Status of LIGO

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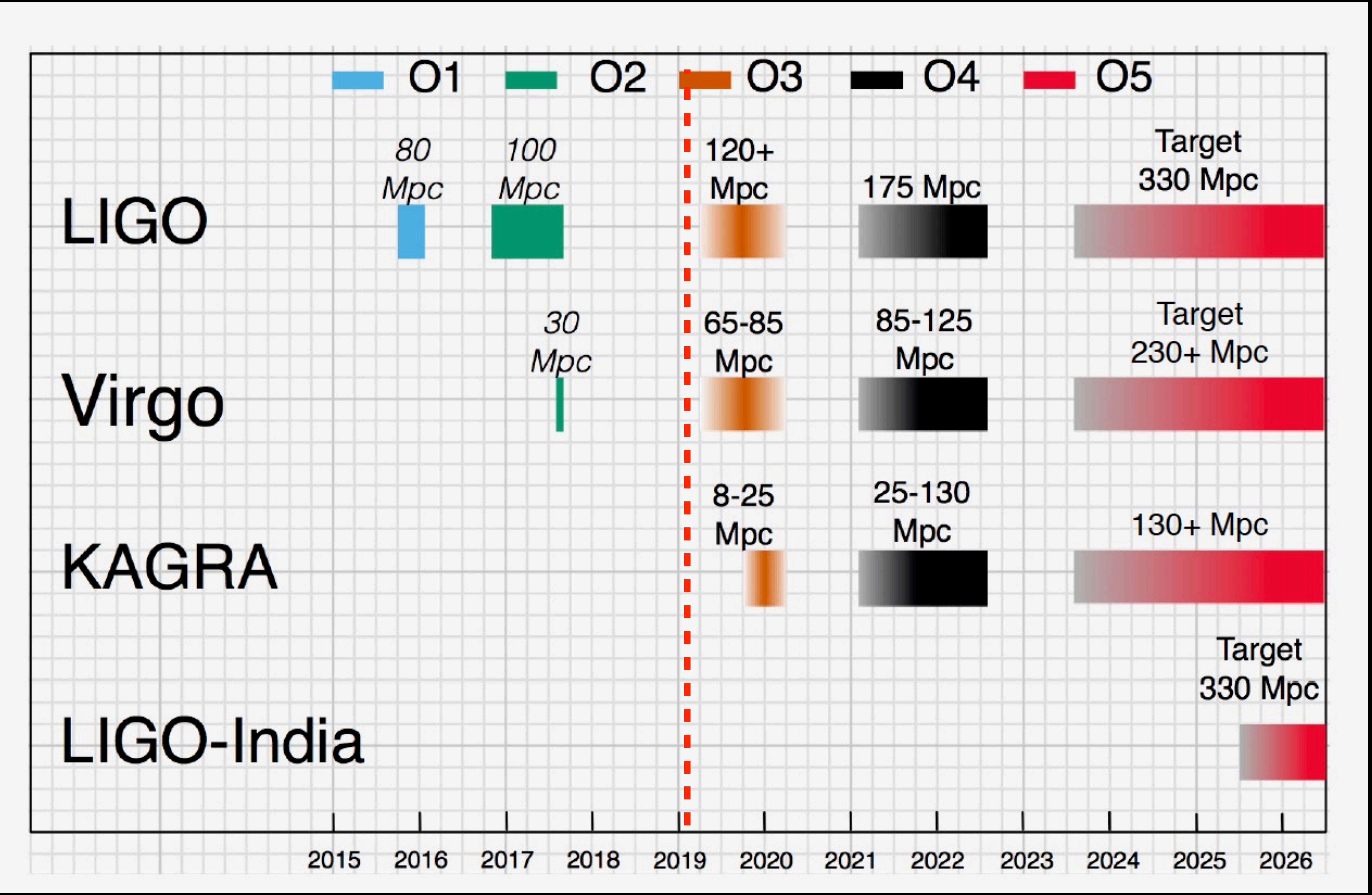
Deputy Spokesperson, LIGO Scientific Collaboration
G1900215

“Colliding Neutron Stars”
NSF/LIGO/Sonoma State University/A. Simonnet

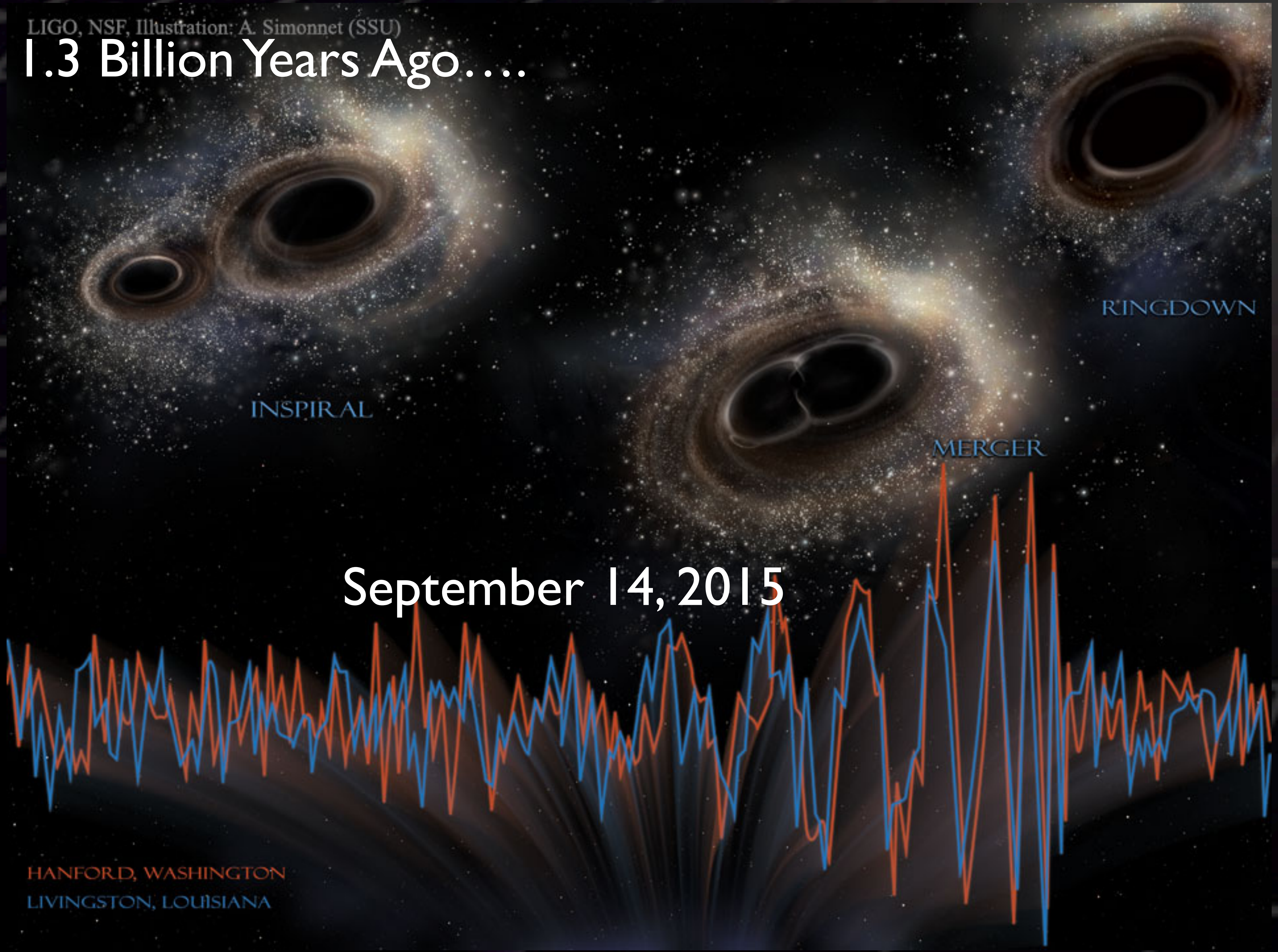
The 5th Kagra International Workshop - Perugia, February 14-15, 2019

Observing Scenarios

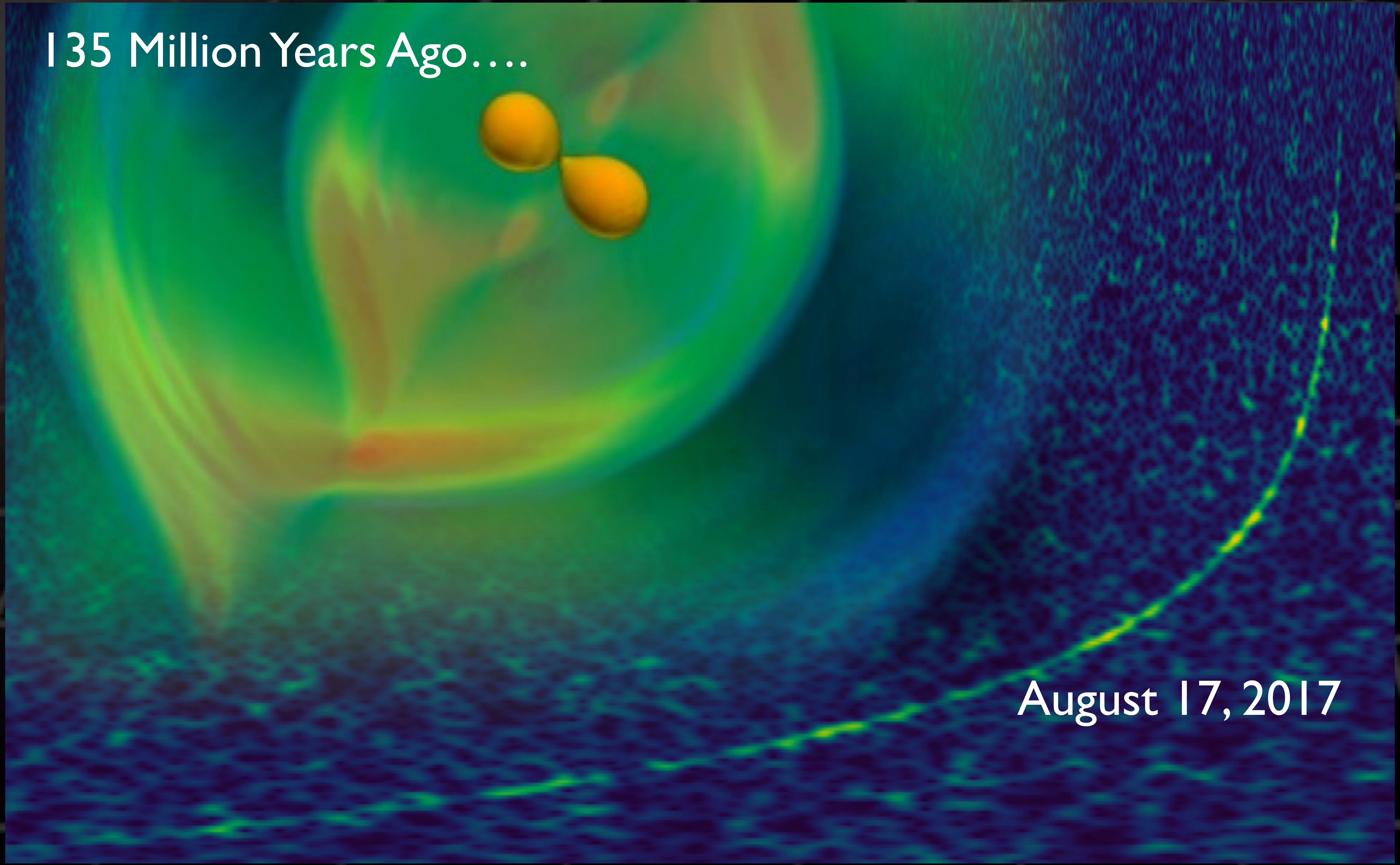


Gravitational Wave astrophysics from O1 and O2

GW150914 and GW170817: Two ground-breaking discoveries that opened a new era in Gravitational Wave Astronomy

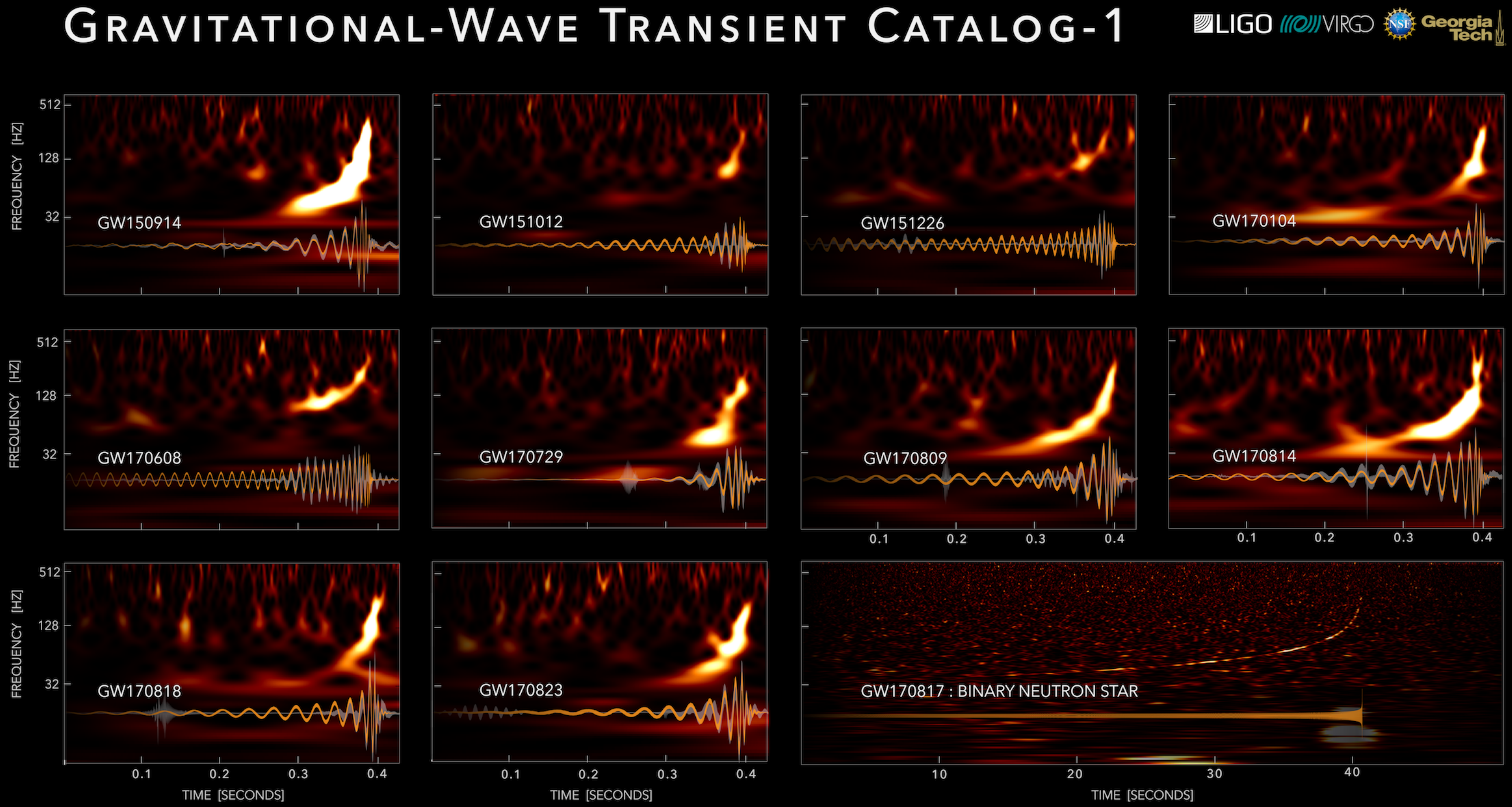


Binary Black Hole Coalescence



Binary Neutron Star Coalescence

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23

WAVELET (UNMODELED) EINSTEIN'S THEORY

S. GHONGE, K. JANI | GEORGIA TECH

Black Hole Masses

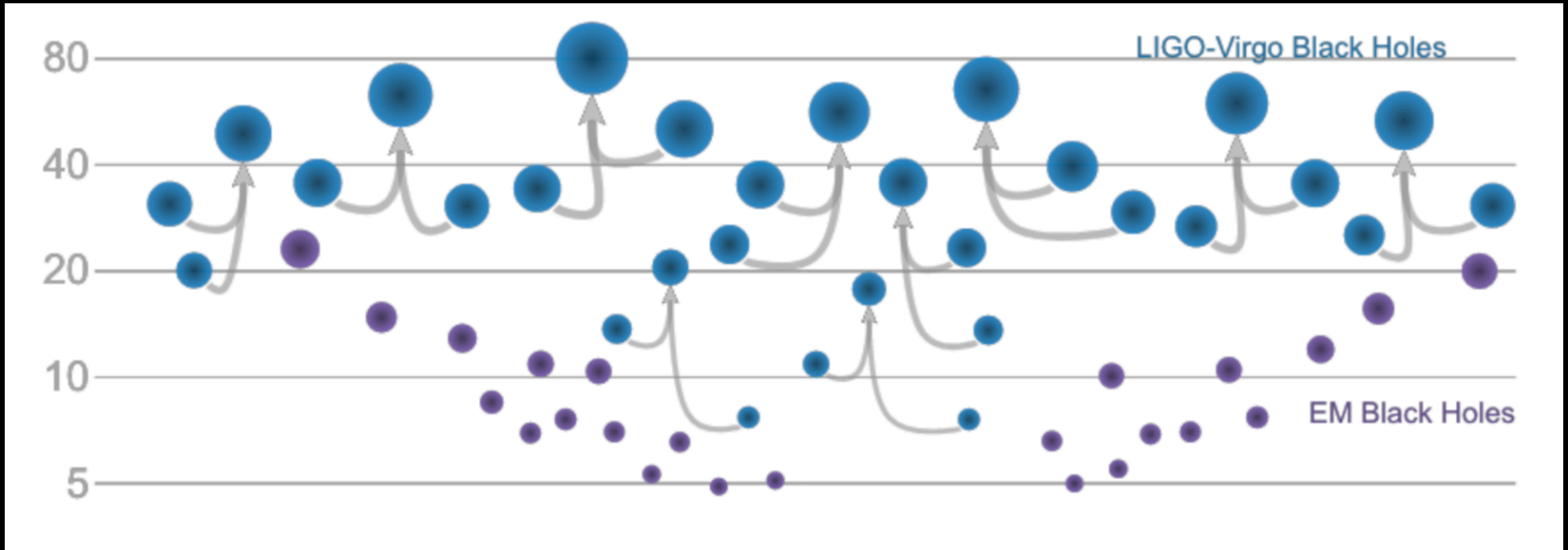
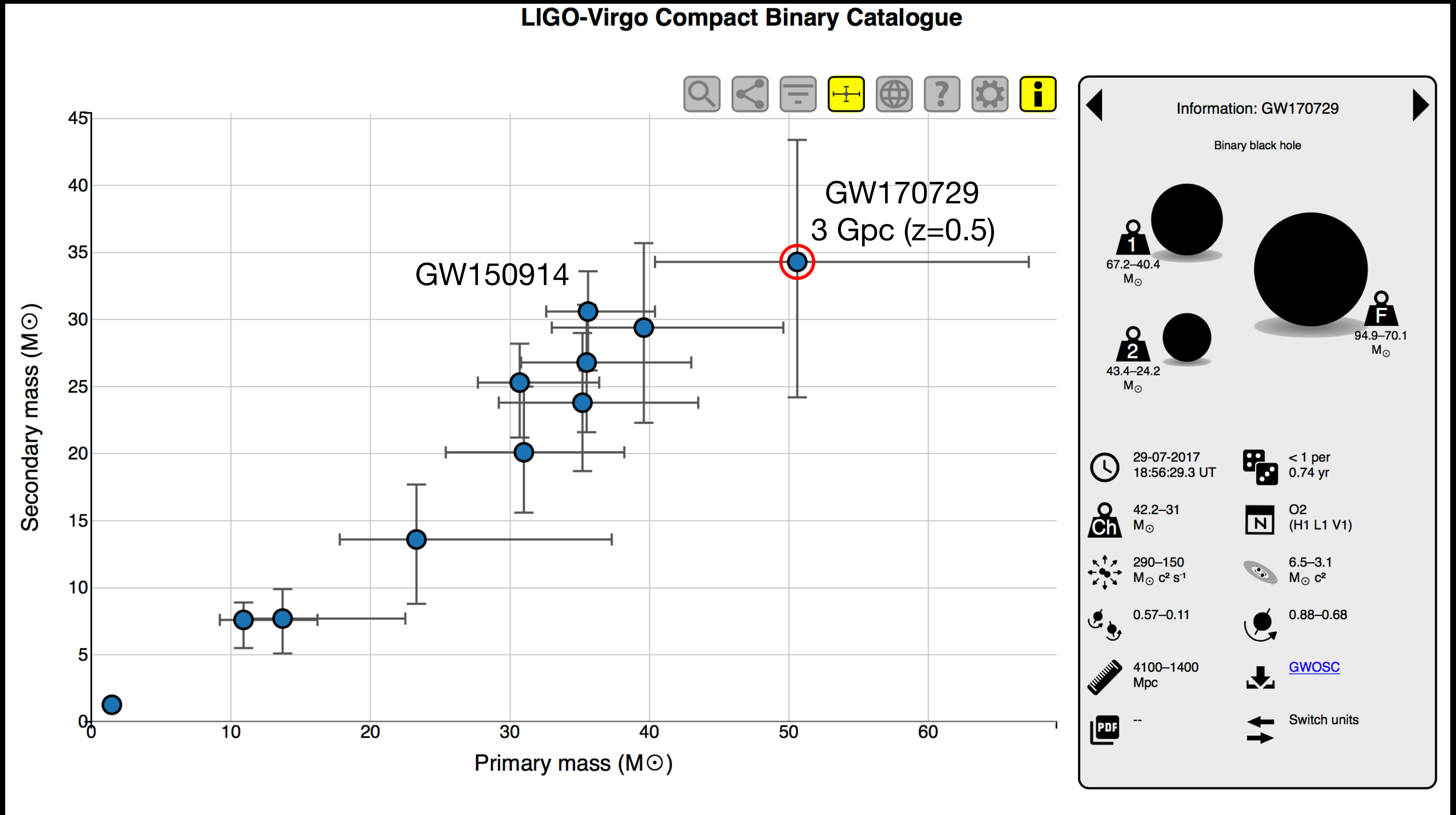


Figure 1: Masses of known black holes, both those detected by LIGO/Virgo via GWs (blue) and those indirectly observed through electromagnetic observations of X-ray binary systems (purple). The masses of the merger products are also shown. Image credit: LIGO-Virgo / Frank Elavsky / Northwestern.



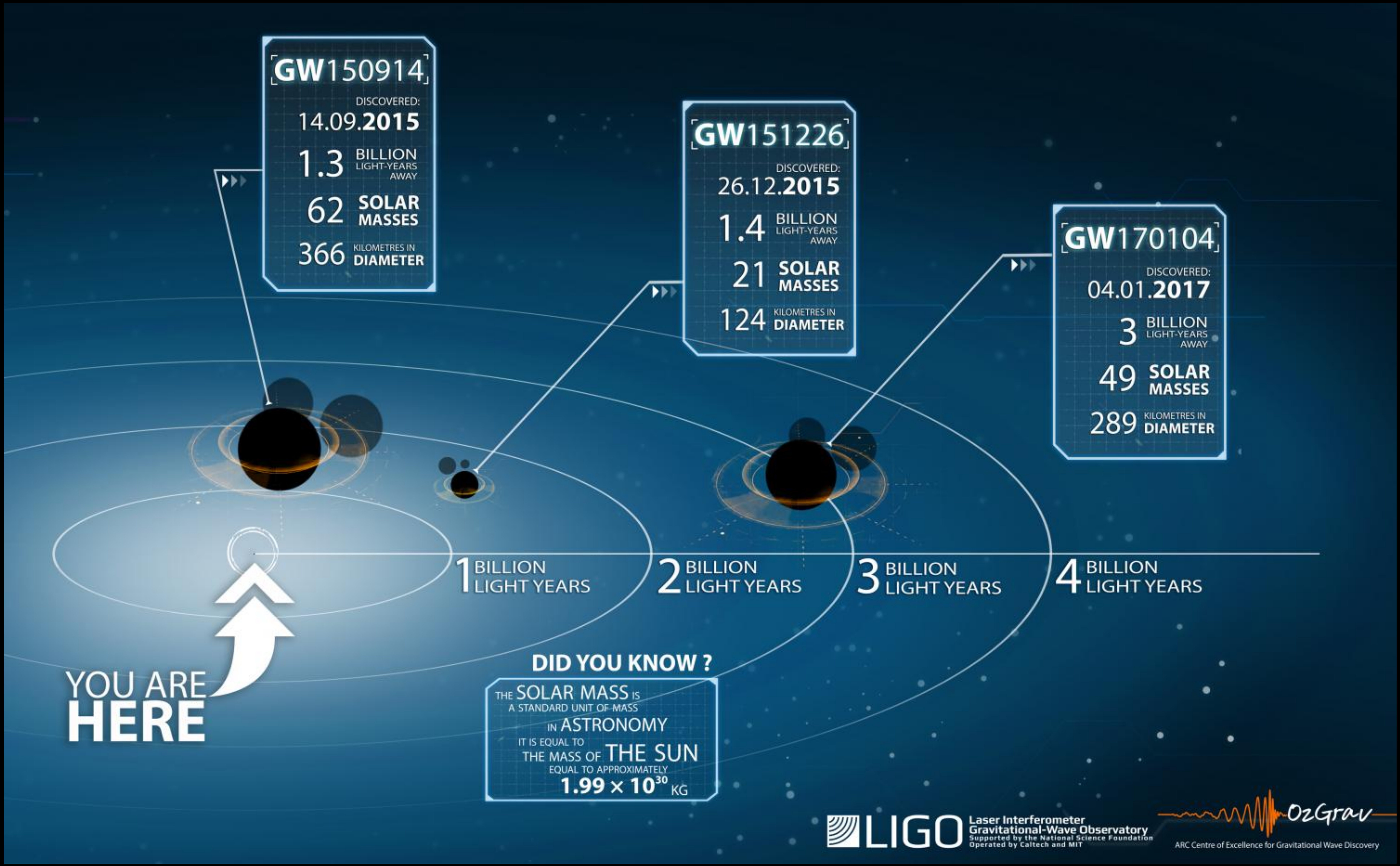
Most robust evidence for existence of ‘heavy’ stellar mass BHs (> 20 $M_{\odot}$)

BBH most likely formed in a low-metallicity environment: < ½ $Z_{\odot}$

Merger rate of stellar mass BBHs:
10 — 100/Gpc³/yr

Bayesian inference disfavors BH’s with mass larger than 50 Msol, consistent with supernova modeling (pulsational-pair-instability SN)

https://gravity.astro.cf.ac.uk/plotgw



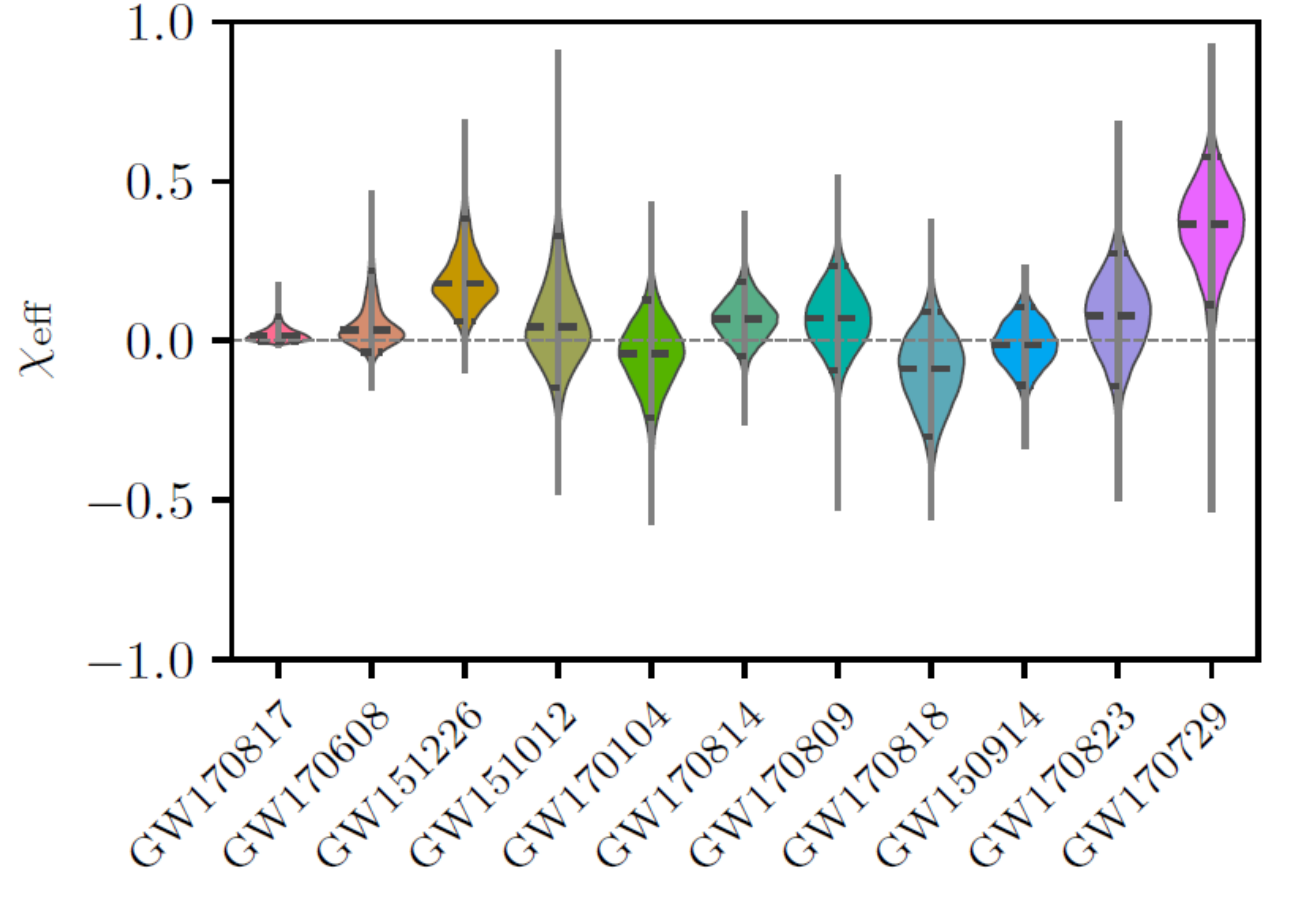
Black Hole Distances

- six sources out of 10 at >1 Gpc
- Most distant (and heaviest) is GW170729, at a distance of 2.76 Gpc, or about 9 billion light-years
- Closest is GW170608 is 0.32 Gpc (or about 1 billion light years distant).

Black Hole Spins

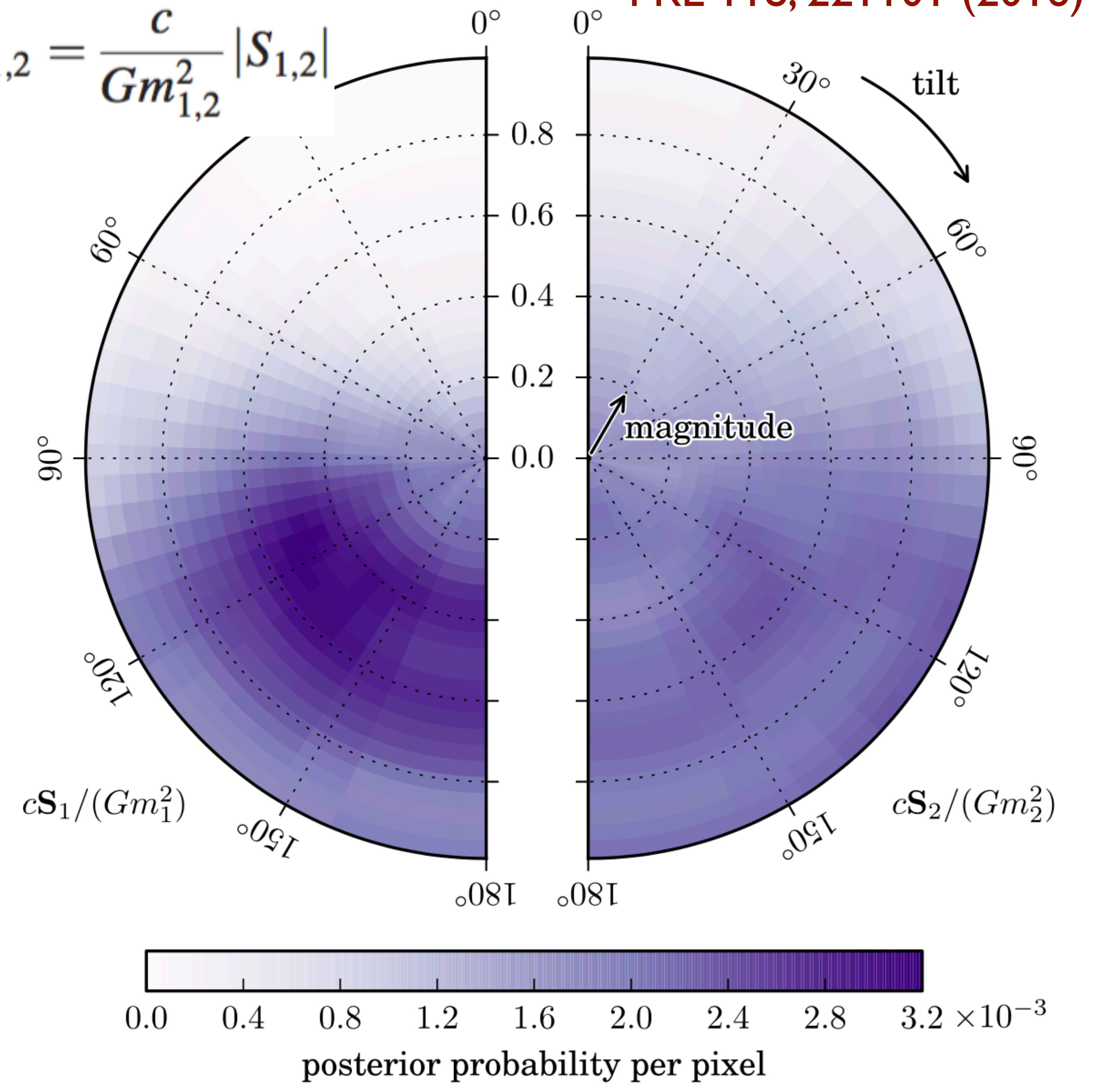
$$\chi_{\rm eff} = \frac{c}{G}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\hat{\boldsymbol{L}}}{M}$$

arXiv: 1811.12907



PRL 118, 221101 (2016)

$$a_{1,2} = \frac{c}{Gm_{1,2}^2}|S_{1,2}|$$



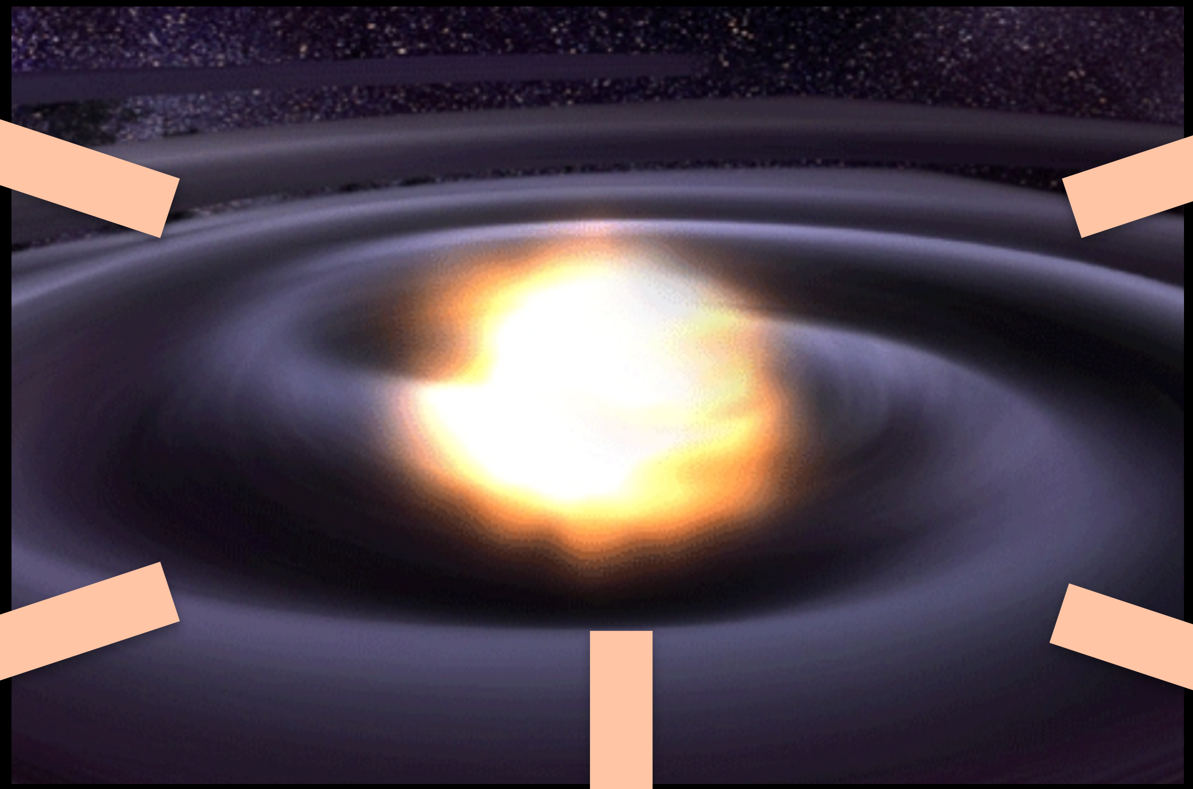
GW170104: first evidence for spin-orbit misalignment

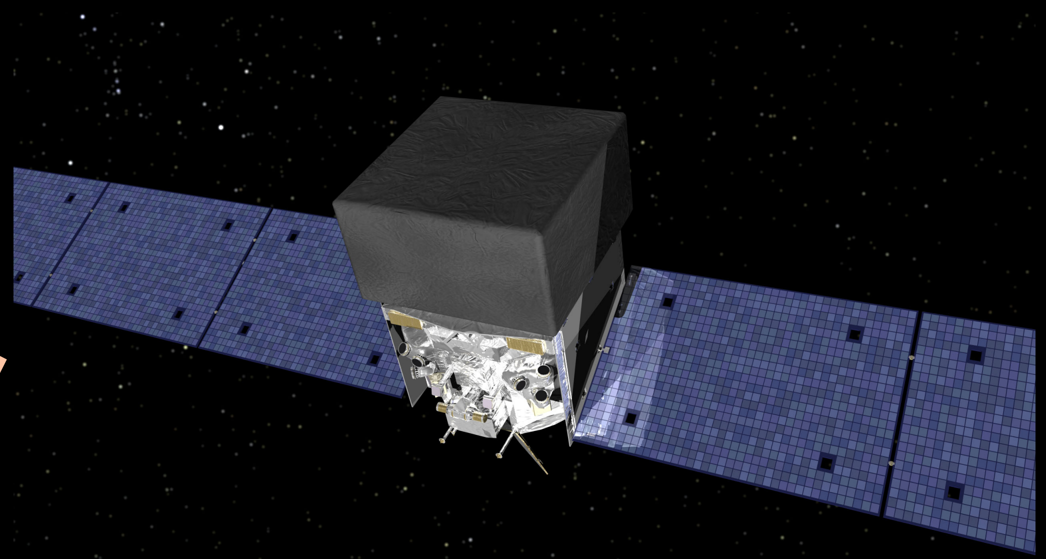
Beginning to inform formation models:
isolated binary evolution vs dynamical formation in dense clusters

Multi-messenger Astronomy with Gravitational Waves

Gravitational Waves

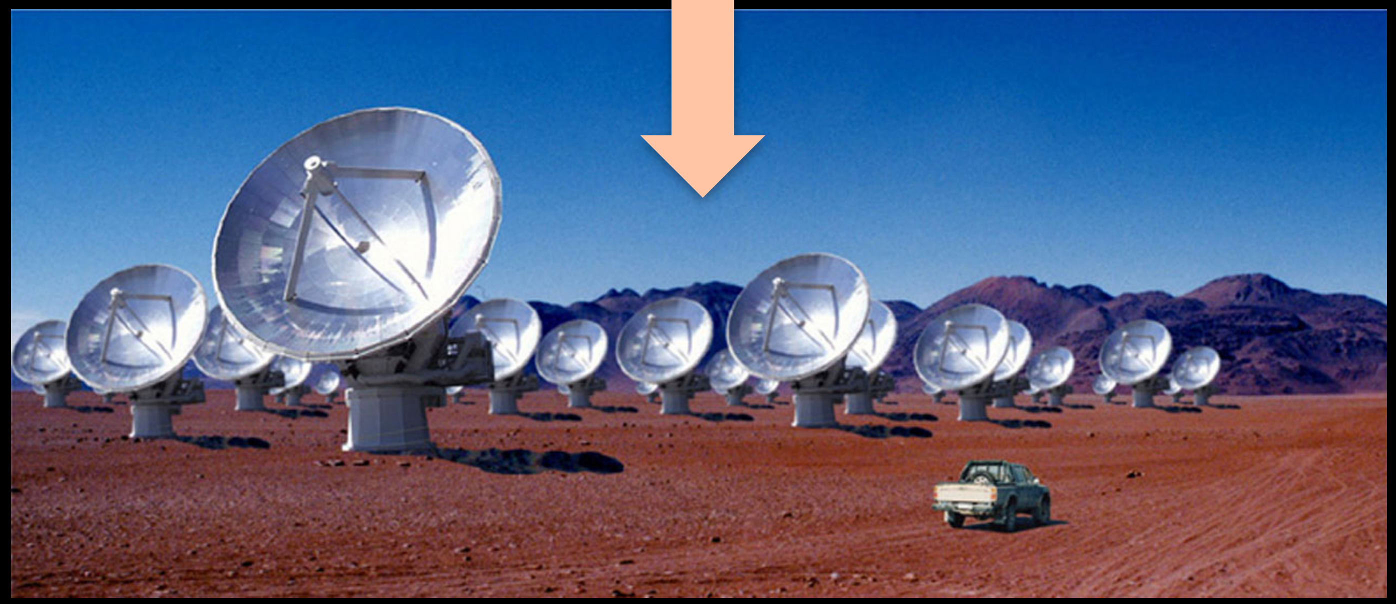
Binary Neutron Star Merger



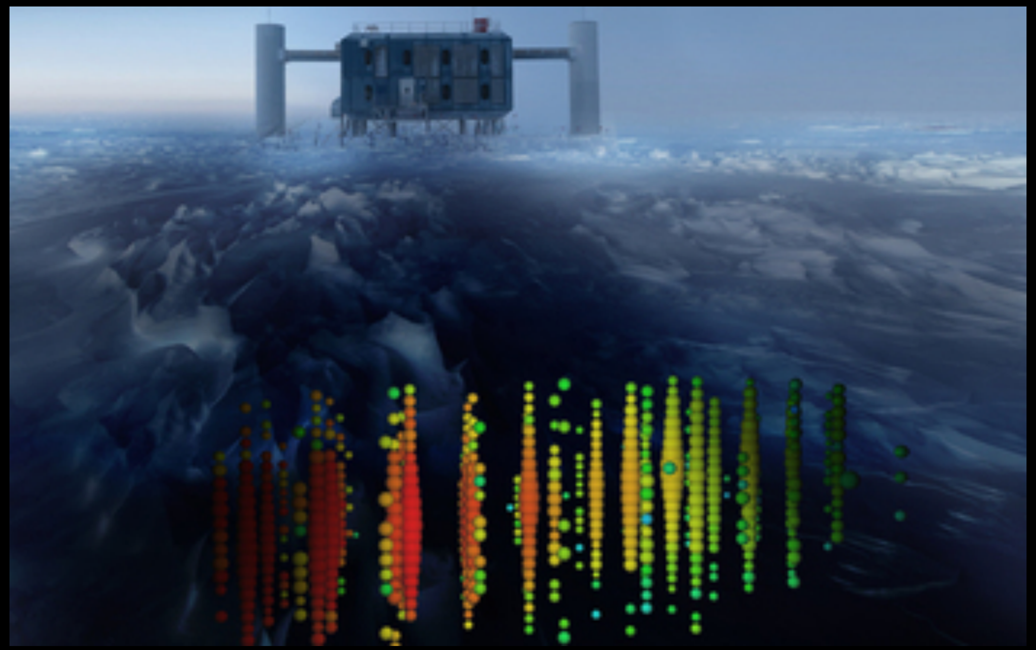


X-rays/Gamma-rays

Visible/Infrared Light



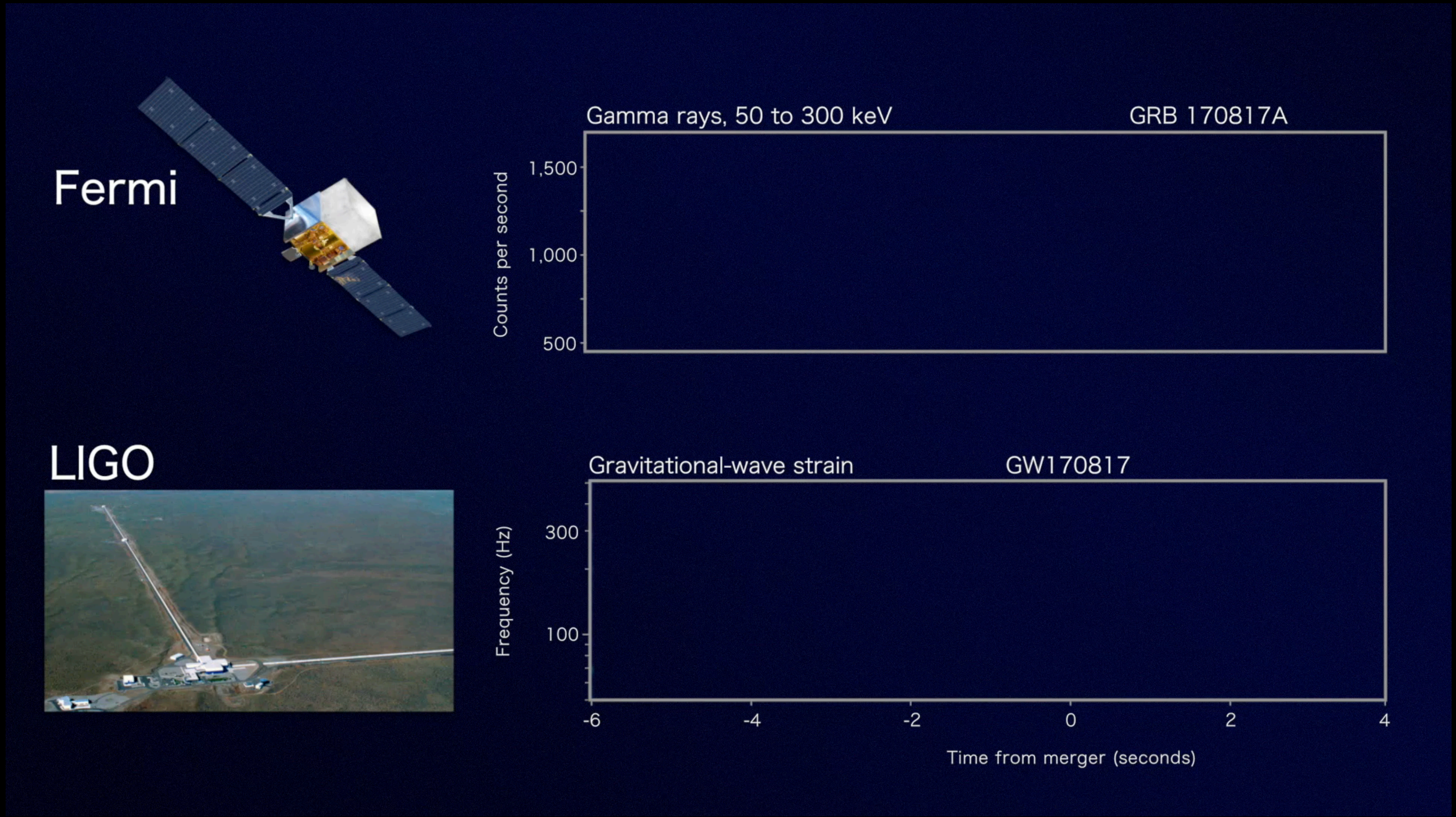
Radio Waves

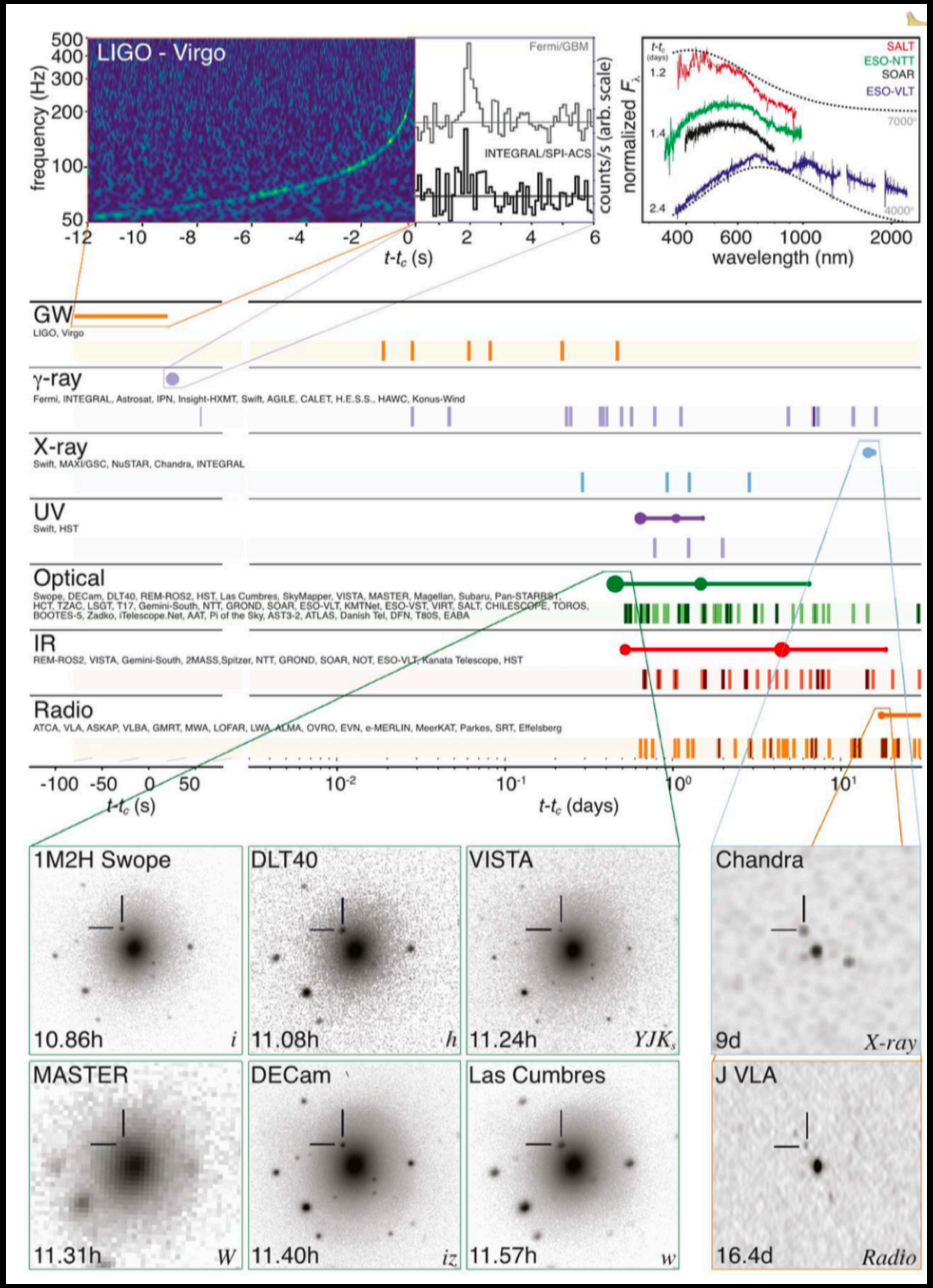


Neutrinos

GW170817 Discovery of a Binary Neutron Star Merger

August 17, 2017 - 12:41:04.4 UTC

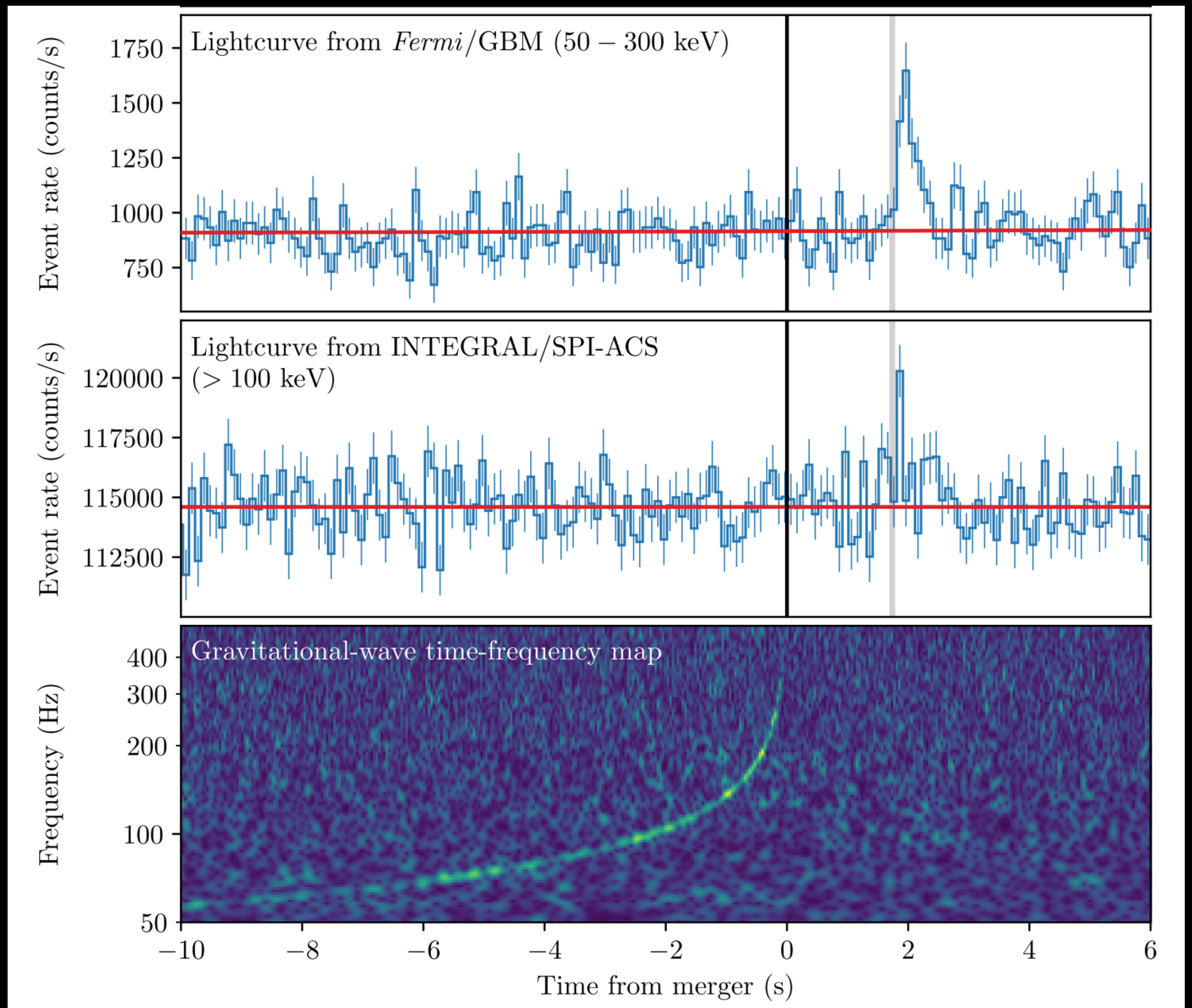




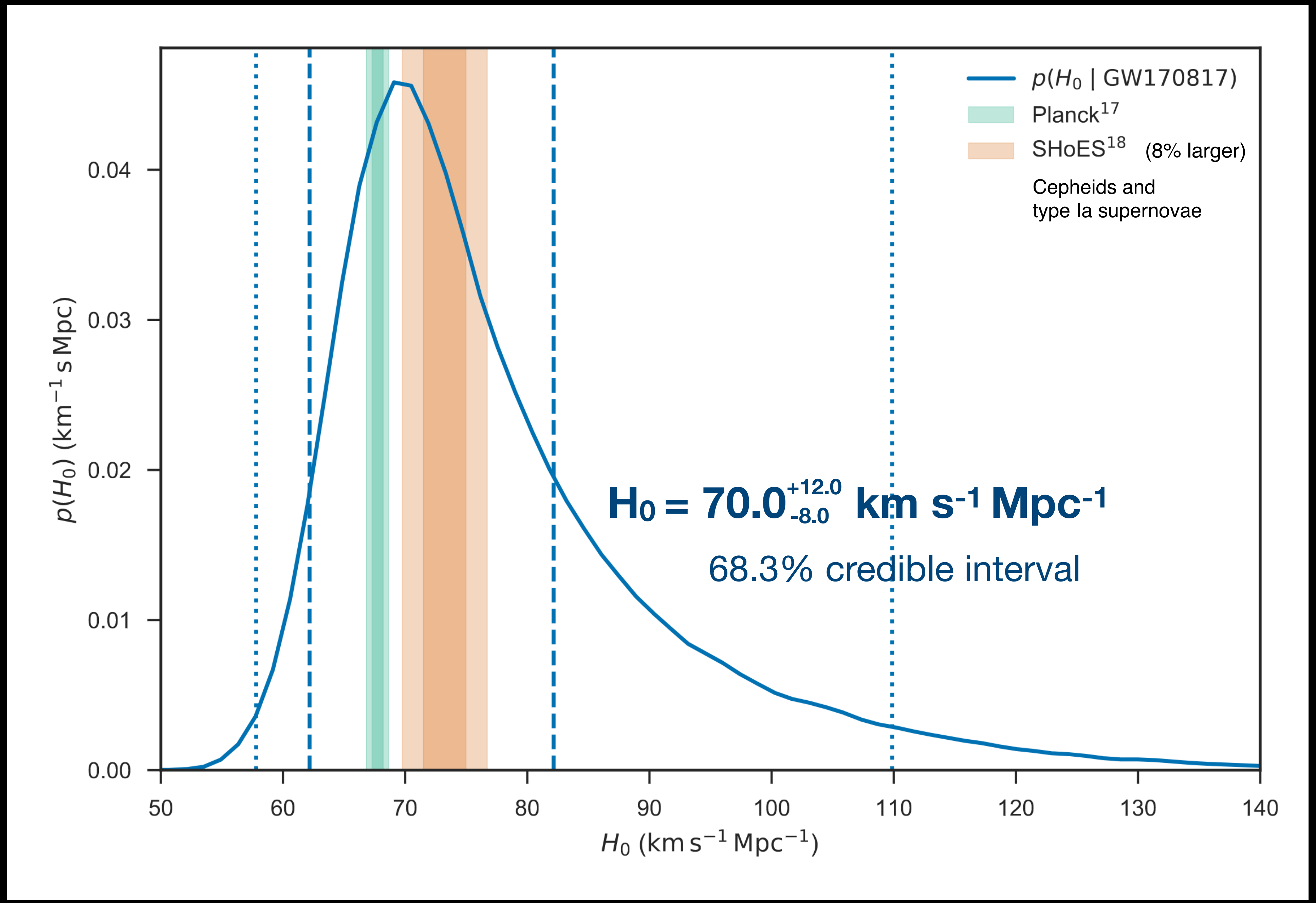
Multi-messenger Observations of a Binary Neutron Star Merger
The Astrophysical Journal Letters, 848:L12, 2017

Credits: LIGO/Fermi

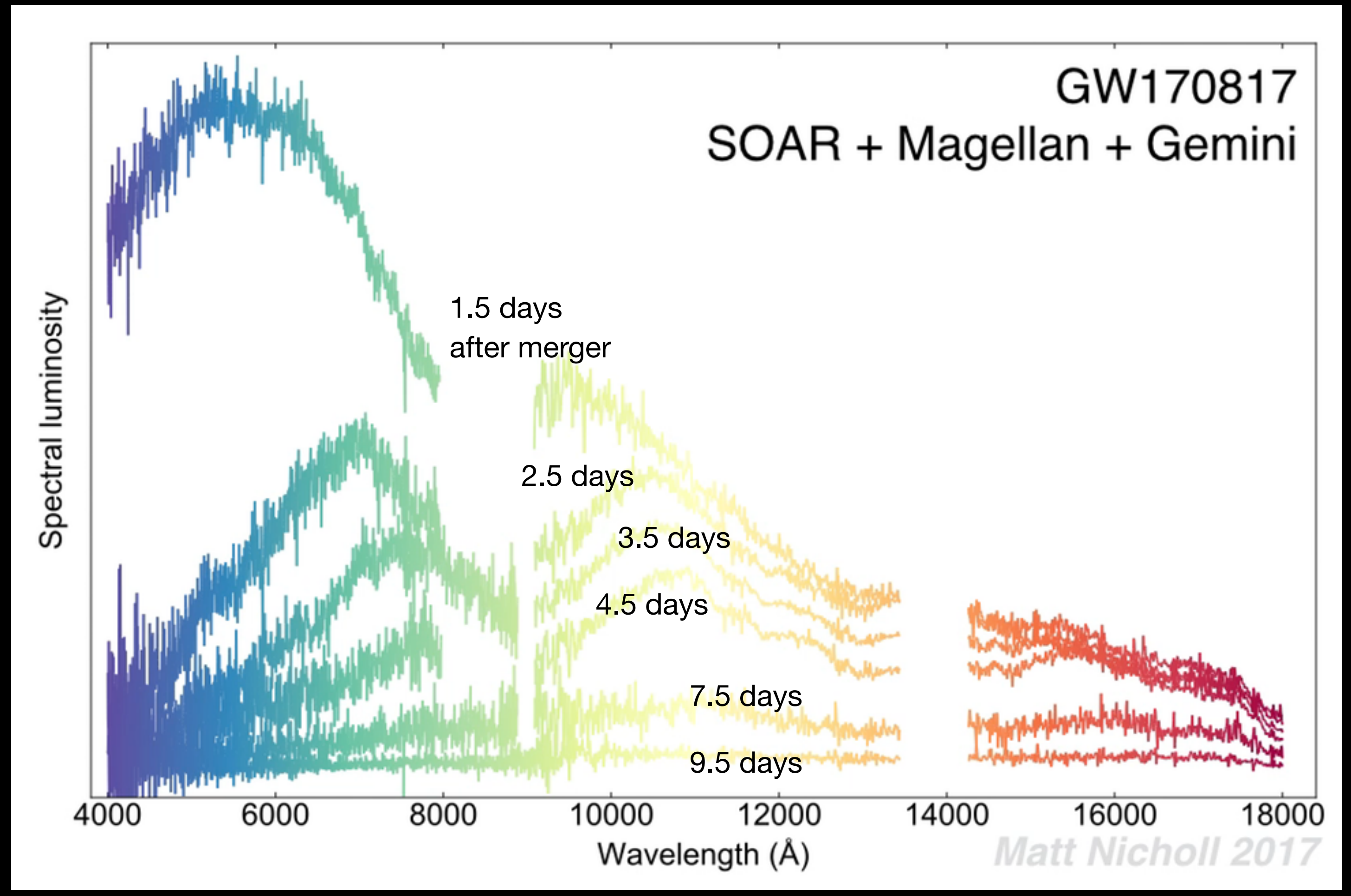
Multi-Messenger Science with GW170817

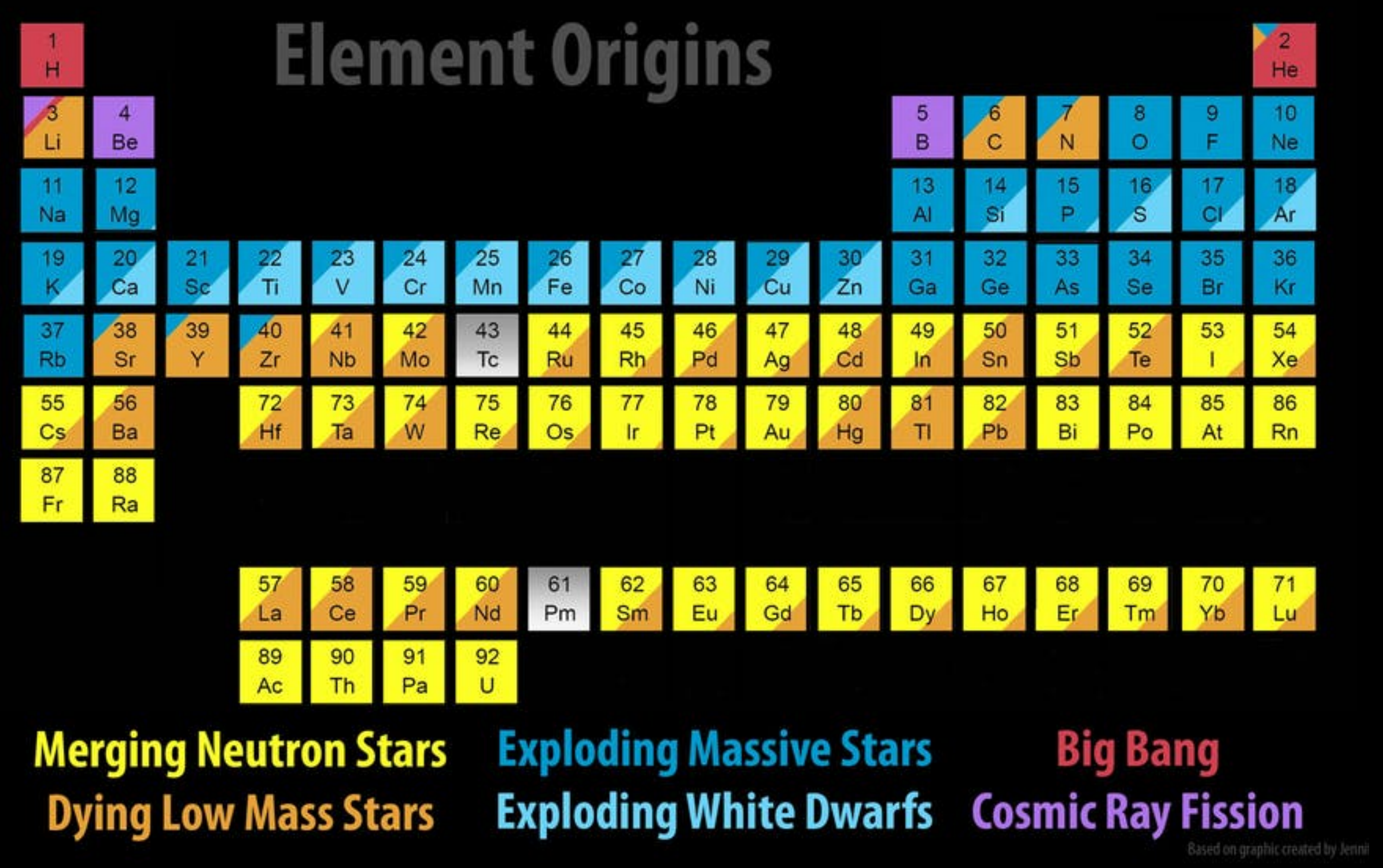


BNS mergers and GRBs



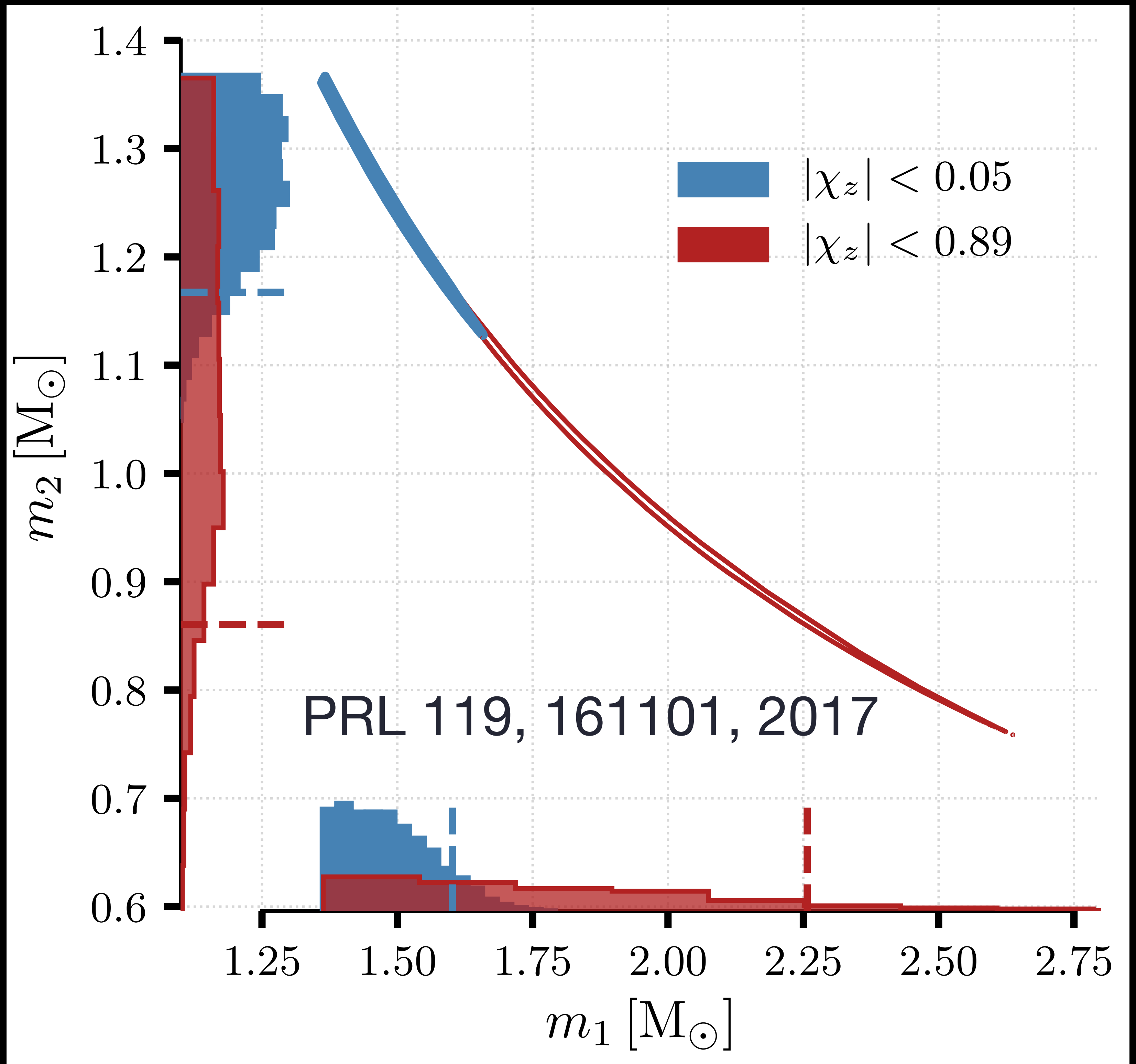
Measuring the Hubble Constant

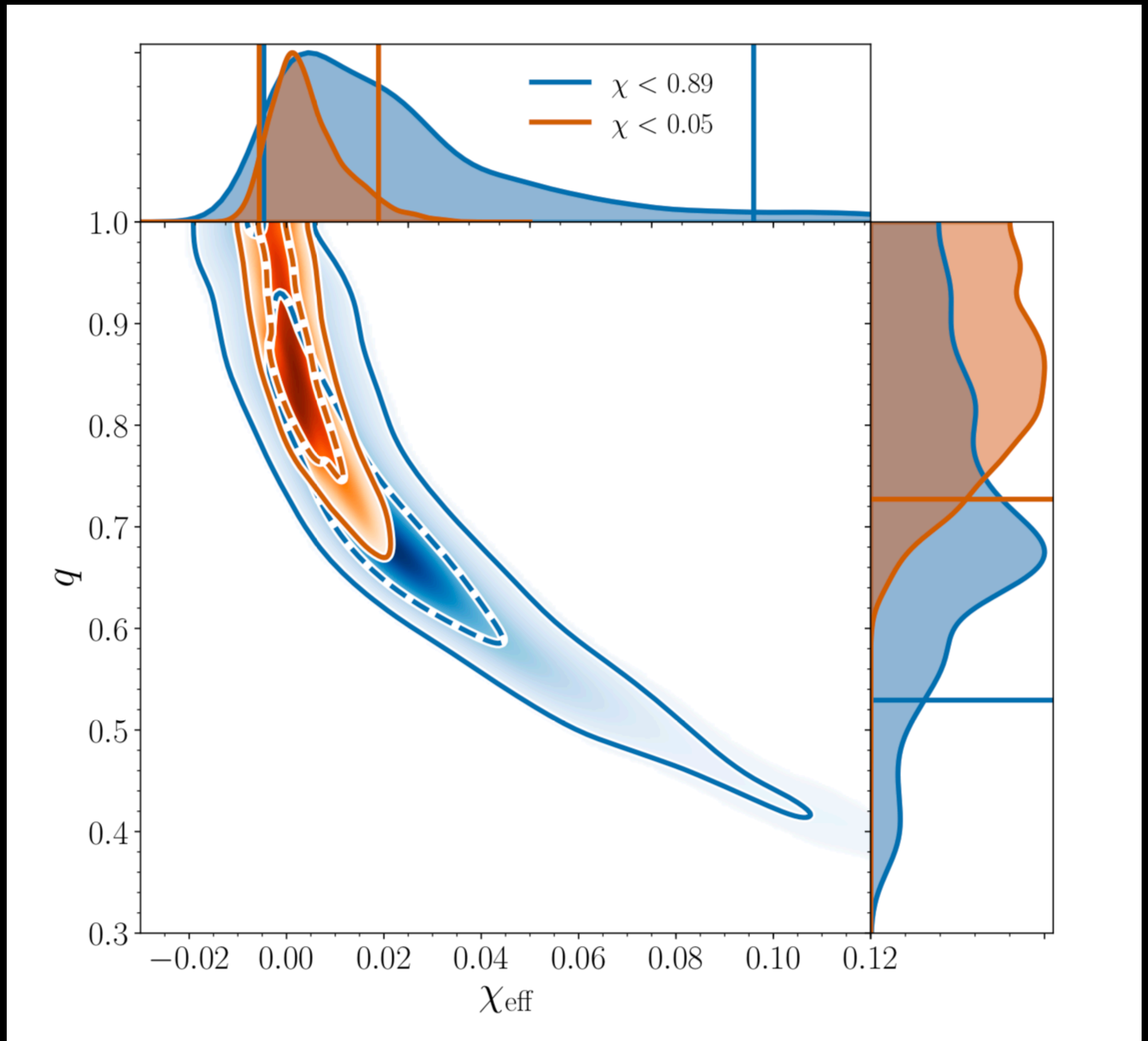




BNS mergers and Kilonovae

Inferring Neutron Star Properties





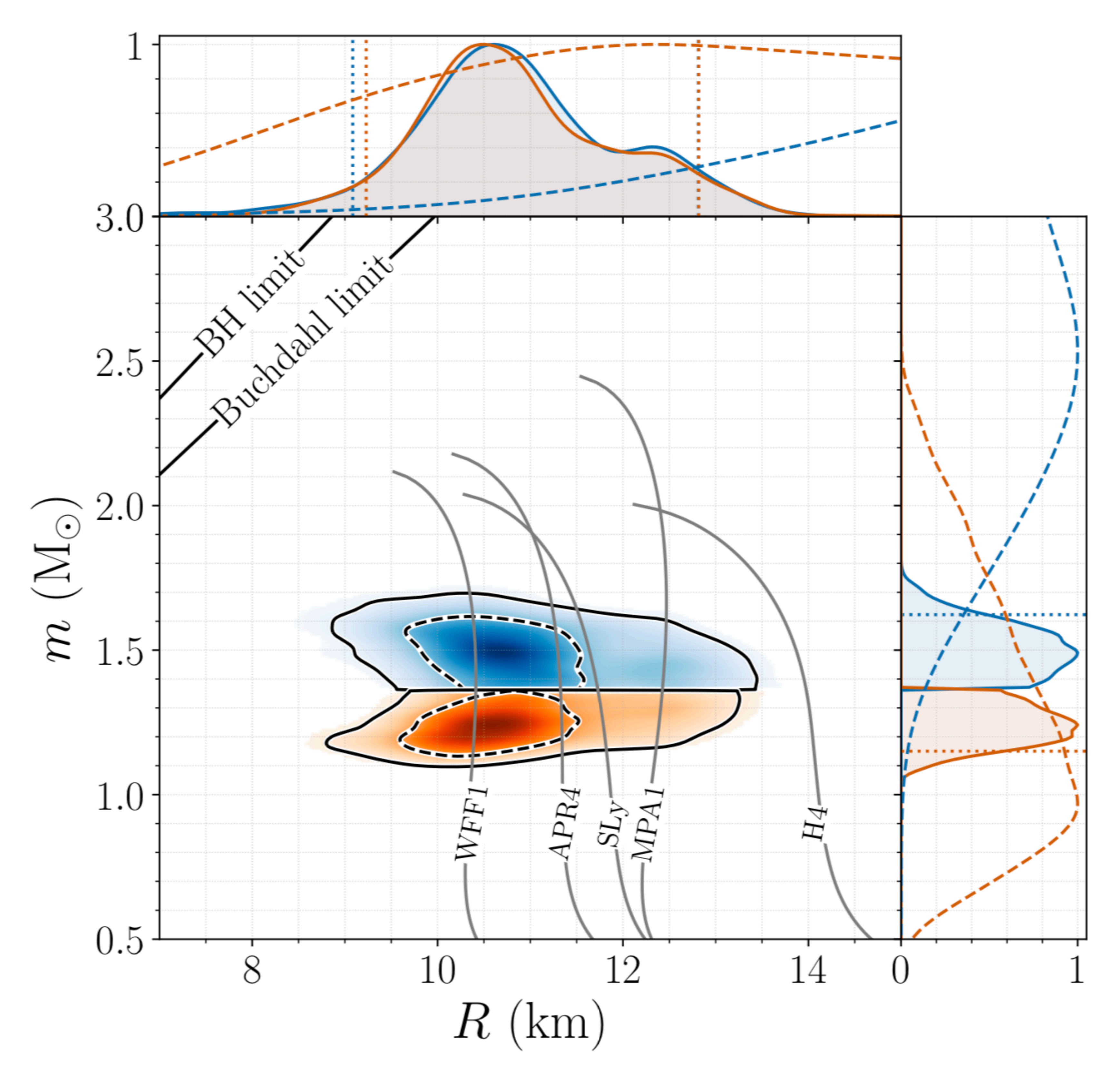
Early estimates now improved using known source location, improved waveform modeling, and re-calibrated Virgo data.

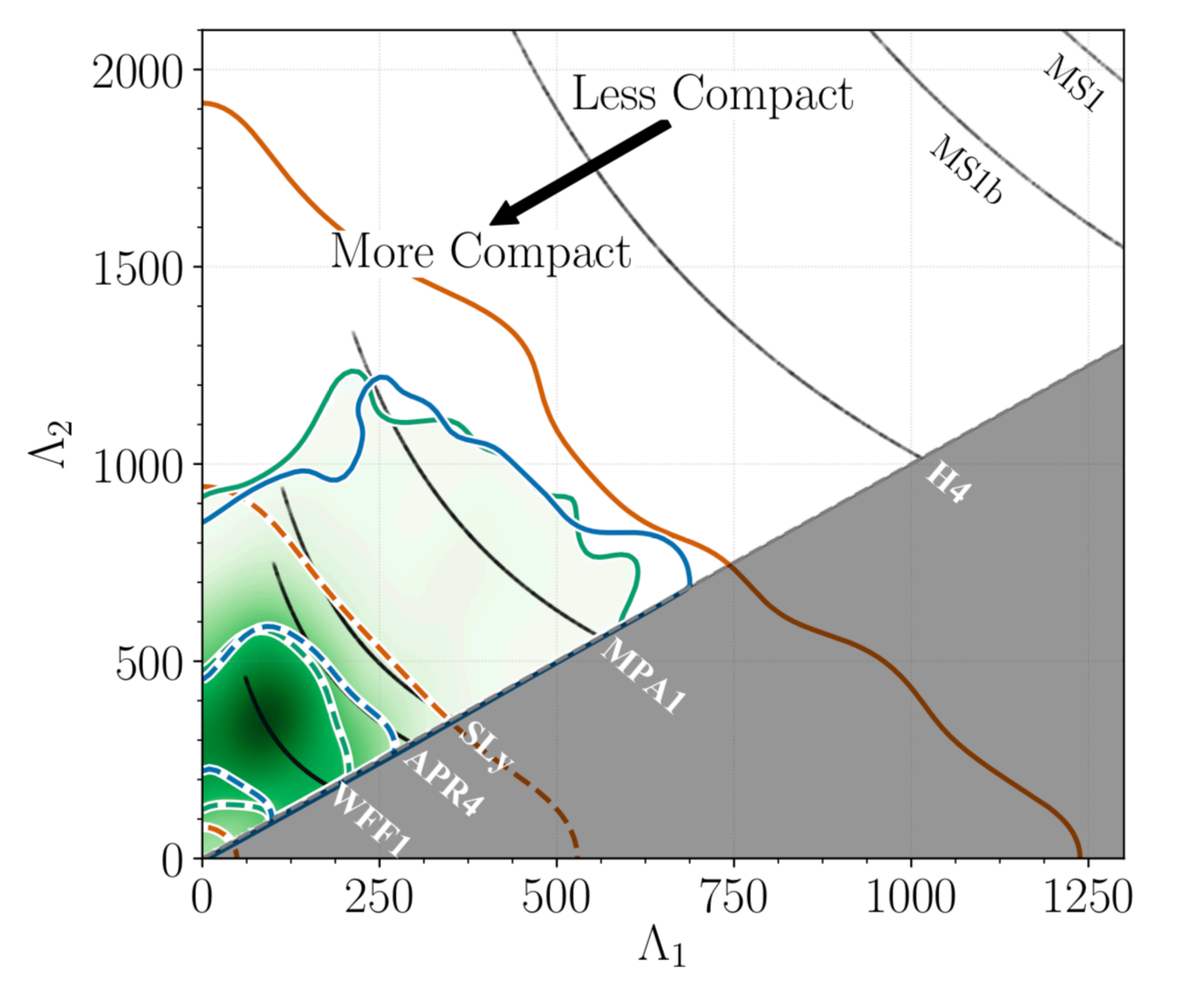
Properties of the binary neutron star merger GW170817 - arXiv:1805.11579

Neutron Star Structure

Properties of the binary neutron star merger GW170817 - arXiv:1805.11579

GW170817: Measurements of neutron star radii and equation of state arXiv:1805.11581

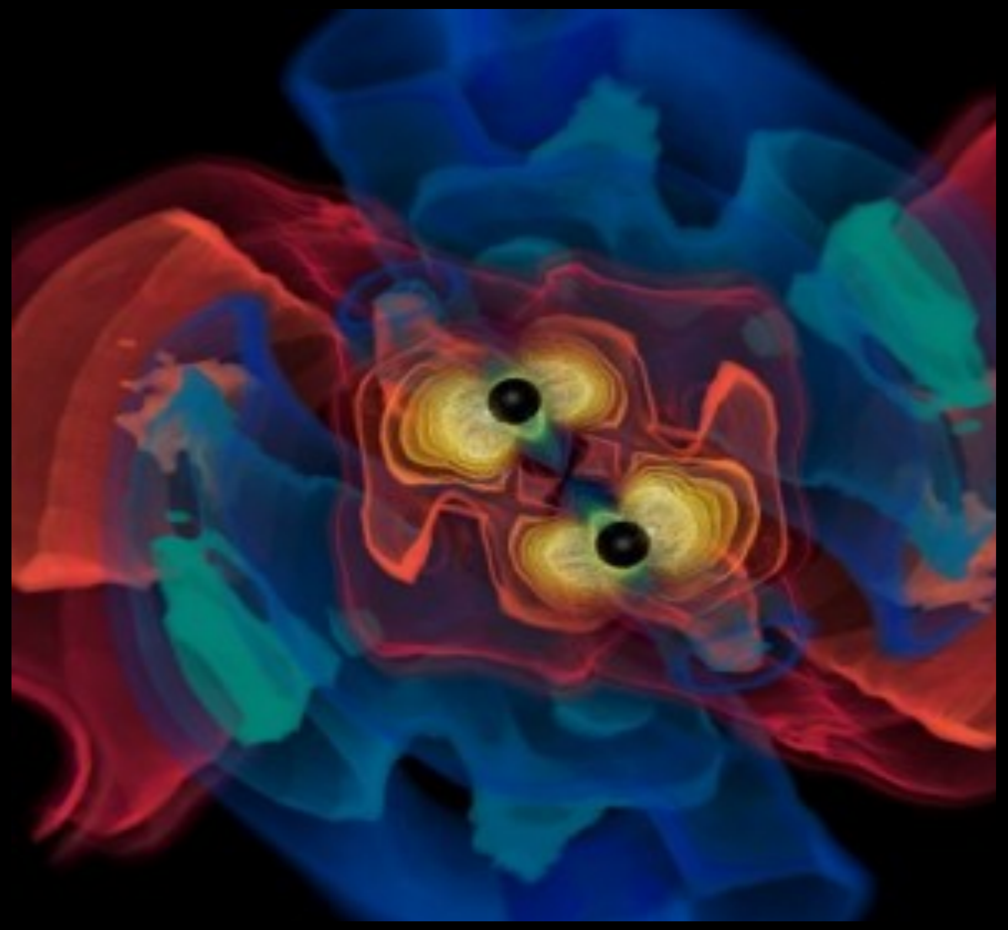




Constraining properties of nuclear matter via neutron star equation of state and tidal disruption, which is encoded in the BNS gravitational waveform

tidal deformability parameter
$\Lambda \sim k_2 (R/m)^5$
k_2 - second Love number
R, m = radius, mass of the neutron star

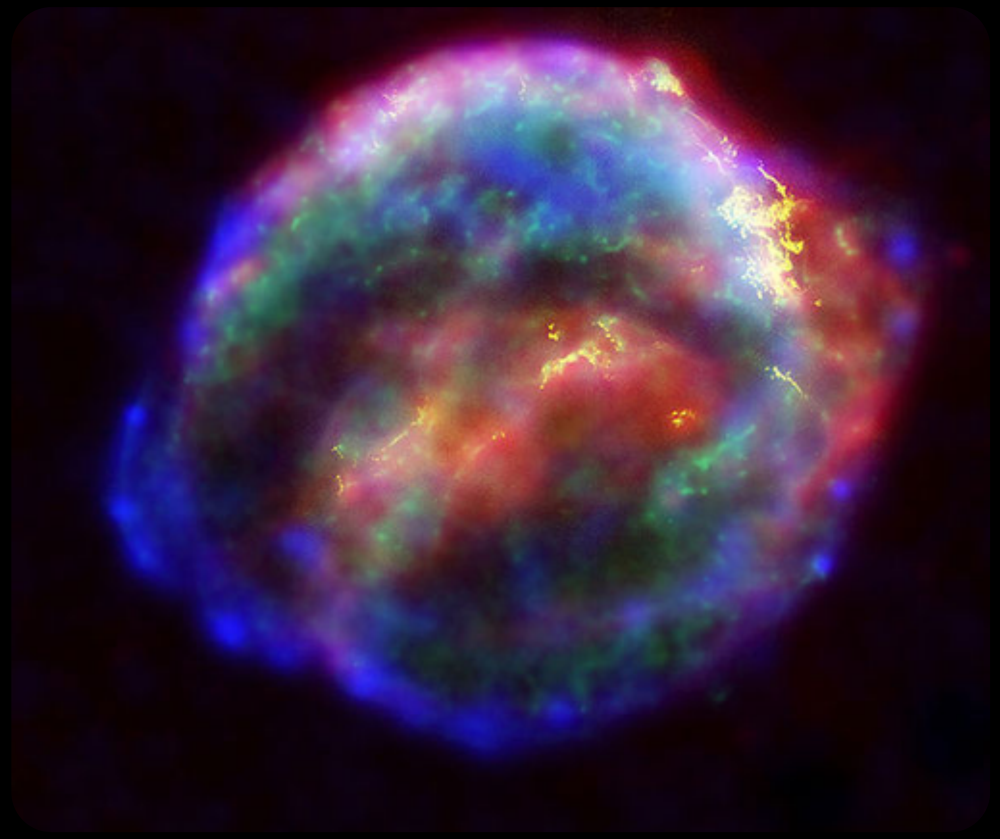
More Results from O2 data in preparation



Credit: AEI, CCT, LSU

Coalescing Binary Systems

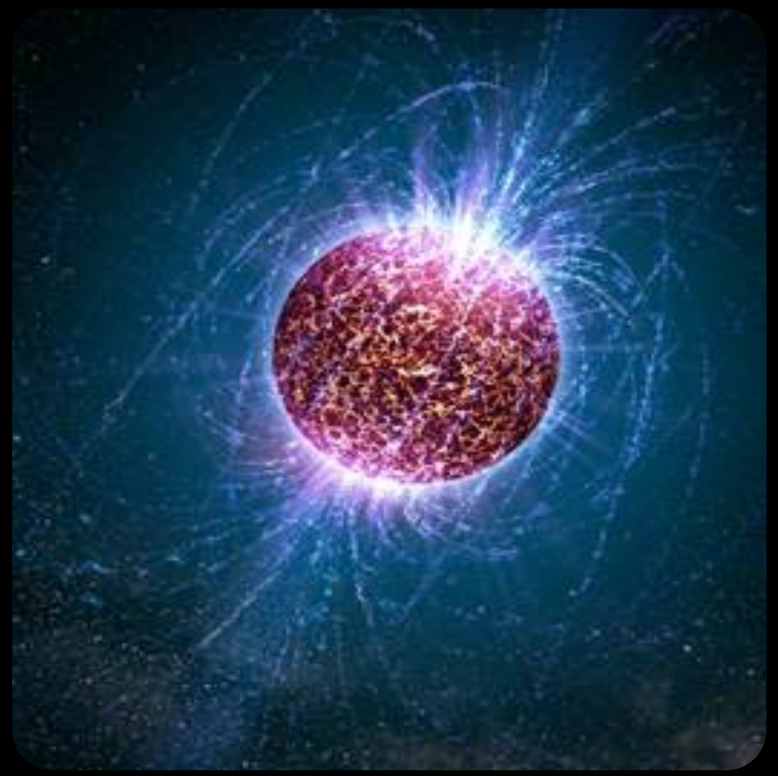
Neutron Stars,
Black Holes



Credit: Chandra X-ray Observatory

'Bursts'

asymmetric core collapse supernovae
cosmic strings
Postmerger
???

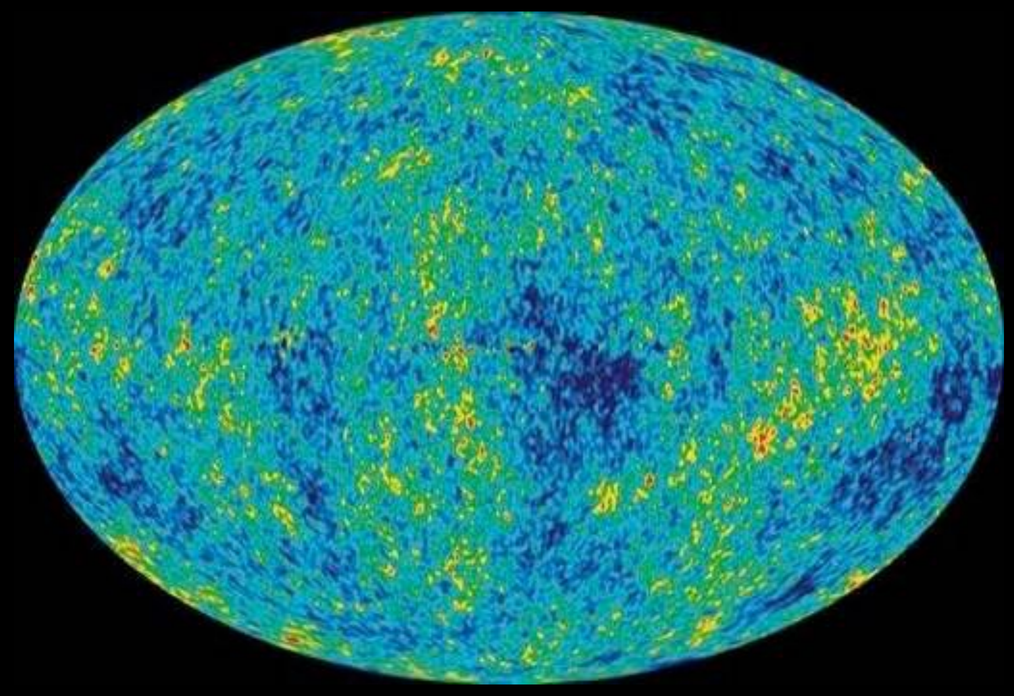


Casey Reed, Penn State

Continuous Sources

Spinning neutron stars

crustal deformations, accretion

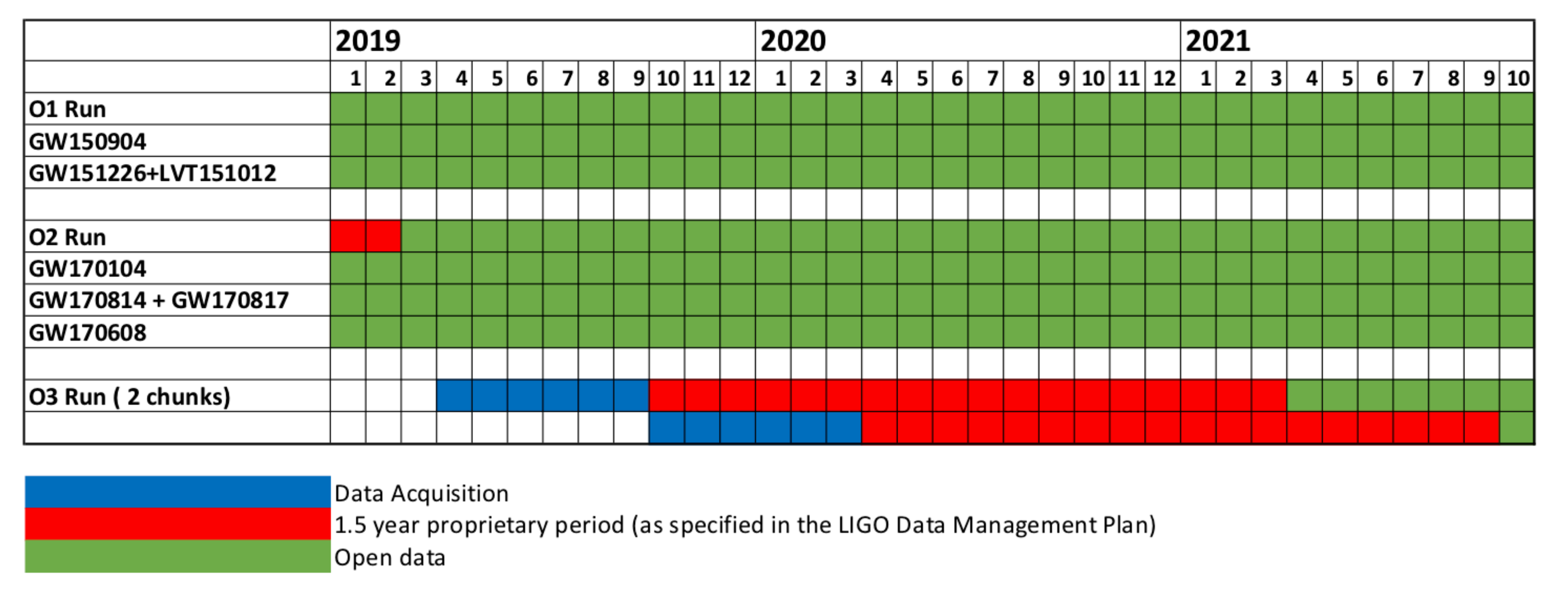


NASA/WMAP Science Team

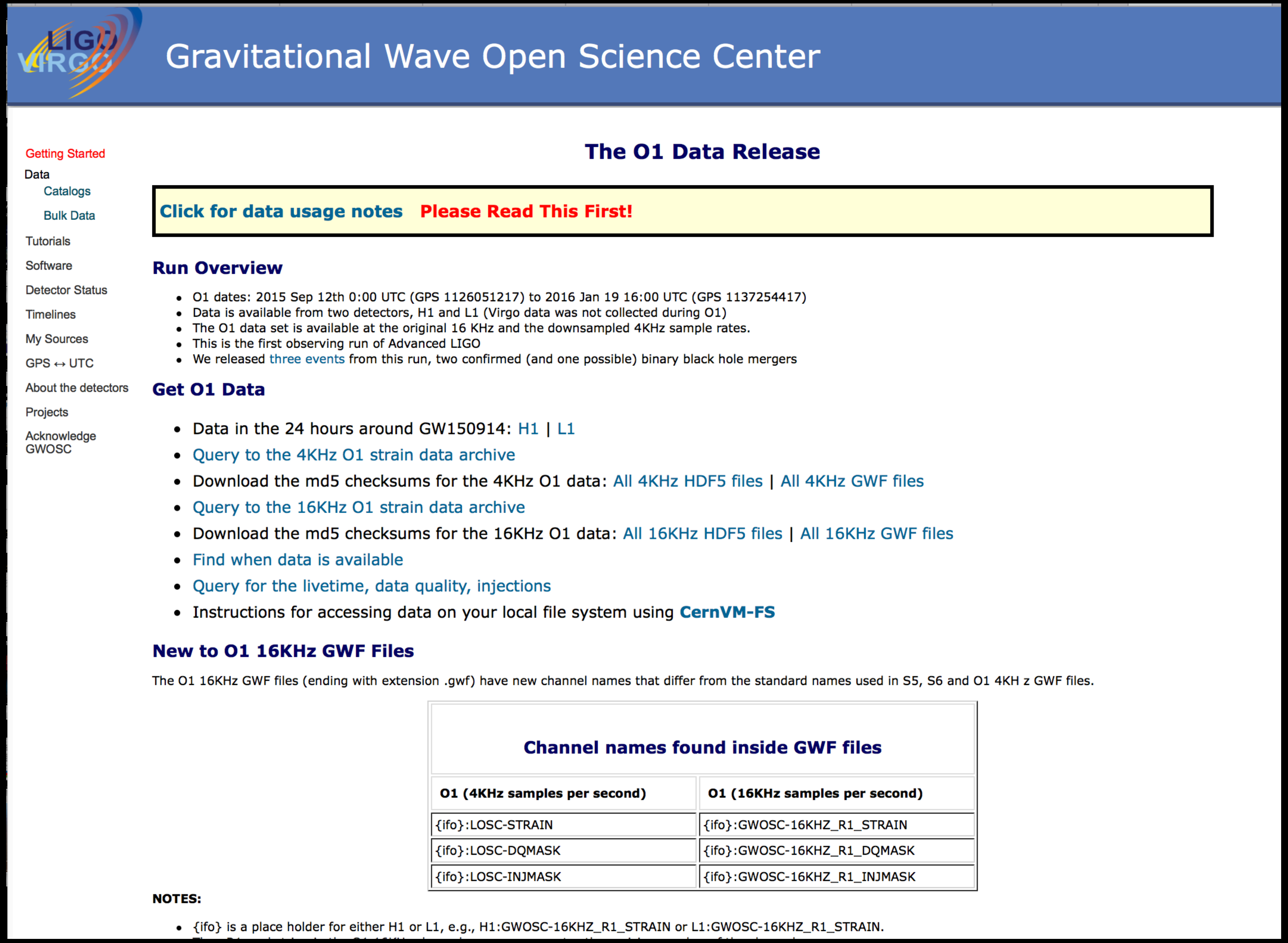
Stochastic GW background

stochastic, incoherent background - cosmological or astrophysical

Data Release Schedule



- Open Data publication policy under discussion with Virgo (part of LIGO-Virgo MoU)



Gravitational Wave Open Science Center

Getting Started
Data
Catalogs
Bulk Data
Tutorials
Software
Detector Status
Timelines
My Sources
GPS ↔ UTC
About the detectors
Projects
Acknowledge GWOSC

The O1 Data Release

Click for data usage notes Please Read This First!

Run Overview

- O1 dates: 2015 Sep 12th 0:00 UTC (GPS 1126051217) to 2016 Jan 19 16:00 UTC (GPS 1137254417)
- Data is available from two detectors, H1 and L1 (Virgo data was not collected during O1)
- The O1 data set is available at the original 16 KHz and the downsampled 4KHz sample rates.
- This is the first observing run of Advanced LIGO
- We released three events from this run, two confirmed (and one possible) binary black hole mergers

Get O1 Data

- Data in the 24 hours around GW150914: H1 | L1
- Query to the 4KHz O1 strain data archive
- Download the md5 checksums for the 4KHz O1 data: All 4KHz HDF5 files | All 4KHz GWF files
- Query to the 16KHz O1 strain data archive
- Download the md5 checksums for the 16KHz O1 data: All 16KHz HDF5 files | All 16KHz GWF files
- Find when data is available
- Query for the livetime, data quality, injections
- Instructions for accessing data on your local file system using CernVM-FS

New to O1 16KHz GWF Files

The O1 16KHz GWF files (ending with extension .gwf) have new channel names that differ from the standard names used in S5, S6 and O1 4KH z GWF files.

Channel names found inside GWF files

O1 (4KHz samples per second)	O1 (16KHz samples per second)
{ifo}:LOSC-STRAIN	{ifo}:GWOSC-16KHZ_R1_STRAIN
{ifo}:LOSC-DQMASK	{ifo}:GWOSC-16KHZ_R1_DQMASK
{ifo}:LOSC-INJMASK	{ifo}:GWOSC-16KHZ_R1_INJMASK

NOTES:

- {ifo} is a place holder for either H1 or L1, e.g., H1:GWOSC-16KHZ_R1_STRAIN or L1:GWOSC-16KHZ_R1_STRAIN.

https://www.gw-openscience.org/

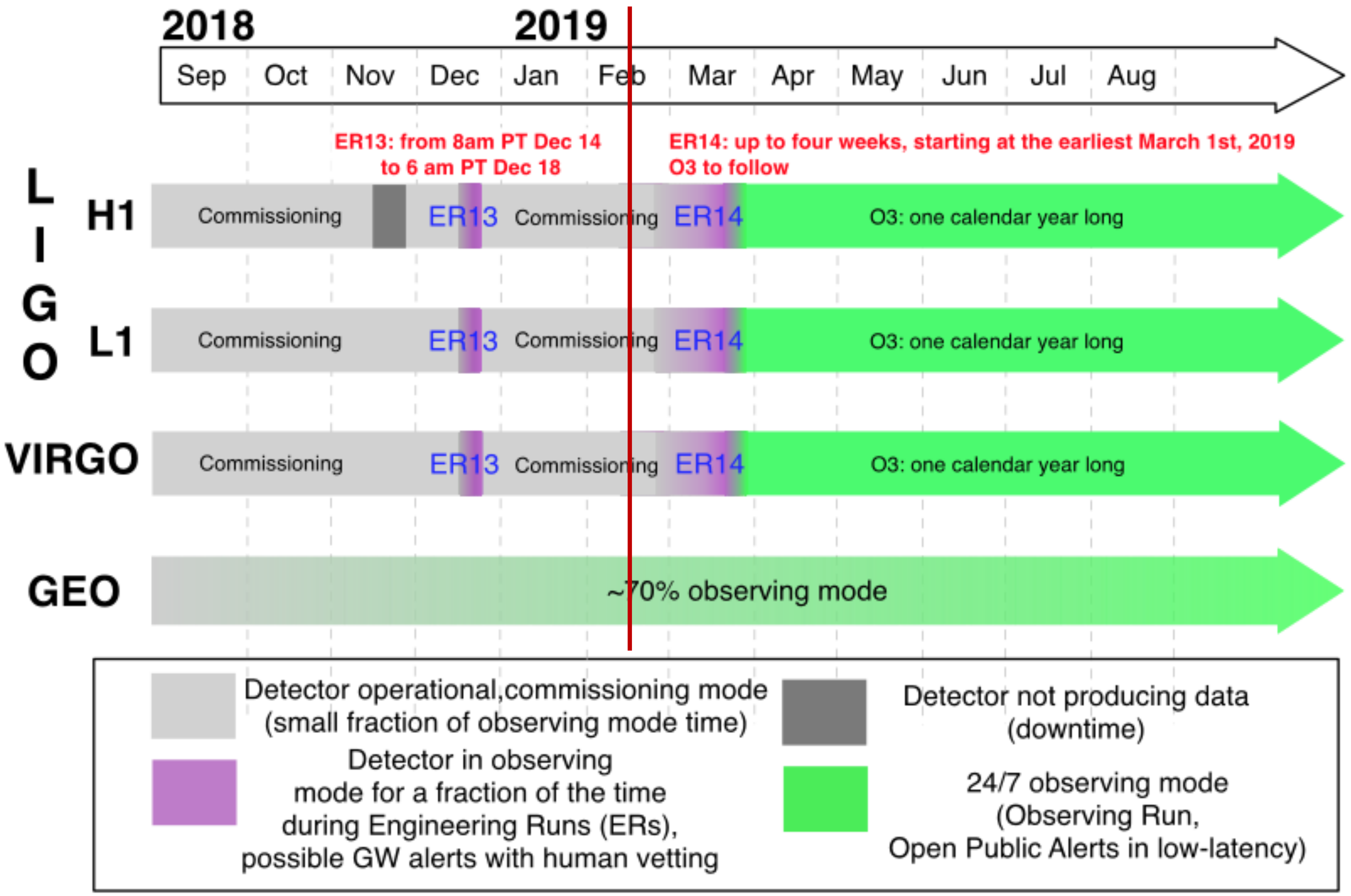
Current Status

LIGO-VIRGO Joint Run Planning Committee

Working schedule for O3

(Public document G1801056-v4, based on G1800889-v7)

LIGO-G1801056



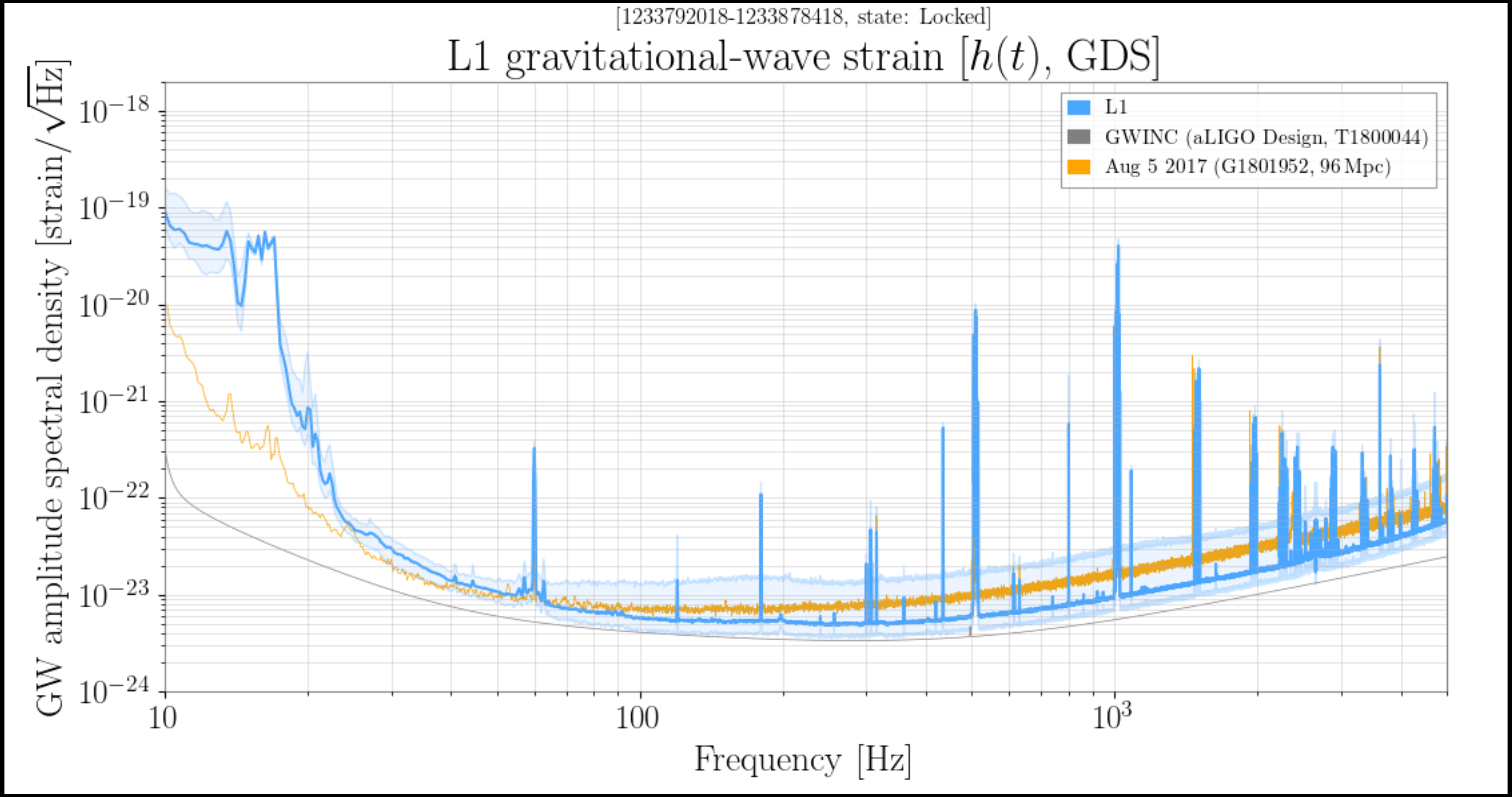
Main upgrades since O2

- Replaced H1's ITMX
- Replaced all End Test Masses
- Installed Tuned-mass Dampers, no Parametric Instability
- Monolithic Signal Recycling Mirrors
- Stray Light Control improvements
- Squeezed Light injection
- 70 W laser amplifier stage

Instrument Status and Plans

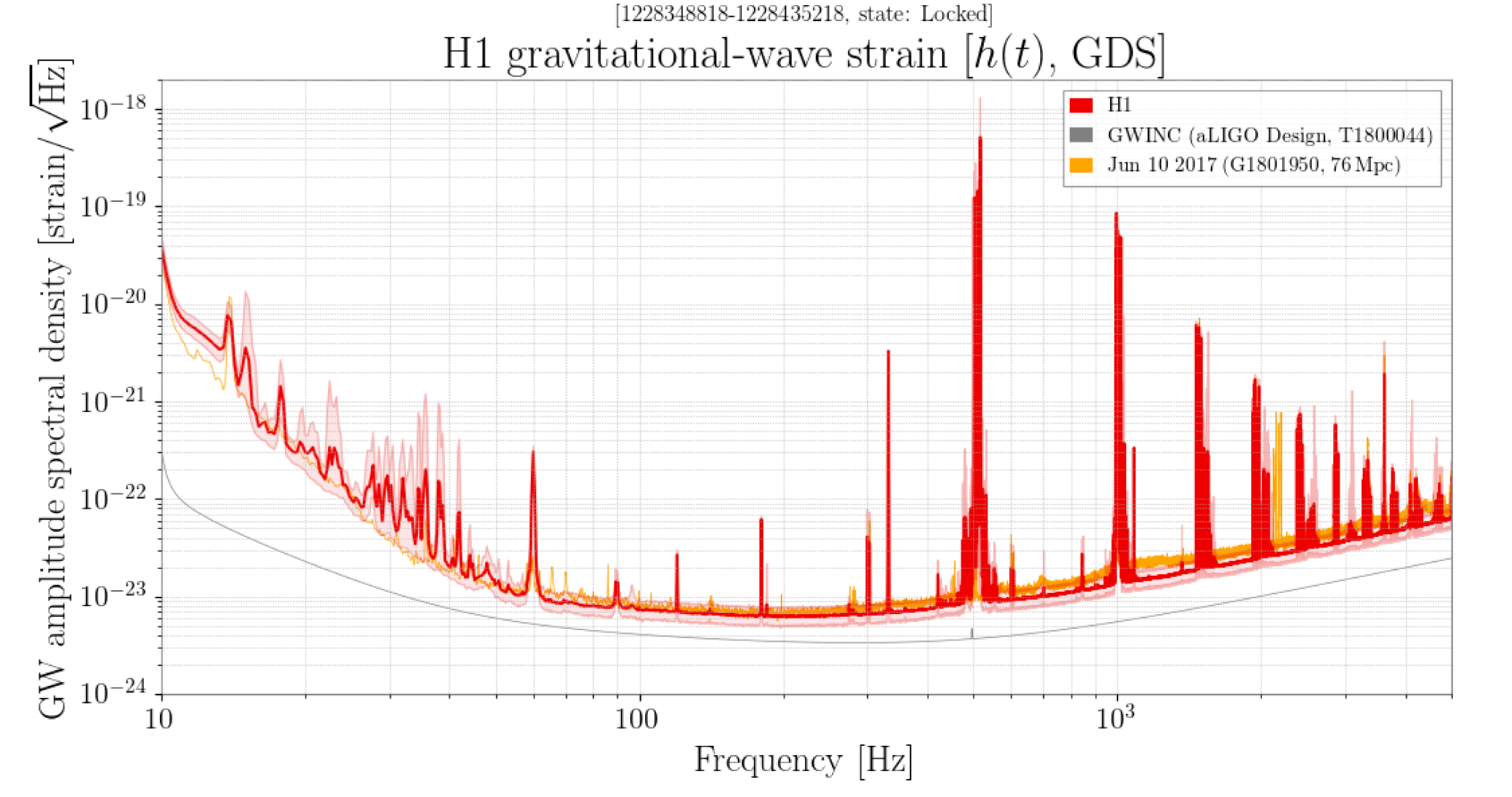
- Better sensitivities from all instruments.
  - So far: L1 up to 135Mpc with SQZ, H1 up to 90Mpc (in O2: L1~100, H1~80)
  - Ongoing work on reliability and SQZ of H1, will continue in the first half of ER14.
- Engineering Run 14 (ER14) planned from Mar 04, 2019
  - Finalize instruments' configuration, calibration etc.
  - End-to-end test of instruments/software.
- O3 planned from Apr 01, 2019
  - 24/7 operation is the goal, except planned downtime.
  - Past experience suggest ~50-60% triple observation availability
  - Planning to be flexible about H1 commissioning for reliable operation if necessary.
- Open Public Alert

Detector Performance So Far: L1



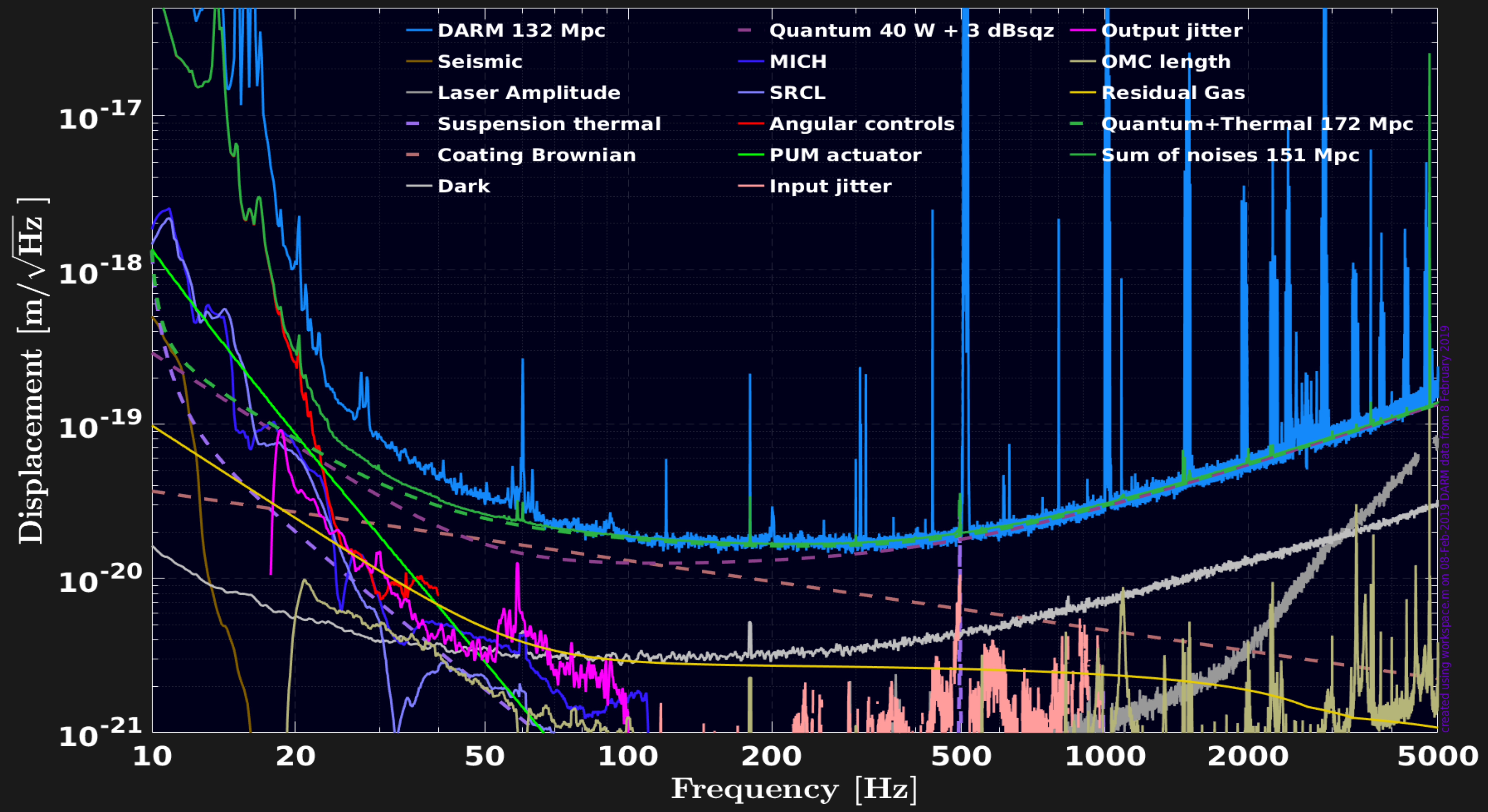
- up to 50W input power (275 kW arm power) (might run at 40W, 225kW)
- 3dB shot noise squeezing
- 135 MPc BNS range

Detector Performance So Far: H1



- at 30W input power (143kW arm power)
- up to 90 Mpc BNS range
- Just observed 0.9dB squeezing last week

Livingston Noise Budget



ER14 Observing strategy

- Planned Mar 04,2019 – Mar 31, 2019
- Part of the time will be used to stabilize and make some last improvements on the interferometers
- We will shift to 24/7 operation, with planned downtime for maintenance and commissioning
  - Hanford and Livingston maintenance, Tuesday 15:00 – 20:00 UTC
  - Virgo maintenance, Tuesday 07:00 – 11:00 UTC
- No automatic alert is expected, we will transmit highly interesting triggers after human vetting

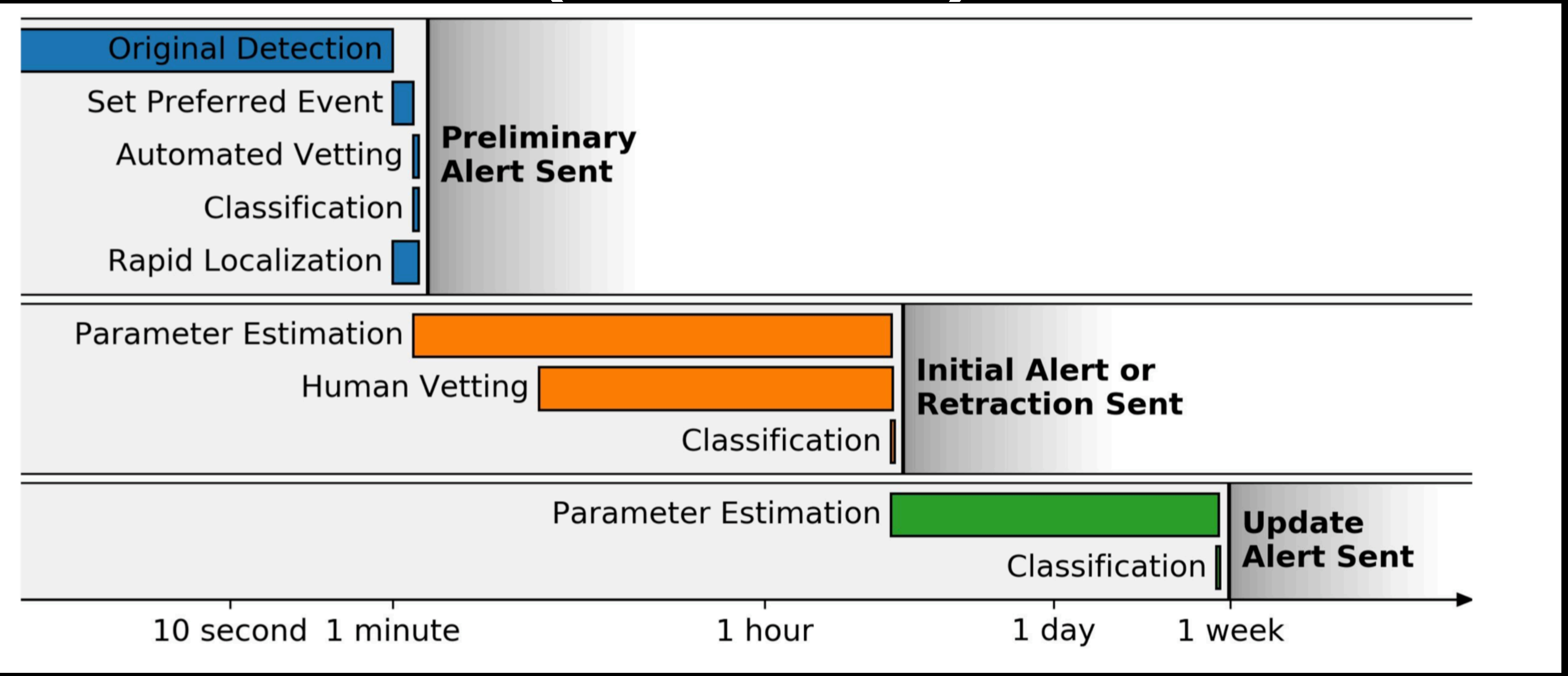
O3 Observing strategy

- Planned to start April 1
- Single IFO duty factor: expect >80%
- 24/7 operation, with planned downtime for maintenance and minimal commissioning: ~ 6%
- Unplanned downtime: environmental disturbances, some of which are simultaneous (large earthquakes), some are local (storms, power outage) → up to 10% downtime in O2 for single interferometer
- Extraordinary downtime: if major problem is observed during the run and need immediate fix, or major noise/data quality problem is identified and we think we can quickly fix it (example in O2: cleaning of one of the input arm mirrors in H1)
- Coordination between the sites to maximize triple coincidence.
  - Hope H1 operates reliably with SQZ by then, but flexible to spend more time if necessary.
  - Will spend time on problems that need immediate attention, or if we think we can make significant improvement in short period.
- Open Public Alerts will be issued for events during O3

Open Public Alerts (OPA)

LIGO/Virgo will release alerts in low latency for transient event candidates

- These alerts will be publicly available through the Gamma-ray Coordinates Network (GCN)
- Event candidates will be publicly available in https://gracedb.ligo.org
- There will be no human vetting for the Preliminary alert



OPA rate estimates:

- Binary neutron stars (BNS): Up to 1/month of data taken; median is 2/year of data taken, Median 90% credible localization 120-180 deg2; 12-21% localized < 20 deg2
- Binary black holes (BBH): 1/month to 1/week of data taken
- Neutron-star black-hole binaries (NSBH): Uncertain, estimates include zero
- Other transients: Unknown

Target contamination of public alerts

- Contamination ~10% of public alerts across all categories together
- BNS, NSBH & other transients may individually have higher contamination

Ligo-Virgo Computing

Compute:

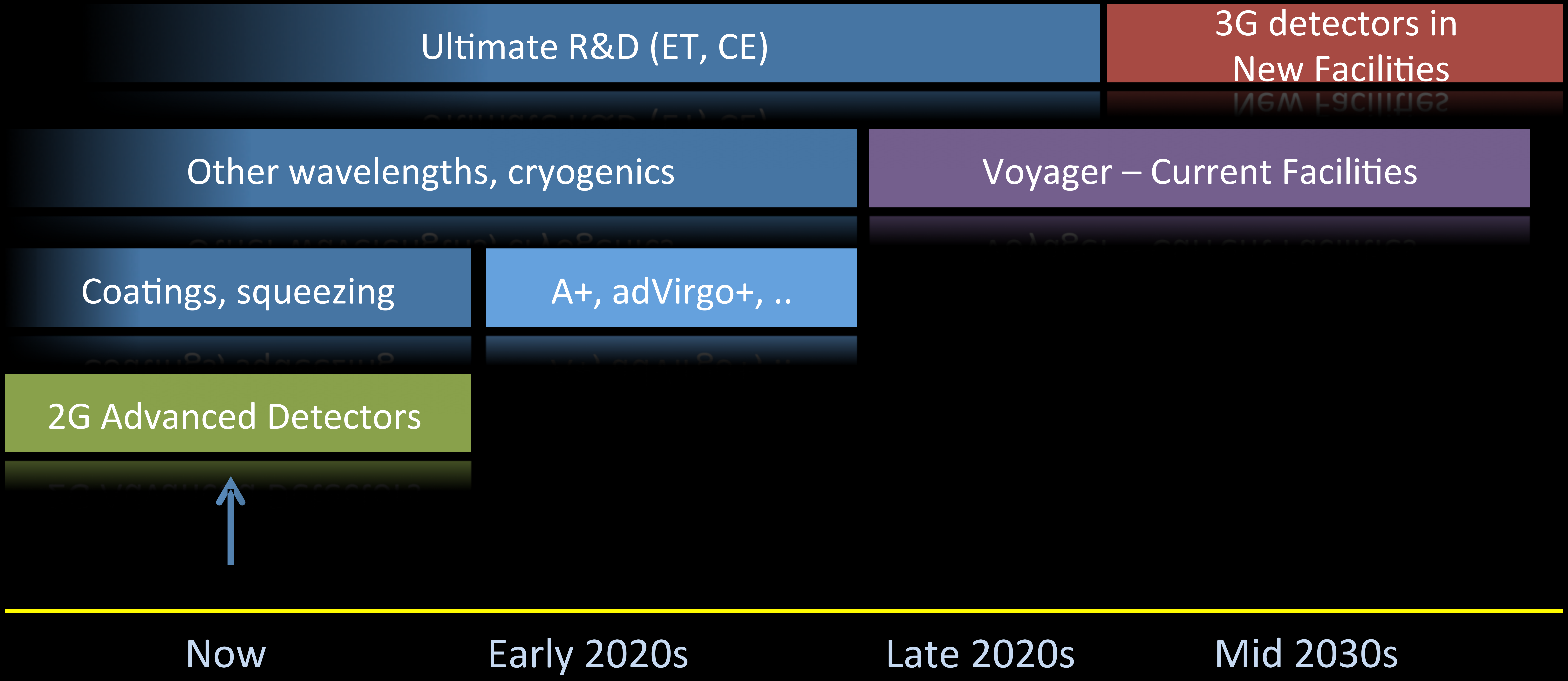
- For the third observing run (O3), the LVC expects to need ~500 million CPU core-hours of data analysis for ~80 astrophysical searches, followup activities, and detector characterization.
- The 10 most demanding of these 80 analyses comprise ~90% of the demand.
- Most of this computing is "pleasingly parallel" High Throughput Computing (HTC) for "deep" offline searches; ~10% is low-latency data analysis needed to generate rapid alerts (OPA)
- Currently ~90% provided by dedicated LIGO-Virgo clusters vs. ~10% from external shared computing resources — but growth of the dedicated resources has flattened while shared component is growing.
- Growing shared, external computing resources are presenting new distributed computing and data access challenges. GPU has been the most successful and cost-effective: deploying at scale for the first time in O3.
- Currently no cloud usage; no major technical obstacles, but logistics are unclear.

Data:

- LIGO h(t) strain data is O(10TB) per IFO per observing year.
- LIGO raw data (all channels, full sample rate) is O(1PB) per IFO per observing year.
- No longer "big data" by 2018 standards — but non-trivial in a distributed HTC environment.

Future

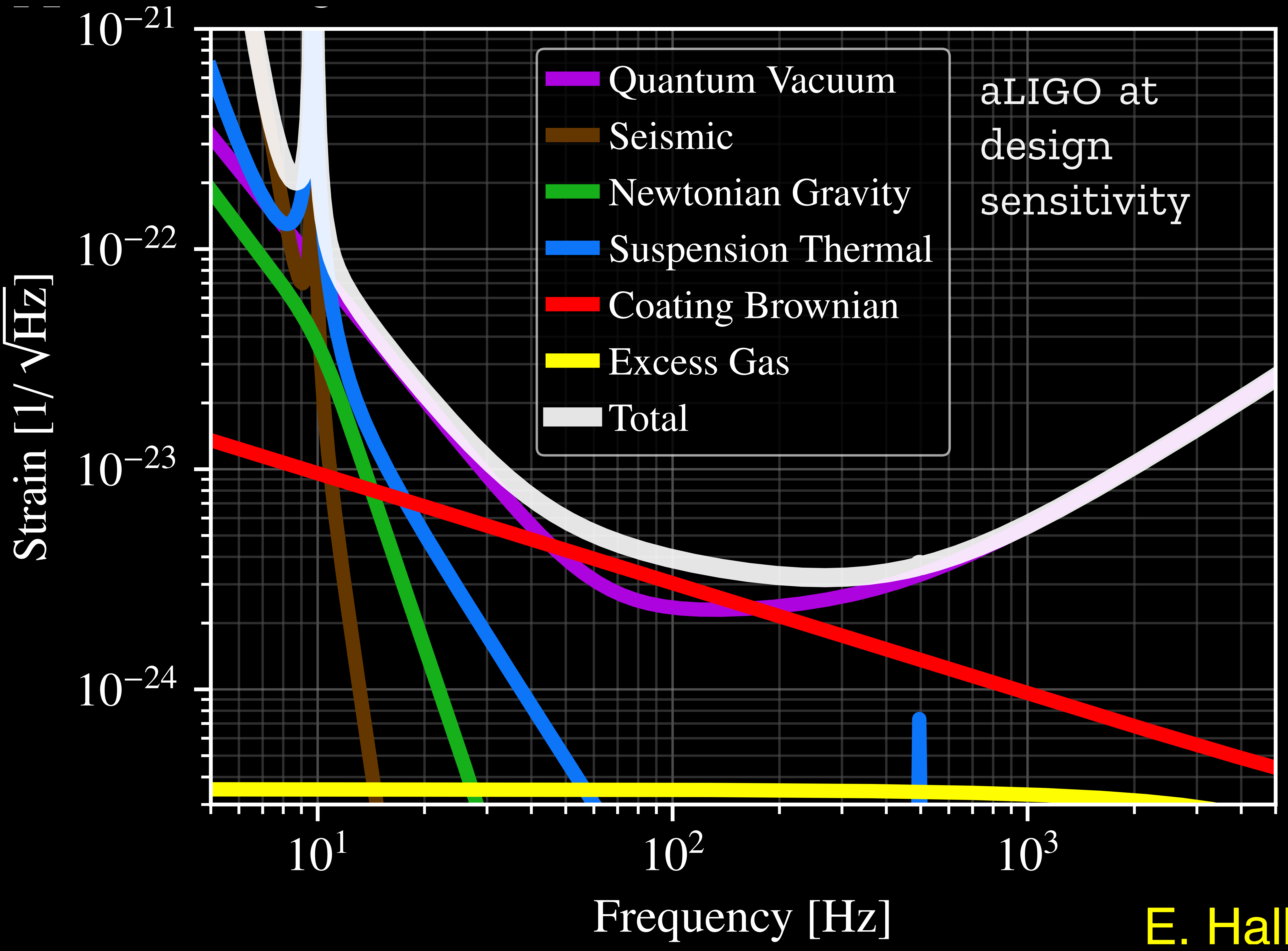
the next 2 decades:
LIGO Concept Roadmap



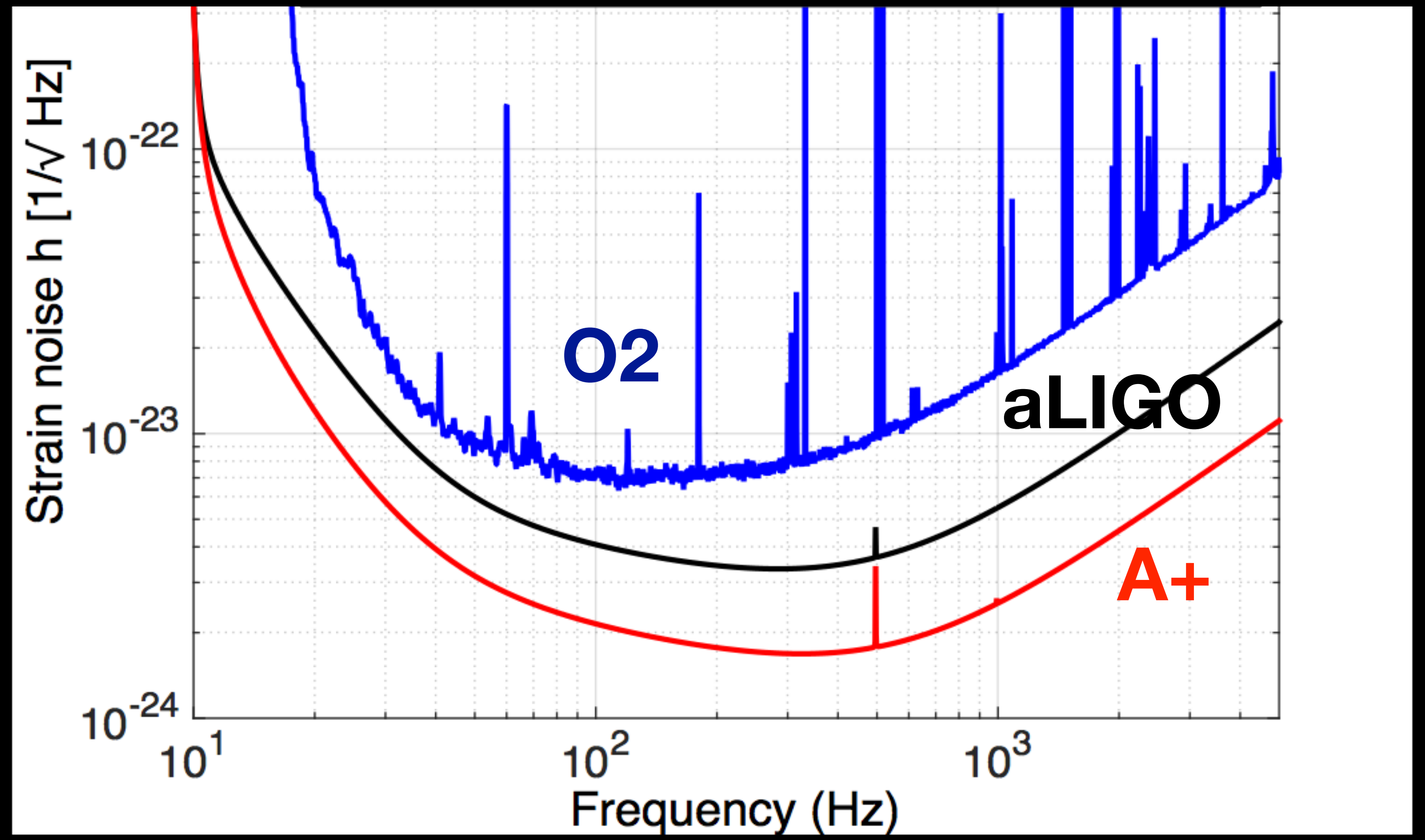
Credit: L. Barsotti

Near-term Future: aLIGO target

~10^2 binary coalescences per year (2021)



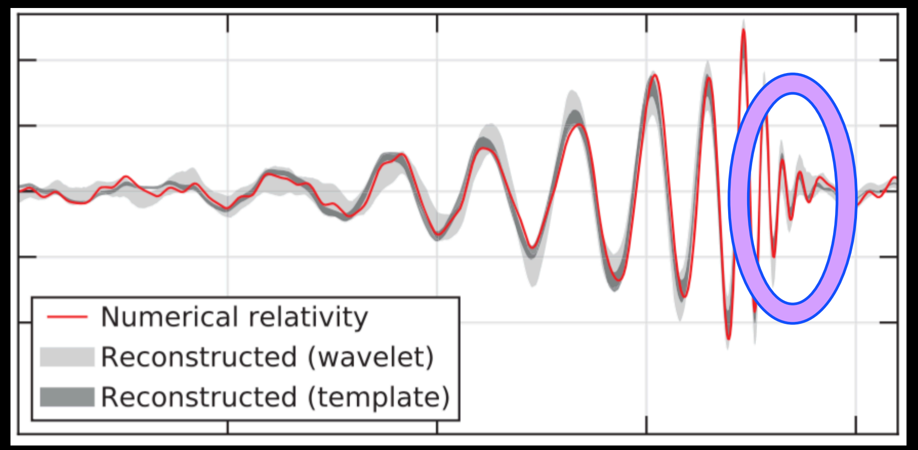
E. Hall



after additional commissioning
Reach: ~ 2x O2
~100 BBH/year (z≲2)
~1-2 NS-BH/year
~20-30 BNS/year (z≲0.1)

4% H_0?

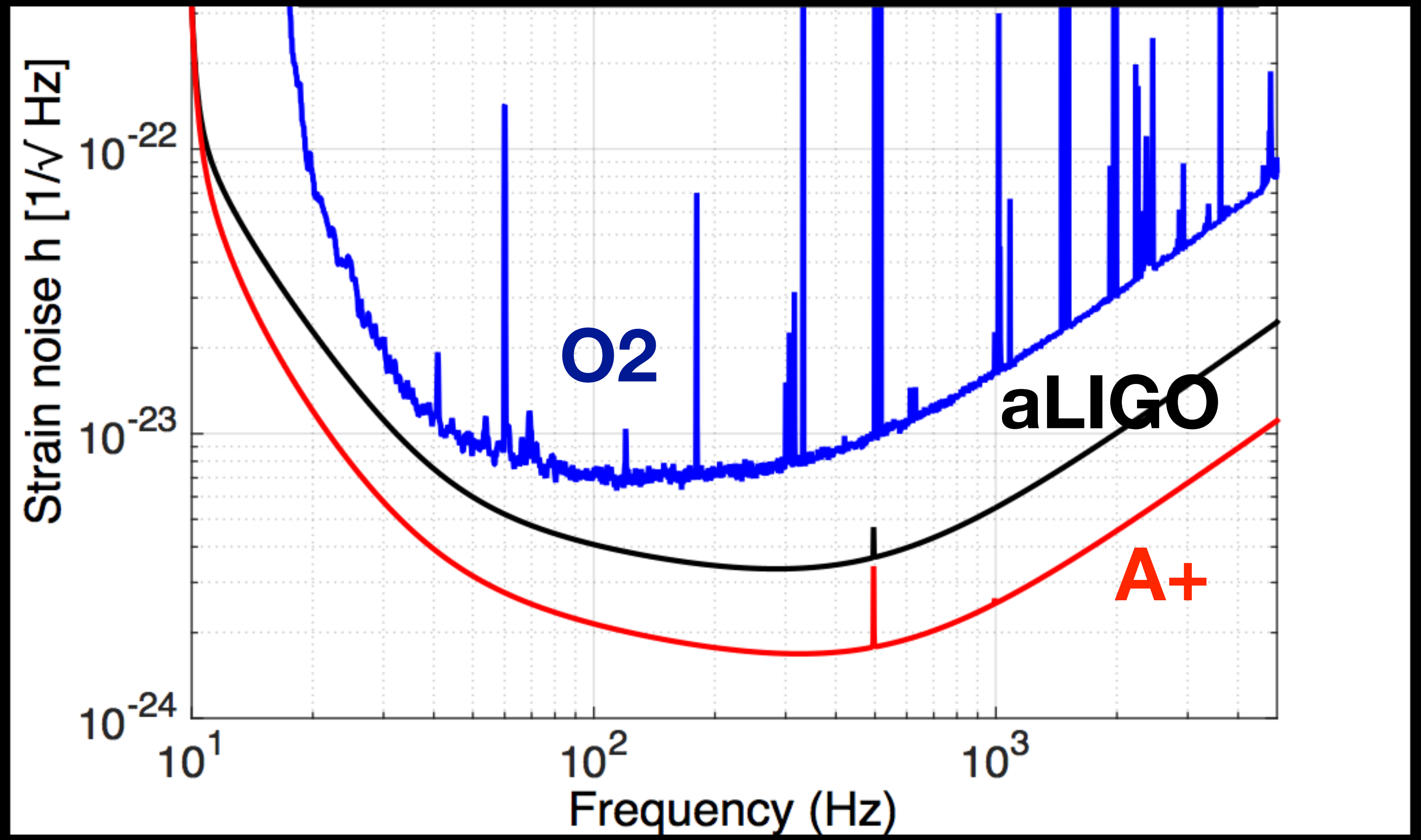
QNM SNR ~20 for an event like GW150914

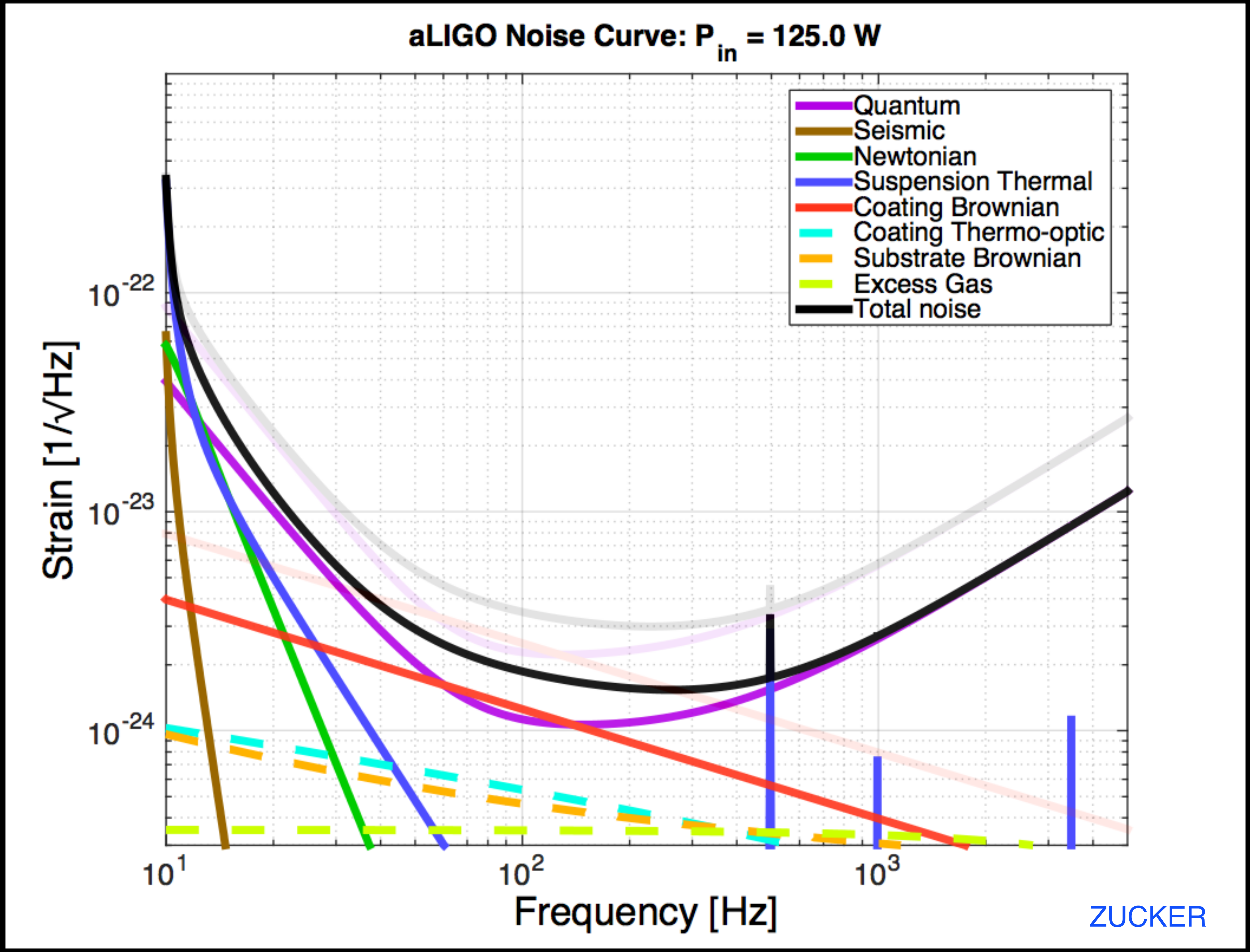


tests of GR?

Medium-term Future: A+

~10^3 binary coalescences per year (circa 2024)

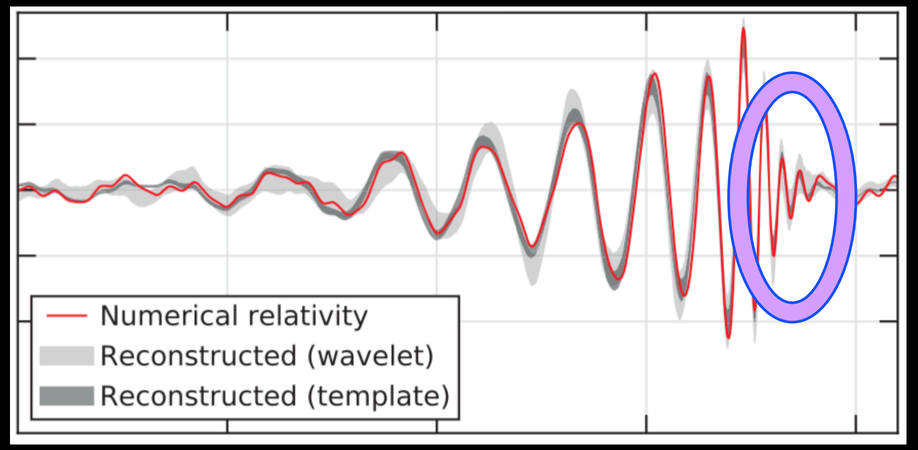




Modest upgrades to aLIGO and AdVirgo
Frequency-dependent squeezing and lower optical coating thermal noise
Reach: ~ 3x O2
~500-1000 BBH/year
~10 NS-BH/year
~200-300 BNS/year

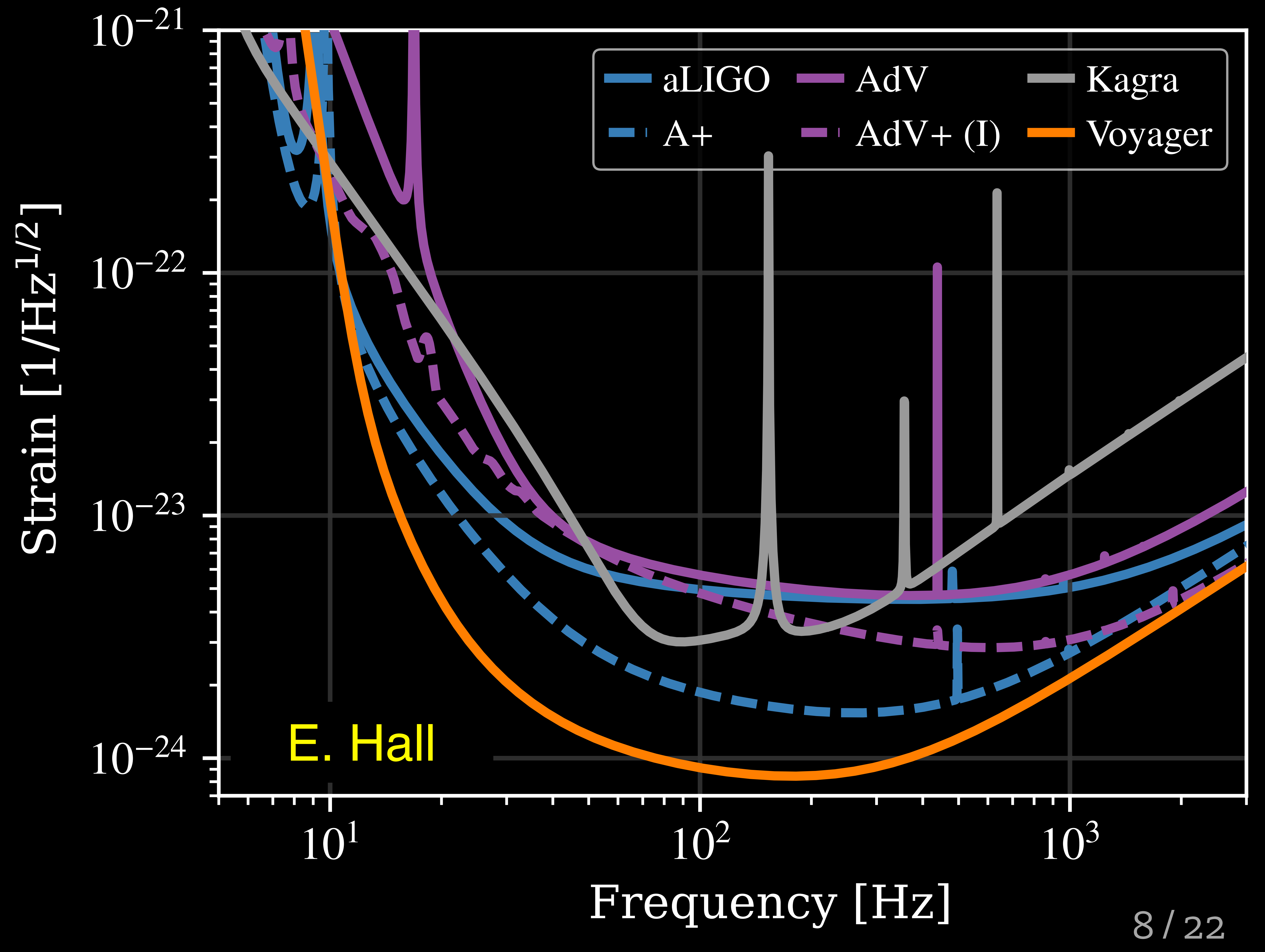
1% H_0?

QNM SNR ~35 for an event like GW150914

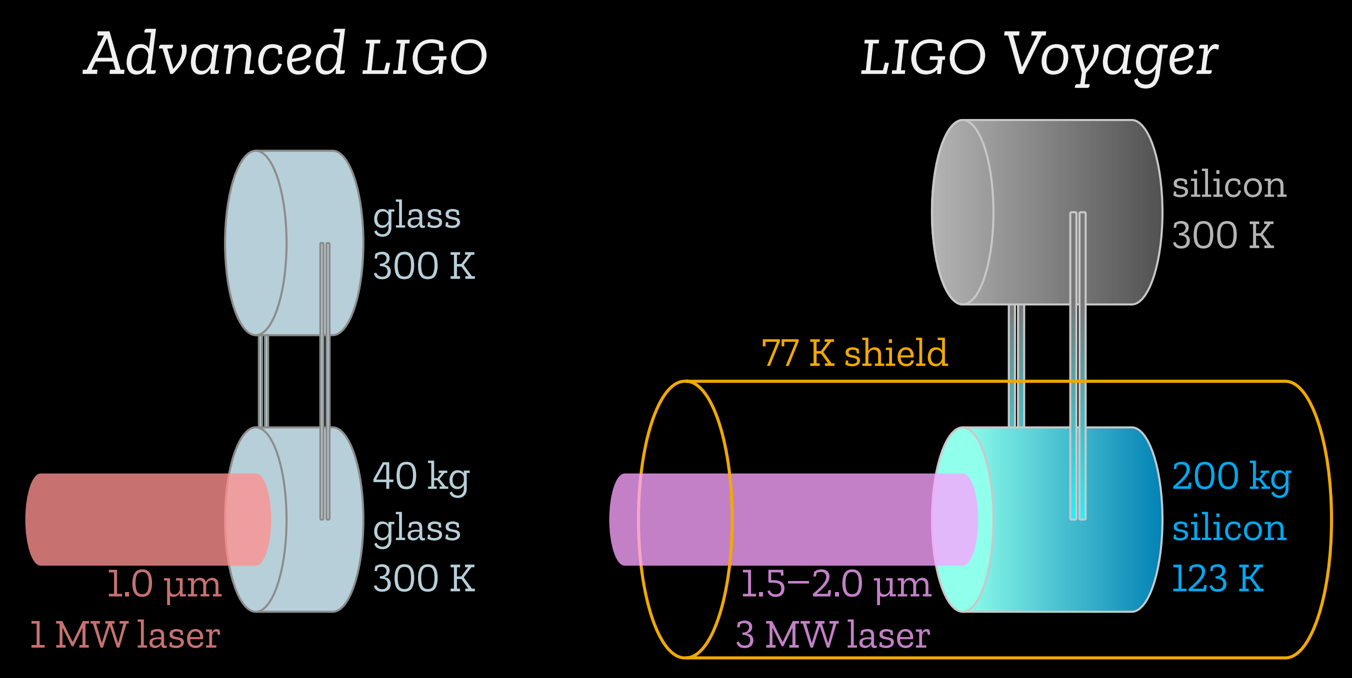


Long-term Future for current facilities: Voyager

~10^4 binary coalescences per year (late 2020s)



A concept under study for incremental performance improvement in late 2020s

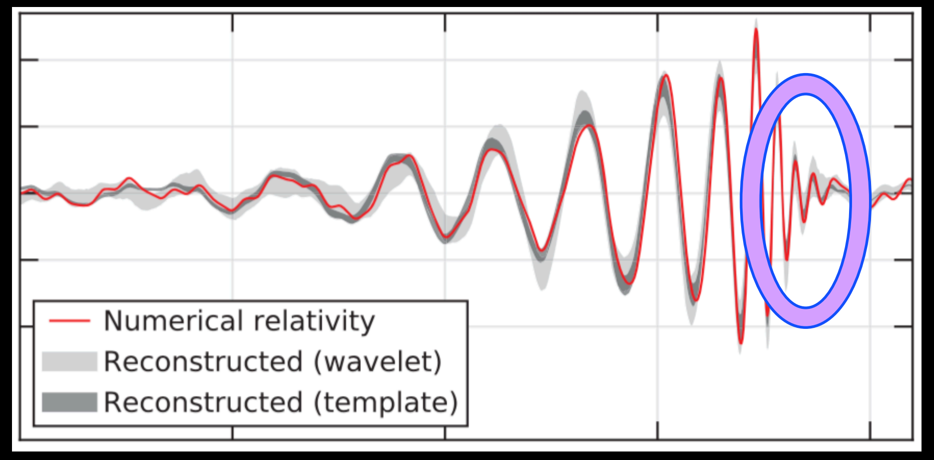


N. Smith and R. Adhkiari, *Cold voyage*, tech. rep. G1500312 (LIGO, 2015)

aLIGO with:
Si optics, > 100 kg;
Si or AlGaAs coatings;
'mildly' Cryogenic;
λ~2 μm, 300 W

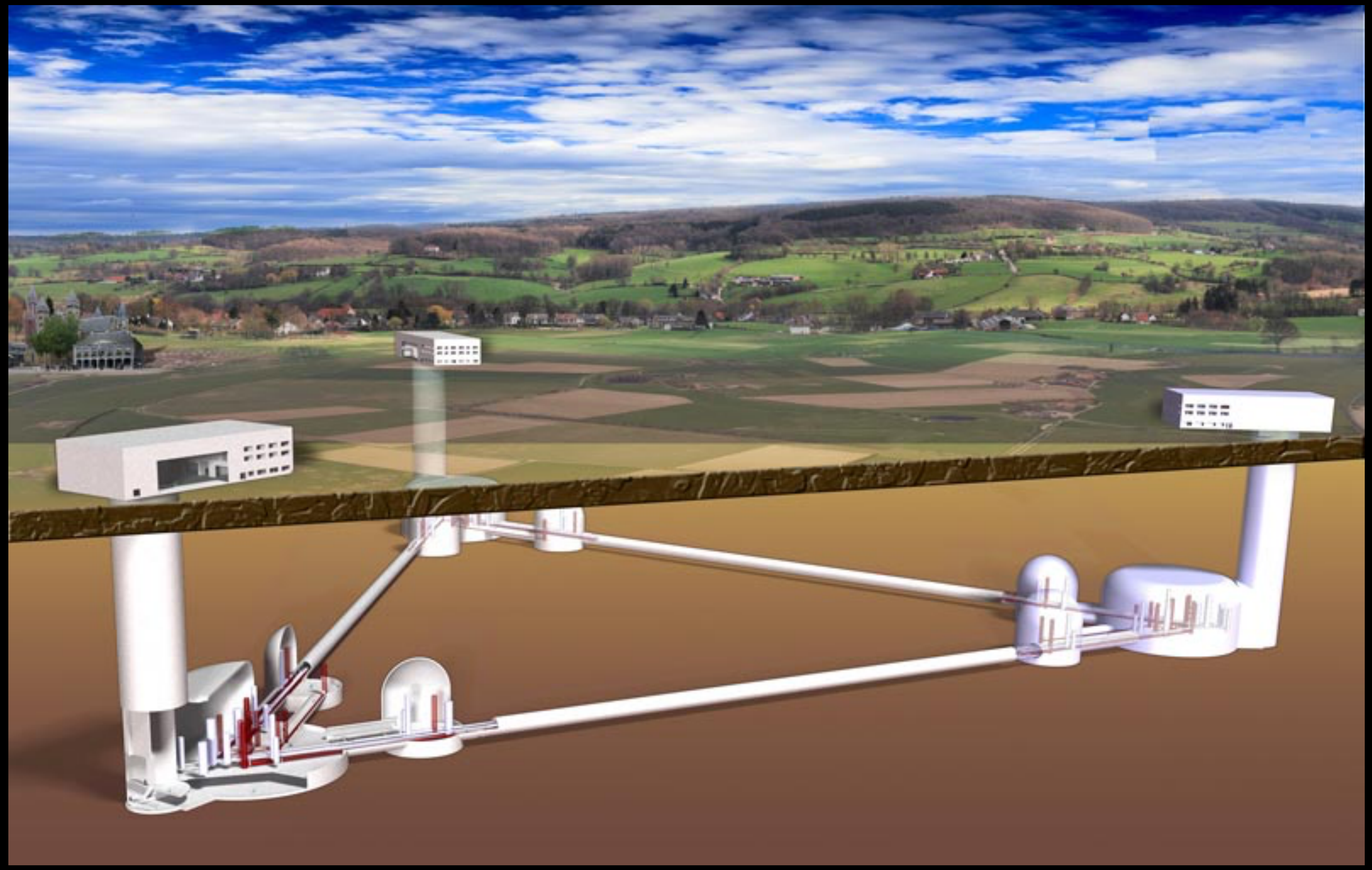
BNS reach: ~10x O2
BBH reach: z~5

QNM SNR ~80
(for an event like GW150914)



The 3rd Generation

~10^5 binary coalescences per year (2030s)

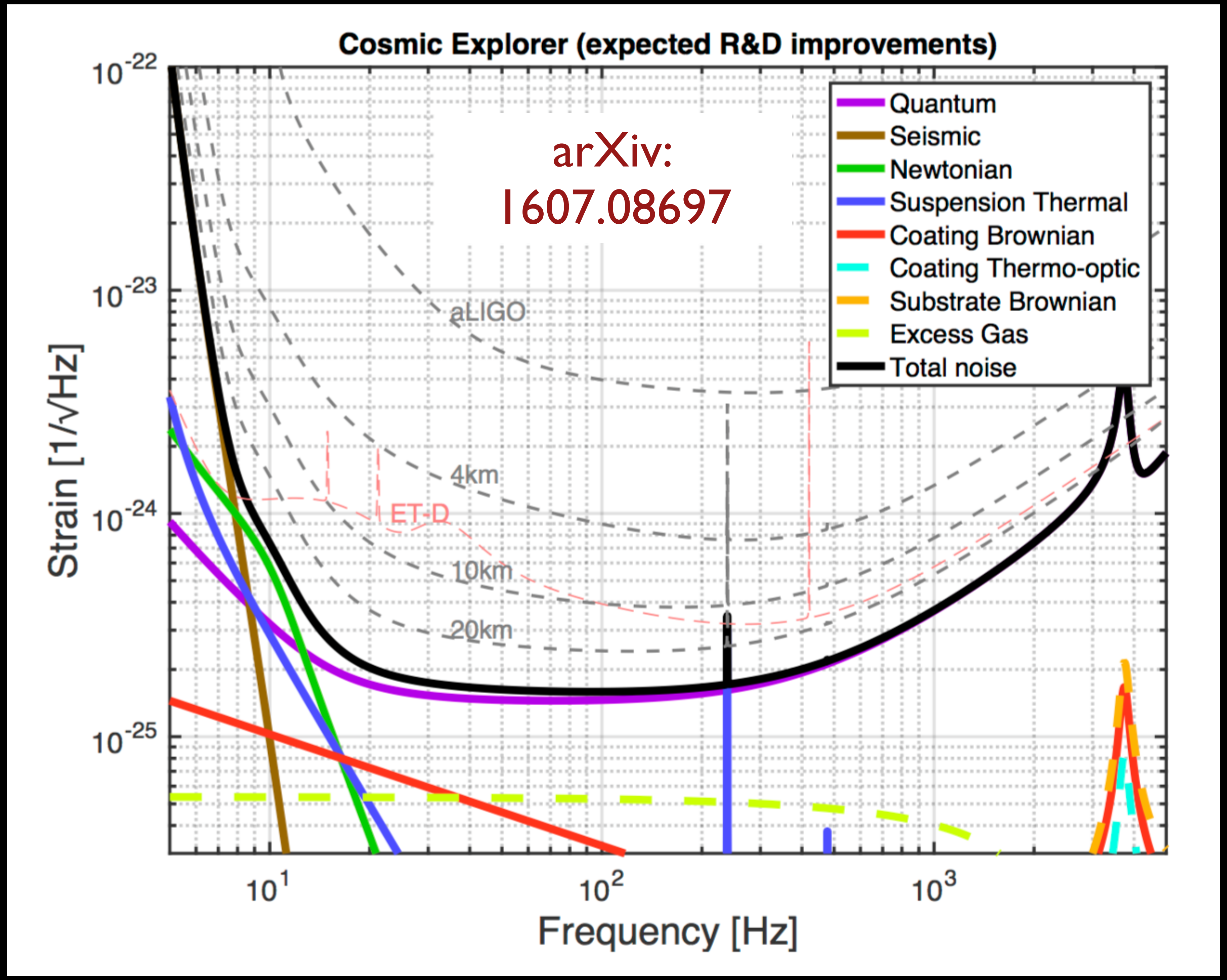


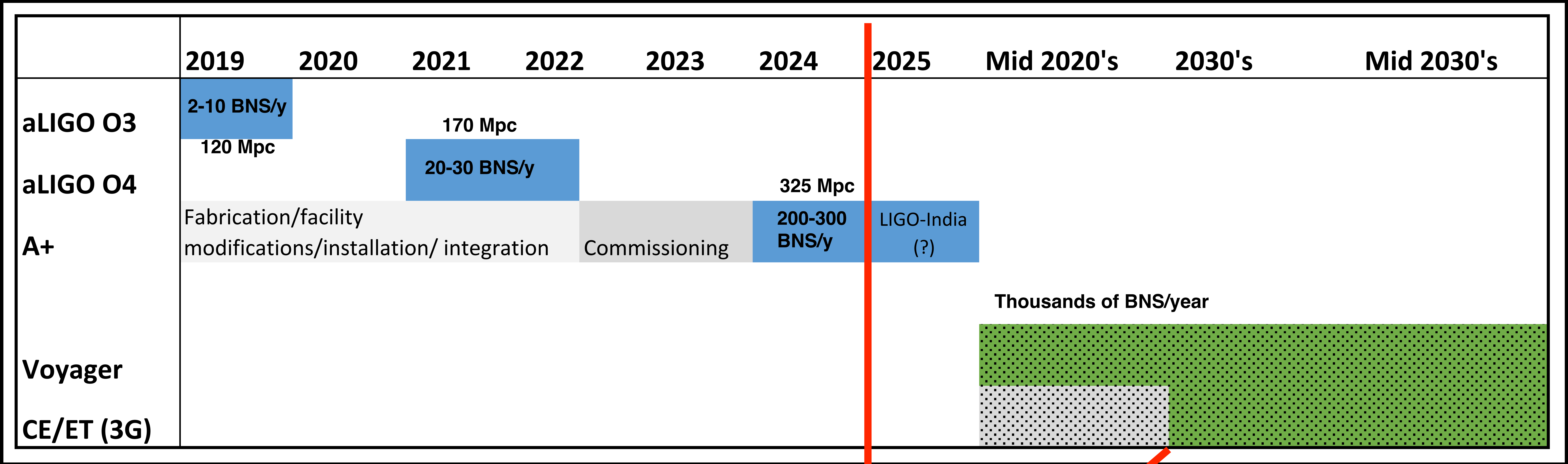
Einstein Telescope

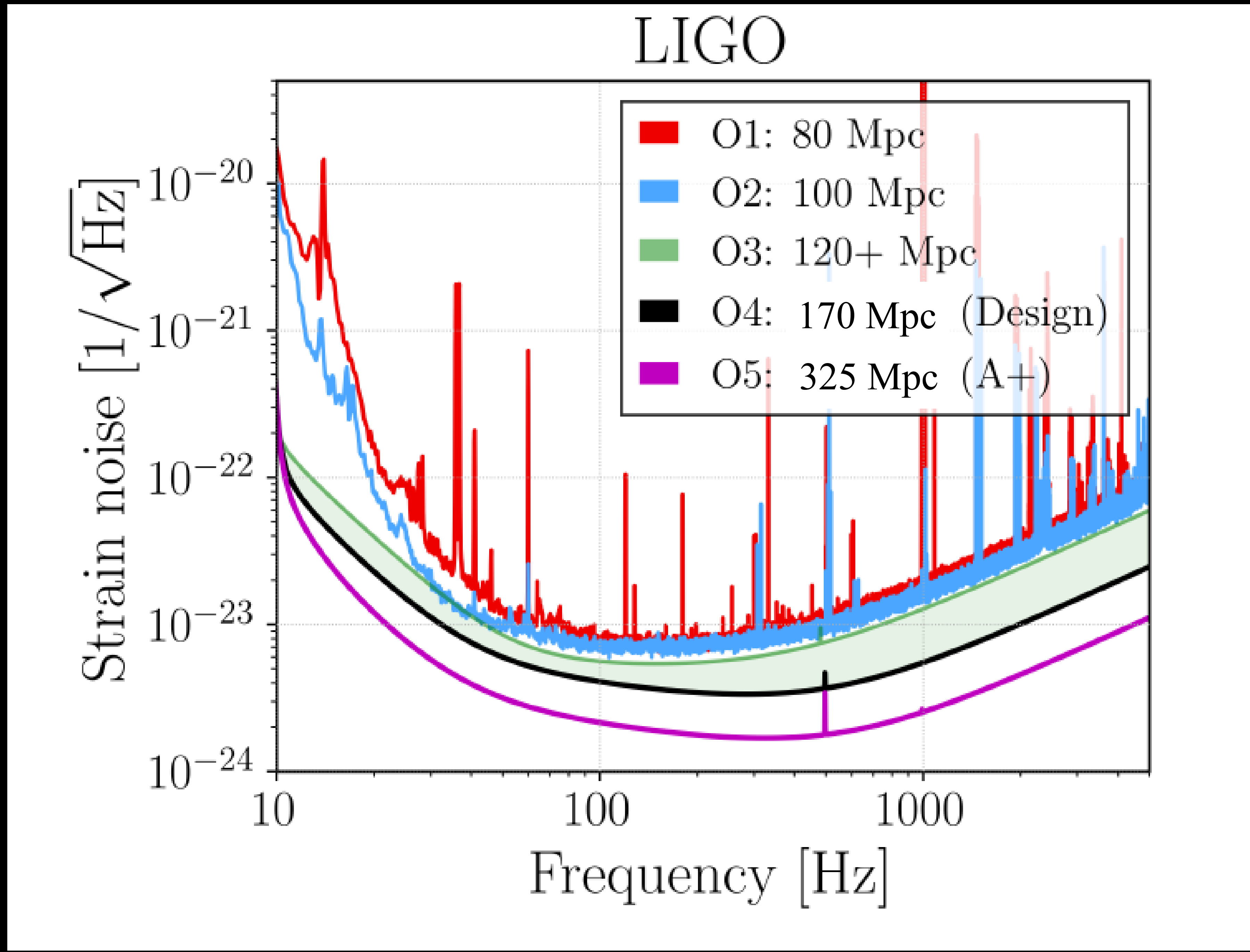
- European conceptual design study
- Multiple instruments in xylophone configuration
- underground to reduce newtonian background
- 10 km arm length, in triangle.
- Assumes 10-15 year technology development.

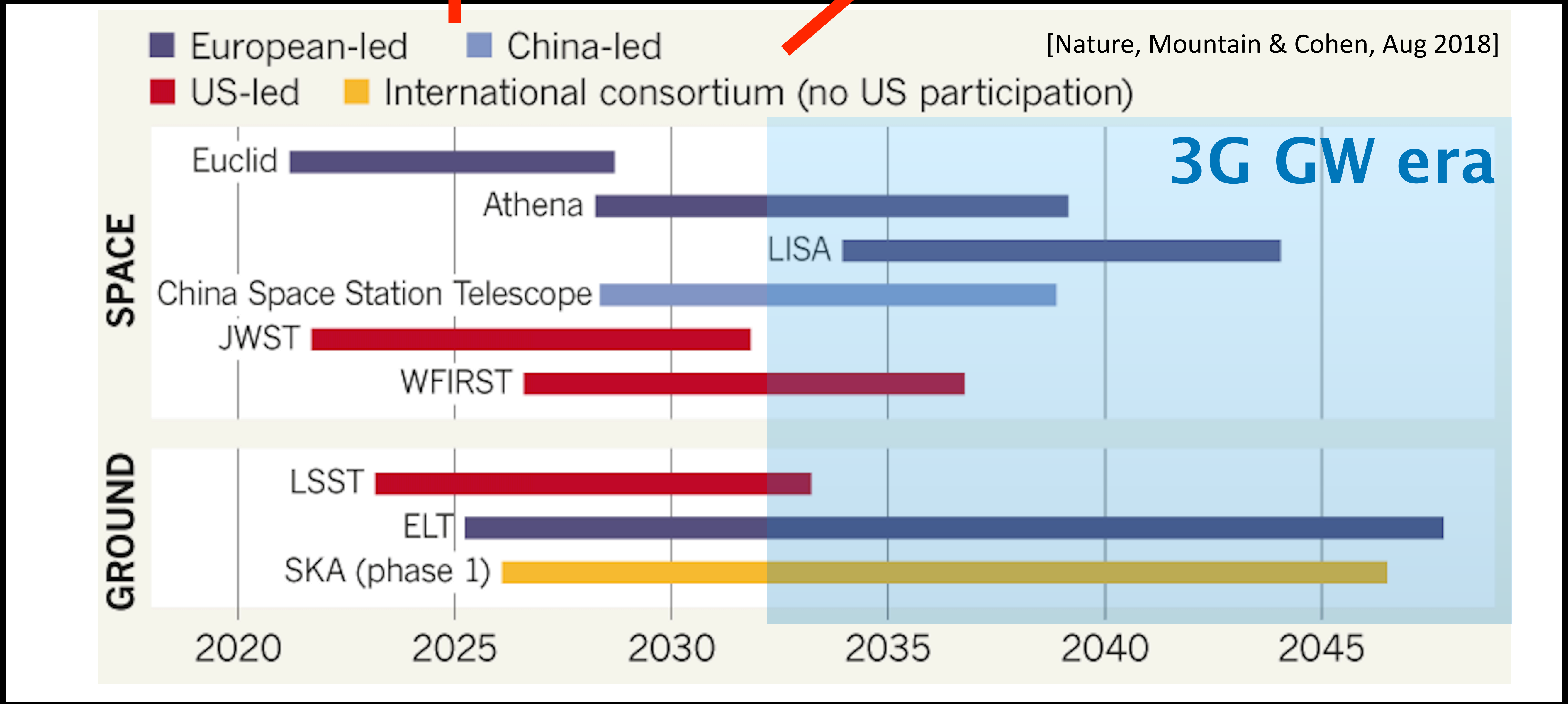
Cosmic Explorer

- NSF-funded US conceptual design study starting now
- 40km surface Observatory baseline
- Signal grows with length – not most noise sources
- Thermal noise, radiation pressure, seismic, Newtonian unchanged; coating thermal noise improves faster than linearly with length




2019
2020
2021
2022
2023
2024
2025
Mid 2020's
2030's
Mid 2030's
aLIGO O3
aLIGO O4
A+
Voyager
CE/ET (3G)
2-10 BNS/y
120 Mpc
170 Mpc
20-30 BNS/y
325 Mpc
Fabrication/facility modifications/installation/ integration
Commissioning
200-300 BNS/y
LIGO-India (?)
Thousands of BNS/year


LIGO
O1: 80 Mpc
O2: 100 Mpc
O3: 120+ Mpc
O4: 170 Mpc (Design)
O5: 325 Mpc (A+)
Strain noise [1/√Hz]
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10
100
1000
Frequency [Hz]


European-led
China-led
US-led
International consortium (no US participation)
[Nature, Mountain & Cohen, Aug 2018]
3G GW era
SPACE
Euclid
Athena
LISA
China Space Station Telescope
JWST
WFIRST
GROUND
LSST
ELT
SKA (phase 1)
2020
2025
2030
2035
2040
2045