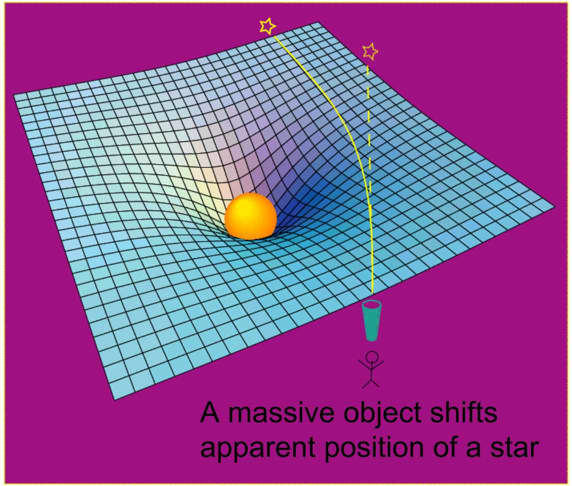
Gravitational waves observations by LIGO-Virgo and prospects for the future

F. Sorrentino - INFN Genova
on behalf of the Virgo collaboration

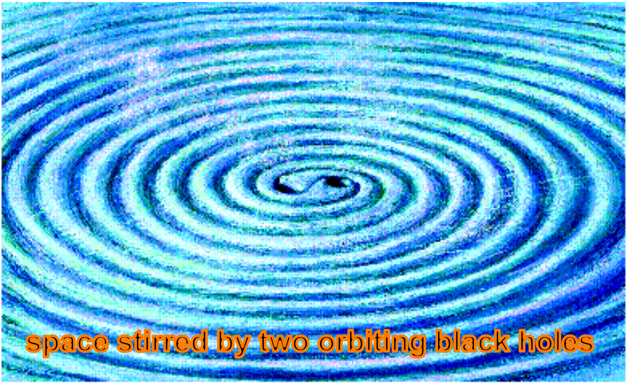
Outline

- Gravitational waves physics
  - GW sources
  - Fundamental physics tests
  - Cosmology
- Gravitational waves detectors
  - Spacetime strain and Michelson interferometry
  - Optical configuration of interferometric detectors
  - Sensitivity limits
  - History of sensitivity evolution
  - Worldwide network of interferometric detectors
- GW observations
  - First detections
  - Observing runs and detectors' upgrades
  - Results from O3
- Present & future of GW detectors
  - Latest LIGO-Virgo upgrades & current status
  - Observing scenario for 2nd generation terrestrial detectors
  - 3rd generation terrestrial detectors
  - Space detectors

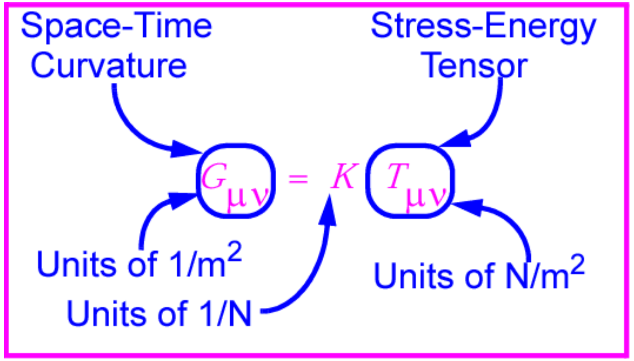
GR & spacetime stiffness



A massive object shifts apparent position of a star



space stirred by two orbiting black holes



Space-Time Curvature

Stress-Energy Tensor

$$G_{\mu\nu} = K\, T_{\mu\nu}$$

Units of 1/m^2

Units of 1/N

Units of N/m^2

$$K \sim [G/c^4] \sim 10^{-44}\ \mathrm{N}^{-1}$$

- GW can carry large energy density with vanishingly small amplitude
- E.g. for a binary coalescence

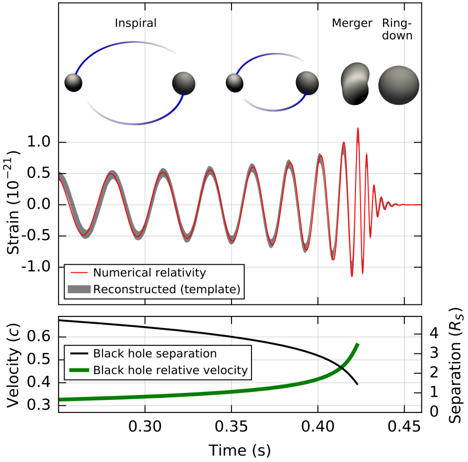
$$h \approx 32\pi^2 \cdot \frac{G}{c^4} \cdot \frac{1}{r} \cdot M \cdot R^2 \cdot f_{orb}^2$$

$M = 1.4\ M_\odot$, $R = 20$ km, $f = 400$ Hz,

$r = 10^{23}$ m (15 Mpc = 48,9 Mlyr)

$h \sim 10^{-21}$

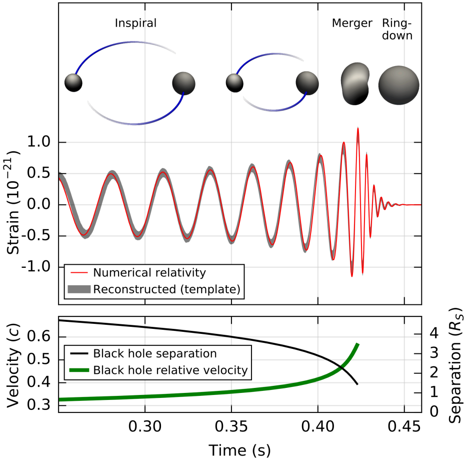
Gravitational waves sources

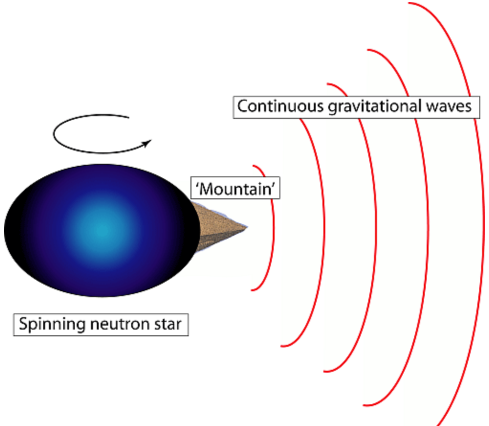


https://www.ligo.org/science/

- **Binary Compact Objects** (BH or NS): strong (transient) emitters, well modeled;

Gravitational waves sources





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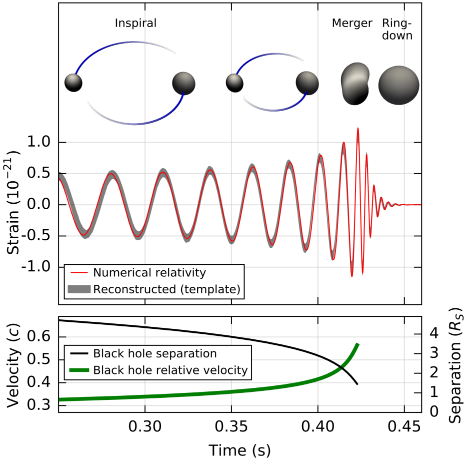
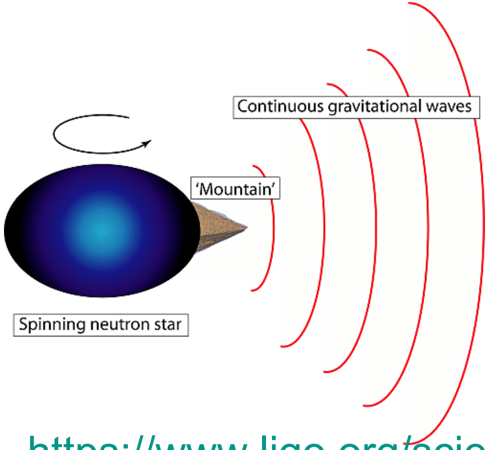
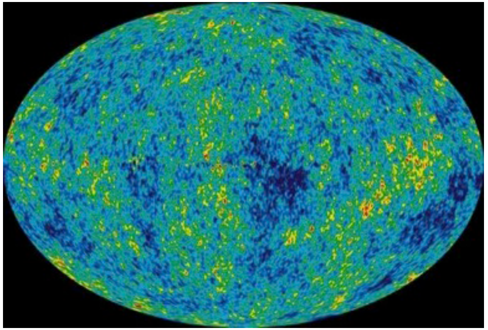
- Non-spherical **spinning NSs:** narrow frequency band signal with well defined spectral components;

Gravitational waves sources







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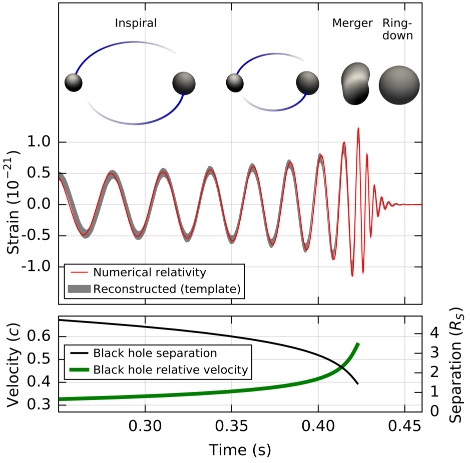
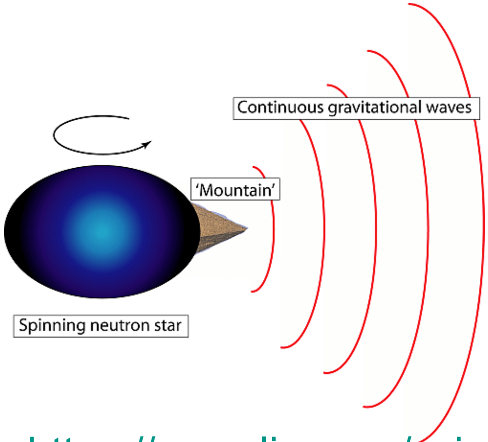
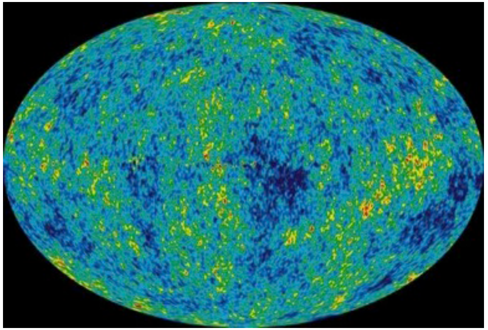
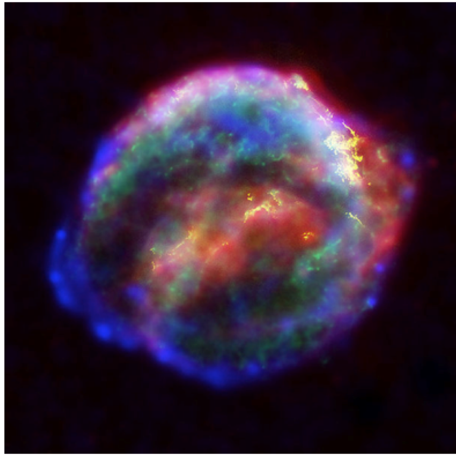
- **Binary Compact Objects** (BH or NS): strong (transient) emitters, well modeled;
- Non-spherical **spinning NSs:** narrow frequency band signal with well defined spectral components;
- GW **stochastic background,** cosmological origin or superposition of unresolved astrophysical sources: continuous GW with broad-band spectra;

Gravitational waves sources







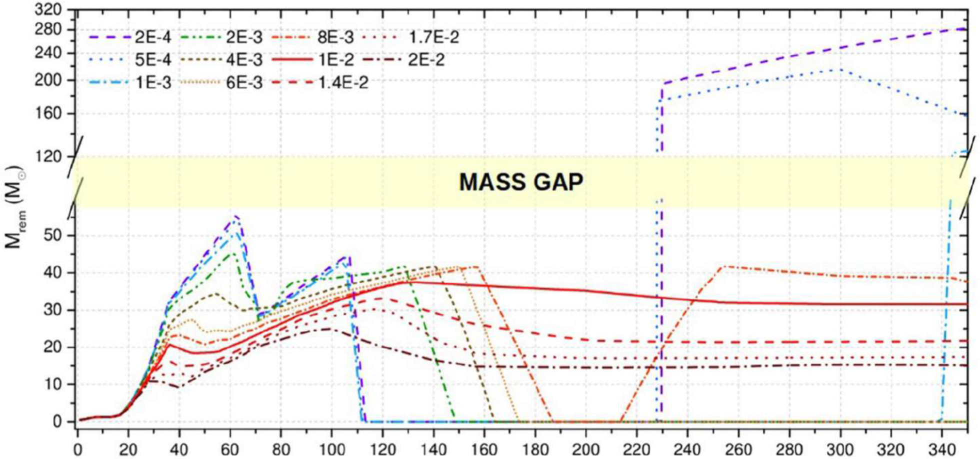


https://www.ligo.org/science/

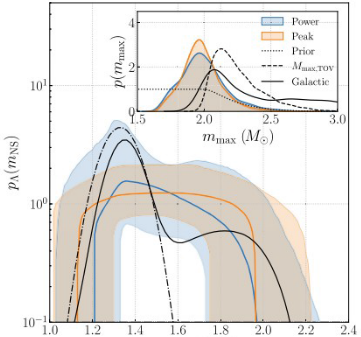
- **Binary Compact Objects** (BH or NS): strong (transient) emitters, well modeled;
- Non-spherical **spinning NSs:** narrow frequency band signal with well defined spectral components;
- GW **stochastic background,** cosmological origin or superposition of unresolved astrophysical sources: continuous GW with broad-band spectra;
- Asymmetric core collapse **Supernovae**: GW burst, poorly modeled .

GW & astrophysics

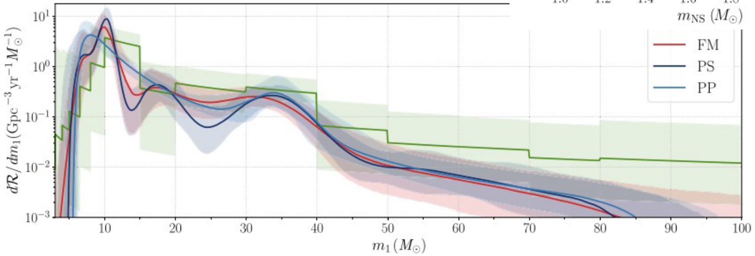
- BH & NS populations
- BH & BBH physics
    - Test of pair instability model from BH mass distribution
- BBH formation mechanism
    - isolated vs dynamical
- NS e.o.s.

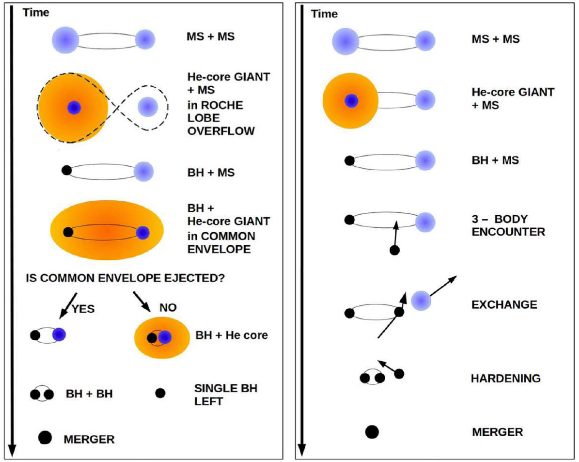


NS



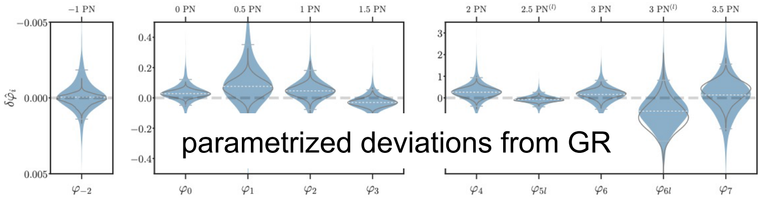
BH



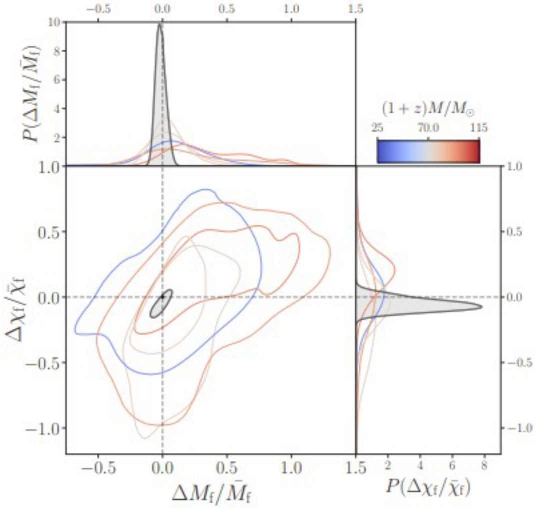


GW & fundamental physics

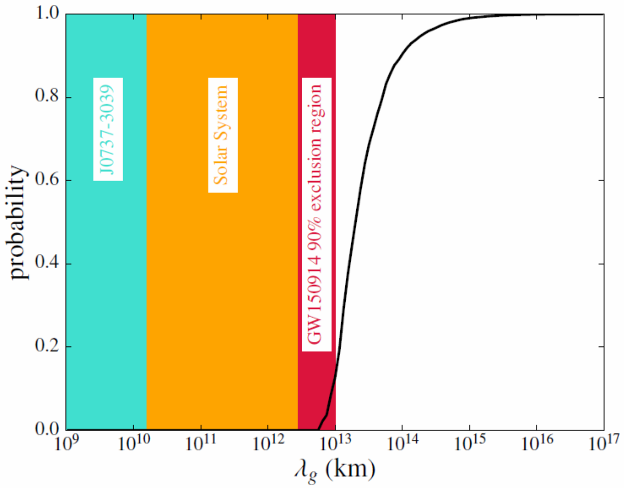
- Testing GR with GW:
    - dispersion of GW No non-GR modes of polarization
    - post-merger echoes
    - GW propagation
    - bound on graviton mass
    - Final mass and spin pre-merger and post-merger part consistency
- So far no evidence of physics beyond general relativity



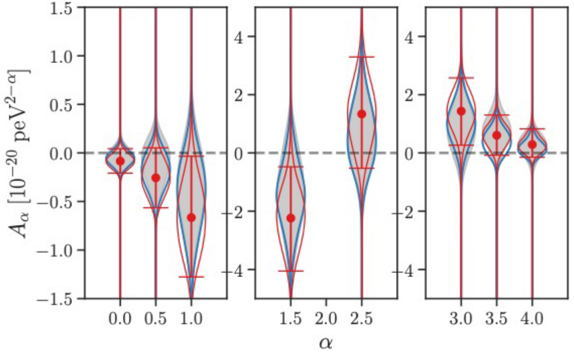
parametrized deviations from GR



Graviton Compton wavelength



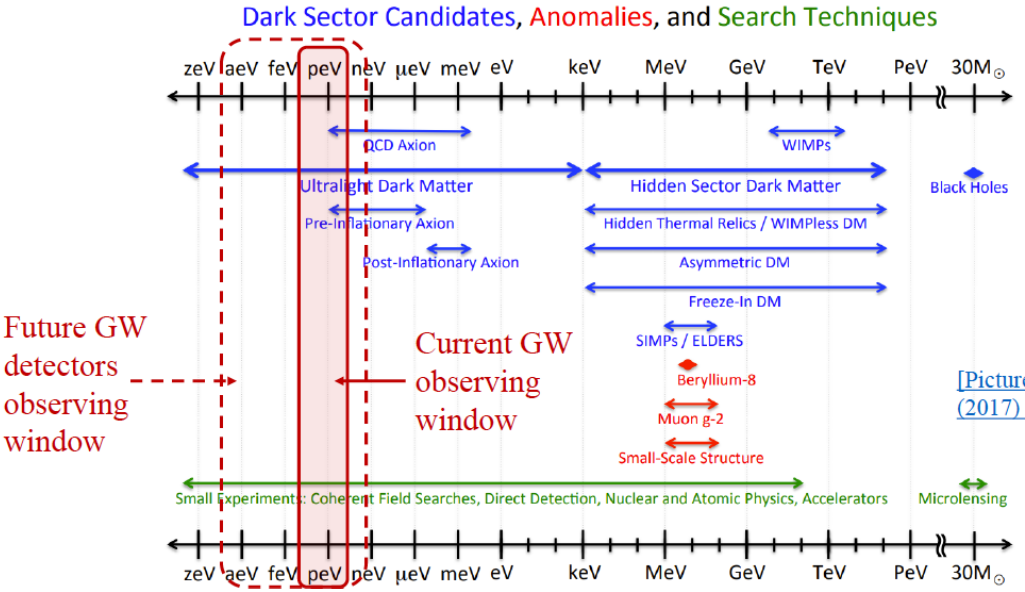
Dispersion during propagation



GW & fundamental physics

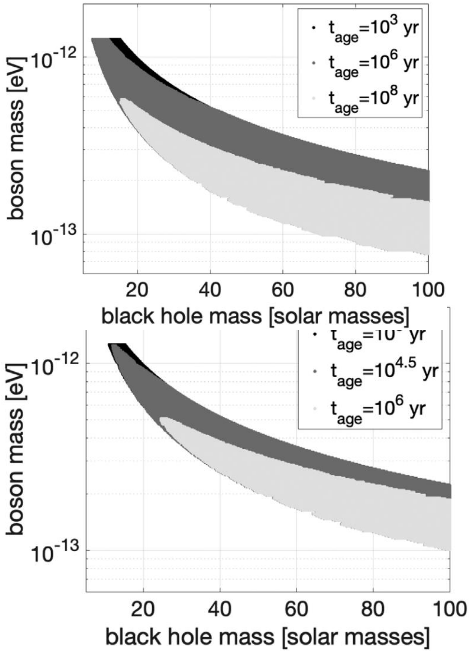
- Dark matter search
  - GW from ultra-light scalar boson clouds

$$h_0 \sim 6\cdot 10^{-24}\left(\frac{\mathrm{M_{bh}}}{10\mathrm{M_\odot}}\right)\left(\frac{\alpha}{0.1}\right)^7\left(\frac{1\,kpc}{r}\right)(\chi_i-\chi_c)\left(1+\frac{t}{\tau_{age}}\right)^{-1}$$



[Picture: Battaglieri et al. (2017) arXiv:1707.04591]

Excluded regions from O3 data

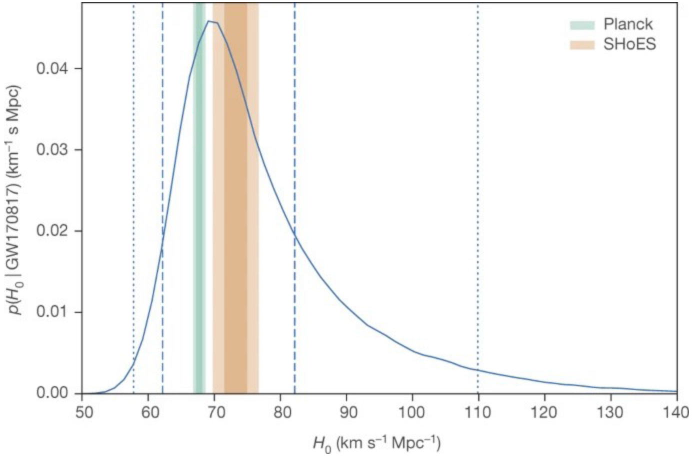


Abbott *et al.* (2022) **PRD 105**, 102001]

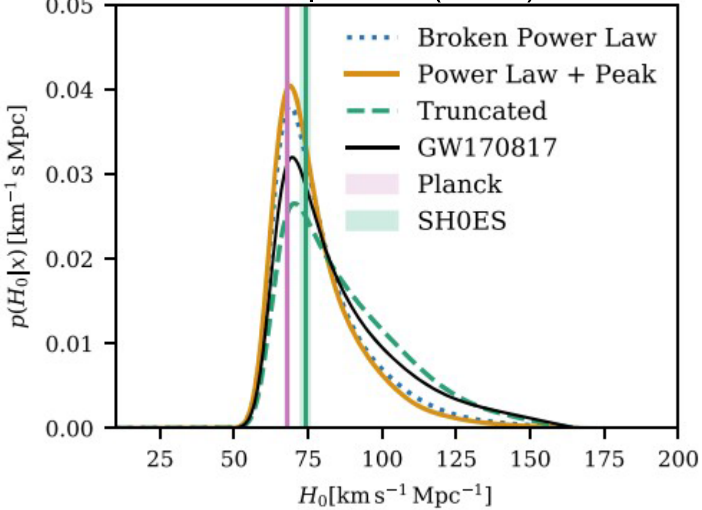
GW & cosmology: Hubble constant

- Two different methods
  - bright sirens (EM counterpart for redshift estimation)
  - dark sirens (no EM counterpart, galaxy catalogues for redshift estimation)

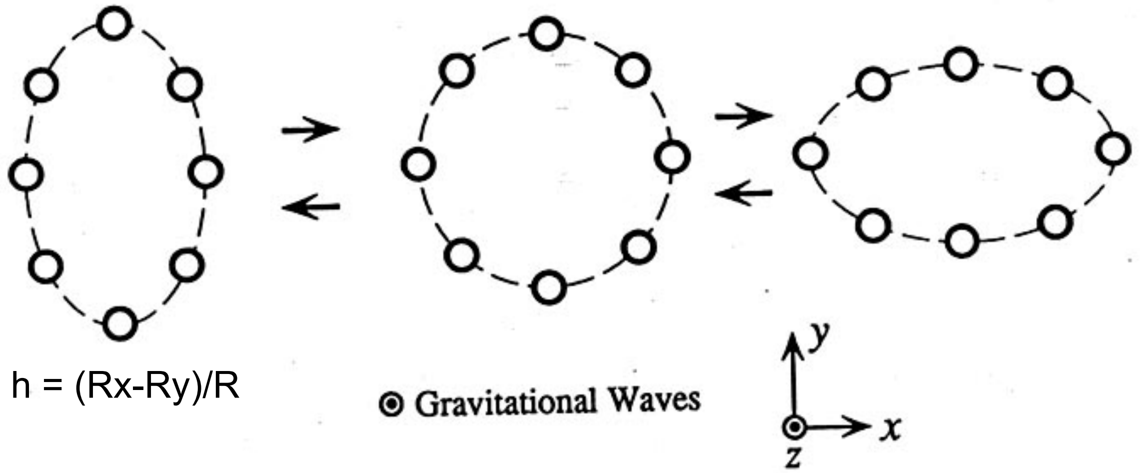
GW170817, bright siren
LVK Nat 551 (2017) 88



42 BBH w/wo GW170817
LVK, ApJ 949 (2023) 76

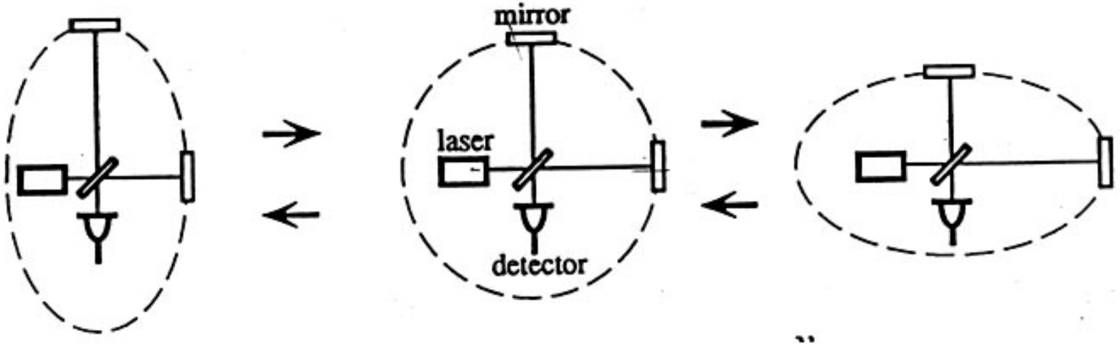


GW strain & Michelson interferometers



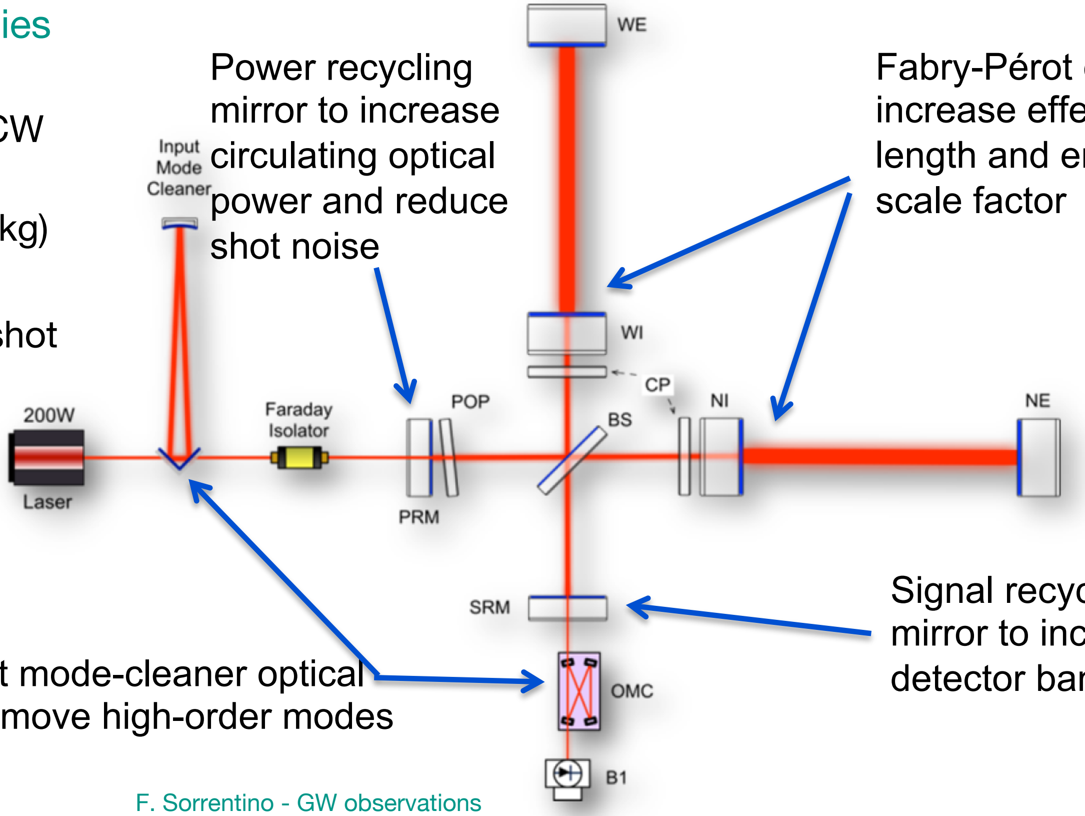
GW amplitude h = (Rx-Ry)/R

Spatial asymmetry induces relative phase shifts on light in arms



Optical configuration of GW detectors

- Doubly recycled Michelson interferometer with arm cavities
  - Km long arms
  - High power, ultrastable CW lasers (10÷100 W)
  - Suspended mirrors (~40 kg)
  - Under ultra-high vacuum
  - Quantum squeezing for shot noise mitigation



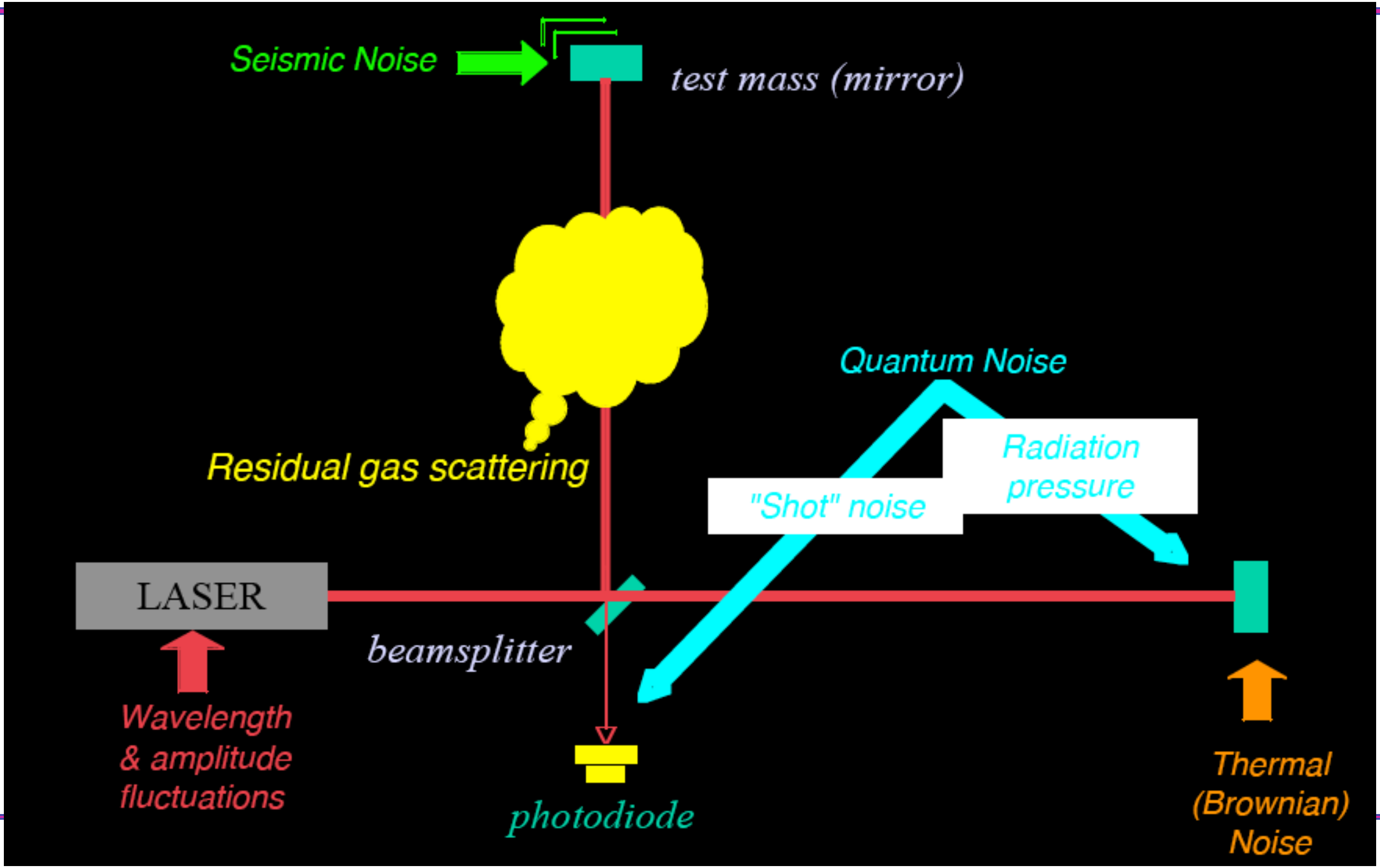
Power recycling mirror to increase circulating optical power and reduce shot noise

Fabry-Pérot cavities to increase effective arm length and enhance scale factor

Signal recycling mirror to increase detector bandwidth

Input and output mode-cleaner optical resonators to remove high-order modes

Noises limiting sensitivity of GW detectors



Quantum noise with suspended optics

While shot noise contribution decreases with optical power, radiation pressure level increases:

wavelength

$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

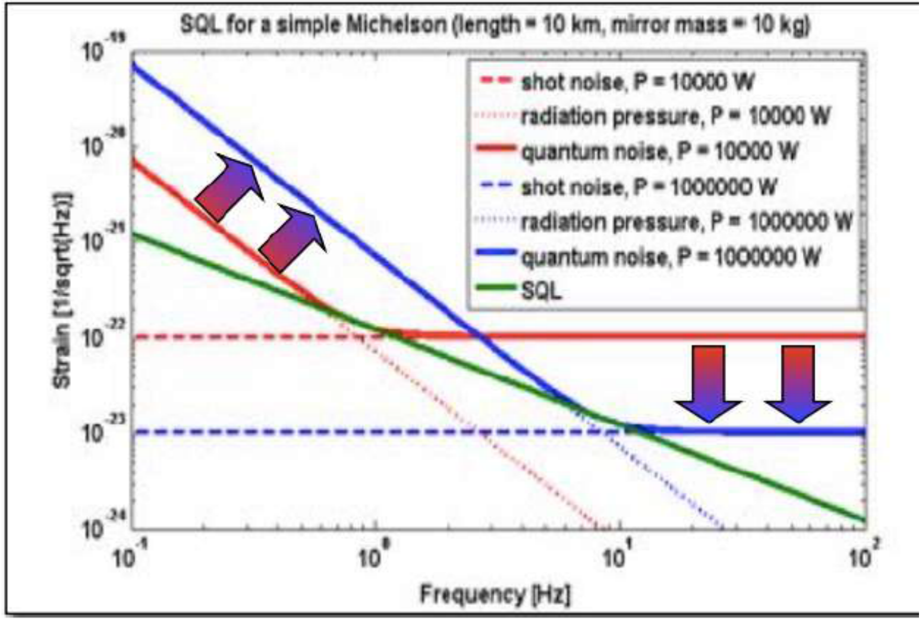
optical power

Arm length

Mirror mass

$$h_{\mathrm{rp}}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

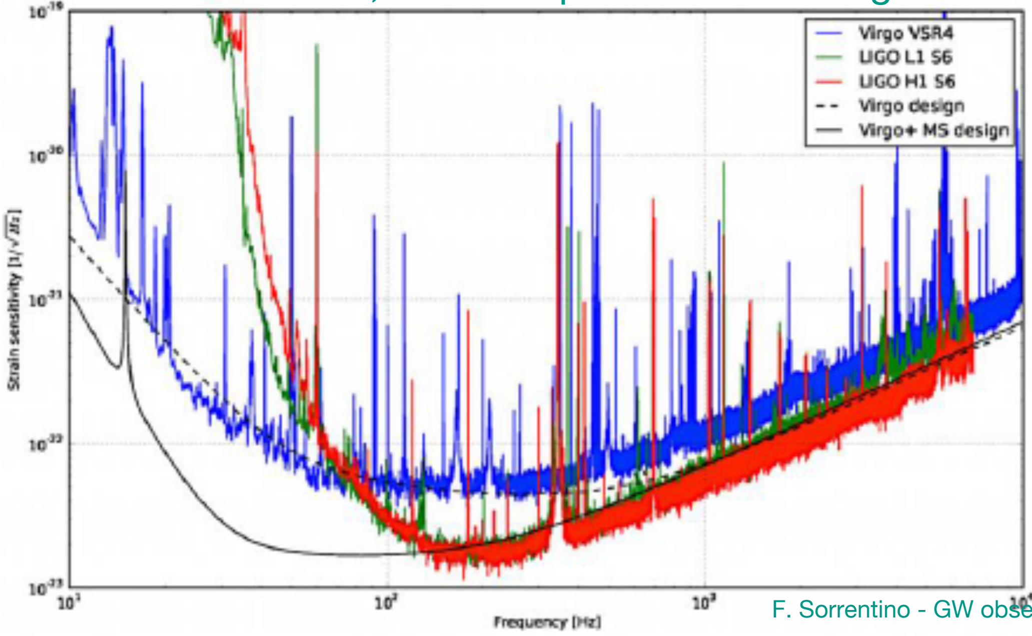
- The SQL is the minimal sum of shot noise and radiation pressure noise
- Using a classical quantum measurement the SQL is the lowest achievable noise

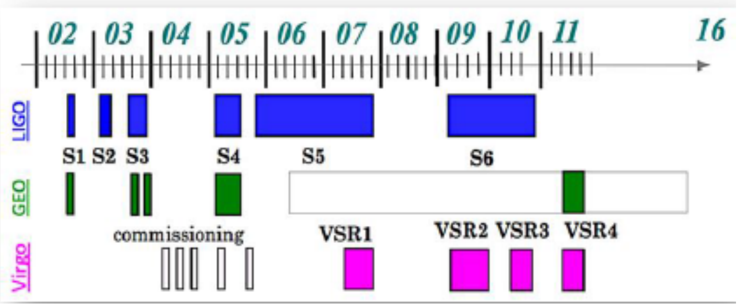


V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)

1st generation GW detectors

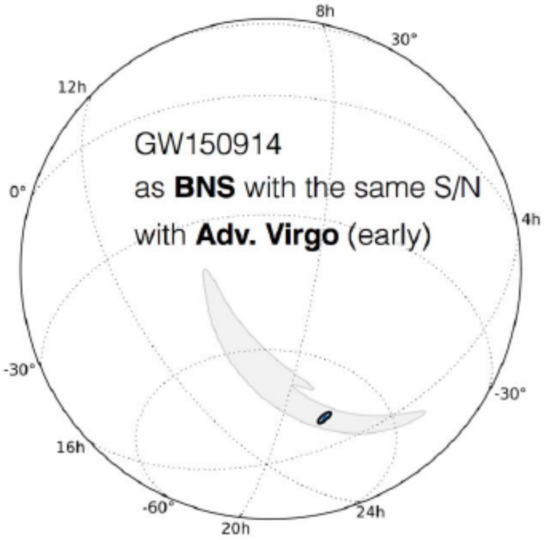
- LIGO, Virgo and GEO600 operated operated for about one decade, reaching design sensitivities
- Demonstrated a reliable technology
  - duty cycle up to 80%
  - good knowledge of limiting noise sources
- No detections, but clear path towards 2nd generation antennas





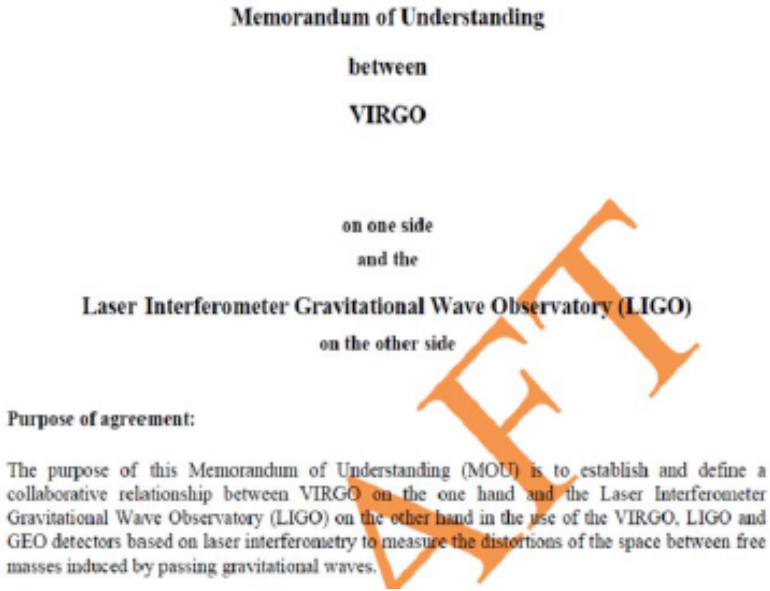
1° generation network of GW detectors

- GW antennas are poorly directional
- Source localization requires simultaneous distant detectors
- MoUs among LIGO, Virgo and GEO since 2007 for full exchange of data



GW150914
as **BNS** with the same S/N
with **Adv. Virgo** (early)

from L SINGER, G1601468



Memorandum of Understanding

between

VIRGO

on one side

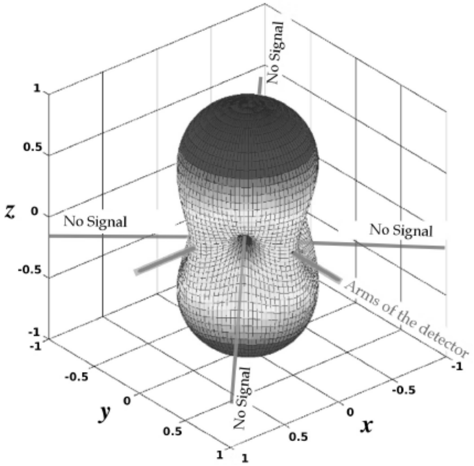
and the

Laser Interferometer Gravitational Wave Observatory (LIGO)

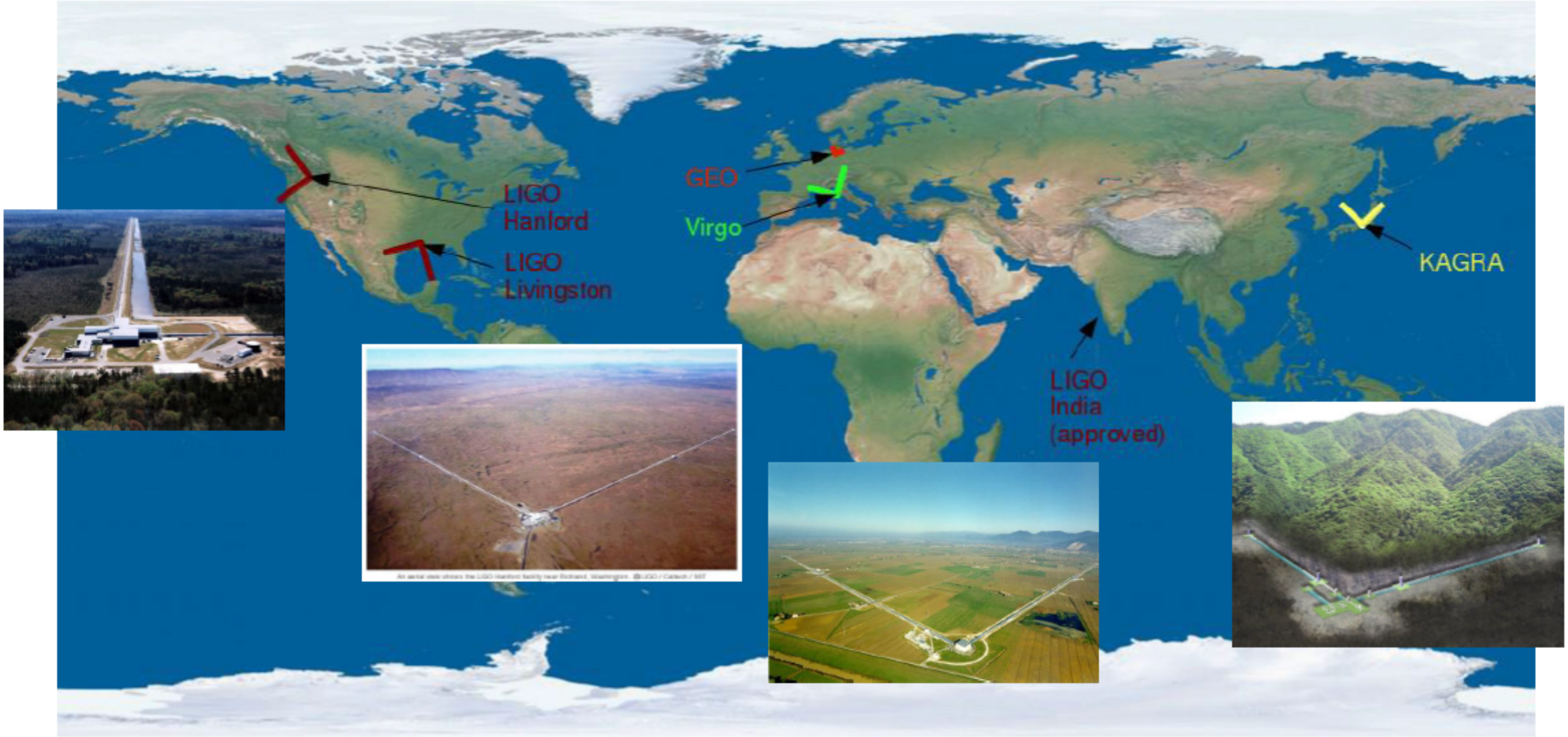
on the other side

Purpose of agreement:

The purpose of this Memorandum of Understanding (MOU) is to establish and define a collaborative relationship between VIRGO on the one hand and the Laser Interferometer Gravitational Wave Observatory (LIGO) on the other hand in the use of the VIRGO, LIGO and GEO detectors based on laser interferometry to measure the distortions of the space between free masses induced by passing gravitational waves.



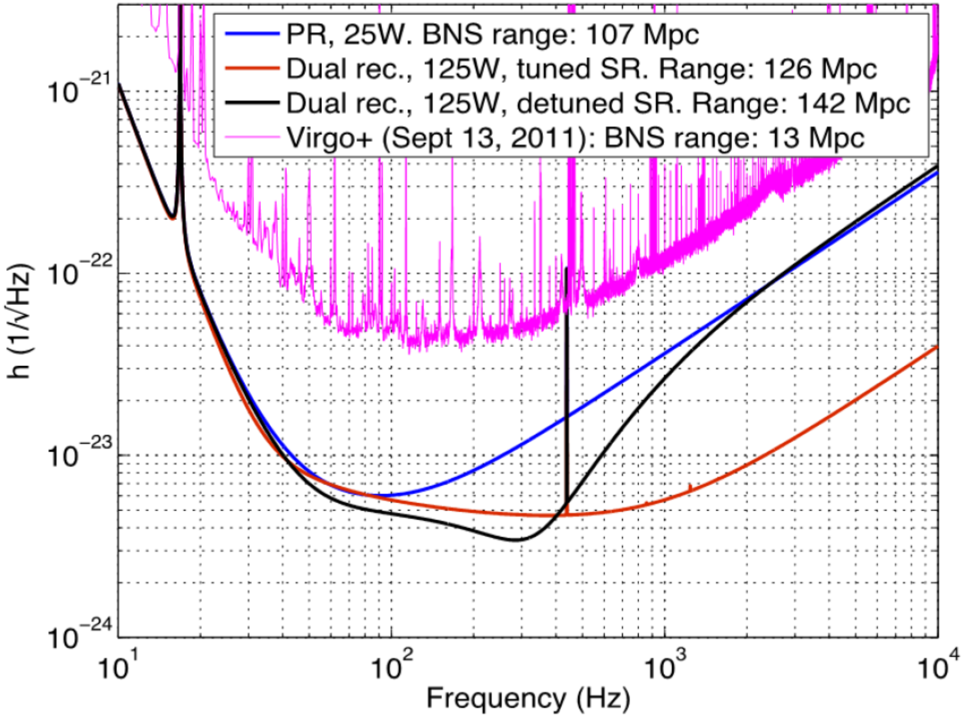
Network of GW detectors

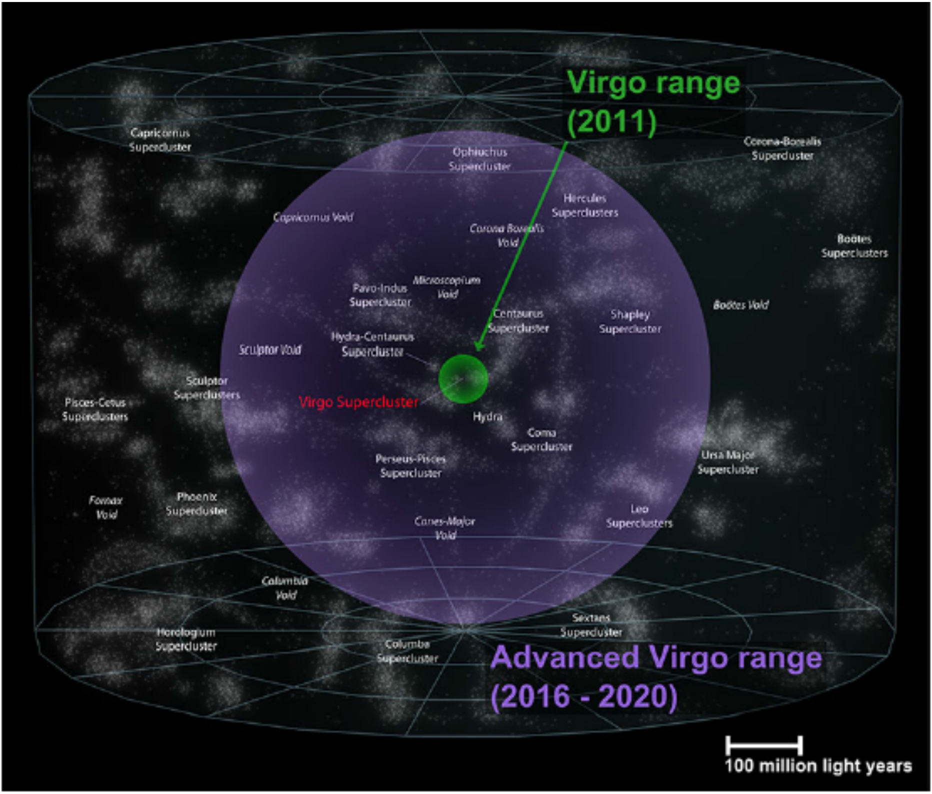


An aerial view shows the LIGO Hanford facility near Richland, Washington. ©LIGO / Caltech / MIT

Advanced detectors

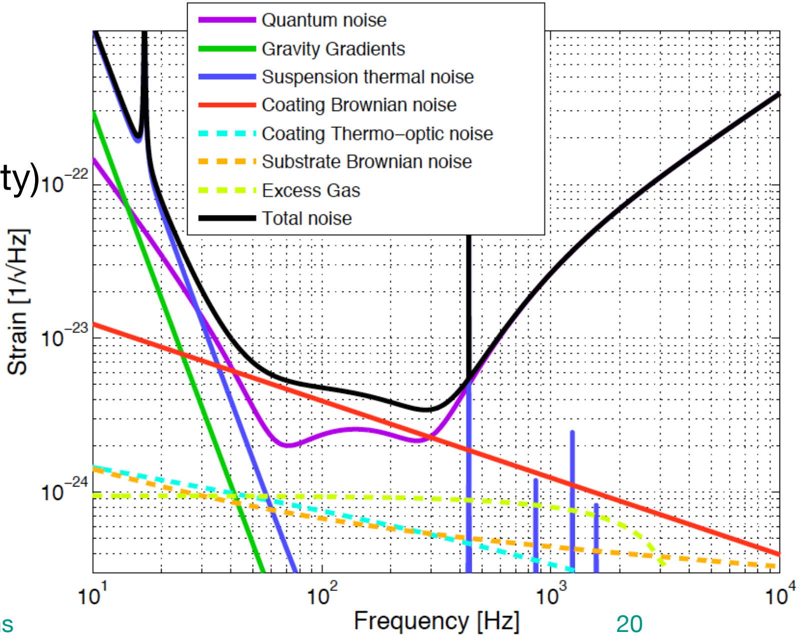
- 10 x sensitivity improvement over 1st generation detectors
- 1000 x increase of observation volume



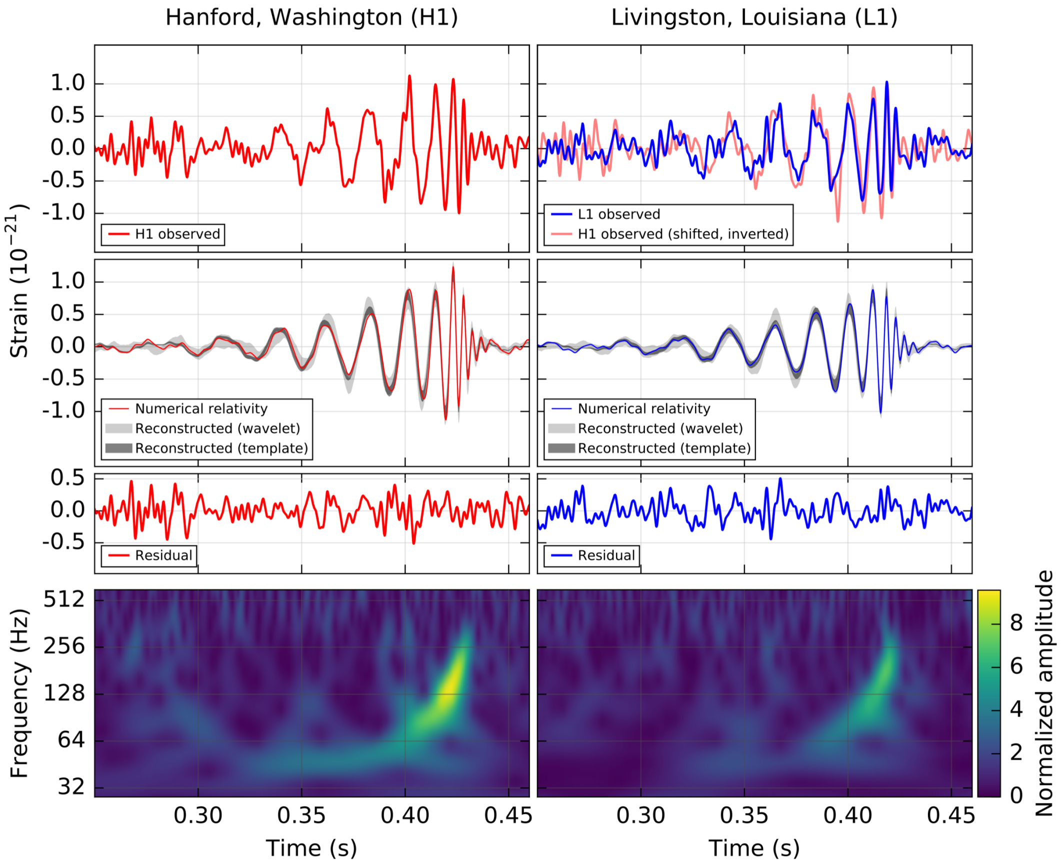


AdV challenges

- Reducing thermal noise:
  - increased beam size @ input TM (2.5 x higher)
  - improved mirrors’ planarity (16 x better)
  - Improved coatings for lower losses (7 x better)
- Reducing quantum noise:
  - Increased finesse of arm cavities (9 x higher than iVirgo, 3 x higher than Virgo+)
  - High power laser (16 x more input power)
  - Heavier test masses (2 x heavier)
- Seismic isolation:
  - iVirgo superattenuators compatible with AdV specs
  - adapted for new payload (added mass and complexity)
  - new electronics
- Thermal compensation (100 x higher power on TM)
  - ring heaters
  - double axicon CO$_2$ actuators
  - CO$_2$ central heating
- Better vacuum (10^{-9} instead of 10^{-7})
- Stray light control
  - Suspended optical benches in vacuum
  - New set of baffles



The first detection: GW150914



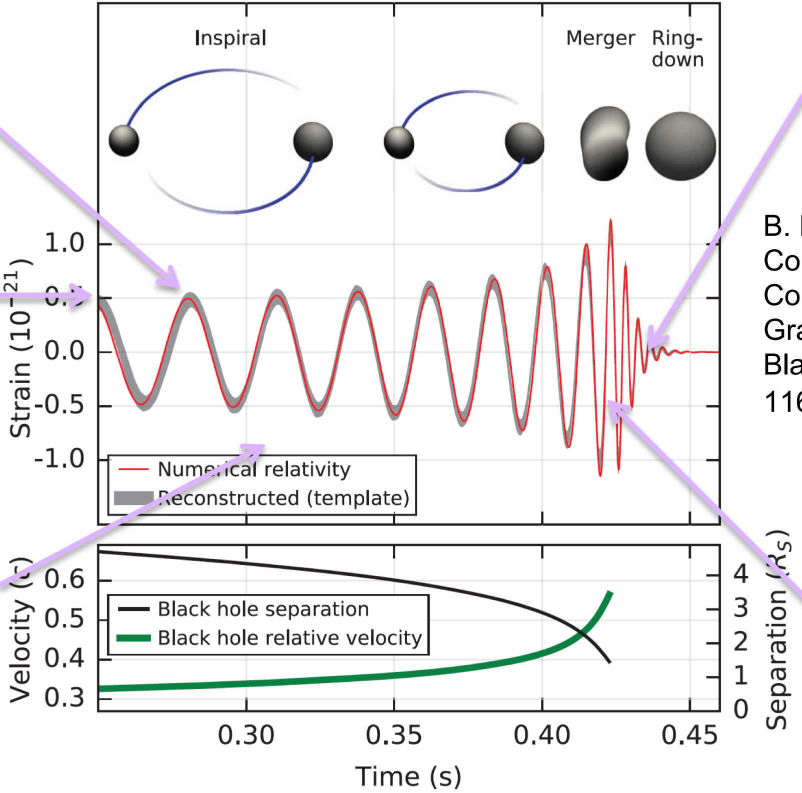
B. P. Abbott et al., Phys. Rev. Lett. 116, 061102

GW from a binary coalescence

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.

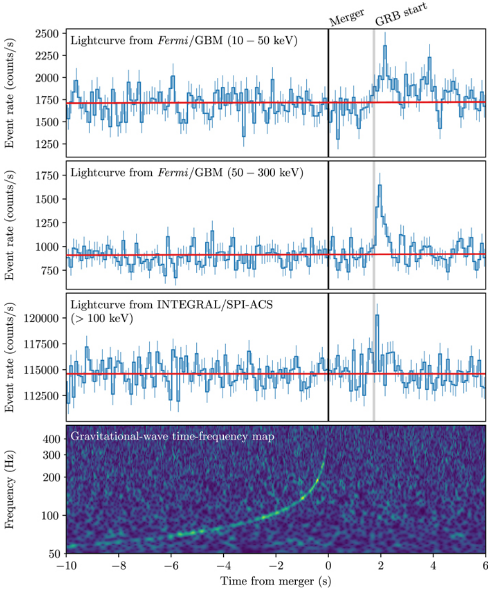
B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Observation of Gravitational Waves from a Binary Black Hole Merger, Phys. Rev. Lett. 116, 061102 (2016)

Highest frequency gives sizes of objects just before merger.

GW170817: birth of multimessenger astronomy

LIGO-Virgo network localization enables discovery of optical counterpart

- Spectra of heavy metals in kilonova emission
- Highlight on nucleosynthesys problem



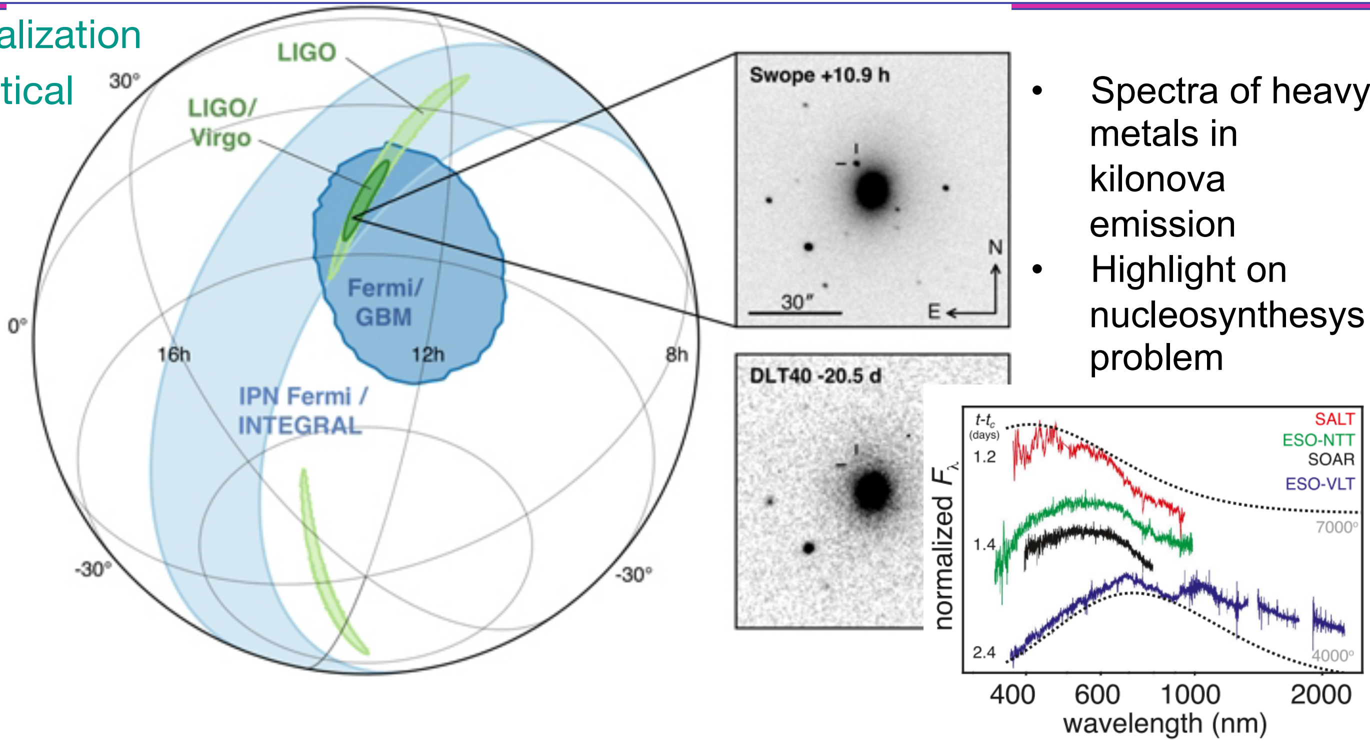
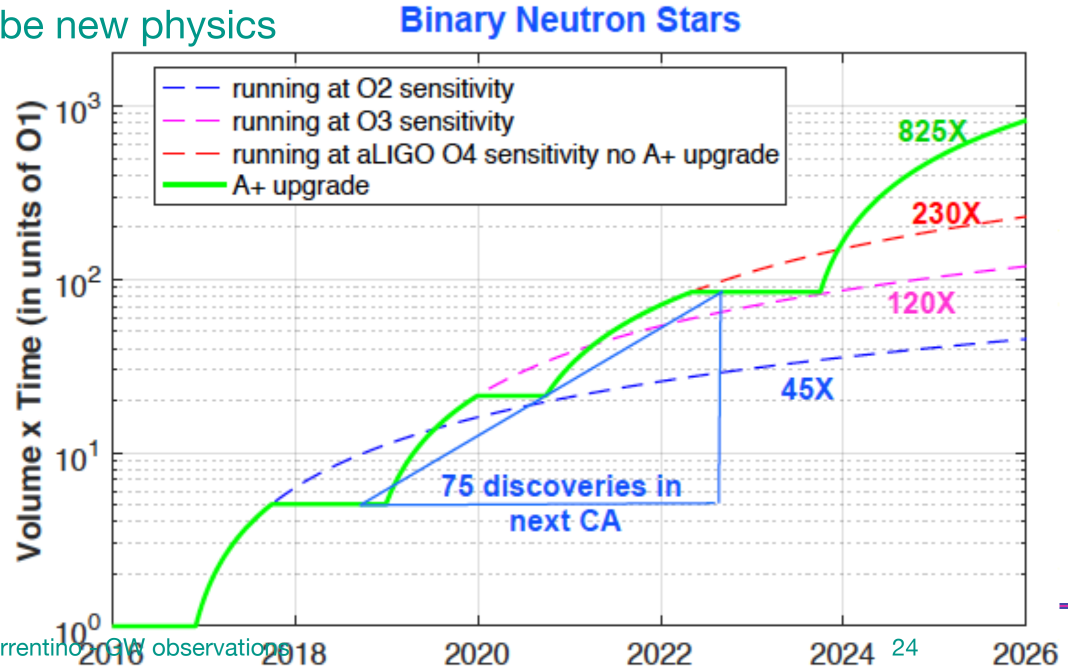


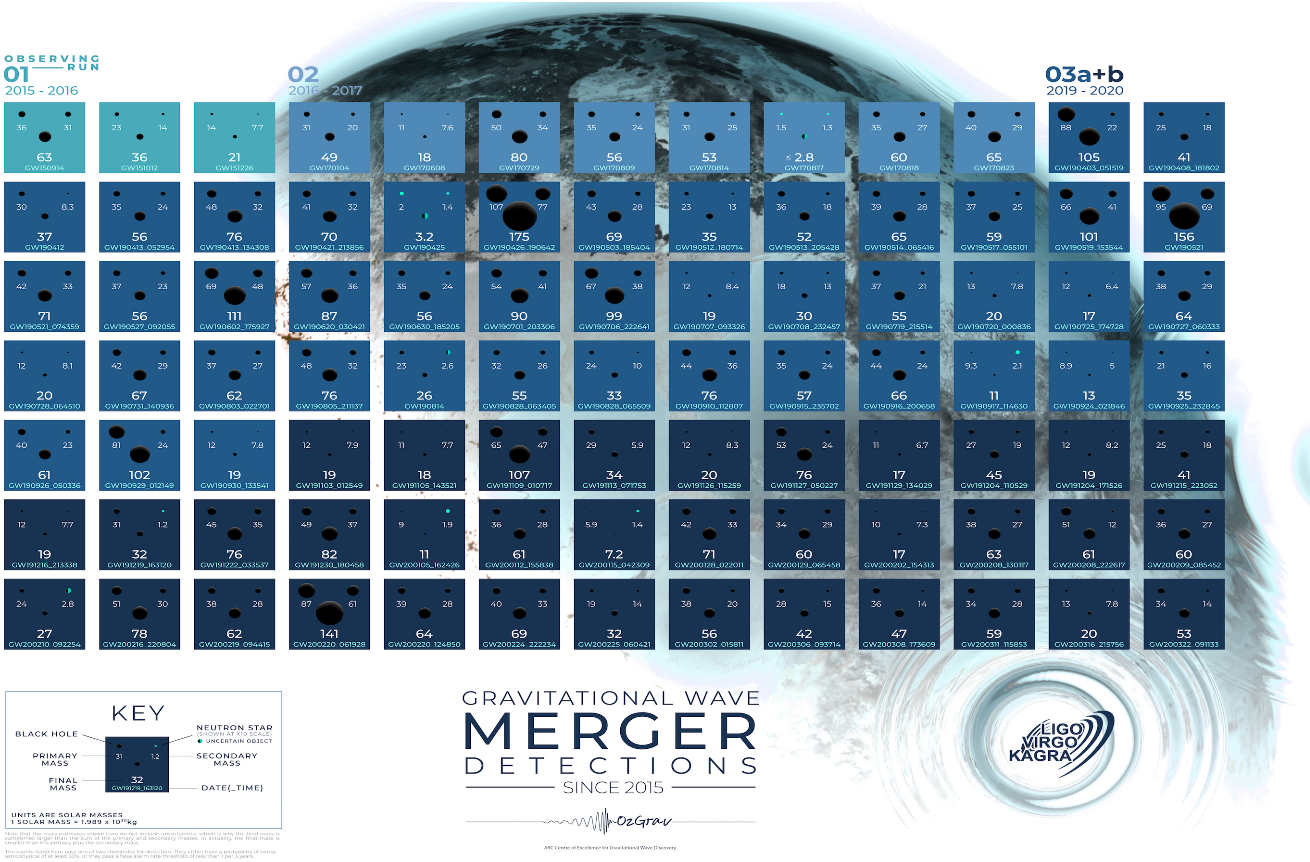
Figure 1 from *Multi-messenger Observations of a Binary Neutron Star Merger*
B. P. Abbott et al. 2017 ApJL 848 L12 doi:10.3847/2041-8213/aa91c9

Observing runs & detectors’ upgrades

- GW science is driven by detectors’ sensitivity
- Number of events ~ T*V
    - T= coincident observing time
    - V=volume probed ~ (Range)^3
- Most sources require high SNR to probe new physics
    - BH ringdown
    - Tidal effects in BNS mergers
    - Stochastic background
    - Galactic supernovae
    - Isolated NS
    - Theories beyond GW



GW catalog from O1 to O3



OBSERVING RUN

O1
2015 - 2016

DATE(_TIME)	PRIMARY MASS	SECONDARY MASS	FINAL MASS
GW150914	36	31	63
GW151012	23	14	36
GW151226	14	7.7	21

O2
2016 - 2017

DATE(_TIME)	PRIMARY MASS	SECONDARY MASS	FINAL MASS
GW170104	31	20	49
GW170608	11	7.6	18
GW170729	50	34	80
GW170809	35	24	56
GW170814	31	25	53
GW170817	1.5	1.3	≤ 2.8
GW170818	35	27	60
GW170823	40	29	65

O3a+b
2019 - 2020

DATE(_TIME)	PRIMARY MASS	SECONDARY MASS	FINAL MASS
GW190403_051519	88	22	105
GW190408_181802	25	18	41
GW190412	30	8.3	37
GW190413_052954	35	24	56
GW190413_134308	48	32	76
GW190421_213856	41	32	70
GW190425	2	1.4	3.2
GW190426_190642	107	77	175
GW190503_185404	43	28	69
GW190512_180714	23	13	35
GW190513_205428	36	18	52
GW190514_065416	39	28	65
GW190517_055101	37	25	59
GW190519_153544	66	41	101
GW190521	95	69	156
GW190521_074359	42	33	71
GW190527_092055	37	23	56
GW190602_175927	69	48	111
GW190620_030421	57	36	87
GW190630_185205	35	24	56
GW190701_203306	54	41	90
GW190706_222641	67	38	99
GW190707_093326	12	8.4	19
GW190708_232457	18	13	30
GW190719_215514	37	21	55
GW190720_000836	13	7.8	20
GW190725_174728	12	6.4	17
GW190727_060333	38	29	64
GW190728_064510	12	8.1	20
GW190731_140936	42	29	67
GW190803_022701	37	27	62
GW190805_211137	48	32	76
GW190814	23	2.6	26
GW190828_063405	32	26	55
GW190828_065509	24	10	33
GW190910_112807	44	36	76
GW190915_235702	35	24	57
GW190916_200658	44	24	66
GW190917_114630	9.3	2.1	11
GW190924_021846	8.9	5	13
GW190925_232845	21	16	35
GW190926_050336	40	23	61
GW190929_012149	81	24	102
GW190930_133541	12	7.8	19
GW191103_012549	12	7.9	19
GW191105_143521	11	7.7	18
GW191109_010717	65	47	107
GW191113_071753	29	5.9	34
GW191126_115259	12	8.3	20
GW191127_050227	53	24	76
GW191129_134029	11	6.7	17
GW191204_110529	27	19	45
GW191204_171526	12	8.2	19
GW191215_223052	25	18	41
GW191216_213338	12	7.7	19
GW191219_163120	31	1.2	32
GW191222_033537	45	35	76
GW191230_180458	49	37	82
GW200105_162426	9	1.9	11
GW200112_155838	36	28	61
GW200115_042309	5.9	1.4	7.2
GW200128_022011	42	33	71
GW200129_065458	34	29	60
GW200202_154313	10	7.3	17
GW200208_130117	38	27	63
GW200208_222617	51	12	61
GW200209_085452	36	27	60
GW200210_092254	24	2.8	27
GW200216_220804	51	30	78
GW200219_094415	38	28	62
GW200220_061928	87	61	141
GW200220_124850	39	28	64
GW200224_222234	40	33	69
GW200225_060421	19	14	32
GW200302_015811	38	20	56
GW200306_093714	28	15	42
GW200308_173609	36	14	47
GW200311_115853	34	28	59
GW200316_215756	13	7.8	20
GW200322_091133	34	14	53

KEY

BLACK HOLE

NEUTRON STAR
(SHOWN AT X10 SCALE)

◐ UNCERTAIN OBJECT

PRIMARY MASS — 31

SECONDARY MASS — 1.2

FINAL MASS — 32

DATE(_TIME) — GW191219_163120

UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

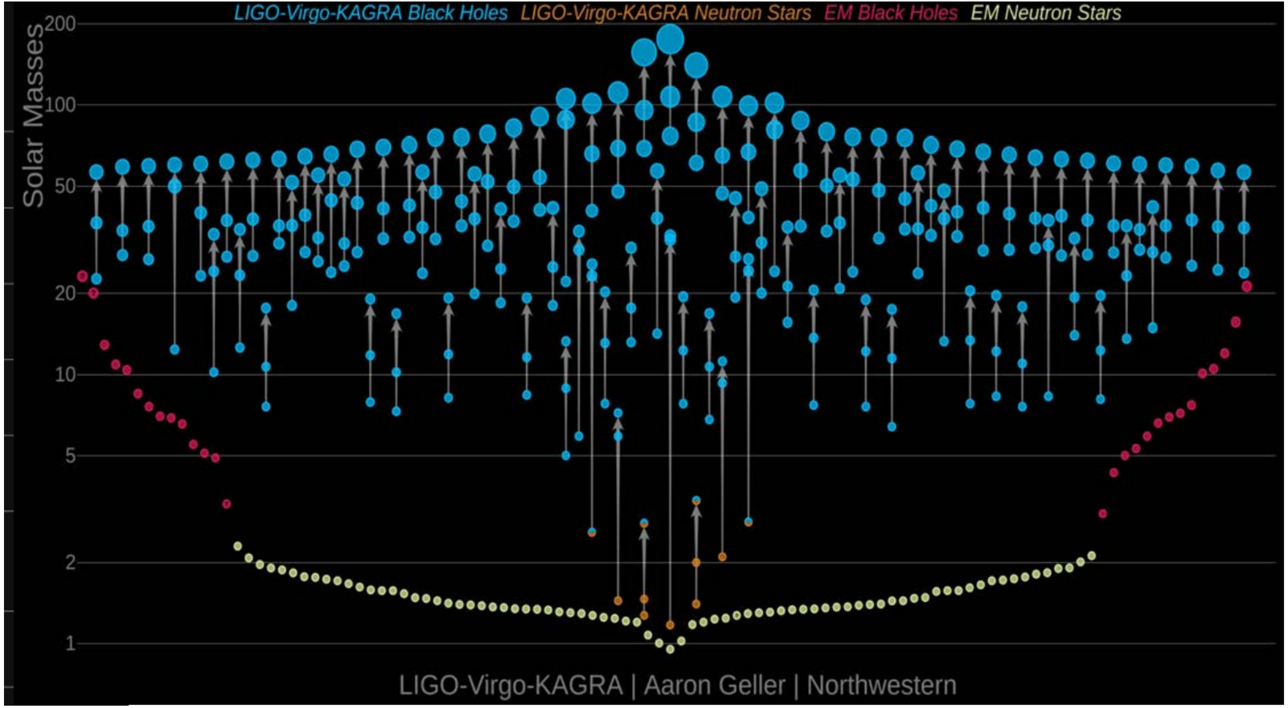
Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015

OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

GW catalog from O1 to O3

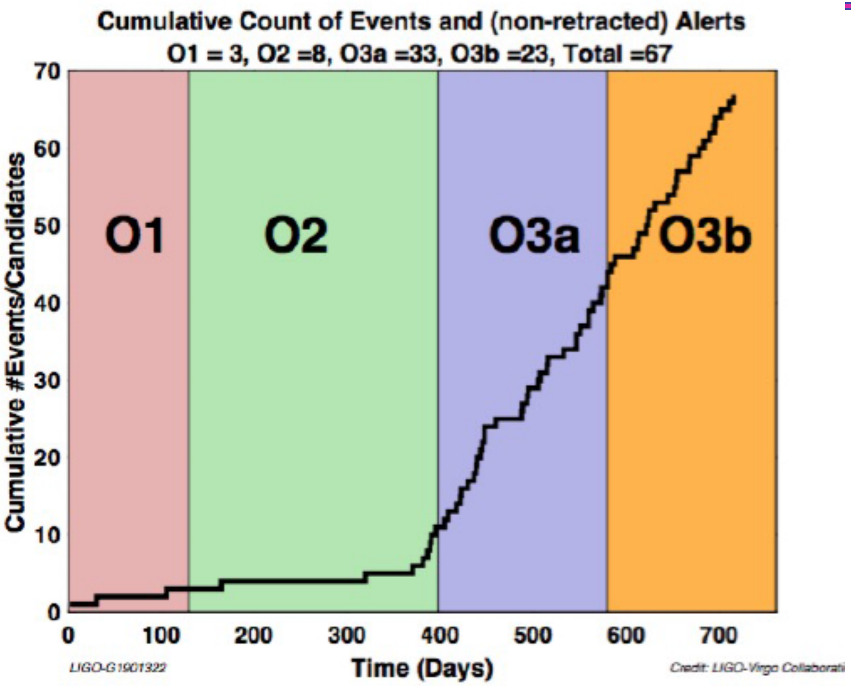


https://www.ligo.org/detections/O3bcatalog/files/gwmerger-poster-white-md.jpg

Highlights from O3

O3 ended on March 2020

- more than 1 GW event/week observed
- Mostly BH-BH coalescences
- Several exceptional events
  - **NS-BH coalescences**
  - **GW191219_163120** : extremely unequal mass components: 31 M⊙ + 1.2 M⊙, and the lightest NS ever observed
  - **GW200115_042309**: the brightest BH-NS coalescence detected up to now 6 M⊙ + 1.4 M⊙
  - **BH-BH coalescences with IMBH**
  - **GW190521_030229**: 85 M⊙ + 66 M⊙ -> 142 M⊙
  - **GW200220_061928**: 87 M⊙ + 61 M⊙ -> 148 M⊙
  - Coalescing BHs in the “pair instability mass gap” ~ 65 -- 120 M⊙



Cumulative Count of Events and (non-retracted) Alerts
O1 = 3, O2 =8, O3a =33, O3b =23, Total =67

- **GW191109_010717:** 65 M⊙ + 47 M⊙ -> 107 M⊙
Negative effective spin of the binary system: spins of the two BHs opposite to the orbital angular momentum

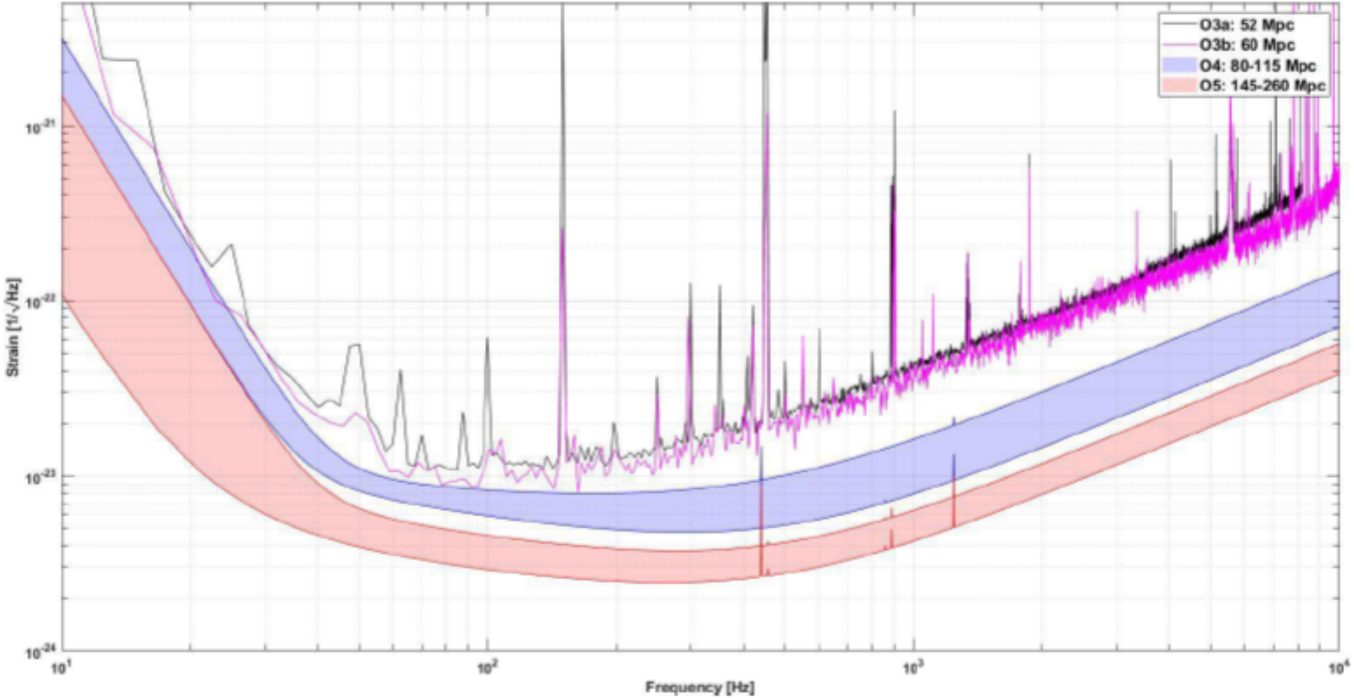
Upgrades for O4 & O5: AdV+

Phase I: reduce quantum noise, hit against coating thermal noise

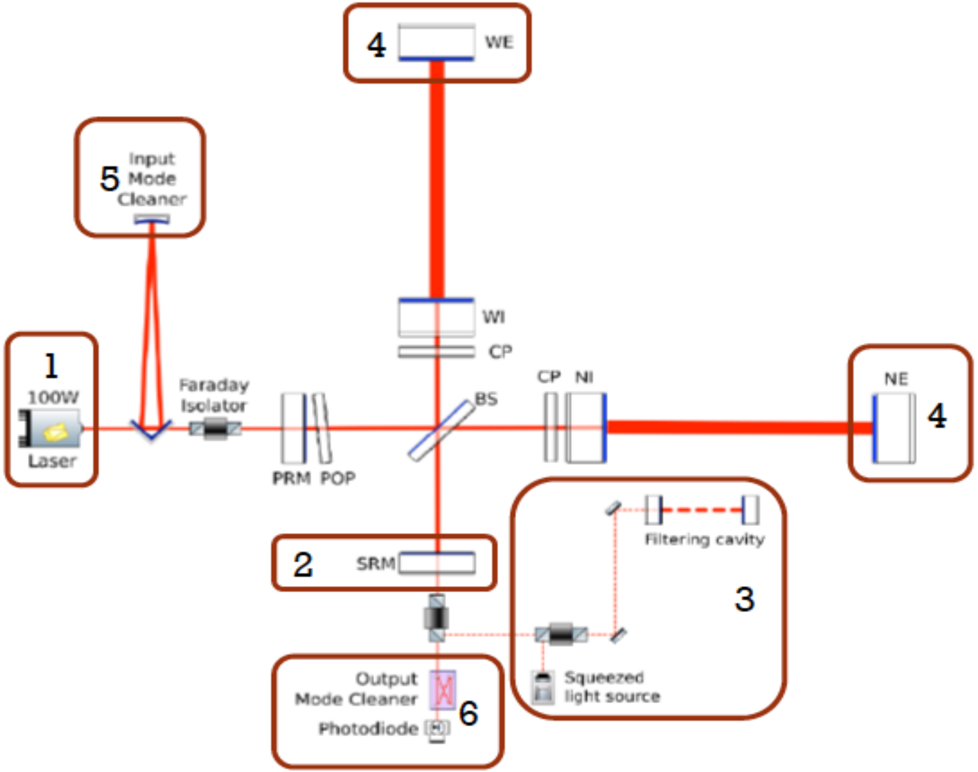
- BNS range ~ 100 Mpc

Phase II: lower thermal noise wall

- BNS range ~ 200 Mpc

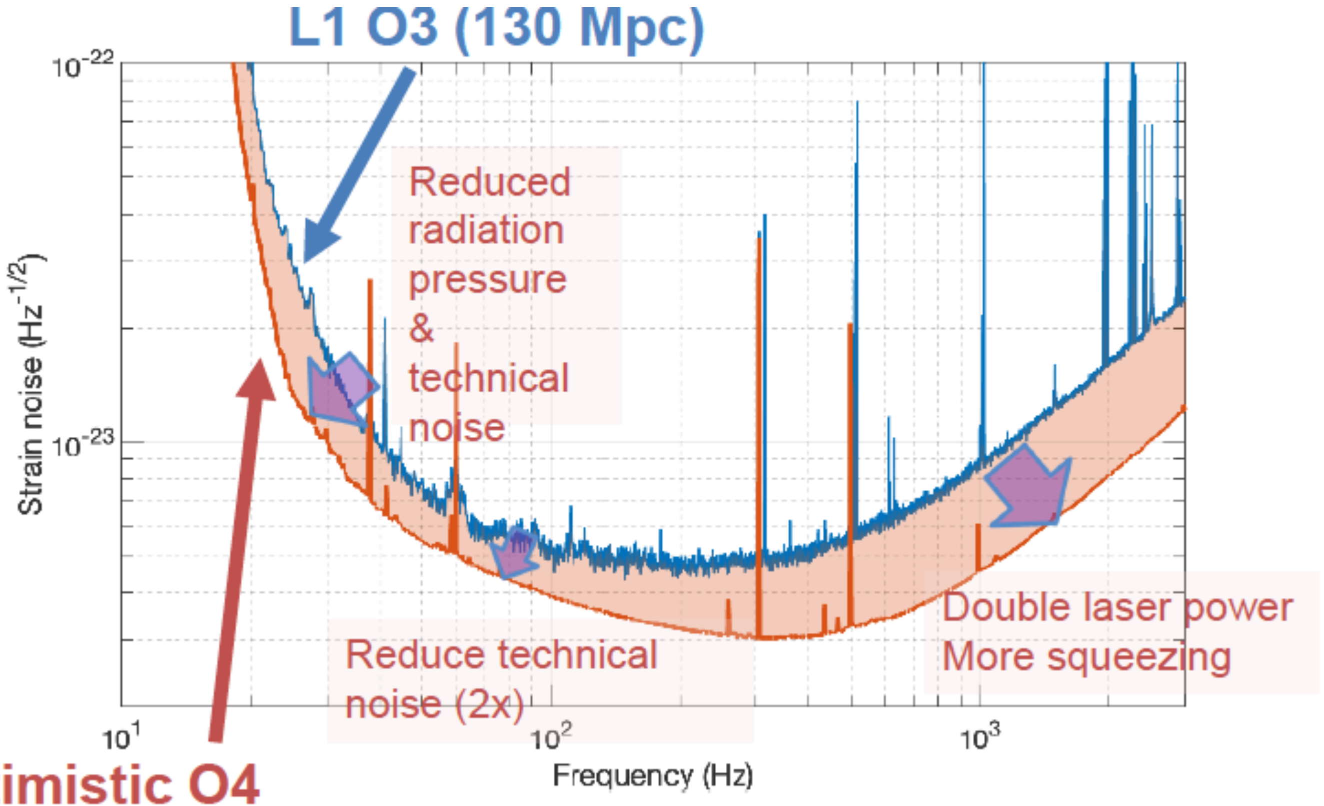


Upgrades for O4 & O5: AdV+



1. High-power fiber laser amplifier
2. Signal recycling mirror
3. Frequency dependent squeezing
4. Green light auxiliary laser system
5. New Input mode Cleaner payload with an instrumented baffle
6. New high finesse output mode cleaner and new read-out photodiodes.
7. HVAC upgrades and reduction of environmental noise.
8. Deployment of accelerometer arrays for Newtonian Noise characterization

Upgrades for O4 & O5: ALIGO+



L1 O3 (130 Mpc)

Reduced radiation pressure & technical noise

Reduce technical noise (2x)

Double laser power
More squeezing

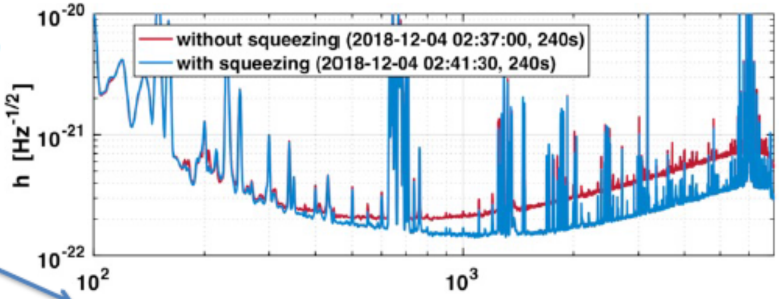
Optimistic O4 projection (190 Mpc)

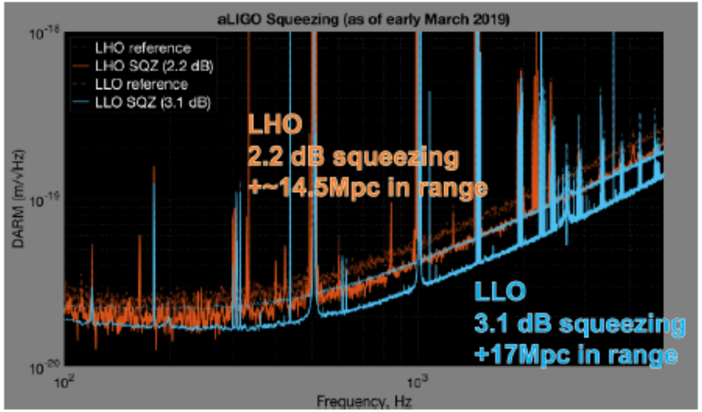
Credit: P. Fritschel, G2300213

Quantum noise – frequency independent squzeeing

Performances during O3

- GEO600: 6 dB
- A-LIGO: 3.1 dB
- AdV: 3.2 dB




aLIGO Squeezing (as of early March 2019)

LHO
2.2 dB squeezing
+~14.5Mpc in range

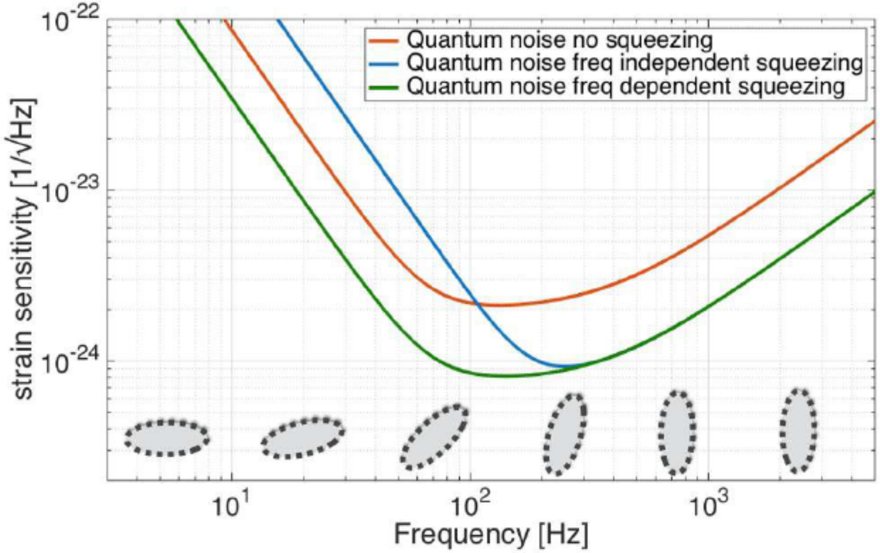
LLO
3.1 dB squeezing
+17Mpc in range

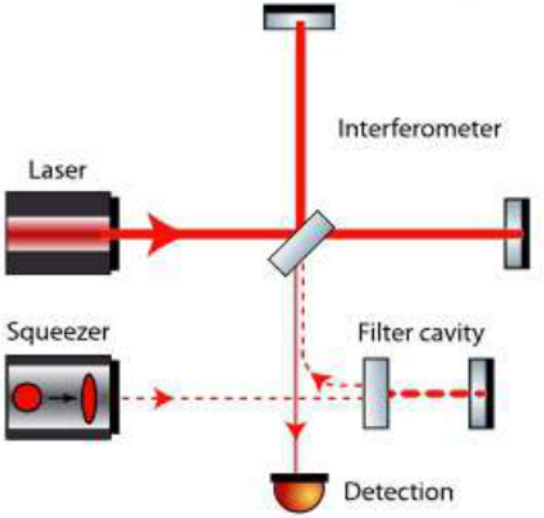
Frequency dependent squeezing

The driving idea
To simultaneously reduce shot noise at high frequencies and quantum radiation pressure noise at low frequencies requires a quantum noise filter cavity with low optical losses to rotate the squeezed quadrature as a function of frequency.

Adopted Method

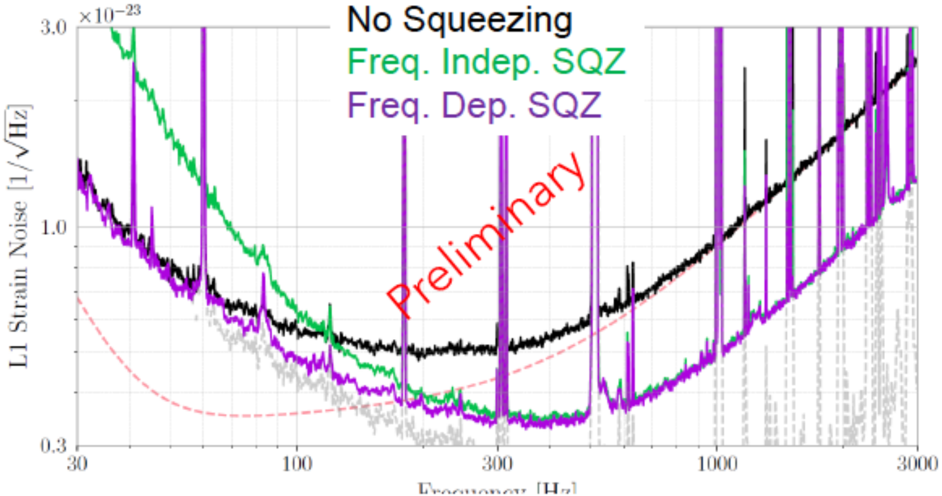
- Reflect frequency independent squeezing off a detuned Fabry-Perot cavity
- Rotation frequency depends on the cavity line-width





Frequency dependent squeezing - status

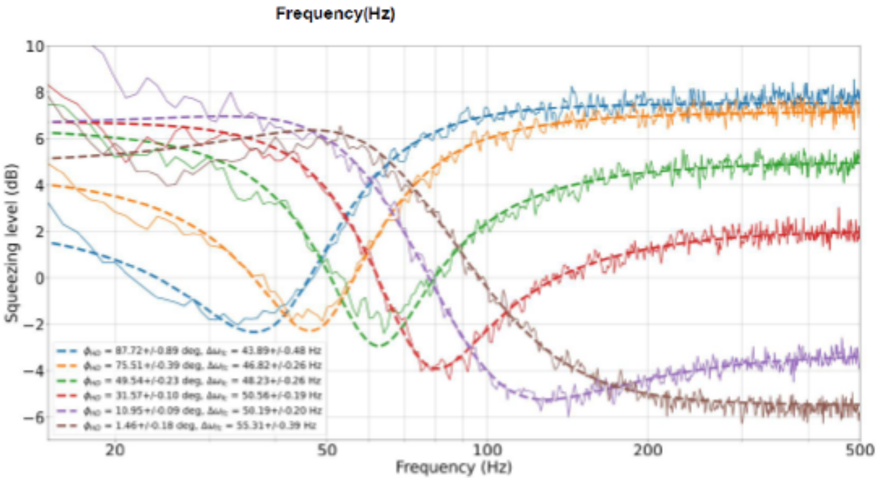
LIGO: FDS injected, 6dB reached(LLO)



In preparation

Broadband quantum enhancement of the LIGO detectors with frequency-dependent squeezing

Virgo: FDS demonstrated in stand alone

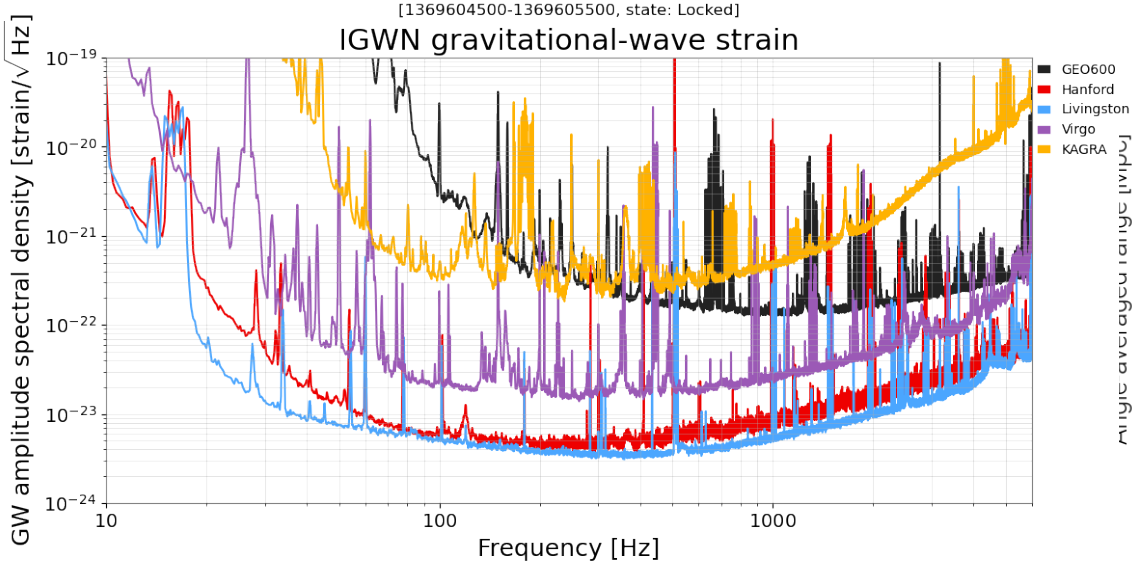


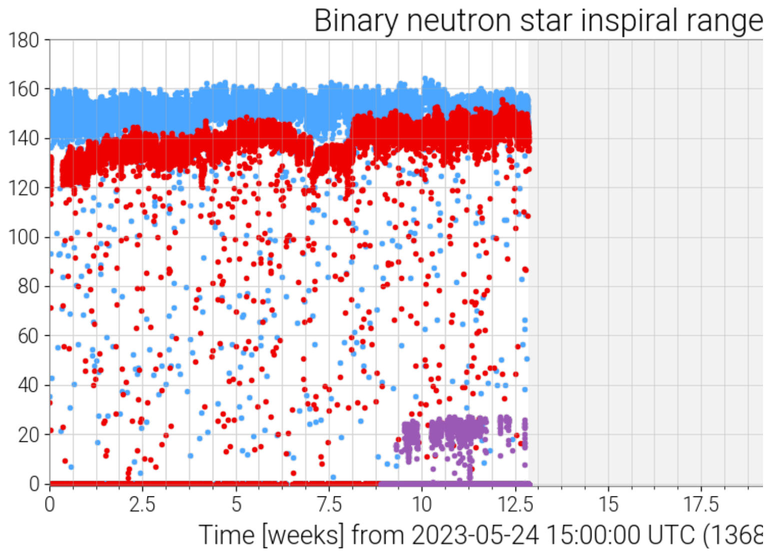
Frequency dependent squeezed vacuum source for the Advanced Virgo gravitational wave detector

F. Acernese *et al.* (the Virgo Collaboration),
H.Vahlbruch, M. Mehmet, H. Lück, and K. Danzmann
Institut für Gravitationsphysik, Leibniz Universität Hannover and Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Callinstr. 38, 30167 Hannover, Germany
(Dated: March 2, 2023)

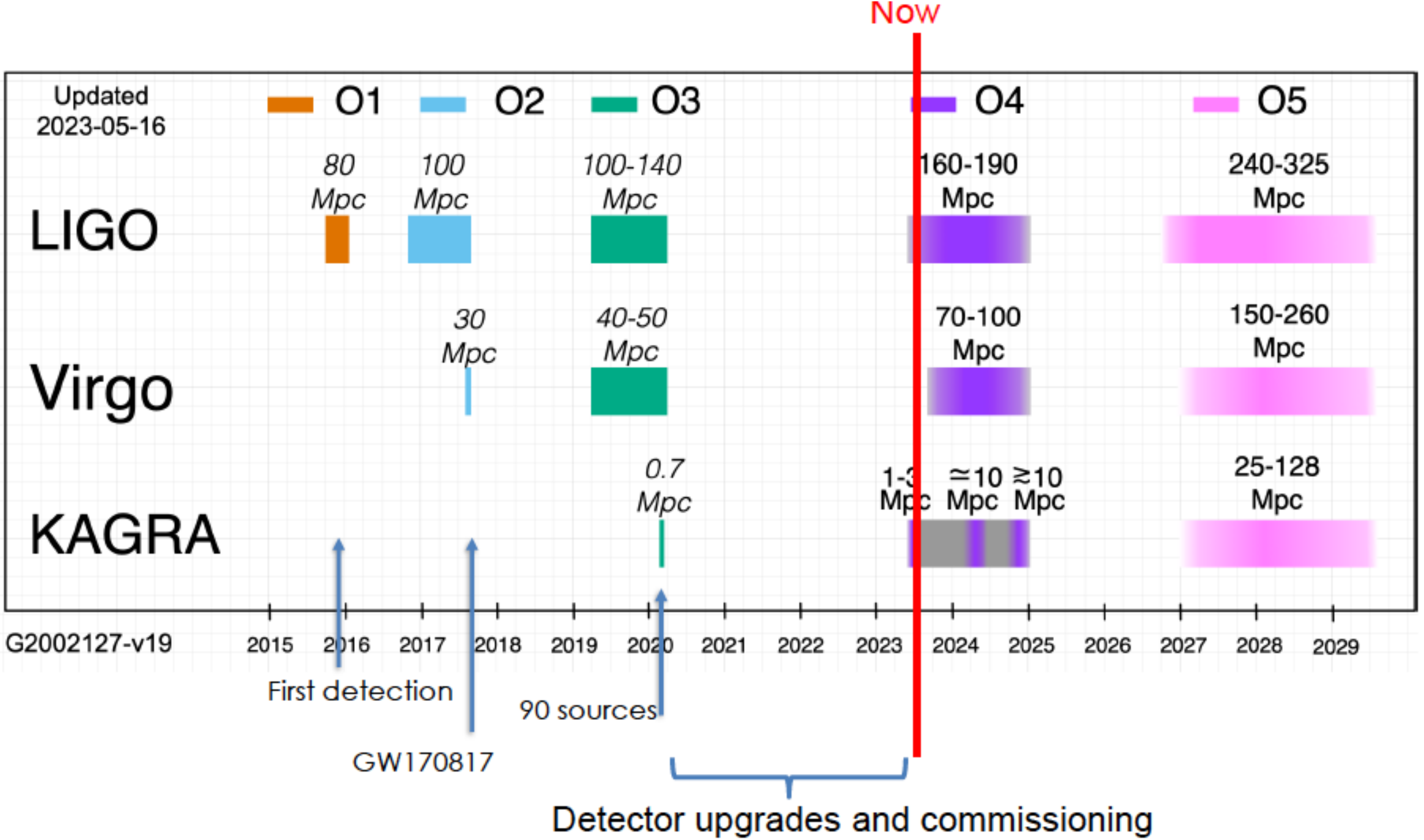
O4: current status

- O4 started on May 24, 2023
  - Currently data taking from LIGO detectors
  - Virgo & Kagra to join a few months later to complete commissioning





Observing scenario for terrestrial GW detectors



Now

First detection

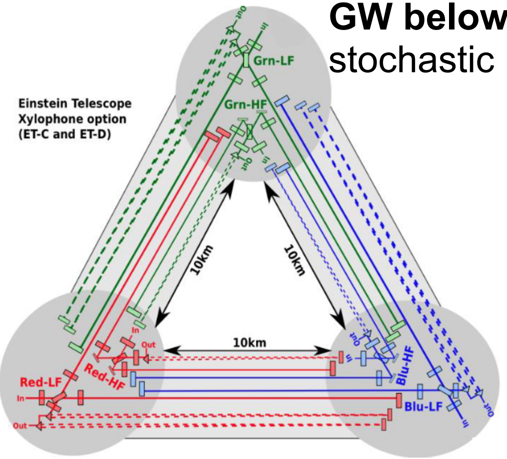
GW170817

90 sources

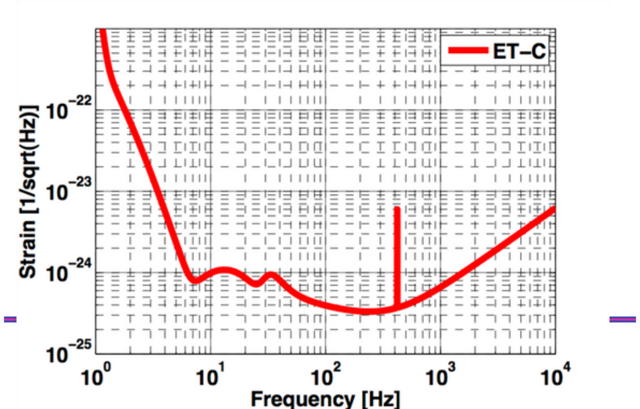
Detector upgrades and commissioning

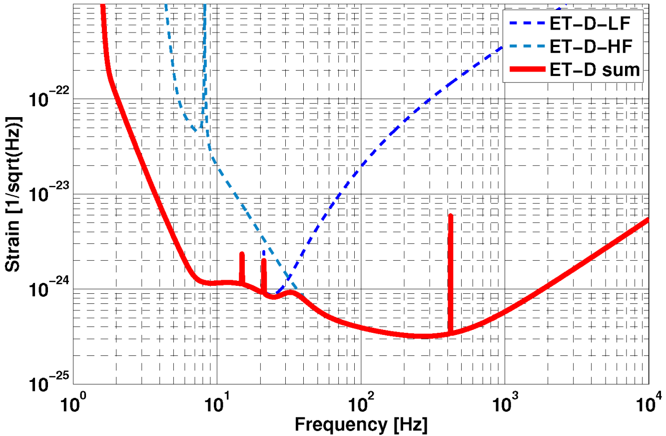
The future: 3rd generation terrestrial detectors

- **Einstein Telescope (ET: EU) & Cosmics Explorere (CE: USA)**
  - **10 times more sensitive** than second-generation detectors;
- ET features
  - Three detector with shared arms;
  - Located underground ⟶ reduce seismic and Newtonian noise;
  - 10 km long arms, in an equilateral triangle configuration: resolve GW polarization and make self localization;
  - **Xylophone configuration**: three nested detectors, each composed of two interferometers, one optimized for operation below 30Hz and one optimized for operation at higher frequencies;

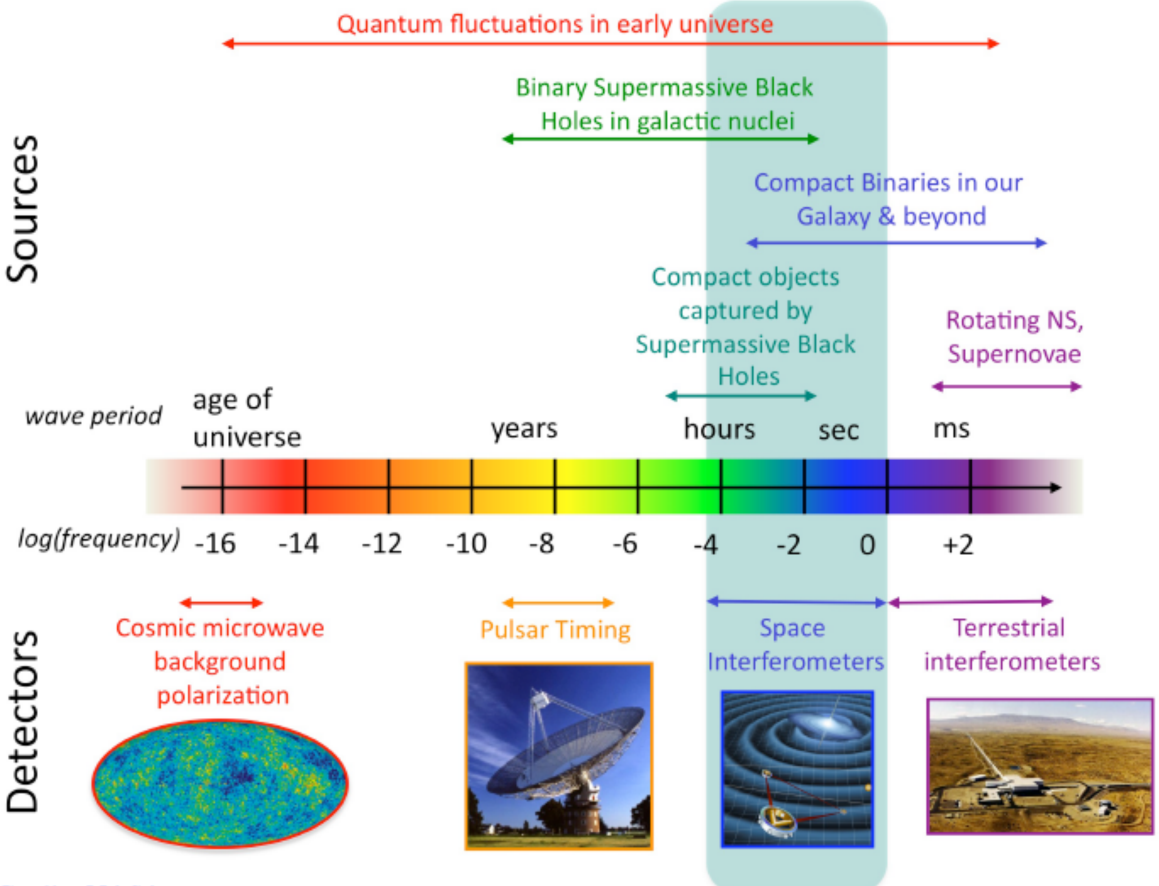


GW below 30 Hz: higher mass mergers, tidal effects on NSs, BHs close encounters, stochastic background.





The future: space detectors



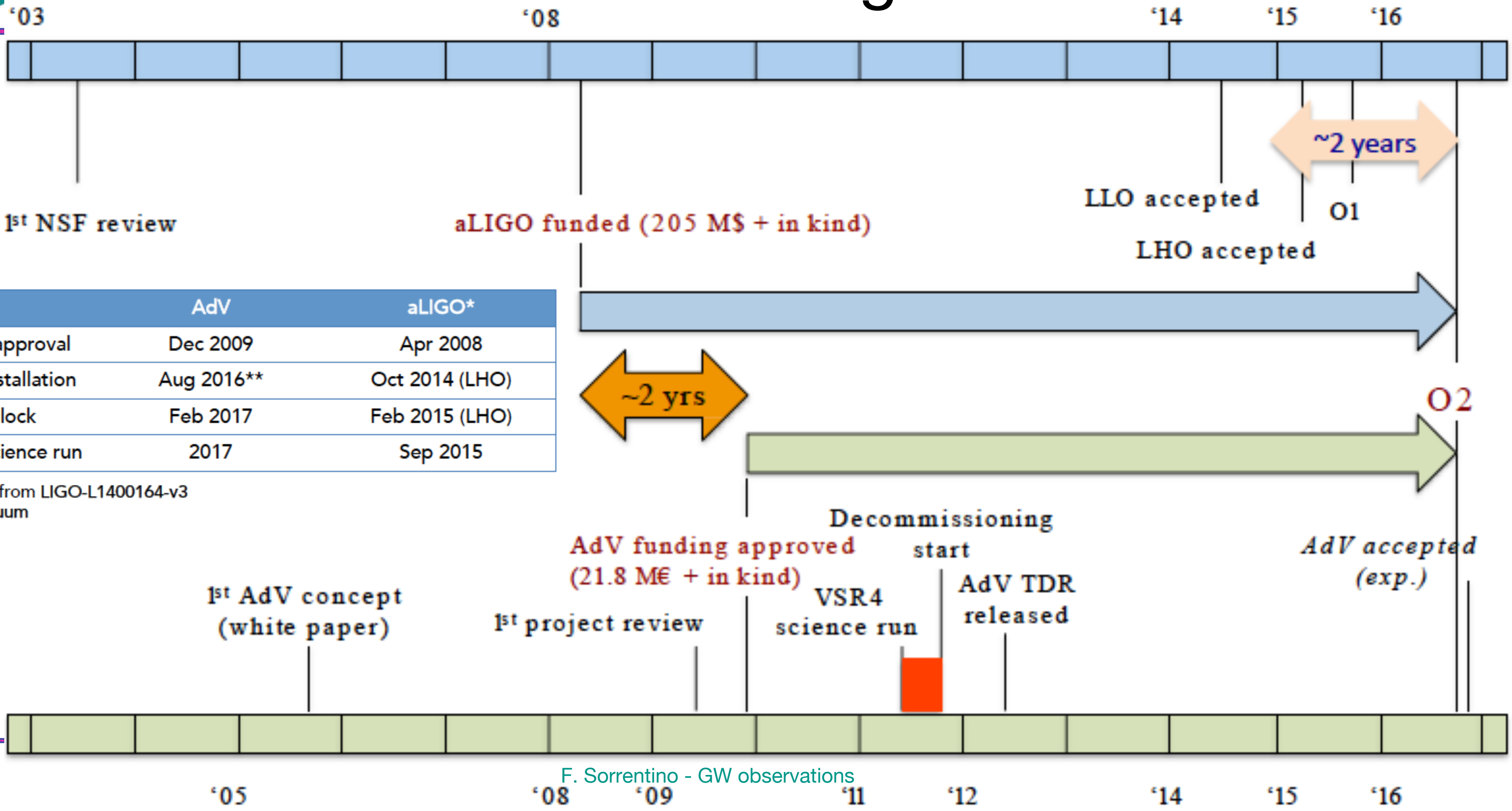
Credit: NASA

Conclusions

- Exciting physics now accessible with GW observation
- Well established network of 2nd generation terrestrial GW detectors
- About 10^2 GW events from binary coalescences detected during the first 3 observing runs
  - Large science yield including GR tests, NS & BH physics, quantum gravity, etc.
- O4 recently started (LIGO alone, Virgo to join in a few months)
  - Rate of detections largely improved (from 1/week to 1/day)
- Prospect to further improve current network
- Currently studying 3rd generation detectors to further improve sensitivity by ~10

Spare slides

Evolution of LIGO & Virgo detectors

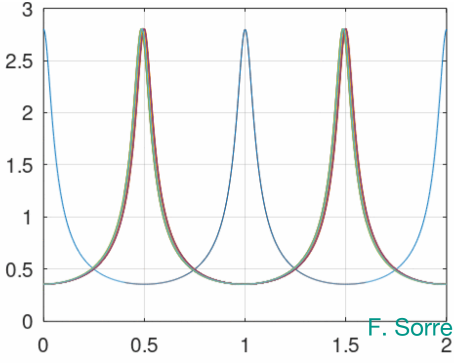


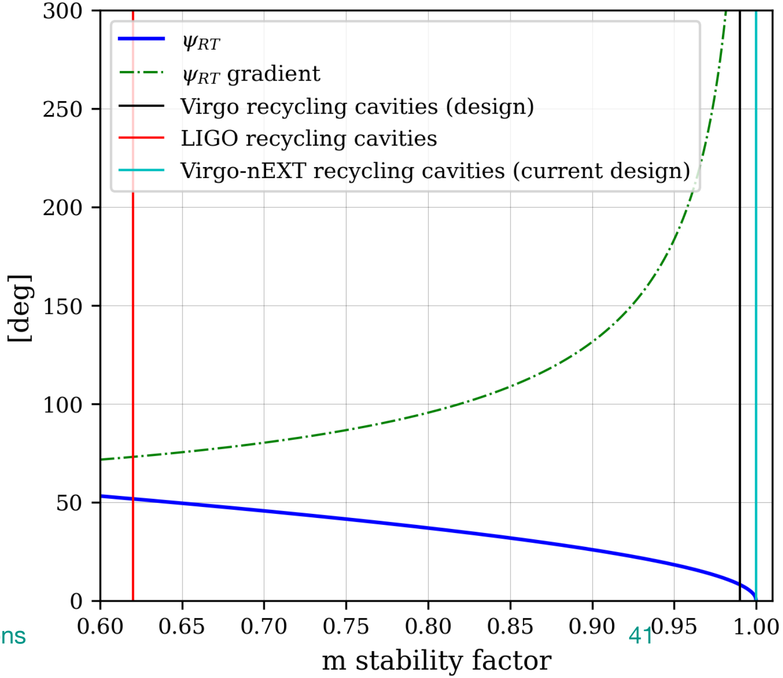
	AdV	aLIGO*
Date of approval	Dec 2009	Apr 2008
End of installation	Aug 2016**	Oct 2014 (LHO)
First lock	Feb 2017	Feb 2015 (LHO)
Start of science run	2017	Sep 2015

*LIGO data from LIGO-L1400164-v3
**ITF in vacuum

The challenge of degenerate recycling cavities

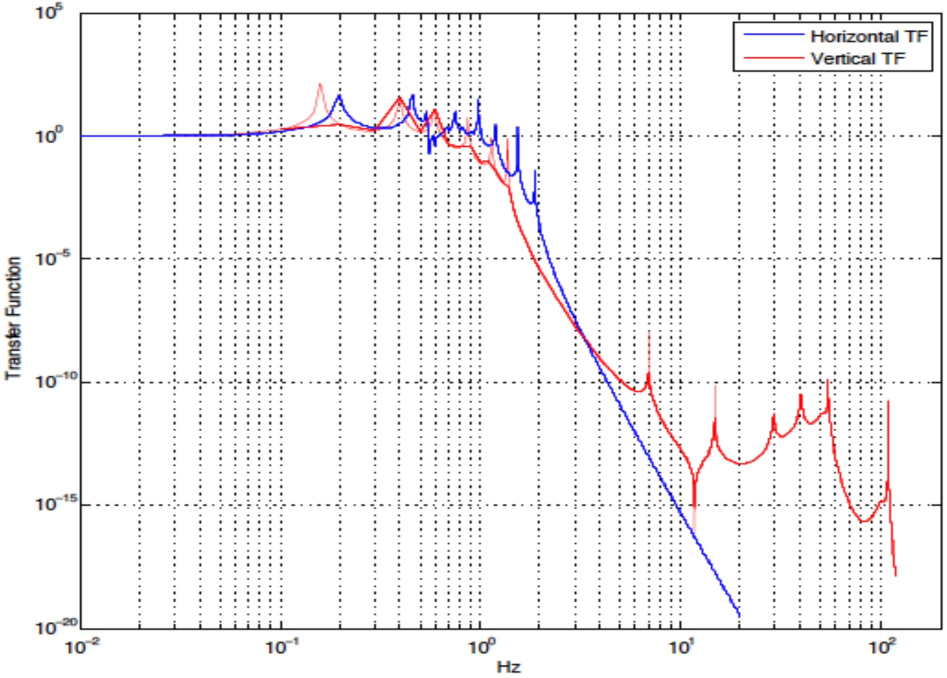
- In AdV design the optical cavities for power & signal recycling are close to the instability region
    - makes mode matching and alignment extremely critical
    - difficult to measure cavity mismatch, as most HOMs resonate simultaneously
    - large SQZ losses expected due to mismatch in central interferometer
- Signal recycling in LIGO
    - Increase detector bandwidth (double cavity pole)
    - Filter out high-order optical modes
- Signal recycling in Virgo
    - Increase detector bandwidth
    - Amplify (recycle) high-order optical modes

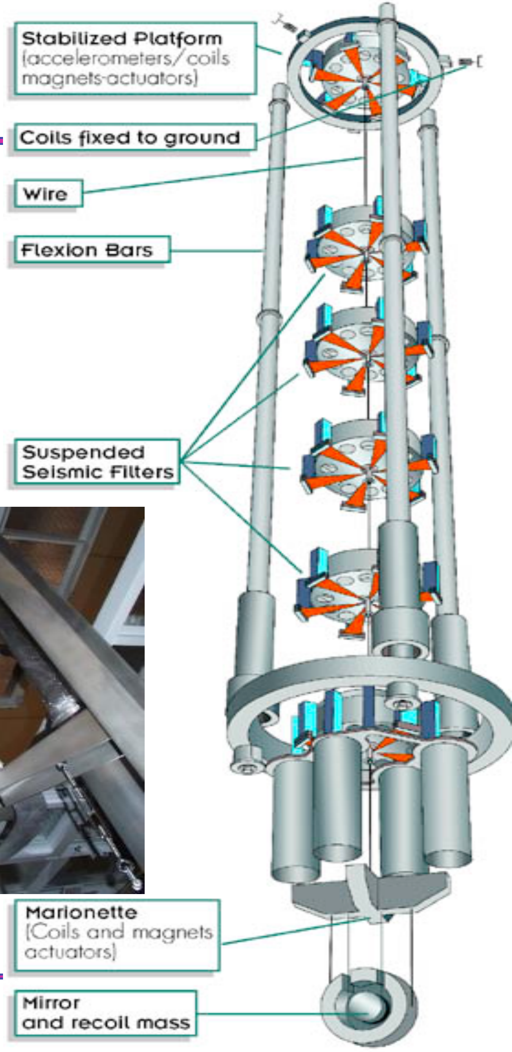




Seismic noise

- *Typical RMS seismic noise in detection band (>10 Hz) is of the order of nm/√Hz*
  - *Need attenuation of about 10 orders of magnitude!*
- *Virgo superattenuator:*
  - *N* cascaded mechanical filters: $(f_0^2/f^2)^N$
  - 6 filters: total isolation 10^{12} @ 10 Hz





Stabilized Platform (accelerometers/coils magnets-actuators)

Coils fixed to ground

Wire

Flexion Bars

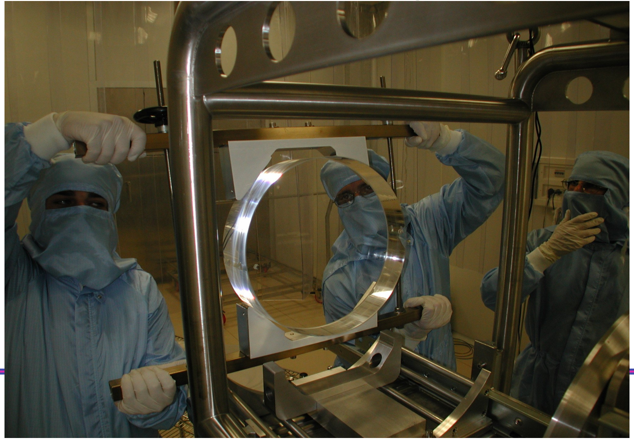
Suspended Seismic Filters

Marionette (Coils and magnets actuators)

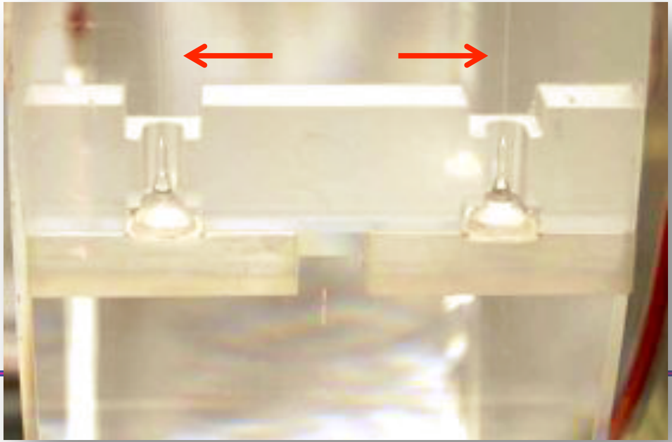
Mirror and recoil mass

Thermal noise

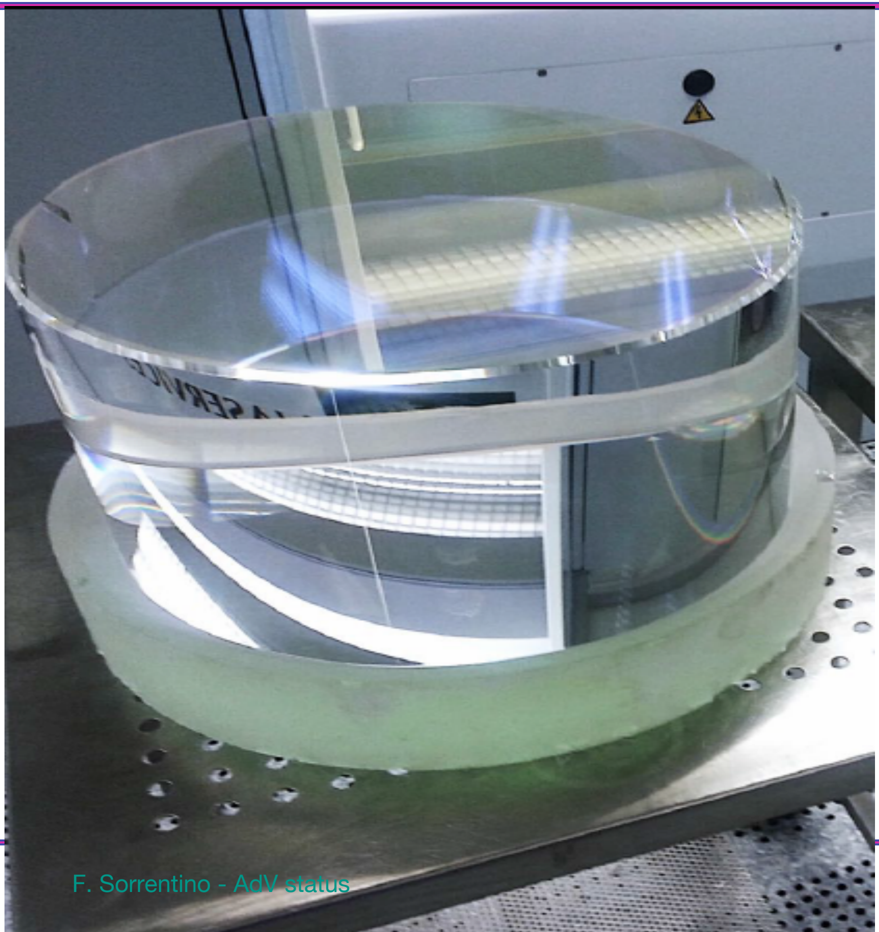
- On mirrors
  - **Brownian motion**
  - Thermo-elastic fluctuations in bulk and coating
  - Thermo-refractive fluctuations
- Improved by
  - larger beam size to sample larger mirror surface
  - low loss coatings



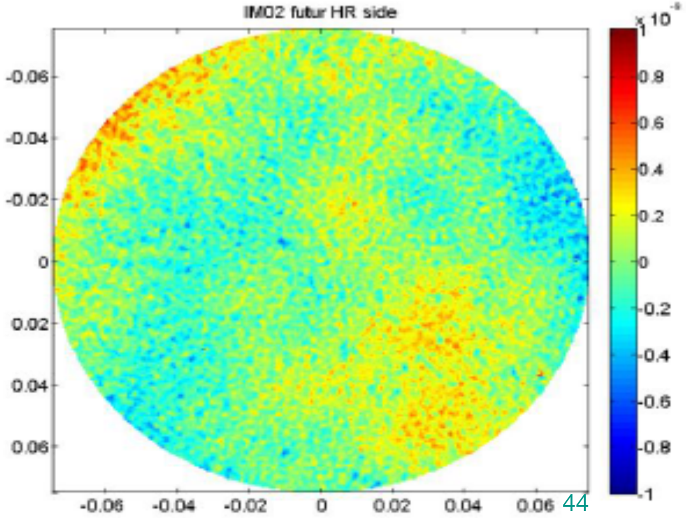
- On suspensions
  - Pendulum thermal fluctuations
  - Vertical thermal fluctuations
  - **Violin modes**
- Improved by monolithic suspensions
  - Only after O2 science run



Mirrors

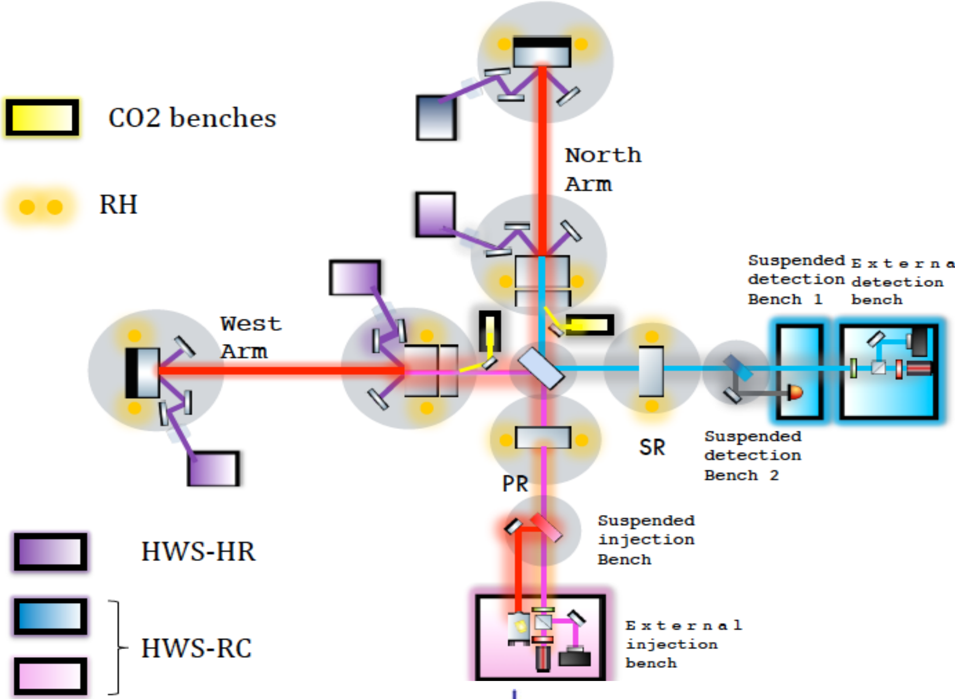


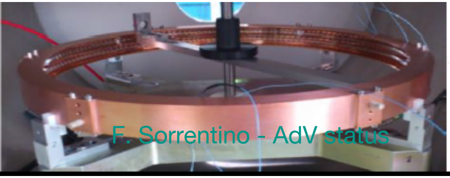
- Low mechanical losses
- Low optical absorption
- Low scattering
- 42 kg, 35 cm diam., 20 cm thick
- Flatness < 0.5 nm rms
- Roughness < 0.1 nm rms
- Absorption < 0.5 ppm

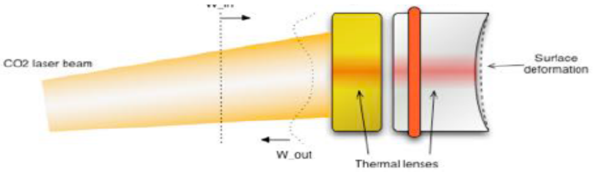


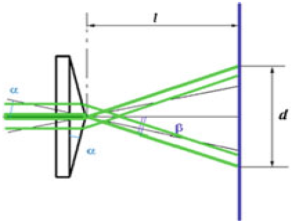
Thermal compensation

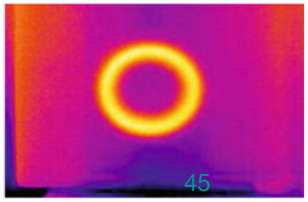
- Some AdV upgrades:
  - Higher laser power (lower shot noise)
  - Higher F-P cavity finesse (scale factor)
- But higher power increases thermal aberrations, and higher finesse makes ITF more sensitive to aberrations
- Thermal aberrations were already relevant in 1st generation detectors
  - Thermal Compensation System (TCS)
- AdV TCS sensing:
  - Hartmann sensors
  - phase cameras
- AdV TCS actuators:
  - CO2 laser projector to correct thermal lensing
    - Double axicon for better thermal lens correction
    - Compensation plates to reduce CO_2 laser noise coupling
  - Ring heater to tune mirror RoCs by thermoelastic deformation of the HR surface





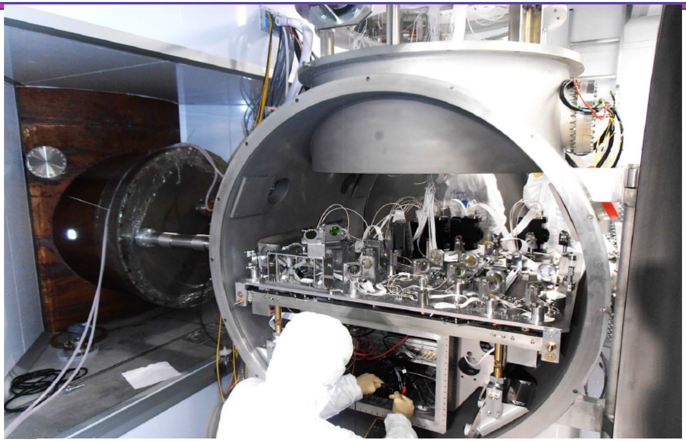


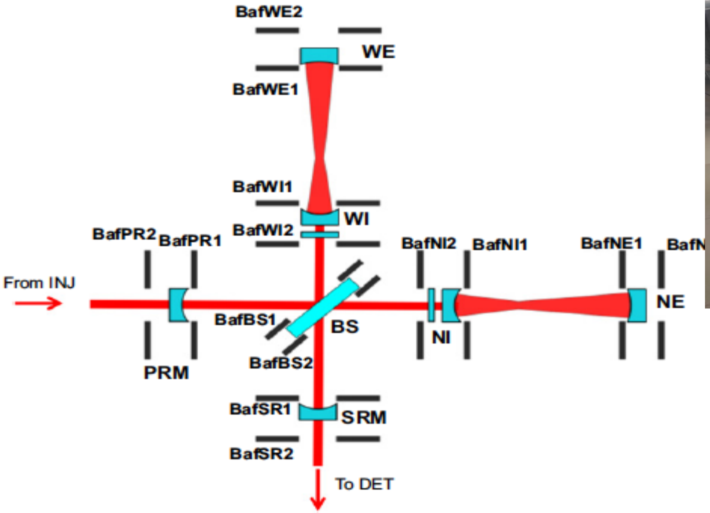


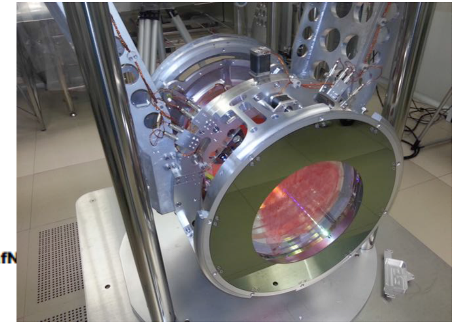


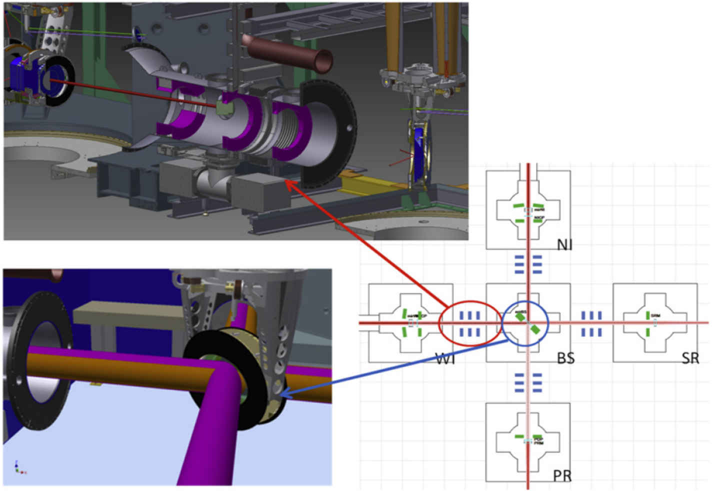
Stray light control

- Reducing amount of scattered light
  - 320 baffles welded to pipes
- Reduce relative motion between scattering surfaces and detection photodiodes
  - Baffles integrated on each suspended payload
  - Photodiodes hosted on suspended benches in vacuum



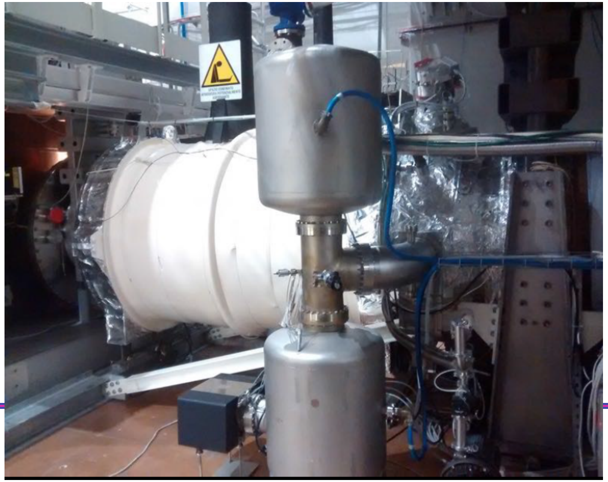




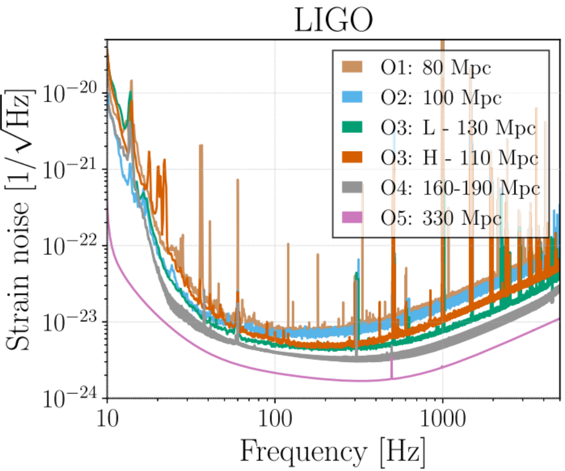


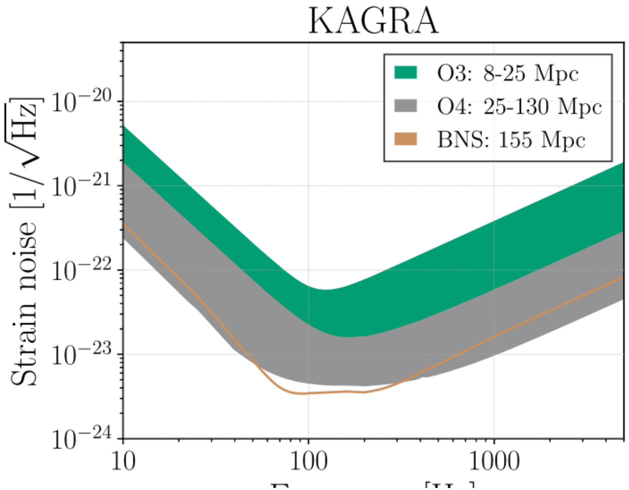
Vacuum

- With iVirgo vacuum level (10^{-7} mbar, dominated by H_2O) phase noise from background gas would limit AdV sensitivity
- Need to reduce phase noise by a factor 10 => improve vacuum by a factor 100 (scaling with $\sqrt{P}$)
- Backing arm tubes already tested to 10^{-9} mbar (dominated by hydrogen)
- Backing TM towers not opportune
- Large cryo-traps close to towers

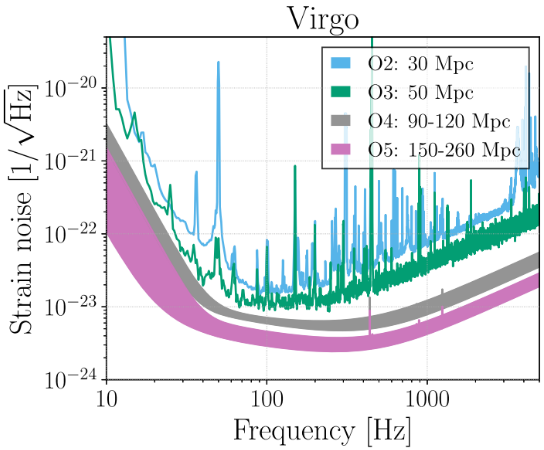


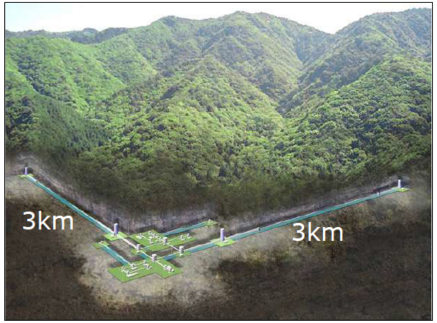
Network of GW detectors





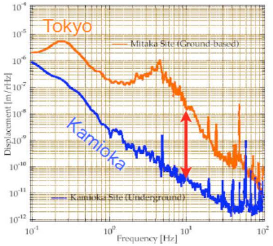
World's first
2.5th generation GW detector





Fabry-Perot Michelson type
Laser interferometer

Cryogenic to reduce
thermal noises
(T=20K @mirrors)
Underground to reduce
seismic noises



Amplitude of seismic motion

The future: space detectors