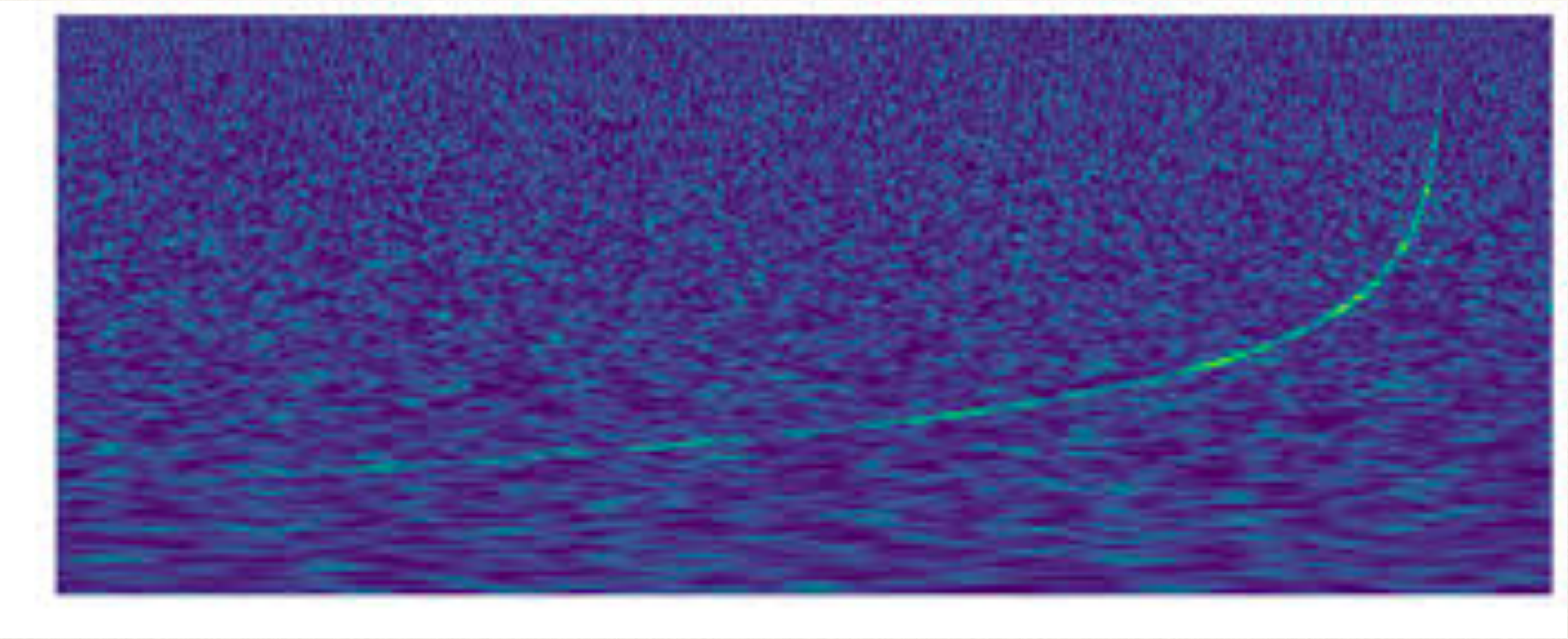
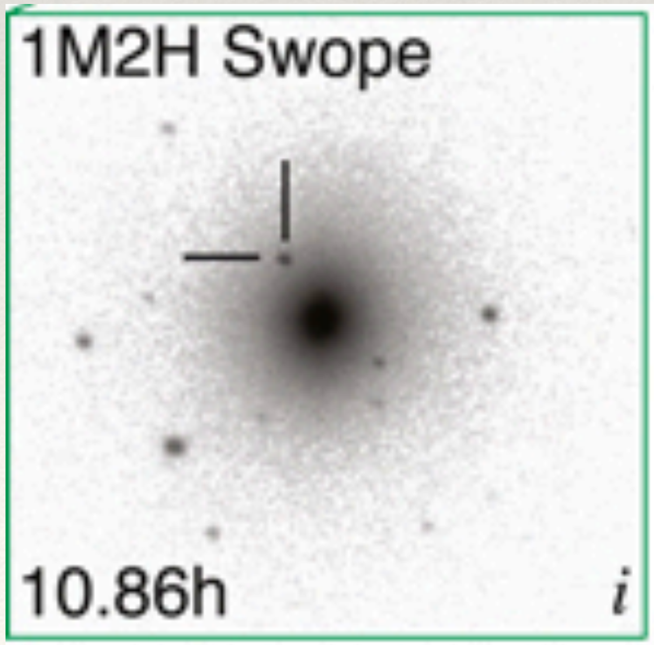


Multi-messenger astronomy

Ian Harry

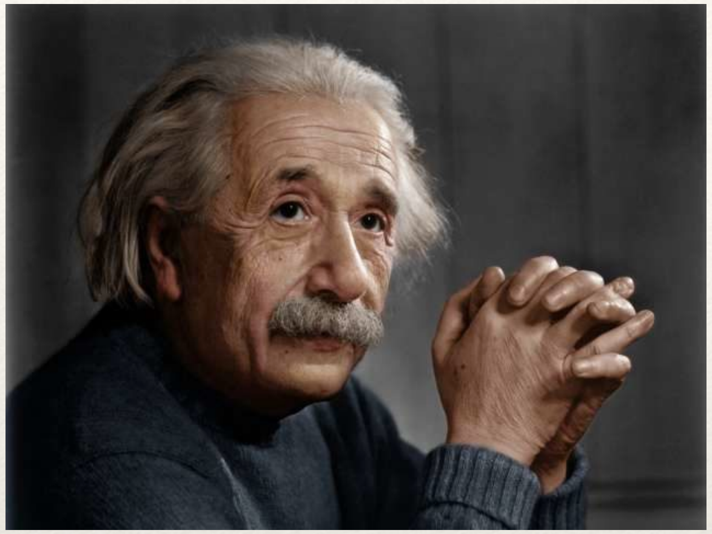


UNIVERSITY OF PORTSMOUTH

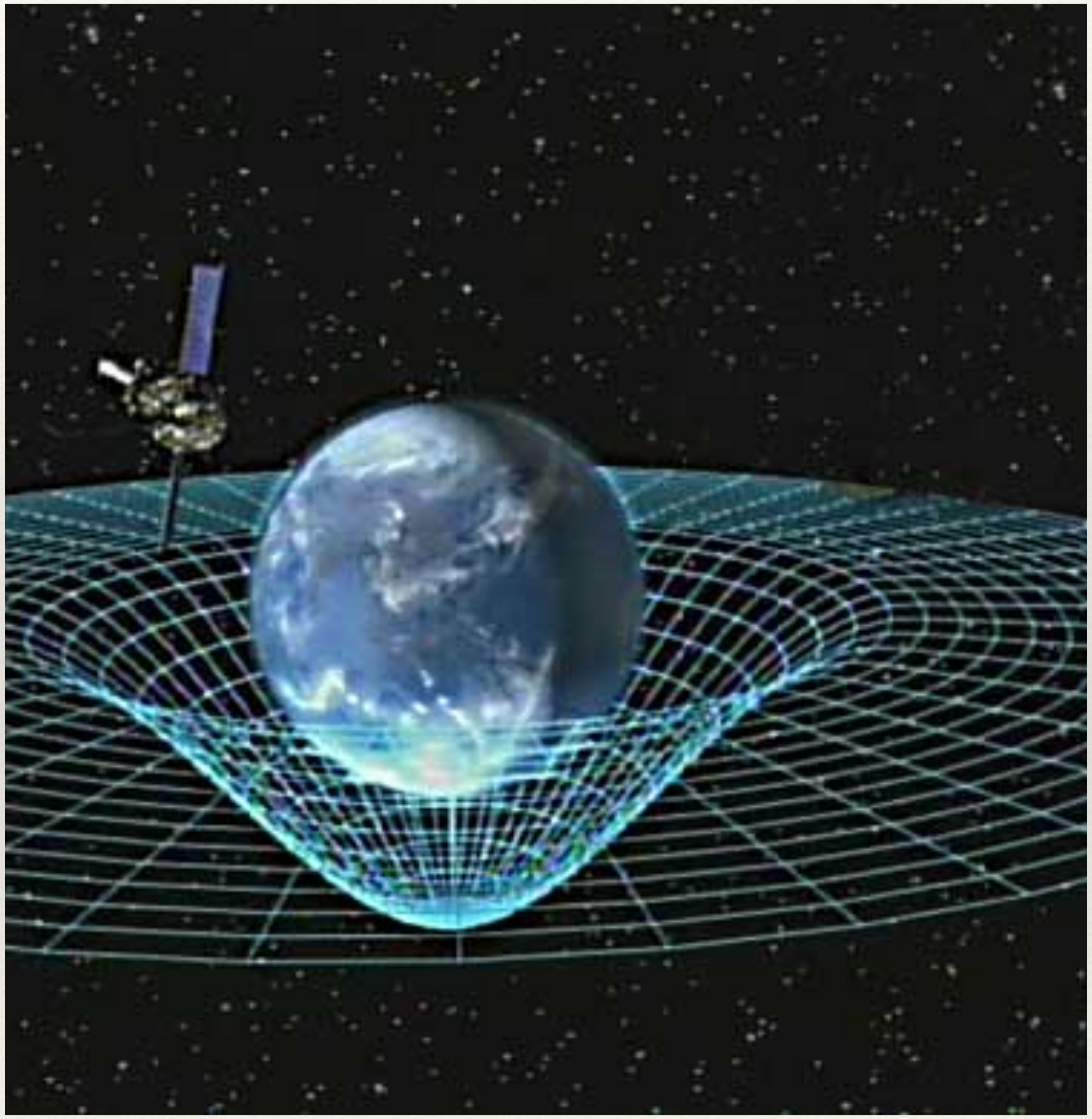
Talk layout

- Introduction to gravitational-wave astronomy
- Why is gravitational-wave astronomy relevant for particle physics?
- What have we learned from a single multi-messenger observation?
- What will we learn in the future?

General relativity and gravitational waves



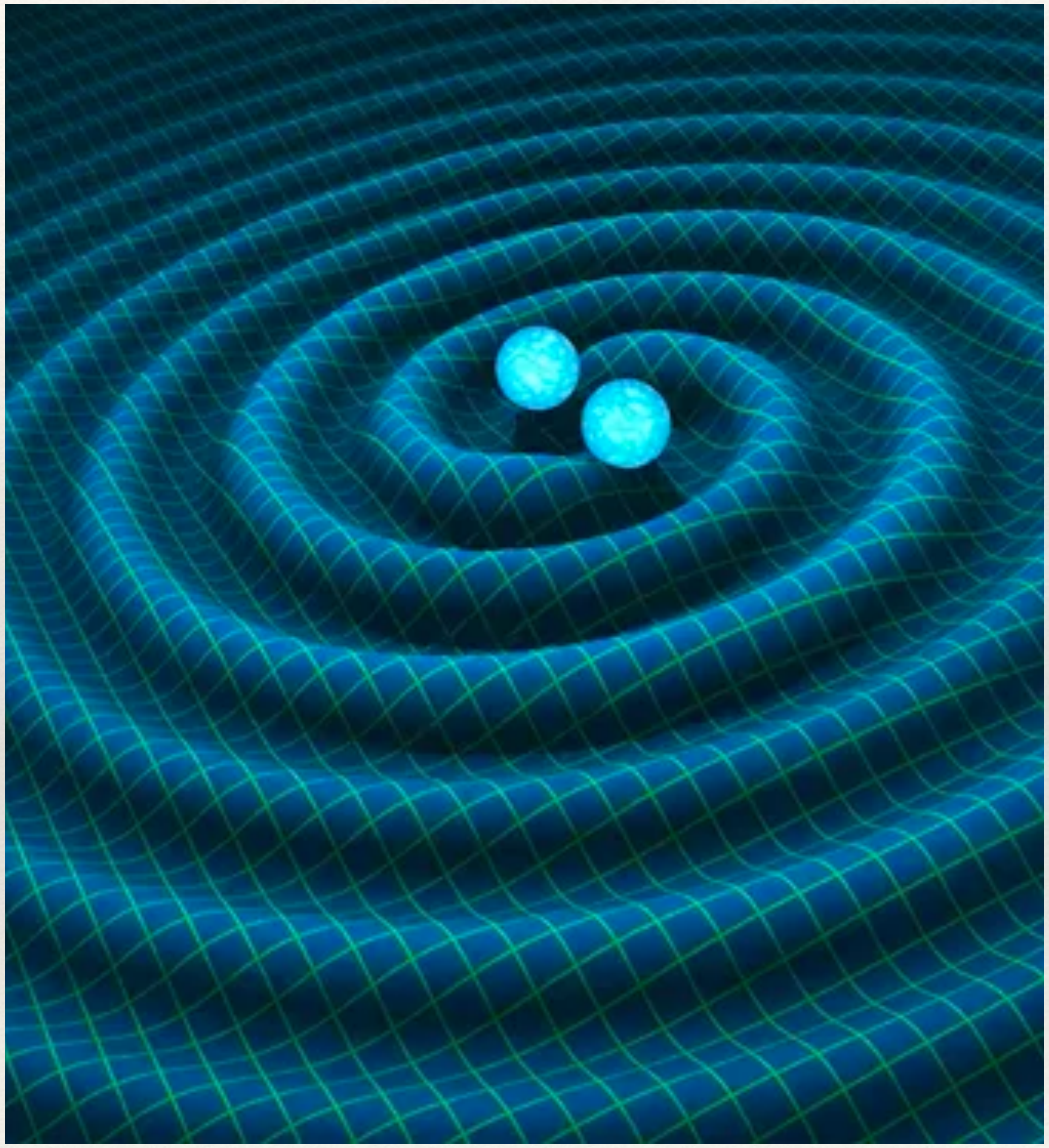
- Einstein's theory of general relativity redefined what we understand as "gravity"
- Gravity can be though of as a warping of space and time
  - Caused by mass and energy in the Universe



Credit: NASA

Gravitational waves

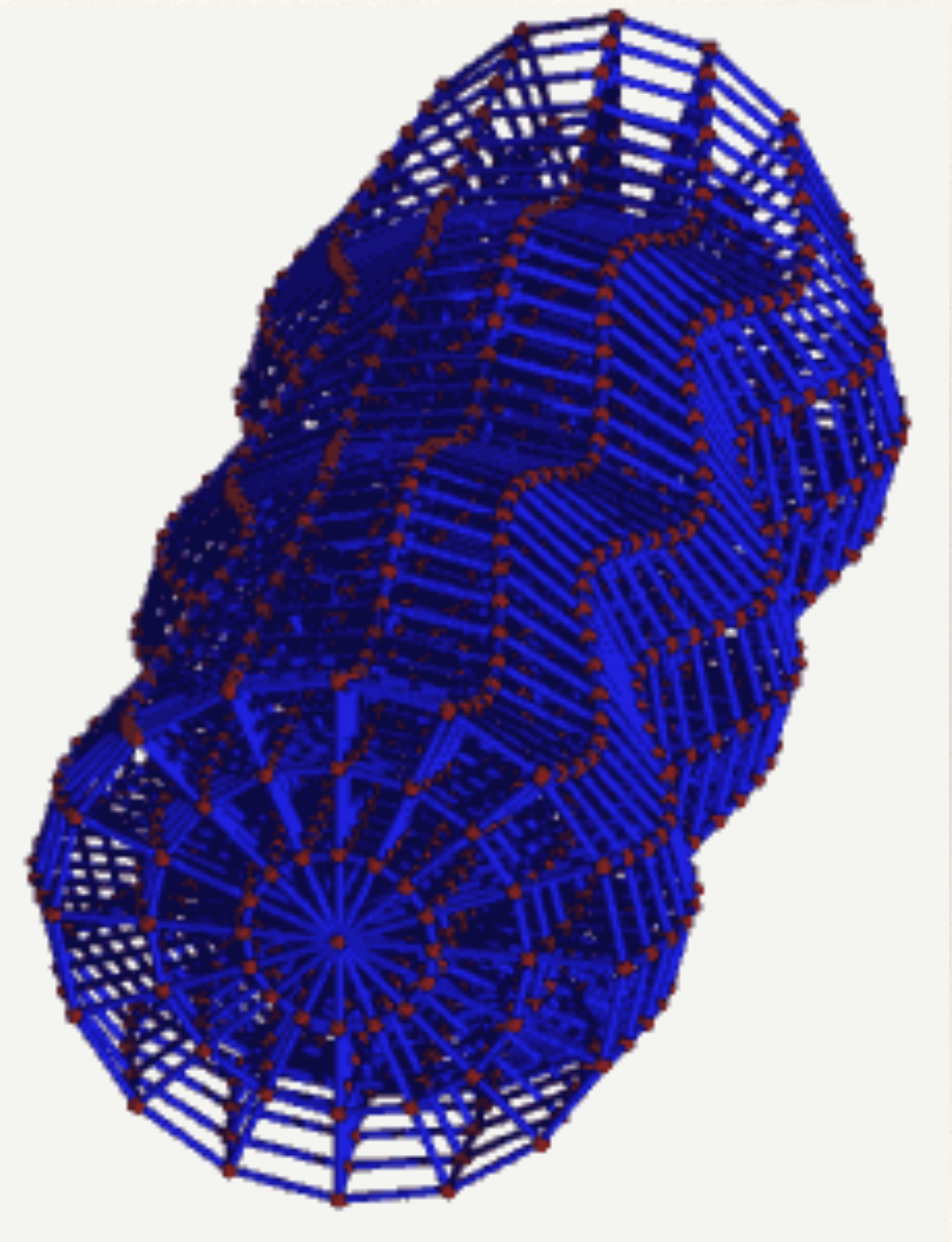
- A new prediction of general relativity, not present in Newtonian physics!
- Wave-like fluctuations in space-time, which propagate at the speed of light
- Emitted by accelerating masses with spherical asymmetry.



Credit: NASA

Effect of a gravitational-wave passage

- All particles affected by gravitational-wave passage
- Passing wave can cause a deformation in a ring of particles
- However, interaction with matter is *extremely* weak
- Observed signals have a strain of 10^{-21}.



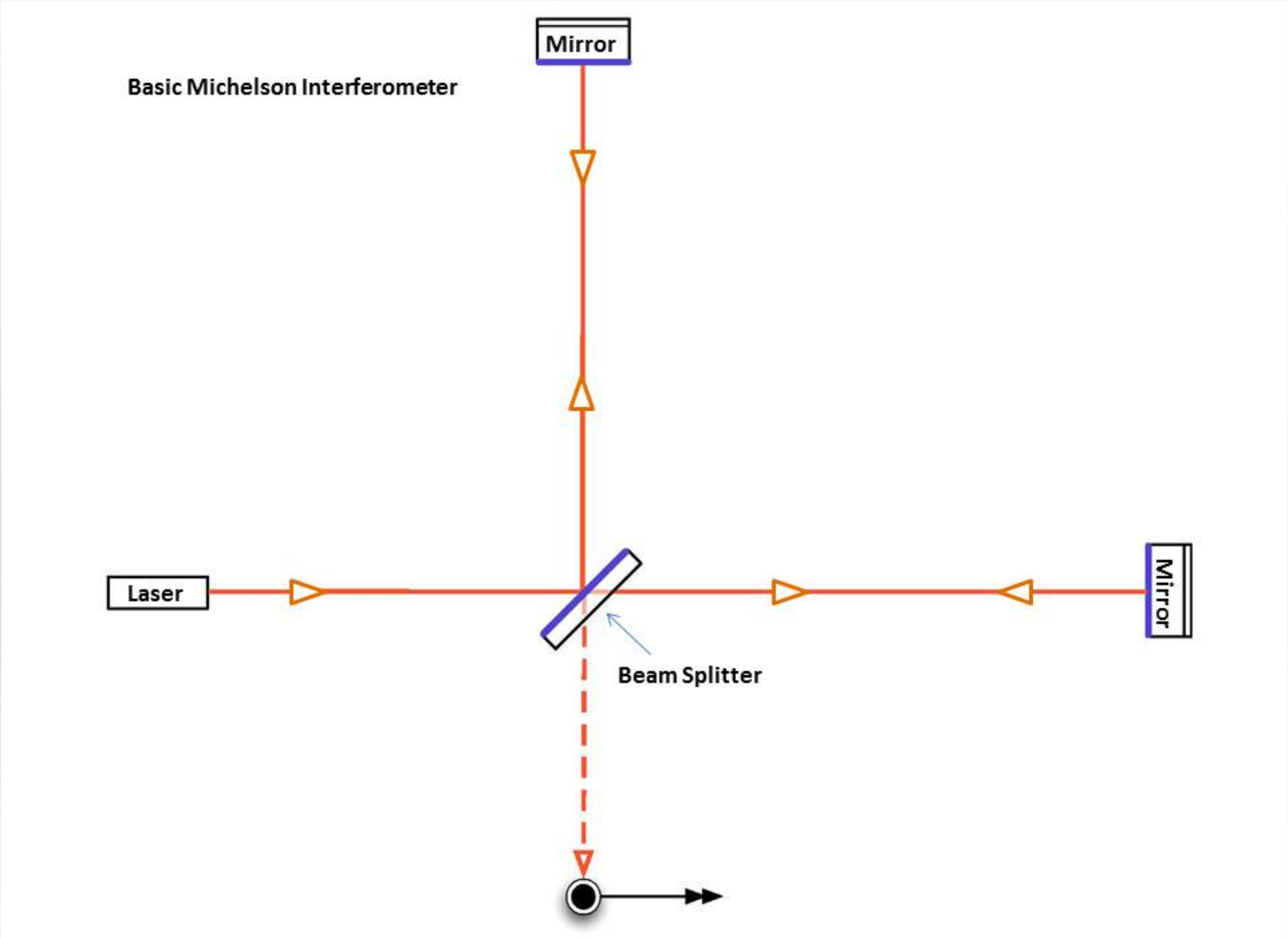
Wikimedia commons

Observing gravitational-waves

LIGO Hanford, WA

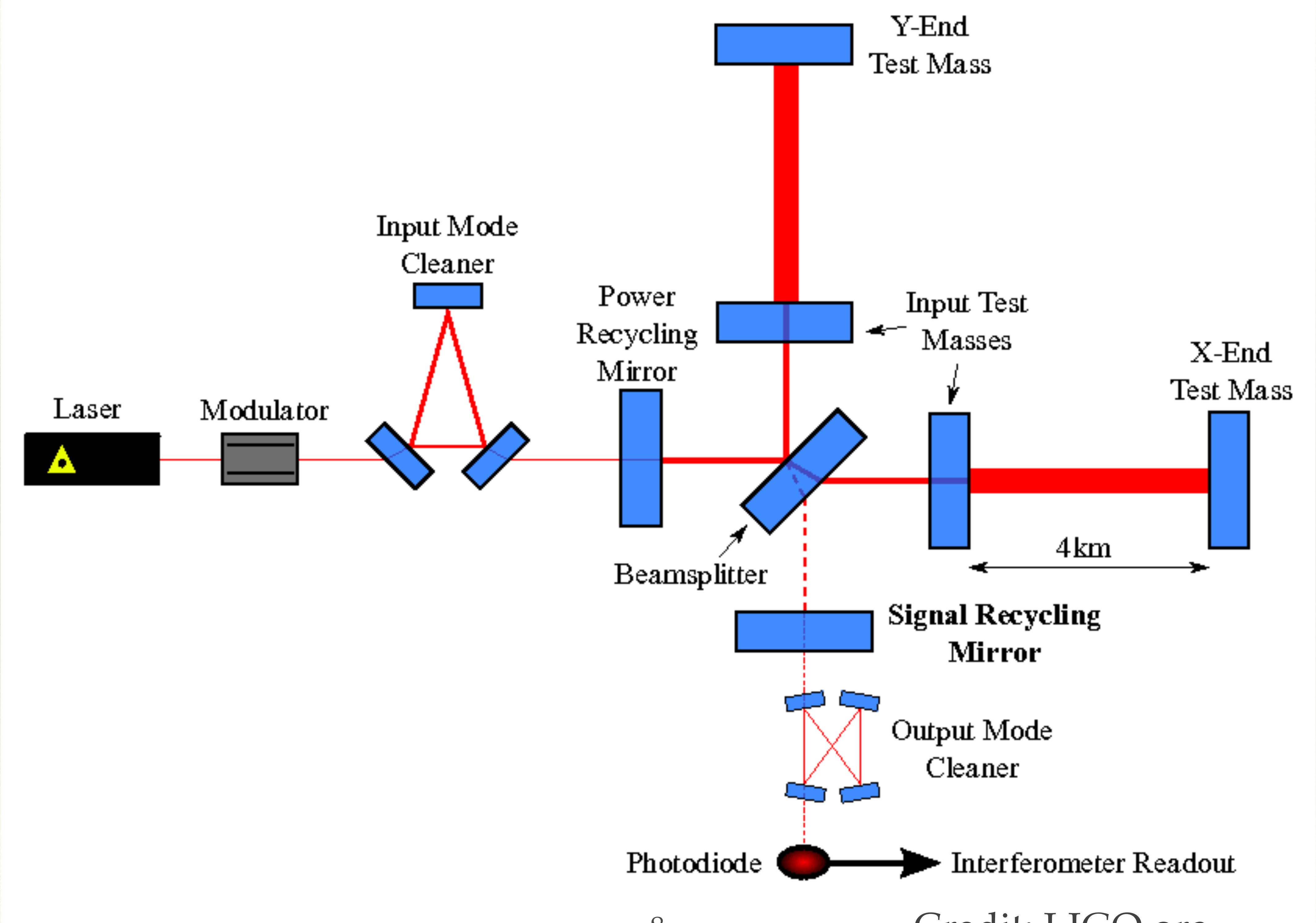
LIGO Livingston, LA

Basic Michelson Interferometer



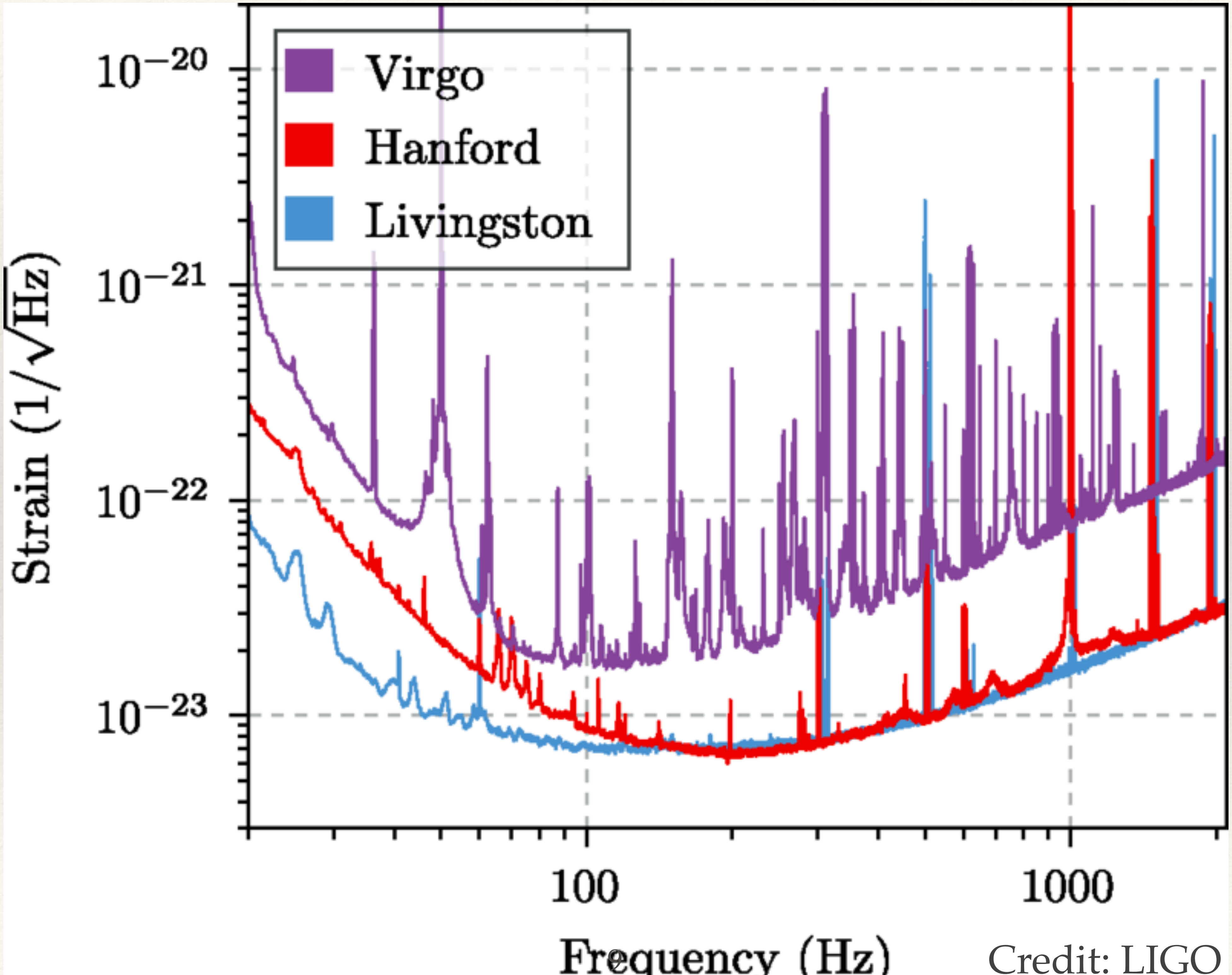
Credit: LIGO.org

Actual LIGO Interferometer



Credit: LIGO.org

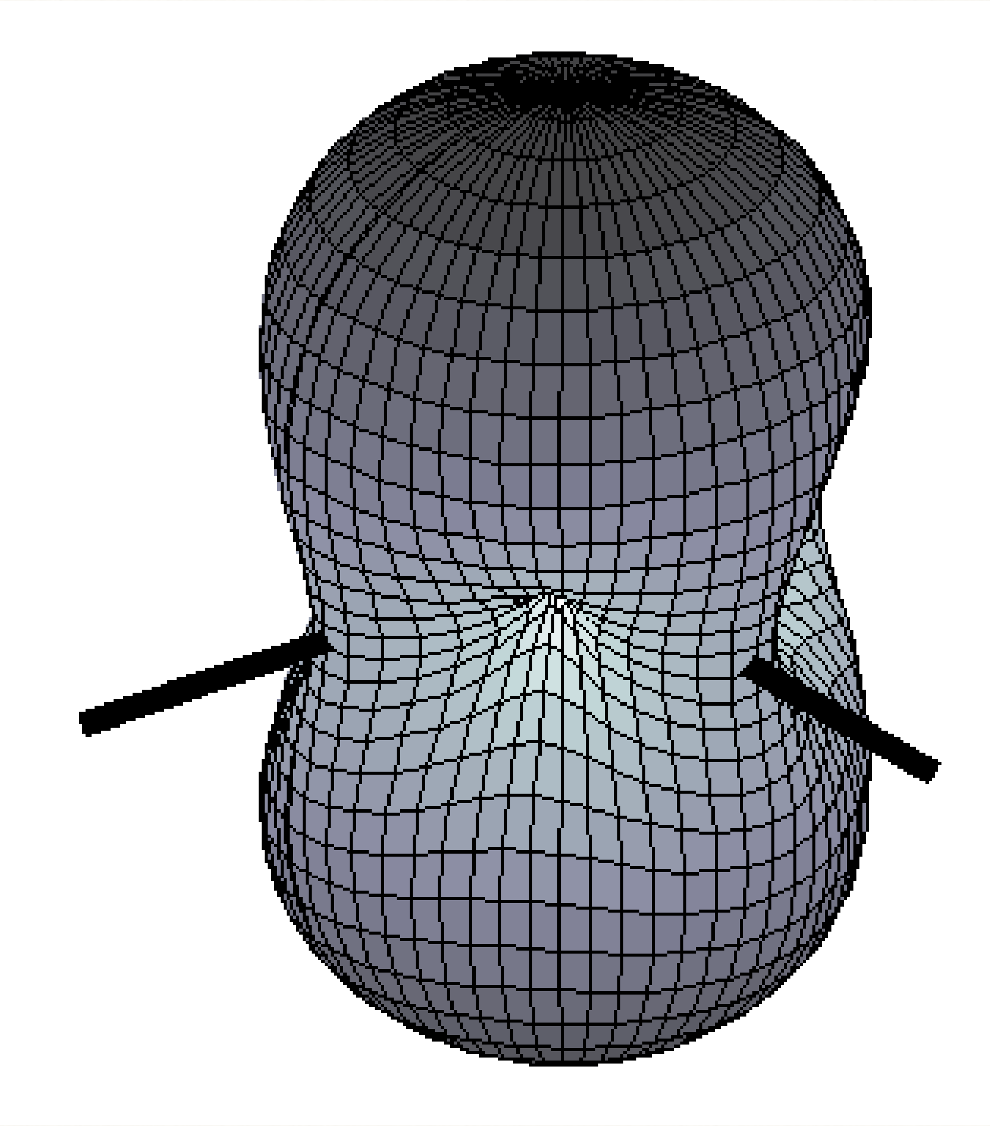
Amplitude Spectral Density



Credit: LIGO

Broad sky sensitivity

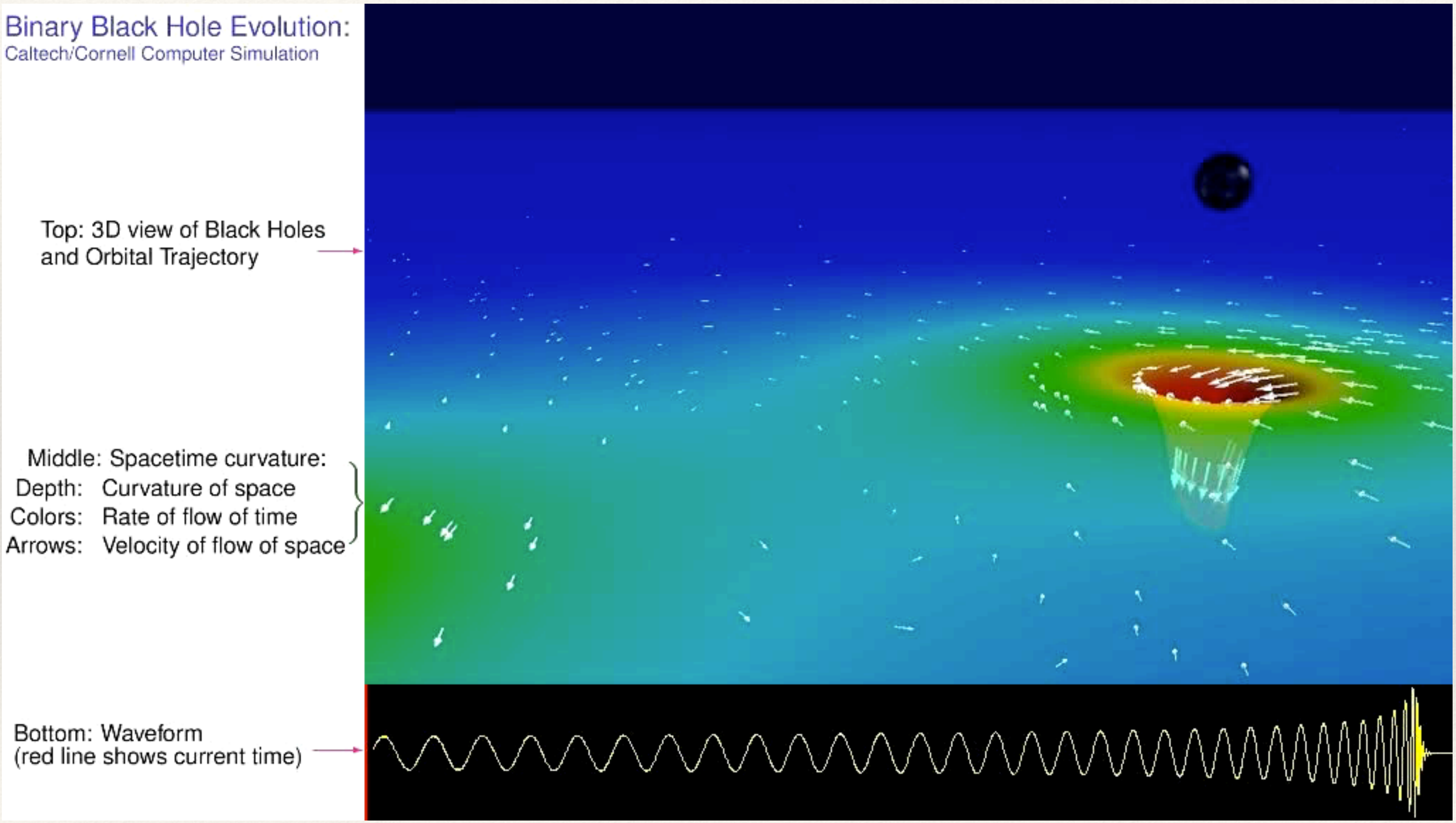
- Sensitivity to most points on the sky
- Best sensitivity to sources overhead (or underhead)
- But difficult to know where in the sky a source came from!



Rept.Prog.Phys. 72 (2009) 076901

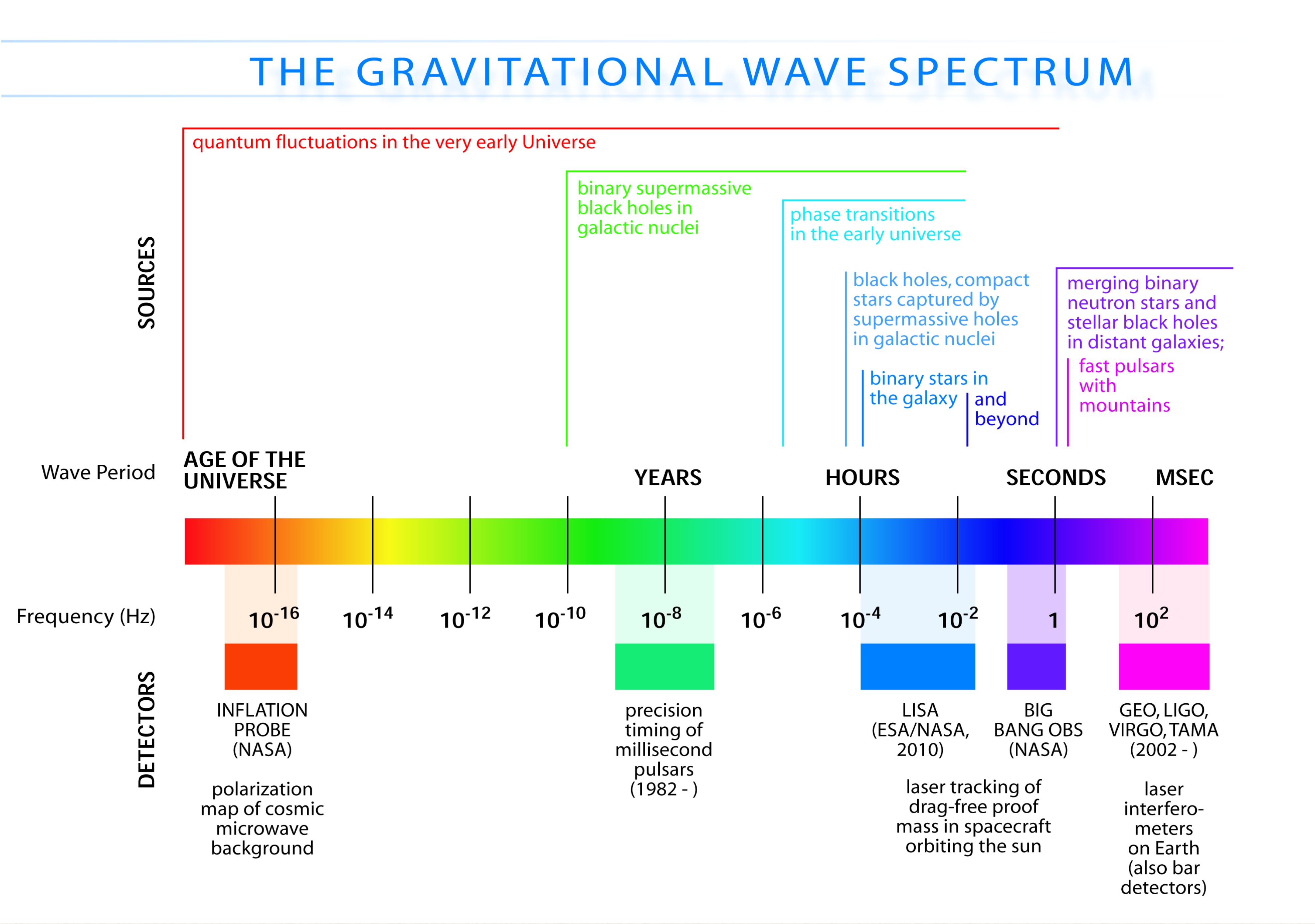
A global network

Observable gravitational wave sources



Simulation courtesy of the Simulating eXtreme Spacetimes (SXS) collaboration

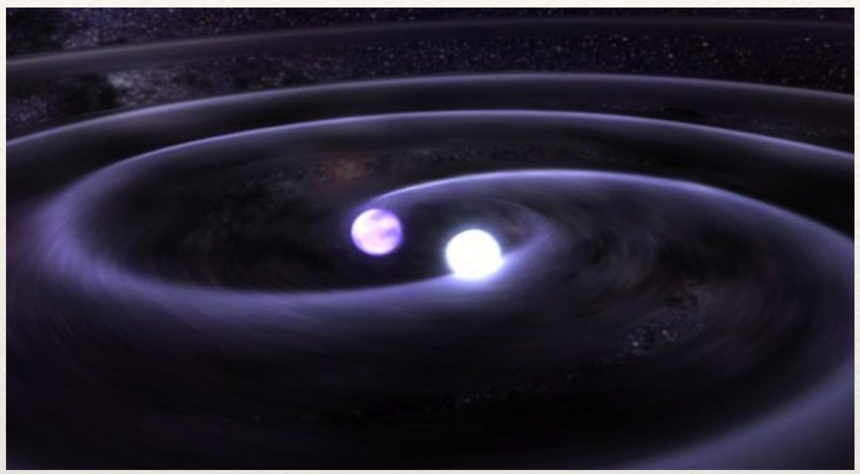
The gravitational-wave spectrum



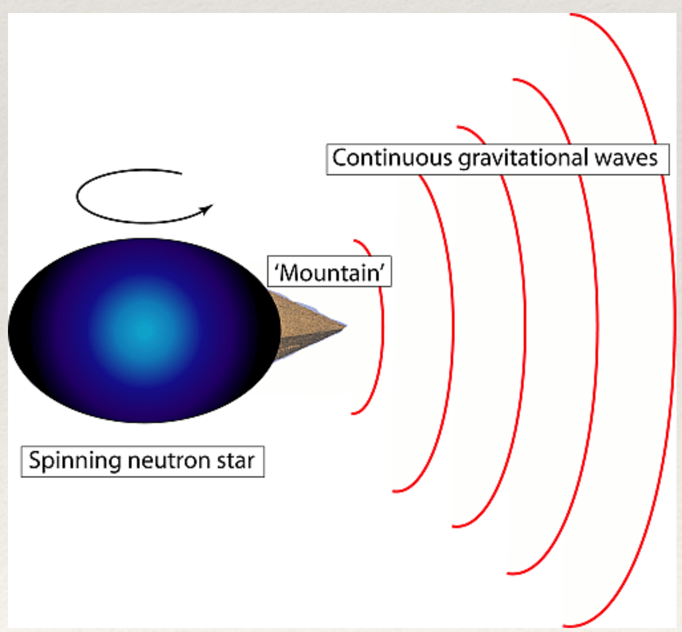
Credit: University of Glasgow

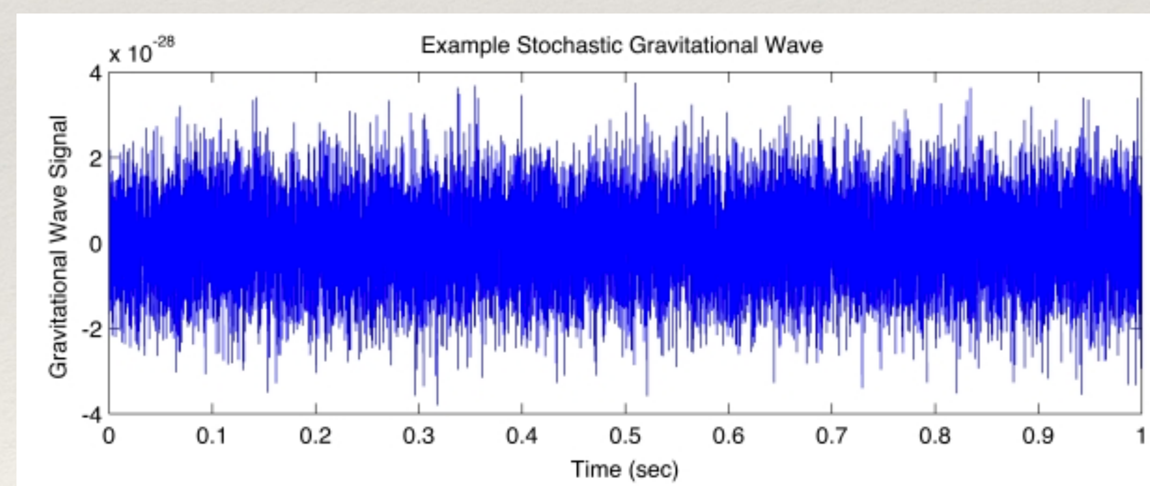
LIGO/Virgo Science Targets

Short Duration



Long Duration

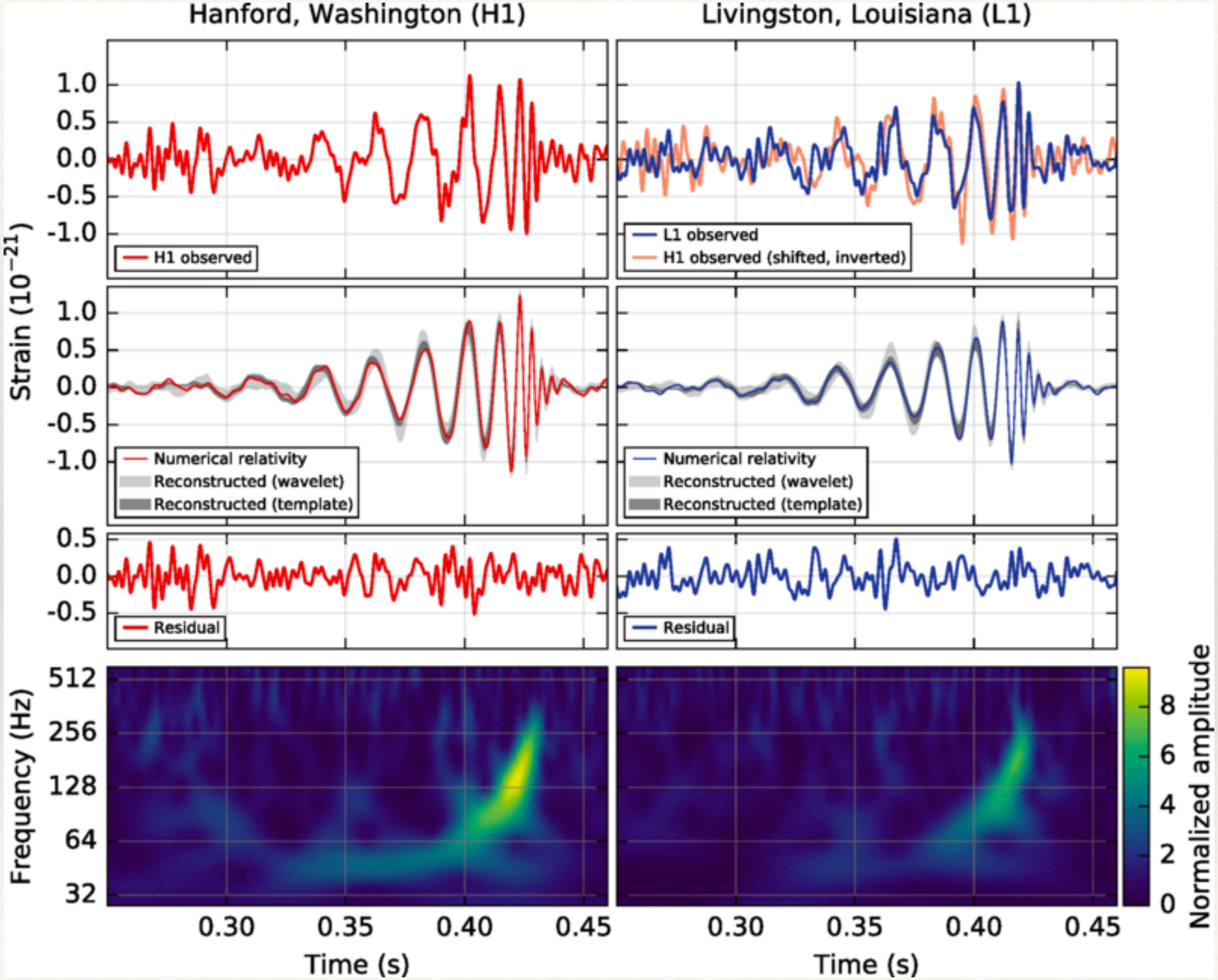




Well Modelled

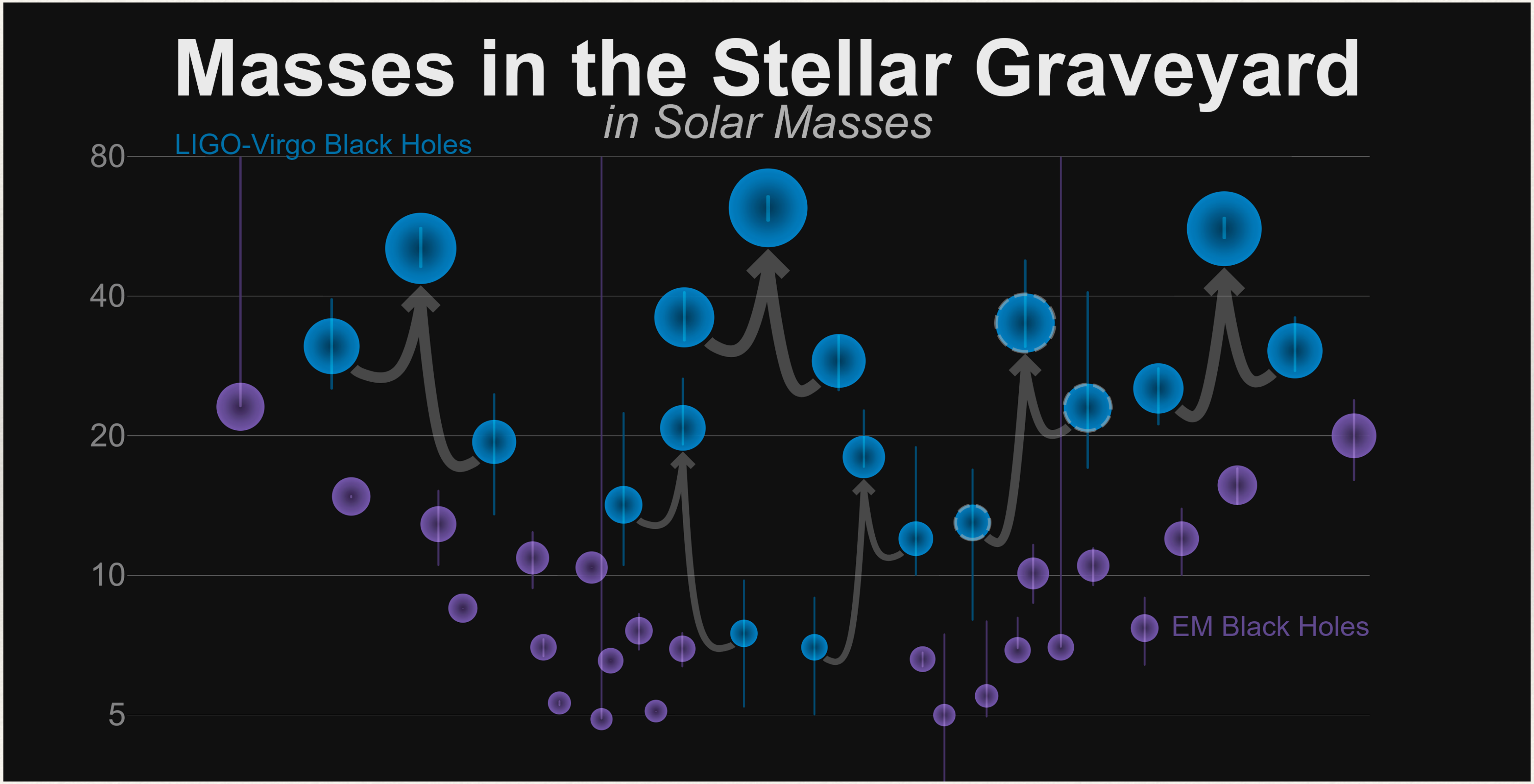
Not well modelled

Quick aside on black holes: GW150914



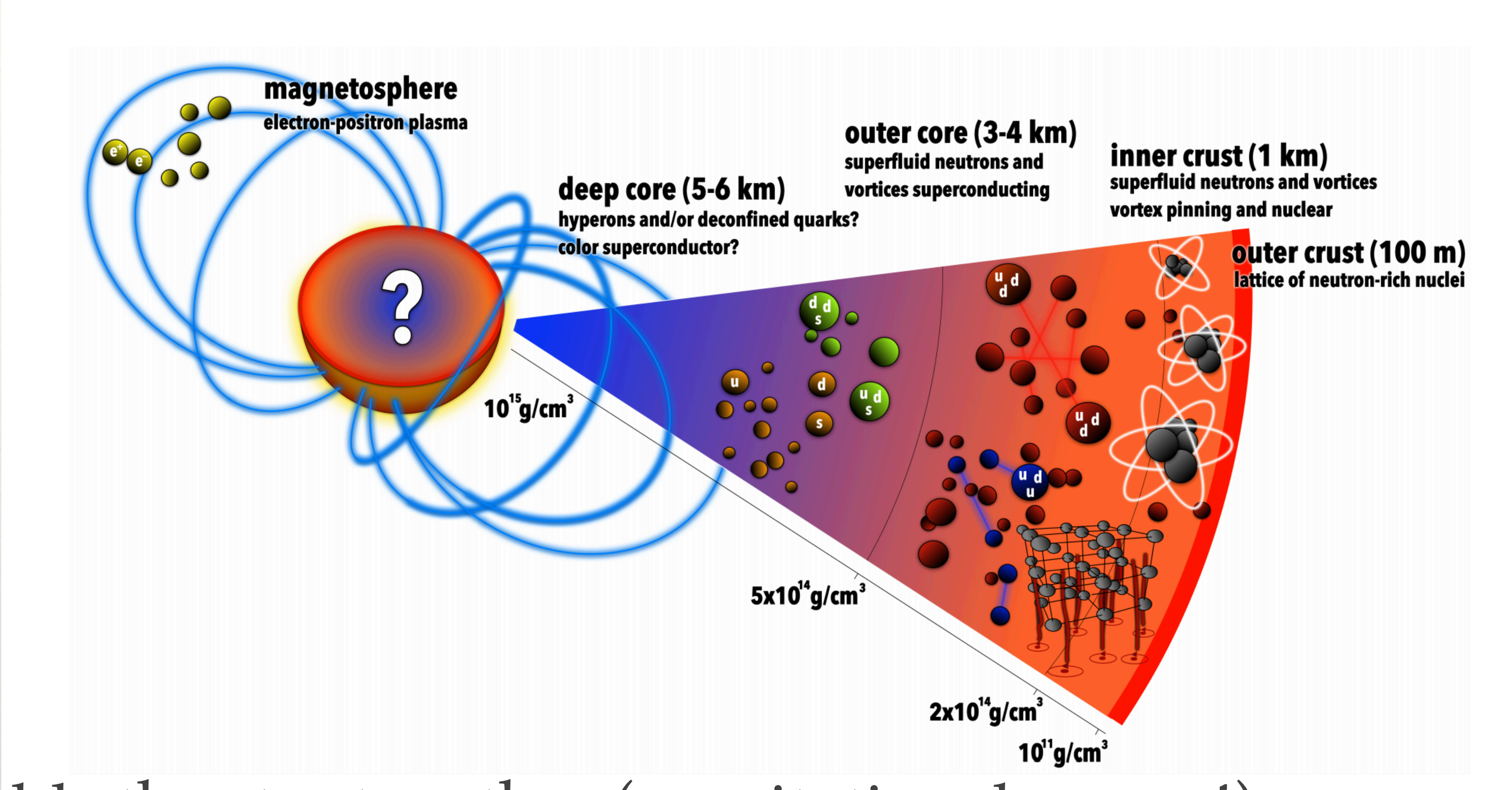
LIGO/Virgo PRL 116, 061102 (2016)

Quick aside on black holes



Plus **22** *potential* new events already in O3 …. Not all binary black holes

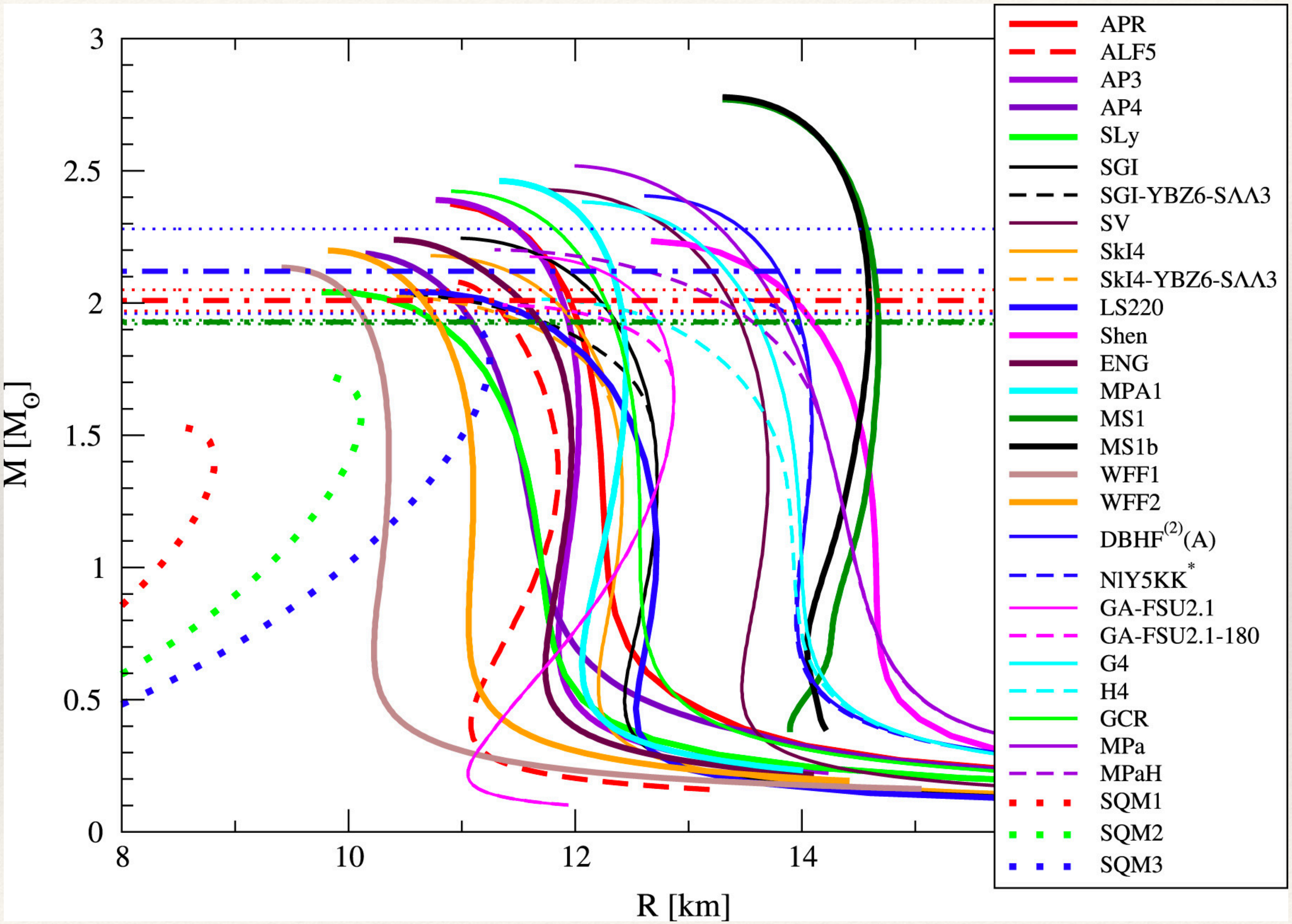
Neutron stars - a “hands off” laboratory for extreme physics



- **Gravity**, holds the star together (gravitational waves!)
- **Electromagnetism**, makes pulsars pulse and magnetars flare
- **Strong interaction**, determines the internal composition
- **Weak interaction**, affects reaction rates - cooling and internal viscosity

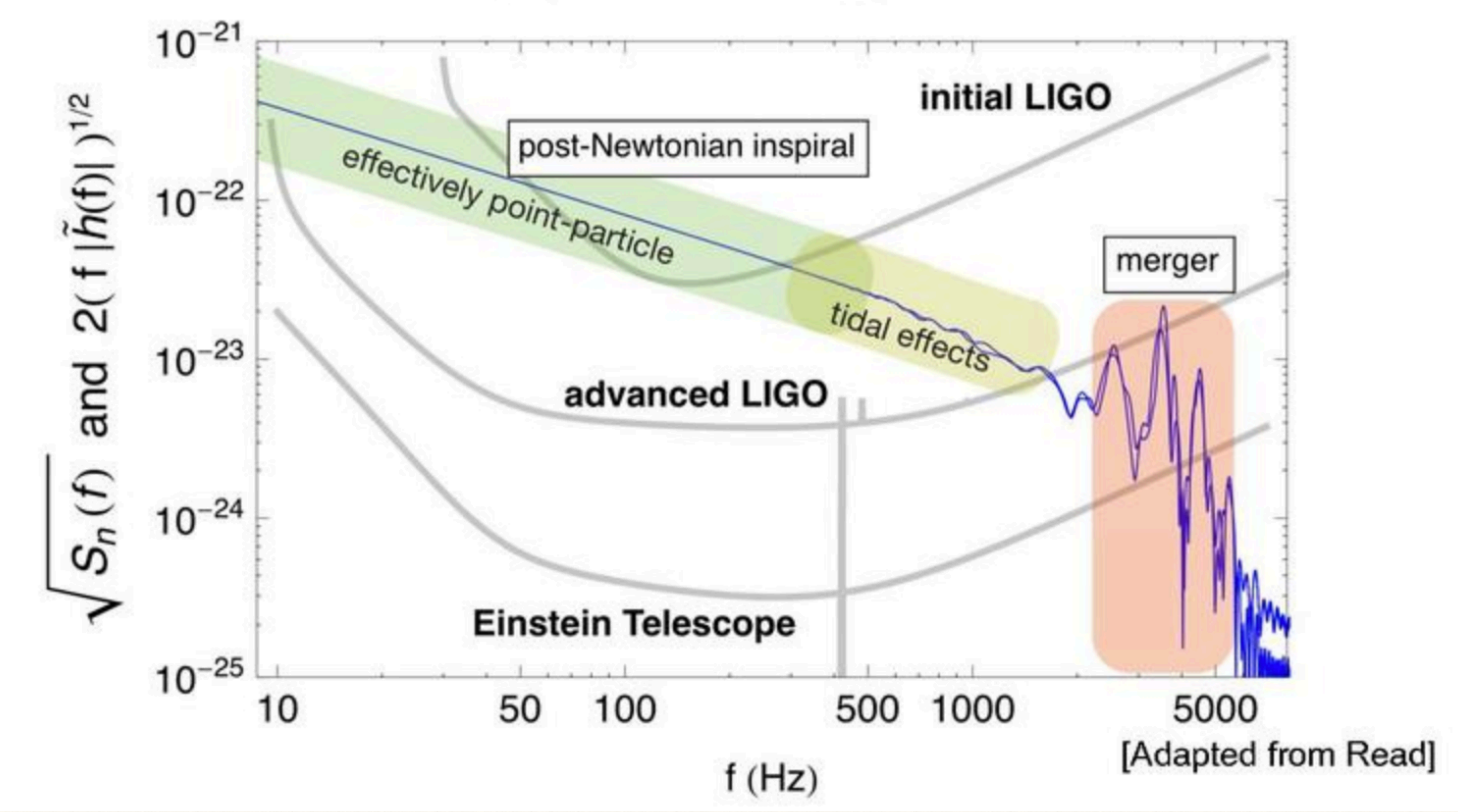
Watts et al., PoS (AASKA14) 215 043
Slide courtesy of N. Anderson

The equation-of-state



Yagi and Yunes Phys.Rept. 681 (2017) 1-72

How colliding neutron stars differ from black holes



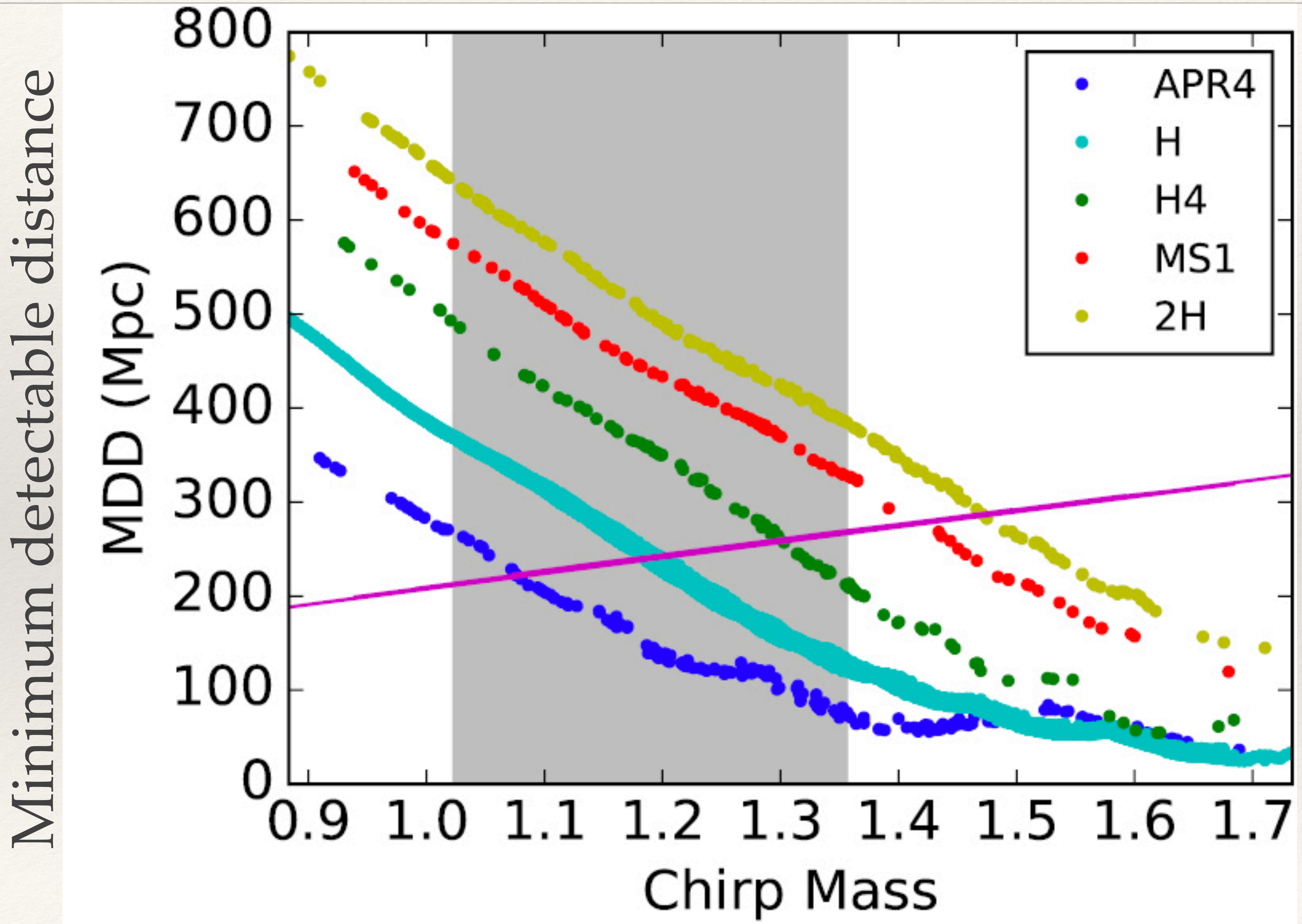
Tidal deformability

$$\lambda_i = \frac{\text{quadropole deformation of star i}}{\text{strength of external tidal field}}$$

$$\Lambda_i = \frac{\lambda_i}{m_i^5} = \frac{2}{3} k_2 \left(\frac{R_i}{m_i} \right)^5$$

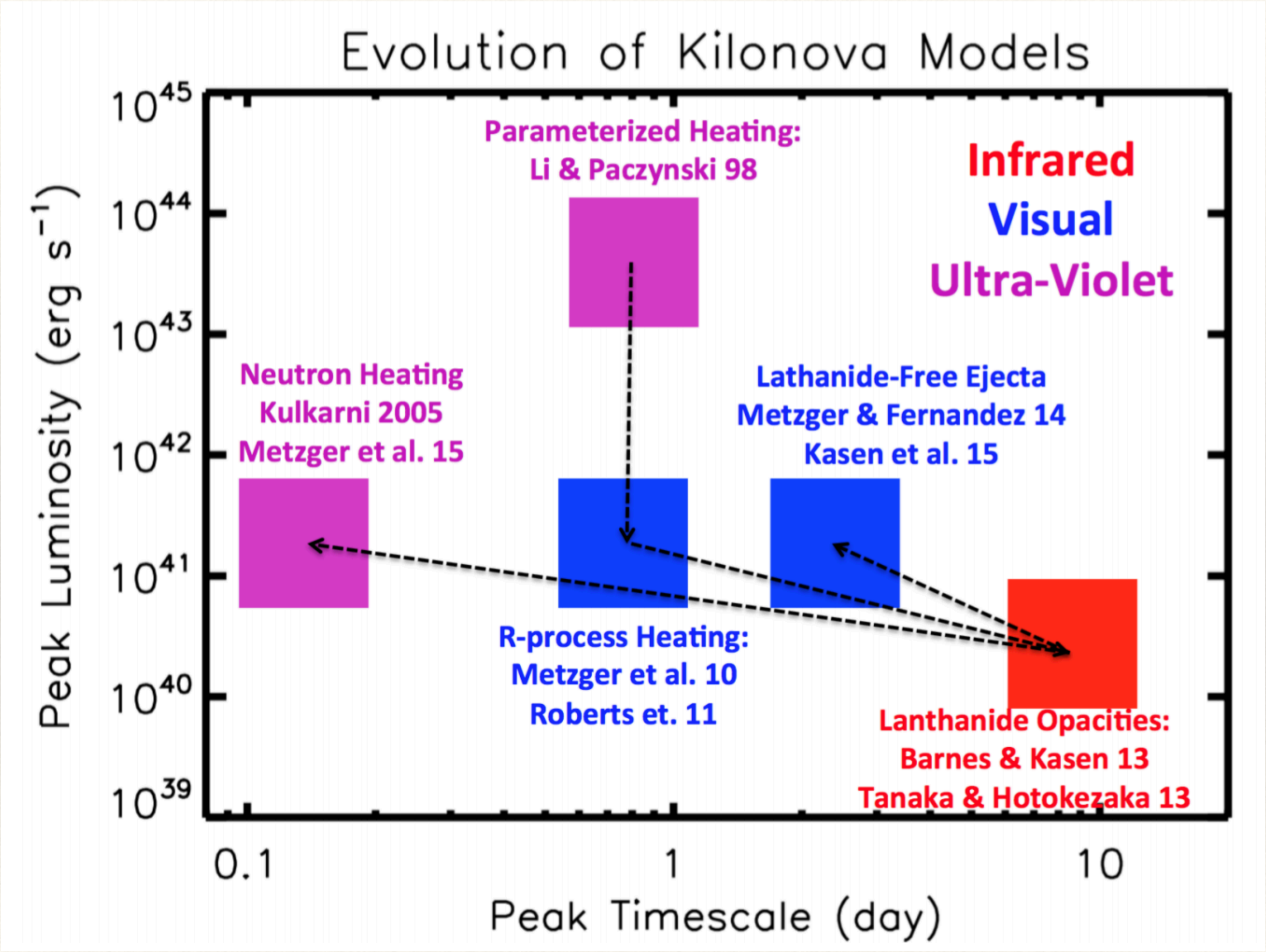
- R: radius; m: mass of star
- k2 relativistic love number (Damour 1983) ~ 0.05-0.15
  - Mass distribution inside the star, not surface deformation

Tidal deformability is a weak effect



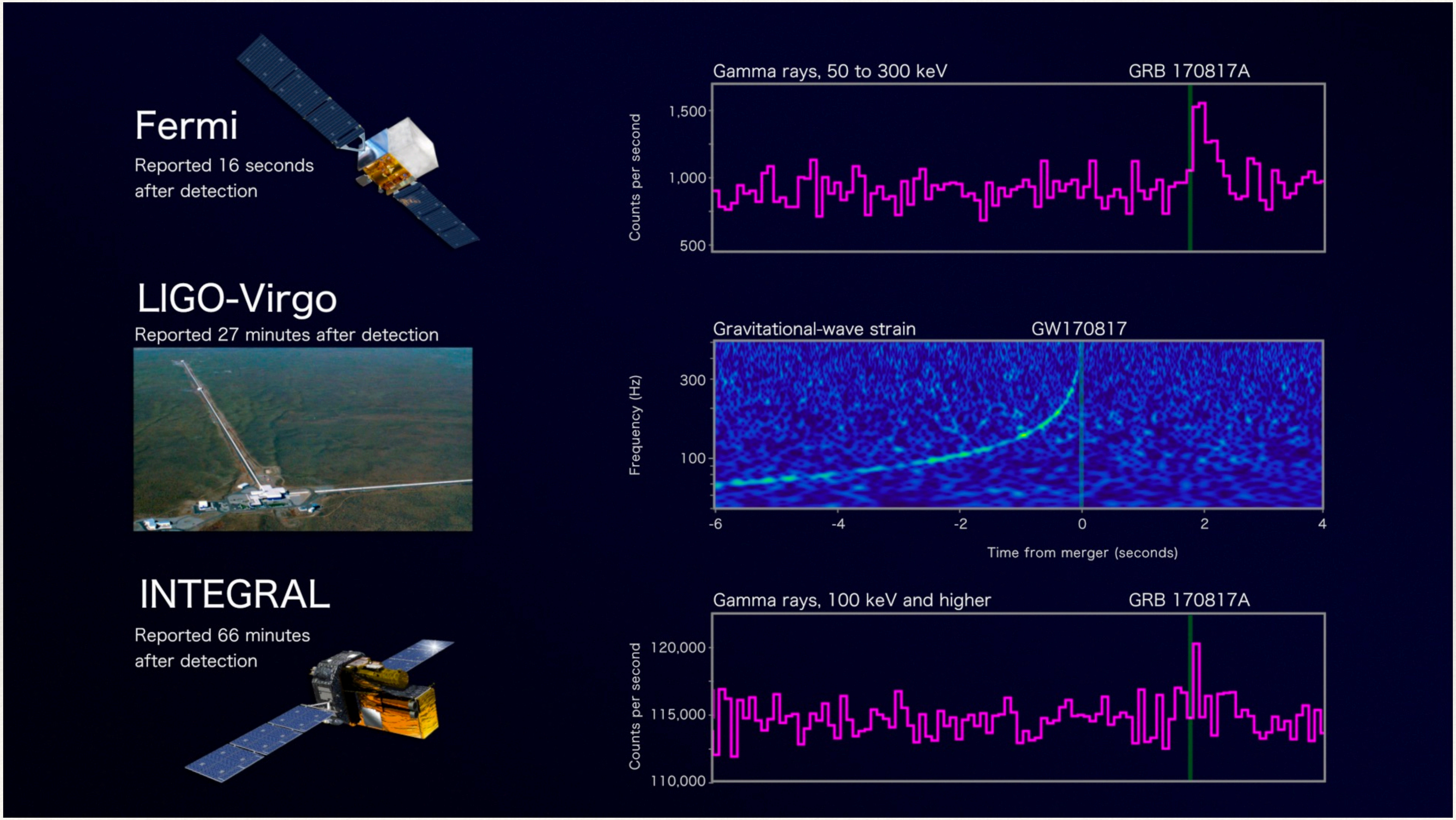
Cullen, IH et al., CQG 34 245003 (2017)

Kilonovae



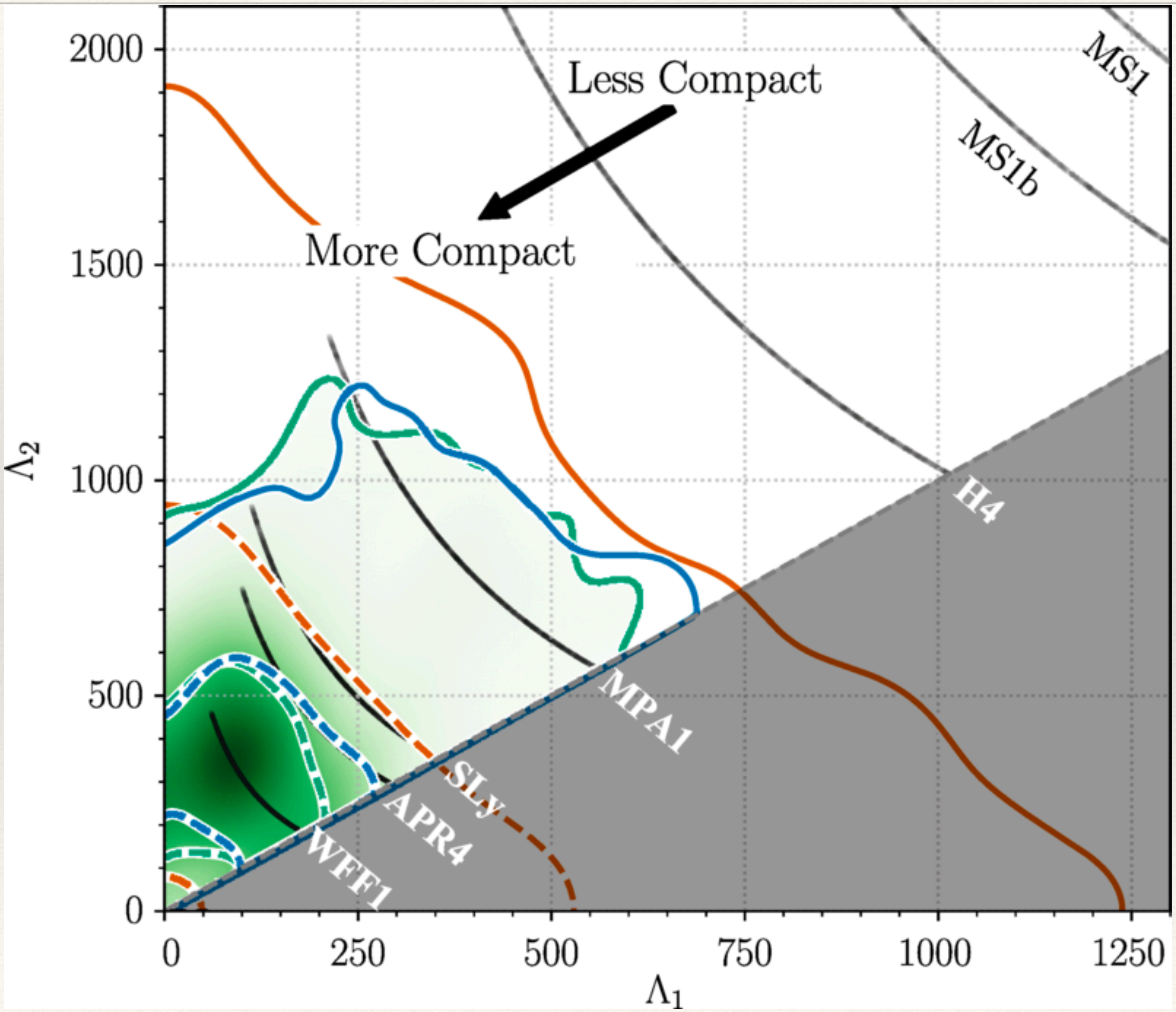
Metzger, Liv. Rev. Rel. 20, 3 (2017)

GW170817 + GRB170817A + AT2017gfo



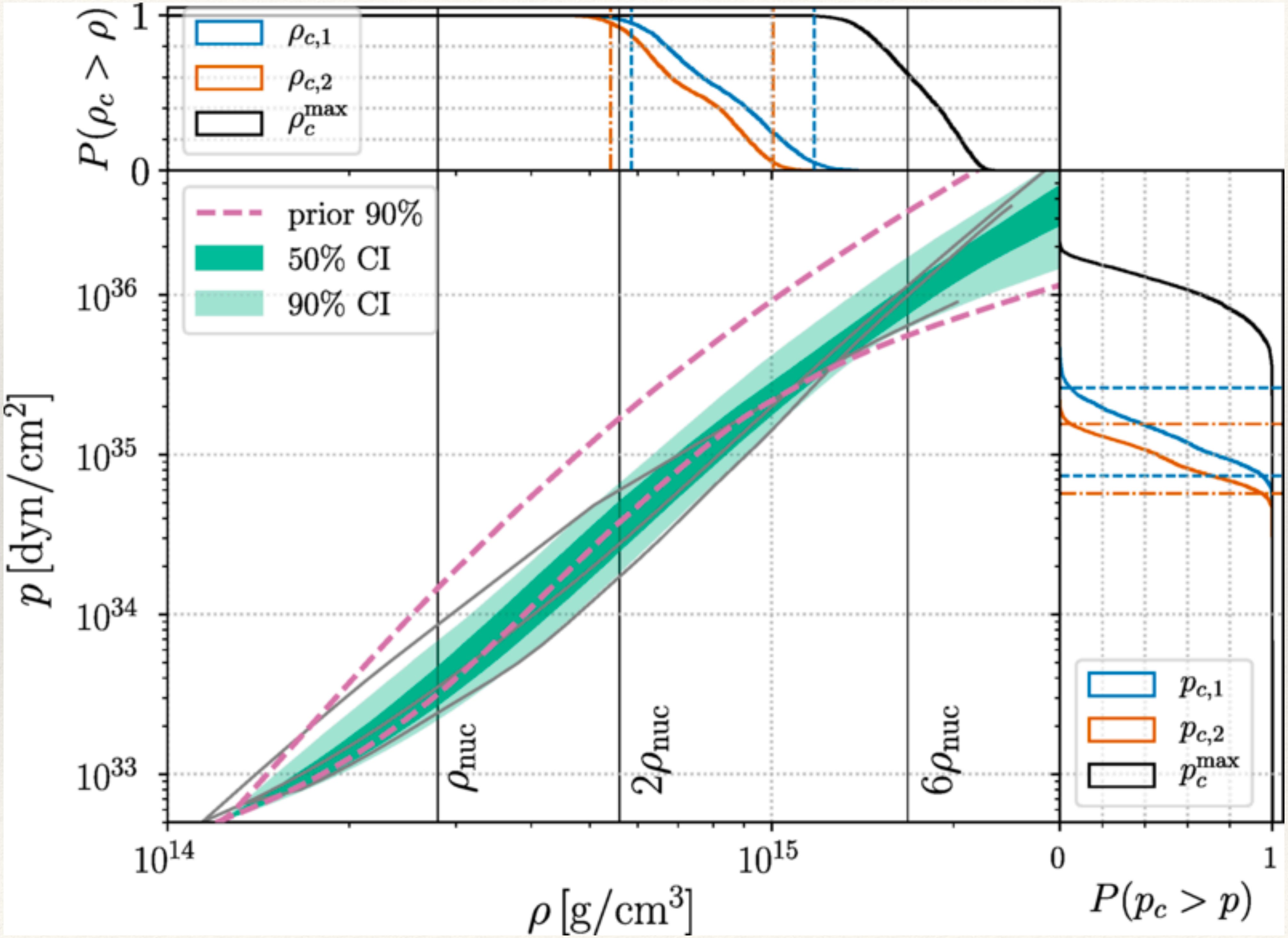
Credit: LIGO/Virgo/Fermi/INTEGRAL

Measuring neutron star tidal deformability



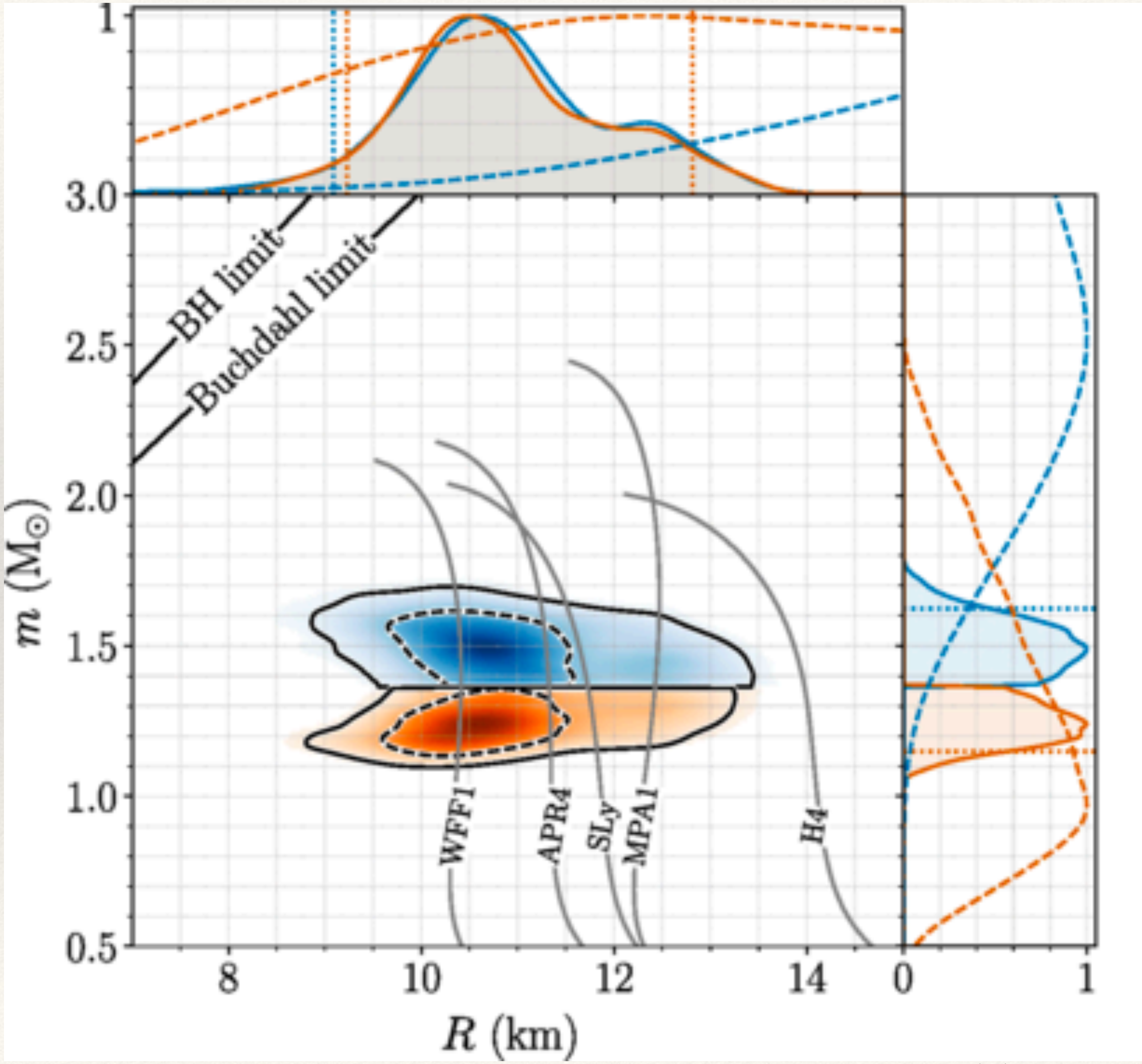
Abbott et al., PRL 121 161101

Constraints on pressure vs density



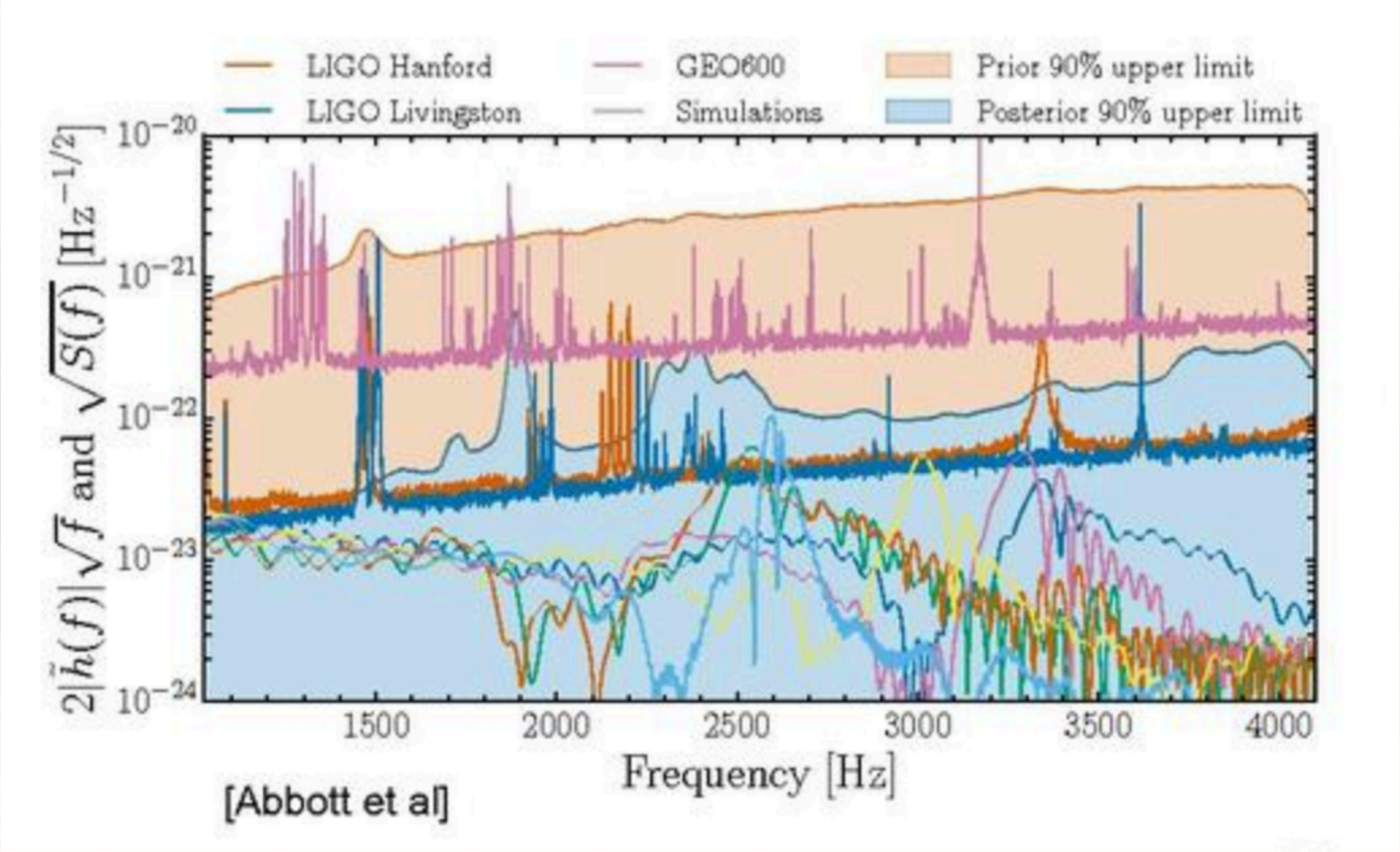
Abbott et al., PRL 121 161101

Constraining on mass vs radius

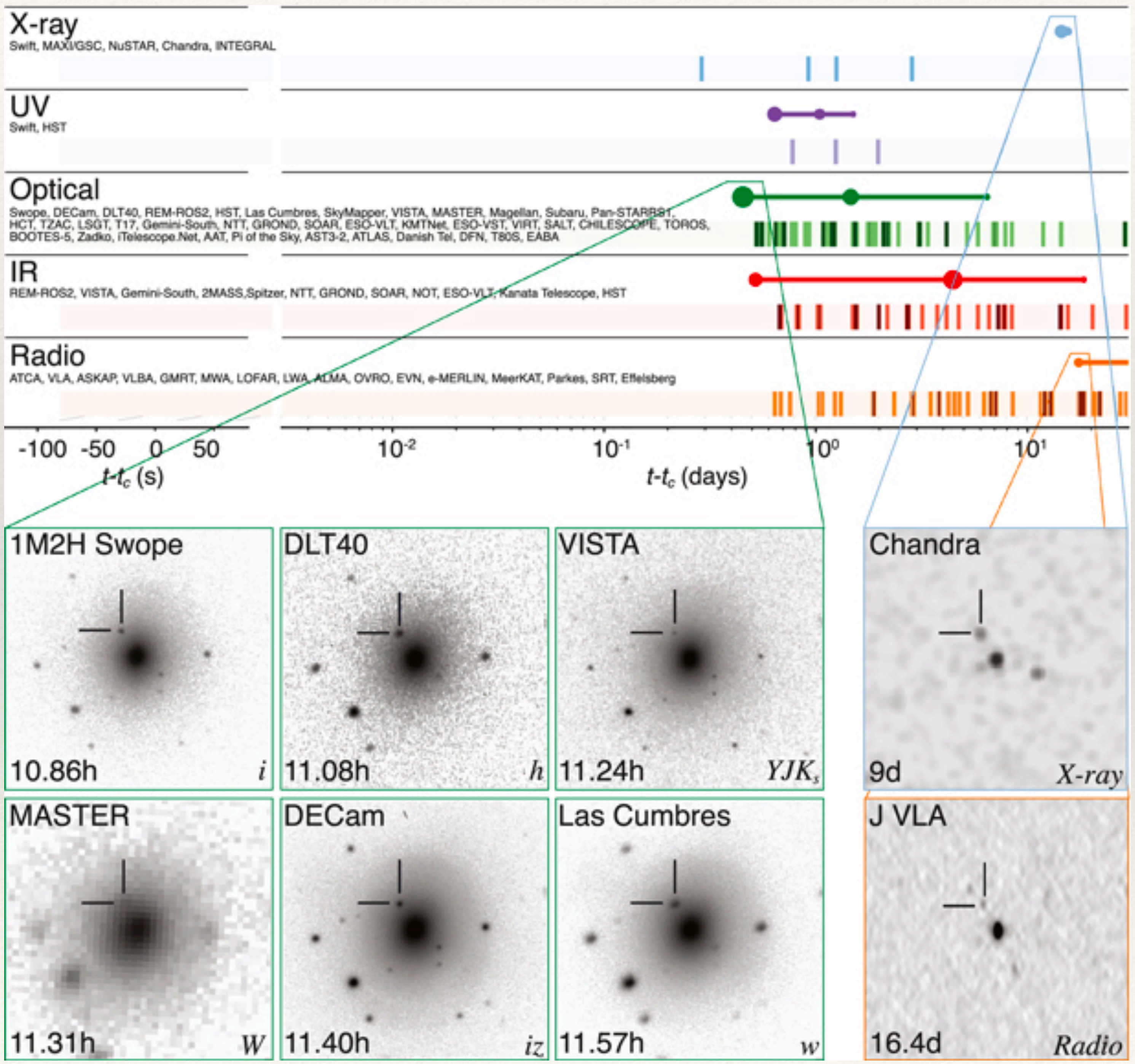


Abbott et al., PRL 121 161101

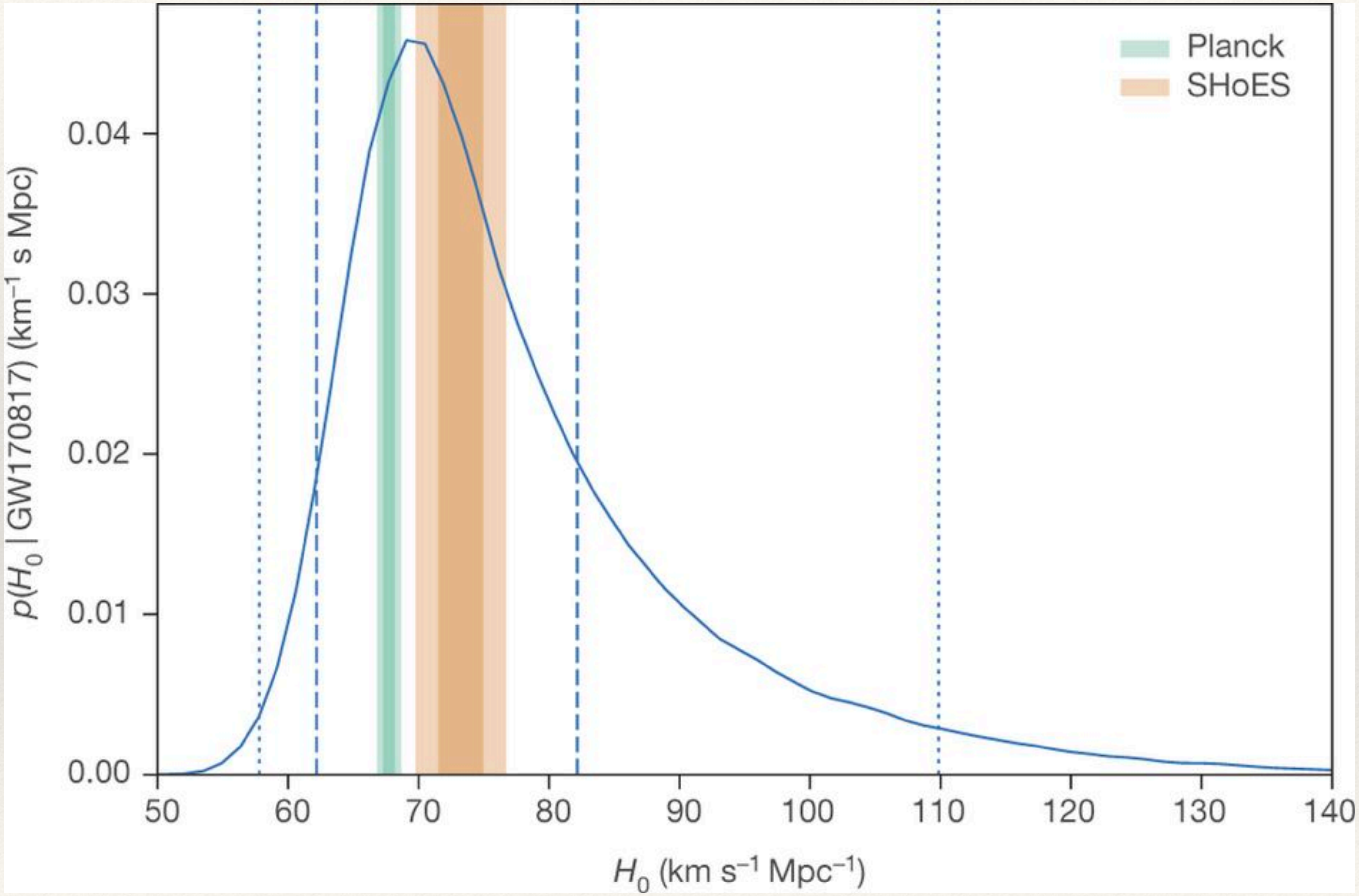
Measuring a post-merger signal



AT2017gfo

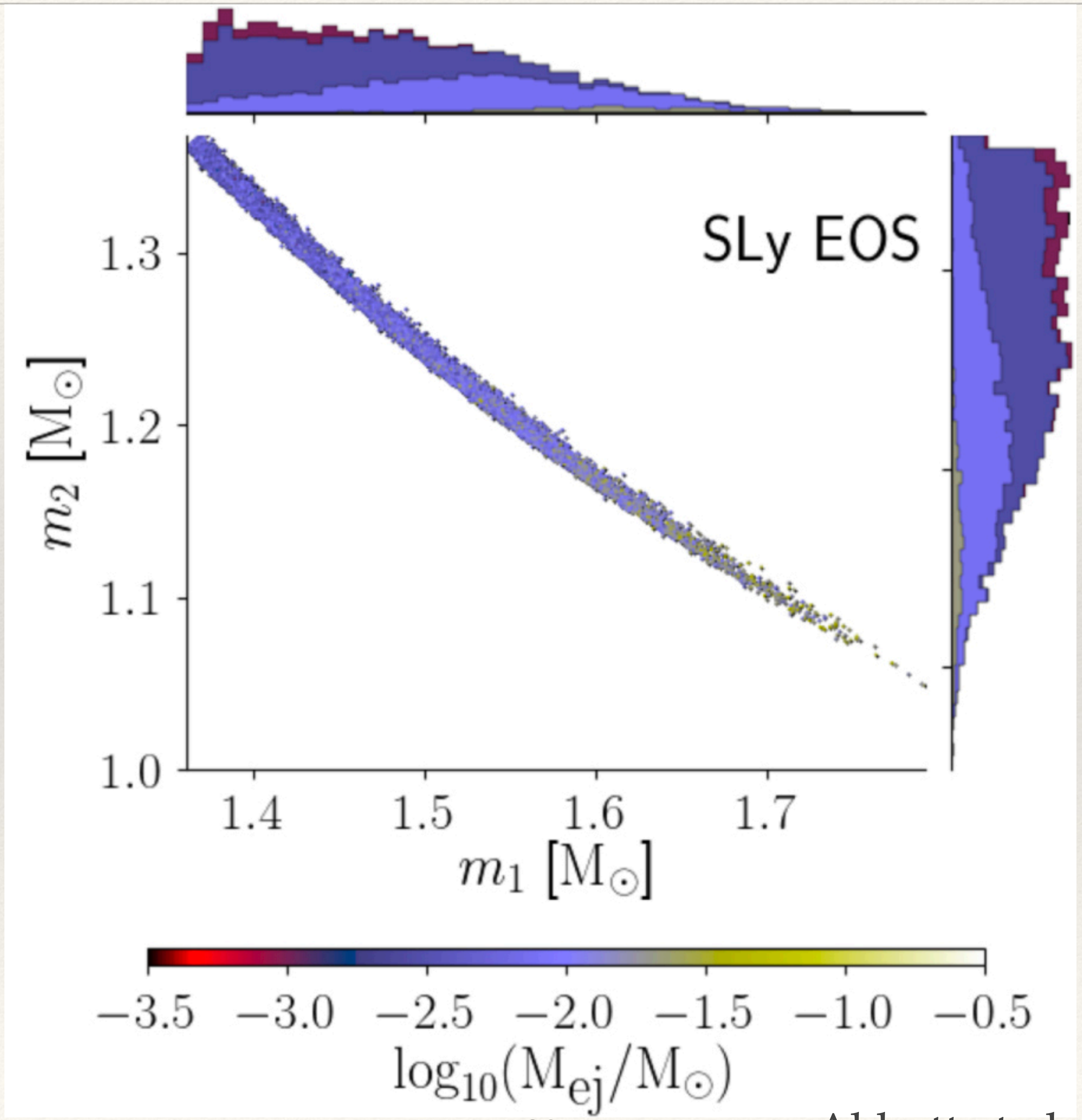

X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100 -50 0 50
t-t_c (s)
10^-2 10^-1 10^0 10^1
t-t_c (days)
1M2H Swope
10.86h i
DLT40
11.08h h
VISTA
11.24h YJK_s
Chandra
9d X-ray
MASTER
11.31h W
DECam
11.40h iz
Las Cumbres
11.57h w
J VLA
16.4d Radio

Measuring Hubble's constant



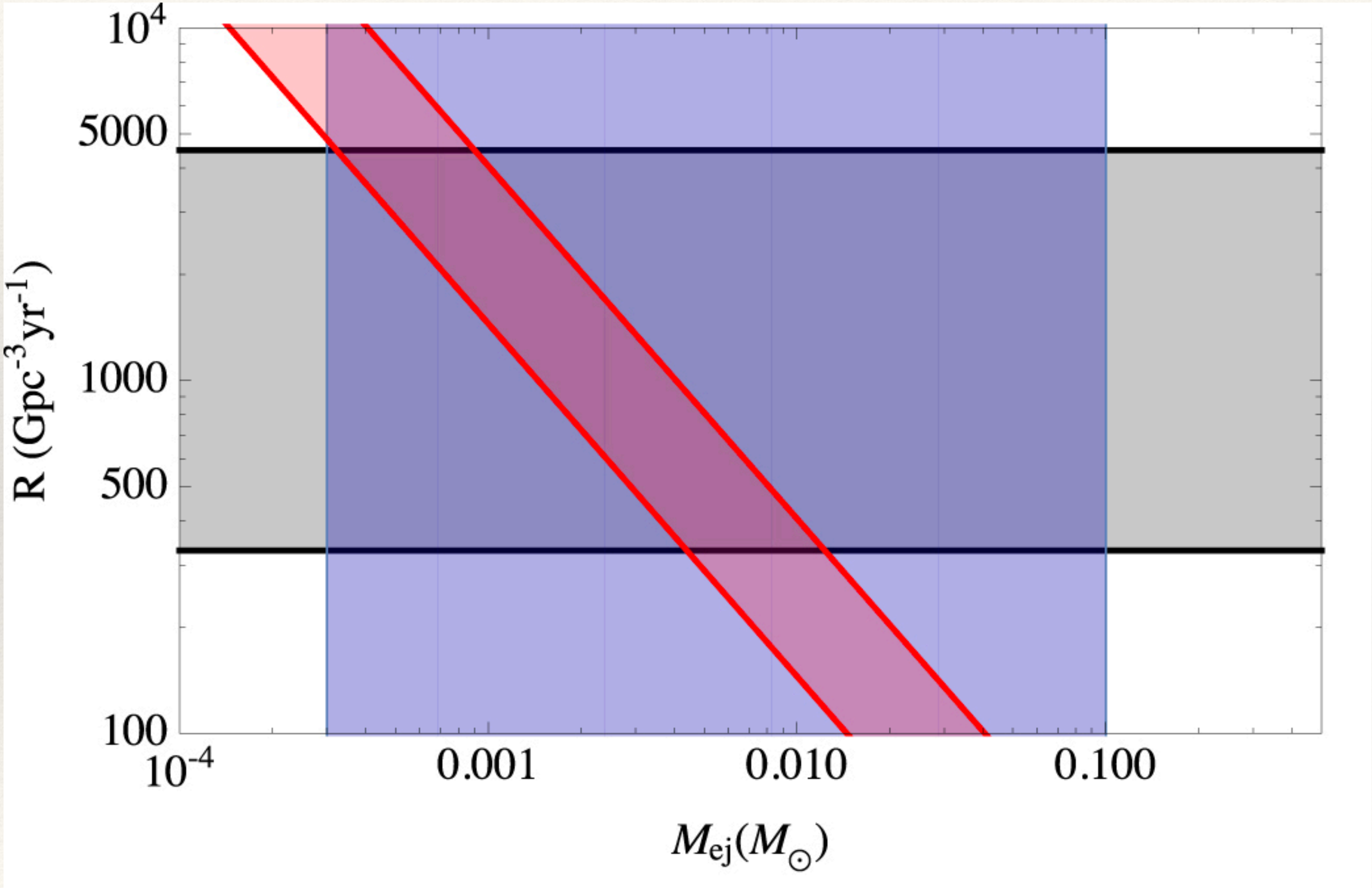
Abbott et al., Nature 551, 85 (2017)

R-process element formation



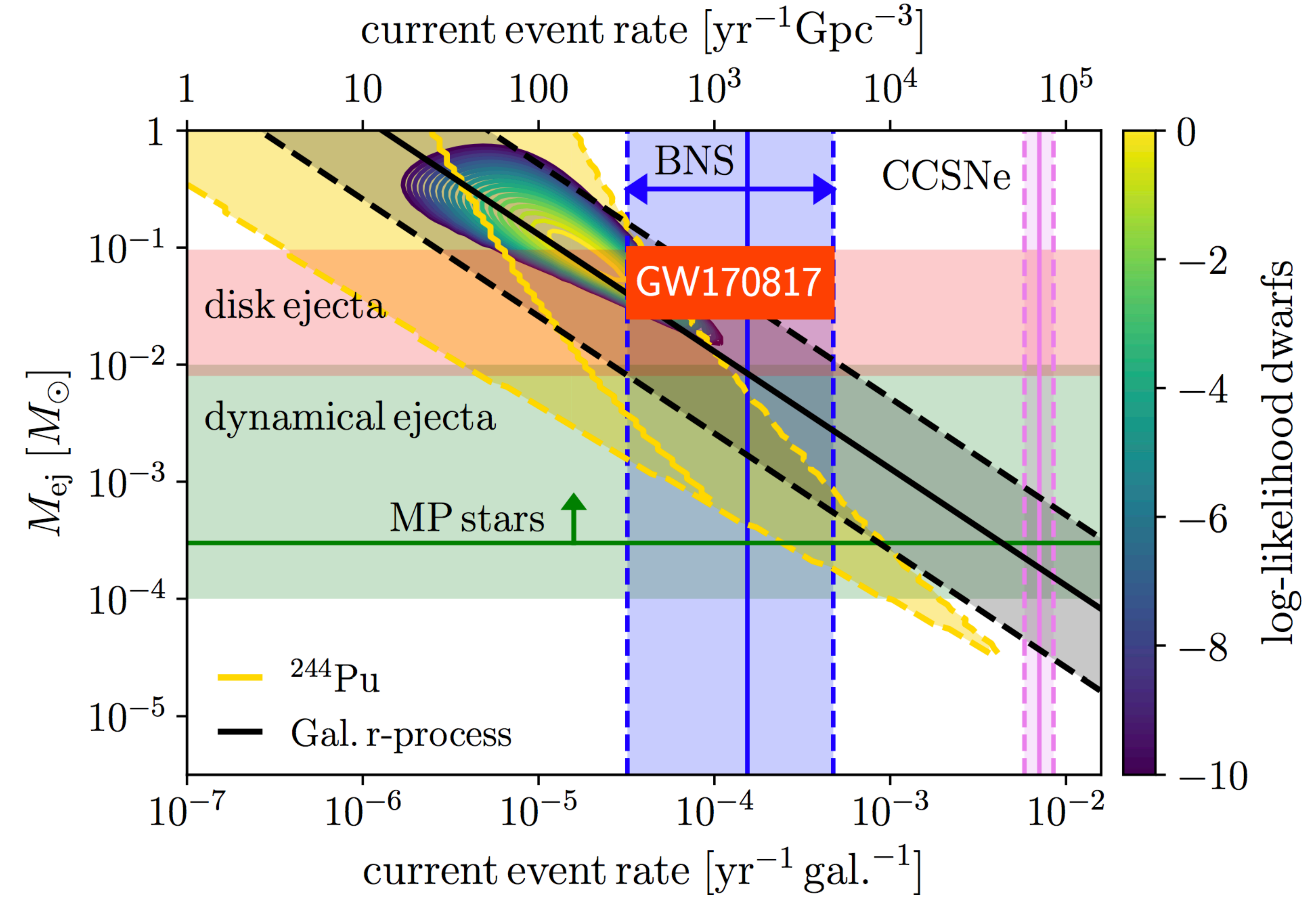
Abbott et al., ApJL 850, L39 (2017)

R-process element formation



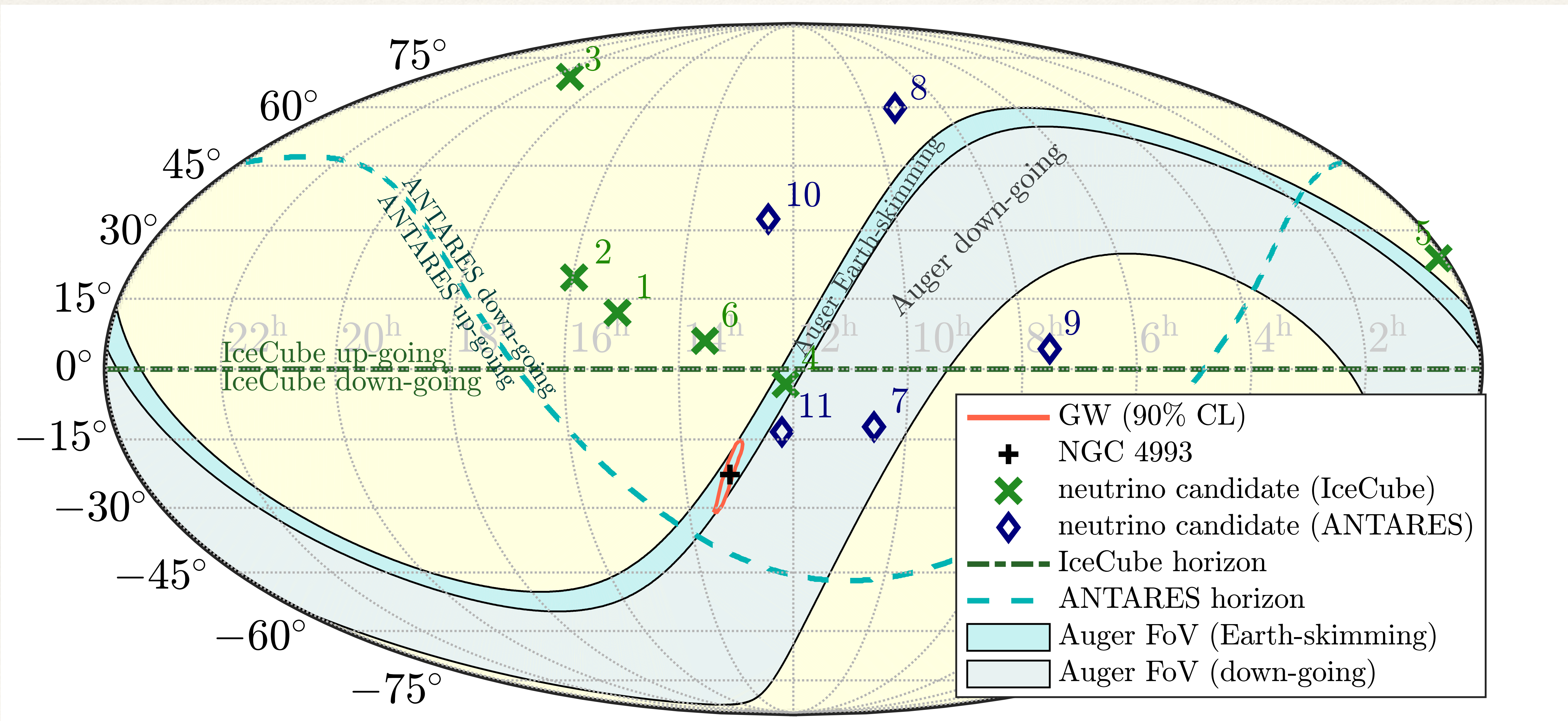
Abbott et al., ApJL 850, L39 (2017)

R-process element formation



D. Siegel, ArXiv:1901.09044 (2019)

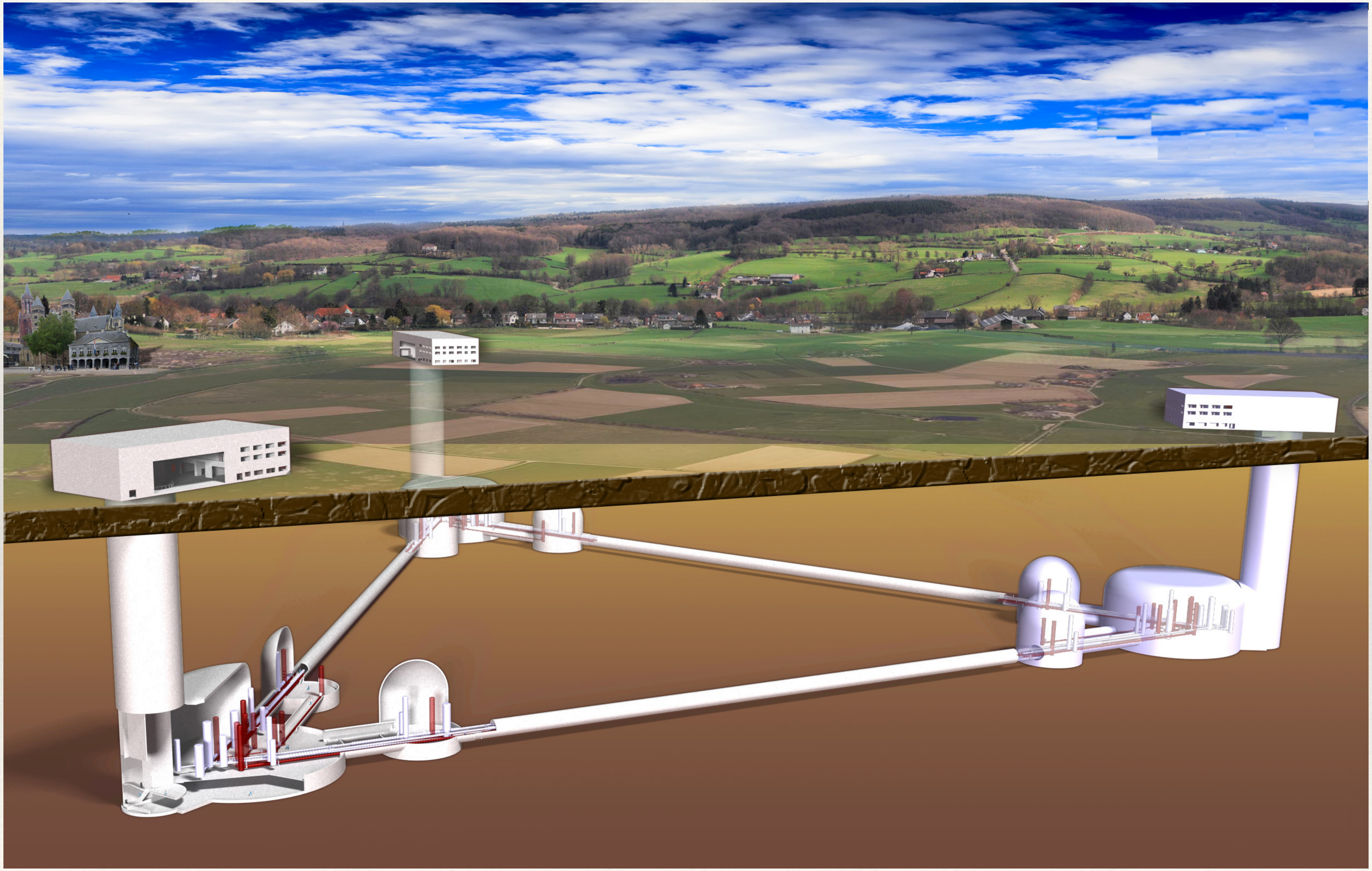
Neutrinos and GW170817



Astrophys. J. Lett. 850, L35 (2017)

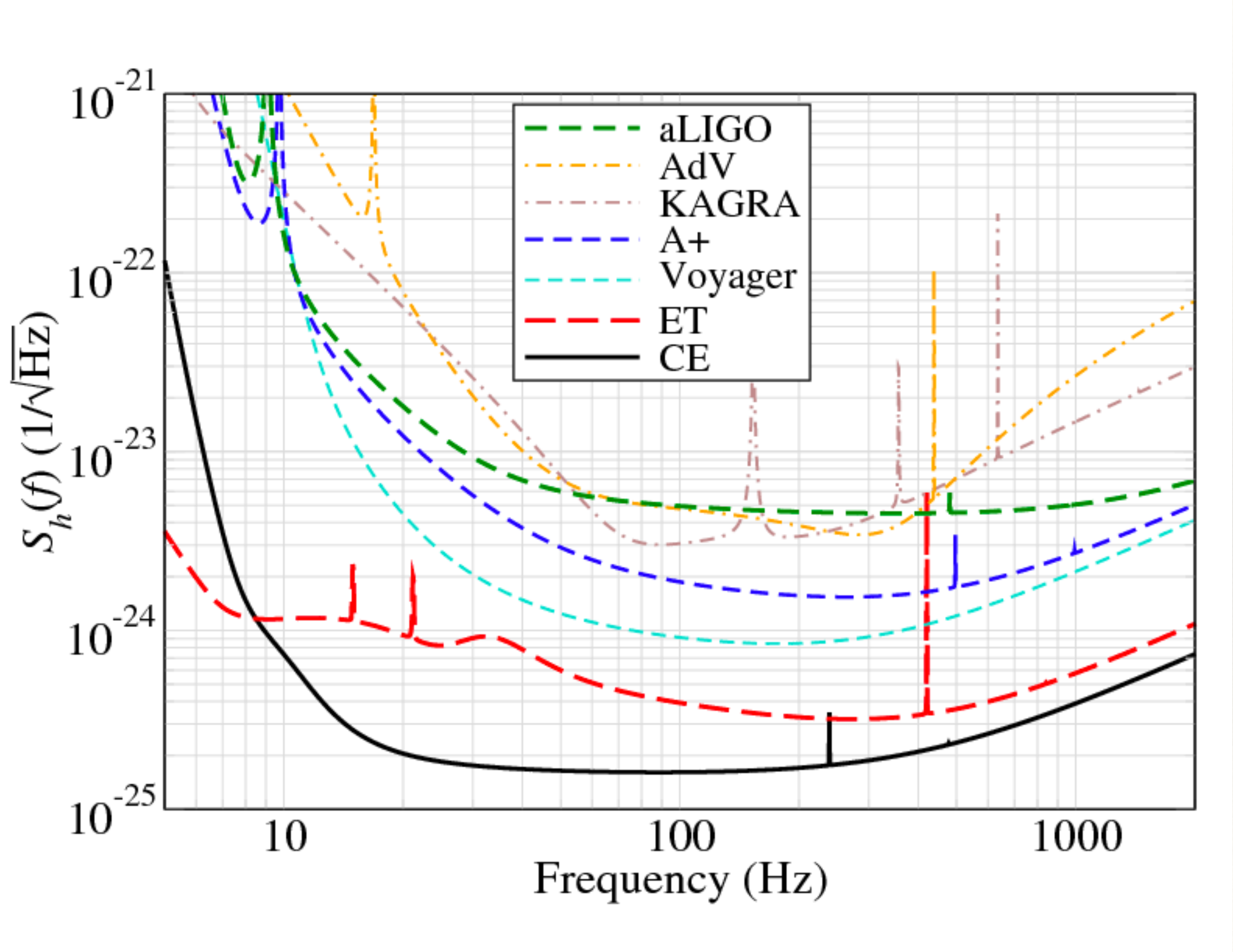
Looking forward

Einstein Telescope

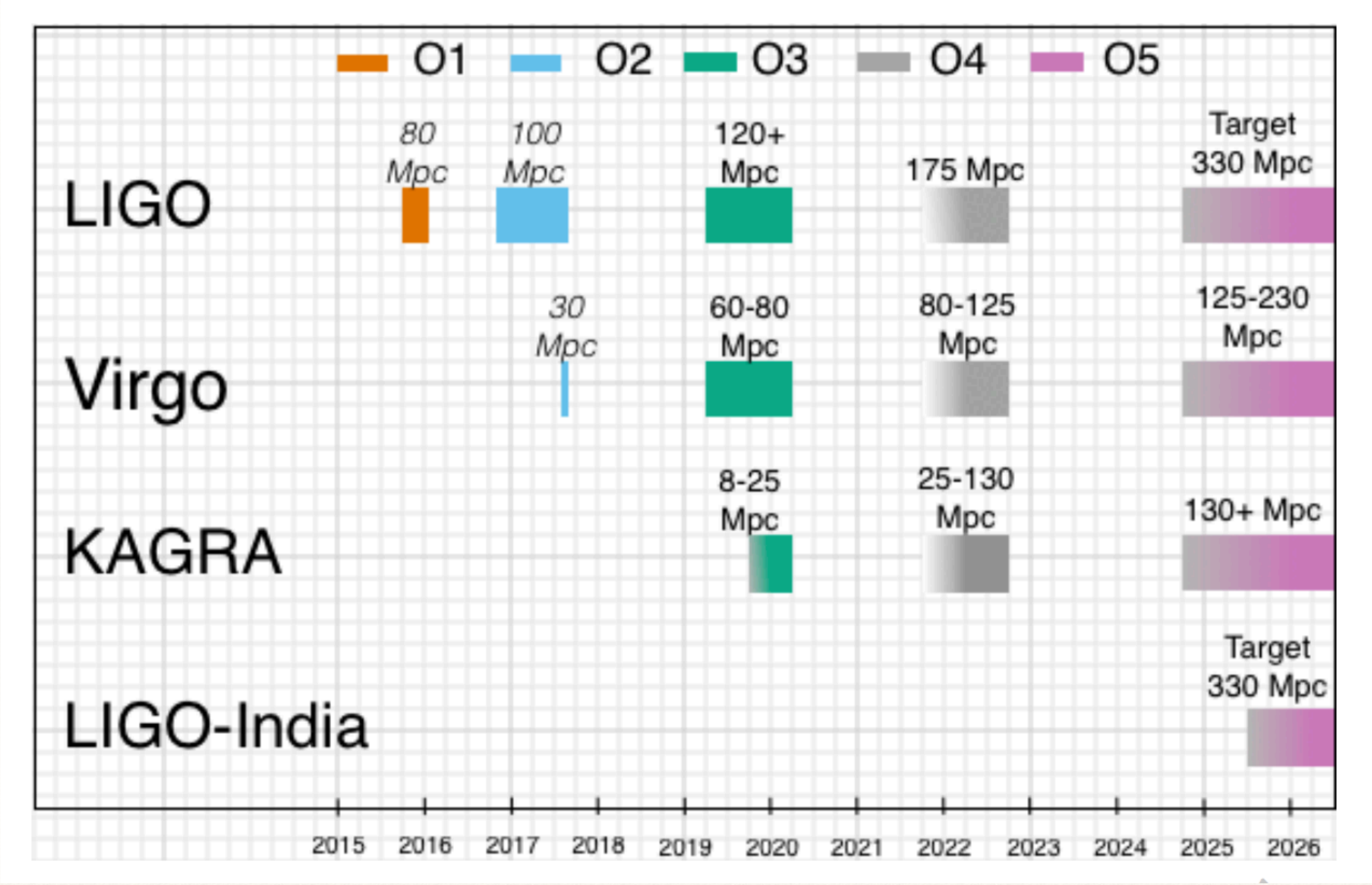


Regimbau et al. PRL 118, 151105 (2017)

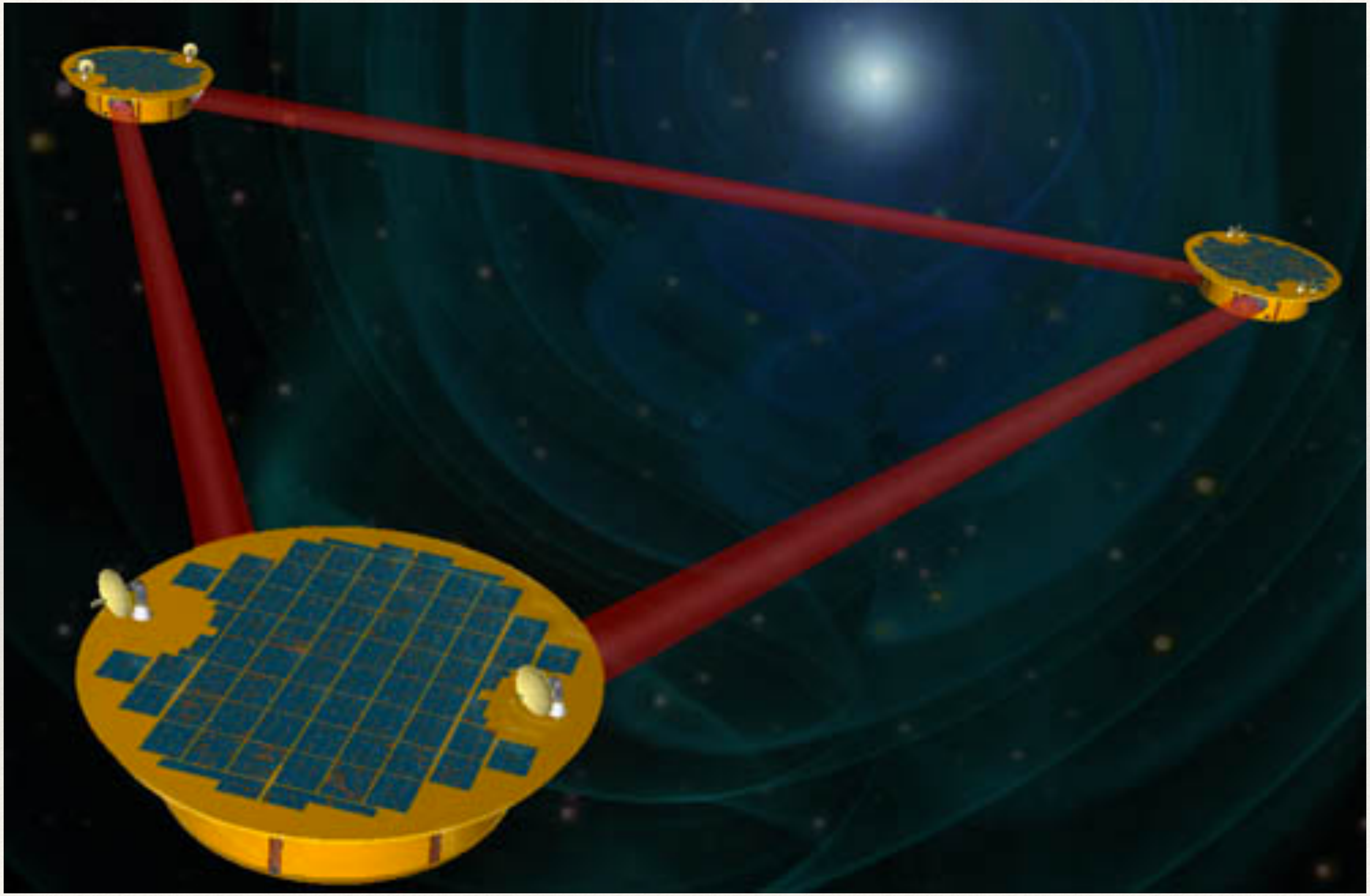
Future plans for gravitational-wave observations



Future plans for gravitational-wave observations



LISA - Space-based GW astronomy



5 Million kilometer arm length

Thanks!