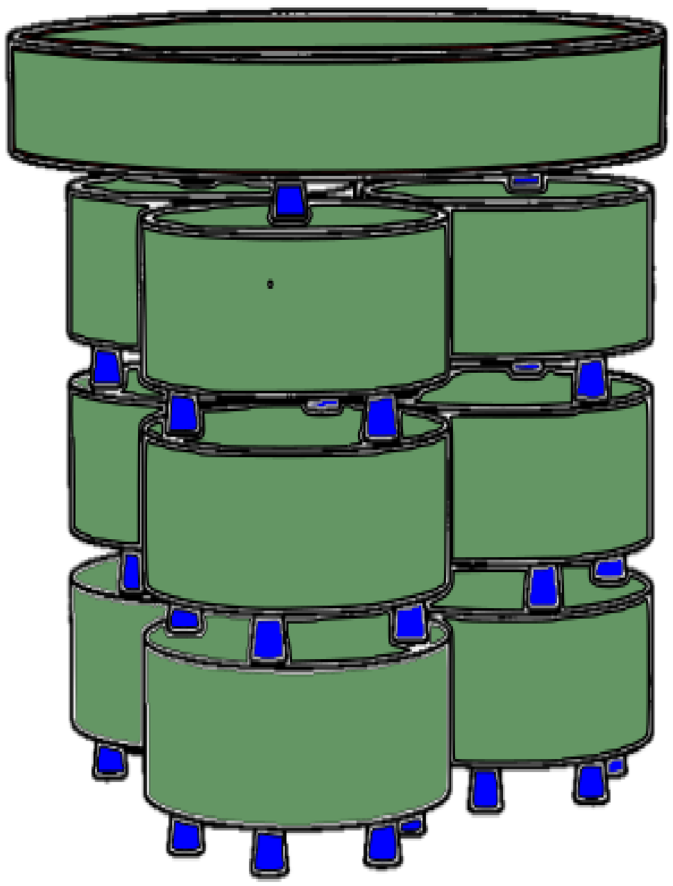
c) Simulated BS motion

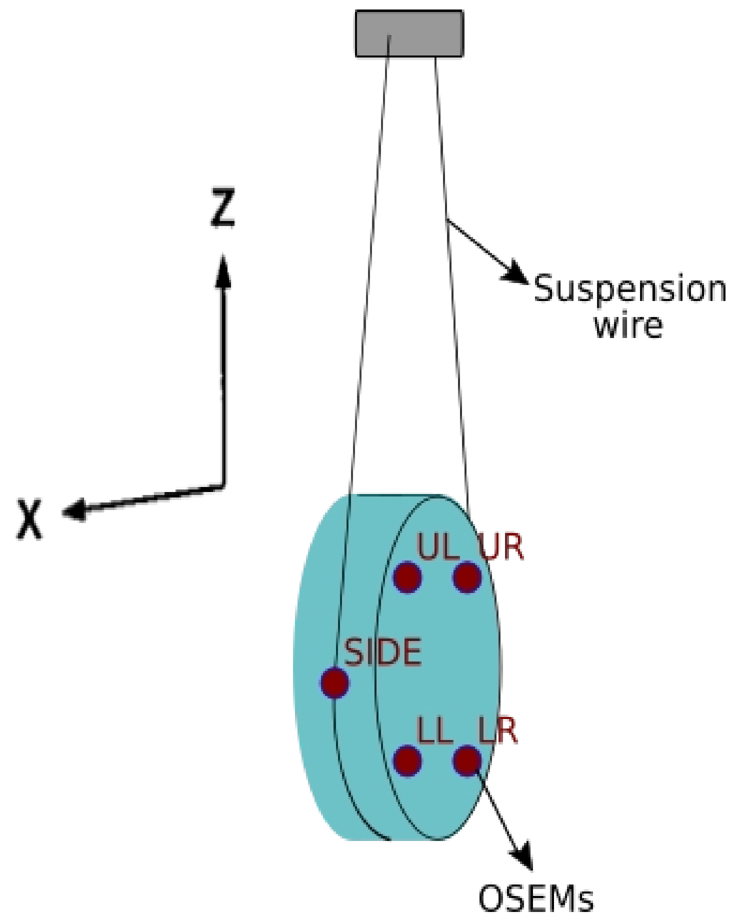


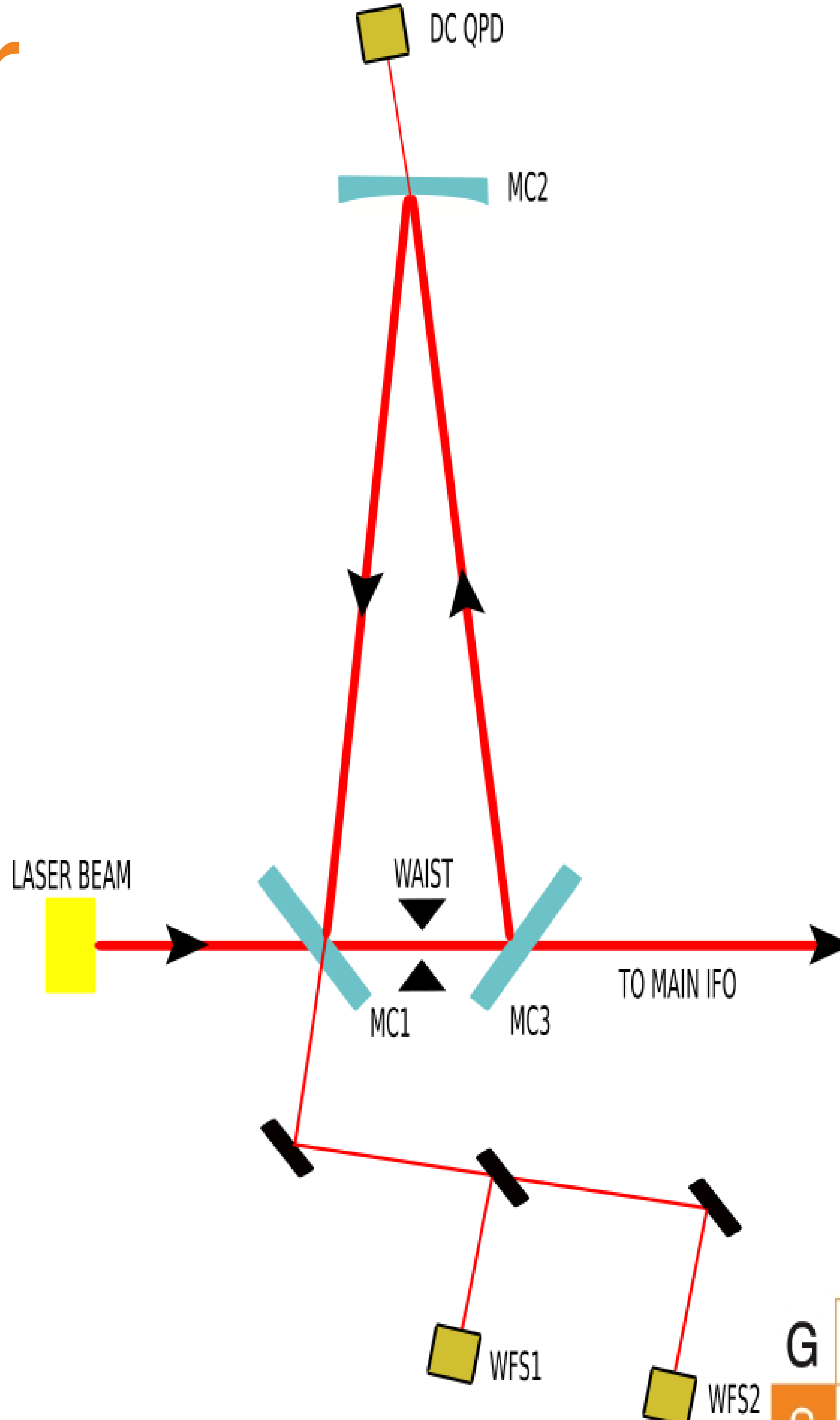
d) Strain noise

Input mode cleaner

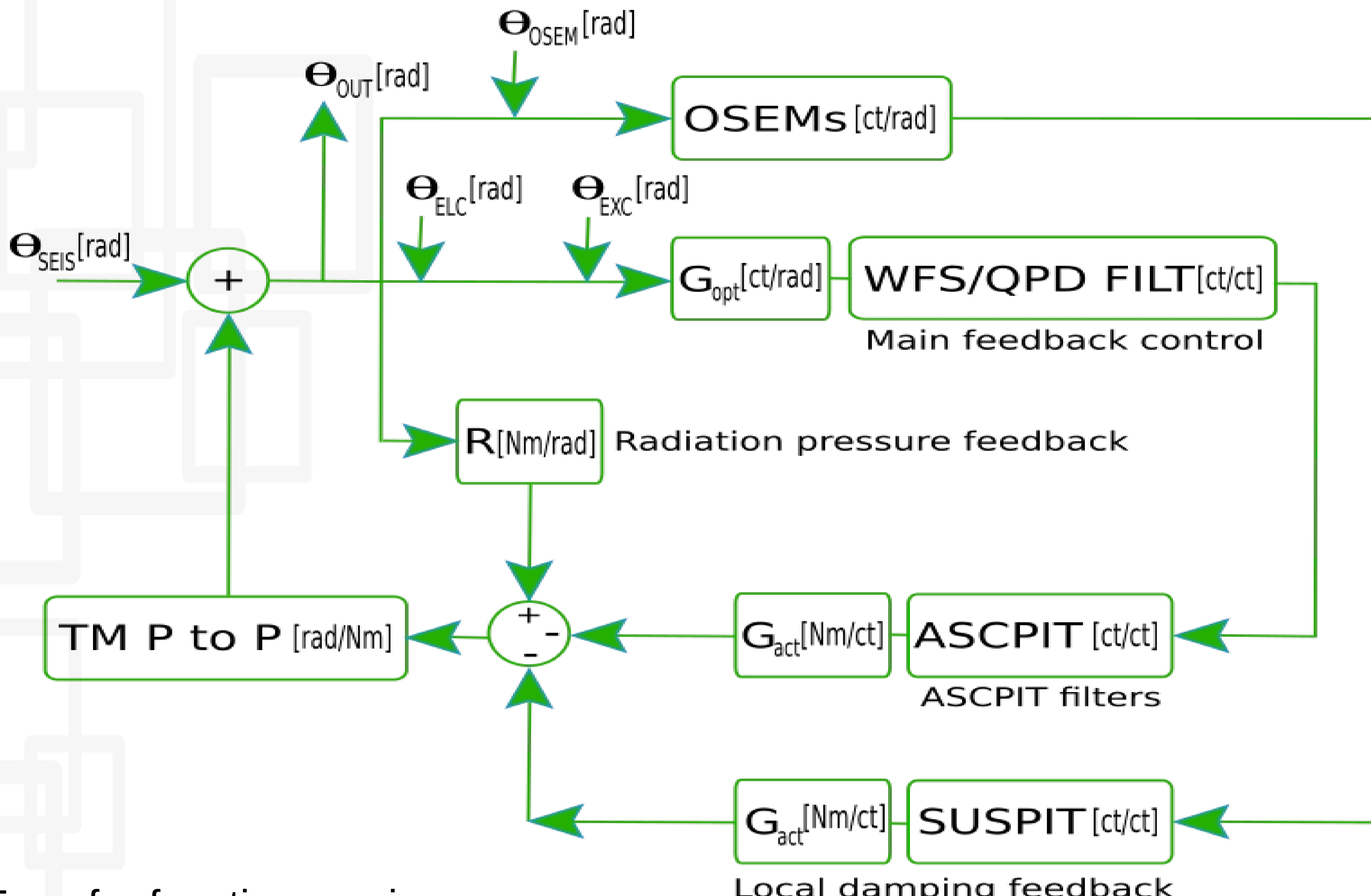
- Multiple-stage seismic vibration isolation stacks
- Single-stage pendula





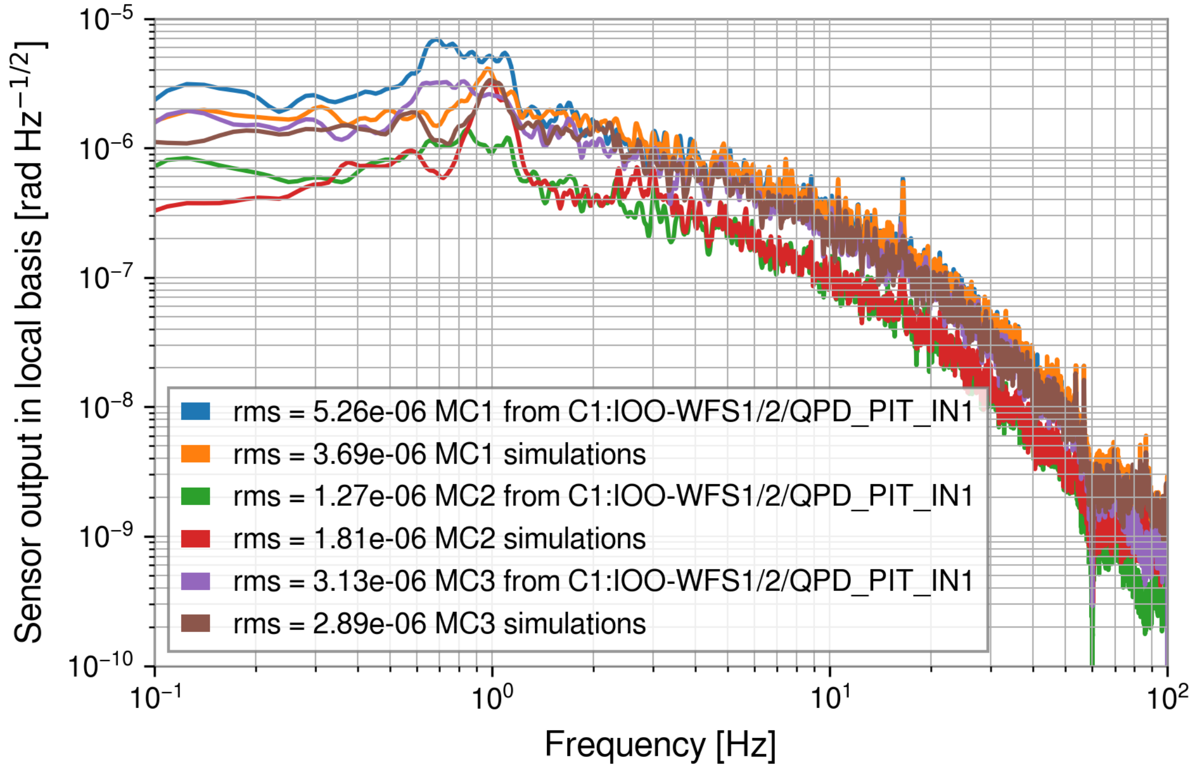


Diagram

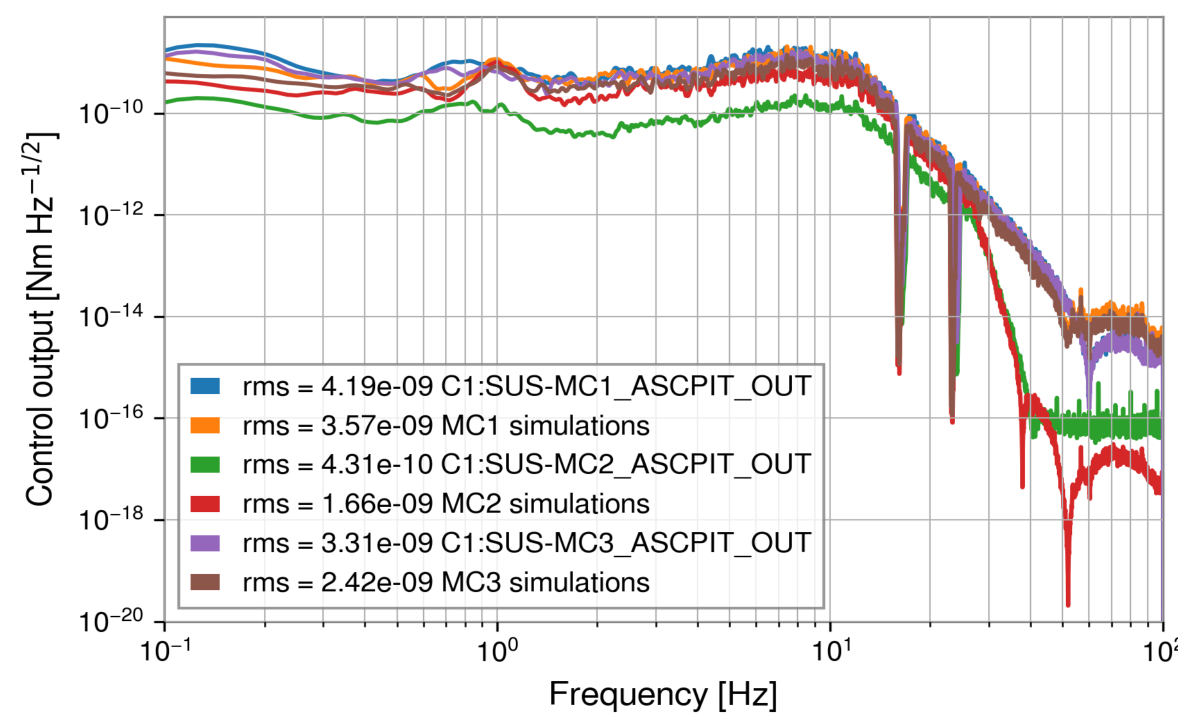


- Transfer functions, noise inputs, calibration

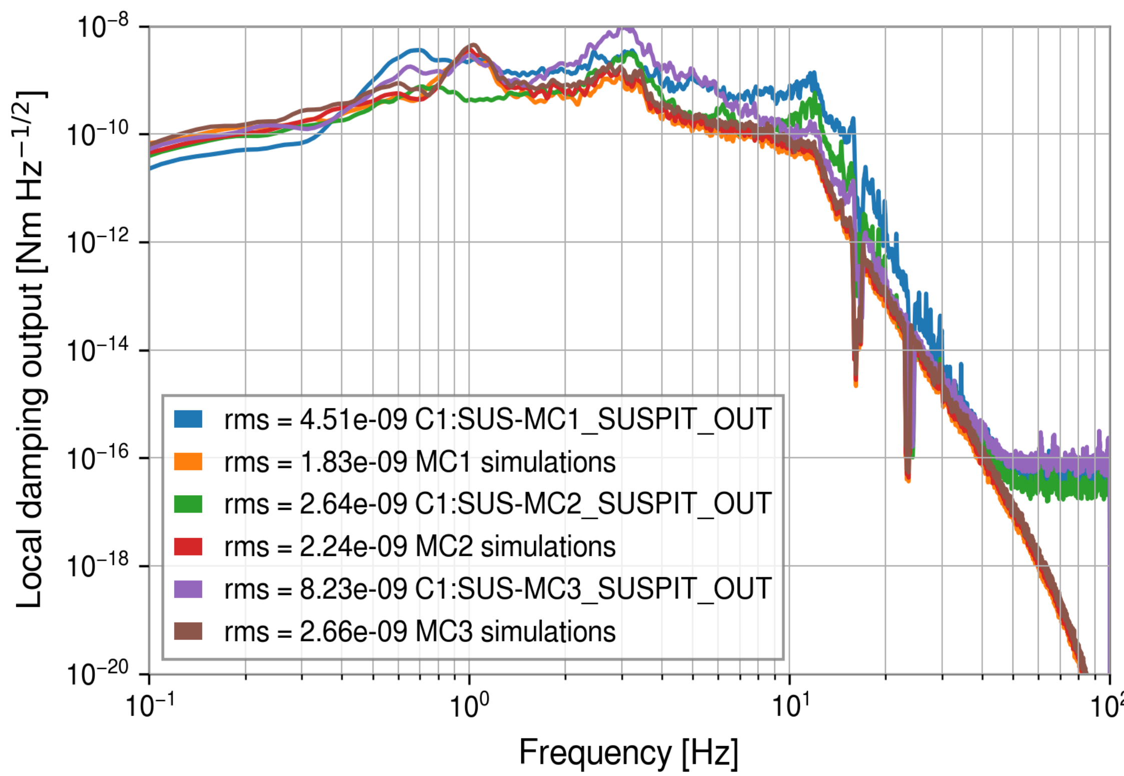
Comparisons with real system



a) Error signal



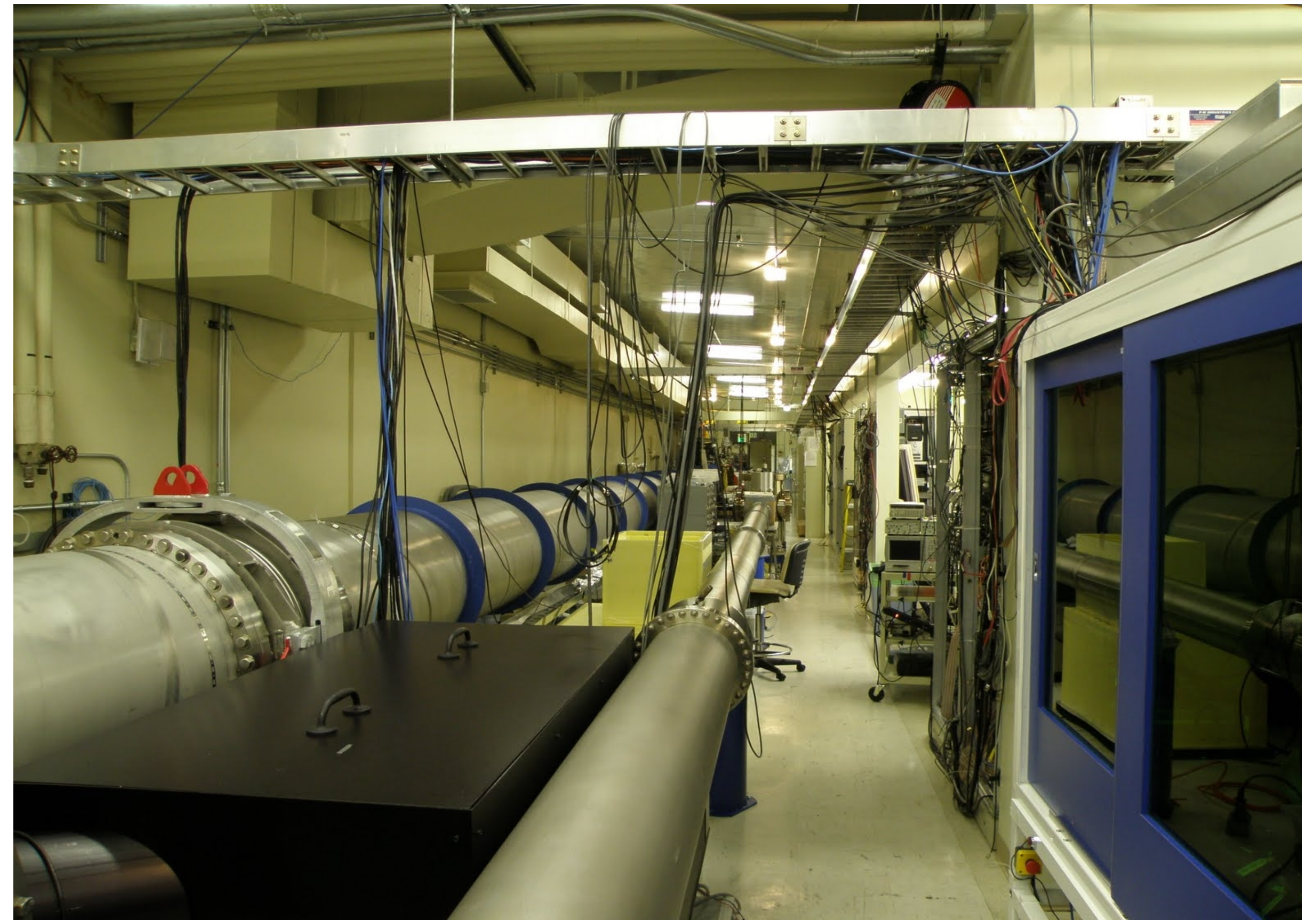
b) Control output



c) Local damping output

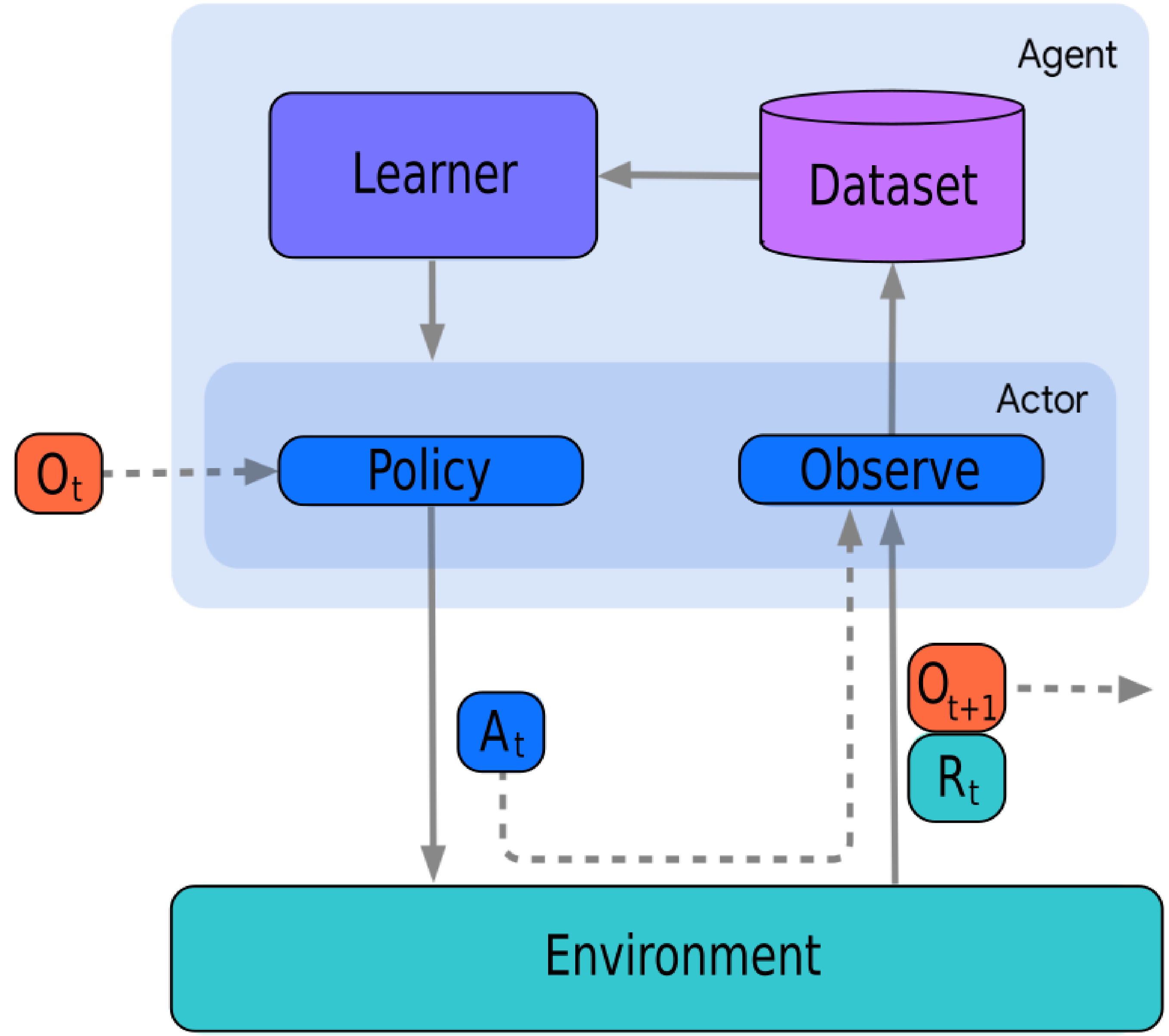
Collaborators

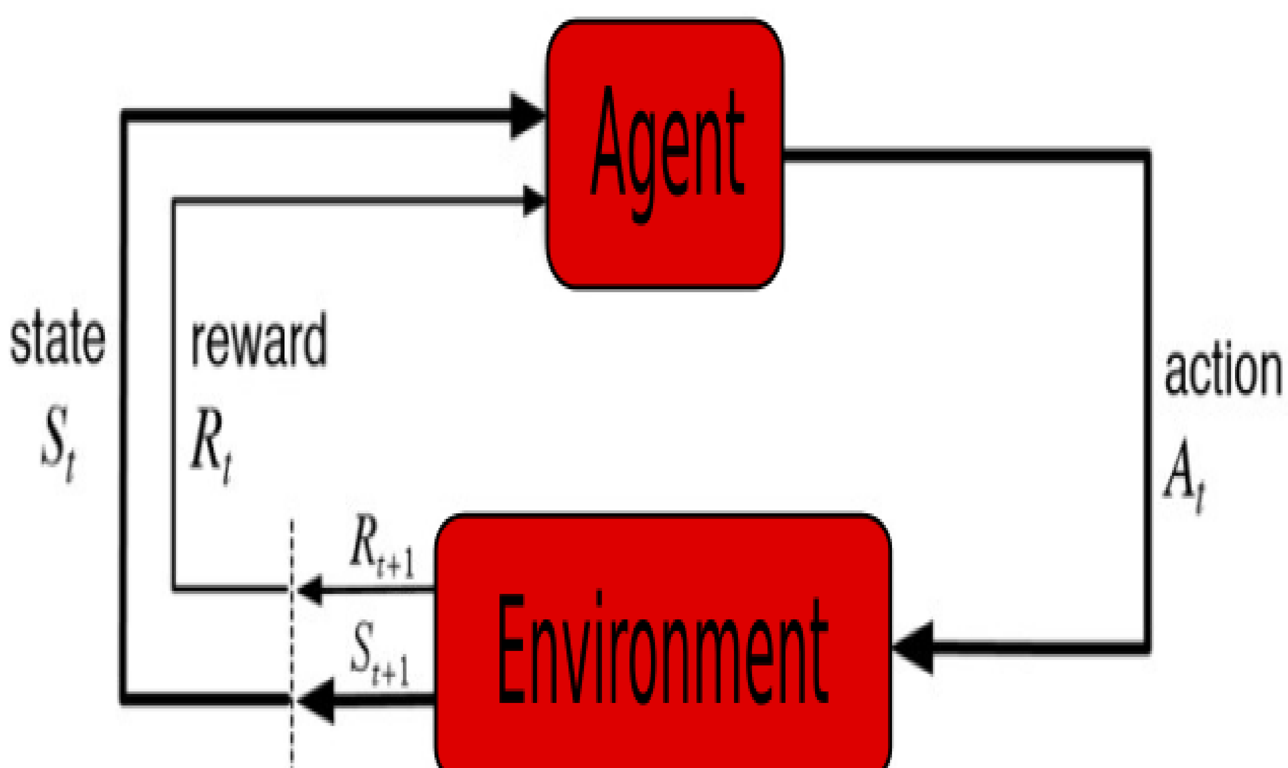
- High demands (robust, stable and optimal) – developed and tested with the time-domain simulations
- DeepMind and Caltech



Reinforcement learning

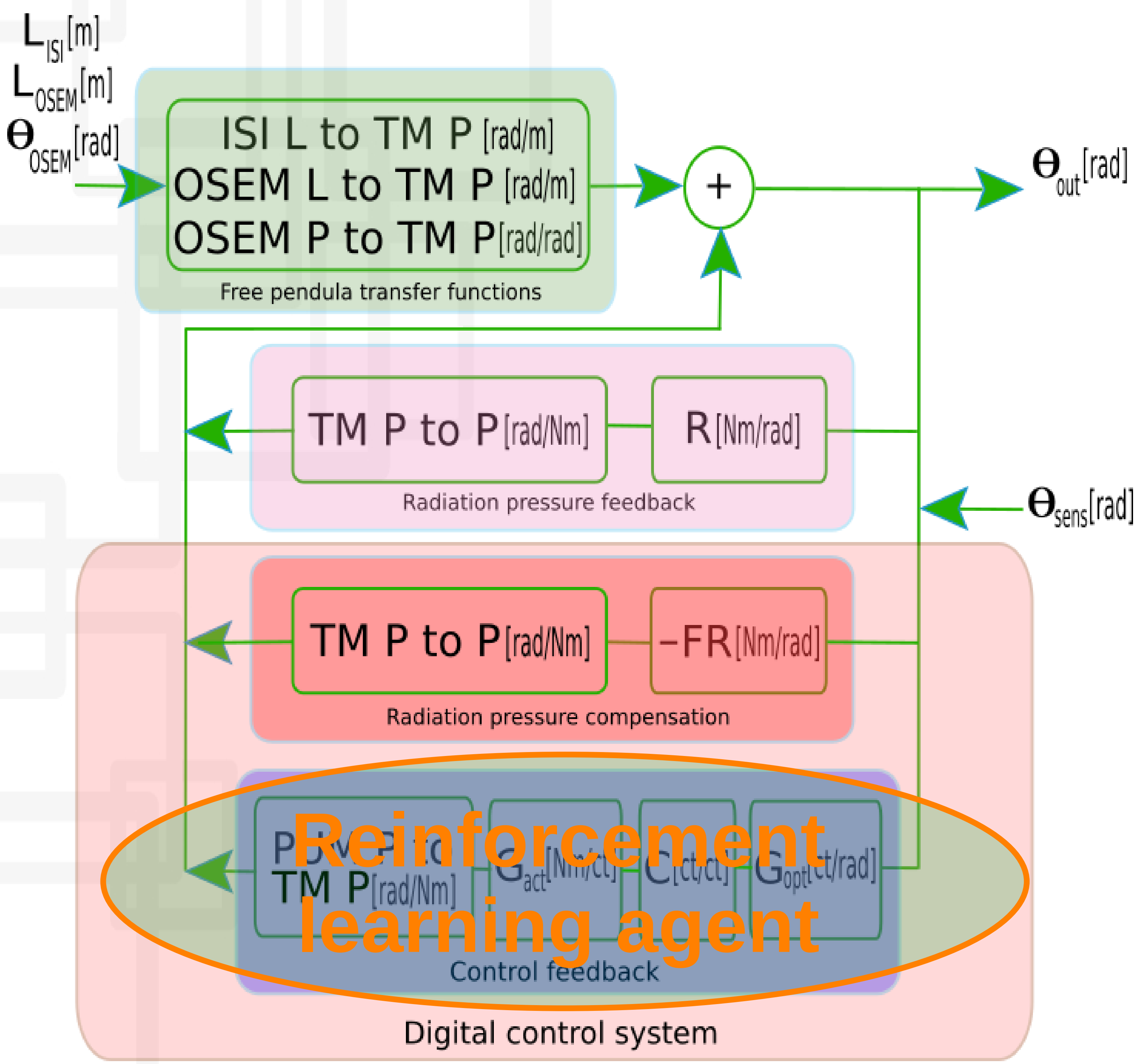
- An 'agent' takes an 'action' on an environment based on the current state of the environment
- Goal: the 'agent' is sufficiently trained so that it takes the best action for every state the environment might be in
- Maximum reward
- Close connections to both optimal control and adaptive control





- Actor pulls weights from the learner components in order to keep its action-selection up-to-date
- Learner pulls experiences observed by the actor through a dataset

Reinforcement learning

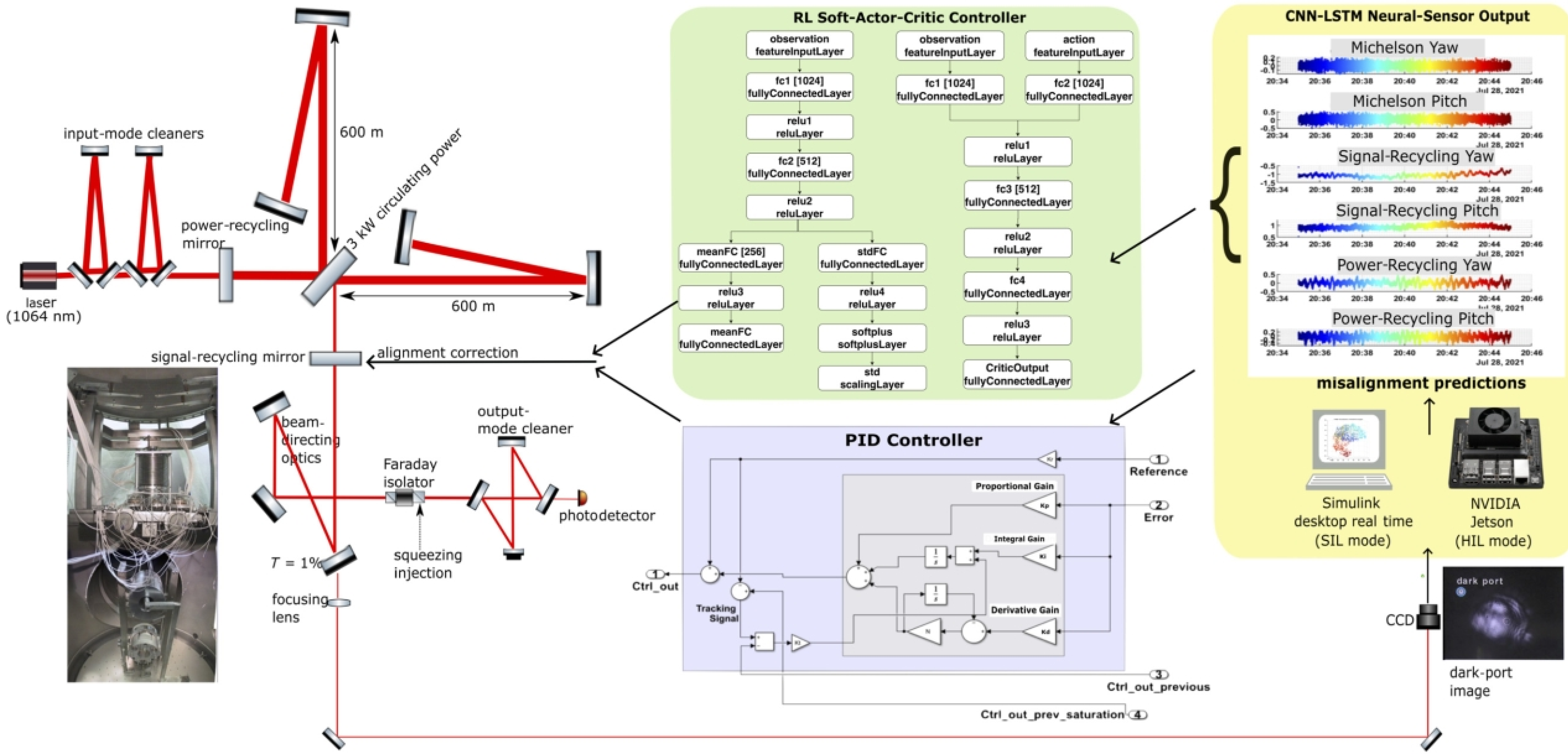


- Acme – library and framework of RL building blocks
- DMPO – Distributional Maximum a-posteriori Policy Optimisation
- It is applicable to complex control problems
- The continuous control stochastic DMPO agent is used

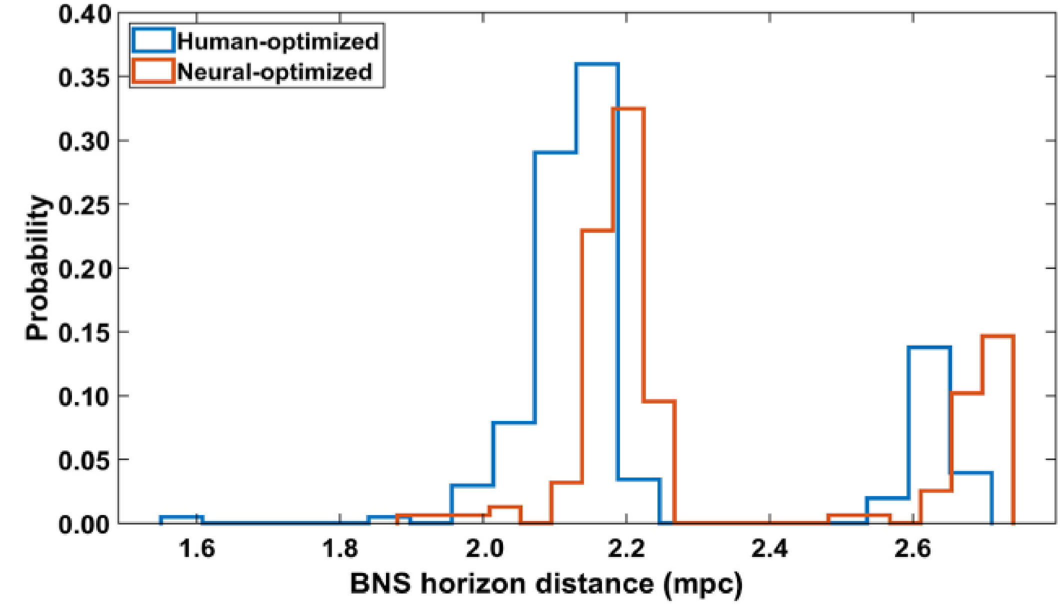
- Lightsaber – the fully nonlinear, time-domain representation allows researchers to test ASC controllers before implementing them in a detector
- RL agent trained against LIGO-Lightsaber

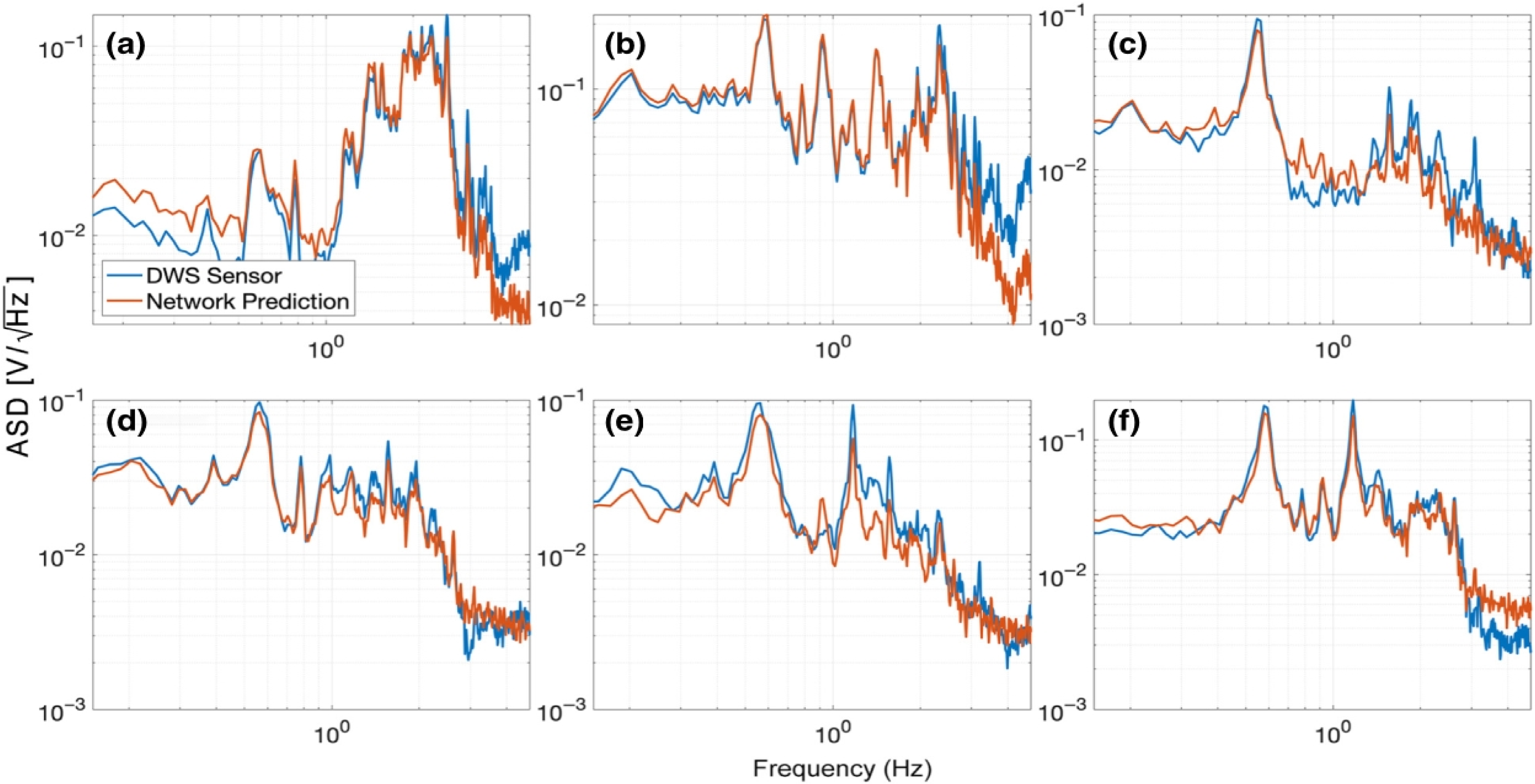
GEO600 RL

- Real-Time Alignment Control with Reinforcement Learning
- GEO600 implemented a novel RL-based control system for angular alignment.
- Uses camera images of the interferometer's dark port beam as input.
- Replaces traditional quadrant photodiode signals with neural-network inference.
- First demonstration of end-to-end RL control in a GW detector
- Demonstrates robustness across changing environmental and optical conditions.



- Implications for Future Detectors and Control Systems
- Enabled improved low-frequency sensitivity at GEO600 by reducing alignment noise.
- Shows viability of ML control for complex interferometric degrees of freedom.
- Reduces reliance on hand-tuned signals and linearized models.
- Paves the way for application in larger detectors (e.g., Virgo, LIGO, ET).
- Highlights potential of RL for control scenarios with image-based or non-Gaussian sensing.
- Supports broader LVK efforts to integrate AI in detector optimization and automation





Conclusions

- **Gravitational waves have opened a new window on the Universe**

  ➤ From binary black holes to neutron star collisions, we are now listening to the cosmos

- **Advanced detectors like LIGO, Virgo, and KAGRA push the boundaries of precision engineering**

  ➤ Measuring distortions in spacetime smaller than a proton's width!

- **We've entered the era of multi-messenger astronomy**

  ➤ Combining gravitational waves with light gives deeper insight into cosmic events

- **Detector upgrades are continuous and essential**

  ➤ Noise reduction, quantum optics, cryogenics, and active isolation drive progress

- **The future is bright with 3rd-generation observatories like the Einstein Telescope and Cosmic Explorer**

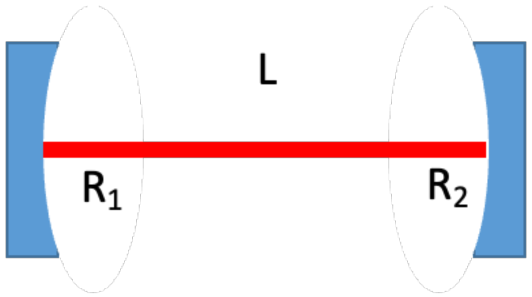
  ➤ Orders-of-magnitude better sensitivity, probing the early Universe and fundamental physics

- **It's a global effort**

  ➤ Thousands of scientists, engineers, and students — and a growing role for machine learning and control systems

Marginally stable cavities in Virgo

•The particularity of Virgo is to have marginally stable recycling cavities (LIGO ones are stable)
→ an historical choice driven by space constraints "Stable cavities are more robust from the optical point of view, but more complicated from mechanical and control ones (there are more mirrors!)"



•Stability condition expressed as : $0 < g_1 g_2 < 1$

g_1 and g_2 are related to the one-way Gouy phase shift $\delta\phi$: $\delta\phi = \text{arcos}\sqrt{(g_1 g_2)}$

$$g_1 = 1 - \frac{L}{R_1}$$
$$g_2 = 1 - \frac{L}{R_2}$$

•For Virgo $g_1 g_2 \sim 1$ → on the edge of stability

•A stable cavity is selective: modes of different orders cannot resonate simultaneously.

•In a marginally stable cavity, high order modes are nearly co-resonant.

→ this makes the detector more sensitive to mirror defects (errors on Radius of Curvature, absorption points, optical aberrations…, induced by cold and hot defects), to cavities mode matching and alignment

→ a major source of difficulties during the commissioning phase (very bright DARM, HOM recycled..)

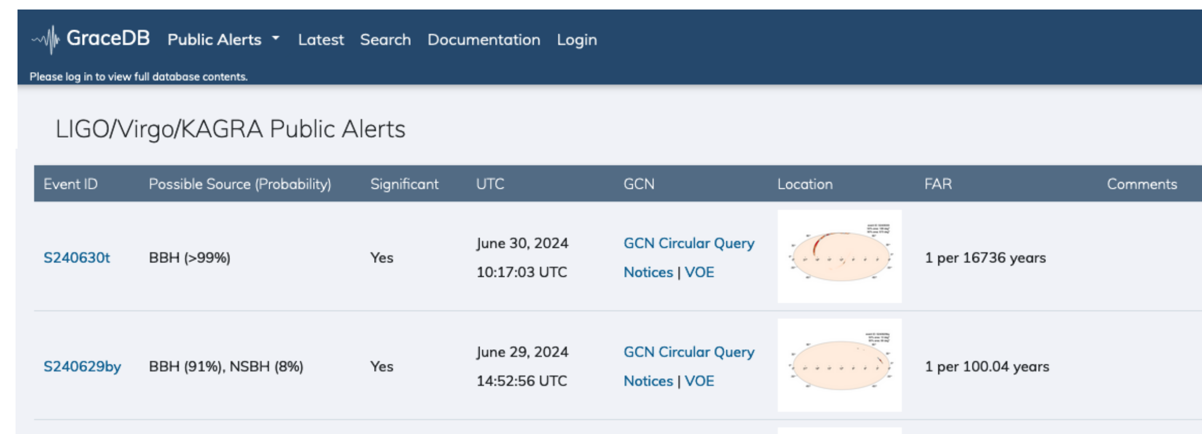
Credit: R. Gouaty

Stay tuned for results!

- Recent results: ultra-light vector DM search using KAGRA interferometer during O3GK run (ArXiV 2403.03004)
- *In preparation*: Gravitational Wave Transient Catalog-4 (GWTC-4) including results from O4a.
  - Coordination between papers using same data sample: GRBs, astrophysical populations, isotropic backgrounds..
- Separated publications expected for special events.

GraceDB

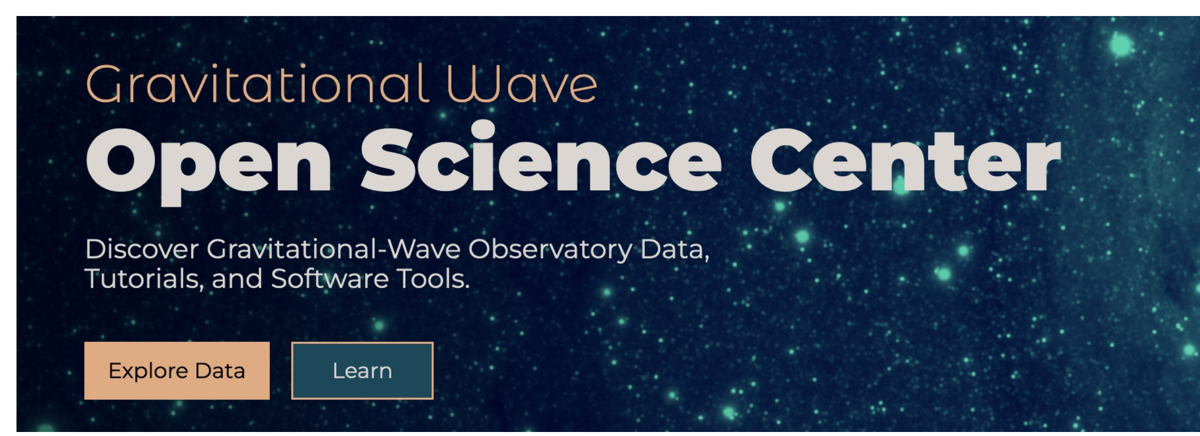
- Information sent via GCN to the astro community
- **High-level** data uploaded by analysis pipelines
- Skymaps, ITF that provides data, FAR, event time, probabilities (pHasMassGap, pRemnant, pHasNS)
- Search engine allows for detailed queries



https://gracedb.ligo.org/

GWOSC: Gravitational Wave Open Science Center

- Mid-level data: **Strain h(t) data passing quality cuts available from all LVKG interferometers after proprietary period**
- Release of data contact to specific publications
- Tutorials and Software for GW data analysis available
- 7th GW Open Data Workshops (hybrid): April 2024 edition hosted in Taiwan



https://www.gw-openscience.org

Calibration and h(t) reconstruction

- The ITF is controlled via control loops to be kept on a working point

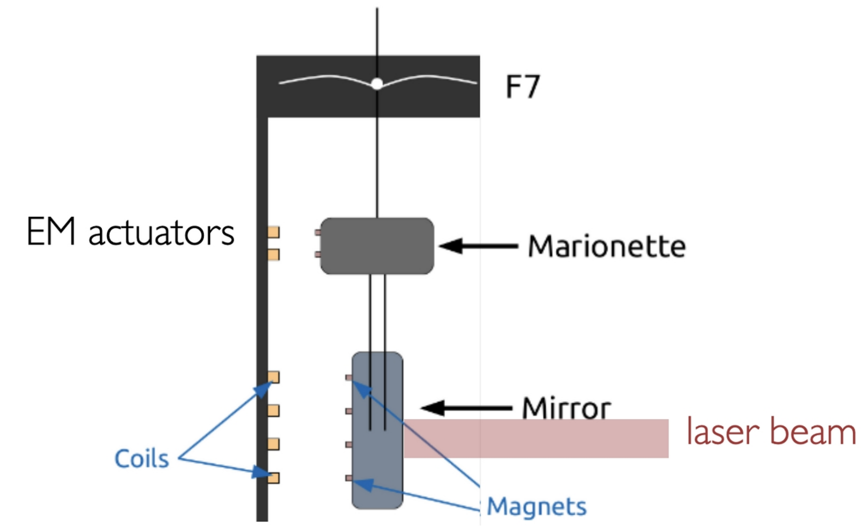
- The ITF needs to be calibrated to obtain h(t)
  - Response of the mirror/marionettes to the EM actuators used in longitudinal control: A_{MIR} and A_{MAR} [m/V]
  - Readout electronics of the output photodiode *S*
  - ITF and mirror optical response function O_i

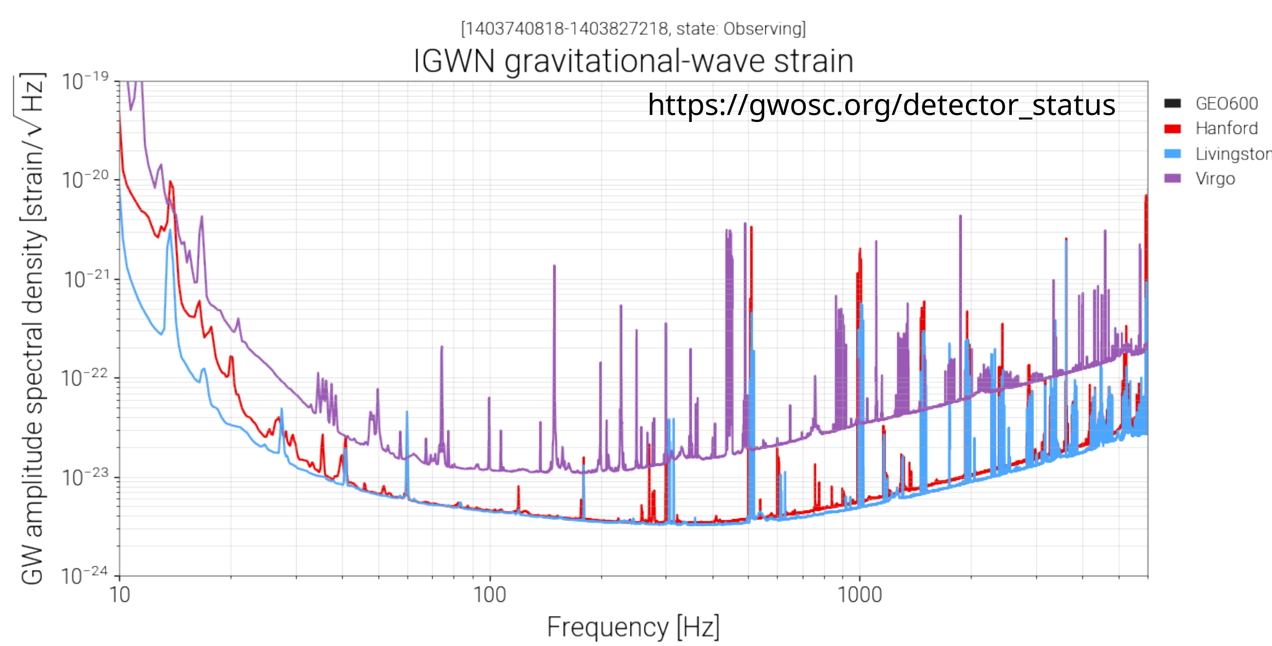
- Add variations of h(t) observed with time from injections

- Total h(t) uncertainties during O3b for LIGO/Virgo in the most sensitive frequency band 20–2000 Hz
  - Depending on the ITF: 5- 10% in magnitude and 2-9 deg in phase (*CQG* 37.22 (2020): 225008., *CQG*39.4 (2022): 045006)

Calibration-h(t) reconstruction connection

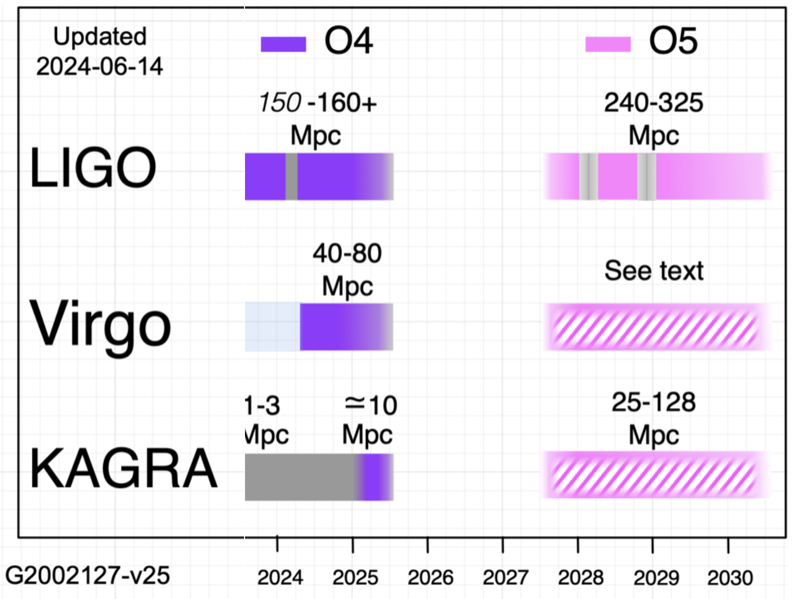
$$\mathcal{E}(f) = S(f)\Big[\sum_i O_i(f)\cdot(\Delta L_{mir,i}(f) + \Delta L_{mar,i}(f)) + O_{ITF}(f)\cdot h(f)\cdot L_0\Big]$$





What's next?

- From O1- nowadays: LVK unveiling the GW sky between 10's Hz-kHz!
- O4 commissioning : GW interferometers are very complex machines!
- O4: total of 24 months of data!
  - O4b a year ahead of 3-ITF, eventually 4-ITF network!



- Goal for O5: Long observing run of ~3 years with commissioning gaps in between.
- Current best understanding of the long-term observing schedule (note 25 versions of the plot !)
- Virgo interferometer: Marginally-stable recycling cavities (Signal Recycling and Power Recycling) are a structural weakness
  - LIGO&KAGRA run with stable recycling cavities
  - Stable recycling cavities: Assessment of the best optical layout modification ongoing

D. Shoemaker tomorrow at 11:10 for status of CE and ET!

S. Nissanke tomorrow at 11:30 for science with CE and ET!

- PostO5: push the infrastructure as much as possible (x2 BNS range) with very good duty cycle