On the origin of binary systems as gravitational wave sources

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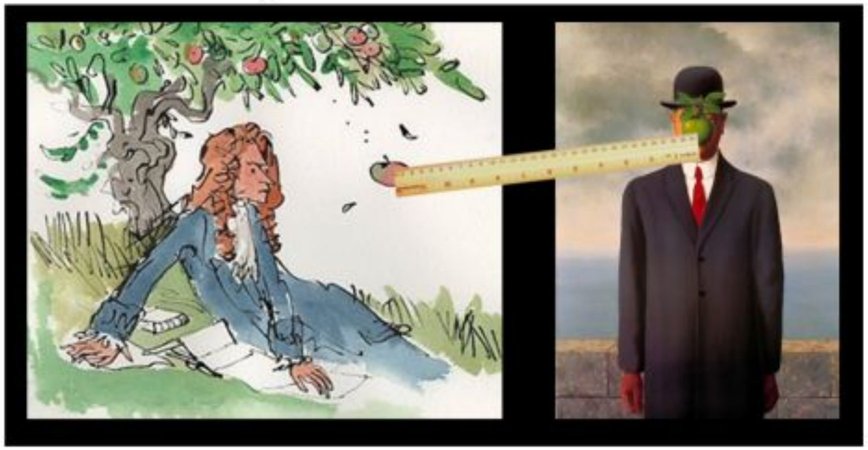
Outline

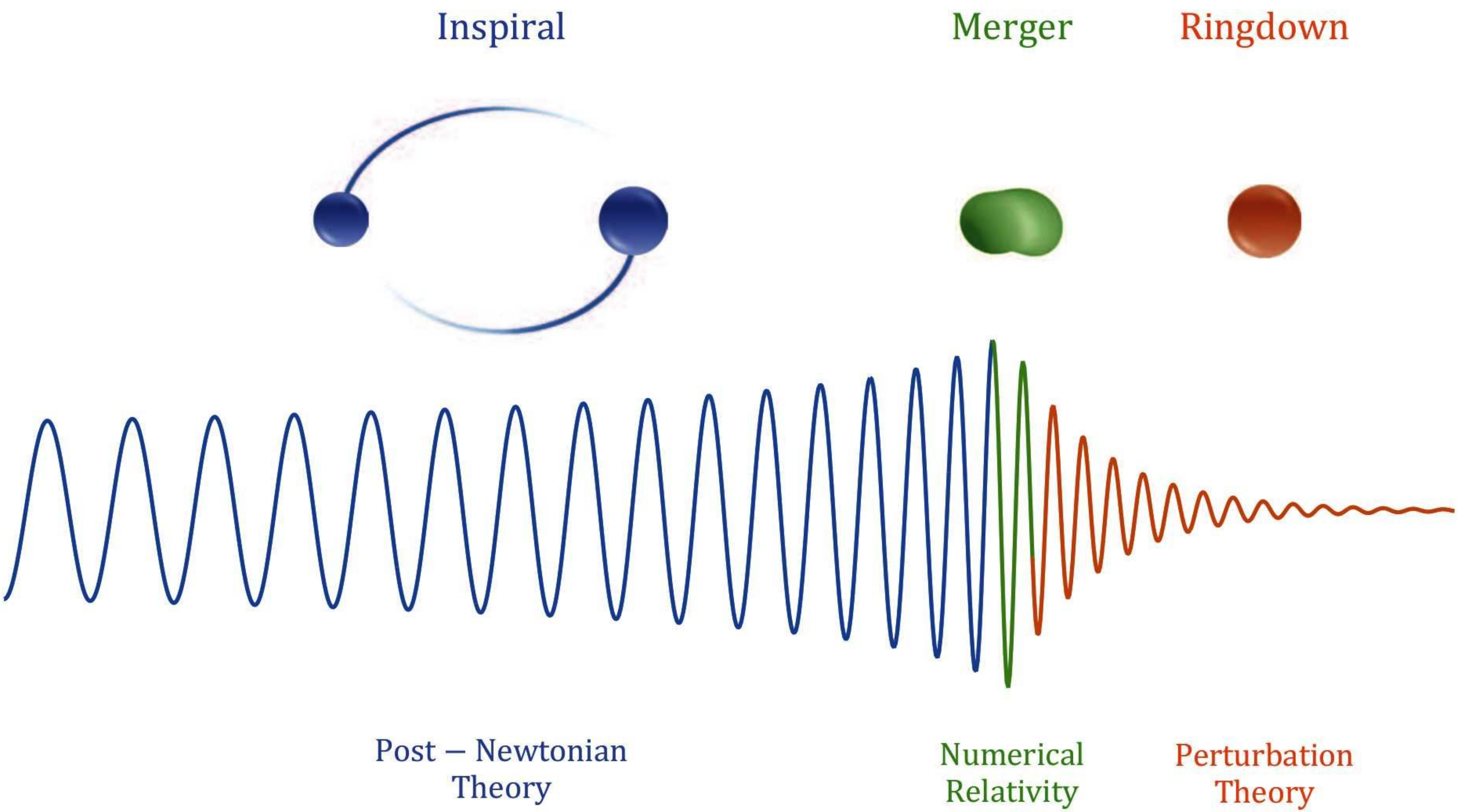
- GW detections
- Source properties
- Data and models
- What’s next?

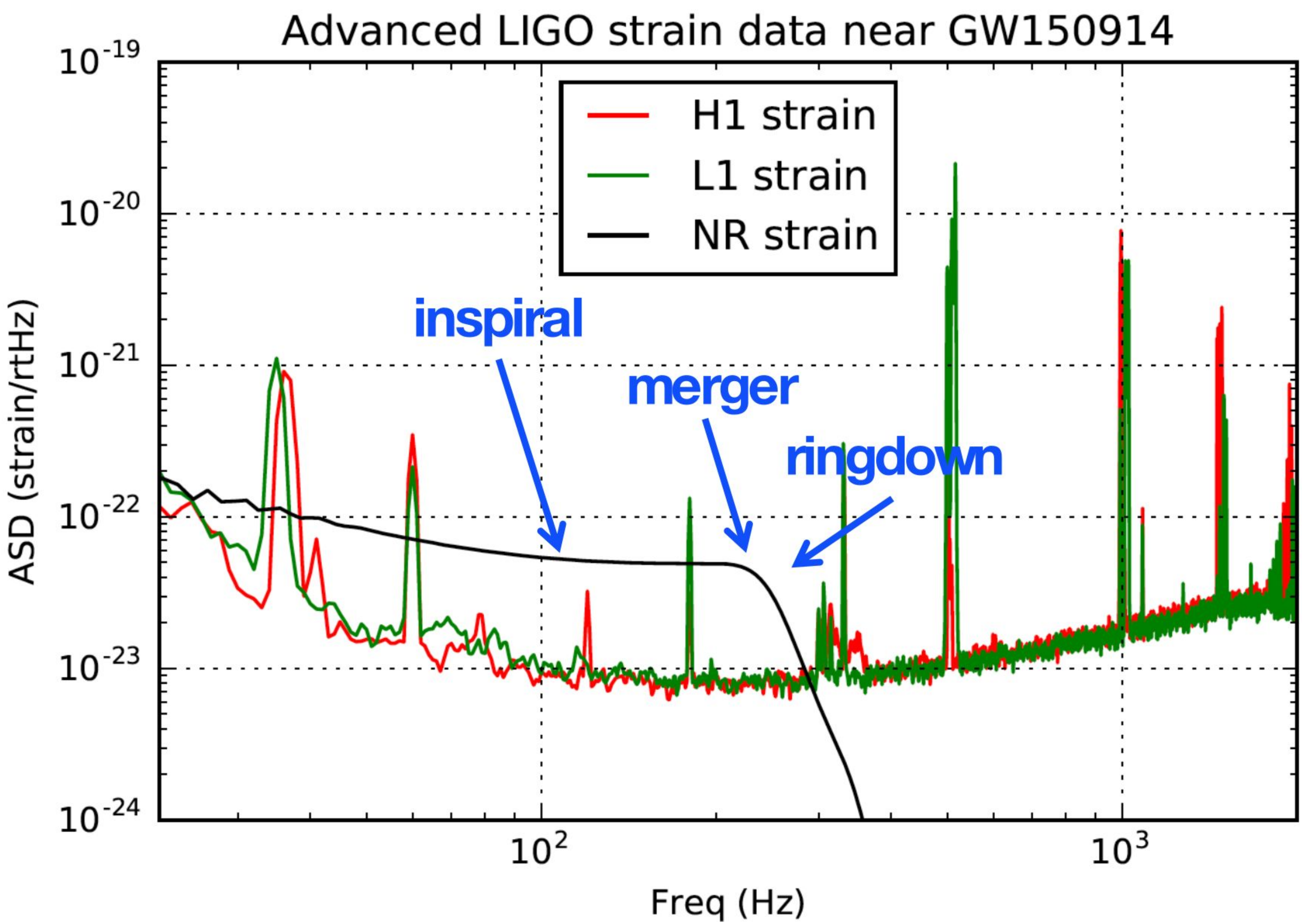
LIGO-Virgo global detector network

Very precise rulers: measuring distances between free-falling bodies with laser light.



Last orbits of a binary system

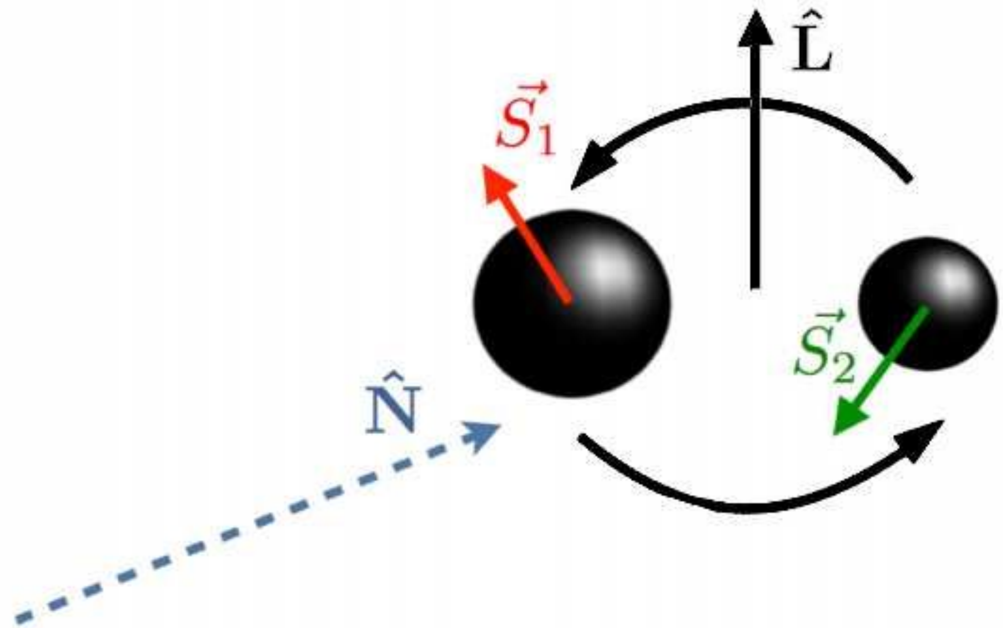


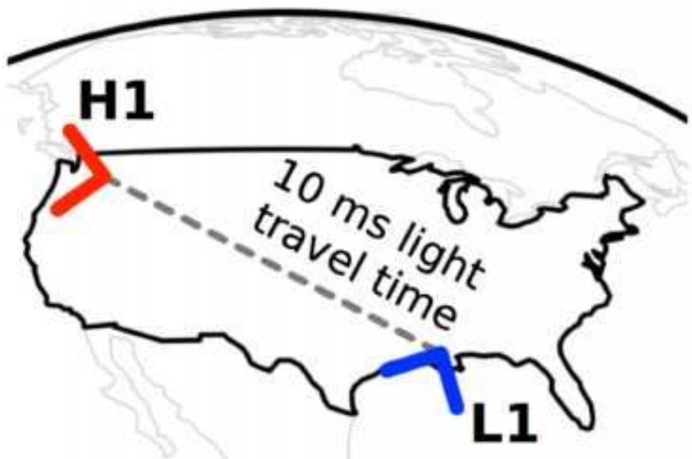


LIGO-Virgo-KAGRA are ‘‘audio band’’ detectors: sensitivity between ~20 Hz and few kHz

Waveform model: 15+ parameters

- Intrinsic:
  - masses
  - spins
  - tidal deformability





Credit: LIGO/Virgo

- Extrinsic:
  - Inclination, distance, polarisation
  - Sky location
  - Time, reference phase

What is measured (directly)

Intrinsic:

- ⋆ Chirp mass $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$,
- ⋆ Mass ratio $q = m_2/m_1$ (at 1PN), alternatively $\nu = m_1 m_2/(m_1 + m_2)^2$,
- ⋆ Spin-orbit and spin-spin coupling (at 2PN and 3PN, resp.) $\rightarrow$

$$\chi_{eff} = (m_1 \chi_{1z} + m_2 \chi_{2z})/(m_1 + m_2)$$

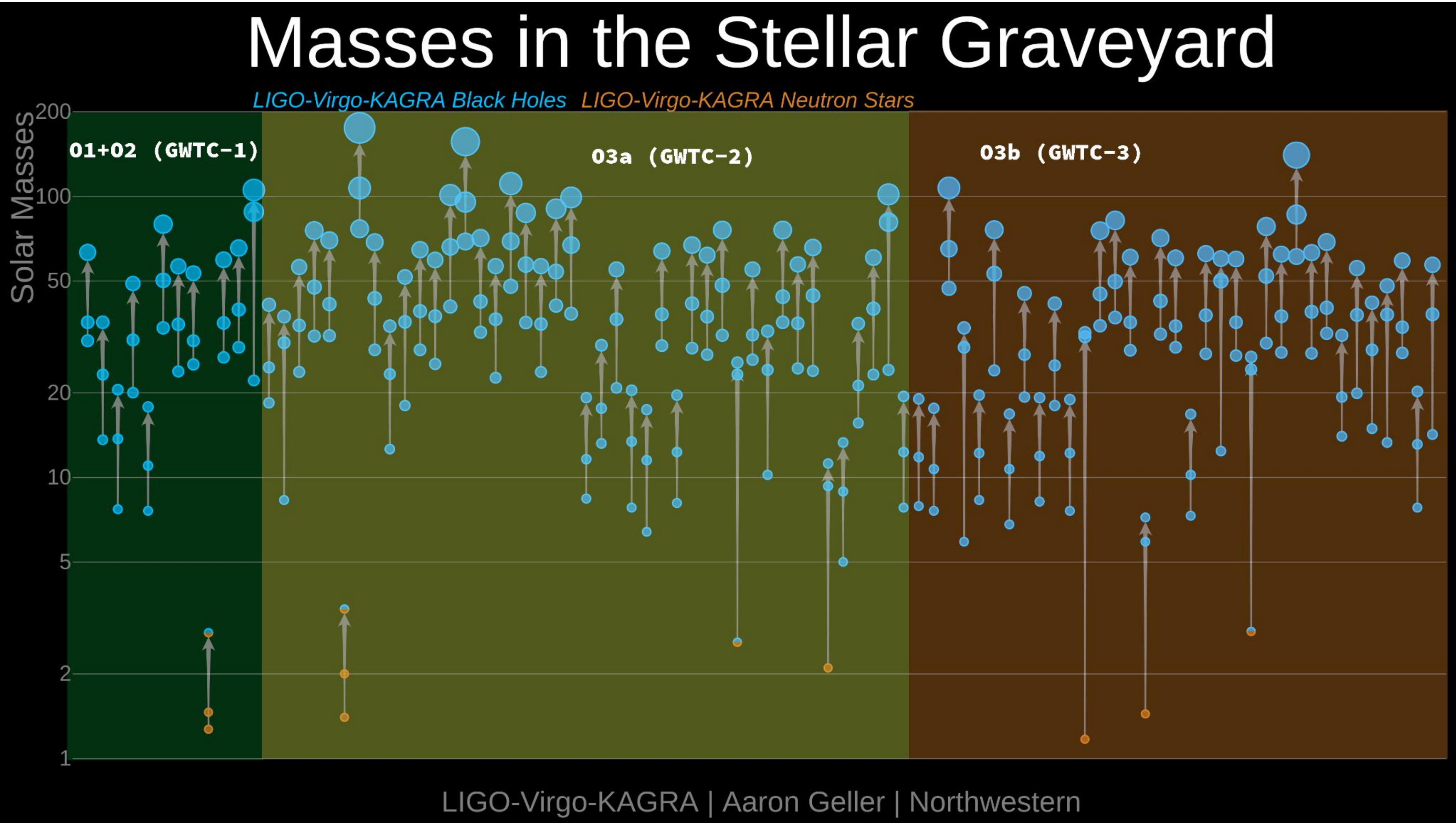
where χ_{iz} are spin components along system's total angular momentum,

- ⋆ Tidal deformability Λ (at 5PN) $\rightarrow$

$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12 m_2) m_1^4 \Lambda_1}{(m_1 + m_2)^5} + (1 \leftrightarrow 2), \qquad \mathcal{R} = 2\mathcal{M}\tilde{\Lambda}^{1/5}$$

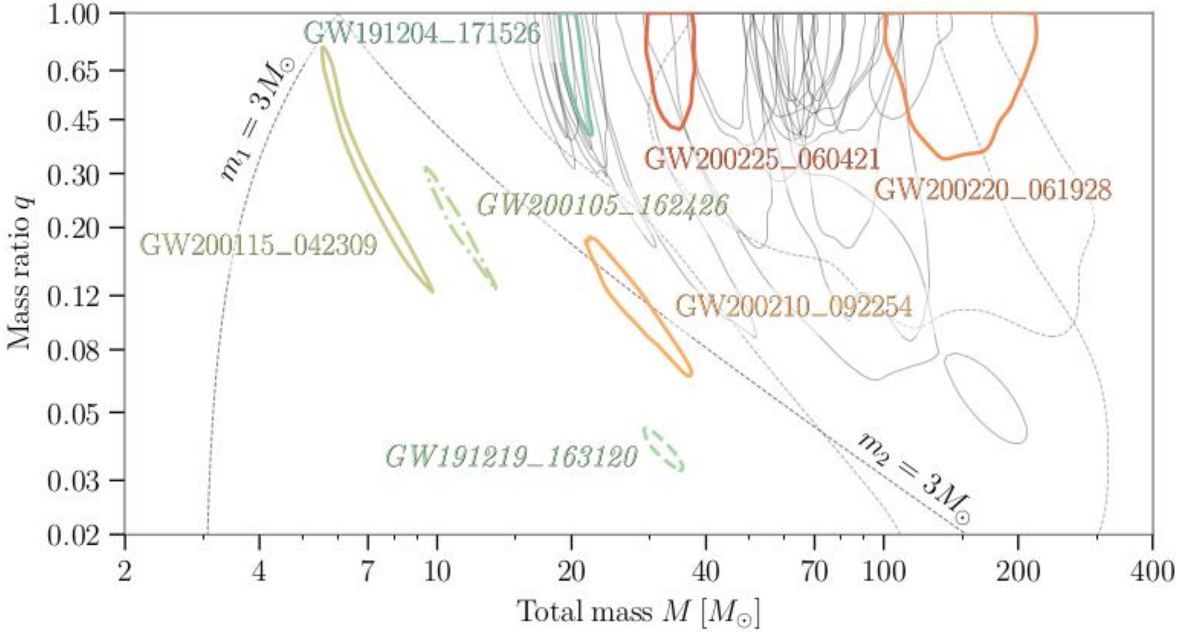
Extrinsic:

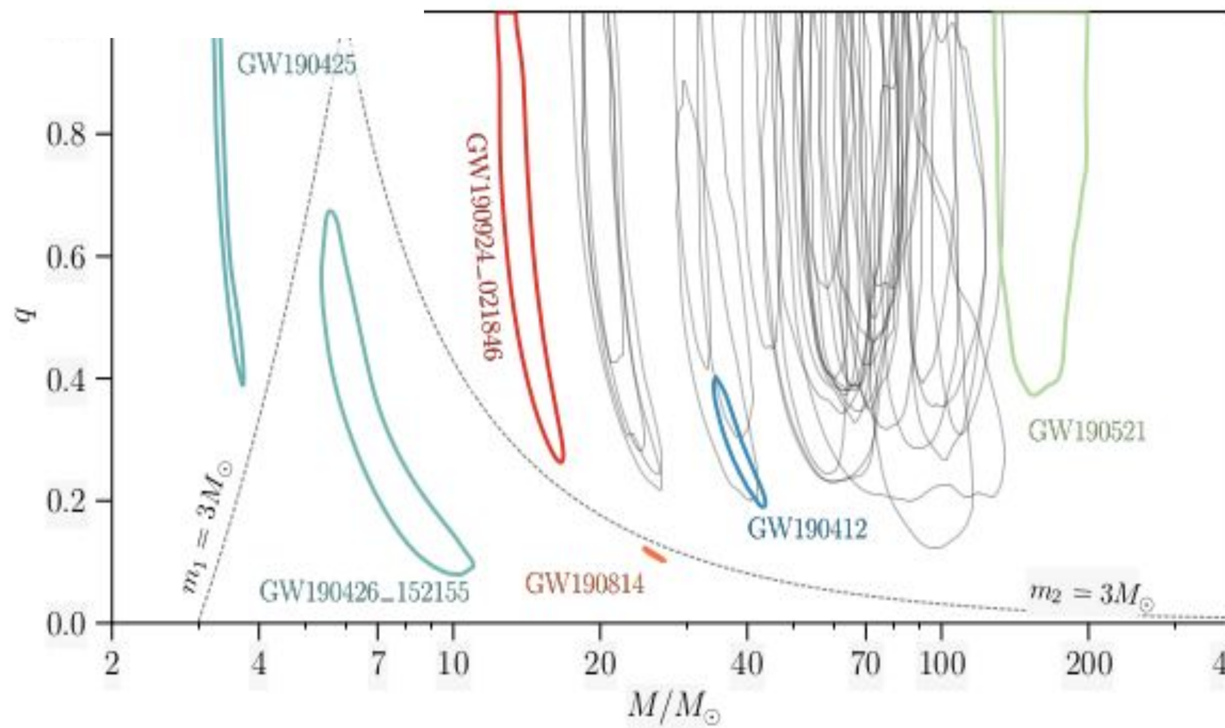
- ⋆ Direct "luminosity" ("loudness") distance: binary systems are "standard sirens".



O4 predictions: sensitivity improvement by factor ~1.5, so 1.5^3 ~ 3 times more events (~300, one per day?)

Masses and mass ratios





Merger rate densities

- BBH estimate $\mathrm{R} = 17.8 - 45\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ (at z=2)
- BNS estimate $\mathrm{R} = 10 - 1700\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- BHNS estimate $\mathrm{R} = 7.8 - 140\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- The local supernova rate ~ $10^5\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- The BH formation rate is ~ $10^4\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- **About 1 BH in a 100-1000 ends up in a merging binary**
- **Similarly for NS: 1 in 100-1000 is in a merging binary!**

An unexpected shortage of neutron-star mergers?

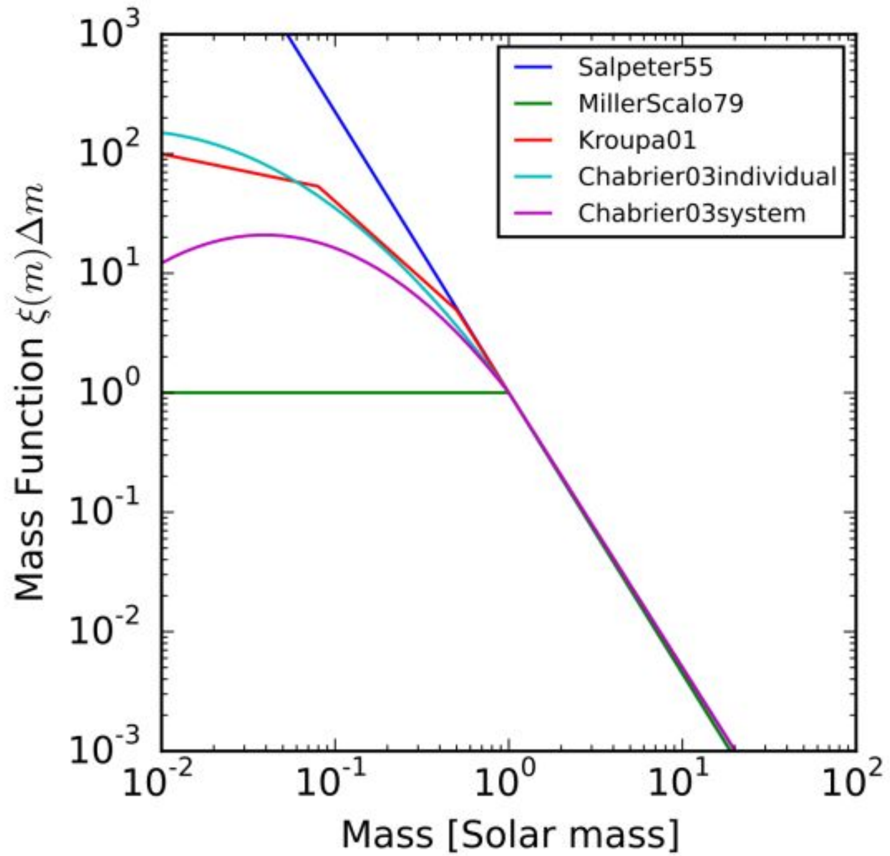
Should we be concerned that LIGO & Virgo detectors detect much more BBH than BNS signals?

Edwin Salpeter's initial mass function is

$$\xi(m)\Delta m = \xi_0 \left(\frac{m}{M_\odot}\right)^{-2.35} \left(\frac{\Delta m}{M_\odot}\right)$$

Integrated for ranges of masses for BHs and NSs progenitor stars, to get relative numbers of progenitors:

$$\frac{N(M > 80M_\odot)}{N(M > 10M_\odot)} = \left(\frac{80M_\odot}{10M_\odot}\right)^{-1.35} \simeq 0.06.$$



An unexpected shortage of neutron-star mergers?

- $\star$ Assuming the same merger rates for BBH and BNS $\rightarrow$ rates proportional to number of progenitor stars:

$$\frac{\mathcal{R}_{BBH}}{\mathcal{R}_{BNS}} = \left(\frac{80M_\odot}{10M_\odot}\right)^{-1.35} \simeq 0.06$$

- $\star$ But how many signals are detected? Signal-to-noise $\propto \mathcal{M}^{5/6}$, detection volume $\propto SNR^3 \propto r^3$

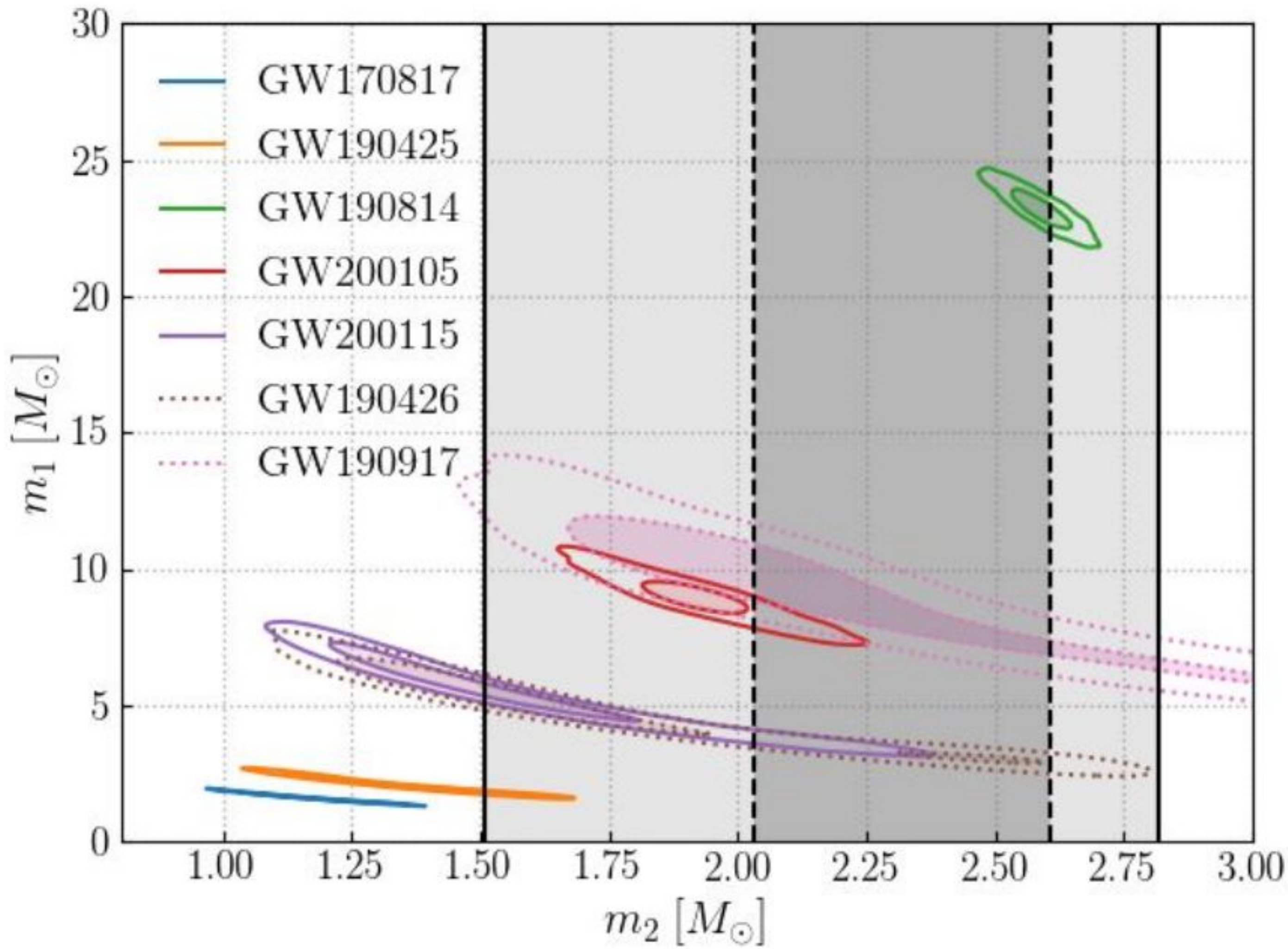
$$\frac{\mathcal{D}_{BBH}}{\mathcal{D}_{BNS}} = \frac{\mathcal{R}_{BBH}}{\mathcal{R}_{BNS}}\left(\frac{\mathcal{M}_{BBH}}{\mathcal{M}_{BNS}}\right)^{5/2} = \left(\frac{80M_\odot}{10M_\odot}\right)^{-1.35}\left(\frac{10M_\odot}{1.4M_\odot}\right)^{5/2} \simeq 8$$

(Phys. Usp. 44 1 2001 [astro-ph/0008481])

Neutron star events

Five events with a low-mass component (m < 3 $M_\odot$)

We infer the distribution of NS masses in merging compact binaries from a subset of these events



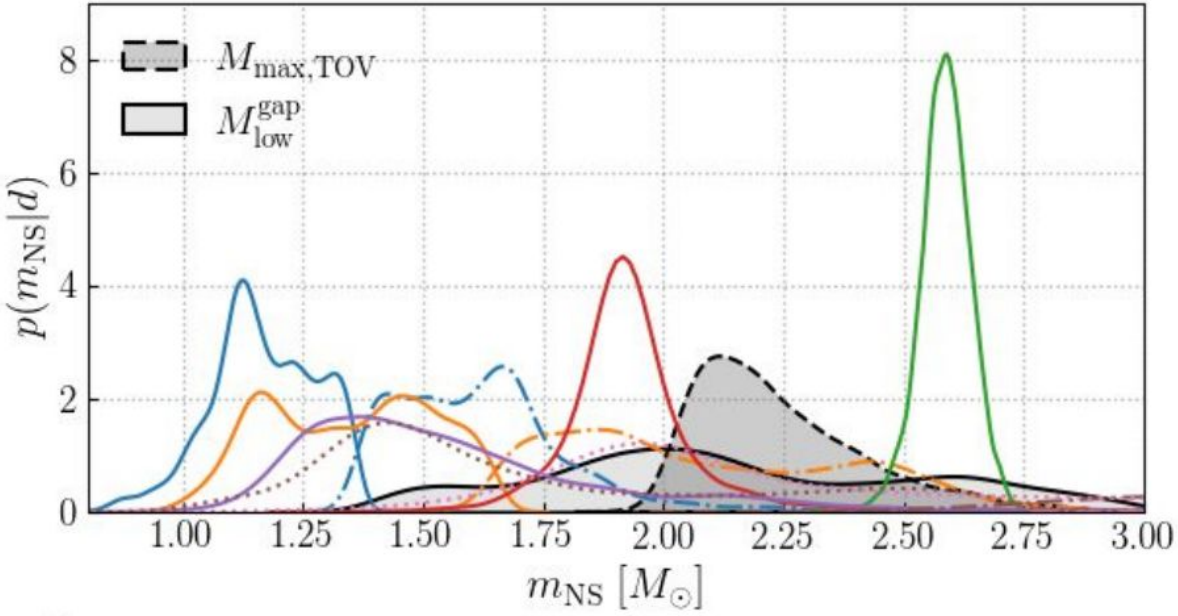
Classifying objects as neutron stars

M_{TOV} is the non-rotating maximum NS mass estimated from current NS equation of state knowledge

M_{low}^{gap} is the inferred lower edge of the mass gap between NSs and BHs

GW190814 is a BBH according to this classification

- Treat low-mass components as NSs if $P(m \le M_{TOV}) > 50\%$
- Obtain same classifications relative to M_{low}^{gap} instead of M_{TOV}



Six NSs in total

GW170817 x 2

GW190425 x 2

GW200105 x 1

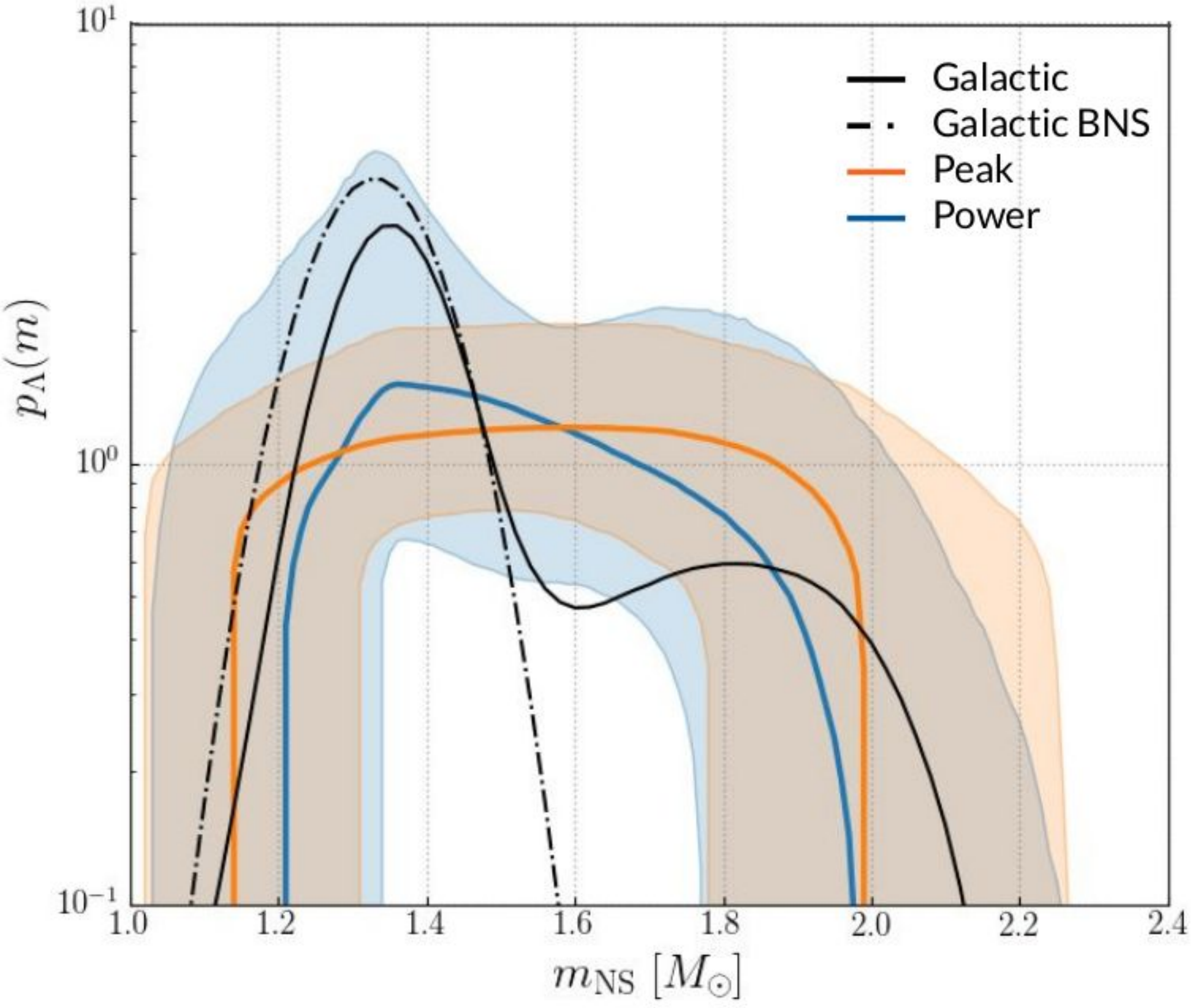
GW200115 x 1

Neutron star mass distribution

Recover broad mass distribution with more support for heavy NSs than Galactic population

Gaussian Peak model does not recover sharp peak at 1.35 $M_\odot$ observed in Galactic BNS population

Power model's exponent $\alpha = -2^{+5}_{-7}$ weakly constrained, but consistent with uniform distribution



Differences w.r.t. the Galactic population: distinct formation channels? Strong selection effects? Overlap of NS and BH mass distributions? Etc.

Evidence for the ‘lower’ mass gap

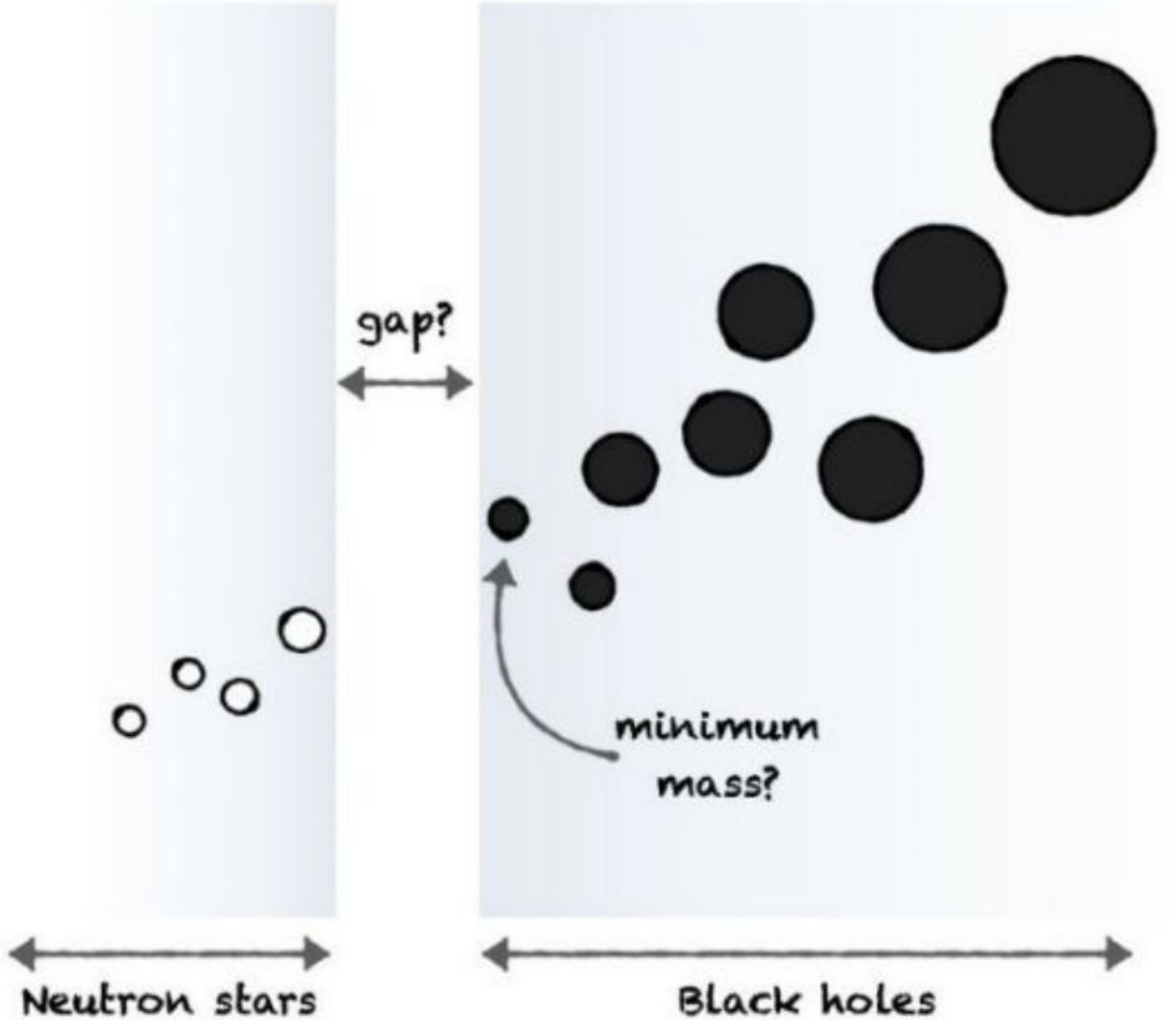
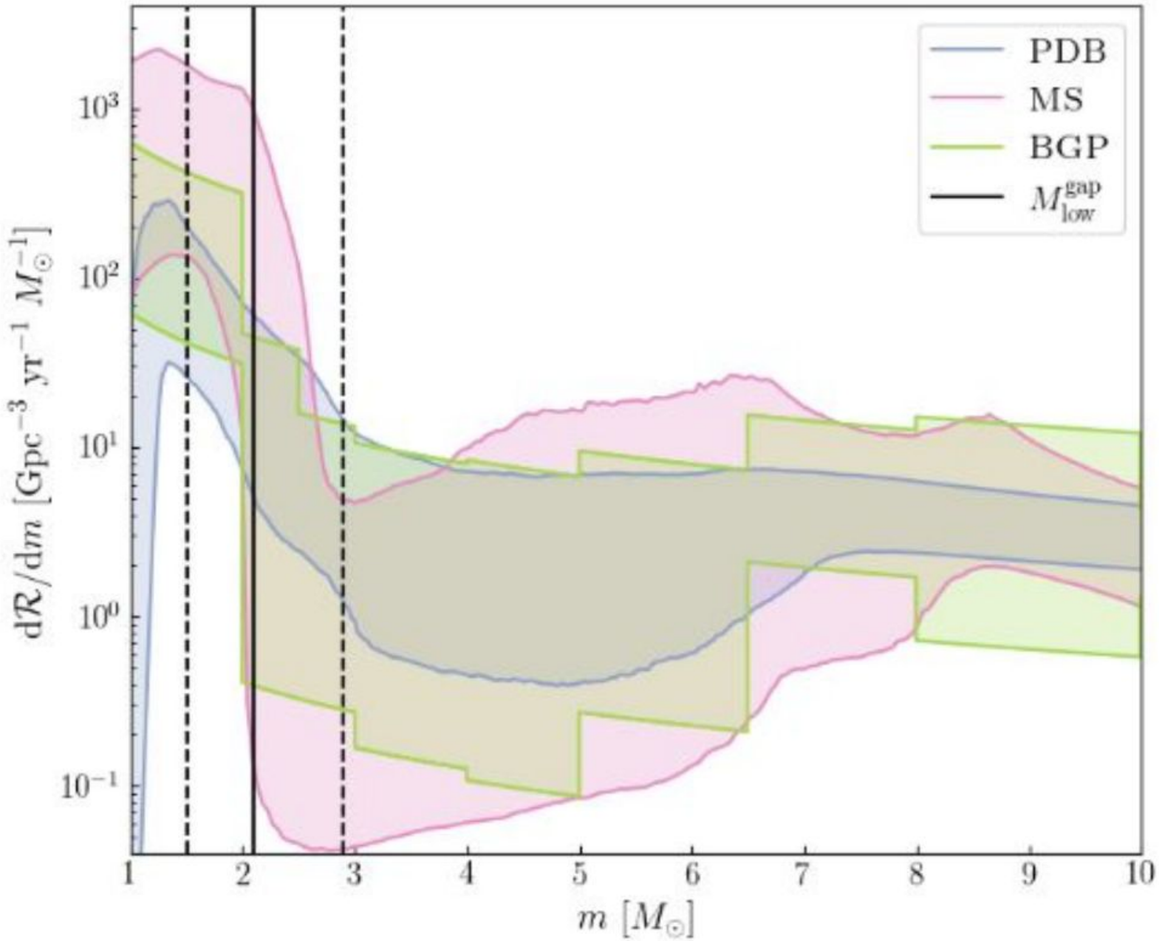


Image Credit: Shanika Galaudage

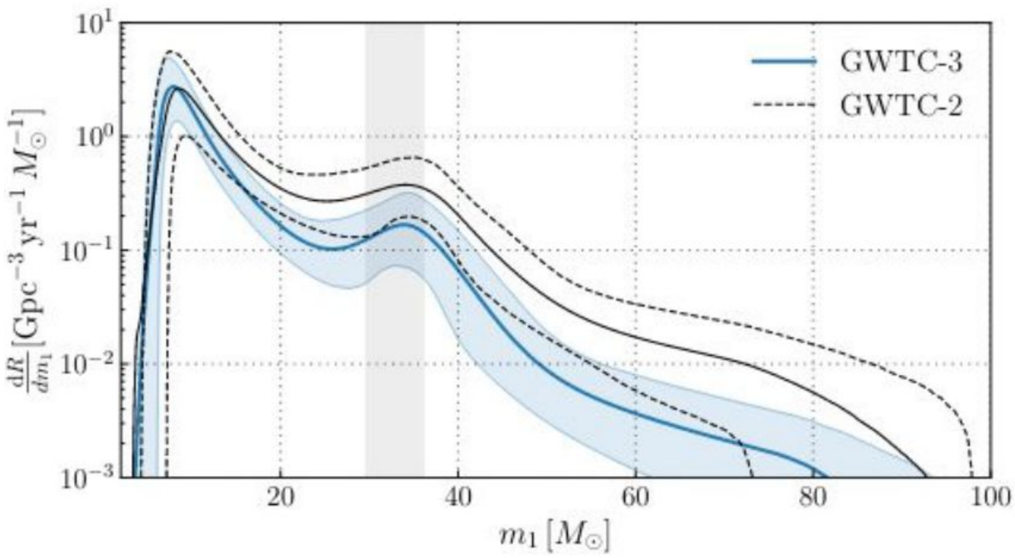
Evidence for the ‘lower’ mass gap

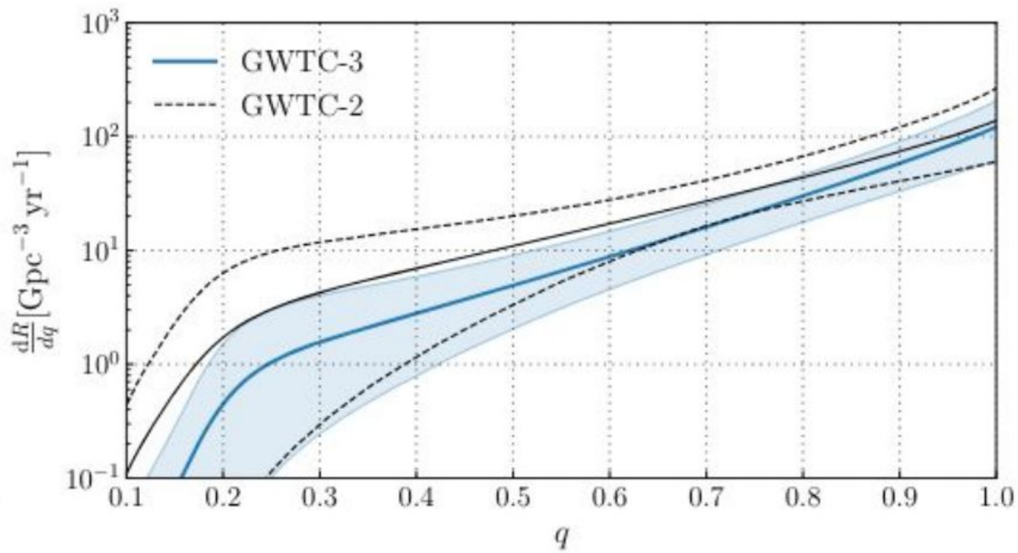
- The joint analyses finds evidence of a sharp drop in the merger rate of compact objects at m~2.4 Msun
- No clear evidence of a rapid rise in merger rate following this to signal the high mass bound of a possible lower mass gap
- Lower gap region IS populated



Population of BBHs in GWTC-3 in comparison to GWTC-2

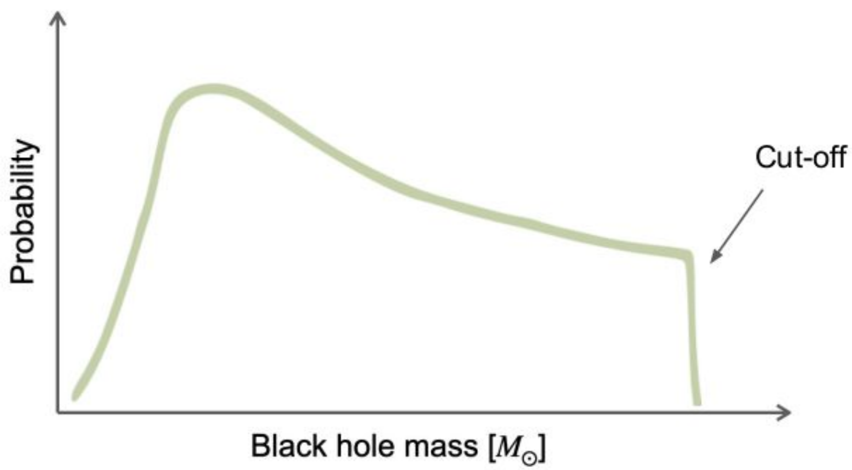
- 69 BBHs allow for the finest resolution in their population properties

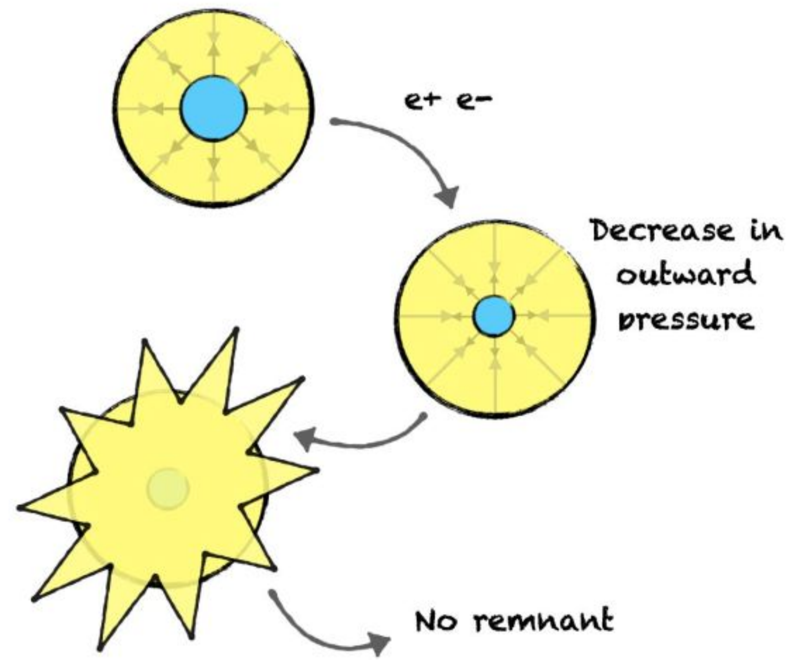




BH mass distribution: high-mass gap

- Very massive stars leave behind no remnant after a supernova.
- No black holes formed beyond a certain mass, suggests a cut-off in the mass distribution

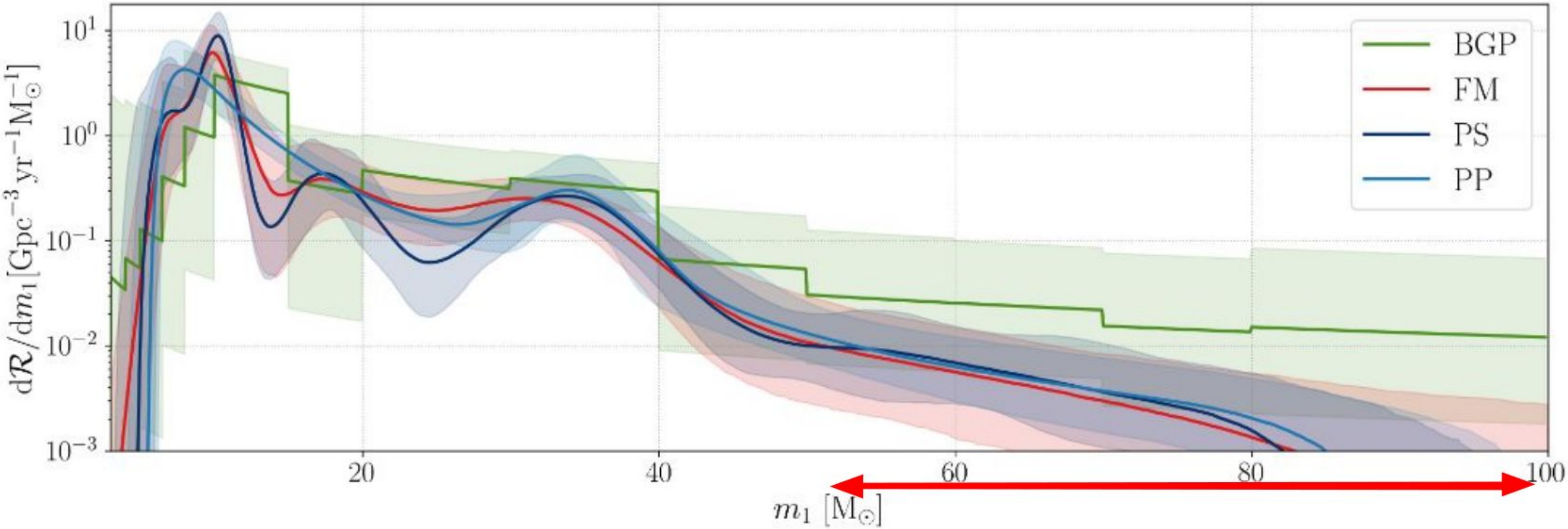




Stars of masses $> 130 M_\odot$ at ZAMS
(ZAMS = Zero Age Main Sequence ~ original mass of star)

Inconclusive evidence for the 'upper' mass gap

- The mass distribution does not exhibit any sharp drop off in merger rate expected at ~45-65 Msun
- Mass gap could start at the maximum mass inferred (~80Msun) or high mass events in catalog could be formed in a way avoiding PISN



- Peaks in the stellar mass region
- Long tail to high masses

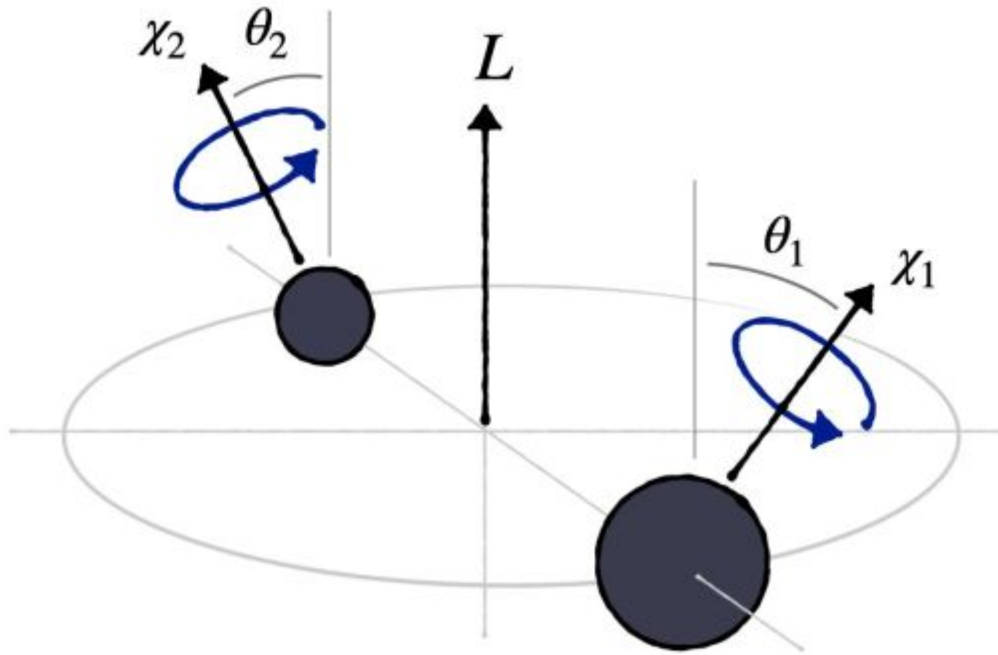
Measurable spin quantities

Effective inspiral spin quantifies total spin parallel to a binary's orbital angular momentum:

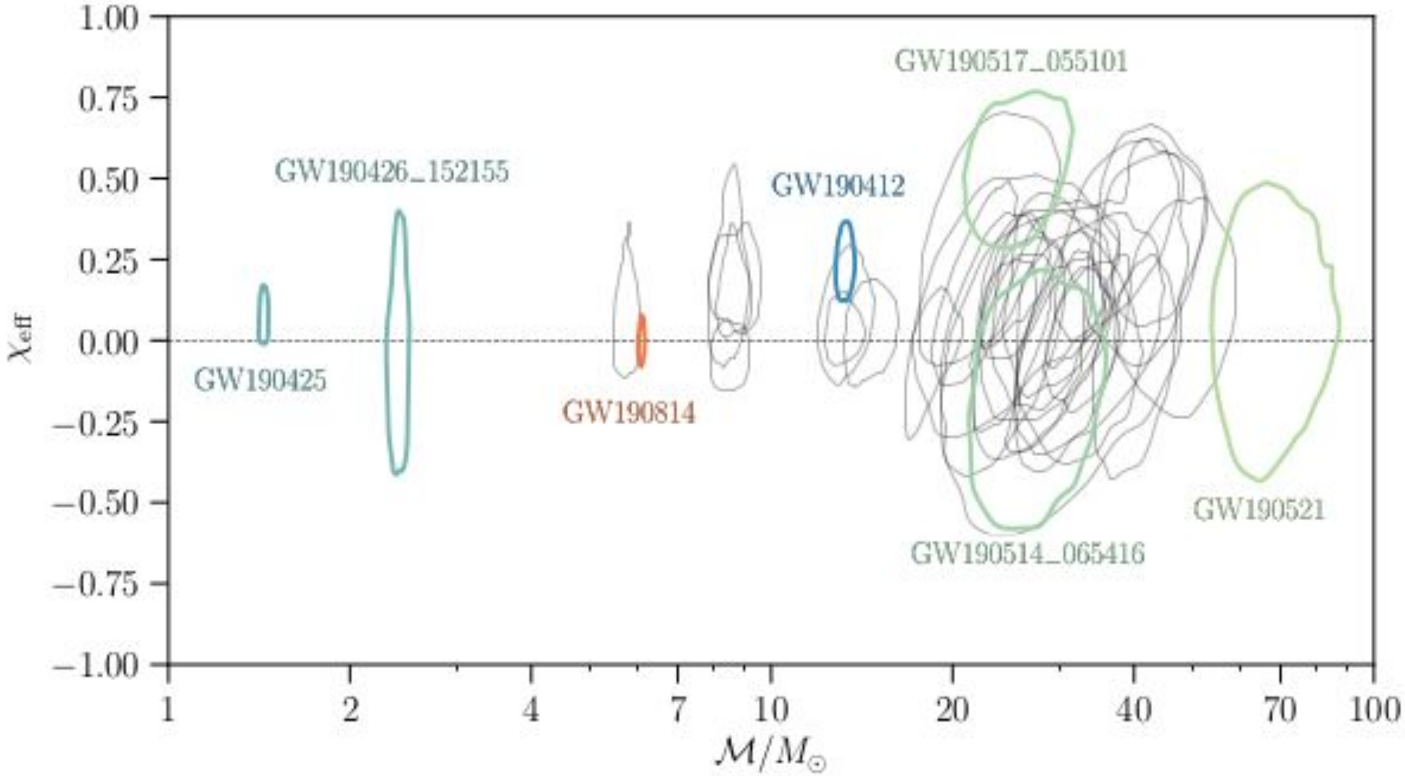
$$\chi_{\mathrm{eff}} = \frac{m_1\,\chi_1 \cos\theta_1 + m_2\,\chi_2 \cos\theta_2}{m_1 + m_2}$$

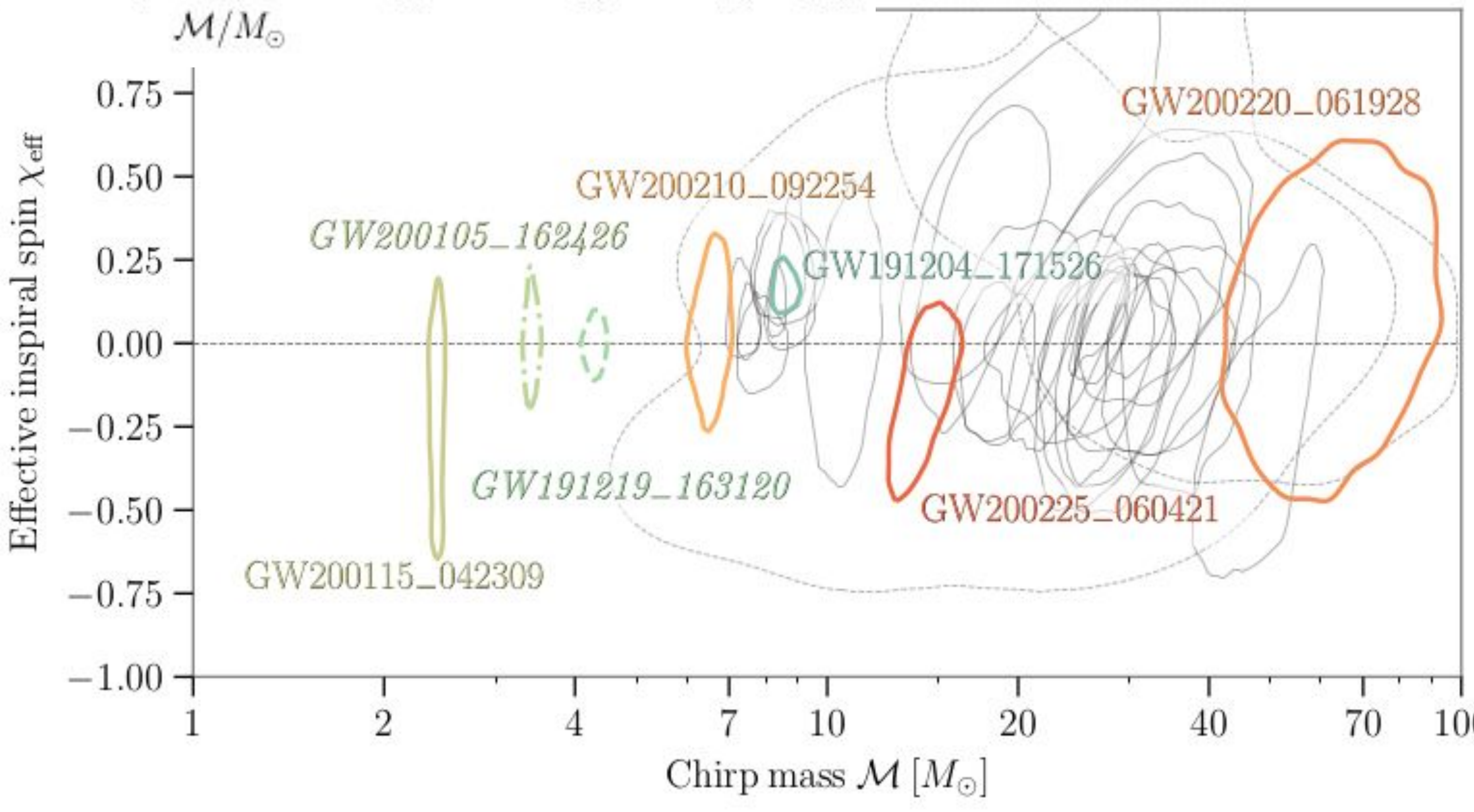
Effective precessing spin is related to degree of spin *perpendicular* to orbit:

$$\chi_{\mathrm{p}} \sim \chi_1 \sin\theta_1$$



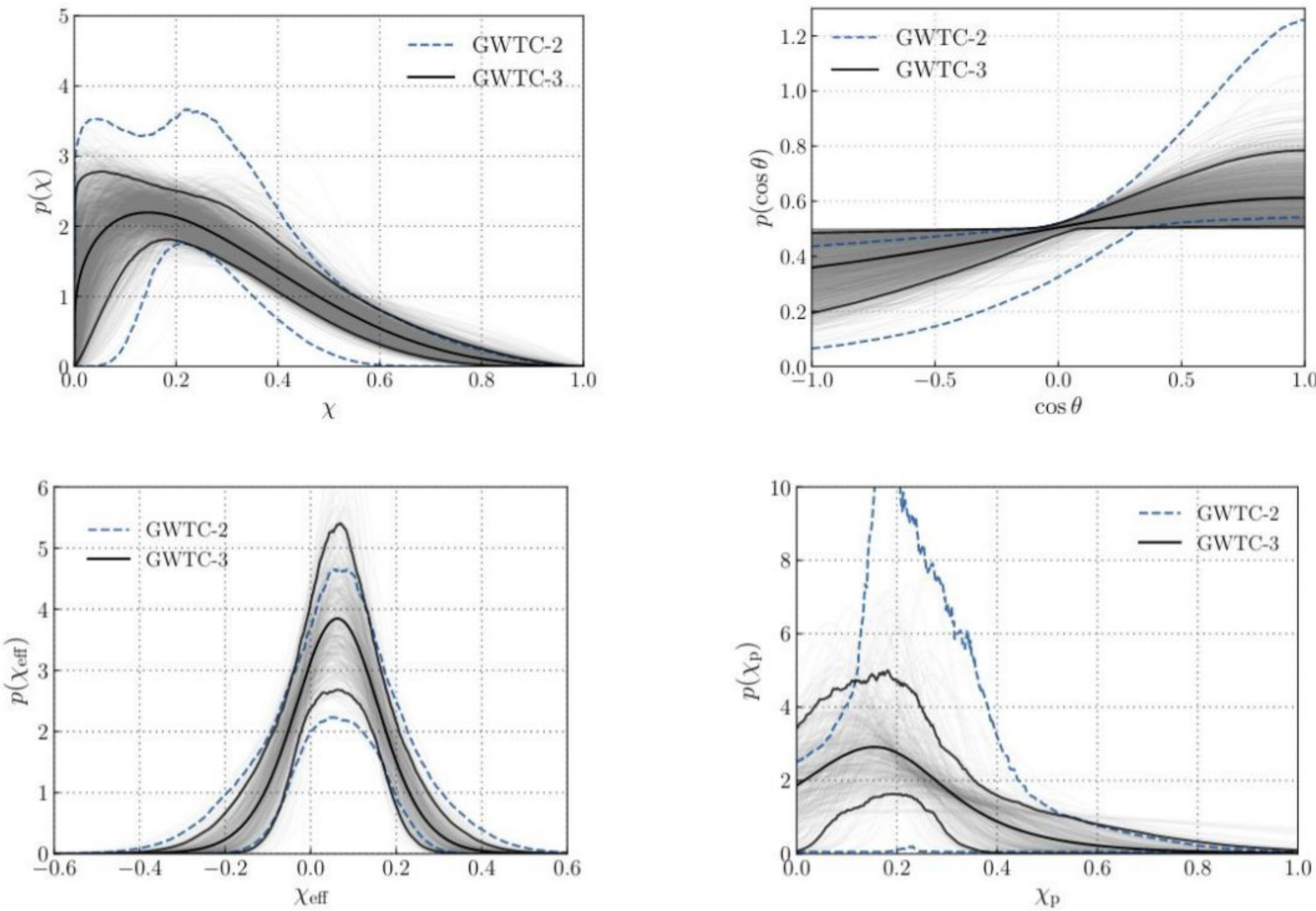
Spins and masses





BBH spin distribution

- Spins can reveal formation mechanisms
- We find support for some misaligned spin in the population
- Now favoring a more isotropic tilt distribution than previous GWTC-2 paper
- Asymmetric chi_eff distribution towards aligned – still non-negligible negative chi_eff in population

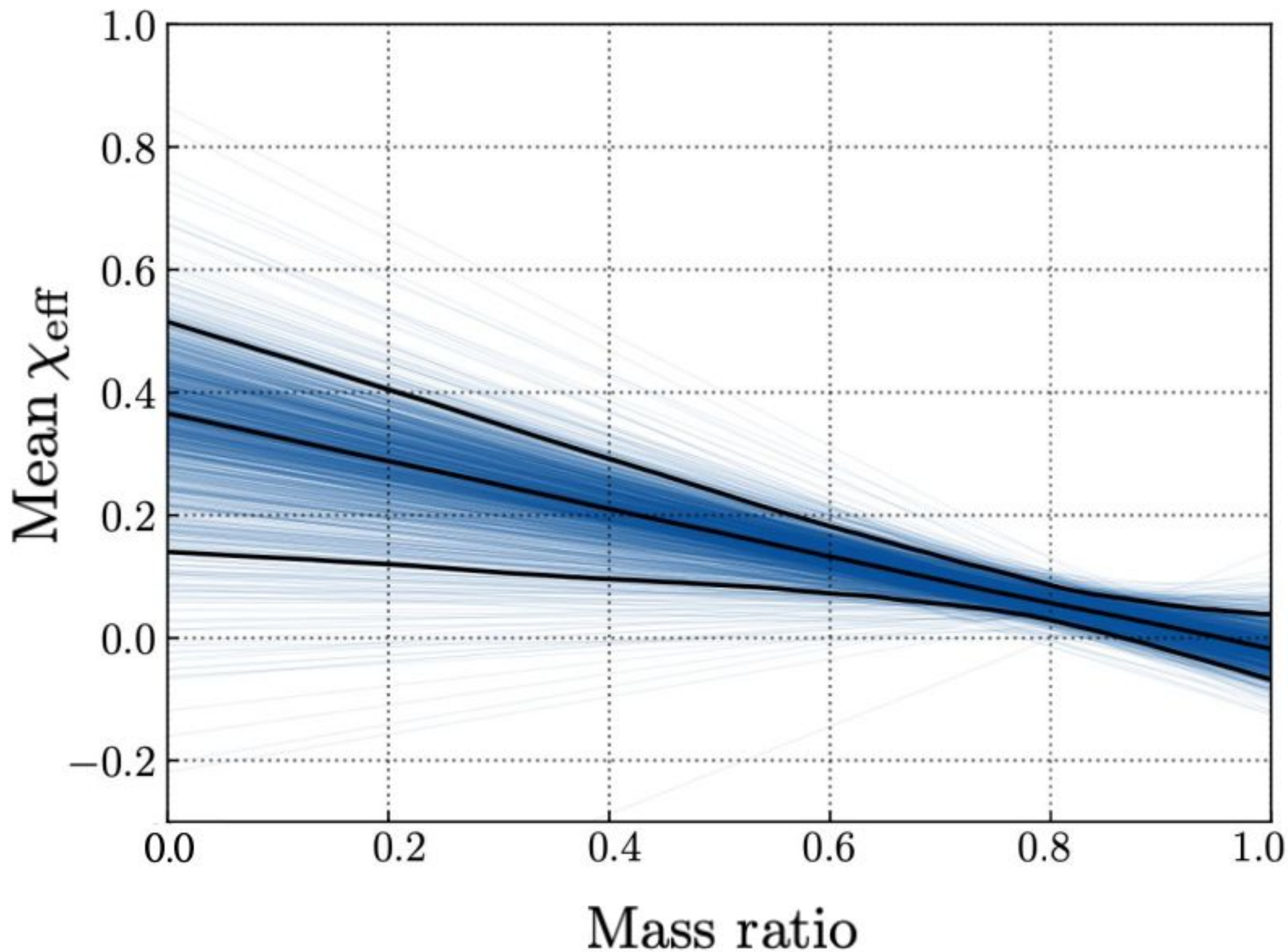


Bottom line: inferred spin distribution has tendency toward small values

Correlations between spin and mass ratio

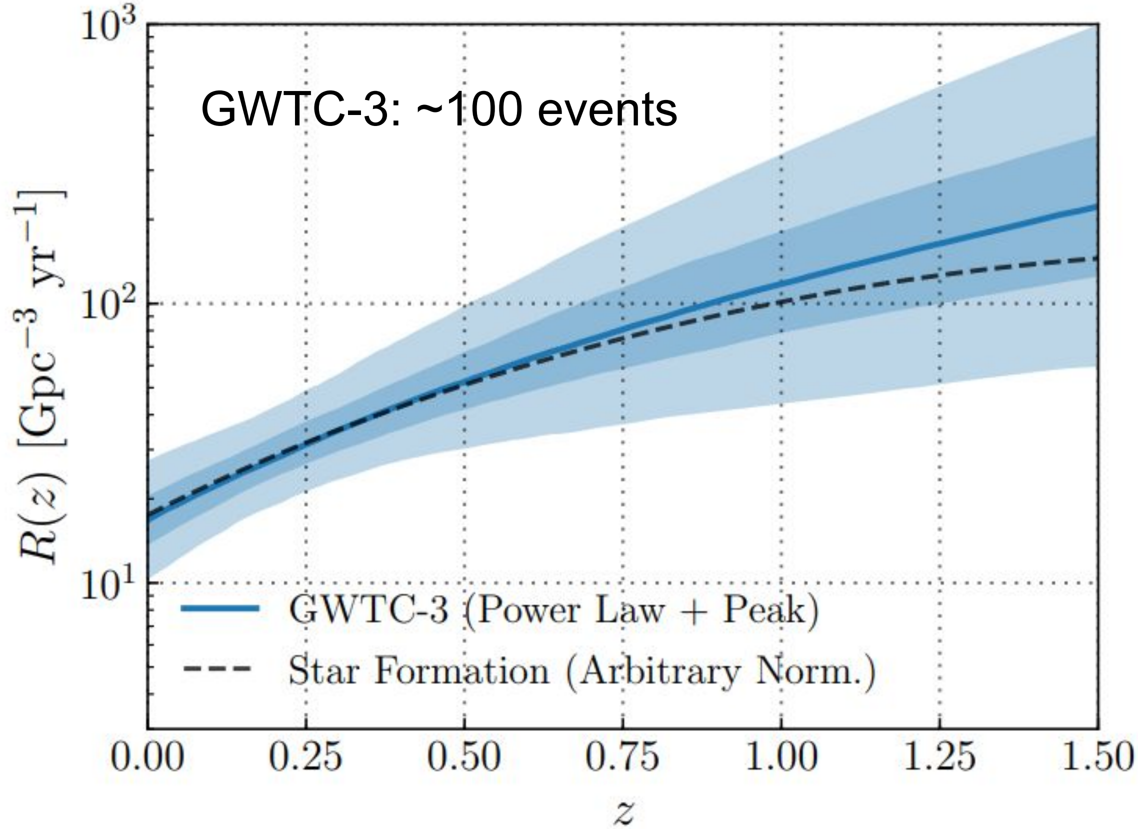
On average, BBHs with more unequal masses have larger effective spins

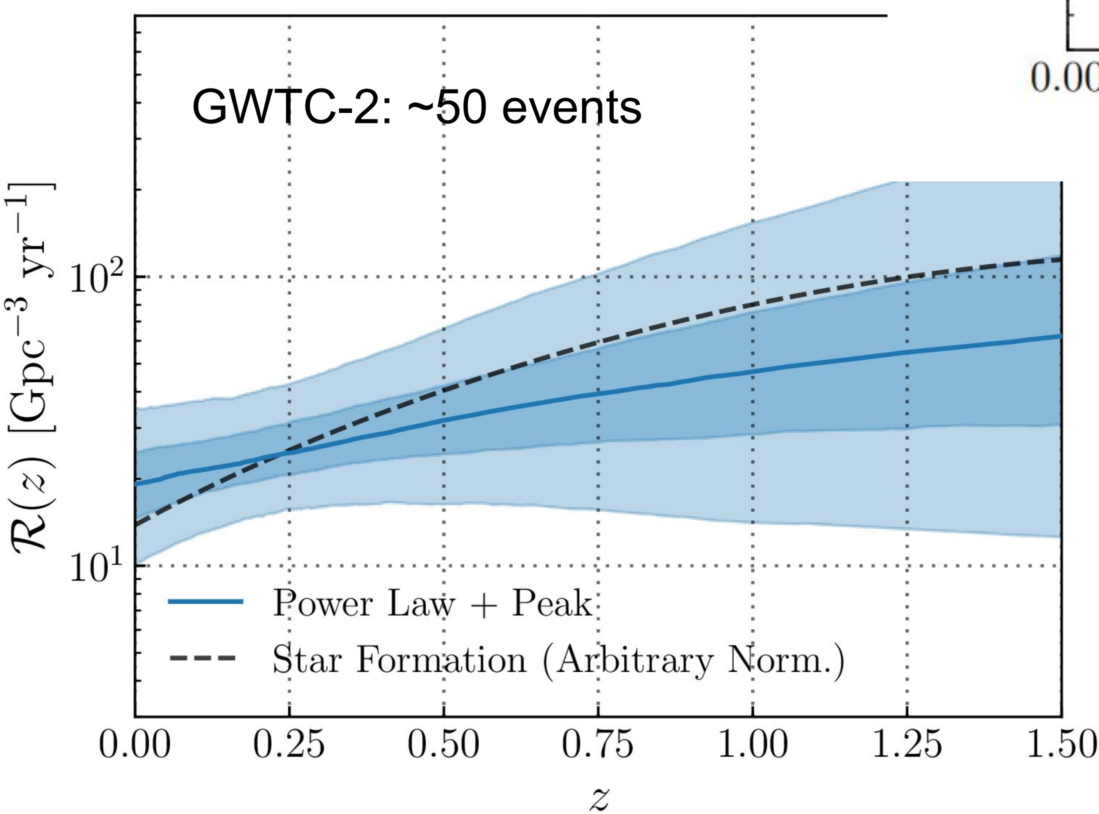
Could signify preferentially larger or more aligned spins with unequal mass ratios

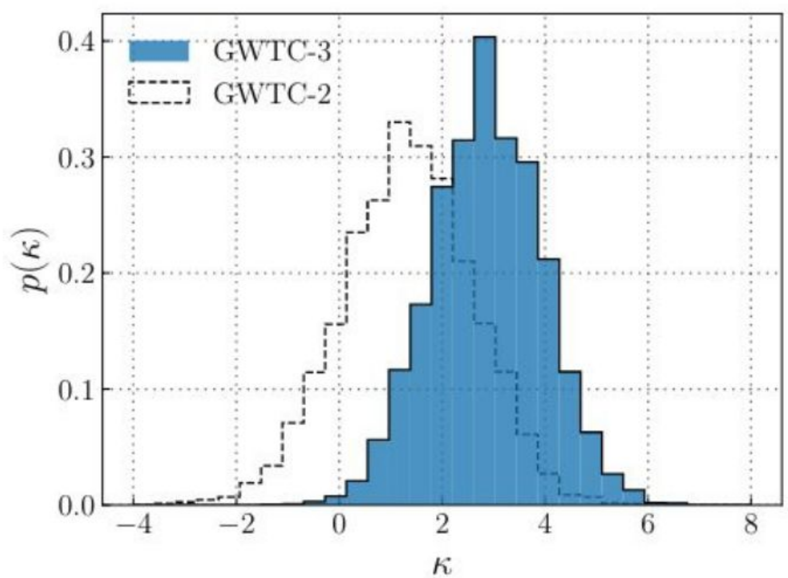


Callister *et al.* 2106.00521

Rates vs redshift







What is their origin?

- Stellar models
  - Binary evolution (field, chemically homogenous, etc.)
  - Cluster evolution (including nuclear clusters)
  - AGN disk model
- Primordial BHs

Isolated binary evolution

- Masses
  - come from stellar evolution
  - mass maximum ~60-70 Msun
- Effective spins
  - should be aligned at least partially
  - Small or large?
- Rates
  - Should follow SFR

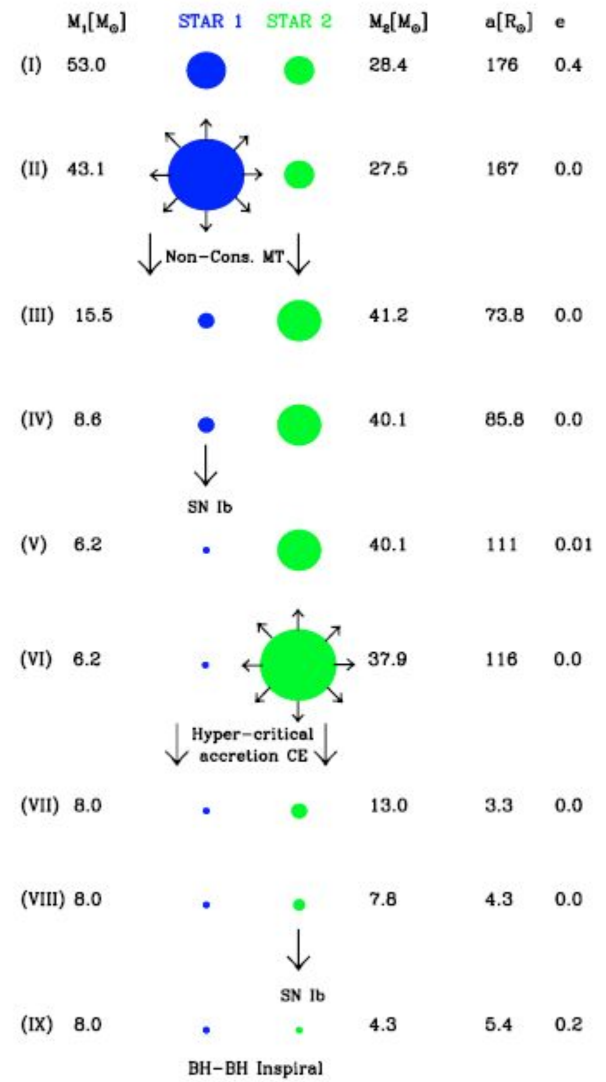
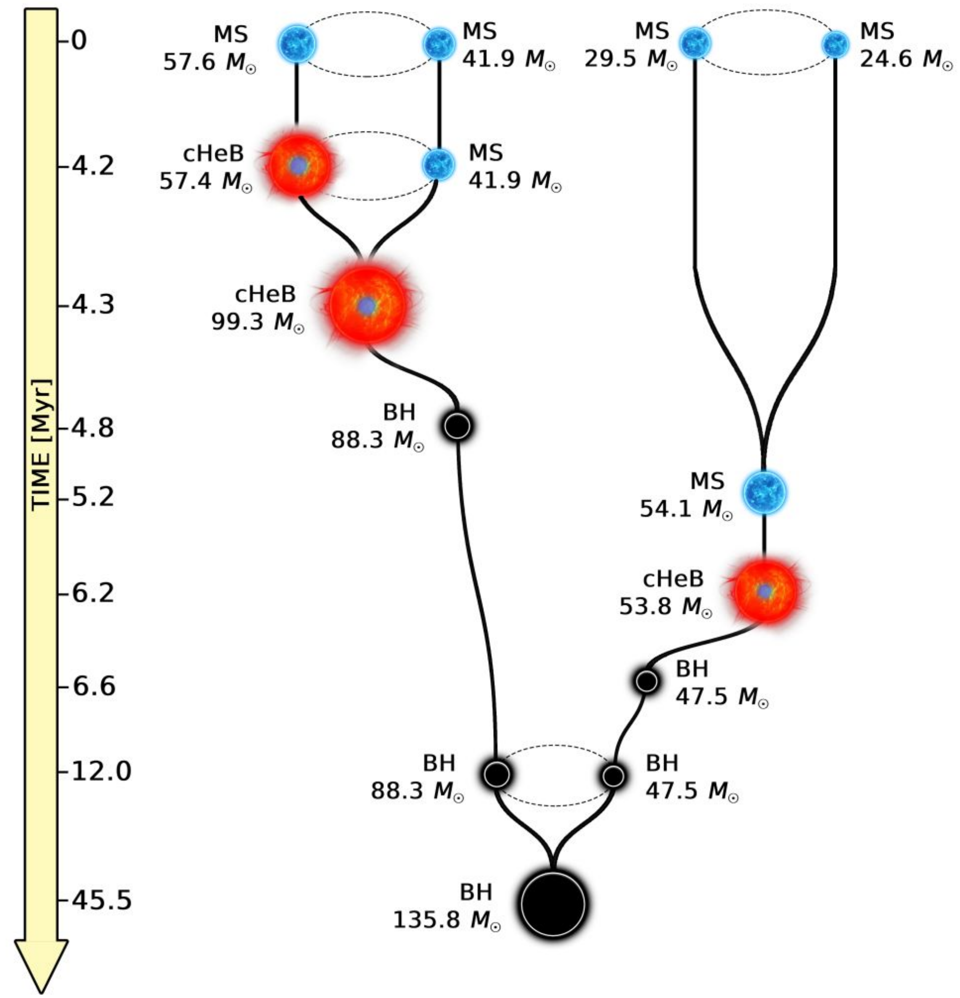


Fig. 1. An example evolutionary scenario leading to formation of a double black hole binary. For details see the text.

Cluster evolution

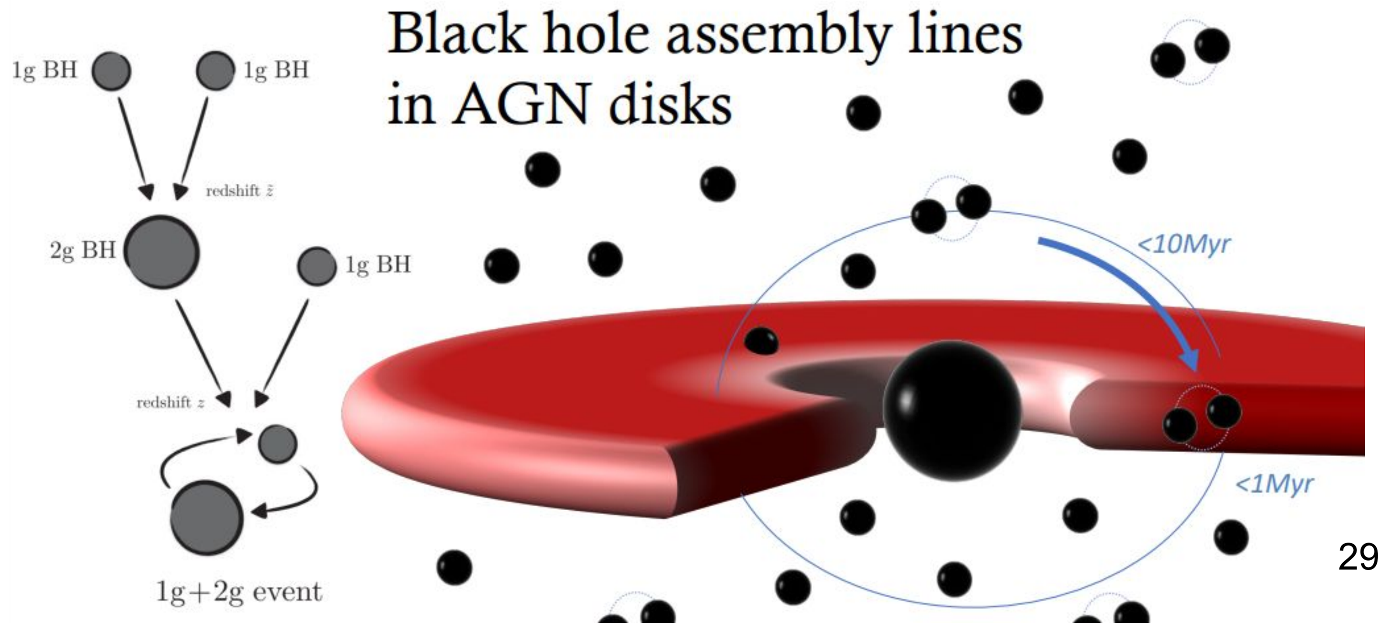
- Masses
  - Can be much larger (hierarchical mergers)
- Spins
  - Random – not aligned
  - Small, large (2nd generation)
- Rates
  - Should peak at higher redshift (peak of GC formation)



Mapelli, 21

AGN disk model

- BH born in stellar evolution
- BBH formed in multi-body interaction in AGN disks – similar to planet formation
- Mergers in disk - possible EM emission (GW190521)?
- Spins isotropic
- Rate - small?

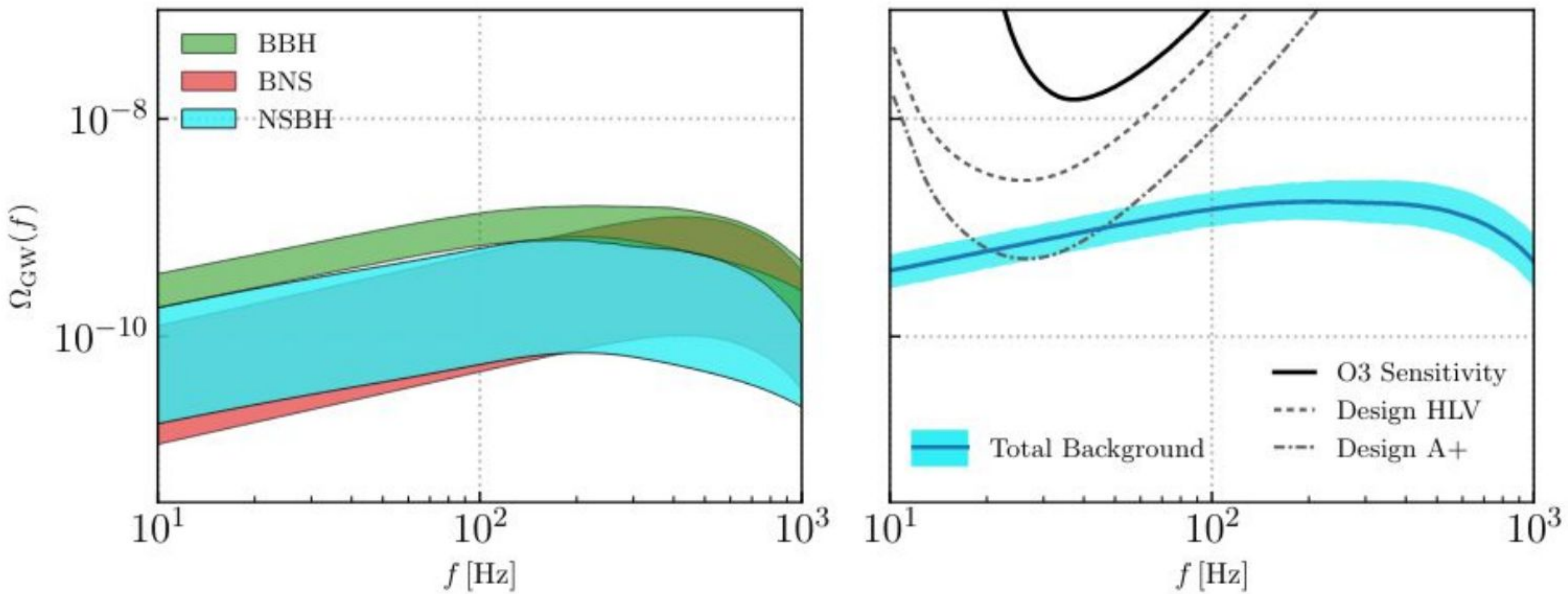


Primordial binaries

- Masses
  - Correspond to phase transitions in the Early universe (can be any mass)
- Spins
  - Random, small (?)
- Rates
  - Do not have to follow SFR

Detecting the BBH background

- Given inferred astrophysical populations we can make projections for what the astrophysical contribution to the stochastic background



Stochastic GW background is usually described as energy density per logarithmic frequency interval with respect to the closure density of the universe ($\rho_c = \frac{3c^2 H_0^2}{8\pi G} \approx 7.6 \times 10^{-9}$ erg/cm^3):

$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}.$$

GW event rates

- BHBH production efficiency:
  - Number of merging BBH per unit mass
- Delay times
- Mass distribution
  - Intrinsic vs observed: range and redshift effects
- Rate density: local and as a function of redshift

Basic rate arguments

- Formation scenario must be generic
- Exceptional environments must produce BBH and BNS with very high efficiency
- Dense regions are not favoured, but do contribute
- How important are exotic models?

Binary evolution

- Masses – we see too heavy BHs
- Spins
  - small and positive
  - are small spins a problem?
    - BH spins measured in accreting binaries are large
    - But: small spins of young pulsars
- Rates increase with z

Cluster evolution

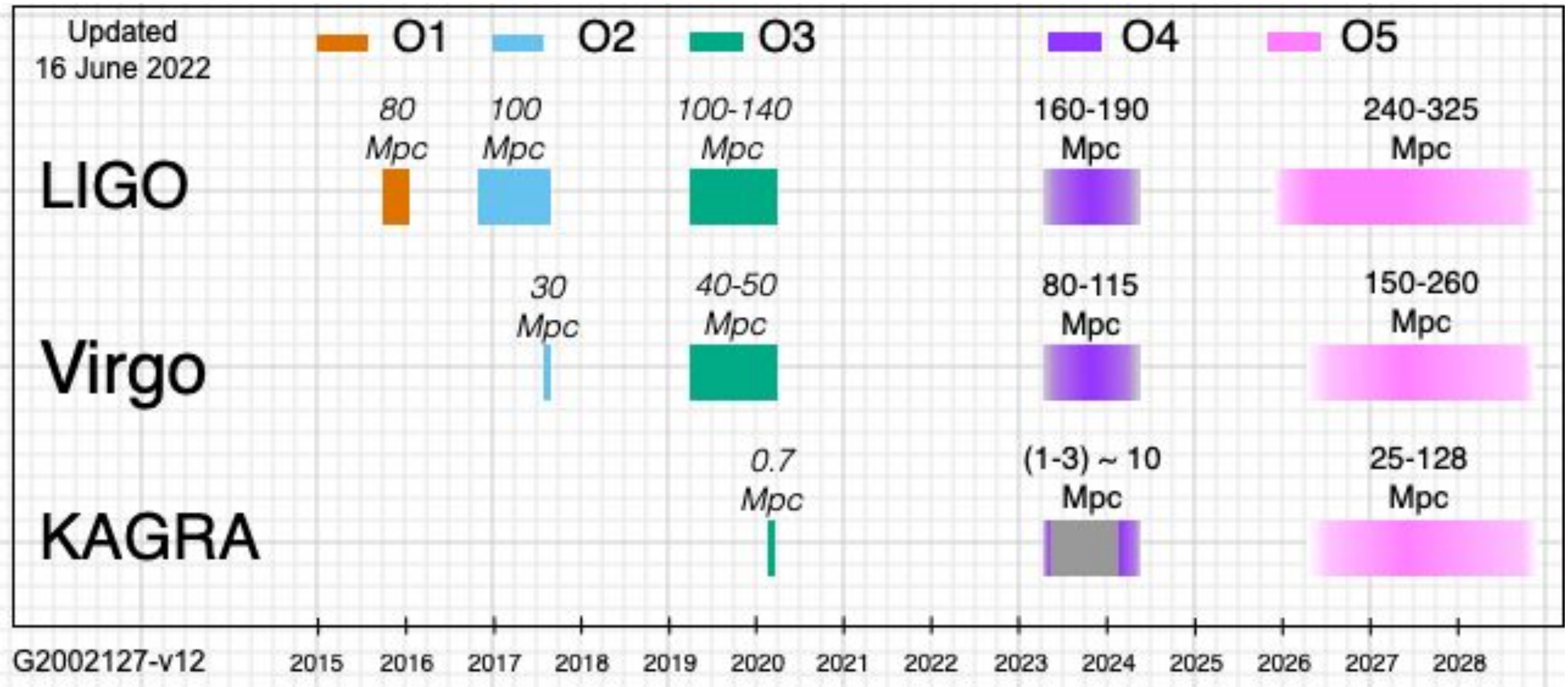
- Masses: clearly extend above PPSN gap
- Components' spins:
  - why positive? Consistent with an isotropic subpopulation
  - In hierarchical mergers should be ~0.7
- Rates:
  - Increase with z, but follow SFR
  - Is there a peak at z=2-3?

How does it look so far

Model	Masses	Spins	Rates
Binary			
Cluster			
Primordial/exotic			

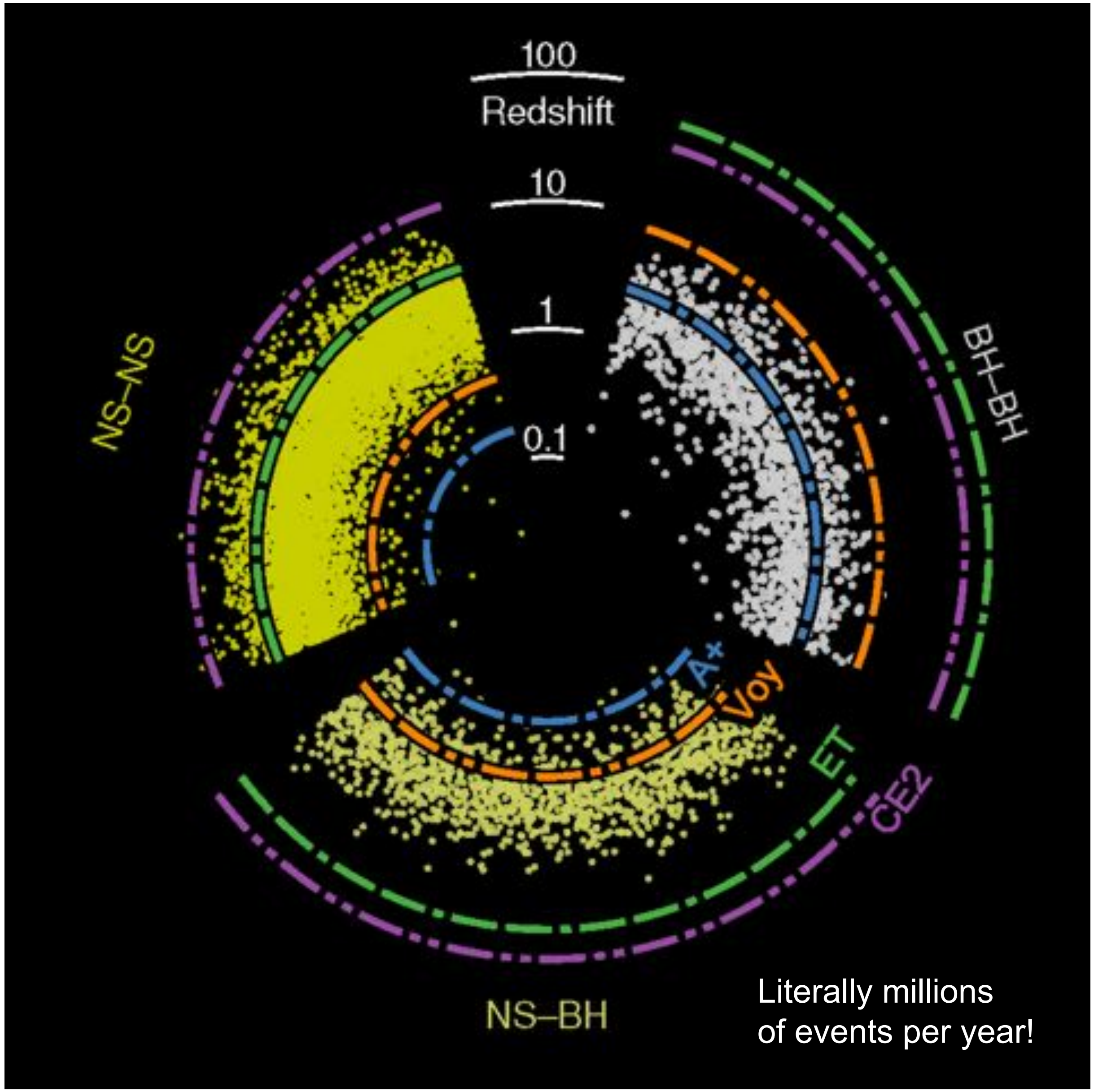
Do we need more than one scenario to explain observations?

What’s next

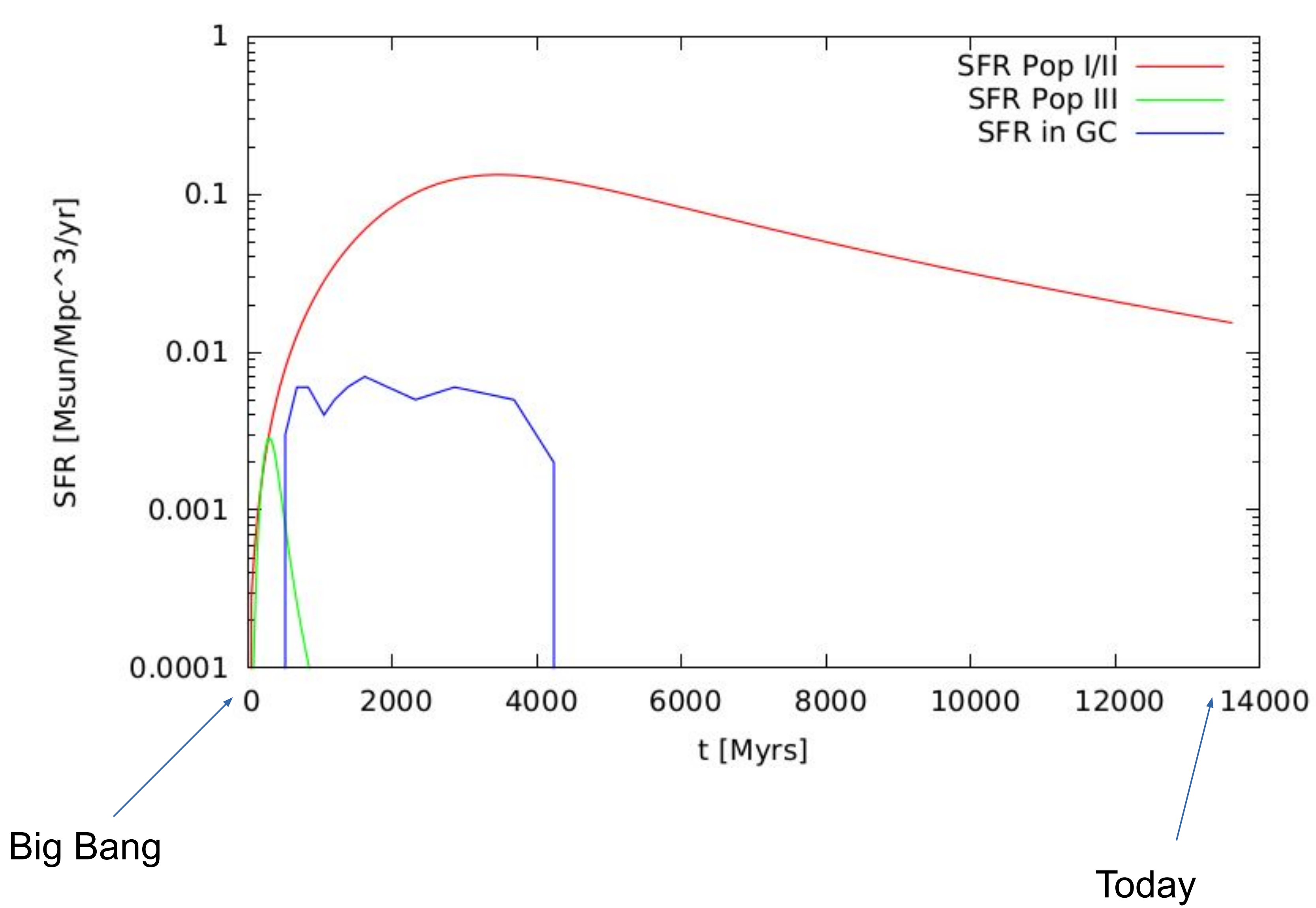


Einstein Telescope and Cosmic Explorer needed!

3rd gen detectors: Einstein Telescope (ET), Cosmic Explorer (CE)



SFR


1
0.1
0.01
0.001
0.0001
SFR [Msun/Mpc^3/yr]
0
2000
4000
6000
8000
10000
12000
14000
t [Myrs]
SFR Pop I/II
SFR Pop III
SFR in GC
Big Bang
Today

Compact object masses

- Neutron star 1.0-2.0(2.5?) Msun
- First mass gap 2.0(2.5?)~5.0 Msun
- Black holes ~5-and up Msun
- Second mass gap 65?~130? Msun