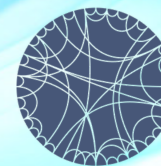


Padova, September 29th 2025



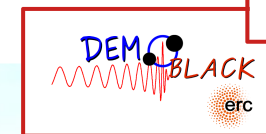
STRUCTURES
CLUSTER OF
EXCELLENCE

Populations Of Binary Compact Objects: The Present (GWTC-4) And The Future (Einstein Telescope)

Michela Mapelli

Heidelberg University

University of Padova
INFN Padova

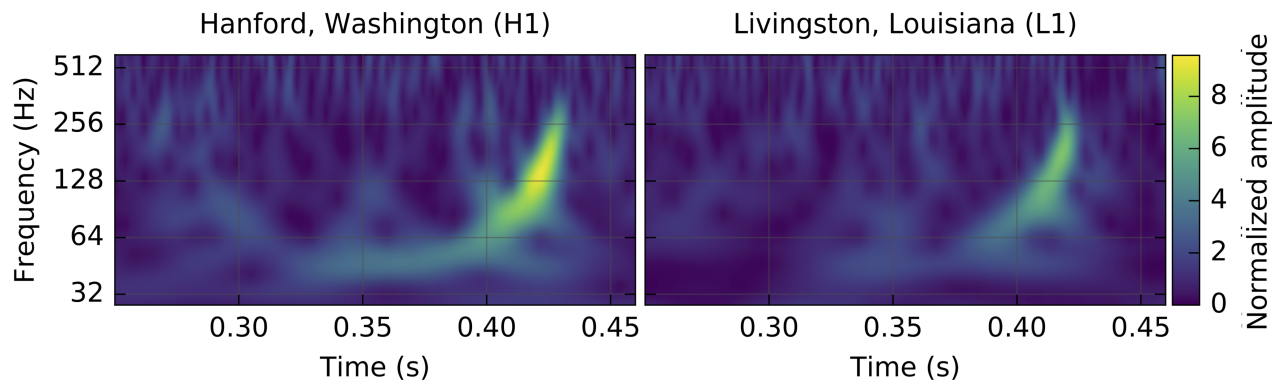


Main collaborators: M. Celeste Artale, Lumen Boco, Marco Dall'Amico, Lukas Fluegel, Giuliano Iorio, Boyuan Liu, Sofia Mesini, Stefano Rinaldi, Cecilia Sgalletta, Stefano Torniamenti, M. Paola Vaccaro

OUTLINE:

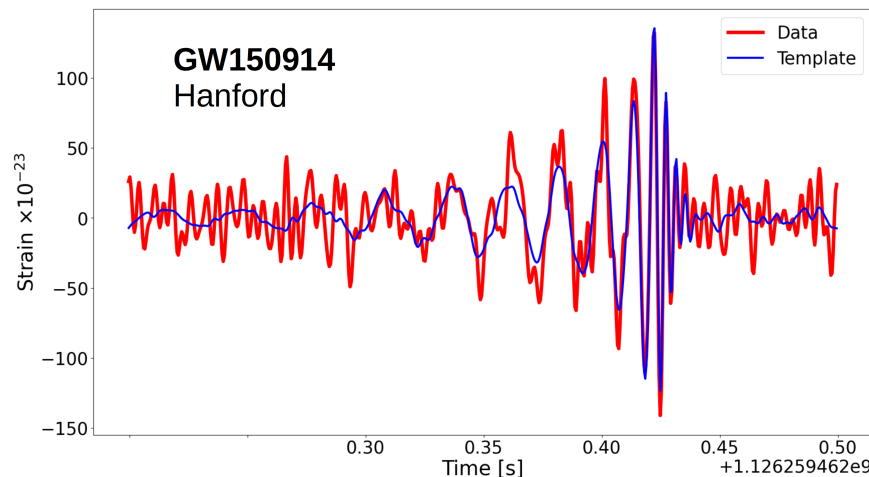
1. The past of gravitational-wave detections
2. The present: Gravitational Wave Transient Catalog 4
3. The future: next generation telescopes and neutrinos
4. Conclusions

1. The past: happy birthday GW150914

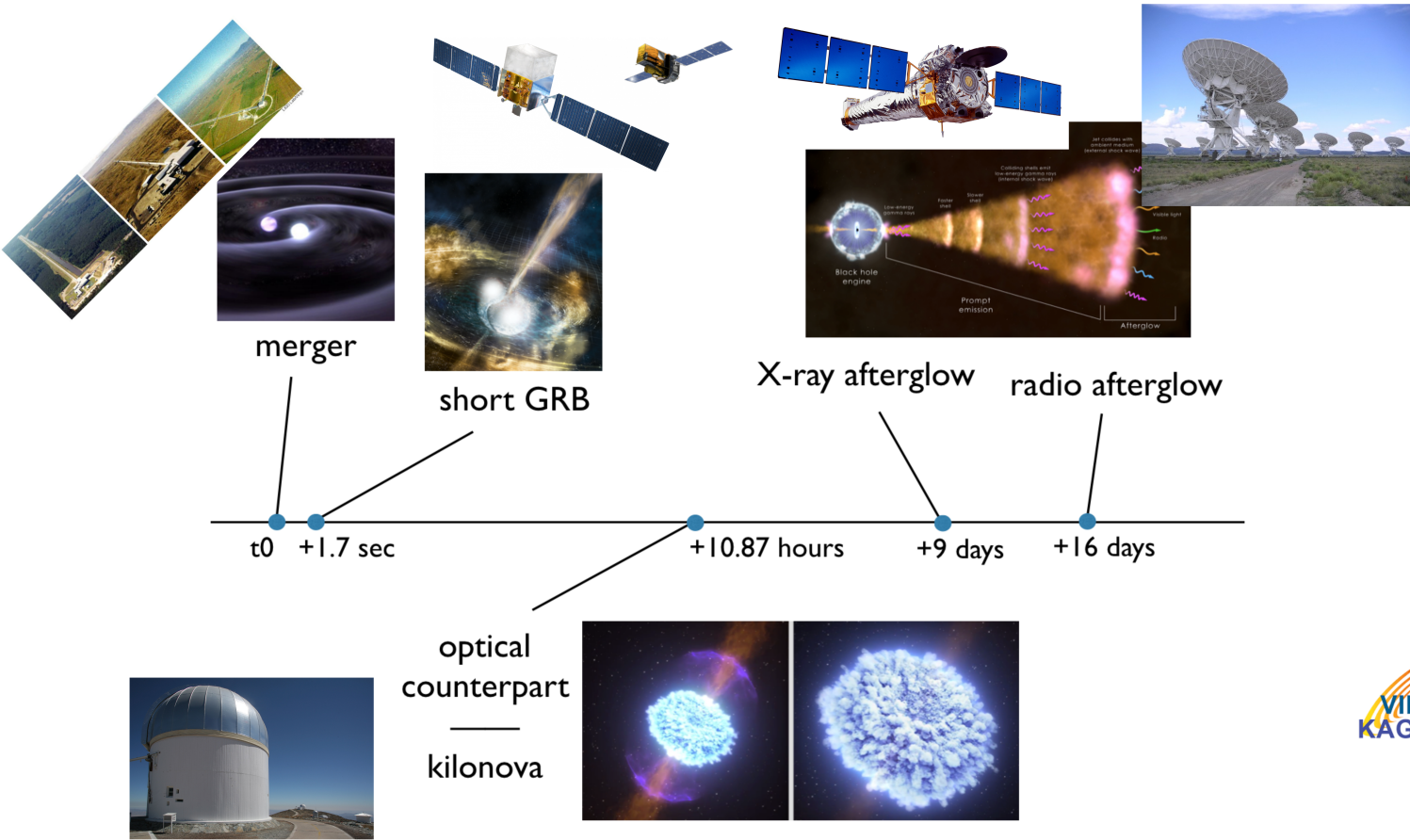


It has been almost exactly 10 years since the first detection of GWs...

- * First detection of gravitational waves
- * First binary black hole
- * First stellar-origin black hole masses $> 20 M_{\text{sun}}$



1. The past: GW170817, a firework through the electromagnetic spectrum



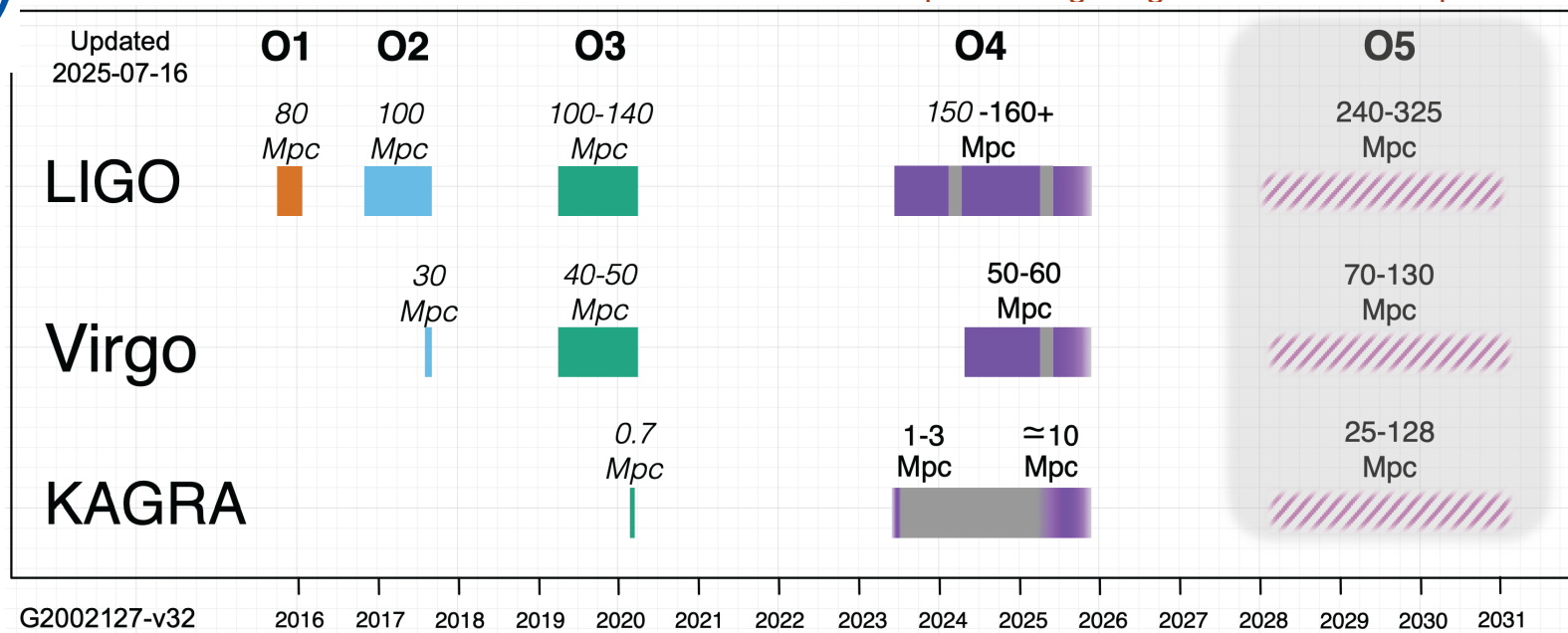
e.g. Abbott+ 2017, ApJ, 848, L13

Credit: slide from Riccardo Ciolfi + LVC

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)



<https://dcc.ligo.org/LIGO-G2002127/public>



Calculate detector horizon
for other systems:

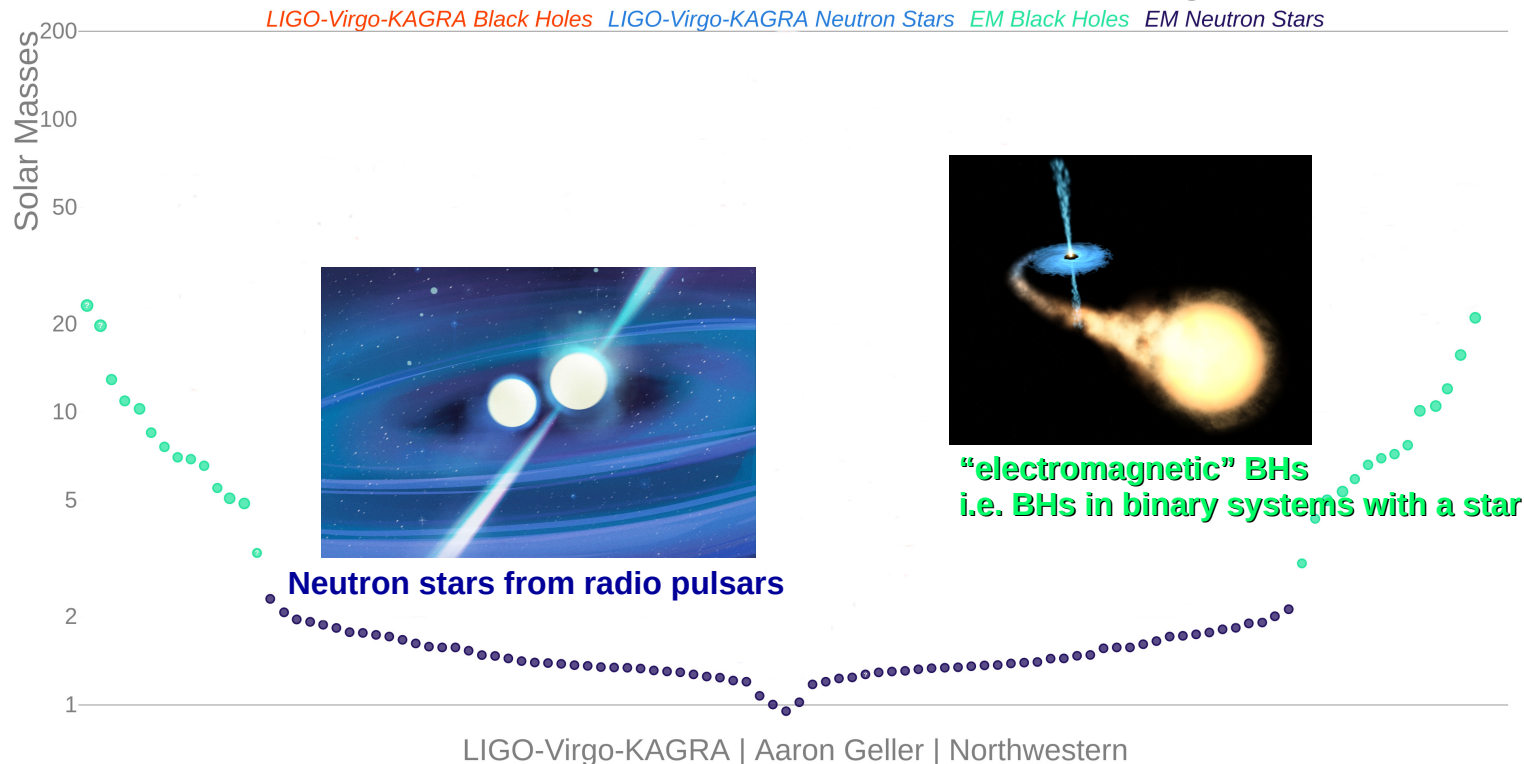
$$d \sim 2 \text{ Gpc} \left(\frac{d_{\text{BNS}}}{130 \text{ Mpc}} \right) \left(\frac{m_{\text{chirp}}}{30 M_{\odot}} \right)^{5/6}$$

$$m_{\text{chirp}} = \frac{m_1^{3/5} m_2^{3/5}}{(m_1 + m_2)^{1/5}}$$

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)



Masses in the Stellar Graveyard

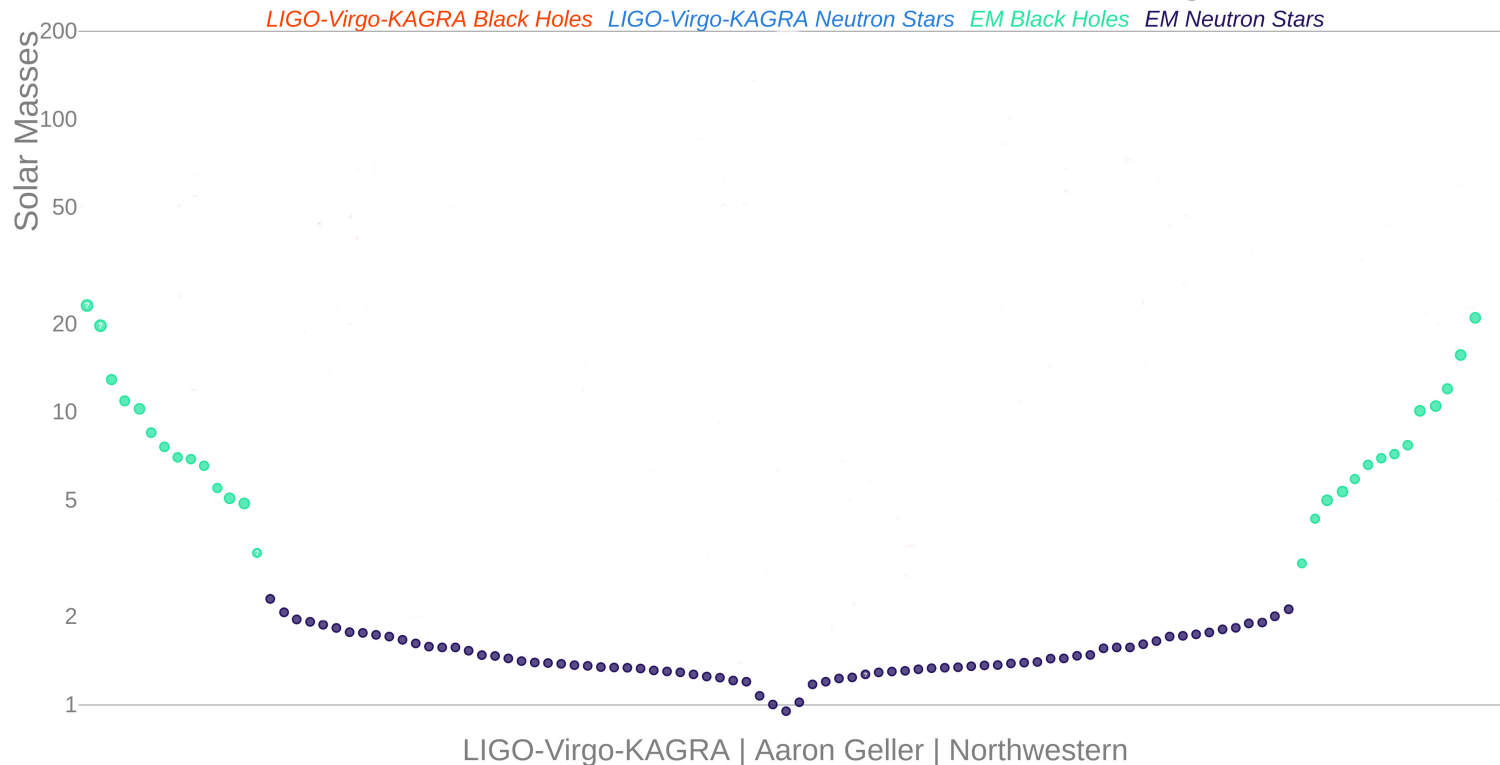


Abbott et al. 2023, GWTC-3

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)



Masses in the Stellar Graveyard

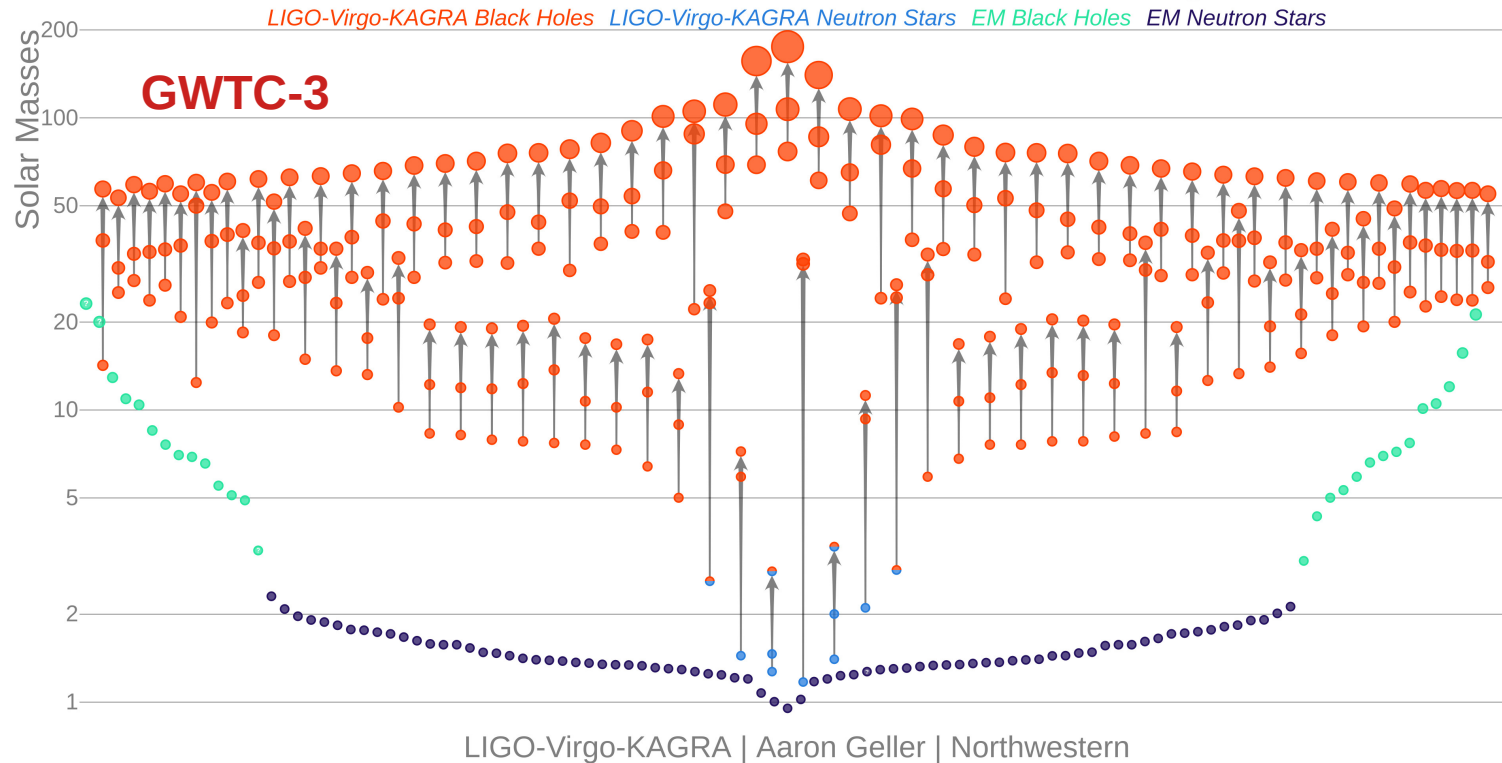


Abbott et al. 2023, GWTC-3

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)



Masses in the Stellar Graveyard

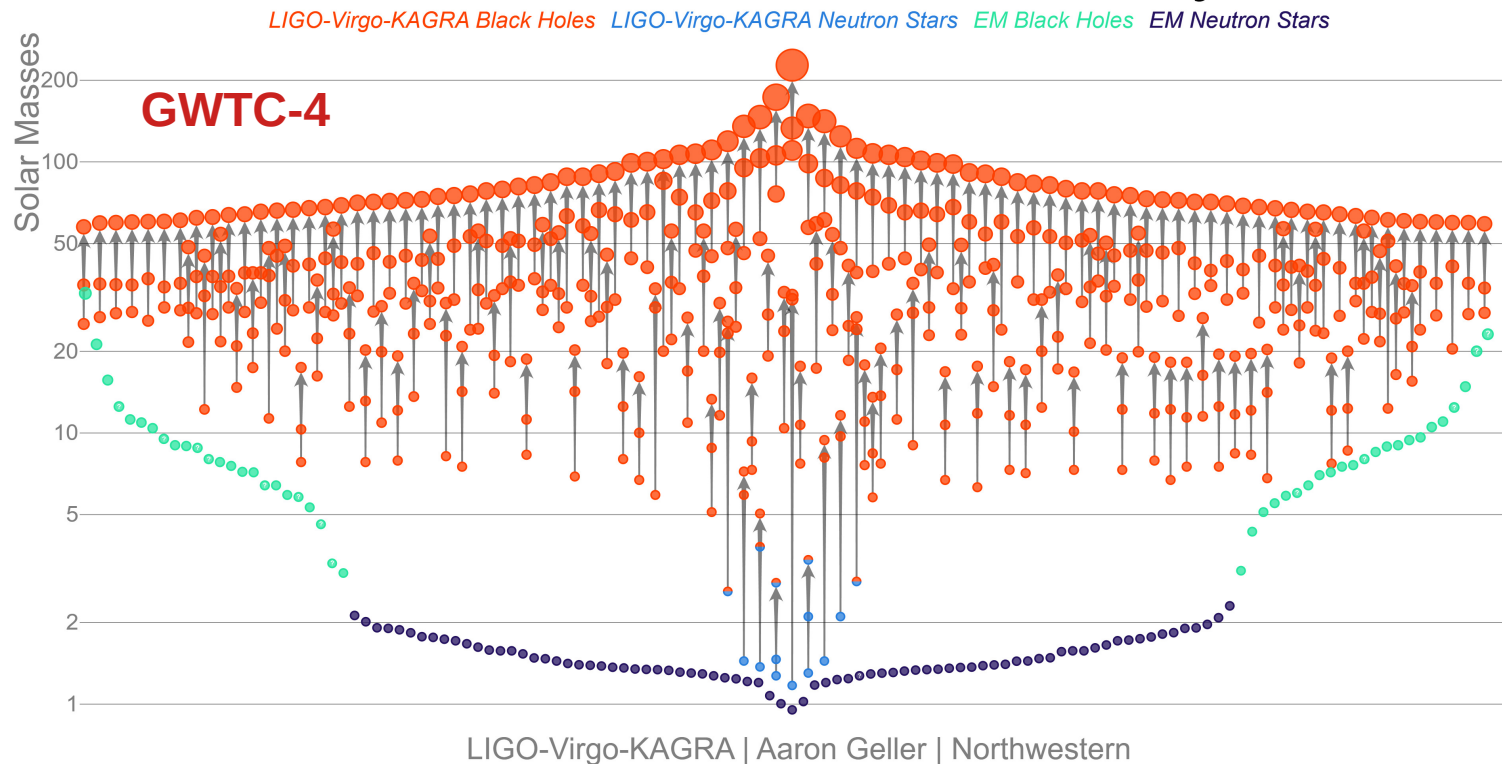


Abbott et al. 2023, GWTC-3

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)



Masses in the Stellar Graveyard

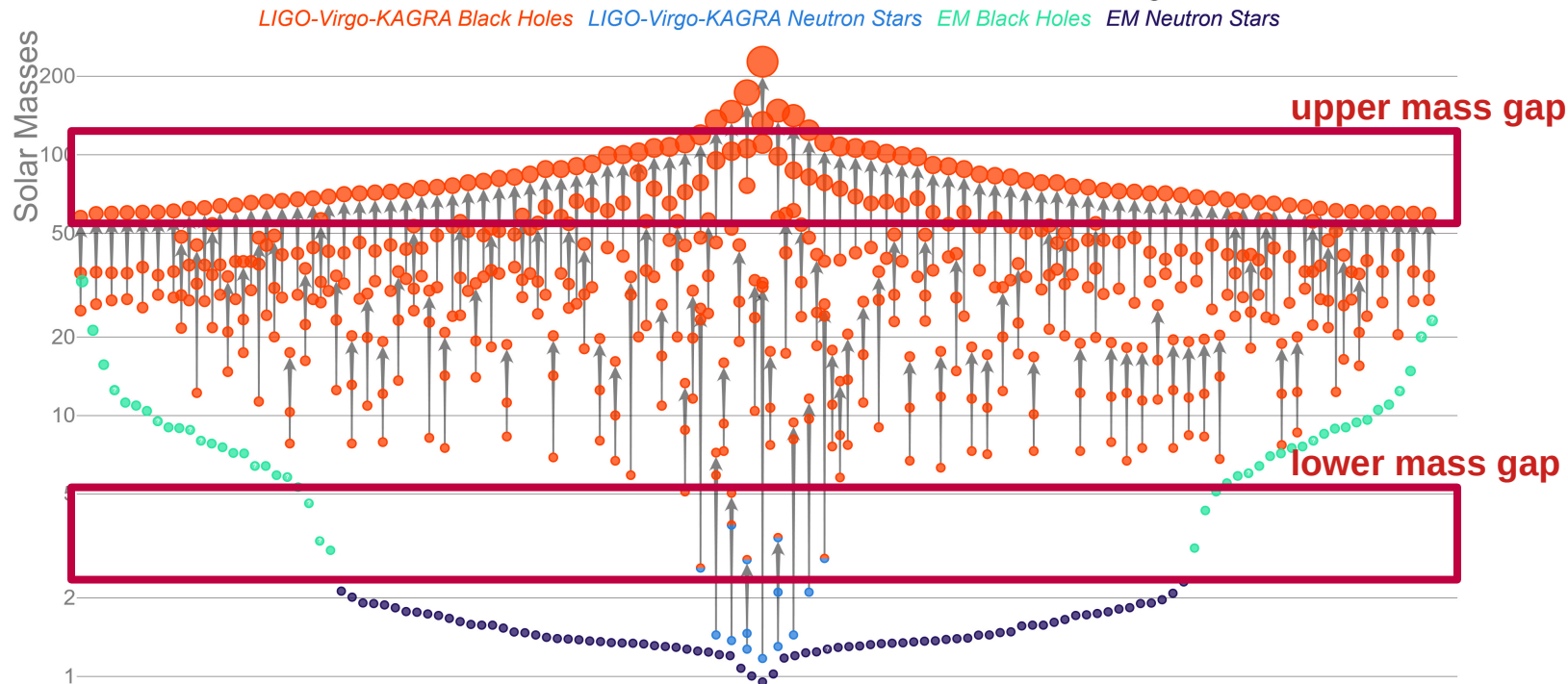


GWTC-4 population paper

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)



Masses in the Stellar Graveyard



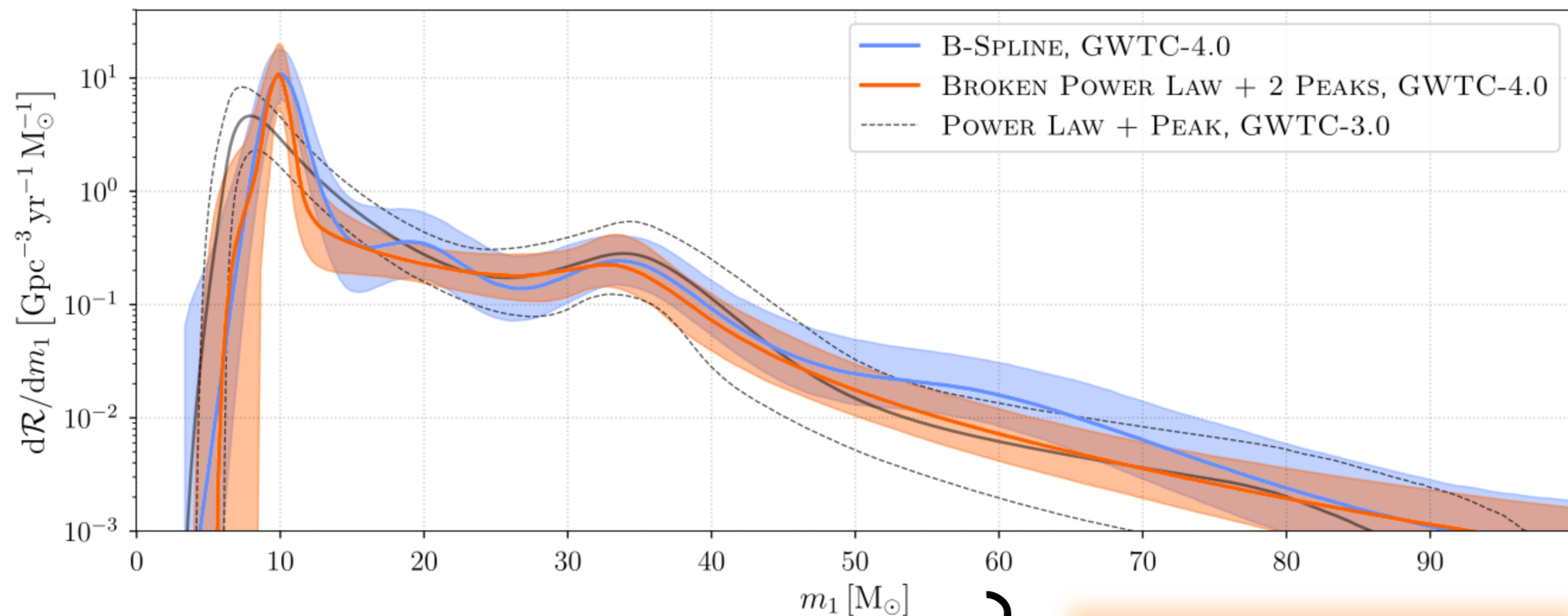
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

GW data revolutionize and challenge our understanding of compact objects

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)



GWTC-4 population paper



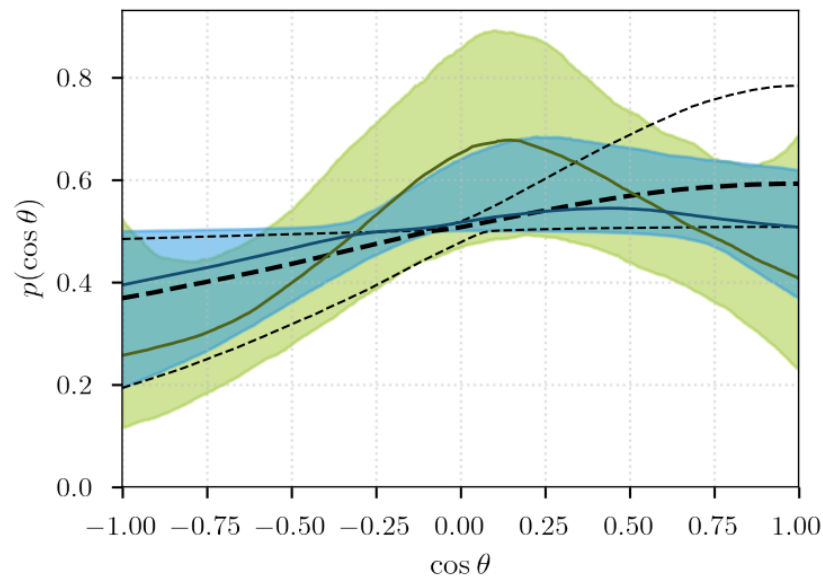
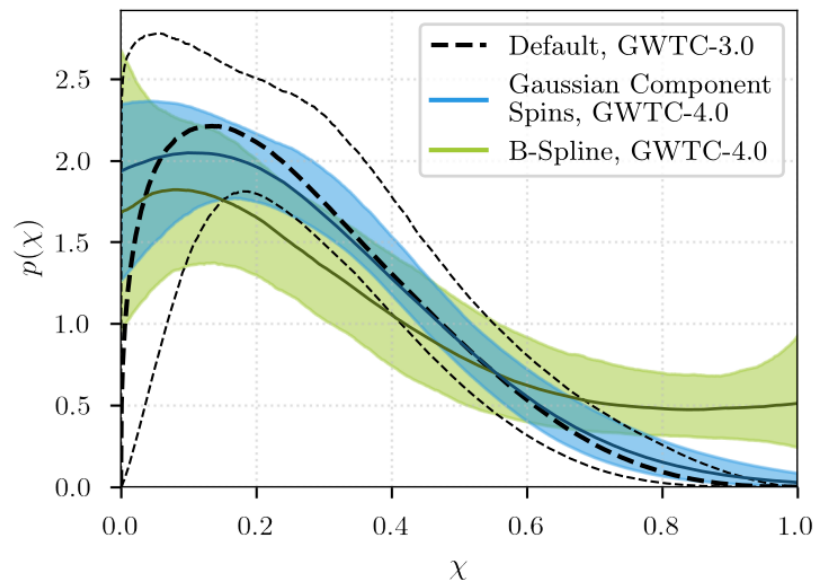
- * Primary black hole mass 10 Msun peak
- * Secondary feature: 35 Msun peak
- * Long tail extending up to ~100 Msun → inside mass gap

Encode key information
about the origin of black holes
from their progenitor stars

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)



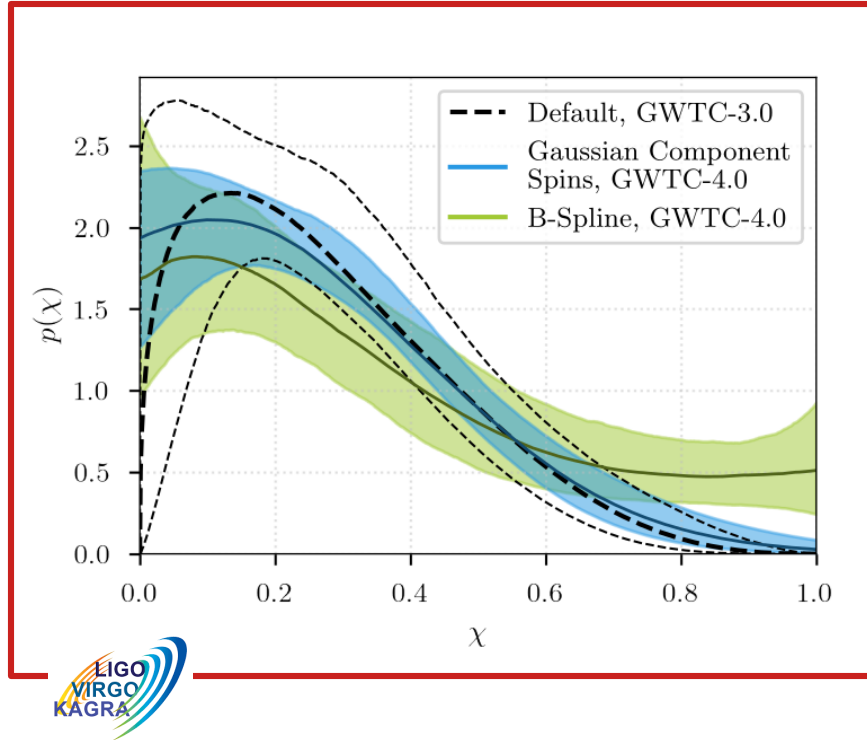
GWTC-4 population paper



Weak preference for alignment with orbital angular momentum

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)

GWTC-4 population paper

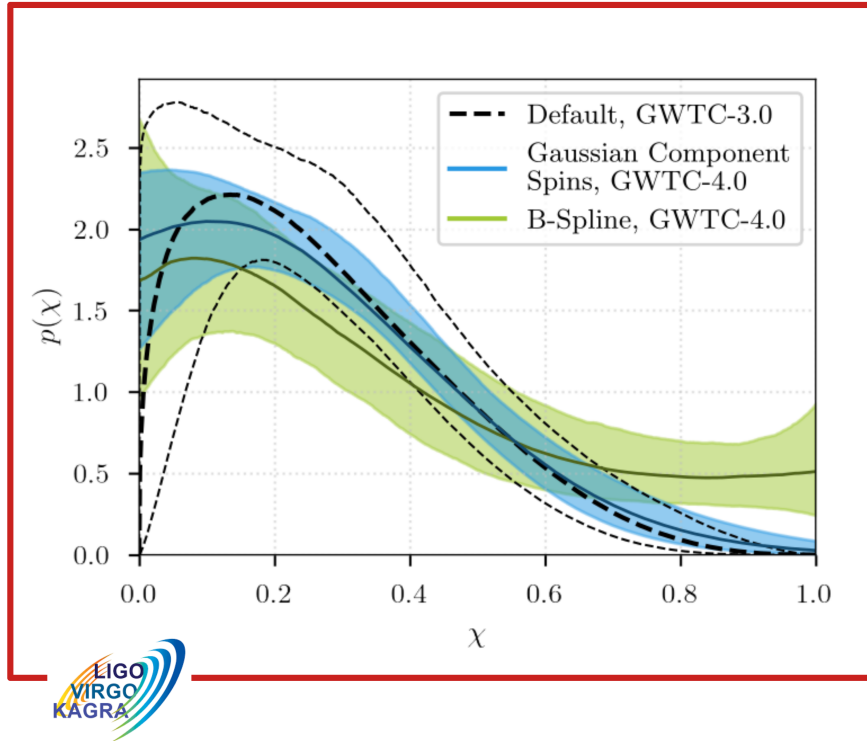


Black holes in binary black holes spin “slowly”

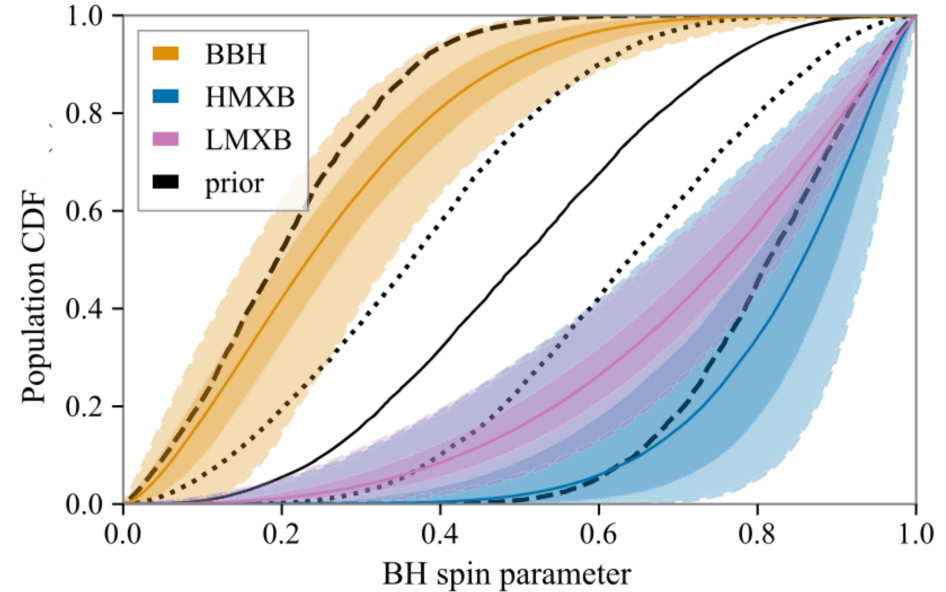
$$\chi \equiv \frac{J c}{G m_{\text{BH}}^2}$$

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)

GWTC-4 population paper



Fishbach & Kalogera 2022, X-ray binaries

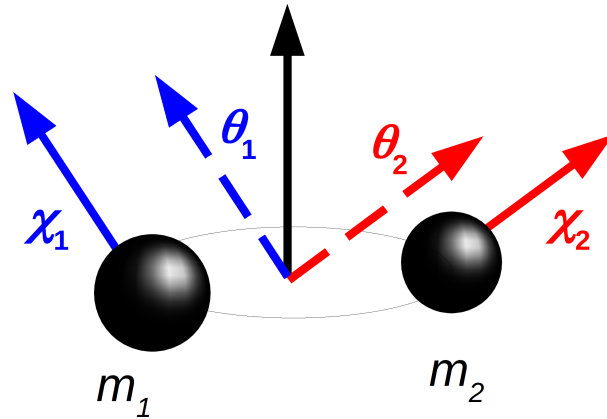


Black holes in binary black holes spin “slowly”

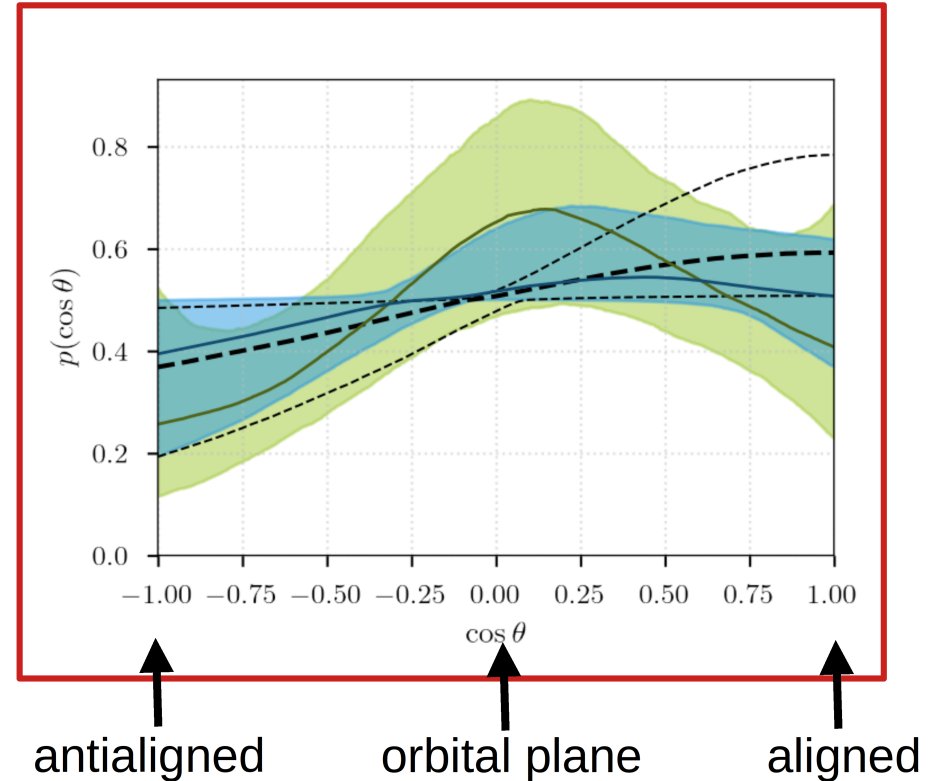
$$\chi \equiv \frac{J c}{G m_{\text{BH}}^2}$$

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)

GWTC-4 population paper



)

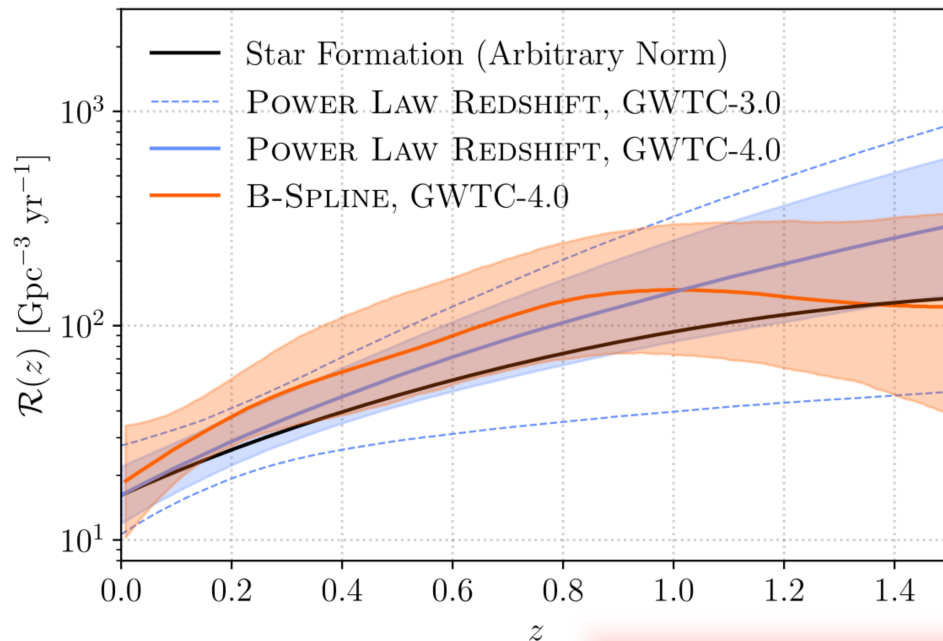


Weak preference for alignment with orbital angular momentum

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)



GWTC-4 population paper



MERGER RATE DENSITY
at redshift $z = 0$

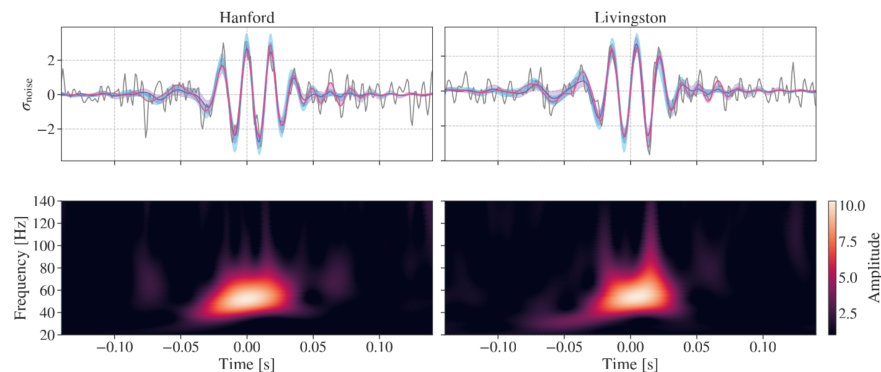
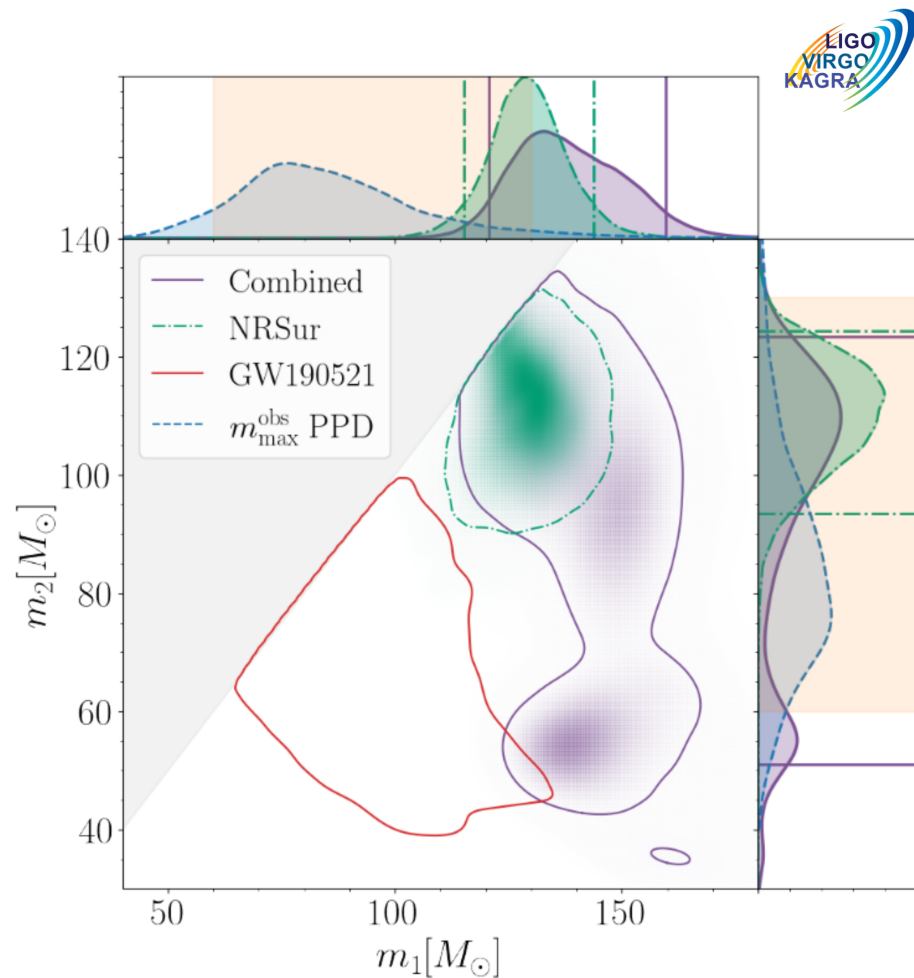
**7.6–250 $\text{Gpc}^{-3} \text{ yr}^{-1}$
for binary neutron stars,**

9.1–84 $\text{Gpc}^{-3} \text{ yr}^{-1}$
for neutron star–black hole
binaries,

**14–26 $\text{Gpc}^{-3} \text{ yr}^{-1}$
for binary black holes**

**Black hole rate is
problematic for the models**

2. The present: the most massive system in GWTC-4: GW231123



Final mass ~ 240 Msun

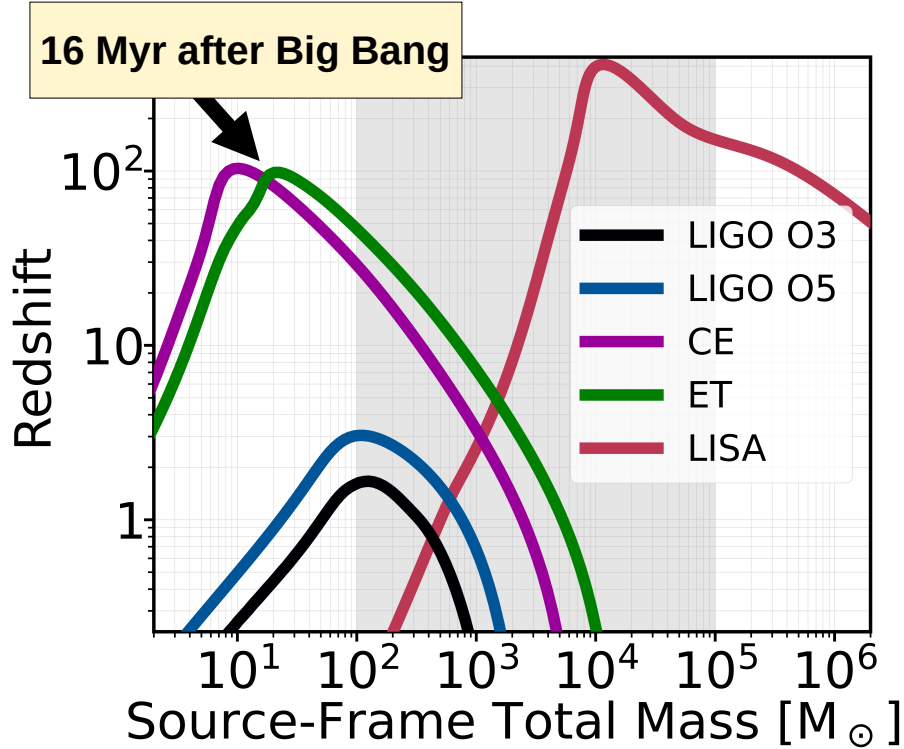
Most massive black hole with
gravitational waves

Primary mass ~ 137 Msun

High spins (0.8-0.9): hierarchical
black hole mergers?

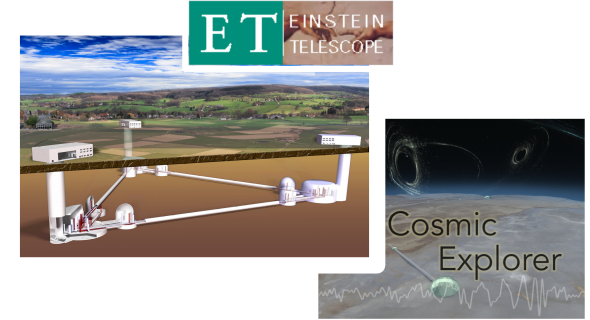
Abac et al. 2025

3. The future: next generation ground-based and space-borne GW interferometers

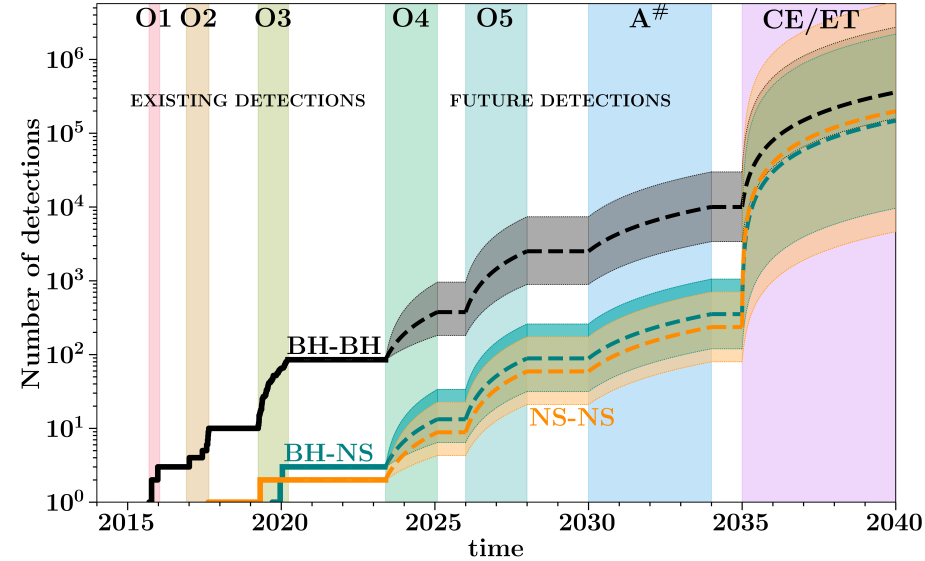


Ground-based: Einstein Telescope & Cosmic Explorer (> 2035)

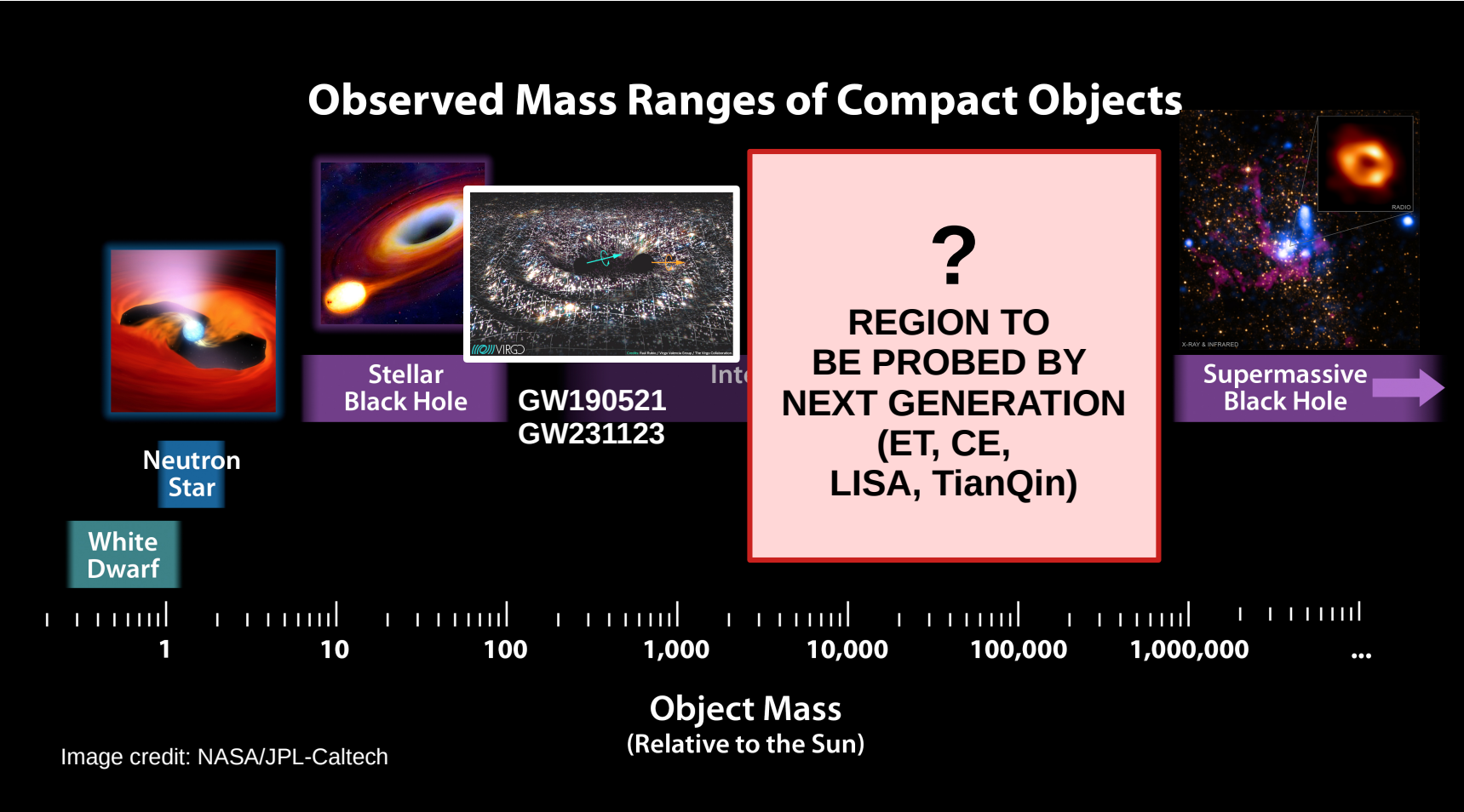
Space-based: LISA (2035), TianQin (2034)



Broekgaarden et al. 2024



3. The future: next generation interferometers & intermediate-mass black holes

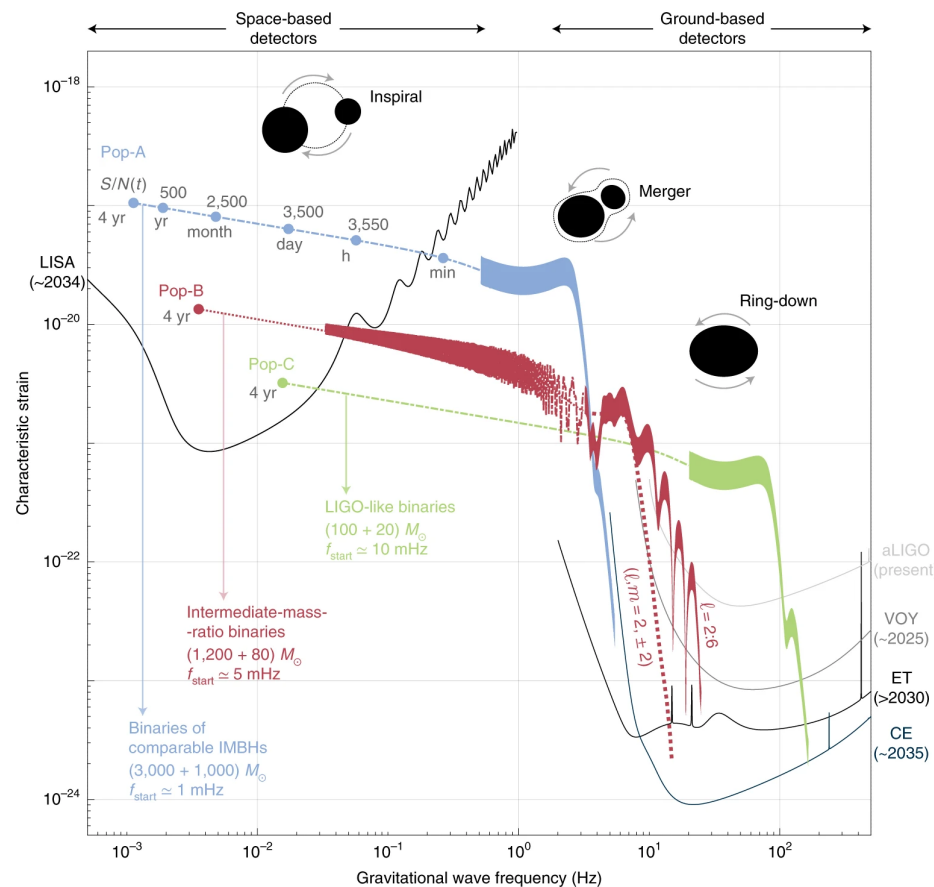


3. The future: Next-Generation and Multi-Band Gravitational-Wave Astronomy

Possible to observe
inspiral with space-borne
detectors (LISA, TianQin)

and merger after months/years
with ground-based detectors
(LIGO#, Virgo_{next}, ET, CE)

- better localization,
- more chances for counterpart,
- information about system evolution (e.g., eccentricity)



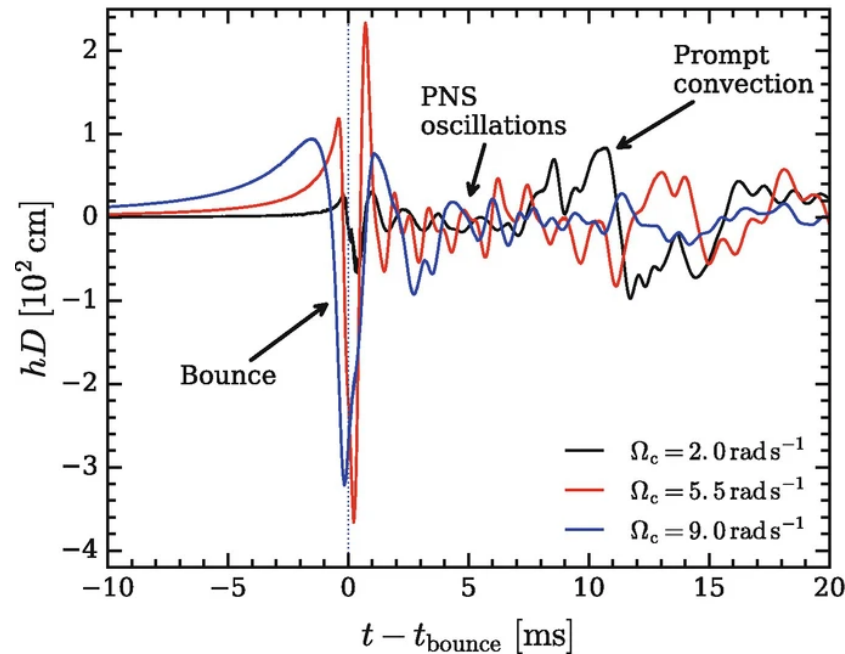
Jani et al. 2020

3. The future: Neutrinos and Gravitational Waves?

Core Collapse Supernovae (CCSNe) in Milky Way and Magellanic Clouds:

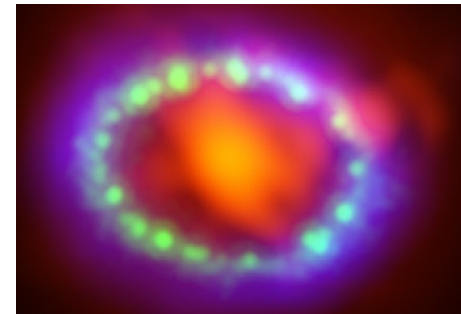
Einstein Telescope horizon for CCSNe up to 100 kpc

Abac et al. 2025 (ET Blue Book)



Abdikamalov+ 2022

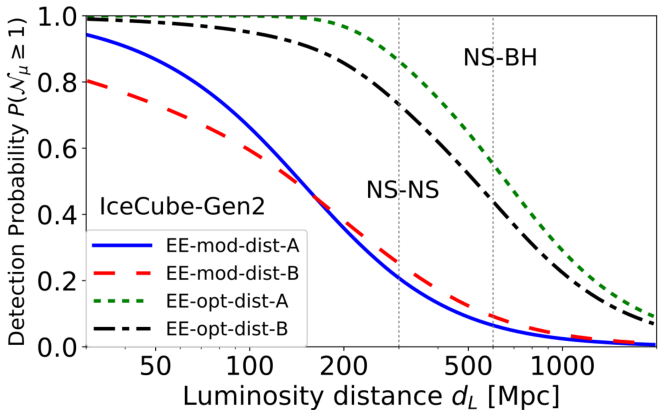
SN1987A



Credit: ESO, ESA, NASA

3. The future: Neutrinos and Gravitational Waves?

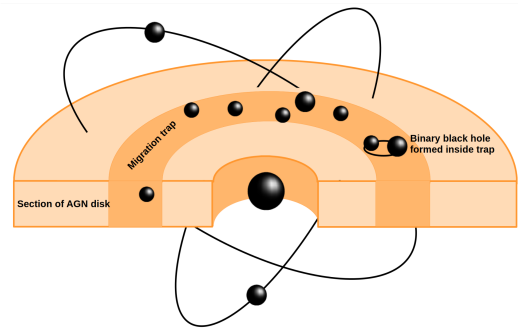
Mergers of compact binaries associated with γ -ray bursts:



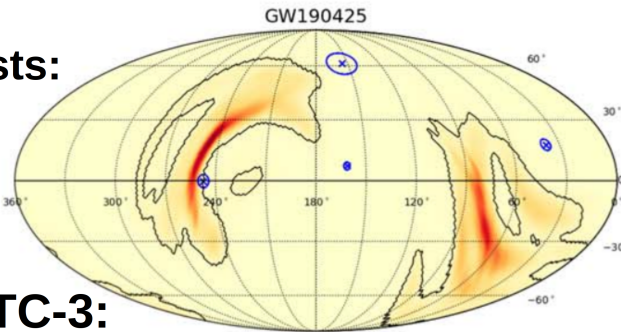
Kimura et al. 2017

Stellar-origin binary black hole mergers in AGN disks:

TeV–PeV neutrinos
from jet or disc shocks

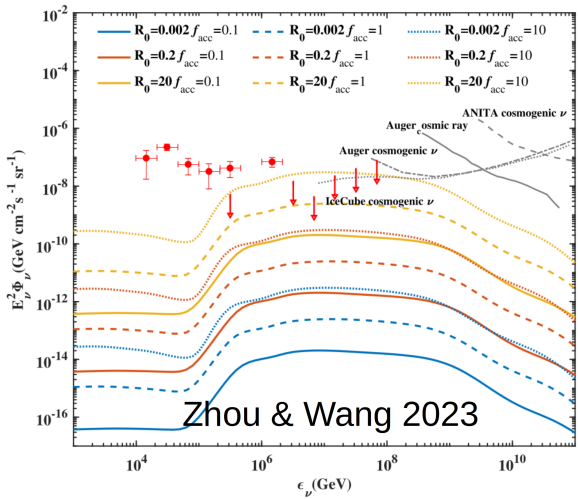


Vaccaro, MM et al. 2024



IceCube & GWTC-3:
“No significant neutrino emission was observed”
Abbasi et al. 2023

Same for ANTARES, Pierre Auger,..

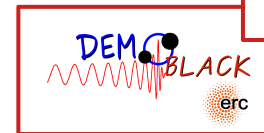


4. Conclusions and future perspective

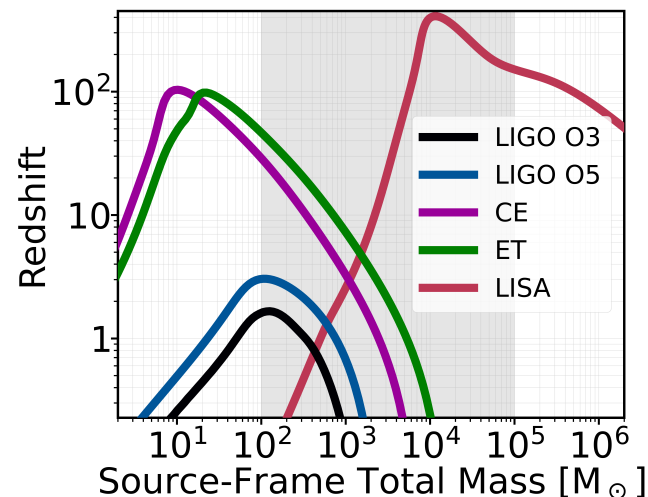
- The present: **more than 200 detections**, mostly binary black holes
- We can study the mass and spin of black holes:
 - astrophysical formation channels (**stellar evolution with GWs**)
 - probes of general relativity and beyond (**gravity with GWs**)

• Next-gen GW detectors

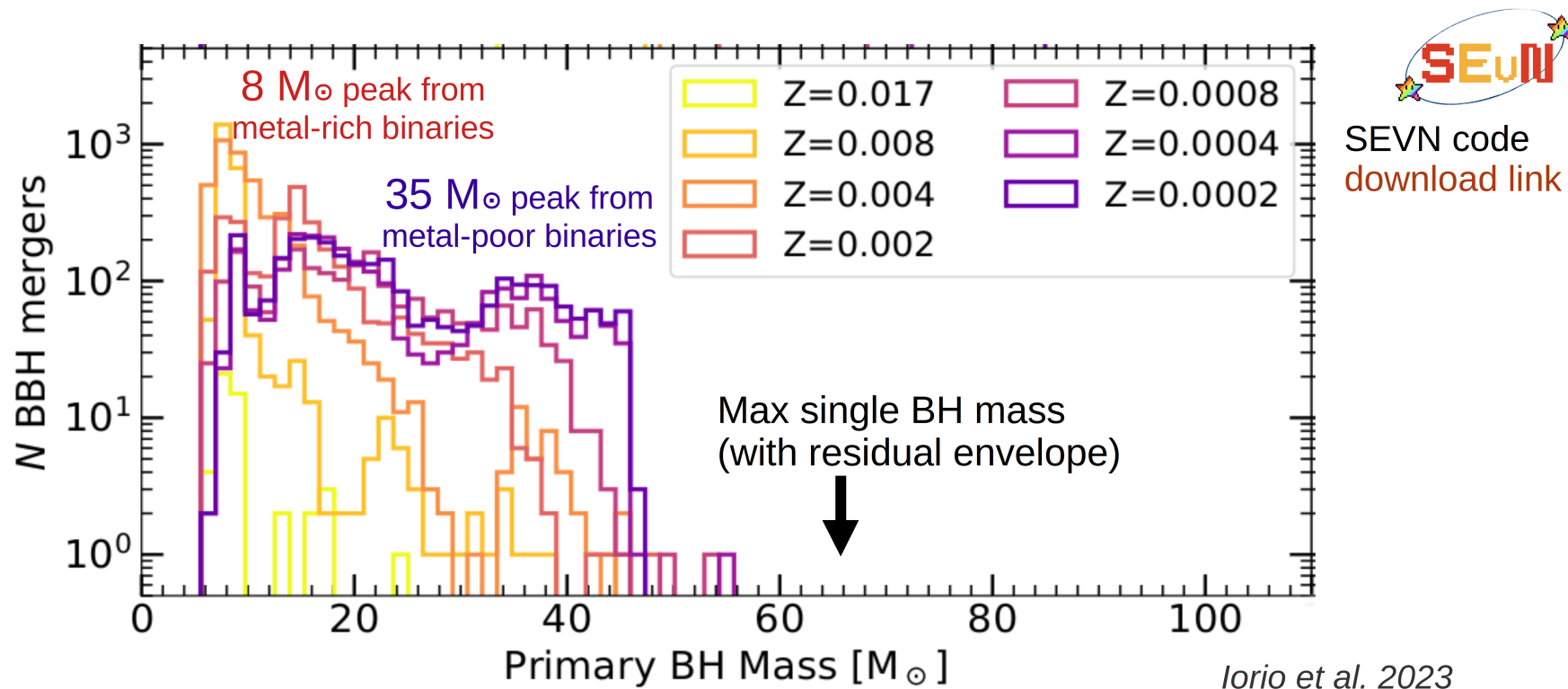
- $> 10^5$ binary black hole detections / yr
- Multi-band GW observations
- 1000 EVENTS with SNR > 100 : excellent mass, spin, eccentricity measurement and tests of gravity
- Sub deg^2 localization
- Mergers up to $z = 100$, 16 Myr after Big Bang (**cosmology with GWs**)
- Evolution of binary neutron stars for 1 day (electromagnetic precursors & **neutrino joint detection**)
- Core collapse SNe up to 100 kpc → **neutrino joint detection**



THANK YOU



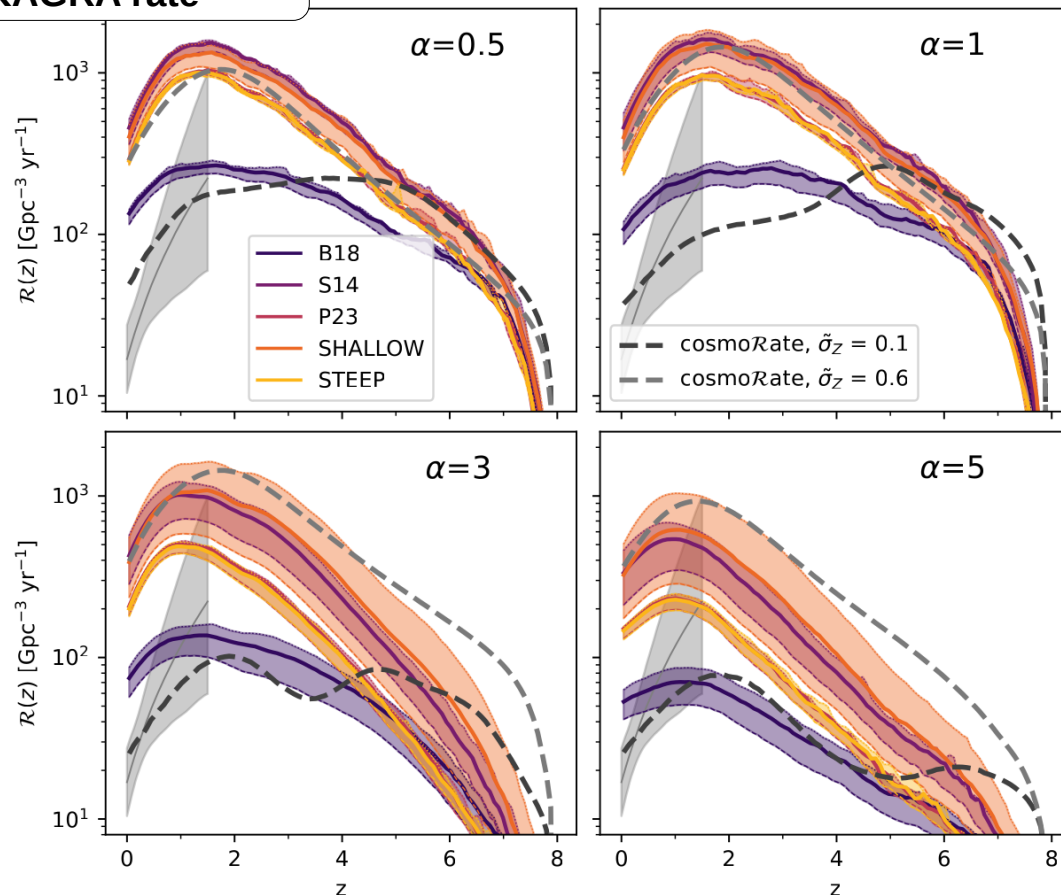
2. The present: the fourth gravitational-wave transient catalog (GWTC-4)



SEVN code
download link

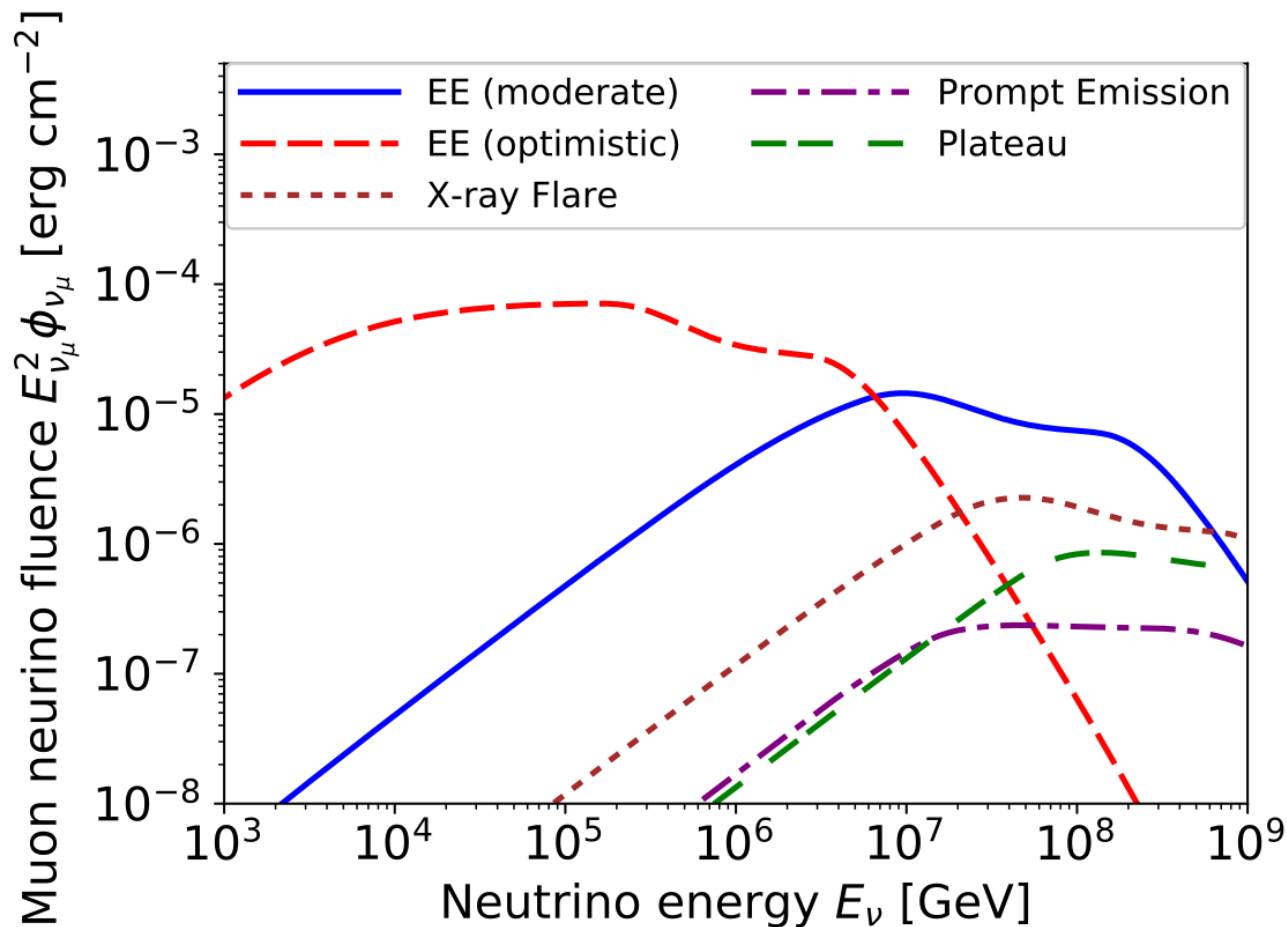
2. The present: the fourth gravitational-wave transient catalog (GWTC-4)

Excess of simulated binary black hole mergers compared to LIGO-Virgo-KAGRA rate



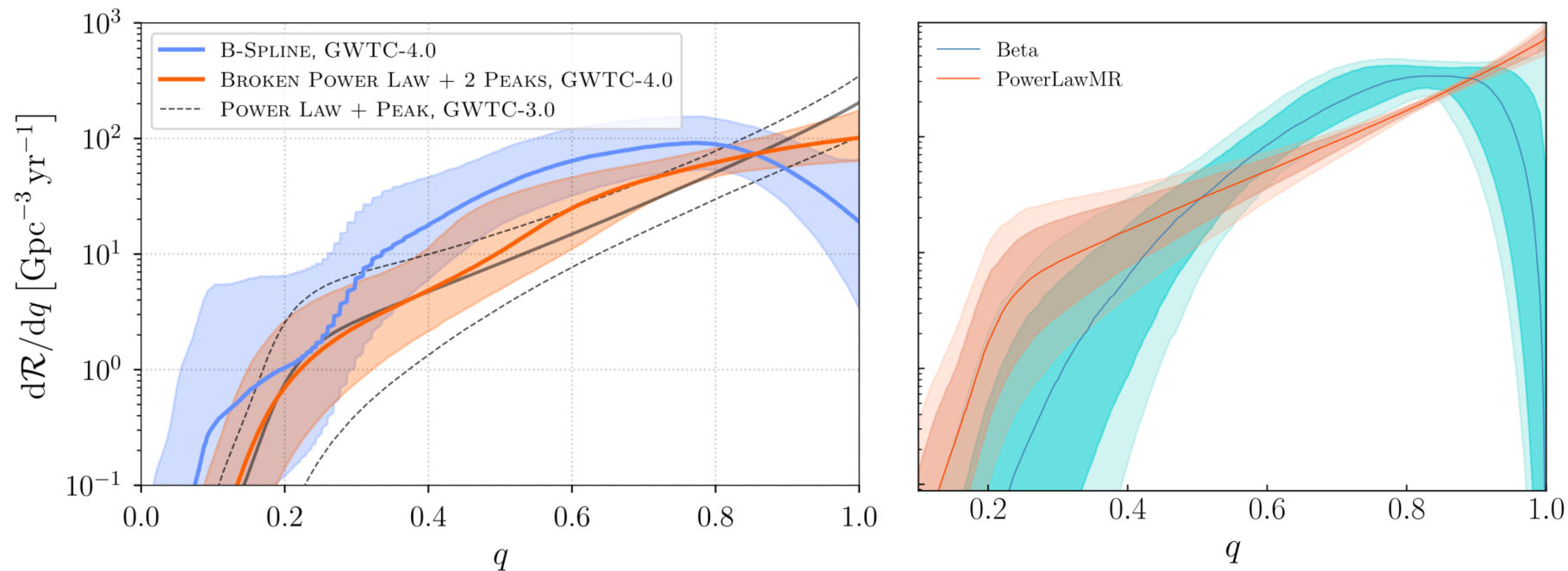
Sgalletta et al. 2024

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)



Kimura et al. 2017

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)

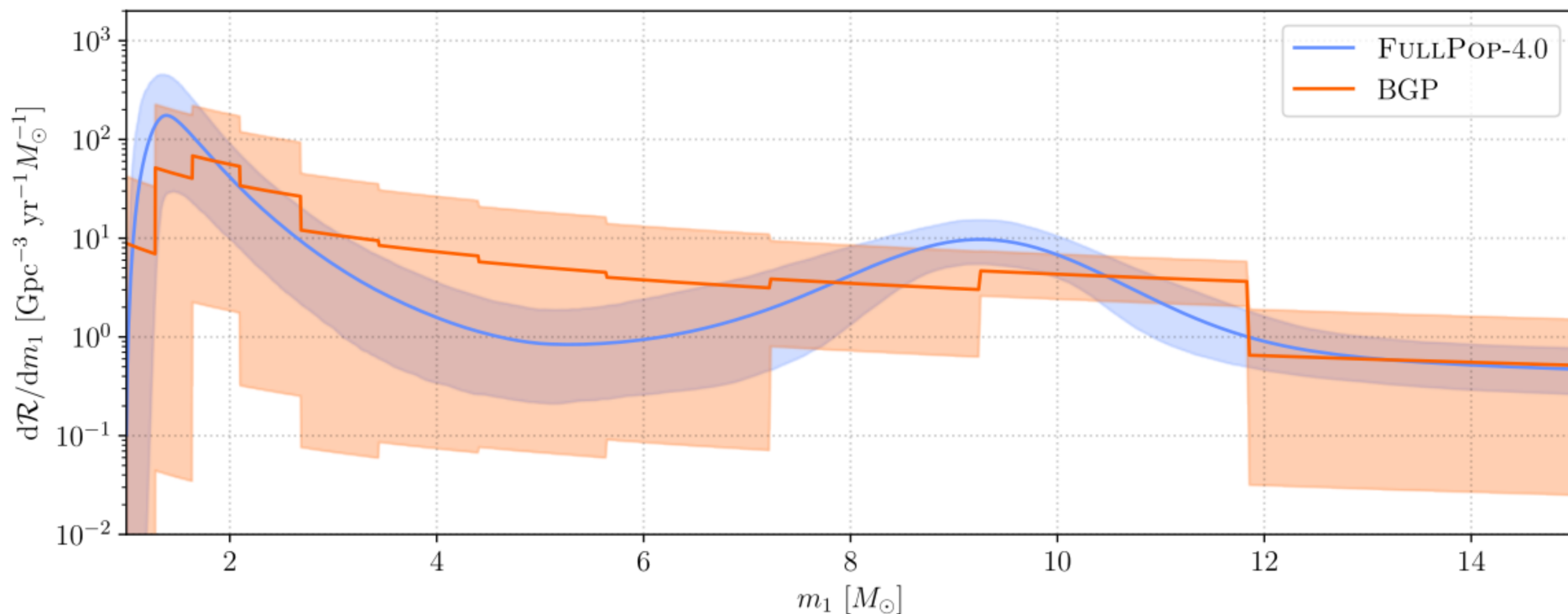


GWTC-4 population paper

Mass ratio: first indication of deviations from equal mass

2. The present: the fourth gravitational-wave transient catalog (GWTC-4)

GWTC-4 population paper



NO GAP between neutron stars and black holes

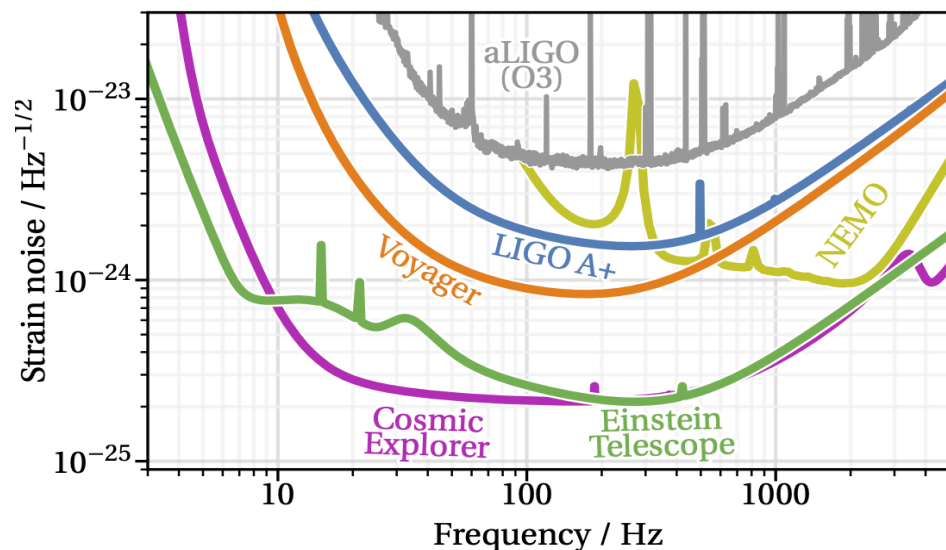
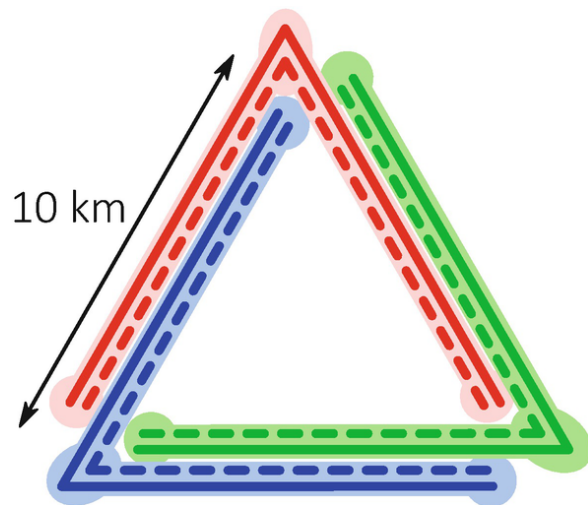
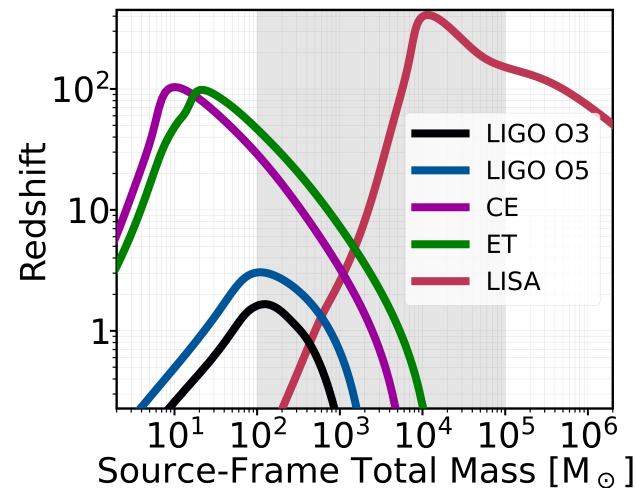
2. Next-Generation Gravitational-Wave (GW) Detectors

Cosmic Explorer:

- * like LIGO but bigger (20km or 40 km)
- * timeframe ?????

Einstein Telescope:

- * like LIGO but bigger (10km or 15 km)
- * UNDERGROUND
(minimizes seismic and Newtonian noise)
- * maybe TRIANGLE (null stream)
- * timeframe > 2035



2. Next-Generation Gravitational-Wave (GW) Detectors

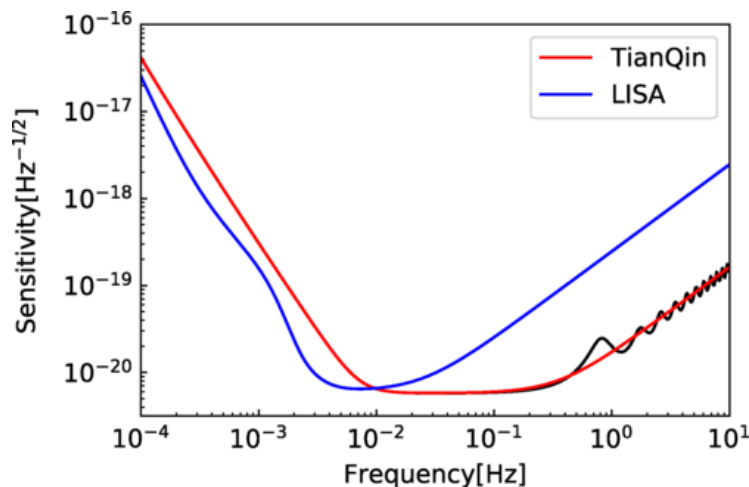
MULTIBAND GW ASTRONOMY

LISA (ESA / NASA)

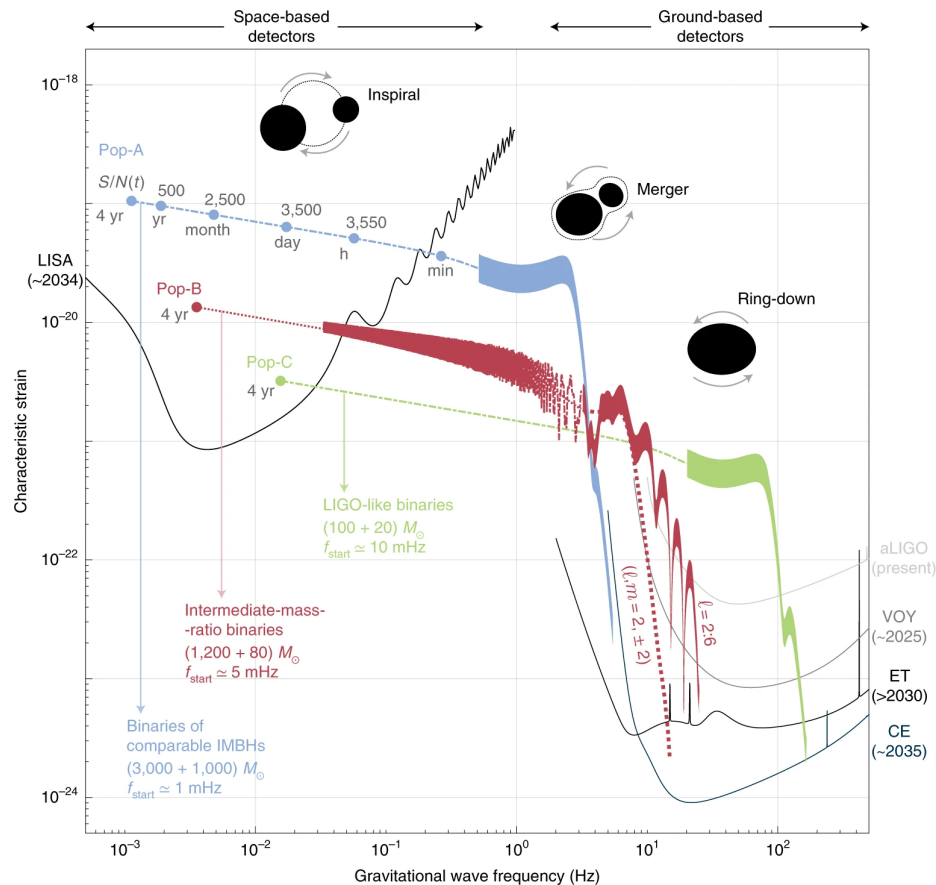
- * 3-spacecraft laser interferometer
- * 2.5M km arms
- * timeframe: 2035 + 4 yr (10 yr?)

TIANQIN (China, Sun Yat Sen University)

- * 3-spacecraft laser interferometer
- * 0.1M km arms
- * timeframe: 2034 + 5 yr (10 yr?)



Huang, Hu, Korol et al. 2019

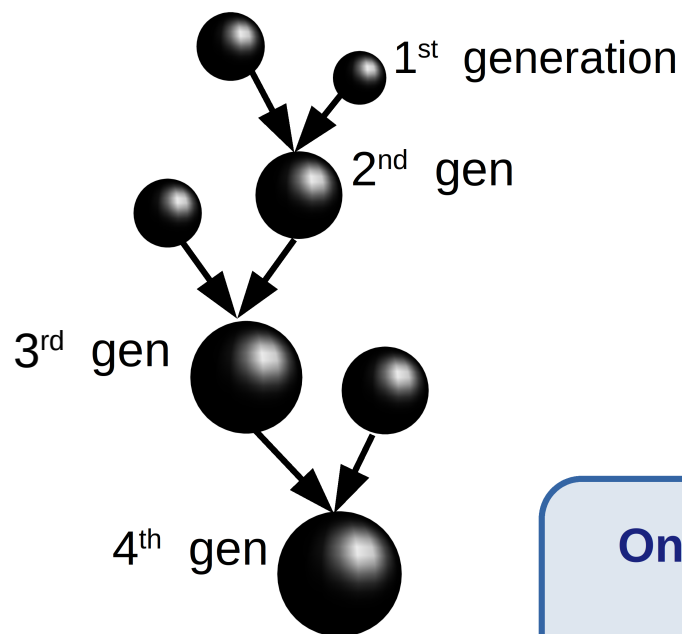


Jani et al. 2020

2. The present: the most massive system in GWTC-4: GW231123

HIERARCHICAL MERGERS

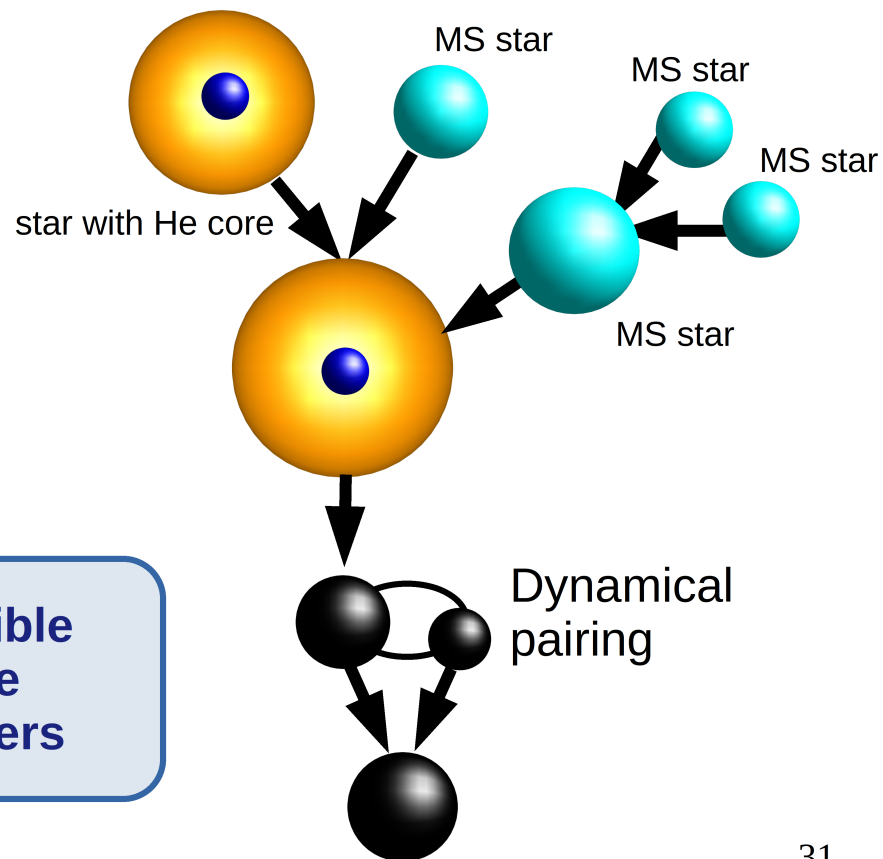
Miller & Hamilton 2002



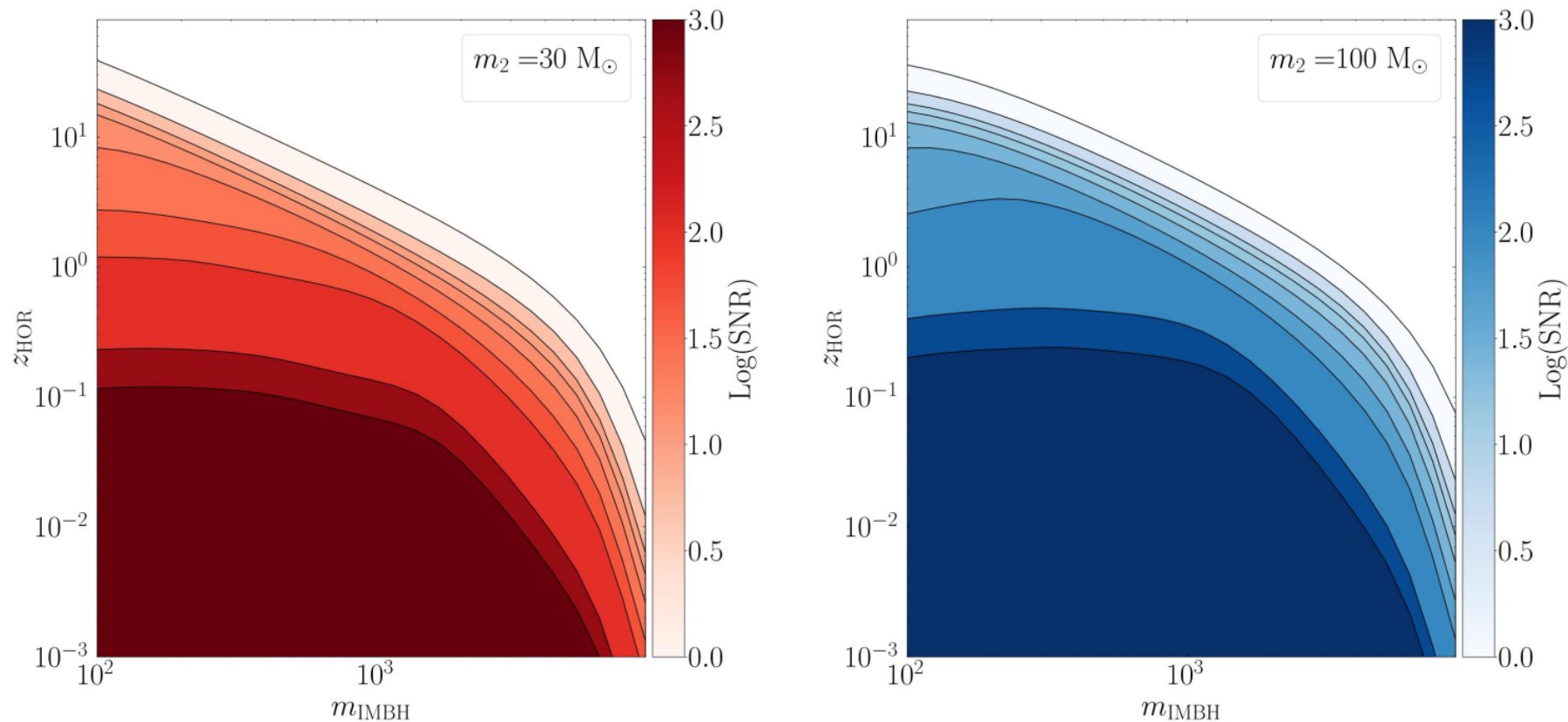
**Only possible
in dense
star clusters**

MULTIPLE STAR COLLISIONS

Portegies Zwart & McMillan 2002



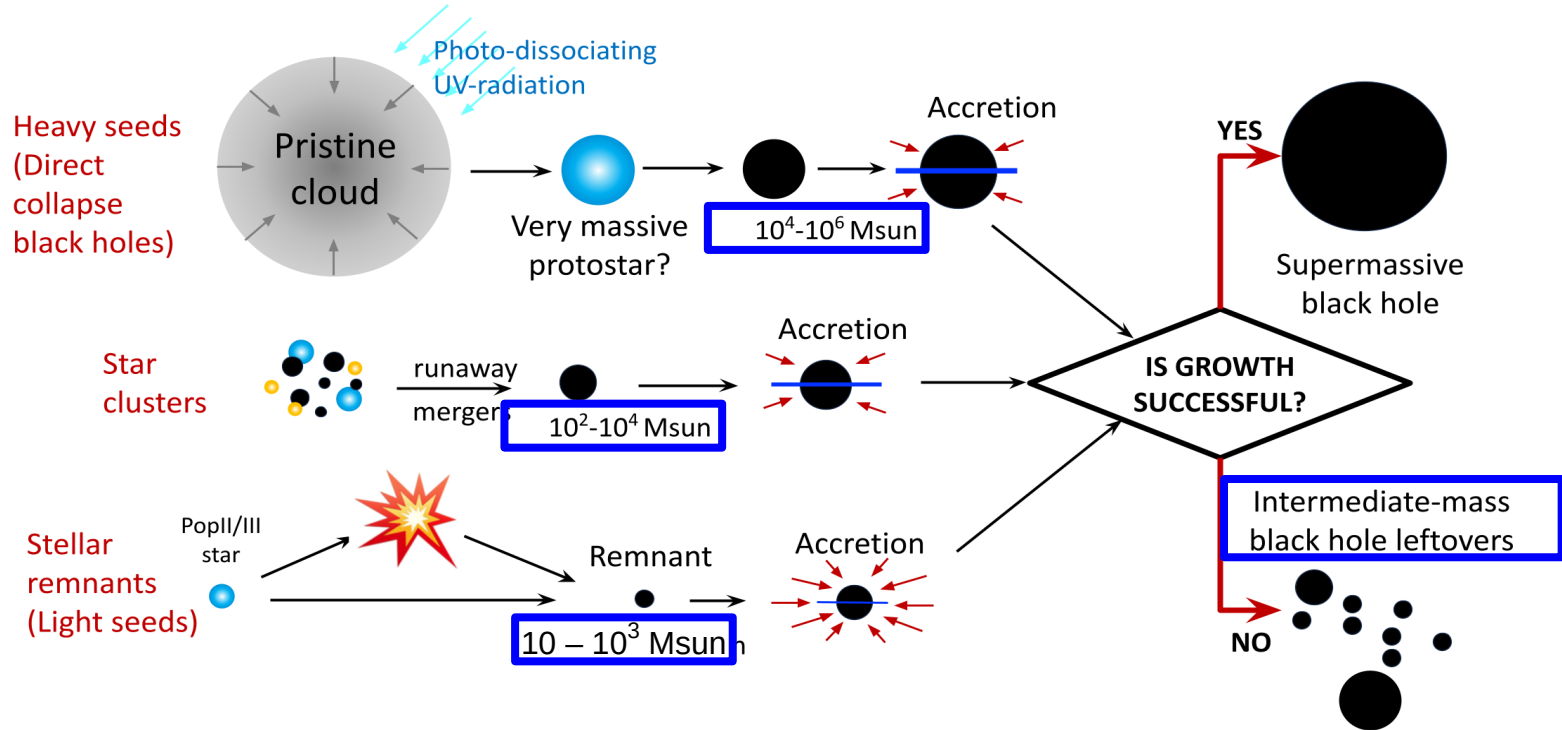
2. Next-Generation Gravitational-Wave (GW) Detectors



Abac et al. 2025, arXiv:2503.12263 (new Einstein Telescope's Blue Book)

1. Intermediate-mass black holes (IMBHs) $\sim 10^2 - 10^5$ Msun

We need them, to form supermassive black holes

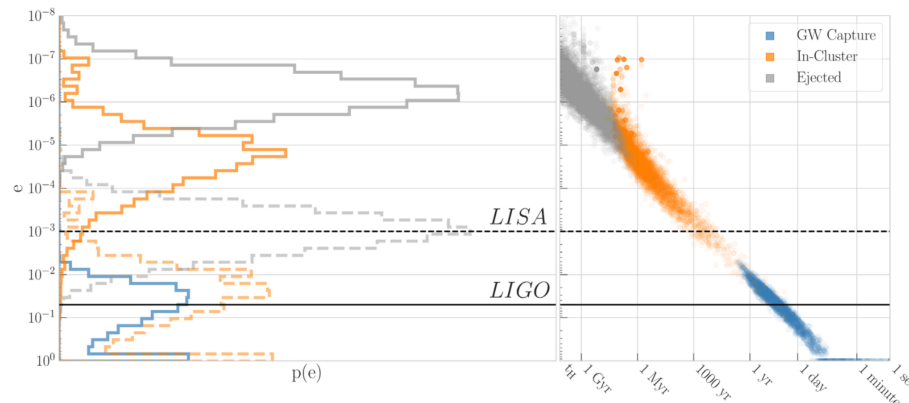


Credit: R. Maiolino, MM, R. Schneider, M. Volonteri

2. Next-Generation Gravitational-Wave (GW) Detectors

LISA/TianQin will see orbital ECCENTRICITY

Zevin et al. 2019

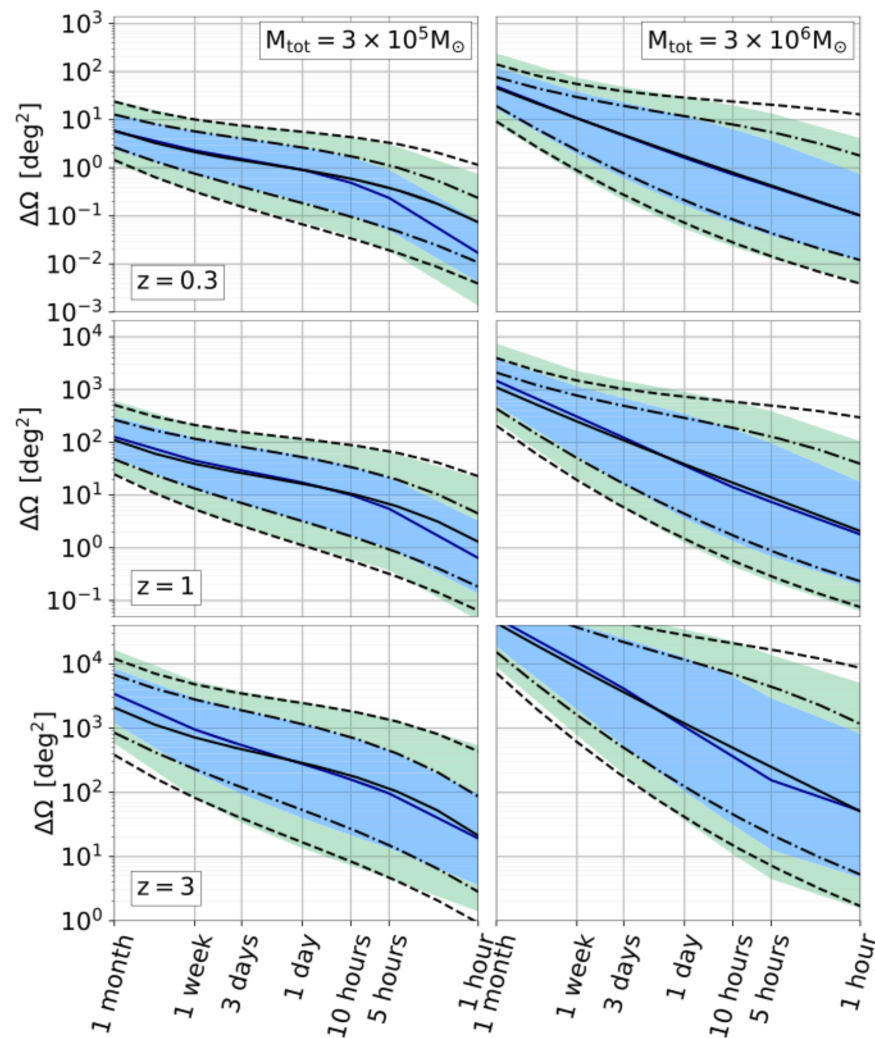


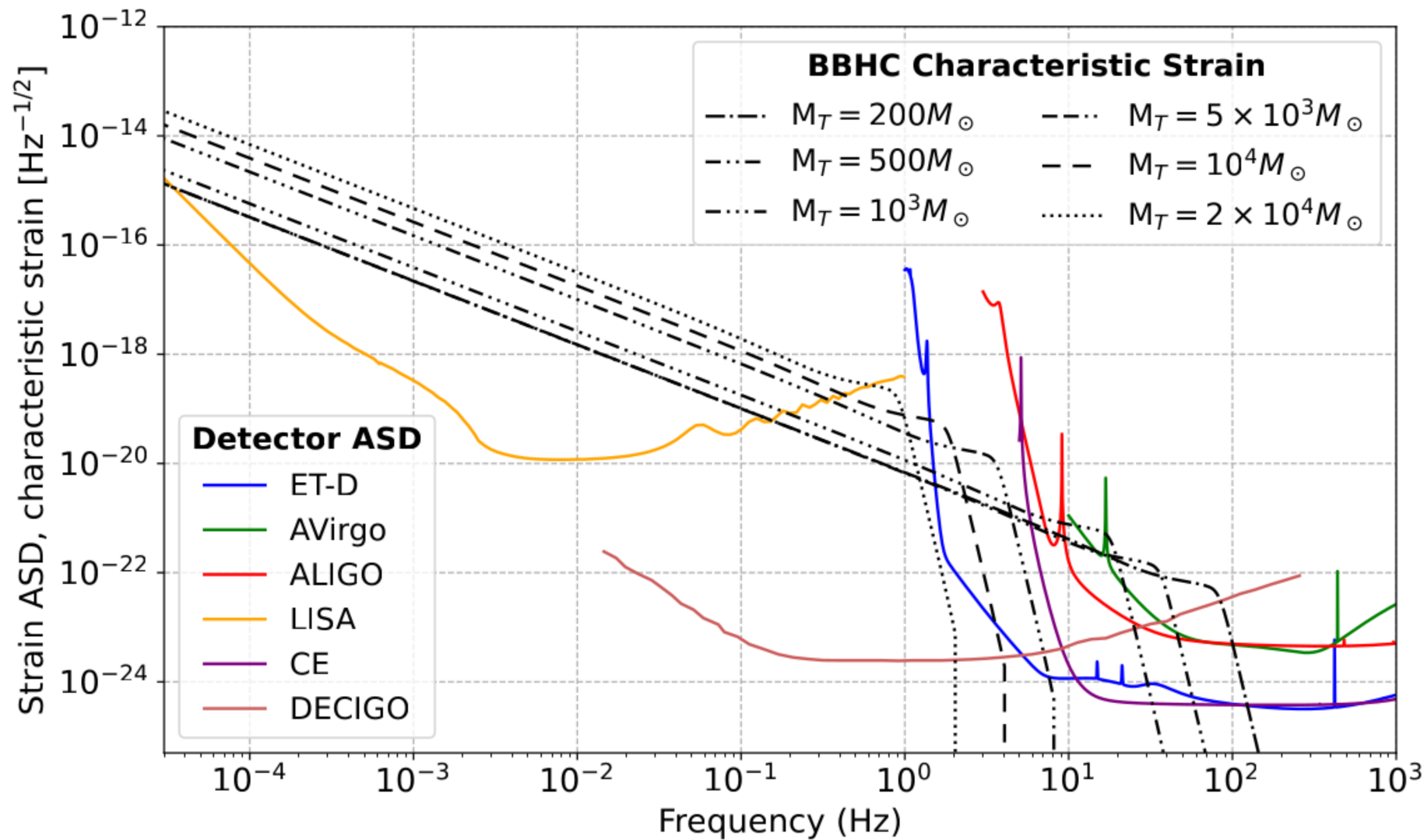
Very good for IMBH formation scenarios

..and yield potentially excellent sky localization

Very good for host galaxy localization and
Electromagnetic counterpart

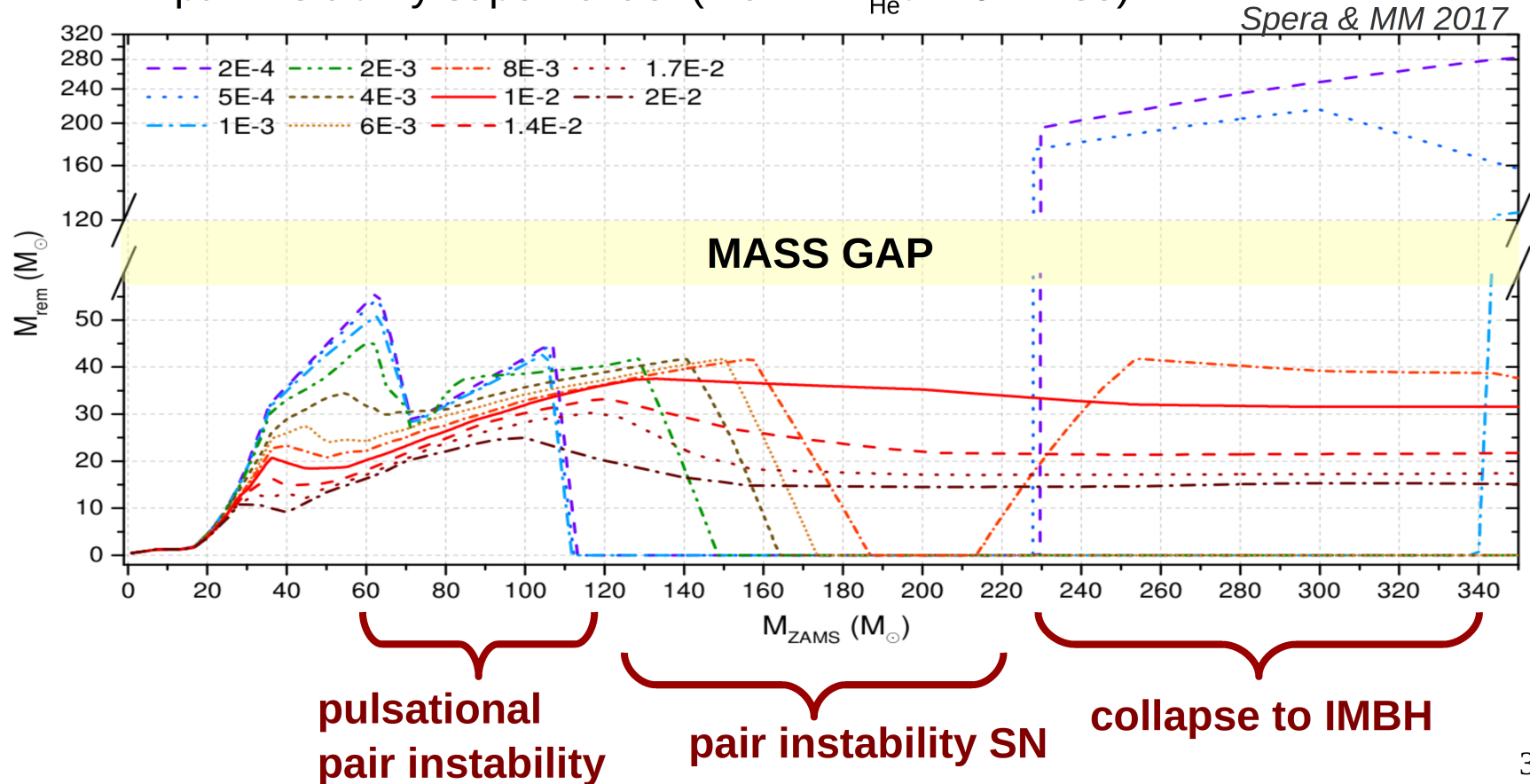
Mangiagli et al. 2020





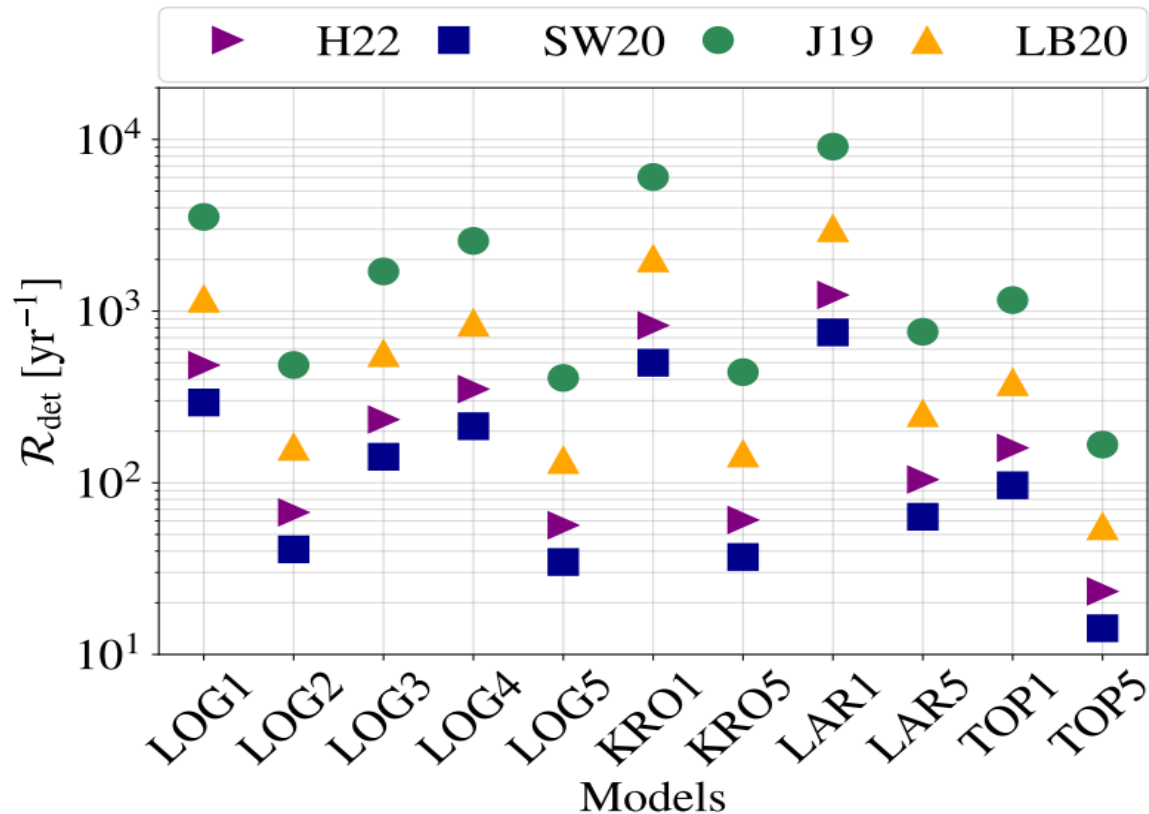
Evolution of very massive stars: impact on IMBH formation

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

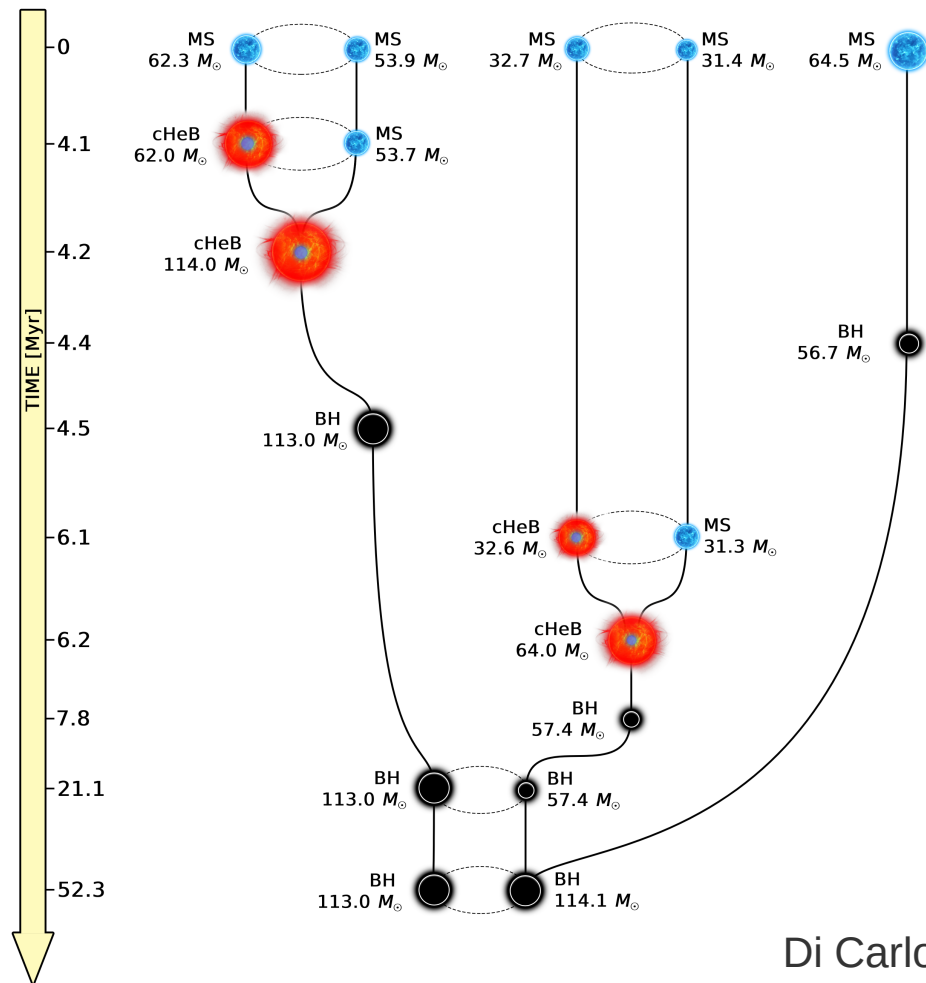


Binary black holes (BBHs) from metal-free and metal-poor stars

Detection rate of Pop. III BBHs from ET



Formation channels of BBHs: stellar mergers



Di Carlo et al. 2021, arXiv2105.01085