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Introduction to gravitational waves observations

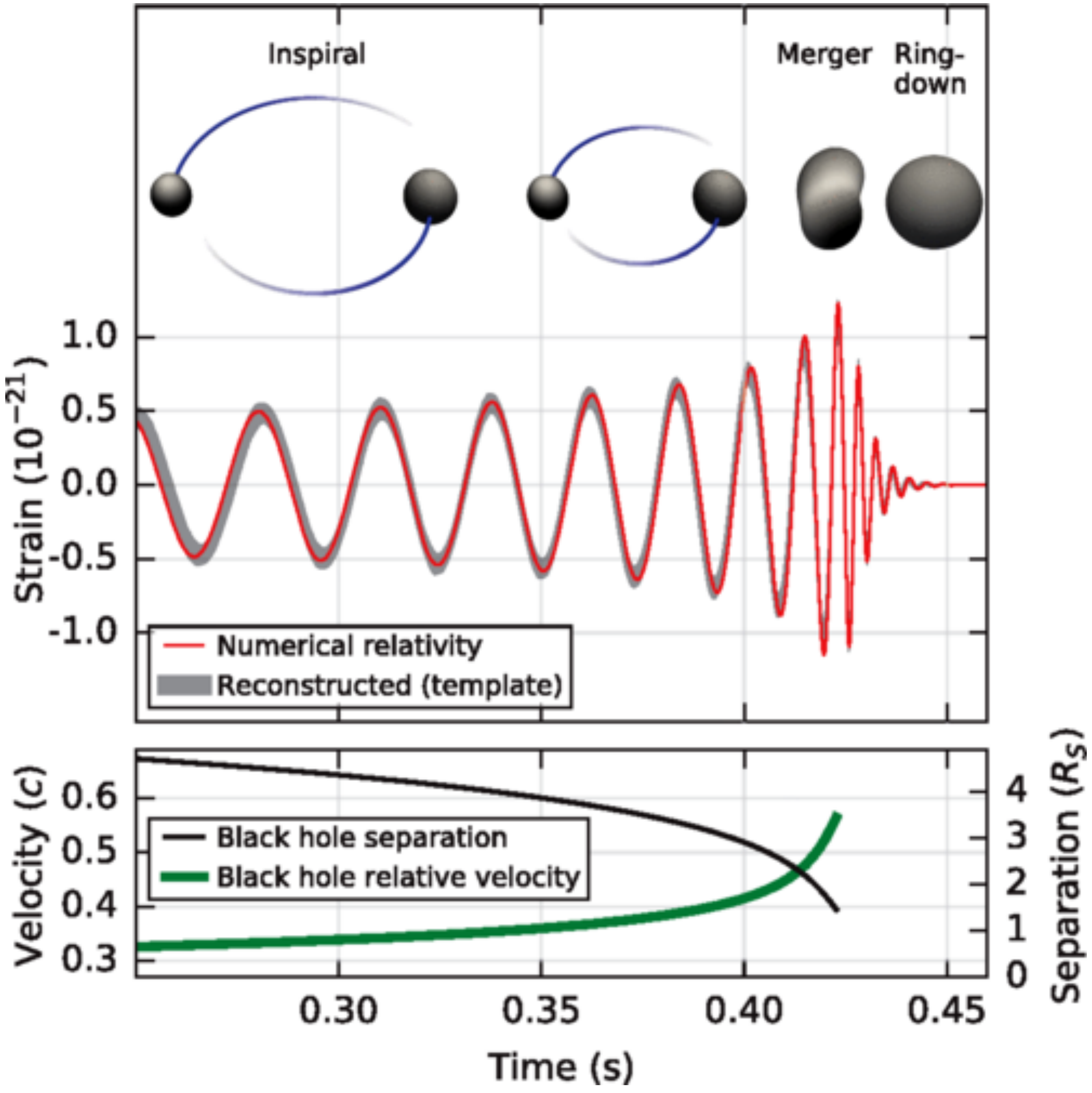
Walter Del Pozzo

Outline

- Fundaments of gravitational waves physics
- Detection and inference
    - overview: binary black holes
    - overview: binary neutron stars
- Conclusions

Gravitational waves

- In GR, gravitational waves (GW) are wave solutions to Einstein's equations generated from time varying mass quadrupoles and propagating at the speed of light
- Shape of GW signal encodes
  - binary dynamics and component nature
  - non-linear dynamics of space-time
  - final object nature



LVC, arXiv:1602.03837

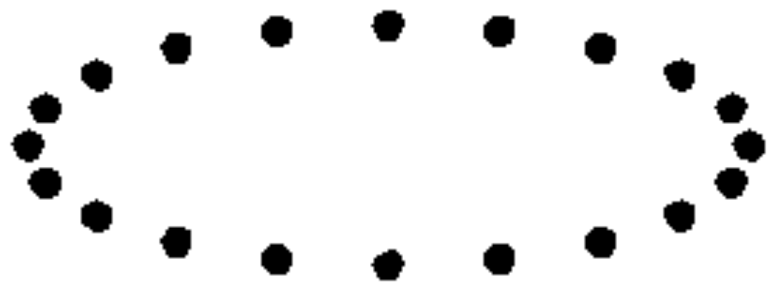
Polarisation states

- In GR two transverse polarisations: + (plus), x (cross)

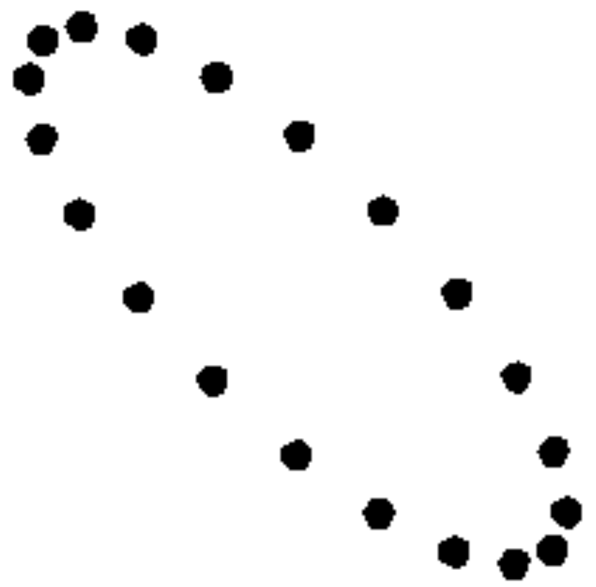
$$h = h_+ e^+ + h_\times e^\times$$

- Extensions of GR predict up to six polarisation states
    - Excluded by GW observations, e.g. LVC, arXiv:1709.09660, arXiv: 1811.00364

+ (plus)

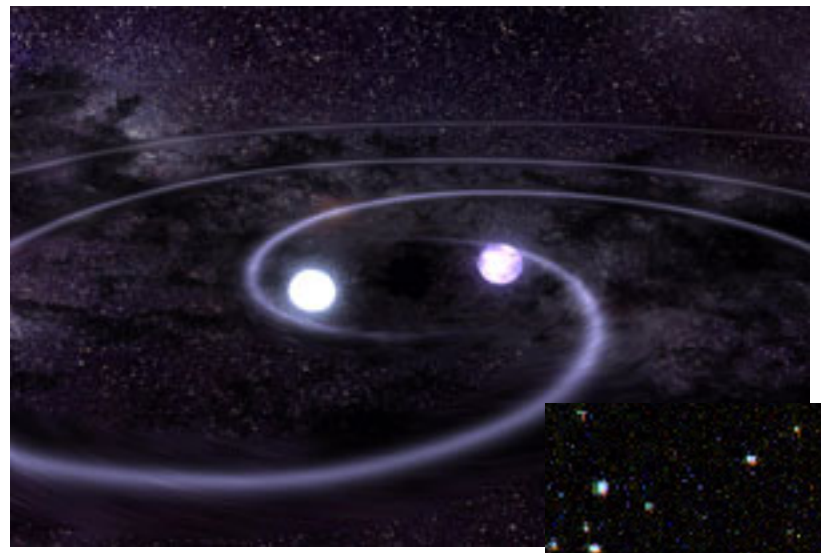


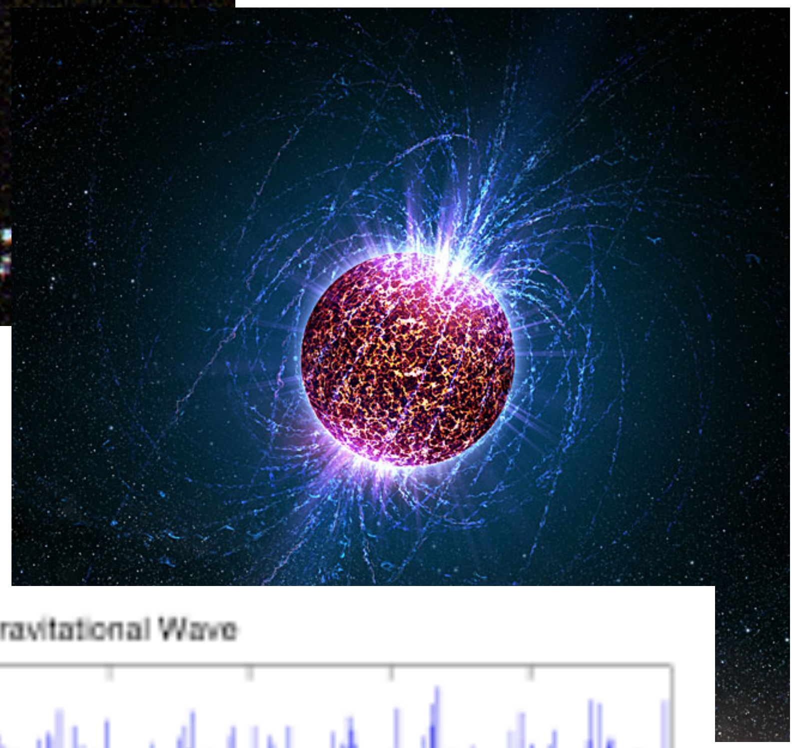
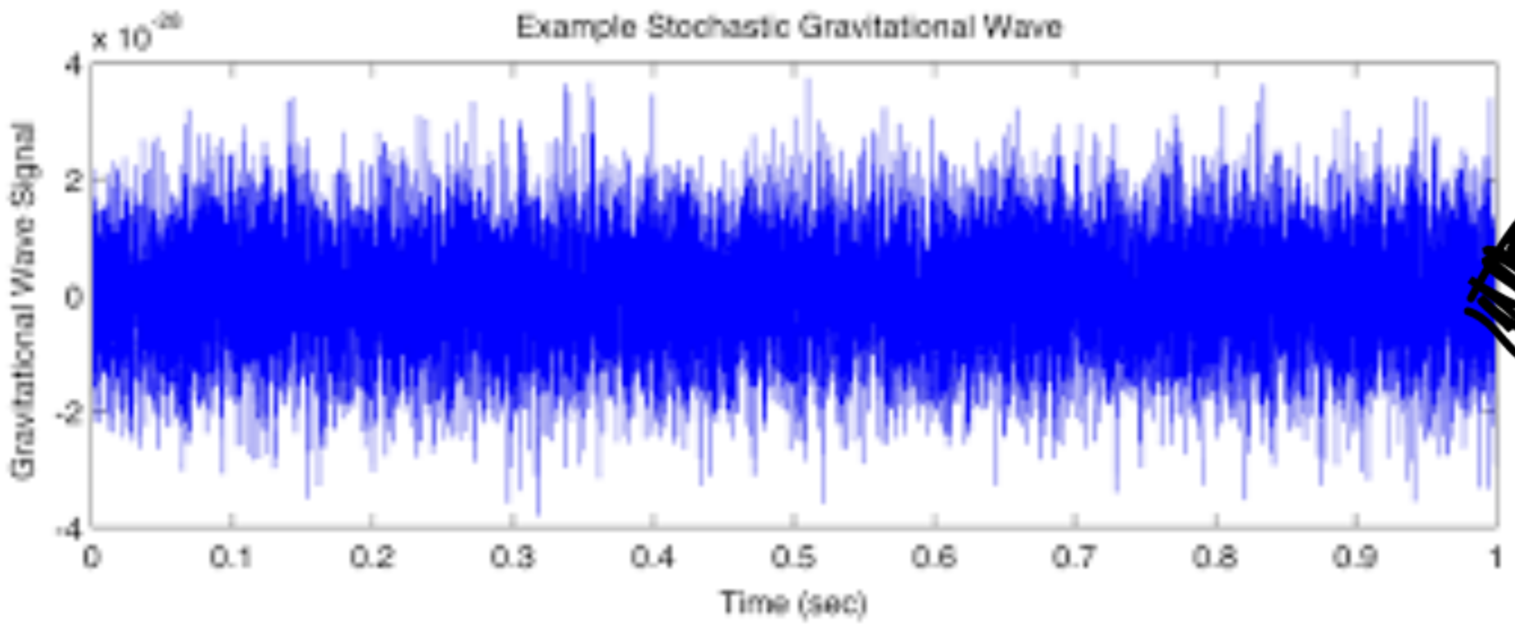
x (cross)



Sources of GW

- Compact binary systems coalescence (CBC)
- Supernovae
- Spinning neutron stars
- Stochastic background
  - astrophysical
  - cosmological
- Unknown



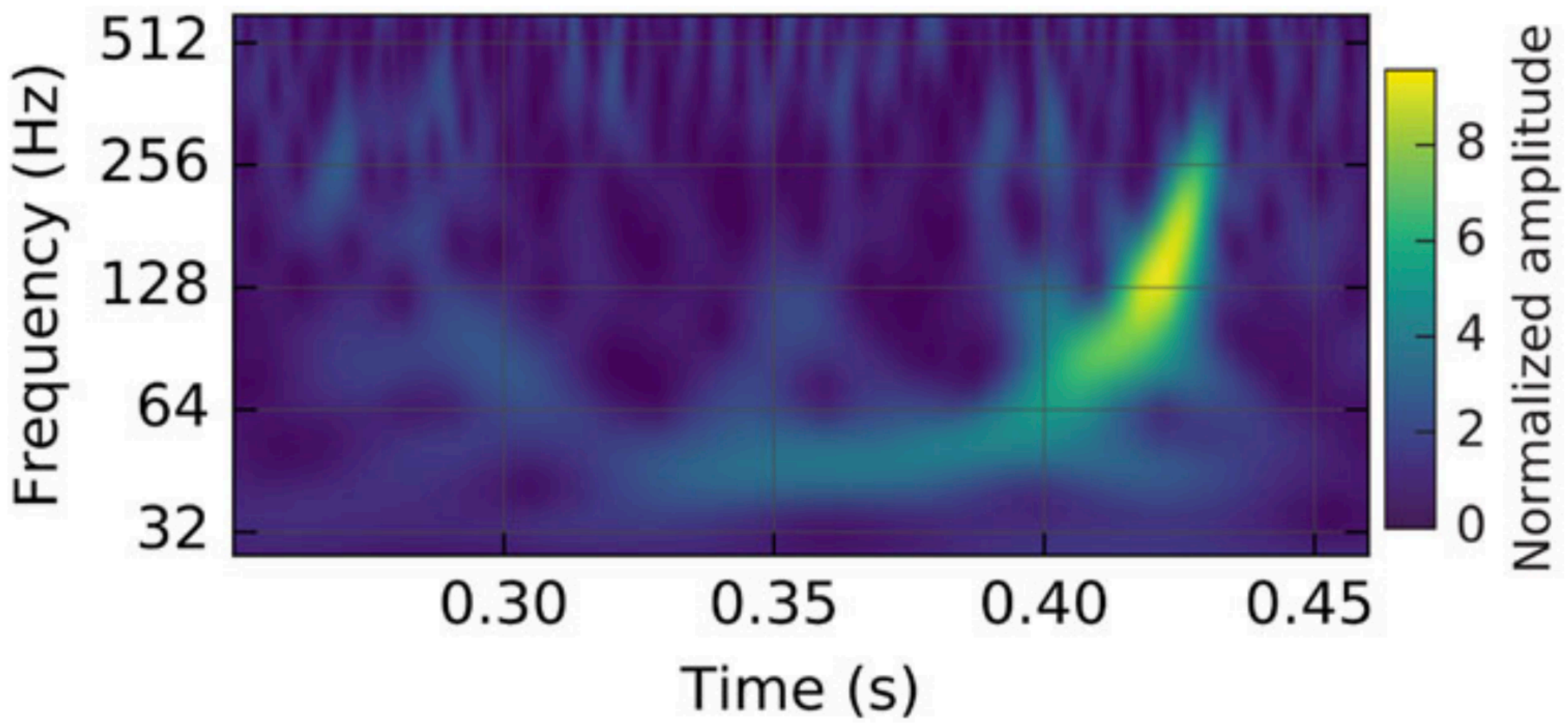
GW primer

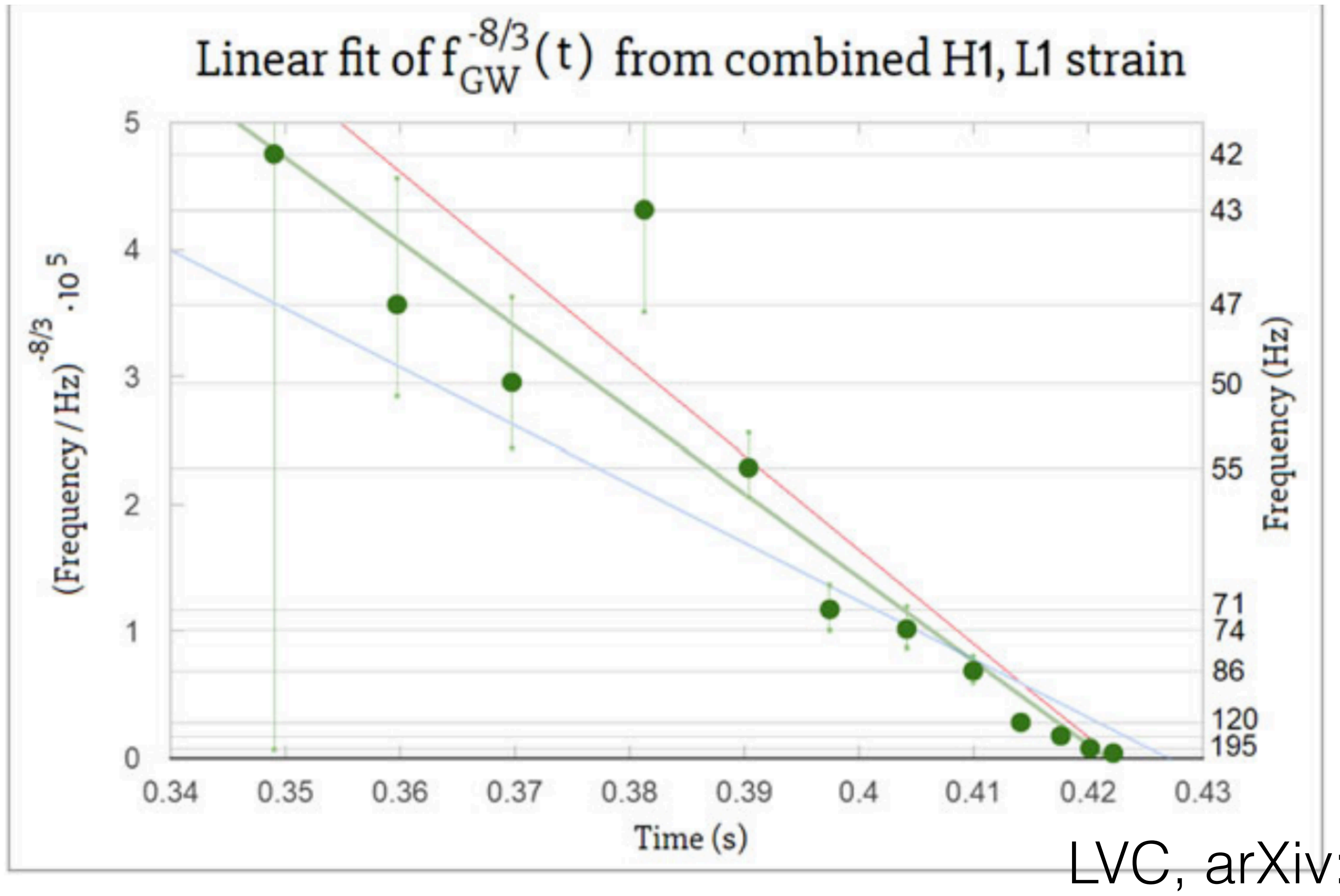
- Complex analytical structure
- Leading order:

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

$$\mathcal{M} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right)^{3/5}$$

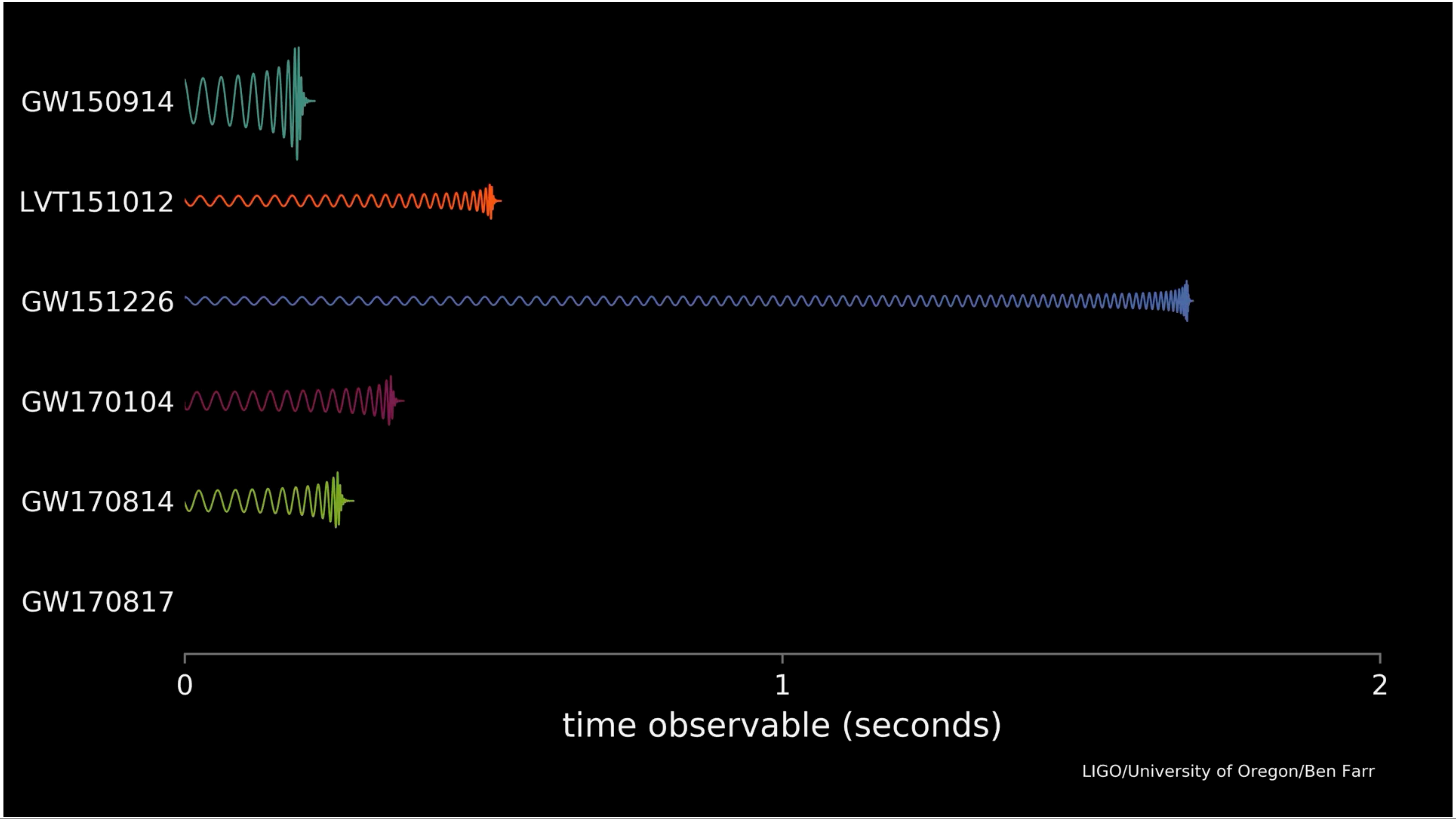
$$f_{\mathrm{GW}}^{-8/3}(t) = \frac{(8\pi)^{8/3}}{5}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3}(t_c - t)$$





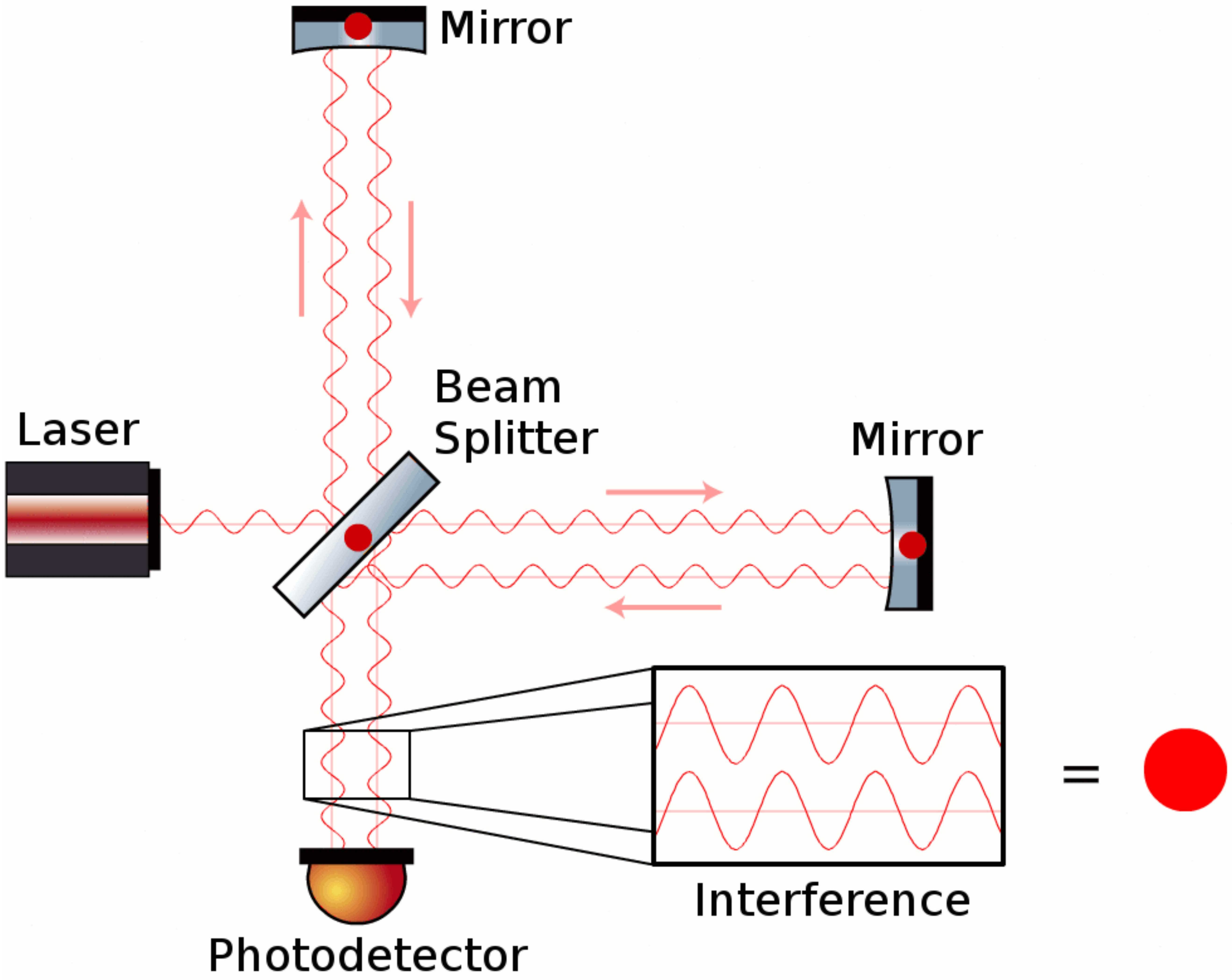
LVC, arXiv:1608.01940

GW primer

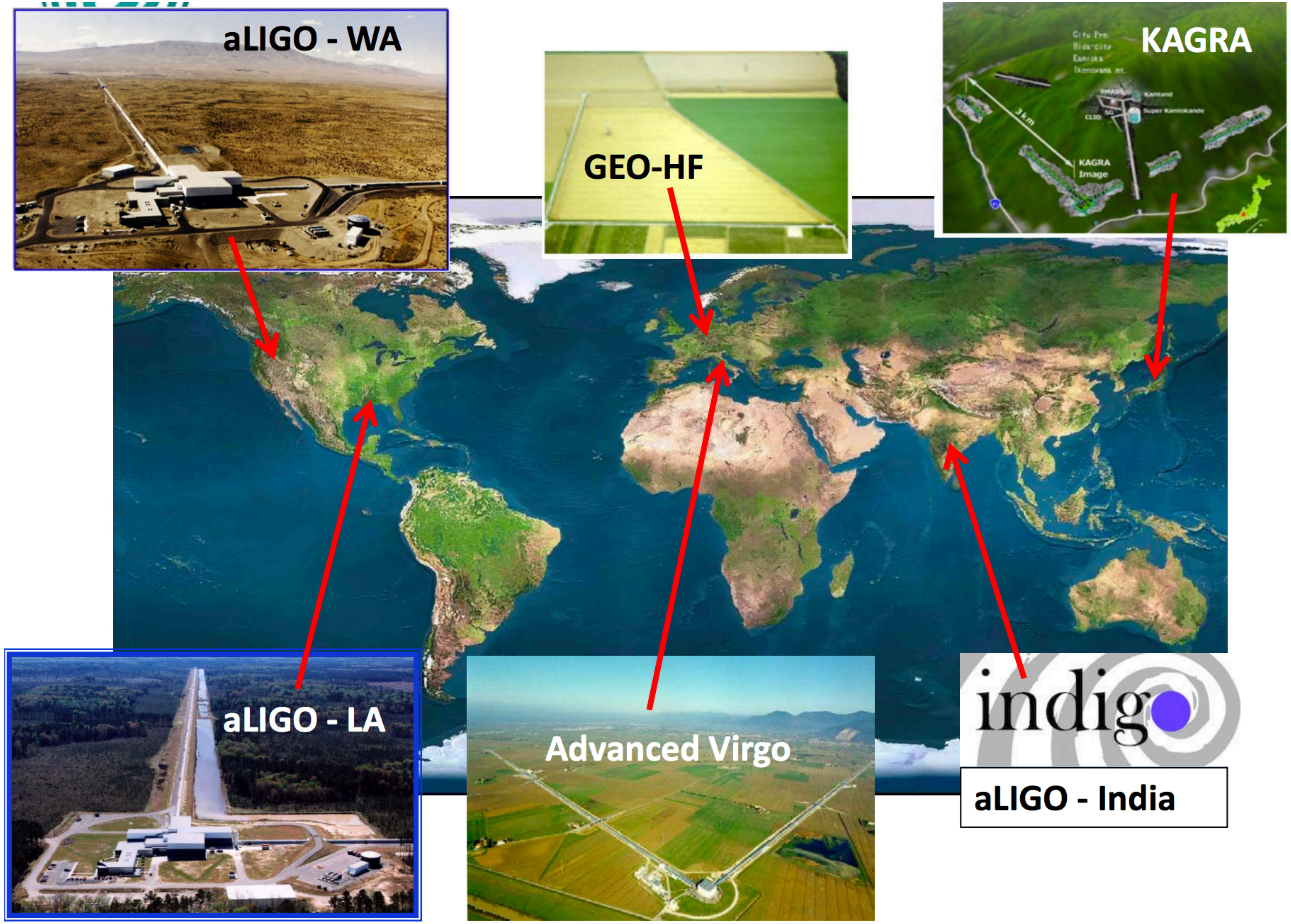


GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0
1
2
time observable (seconds)
LIGO/University of Oregon/Ben Farr

Interferometric detection of GW

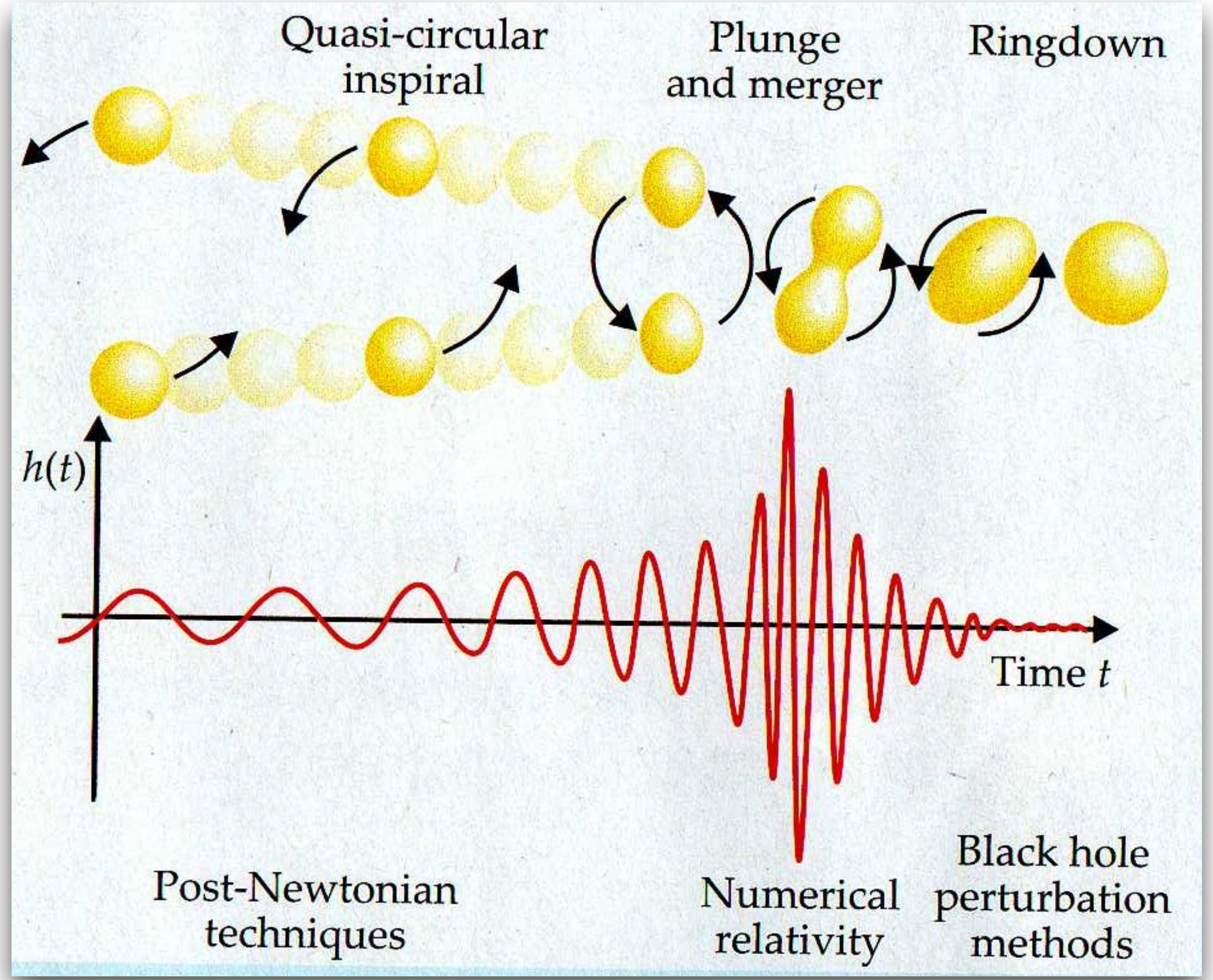


The gravitational wave detectors network



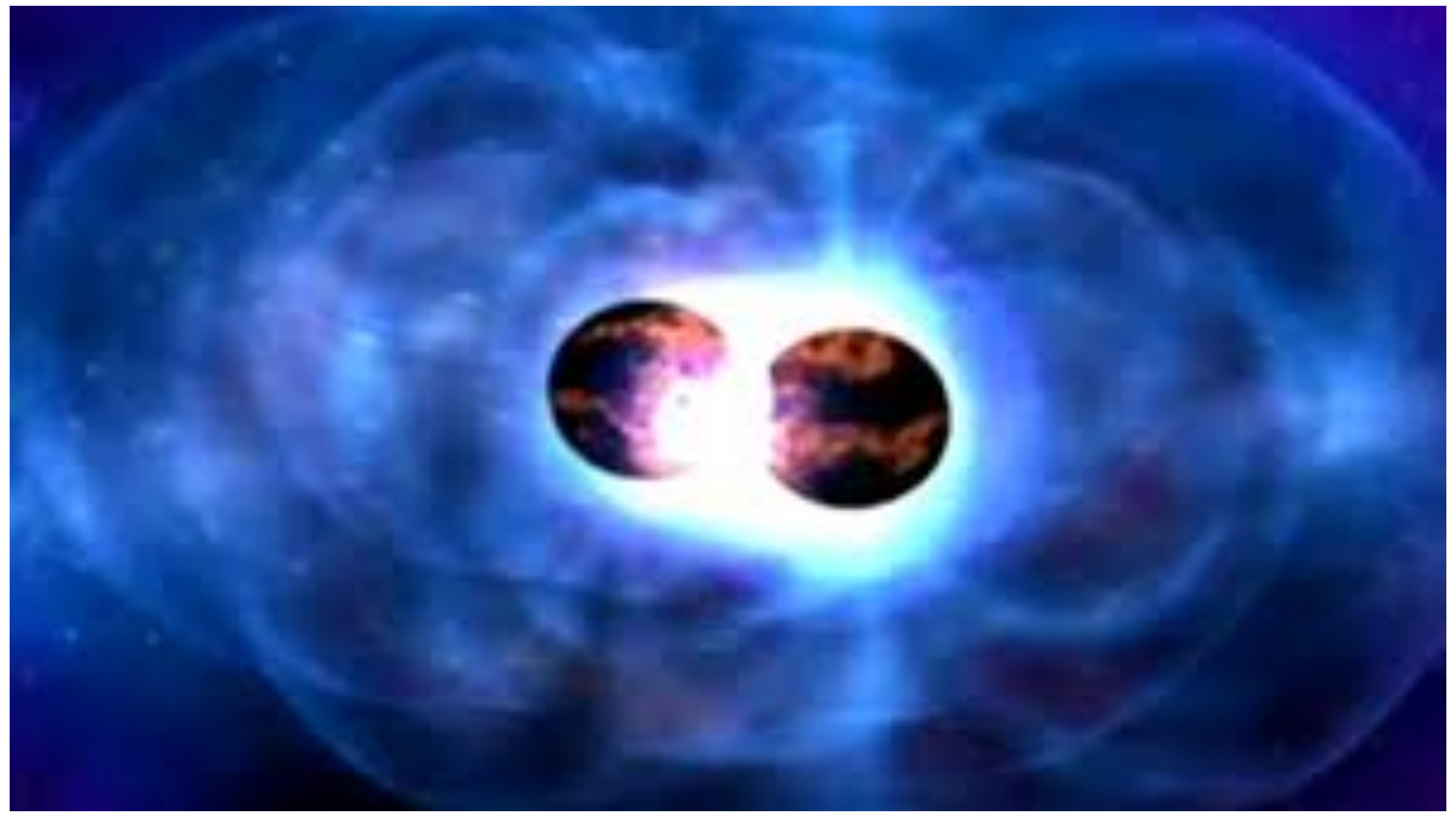
CBC solutions in GR

- Binary black holes solutions are constructed combining:
  - post-Newtonian theory in the weakly non-linear inspiral regime (Blanchet, LRR 2014)
  - direct numerical solution in the highly non-linear merger regime (Lehner & Pretorious, arXiv:1405.4840)
  - perturbation theory in the ringdown regime (Berti et al, arXiv:0905.2975)
- Effective one body (Buonanno & Damour, arXiv: 9811091, Bohe+,arXiv:1611.03703)
- Phenomenological (e.g. Khan+,arXiv:1508.07253)



What physics can be probed

- Matching observed data with a solution to Einstein's equations allows to probe (Sathyaprakash & Schutz, LLR 2009)
    - Laws of space-time dynamics
    - Nature of black holes
    - Neutron star interiors
    - Large scale structure and cosmology

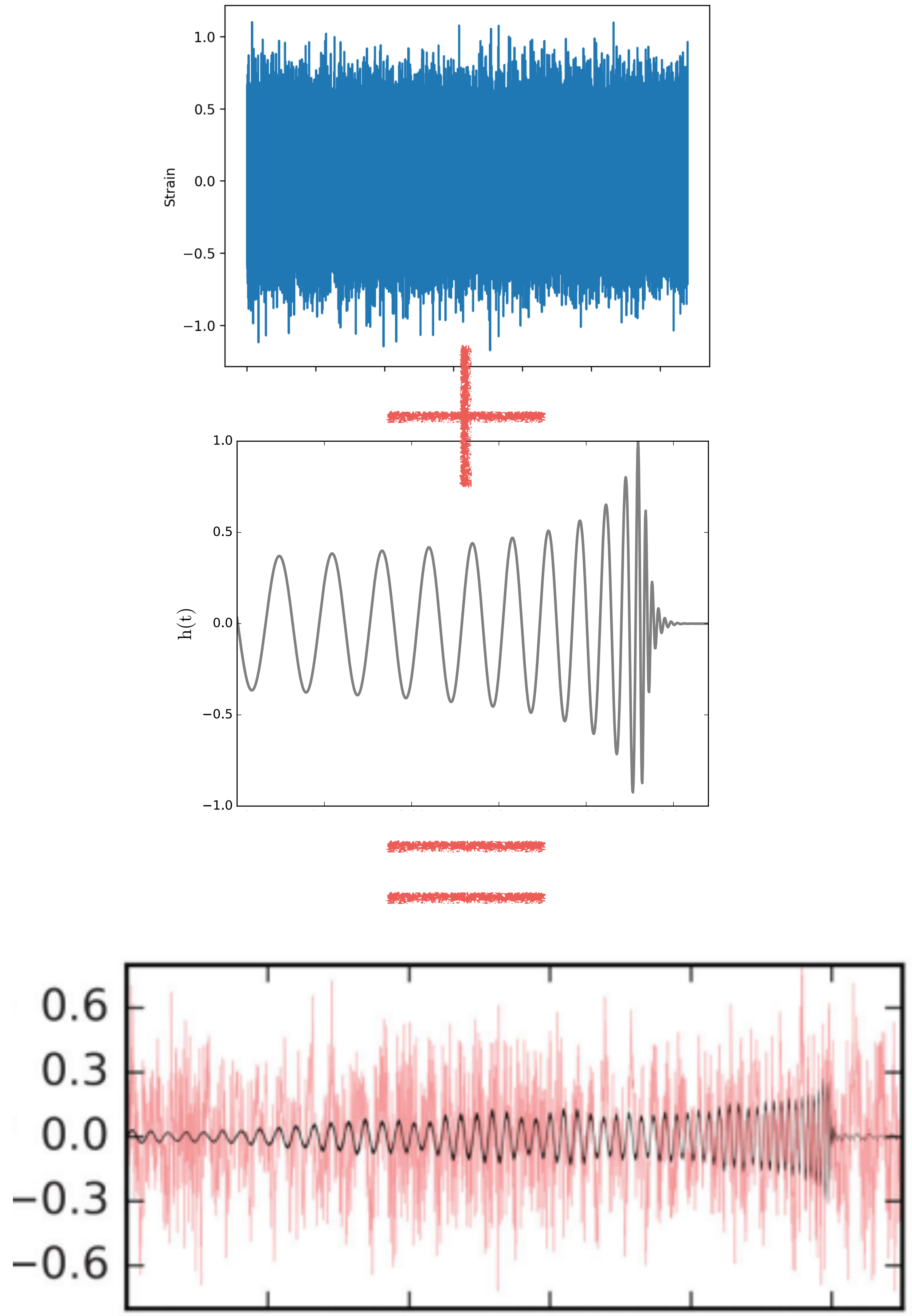


CBC analysis

- The detector output is linear

$$d(t) = h(t;\theta) + n(t)$$

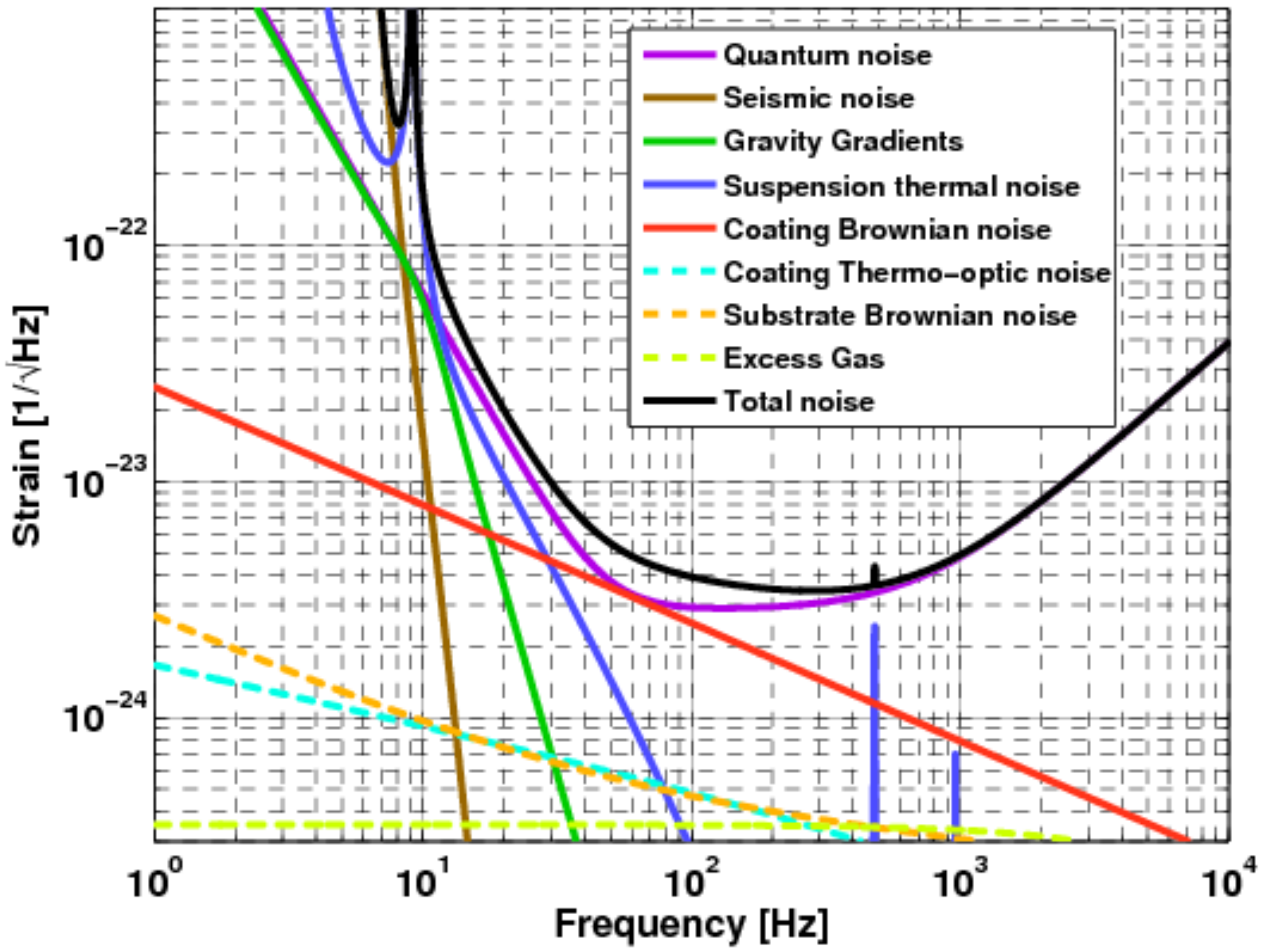
- where $h(t;\theta)$ is the gravitational wave strain and $n(t)$ is the noise time series



Noise

- IFO noise is a superposition of several processes
  - Noise is a wide-sense stationary stochastic process
  - All information about $n(t)$ encoded in the power spectral density $S(f)$

$$\log L = -\frac{2}{T}\sum_i \frac{(\tilde{d}(f_i) - \tilde{h}(f_i;\theta))^2}{S(f_i)}$$

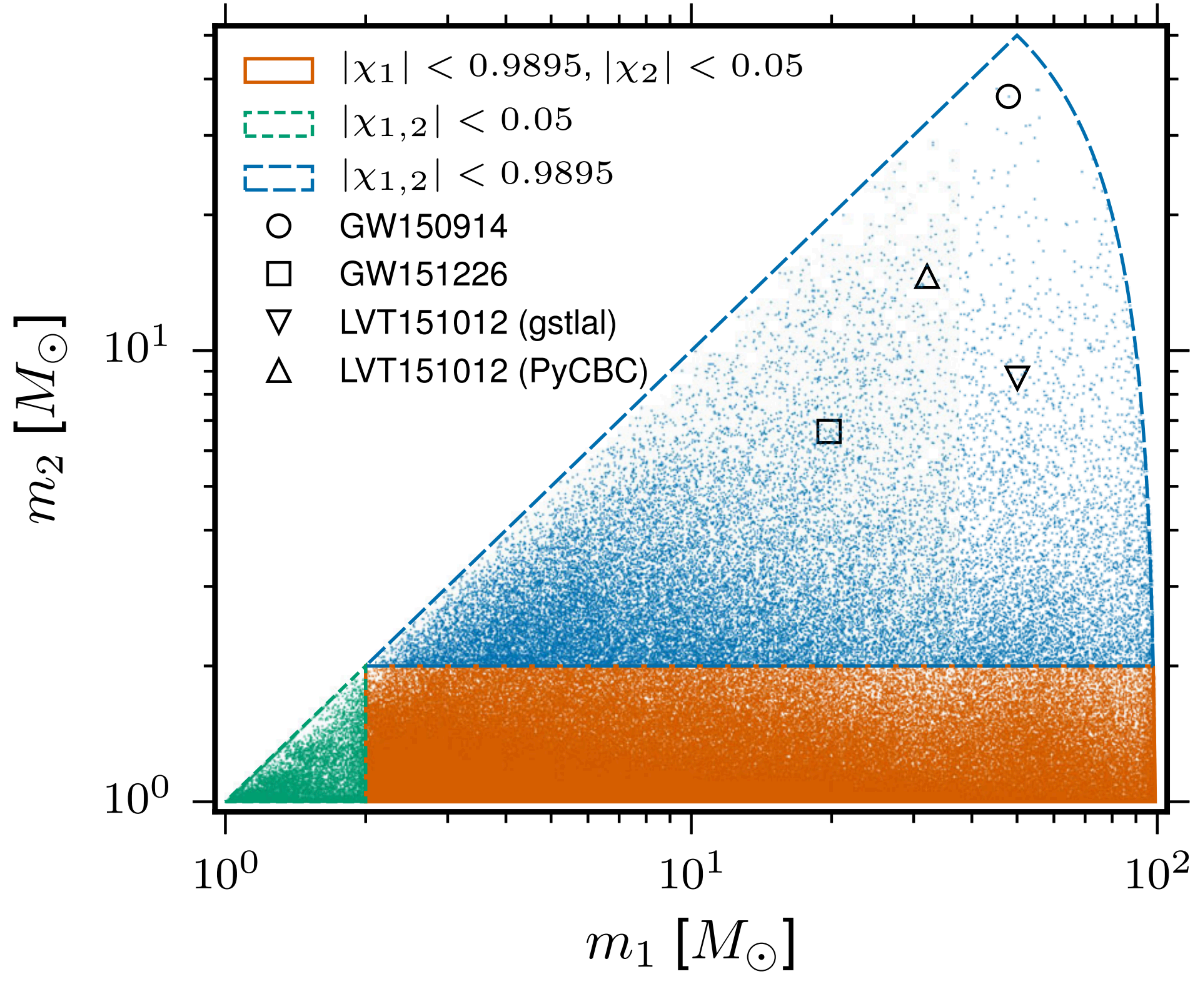


GW signal models

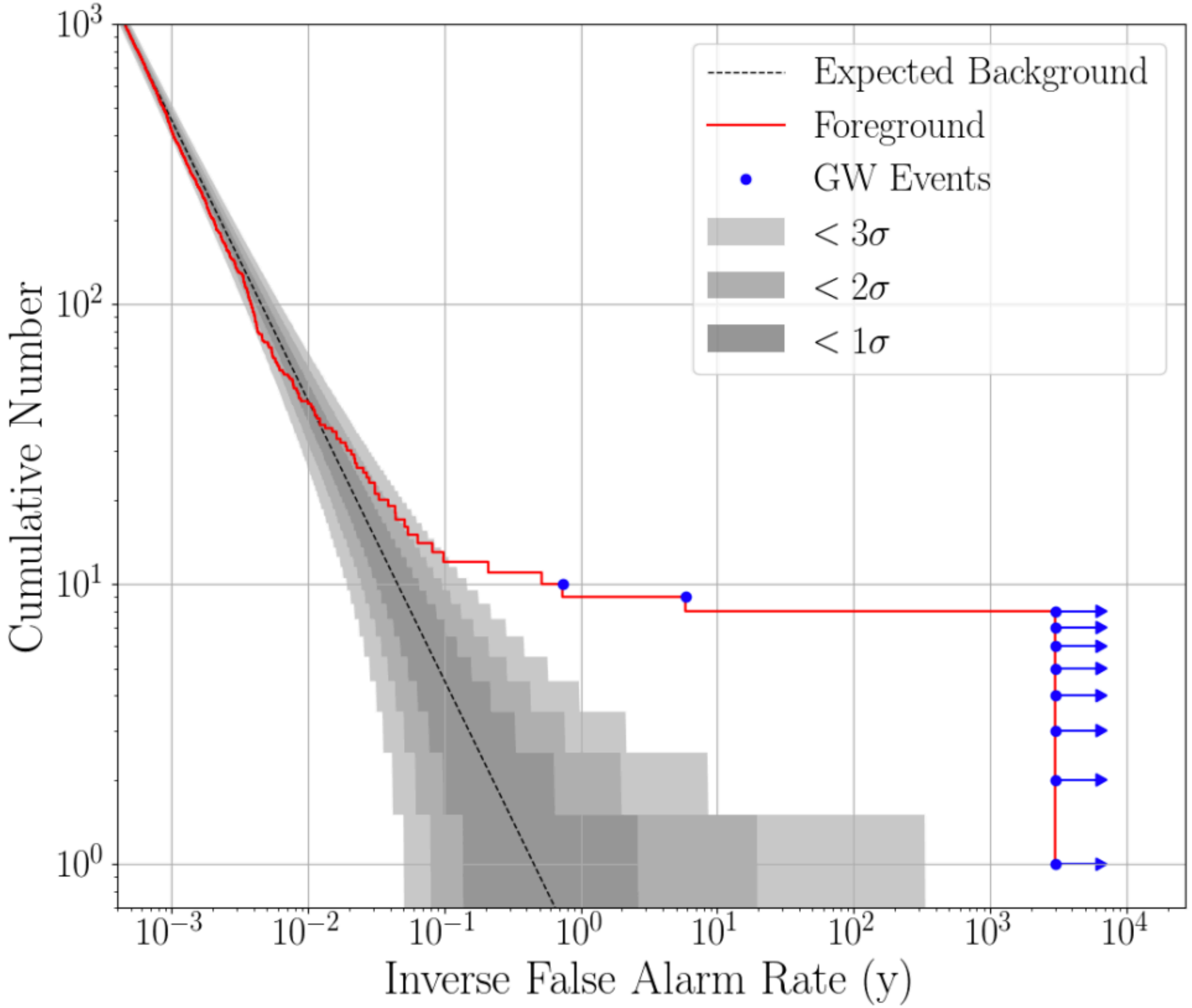
- $\tilde{h}(f;\theta)$ depends on a set of D parameters θ
  - D=15 in general: masses, orientation, sky location, reference time and phase, luminosity distance, spin vectors
  - More parameters for extra physics (e.g. BH charges, tests of GR, tidal effects, etc…)

Detection of CBC

- Construct a template bank
- Compute likelihood ratio between the hypotheses
  - S: signal of known shape plus noise
  - N: noise
- Compute *signal-to-noise ratio* (SNR)
  - Rank according to the empirical noise distribution



Significance estimation

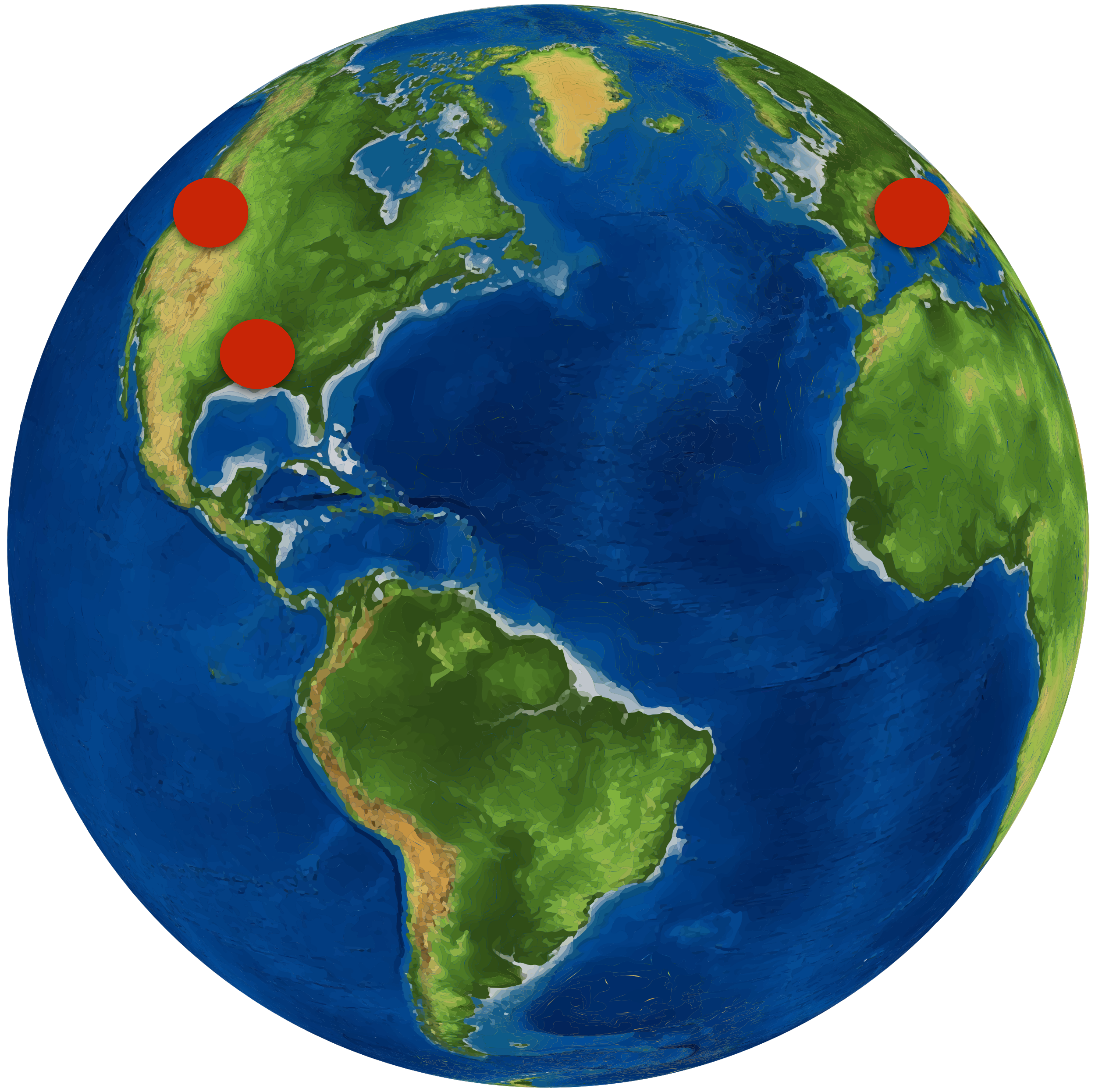


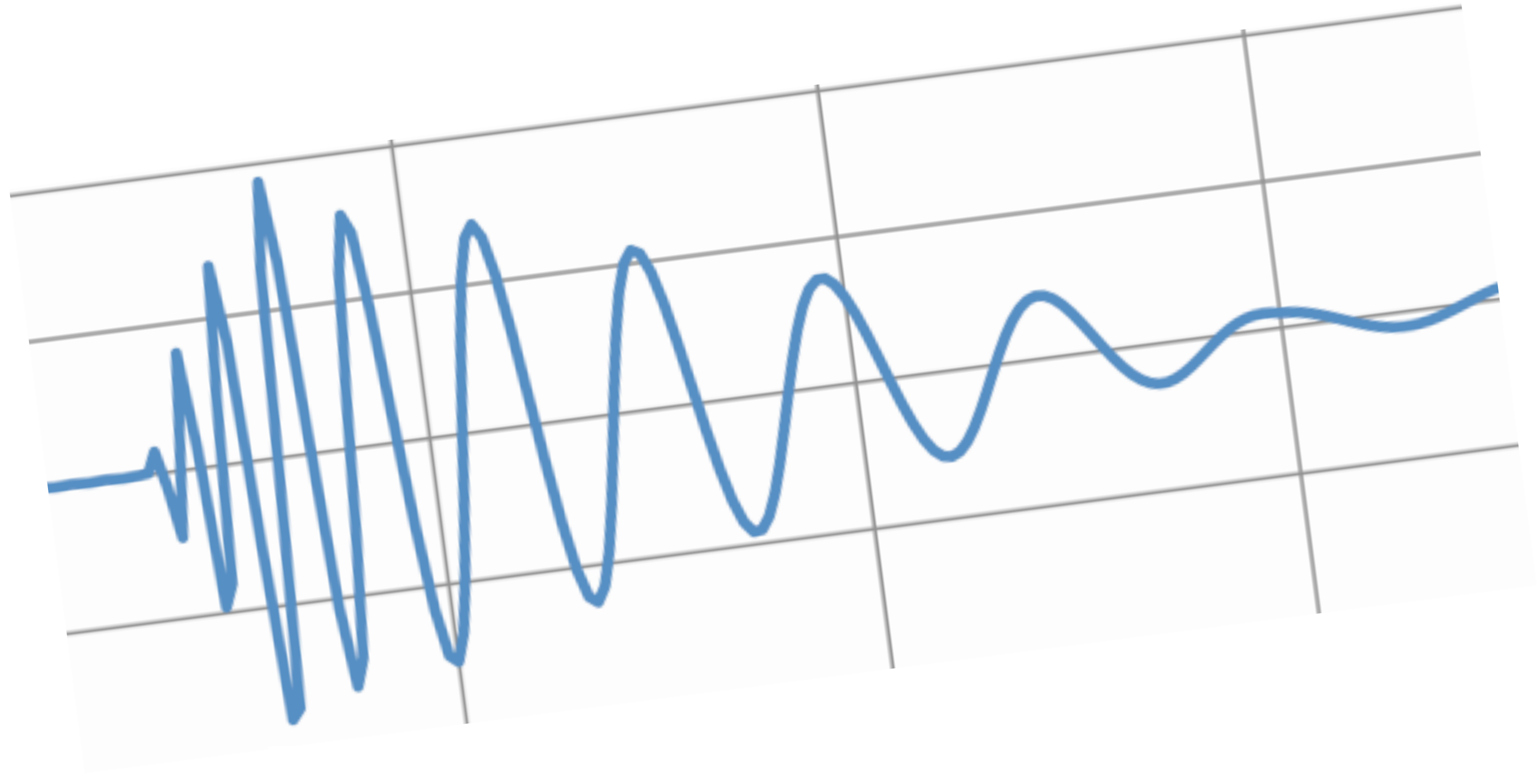
LVC, arXiv:1811.12907

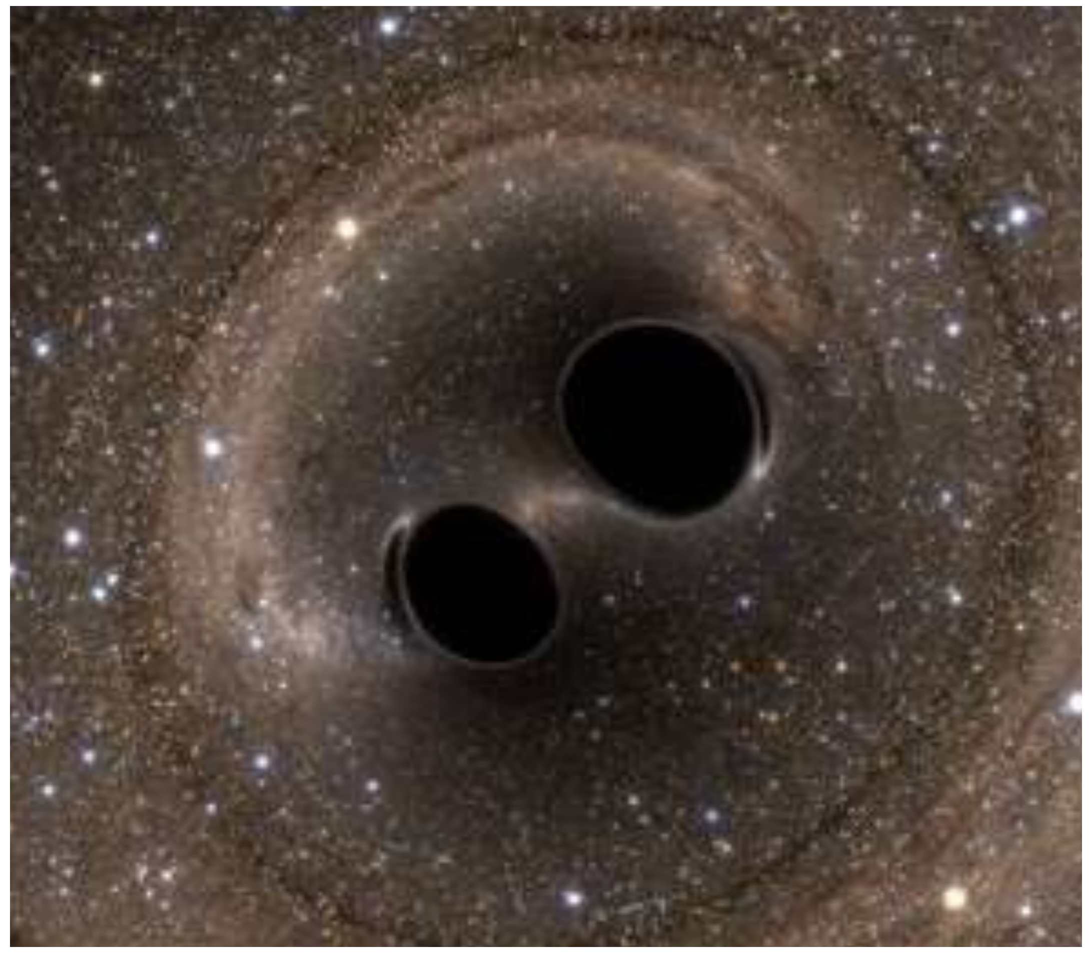
GW localisation

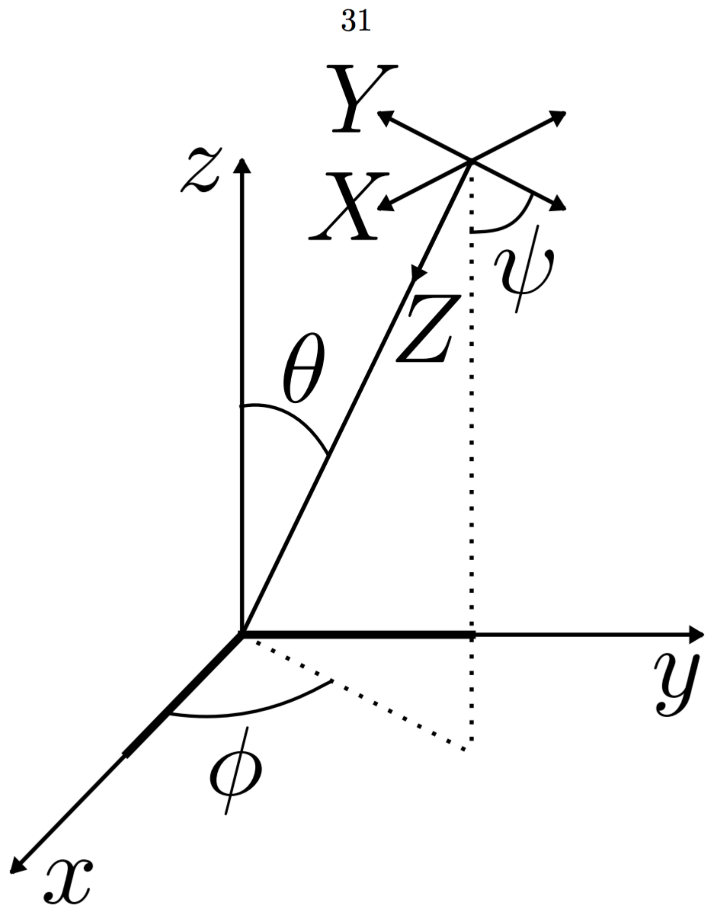
- Each detector sees a different signal

$$h = e^{2\pi i \vec{r}\cdot\vec{n} f}\left[F_+ h_+(\theta, f) + F_\times h_\times(\theta, f)\right]$$







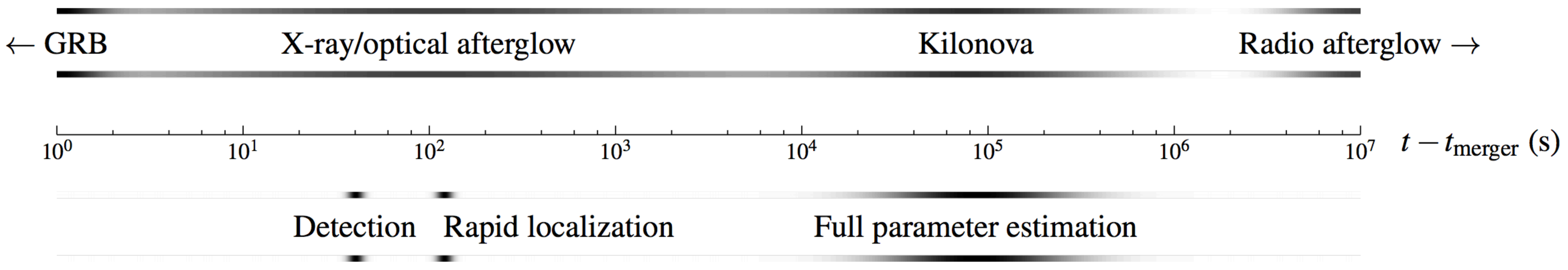


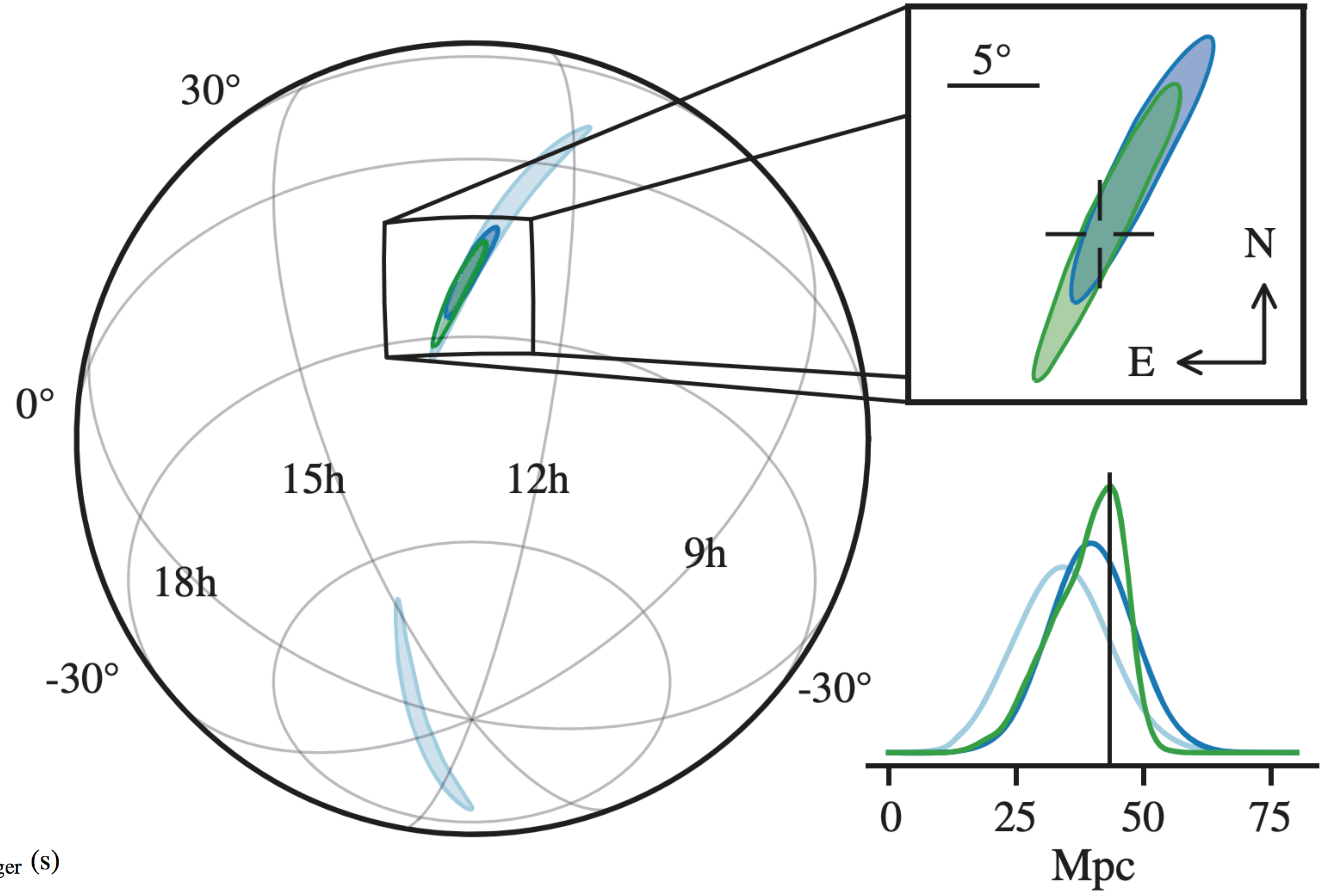
$$F_+ = \frac{1}{2}\left(1+\cos^2\theta\right)\cos 2\phi \cos 2\psi + \cos\theta \sin 2\phi \sin 2\psi$$

$$F_\times = \frac{1}{2}\left(1+\cos^2\theta\right)\cos 2\phi \sin 2\psi + \cos\theta \sin 2\phi \cos 2\psi$$

GW rapid localisation

- Relative amplitudes and time differences allow for rapid localisation O(100) s
- Localisation of GW170817 (arXiv:1710.05833)





Singer at al, arXiv:1404.5623

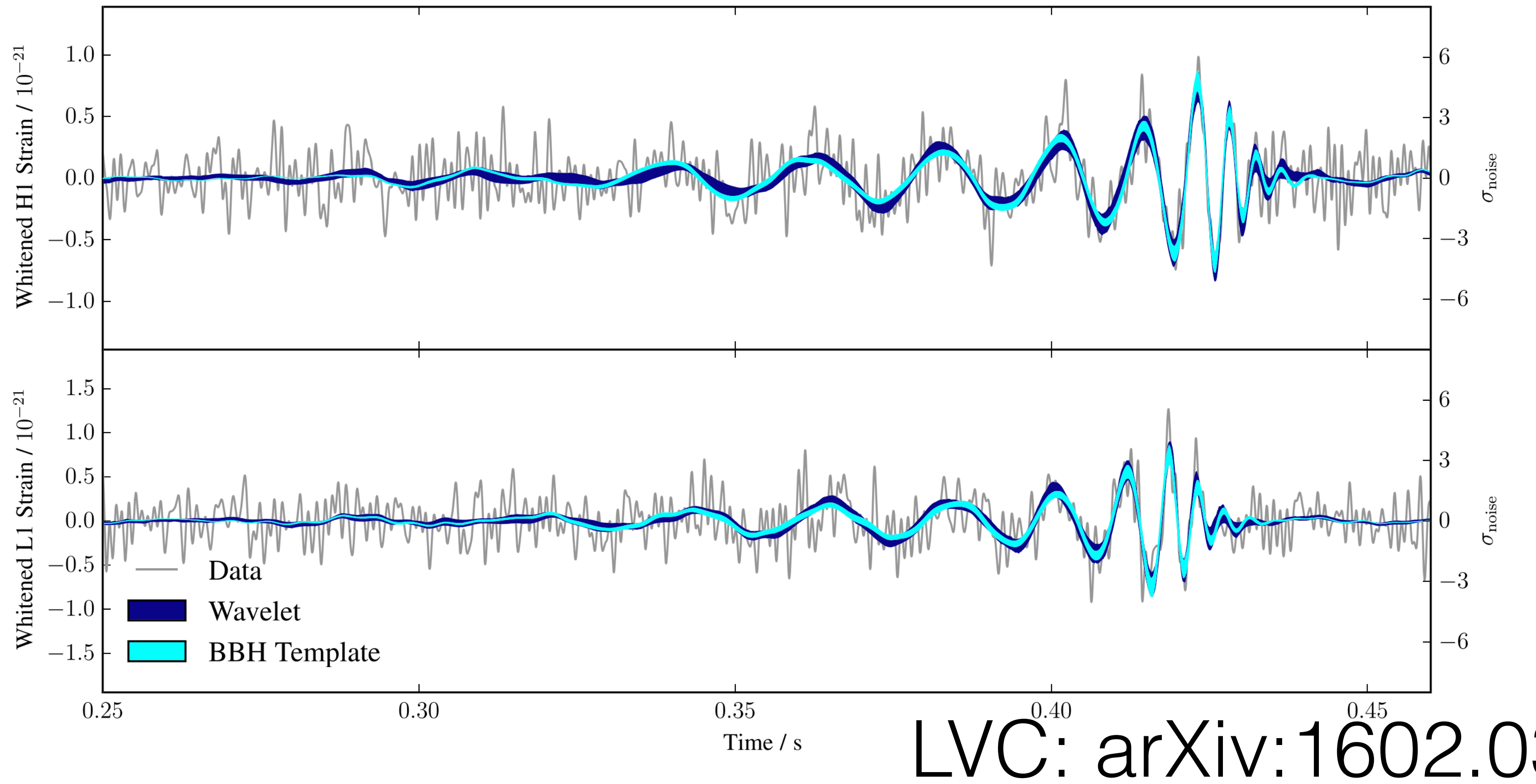
LVC, arXiv:1710.05832

Inference

- For candidate events, estimate posterior distributions using Bayes' theorem
- High dimensional parameter space
  - Markov Chain Monte Carlo
  - Nested Sampling
- Open source (Veitch et al, arXiv:1409.7215): https://github.com/lscsoft/lalsuite

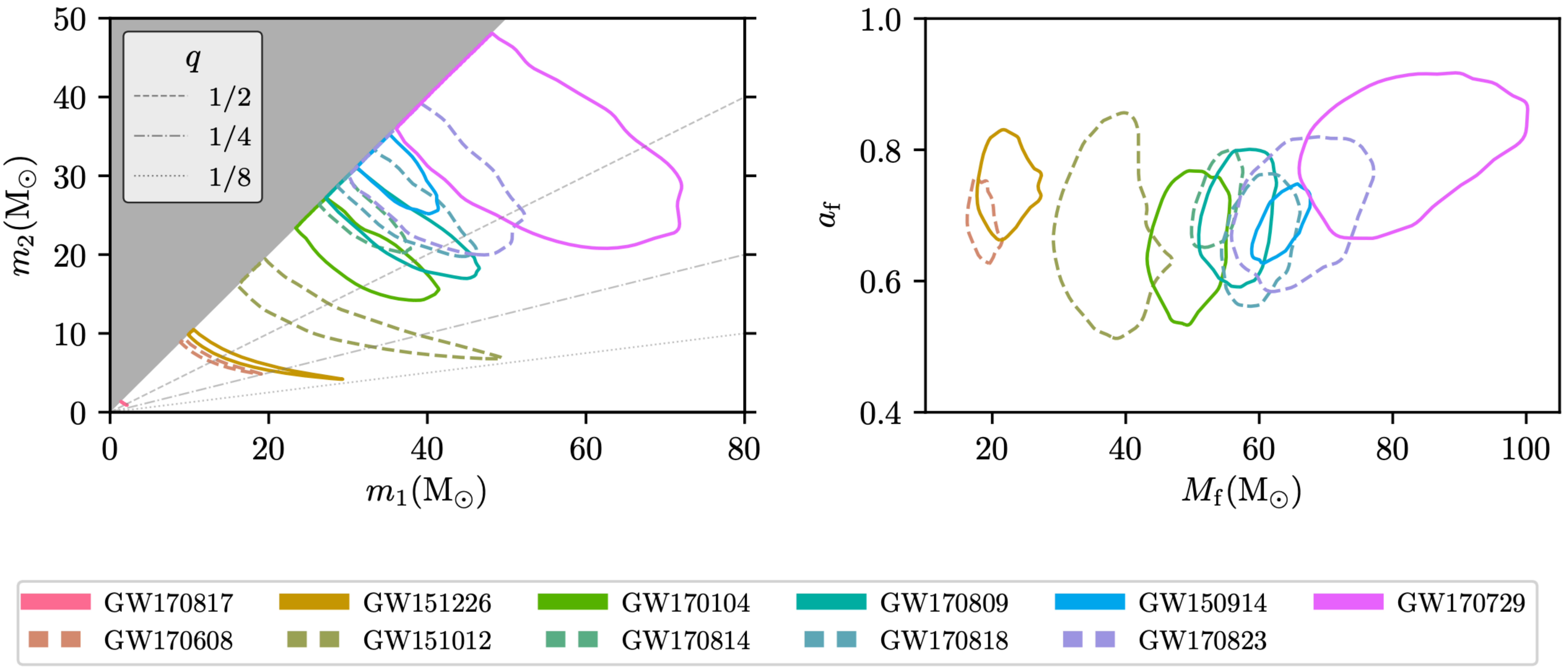
$$p(\theta|DSI) = \frac{p(\theta|SI)p(D|\theta SI)}{\int_\Theta p(\theta|SI)p(D|\theta SI)}$$

$\tau \sim 1 - 30$ days



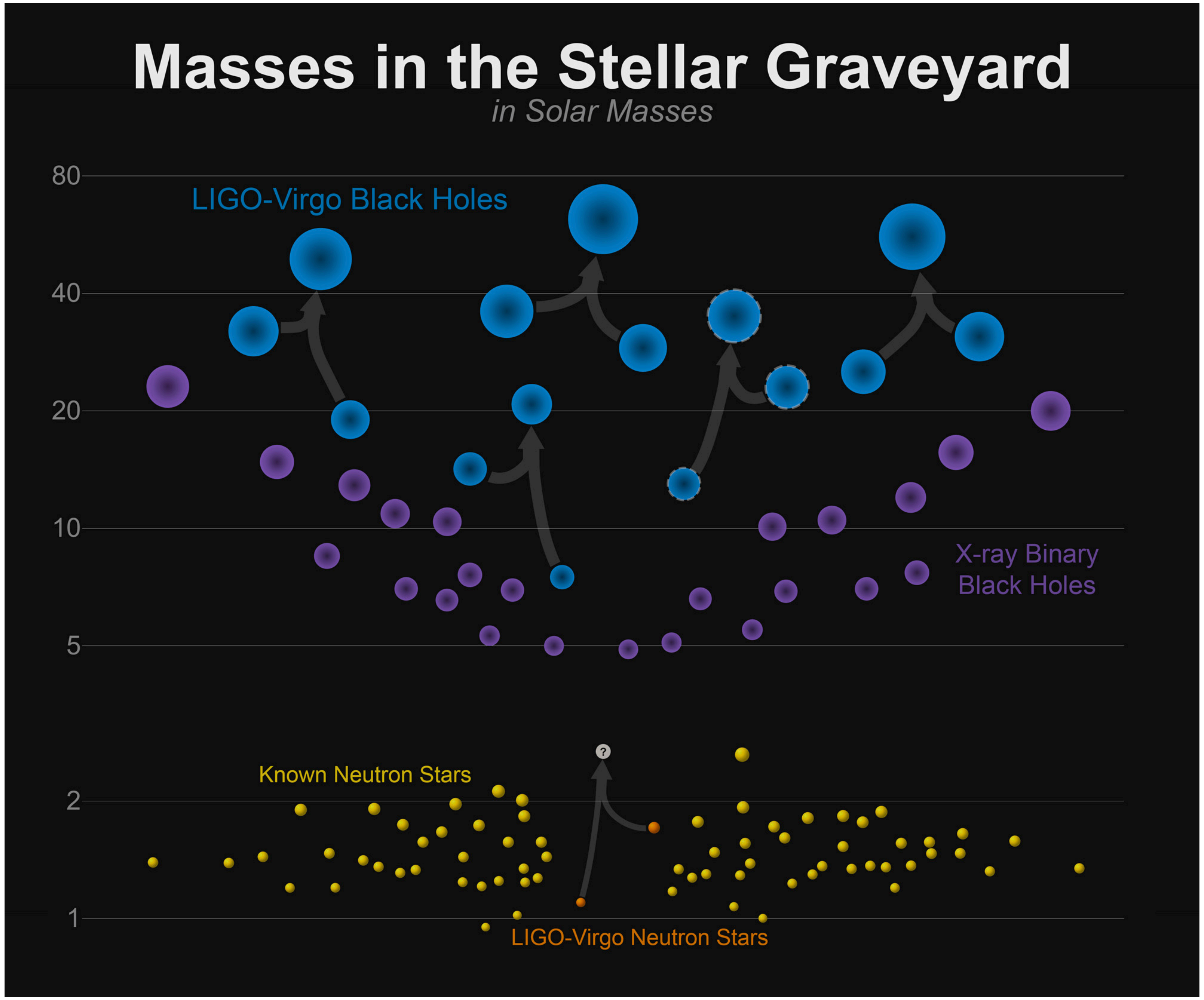
LVC: arXiv:1602.03840

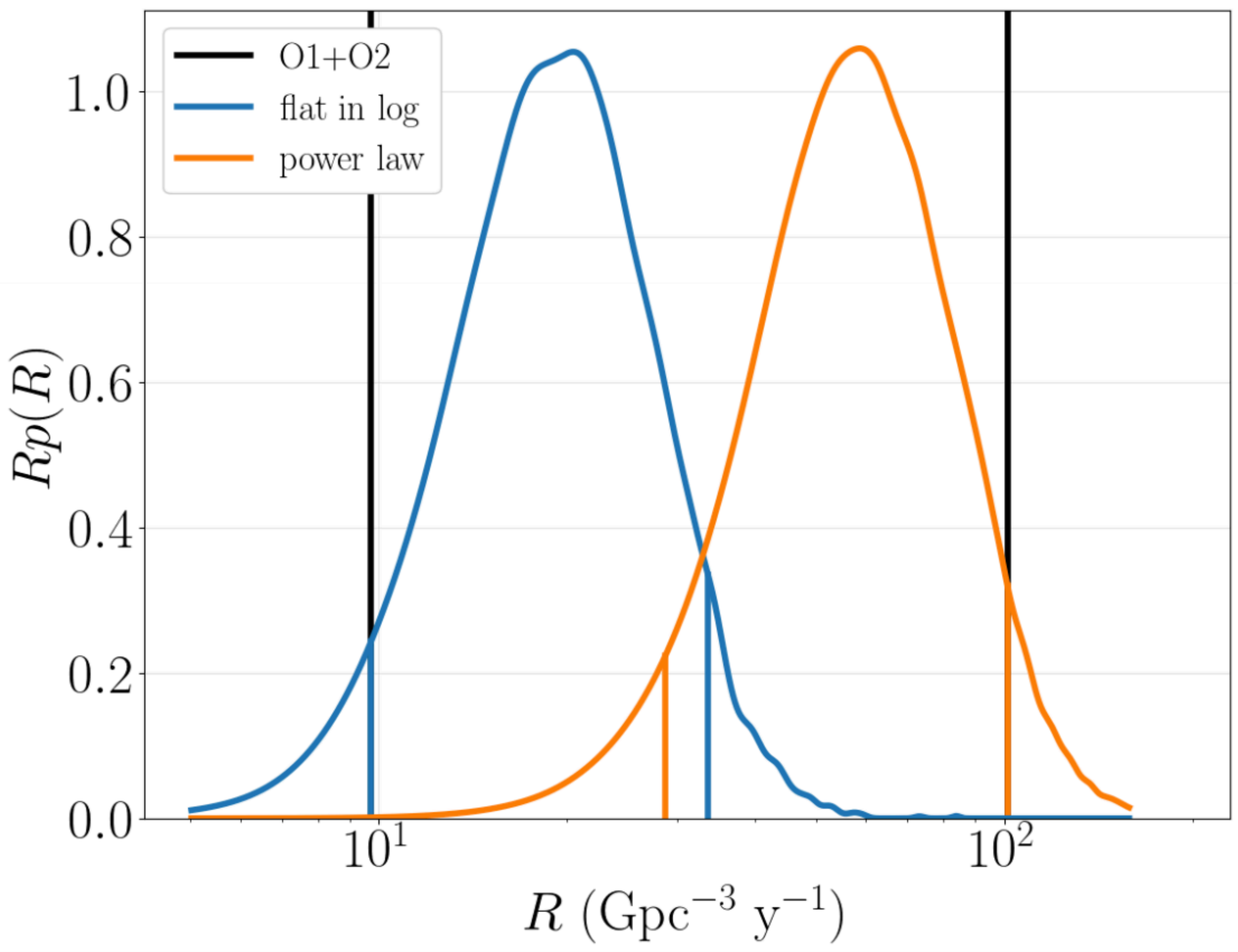
Overview of known signals



LVC: arXiv:1811.12907

How many black hole binaries?





$$R_{BBH} \in 10 - 100\,\mathrm{Gpc}^3\,\mathrm{yr}^{-1}$$

LVC: arXiv:1811.12907

Neutron Stars

- Latest stages in stellar life

$$m \simeq 1 - 3\,\mathrm{M}_\odot$$

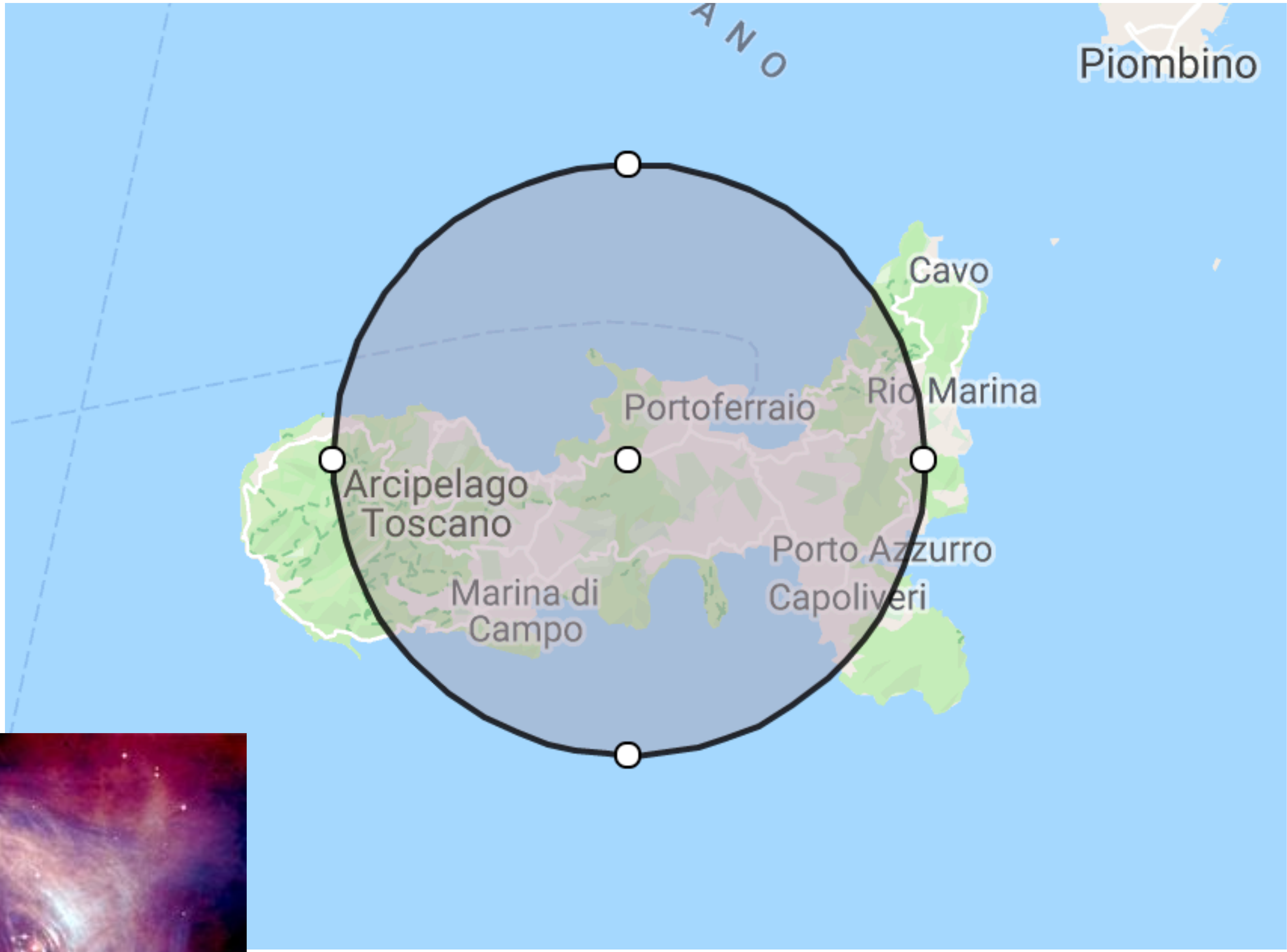
- Very compact

$$R \simeq 10 - 20\,\mathrm{km}$$

- Very dense

$$\rho_c \simeq 10^{17-18}\,\mathrm{kg\,m^{-3}}$$

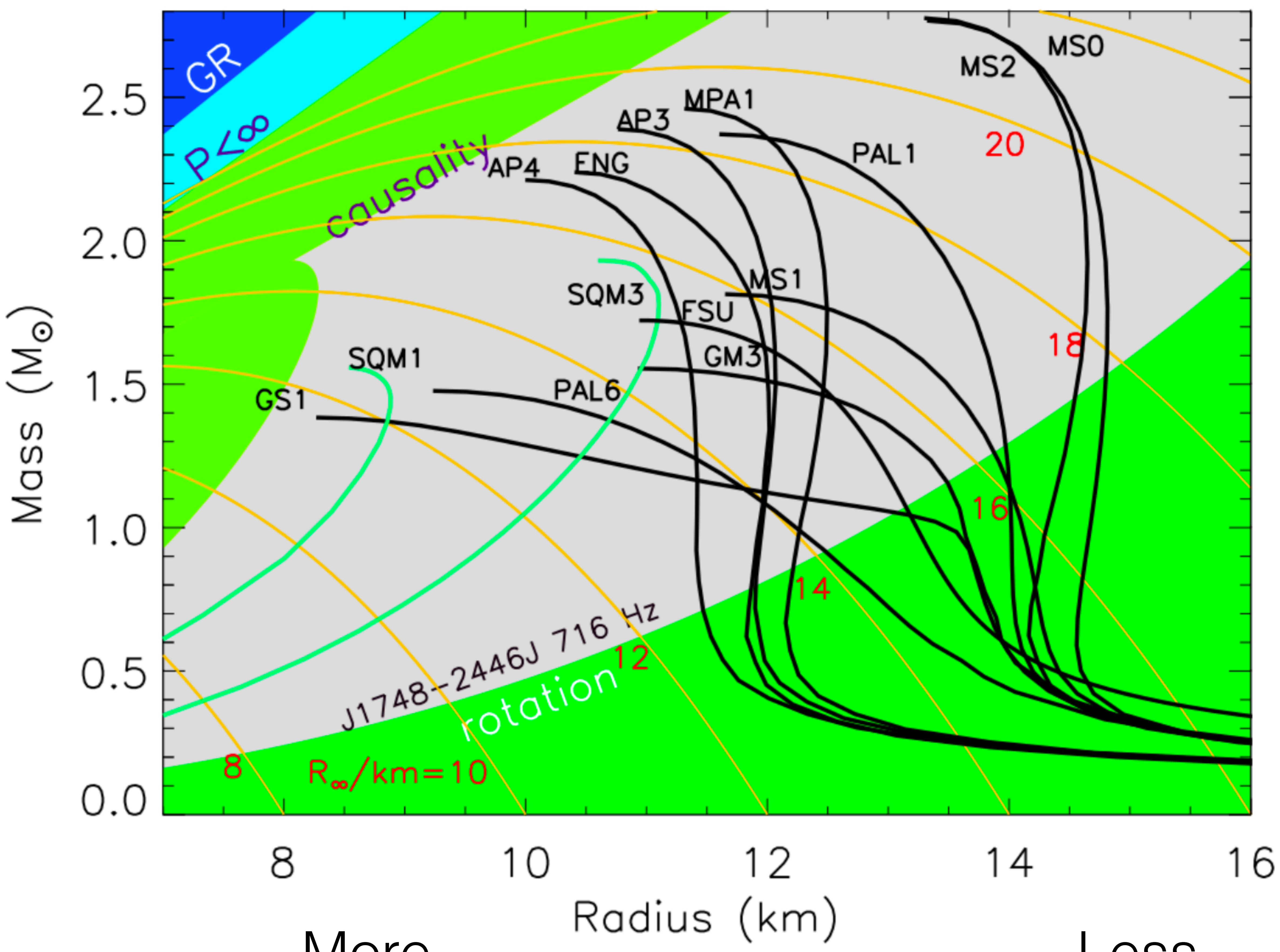
- Pulsars
  - Often found in binaries



Neutron Star equation of state and perturbations

- Densities are such that details of nuclear interaction matter macroscopically
- Equation of state
  - Relation between density and pressure
  - Relation between mass and radius
- Perturbations are observables for EOS
  - deformations
  - oscillations

Soft ← → Stiff



More Compact → Less Compact

Lattimer, arXiv:1305.3510

Binary Neutron Stars

- Tidal field of the companion deforms neutron star

- Tidal deformability function

$$Q_{ij} = -\lambda(\mathrm{EOS}; m)\tau_{ij}$$

quadrupole moment

tidal field of companion star

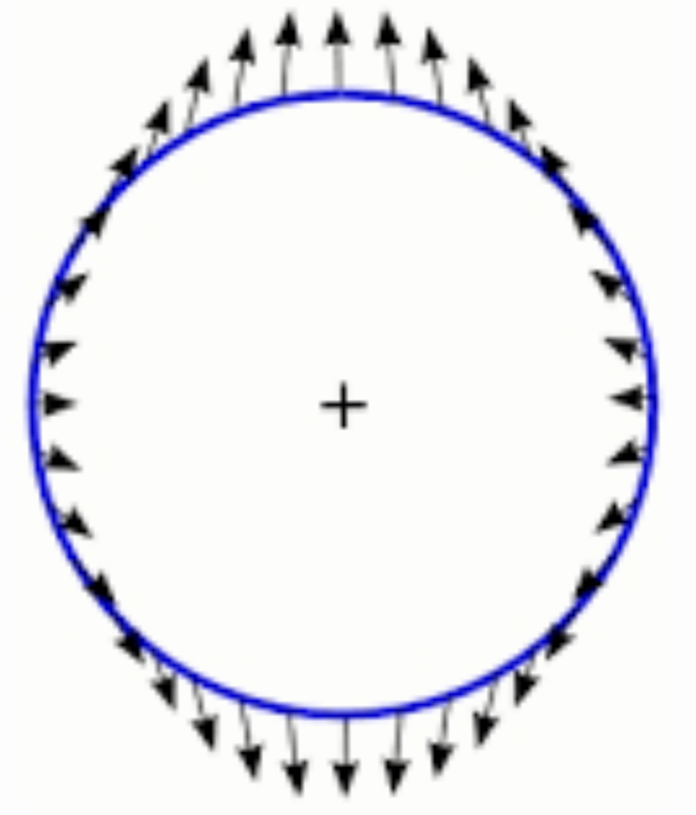
$$\lambda(m) = \frac{2}{3}k_2 R^5(m)$$

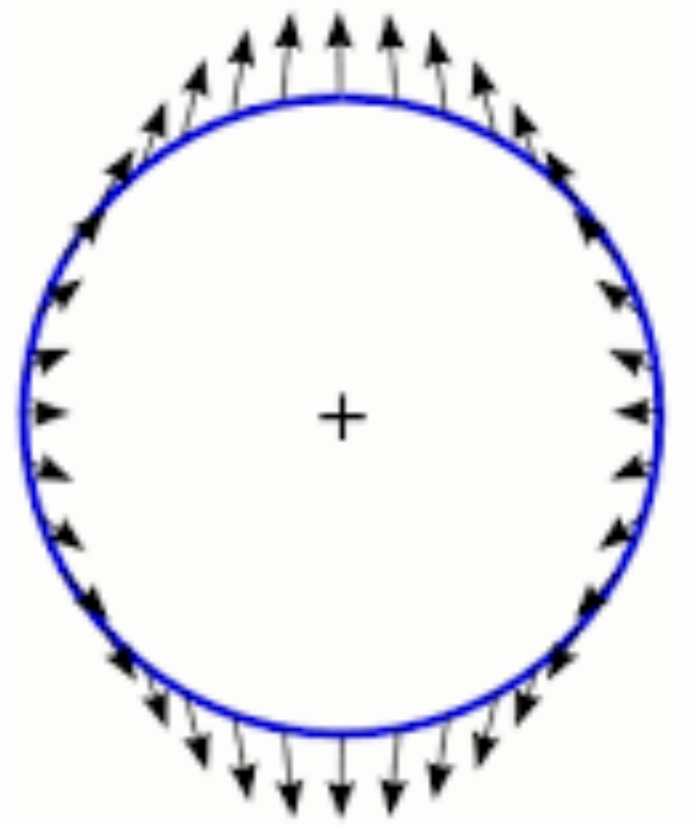
second Love number

NS radius

- Time-varying quadrupole => gravitational waves

- Energy exchange between internal and external degrees of freedom

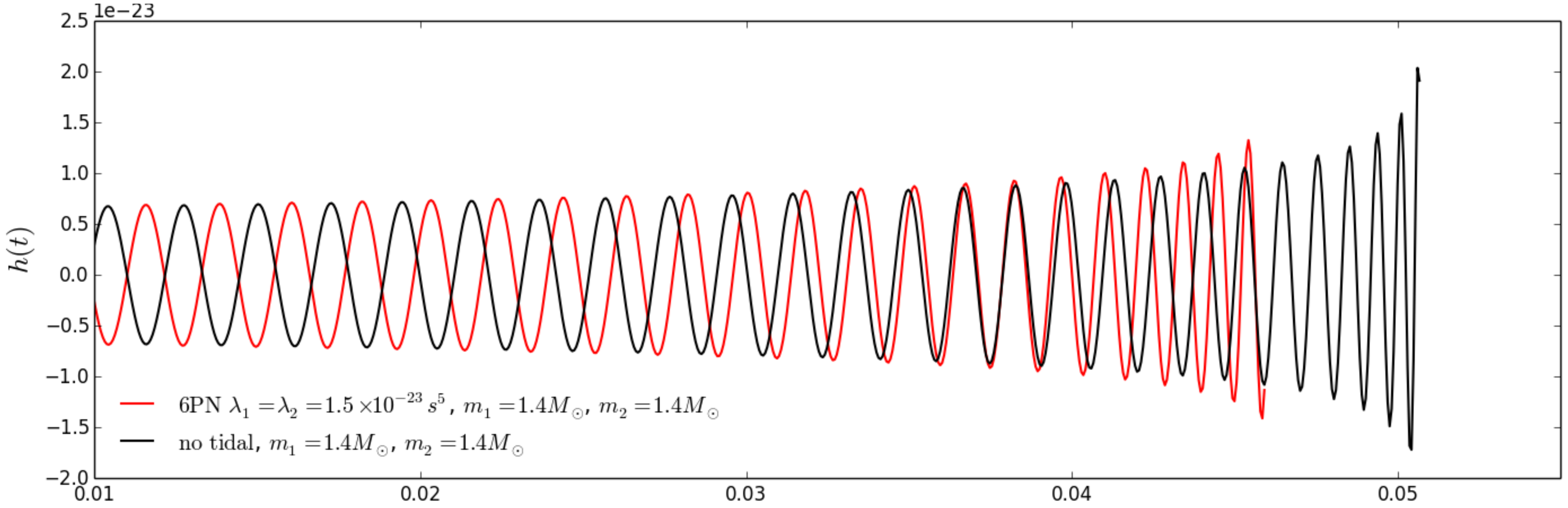




EOS signature during the inspiral

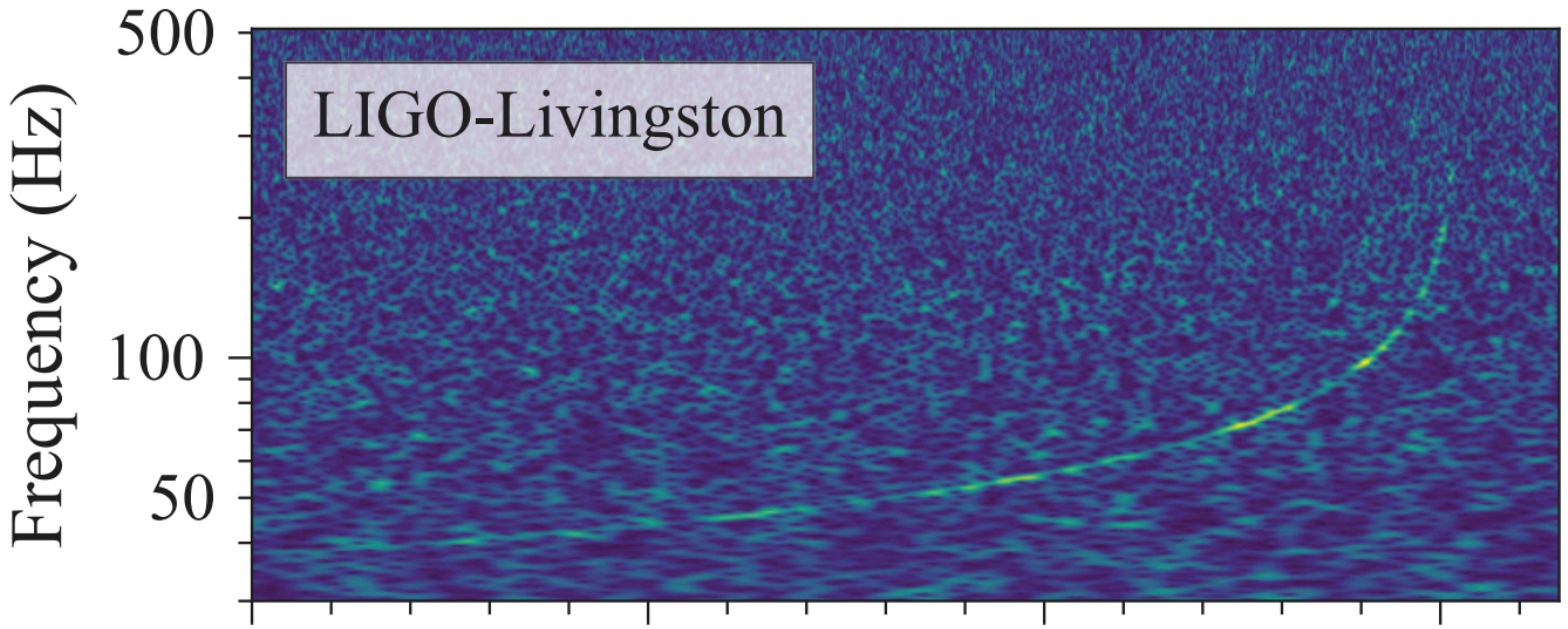
- Tidal deformations change the phase of the gravitational wave

$$\Phi(t) = \Phi_{\mathrm{PP}}(t) + \Phi_{\mathrm{tidal}}(t)$$



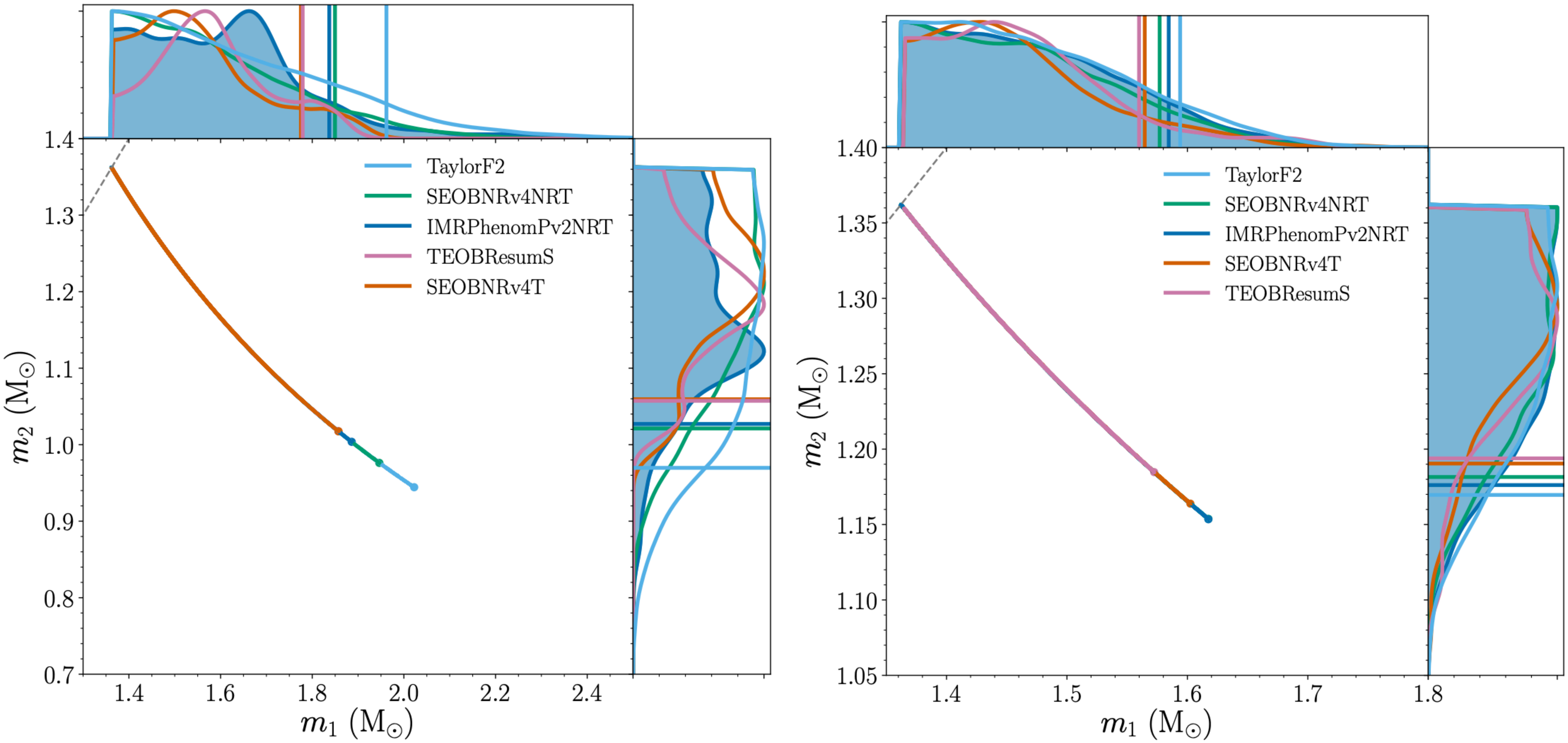
$$\Phi_{\mathrm{tidal}}(v) = \sum_{a=1}^{2} \frac{3\lambda_a}{128\eta M^5}\left[-\frac{24}{\chi_a}\left(1+\frac{11\eta}{\chi_a}\right)\left(\frac{v}{c}\right)^5 - \frac{5}{28\chi_a}\left(3179 - 919\,\chi_a - 2286\,\chi_a^2 + 260\,\chi_a^3\right)\left(\frac{v}{c}\right)^7\right]$$

- Detectors are sensitive to the inspiral part of the signal (20 - 1000 Hz)



Hinderer et al, arXiv:0911.3535
Vines et al, arXiv:1101.1673

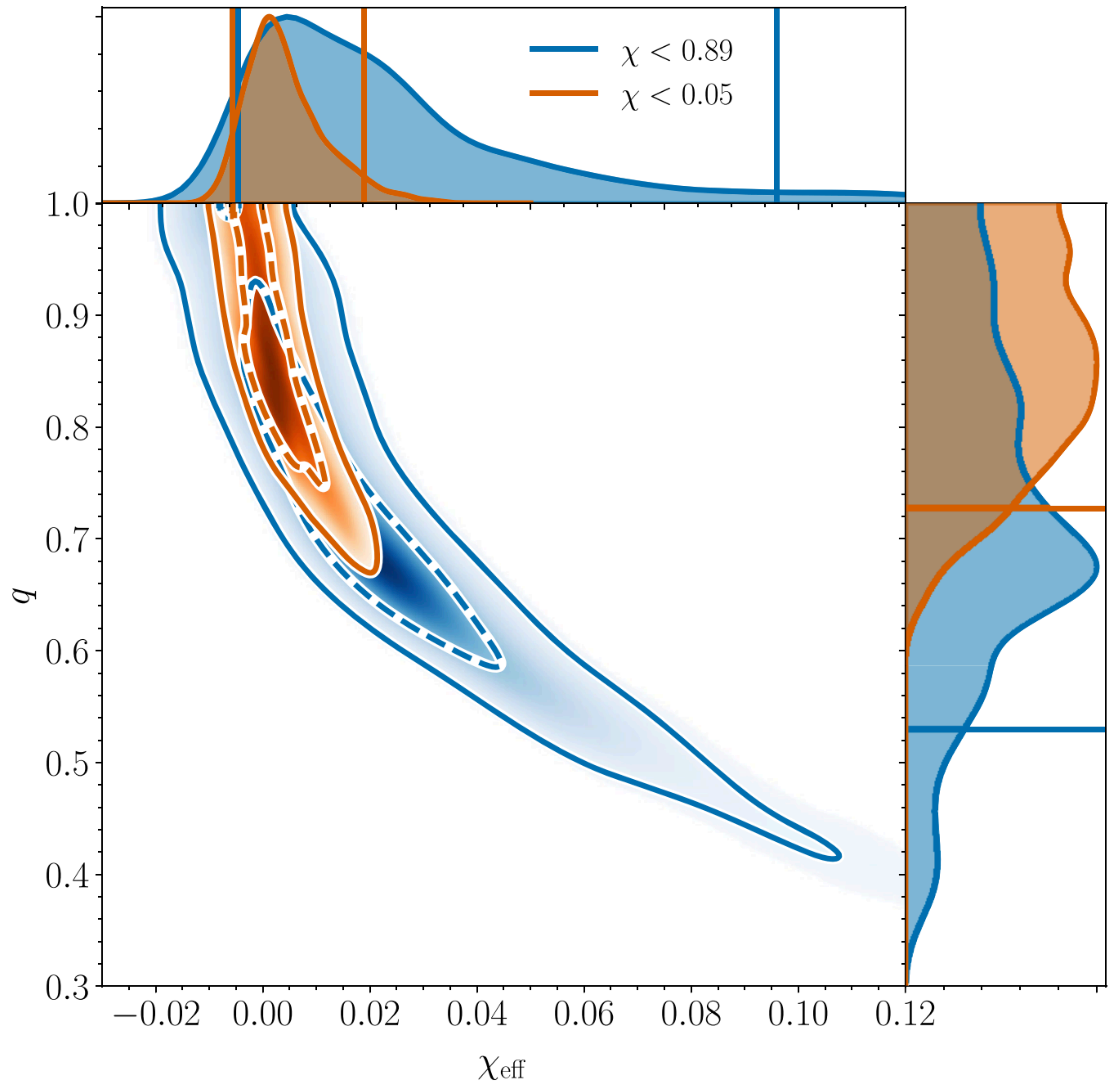
GW170817: masses



LVC, arXiv:1805.12197

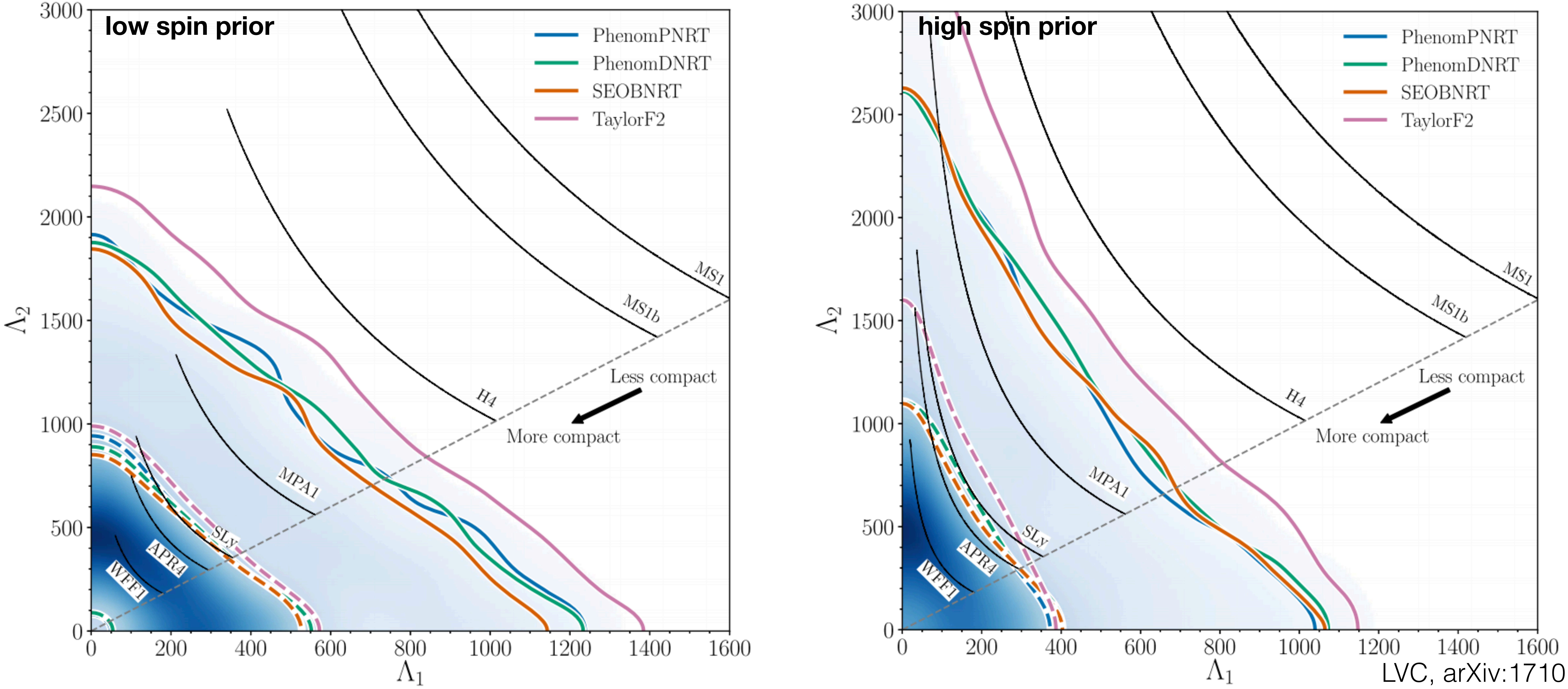
Spin-mass-lambda degeneracy

- Spin - mass ratio - lambda degeneracy
- Constraints on lambda depend on choice of spin prior



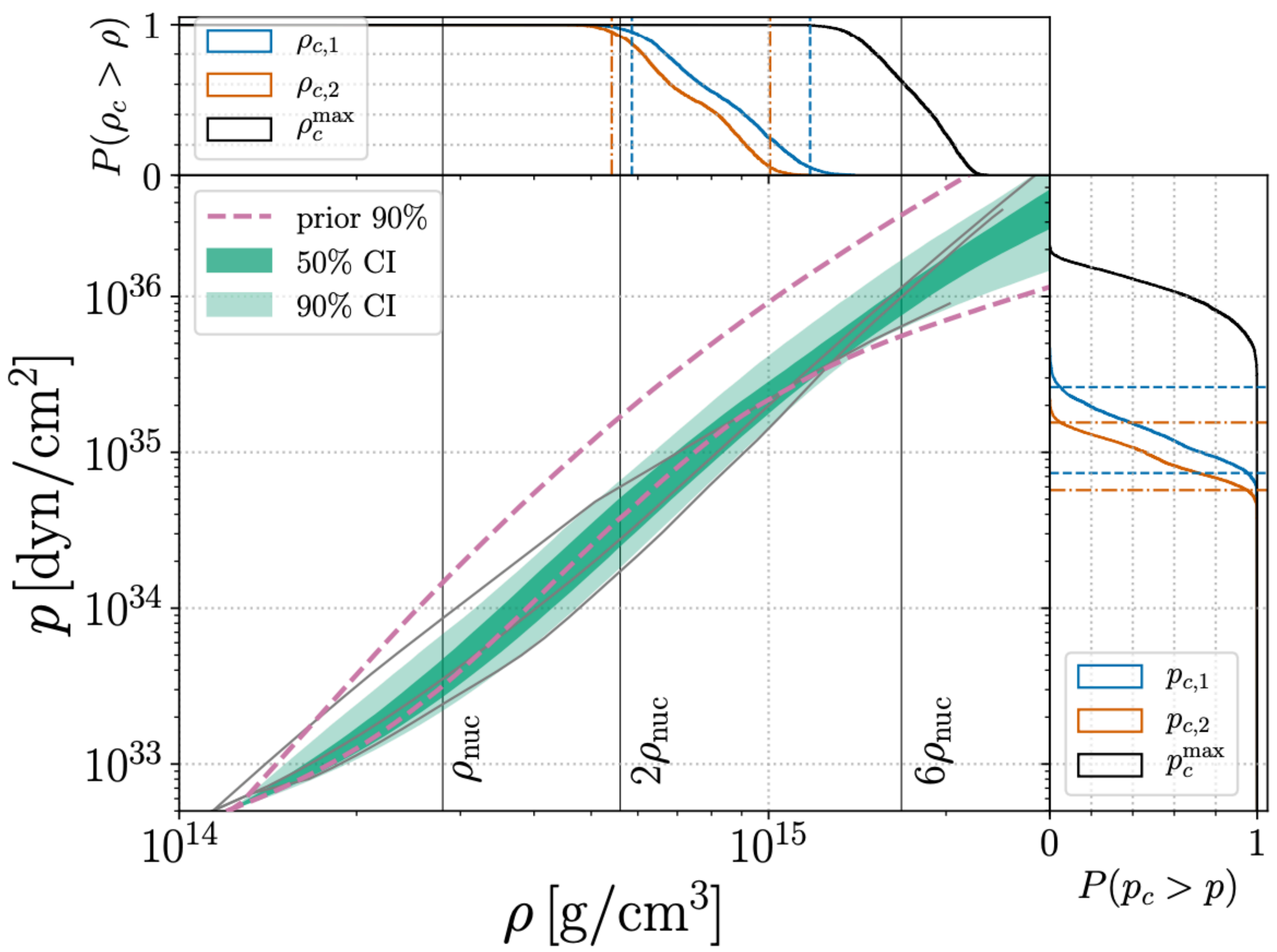
LVC, arXiv:1805.11579

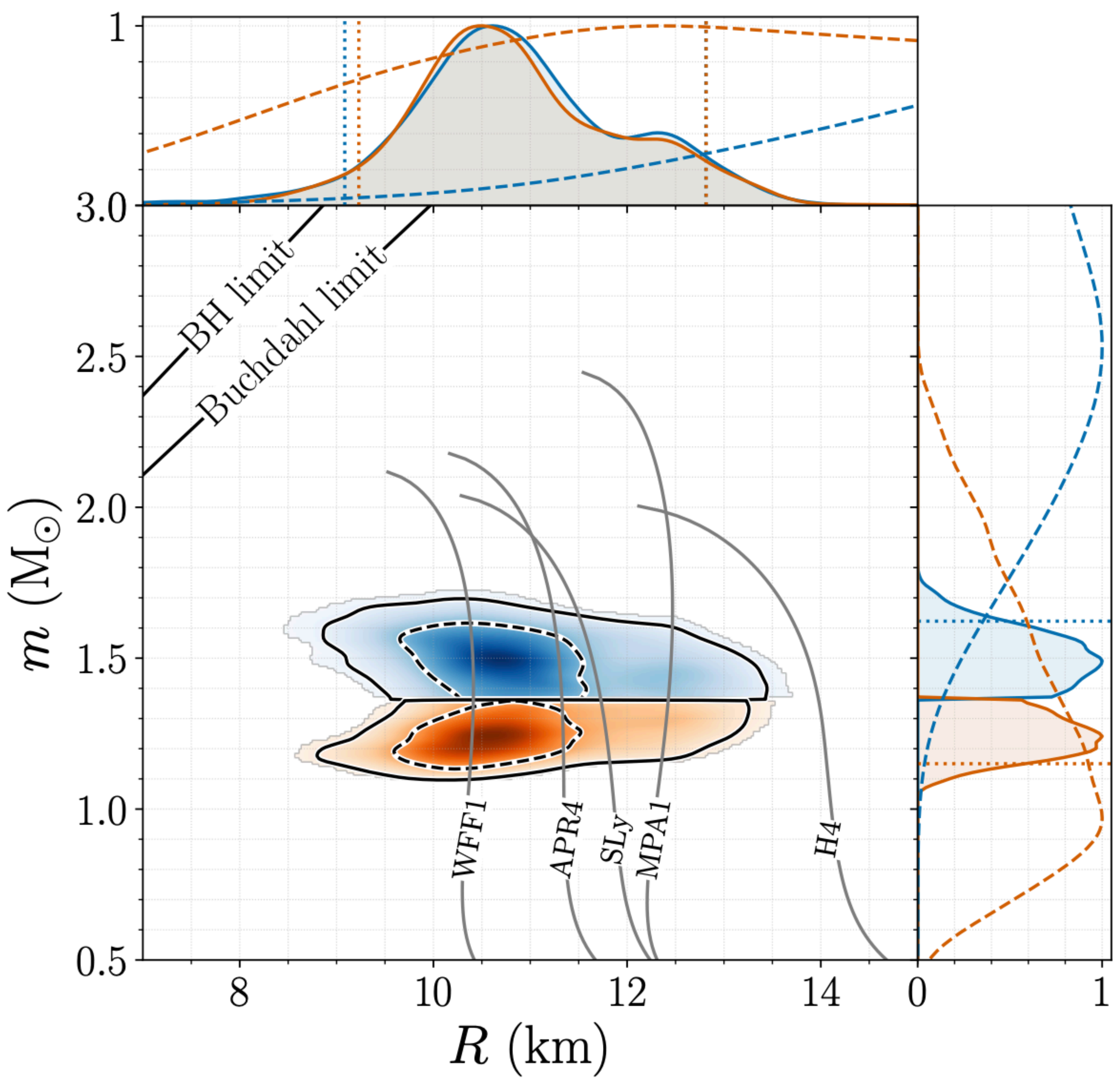
Lambda constraints

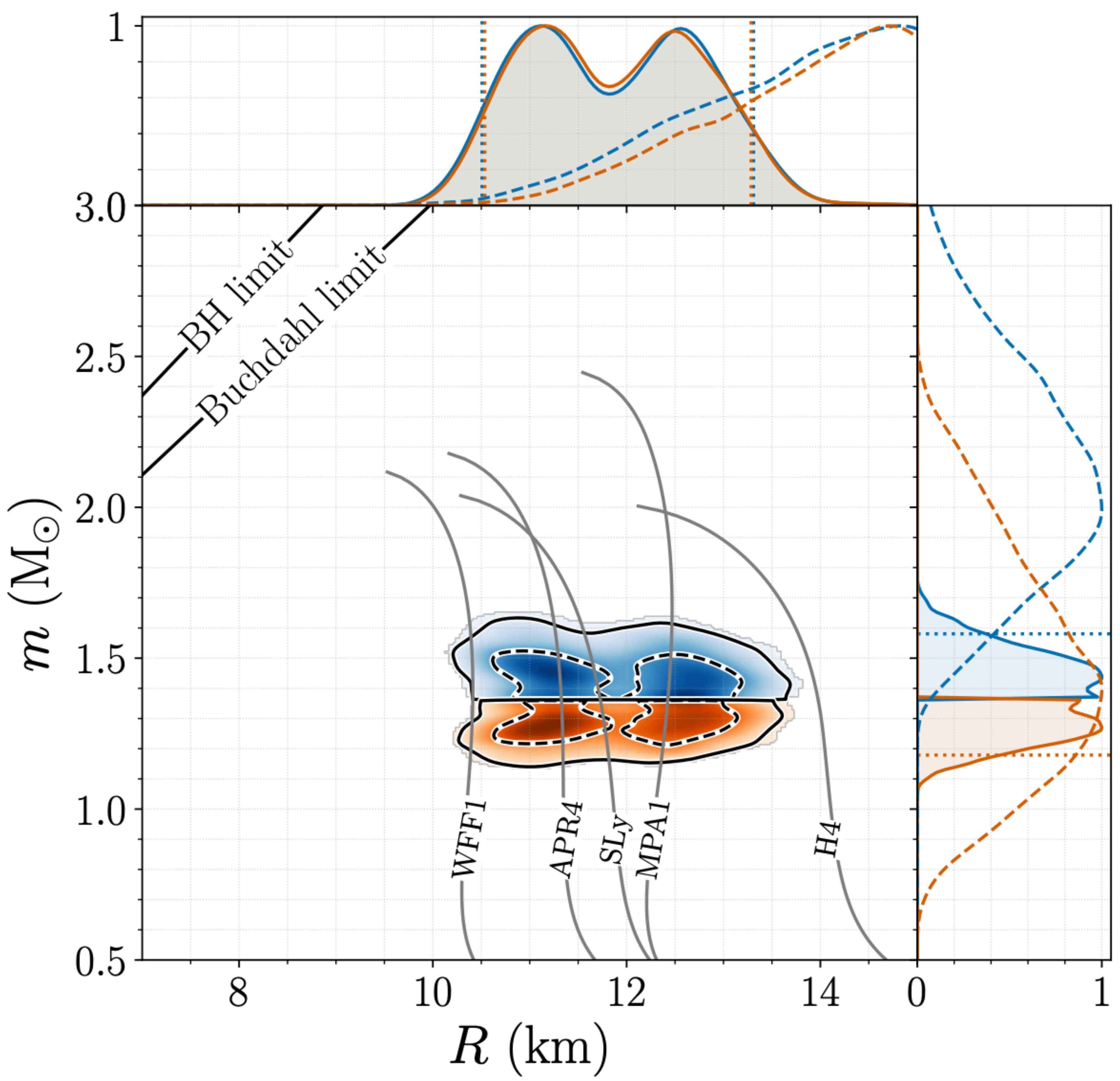


LVC, arXiv:1710.05832
LVC, arXiv:1805.11579

NS Radii



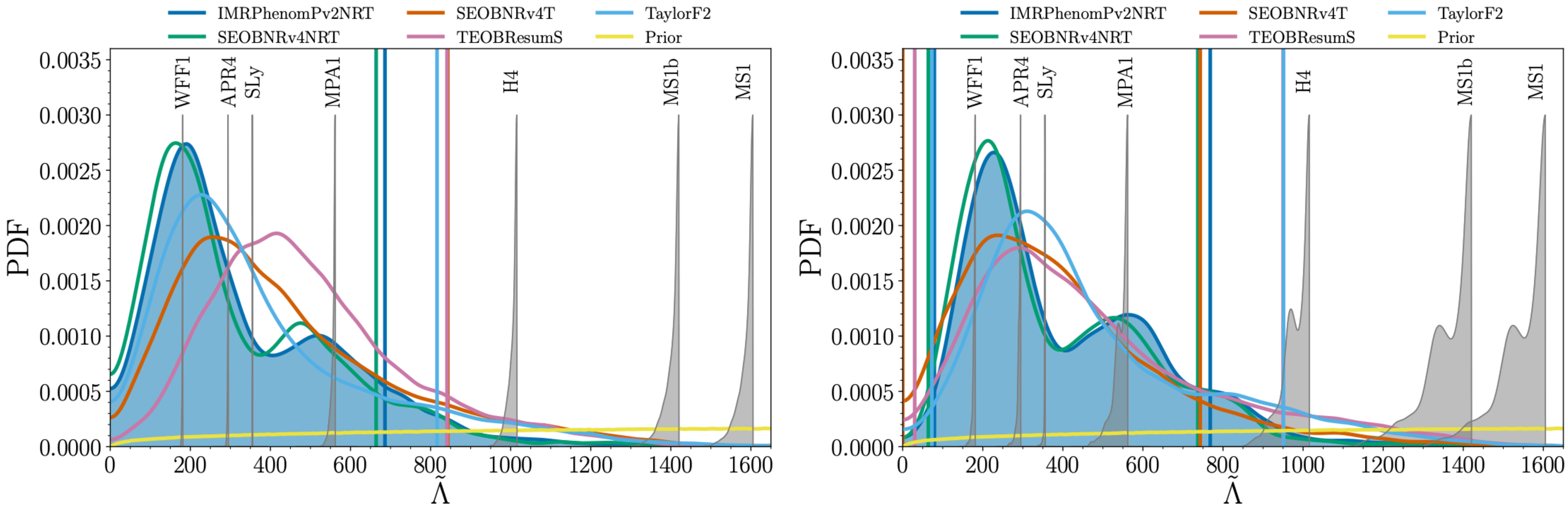




$$\rho_s = 3.5^{+2.7}_{-1.7} \times 10^{34}\,\mathrm{dyn/cm^2}$$

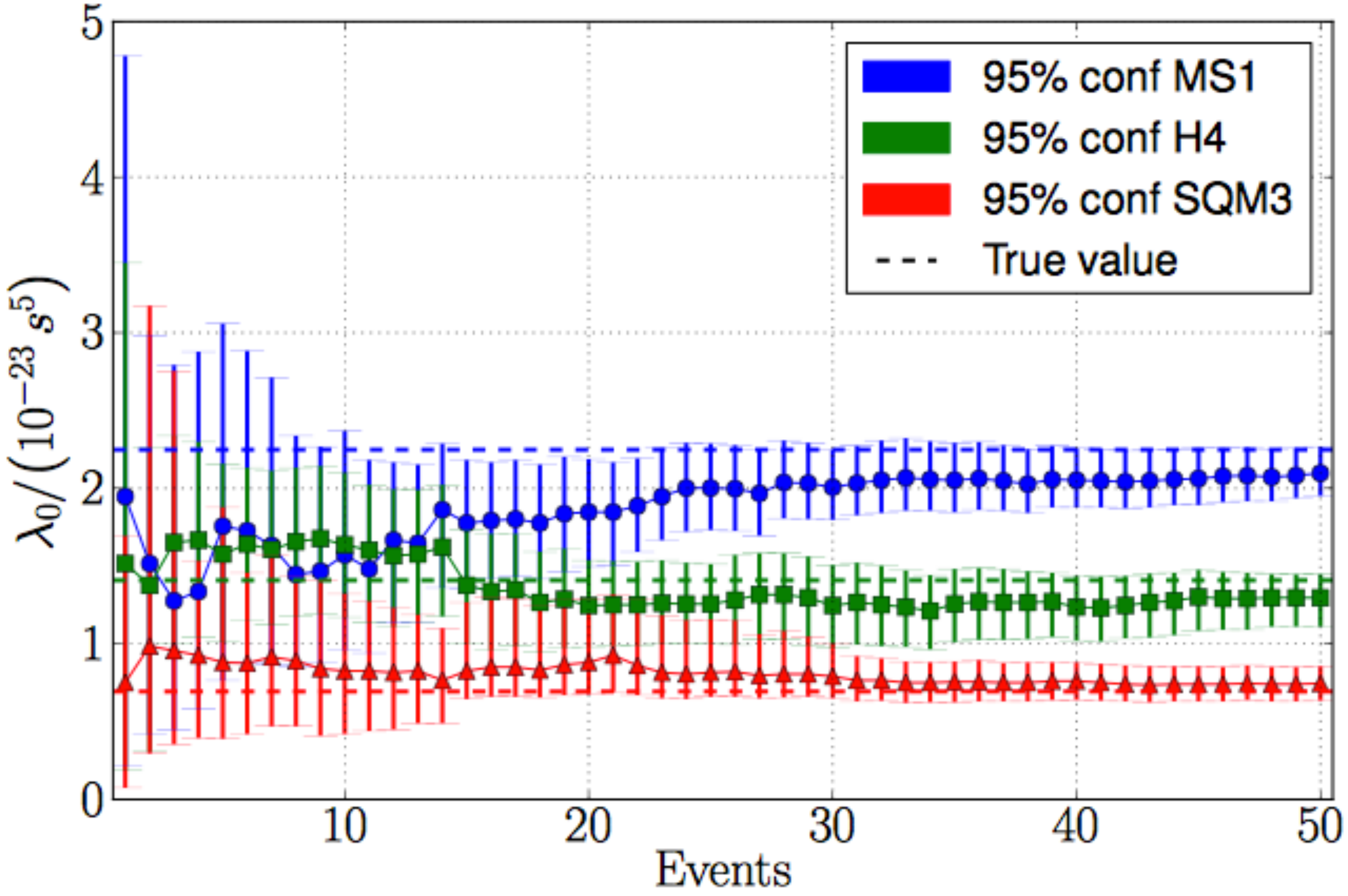
LVC, arXiv:1805.11581

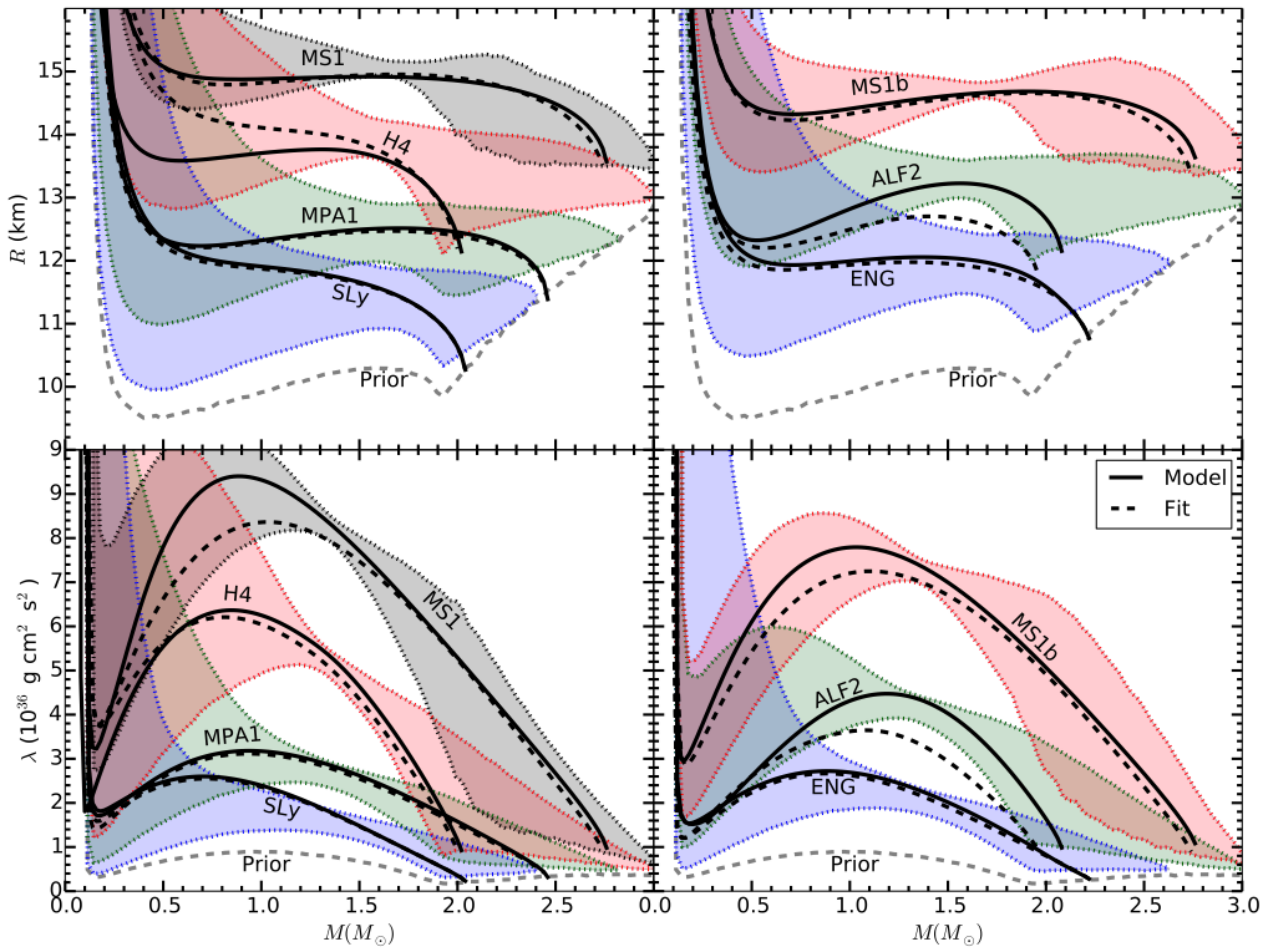
Which EOS?



LVC, arXiv:1805.12197

Perspectives on λ(m)





Del Pozzo et al, arXiv:1307.8338

Lackey & Wade, arXiv:1410.8866

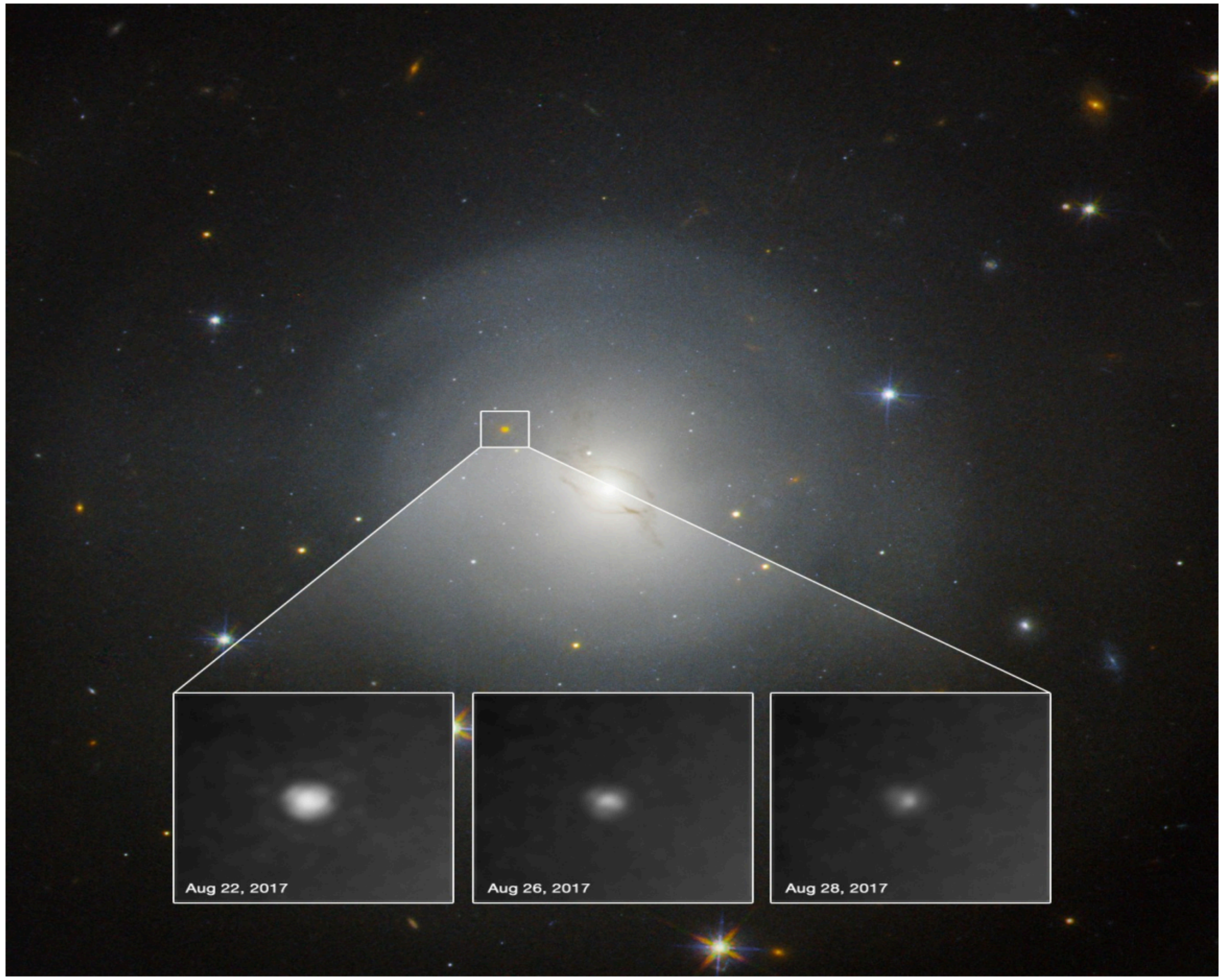
Multi-messenger observations

- Multi-messenger observation
- BNS are progenitors for
  - sGRB
  - kilonovae
- GW travel at c (LVC, arXiv: 1811.00364)

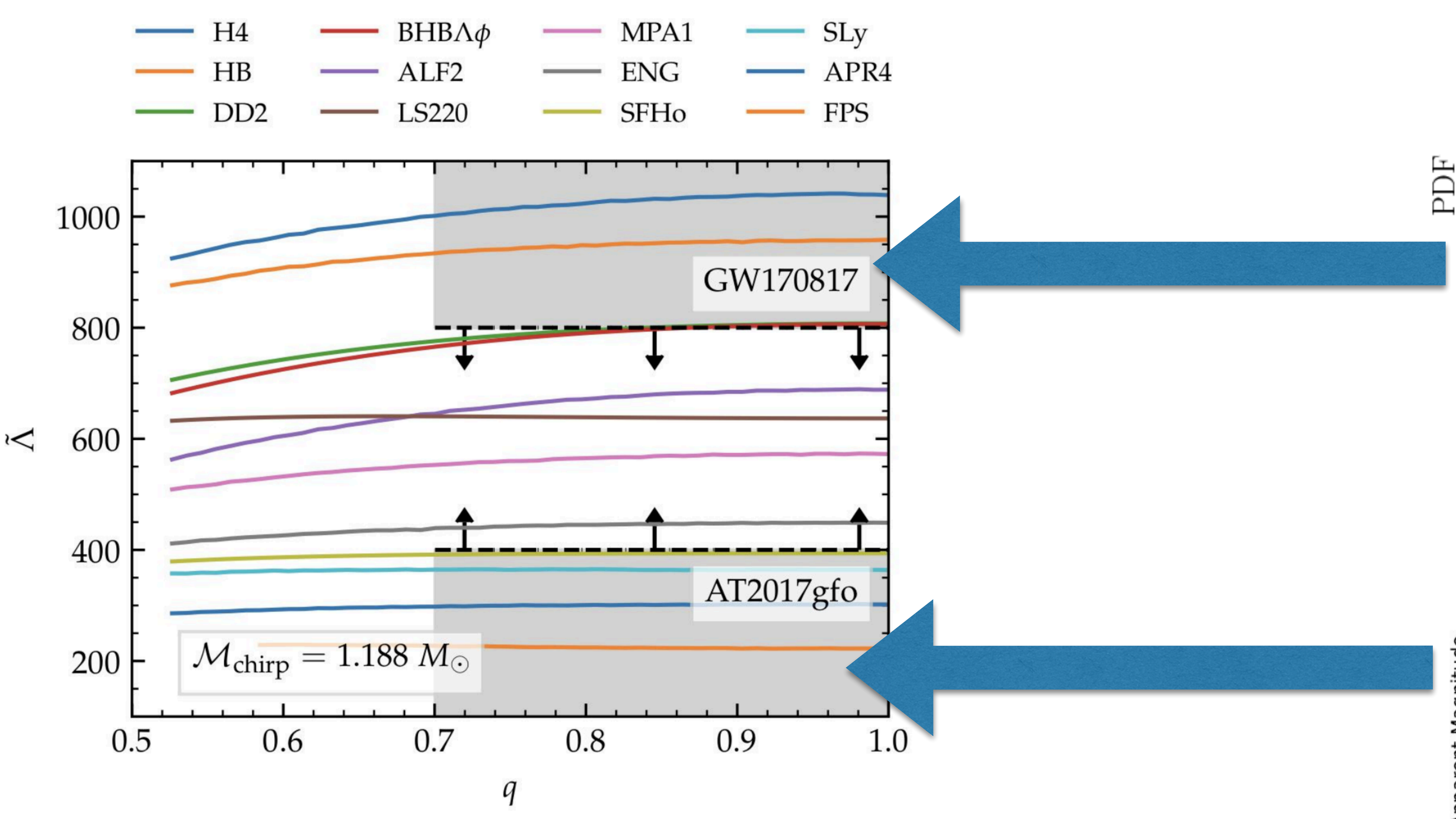
$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{EM}} \leq 7 \times 10^{-16}$$

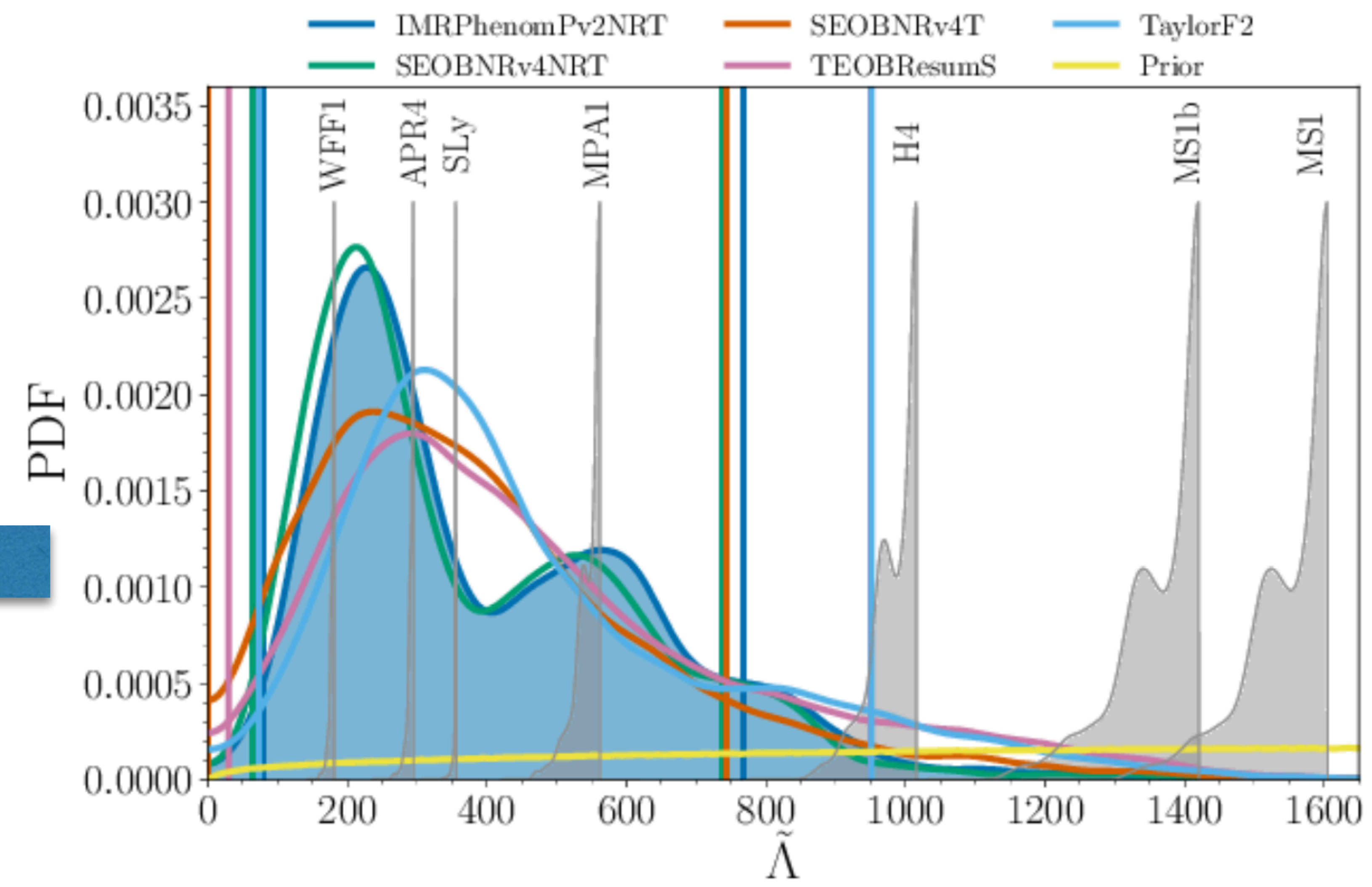
- First GW determination of Hubble constant (LVC, arXiv:1710.05835)

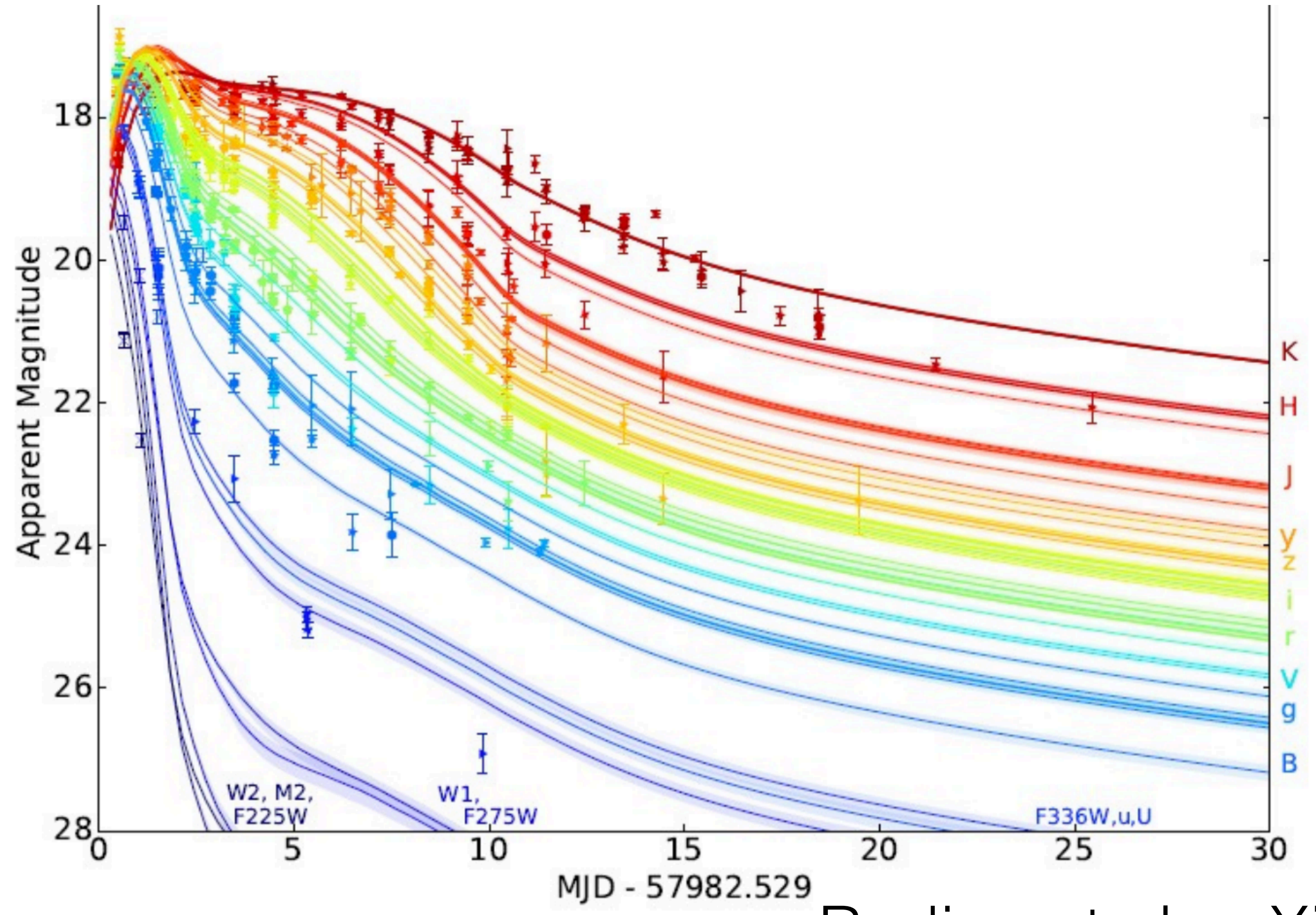
$$H_0 = 70^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$



Multi-messenger constraints



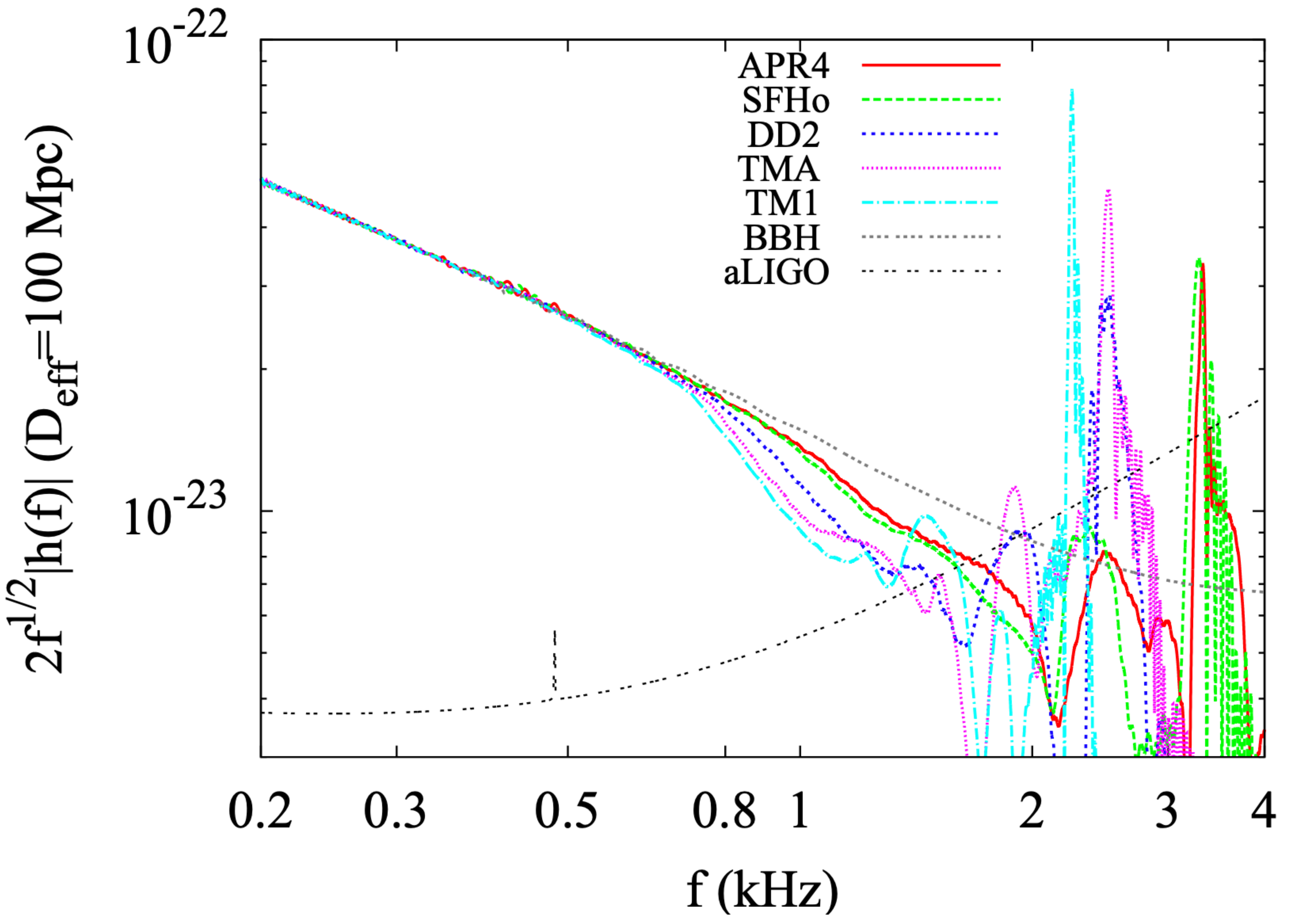




Radice et al, arXiv:1711.03647

On the merger remnant

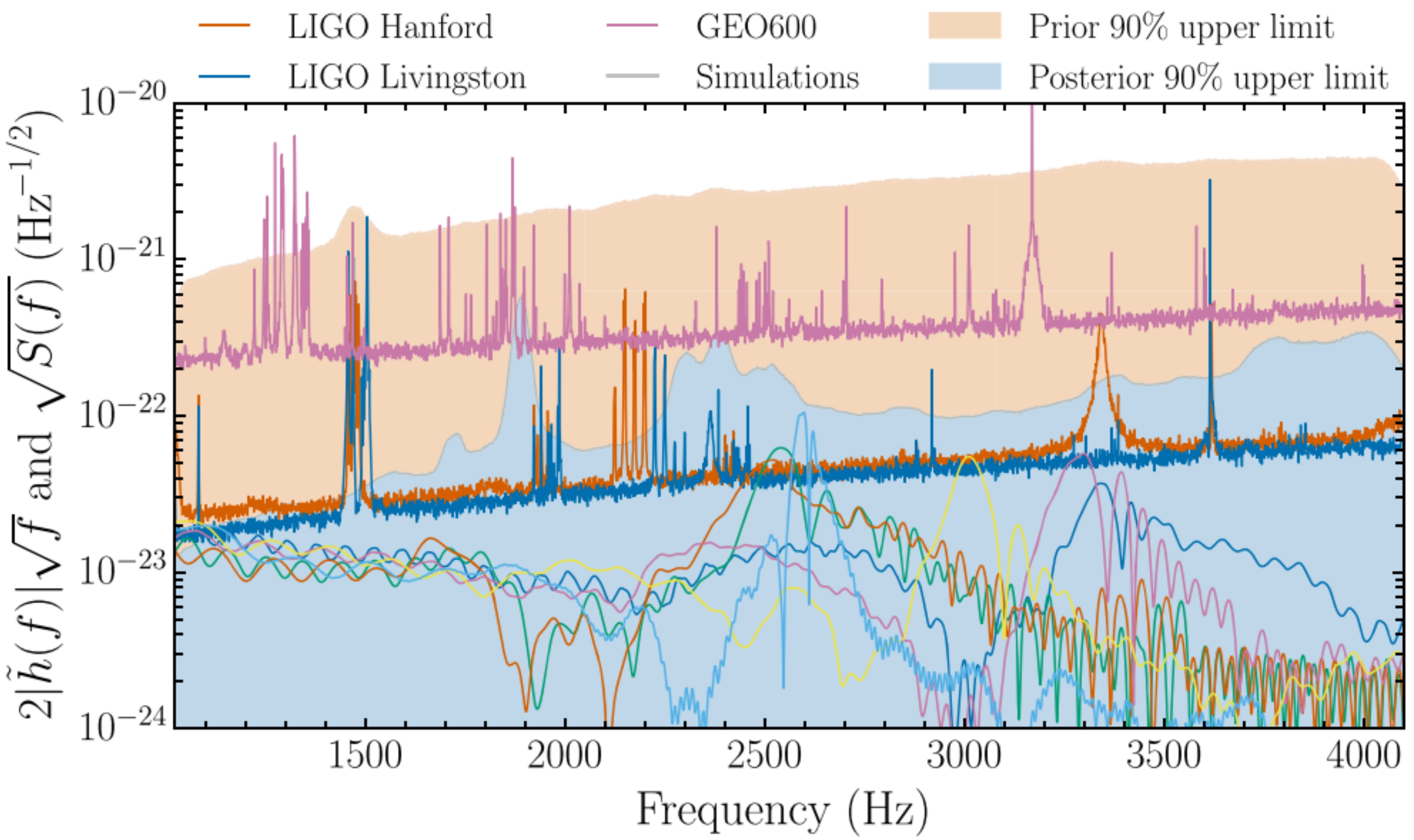
- Post-merger emission contains details of non-zero temperature EOS
- From simulations characteristic emission frequencies
  - EOS dependent
- Likely observable with 3rd generation interferometers



Hotokezaka et al, arXiv:1603.01286

GW170817 post-merger

- No detectable post-merger signal (but see Van Putten et al, arXiv:1806.02165)
- Unknown fate for the remnant
  - Collapse to a BH in ~ 1s? (Gill et al, arXiv:1901.04138)



LVC, arXiv:1710.09320

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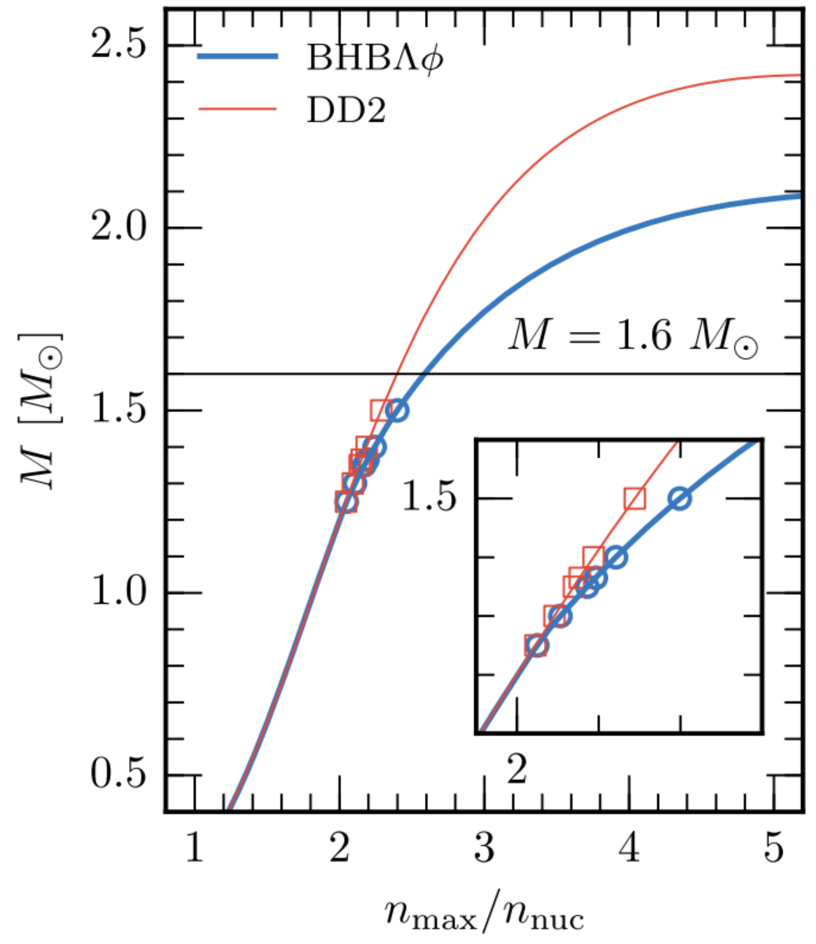
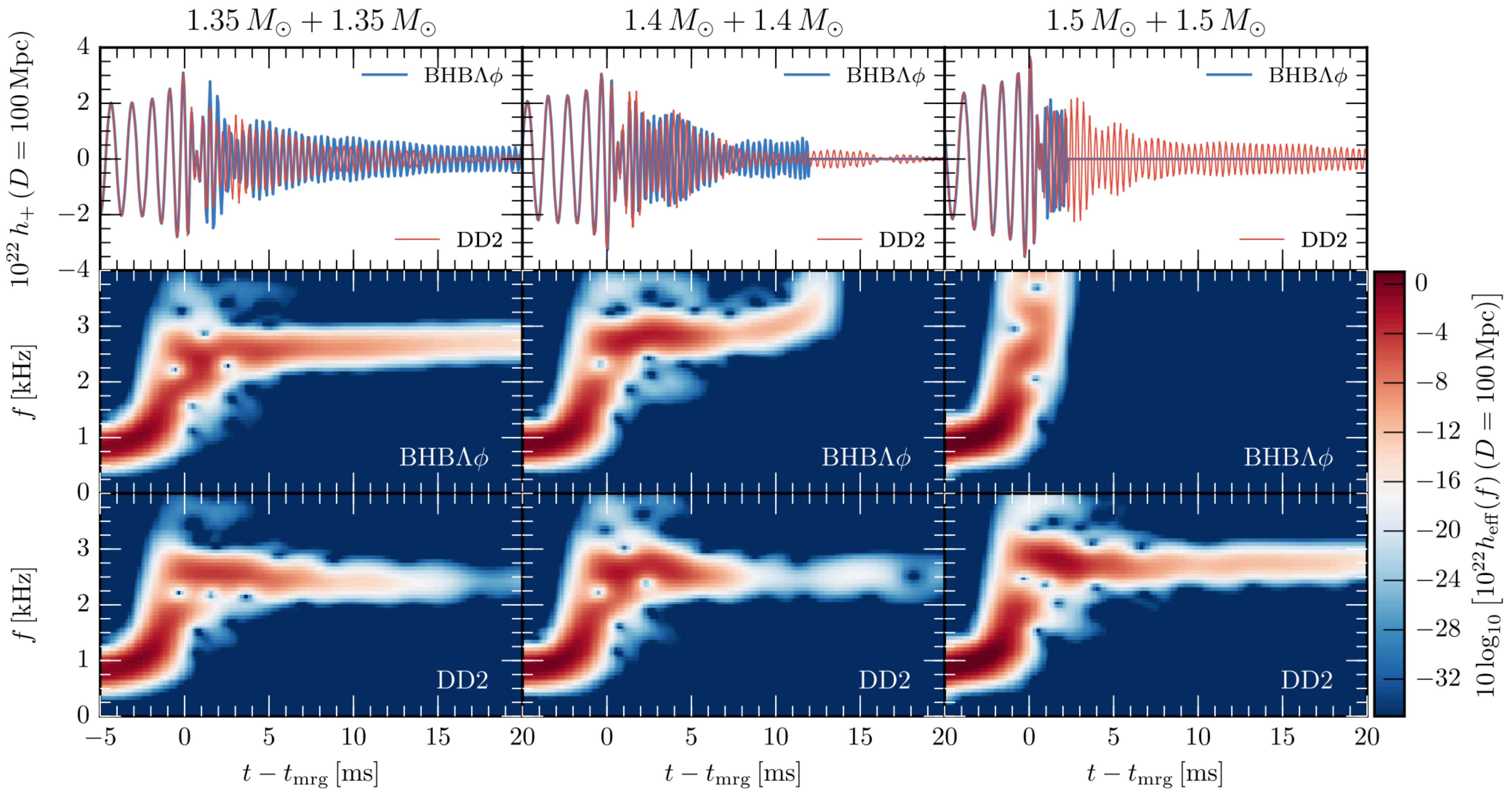
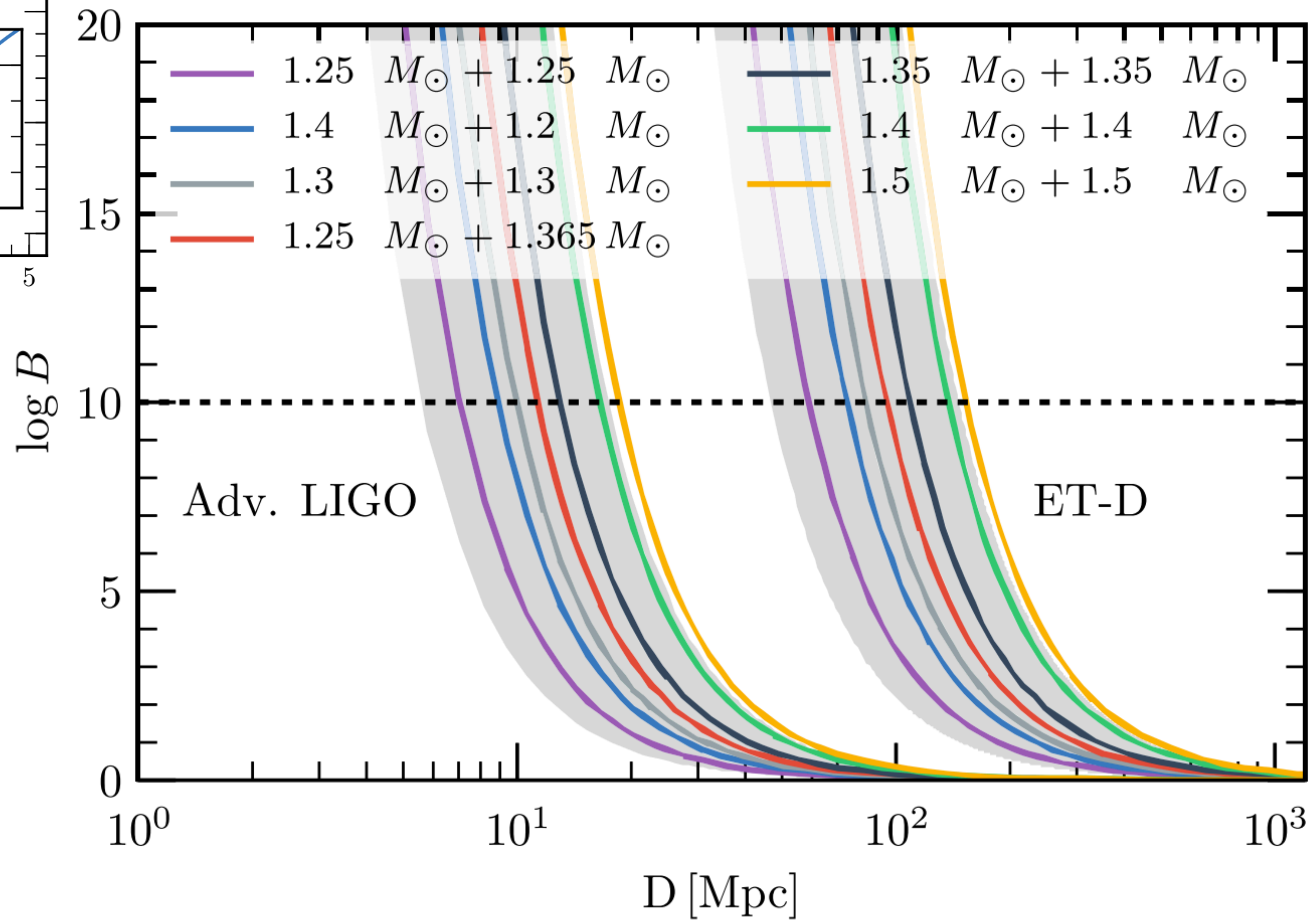
Phase transitions

- Post-merger emission could constraint nuclear phase transitions

- Detectable with 3rd generation interferometers



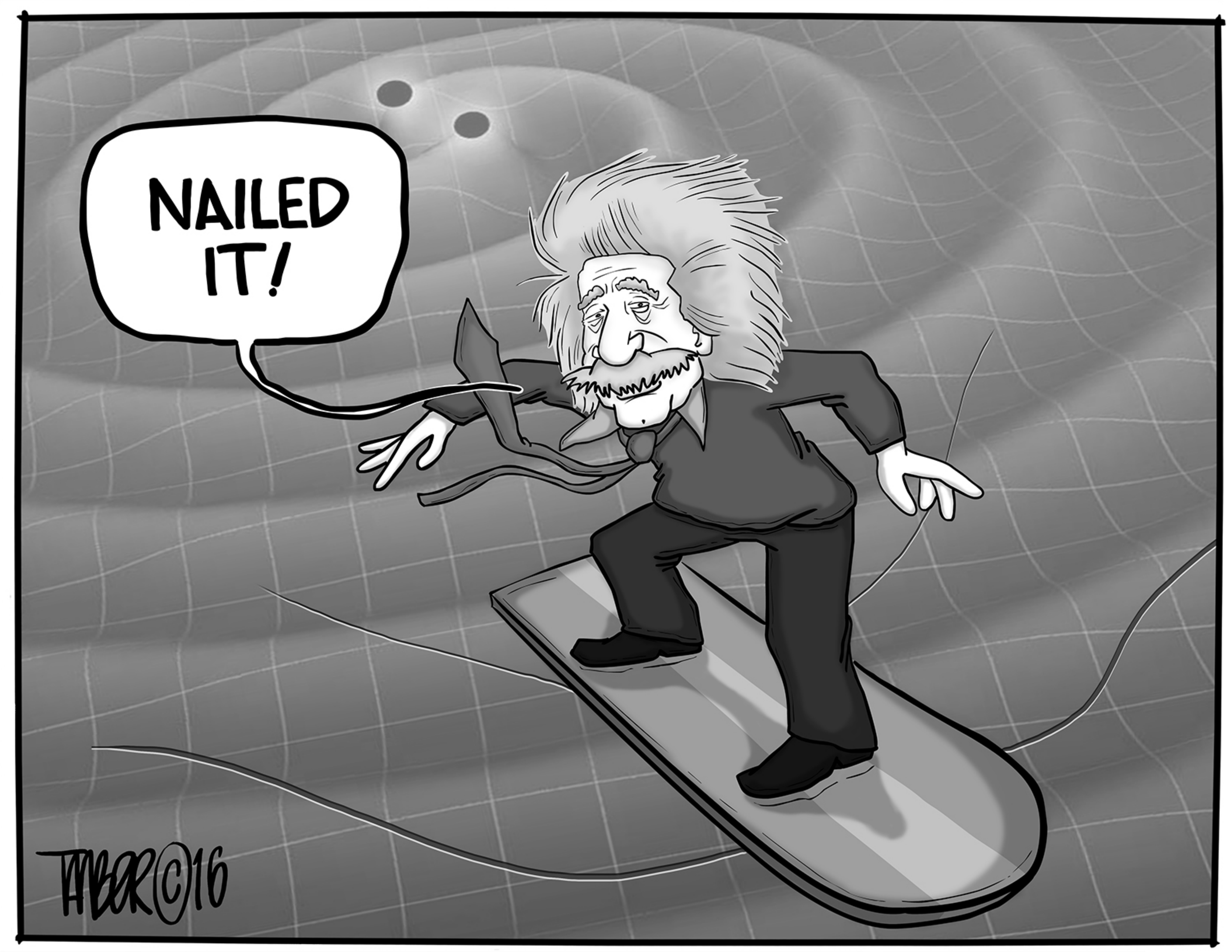




Radice et al, arXiv:1612.06429

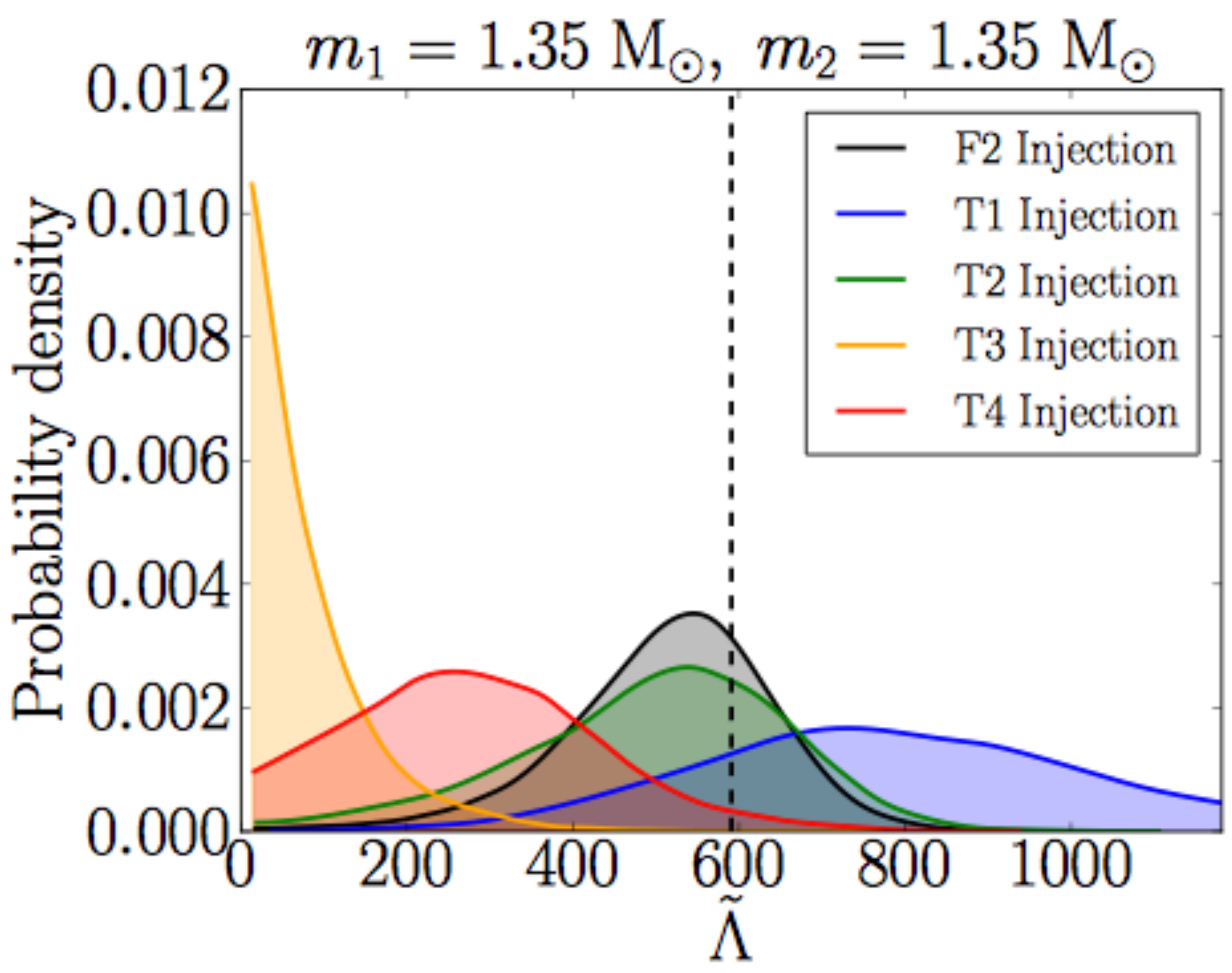
Summary

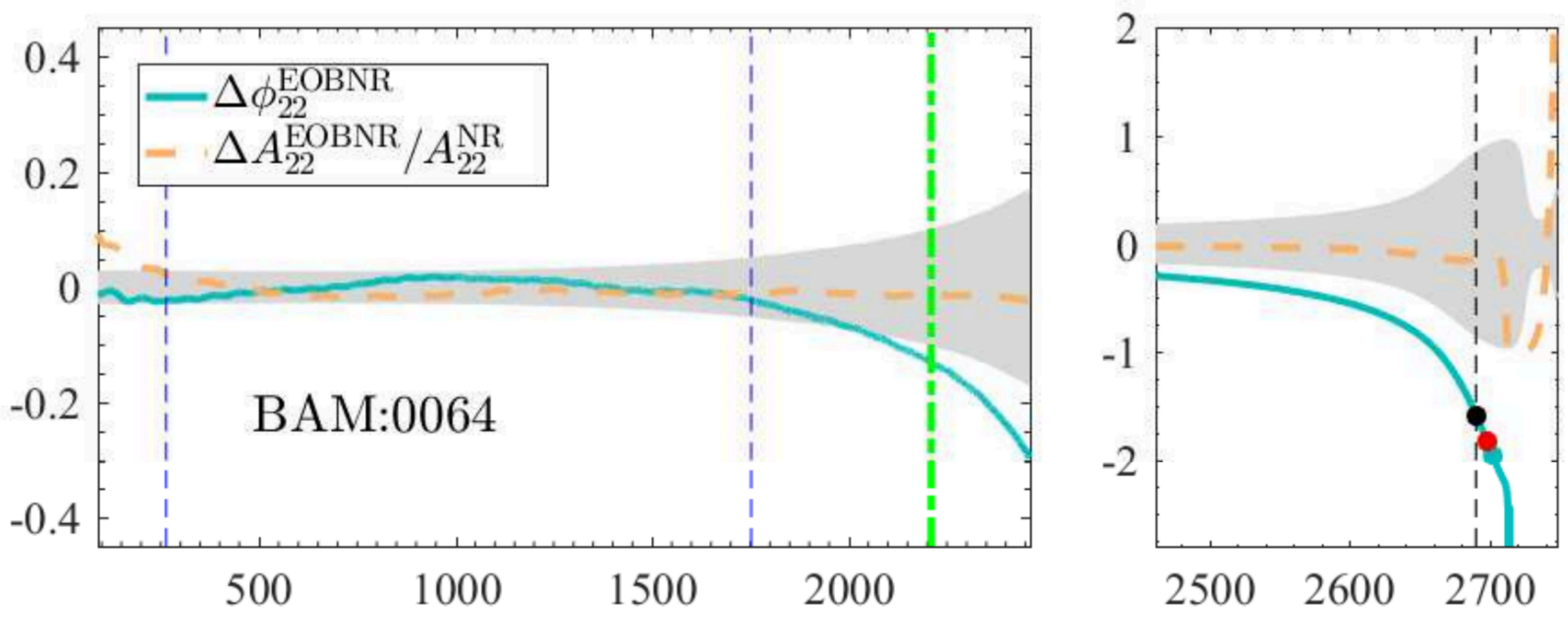
- The dawn of GW astrophysics
  - **BBHs and GW behave just like GR predicts**
  - **Initial constraints on neutron star EOS:**
  - many more detections in the future
  - improved sensitivities
  - multi-wavelength studies
- Look forward to a prolific season in gravitational physics
  - Cosmography



Waveform systematics

- Unknown PN (Favata, arXiv:1310.8288, Wade et al, arXiv:1402.5156)
- However, EOB (Bernuzzi et al, arXiv:1412.4553, Hinderer et al, arXiv:1602.00599, Dietrich et al, arXiv:1804.02235, Nagar et al, arXiv:1806.01772)



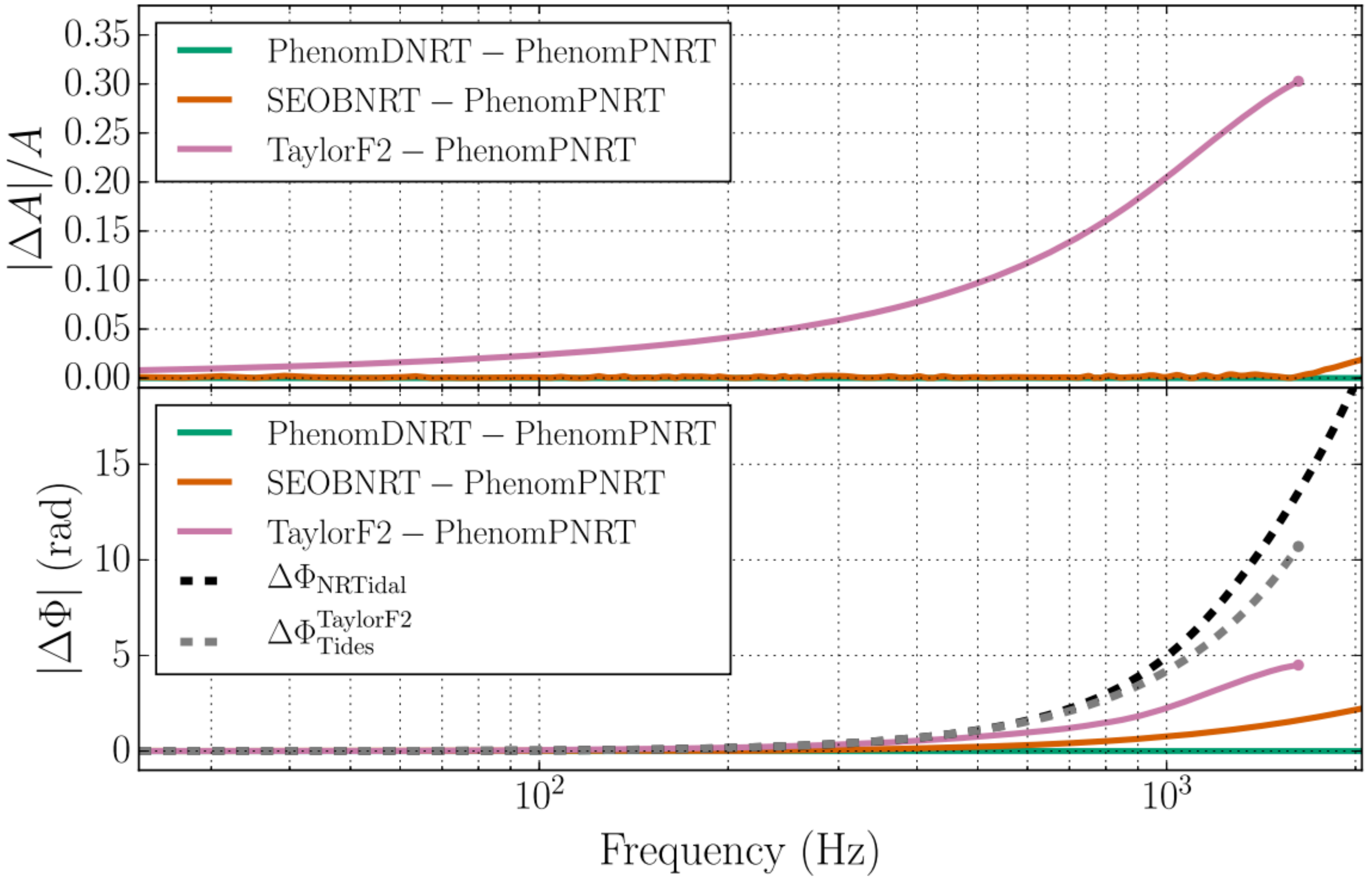


Nagar et al, arXiv:1806.01772

Wade et al, arXiv:1402.5156

Waveform systematics

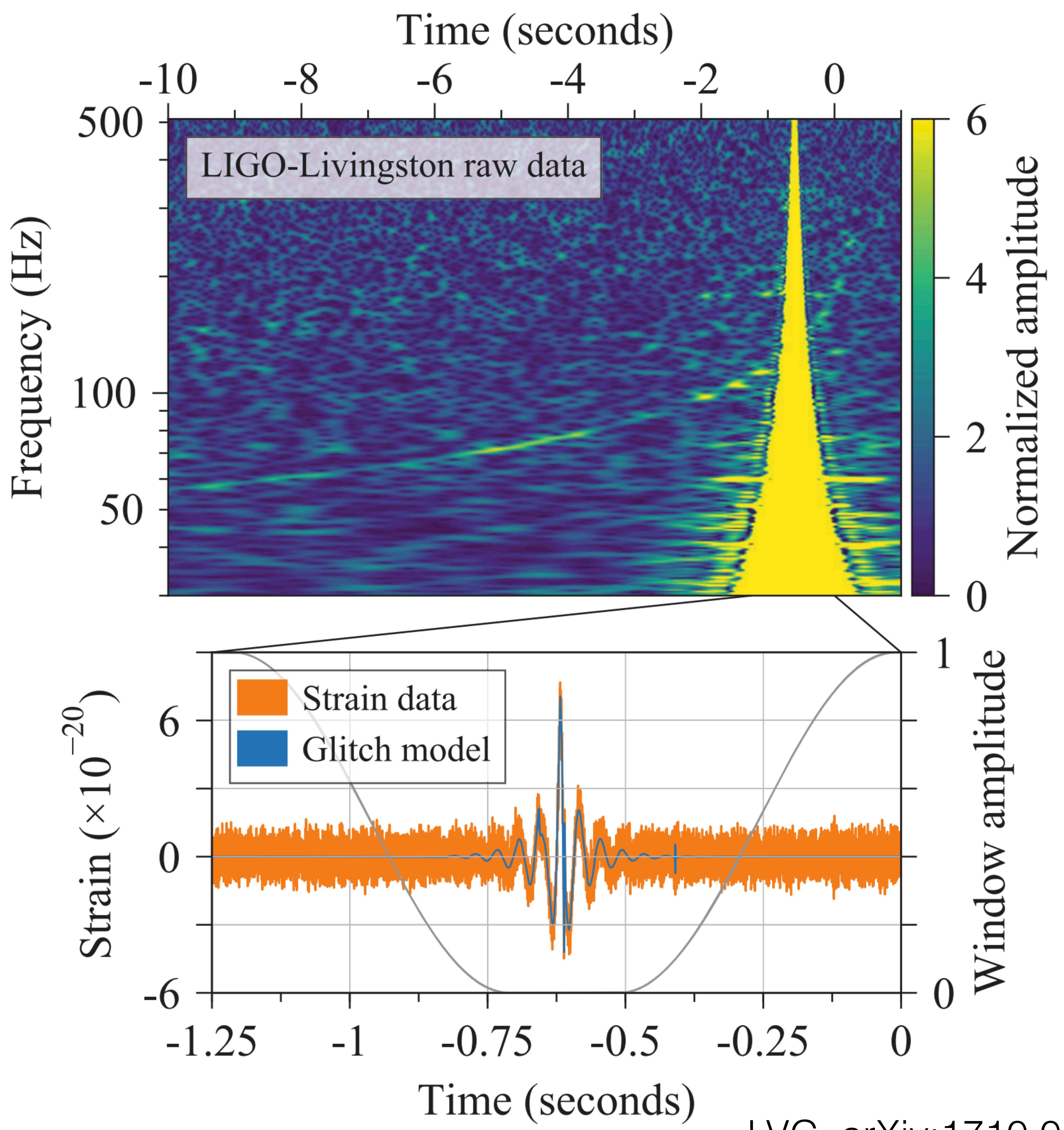
- Several approximants
  - PN taylorF2
  - IMRPhenom
  - SEOB
- non-detectable differences in GW170817



LVC, arXiv:1805.11579

Long noise transients

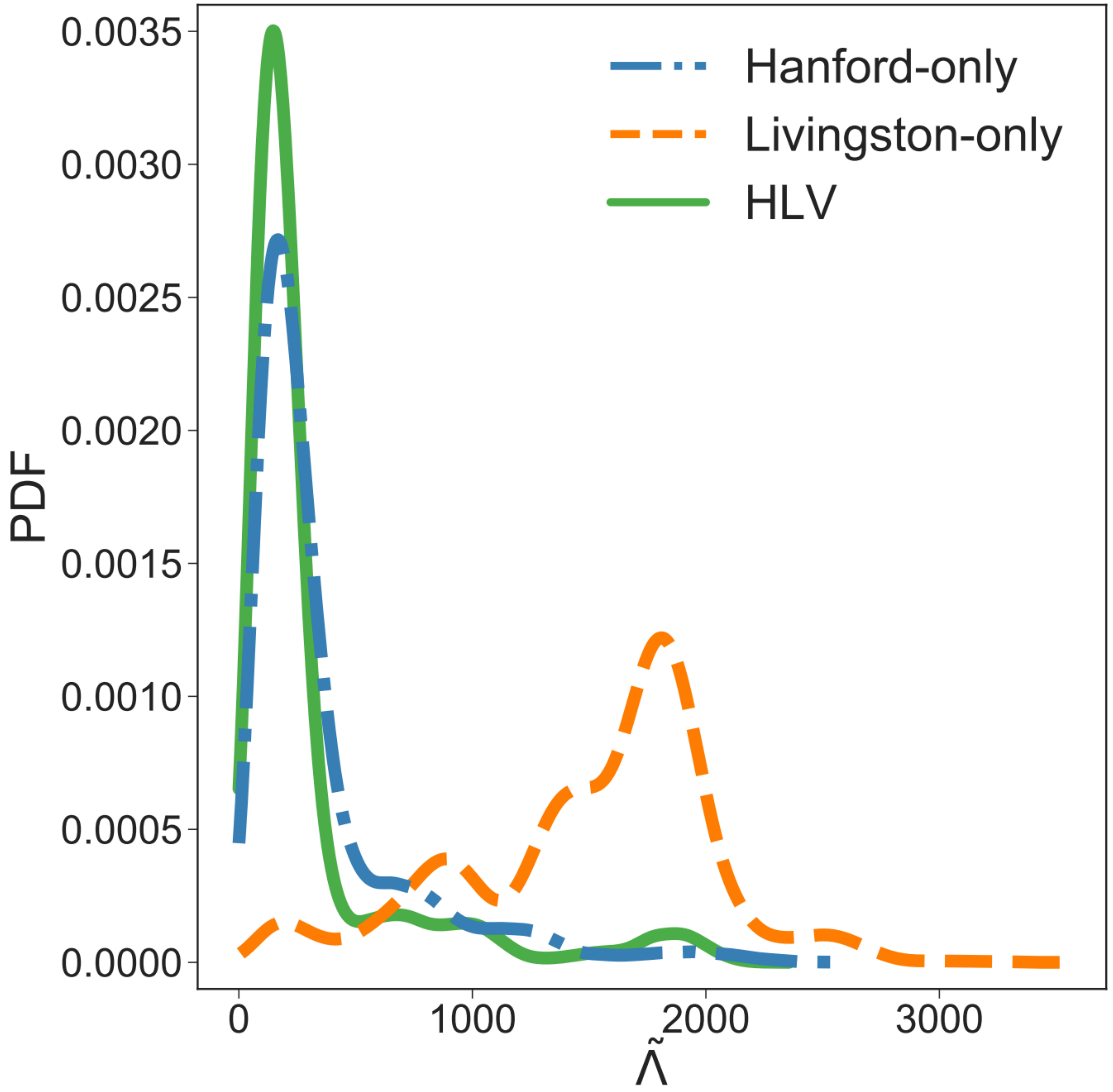
- Transients (glitches) with long duration and high SNR
- BNS signals last O(minutes)
- Glitch removal (e.g. BayesWave, Cornish & Littenberg, 2011)
- Effect on λ(m)?



LVC, arXiv:1710.05832

Long noise transients

- Transients (glitches) with long duration and high SNR
- BNS signals last O(minutes)
- Glitch removal (e.g. BayesWave, Cornish & Littenberg, 2011)
- Effect on $\lambda(m)$? Can it explain Narikawa, arXiv:1812.06100?



Narikawa, arXiv:1812.06100

Cosmography with GW

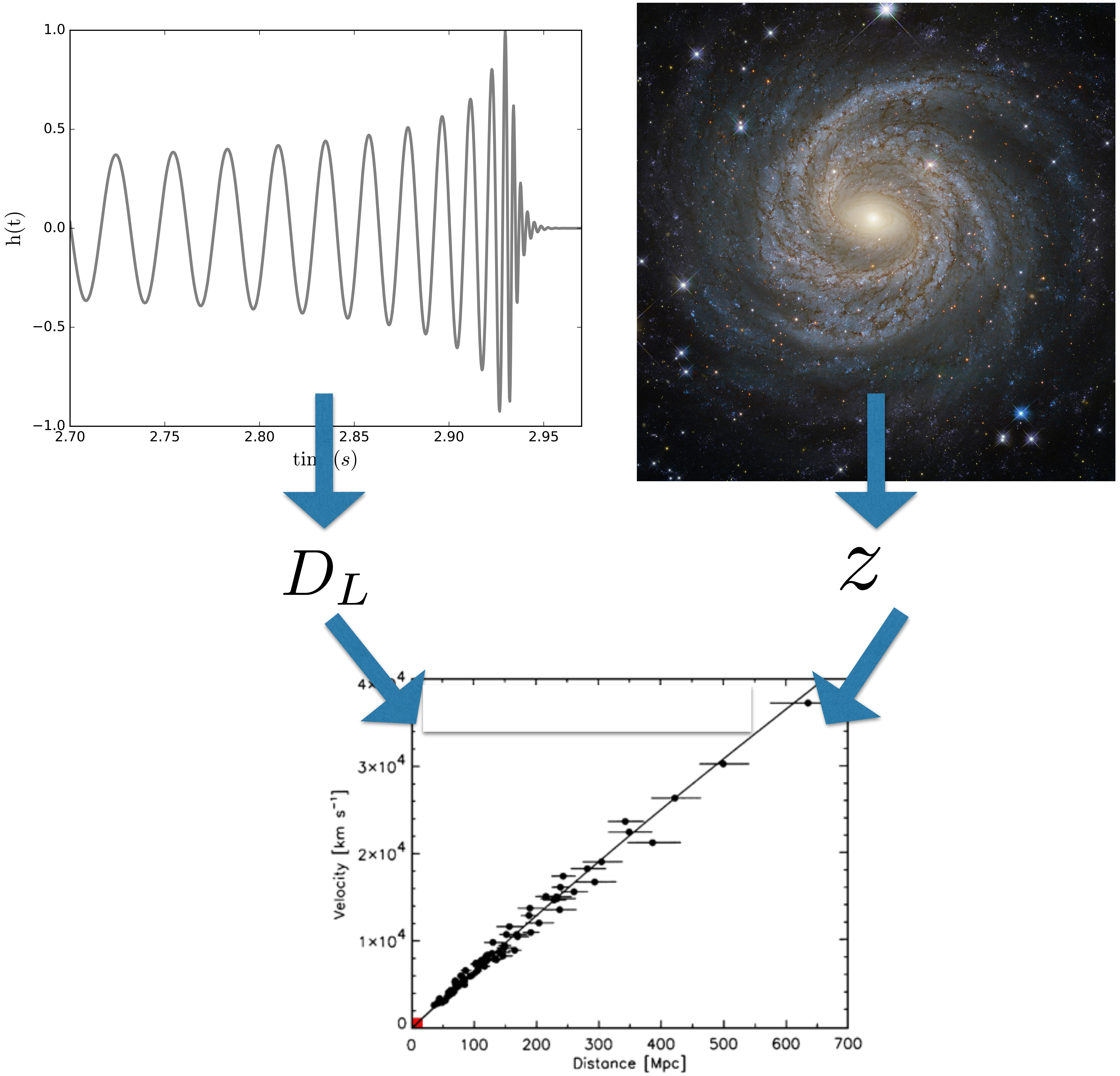
- GW are self-calibrating sources

$$h \sim D_L^{-1}$$

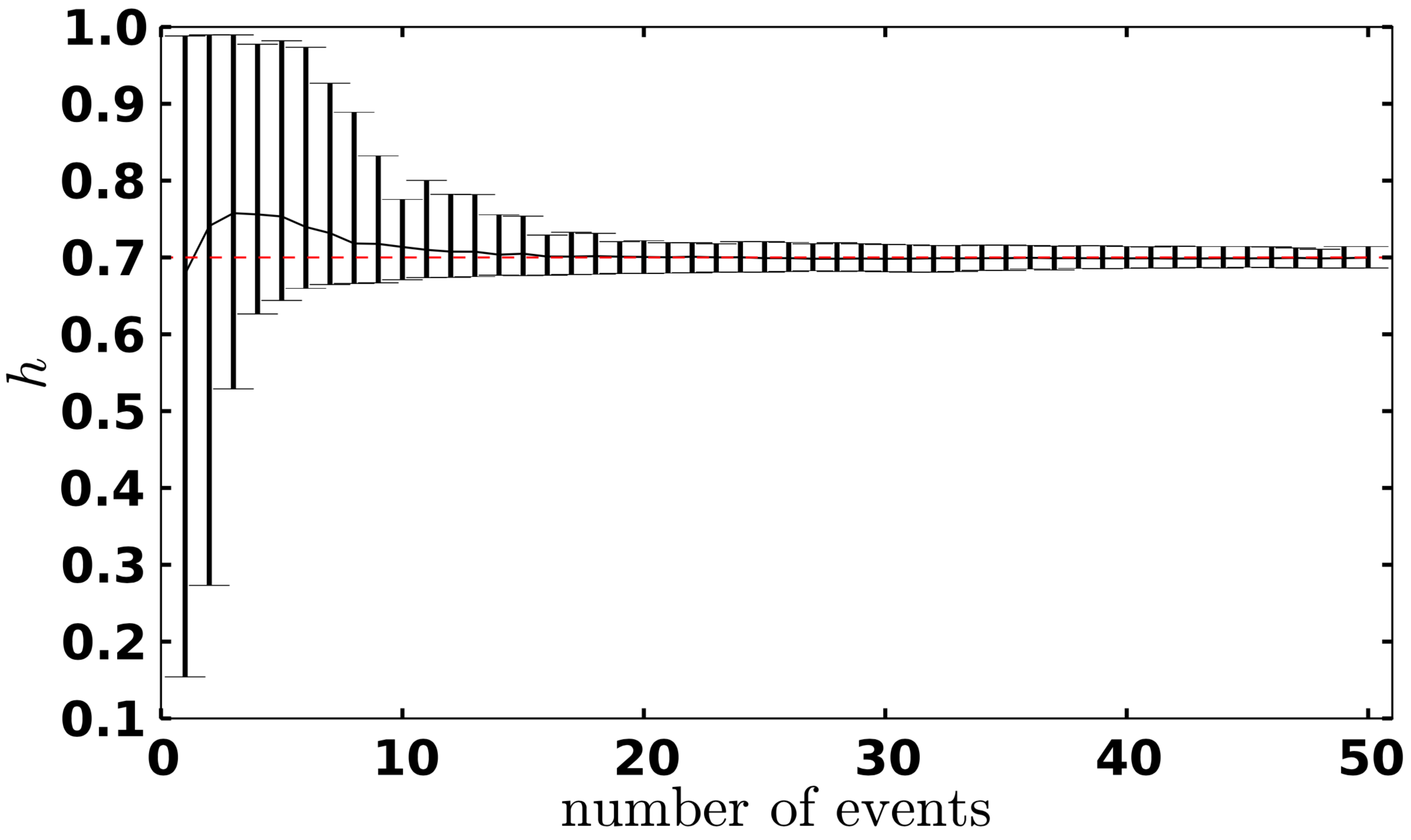
  - Direct measurement of luminosity distance

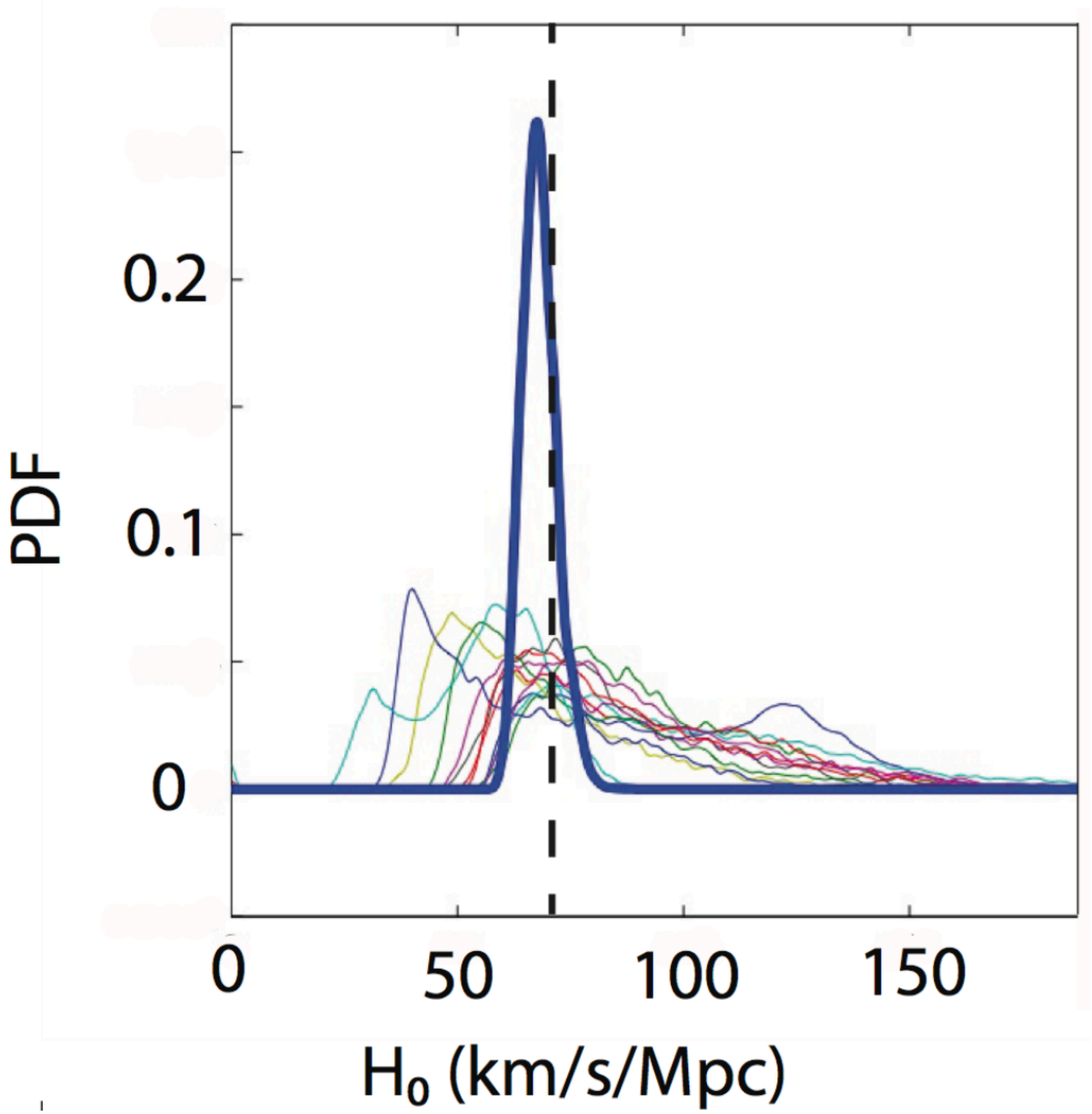
- Complemented with redshift information
  - EM counterpart
  - Host galaxy

- Determination of cosmological parameters



Cosmography with GW





Del Pozzo, arXiv:1108.1317

Nissanke et al, arXiv:1307.2638