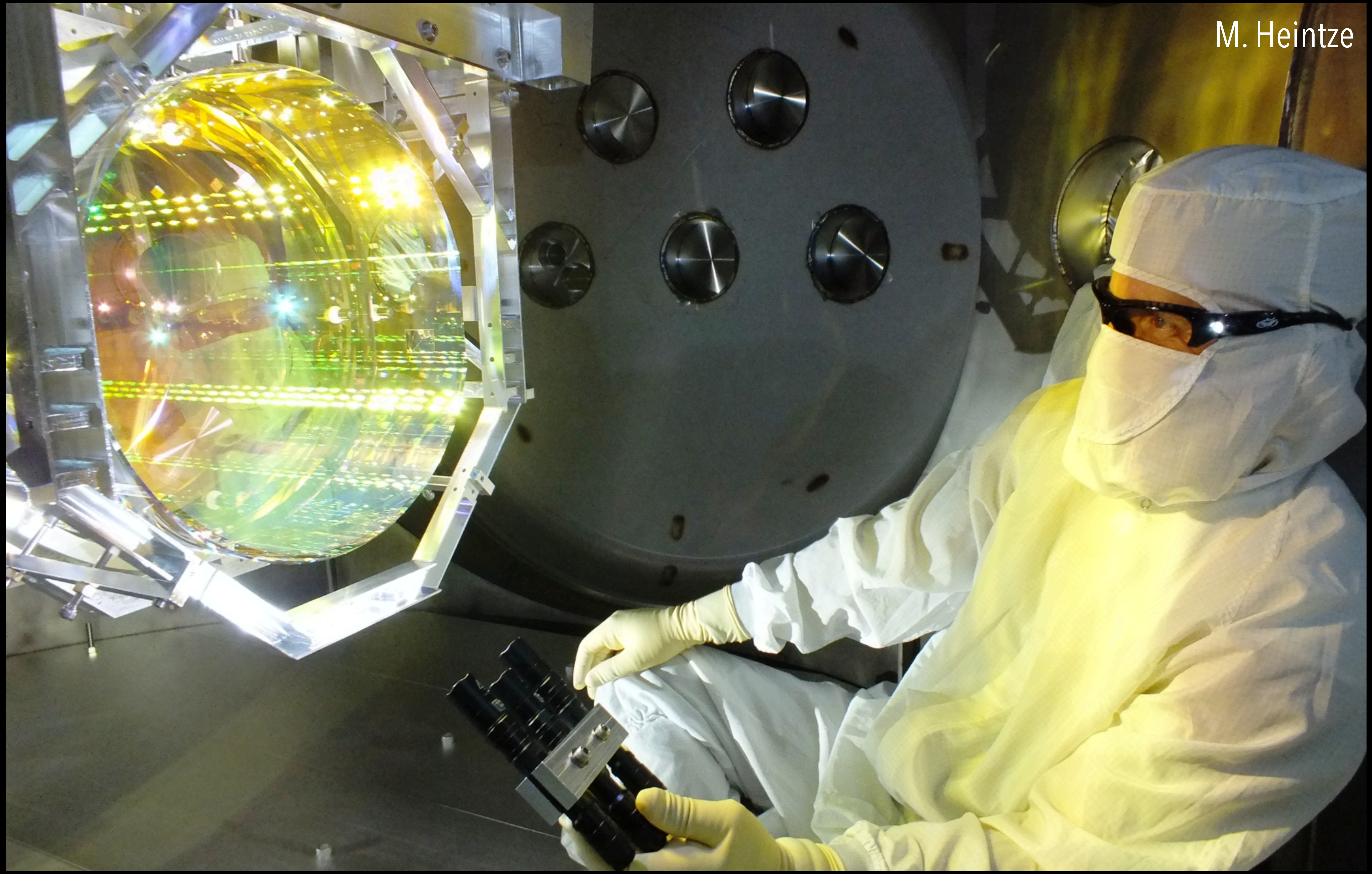
The future of gravitational wave astrophysics



Dr. Jess McIver
CAP Congress - 2023
LIGO DCC G2301191

Stewart Blusson Quantum Matter Institute
THE UNIVERSITY OF BRITISH COLUMBIA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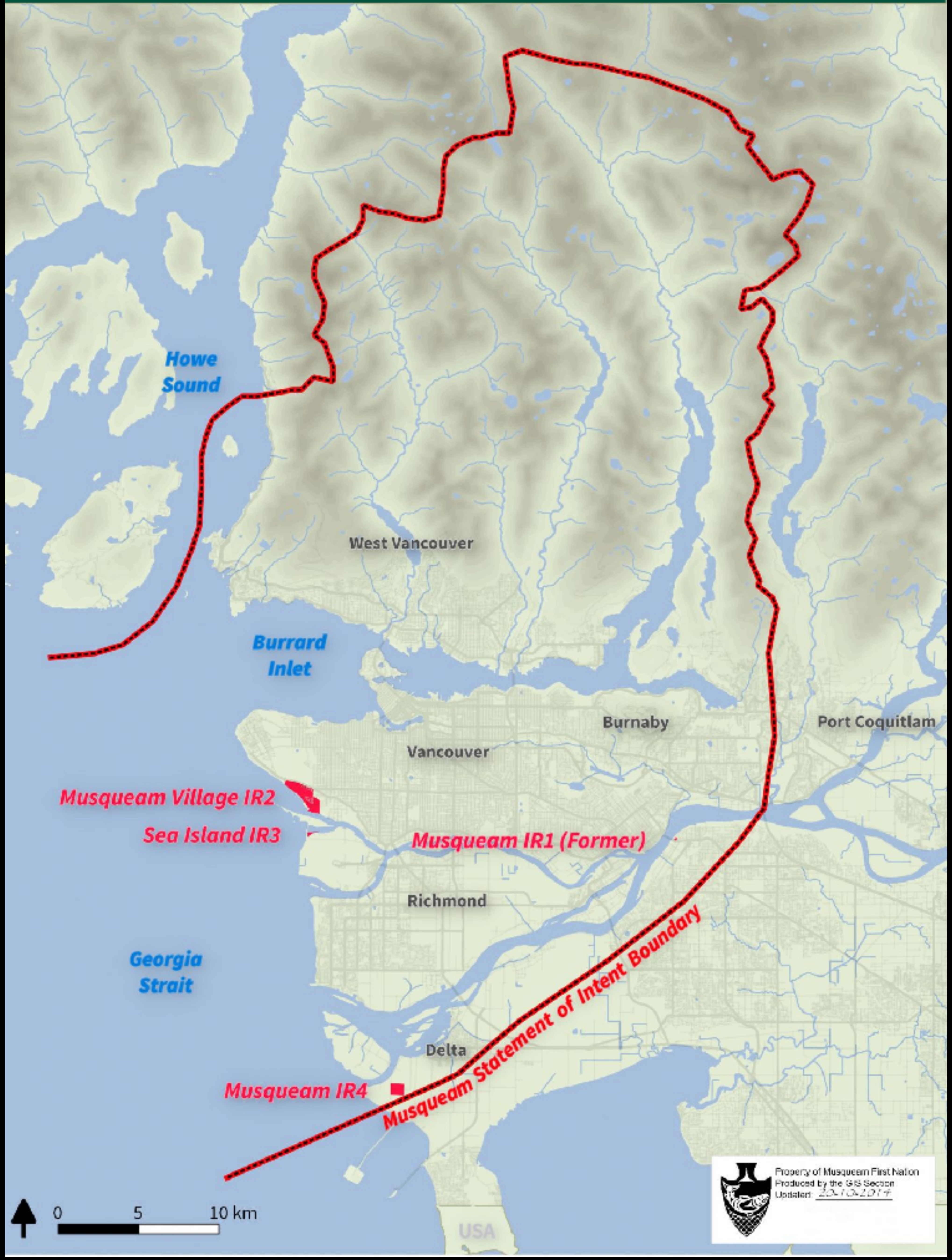
Mi'kma'ki
Wabanaki (Dawnland Confederacy)
Wolastoqiyik (Maliseet)
Mi'kma'ki
Wabanaki (Dawnland Confederacy)
Wolastoqiyik (Maliseet)

Musqueam Statement of Intent Boundary



One way to support the Musqueam community:

The Aboriginal Housing Management Association (AHMA) provides a spectrum of culturally safe housing including affordable housing units, homeless shelters, transition homes, supportive housing, and assisted living facilities. Many of AHMA's members also offer support services and more. AHMA members make up over one-third of Indigenous housing providers in Canada.

If you like, you can endorse the **AHMA's Provincial Urban Rural and Northern Indigenous Housing Strategy**: https://www.ahma-bc.org/how-to-support


NASA

gravitational waves

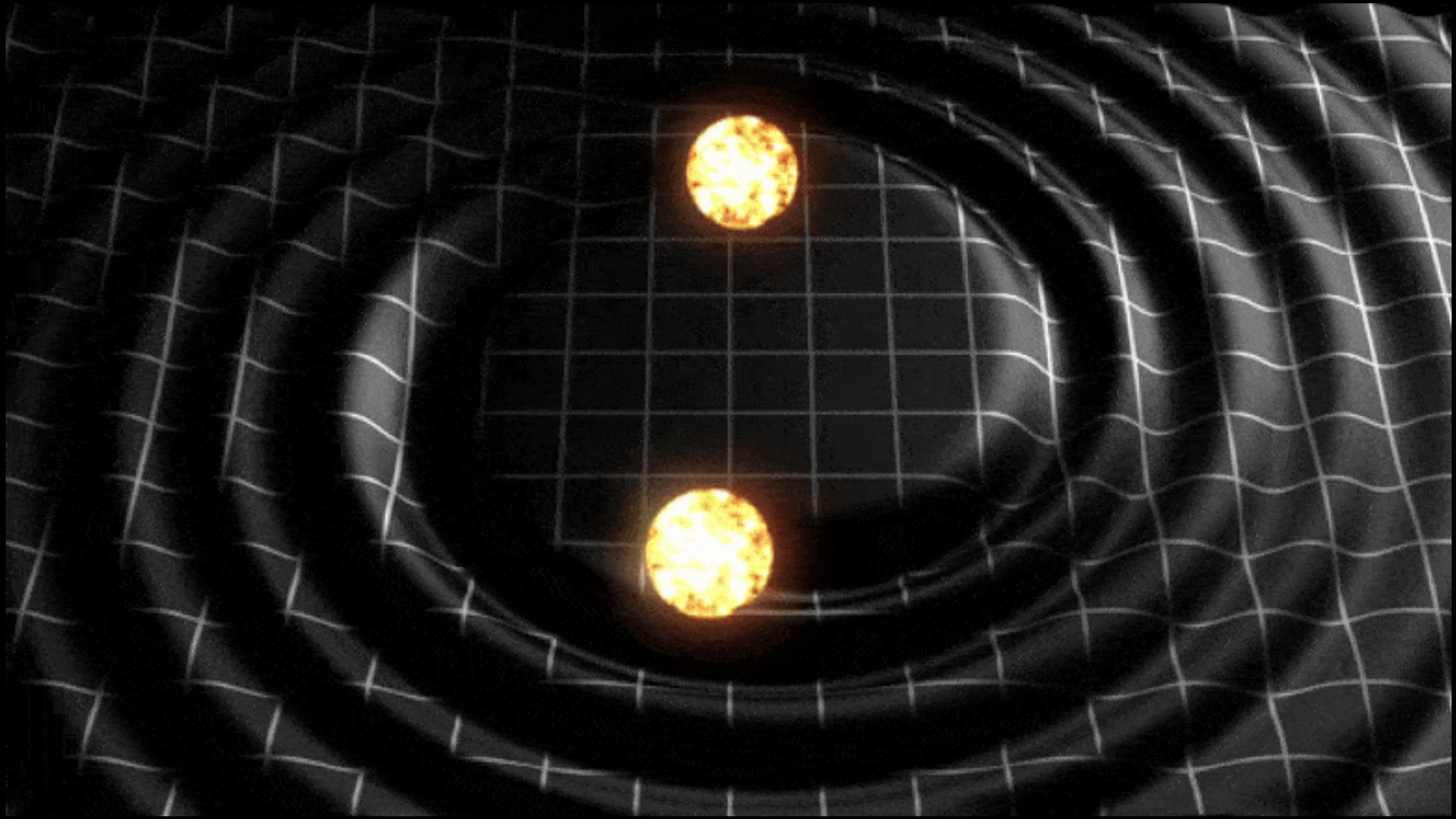
a new view of the universe

Gravitational waves

Gravitational wave strain, *h*:

$$h_{ij}(t) \propto \frac{G}{c^4}\frac{d^2 I_{ij}}{dt^2}\frac{1}{r}$$

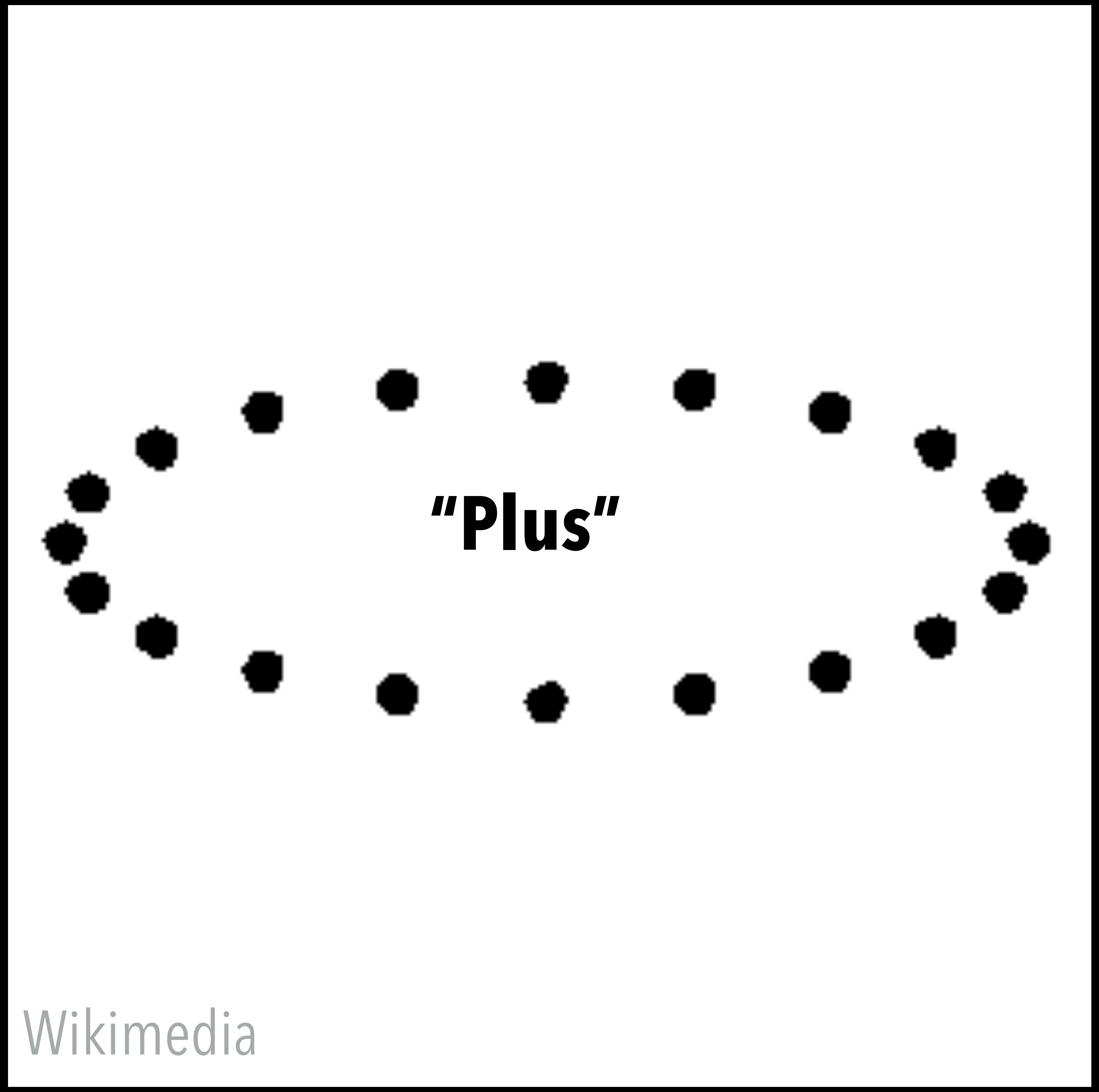
Signal strength scales with $\frac{1}{r}$!

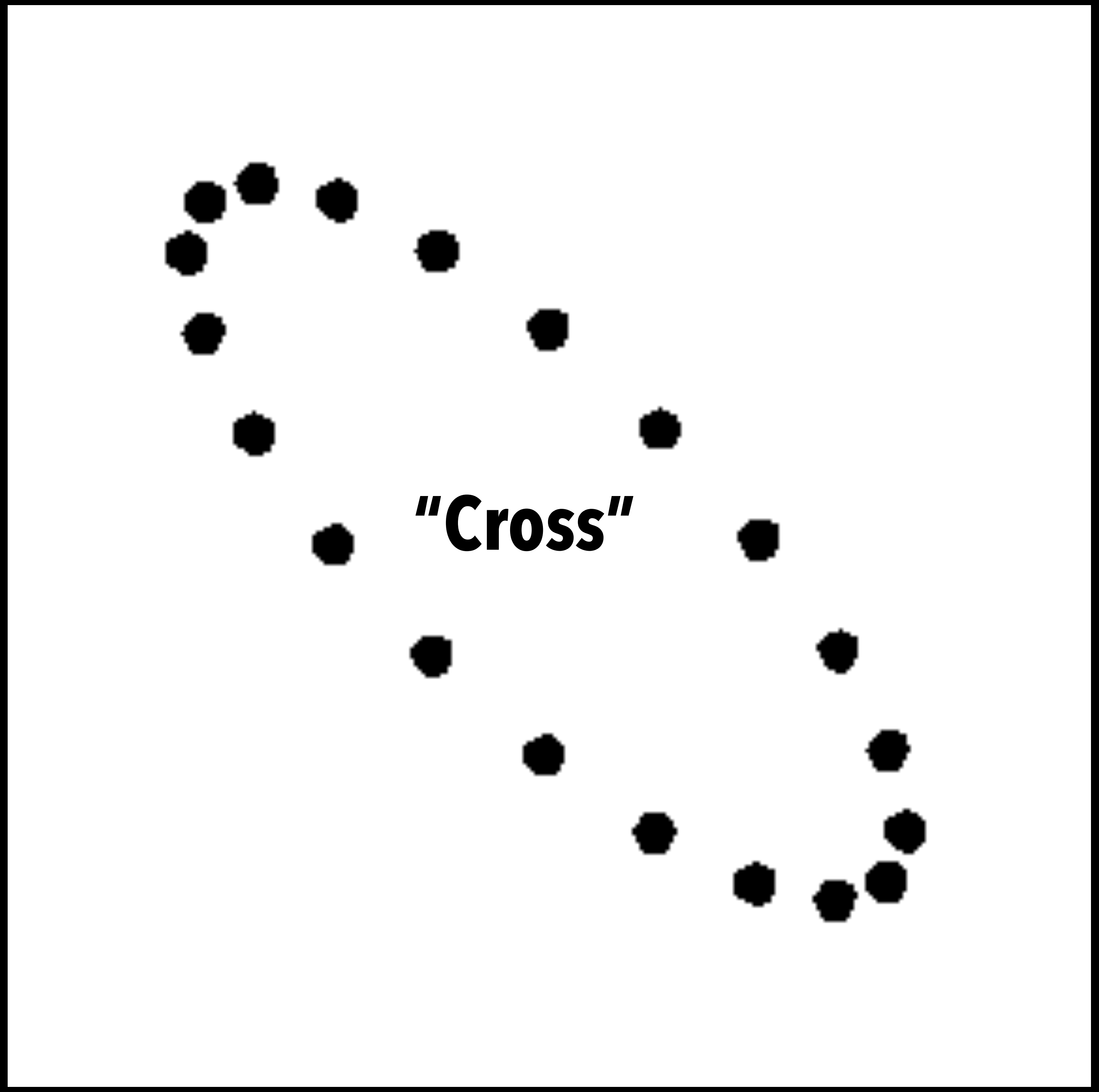


OzGrav

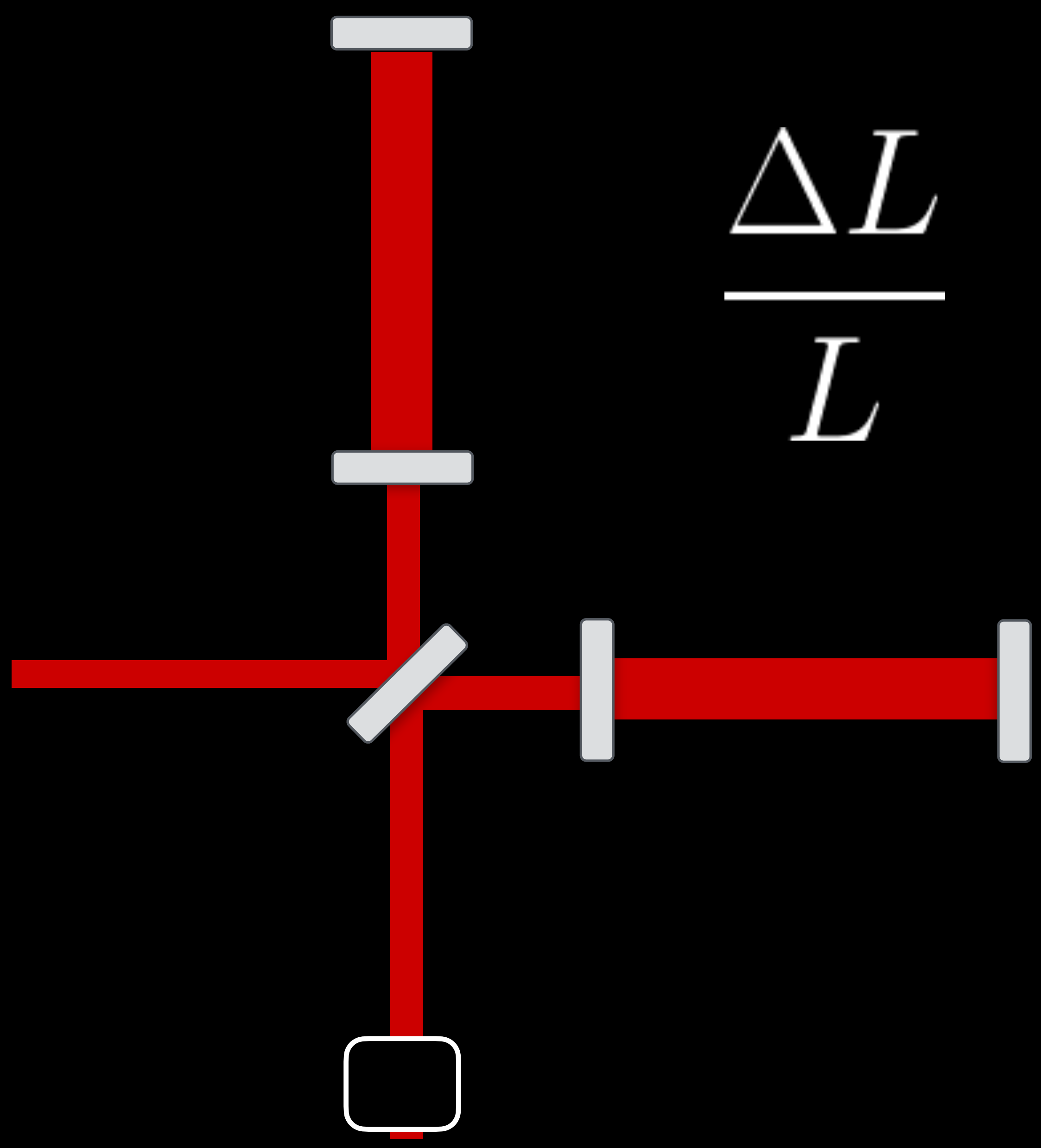

-0.64s
SXS

Gravitational wave propagation





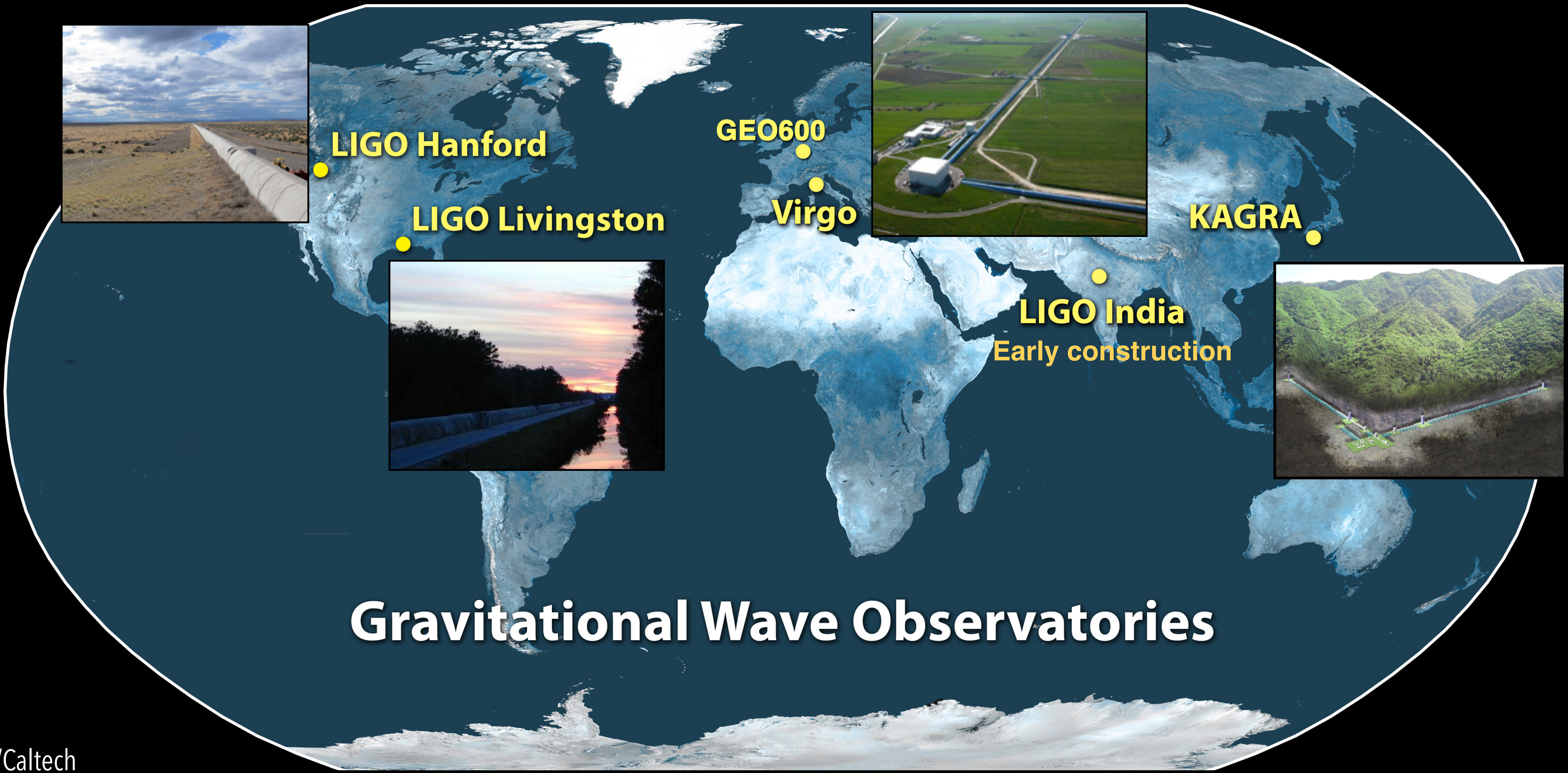
Measured spacetime strain h(t)




LIGO/Caltech

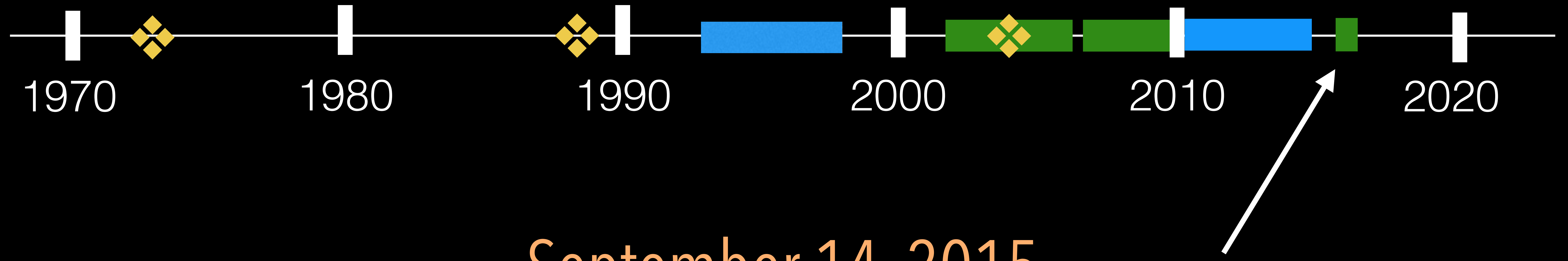
Science/AAAS

Current GW detector network (IGWN)

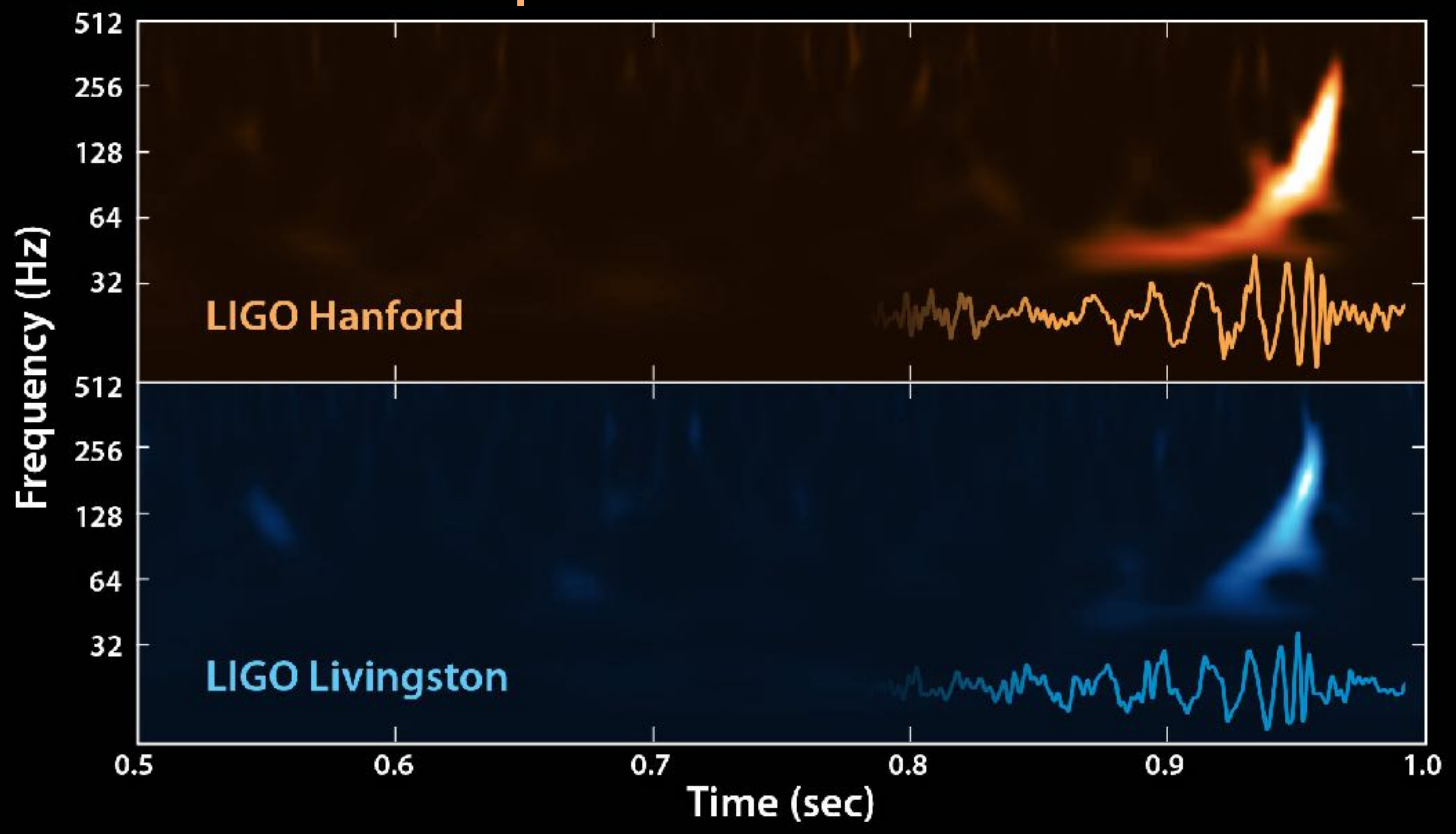


LIGO/Caltech

A landmark detection

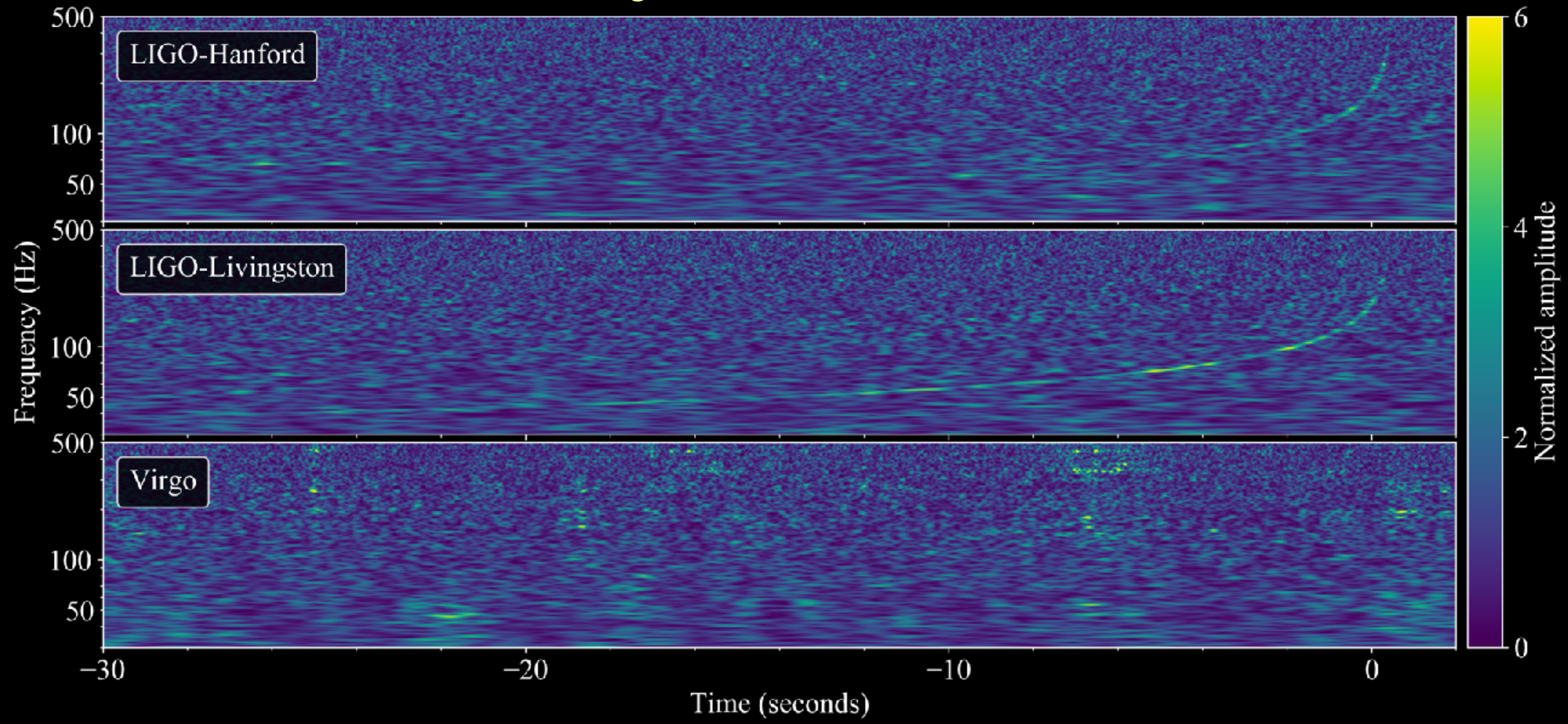


September 14, 2015



The first multi-messenger event with GWs

August 17, 2017

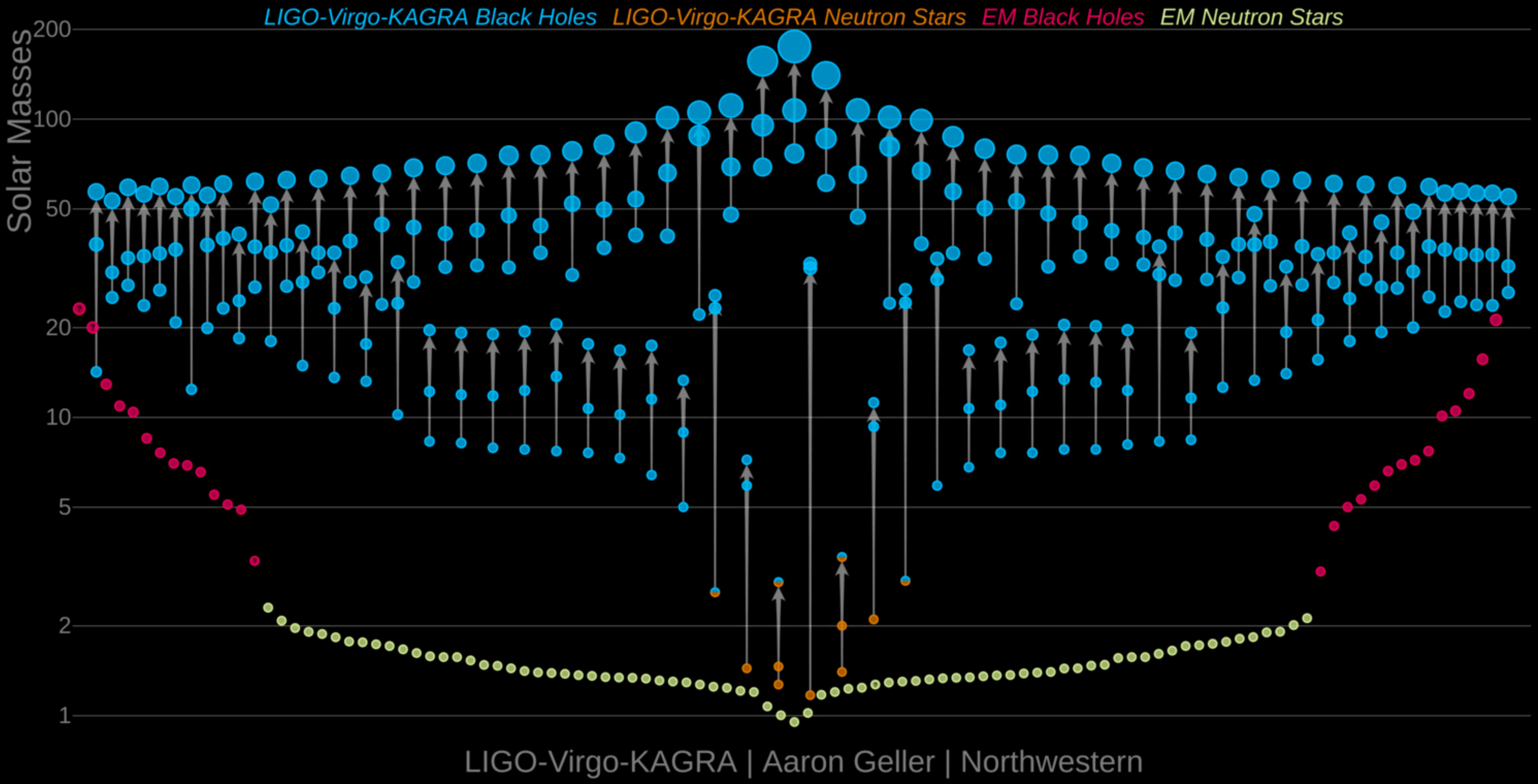


LIGO/Virgo/Lovelace, Brown, Macleod, McIver, Nitz

See talks by *Phil Landry, Nicole Vassh*
DTP T3-4

NASA/Goddard Space Flight Center/CI Lab

Significant LVK candidates from O1, O2, O3



LIGO-Virgo-KAGRA results

Since 2016:
>100 LVK papers
> 80,000 citations

Topics include:

- Stellar remnant catalogs
- Tests of general relativity
- Instrumentation
- Noise studies
- Dense matter
- Searches for novel GW sources (lensing, CW, stochastic, CCSN..)
- Independent measurement of H_0

pnp.ligo.org/ppcomm/Papers.html

LIGO-Virgo-KAGRA Publications

LSC VIRGO KAGRA

The LIGO Scientific Collaboration and Virgo collaboration have been co-authoring observational result papers since 2010. Beginning in 2021, the KAGRA Collaboration too is co-authoring observational results from the full O3 run. See here for additional information.

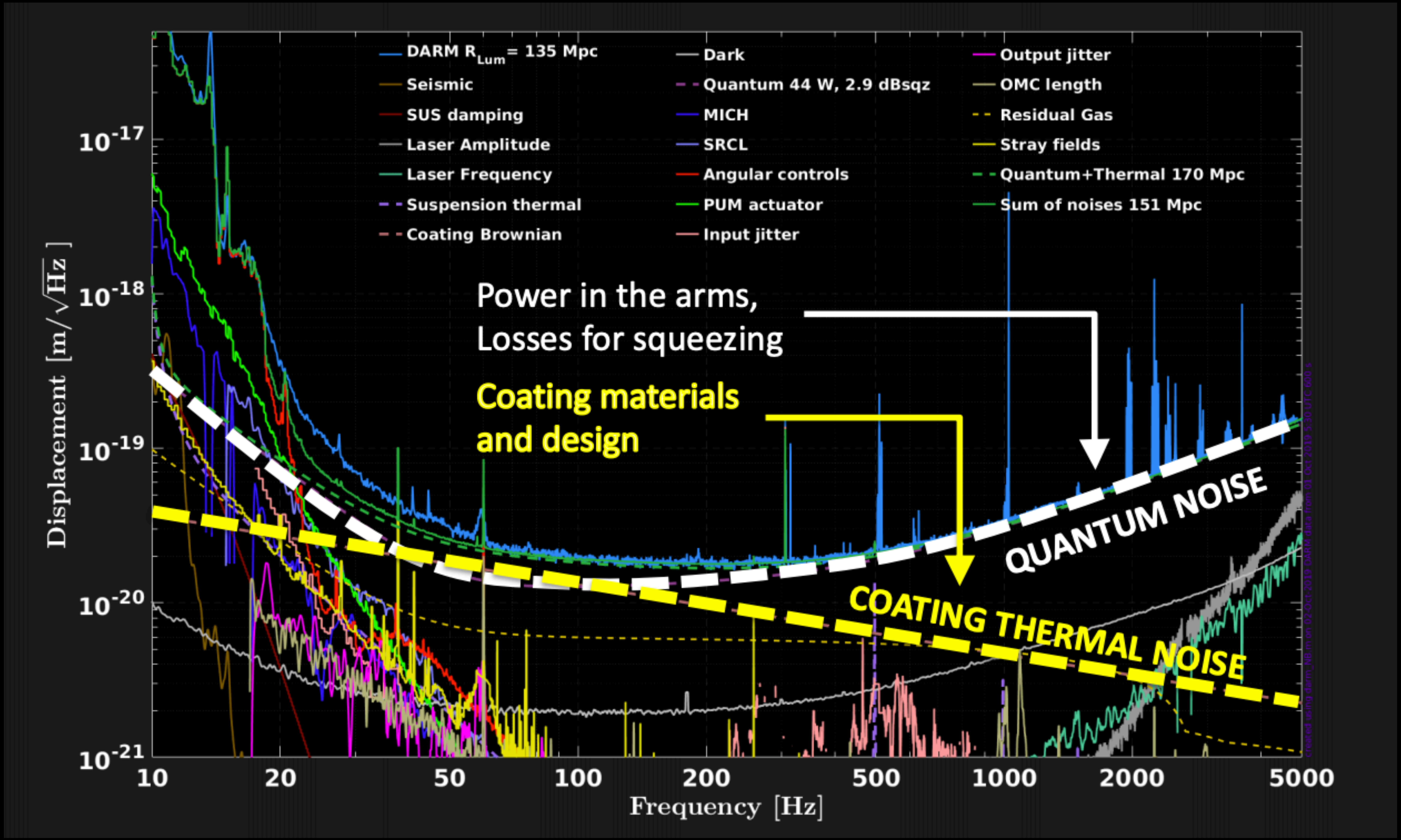
BibTeX file for these papers | Click to toggle doi information | Click on any keyword to filter on that keyword

Highlighting: Event discoveries | Multi-messenger

Release Date	Title	Keywords (clear filter)	Science Summary	Journal citation	arXiv Preprint	Public Report
Apr 17, 2023 *Recent*	**Search for gravitational-lensing signatures in the full third observing run of the LIGO-Virgo network** (*by LSC, Virgo and KAGRA*)	O3 CBC LVK	summary	*Submitted to ApJ*	2304.08393	P2200031
Feb 7, 2023	**Open data from the third observing run of LIGO, Virgo, KAGRA and GEO** (*by LSC, Virgo and KAGRA*)	O3 data LVK	summary	*Accepted by ApJS*	2302.03676	P2200316
Dec 2, 2022	**Search for subsolar-mass black hole binaries in the second part of Advanced LIGO and Virgo's third observing run** (*by LSC, Virgo, KAGRA, S. Shandera and D. Jeong*)	O3 CBC LVK	summary	Monthly Notices of the Royal Astronomical Society, stad588 (Accepted Manuscript)	2212.01477	P2200139
Oct 20, 2022	**Search for gravitational-wave transients associated with magnetar bursts in Advanced LIGO and Advanced Virgo data from the third observing run** (*by LSC, Virgo and KAGRA*)	O3 magnetars LVK	summary	*Submitted to ApJ*	2210.10931	P2100387

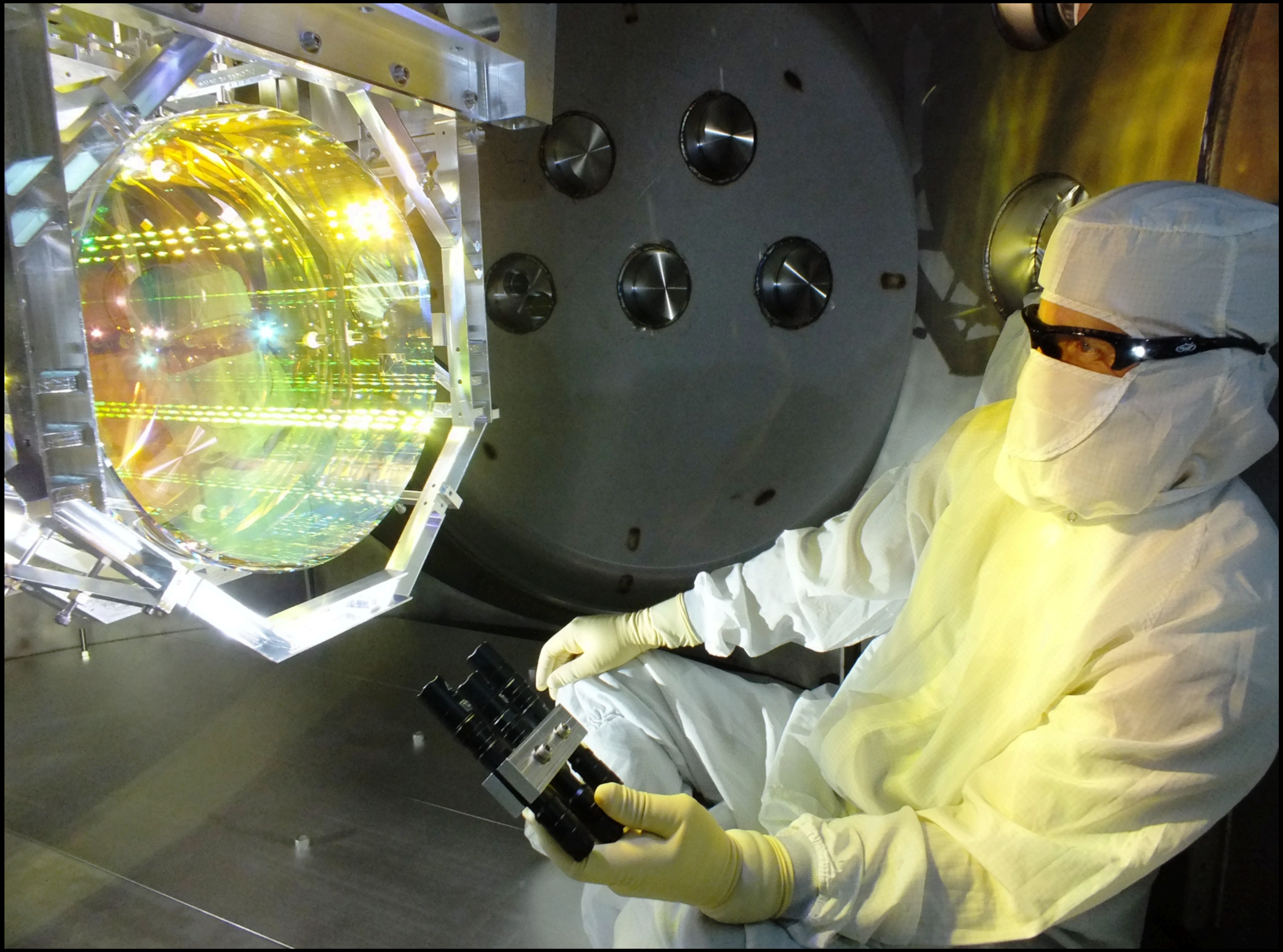
LIGO/Caltech

Advanced LIGO noise budget

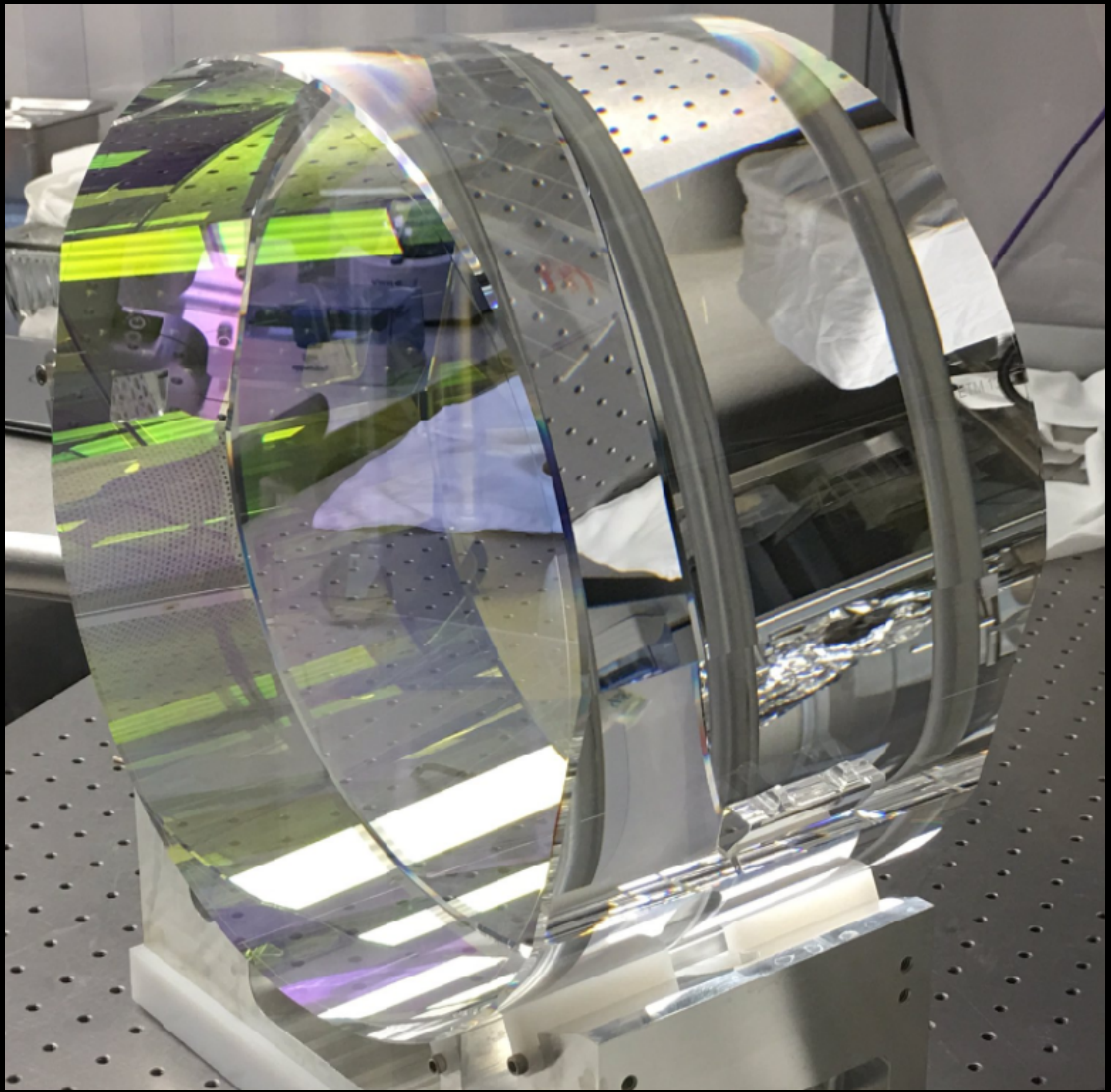


https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=48889. Slide by G. Vajente

Advanced LIGO optics and coatings

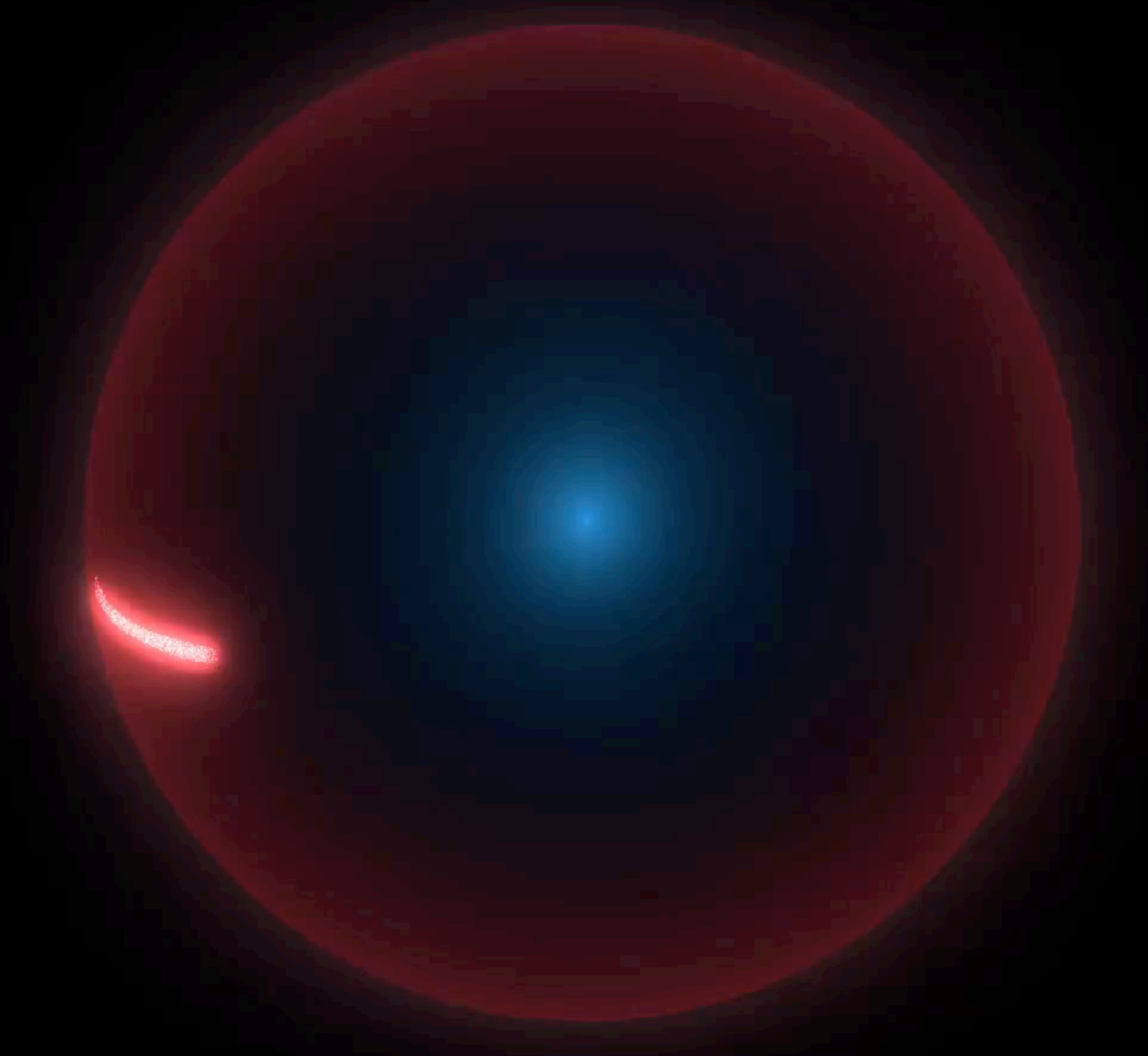


M. Heintze



K. Toland

GW detector sensitivity

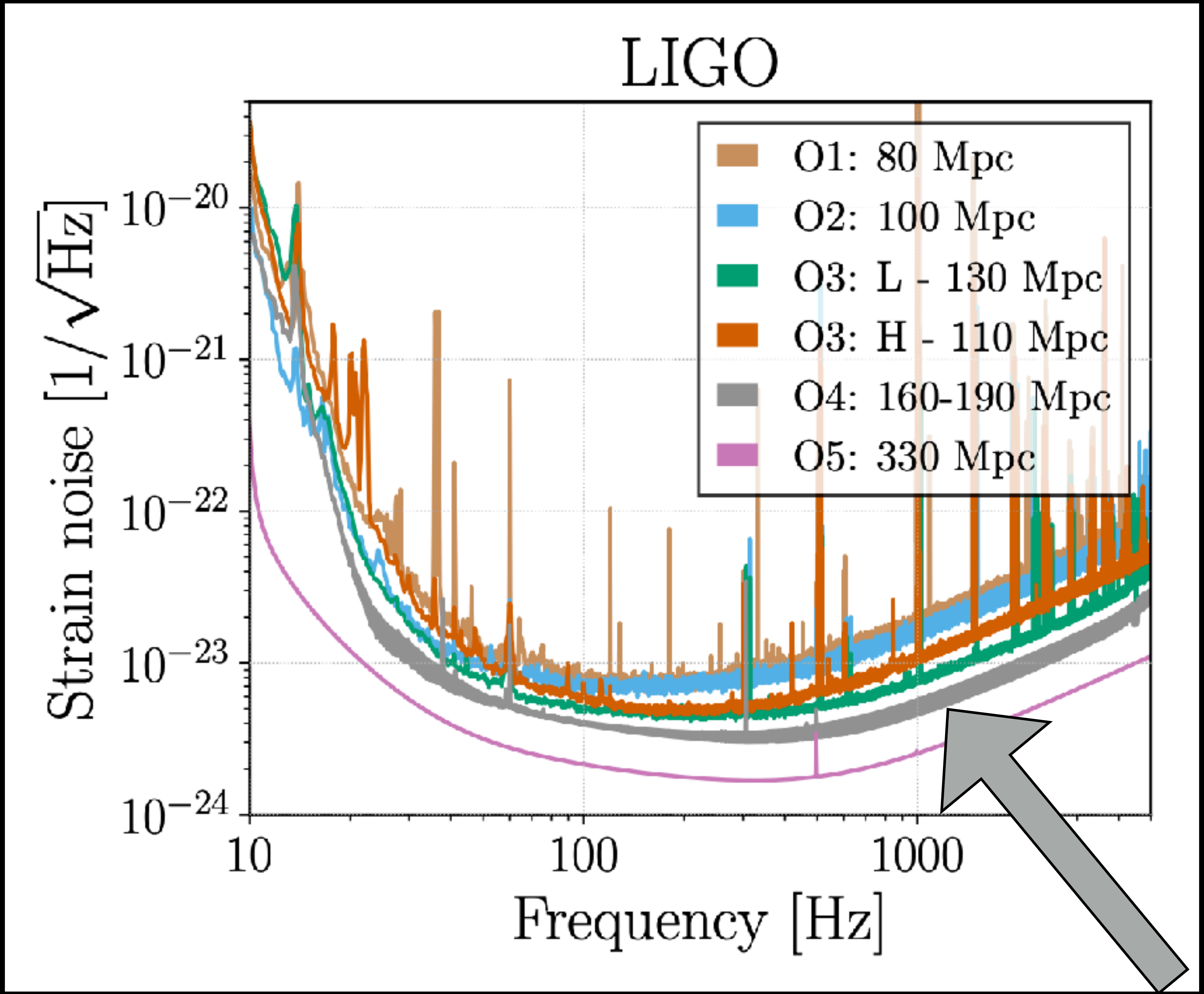


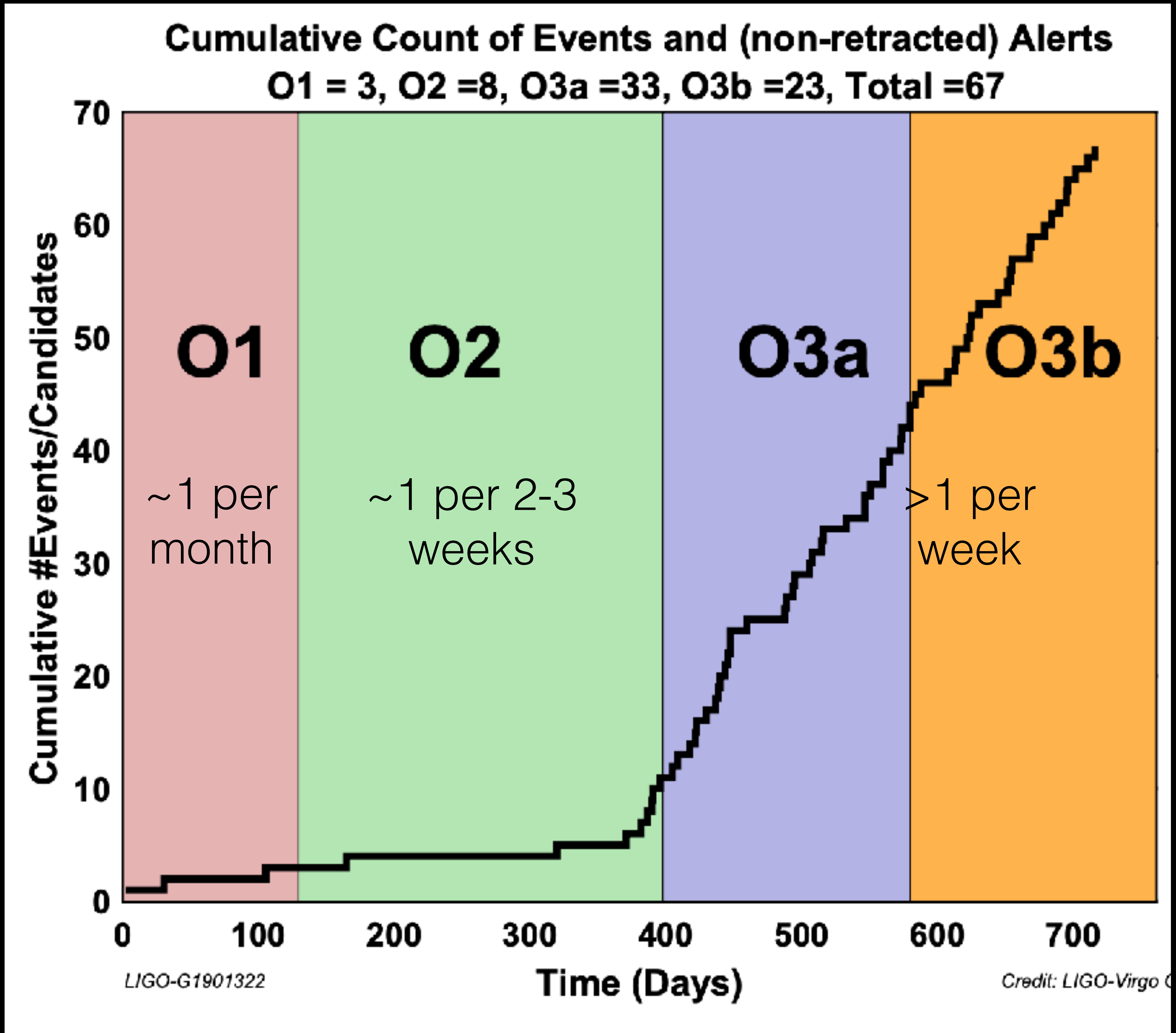
LIGO/Caltech

Sensitivity and detection rate

O4 started on May 24!

As the GW detection rate increases, automation will become more important.

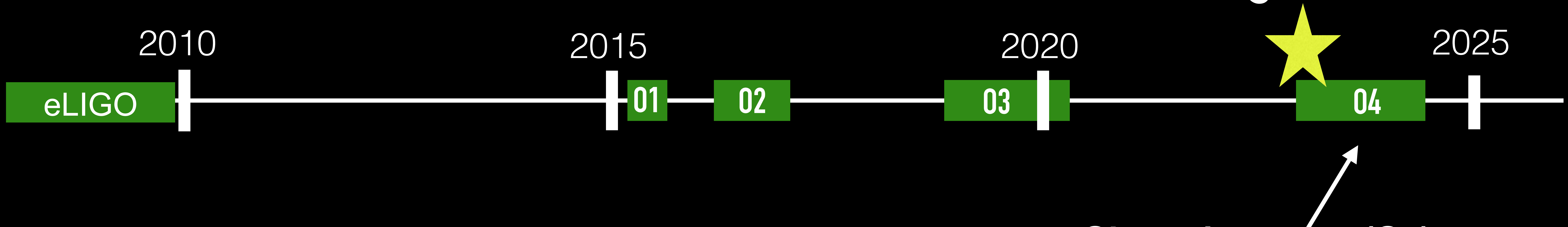




LIGO-Virgo arXiv 1304.0670 v11

O4 expectation: up to a few signals per week

Timeline of Advanced LIGO and Advanced Virgo



O4 aLIGO improvements

- Upgrade pre-stablized lasers to input100W into the interferometer (for 400 kW in the arm cavities)
- New baffles to combat stray light noise
- Replace some test mass mirrors to improve coatings
- New 300 meter cavity for frequency-dependent squeezed light

Observing run 4 (O4)

- Began May 24 (2 LIGO detectors) with improved detector sensitivity
- Target: move toward Advanced LIGO and Advanced Virgo design sensitivity
- KAGRA also plans to join at a reduced sensitivity

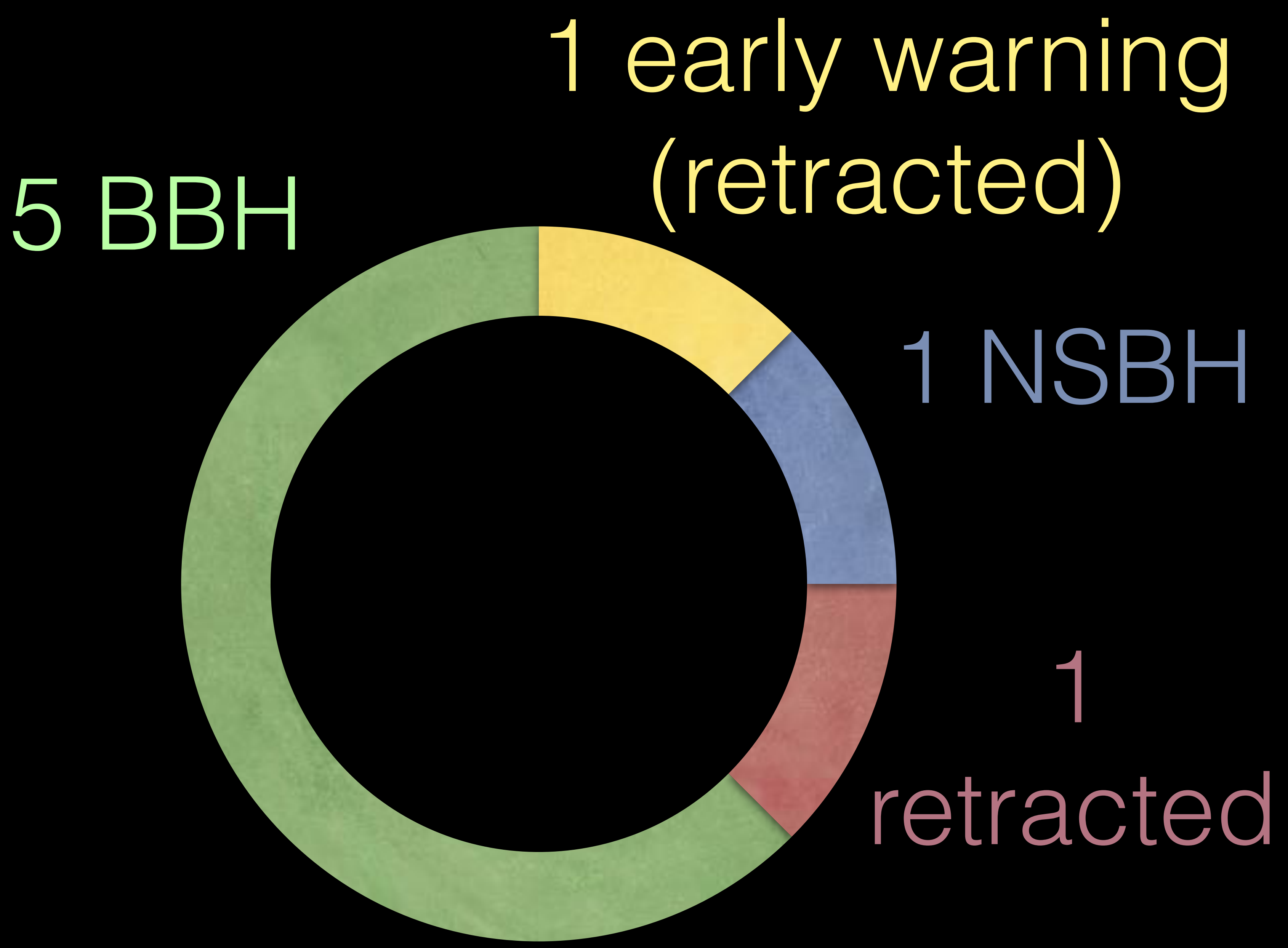
O4 snapshot so far

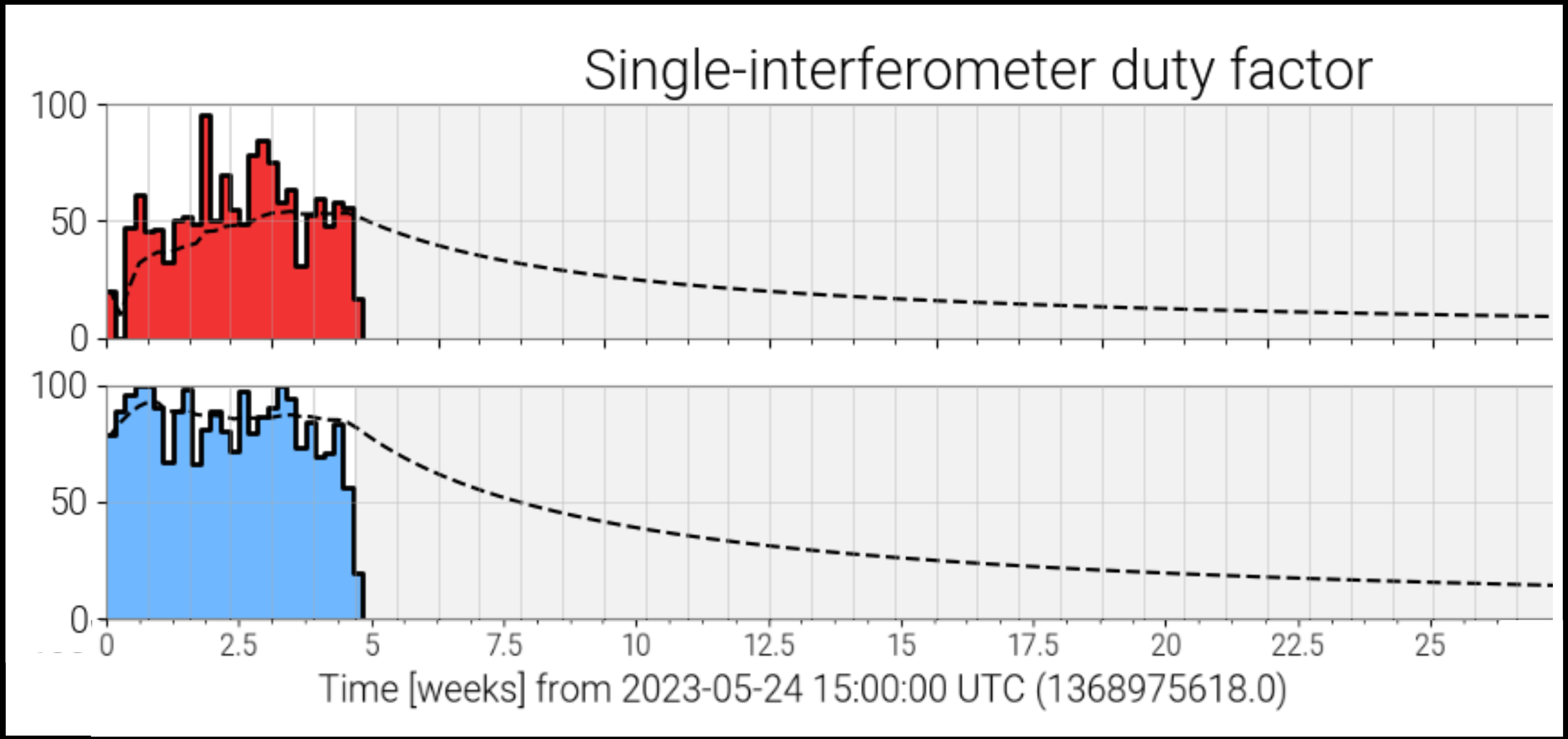
https://gracedb.ligo.org/superevents/public/O4/

Started May 24, 2023
with the 2 LIGO detectors

O4 Significant Detection Candidates: **6** (7 Total - 1 Retracted)

O4 Low Significance Detection Candidates: **63** (Total)





https://ldas-jobs.ligo.caltech.edu/~detchar/summary/







LSC

Over **1400** people from **127** institutions and **19** countries worldwide!



Canadian LIGO groups

- Extreme matter co-chair: Phil Landry (CITA)
- Rates and populations co-chair: Maya Fishbach (CITA)
- Optics working group co-chair: François Schiettekatte (UdeM)
- Deputy Spokesperson: JM (UBC)

UBC: 21

Perimeter: 12

CITA: 7

UMontreal/ Polytechnique: 7

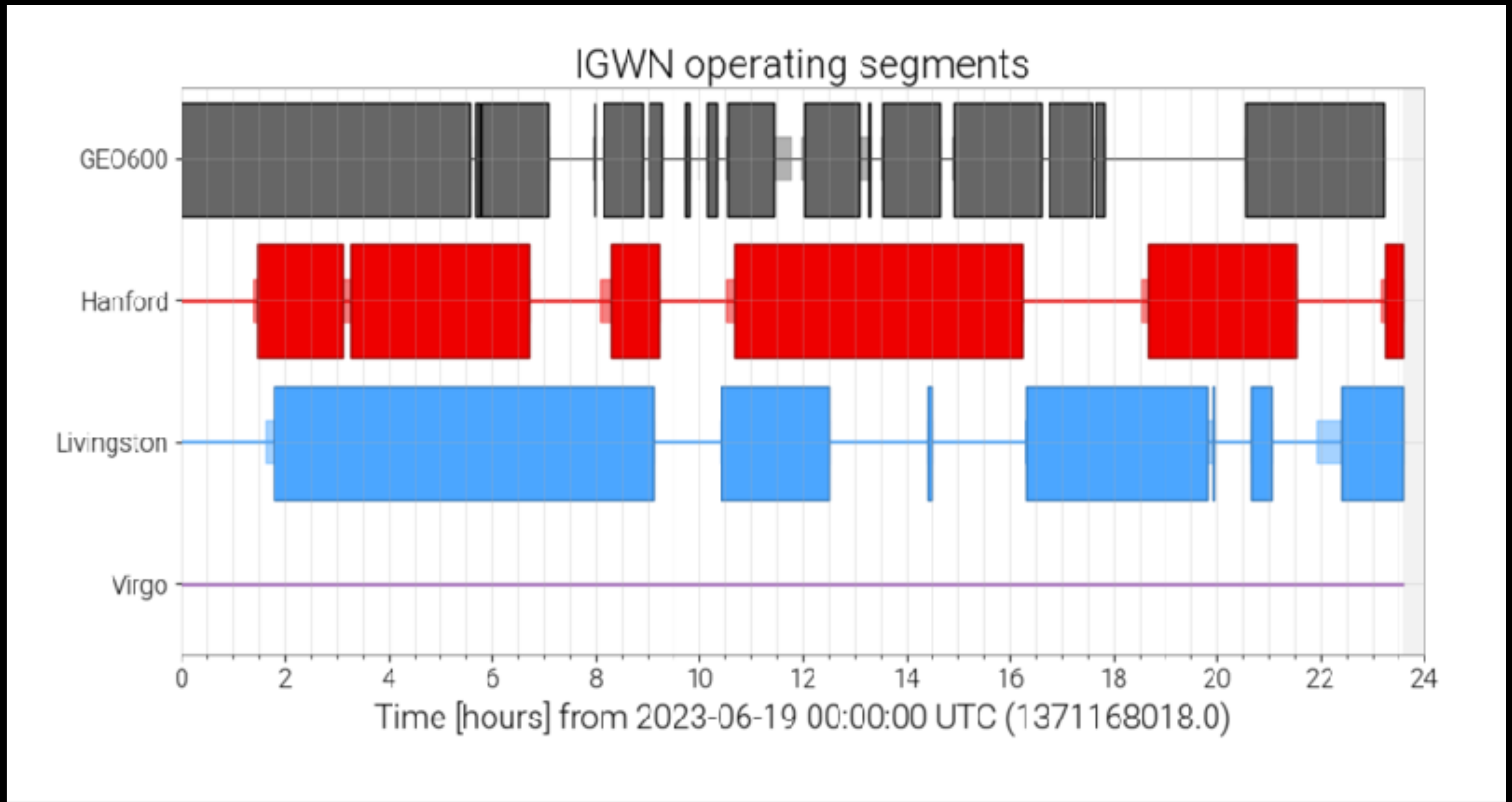
Canadians: 47 of 1400+ LSC members (~3%)

Canadian contributions to LIGO operations

~10% of LIGO-Virgo-KAGRA (2500+ researchers!)
computing power provided by DRAC

Digital Research Alliance of Canada | Alliance de recherche numérique du Canada

Plus dozens of scientific studies and other leadership!

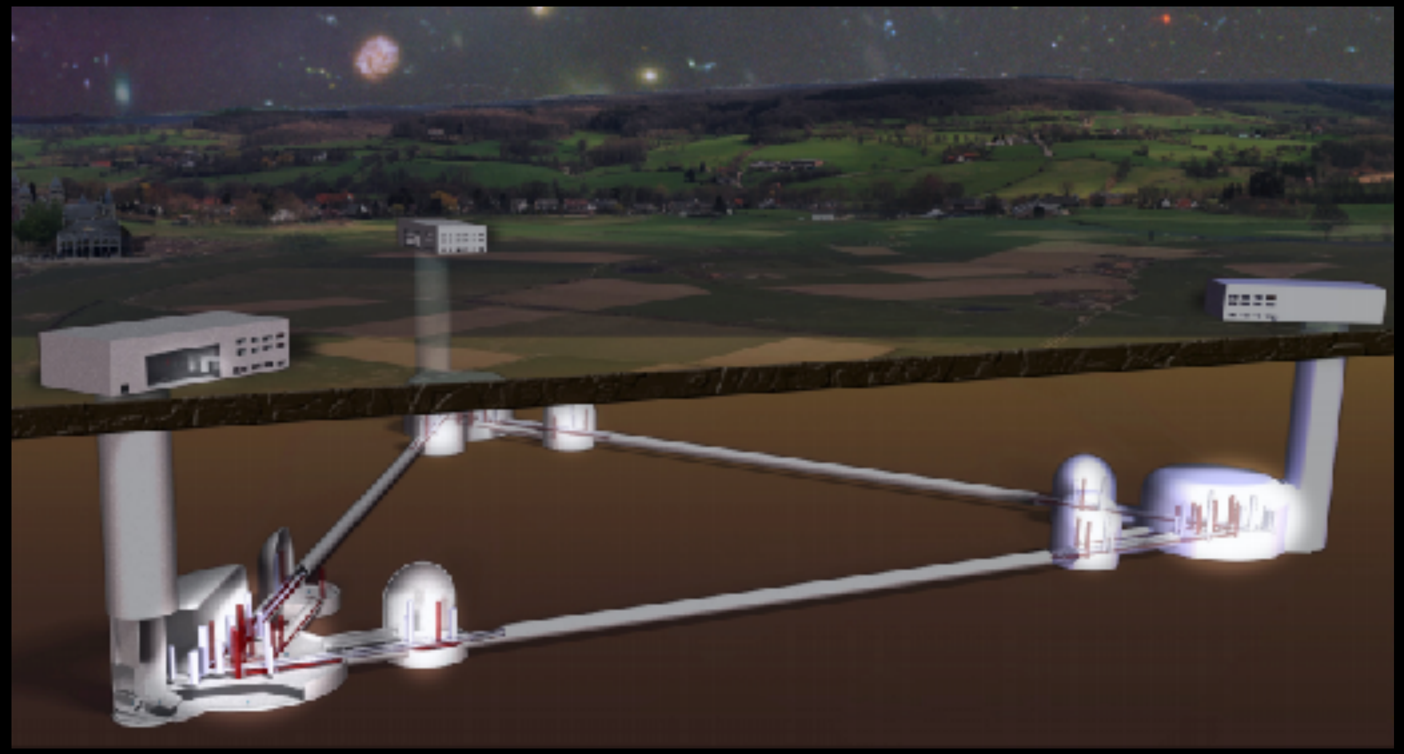


INNOVATION
Canada Foundation for Innovation | Fondation canadienne pour l'innovation

Flagship LIGO calibration software

LIGO detector monitors that power public status page: https://gwosc.org/detector_status/

The next generation of GW detectors



A+/AdV+
- 3-4 km detectors
- **300 K**
- 1064 nm laser
- 40 kg mirrors

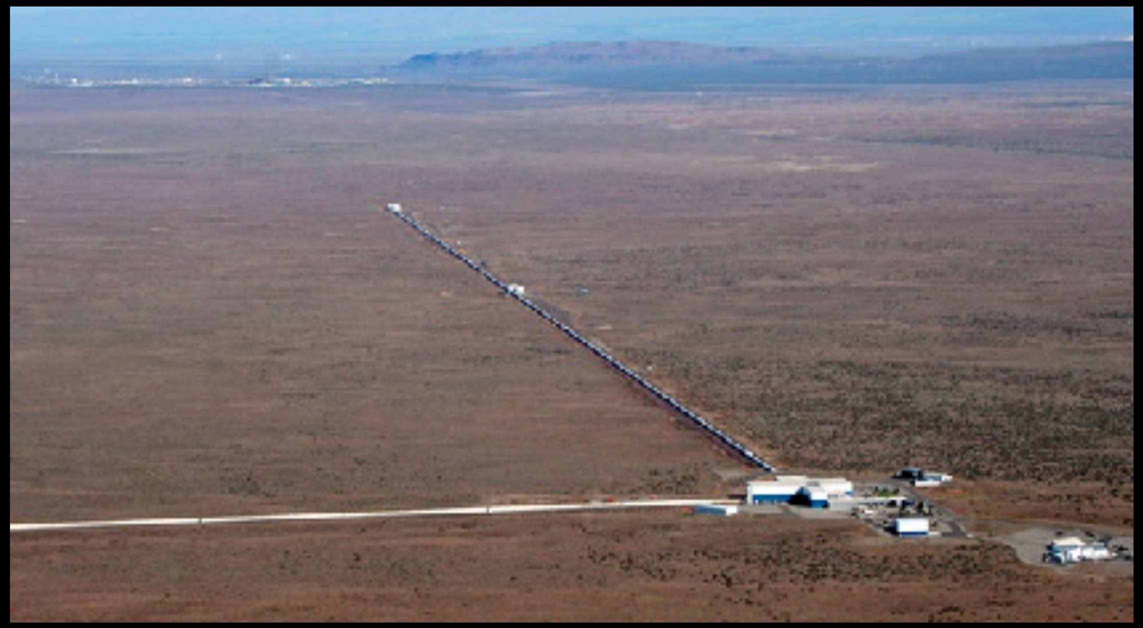
Einstein Telescope
- 10 km detectors
- **300 K** and **< 23 K**
- 2 microns
- 200 kg mirrors

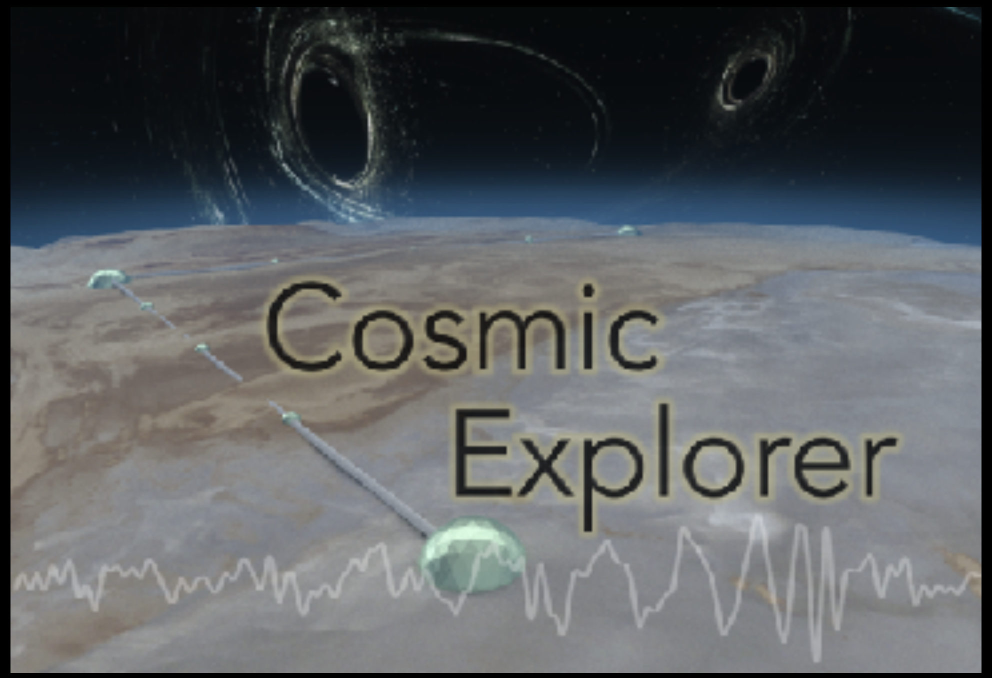
Cosmic Explorer 2
- 20-40 km detectors
- **123 K**
- 1-2 microns (?)
- 320 kg mirrors

2025 — 2030 — 2035 — 2040

Voyager
- 4 km detectors
- **123 K**
- 1.5-2 microns
- 160 kg mirrors

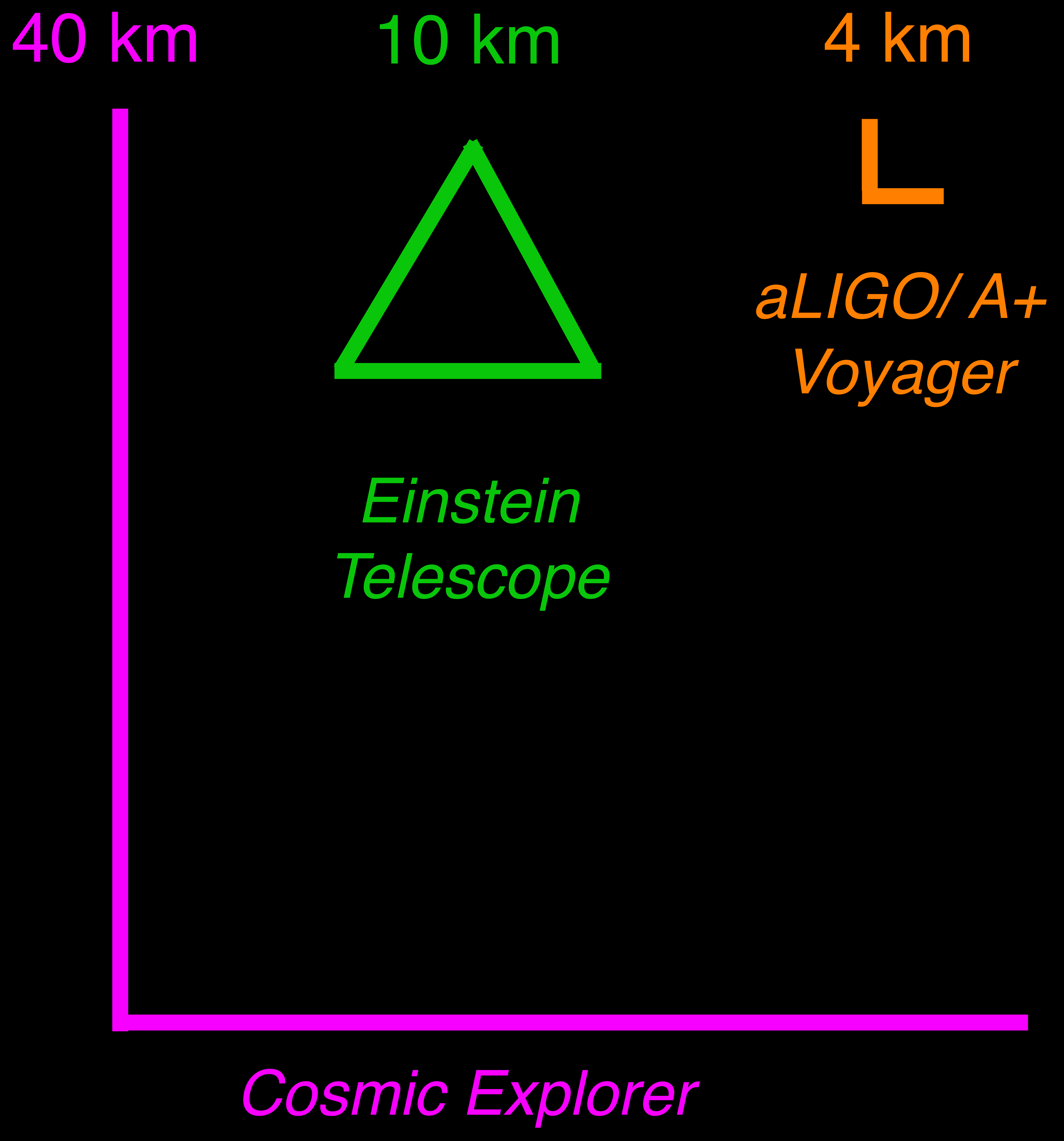
Cosmic Explorer 1
- 20-40 km detectors
  300 K
- 1-2 microns (?)
- 320 kg mirrors

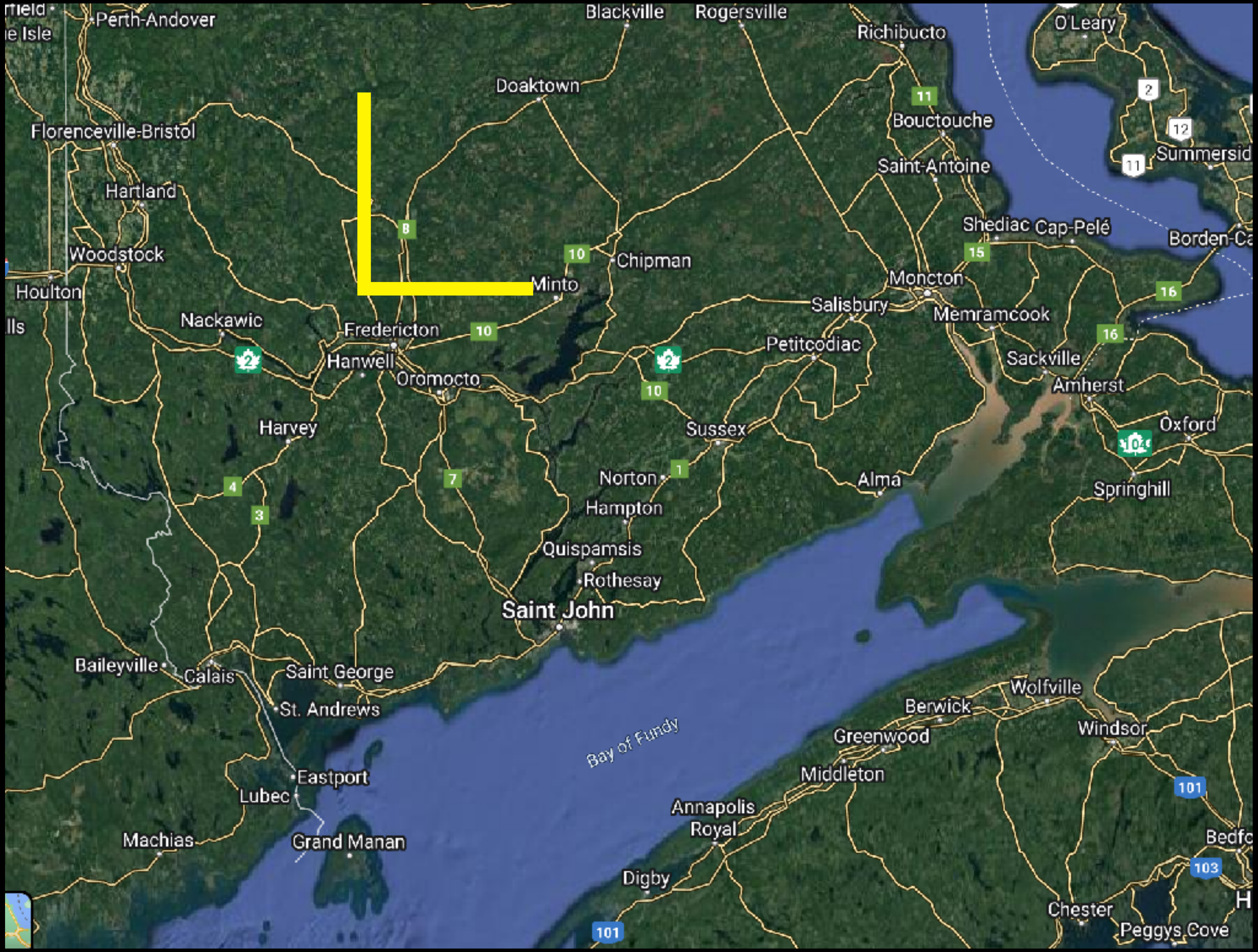


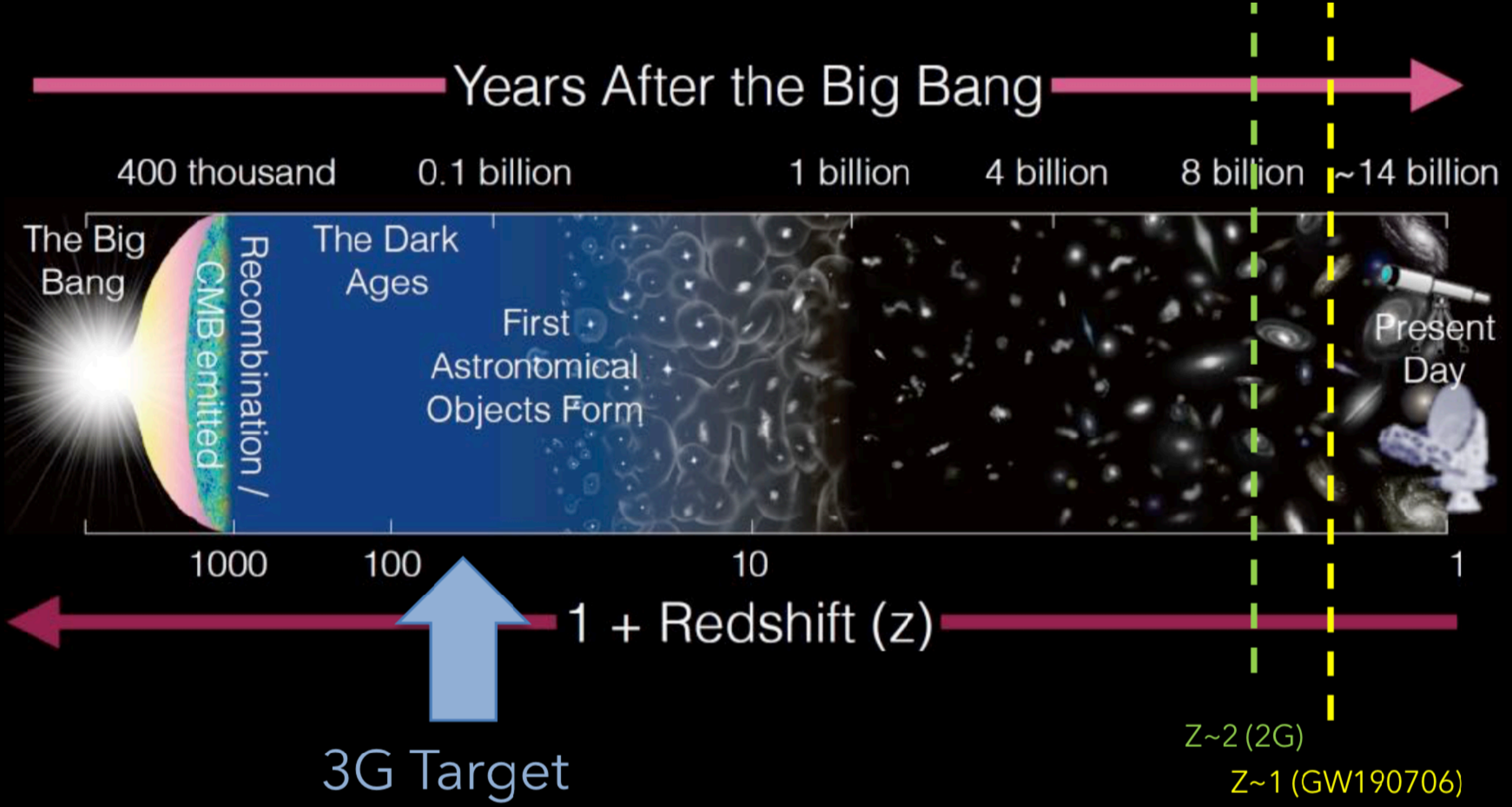


Dawn IV workshop report (McIver et al, 2019); Cosmic Explorer Astro 2020 decadal submission (Reitze et al 2020); Einstein Telescope Conceptual Design Study (Punturo et al 2020)

The next generation GW detectors





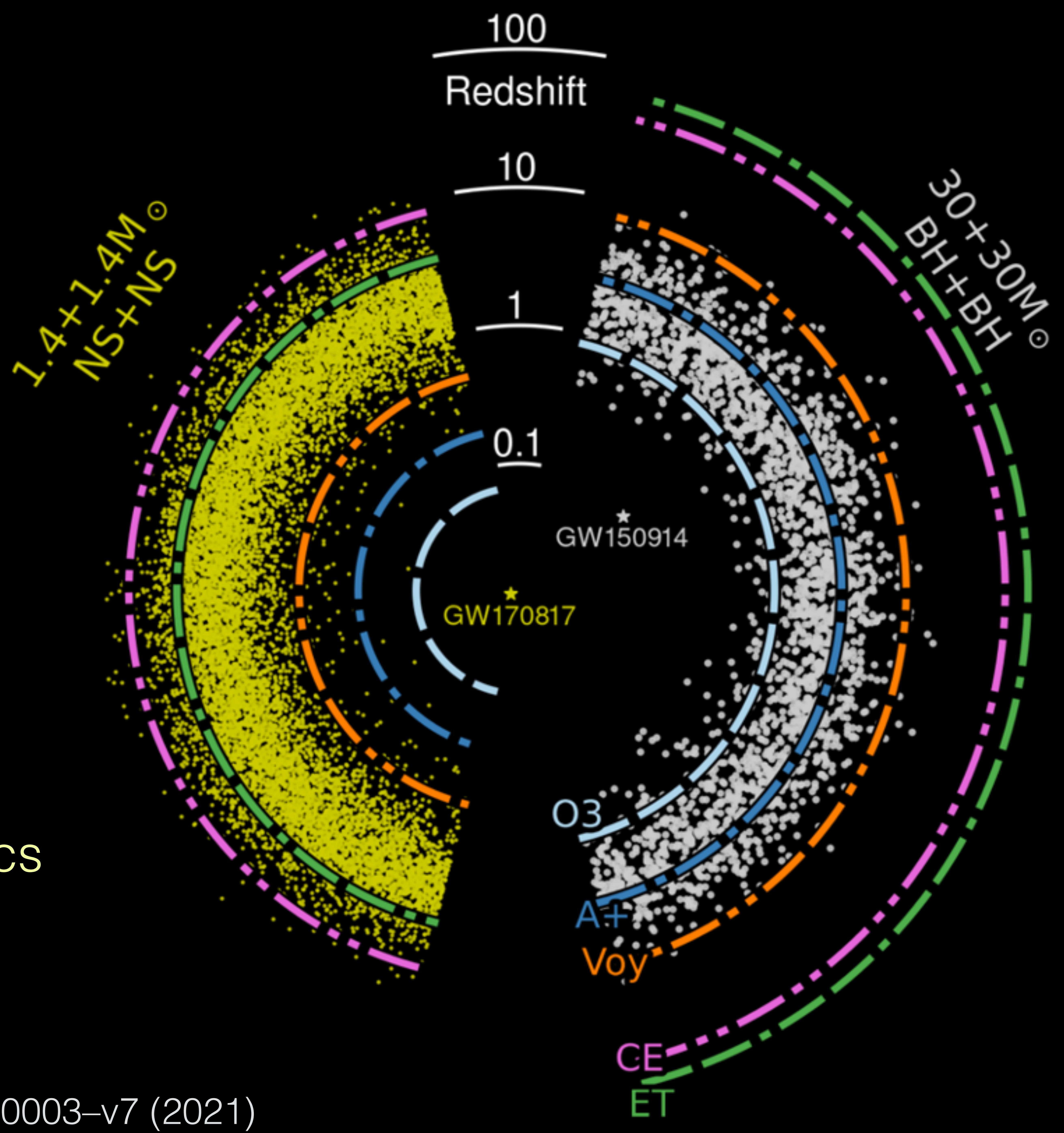


Slide by G. Losurdo

300,000 BNS mergers!

1 merger every 100 seconds!

~5 will have SNR >300, unlocking post merger physics (NS EoS)



100,000 BBH mergers!

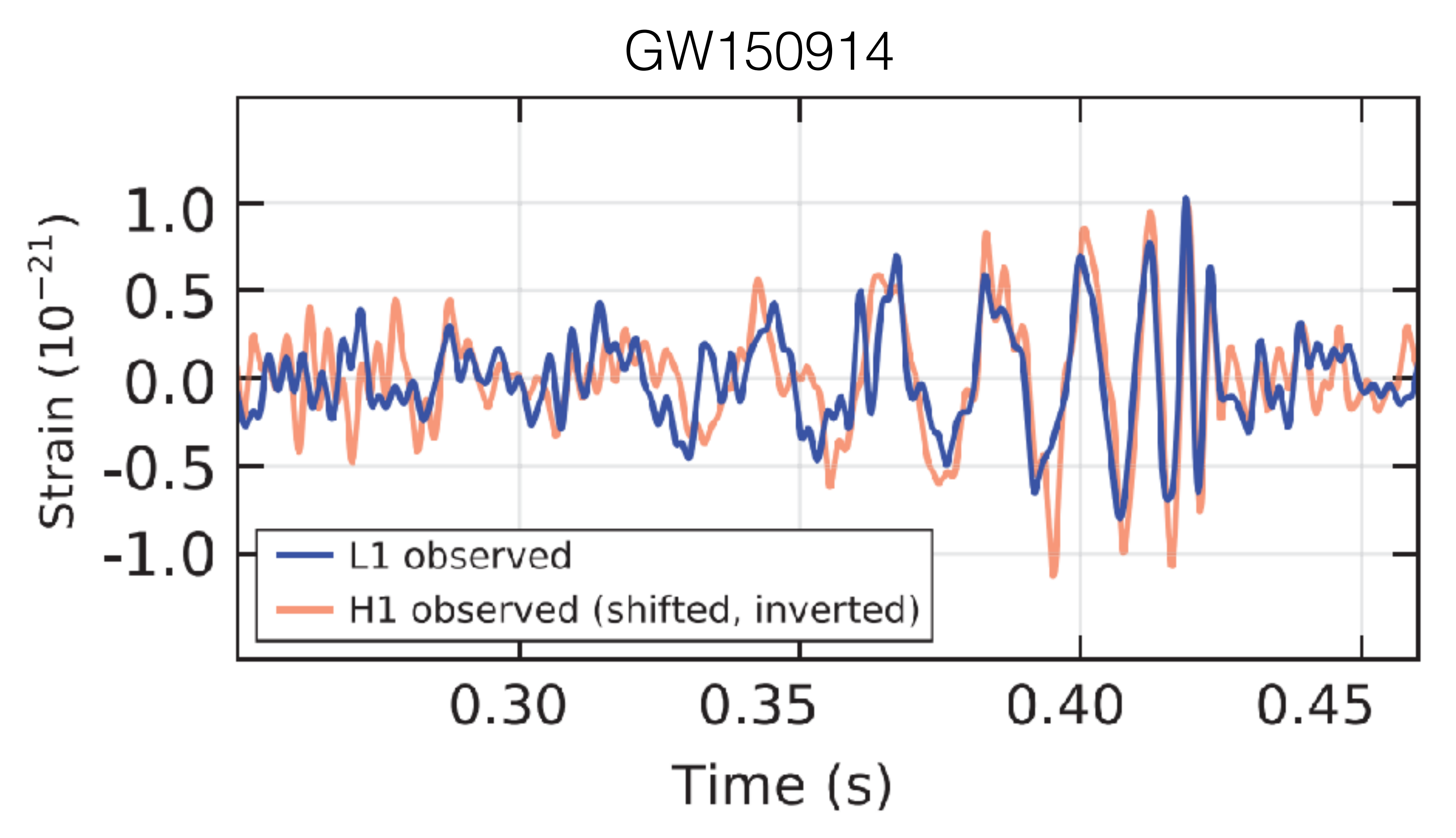
1 merger every 5 minutes!

~8 will be nearby (z<0.1) with median SNR of 600, up to SNR of ~2500!

Hall and Evans, 2019

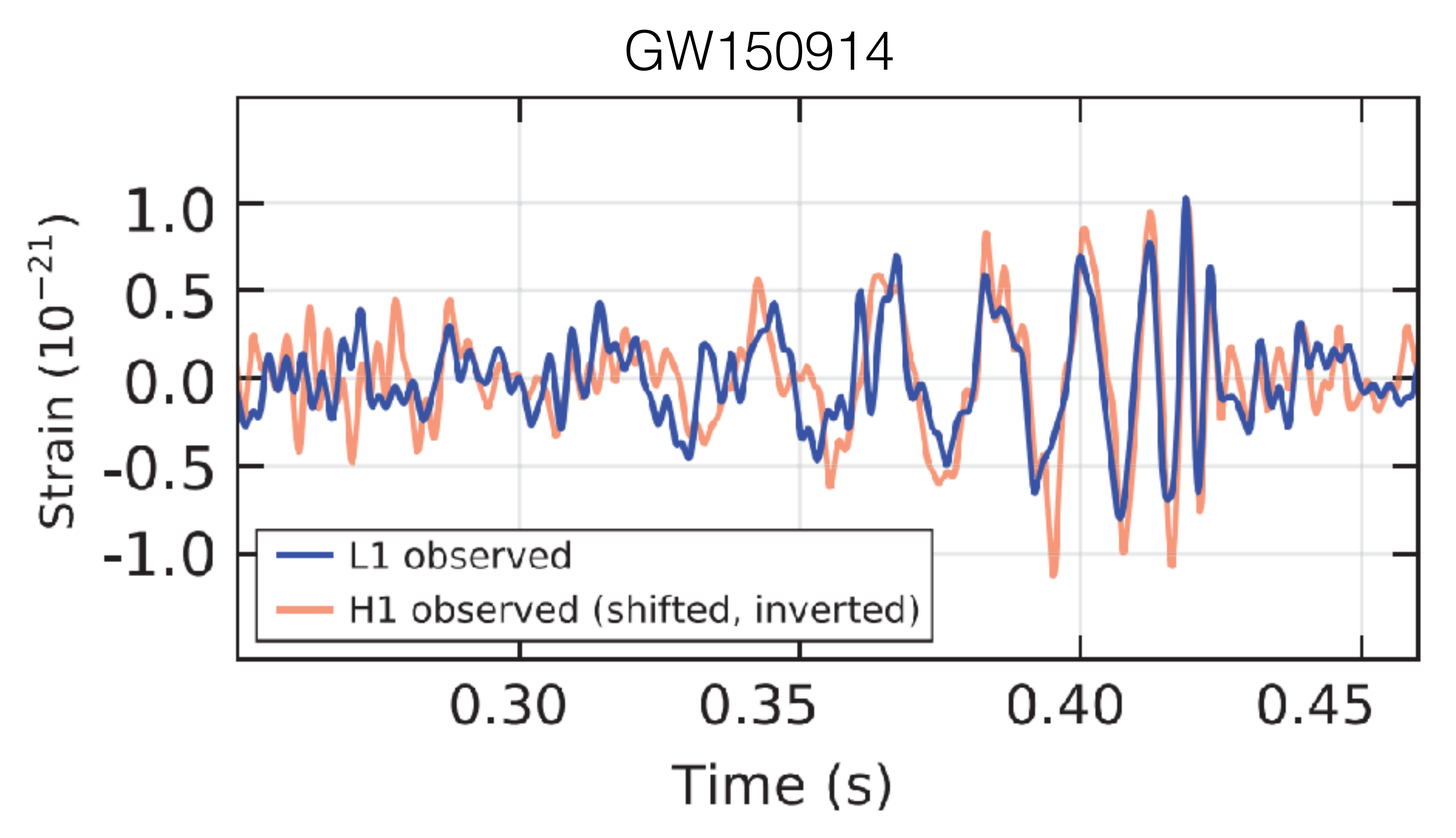
CE Horizon Study, CE–P2100003–v7 (2021)

Along with cosmological reach: large SNRs

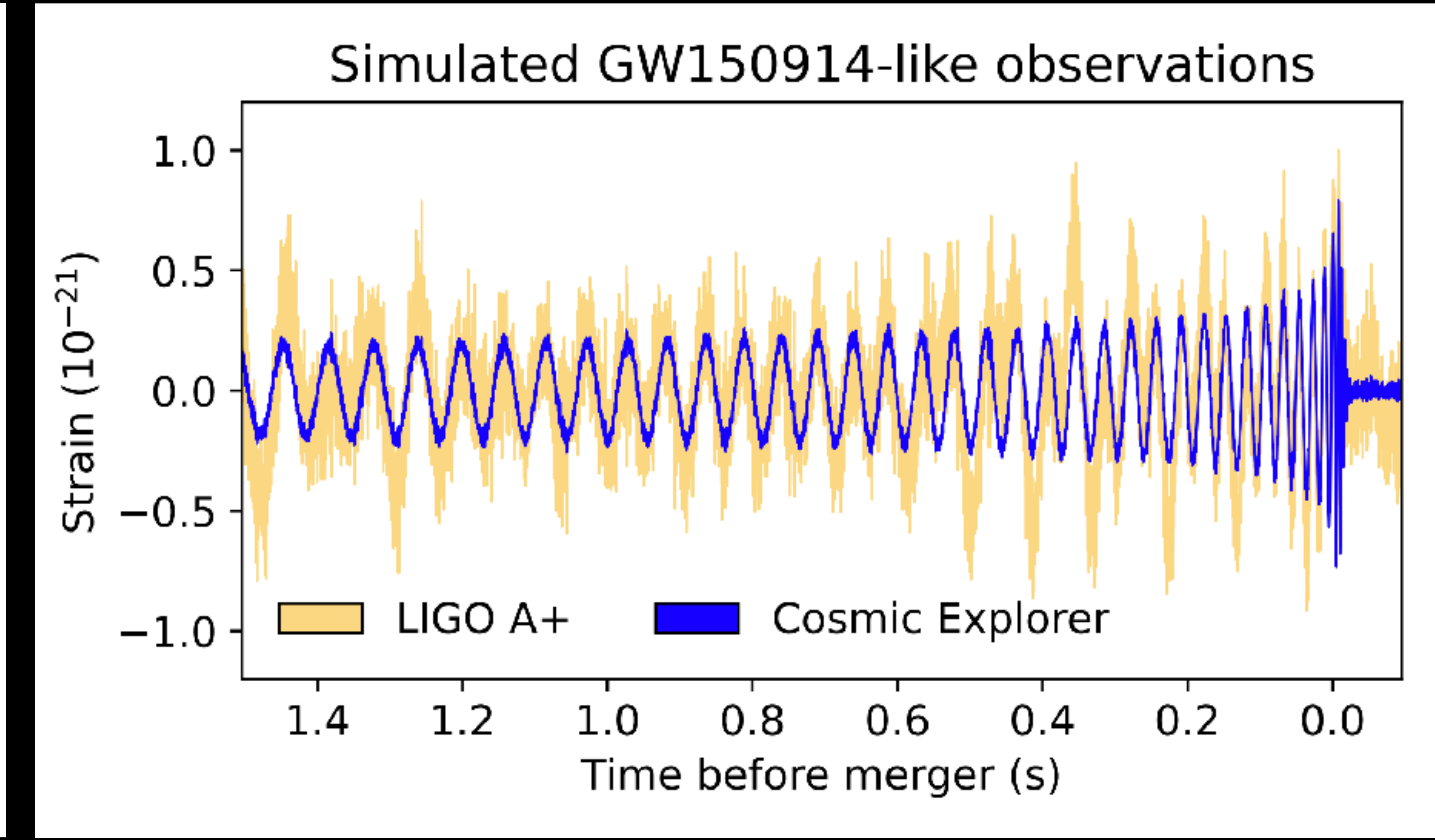


LIGO-Virgo, PRL 116.061102 (2016)

Along with cosmological reach: large SNRs



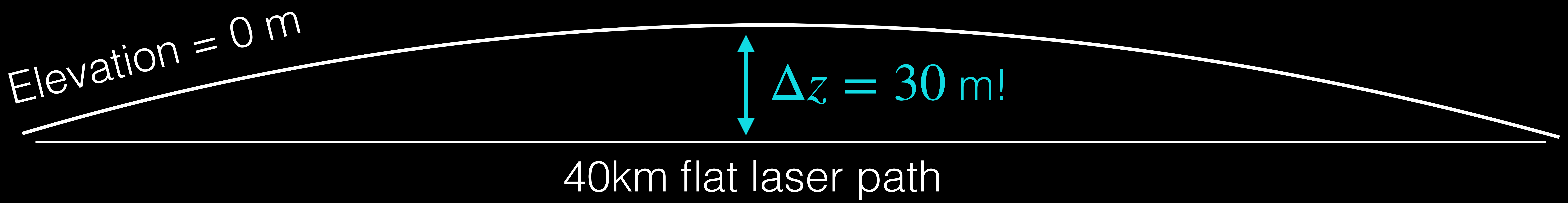
LIGO-Virgo, PRL 116.061102 (2016)



CE Horizon Study, CE–P2100003–v7 (2021)

Where would CE be built?

Where would CE be built?



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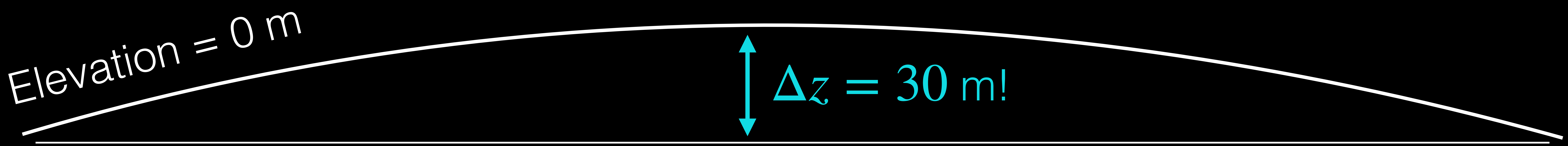
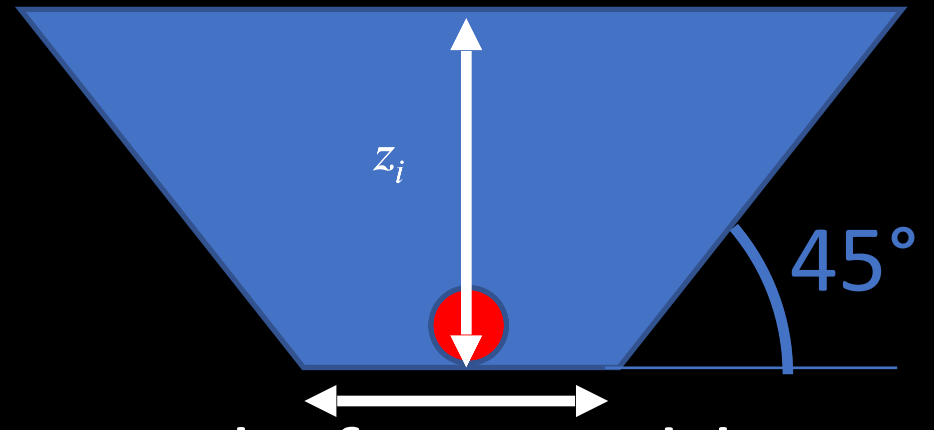


40km flat laser path

Digging/filling volume

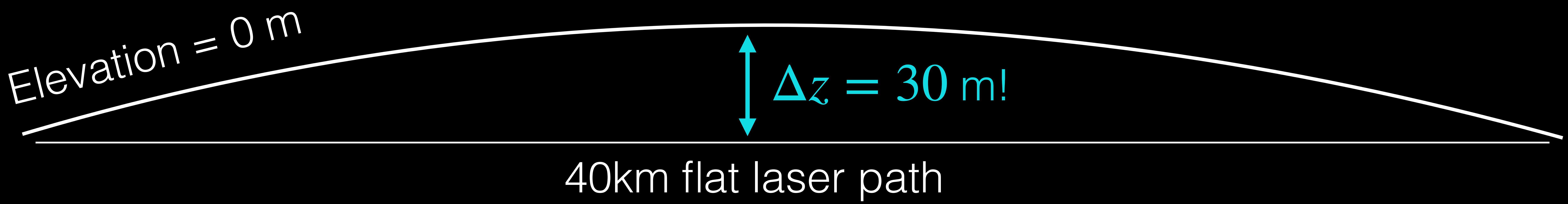


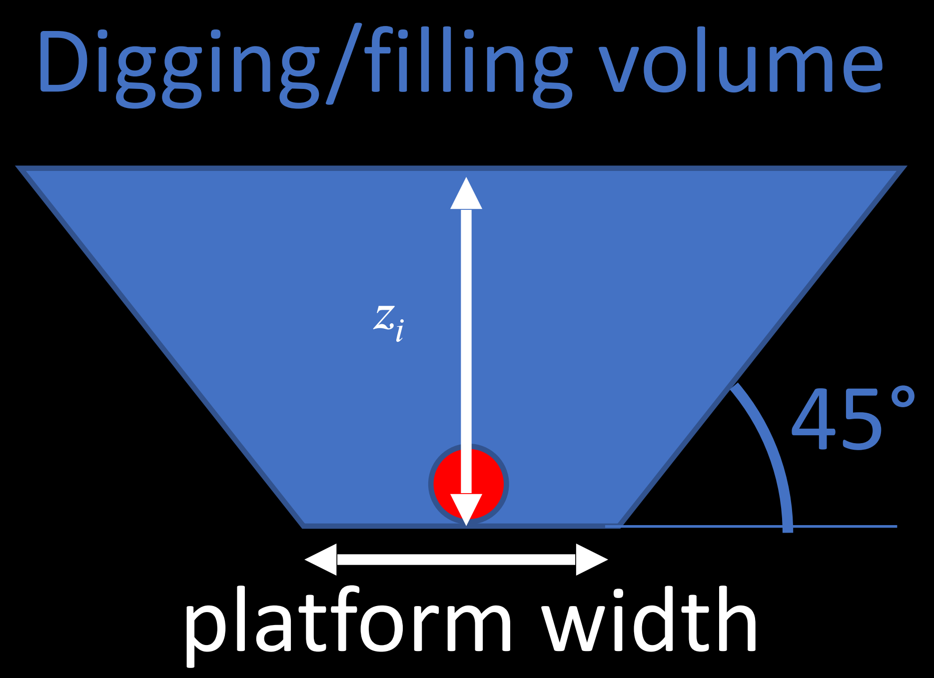
Assuming 4 m platform width and ~10\$/m³*

Analysis and slide by François Schiettekatte, UdeMontreal

* *Cosmic Explorer site and infrastructure*, Kevin Kuns for the Cosmic Explorer Project (September 2019) CE-G1901564

Where would CE be built?





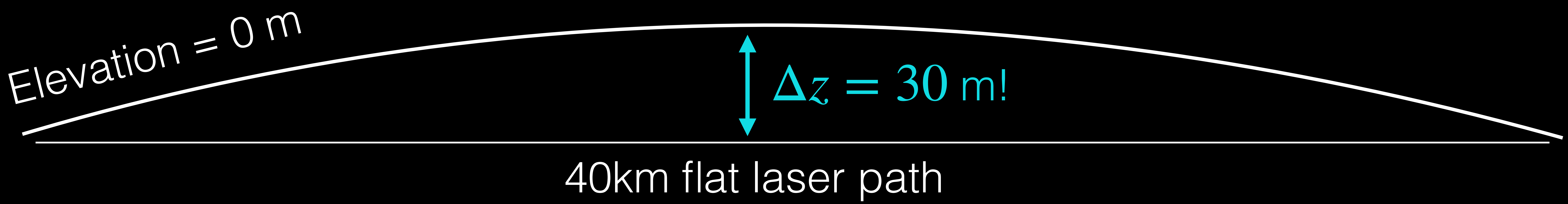
Assuming 4 m platform width and ~10$/m³*

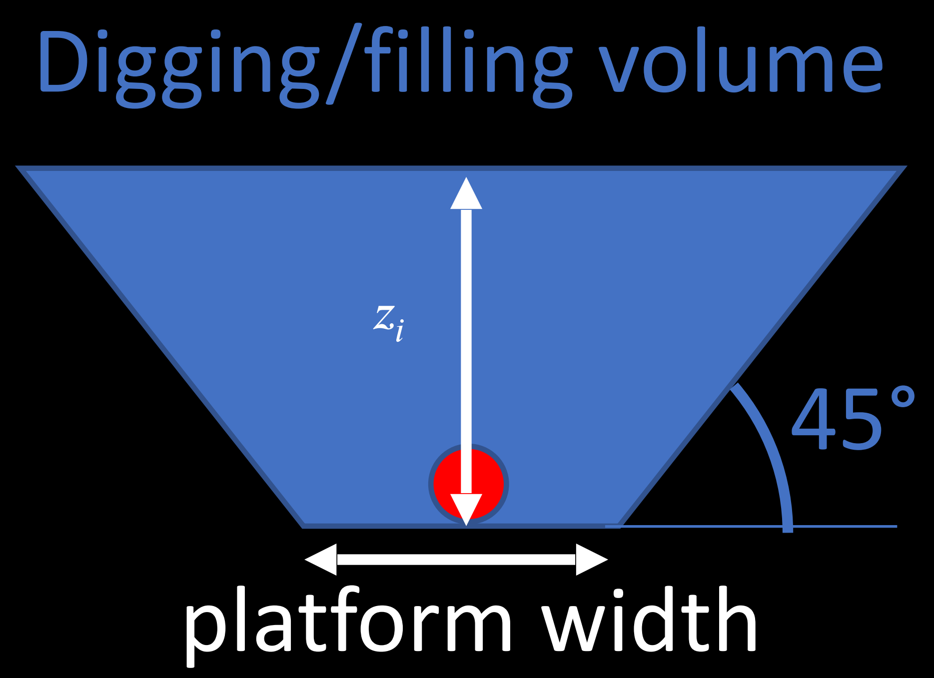
For each 40 km *arm*:
V = 43 000 x 10^3 m^3 (~430 M$)

Analysis and slide by François Schiettekatte, UdeMontreal

* *Cosmic Explorer site and infrastructure*, Kevin Kuns for the Cosmic Explorer Project (September 2019) CE-G1901564

Where would CE be built?





Assuming 4 m platform width and ~10$/m³*

For each 40 km *arm*:

V = 43 000 x 10^3 m^3 (~430 M$)

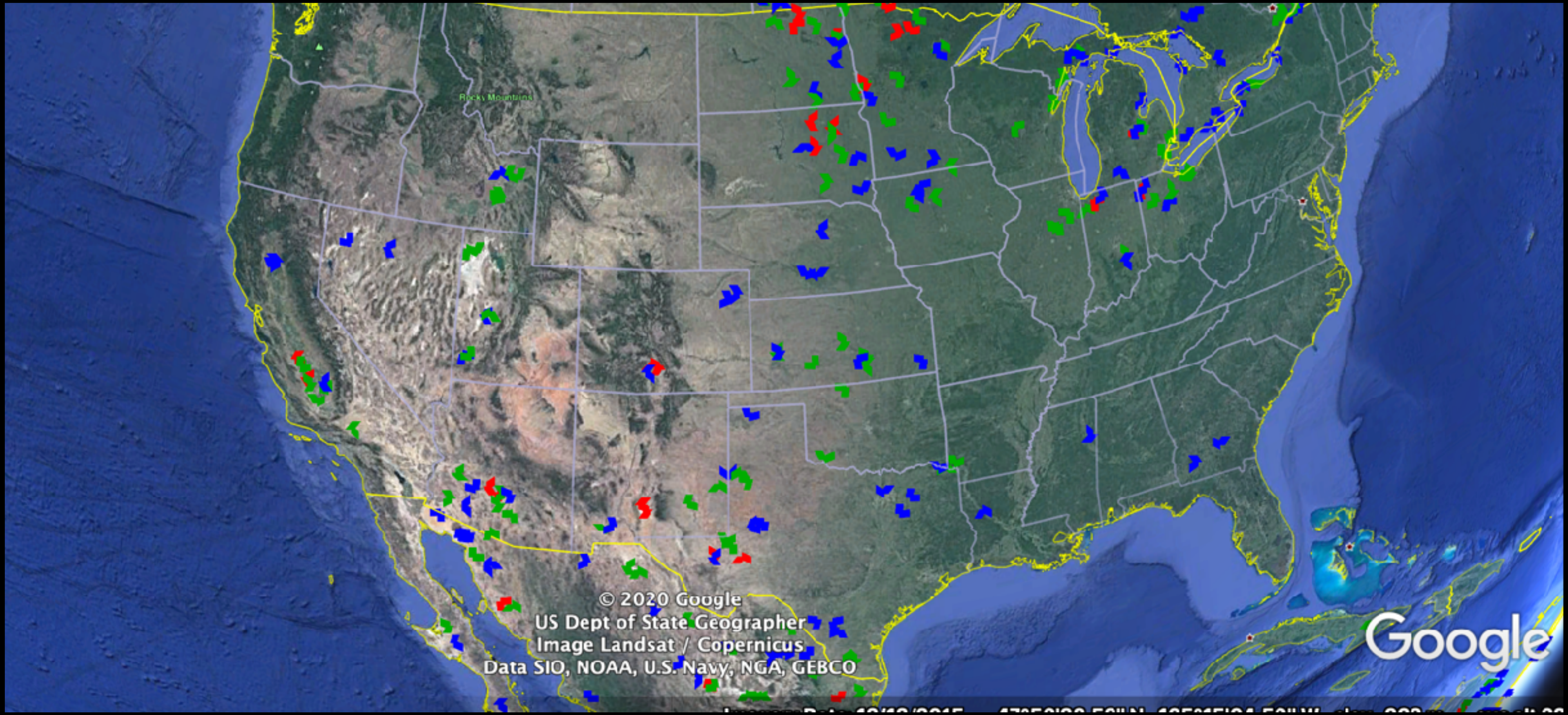
Choose a site with concave elevation such that $\Delta z \approx 0$

V = 375 x 10^3 m^3 (3-4 M$!!)

Analysis and slide by François Schiettekatte, UdeMontreal

* *Cosmic Explorer site and infrastructure*, Kevin Kuns for the Cosmic Explorer Project (September 2019) CE-G1901564

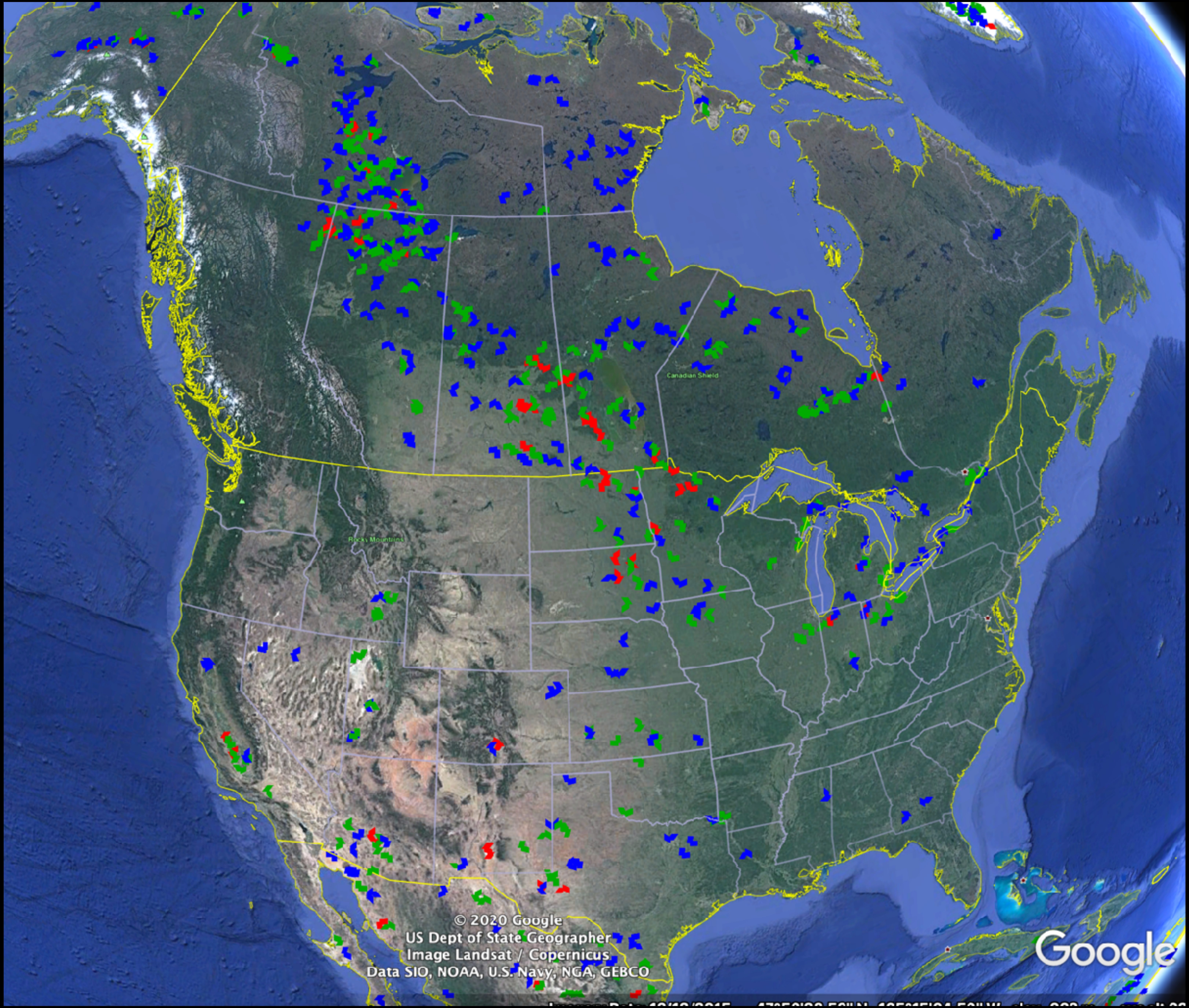
red
300-900
green
900-1400
blue
1400-2000
x 10^3 m^3



Analysis by François Schiettekatte, UdeMontreal

Based on approach by Kevin Kuns, MIT.
This is not a CE Consortium analysis

red
300-900
green
900-1400
blue
1400-2000
x 10^3 m^3



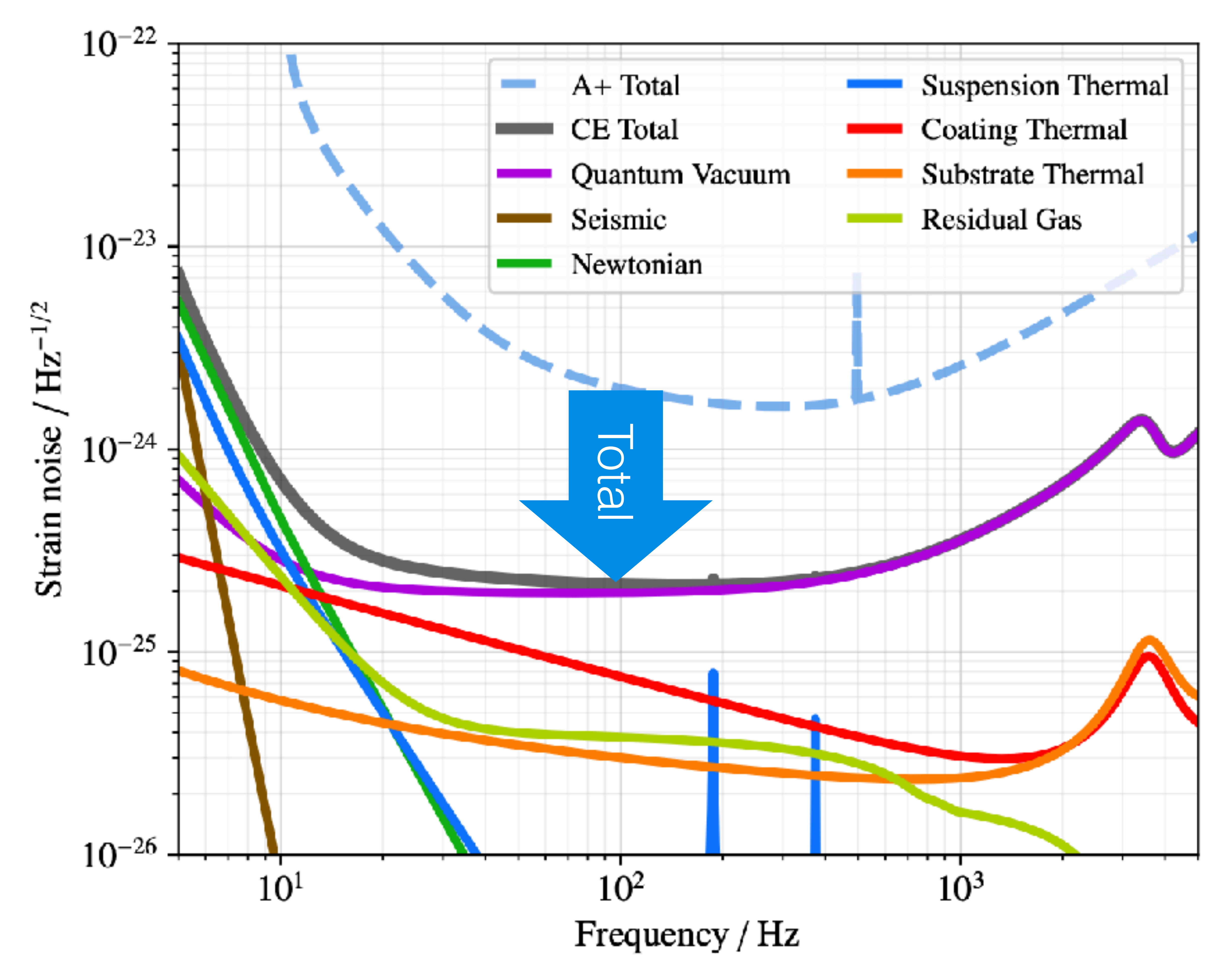
All sites overlap with unceded indigenous territories and/or nations.

Many locations in Canada!

Analysis by François Schiettekatte, UdeMontreal

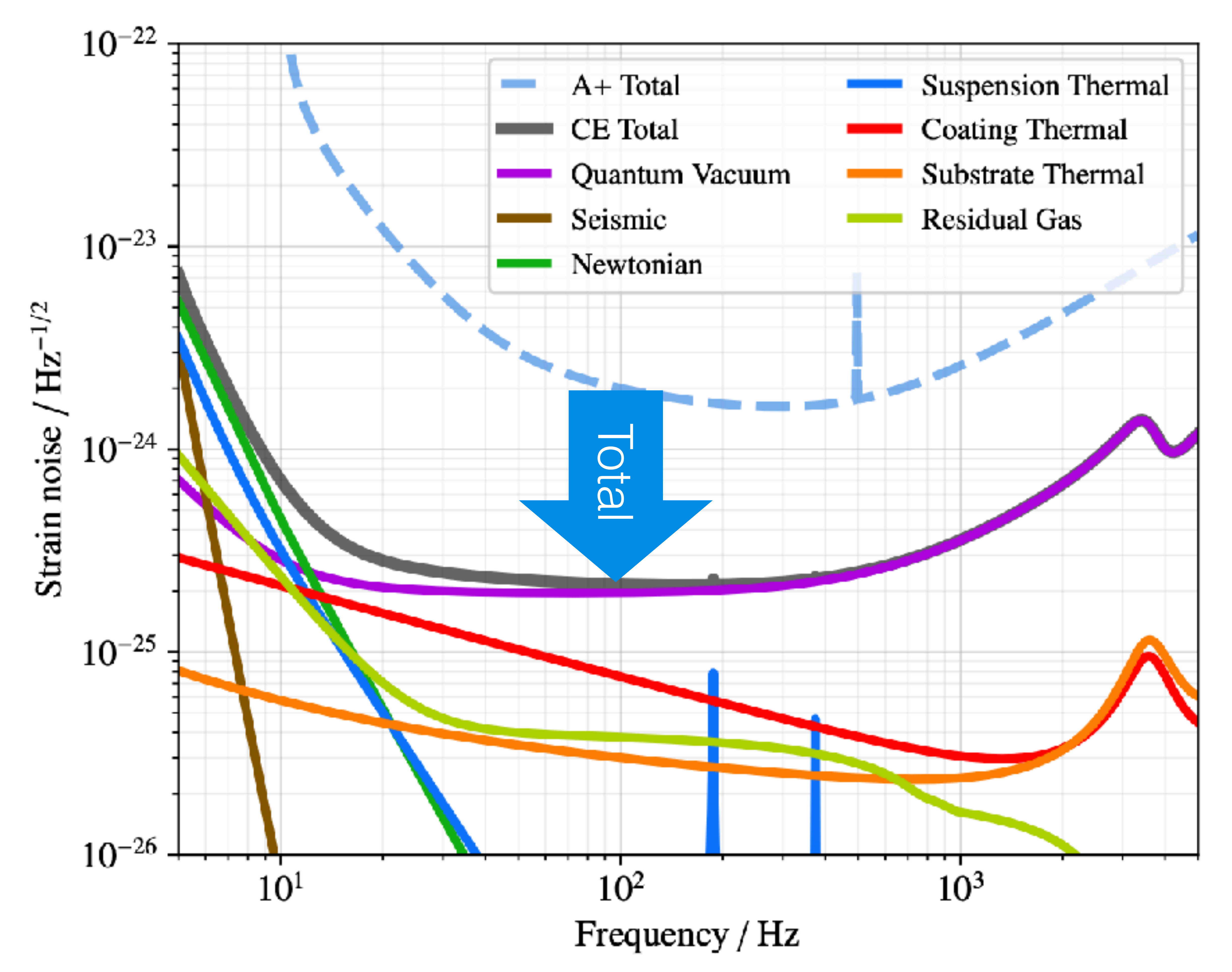
Based on approach by Kevin Kuns, MIT.
This is not a CE Consortium analysis

Cosmic Explorer noise budget



CE Horizon Study, CE–P2100003–v7 (2021)

Cosmic Explorer noise budget



	Quantity	Units	LIGO A+	CE	CE (2 µm)
	Arm length	km	4	40	40
	Laser wavelength	µm	1	1	2
	Arm power	MW	0.8	1.5	3
	Squeezed light	dB	6	10	10
	Susp. point at 1 Hz	pm/$\sqrt{\text{Hz}}$	10	0.1	0.1
Test masses	Material		Silica	Silica	Silicon
	Mass	kg	40	320	320
	Temperature	K	293	293	123
Suspensions	Total length	m	1.6	4	4
	Total mass	kg	120	1500	1500
	Final stage blade		No	Yes	Yes
Newtonian noise	Rayleigh wave suppr.	dB	0	20	20
	Body wave suppr.	dB	0	10	10
Optical loss	Arm cavity (round trip)	ppm	75	40	40
	SEC (round trip)	ppm	5000	500	500
	BNS horizon redshift		0.19	8.3	11.7
	BBH horizon redshift		2.7	41	41
	BNS SNR, $z = 0.01$		75	1260	1460
	BNS warning, $z = 0.01$	min	4	103	103

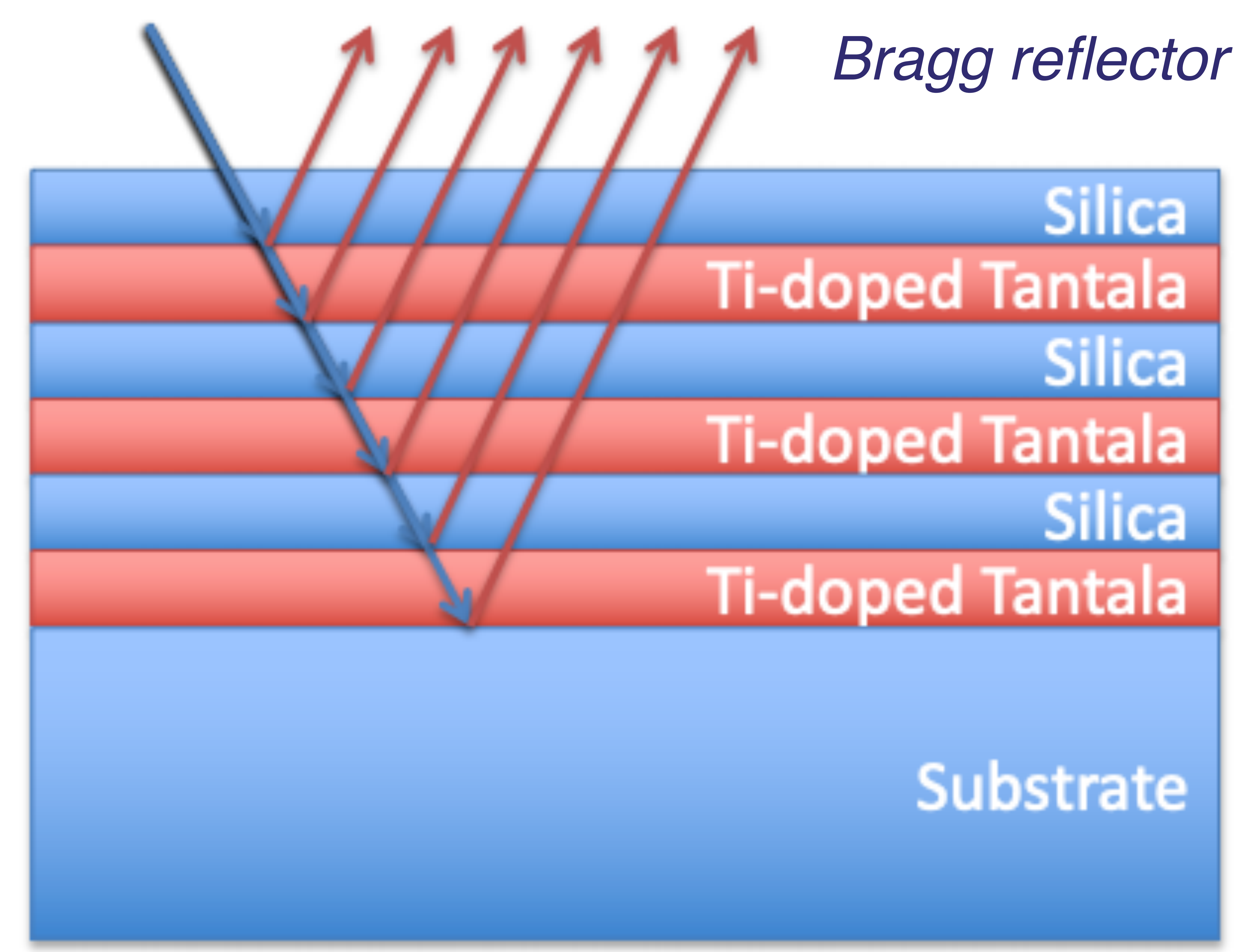
CE Horizon Study, CE–P2100003–v7 (2021)

The GW detector coatings team at the Stewart Blusson Quantum Matter Institute

LIGO @ Université de Montréal/Polytechnique Montréal

Coatings thermal noise: where are we starting from?

Current aLIGO coatings at *room temperature:*



- high reflectivity > 99.9995 %
- low absorption < 0.5 ppm
- scattering < 13 ppm

Material	Refractive index	Loss angle
Silica SiO_2	1.45	0.4×10^{-4}
Titania-doped tantala Ta_2O_5-TiO_2	2.07	~3.6×10^{-4}

Coating thermal noise: a materials breakthrough is needed

Temperature

Coating thickness

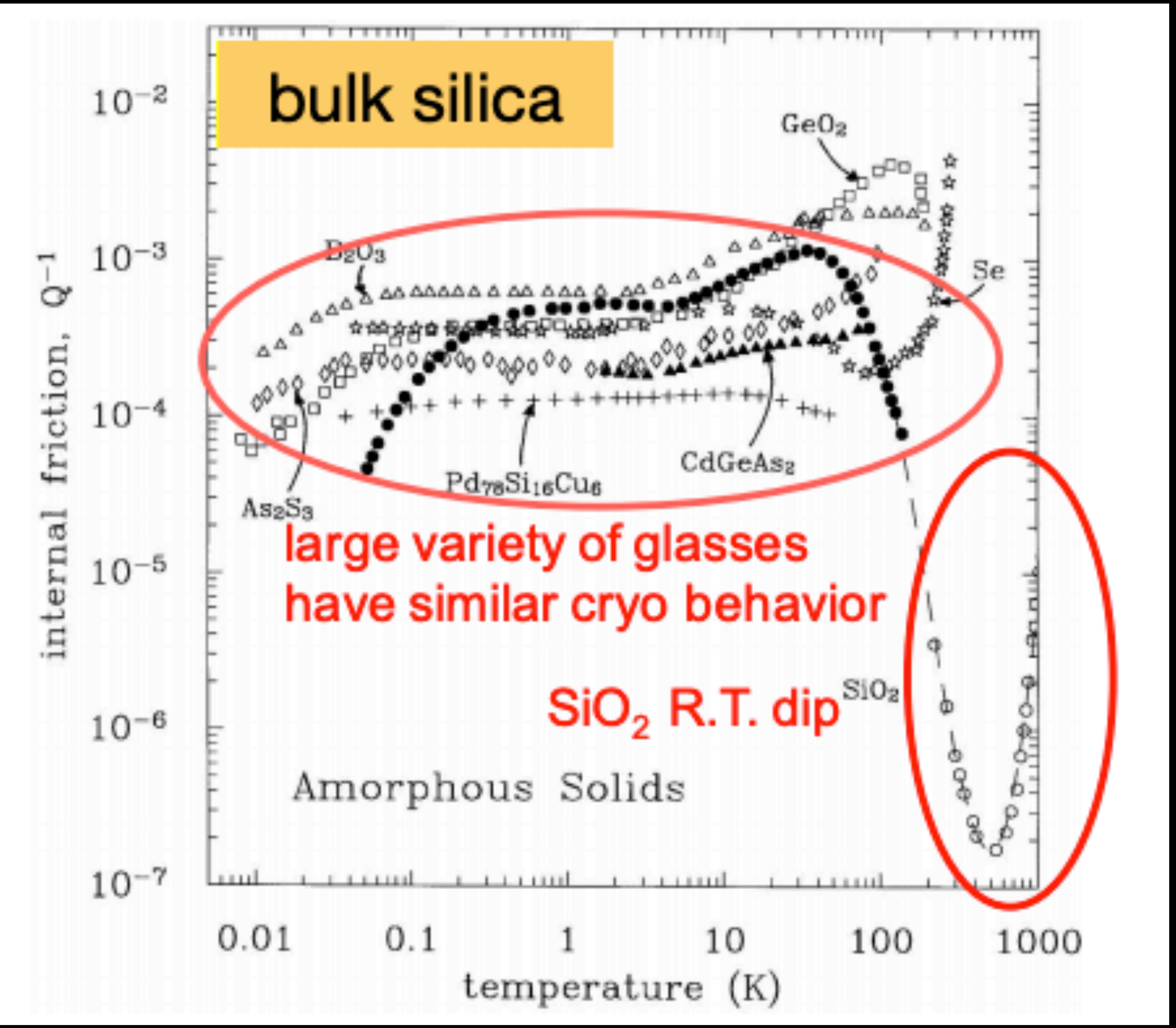
$$S_x(f) = \frac{4k_BT}{\pi^2 f}\frac{d}{Y_s\omega^2}\phi$$

Mechanical loss (much higher for current materials at lower temp)

Substrate Young's modulus

Beam radius

Harry et al. 2002



K.A. Topp Physik B Condensed Matter 101 235-45 (1996)

Still need (for target laser wavelength):

- High reflectivity
- Low absorption
- Low scattering

Up to 60 cm diameter mirrors.

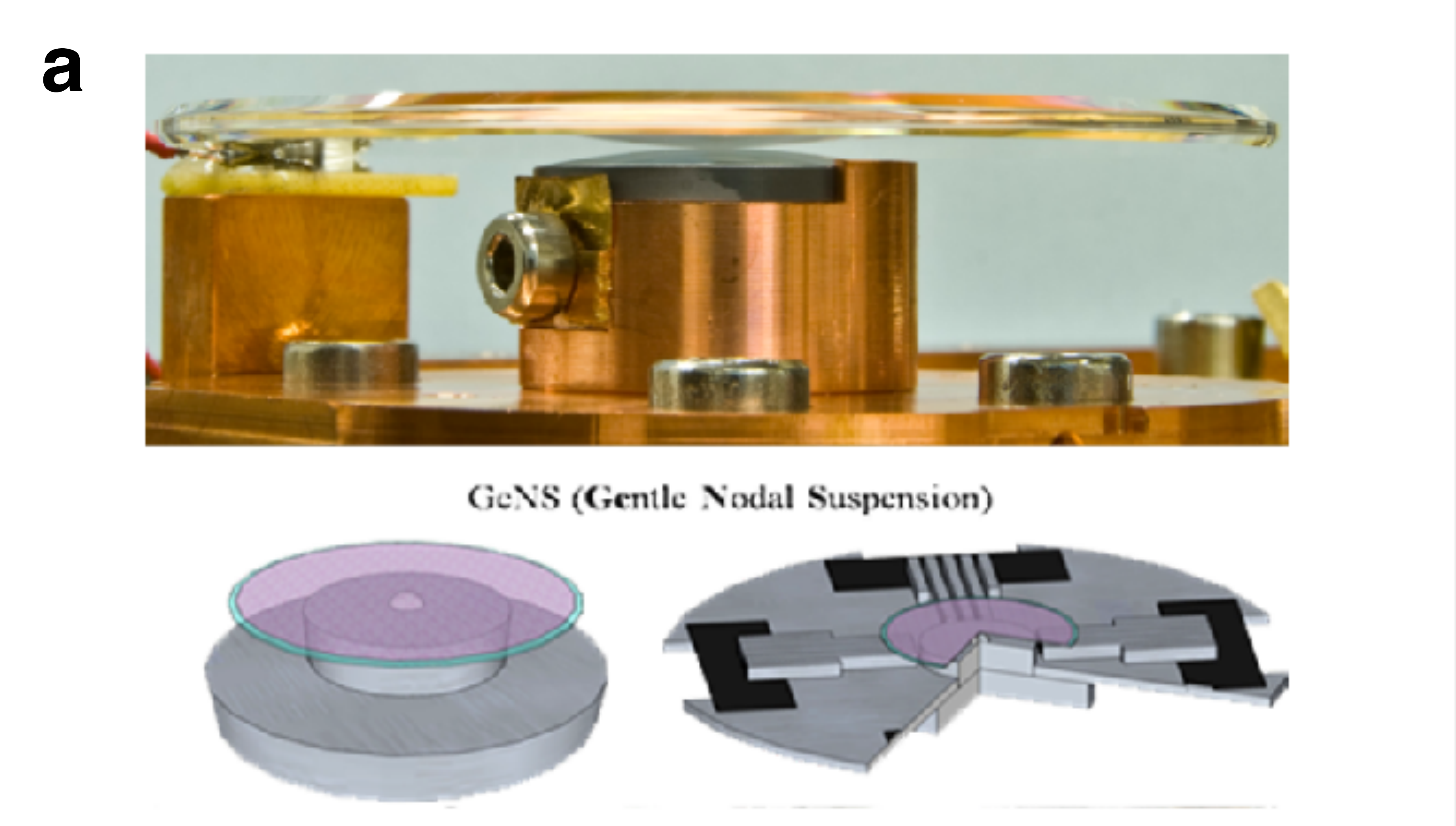
Doped Germanium? *Crystalline GaAs/AlGaAs ?*

Amorphous SiO_2/Si? *TiO2:GeO2 ?*

Current methods of measuring loss angle

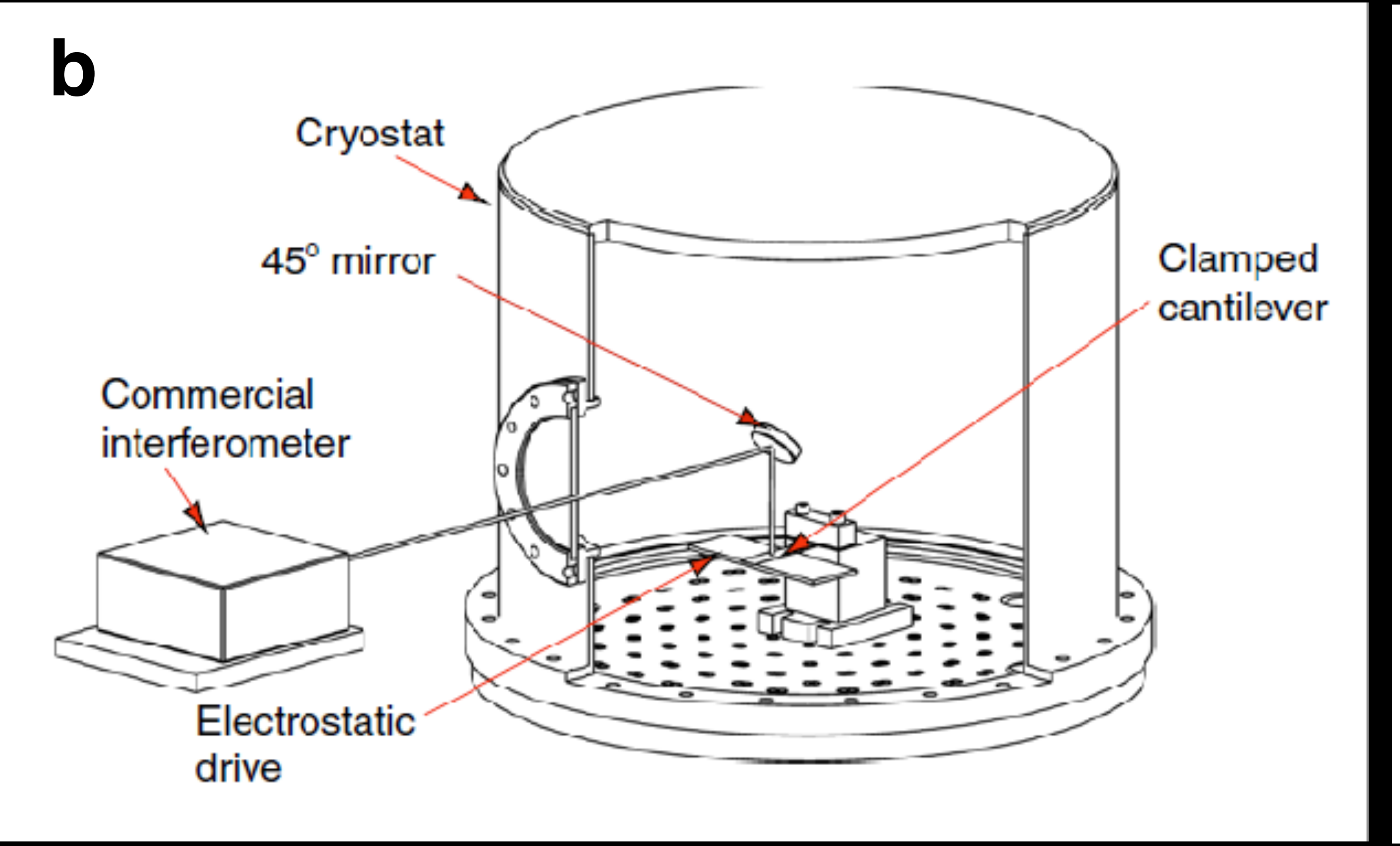
- Very high quality!
- Low throughput
- Tend to require a larger amount of material to be tested

Gentle Nodal Suspensions (GeNS)



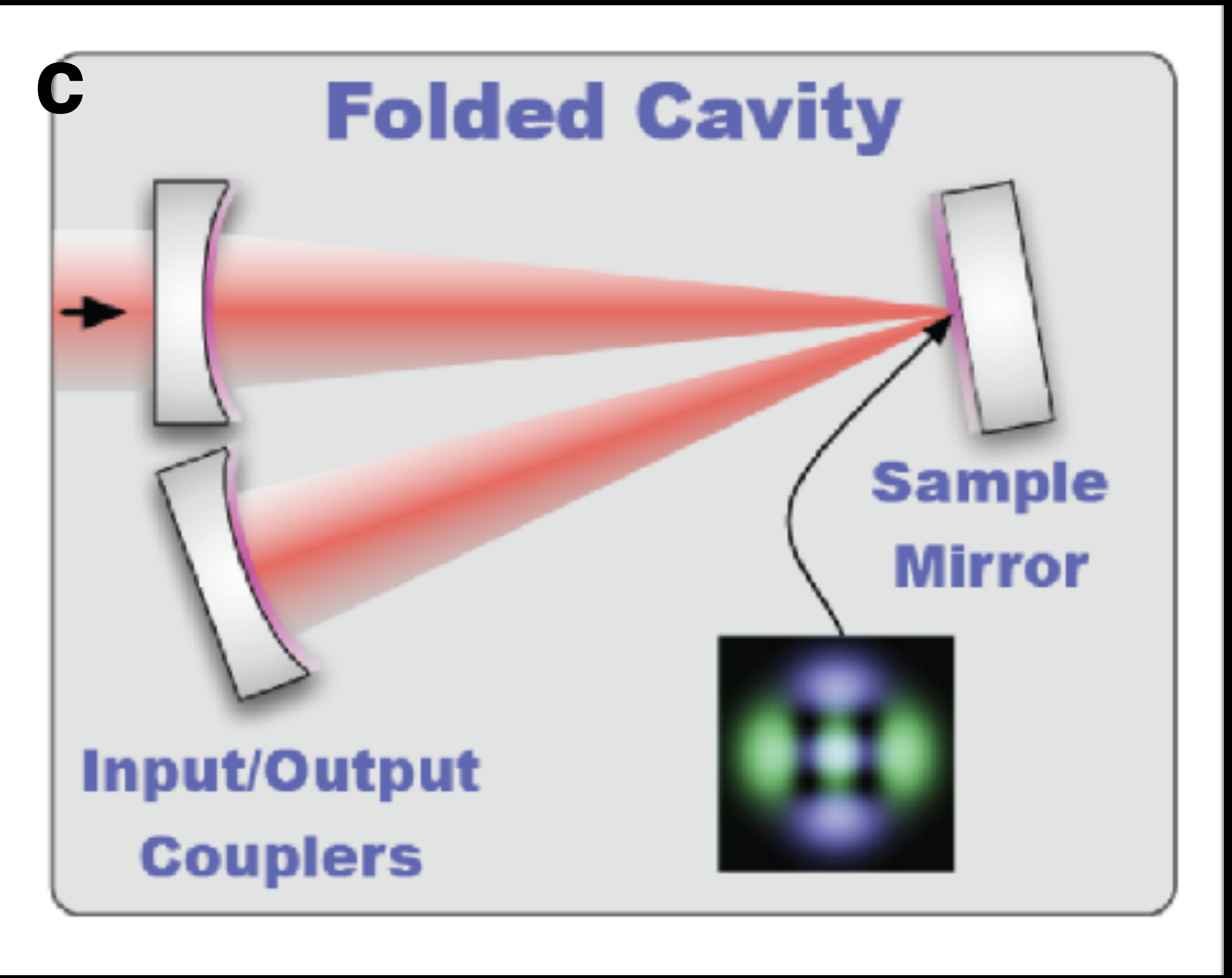
Cesarini, E. *et al. Proceedings of Gravitational-waves Science&Technology Symposium — PoS(GRASS2018)* 006 (2018)

Large cantilever



Martin, I. *et al. Class. Quantum Grav.* **25**, 055005 (2008).

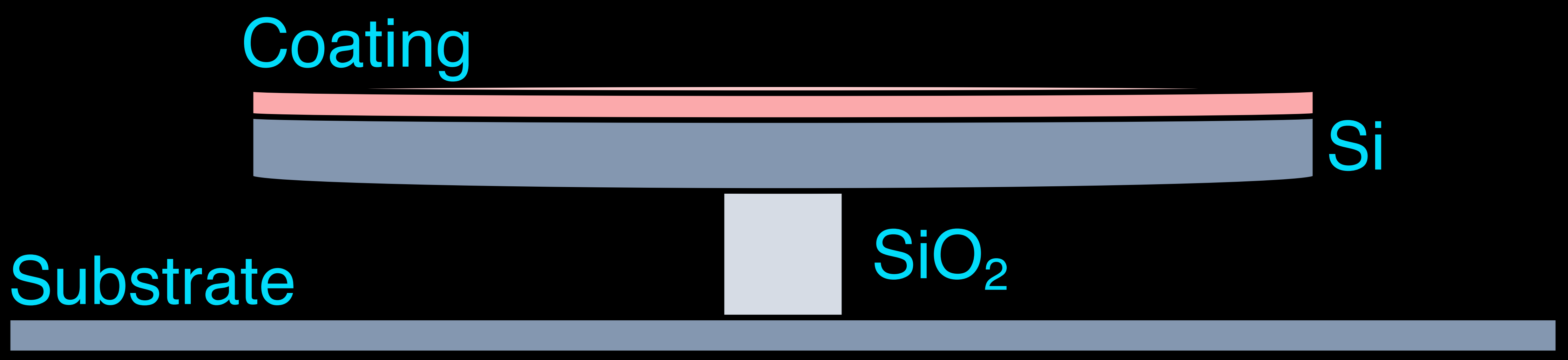
Folded cavity



Gras, S. & Evans, M. *Phys. Rev. D* **98**, 122001 (2018)

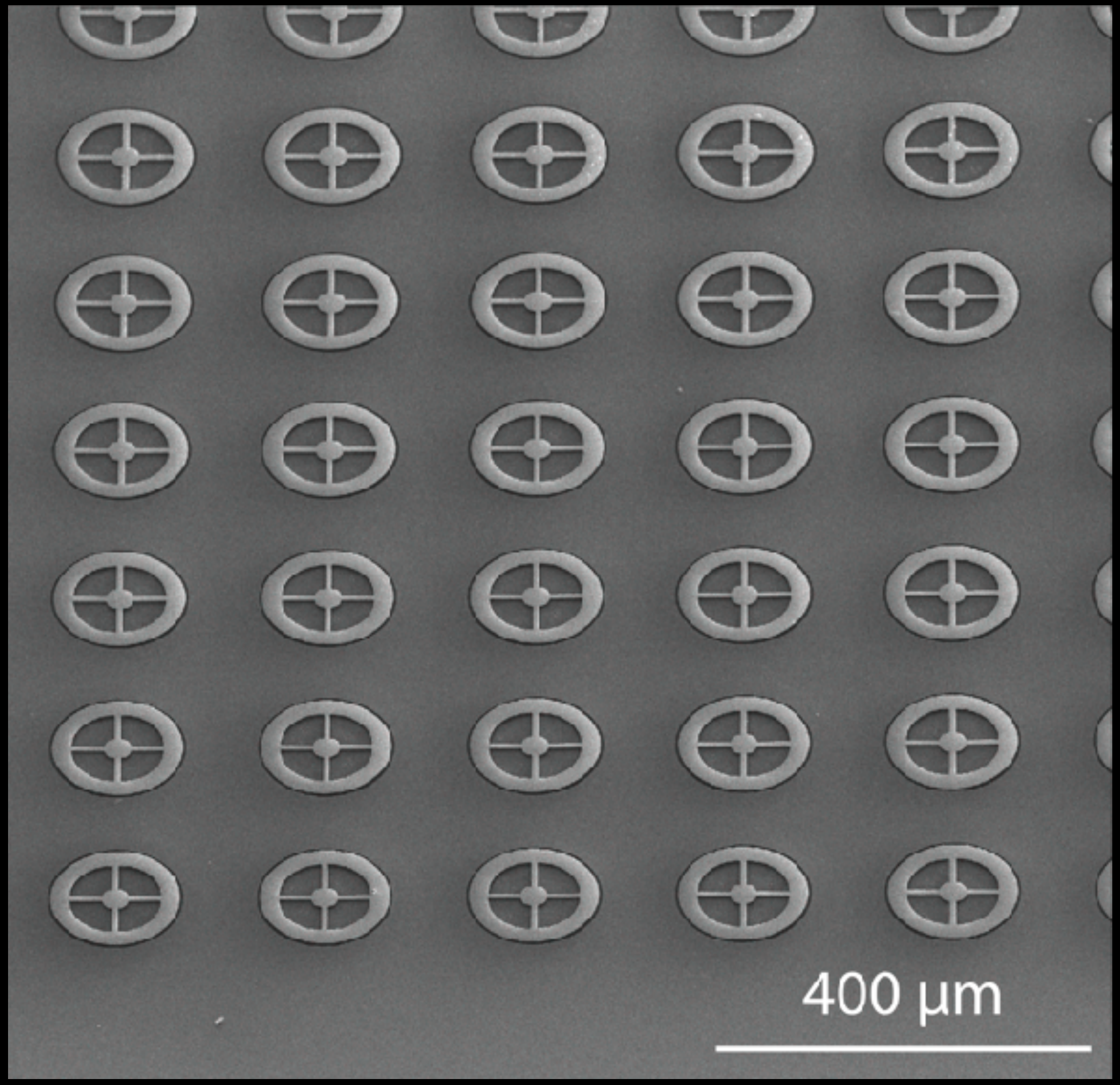
UBC's method of measuring loss angle

The UBC team uses microdisks fabricated from silicon-on-insulator (SOI) wafer



Kirsty Gardner

- ~100 microdisks per chip enables high throughput testing
- Microdisks use minimal material for testing

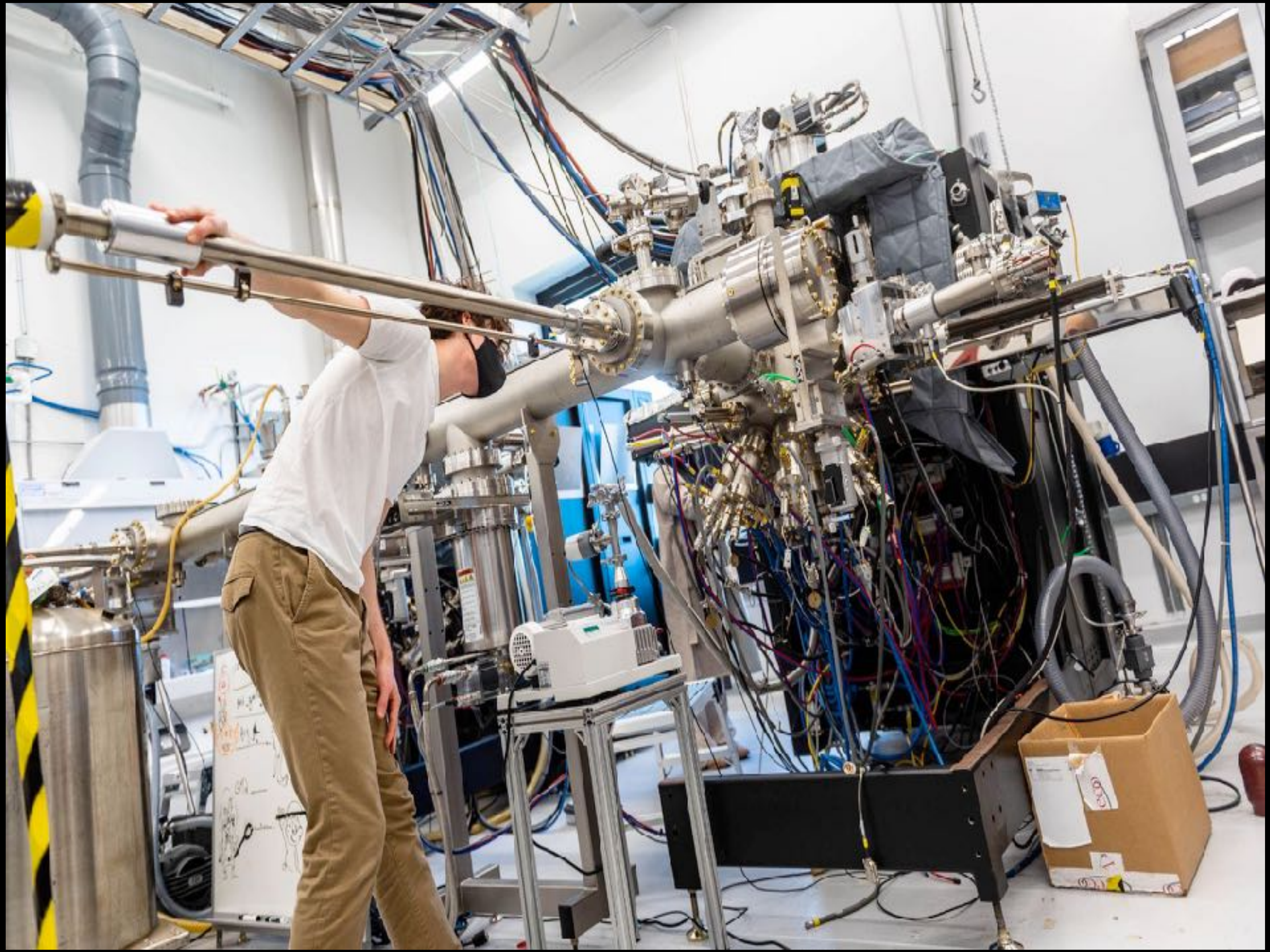


Matthew Mitchell

Molecular Beam Epitaxy deposition

Developing GW detector coatings at SBQMI

MBE system at UBC.

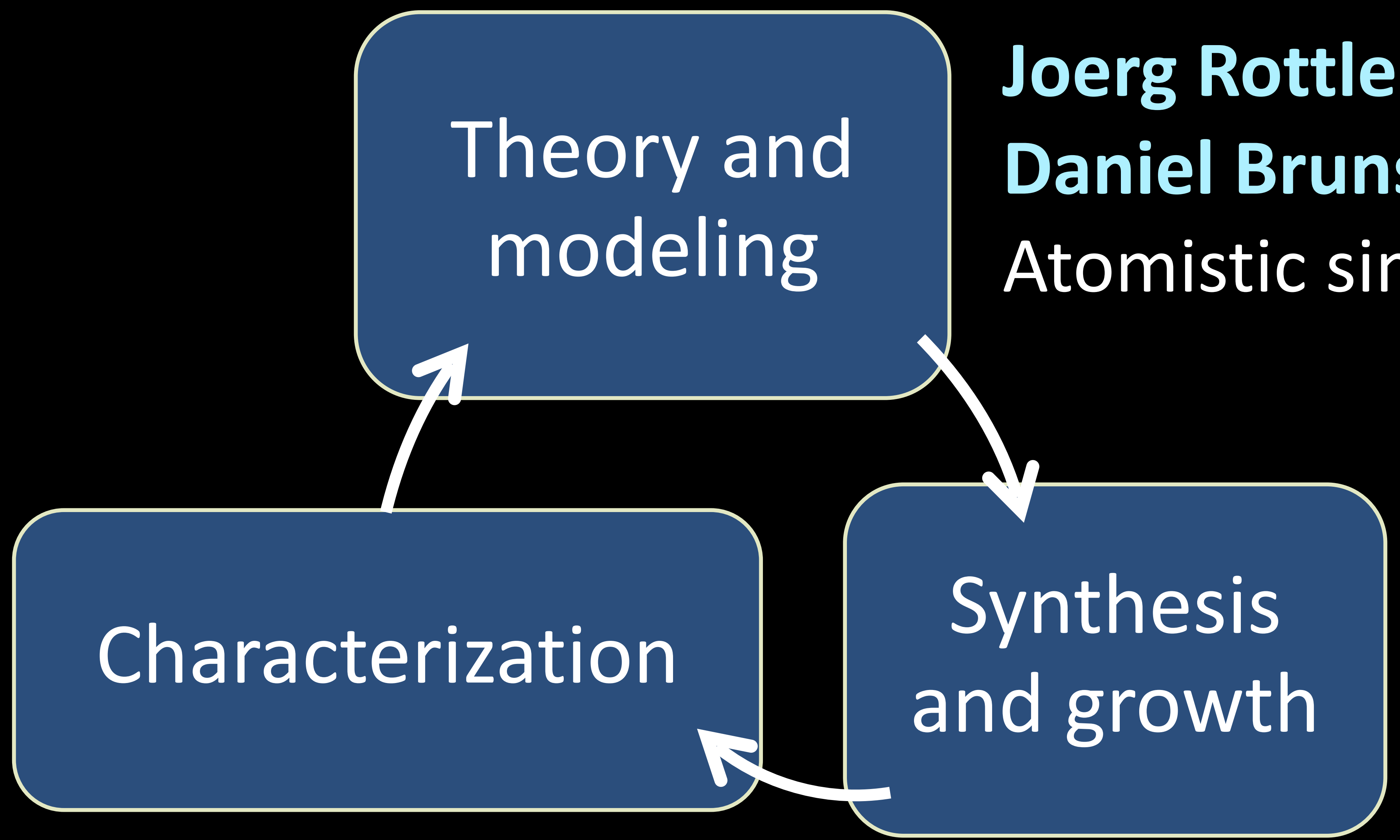


- High quality thin films
- Large variety of materials (Ti, Ni, La, Nd, Sr, Mg, Ag, Fe, Ge, Te, Bi, and Se)
- Ultra-high vacuum chamber (10^{-11} Torr) to minimize chamber impurities
- Amorphous growth at low temperature and crystal growth at high temperature

Slide by Dr. Kirsty Gardner

Developing GW detector coatings at SBQMI

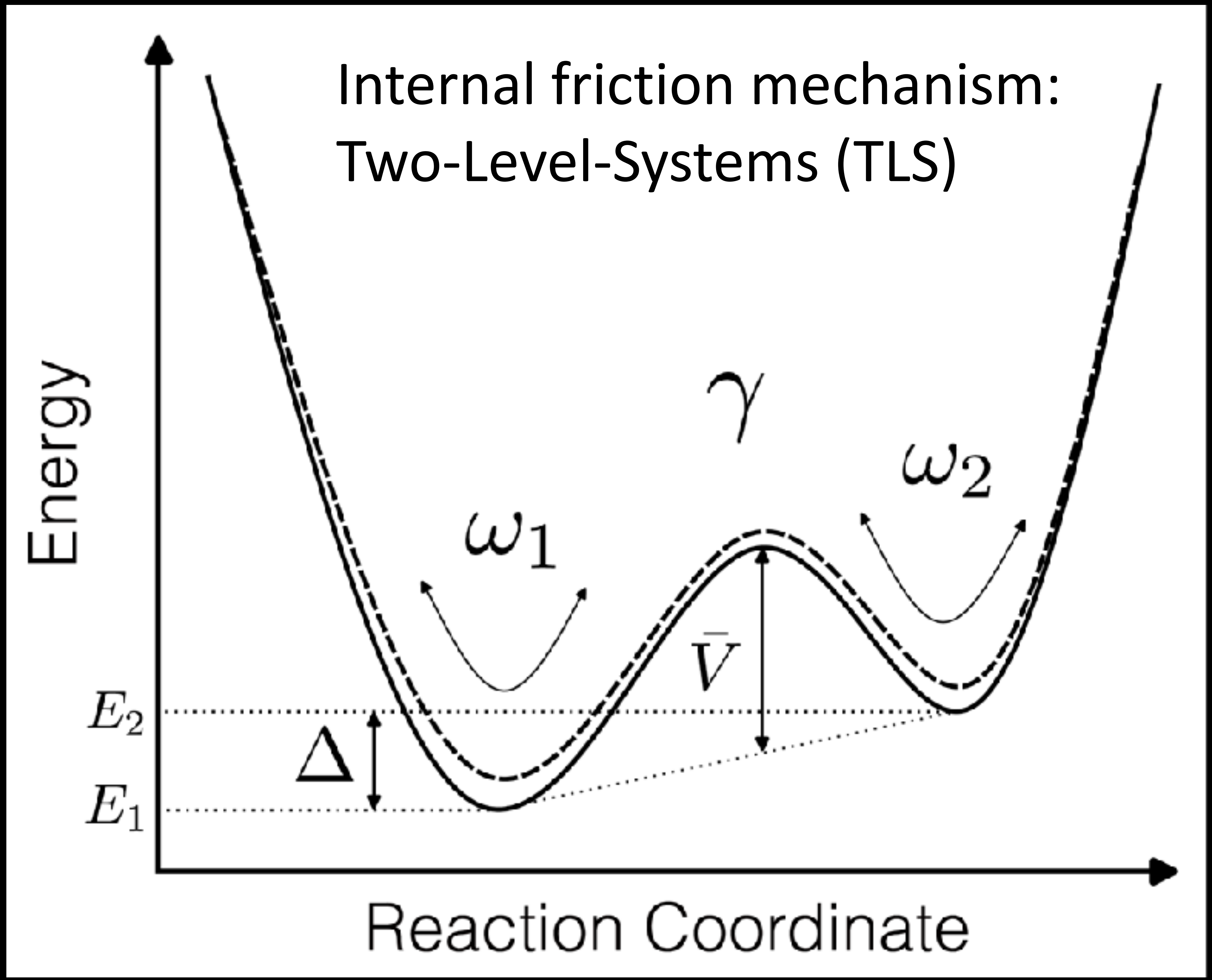
Jess McIver
Liaise with the LIGO collaboration and GW community



Joerg Rottler, Daniel Wong, Daniel Bruns, Steven Blaber
Atomistic simulations

Jeff Young, Kirsty Gardner, Matthew Mitchell
Measure mechanical loss of synthesized materials

Ke Zou, Fengmiao Li
Thin film growth of candidate materials



New Frontiers in Research Fund
Fonds Nouvelles frontières en recherche

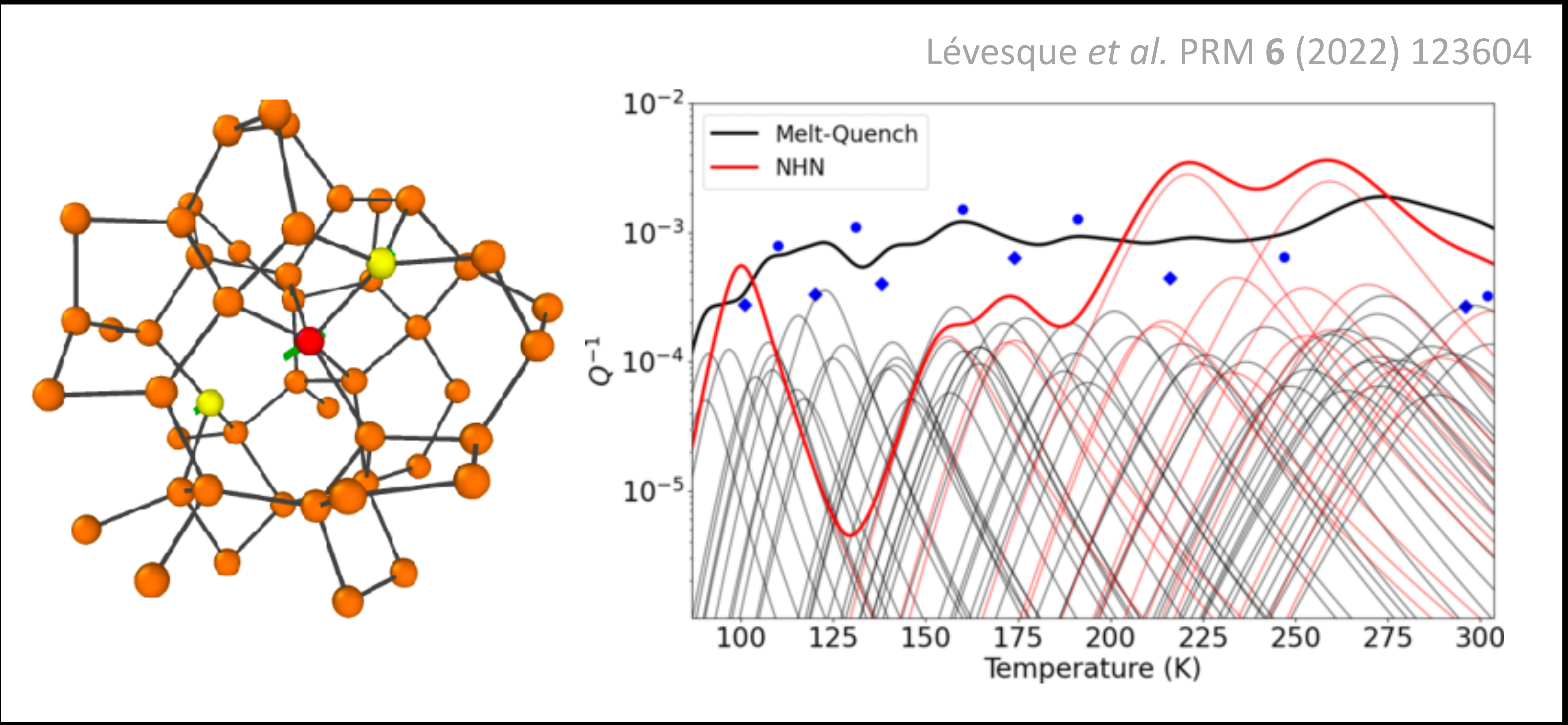
Slide by Dr. Kirsty Gardner, plot by Daniel Wong

Updates from Université de Montréal/Polytechnique Montréal

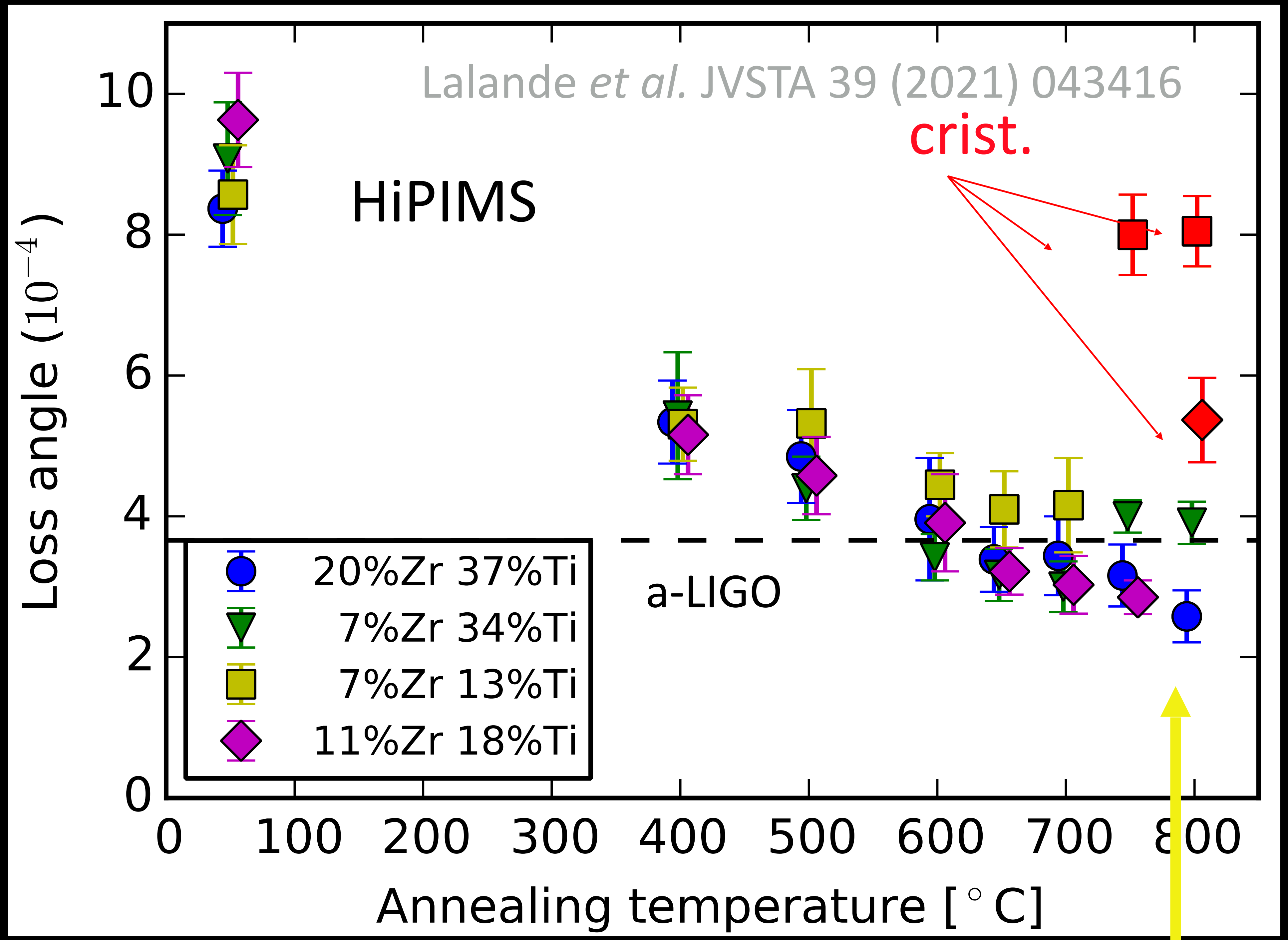
Slide by François Schiettekatte (UdeM)

See poster presented by François and team earlier this week!

Mechanisms in *a*-Si: bond exchange and bond diffusion



Adding other oxides to the mix: Ti, Zr



Low ϕ, but layer cracks!

General trend:

More relaxation ⟷ Local atomic configuration closer to crystal's

More relaxation ⟷ Lower ϕ

Local atomic configuration closer to crystal's ⟷ Lower ϕ

Gravitational Wave Periods

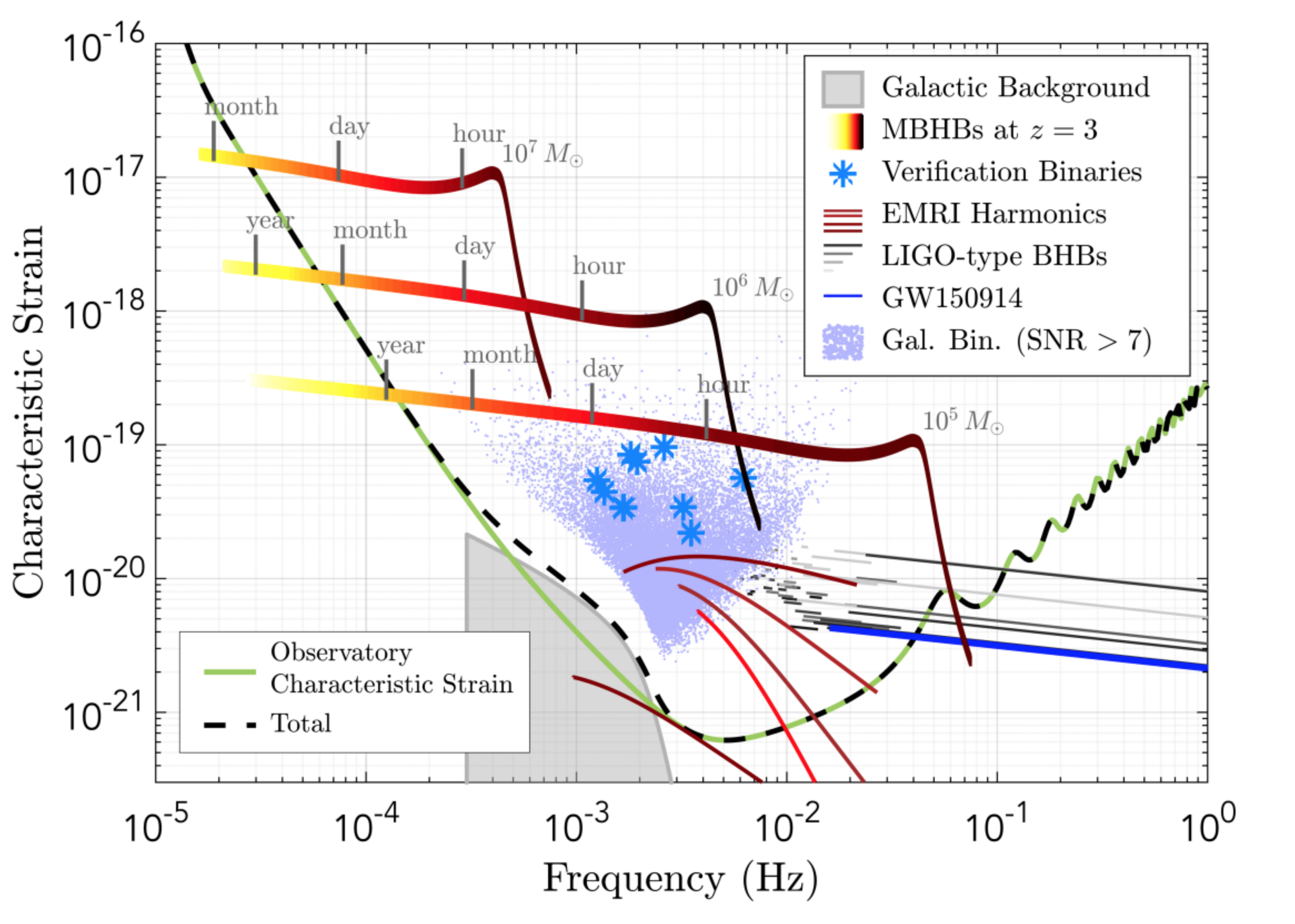
Milliseconds	Minutes to Hours	Years to Decades	Billions of Years

LIGO/Virgo	LISA	Pulsar timing	CMB polarization

The LISA mission

NASA

LISA discovery space

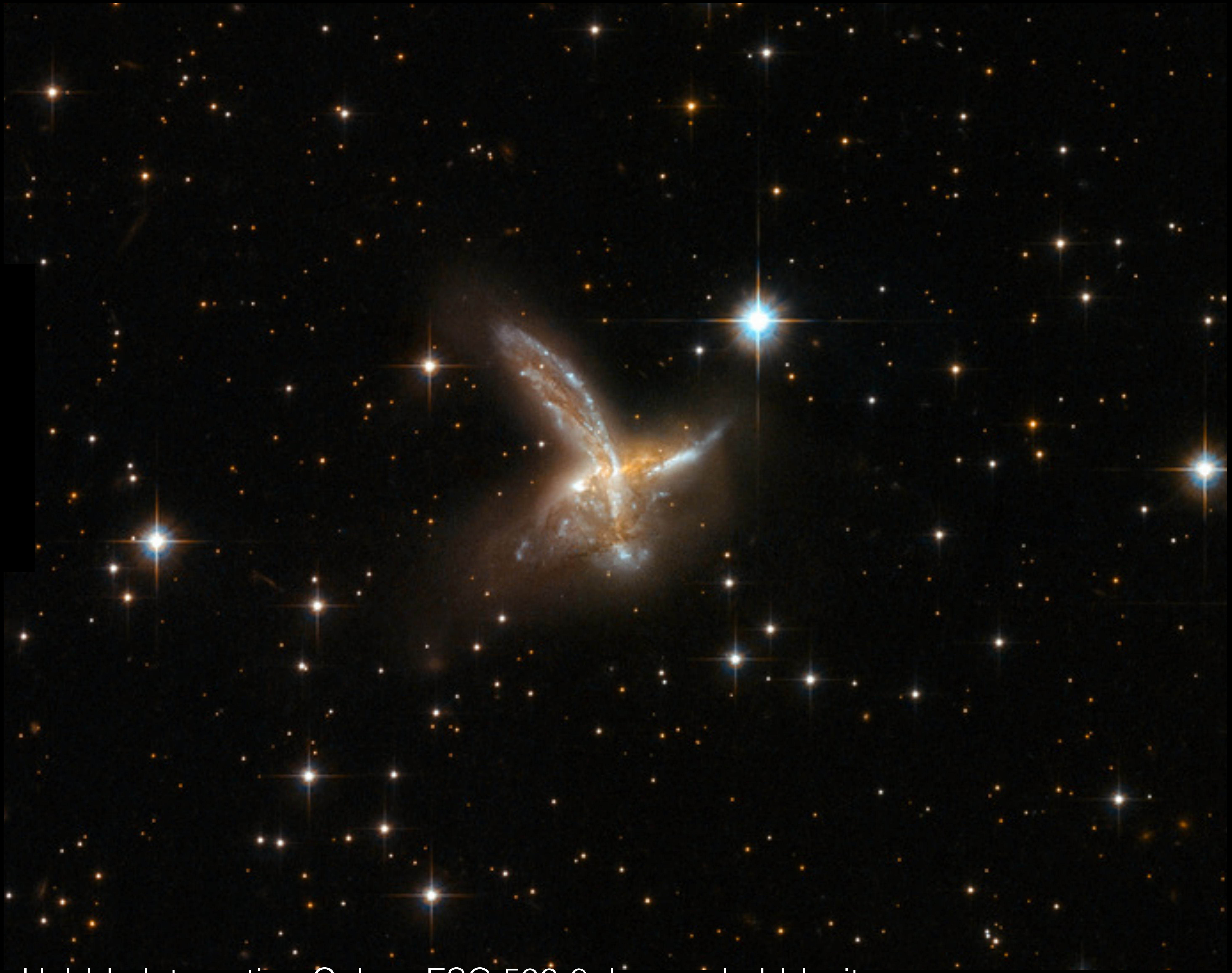


LISA core team + consortium - 2017

Galaxy formation and evolution

LISA will be able to localize massive BH sources to a few arcminutes at z=1!

S. McWilliams et al. 2011 arXiv 1104.5650



Hubble Interacting Galaxy ESO 593-8. Image: hubblesite.org

LISA will be able to measure massive BH distance with less than 10% error at z=4!

E. Berti et al. 2005. arXiv 0504017

A snapshot of current LISA Canada efforts

Experiment/analysis


Jess McIver


Scott Oser

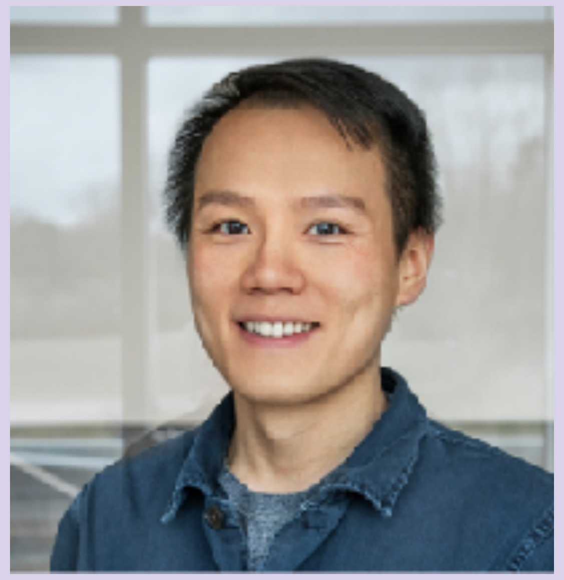
UBC

Multi-messenger


Daryl Haggard

TSI
Trottier Space Institute at McGill

UNIVERSITÉ BISHOP'S UNIVERSITY

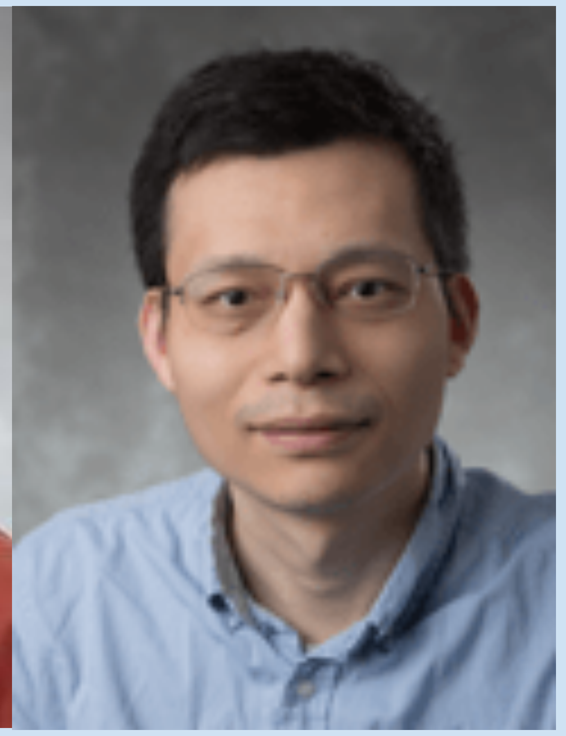

John Ruan


Nahee Park

Queen's UNIVERSITY

Theory


Liliana Caballero


Huan Yang

UNIVERSITY of GUELPH


Will East

TRIUMF

PERIMETER INSTITUTE

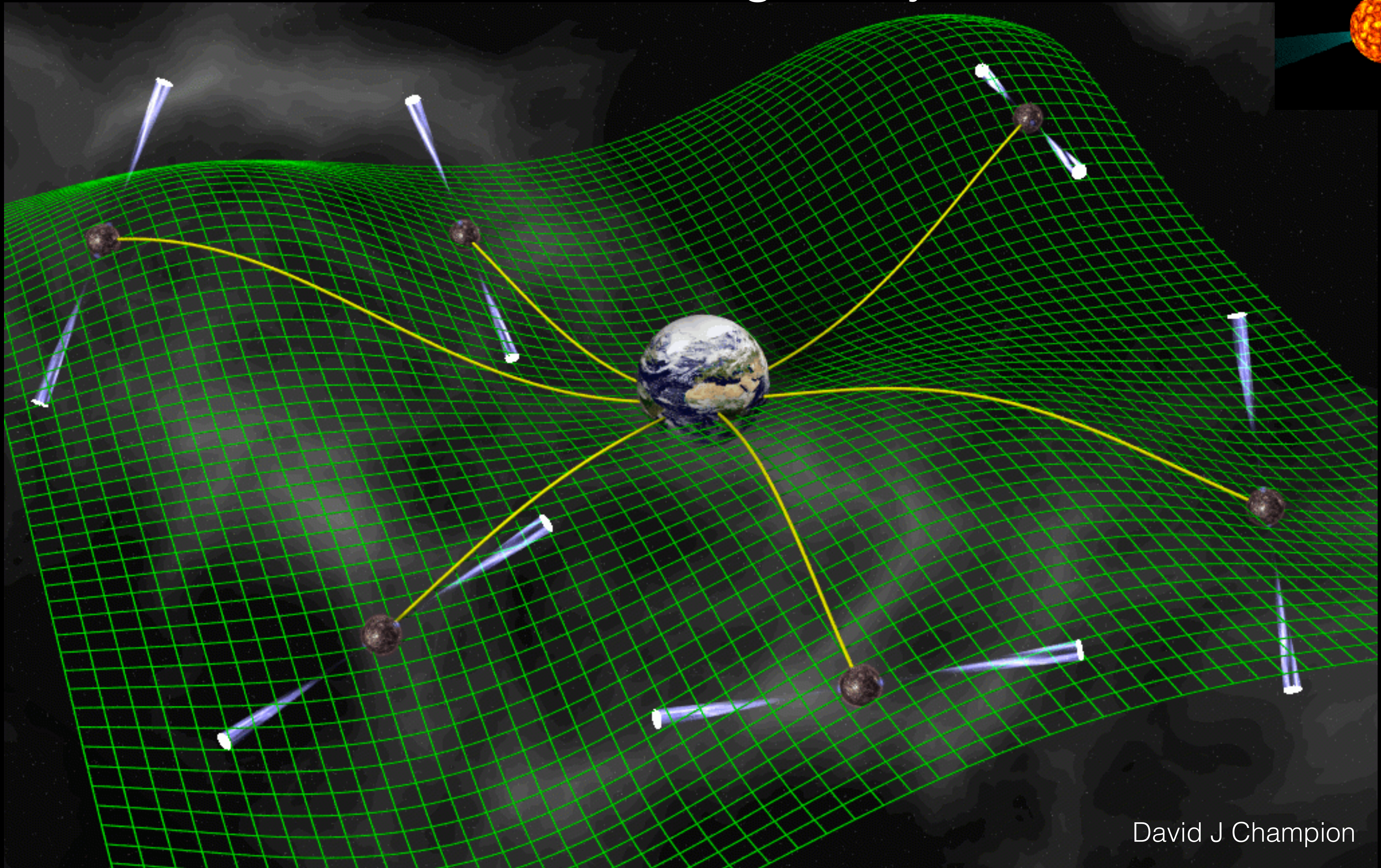

David Morrissey

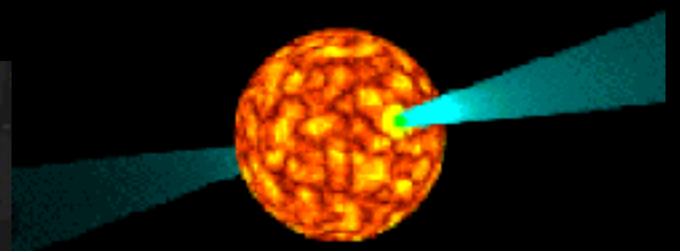

Saeed Rastgoo

University of Lethbridge
FIAT LUX


Saurya Das

Pulsar Timing Arrays

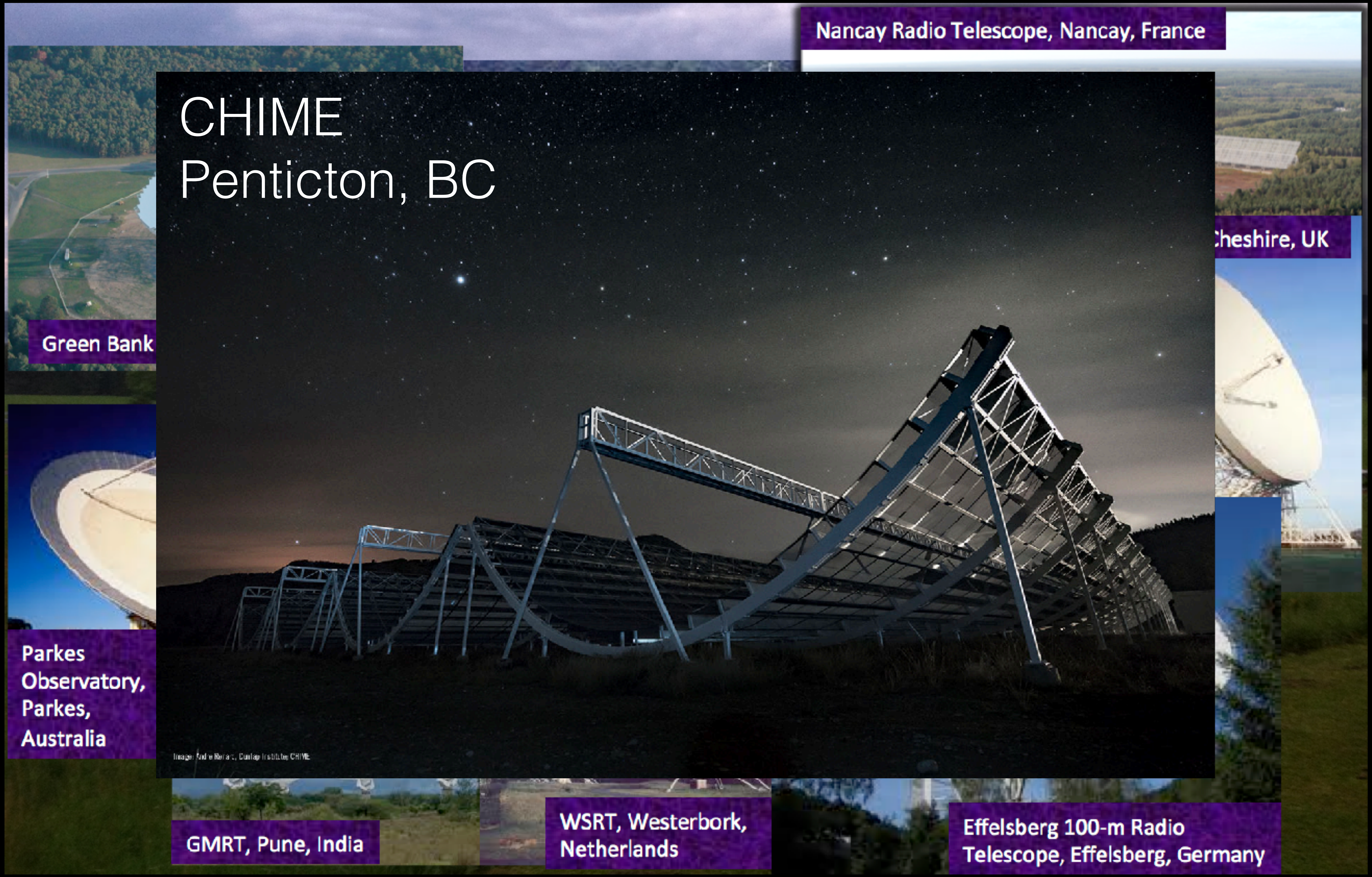




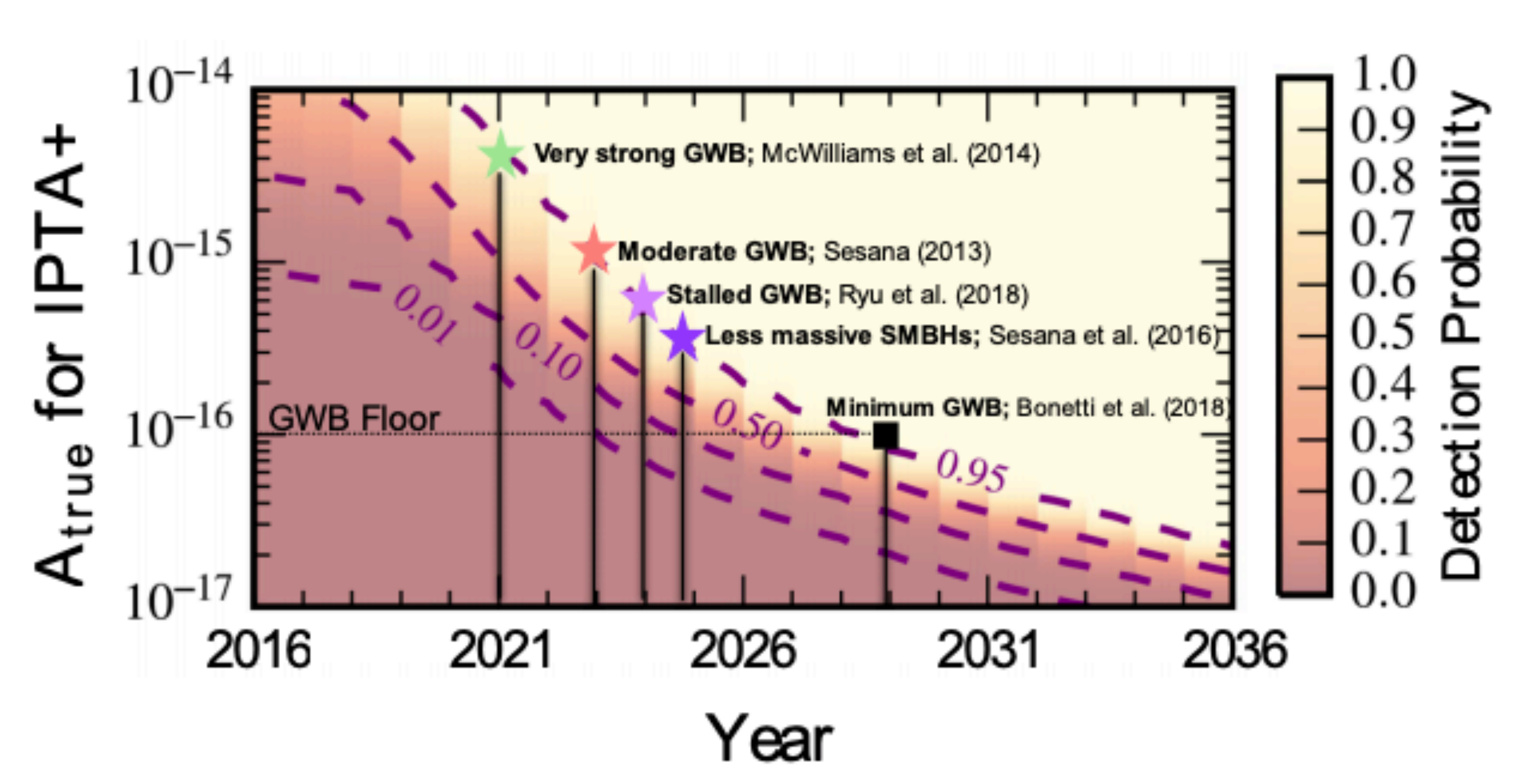
David J Champion

An International Radio Telescope Effort

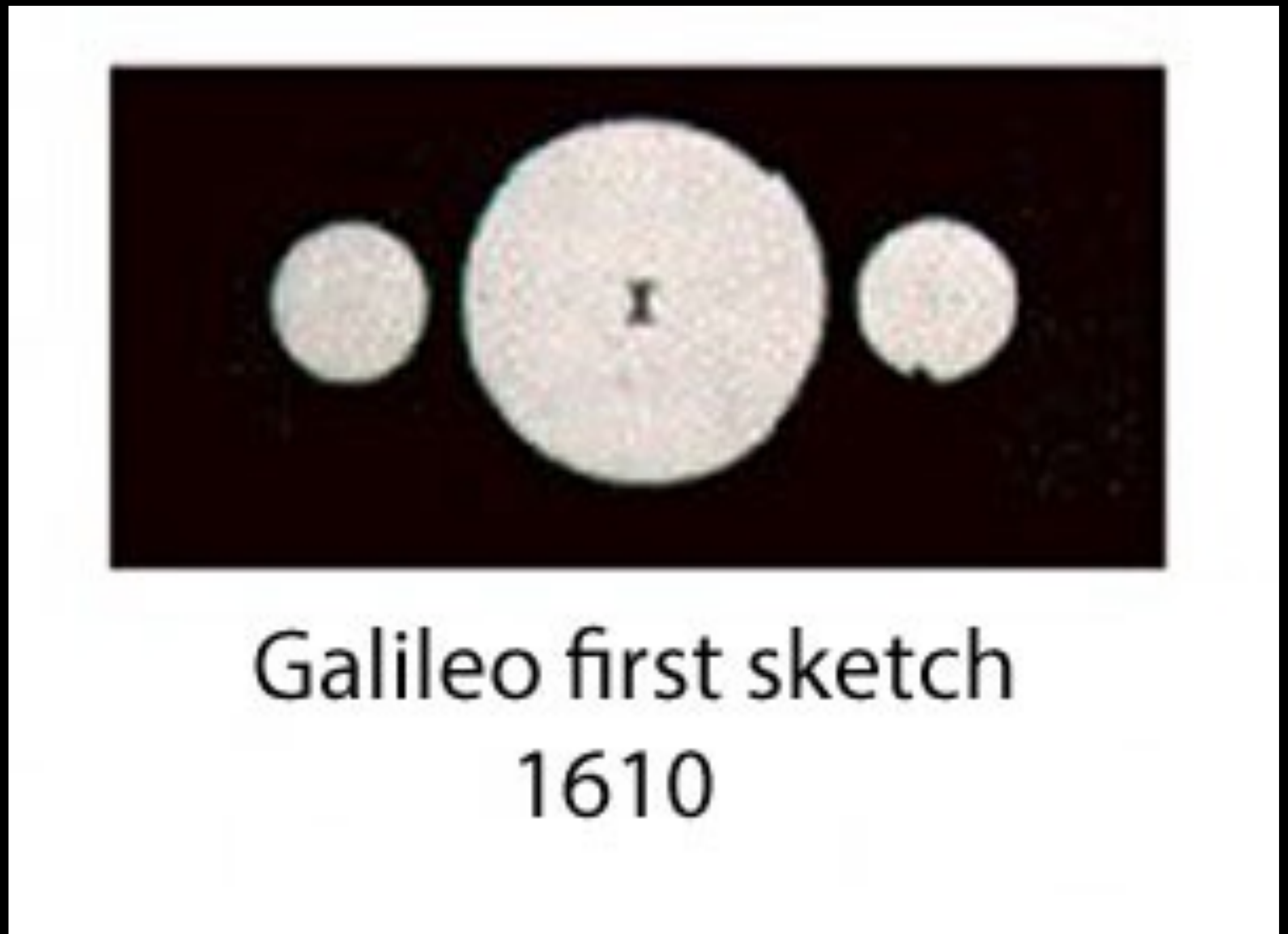
An International Radio Telescope Effort

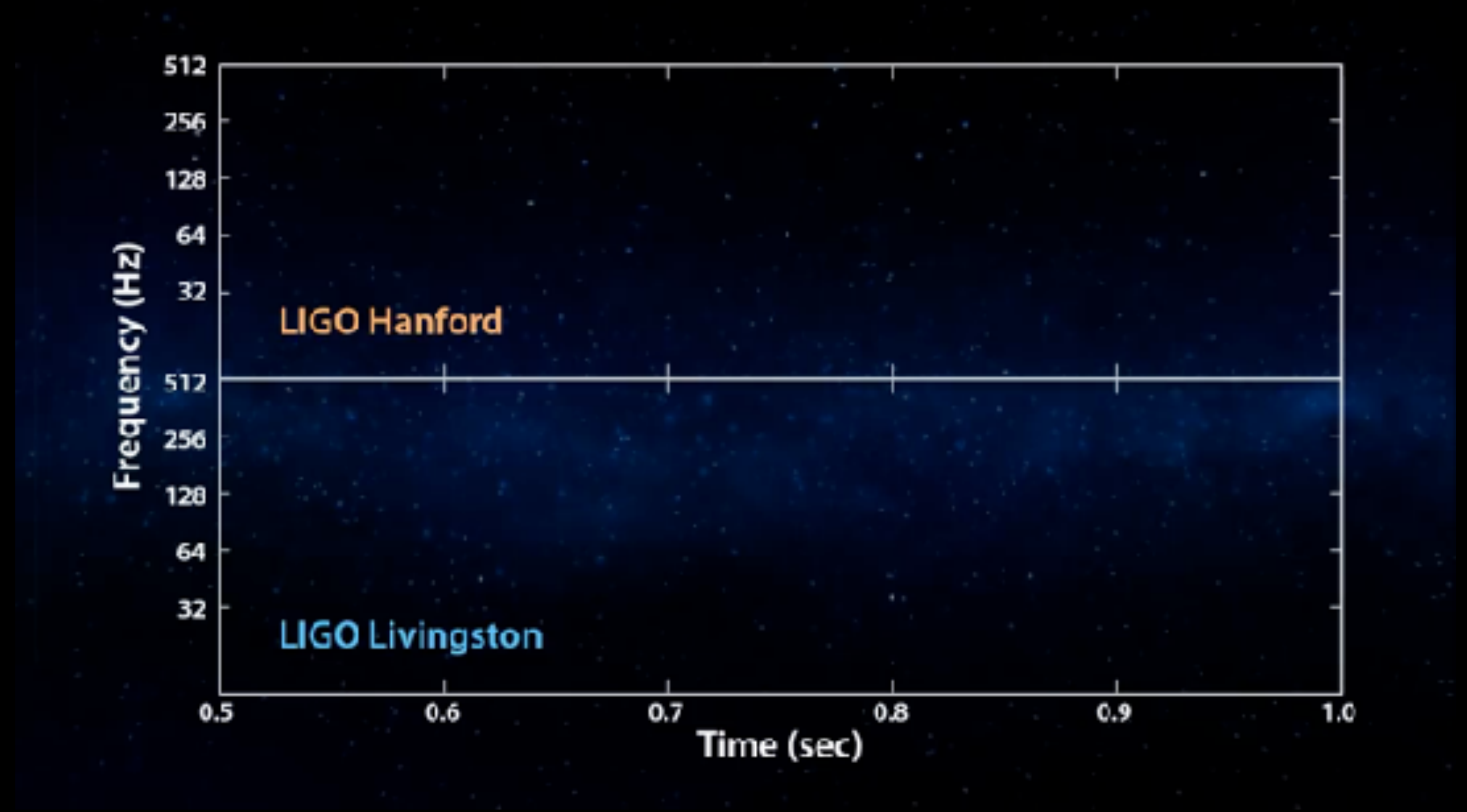


IPTA detection prospects

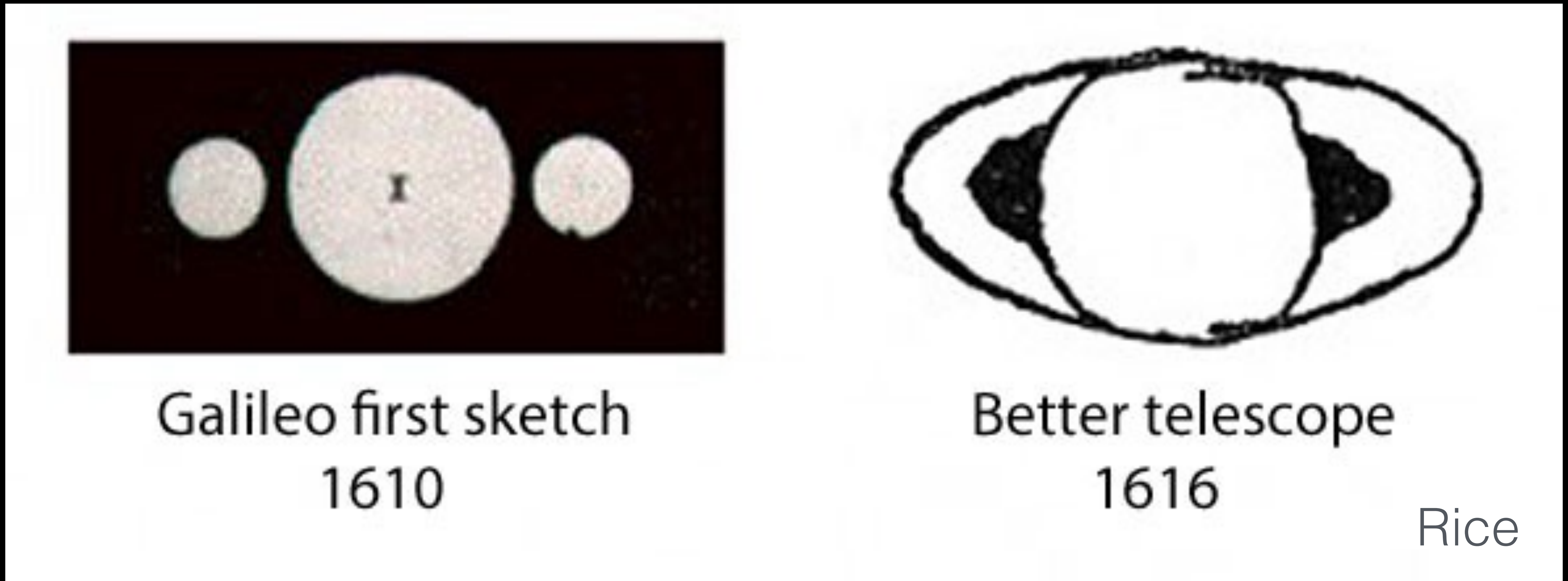


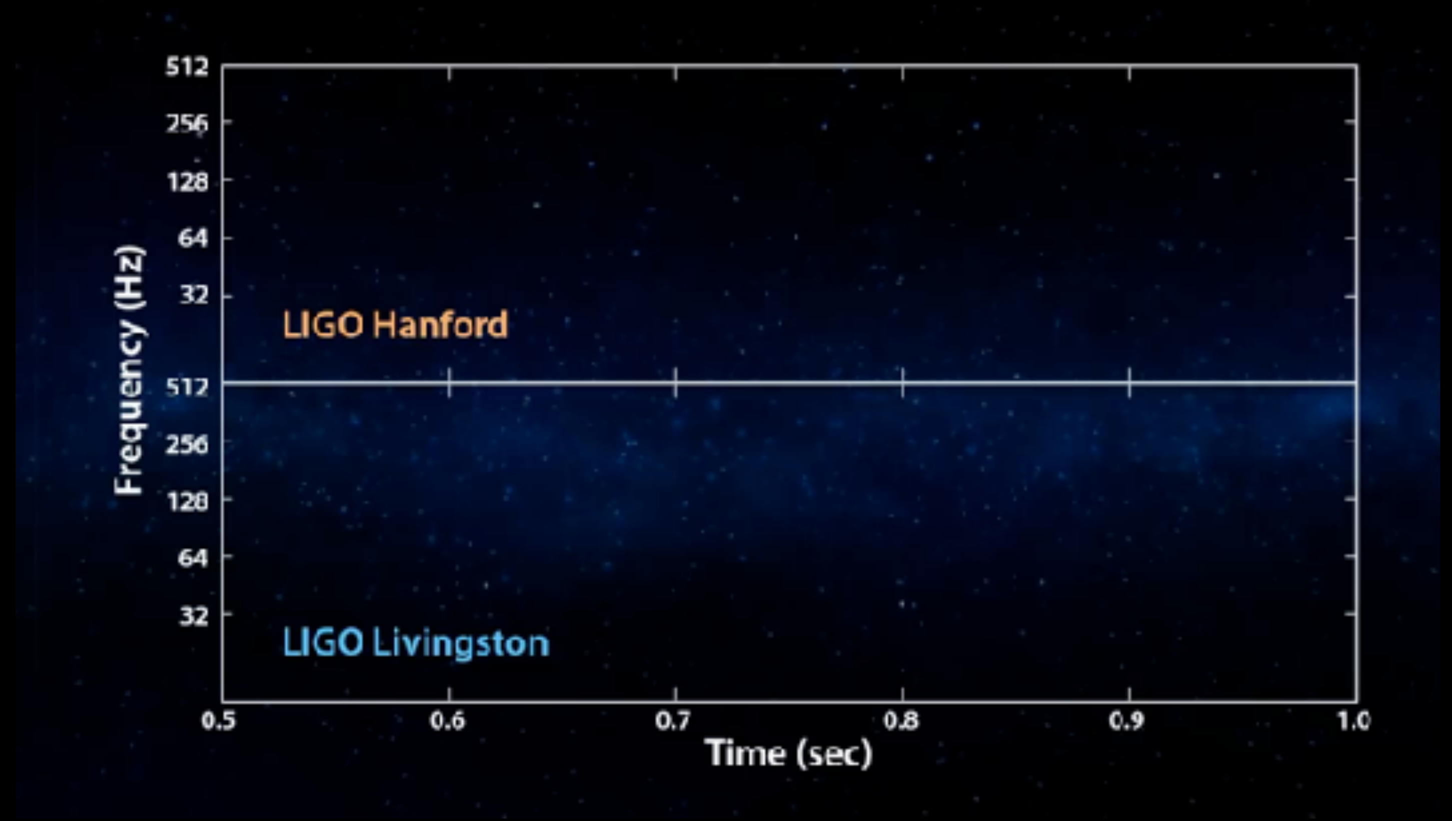
This is just the beginning of gravitational wave astrophysics!

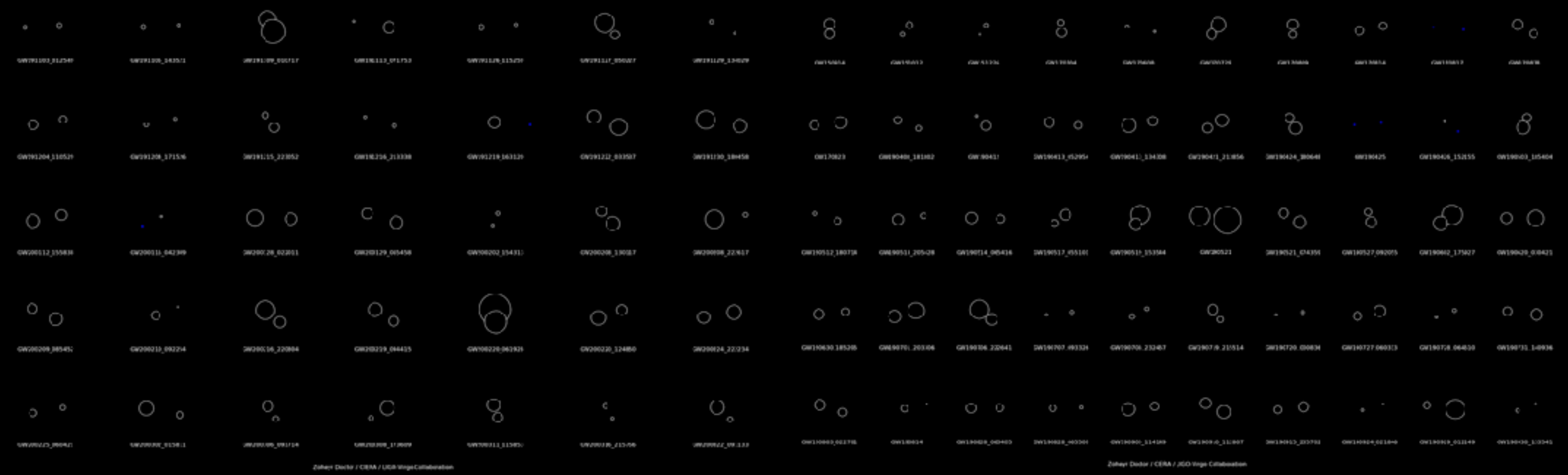




This is just the beginning of gravitational wave astrophysics!







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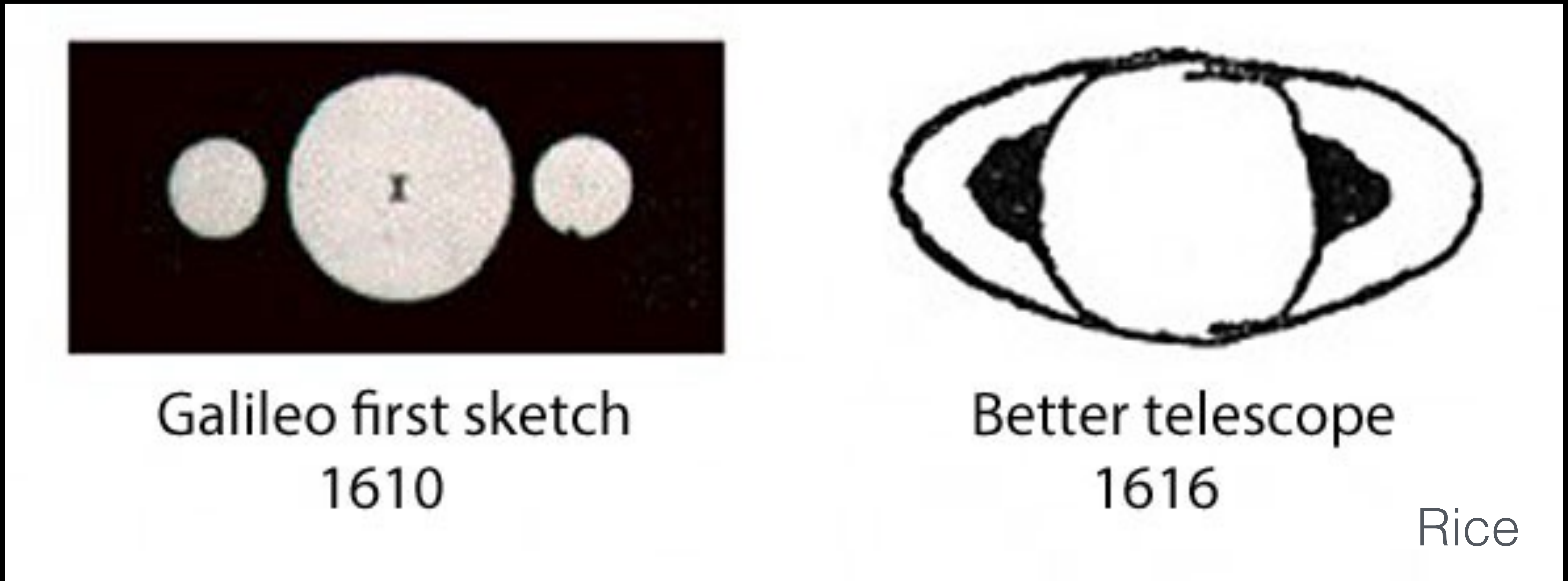
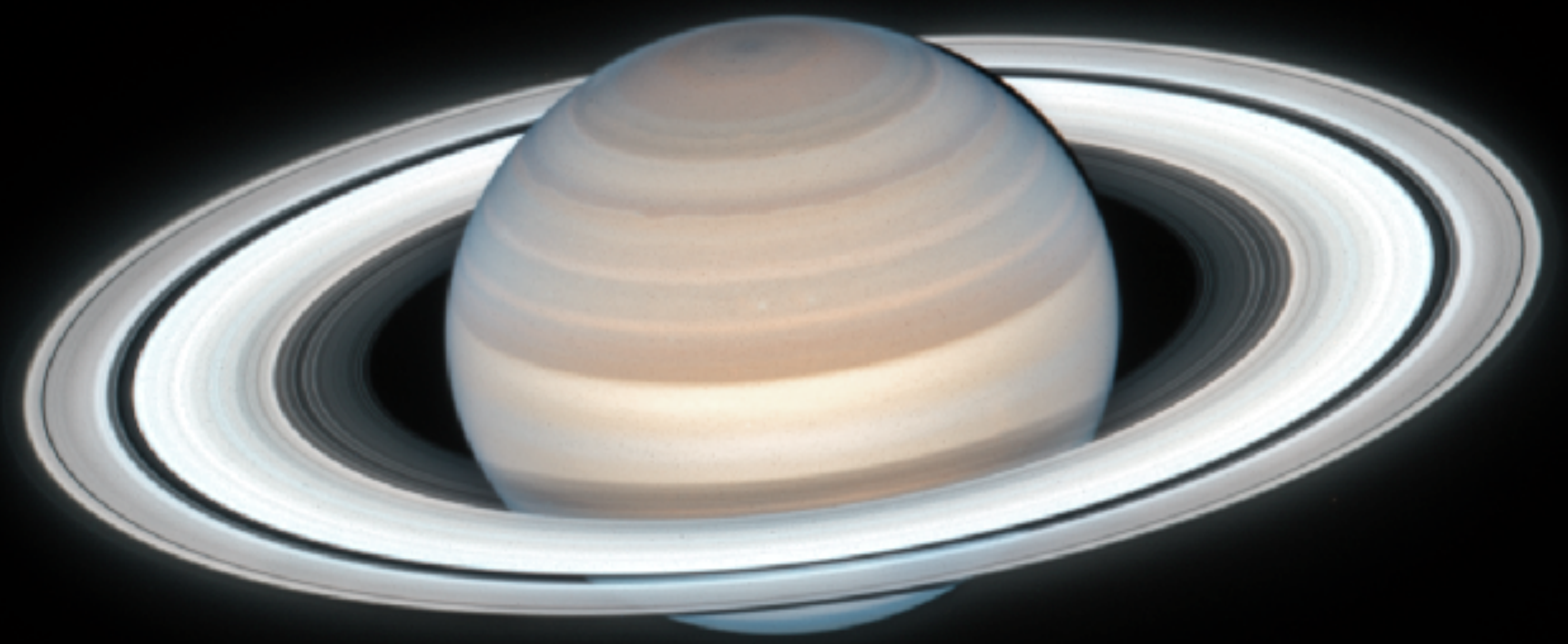
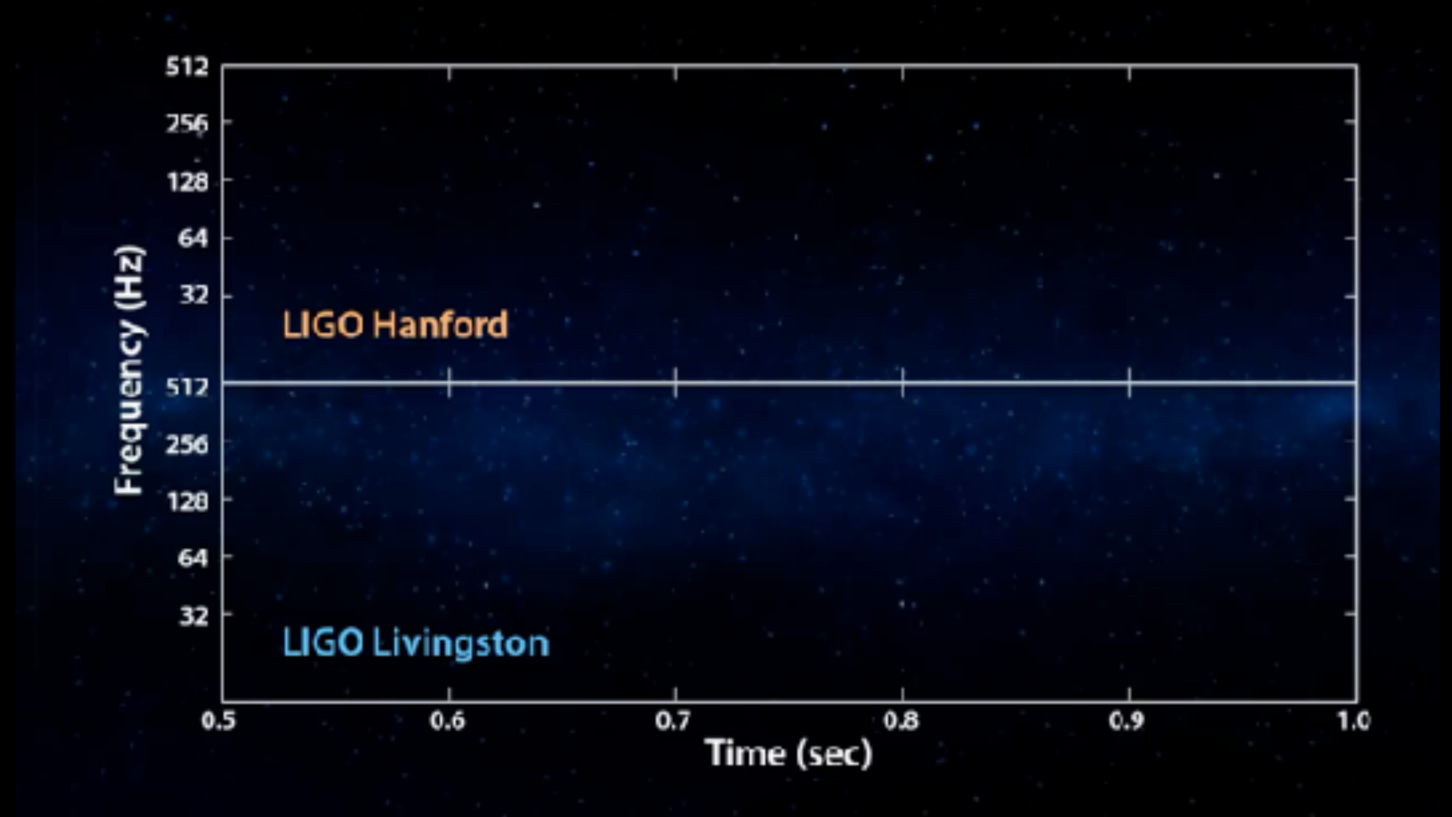
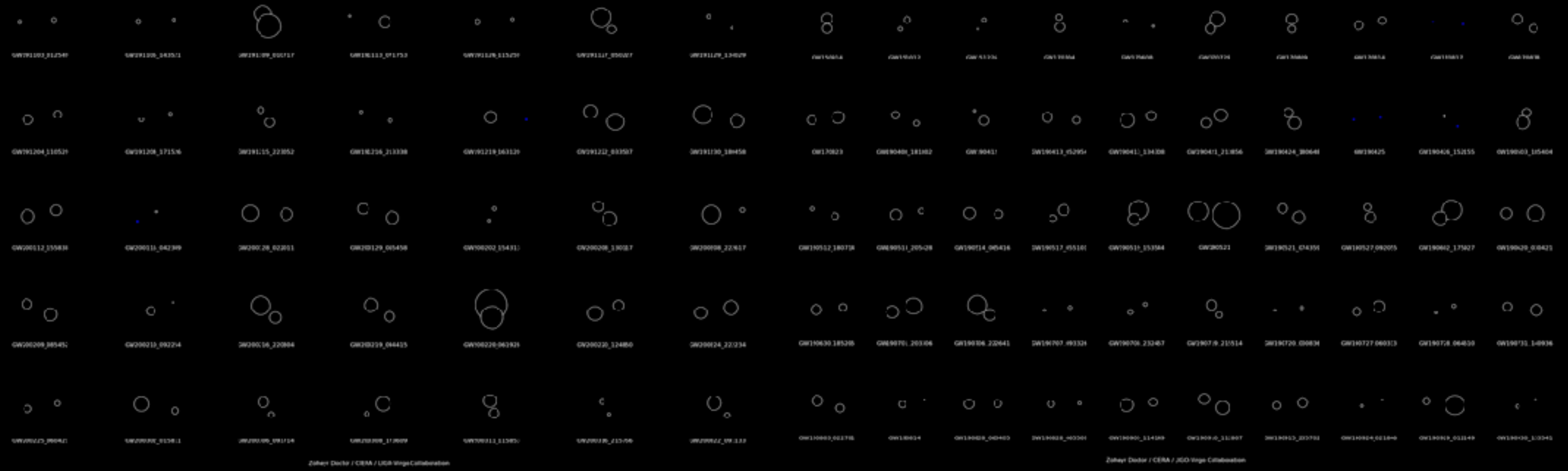


400 years later…



HST





?

Get involved with GW physics/astrophysics

Open invitation to join the **CITA GW astrophysics focus group** (meets weekly on Tuesdays at 3pm Eastern) led by Phil Landry (CITA) - reach out to Phil at plandry@cita.utoronto.ca

Join the **Cosmic Explorer Consortium** - open membership: https://cosmicexplorer.org/

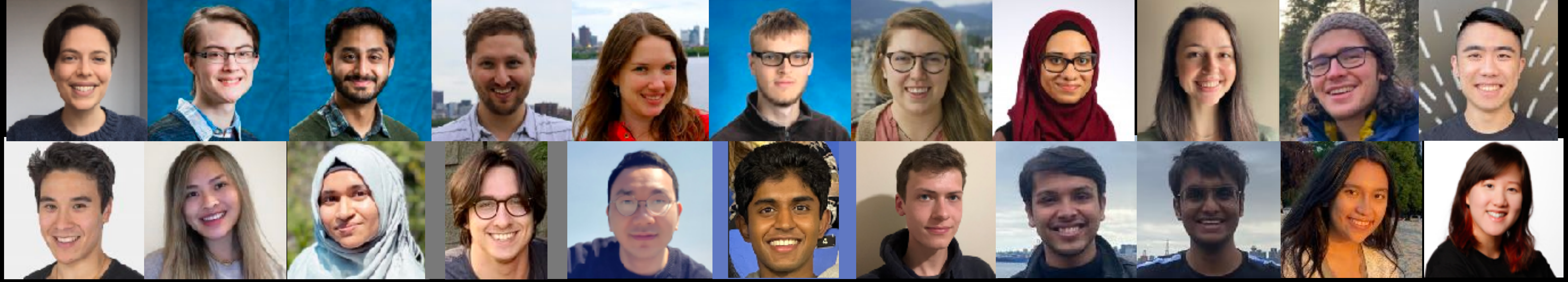
Explore the **Gravitational Wave Open Science Centre** (host of LIGO/Virgo data and analysis tutorials/web courses) - gwosc.org

Join the **LISA Consortium** - lisamission.org/signup

Explore previous **LISA Canada workshops** - LISA Canada 2021 white paper, Talks on YouTube

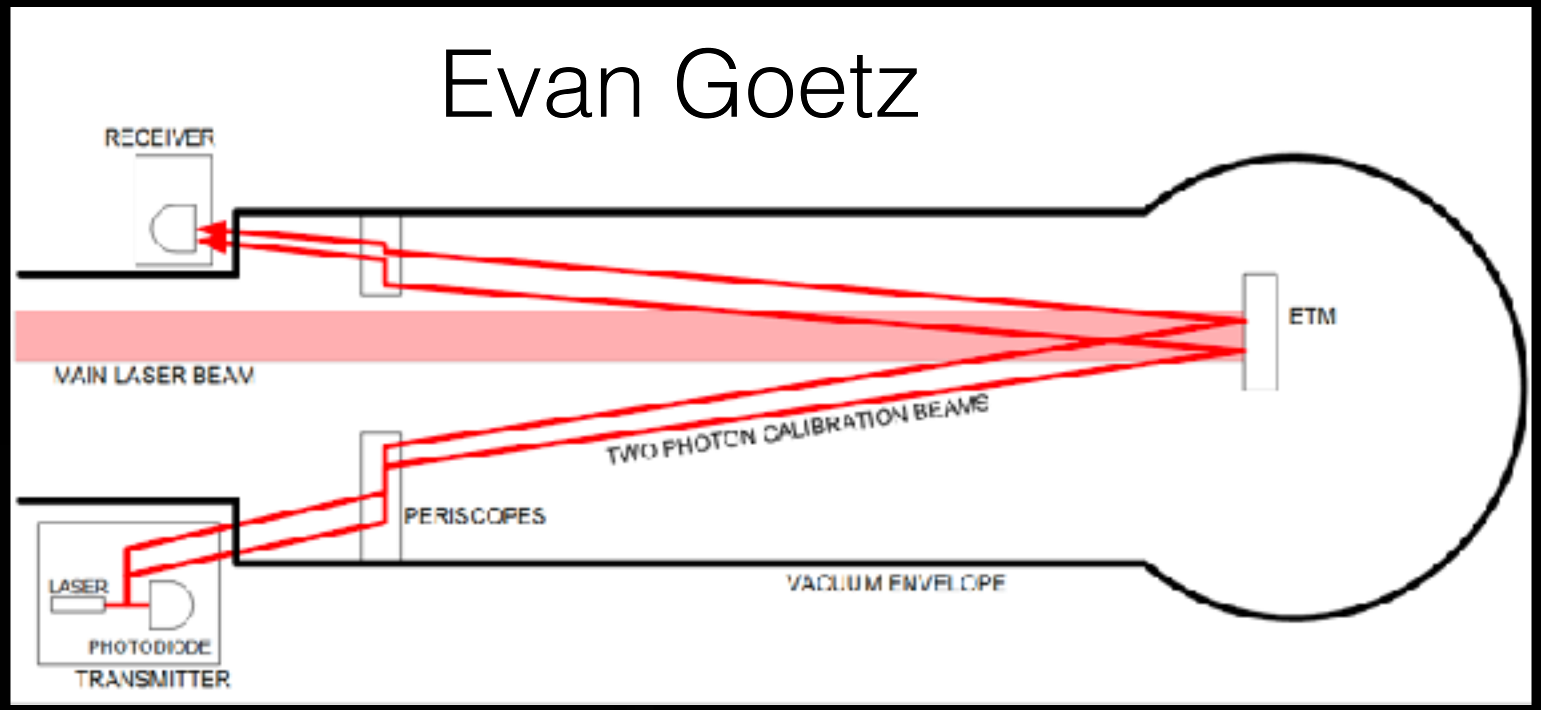
Apply to join the **LIGO Scientific Collaboration** - chat with the LSC Deputy Spokesperson (Jess!)

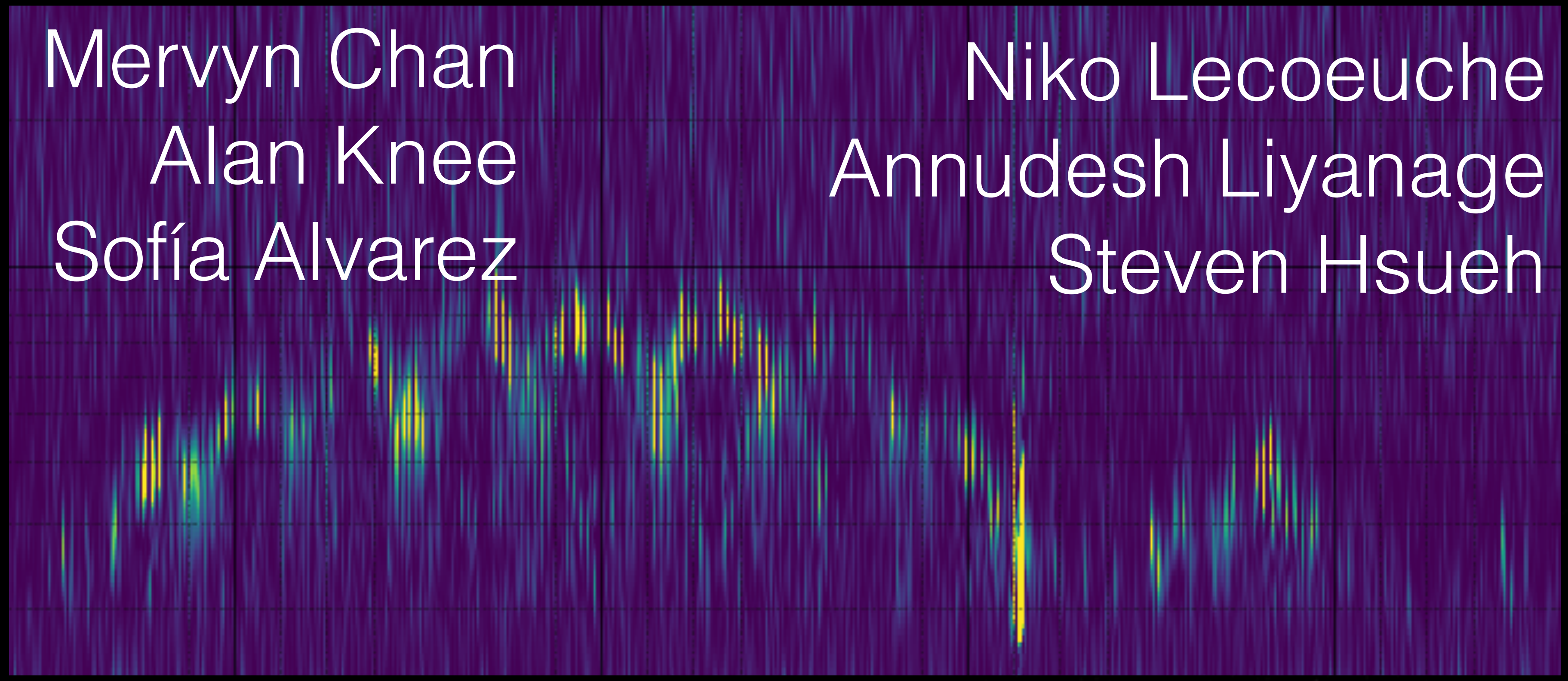
The UBC GW astrophysics group



https://gravitational-waves.phas.ubc.ca/

Evan Goetz



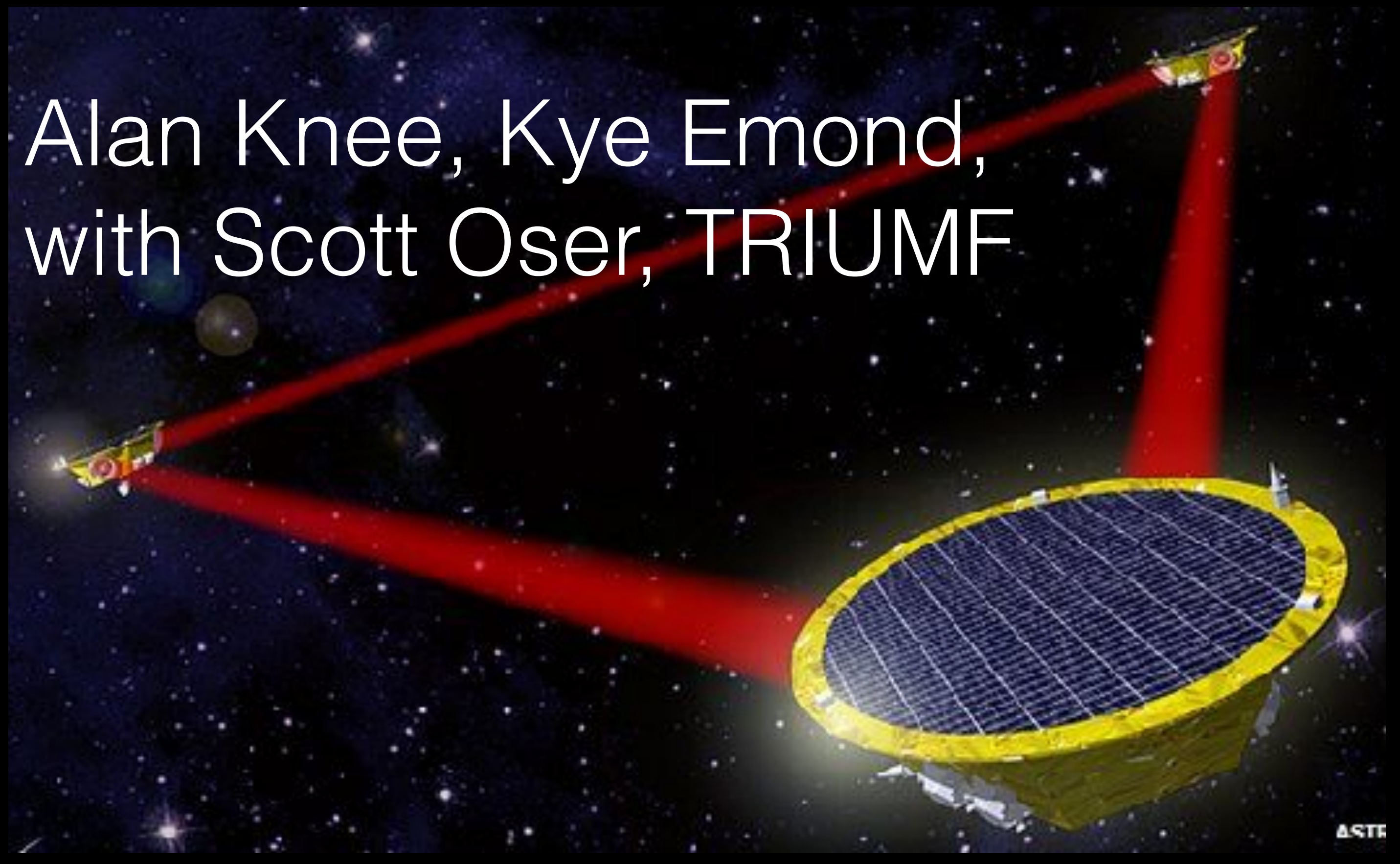


Mervyn Chan
Alan Knee
Sofía Alvarez

Niko Lecoeuche
Annudesh Liyanage
Steven Hsueh

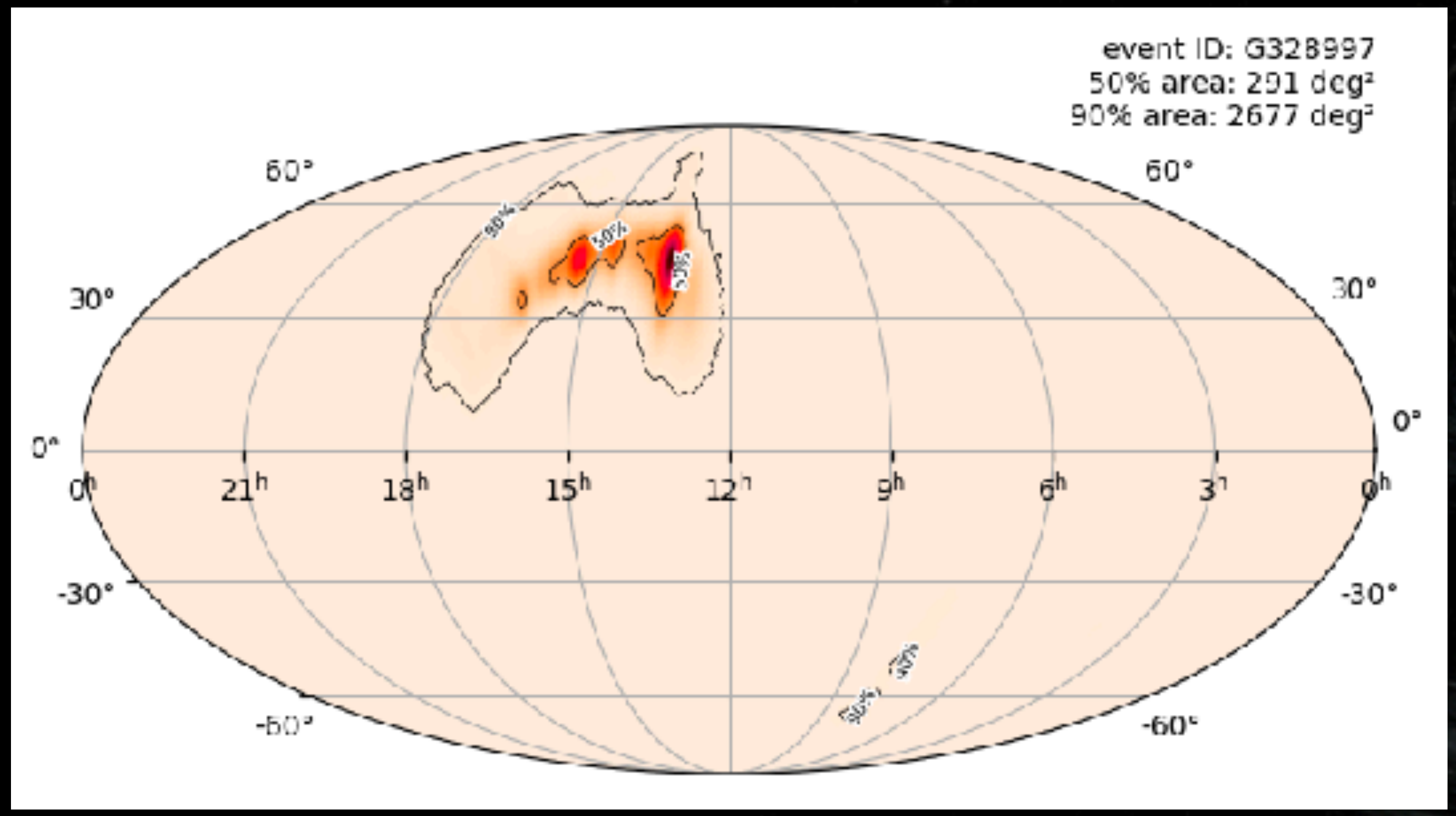
Evan Goetz, Alan Knee,
Neev Shah, Kat Nell

Evan Goetz
Helen Du
Alan Knee



Alan Knee, Kye Emond,
with Scott Oser, TRIUMF

Mervyn Chan, Miriam Cabero



Alan Knee
Heather Fong
Neev Shah
Vaibhav Garg

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

How do fundamental noises scale?

Lisa Barsotti (MIT) - Dawn IV Workshop (2018)

Shot Noise
while maintaining bandwidth

$$\frac{h_{\rm shot}}{h_{0\,\rm shot}} = \sqrt{\frac{2\ \rm MW}{P_{\rm arm}}}\sqrt{\frac{\lambda}{1.5\ \mu\rm m}}\left(\frac{3}{r_{\rm sqz}}\right)\sqrt{\frac{40\ \rm km}{L_{\rm arm}}}$$

Radiation Pressure Noise
while maintaining bandwidth

$$\frac{h_{\rm RPN}}{h_{0\,\rm RPN}} = \sqrt{\frac{P_{\rm arm}}{2\ \rm MW}}\sqrt{\frac{1.5\ \mu\rm m}{\lambda}}\left(\frac{3}{r_{\rm sqz}}\right)\left(\frac{320\ \rm kg}{m_{\rm TM}}\right)\left(\frac{40\ \rm km}{L_{\rm arm}}\right)^{3/2}$$

Coating Thermal Noise
loss angle dependence?

$$\frac{h_{\rm CTN}}{h_{0\,\rm CTN}} = \sqrt{\frac{T}{123\ \rm K}}\sqrt{\frac{\phi_{\rm eff}(T)}{5\times10^{-5}}}\left(\frac{40\ \rm km}{L_{\rm arm}}\right)^{3/2}$$

Residual Gas Noise
facility limit…

$$\frac{h_{\rm gas}}{h_{0\,\rm gas}} = \sqrt{\frac{p_{\rm gas}}{4\times10^{-7}\ \rm Pa}}\sqrt{\frac{40\ \rm km}{L_{\rm arm}^{3/2}}}$$

Fundamental noises scale with length, but not as 1/L as one might guess from h = ΔL/L

40 km is a nearly optimal choice

Free-Spectral-Range for a 40km detector is 3.75kHz, going beyond 40km would reduce the interferometer bandwidth and compromise its scientific potential (like neutron-star merger and supernovae)