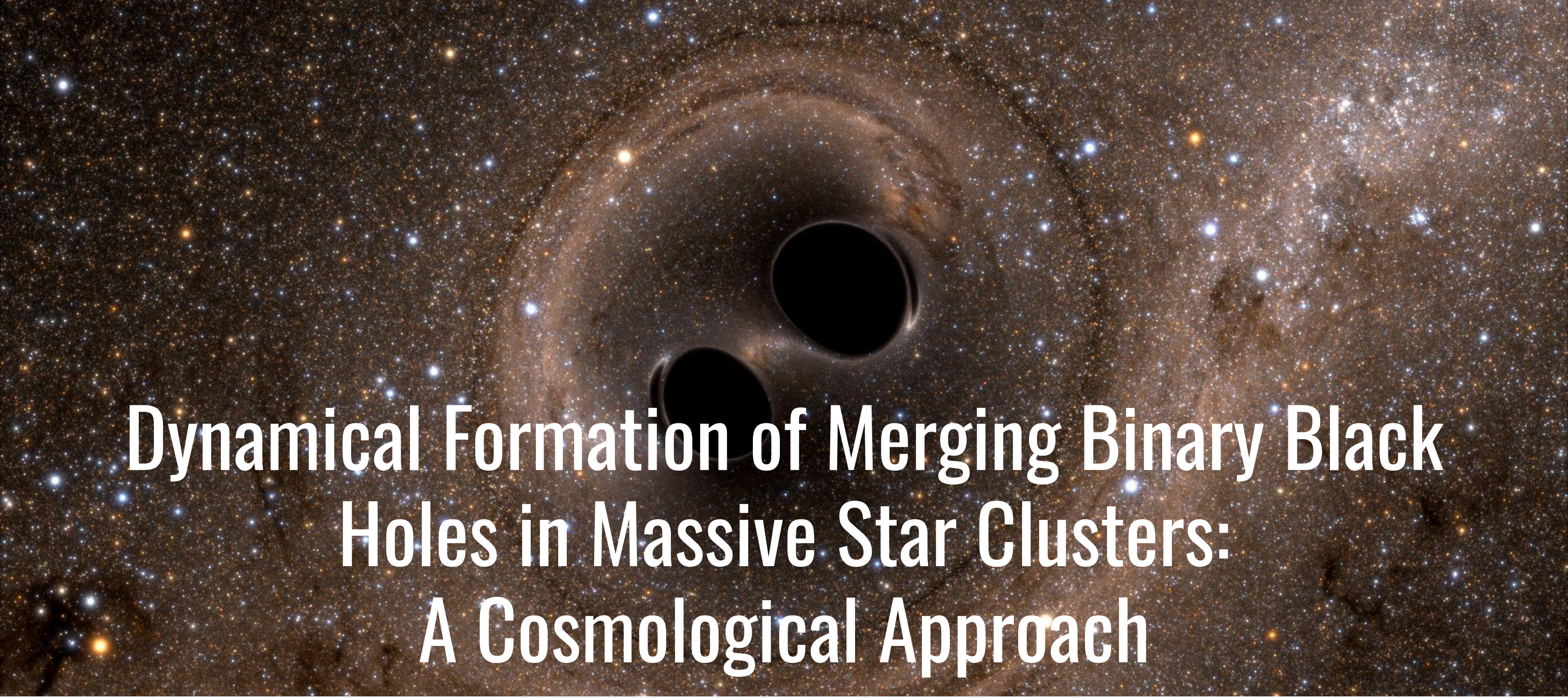

Dynamical Formation of Merging Binary Black Holes in Massive Star Clusters: A Cosmological Approach

OBSERVATOIRE DE LA CÔTE D'AZUR
UNIVERSITÉ CÔTE D'AZUR
LAGRANGE

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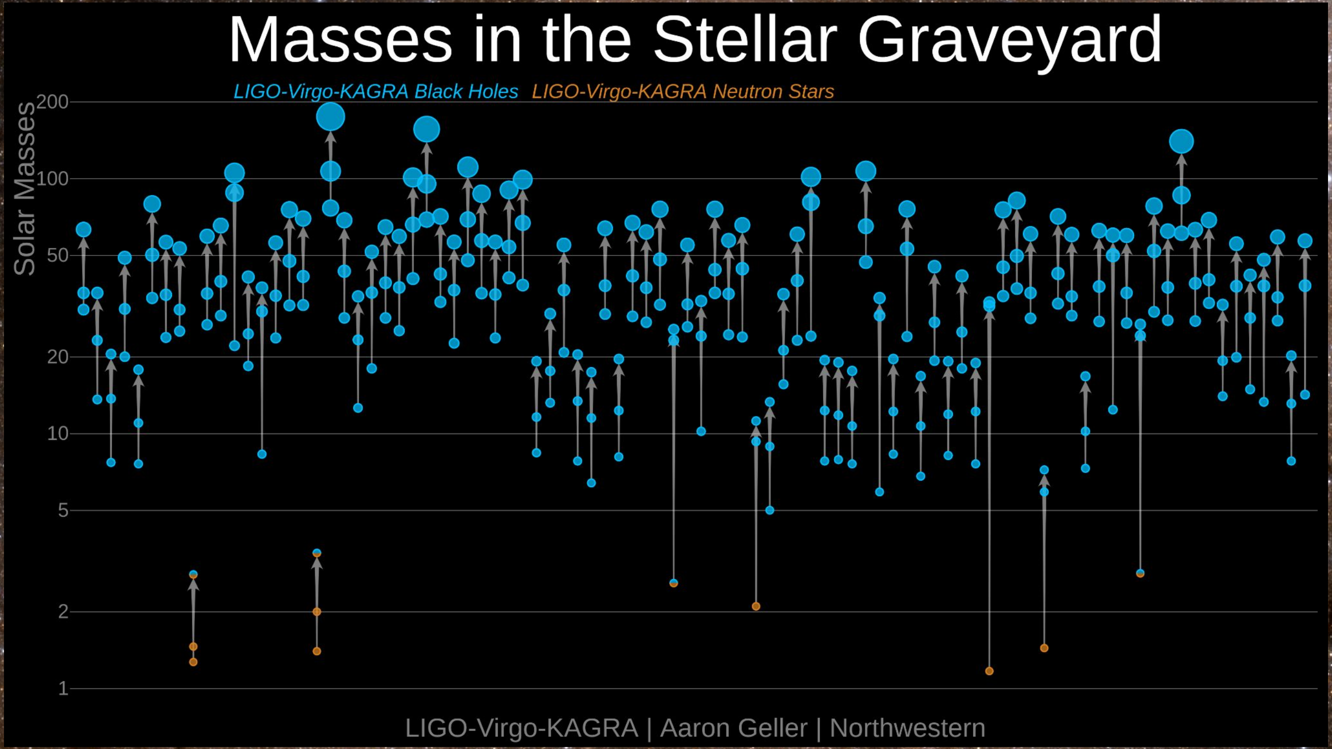
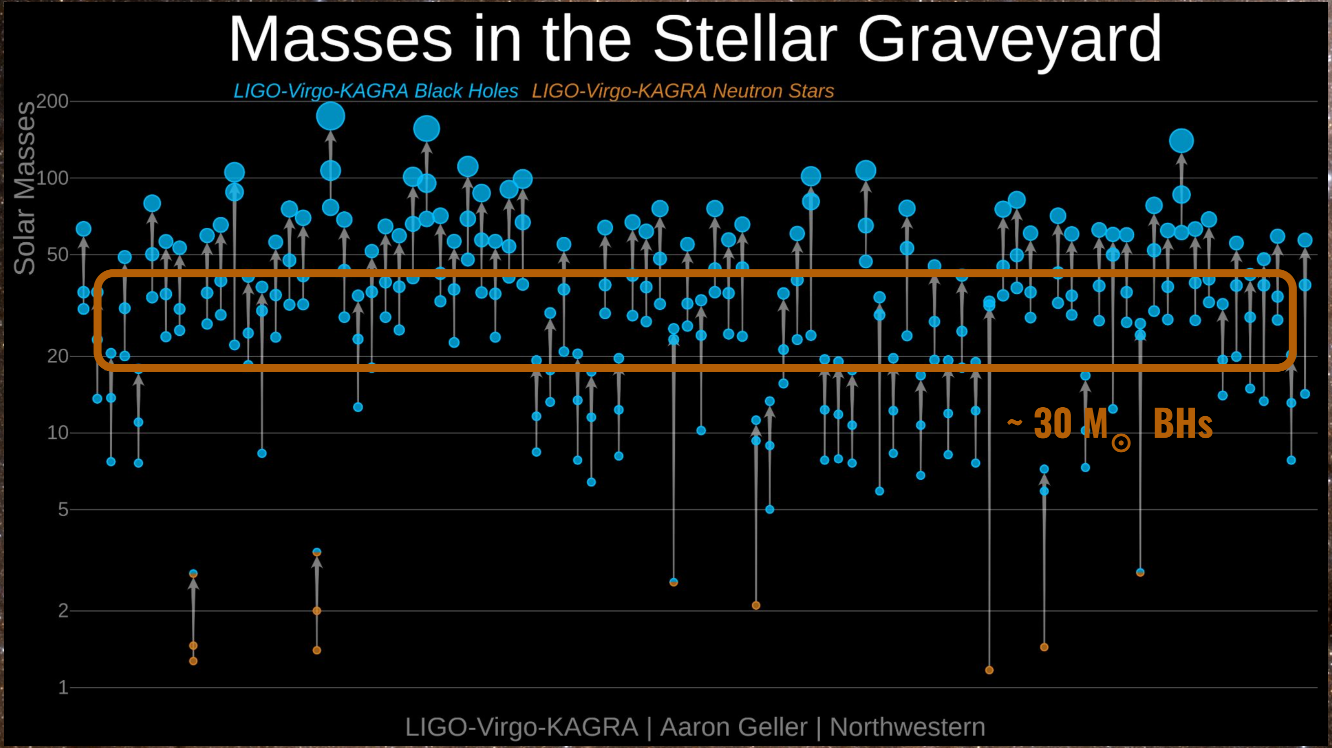
3rd year PhD student
Supervisor: Astrid Lamberts

PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR
ANR
COSMERGE

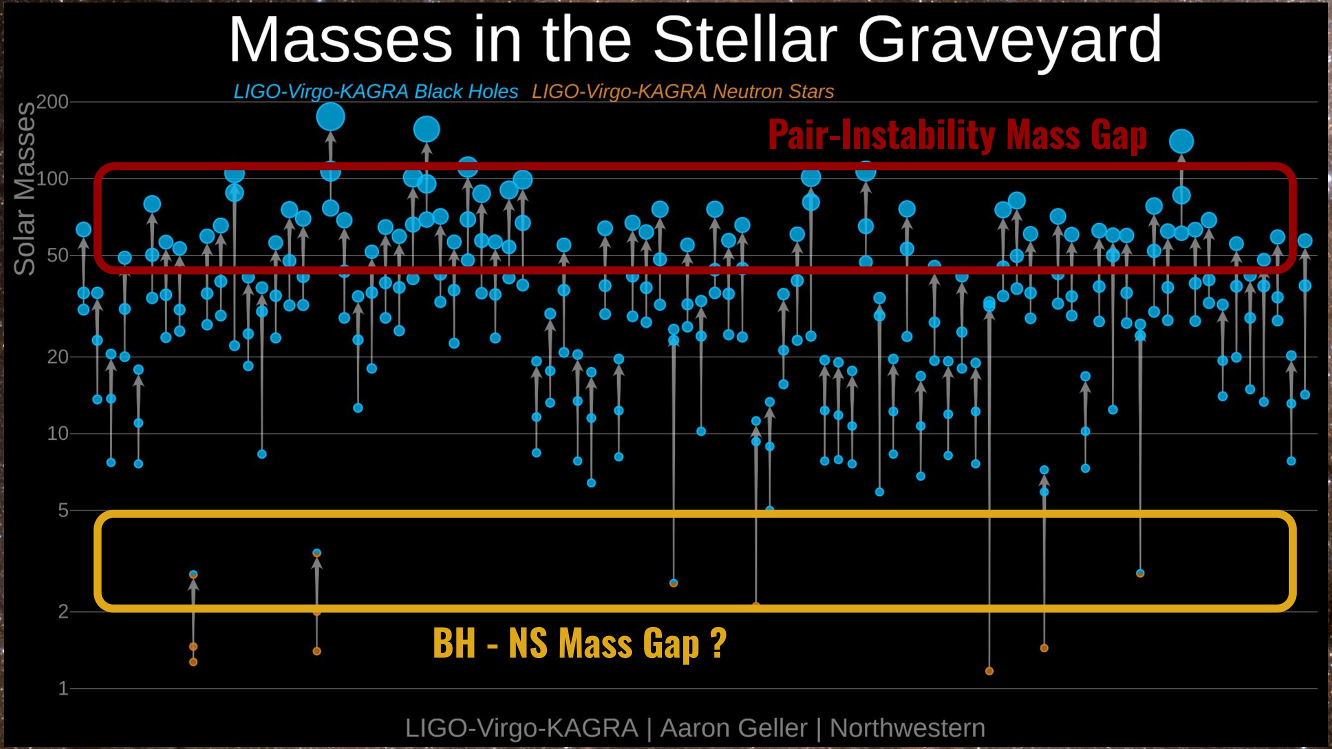
LIGO-Virgo-KAGRA observed GW events (GWTC-3)



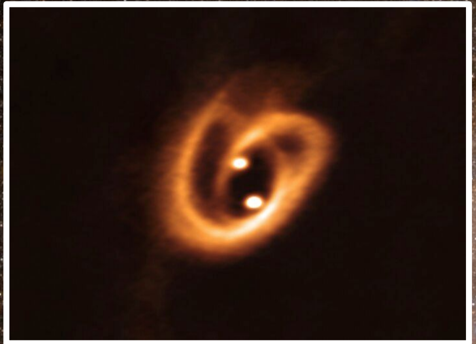
LIGO-Virgo-KAGRA observed GW events (GWTC-3)



LIGO-Virgo-KAGRA observed GW events (GWTC-3)

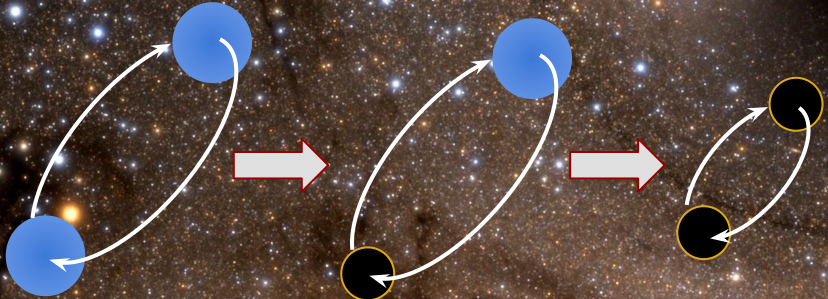


Formation scenarios



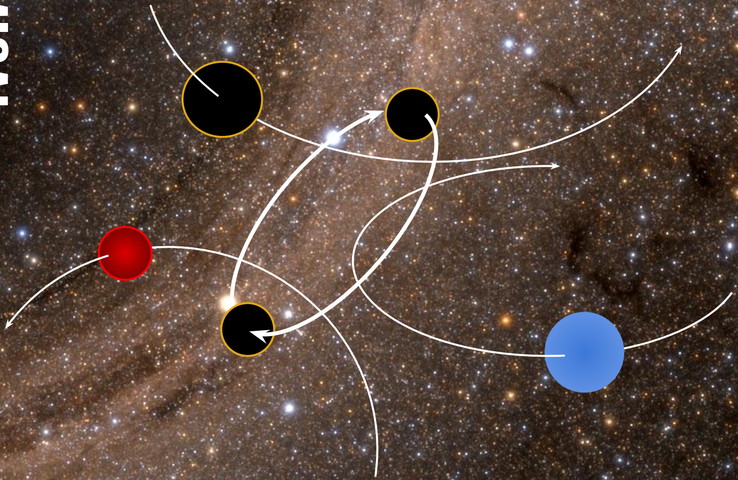
Credits: ALMA (ESO/NAOJ/NRAO), Alves et al.

ISOLATED

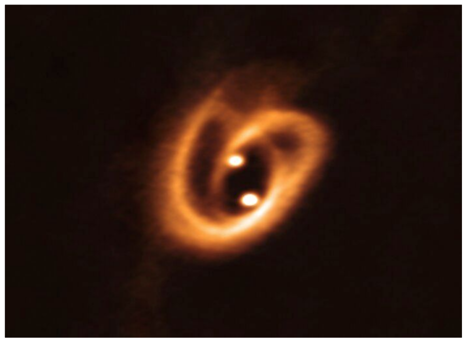


DYNAMICAL

Credits: NASA/ESA HST



Formation scenarios



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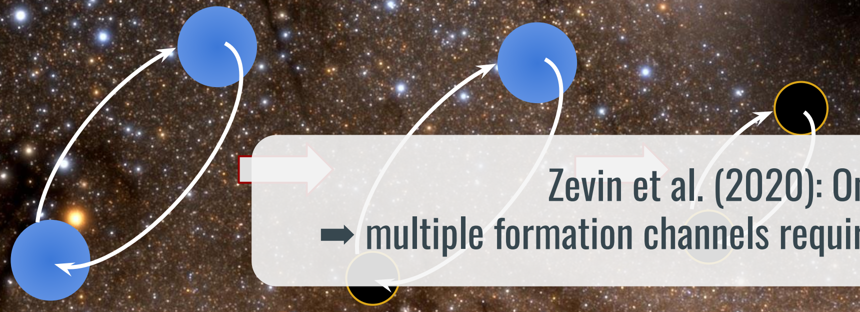

DYNAMICAL

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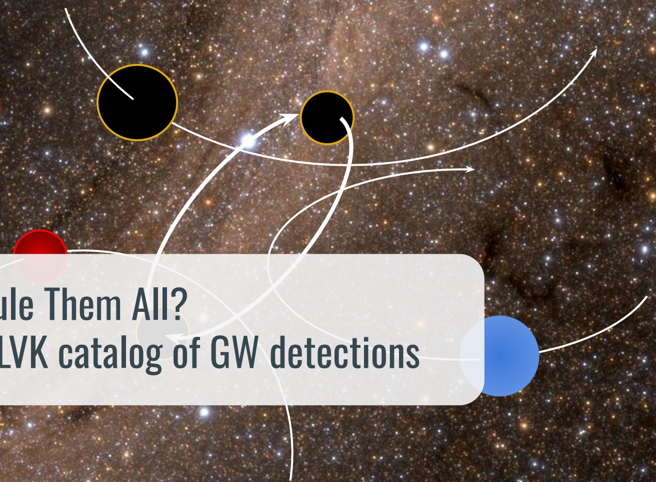


Zevin et al. (2020): One Channel to Rule Them All?
➡ multiple formation channels required to interpret LVK catalog of GW detections

Population of BBHs in cosmological simulations

~ 10 kpc ~ 100 pc

Cosmological simulation

Structure Finder

Giant Molecular Clouds

Grudic et al. (2022), Rodriguez et al. (2023)
Bruel et al. (2023)

Population of BBHs in cosmological simulations

~ 10 kpc ~ 100 pc ~ 1 pc

Cosmological simulation

Structure Finder

Giant Molecular Clouds

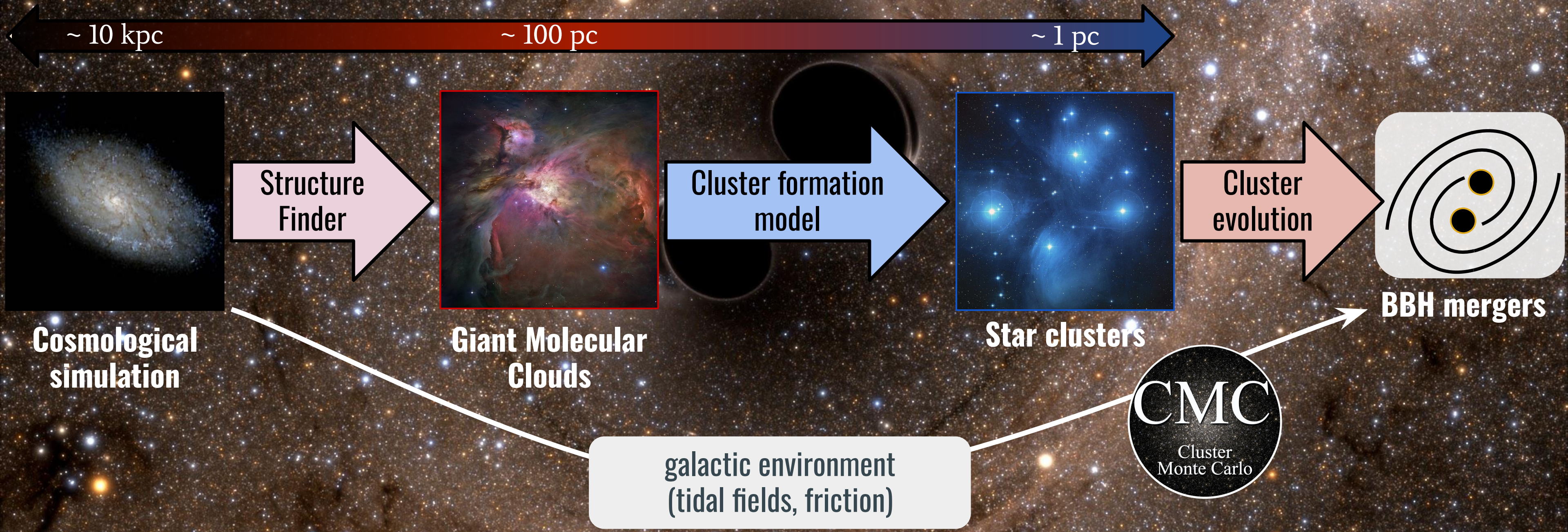
Cluster formation model

Star clusters

Cluster formation model: Grudic et al (2021)

$\Sigma_{GMC} \Rightarrow M_{\star}, \varepsilon_{int}, f_{bound}, \alpha$ ...

Population of BBHs in cosmological simulations



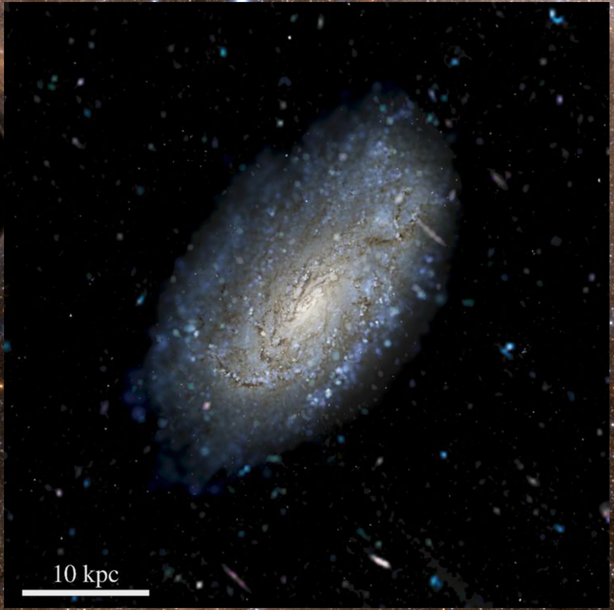
Grudic et al. (2022), Rodriguez et al. (2023)
Bruel et al. (2023)

Cosmological simulations as realistic environments for star and star cluster formation

FIRE: Feedback In Realistic Environments (Hopkins et al. 2014)

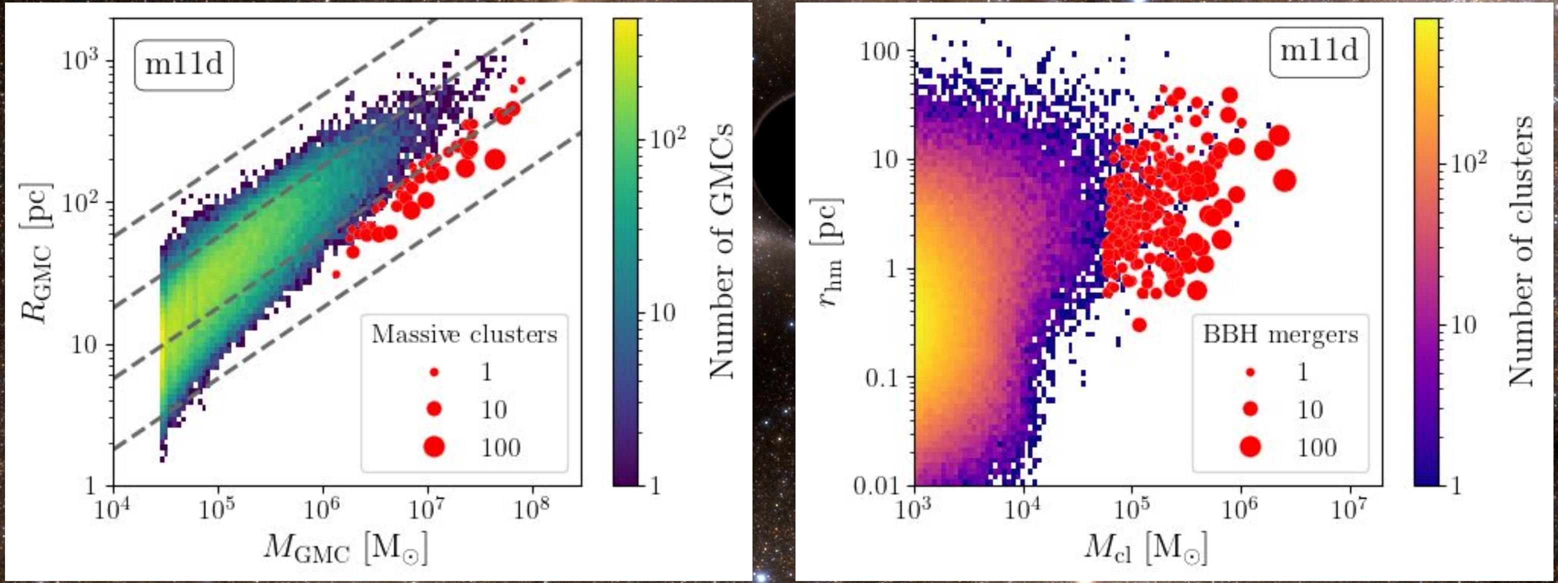
	Simulation	$\mathcal{M}_h$ [$M_\odot$]	$\mathcal{M}_\star$ [$M_\odot$]
~ SMC	m11q	1.6×10^{11}	6.1×10^{8}
	m11i	7.8×10^{10}	9.2×10^{8}
	m11e	1.7×10^{11}	1.4×10^{9}
~ LMC	m11h	2.1×10^{11}	3.6×10^{9}
	m11d	3.2×10^{11}	3.9×10^{9}
~ MW	m12i	1.2×10^{12}	6.7×10^{10}

El-Badry et al. (2017)



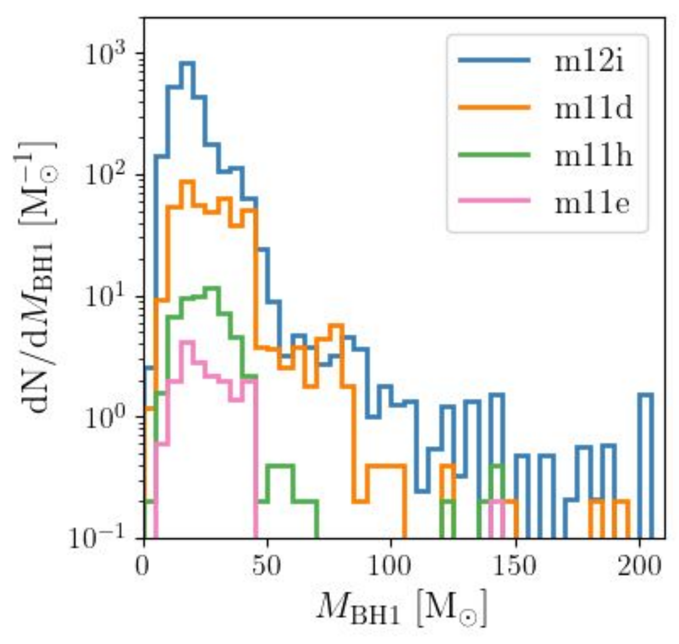
Mock HST image of m12i
Credits: P. Hopkins

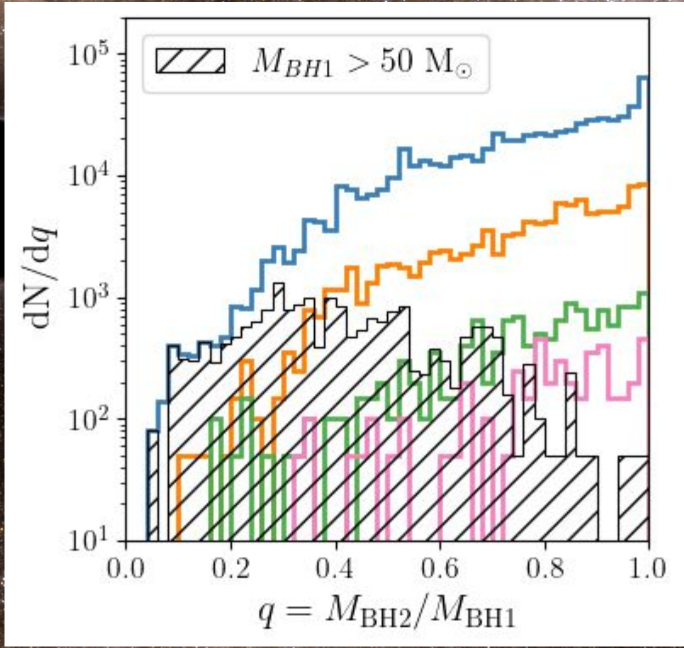
Giant Molecular Clouds (GMCs) and massive cluster formation



Bruel et al. (2023)

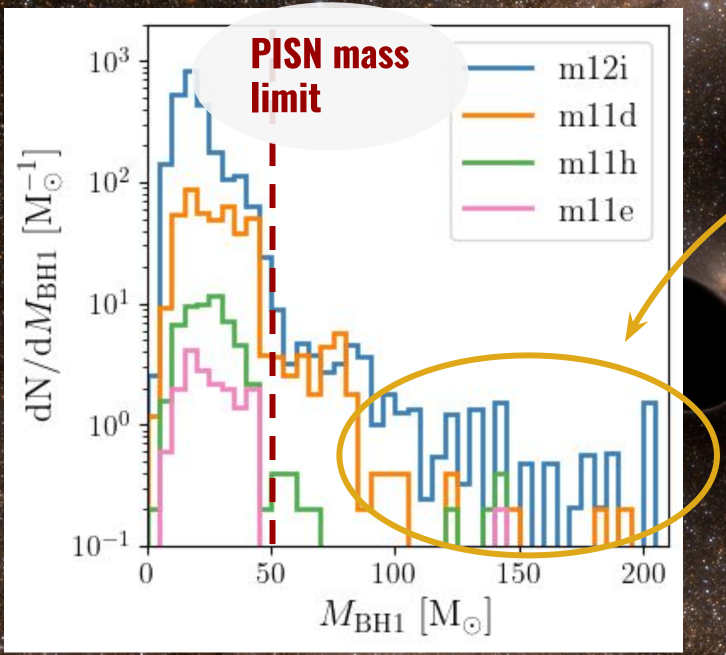
BBH primary masses and mass ratios

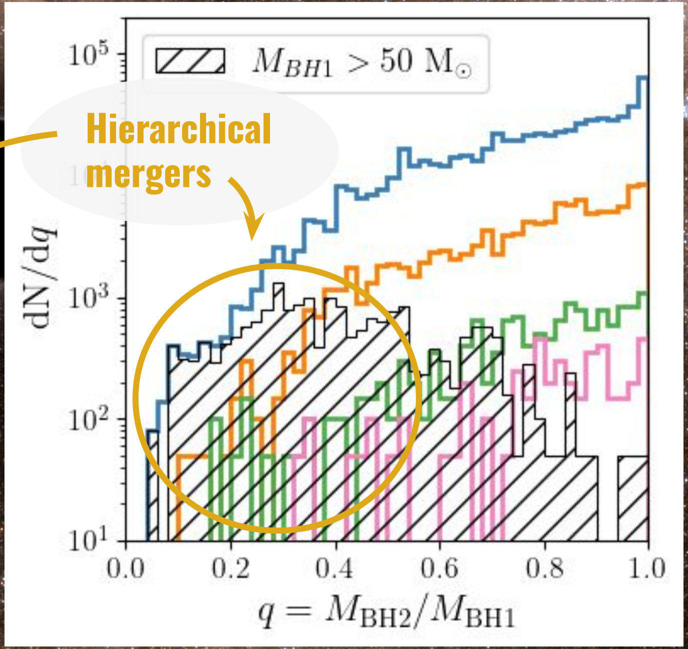




Bruel et al. (2023)

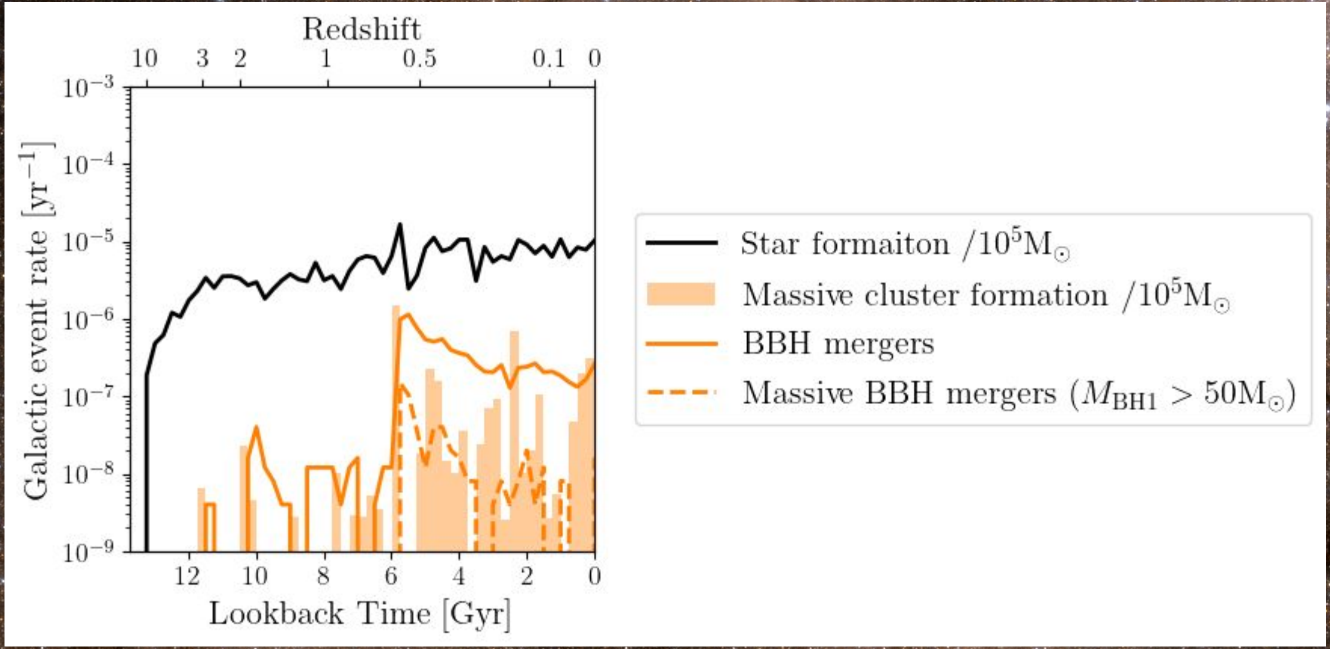
BBH primary masses and mass ratios





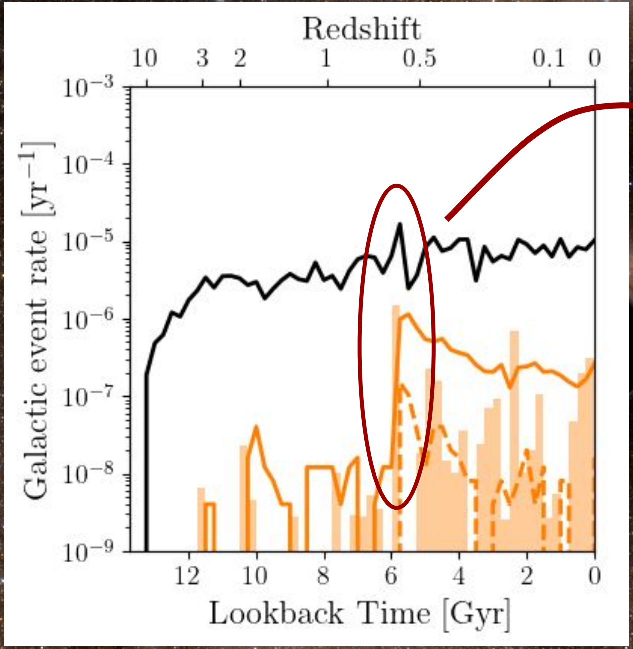
Bruel et al. (2023)

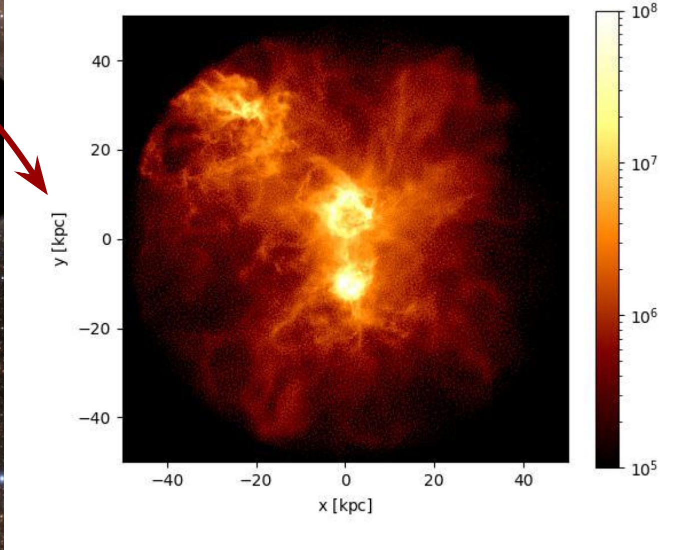
BBH merger rate



Bruel et al. (2023)

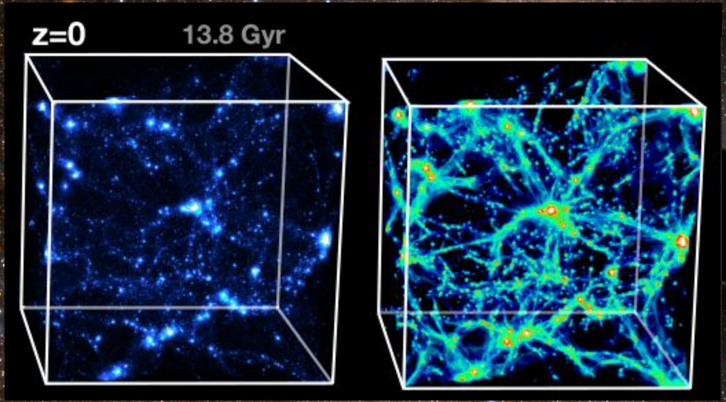
BBH merger rate





Bruel et al. (2023)

Large volume cosmological simulation

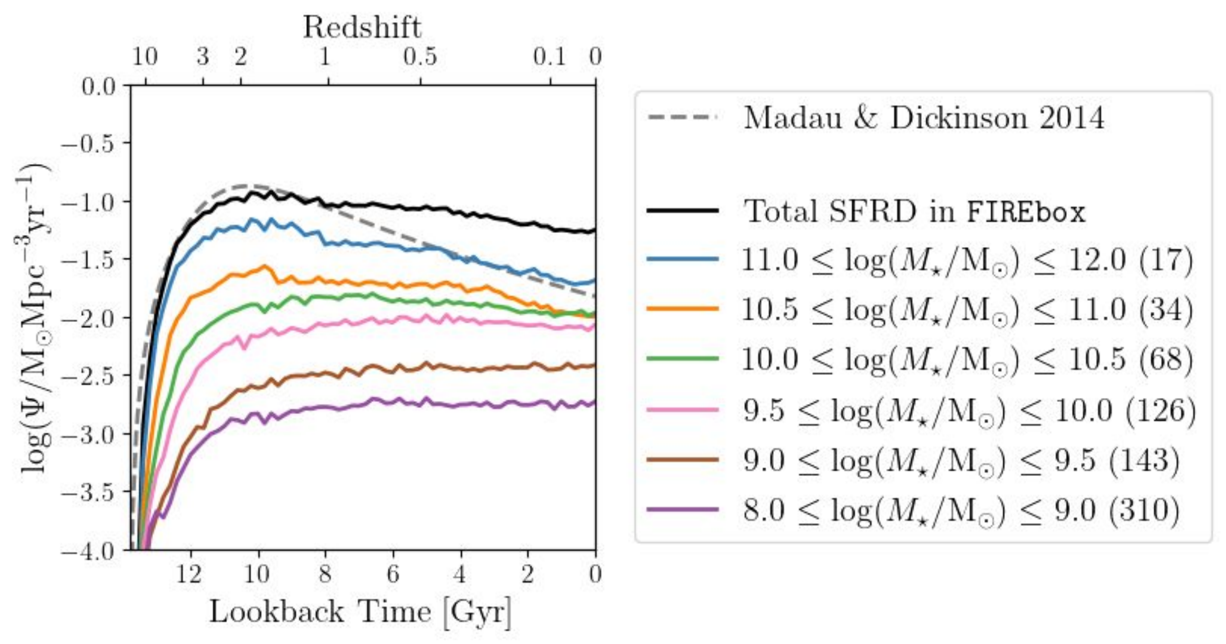


Feldmann et al. (2023)

FIREbox

- (22.1 cMpc)^3 cosmological simulation
- FIRE-2 baryonic physics model (same as the 6 zoom-in simulations)
- ~ 1000 galaxies with stellar mass $\mathcal{M}_\star \geq 10^8\ M_\odot$

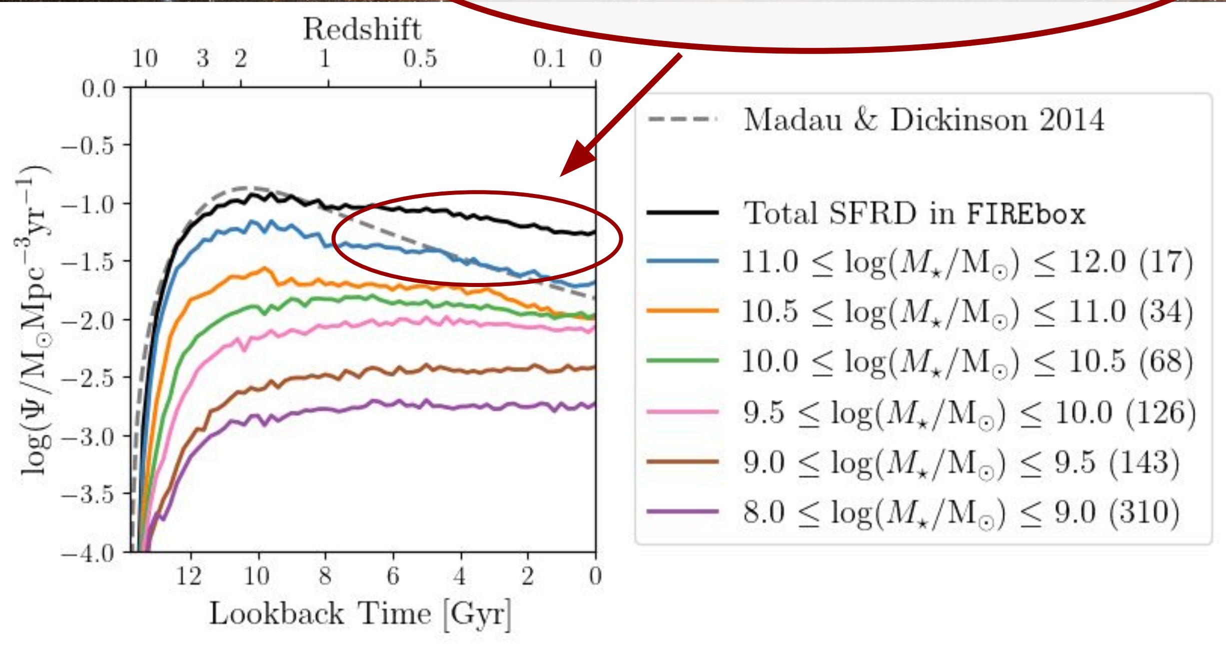
SFRD in FIREbox



Bruel et al. (in prep)

SFRD in FIREbox

No AGN feedback -> lack of quiescent massive galaxies



Bruel et al. (in prep)

Cluster formation model

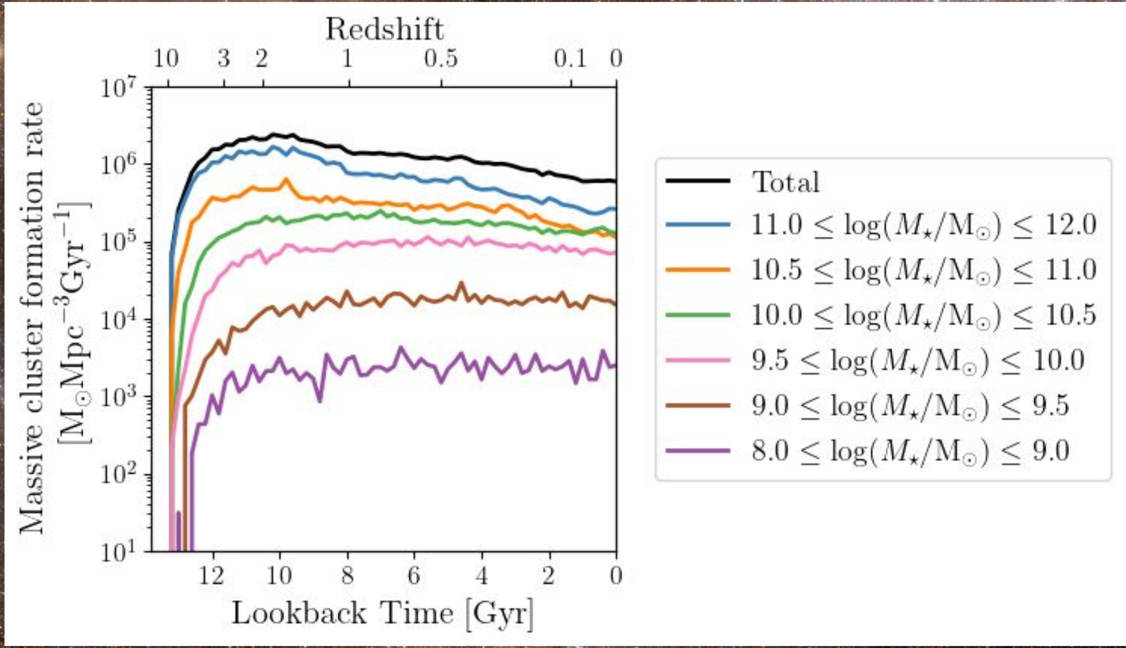
Cluster formation model
El Badry et al. 2018

$\Gamma_{GCs} \equiv \dot{M}_{GCs}$ / SFR

$= \alpha / 1+(\Sigma_{GMC}/\Sigma_{crit})^{-\beta}$

Σ_{crit} = 3000 $M_\odot pc^{-2}$, β = -1

α fit to formation efficiency in our set of zoom-in simulations

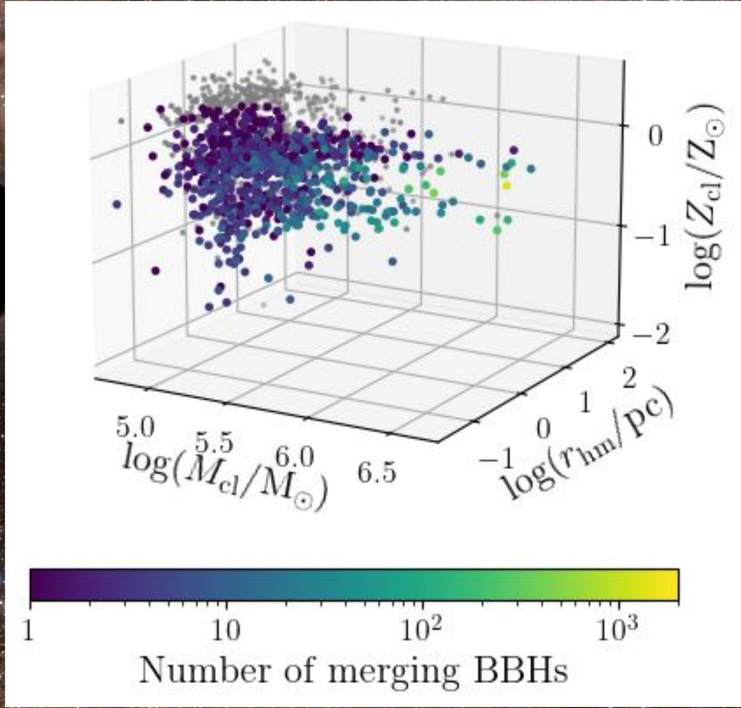


Bruel et al. (in prep)

BBH mergers in large population of massive star clusters

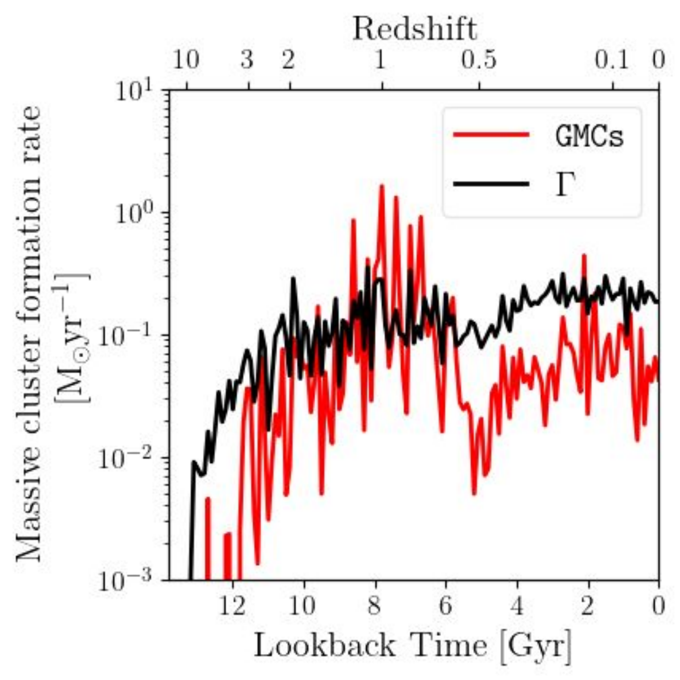
Grid-matching method

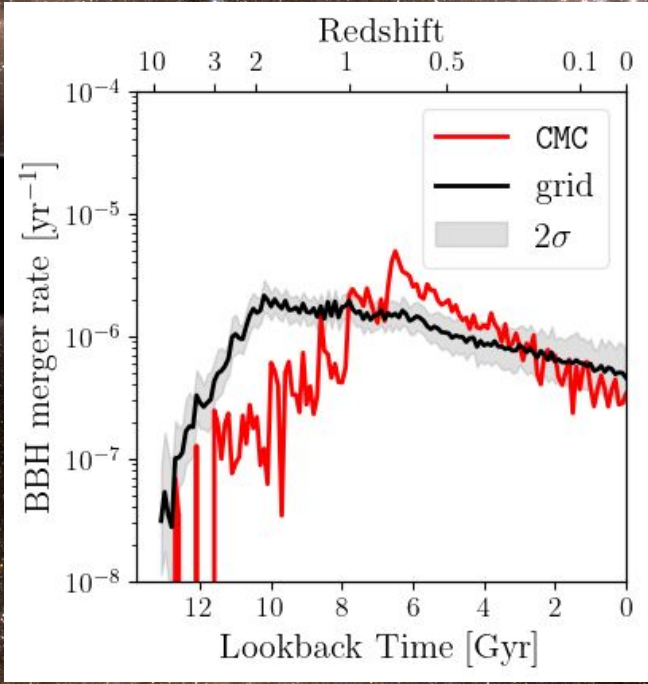
- total of 1500 clusters integrated with CMC in the 6 zoom-in simulations (including interactions with galactic environment)
- parameter space (M_{cl} , r_{hm} , Z_{cl})
- for each cluster sampled associate the BBHs from the closest neighbour in the grid (euclidean distance in log space)



Bruel et al. (in prep)

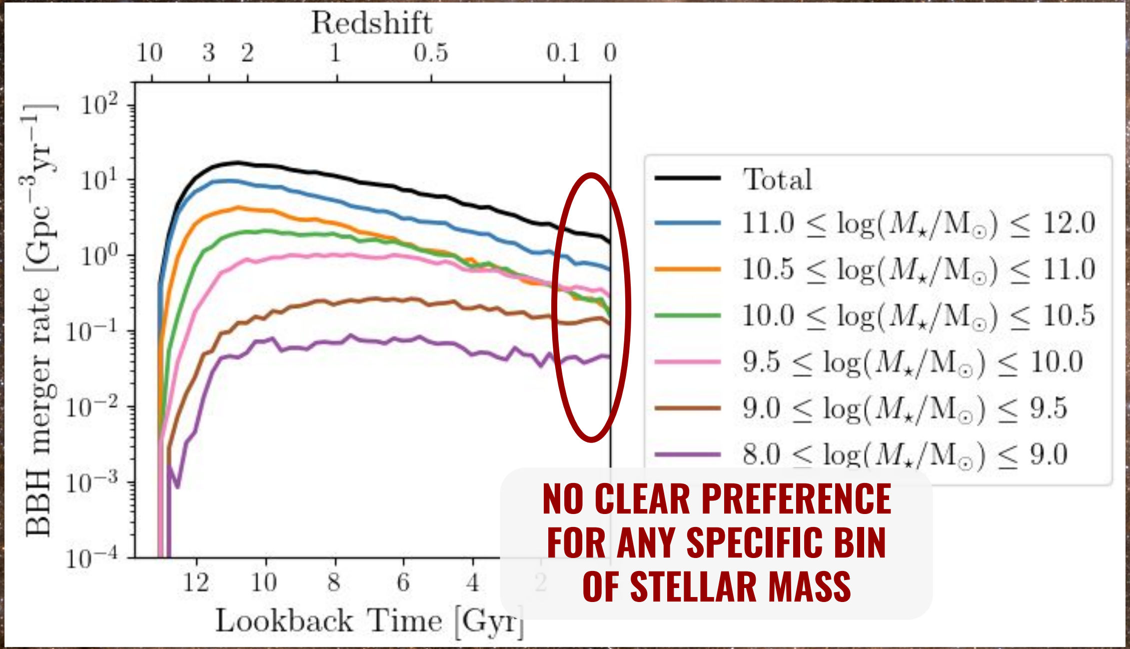
Validation test: cluster formation + grid-matching in MW-like m12i





Bruel et al. (in prep)

BBH merger rate density in different bins of galaxy stellar mass

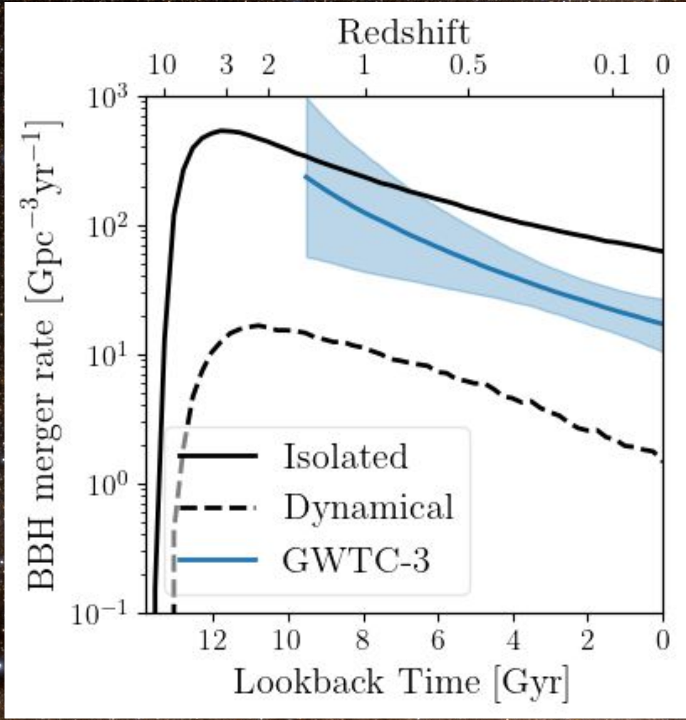


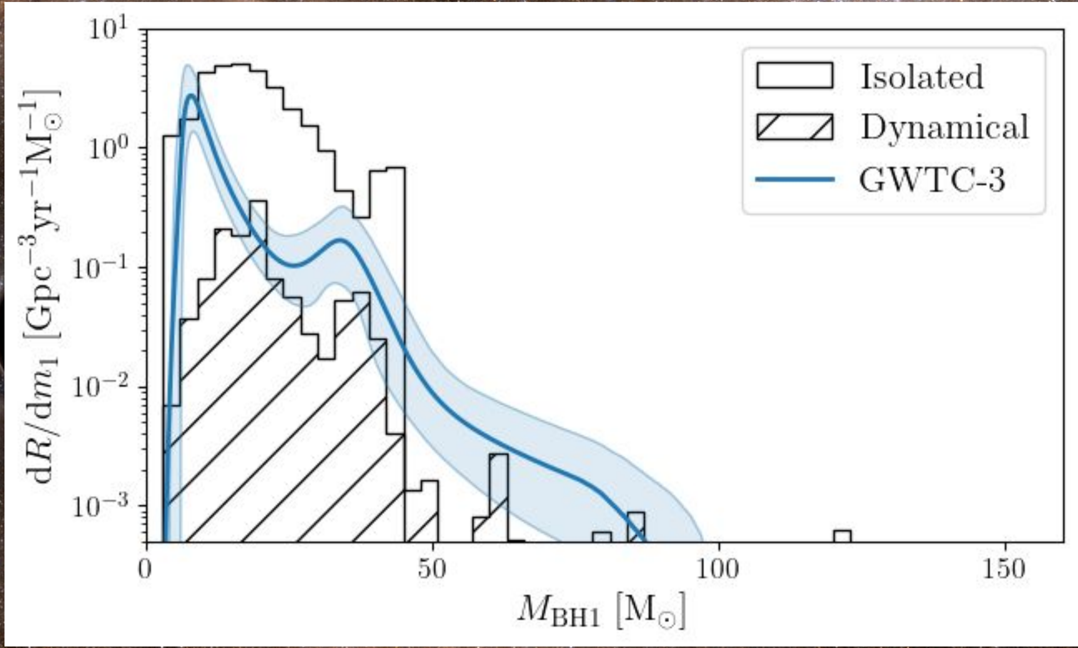
NO CLEAR PREFERENCE FOR ANY SPECIFIC BIN OF STELLAR MASS

Bruel et al. (in prep)

Comparison with isolated channel

COSMIC





Summary

- **formation** and **evolution** of massive star clusters in 'realistic' environments
  - ➢ large collection (1500) CMC clusters in wide parameter space, with treatment of tidal fields and dynamical friction

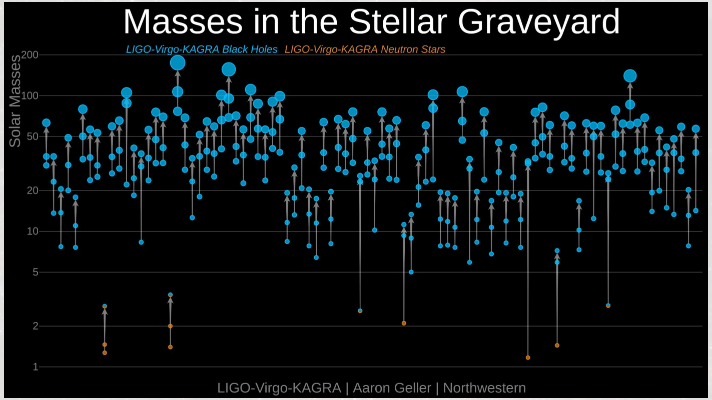
- correlations found between **galaxy interactions** and the production of **massive BBH mergers**
  - ➢ possible hint to constrain host galaxy for some of the most massive BBH mergers detected

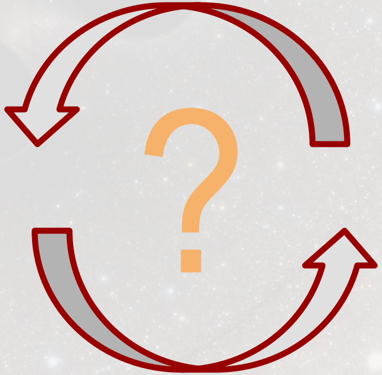
- study of two BBH formation channels using a **consistent** environment of star and star cluster formation + **compatible** evolution codes

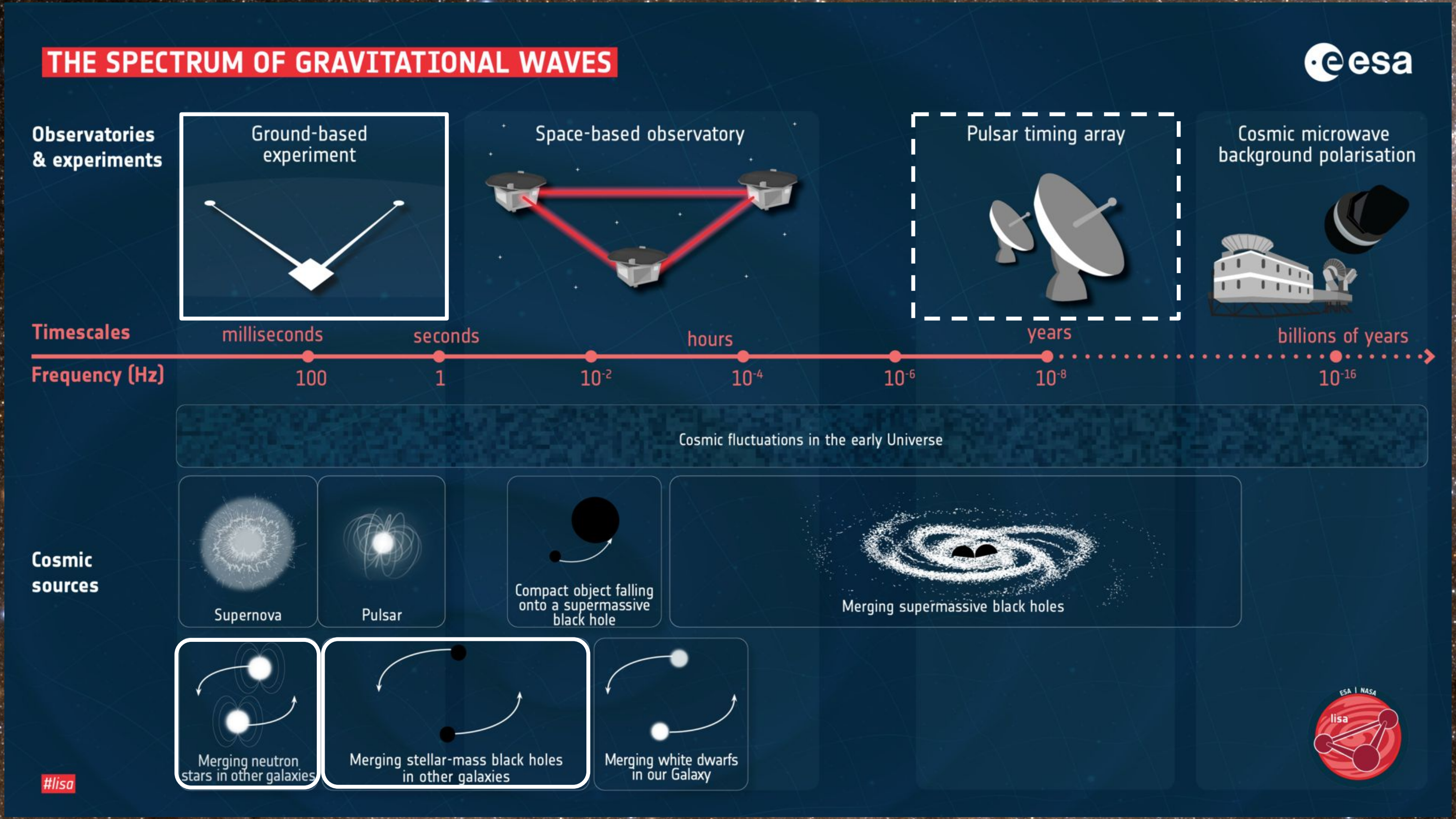
Outlook

- What can we learn about cluster dynamics from GW observations ?

- What can we learn about the formation of double compact objects from cluster theory/observations ?

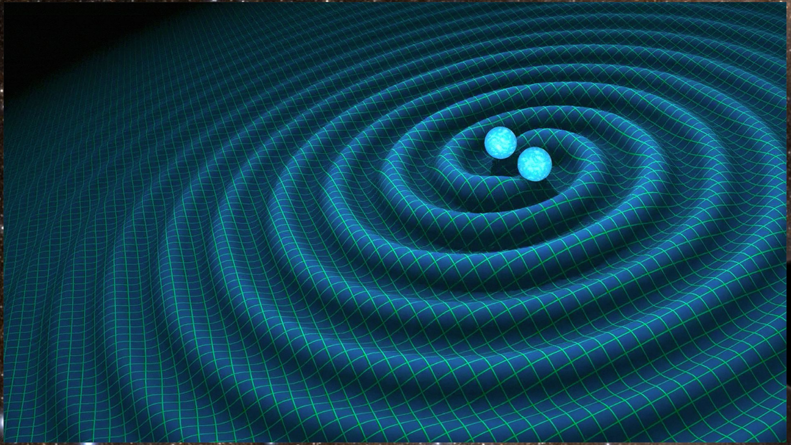





THE SPECTRUM OF GRAVITATIONAL WAVES
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations in the early Universe
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
#lisa
ESA | NASA
lisa

Credits: ESA

Gravitational Spiraling of Binary Black Holes (BBHs)



Credits: R. Hurt/Caltech-JPL

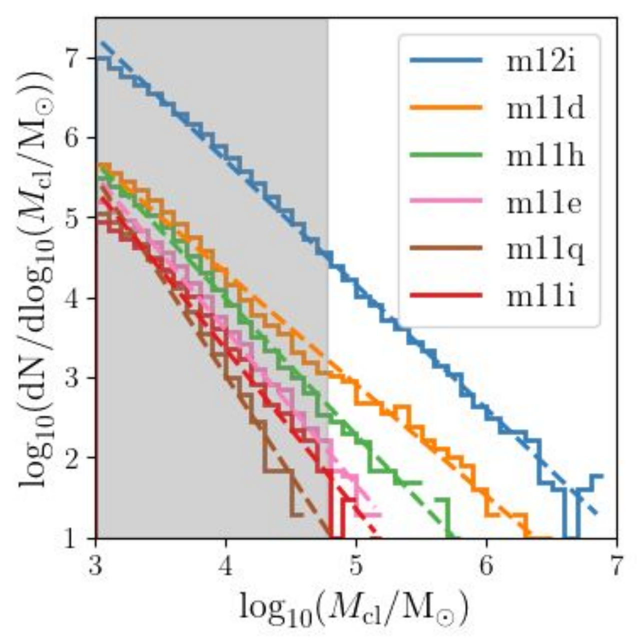
Merger time of a BBH:

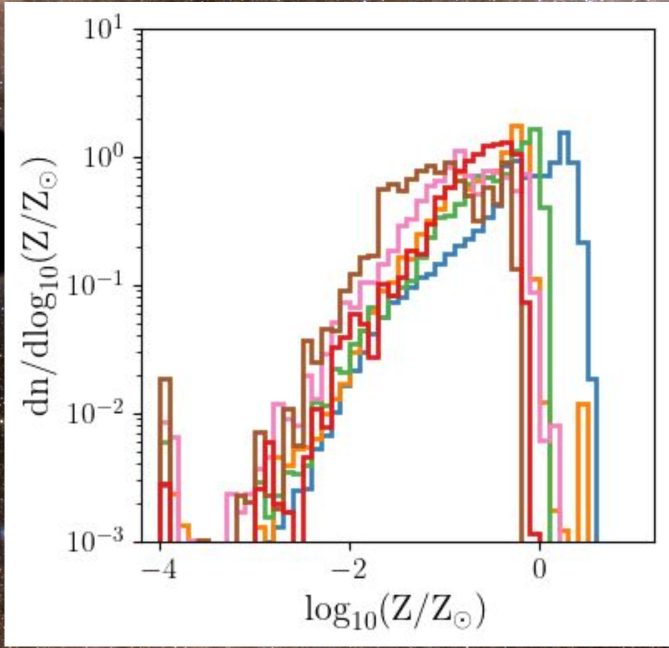
$$\tau_{\rm GW} \sim 14 \left(\frac{M}{30 M_\odot} \right)^{-3} \left(\frac{a_{\rm ini}}{50 R_\odot} \right)^{4} \,\mathrm{Gyr}$$

Mandel et al. (2022)

PROBLEM: Radius of a Red Supergiant Star: $R \sim 100 - 1000\ R_\odot$

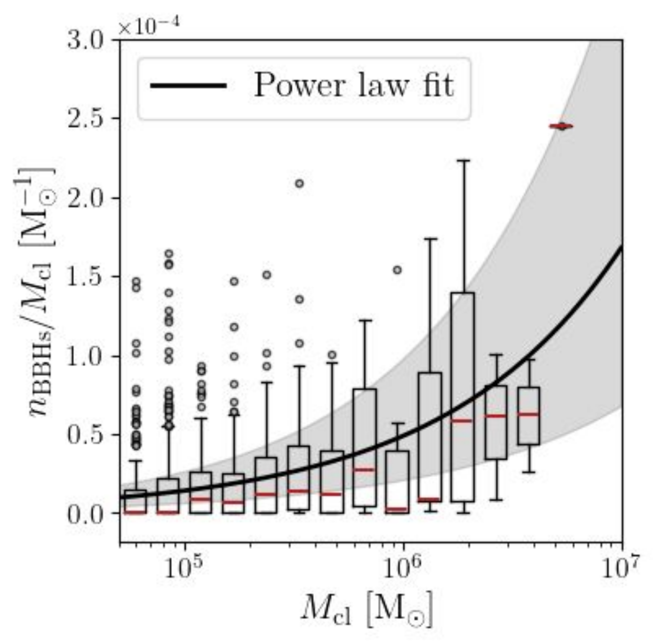
Star clusters masses and metallicities

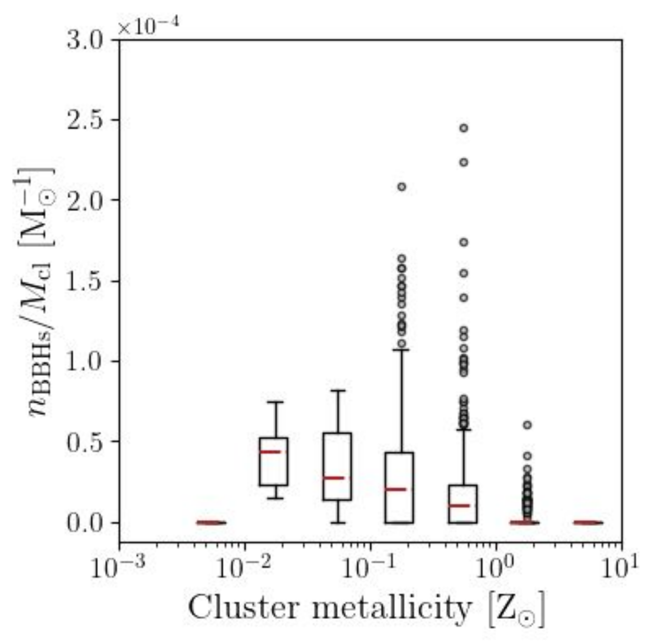




Bruel et al. (2023)

Cluster efficiency at producing BBH mergers





Re-weighting operation in FIREbox