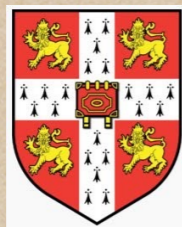# The dawn of a new era: Exploring the Universe with Gravitational Waves

Ulrich Sperhake

DAMTP, University of Cambridge
LIGO Scientific Collaboration

Cambridge University Astronomical Society
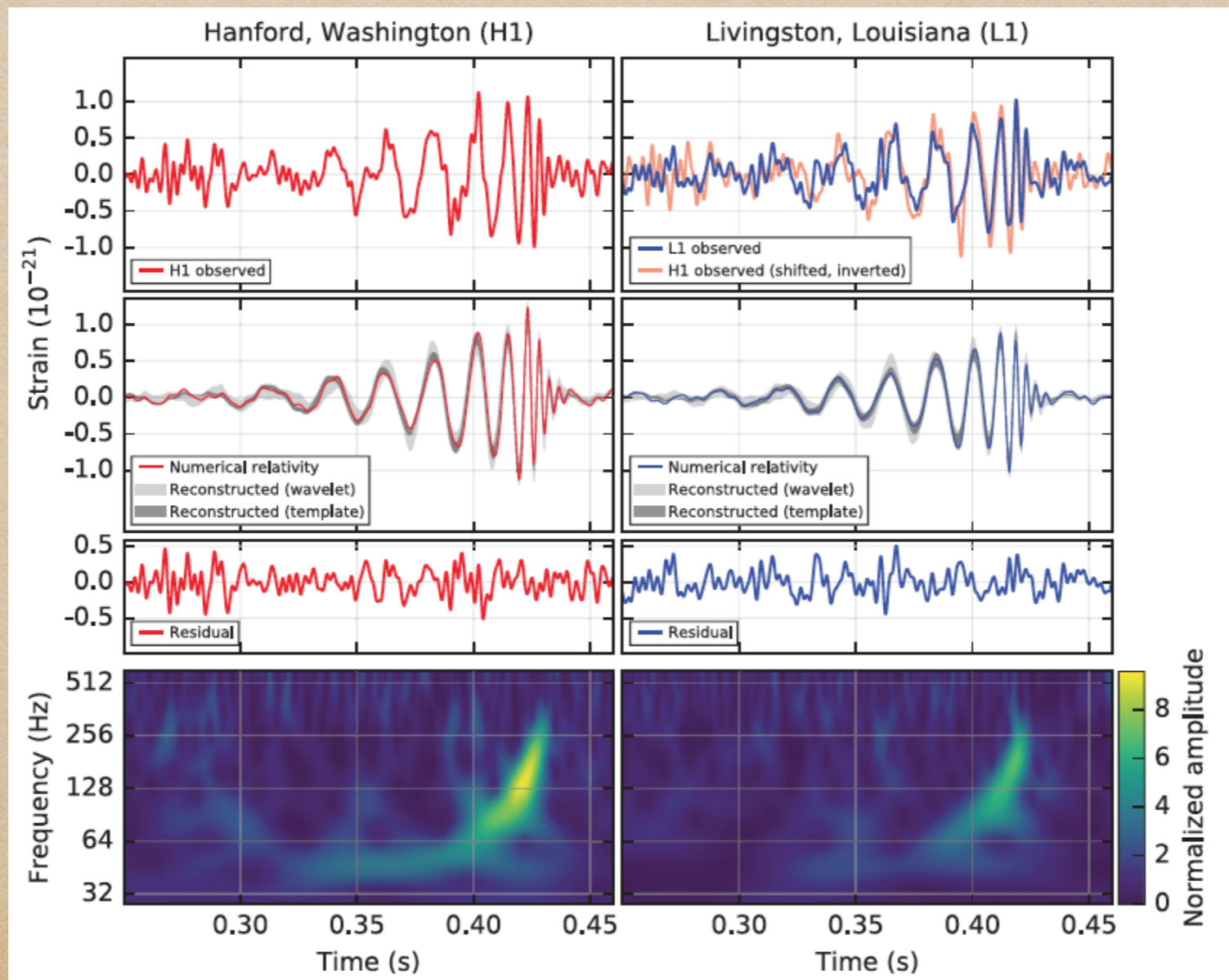### Cambridge, 24 Nov 2020

Gravitational Waves: Ripples in spacetime

- Unusual news headlines on 11/12 February 2016
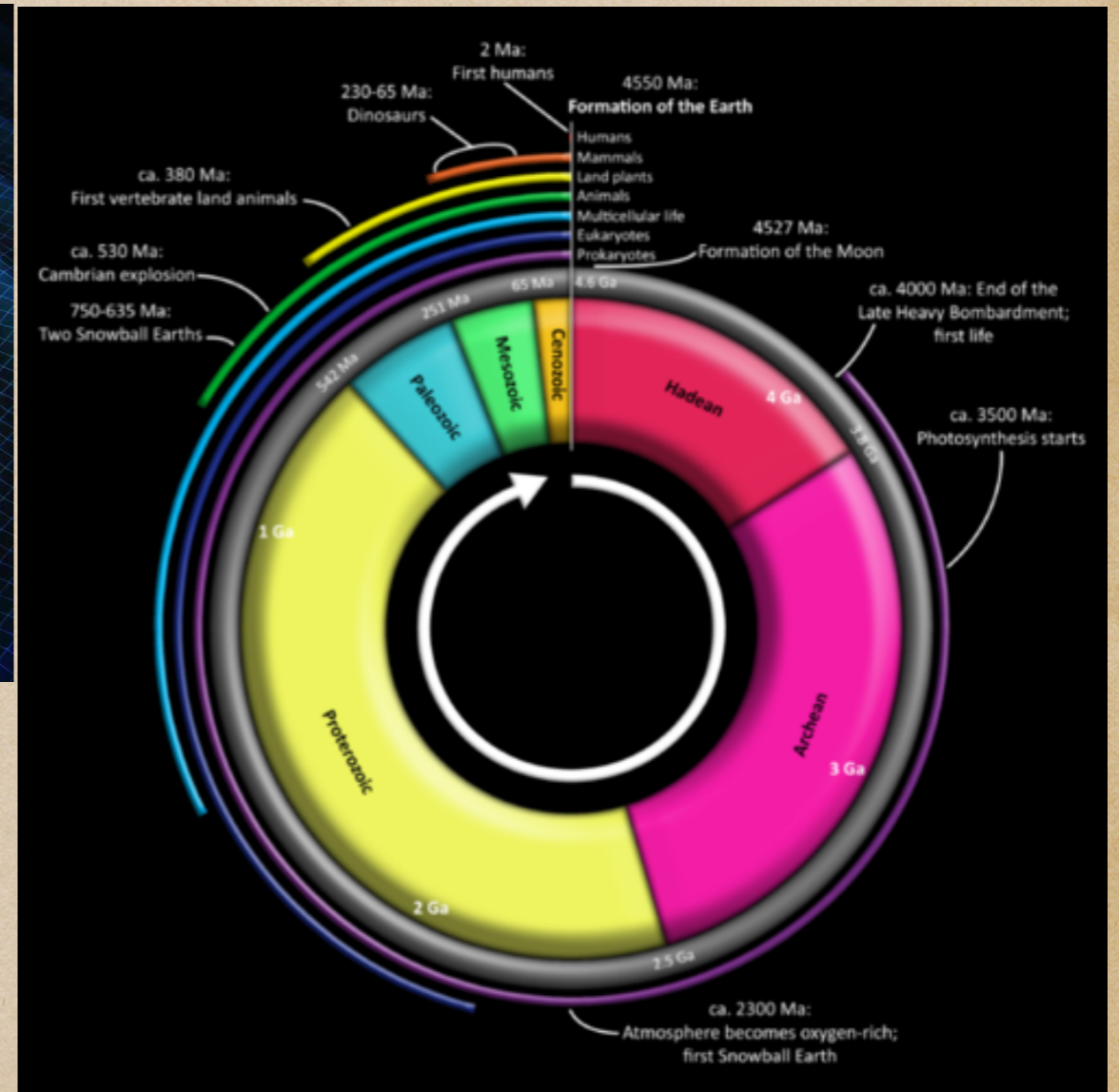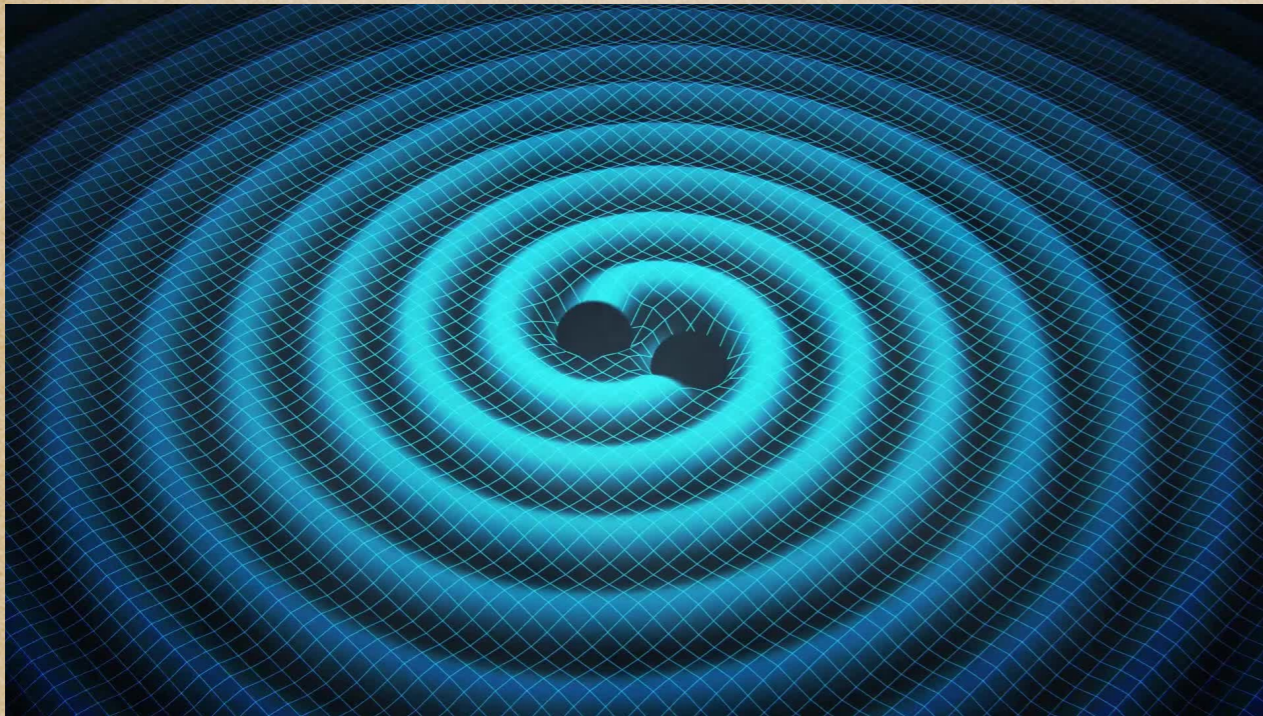- First direct detection of gravitational waves: GW150914

So, what happened?

- Sep 14, 2015 at 09:50:45 UTC: SNR ~ 24

  Abbott et al. PRL 2016,   Abbott et al. 1606.01210

- BBH inspiral, merger and ringdown: $m_1 = 35^{+5}_{-3} \, m_\odot$, $m_2 = 30^{+3}_{-4} \, M_\odot$

What really happened...

- Once upon a time: $1.34^{+0.52}_{-0.59}$ Gyr ago, somewhere in the universe
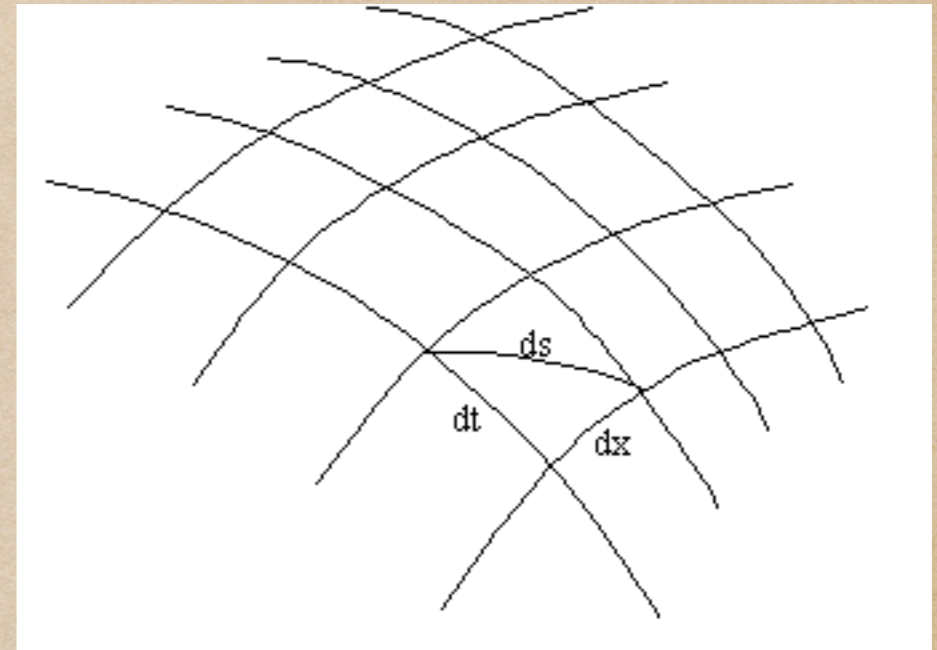

- Deep Precambrian

Overview

- A brief theory of gravitational waves

- Frequency windows, sources and detectors

- Parameter estimation and source modeling

- The GW events

- Some future applications

- Conclusions

Gravitational waves

General relativity in 30 seconds

- Spacetime as a curved manifold

- Key quantity: spacetime metric $g_{\alpha\beta}$

- Curvature, geodesics etc. all follow

- Einstein equations

$$R_{\alpha\beta} - \frac{1}{2}g_{\alpha\beta}R + \Lambda g_{\alpha\beta} = \frac{8\pi G}{c^4}T_{\alpha\beta}$$

- 10 non-linear PDEs for $g_{\alpha\beta}$

- $T_{\alpha\beta} =$ Matter fields

- Conceptually simple,

- hard in practice

- E.g. Schwarzschild

$$g_{\mu\nu} = \begin{pmatrix} \left(1 - \frac{2GM}{rc^2}\right) & 0 & 0 & 0 \\ 0 & -\left(1 - \frac{2GM}{rc^2}\right)^{-1} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2\sin^2\theta \end{pmatrix}$$

$$ds^2 = c^2 dt^2\left(1 - \frac{2GM}{rc^2}\right) - \frac{dr^2}{1 - 2GM/rc^2} - r^2 d\theta^2 - r^2\sin^2\theta\, d\phi^2$$

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Gravitational waves: weak-field solutions

- Consider small deviations from Minkowski in Cartesian coordinates

- "Background": Manifold $\mathcal{M} = \mathbb{R}^4, \quad \eta_{\mu\nu} = \mathrm{diag}(-1,\,1,\,1,\,1)$

- "Perturbation": $h_{\mu\nu} = \mathcal{O}(\epsilon) \ll 1 \quad \Rightarrow \quad g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

- Coordinate freedom: "Transverse-traceless (TT)" gauge

$$h^\mu_{\ \mu} = 0, \quad \partial^\nu h_{\mu\nu} = 0$$

- Vacuum, no cosmological constant: $T_{\mu\nu} = 0, \quad \Lambda = 0$

- Einstein's eqs.: $\Box h_{\mu\nu} = 0$

- Plane wave solution in **z** direction: $h_{\mu\nu} = H_{\mu\nu} e^{ik_\sigma x^\sigma}$

$$k^\mu = \omega(1,\,0,\,0,\,1) \qquad H_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & H_+ & H_\times & 0 \\ 0 & H_\times & -H_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Effect on particles

- Geodesic eq.

- Particle at rest at x^μ stays at $x^\mu = \text{const}$ in TT gauge
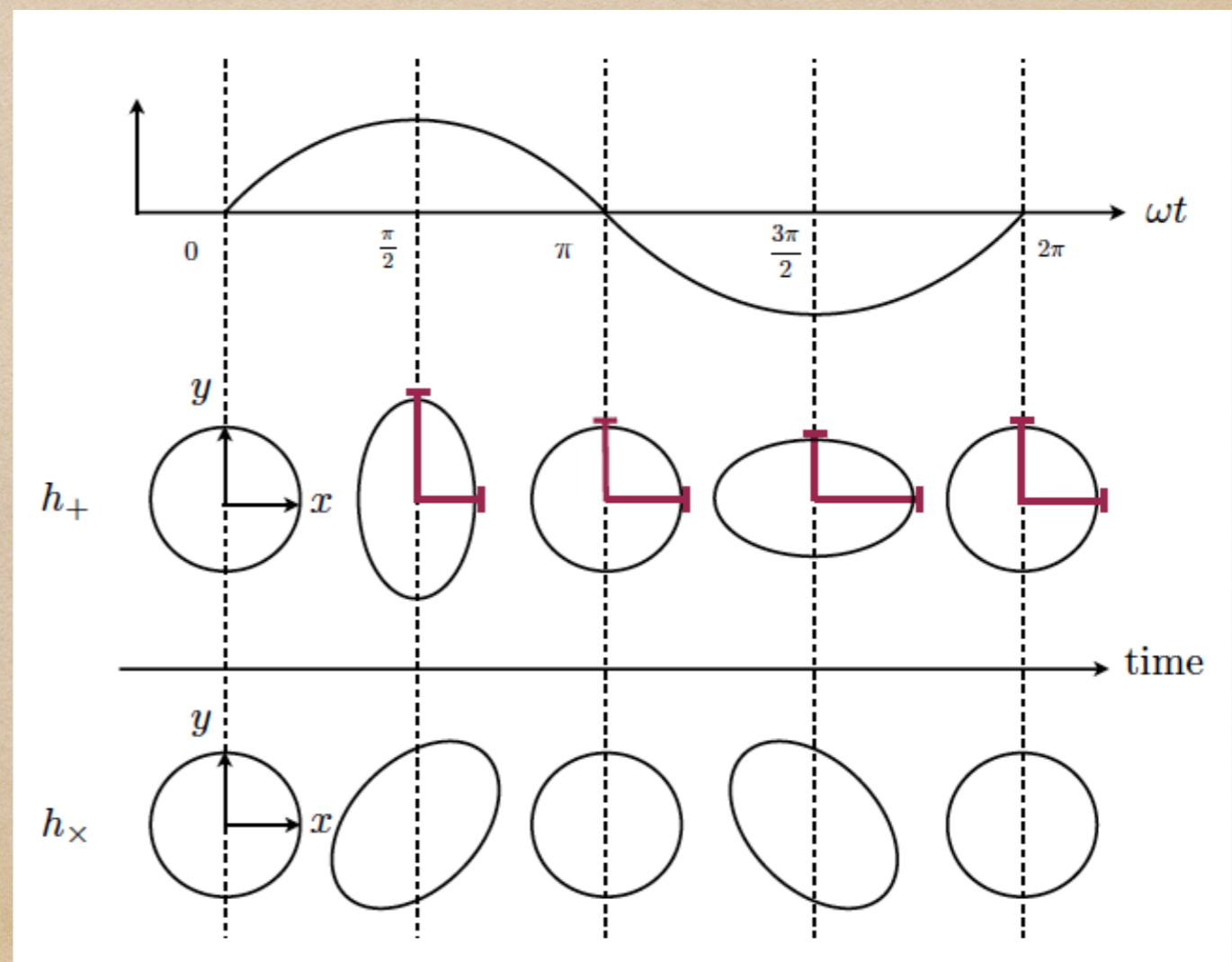
- Proper separation:

$$ds^2 = -dt^2 + (1 + h_+)\, dx^2 + (1 - h_+)\, dy^2 + 2h_\times\, dx\, dy + dz^2$$

- Effect on test particles:

  Mirshekari 1308.5240
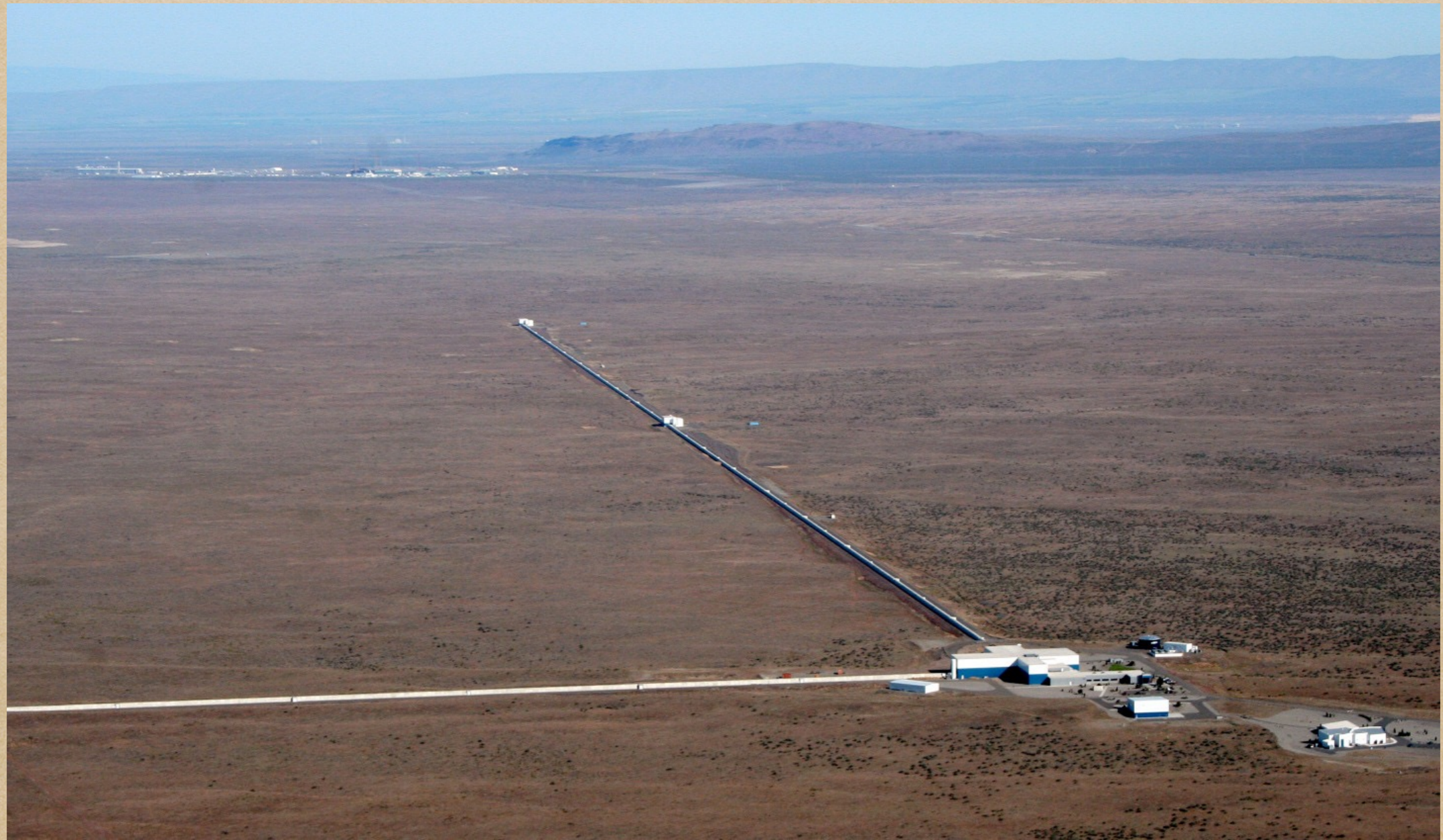
- Debate on physical
  reality until late 1950s

  e.g. Saulson GRG (2011)

Effect on particles

- Measure this effect; Michelson-Morley type interferometer

The GW spectrum, sources and detectors

The gravitational wave spectrum

- Source types and detection strategies $\Rightarrow$ 4 regimes

  Ultra low $f \sim 10^{-18} \ldots 10^{-15}$ Hz

  Very low $f \sim 10^{-9} \ldots 10^{-6}$ Hz

  Low $f \sim 10^{-4} \ldots 10^{-1}$ Hz

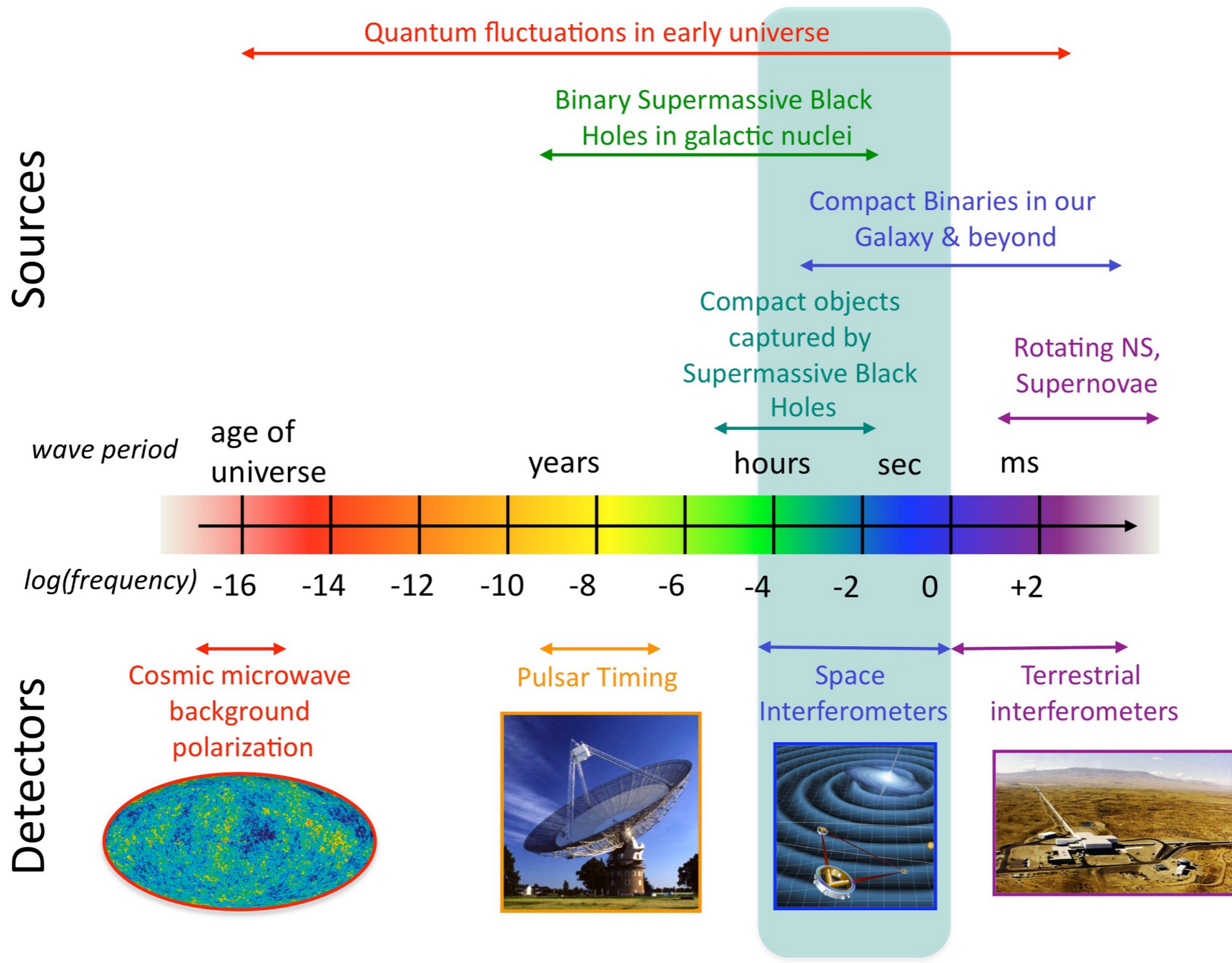 High $f \sim 10^{1} \ldots 10^{3}$ Hz

- Major sources

  Ultra low: Fluctuations in the early universe

  Very low: Supermassive BH binaries (high *M, z*)

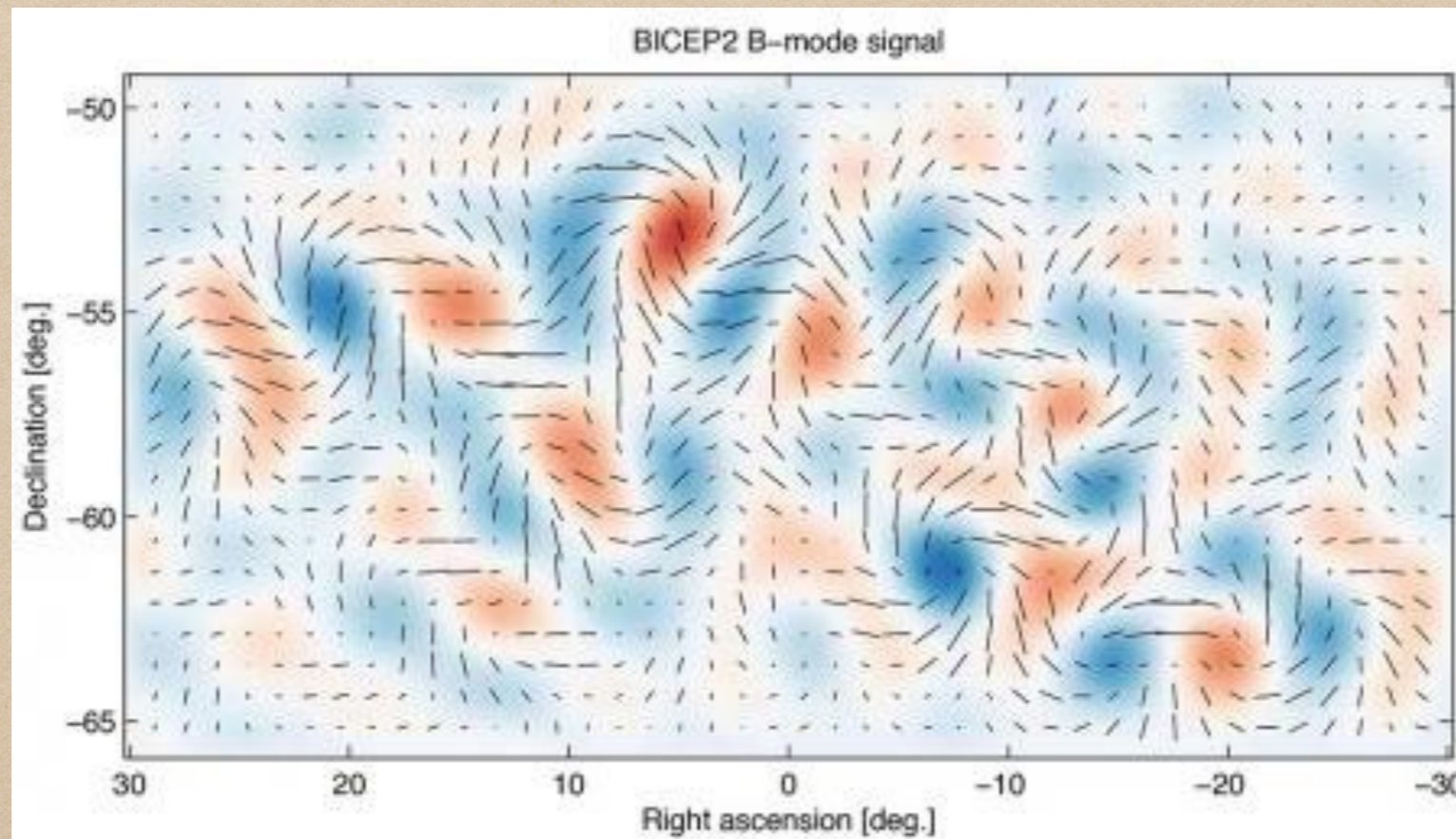 Low: SMBHs, EMRIs, Compact binaries,…

  High: Neutron star / BH binaries, supernovae,…

The gravitational wave spectrum
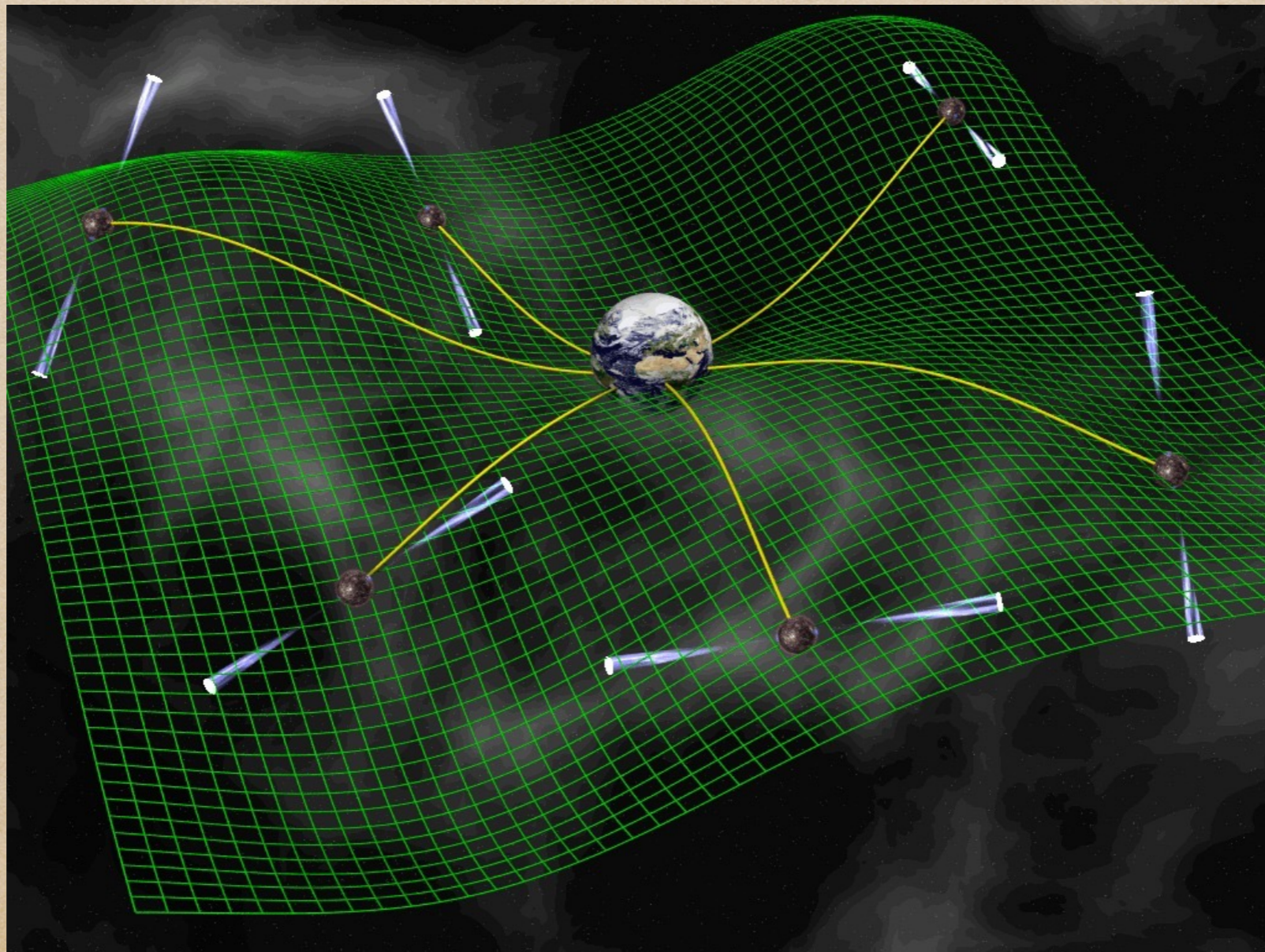
The ultra low frequency regime

- Wave periods $\sim$ Hubble time

- Primordial GWs $\rightarrow$ Signature in polarization of CMB

- E.g. BICEP2

- Problem: Pattern can be attributed to galactic dust (BICEP2, Planck)

  See e.g. Flauger, Hill, Spergel 1405.7351

The very low frequency regime

- Pulsar timing arrays   PPTA, EPTA, NANOGrav

- Search for correlated arrival time delays of pulses

The very low frequency regime

- Exotic sources: Topological defects, cosmic strings (early Universe)

- SMBH binaries $\gtrsim 10^8 \ M_\odot$

  Most/all galaxies host BHs hole-halo correlation: $M_{\rm bh} \propto \sigma^{4.8 \pm 0.5}$

  Ferrarese & Merrit ApJ (2000), Gültekin et al, ApJ (2009)

- Galaxies merge $\Rightarrow$ SMBH merger

  But "Final parsec problem"
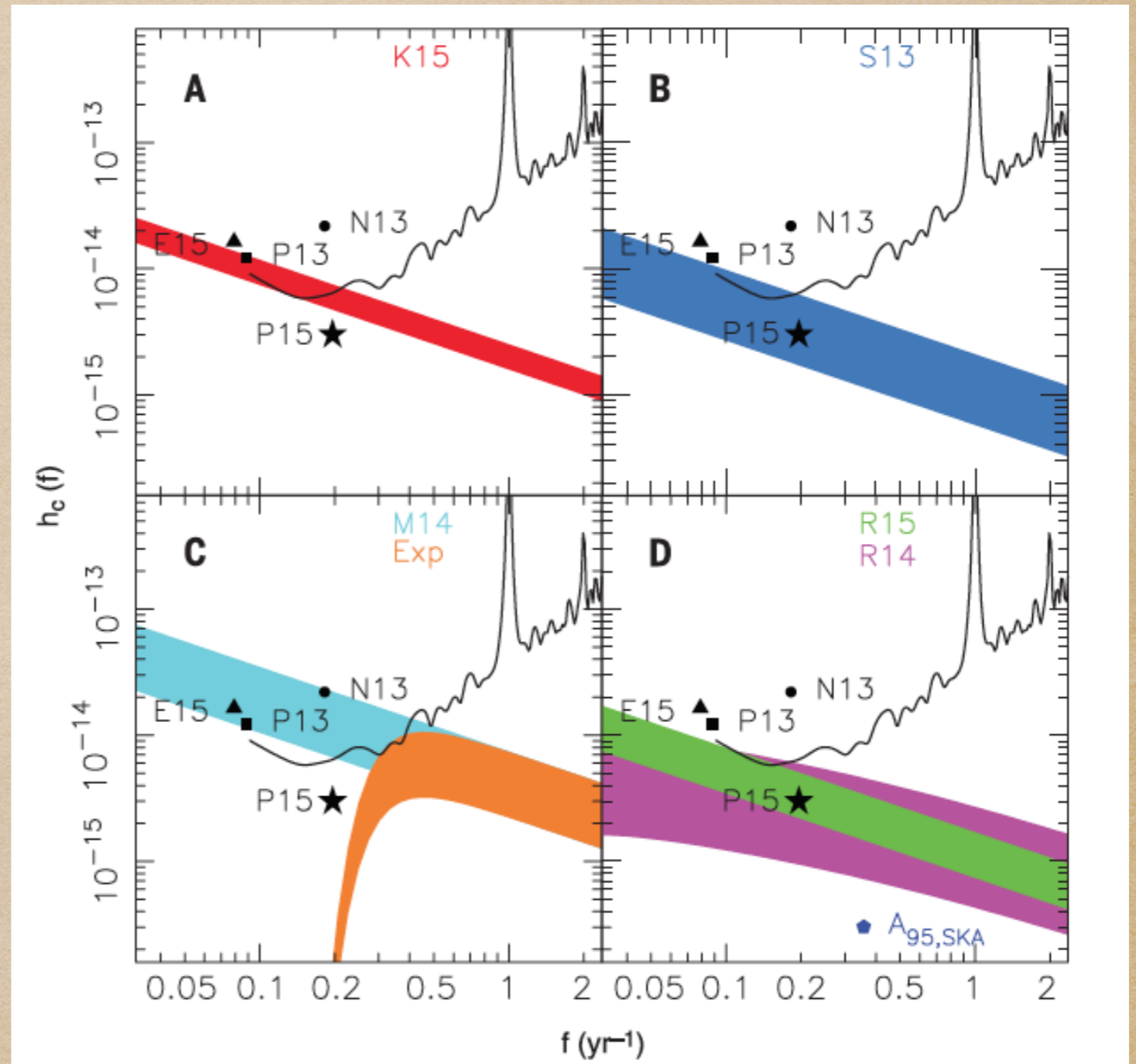
- Few individually observed systems possible.

  But mostly stochastic background.

  Model as power law

  $$h_c = A \left(\frac{f}{\rm yr^{-1}} \right)^\alpha$$

The very low frequency regime

- So far: upper limits

- E.g. PPTA

- Models excluded?

- Possible explanations:

  Binaries stalled

  Accelerated mergers

  Eccentric orbits

  ...

- Models too simple

Shannon et al (2015) Science
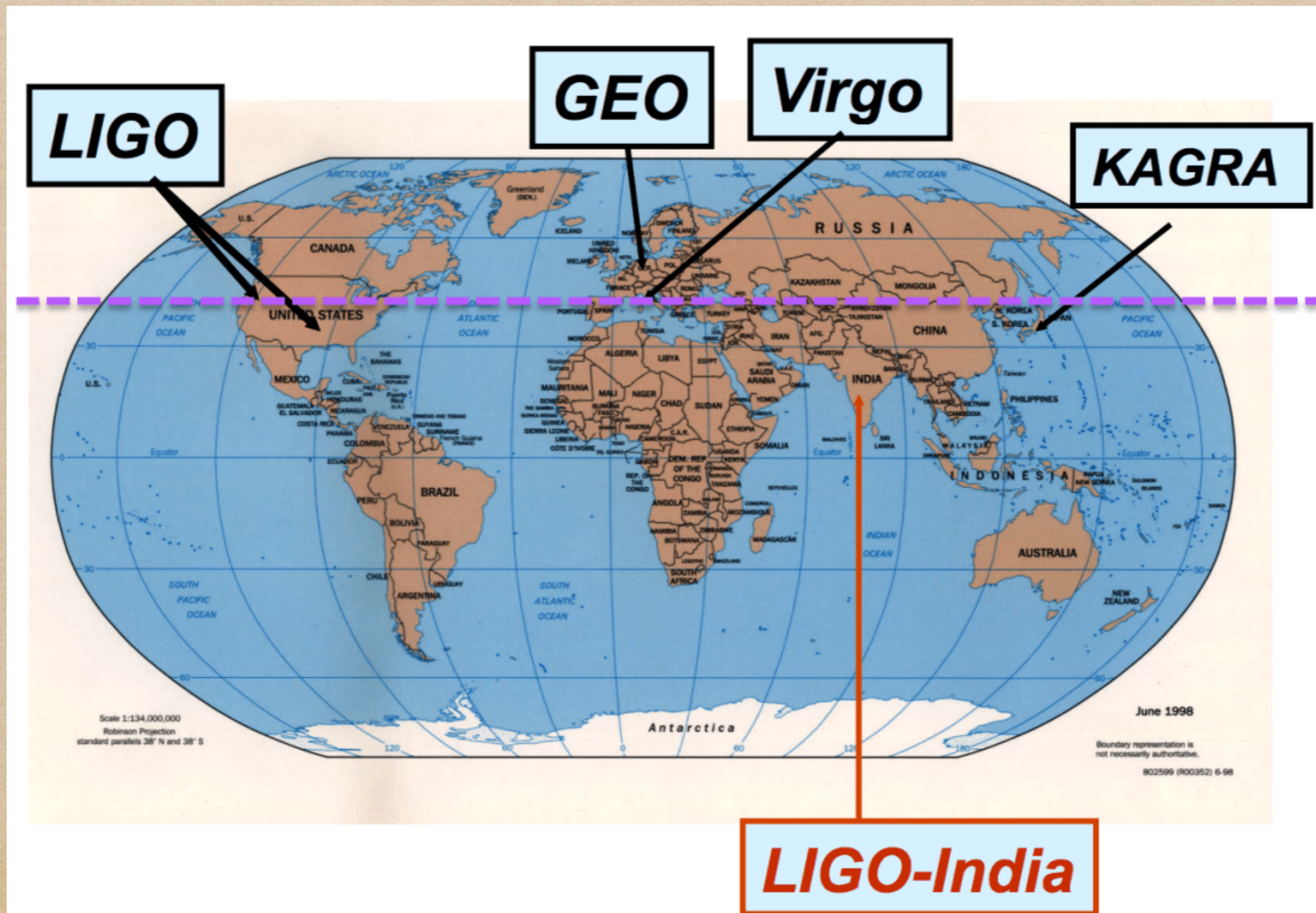
The low frequency regime

The low frequency regime

- Interferometry with $\sim 10^6$ km arms

- Realm of space missions

- LISA: L3 mission of ESA's "Cosmic Vision"   Launch: ~ 2034

- Configuration still uncertain:

  2 arms vs. 3 arms

  10^6 km vs. 5×10^6 km

  2 yr   vs. 5 yr life span

- Verification binaries (WDs)

- Outstanding SNR

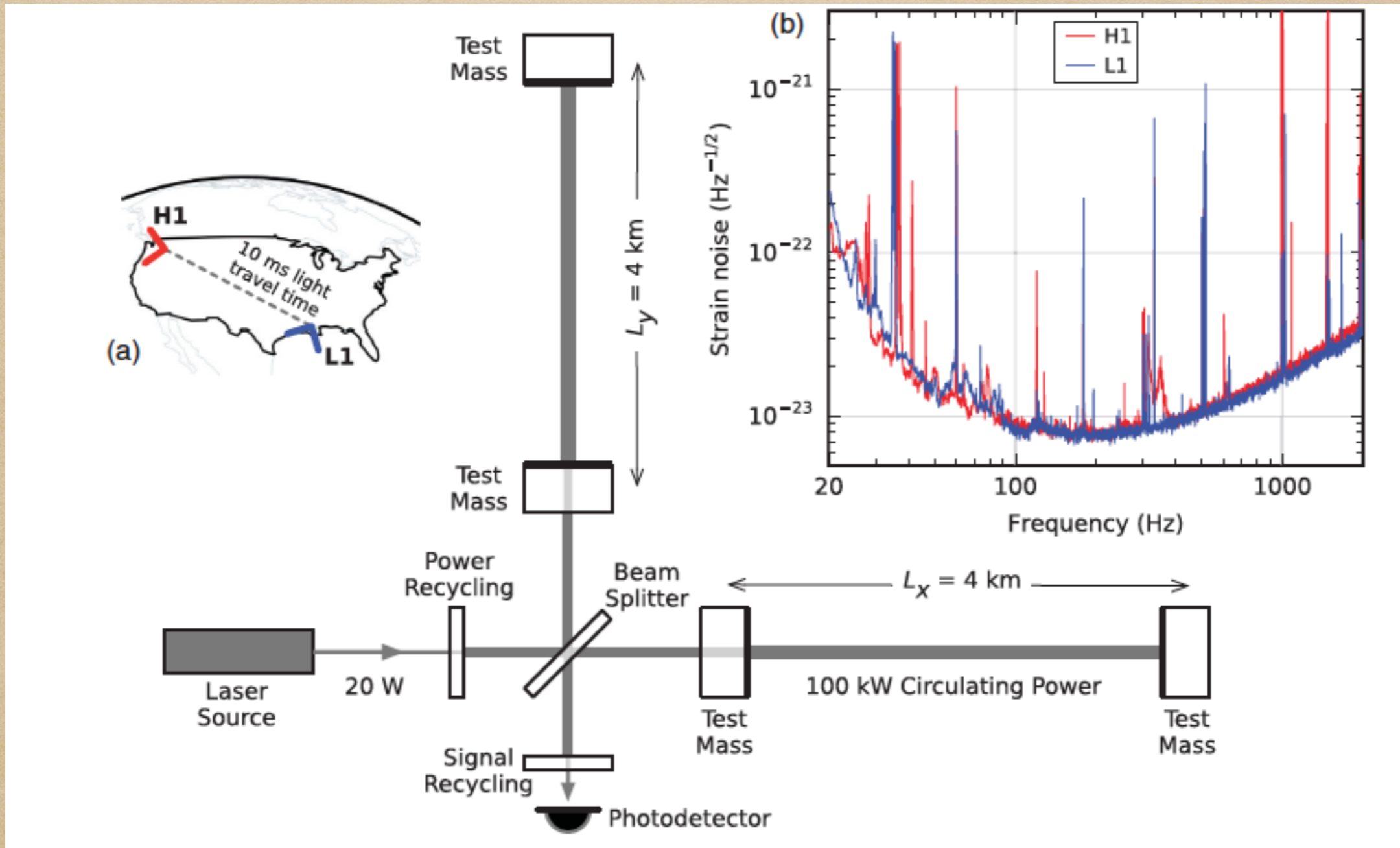- LISA Pathfinder: Test mission

  Launched 3 Dec 2015

  Major success!!!

The high frequency regime

- Interferometry with $\sim \mathrm{km}$ arms

- Detector nework:

2 LIGO (2015), Virgo (2017), GEO600, KAGRA (2020), LIGO-India
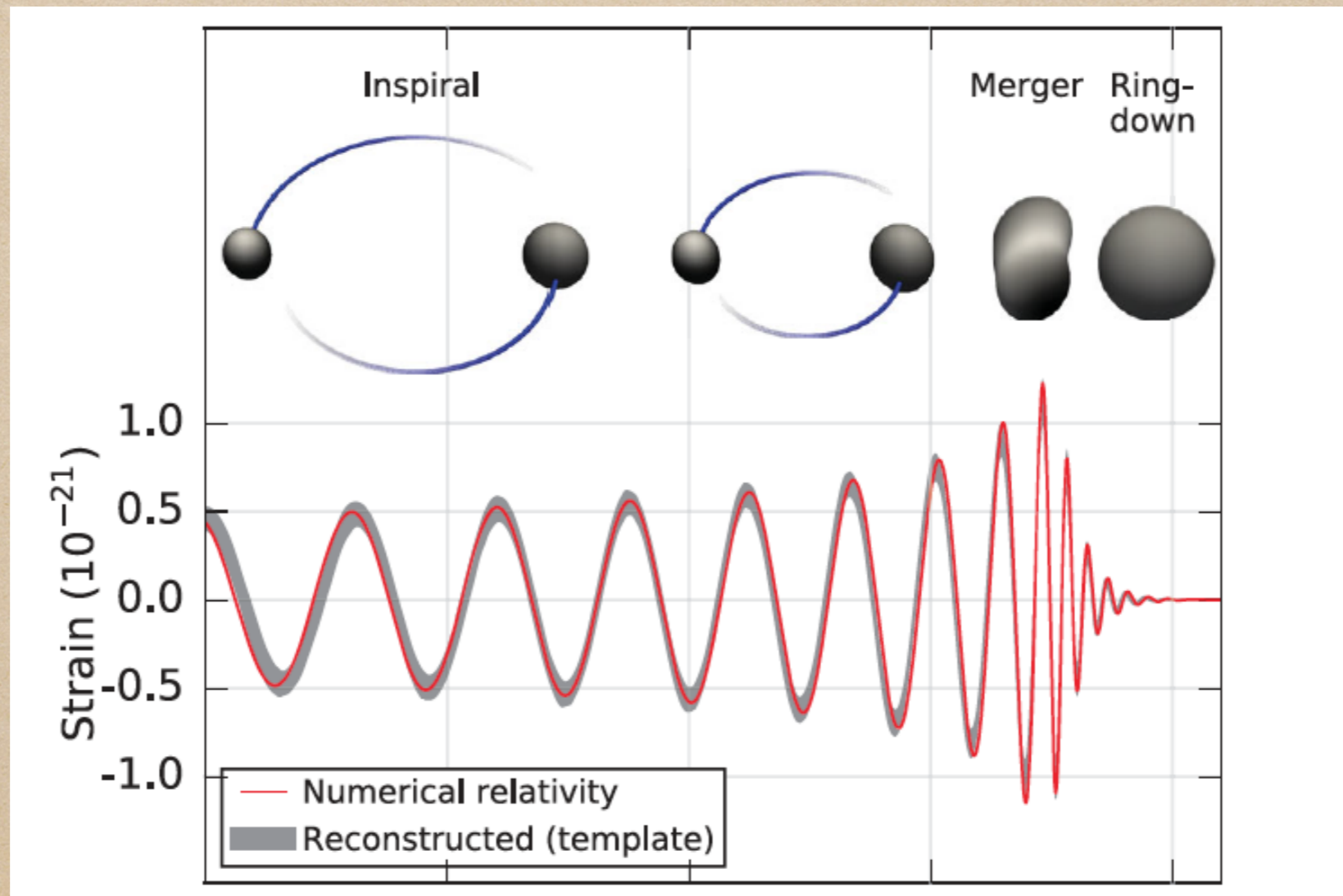
The interferometer diagram: LIGO

Abbott et al, PRL 116 (2016) 061102
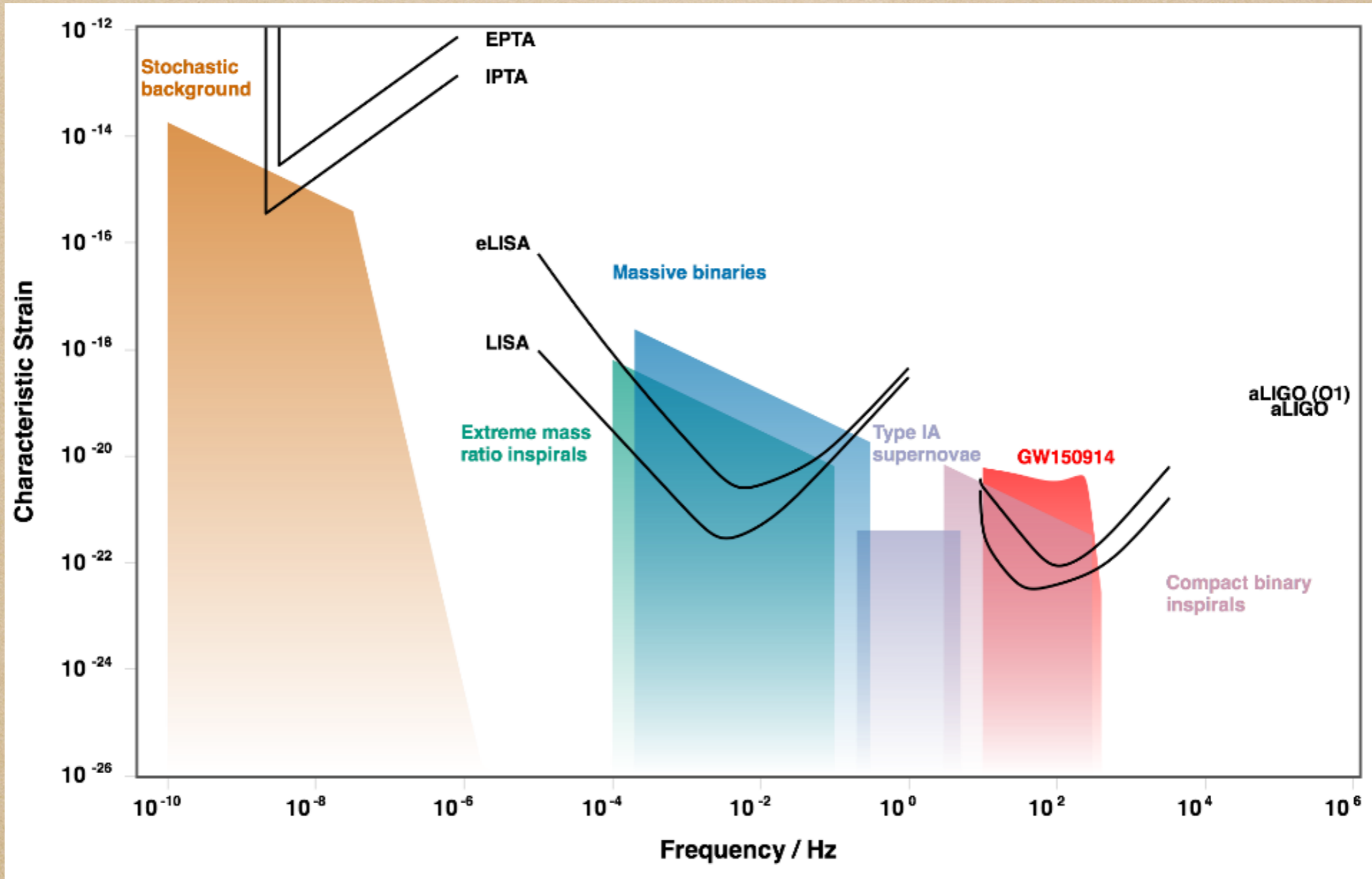
Seismic, thermal, shot noise

The high frequency regime

- Supernovae

- Neutron star oscillations

- Neutron star / stellar-mass black hole binaries

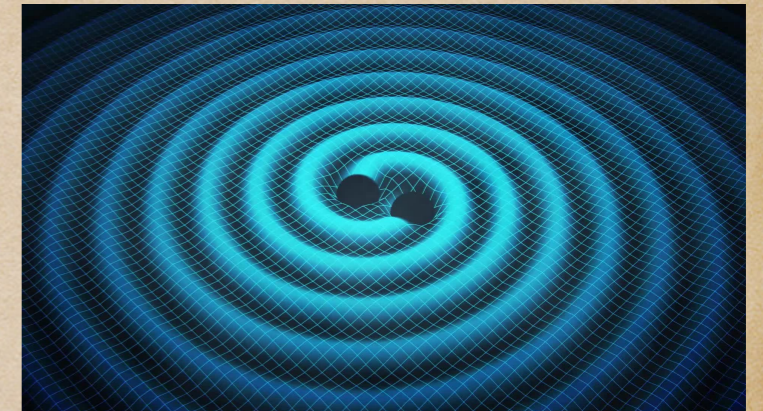Abbott et al, PRL 116 (2016) 061102

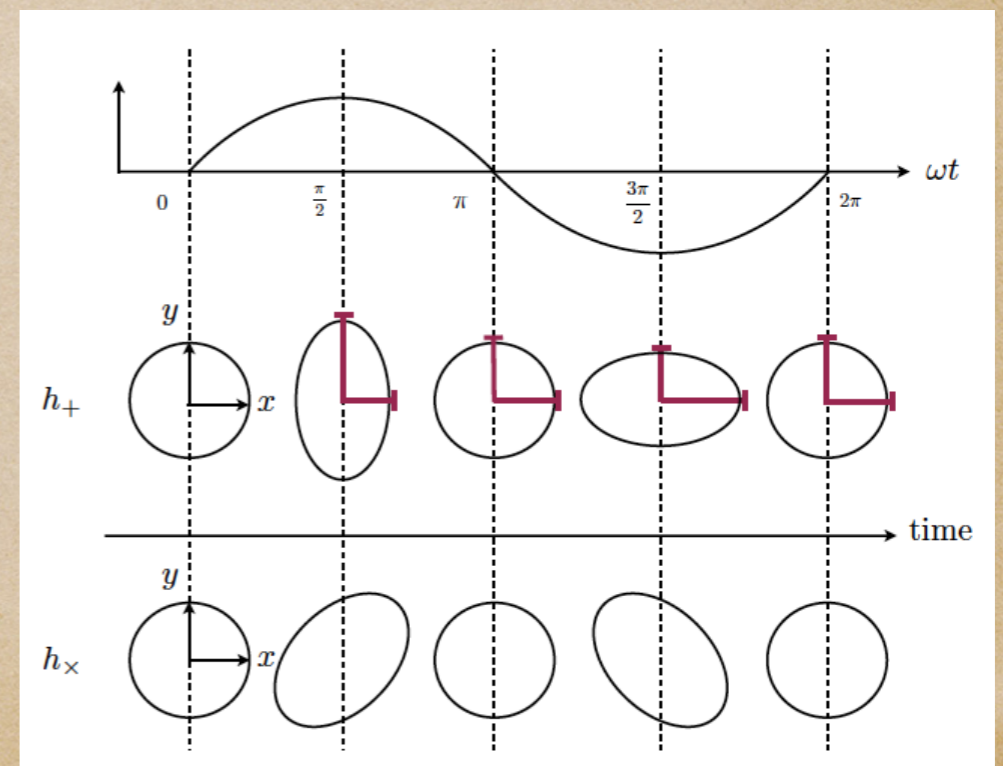# Summary: sensitivity curves

Parameter estimation and source modeling

- Einstein's field equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}; \quad \frac{8\pi G}{c^4} = 2.07 \times 10^{-43} \frac{\text{s}^2}{\text{m}\,\text{kg}}$$

- Weak effect of matter on geometry

- GWs carry huge energy but barely interact with anything

- Induced changes in length: < atomic nucleus / km

Detection and parameter estimation

Generic transient search

- No specific waveform model

- Identify excess power in detector strain data

- Use multi detector maximum likelihood   Klimenko et al. 1511.05999

Binary coalescence search

- "Matched Filtering"

- Compare data stream

  with GW templates

  ("Finger print search")

- Bayesian analysis:

  Prior $\longrightarrow$ Posterior

Black-hole binaries: parameters

- **8+1 Intrinsic parameters**

  Masses m_1, m_2

  Spins S_1, S_2

  Eccentricity (often ignored; GW emission circularizes orbit)

- **7 Extrinsic parameters**

  Location: Luminosity distance D_L, Right ascension α, Declination δ

  Orientation: Inclination ι, Polarization ψ

  Time t_c and Phase ϕ_c of coalescence

- **Other parameters**

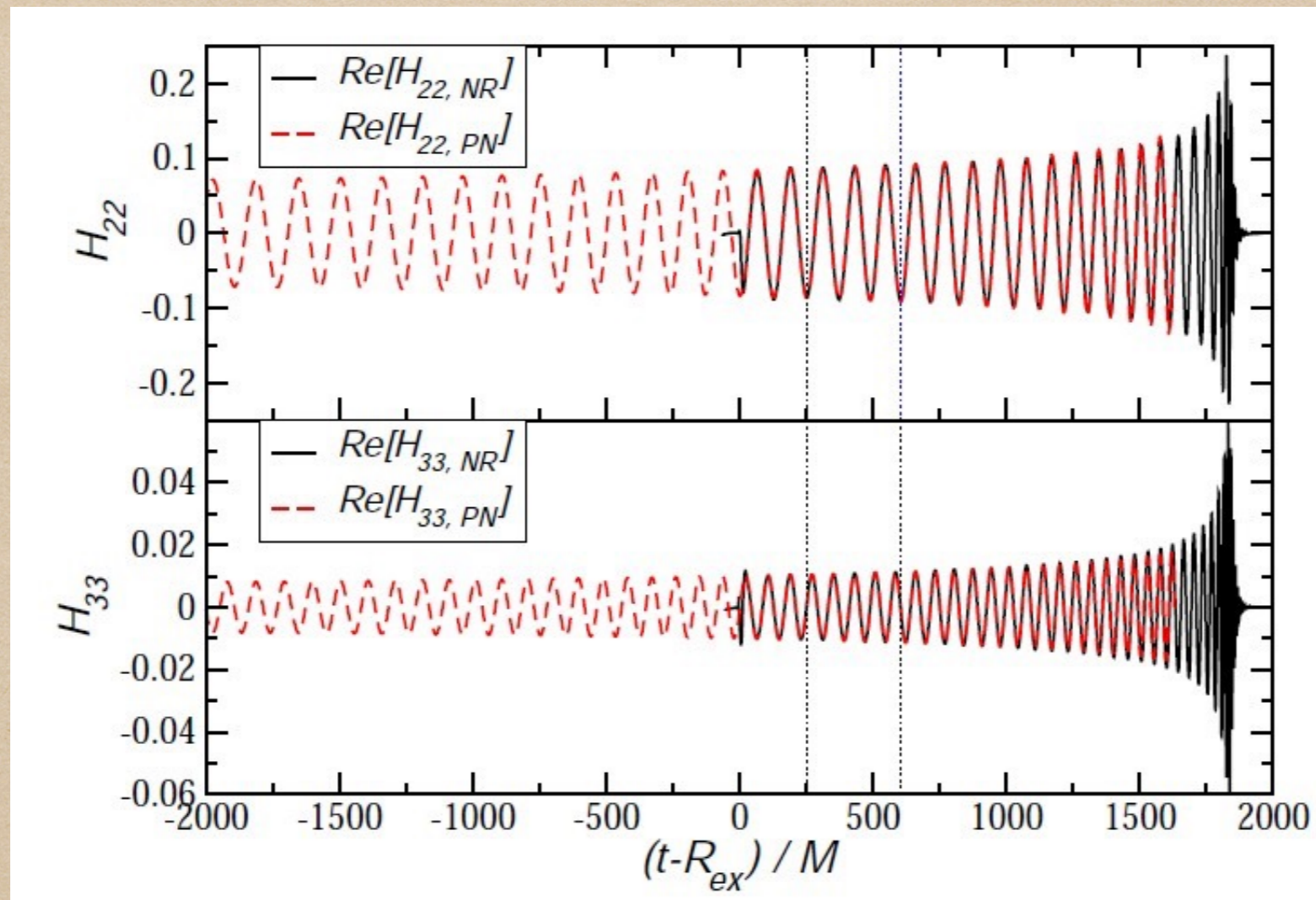 Anything beyond vacuum GR.... (ignored for starters...)

GW source modeling

- Key requirement for matched filtering: GW template catalog
- Model black holes in general relativity

  - Post Newtonian theory $\to$ Inspiral   Blanchet Liv.Rev.Rel. 2006

  - Numerical relativity $\to$ final orbits, merger

    Pretorius PRL 2005, Baker et al PRL 2006, Campanelli et al PRL 2006

  - Perturbation theory $\to$ Ringdown

- Combine "NR" with "Post-Newtonian", "Effective one body" methods
- 2 families in use: Phenomenological, Effective one body
- Use reduced bases or similar to cover parameter space
- Multipolar decomposition

$$h_+ - i h_\times = \sum_{\ell m} {}_{-2}Y_{\ell m}(\theta, \phi) h_{\ell m}(t)$$

Hybrid waveforms and catalogs

- Stitch together PN and NR waveforms

US et al CQG 2011

- Mass produce waveforms;

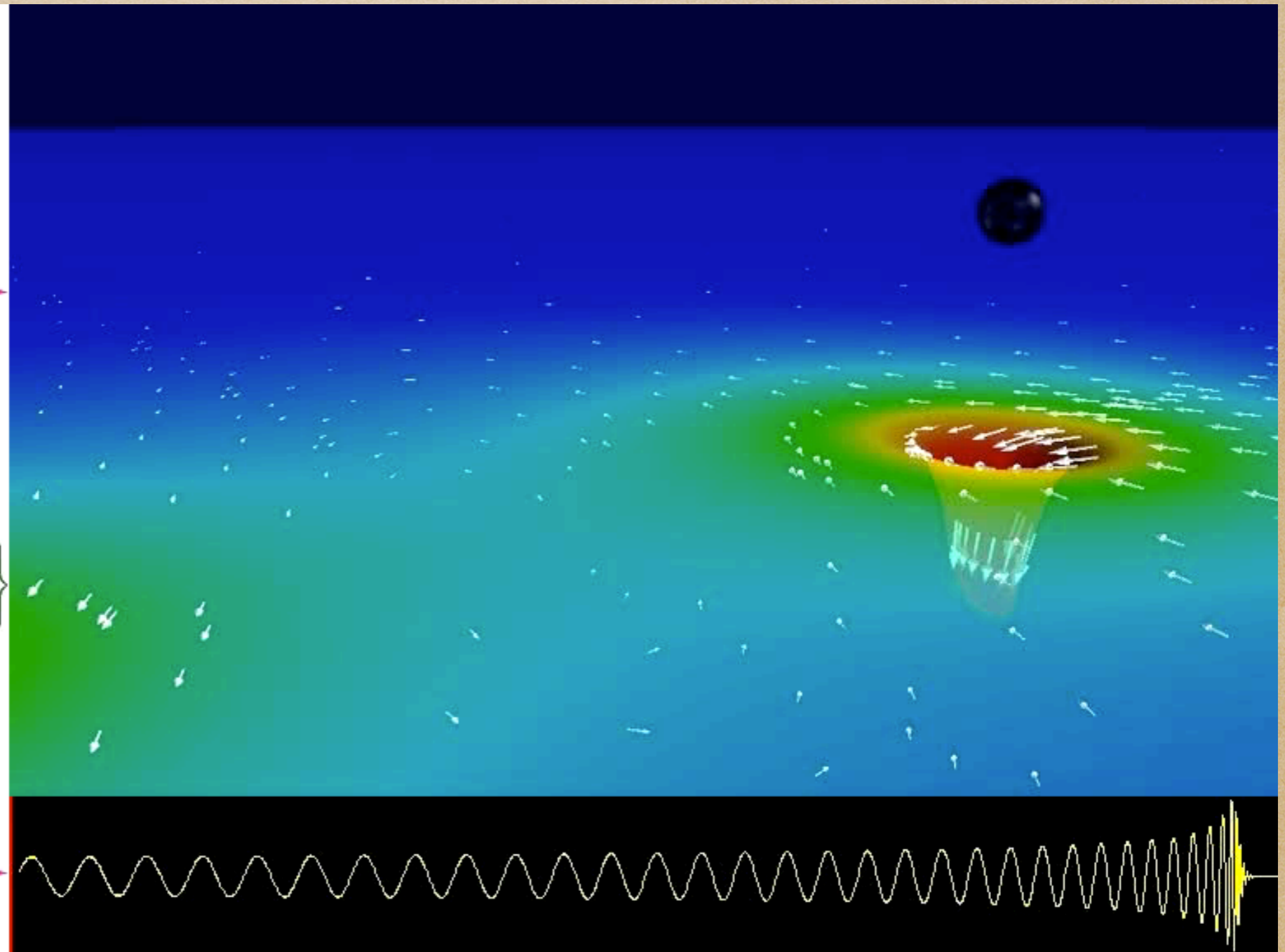Hinder et al CQG 2013,   Mroué et al PRL 2013,   Boyle et al CQG 2019

Anatomy of a BHB coalescence

Thanks to Caltech-Cornell groups

The GW events

GW detections as of 2020

Masses in the Stellar Graveyard
in Solar Masses

GW150914

Masses in the Stellar Graveyard
in Solar Masses

GW150914

LIGO-Virgo Black Holes

EM Black Holes

EM Neutron Stars

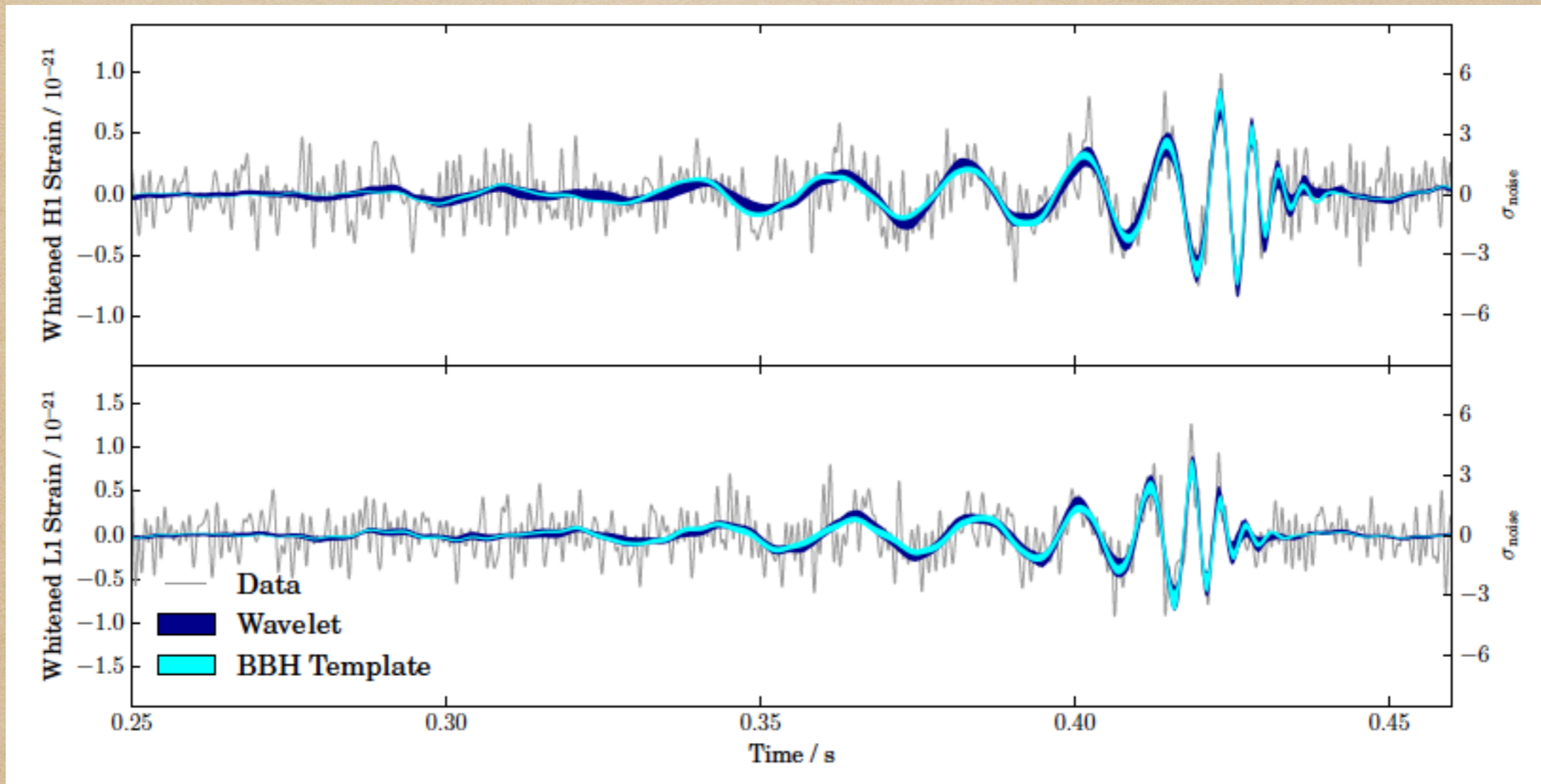LIGO-Virgo Neutron Stars

Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GW150914: The signal

Abbott et al 1602.03840

- Whitened by power spectral density

- Wavelet = Linear combination of sine-Gaussian pieces

GW150914: BH masses

- Source frame
- 2 Waveform models

Abbott et al. 1602.03840

$$m_1 = 36^{+5}_{-4} \; M_\odot$$
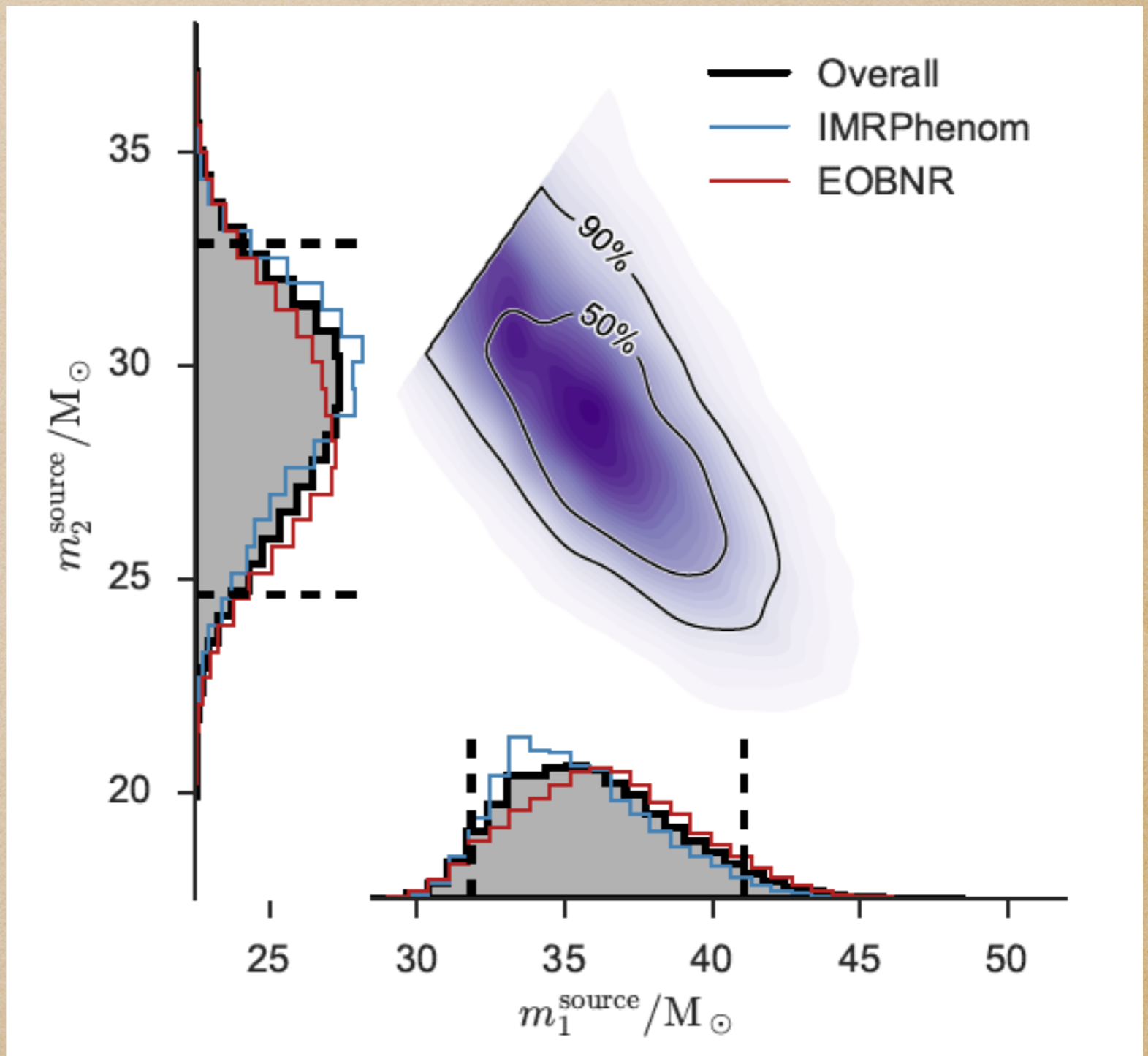
$$m_2 = 29^{+4}_{-4} \; M_\odot$$

$$M_{\mathrm{fin}} = 62^{+4}_{-4} \; M_\odot$$

- Deficit in GWs!

$$\Delta M \approx 3 \; M_\odot$$

$$\approx 5.4 \times 10^{54} \; \mathrm{erg}$$

$$L_{\mathrm{max}} \approx 3.6 \times 10^{56} \; \mathrm{erg/s}$$

Abbott et al 1602.03840

GW150914: BH parameters

- Mass ratio $\quad q \equiv \dfrac{m_2}{m_1} = 0.65 \pm 0.03$

- Spins harder to measure: few cycles, no full-precession catalog

$$\chi_1 = \frac{|\boldsymbol{S}_1|}{m_1^2} < 0.7 \,, \quad \chi_2 = \frac{|\boldsymbol{S}_2|}{m_2^2} < 0.9$$
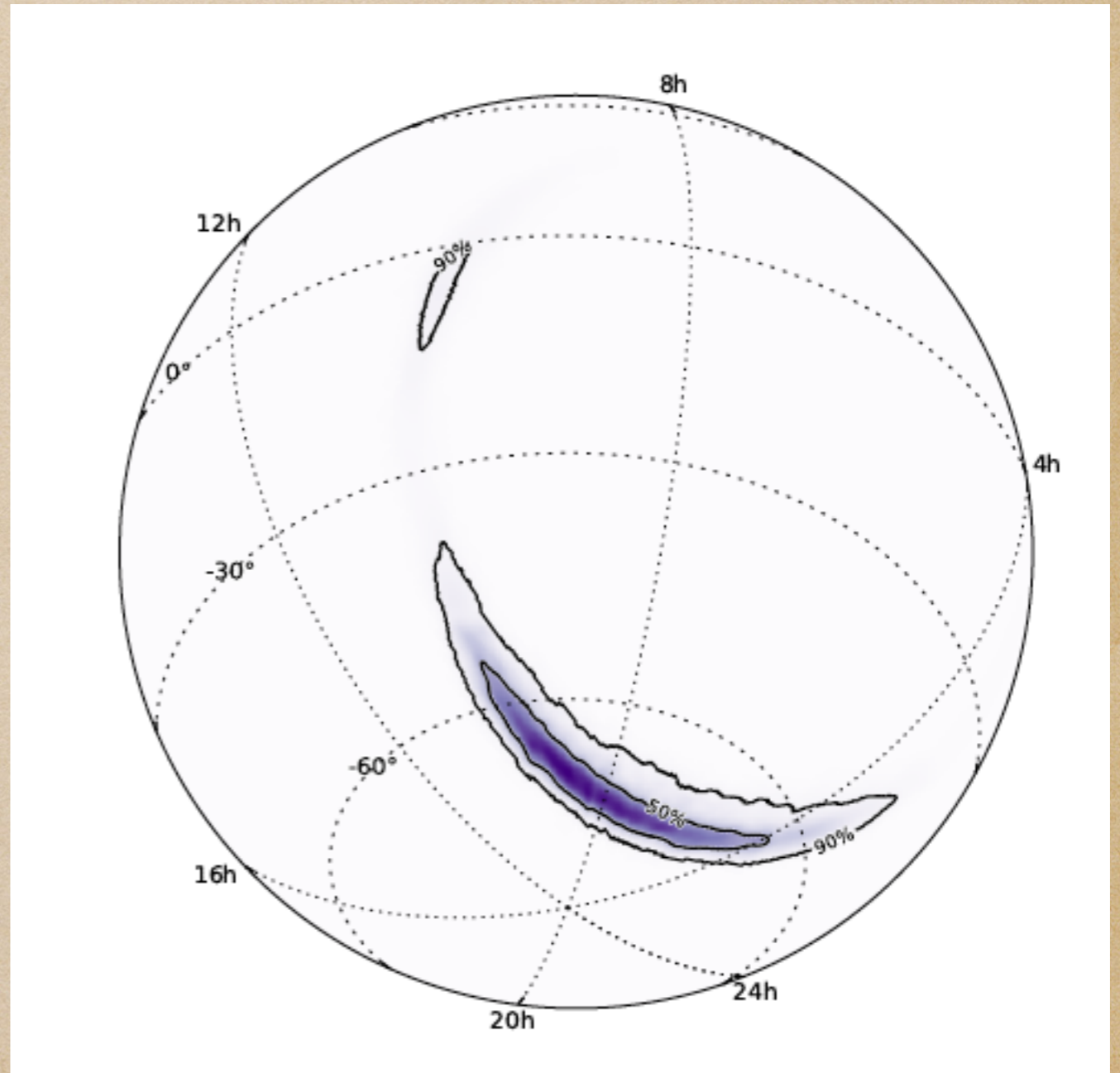
$$\chi_{\text{fin}} = 0.67^{+0.05}_{-0.07}$$

- Luminosity distance $\quad D_L = 410^{+160}_{-180} \text{ Mpc}$

- Source redshift $\quad z = 0.088^{+0.031}_{-0.038}$

GW150914: Sky location

- Important for EM follow-up
- GW detectors are all-sky
- Via triangulation
- 2 detectors

  $\sim 590 \ \mathrm{deg}^2$

- Southern hemisphere
- To be improved with
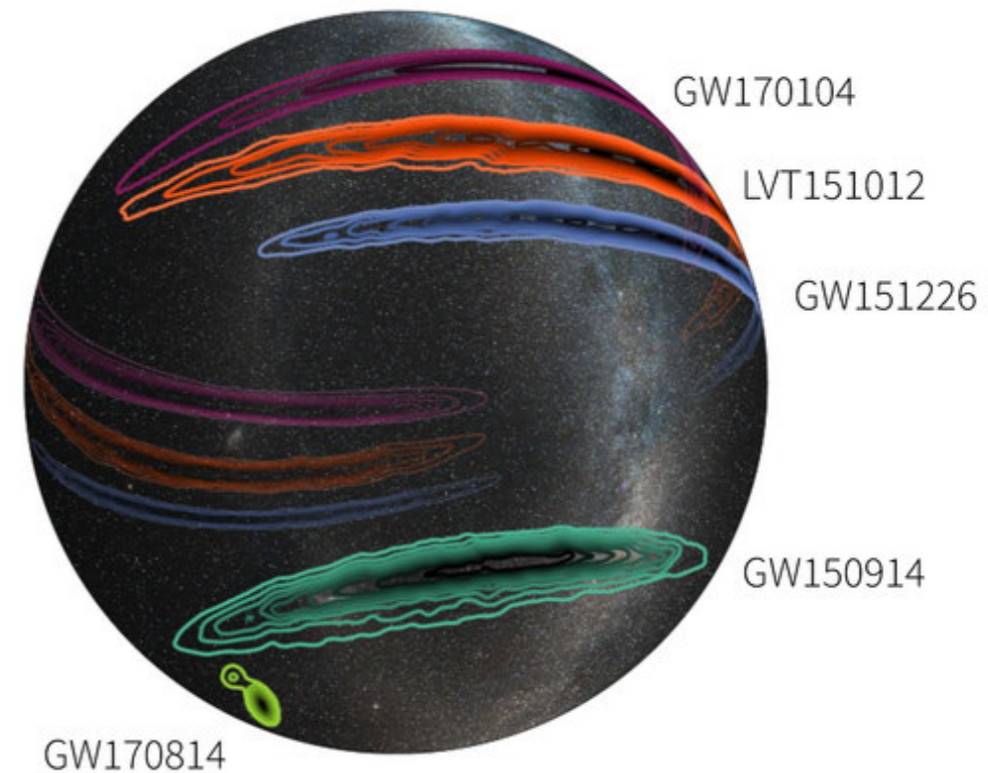
  Virgo, KAGRA, LIGO India
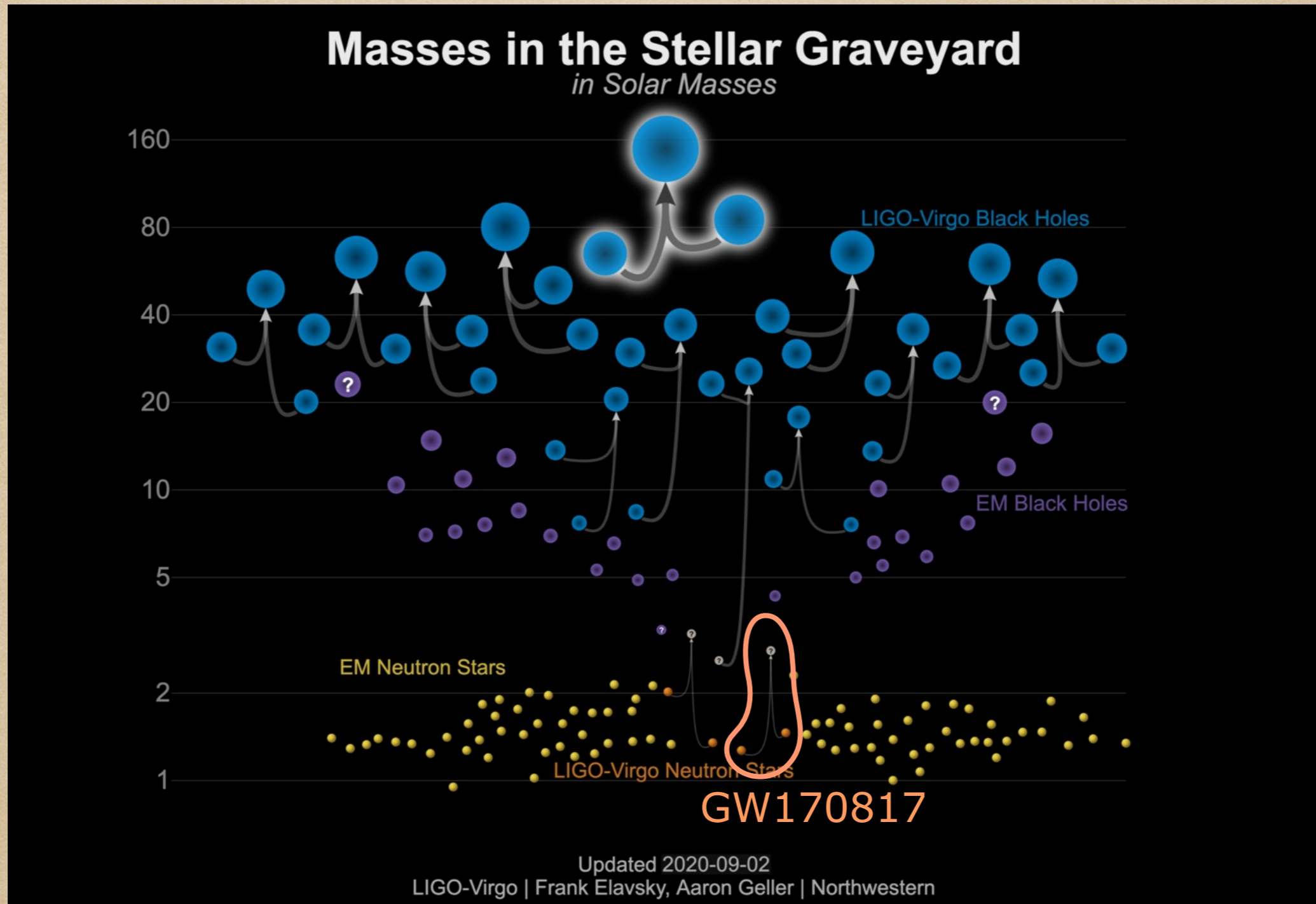

Abbott et al 1602.03840

2017: Virgo joins O2

-
- 3 detectors
-   much improved
    sky location!
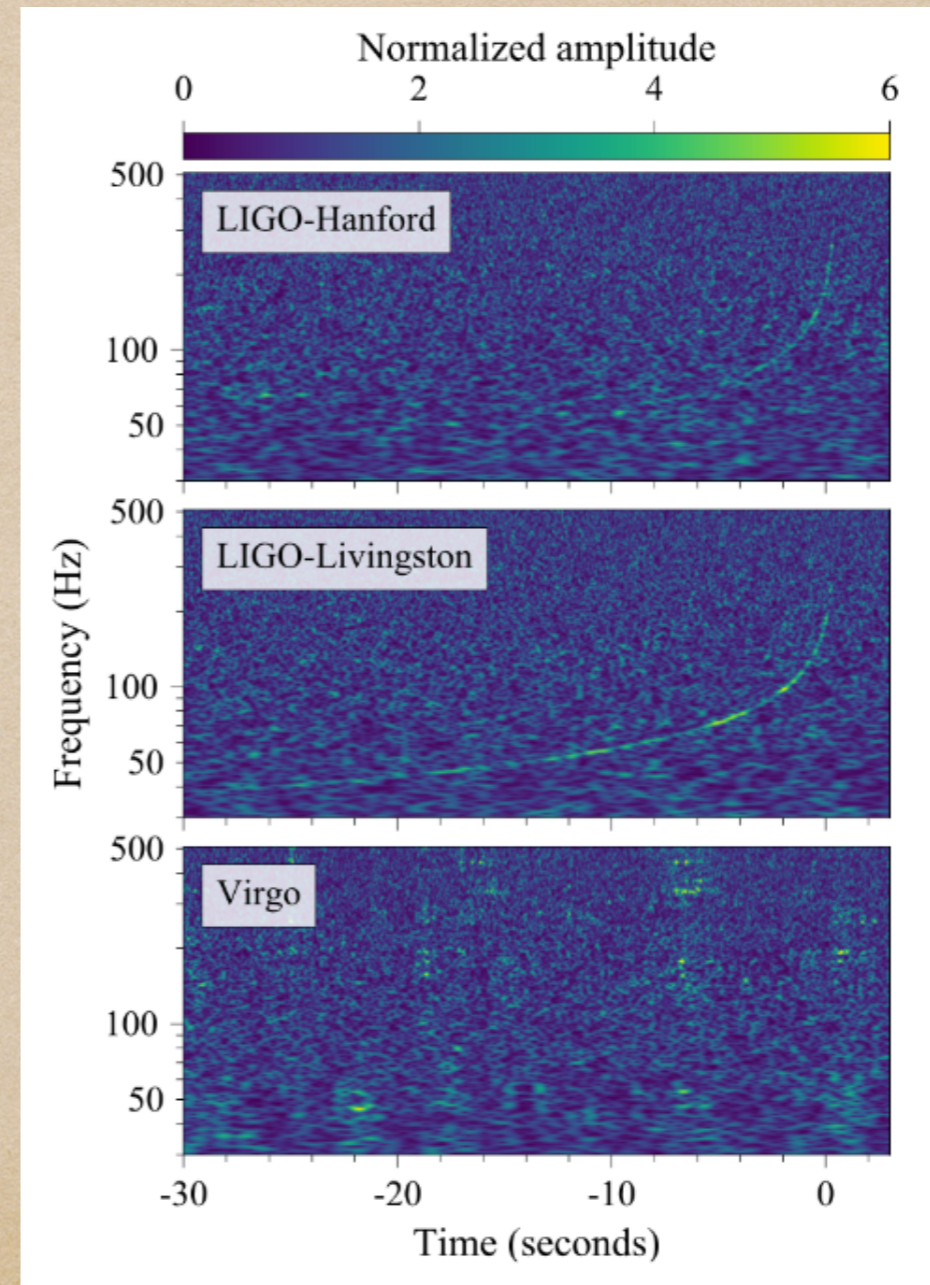-
First triple coincidence
    detection GW170814

GW170817

Masses in the Stellar Graveyard in Solar Masses

GW170817: Binary Neutron Star Merger

- Fermi and Gamma-Ray Burst Monitor send GRB170817A alert
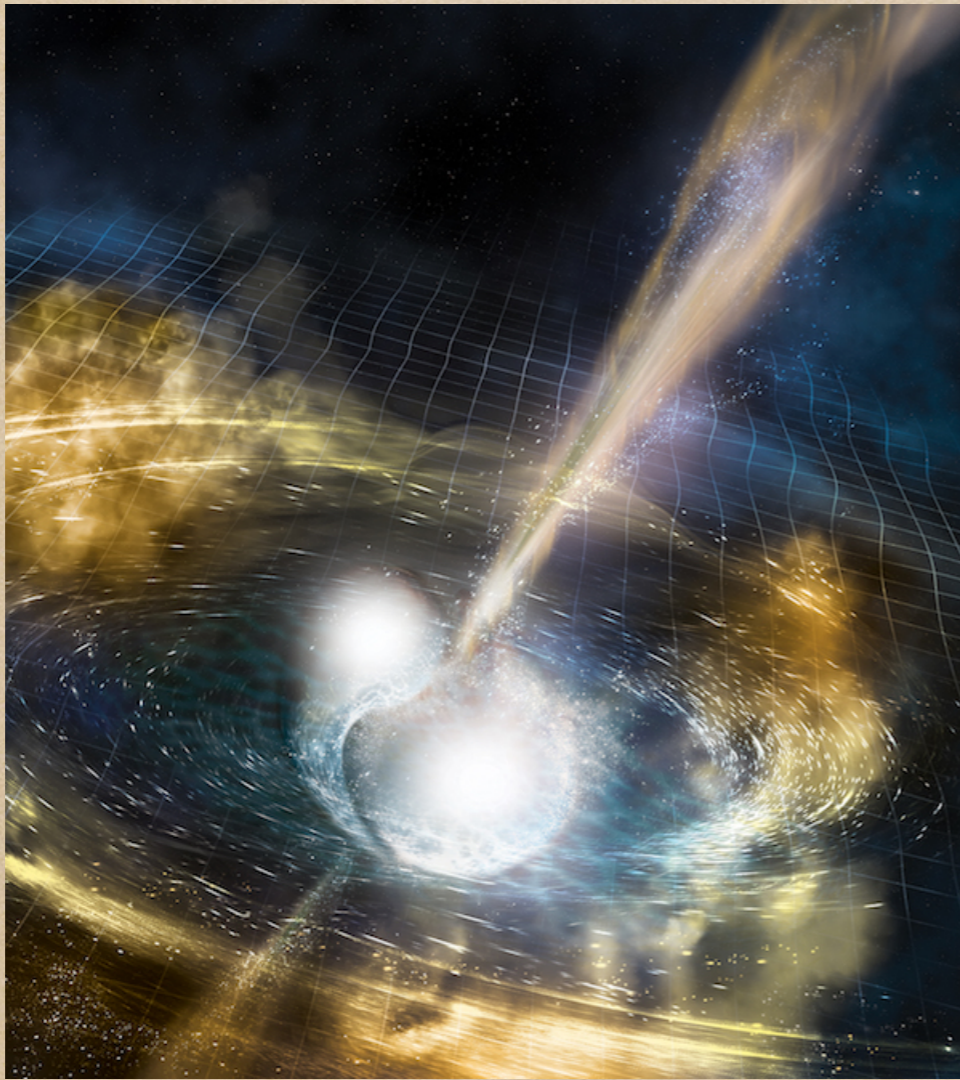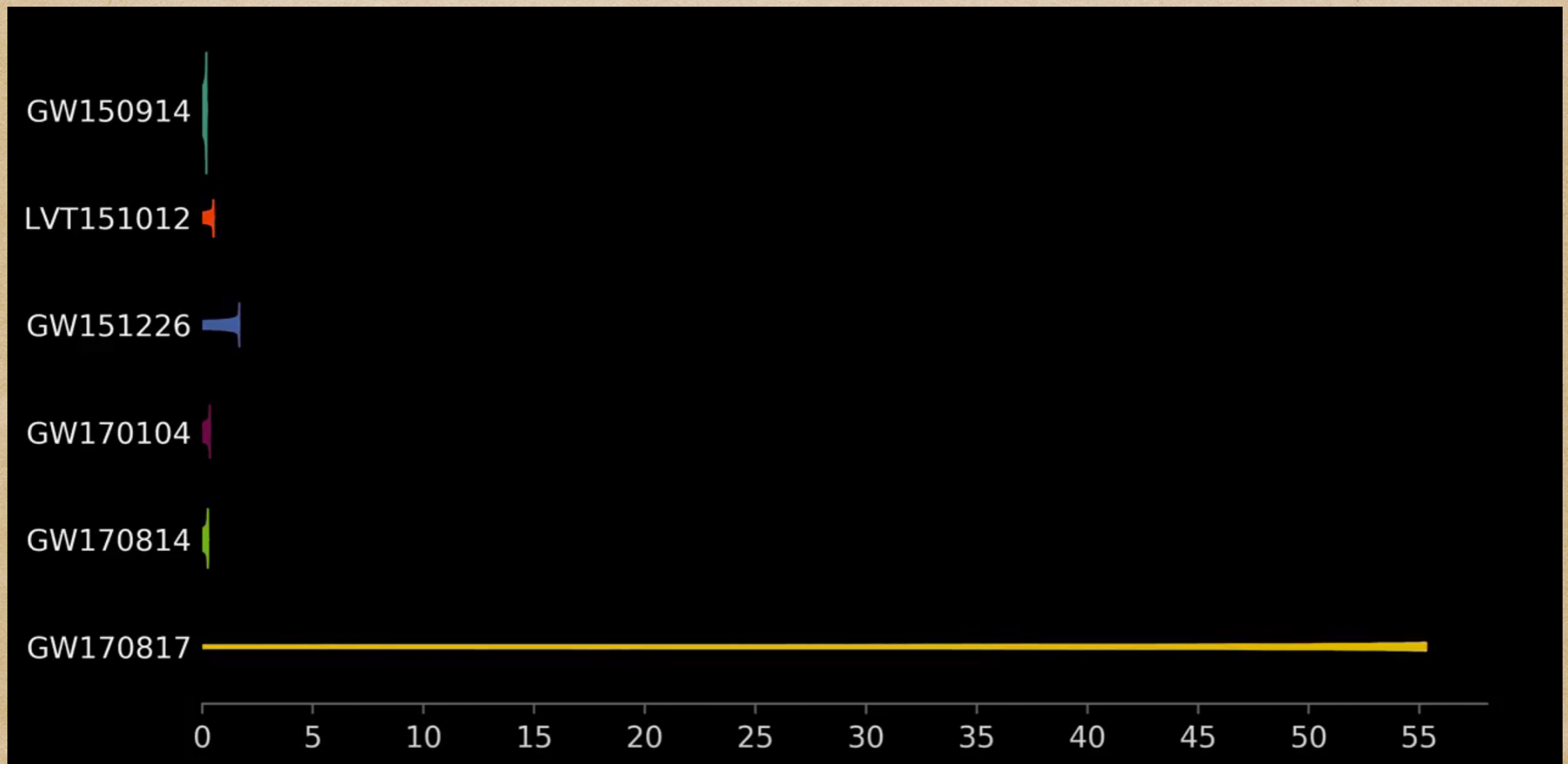- Within 6 minutes, LIGO, Virgo find GW170817 in the data stream
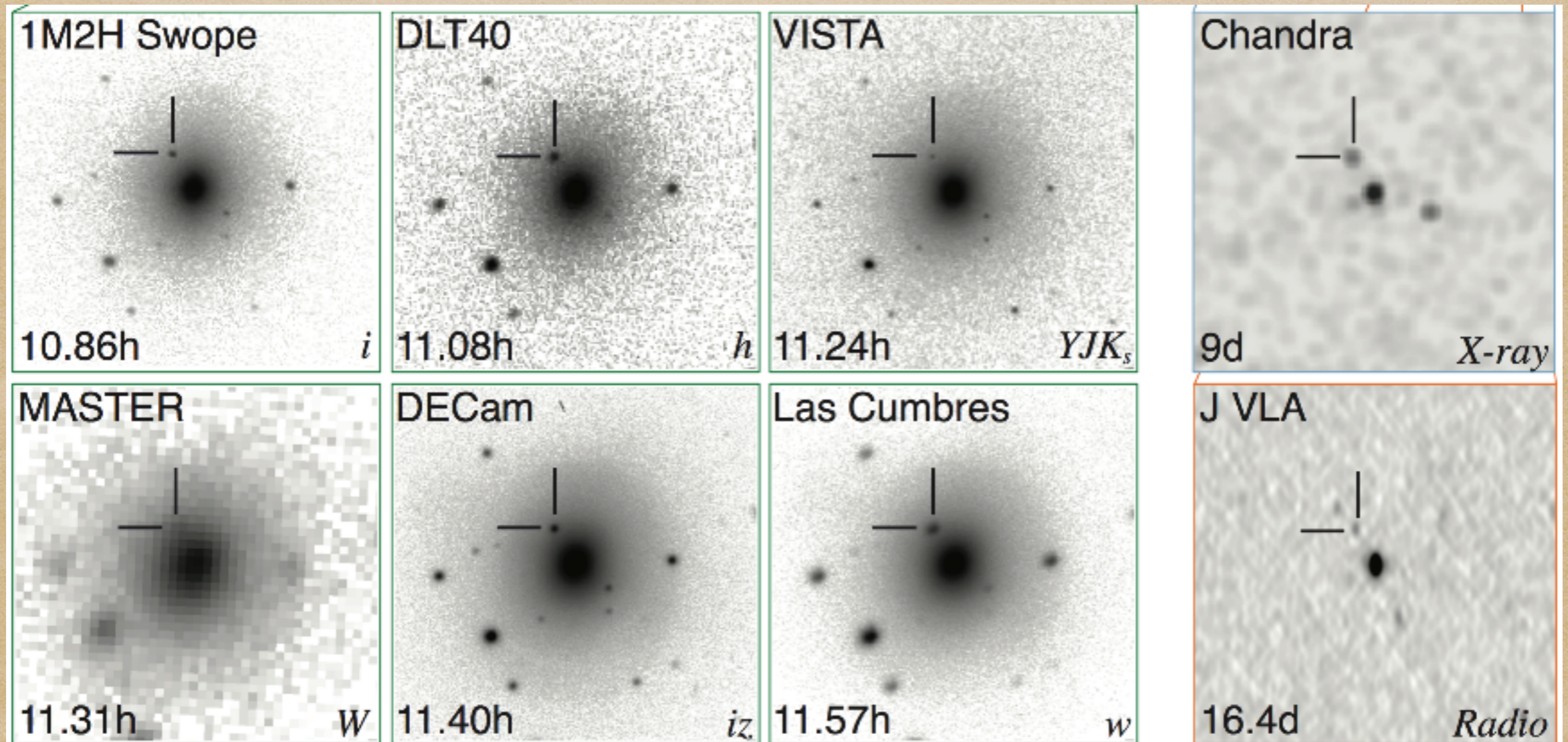
GW170817: Binary Neutron Star Merger

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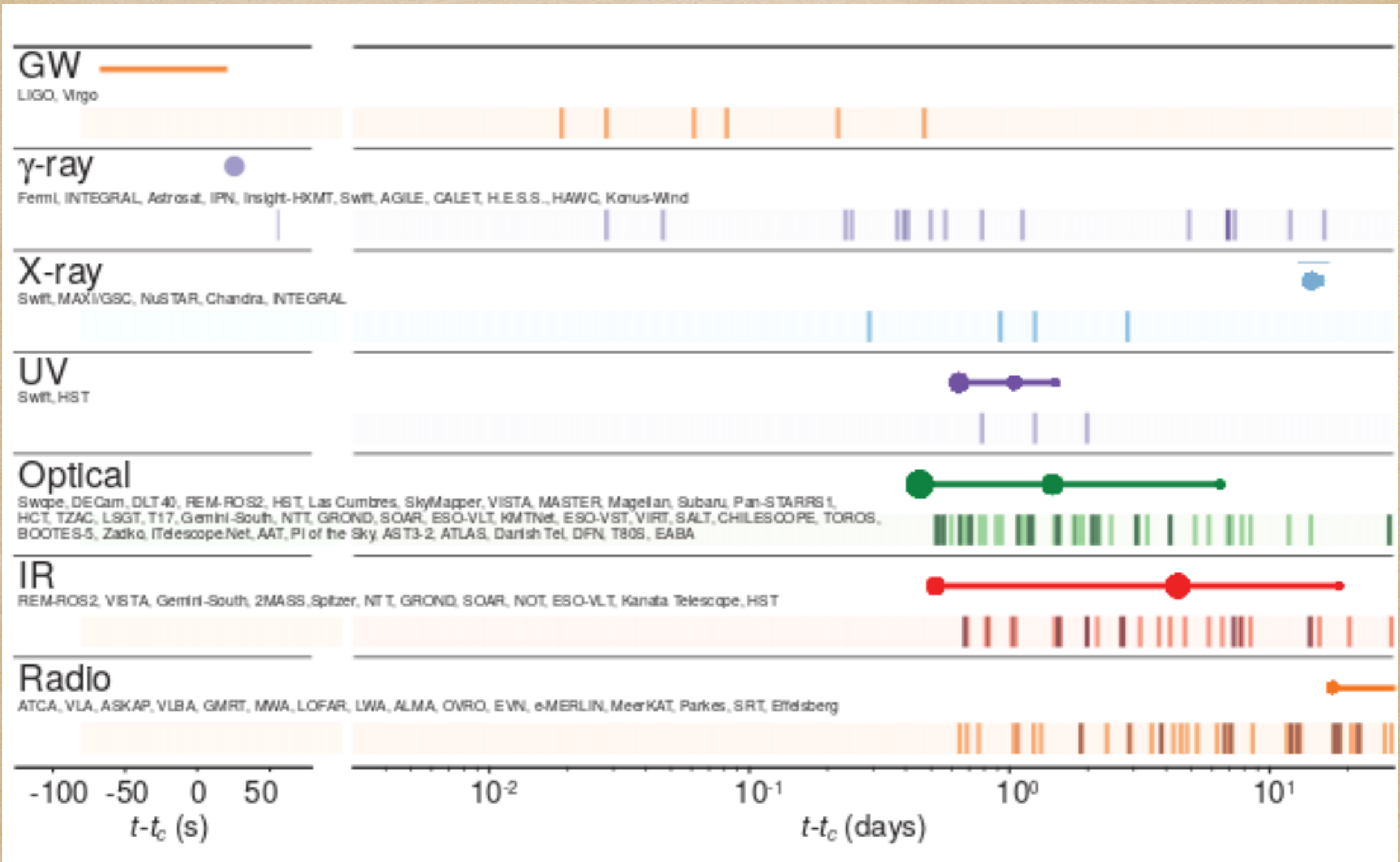- Note the duration!!!

GW170817: Multi messenger astronomy

- Gravitational Waves, Gamma rays
- Optical: 6 left panels
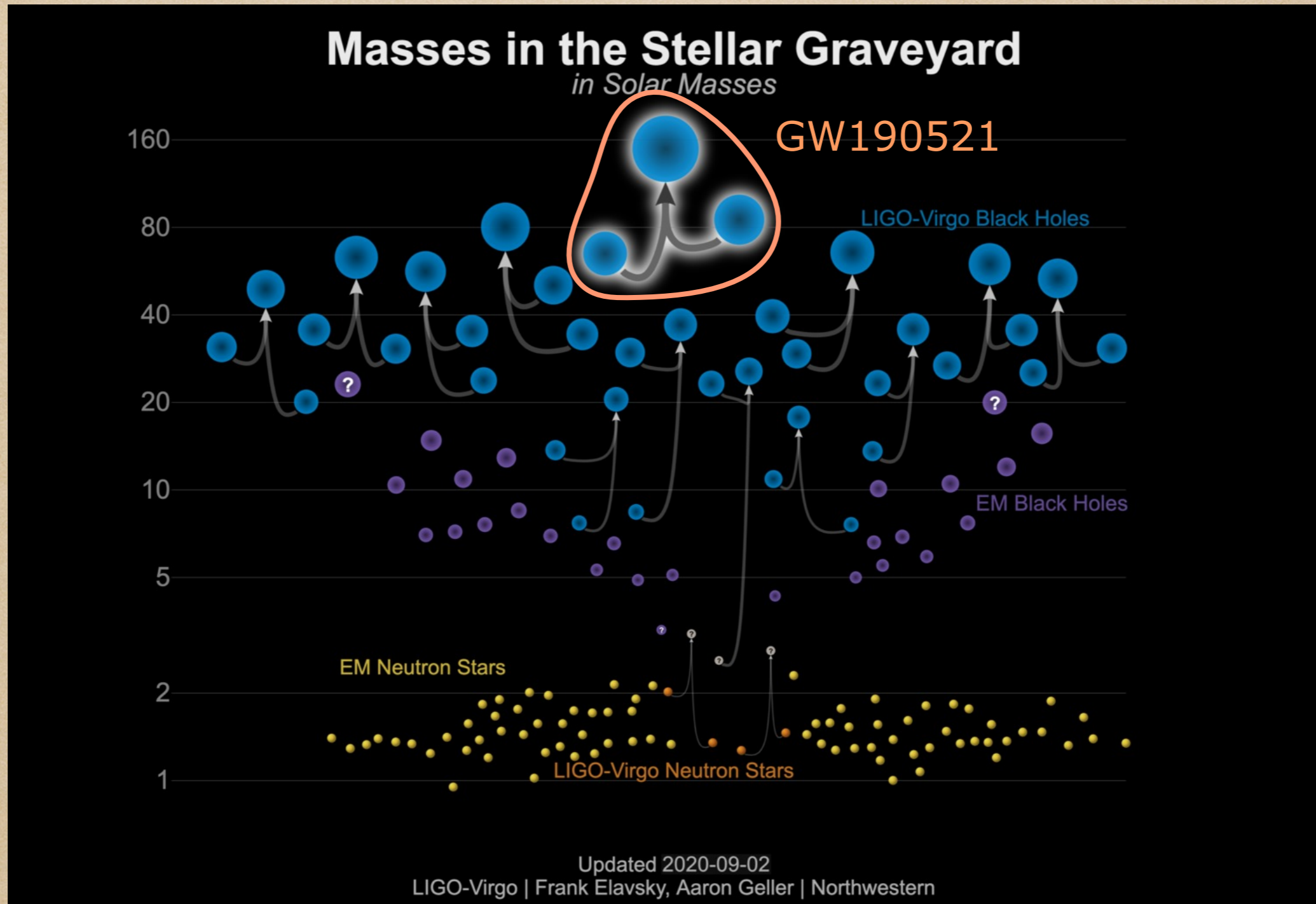- X-ray, Radio: Chandra, Jansky VLA
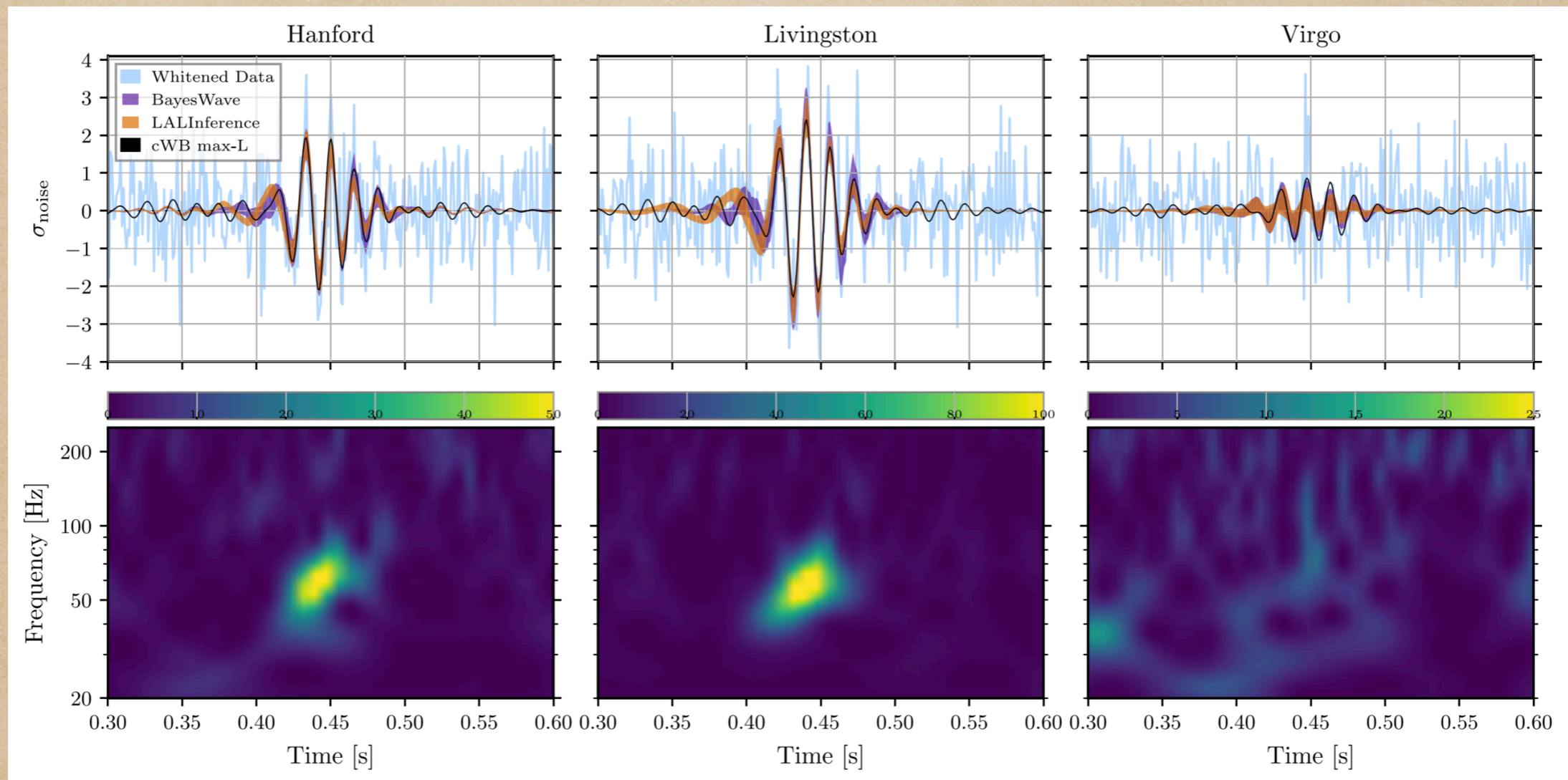
GW170817: Multi messenger astronomy

Some things we have learned

- GRB associated with Binary Neutron Star Merger

- Kilonova (infrared transient) due to decay of heavy elements

- Independent measurement of Hubble constant:

$$H_0 = 70^{+12}_{-8} \ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$

- Binary NS merger rate: $1540^{+3200}_{-1220} \ \mathrm{Gpc^{-3}\,yr^{-1}}$

- First insight into EOS at supernuclear densities through tidal effects

- Results will improve with more NS events

GW190521

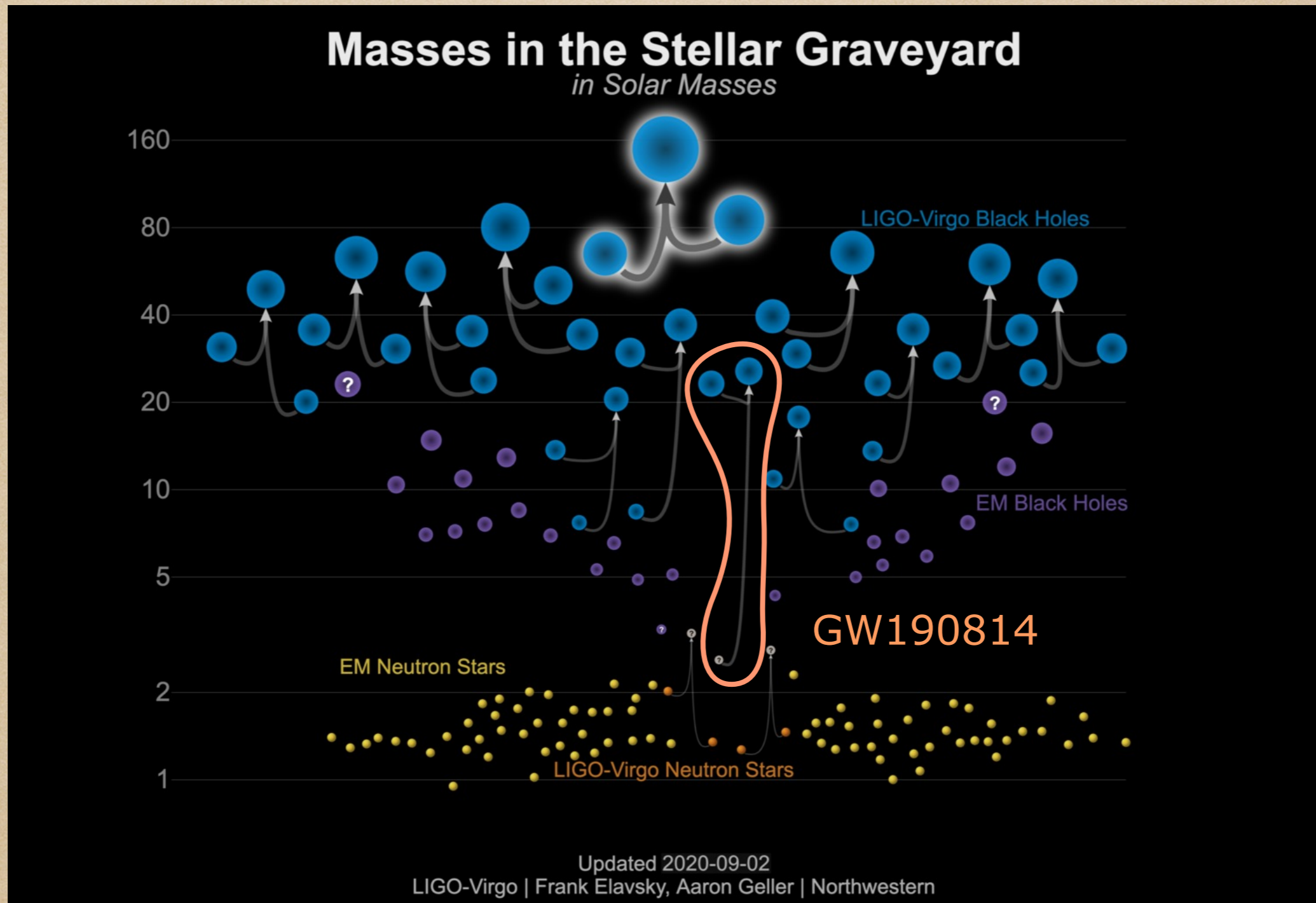Masses in the Stellar Graveyard
in Solar Masses

GW190521

LIGO-Virgo Black Holes

EM Black Holes

EM Neutron Stars

LIGO-Virgo Neutron Stars

Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GW190521

- Progenitor masses: $m_1 = 91\,M_\odot\,,\quad m_2 = 67\,M_\odot$

- Remnant mass: $M = 150\,M_\odot \overset{!}{=} m_1 + m_2$ Abbott et al. 2010.14527

- Mass defect $\Delta M \approx 8\,M_\odot$; cf. Tsar Bomba: $\Delta M \approx 2.65\,\mathrm{kg}$

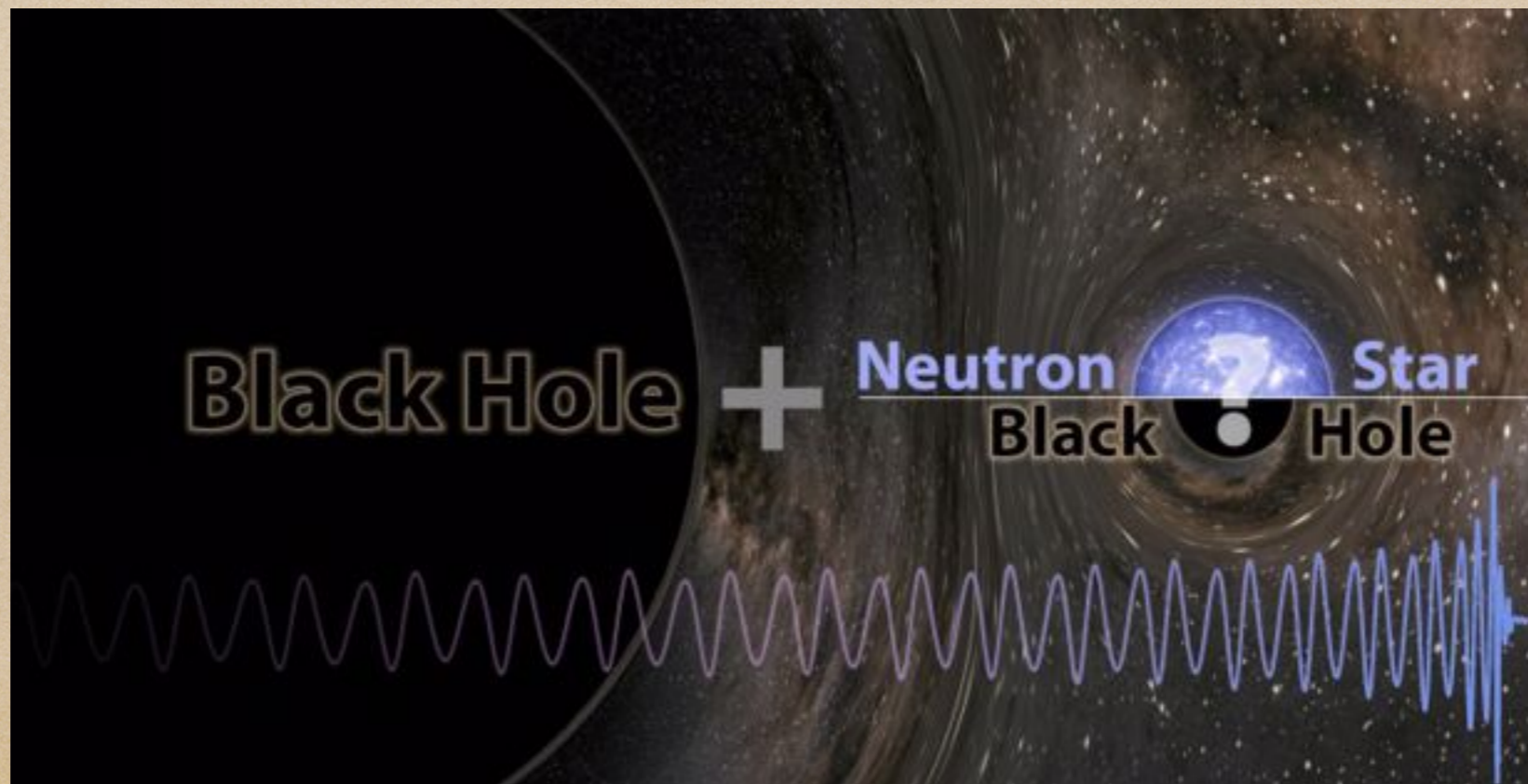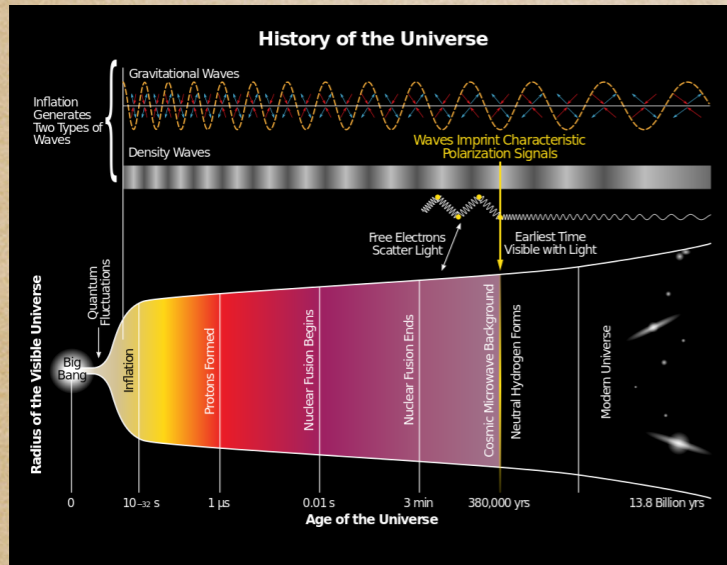- Open questions: How did the progenitor BHs form? Is it a BBH?

GW190814

Masses in the Stellar Graveyard
in Solar Masses

GW190521

- Progenitor masses: $m_1 = 23.2\,M_\odot\,,\quad m_2 = 2.59\,M_\odot$

- Remnant mass: $M = 25.6\,M_\odot$ Abbott et al. 2010.14527

- Key question: What is the secondary?

  - The heaviest neutron star ever seen?

  - The lightest black hole ever seen?

  - An exotic compact object? Wormhole or Boson Star or …

(Selected) Future applications
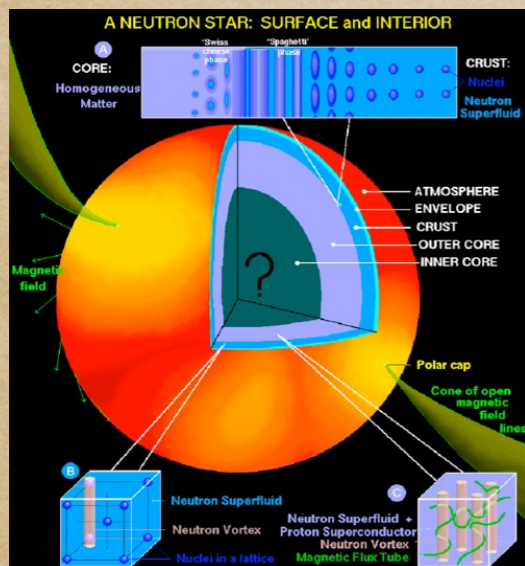
Overview

Early Universe

Testing Einstein's theory

Galaxy history

Equation of state

BH populations

The unknown…

Testing GR with GW170817: Graviton mass

- Phenomenological model

- Massive graviton $\Rightarrow$ Compton wavelength $\quad \lambda_g = \dfrac{h}{m_g c}$

- Dispersion relation: $\dfrac{v_g^2}{c^2} = 1 - \dfrac{h^2 c^2}{\lambda_g^2 E^2}$
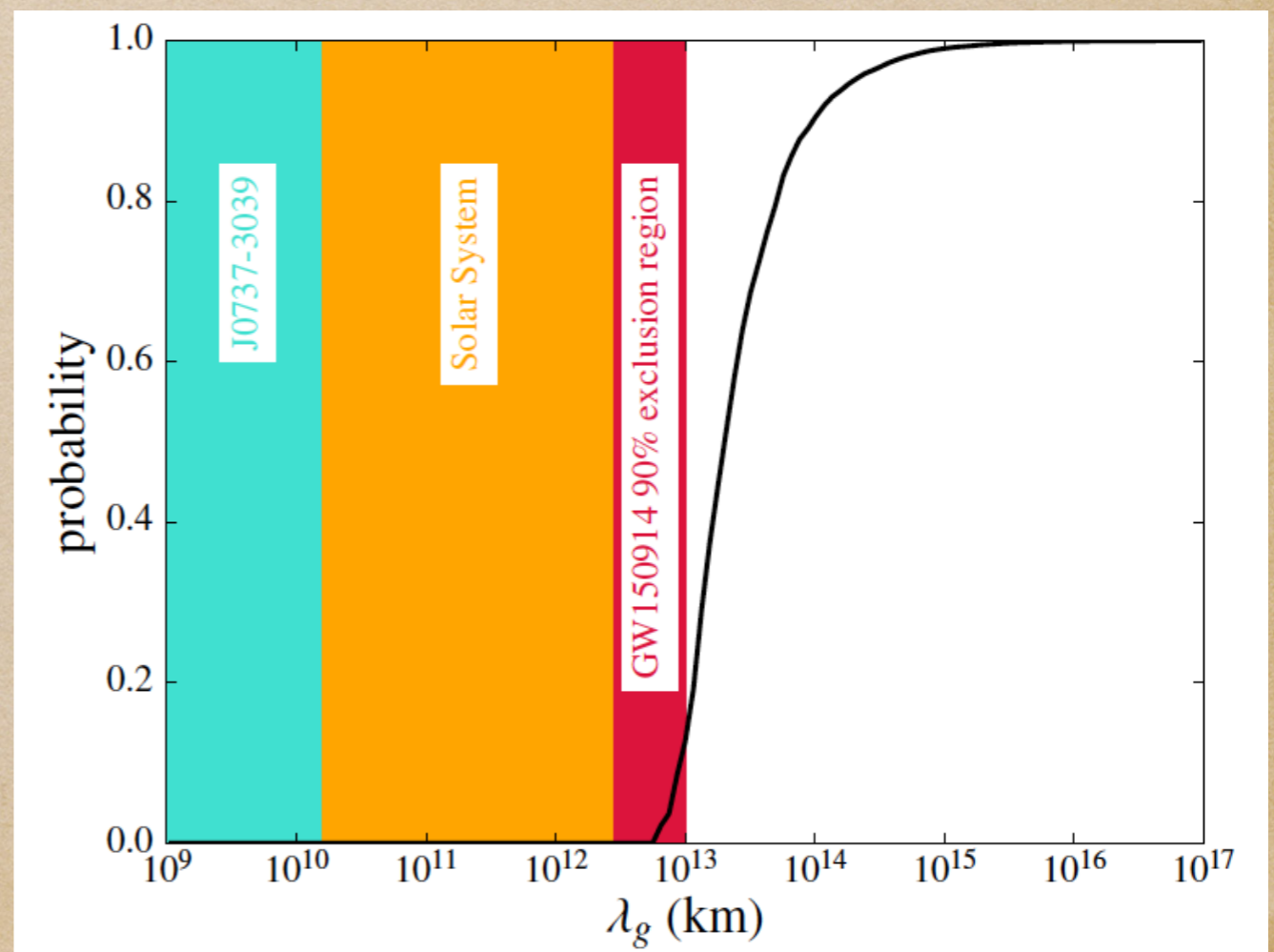
$\Rightarrow$ Quasi-1PN phase term

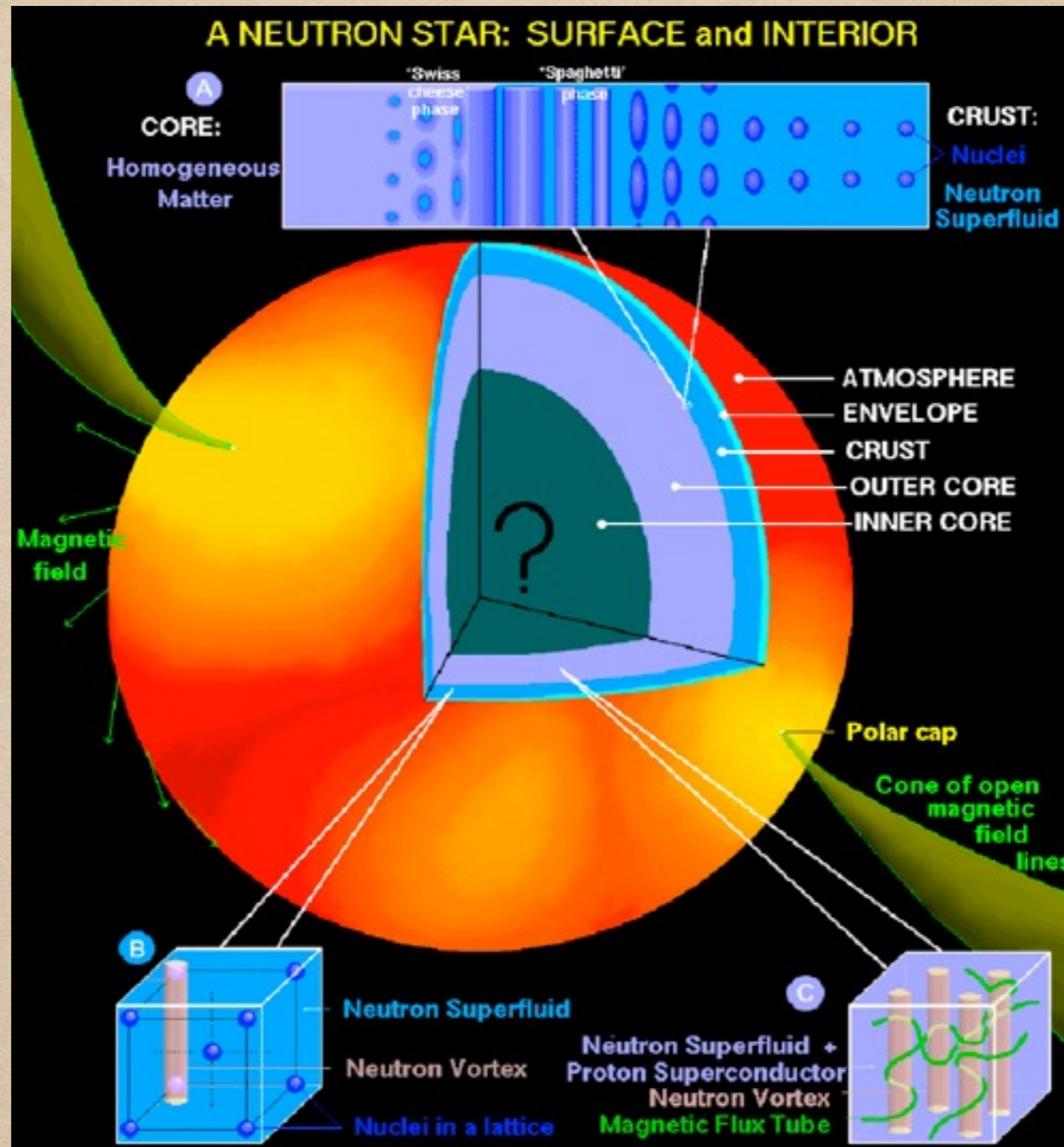$$\phi_{\mathrm{MG}}(f) = -\frac{\pi D c}{\lambda_g^2 (1+z) f}$$

Will 1998 PRD

$$\boxed{m_g \leq 1.2 \times 10^{-22} \ \mathrm{eV}/c^2}$$

Abbott et al 1602.03841

Equation of state of matter

- E.g. through tidal effects

Need electromagnetic counterpart or large number of events !

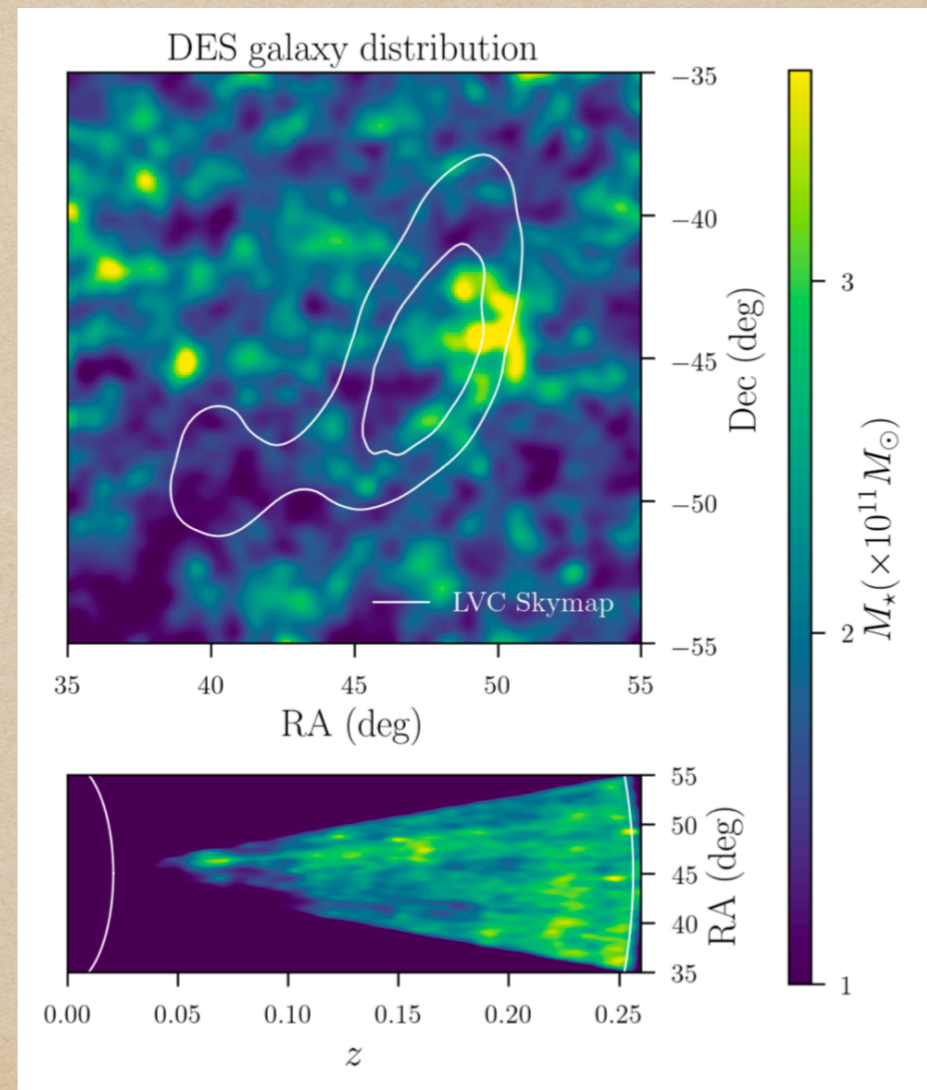# Standard Sirens: H0 from GW170817

Abbott et al 1710.05835

- Redshift z from EM, Luminosity distance D_L from GWs
- $H_0 = 70^{+12.0}_{-8.0} \, \mathrm{km \, s^{-1} \, Mpc^{-1}}$
- More sirens needed to resolve tension

Dark Sirens: H0 from BH binaries

- No EM signal $\Rightarrow$ redshift unknown

- Solution: Statistical analysis using galaxies in sky window

  Combine sky localization from LIGO with galaxy surveys

- Here for GW170814

  - Prather well localized!

  - Dark Energy Survey "DES"

  - Not yet competitive, but will

    improve with many events

Soares-Santos et al 1901.01540

Conclusions

Conclusions

- GW150914 marks the dawn of GW astronomy

- "We" measured the change in length by a fraction

  of an atomic nucleus caused by sth. 1 Gyr away!

- >1 BBH! Not merely a lucky shot.

- First surprises: BHs heavier than expected   GW190521

  Compact objects in the mass gap GW190814

- GW170817 marks the dawn of multi messenger astronomy!

- Applications: Test GR, BH census, History of universe, EOS,…

- A new window to the universe reveals interesting things…

GW detections as of 2020

Masses in the Stellar Graveyard
in Solar Masses