New discoveries with gravitational-wave astrophysics

Jess McIver

CanPAN Jam 2024

May 3, 2024

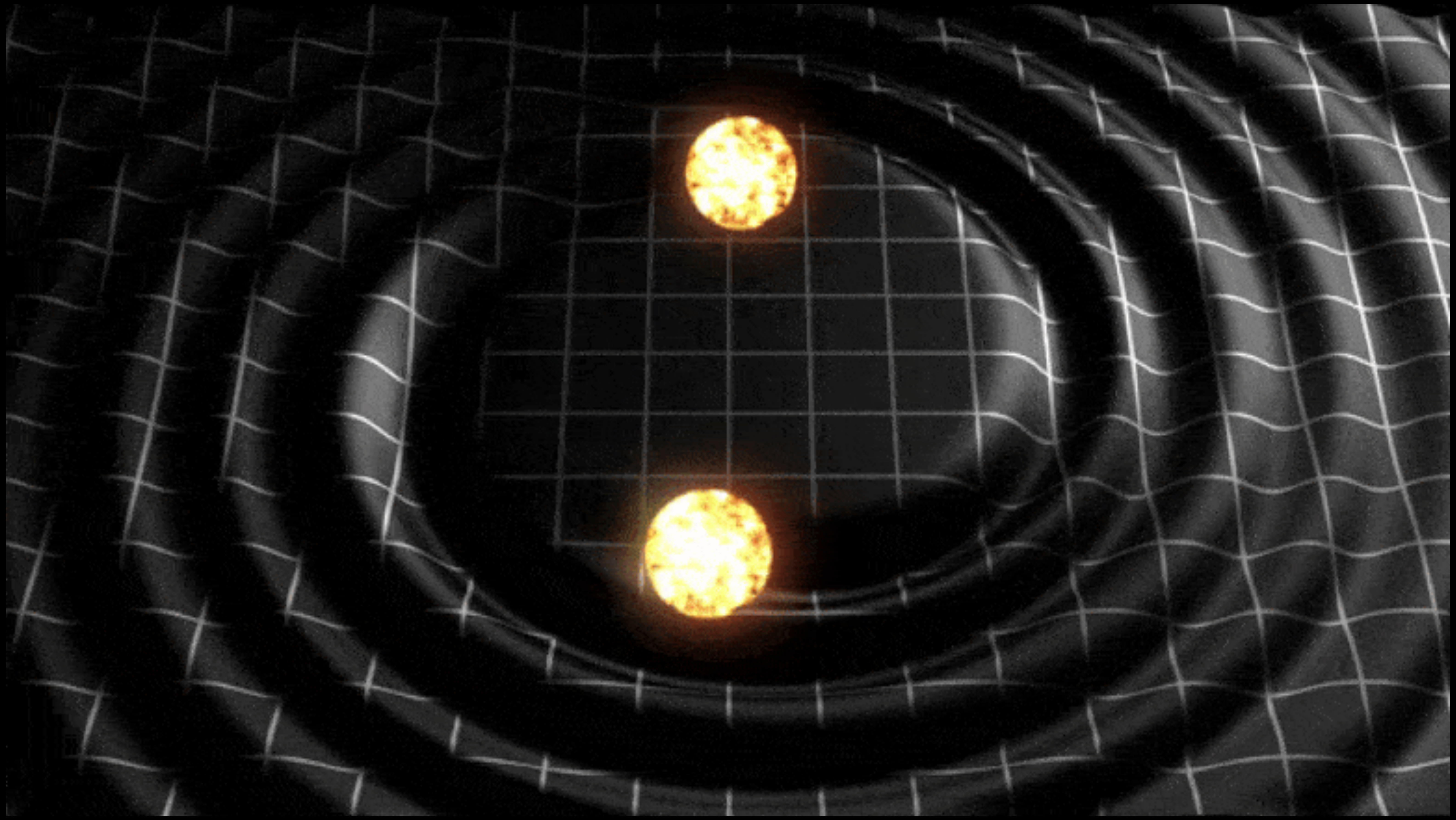
gravitational waves

a new view of the universe

Gravitational waves

Gravitational wave strain, h:

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



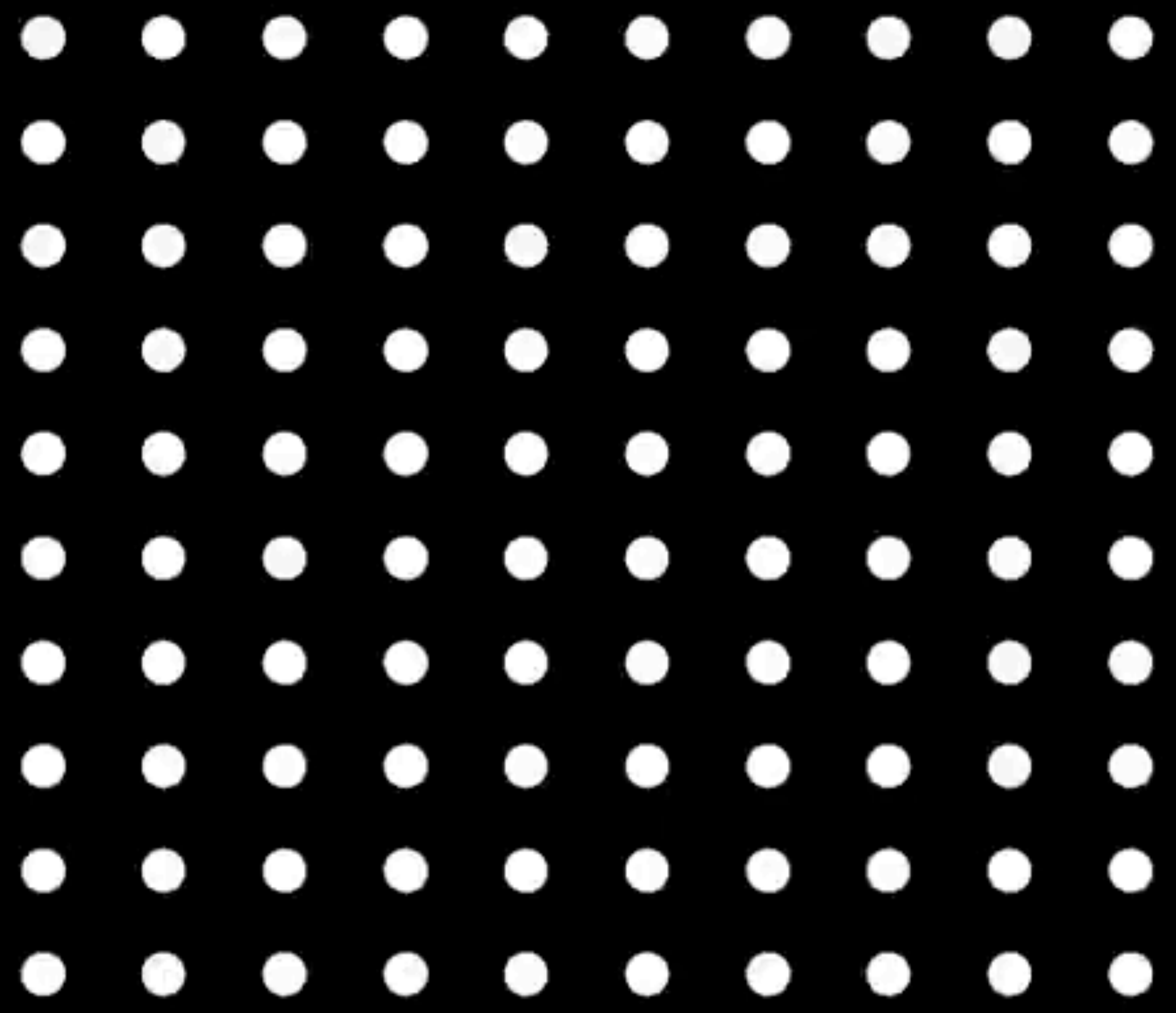
OzGrav

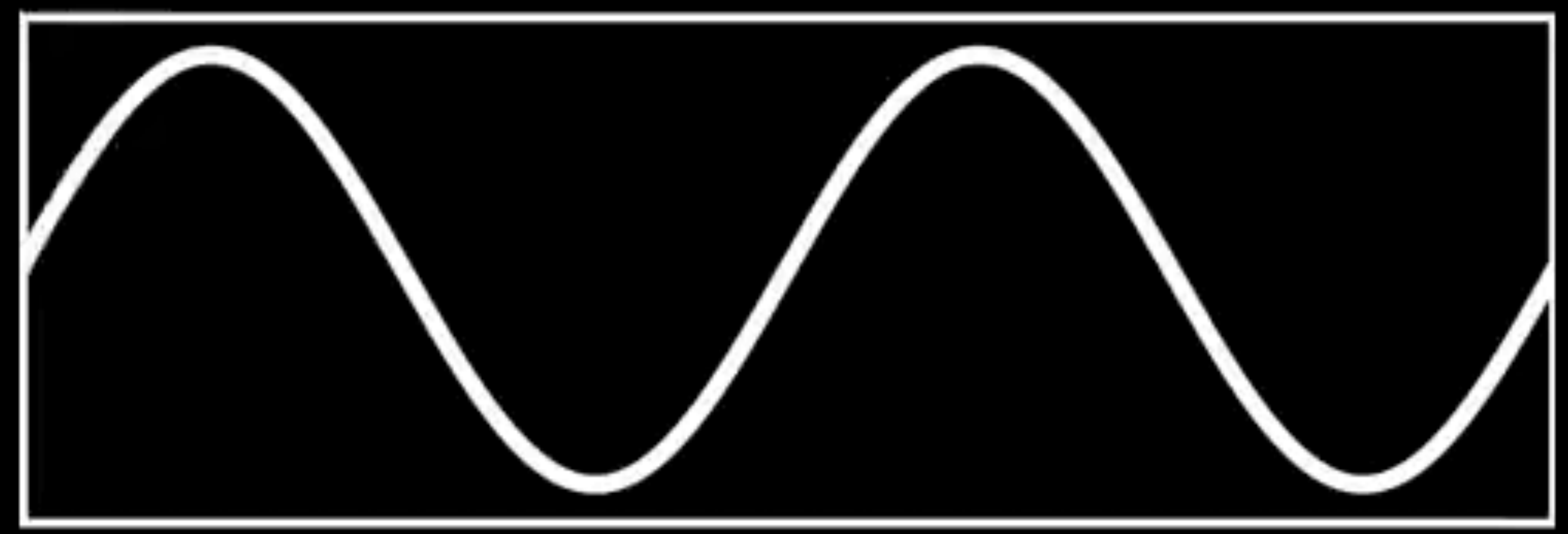

-0.69s
SXS

Gravitational wave strain

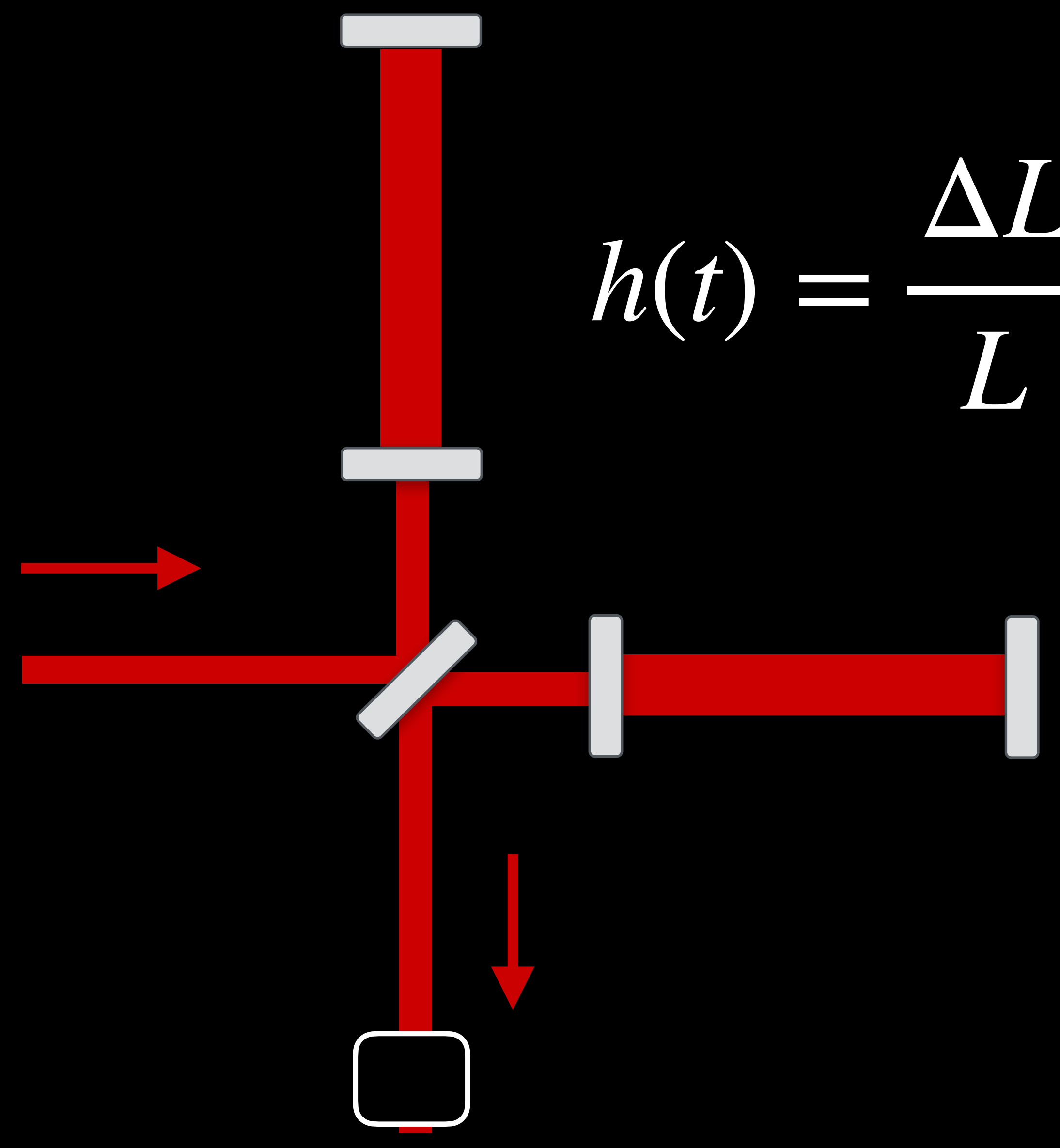
Induced spacetime strain h(t)

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





Measured spacetime strain h(t)

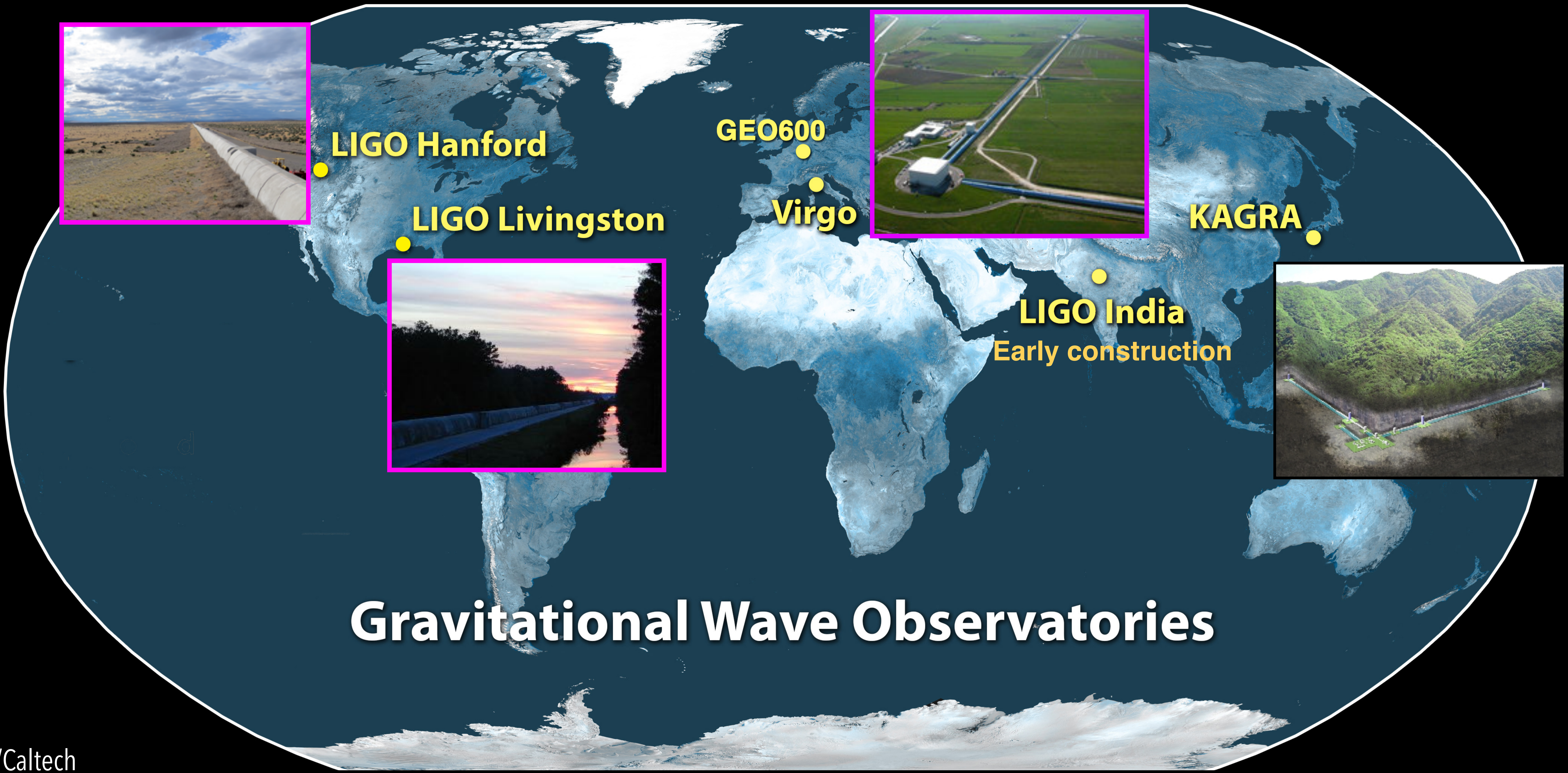


$$h(t) = \frac{\Delta L}{L}$$

Movie: Carl Rodriguez


Science/AAAS

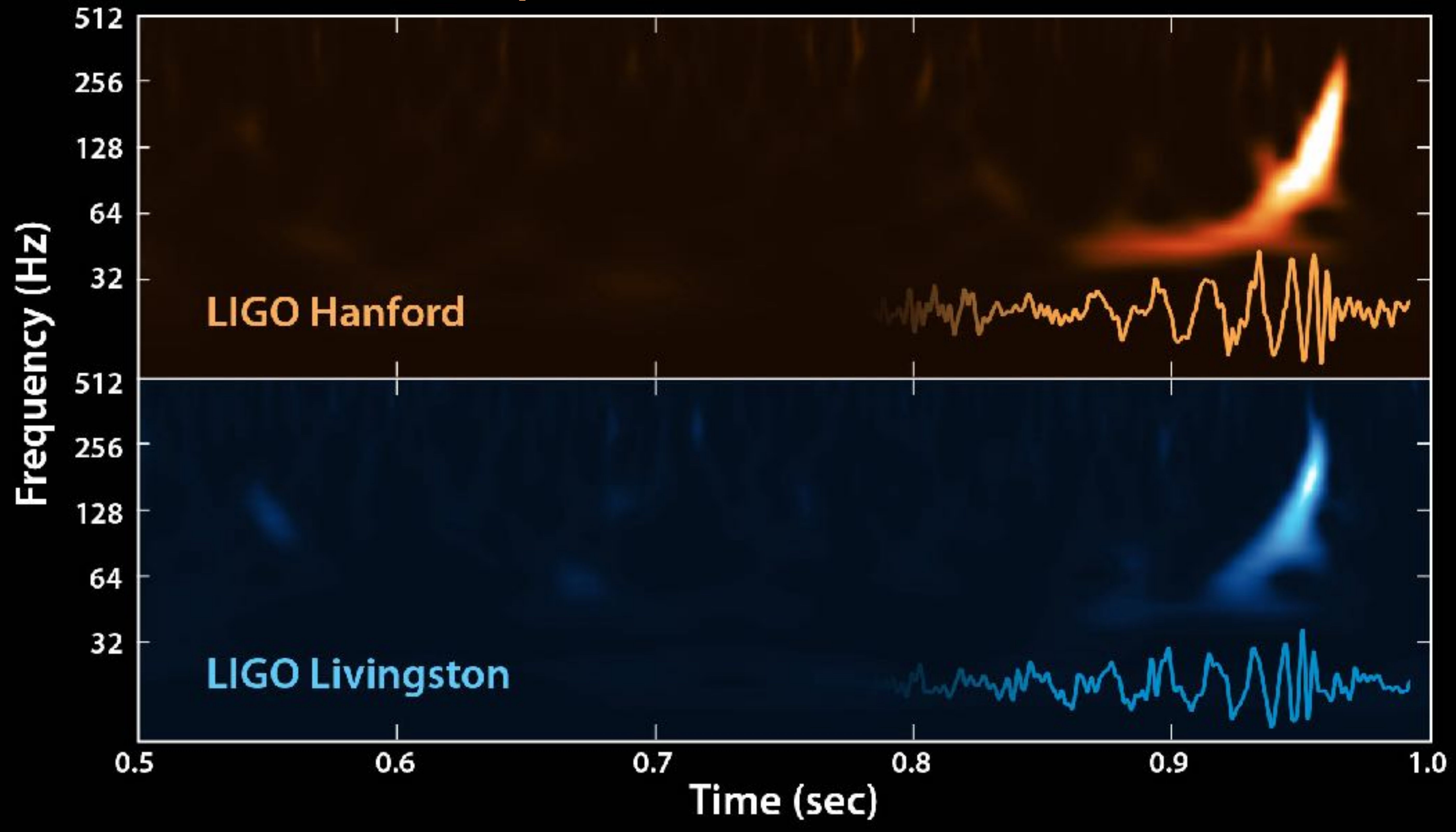
Current GW detector network (IGWN)



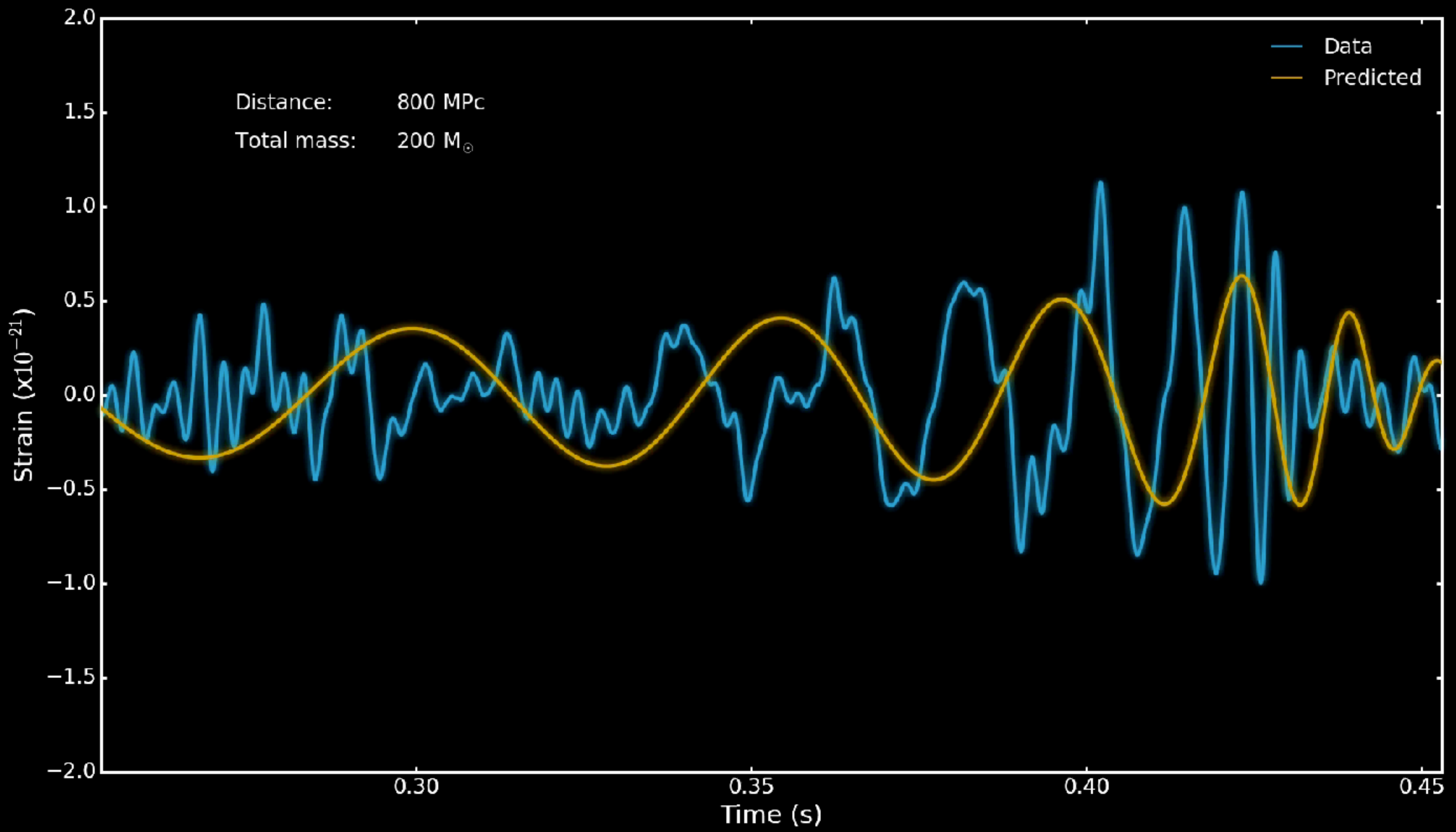
LIGO/Caltech

A landmark detection

September 14, 2015



Inferring mass and distance



Credit: LIGO/Cardiff University/C.North/M.Hannam

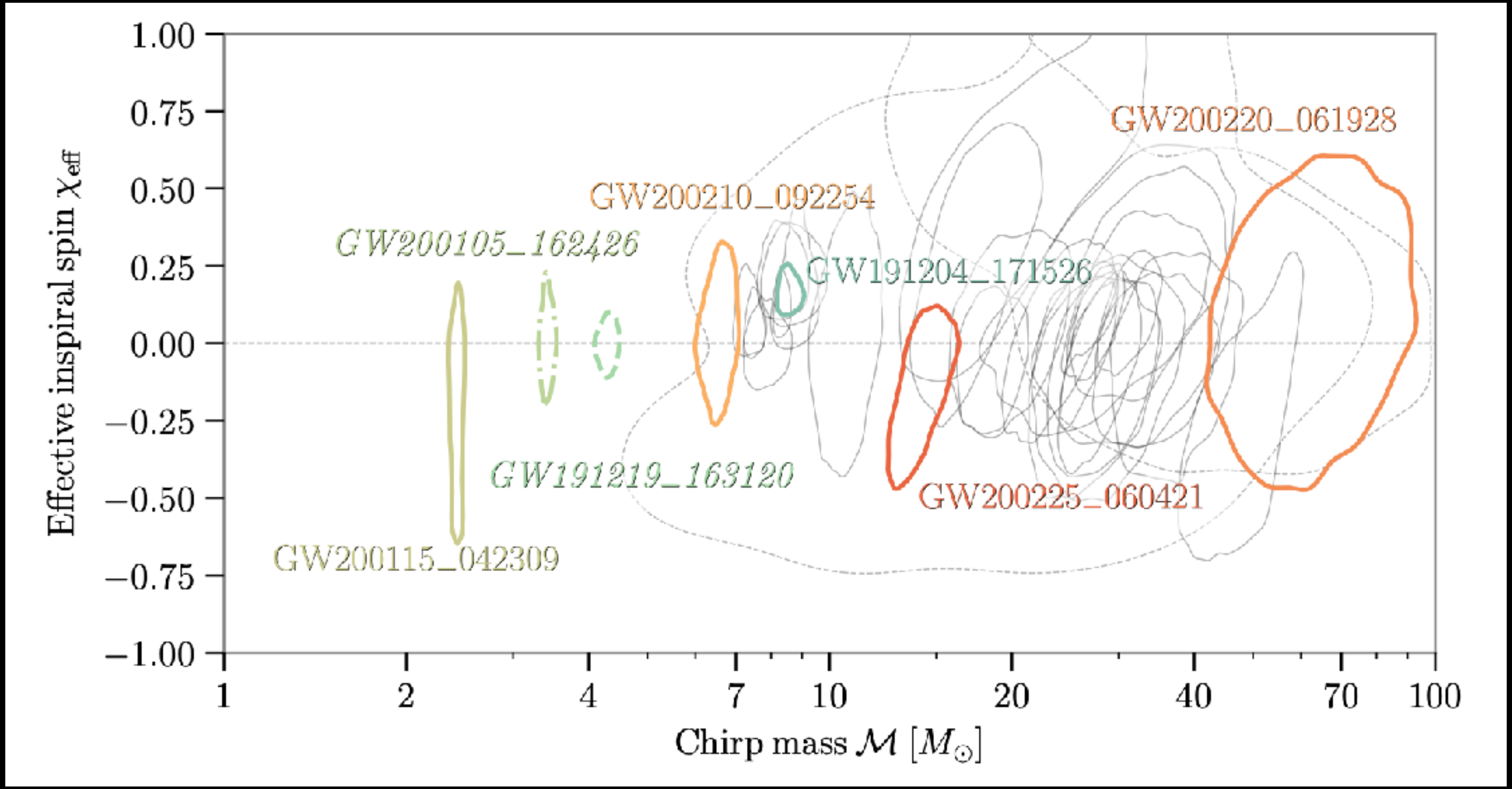
Inference of source properties

$$\boldsymbol{d} = \boldsymbol{h} + \boldsymbol{n}.$$

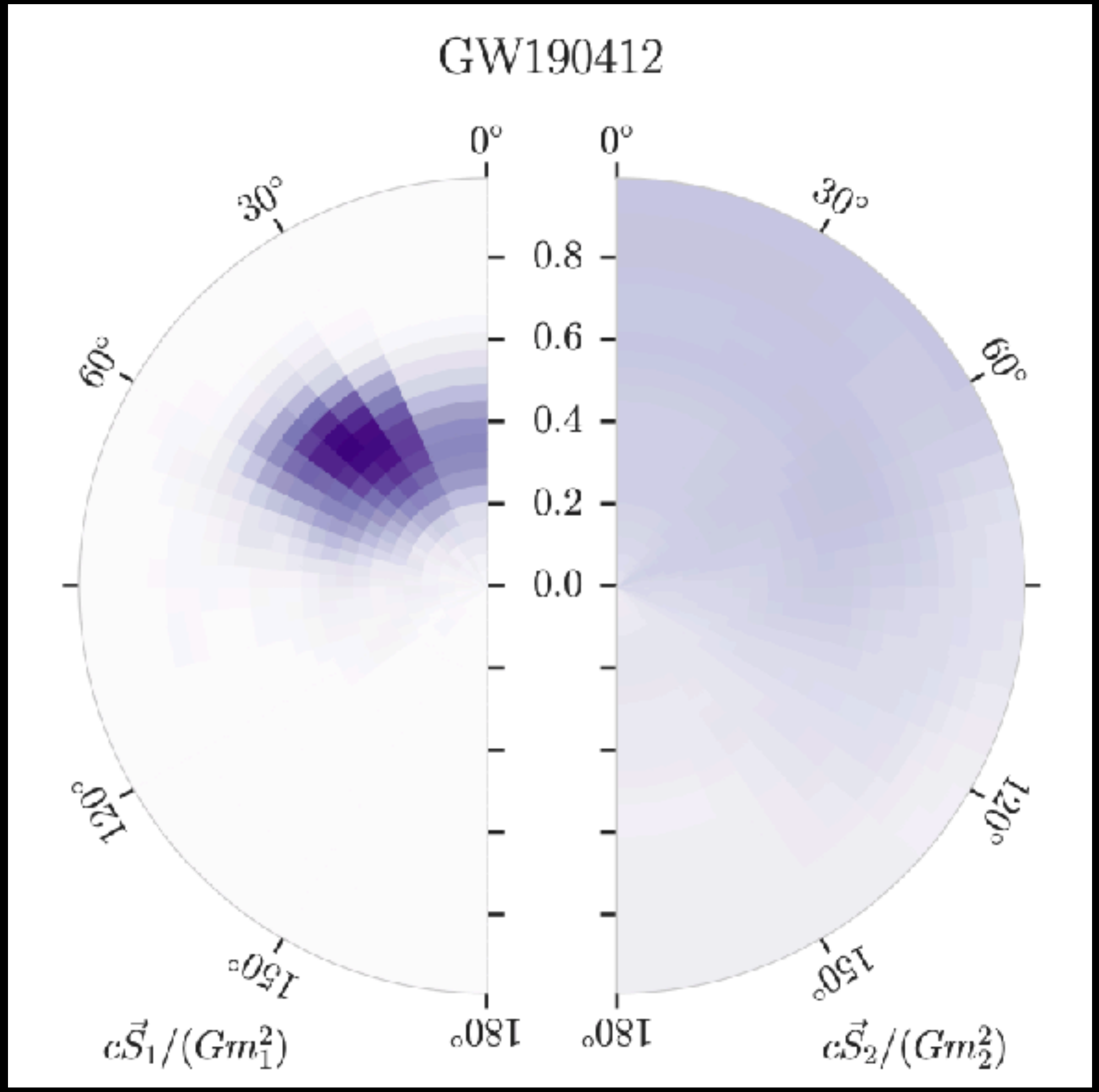
⟵ Data model d = signal (through lens of detector network) h + detector noise n

$$p(\boldsymbol{d}|H_N, S_n(f)) = \exp \sum_i \left[-\frac{2|\tilde{d}_i|^2}{T S_n(f_i)} - \frac{1}{2}\log(\pi T S_n(f_i)/2) \right]$$

⟵ Likelihood: we expect the residual of d-h to be consistent with Gaussian noise



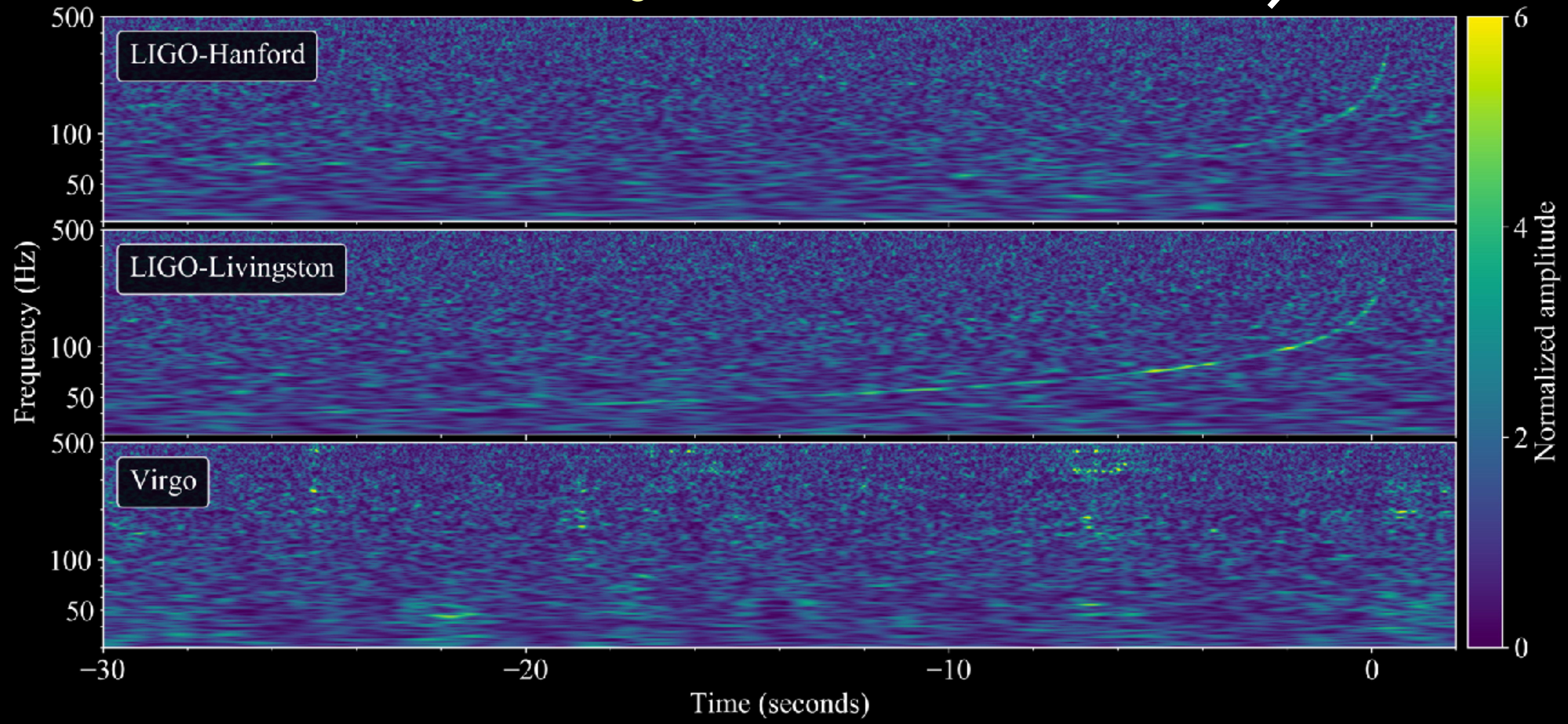
LIGO/Virgo GWTC-3 (2021)



LIGO/Virgo GWTC-2 (2020)

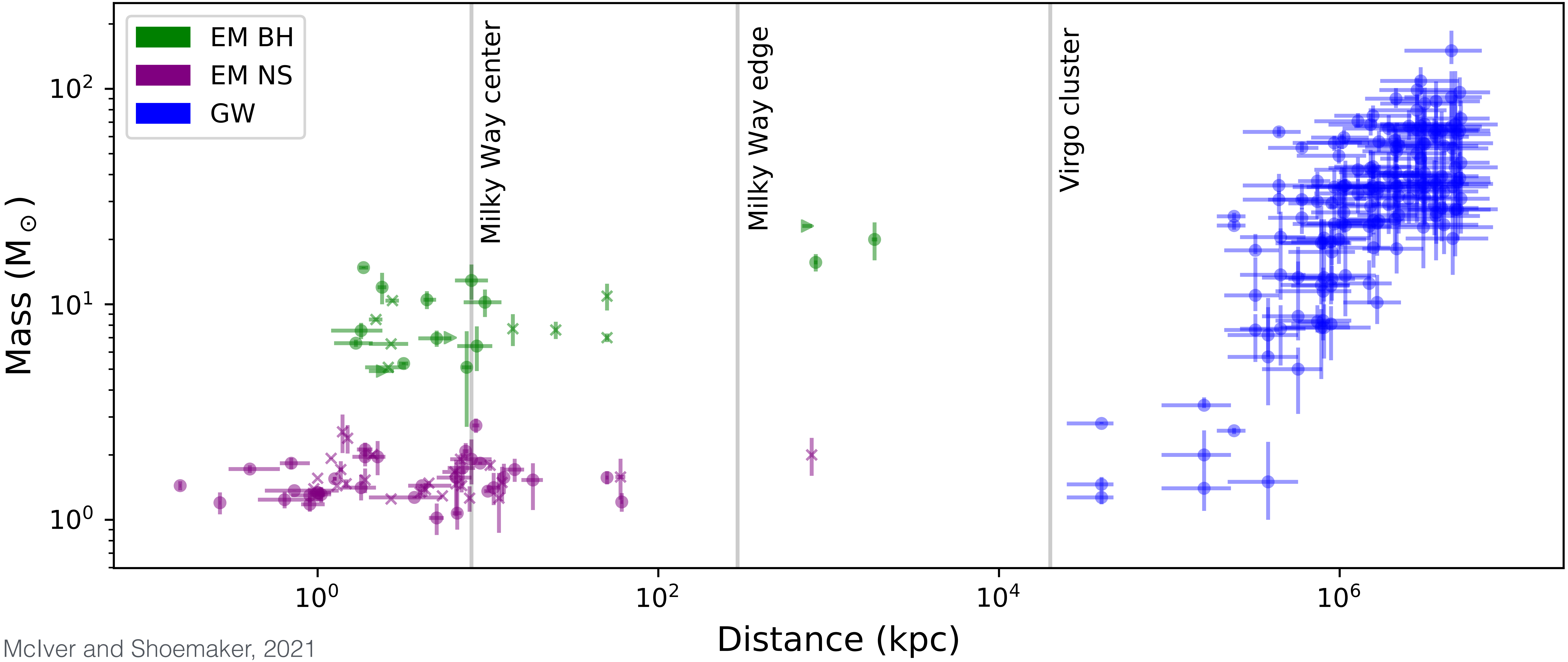
The first multi-messenger event with GWs

August 17, 2017



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

GWs reveal a new population of stellar remnants!



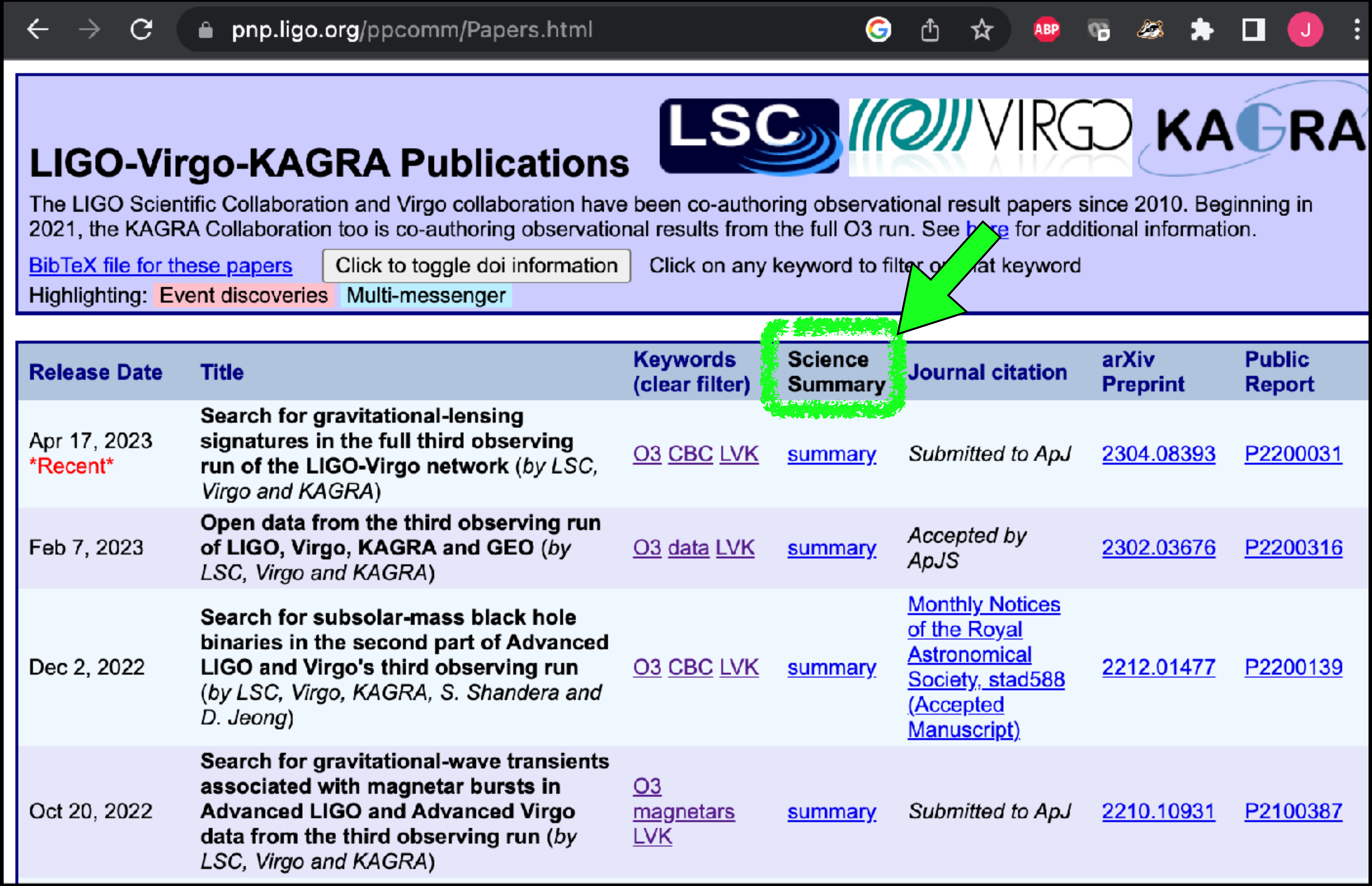
McIver and Shoemaker, 2021

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

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.

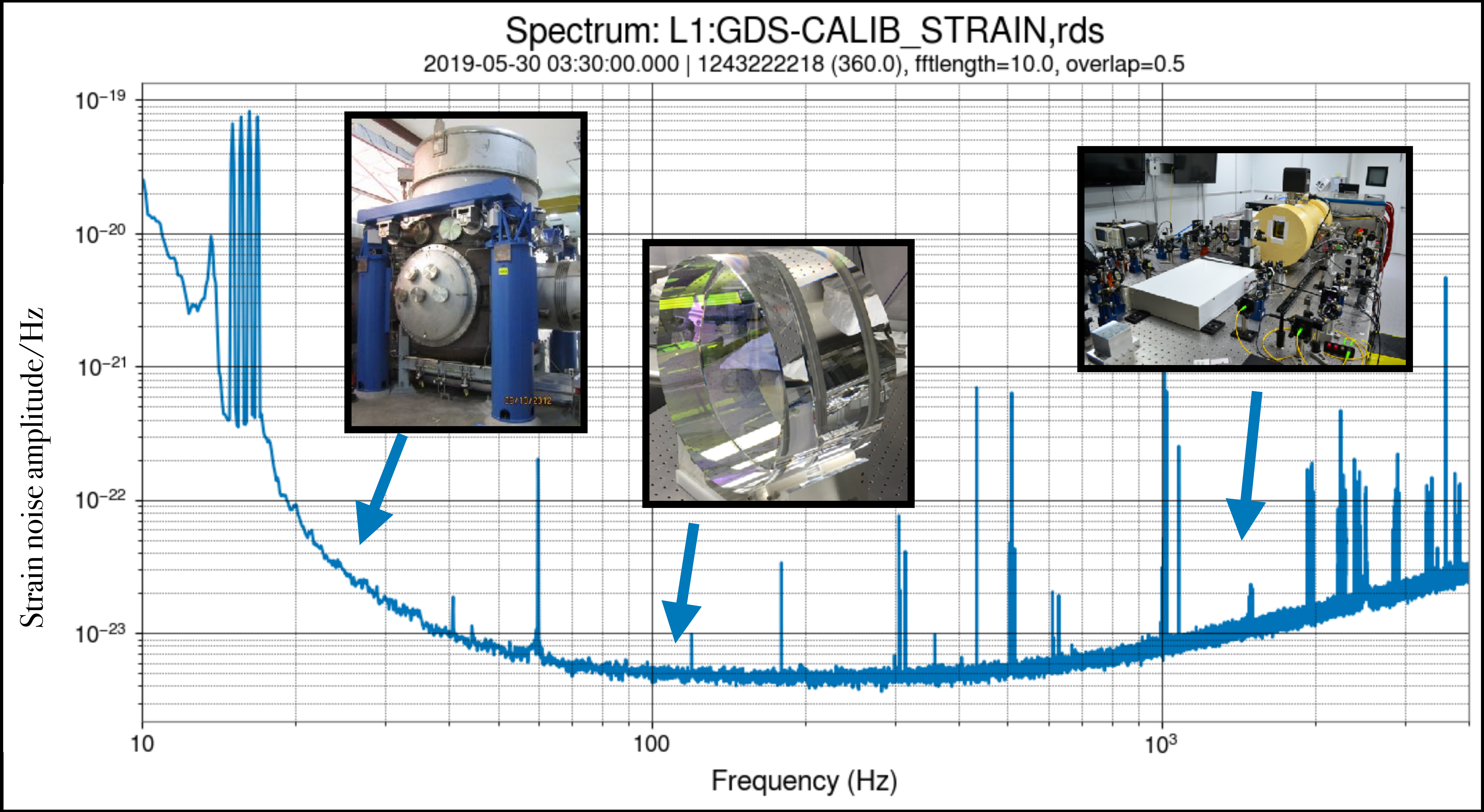
BibTeX file for these papers | Click to toggle doi information | Click on any keyword to filter on that keyword

Highlighting: Event discoveries Multi-messenger

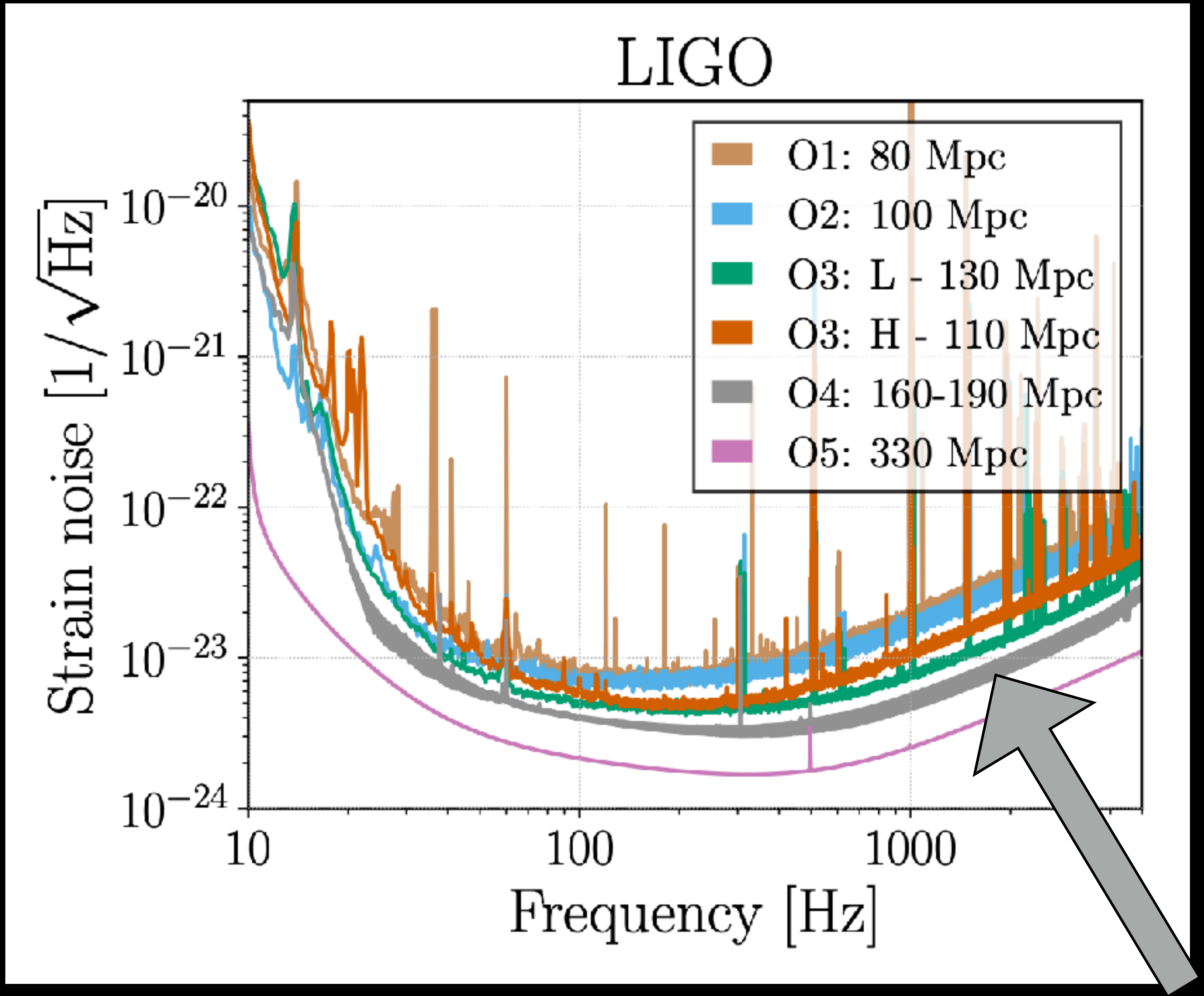
Release Date	Title	Keywords (clear filter)	Science Summary	Journal citation	arXiv Preprint	Public Report
Apr 17, 2023 *Recent*	**Search for gravitational-lensing signatures in the full third observing run of the LIGO-Virgo network** (*by LSC, Virgo and KAGRA*)	O3 CBC LVK	summary	*Submitted to ApJ*	2304.08393	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

Kai Staats

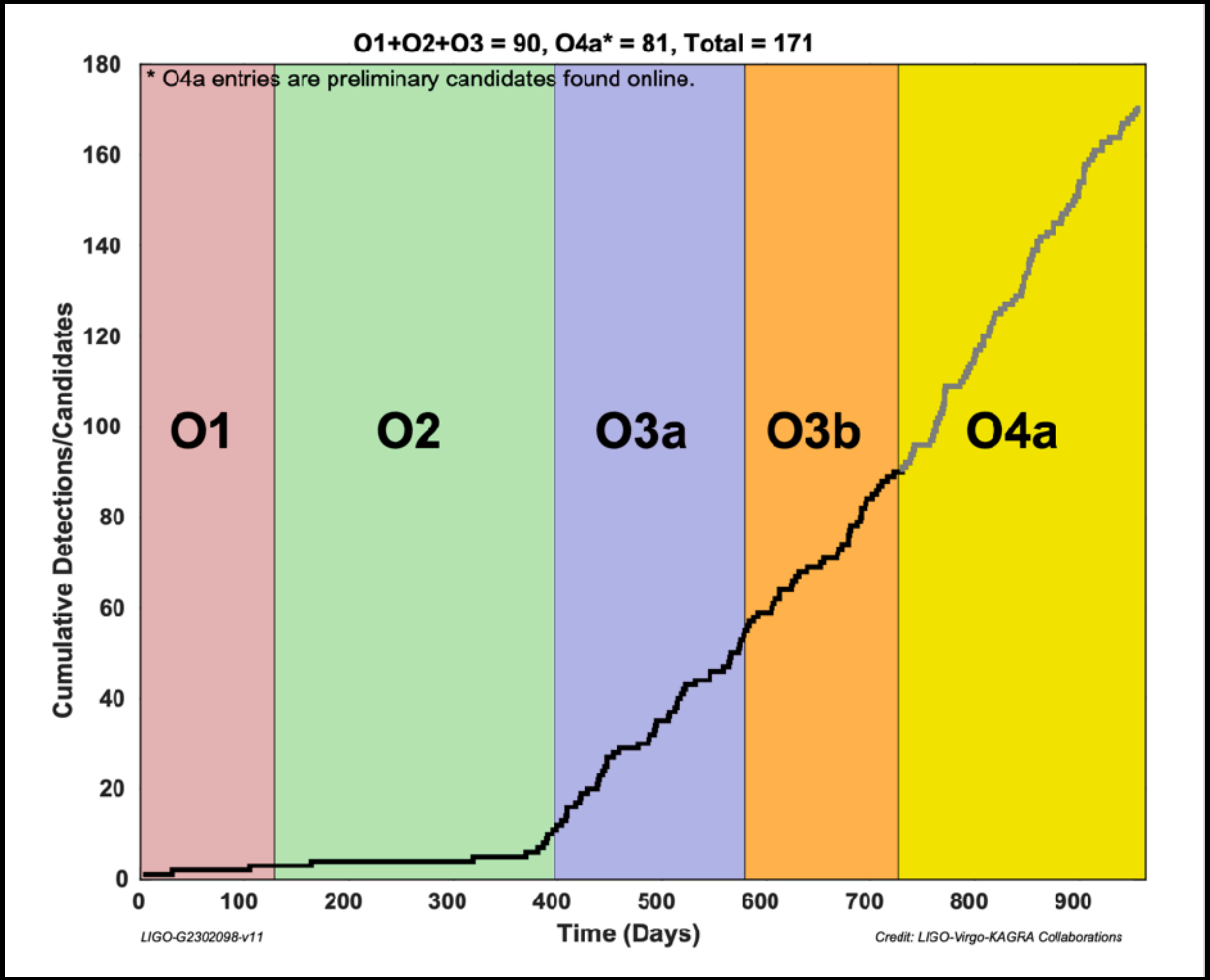
Advanced LIGO noise



Sensitivity and detection rate



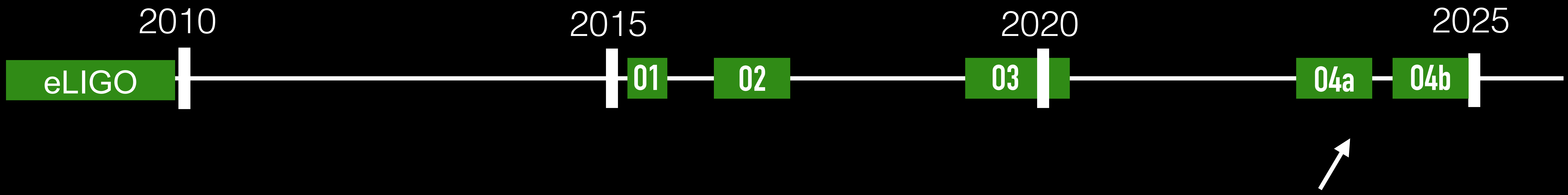
***O4a:**May 24 2023 - Jan 16 2024*



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)

- O4a: May 24 2023 - Jan 16 2024
  - 2 LIGO detectors with improved detector sensitivity (+ KAGRA)
- Commissioning break Jan - April 2024
- O4b: April 10 2024 - early 2025 (TBC)
  - LIGO and Virgo

O4 snapshot

graceb.ligo.org

GraceDB Public Alerts ▾ Latest Search Notifications Pipelines Documentation Logout

Authenticated as: Jess McIver

LIGO/Virgo/KAGRA Public Alerts

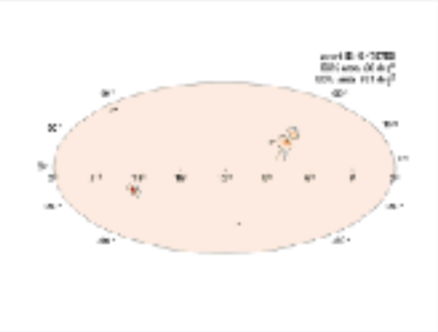
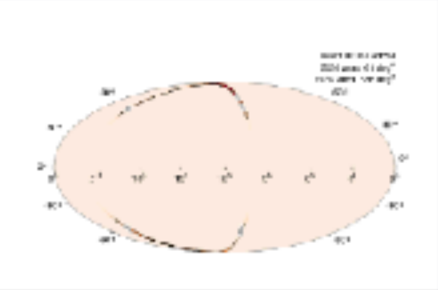
O4 Significant Detection Candidates: **89** (102 Total - 13 Retracted)

O4 Low Significance Detection Candidates: **1782** (Total)

Show All Public Events

Page 1 of 7. next last »

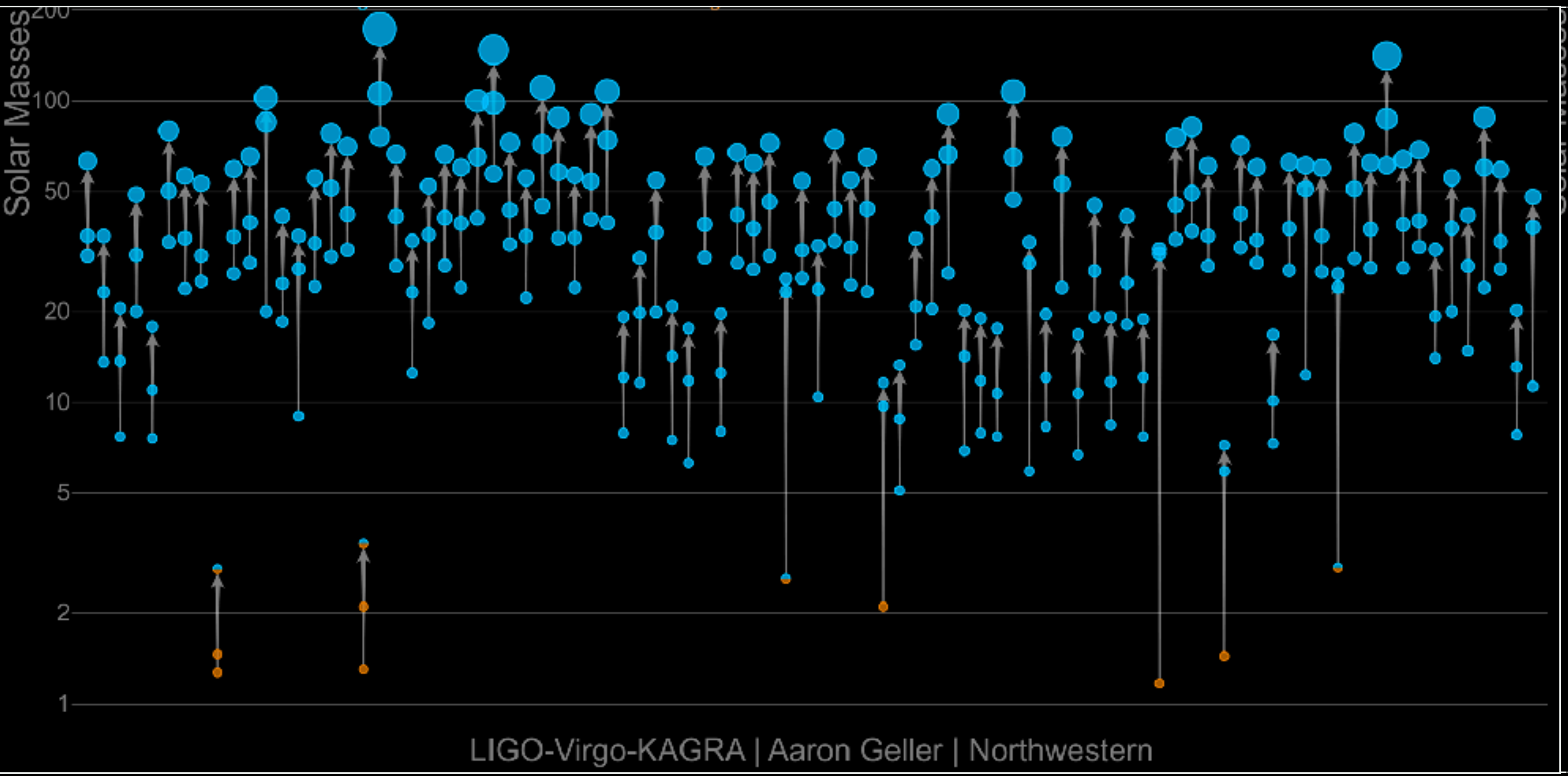
SORT: EVENT ID (A-Z) ▾

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR
S240429an	Terrestrial (98%), BNS (2%)	Yes	April 29, 2024 05:23:03 UTC	GCN Circular Query Notices | VOE		1 per 11.049 years
S240428dr	BBH (>99%)	Yes	April 28, 2024 22:54:40 UTC	GCN Circular Query Notices | VOE		1 per 1.5024e+06 years

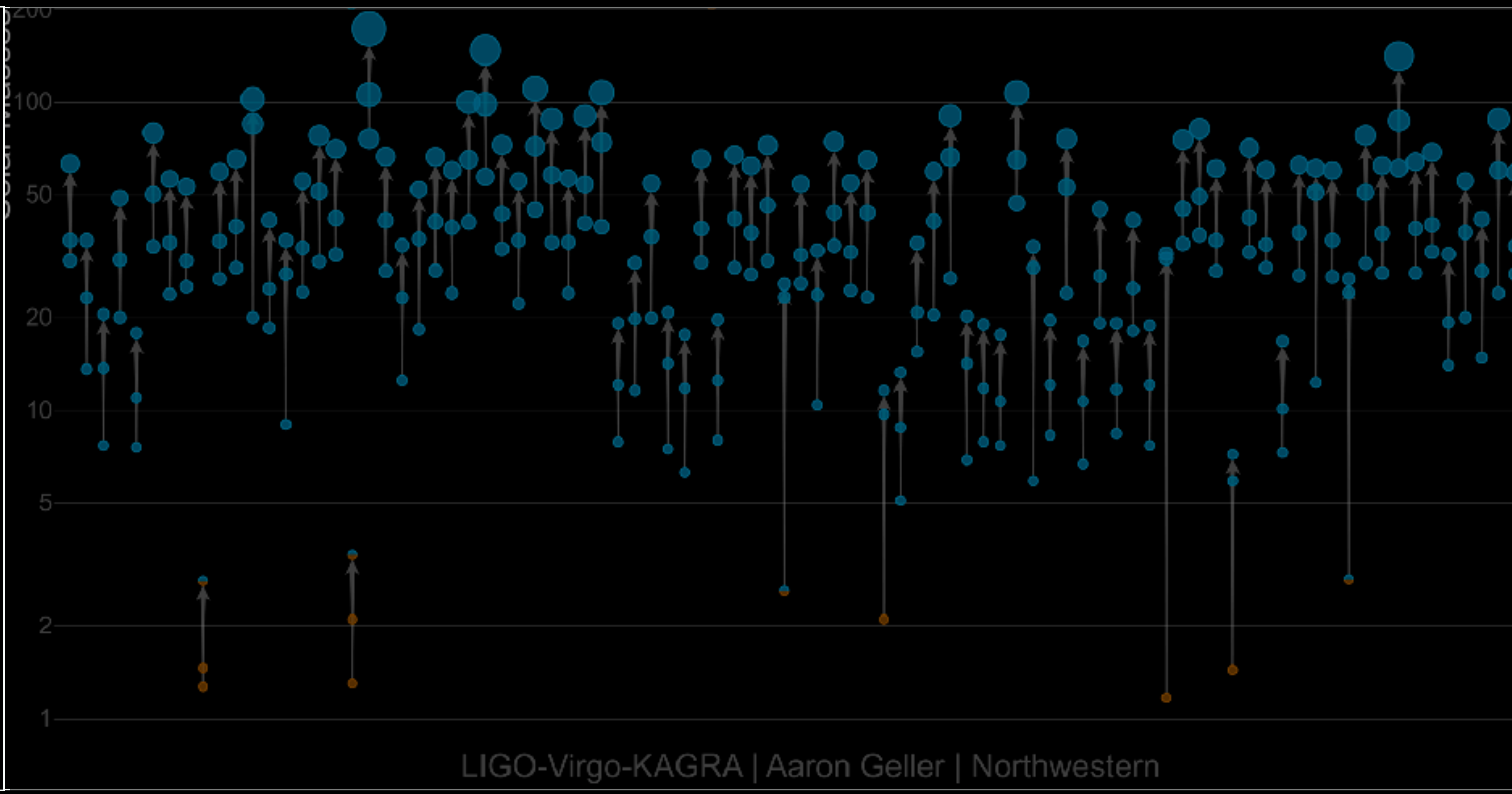
Sensitivity and detection rate

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

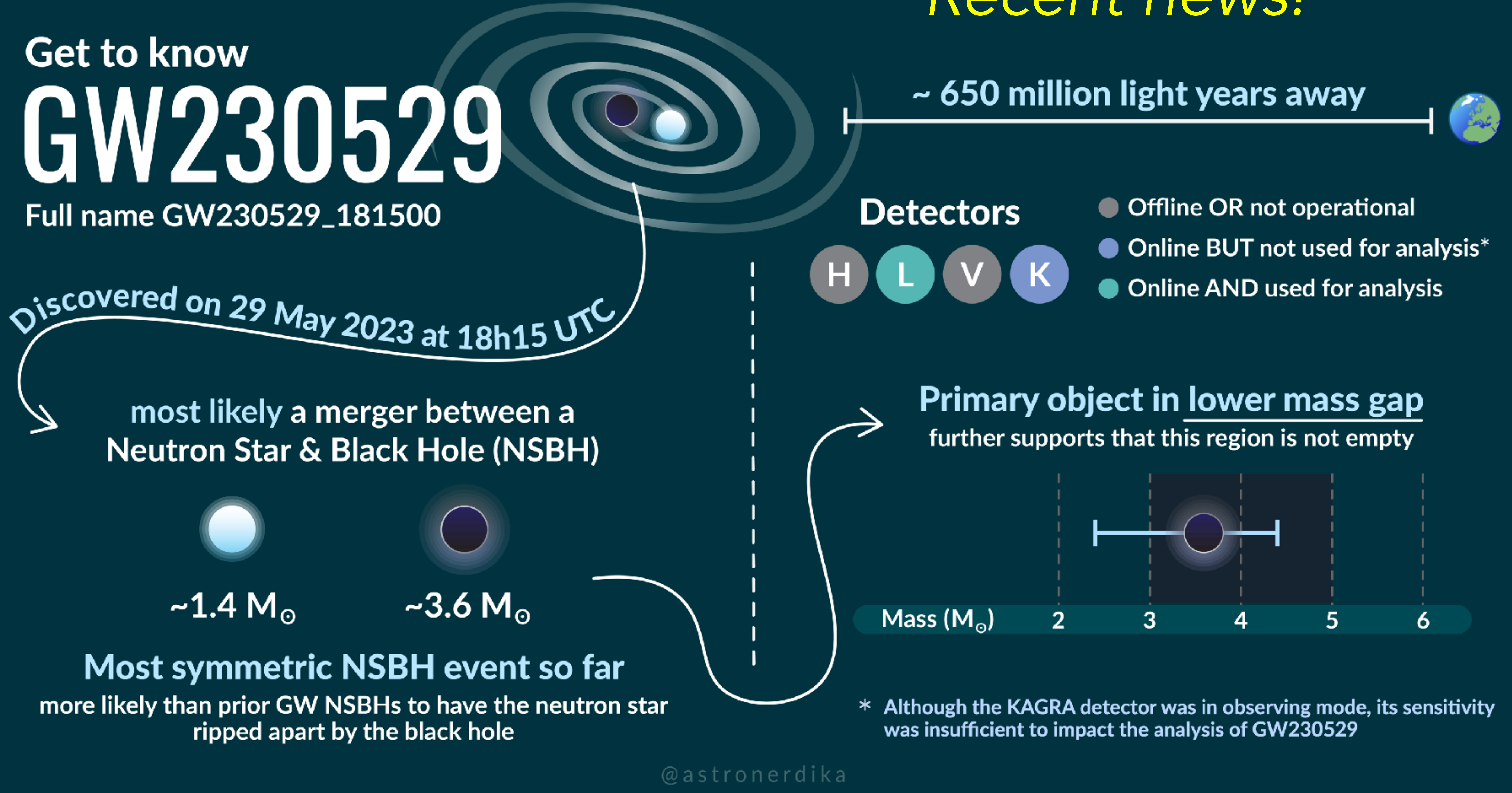
O1, O2, O3
Over 2 years of collective observing time



Nearly the same number of alert candidates so far in O4a *(May 24 - Jan 16)***!**

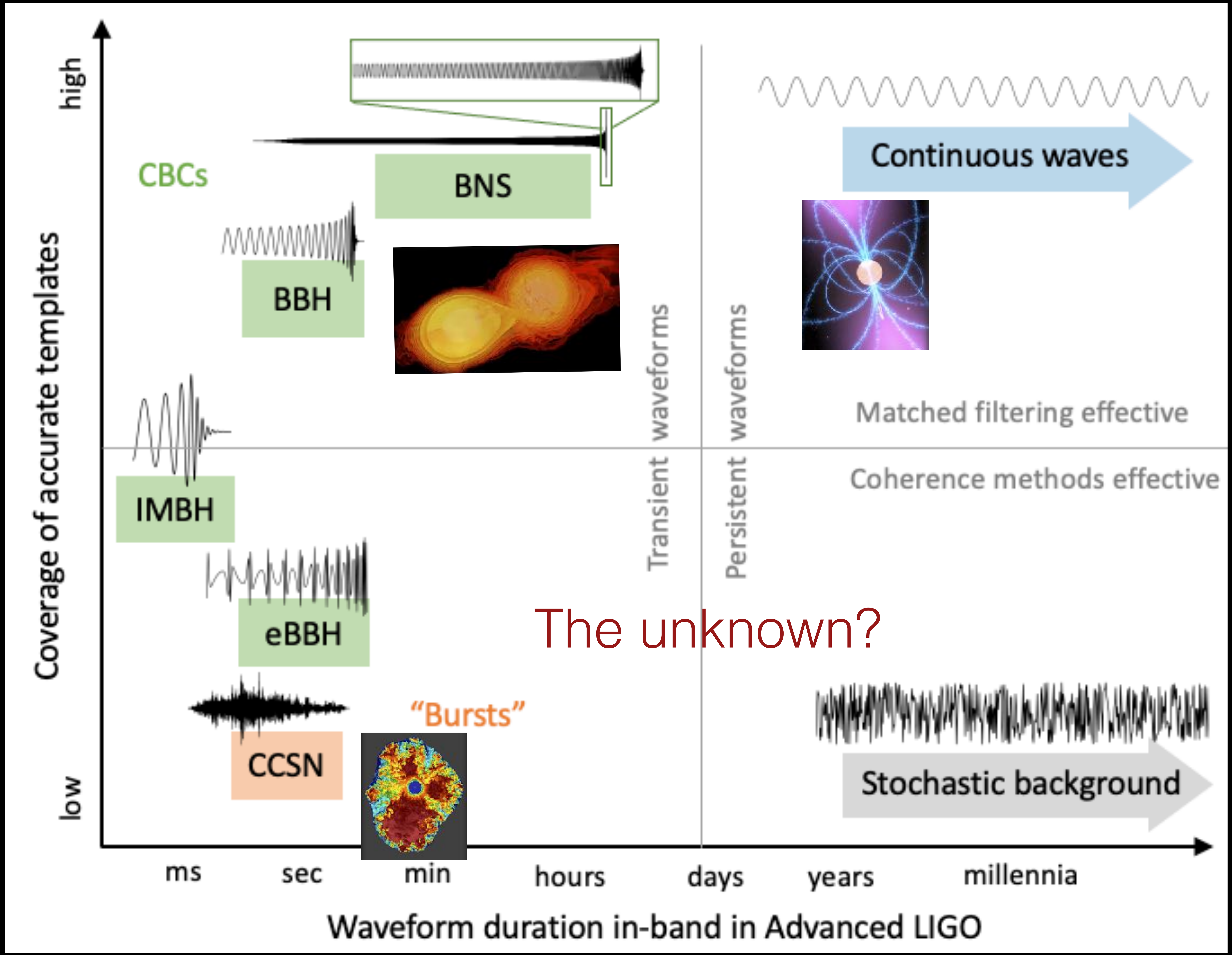


Recent news!



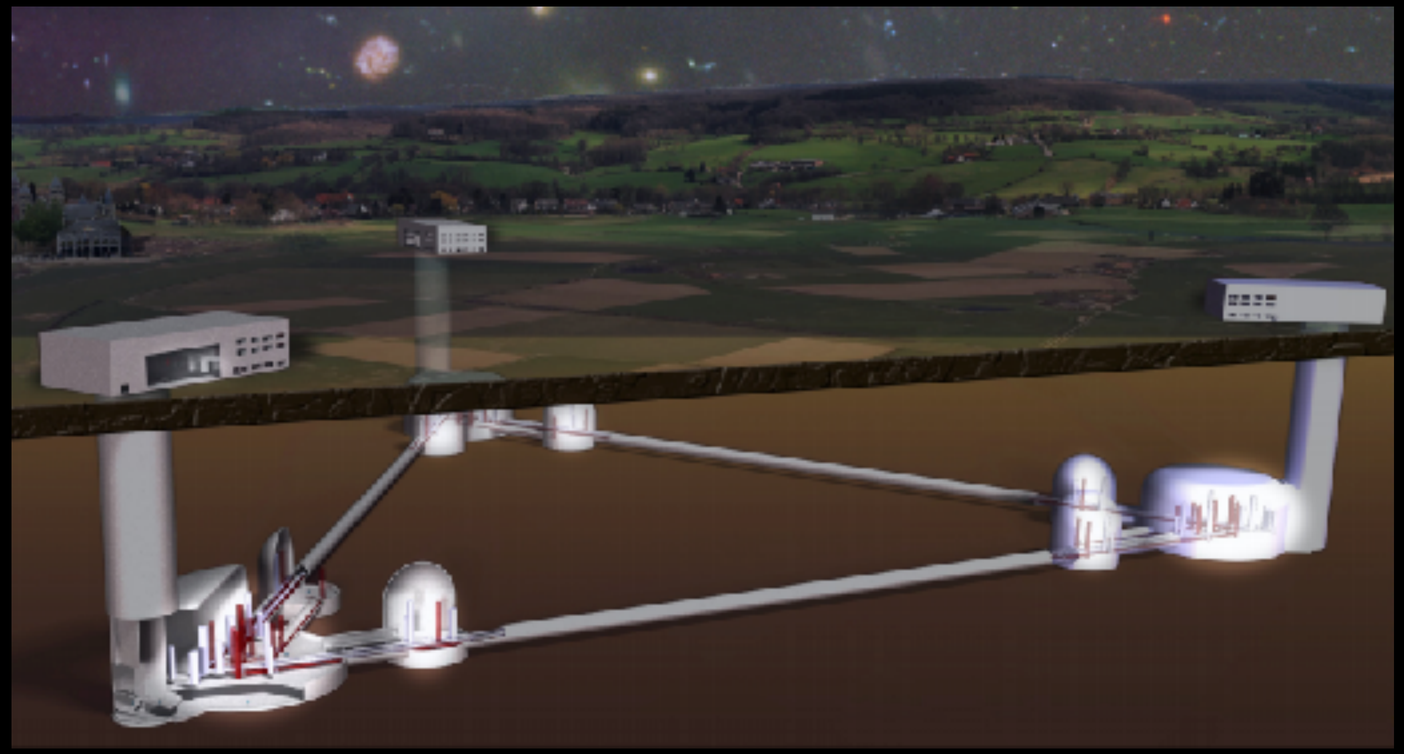
Get to know
GW230529
Full name GW230529_181500
Discovered on 29 May 2023 at 18h15 UTC
most likely a merger between a
Neutron Star & Black Hole (NSBH)
~1.4 M⊙
~3.6 M⊙
Most symmetric NSBH event so far
more likely than prior GW NSBHs to have the neutron star ripped apart by the black hole
~ 650 million light years away
Detectors
H
L
V
K
Offline OR not operational
Online BUT not used for analysis*
Online AND used for analysis
Primary object in lower mass gap
further supports that this region is not empty
Mass (M⊙)
2
3
4
5
6
* Although the KAGRA detector was in observing mode, its sensitivity was insufficient to impact the analysis of GW230529
@astronerdika

What else might we detect with current detectors?



McIver and Shoemaker, 2021

The next generation of GW detectors

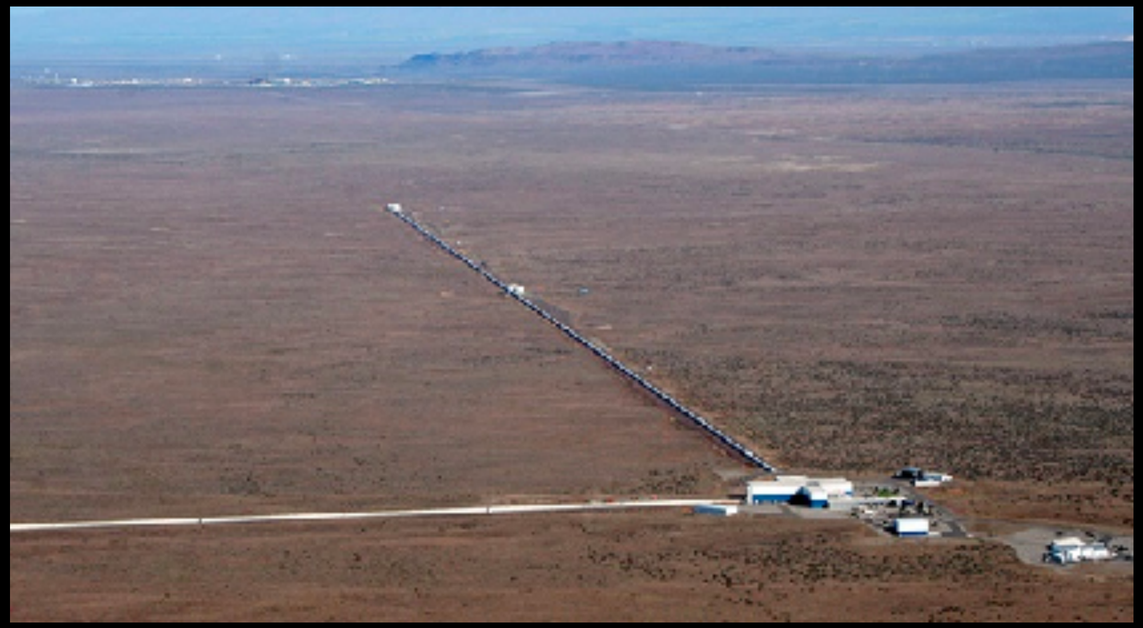


A+/AdV+
- 3-4 km detectors
- **300 K**
- 1064 nm laser
- 40 kg mirrors

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

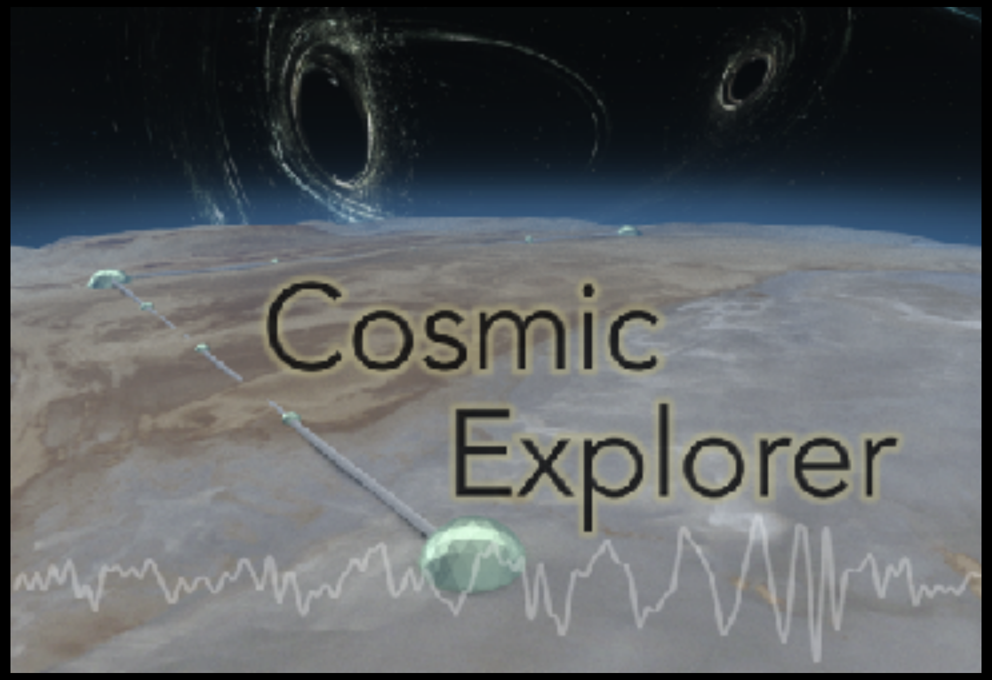
Cosmic Explorer 2
- 20-40 km detectors
- **123 K**
- 1-2 microns (?)
- 320 kg mirrors

2025 — 2030 — 2035 — 2040



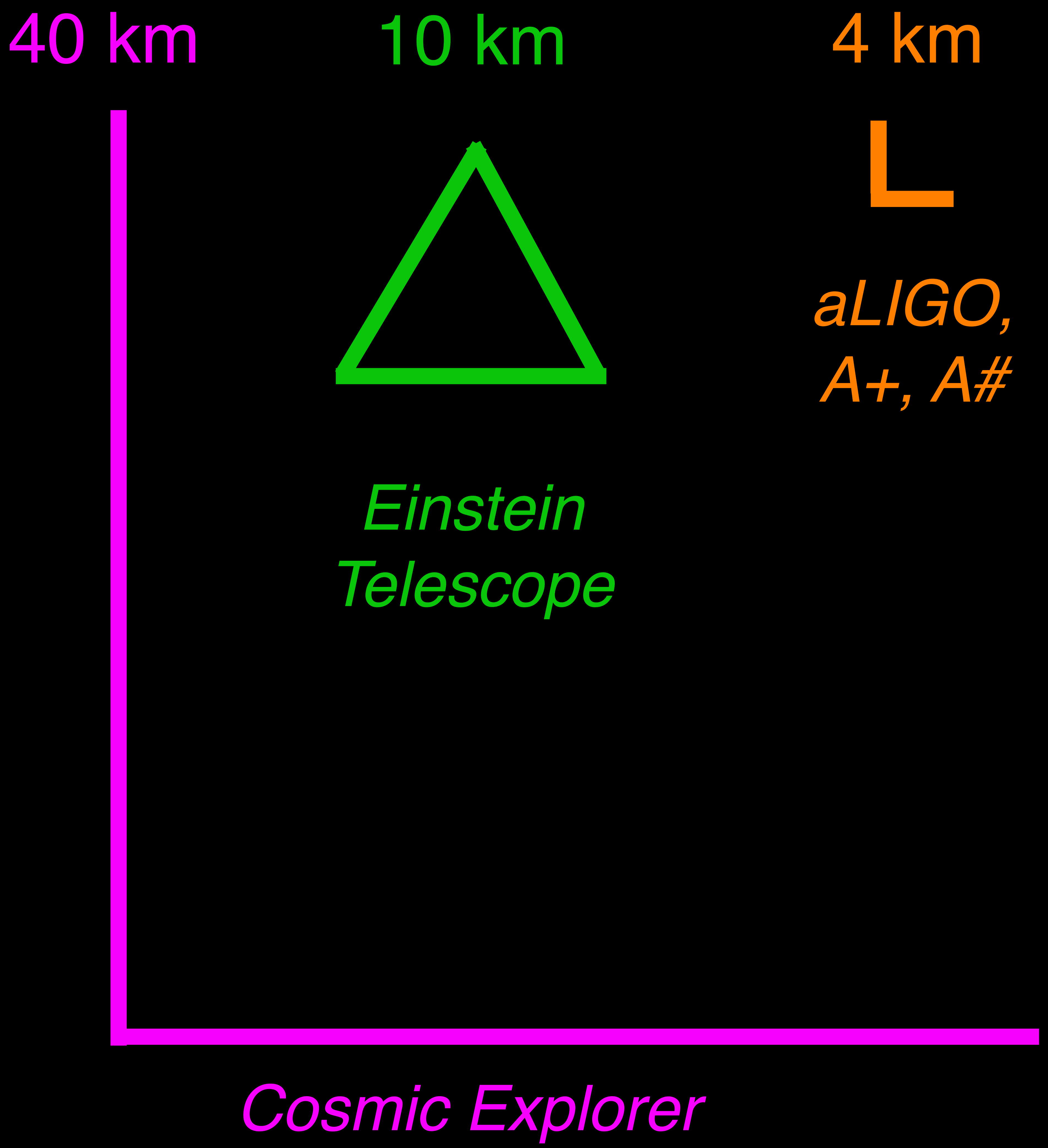
A#/VirgoNEXT
- 4 km detectors
- **300 K**
- 1064 nm laser
- 100 kg mirrors

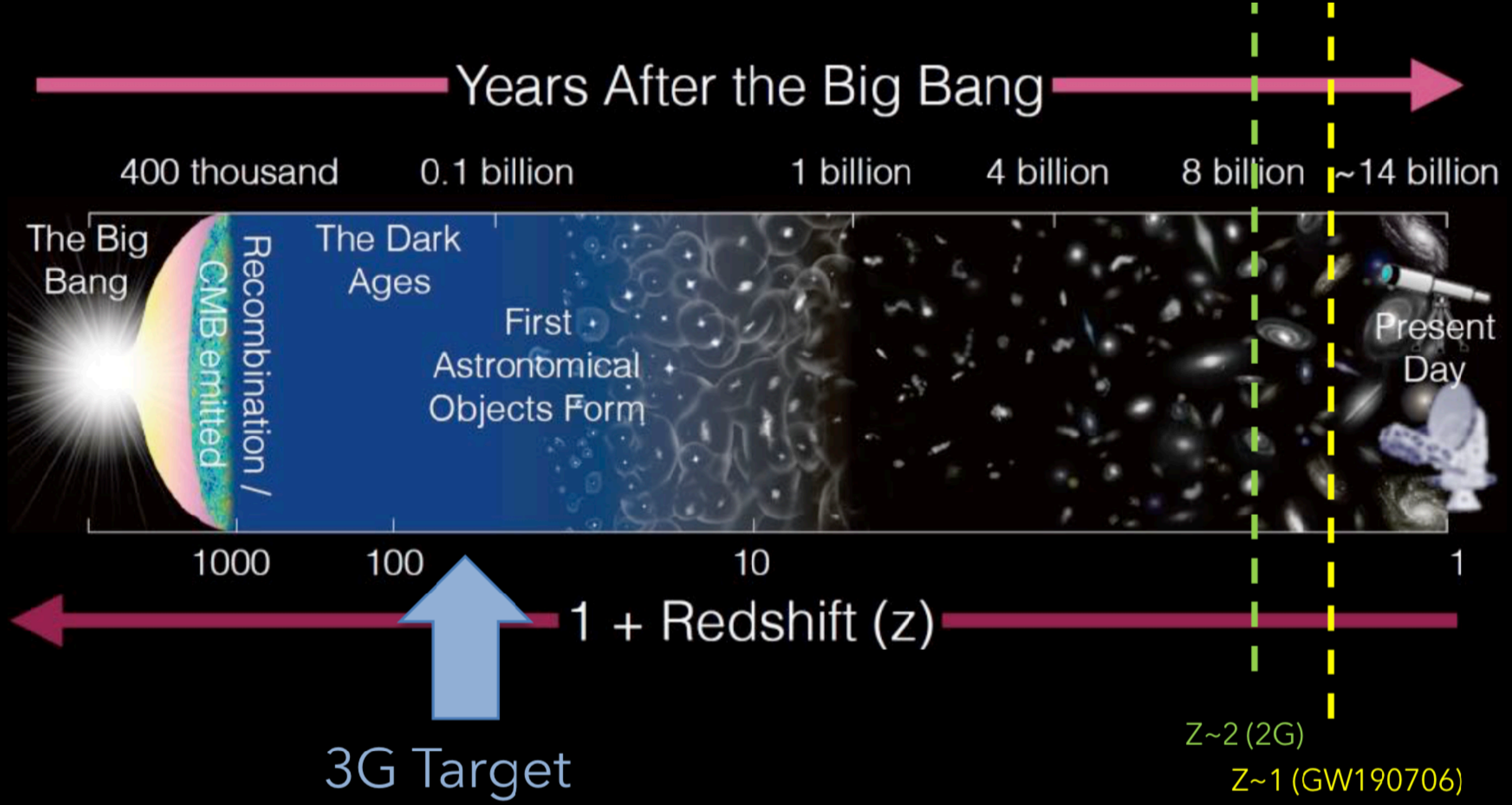
Cosmic Explorer 1
- 20-40 km detectors
  300 K
- 1-2 microns (?)
- 320 kg mirrors



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



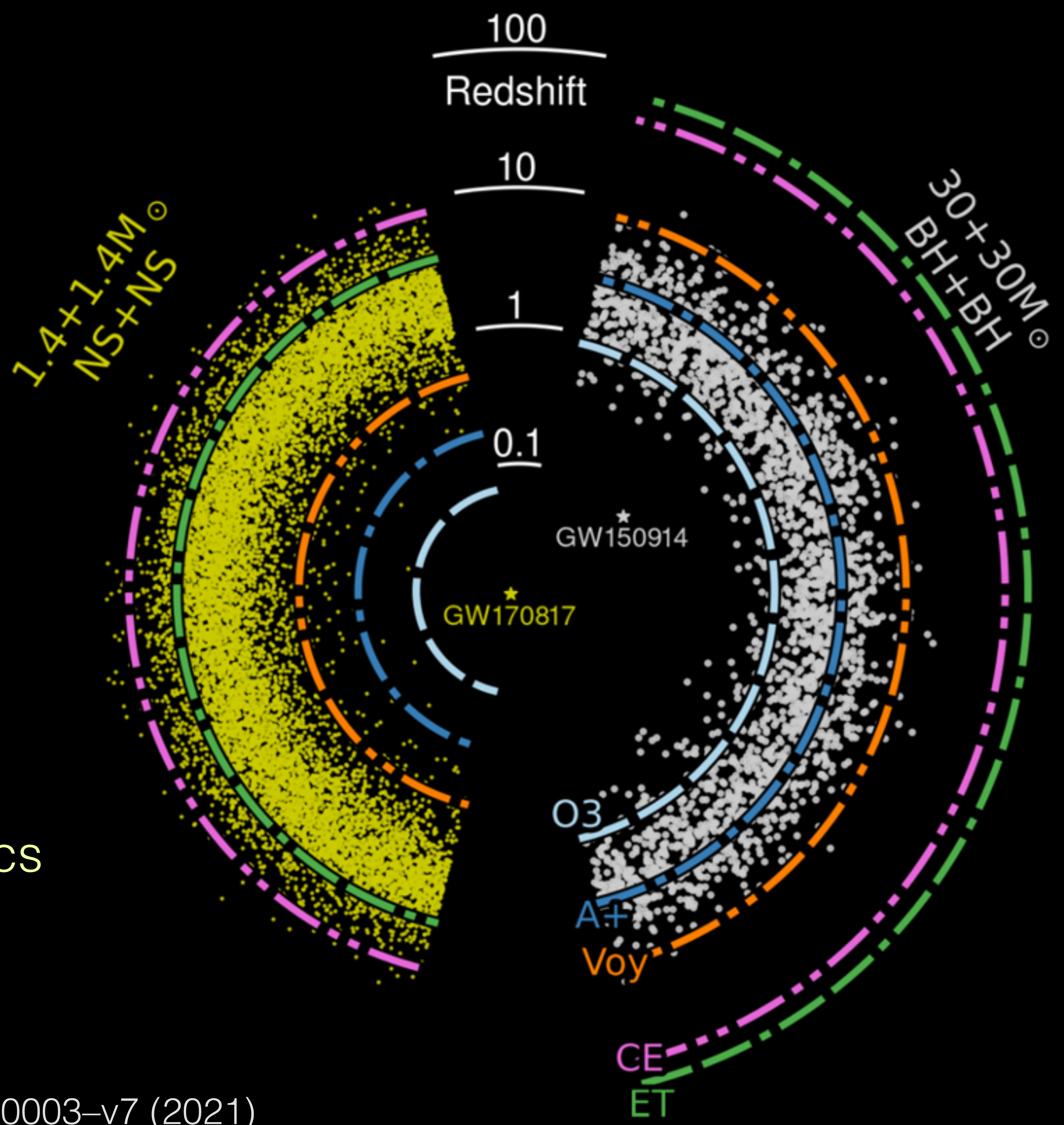


Slide by G. Losurdo

300,000 BNS mergers!

1 merger every 100 seconds!

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



100,000 BBH mergers!

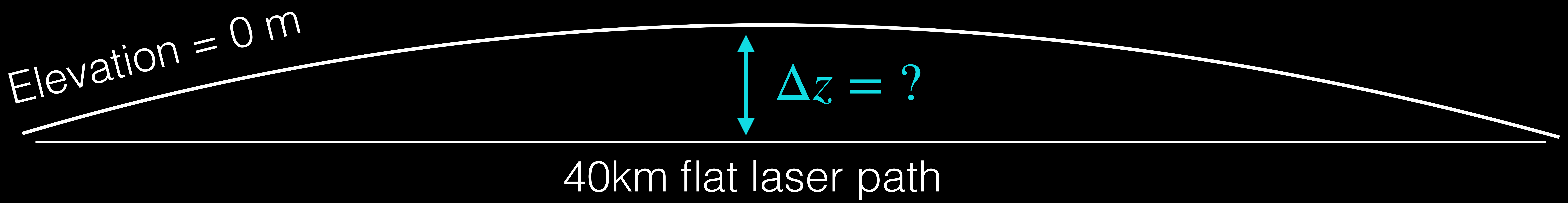
1 merger every 5 minutes!

~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)

Where would CE be built?

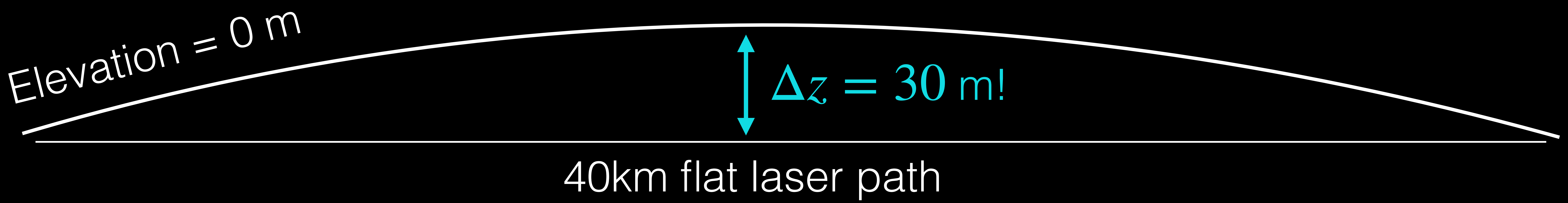


$\Delta z = 0.3$ m ?

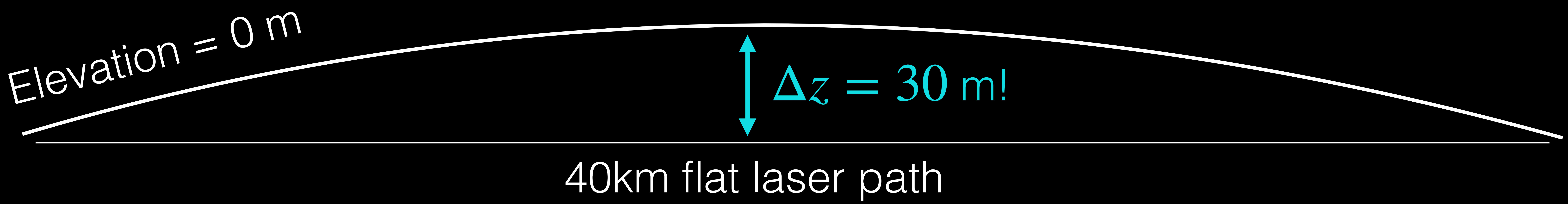
$\Delta z = 3$ m ?

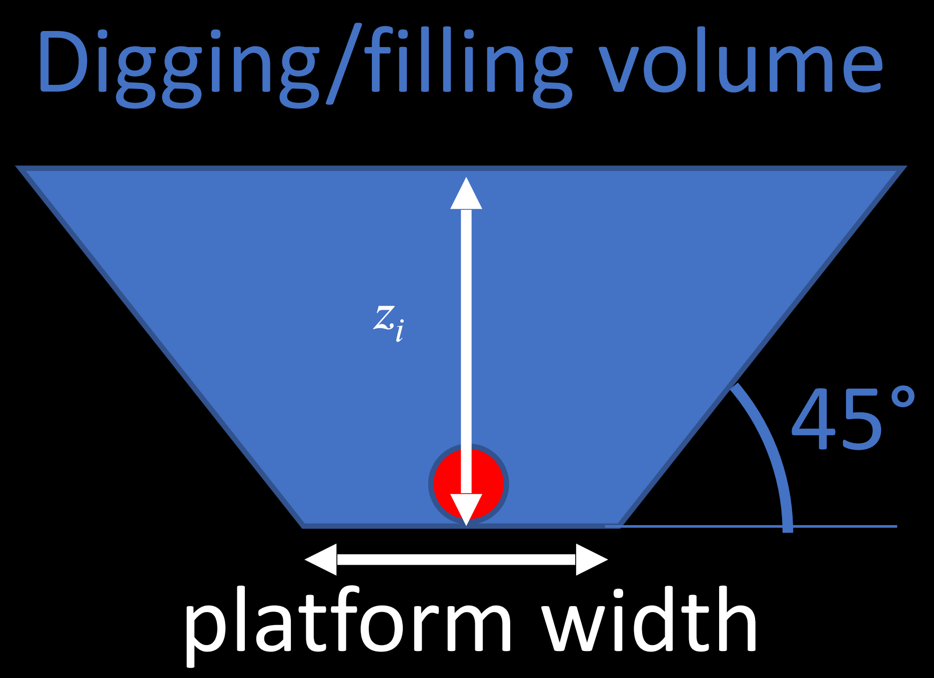
$\Delta z = 30$ m ?

Where would CE be built?



Where would CE be built?





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

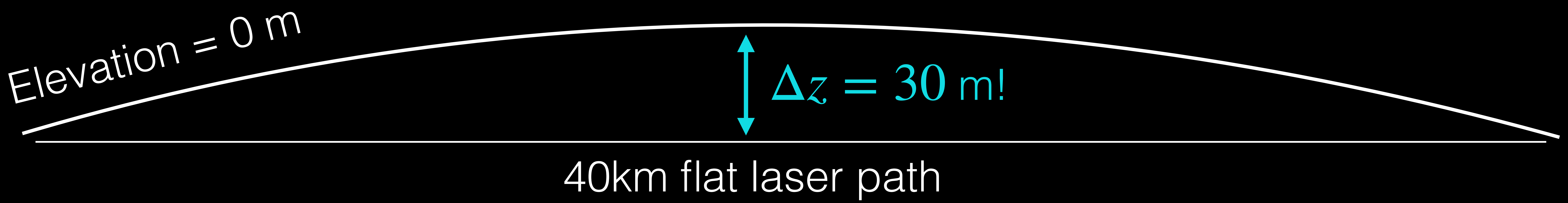
For each 40 km *arm*:

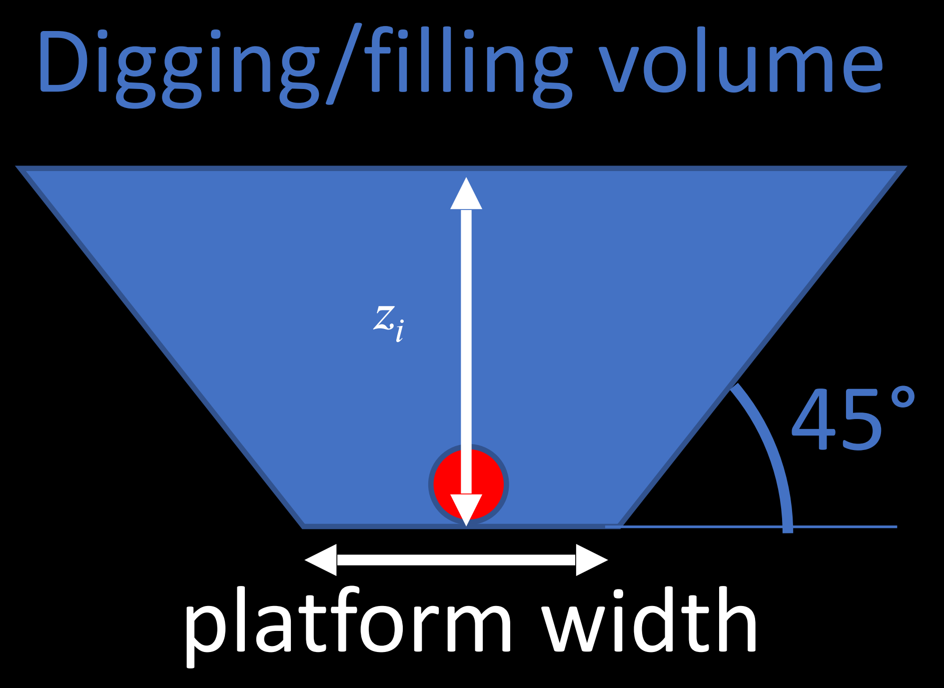
V = 43 000 x 10³ m³ (~430 M$)

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 10³ m³ (~430 M$)

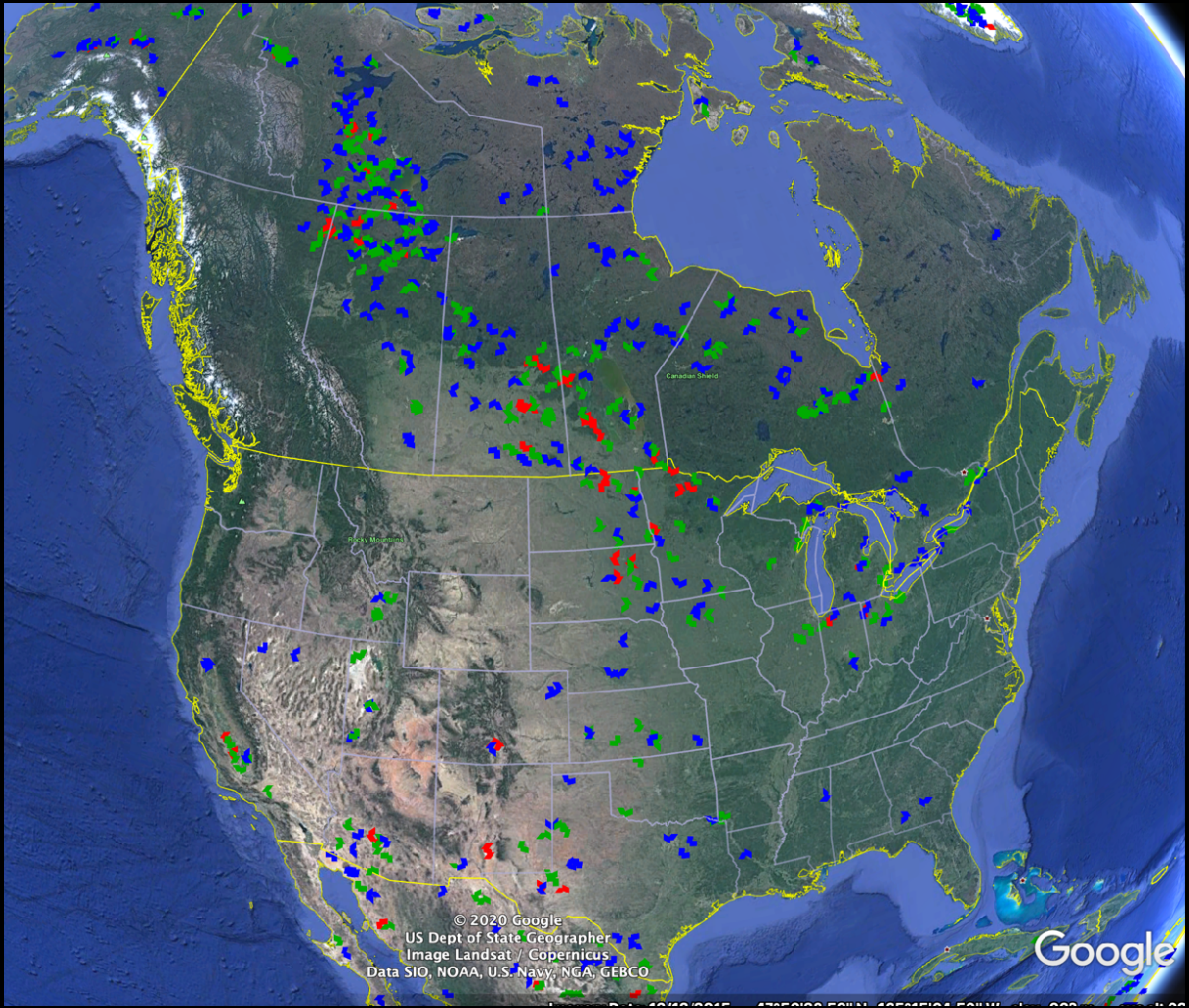
Choose a site with concave elevation such that $\Delta z \approx 0$

V = 375 x 10³ m³ (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



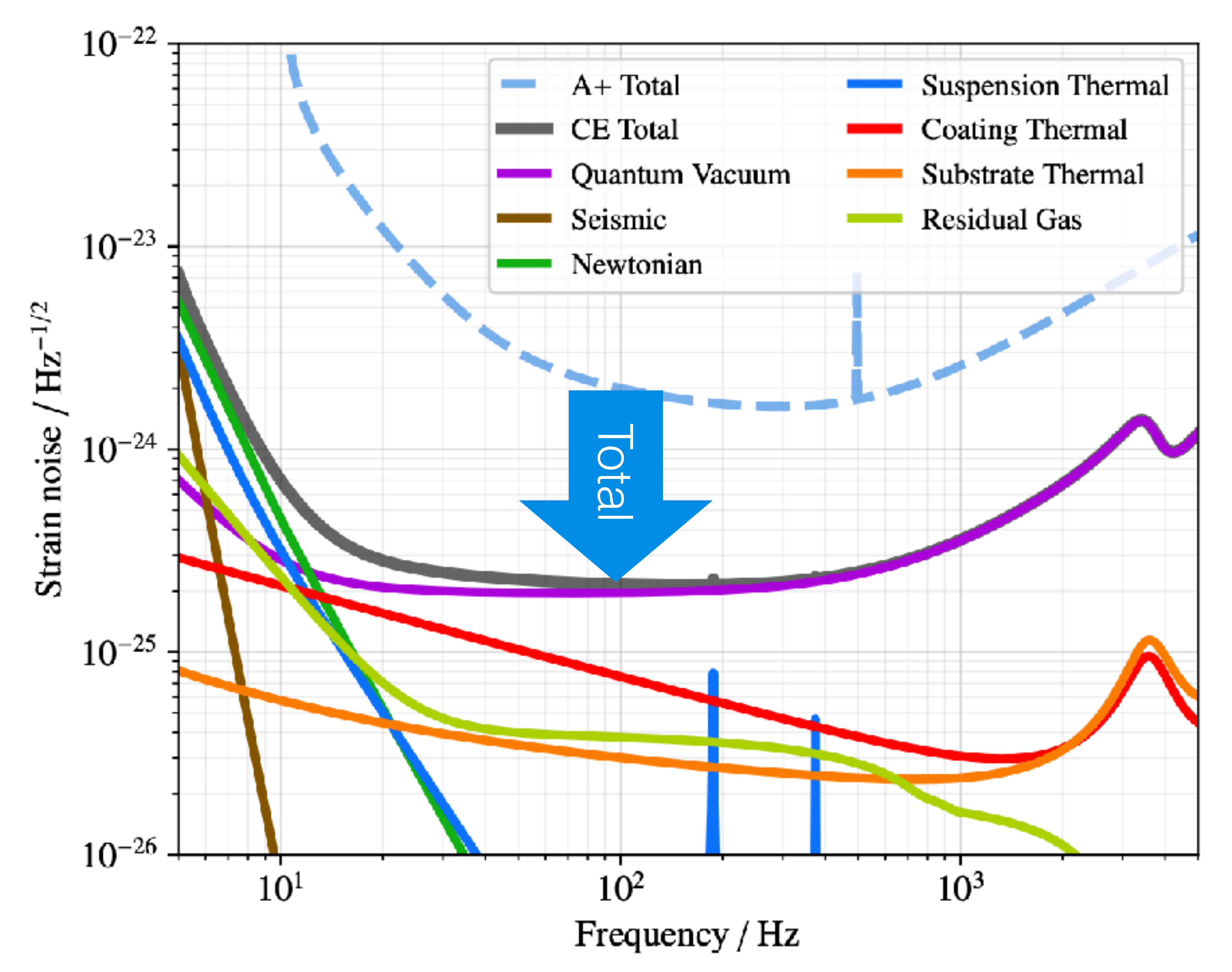
All sites overlap with unceded indigenous territories and/or nations.

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



	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

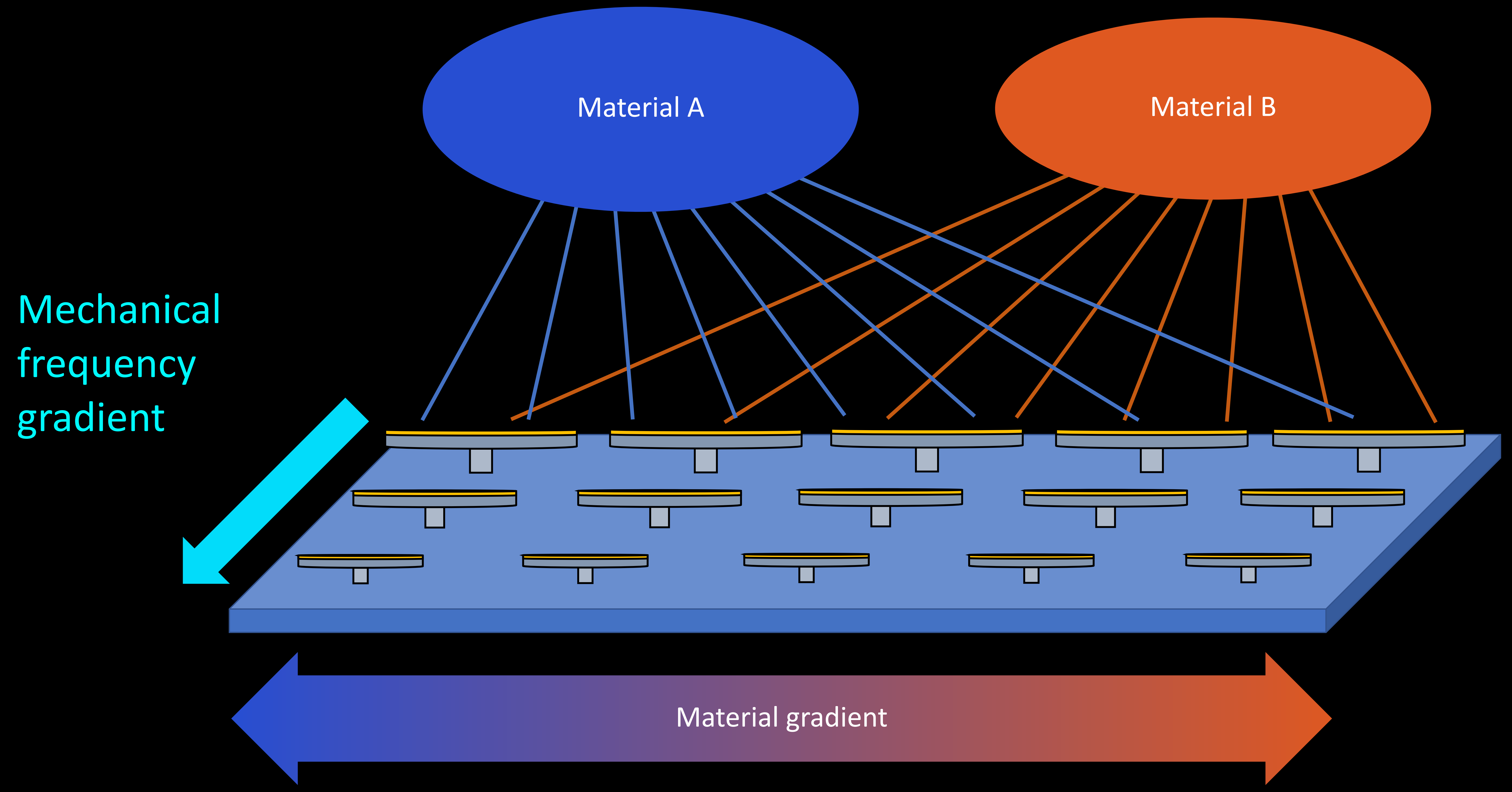
CE Horizon Study, CE–P2100003–v7 (2021)

GW detector coatings teams in Canada

UBC's Stewart Blusson
Quantum Matter Institute

Mechanical microresonators
Developing GW detector coatings at SBQMI

Gradient coatings: test different materials on the same chip

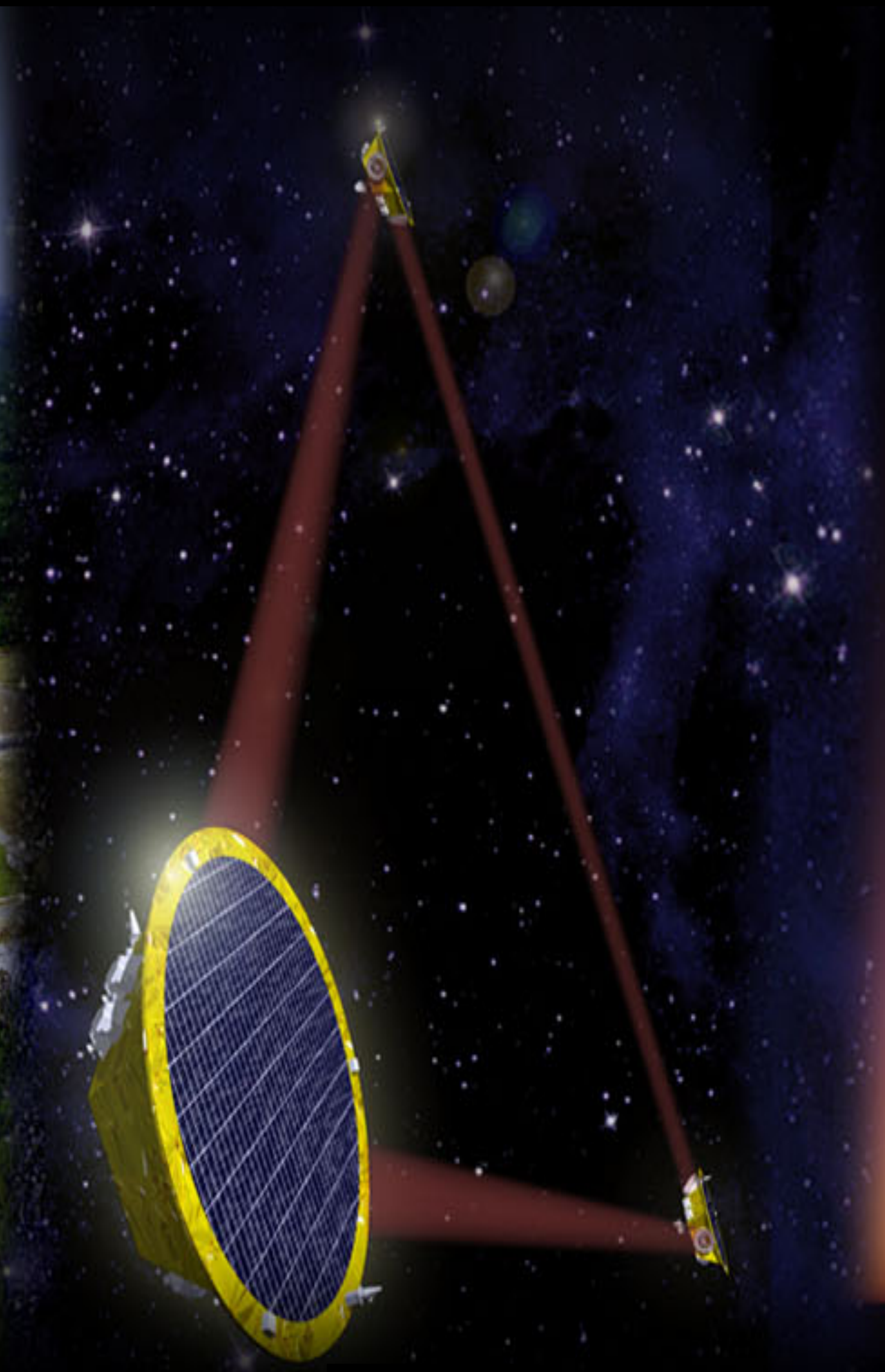


Gravitational Wave Periods

Milliseconds

LIGO/Virgo

Minutes to Hours

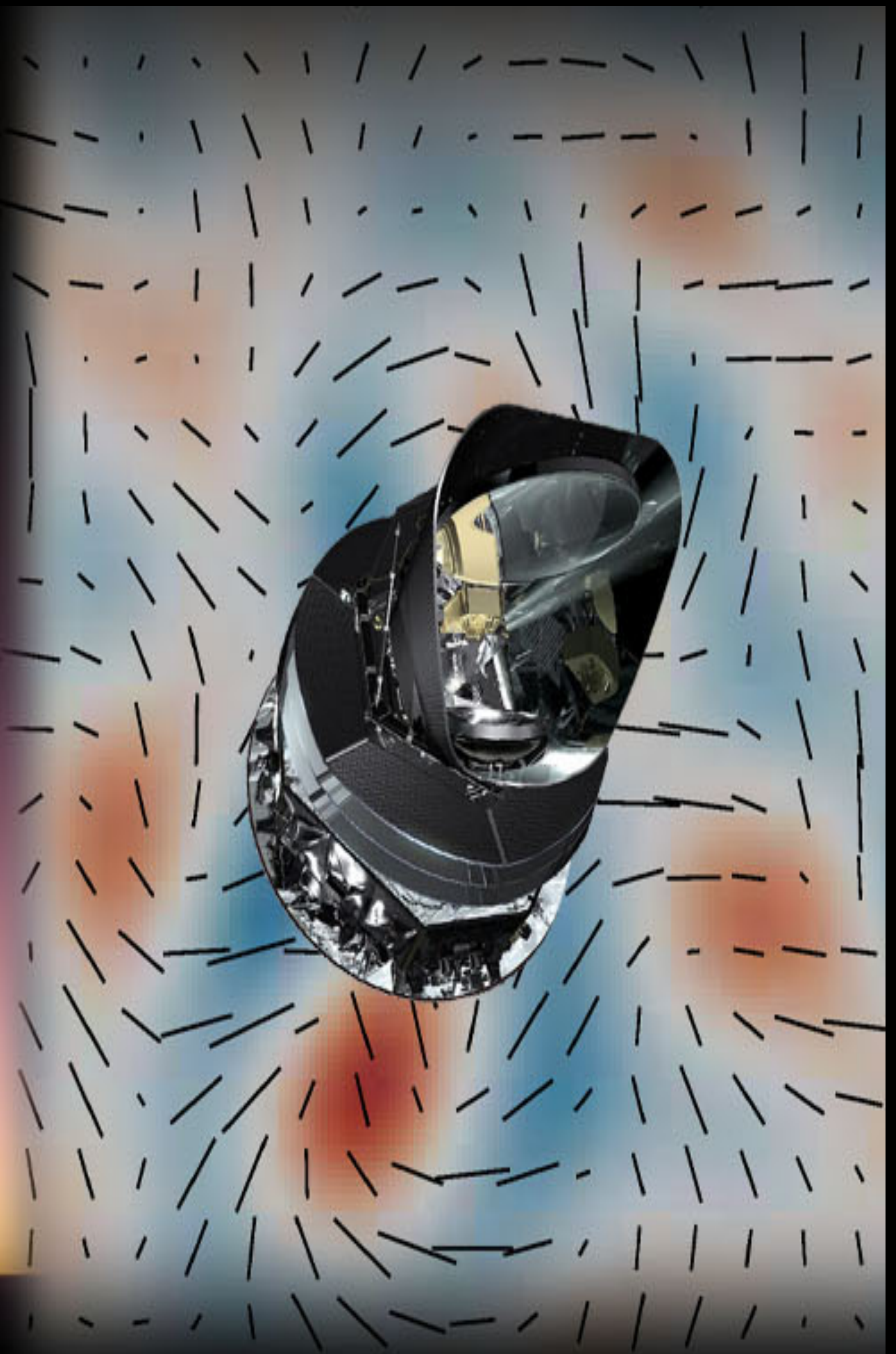


LISA

Years to Decades

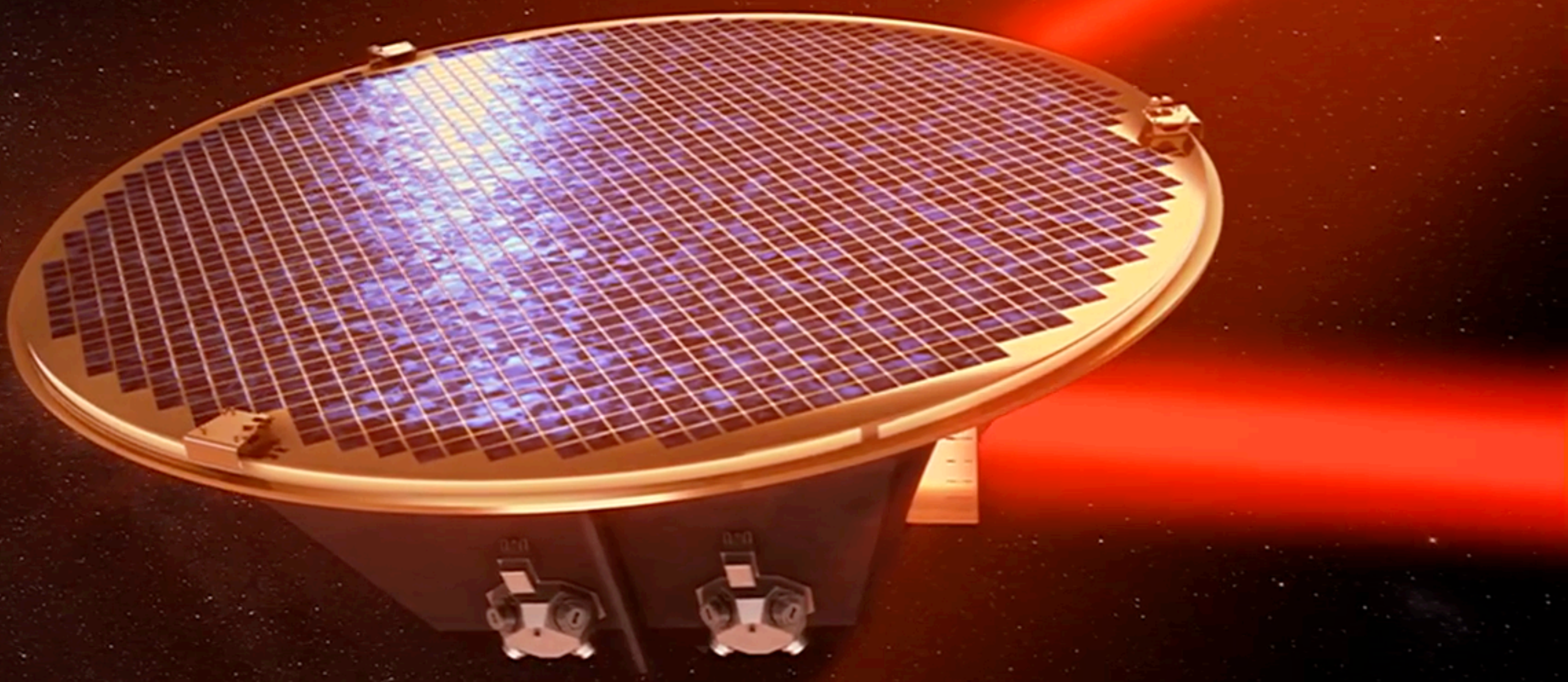
Pulsar timing

Billions of Years



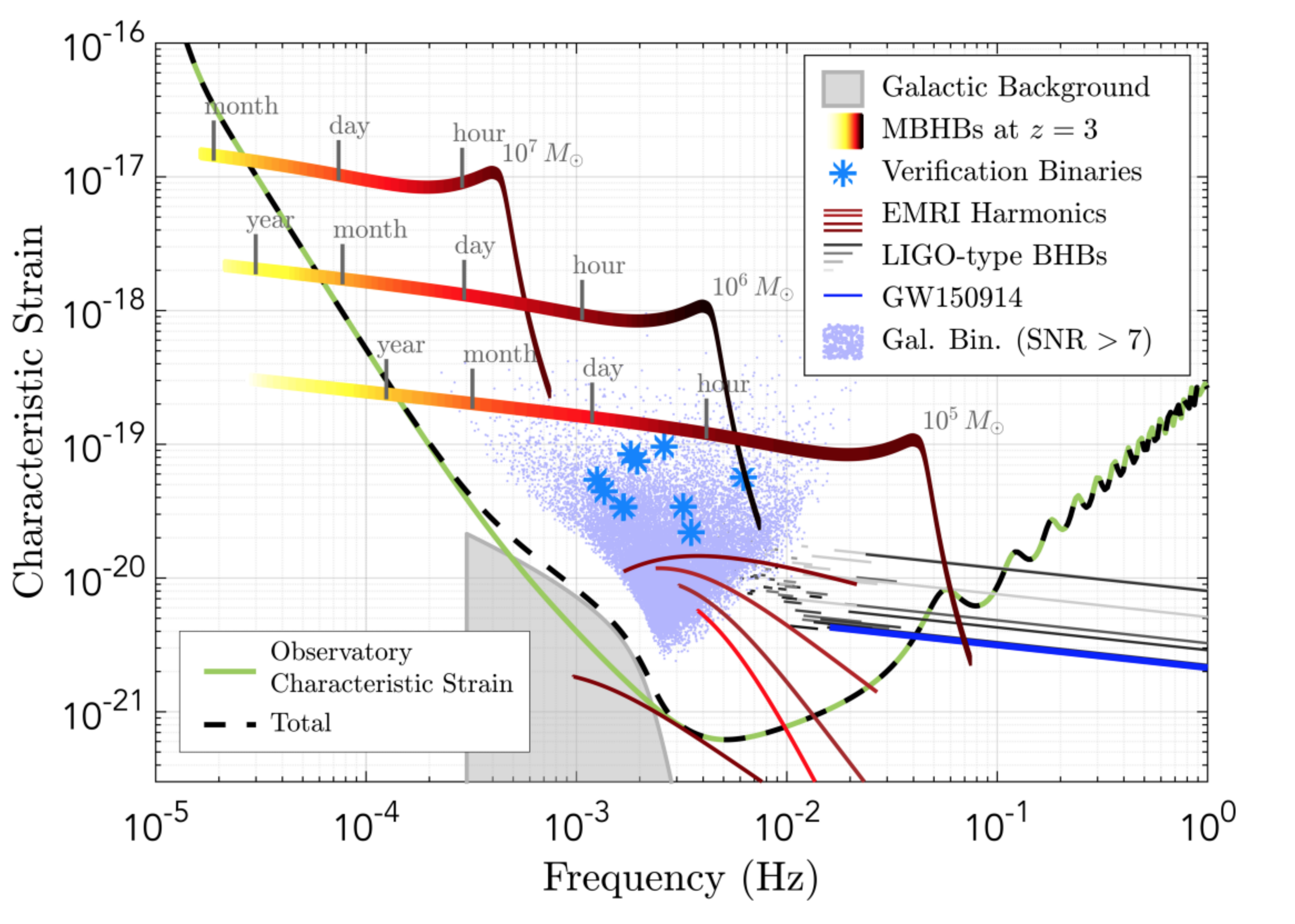
CMB polarization

The LISA mission



NASA

LISA discovery space

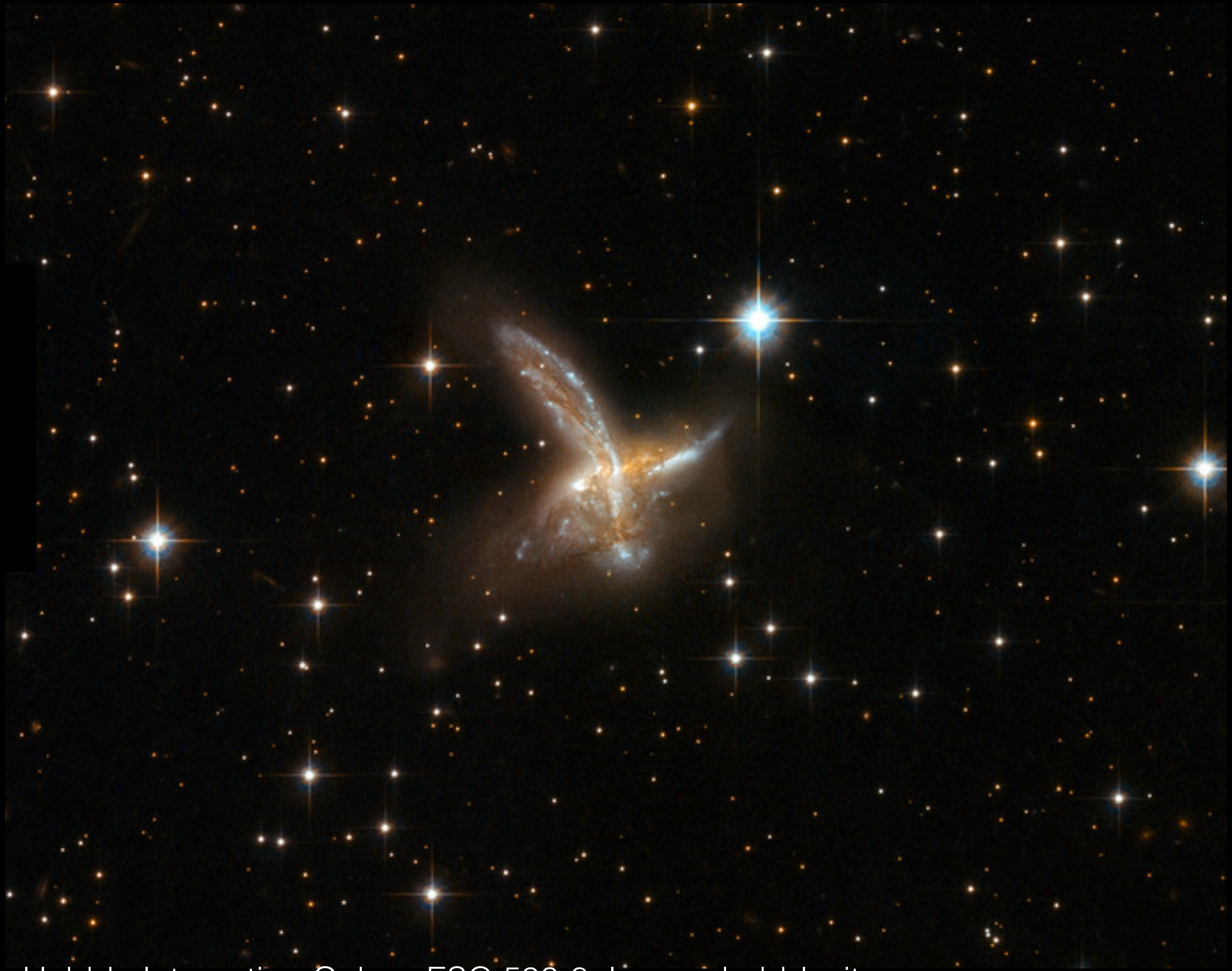


LISA core team + consortium - 2017

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

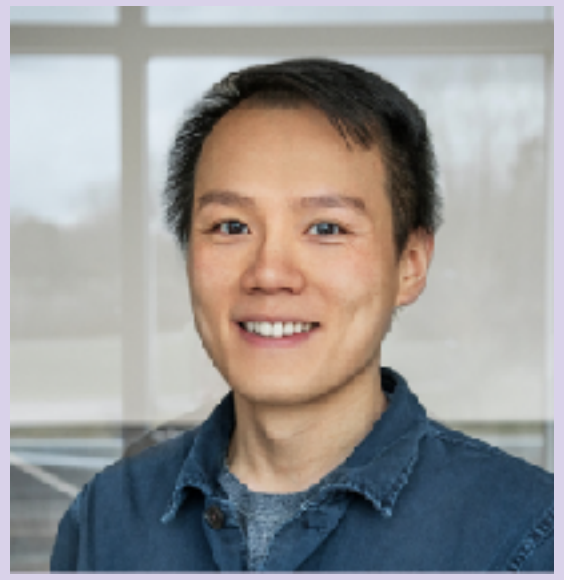
UBC

Multi-messenger


Daryl Haggard

Trottier Space Institute at McGill

UNIVERSITÉ BISHOP'S UNIVERSITY

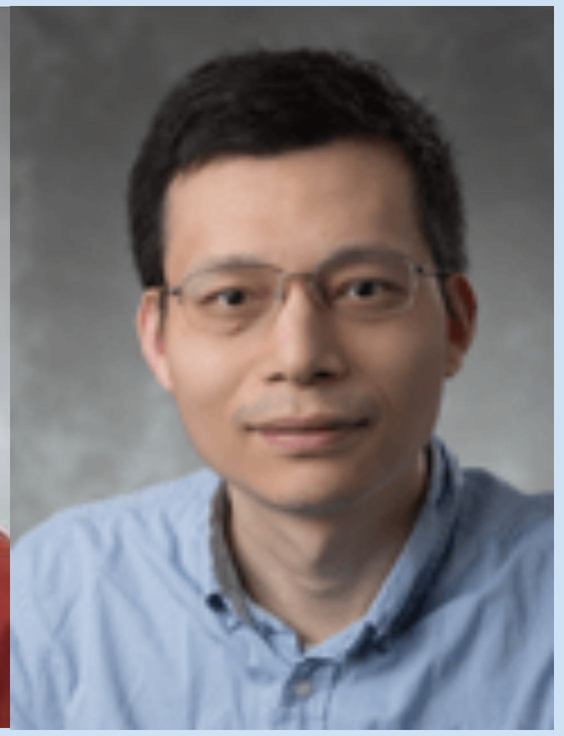

John Ruan


Nahee Park

Queen's UNIVERSITY

Theory


Liliana Caballero


Huan Yang

UNIVERSITY of GUELPH

TRIUMF


Will East

PERIMETER INSTITUTE


David Morrissey


Saeed Rastgoo

University of Lethbridge

FIAT LUX


Saurya Das

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)

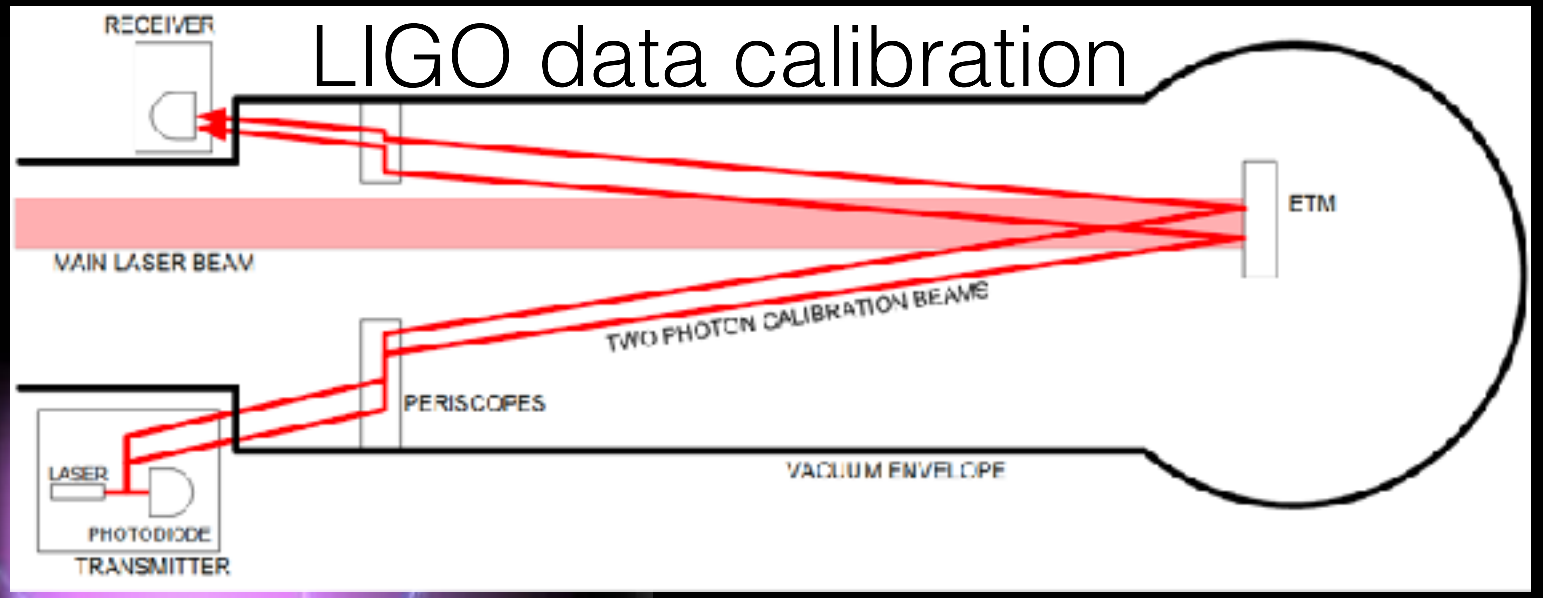
We are excited to announce that Dawn VII 2024 will be held in person at the University of British Columbia Wednesday, June 12 – Thursday, June 13, 2024 with satellite meetings on Friday, June 14.

https://dawn7.phas.ubc.ca/

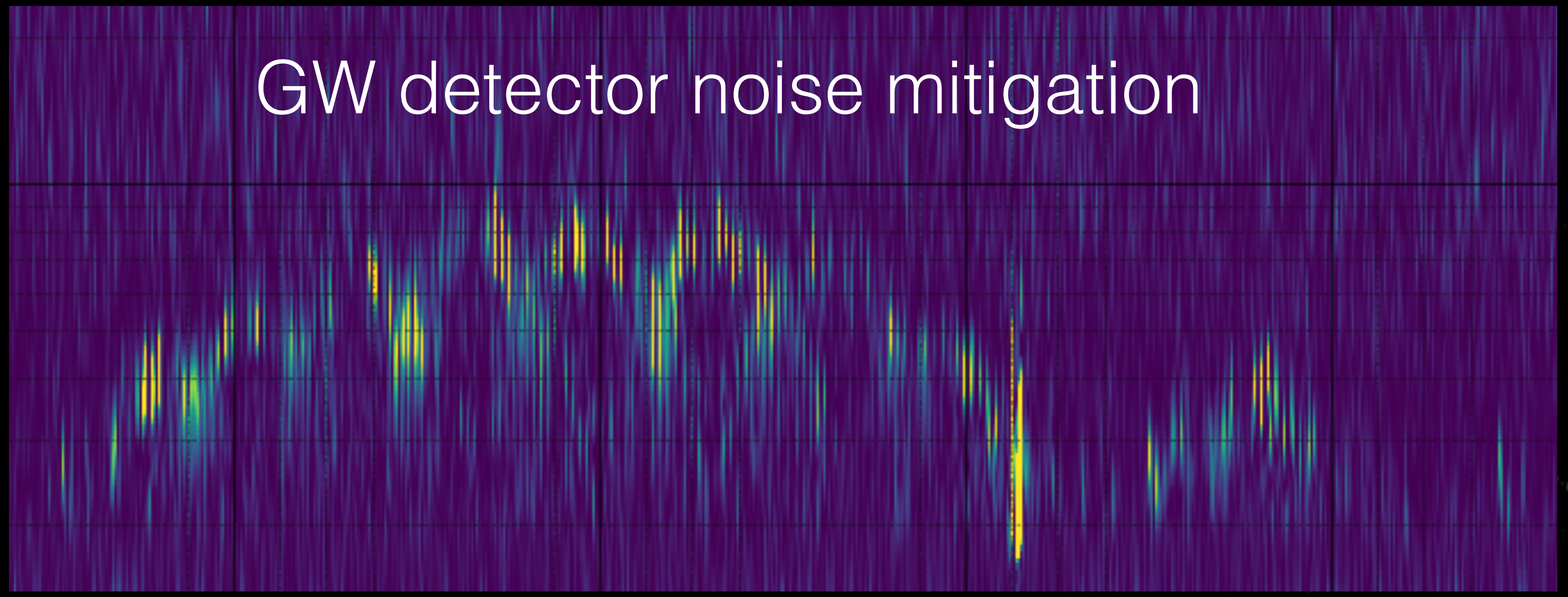
Jess McIver
Asst. Prof UBC,
CRC T2 in GW atrophys.

The UBC GW astrophysics team: https://gravitational-waves.phas.ubc.ca/

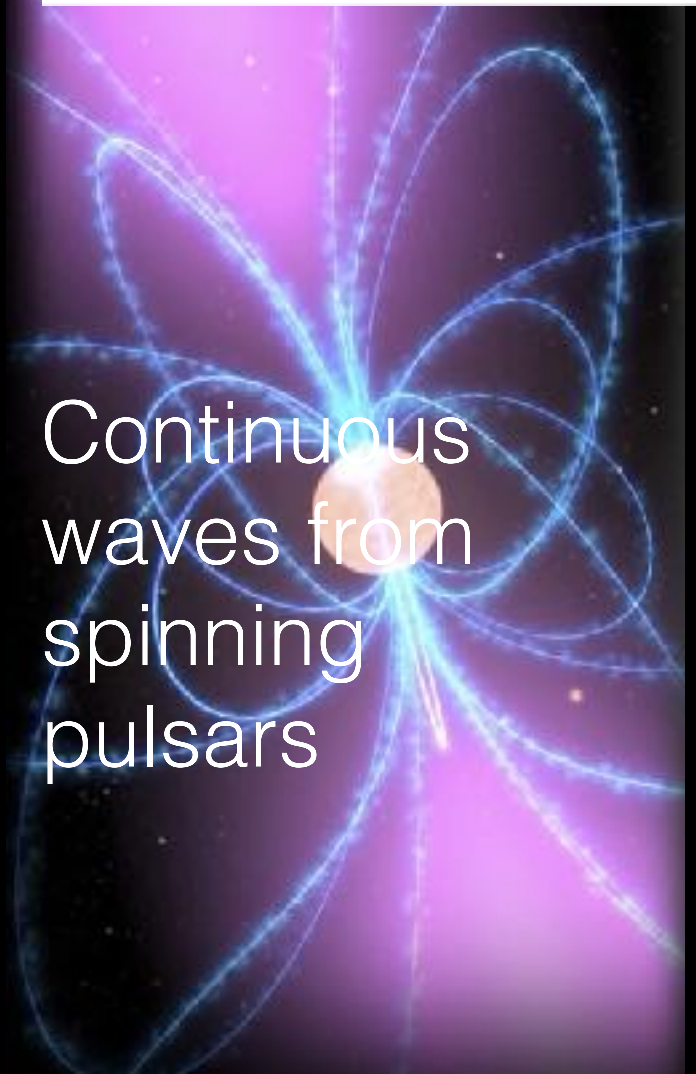
Gravitational wave science that our team is excited about:

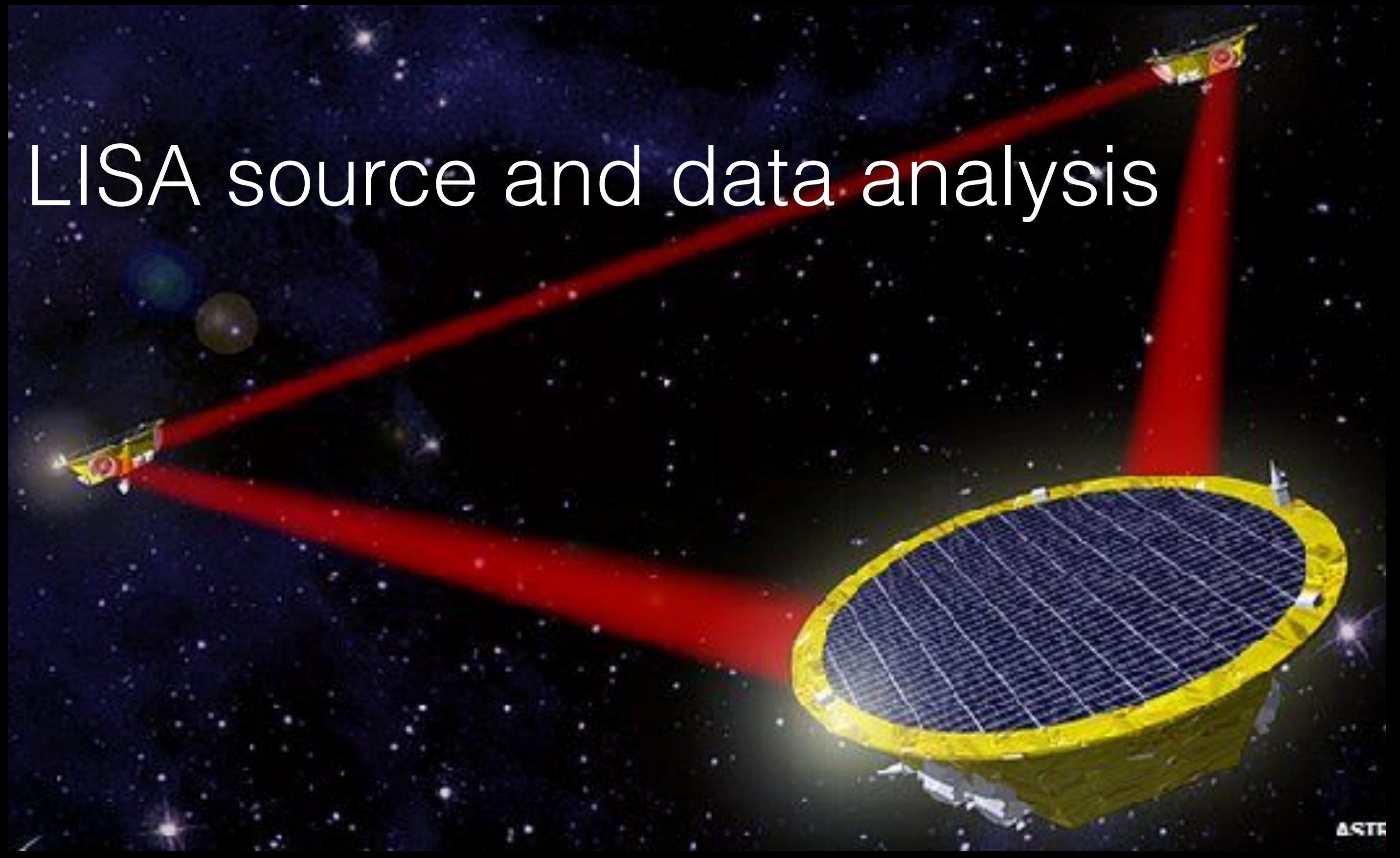


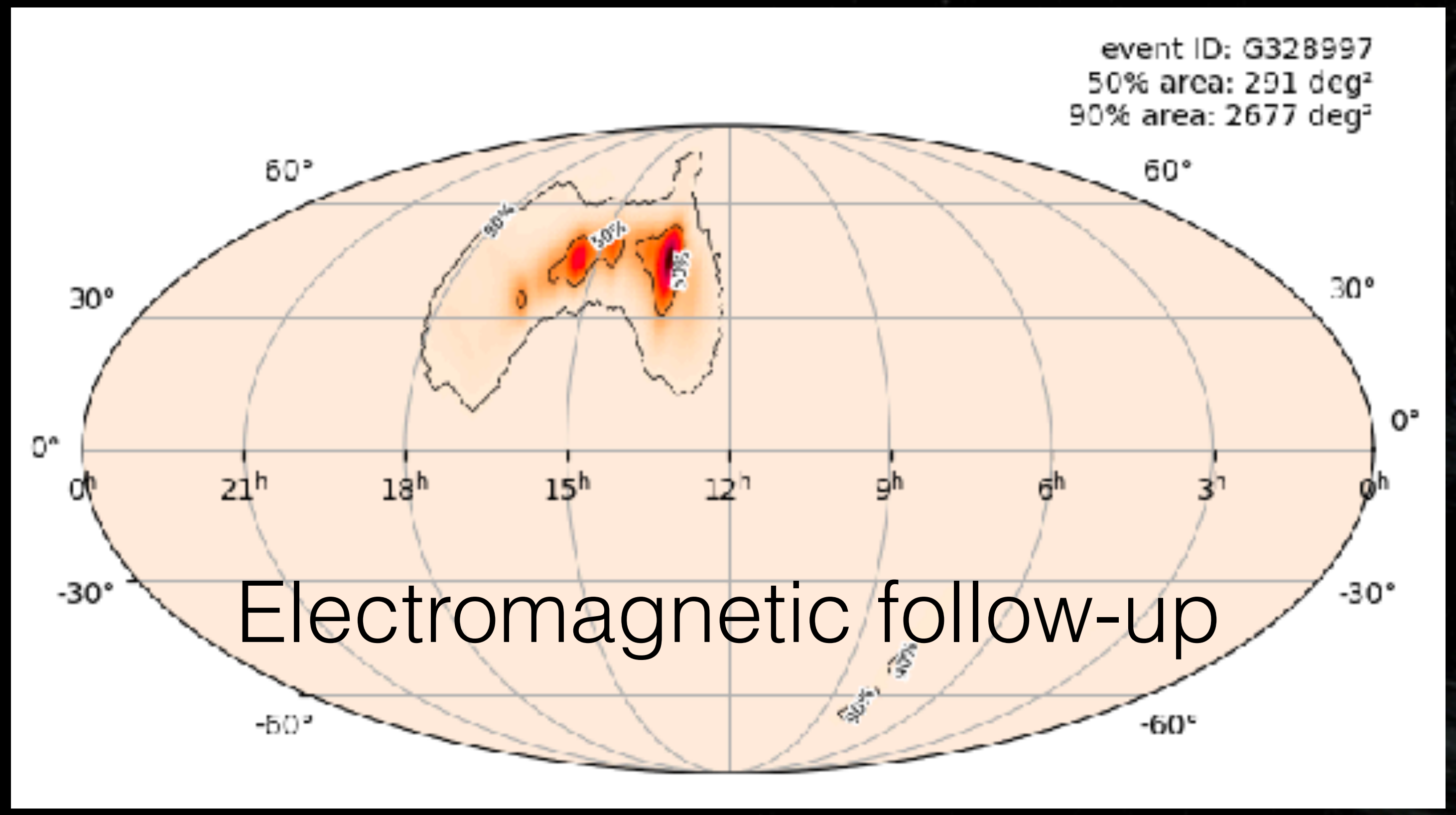
LIGO data calibration


GW detector noise mitigation

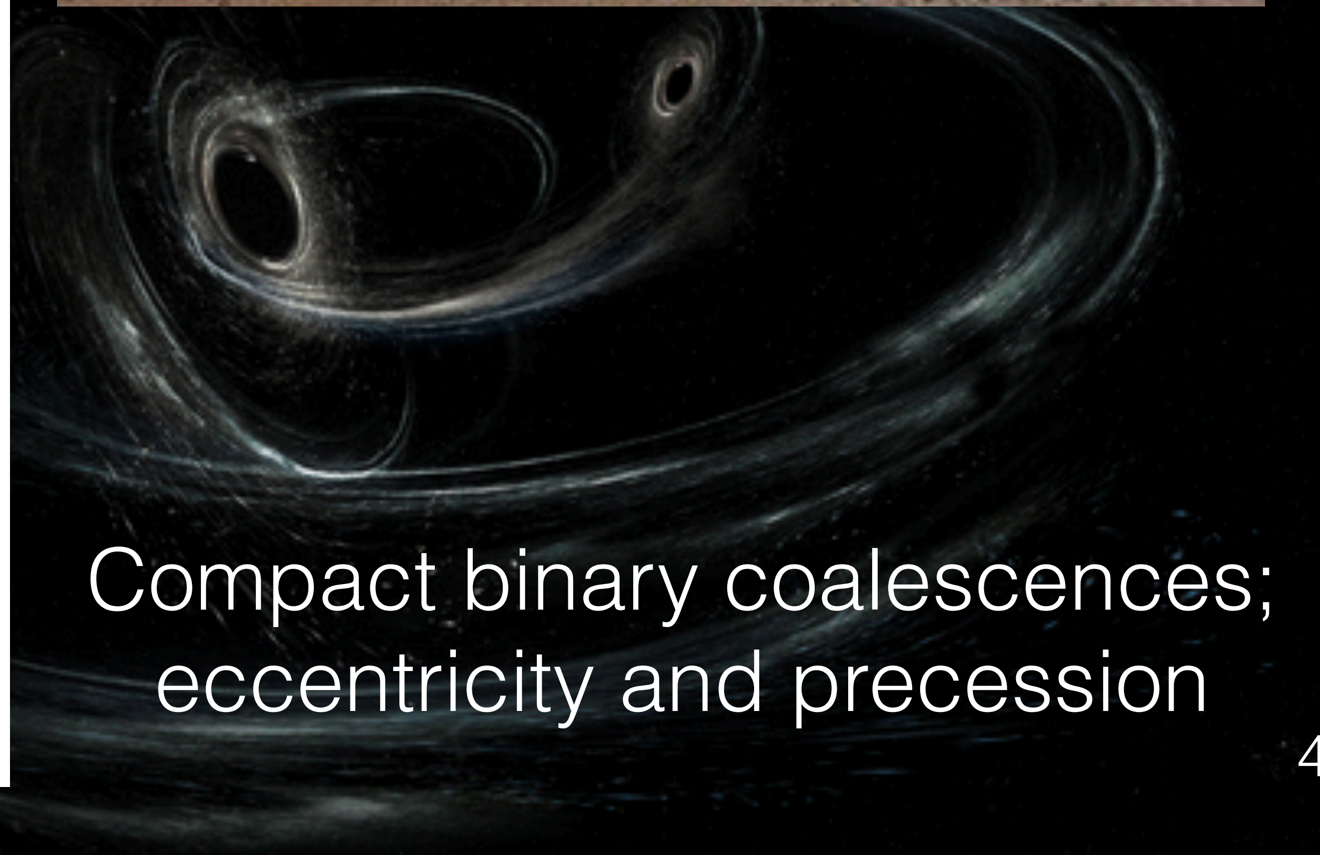

LIGO detector characterization


Continuous waves from spinning pulsars


LISA source and data analysis



Electromagnetic follow-up


Compact binary coalescences; eccentricity and precession

NSF

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British Columbia Knowledge Development Fund

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Research Chairs