Inspiral, merge, repeat:

hierarchical black-hole mergers and their gravitational-wave signatures

Davide Gerosa

University of Milan-Bicocca

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davide.gerosa@unimib.it

www.davidegerosa.com

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Outline

1. How do two black holes get together?
2. Gravitational-wave observables
3. Repeated black-hole mergers for LIGO and Virgo

All in a new Nature Astronomy review: **DG** Fishbach 2021 (arXiv:2105.03439)

Can BHs really make it?

At lowest order, GW emission causes the orbit to shrink: Peters and Mathews 1963

separation $$\frac{da}{dt} = -\frac{64}{5}\frac{G^3M^3}{c^5a^3}\frac{q}{(1+q)^2}(1-e^2)^{-7/2}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

eccentricity $$\frac{de}{dt} = -\frac{304}{15}e\frac{G^3M^3}{c^5a^4}\frac{q}{(1+q)^2}(1-e^2)^{-5/2}\left(1+\frac{121}{304}e^2\right)$$

Inspiral timescale

$$t_{\rm GW} \sim a\frac{dt}{da} \sim a^4$$

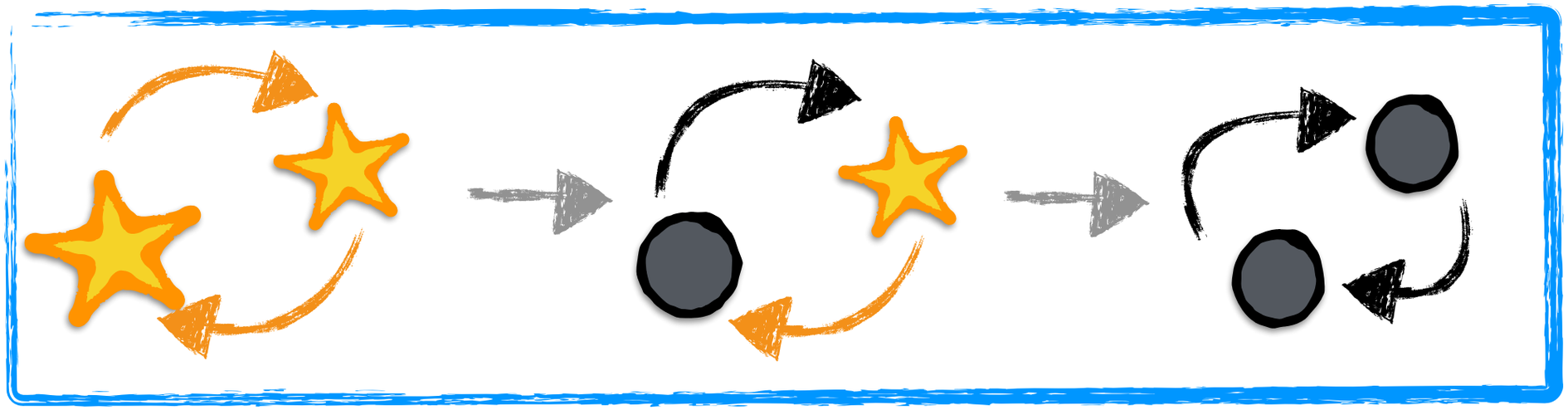
Gravitational waves are efficient below

$$a_{\rm GW} = 1.2\times10^{11}\left(\frac{t_{\rm GW}}{1.4\times10^{10}{\rm yr}}\right)^{1/4}\left(\frac{M}{M_\odot}\right)^{3/4}{\rm cm}$$

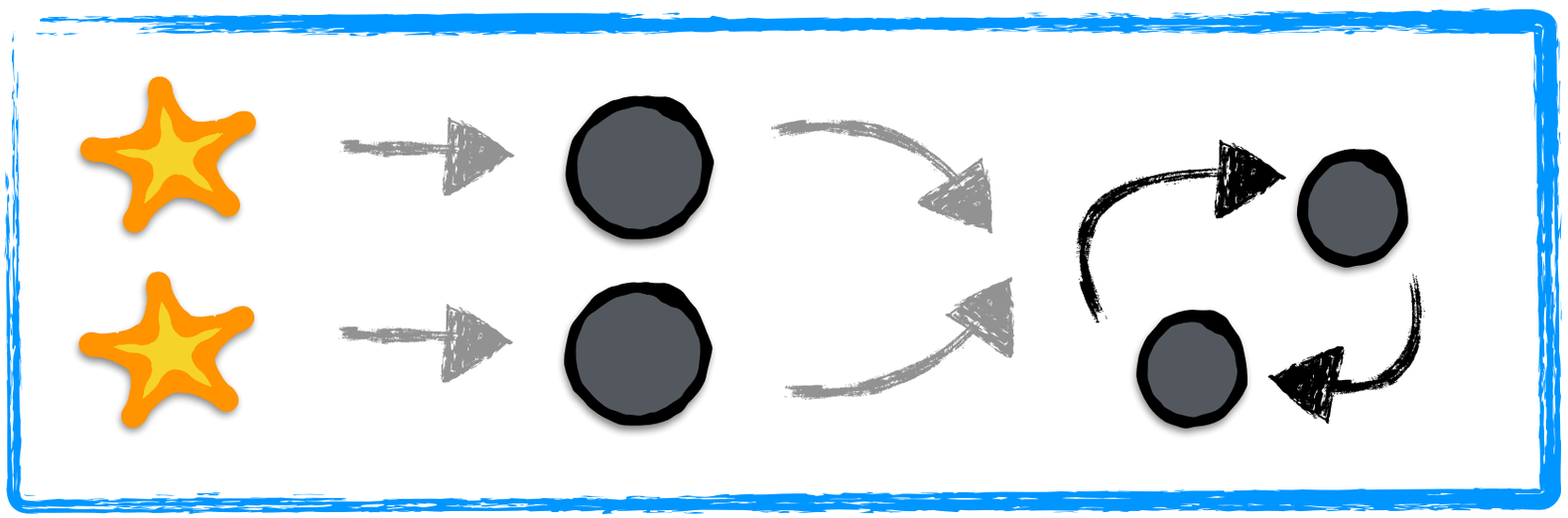
$\sim 10R_\odot$ for stellar-mass BHs

Relativity alone is great to model the LIGO signals…
…but some **astrophysics** is needed to explain them

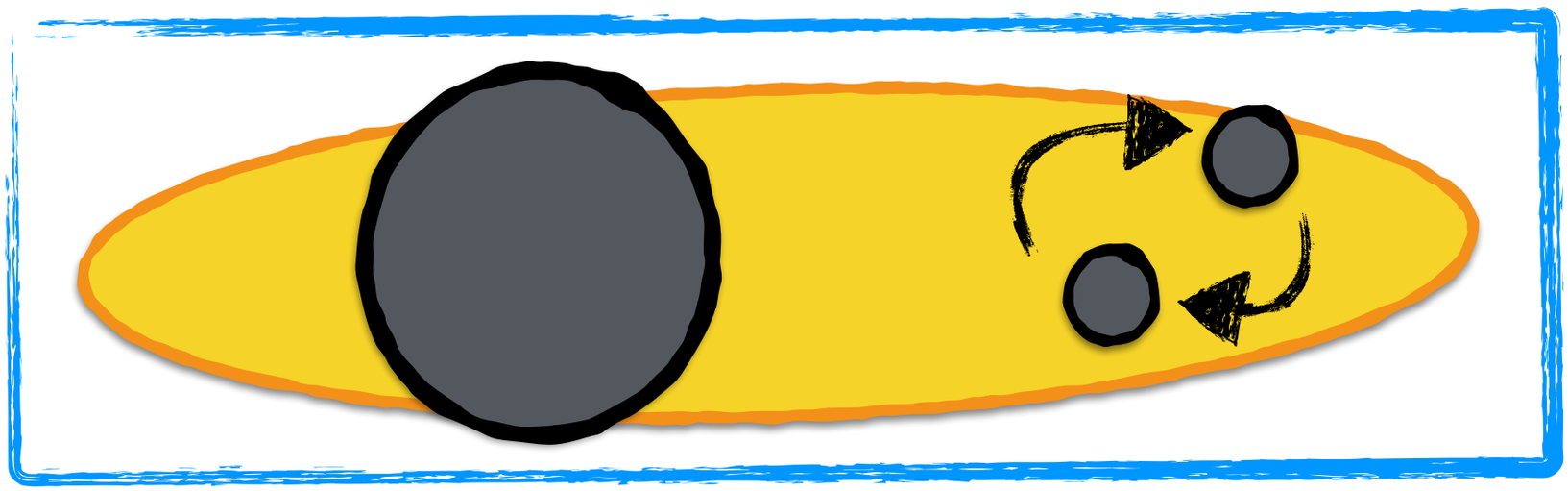
Have we been together for so long?



Yes! I've known you since you were a star



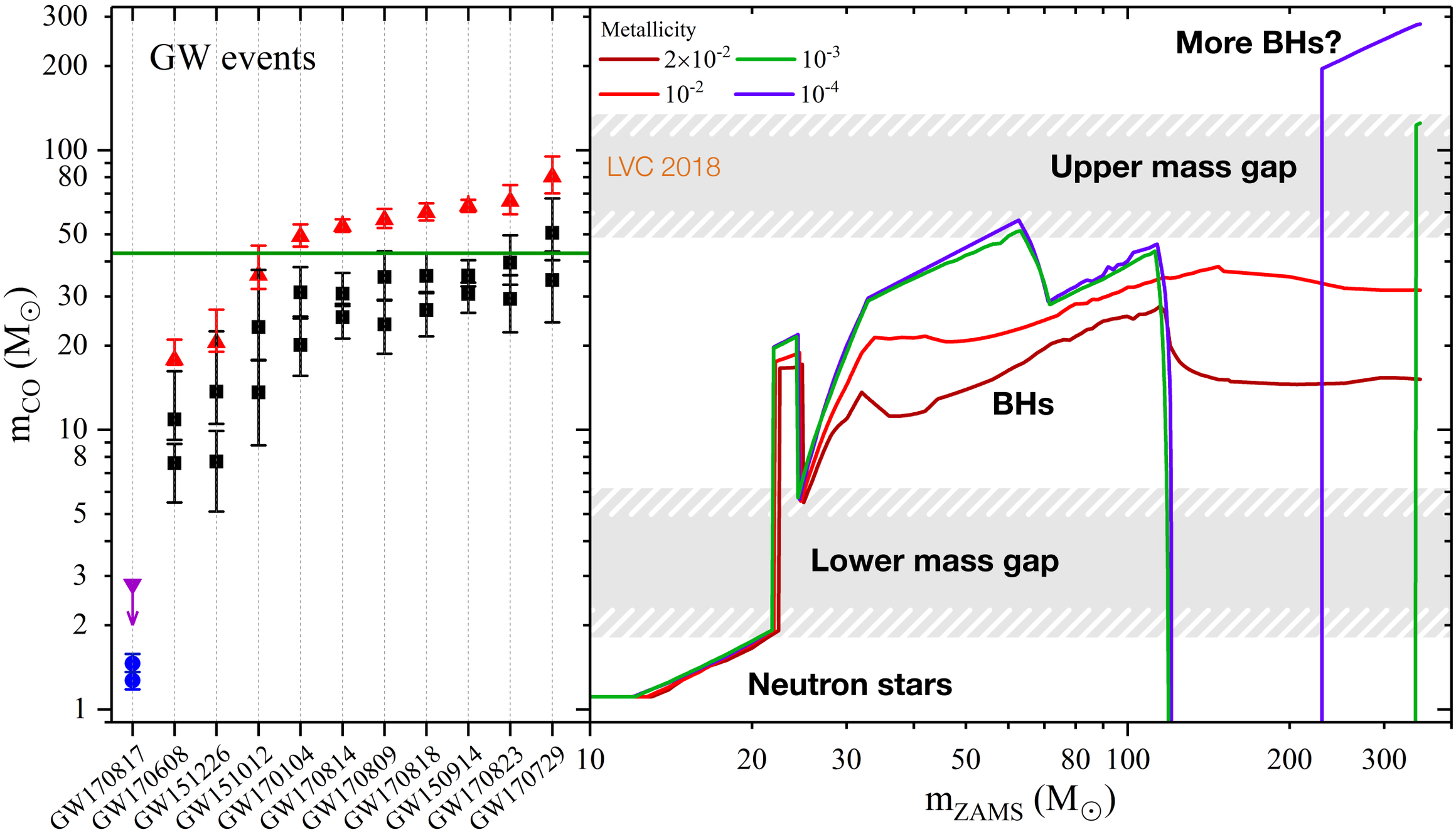
Nah, we just met in cluster



Our neighbour is so messy, we should move

Mass predictions: the gaps

- **Lower mass gap**: between BHs and NSs
- **Upper mass gap**: supernova instabilities



Pair-instability supernovae

As the mass of the core increases:

1. Electron-positron production
2. Radiation pressure drops
3. Core contracts
4. Temperature goes up
5. Explosive oxygen burning
6. Entire star is gone (PISN)
7. Repeated pulsations (PPISN)

Heger Woosley 2002, Belczynski+ 2016, Woosley+ 2017, Spera Mapelli 2017, Marchant+ 2018, Stevenson+ 2019

BH forbidden for

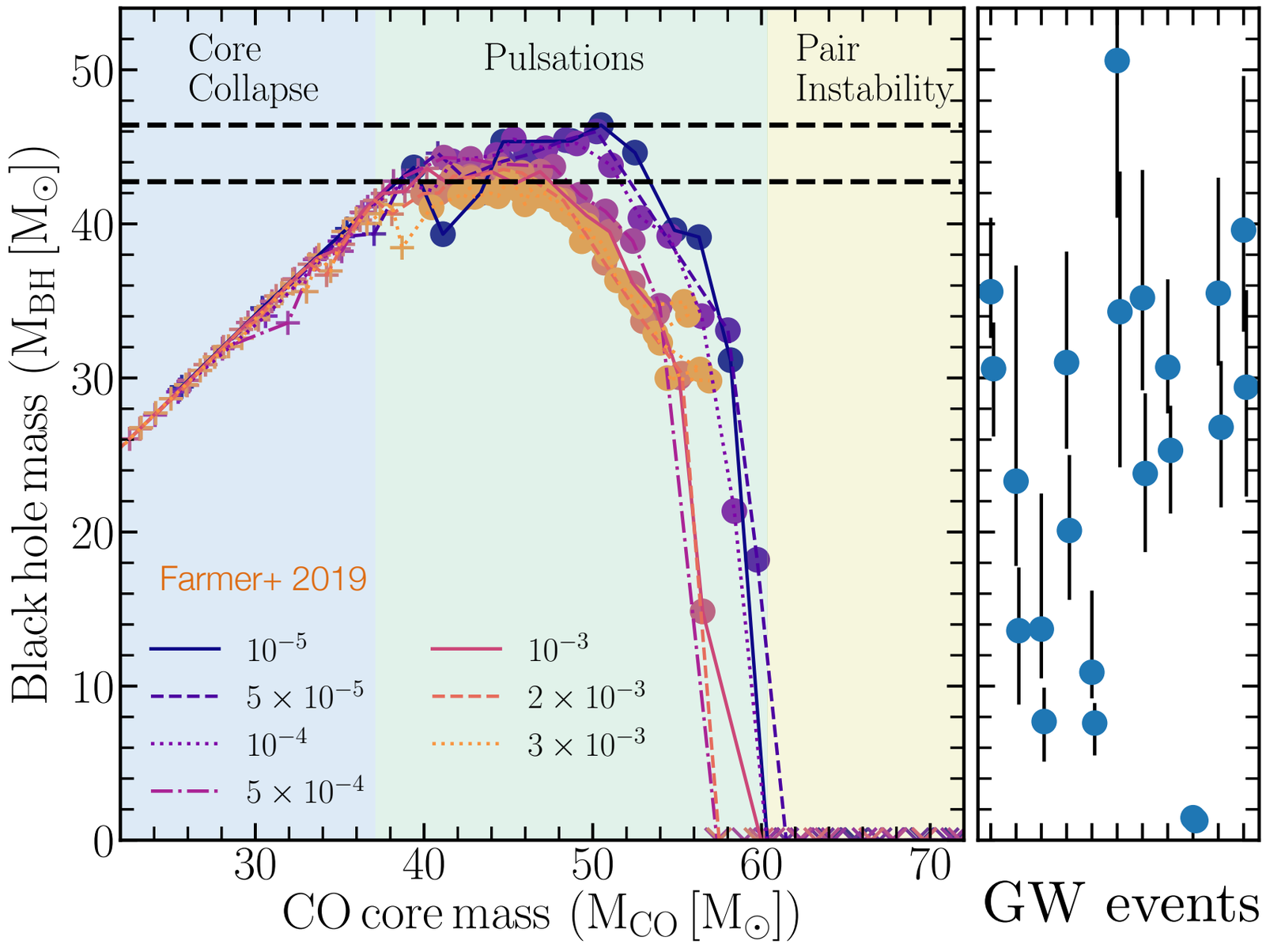
$$M \gtrsim 50 M_\odot$$

This limit is very solid…

Farmer+ 2019, Renzo+ 2020

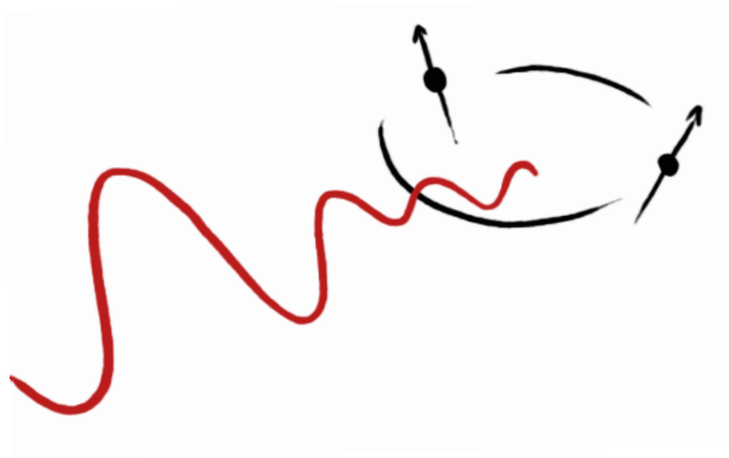
…maybe

Belczynski+ 2019, 2020, Farmer+ 2020, Costa+ 2021



Can we bypass stars and use black holes?

Spin predictions



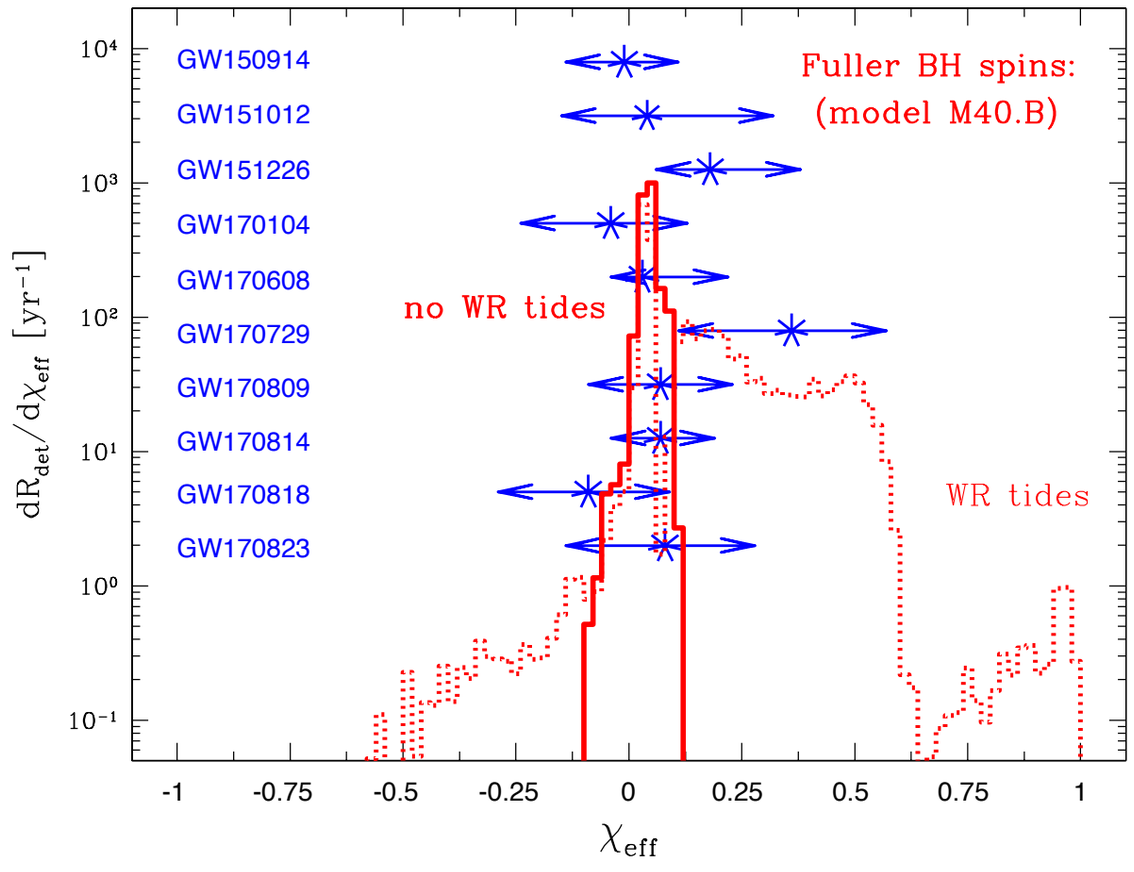
Extremely sensitive to details

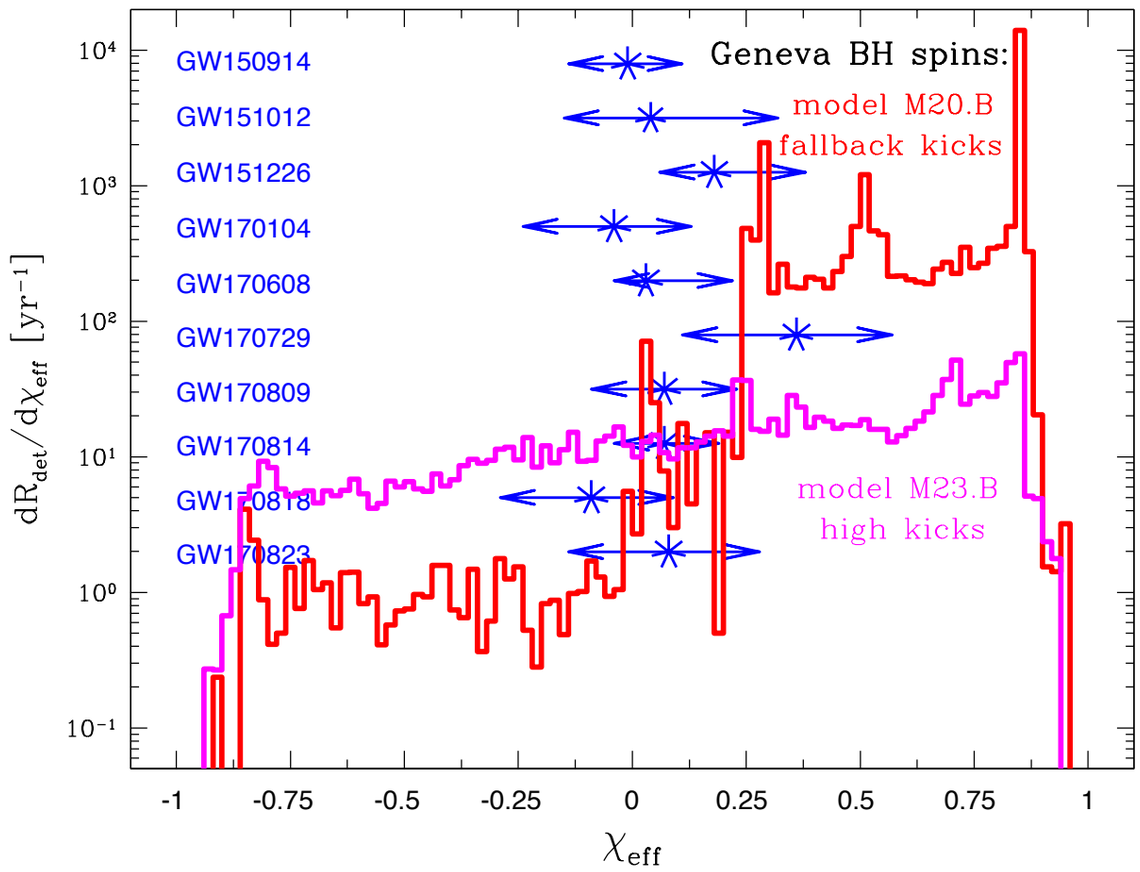
- Core-envelope interactions in massive stars Fuller Ma 2019
- Tidal realignment in the Wolf-Rayet phase Zaldarriaga+ 2017
- Supernova kicks Kalogera 2000
- Mass transfer Stegmann+ 2020
- Relativistic precession till merger **DG**+ 2013, 2018

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

Sets the lenght of the waveform

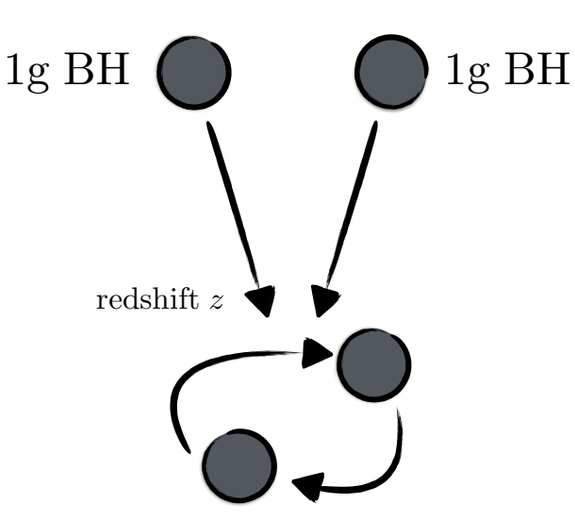
Belczynski, **DG**+ 2020



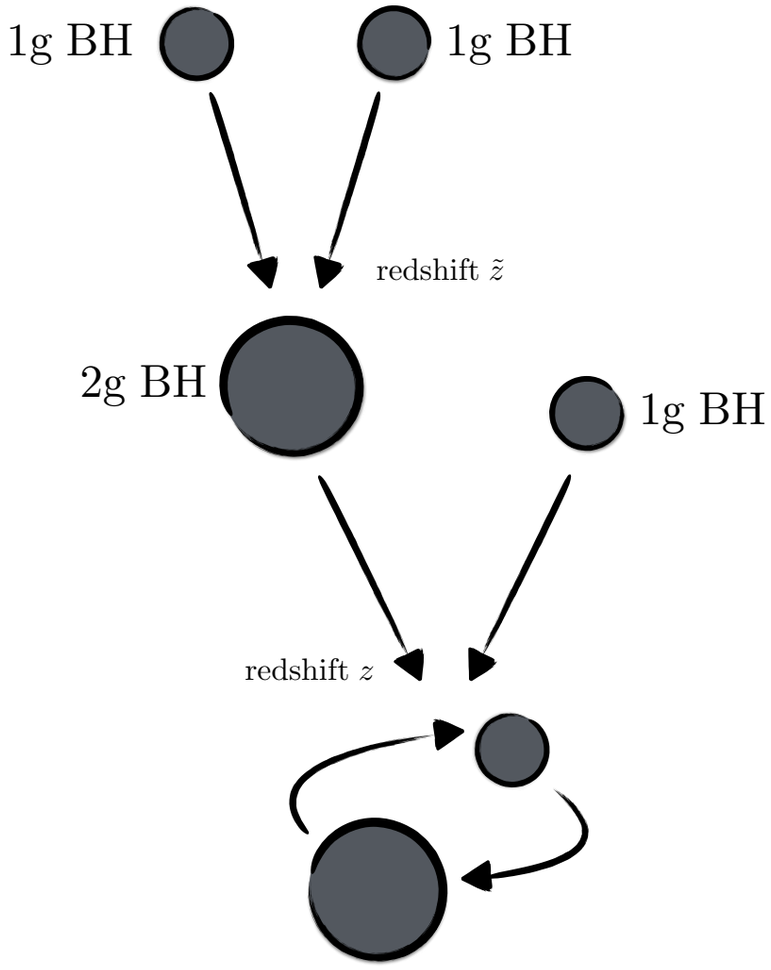


Black hole generations

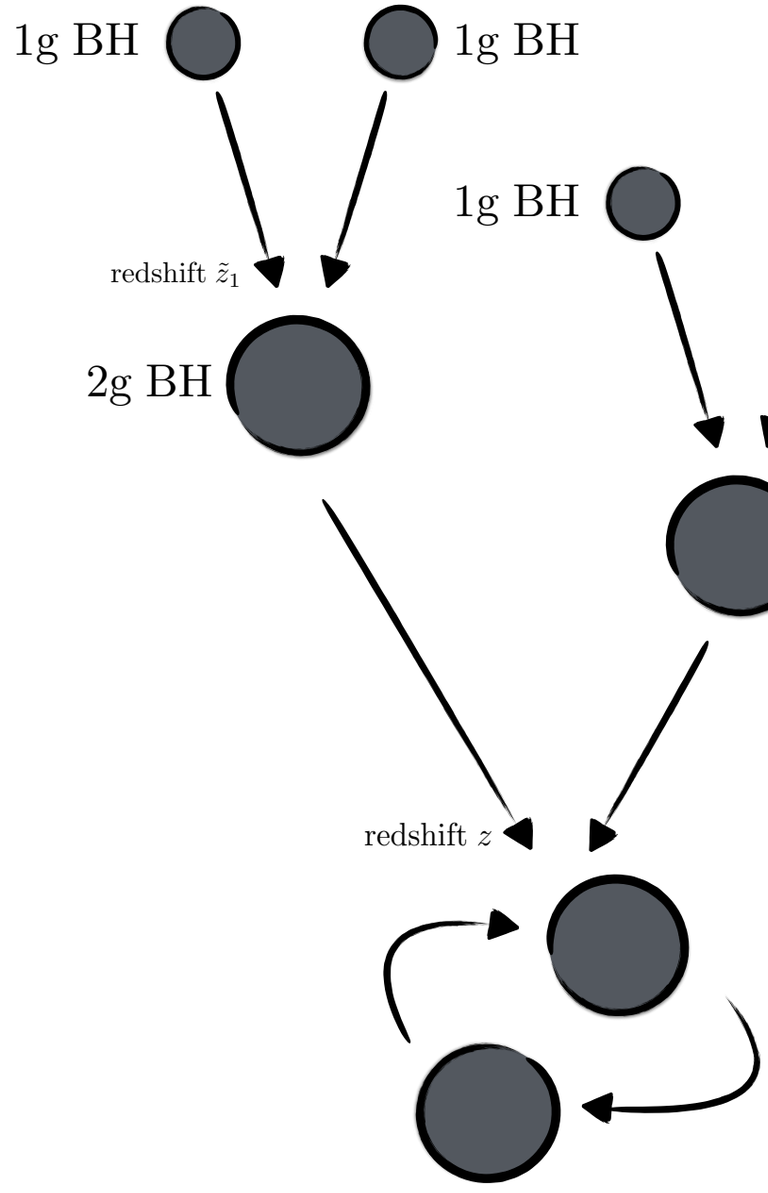
DG Berti 2017



1g+1g event



1g+2g event

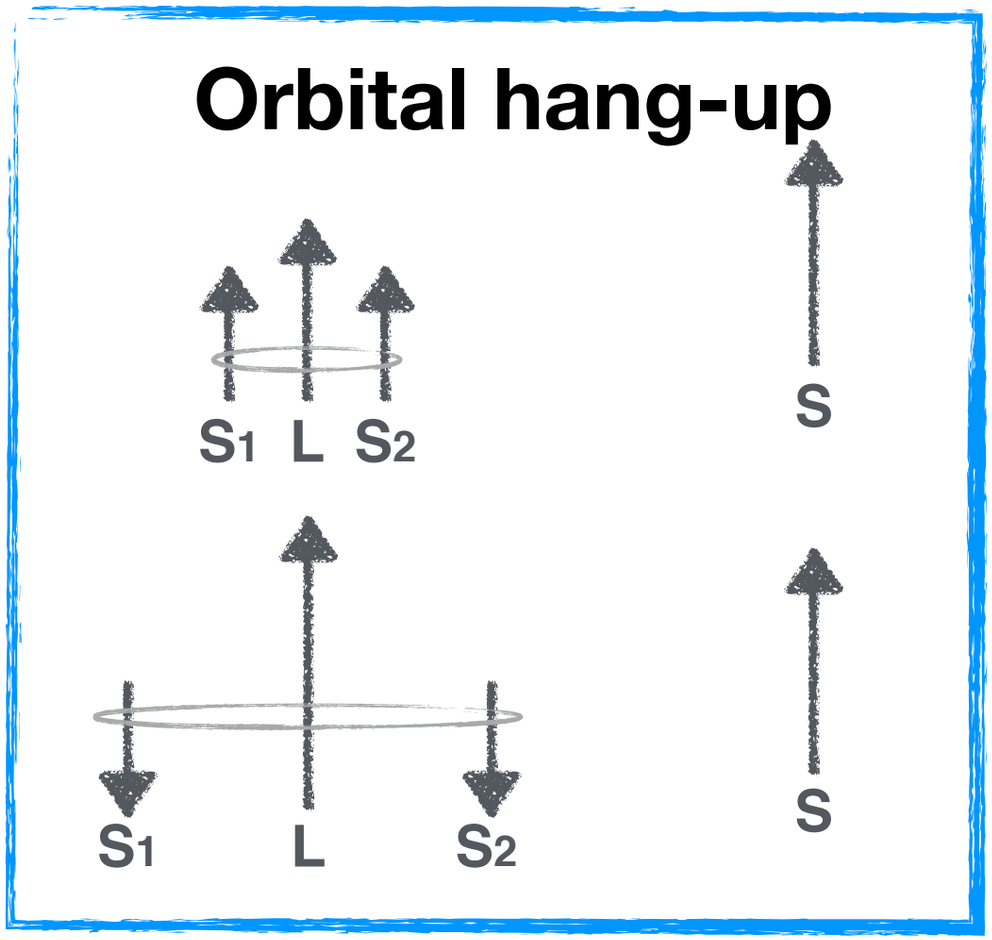


2g+2g event

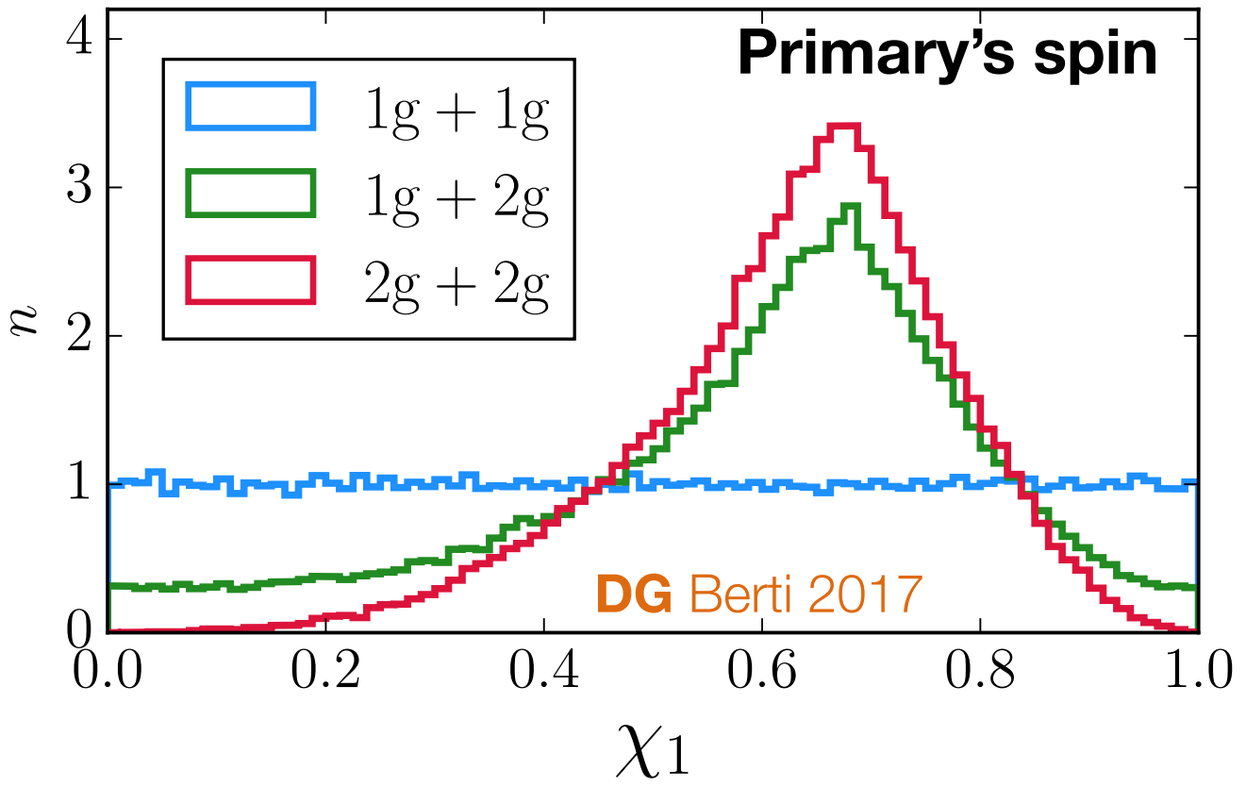
Orthogonal, but complementary, direction to the usual field vs. cluster debate

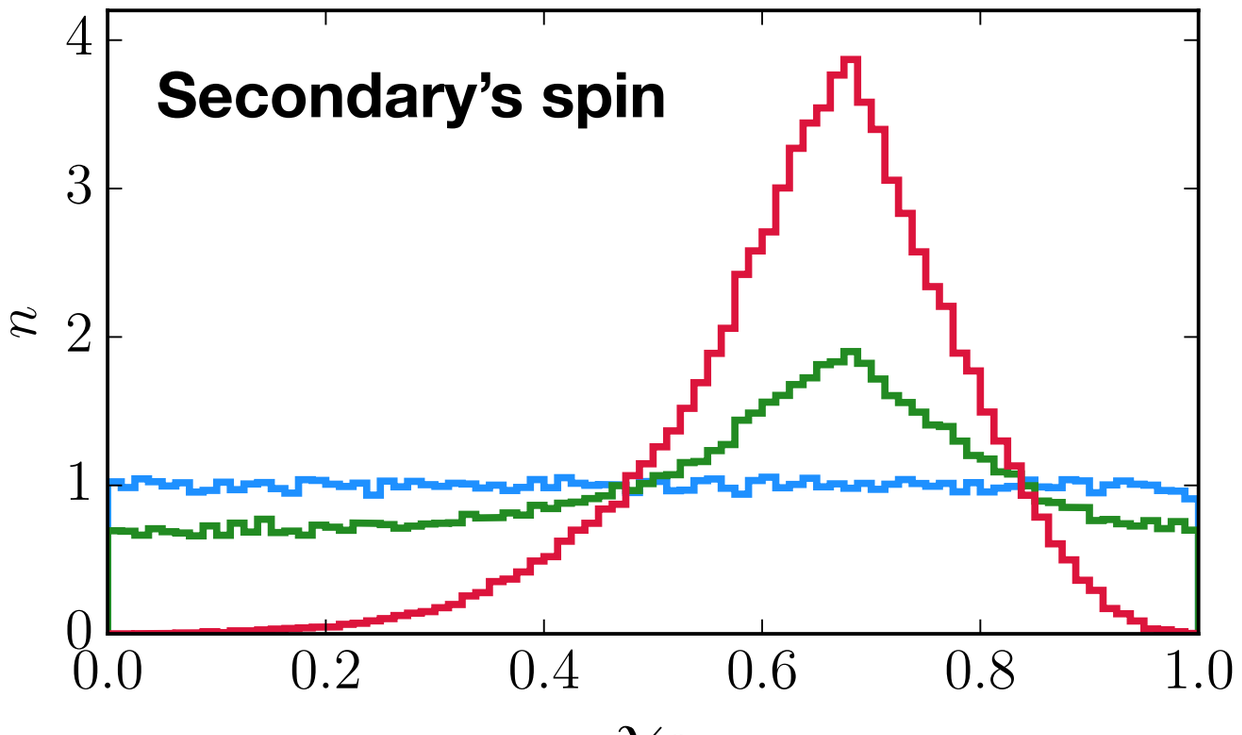
Spins: the magic number

DG Berti 2017, Fishbach+ 2017, Berti Volonteri 2008

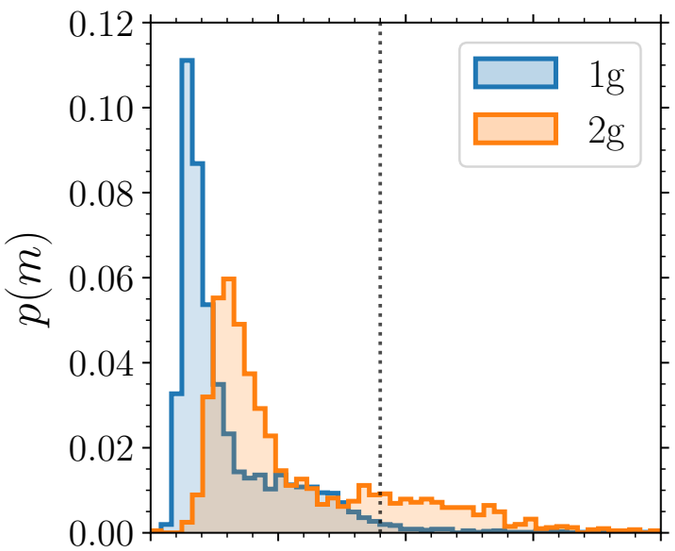


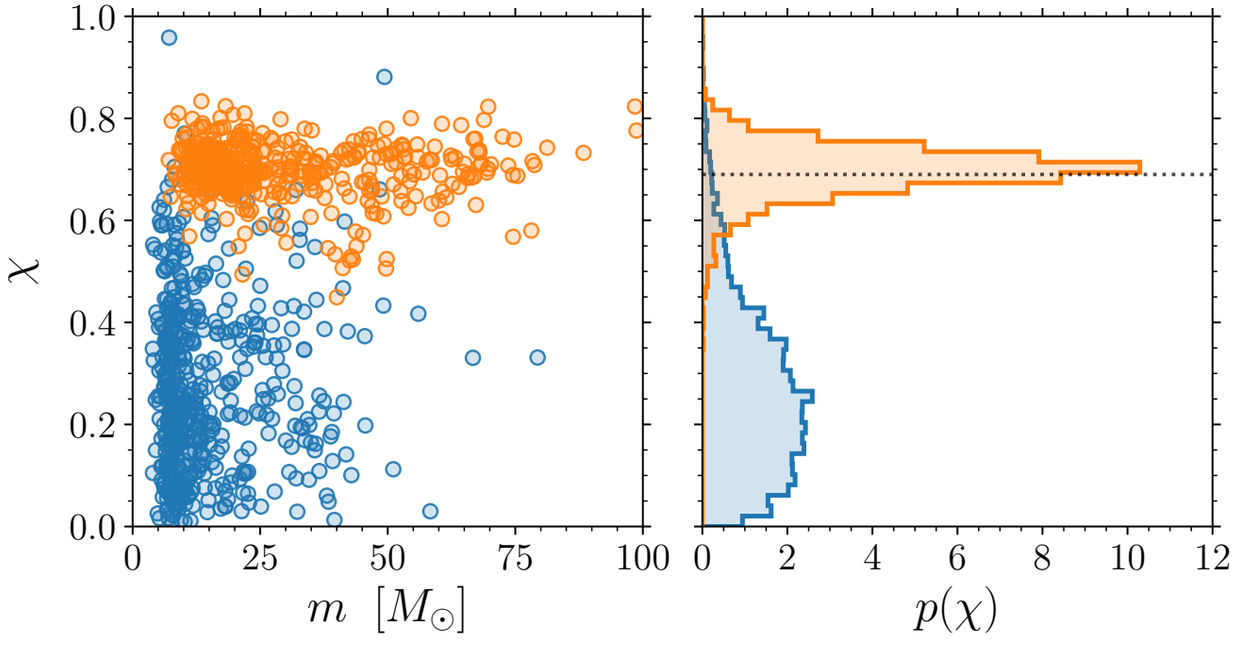
Peculiar spin distribution peaked at **0.7**





An explosion of new predictions





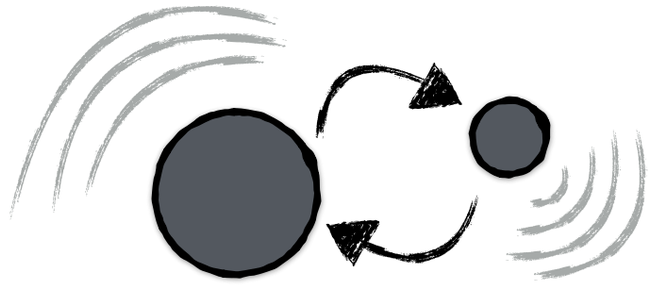
New review **DG** Fishbach 2021

- Masses in the pair-instability mass gap
  Heger+ 2003, Woosley+ 2007
- Peculiar spin distribution peaked at 0.7
  DG Berti 2017, Fishbach+ 2017
- But GW kicks impose large escape speed
  DG Berti 2019
- Very frequent in AGNs
  Yang+ 2019, Tagawa+ 2020
- Promising for GW190412
  DG Vitale Berti 2020
- Leading explanation for GW190521
  LIGO/Virgo 2020
- Perhaps a several events in the new LIGO catalog?
  Kimball+ 2020
- Inferring the properties of the parents
  Baibhav, **DG**+ 2021
- A model that can be ruled out!
  DG Giacobbo Vecchio 2021
- Parametric inference with deep learning
  Mould, **DG**+ (soon!)

More spin means more kick

- **Non spinning BHs:** up to ~160 Km/s

  Gonzales+ 2007



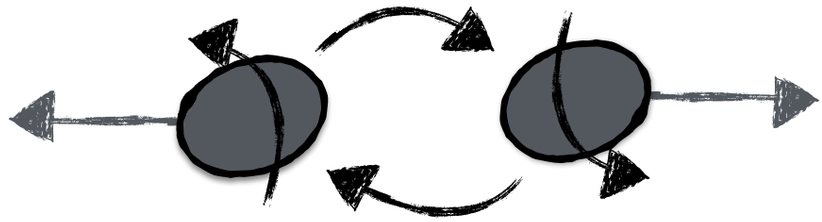
- **Misaligned spins:**

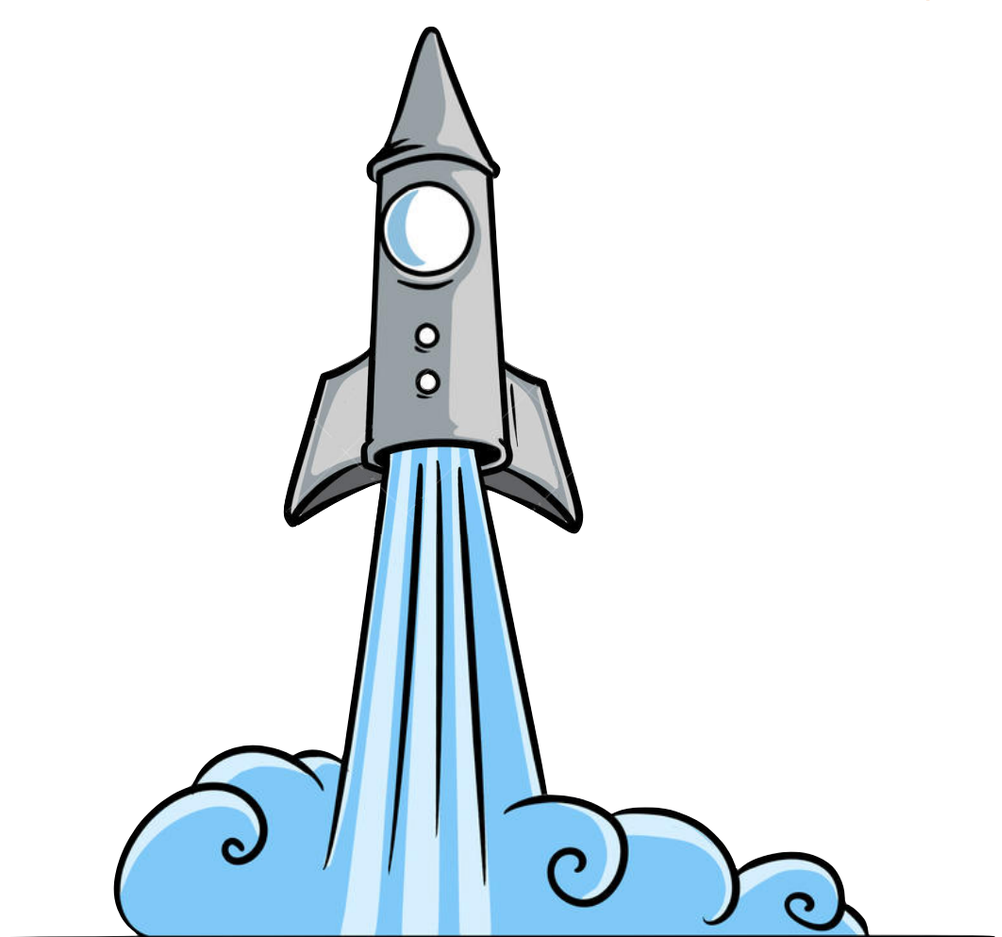
  “Superkick” up to ~5000 Km/s

  Gonzales+ 2007; Campanelli+ 2007, Lousto Zlochower 2011,2013

  Enhanced by ~25% for eccentric binaries

  Sopuerta+ 2007, Sperhake, **DG**+ 2020



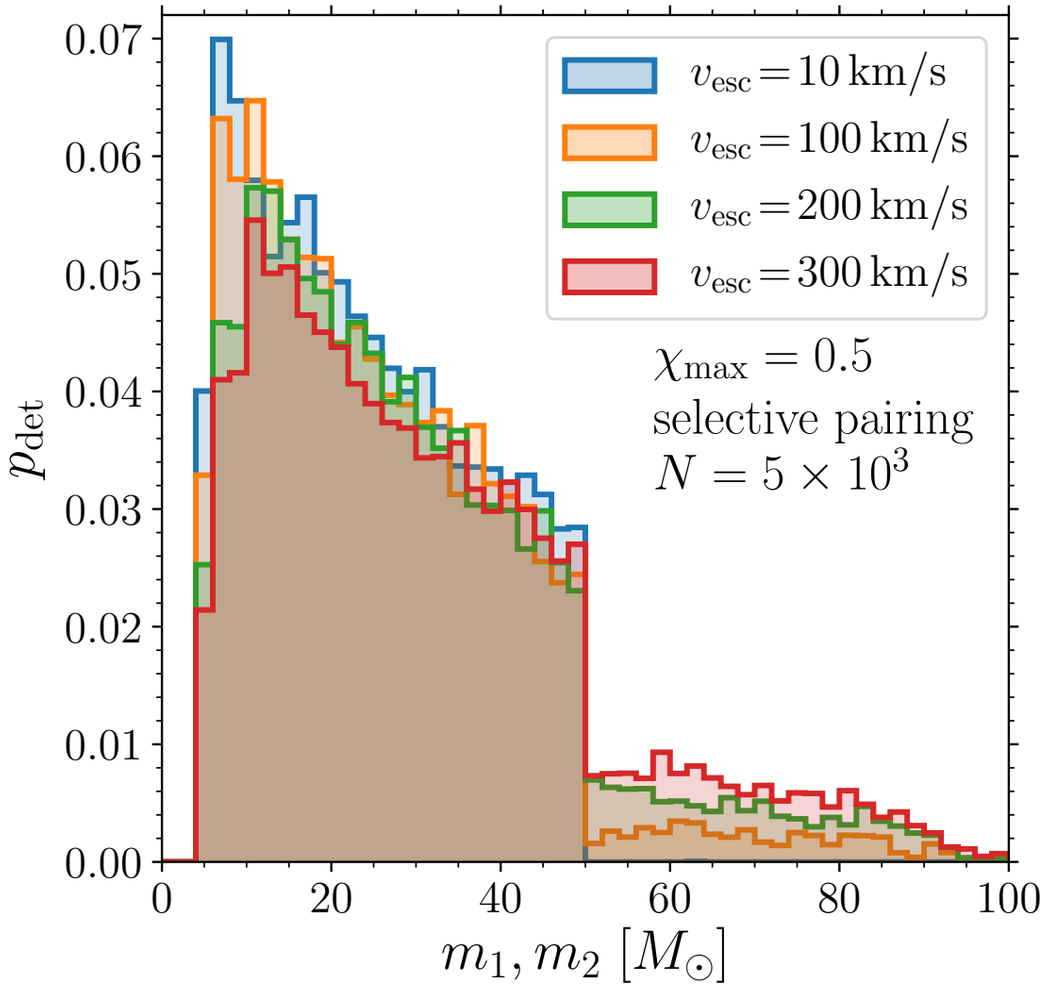


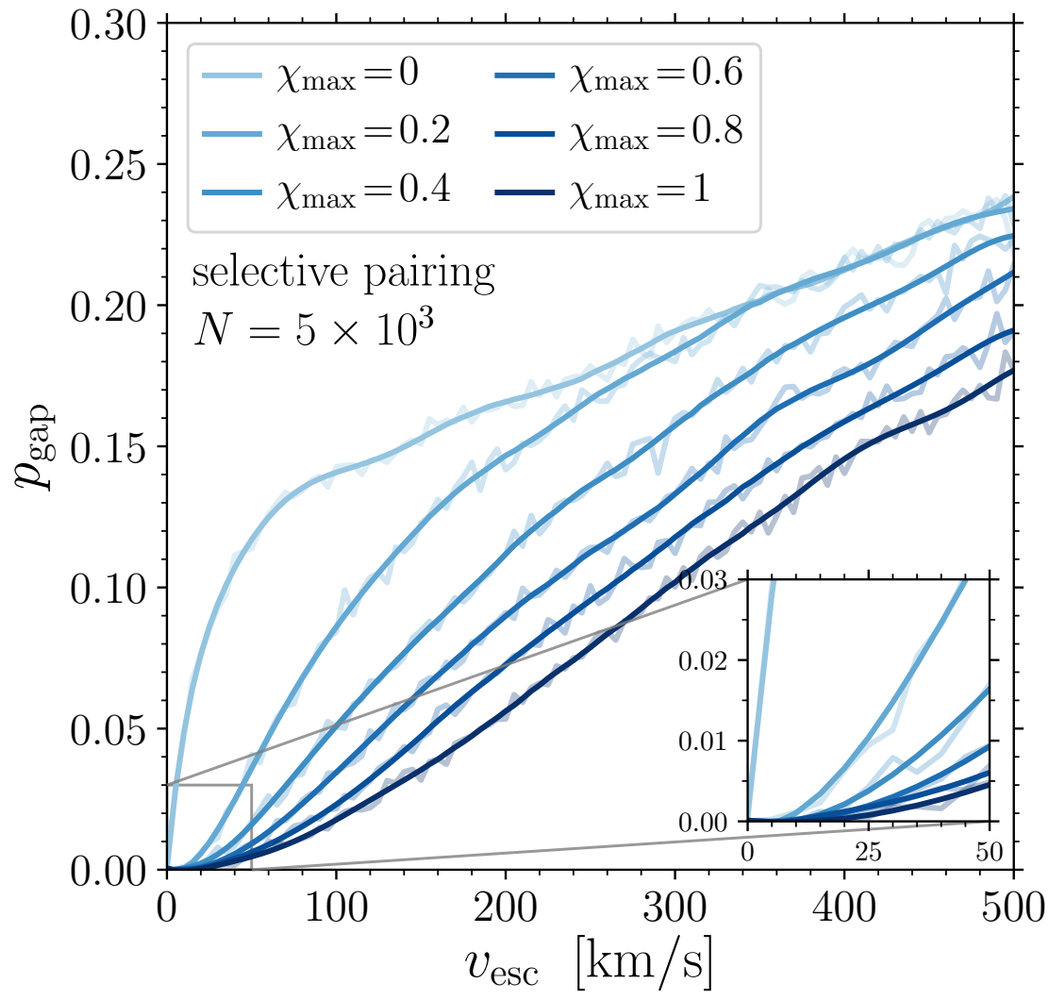
Large spins have a critical impact on the kick: can black holes really merge again?

The role of the escape speed

An escape speed of ~50 km/s is necessary to populate the mass gap

DG Berti 2019



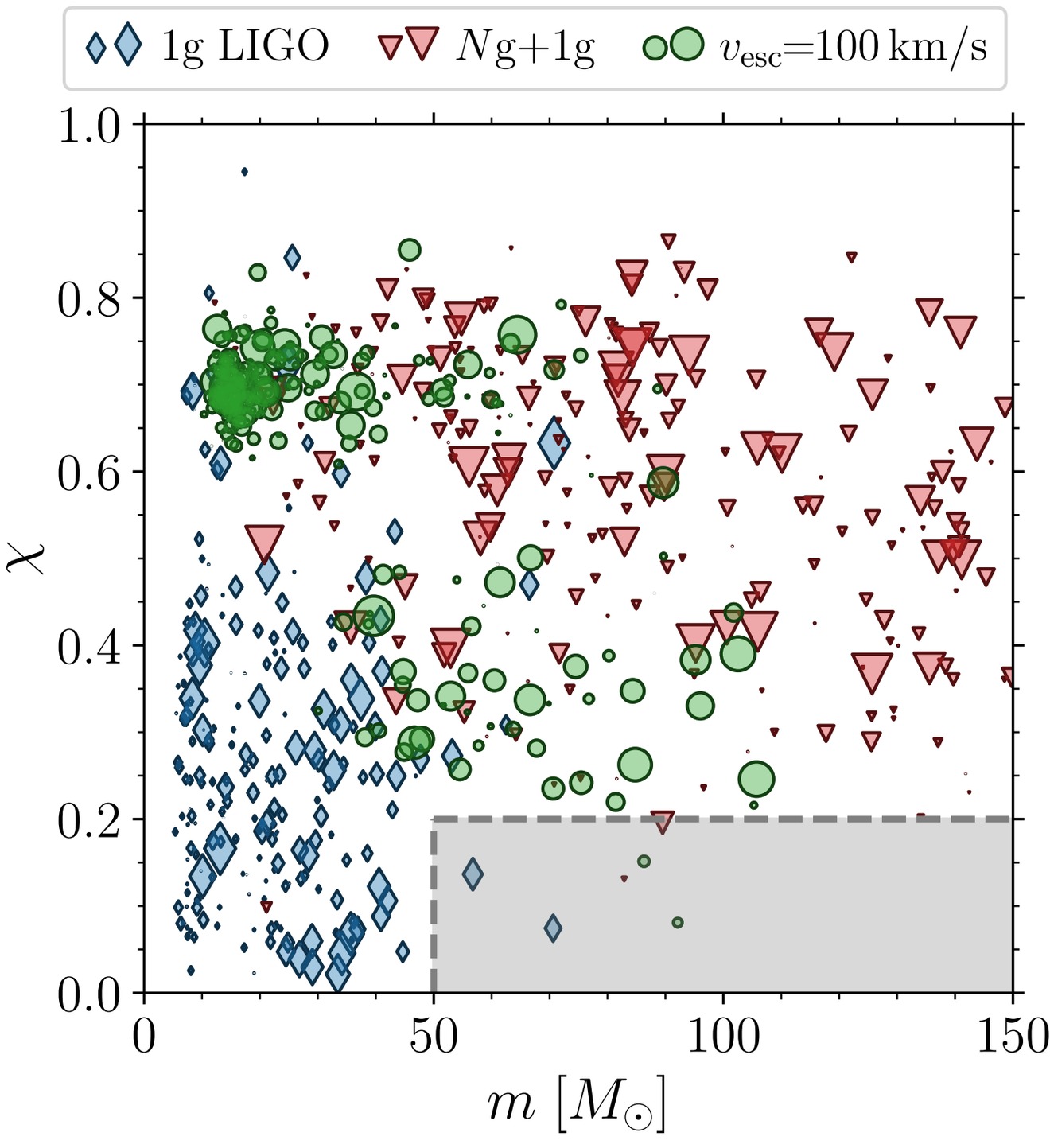


~50 km/s is more than most globular clusters.

- Nuclear star cluster Antonini+ 2016
- Triples Antonini+ 2017, Bin+ 2019
- Disc-assisted migration
  Stone+ 2017, Bartos+ 2017

High mass but low spin?

DG, Giacobbo, Vecchio 2021



Hierarchical mergers cannot do it

(even if you try hard)

If a future event is there…
we need something else!

- Lowered CO reaction rate
  e.g Farmer+ 2020, Costa+ 2021
- Weaker stellar winds
  e.g. Leung+ 2019, Belczynski+ 2020
- Rotation
  e.g Marchant Moriya 2020, Woosley Heger 2021
- Stellar collisions
  e.g. Di Carlo+ 2019, Renzo+ 2020
- Accretion
  e.g. van Son et al. 2020, Natarajan 2021
- Pop III stars
  e.g. Farrell et al. 2020, Kinugawa et al. 2021

The gaps are precious

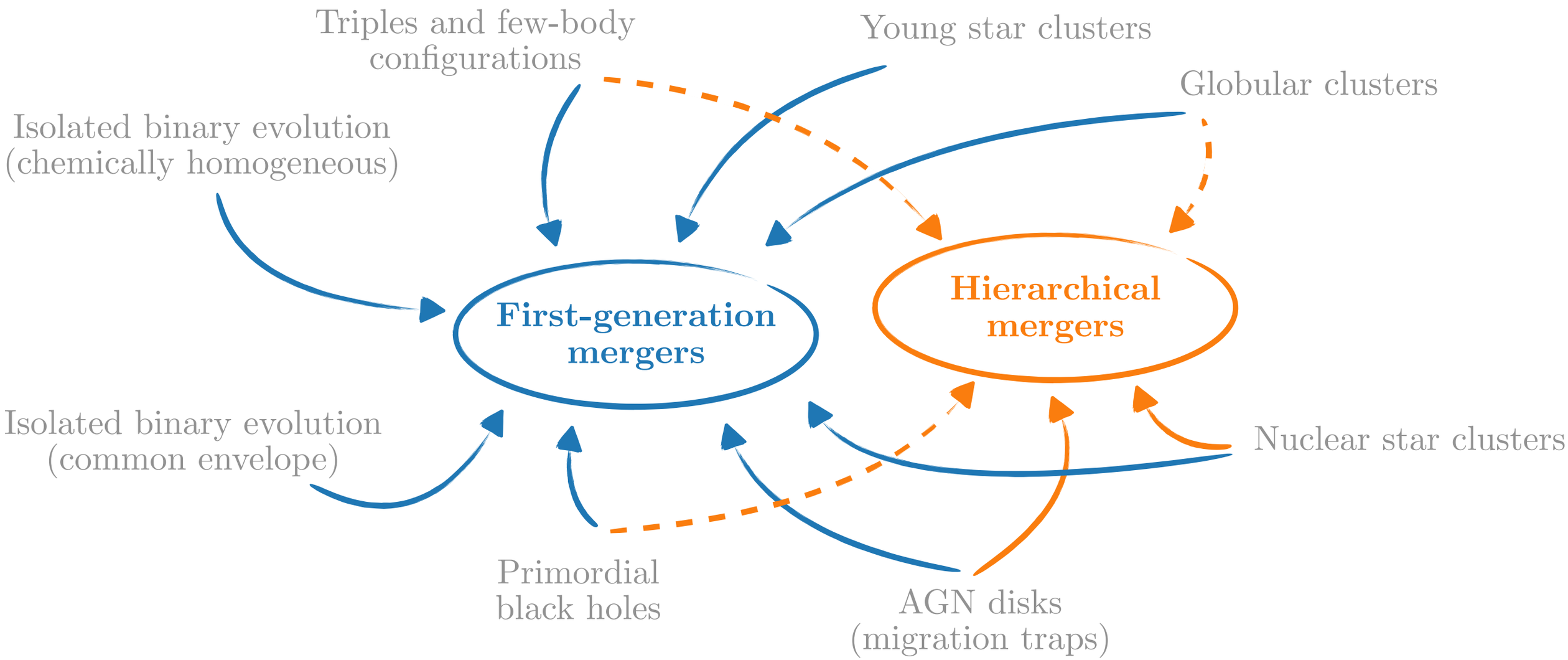
Baibhav, **DG**+ 2020

- Two channels “field” and “cluster”: $N = N_{\rm field} + N_{\rm cluster}$
- Some are in the gap: $N = N_{\rm no\,gap} + N_{\rm gap}$
- The gap is exclusive: $N_{\rm field,gap} = 0 \qquad N_{\rm cluster,gap} = N_{\rm gap}$
- A predicted efficiency: $\lambda \equiv \dfrac{N_{\rm cluster,gap}}{N_{\rm cluster}}$
- Individual contributions:

$$N_{\rm cluster} = \frac{N_{\rm gap}}{\lambda} \qquad\qquad N_{\rm field} = N - \frac{N_{\rm gap}}{\lambda}$$

Where do hierarchical BH mergers come from?

DG Fishbach (2021)



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