Gravitational-wave Transient Astronomy on the Rise

Chris Pankow (CIERA/Northwestern)

CIPANP 2018: Palm Springs, Florida

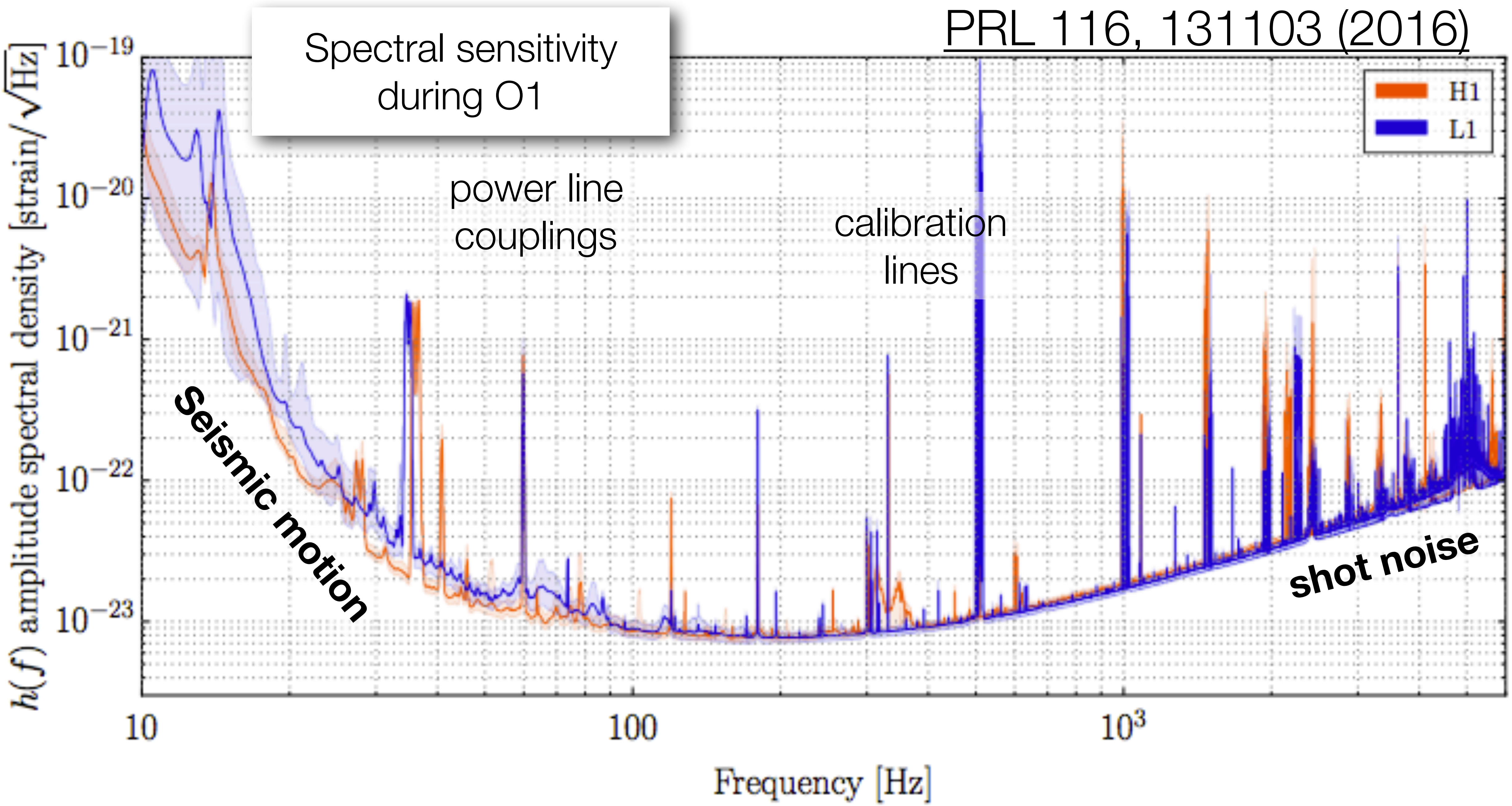
DCC: G1800710

2015 — 2016: First Observing Run

GW150914 and the birth of gravitational-wave astronomy

Advanced Interferometer Spectral Sensitivity

PRL 116, 131103 (2016)



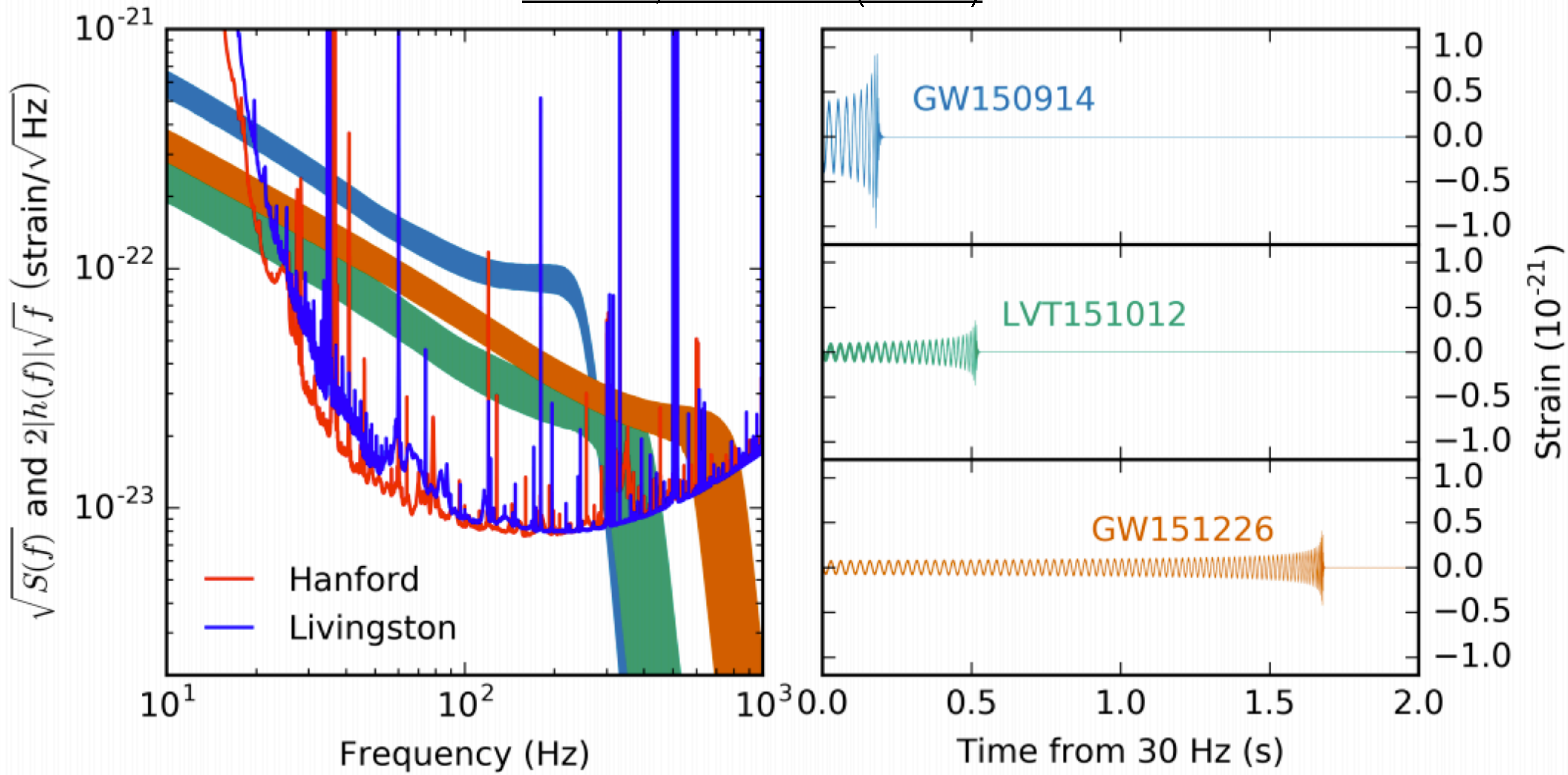
Low Frequency:
motion of the Earth coupling into motion of the test masses

Monochromatic Lines:
calibration lines, 60 Hz power line and harmonics thereof

High Frequency:
uncertain photon arrival times at photodetector

O1 BBH Events

PRX 6, 041015 (2016)

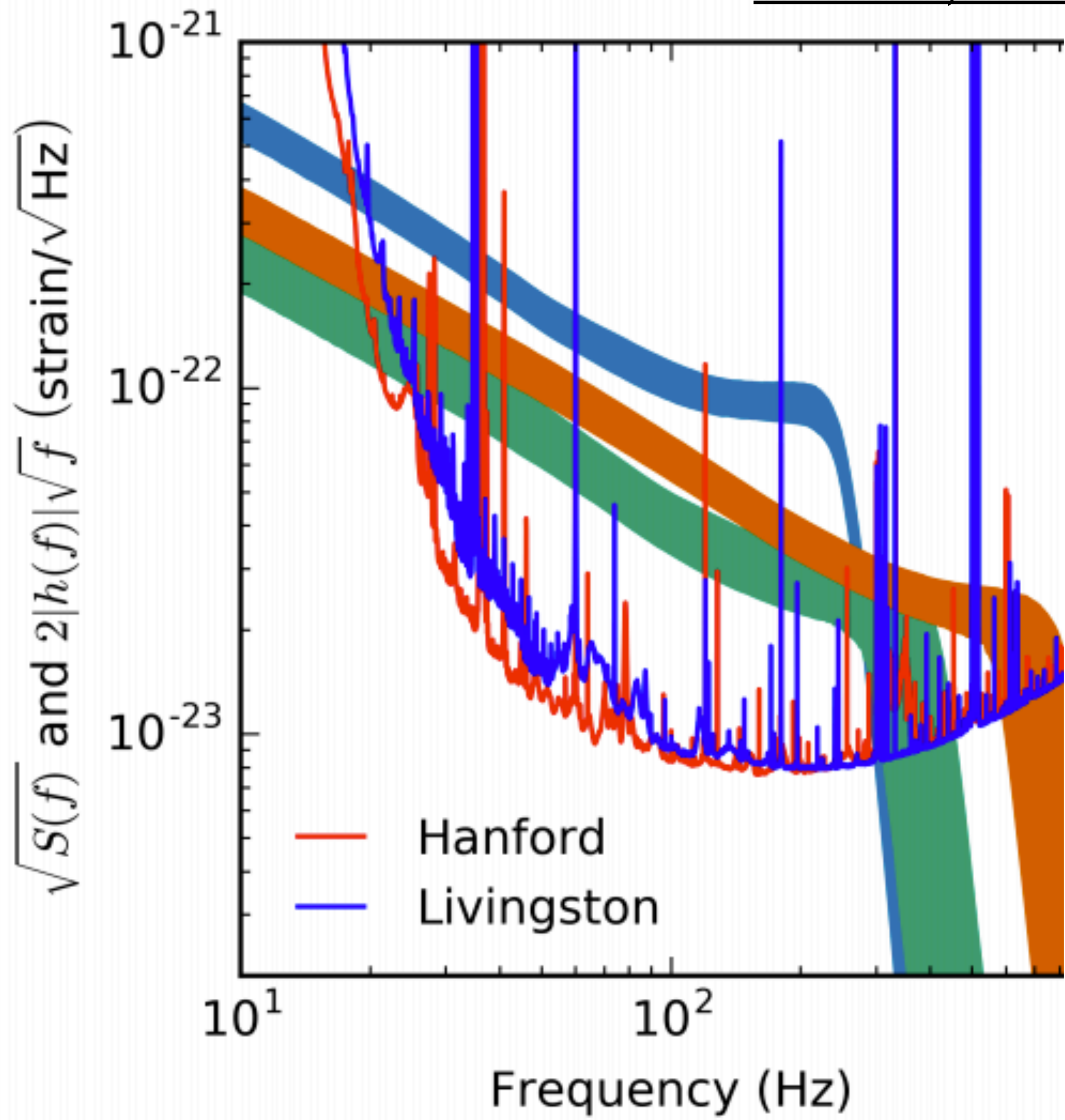


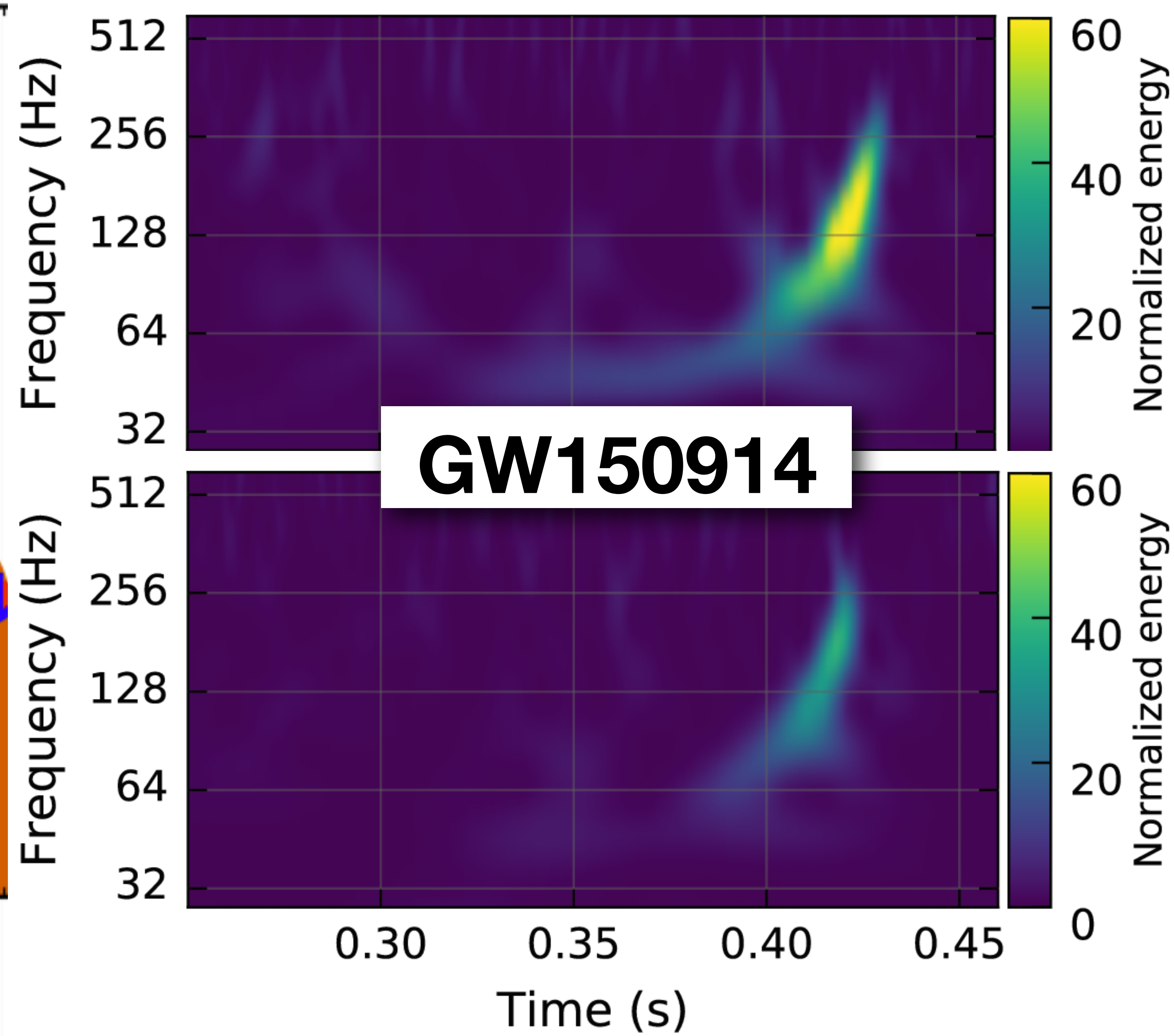
"Chirps" in the time domain (monotonically increasing in frequency vs time)

Lower mass → Higher frequency content / longer "in band"

O1 BBH Events

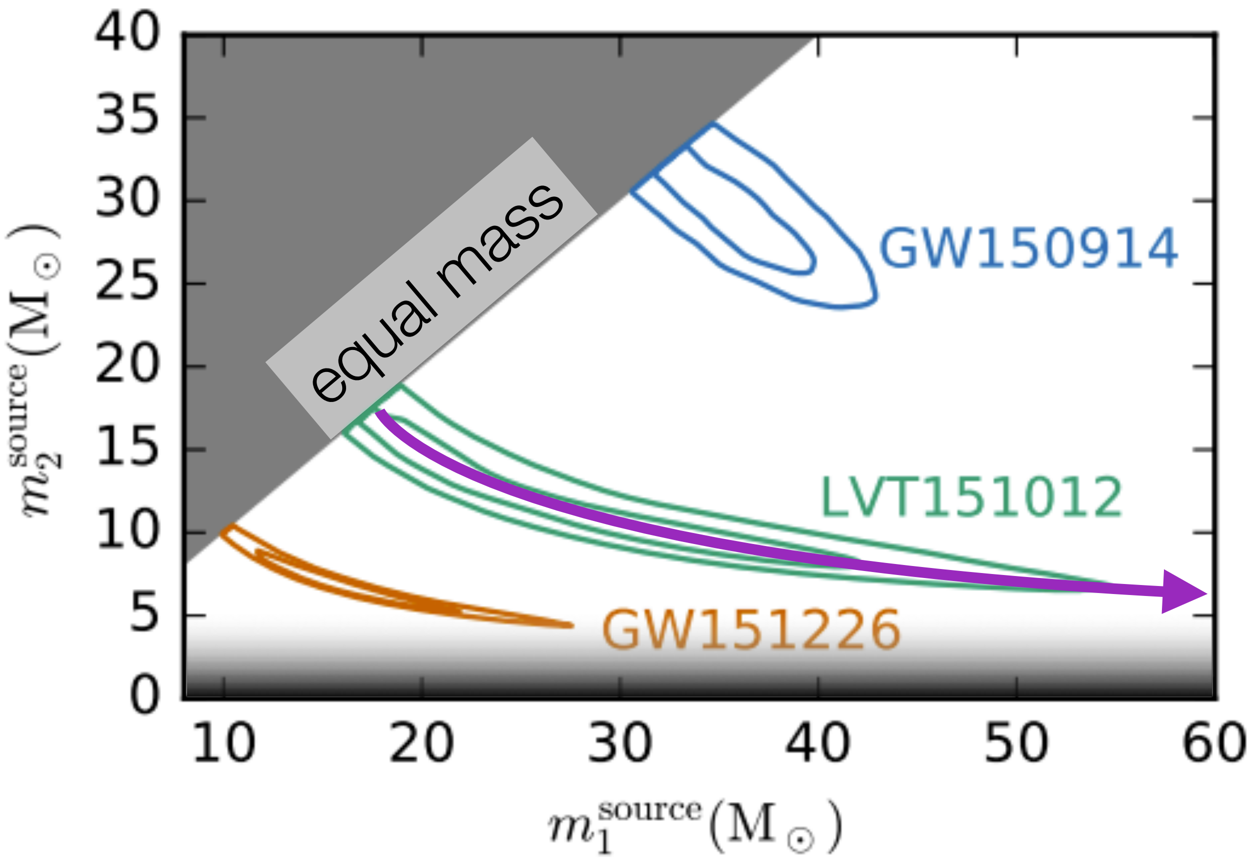
PRX 6, 041015 (2016)



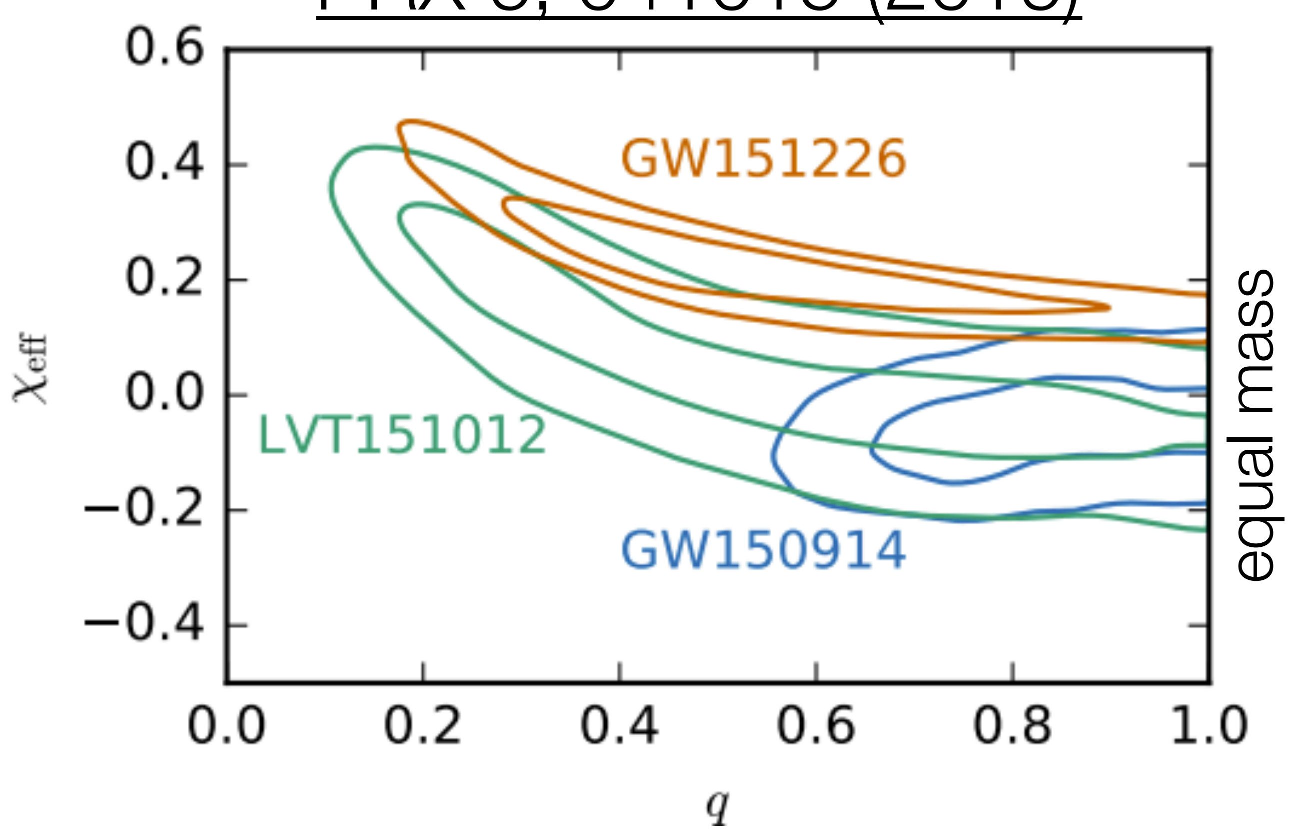


“Chirps” in the time domain (monotonically increasing in frequency vs time)
Lower mass → Higher frequency content / longer “in band”

BBH Masses and Spins



PRX 6, 041015 (2016)

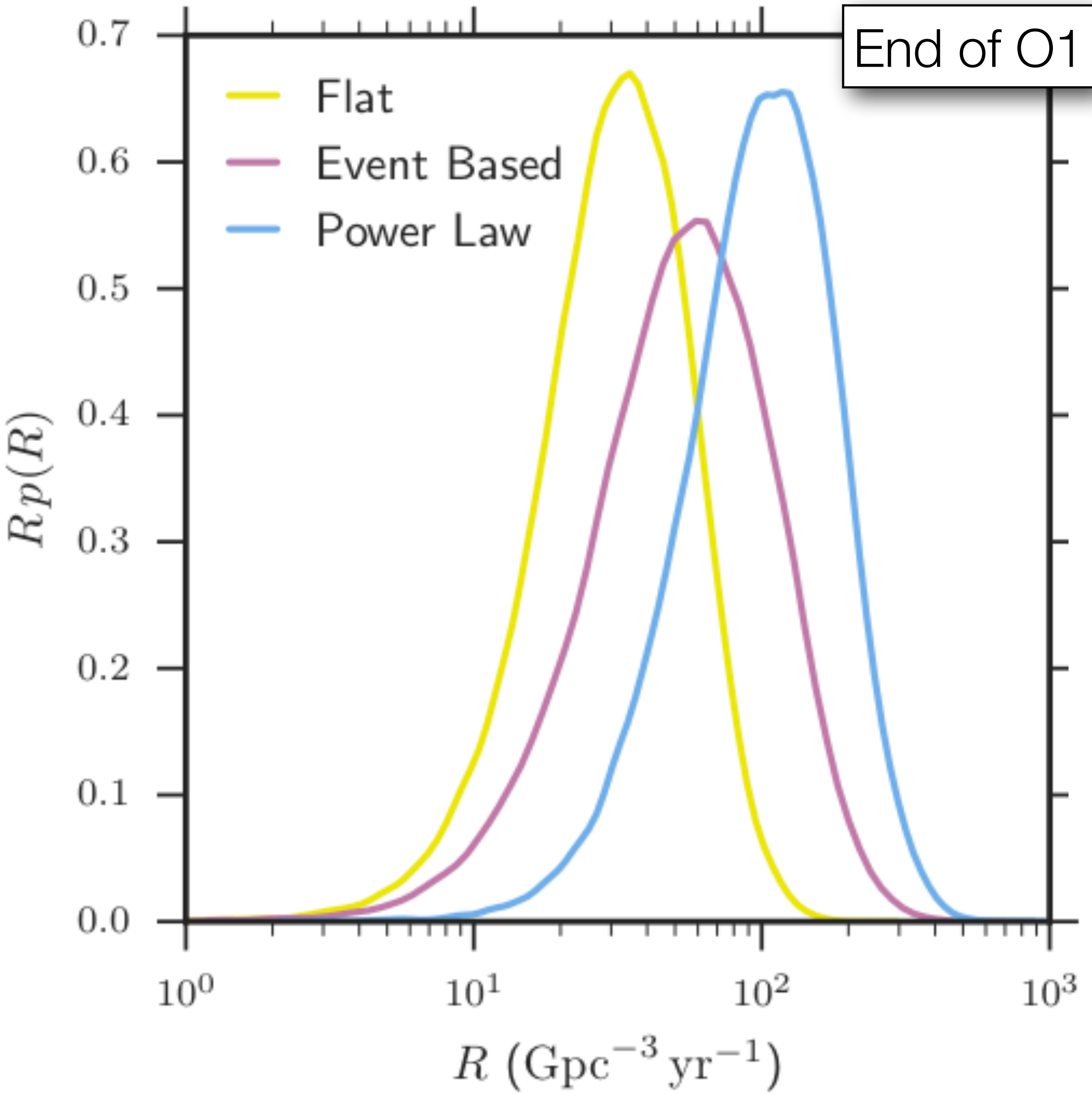


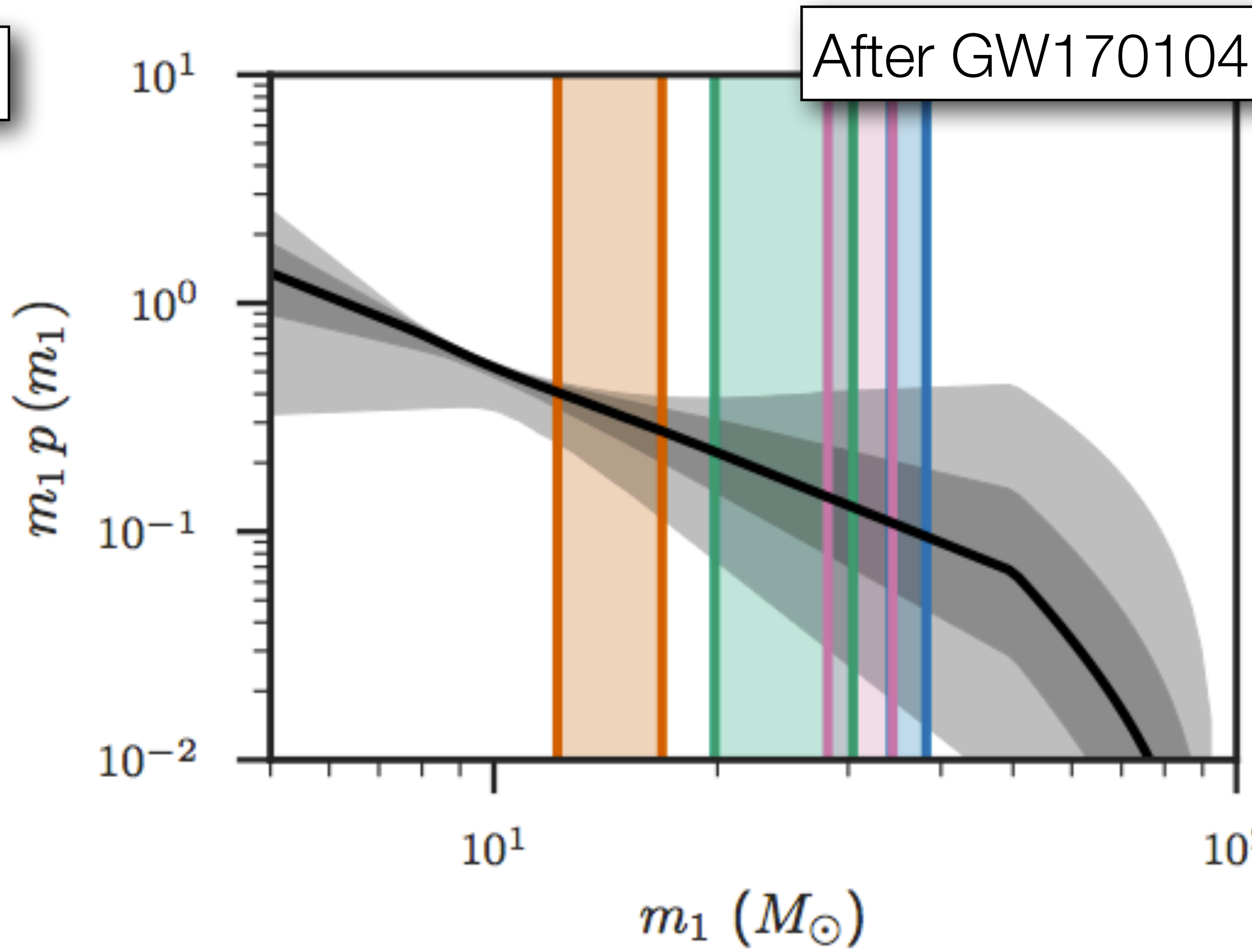
Parameter Degeneracies: Primarily sensitive to the *chirp mass* — leaves **large degeneracies** along contours of chirp mass

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

$$\chi_{\rm eff} = \frac{m_1 s_{1,z} + m_2 s_{2,z}}{m_1 + m_2}$$

Frequency content (and thus "length in band" affected by both *effective spin* and *mass ratio* at same order in expansion of radiation amplitude/phase





$$p(m_1|\alpha) \propto m_1^{-\alpha}$$

After GW170104:
12 - 213 Gpc^{-3}yr^{-1}
Power law (**α**=-2.35) *only*:
40 - 213 Gpc^{-3}yr^{-1}

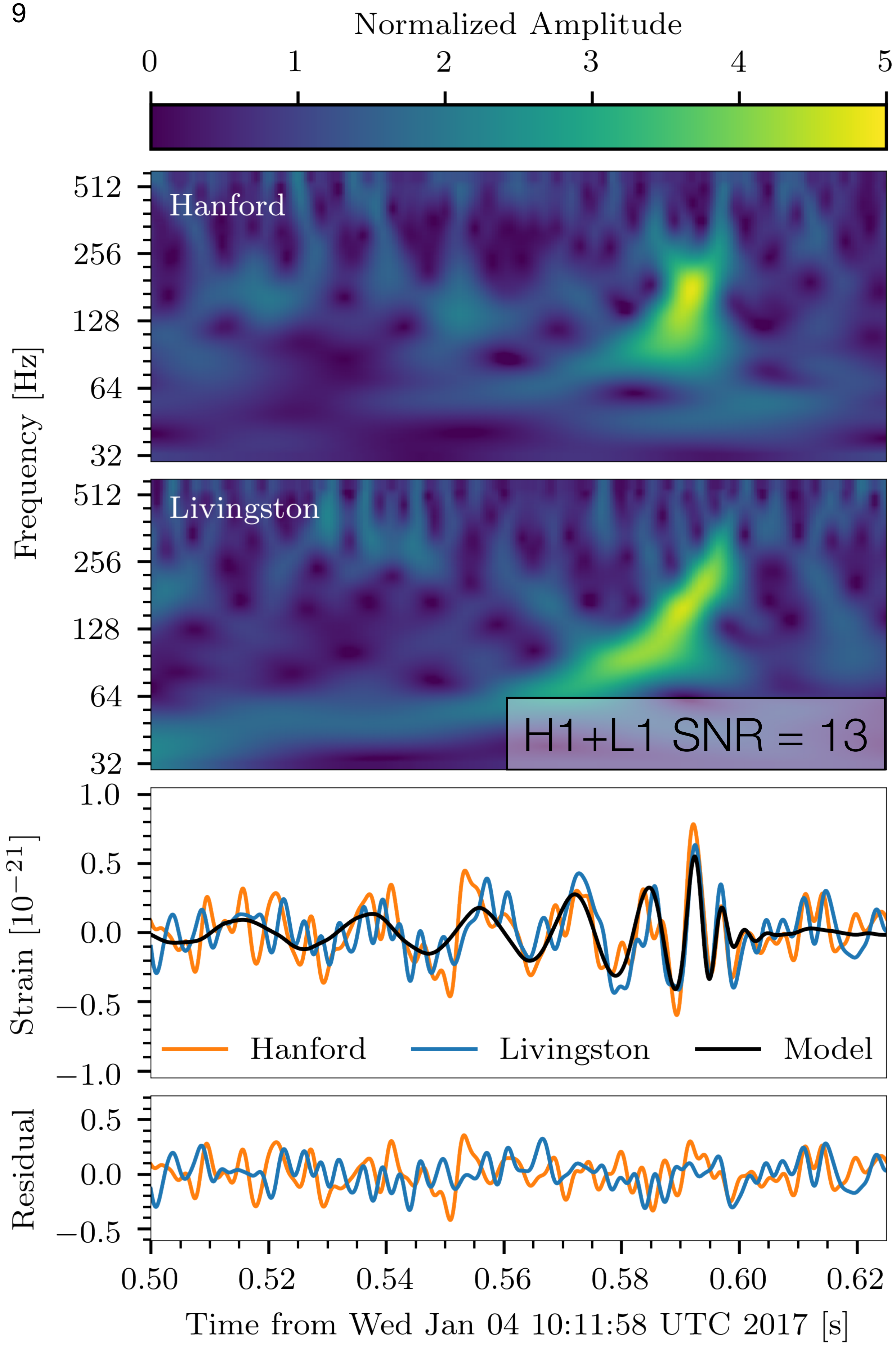
Towards Pop. Distributions:
Constraints on the primary mass distribution from BBH observations — alpha ~ 2.5\pm1 but new obs. and other features change the distribution

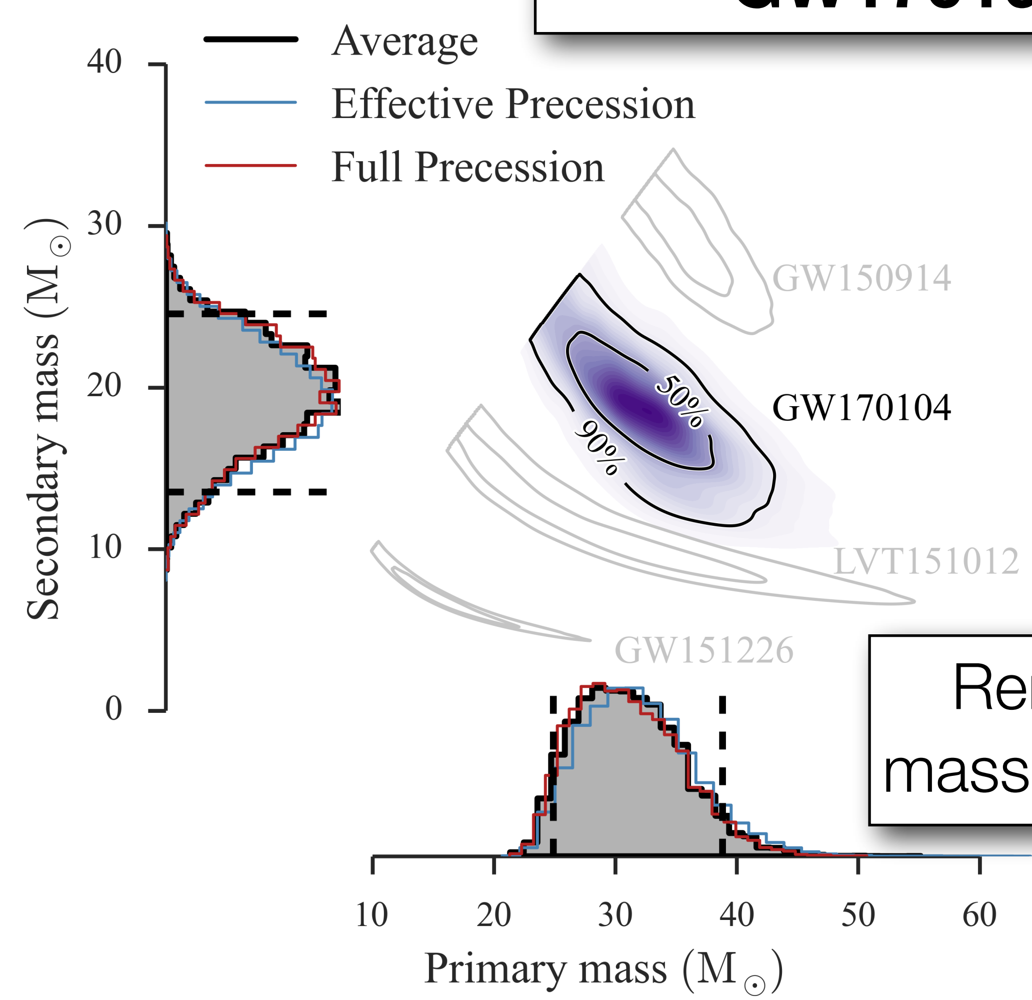
PRX 6, 041015 (2016)

2016 — 2017: Second Observing Run

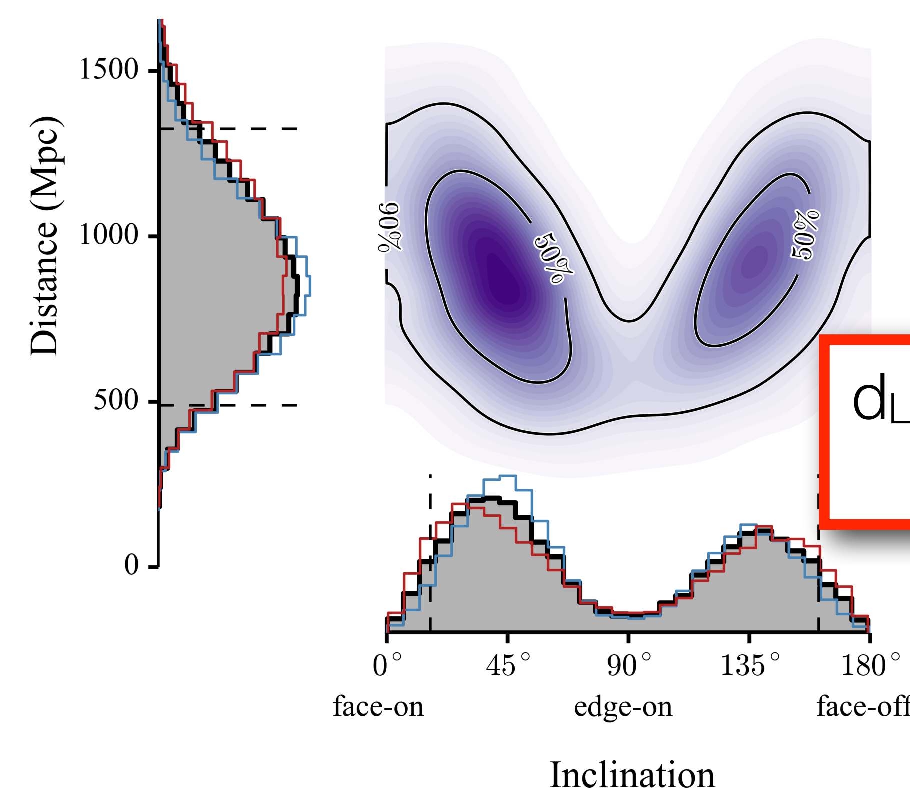
Binary black hole astrophysics, an international network of interferometers, and huge steps forward in multi-messenger astronomy

GW170104





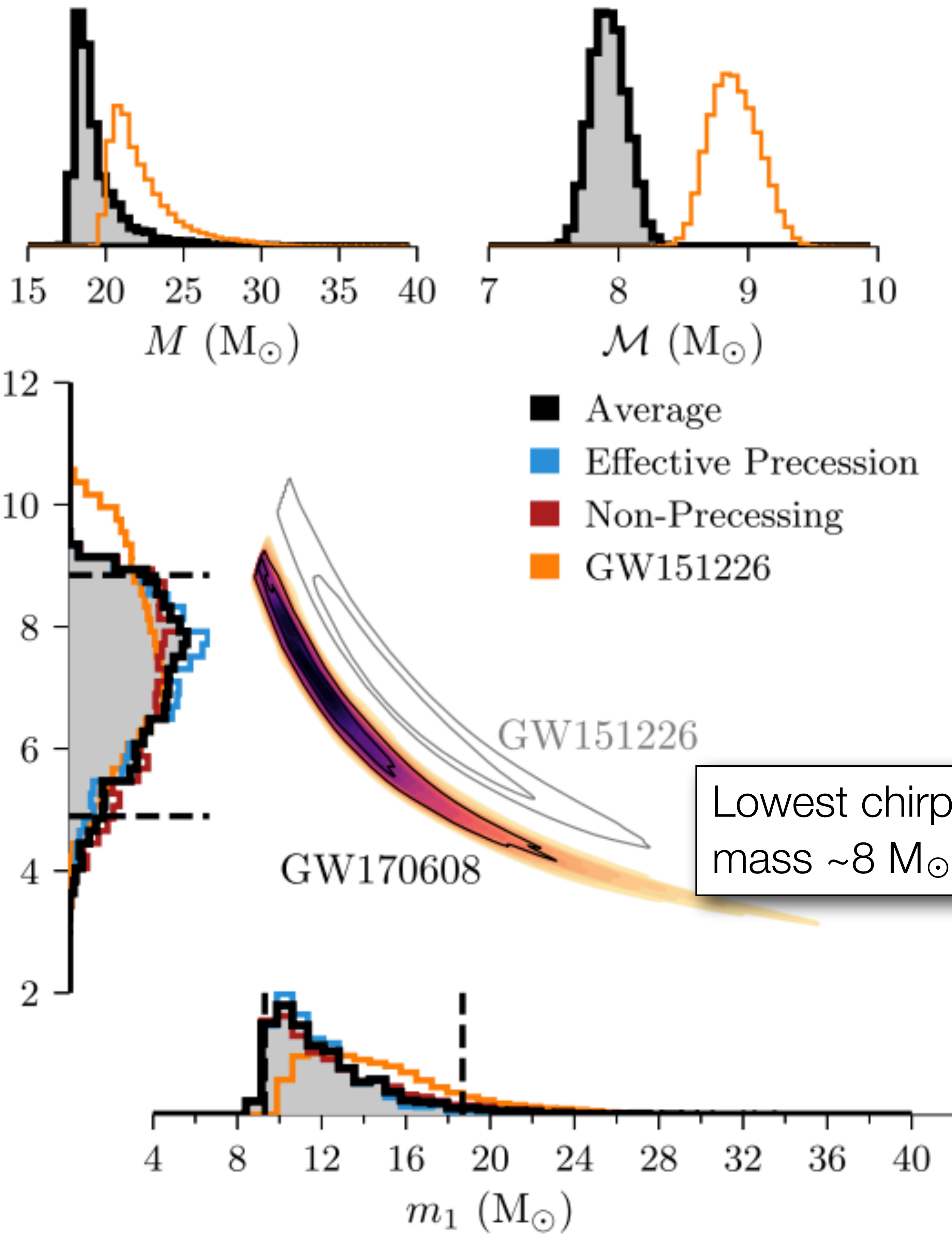
Remnant mass ~47 M☉

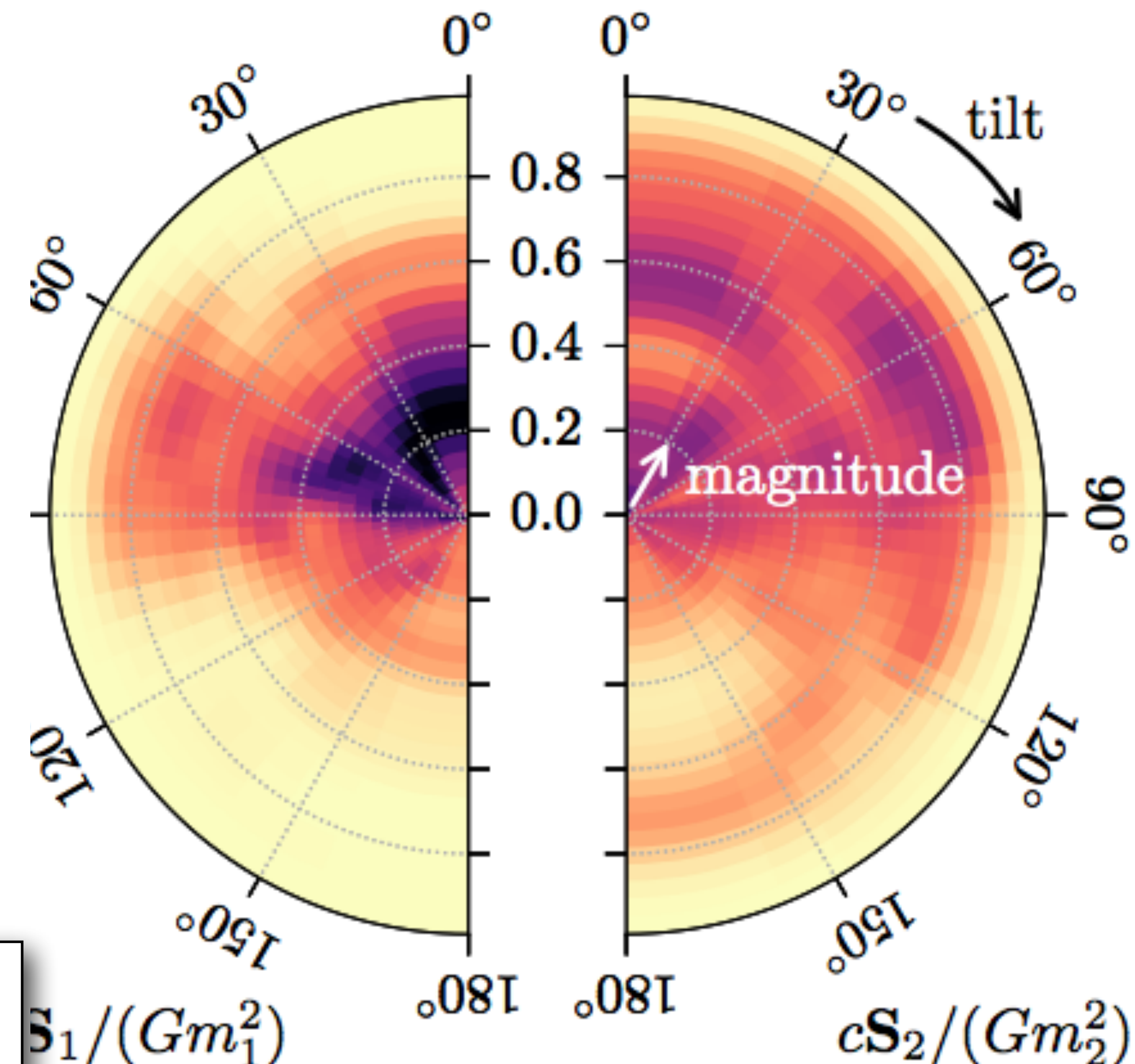


d_L = 880 Mpc
z = 0.18

PRL 118, 221101 (2017)

GW170608





Lowest chirp mass ~8 $M_\odot$

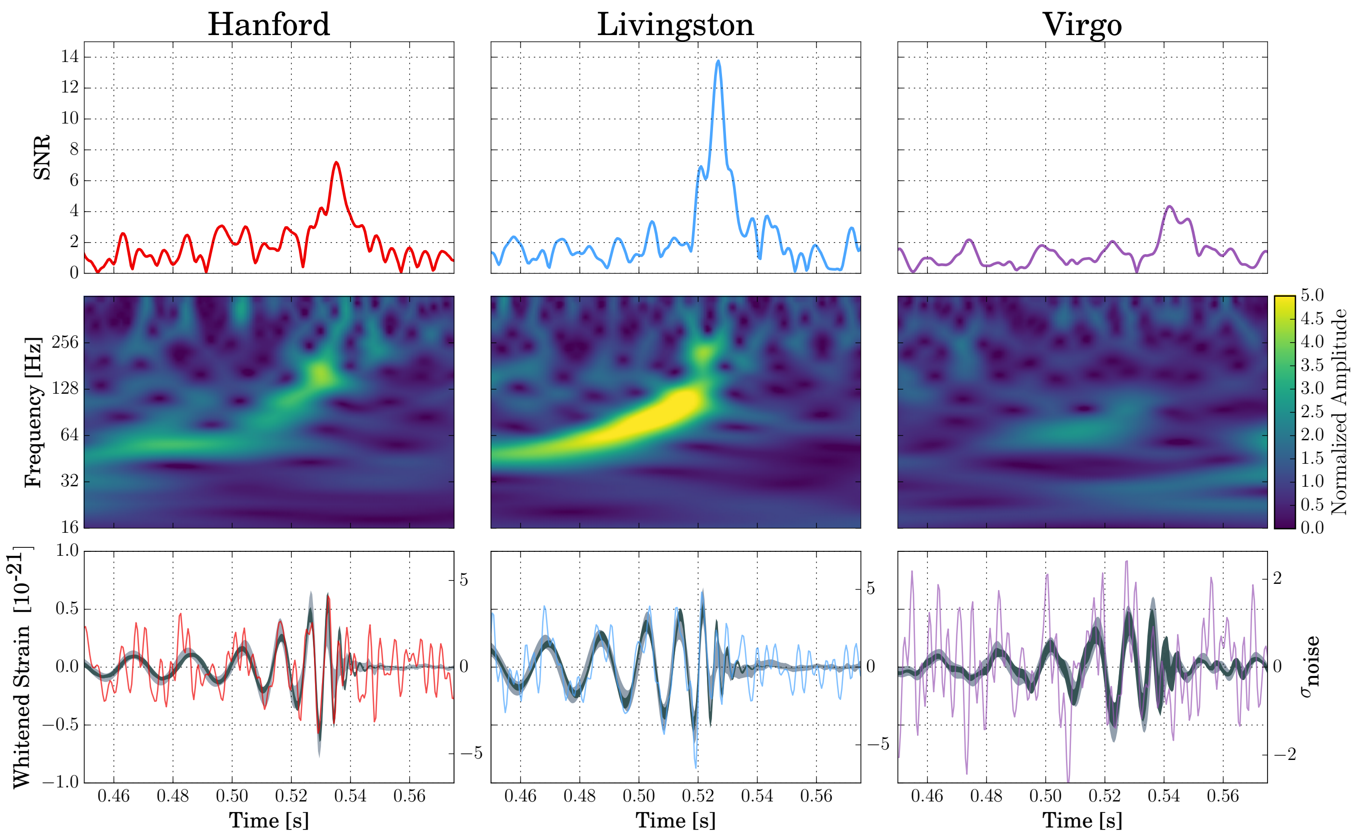
ApJL 851, 2 L35

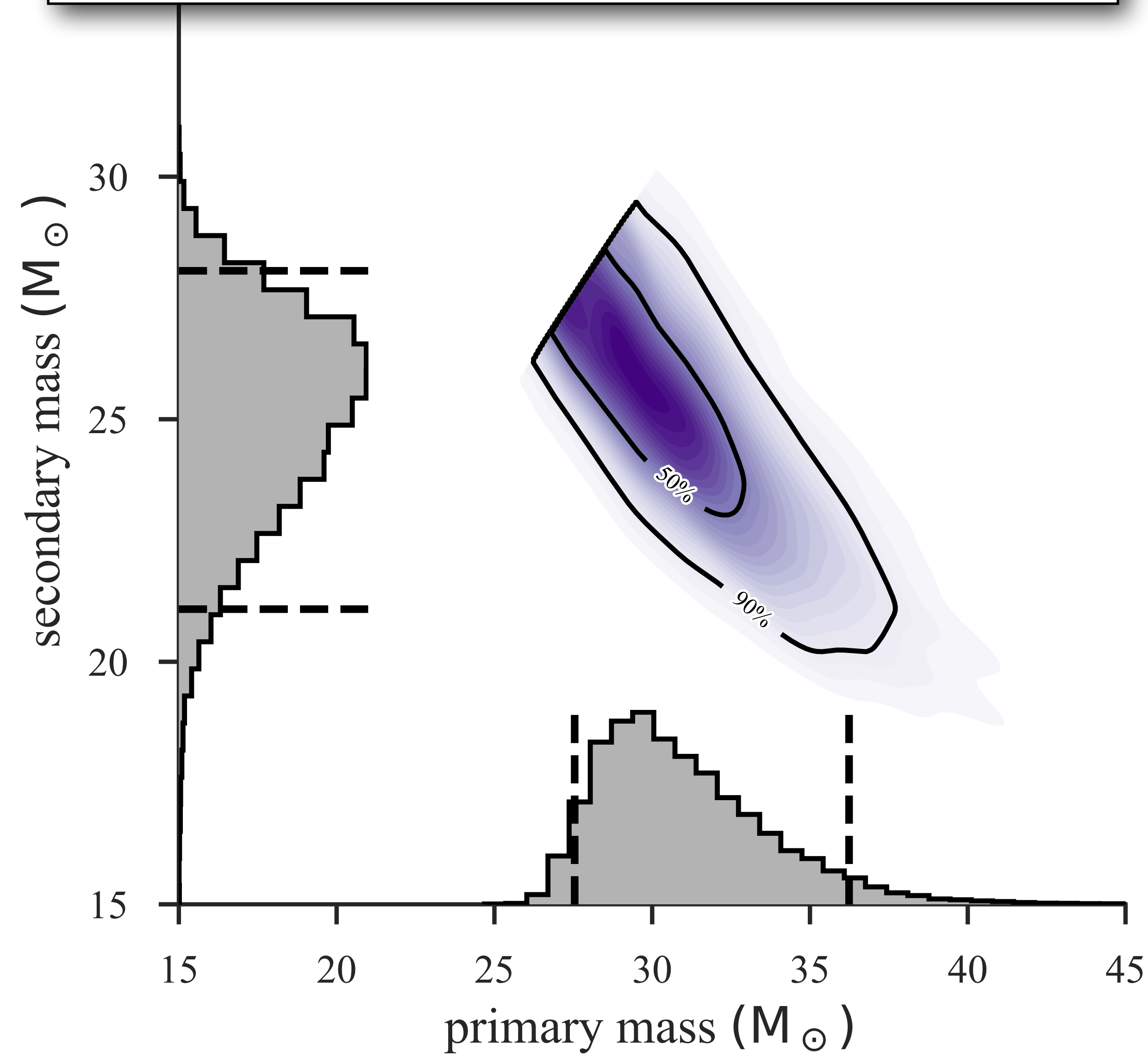
GW170814

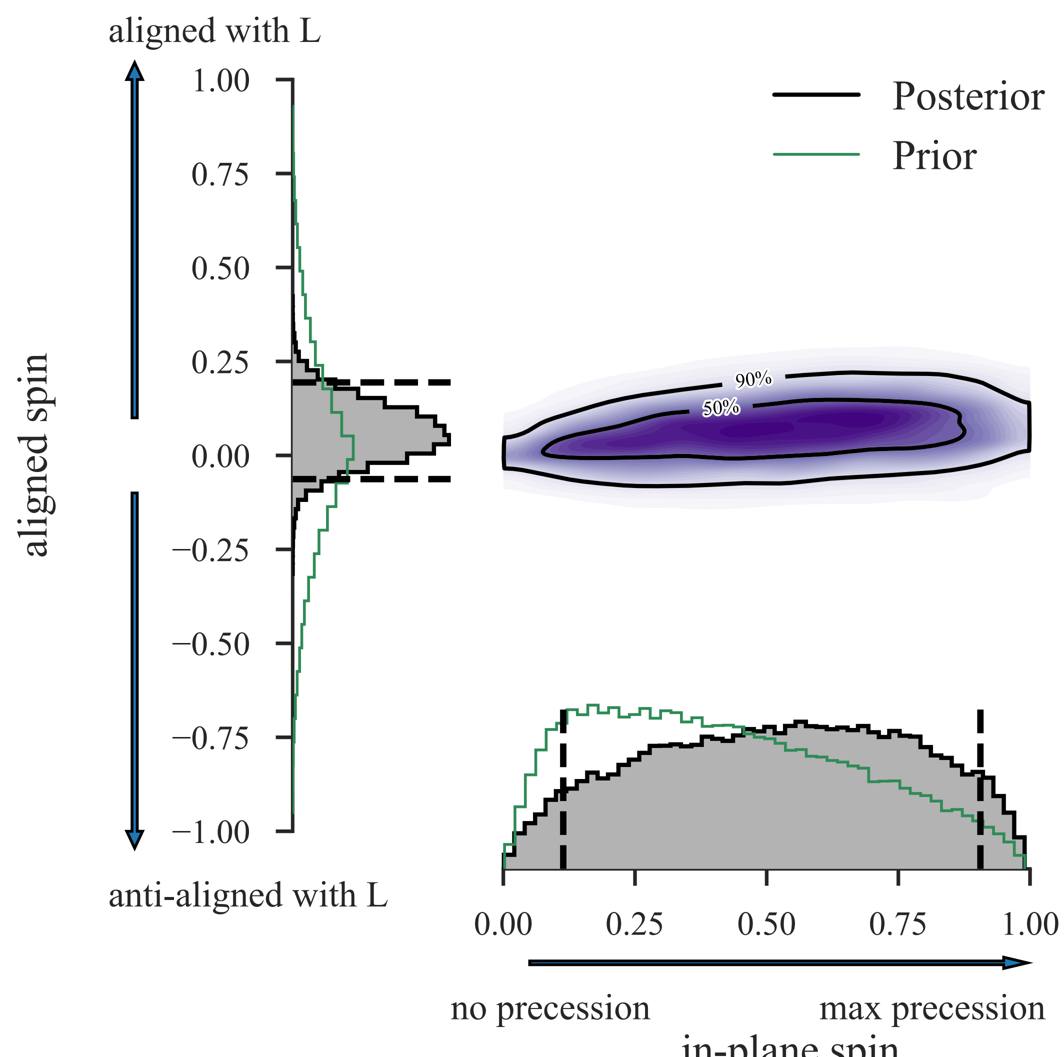
PRL 119, 141101 (2017)

The first three detector network detection

H ~ 7.3 / L ~ 13.7 / V ~ 4.4







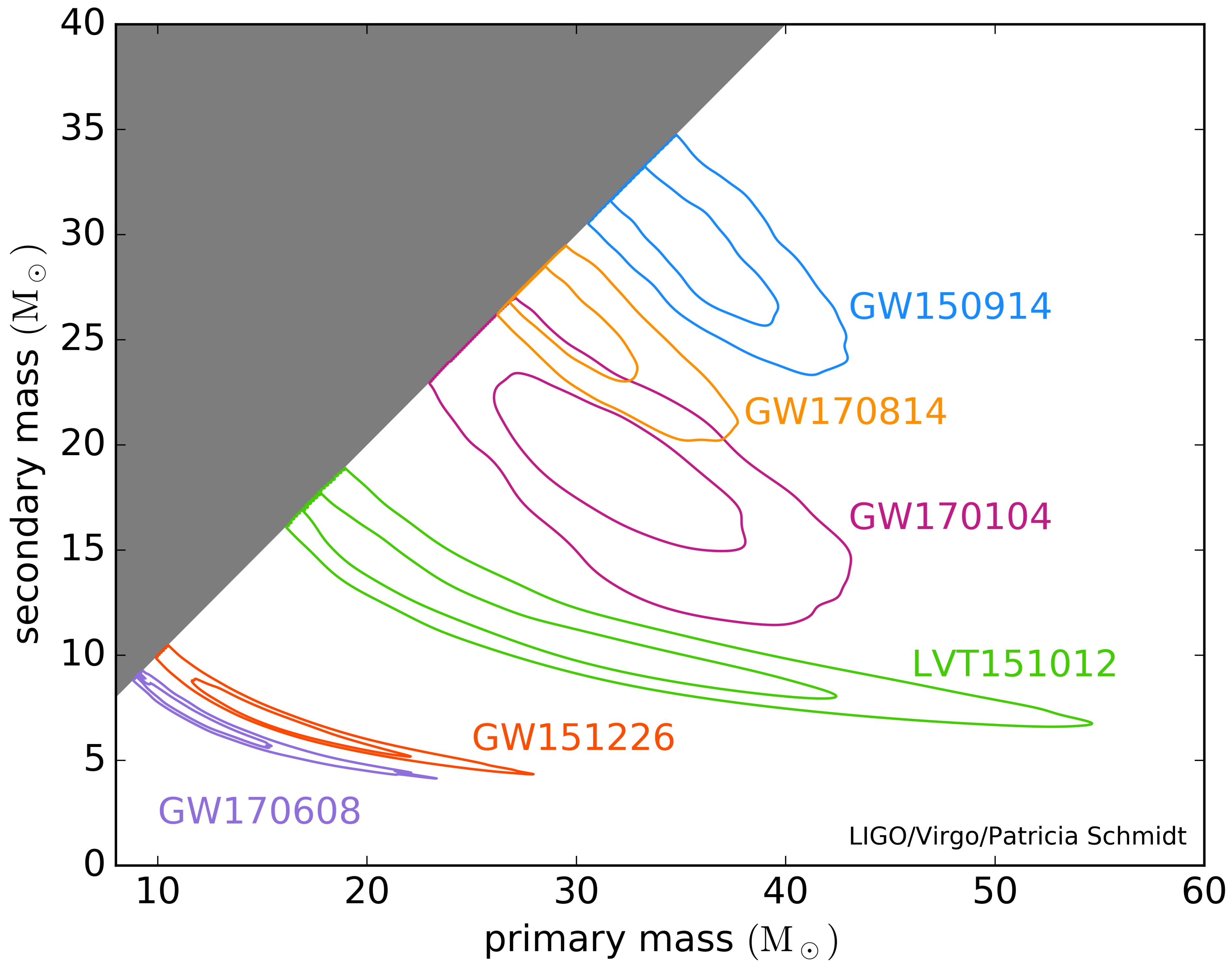
Precession:
distribution tilted further towards hints of precession

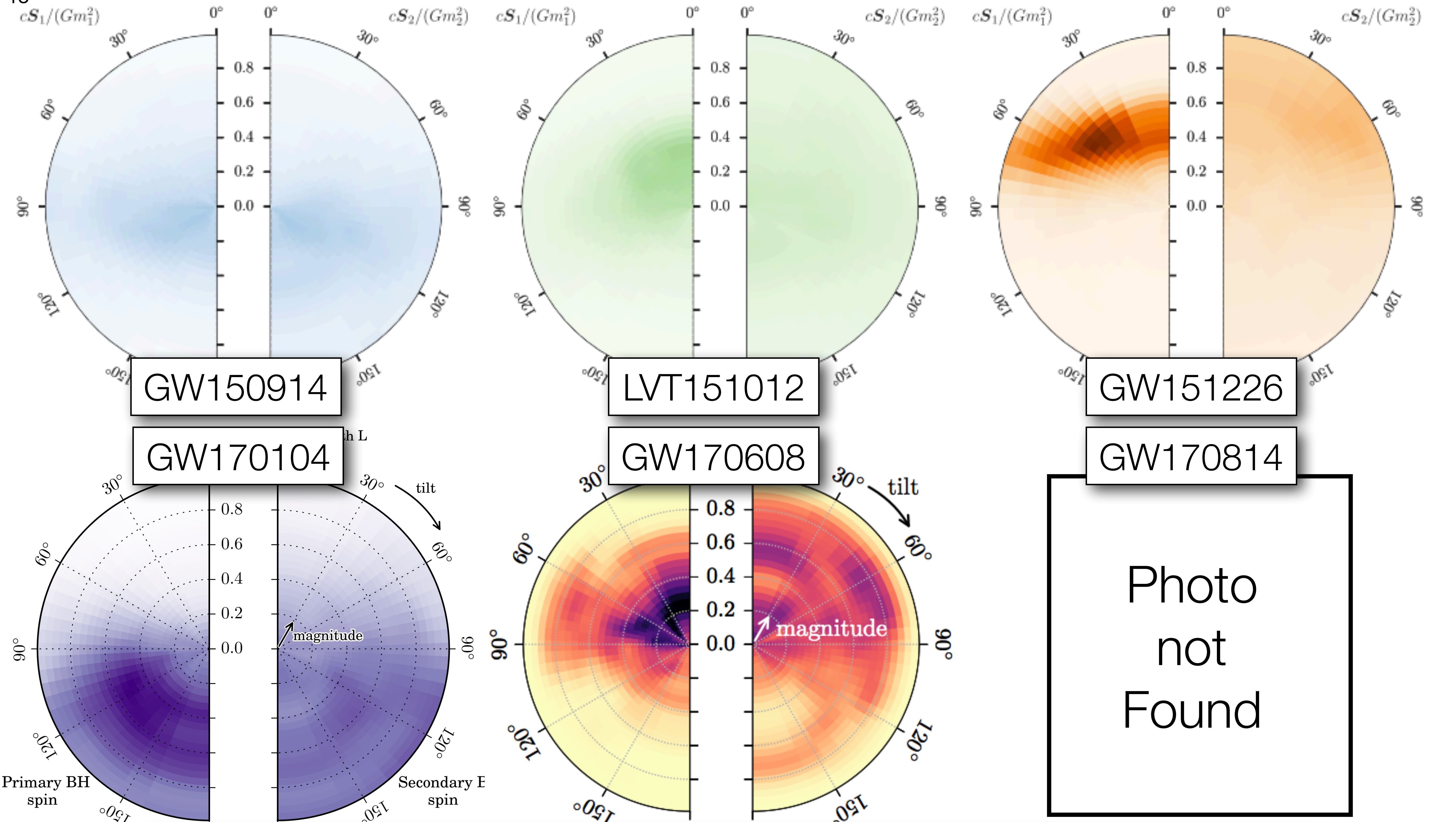
All mass posteriors in context:

→ Heavier BBH more sensitive to total mass, not chirp mass

→ LVT151012 weakest signal, large ambiguity

→ Volumetric sensitivity increases along the diagonal





All spin posteriors in context:

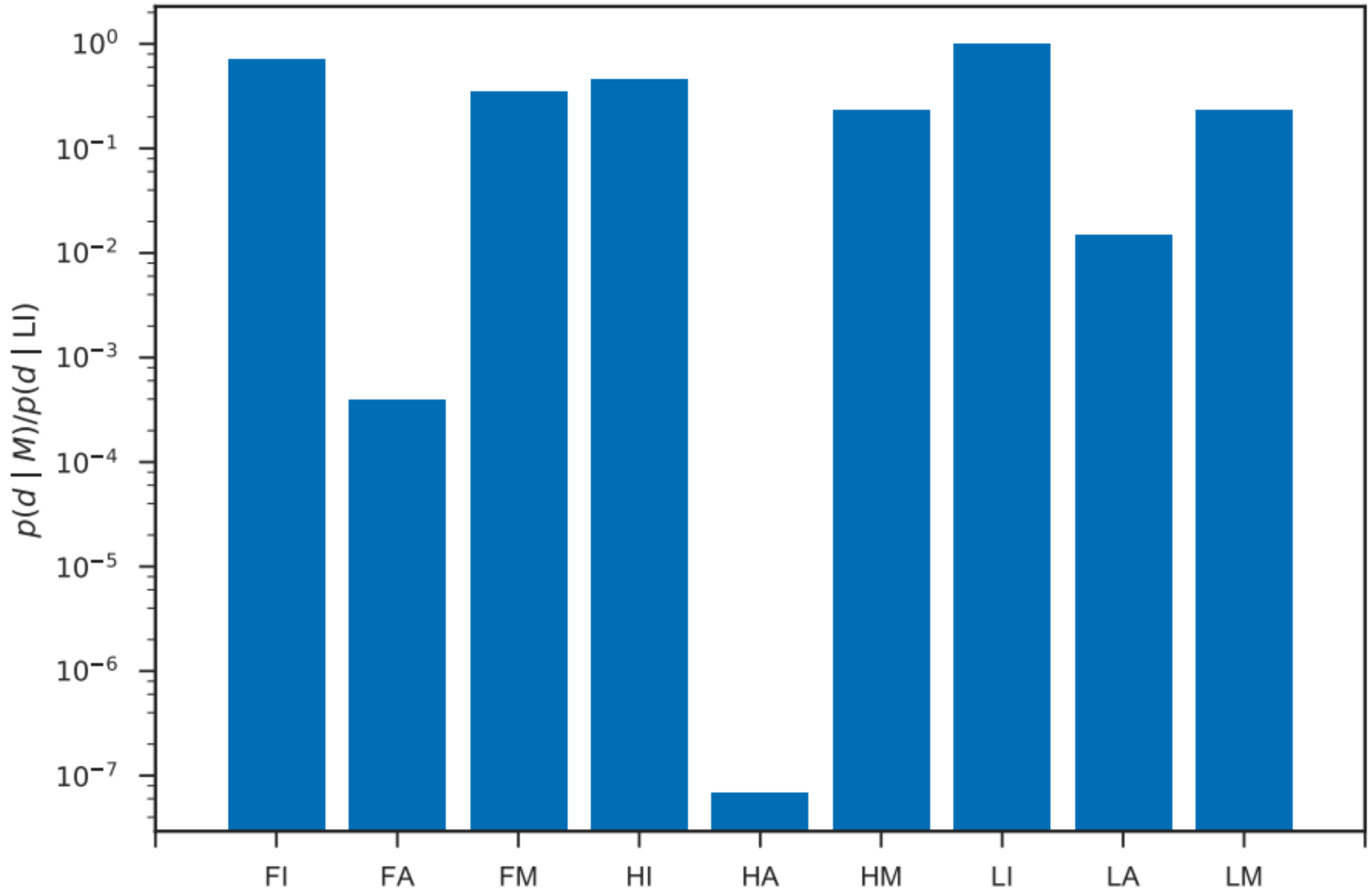
→ Mass ratio usually means second spin is unconstrained

→ Most distributions have significant weight near zero spin

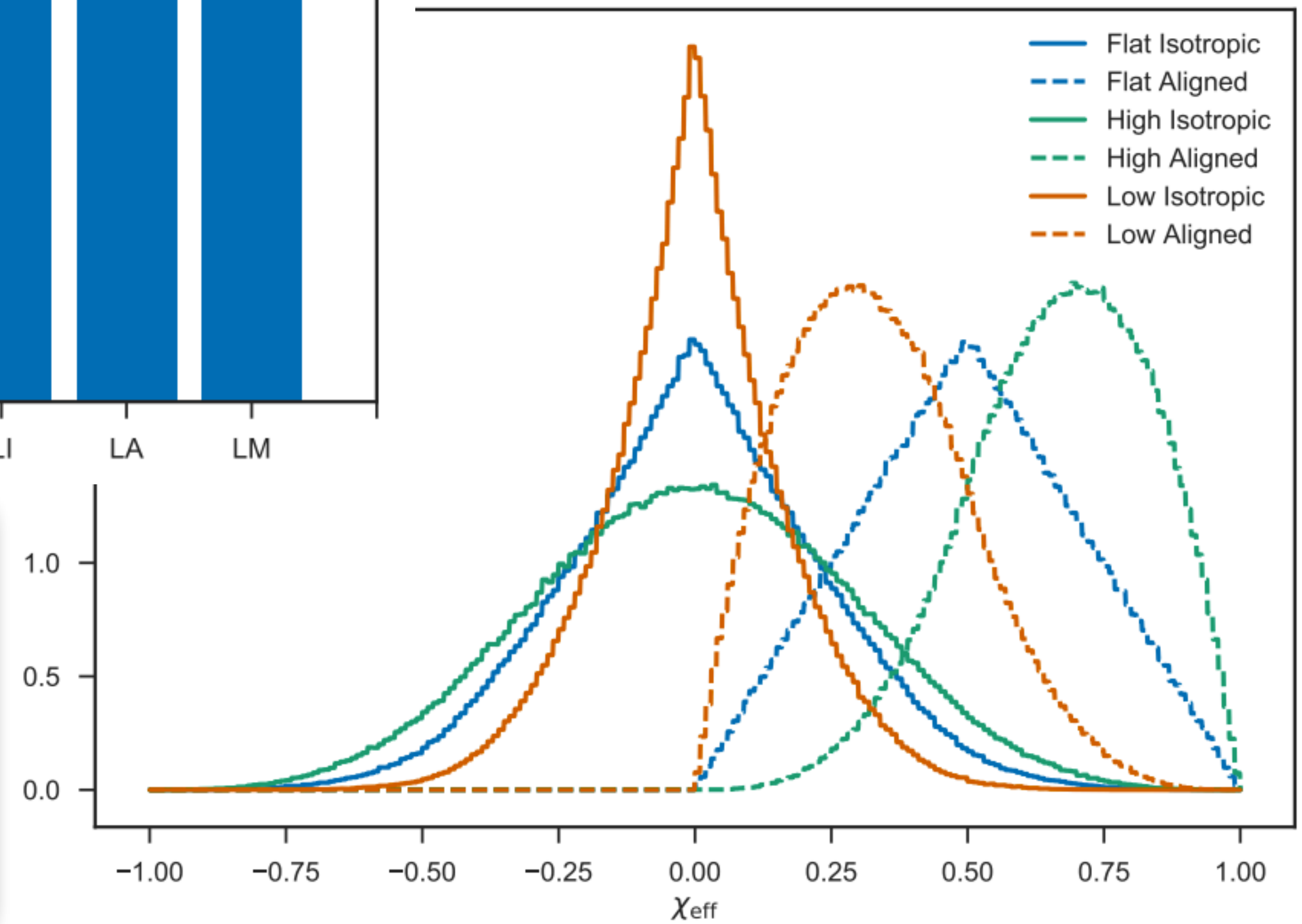
→ GW *searches* do *not* include precession effects (could lead to observational bias)

Farr, et al. 2017 (Nature)

Assume various simple distributions of spin magnitude. Use these as proxies for low, high, and flat. Using existing observations, infer a virtual "population" giving rise to those distributions in *effective spin.*



FI: Flat mag., isotropic dir.
FA: Flat mag. aligned dir.
HI: High mag, isotropic dir.
HA: High mag, aligned dir
LI: Low mag, isotropic dir
LA: Low mag, aligned dir

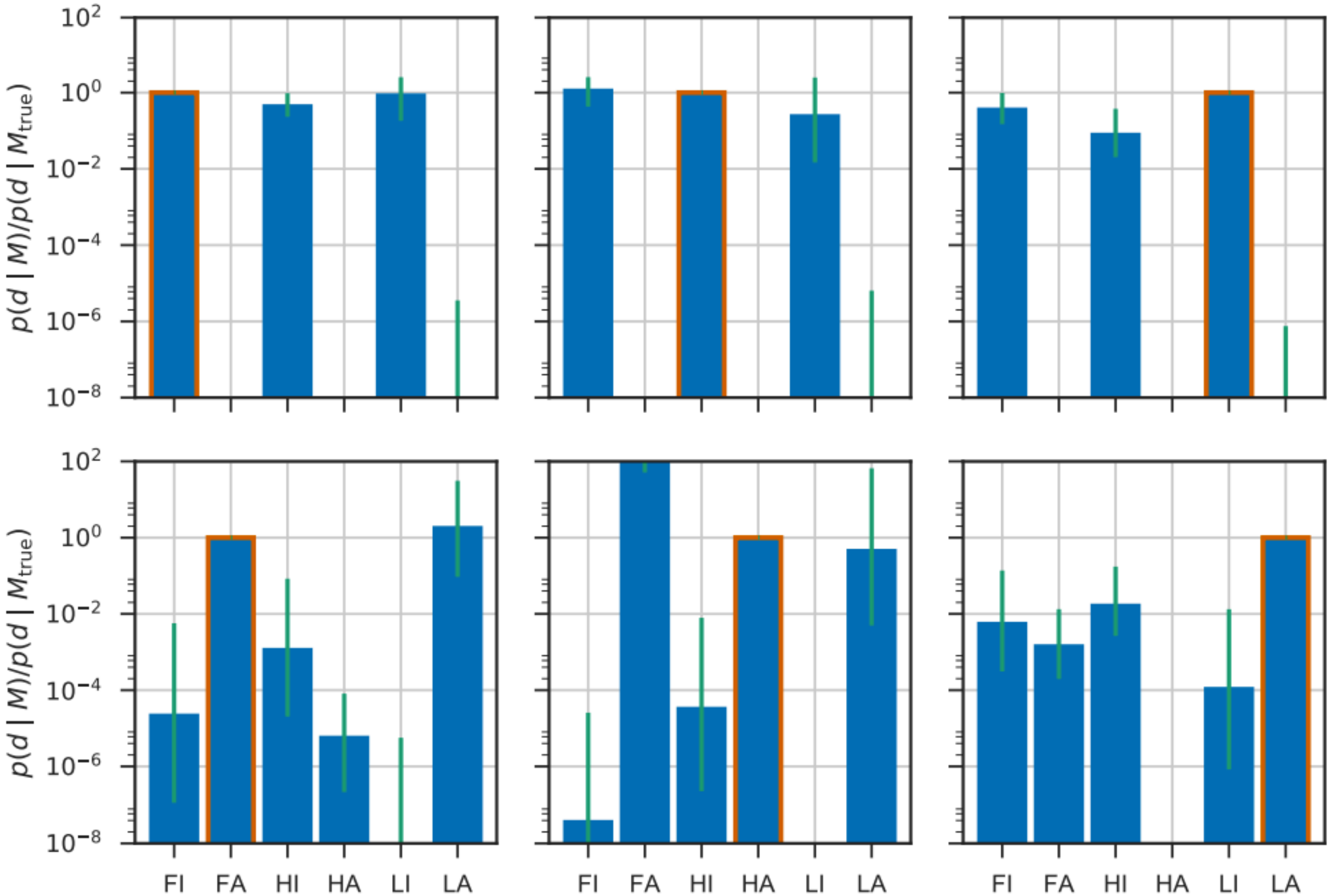


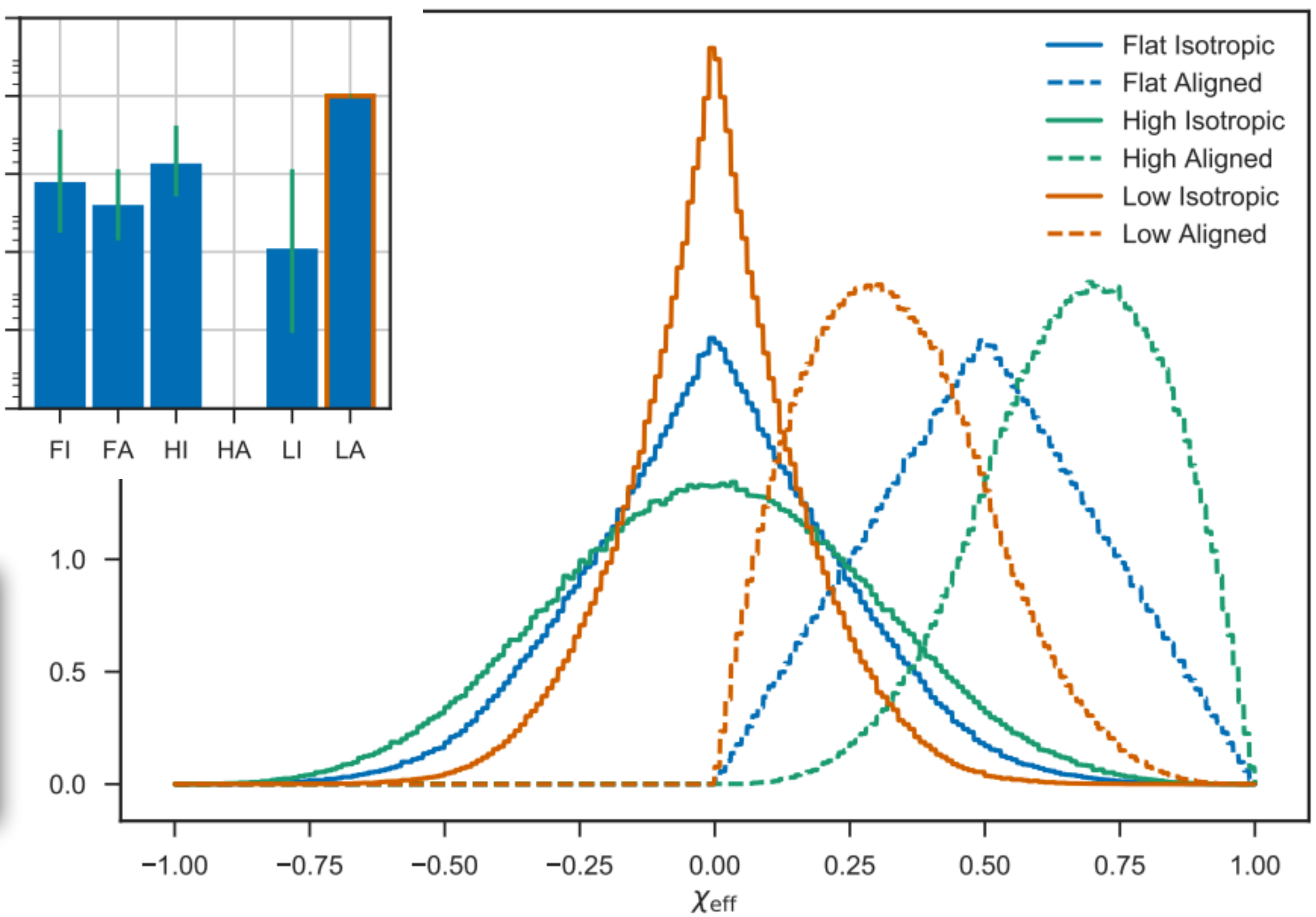
Current detections:
Bayes Factors (evidence for one model versus another) already disfavors high/flat mag. aligned spin

Farr, et al. 2017 (Nature)

Assume various simple distributions of spin magnitude. Use these as proxies for low, high, and flat. Using existing observations, infer a virtual "population" giving rise to those distributions in *effective spin.*

FI: Flat mag., isotropic dir.
FA: Flat mag. aligned dir.
HI: High mag, isotropic dir.
HA: High mag, aligned dir
LI: Low mag, isotropic dir
LA: Low mag, aligned dir

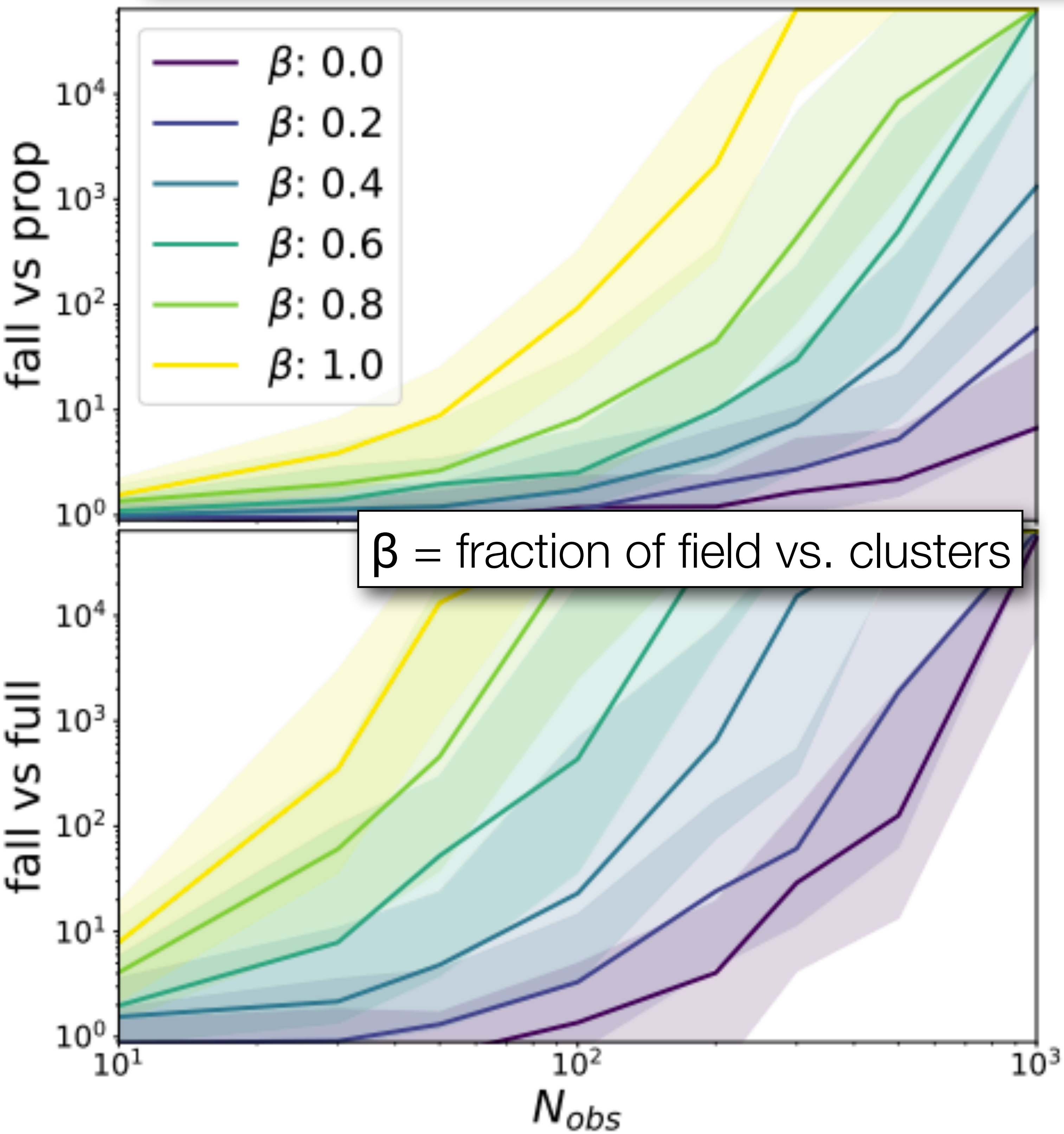




Additional detections:
After *10 additional detections* from *each* model

Zevin, et al. 2017 (ApJ)

Similar statistical procedure, but use mass distributions to determine how many mass observations are required to confidently discern a given BH natal kick prescription



Kick Prescription:

Full: $v_{BH} = v_{NS}$

Fallback: $v_{BH} = (1-f)\ v_{NS}$

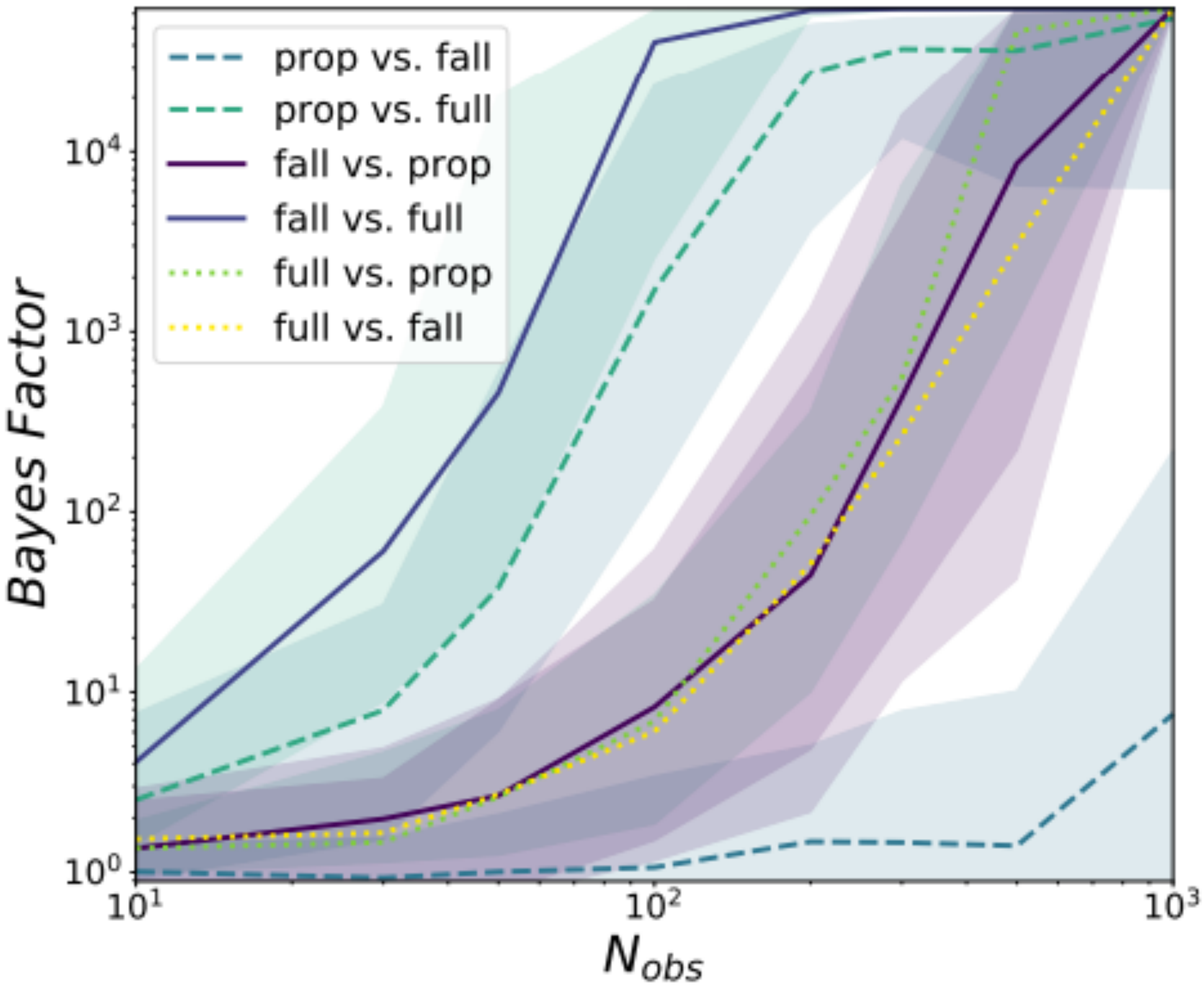
Proportional: $v_{BH} = M_{NS}/M_{BH}\ v_{NS}$

Distinguishability:

Cluster populations are very similar across prescriptions, so β becomes easier to measure — Kick disruption changes the mass population density and so some prescriptions (proportional) can be distinguished easier than others even with only mass

Zevin, et al. 2017 (ApJ)

Similar statistical procedure, but use mass distributions to determine how many mass observations are required to confidently discern a given BH natal kick prescription



Kick Prescription:

Full: $v_{BH} = v_{NS}$

Fallback: $v_{BH} = (1\text{-}f)\ v_{NS}$

Proportional: $v_{BH} = M_{NS}/M_{BH}\ v_{NS}$

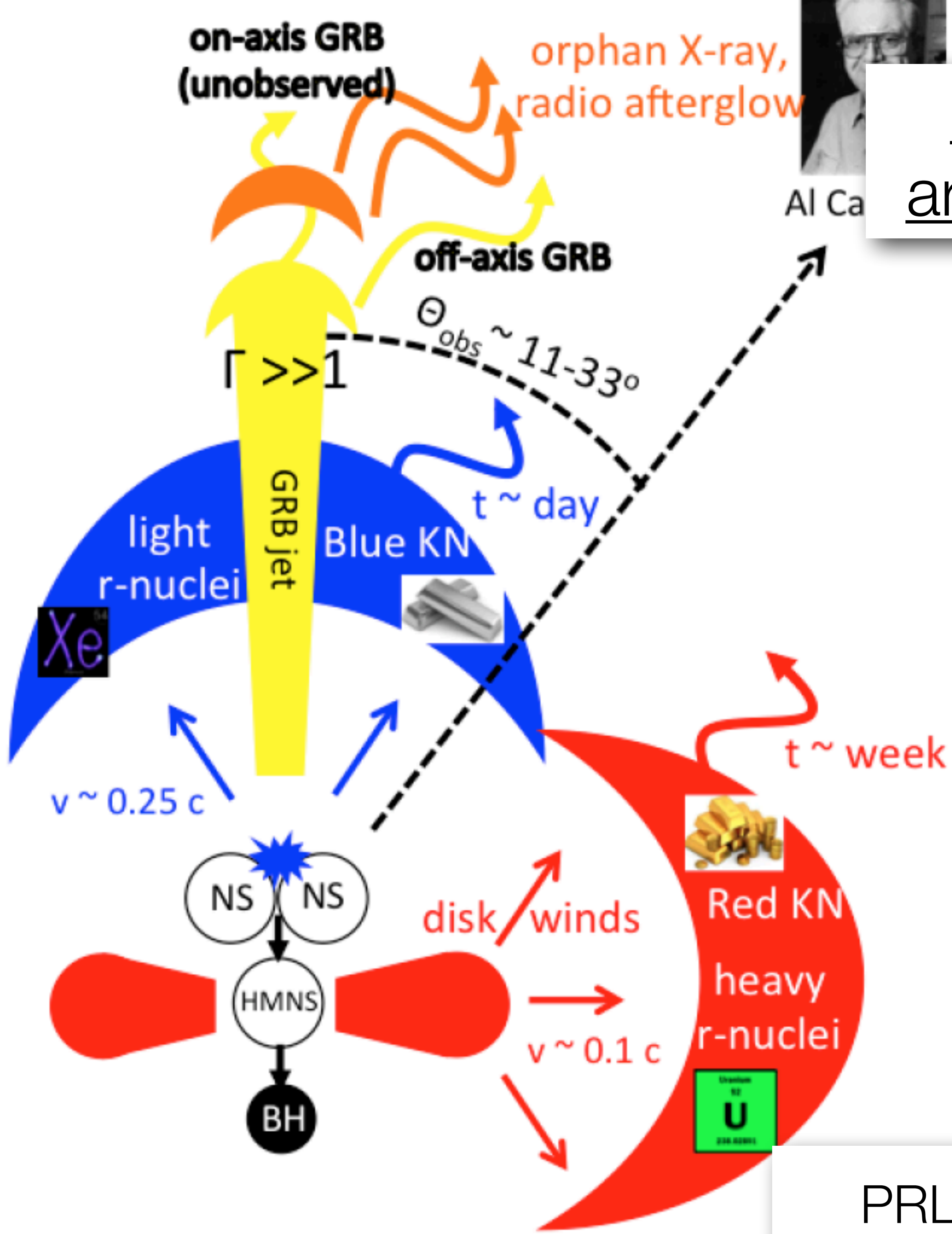
Distinguishability:

Cluster populations are very similar across prescriptions, so β becomes easier to measure — Kick disruption changes the mass population density and so some prescriptions (proportional) can be distinguished easier than others even with only mass

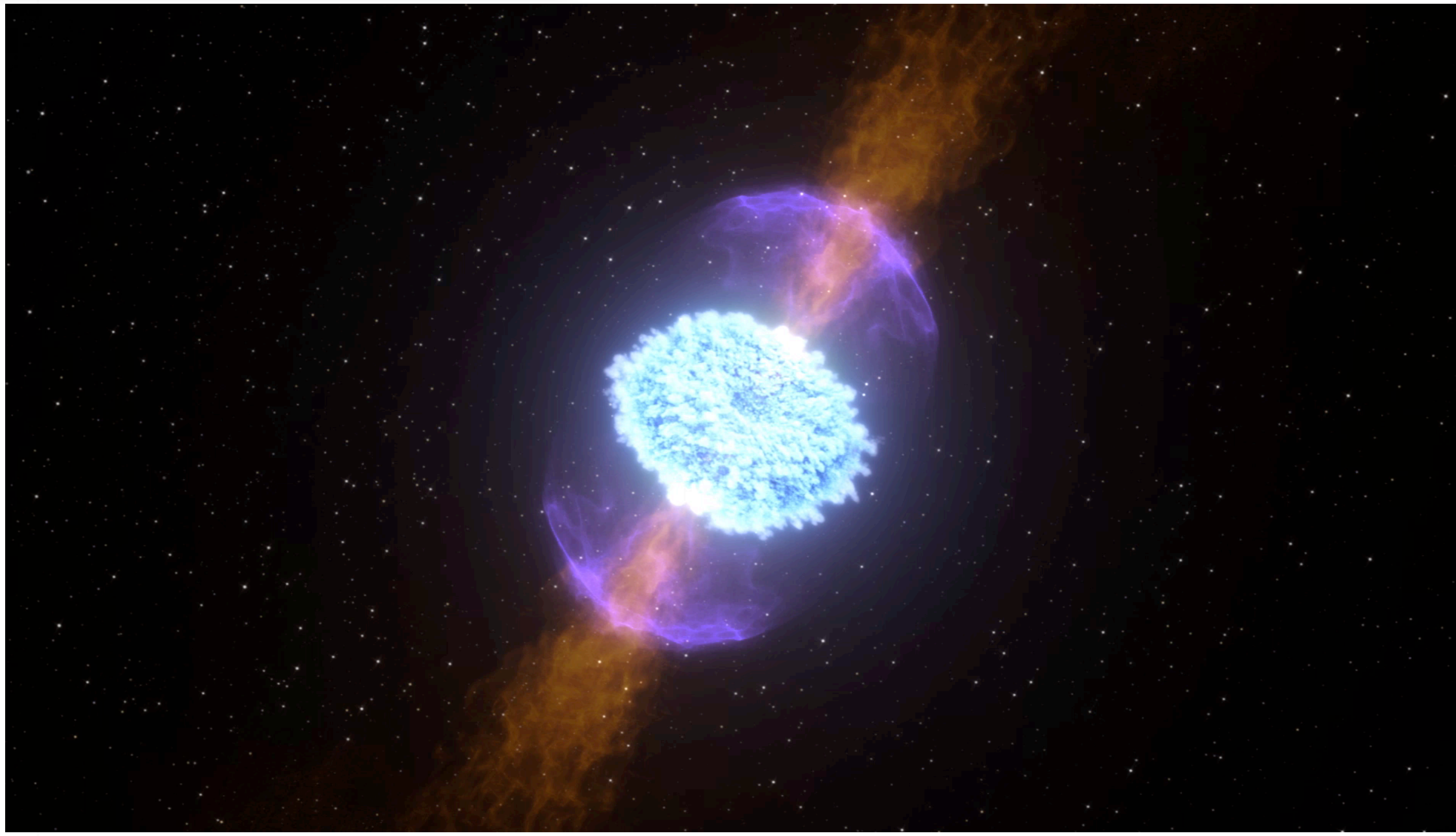
O2 Part 2

GW170817/GRB170817A, astrophysics with neutron stars

GW170817

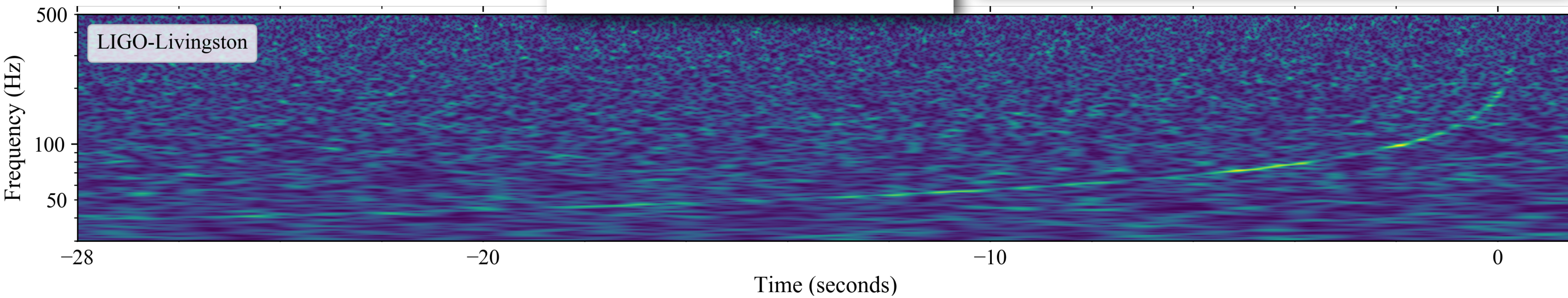


Metzger 2018, arXiv:1710.05931



https://youtu.be/x_Akn8fUBeQ
NASA Goddard SFC

PRL 119, 161101



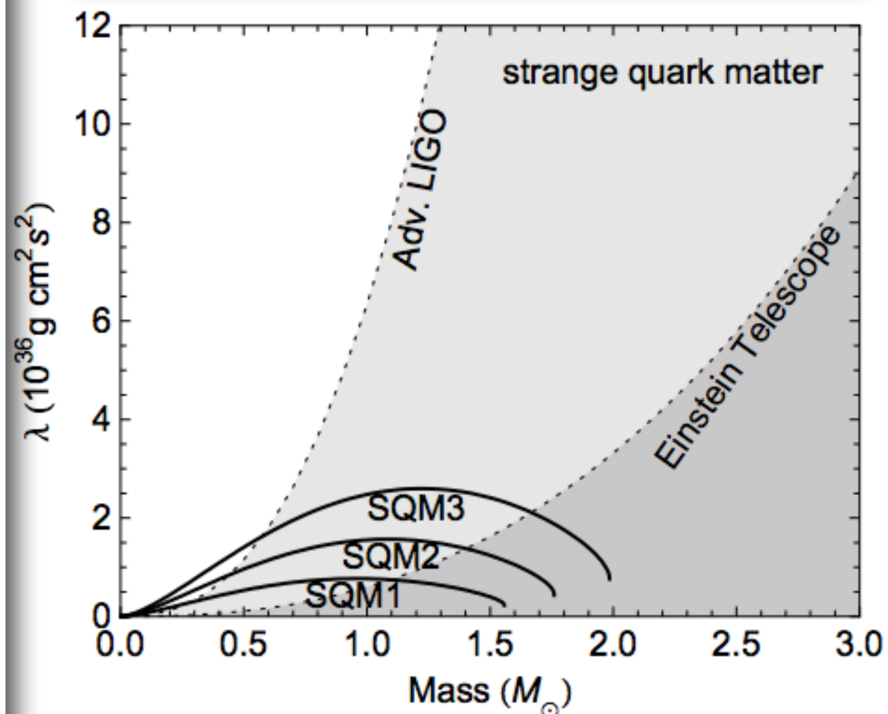
20

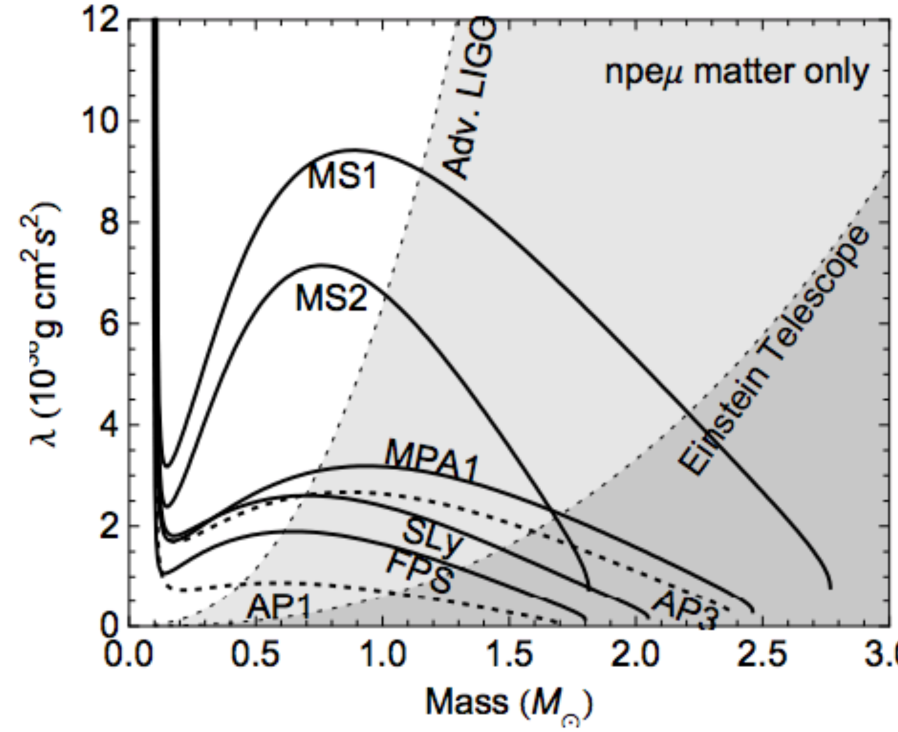
Binary dynamics is affected by the EoS through the **tidal deformation** of neutron stars

…but is highly subdominant… enters into the analytical phase expression used by searches and "PE" at **O((v/c)^{10})**

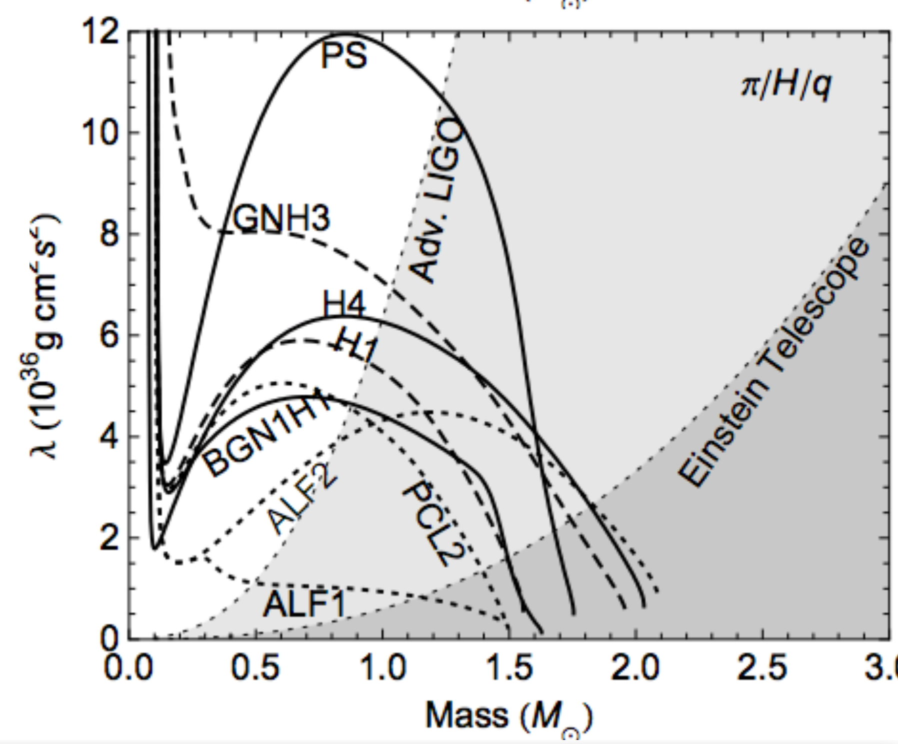
This is subordinate to the masses, mass ratio, spins, spin interactions, …

Hinderer, et al. (2009)





$$\lambda \equiv \frac{2k_2R^5}{3G}$$

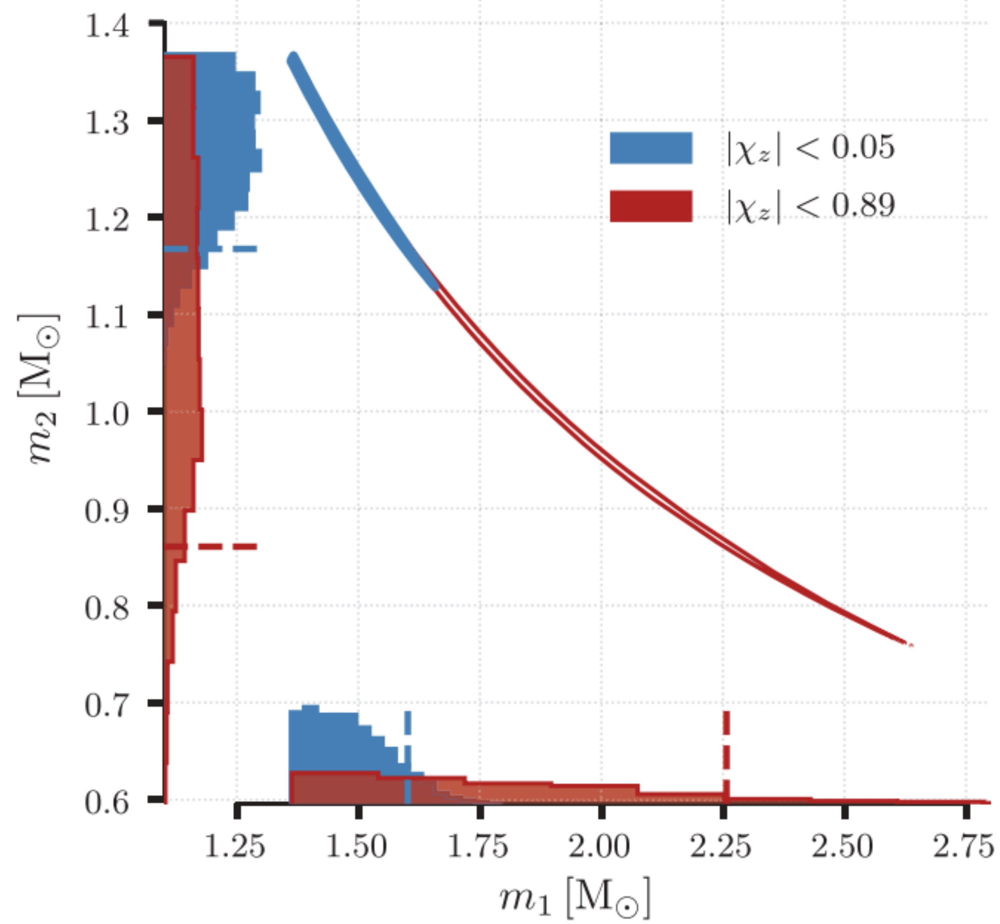


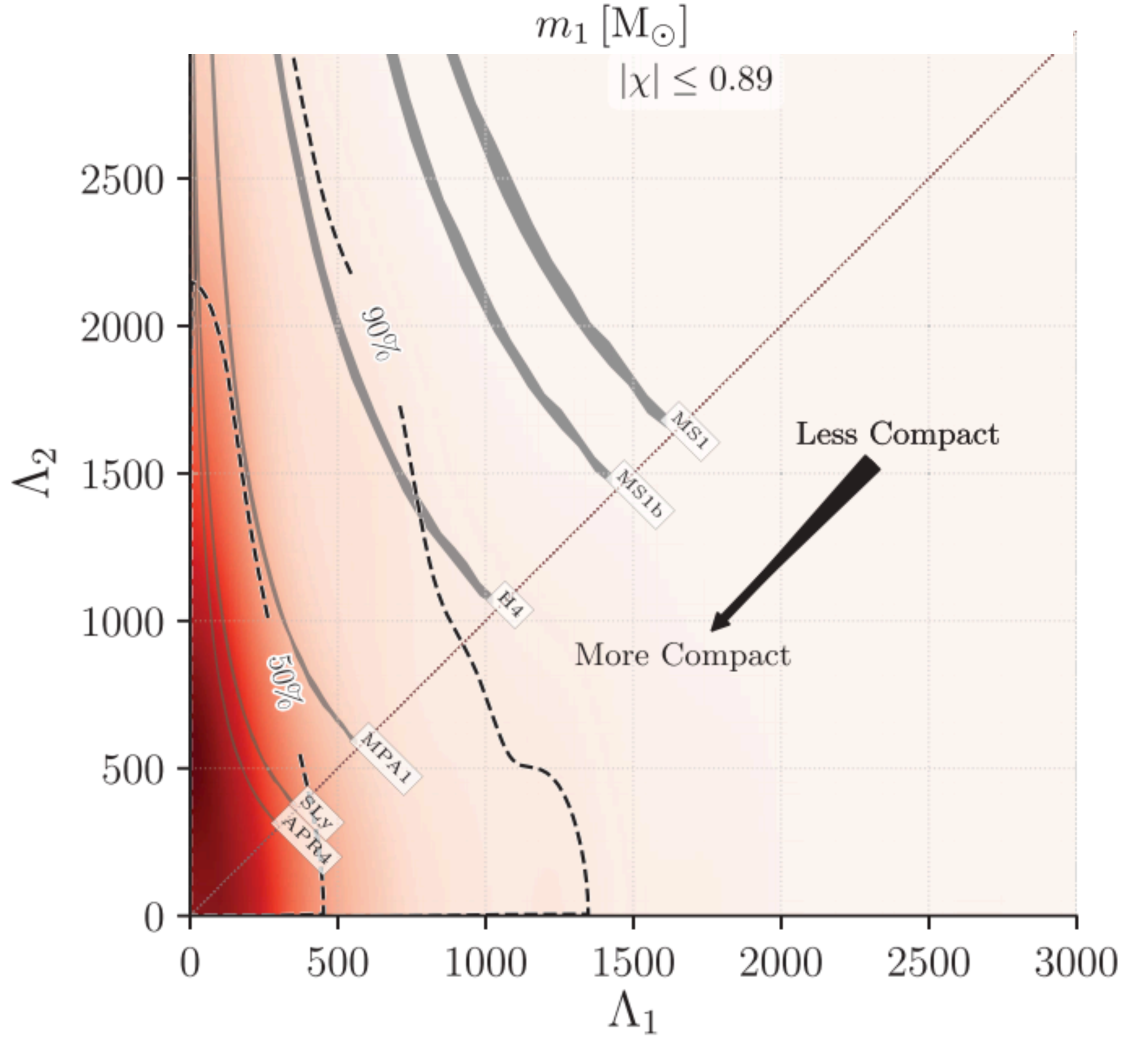
k_2: Tidal Love number — encodes the **rigidity** of the star

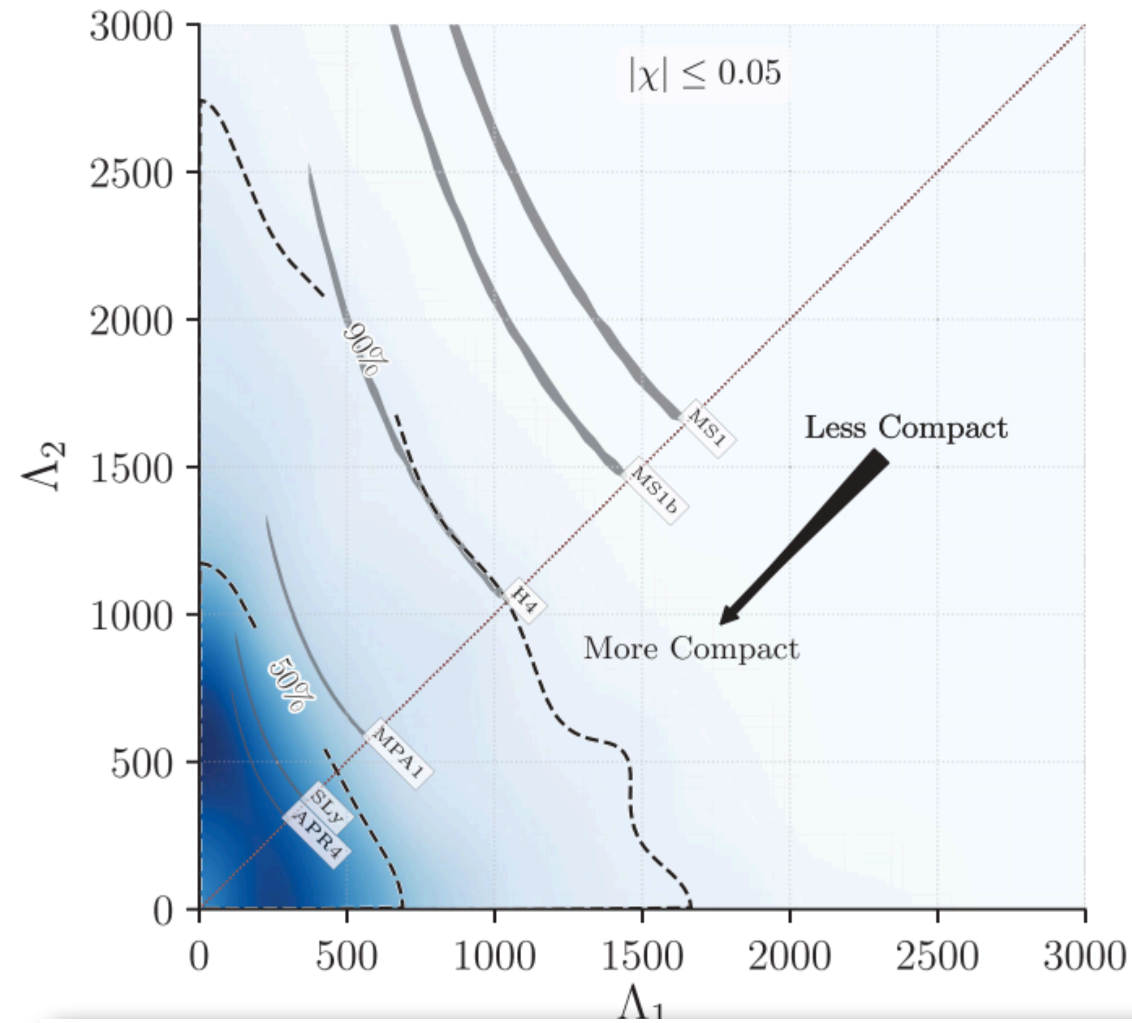
More on EoS in talk by J. Read

GW170817

chirp mass: measured to within ~10^{-3}
EoS (through Λ): disfavor stiff (R(M) > 14 km)
inclination: GW alone cannot exclude 0, but host galaxy association can
spin ($\chi_i = c|S_i|/Gm_i^2$): Cannot place strong constraint



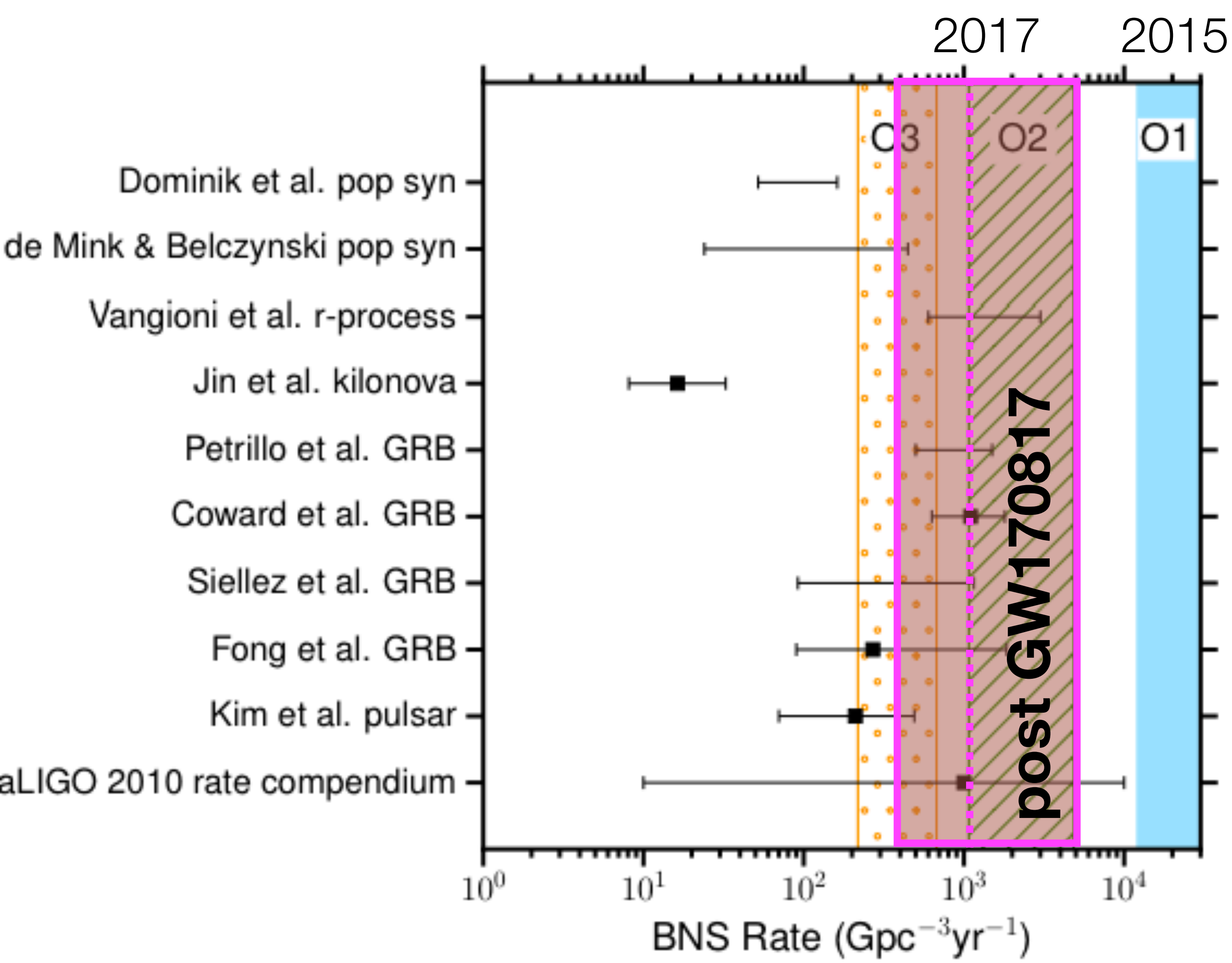


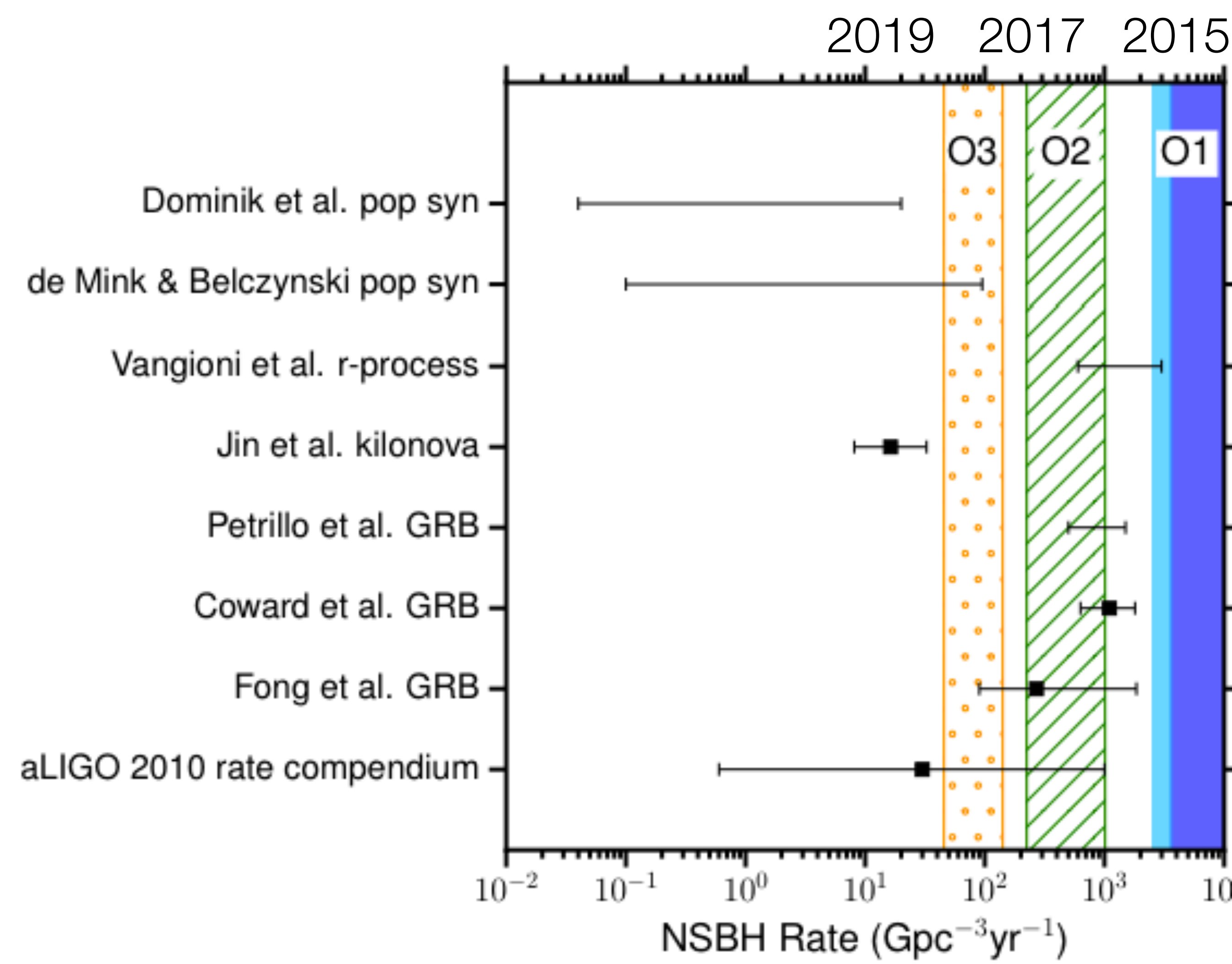


Updated plots in talk by B. Lackey

O1 BNS / NSBH Upper Limits

ApJL 832, 2 (2016)



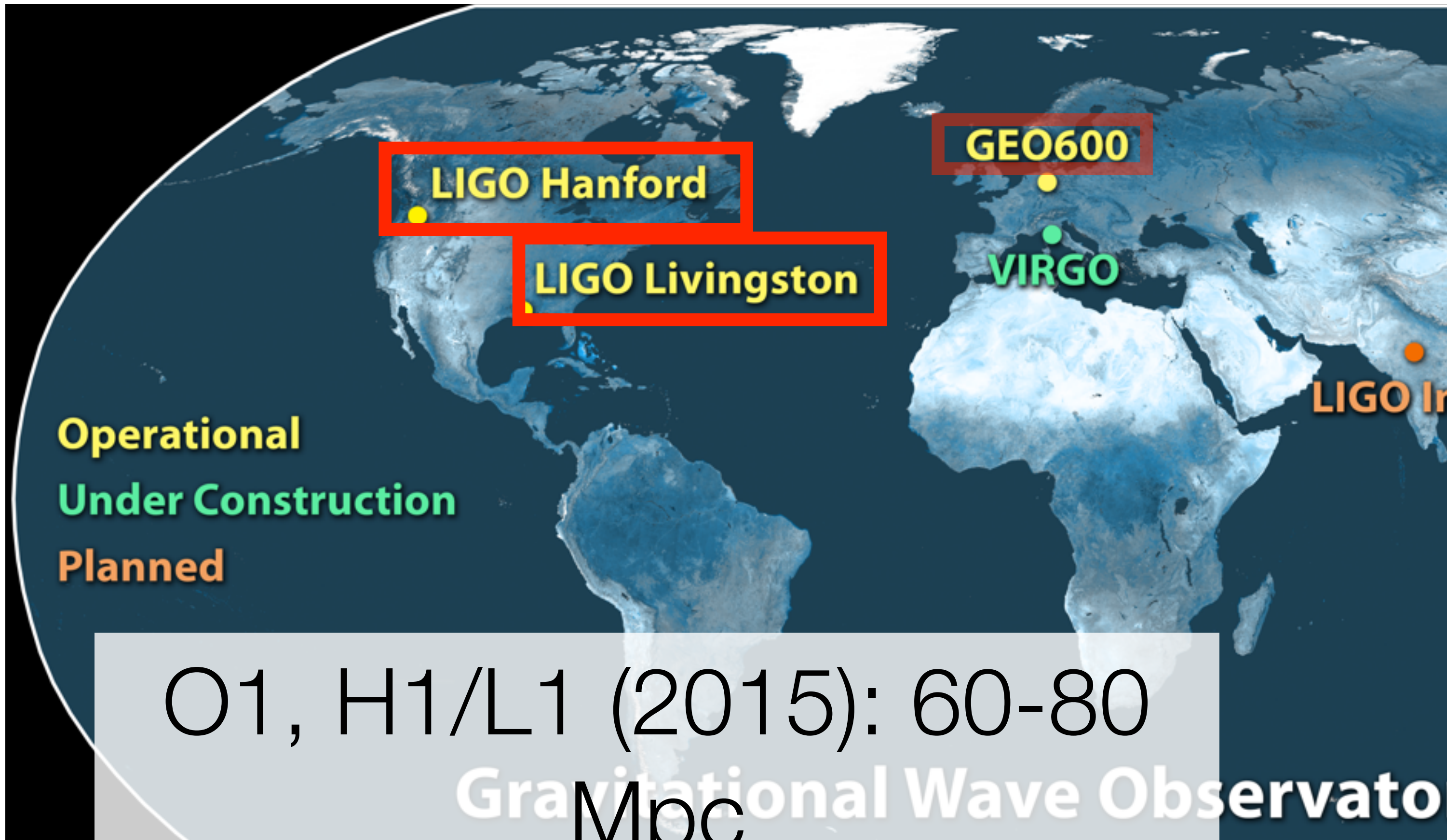


NSBH remain elusive, but expected to constrain models in the coming observing runs

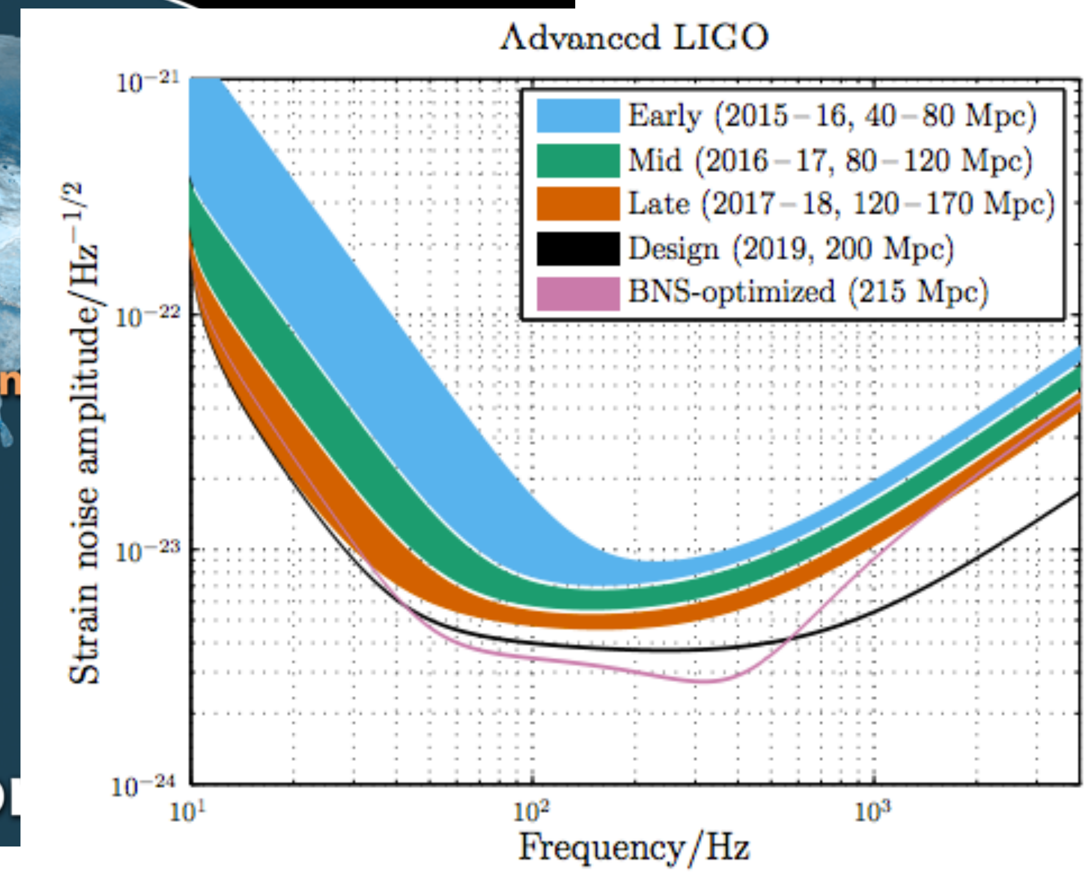
2019 and beyond: towards design sensitivity

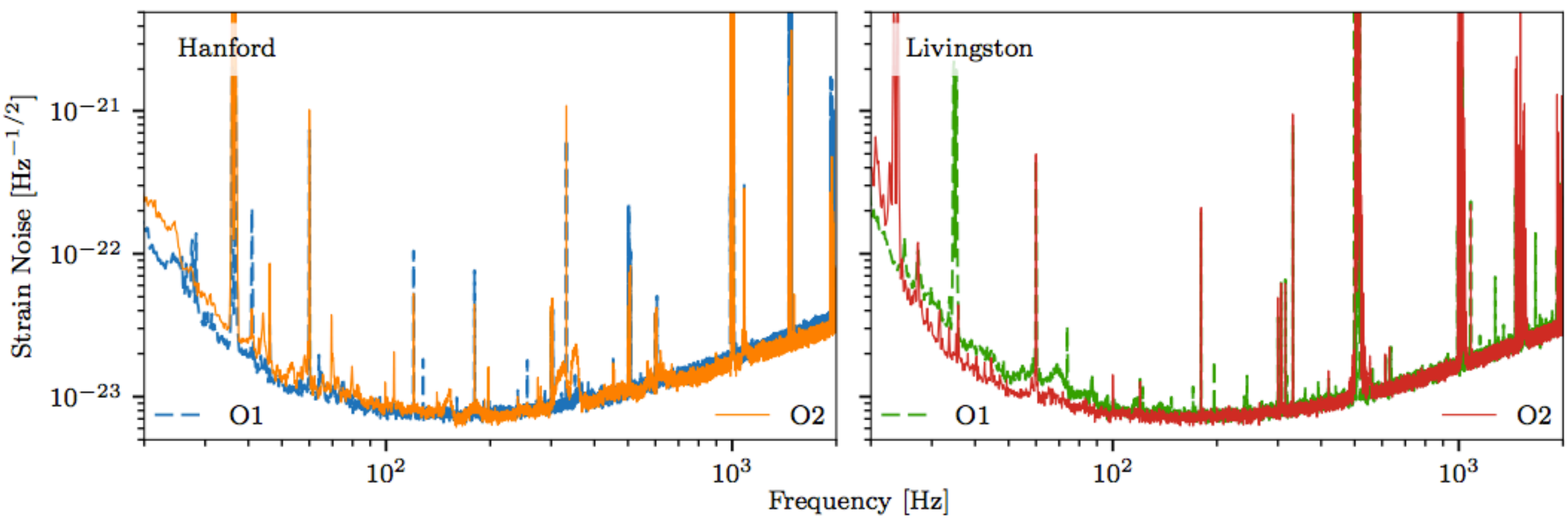
Future of gravitational-wave binary astrophysics

The Next ~5 Years



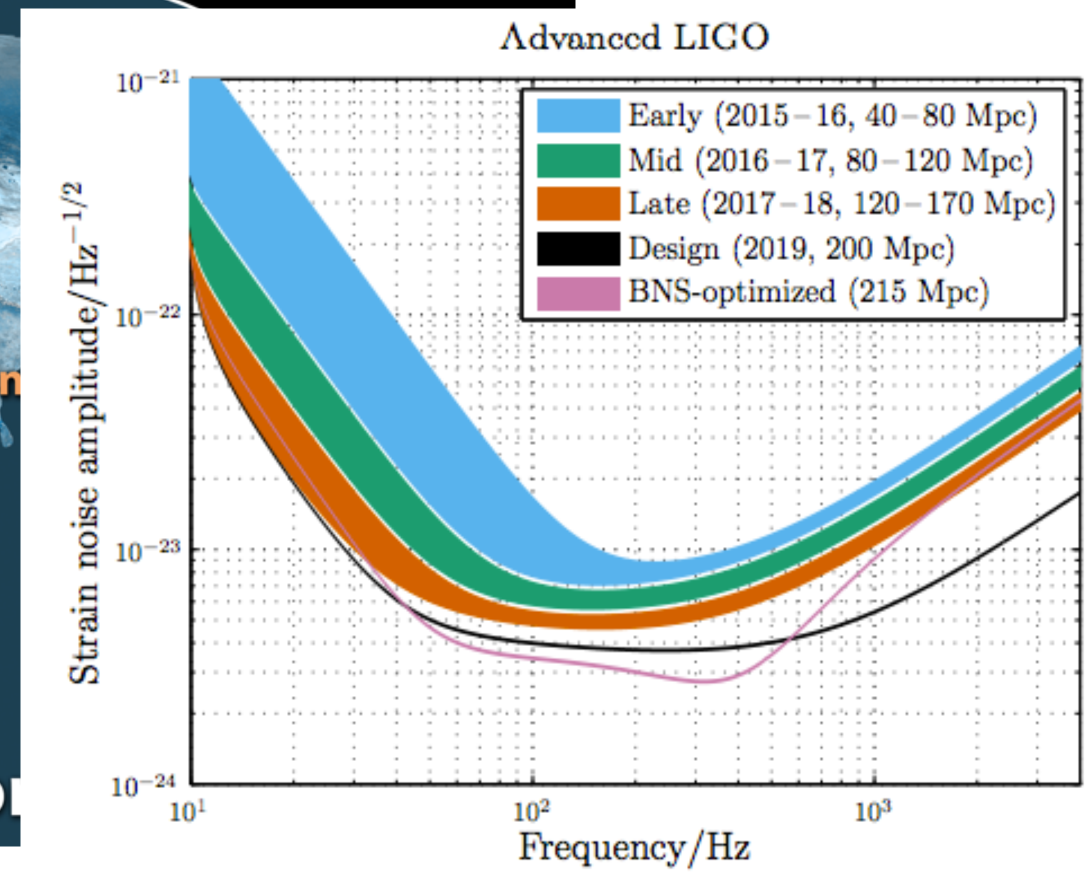
O1, H1/L1 (2015): 60-80 Mpc

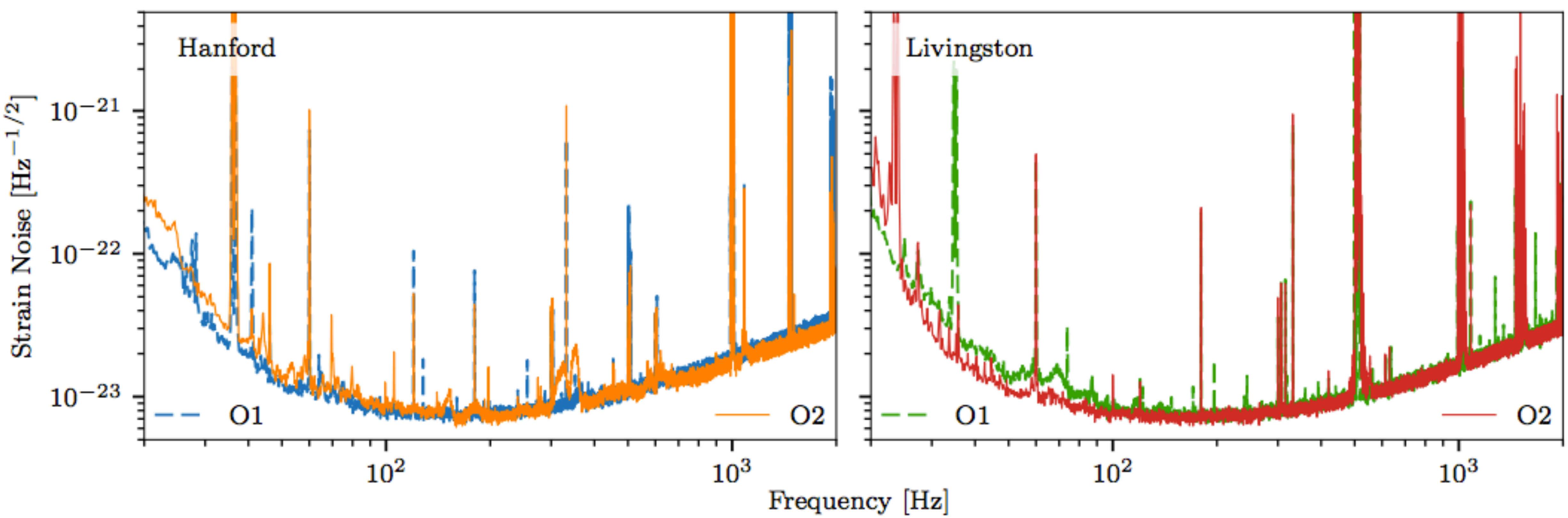




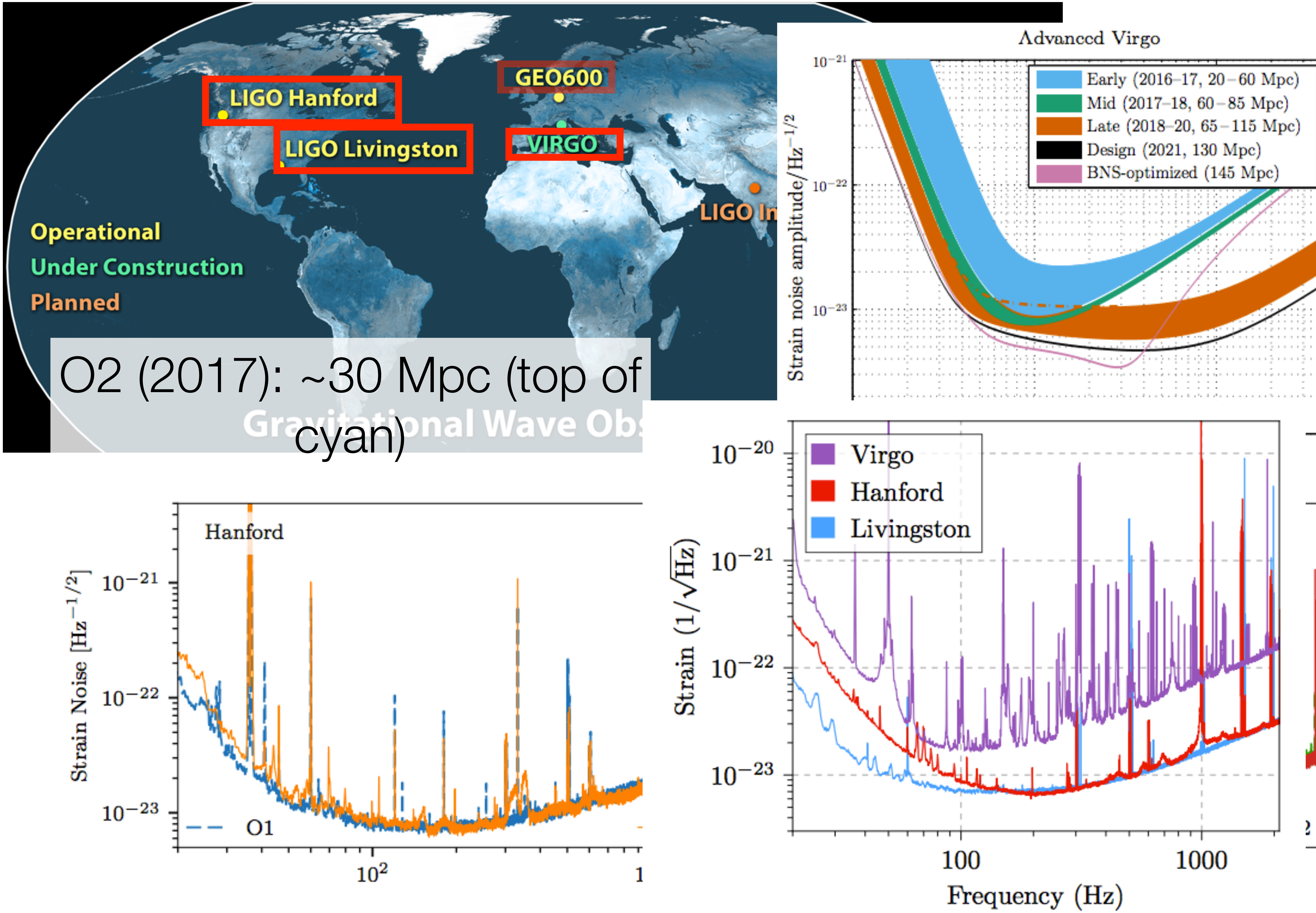
The Next ~5 Years

O2, H1/L1 (2016-2017):
60-100 Mpc (middle green)



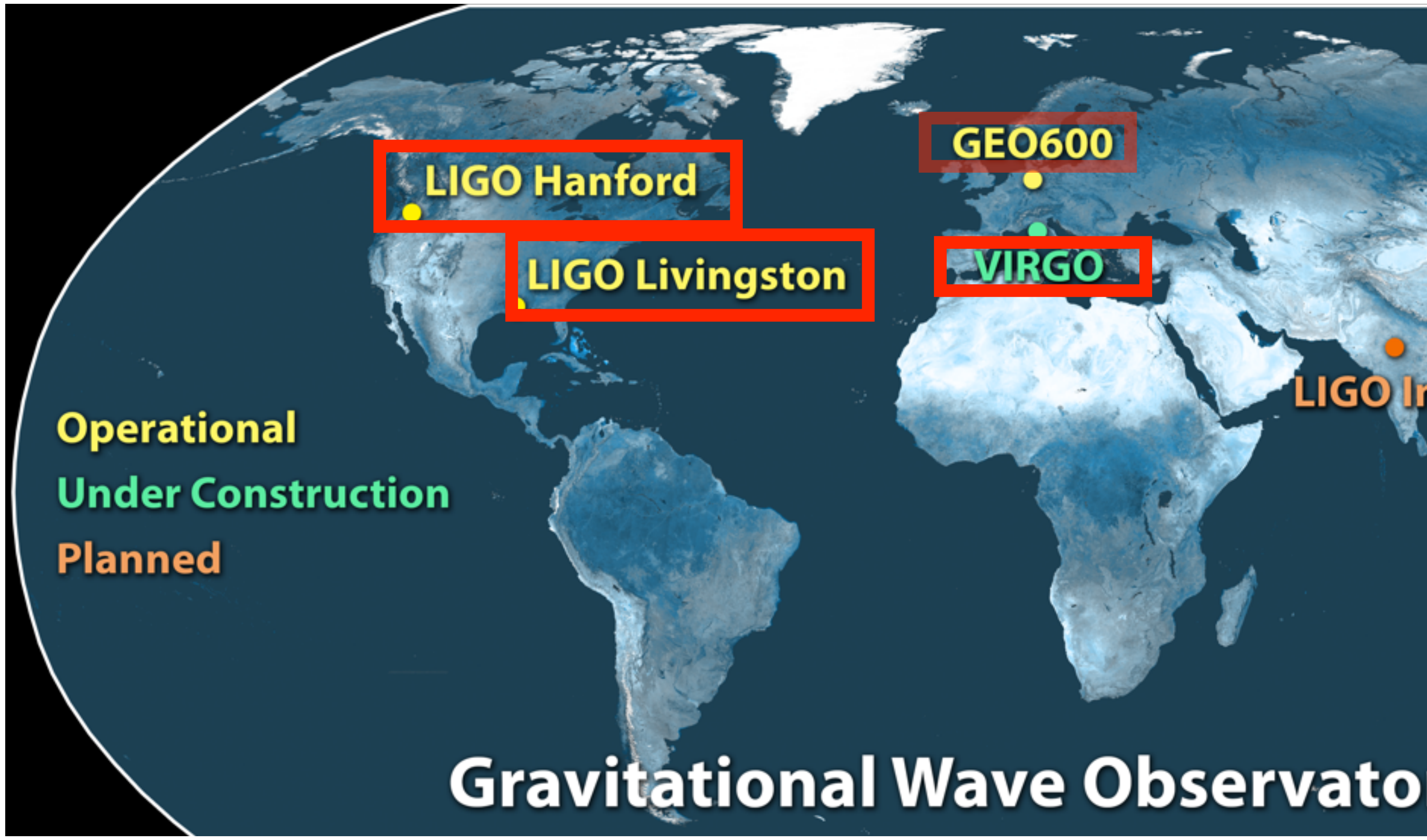


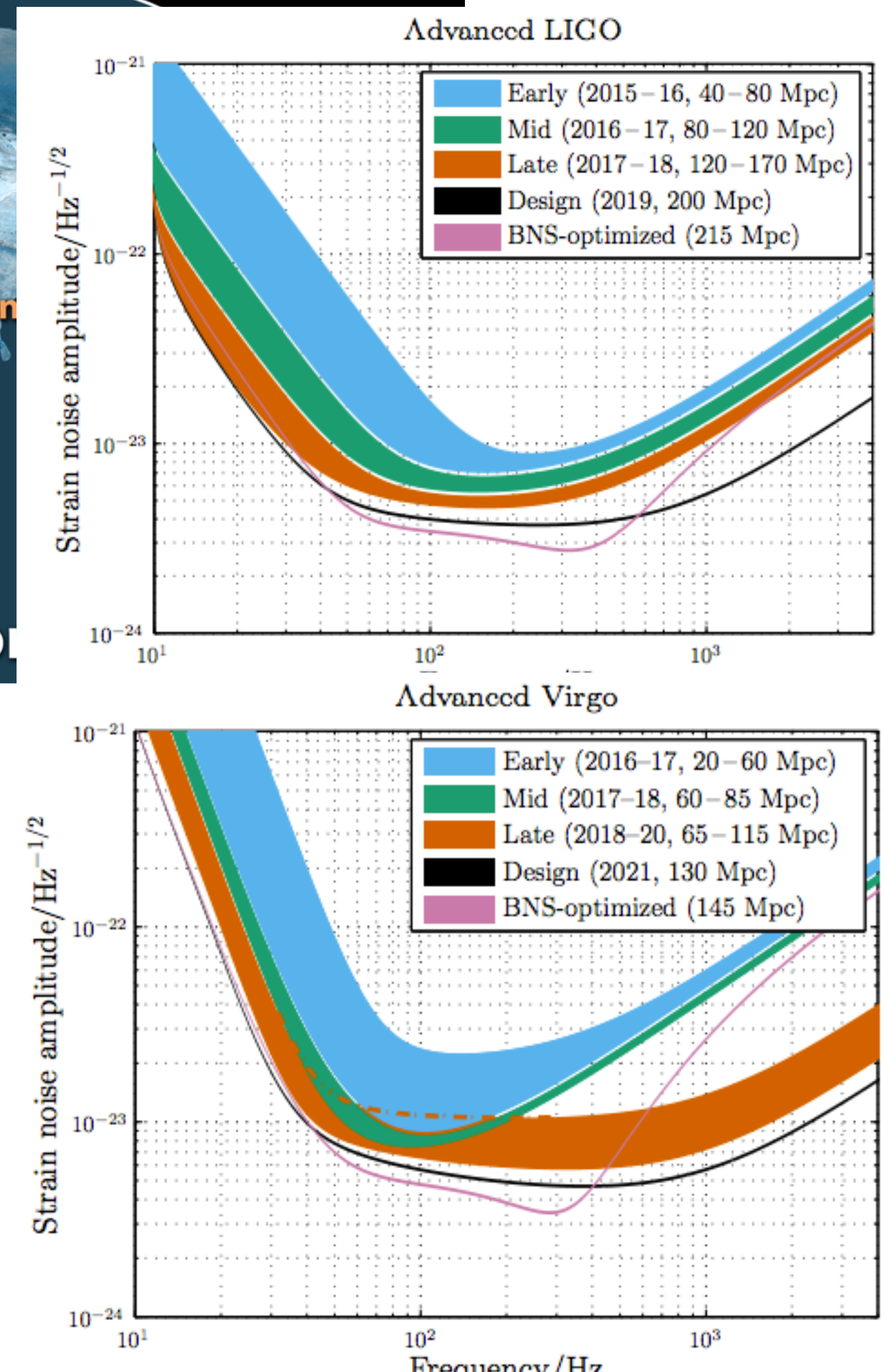
The Next ~5 Years



O2 (2017): ~30 Mpc (top of cyan)

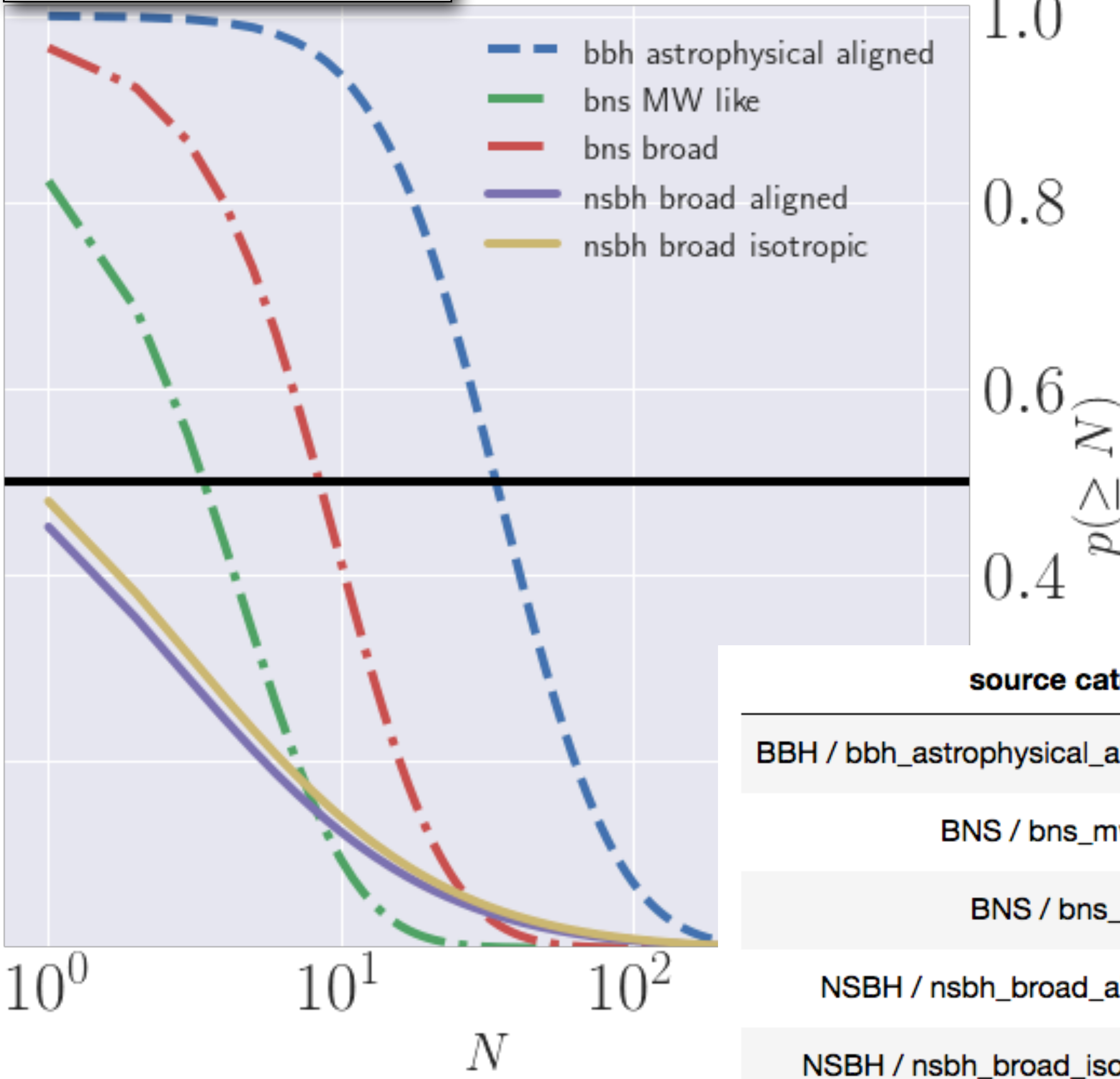
The Next ~5 Years





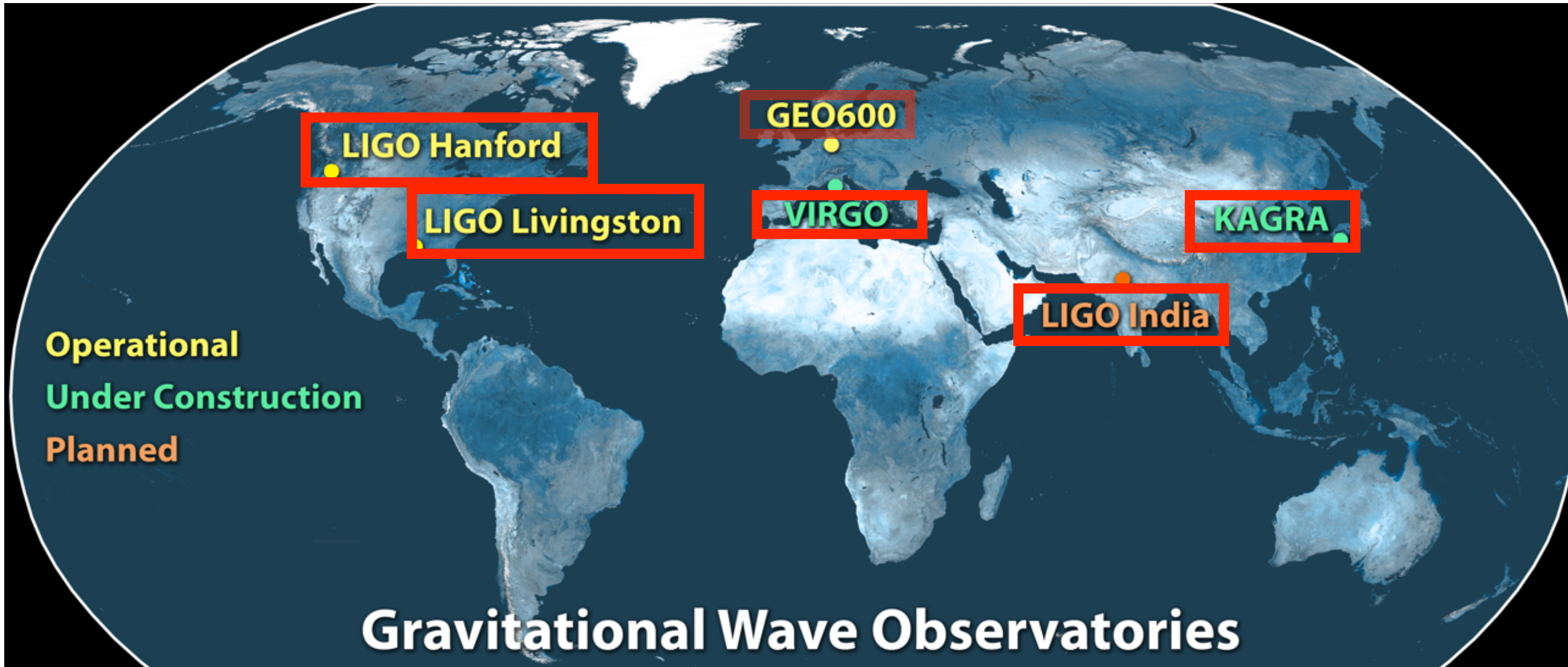
O3+, H1/L1/V1 (2019): H1/L1 120 Mpc (proj.) V1 60 Mpc (proj.)

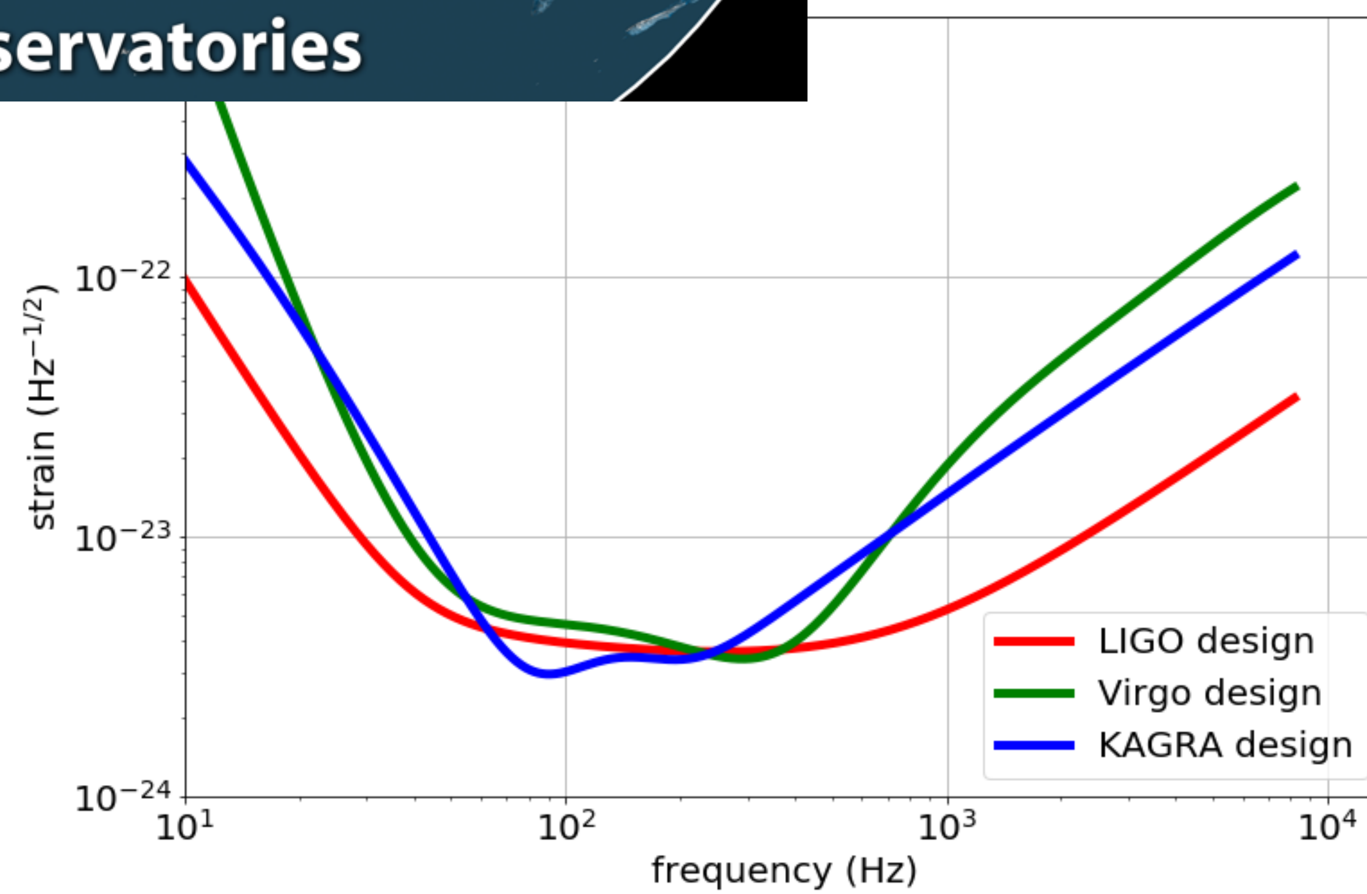
Detection Potential



source category	full year VT	N_d
BBH / bbh_astrophysical_aligned	6.8×10^8 Mpc^3 yr	35^{+78}_{-26}
BNS / bns_mw_like	3.2×10^6 Mpc^3 yr	4^{+9}_{-4}
BNS / bns_broad	7.3×10^6 Mpc^3 yr	9^{+19}_{-7}
NSBH / nsbh_broad_aligned	4.9×10^7 Mpc^3 yr	1^{+24}_{-1}
NSBH / nsbh_broad_isotropic	5.7×10^7 Mpc^3 yr	1^{+28}_{-1}

The Next ~5 Years





→ 4 and 5 detector networks by mid 2020s

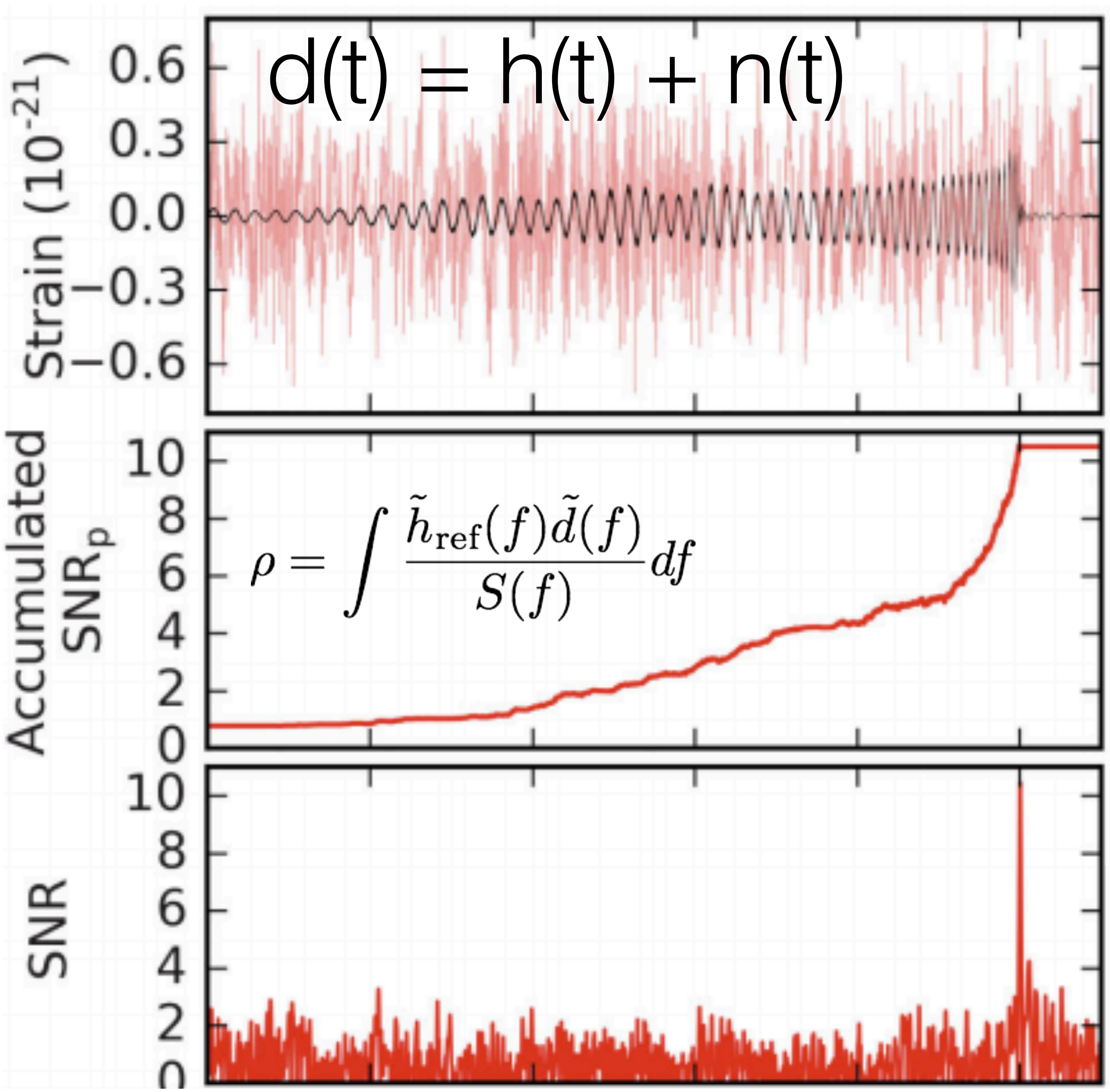
→ 202X LIGO to meet design sensitivity (blue curve)

→ Kagra online before 2020

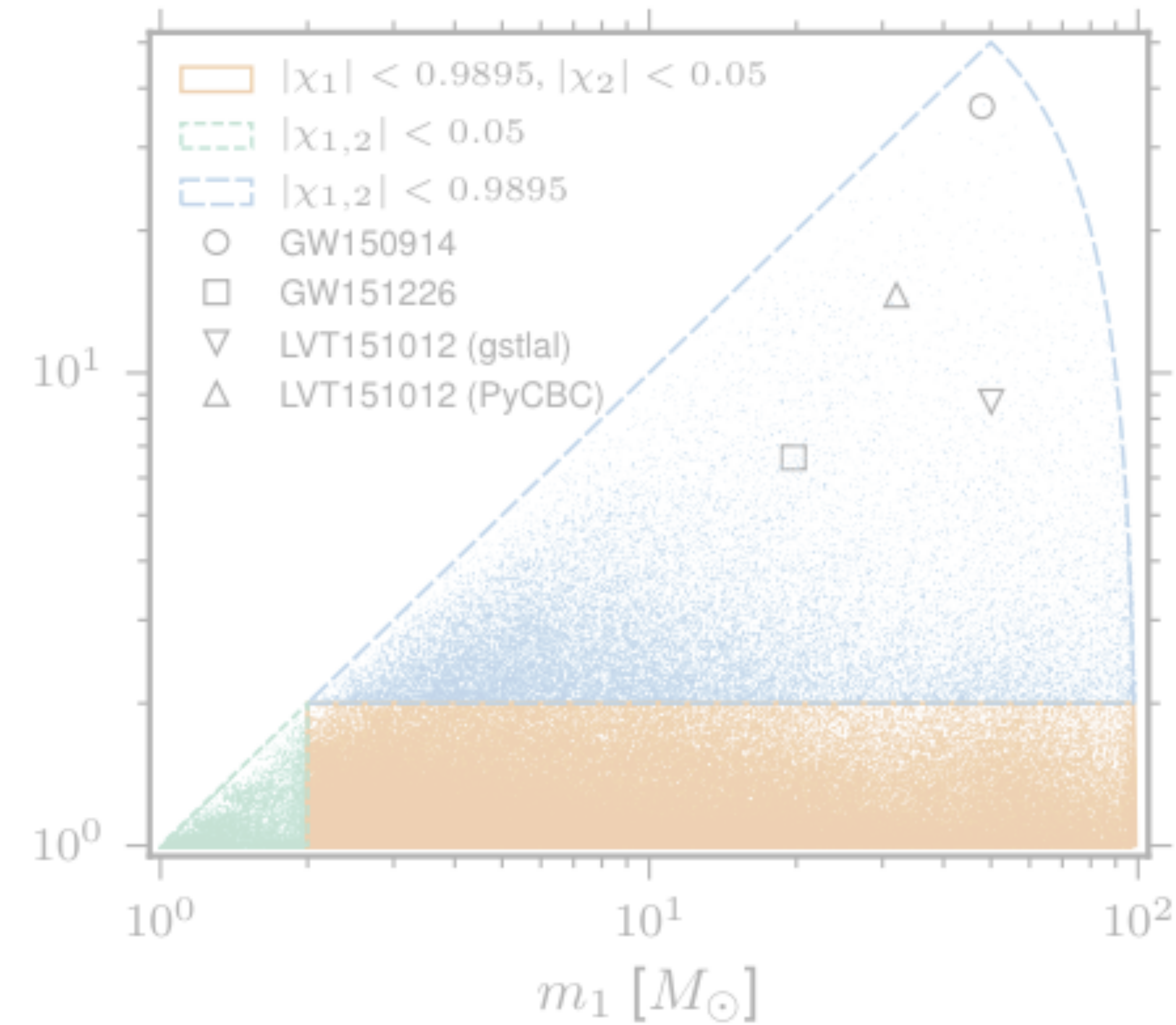
→ LIGO India tentatively for 2024

Extra Slides

GW Signal Detection Primer



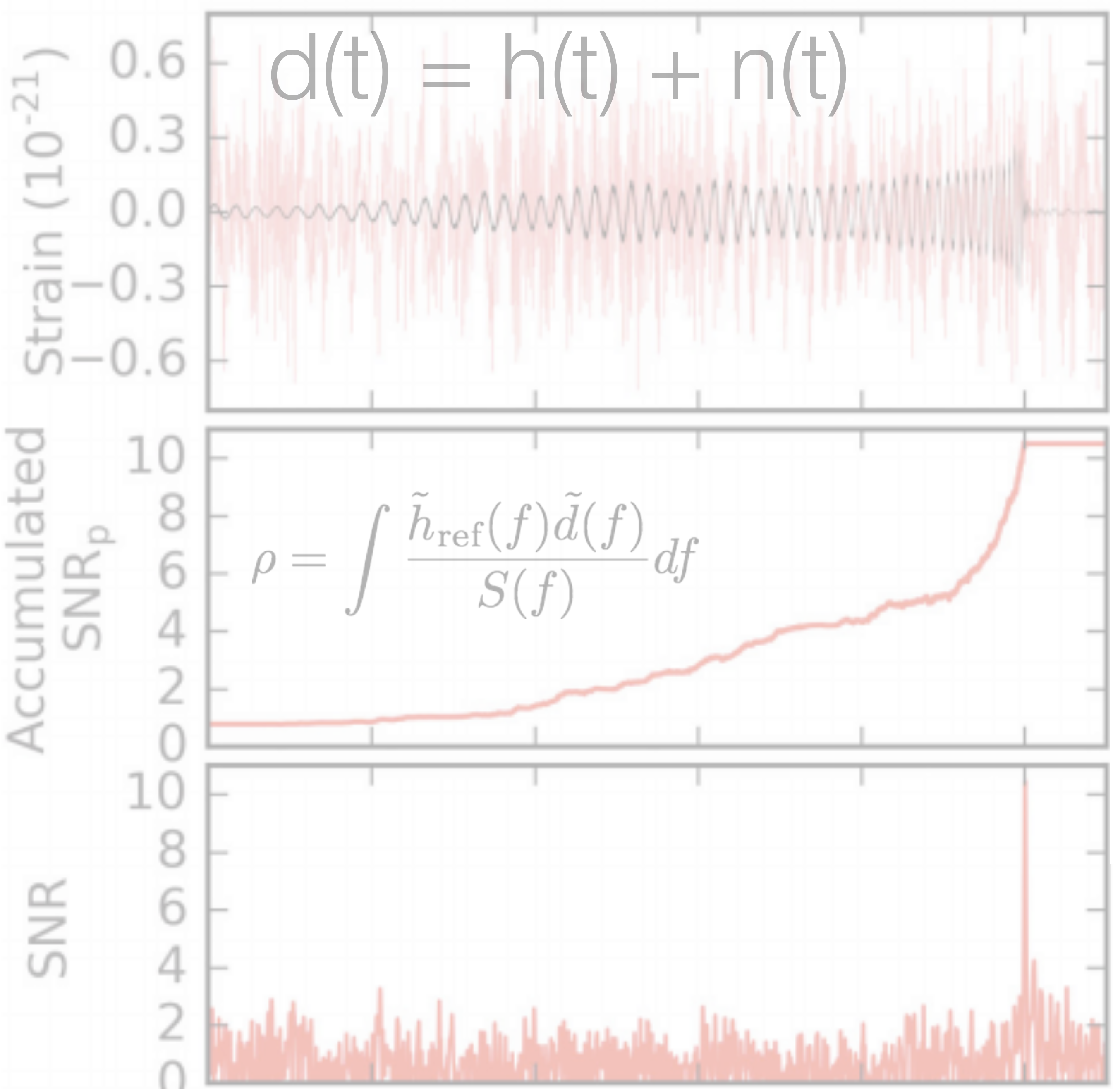
Putative strain is embedded in detector noise — cross correlate the model with the data to extract a signal-to-noise ratio (SNR, ρ) statistic — this maximizes the likelihood (probability of signal vs probability of noise)

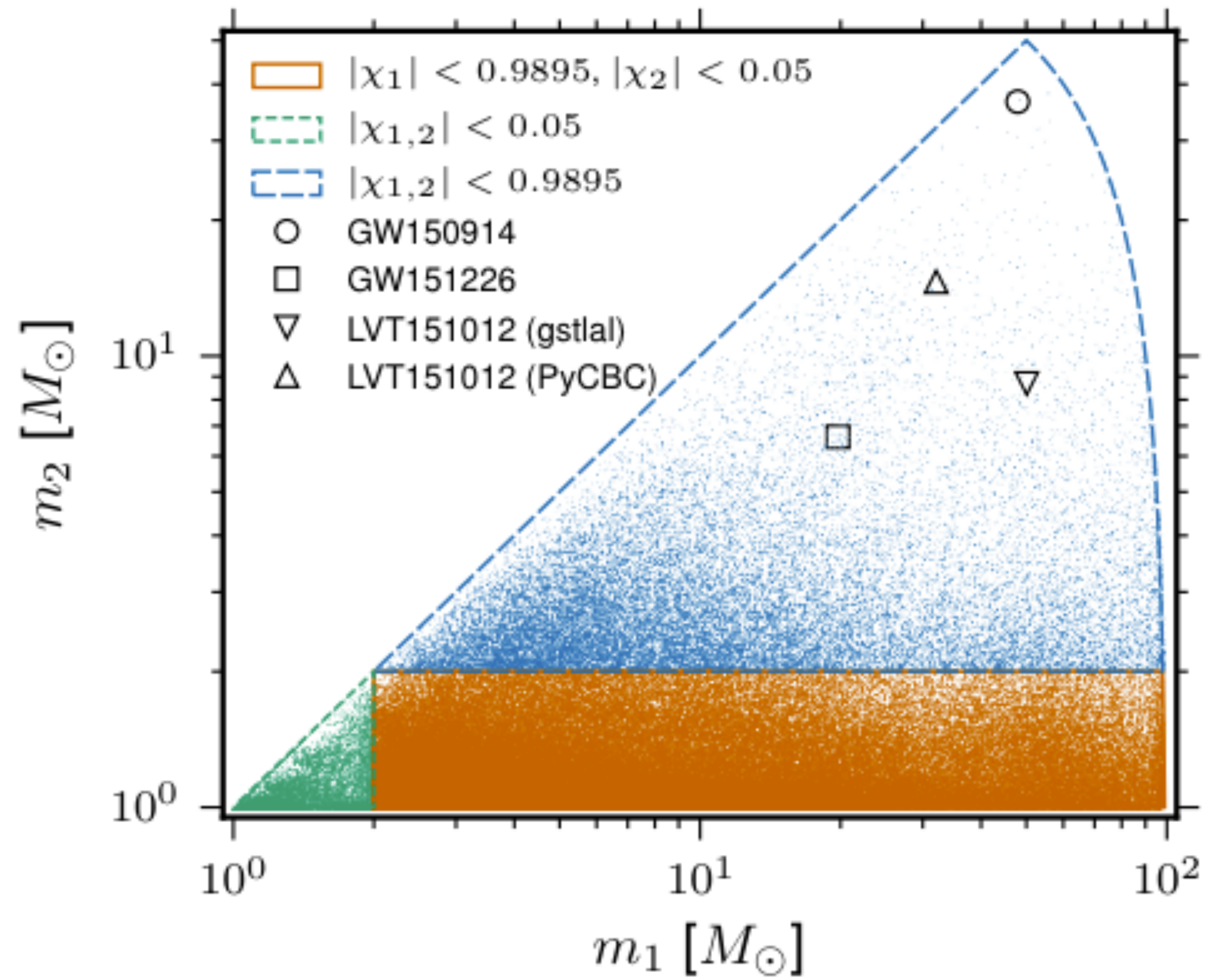


Searches maximize likelihood analytically for speed and over masses/spins by brute force (template banks)

arxiv:1606.04856

GW Signal Detection Primer





Putative strain is embedded in detector noise — cross correlate the model with the data to extract a signal-to-noise ratio (SNR, ρ) statistic — this maximizes the likelihood (probability of signal vs probability of noise)

Searches maximize likelihood analytically for speed and over masses/spins by brute force (template banks)

arxiv:1606.04856

Basic Terminology

$$d(t) = n(t) + h(t)$$

observations: Putative strain from **gravitational wave** is embedded in **detector noise**

$$S(|f|) = 2\delta(f - f')\langle\tilde{n}(f)\tilde{n}(f')\rangle$$

Noise power spectrum: Autocorrelation of the noise in the frequency domain — “limiting factor” of the sensitivity of the instrument

$$(a|b) \equiv 2\int_{\infty}^{\infty} \frac{\tilde{a}^{\star}(f)\tilde{b}(f)}{S(f)}$$

Noise weighted inner product: frequency-domain cross-correlation between two quantities

Null Hypothesis (H_0): Data samples are uncorrelated Gaussian noise with variance proportional to S(f)

$$p(H_0) \propto \exp(-(d|d)/2)$$

Alternative Hypothesis (H_1): data are distributed as in null, *after* subtraction of the signal model (h)

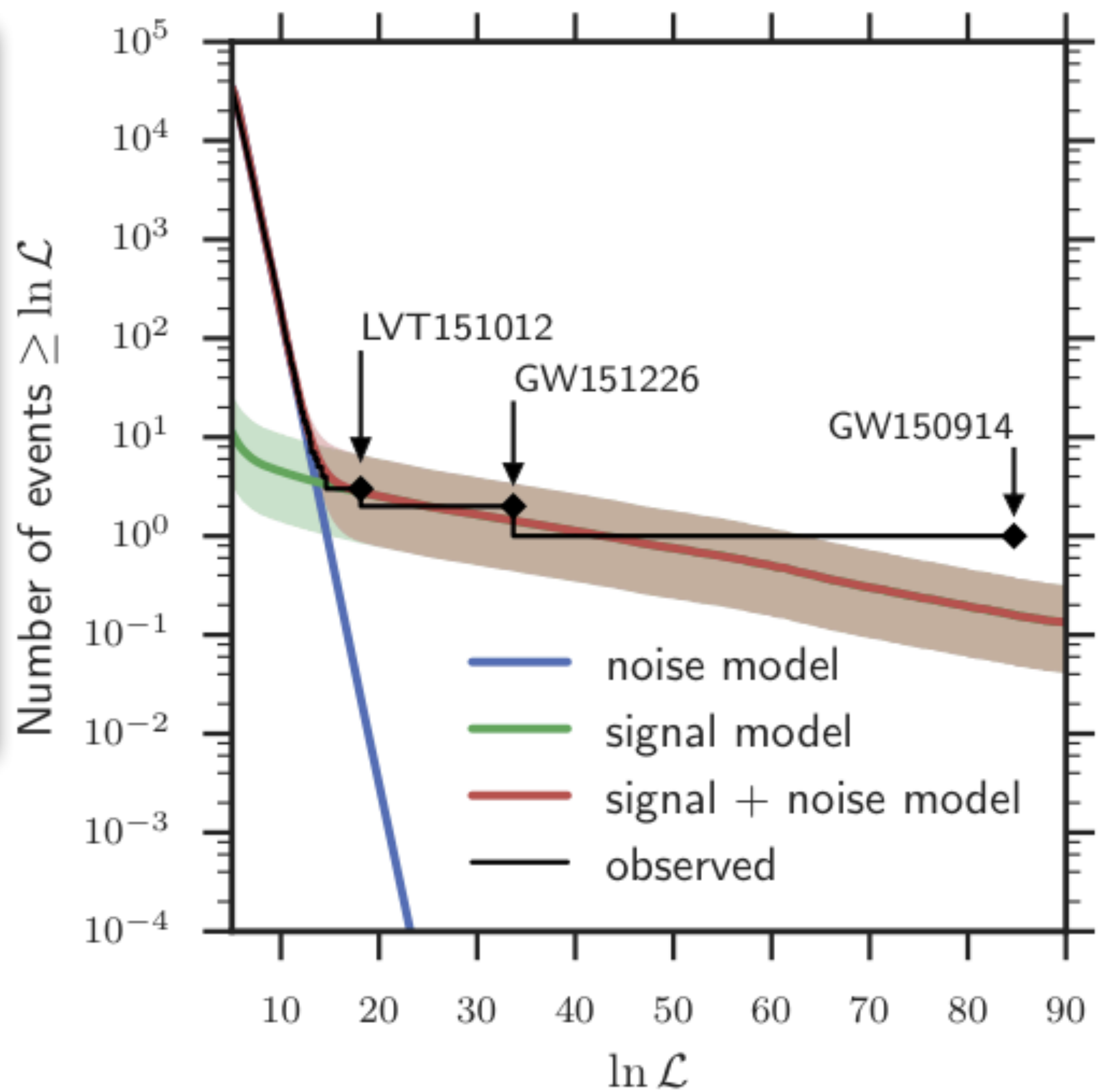
$$p(H_1) \propto \exp(-(d-h|d-h)/2)$$

Inferred Rates / Probability of Astrophysical Origin

$$\mathscr{L} = \left\{ \prod_i \Lambda_{\rm bg} p_{\rm bg}(x_i) + \Lambda_{\rm fg} p_{\rm fg}(x_i) \right\} \exp(-\Lambda_{\rm bg} - \Lambda_{\rm fg})$$

Likelihood of obtaining ensemble of ranking statistics $\boldsymbol{x_i}$ with two categories of events: background (terrestrial) and foreground (astrophysical)
$\Lambda_{fg,bg}$ ~ expected counts from each category
p_{fg}, p_{bg} - modeled or measured, for astrophysical distribution of binaries $p_{fg} \sim \rho^{-4}$

arxiv:1302.5341

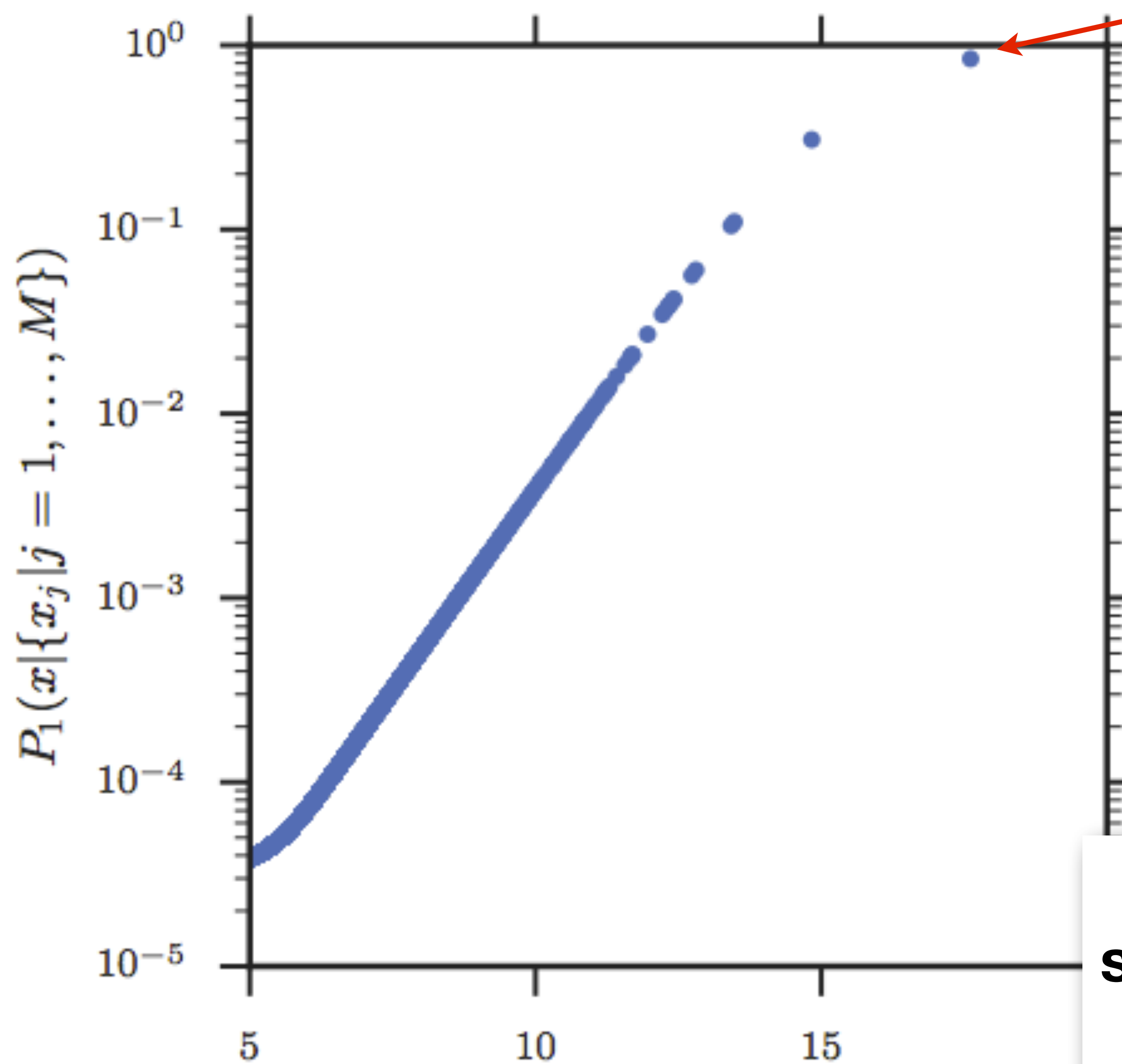


Inferred Rates / Probability of Astrophysical Origin

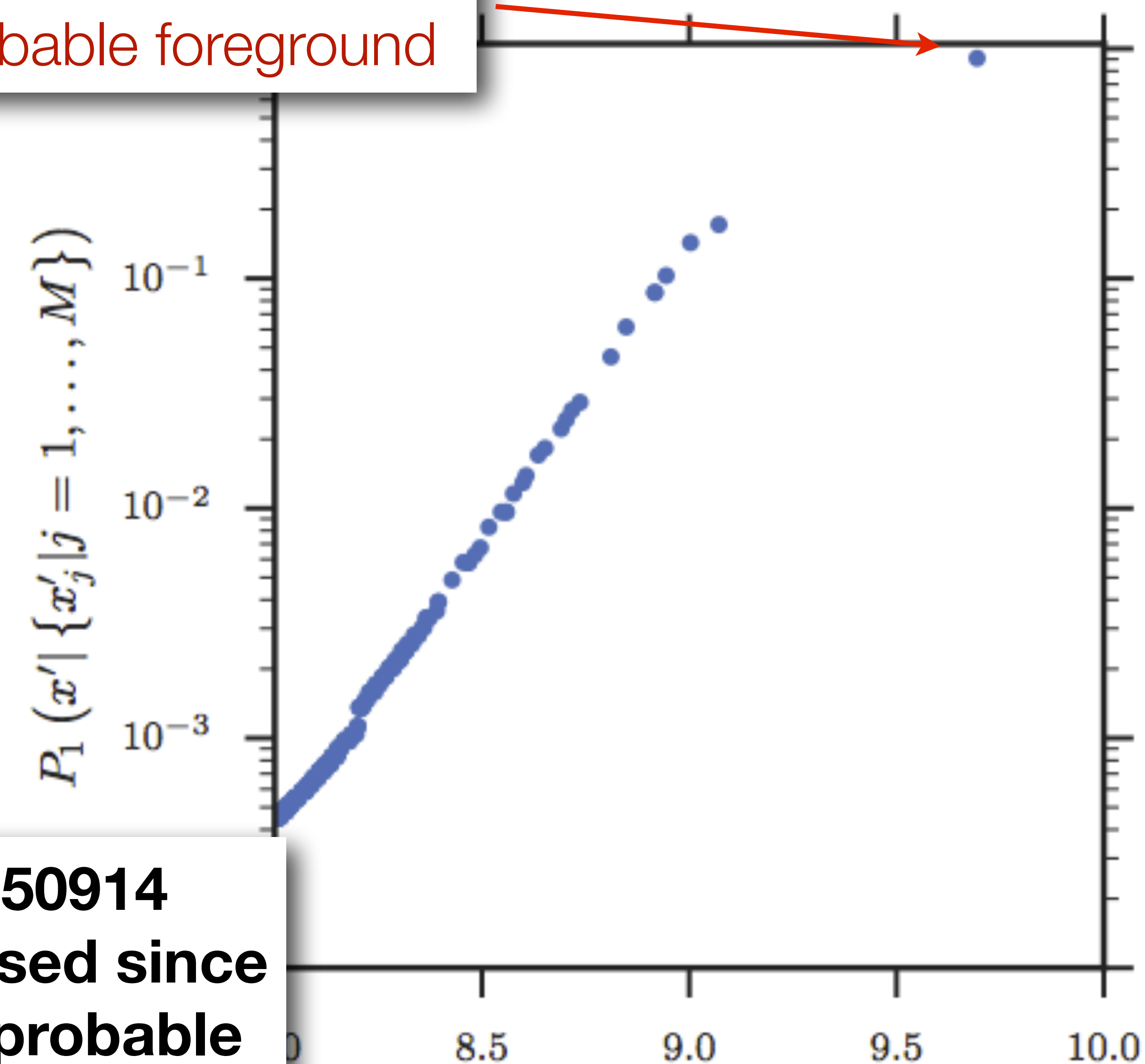
Obtain probability of astrophysical origin by marginalizing against the counts

$$p_{\rm astro}(x|x_i) = \int d\Lambda_{\rm fg} d\Lambda_{\rm bg} \frac{\Lambda_{\rm fg} p_{\rm fg}(x)}{\Lambda_{\rm fg} p_{\rm fg}(x) + \Lambda_{\rm bg} p_{\rm bg}(x)} p(\Lambda_{\rm fg}, \Lambda_{\rm bg}|x_i)$$

LVT151012 ~ 87% probable foreground



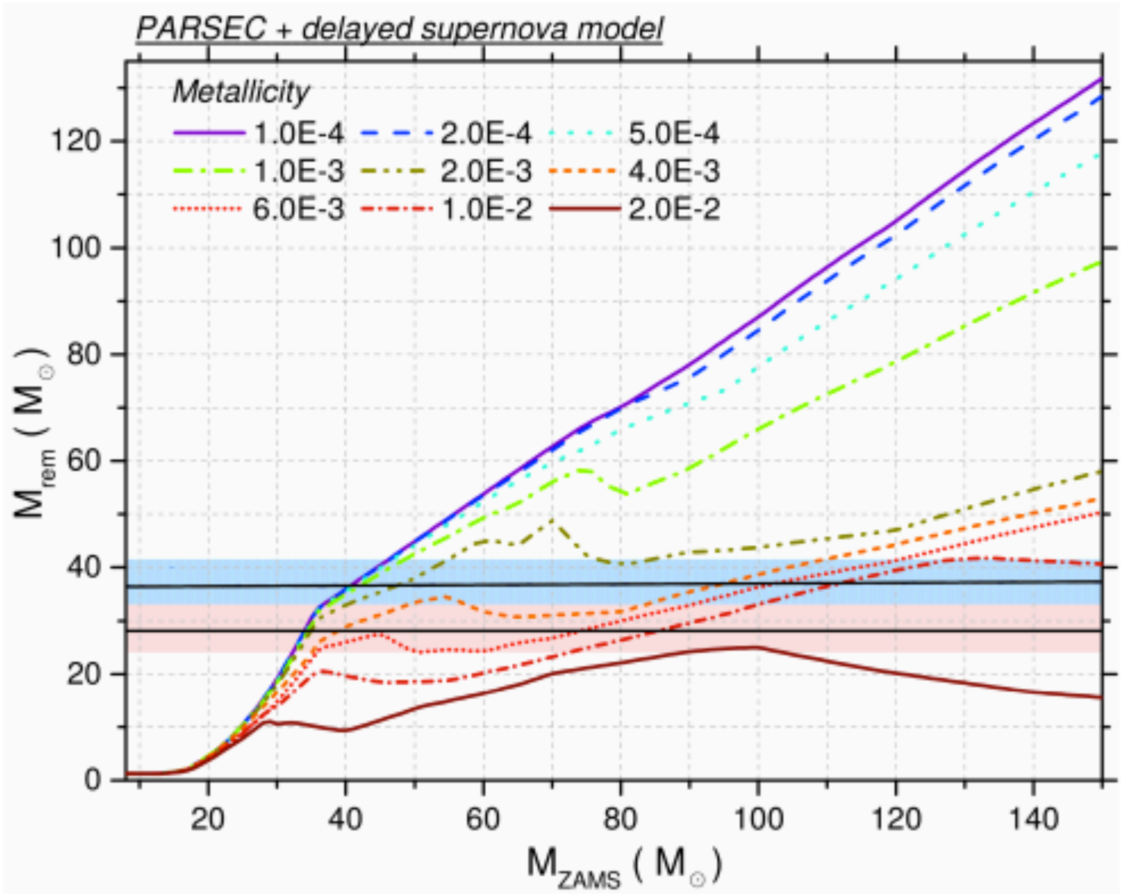
Model 2 ranking stat.

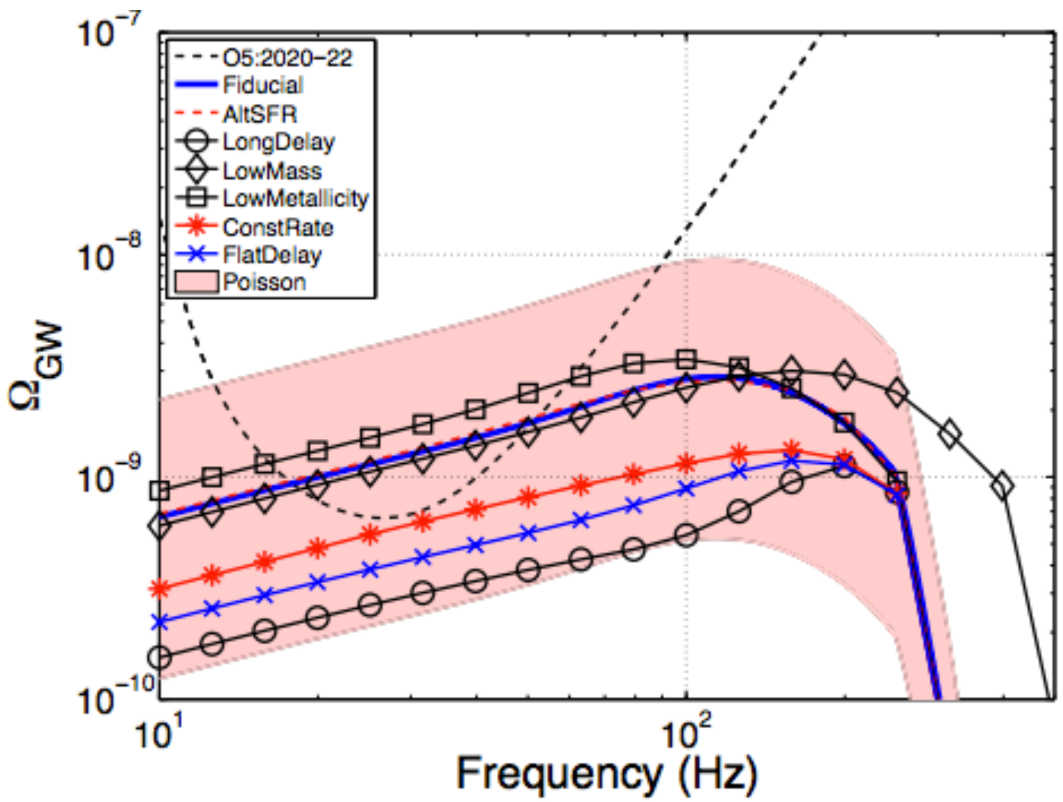


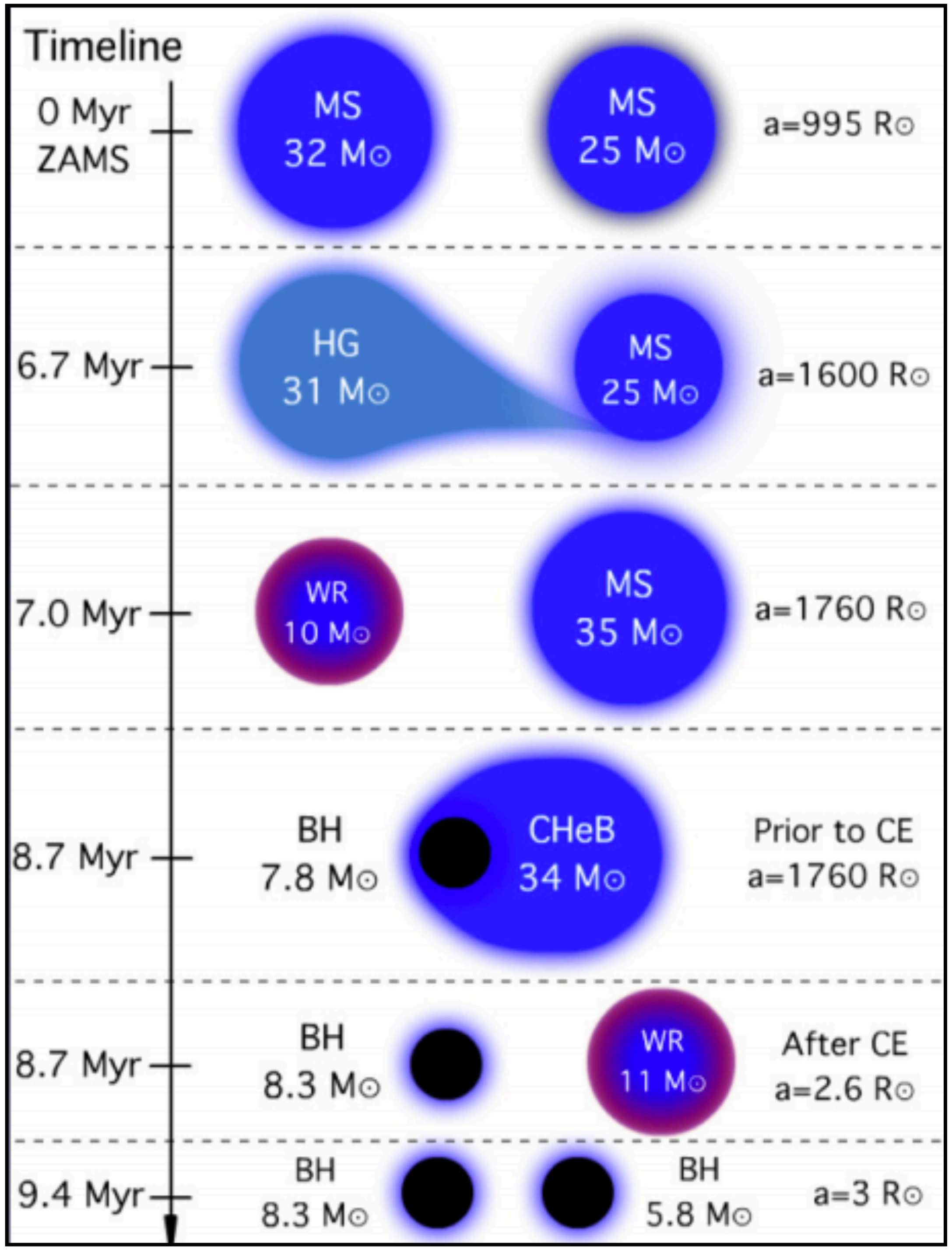
Model 1 ranking stat.

GW150914 suppressed since > 99% probable and far to the right

Astrophysics Implications







Ap. JL. L22 2016