The dawn of gravitational-wave astronomy

Ulrich Sperhake

DAMTP, University of Cambridge

CERN Theory Seminar
08 Jun 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

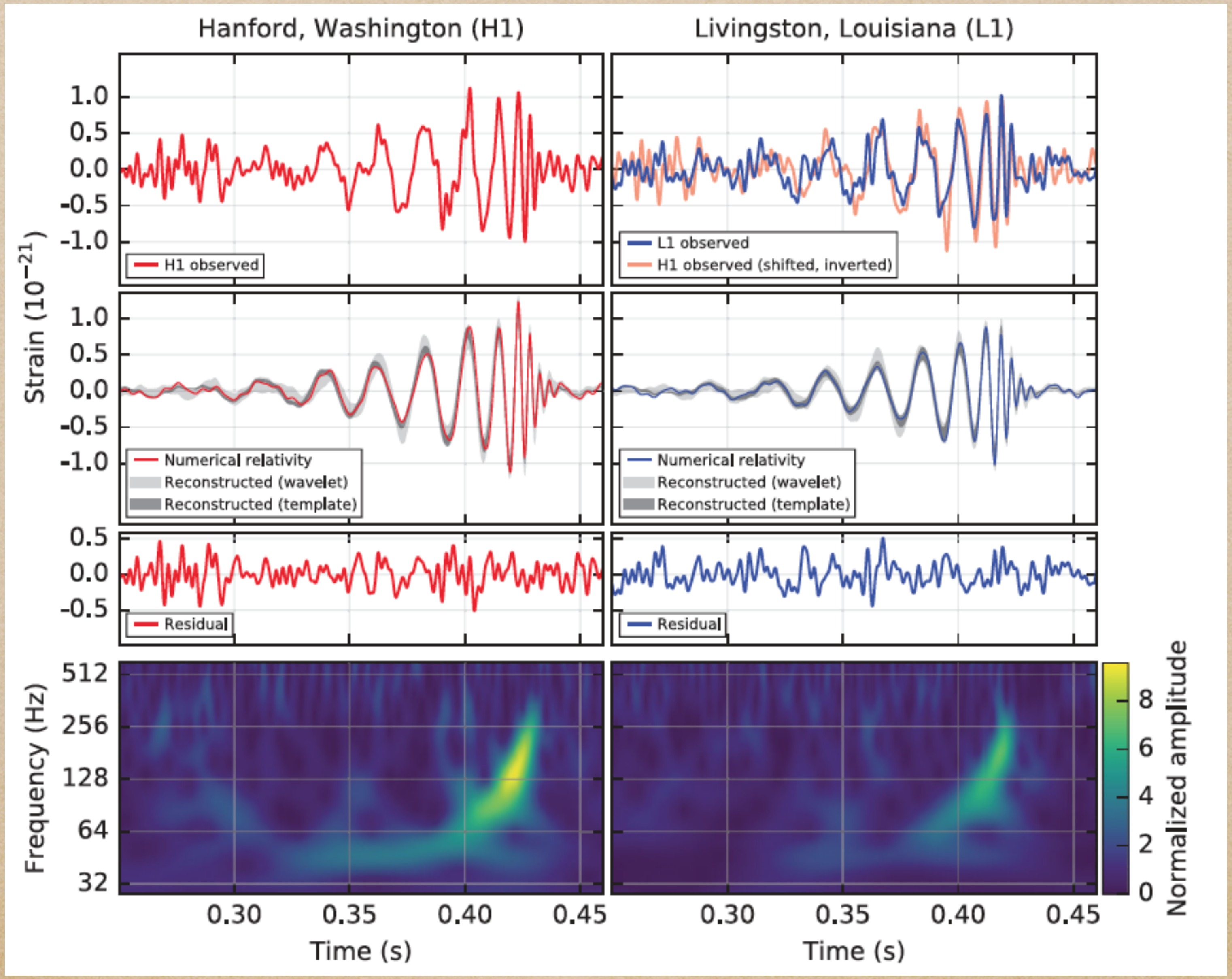
- Unusual news headlines on 11/12 February 2016
- First direct detection of gravitational waves: GW150914

So, what happened?

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

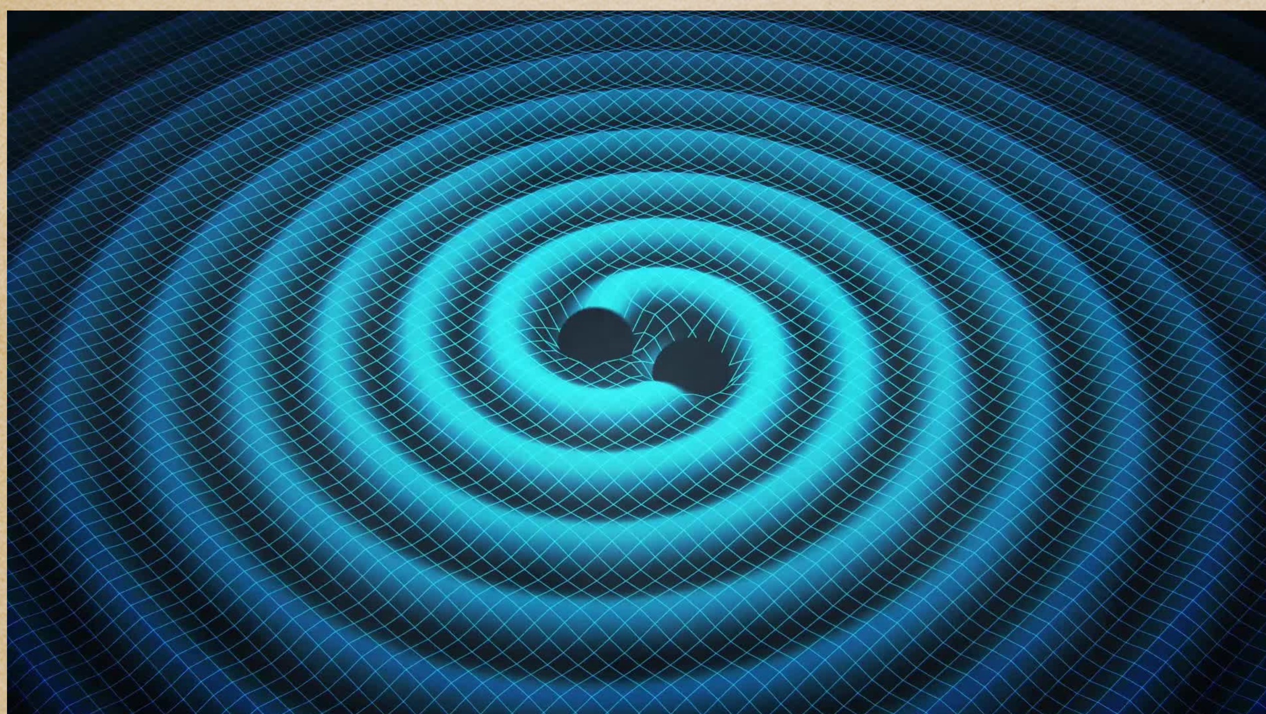
  Abbott et al. PRL 2016, Abbott et al. 1606.01210

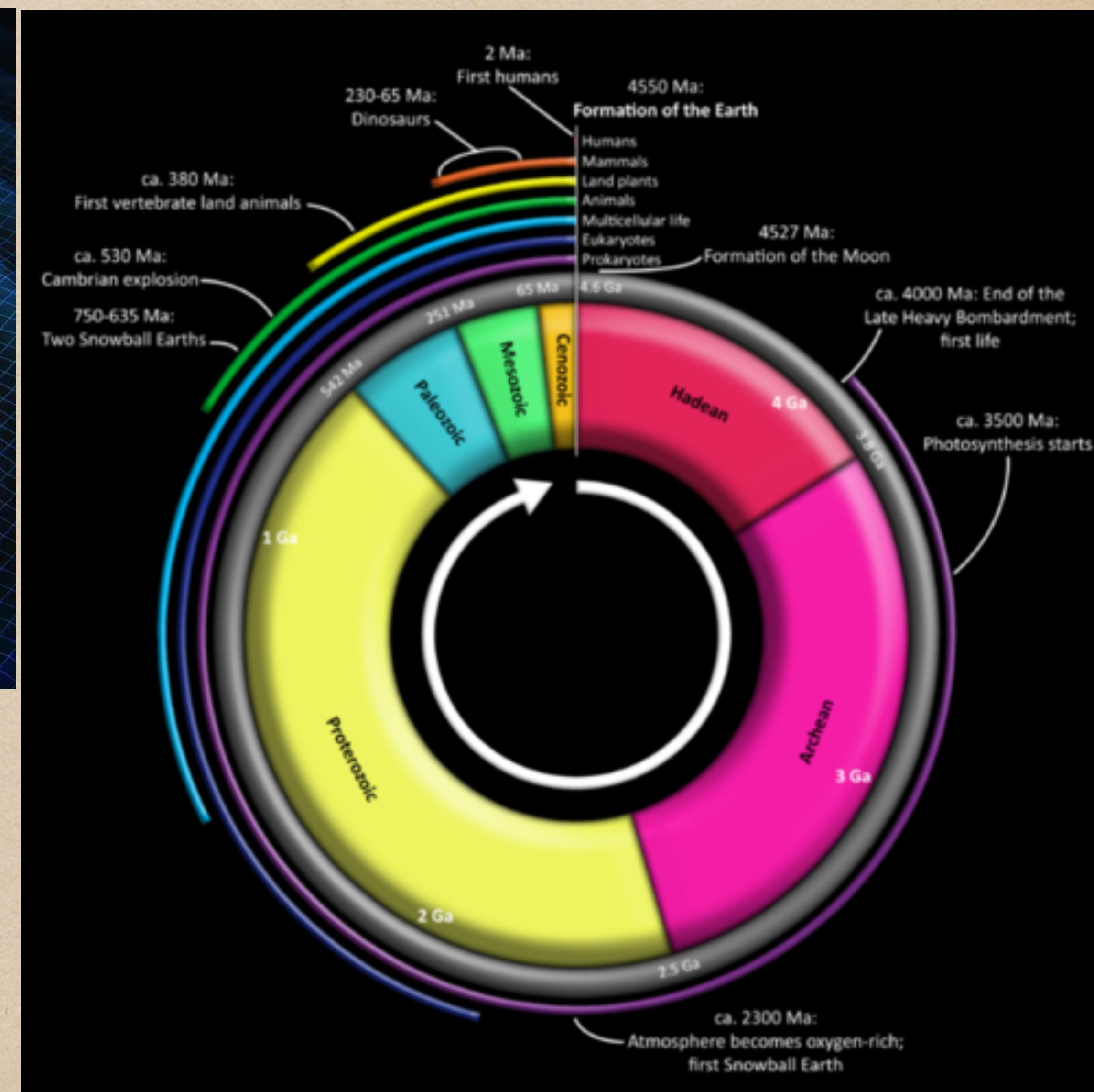
- BBH inspiral, merger and ringdown: $m_1 = 35^{+5}_{-3}\, m_\odot\,,\quad m_2 = 30^{+3}_{-4}\, M_\odot$



What really happened…

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





- Deep Precambrian

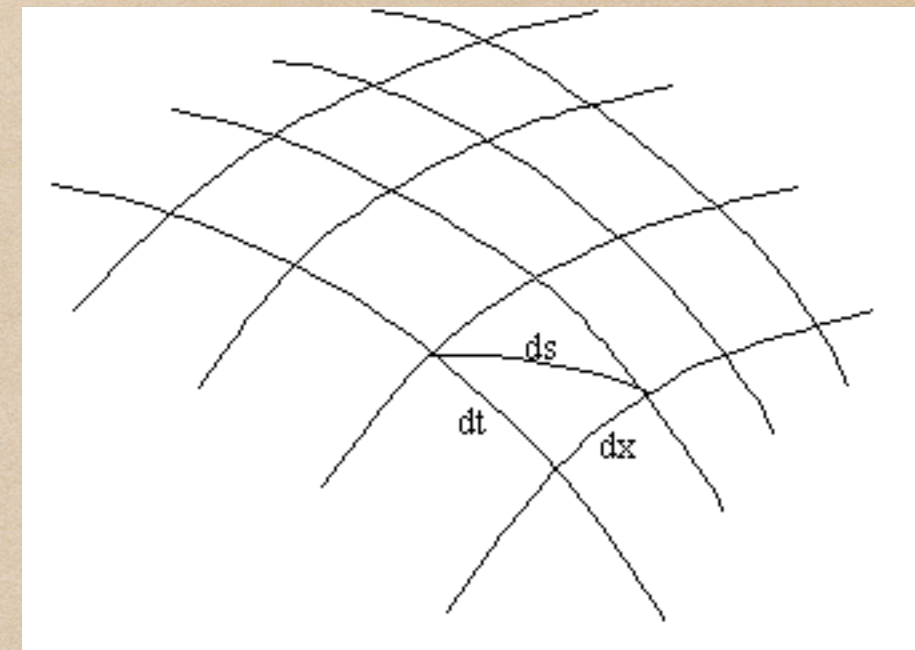
Overview

- 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 $x^\mu = \text{const}$ in TT gauge

- Proper separation:

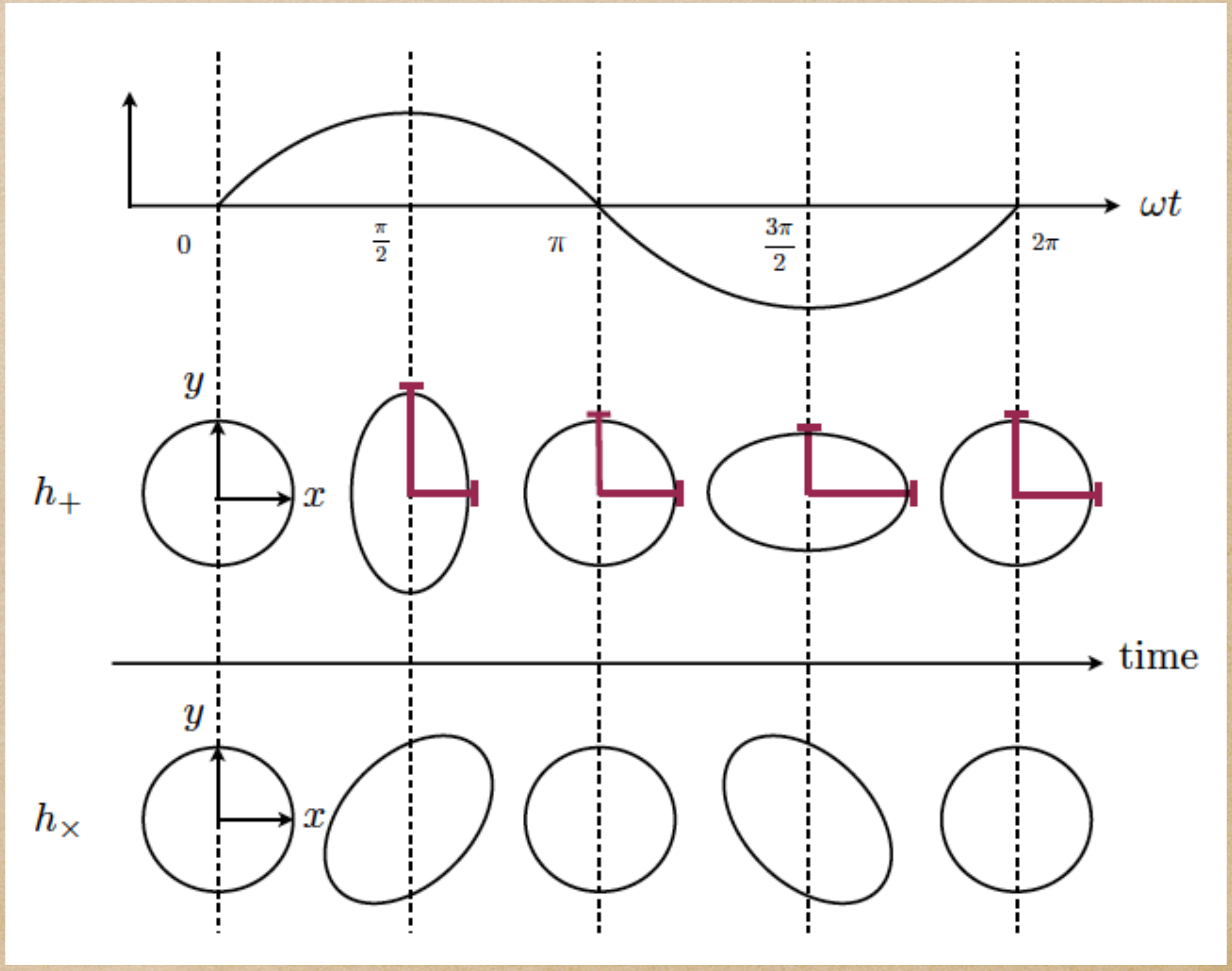
$$ds^2 = -dt^2 + (1+h_+)\,dx^2 + (1-h_+)\,dy^2 + 2h_\times\,dx\,dy + dz^2$$

- Effect on test particles:

  Mirshekari 1308.5240

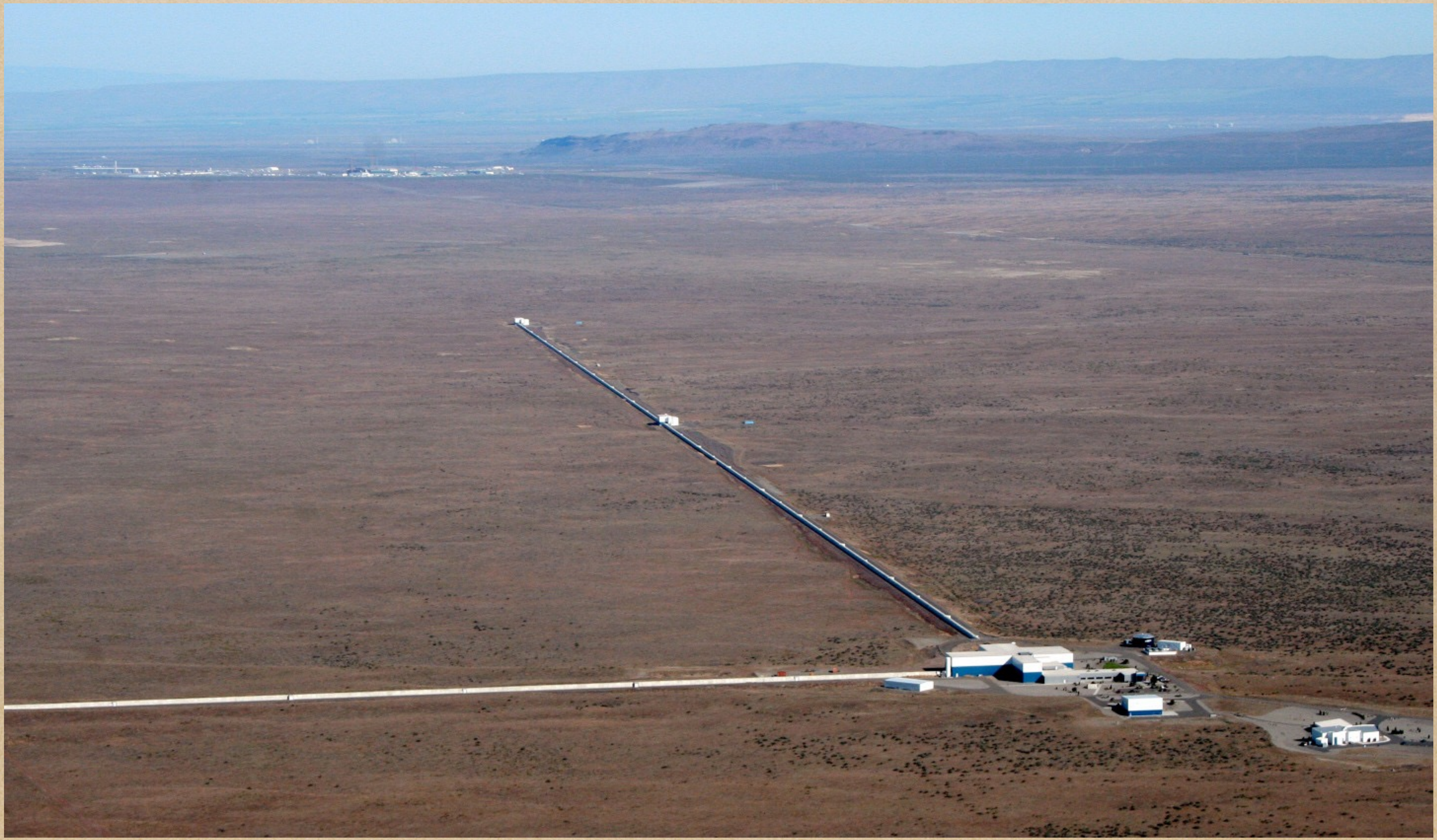
- Debate on physical reality until late 1950s

  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

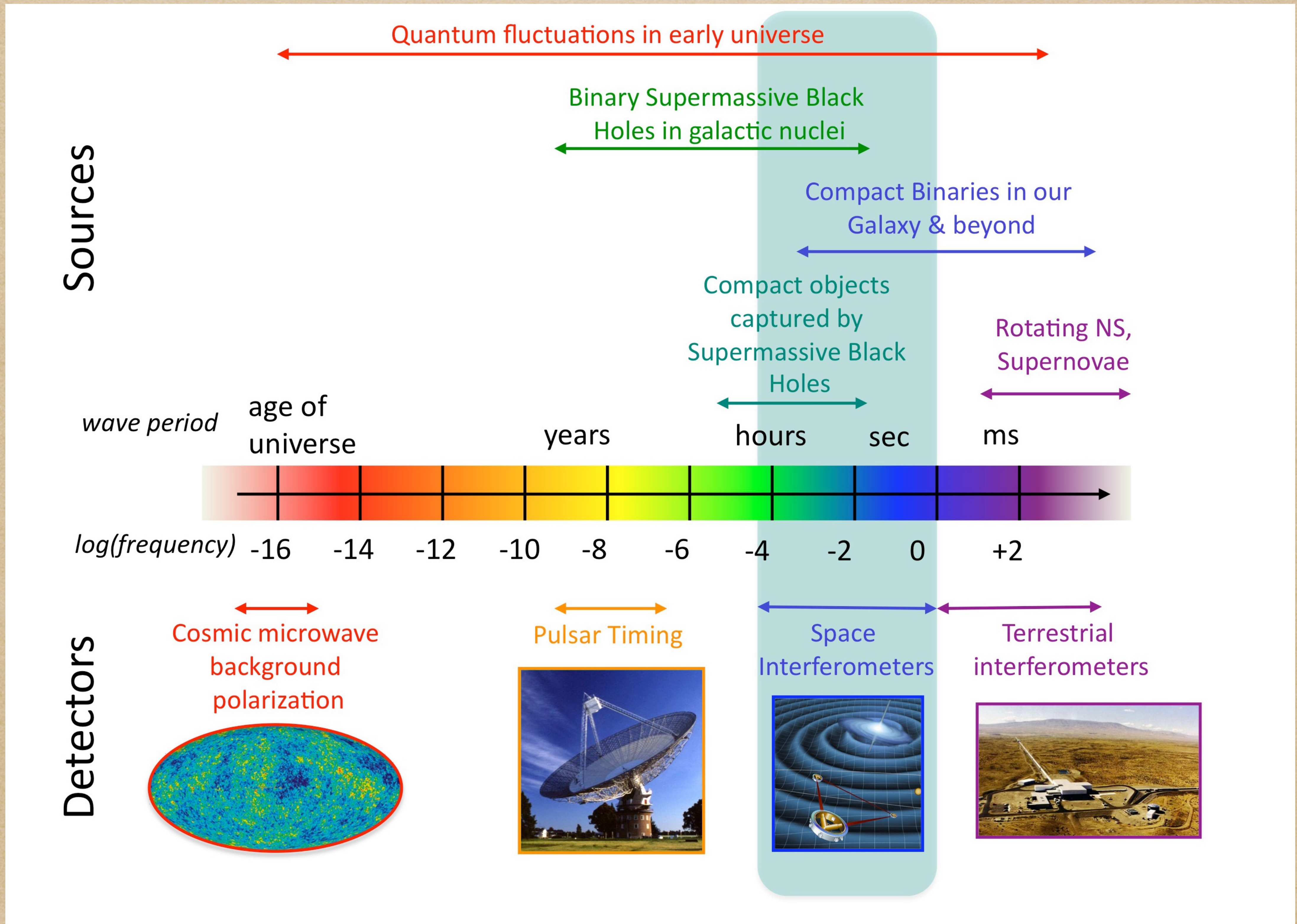
- Source types and detection strategies $\Rightarrow$ 4 regimes

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

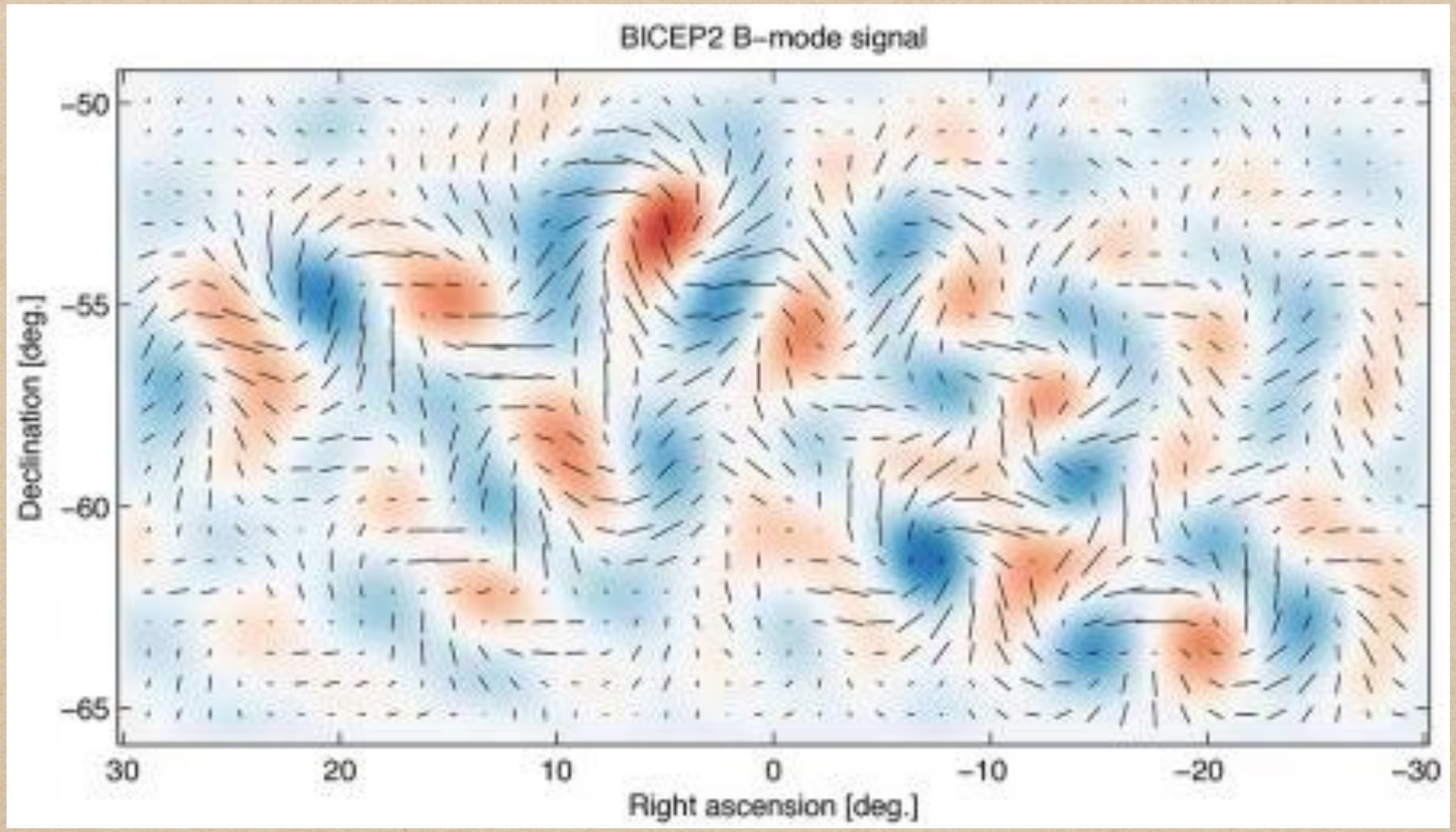
Ultra low:	Fluctuations in the early universe
Very low:	Supermassive BH binaries (high M, z)
Low:	SMBHs, EMRIs, Compact binaries,...
High:	Neutron star / BH binaries, supernovae,...

The gravitational wave spectrum



The ultra low frequency regime

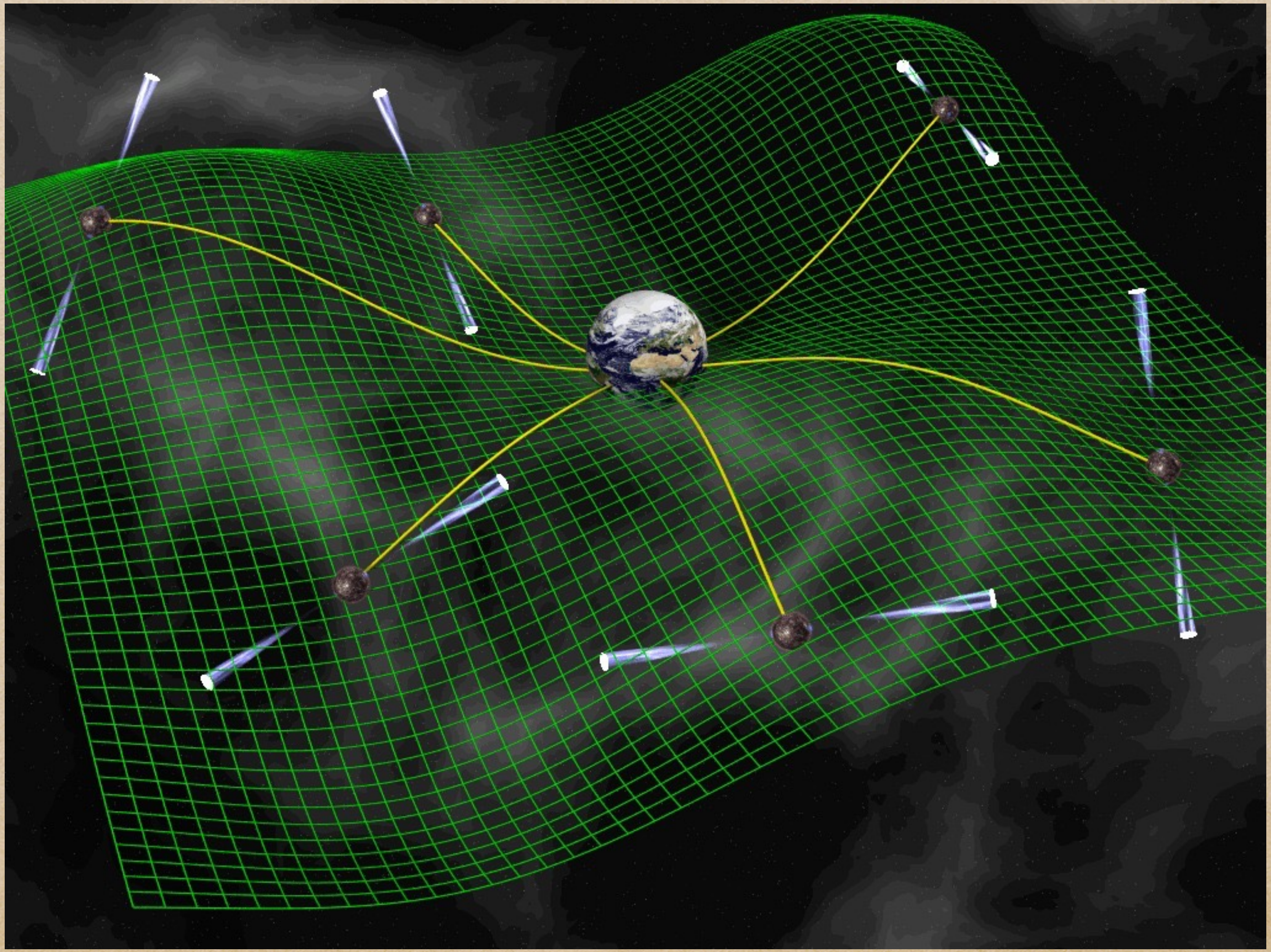
- Wave periods $\sim$ Hubble time
- Primordial GWs $\longrightarrow$ Signature in polarization of CMB
- E.g. BICEP2



- 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

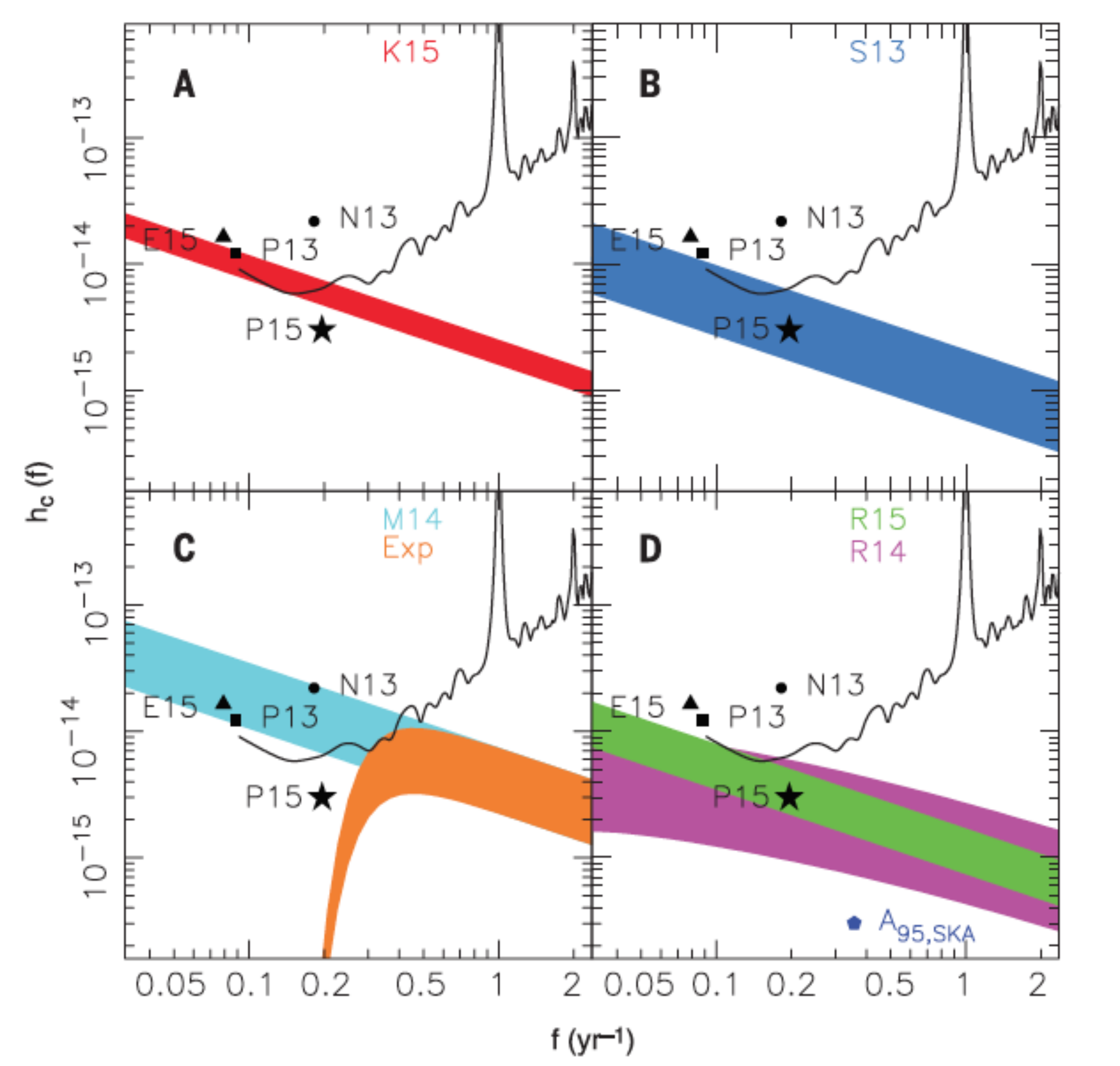
  Binaries stalled

  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
- eLISA: 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

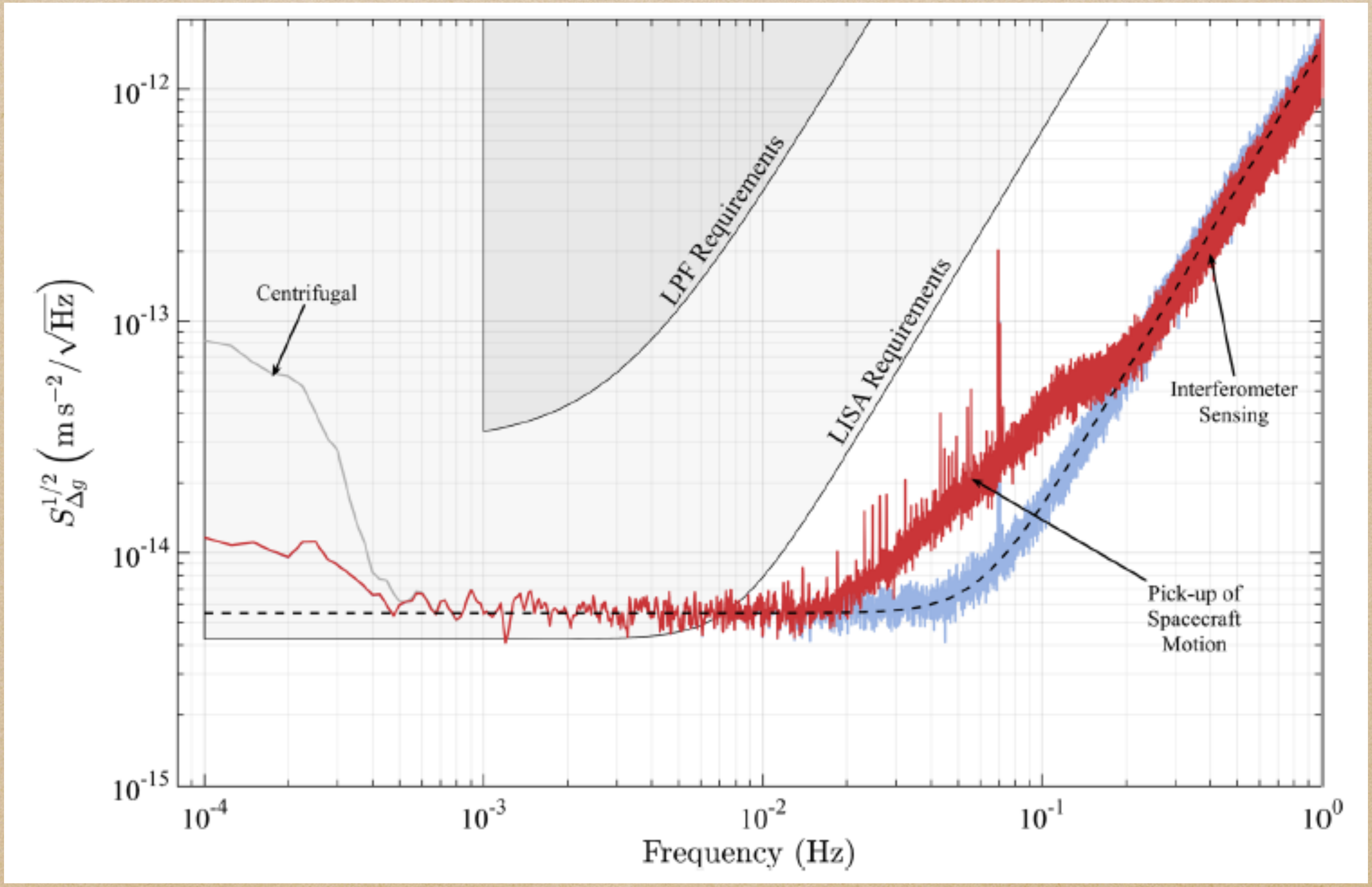
  2 yr vs. 5 yr life span
- Calibration binaries (WDs)
- Outstanding SNR
- LISA Pathfinder: Test mission

  Launched 3 Dec 2015

LISA Pathfinder Latest: 7 Jun 2016

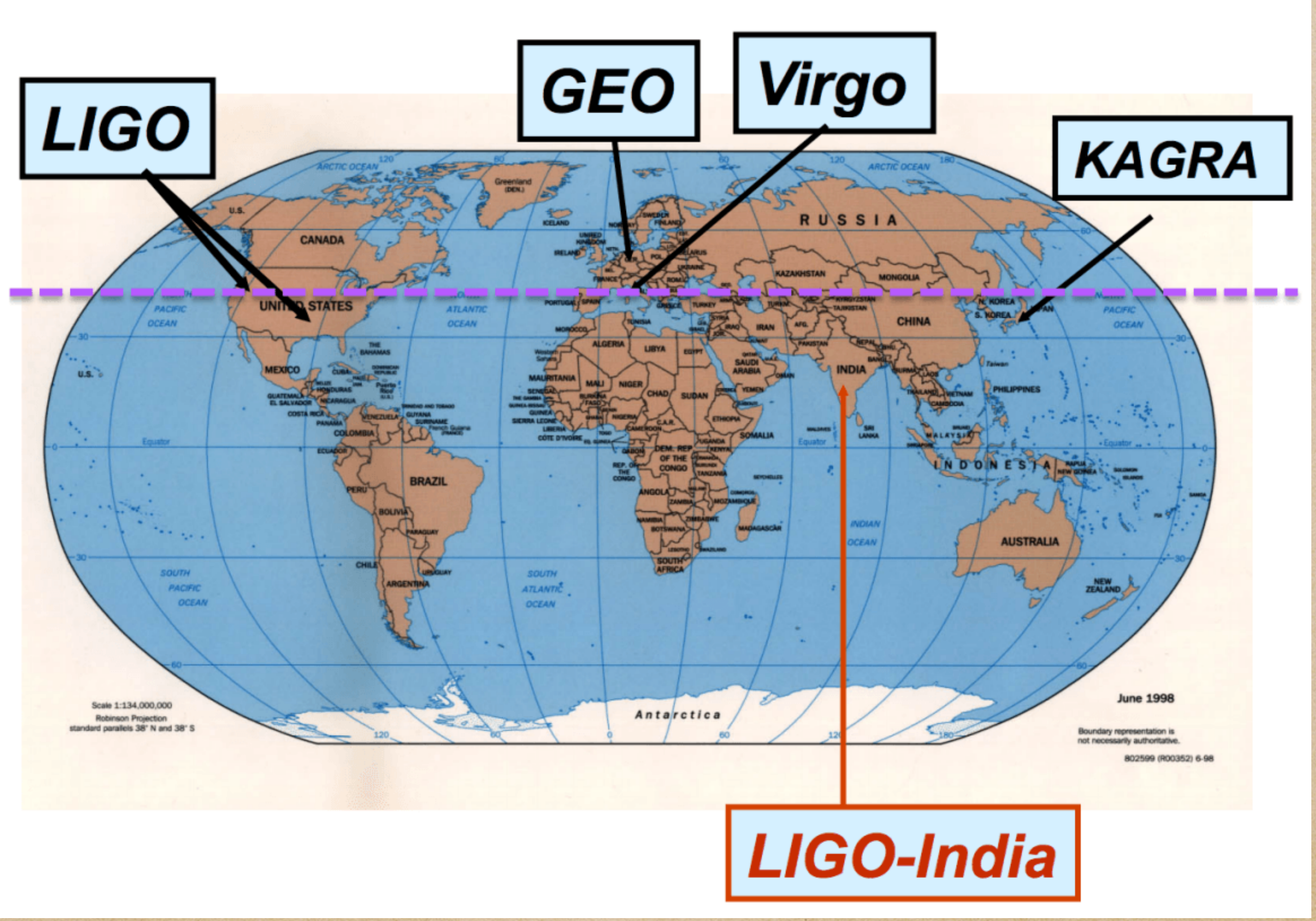
- Noise curve exceeds LISA requirements

Armano et al. PRL (2016)

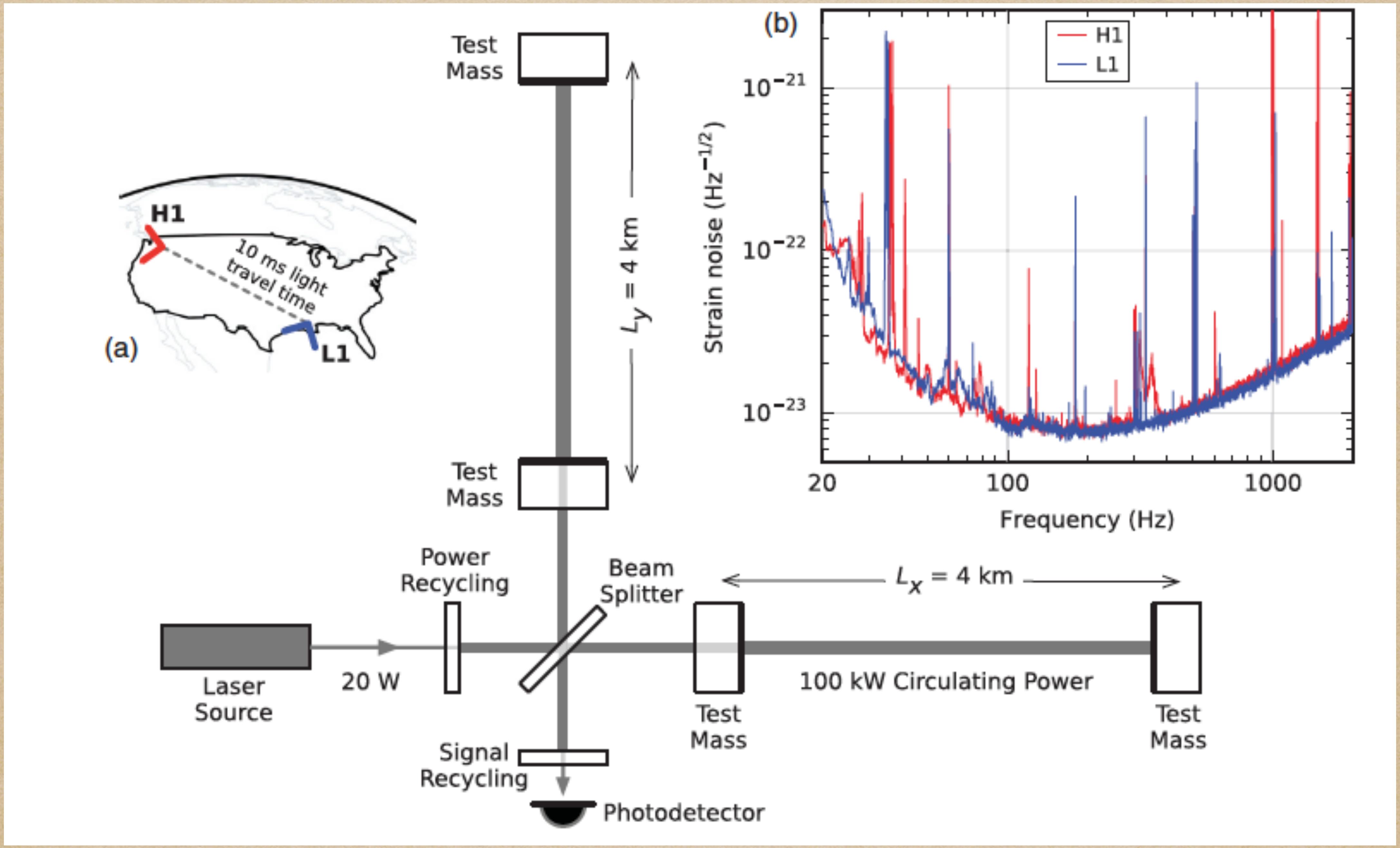


The high frequency regime

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



The interferometer diagram: LIGO

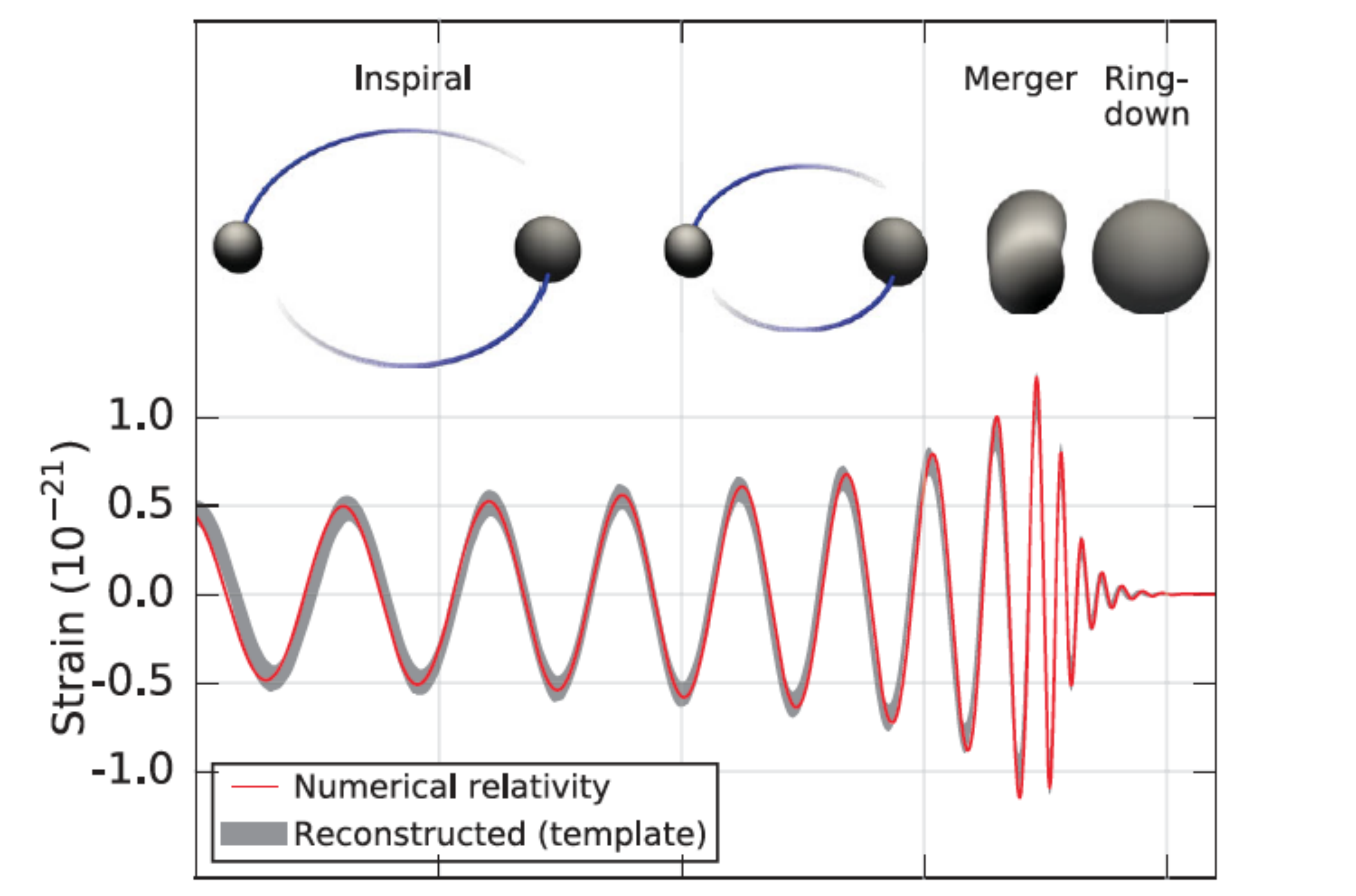


Abbott et al, PRL 116 (2016) 061102

Seismic, thermal, shot noise

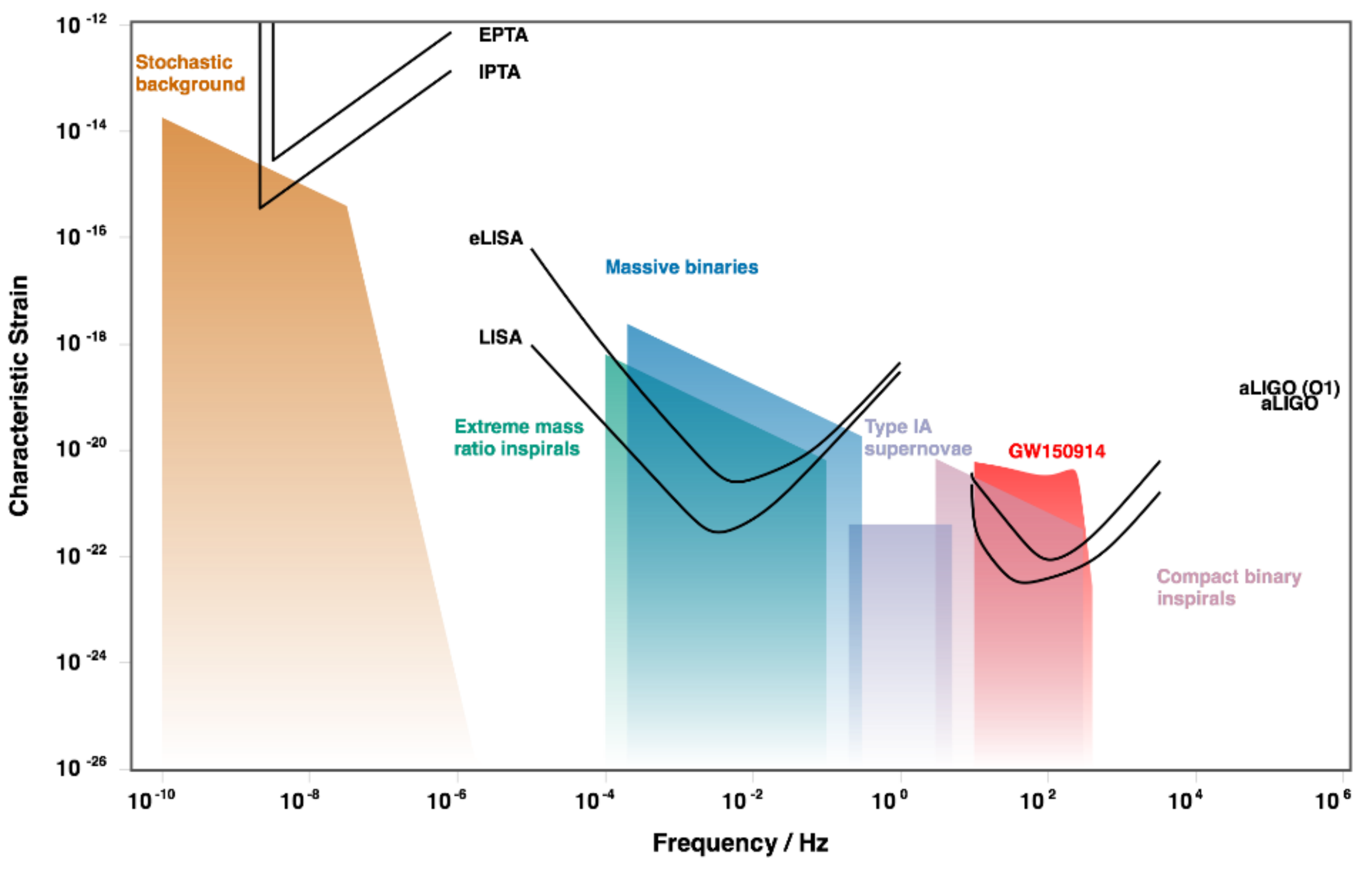
The high frequency regime

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



Abbott et al, PRL 116 (2016) 061102

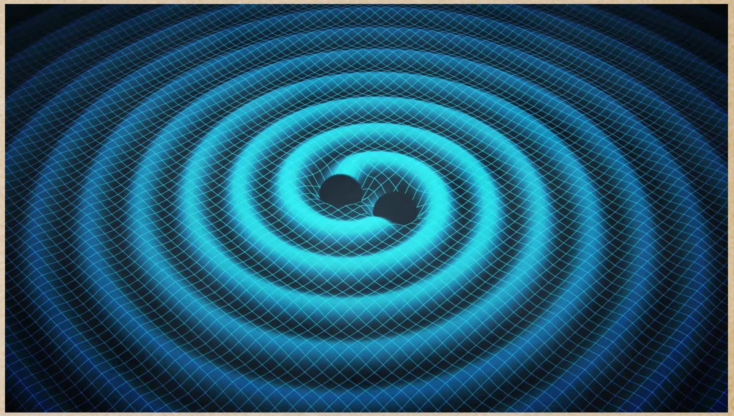
Summary: sensitivity curves



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

Parameter estimation and source modeling

The search for GWs in the data stream



- BH/NS binaries generate ripples in spacetime
- Key difficulty: Tiny effect

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

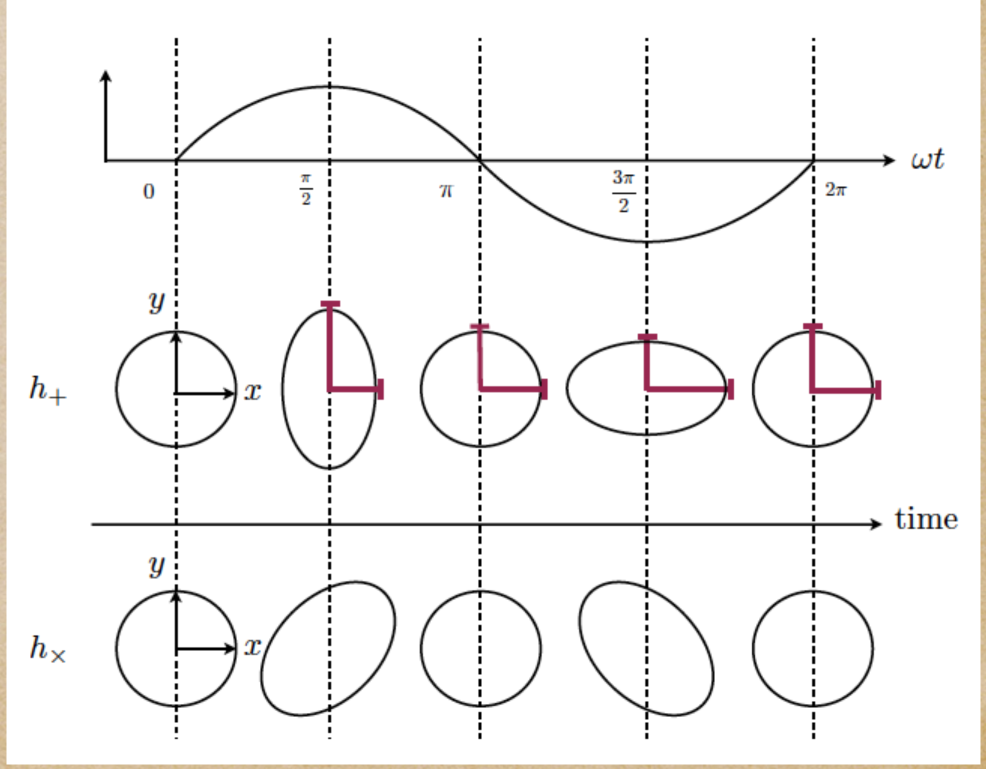
  - Weak effect of matter on geometry
  - GWs carry huge energy but barely interact with anything
  - Induced changes in length: < atomic nucleus / km

- Indirect evidence: 1993 Nobel Prize

  Hulse & Taylor

- Direct detection with LIGO:

  Abbott et al. PRL 2016



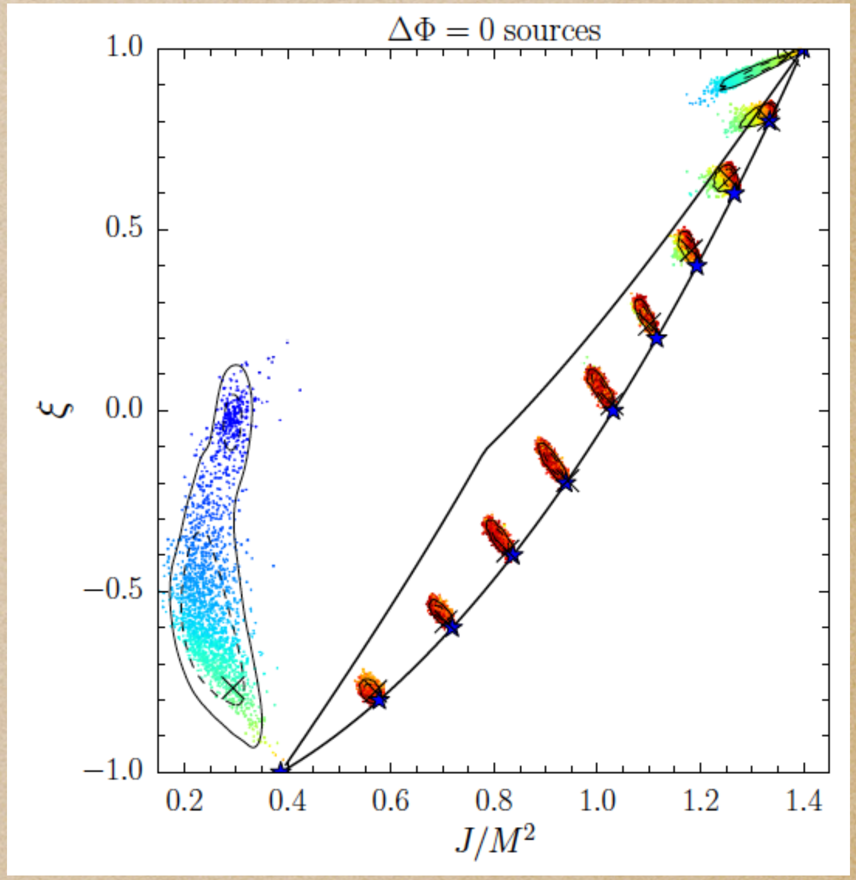
Detection and parameter estimation

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

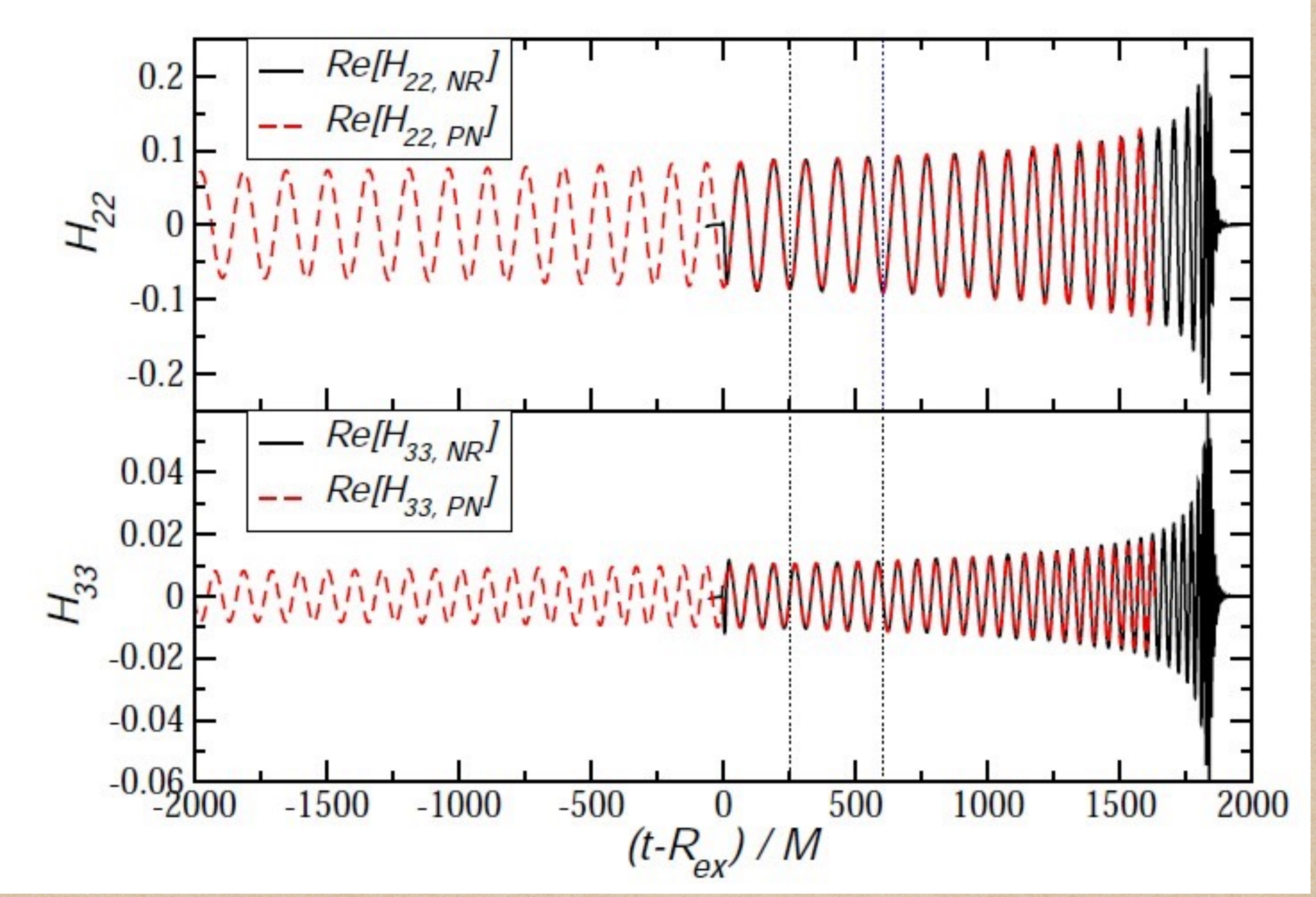
- Key requirement for matched filtering: GW template catalog
- Model black holes in general relativity
  - Post Newtonian theory $\rightarrow$ Inspiral   Blanchet Liv.Rev.Rel. 2006
  - Numerical relativity $\rightarrow$ final orbits, merger

    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

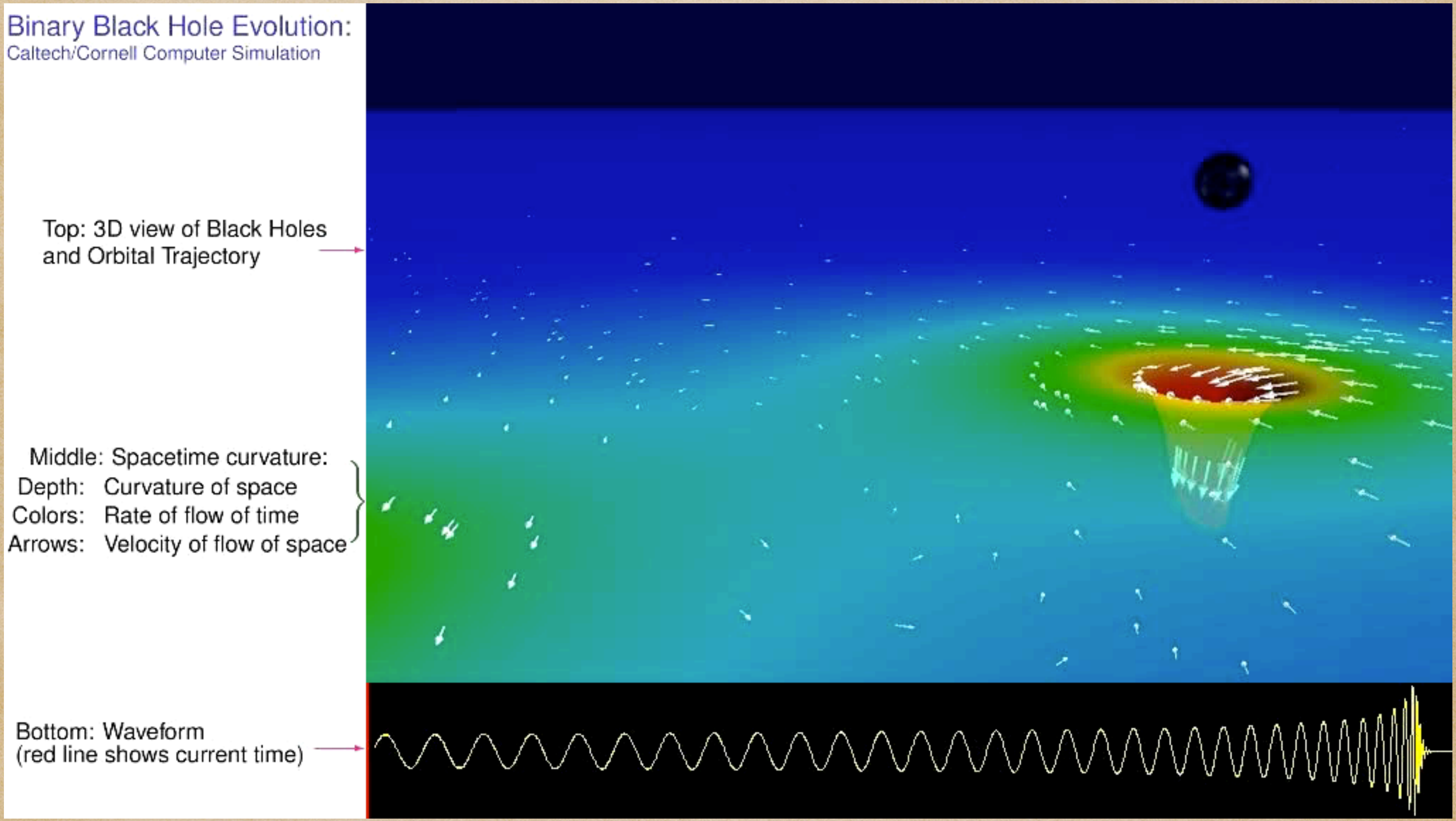
- Stitch together PN and NR waveforms



US et al CQG 2011

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

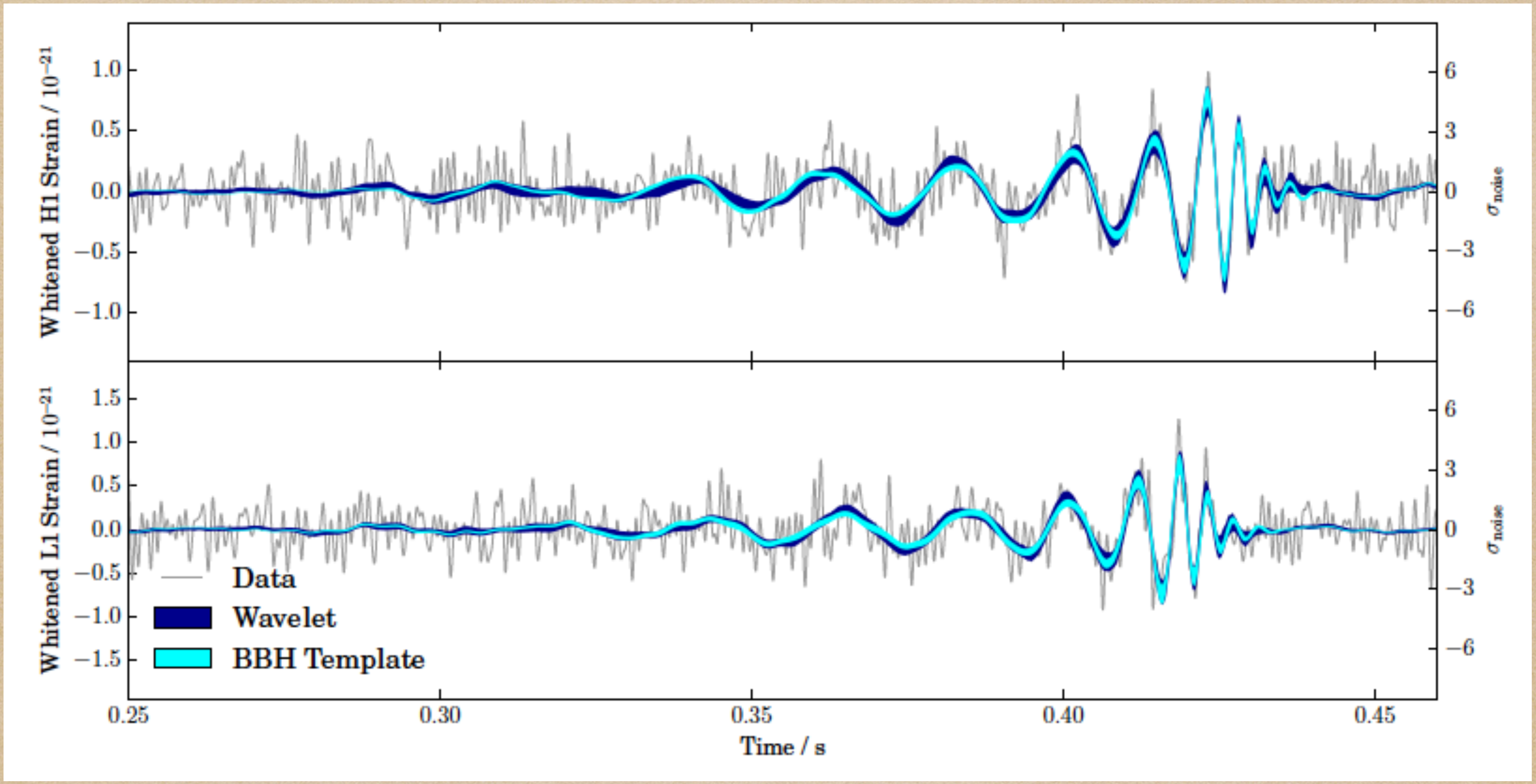
Anatomy of a BHB coalescence



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

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

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

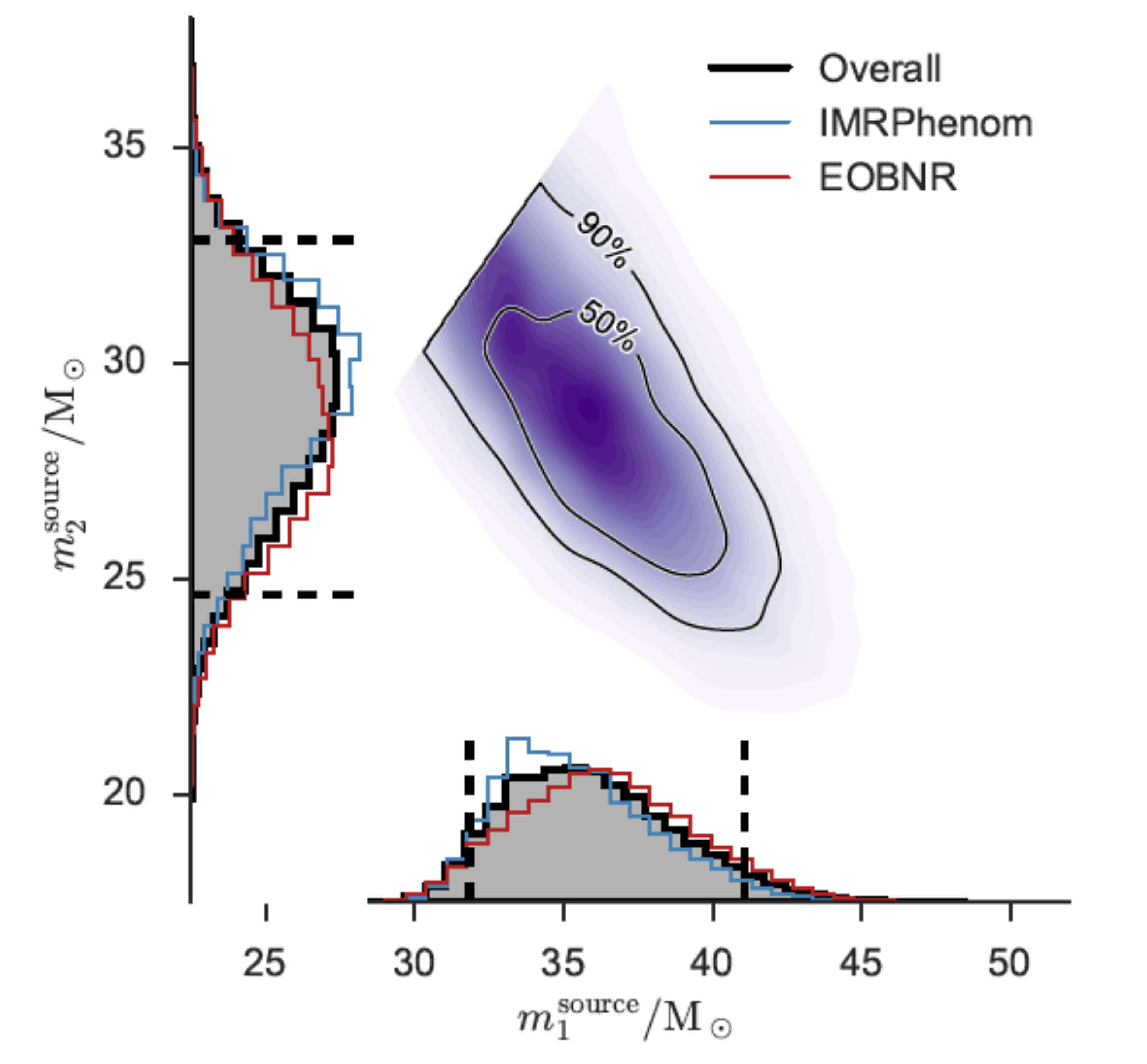
$$M_{\rm fin} = 62^{+4}_{-4}\ M_\odot$$

- Deficit in GWs!

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

$$\approx 5.4 \times 10^{54}\ \rm erg$$

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



Abbott et al 1602.03840

GW150914: BH parameters

- Mass ratio $q \equiv \dfrac{m_2}{m_1} = 0.65 \pm 0.03$
- Spins harder to measure: few cycles, no full-precession catalog

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

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

- Luminosity distance $D_L = 410^{+160}_{-180}$ Mpc
- Source redshift $z = 0.088^{+0.031}_{-0.038}$

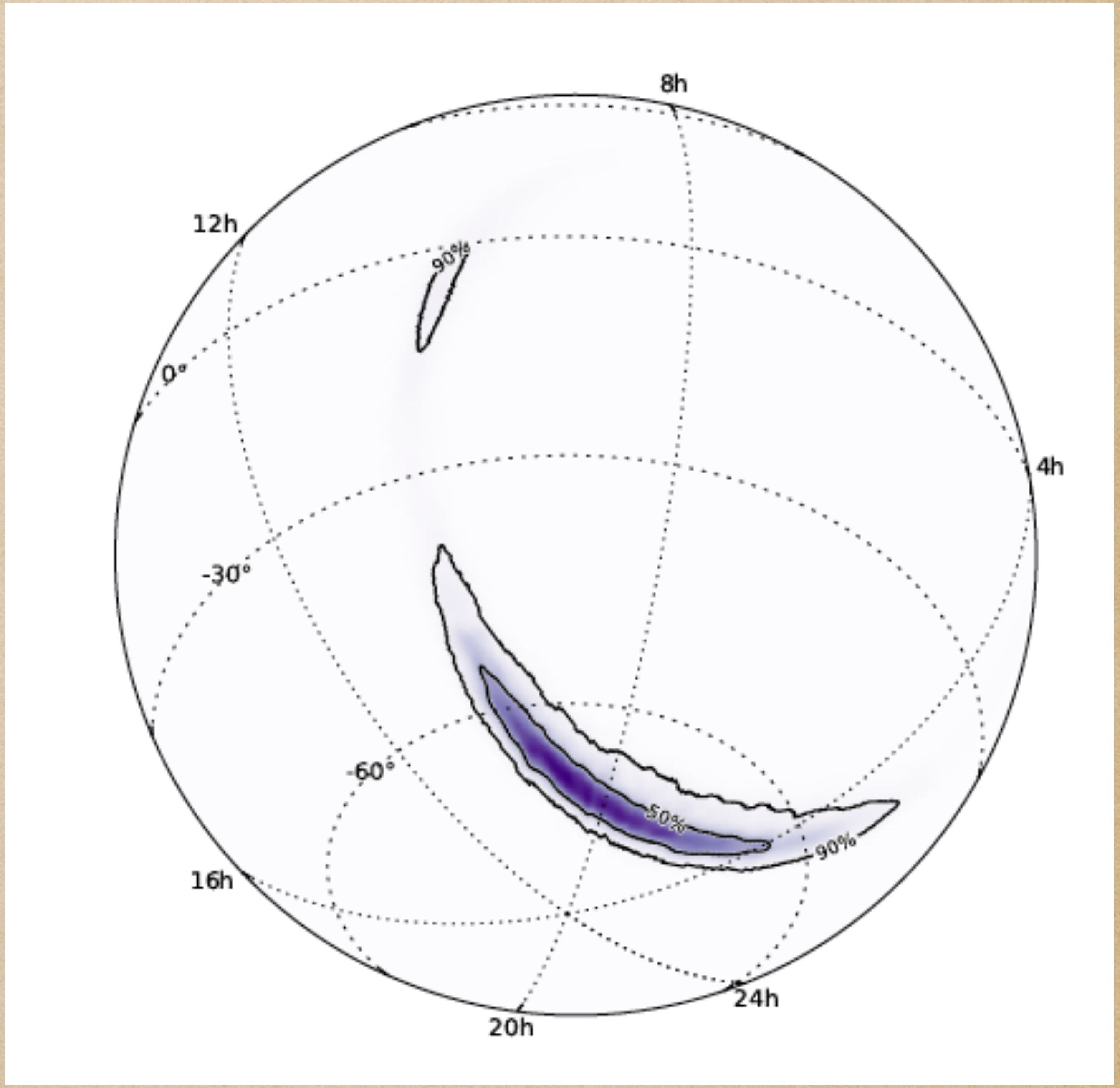
GW150914: Sky location

- 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

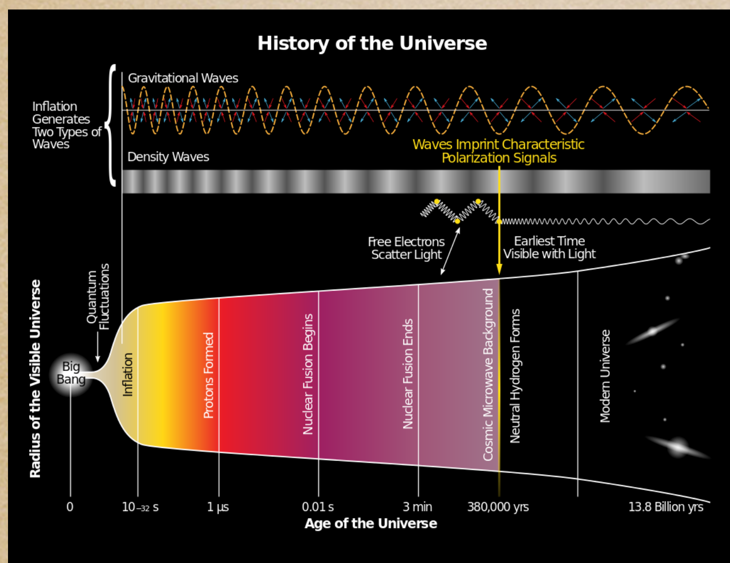


Abbott et al 1602.03840

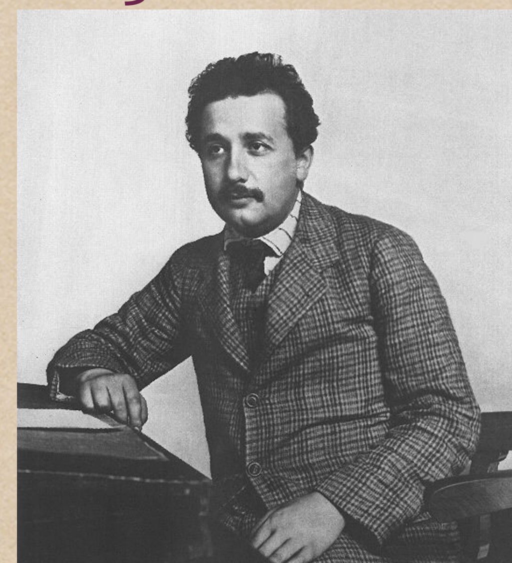
(Selected) Present and future applications

Overview

Early Universe

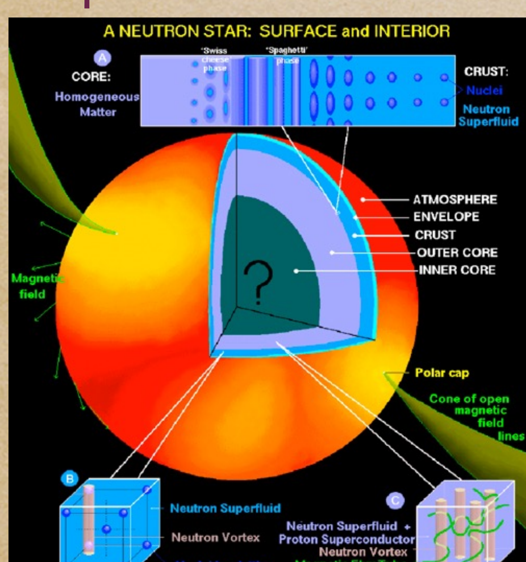


Testing Einstein's theory



Galaxy history

Equation of state

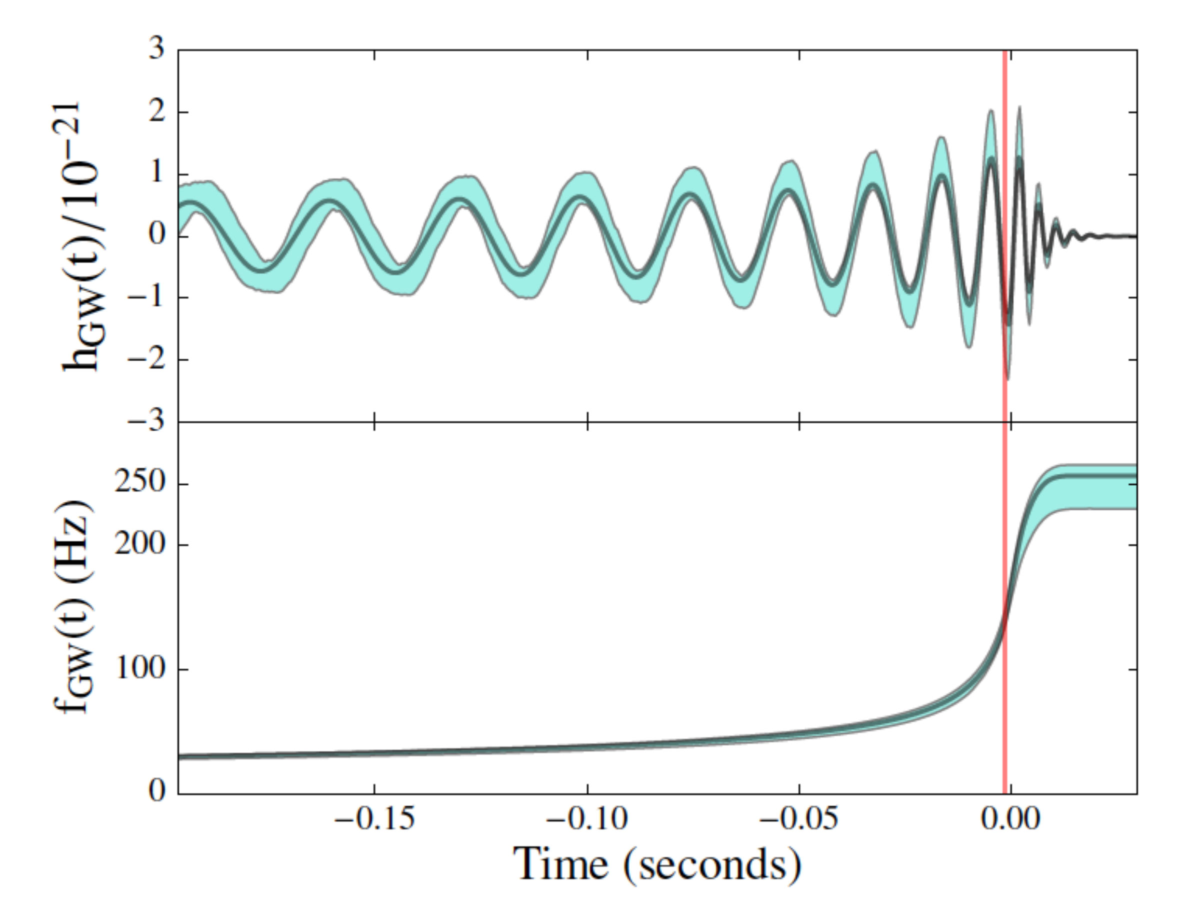


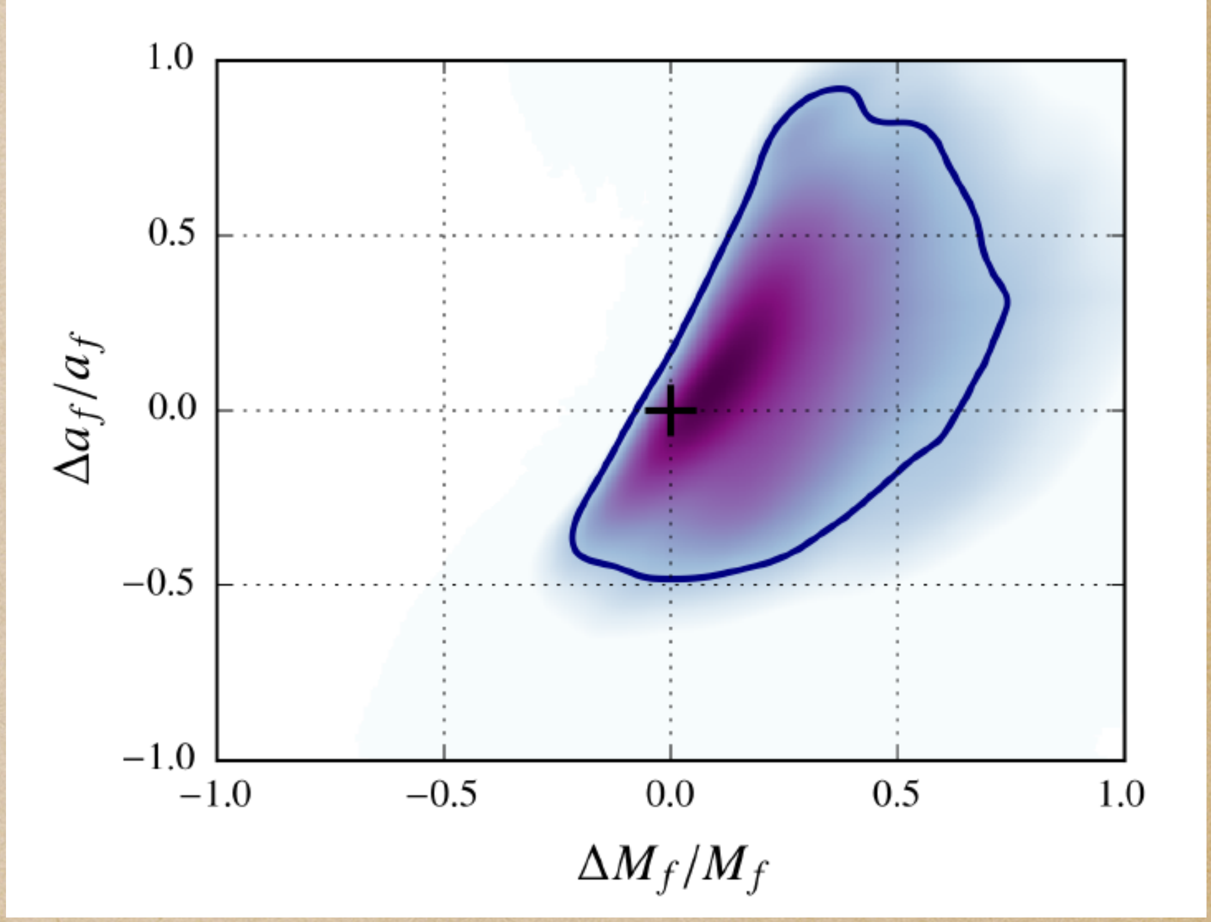
BH populations

The unknown…

Testing GR with GW150914: Consistency

- Measure $M_{\rm f},\ a_{\rm f}$ 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

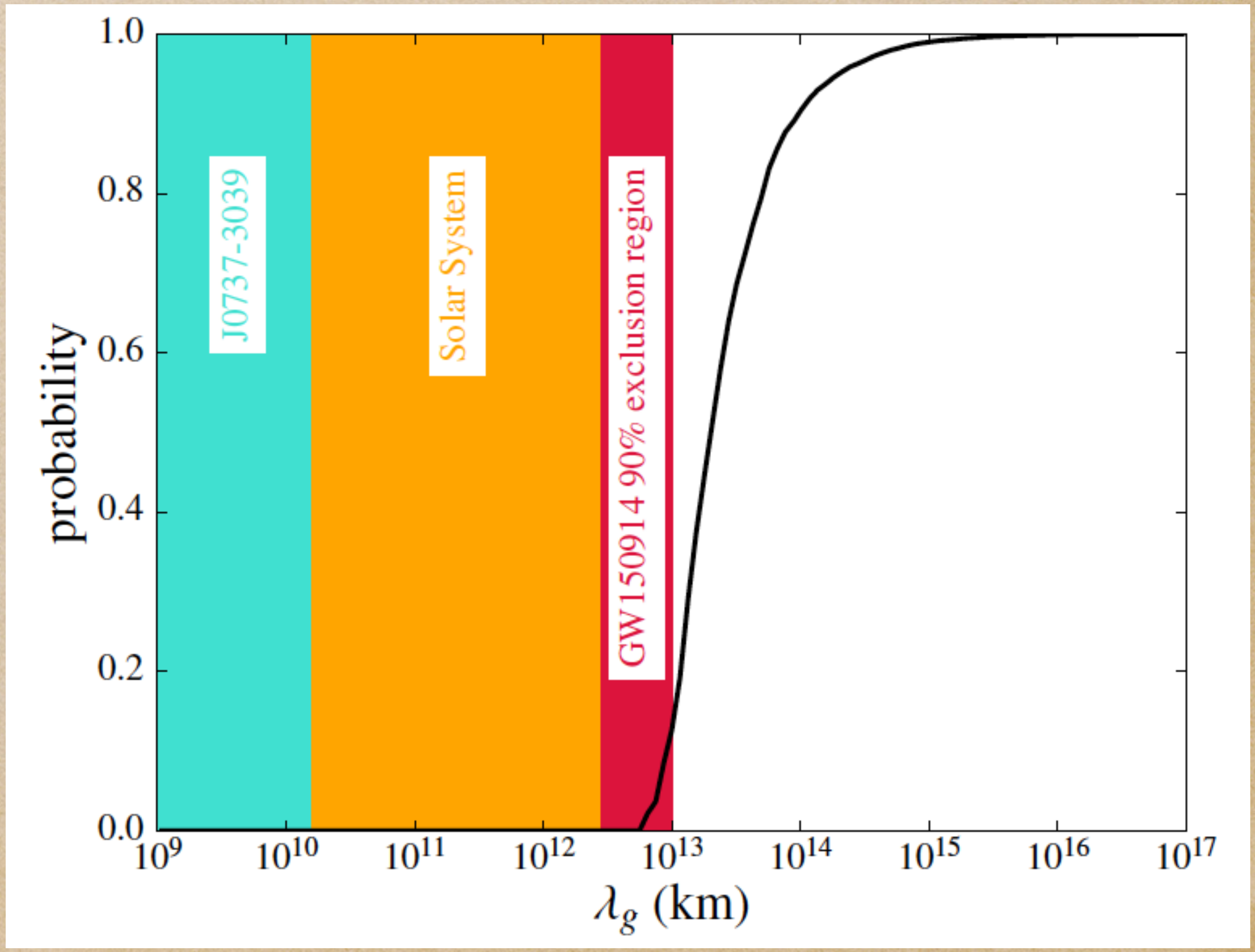
- Phenomenological model
- Massive graviton $\Rightarrow$ Compton wavelength $\lambda_g = \dfrac{h}{m_g c}$
- Dispersion relation: $\dfrac{v_g^2}{c^2} = 1 - \dfrac{h^2 c^2}{\lambda_g^2 E^2}$
- $\Rightarrow$ Quasi-1PN phase term

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

Will 1998 PRD

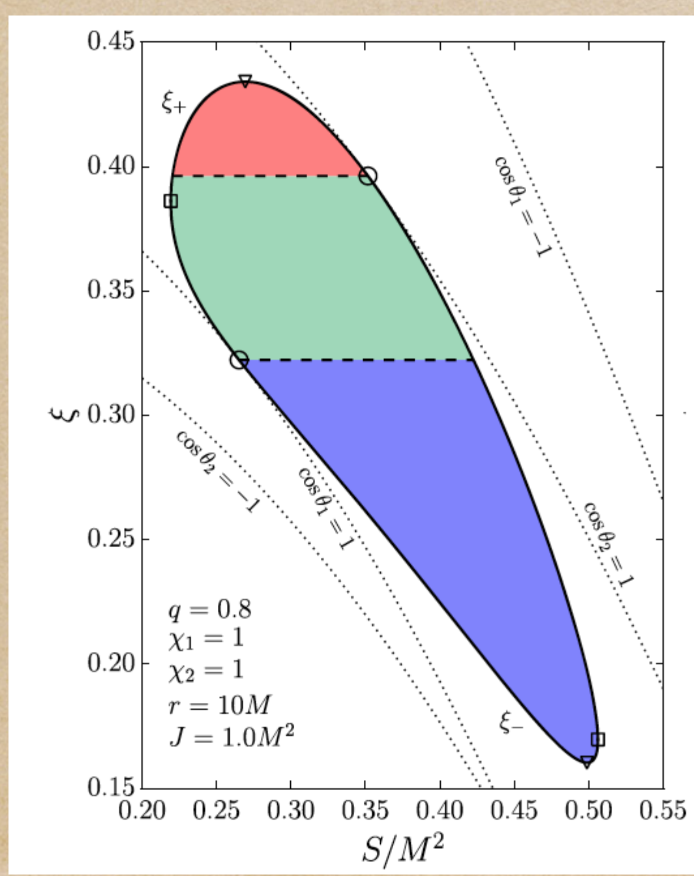
$$\boxed{m_g \leq 1.2 \times 10^{-22}\ \mathrm{eV}/c^2}$$

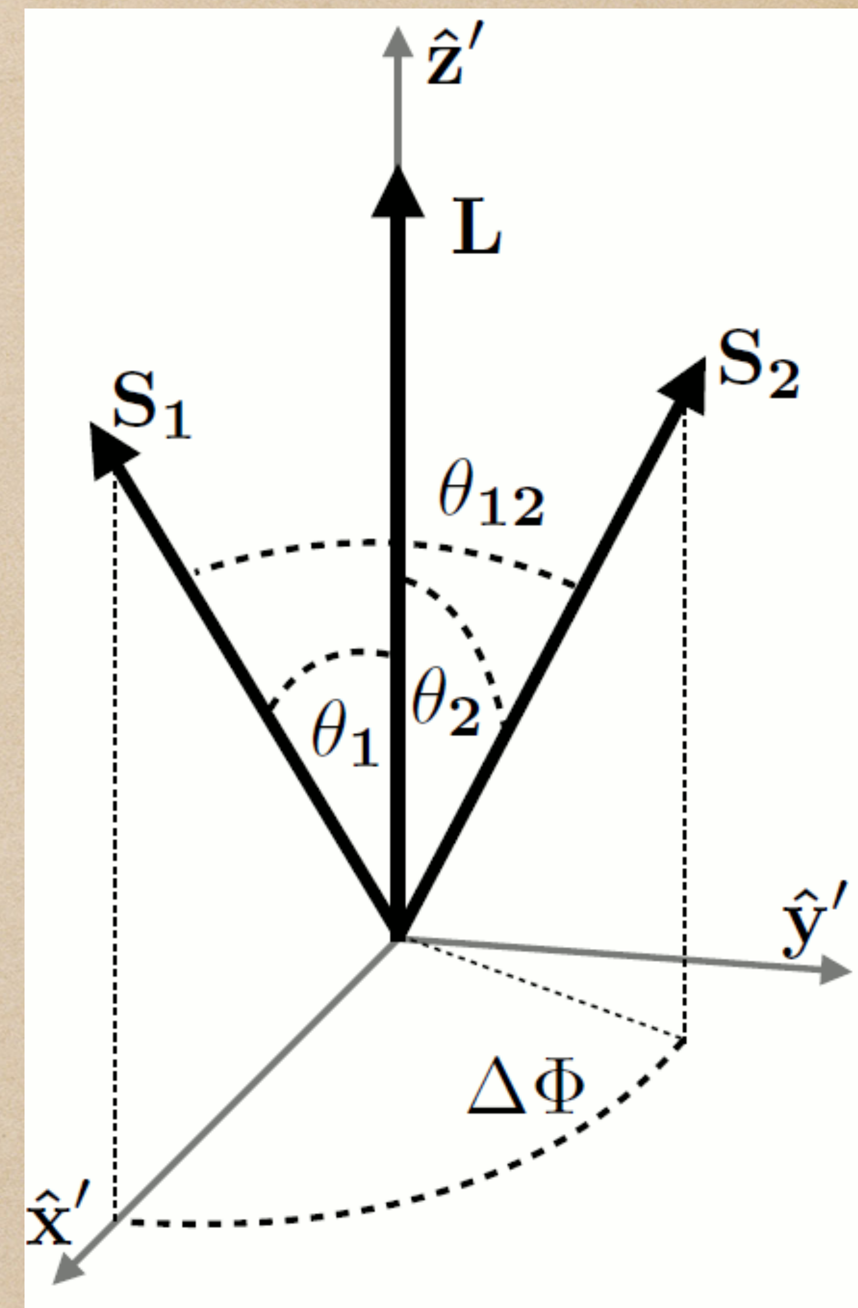
Abbott et al 1602.03841



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

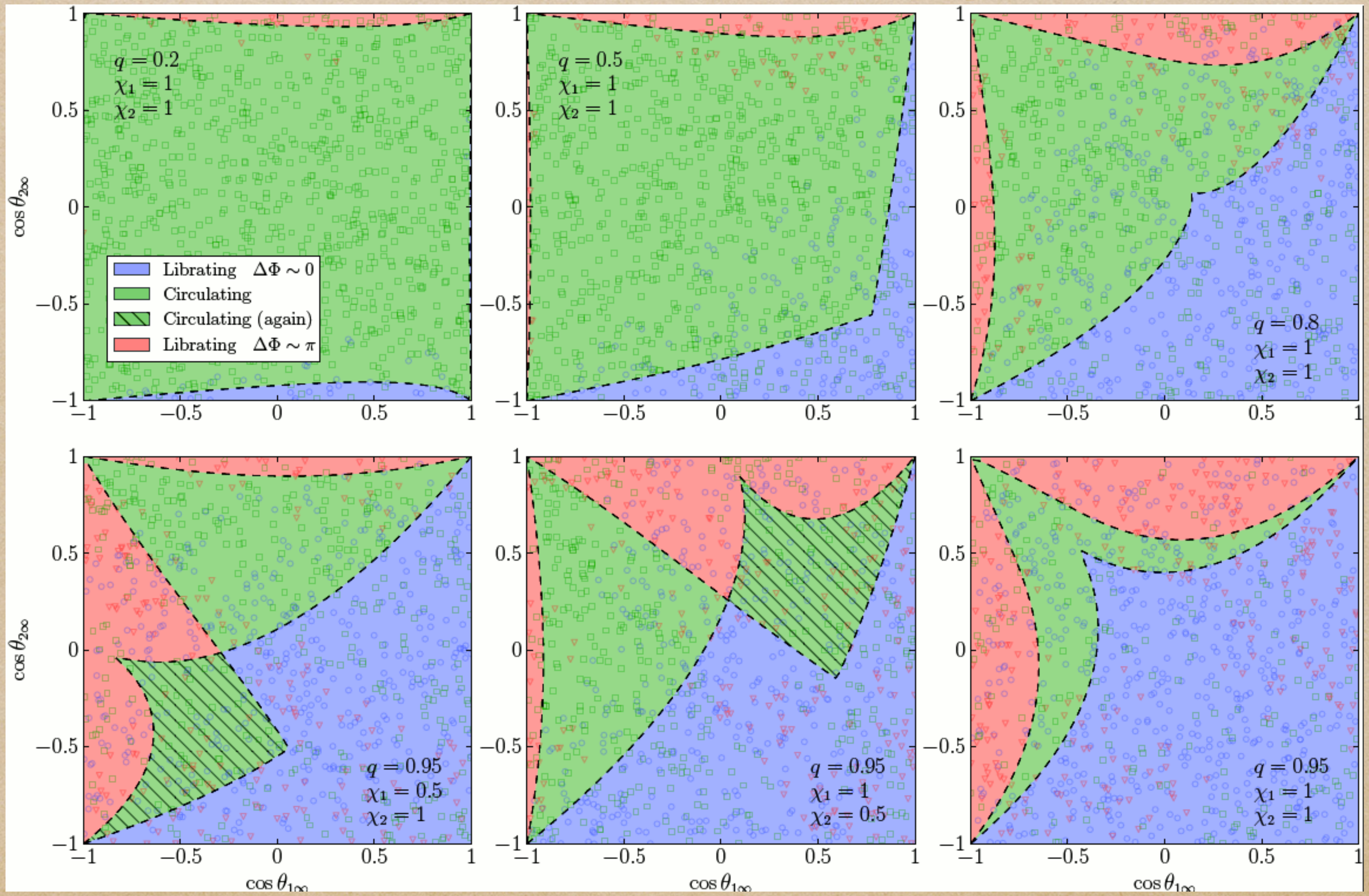




Kesden et al 2015 PRL, Gerosa et al 2015 PRD

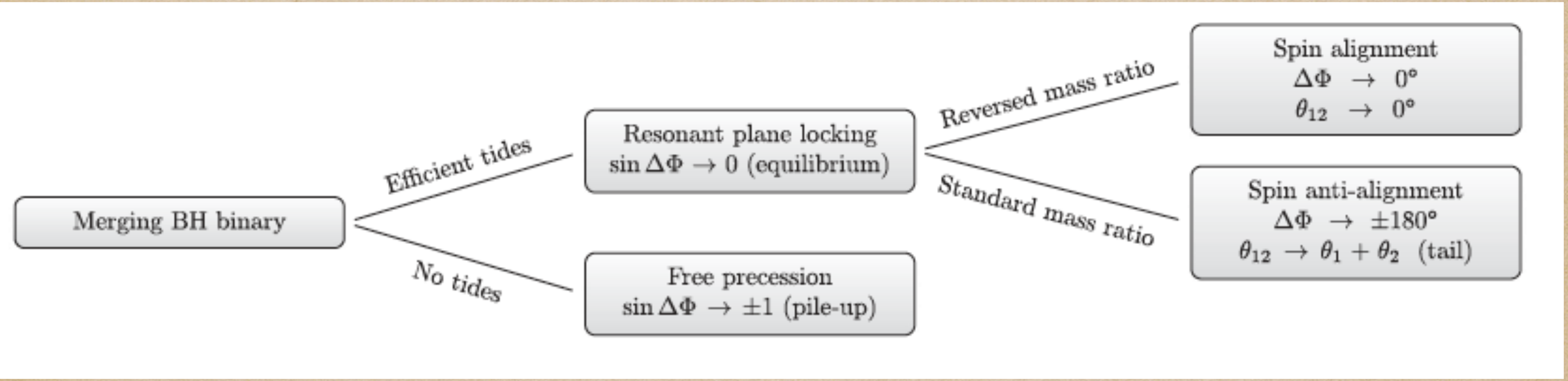
Morphologies and phase transitions in BHBs

- 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

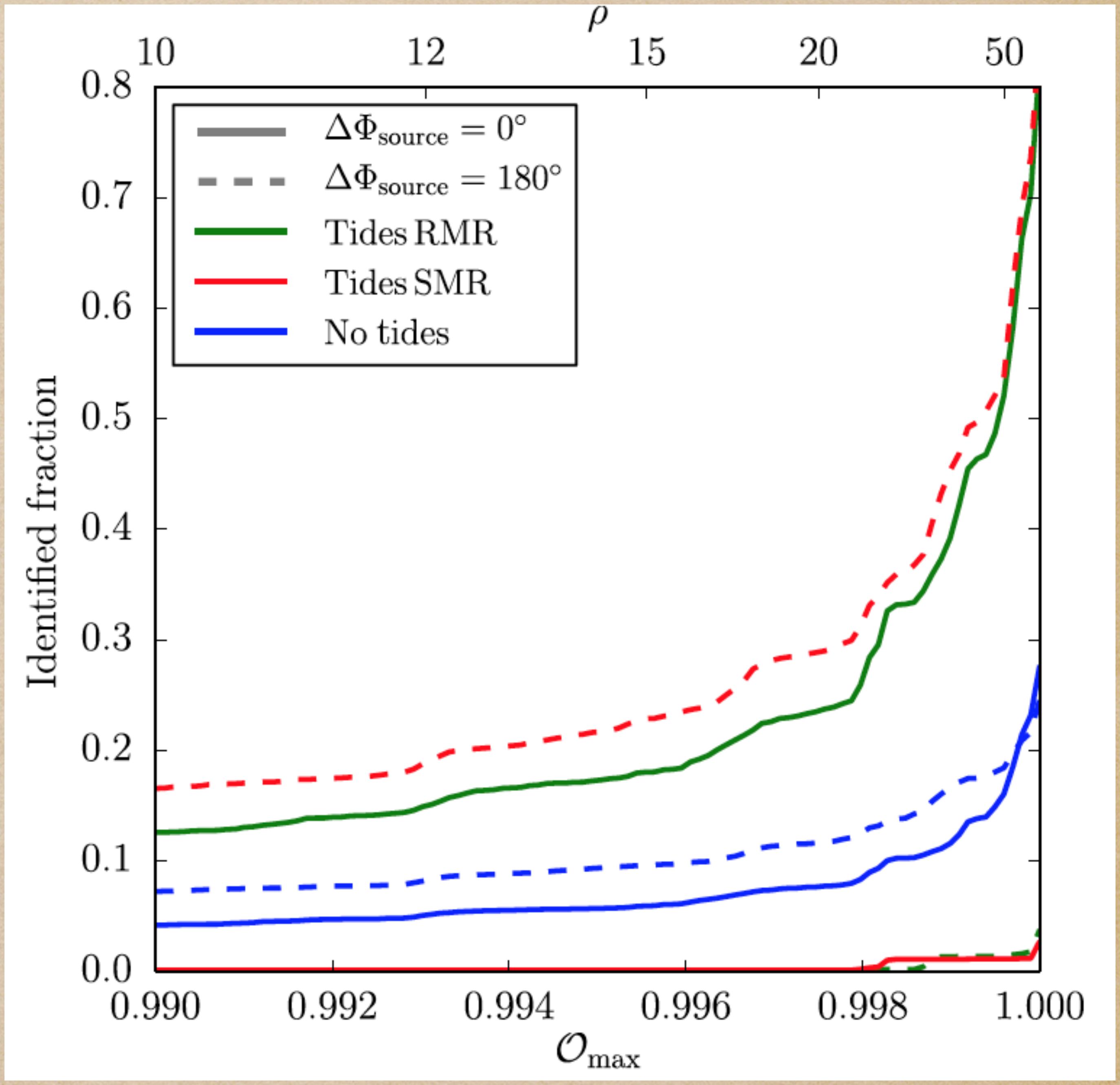
- Two massive stars in orbit
- Mass transfer may reverse mass ratio
- More massive star goes supernova $\rightarrow$ kick
- Tidal interaction may align spin with $\boldsymbol{L}$
- 2nd supernova $\rightarrow$ kick
- GW driven inspiral $\rightarrow$ preference of one morphology



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!
- First direct observation of a BH binary
- 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...