Title: Host Galaxies of Binary Compact Objects Across Cosmic Time

Speakers: Maria Artale

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

Date: May 05, 2025 - 1:00 PM

URL: https://pirsa.org/25050031

Abstract:

The advent of gravitational wave (GW) detections has opened a new window into our understanding of stellar-mass black holes and neutron stars. Ongoing advancements and upcoming third-generation GW detectors are expected to provide increasingly detailed insights into the properties of compact object binaries across cosmic time. In this context, the merger rate density inferred from GW detections can be interpreted as the convolution of the cosmic star formation history, chemical evolution, and binary stellar evolution.Studying this connection from the perspective of the host galaxies of binary compact objects offers a complementary approach, not only shedding light on the physical conditions that favor different formation channels but also enhancing our ability to interpret GW observations. In this talk, I will discuss two different approaches to modeling the host galaxies of binary compact objects: one based on population synthesis models combined with galaxy catalogs from cosmological simulations, and another based on empirical galaxy scaling relations. I will highlight some of the key results from these models and discuss the next steps where host galaxy properties can provide critical constraints on the origin and evolution of compact object binaries.

Zoom link: https://pitp.zoom.us/j/98089871850

Modeling the host galaxies of binary compact objects across cosmic time

M. Celeste Artale

in collaboration with Giuliano Iorio, Michela Mapelli, Nicola Massetti, Rosalba Perna, Filippo Santoliquido, Cecilia Sgalletta, Mario Spera, Stefano Torniamenti, M. Paola Vaccaro, Felipe Vivanco

Agencia Nacional de Investigación y Desarrollo
Ministerio de Ciencia, Tecnología, Conocimiento e Innovación
Gobierno de Chile

Universidad Andrés Bello
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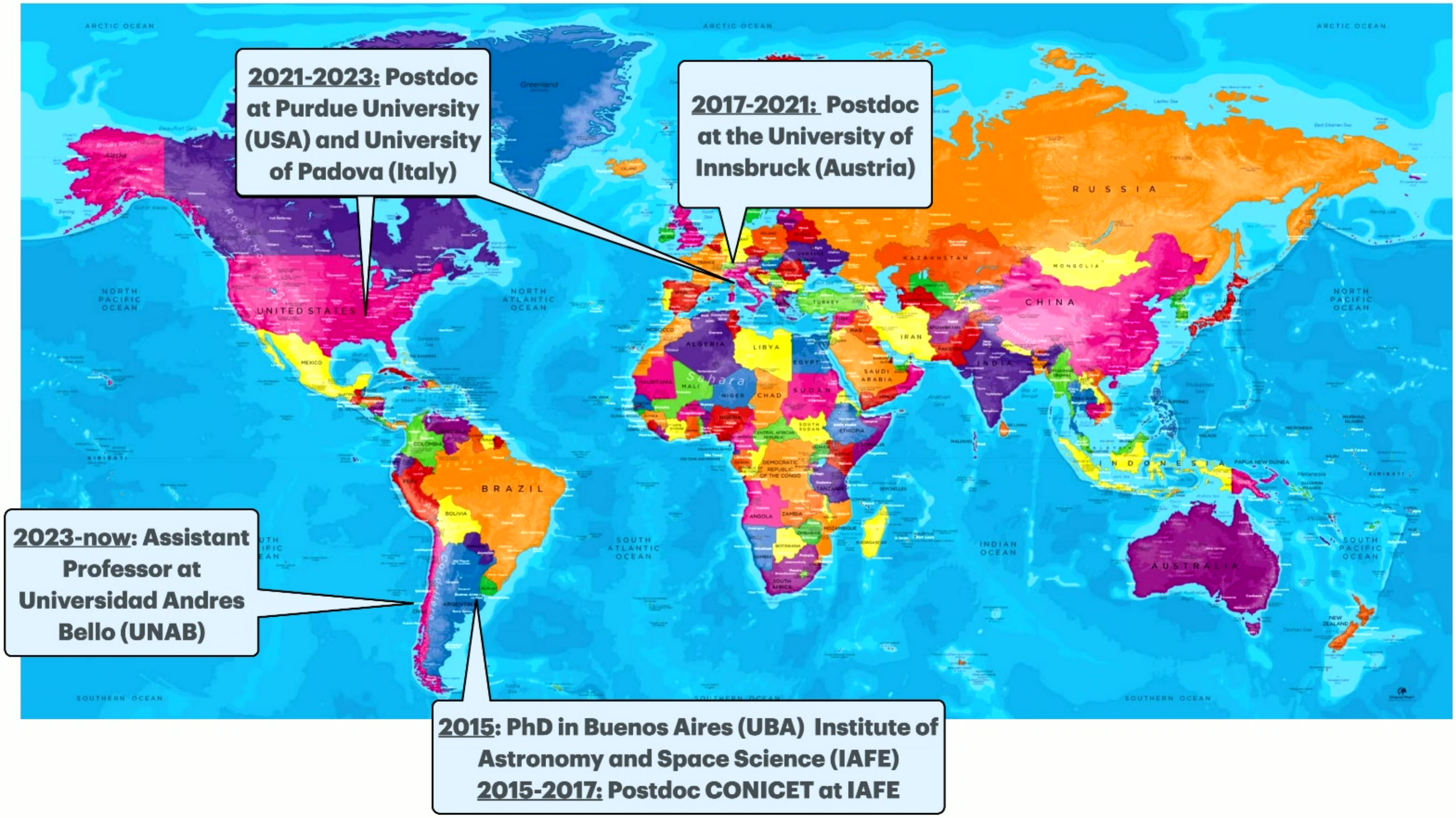
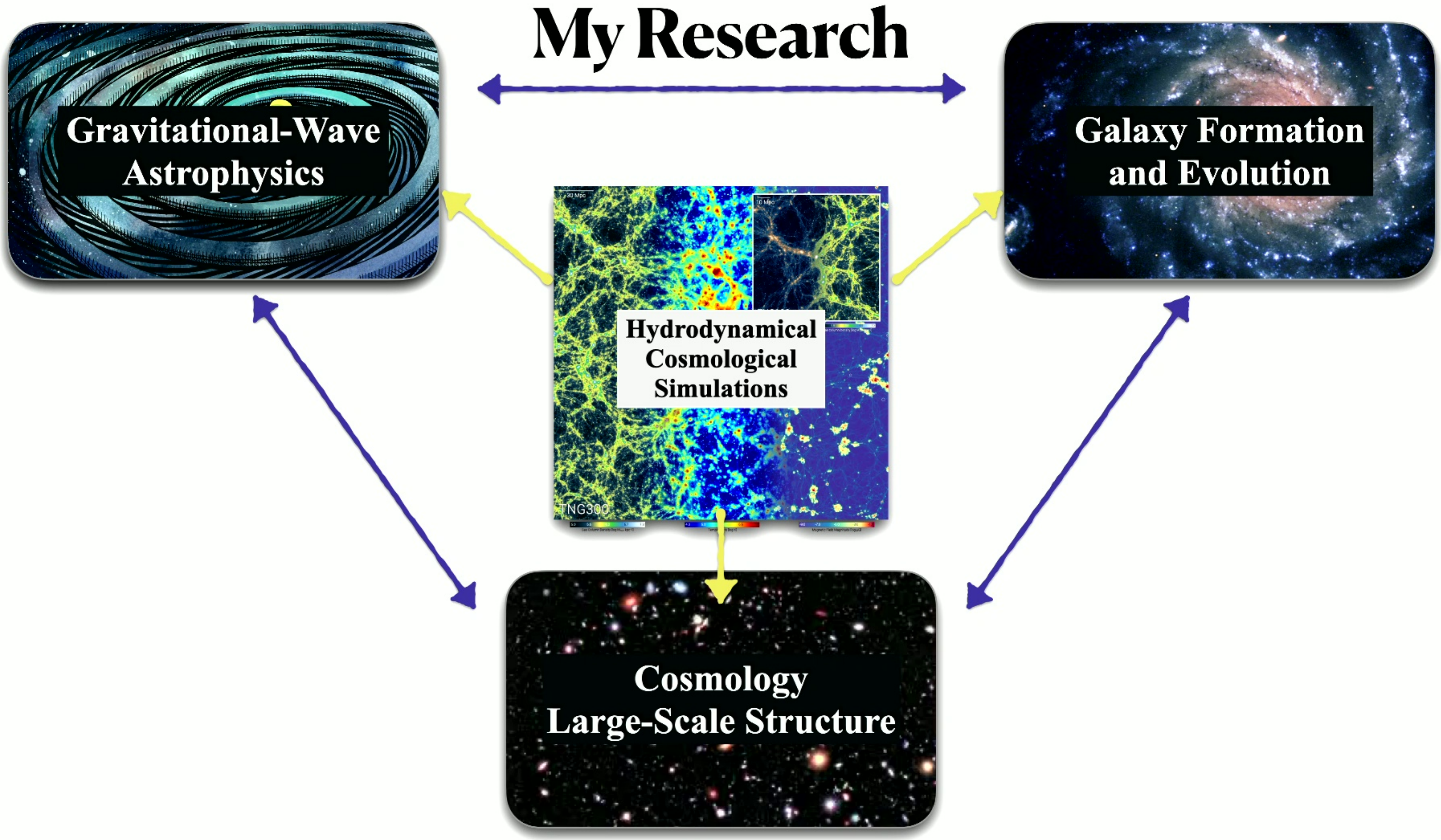
Cosmology Meeting - Perimeter Institute
May 2025

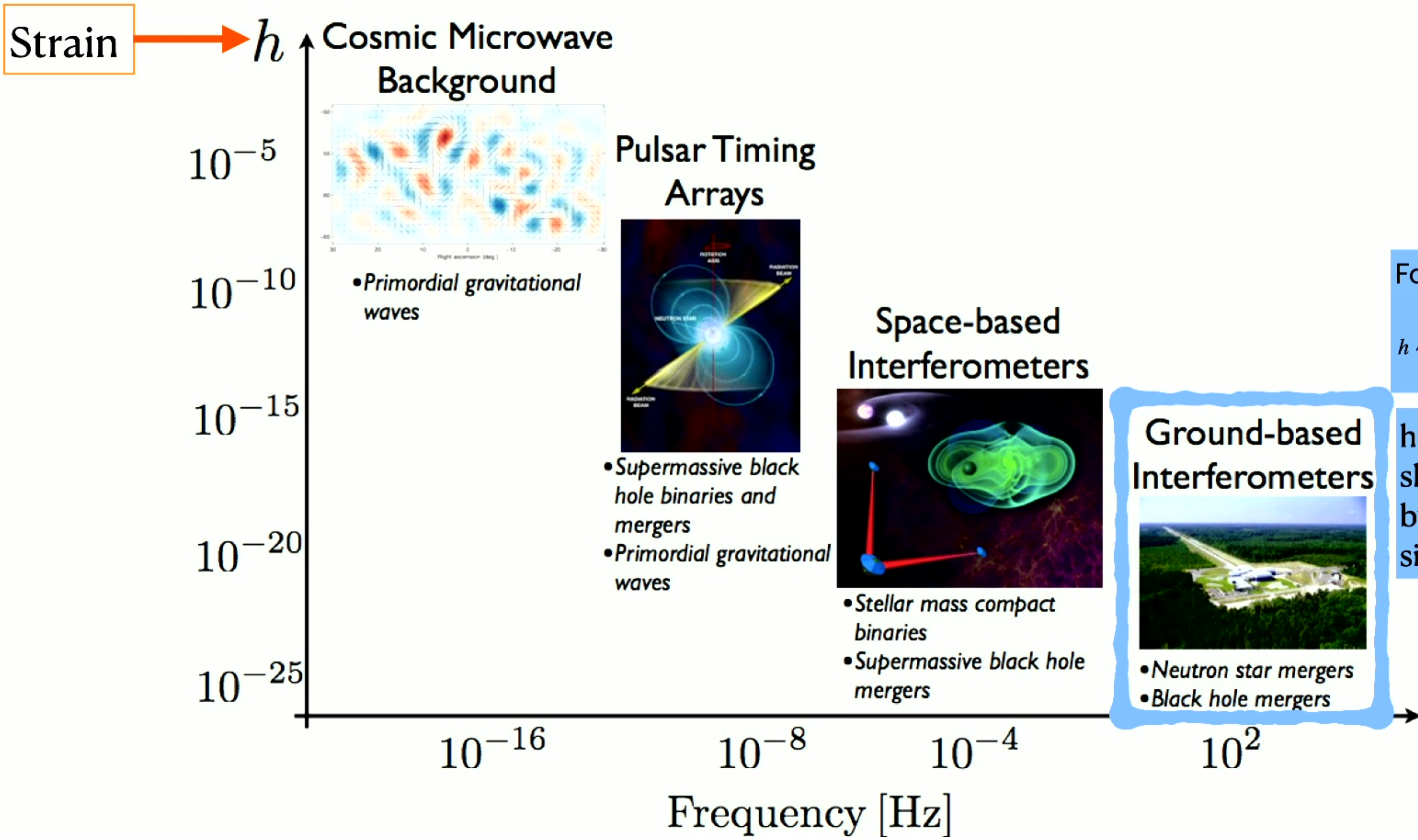
CATA
CENTRO DE ASTROFÍSICA Y TECNOLOGÍAS AFINES

My Life in Research




My Research
Gravitational-Wave Astrophysics
Galaxy Formation and Evolution
Hydrodynamical Cosmological Simulations
TNG300
Cosmology
Large-Scale Structure

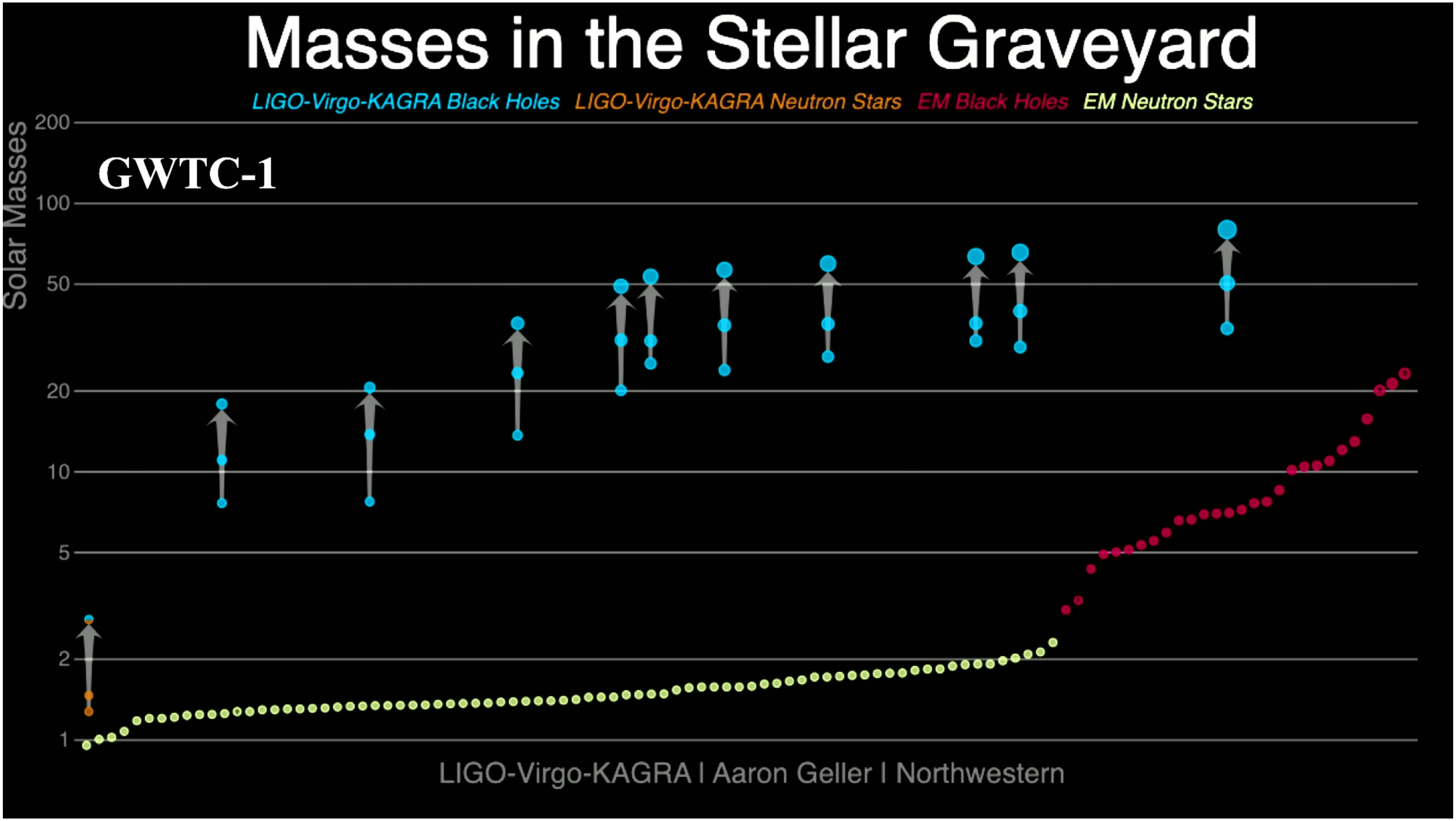
What are the Gravitational Waves (GW)?



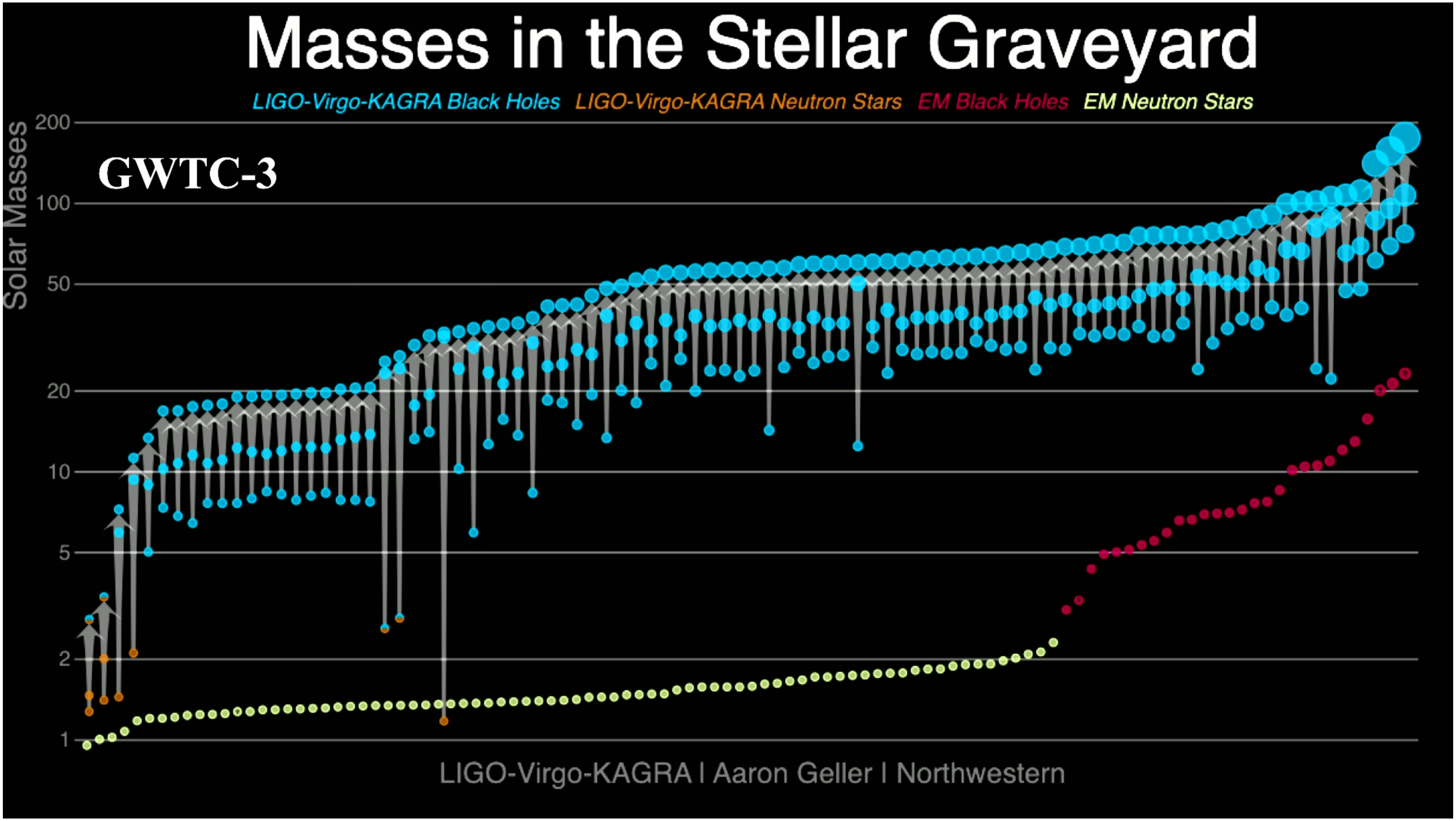
For binary systems:

$$h \sim 10^{-21}\left(\frac{M}{M_\odot}\right)^2 \frac{1\text{kpc}}{r}\frac{1R_\odot}{a}$$

$h \sim 10^{-20}$ distort the shape of the Earth by 10^{-13}m (~1% the size of an atom)



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
GWTC-1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern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200
100
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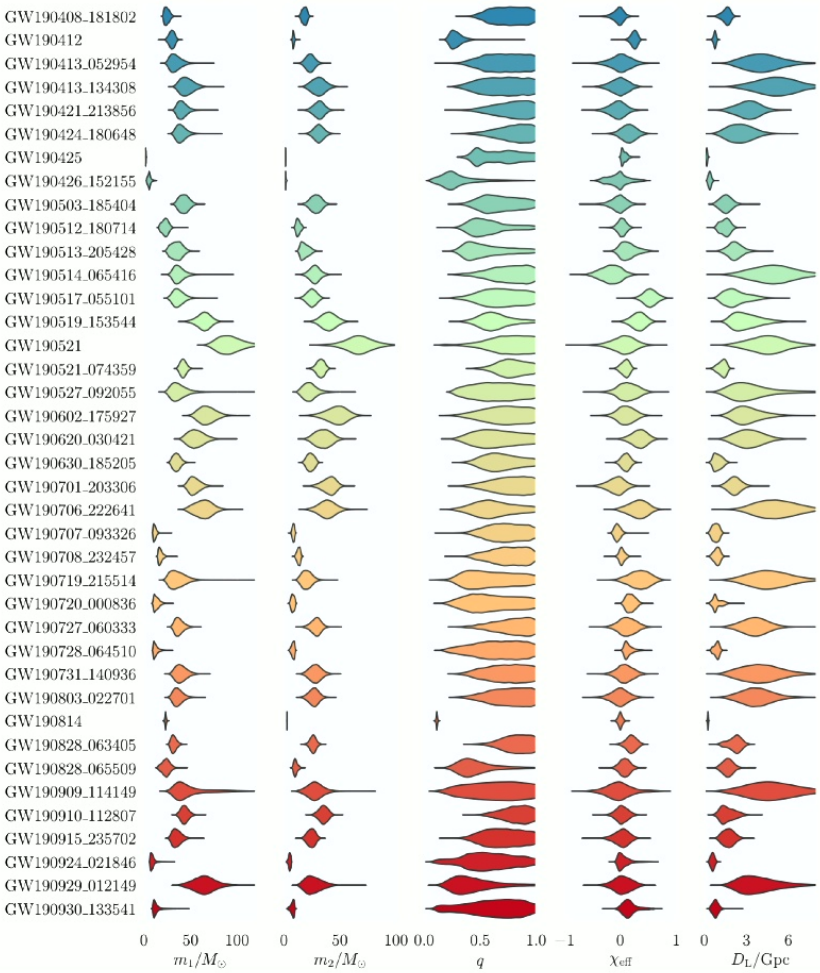
10
5
2
1
GWTC-3
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Lessons from GWTC-1, -2 and -3

Abbott+2020



- What is the origin of BH with masses above 45 $M_\odot$?
- Is there a mass gap between NS and BH?
- Are the systems with misaligned spins the result of dynamical assembly?
- Are the observing binary BH from multiple formation channels?
- Have we detected the collapse of primordial BH binaries?
- What are the most important features to detect the EM counterpart of GW sources?

How do Binary Compact Objects (BCO) Form?

In the "field"

stars born in isolated binary/triple systems

- Isolated Binaries
- Population-III stars
- Chemically homogeneous evolution
- Isolated Triples/Multiples

"Dynamical"

stars born in dense stellar environments

- Globular Clusters
- Young/Open Star Clusters
- Nuclear star clusters

"Other"

- Primordial
- Fly-bys

Credits: Floor Broekgaarden

How do Binary Compact Objects (BCO) Form?

In the "field"
stars born in isolated binary/triple systems

- Isolated Binaries
- Population-III stars
- Chemically
- Isolated

Example of some tools:
Population synthesis codes (BSE, SEVN, MOBSE, COSMIC, etc)
Hydrostatic stellar evolution codes (MESA, etc)

"Dynamical"
stars born in dense stellar environments

- Globular Clusters
- Young/Open Star
- Nuclear star

Example of some tools:
Semi-analitic models, Monte-Carlo Simulations (e.g., FASTCLUSTER, DRAGON-II, etc), N-Body codes (PETAR, Nbody6++,etc)

"Other"

- Primordial
- Fly-bys

Credits: Floor Broekgaarden

How we can account for stellar and binary evolution "in the field"?

Hydrostatic stellar evolution codes

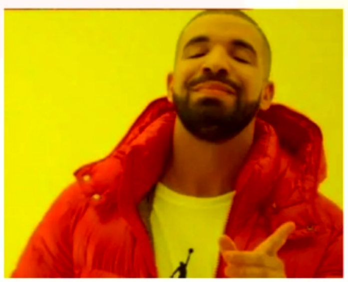
(e.g. PARSEC, Bressan+12; MESA, Paxton+19)

From minute to hours for a single model

Hydrodynamical simulations

(e.g. Starsmasher, Lombardi+06; Phantom, Price+18)

Millions of CPU hours for simulating a binary process



Rapid population synthesis codes

Analytic, semianalytic formalisms for:

- Stellar evolution
- Binary processes

<< second for a complete binary evolution

Millions binaries in hours!

Credits: G. Iorio

Stellar EVolution N-body

Iorio+23 (Based on the original idea by Spera+19)

Gitalb Public repository: https://gitlab.com/sevncodes/sevn

Single Stellar Evolution

- Stellar evolution through **interpolation of precomputed stellar tracks**
- Precomputed stellar tracks can be easily added to use the **most updated stellar evolution models**

```
./sevnB.x  −tables tables/SEVNtracks_parsec_AGB
```

Enable the explorations of different stellar evolution models

Binary evolution

- **Analytic/Semi-analytic prescriptions:**
  - Wind mass accretion
  - Roche-Lobe overflow
  - Stellar tides
  - Common Envelope
  - GW orbital decay
  - Hardening

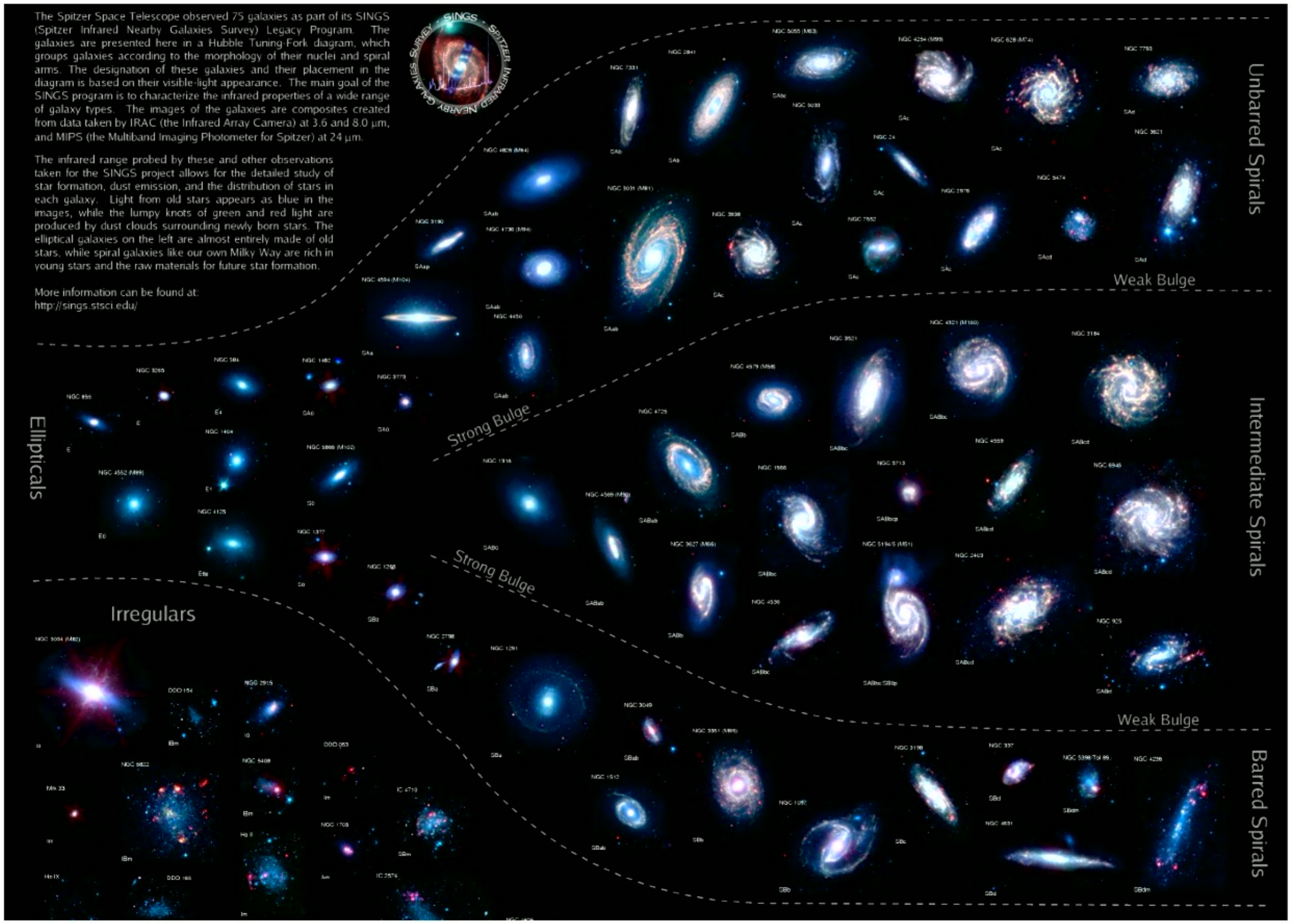
>4 SN models and variations

(Fryer+12, Wooesly+19, Mapelli+20, Patton&Sukhbold+20,Woosley+20)

2 PISN models

(Farmer+19,Mapelli+20)

Why the Host Galaxies of Merging Binary Compact Objects?



<u>Star forming vs. Quenched galaxies</u>

Dependence with cosmic star formation rate? Old globular clusters vs young stellar clusters? (Antonini & Rasio 2016, Choksi+2018,2019, Di Carlo+2020, Portegies Zwart & McMillan 2020, Rastello+2020, Rodriguez+2021)

<u>Metal poor vs. Metal rich galaxies</u>

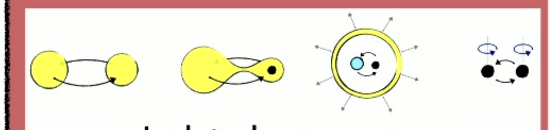
The metallicity of the stellar progenitors is a main driver of the compact object masses (Eldridge & Stanway 2016 Stevenson+2017, Mapelli+2017, Giacobbo & Mapelli 2018, Spera+2019)

<u>AGN vs. No AGN</u>

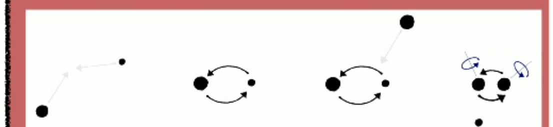
BBH dynamically formed in accretion disks (Bartos+2017, McKernan+2018, Tagawa+2020, Vaccaro+2024)

Why the Host Galaxies of Merging Binary Compact Objects?

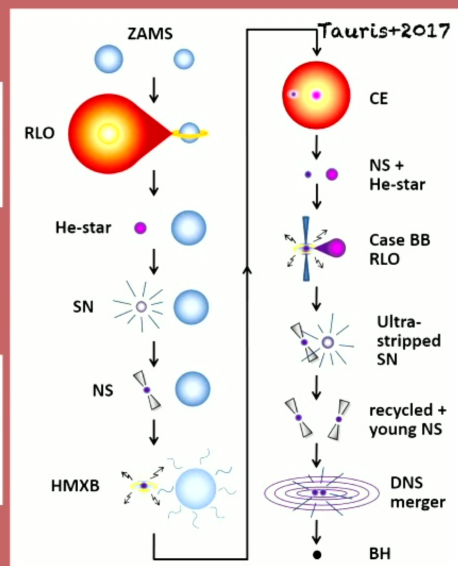
Constrain stellar evolution pathways and possible formation channels



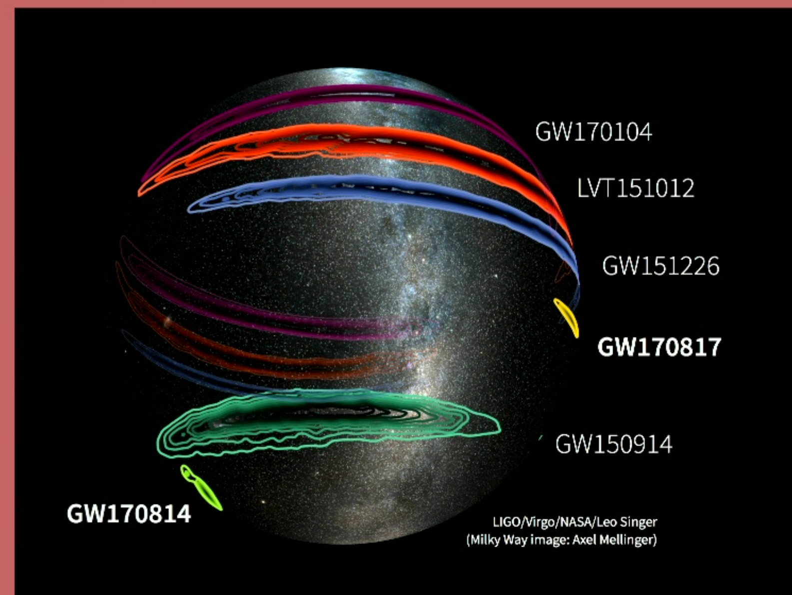
Isolated common envelope evolution



Dynamical formation in stellar clusters



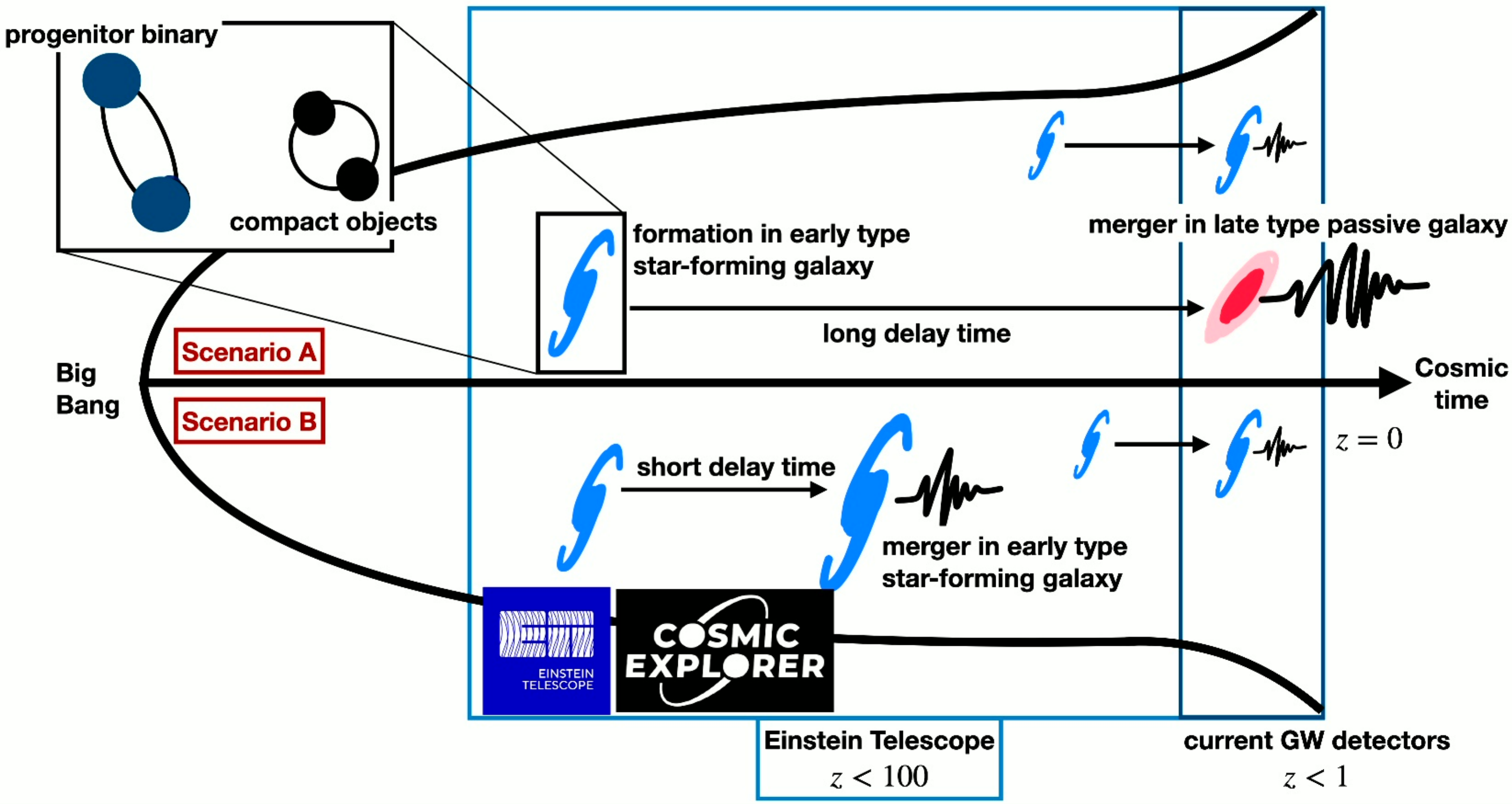
Help to identify the EM counterpart of GW events



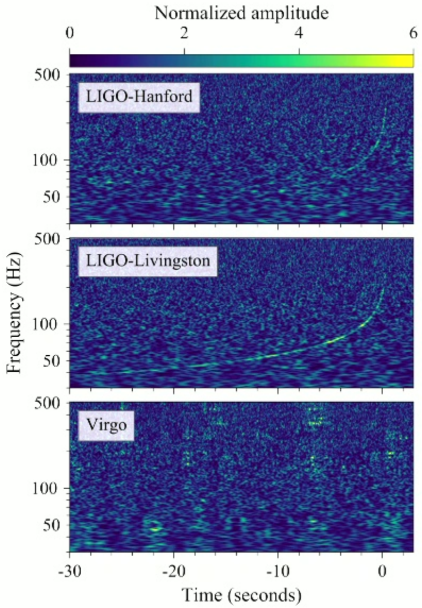
Sky localisation (O1, O2, O3) ~ 10 - 1000 deg^2

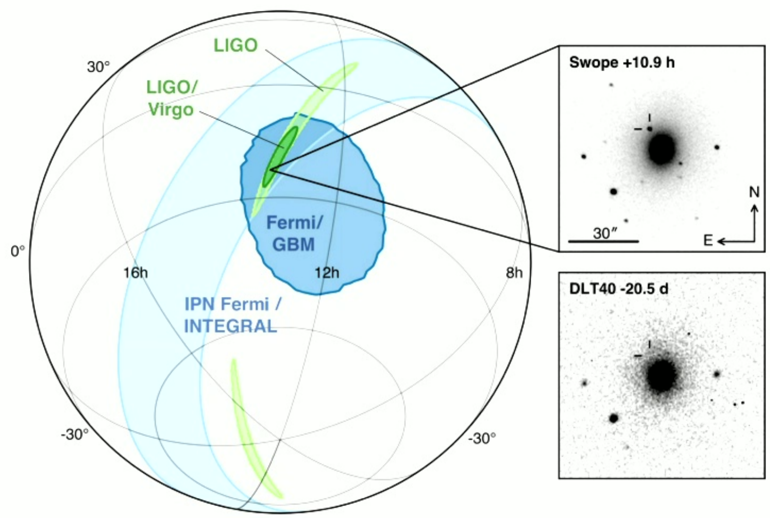
AMONG OTHERS!

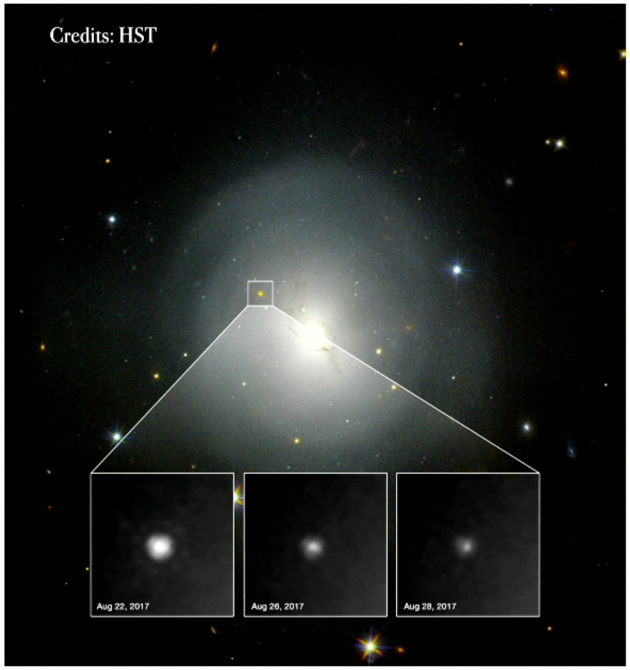
Mix of GW inspired times: unique proves to study stars and stellar mass remnants across cosmic time



Special cases: GW170817
First BNS detected + electromagnetic counterpart



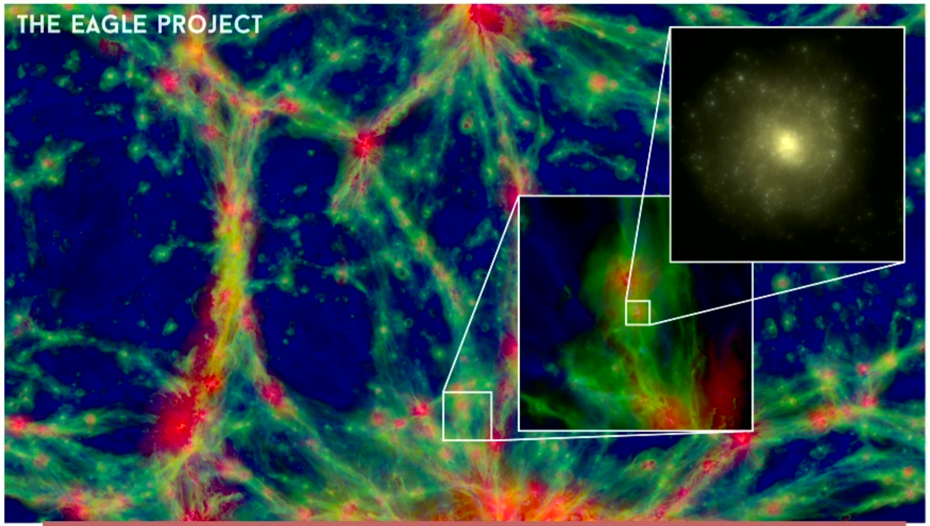


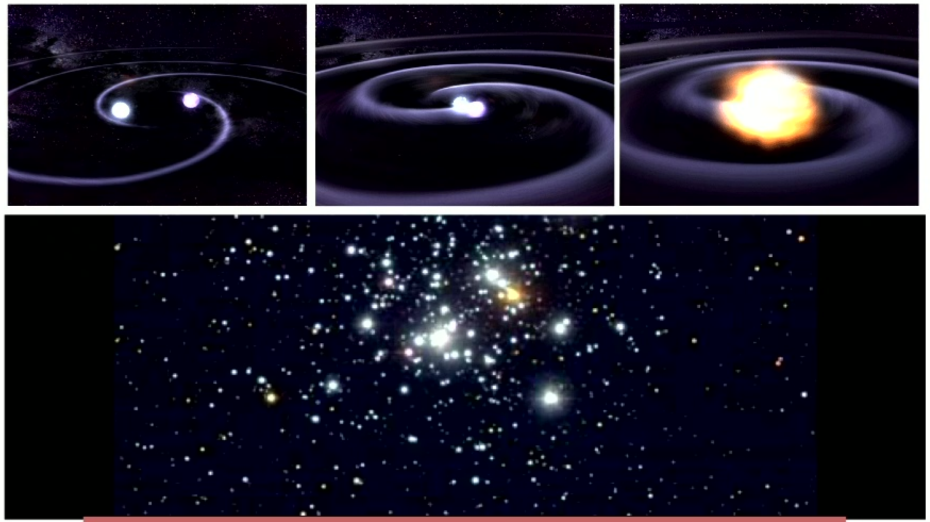


The Host Galaxy
NGC 4993: Early-type galaxy
$M_* = (0.3\text{-}1.3)\times10^{11}\ M_\odot$
Most of its SF taken place ~11Gyr ago

Tension between the models and NGC 4993?

Methodologies for Binary Compact Objects and Host Galaxies

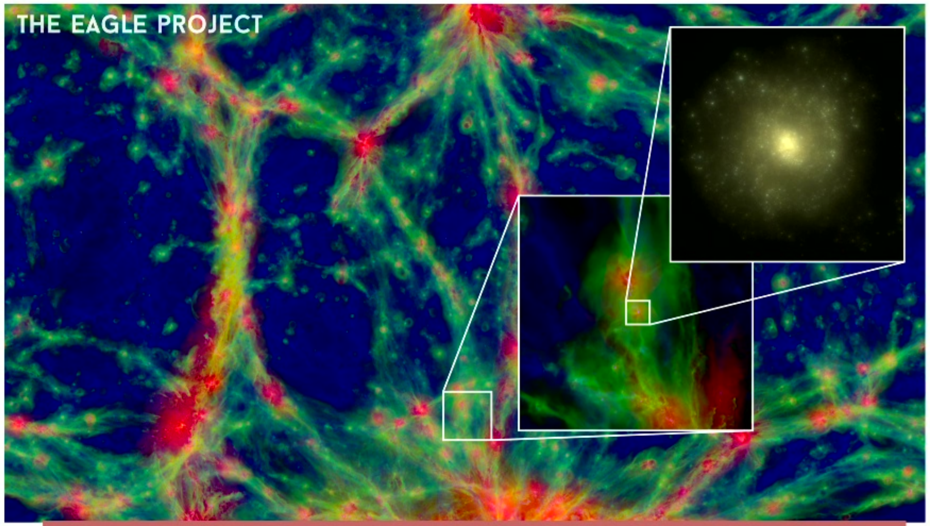




Galaxy Formation and Evolution:
- Hydrodynamical cosmological simulations
- Empirical models (merger trees + scaling relations)
- Observations

Stellar Evolution:
- Population synthesis models (isolated binaries)
- N-body simulations (stellar clusters)
- Analytical descriptions/models

Methodologies for Binary Compact Objects and Host Galaxies



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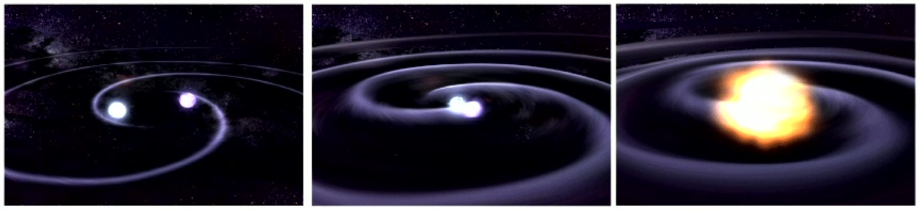


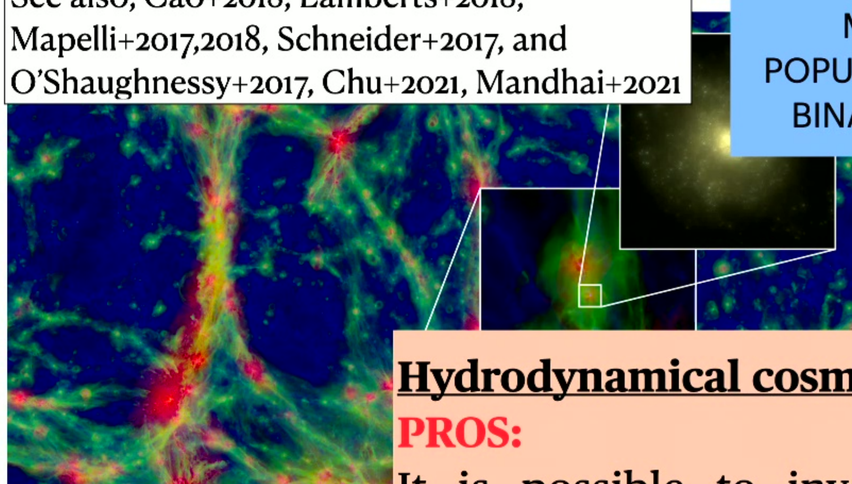
<u>Stellar Evolution:</u>

- Population synthesis models (isolated binaries)
- N-body simulations (stellar clusters)
- Analytical descriptions/models

Methodology I: Using Cosmological Simulations

We mimic the population of binary compact objects in simulated galaxies:
galaxy catalog + binary compact object models

See also, Cao+2018, Lamberts+2018, Mapelli+2017,2018, Schneider+2017, and O'Shaughnessy+2017, Chu+2021, Mandhai+2021



MONTE CARLO CODE
POPULATE THE GALAXIES WITH
BINARY COMPACT OBJECTS

Hydrodynamical cosmological simulations

PROS:

It is possible to investigate the internal properties and distribution of the binary compact object mergers within the galaxies

CONS:

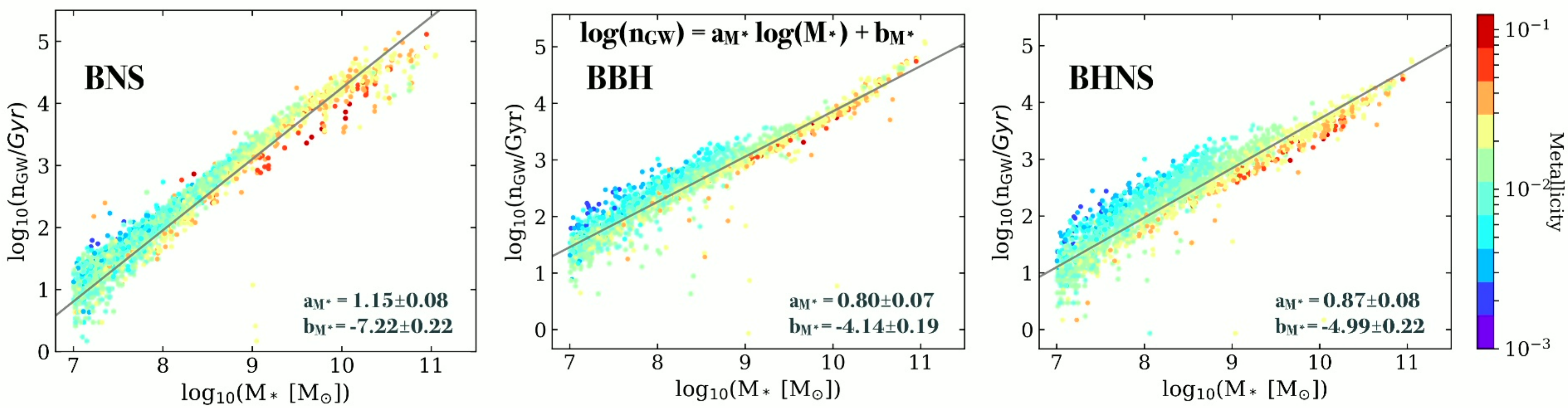
i) demands significant number of CPU hours

ii) depends on the sub-grid physics behind the simulation

Host galaxies in the local Universe

Merger rate per galaxy (nGW): the number of compact object mergers per galaxy per unit time

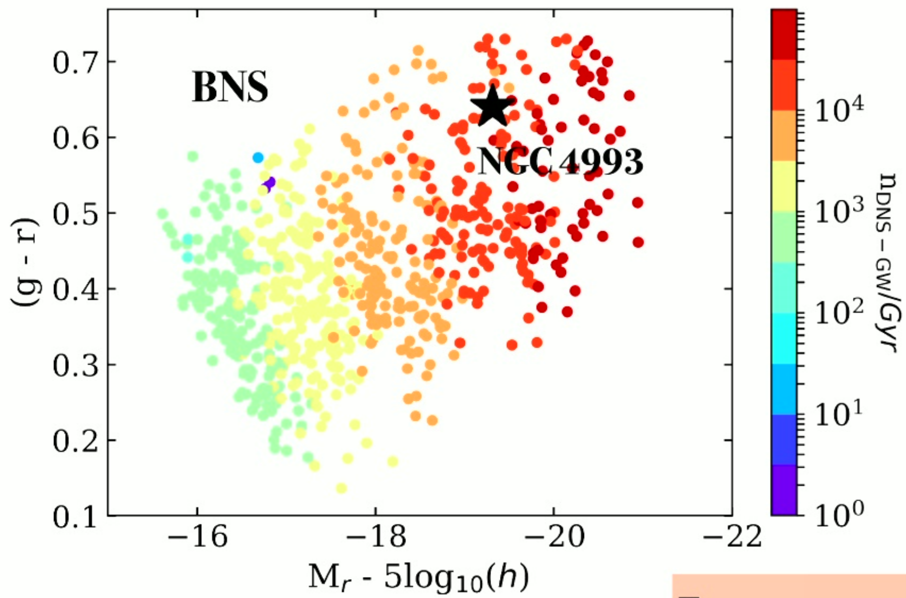
Massive galaxies are the best place to look for merging binary compact objects

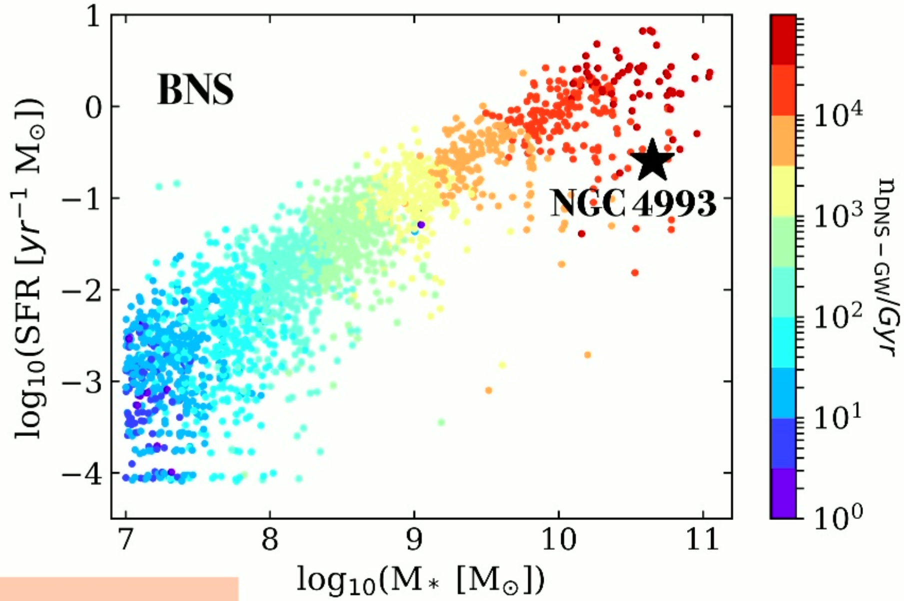


The trend is more important for BNS than for BBH and BHNS. BBH and BHNS show a strong dependence with metallicity

See Artale+2019, Artale+2020a, Artale+2020b

Host galaxies in the local Universe
In the context of NGC 4993



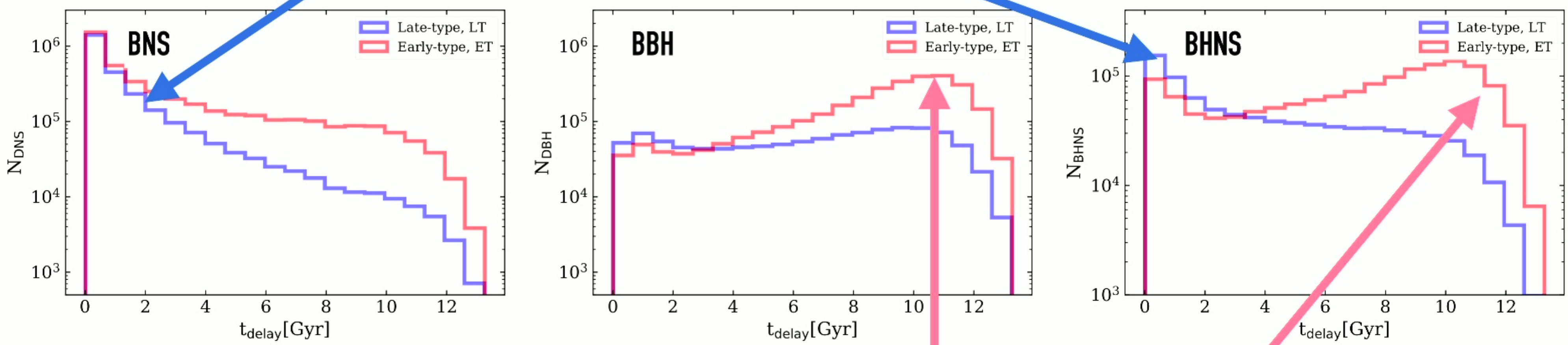


From our results:
$n_{GW,NGC4993} \sim 3 - 107$ Myr^{-1}
$n_{GW,MW\text{-}type} \sim 16 - 121$ Myr^{-1}
(in agreement with Pol+2019)

See Artale+2019, Artale+2020a, Artale+2020b

Host galaxies in the local Universe

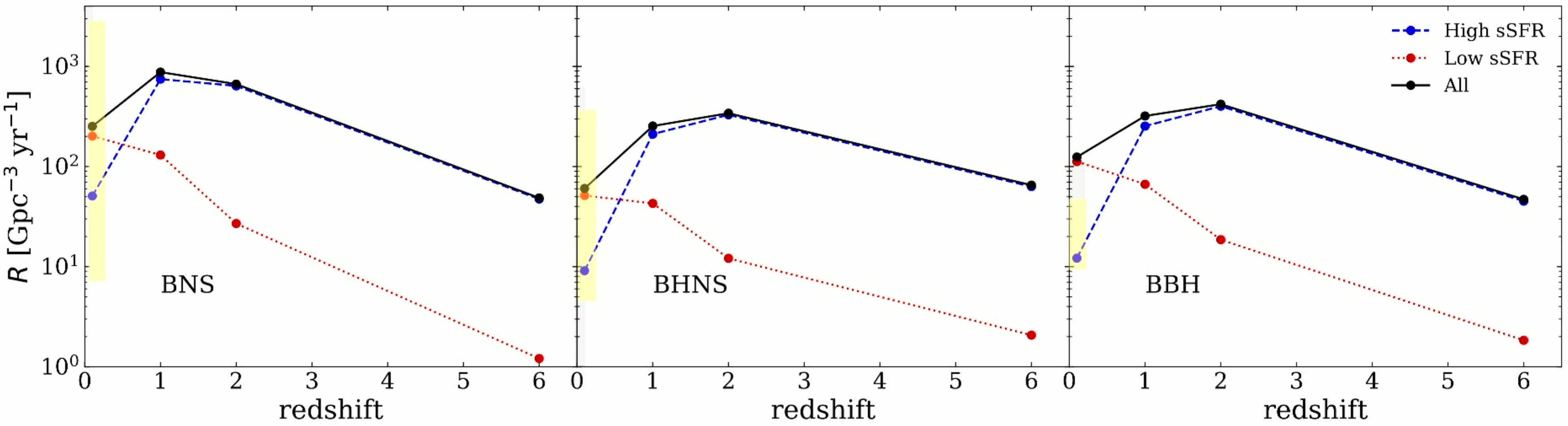
BNS and BHNS: the delay time distribution in LT galaxies ~ t^{-1}
Dominated by compact objects recently formed



BBH and BHNS: ET galaxies has a long delay time. The main episodes of star formation ended several Gyr ago.

See Artale+2019, Artale+2020a, Artale+2020b

The most likely Host Galaxies of GW

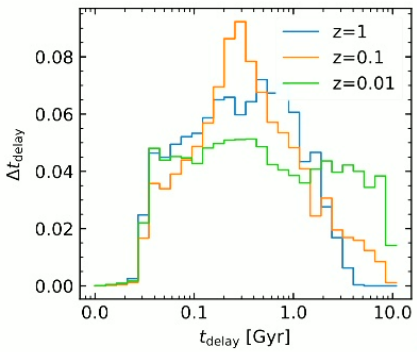


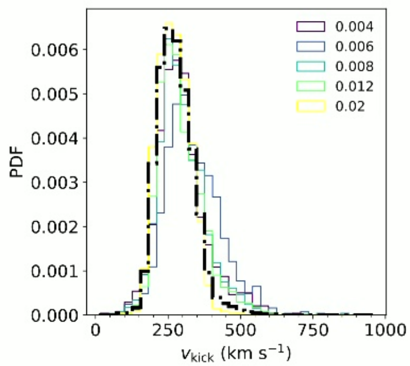
z<0.1: low sSFR galaxies have a larger contribution to the merger rate density than high sSFR galaxies.

This trend reverts at z>1

See Artale+2019, Artale+2020a, Artale+2020b

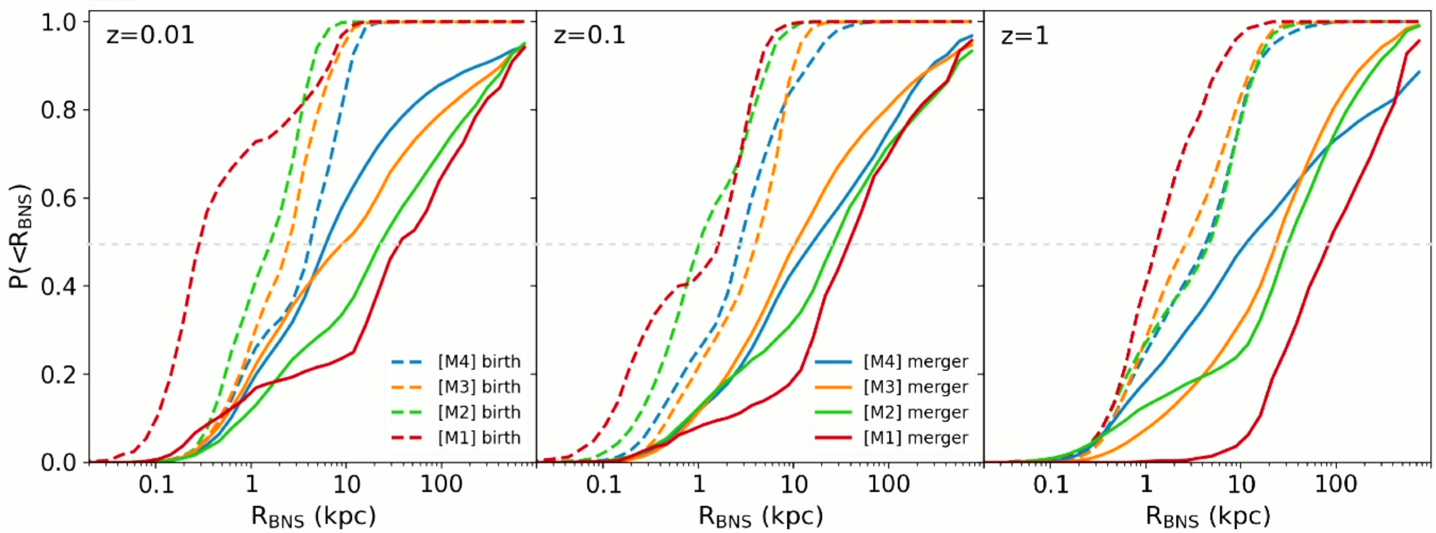
Host Galaxies and EM counterparts of BNS mergers: detectability of GW170817-like events





[M1]: $8 < \log_{10}(M_*/M_\odot) < 8.75$
[M2]: $8.75 < \log_{10}(M_*/M_\odot) < 9.5$
[M3]: $9.5 < \log_{10}(M_*/M_\odot) < 10.25$
[M4]: $10.25 < \log_{10}(M_*/M_\odot) < 11$

With TNG50



BNSs travel more in the smaller galaxies, due to their smaller gravitational potentials.
~40% of BNSs from the galaxy group M1 is found at distances > 25 kpc.

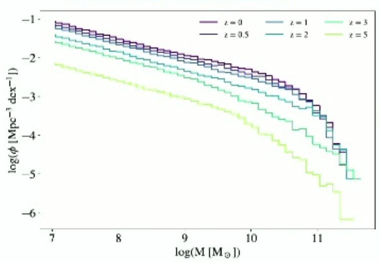
Perna, MCA, Wang, Mapelli, Lazzati, Sgalletta, Santoliquido, MNRAS, 512, 2654 (2022)

Methodology II: Using Scaling Relations

Filippo Santoliquido
(GSSI, Italy)

Based on observational scaling relations between the **stellar mass, SFR and metallicity of the galaxies**

Chruslinska et al. 2019



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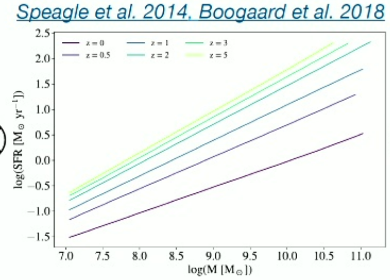
Speagle et al. 2014, Boogaard et al. 2018



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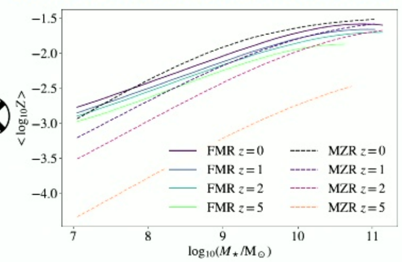
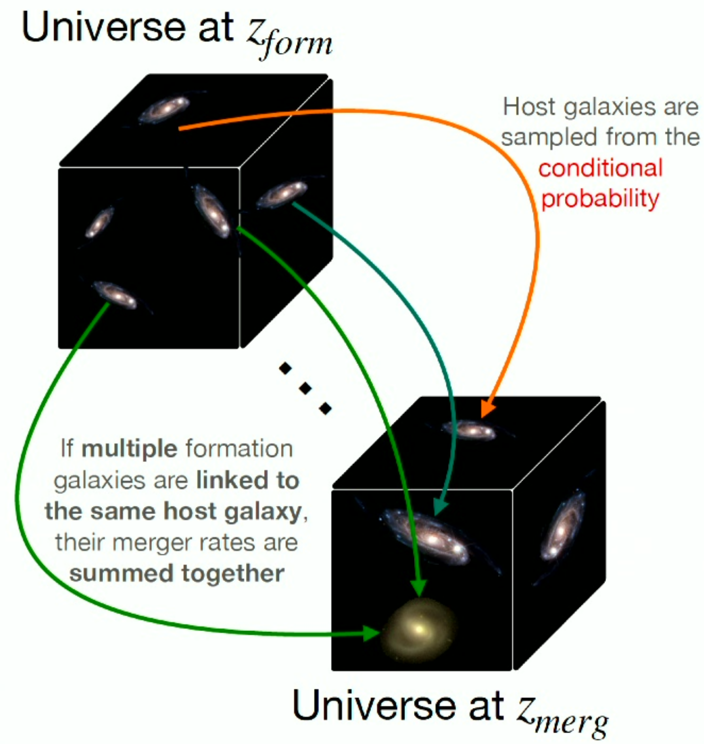
Mannucci et al. 2009, Mannucci et al. 2011

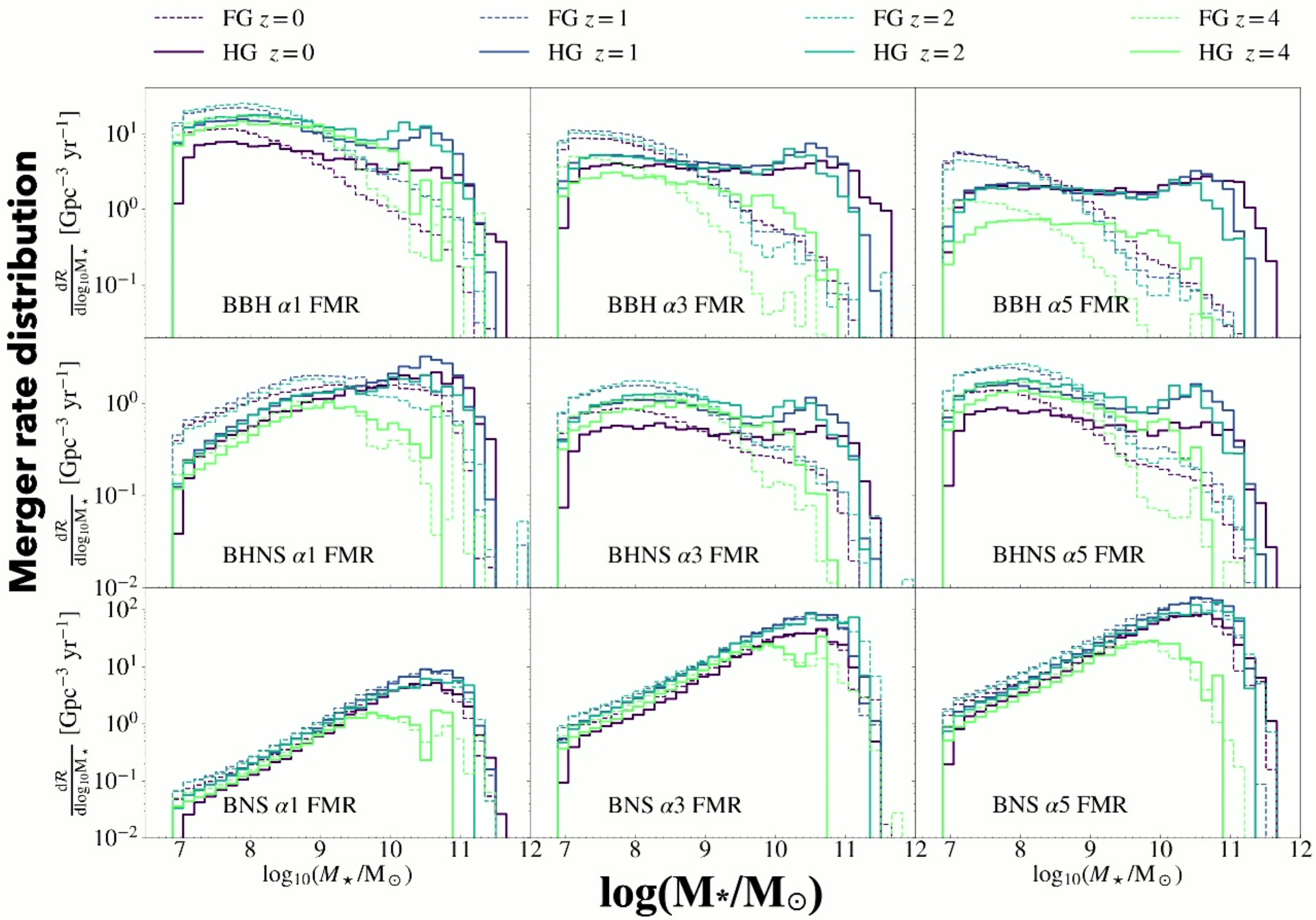




We **link** the properties of the Formation Galaxies (FG) to the properties of Host Galaxies (HG).

1. **Conditional probability.** from the galaxy merger trees of the EAGLE cosmological simulation
2. **Sampling and summing.** one host galaxy for each formation galaxy. Sum together the merger rates that end up in the same host galaxy

GalaxyRate (Using Galaxy Scaling Relations)



FG: galaxies where the binary compact objects <u>form</u>
HG: galaxies where the binary compact objects <u>merge</u>

- Large fraction of BBH is hosted in low-mass galaxies
- The contribution of massive HG increases as alpha increases (longer delay times)

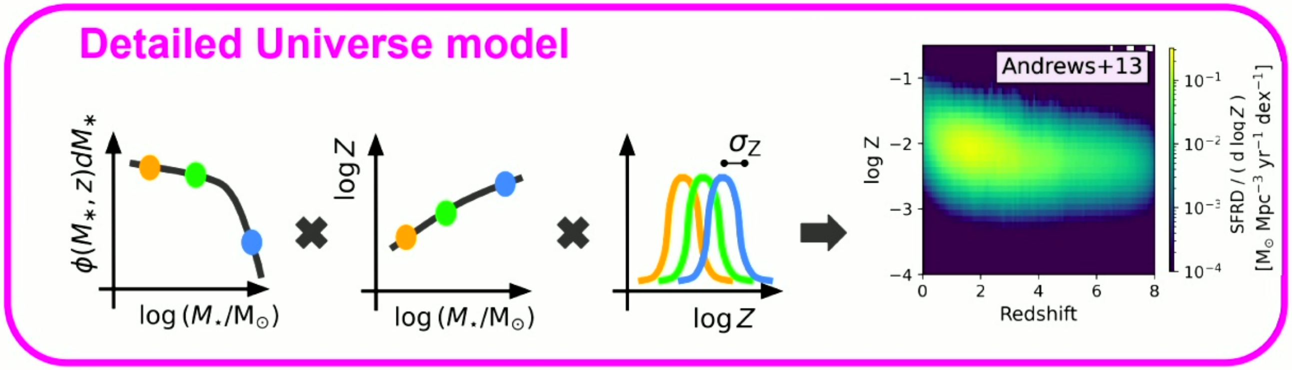
Santoliquido, Mapelli, Artale & Boco, MNRAS, 516, 3297 (2022)

A higher α indicates orbital energy goes into unbinding the envelope (in common envelope phase) more efficiently: wider orbits

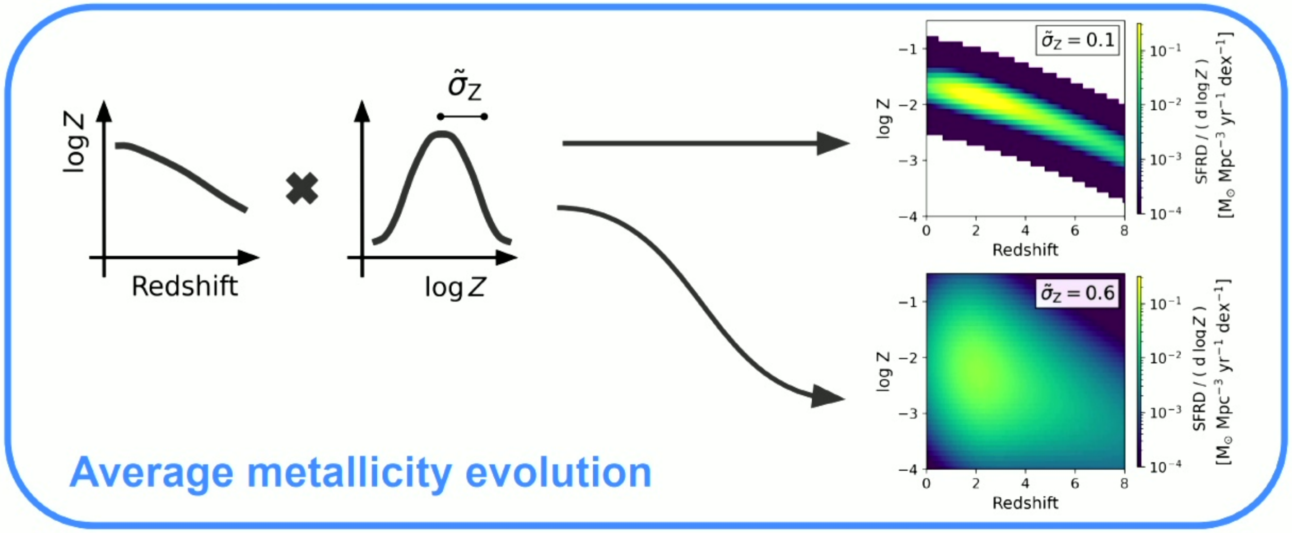
Global vs. Galaxy Scaling Relations

Cecilia Sgalletta
(SISSA, Italy)

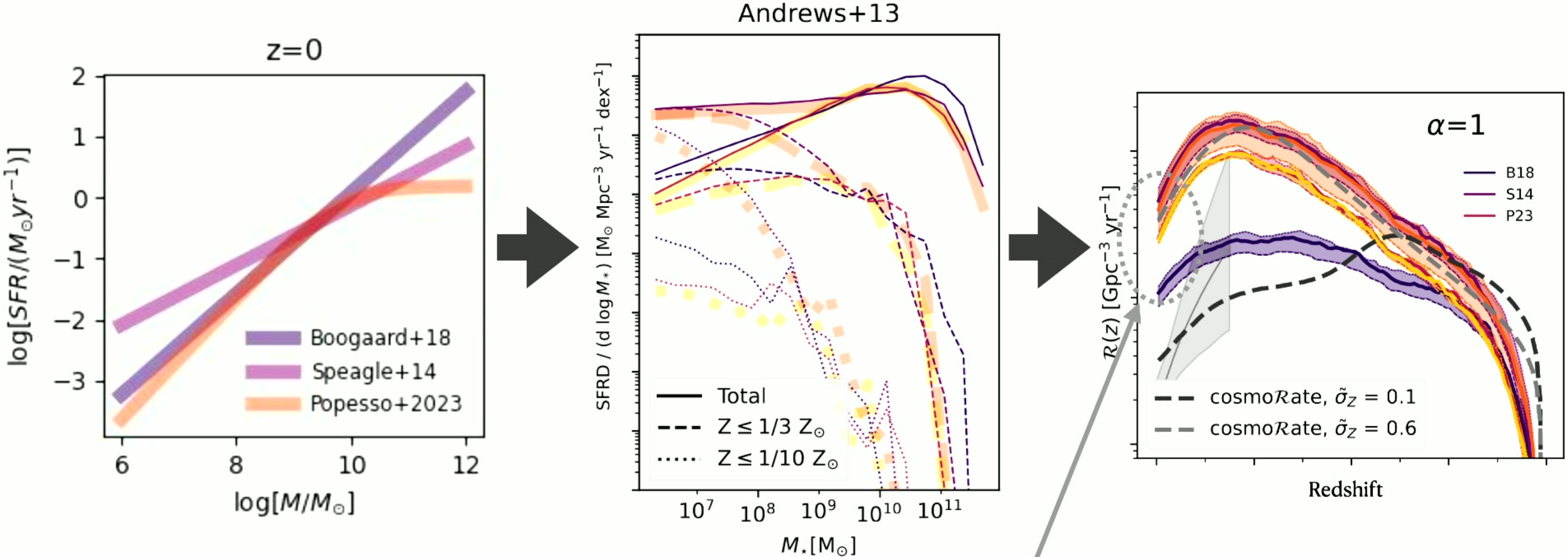
Code: GalaxyRate



Code: CosmoRate

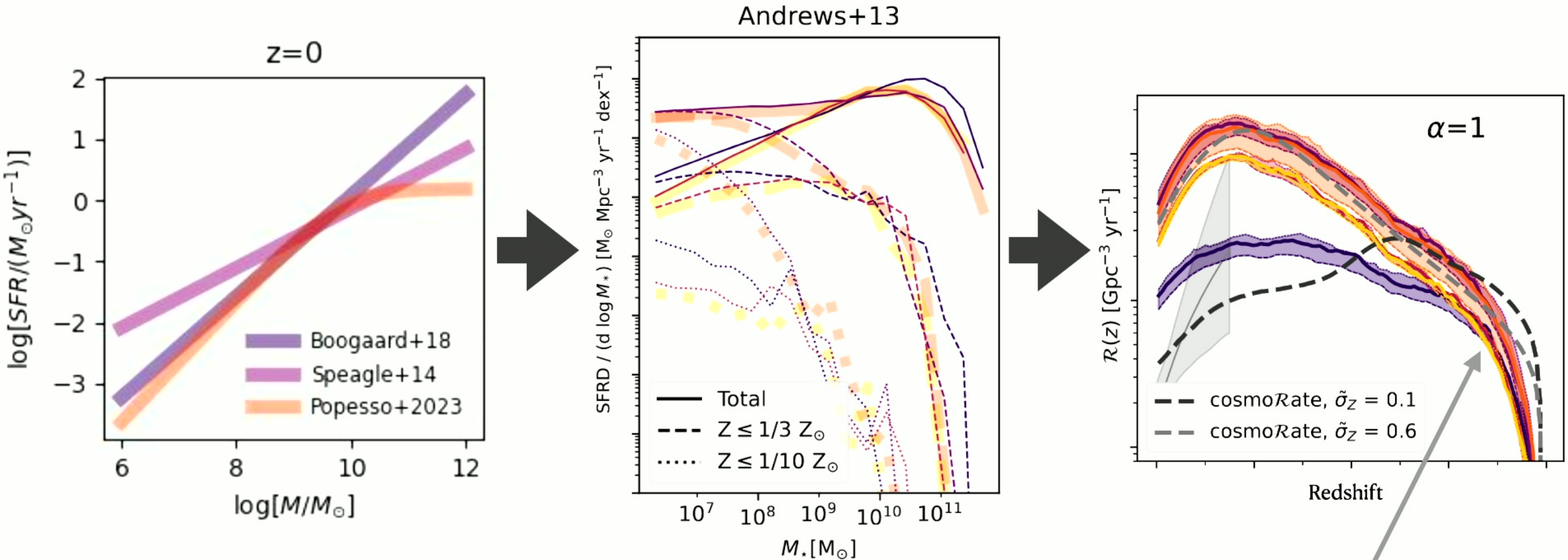


Sgalletta, Mapelli, Boco, Santoliquido, Artale, Iorio, Lapi, Spera (arXiv:241021401)



Low-mass galaxies ($M_{\star} < 10^8 M_{\odot}$) **do not contribute more than a factor of ~2** to the overall BBH merger rate density. Their relative contribution depends on the assumed SFR – galaxy mass relation.

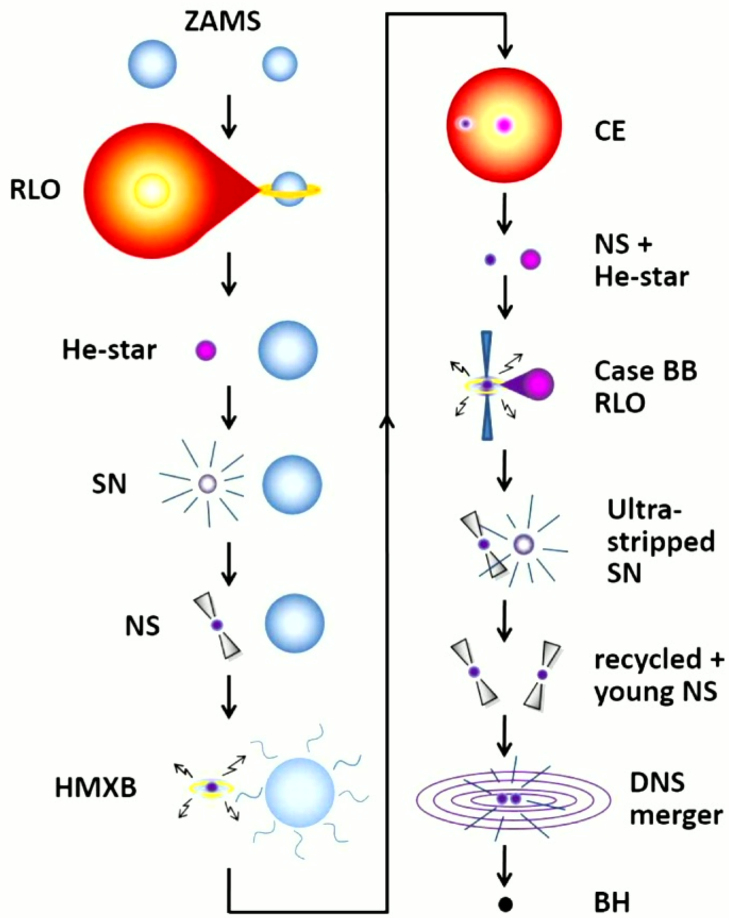
Sgalletta, Mapelli, Boco, Santoliquido, Artale, Iorio, Lapi, Spera (arXiv:241021401)



The merger rate density we obtain modeling the host galaxies with observational scaling relations and the assuming an average SFR density **agree only when we assume a large metallicity spread**

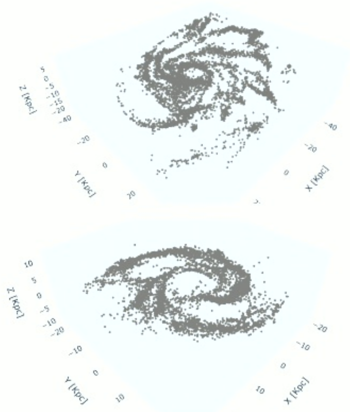
Sgalletta, Mapelli, Boco, Santoliquido, Artale, Iorio, Lapi, Spera (arXiv:241021401)

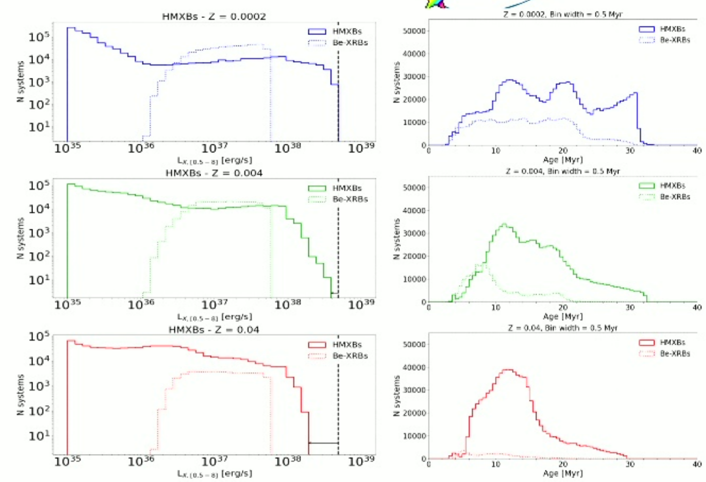
Modelling HMXB in the MW

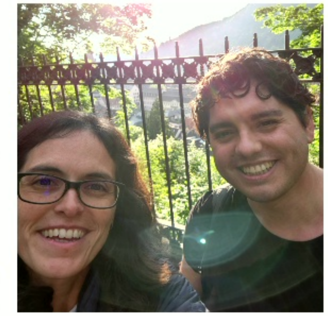


Modelling HMXB in the MW

TNG50 (MW-like)







Felipe Vivanco
(UNAB, Chile)

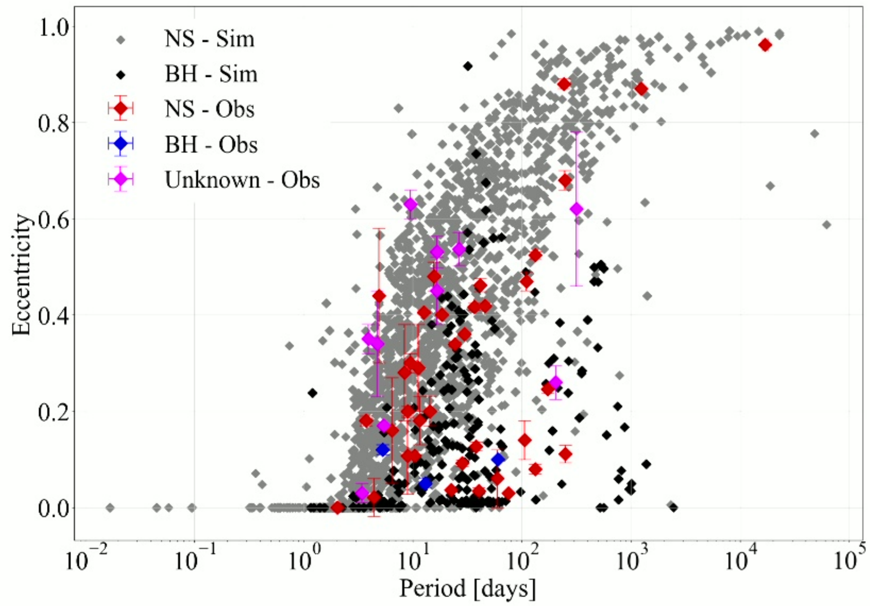
$$N_{HMXBs}\left(Z_*,\ m_*^{TNG50},\ t_*,\ m^{SEVN}_{\odot,Z_*}\right) = \frac{N_i(t_*)}{m^{SEVN}(Z_*)} m_*^{TNG50} f_{corr} f_{bin}$$

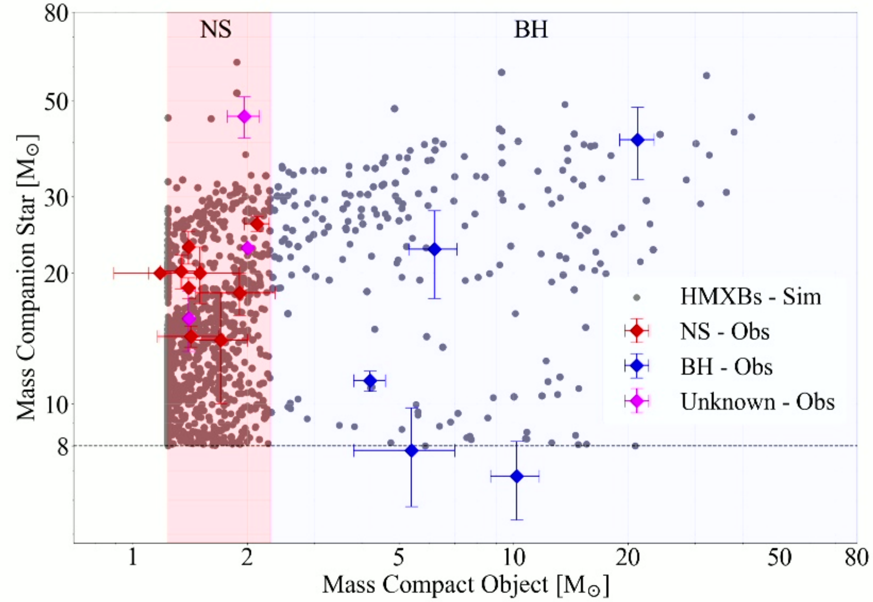
↓

Populated galaxies with HMXBs from the MW/M31-like galaxies from TNG50

Preliminary Results: HMXBs in the MW

Observational data from Fortin+2022





Overall we find good agreement matching the observed HMXB population in the MW

Summary / Take Home Message

We developed two different approaches to investigate the host galaxies of binary compact object mergers (see Mapelli+2017,2018, Artale+2019, 2020a,b, Santoliquido+2022, Sgalletta+2024):

Galaxy catalogs combined with stellar evolution models

Hydrodynamical cosmological simulations

PROS:

It is possible to investigate the internal properties and distribution of the binary compact object mergers within the galaxies

CONS:

i) demands significant number of CPU hours

ii) depends on the sub-grid physics behind the simulation

Empirical models (merger trees + scaling relations)

PROS:

Extremely fast to run (~2.5×10^2 CPU hours). We can explore the parameter space of stellar evolution models and galaxy constrains

CONS:

investigate the internal properties of the binary compact object mergers within galaxies is not possible

Summary / Take Home Message

- Strong correlation between the binary compact object merger rate per galaxy and the host galaxy stellar mass (see Artale+2019, 2020a,b, Santoliquido+2022)
- Contribution of high-mass galaxies increases with increasing alpha (Santoliquido+2022)
- Large fraction of BBHs is hosted in low-mass galaxies (Mapelli+2018, Artale+2019, Santoliquido+2022)
- In the local Universe: the merger rate density is dominated by the merging binary compact objects in galaxies with sSFR $< 10^{-10}$ yr^{-1}. This trend reverts at $z>1$ (Artale+2020a, Santoliquido+2022)
- Next? Understanding more from the point of view of other scenarios (see e.g., Vaccaro et al. 2024 for AGN scenario)