What could possibly be ...

The origin and sites of binary black hole (BBH) mergers

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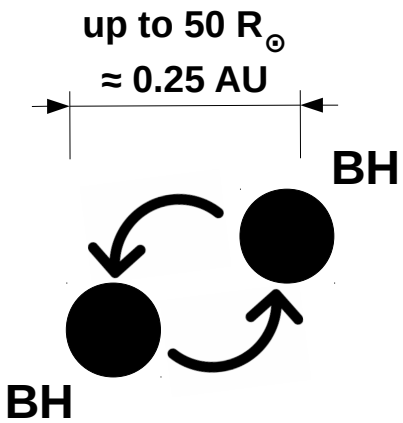
Merger rate densities

- BBH merger rate estimate: **12 – 213 $\mathbf{Gpc^{-3}\,yr^{-1}}$**
- Local supernova rate: ~ 10^5 $Gpc^{-3}\,yr^{-1}$
- BH formation rate: ~ 10^4 $Gpc^{-3}\,yr^{-1}$ d
- **~ 1 BH in 100** ends up in a **merging BBH**
- **<u>That is a lot!</u>**

The separation problem

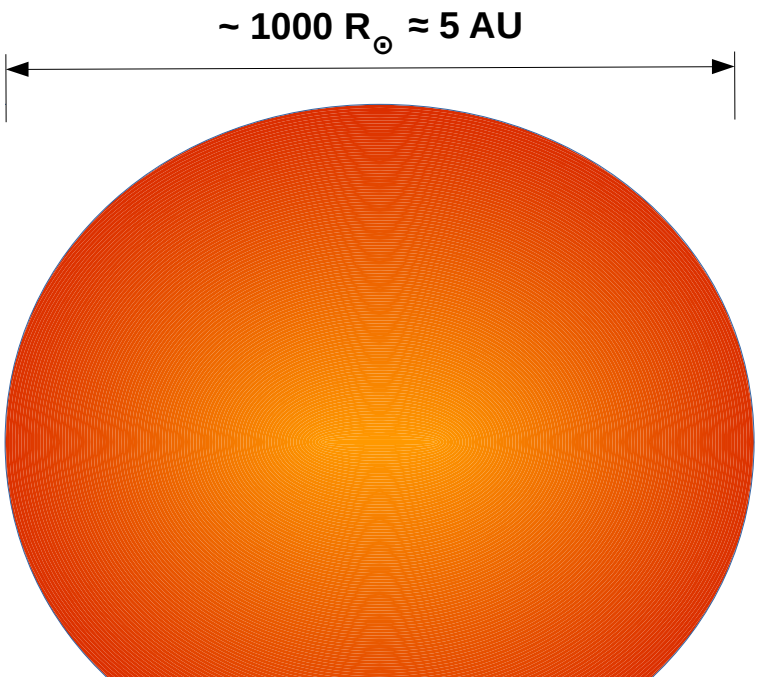
BBH that merges within the Hubble time (~14 Gyr)

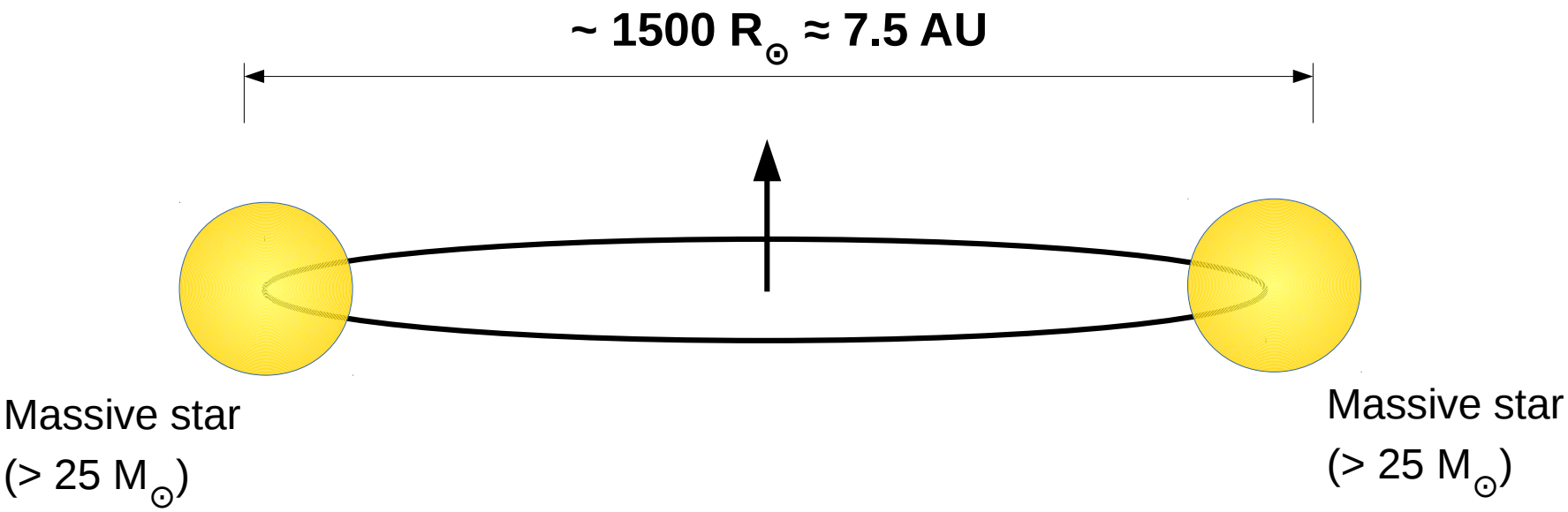


<u>Time to coalescence:</u>

$$T_{GW} \propto a^4 (1-e^2)^{7/2} (m_1 m_2 M)^{-1}$$

Massive star (> 25$_\odot$)
→ a single BH progenitor




~ 1500 R⊙ ≈ 7.5 AU
Massive star
(> 25 M⊙)
Massive star
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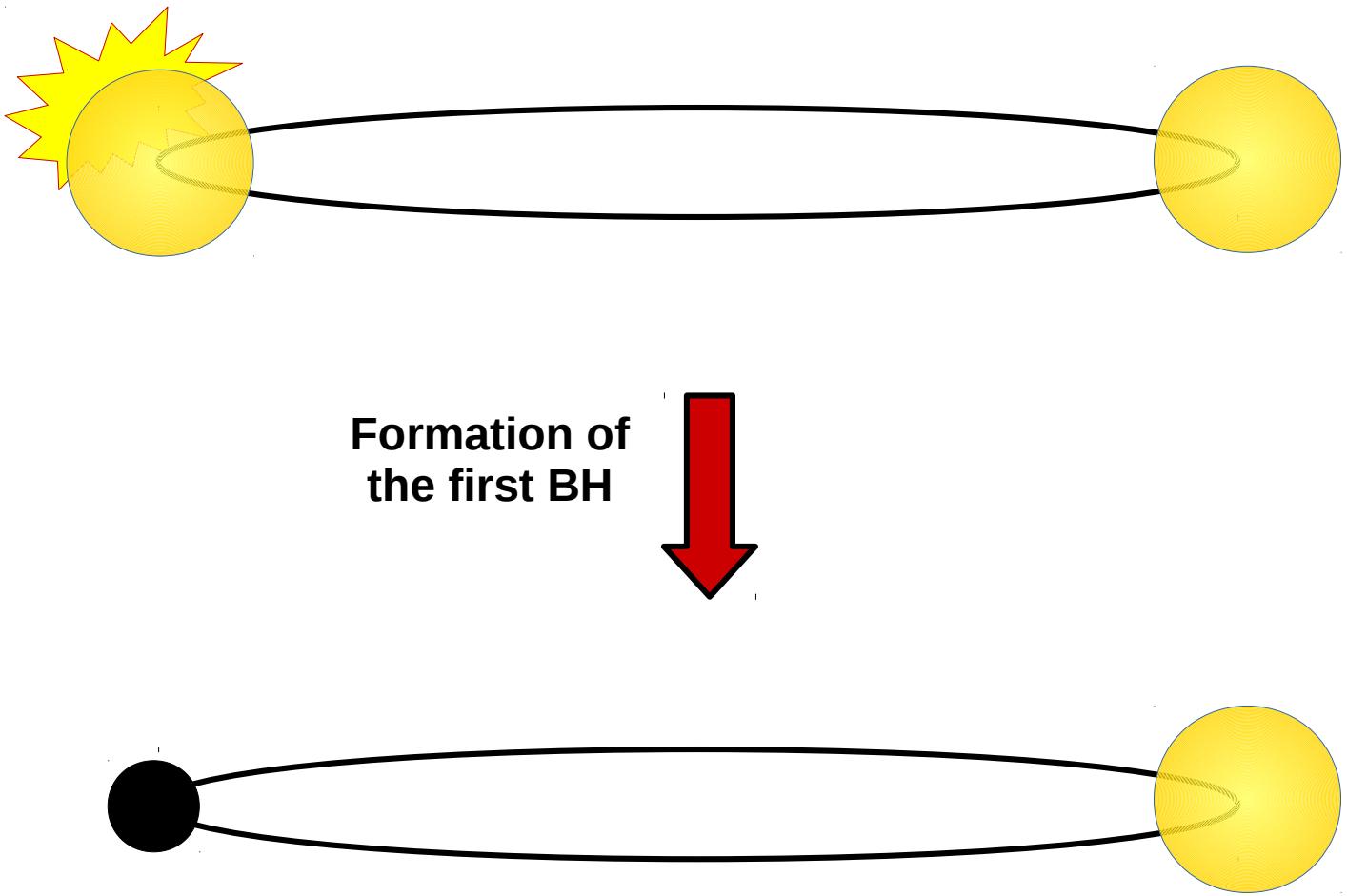
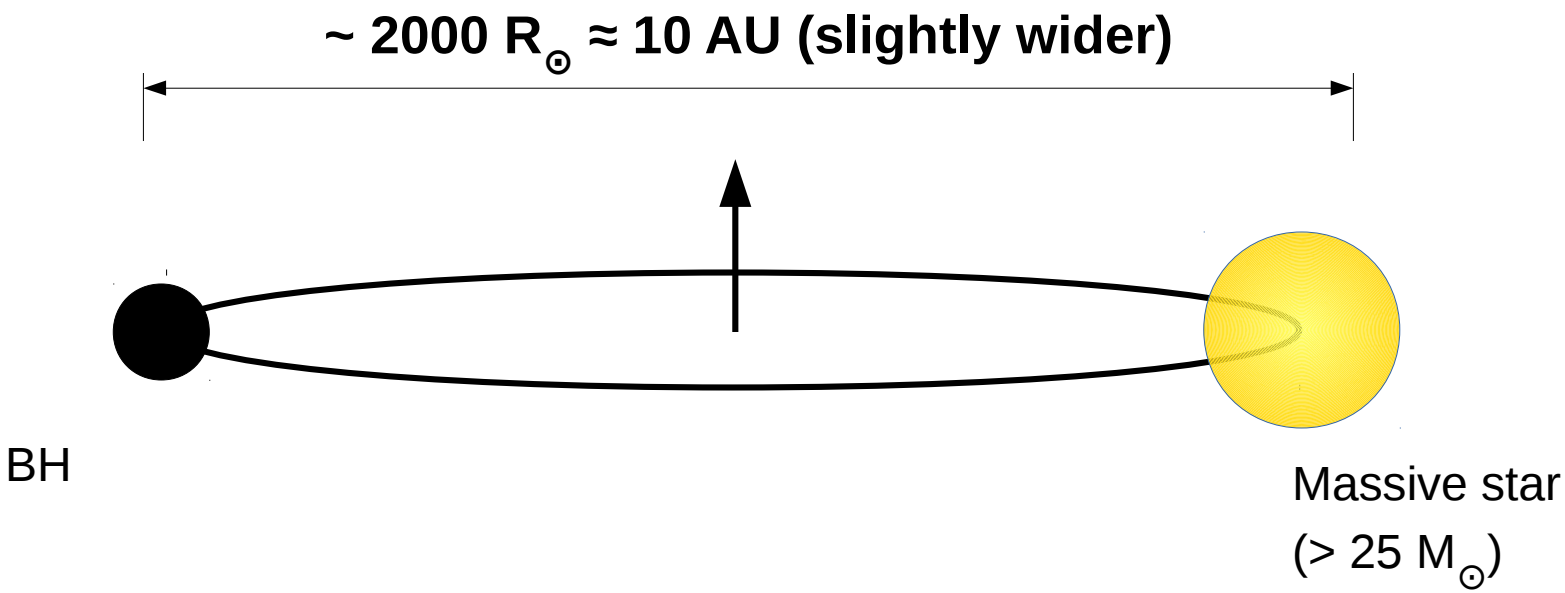
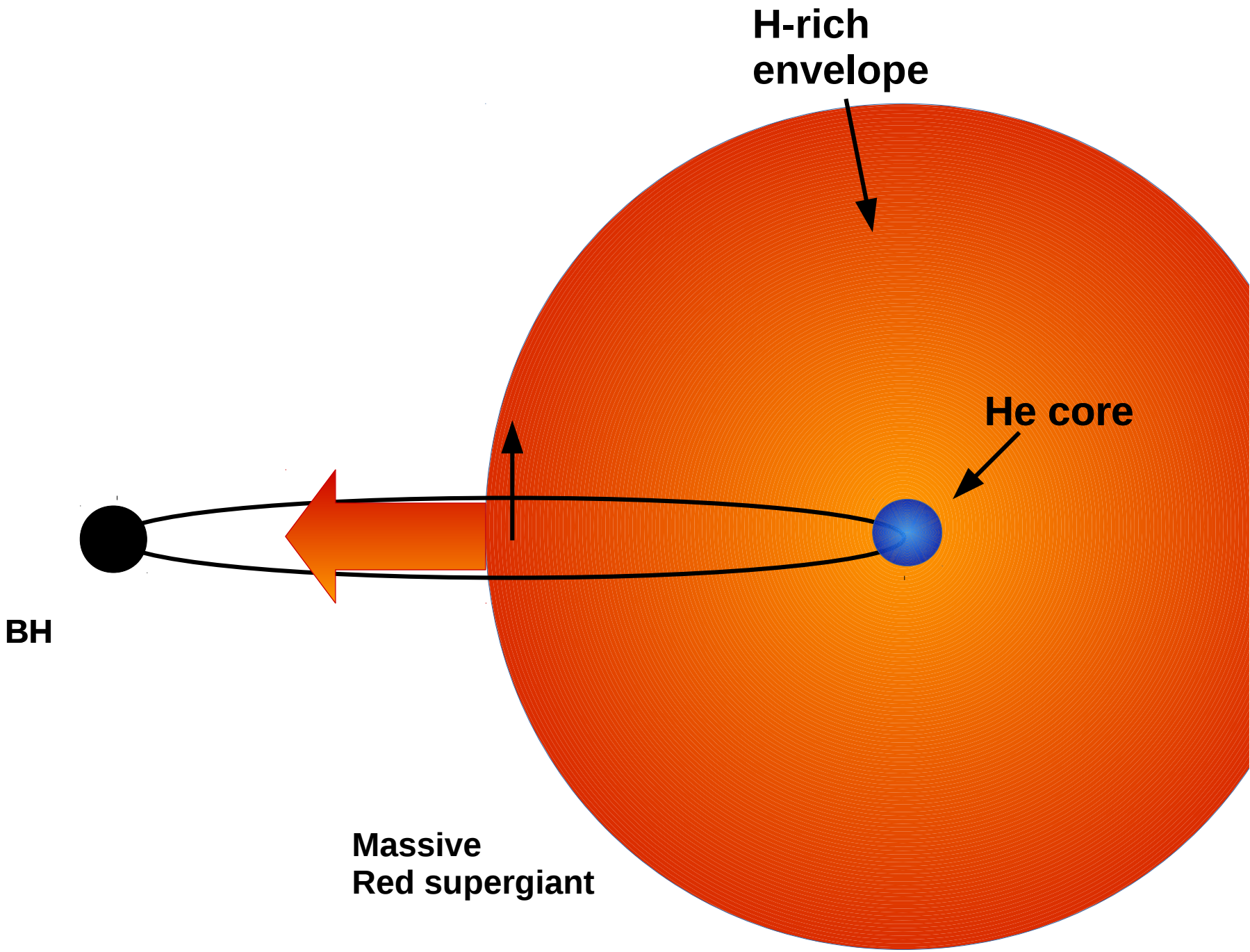
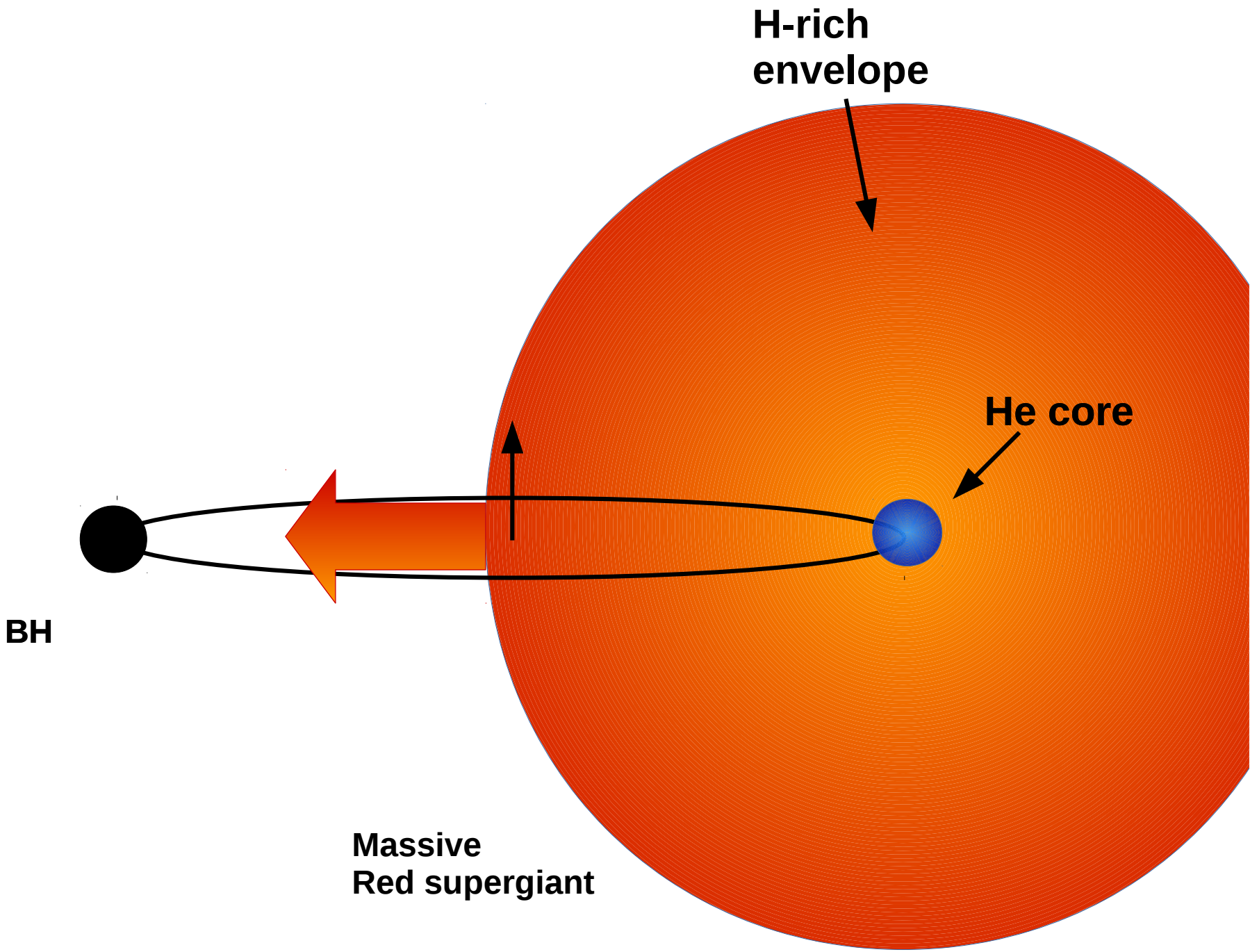


BH formed in direct collapse / failed SN
little (eg. 100 km/s) or no natal kick
guided by Galactic BH X-ray binaries (Nelemans+1999, Mandel 2016, Repetto+ 2017, Mirabel 2017)
Galactic pulsar velocities ~ 400 km/s


~ 2000 R⊙ ≈ 10 AU (slightly wider)
BH
Massive star
(> 25 M⊙)


H-rich
envelope
He core
BH
Massive
Red supergiant


H-rich
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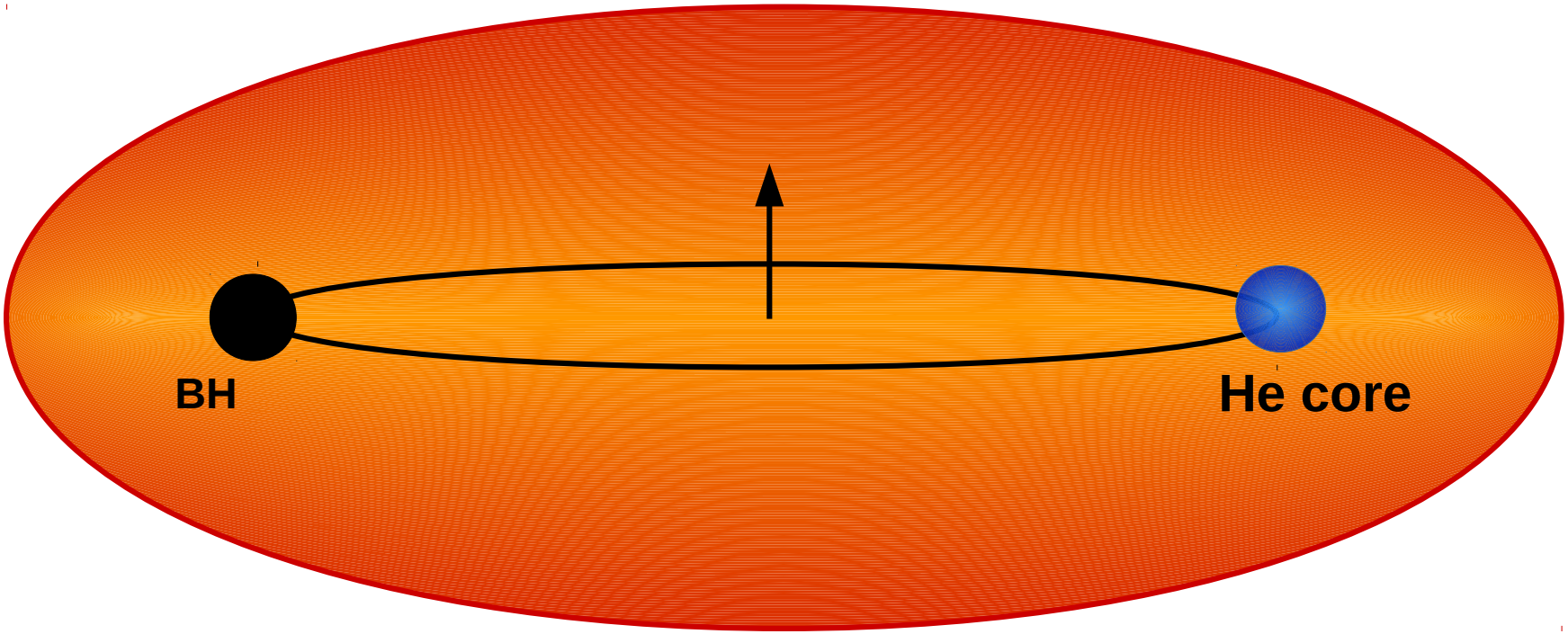
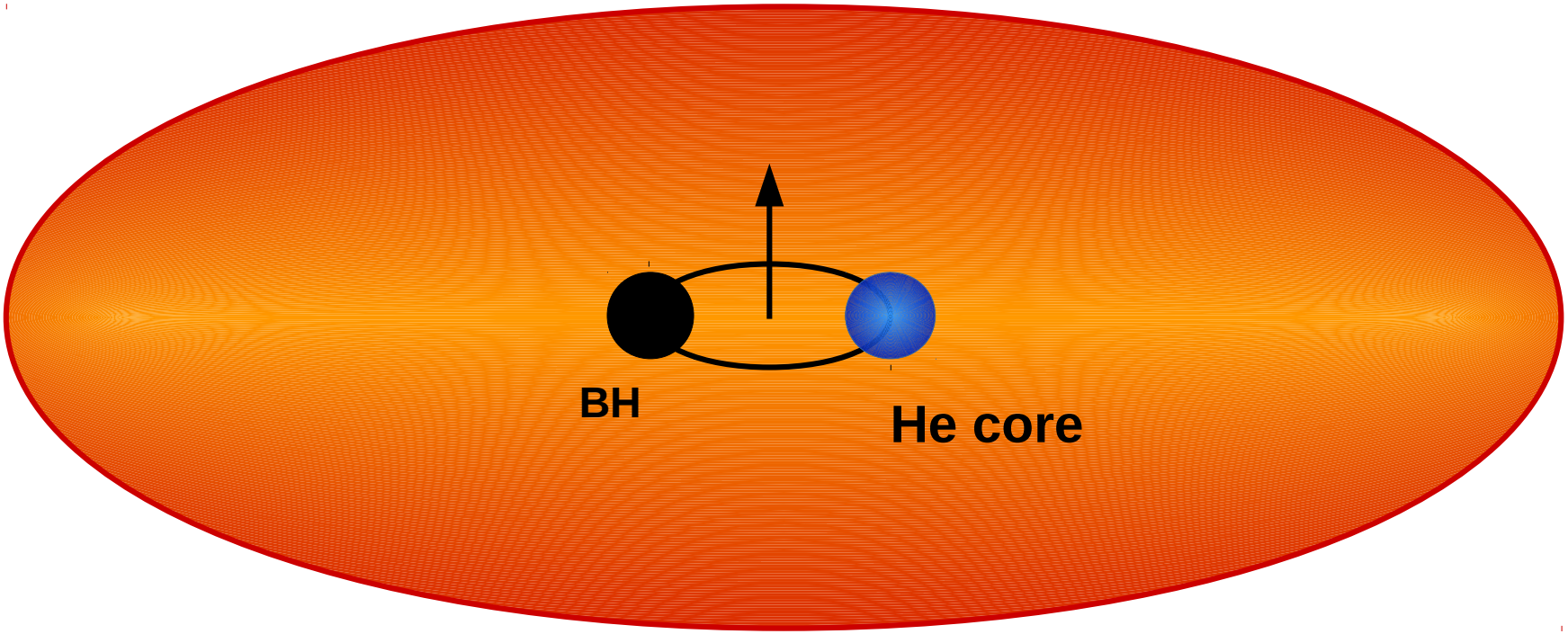
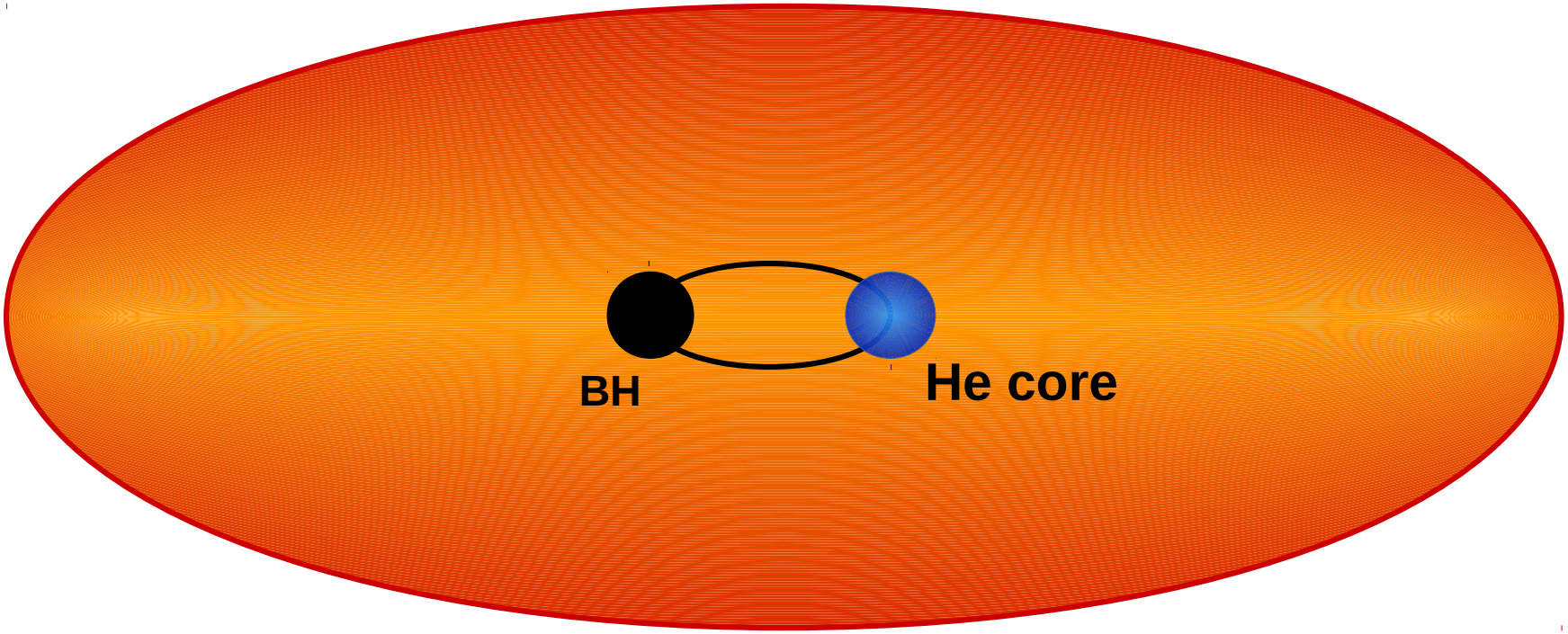
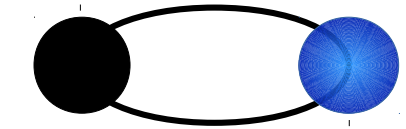
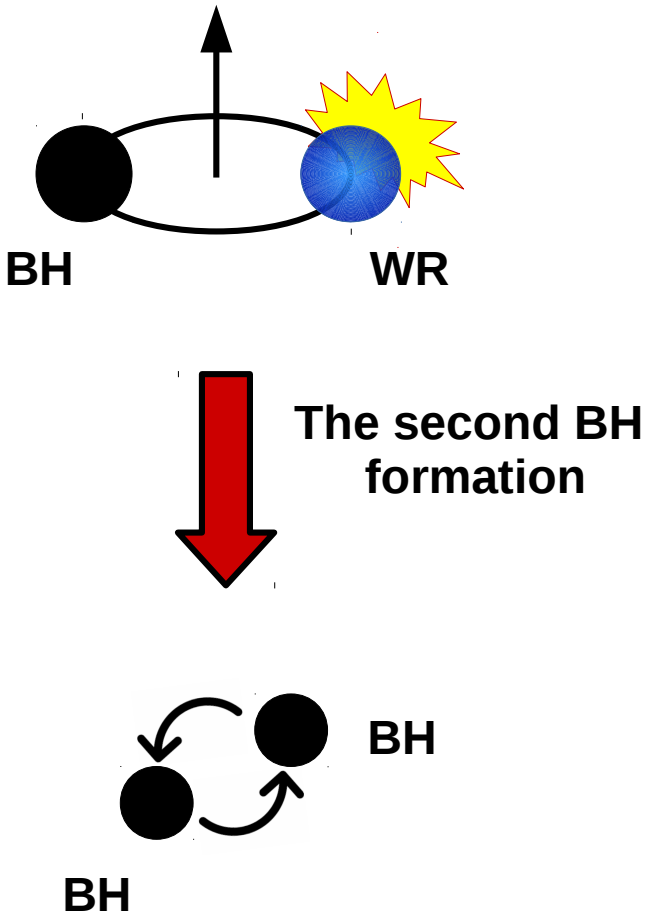

BH
He core


BH
He core



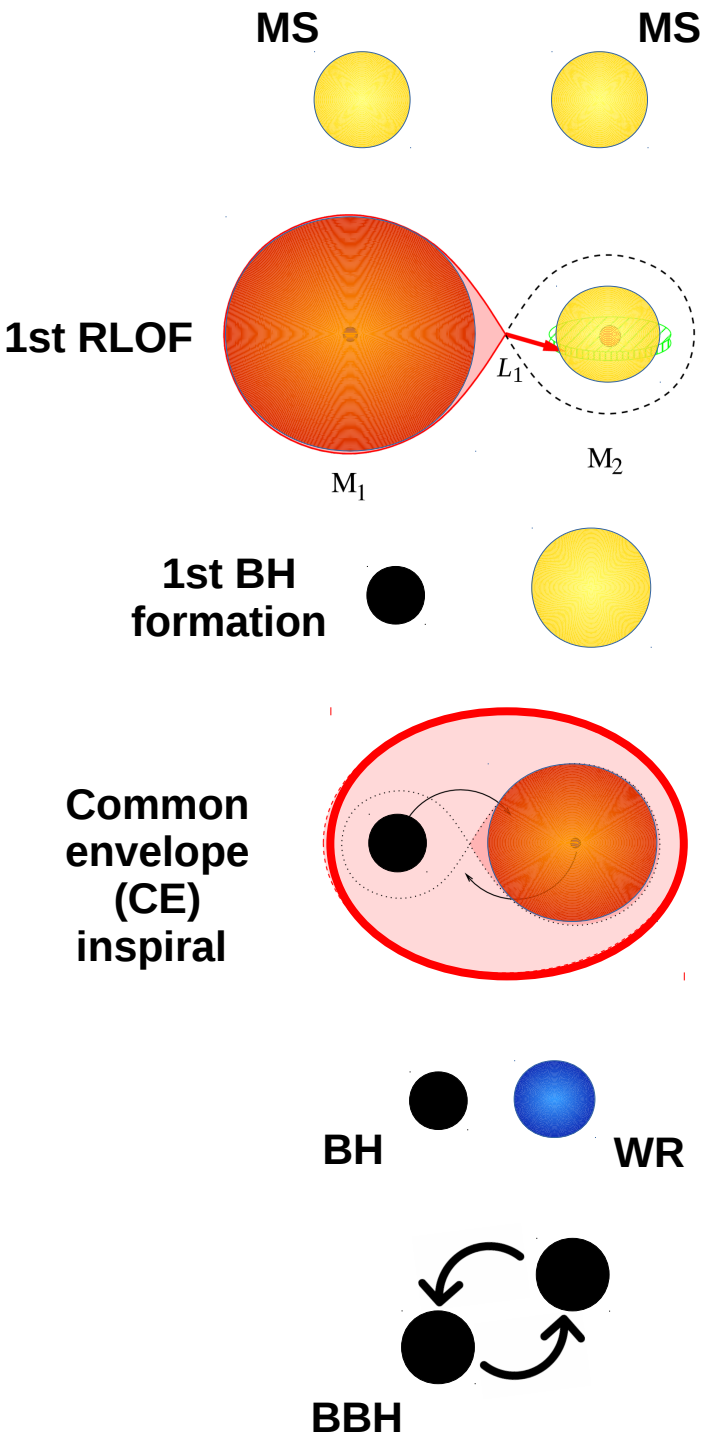
if Energy from the inspiral > Binding energy of the envelope then





Compact BH-BH system
that merger within the Hubble time

The Common Envelope channel



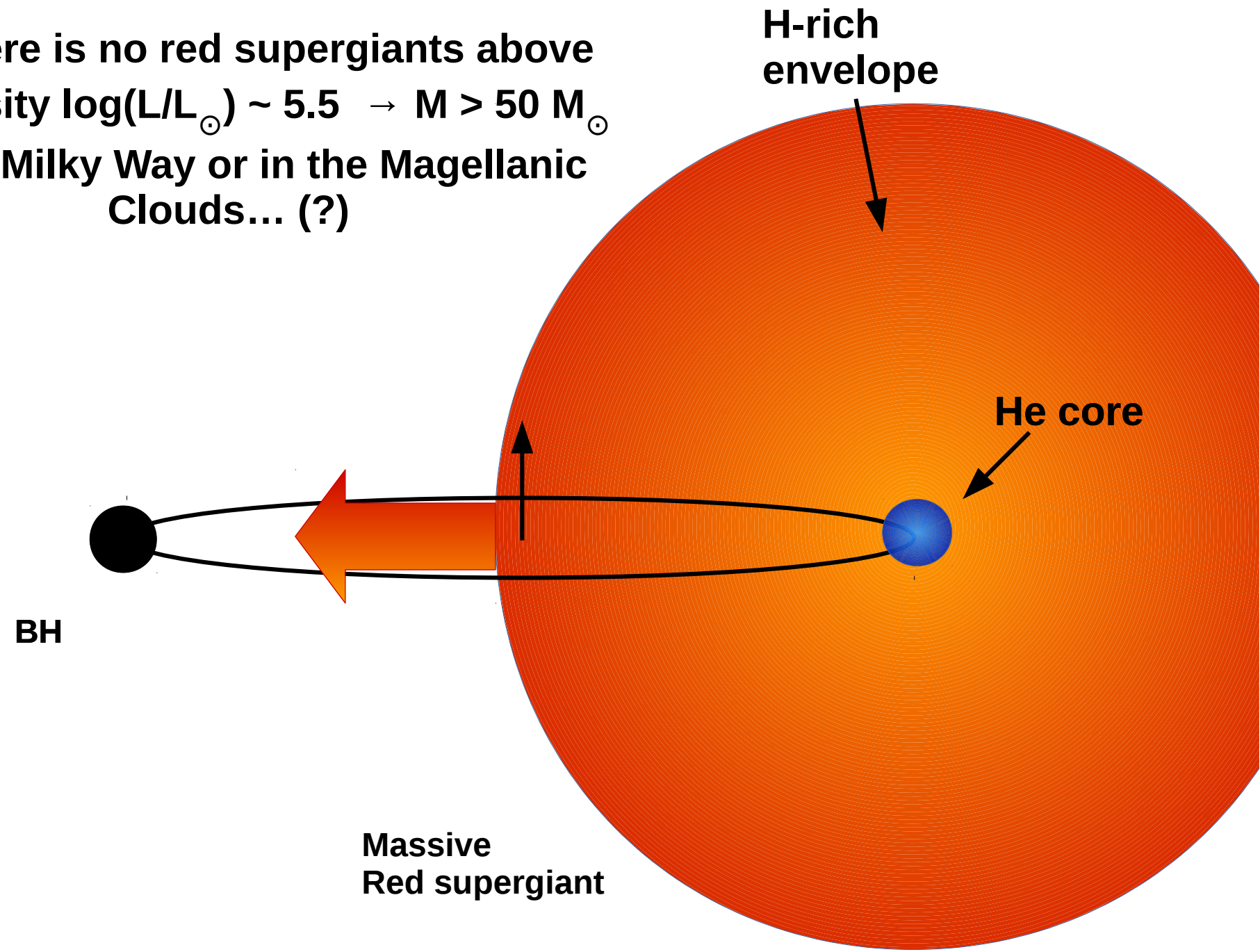
Tutukov & Yungelson (1993), Voss & Tauris (2003), Nelemans (2003), Dewi+ (2006), Kalogera+(2007), Dominik+(2012,2014,2015),Belczynski+(2010,2016,2018), Postnov & Yungelson (2014), Eldridge & Stanway (2016), Belczynski, JK+(2017), Mapelli+ (2018,2019), JK+(2018), Chruslinska+(2018), Kruckow+(2018), Giacobbo+(2018,2019)

– uncertain!
– short-lived
– observational evidence only for lower mass stars

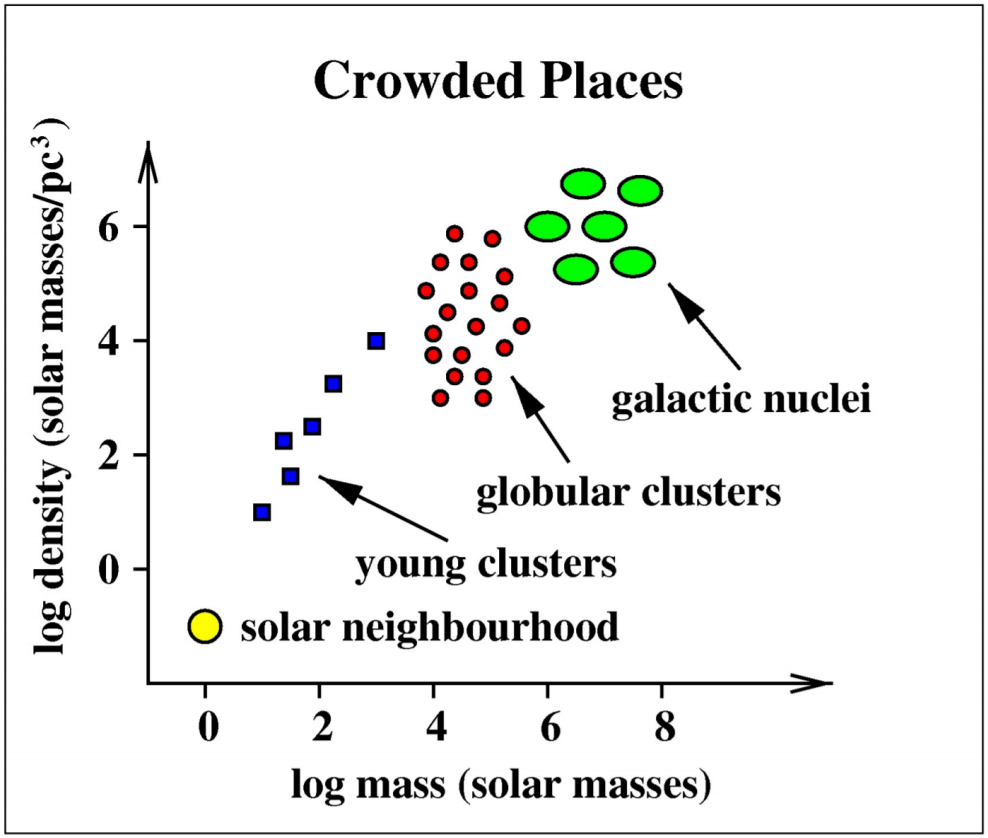
We know such BH-WR exist:
IC10 X-1, NGC300 X-1

(Bulik, Belczynski, Prestwich 2010)

But there is no red supergiants above luminosity $\log(L/L_\odot) \sim 5.5 \rightarrow M > 50\ M_\odot$ in the Milky Way or in the Magellanic Clouds… (?)



Dynamical formation of BBHs



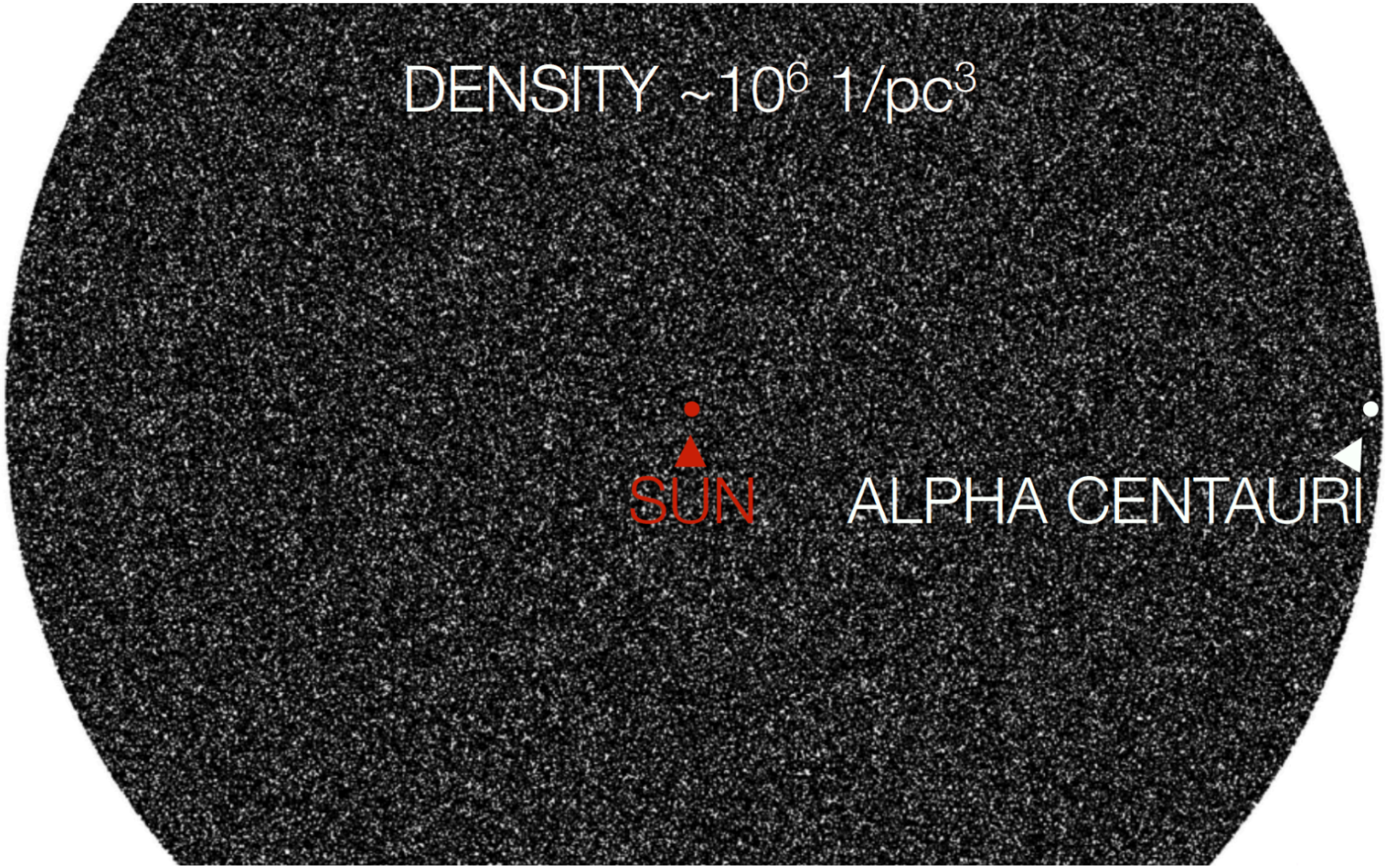
NGC 104 (aka 47 Tucanae)

radius ~ 75 lyr

mass ~ 7 x 10^5 $M_\odot$

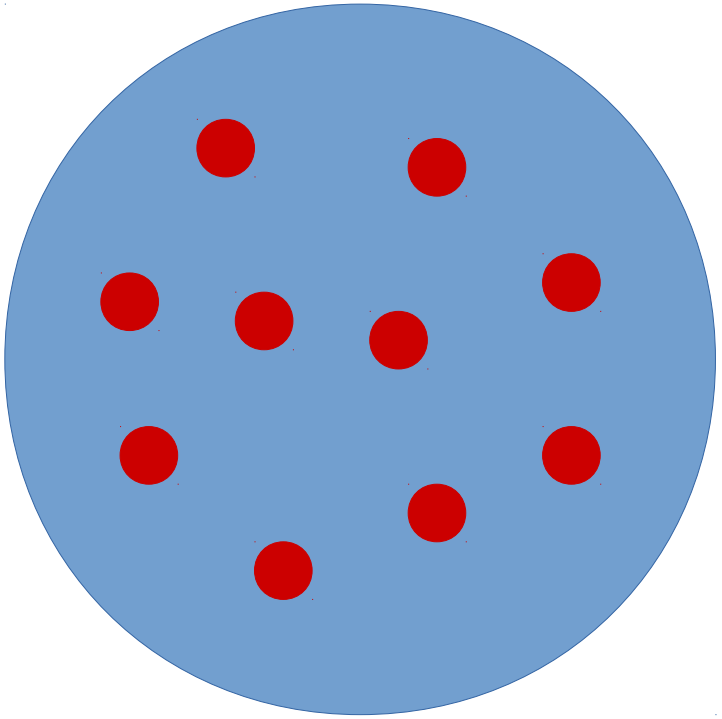
age ~ 13 Gyr

Dynamical formation of BBHs



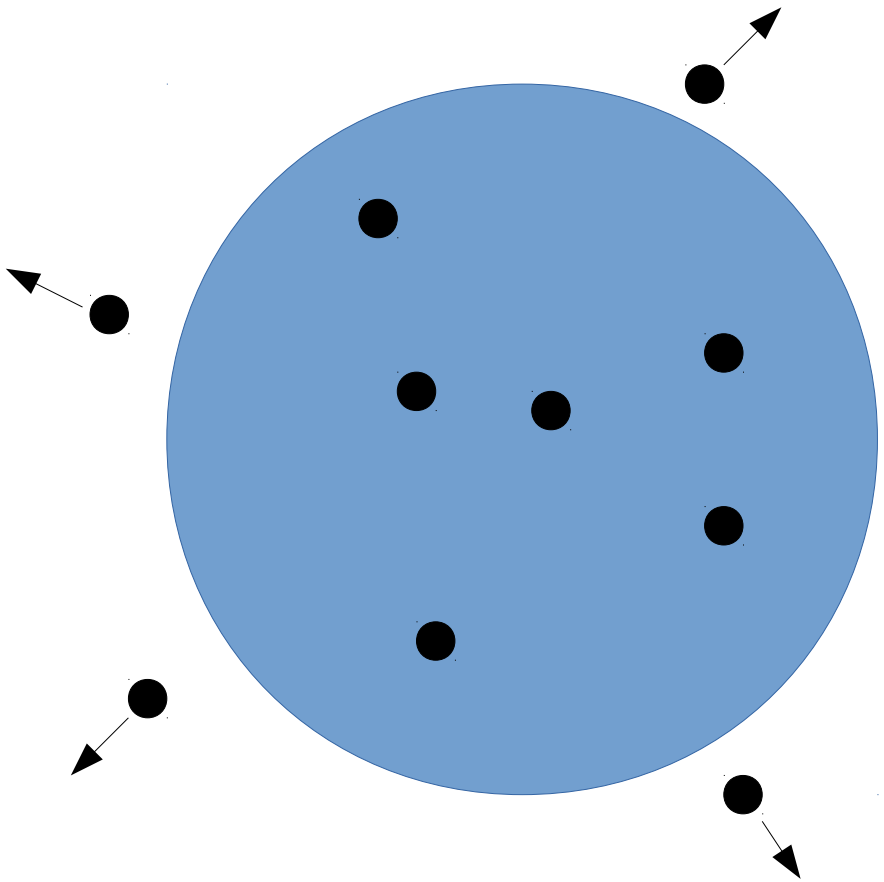
Credit: N. Lüetzgendorf

BBH formation in globular clusters



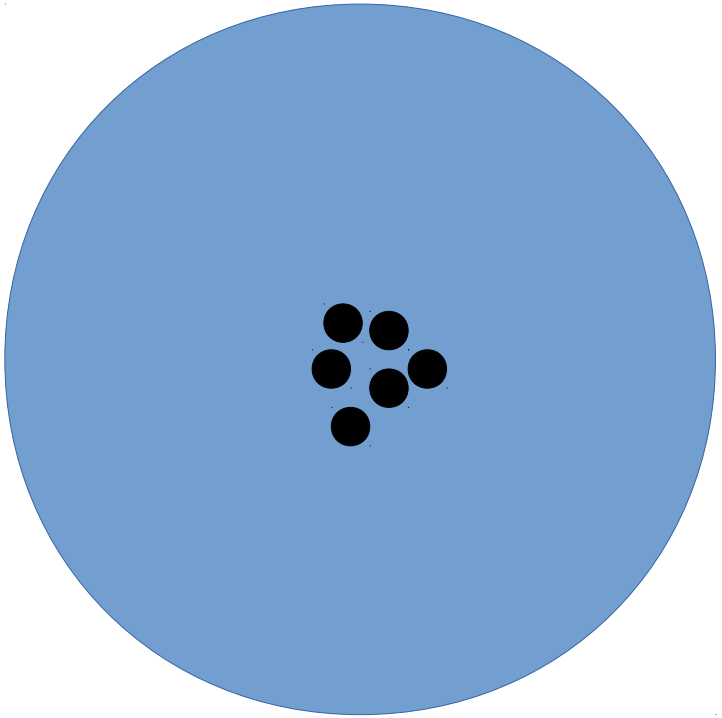
Massive stars in a cluster → BH progenitors

BBH formation in globular clusters



– massive stars collapse to BHs
– some BHs kicked from the cluster

BBH formation in globular clusters

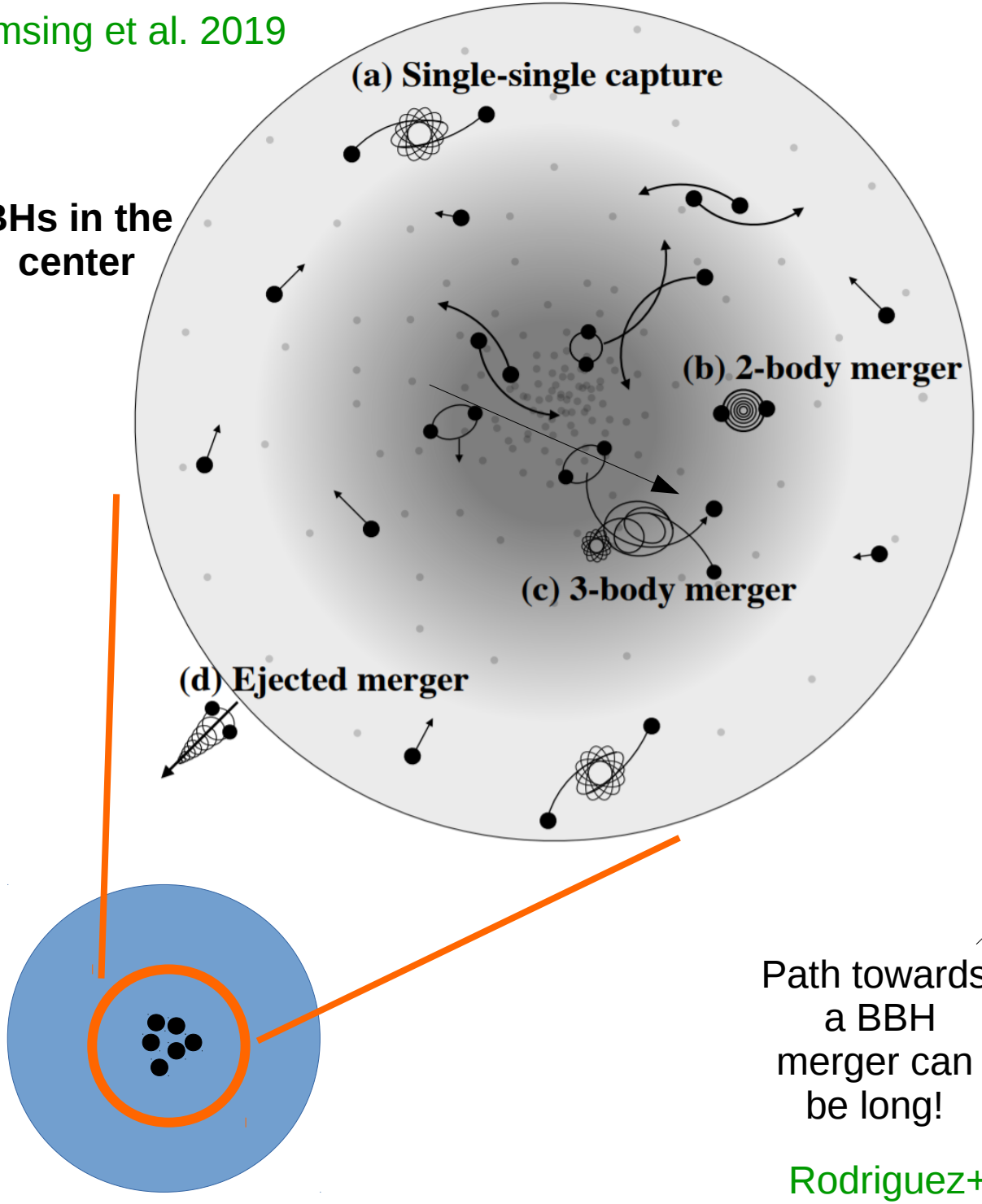


– the remaining BHs migrate to the center (mass segregation)

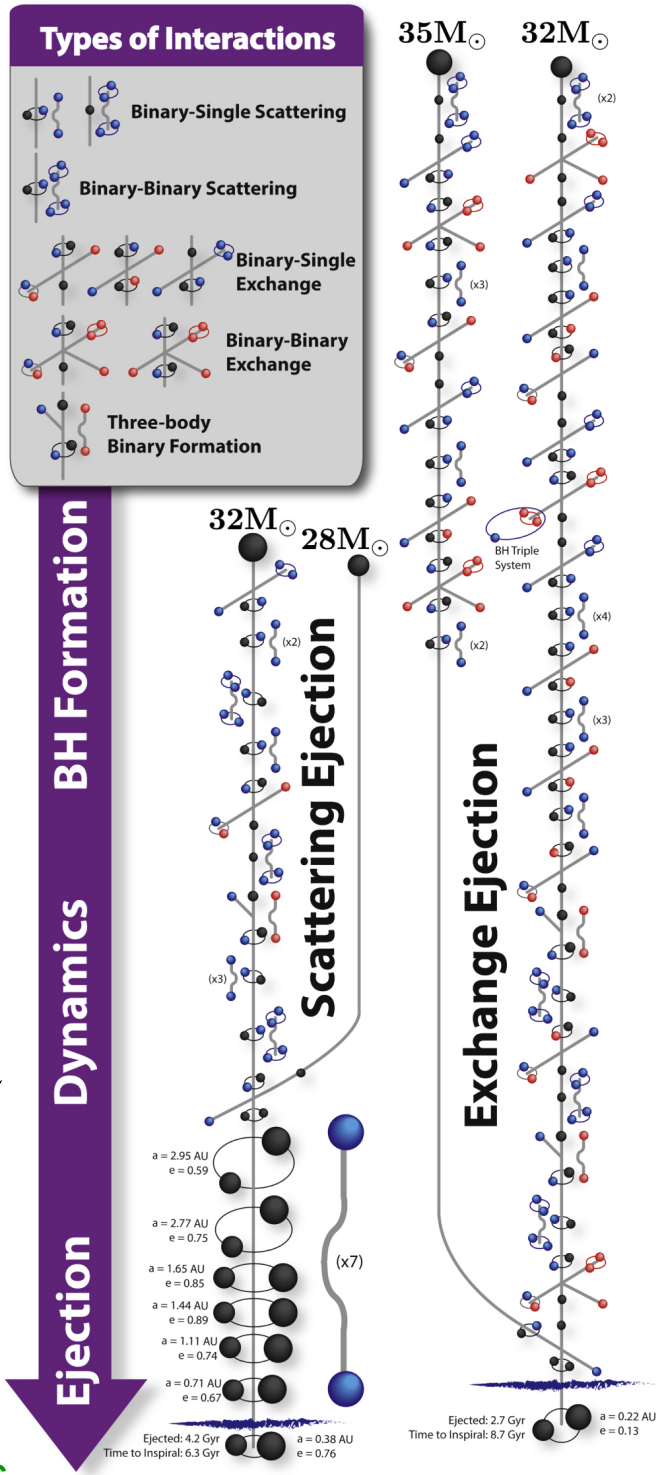
– <u>dynamical interactions!</u>

Samsing et al. 2019

BHs in the center

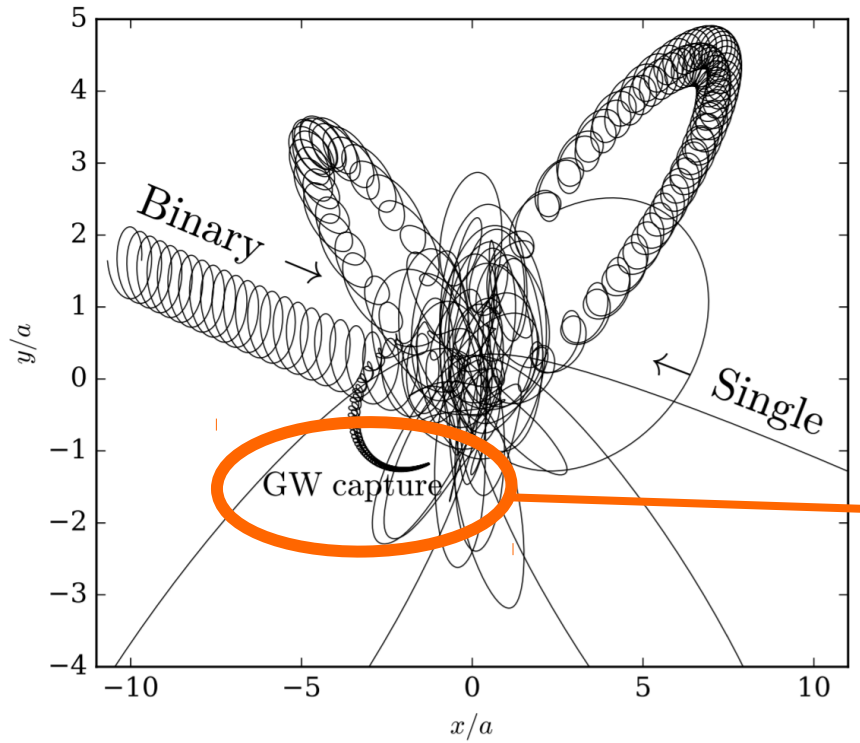


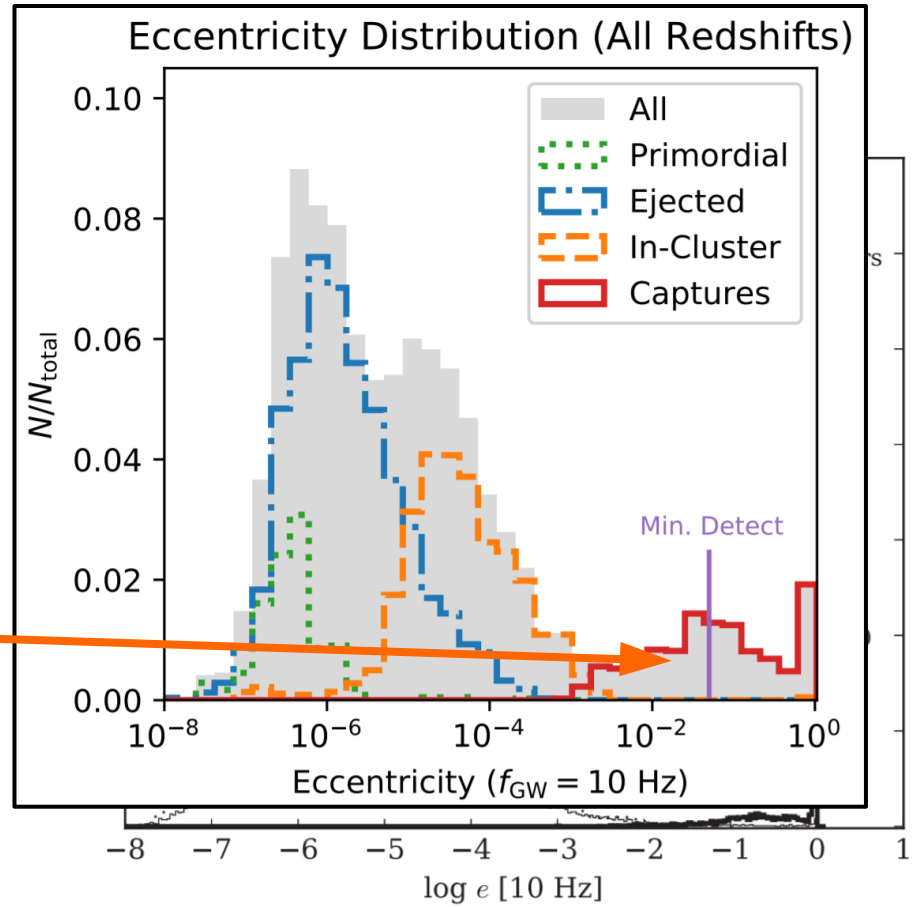
Path towards a BBH merger can be long!



Rodriguez+2016

BBH formation in globular clusters



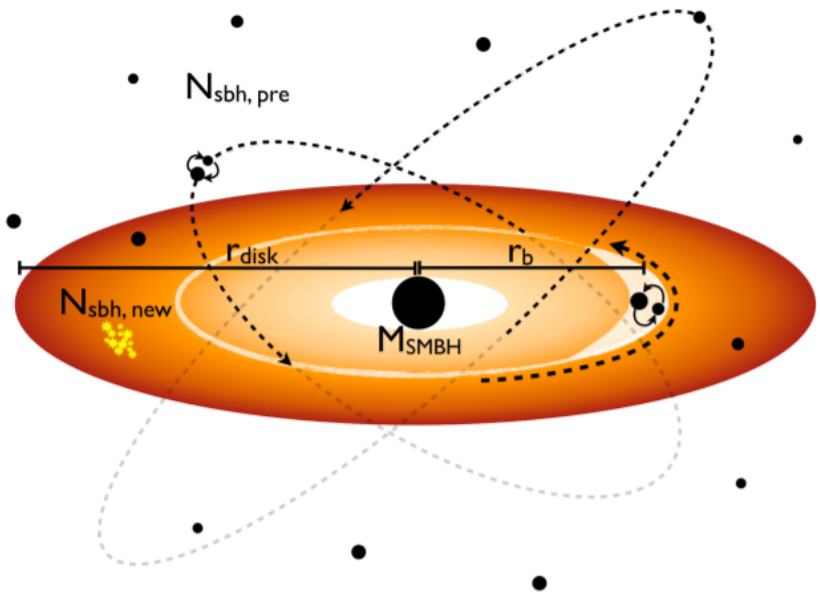


Samsing 2018

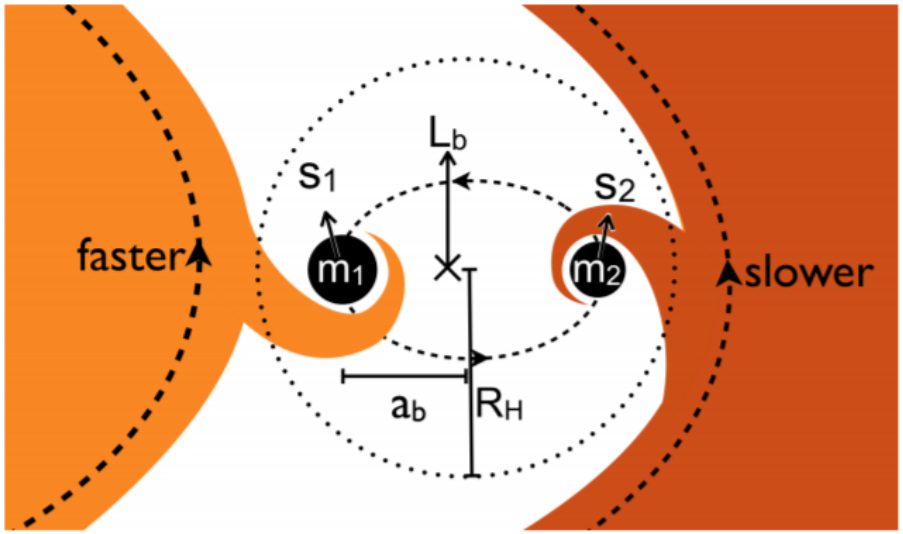
$T_{GW} \propto a^4 (1-e^2)^{7/2}$

With post-Newtonian terms **~4% of all BBH mergers in GCs with e > 0.1 at 10 Hz**
(Rodriguez+2018)
also: Samsing & Ramirez-Ruiz 2017

BBH Mergers in AGN disks



from McKernan, Ford, et al. (2018)

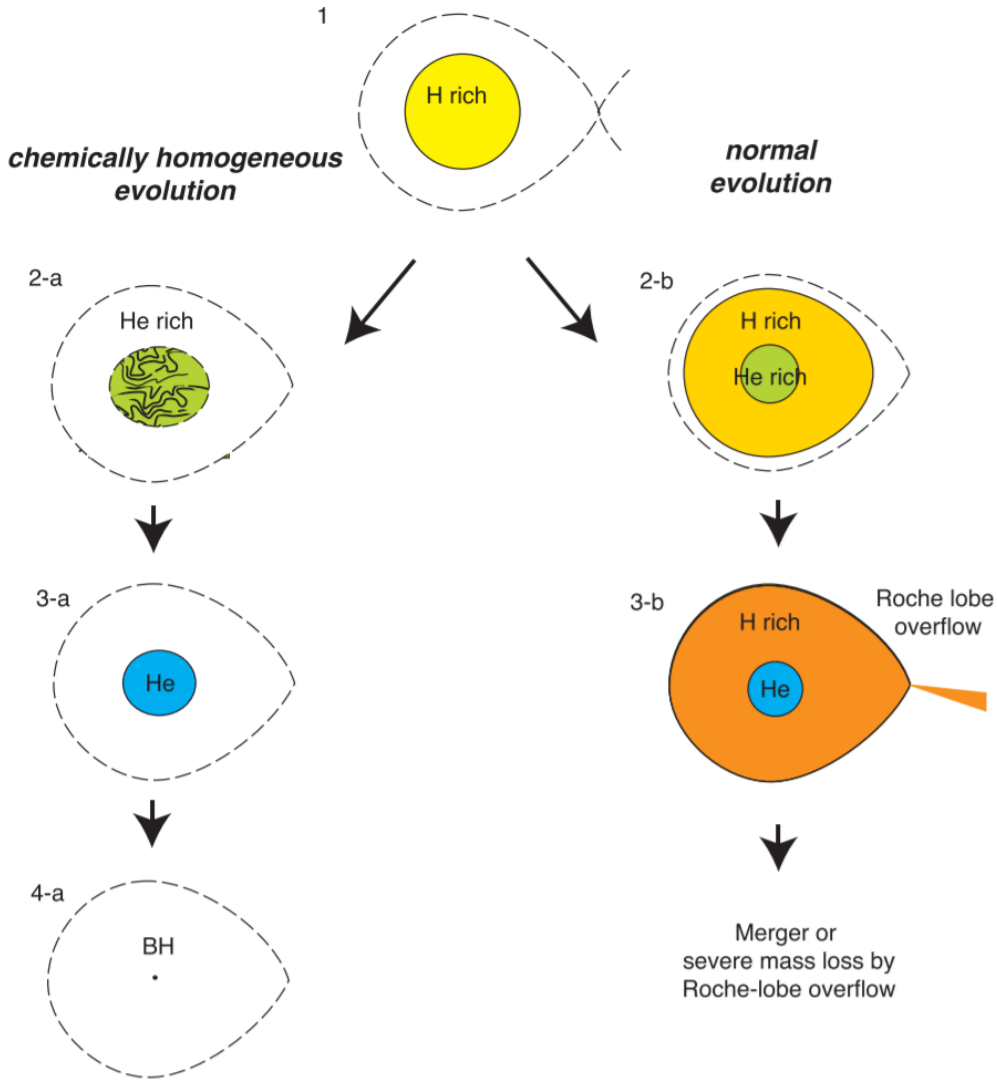


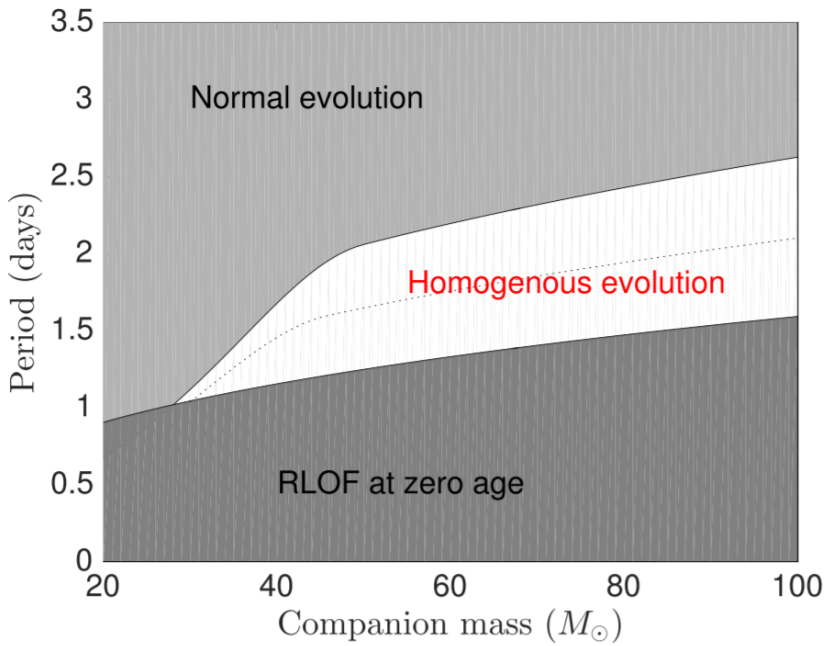
Exchange of angular momentum with the AGN disk

– rates very uncertain (from negligible to very significant)
– testable association of localizations with AGNs!

McKernan et al. (2012,2014,2018)
Stone et al. (2017)
Barton et al. (2017)
Bellovary et al. (2016)

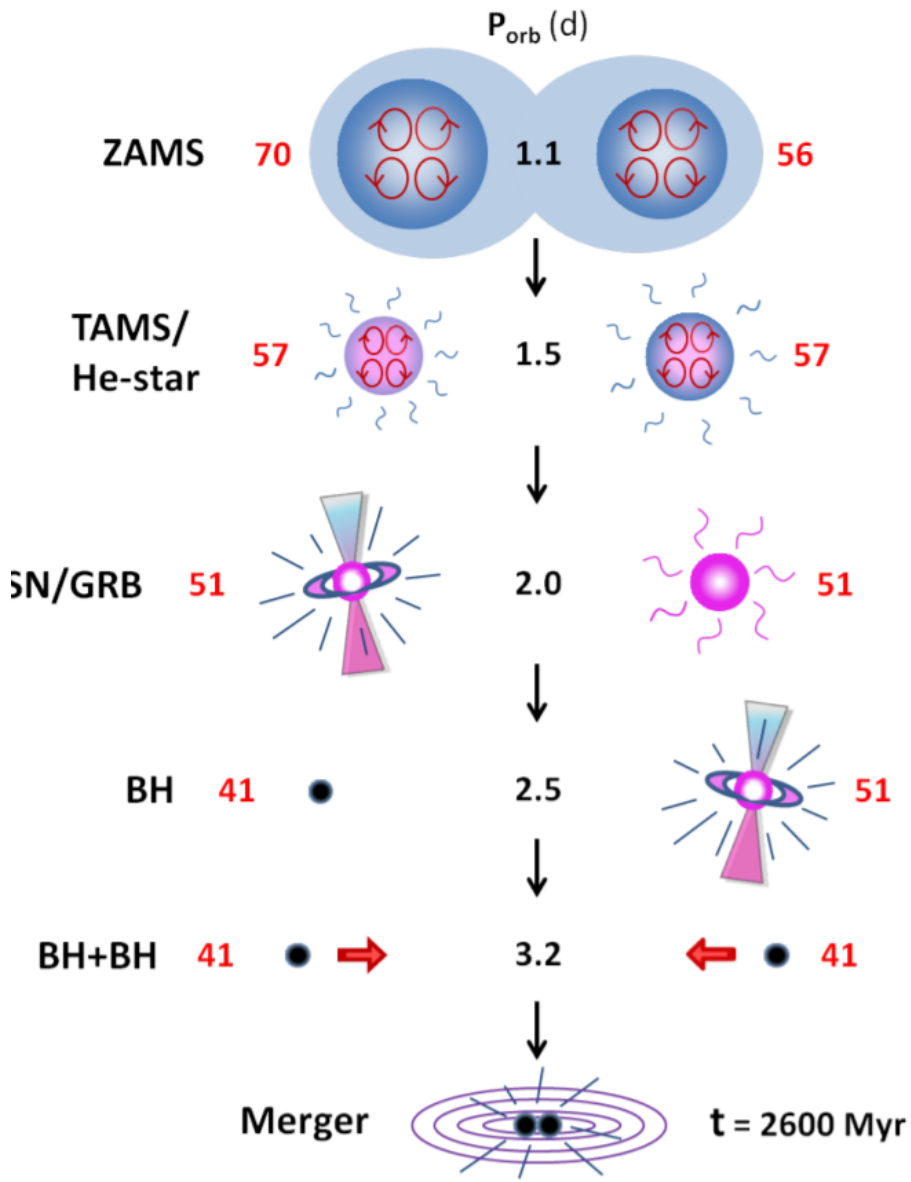
BBH from chemically-homogeneous evolution

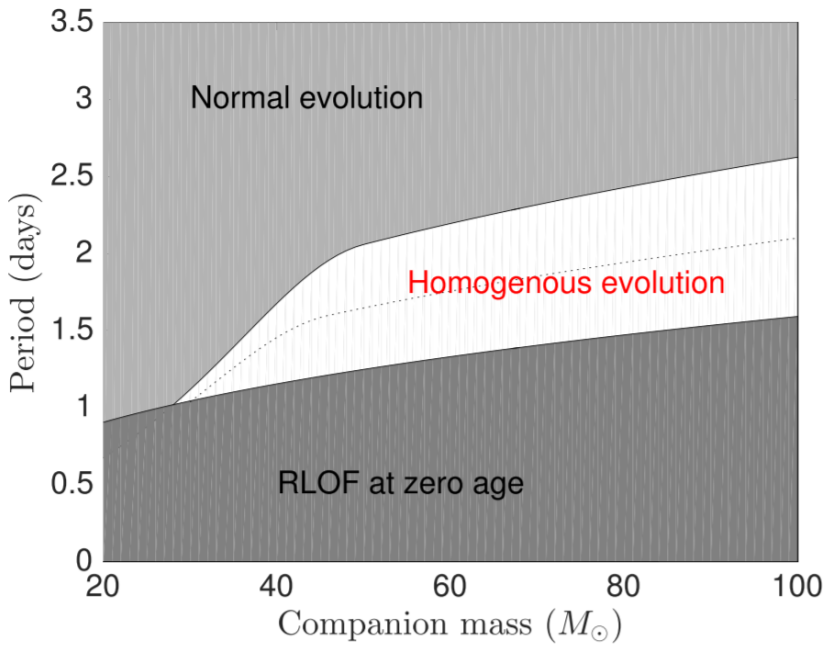




Madel & de Mink 2016
de Mink & Mandel 2016
Marchant et al. 2016

BBH from chemically-homogeneous evolution





Prediction:
– equal mass BHs
– likely highly spinning and aligned
– rare

BBH formation channels

Isolated binary evolution

– common envelope
– chemically-homogenous evolution
– stable mass transfer (?)
– ...

Dynamical formation

– globular and nuclear clusters
– AGN disks
– open clusters
– highly-eccentric tidal captures
– triples with a SMBH
– …

– stellar triples
(Lidov-Kozai oscillations)

– primordial BHs
(talk by Ranjan Laha on Thursday!)

BBH formation channels

Isolated binary evolution

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– pop. III binaries
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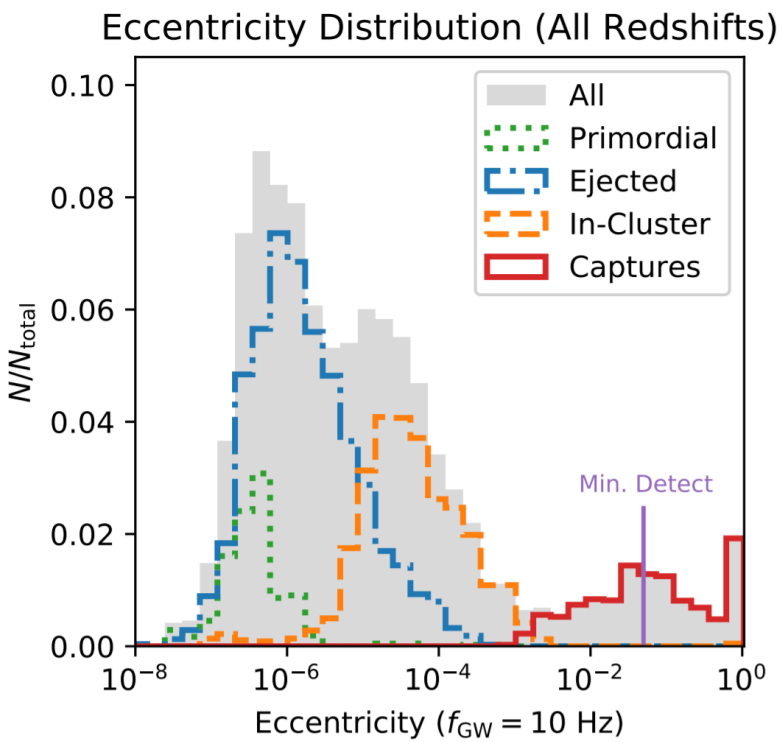
CAN WE TELL THEM APART?

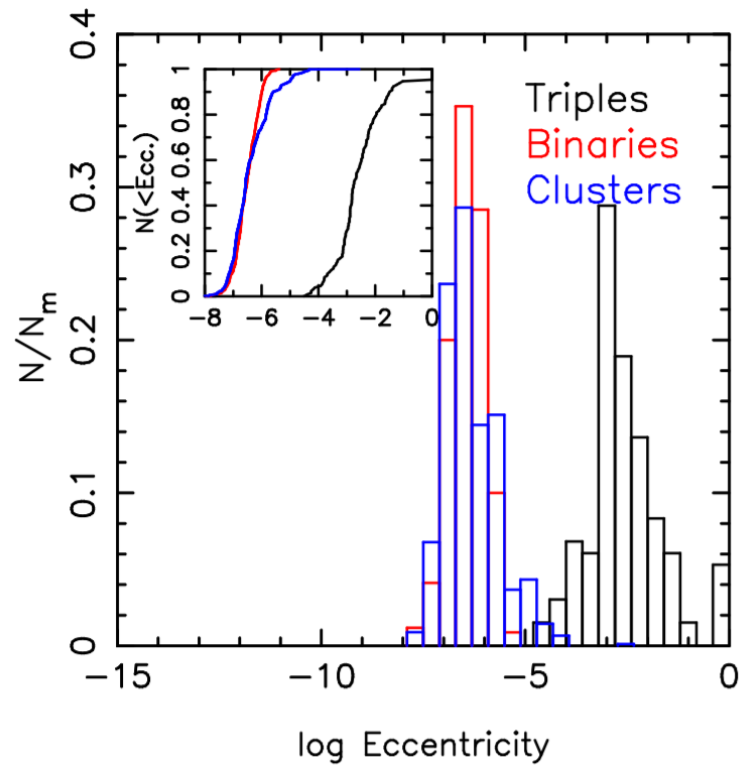
Eccentricities

Tidal captures in dynamical channels, eg.:



Rodriguez+ (2018)

But also in triple systems! (Lidov-Kozai oscillations)



Antonini+ (2017)

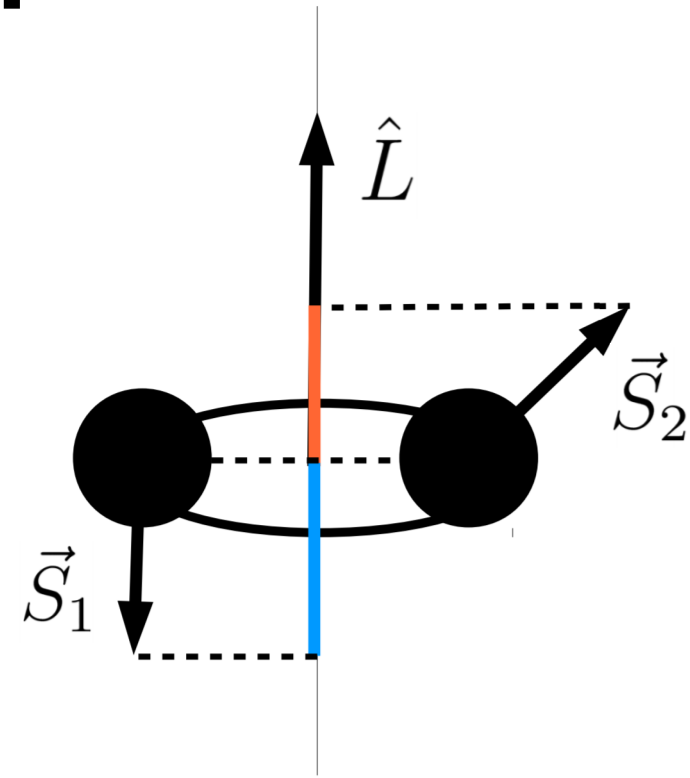
Effective spin

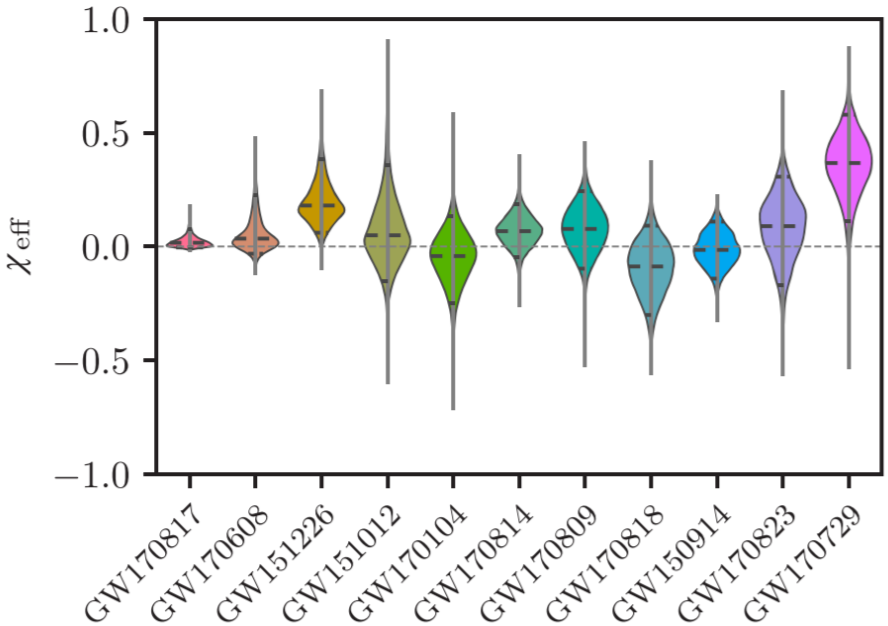
Effective spin:

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

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

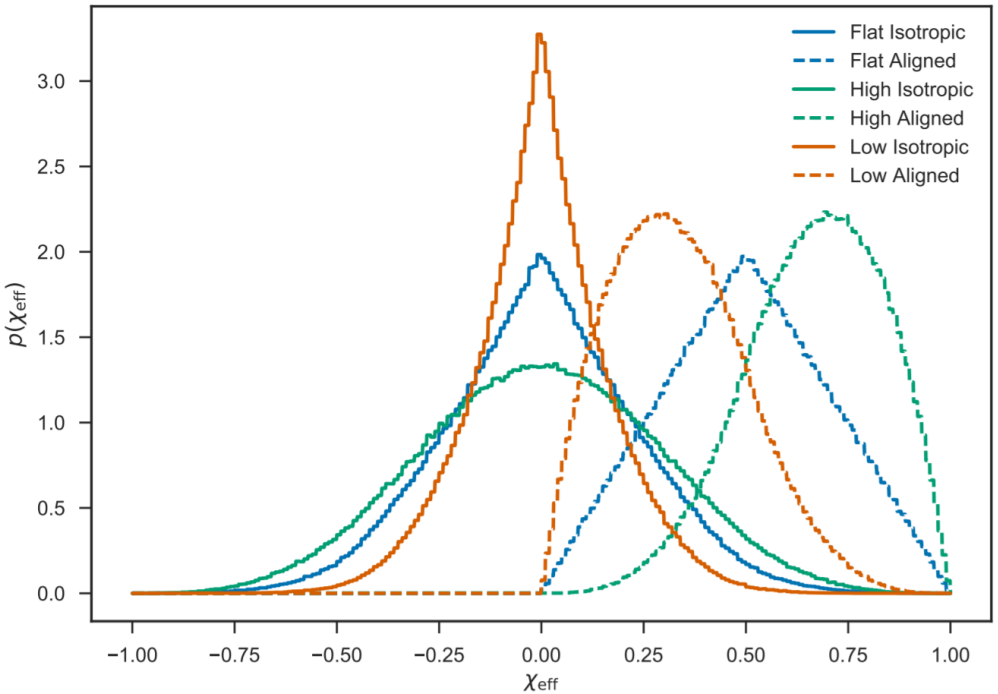
|S| = [0,1]





Abbott+2019
(GWTC-1)

Can spins distinguish between channels?

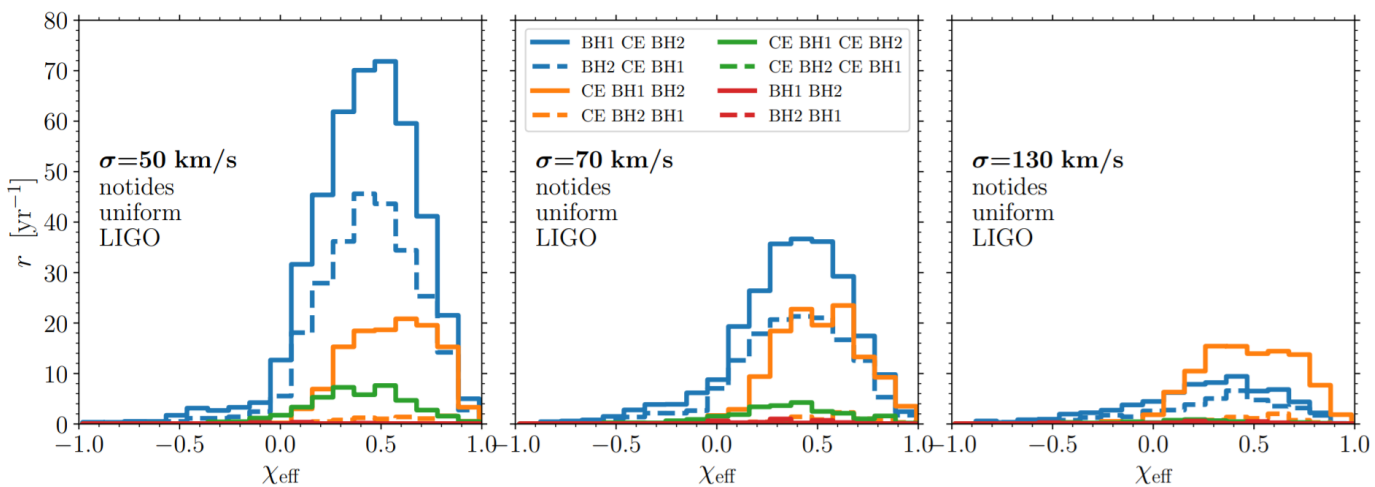


Field binary evolution – aligned spins

Dynamical formation – isotropic spins

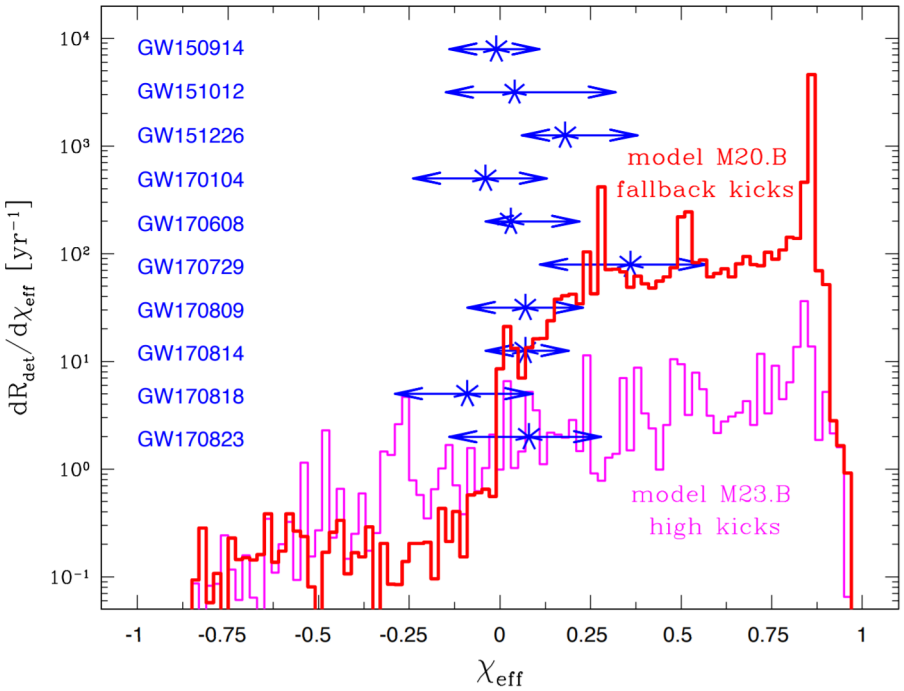
Farr+2017 (Nature)
see also Farr, Holz, Farr (2018)

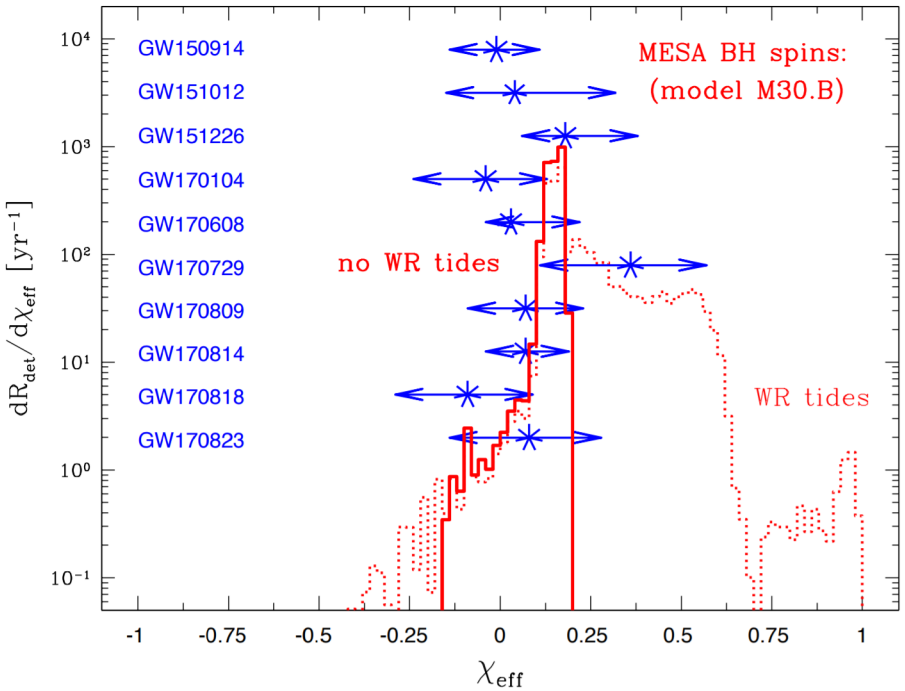
Aligned spins
modified by natal kicks



Gerosa+2018

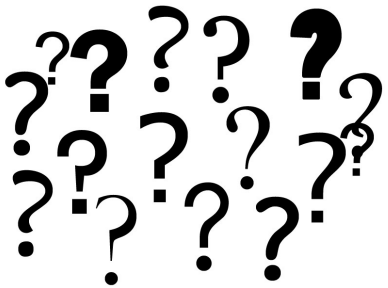
Not if BH spins are intrinsically low





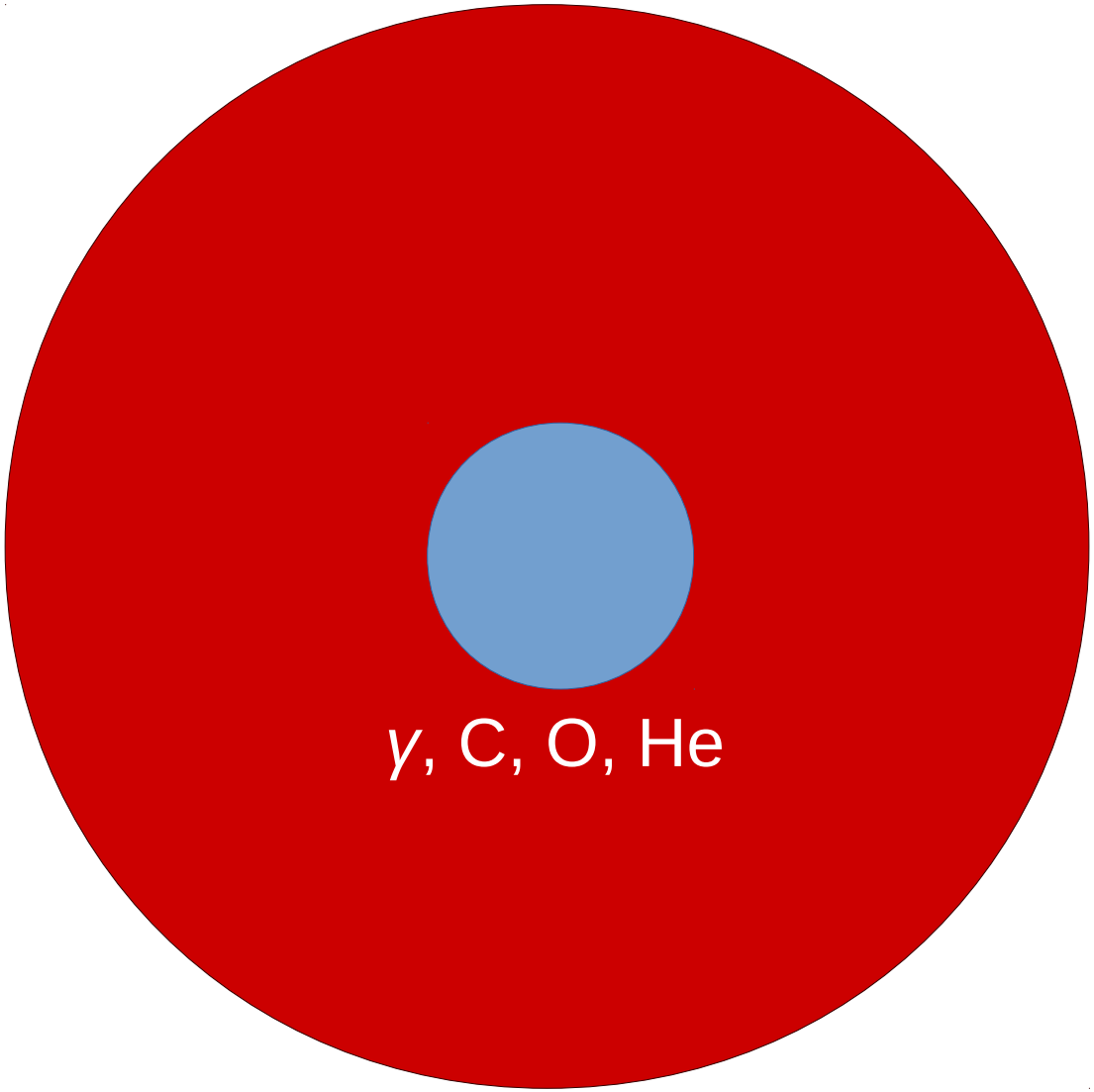
Inefficient angular momentum transport – **high BH spins**

Efficient angular momentum transport – **low BH spins**

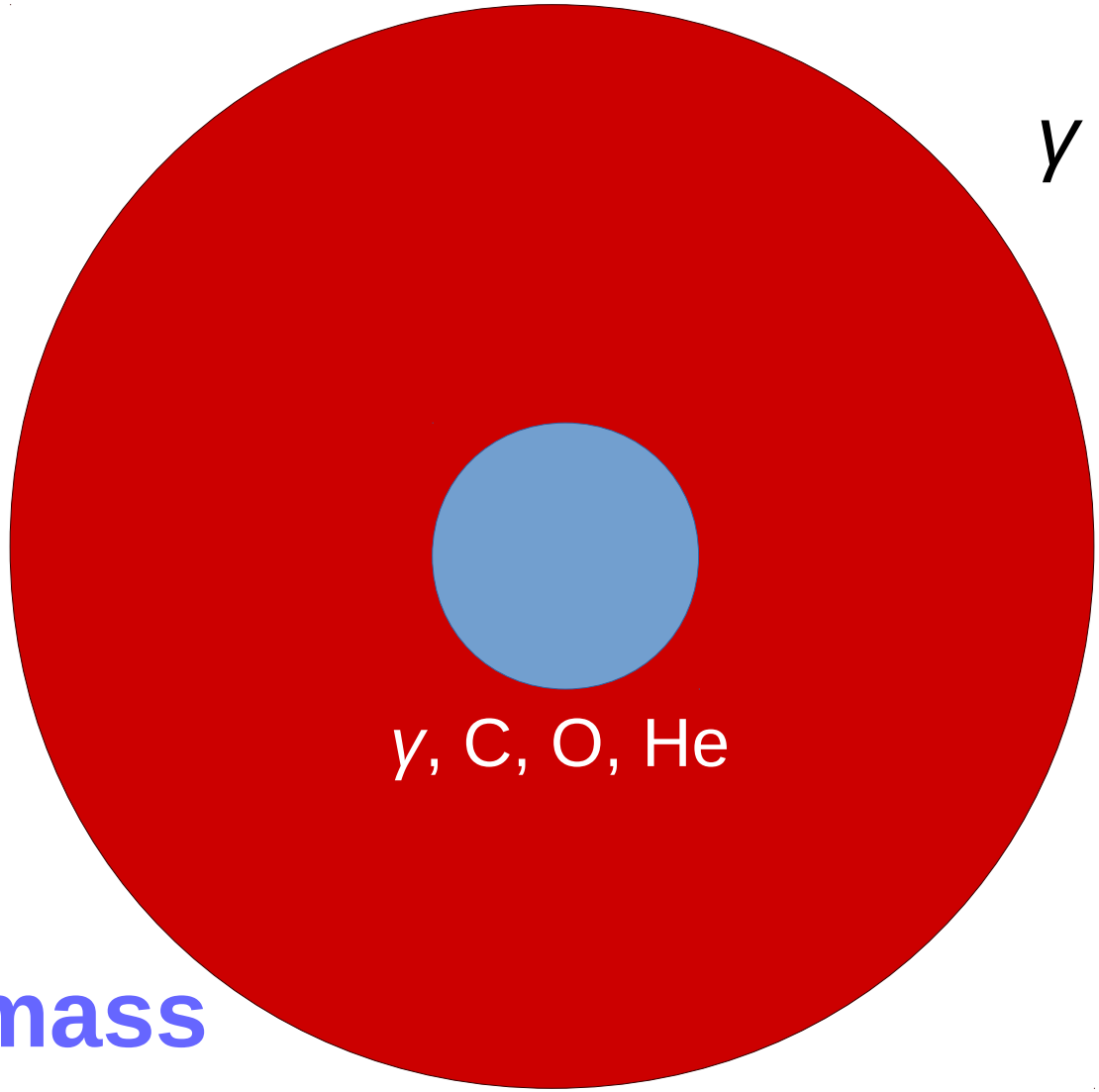


Belczynski, JK, + (2017)
(see also Bavera+2019)

Pair-instability mass gap



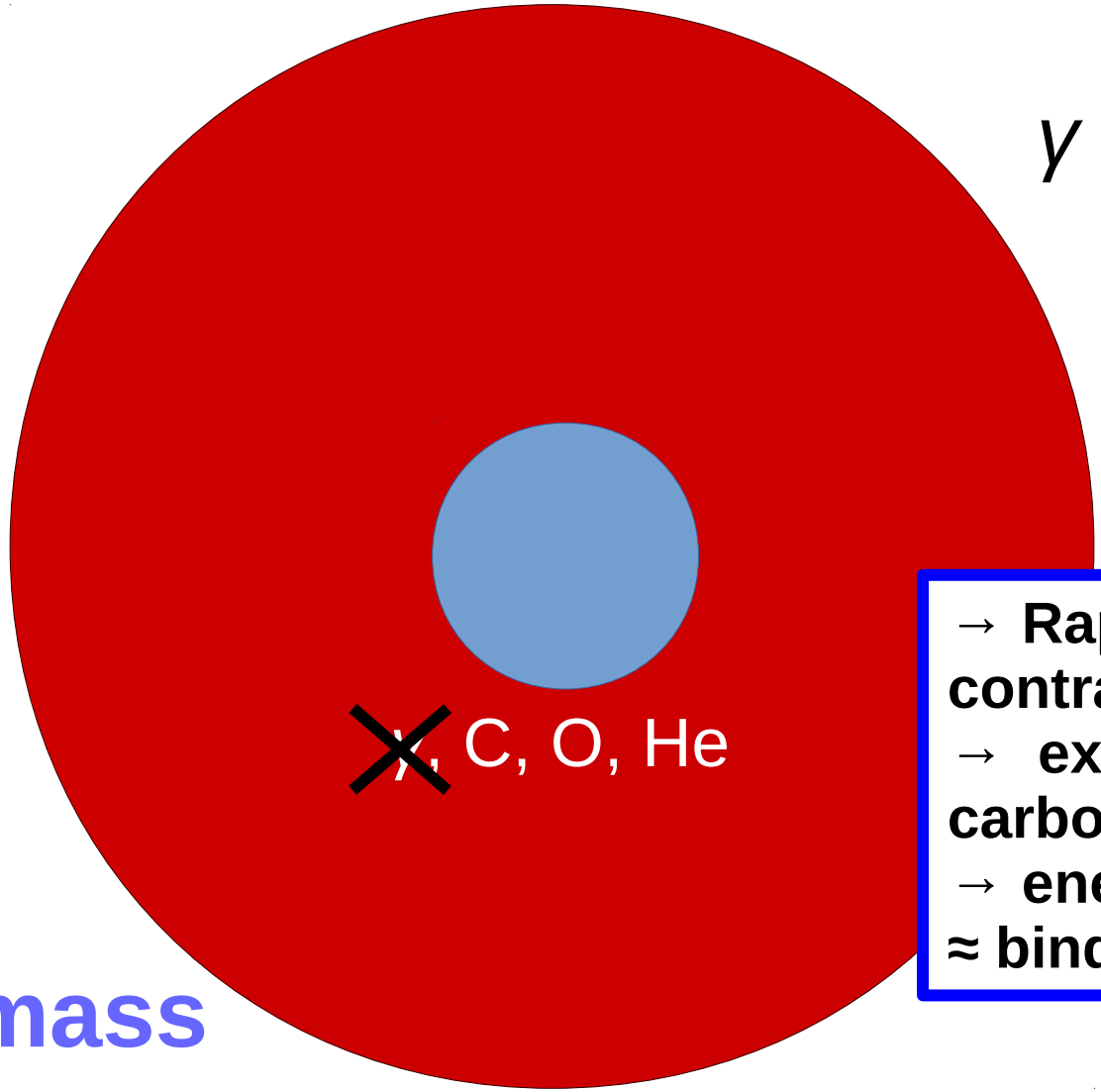
Pair-instability mass gap



CO core mass

M_{CO} > ~40 $M_{\odot}$

Pair instability in the core



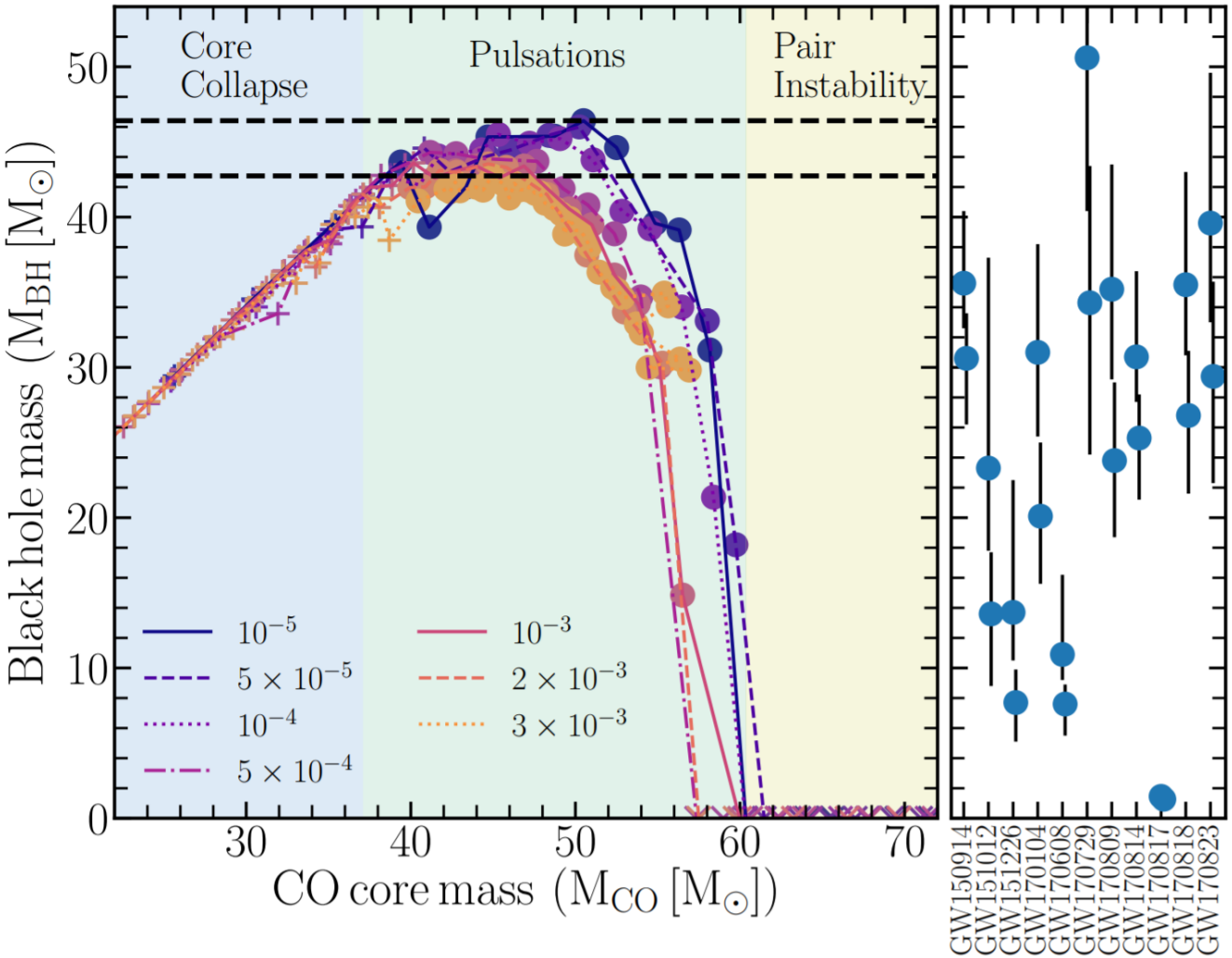
$$\gamma \rightarrow e^{+} + e^{-}$$

→ **Rapid core contraction**
→ **explosive carbon burning**
→ **energy released ≈ binding energy**

CO core mass

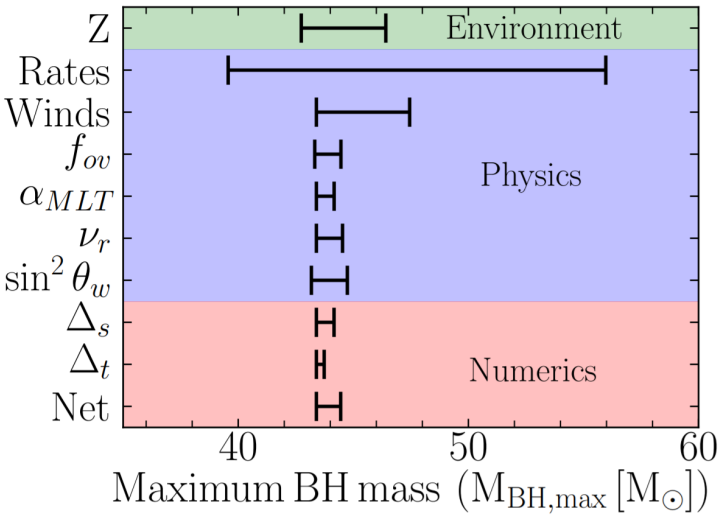
$M_{CO} > \sim 40\ M_{\odot}$

The maximum BH mass?



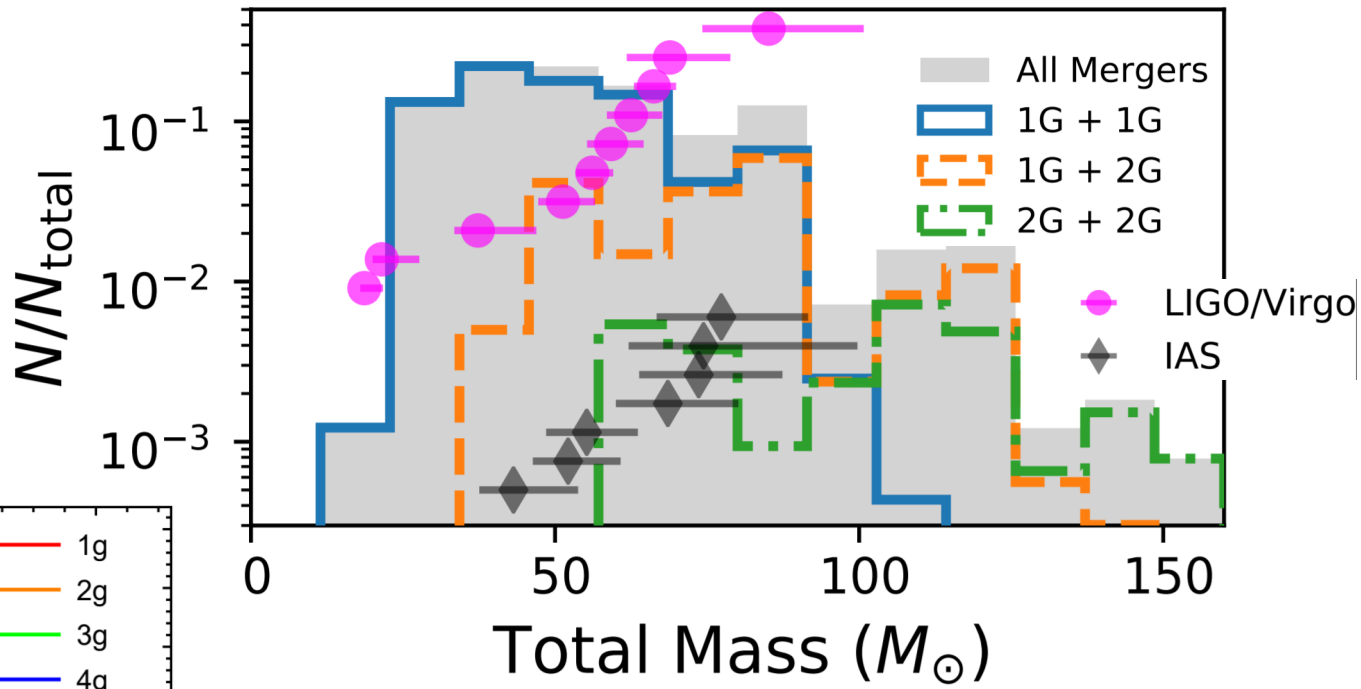
No BHs with masses between 50 $M_\odot$ and ~130 $M_\odot$ from normal stellar evolution

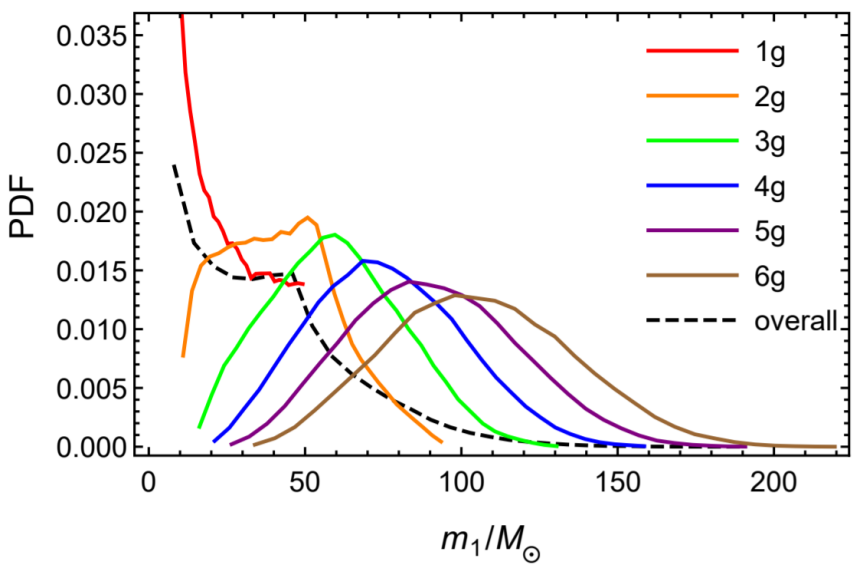
eg. Farmer+2019
Heger+2003



Farmer+2019
see also: Heger & Woosley (2002), Woosley+(2007),Belczynski+(2016), Woosley(2019), Stevenson+(2019), Marchant+(2019)

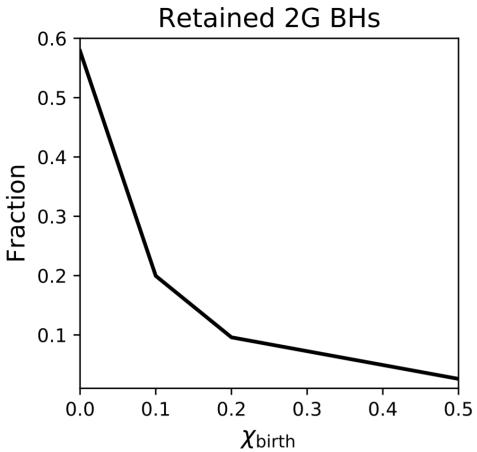
Multiple mergers in dynamical channels!



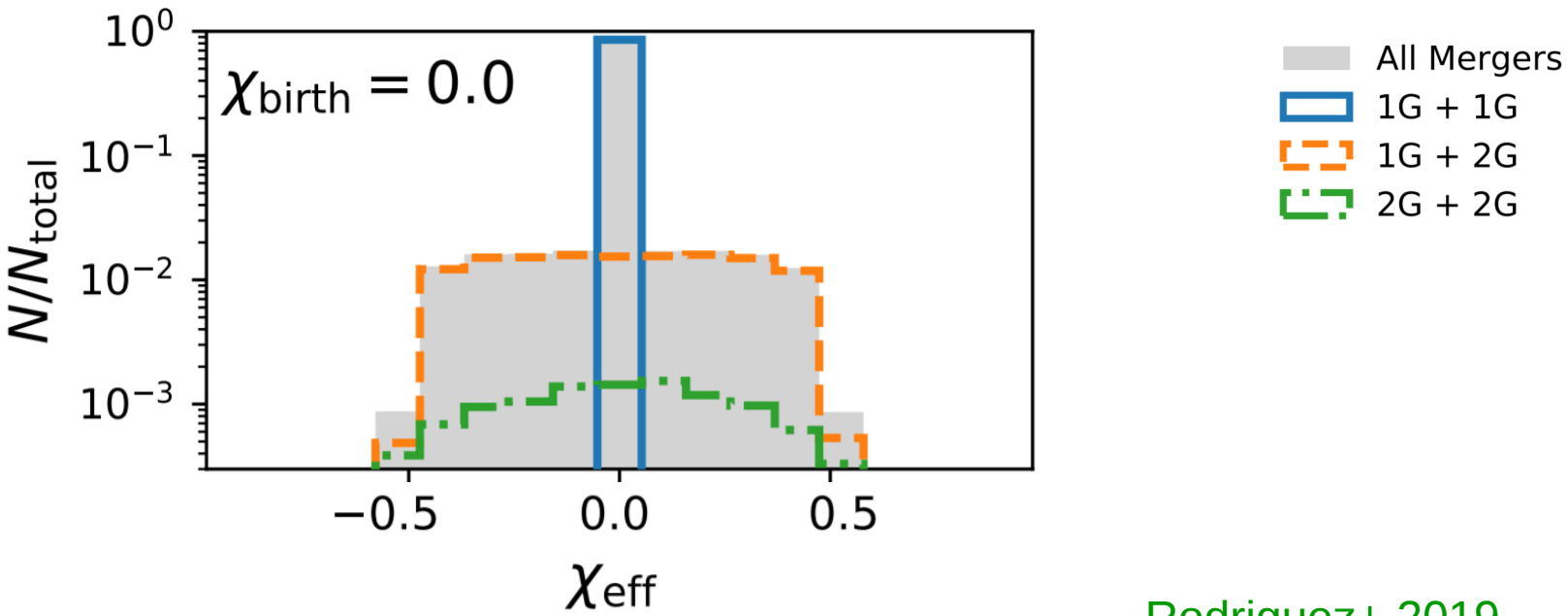


Yang+ 2019 – hierarchical mergers in AGN disks

Rodriguez+ 2019 – second generation in clusters



Multiple mergers – imprint on the spins



Rodriguez+ 2019

Fraction of hierarchical mergers possibly constrained with O(100) of BBH mergers (Fishbach, Holz, Farr 2017)

Conclusions

- **Many different channels** for BBH mergers, two types: isolated evolution or dynamical formation
- **Difficult to distinguish** based on: rates, mass distribution, mass ratio distribution
- May be possible to distinguish based on: **eccentricity, spins, and, especially, BH mass in the pair instability gap**