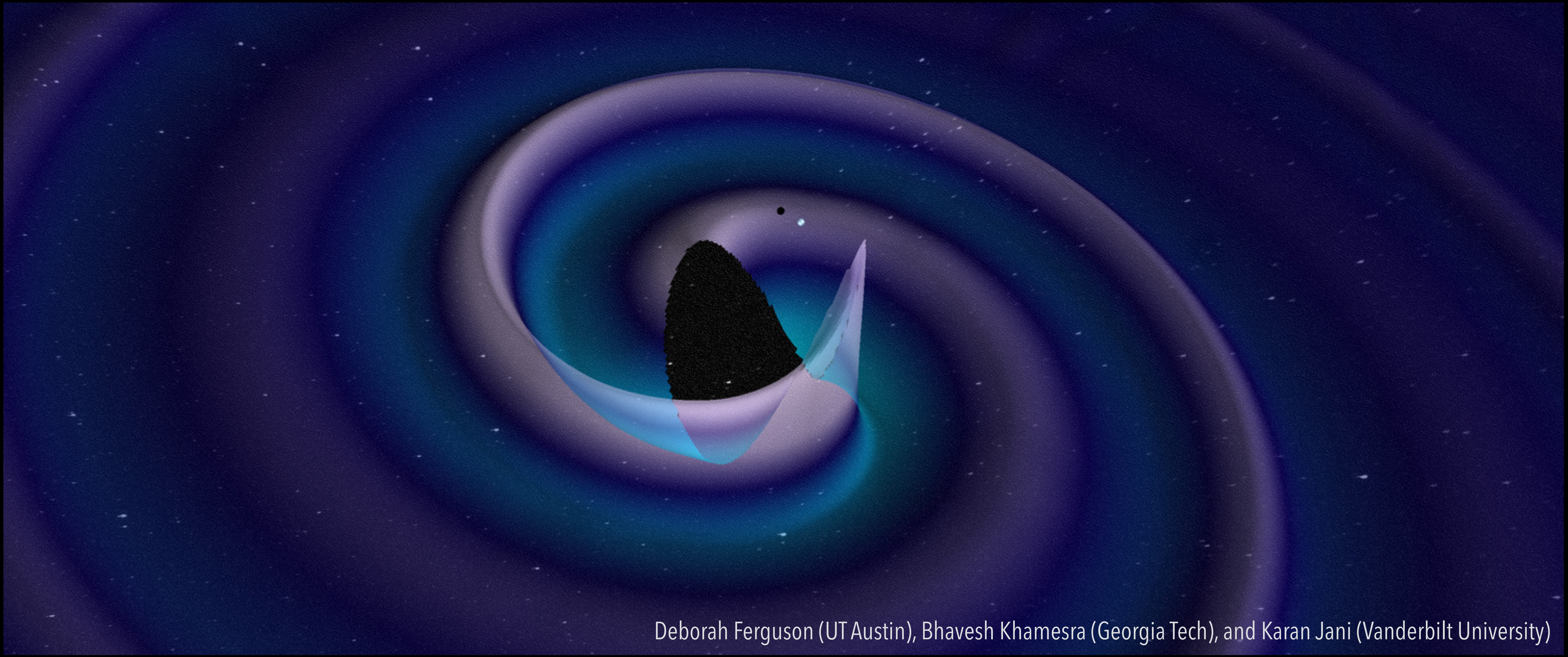
The Universe in High Fidelity



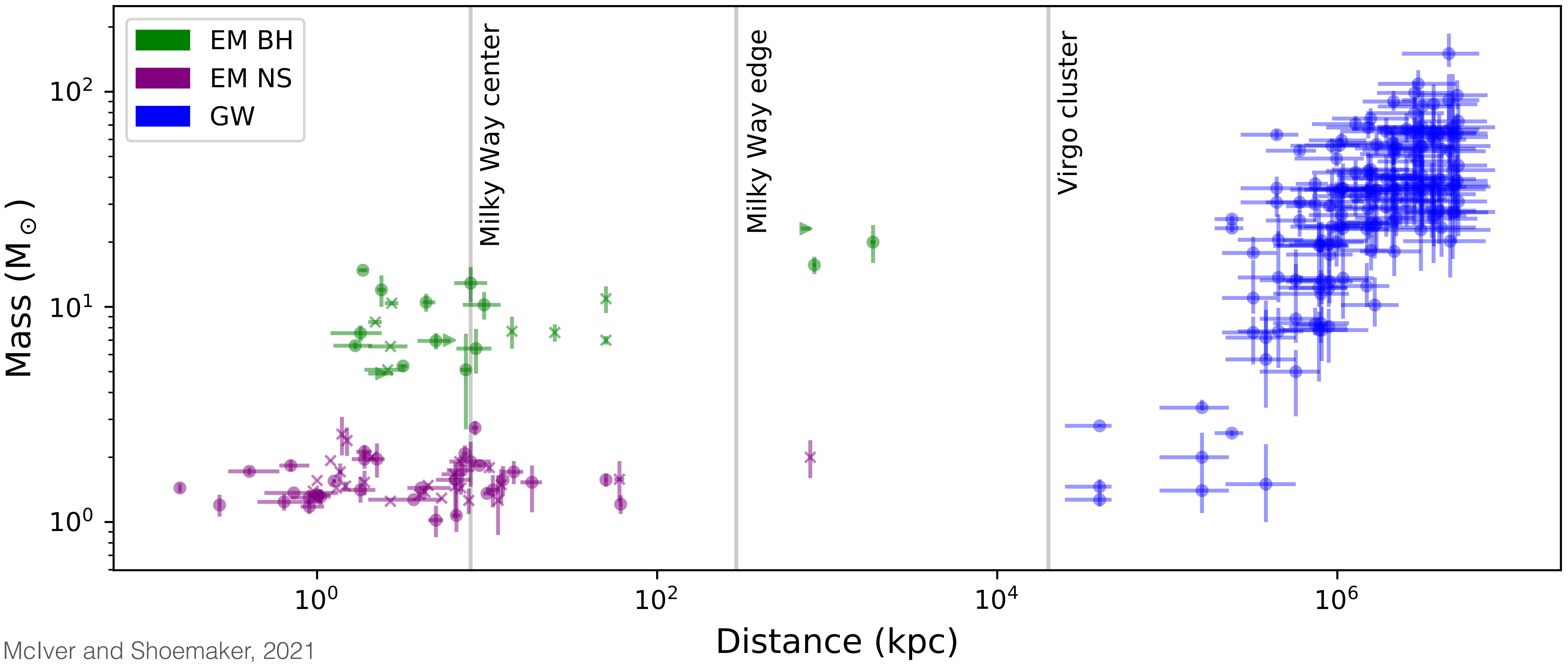
Dr. Jess McIver

Werner Isreal Memorial Symposium

May 19, 2023 - Victoria, BC

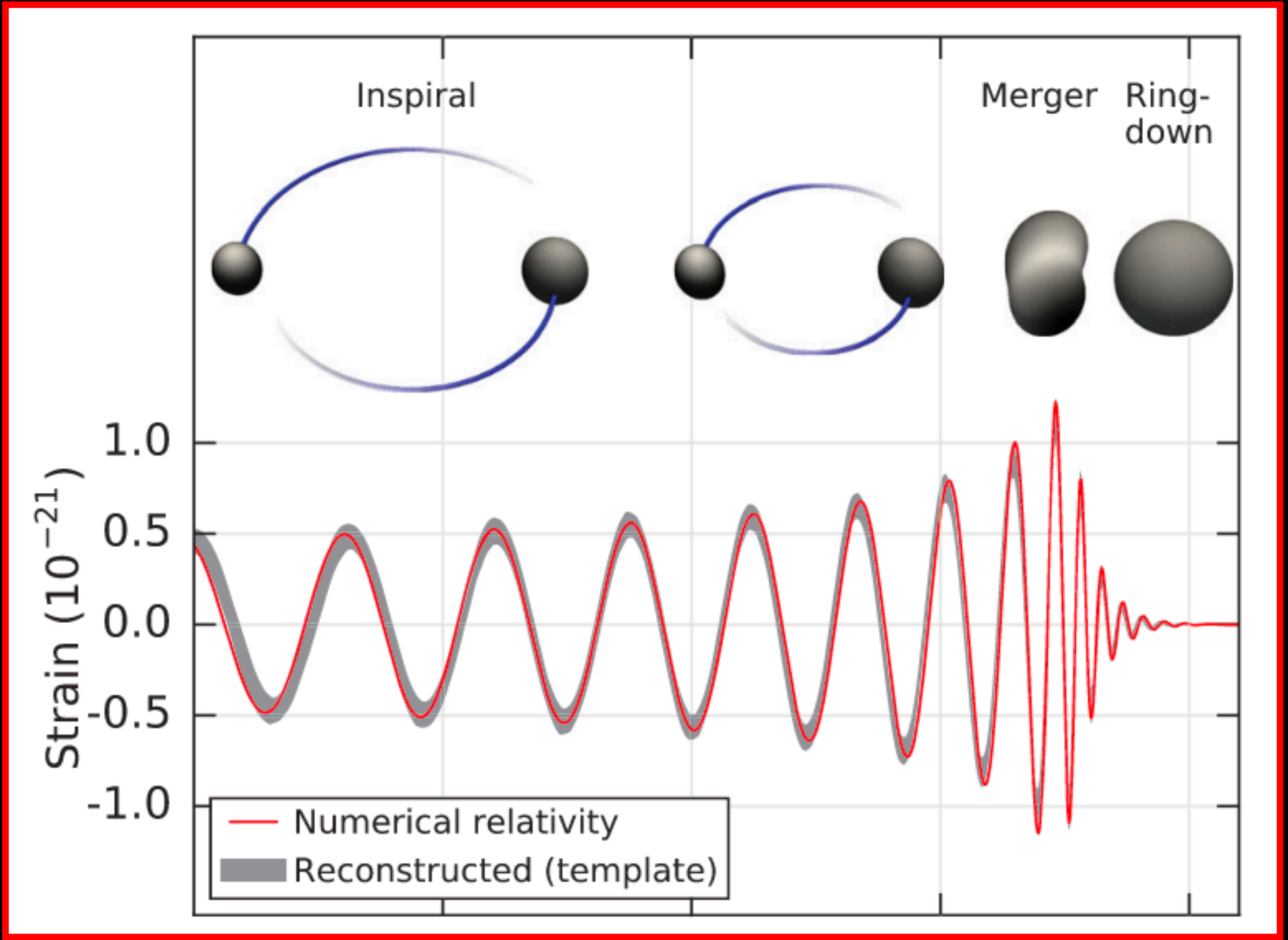
LIGO DCC G2301044

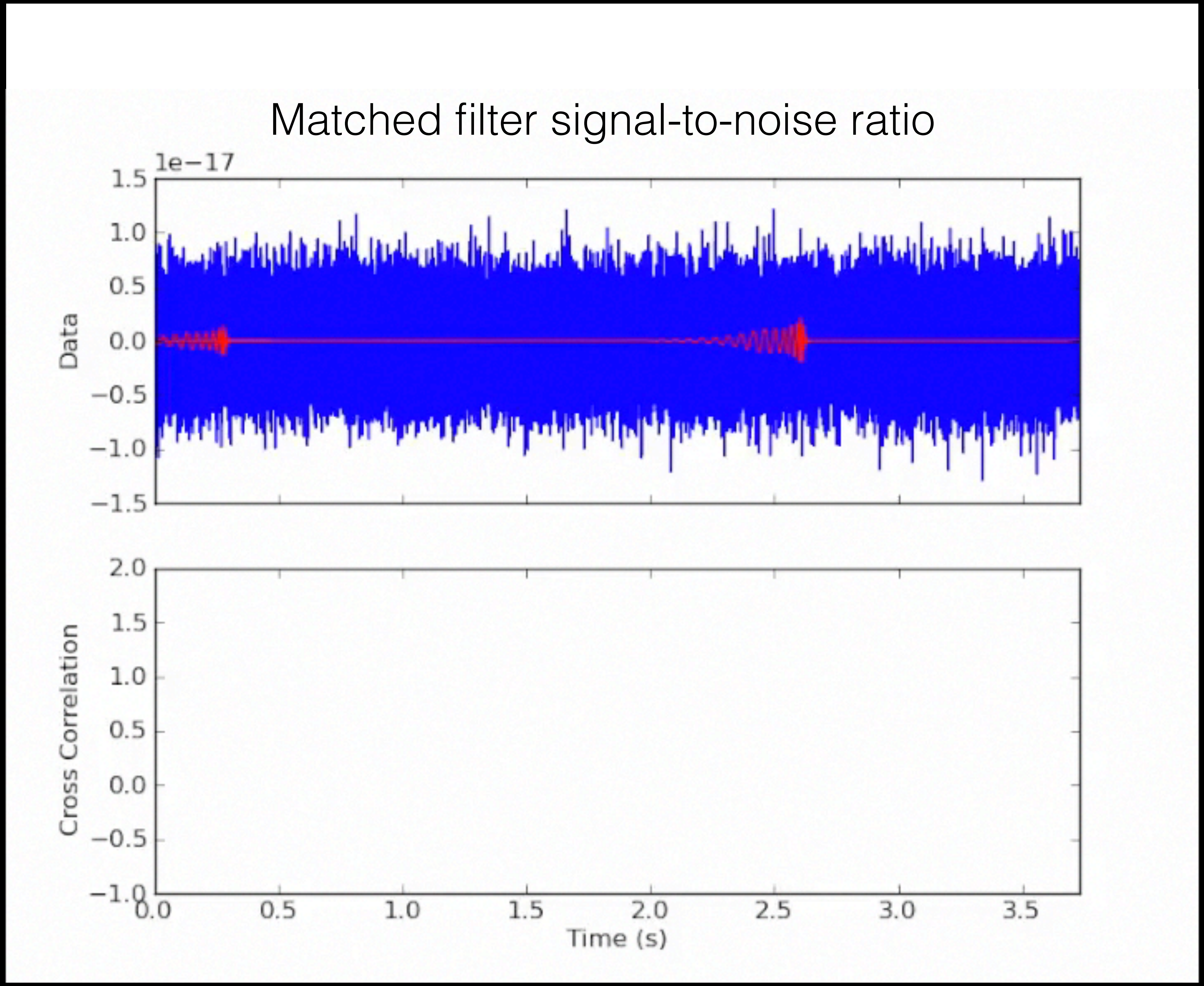
Known compact object masses vs. estimated distance



McIver and Shoemaker, 2021

Searching for signals with matched filtering

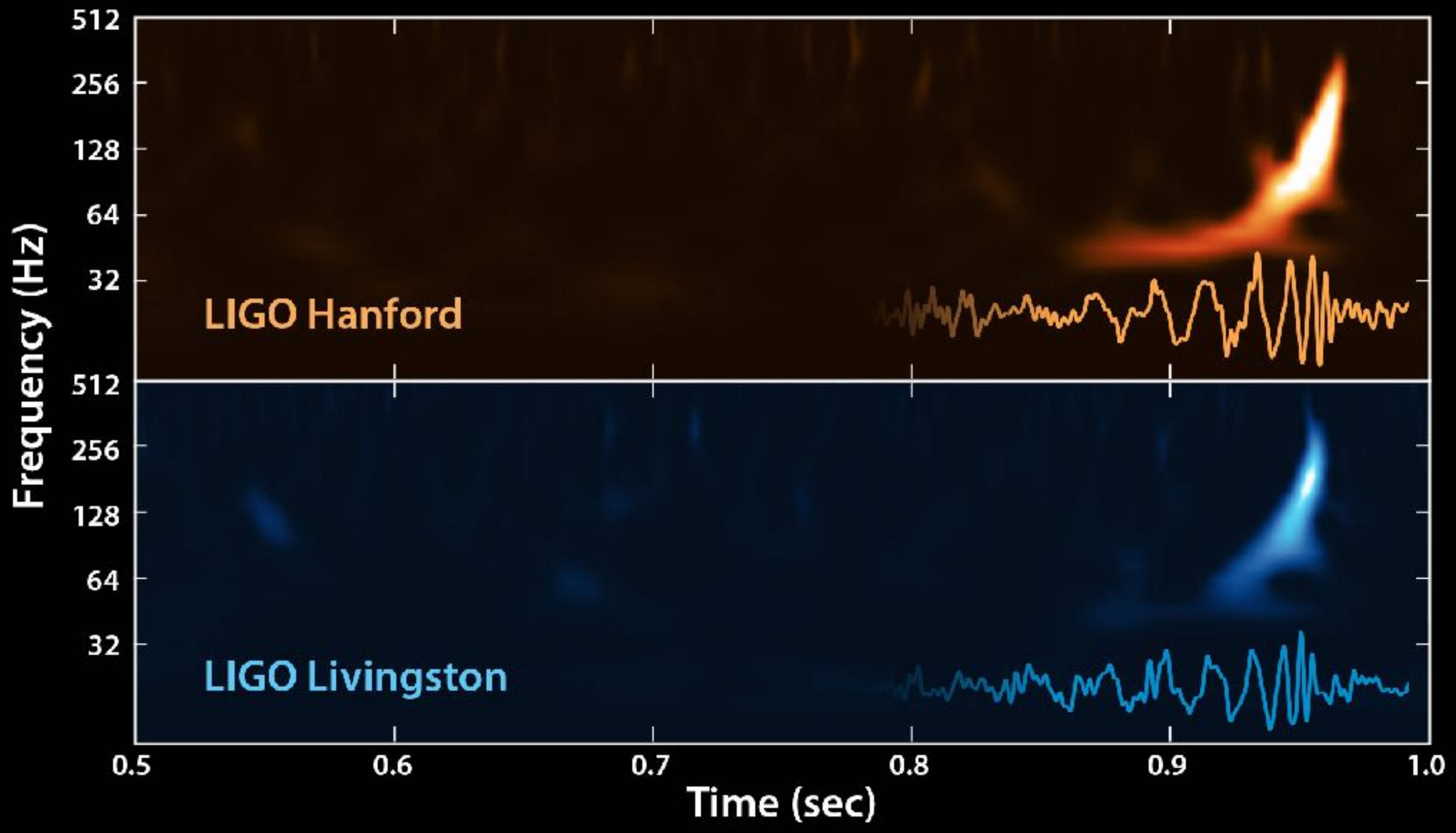




B. P. Abbott et al. Phys. Rev. Lett. (2016)

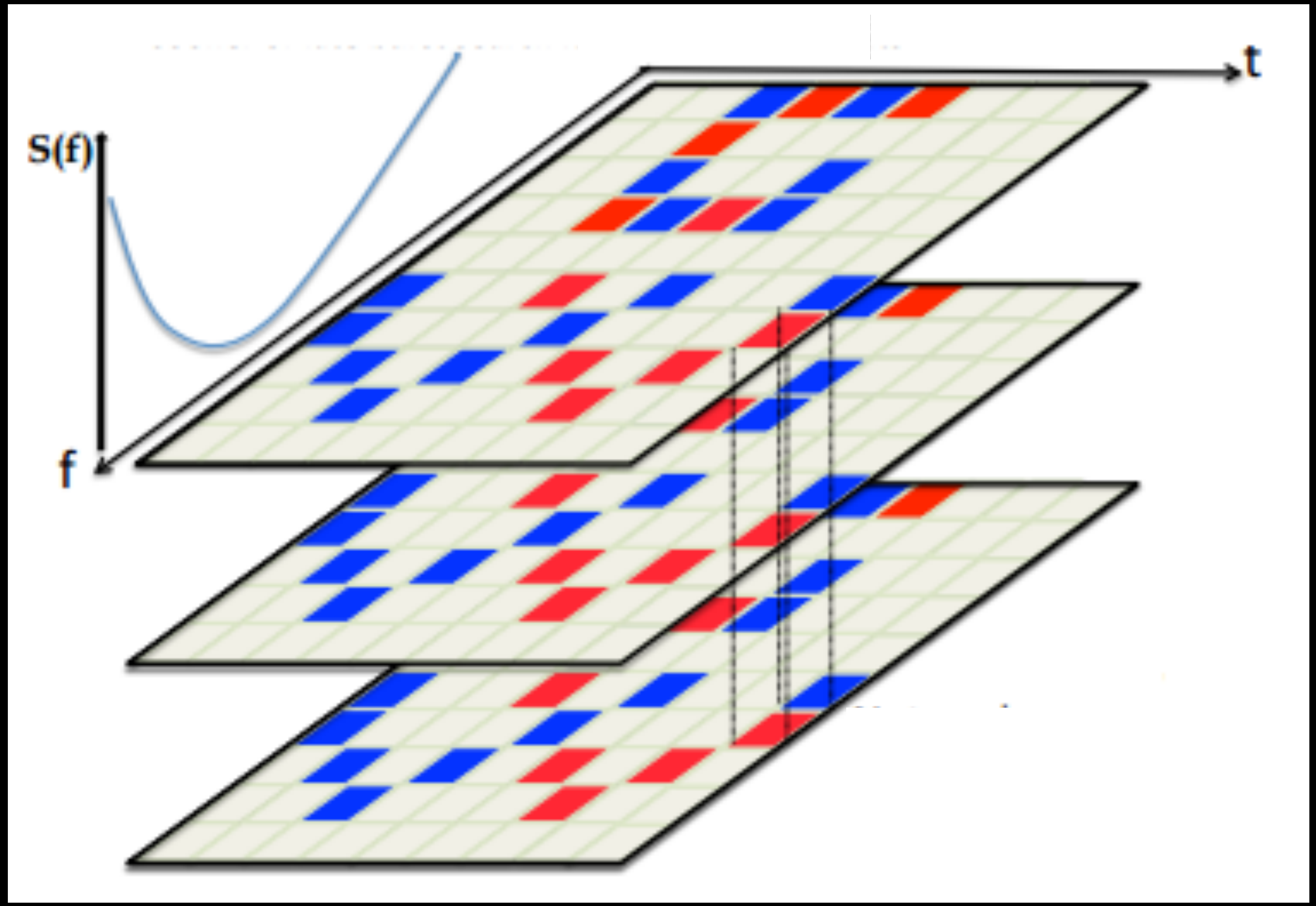
S. Caudill

Unmodeled transient GW searches



LIGO/Caltech

Example: coherent WaveBurst (cWB)



Klimenko et al. CQG 25,114029 (2008)

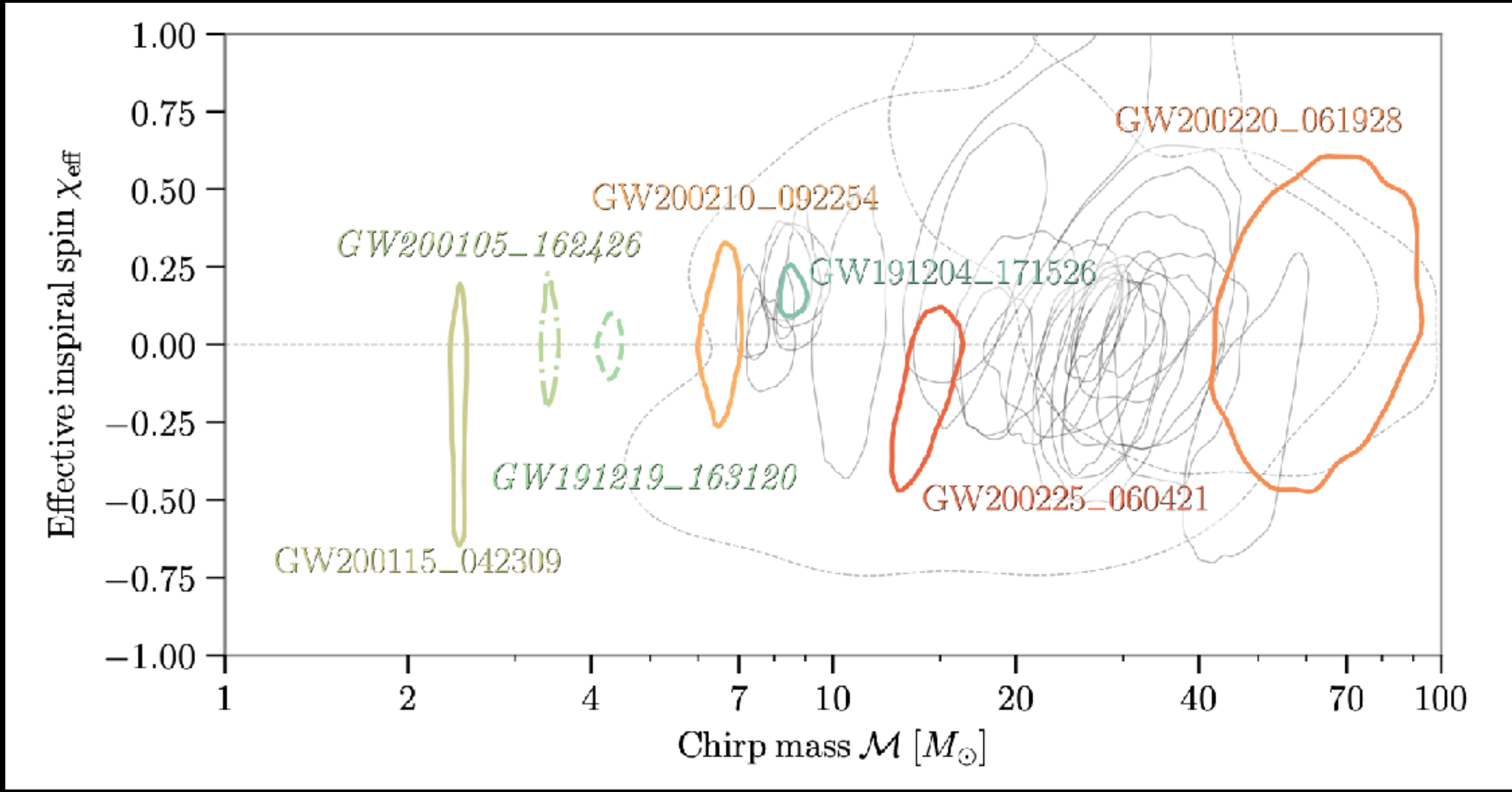
Inference of source properties

$$d = h + n.$$

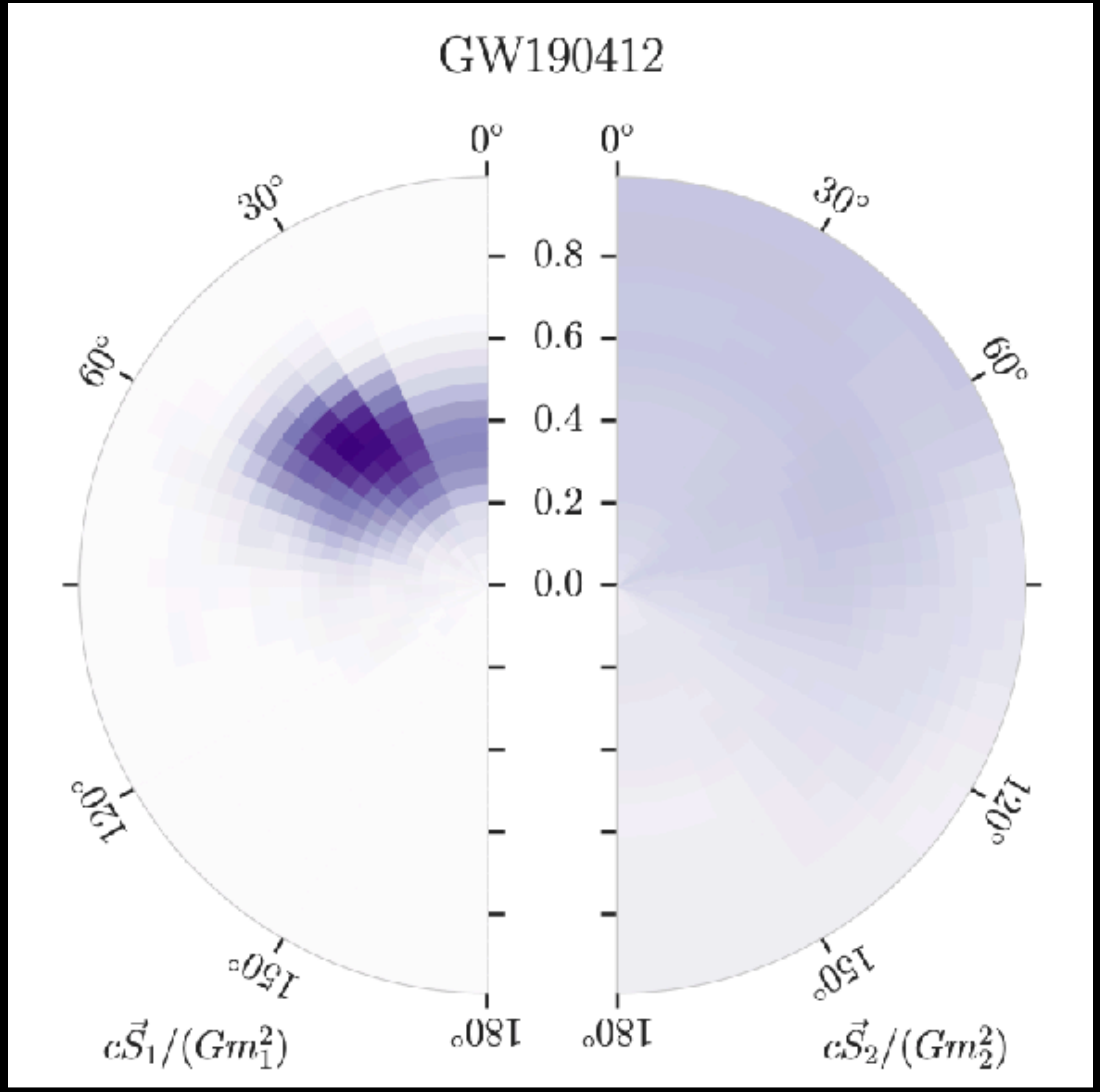
Data model d = signal (through lens of detector network) h + detector noise n

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

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



LIGO/Virgo GWTC-3 (2021)



LIGO/Virgo GWTC-2 (2020)

Generic vs CBC inference models

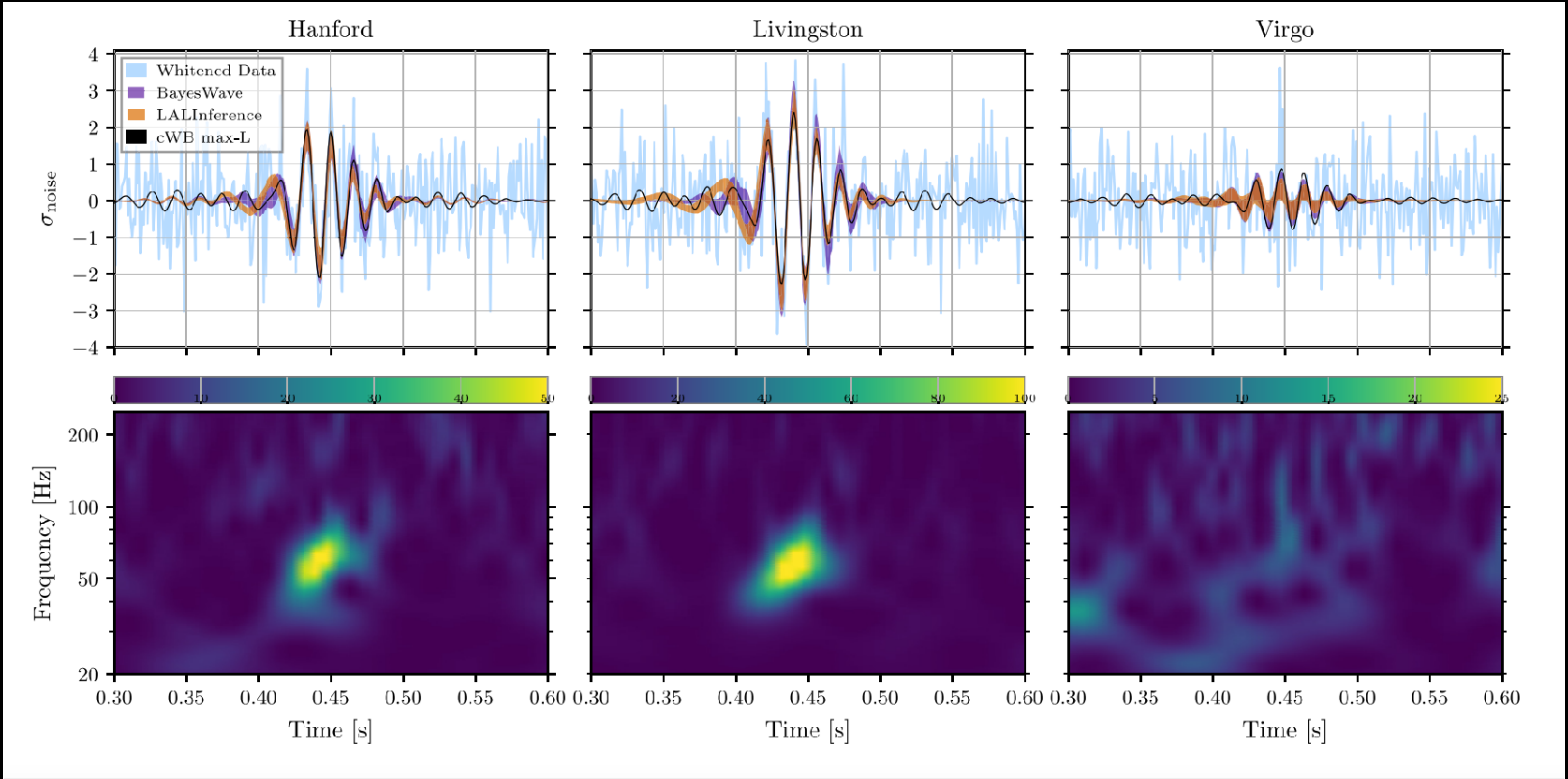


Fig 1 from GW190521 discovery paper; LIGO-Virgo PRL 125, 101102 (2020).

LALInference reconstruction used NRSur7dq4 waveform (Varma+ 2019)

Most recent LVK result: tests of GR with GWTC-3

15 of 35 new LVK candidates considered for tests of GR:

See also a summary of this paper by Abhirup Ghosh for the LVK: arXiv 2204.00662

RT = residuals test
IMR = inspiral–merger–ringdown consistency test
PAR = parametrized tests of GW generation
SIM = spin-induced moments
MDR = modified GW dispersion relation
POL = polarization content
RD = ringdown
ECH = echoes searches

Test	Parameter	Improvement w.r.t. GWTC-2
RT	p-value	Not applicable
IMR	$\left\{\frac{\Delta M_f}{\bar{M}_f}, \frac{\Delta \chi_f}{\bar{\chi}_f}\right\}$	1.1–1.8
PAR	$\delta\hat{\phi}_k$	1.2–3.1
SIM	$\delta\kappa_s$	1.1–1.2
MDR	$\lvert A_\alpha \rvert$	0.8–2.1
POL	$\log_{10} \mathcal{B}^{\mathrm{X}}_{\mathrm{T}}$	New Test
RD	$\delta\hat{f}_{221}$	1.1
	$\{\delta\hat{\tau}_{220}, \delta\hat{f}_{220}\}$	1.7–5.5
ECH	$\log_{10} \mathcal{B}_{\mathrm{S/N}}$	New Test

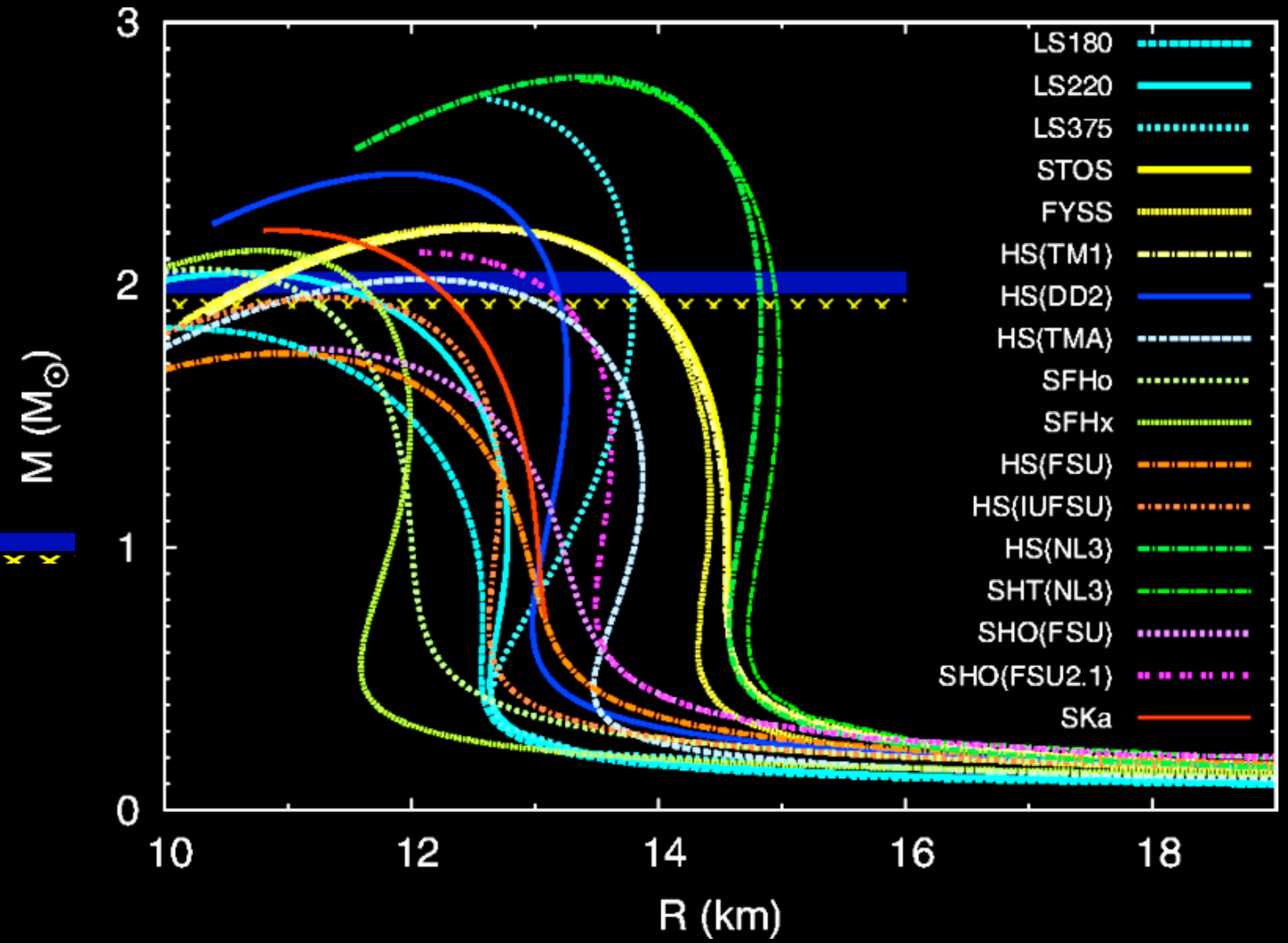
LIGO-Virgo-KAGRA 2021 arXiv 2112.06861

Other LIGO-Virgo-KAGRA analyses also account for alternate theories of gravity!
Example: in Nov the LVK published a search for GWs from known pulsars, including non-GR polarization following the Brans-Dicke theory. LVK 2022, arXiv 2111.13106

Observing extreme matter with GWs: NSs

Models for the neutron star equation of state (with nucleons only)

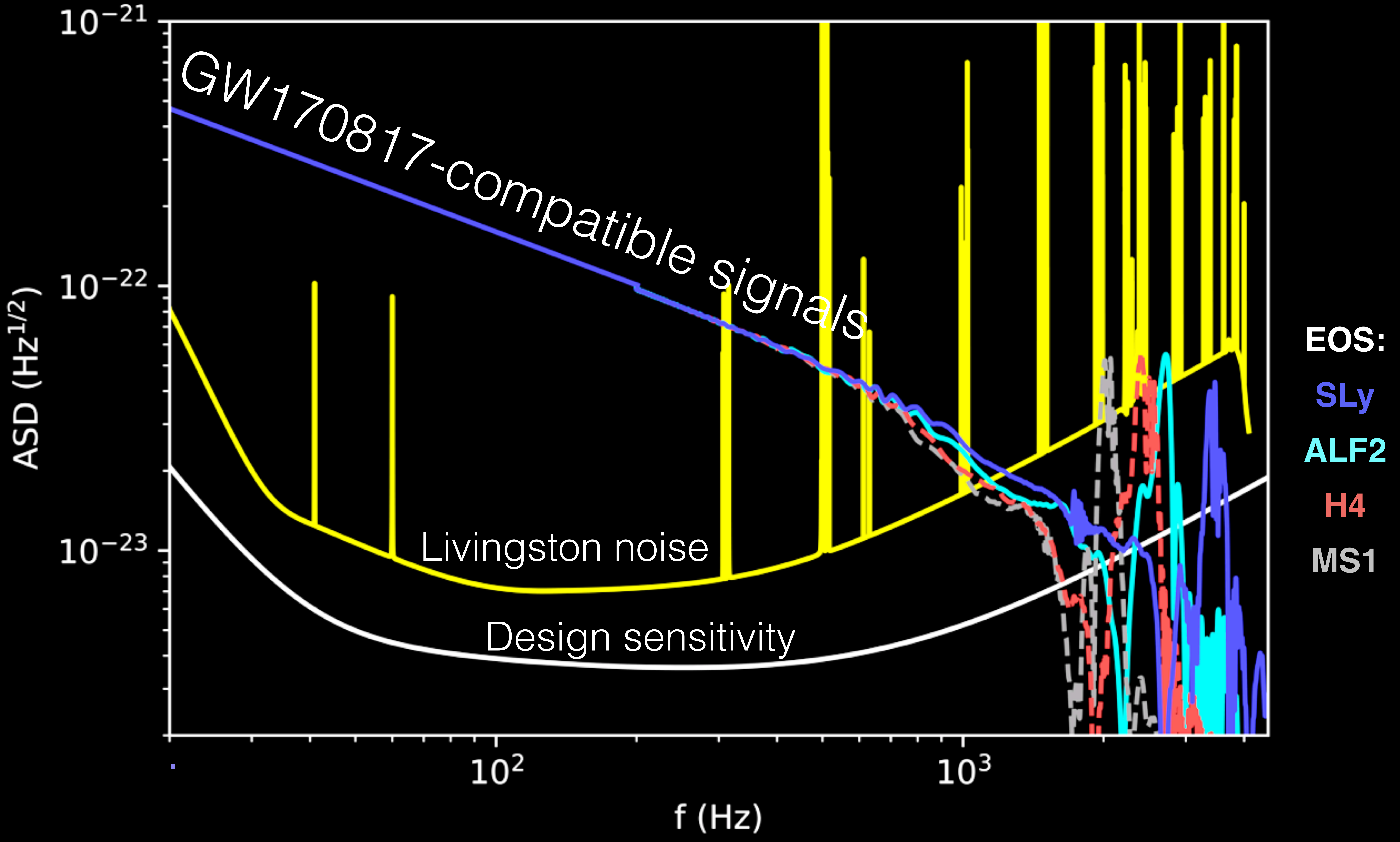
Observed neutron-star max mass



Oertel et al Rev. Mod. Phys. ***89****, 015007 (2017)*
Slide by Jocelyn Read

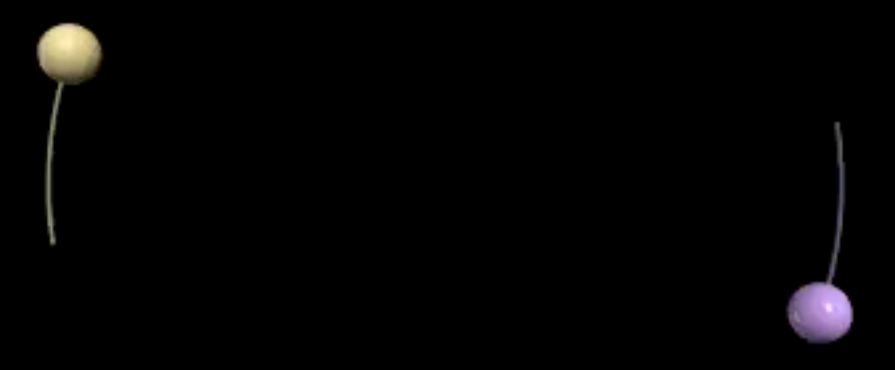
Observing GW170817

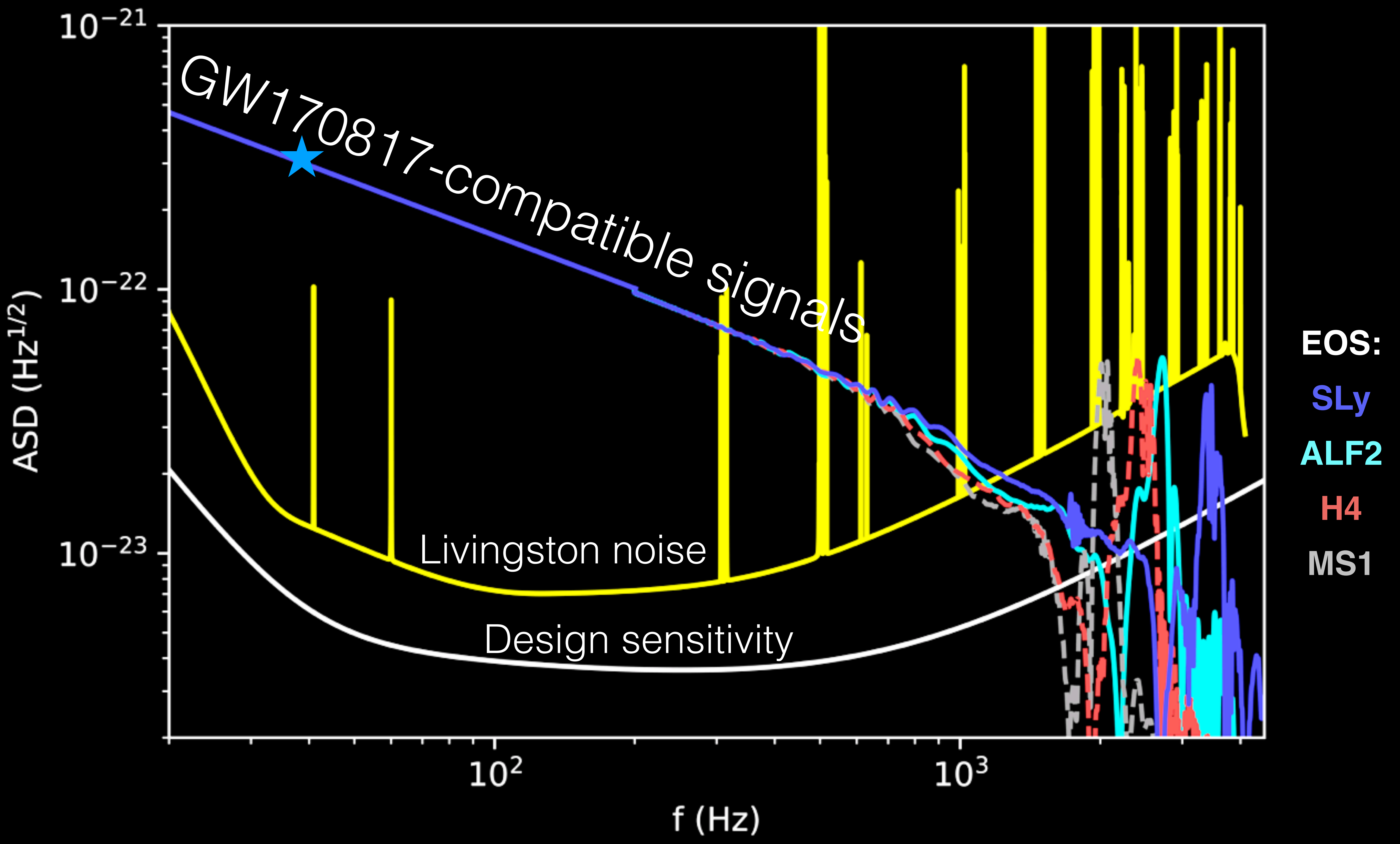
Slide by Jocelyn Read



E. Leon/LIGO/Virgo. Noise curves from LIGO-P1800061-v11. Effective distance from GraceDB.
Numerical simulation data (above ~500 Hz) courtesy Tim Dietrich (AEI/FSU/BAM Collaboration)
Simulations published in Phys. Rev. D95(12):124006 and Phys. Rev. D95(2):024029

Observing GW170817



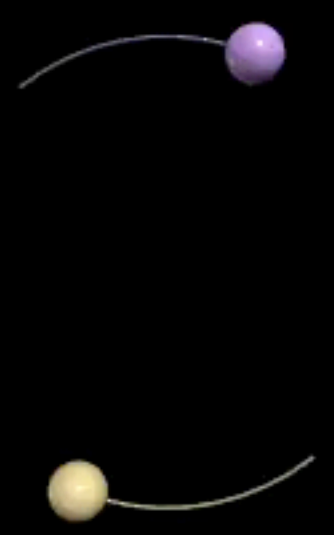


40 seconds before merger
orbital distance 320 km
GW frequency 34 Hz
video slowed 80x

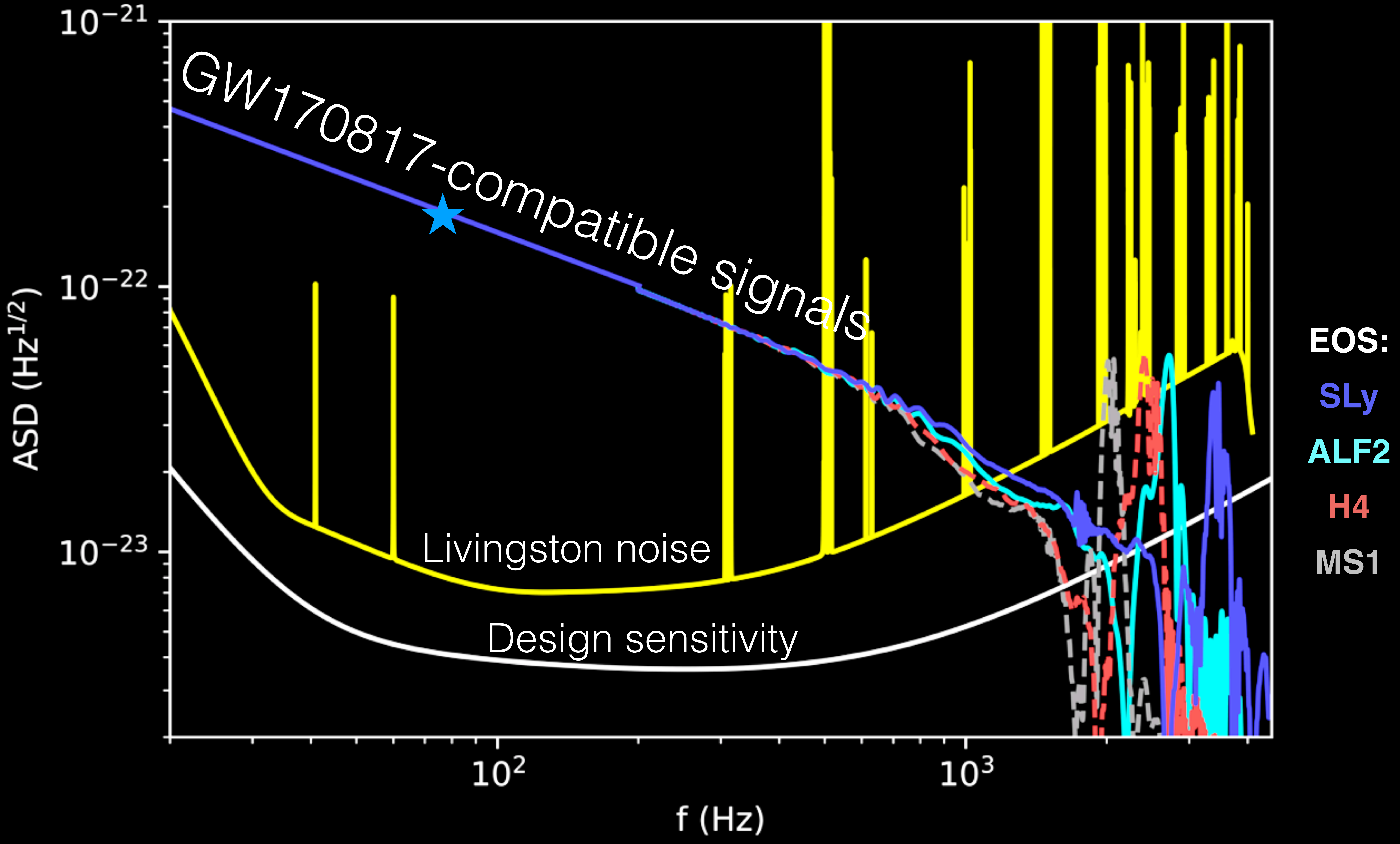
Movie by GWPAC
Intern Megan Loh

E. Leon/LIGO/Virgo. Noise curves from LIGO-P1800061-v11. Effective distance from GraceDB.
Numerical simulation data (above ~500 Hz) courtesy Tim Dietrich (AEI/FSU/BAM Collaboration)
Simulations published in Phys. Rev. D95(12):124006 and Phys. Rev. D95(2):024029

Observing GW170817



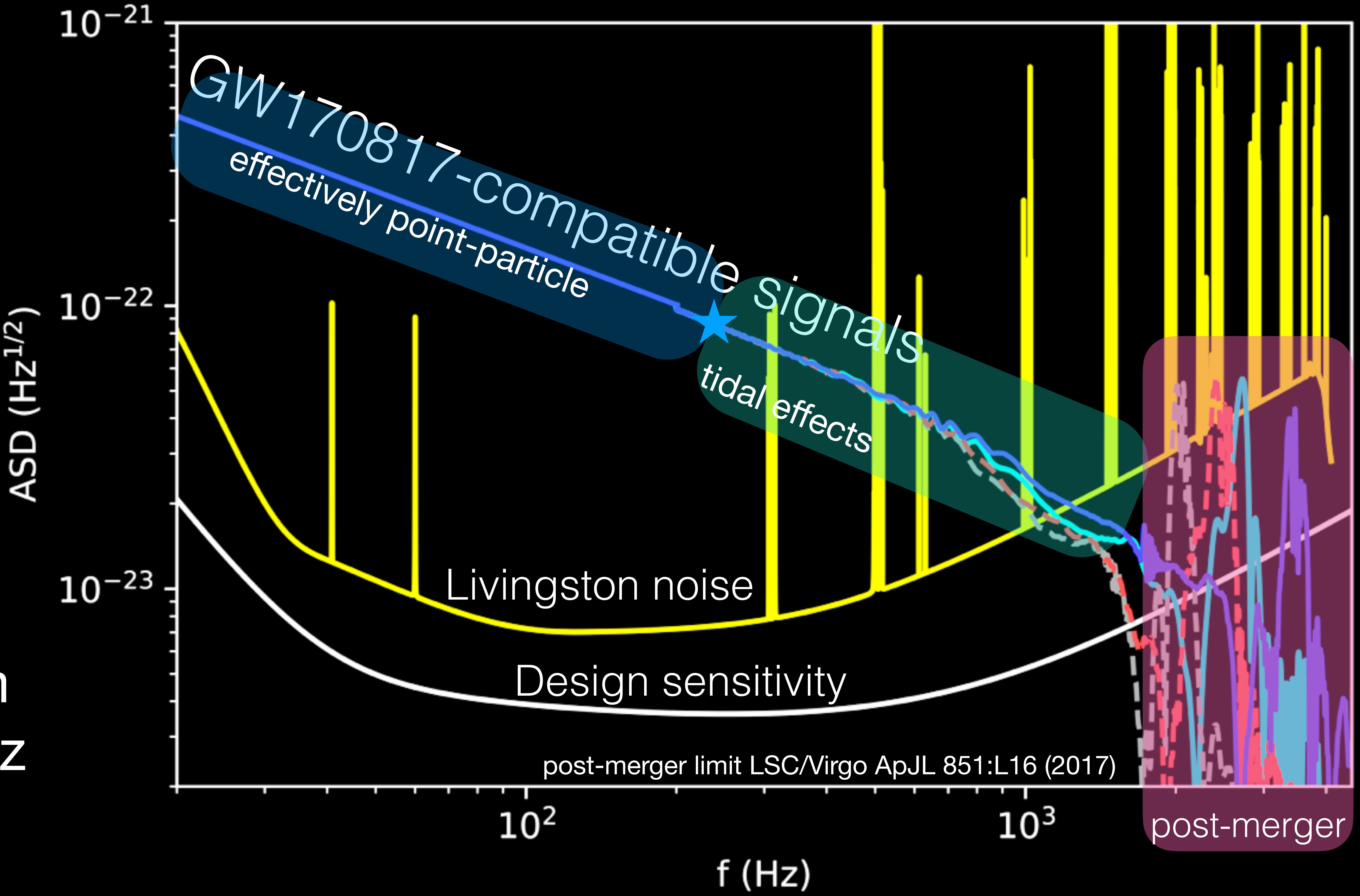
5 seconds before merger
orbital distance 190 km
GW frequency 73 Hz
video slowed 80x



Movie by GWPAC
Intern Megan Loh

E. Leon/LIGO/Virgo. Noise curves from LIGO-P1800061-v11
Numerical simulation data (above ~500 Hz) courtesy Tim Dietrich (AEI/FSU/BAM Collaboration)
Simulations published in Phys. Rev. D95(12):124006 and Phys. Rev. D95(2):024029

Observing GW170817



Final 0.25 seconds
orbital distance 89 – 24 km
GW frequency 210 to >1kHz
video slowed 80x

Movie by GWPAC
Intern Megan Loh

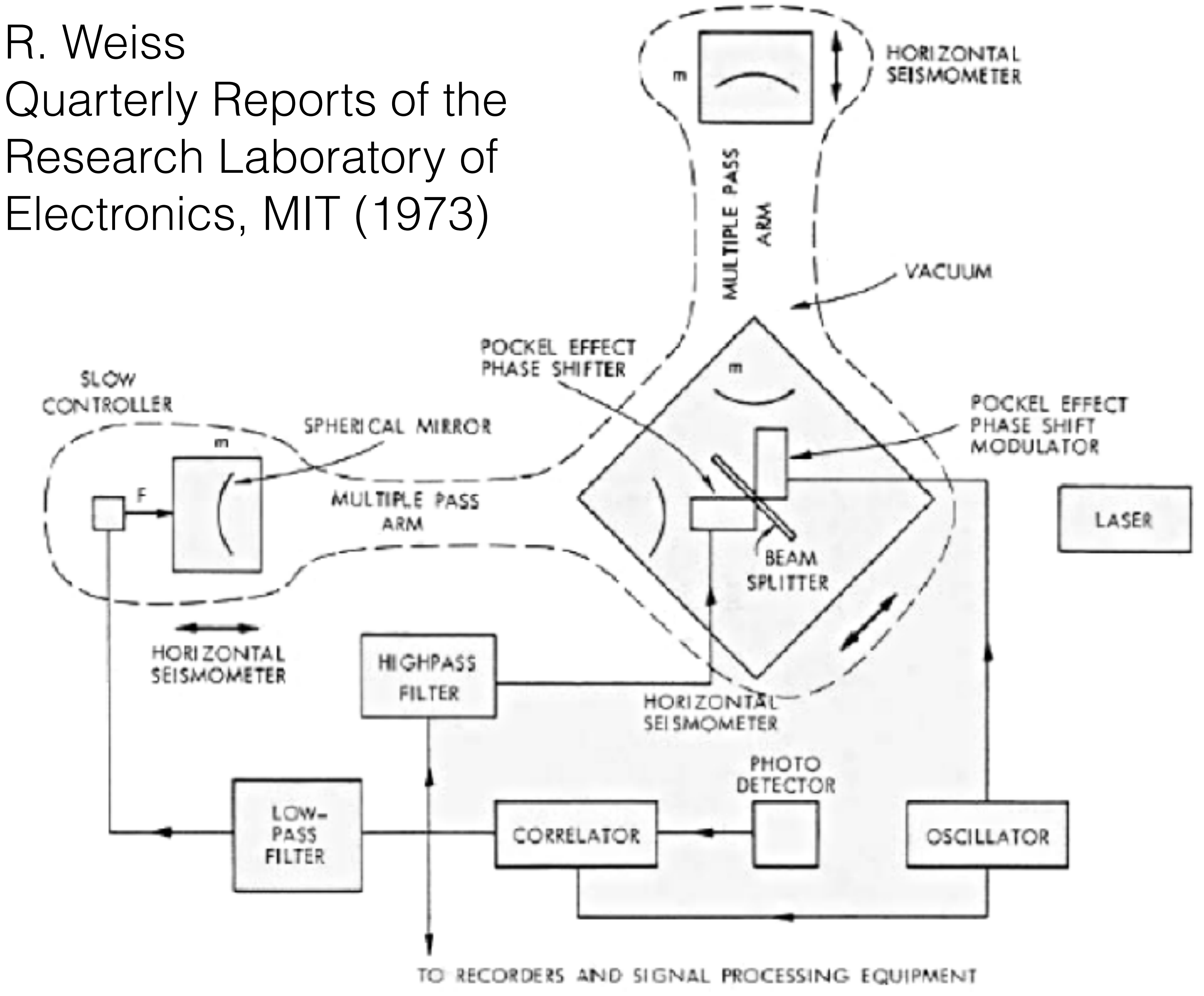
E. Leon/LIGO/Virgo. Noise curves from LIGO-P1800061-v11. Effective distance from GraceDB.
Numerical simulation data (above ~500 Hz) courtesy Tim Dietrich (AEI/FSU/BAM Collaboration)
Simulations published in Phys. Rev. D95(12):124006 and Phys. Rev. D95(2):024029

A brief history of LIGO

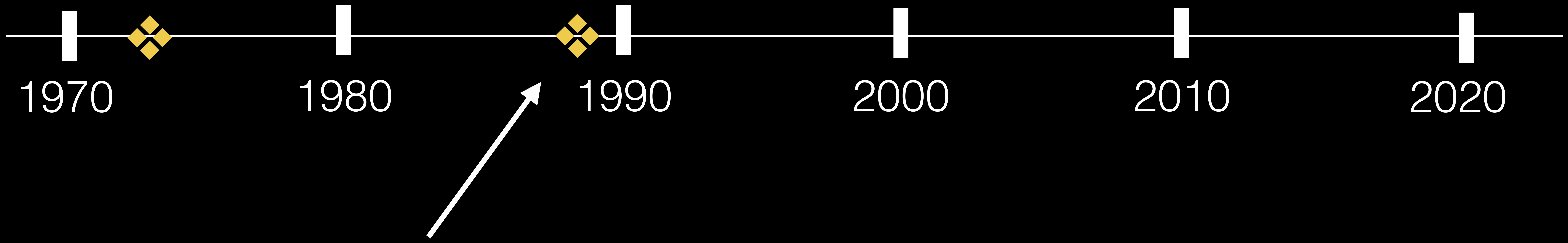
A brief history of LIGO

1973: Concept design

R. Weiss
Quarterly Reports of the Research Laboratory of Electronics, MIT (1973)

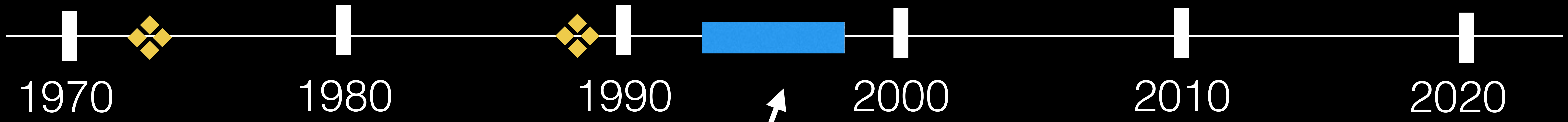


A brief history of LIGO



1989: NSF proposal for LIGO construction

A brief history of LIGO



1994-1997: Initial LIGO construction

A brief history of LIGO

2002-2007: Initial LIGO operation

Upper limits

First upper limits from LIGO on gravitational wave bursts

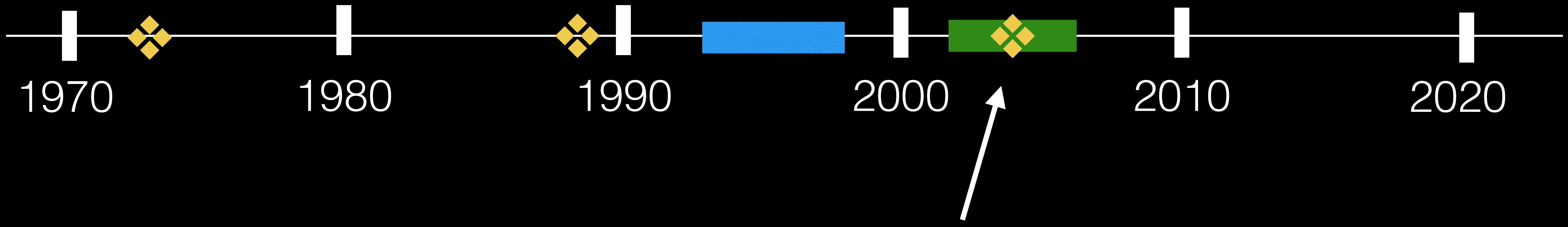
B. Abbott *et al.* (LIGO Scientific Collaboration)
Phys. Rev. D **69**, 102001 – Published 7 May 2004

Search for gravitational waves from primordial black hole binary coalescences in the galactic halo

B. Abbott *et al.* (LIGO Scientific Collaboration)
Phys. Rev. D **72**, 082002 – Published 25 October 2005

S1-S5:
0 detections

A brief history of LIGO



2004: NSB approves the Advanced LIGO project

A brief history of LIGO

2008-2010: Enhanced LIGO operation

Better upper limits!

Search for gravitational waves from binary black hole inspiral, merger, and ringdown in LIGO-Virgo data from 2009–2010

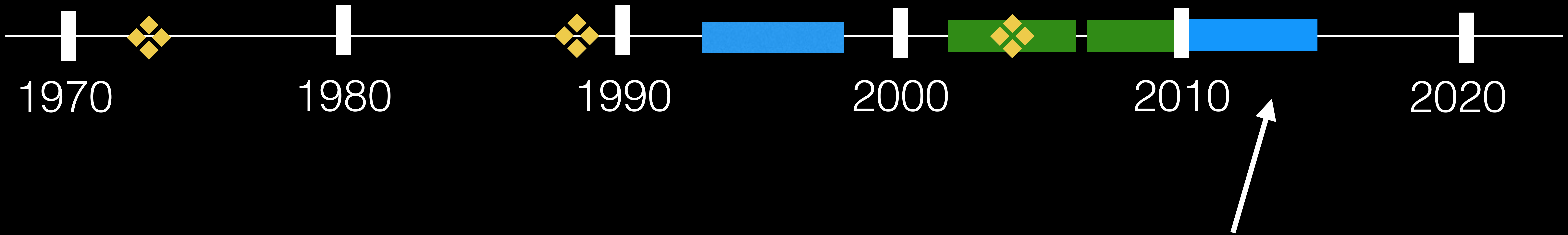
J. Aasi *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. D **87**, 022002 – Published 23 January 2013

Search for gravitational wave ringdowns from perturbed intermediate mass black holes in LIGO-Virgo data from 2005–2010

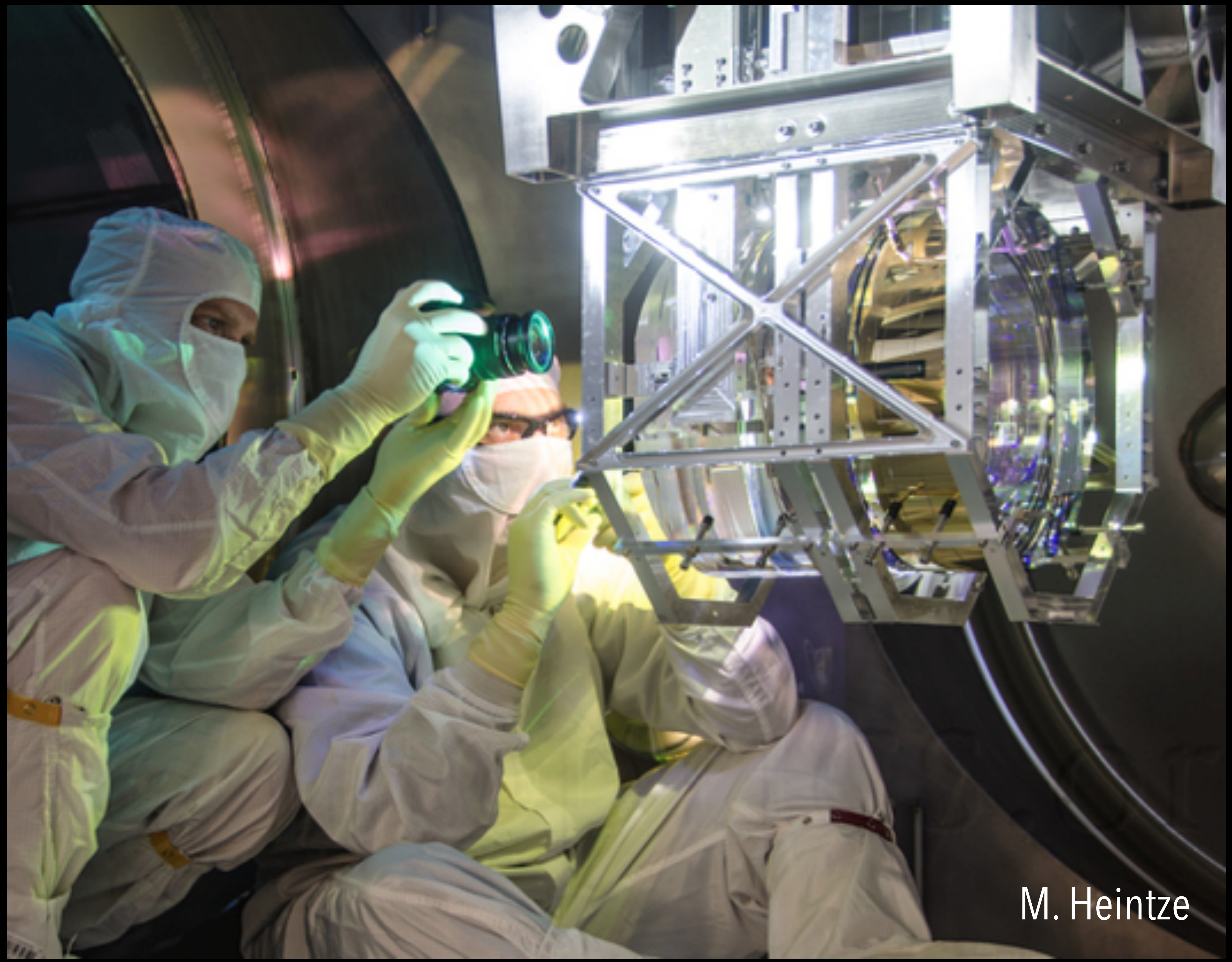
J. Aasi *et al.* (The LIGO Scientific Collaboration and the Virgo Collaboration)
Phys. Rev. D **89**, 102006 – Published 27 May 2014

S6:
0 detections

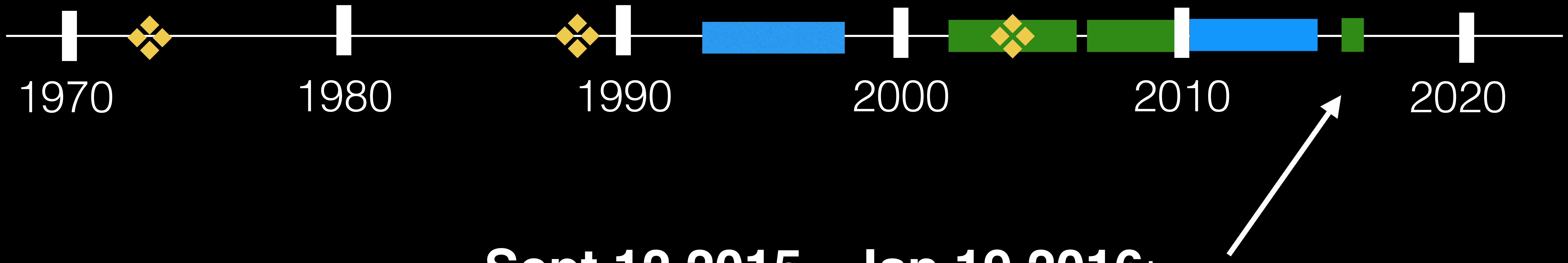
A brief history of LIGO



2010-2015: Advanced LIGO installation

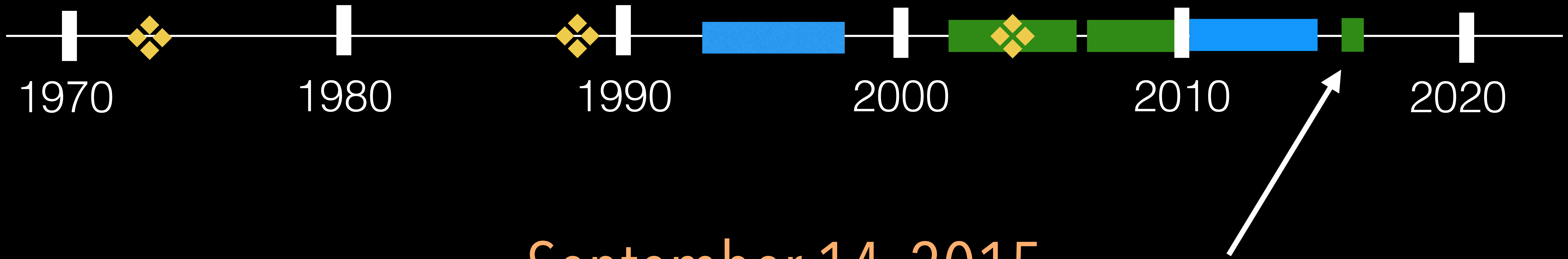


A brief history of LIGO

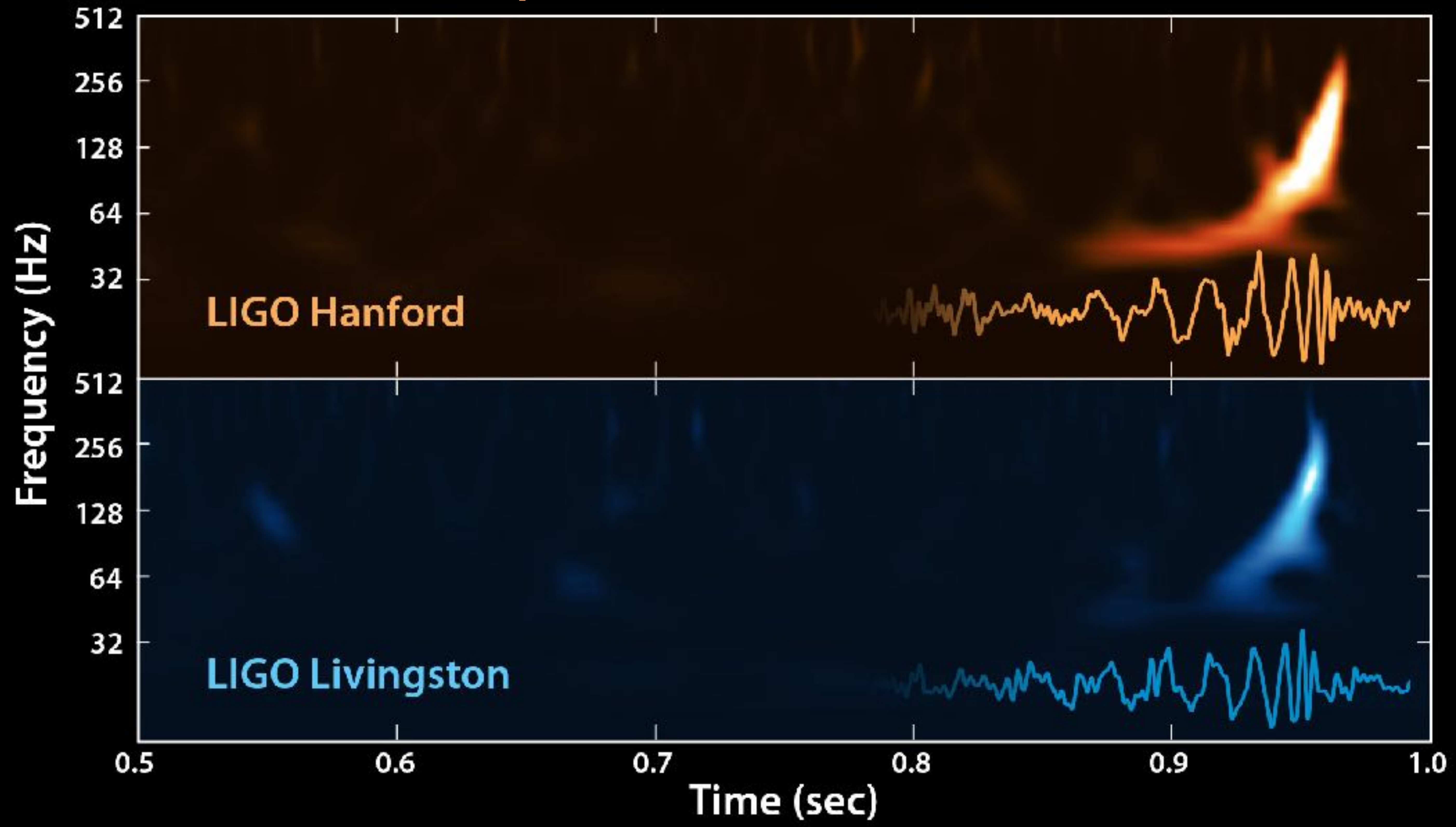


Sept 12 2015 - Jan 19 2016:
Advanced LIGO's first observing run
(O1)

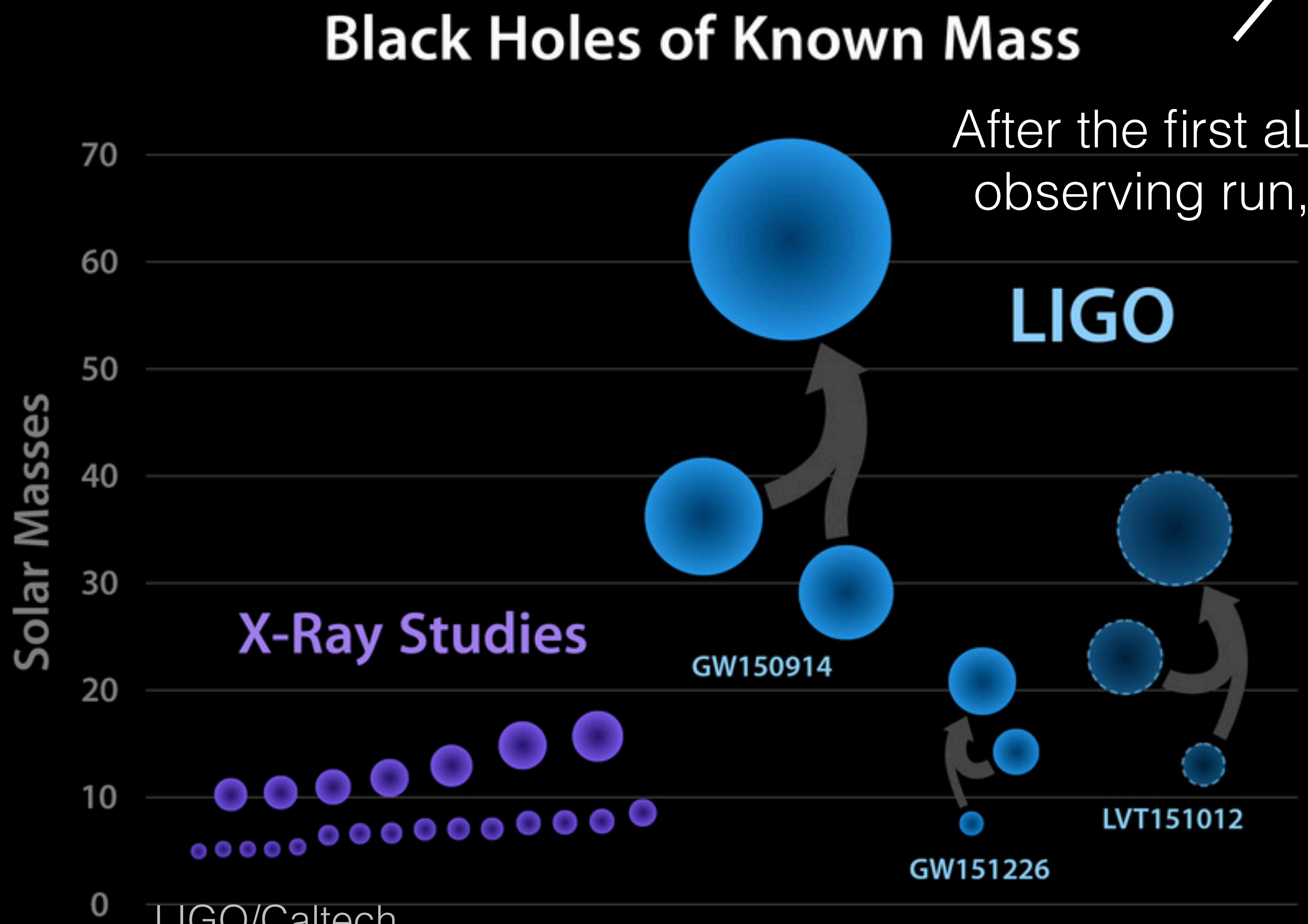
A brief history of LIGO



September 14, 2015



A brief history of LIGO

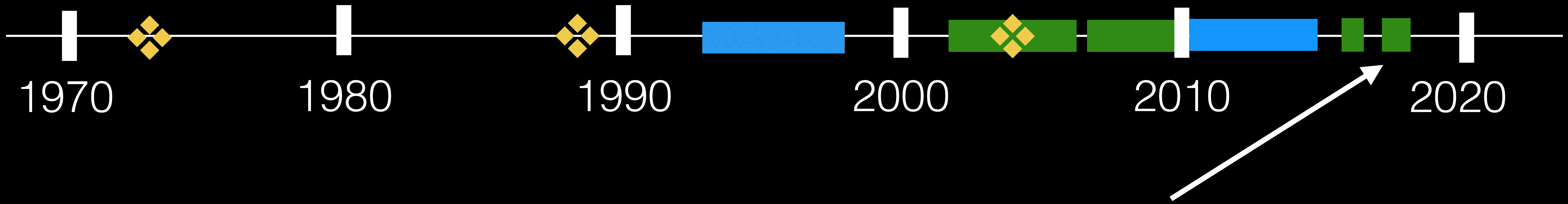


After the first aLIGO observing run, O1

O1: ~1 detection per month

LIGO/Caltech

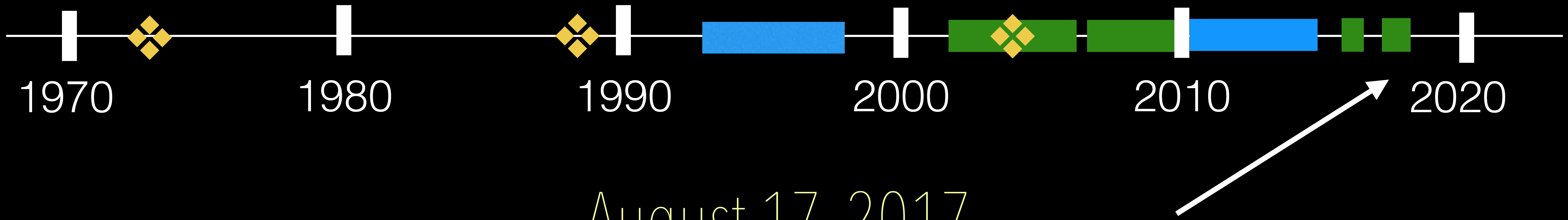
A brief history of LIGO



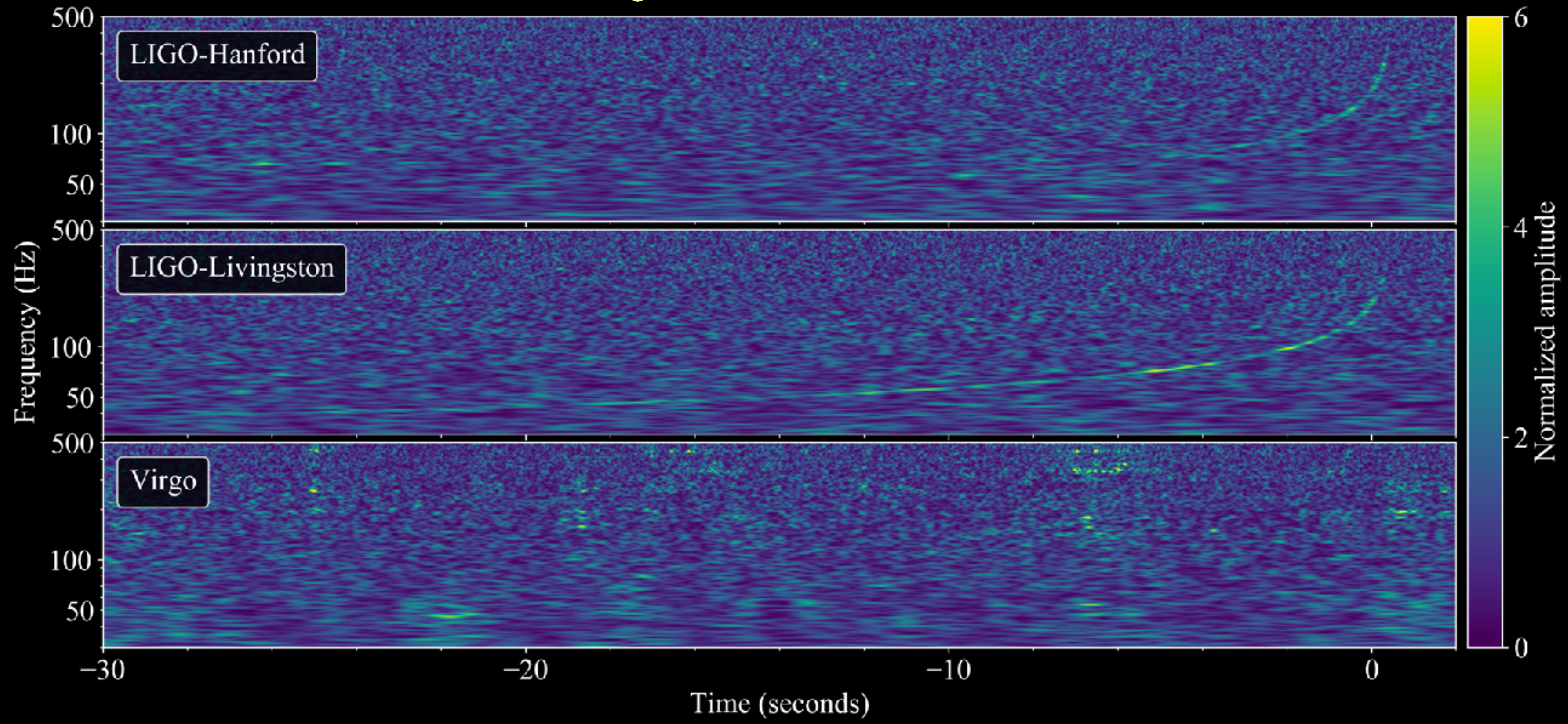
Nov 30 2016 - Aug 26 2017:

Advanced LIGO's second observing run (O2)

A brief history of LIGO

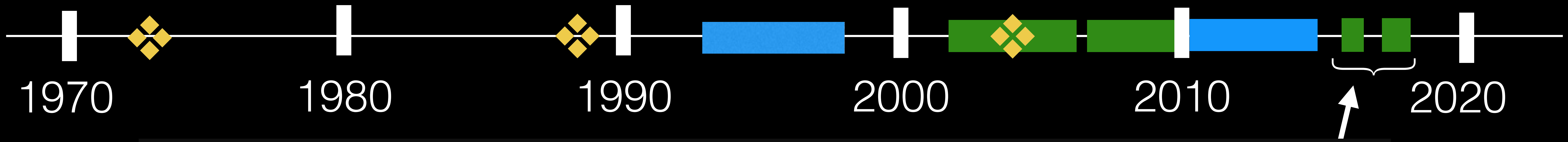


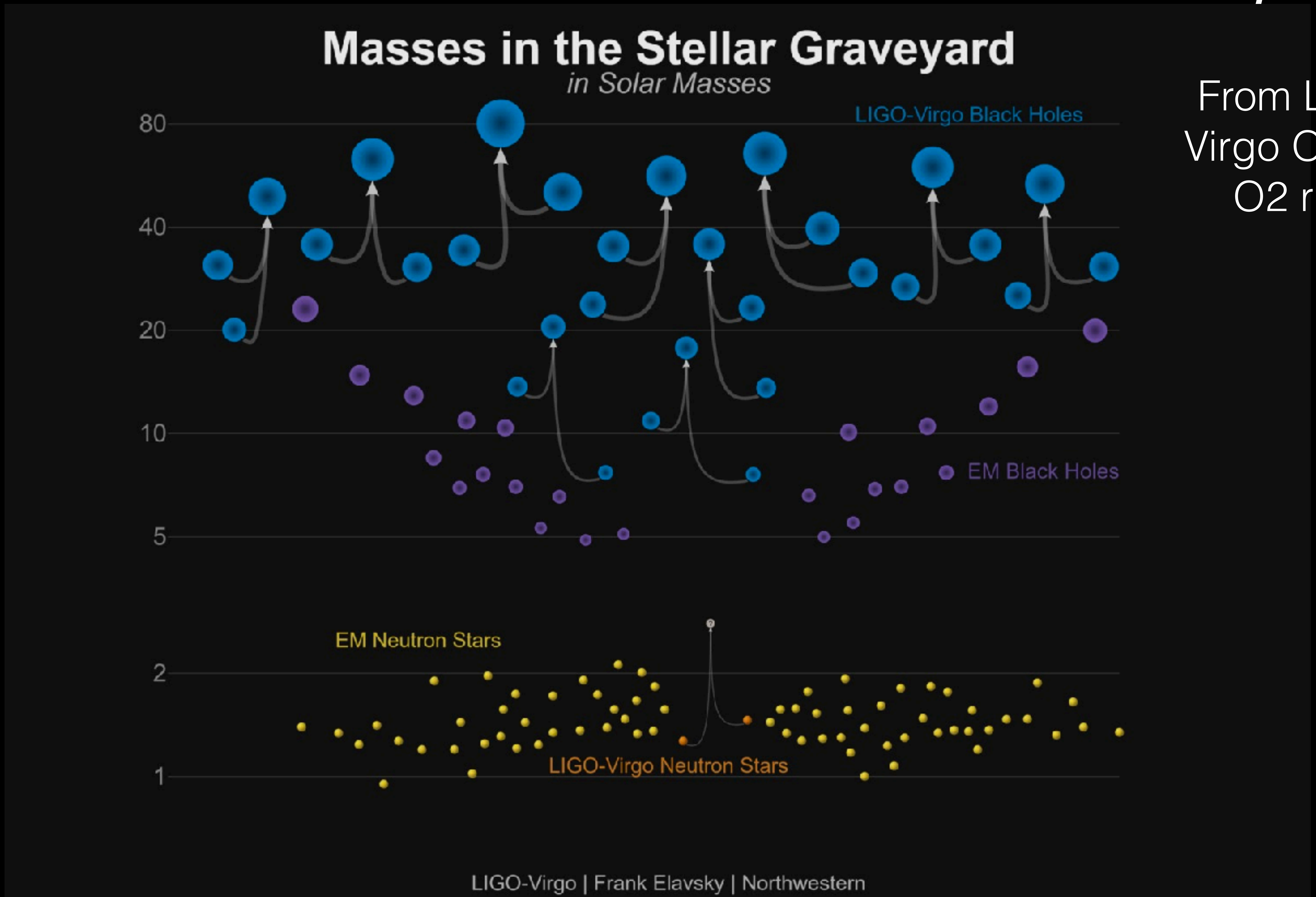
August 17, 2017



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

A brief history of LIGO: results from O2

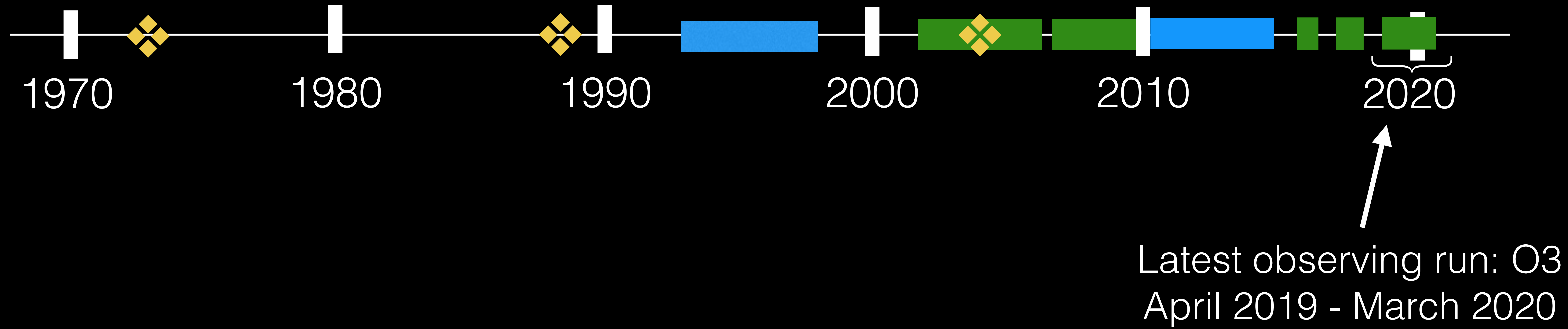




From LIGO-Virgo O1 and O2 runs

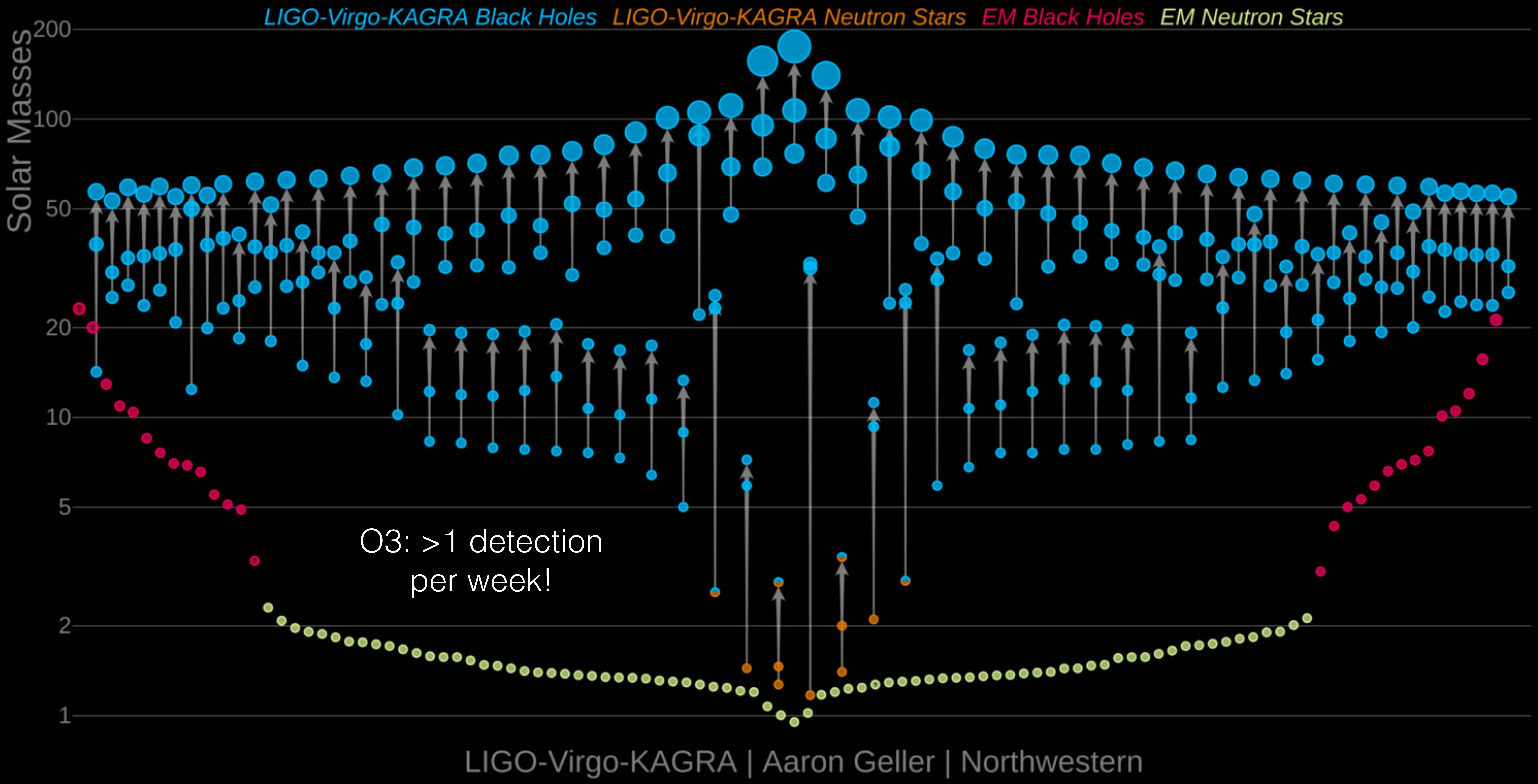
O2: ~1 detection every 2.5 weeks

A brief history of LIGO



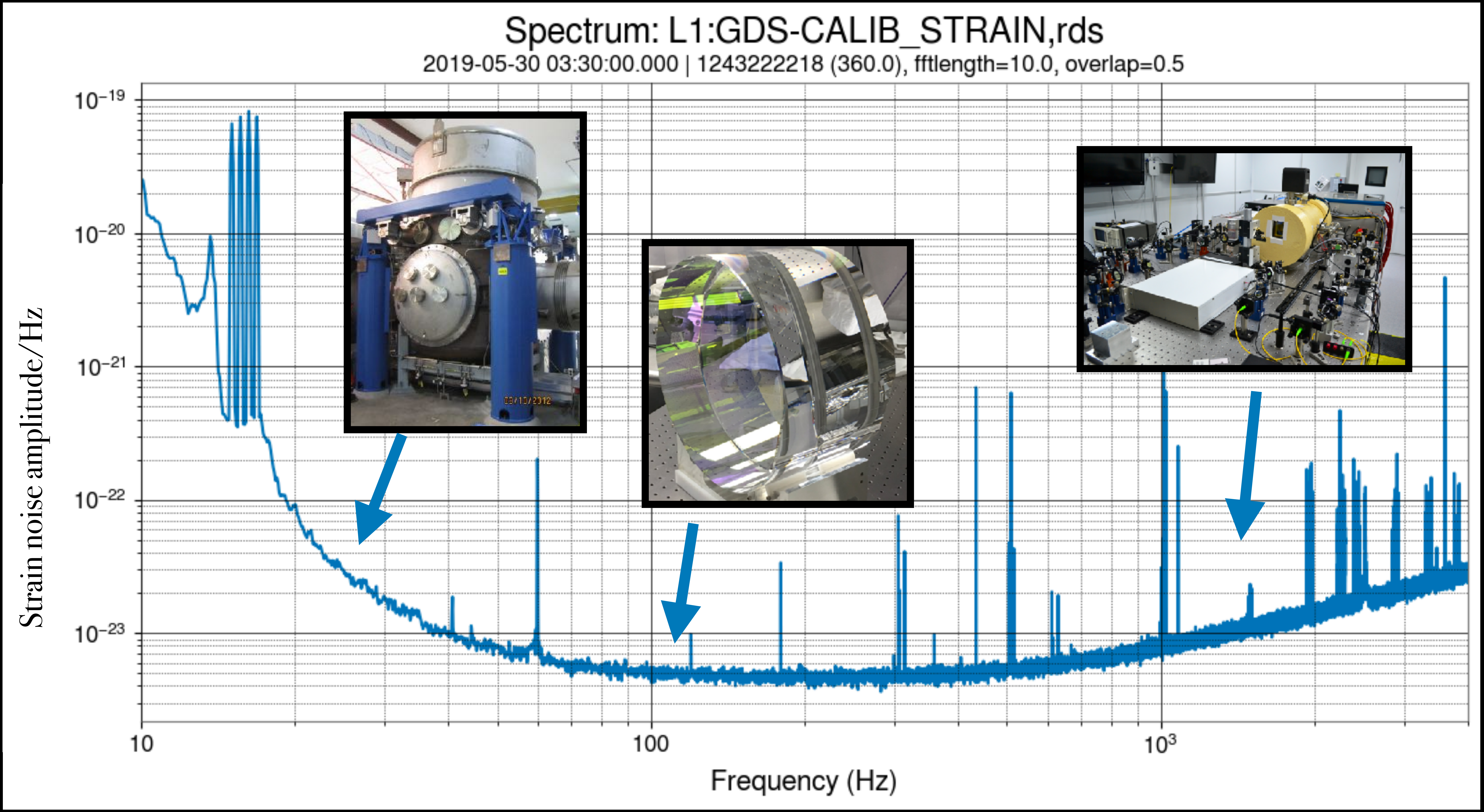
LIGO-Virgo/Frank Elavsky/Northwestern University

Current results (O1, O2, and O3)



Kai Staats

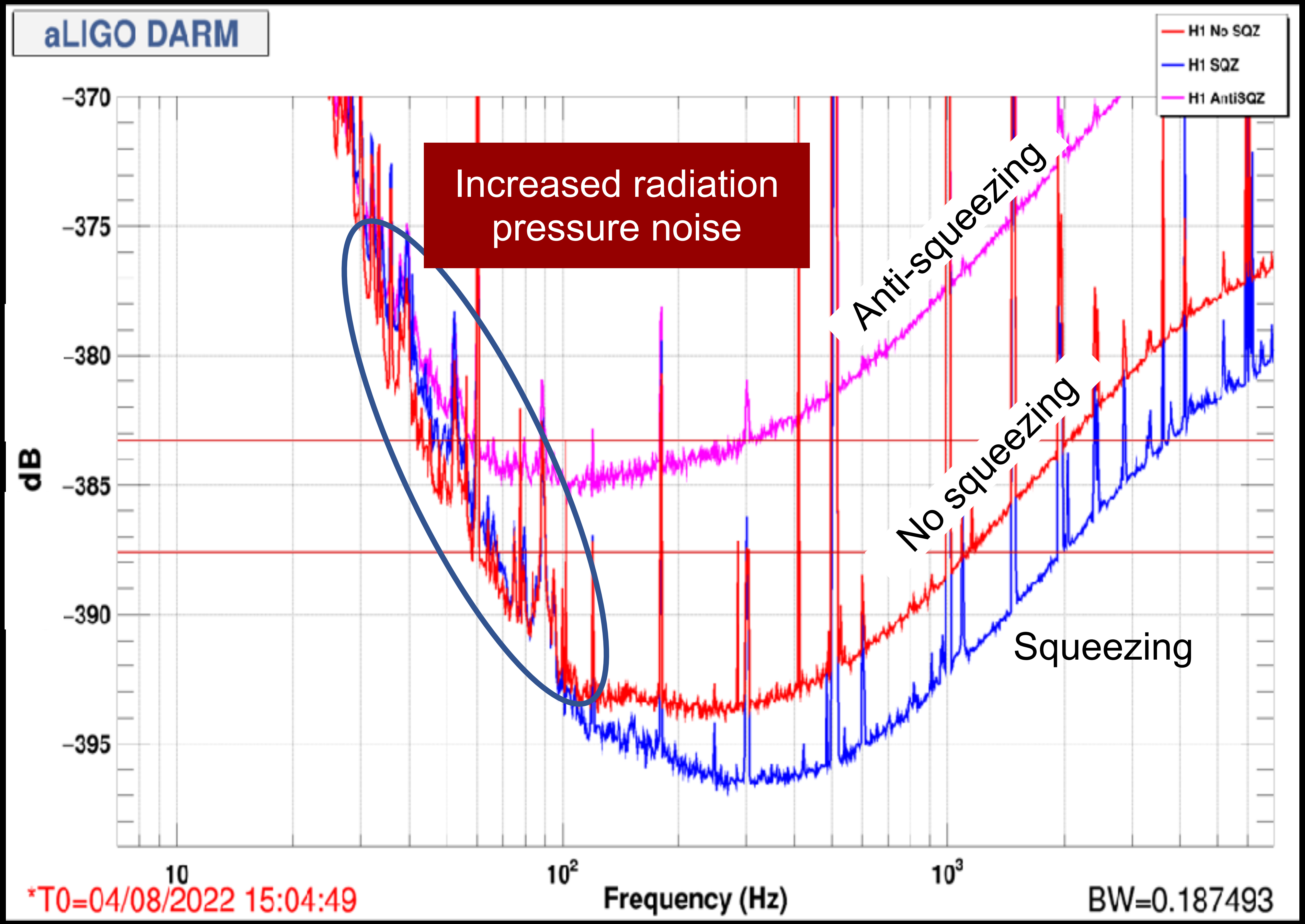
Advanced LIGO noise

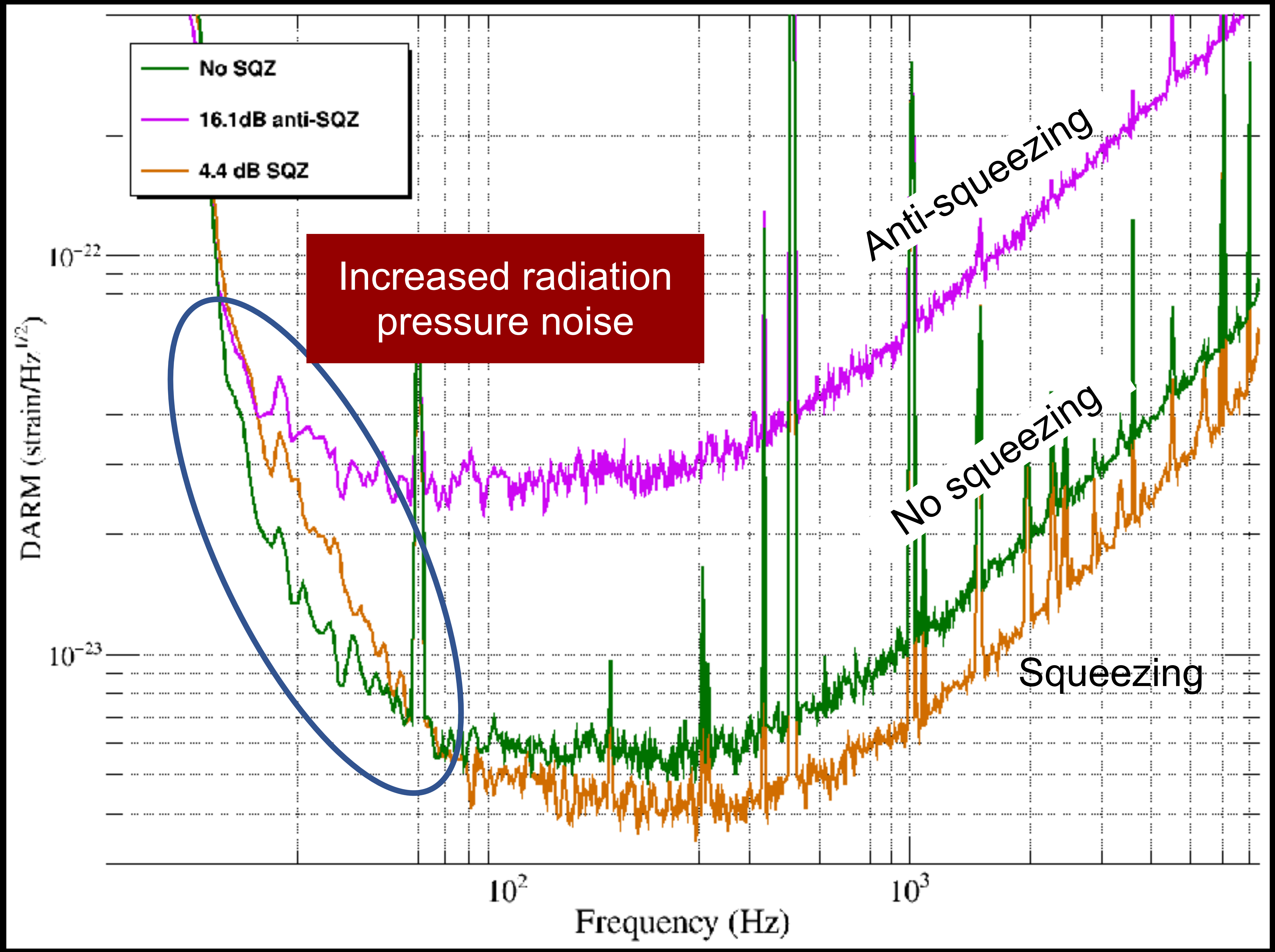


Frequency-Independent Squeezing in LIGO detectors

LHO 64389, 64346

LLO 60854



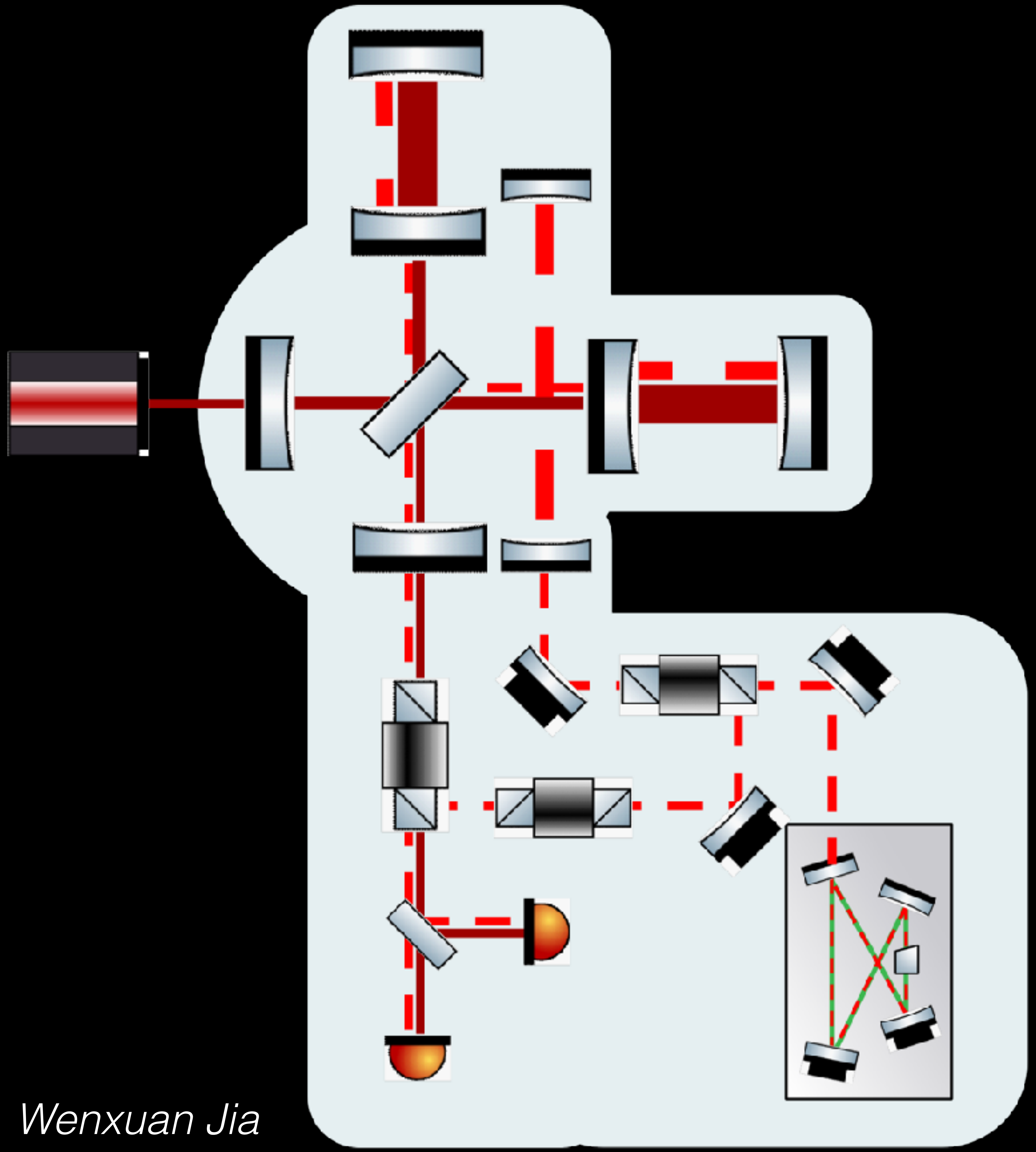


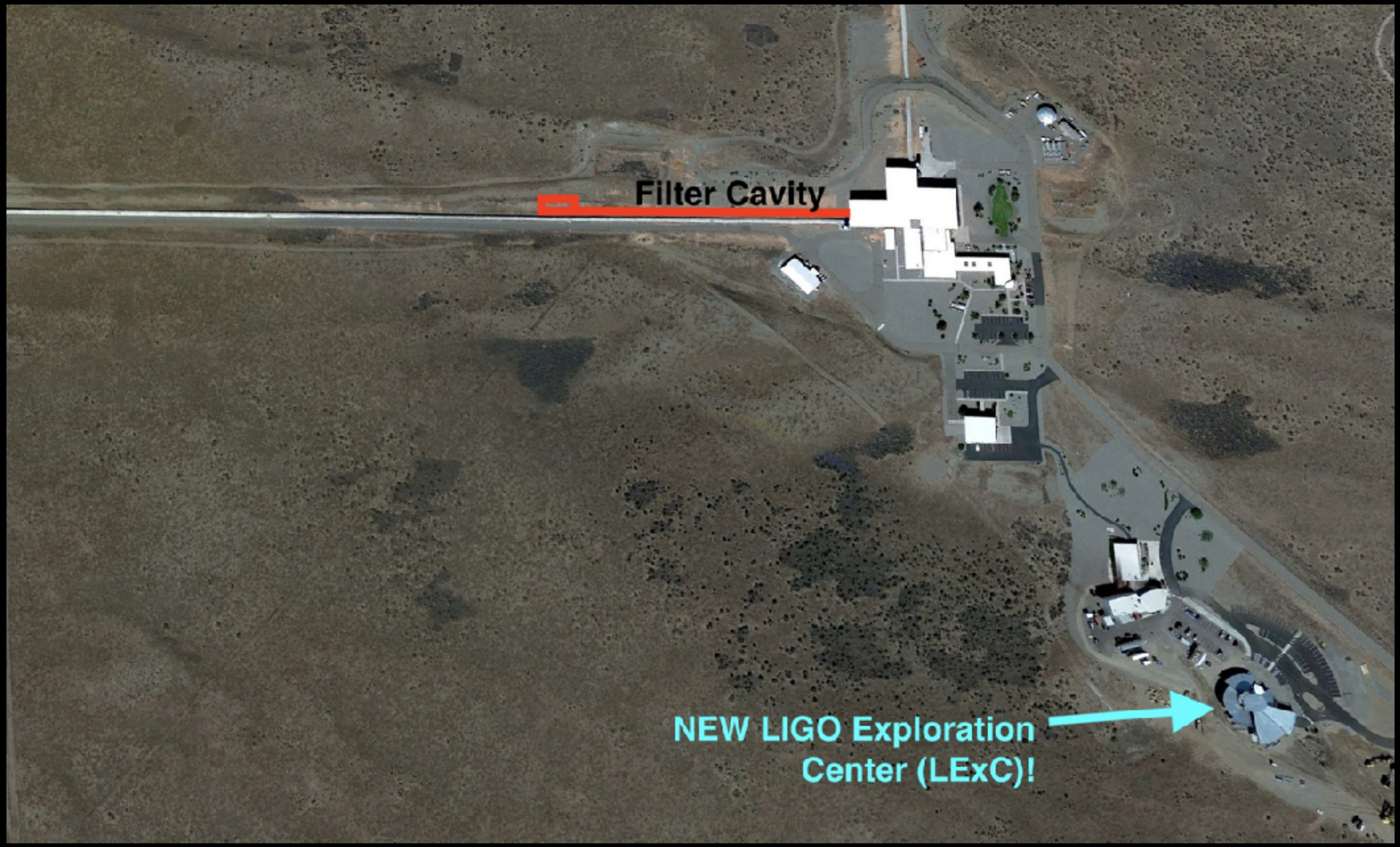
Both sites achieved 4.4 dB squeezing on shot noise:

- More squeezing than O3 (~3 dB)
- But sacrificed radiation pressure noise → **need for filter cavity**

Slide by Wenxuan Jia

New for O4: a 300 m filter cavity



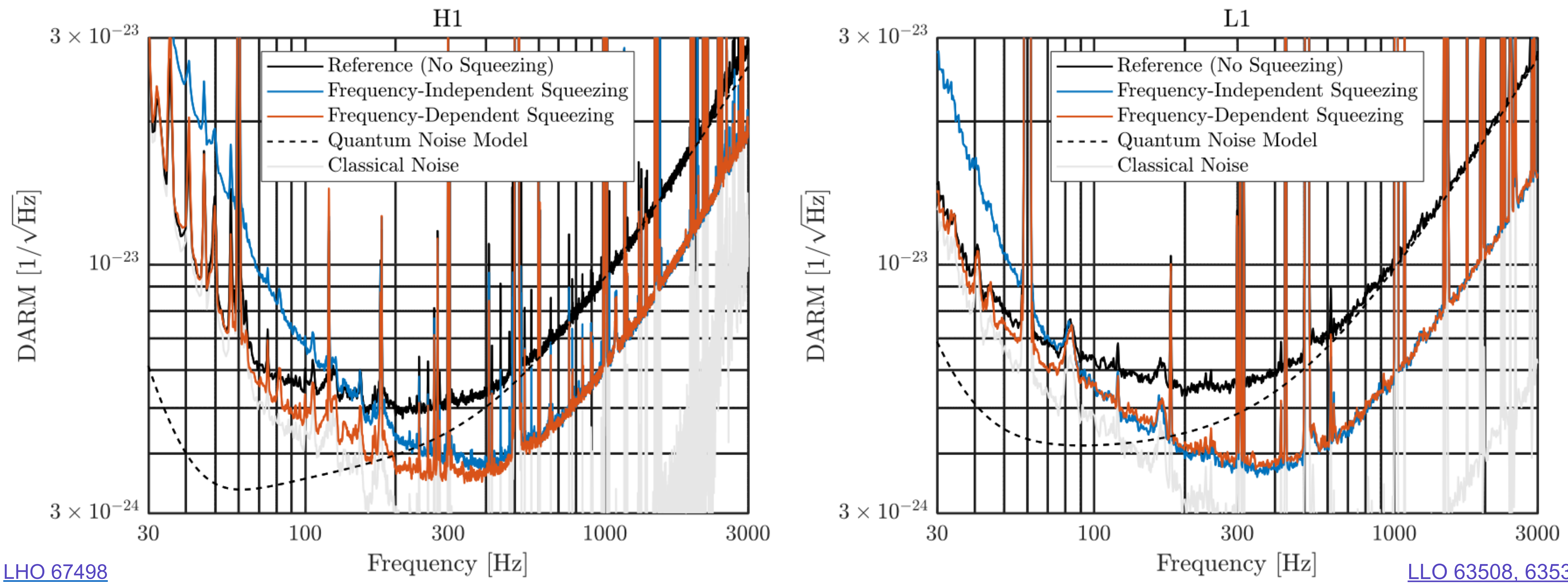


Wenxuan Jia

LIGO Lab

Corey Gray
@QuantumOfSalsa

Frequency Dependent Squeezing in LIGO detectors



LHO 67498

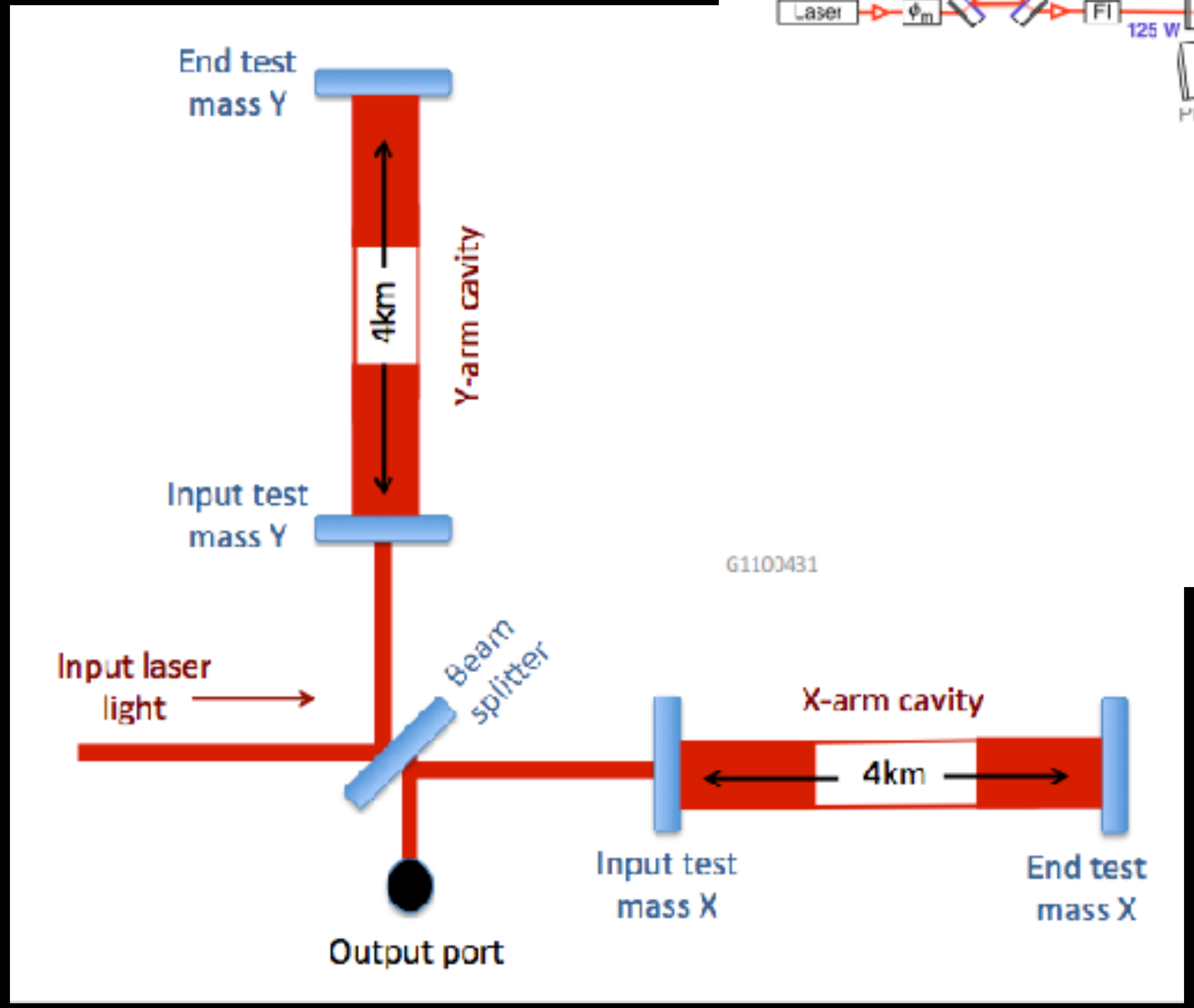
LLO 63508, 63533

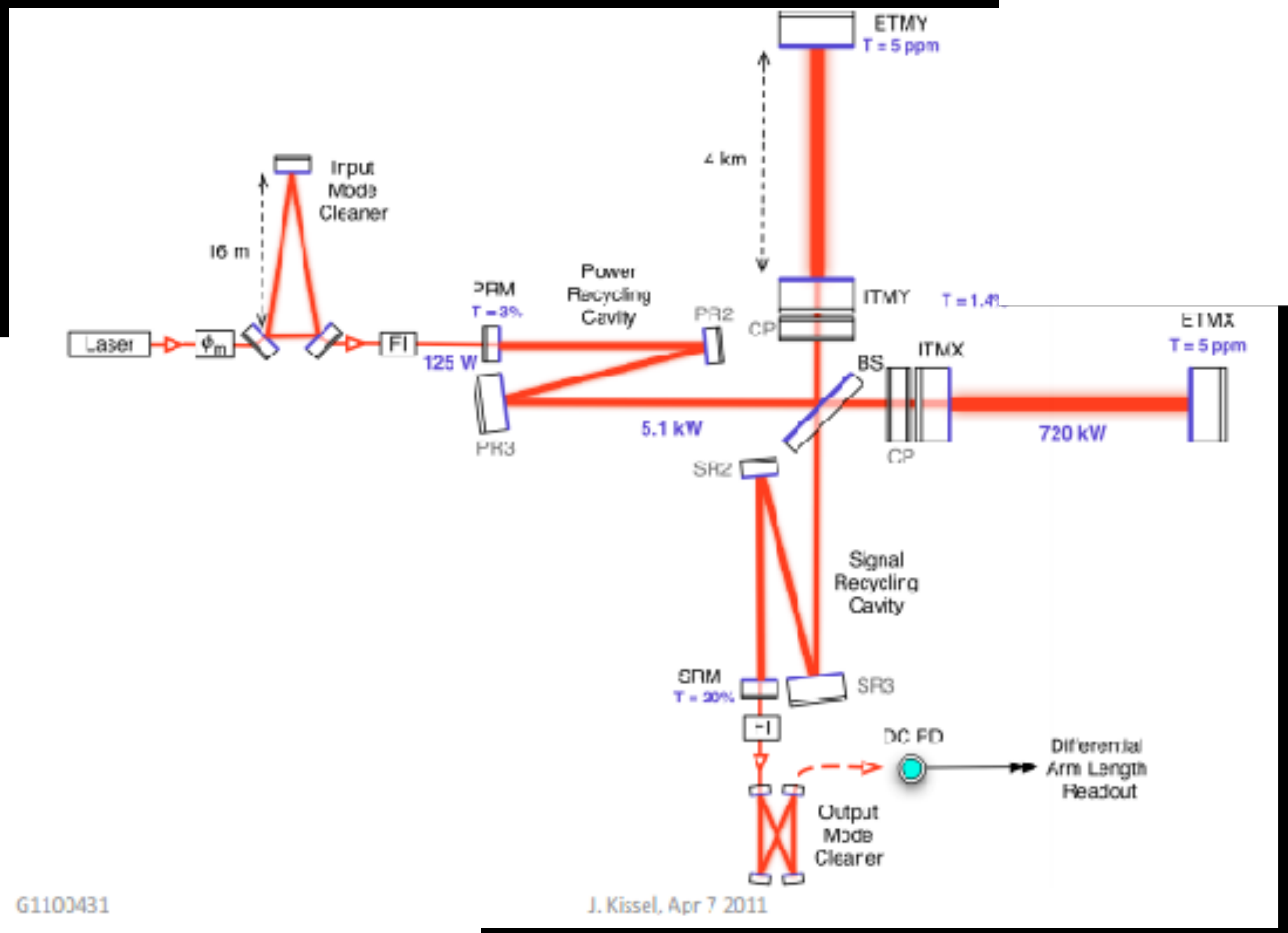
- 330-390 kW power
- 4 dB noise reduction visible on DARM at ~2 kHz
- 1 dB at ~80 Hz

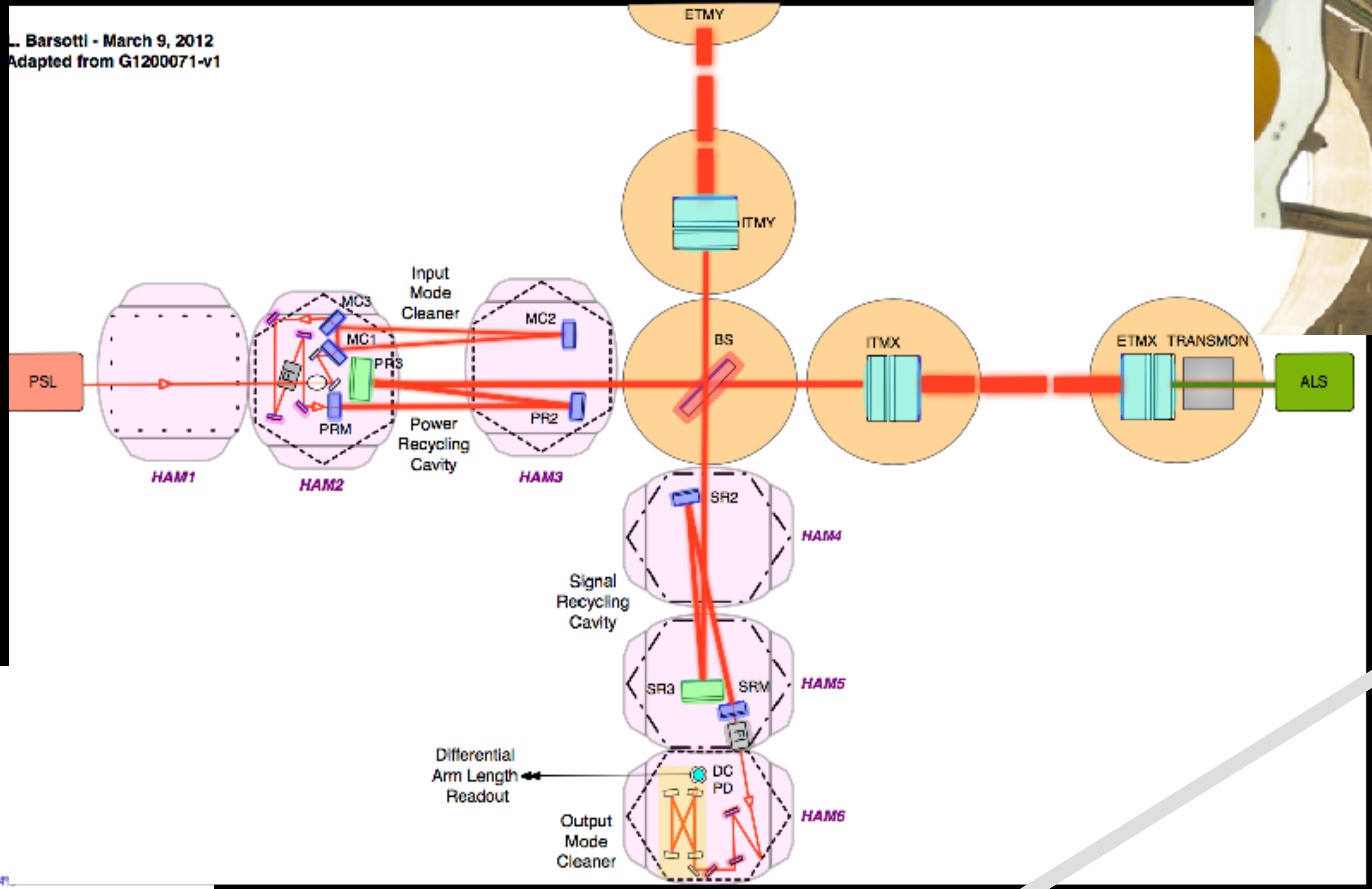
- 250 kW arm power
- 5.1 dB noise reduction visible on DARM at ~2 kHz
- 1 dB at ~80 Hz

Slide by Wenxuan Jia

Interferometric GW detectors are extremely complex.







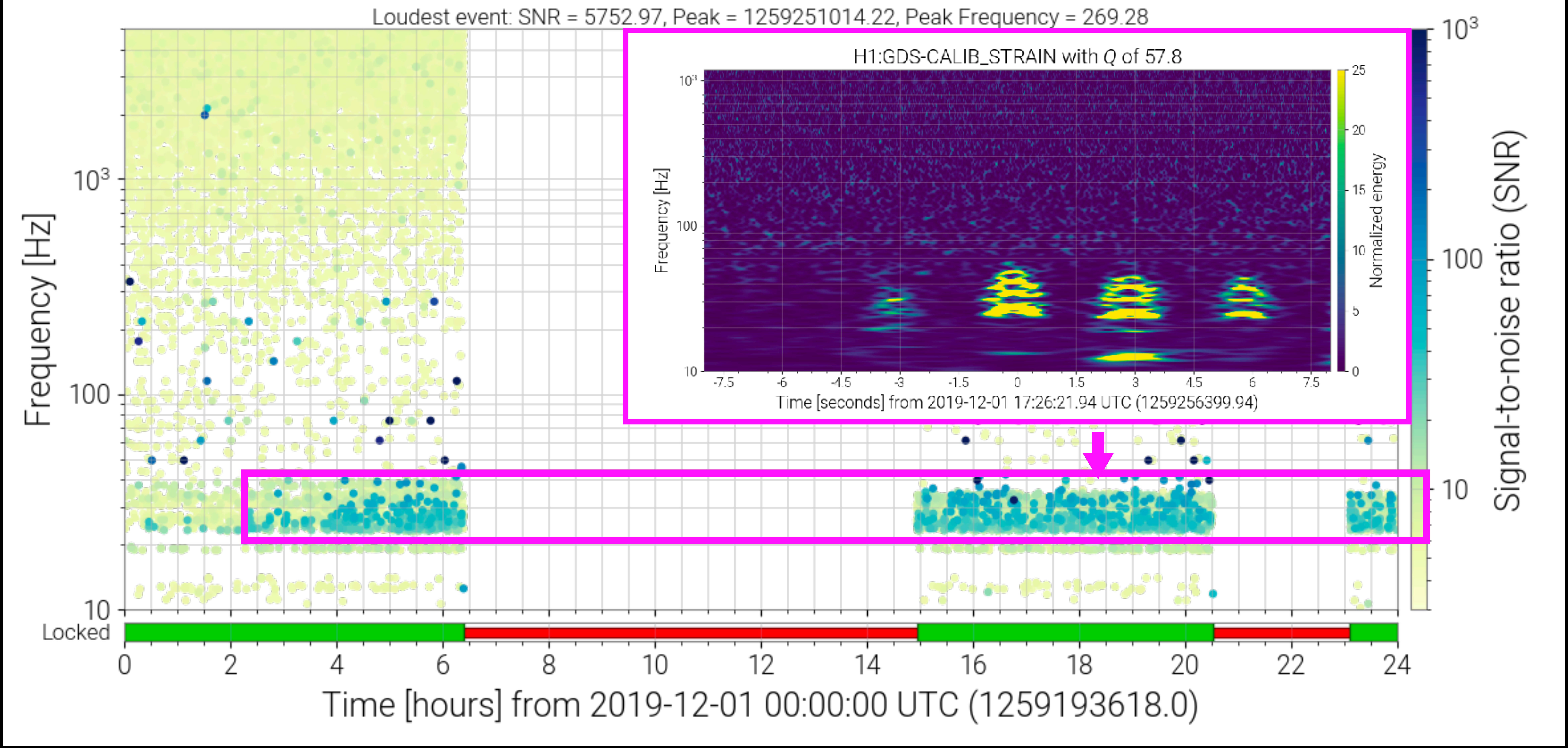
Reality

Adapted from D. Shoemaker

Challenge: what causes GW detector glitches?

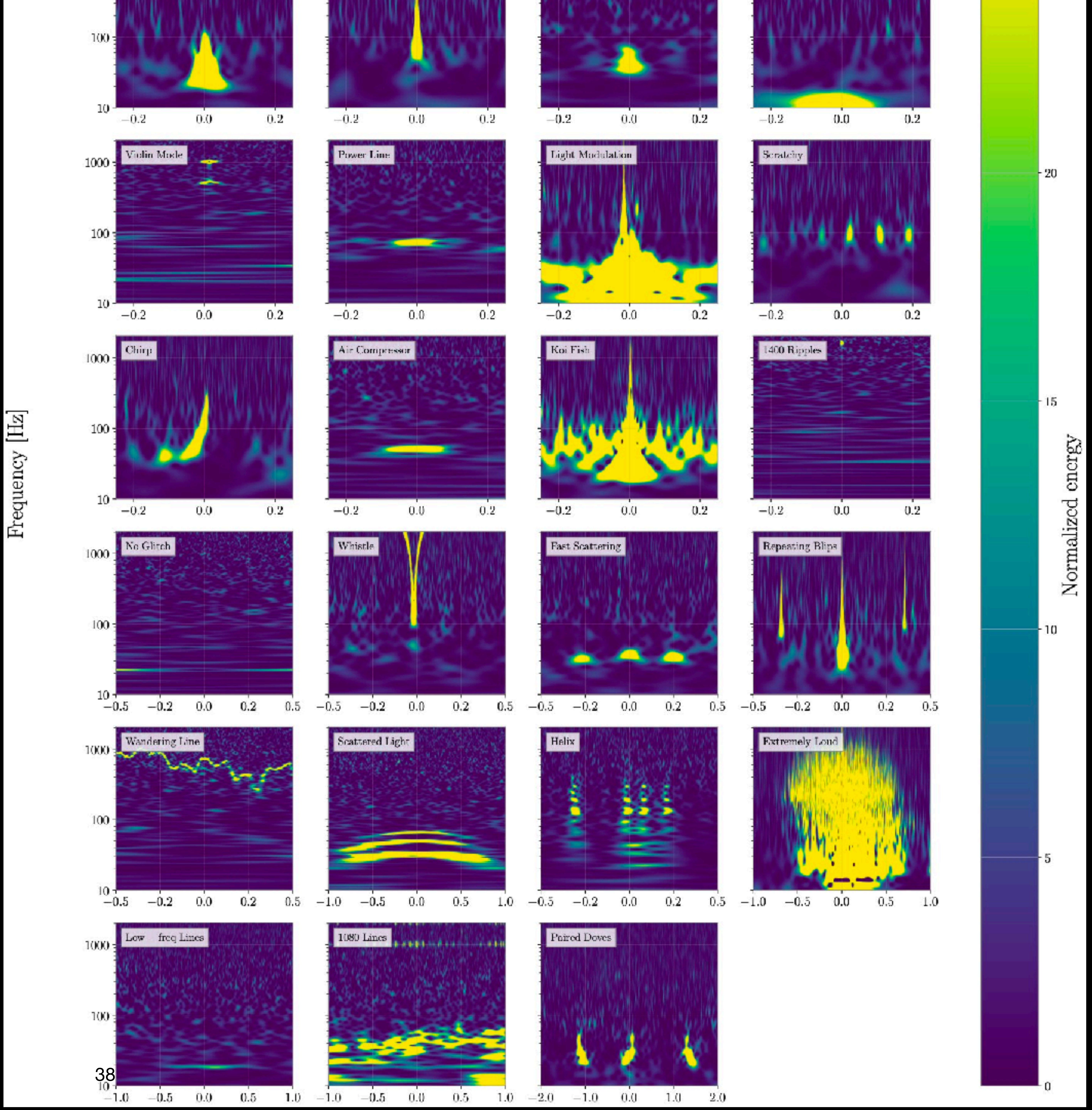
Lightning	Birds	Refrigerators	RF contamination
Ocean waves	Earthquakes	Air conditioners	Telephones
Low humidity	Trains	Snow plows	Thunder
Forklifts	Helicopters	Airplanes	Bill's heartbeat

Challenge: GW detector transient noise



The LIGO summary pages

A menagerie of GW detector glitches



Time-frequency visualizations used for training Gravity Spy
M.. Zevin et al.,CQG (2017).

Mitigation of nearby glitches

Example: GW191109_010717

LVK Tests of GR conducted in 2112.06861: Residuals test, Polarization, Ringdown, Echoes

Plots by D. Davis. Glitch modelling and subtraction using **BayesWave**: Cornish & Littenberg 2014 & 2020; Davis et al 2021.

The curious case of GW200129 - signs of precession?

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JANUARY SALES - THE DEALS YOU CAN'T AFF

Colliding black holes produce most extreme 'wobble' ever seen in 'one-in-1,000' event

This is the first time that this effect - known as precession - has been seen with black holes, where the "wobble" is 10 billion times faster than in observations o other bodies.

SciTechDaily

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Most Extreme "Wobbling Black Hole" Ev Detected – Exotic Phenomenon Predicte Einstein's Theory of Gravity

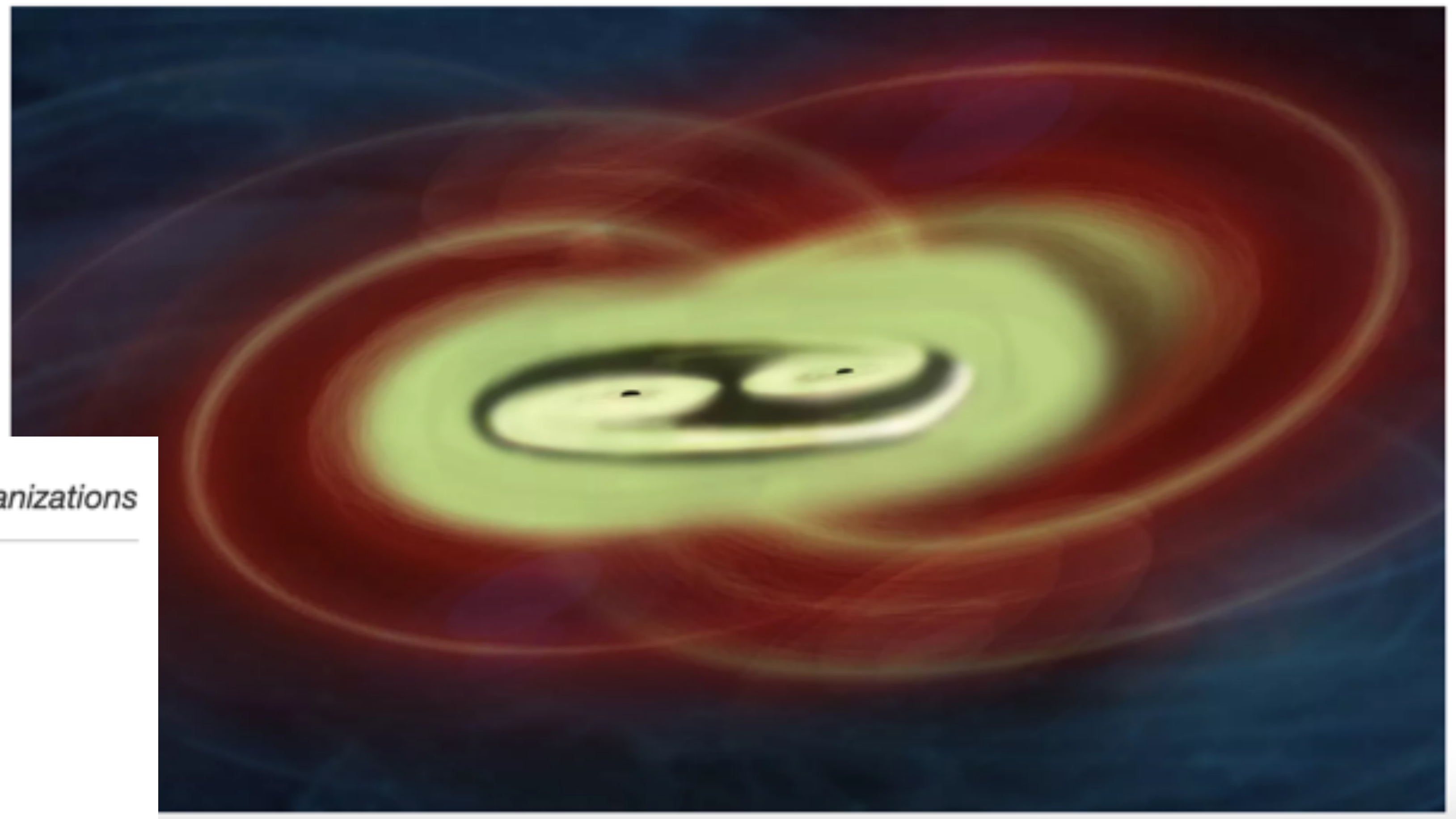
TOPICS: Astrophysics Black Hole Cardiff University Gravitational Waves

Home > News

One of the most extreme black hole collisions in the universe just proved Einstein right

By Brandon Specktor published October 12, 2022

The black hole twisted 10 billion times faster than any ever observed.



Science News *from research organizations*

'Wobbling black hole' most extreme example ever detected

Gravitational waves identify what could be a rare one-in-1000 event

Date: October 12, 2022

Source: Cardiff University

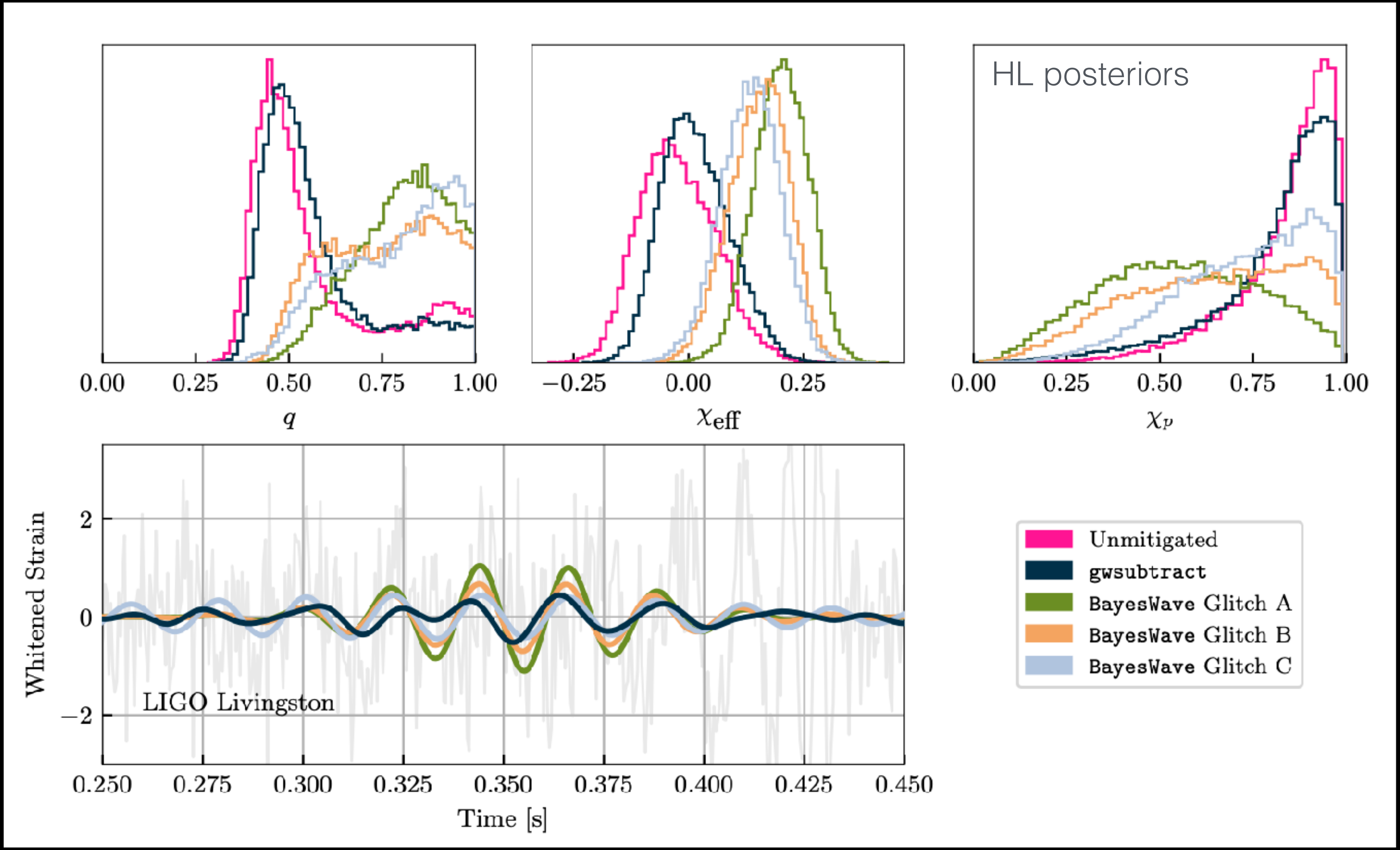
Summary: Researchers have identified a peculiar twisting motion in the orbits of two colliding black holes, an exotic phenomenon predicted by Einstein's theory of gravity. Their study reports that this is the first time this effect, known as precession, has been seen in black holes, where the twisting is 10 billion times faster than in previous observations.

Hannam et al, Nature, 2022

The curious case of GW20129

Plots by Derek Davis; Davis et al 2022.

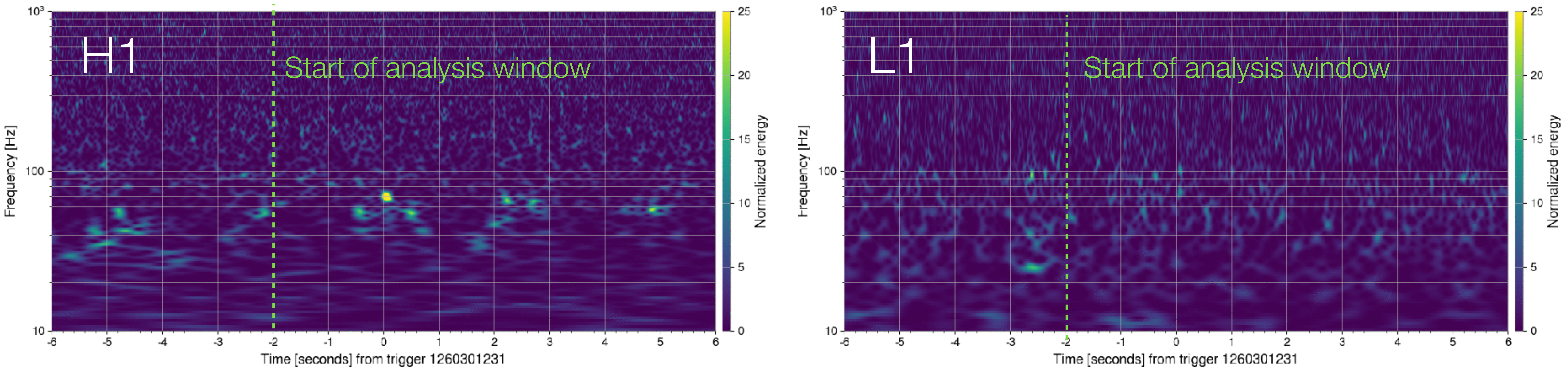
The curious case of GW200129



Payne et al. Phys Rev D. 2022

Example of more subtle noise features: S191213bb

S191213g was found in low latency by matched filter search GstLAL in both LIGO Hanford and LIGO Livingston with FAR of 1.1 yr^{-1}.

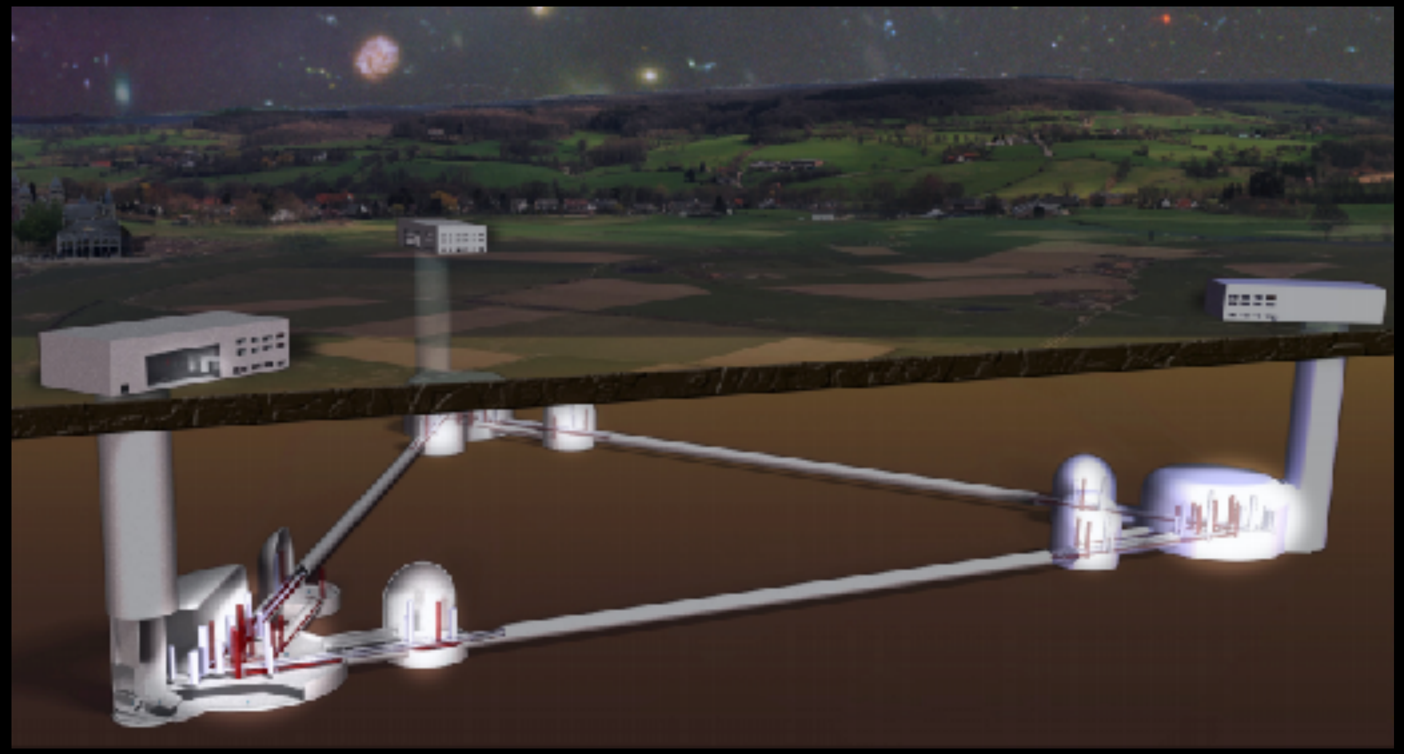


Plots by D. Davis

Insider tips for inferring subtle features from LIGO-Virgo data

- Detector glitches and non-stationarity are very common - visualize the data before analysis!
- The LVK releases de-glitched frames for individual events with **limited valid time range** (usually just surrounding the LVK parameter estimation analysis).
- When calculating p_values (how likely is it that noise produced this data?) not all times are equal; detector noise follows patterns on the scale of days, hours, and minutes in response to environmental stimulus.
- Detectors share common noise coupling mechanisms: it is not uncommon for detectors to manifest glitches with similar time-frequency morphologies.
- Exercise caution.

The next generation of GW detectors



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

2025

2030

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

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

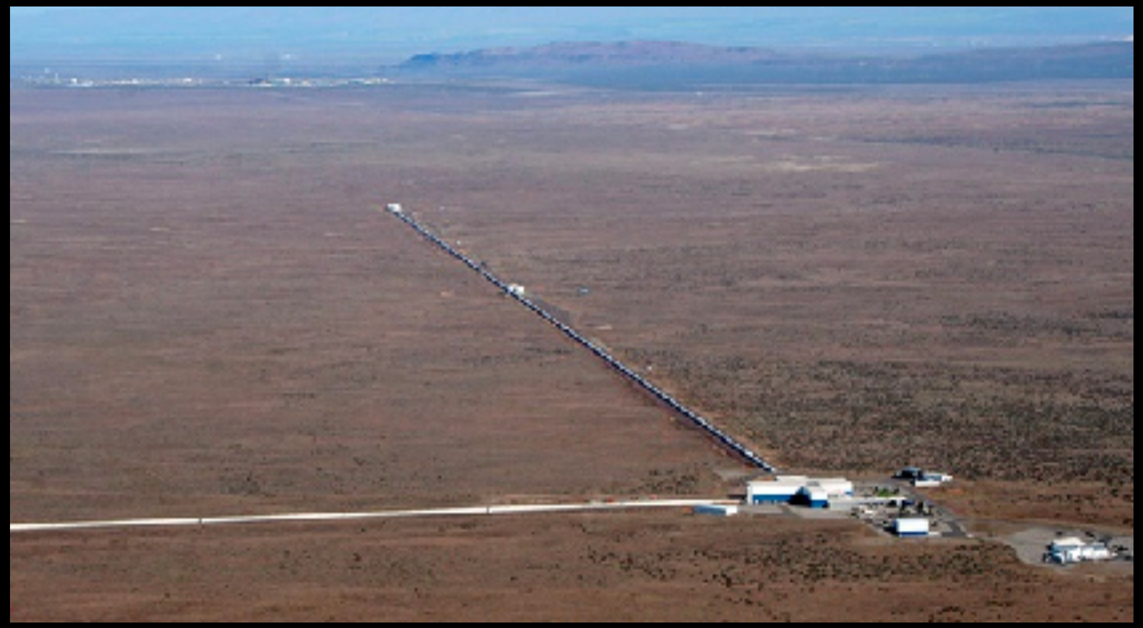
2035

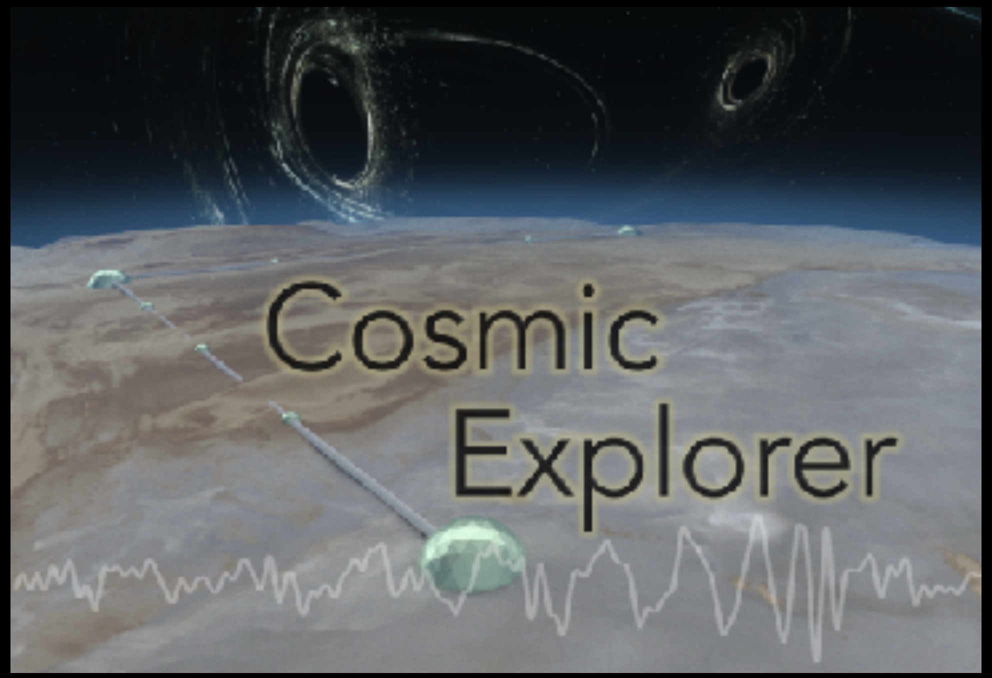
Cosmic Explorer 1
- 20-40 km detectors

  300 K
- 1-2 microns (?)
- 320 kg mirrors

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

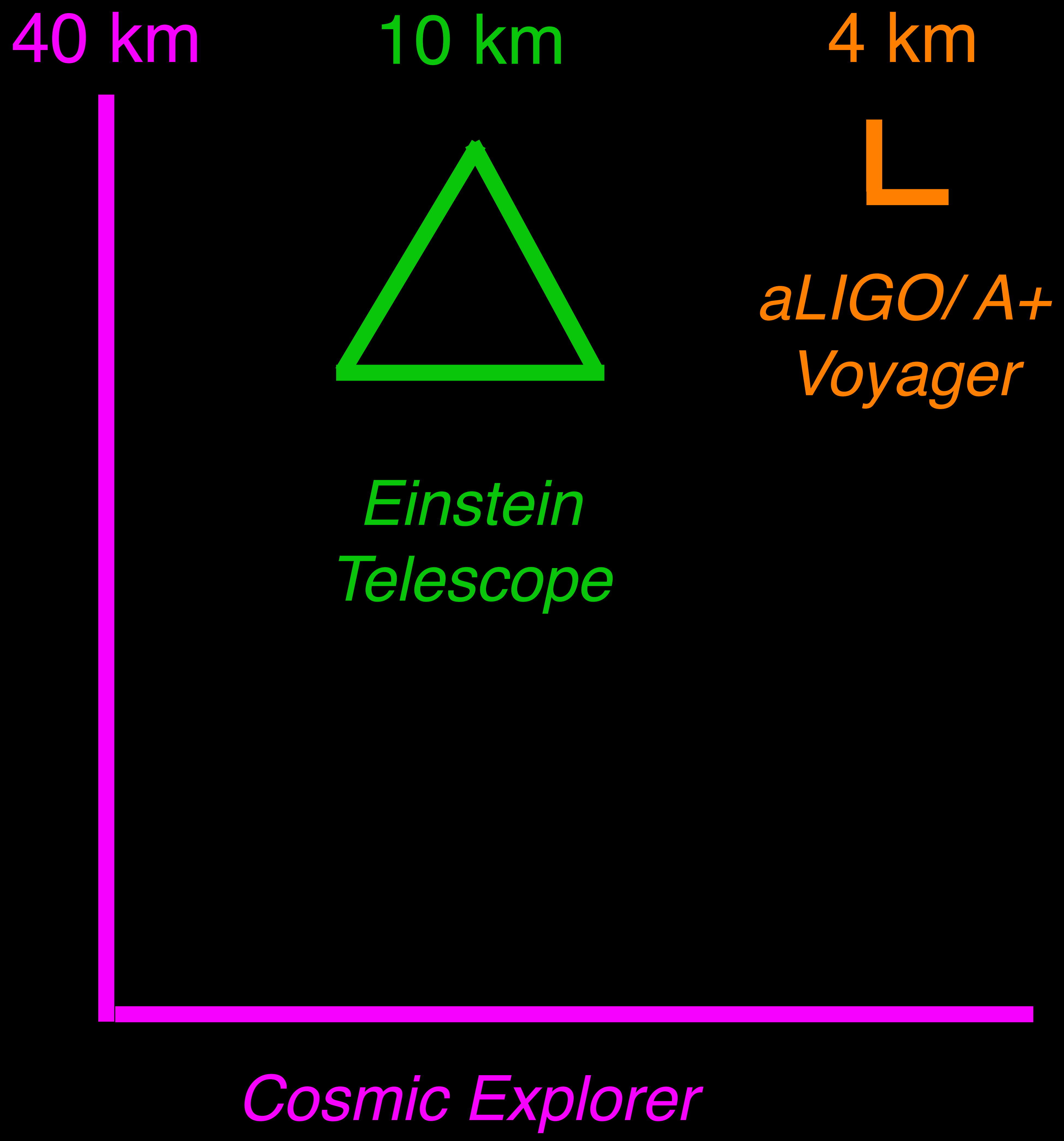
2040

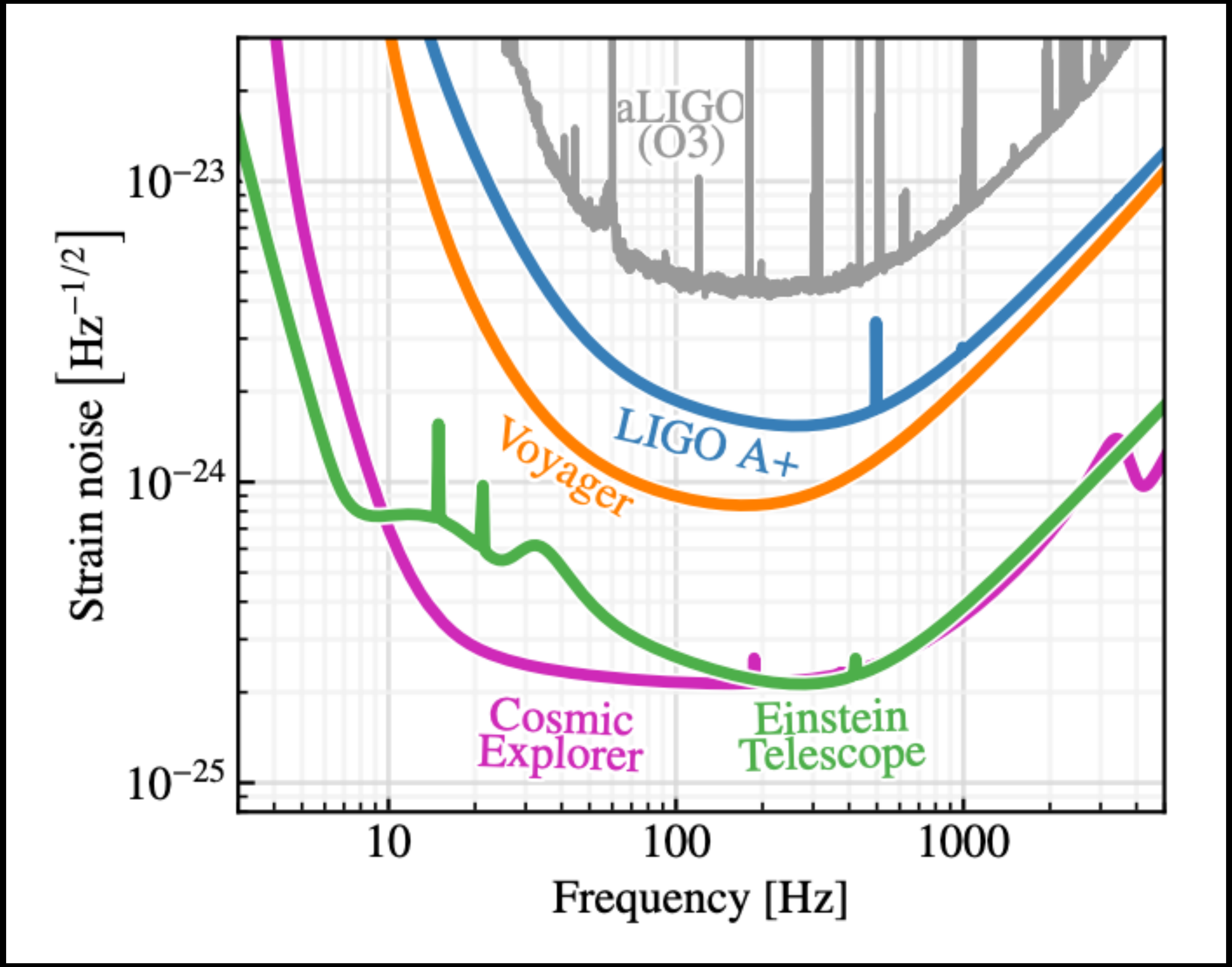




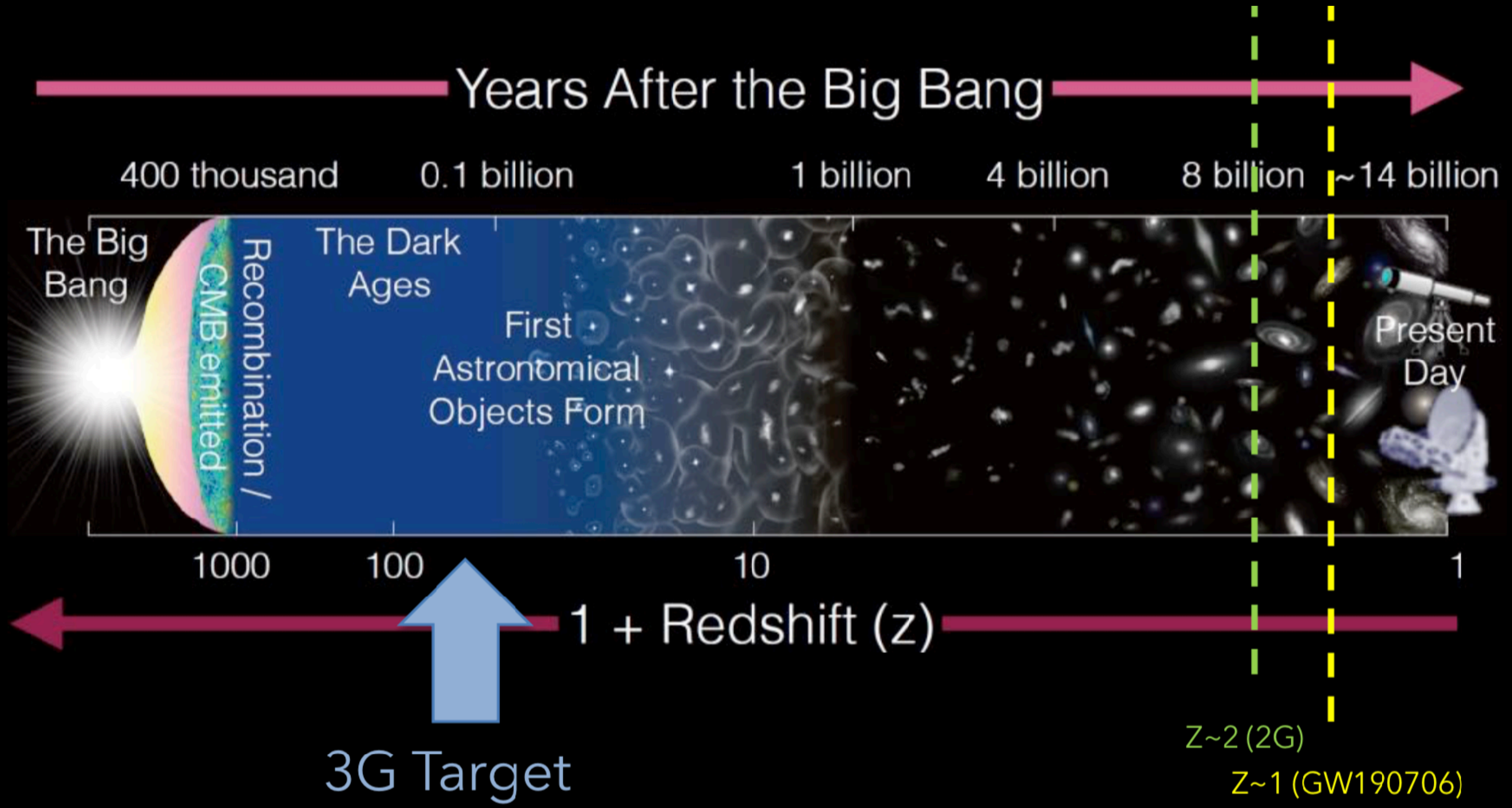
Dawn IV workshop report (McIver et al, 2019); Cosmic Explorer Astro 2020 decadal submission (Reitze et al 2020); Einstein Telescope Conceptual Design Study (Punturo et al 2020)

The next generation GW detectors



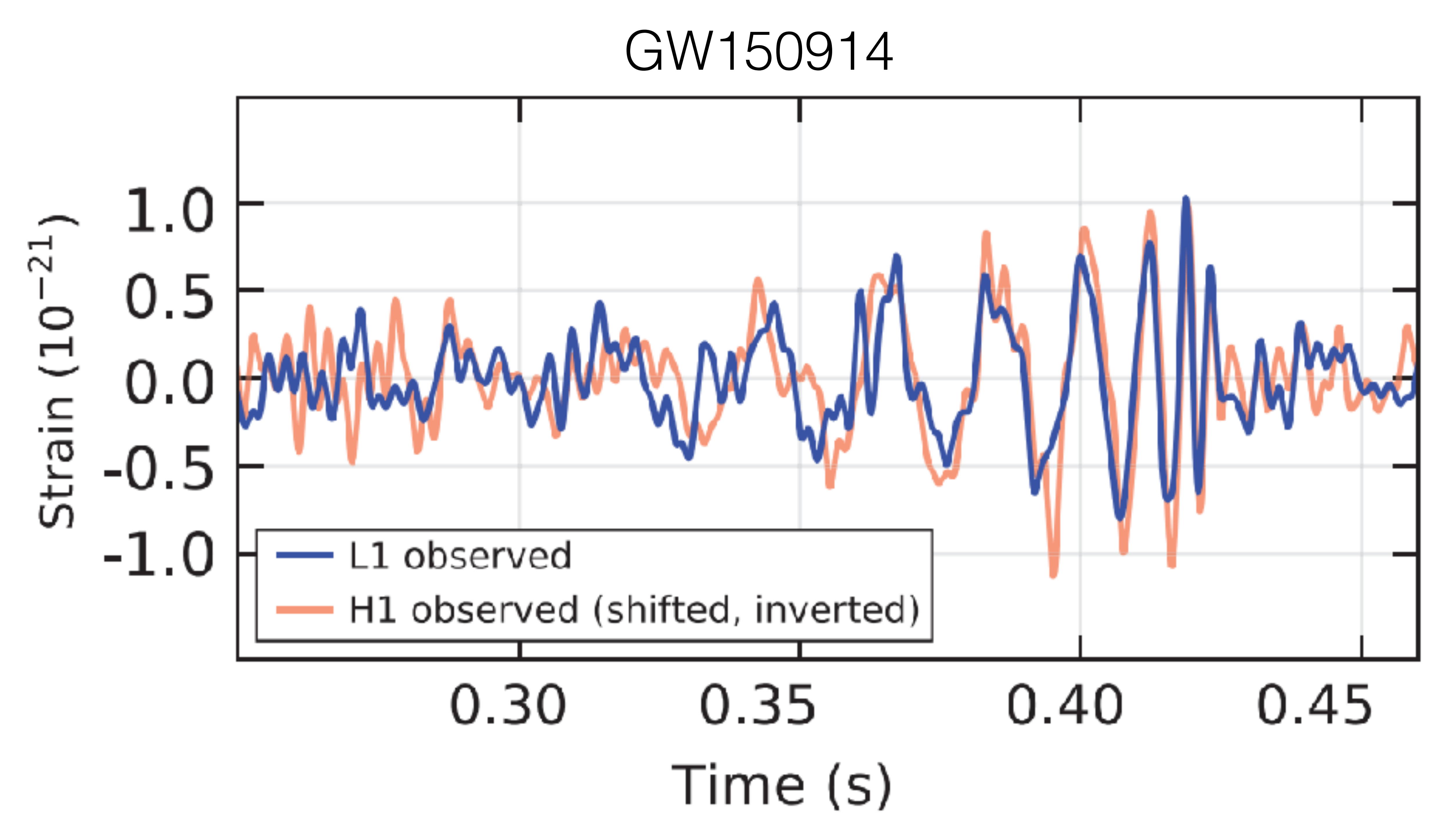


S. Gossan et al. ApJ 926 231 (2022)



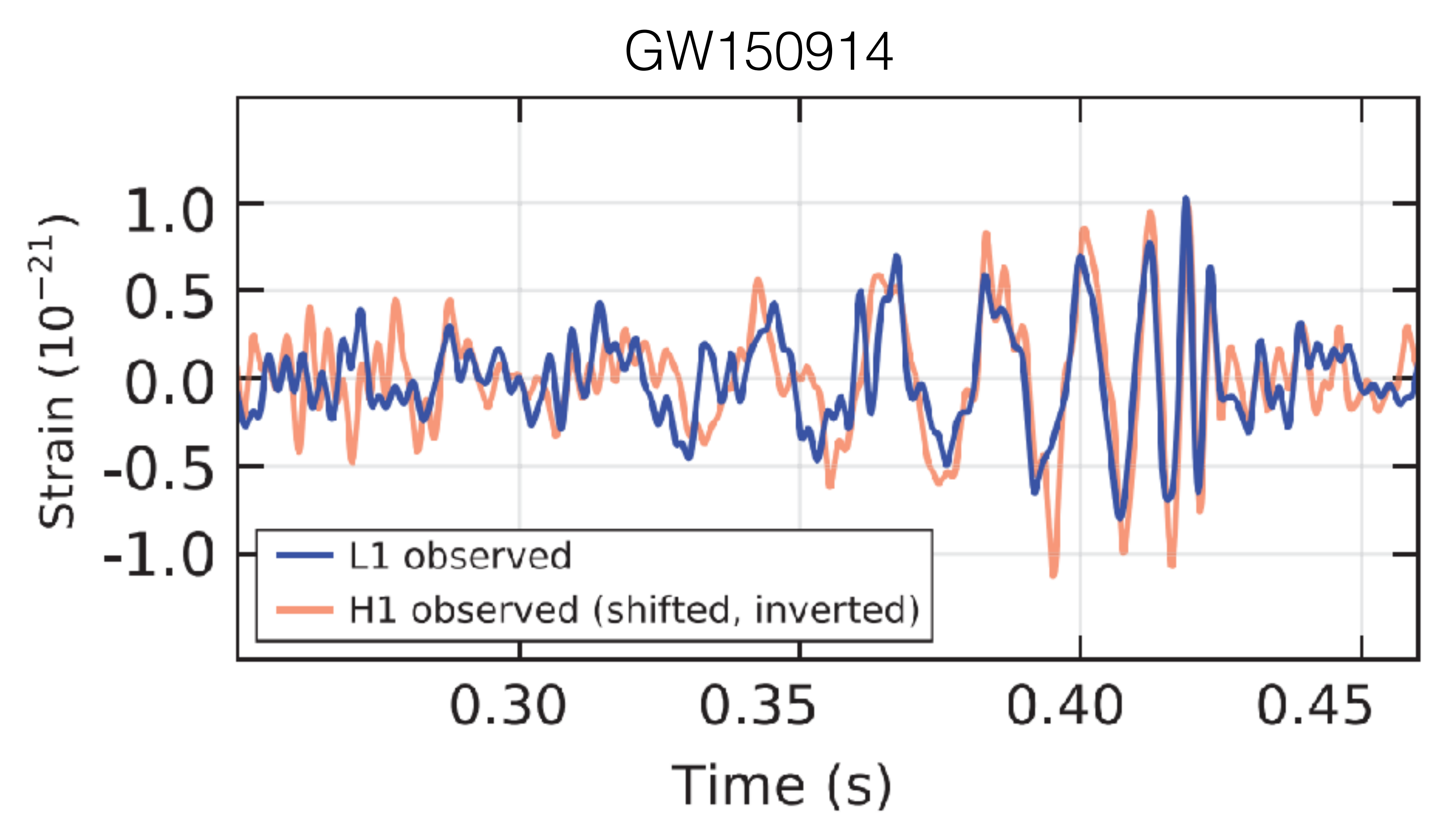
Slide by G. Losurdo

Along with cosmological reach: large SNRs

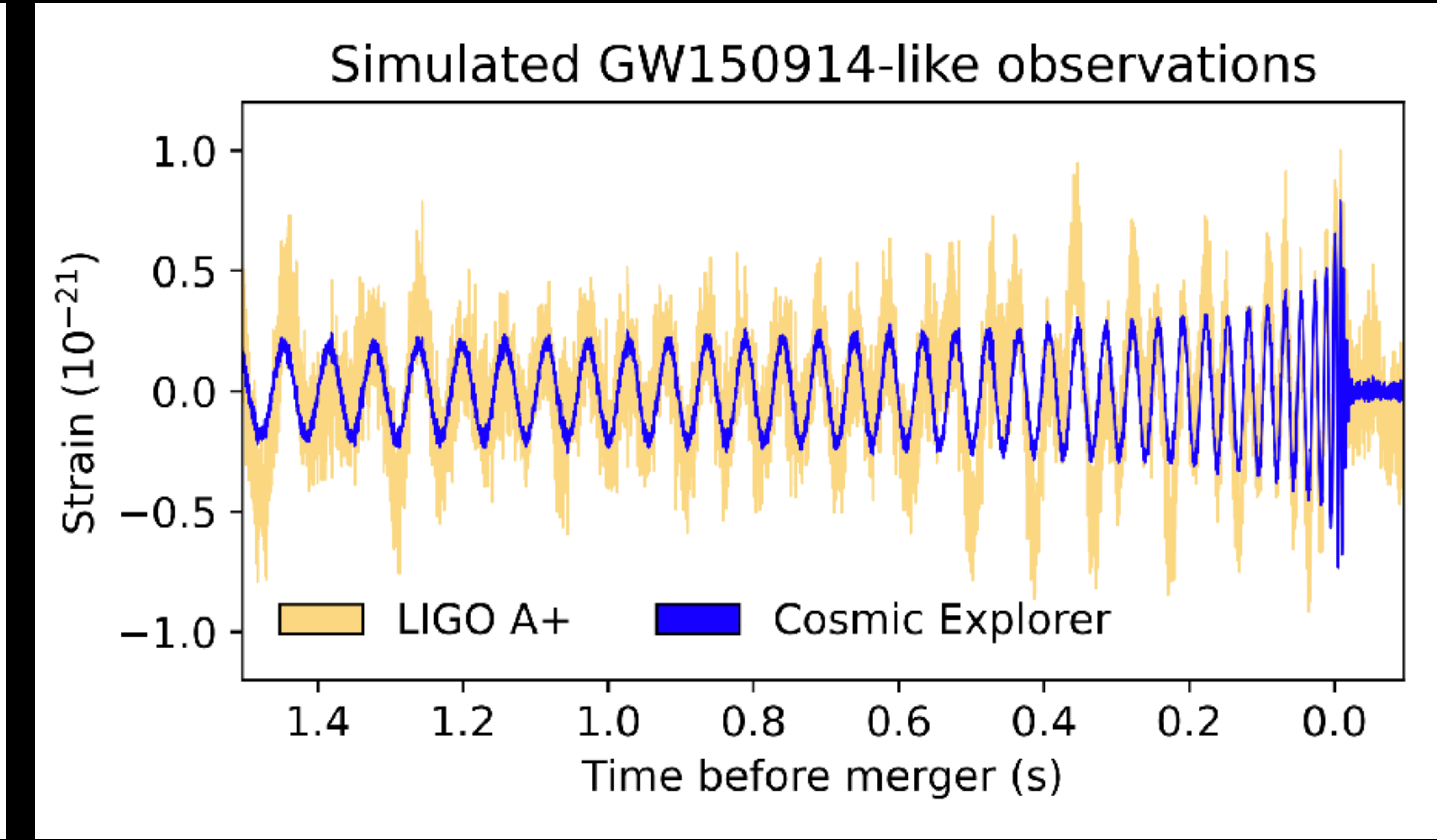


LIGO-Virgo, PRL 116.061102 (2016)

Along with cosmological reach: large SNRs

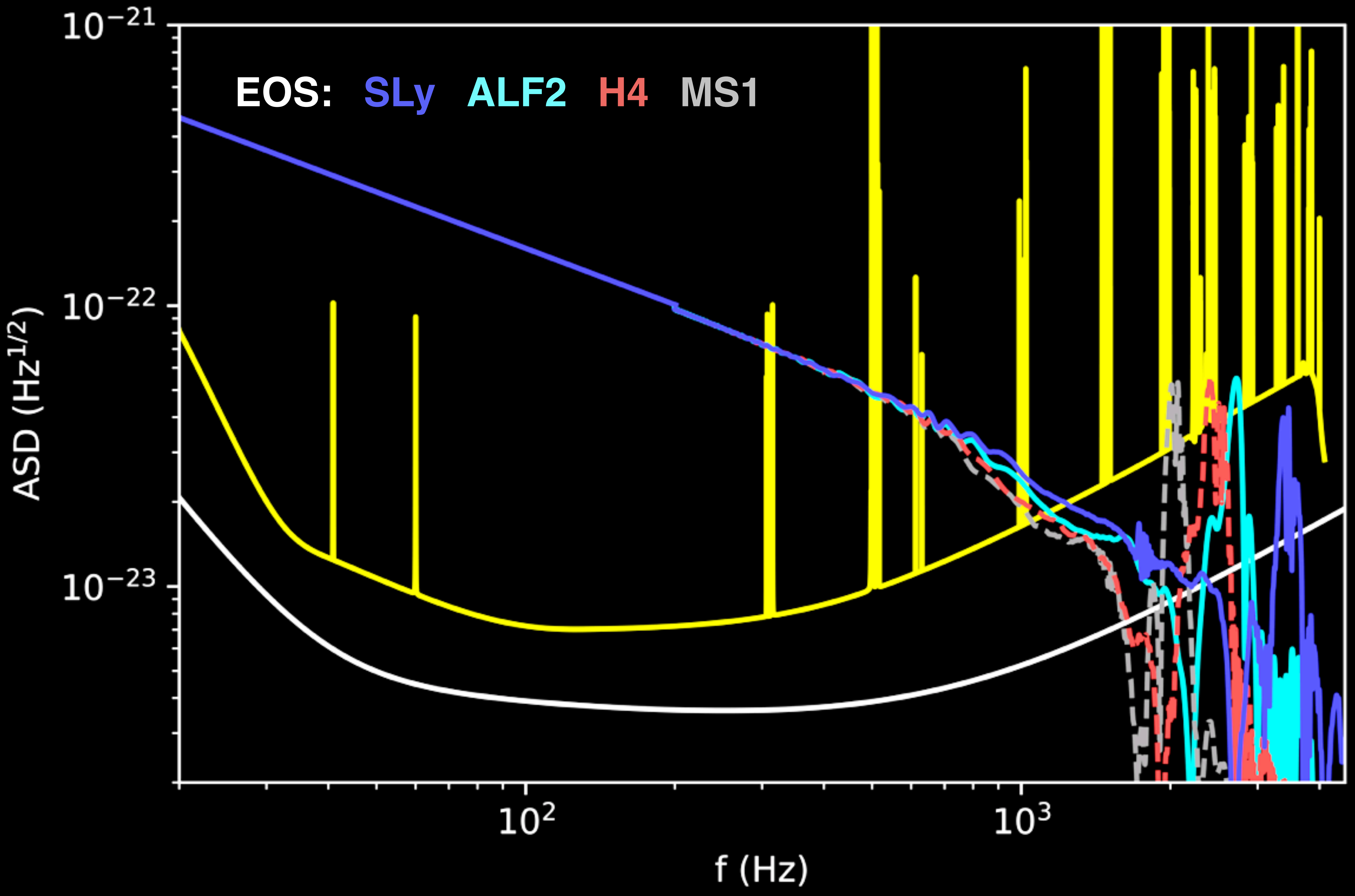


LIGO-Virgo, PRL 116.061102 (2016)



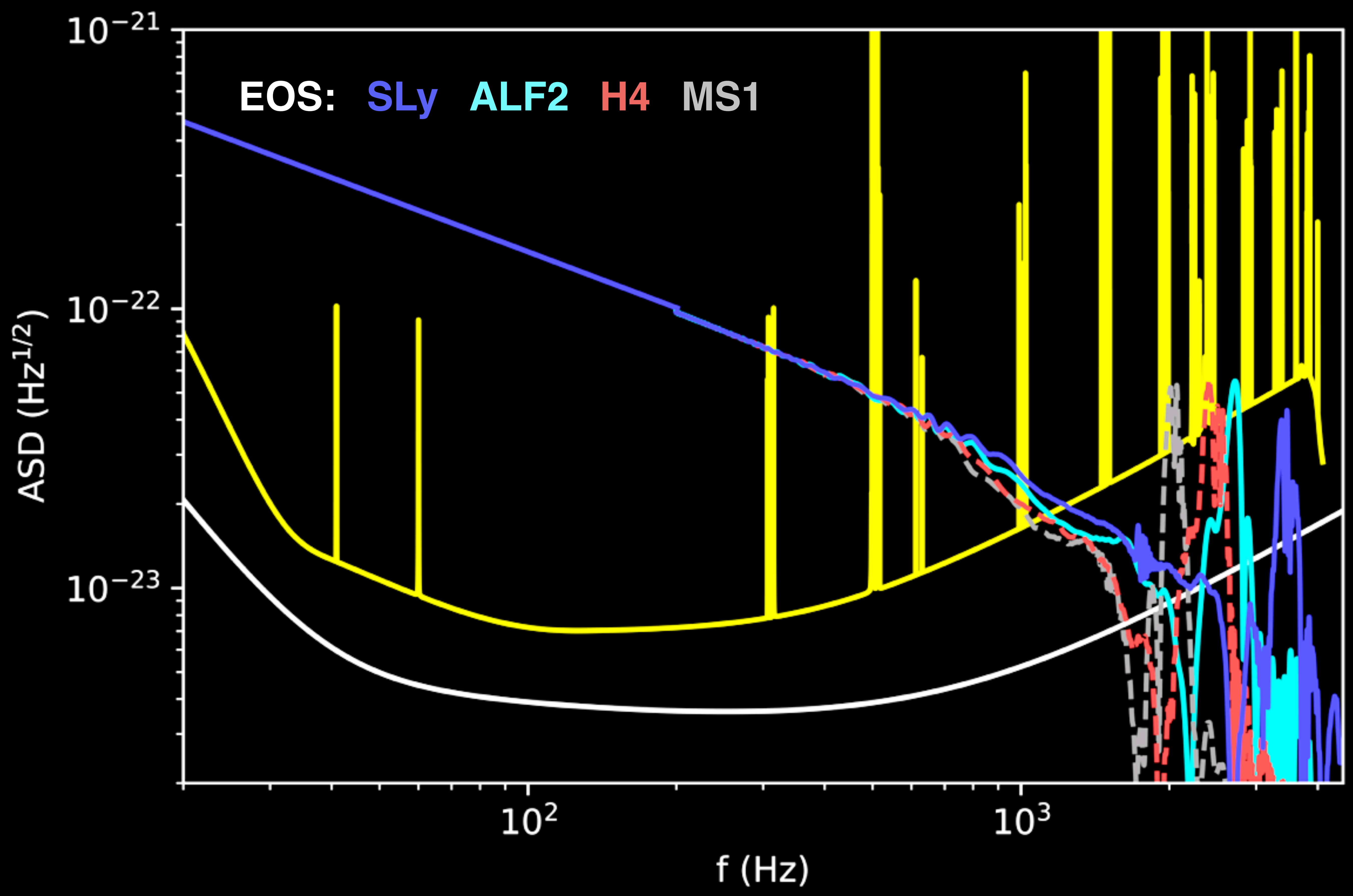
CE Horizon Study, CE–P2100003–v7 (2021)

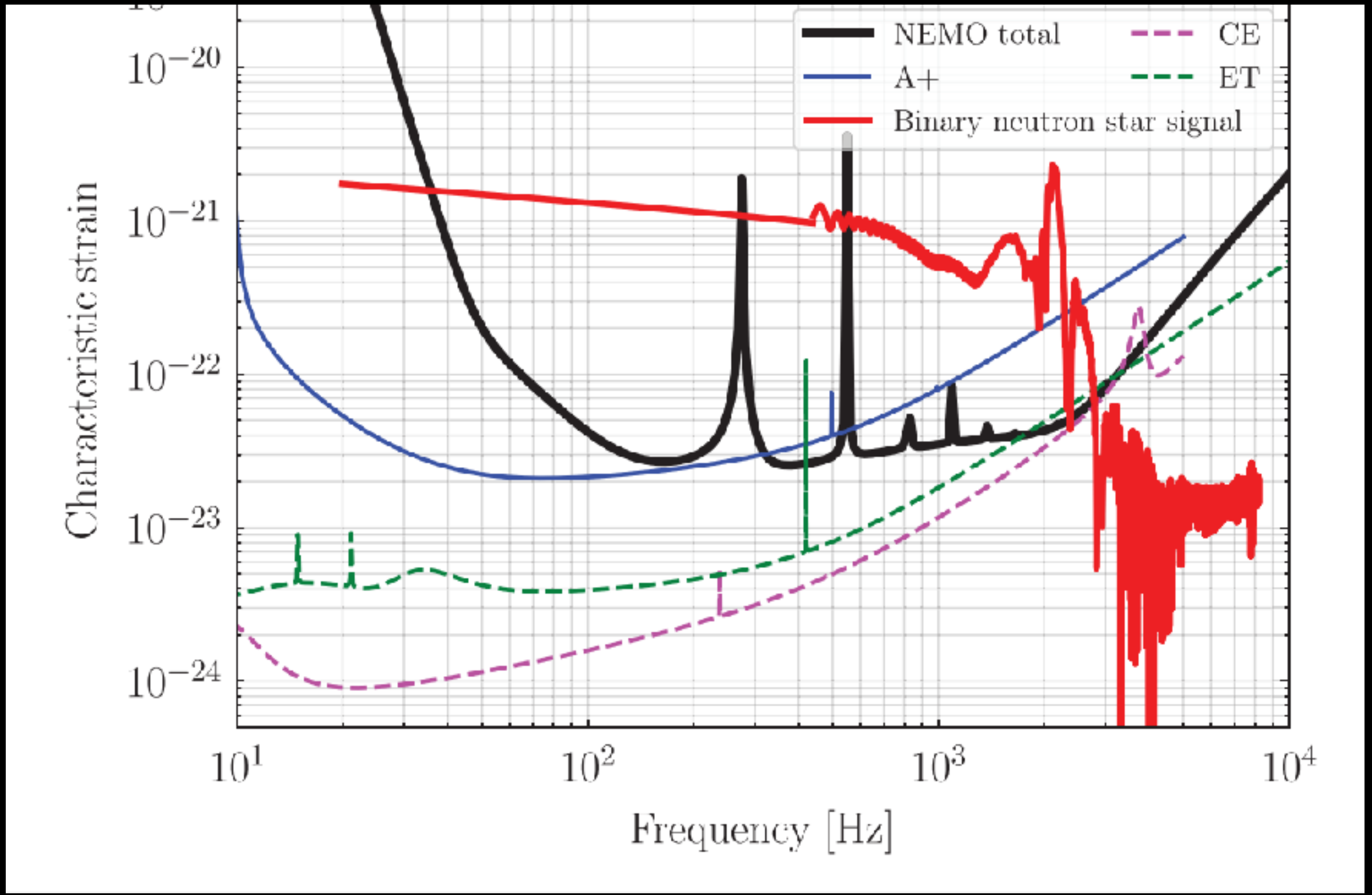
Broadband observations with next generation detectors



Jocelyn Read

Broadband observations with next generation detectors





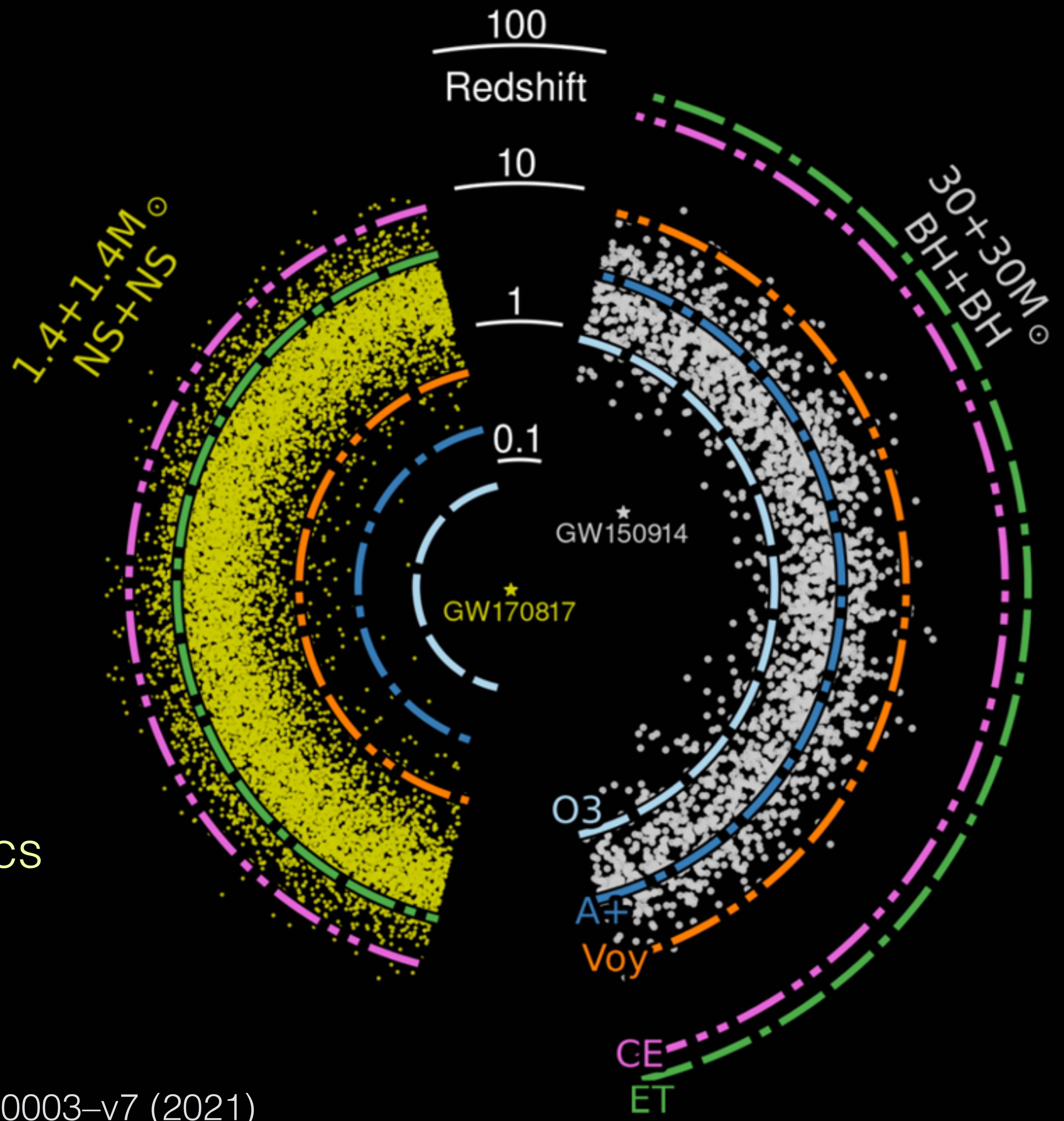
Jocelyn Read

NEMO design paper, AAAP, Ackley et al, 2020

~300,000 BNS mergers!

1 merger every 100 seconds!

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



~100,000 BBH mergers!

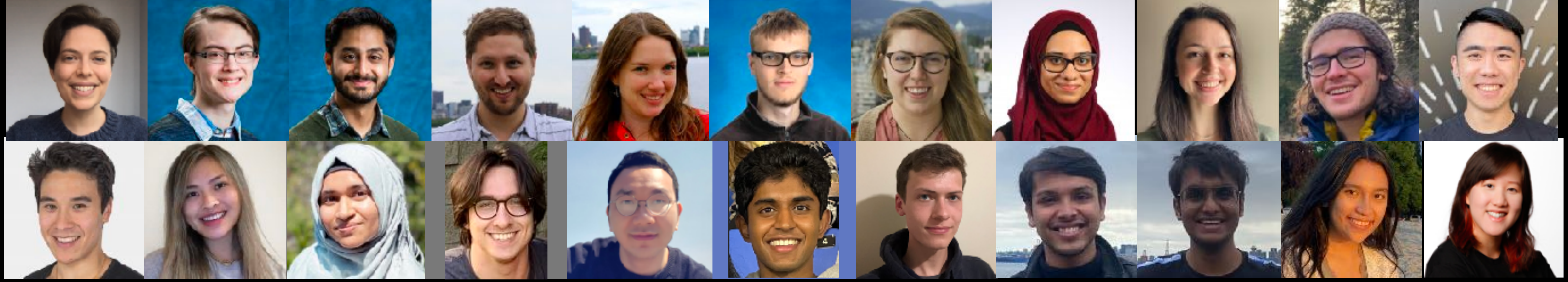
1 merger every 5 minutes!

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

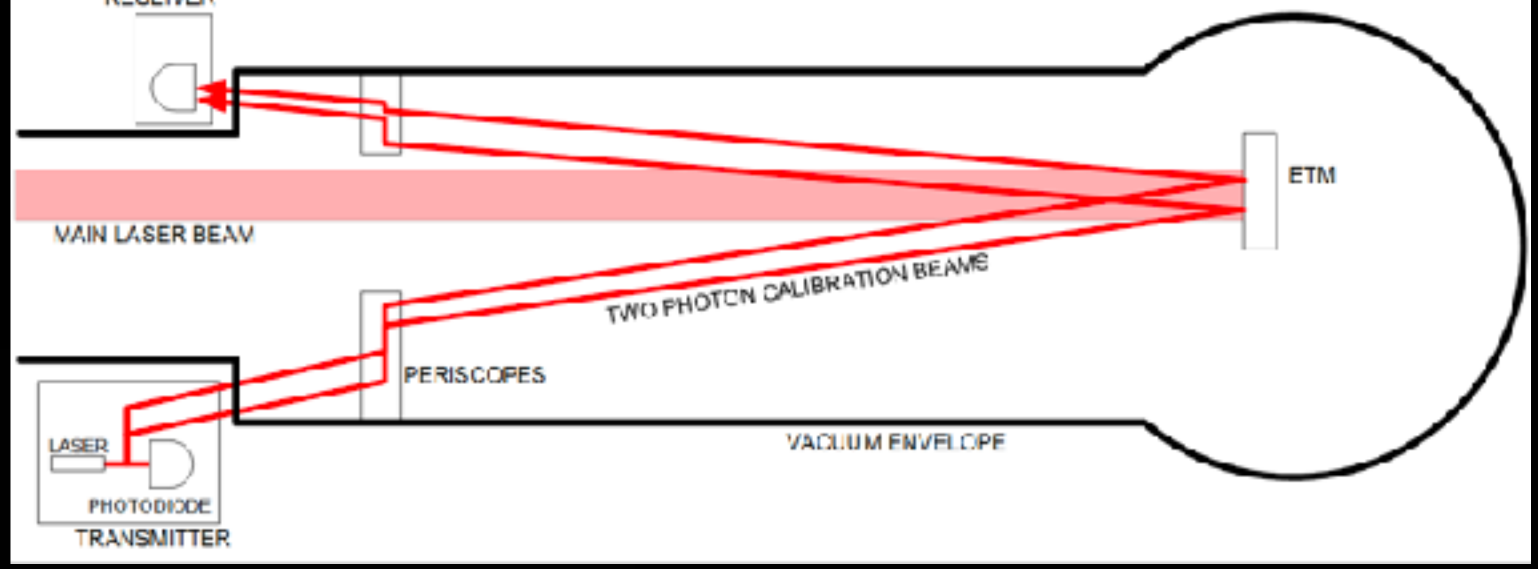
Hall and Evans, 2019

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

The UBC GW astrophysics group

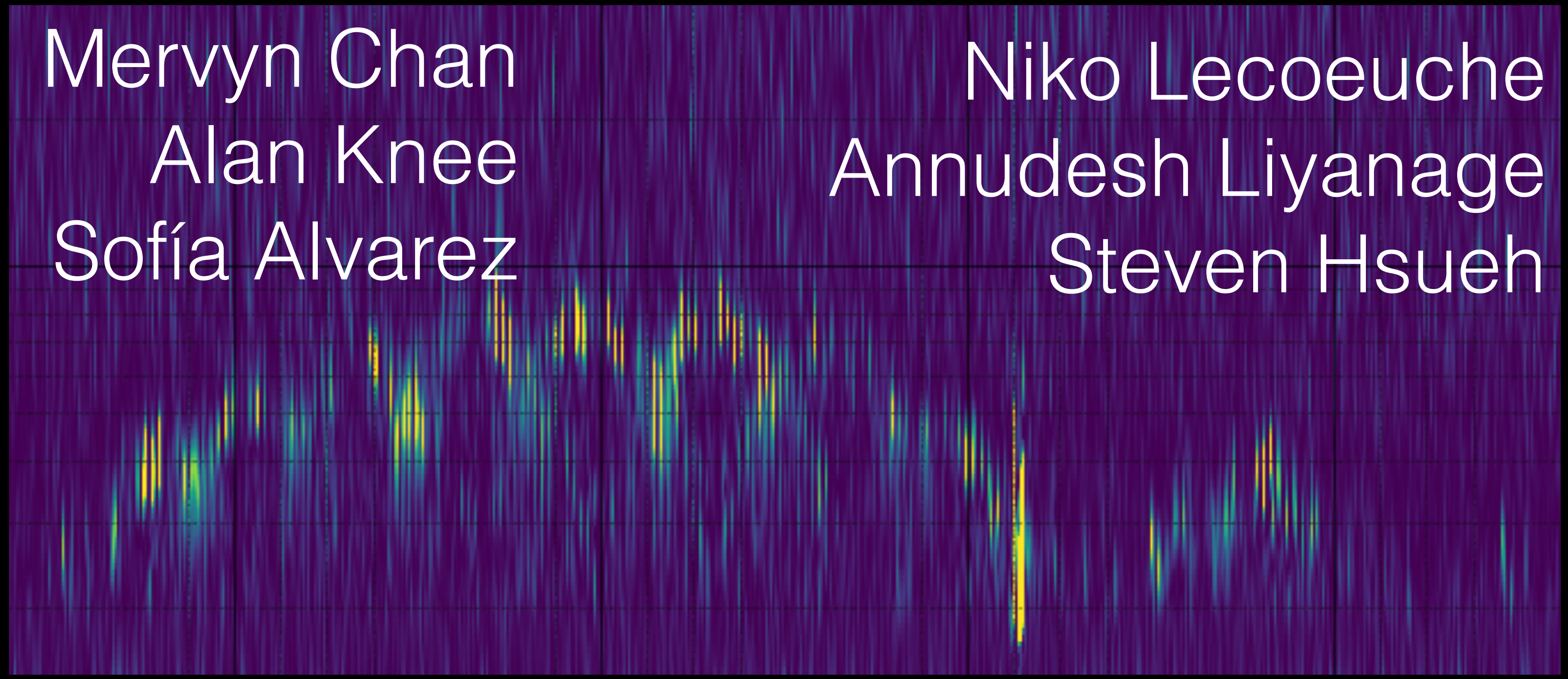


Evan Goetz



Mervyn Chan
Alan Knee
Sofía Alvarez

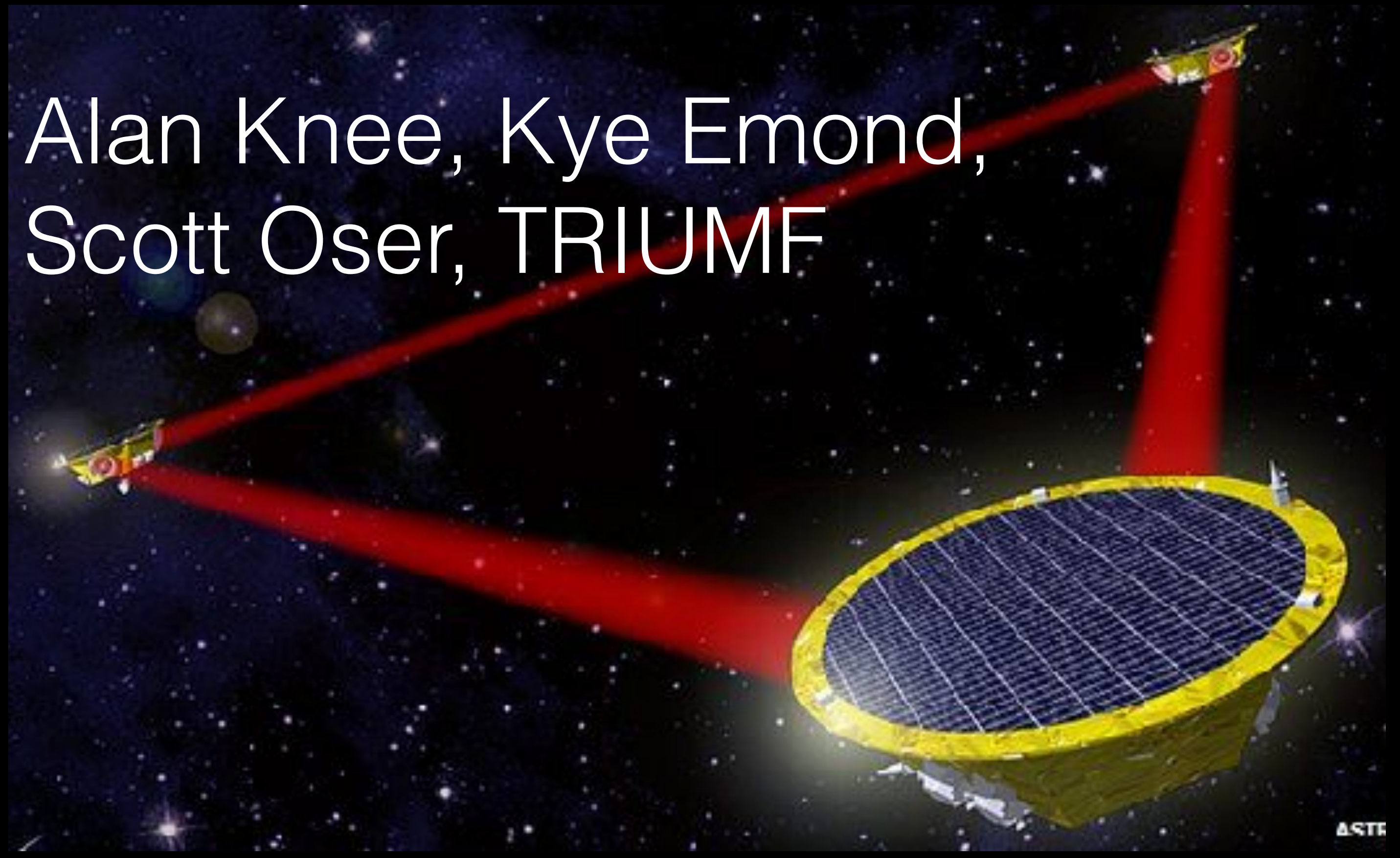
Niko Lecoeuche
Annudesh Liyanage
Steven Hsueh



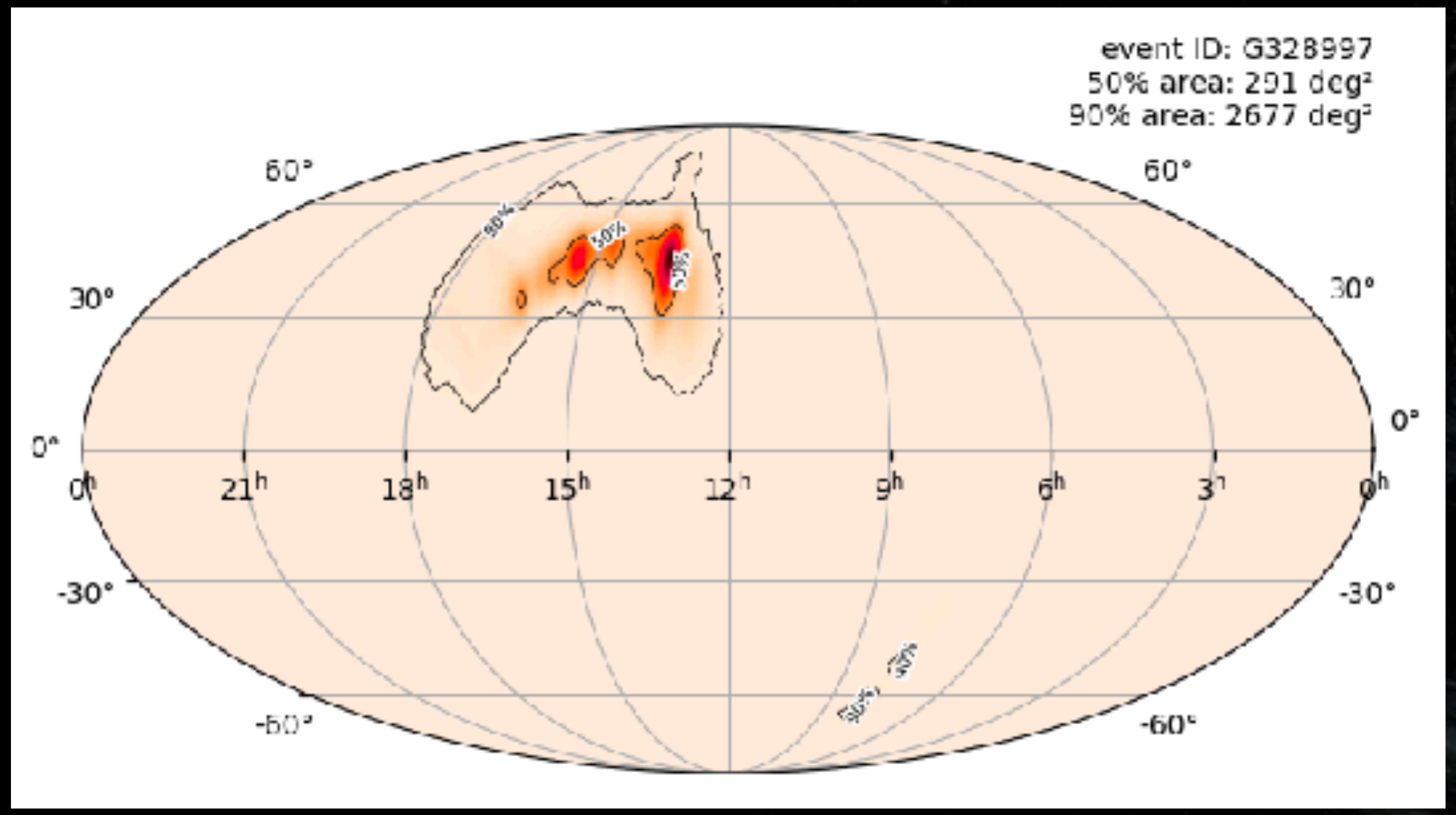
Evan Goetz, Alan Knee,
Neev Shah, Kat Nell

Evan Goetz
Helen Du
Alan Knee

Alan Knee, Kye Emond,
Scott Oser, TRIUMF



Mervyn Chan, Miriam Cabero



Alan Knee
Heather Fong
Neev Shah
Vaibhav Garg