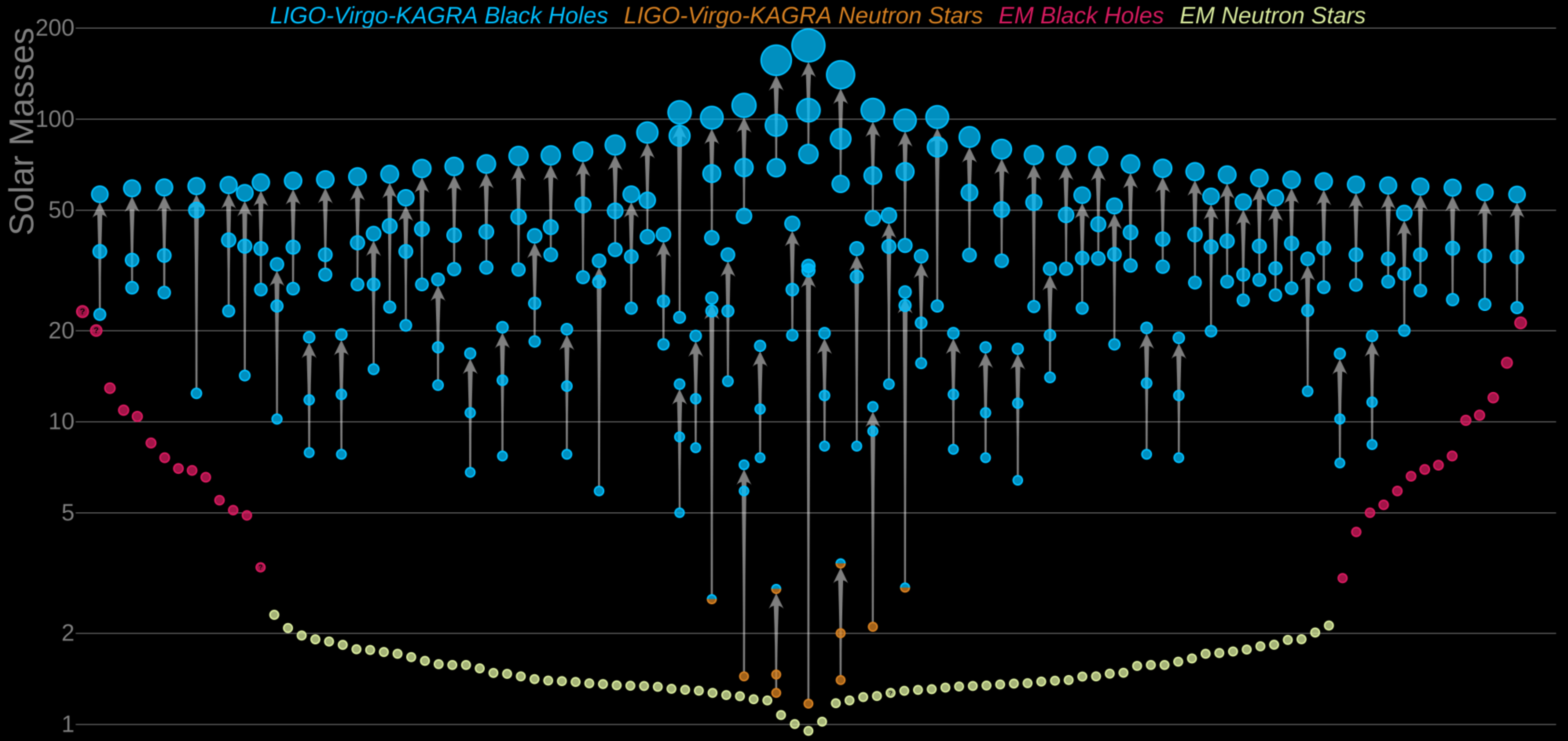
Binary black hole mergers in young star clusters

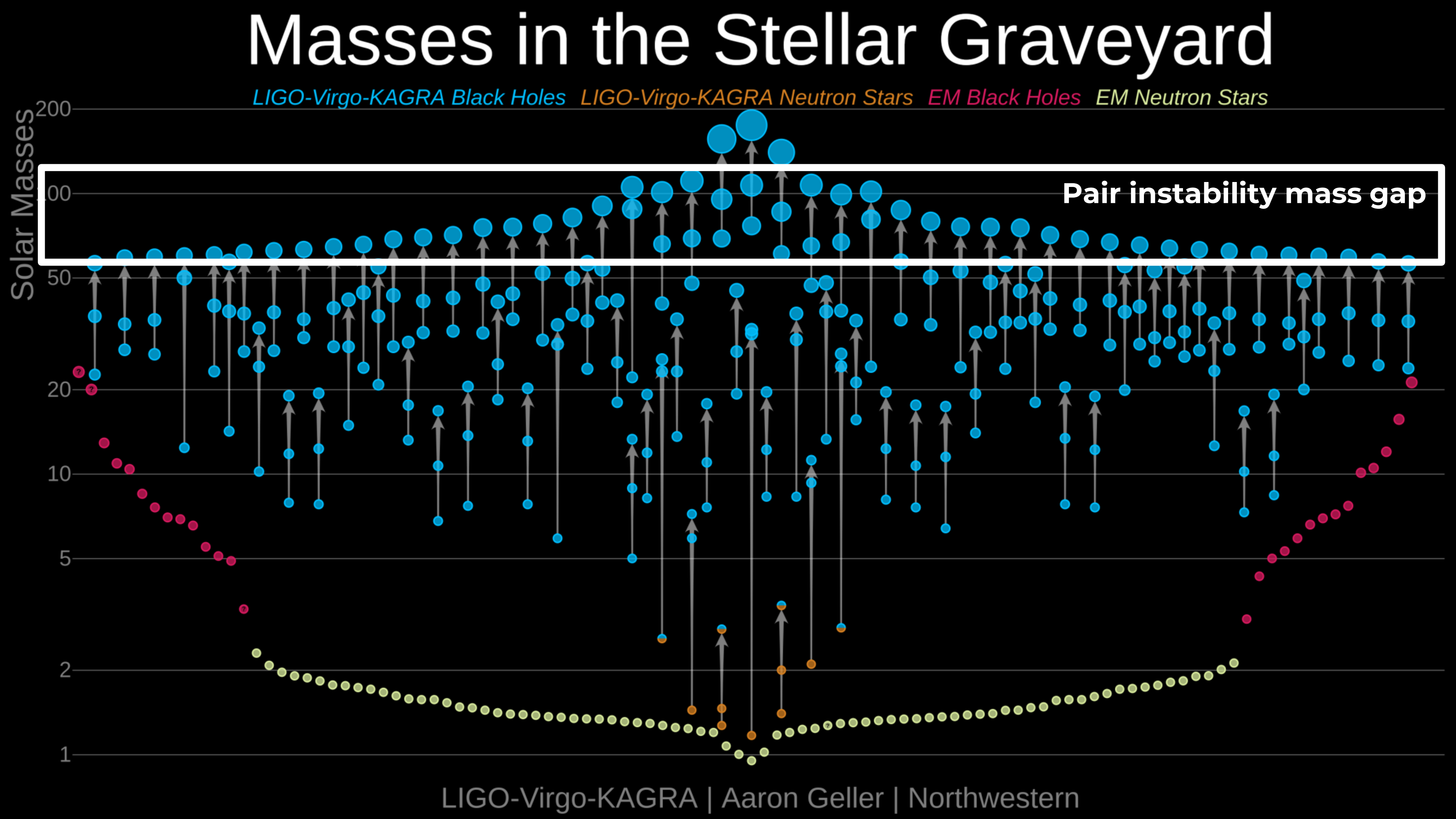
Stefano Torniamenti

Main collaborators: M. Mapelli, S. Rastello, A. Ballone, M. Dall'Amico, U. N. Di Carlo

Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
Pair instability mass gap
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Formation channels of BBHs

LIGO-VIRGO O3: ~ 90 objects interpreted as the mergers of binary black holes (BBHs).

A few hundreds of GW detections might be sufficient to disentangle the main **formation pathways** of BBHs (Fishbach et al. 2017; Gerosa & Berti 2017; Bouffanais et al. 2019, 2020, 2021).

Isolated formation

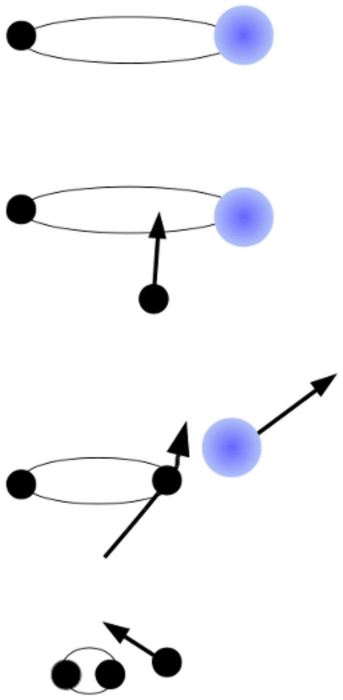
- $m_1 \lesssim$ 40−65 $\mathrm{M}_{\odot}$,
- mostly equal-mass systems ($q = m_2/m_1 \approx$1),
- mostly aligned spins,
- zero eccentricity in the LVC band.

Dynamical formation in star clusters

- larger m_1,
- mass ratios: $0.1 \lesssim q \lesssim$1,
- isotropic spin distribution,
- non-zero eccentricity in the LVC band (rare but not negligible).

Formation channels of BBHs

Dynamical interactions can favor the coalescence of BH binaries through dynamical hardening, and the formation of new BBHs via dynamical exchanges.



Credits: Michela Mapelli

Dynamical formation in star clusters

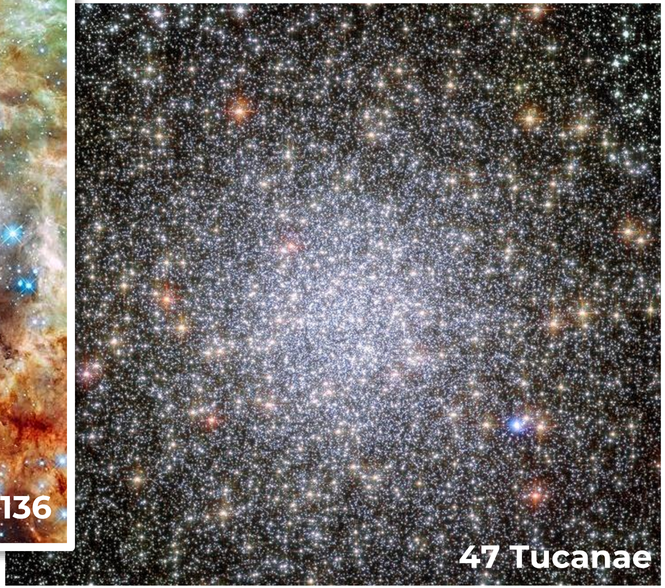
- larger m_1,
- mass ratios: $0.1 \lesssim q \lesssim 1$,
- isotropic spin distribution,
- non-zero eccentricity in the LVC band (rare but not negligible).

Dynamical formation in star clusters

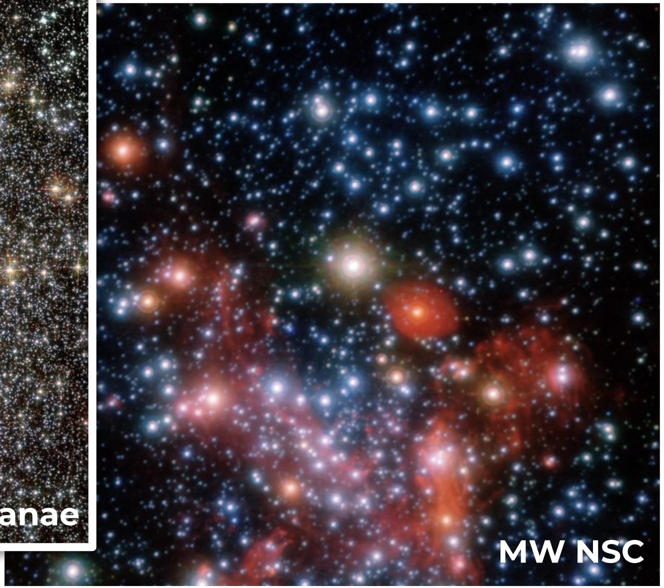
Dynamics are important only in dense environments:

$$\rho > 10^3 \; stars \; pc^{-3}$$

Young star clusters



Globular clusters



Nuclear star clusters

Credits: NASA - NASA/ESA/HST - ESO

Young star clusters

Mass: $10^2 - 10^5\ \mathrm{M}_\odot$

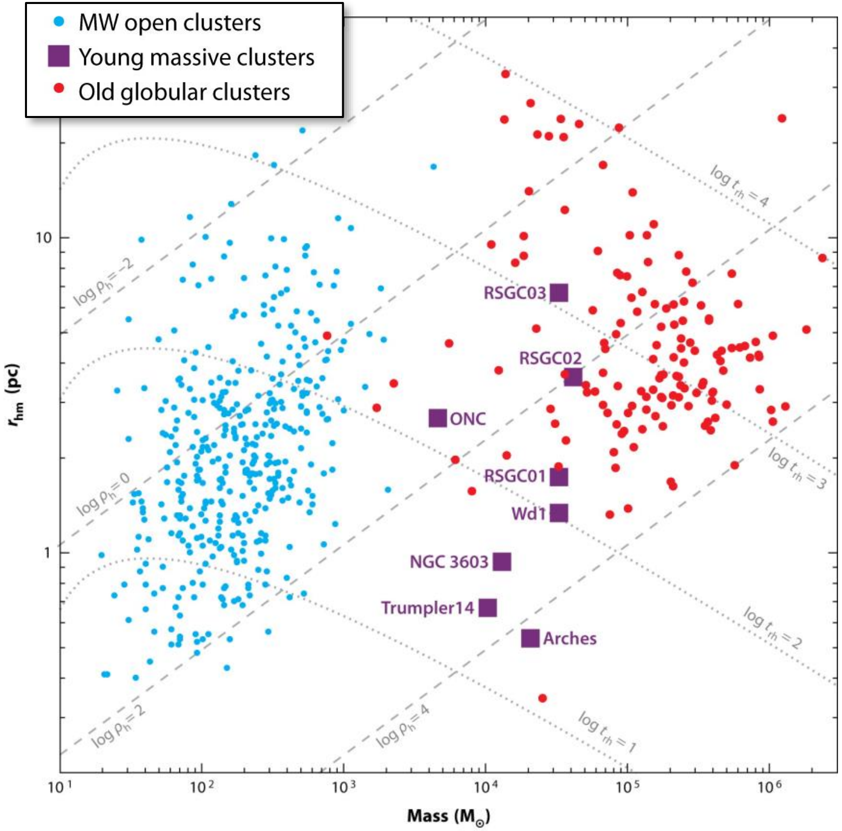
Age: $0 - 100$ Myr

- Nursery of most massive stars (Lada & Lada 2003), which mainly form in binary systems (Moe & Di Stefano 2017).

- Short evolution time scales: $t_{rlx} \sim 10 - 100$ Myr (Portegies Zwart et al. 2010).

- Massive stars sink to the YSC center and interact with each other in $\lesssim 3$ Myr.

- Eventually disrupted by tidal interaction with the host galaxy.



Portegies Zwart et al. 2010

N-body simulations

NBODY6++GPU (Wang et al., 2015, 2016) & **MOBSE** (Giacobbo et al., 2018, Giacobbo & Mapelli 2018, 2019)

Initial conditions

Fractal initial conditions (Di Carlo et al., 2019).

Half-mass radius: $0.5\ \mathrm{pc} < r_{hm} < 2\ \mathrm{pc}$.

Two sets of star-clusters (Lada & Lada, 2003):

- **Low-mass clusters**:

$$500\ \mathrm{M}_{\odot} < M_{SC} < 800\ \mathrm{M}_{\odot}$$

- **High-mass clusters**:

$$5000\ \mathrm{M}_{\odot} < M_{SC} < 8000\ \mathrm{M}_{\odot}$$

Observation-based (Sana et al. 2012, Moe & Di Stefano 2017) populations of stars and binaries **(Torniamenti et al., 2021).**

Metallicity: Z=0.002.

The star clusters are evolved up to 1.5 Gyr.

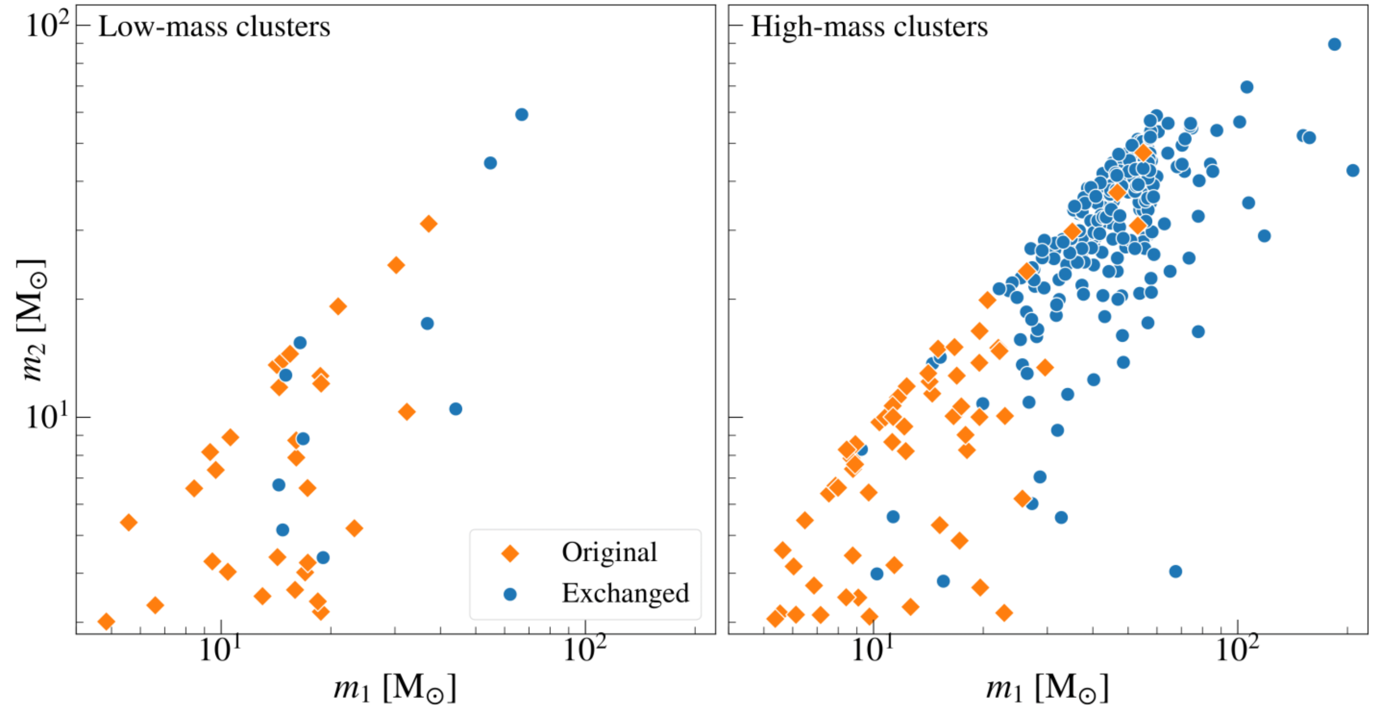
This work:

Compare the population of BBH mergers in low-mass and high-mass star clusters.

BBH mergers

BBHs that have merged during the simulation + BBHs that will merge within a Hubble time (Peters 1964).

Original: binaries bound since the origin of the cluster - **Exchanged:** formed trough dynamical encounters.



Low-mass clusters

- Most BBH mergers are original.

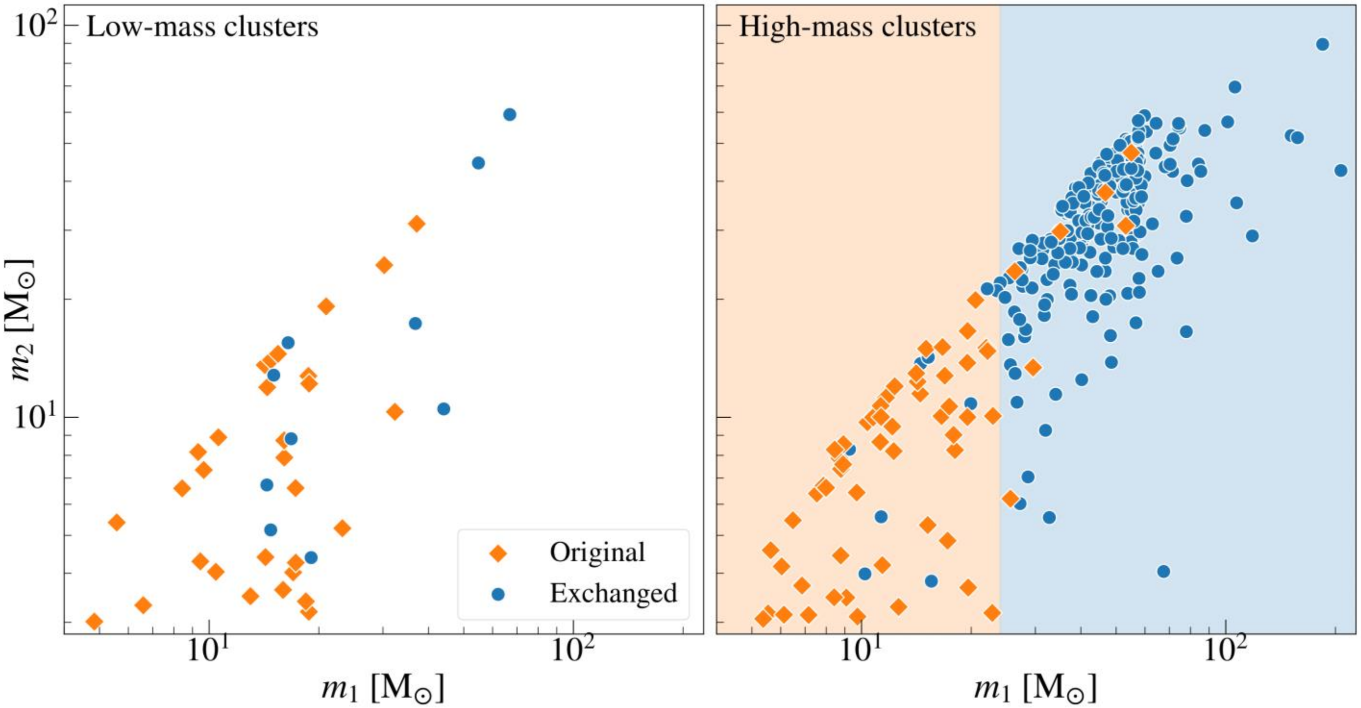
High-mass clusters

- Larger number (5x) of BBH mergers.
- 75% of BBH mergers are exchanged.

BBH mergers

BBHs that have merged during the simulation + BBHs that will merge within a Hubble time (Peters 1964).

Original: binaries bound since the origin of the cluster - **Exchanged:** formed trough dynamical encounters.



Original BBHs

Result of the hardening due to common envelope.

⇩

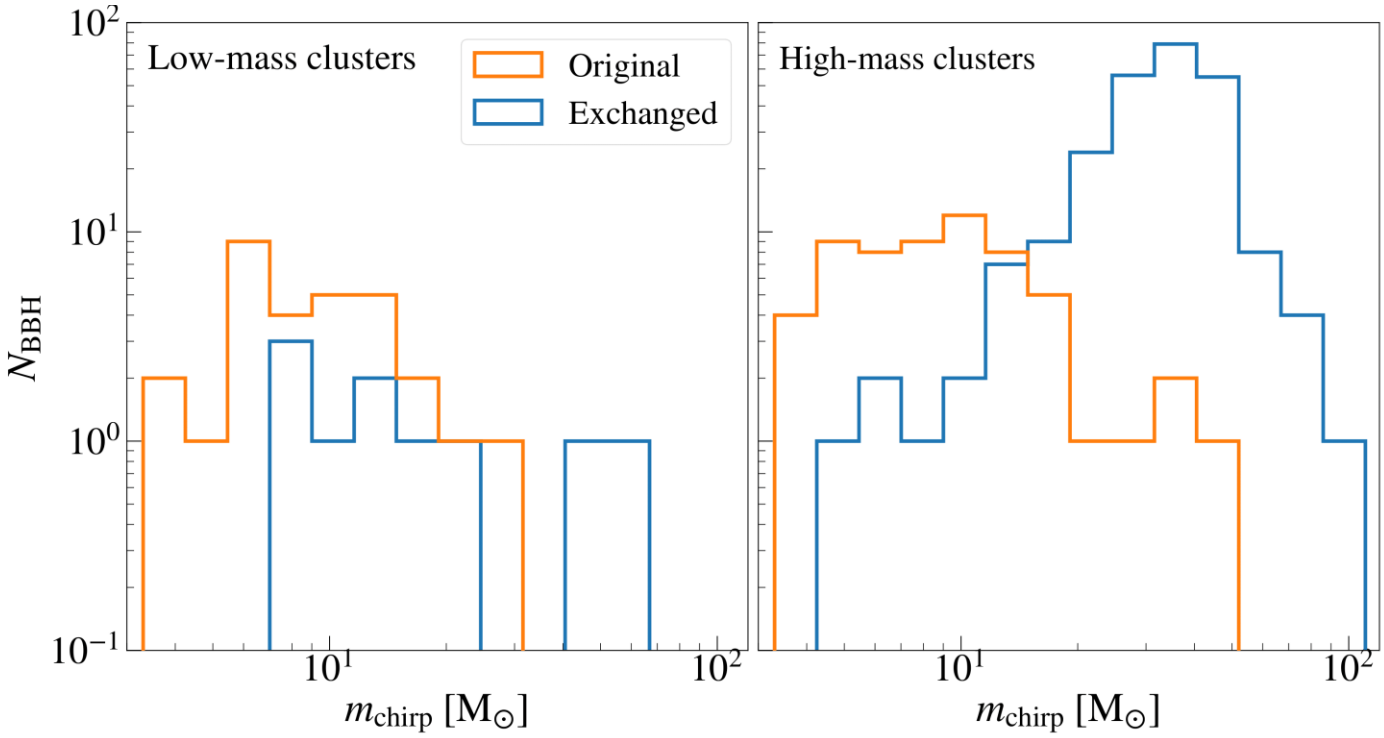
Common envelope: large mass loss

⇩

Smaller BH masses than the exchanged ones.

BBH mergers

BBHs that have merged during the simulation + BBHs that will merge within a Hubble time (Peters 1964).



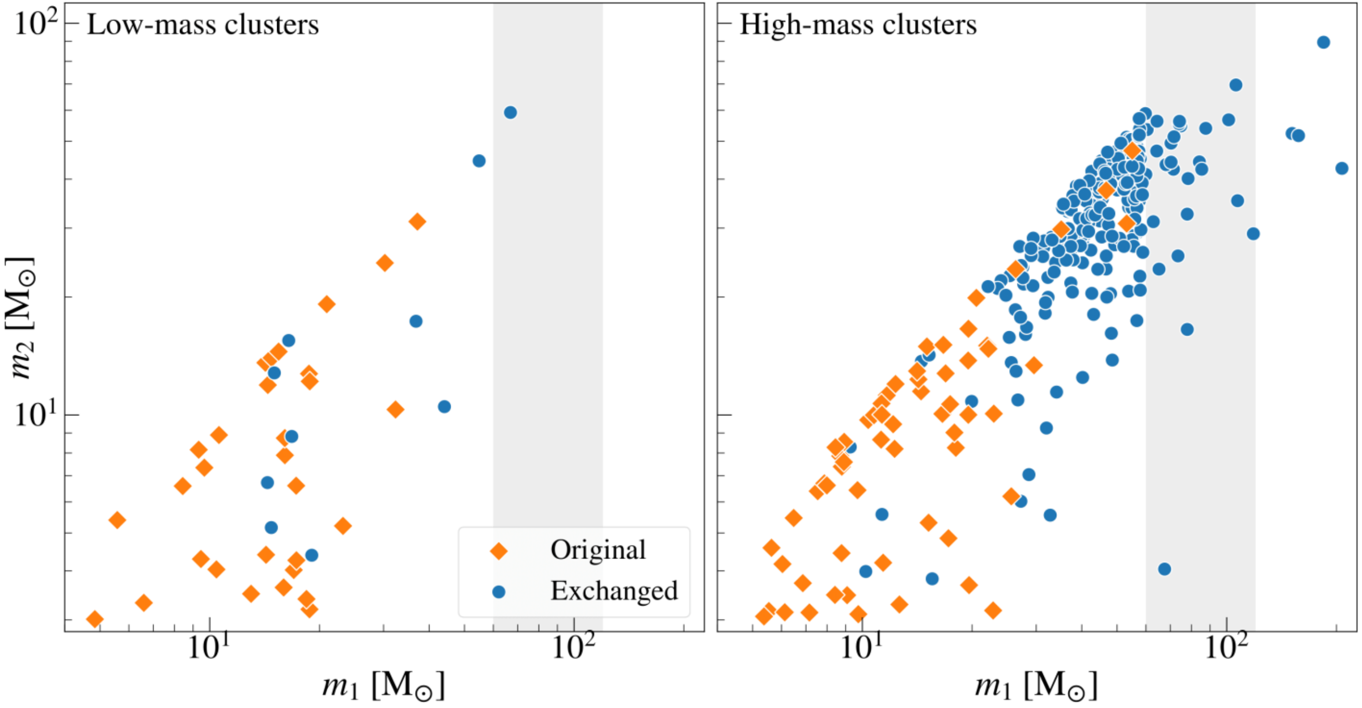
Chirp masses

$$m_{chirp} = \frac{(m_1\, m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Dynamical encounters trigger a large increase in the number of mergers with $m_{chirp} \sim 35 - 40\ M_\odot$.

BBH mergers

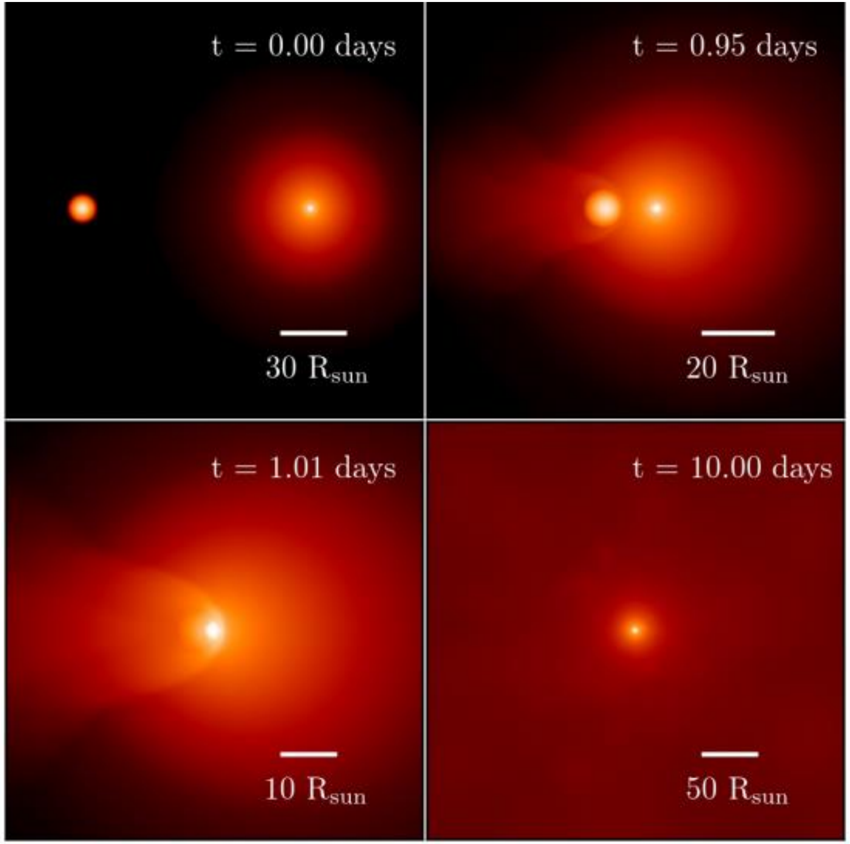
BBHs that have merged during the simulation + BBHs that will merge within a Hubble time (Peters 1964).



High-mass clusters

- 15% of BBH mergers produce a IMBH remnant ($m_{tot} \geq 100$ M$_\odot$)
- 8% of BBHs have m_1 in the PI mass gap.
- In the 8 most massive cases: $m_1 \geq 100$ M$_\odot$.

BHs in the PI mass gap

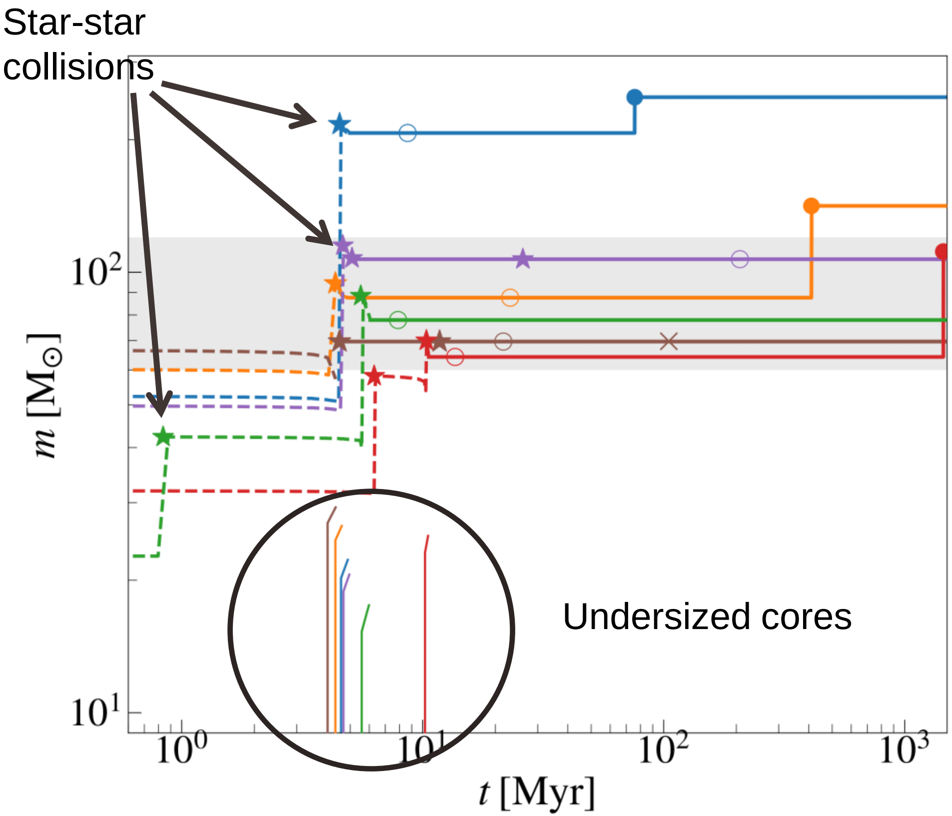


BHs in the PI mass gap can form from stellar mergers

- Merger product: exotic star, with an undersized He core with respect to the hydrogen-rich envelope.
- Its central properties (temperature and density) do not fall within the PI regime (e.g., Renzo et al. 2020; Costa et al. 2021, 2022; Ballone et al. 2022).
- Eventually, the stellar product directly collapses into a BH with $m_{\rm BH} > 60~{\rm M}_\odot$ (see also Di Carlo et al. 2019, 2020).

Ballone et al. 2022, arXiv:2204.03493
Costa et al. 2022, arXiv:2204.03492

BHs in the PI mass gap



High-mass clusters

- All BBHs with primary mass in the PI mass gap born via stellar collisions.
- Stellar collisions: explain the formation of intermediate-mass black holes above the upper mass gap ($m_1 > 200$ M$_{\odot}$).

Take-home messages

Low-mass clusters:

- Most BBH mergers come from original binaries that undergo a common envelope phase.

High-mass clusters:

- Most BBH mergers are produced by dynamical encounters. These mergers have larger masses because they did not undergo a common envelope phase.
- Dynamical interactions produce a large number of mergers with $m_{\rm chirp} \sim 35 - 40\ \mathrm{M}_{\odot}$.
- A non-negligible number of BH in the pair-instability mass gap and of IMBHs form.
- All the BHs in the pair-instability mass gap result from star-star mergers.

Thank you for your attention