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STRUCTURES
CLUSTER OF
EXCELLENCE

Formation and merger rate of binary compact objects

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OUTLINE:

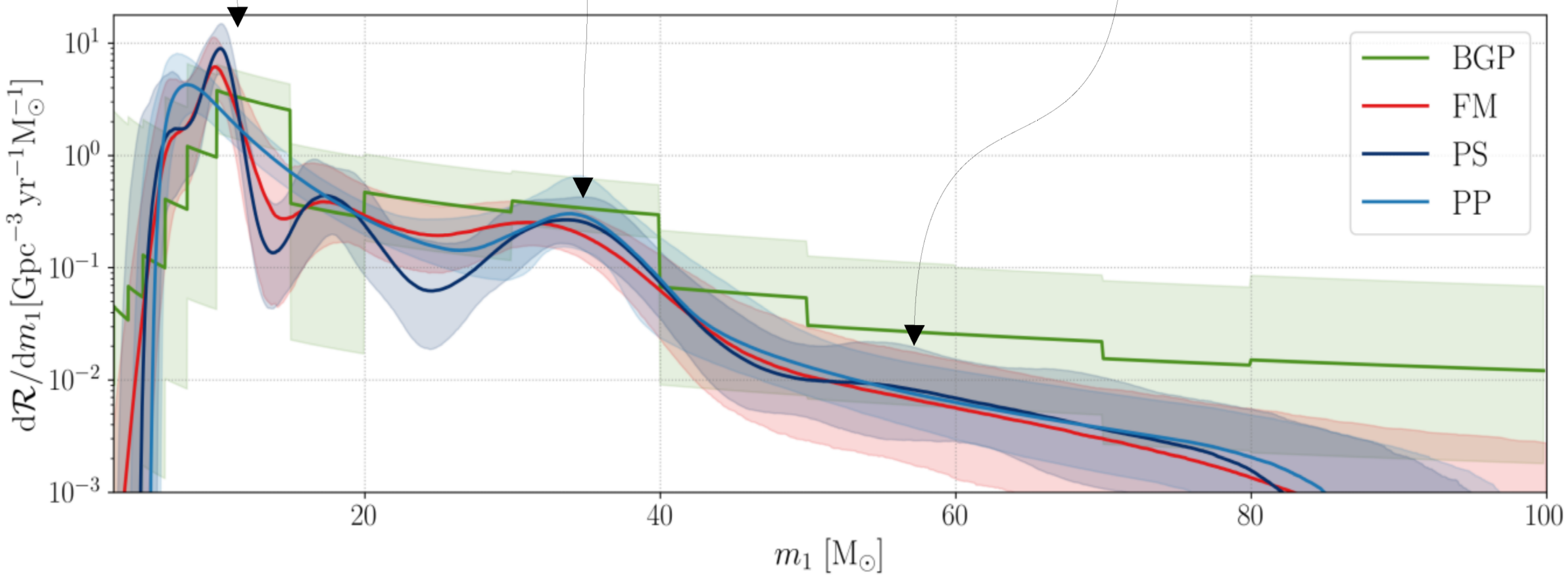
1. A brief recap of gravitational-wave populations
2. Formation of binary compact objects: open questions and problems
3. The merger rate density
4. Host galaxies
5. Conclusions and outlook: Einstein Telescope

1. A brief recap of gravitational-wave (GW) populations

8 – 10 M⊙ peak

~35 M⊙ peak

High-mass tail
(inside pair instability)



Reconstructed
primary mass function:

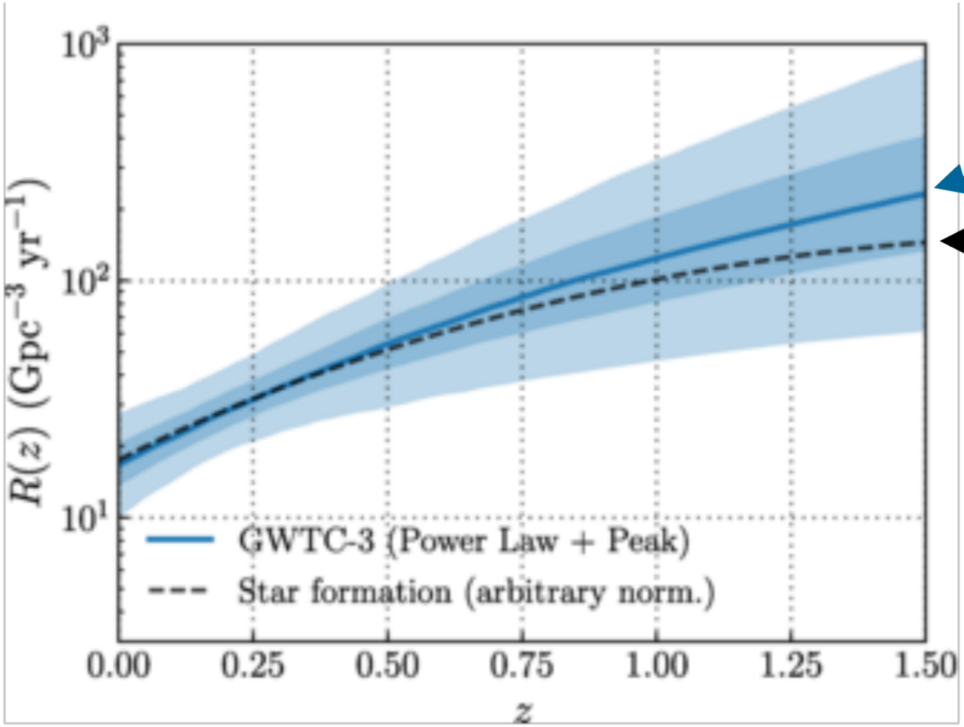
possible peaks at ~ 10 and 35 M⊙
tail up to ~ 80 M⊙

What causes these structures in the mass function?

Abbott et al. 2023, population paper

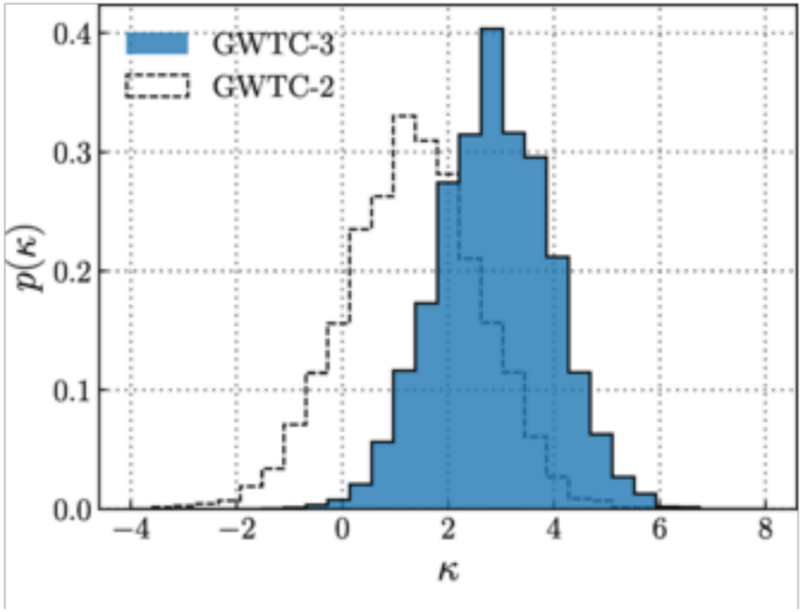
1. A brief recap of gravitational-wave (GW) populations

Binary black hole merger rate density evolution inferred from LVK data



BBH merger rate density

Cosmic star formation rate density

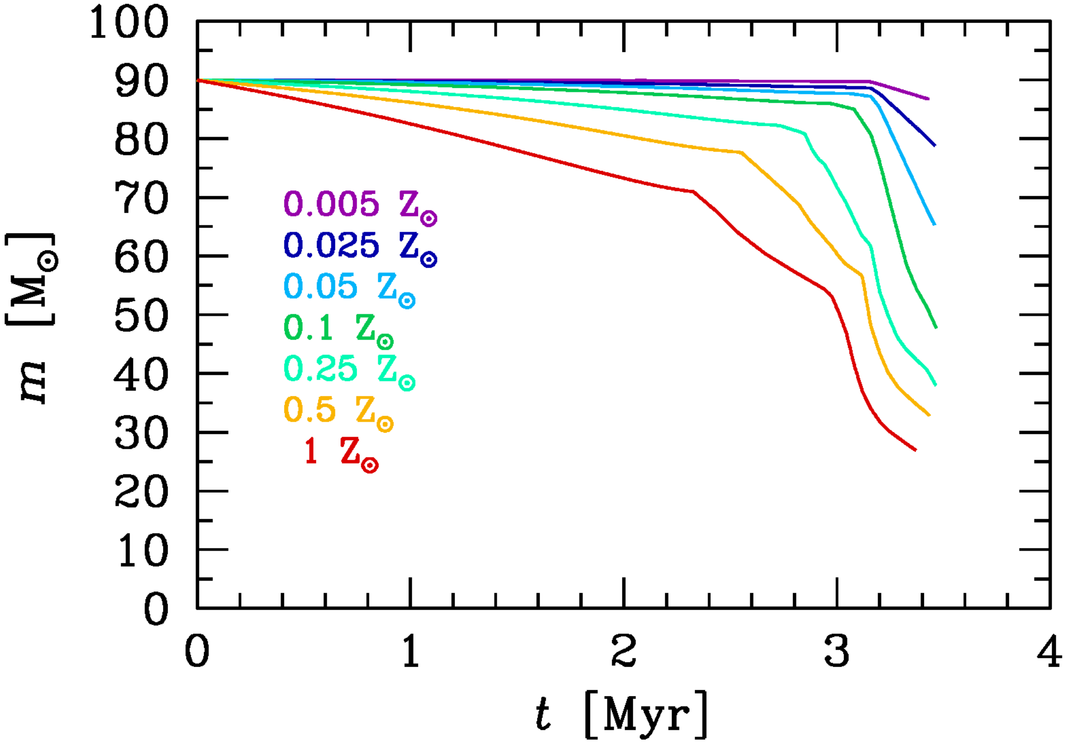


Abbott et al. 2023, population paper

2. Formation of compact objects: winds

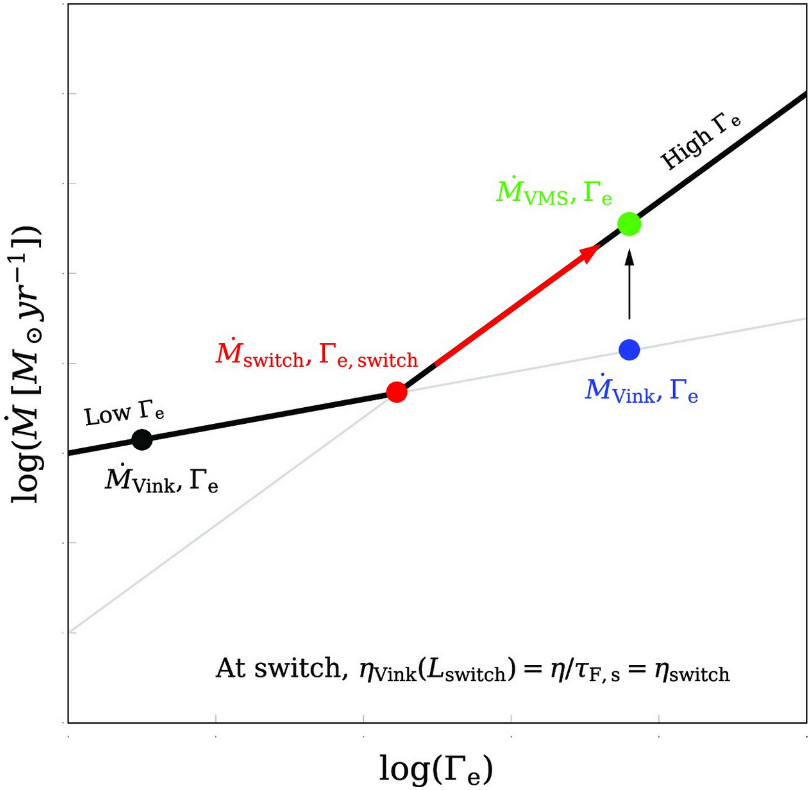
Massive stars (especially black hole progenitors) lose mass by stellar winds

Mass loss higher for metal-rich than metal-poor stars
(e.g. Vink et al. 2001; Vink et al. 2011; Sabhahit et al. 2023)



MM 2021; models by Chen et al. 2015

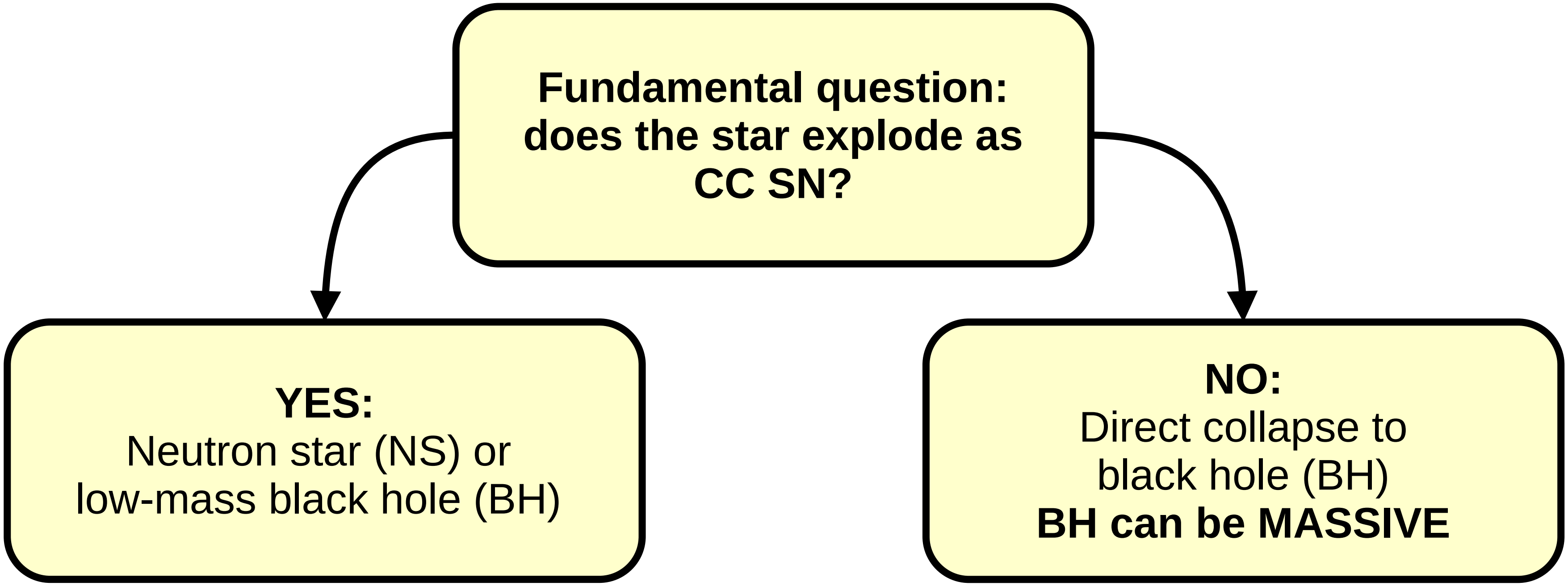
Mass loss higher for radiation-pressure dominated stars, near Eddington limit
(e.g., Graefener & Hamann 2008; Vink et al. 2011; Bestenlehner 2020; Sabhahit et al. 2022)



Sabhahit et al. 2023

2. Formation of compact objects: core collapse supernova

CORE – COLLAPSE SUPERNOVA (CC SN) / DIRECT COLLAPSE:



Fundamental question: does the star explode as CC SN?

YES:
Neutron star (NS) or
low-mass black hole (BH)

NO:
Direct collapse to
black hole (BH)
BH can be MASSIVE

**Since metal-poor stars have larger pre-supernova masses,
they are more likely to directly collapse, producing more massive BHs**
(Heger et al. 2003; MM et al. 2009, 2010, 2013; Belczynski et al. 2010; Fryer et al. 2012)

2. Formation of compact objects: pair instability

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

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

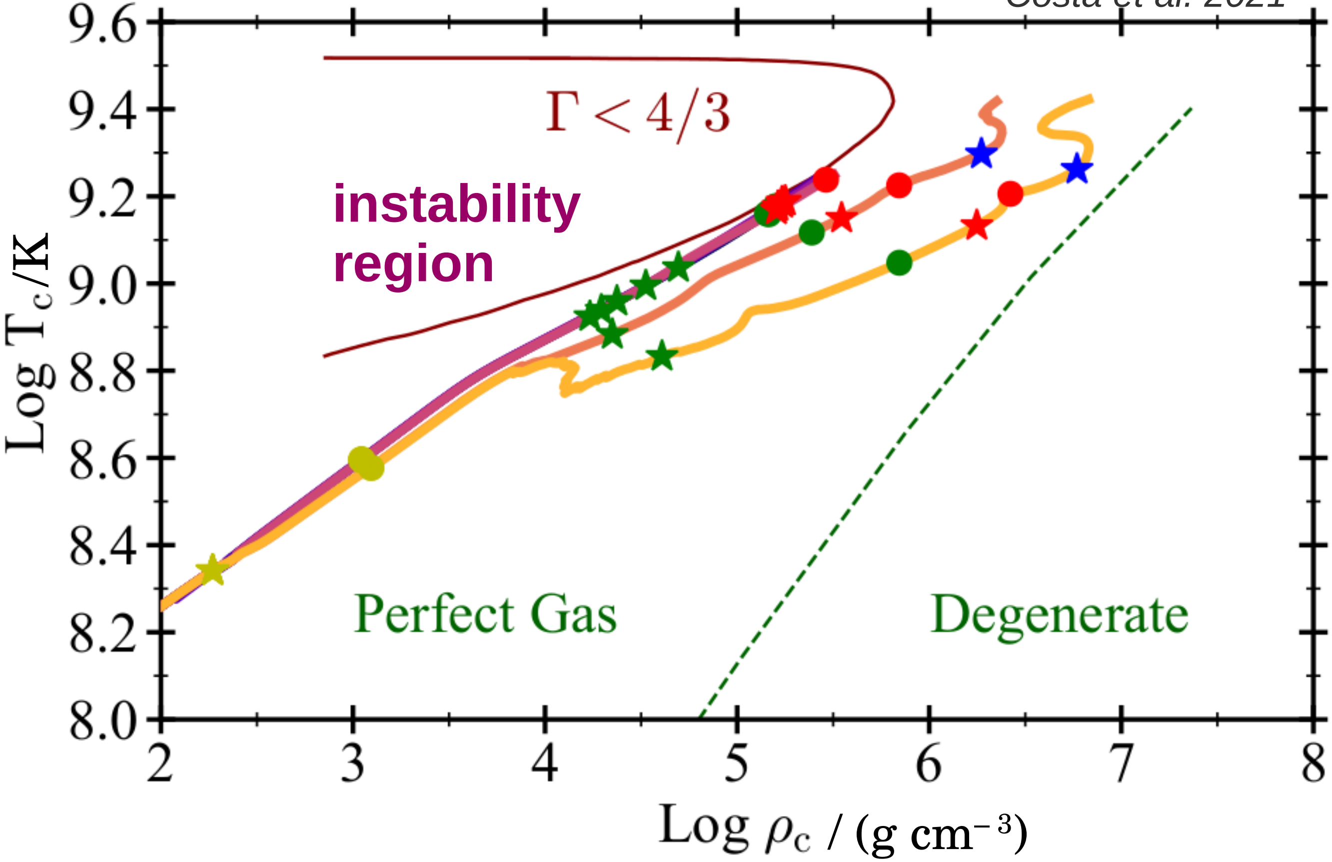
Leading to formation of
electron-positron pairs

Missing photon pressure
triggers instability:

PAIR INSTABILITY

* contraction of
stellar core

* premature ignition of
neon, oxygen, silicon



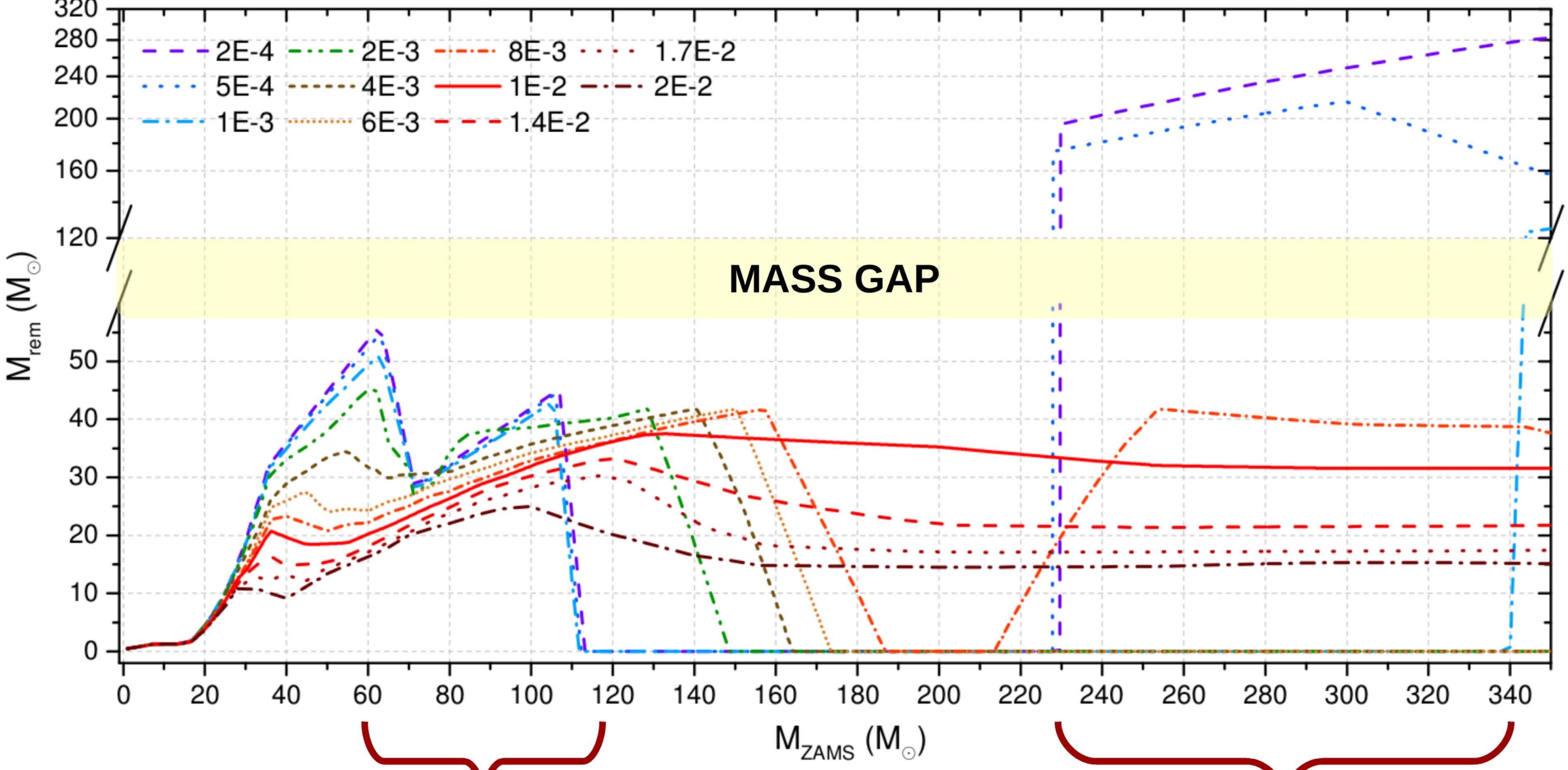
Costa et al. 2021

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

2. Formation of compact objects: pair instability

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



pulsational pair instability

pair instability SN

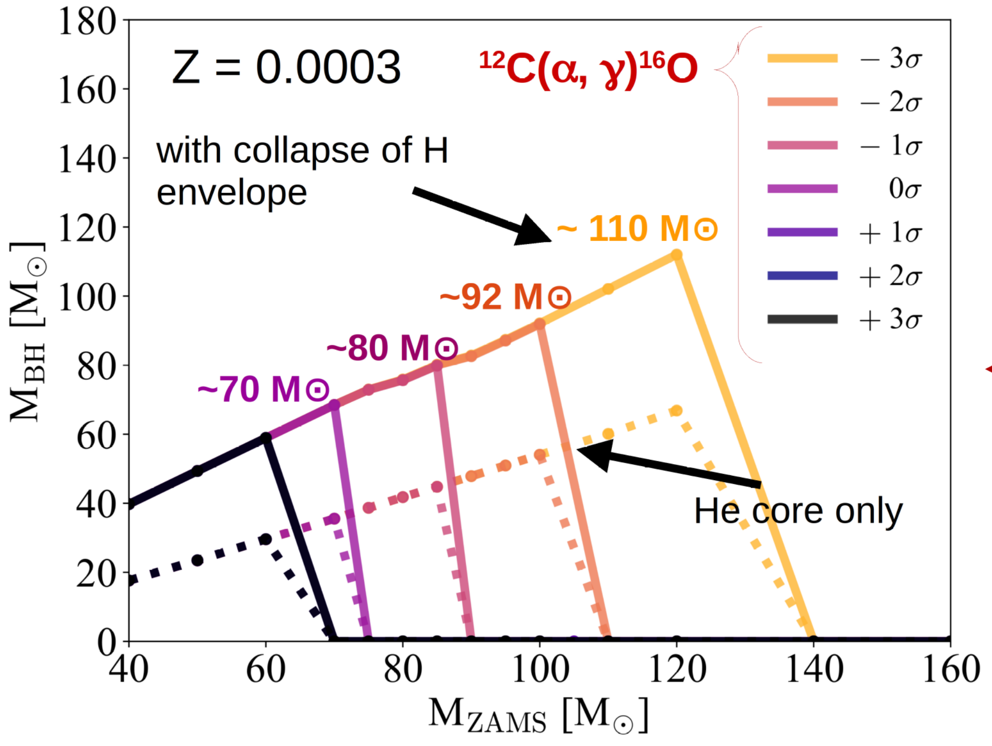
collapse to IMBH

2. Formation of compact objects: pair instability

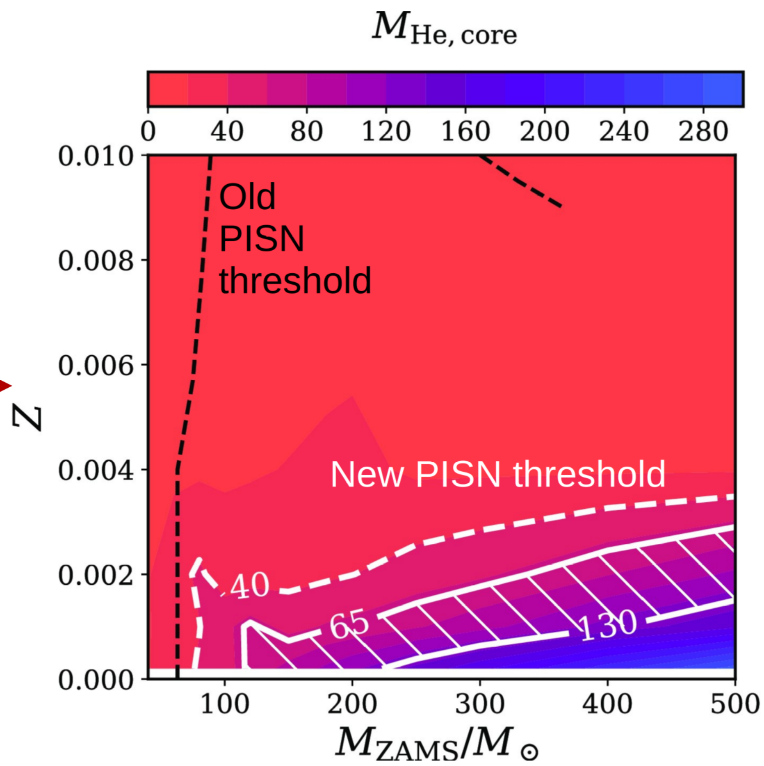
Pair-instability supernovae
cause a **mass gap in the range 50 (?) – 120 (?) Msun**

Envelope undershooting, core overshooting, rotation,
impact of dredge-up, nuclear reactions,
envelope binding energy,
affect the gap and are entangled

Leung et al. 2019; Farmer et al. 2019, 2020; MM et al. 2020; Marchant & Moriya 2020; Renzo et al. 2020; Song et al. 2020; Tanikawa et al. 2021; Farrell et al. 2021; Vink et al. 2021; Woosley & Heger 2021; Farag et al. 2022; Hendriks et al. 2023



Costa et al. 2021



Wind models by *Sabhahit et al. (2023)* move the threshold for pair instability to much lower metallicity (!)

We can shift the mass gap (or even fill it) if H-rich envelope collapses, dredge-up is efficient, etc.

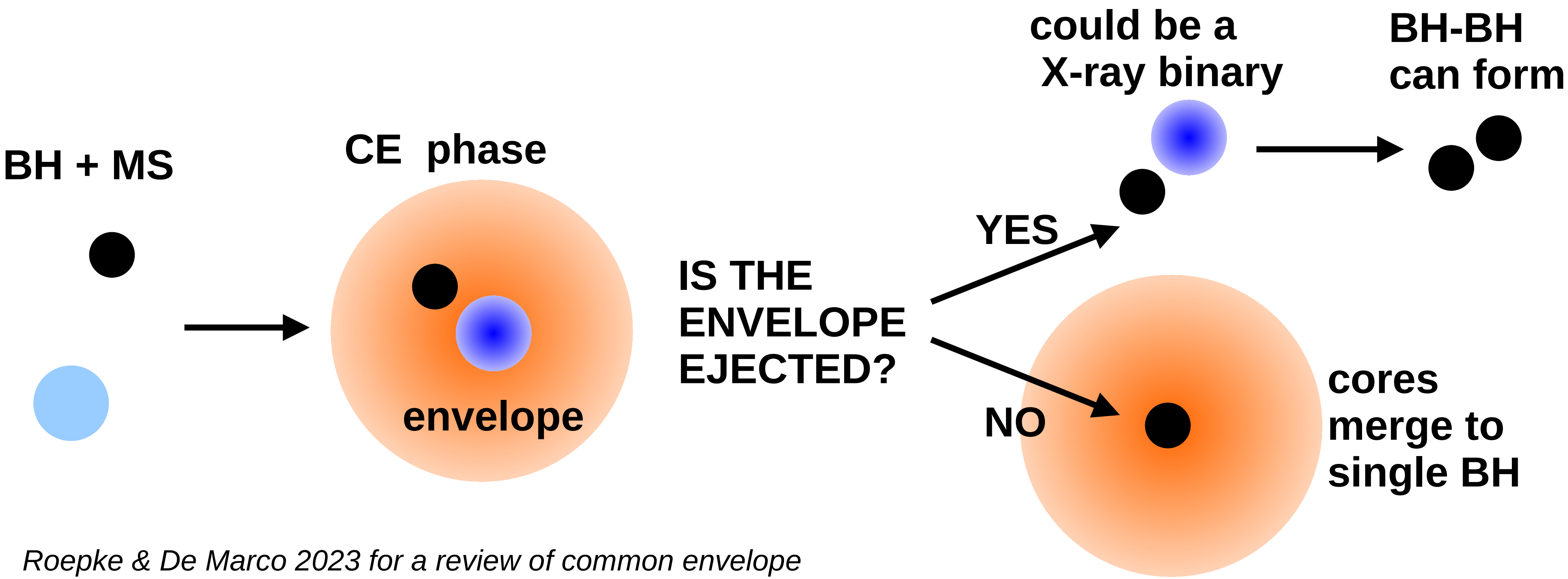
2. Formation of compact objects: mass transfer

Stable/unstable mass transfer:

- envelope removal for one of the two stars
- possible collisions between stars
- unstable mass transfer leads to
  COMMON ENVELOPE phase:
  two stars share same envelope

Credit: ESO, M. Kornmesser,
S.E. de Mink

Marchant & Bodensteiner 2023 for a review of binary evolution



BH + MS

CE phase

envelope

IS THE ENVELOPE EJECTED?

YES

could be a X-ray binary

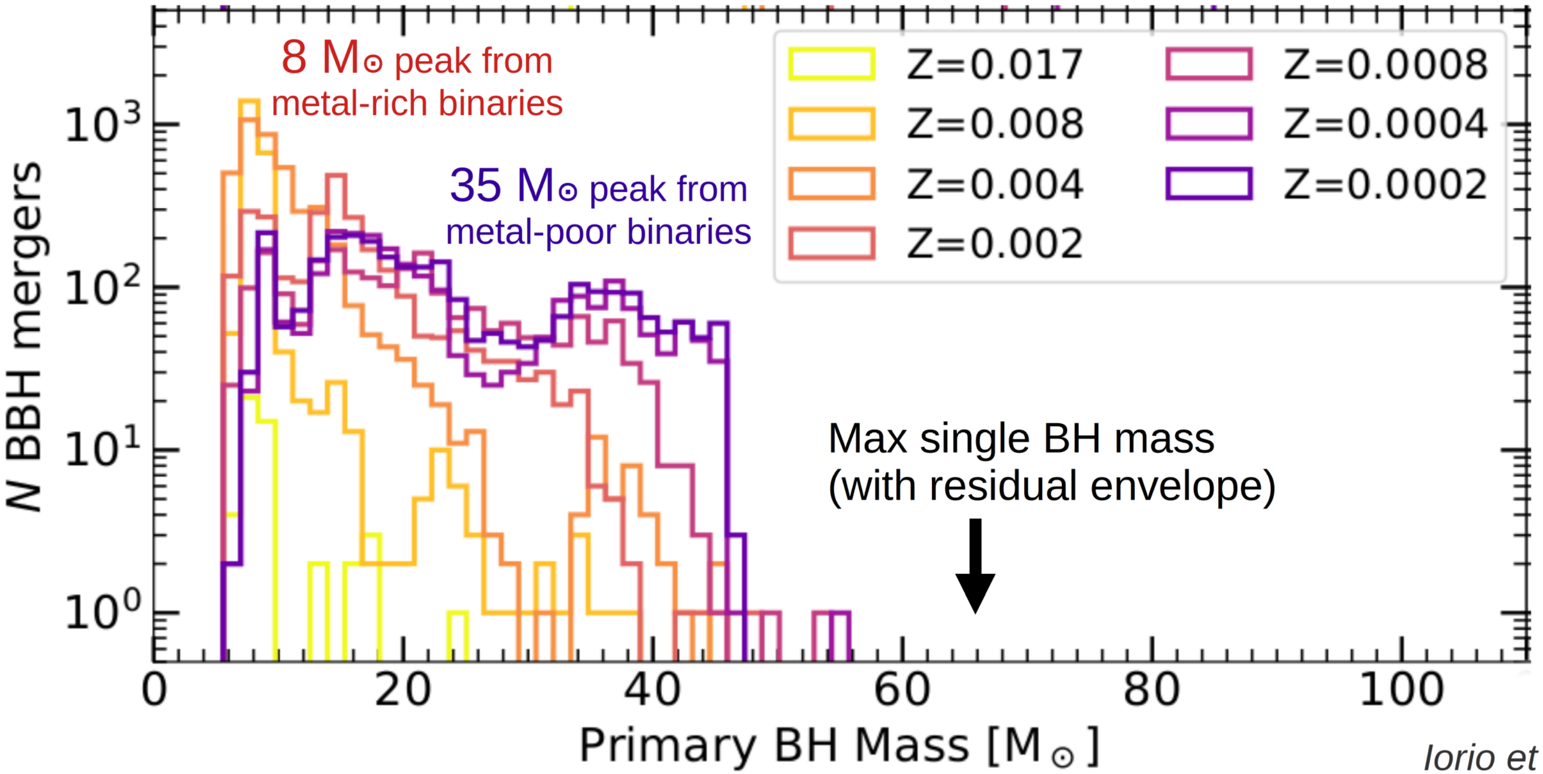
BH-BH can form

NO

cores merge to single BH

Roepke & De Marco 2023 for a review of common envelope

2. Formation of compact objects: “standard” binary evolution scenario



8 M⊙ peak from metal-rich binaries

35 M⊙ peak from metal-poor binaries

Max single BH mass (with residual envelope)

SEVN code
download link

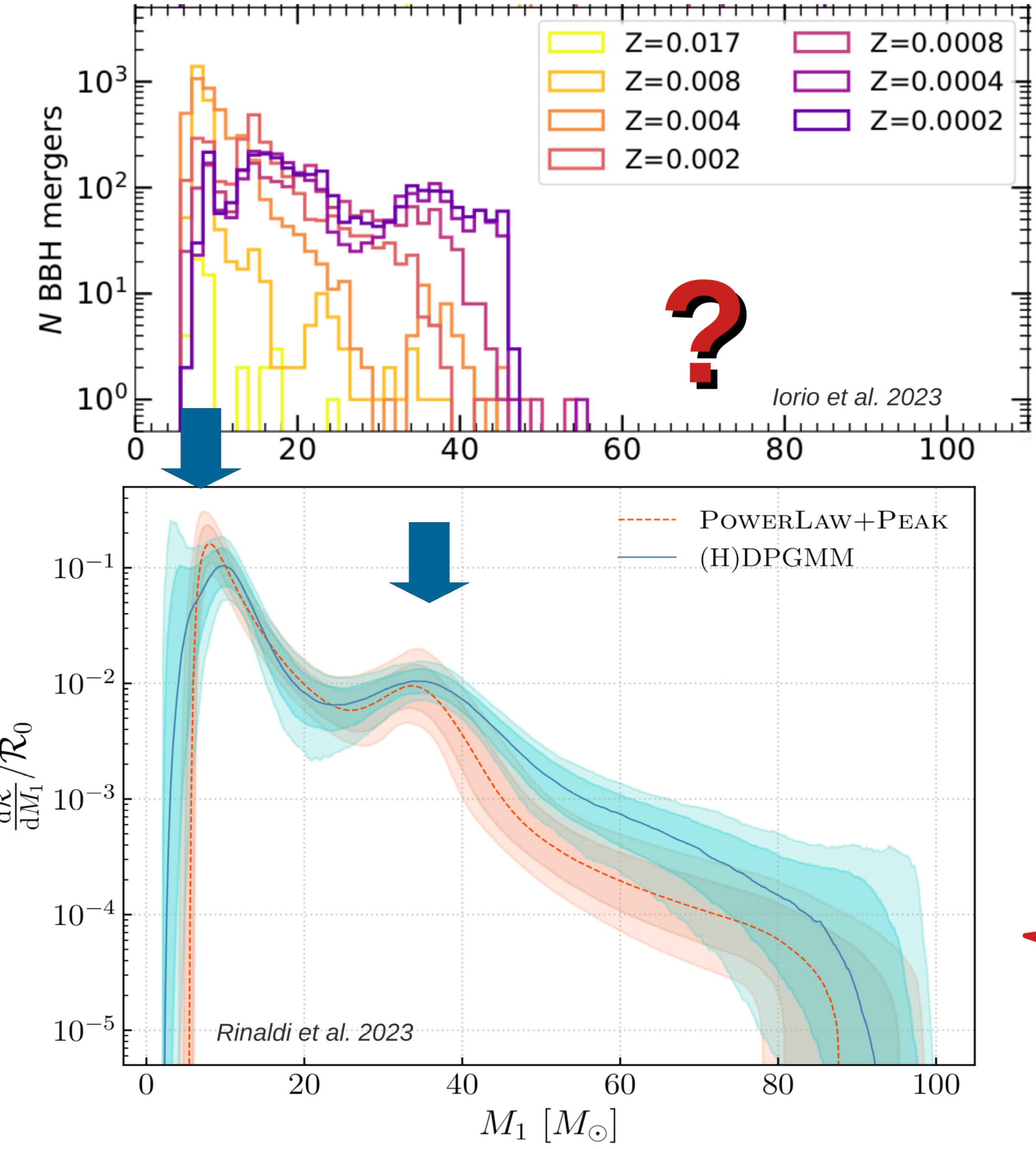
Iorio et al. 2023

* High-metallicity peak at 8 – 10 M⊙ & **Low-metallicity peak at ~35 M⊙**

* BHs with mass ≤ 50 M⊙ merge in isolation (even if max BH mass ~65 M⊙)
because of envelope stripping in binary evolution

*** BBH formation more efficient at low metallicity than high metallicity**
→ most BBH we observe should come from metal-poor objects

2. Formation of compact objects: “standard” binary evolution scenario



Iorio et al. 2023

Rinaldi et al. 2023

Is metallicity the origin of LVK mass peaks?

It may be a coincidence:

- Uncertainties on **core-collapse & pair-instability** SNe
- Uncertainties on **mass transfer**
- Uncertainties on **stellar rotation** (e.g., chem. homogeneous evolution)
- **Merger rates are problematic**

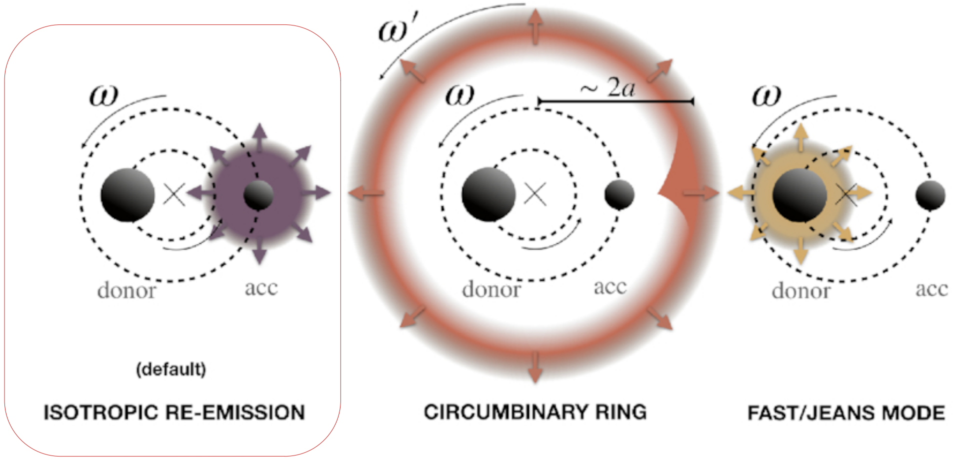
Where do the high BH masses come from?

Dynamics?
see Abbas Askar’s talk

2. Formation of compact objects: uncertainties on mass transfer

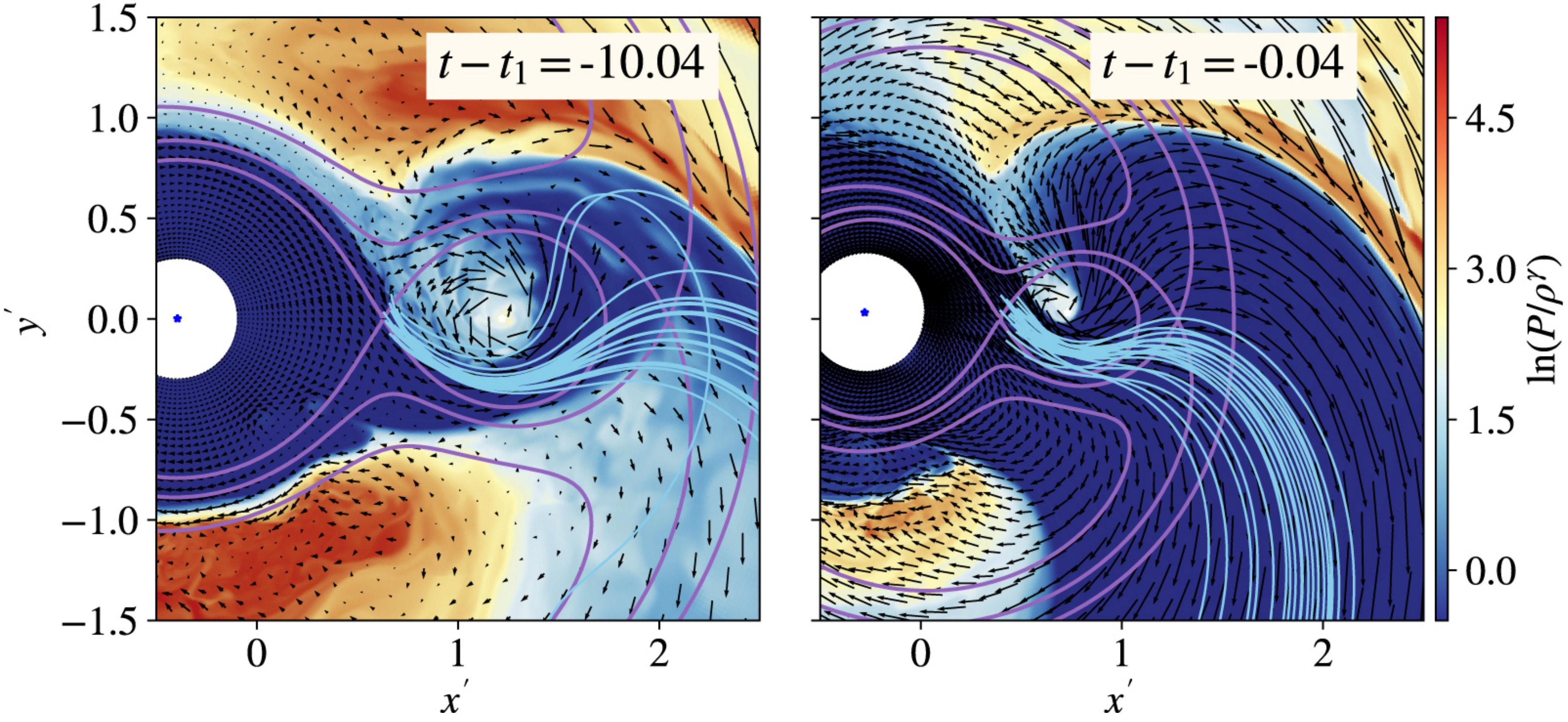
Efficiency of accretion and angular momentum loss

Hydrodynamical simulations by *MacLeod et al. (2018)* suggest matter and angular momentum are lost via L2



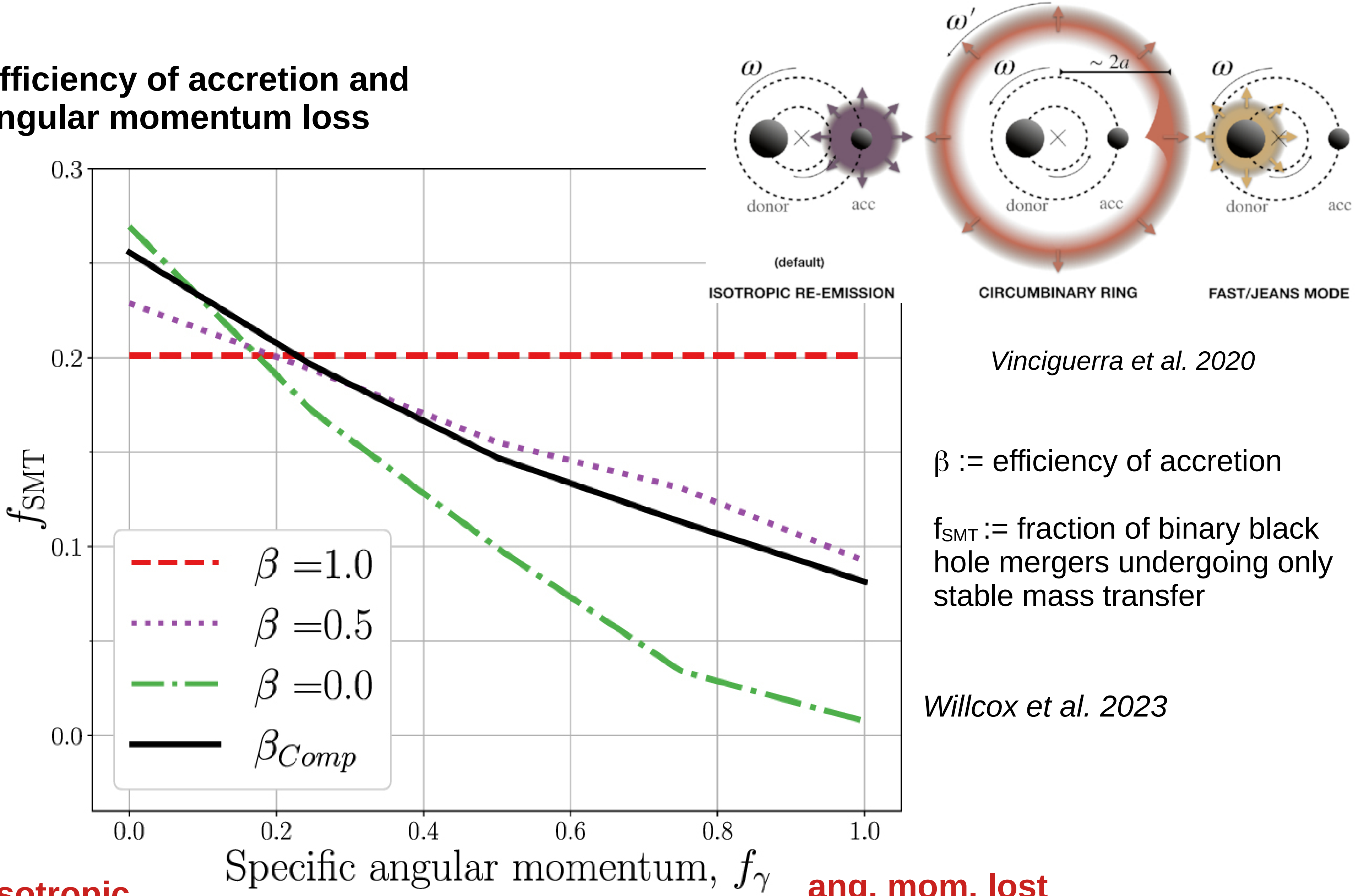
Standard assumption in pop. synthesis

Vinciguerra et al. 2020



2. Formation of compact objects: uncertainties on mass transfer

Efficiency of accretion and angular momentum loss



Vinciguerra et al. 2020

β := efficiency of accretion

$f_{\rm SMT}$:= fraction of binary black hole mergers undergoing only stable mass transfer

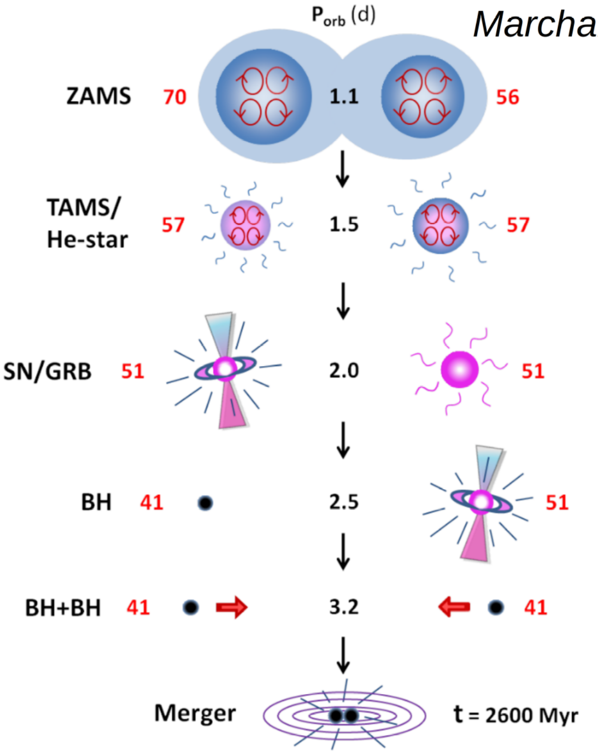
Willcox et al. 2023

isotropic re-emission

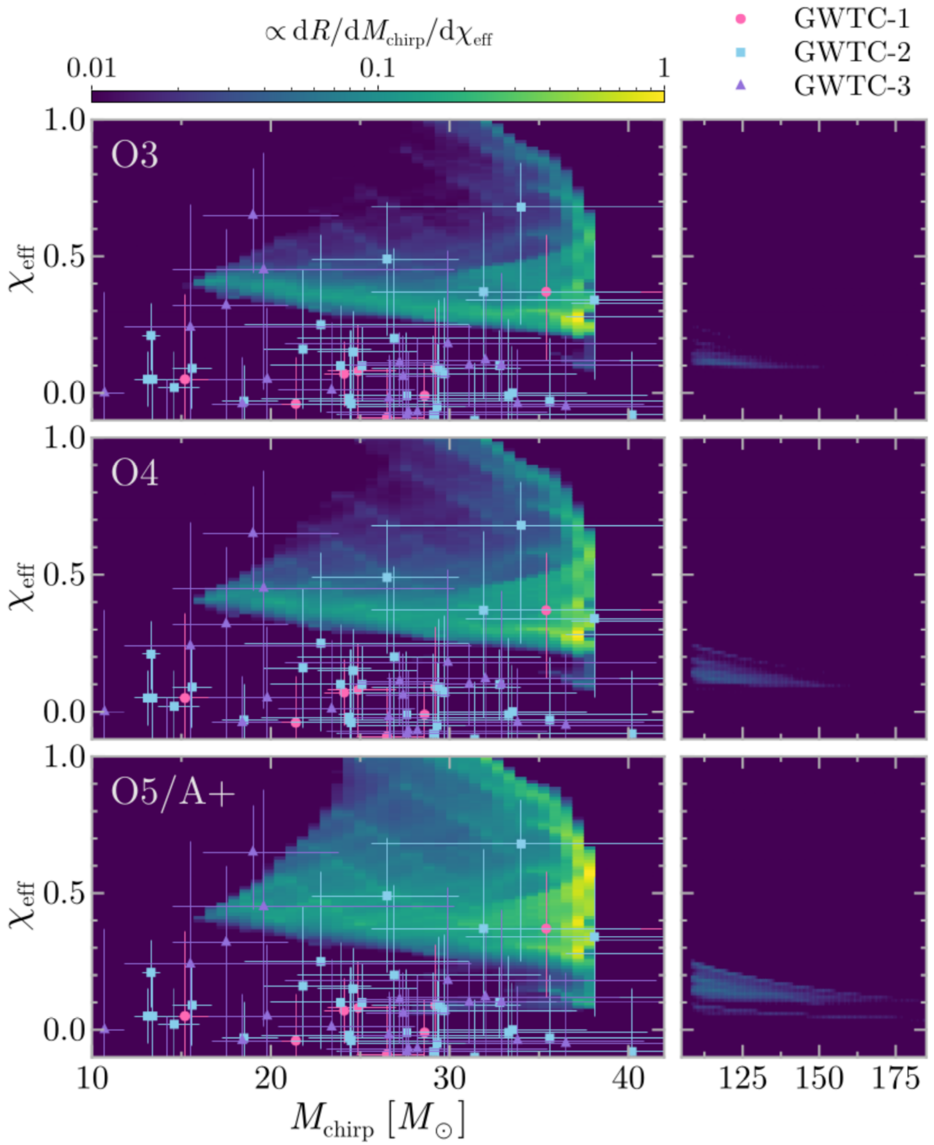
ang. mom. lost from L2

2. Formation of compact objects: uncertainties on rotation

If massive metal-poor binary stars
evolve chemically homogeneous,
they leave completely different binary black holes



Marchant et al. 2016

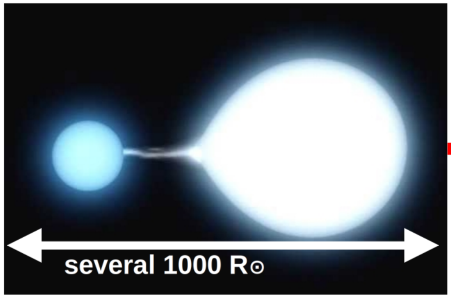


Marchant et al. 2024

- * how many binary black holes from chemically homogeneous evolution?
- * only equal mass or also unequal?
- * always high spin?
- * longer delay times?

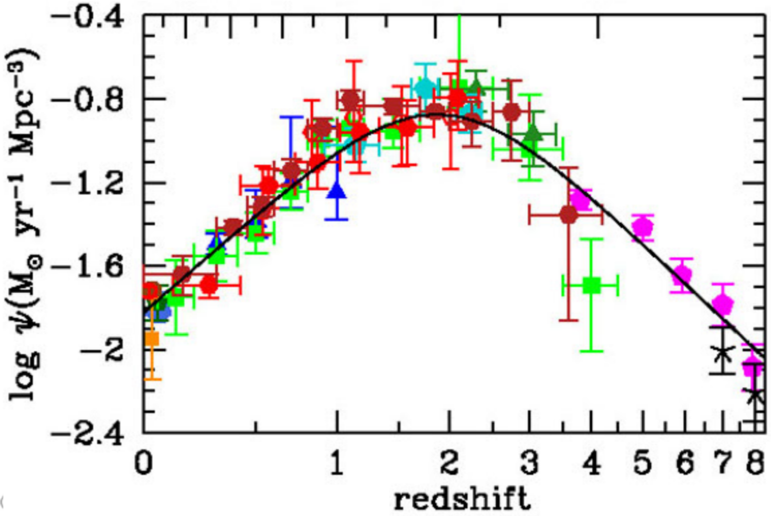
See also:
Mandel & de Mink 2016; de Mink & Mandel 2016;
du Buisson et al. 2020; Ghodla et al. 2023; Marchant et al. 2024;
Dall'Amico et al. 2025; van Son et al. 2025

3. The merger rate density: bridging scales

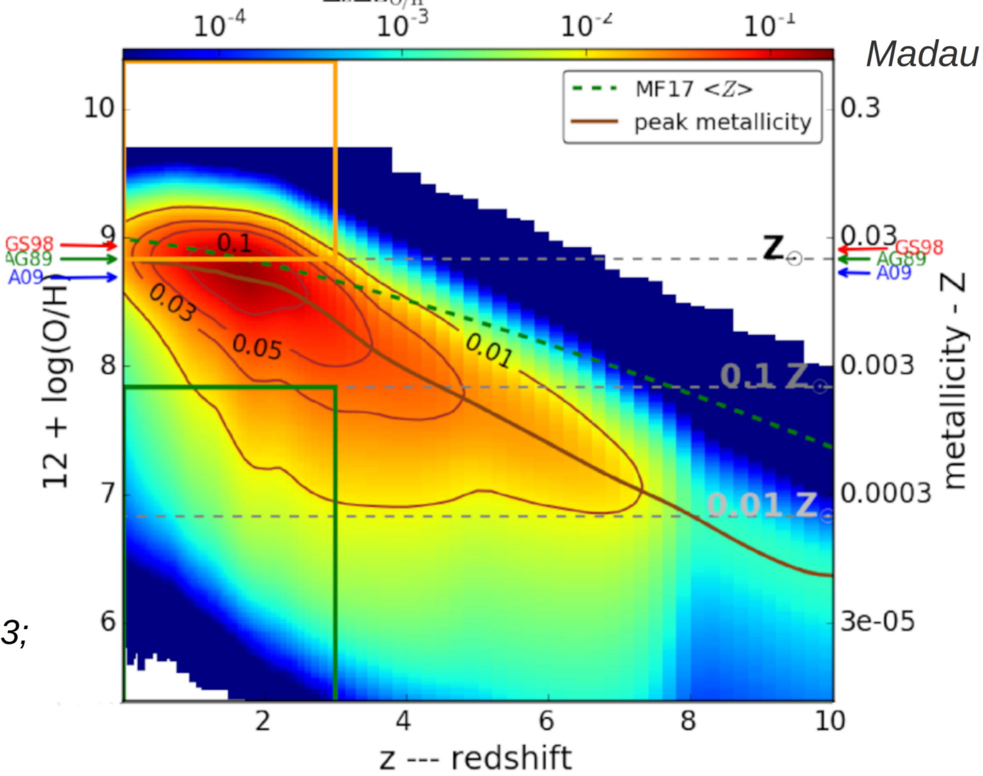


Small-scale simulations of binary compact object formation

Evolution of star formation rate and metallicity in galaxies



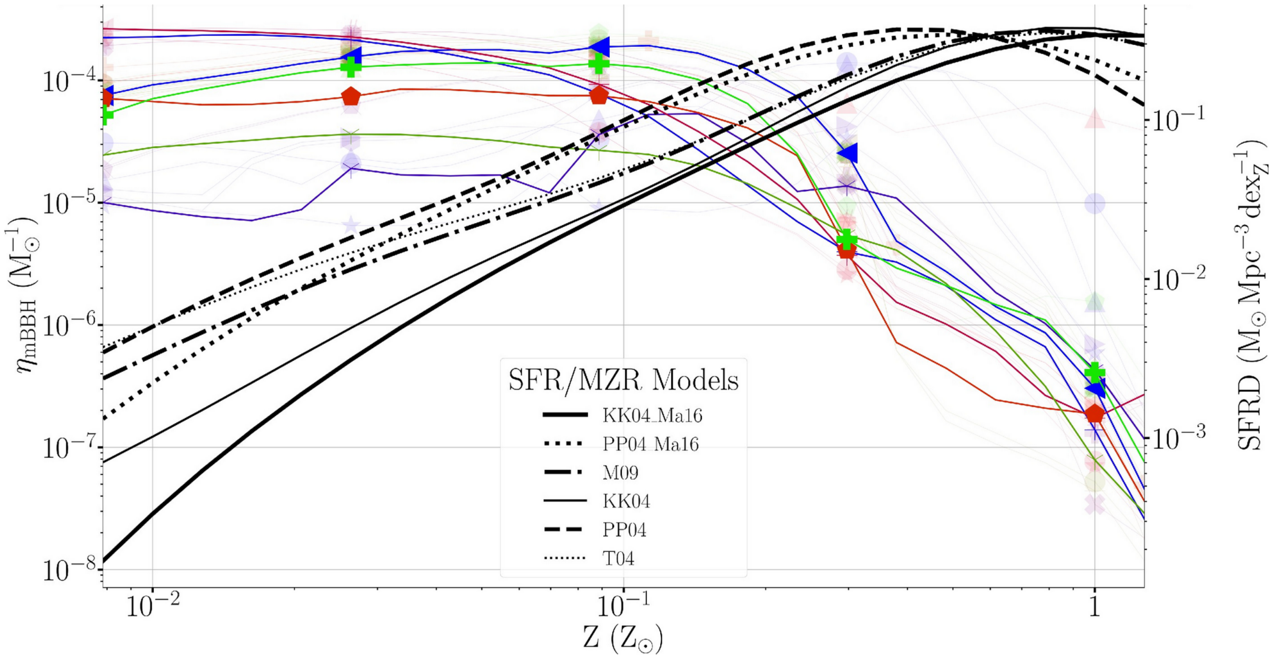
Madau & Dickinson 2014



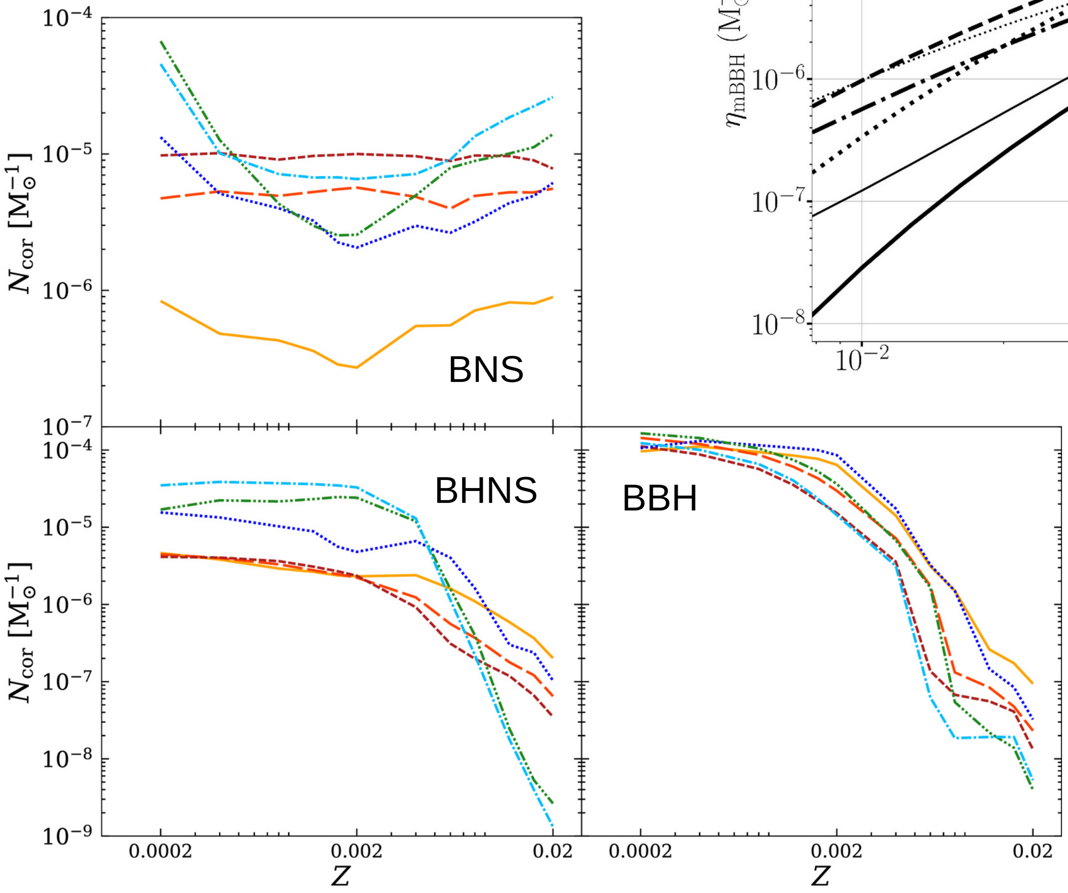
Chruslinska et al. 2019
Chruslinska 2024 for a review

see also:
Boco et al. 2019, 2021;
Chruslinska et al. 2020, 2021;
Broekgaarden et al. 2022;
Santoliquido et al. 2020, 2021, 2022, 2023;
Mandel & Broekgaarden 2022;
Bruel et al. 2024; de Sa et al. 2024;
Boesky et al. 2024; van Son et al. 2025

3. The merger rate density: merger efficiency



Srinivasan et al. 2023



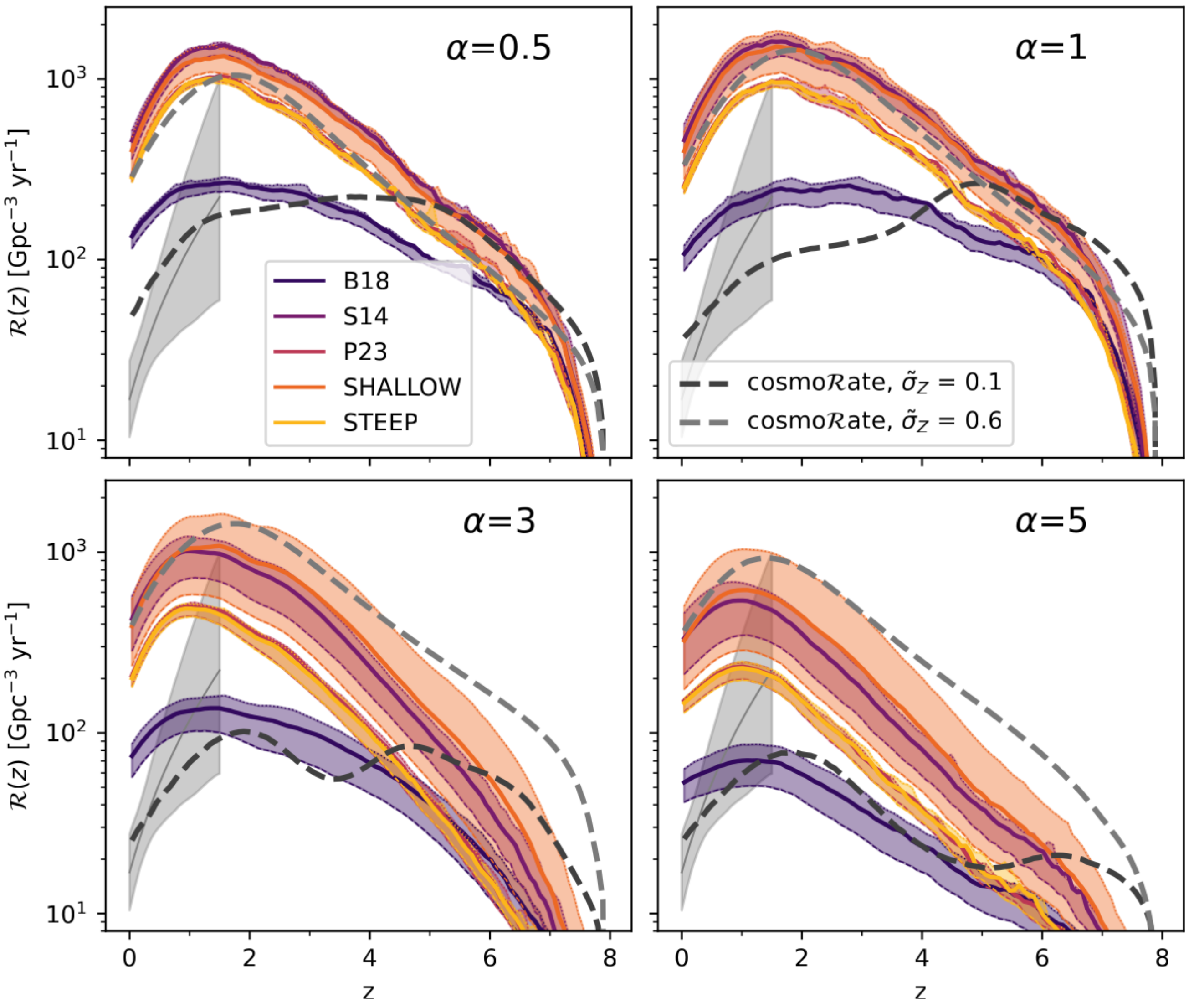
Dominik et al. 2013
Giacobbo & MM 2018
Klencki et al. 2018
van Son et al. 2025

MERGER EFFICIENCY

Metal-poor black hole progenitors merge more efficiently (mass loss rate)

Neutron stars less sensitive to *Z* but very sensitive to mass transfer and progenitor's radii

3. The merger rate density: Houston we have a problem with BBHs



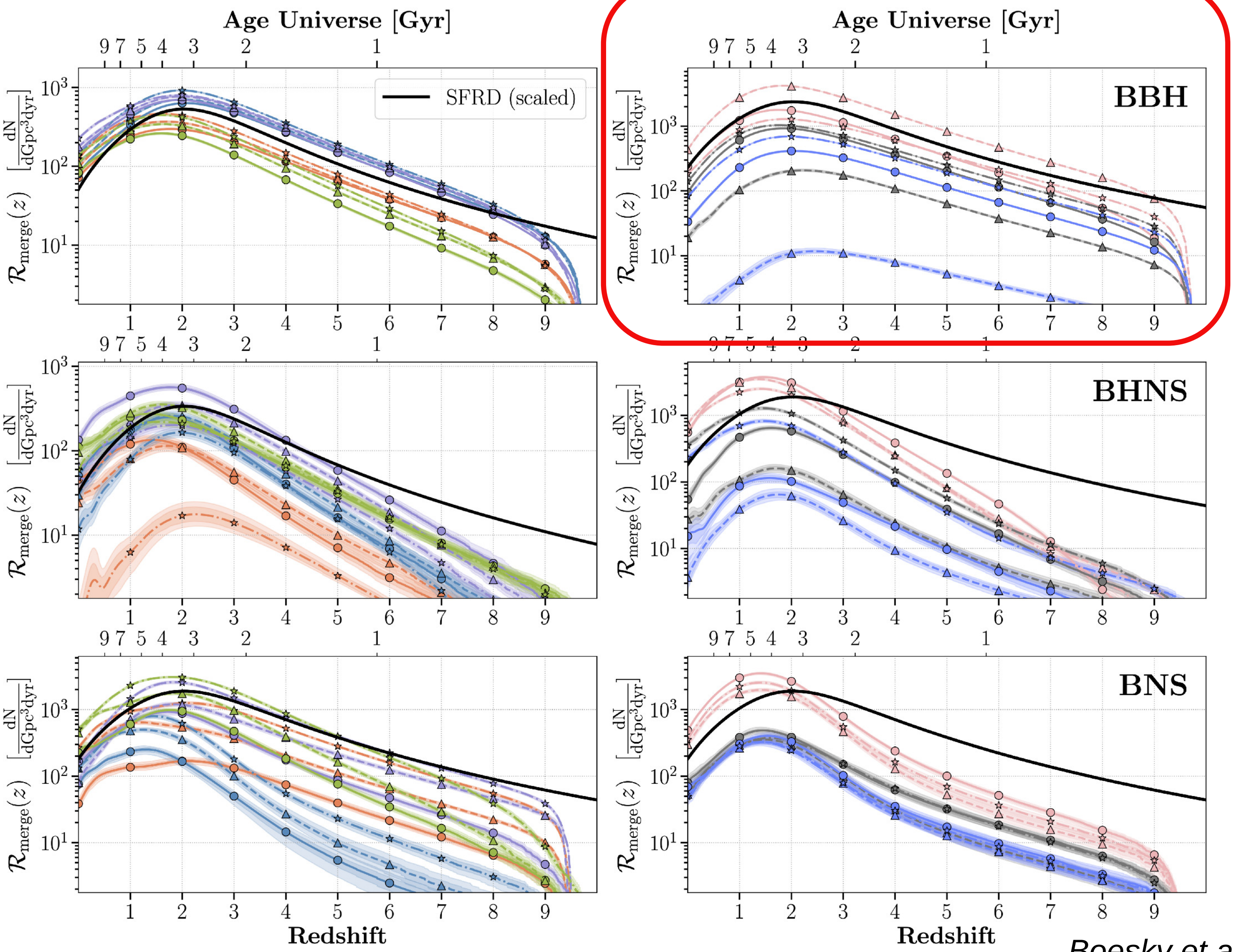
Sgalletta et al. 2024

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

3. The merger rate density: Houston we have a problem with BBHs

Uncertainties about mass transfer and common envelope

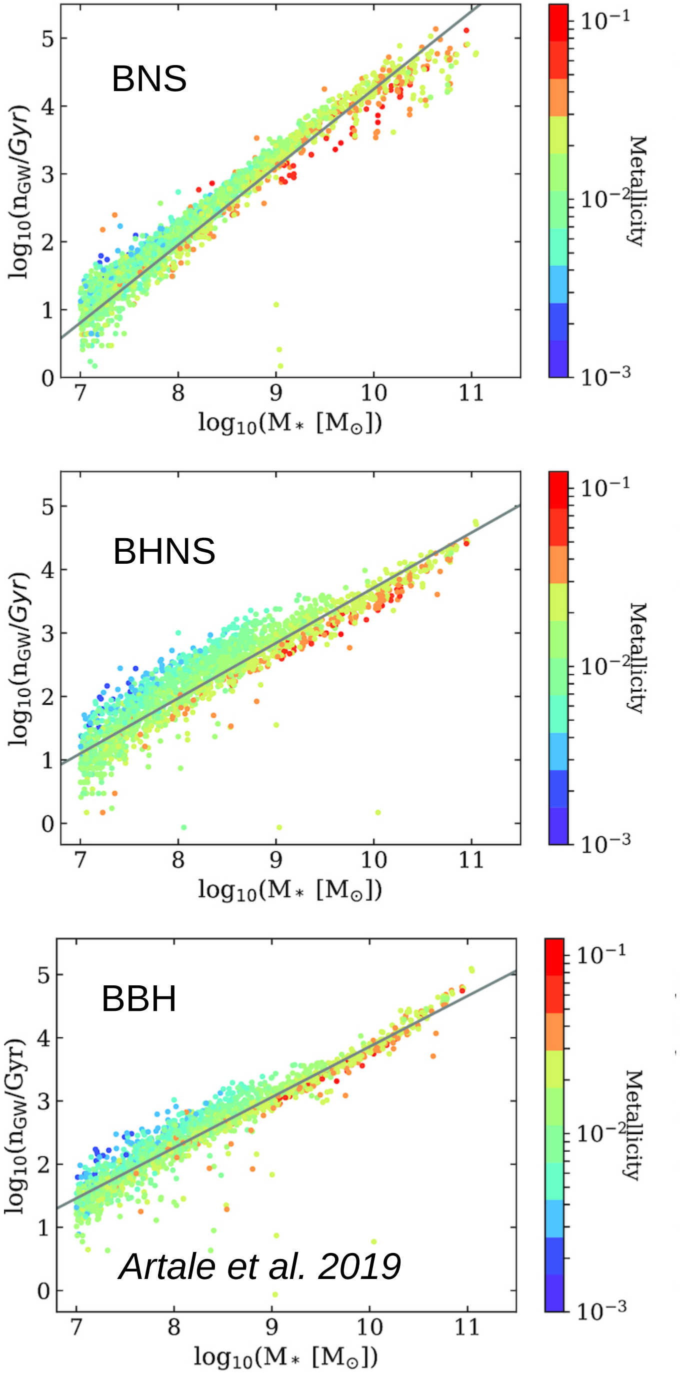
Some assumptions about natal kick



Boesky et al. 2024

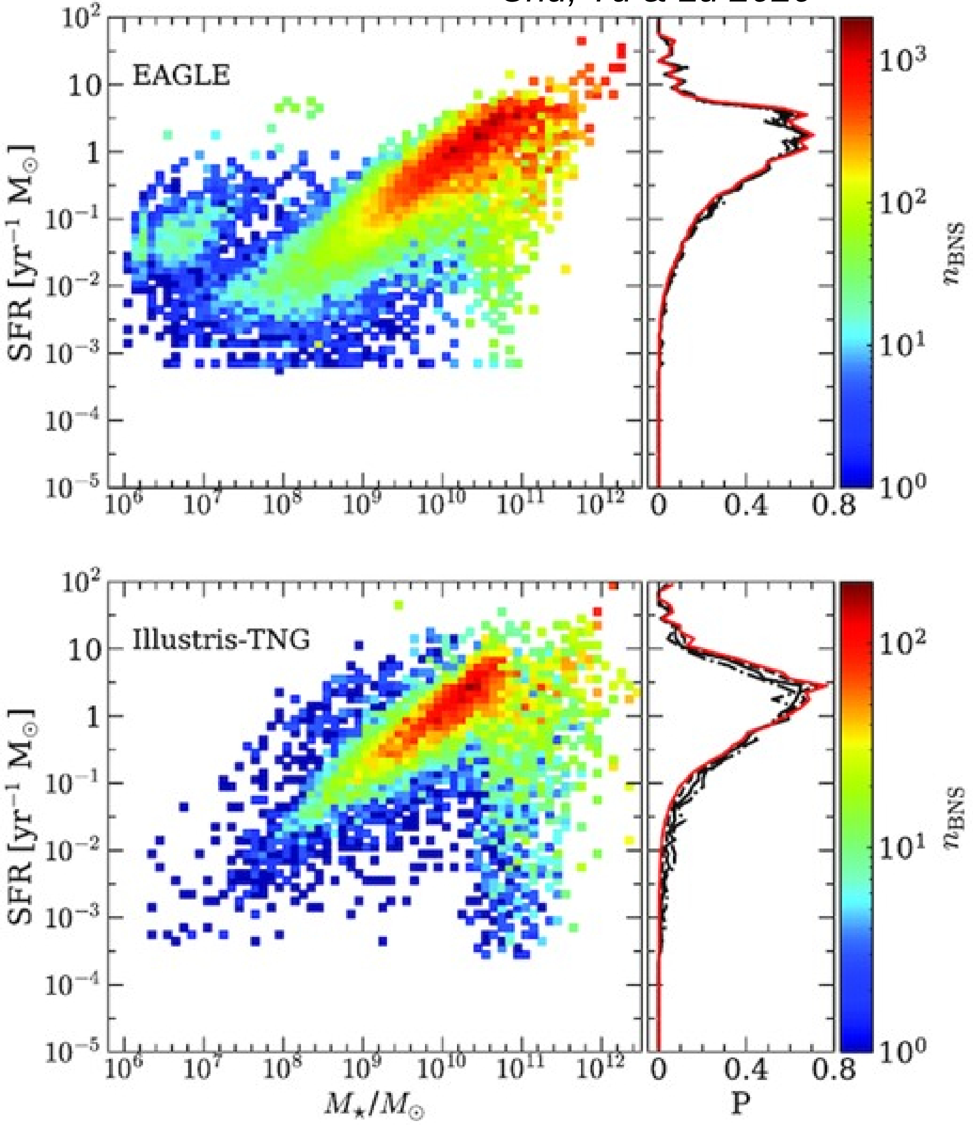
Consistent with LVK only for large natal kicks

4. The host galaxies: merger rate per galaxy scales with galaxy mass



Artale et al. 2019

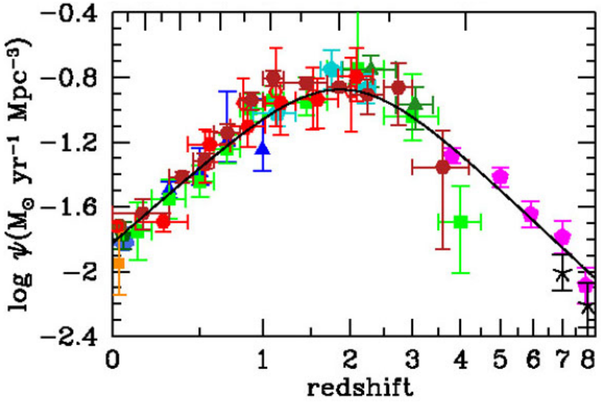
Chu, Yu & Lu 2020

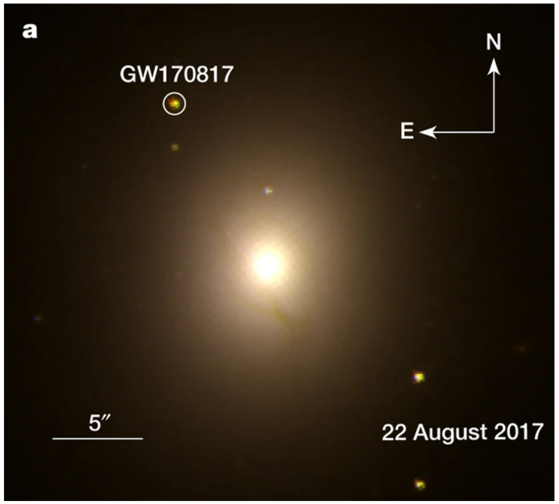


See also: MM et al. 2018; Artale et al. 2020; Santoliquido et al. 2022; Mandhai et al. 2022; Rauf et al. 2023; Vijaykumar et al. 2024

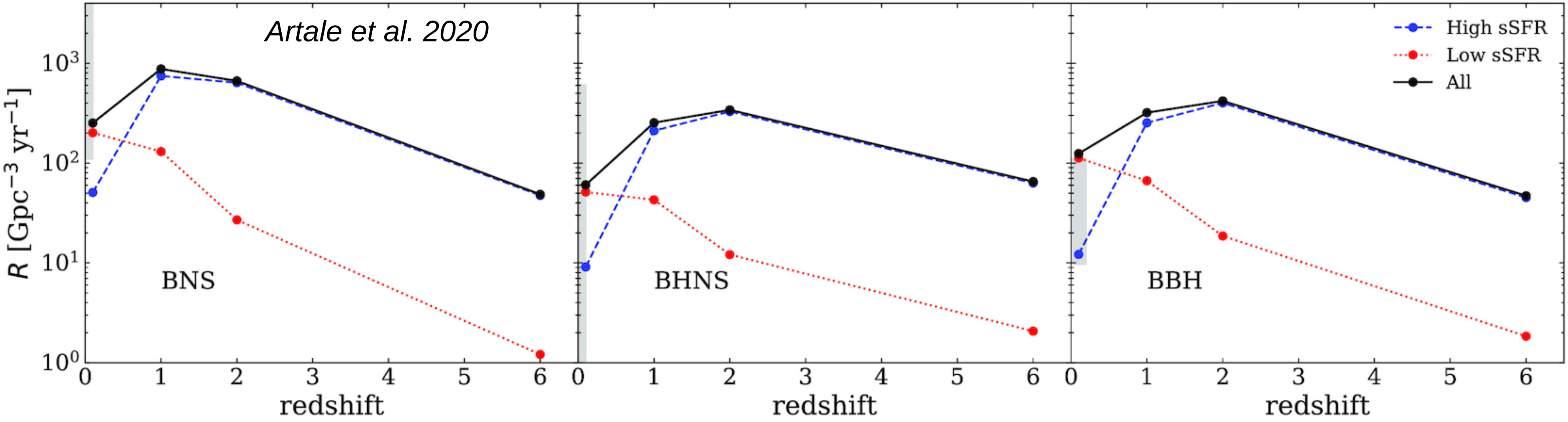
4. The host galaxies: should we be surprised about NGC4993?

The only known host galaxy has negligible star formation (most stars ~ 10 Gyr old)





Coulter et al. 2017; Abbott et al. 2017; Blanchard et al. 2017; Levan et al. 2017; Troja et al. 2017



Galaxies with high specific SFR are most likely merger hosts at z>1, but not at low redshift (z<1) because

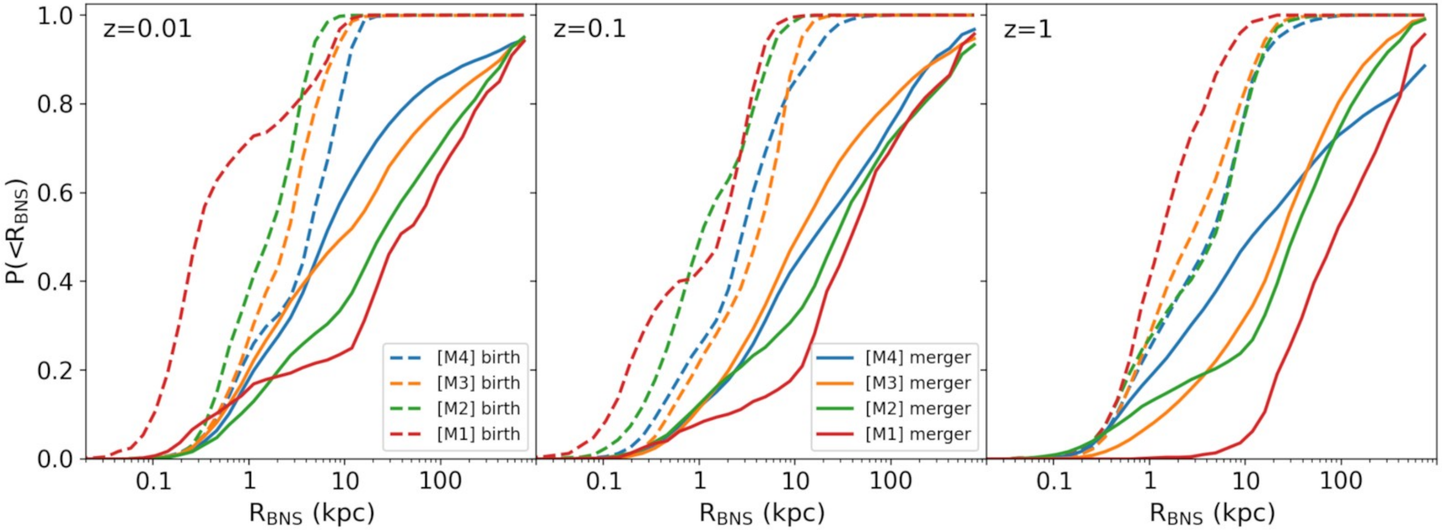
* peak of cosmic star formation rate is at z~2

* most stellar mass now locked in galaxies with low specific SFR

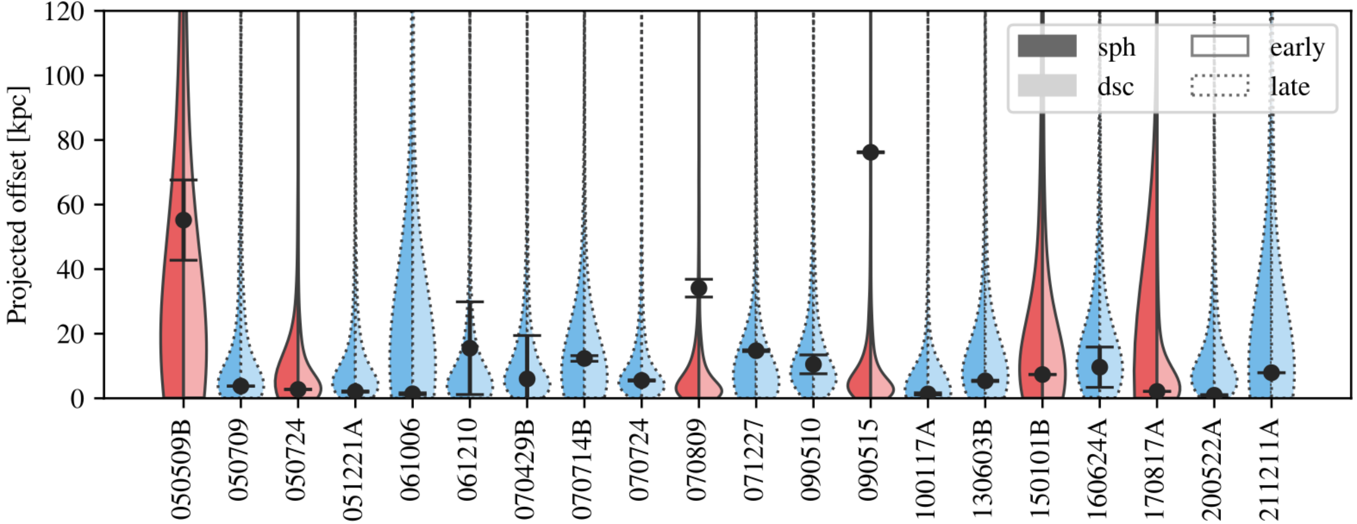
4. The host galaxies: the offset

Birth versus merger location of BNSs

Perna et al. 2022



Gaspari et al. 2025



- affected by both natal kick and delay time!
- to be constrained with electromagnetic counterparts, kilonovae, gamma-ray bursts

5. Conclusions & outlook

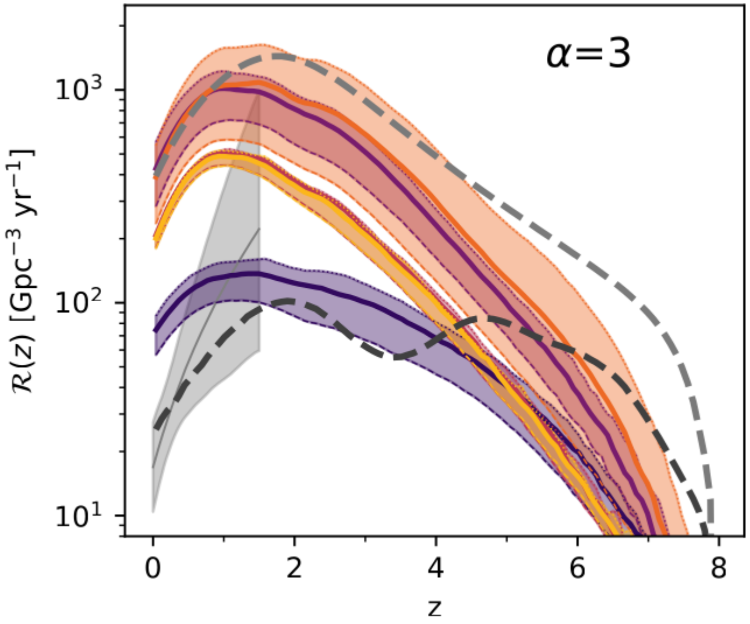
* Metallicity is key aspect of binary black hole formation,
less for binary neutron stars 🙂

* Major uncertainties from star evolution concern winds, core collapse,
and pair-instability supernovae 🙁

* Major uncertainties from binary evolution concern mass transfer and
the effects of stellar rotation 🙁

* The BBH merger rate density predicted by
models is in tension with LVK
(unless very high natal kicks or
unrealistically low metallicity spread) 🙁

* Models of host galaxies expect merger rate
per galaxy maximum for high mass
(relatively high SFR) galaxies 🙂



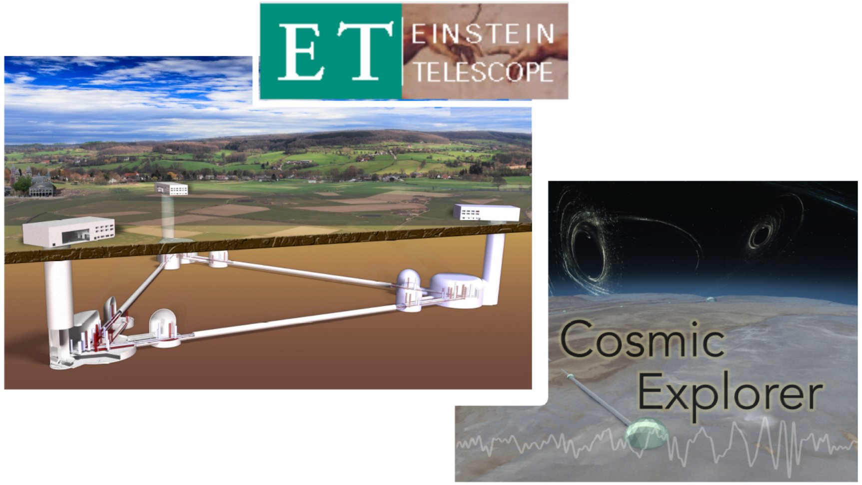
5. Conclusions & outlook

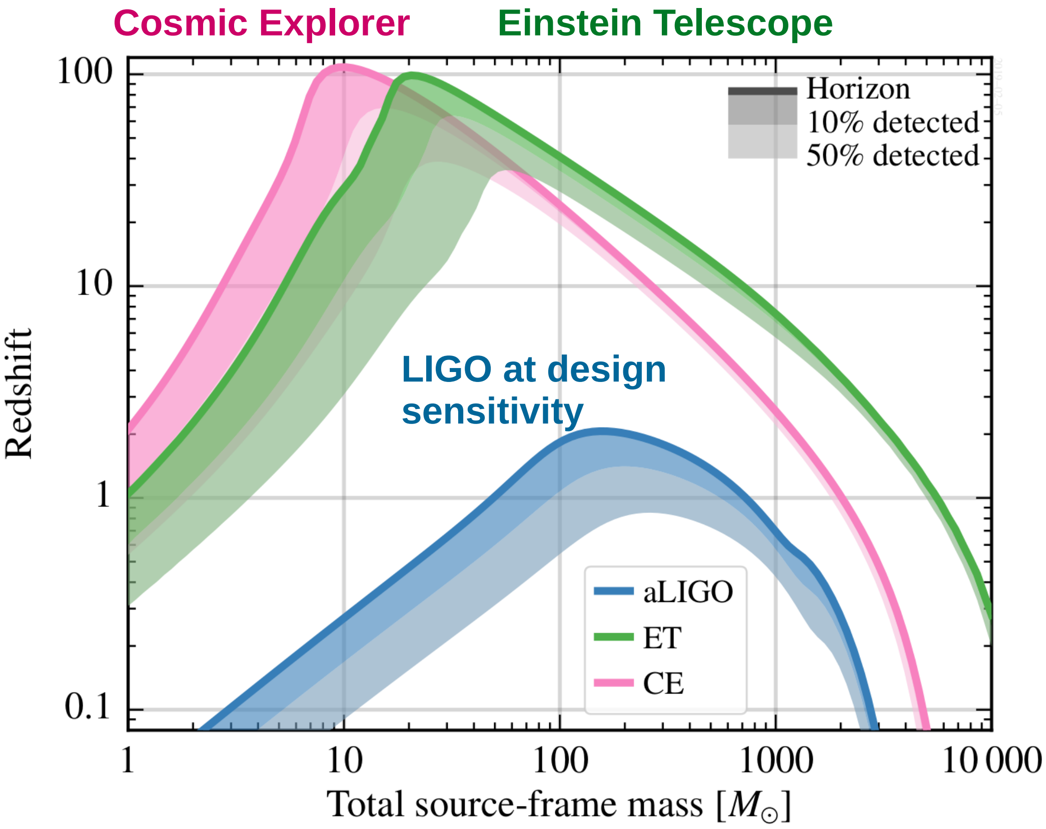
With next-generation detectors (Einstein Telescope + Cosmic Explorer)

BBH mergers out to z ~ 100
when Universe was in its infancy

>300 detections every day
(now 1 every 3 days)

>1000 events/yr with signal-to-noise ratio SNR > 100
(0 with current detectors)

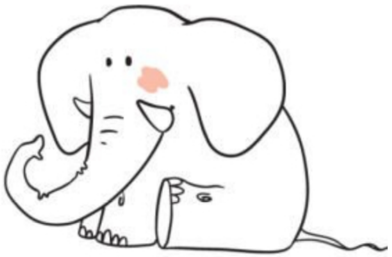




ET Blue Book:
Abac et al. 2025, https://arxiv.org/abs/2503.12263

2. Formation of compact objects: uncertainties on mass transfer

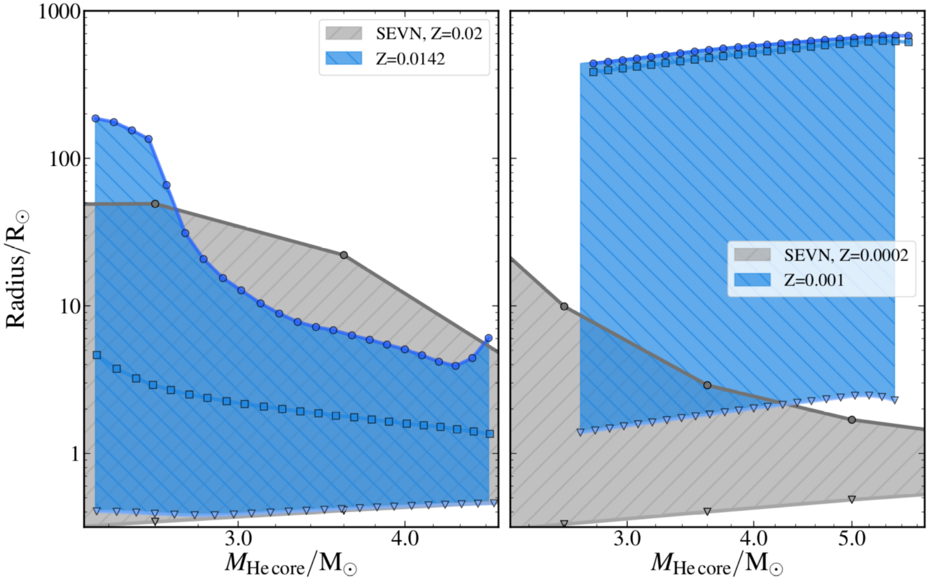
Response of donor/accretor star to mass transfer
(usually not in pop. synth.)



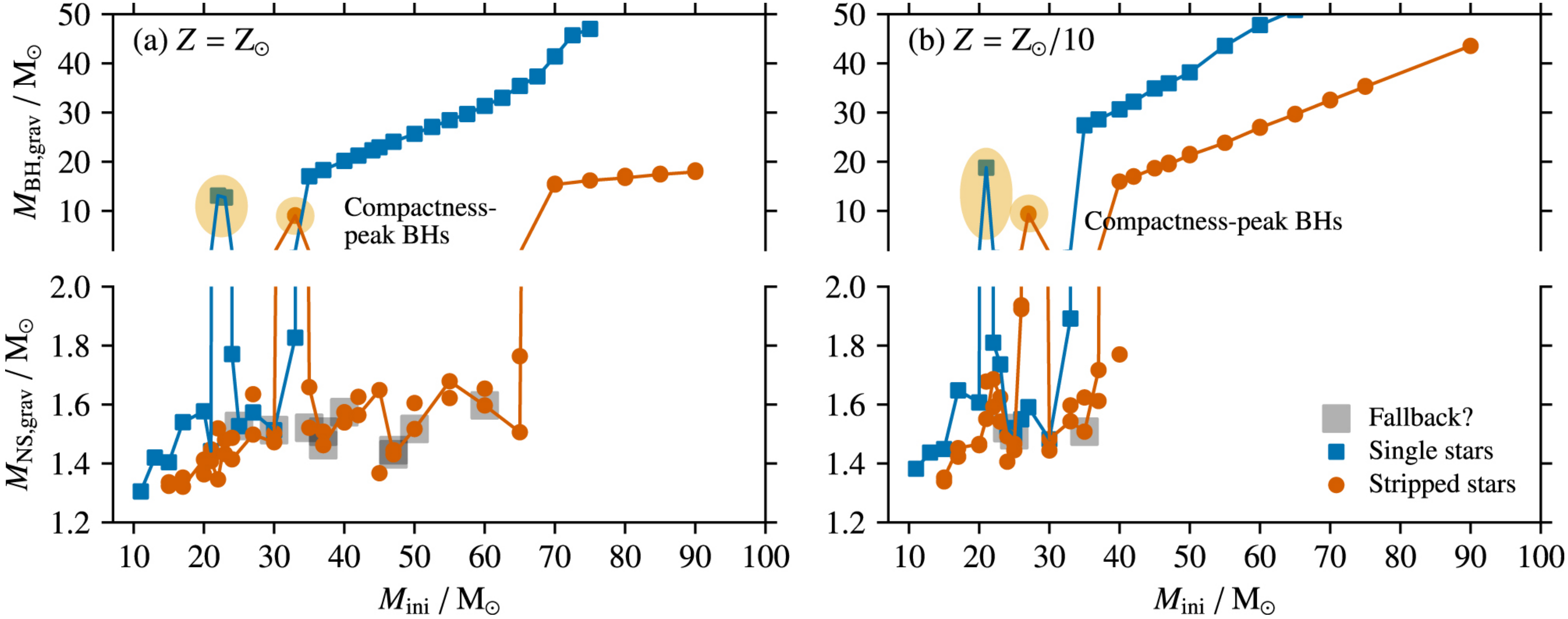
During/After mass transfer the **structure of the donor can change wildly**

→

This affects further mass transfer & final fate (**stripped models explode more easily than unperturbed models**)



Laplace et al. 2020



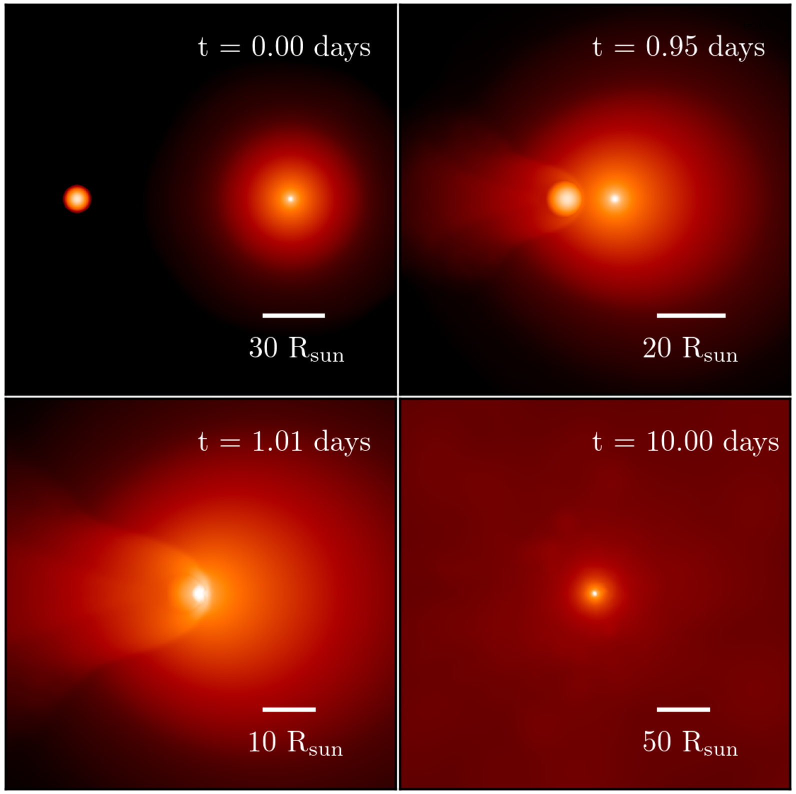
Schneider et al. 2023, 2024

2. Black holes (BHs) in the pair-instability mass gap: star collisions

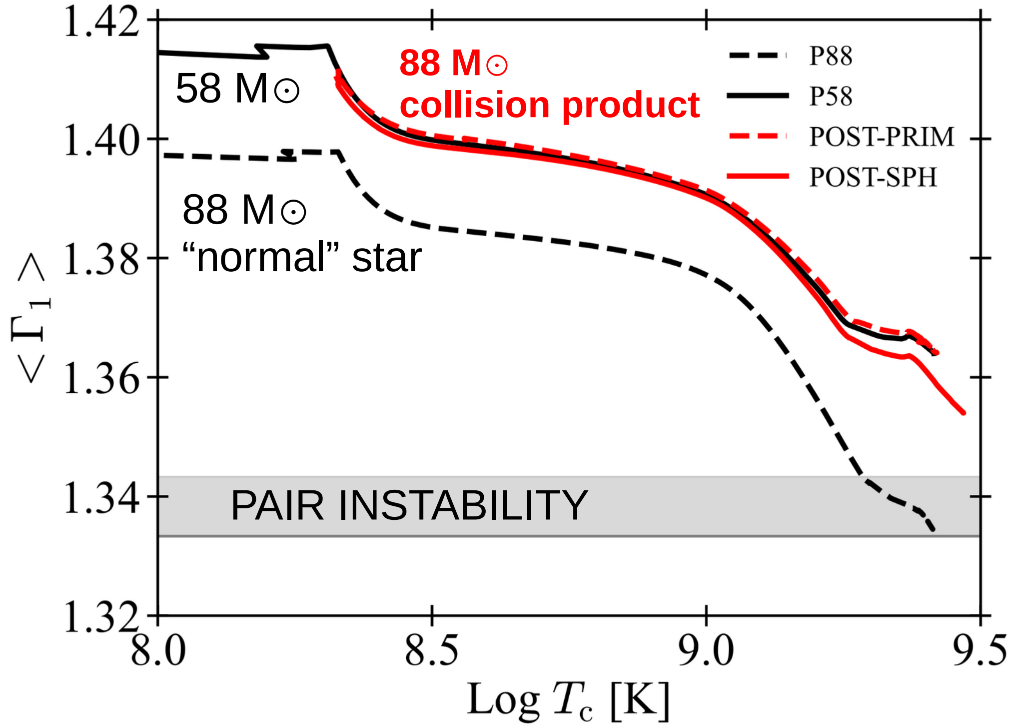
Mass loss during collision and further evolution?
→ needs hydro-dynamical simulations of the collision
→ needs accurate stellar evolution model

$$\Gamma_1 = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_{\rm ad}$$

$$\langle \Gamma_1 \rangle = \frac{\int_0^M \Gamma_1 \, P \, \rho^{-1} \, dm}{\int_0^M P \, \rho^{-1} \, dm}$$



Max 12% mass loss during head-on star – star collision
(*Ballone et al. 2023*)

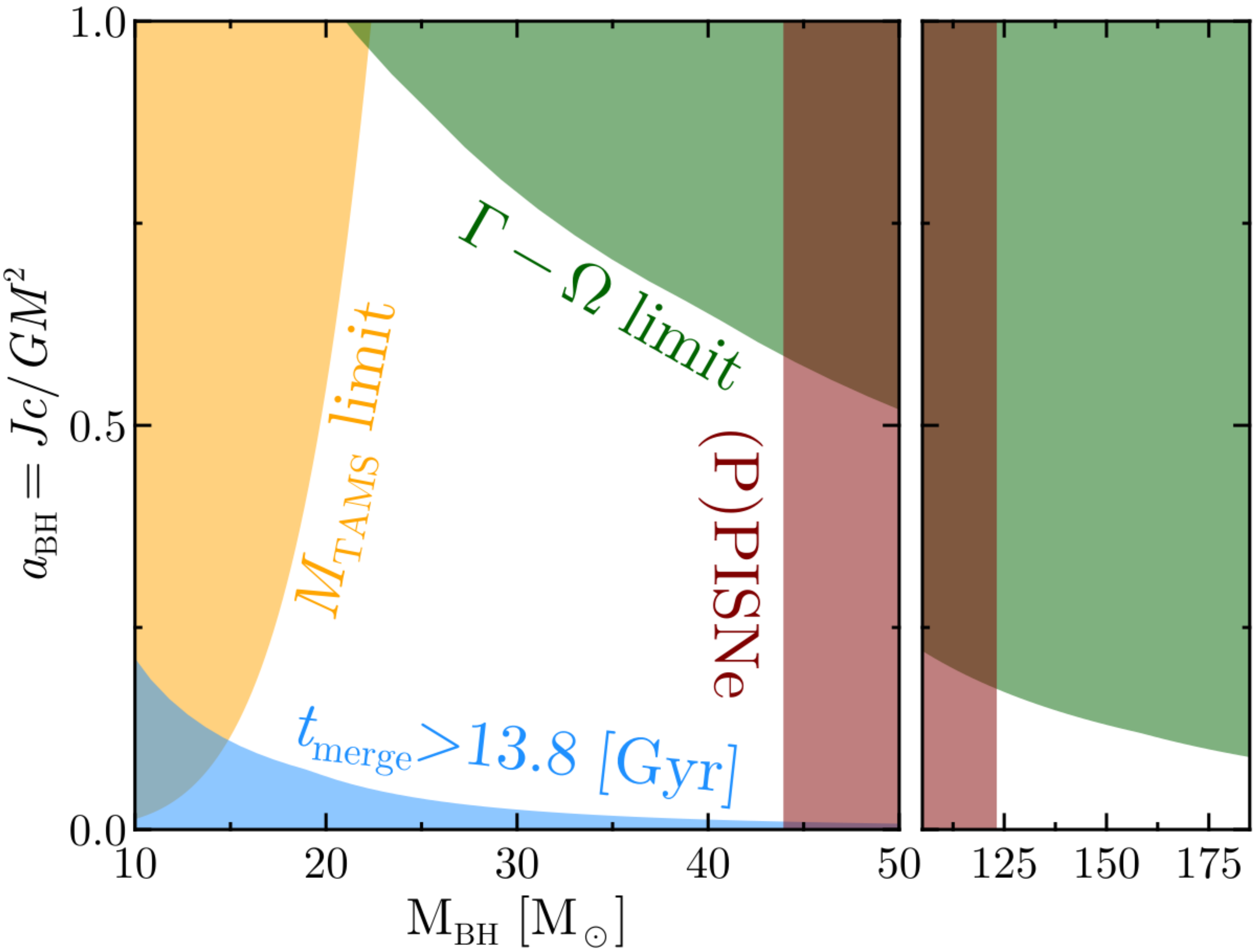


A normal 88 M⊙ star undergoes pair instability

The collision product avoids pair instability (like a 58 M⊙ star)
→ final BH mass ~ 87 M⊙

Costa et al. 2022

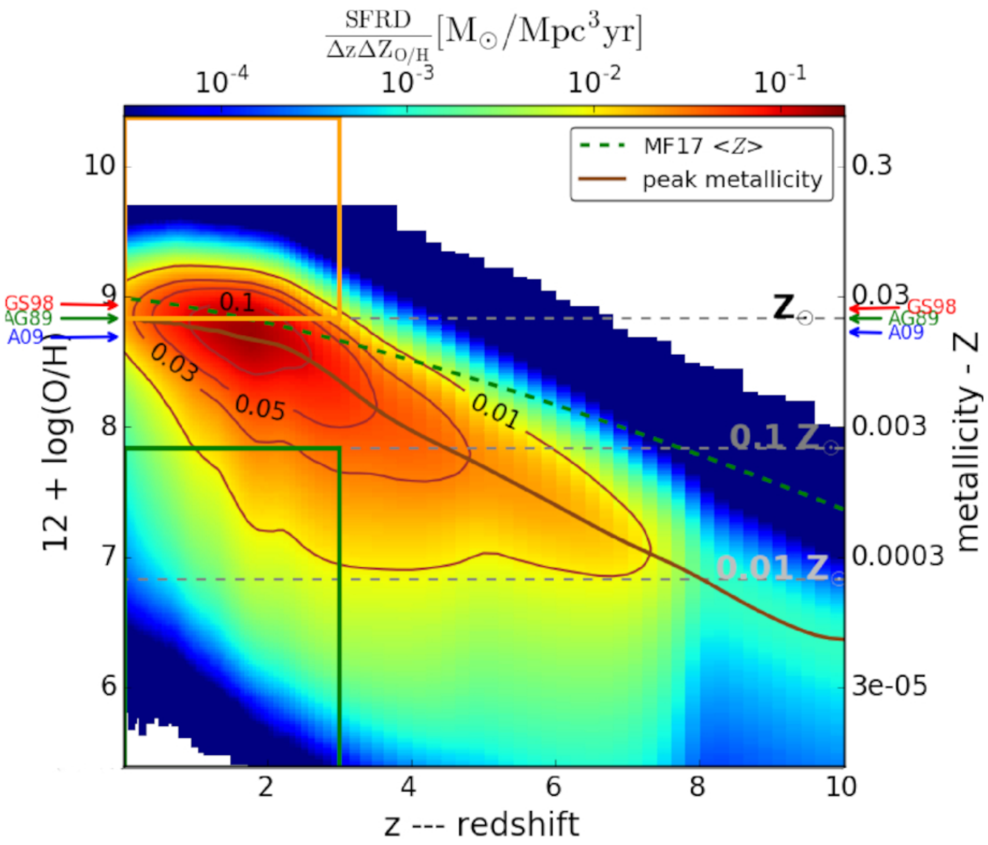
2. Formation of compact objects: uncertainties on rotation

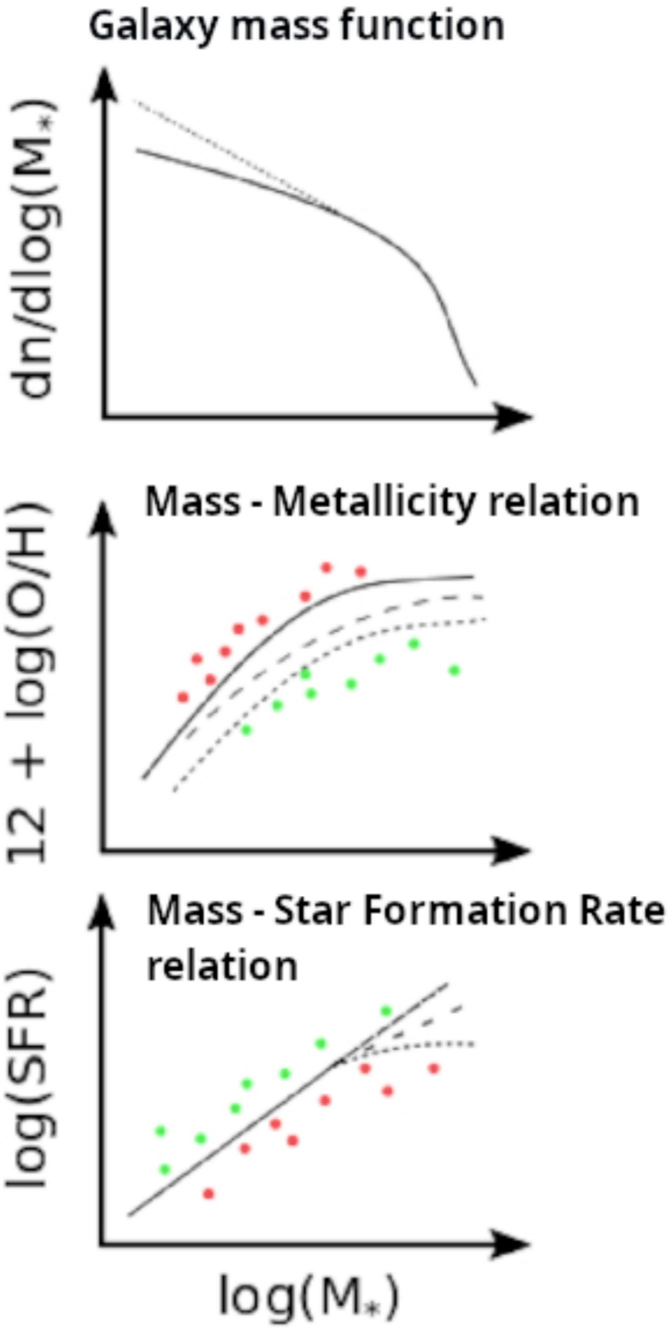


Marchant et al. 2024

3. The merger rate density: mass, metallicity, SFR

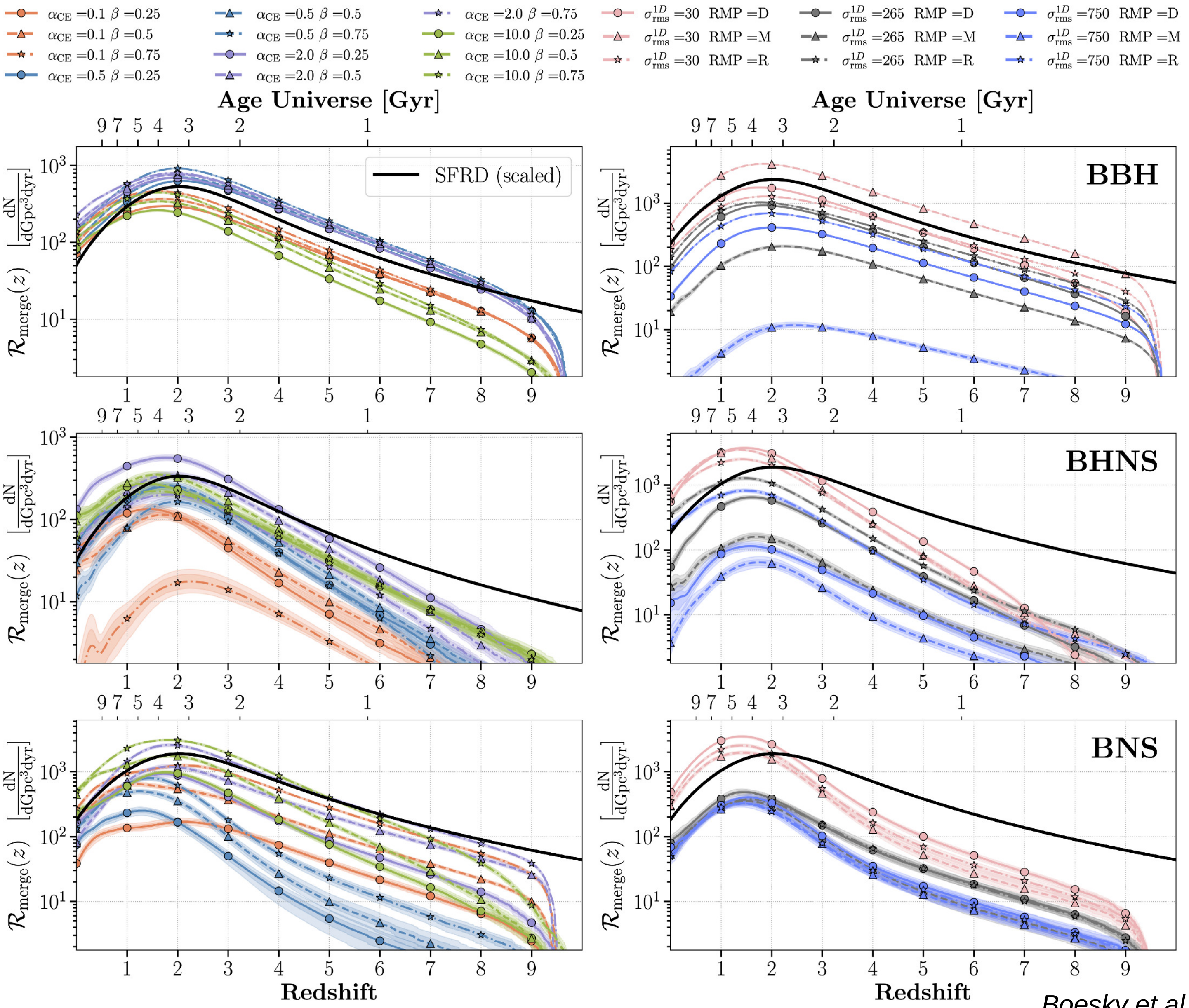
Chruslinska et al. 2019
Chruslinska 2024 for a review





see also:
Boco et al. 2019, 2021; Chruslinska et al. 2020, 2021; Broekgaarden et al. 2022; Santoliquido et al. 2020, 2021, 2022, 2023; Mandel & Broekgaarden 2022; Bruel et al. 2024; de Sa et al. 2024; Boesky et al. 2024; van Son et al. 2025

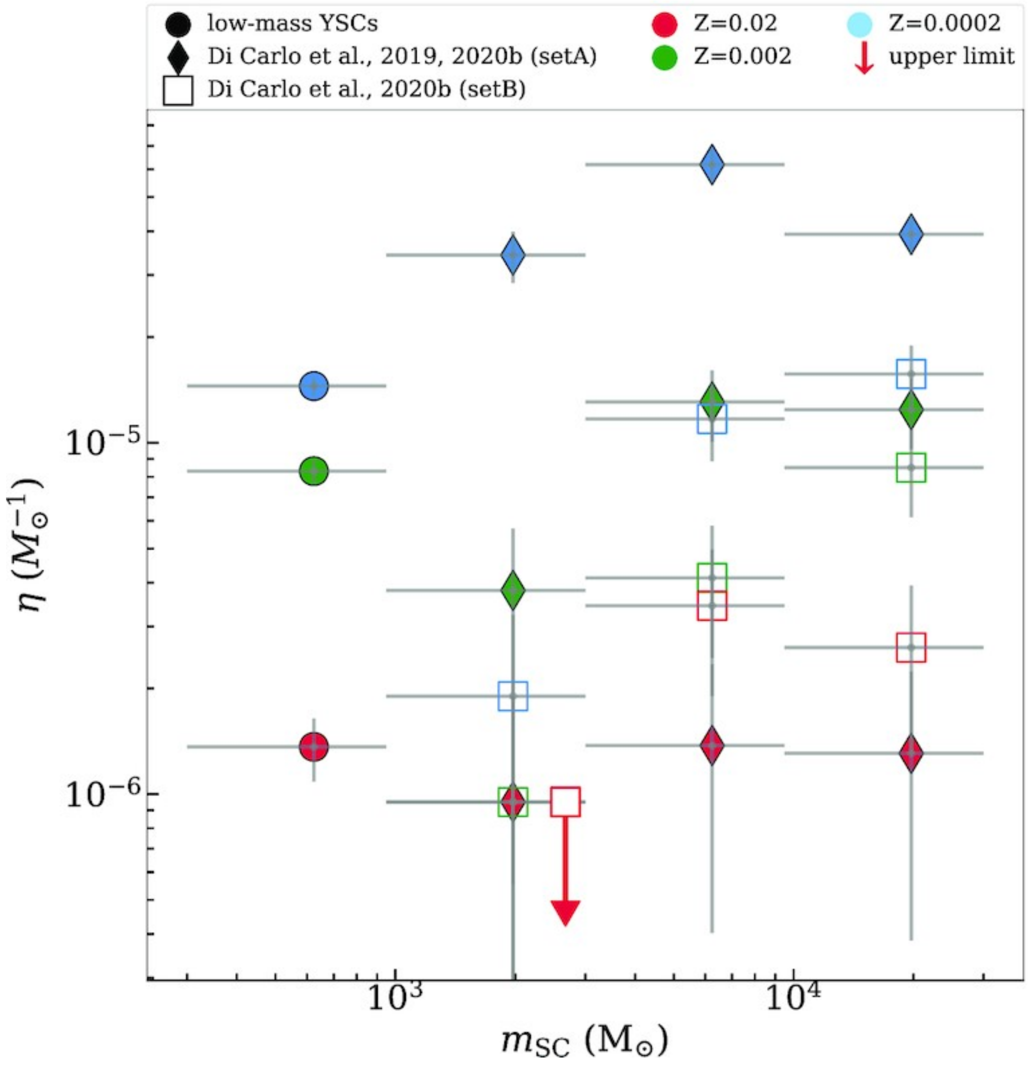
3. The merger rate density



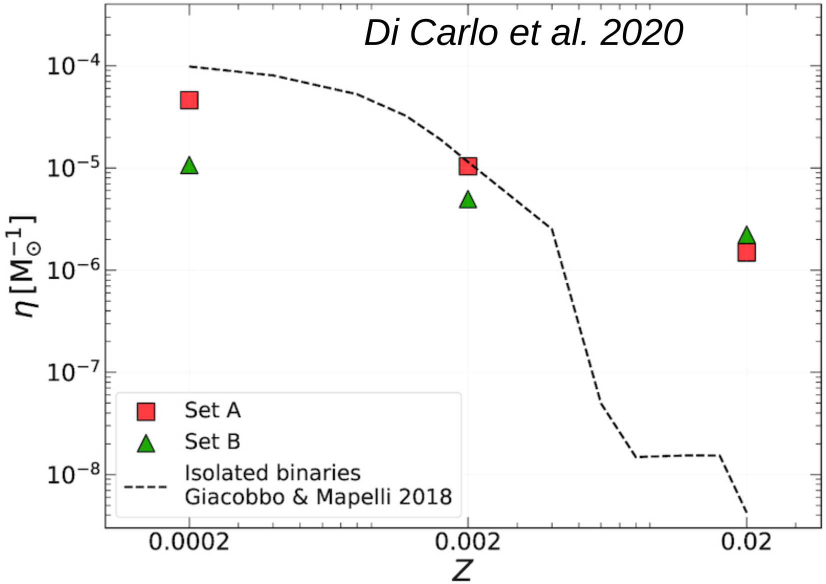
Boesky et al. 2024

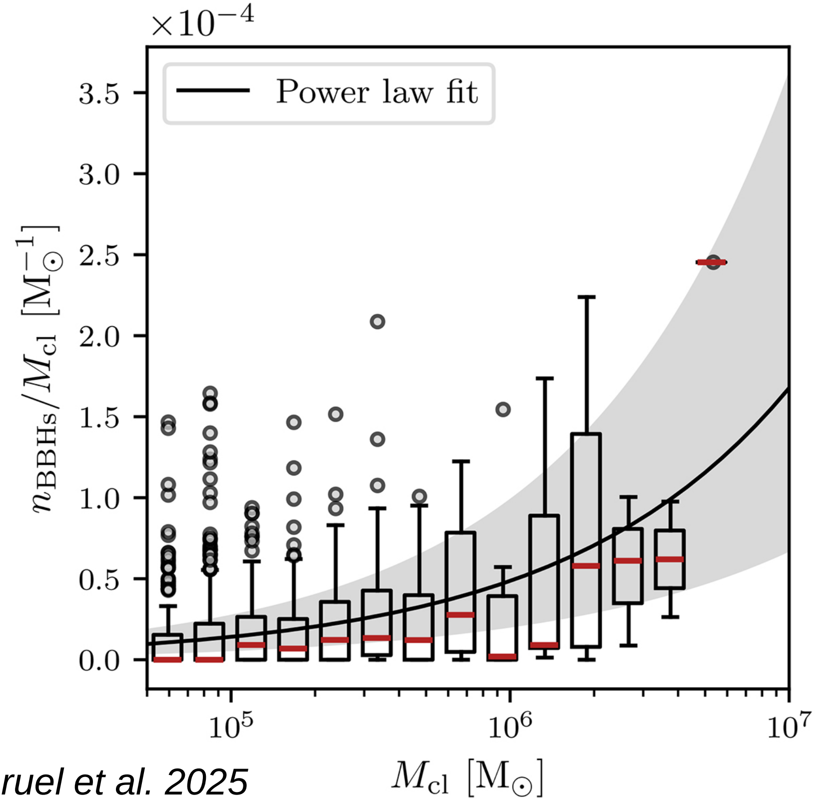
Consistent with LVK only for large natal kicks

3. The merger rate density: efficiency in star clusters



Rastello et al. 2021

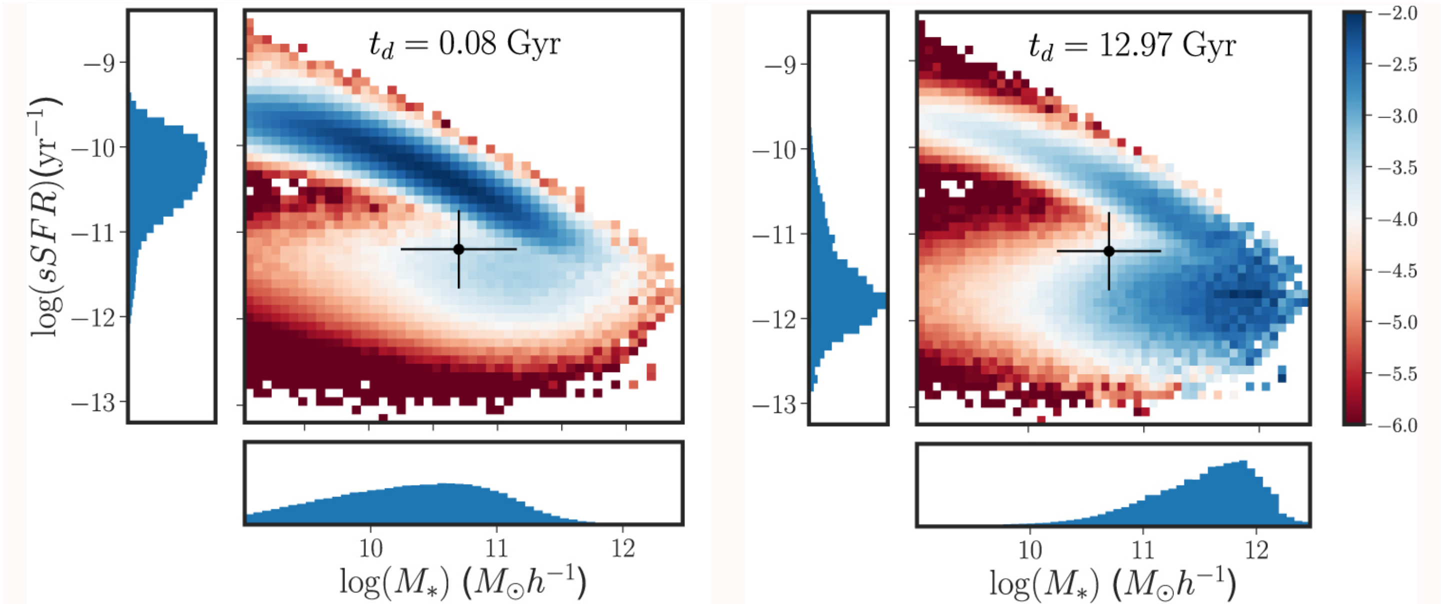




Bruel et al. 2025

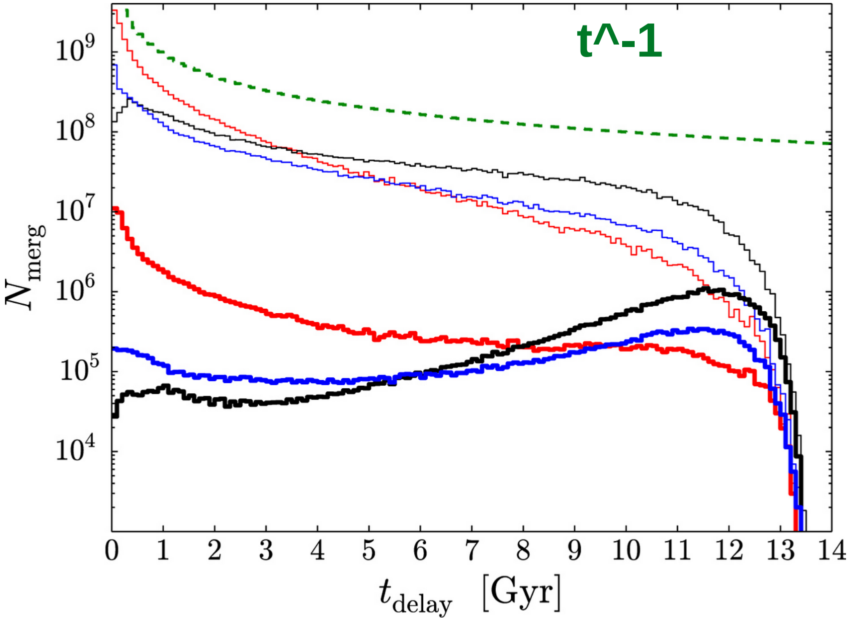
4. The host galaxies: a way to infer the delay time?

Using host galaxy properties to infer delay time (assuming delta Dirac for delay time)



Adhikari et al. 2020

...but delay-time distribution might be too complicated for this analysis

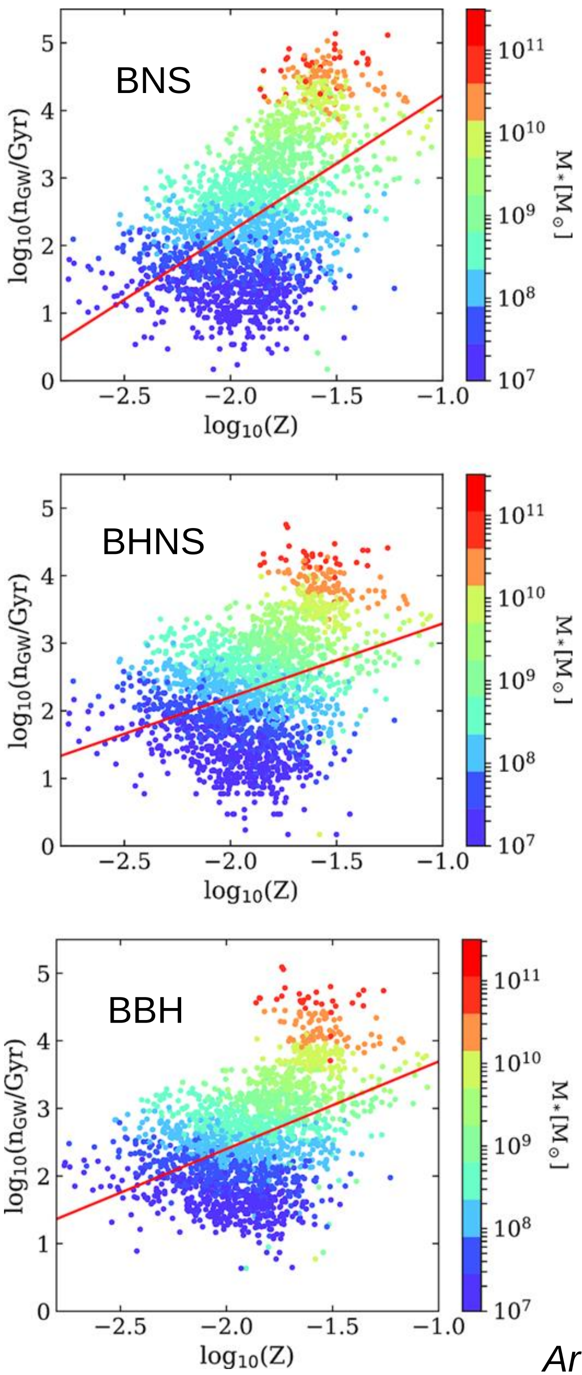


BNS, coeval population
BHNS, coeval population
BBH, coeval population

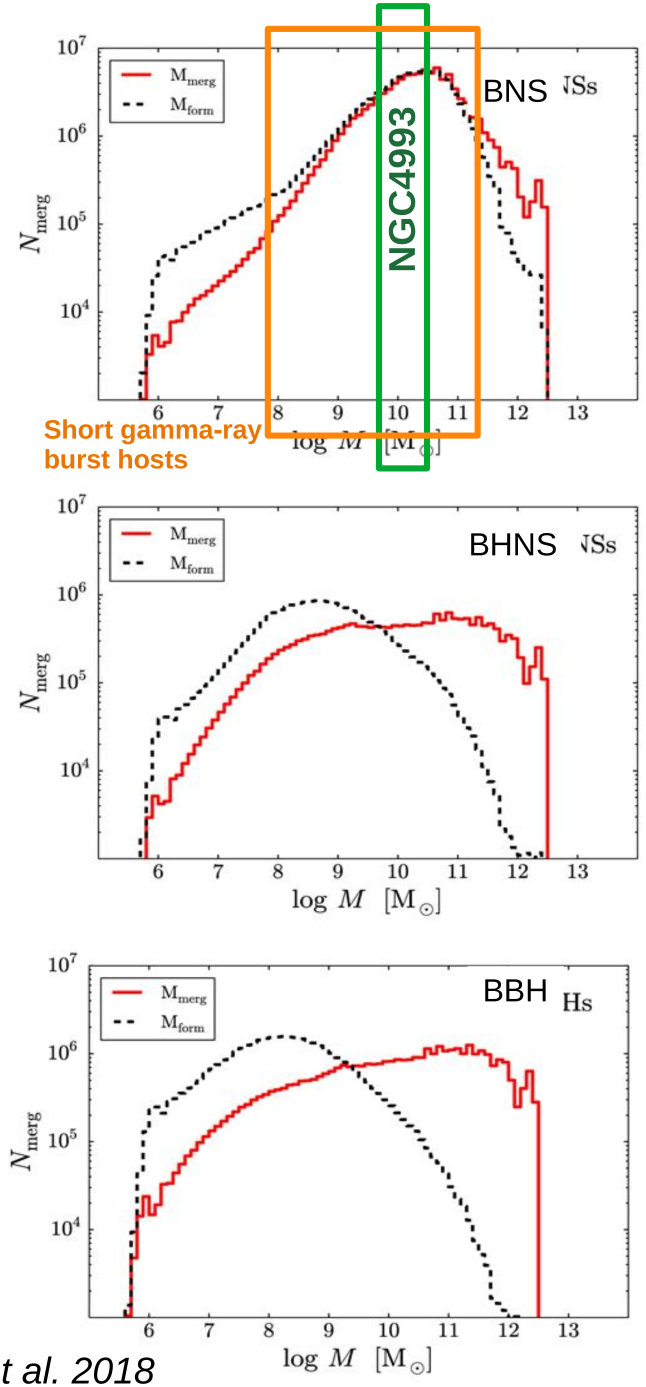
BNS, synthetic Universe at *z*=0
BHNS, synthetic Universe at *z*=0
BBH, synthetic Universe at *z*=0

MM et al. 2018

4. The host galaxies: metallicity, formation host vs merger host

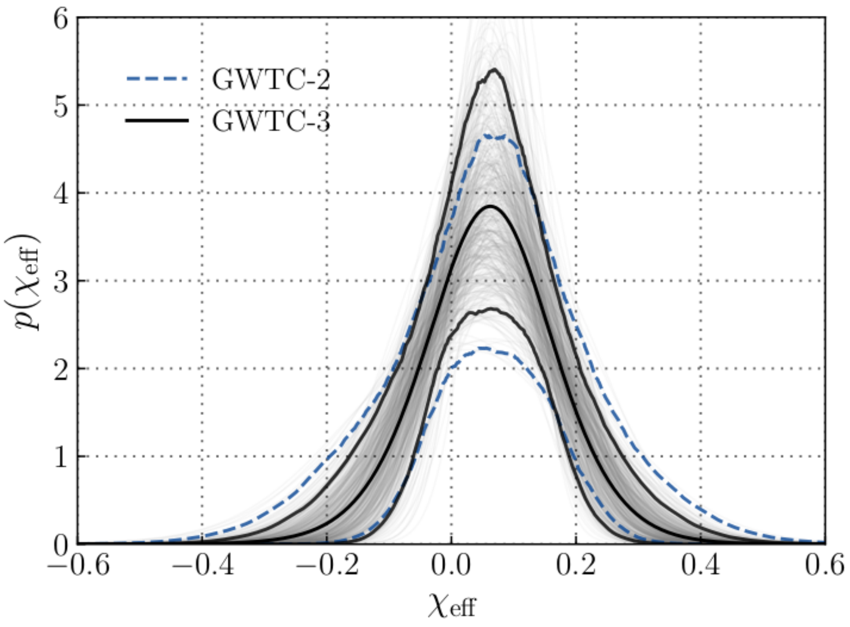


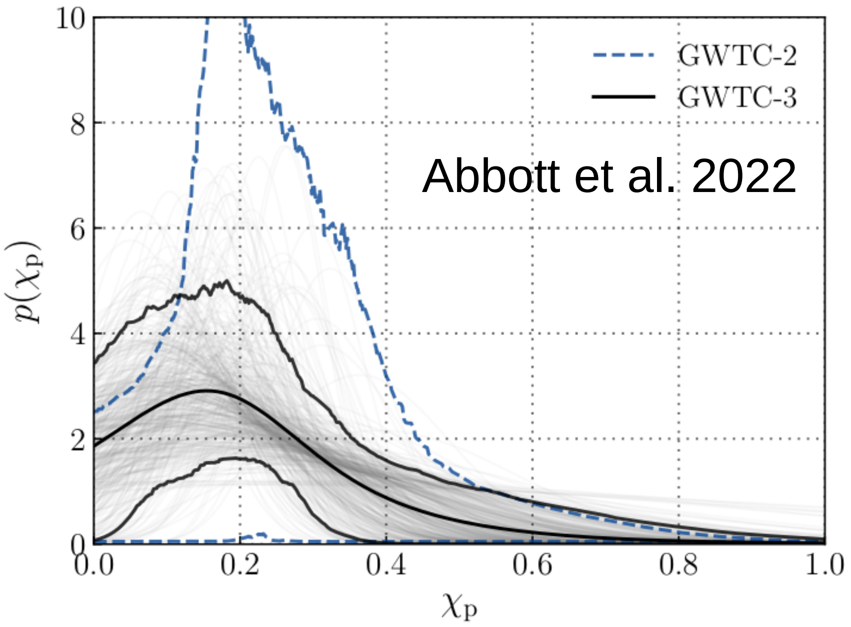
Artale et al. 2019



MM et al. 2018

1. Gravitational waves and black holes



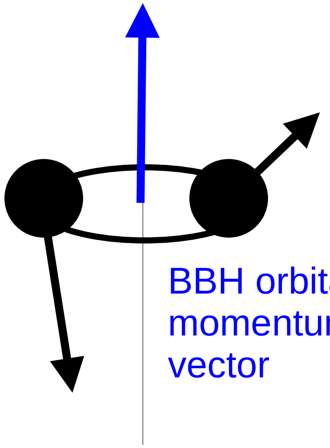


Abbott et al. 2022

Effective spin: mass weighted component of spins along angular momentum vector

$$\chi_{\rm eff} = \frac{(m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2)}{(m_1 + m_2)} \cdot \frac{\vec{L}}{L}$$

$$-1 \leq \chi_{\rm eff} \leq 1$$



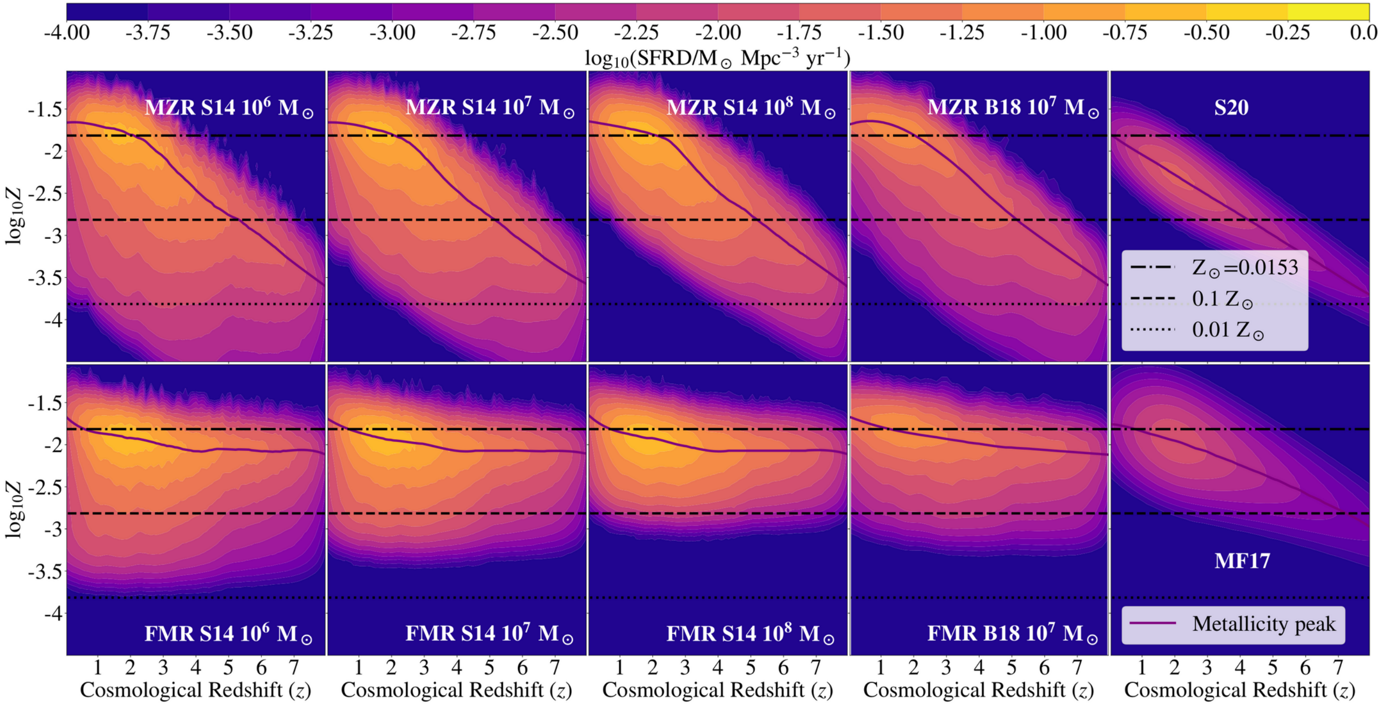
BBH orbital angular momentum vector

Precession spin: parameter measuring dominant spin component in the orbital plane

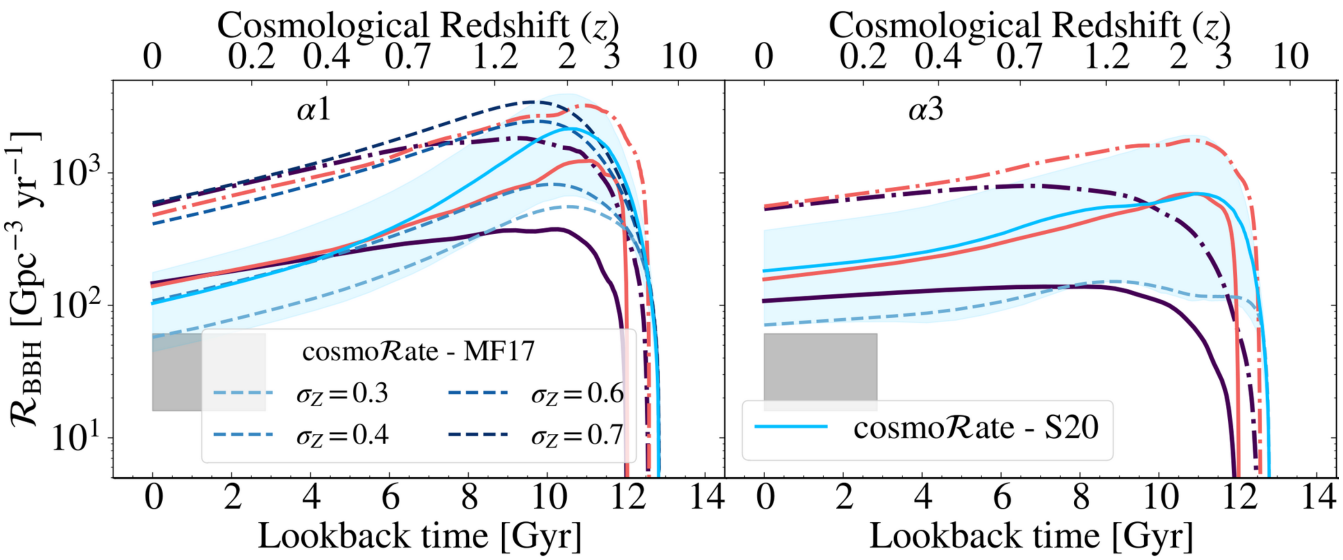
$$\chi_p = \frac{1}{B_1\, m_1^2} \max(B_1\, S_{1,\perp},\ B_2\, S_{2,\perp}) > 0$$

$$B_1 = 2 + 3\,\frac{q}{2} \qquad B_2 = 2 + \frac{3}{2\,q}$$

3. BBHs from metal-free and metal-poor stars: Rates are problematic



Metallicity – SFR evolution with redshift from observational relations



Merger rate density of BBHs too HIGH wrt LVK data:

too many metal-poor stars?
or issues with modeling mass transfer &
collapse of stars?

Santoliquido, MM et al. 2022