NORTHWESTERN UNIVERSITY

CIERA

LIGO's First Observing Run: Gravitational-Wave Astronomy on the Rise

Chris Pankow (*CIERA / Northwestern University*)
on behalf of the **LIGO** Scientific Collaboration and **Virgo** Collaboration

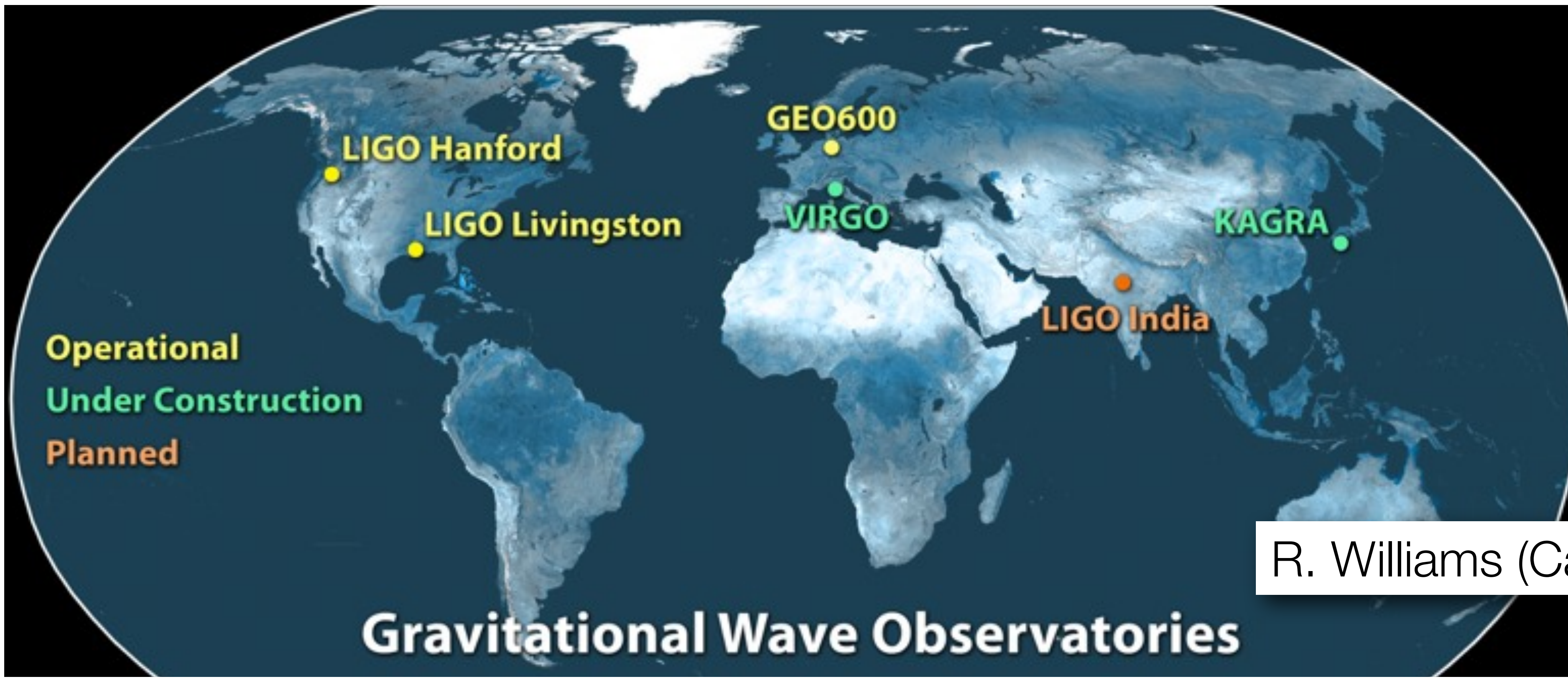
GW Available in this Talk

LIGO-G1601533

ICHEP: August 6, 2016

The LVC: Who We Are

- **The LIGO and Virgo Collaborations**: 1000+ scientists, engineers, and others spread amongst 50+ academic institutions world wide (presence on all continents except Africa and Antarctica)



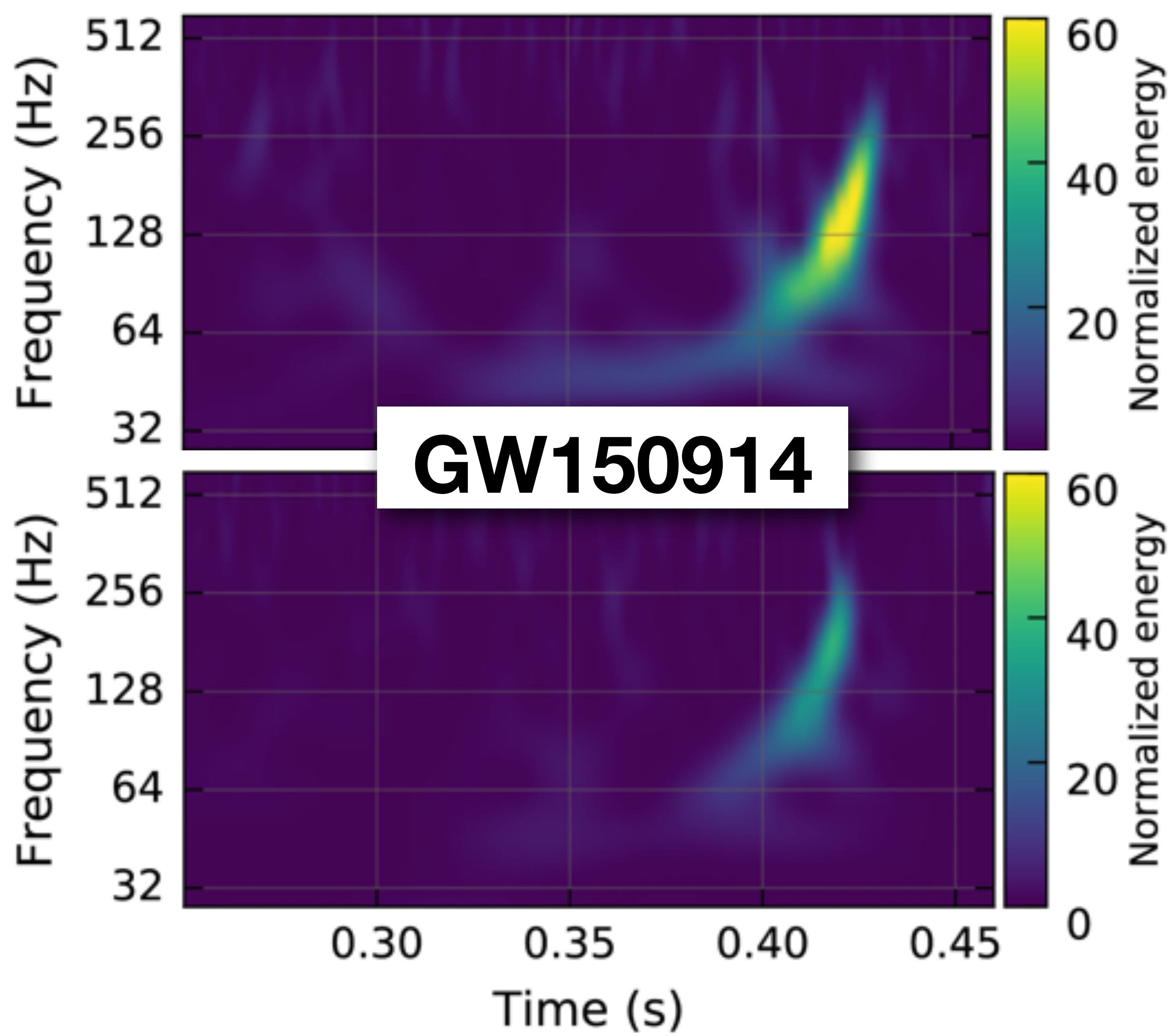
R. Williams (Caltech)

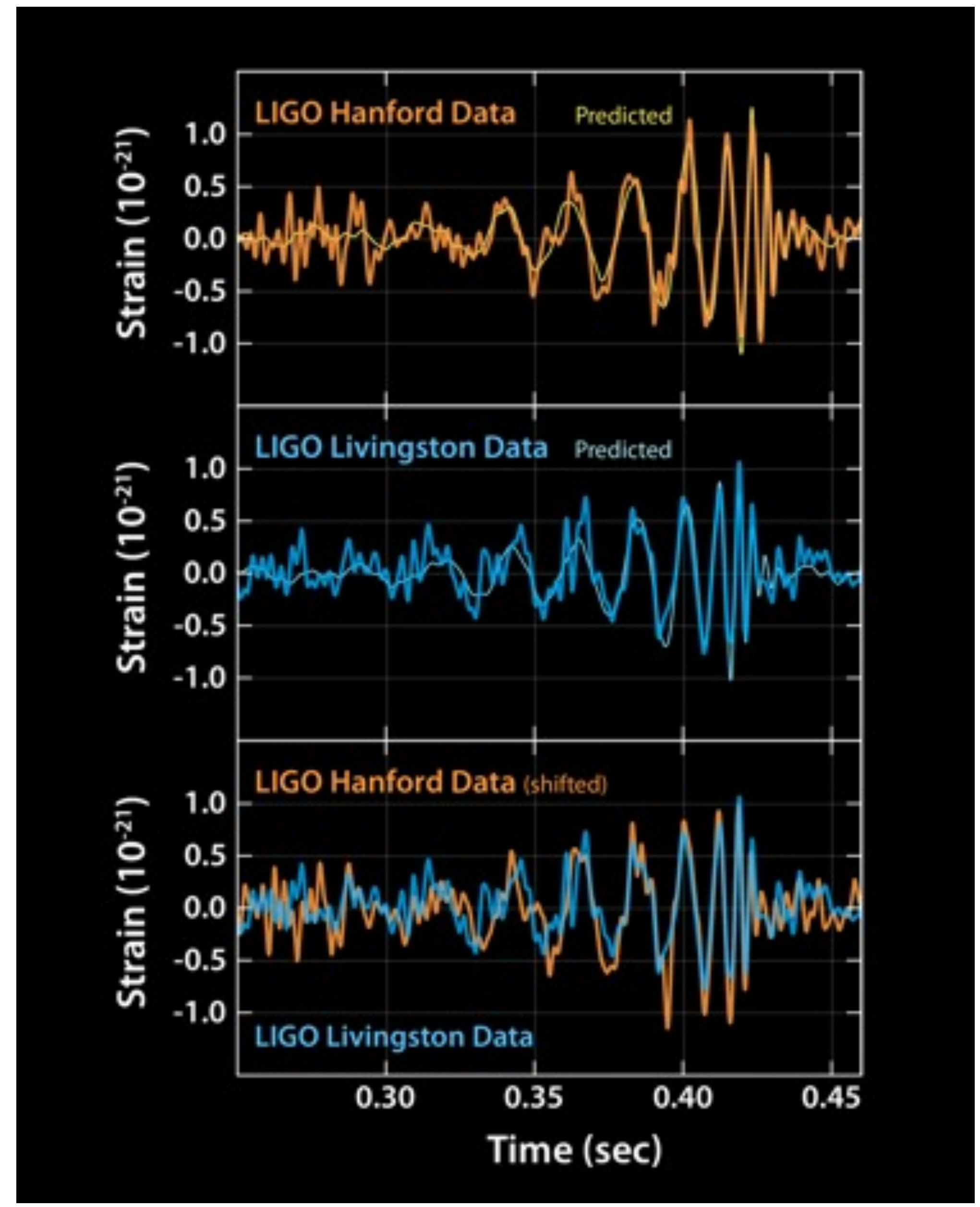
- Collectively develop and operate a network of three kilometer scale interferometers (LIGO Hanford, LIGO Livingston, Virgo), and a 600m pathfinder interferometer (GEO600)

- Two kilometer scale interferometers under construction (KAGRA collaboration, Japan) or in design process (LIGO India)

In Case You Hadn't Heard...

"We.. have... detected gravitational waves... We did it!" — Dave Reitze, LIGO Lab Director (February 11, 2016)

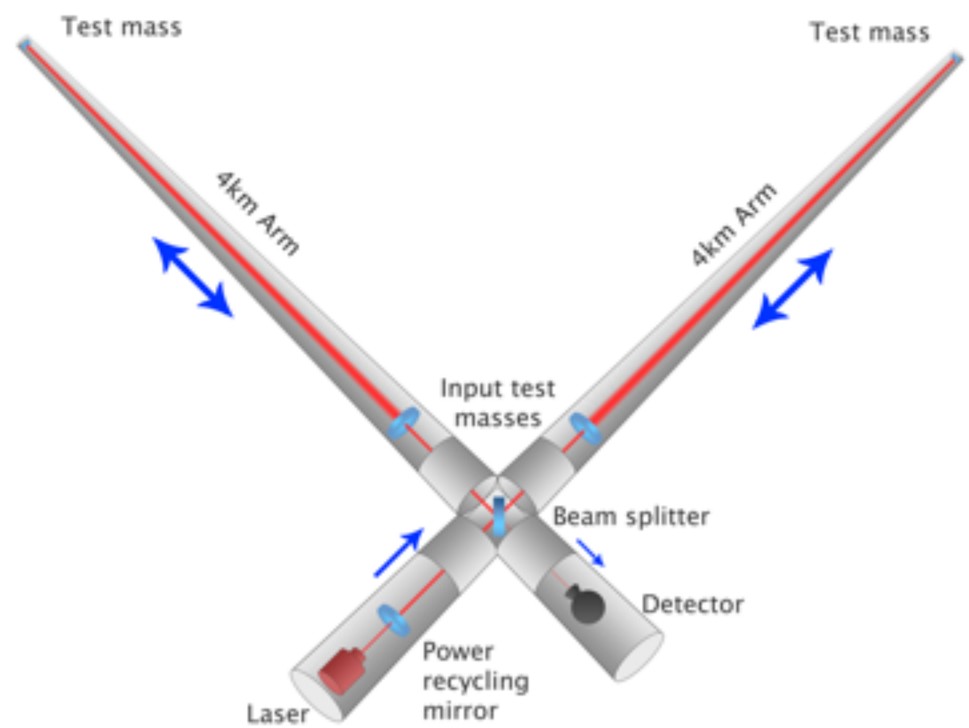




https://losc.ligo.org/events/GW150914/

Advanced LIGO's First Observational Run

The Instruments: two near-identical 4 km long Fabry-Perot dual-recycled laser interferometers



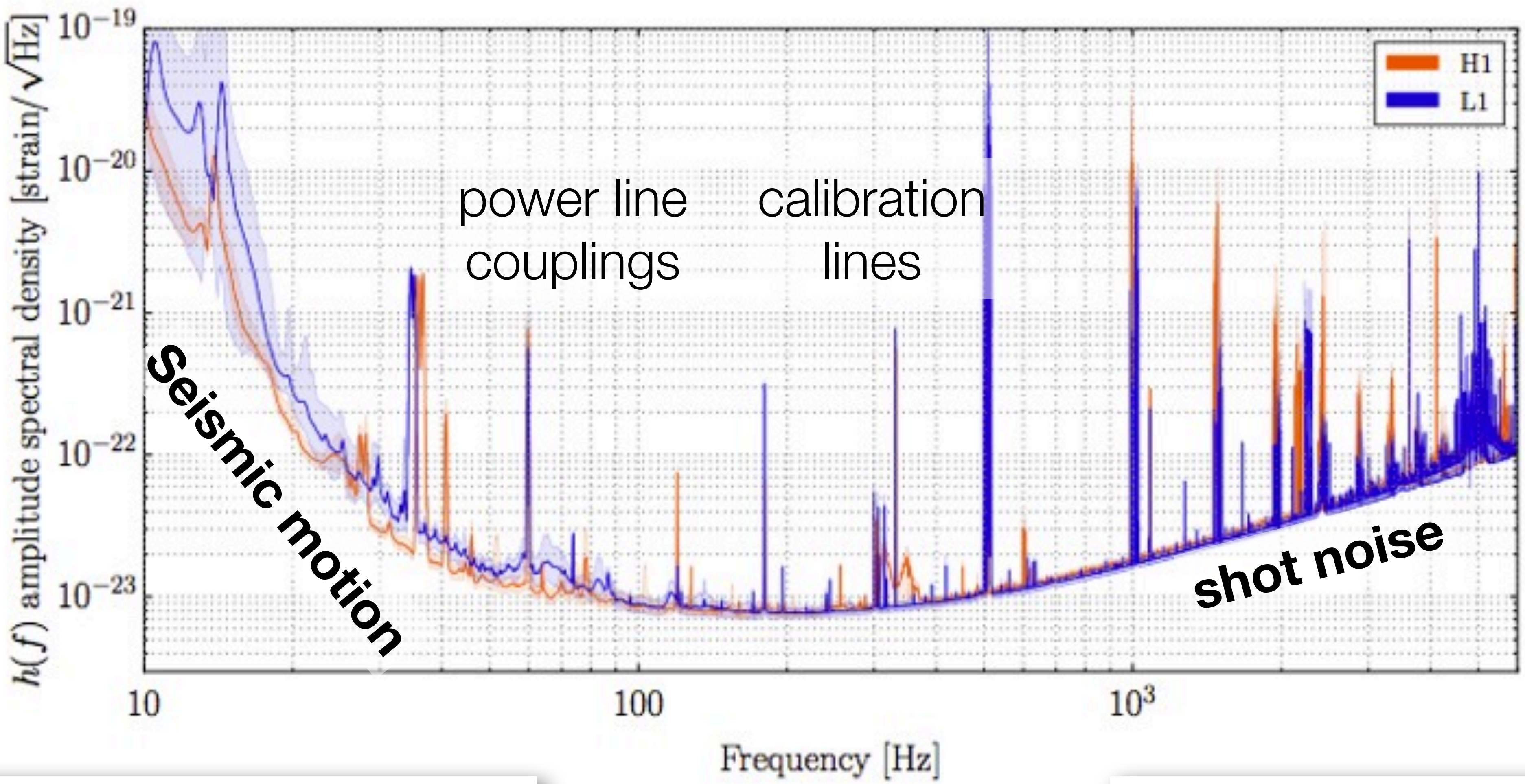
C. North (Cardiff)

LIGO Livingston

LIGO Hanford

Strain: Differential phase measurement of highly coherent laser beams translated from perturbations of space-time curvature at the level of 10^{-18} m along arms

Advanced LIGO's First Observational Run

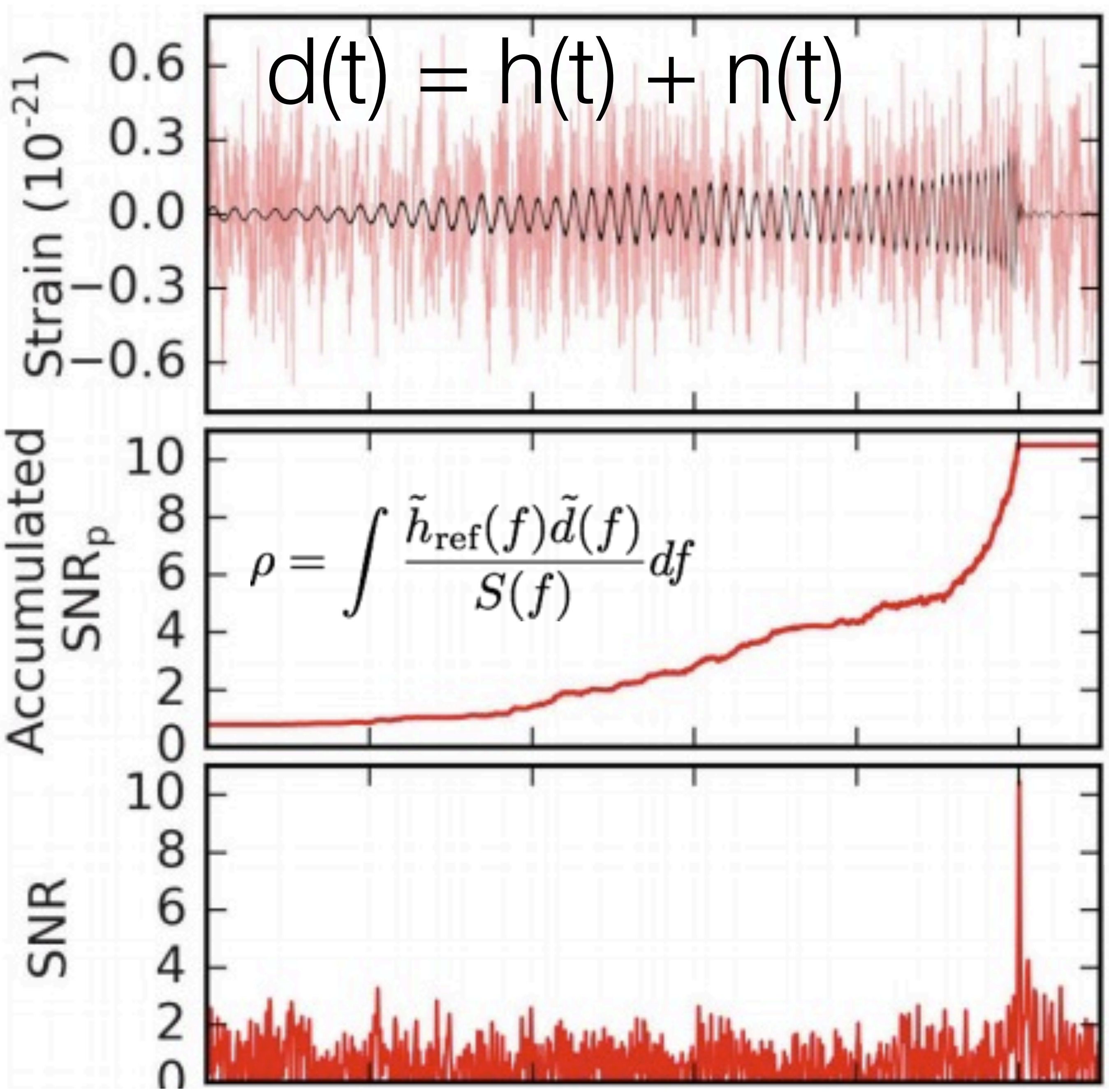


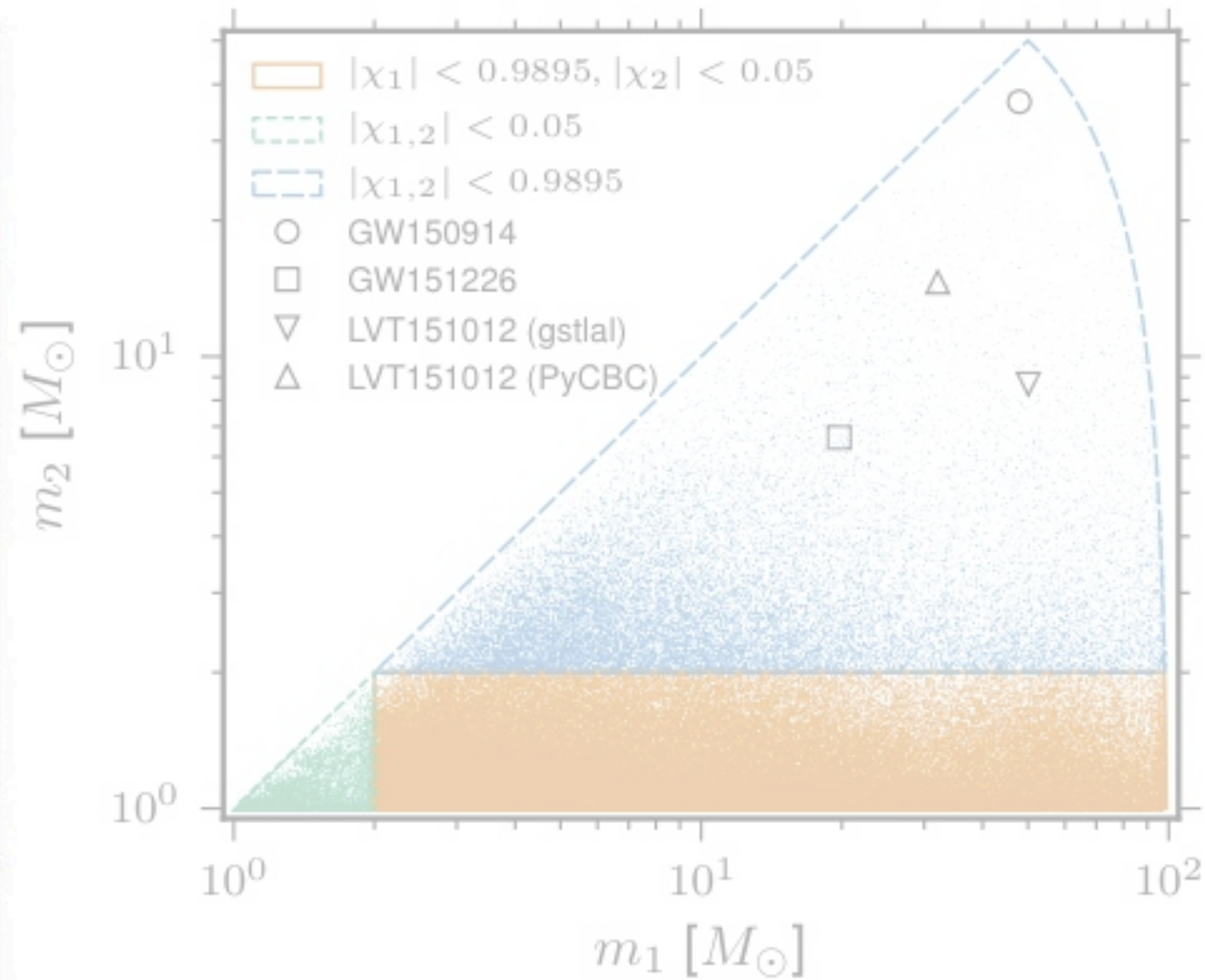
Low Frequency: motion of the Earth coupling into motion of the end test masses

High Frequency: uncertain photon arrival times at photodetector

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

GW Signal Detection Primer



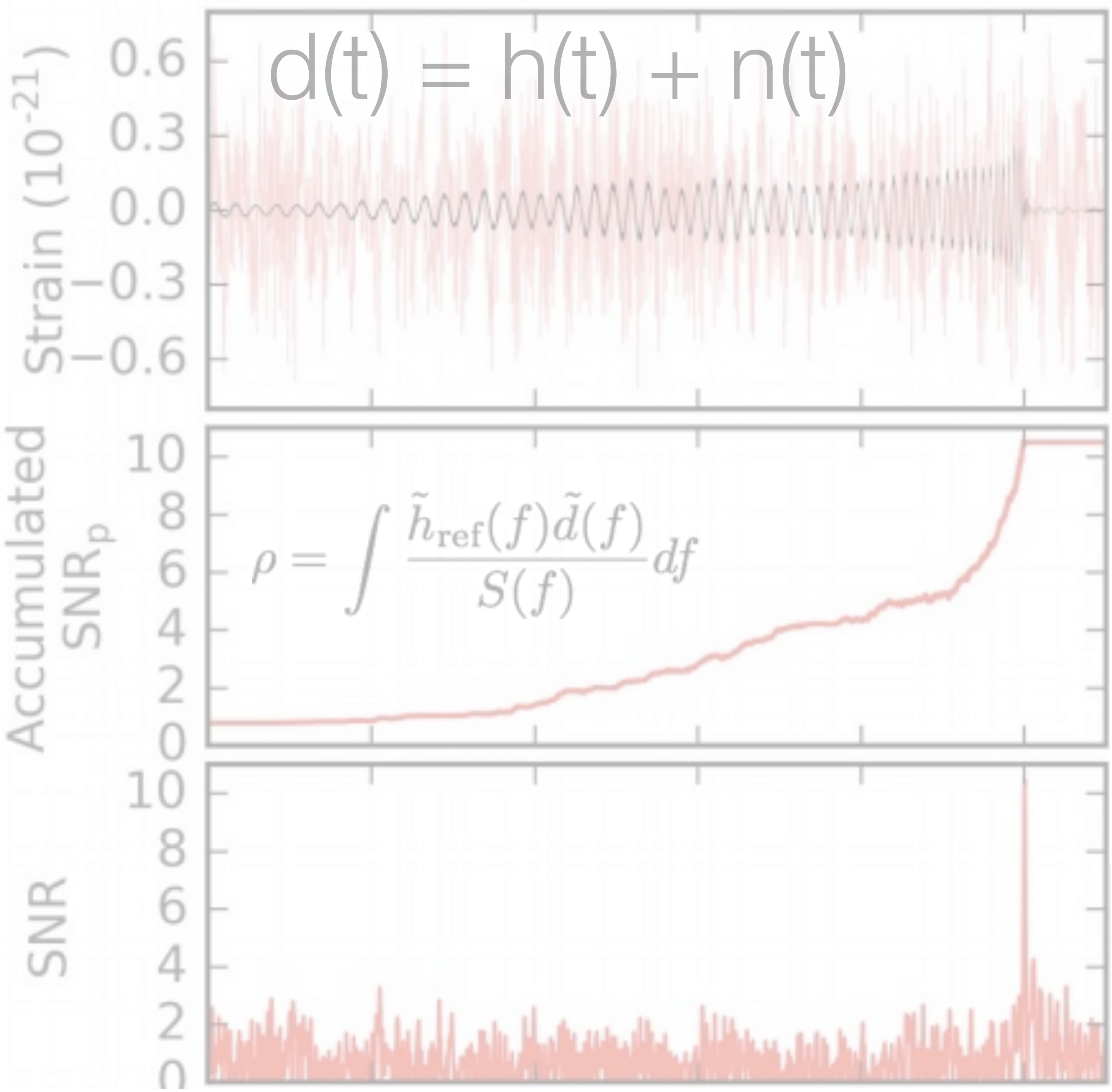


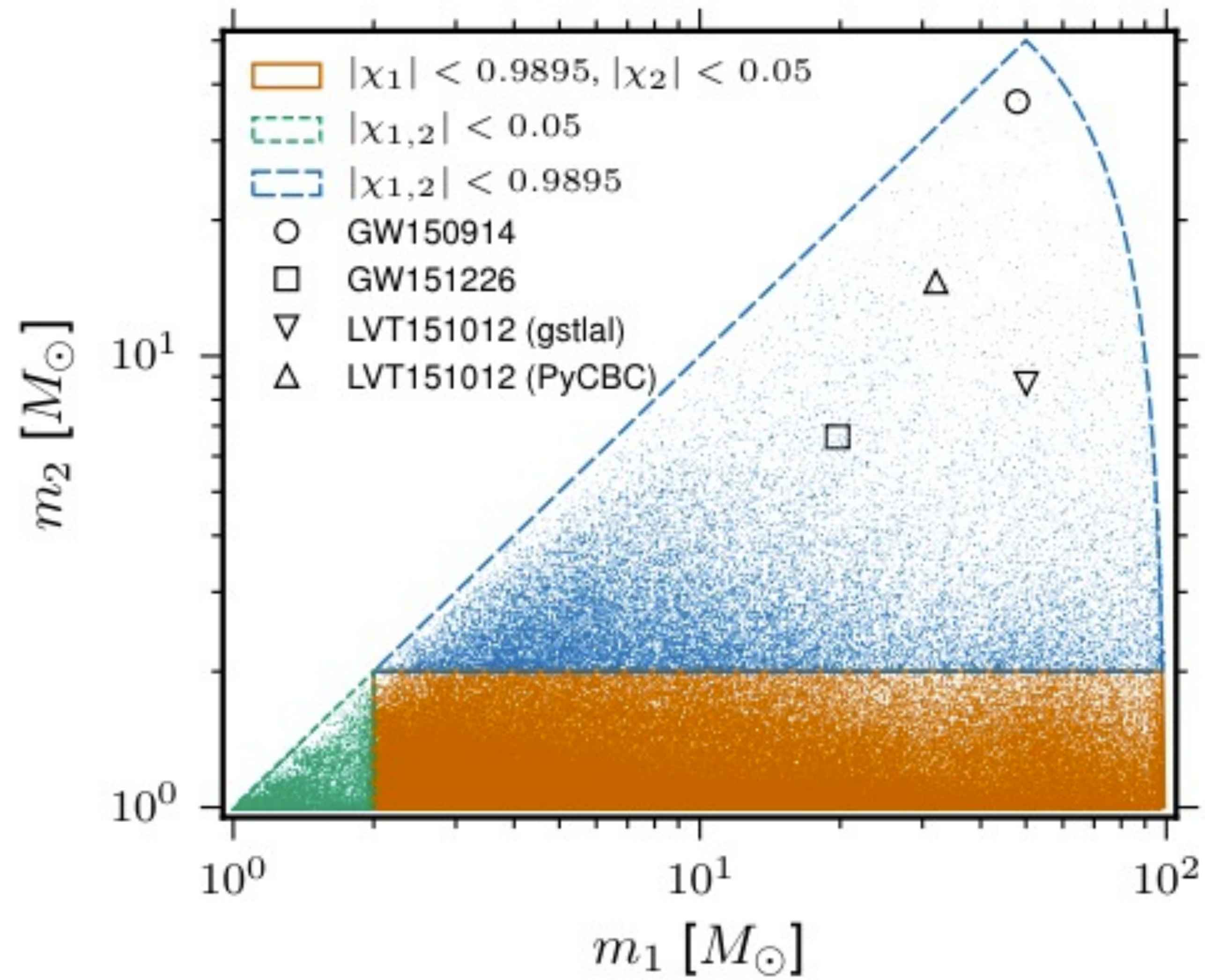
Putative strain is embedded in detector noise — cross correlate the model with the data to extract a signal-to-noise ratio (SNR, ρ) statistic — this maximizes the likelihood (probability of signal vs probability of noise)

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

arxiv:1606.04856

GW Signal Detection Primer





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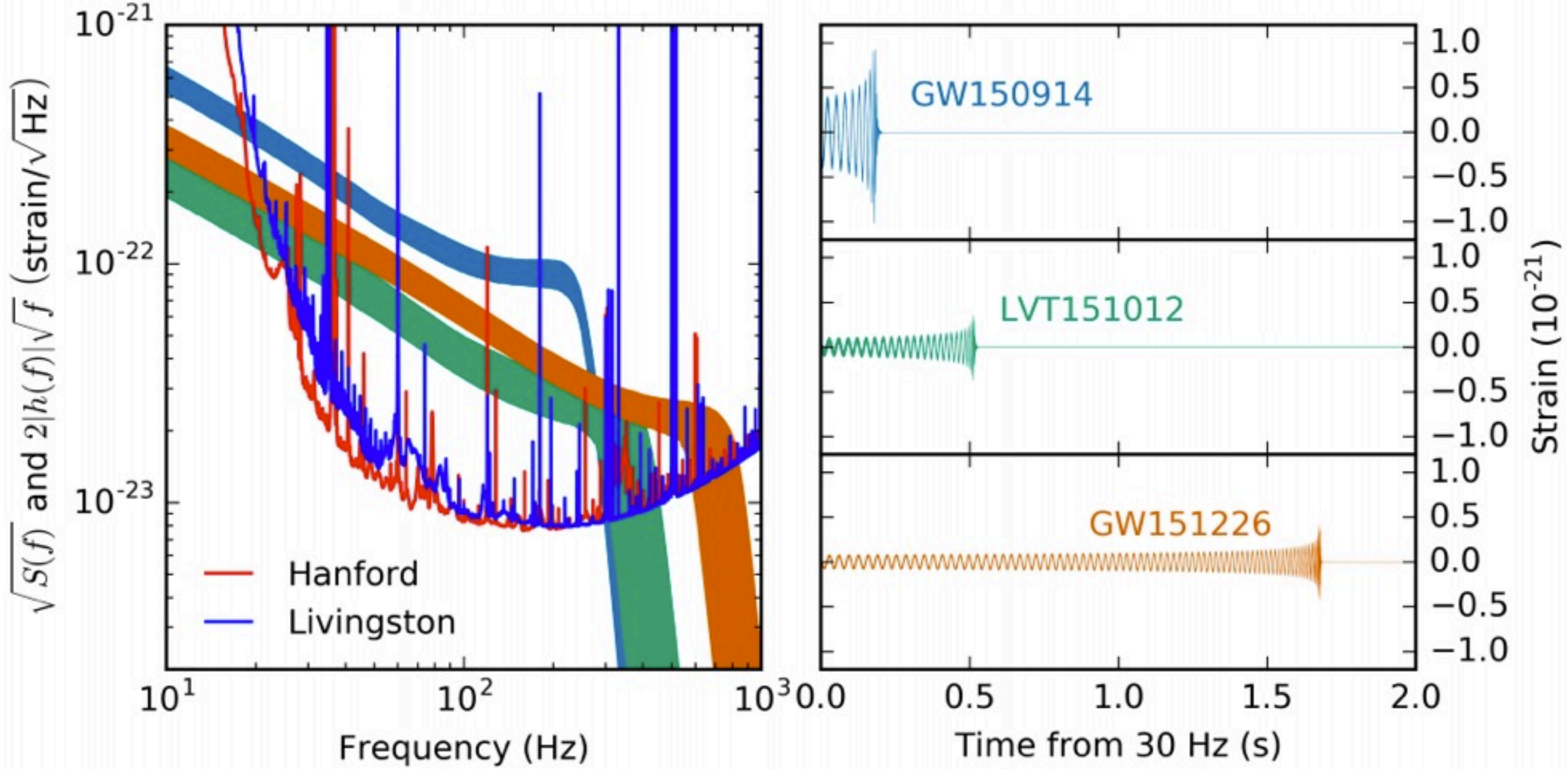
arxiv:1606.04856

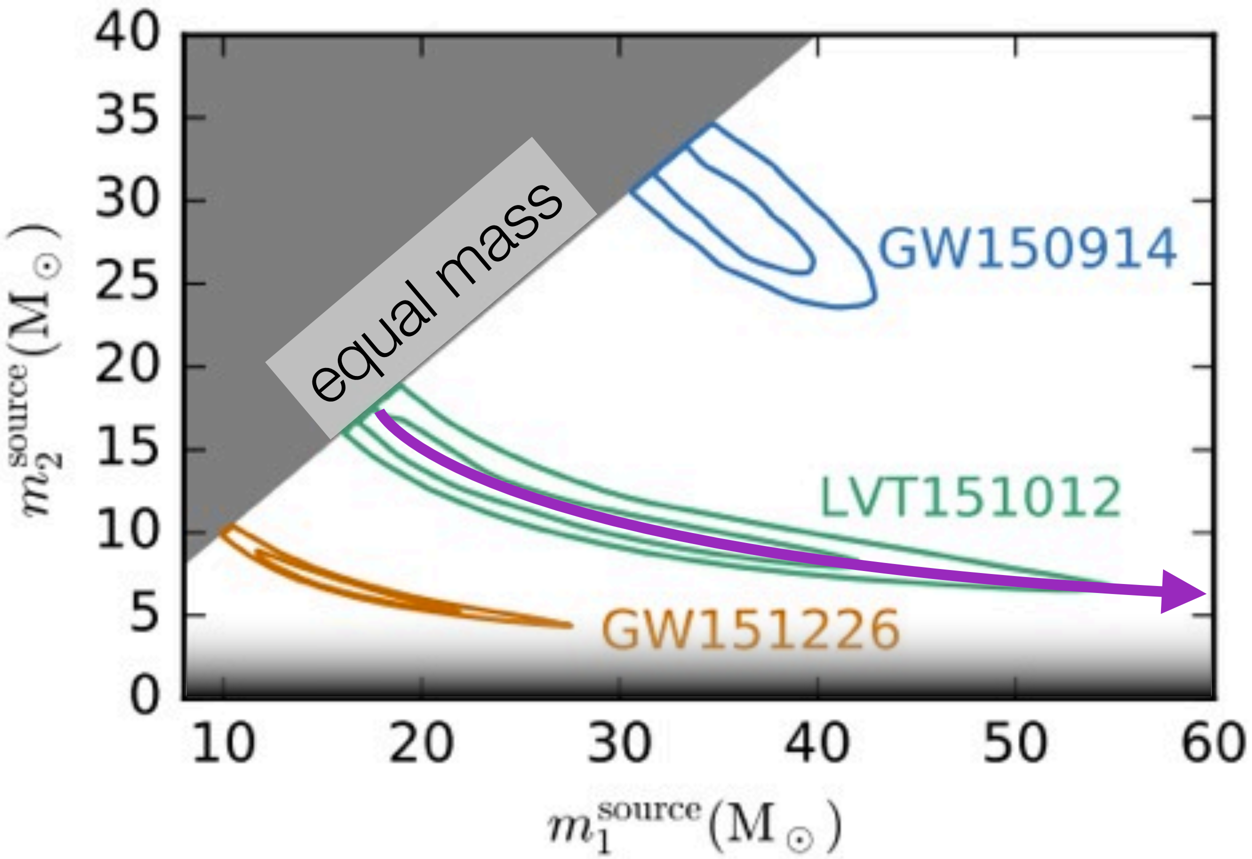
O1 BBH Events

arxiv:1606.04856

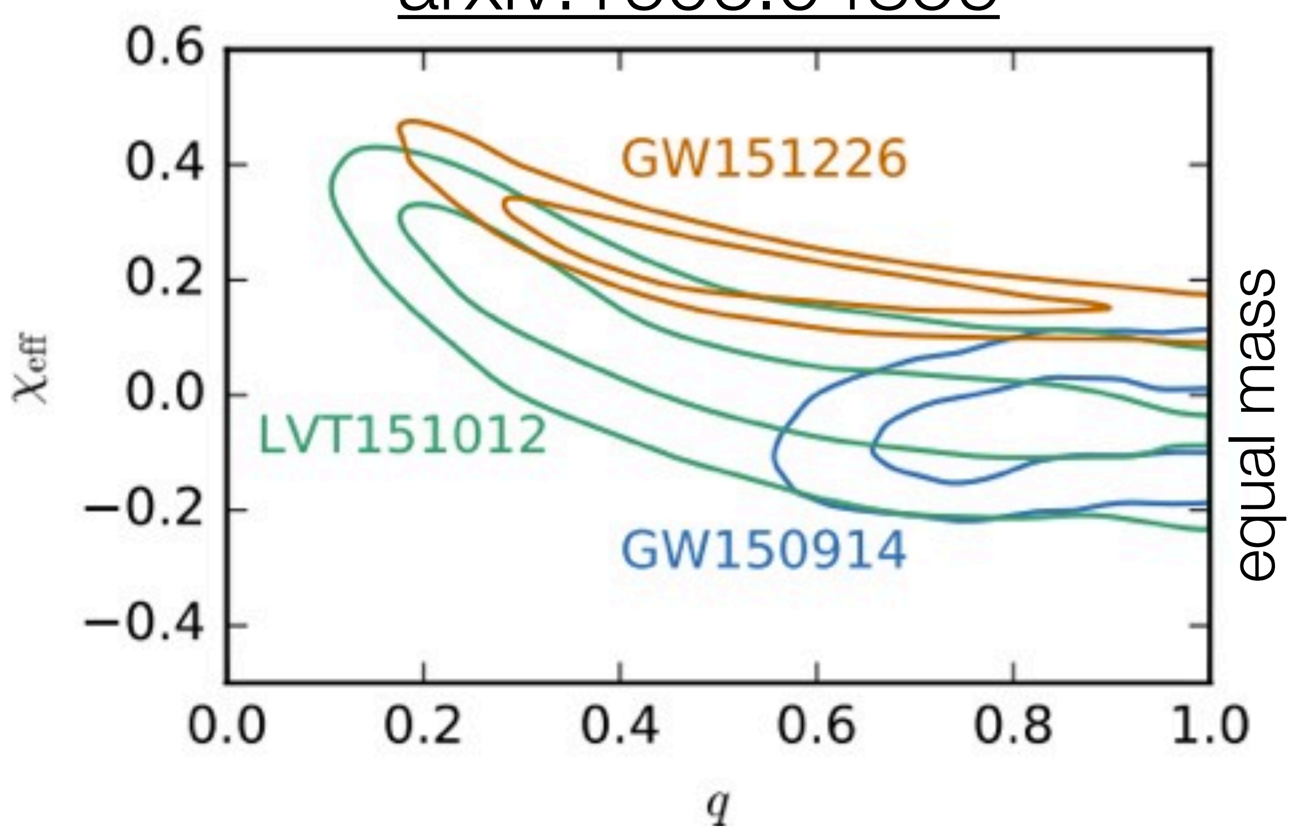


"Chirps" in the time domain (monotonically increasing in frequency vs time)
Lower mass → Higher frequency content / longer "in band"

BBH Masses and Spins



arxiv:1606.04856



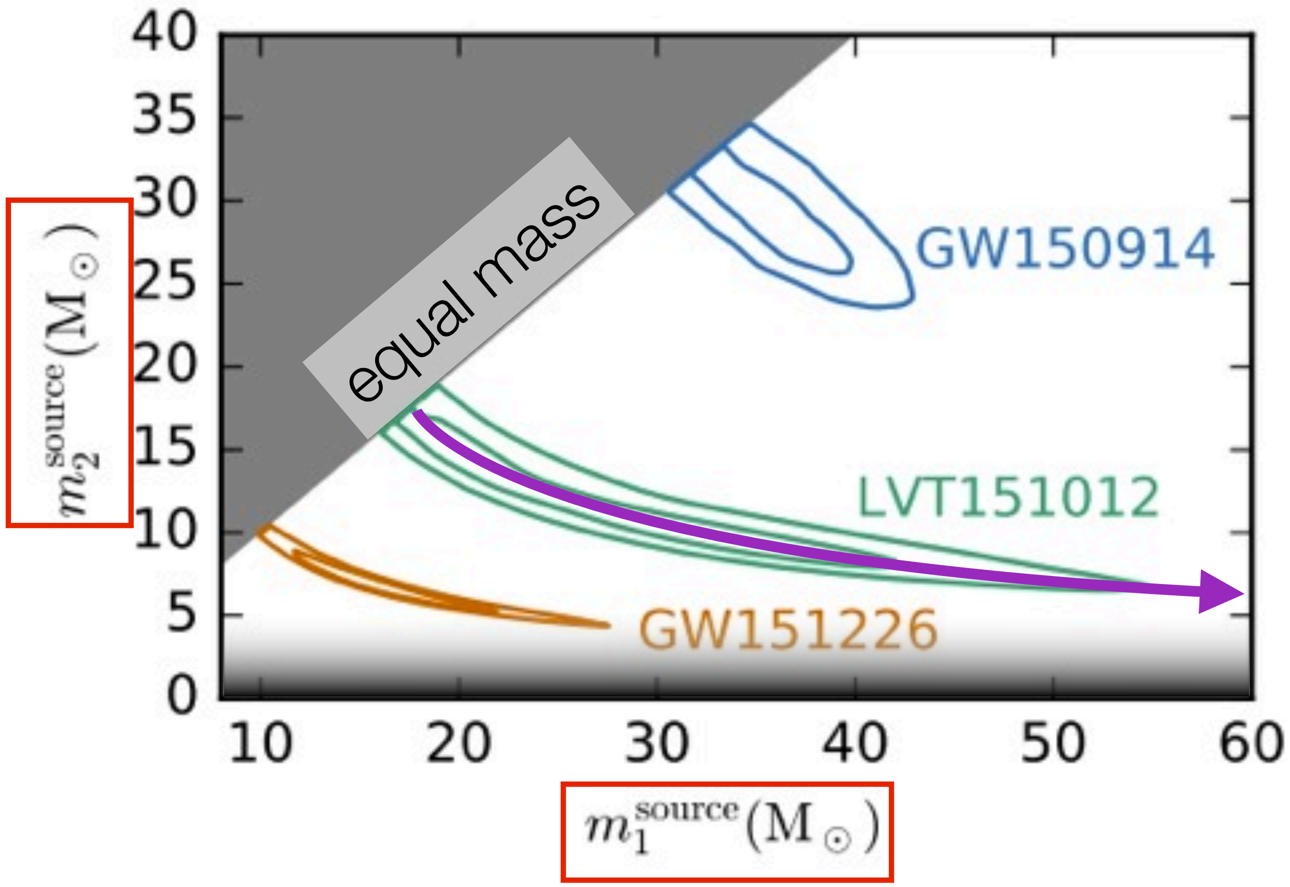
Parameter Degeneracies:
Primarily sensitive to the *chirp mass* — leaves **large degeneracies** along contours of chirp mass (**GW151226** approaching $m_2 < 3$ region)

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

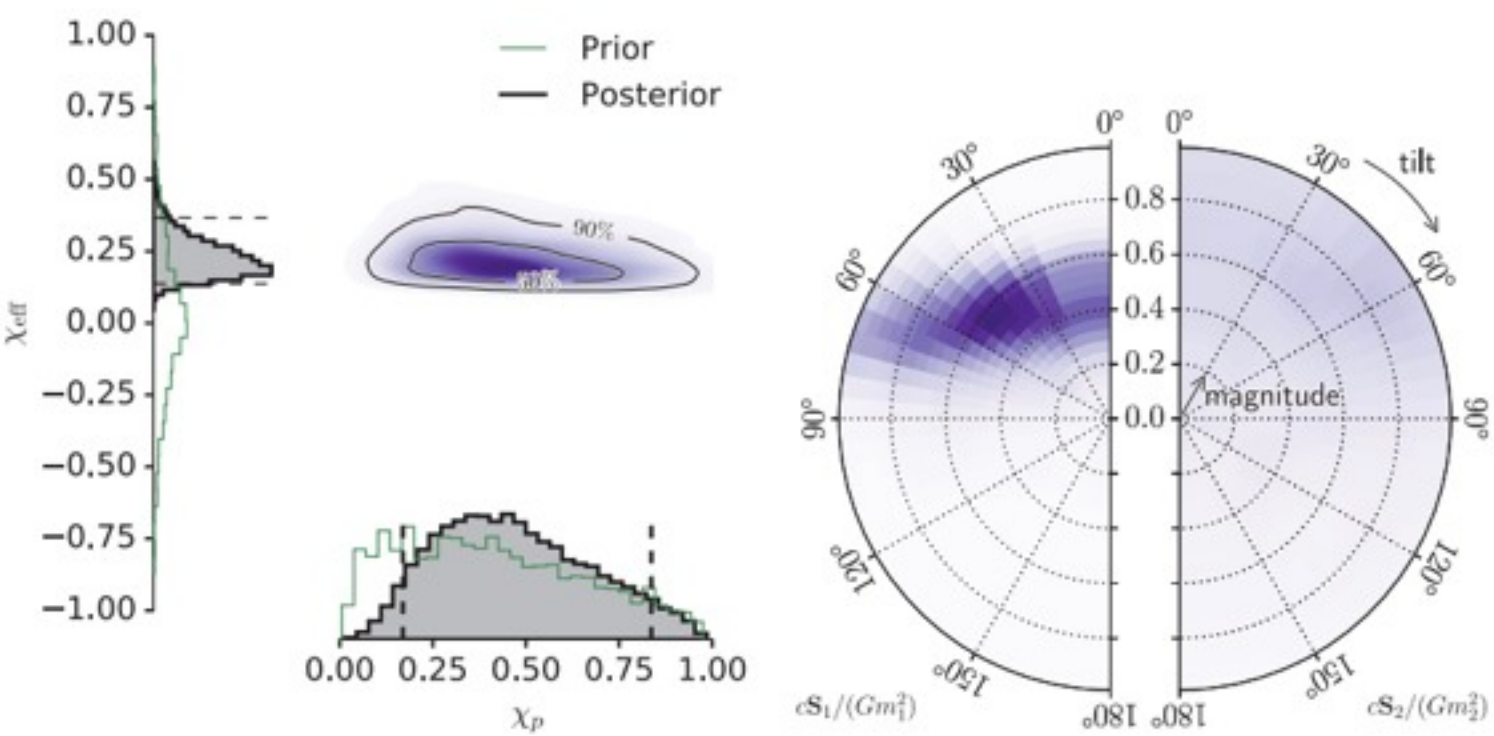
$$\chi_{\mathrm{eff}} = \frac{m_1 s_{1,z} + m_2 s_{2,z}}{m_1 + m_2}$$

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

BBH Masses and Spins



Cosmological Effects:
All events at distances with significant redshifts — all masses need to be adjusted to account for frequency “stretching” from GW traversing expanding universe

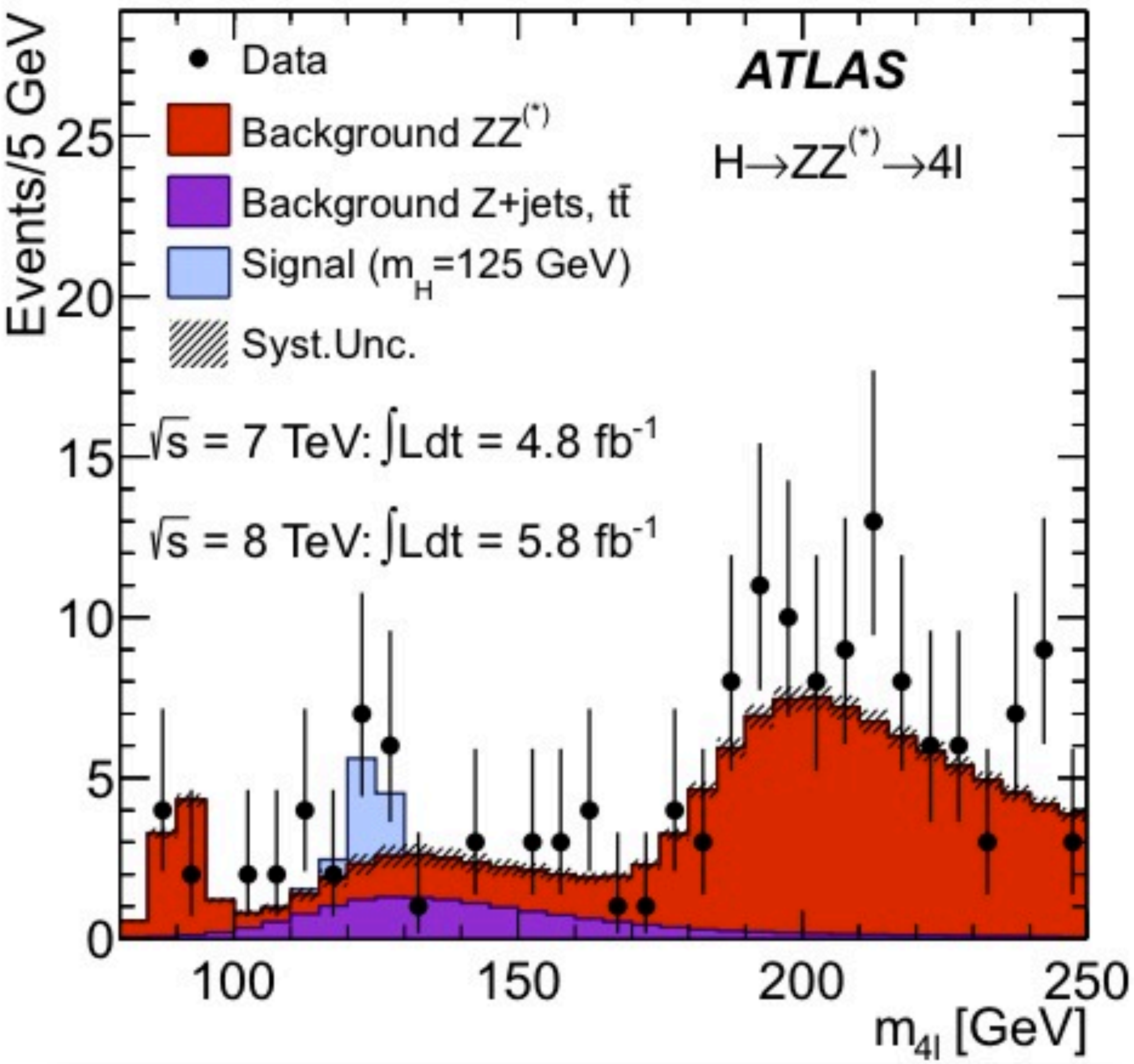


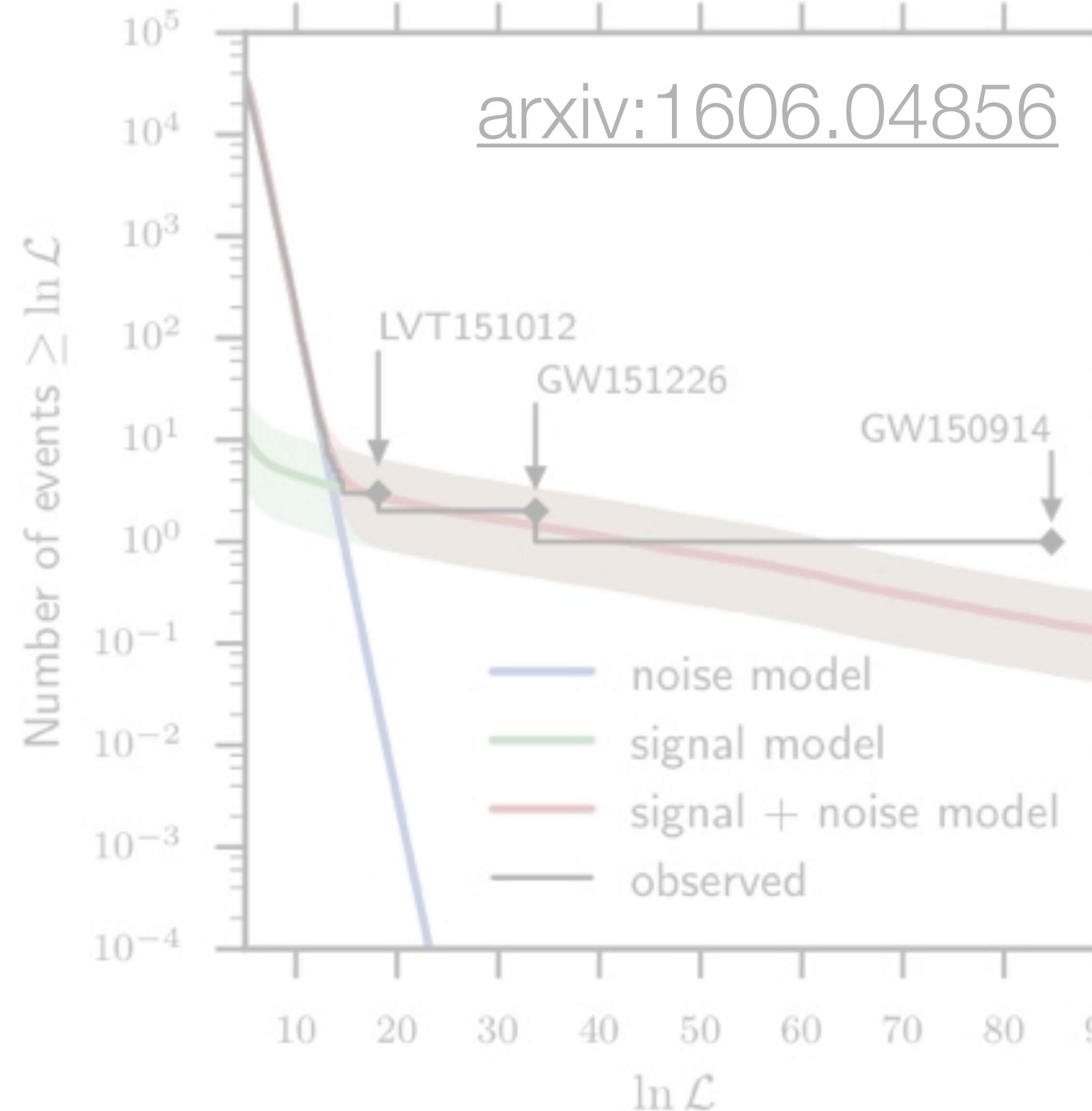
Phys. Rev. Lett. 116/241103

Precession?
GW151226 has posterior on “in plane spin” component bounded away from zero — spin-orbit coupling causes plane of binary to **precess** around total angular momentum. Also, at least **one** BH must be a **Kerr black hole** (as are the final remnants in all cases)

BBH Detection

Phys. Lett. B (716) 1
Phys. Lett. B (716) 1





Signal and Background (Higgs):
For a given decay channel (4 lepton), this shows the background levels and expected Higgs signal decay rates along with the data collected — clear statistical excess ~125 MeV

Signal and Background (GW):
Different parameterization, using a likelihood ranking statistic modeling background with the expected volumetric (ρ^{-4}) distribution superimposed

BBH Detection

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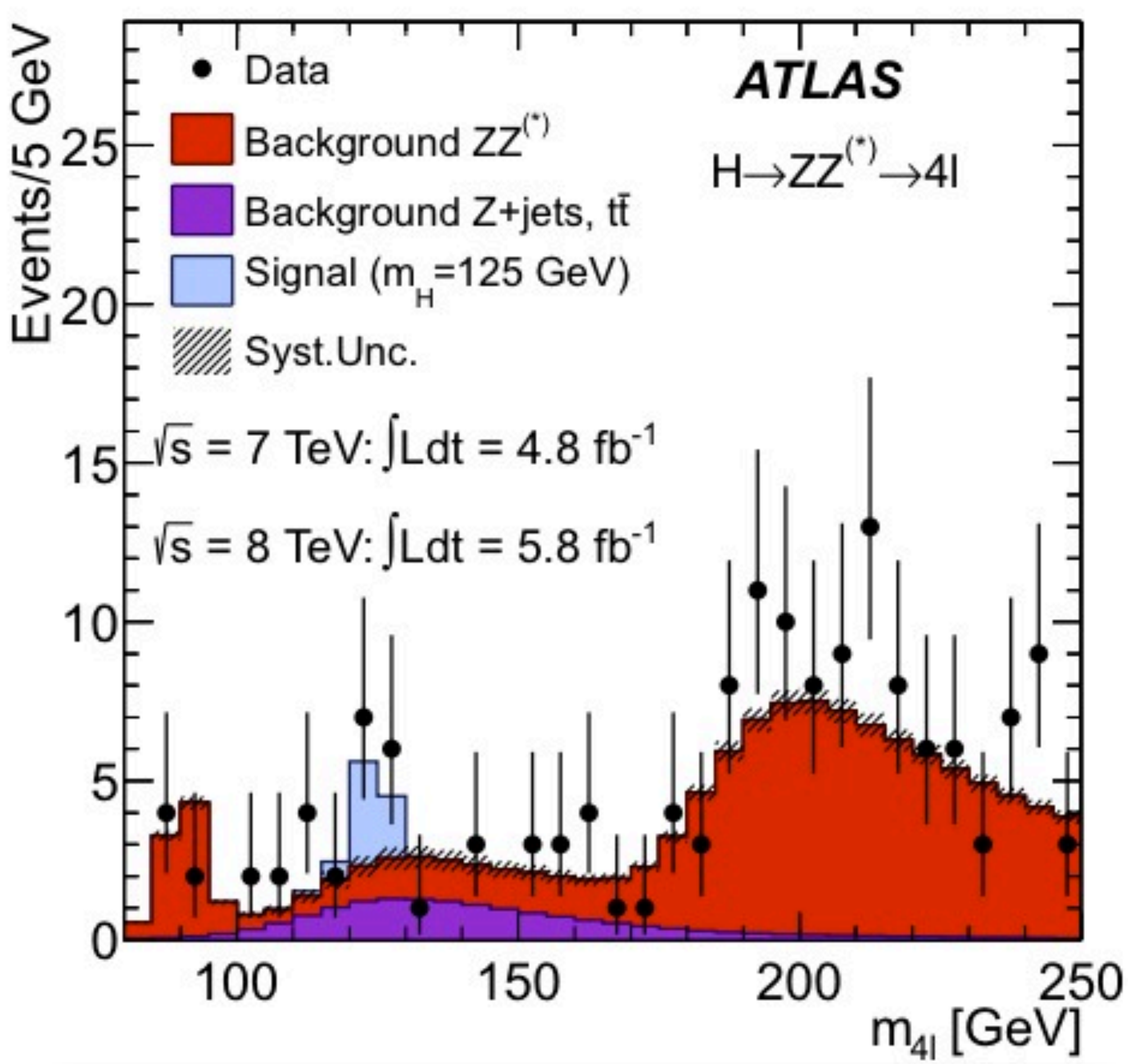

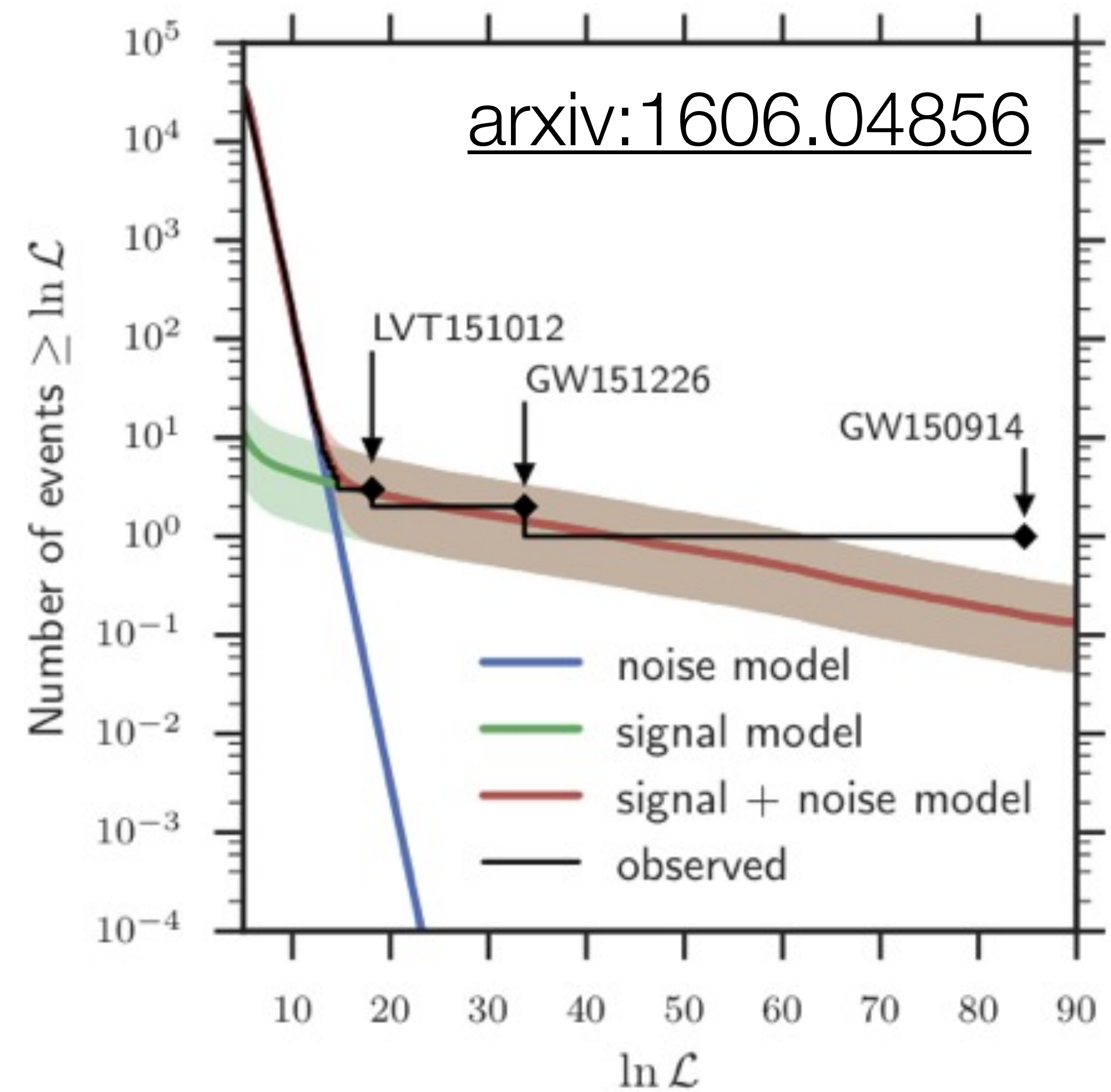

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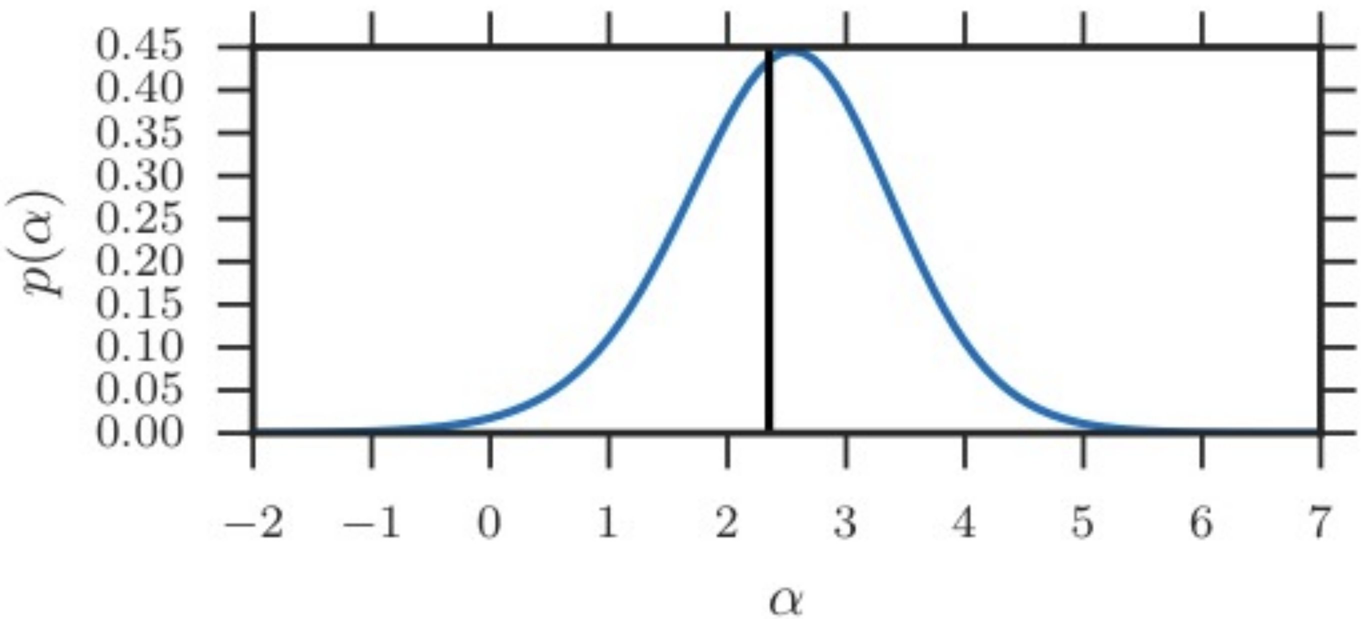
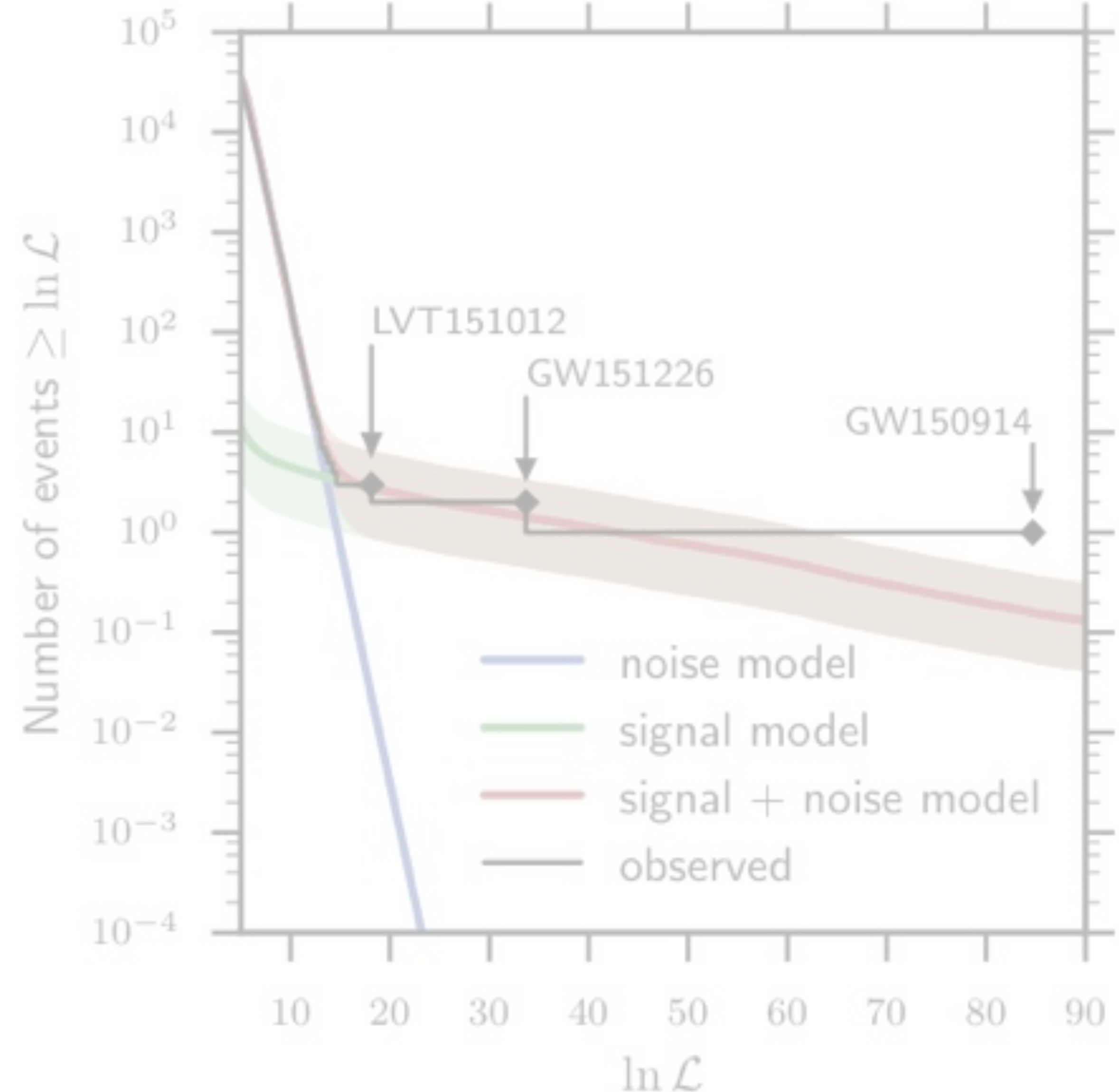
arxiv:1606.04856



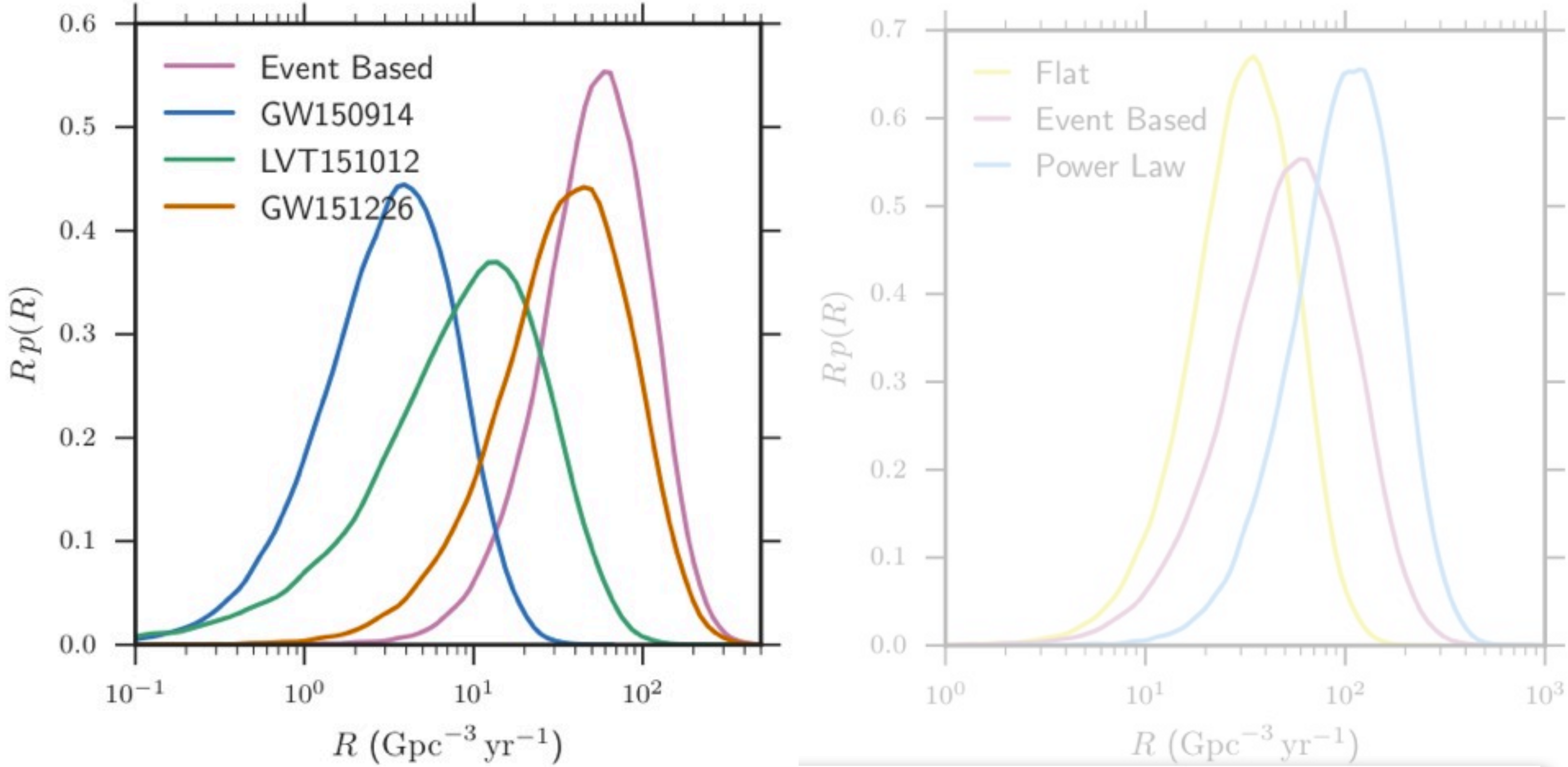


Towards Measuring Mass Distributions:
Posterior distribution for exponent of m_1 inferred from three astrophysically distinguished events — note peak very close to **α** = 2.35 (black vertical line)

Signal and Background (GW):
Different parameterization, using a likelihood ranking statistic modeling background with the expected volumetric (ρ^{-4}) distribution superimposed

BBH Event Rates

arxiv:1606.04856

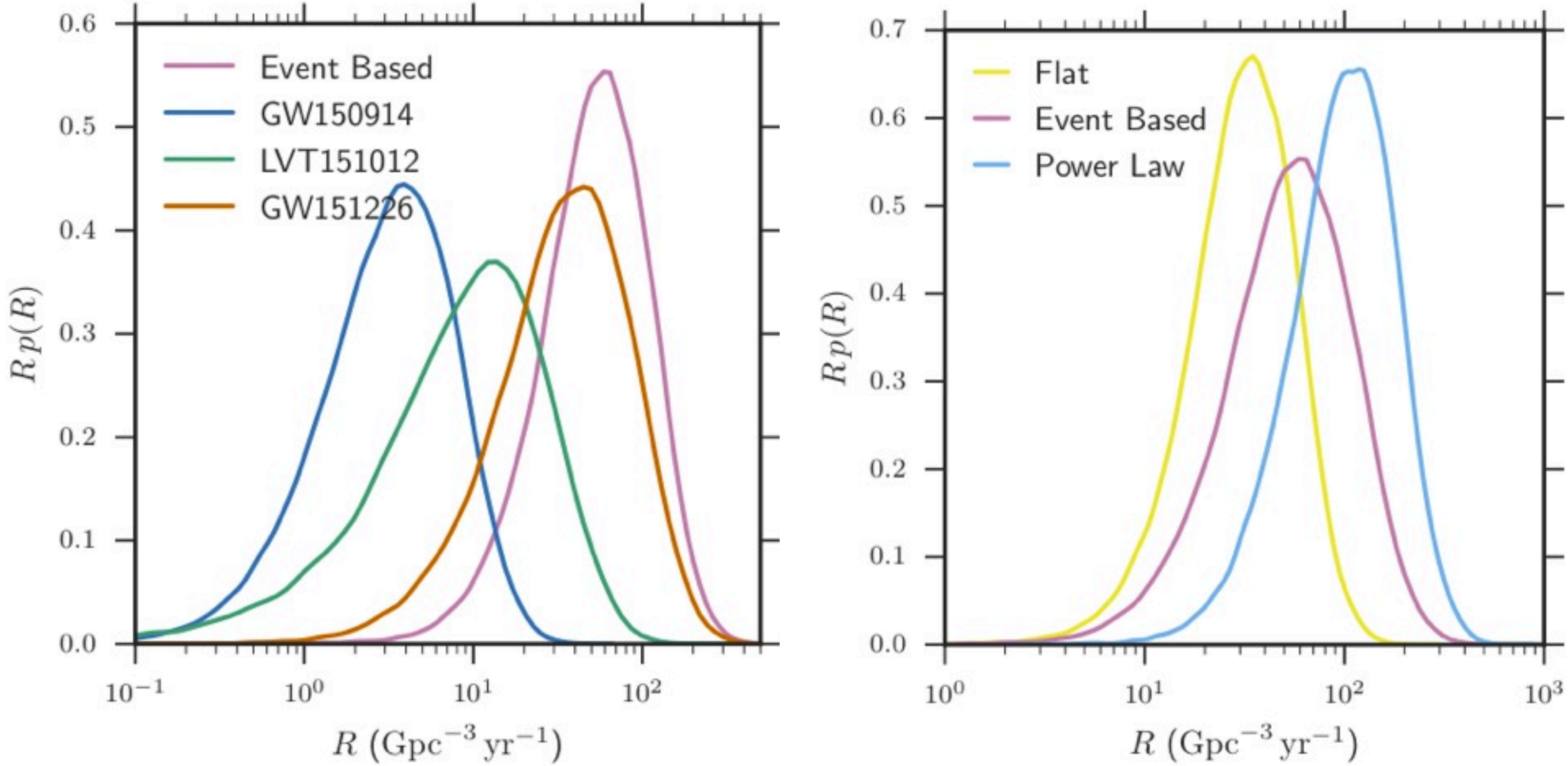


Dealing with Multiple Event Categories:

Being unsure of the intrinsic source populations and origins, we calculate the event rates for all three events and take the union to derive the overall event rate of BBH coalescence. Also test distributions of events according to uniform in the logarithm of component mass and according to the stellar initial mass function: $\mathbf{p(m_1) \propto m_1^{2.35}}$

BBH Event Rates

arxiv:1606.04856



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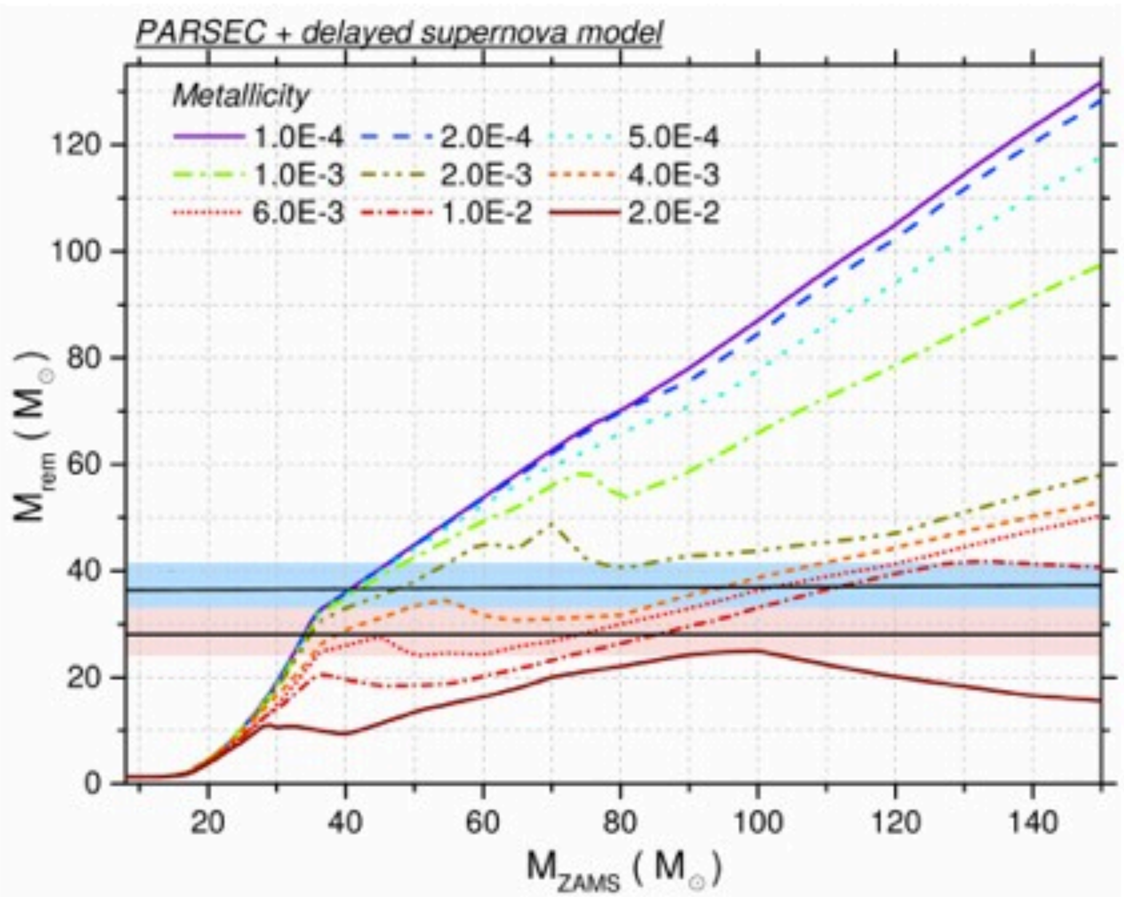
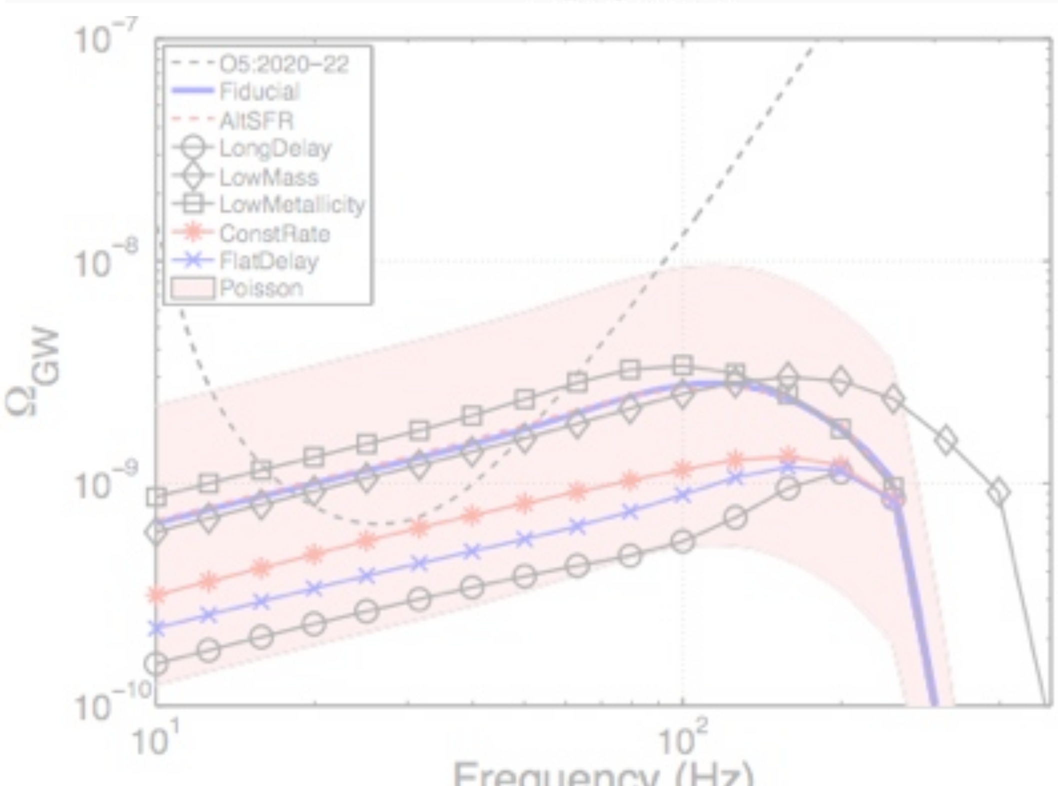
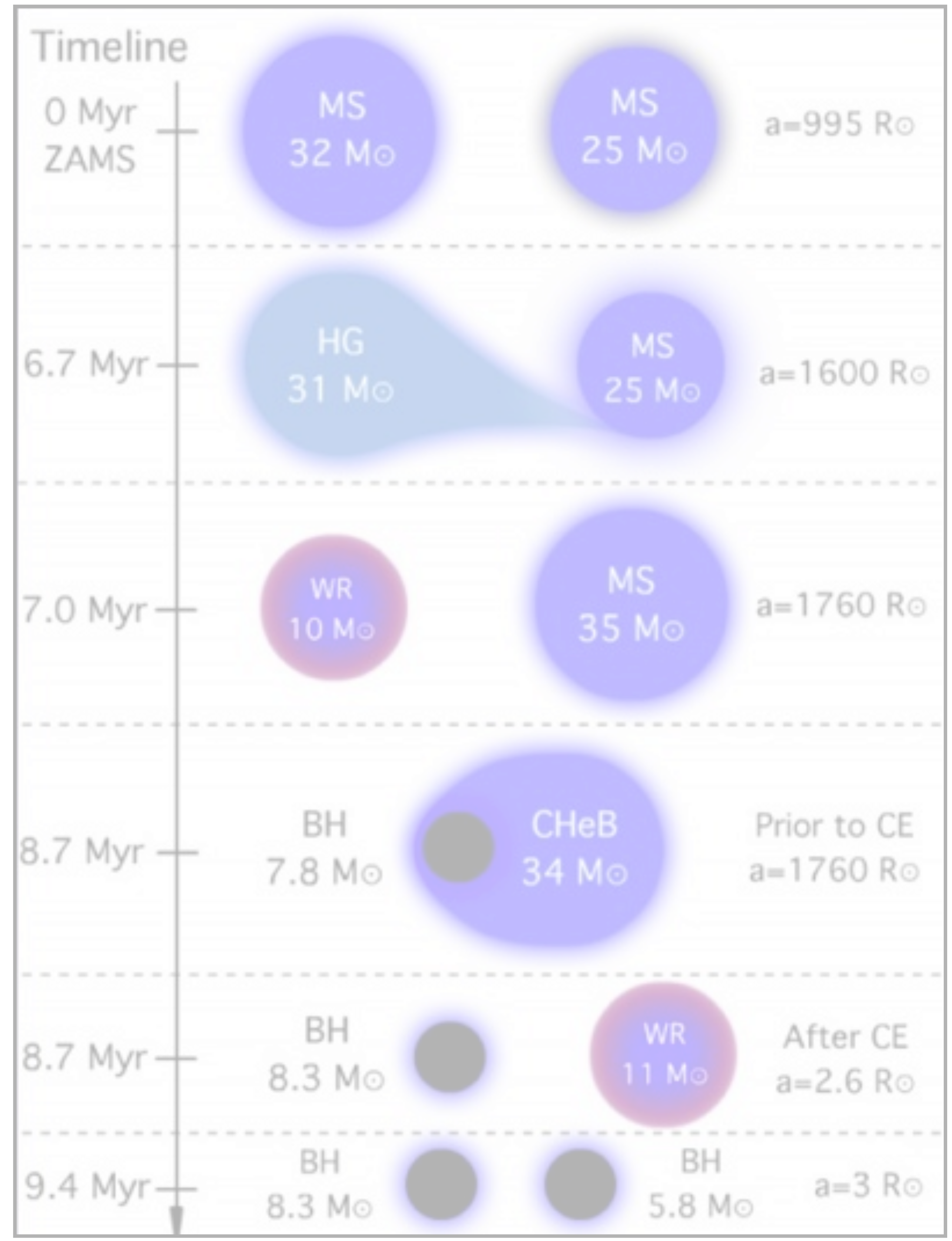
Astrophysics Implications

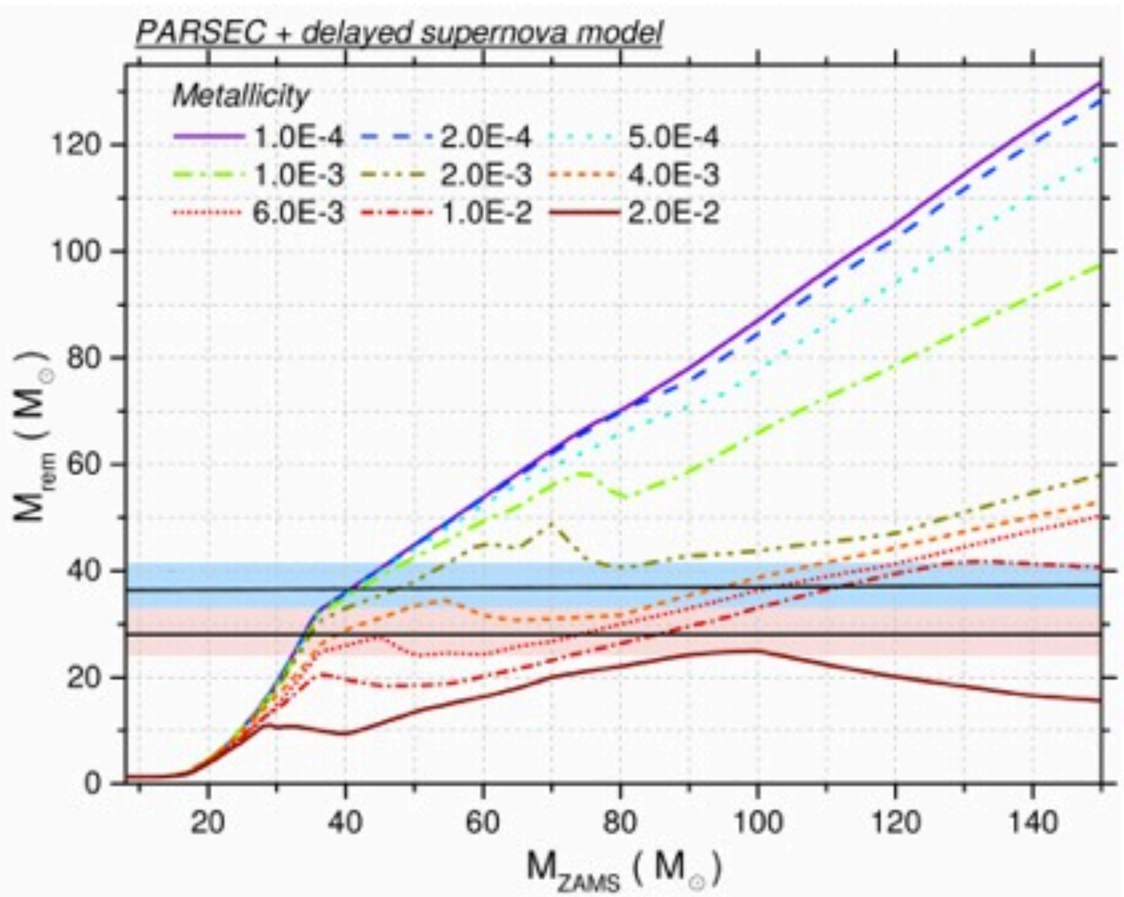


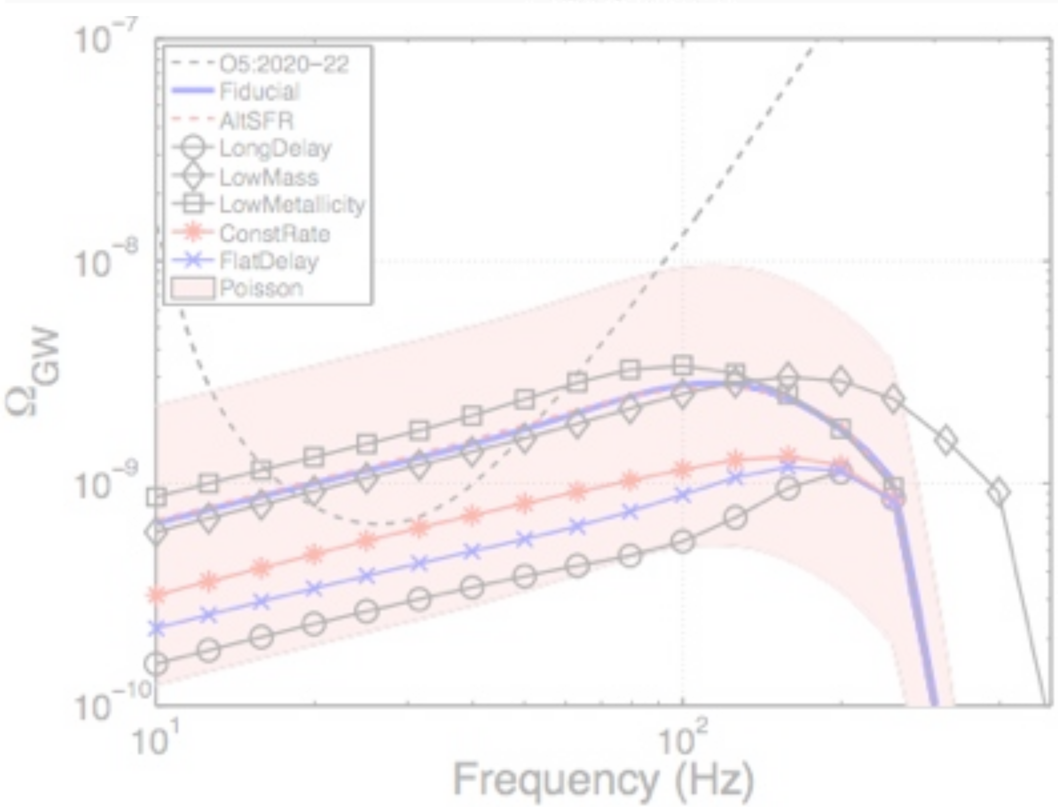


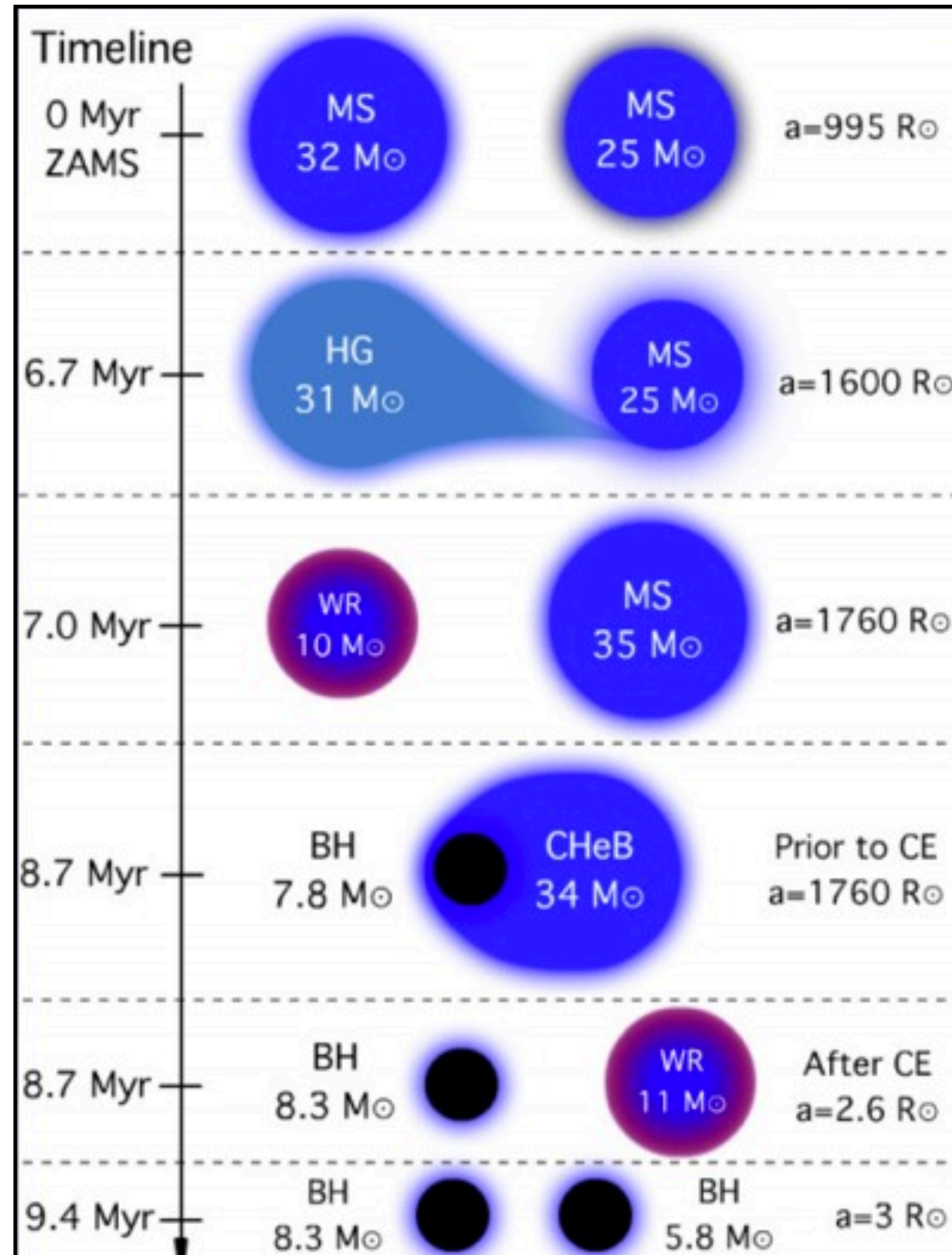


Ap. JL. L22 2016

Astrophysics Implications







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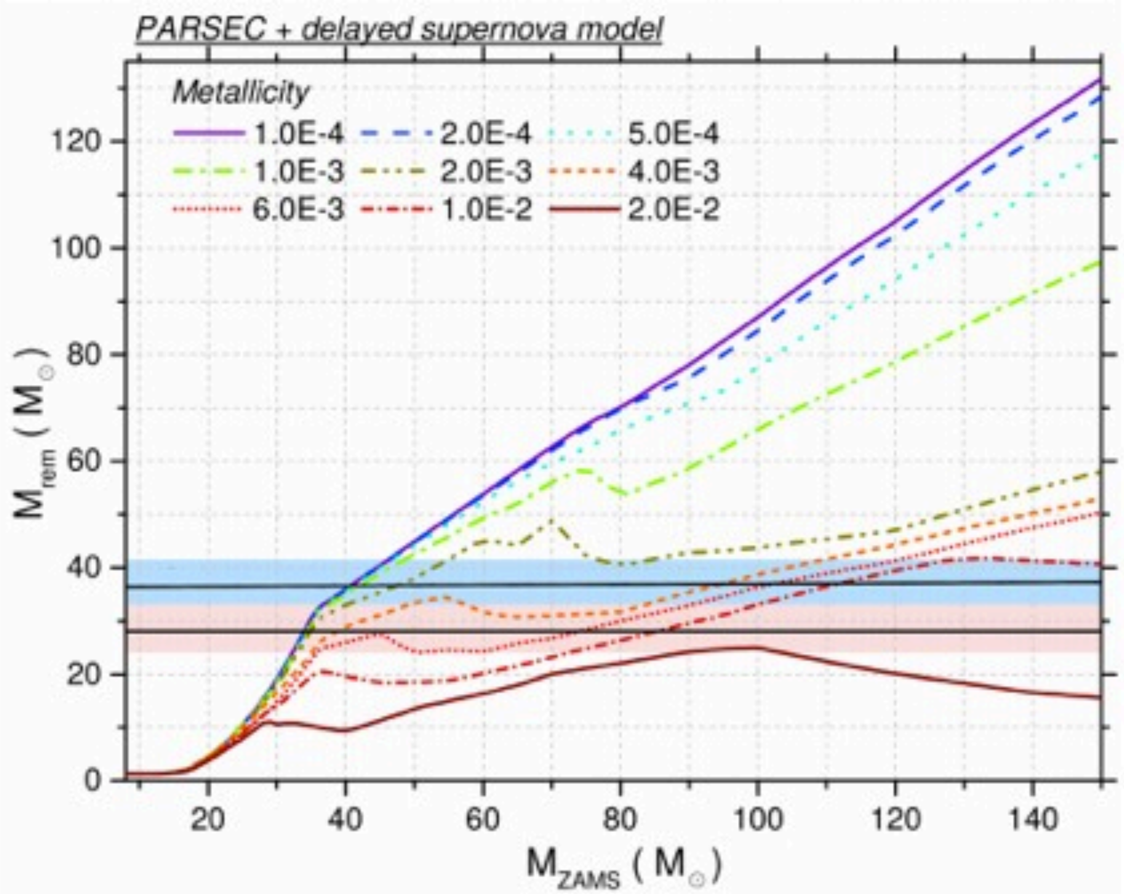

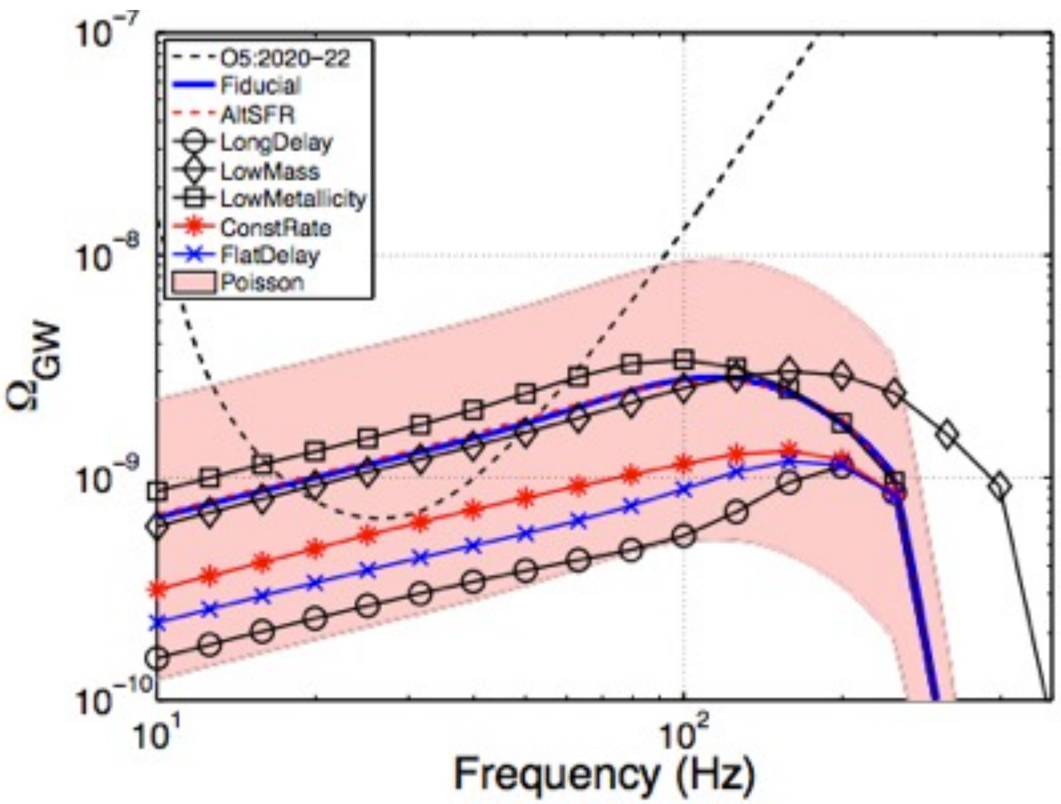

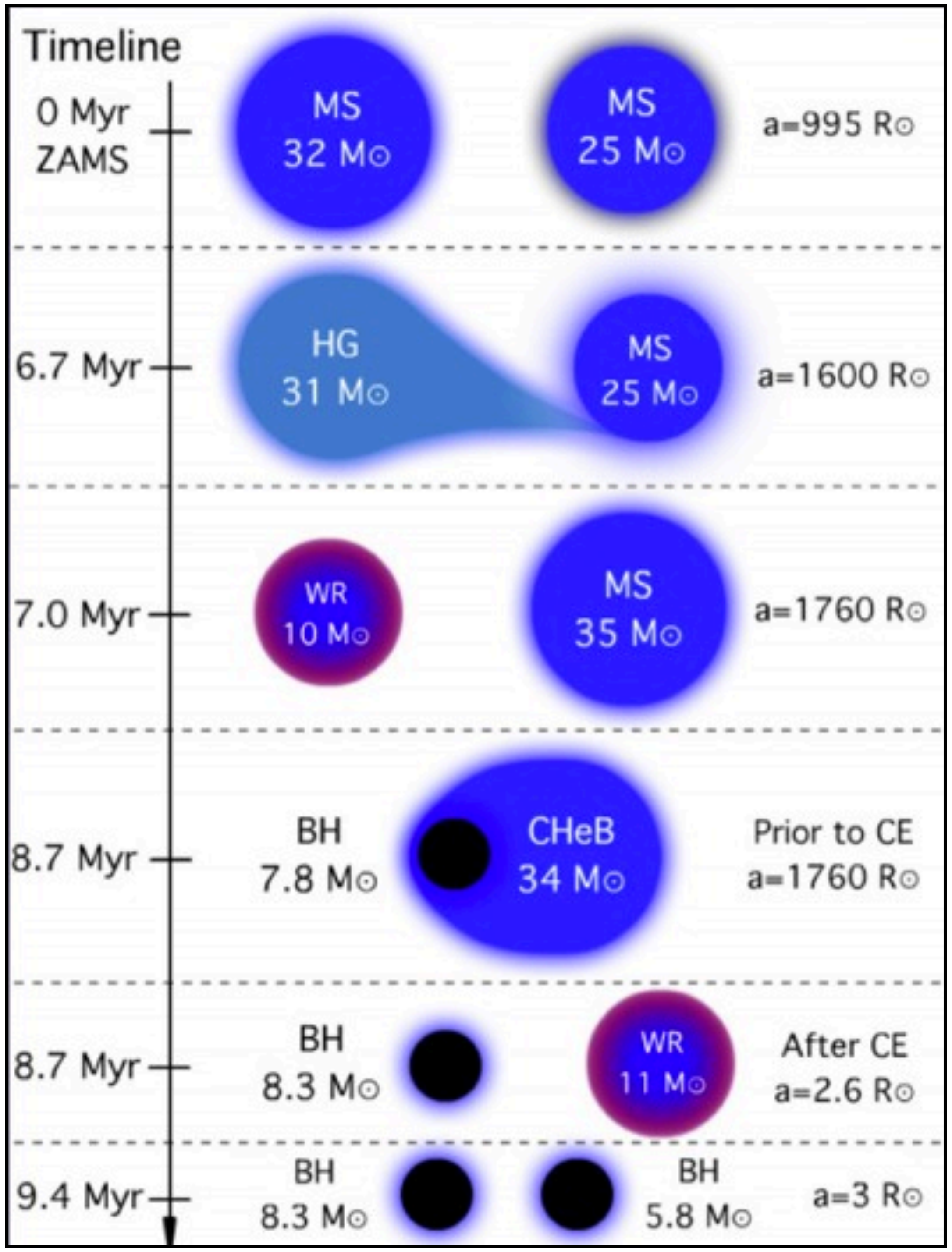

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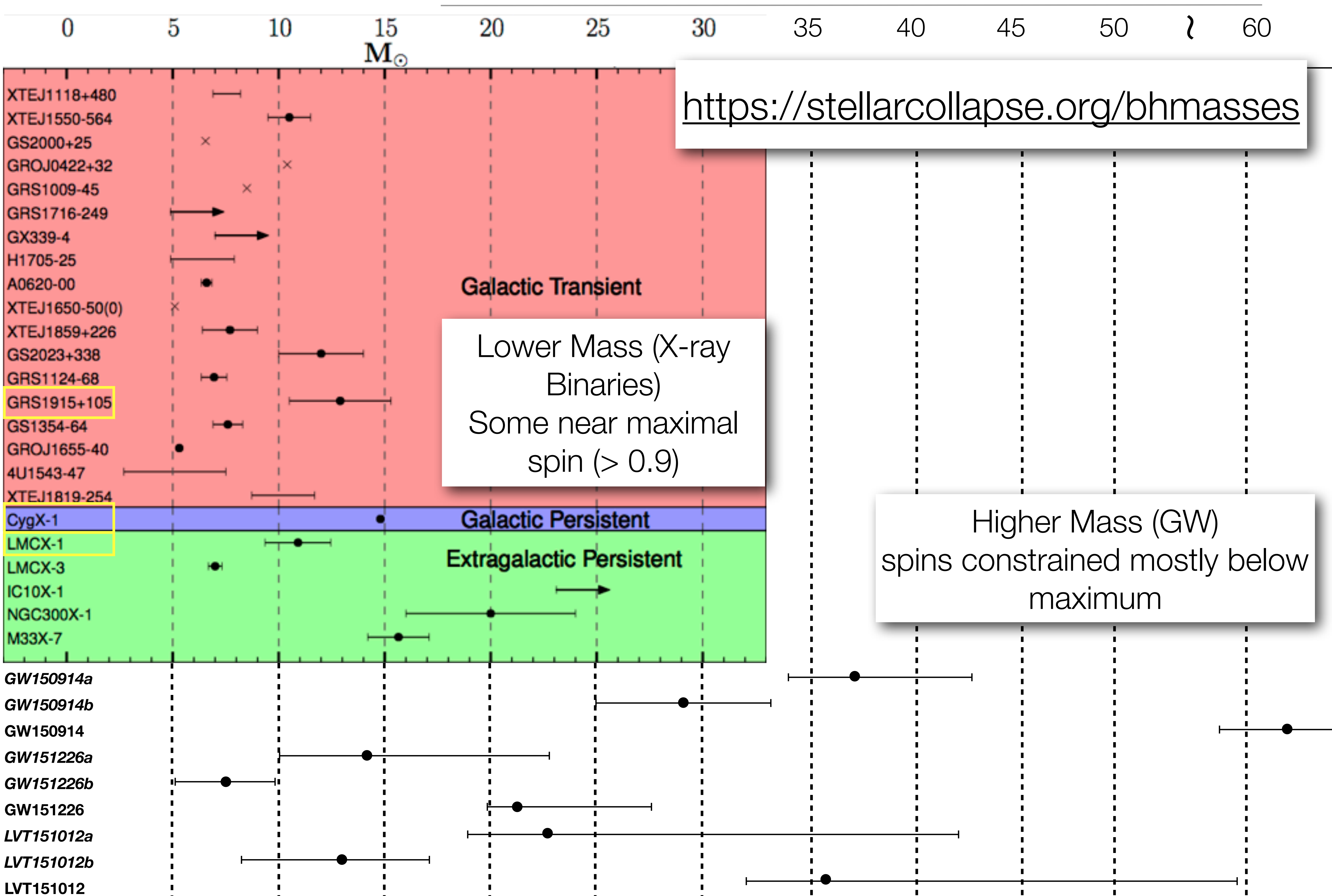
In Context



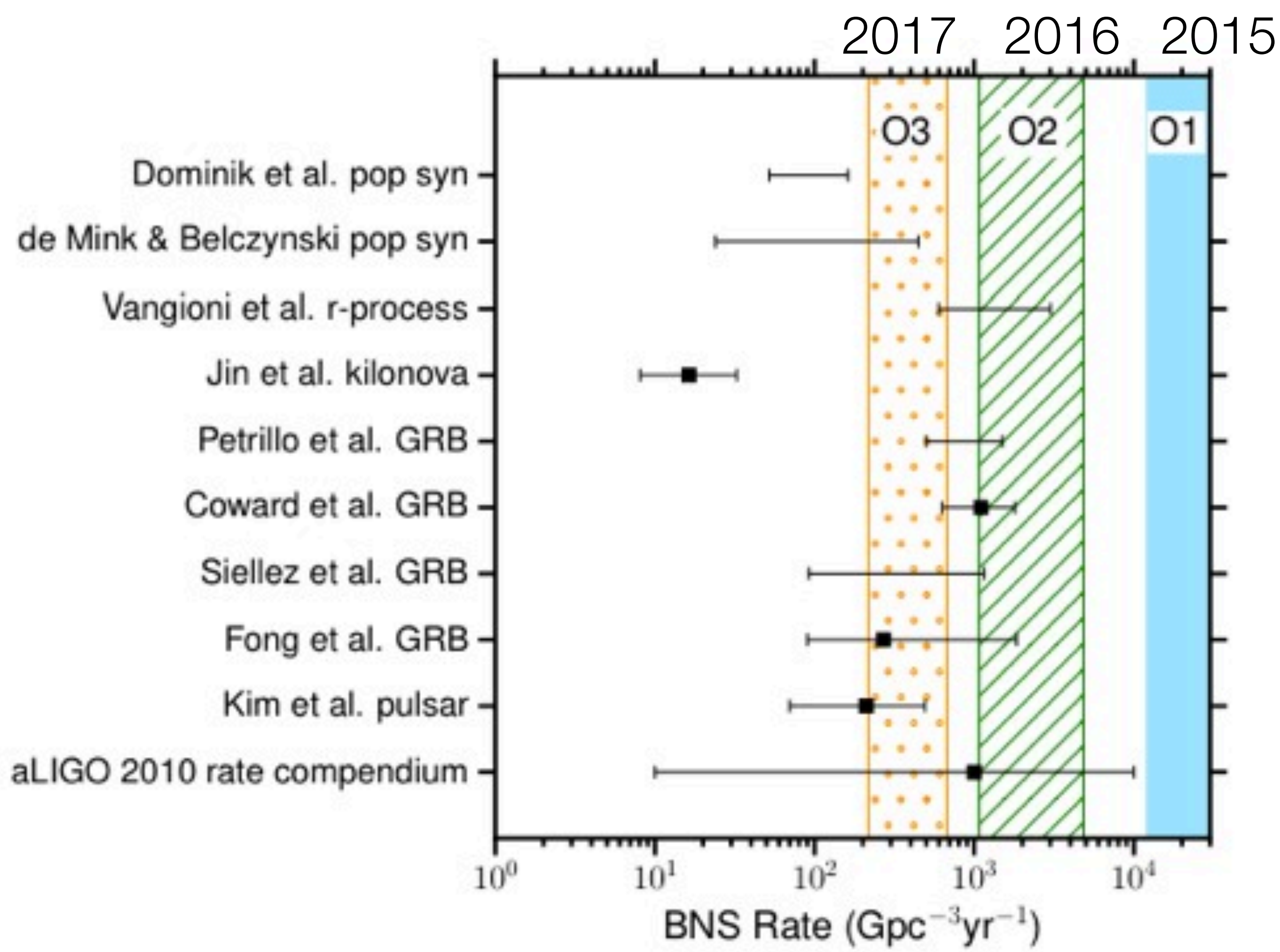
https://stellarcollapse.org/bhmasses

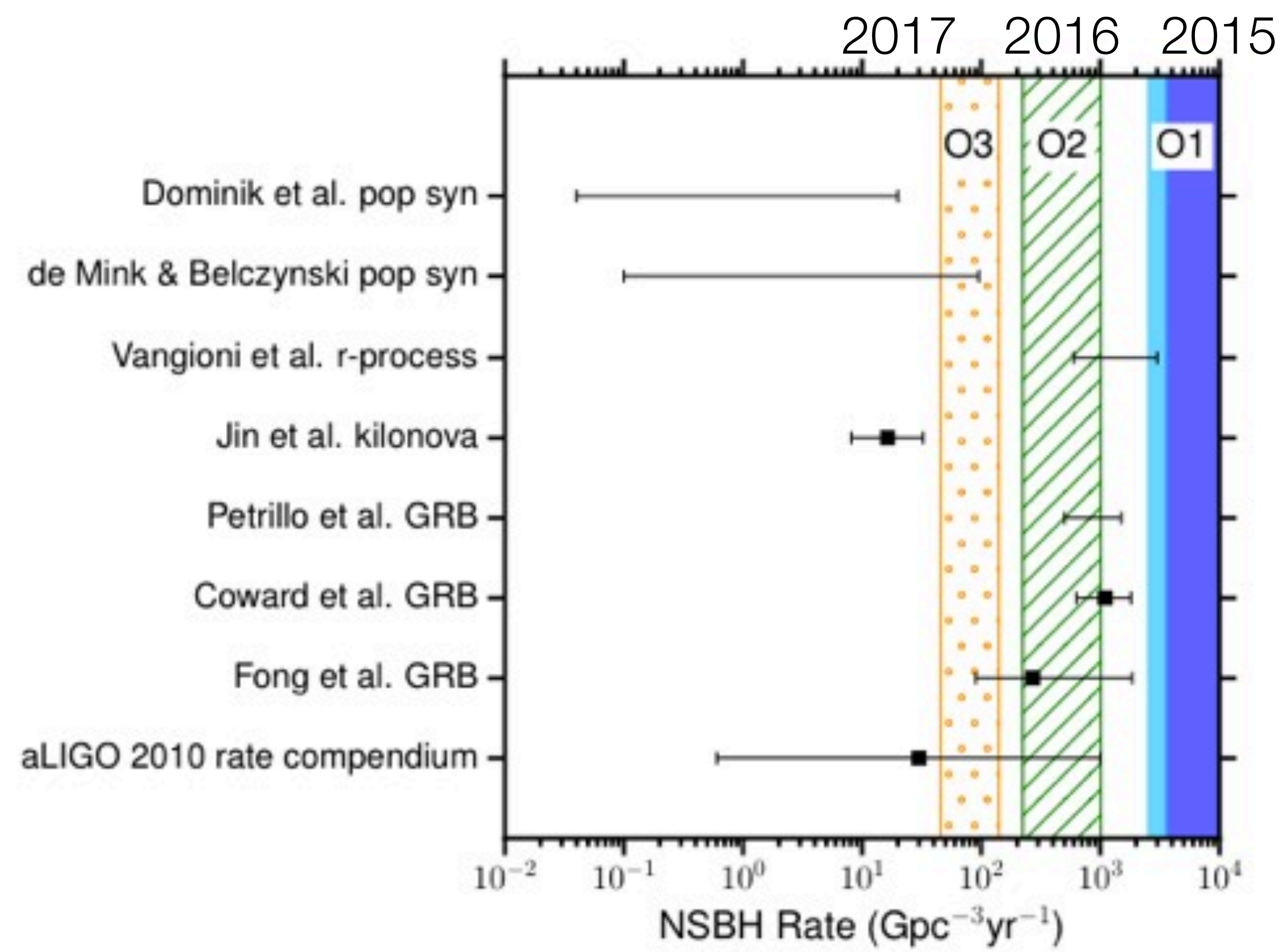
Lower Mass (X-ray Binaries)
Some near maximal spin (> 0.9)

Higher Mass (GW)
spins constrained mostly below maximum

BNS / NSBH Upper Limits

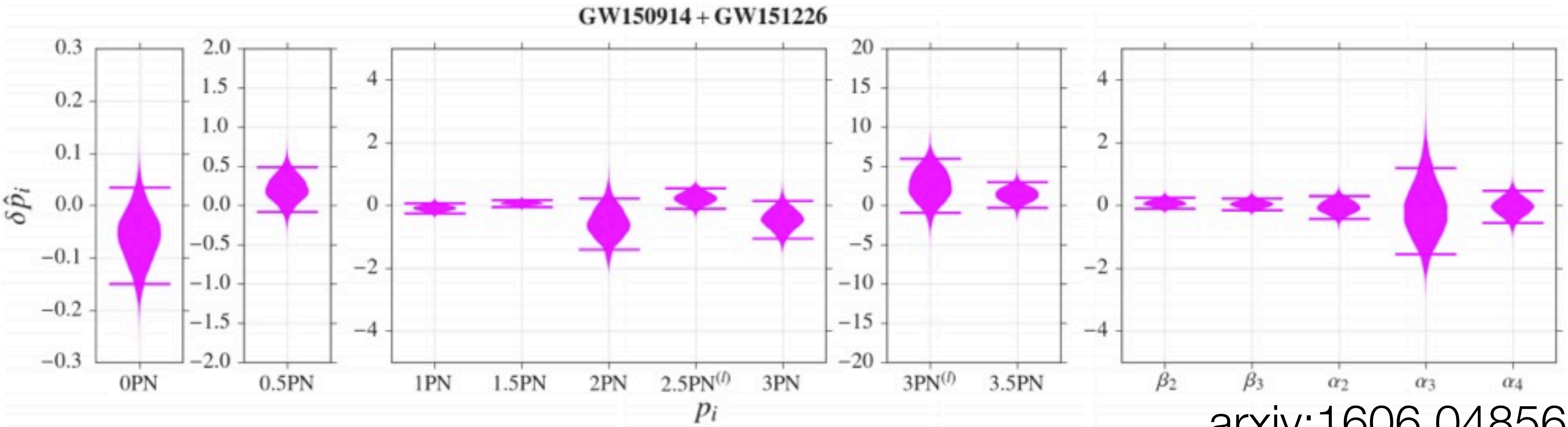
https://arxiv.org/abs/1607.07456





Compact Sources: Only BBH detections so far, NSBH and BNS remain elusive, but expected to constrain models in the next year

Testing GR



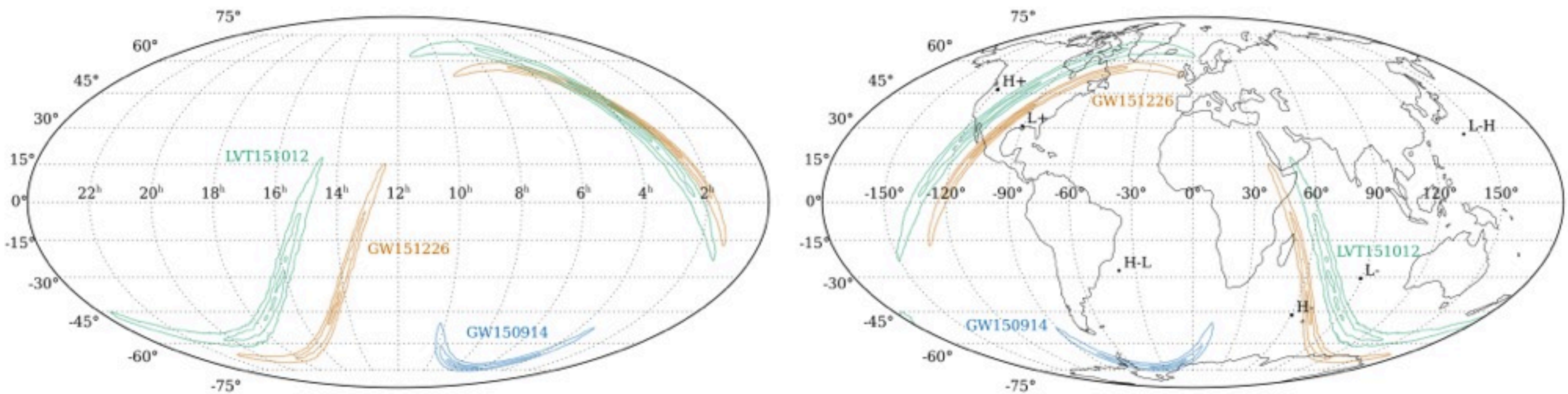
arxiv:1606.04856

Expand Einstein's equations in velocity (PN order) and introduce deviations — use MCMC to test for phase evolution deviations from GR

The **single-parameter** analysis corresponds to minimally extended models, that can capture deviations from GR that predominantly, but not only, occur at a specific PN order

Graviton Mass: Confined Compton wavelength > 10^{13} km (best *dynamical bound)*, by testing *dispersion* in the expected frequency content of the waveform

Sky Localization

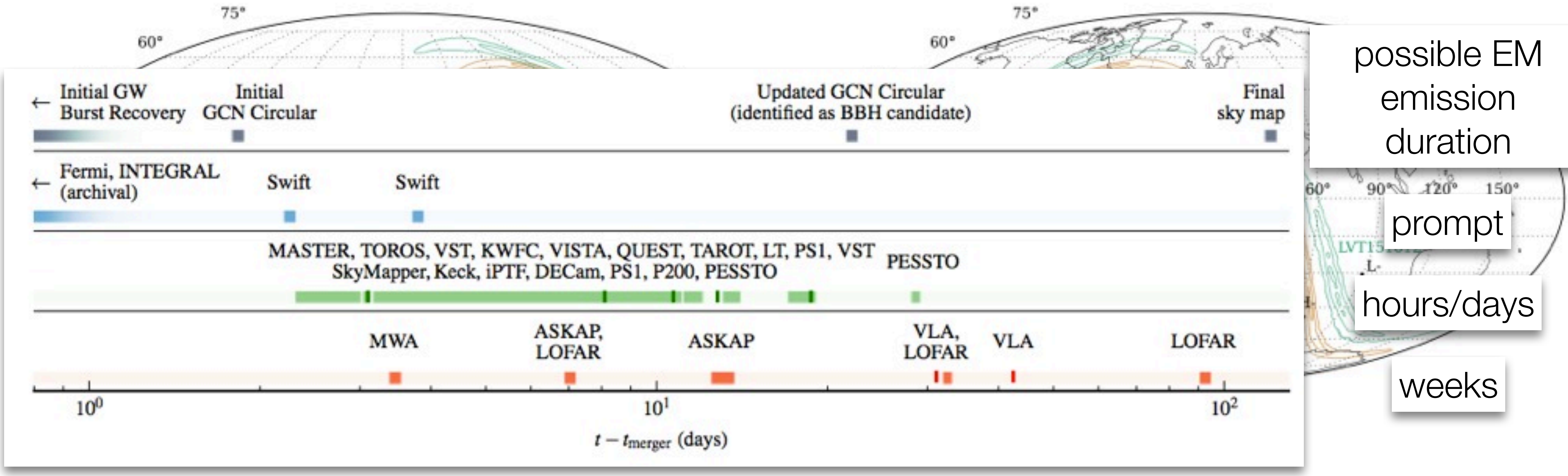


https://arxiv.org/abs/1602.08492

Sky Localization: Two detectors with coherence still restricted to partial annulus on sky

Observation Biases: Optimal location for single detector: directly overhead — preference to detect over North America and Indian Ocean

Sky Localization

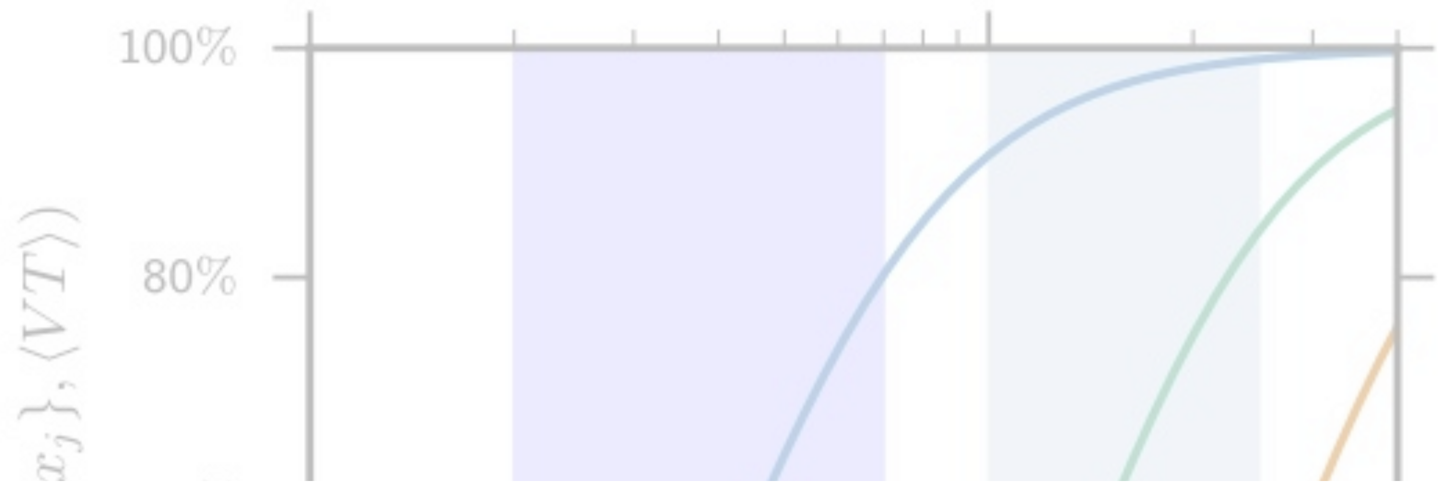


https://arxiv.org/abs/1602.08492

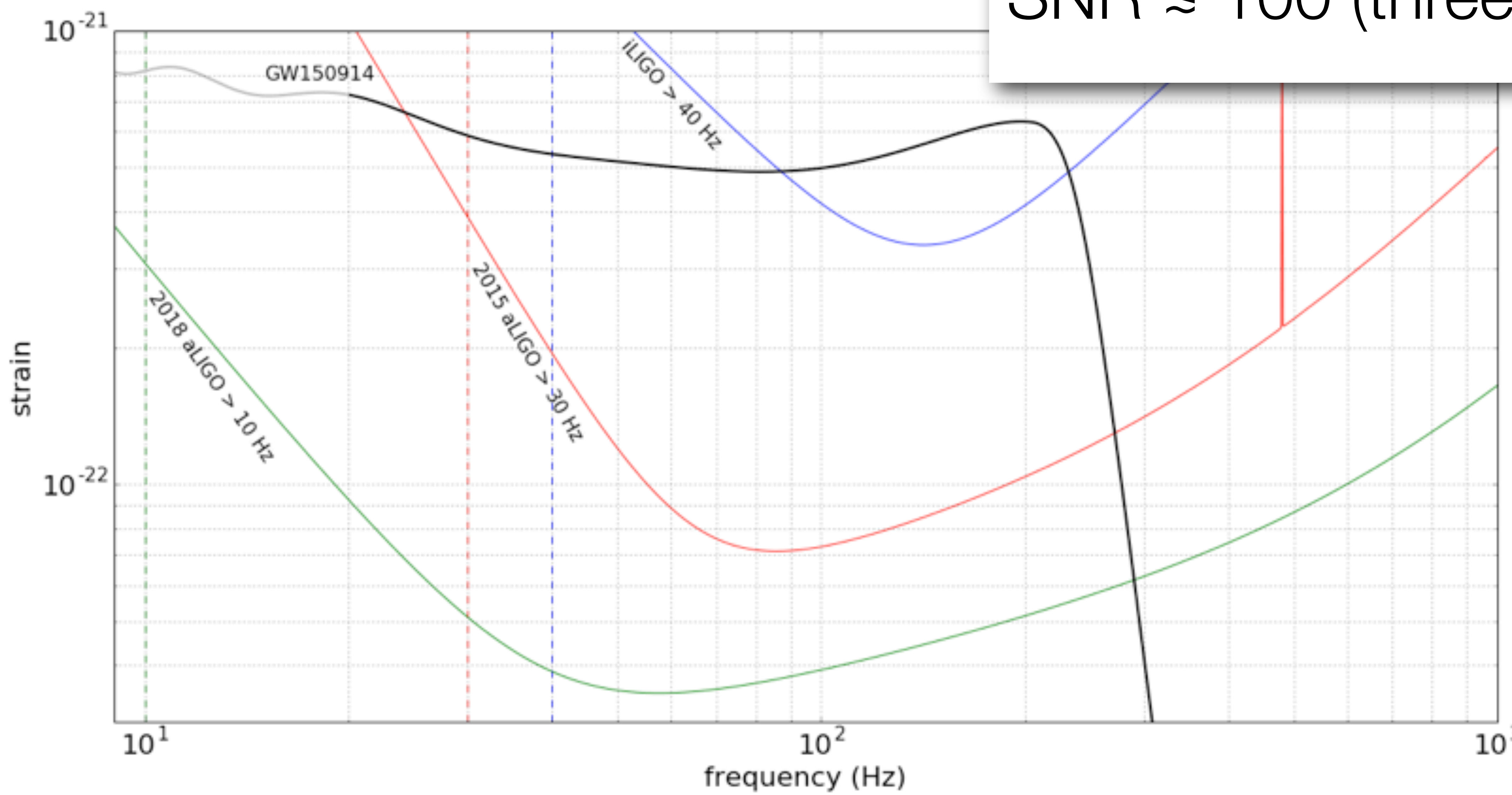
Sky Localization Timeline: Sky position information released within two days — huge follow up program followed thereafter

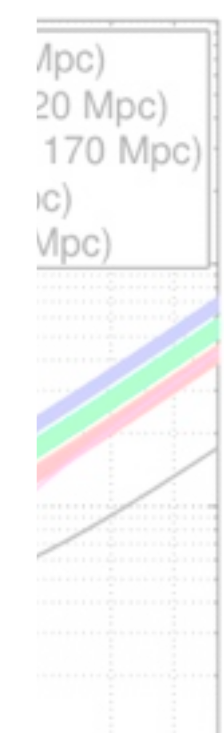
Towards Joint Astronomy: If a binary with a neutron star component is detected, possibility of multi-wavelength electromagnetic emission as well!

O2 and Beyond



GW150914 in 2018: Events like GW150914 could have SNR 40 / detector with total SNR ≲ 100 (three detectors)





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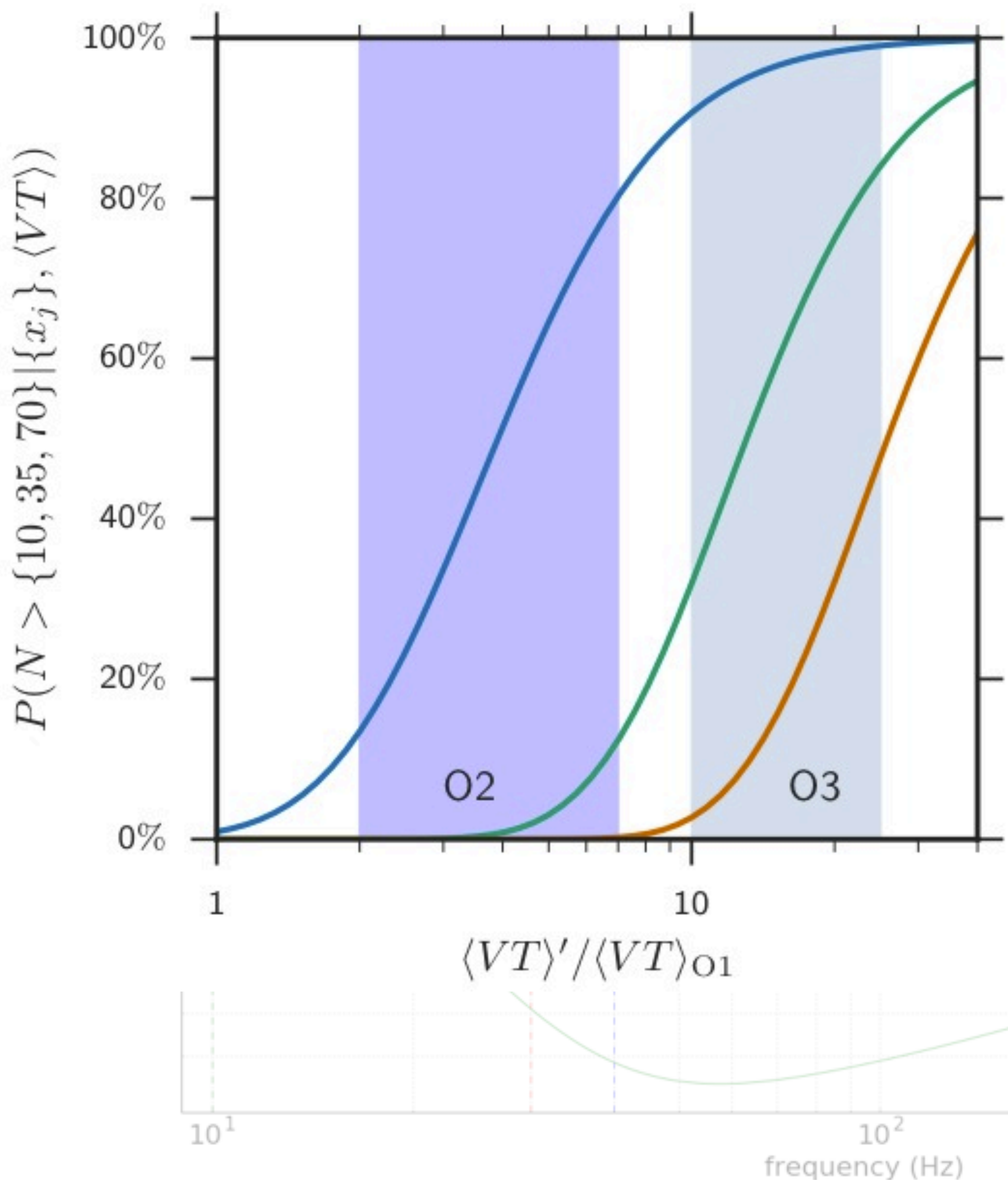
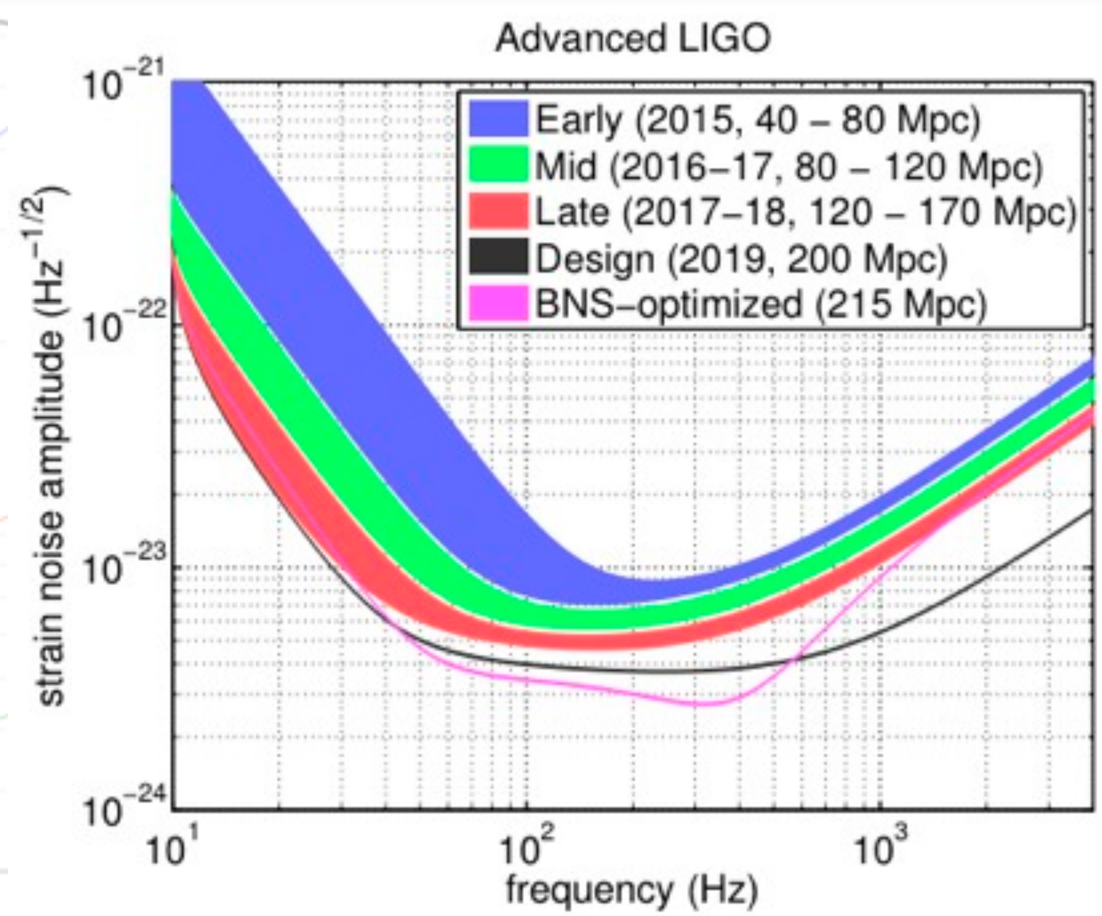
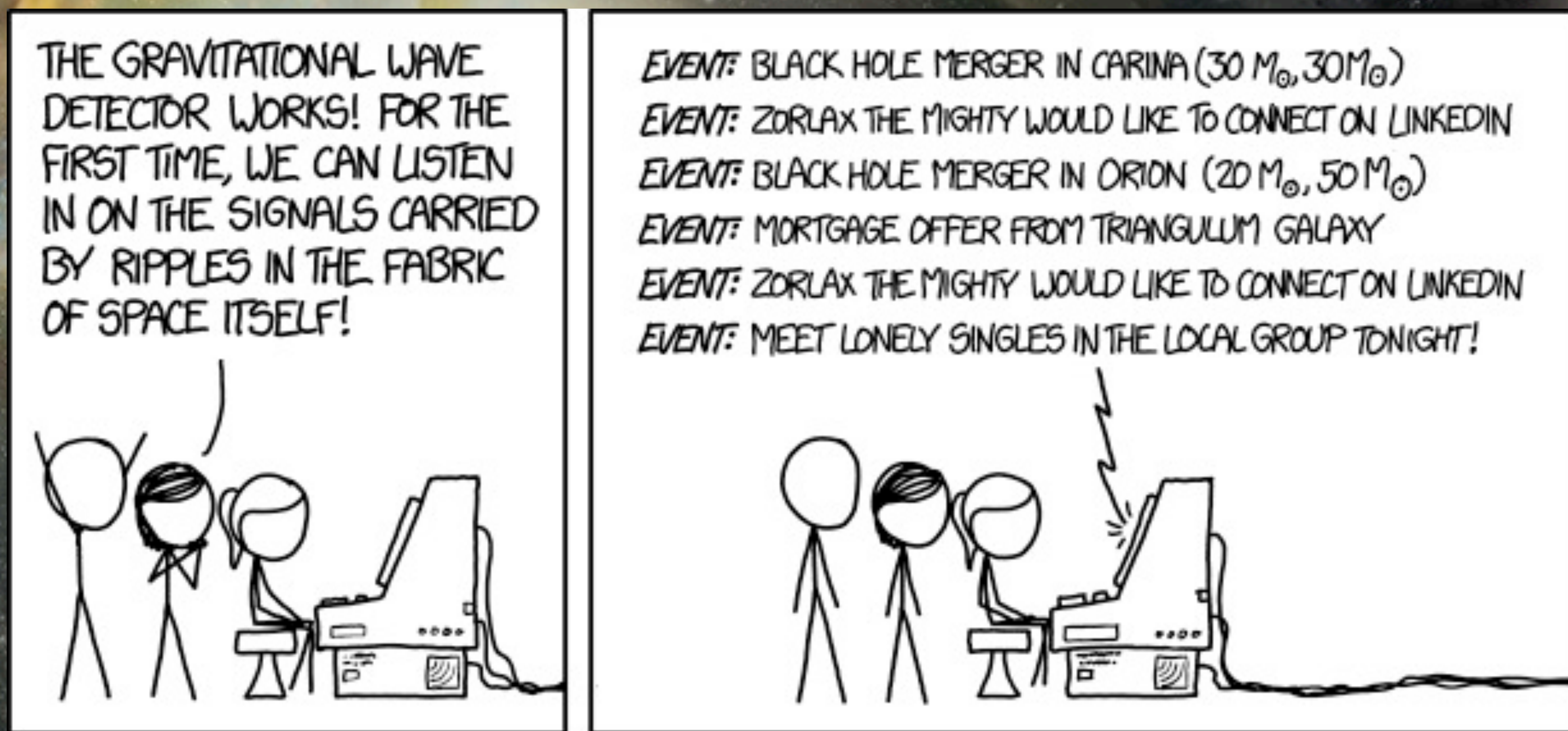


Future Detections:
Depending on sensitivity, could *optimistically* see **tens of BBH** in **O2**, perhaps **x2** in **O3**?



Finally...



GW150914 Fun Facts

GW15094 L_{peak} ~ 50 visible universes

GW150914 ∫ L(t) dt ~ 10^{54} TeV (3 $M_\odot c^2$)

Stay tuned for talk by Lisa Barsotti for the exciting details on how these feats are accomplished with laser interferometry and the future of the experiment

Come visit us and see our GW data releases: https://losc.ligo.org/about/

DIRECT OBSERVATION OF GRAVITATIONAL WAVES FROM A BINARY BLACK HOLE MERGER

A. Simonnet (Sonoma State)