At the dawn of a new era in astrophysics: Gravitational waves have arrived

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National Meeting of Astronomy and Astrophysics

Aveiro, 08 Sep 2016

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 690904, from H2020-ERC-2014-CoG Grant No. "MaGRaTh" 646597, from NSF XSEDE Grant No. PHY-090003 and from STFC Consolidator Grant No. ST/L000636/1.

Gravitational Waves: Ripples in spacetime

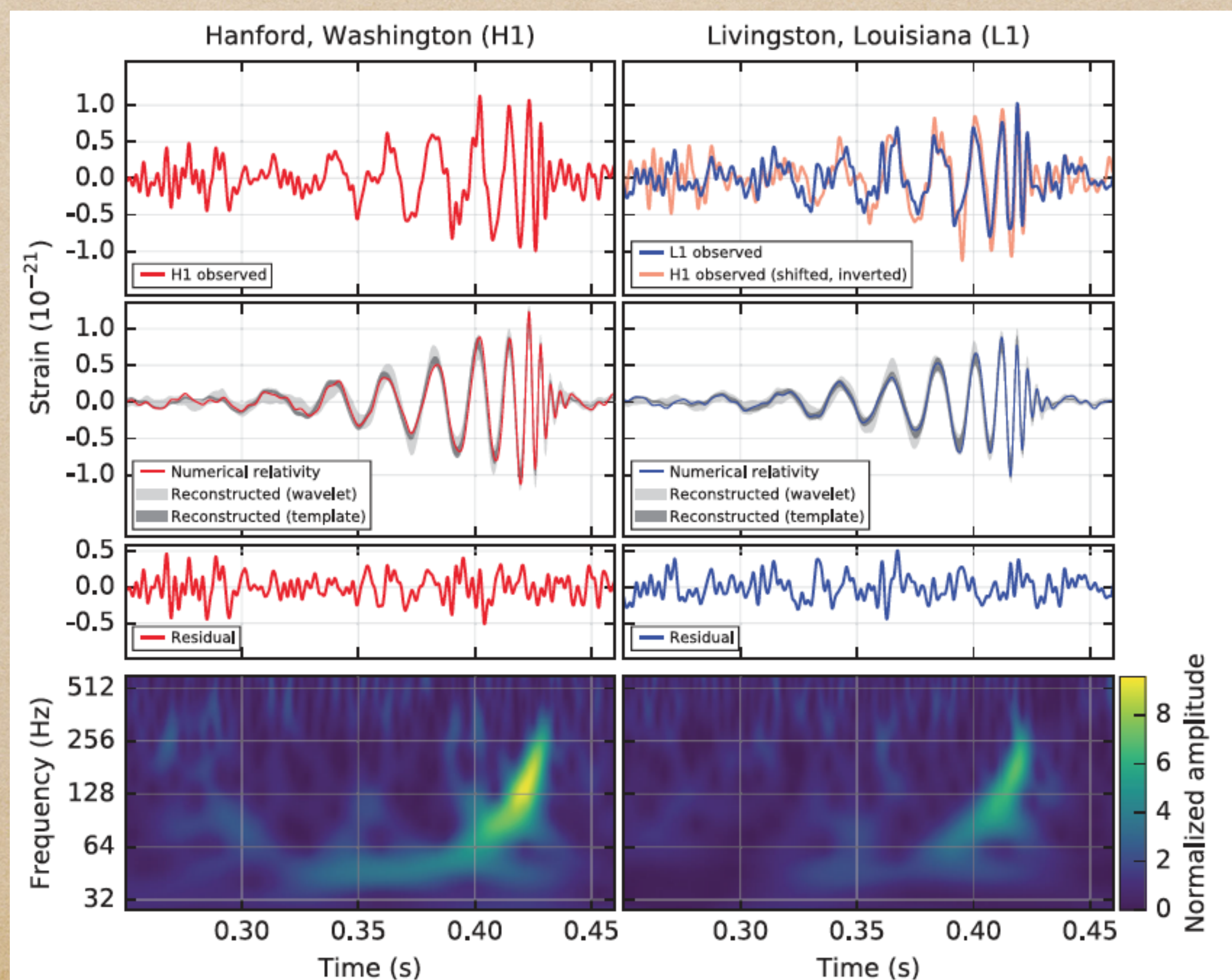
- Unusual news headlines on 11/12 February 2016
- First direct detection of gravitational waves: GW150914

So, what happened?

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

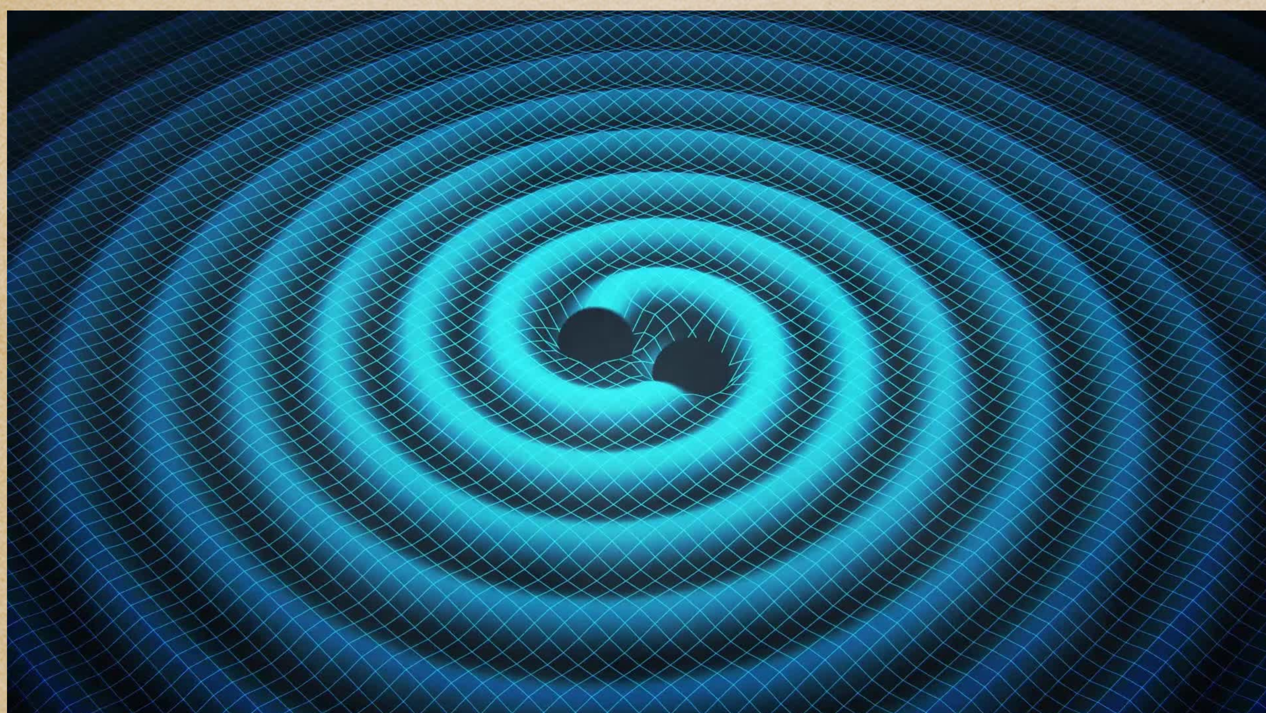
  Abbott et al. PRL 2016, Abbott et al. 1606.01210

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

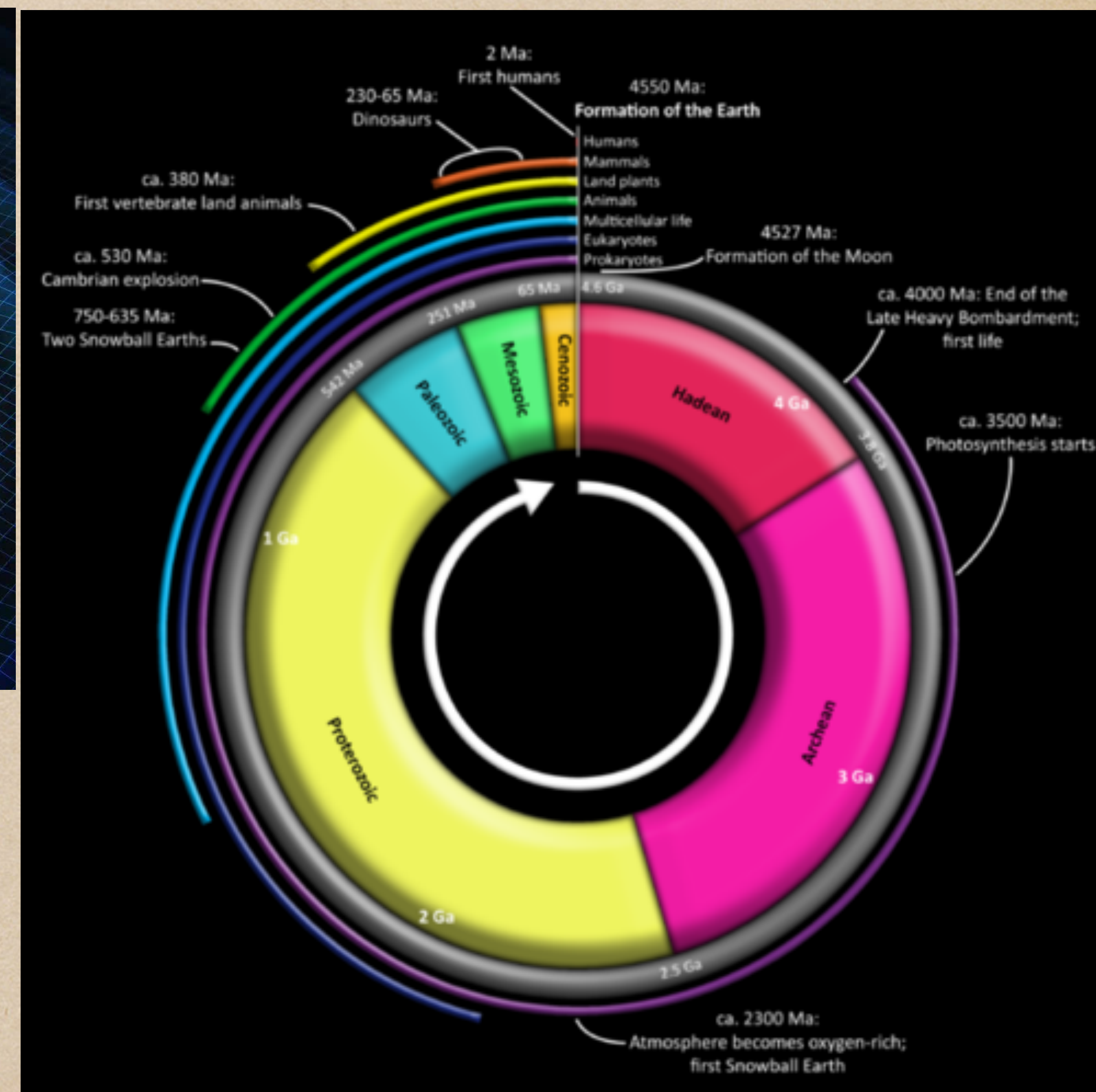


What really happened...

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



- Deep Precambrian



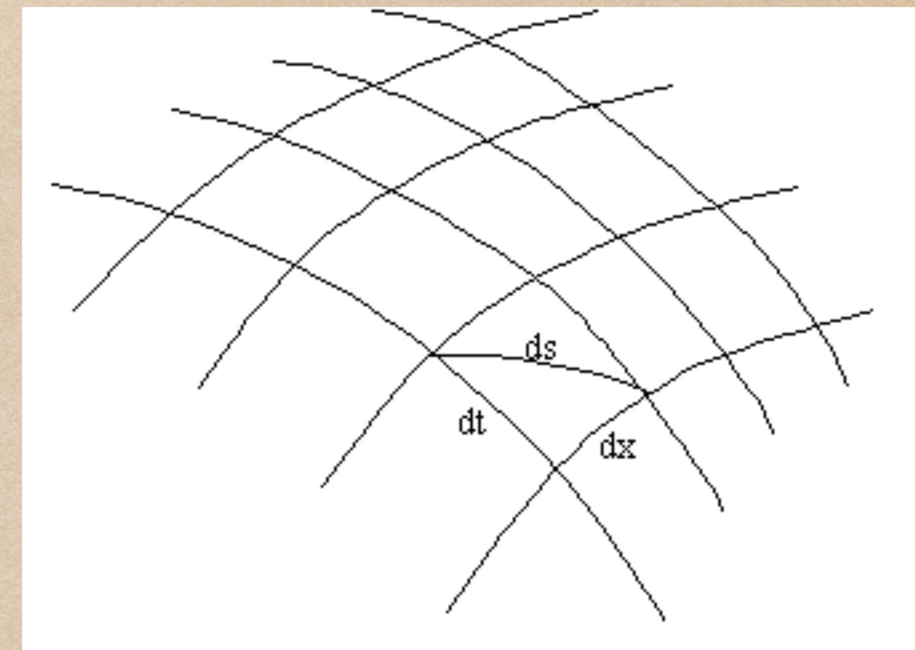
Overview

- A brief theory of gravitational waves
- Frequency windows, sources and detectors
- Parameter estimation and source modeling
- GW150914
- 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

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

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

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: $h_{\mu\nu} = H_{\mu\nu} e^{i k_\sigma x^\sigma}$

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

Effect on particles

- Geodesic eq.

  Particle at rest at x^μ stays at $x^\mu = \mathrm{const}$ in TT gauge

- Proper separation:

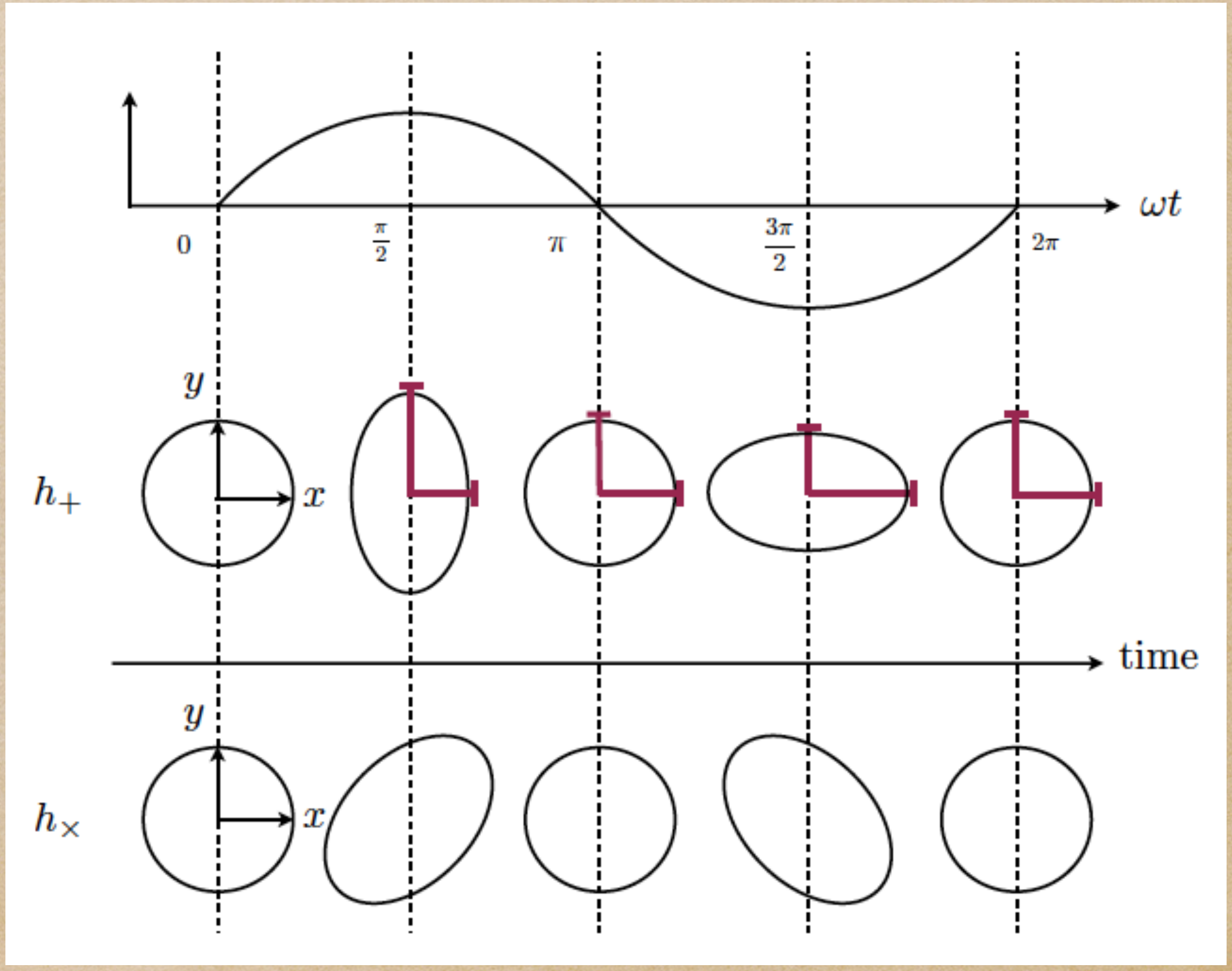
$$ds^2 = -dt^2 + (1 + h_+)\, dx^2 + (1 - h_+)\, dy^2 + 2h_\times\, dx\, dy + dz^2$$

- Effect on test particles:

  Mirshekari 1308.5240

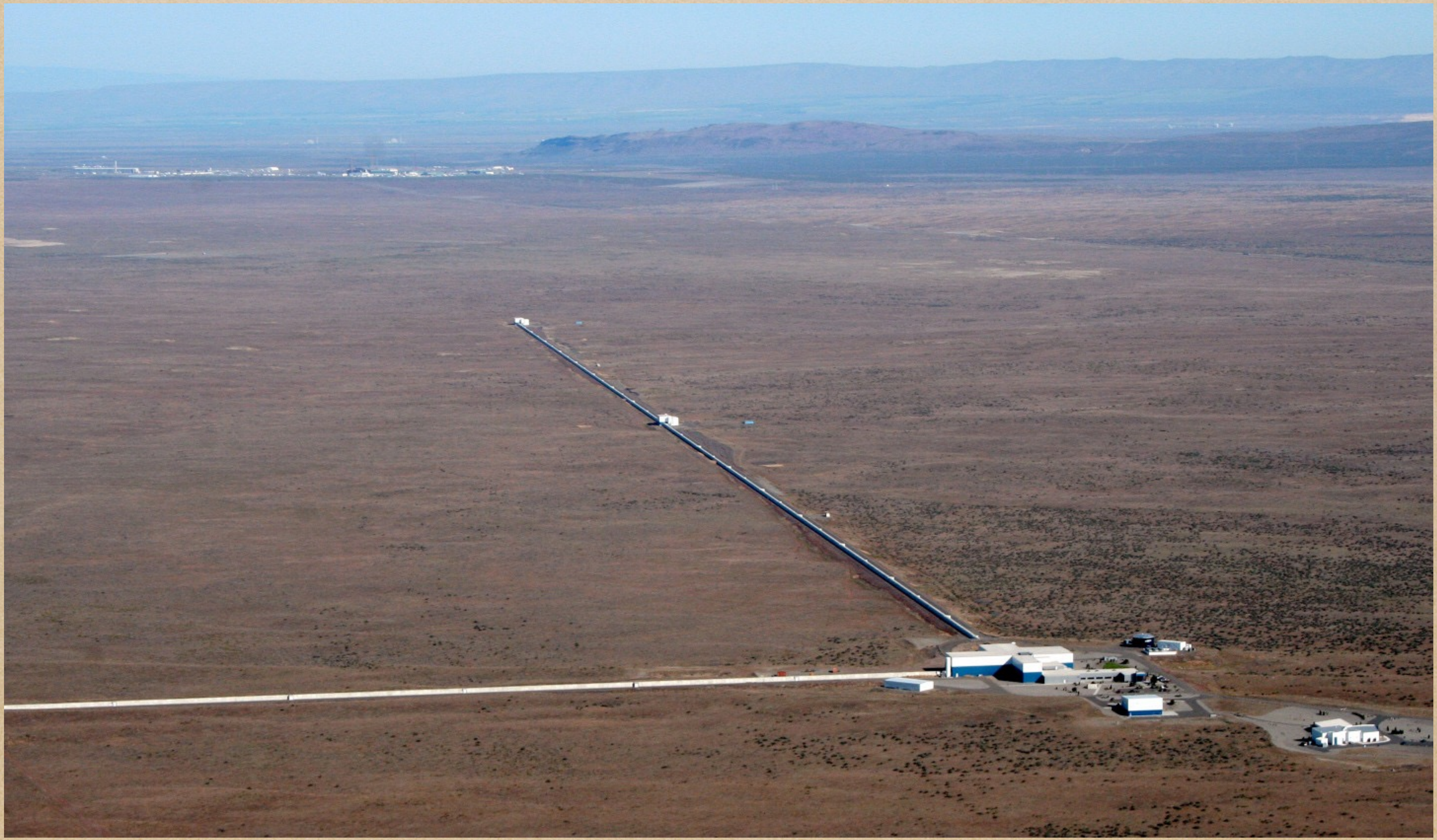
- Debate on physical reality until late 1950s

  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

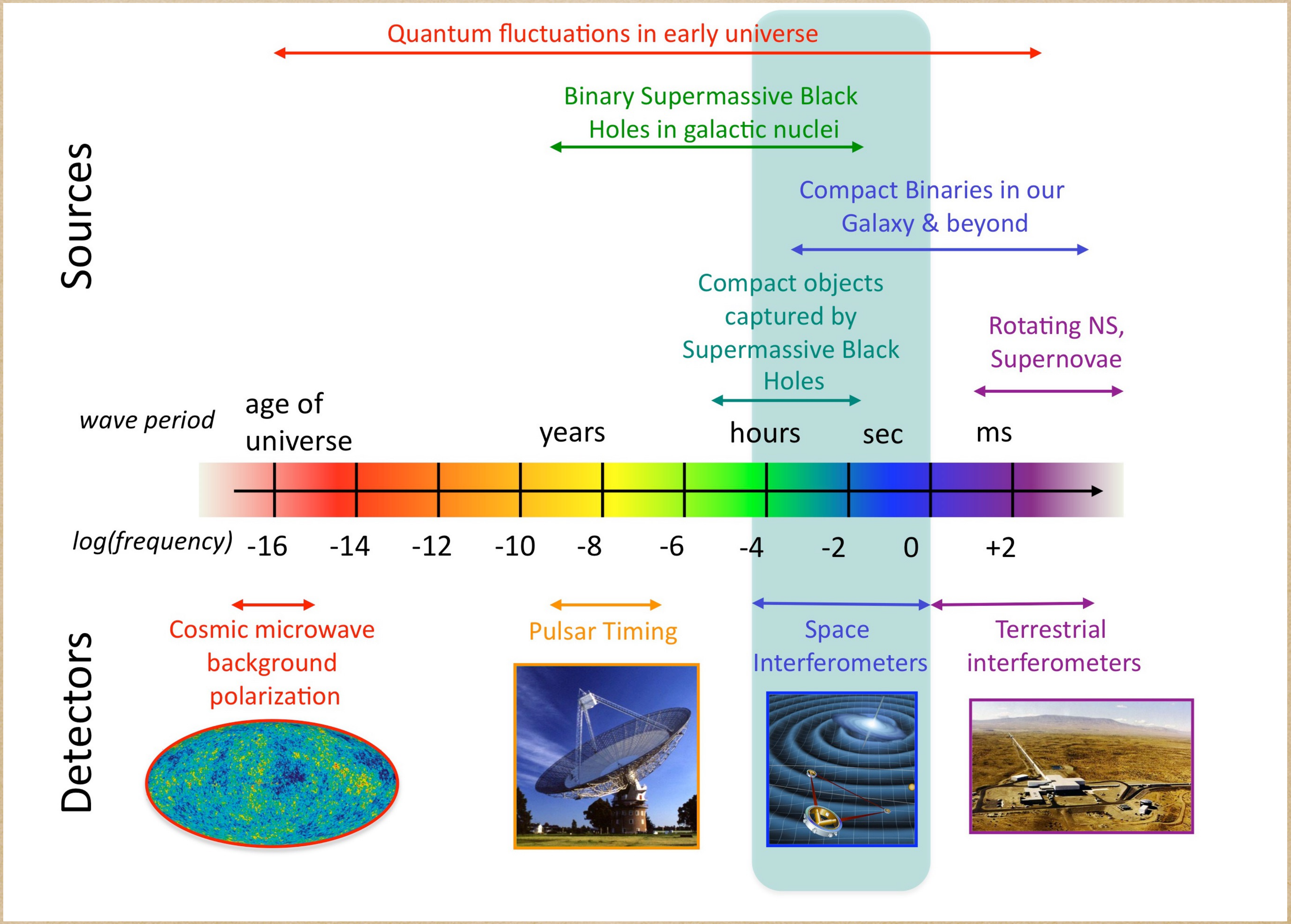
- Source types and detection strategies $\Rightarrow$ 4 regimes

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

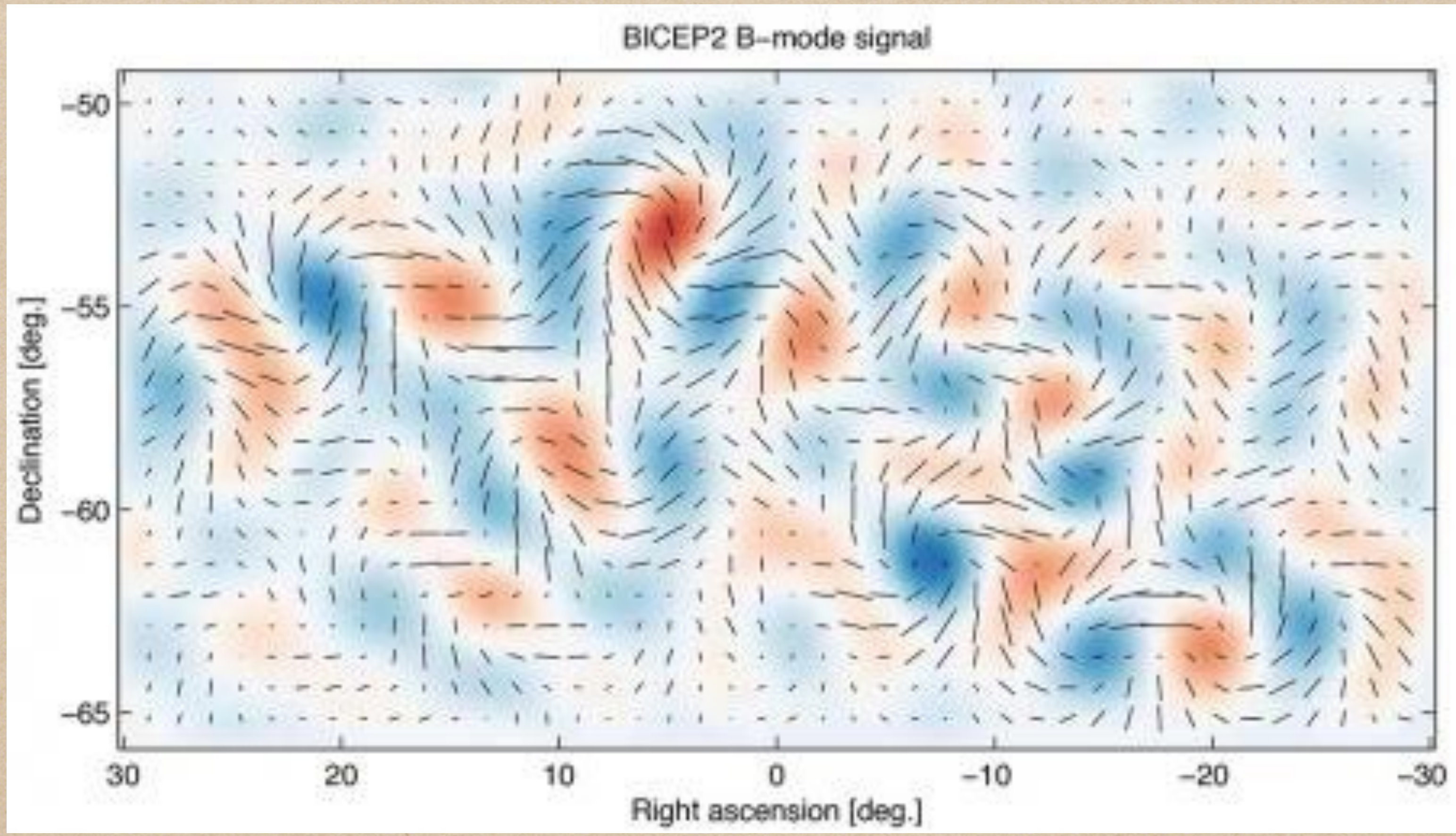
Ultra low:	Fluctuations in the early universe
Very low:	Supermassive BH binaries (high M, z)
Low:	SMBHs, EMRIs, Compact binaries,...
High:	Neutron star / BH binaries, supernovae,...

The gravitational wave spectrum



The ultra low frequency regime

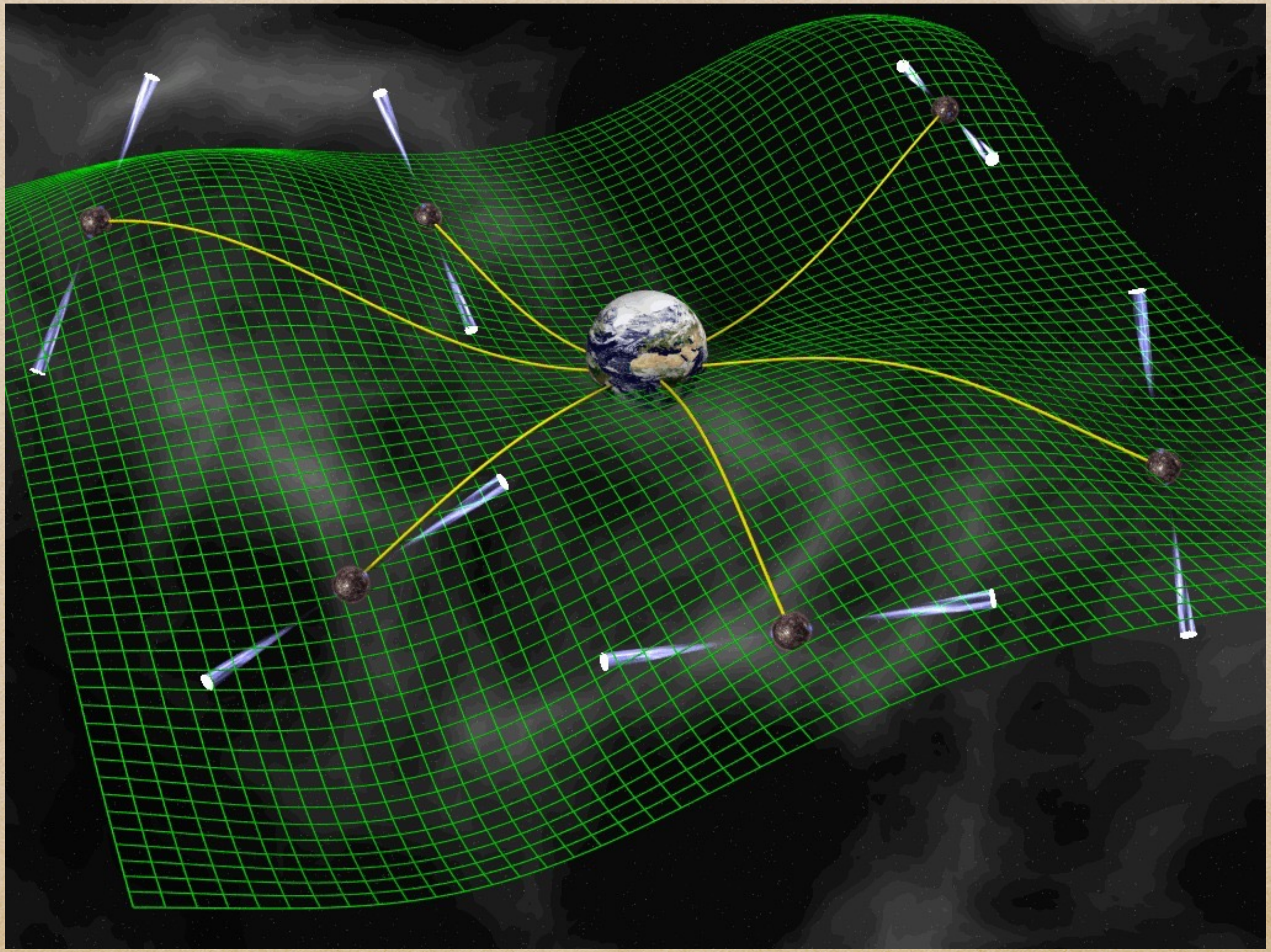
- Wave periods $\sim$ Hubble time
- Primordial GWs $\rightarrow$ Signature in polarization of CMB
- E.g. BICEP2



- 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

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

The very low frequency regime

- So far: upper limits
- E.g. PPTA
- Models excluded?
- Possible explanations

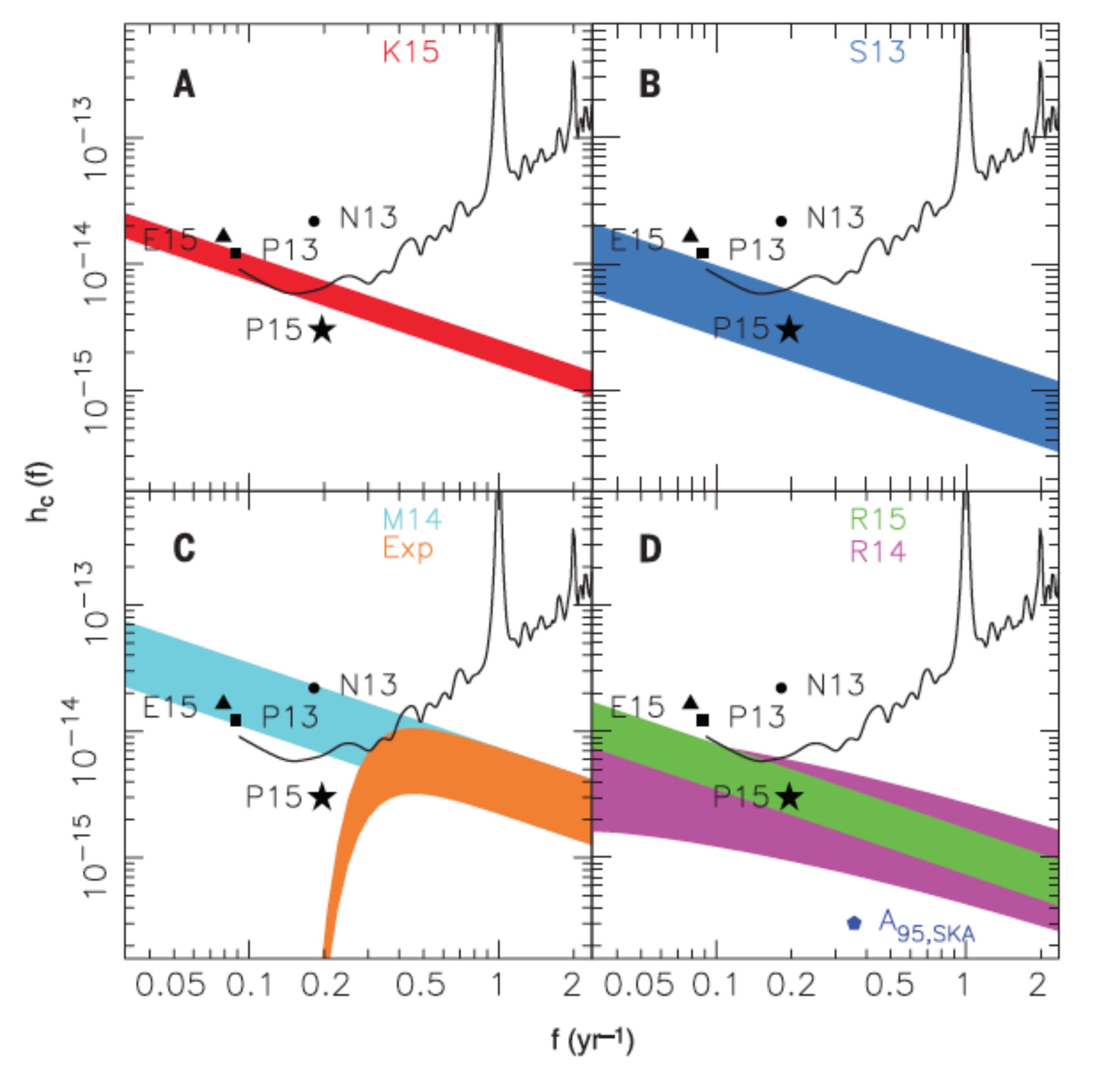
  Binaries stalled

  Accelerated mergers

  Eccentric orbits

  …

  Models too simple



Shannon et al (2015) Science

The low frequency regime

The low frequency regime

- Interferometry with $\sim 10^6\ \mathrm{km}$ arms
- Realm of space missions
- eLISA: L3 mission of ESA's "Cosmic Vision" Launch: ~ 2034
- Configuration still uncertain:

  2 arms vs. 3 arms

  $10^6\ \mathrm{km}$ vs. $5\times10^6\ \mathrm{km}$

  2 yr vs. 5 yr life span

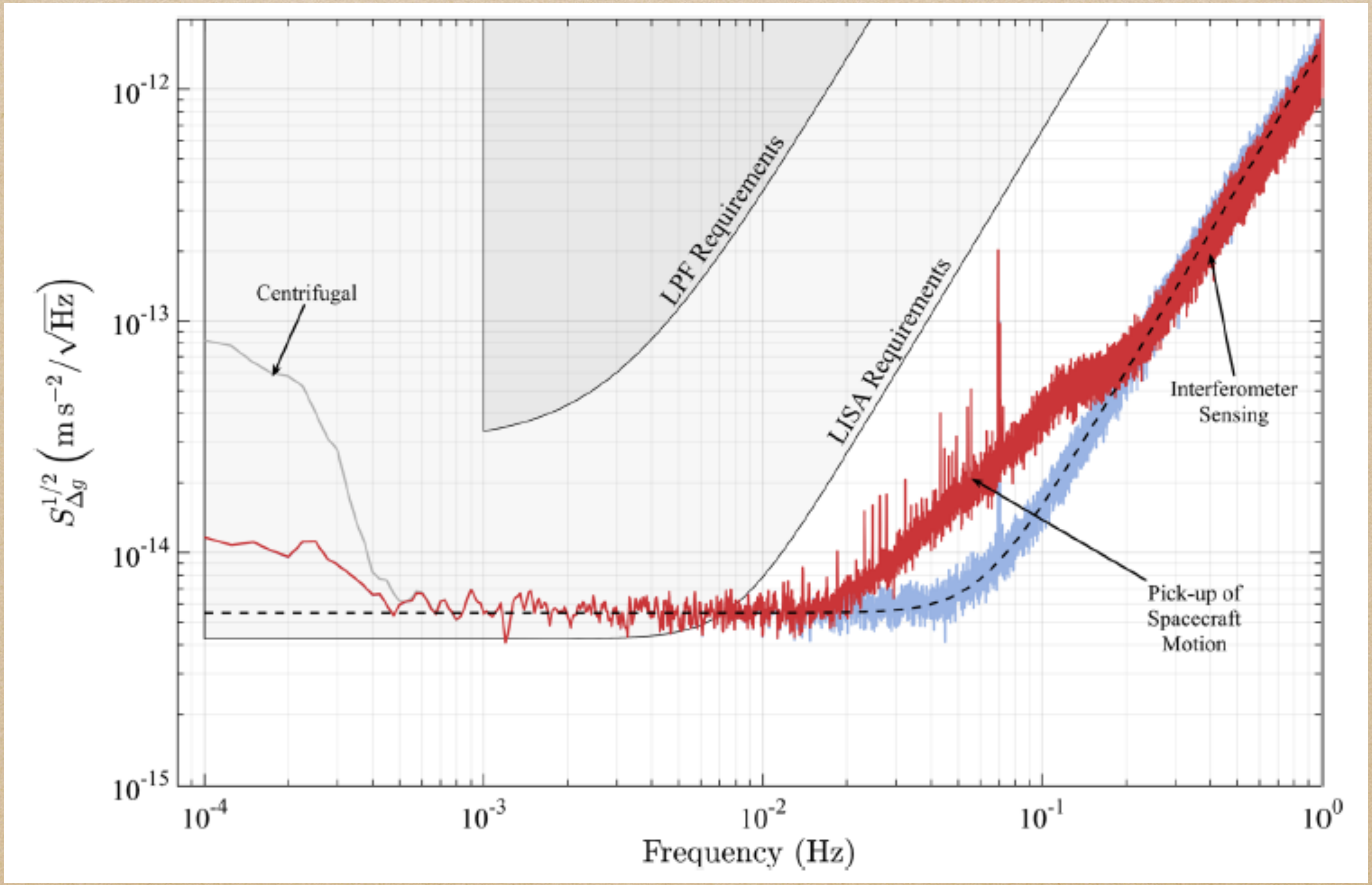
- Calibration binaries (WDs)
- Outstanding SNR
- LISA Pathfinder: Test mission

  Launched 3 Dec 2015

LISA Pathfinder Latest: 7 Jun 2016

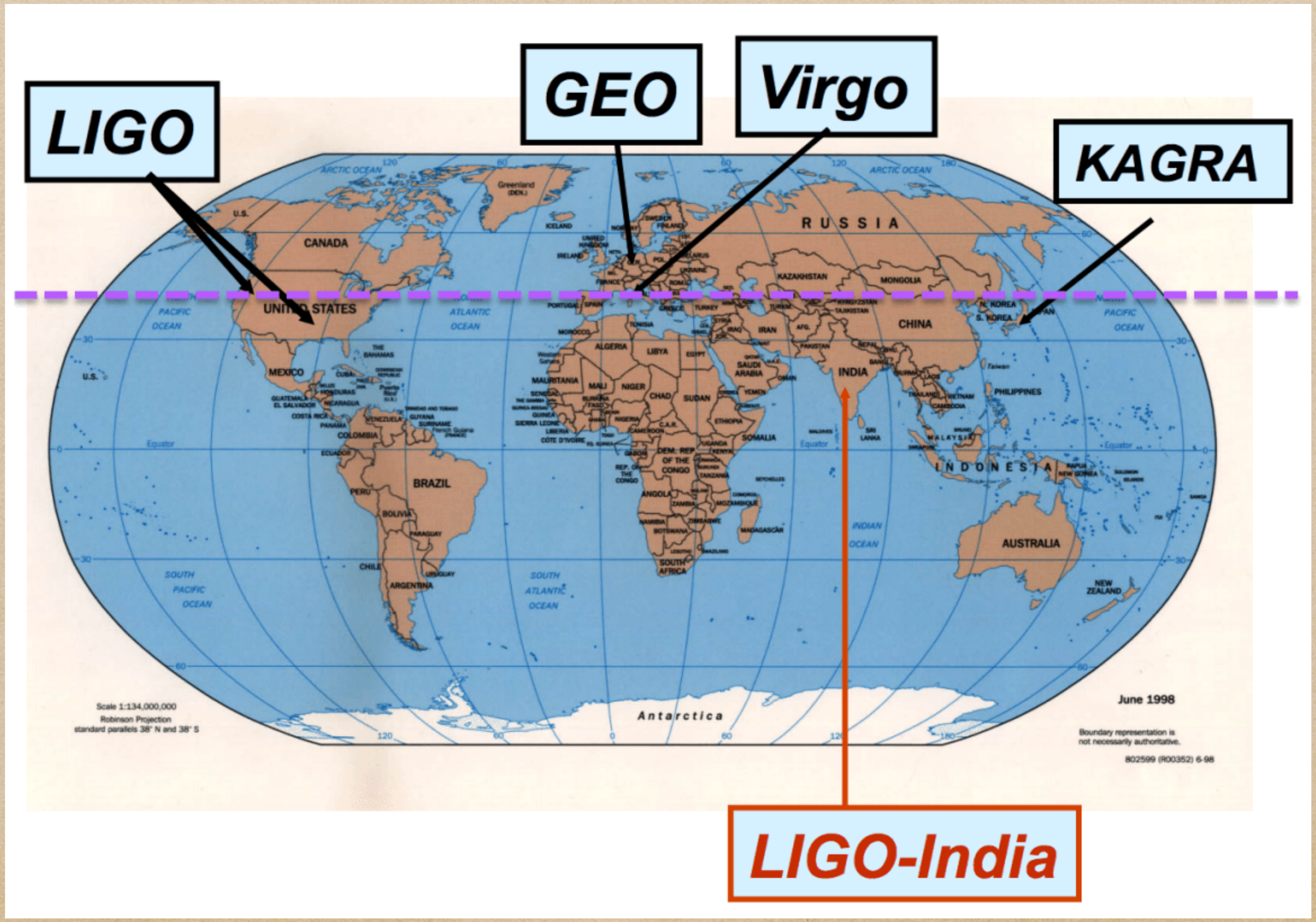
- Noise curve exceeds LISA requirements

Armano et al. PRL (2016)

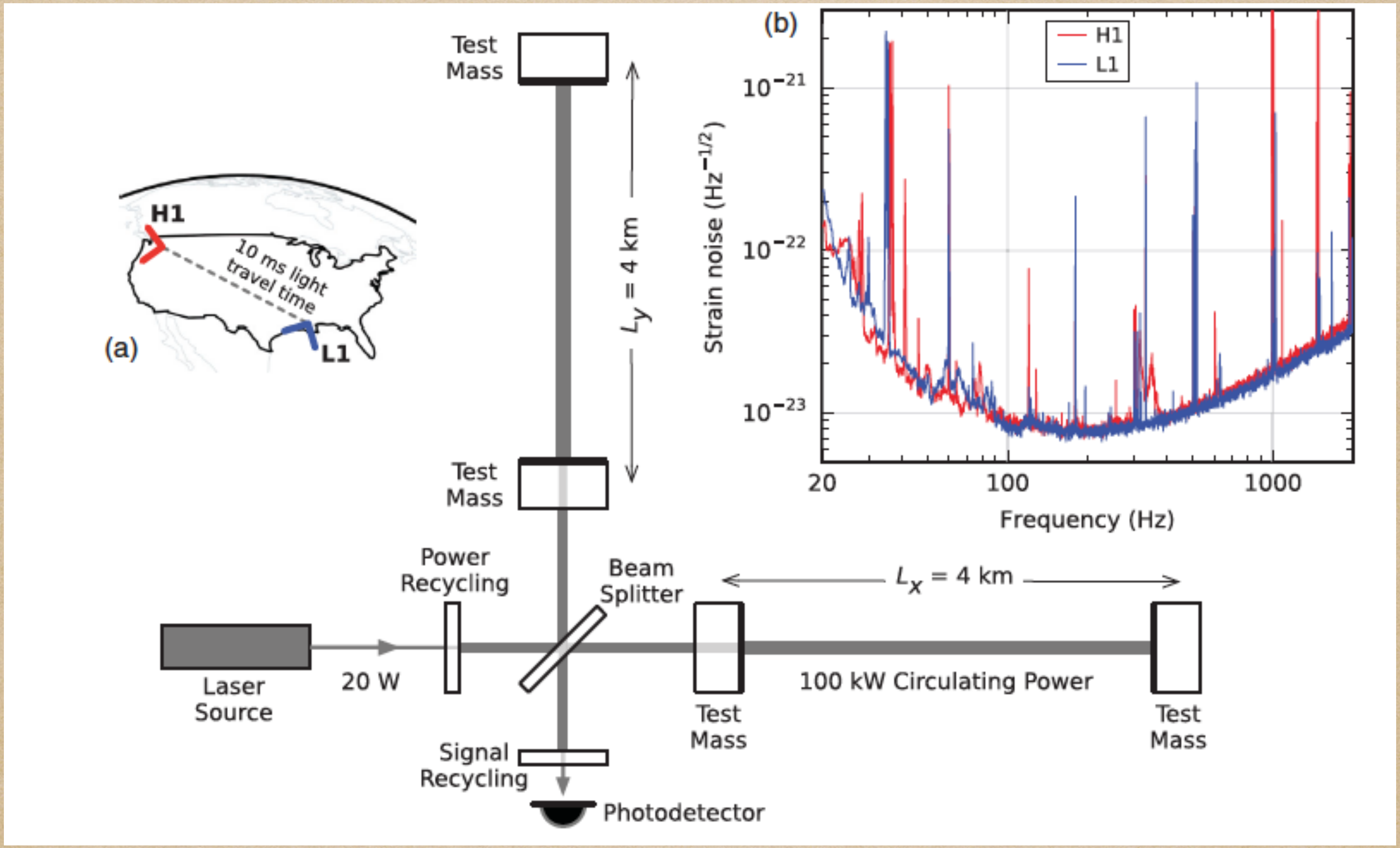


The high frequency regime

- Interferometry with $\sim \mathrm{km}$ arms
- Detector: 2 LIGO, Virgo (2016), GEO600, KAGRA (2018), LIGO-India



The interferometer diagram: LIGO

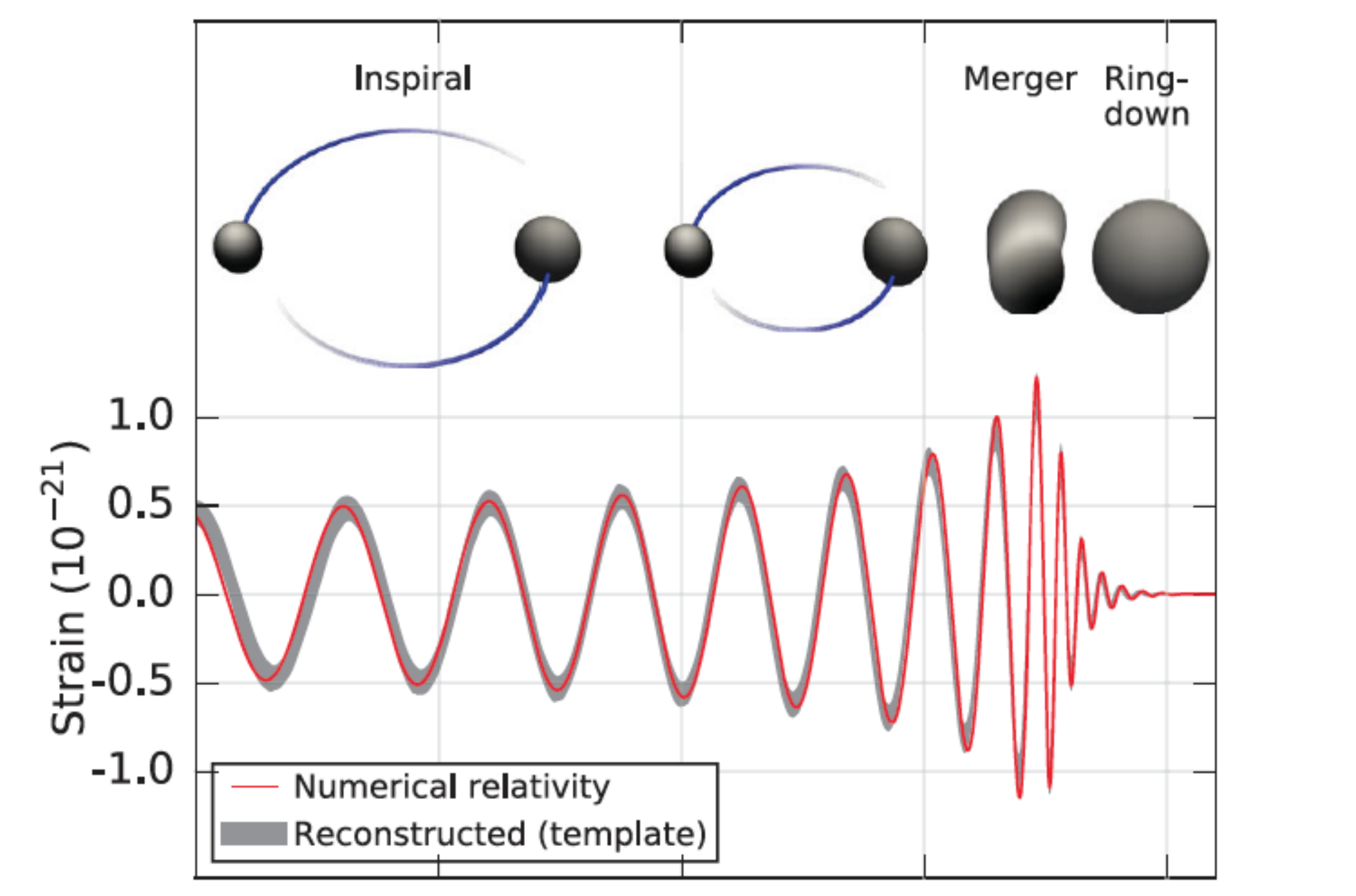


Abbott et al, PRL 116 (2016) 061102

Seismic, thermal, shot noise

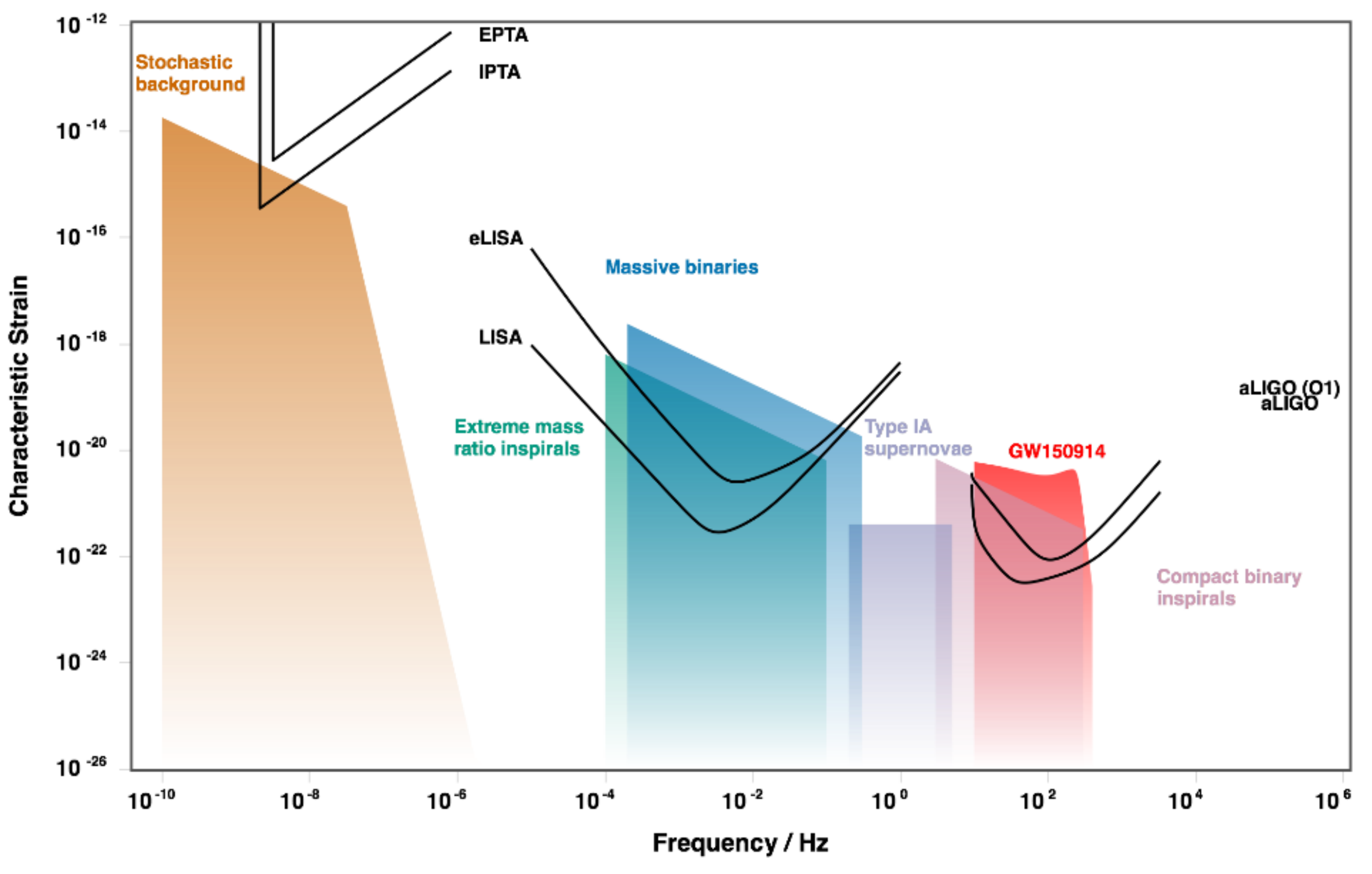
The high frequency regime

- Supernovae
- Neutron star oscillations
- Neutron star / stellar-mass black hole binaries



Abbott et al, PRL 116 (2016) 061102

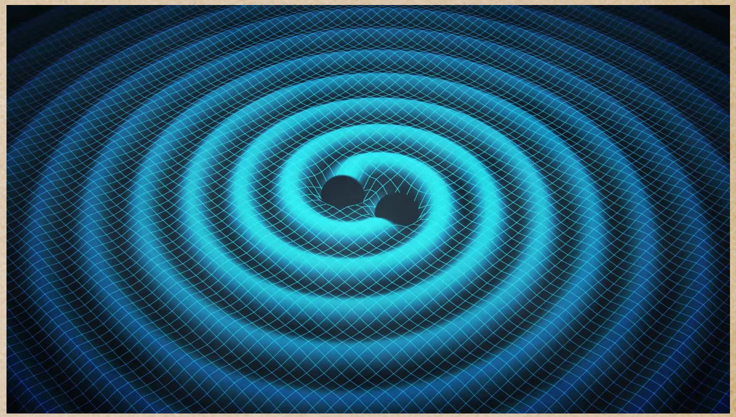
Summary: sensitivity curves



http://rhcole.com/apps/GWplotter/

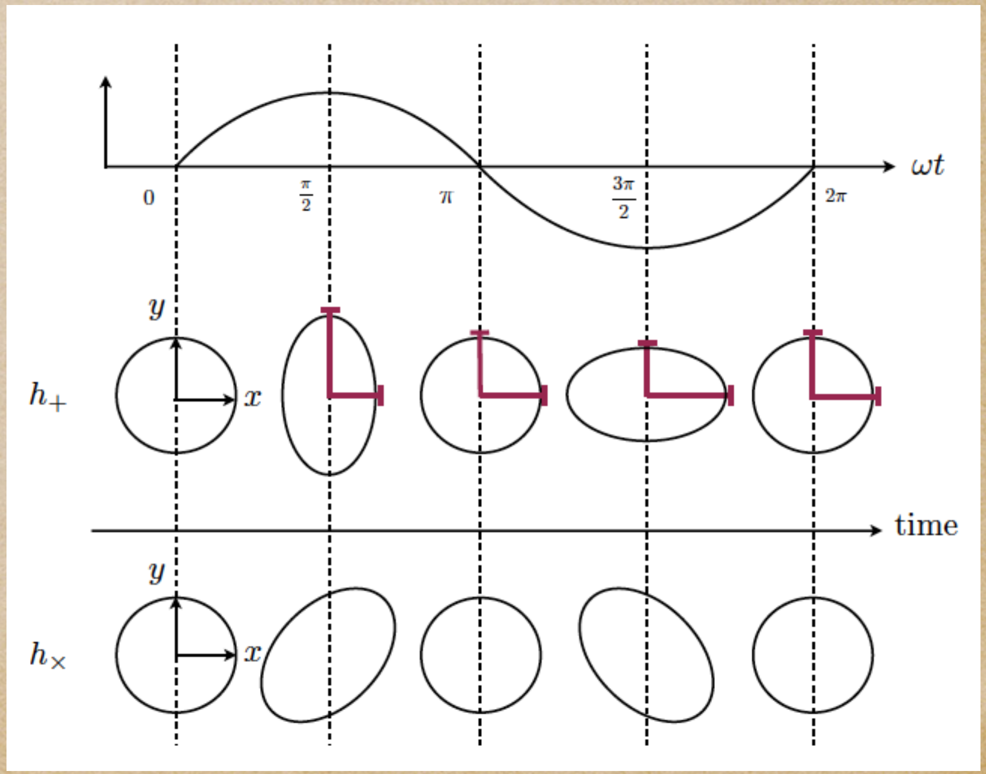
Parameter estimation and source modeling

The search for GWs in the data stream



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

- Weak effect of matter on geometry
- GWs carry huge energy but barely interact with anything
- Induced changes in length: < atomic nucleus / km



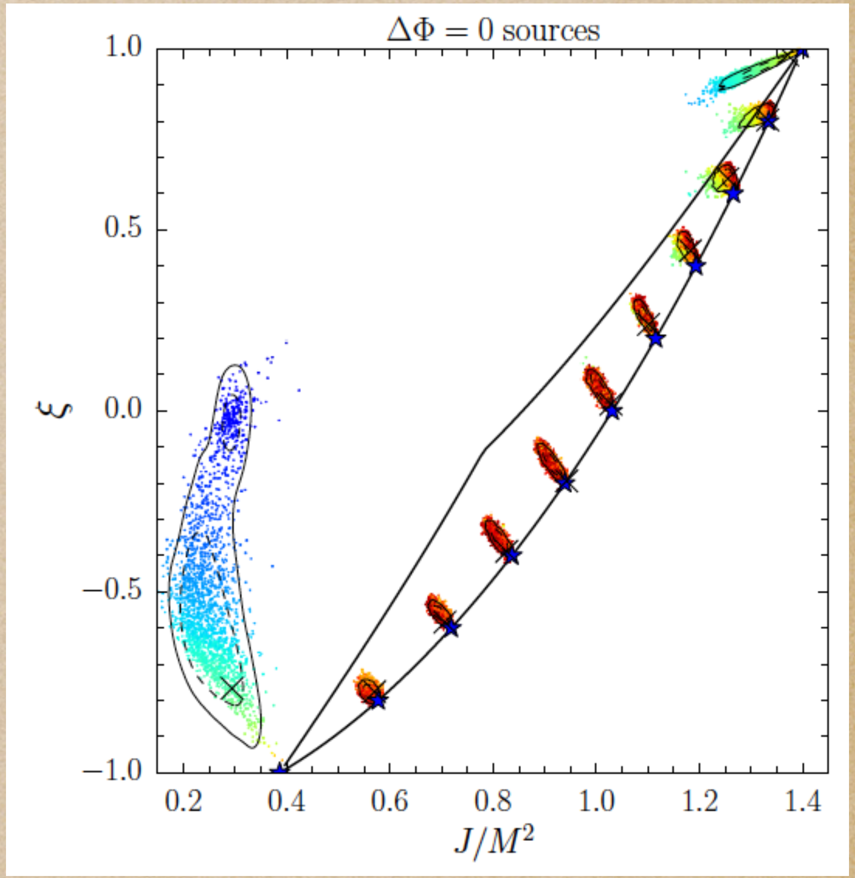
Detection and parameter estimation

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" e.g. Allen et al. PRD 2012
- Compare data stream with GW templates ("Finger print search")
- Bayesian analysis: Prior $\rightarrow$ Posterior



Trifiró al. 1507.05587

Black-hole binaries: parameters

- 8+2 Intrinsic parameters

  Masses $m_1\,,\ m_2$

  Spins $\boldsymbol{S}_1\,,\ \boldsymbol{S}_2$

  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

GW source modeling

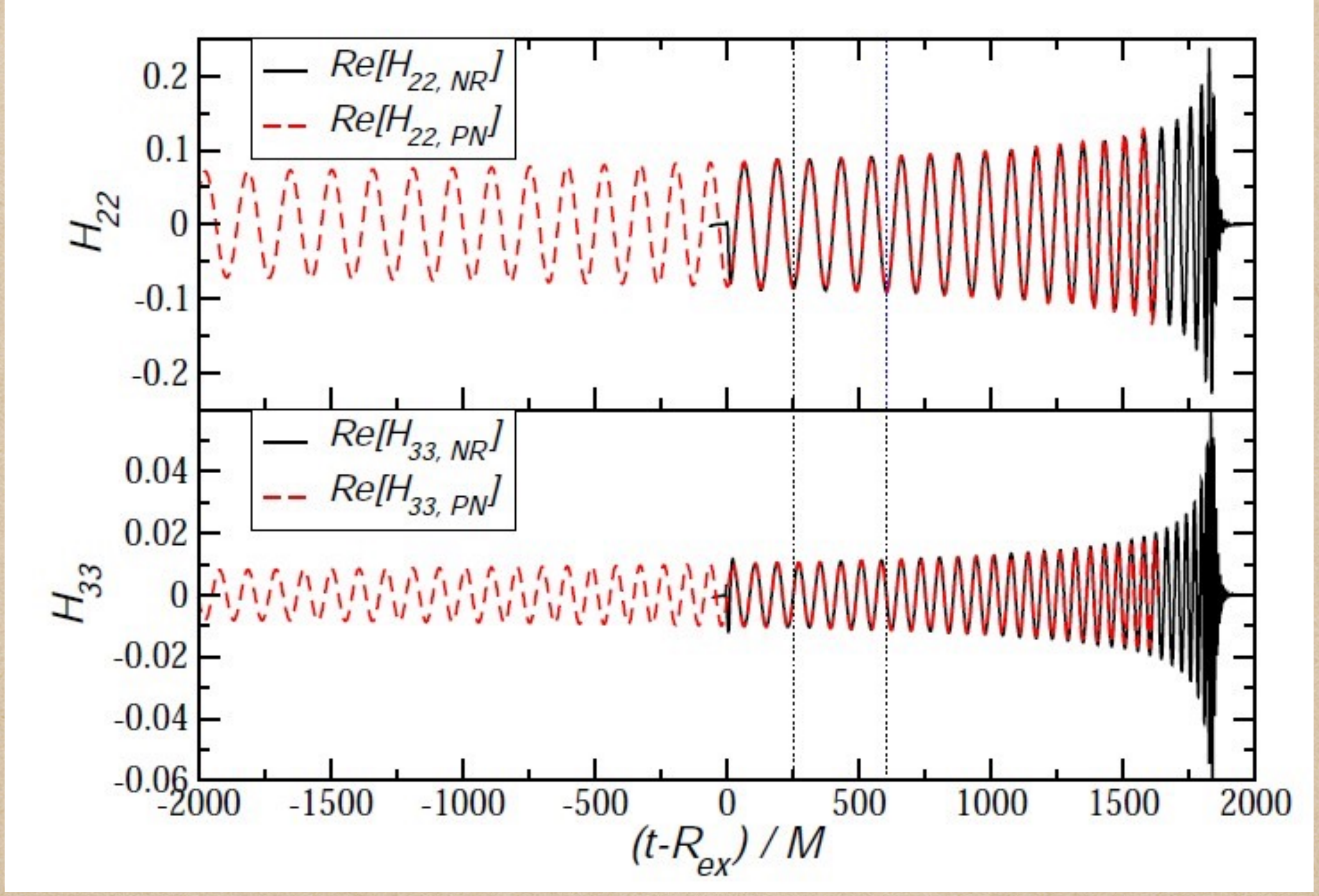
- Key requirement for matched filtering: GW template catalog
- Model black holes in general relativity
  - Post Newtonian theory $\rightarrow$ Inspiral Blanchet Liv.Rev.Rel. 2006
  - Numerical relativity $\rightarrow$ final orbits, merger

    Pretorius PRL 2005, Baker et al PRL 2006, Campanelli et al PRL 2006
  - Perturbation theory $\rightarrow$ 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

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

Hybrid waveforms and catalogs

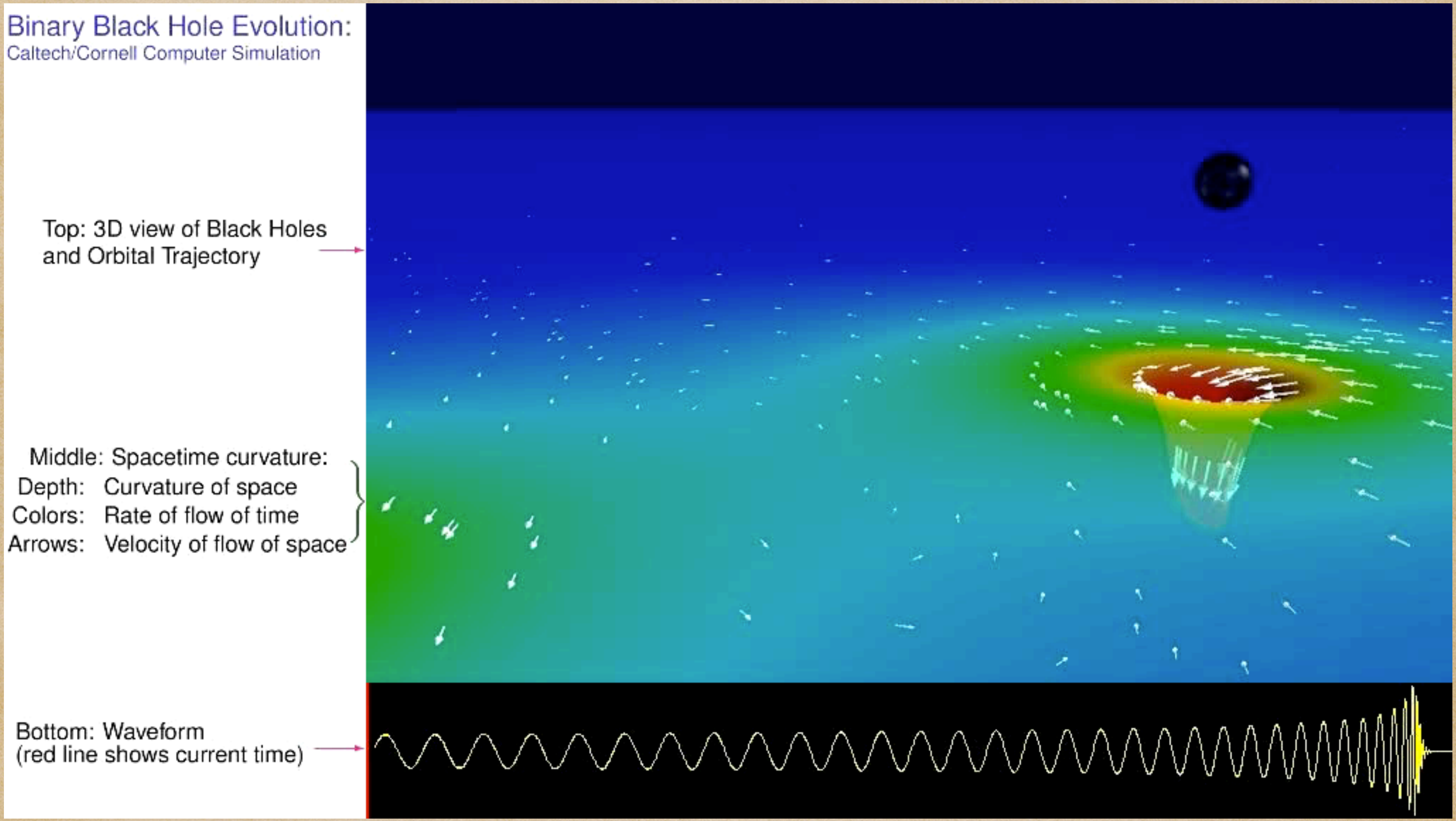
- Stitch together PN and NR waveforms



US et al CQG 2011

- Mass produce waveforms; Hinder et al CQG 2013, Mroué et al PRL 2013

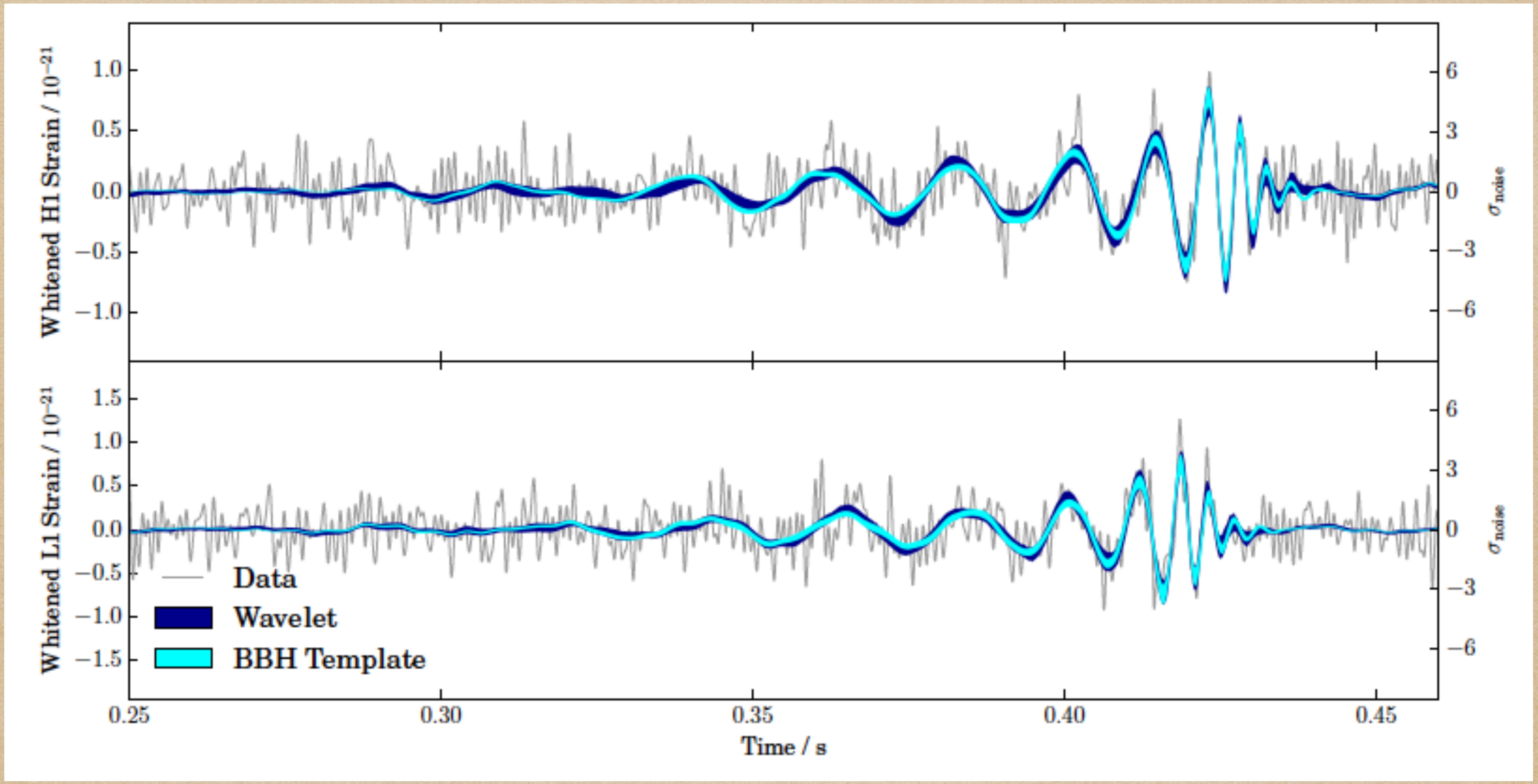
Anatomy of a BHB coalescence



Thanks to Caltech-Cornell groups

GW150914

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

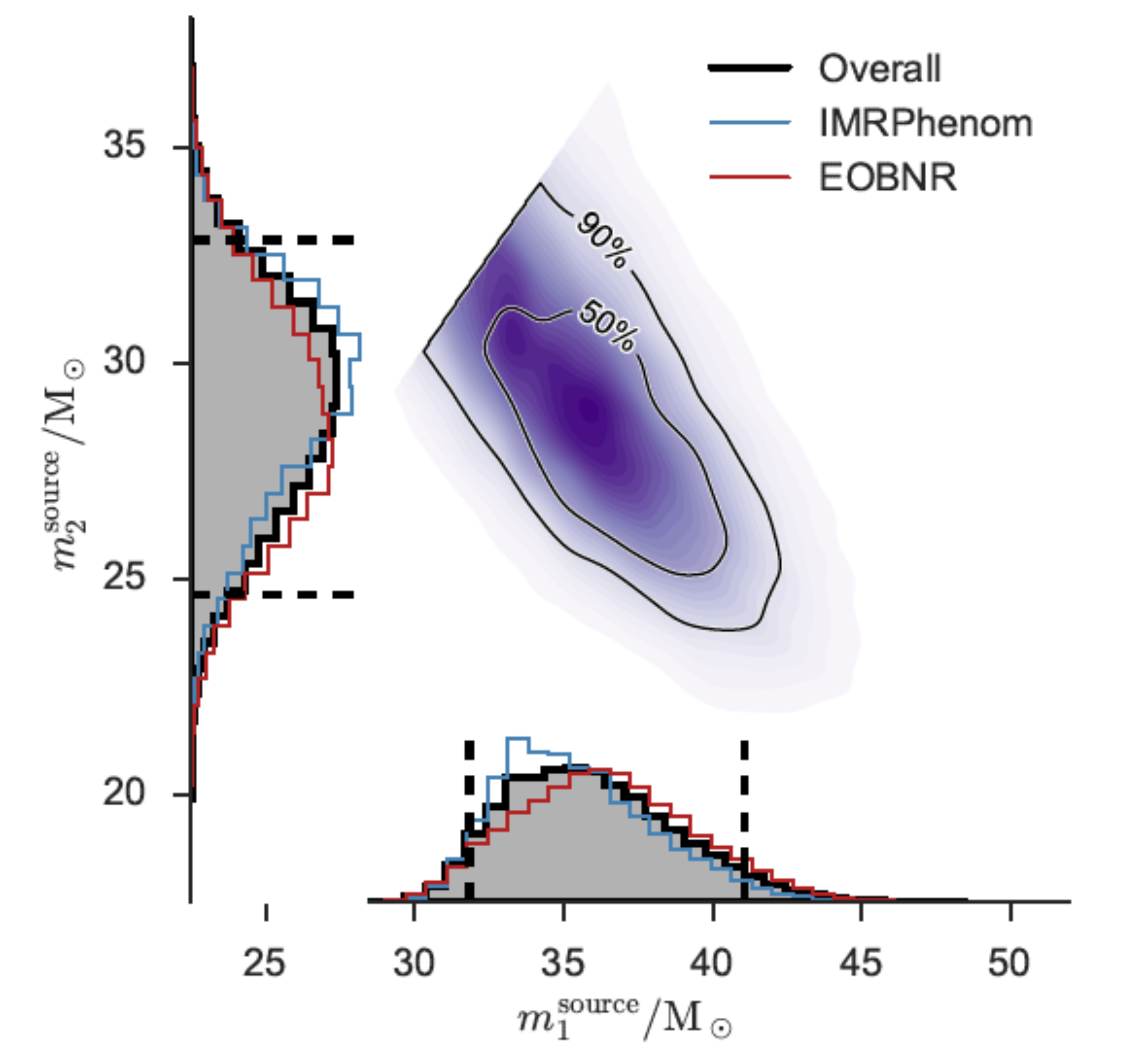
$$m_1 = 36^{+5}_{-4}\ M_\odot$$

$$m_2 = 29^{+4}_{-4}\ M_\odot$$

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

- Deficit in GWs!

$$\Delta M \approx 3\ M_\odot$$
$$\approx 5.4 \times 10^{54}\ \mathrm{erg}$$
$$L_{\rm max} \approx 3.6 \times 10^{56}\ \mathrm{erg/s}$$



Abbott et al 1602.03840

GW150914: BH parameters

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

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

  $$\chi_1 = \frac{|\boldsymbol{S}_1|}{m_1^2} < 0.7\,, \quad \chi_2 = \frac{|\boldsymbol{S}_2|}{m_2^2} < 0.9$$

  $$\chi_{\rm fin} = 0.67^{+0.05}_{-0.07}$$

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

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

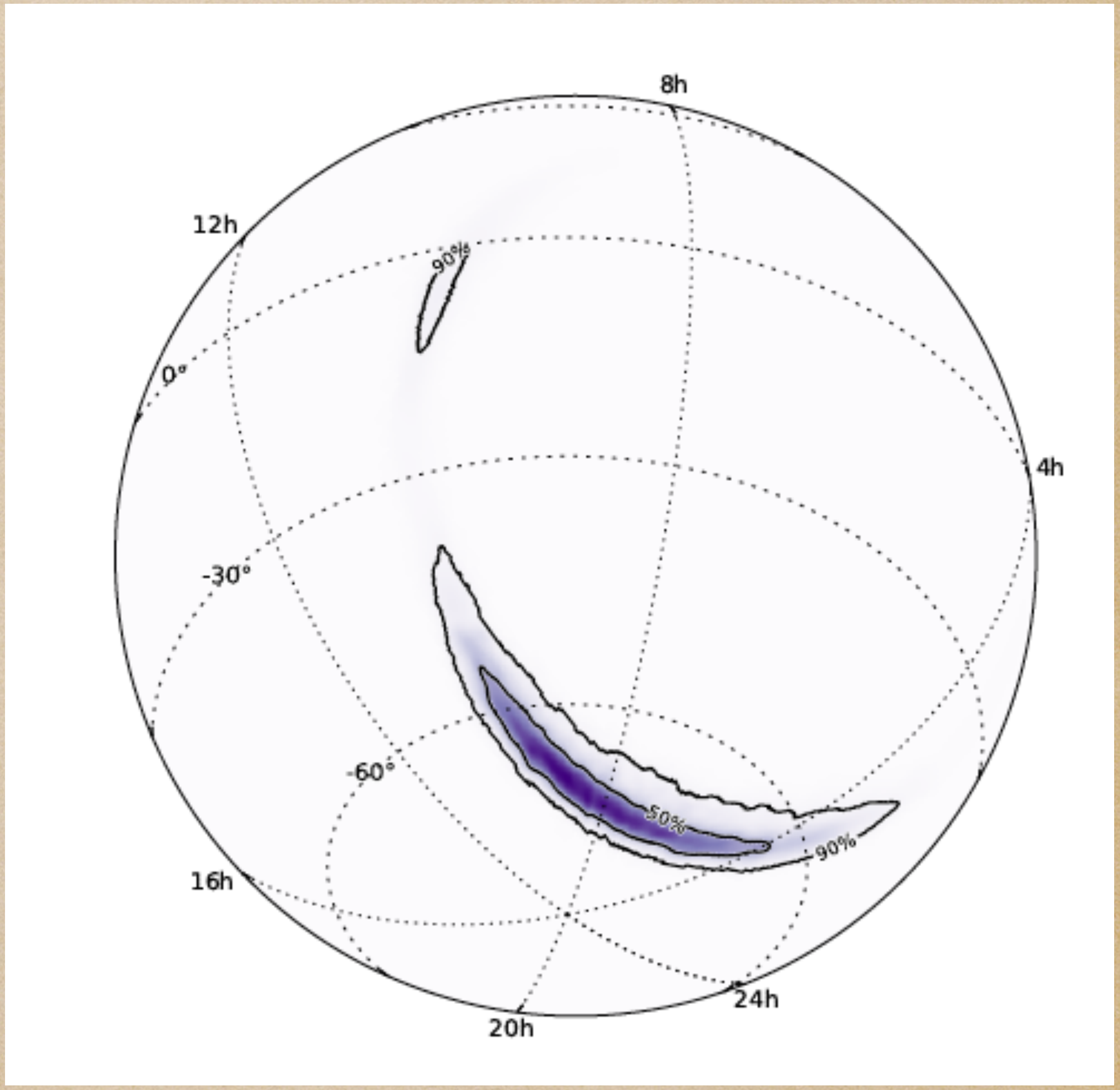
GW150914: Sky location

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

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

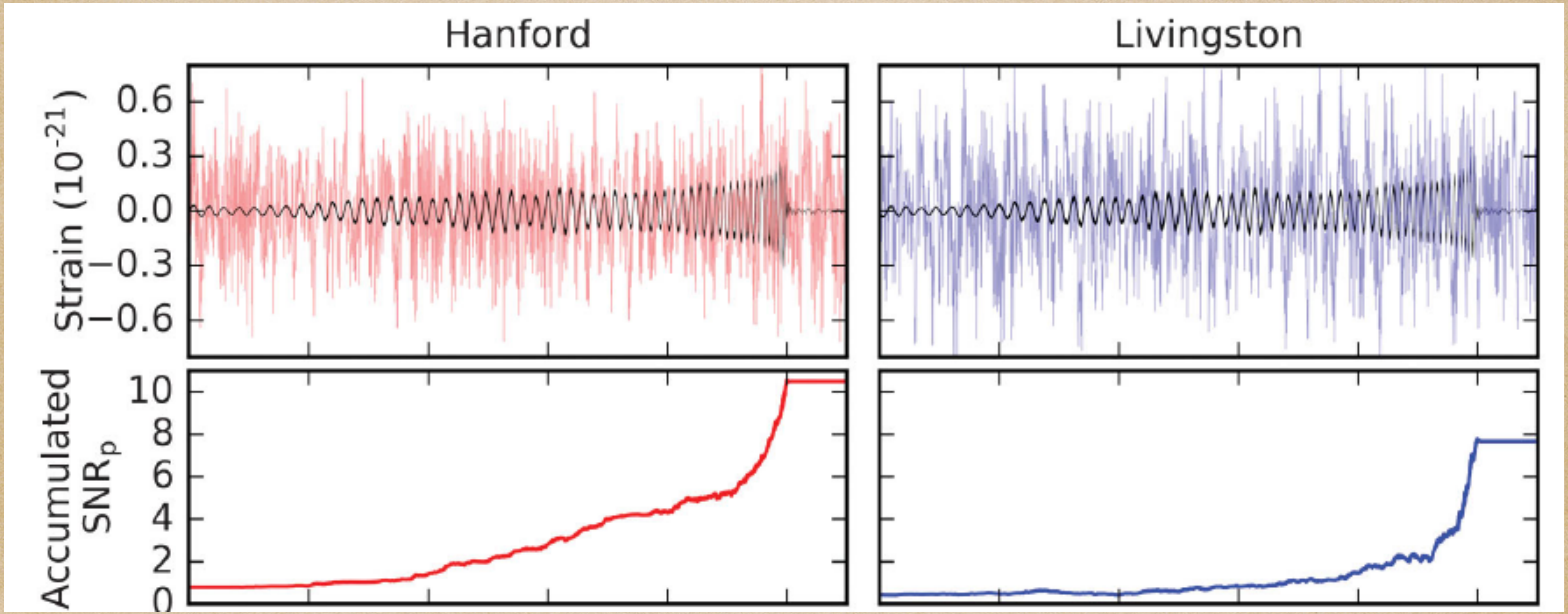
  Southern hemisphere
- To improve with

  Virgo, KAGRA, LIGO India



Abbott et al 1602.03840

GW151226: The signal



Abbott et al 1606.04855

- Filtered by $30 - 600\ \mathrm{Hz}$ band pass
- Duration $\sim 1\ \mathrm{s}$; ~ 55 orbits; $f \approx 35 \ldots 450\ \mathrm{Hz}$

GW151226: BH masses

- Source frame
- 2 searches

Abbott et al. 1606.04855

$$m_1 = 14.2^{+8.3}_{-3.7}\ M_\odot$$

$$m_2 = 7.5^{+2.3}_{-2.3}\ M_\odot$$

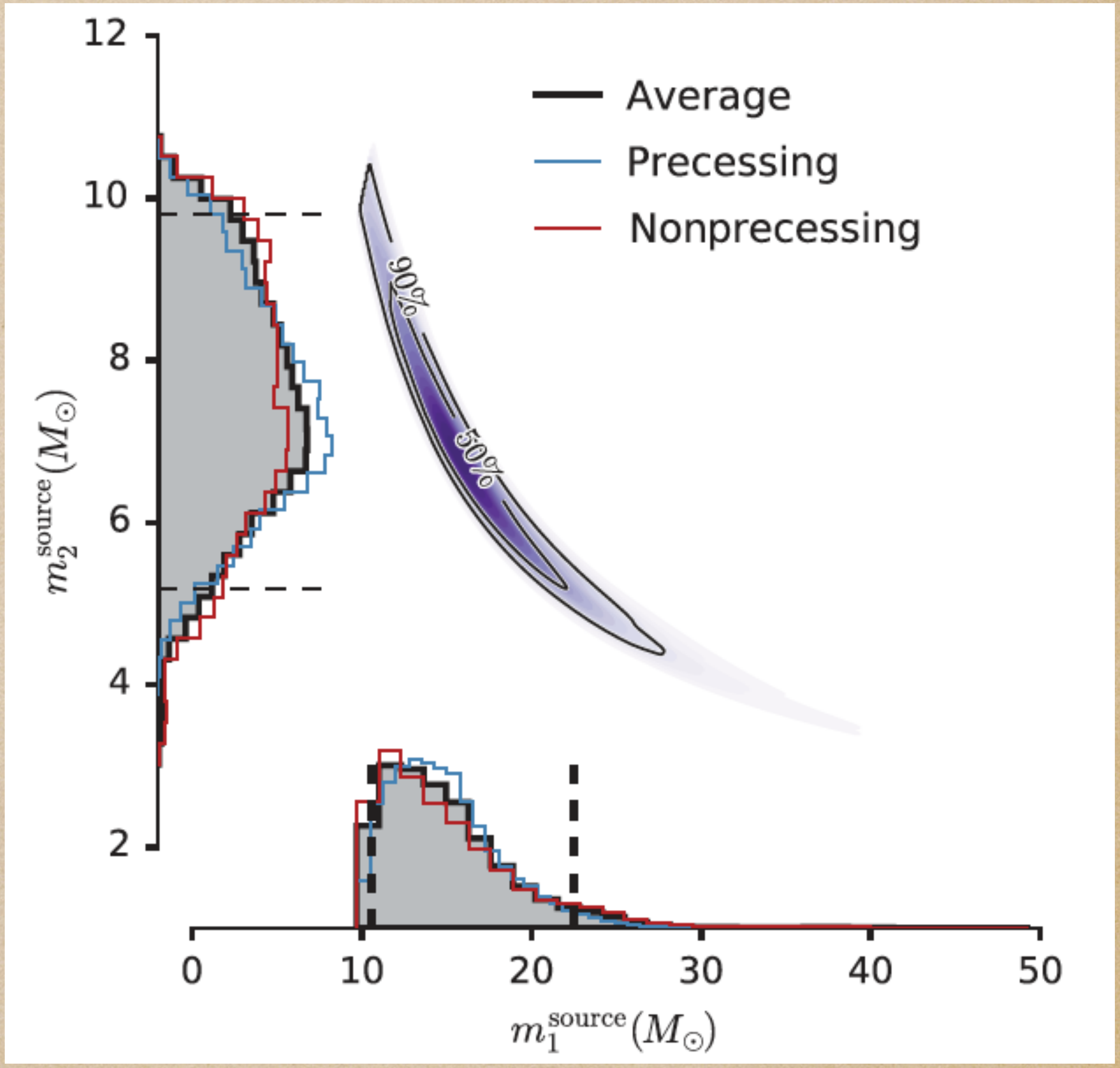
$$M_{\rm fin} = 20.8^{+6.1}_{-1.7}\ M_\odot$$

- Deficit in GWs!

$$\Delta M \approx 1.0^{+0.1}_{-0.2}\ M_\odot$$

- Spins:

$$\chi_{\rm eff} \sim 0.25\,, \quad \chi_p \sim 0.5$$

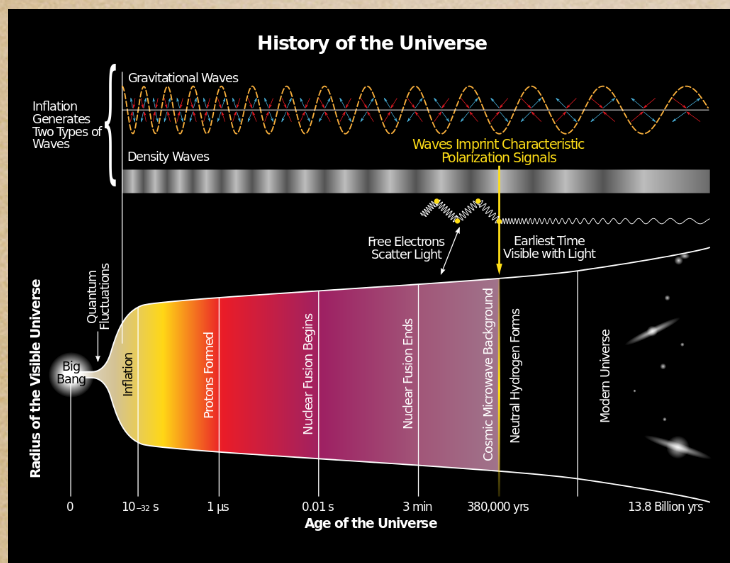


Abbott et al 1606.04855

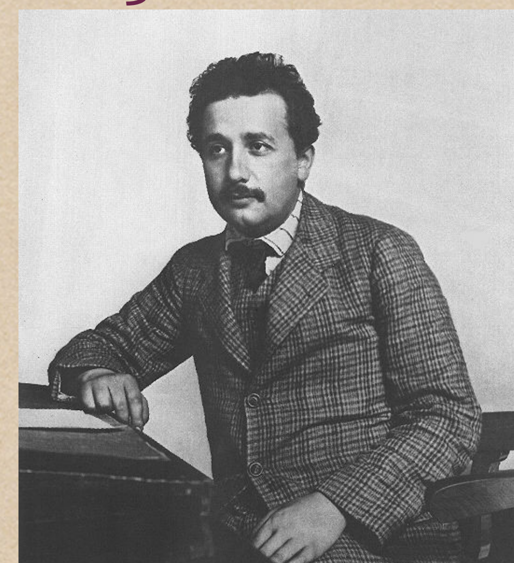
(Selected) Present and future applications

Overview

Early Universe

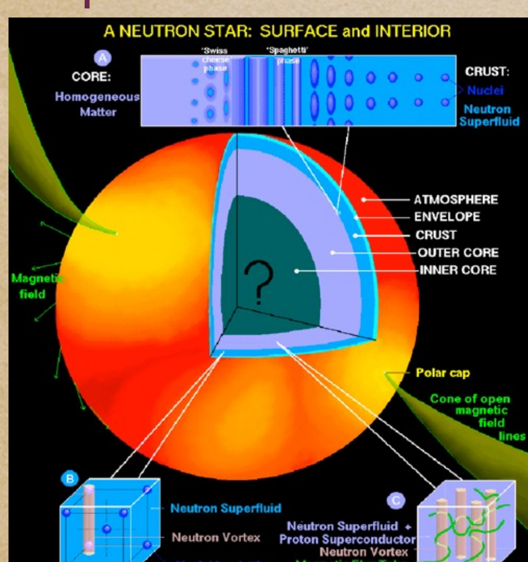


Testing Einstein's theory



Galaxy history

Equation of state

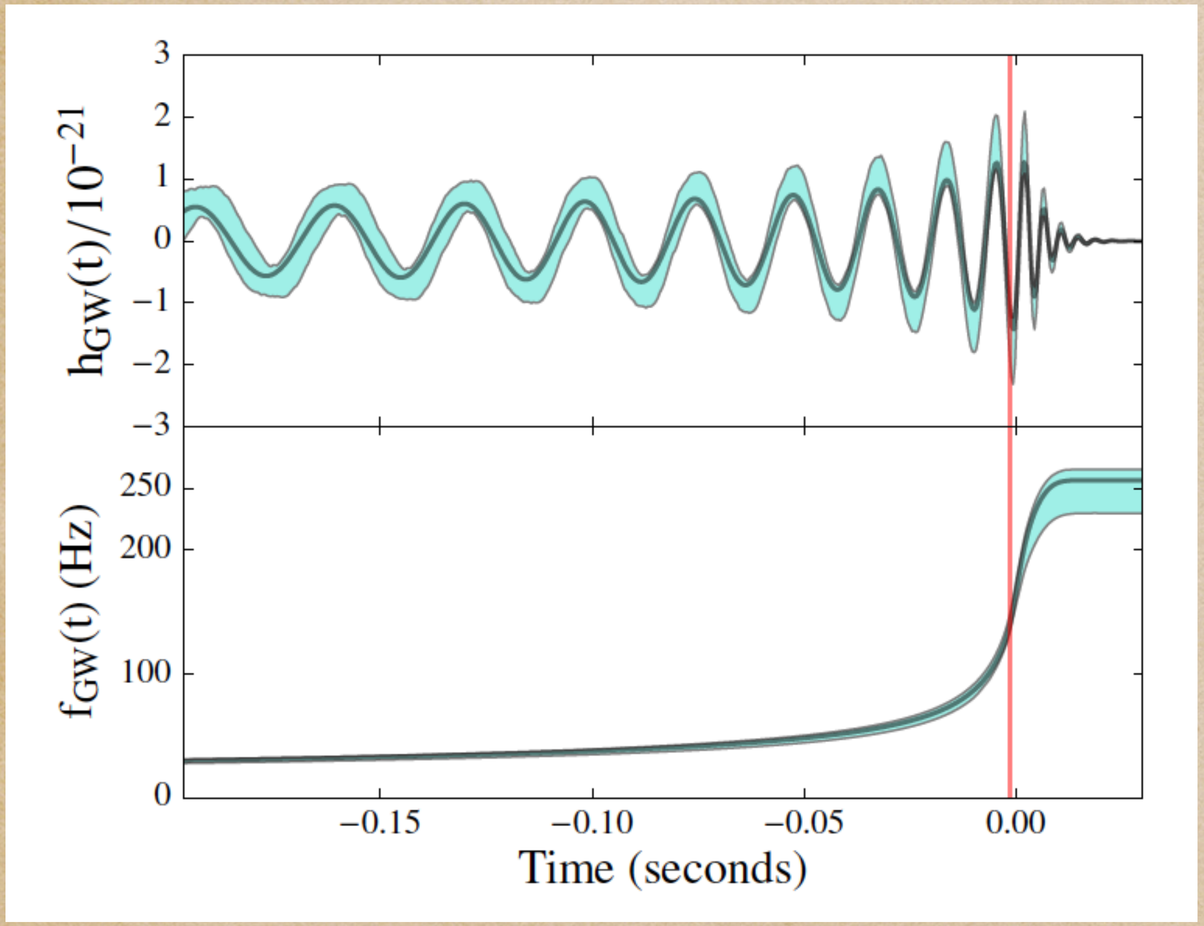


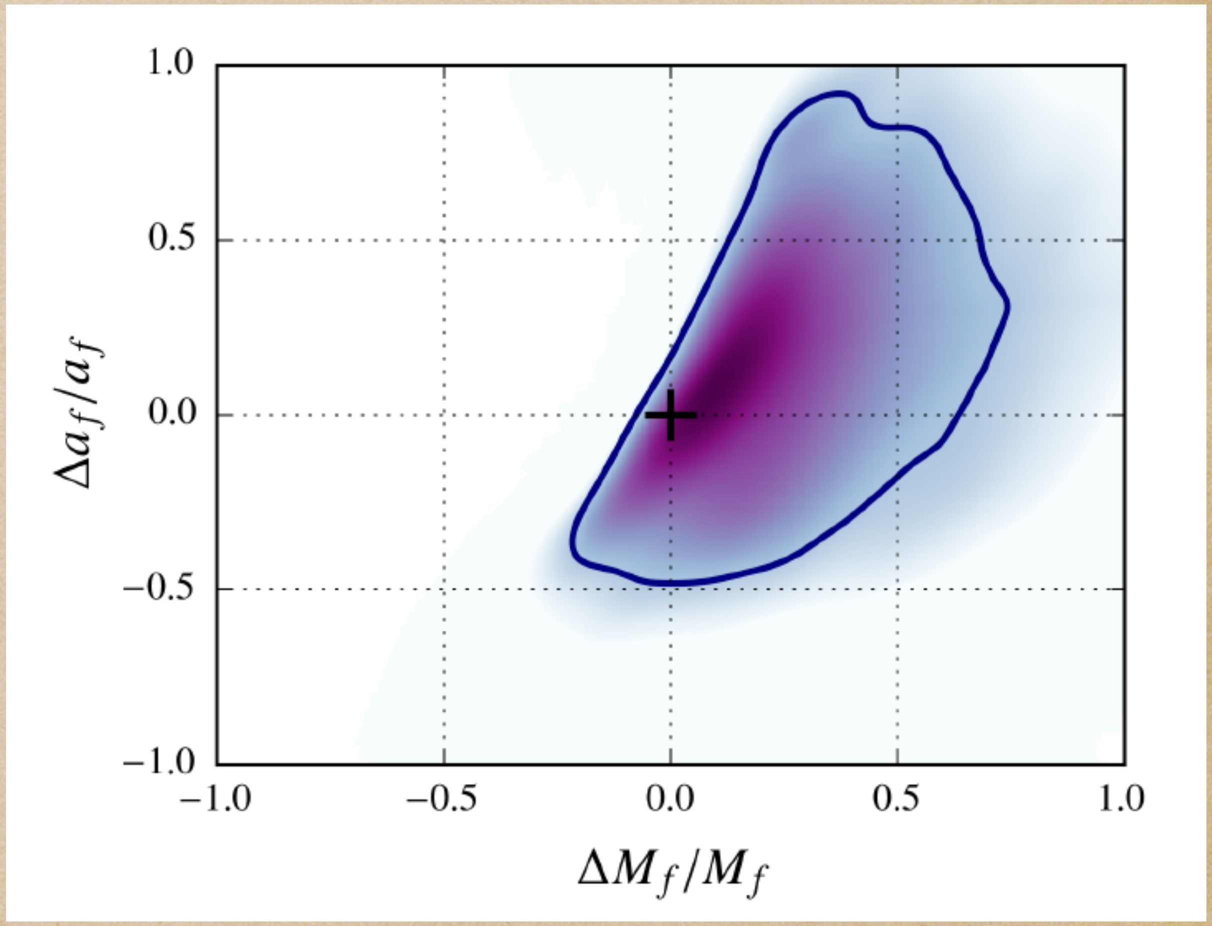
BH populations

The unknown…

Testing GR with GW150914: Consistency

- Measure $M_\mathrm{f},\ a_\mathrm{f}$ using only-inspiral or post-inspiral
- Results consistent with GR waveform model
- Quality factor from ringdown hard: Little SNR





Abbott et al 1602.03841

Testing GR with GW150914: Graviton mass

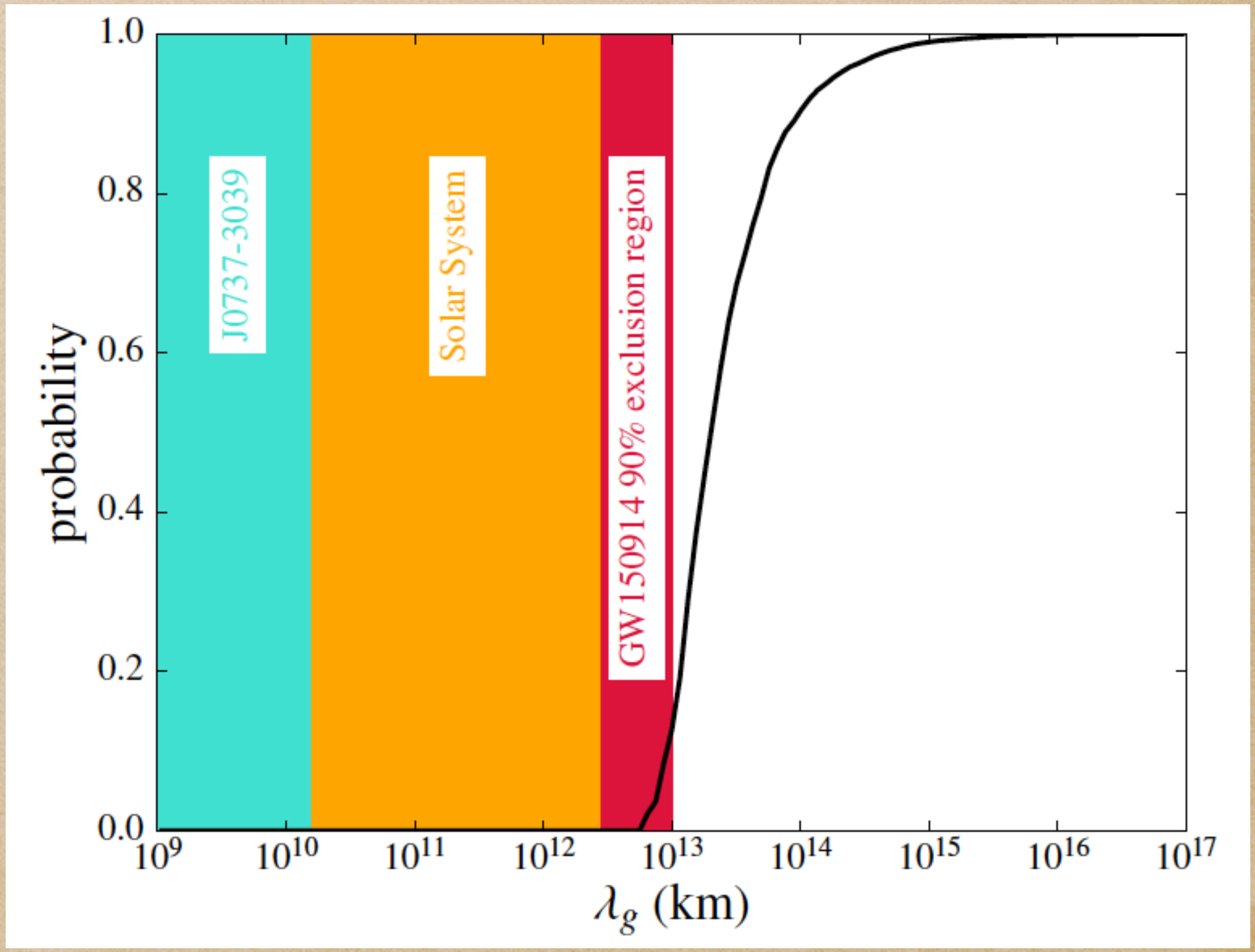
- Phenomenological model
- Massive graviton $\Rightarrow$ Compton wavelength $\lambda_g = \dfrac{h}{m_g c}$
- Dispersion relation: $\dfrac{v_g^2}{c^2} = 1 - \dfrac{h^2 c^2}{\lambda_g^2 E^2}$
- $\Rightarrow$ Quasi-1PN phase term

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

Will 1998 PRD

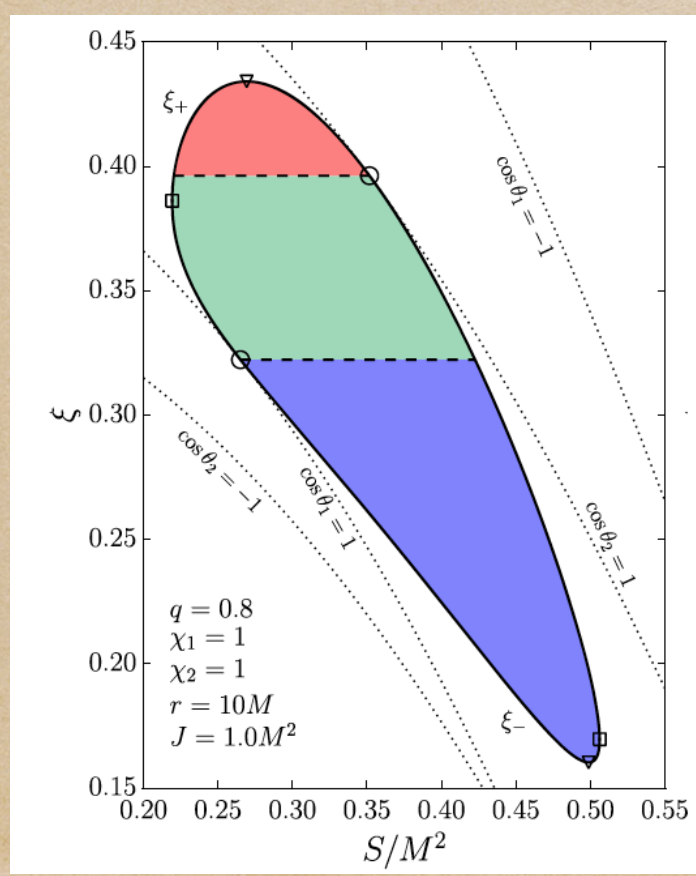
$$\boxed{m_g \le 1.2 \times 10^{-22}\ \mathrm{eV}/c^2}$$

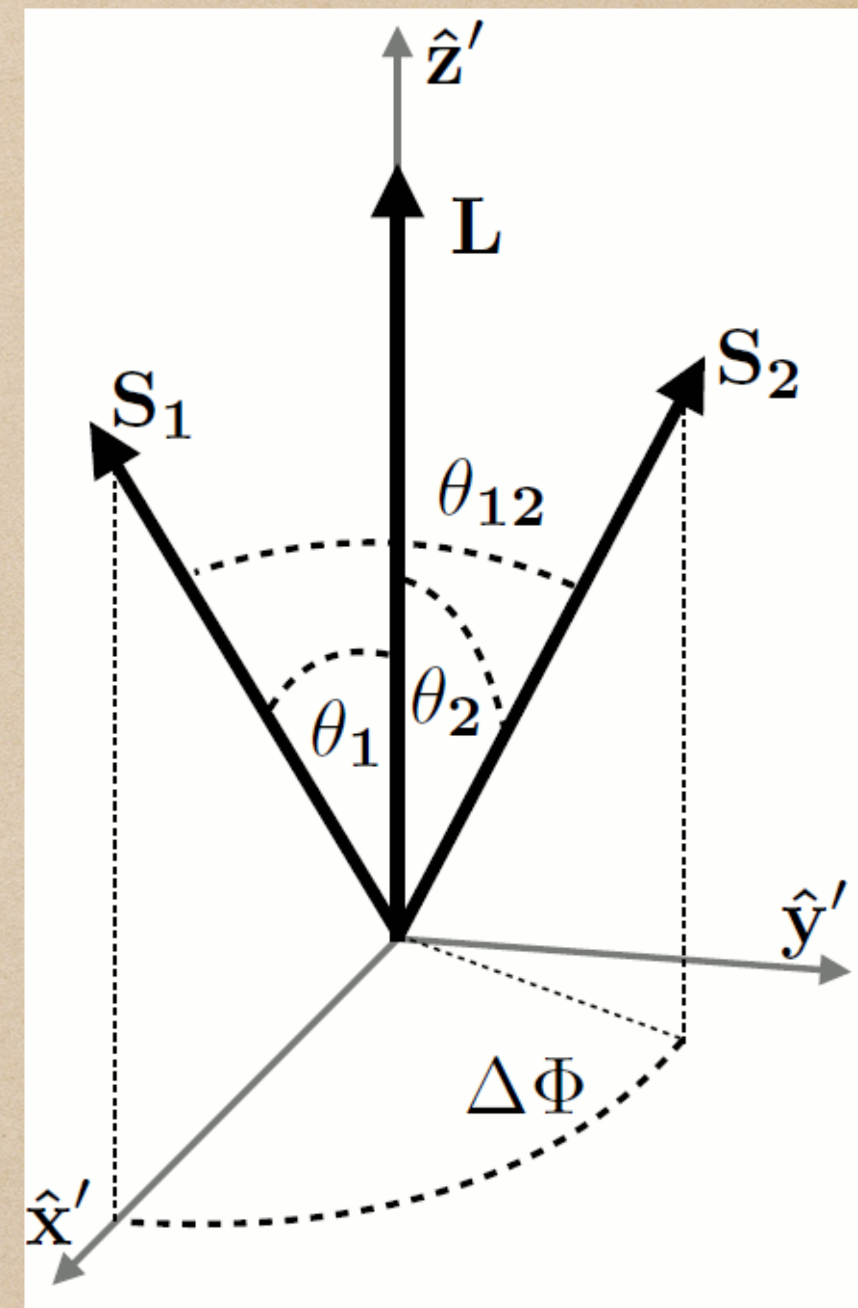
Abbott et al 1602.03841



Morphologies and phase transitions in BHBs

- Consider spin precessing binaries in PN
- 3 morphologies
  - $\Delta\Phi$ librates about 0
  - $\Delta\Phi$ librates about π
  - Circulating $\Delta\Phi \in [-\pi, \pi]$
- Morphology can change during inspiral

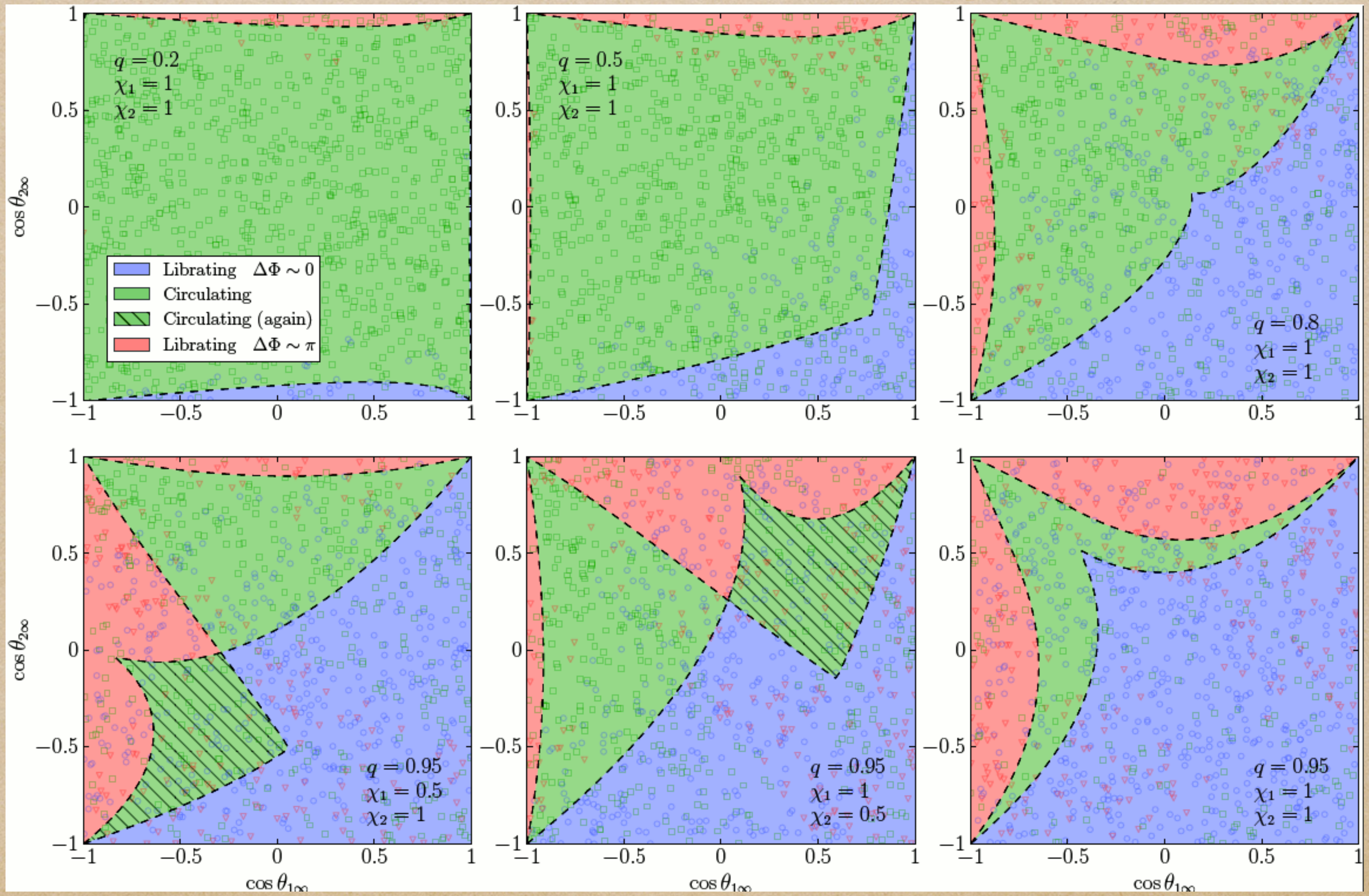




Kesden et al 2015 PRL, Gerosa et al 2015 PRD

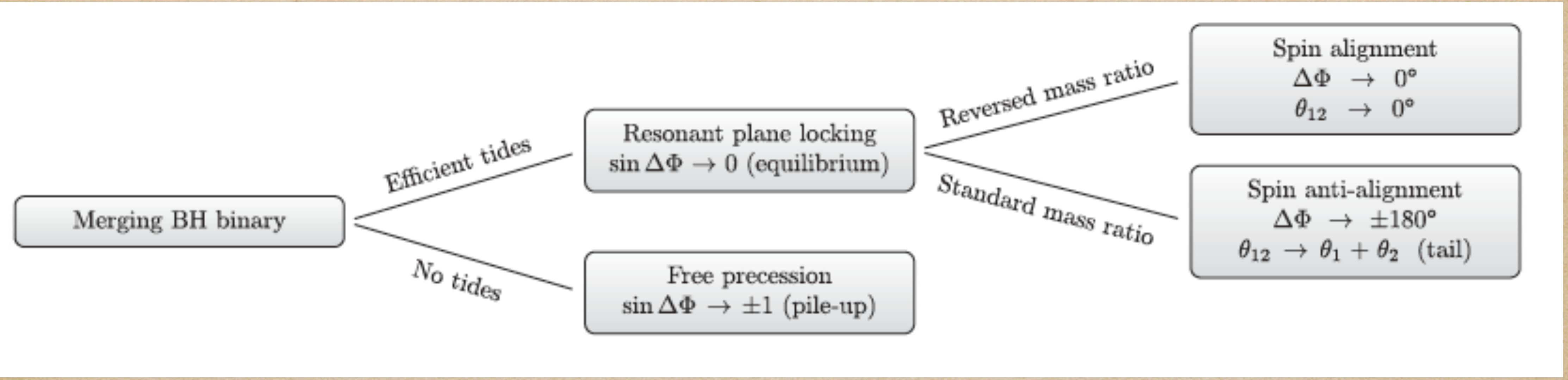
Morphologies and phase transitions in BHBs

- The morphology is closely related to the spin inclination at $r \to \infty$
- Binary formation leaves a memory on the morphology



A simple model for BH binary formation

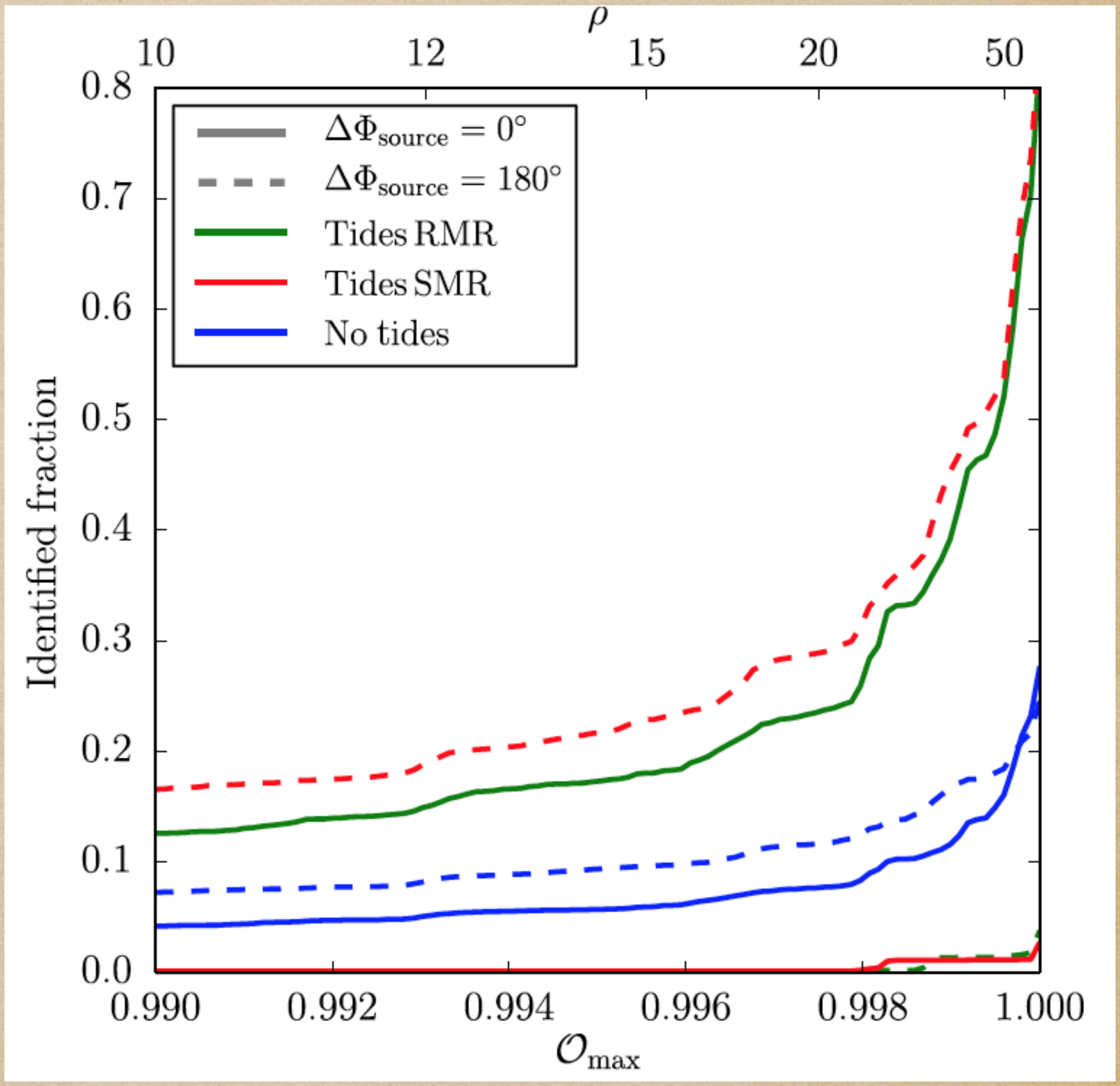
- Two massive stars in orbit
- Mass transfer may reverse mass ratio
- Initially more massive star goes supernova $\rightarrow$ kick
- Tidal interaction may align spin with $\boldsymbol{L}$
- 2nd supernova $\rightarrow$ kick
- GW driven inspiral $\rightarrow$ preference of one morphology



Gerosa et al 2013 PRD

A simple model for BH binary formation

- Can we measure this?
- Inject binary population including all 3 scenarios
- Identify morphology; does it match expectations?
- Statistically yes!
- Tides + mass reversal $\rightarrow$ prefered $\Delta\Phi \sim 0$
- Tides + mass reversal $\rightarrow$ prefered $\Delta\Phi \sim \pi$
- No tides $\rightarrow$ no prefered libration



Gerosa et al 2014 PRD

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 surprise: BHs heavier than expected
- Parameter estimation requires GW modeling
- Applications: Test GR, BH census, History of universe, EOS,…
- A new window to the universe reveals interesting things…