You'll never merge alone

Davide Gerosa

University of Milano-Bicocca

with M. Mould, S. Taylor, M. Fishbach,
E. Berti, A. Vecchio, N. Giacobbo,
M. Mancarella, V. Baibhav

Dec 5, 2022
Unsolved problems in astrophysics
Jerusalem, Israel

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You'll never merge alone
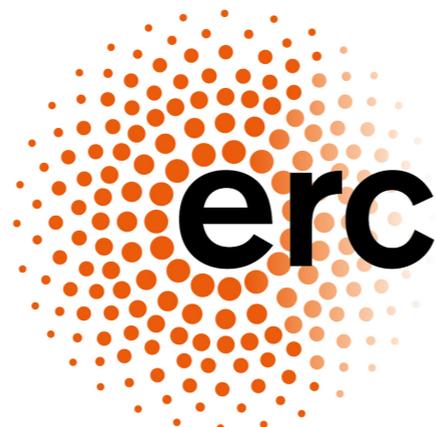
Davide Gerosa

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On the job market!

with M. Mould, S. Taylor, M. Fishbach,
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Sorry, I just couldn't resist

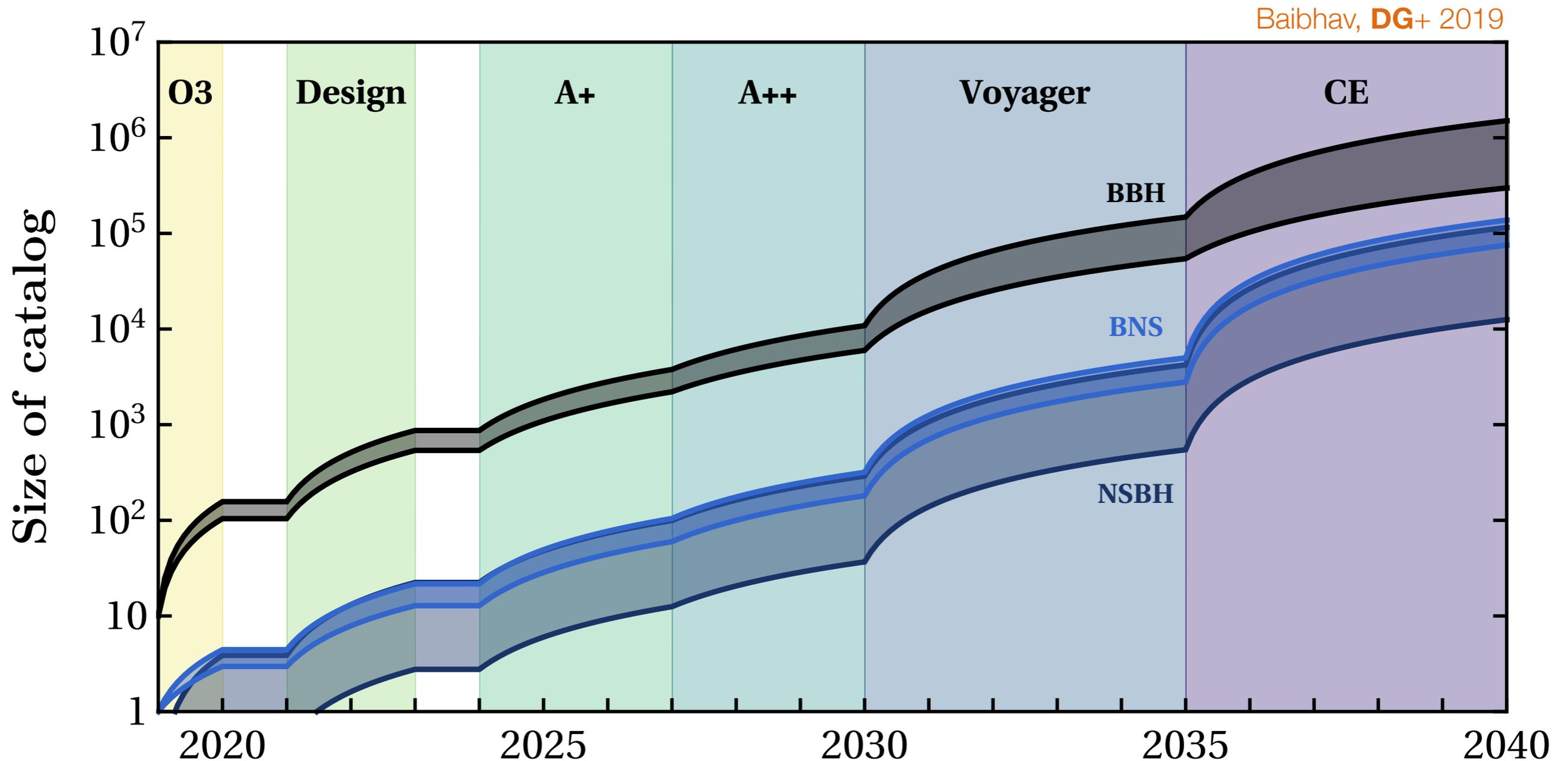# Sorry, I just couldn't resist

MERGE

LIGO/Virgo: 90 waves and counting

Discovering are piling up!

About 90 black-hole binary mergers detected so far.

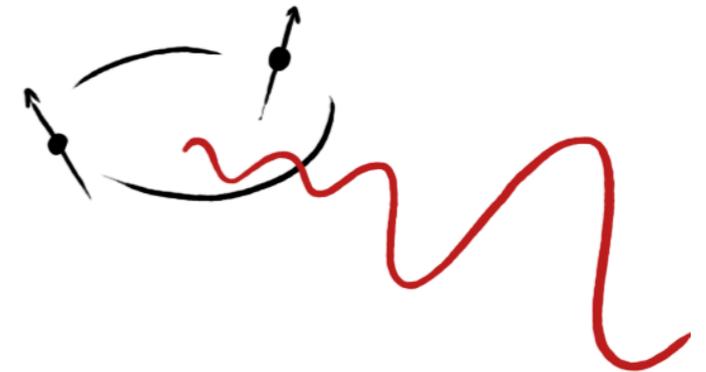Will become millions in ~20 years!

LIGO 2021

Baibhav, **DG**+ 2019

Can black holes really make it?

Power emitted in gravitational waves:

$$\frac{da}{dt} = -\frac{64}{5}\frac{G^3 M^3}{c^5 a^3}\frac{q}{(1+q)^2}$$
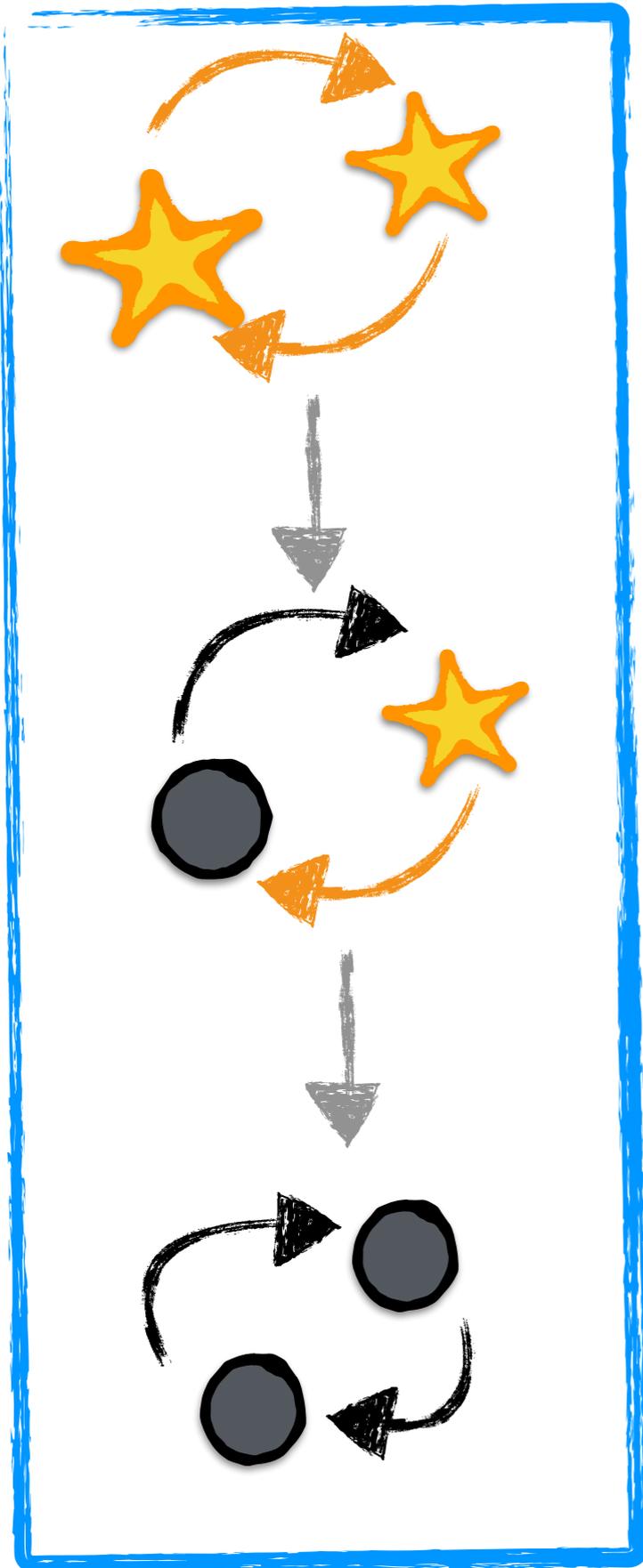
Peters 1964

GW-driven inspiral timescale

$$t_{\mathrm{GW}} \sim a\frac{dt}{da} \sim a^4$$
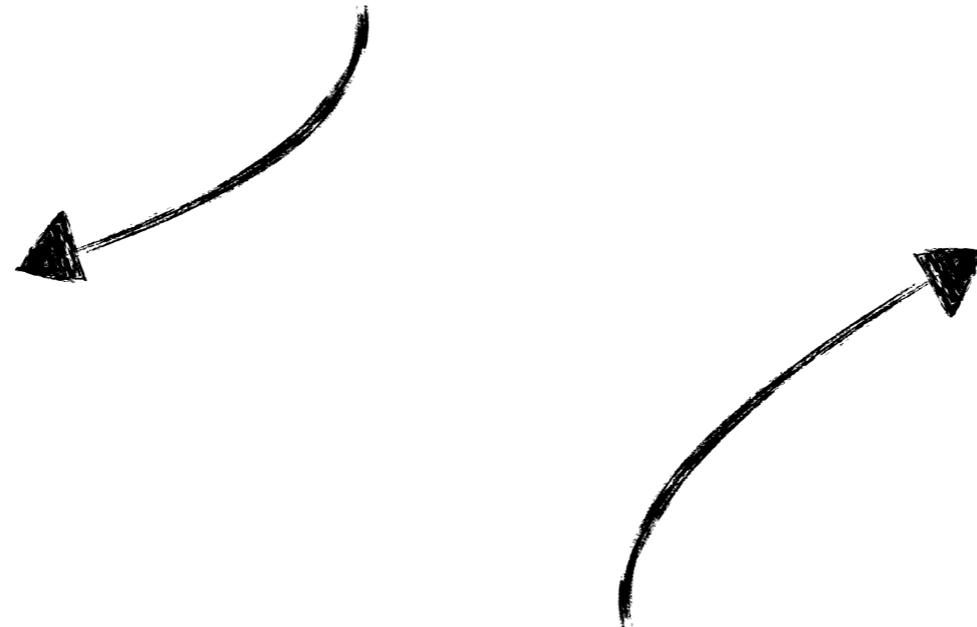
Gravitational waves are efficient below

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

stellar-mass BHs

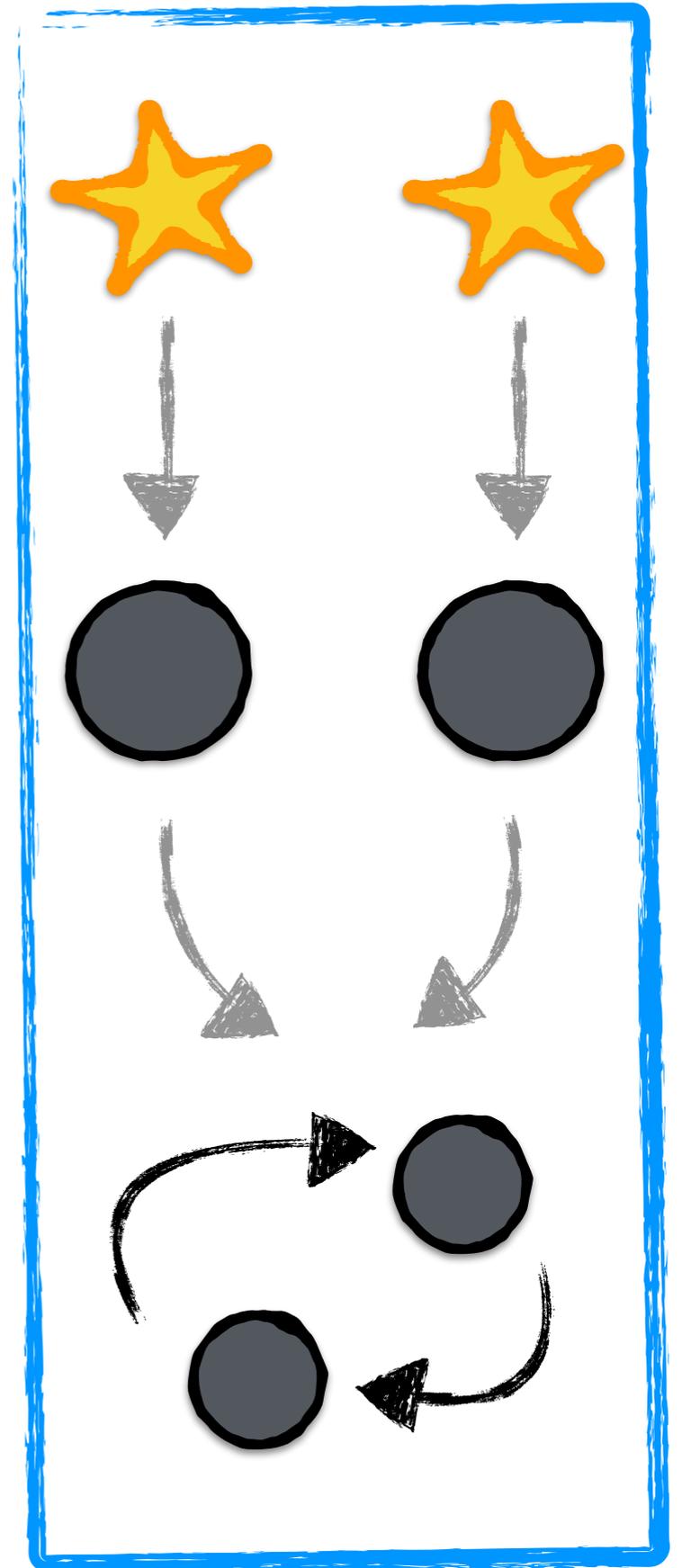**Relativity** alone cannot explain the LIGO events, we need some **astrophysics**
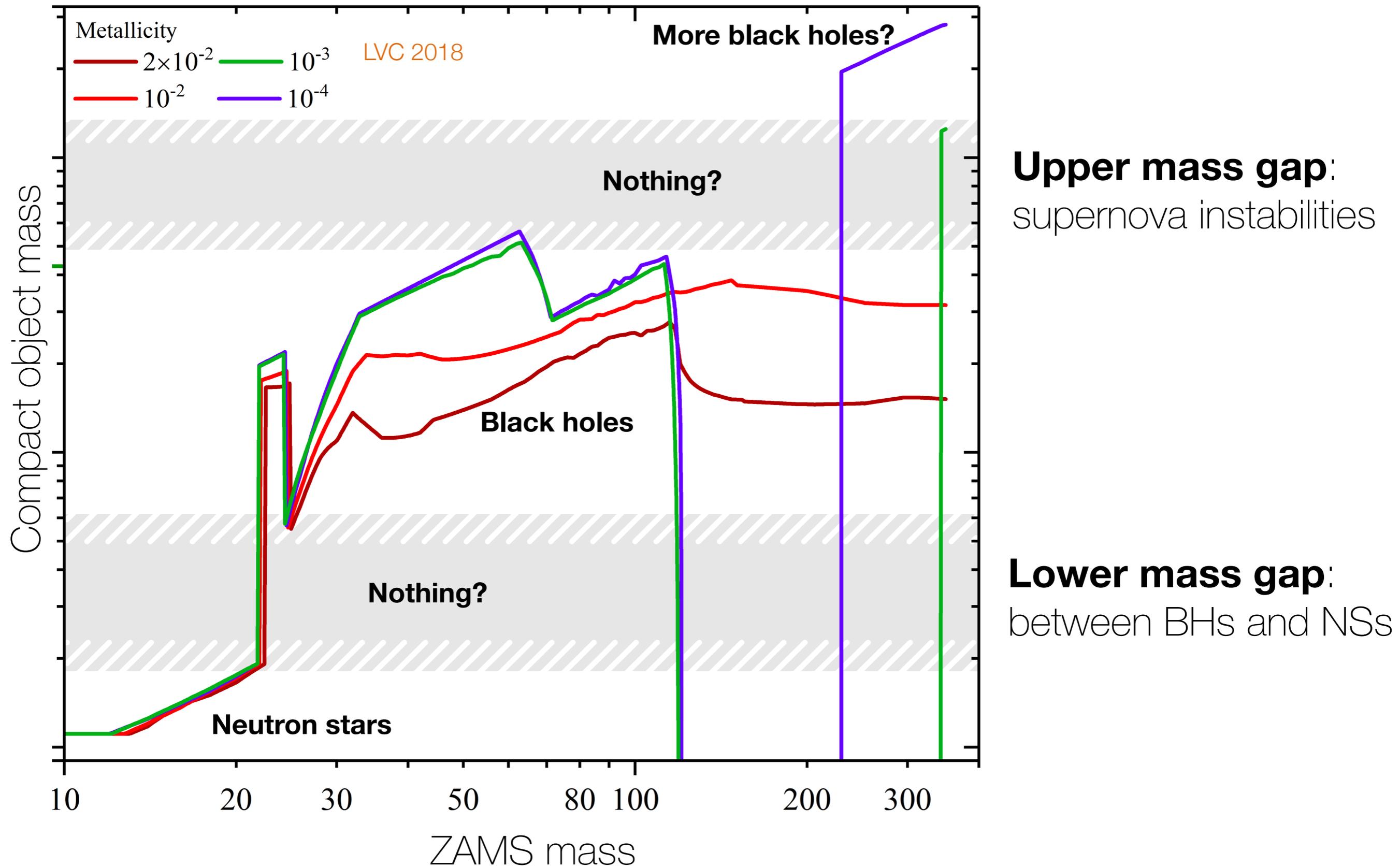
Have we been together for so long?

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

Don't you remember? We just met in cluster

Mass predictions: the gaps

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

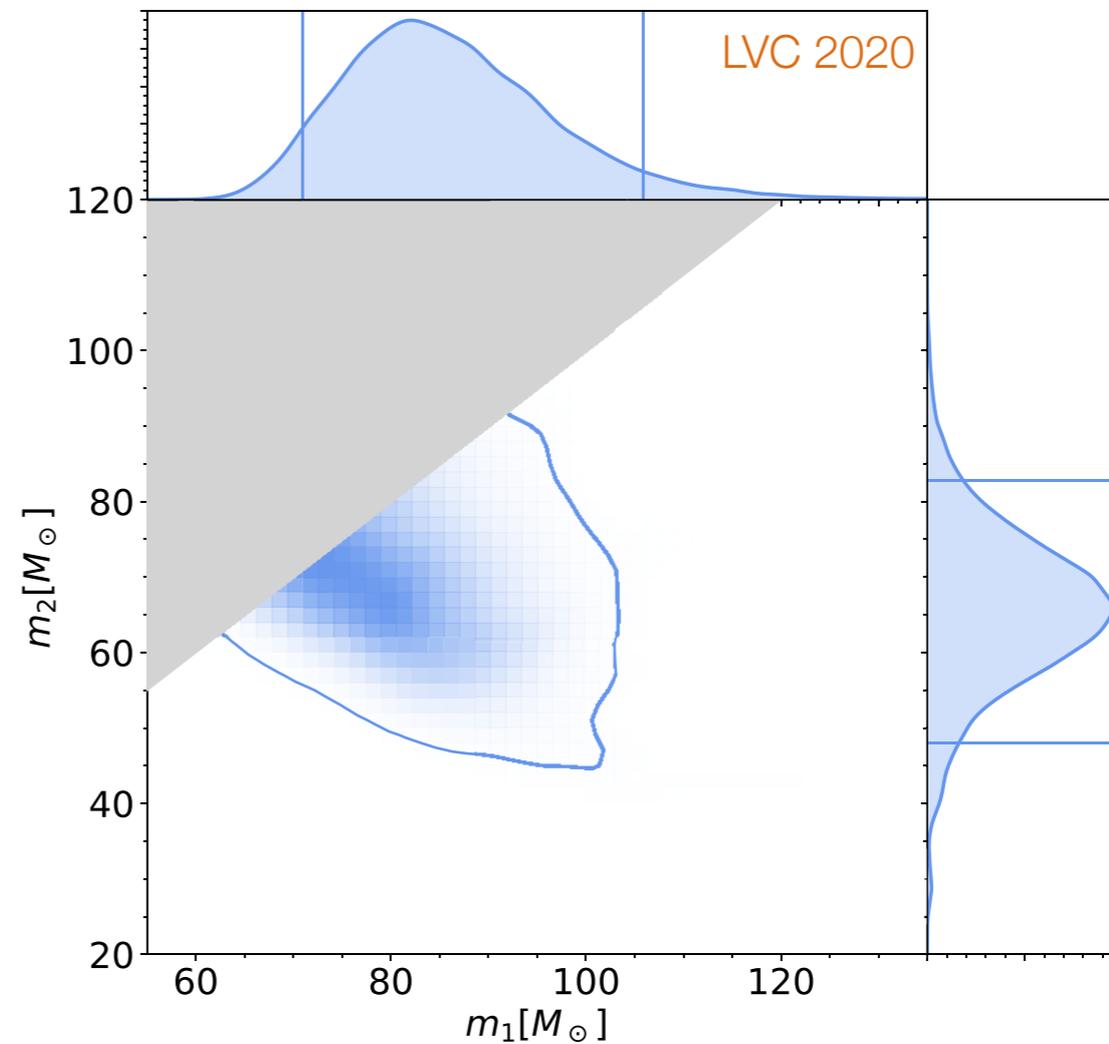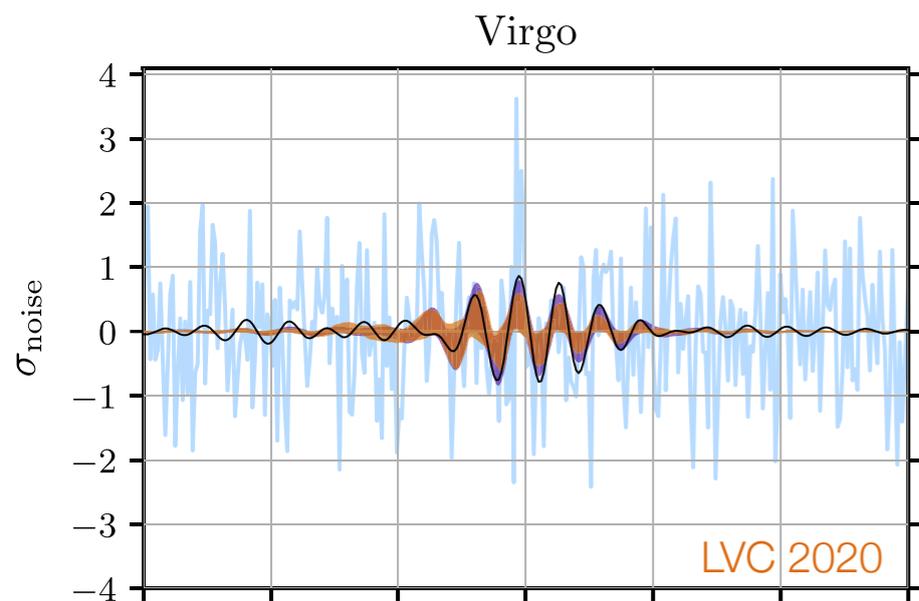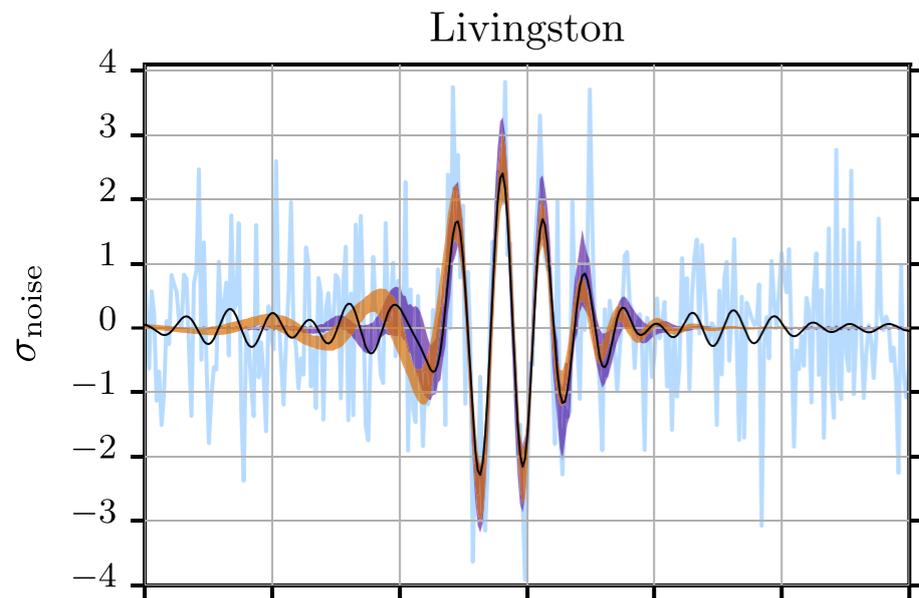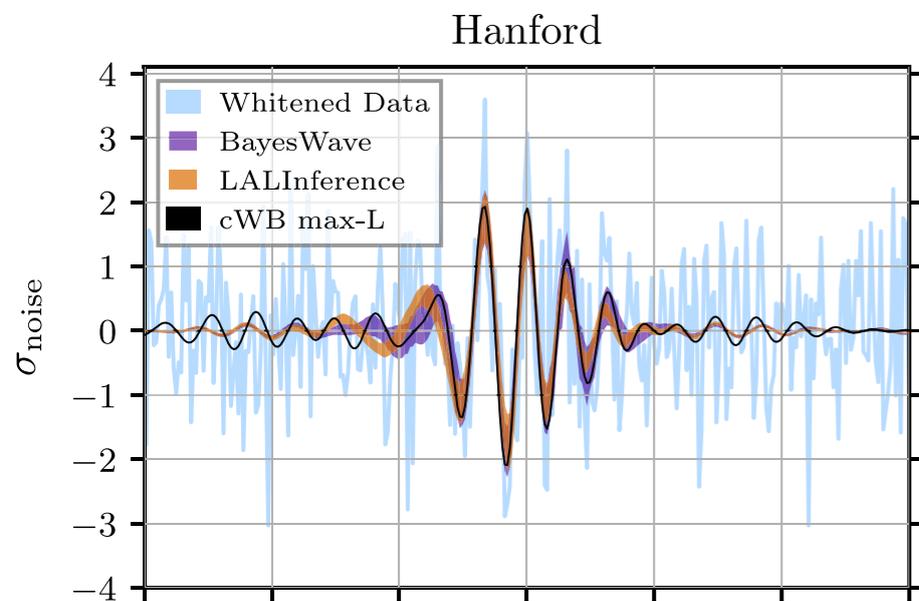BH forbidden for
$$M \gtrsim 50 M_\odot$$
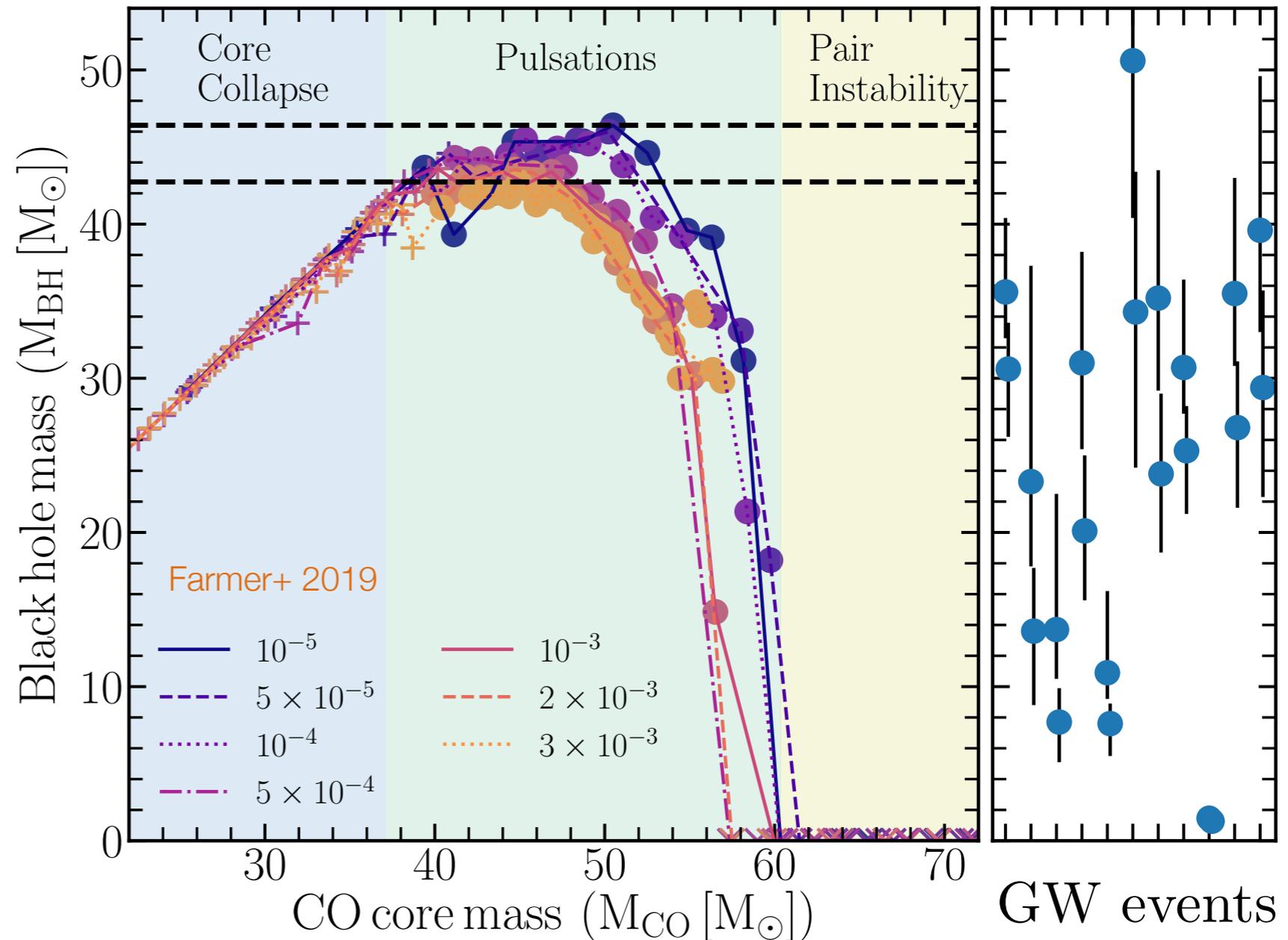
This limit is very solid…
Farmer+ 2019, Renzo+ 2020
…until it isn't
Belczynski+ 2019, 2020, Farmer+ 2020, Costa+ 2021, Farag 2022
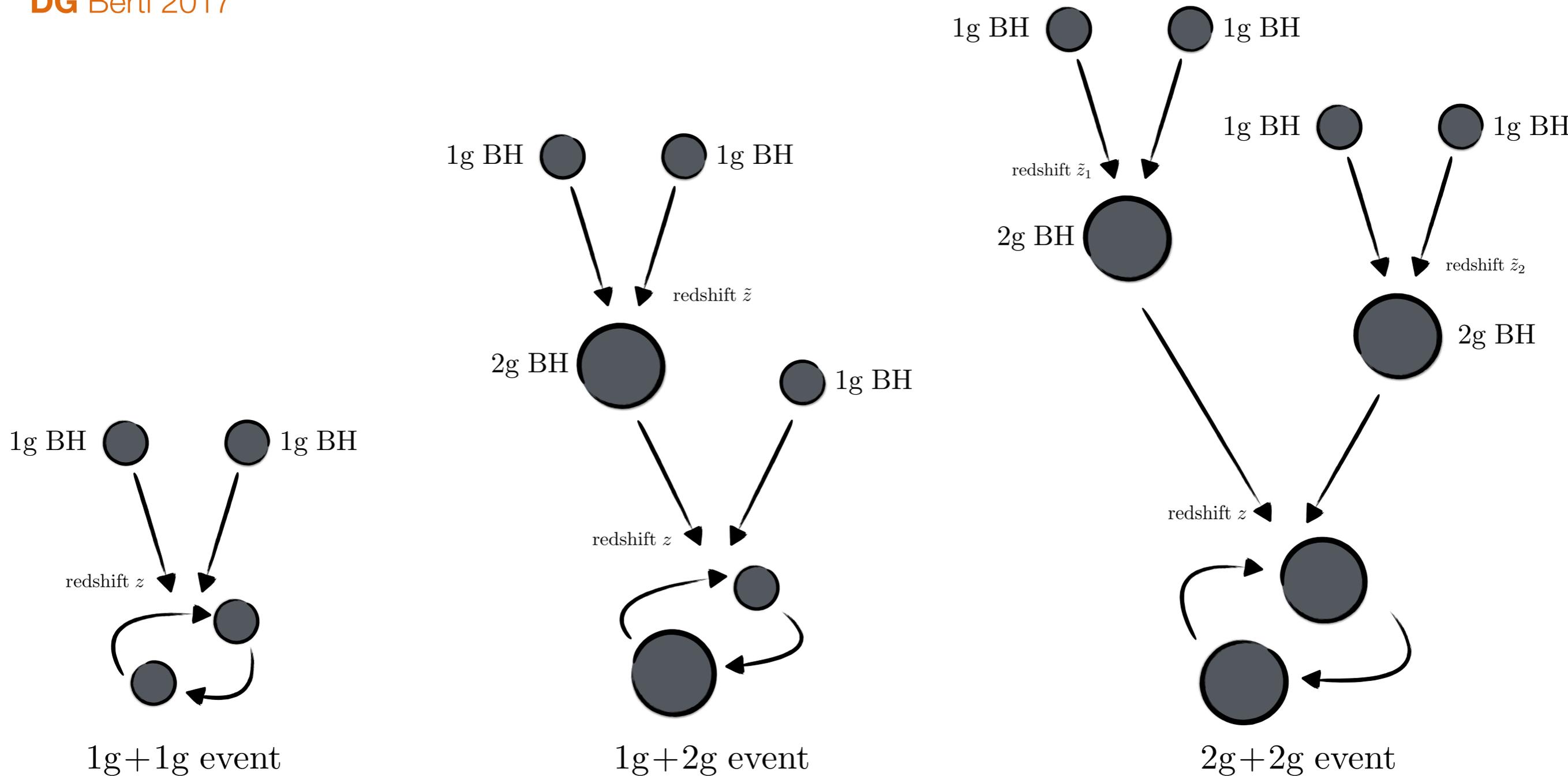

Can we bypass stars and use black holes?

GW190521.
Who ordered that?

An extremely confident detection of black holes with ~65 M$_\odot$ and ~85 M$_\odot$

Black hole generations

1g+1g event

1g+2g event

2g+2g event

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

Black hole generations

Da Berti 2017

1g BH, 1g BH

redshift $\tilde{z}_1$

2g BH

1g BH, 1g BH

redshift $\tilde{z}_2$

2g BH

1g B

redshift z

2g+2g event

Earlier this morning...

Unsolved Problem 1: How Do Planetesimals

"collisions"

"gravi...
coll...
(of s...

Bottom up

Top...
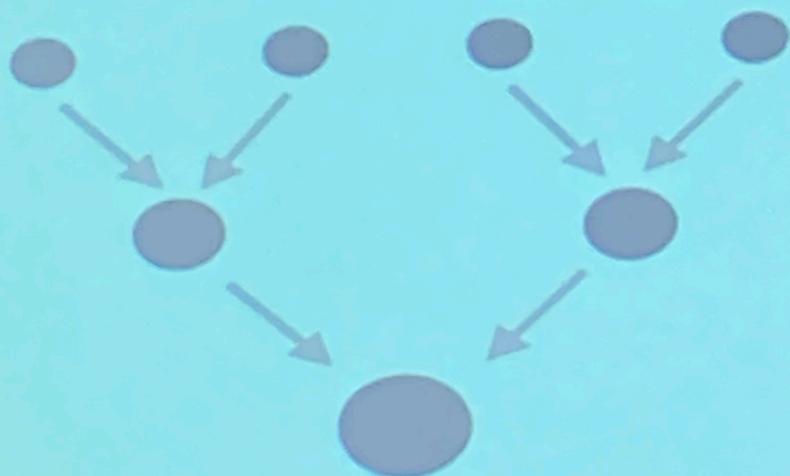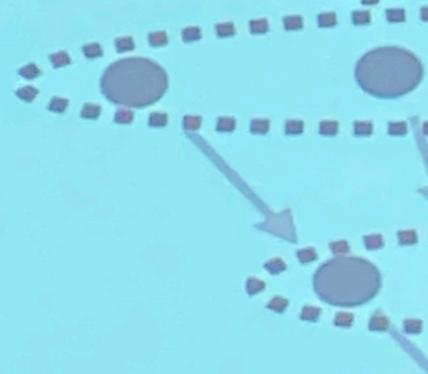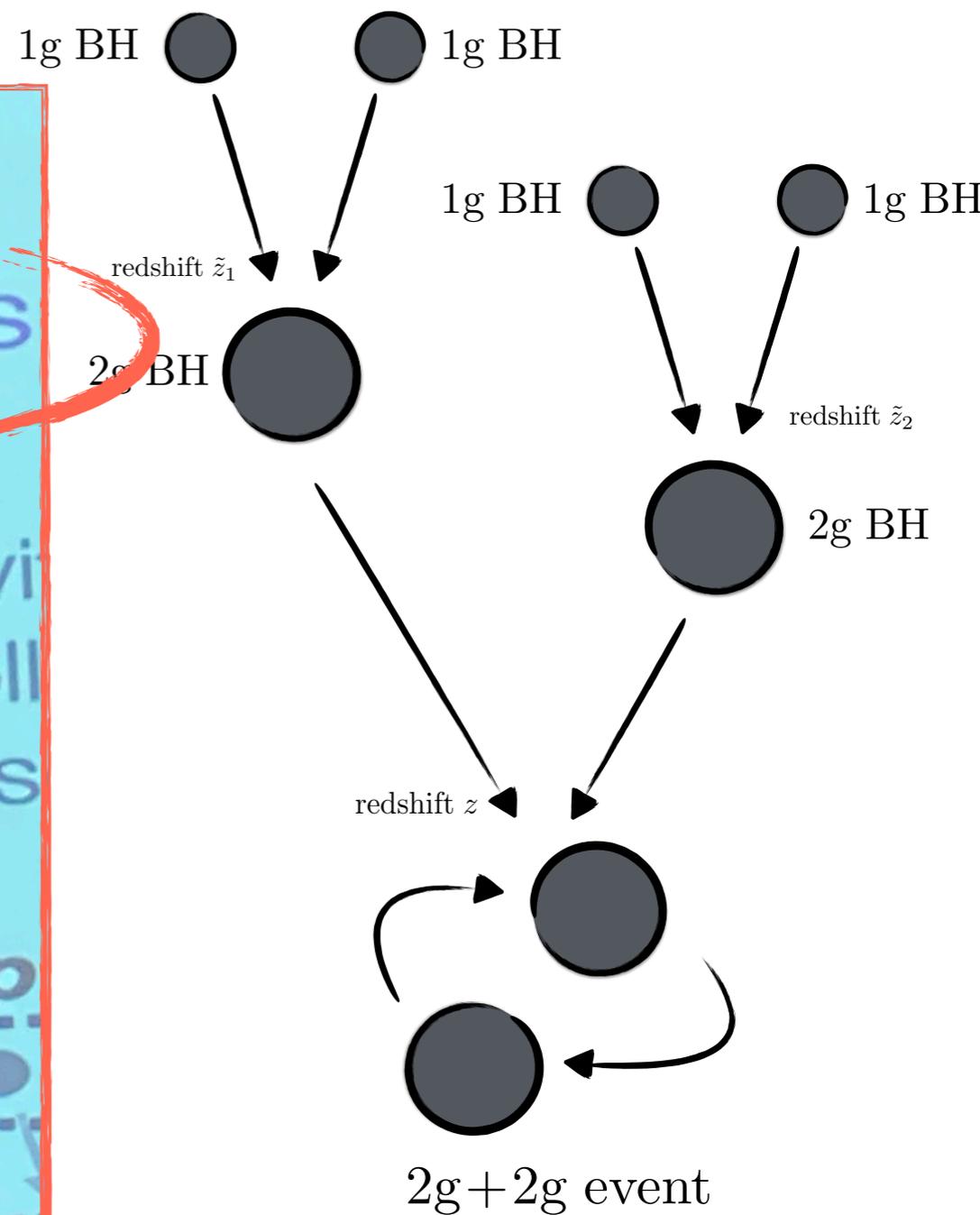
...ary, direction
...ate

Spins: the magic number

Orbital hang-up

S1 L S2

S

S1 L S2

S

Peculiar spin distribution peaked at **0.7**

Primary's spin

Legend:
- 1g + 1g (blue)
- 1g + 2g (green)
- 2g + 2g (red)

n versus χ_1

Secondary's spin

n versus χ_2
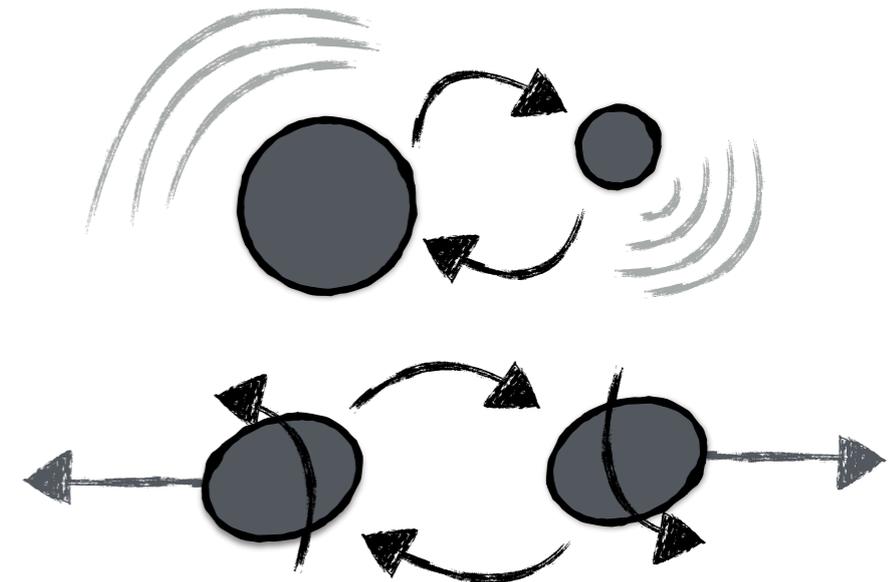
An explosion of new predictions
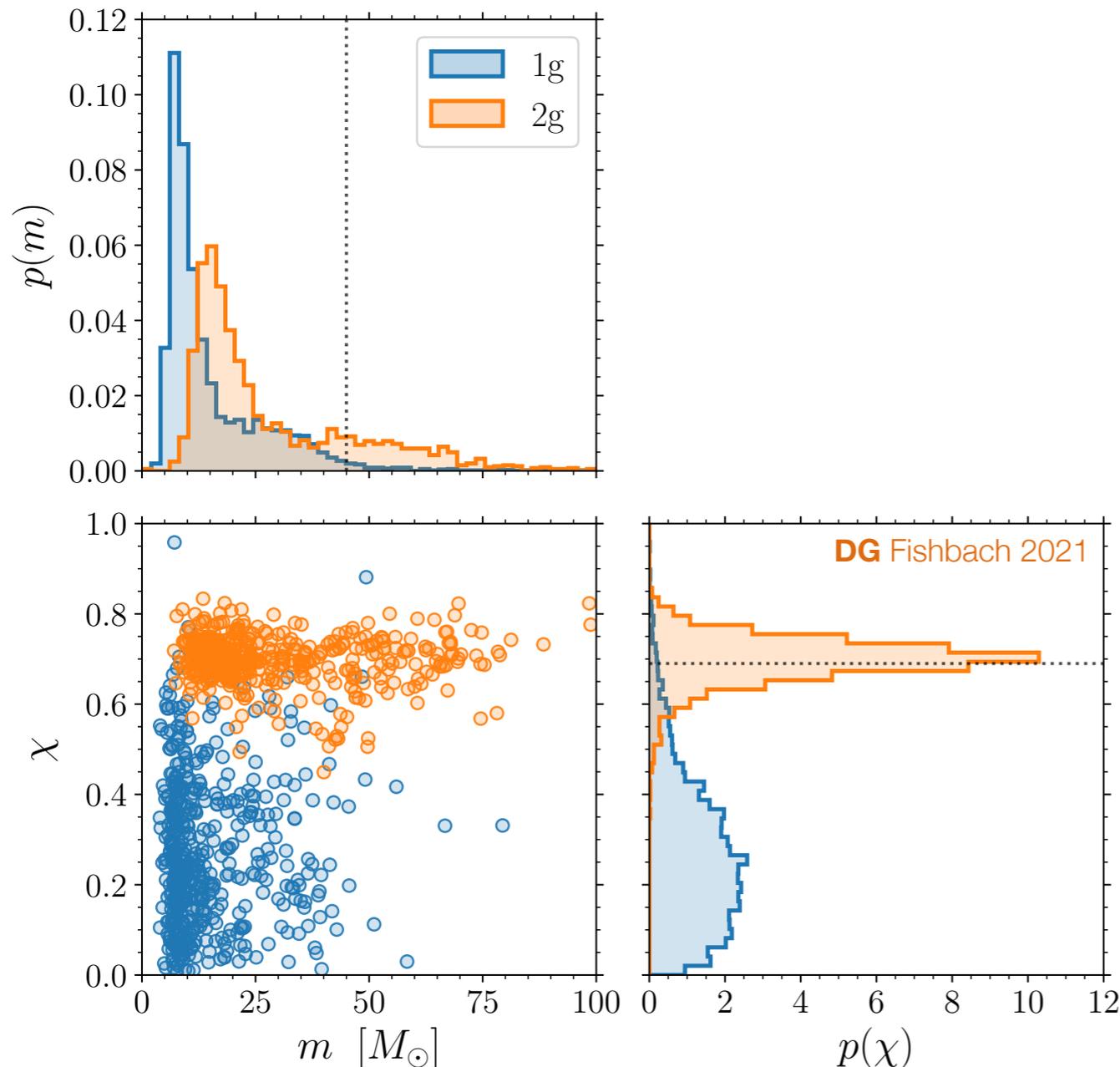
- Masses in the pair-instability mass gap
  Heger+ 2003, Woosley+ 2007
- Peculiar spin distribution peaked at 0.7
  DG Berti 2017, Fishbach+ 2017
- GW kicks require large escape speed
  DG Berti 2019
- Very frequent in AGNs
  Yang+ 2019, Tagawa+ 2020
- Promising for GW190412
  DG Vitale Berti 2020, Rogriguez+ 2020
- Leading explanation for GW190521
  LIGO/Virgo 2020
- Several events in the LIGO catalog?
  Kimball+ 2021
- An exclusion region…
  DG Giacobbo Vecchio 2020, Baibhav, **DG**+ 2020
- Don't overdo it!
  Zevin Holz 2022
- Used to prototype a deep-learning pipeline
 Mould **DG** Taylor 2022

And many more! Enough for a dedicated review **DG** Fishbach 2021

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

$t = -1063M$

$q = 0.5$
$\chi_1 = [0.8, 0, 0]$
$\chi_2 = [-0.8, 0, 0]$
$v_k = 1153 \text{ km/s}$

$z \; [M]$

$x \; [M]$ $y \; [M]$

DG+ 2018
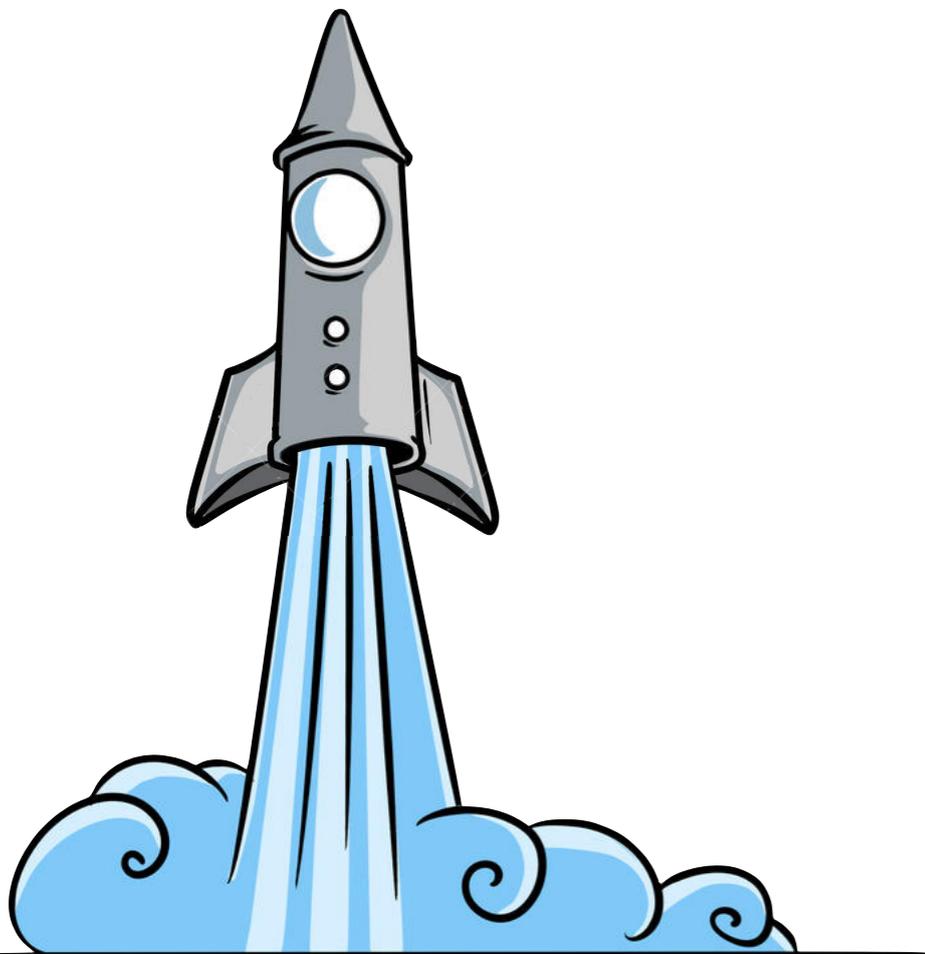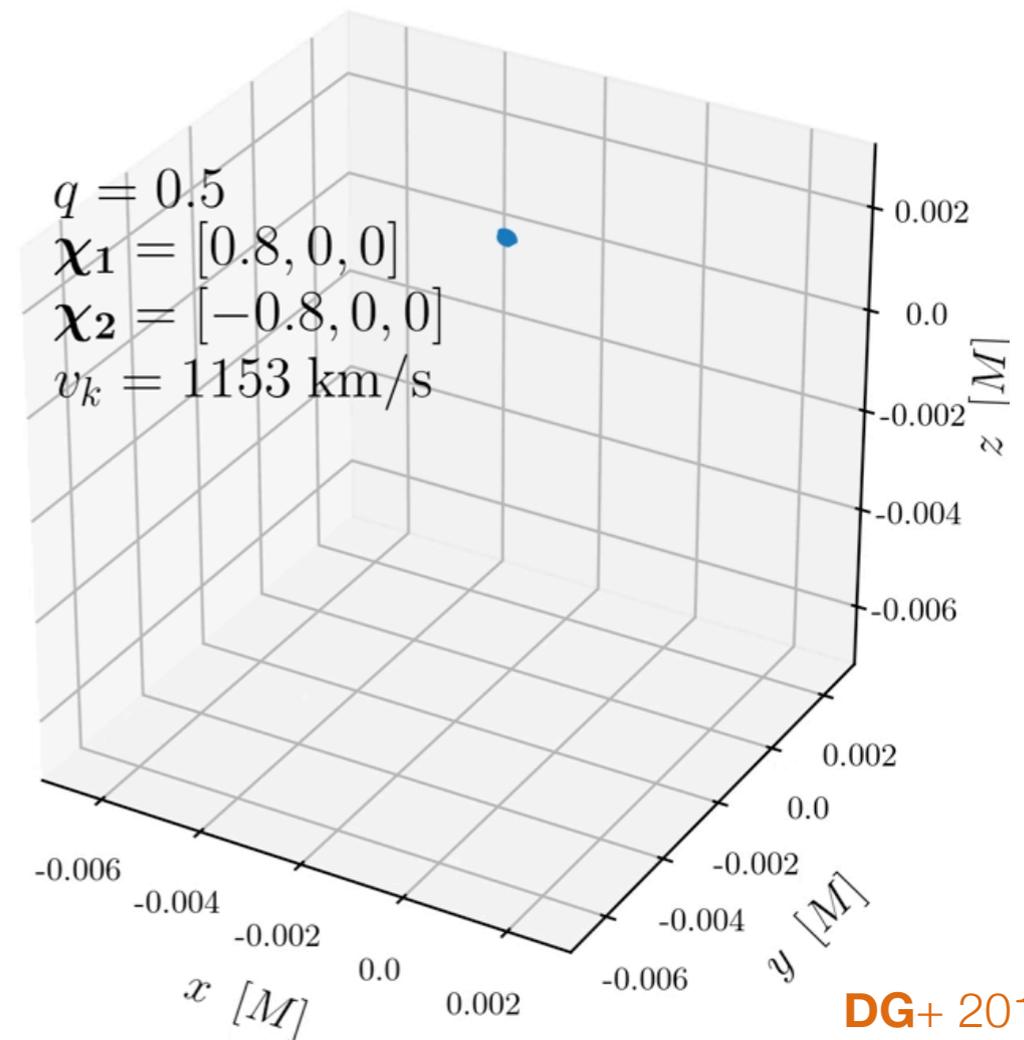
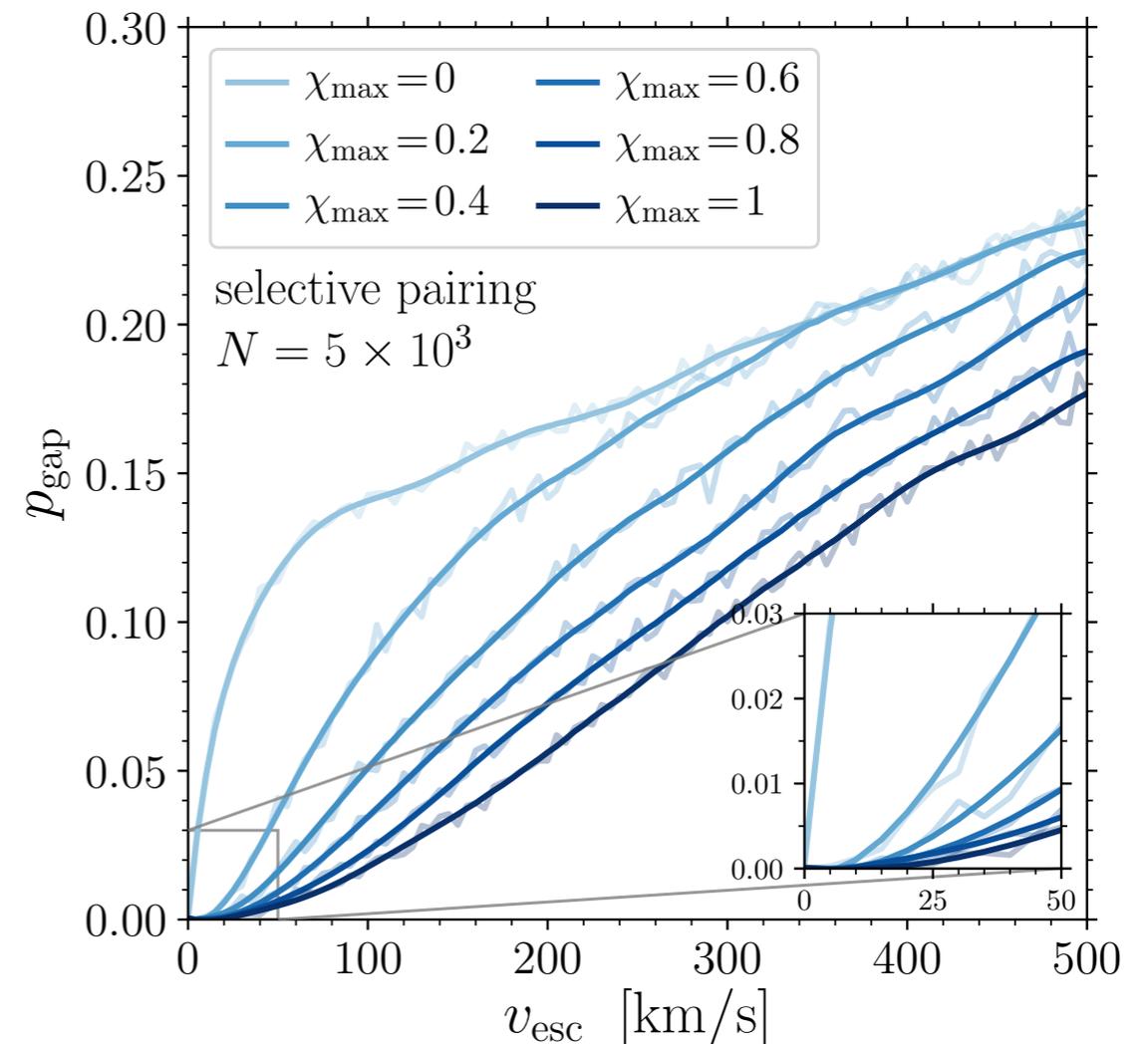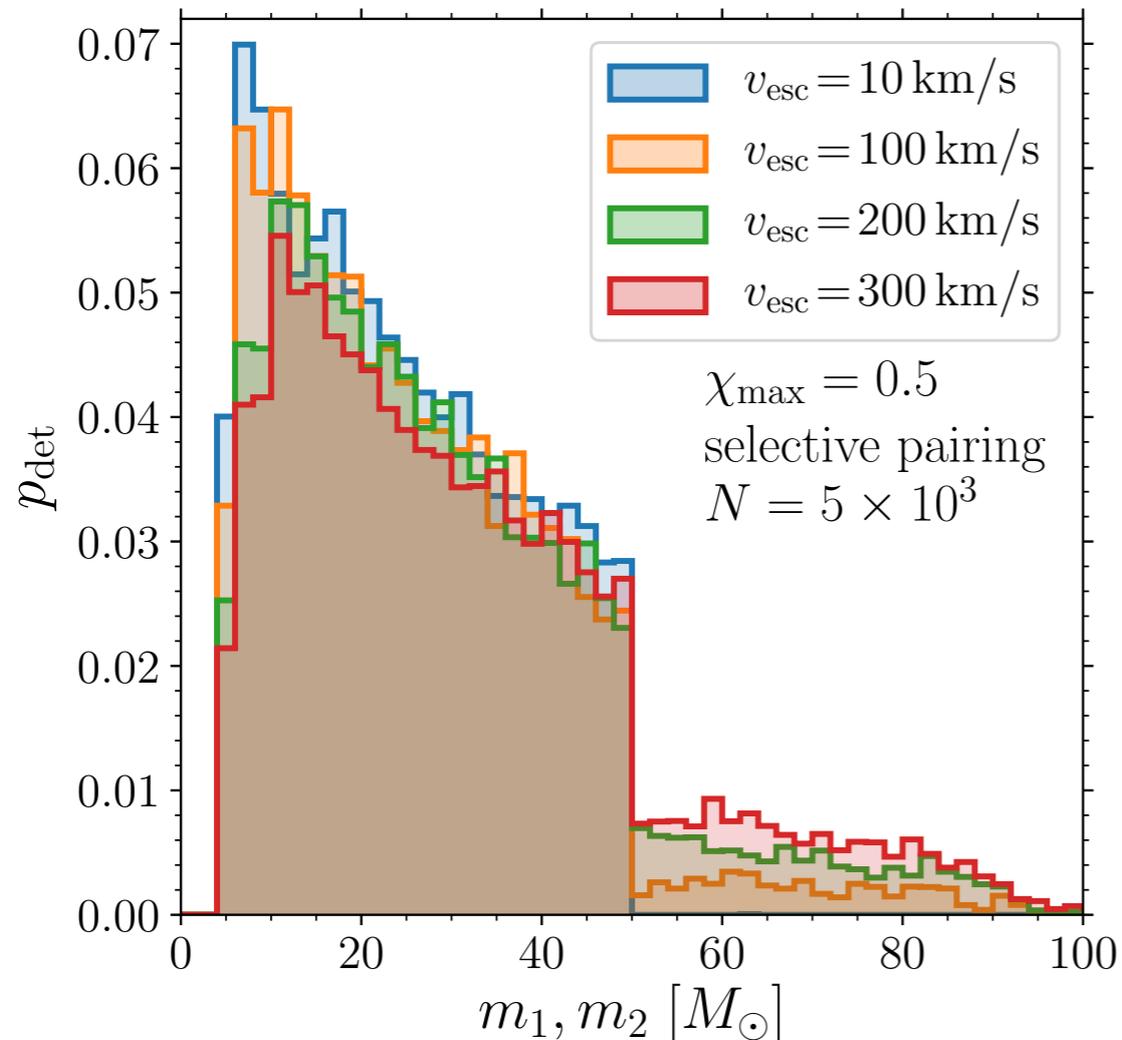# The role of the escape speed

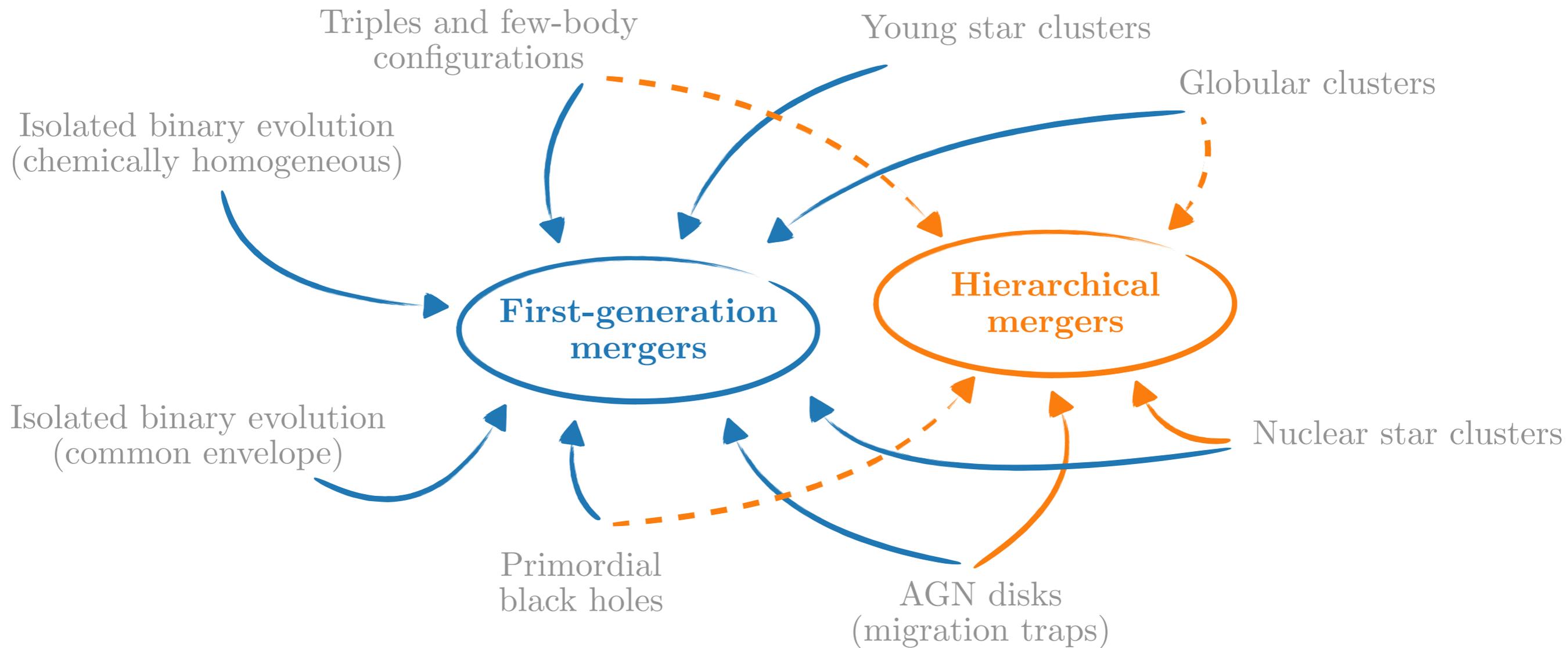An escape speed of ~50 km/s is necessary to populate the mass gap

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

Where do hierarchical black-hole mergers come from?

DG Fishbach (2021)

The gaps are precious
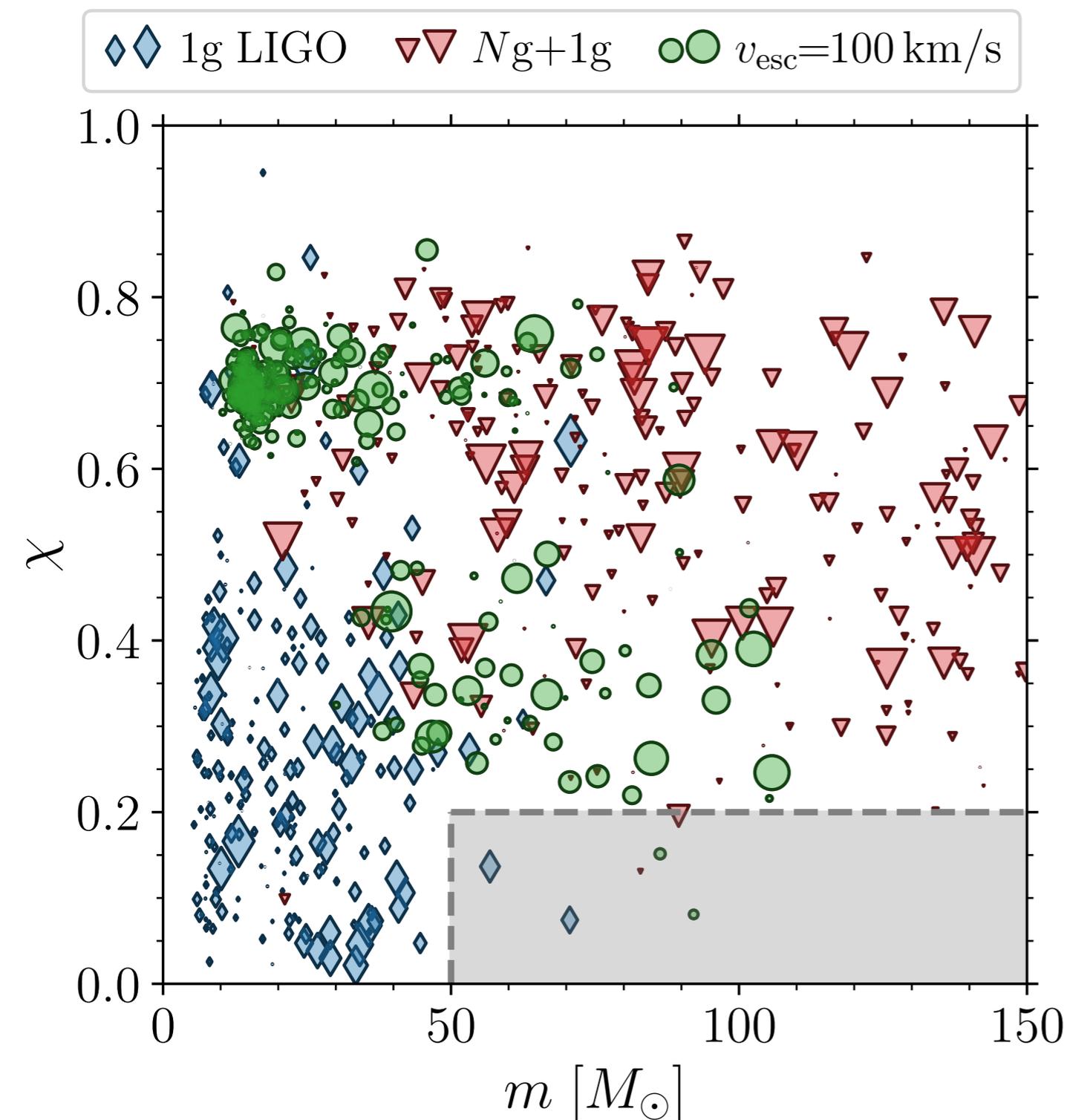
- Two channels "field" and "cluster": $N = N_{\text{field}} + N_{\text{cluster}}$

- Some are in the gap: $N = N_{\text{no gap}} + N_{\text{gap}}$

- The gap is exclusive: $N_{\text{field,gap}} = 0 \qquad N_{\text{cluster,gap}} = N_{\text{gap}}$

- A predicted efficiency: $\lambda \equiv \dfrac{N_{\text{cluster,gap}}}{N_{\text{cluster}}}$

- Individual contributions:

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

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, Farag+ 2022
- 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
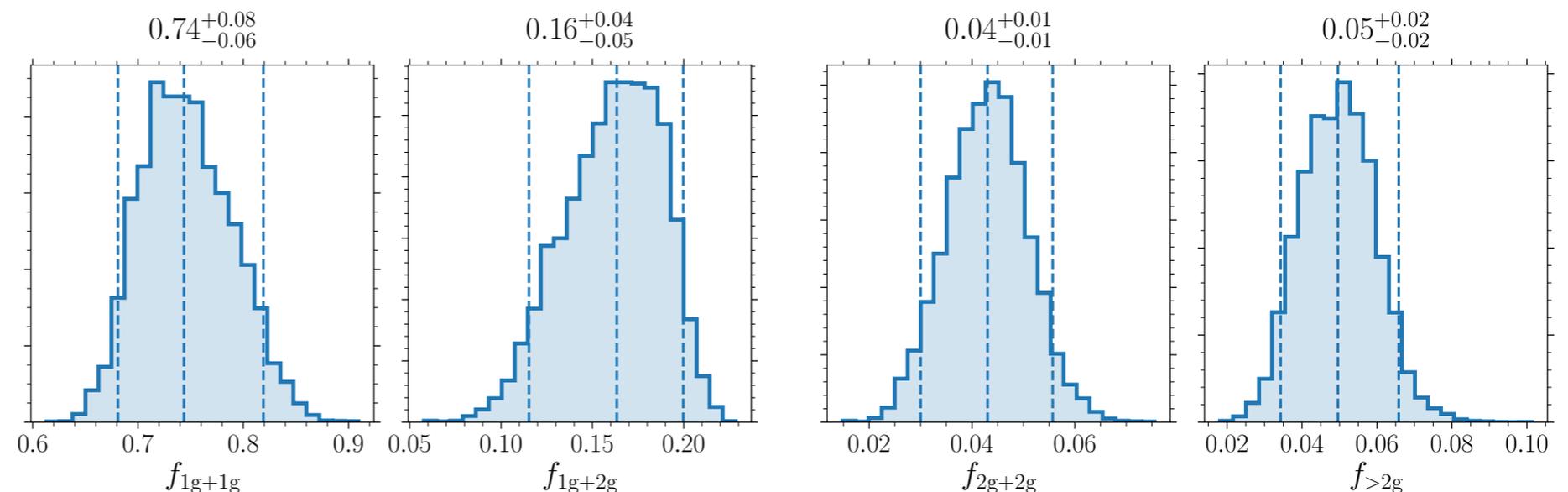 e.g. Farrell et al. 2020, Kinugawa et al. 2021

Here comes deep learning

Mould, **DG**, Taylor 202

Consistently includes hierarchical mergers when fitting the data?
Awesome but the population is not analytic anymore.

- Cluster-inspired training simulations
- FFT-based KDEs
- Neural network **~70k parameters**
- Selection-effect modeling
- Hierarchical Bayesian analysis with nested sampling
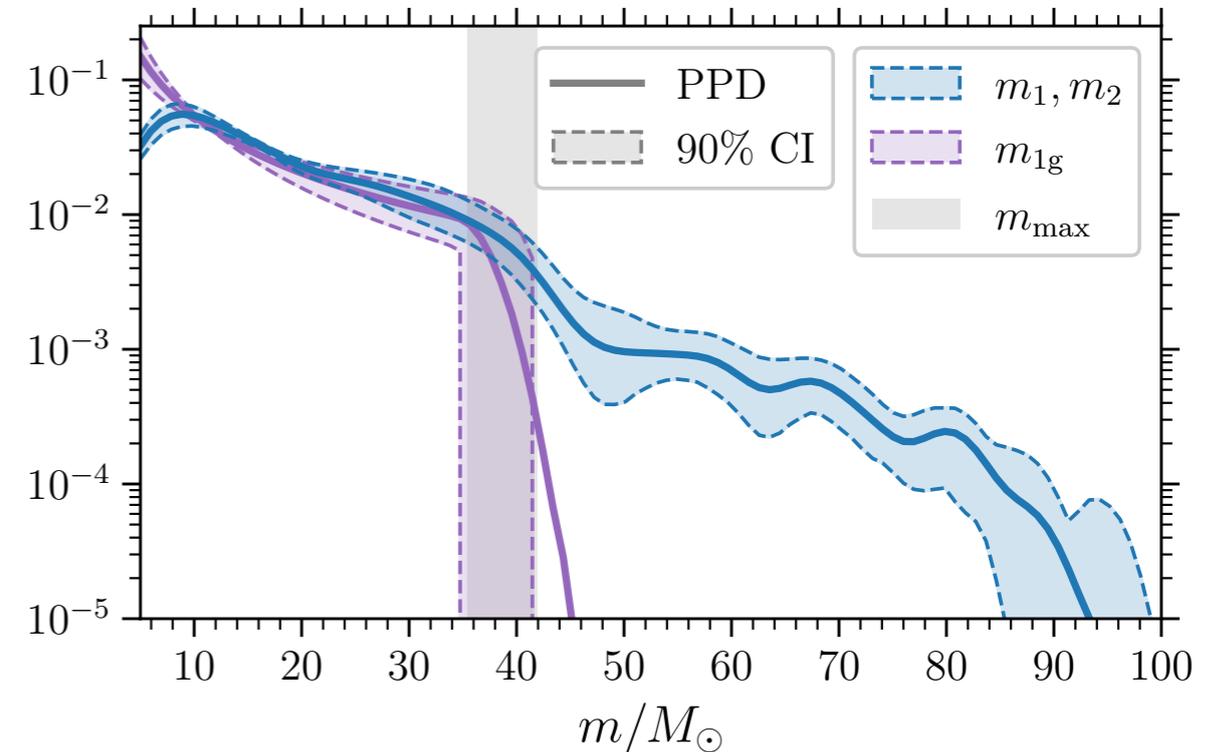
- **We can tell the generations apart!**
- Additional structure <u>in the gap</u> due to higher generations

Please ask for more!

$0.74^{+0.08}_{-0.06}$ $0.16^{+0.04}_{-0.05}$ $0.04^{+0.01}_{-0.01}$ $0.05^{+0.02}_{-0.02}$

$f_{\mathrm{1g+1g}}$ $f_{\mathrm{1g+2g}}$ $f_{\mathrm{2g+2g}}$ $f_{\mathrm{>2g}}$
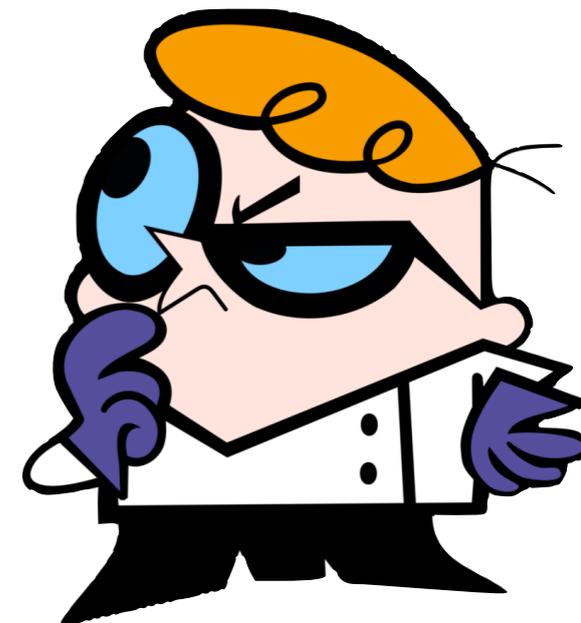
Why I think repeated mergers are exciting!

Remember that

gravitational waves = relativity + astrophysics
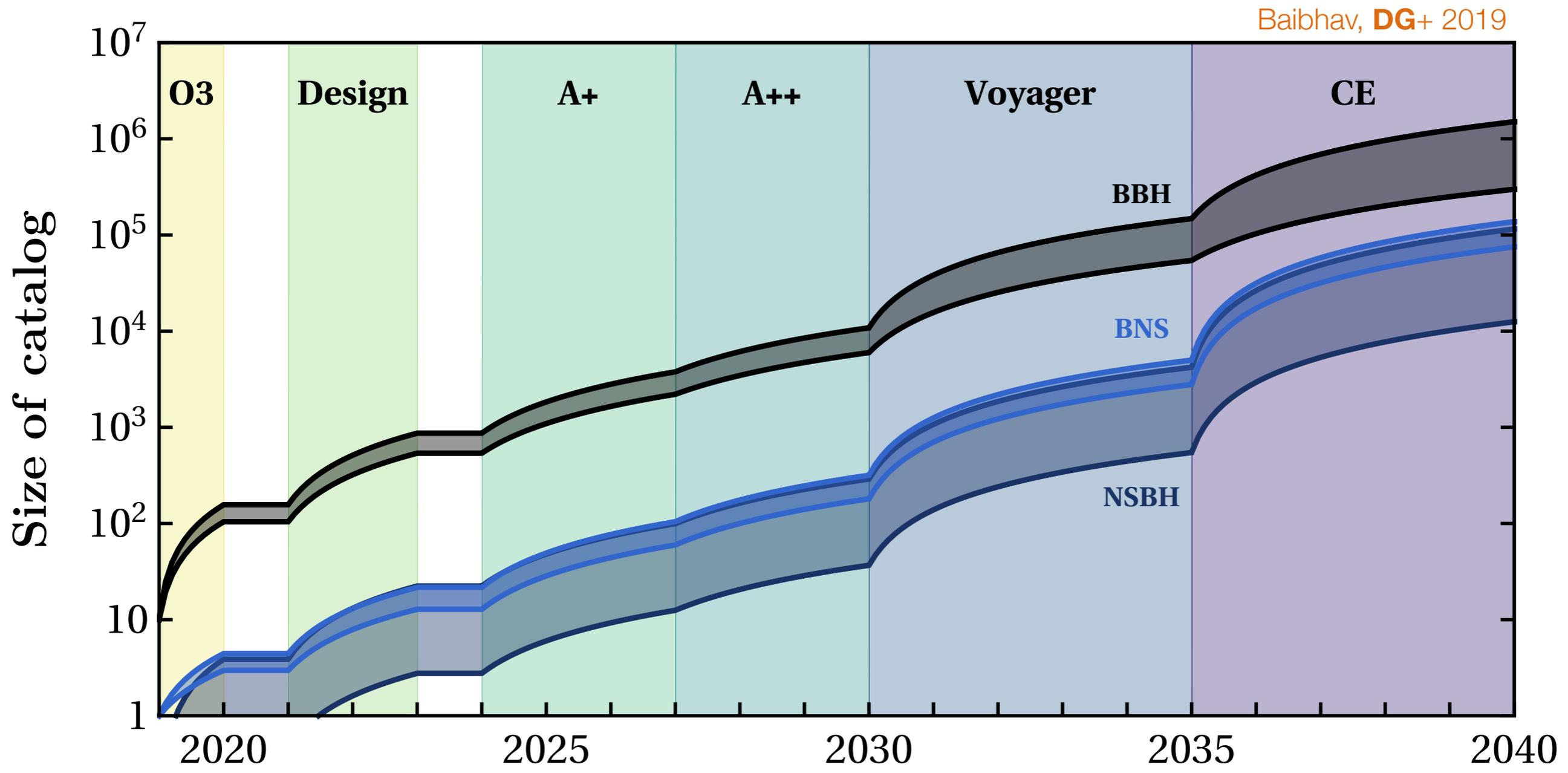
Relativity is clean, astrophysics is dirty…
… but relativity is "vacuum", astrophysics is full of stuff to discover

Hierarchical mergers largely rely on **relativity** while providing key insights on the underlying **astrophysics**
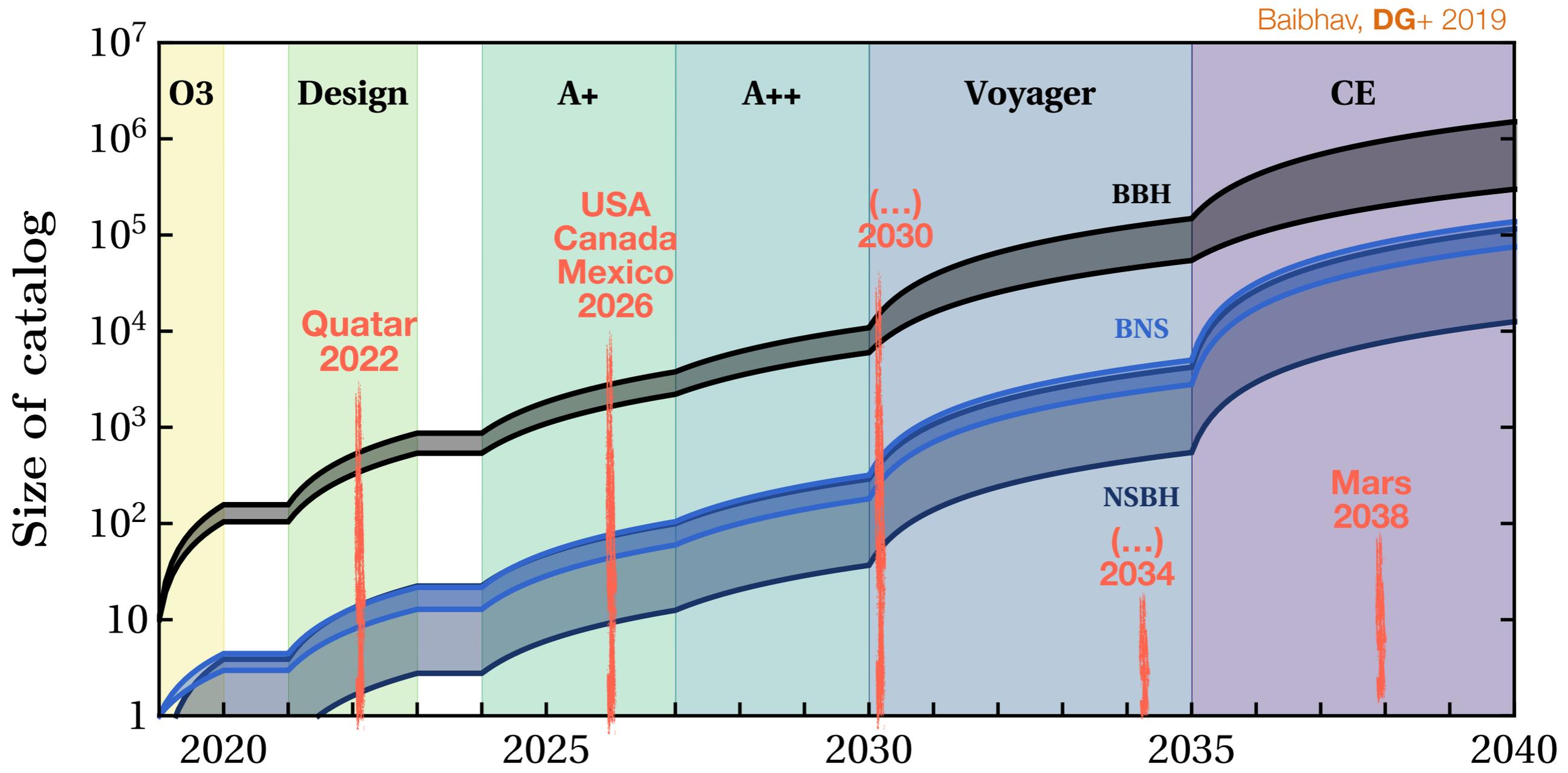
Toward the next football world cup…

- Large statistics: details emerging at the **population** level
- Many events means **rare outliers**

Baibhav, **DG**+ 2019

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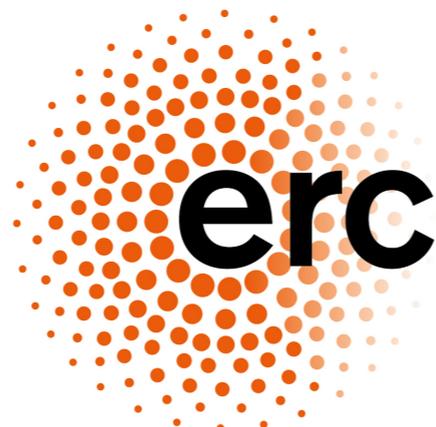

Baibhav, **DG**+ 2019

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