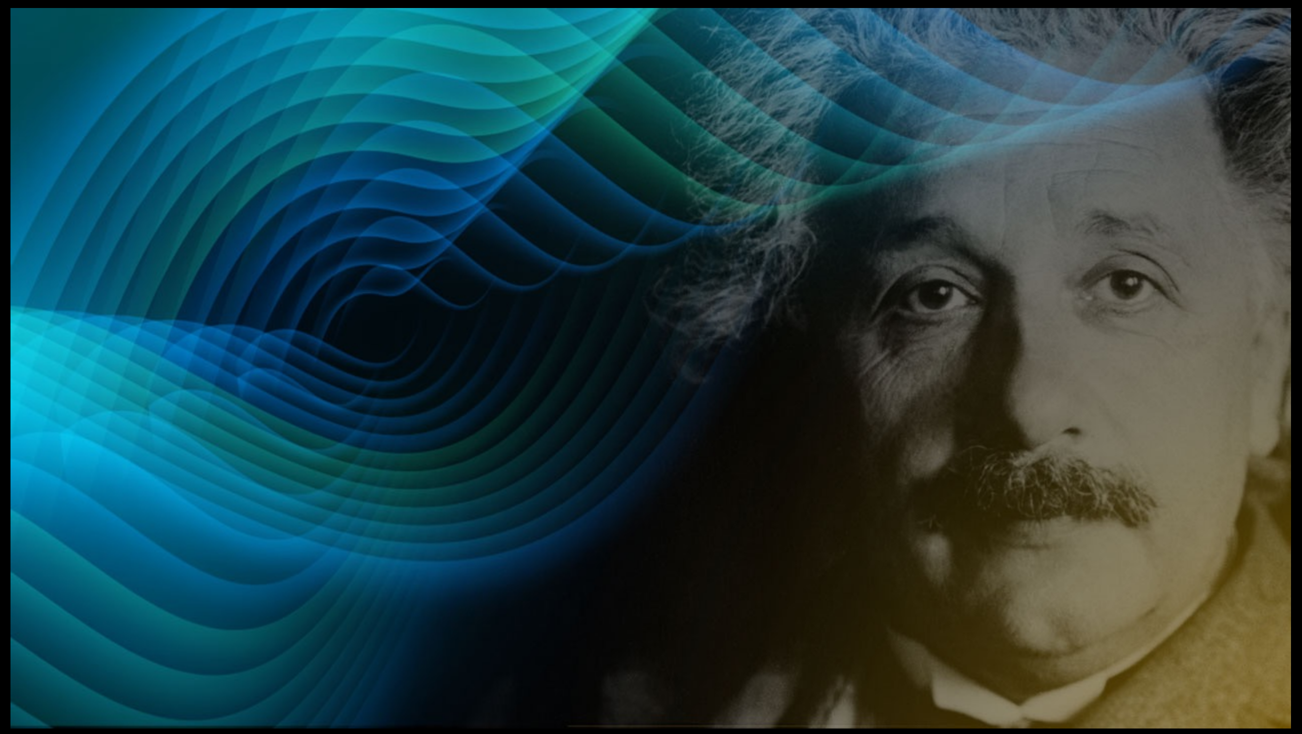
Ground-Based Gravitational Wave Detector Network

Laura Cadonati, Georgia Tech
LIGO Scientific Collaboration

Eighth International Fermi Symposium - October 15, 2018

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

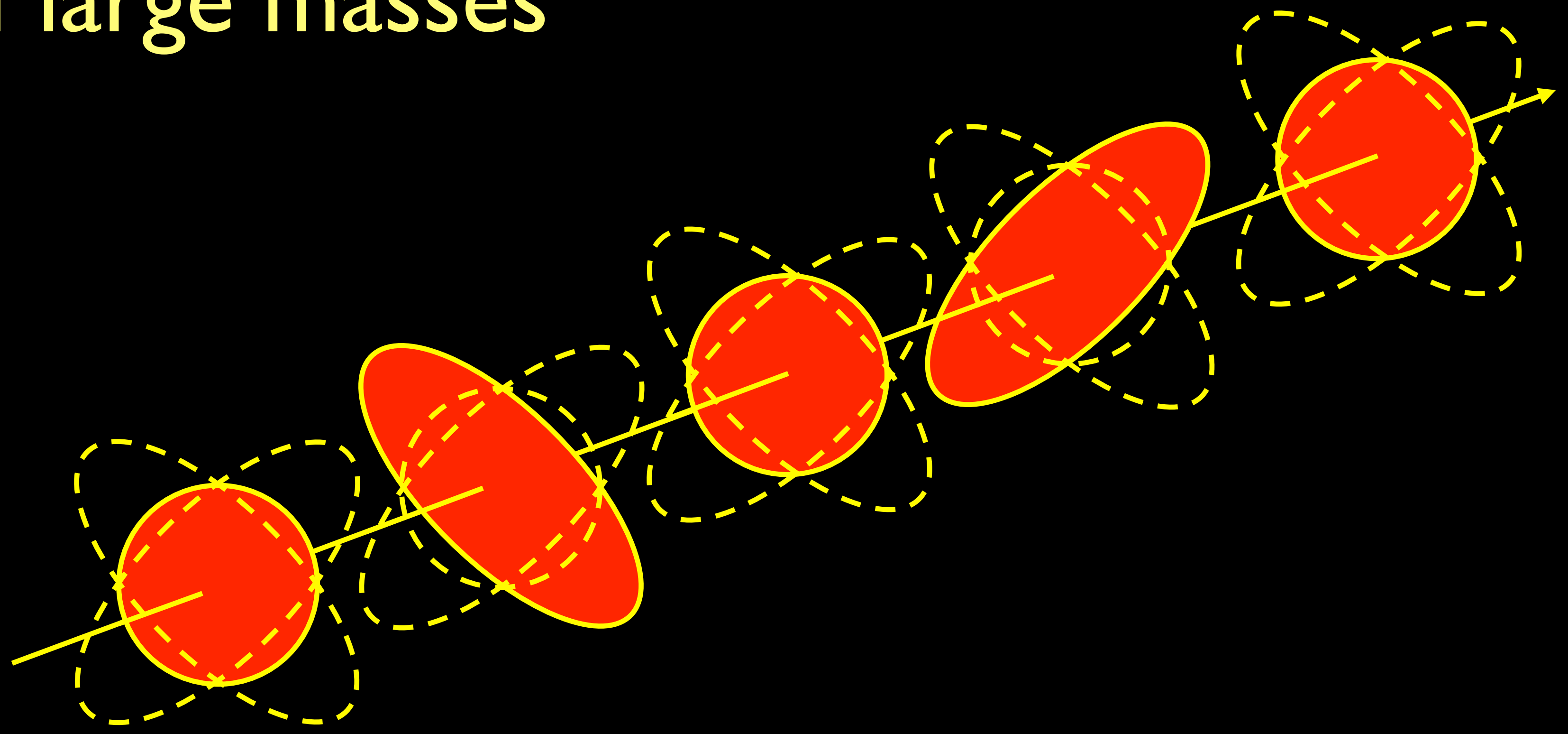
Gravitational Waves: Einstein's Messengers

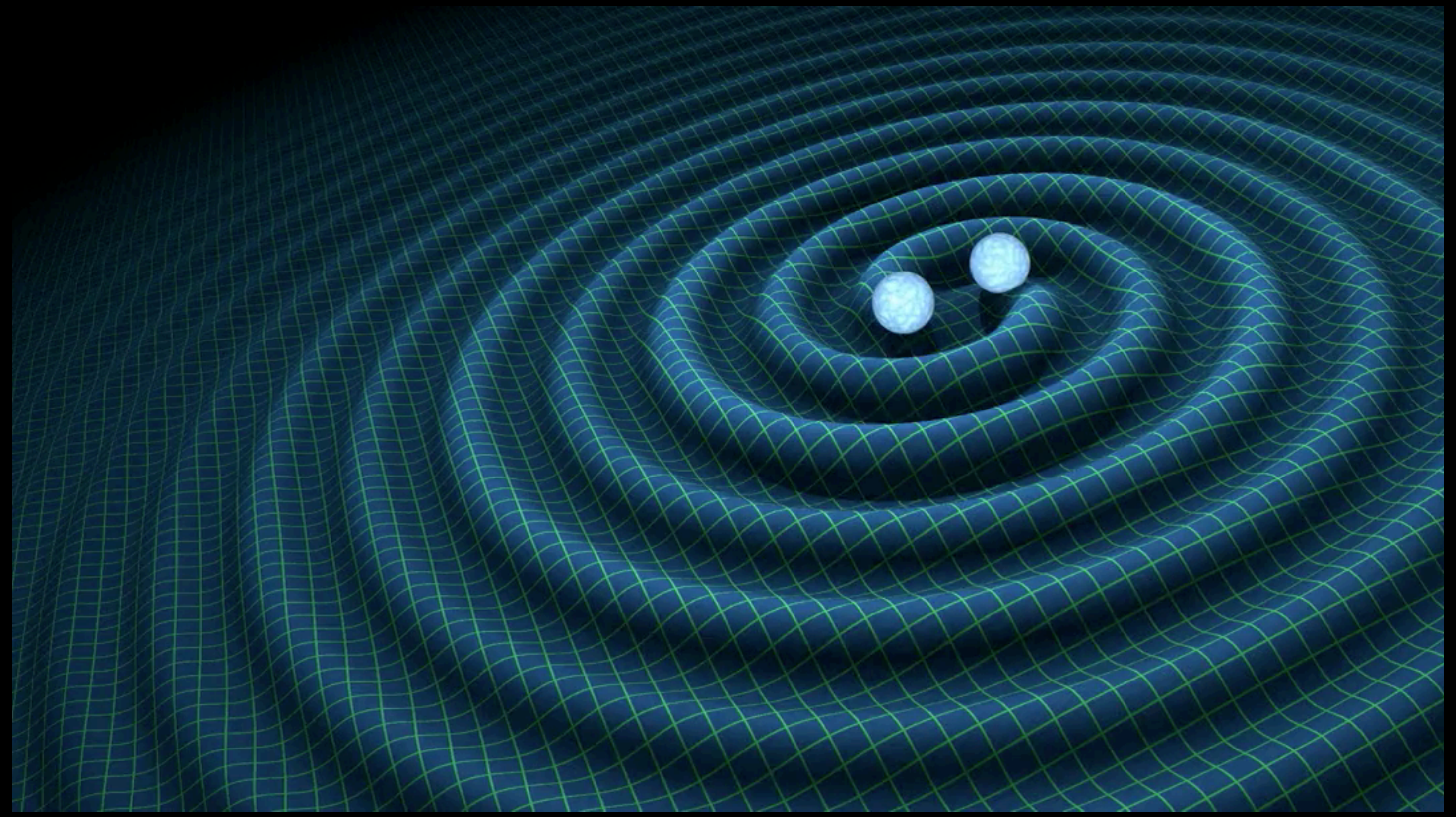


Perturbations of the space-time metric produced by rapid changes in shape and orientation of massive objects.

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Gravitational waves carry information from the coherent, relativistic motion of large masses





Credits: R. Hurt - Caltech / JPL

speed of light

2 polarizations (plus, cross)

Dimensionless strain:

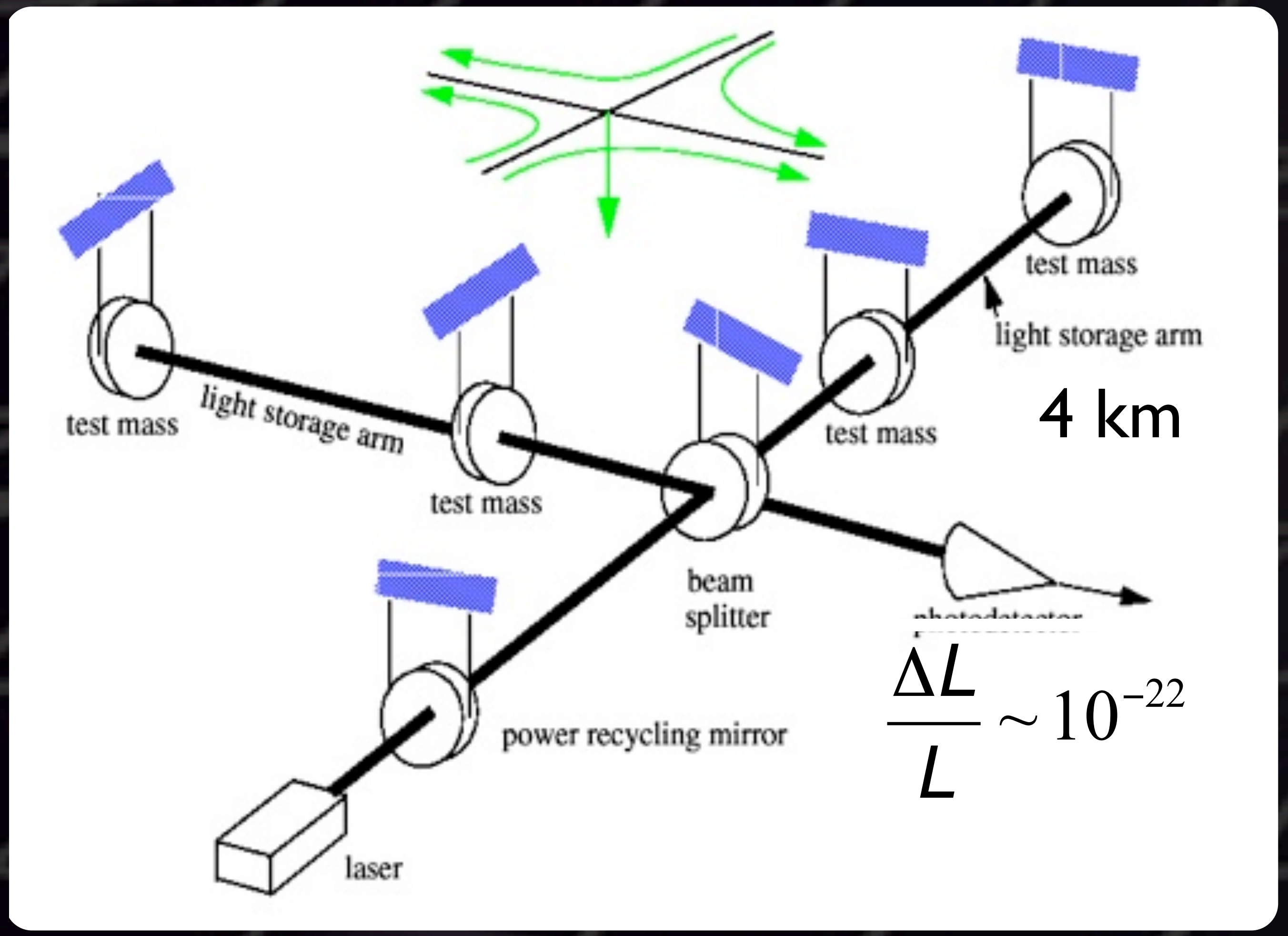
$$h(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}(t)$$

I = source mass quadrupole moment

R = source distance

LIGO: Laser Interferometer Gravitational-wave Observatory

Suspended Mirrors as Test Masses



Goal: measure difference in length to one part in 10^{22}, or 10^{-19} meters

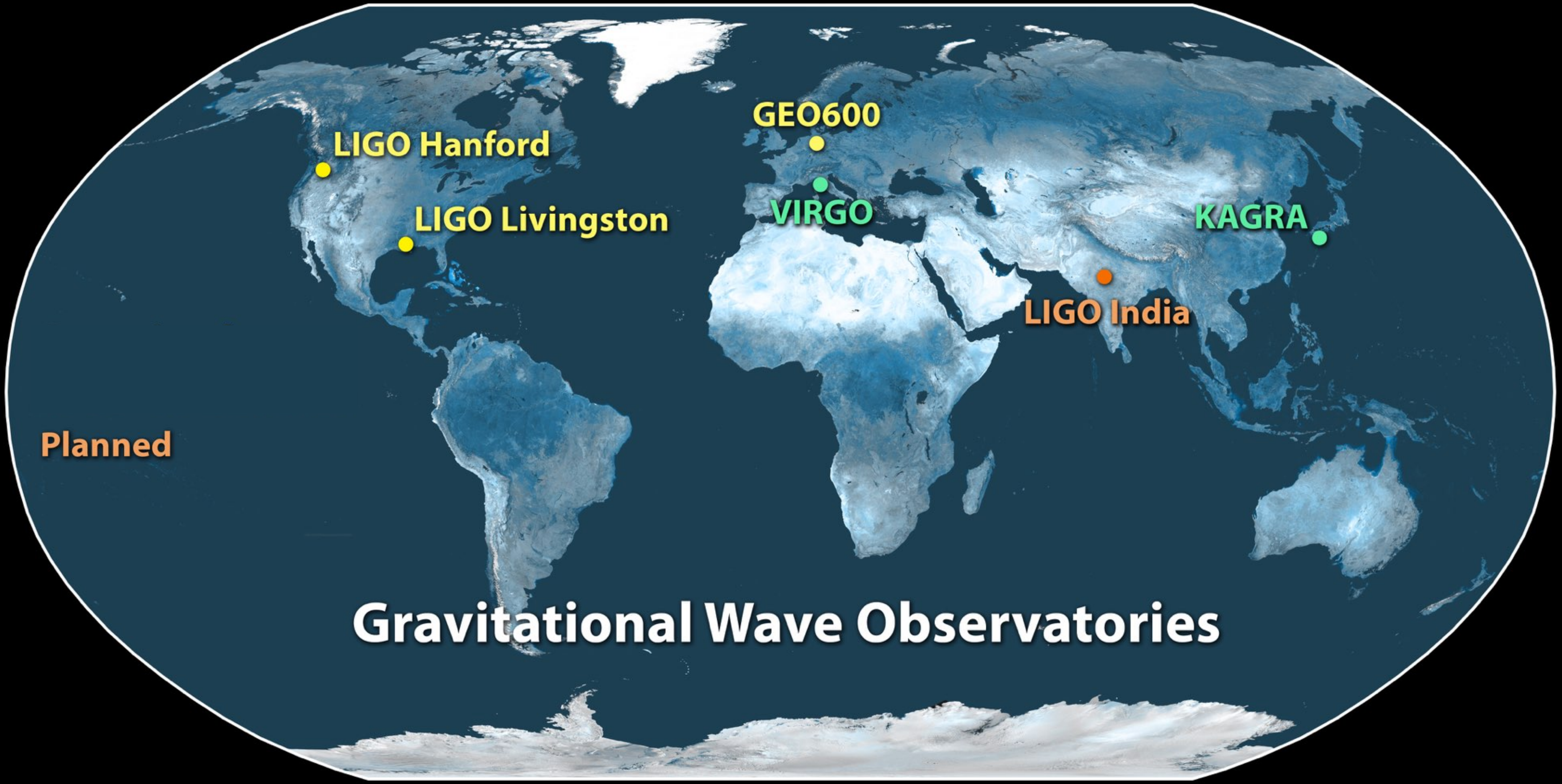
Hanford, WA

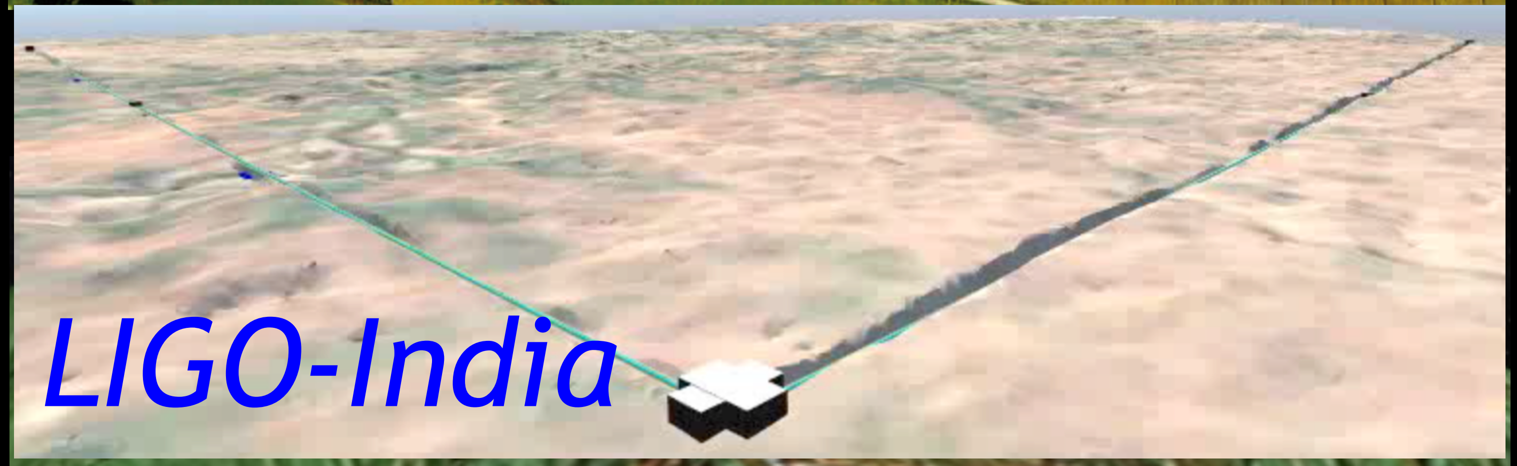
Livingston, LA

- LIGO Observatories construction: 1994-2000
- Initial LIGO operation: 2002-2010
- Advanced LIGO:
  - O1: Sept 12, 2015 - Jan 12, 2016
  - O2: Dec 1, 2016 - Aug 25, 2017

The LIGO Laboratory is jointly operated by Caltech and MIT through a Cooperative Agreement between Caltech and the National Science Foundation

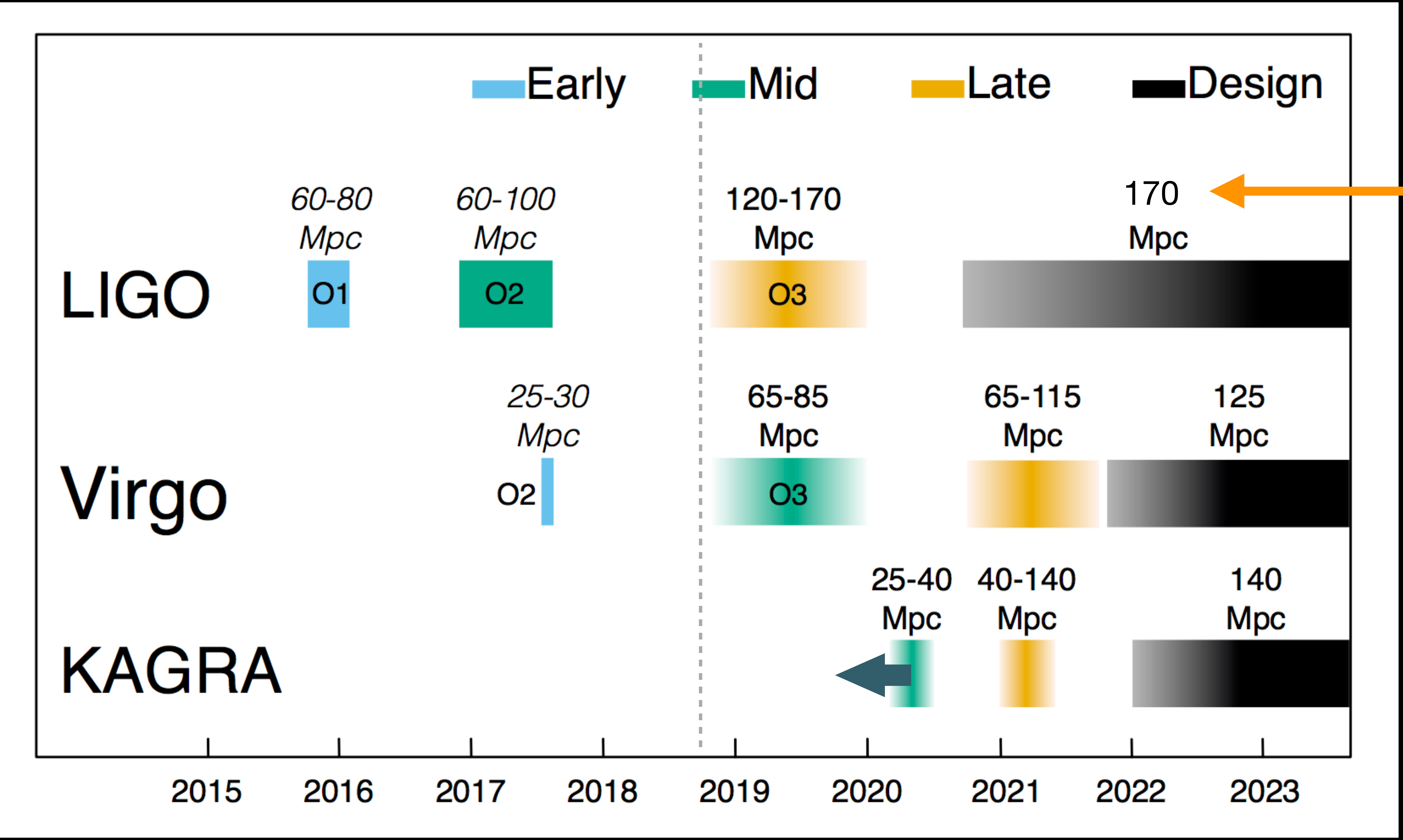
A Global Quest





LIGO, Virgo: Km-scale, on the surface, room temperature, fused silica mirrors
KAGRA: Km-scale, underground, sapphire test masses at 10K

Short-term Plans

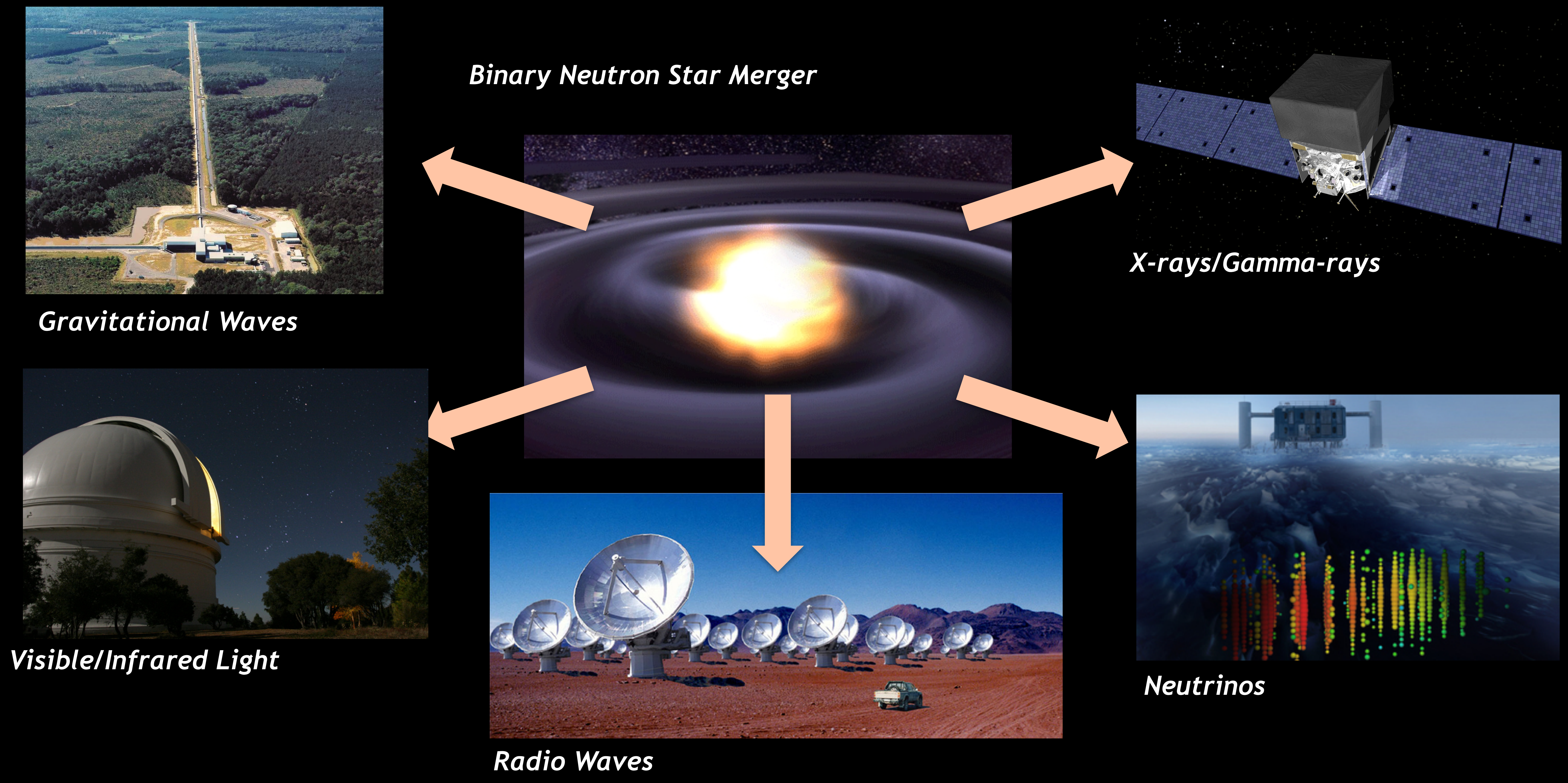


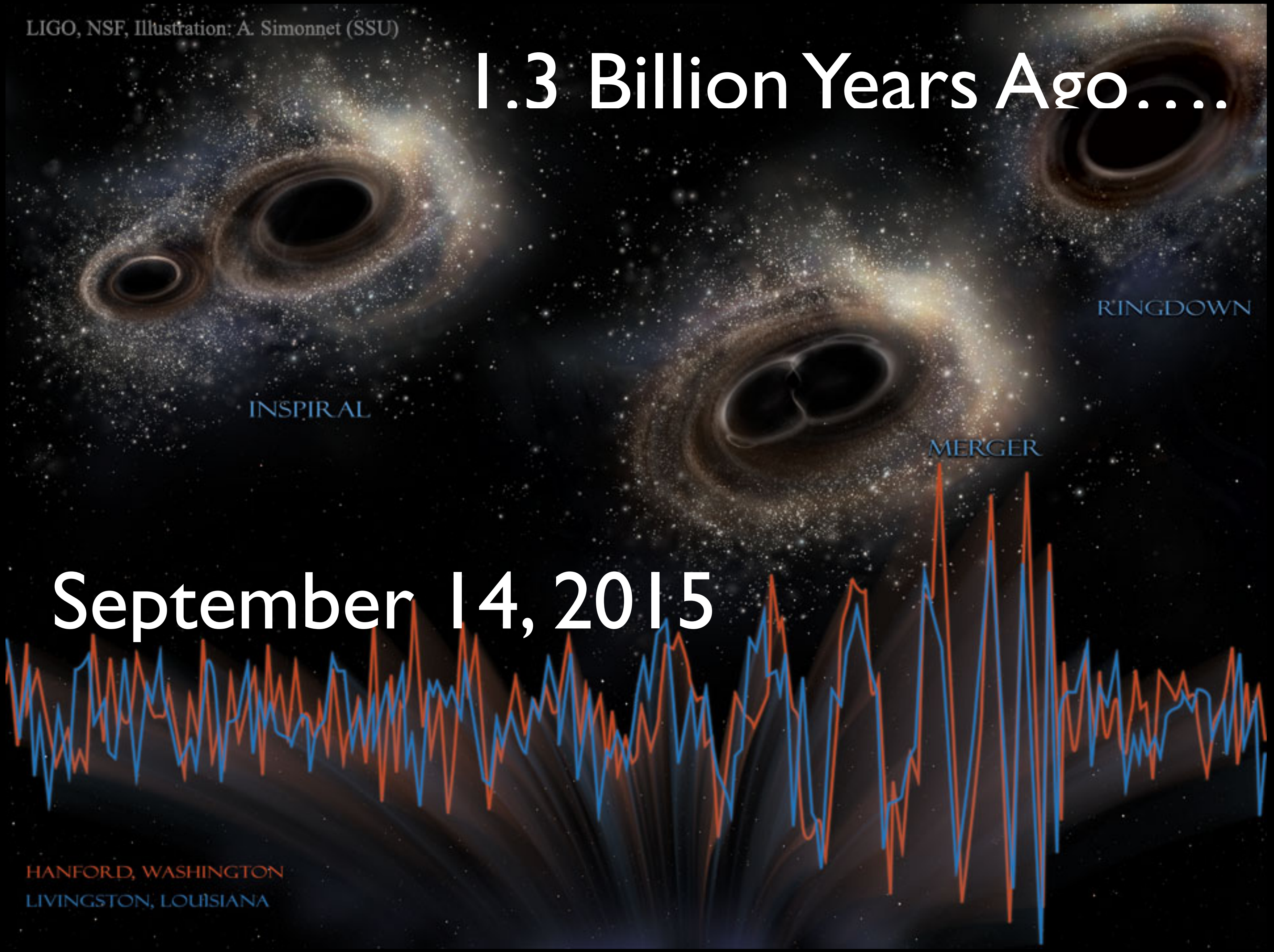
BNS range

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo and KAGRA — https://dcc.ligo.org/LIGO-P1200087/public

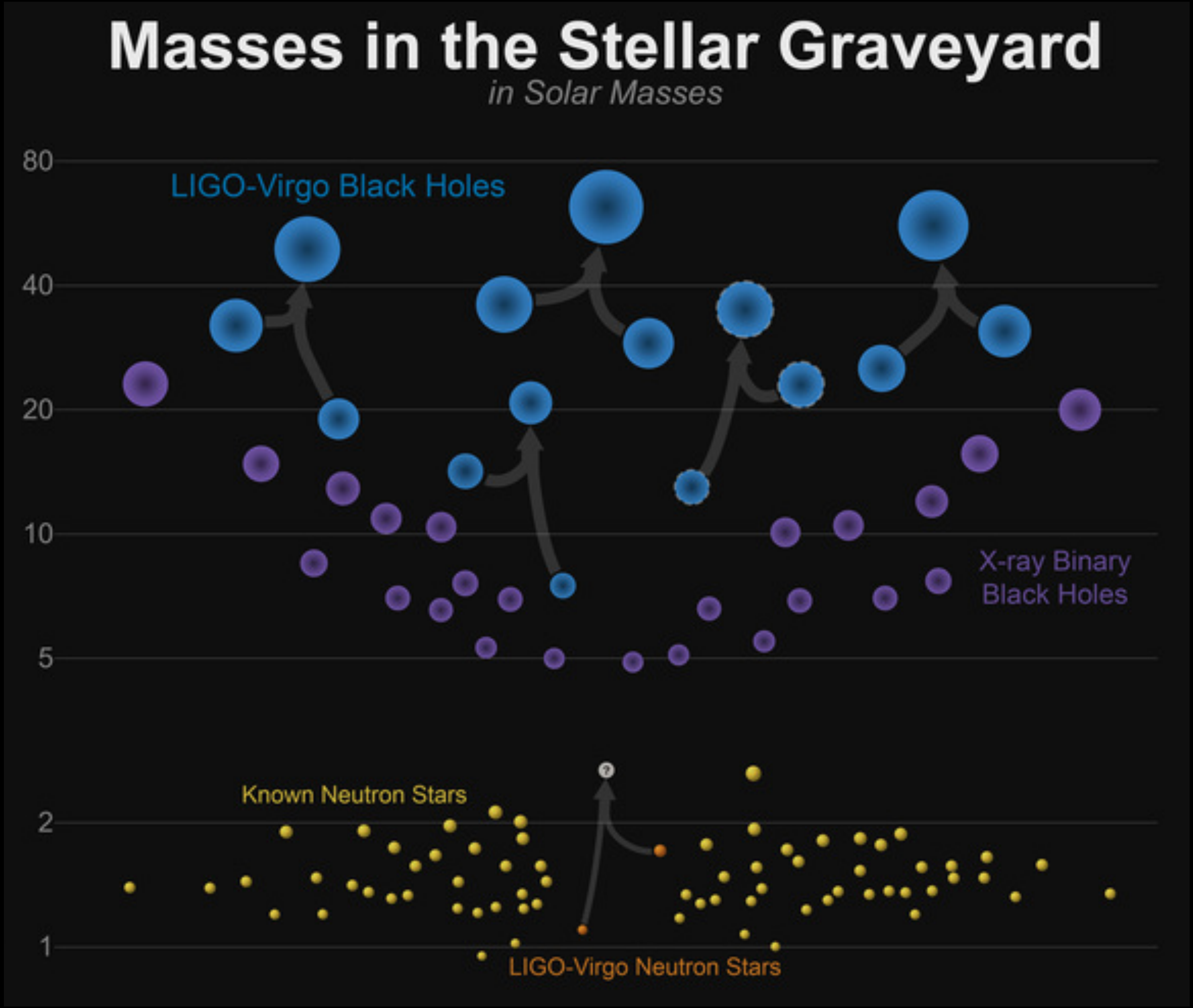
See also: https://www.ligo.org/scientists/GWEMalerts.php

Multi-messenger Astronomy with Gravitational Waves




LIGO, NSF, Illustration: A. Simonnet (SSU)
1.3 Billion Years Ago….
RINGDOWN
INSPIRAL
MERGER
September 14, 2015
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

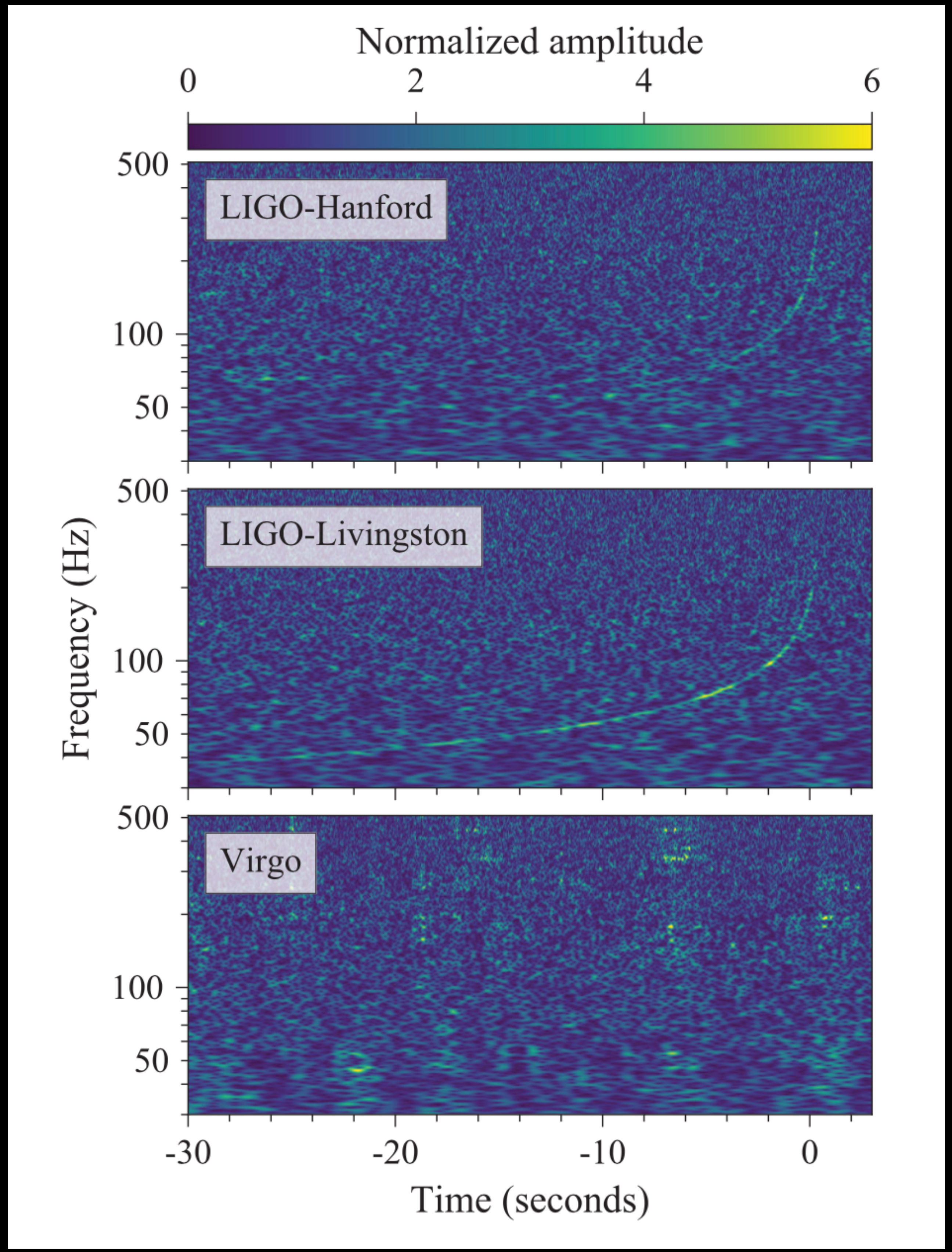

135 Million Years Ago….
August 17, 2017


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars

GW170817: Discovery of a Binary Neutron Star Merger

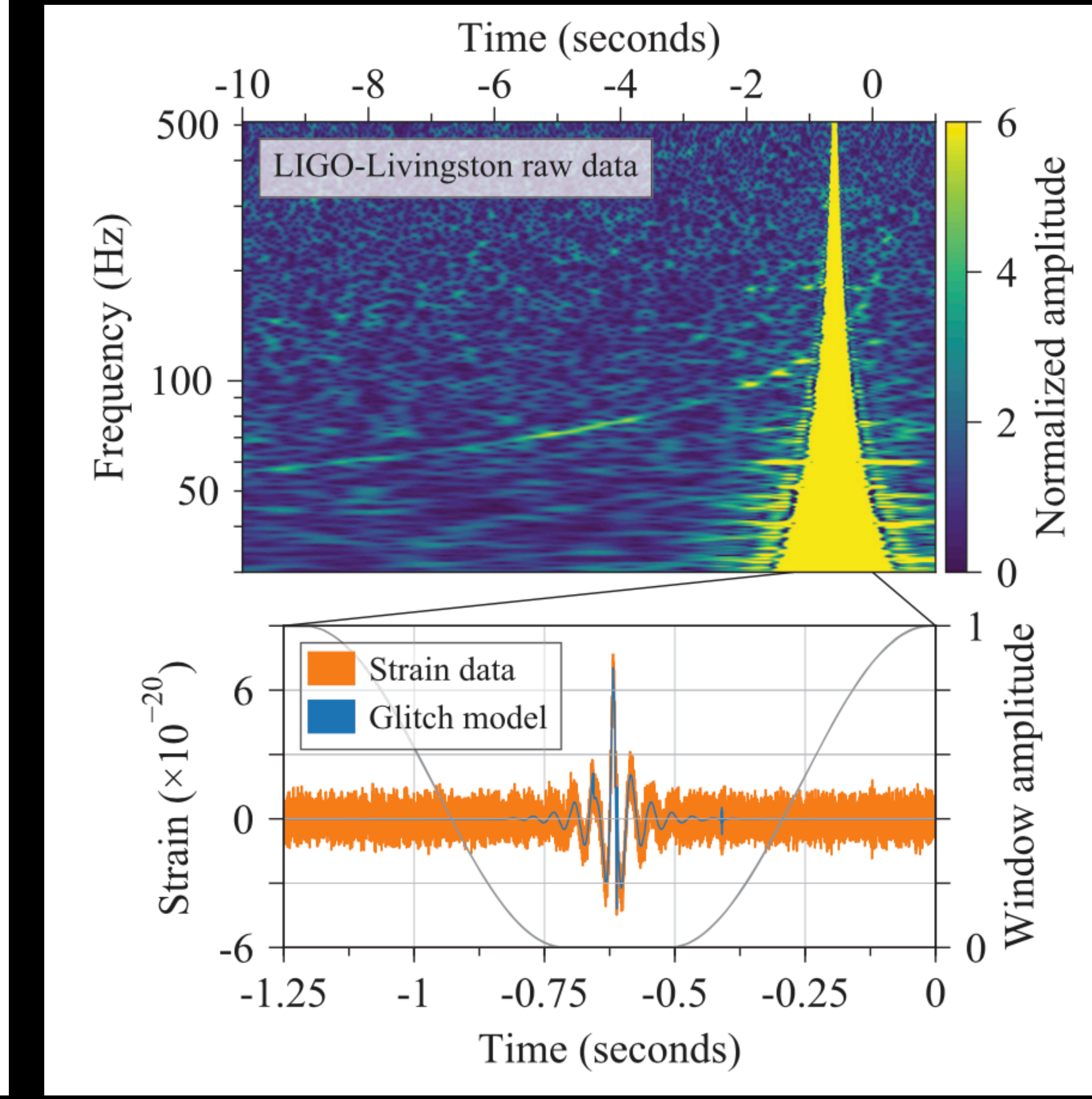
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral
Phys. Rev. Lett., 119:161101, 2017

August 17, 2017 - 12:41:04.4 UTC



GW170817 swept the detectors' sensitive band in ~100s (f_{start} = 24Hz)

Most significant (network SNR of 32.4), closest and best localized signal signal ever observed by LIGO/Virgo

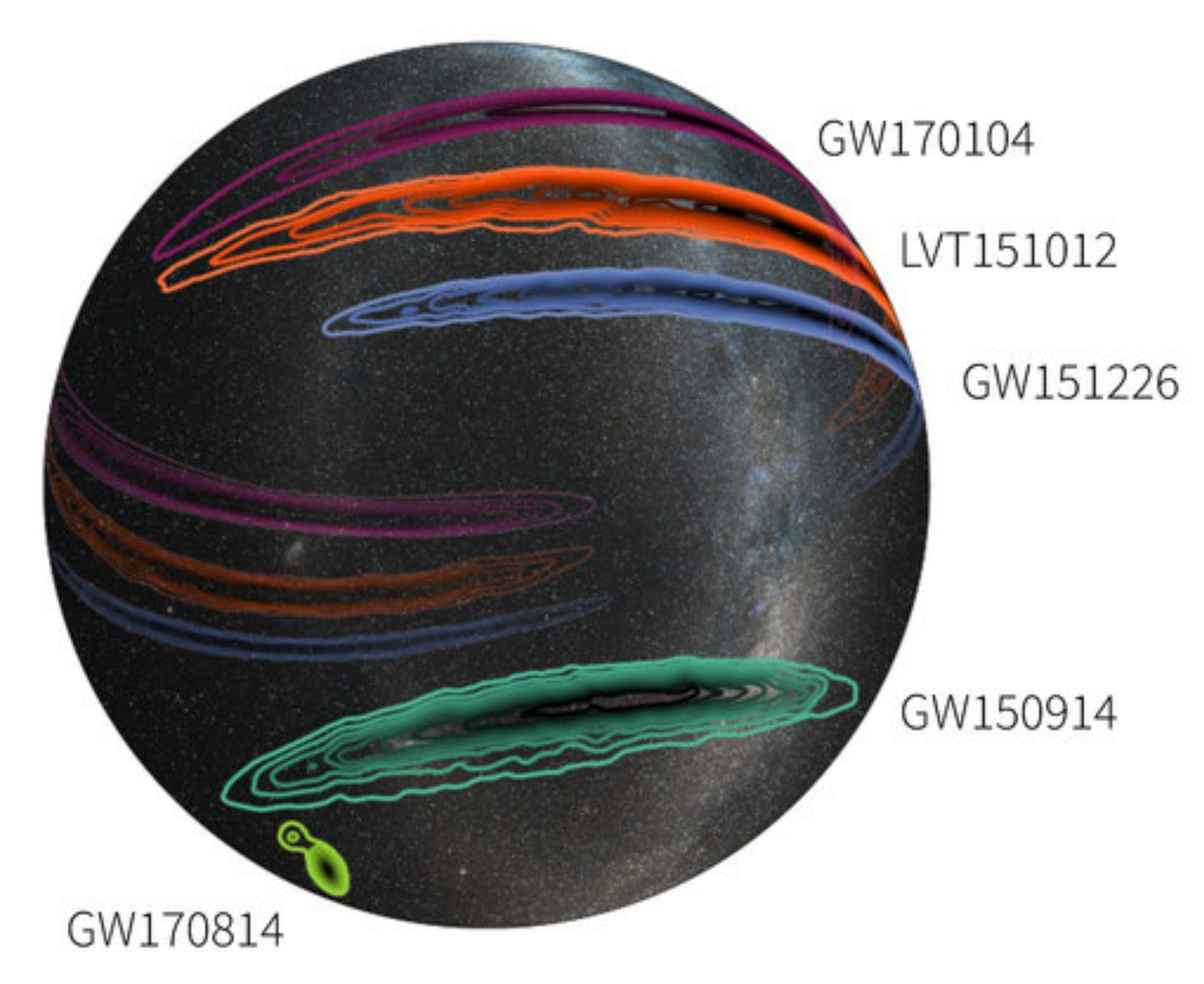


Glitch in L1 1.1 seconds before the coalescence

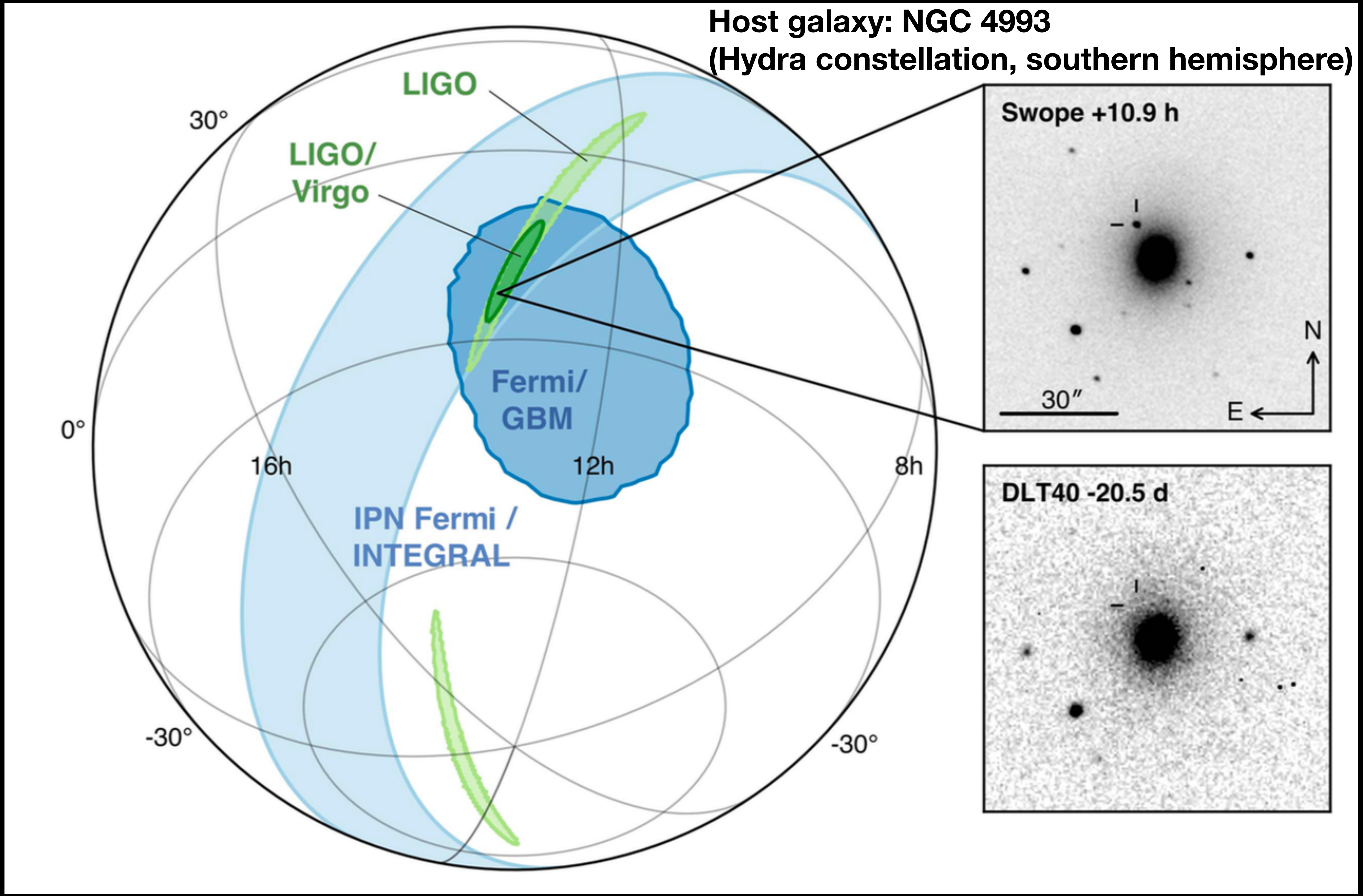
Similar noise transients are registered roughly once every few hours in each of the LIGO detectors - no temporal correlation between the LIGO sites

glitch cleaning

Localization

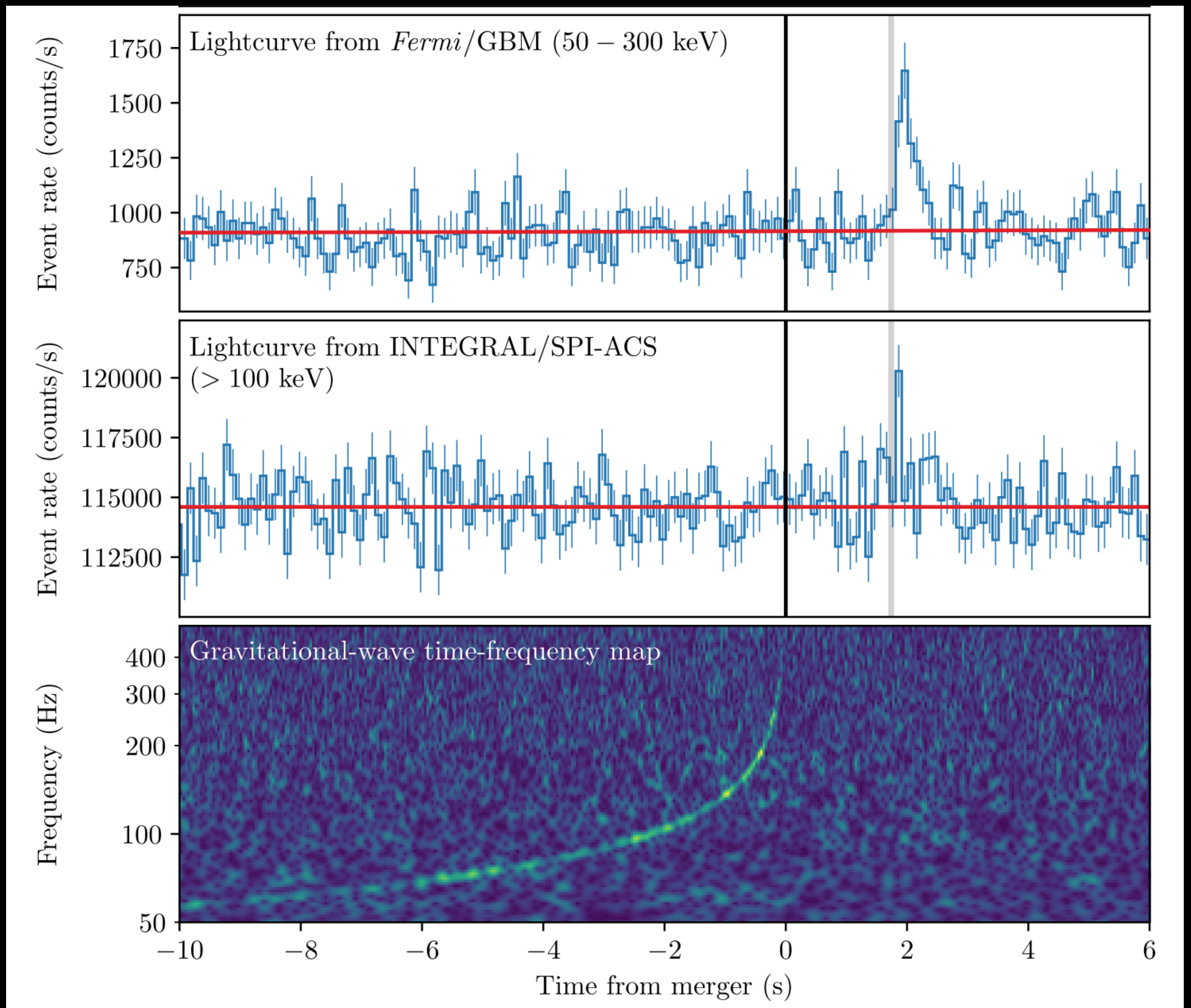


A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence
Phys. Rev. Lett., 119:141101, 2017

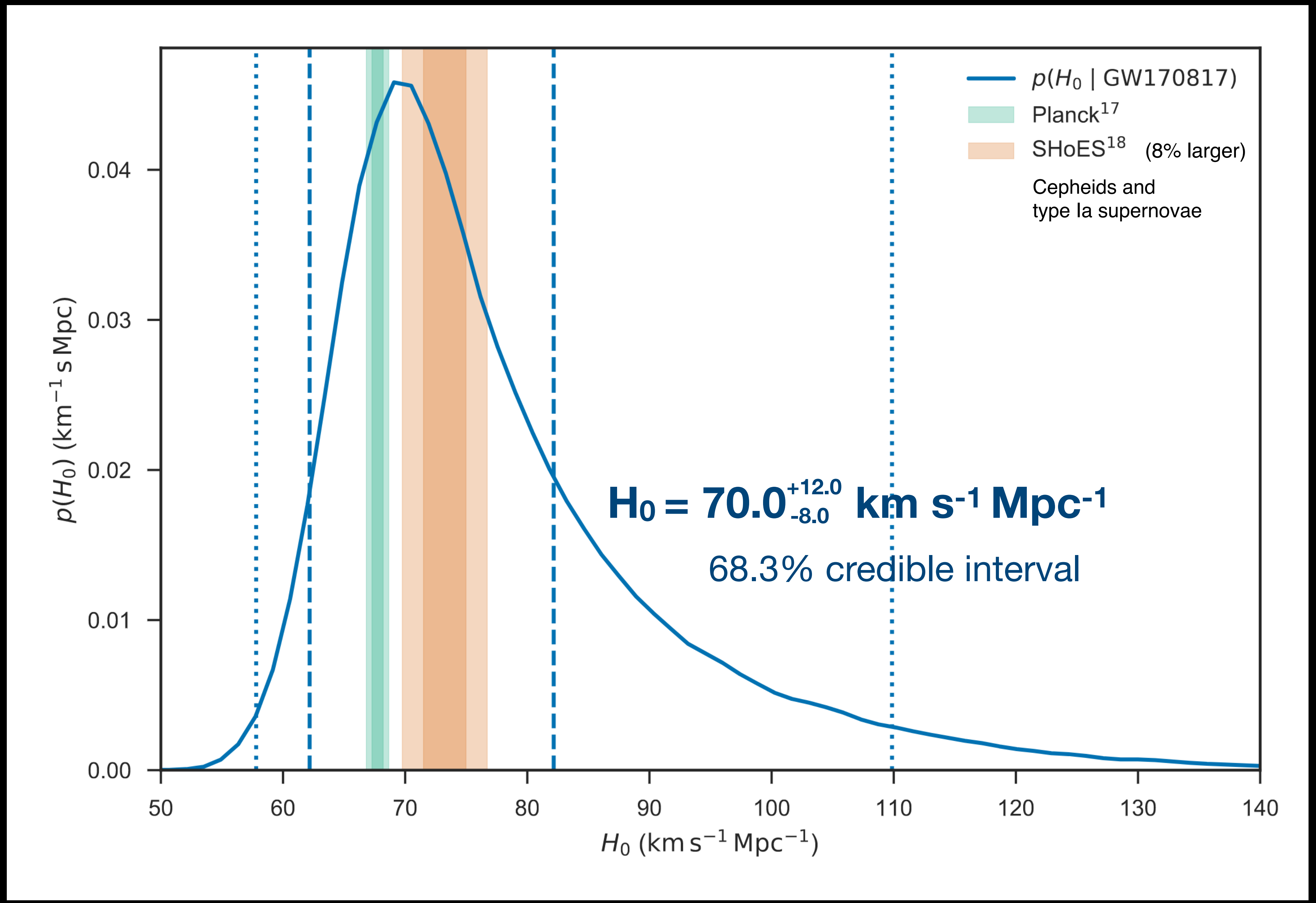


Multi-messenger Observations of a Binary Neutron Star Merger
The Astrophysical Journal Letters, 848:L12, 2017

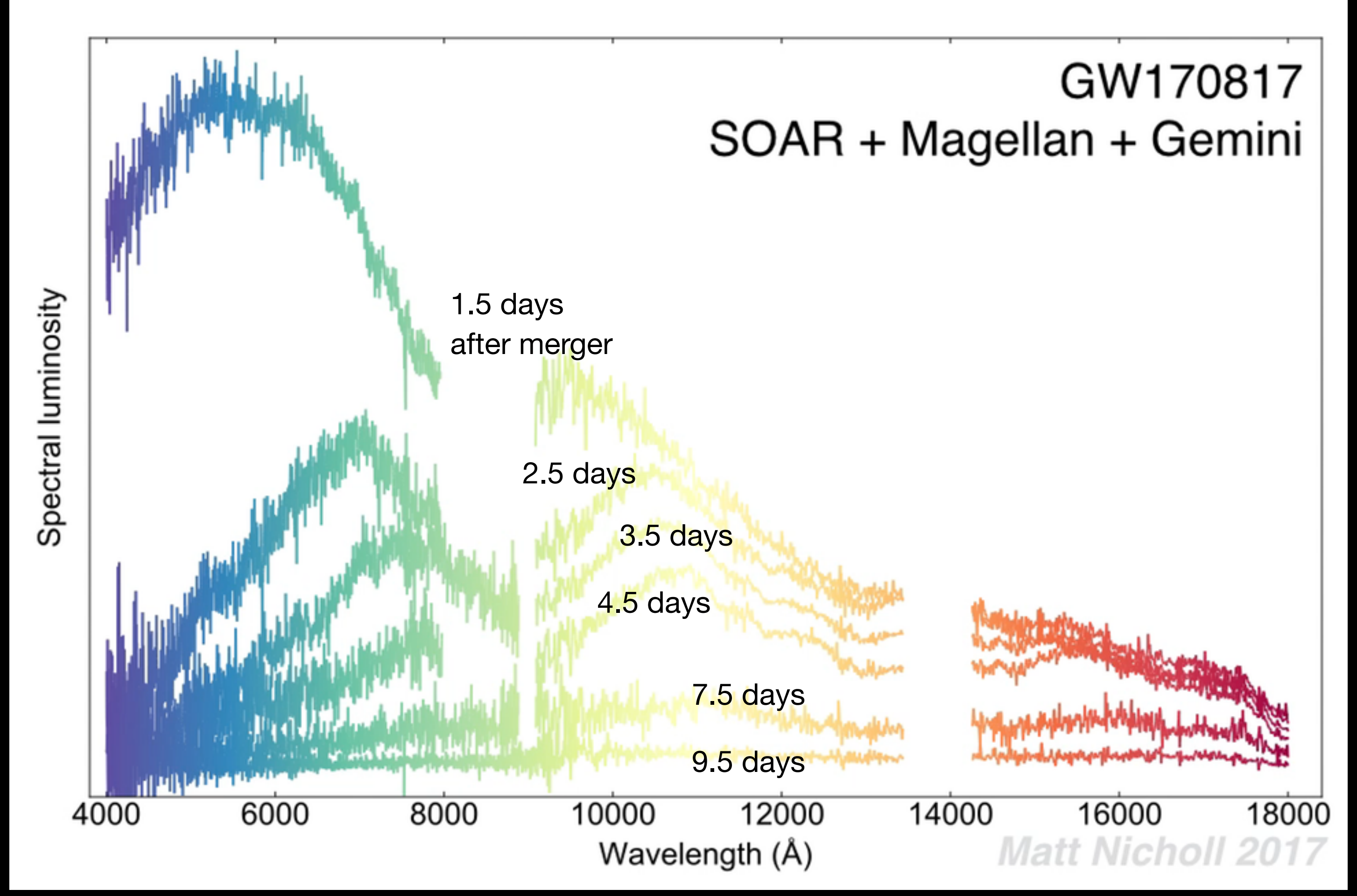
Multi-Messenger Science with GW170817

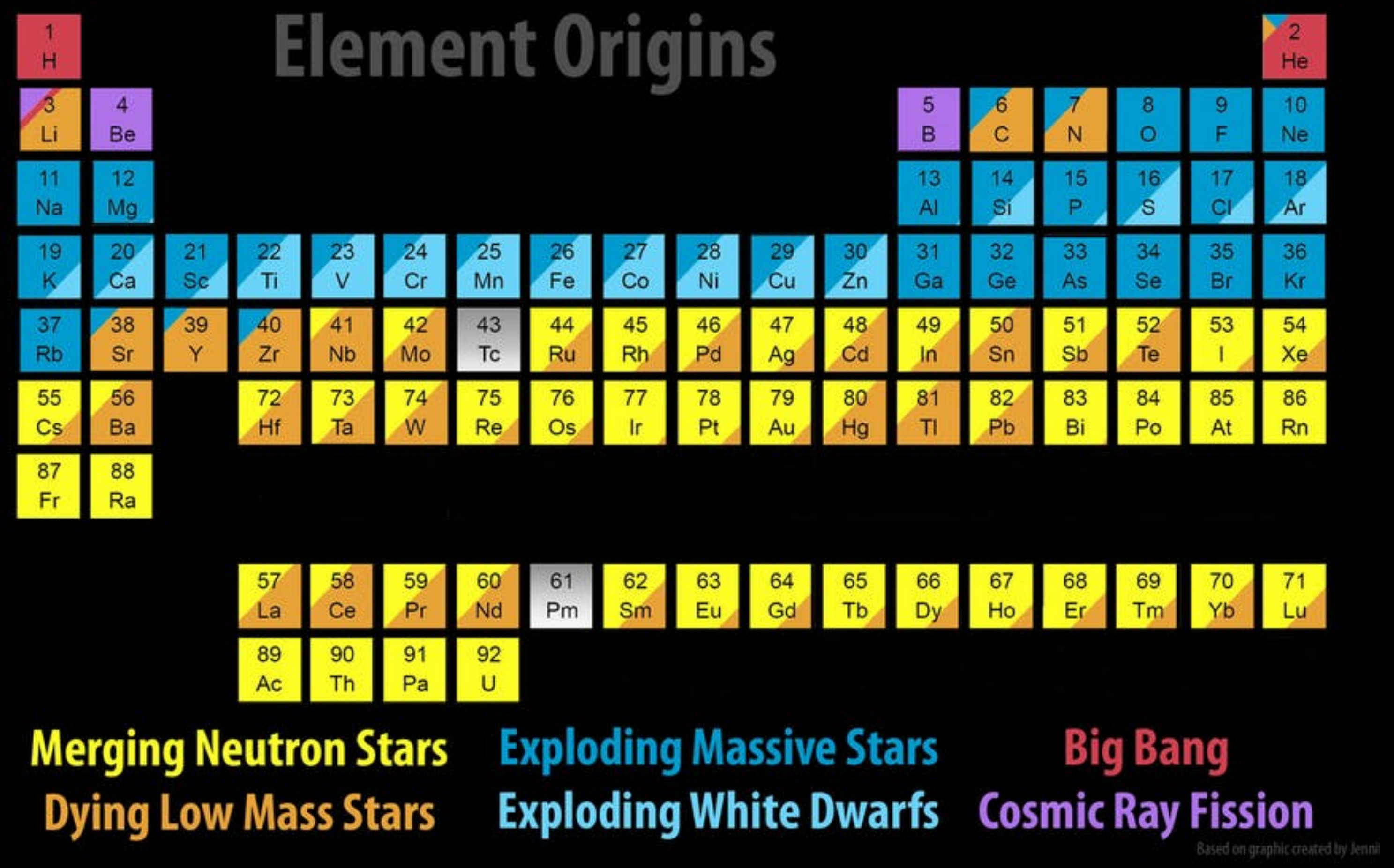


BNS mergers and GRBs



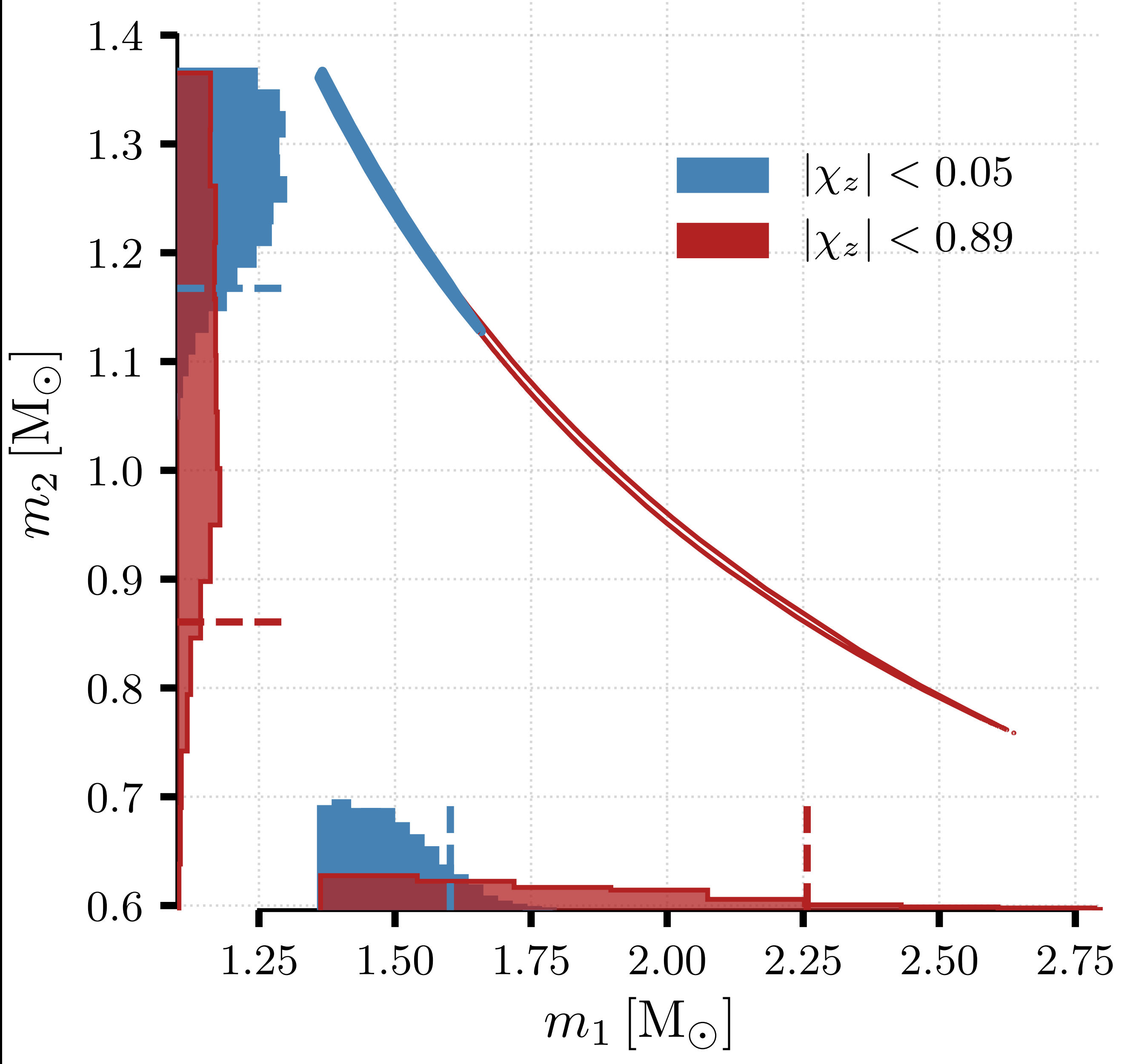
Measuring the Hubble Constant





BNS mergers and Kilonovae

BNS properties



PRL 119, 161101, 2017

The properties of gravitational-wave sources are inferred by matching the data with predicted waveforms

For low orbital and gravitational-wave frequencies the evolution of the frequency is dominated by chirp mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

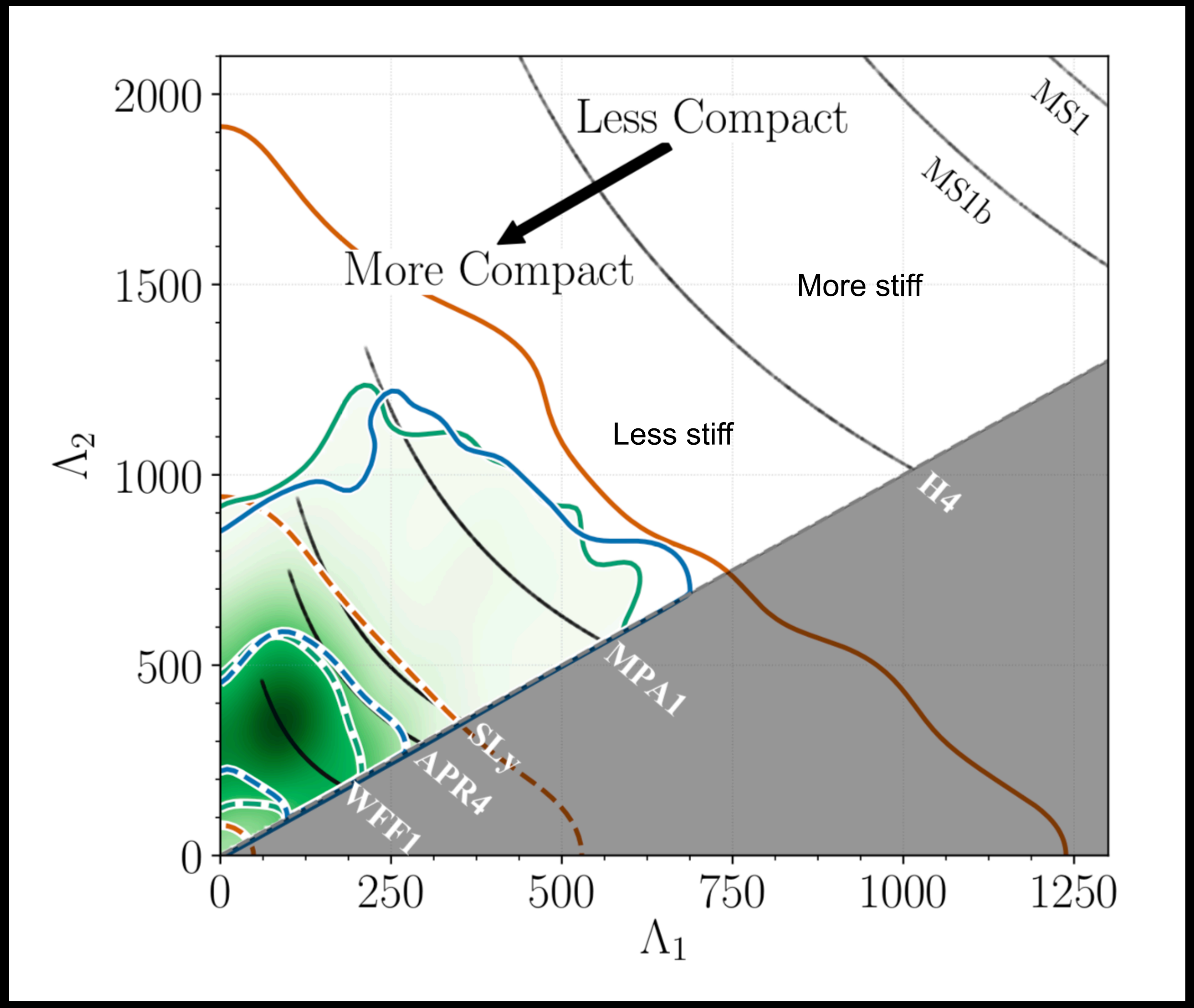
As orbit shrinks the gravitational-wave phase is increasing influenced by relativistic effects related to the mass ratio

Component masses are affected by the degeneracy between mass ratio and the aligned spin components χ_{1z} and χ_{2z}

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

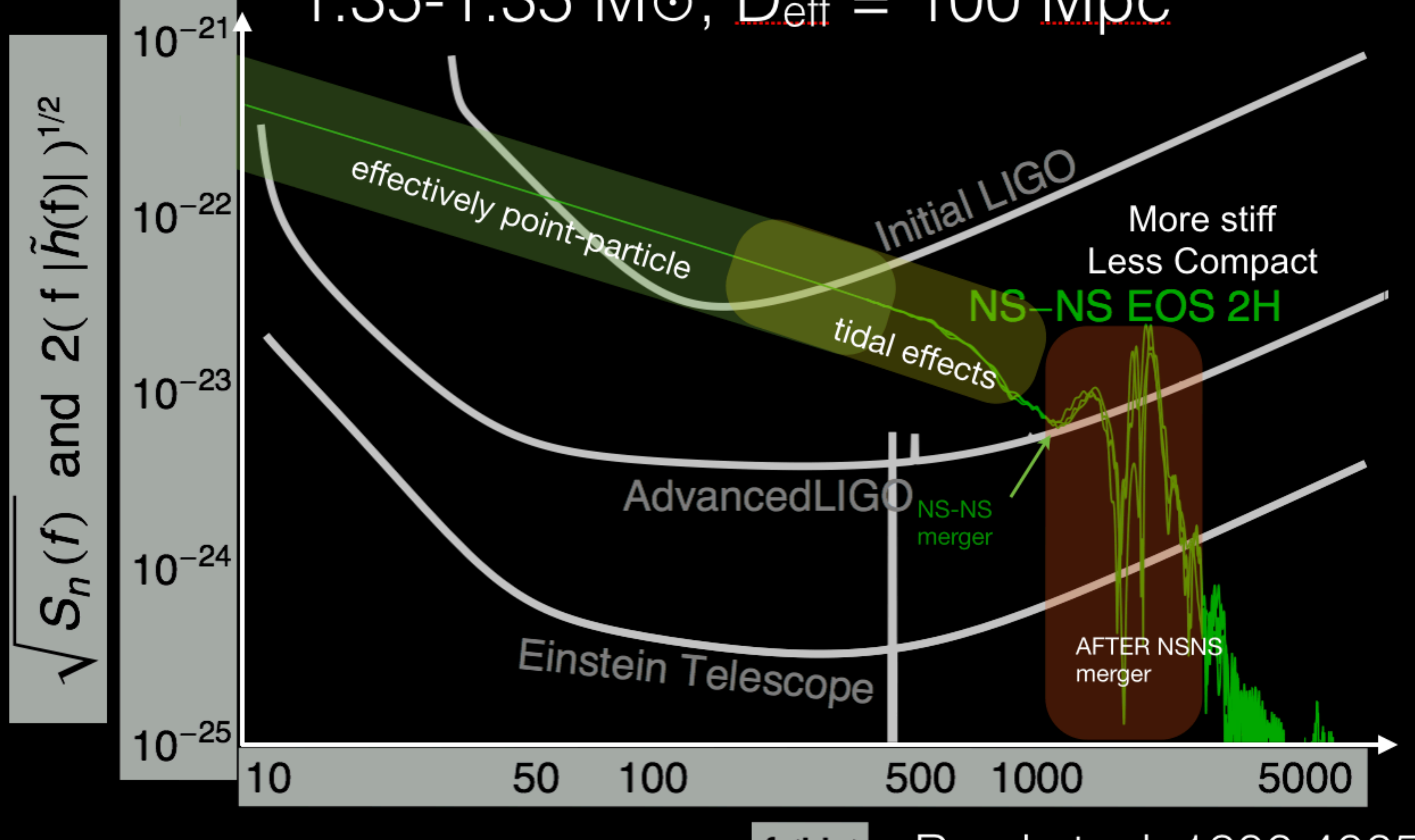
Properties of the binary neutron star merger GW170817 - arXiv:1805.11579

Neutron Star Structure



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

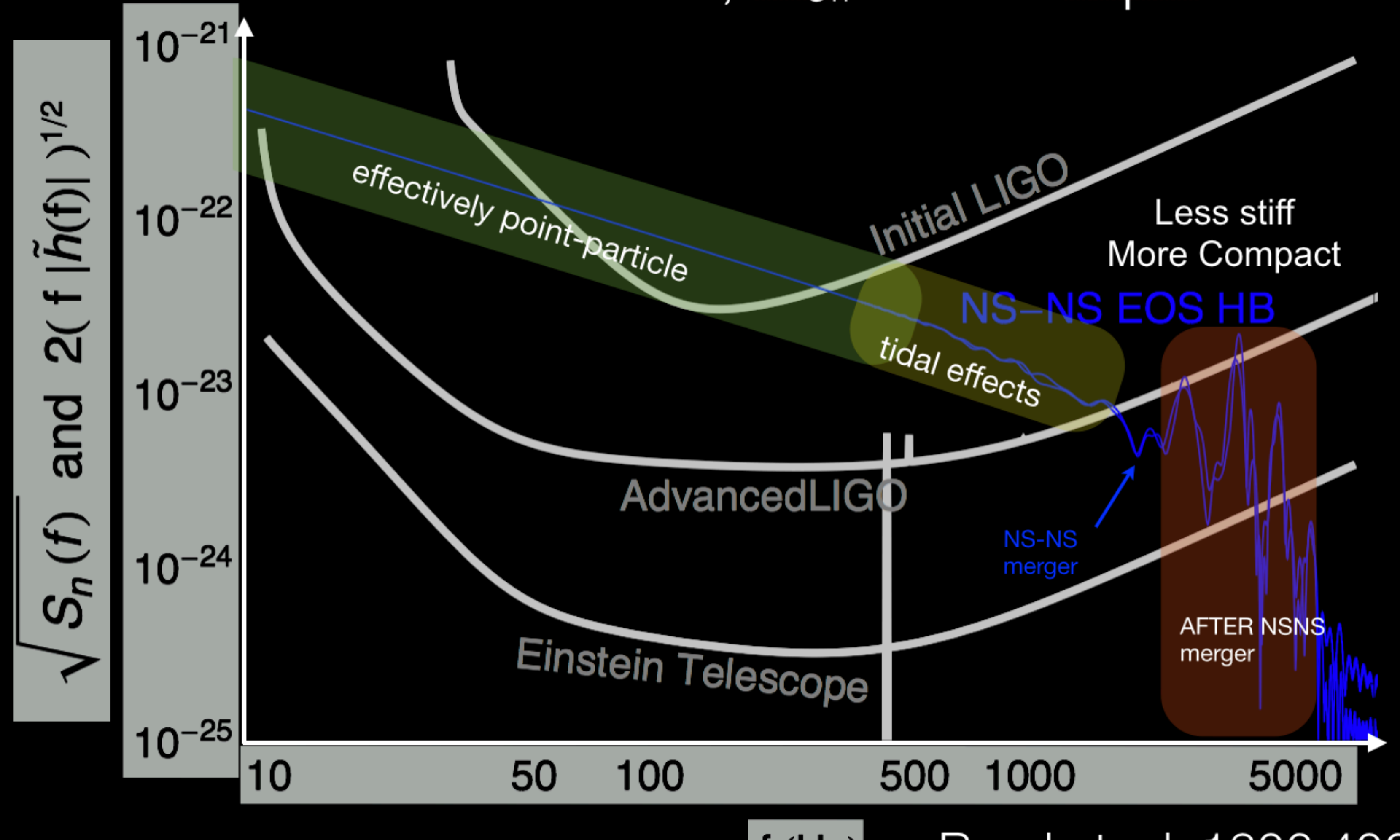
tidal deformability parameter $\Lambda \sim k_2 (R/m)^5$
k_2 - second Love number
R, m = radius, mass of the NS



Slide credit: J. Read

Read et. al. 1306.4065

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



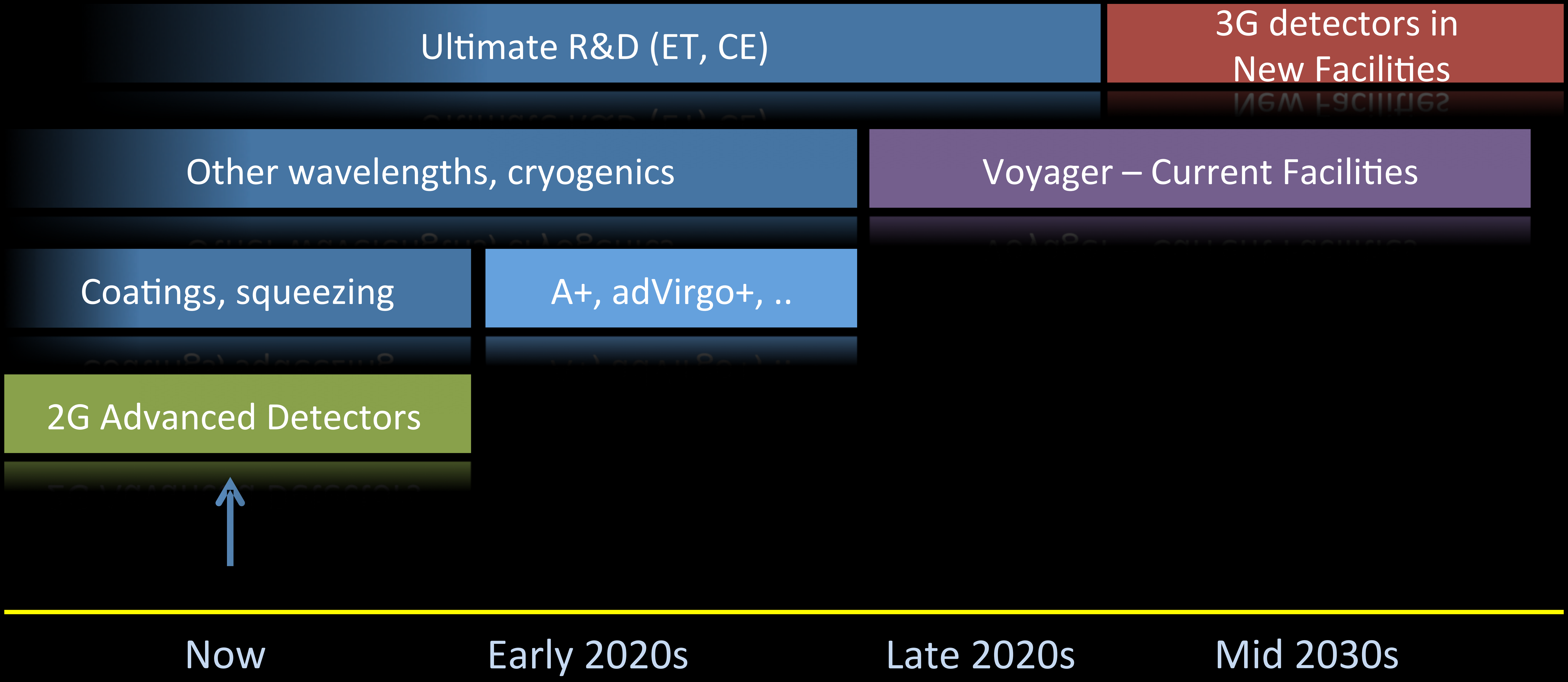
Slide credit: J. Read

Read et. al. 1306.4065

Also, the outcome of a BNS merger depends on the progenitor masses and also on the NS equation of state - searches for post-merger oscillations are still limited by sensitivity

ApJ Lett., 851:16, 2017

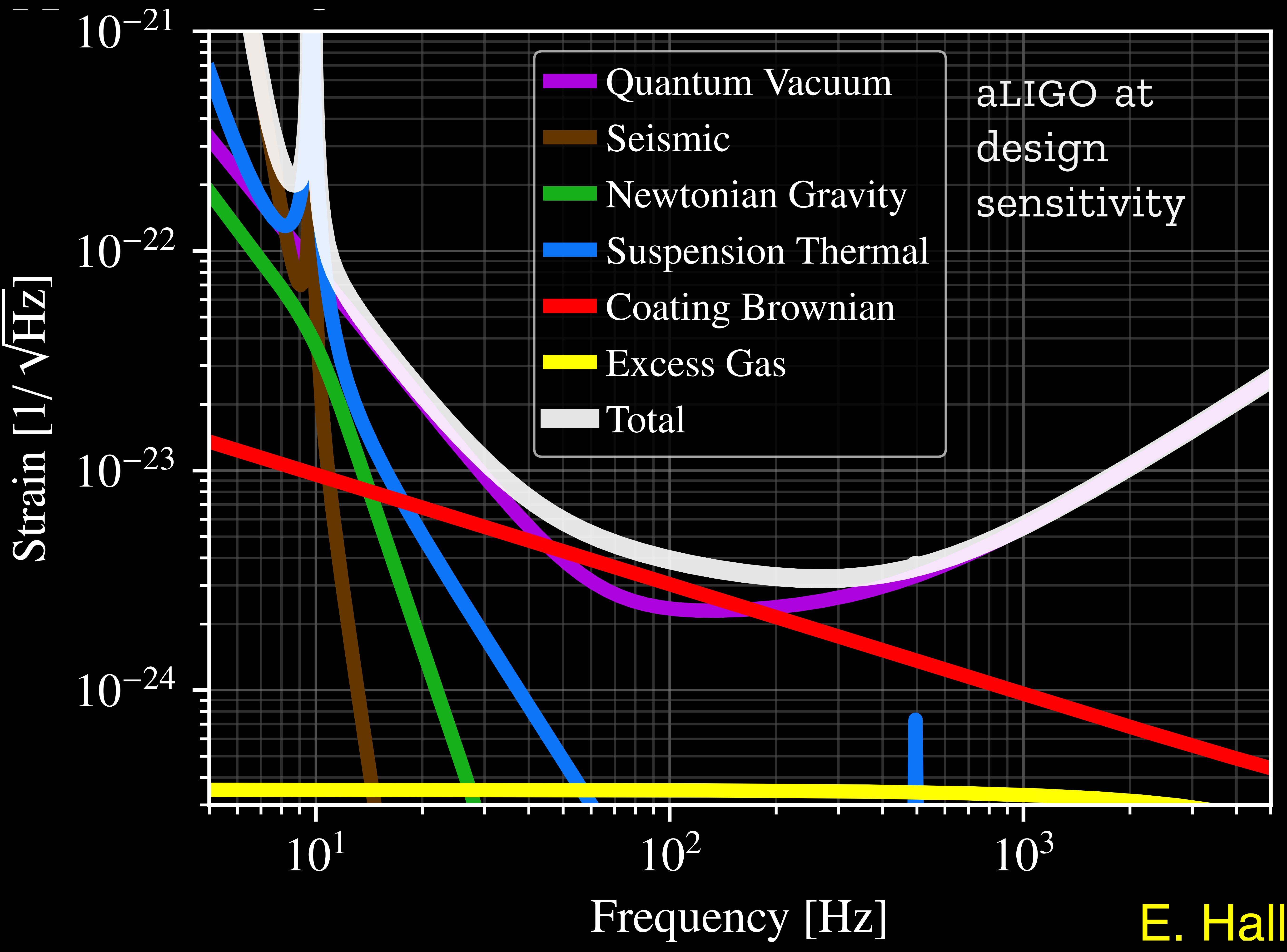
the next 2 decades:
LIGO Concept Roadmap



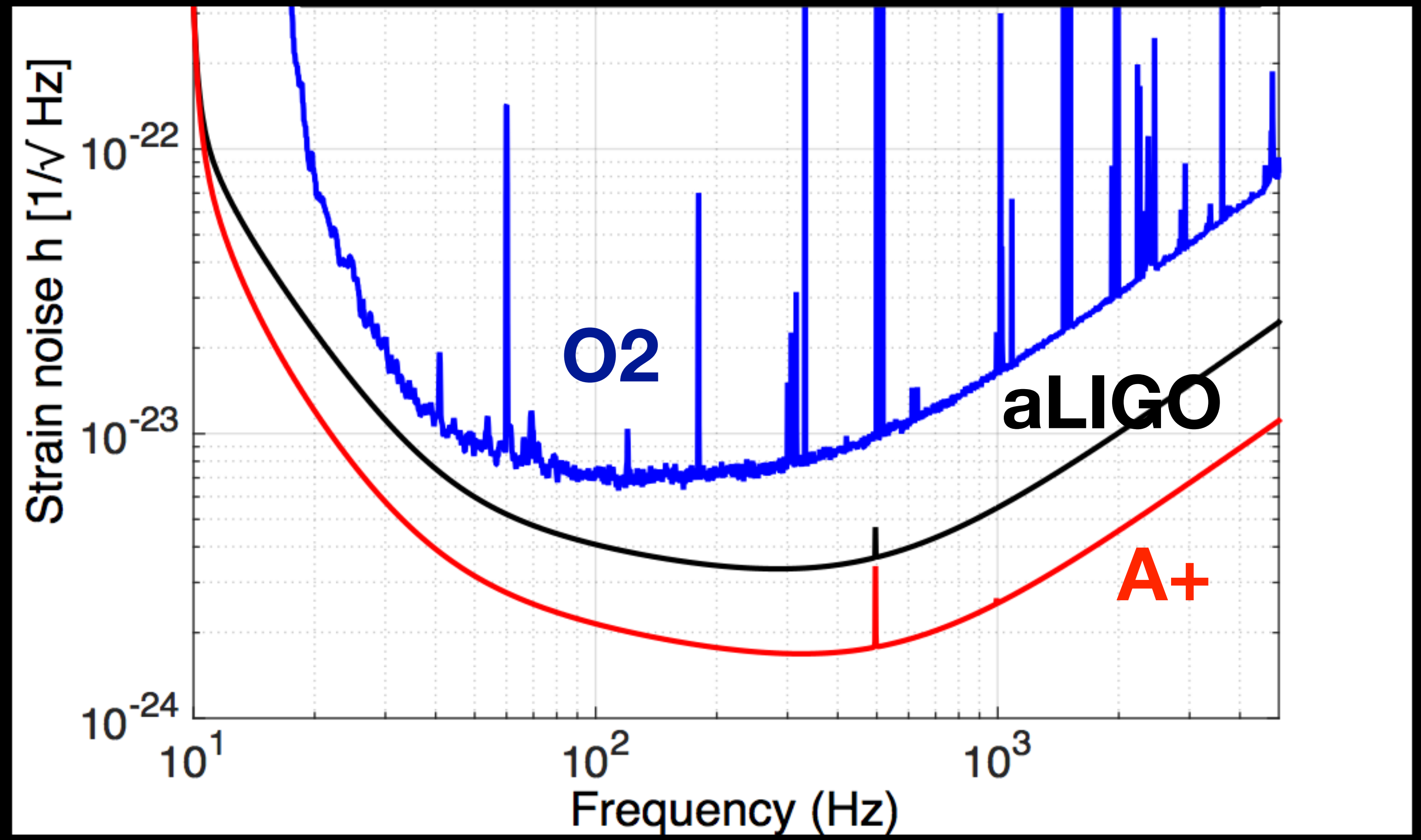
Credit: L. Barsotti

Near-term Future: aLIGO target

~10^2 binary coalescences per year (2020)



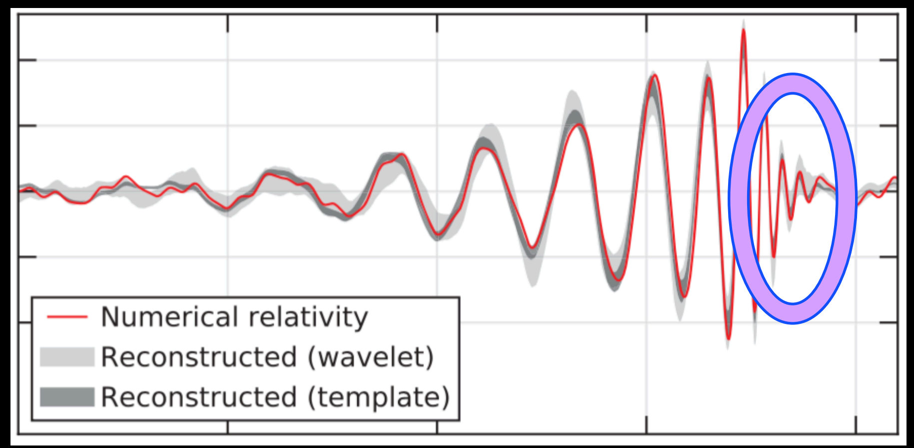
E. Hall



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?

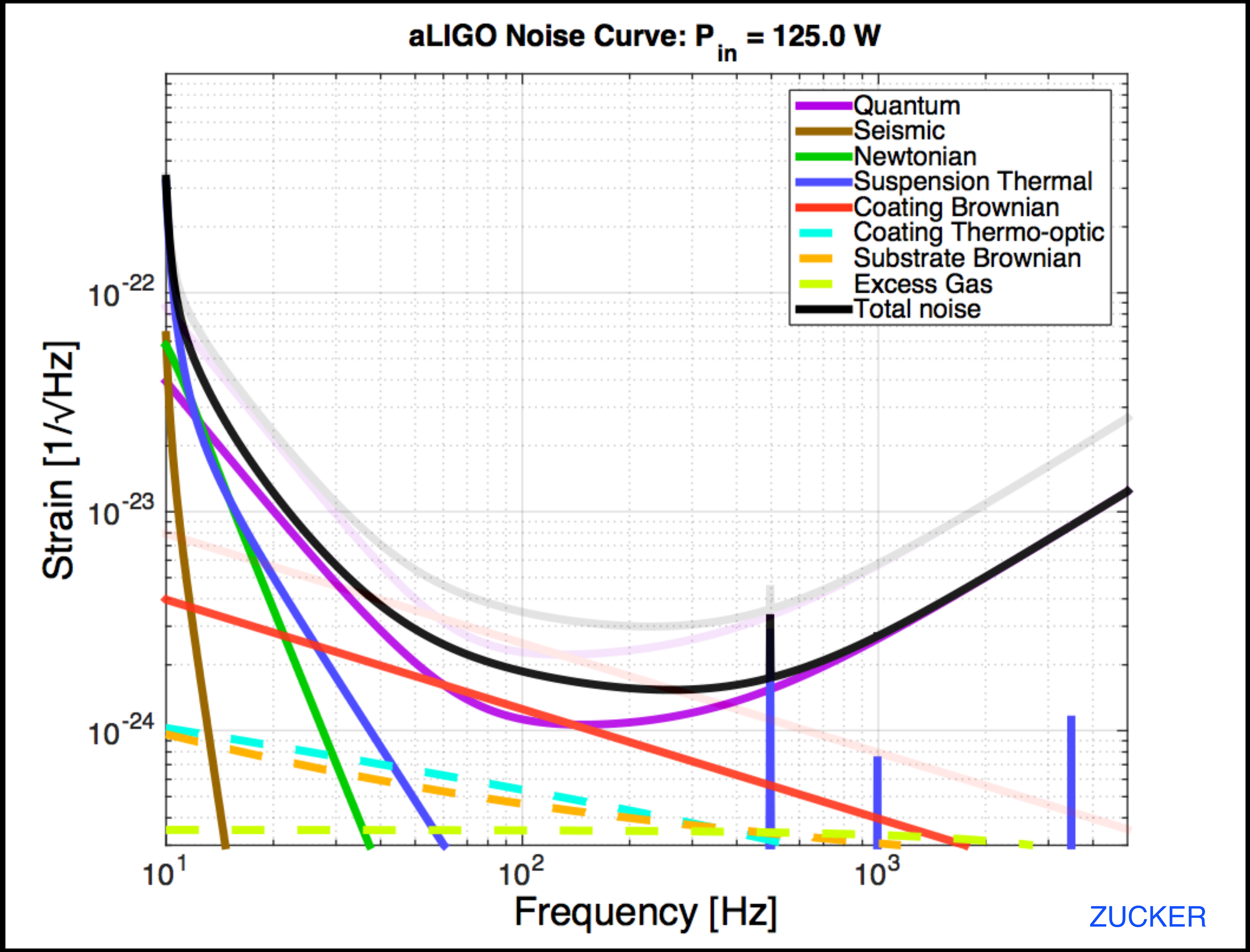
QNM SNR ~20 for an event like GW150914

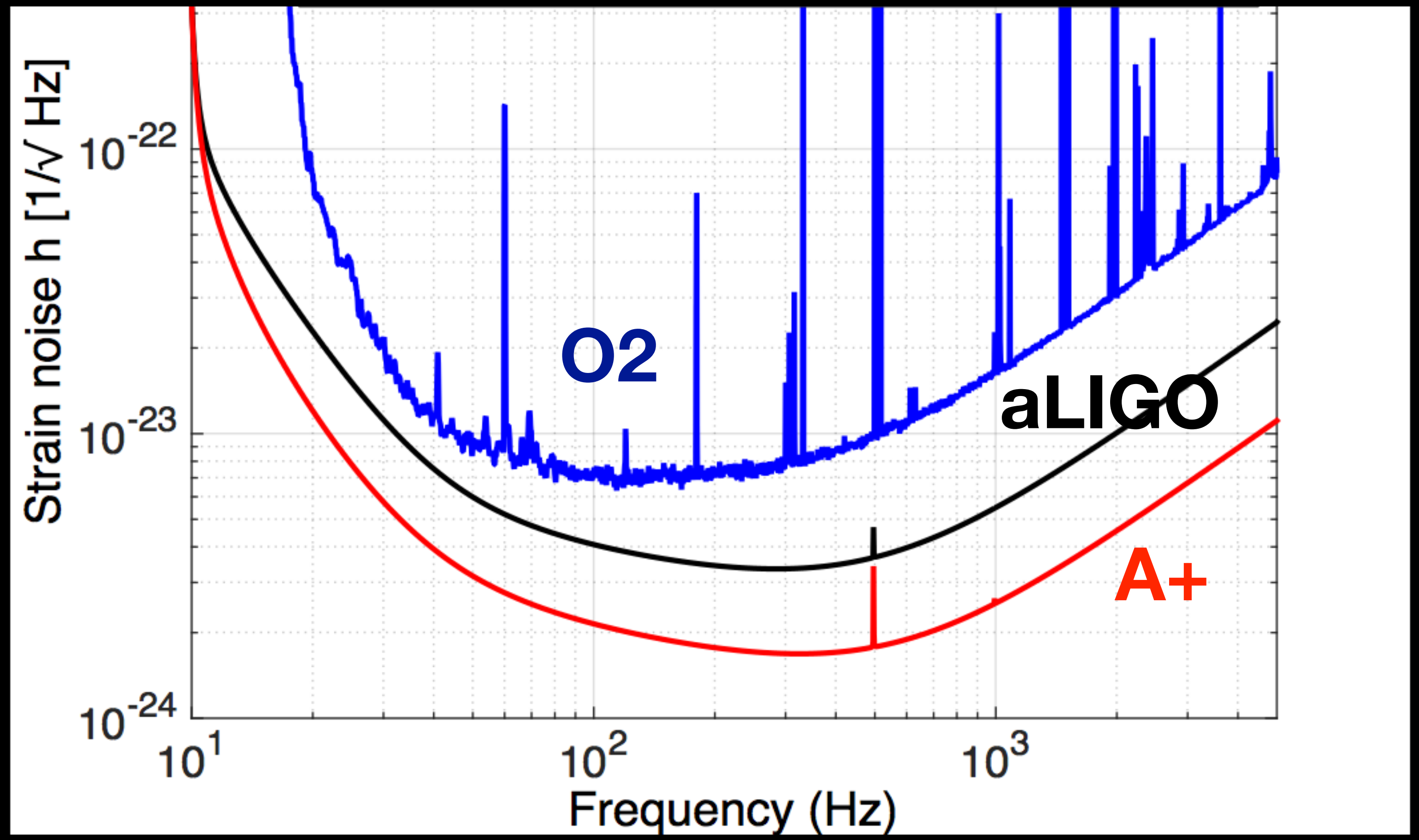


tests of GR?

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

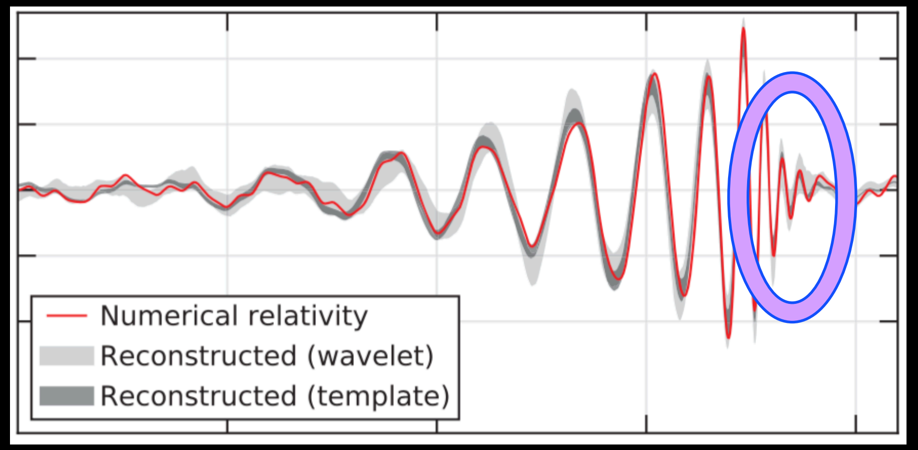
~500-1000 BBH/year

~10 NS-BH/year

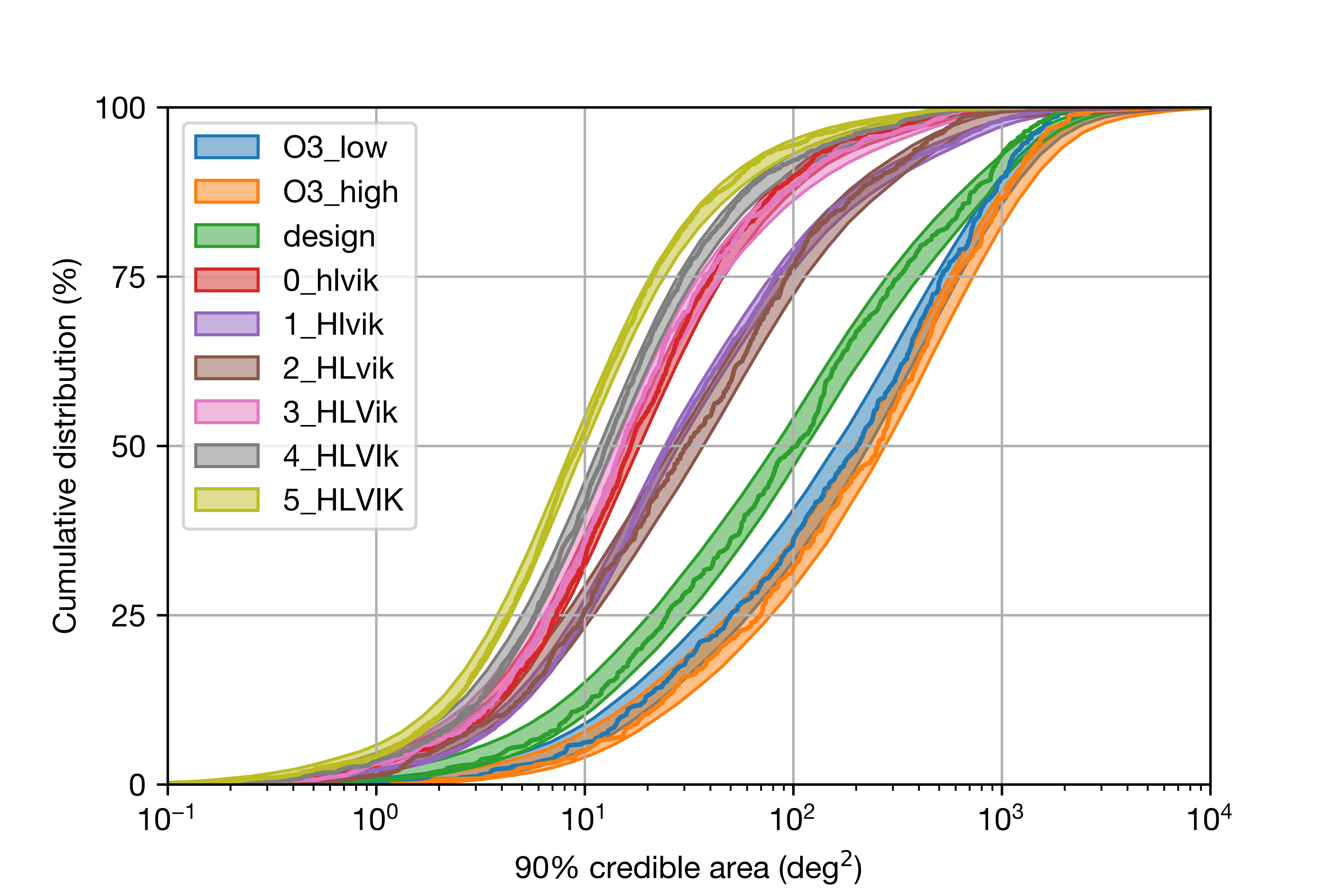
~200-300 BNS/year

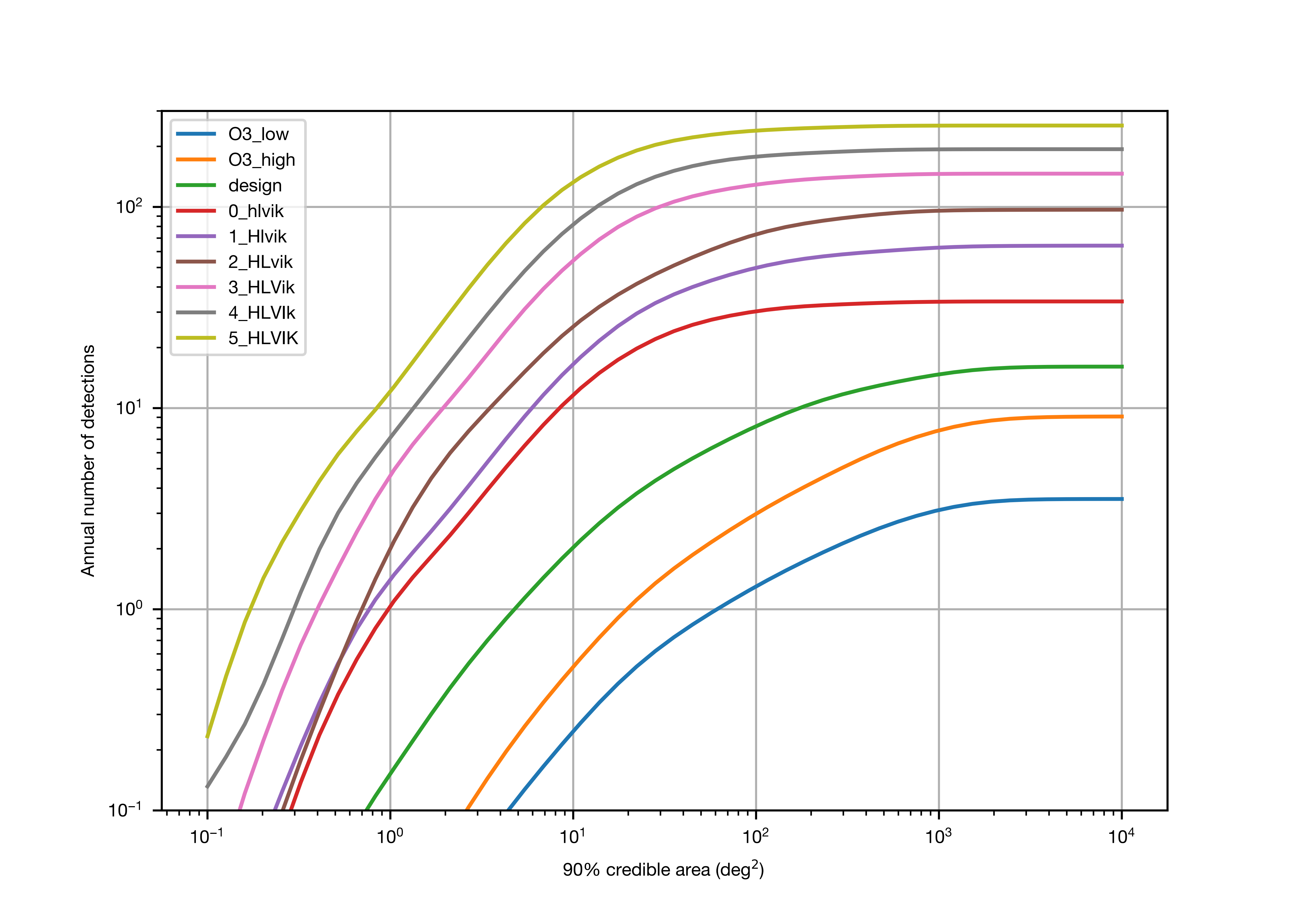
1% H_0?

QNM SNR ~35 for an event like GW150914



Localization in the A+ era

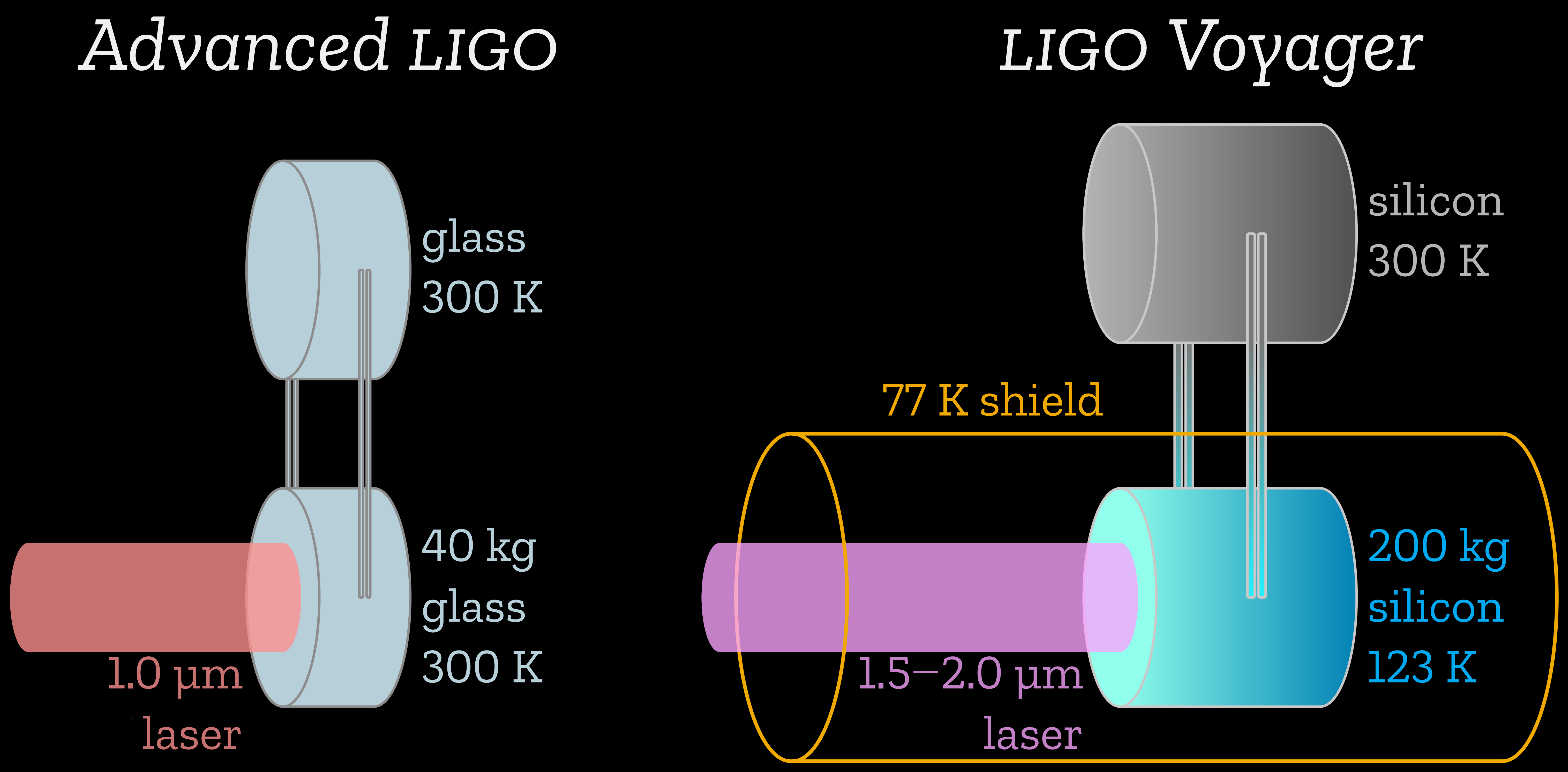




Credits: Singer, Corley, Williams et al., in prep.

Long-term Future for current facilities: Voyager

Voyager: a next-gen detector in the LIGO facilities



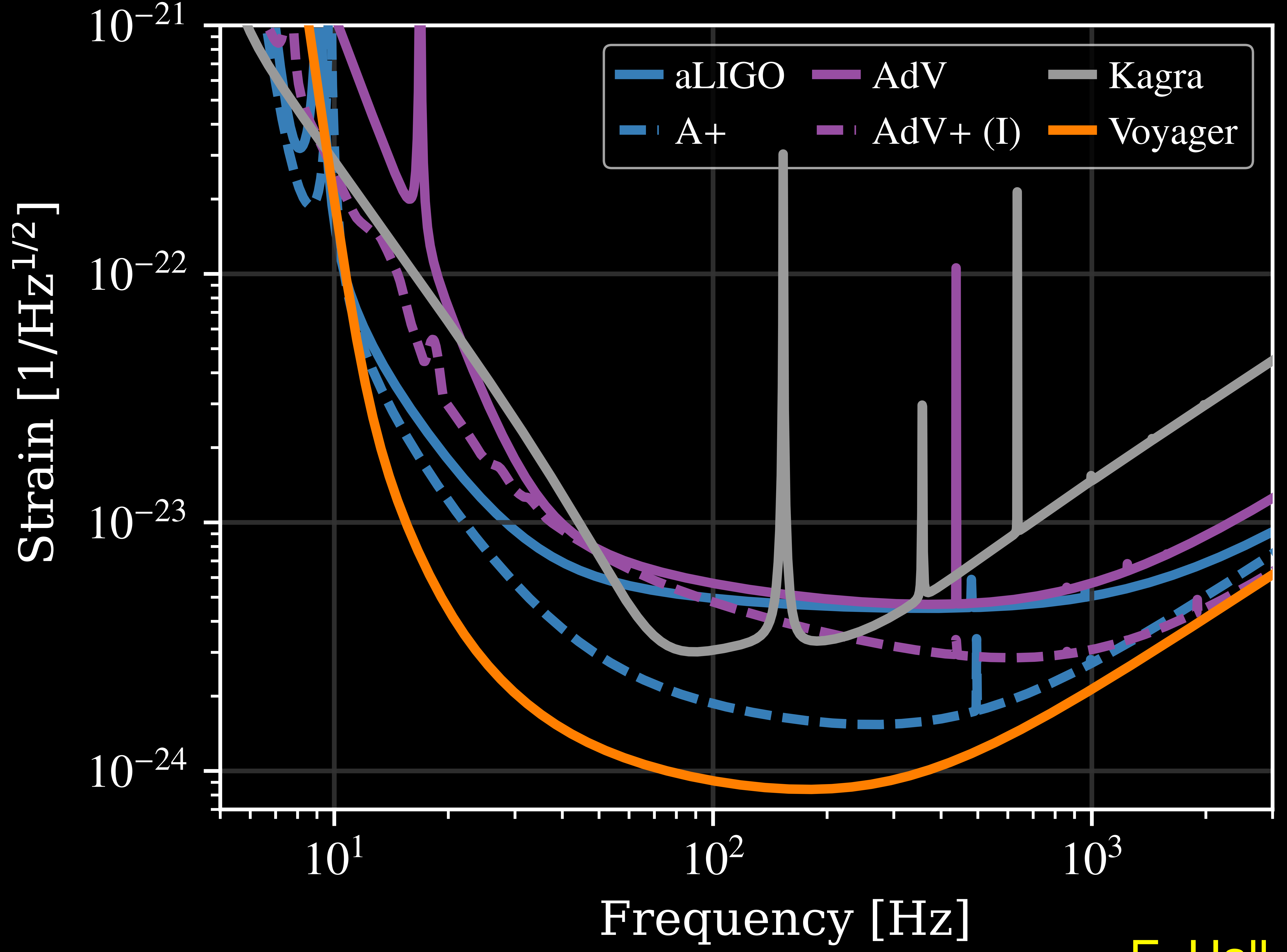
A concept under study for incremental performance improvement in late 2020s

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

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

Long-term Future for current facilities: Voyager

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

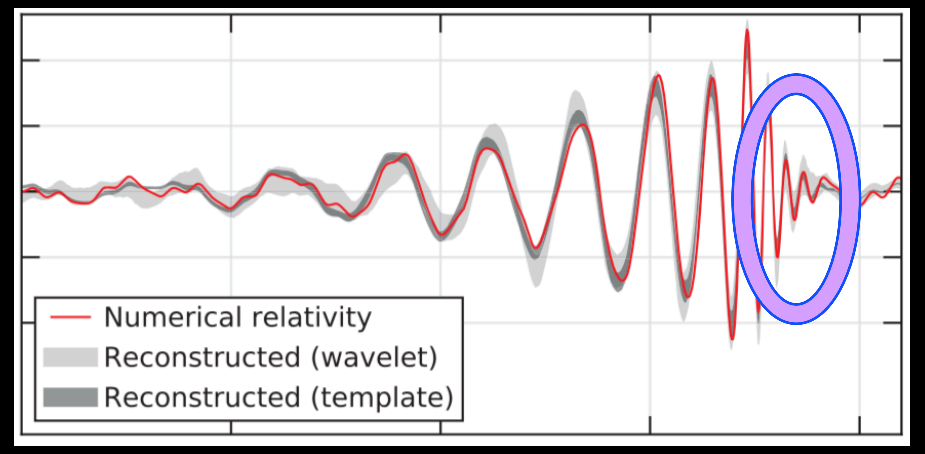


E. Hall

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)

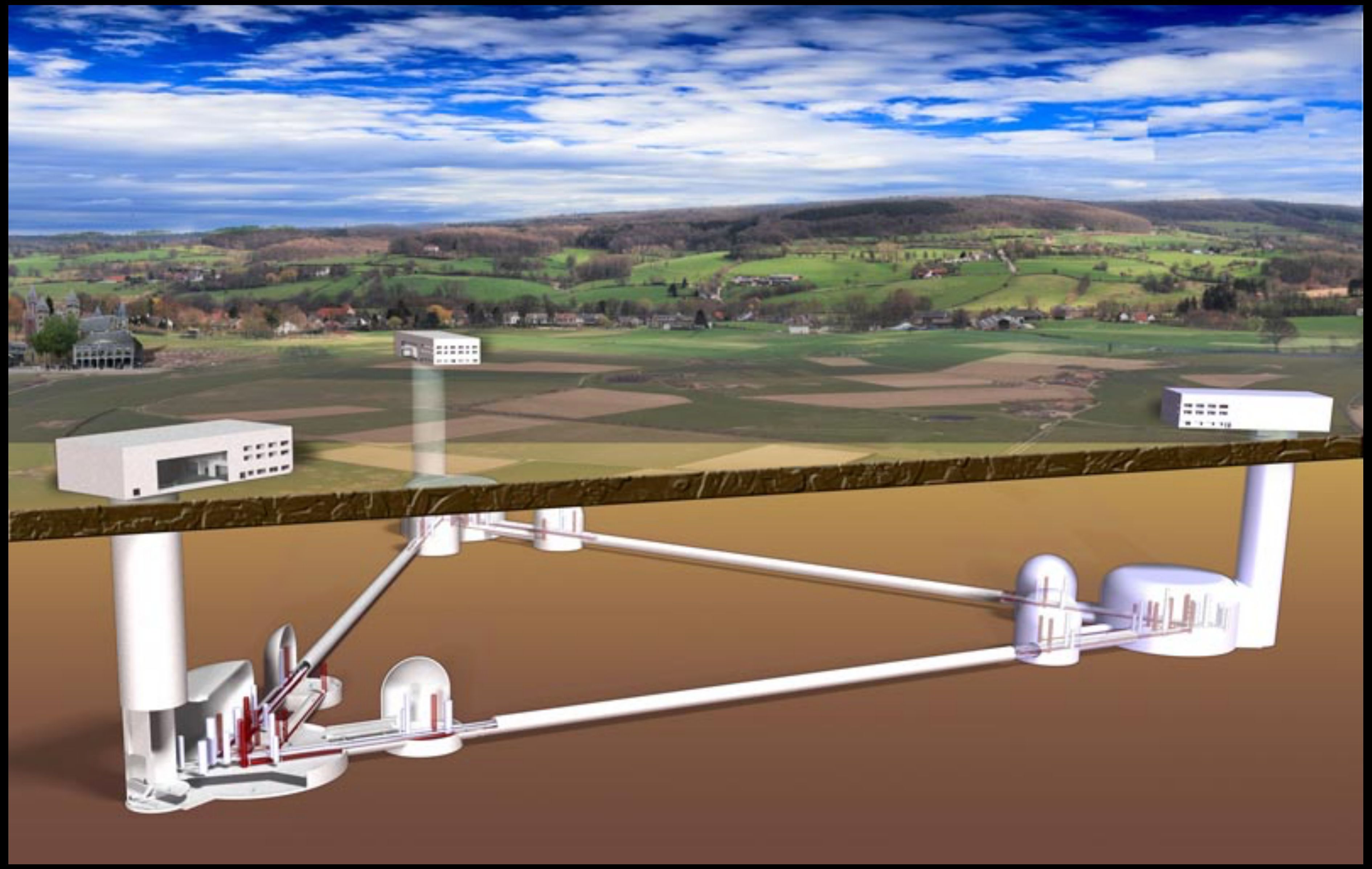


The 3rd Generation

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

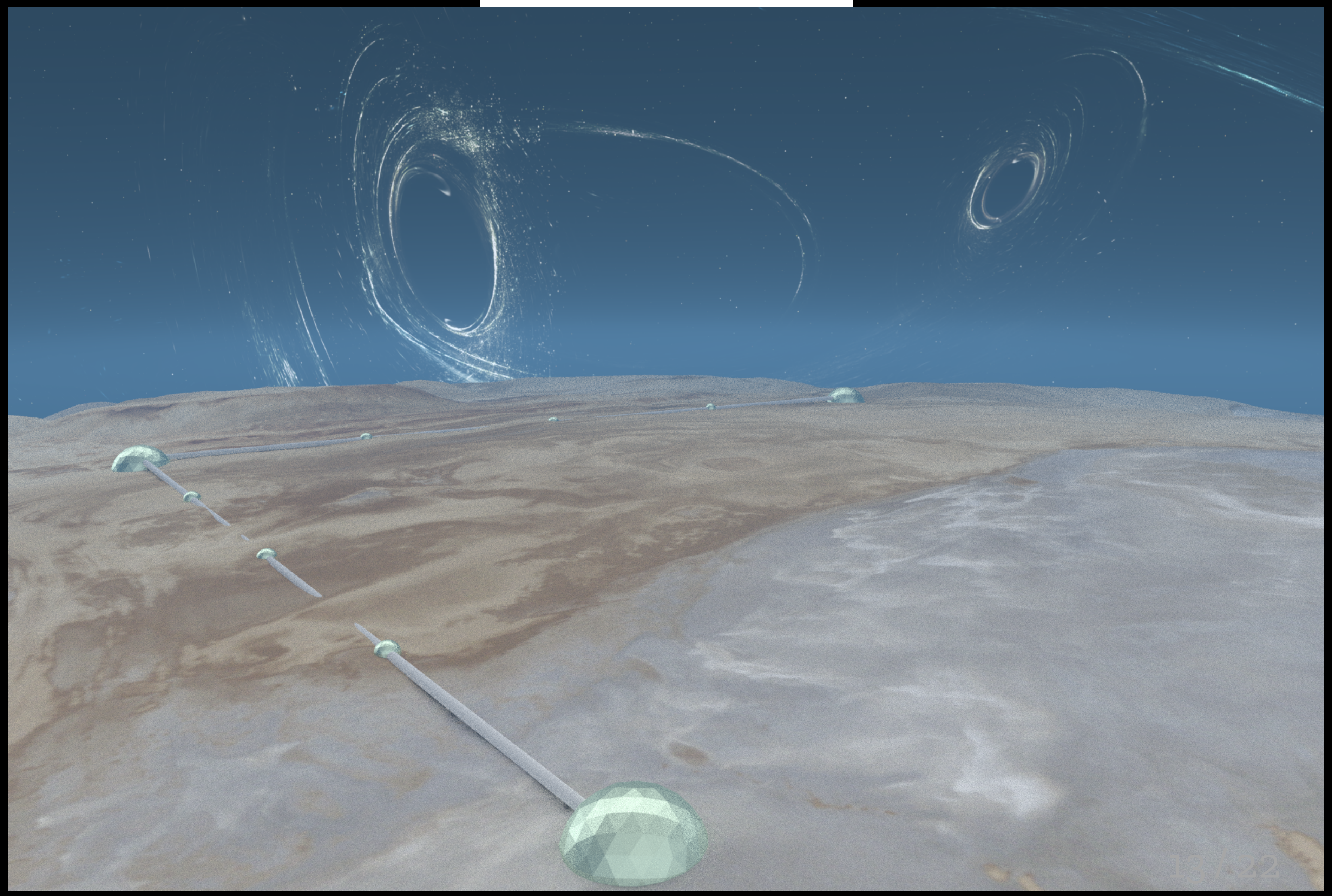
Einstein Telescope

- 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.

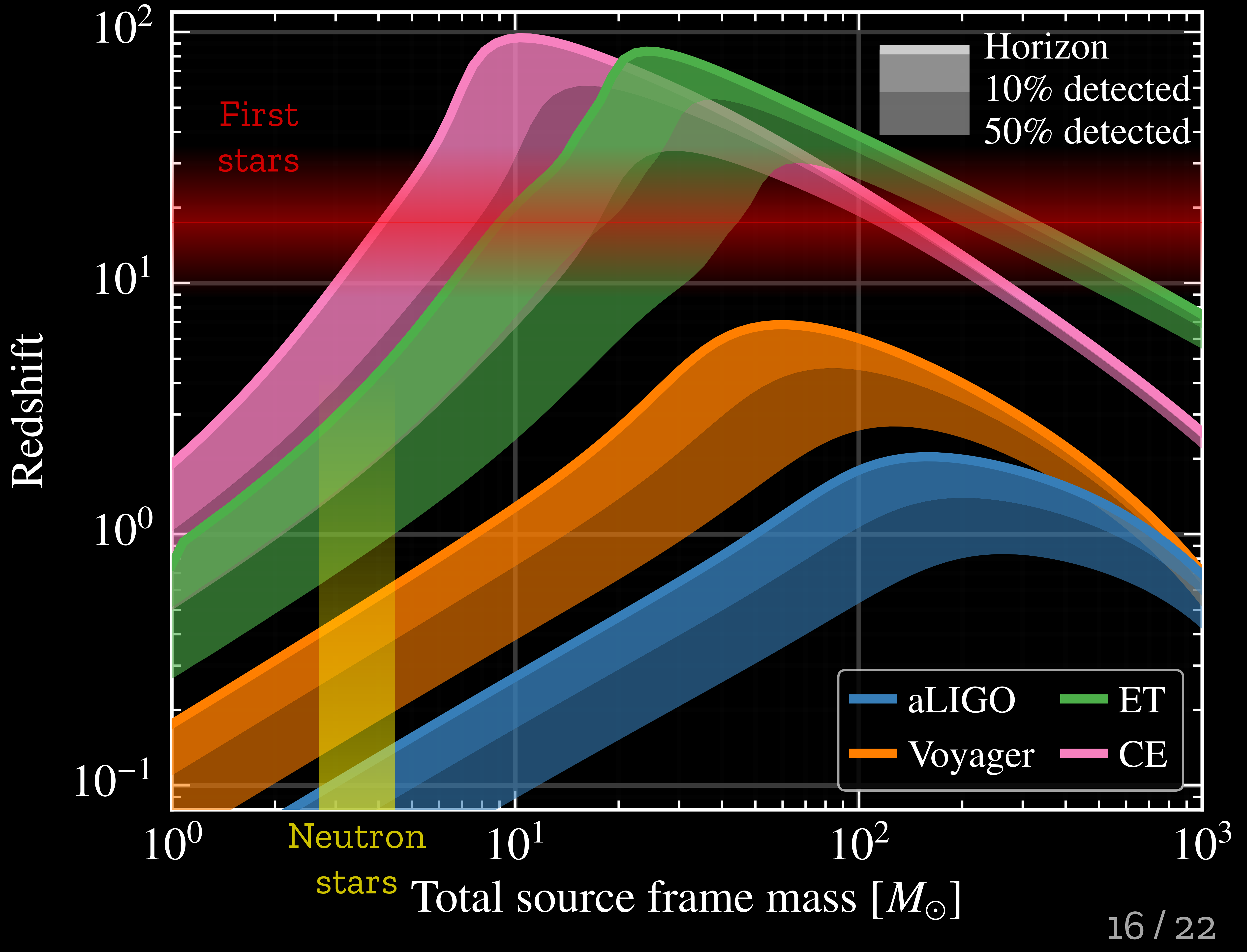


Cosmic Explorer

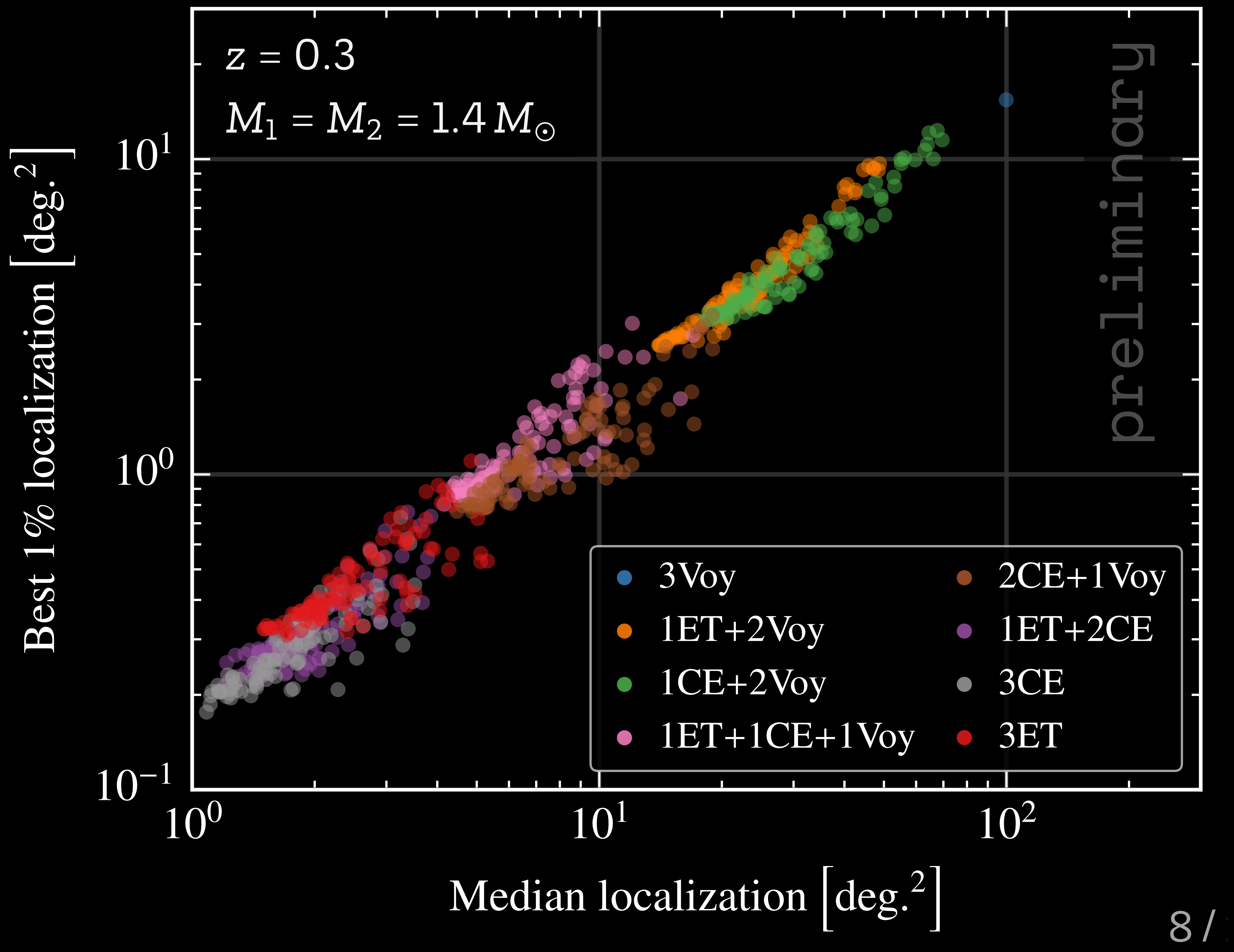
- NSF-funded US conceptual design study starting now
- 40km surface Observatory baseline
- Signal grows with length – not most noise sources
- Thermal noise, radiation pressure, seismic, Newtonian unchanged; coating thermal noise improves faster than linearly with length



Sensitivity



Localization: median vs best



Credit: E. Hall


Thank you