PASCOS 2022, 27th International Symposium on Particles, Strings and Cosmology

Gravitational-wave observations and populations of binary compact objects

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LIGO VIRGO

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ET EINSTEIN TELESCOPE

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No War

MPIK, Heidelberg, 25 – 29 July 2022

OUTLINE:

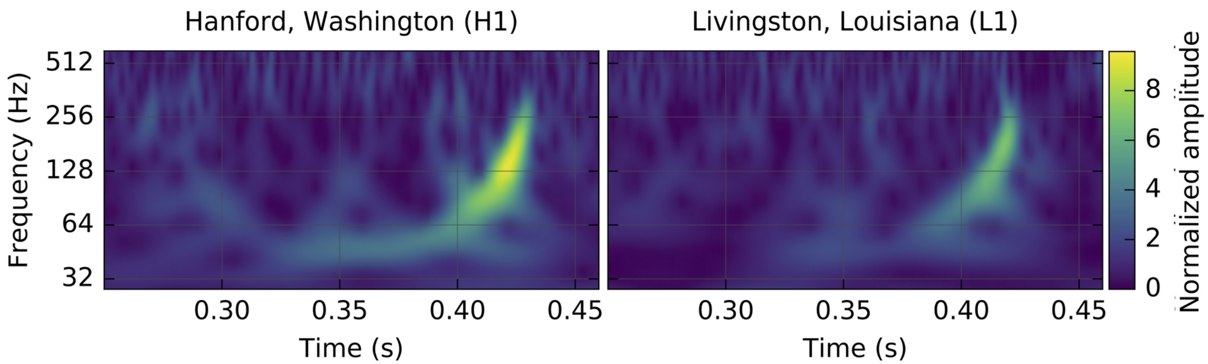
1. LIGO - Virgo binary compact objects

2. Populations of binary compact objects:
   isolated binary evolution vs dynamical

3. Conclusions: next generation
   gravitational wave detectors

1. LIGO – Virgo binary compact objects

GW150914: the first binary black hole (BBH)

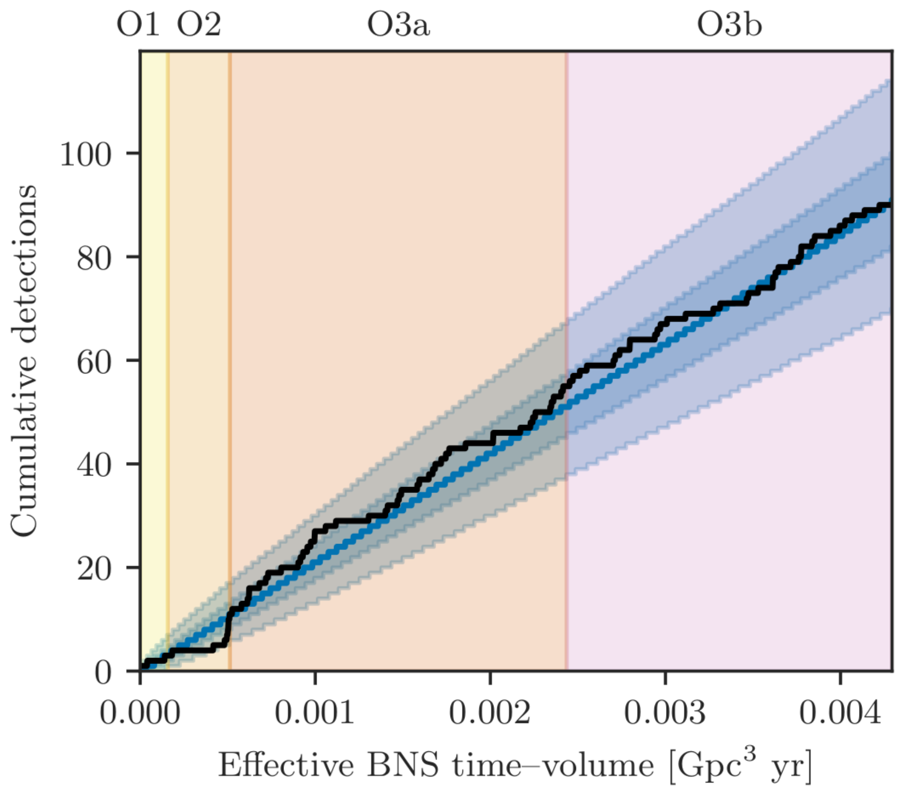


Abbott et al. 2016, PhRvL, 116, 1102

3 observing runs (O1, O2, O3):

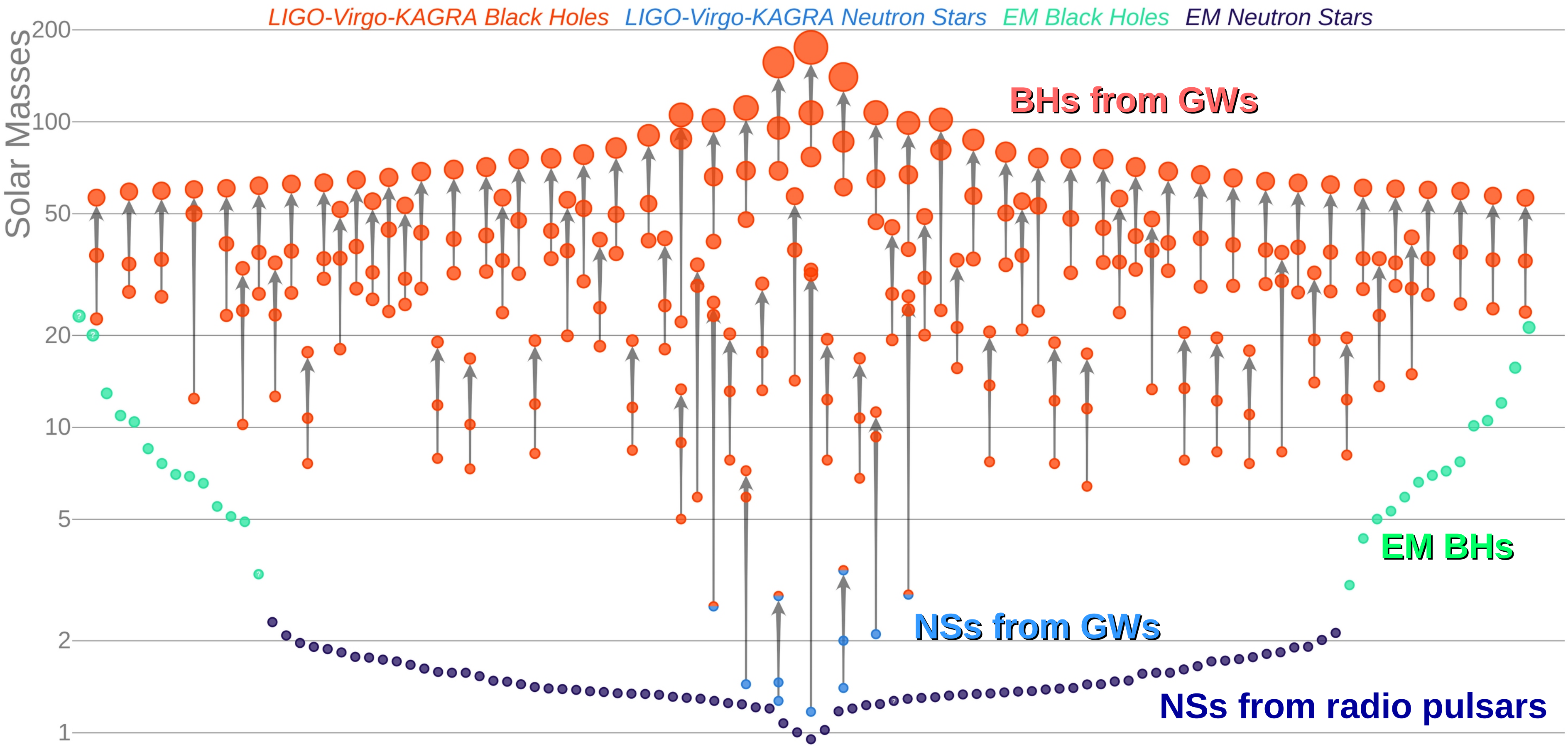
90 GW event candidates
most of them BBHs

(Abbott et al. 2021, GWTC-2;
Abbott et al. 2022, GWTC-2.1;
Abbott et al. 2022, GWTC-3)



1. LIGO – Virgo binary compact objects

Abbott et al. 2022, GWTC-3; credit: LIGO-Virgo-KAGRA | A. Geller | Northwestern



Before LIGO – Virgo:

* No BBHs known

* A dozen stellar-origin BHs with dynamical mass measure

* No stellar-origin BHs with mass >20 M⊙

Now:

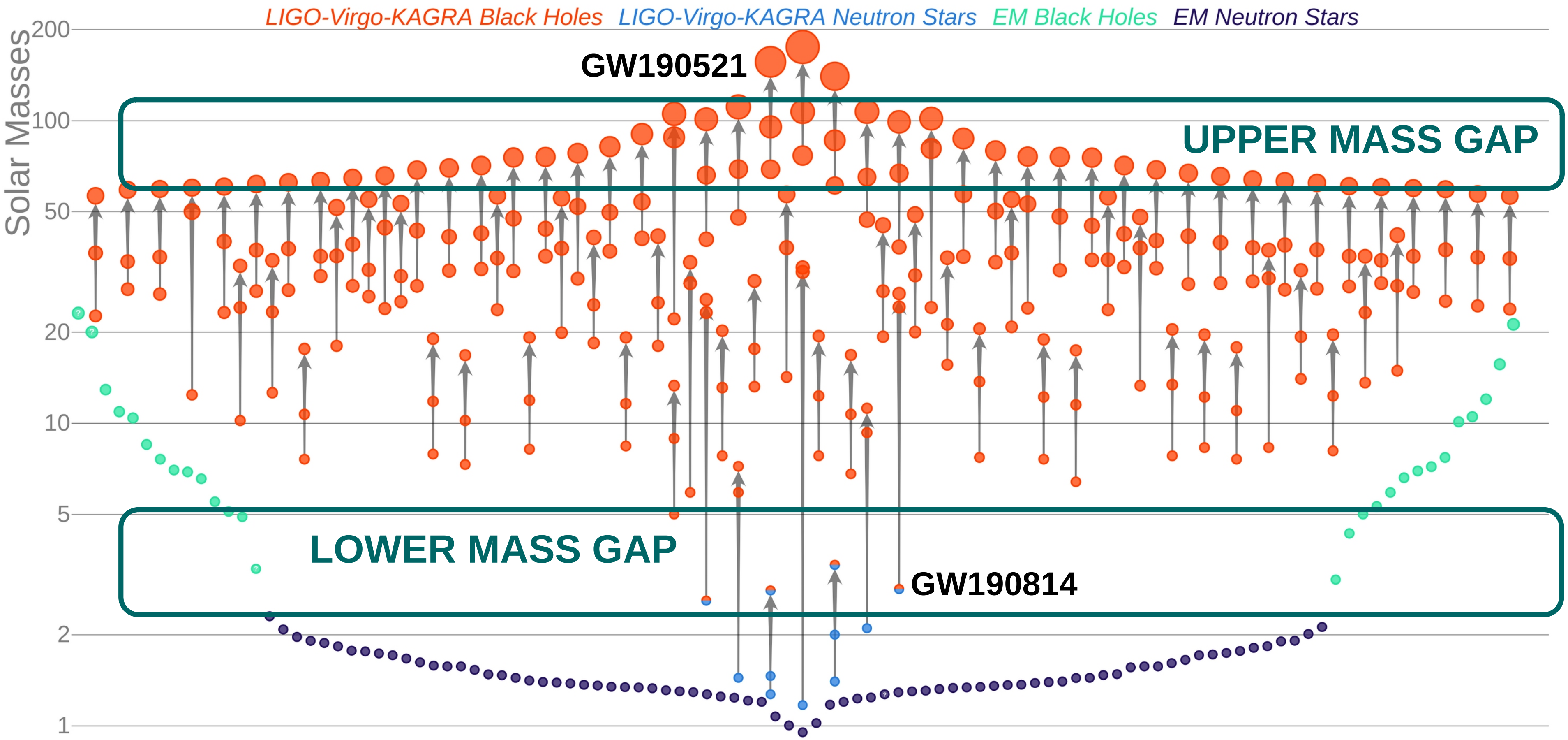
* 85 BBHs from gravitational waves

* 3 BH – neutron star candidates

* BH masses in the range ~ 3 – 200 M⊙

1. LIGO – Virgo binary compact objects

Abbott et al. 2022, GWTC-3; credit: LIGO-Virgo-KAGRA | A. Geller | Northwestern



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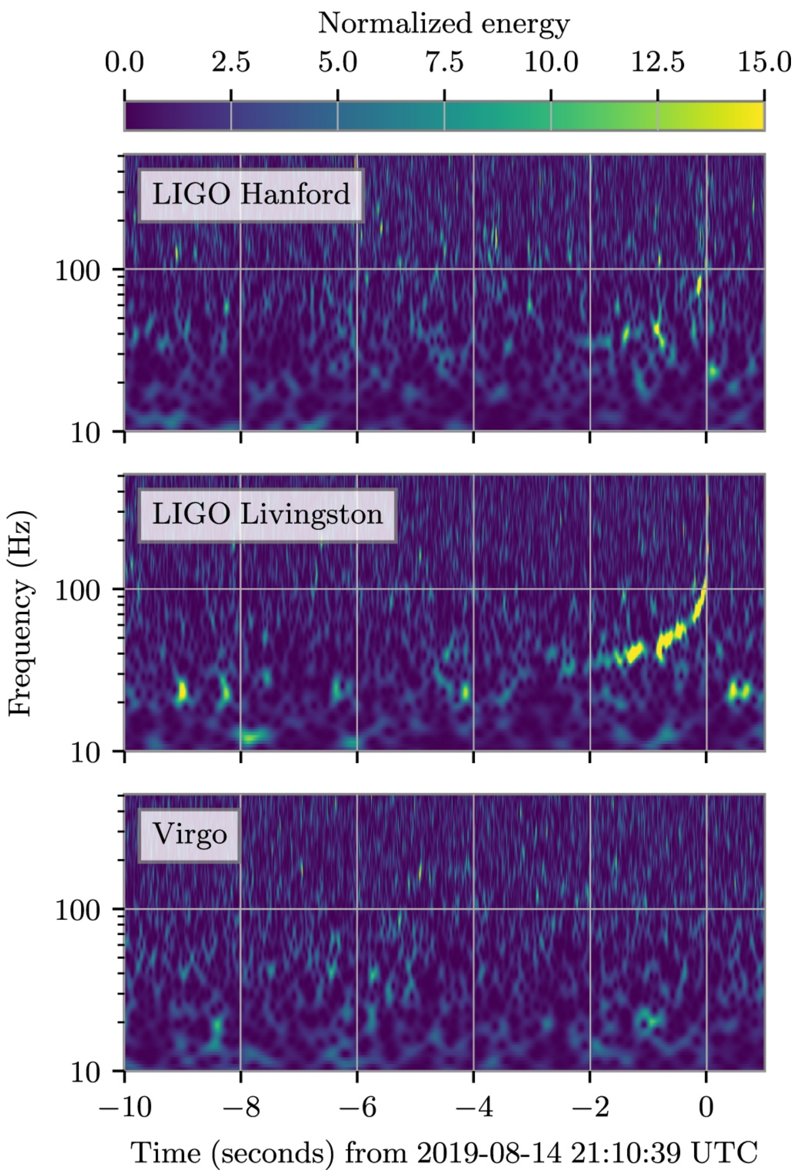
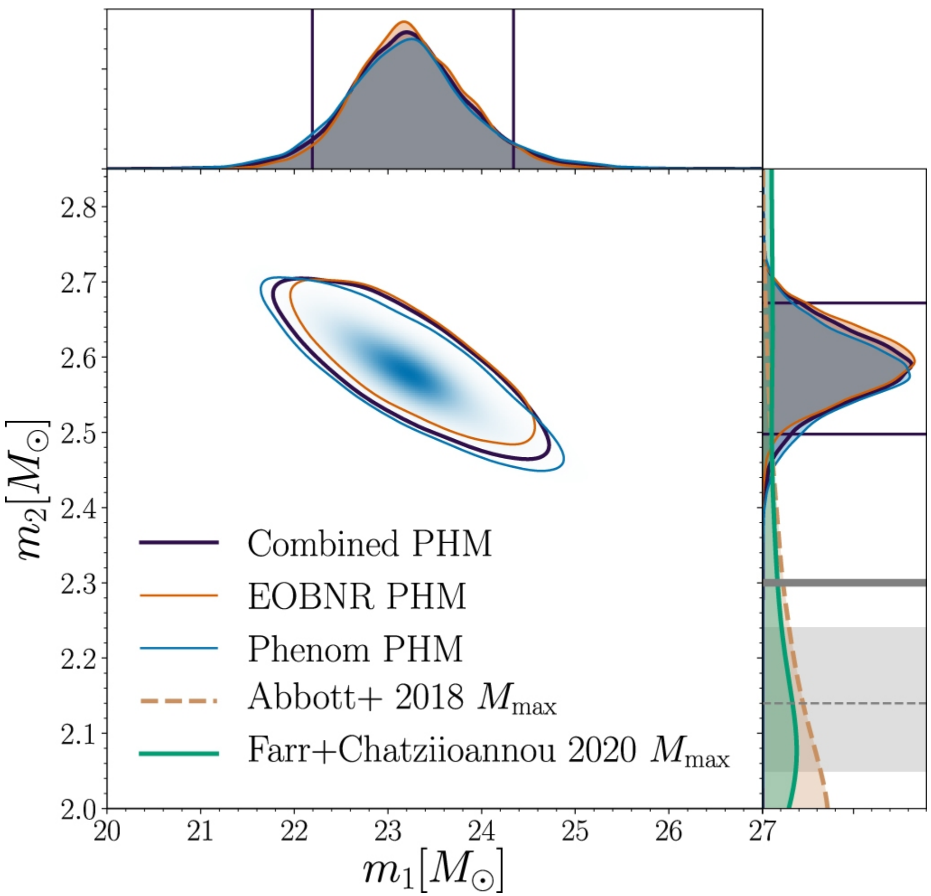
1. LIGO – Virgo binary compact objects: GW190814



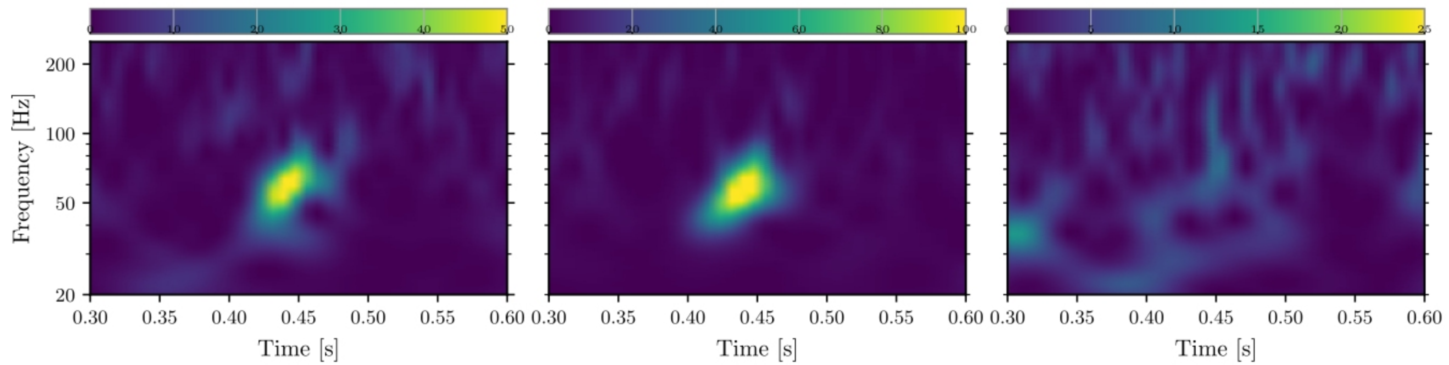


Secondary mass in the lower mass gap
Neutron star or black hole?
Mass ratio ~0.1

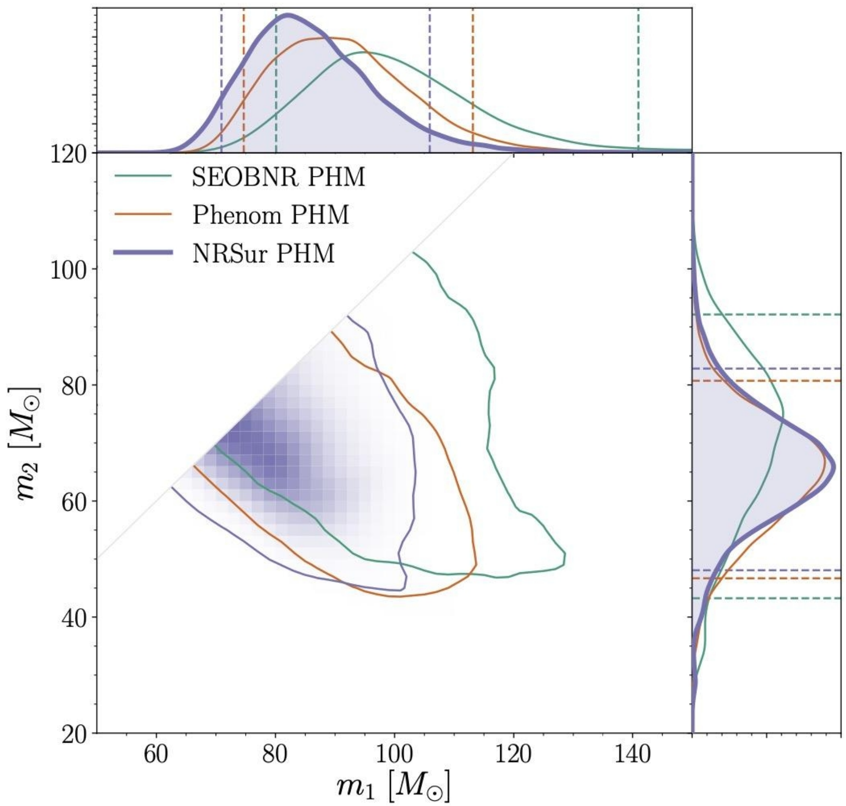
Abbott et al. 2020, GW190814

1. LIGO – Virgo binary compact objects: GW190521

Normalized energy



LIGO Livingstone LIGO Hanford Virgo



Remnant mass ~ 140 Msun
First intermediate-mass black hole with gravitational waves

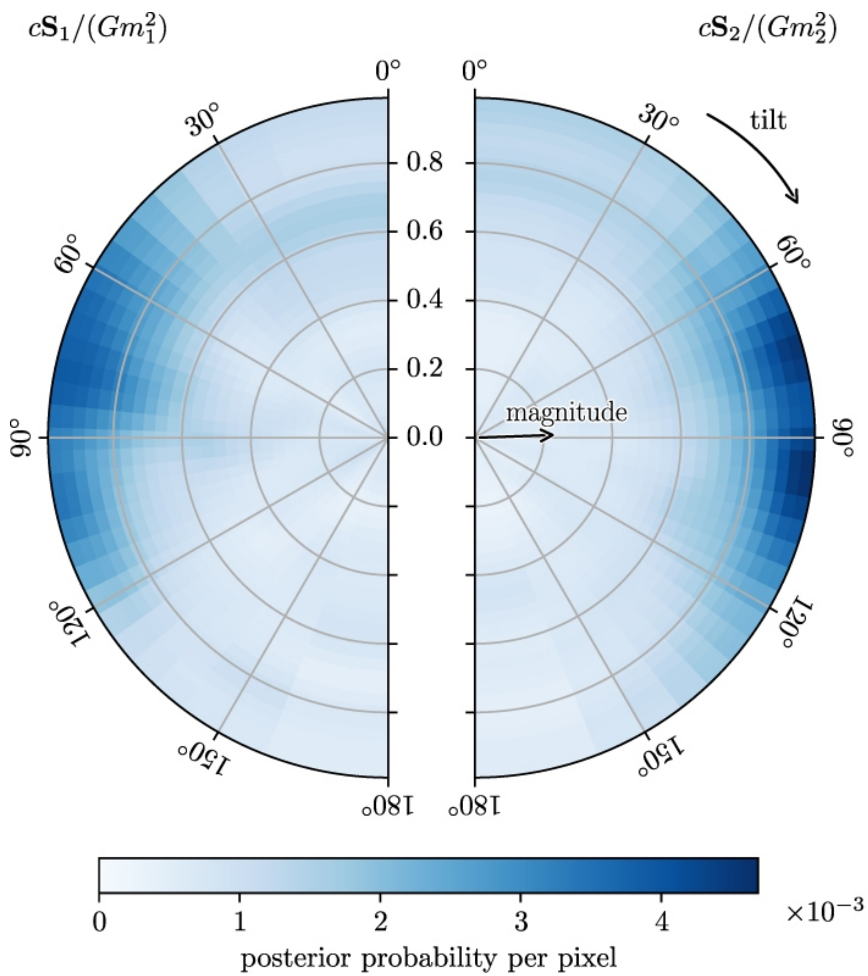
Primary mass ~ 85 Msun
First black hole in the pair-instability mass gap

$$m_1 = 85^{+21}_{-14} M_\odot \qquad m_2 = 66^{+17}_{-18} M_\odot$$

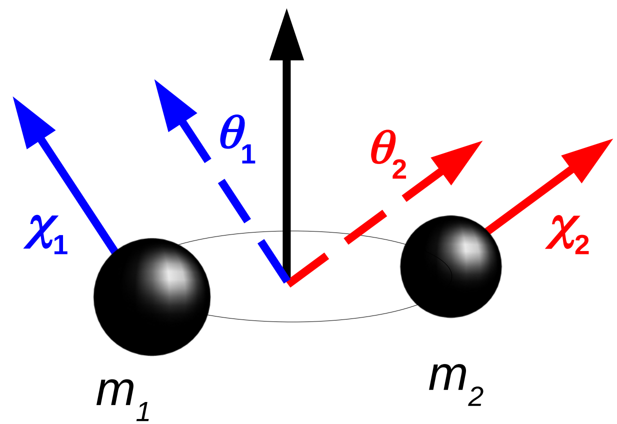
Abbott et al. 2020, detection paper

Abbott et al. 2020, astrophysical implications

1. LIGO – Virgo binary compact objects: GW190521



Mild evidence for
large spins
nearly in the orbital plane



$$\chi = c\,\mathbf{S}_1 / (G\, m_1^2)$$

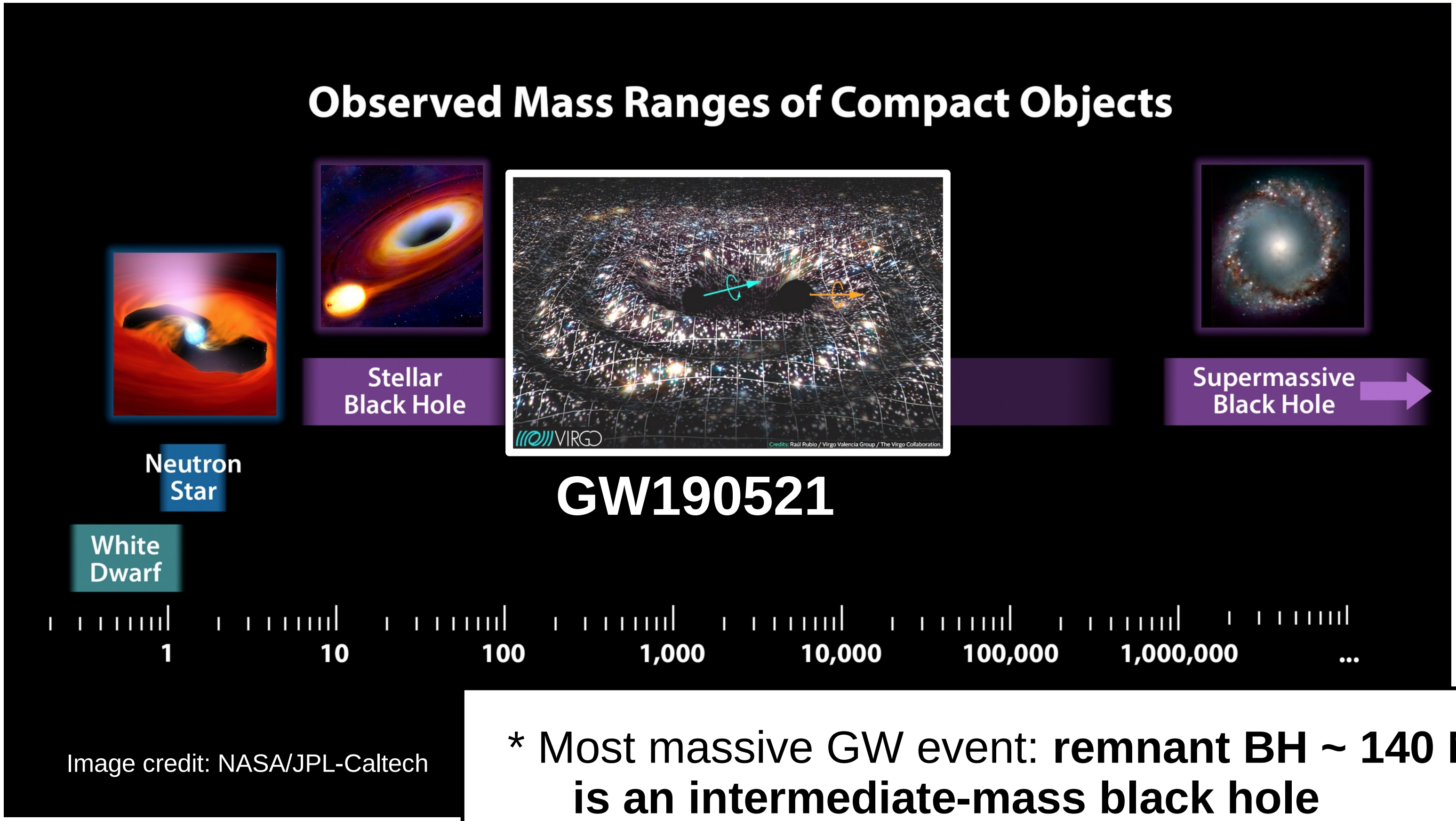
dimensionless spin

θ := tilt angle

Abbott et al. 2020, detection paper

Abbott et al. 2020, astrophysical implications

1. LIGO – Virgo binary compact objects: GW190521



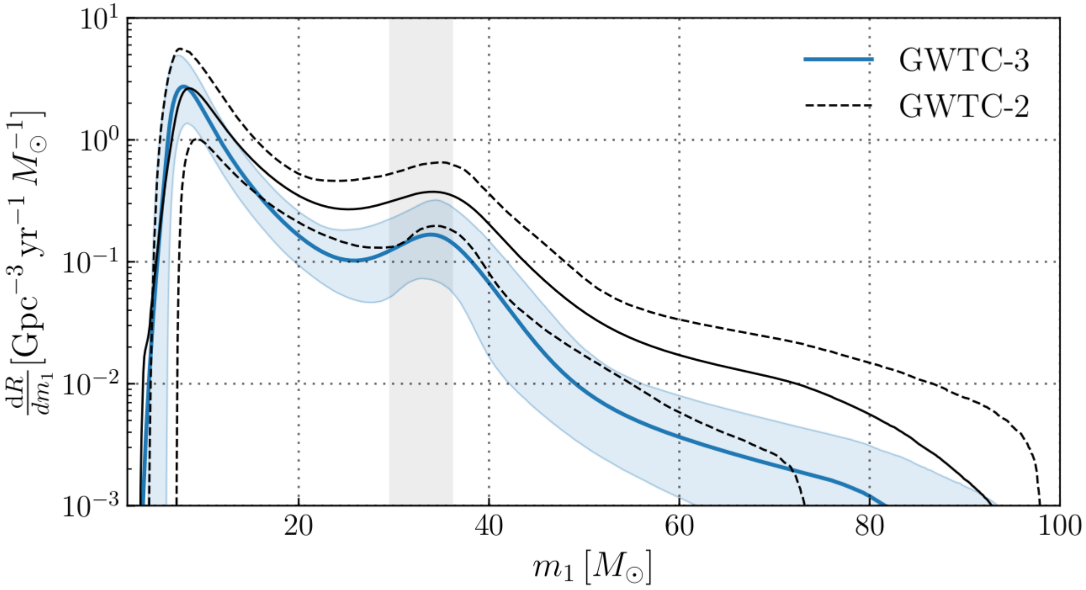
* Most massive GW event: **remnant BH ~ 140 M⊙ is an intermediate-mass black hole**

* Evidence for large spin components in the orbital plane → dynamical origin?

* Primary mass ~ 85 M⊙ in the “pair instability mass gap”

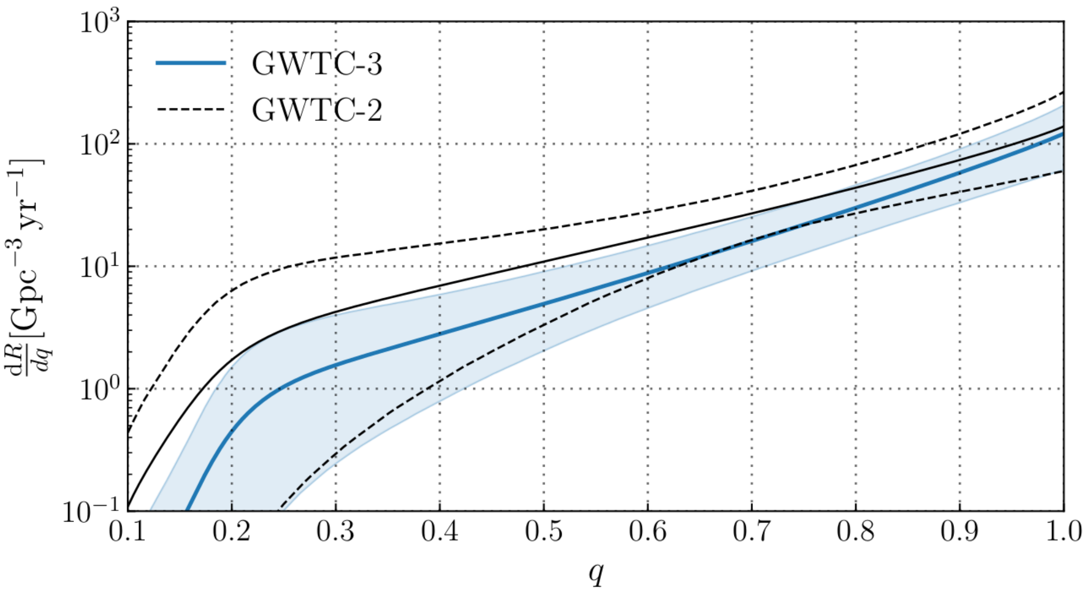
Abbott et al. 2020, GW190521 discovery, https://arxiv.org/abs/2009.01075
Abbott et al. 2020, GW190521 implications, https://arxiv.org/abs/2009.01190

1. LIGO – Virgo binary compact objects



Reconstructed
primary mass function:

possible peaks at ~ 10 and 35 M⊙
tail up to ~ 80 M⊙

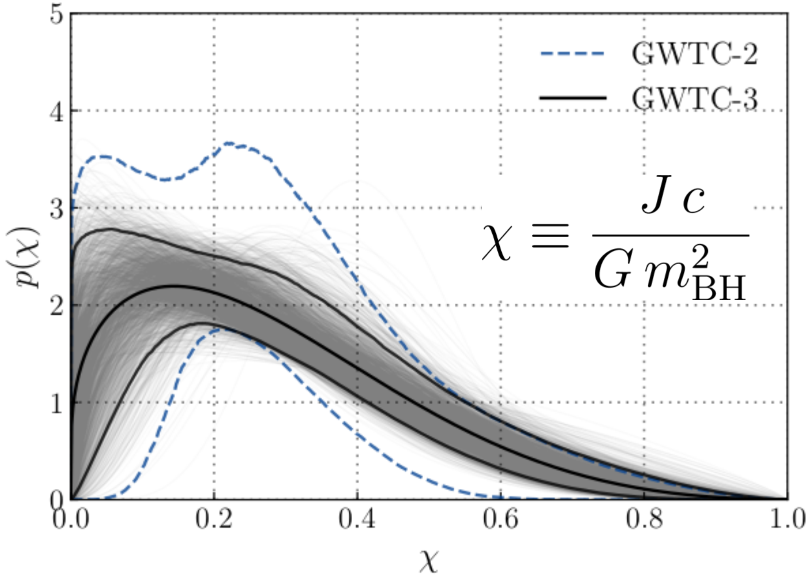


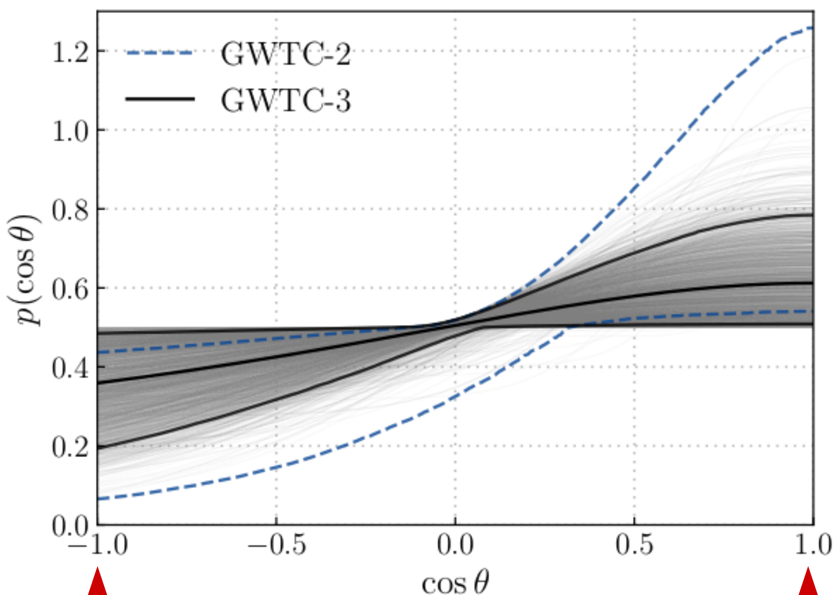
Reconstructed mass ratio:

preference for equal-mass BBHs

Abbott et al. 2022, population

1. LIGO – Virgo binary compact objects

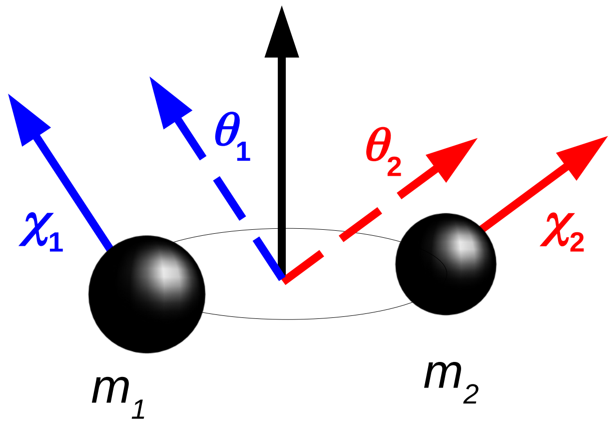




anti-aligned **aligned**

Reconstructed spin magnitude:

preference for **relatively low spins (~0.1–0.2) with long tail up to high spins**

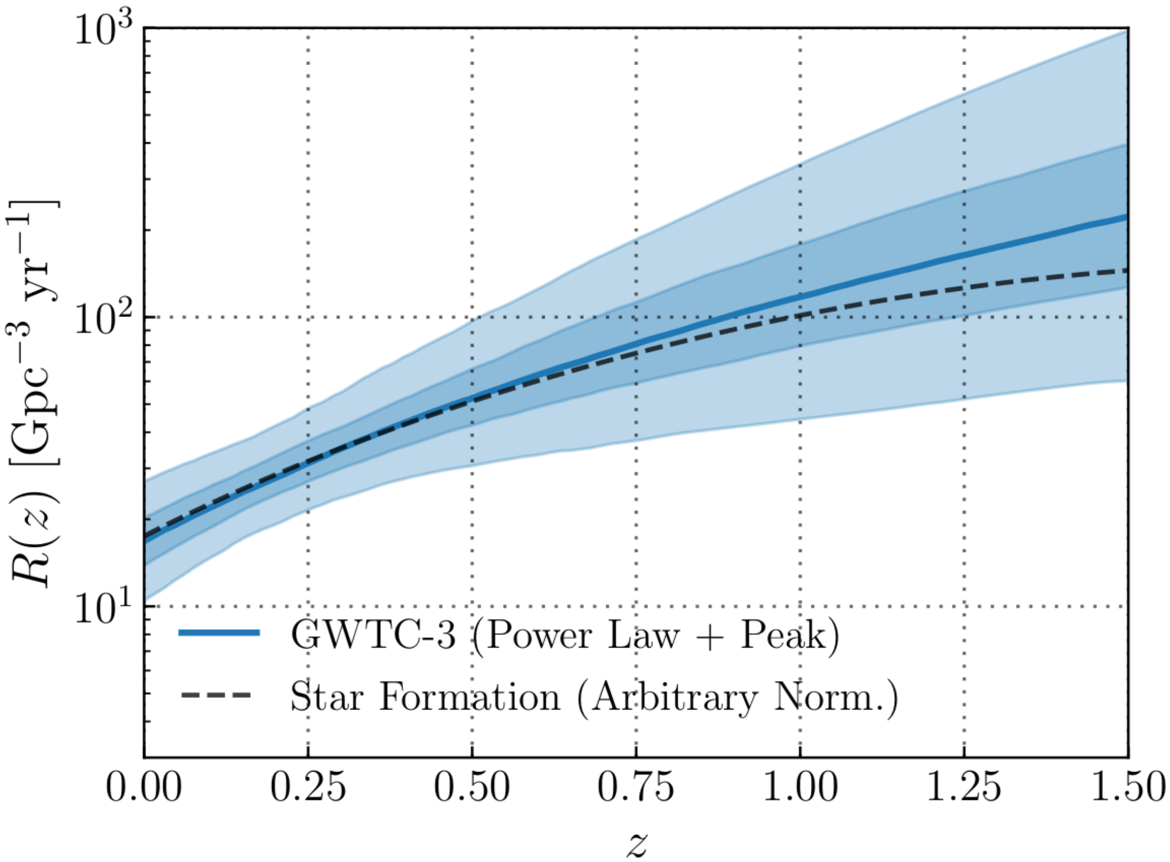


Reconstructed spin-orbit tilt:

mild preference for aligned systems

Abbott et al. 2022, population

1. LIGO – Virgo binary compact objects



Reconstructed merger rate density of BBHs in the comoving frame:

- exclude non evolving rate

- trend similar to cosmic SFR

Merger rate densities at $z = 0$

BNS Rate ~ 10 – 1700 Gpc^{-3} yr^{-1}

BHNS Rate ~ 8 – 140 Gpc^{-3} yr^{-1}

BBH Rate ~ 18 – 44 Gpc^{-3} yr^{-1}

Abbott et al. 2022, population

Open questions from GWs

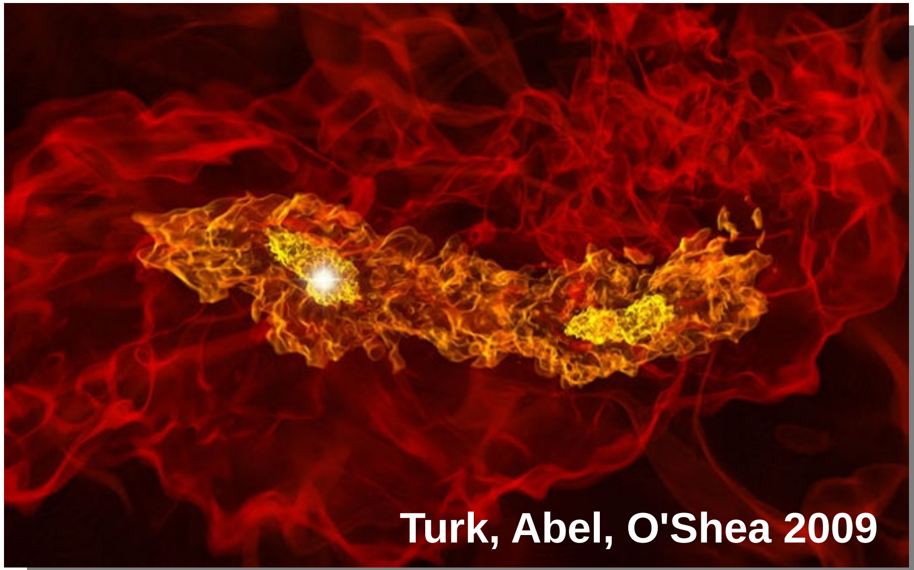
1. What are the formation channels of BBHs?
2. What determines BBH mass and spin?
3. What is the evolution of BBHs with redshift?

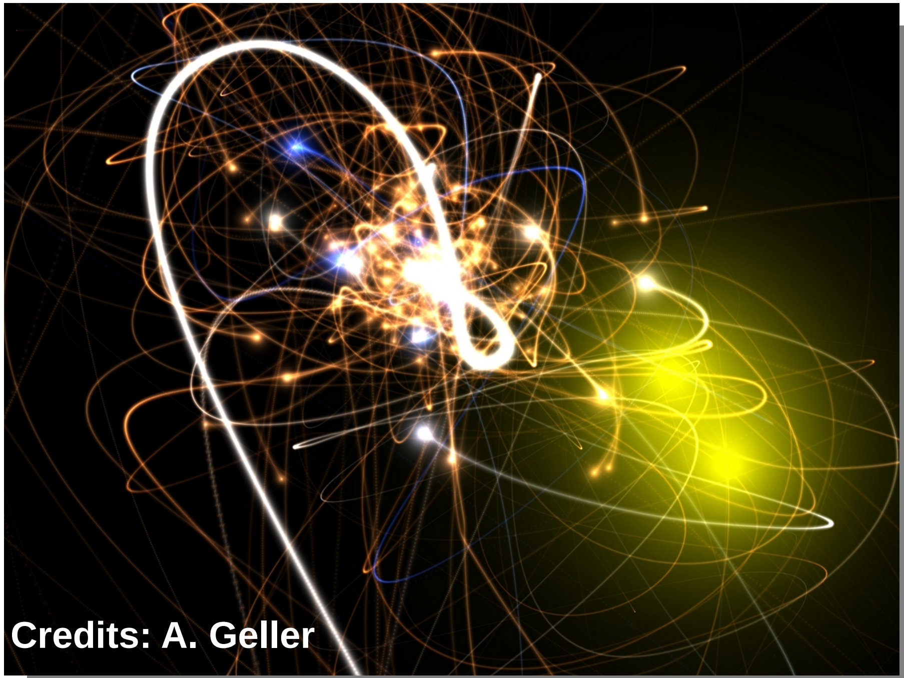
2. Populations of binary compact objects

ISOLATED BINARIES:

two stars form gravitationally bound and evolve into a BBH

physical processes involved:
stable and unstable mass transfer,
common envelope, tides, natal kicks,..





DYNAMICAL BINARIES:

BBHs form and/or evolve
by dynamical processes
in dense star clusters

2. Populations of binary compact objects

$$\Gamma = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_{\rm ad}$$

Very massive metal poor stars
efficiently produce gamma-ray (~1 MeV) photons
at the end of carbon burning

Leading to formation of
electron-positron pairs

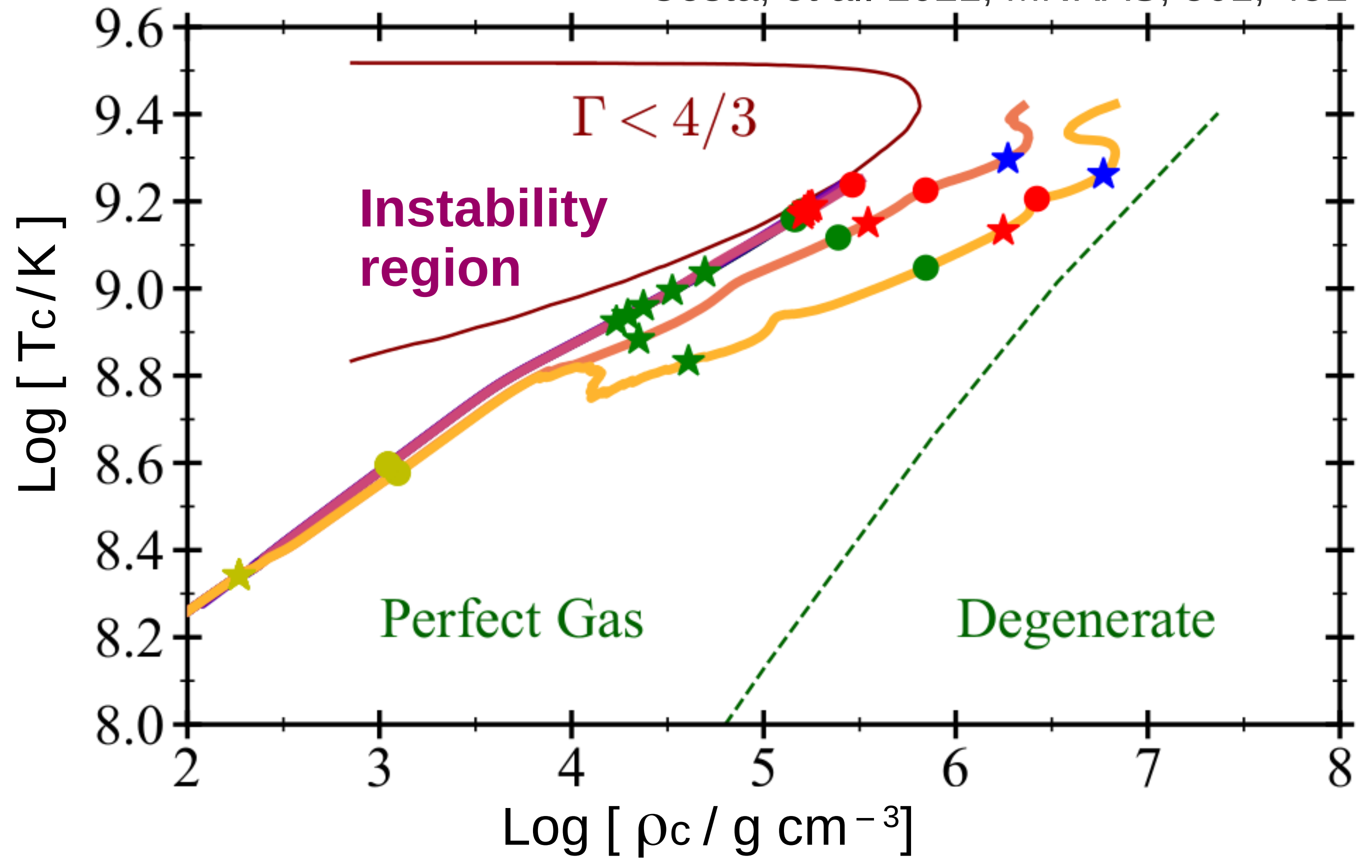
Missing photon pressure
triggers instability:

PAIR INSTABILITY

* contraction of
  stellar core

* premature ignition of
  neon, oxygen, silicon

Costa, et al. 2021, MNRAS, 501, 4514



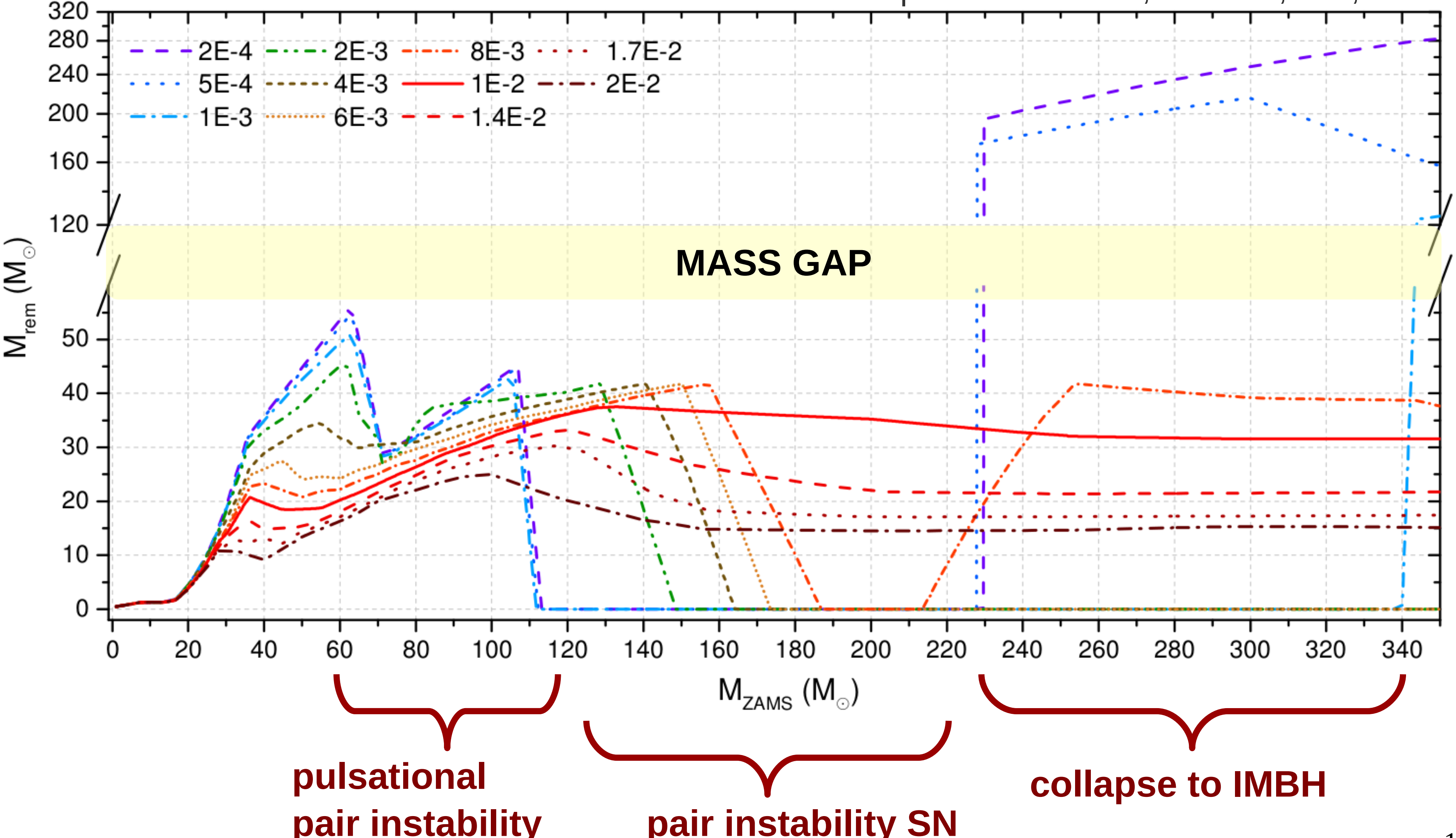
Stars (Circles): beginning (end) of helium, carbon, neon, and oxygen burning

2. Populations of binary compact objects

Impact of pulsational pair instability (if $32 < m_{He} / M_\odot < 64$) and

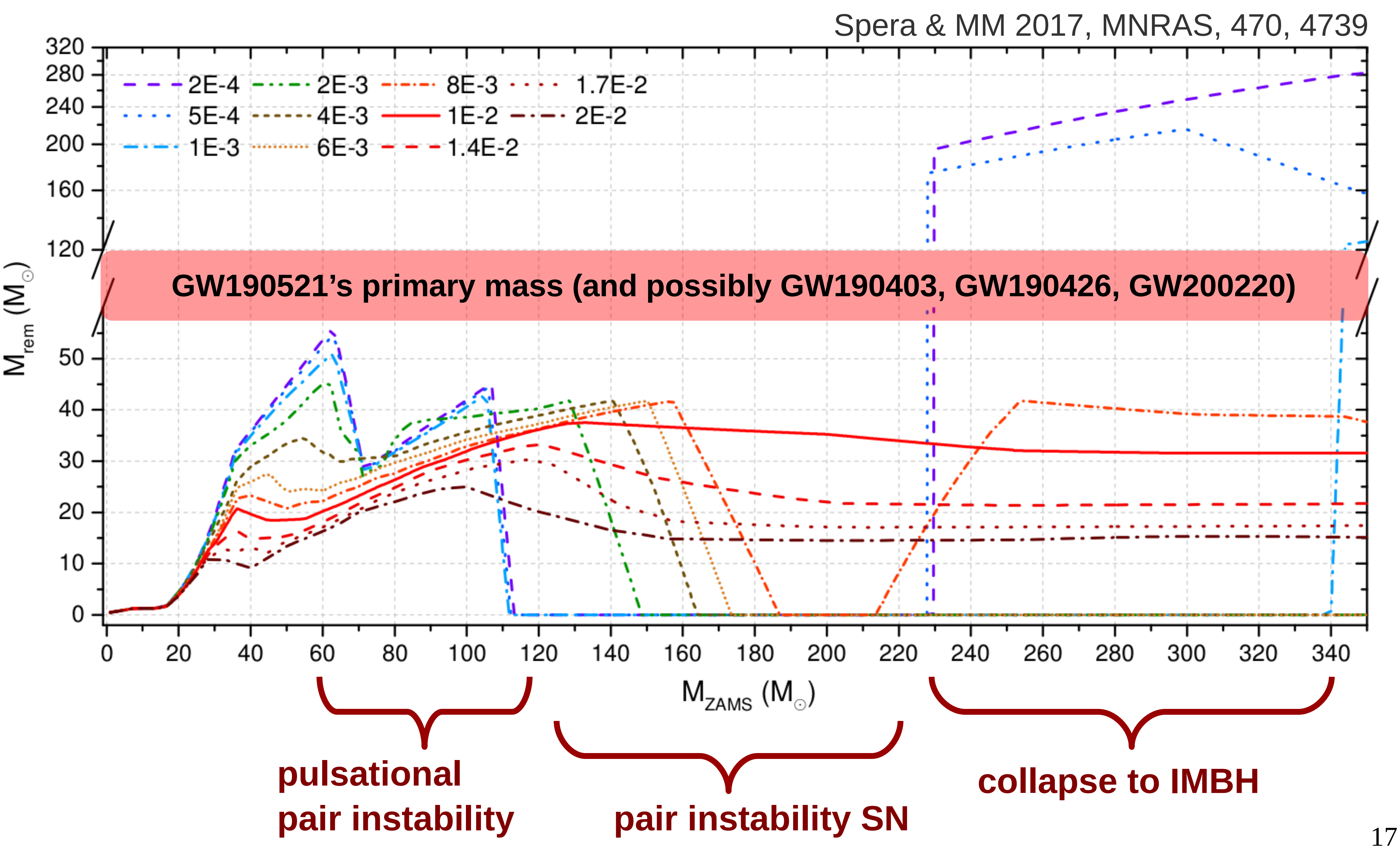
pair instability supernovae (if $64 < m_{He} / M_\odot < 135$)

Spera & MM 2017, MNRAS, 470, 4739



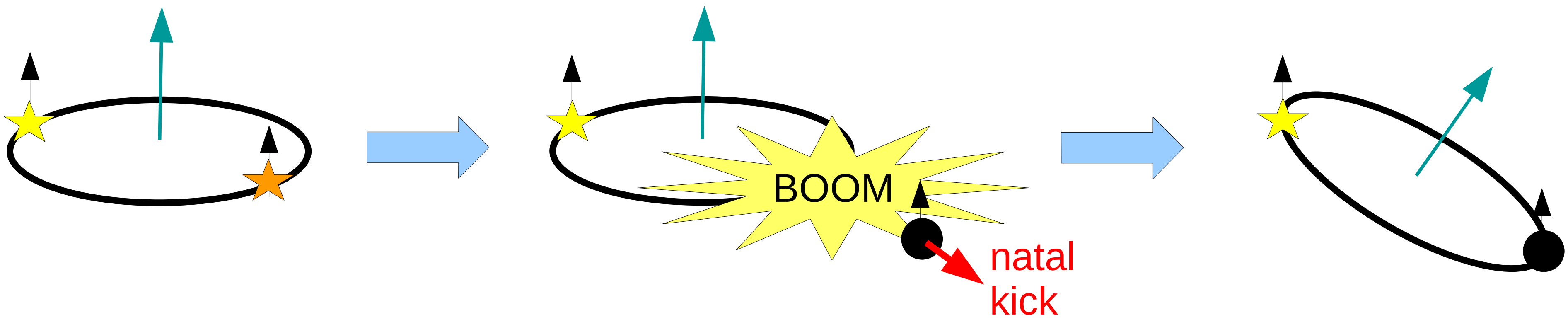
2. Populations of binary compact objects

Impact of pulsational pair instability (if $32 < m_{He} / M_\odot < 64$) and pair instability supernovae (if $64 < m_{He} / M_\odot < 135$)

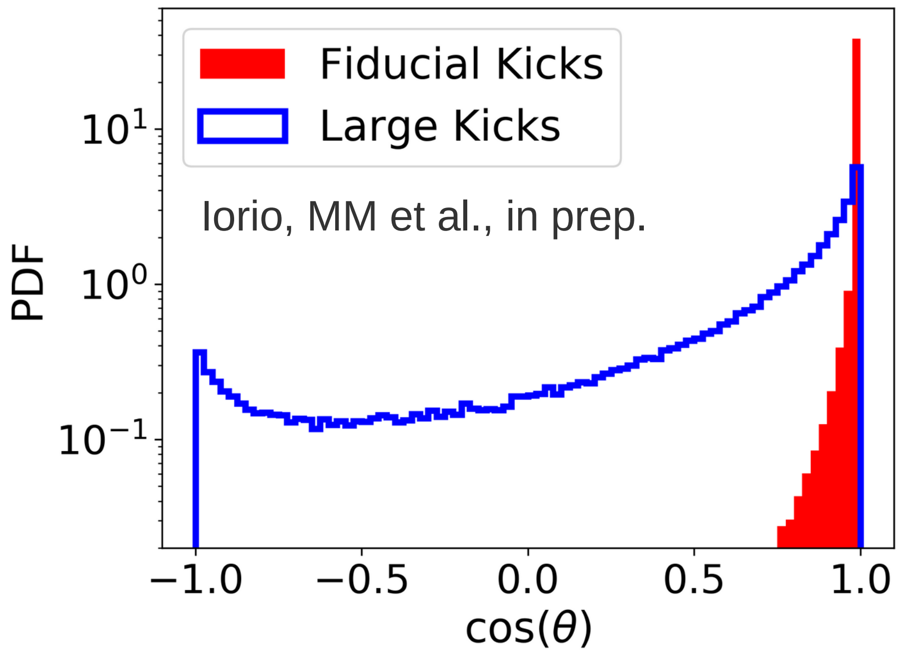


2. Populations of binary compact objects: isolated

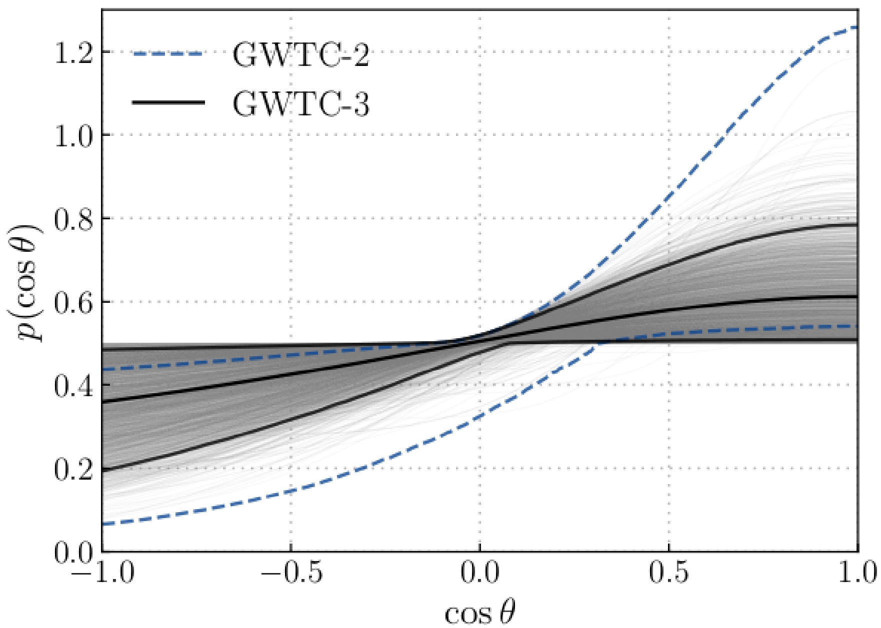
Tides tend to align the spins; only the supernova kick tilts the orbital plane



Distribution of tilts predicted by population synthesis



LVC constraints on tilts



Isolated binary systems do not match observed spin tilts, unless large natal kicks

Abbott et al. 2022, population

2. Populations of binary compact objects: dynamical

DYNAMICS is IMPORTANT ONLY IF **density > 10^3 stars pc^{-3}**

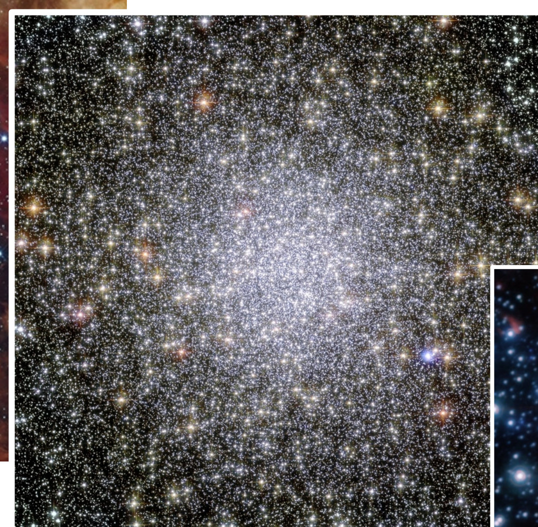
i.e. only in dense star clusters

but massive stars (BH progenitors) form in star clusters

(Lada & Lada 2003; Weidner & Kroupa 2006; Weidner, Kroupa & Bonnell 2010; Gvaramadze et al. 2012; Portegies Zwart et al. 2010)

R136, credit: NASA

Young star clusters



47 Tucanae, credit: NASA/ESA/HST

Globular clusters

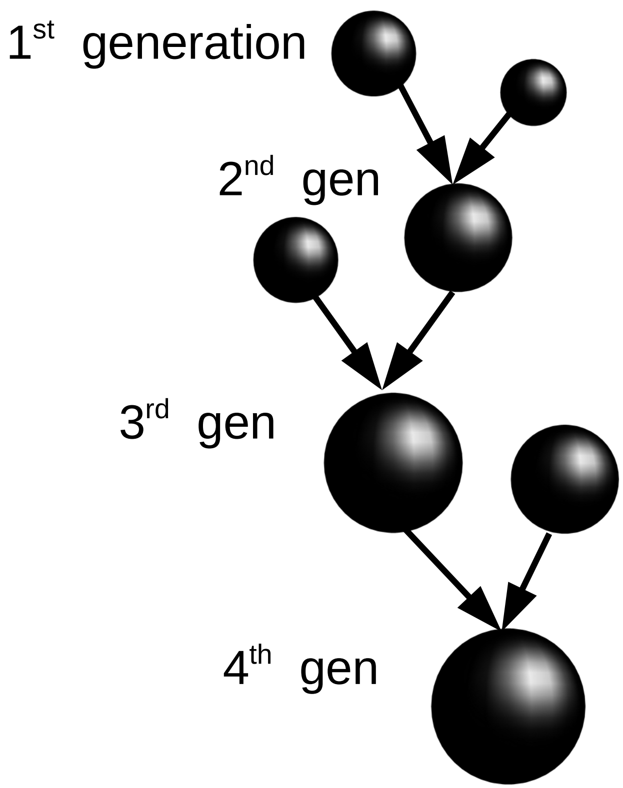
Nuclear star clusters

Credit: ESO, Gillessen et al.

2. Populations of binary compact objects: dynamical

HIERARCHICAL MERGERS

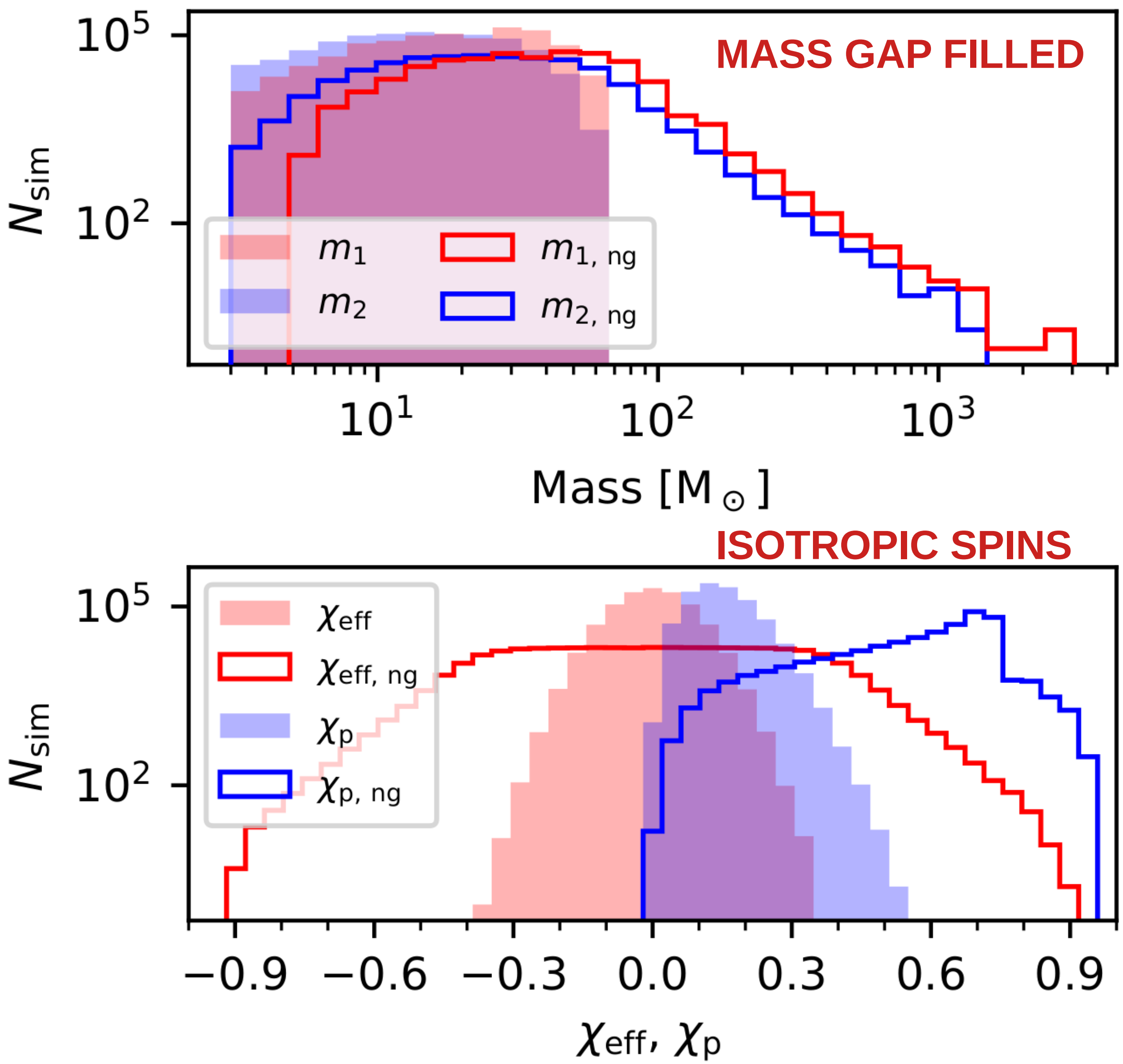
Miller & Hamilton 2002



MM et al. 2021, MNRAS, 505, 339

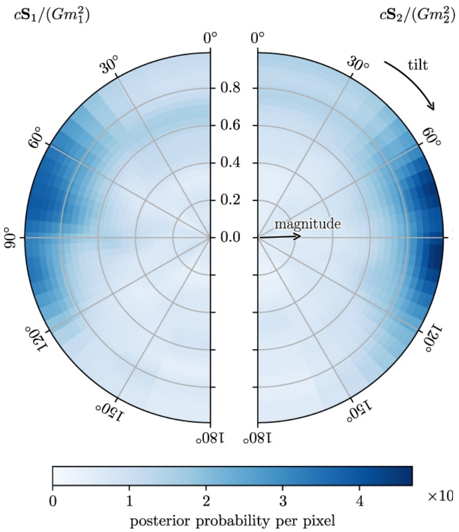
Filled histograms:
first generation BBH mergers

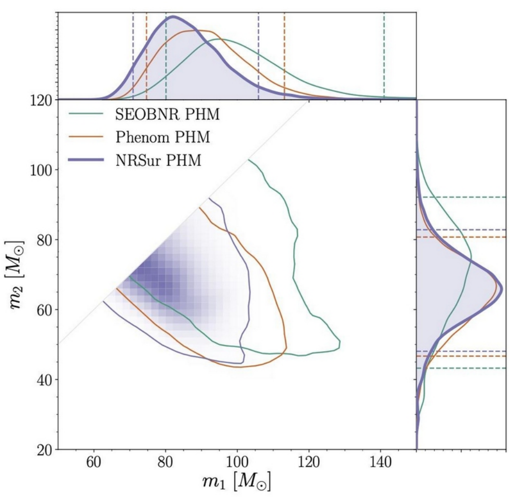
Unfilled histograms: 2nd or Nth generation BBH mergers

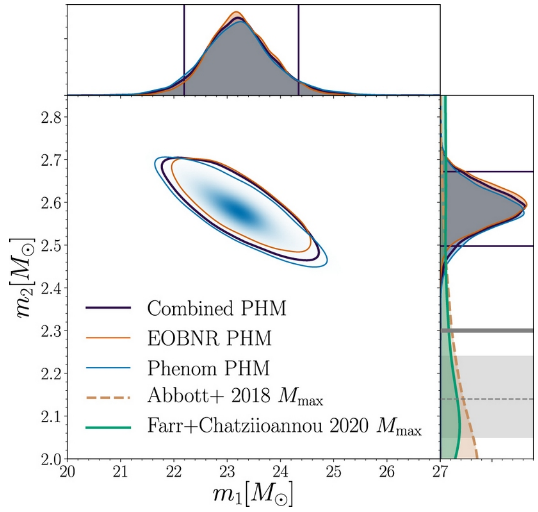


2. Populations of binary compact objects: dynamical vs isolated

	Isolated	Dynamics
Masses	< 60 Msun	up to IMBH regime
Mass ratios	mostly equal mass	any mass ratios
Spin direction	mostly aligned	isotropic
Spin magnitude	uncertain	~ 0.7 – 0.8 for 2g

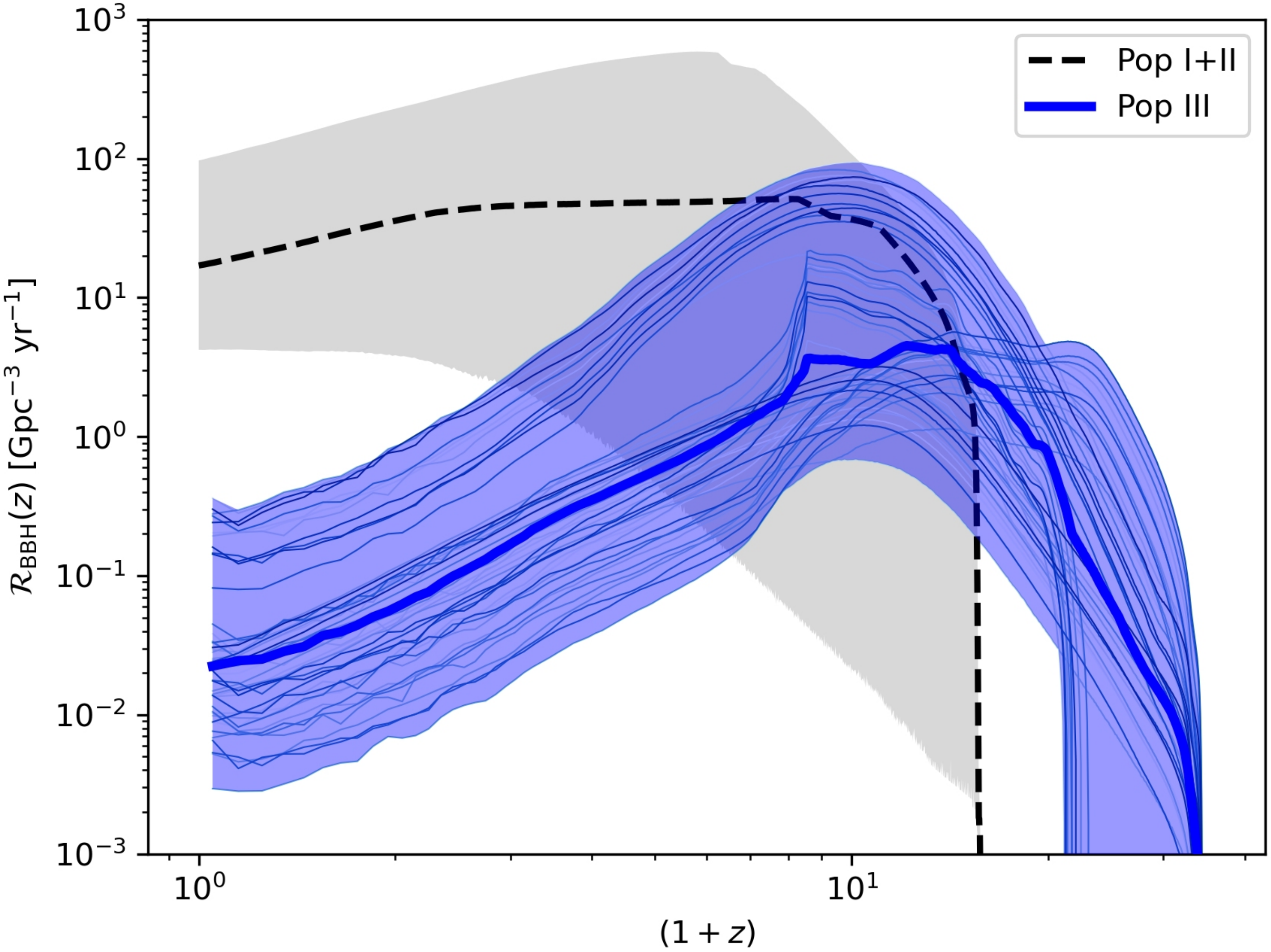






likely for GW190521 GW190814

2. What about high redshift evolution (pop III stars)?

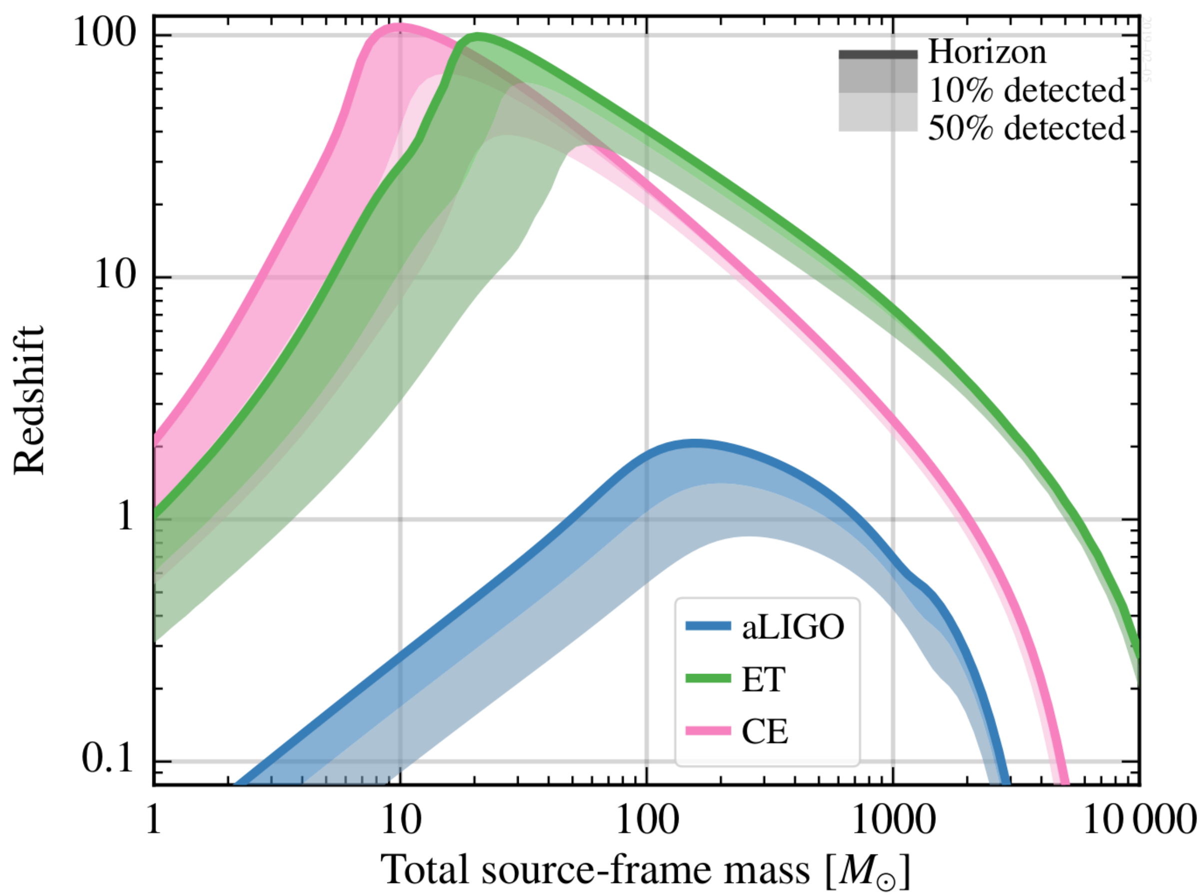


Santoliquido, MM et al. in prep

3. Conclusions

Gravitational waves (GWs) open a **new perspective** to study binary compact objects with gravitational waves

Future ground-based GW detectors (>2035): Einstein Telescope, Cosmic Explorer



THANK YOU