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Astrophysical models of binary compact objects:
open questions and main uncertainties

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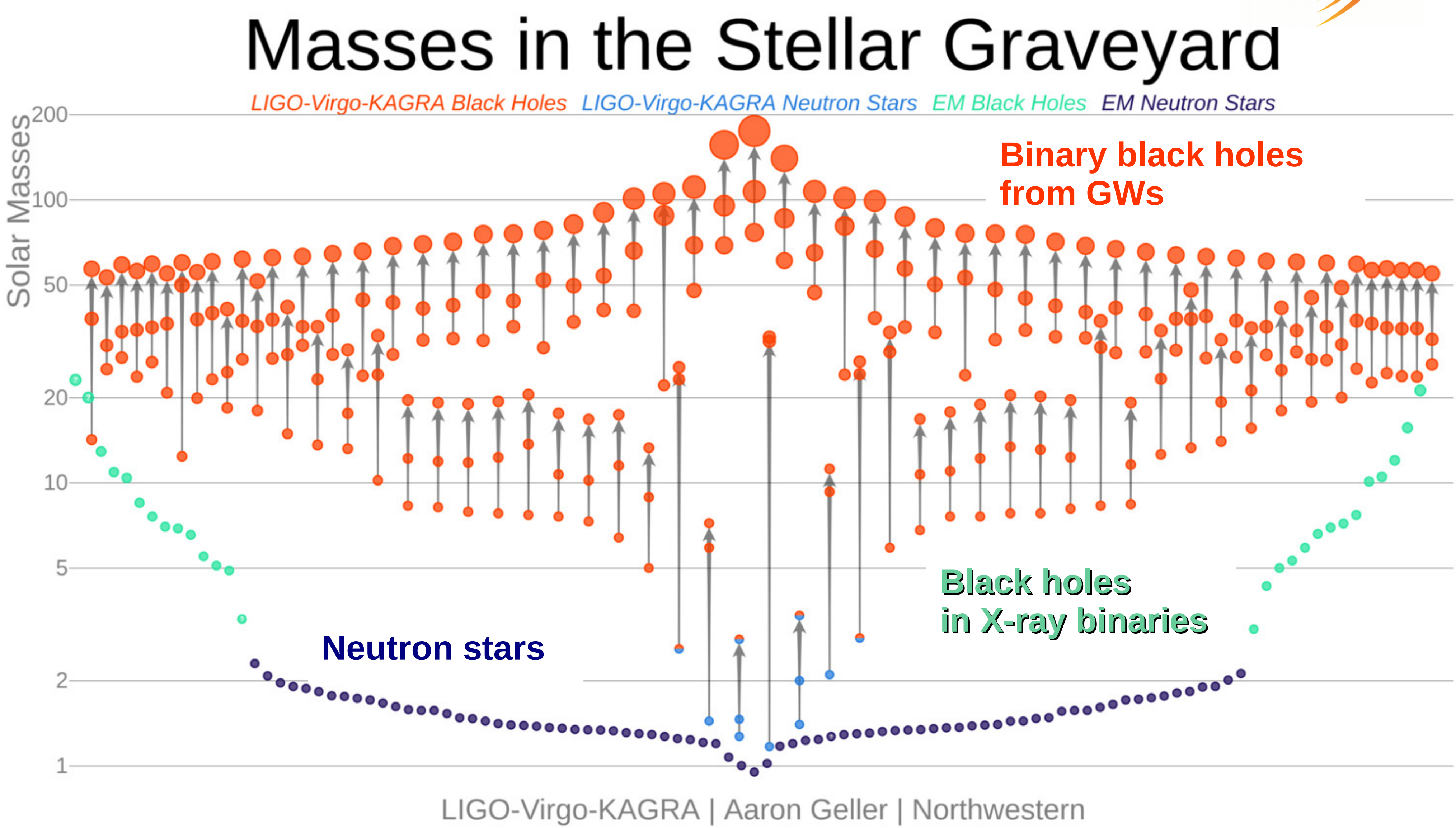
IPAM Workshop, November 15 – 19, 2021

OUTLINE:

1. Lessons learned from gravitational waves (GWs)
2. The mass of black holes (BHs) and neutron stars (NSs)
3. Formation channels of binary compact objects
   → isolated binary formation
   → dynamical formation in star clusters
4. Future challenges
5. Conclusions

1. Lessons learned from GW detections

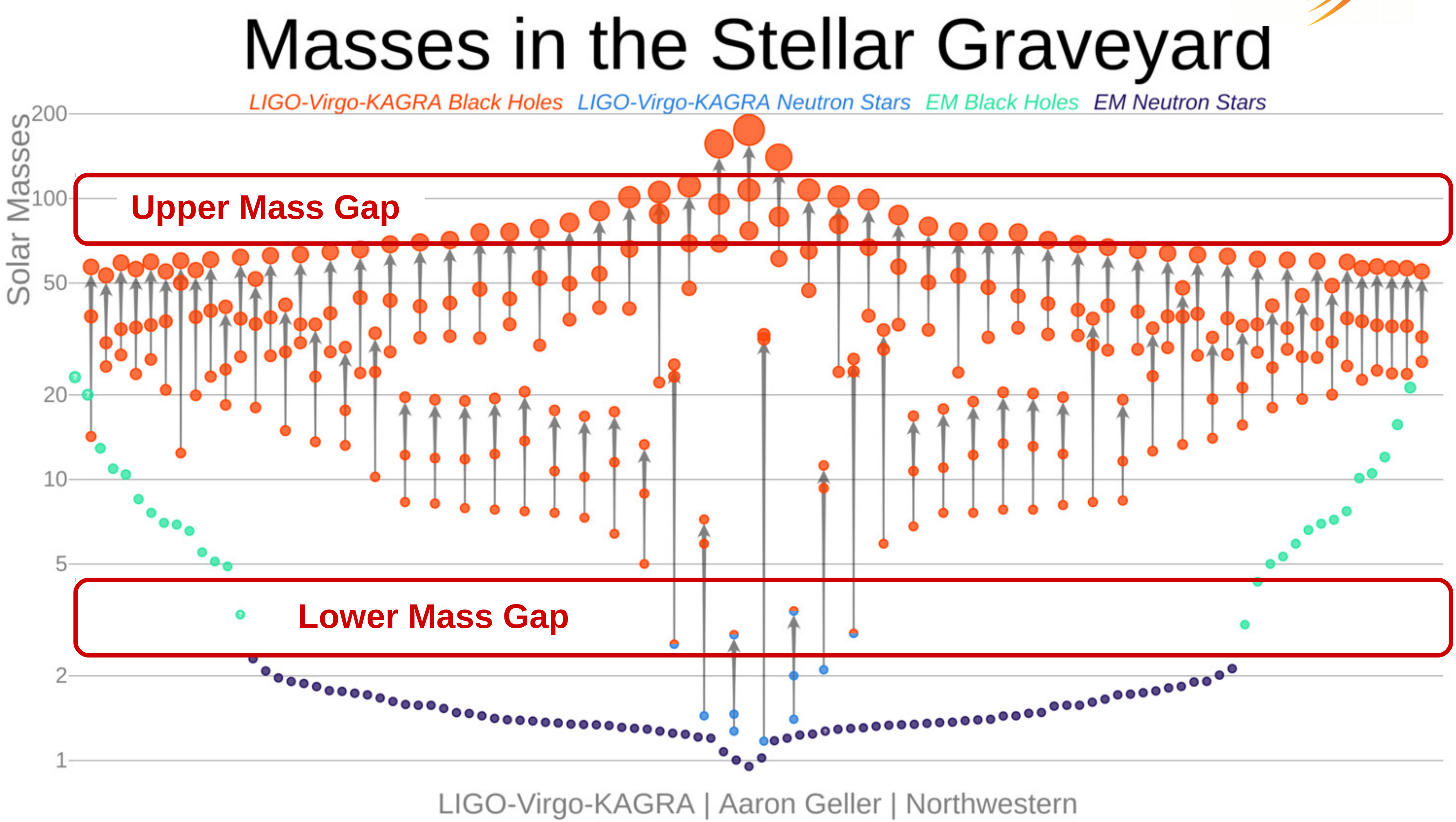


Abbott et al. 2021, GWTC-2, PhRvX, 11, 1053

Abbott et al. 2021, GWTC-2.1, arXiv

Abbott et al. 2021, GWTC-3, arXiv

1. Lessons learned from GW detections

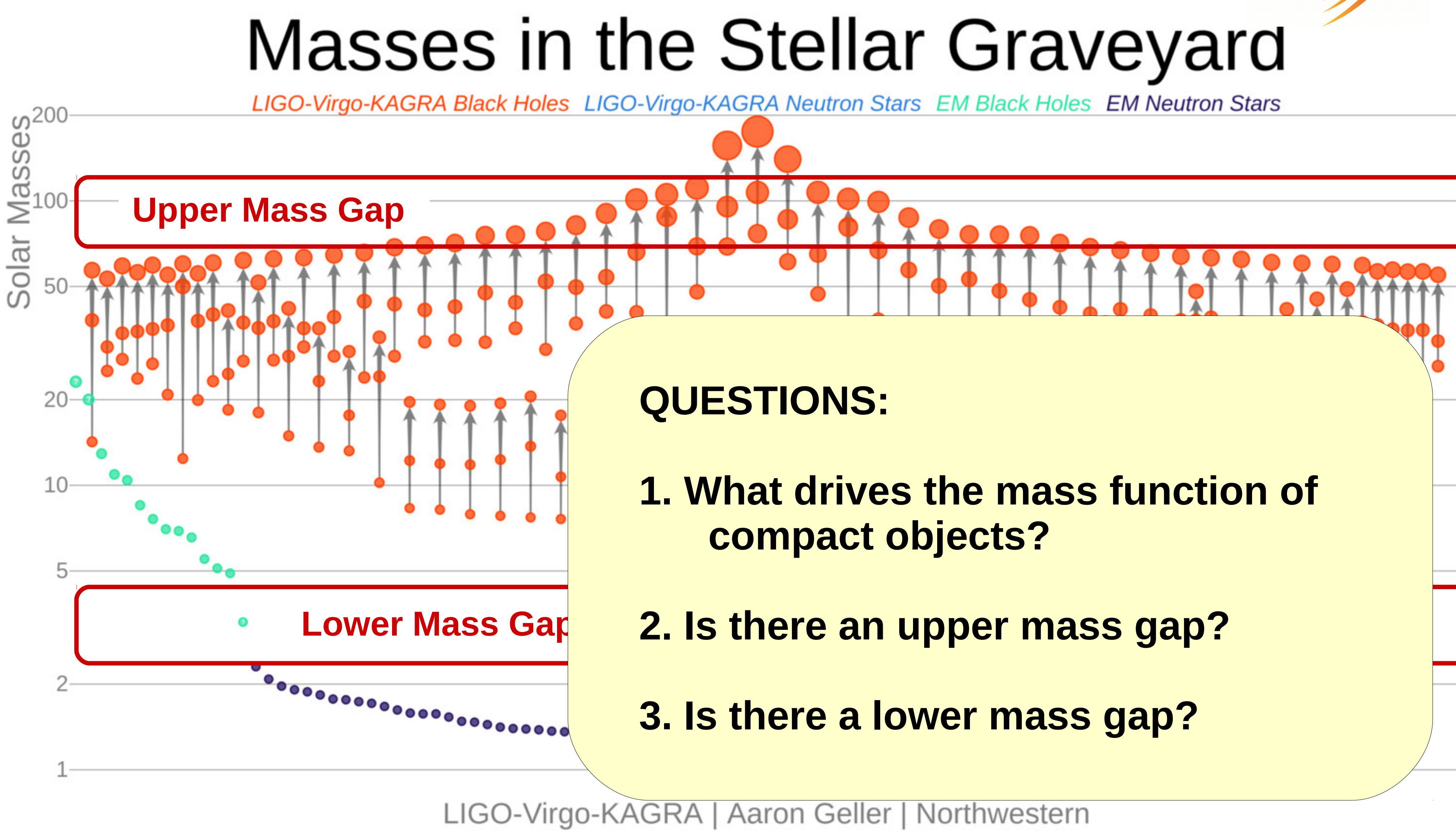


Abbott et al. 2021, GWTC-2, PhRvX, 11, 1053

Abbott et al. 2021, GWTC-3, arXiv

Abbott et al. 2021, GWTC-2.1, arXiv

1. Lessons learned from GW detections



QUESTIONS:

1. **What drives the mass function of compact objects?**

2. **Is there an upper mass gap?**

3. **Is there a lower mass gap?**

Abbott et al. 2021, GWTC-2, PhRvX, 11, 1053

Abbott et al. 2021, GWTC-2.1, arXiv

Abbott et al. 2021, GWTC-3, arXiv

2. The mass of BHs and NSs

MASSIVE STARS lose mass by stellar WINDS

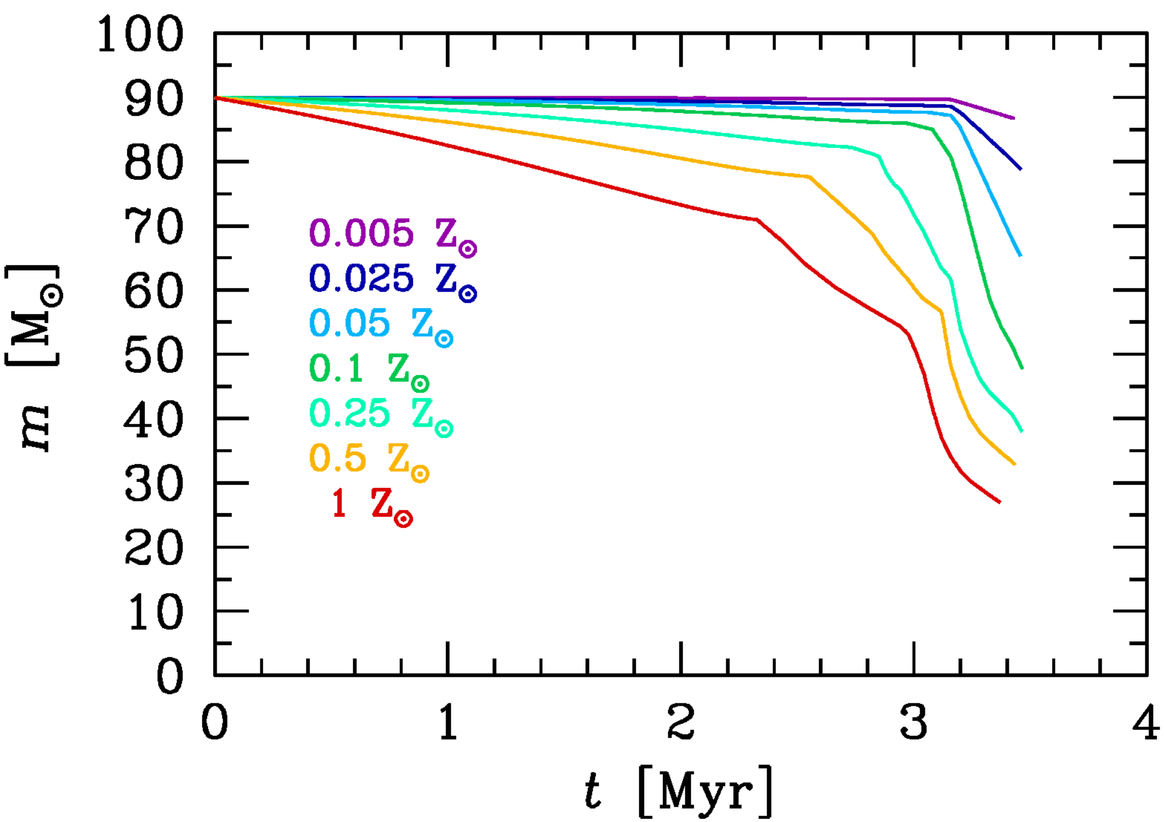
Stellar winds depend on metallicity & stellar luminosity
(e.g. Vink et al. 2001; Graefener & Hamann 2008; Vink et al. 2011)

$$\dot{M} \propto Z^{\alpha}$$

$$\alpha = 0.85 \quad [\text{if } \Gamma < 2/3]$$
$$\alpha = 2.45 - 2.4\,\Gamma \quad [\text{if } \Gamma > 2/3]$$

$$\Gamma = \frac{L_*}{L_{\rm Edd}}$$

Chen, Bressan et al. (2015)



Massive metal-poor stars end their life with higher mass than metal-rich ones

2. The mass of BHs and NSs

CORE – COLLAPSE SUPERNOVA / DIRECT COLLAPSE:

Fundamental question: does the star explode as core collapse 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. The mass of BHs and NSs: winds + core collapse SN

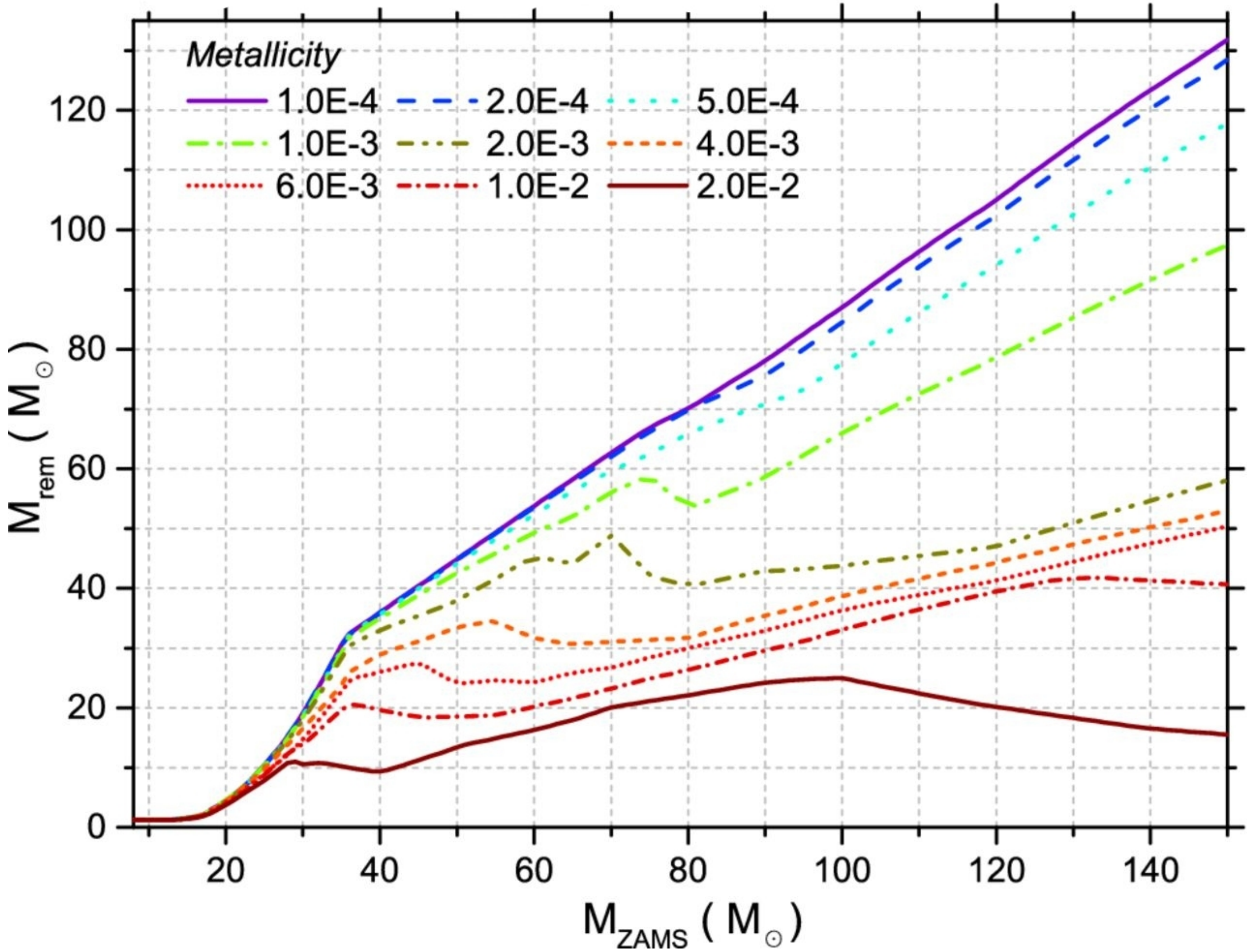


Figure from Spera, MM & Bressan 2015
see also Heger et al. 2003;
MM et al. 2009, 2010, 2013;
Belczynski et al. 2010; Fryer et al. 2012

2. The mass of BHs and NSs: pair instability and the upper mass gap

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

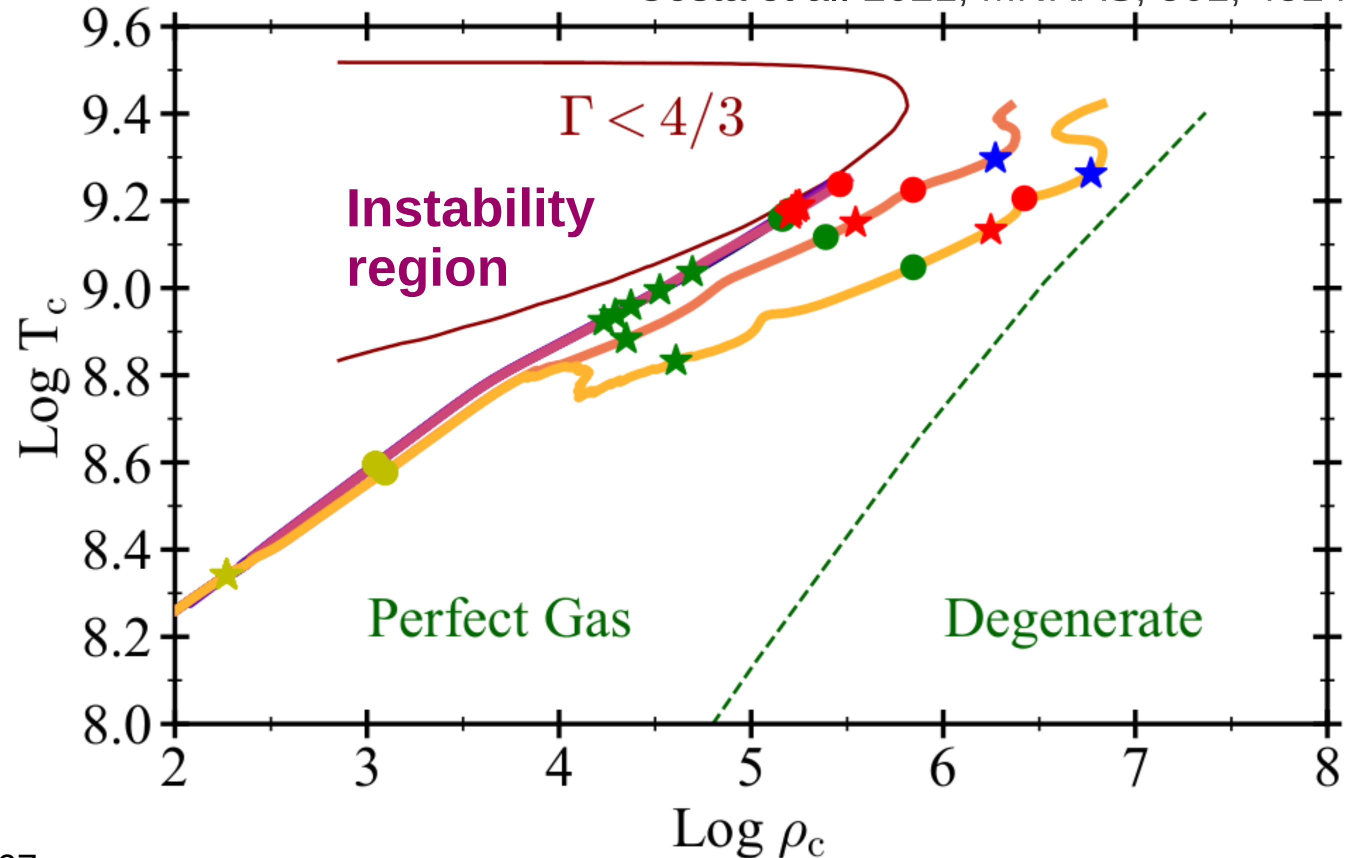
Missing photon pressure
triggers instability:

PAIR INSTABILITY

* Contraction of
 stellar core

* premature ignition of
 neon, oxygen, silicon

Costa et al. 2021, MNRAS, 501, 4514



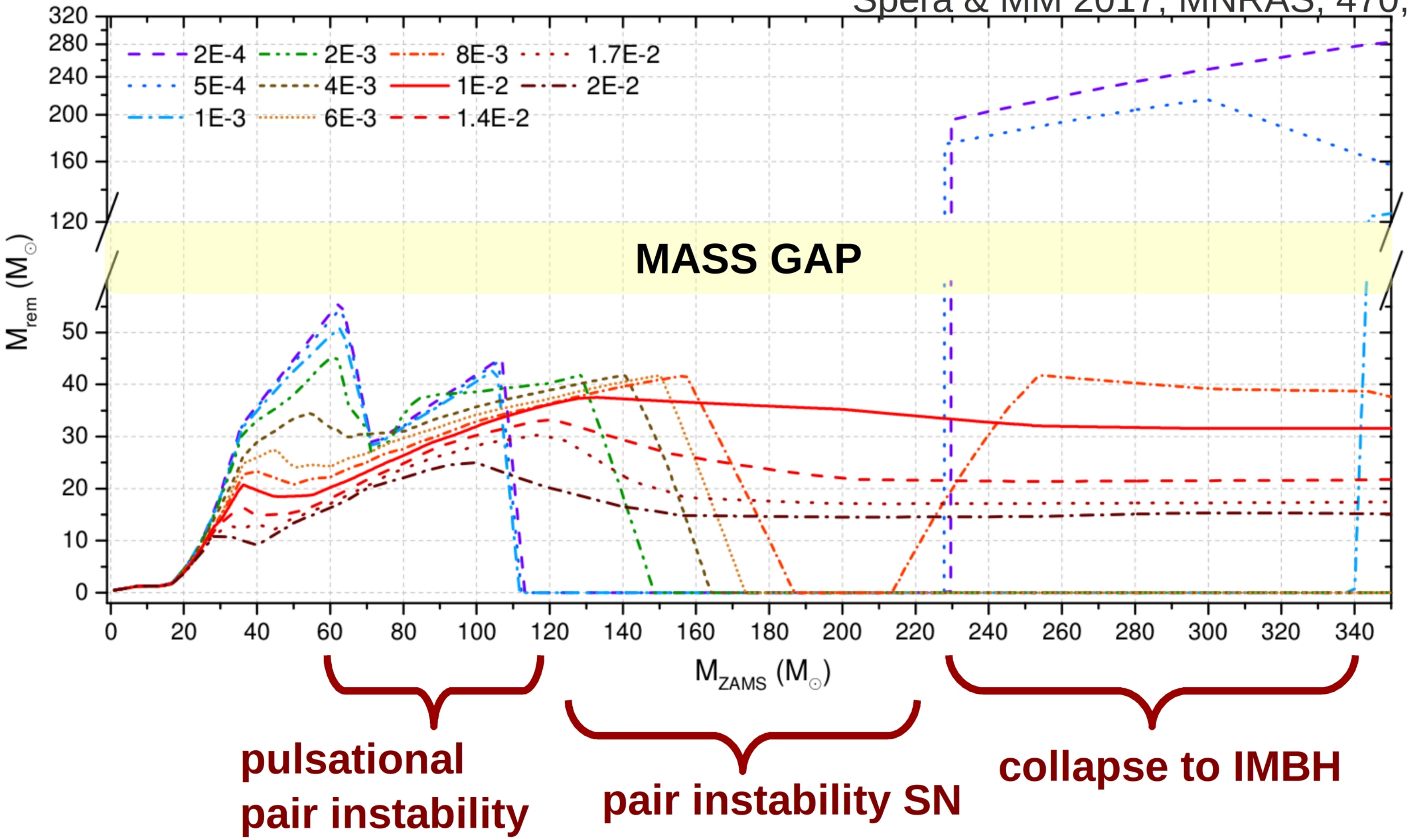
Stars (Circles): beginning (end) of helium, carbon, neon, and oxygen burning

Fowler & Hoyle 1964; Barkat et al. 1967; Rakavy & Shaviv 1967; Ober et al. 1983; Bond et al. 1984; Woosley et al. 2002; Heger & Woosley 2002; Woosley et al. 2007

2. The mass of BHs and NSs: pair instability and the upper mass gap

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



see also Yoshida et al. 2016; Belczynski et al. 2016; Woosley 2017, 2019; Giacobbo et al. 2018; Marchant et al. 2018, 2019; Stevenson et al. 2019; Farmer et al. 2019, 2020; Woosley & Heger 2021

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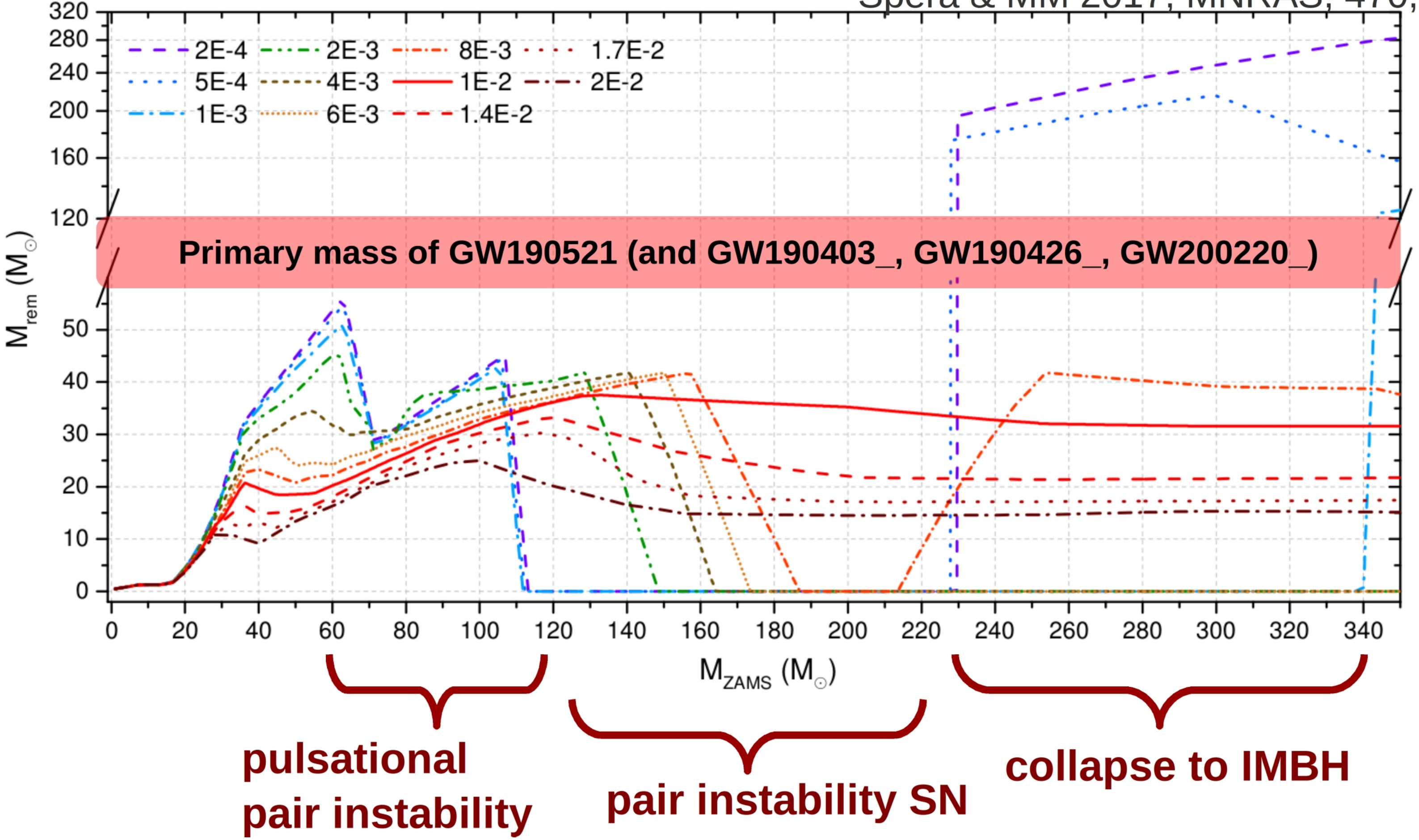
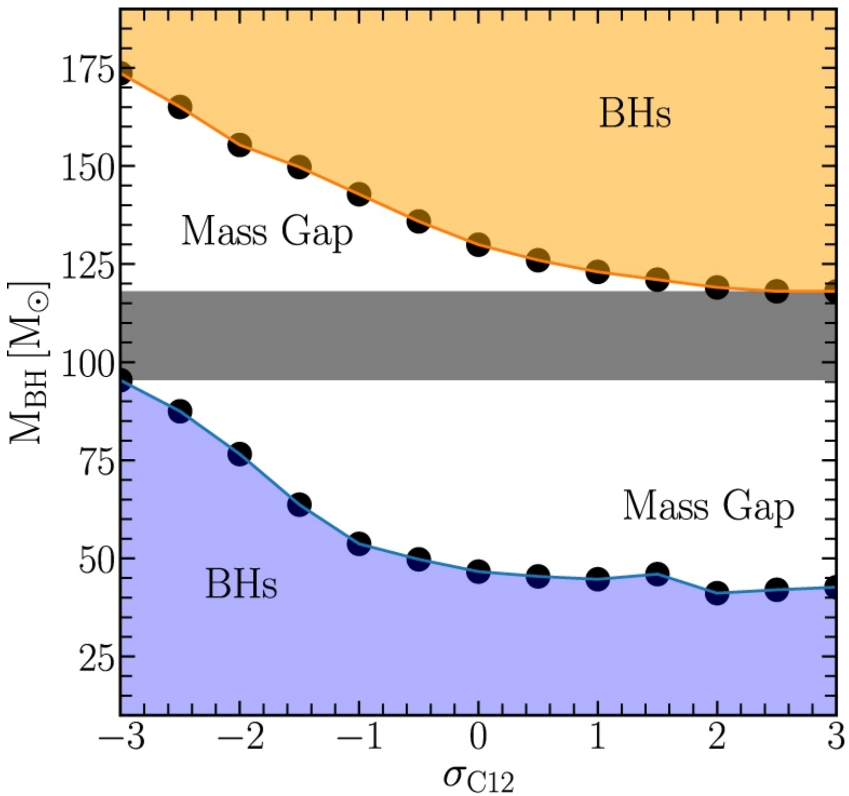


see also Yoshida et al. 2016; Belczynski et al. 2016; Woosley 2017, 2019; Giacobbo et al. 2018; Marchant et al. 2018, 2019; Stevenson et al. 2019; Farmer et al. 2019, 2020; Woosley & Heger 2021

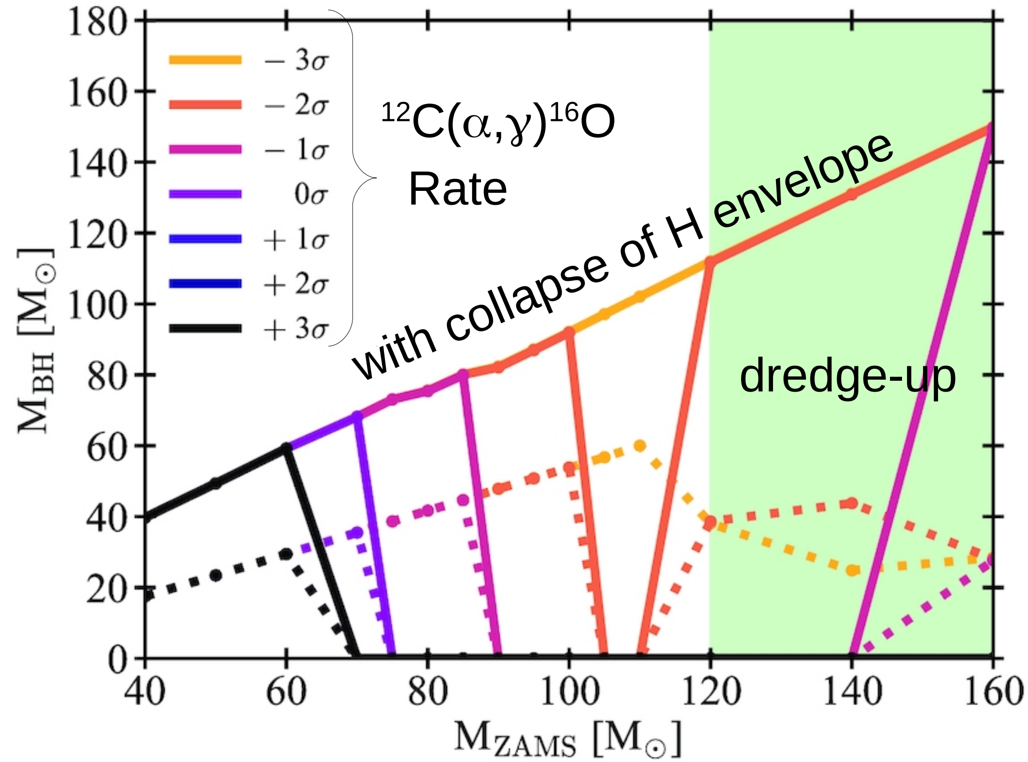
2. The mass of BHs and NSs: uncertainties on the upper mass gap

- nuclear reaction rates ($^{12}C(\alpha,\gamma)^{16}O$)
- core overshooting / envelope undershooting

- rotation of progenitor
- treatment of convection
- collapse of H envelope



Uncertainty on $^{12}C(\alpha,\gamma)^{16}O$ rate (Farmer et al. 2020)

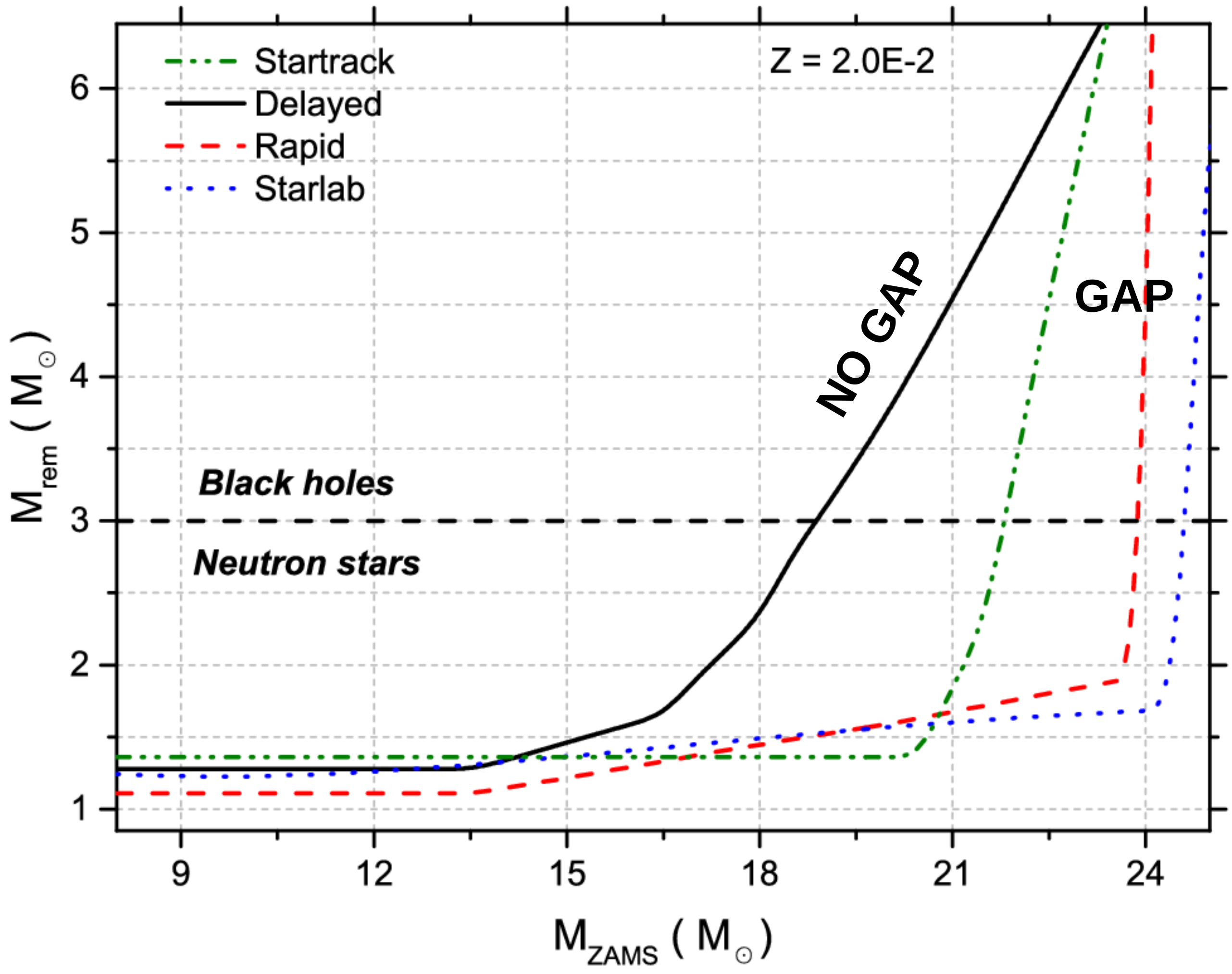


Uncertainty on envelope collapse (Costa et al. 2021)

See also: Takahashi 2018; Leung et al. 2018; Farmer et al. 2019, 2020; MM et al. 2020; Marchant et al. 2019, 2020; Tanikawa et al. 2020; Farrell et al. 2020; Renzo et al. 2020; van Son et al. 2020; Liu & Bromm 2020; Safarzadeh & Haiman 2020; Belczynski 2020; Kinugawa et al. 2020; Umeda et al. 2020; Woosley & Heger 2021; Vink et al. 2021; Costa et al. 2021

2. The mass of BHs and NSs: uncertainties on the lower mass gap

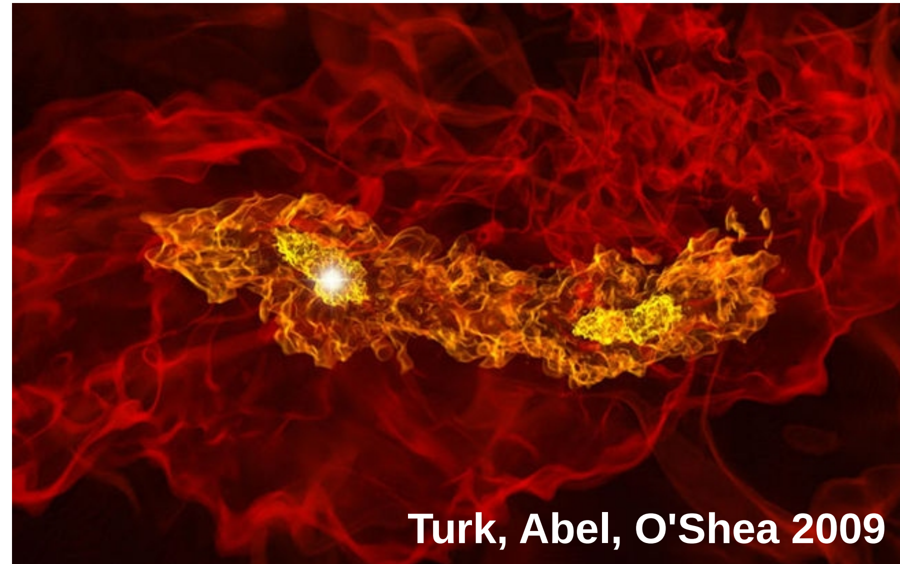
Uncertainties on the outcome of a core collapse supernova are even larger than uncertainties on pair instability

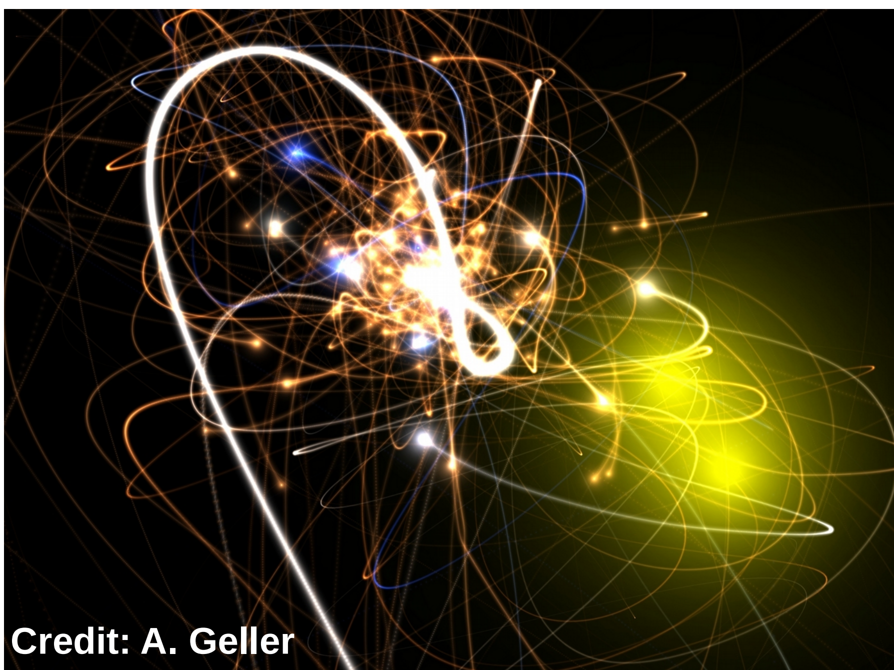


Belczynski et al. 2010 (Startrack model); Fryer et al. 2012 (Delayed and Rapid model); Spera et al. 2015 (Starlab model); Zevin et al. 2020

3. What are the formation channels of binary compact objects?

ISOLATED BINARIES:
two stars form from same cloud
and evolve into two compact objects
gravitationally bound





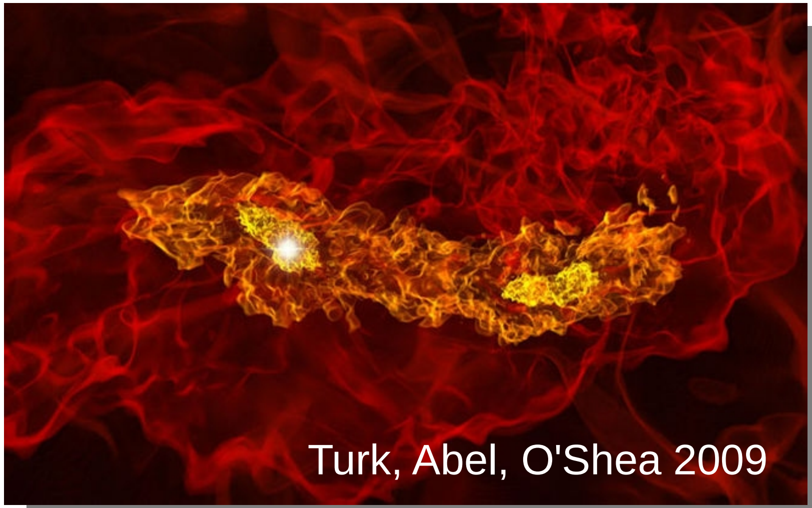
DYNAMICAL BINARIES:
Binary compact objects
(especially BBHs and BHNSs)
form and/or evolve
by dynamical processes
in star clusters

3. Formation channels: isolated binaries

ISOLATED BINARIES:

Two stars form from same cloud and become a binary compact object

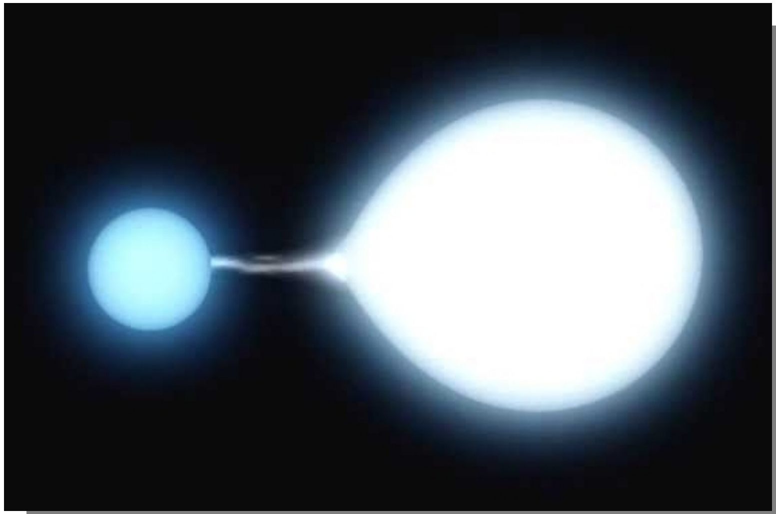
Massive stars form preferentially in binary – multiple systems (Sana et al. 2012; Moe & Di Stefano 2017)



Many evolutionary processes affect a close binary

- Wind mass transfer
- Roche lobe overflow
- Common envelope
- Tidal evolution
- SN kick
- Gravitational wave decay

Credit: ESO

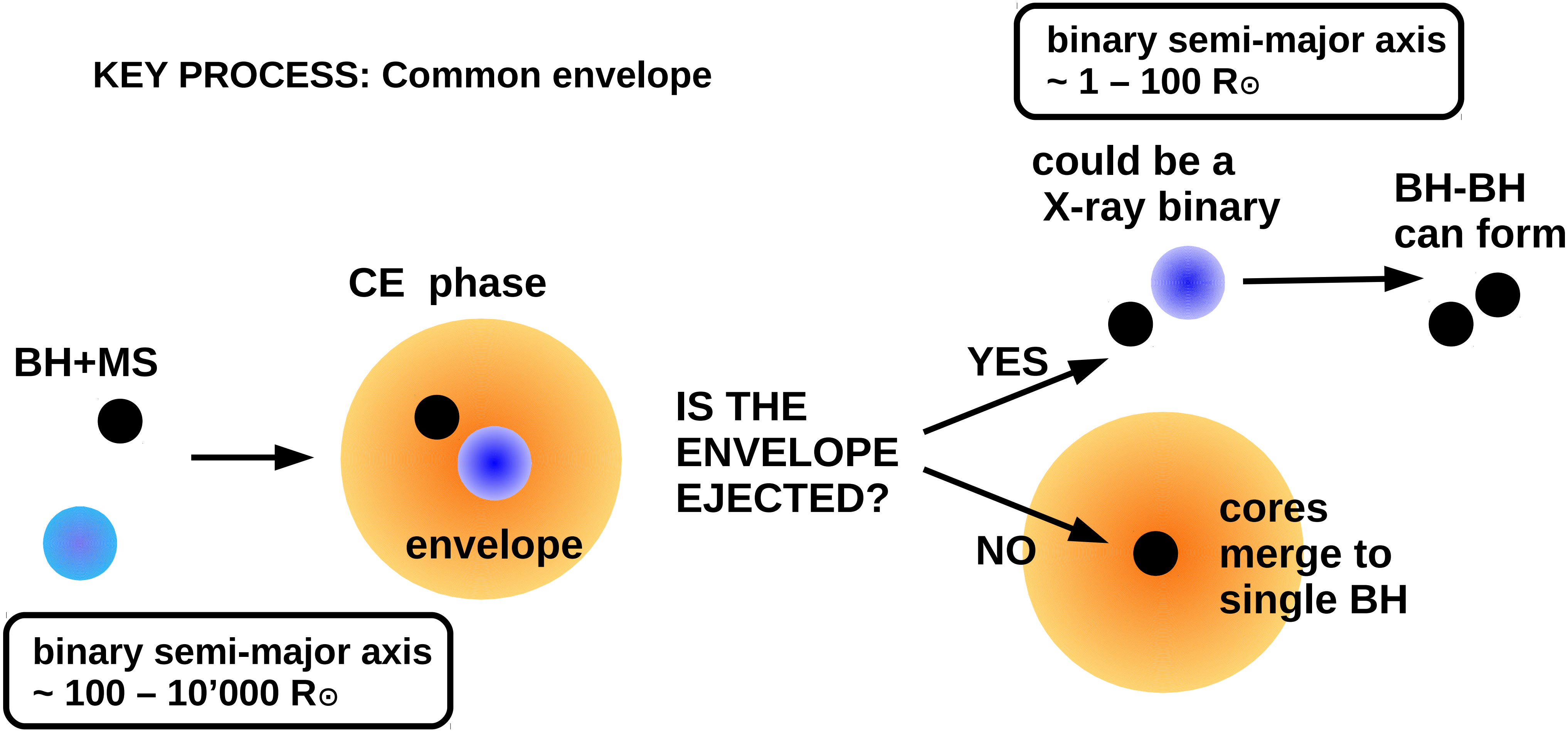


3. Formation channels: isolated binaries

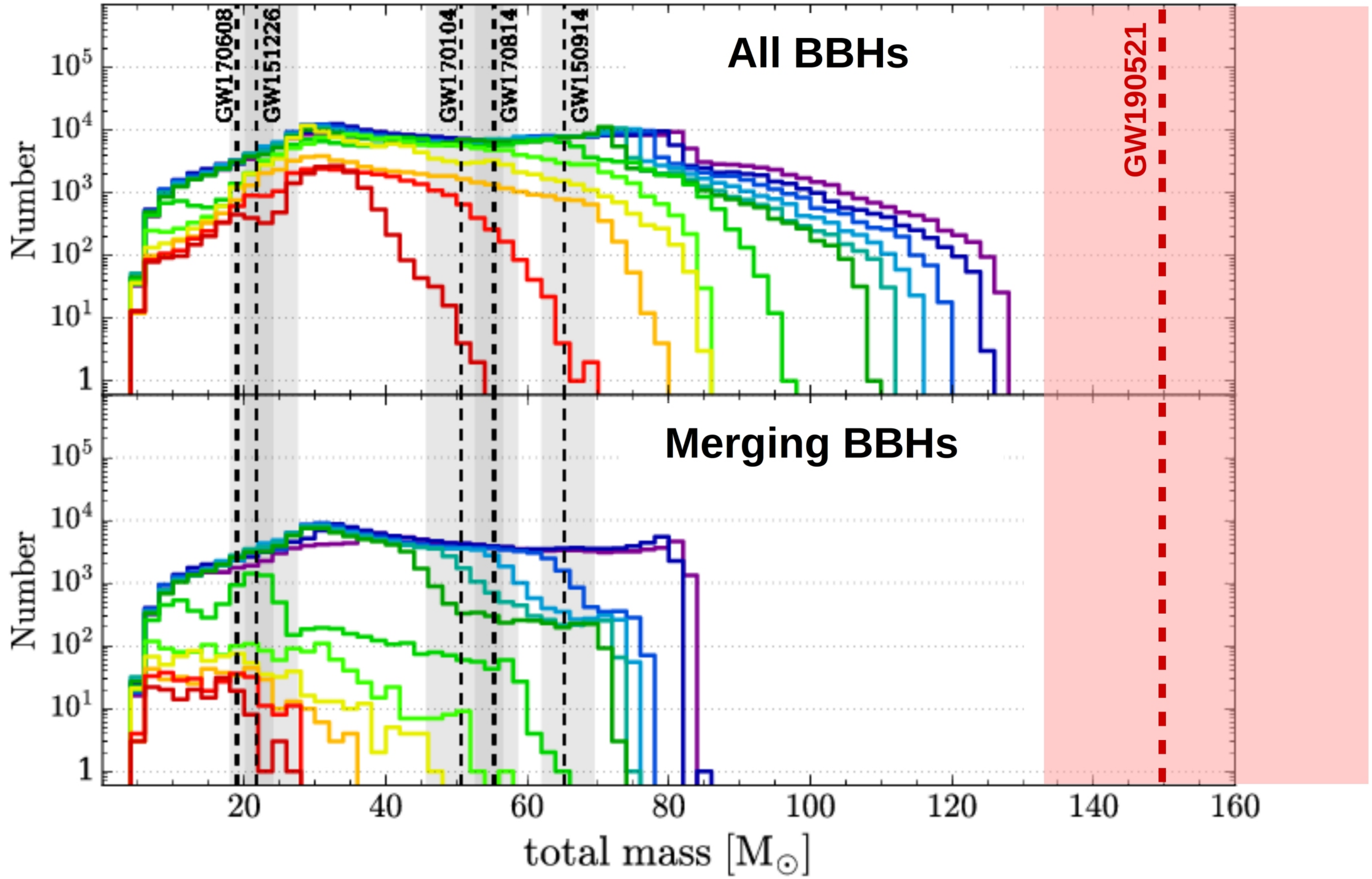
BOTTLENECK:
A BBH merges only if its initial orbital separation < 100 $R_\odot$

but the radius of BH progenitors grows (much) larger than 100 $R_\odot$

KEY PROCESS: Common envelope



3. Formation channels: mass of isolated binaries



Giacobbo & MM 2018

* Mass and number of BBHs depend on metallicity (Z)

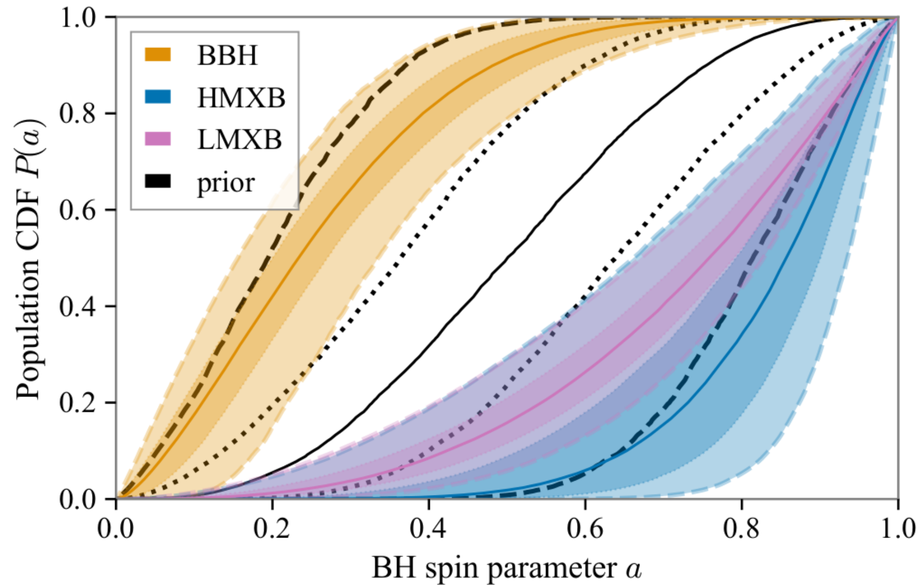
* BHs with mass ≤ 65 $M_\odot$ form, but only BHs with mass ≤ 40 $M_\odot$ merge in isolation

because of envelope loss in common envelope and mass transfer

3. Formation channels: spins of isolated binaries

* Gravitational wave events support
relatively low-spinning BHs
(Abbott et al. 2021, ApJ, 2021, ApJ, 913, L7)

* Some BHs in high-mass X-ray binaries
are extremely fast spinning
(e.g., Reynolds 2020; Miller-Jones et al. 2021)

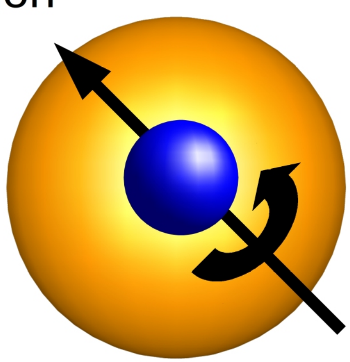


Fishbach & Kalogera 2021

How can we explain these two populations?

BH spin should be related to spin of the core at the end of stellar evolution

→ **PROBLEM:** ←
we do not know how efficient is **angular momentum transport** from stellar core to envelope



if inefficient → population of FAST SPINNING BHs
if efficient → population of SLOW SPINNING BHs

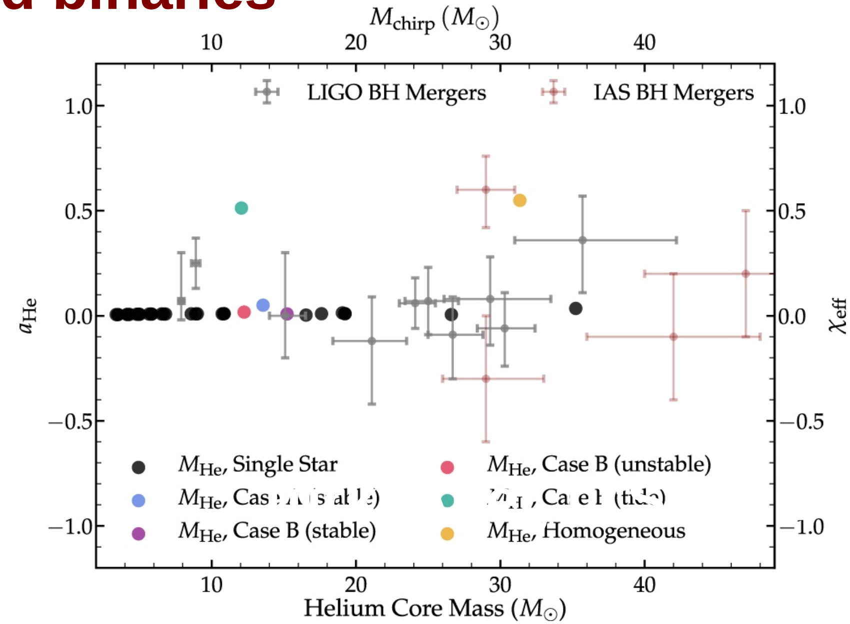
Limongi & Chieffi 2018; Fuller et al. 2019; Fuller & Ma 2019; Belczynski et al. 2020

3. Formation channels: spins of isolated binaries

Tayler – Spruit dynamo (Spruit 2020):
angular momentum efficiently dissipated via magnetic effect

→ produces only non-spinning BHs

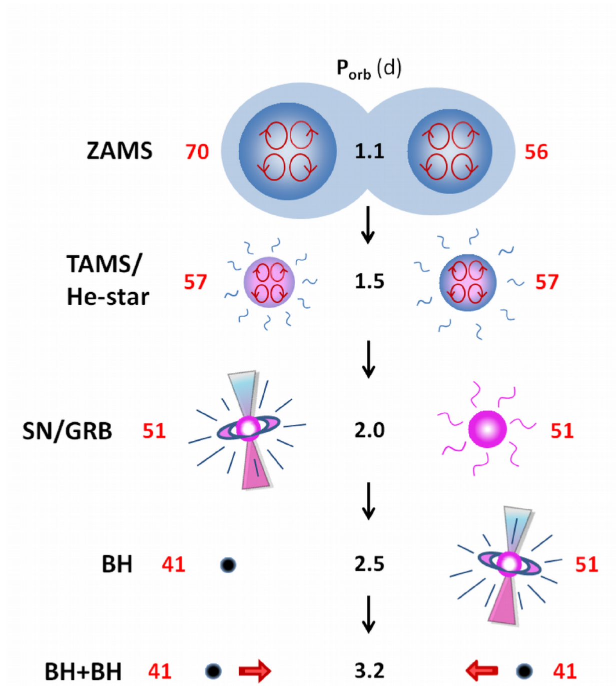
PROBLEM:
how do we explain fast-spinning BHs in high-mass X-ray binaries?



Fuller & Ma 2019, ApJ, 881, L1

Fast spinning BHs from
chemically homogeneous evolution (CHE)
(e.g., Marchant et al. 2016;
Mandel & de Mink 2016; de Mink & Mandel 2016)

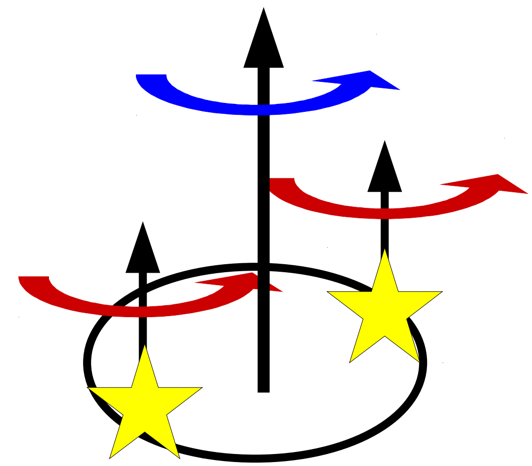
Second-born BH in a binary BH might be fast spinning thanks to
TIDAL INTERACTIONs
in the progenitor binary
(Bavera et al. 2020; Bavera et al. 2021)



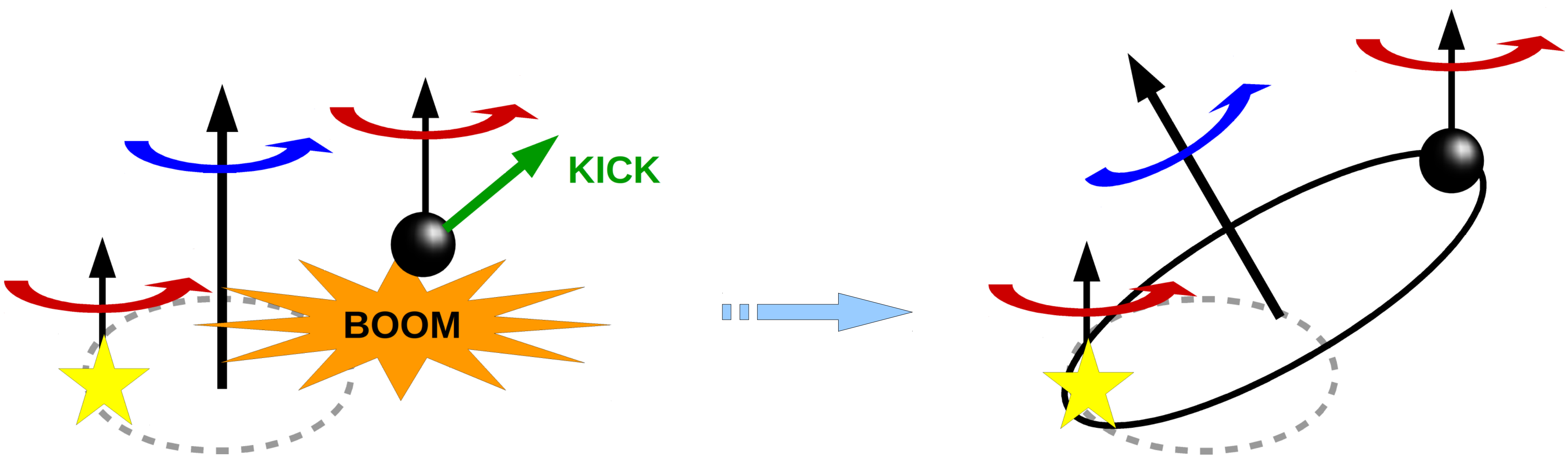
3. Formation channels: spins of isolated binaries

We do not understand spin magnitudes
but maybe we do understand spin orientations

SPINS mostly ALIGNED to the
orbital angular momentum
of the binary by tides and mass transfer

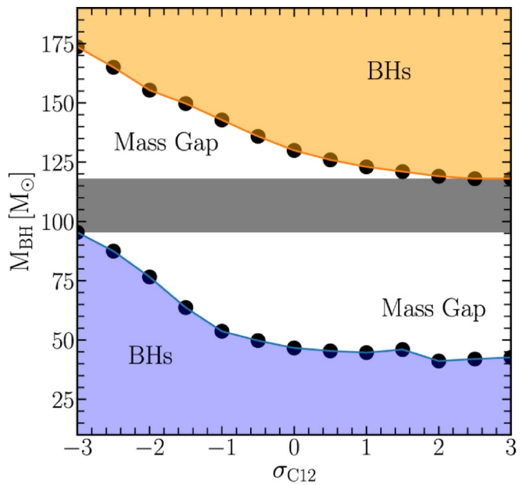


ONLY **SUPERNOVA EXPLOSION**
can misalign it by a few / a few ten degrees
(Kalogera 2000; Rodriguez et al. 2016; Gerosa et al. 2018; Belczynski et al. 2020)

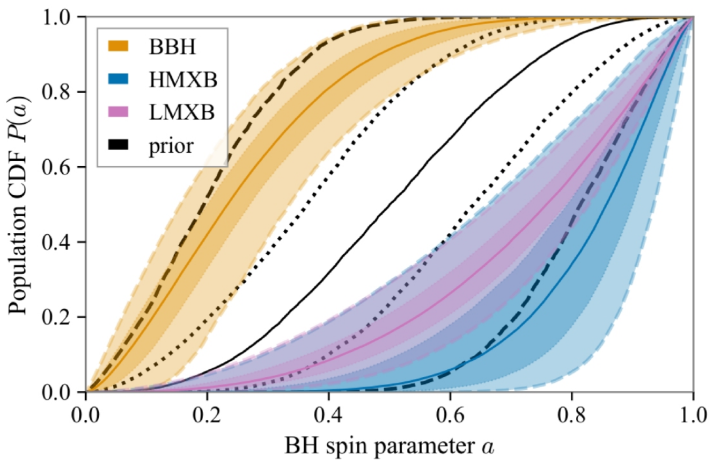


3. Take home message for isolated binaries

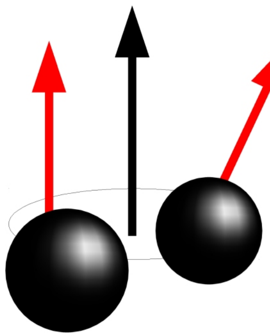
- Relatively low-mass BBHs (m_1<50 $M_\odot$)
  from isolated evolution
  but large uncertainties
  from stellar evolution



- We do not understand spin magnitudes



- Spin directions of isolated BBHs
  mostly aligned with orbital
  angular momentum of binary



3. Formation channels: dynamics

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

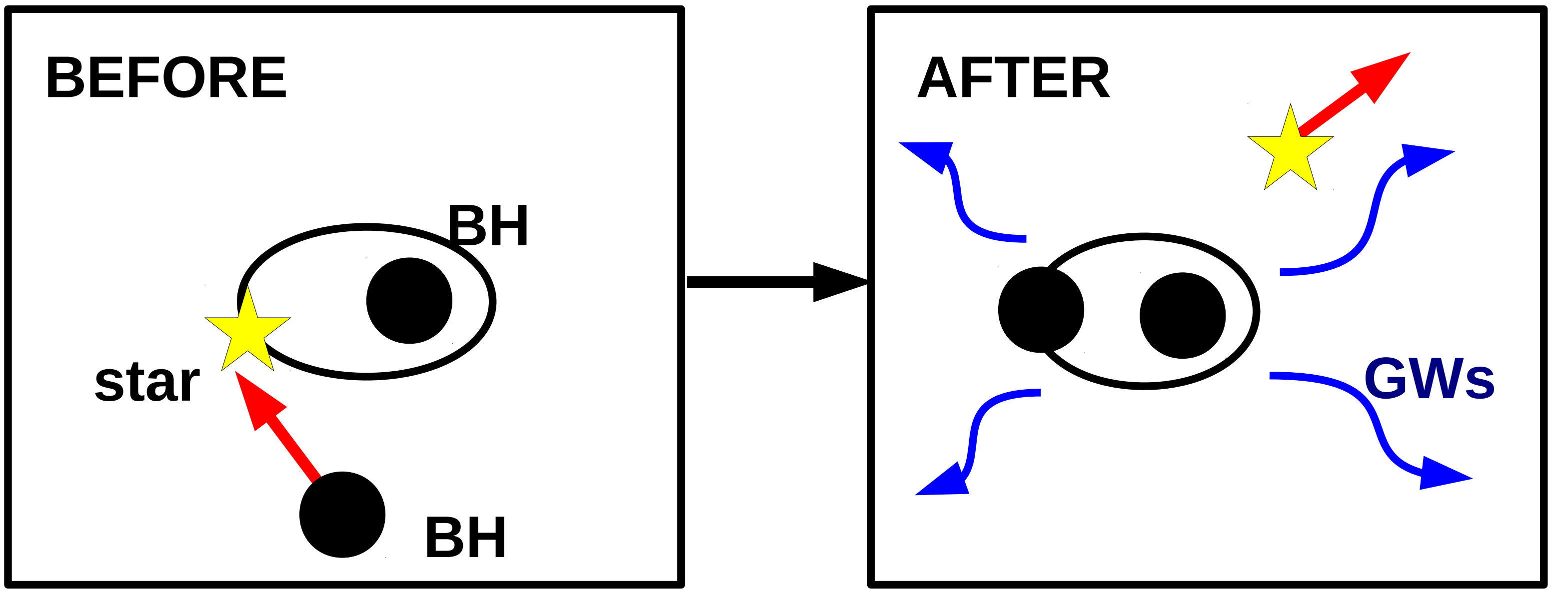
(Lada & Lada 2003; Weidner & Kroupa 2006; Weidner, Kroupa & Bonnell 2010; Gvaramadze et al. 2012; Portegies Zwart et al. 2010)

R136
in the LMC

HST – NASA

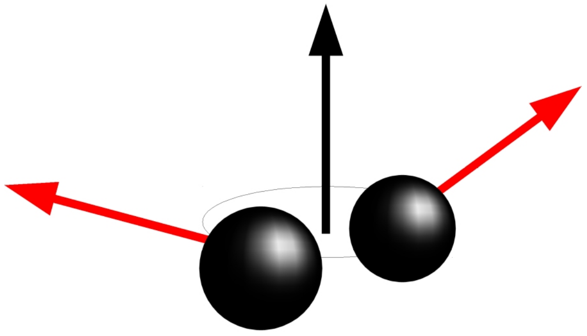
3. Formation channels: dynamics

Exchanges bring BHs in binaries



<u>Properties of BBHs formed via exchange:</u>

*** more massive than field BBHs**
* high initial eccentricity
*** isotropically oriented spins**
→ spin components can be in the orbital plane



Ziosi et al. 2014, MNRAS, 441, 3703

3. Formation channels: exchanges and stellar mergers

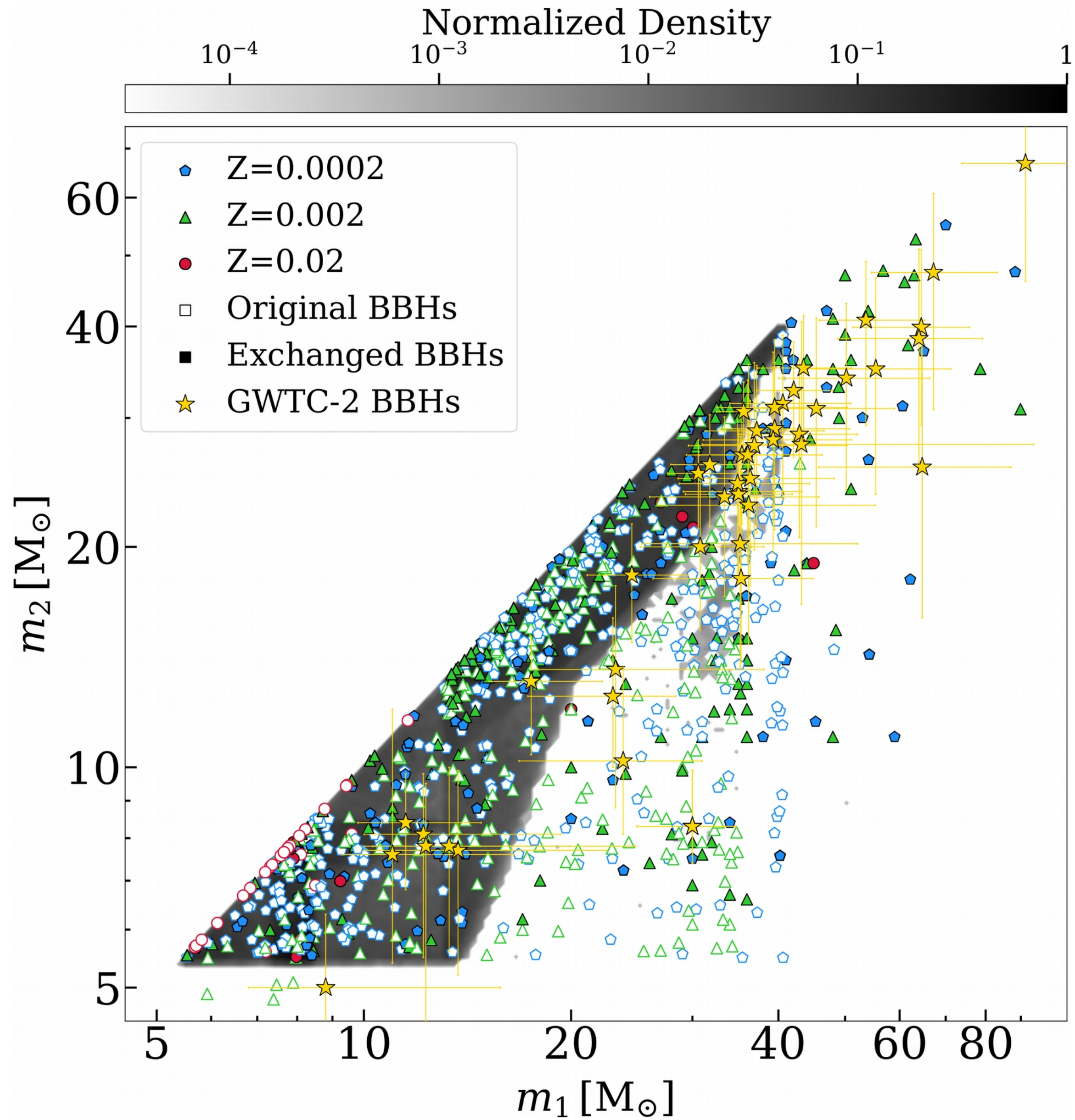
1. Dynamics favours mass ratios < 1

2. Dynamics favours large BBH mass

Isolated BBHs only
primary mass up to ~50 M⊙

Dynamical BBHs with
primary mass > 50 M⊙

~ 1 % BBH mergers
with mass in the pair instability
mass gap,
corresponding to ~ 5% of
detectable events



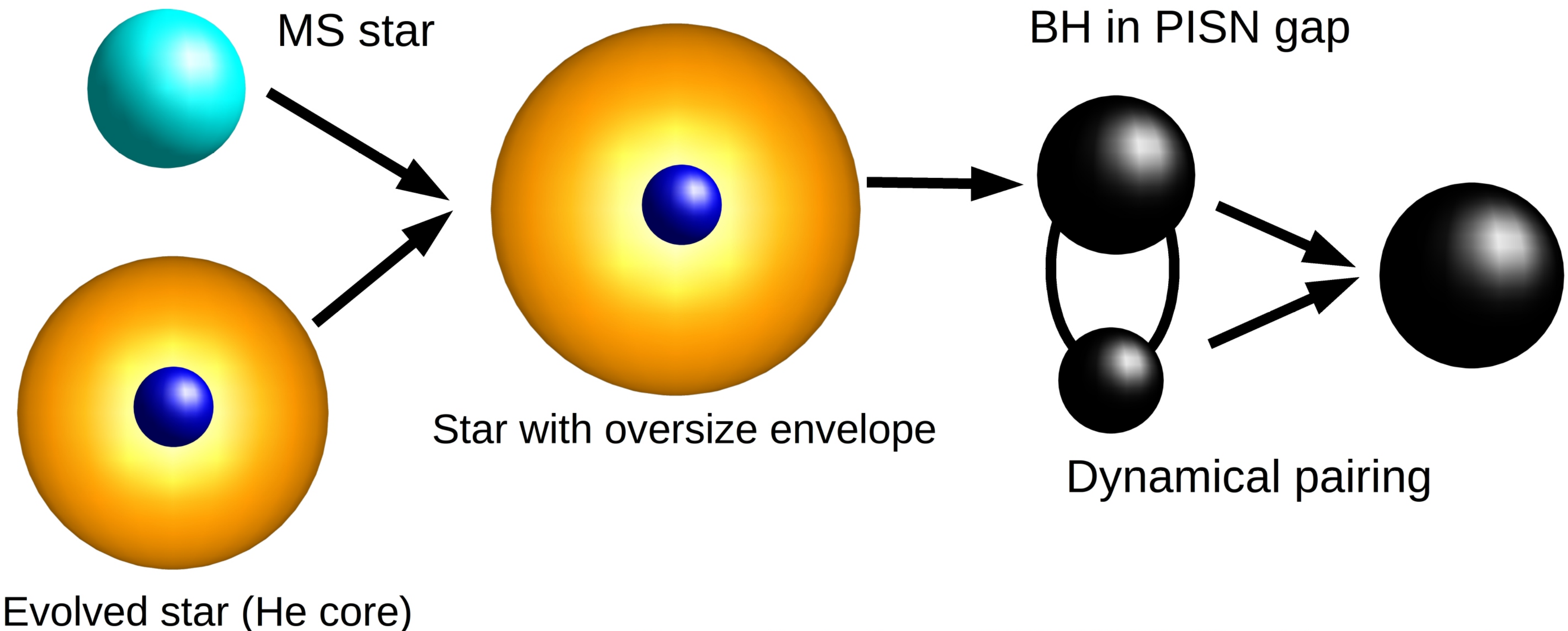
Di Carlo et al. 2019, MNRAS 487, 4947

Rastello et al. 2021, MNRAS, 507, 3612

Banerjee, 2021, MNRAS, 500, 3002

3. Formation channels: exchanges and stellar mergers

What produces BHs with mass > 60 M⊙ in the previous plot?



Scenario to form GW190521-like binary systems

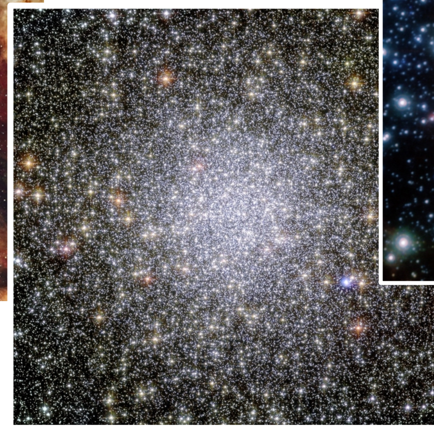
Di Carlo et al. 2019, MNRAS 487, 4947
Di Carlo et al. 2020a, MNRAS, 497, 1043

3. Formation channels: hierarchical mergers


R136, credit: NASA

Young star clusters:
$10^{2-5}\,M_\odot$, < 100 Myr

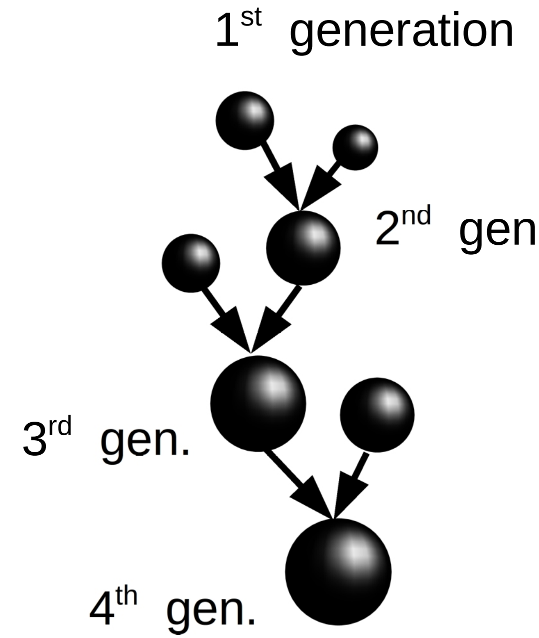
47 Tucanae, credit: NASA/ESA/HST



Globular clusters:
$10^{4-6}\,M_\odot$, > 10 Gyr


Credit: ESO, Gillessen et al.

Nuclear clusters:
$>10^{6}\,M_\odot$, >10 Gyr



Hierarchical mergers of BHs
Repeated mergers of BHs building a more massive one

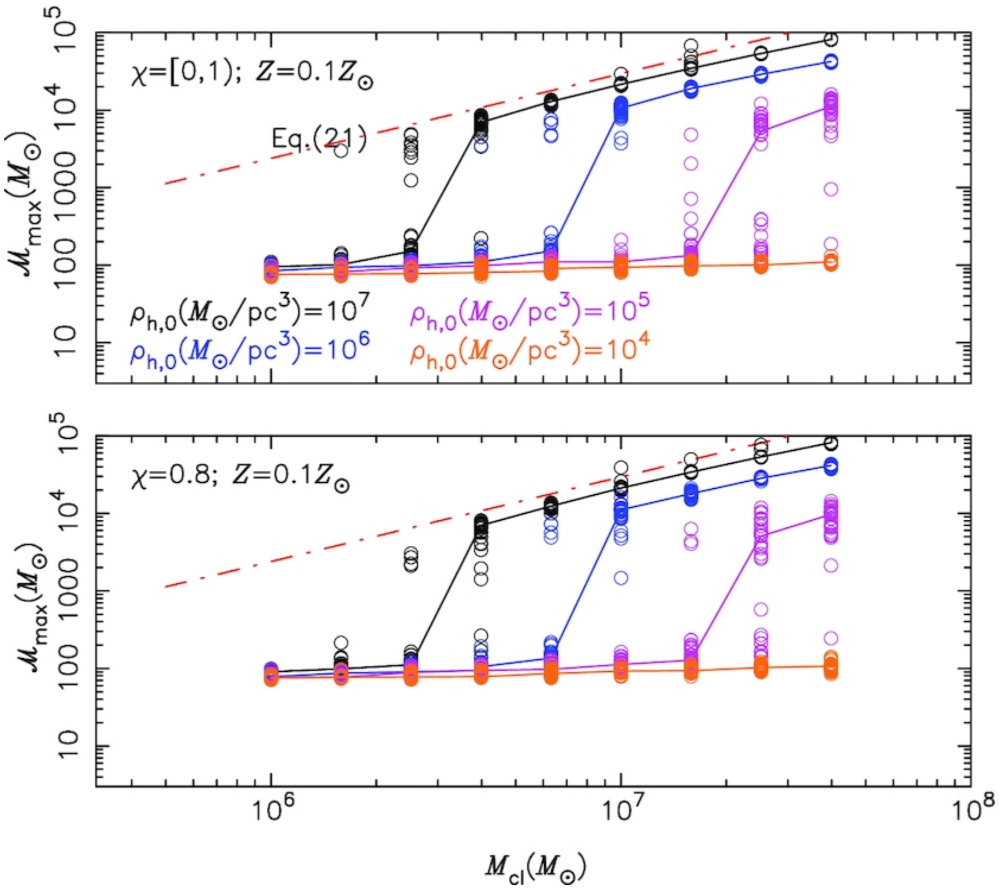
Possible only in star clusters:
the merger remnant can find a companion by dynamical exchange (e.g. Miller & Hamilton 2002)

Main obstacle to hierarchical chains:
Gravitational wave recoil up to a few x 1000 km/s (e.g., Lousto et al. 2012)

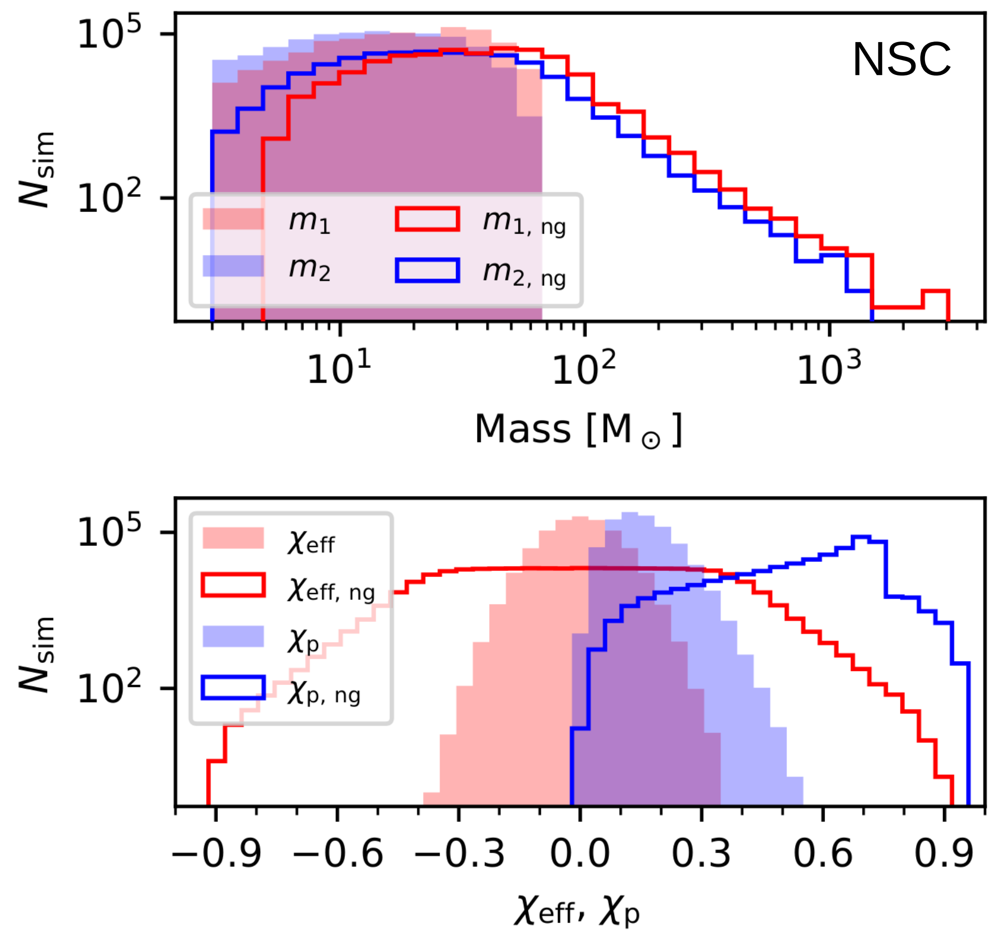
Higher than the escape velocity from least massive star clusters

3. Formation channels: hierarchical mergers

Nuclear star clusters can build up intermediate-mass black holes in this way



Antonini et al. 2019, MNRAS, 486, 5008

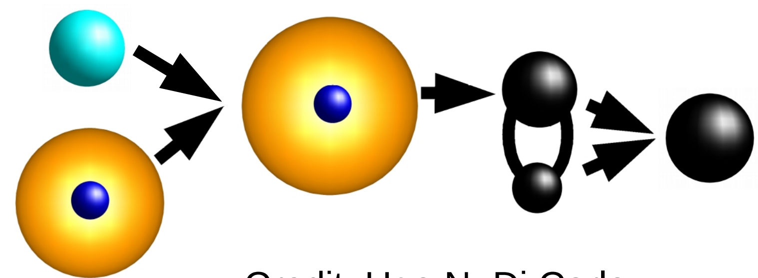


MM et al. 2021, MNRAS, 505, 339

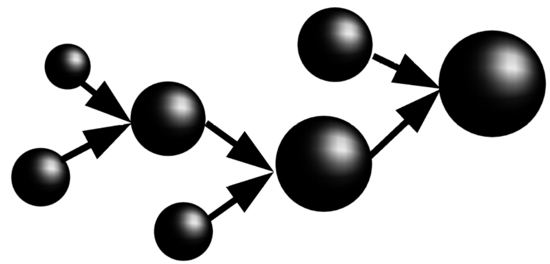
See also Rodriguez et al. 2019; Arca Sedda et al. 2020; Fragione et al. 2020; Gerosa et al. 2019, 2021

3. Take home message for dynamical binaries

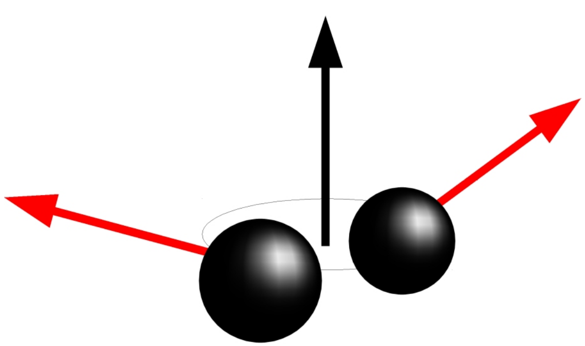
- Several dynamical channels can fill the upper mass gap:
  - Stellar collisions
  - Hierarchical mergers in different star clusters and AGN disks

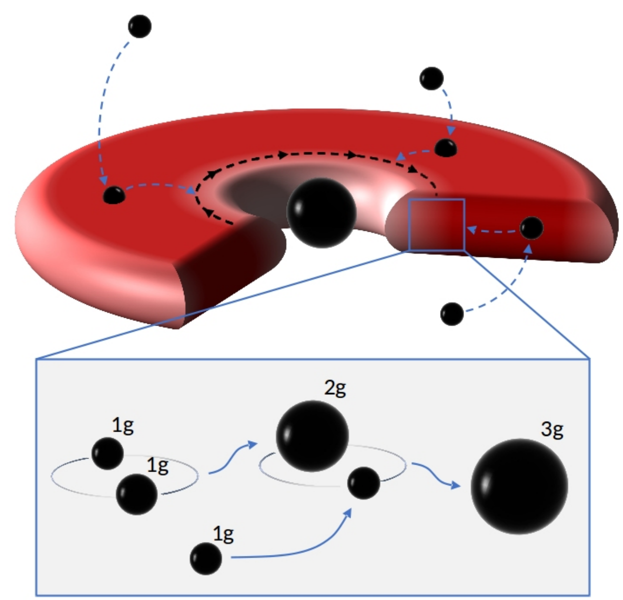


Credit: Ugo N. Di Carlo



- Spin directions isotropically distributed

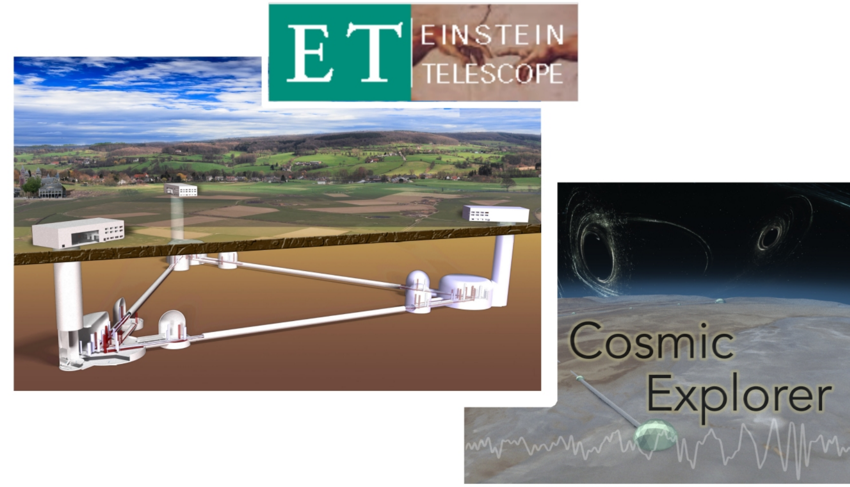




Credit: Imre Bartos

4. Future challenges: getting ready for 3G detectors

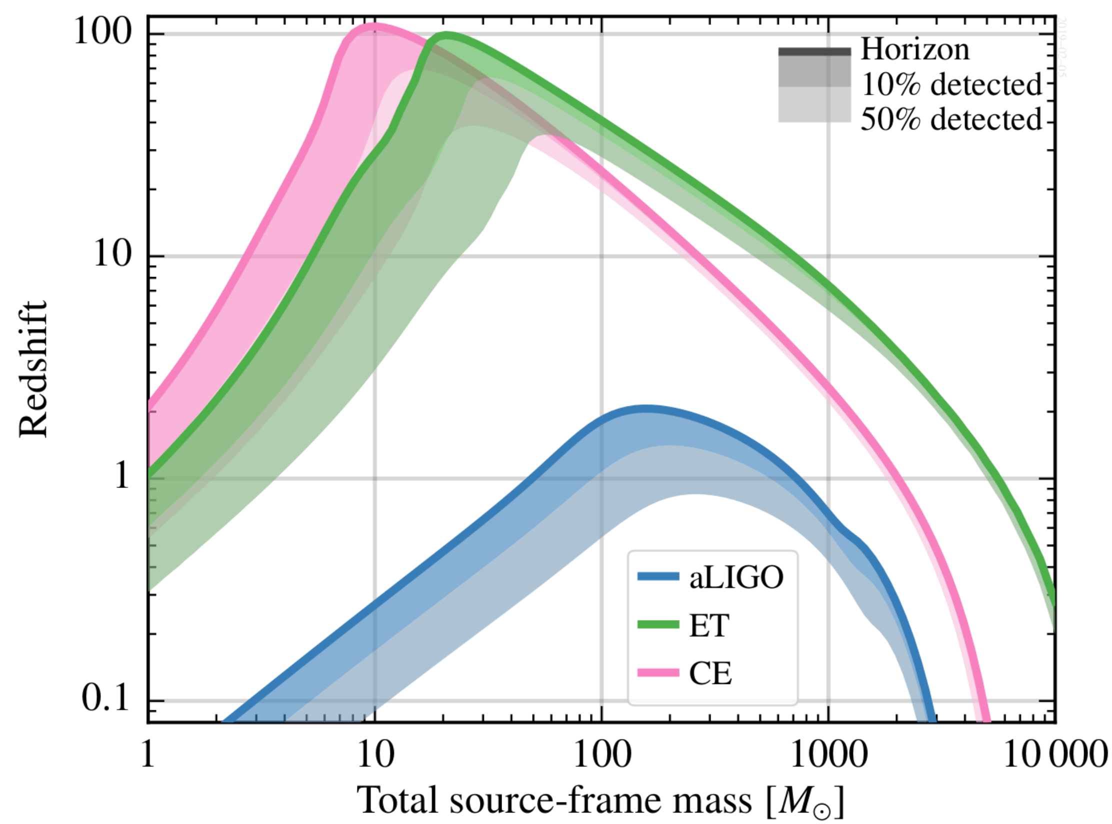
Einstein Telescope and Cosmic Explorer will observe BBH mergers
up to z ~ 30 (~100 Myr after Big Bang)
and BNS mergers
up to z ~ 2 (cosmic noon)



→ Develop the main science case

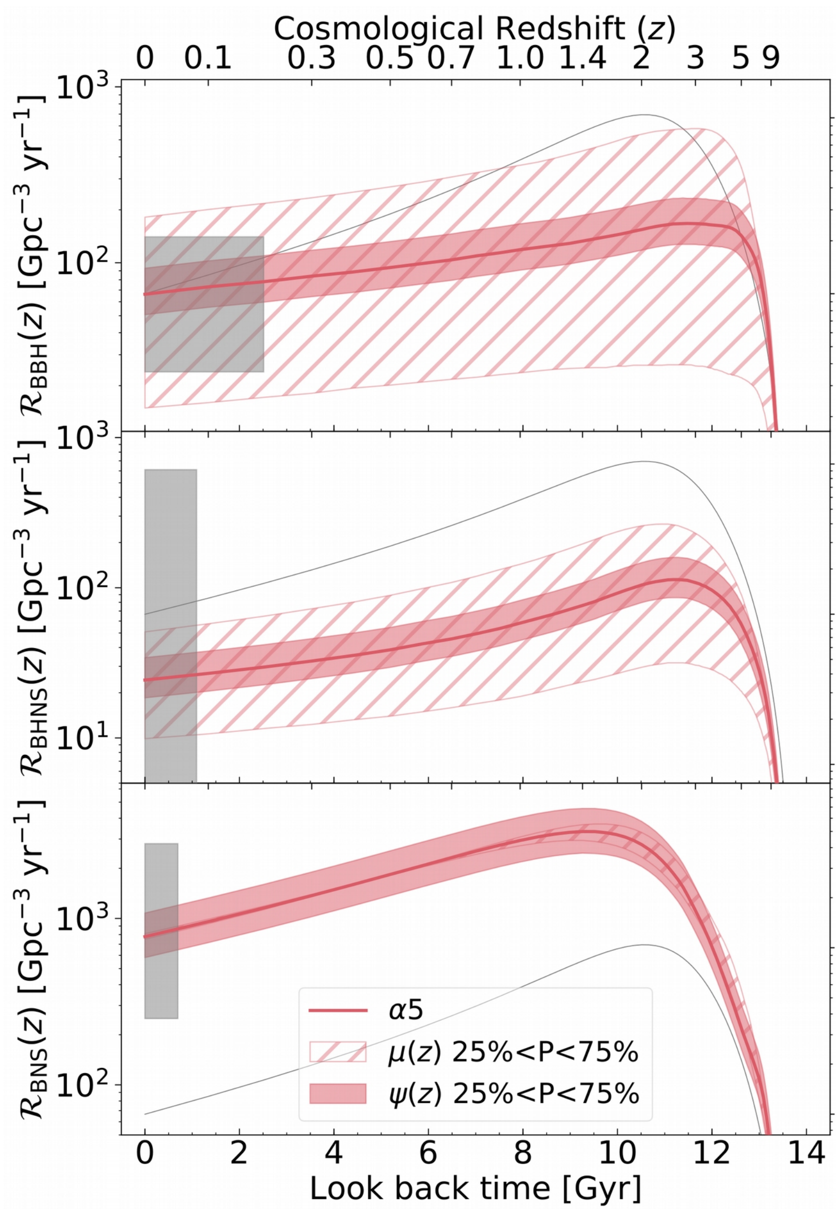
→ Build an active and inclusive scientific community ready to exploit 3G data

→ Maximize the scientific impact



4. Future challenges: merger rate evolution

Uncertainties on ISOLATED binaries (star formation, metallicity, binary evolution)

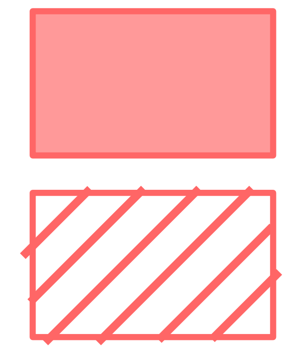


Santoliquido et al. 2021, MNRAS, 502, 4877

Fixed binary evolution model

Changing star formation rate
(within 50% C.I. of observations)

Changing metallicity
(within 50% C.I. of observations)



See also
Chruslinska et al. 2019
Neijssel et al. 2019
Broekgaarden et al. 2021
van Son et al. 2021
Chruslinska et al. 2021
Tanikawa et al. 2021
Mandel & Broekgaarden 2021
Boco et al. 2021

For pop III stars
Liu & Bromm 2020
Ng et al. 2021

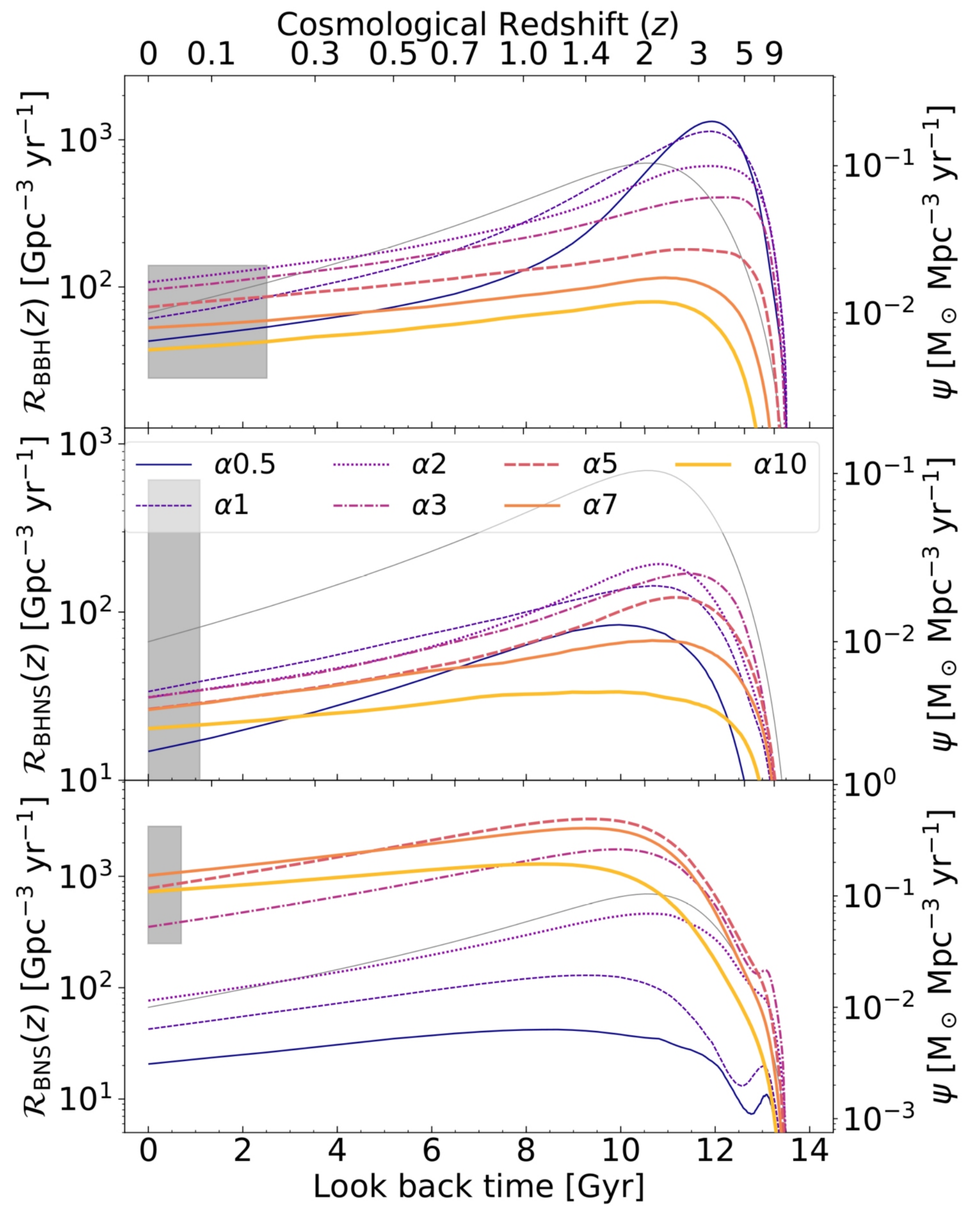
4. Future challenges: merger rate evolution

Uncertainties on ISOLATED binaries (star formation, metallicity, binary evolution)

Fixed star formation rate and metallicity

Changing efficiency parameter of common envelope α

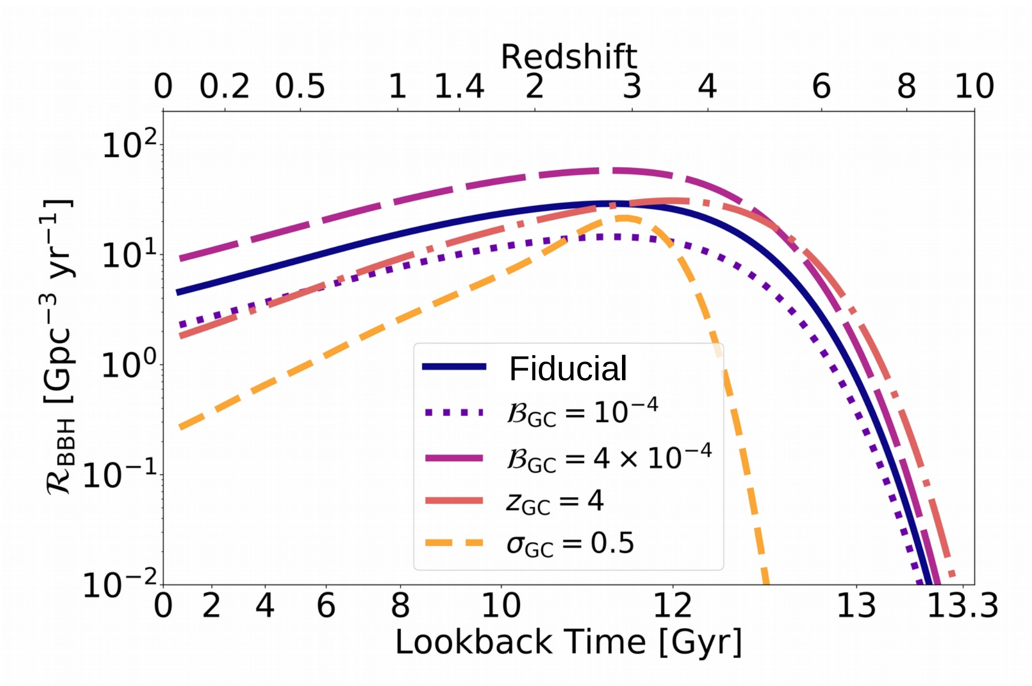
See also
Mandel & Broekgaarden 2021
Neijssel et al. 2019
Broekgaarden et al. 2021
van Son et al. 2021
Chruslinska et al. 2021
Tanikawa et al. 2021

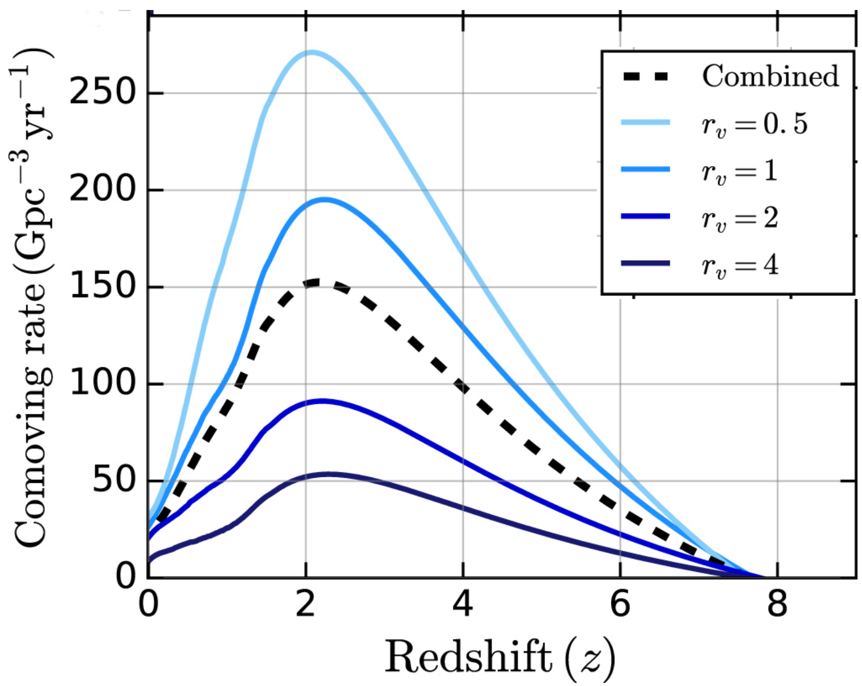


Santoliquido et al. 2021, MNRAS, 502, 4877

4. Future challenges: merger rate evolution and mass evolution

Uncertainties on BBH merger rate evolution in **globular clusters**





Uncertainties on the formation rate of globular clusters:

$$\psi_{\rm GC}(z) = \mathcal{B}_{\rm GC}\,\exp\left[-\left(z - z_{\rm GC}\right)^2 / \left(2\,\sigma_{\rm GC}^2\right)\right]$$

Uncertainty about globular cluster density

MM et al. 2021

Kremer et al. 2020

5. Conclusions

demoblack.com

The future of binary compact object studies is bright (or loud):
LIGO – Virgo – KAGRA O4 and O5
Einstein Telescope & Cosmic Explorer, LISA

but we have a lot of work to do:

Predictive power of astrophysical models on BHs and NSs is hampered by

- Uncertainties on massive star evolution:
  stellar winds, rotation, ang. mom. transport,
  core/envelope overshooting, nuclear reactions,..
  (affect the upper mass gap and BH spins)
- Uncertainties on binary evolution
  common envelope, mass transfer efficiency..
- Uncertainties on stellar collision products

→ **uncertainties on stellar and binary evolution**

- Uncertainties on core collapse supernovae
  (mainly affect the lower mass gap)
- Uncertainties on natal kicks

→ **uncertainties on supernovae**

- Uncertainties on star cluster formation
- Uncertainties on star cluster evolution
  (e.g. equipartition, gravothermal catastrophe,..)

→ **uncertaintes on stellar / gas dynamics**

- Uncertainties on cosmic star formation rate
- Uncertainties on cosmic metallicity evolution

→ **uncertainties on cosmic star formation**

\+ **extremely large parameter space → computational challenge**