What can we learn about stellar-mass black holes from multi-messenger observations?

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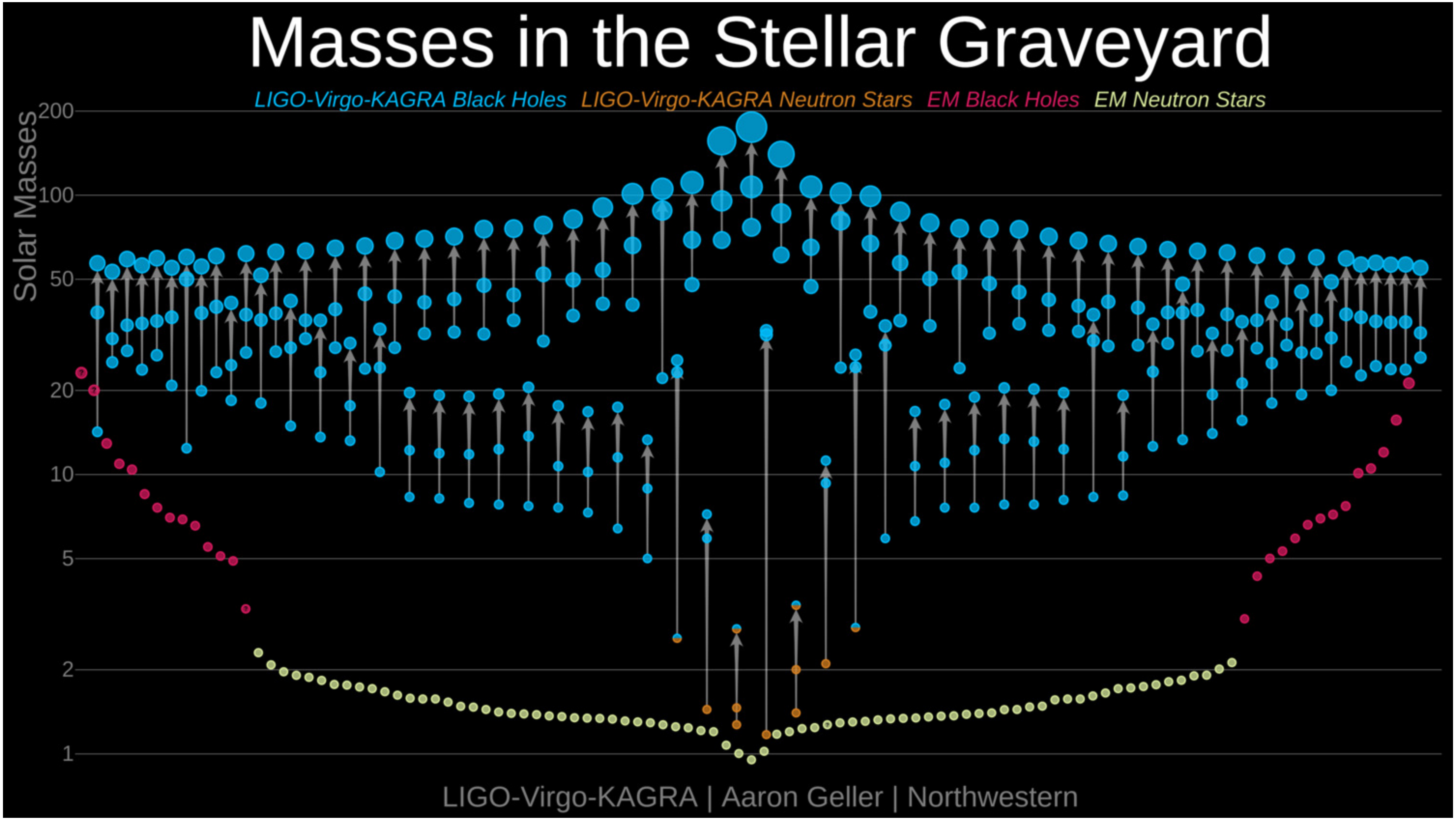
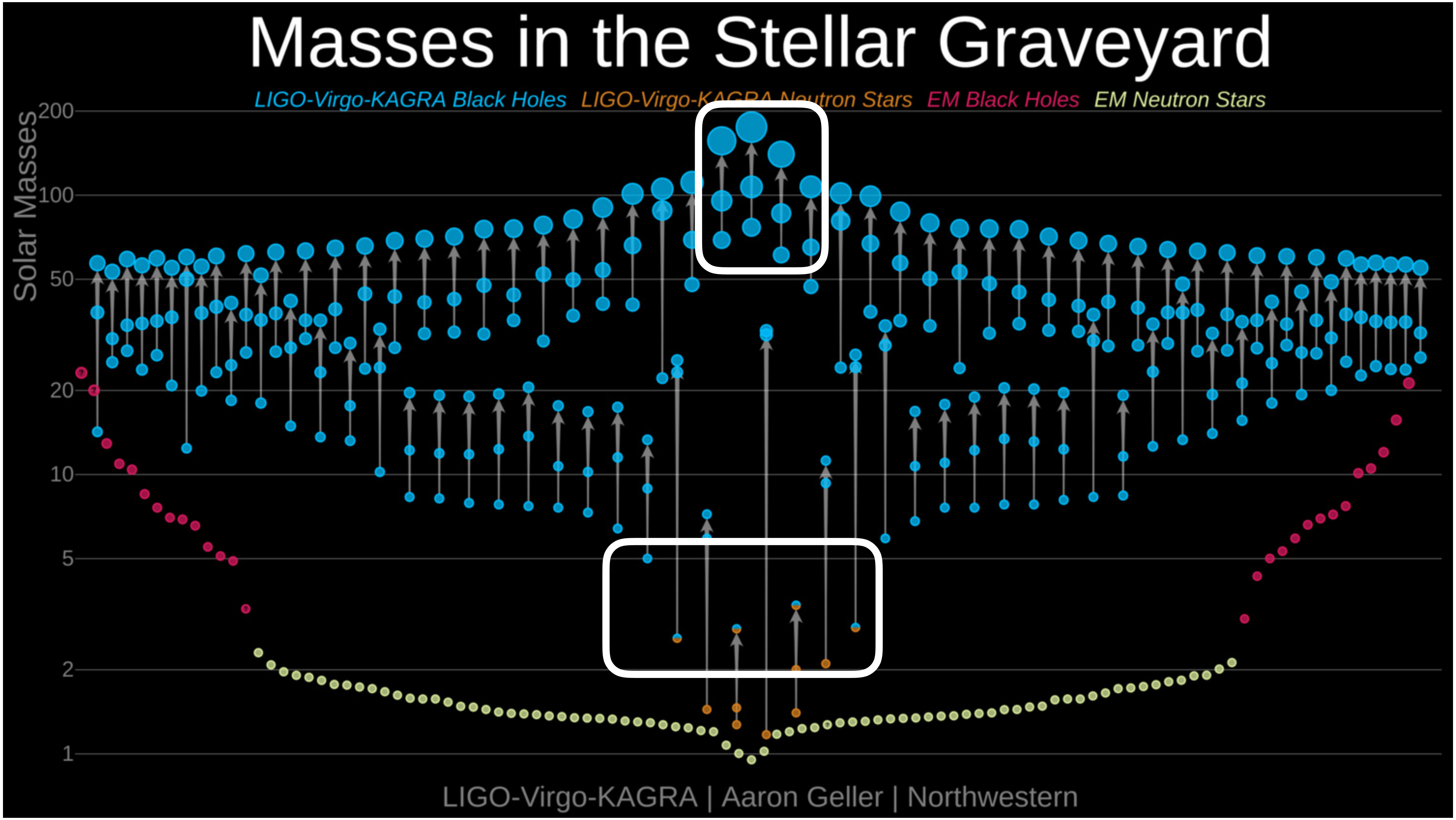


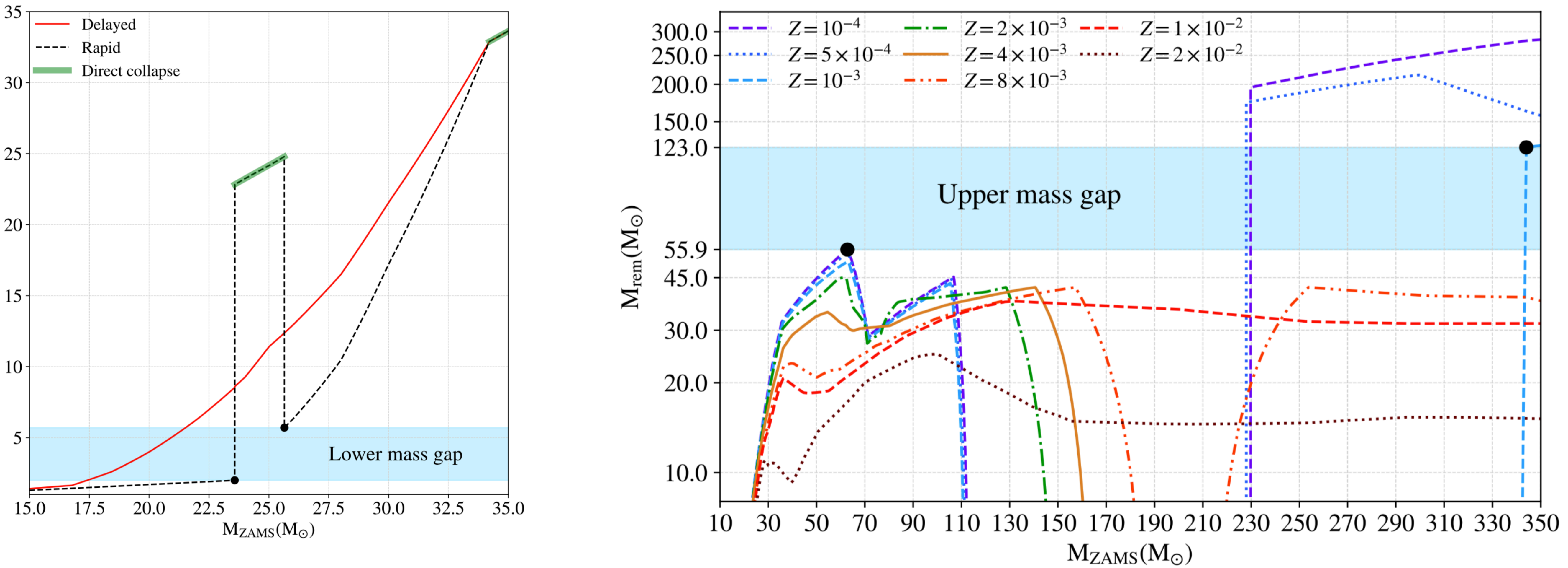
Credit: LIGO-Virgo / Aaron Geller / Northwestern University.



Credit: LIGO-Virgo / Aaron Geller / Northwestern University.

Stellar-mass black holes

- Can standard stellar theory explain BH masses in upper and lower mass gaps?
  - SN explosion mechanism
  - Uncertainties in nuclear reaction rates
- Are GW sources different from Galactic X-ray binaries?



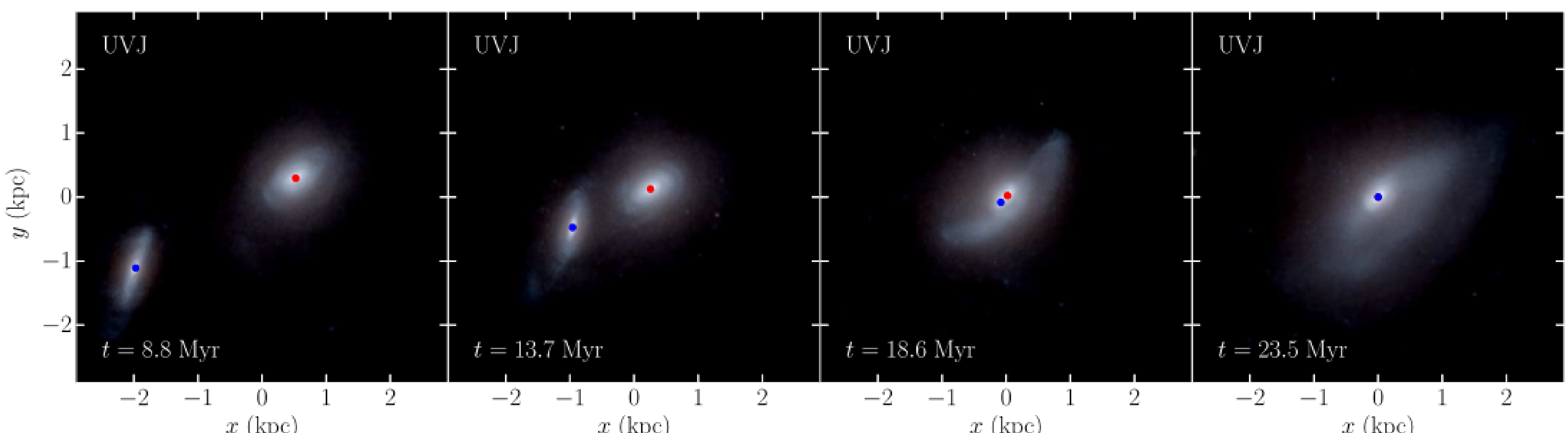
[Spera+2022]

$$M_{BH} \sim 10^5 - 10^9 M_\odot$$

Evolution of massive BH binaries:

[e.g. Barausse 2012; Sesana+2014; Klein+2016; Dayal+2019; Bonetti+2019; Katz+2019; …]

- **Seed BHs** grow through accretion in galactic centers
- Two galaxies that host BHs merge ***(10-100 kpc)***
- Dynamical friction of BHs with surrounding gas —> bound BH binary ***(kpc)***
- Orbit decay through interactions with surrounding gas and stars ***(pc)***
- Emission of GW —> merger ***(milli-pc)***

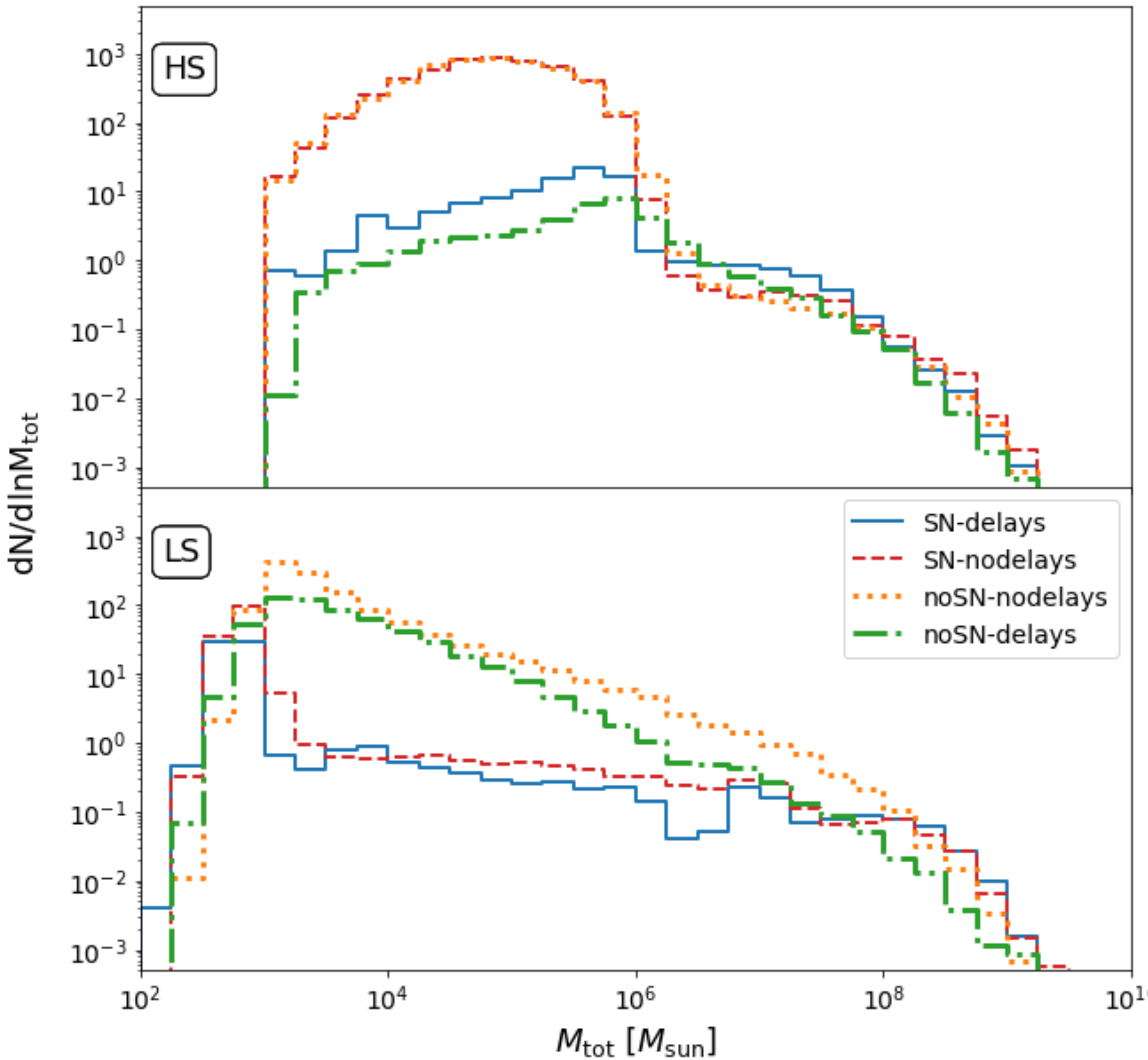


[Khan et al. (2016)]

- Massive black hole binaries are prime target for **LISA**
- Large uncertainties in expected rates
- **IMBH seeds for MBH?**

Tentative detection of a correlated signal by Pulsar Timing Arrays…

[Arzoumanian+20, Goncharov+21, Chen+21]

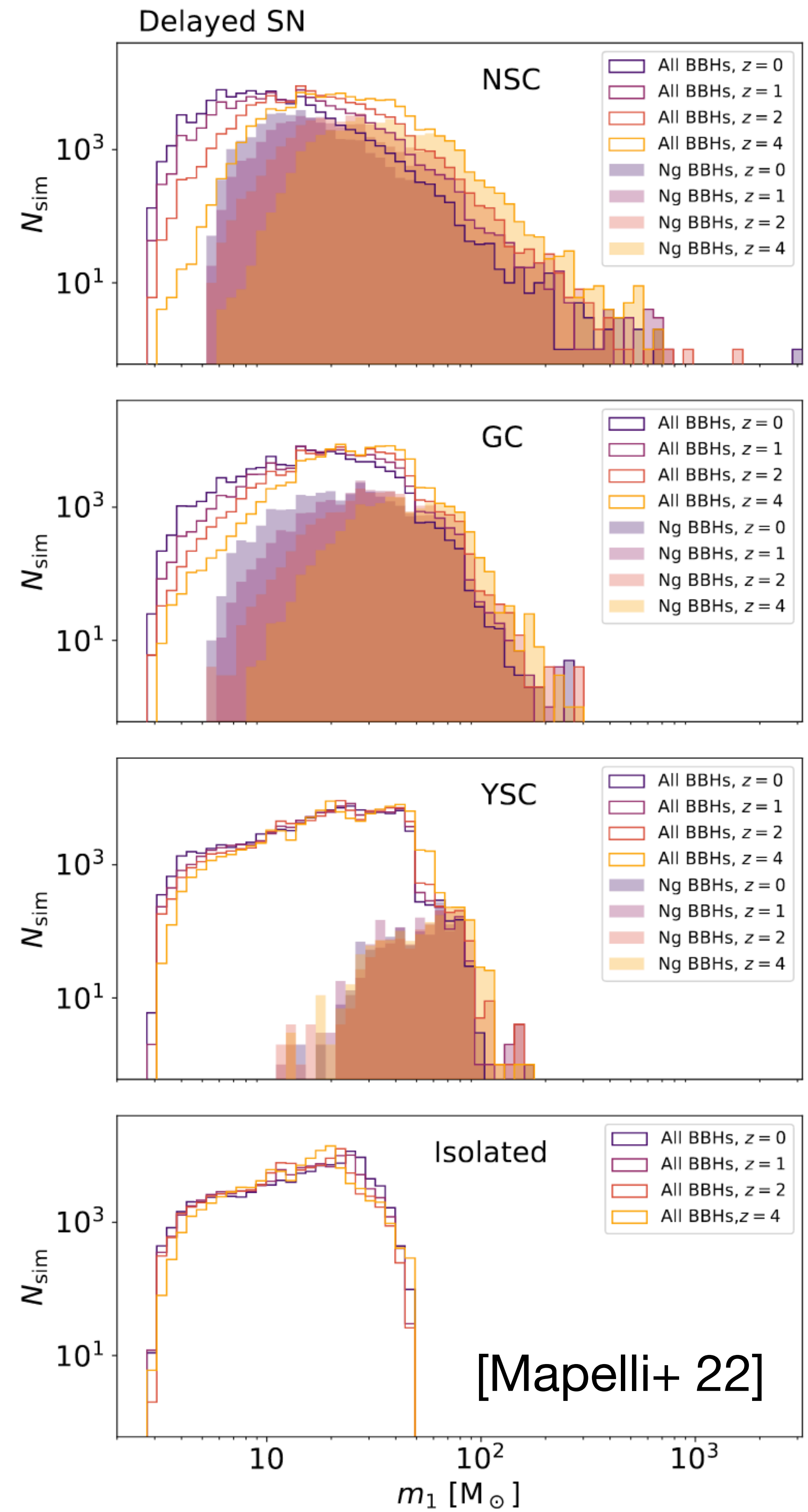


[Barausse, **ID**, Tremmel, Volonteri, Bonetti 2020]

Stellar-mass black hole binaries: formation channels

- Isolated binaries
- Hierarchical formation in dense stellar systems
- AGN disks
- Primordial black holes
- ...

> - Mass distribution
> - Redshifts
> - Host galaxies
> - **EM signal?**



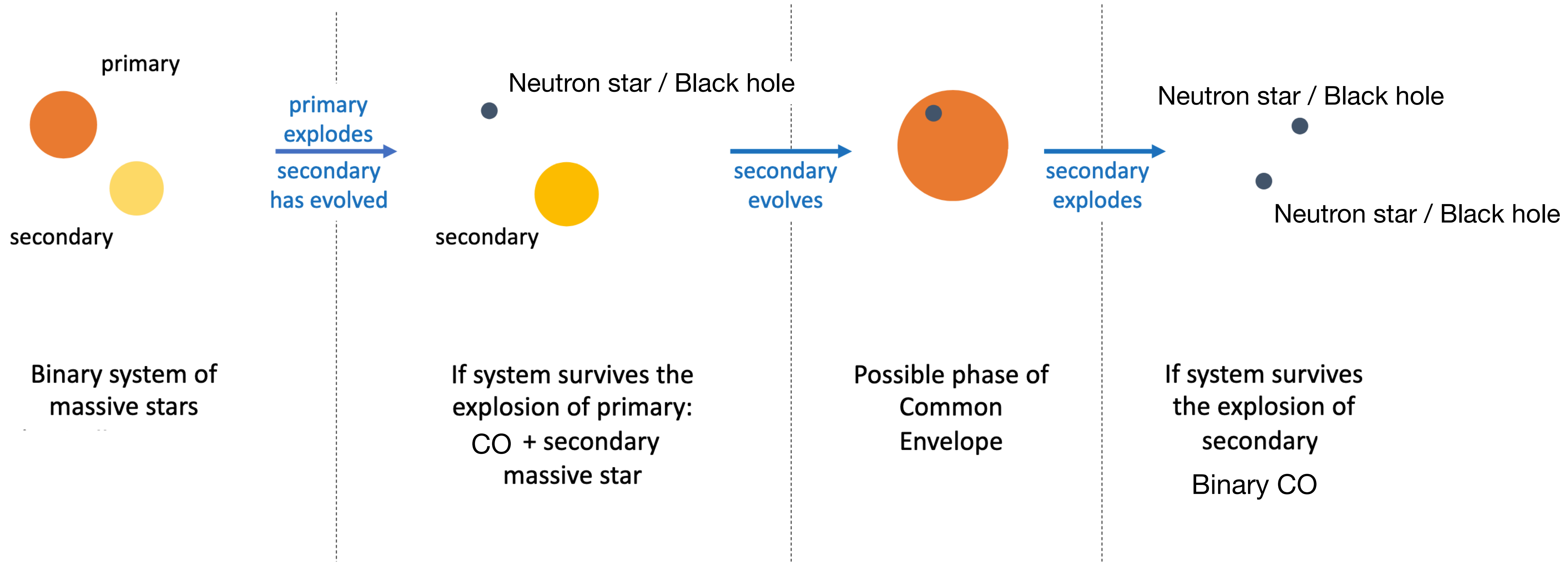
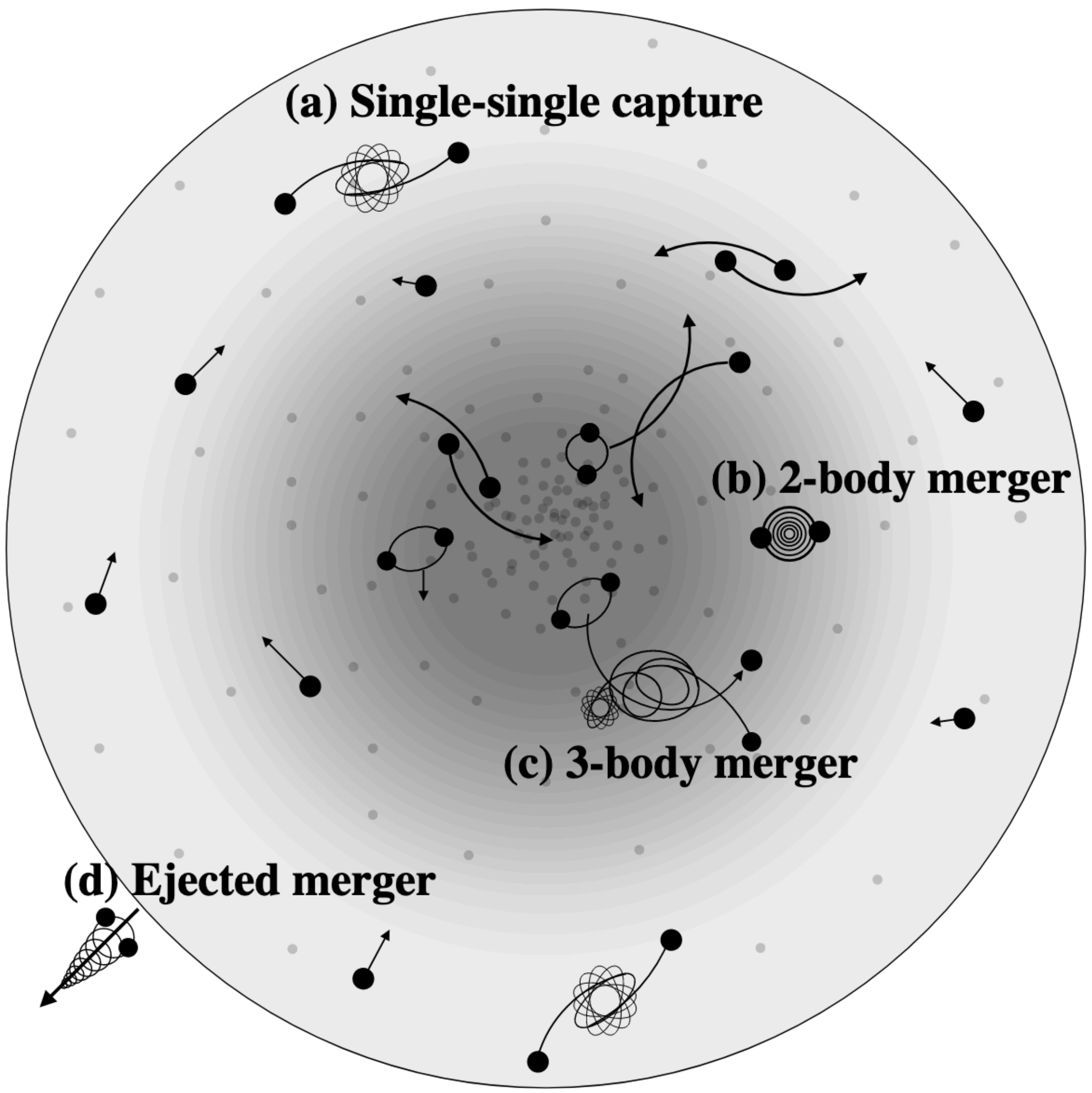
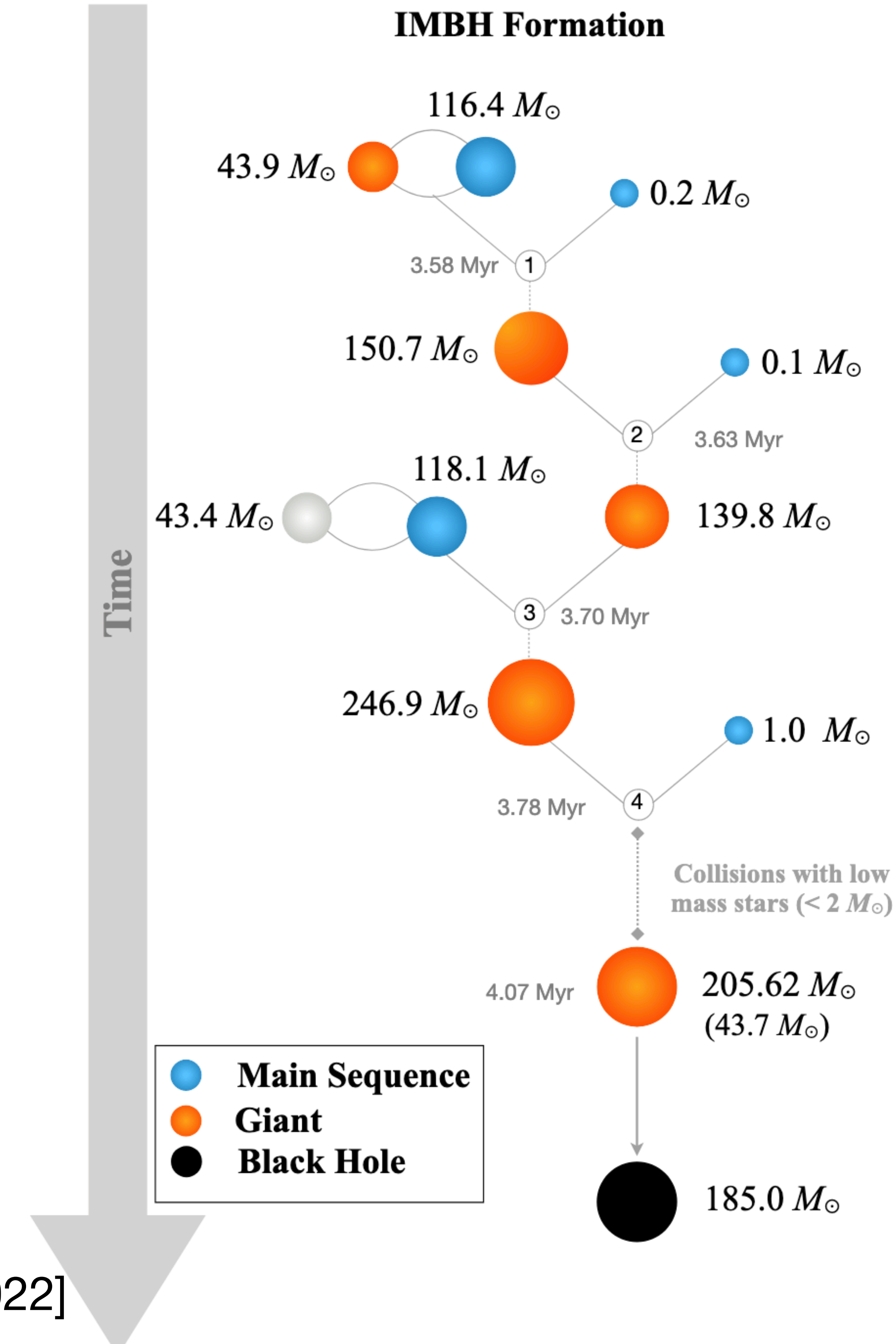


Figure by C. Pellouin

Stellar-mass binaries: dynamical formation channel



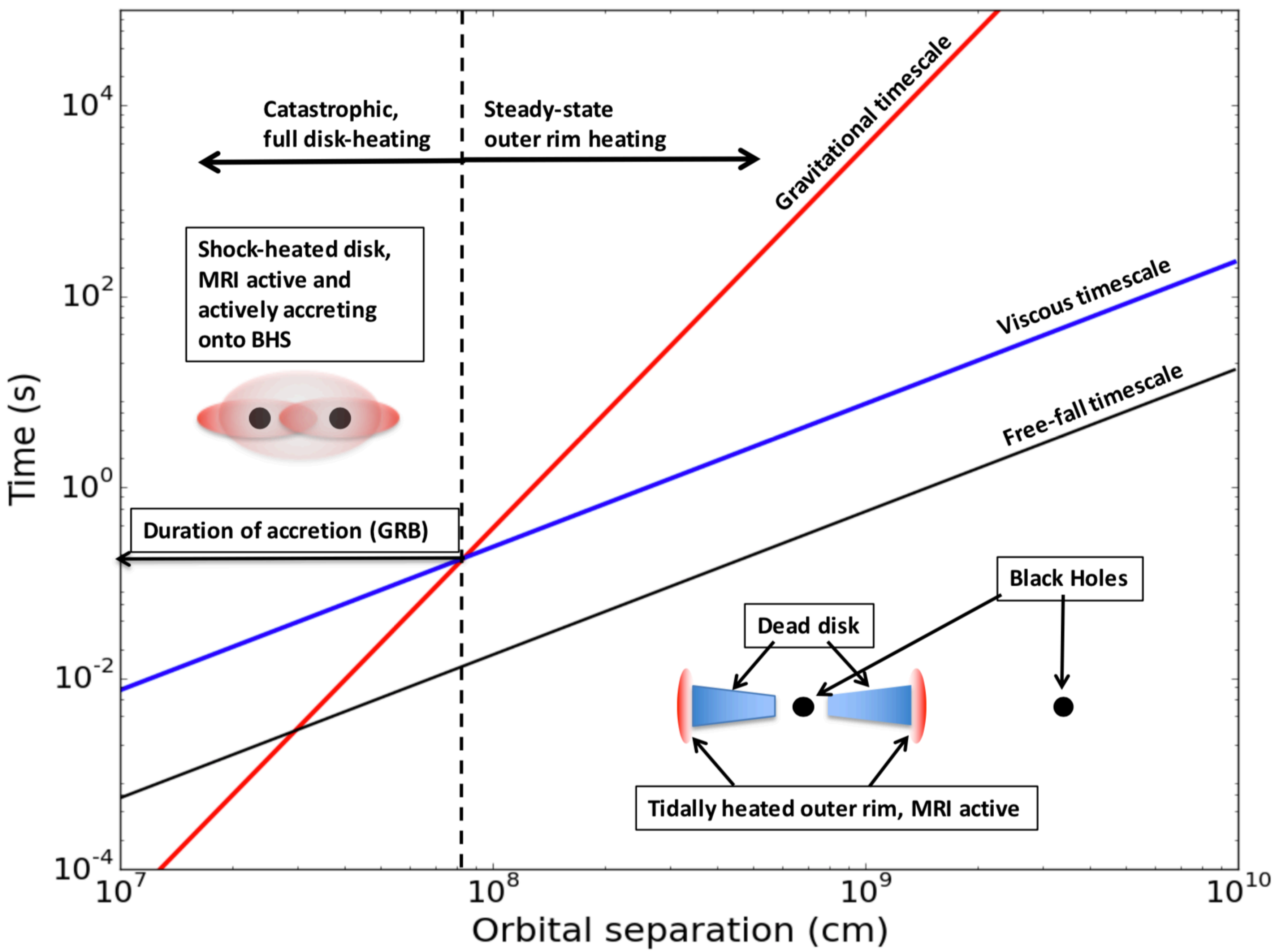
[Samsing+2020]



[Gonzalez Prieto+2022]

- High specific angular momentum of outer layers + weak explosion —> accretion disk
- Disk cools and accretion chokes
- 'Dead' accretion disk surrounding one of the two black holes

[Perna+2016, Murase+2016, Perna+2019]



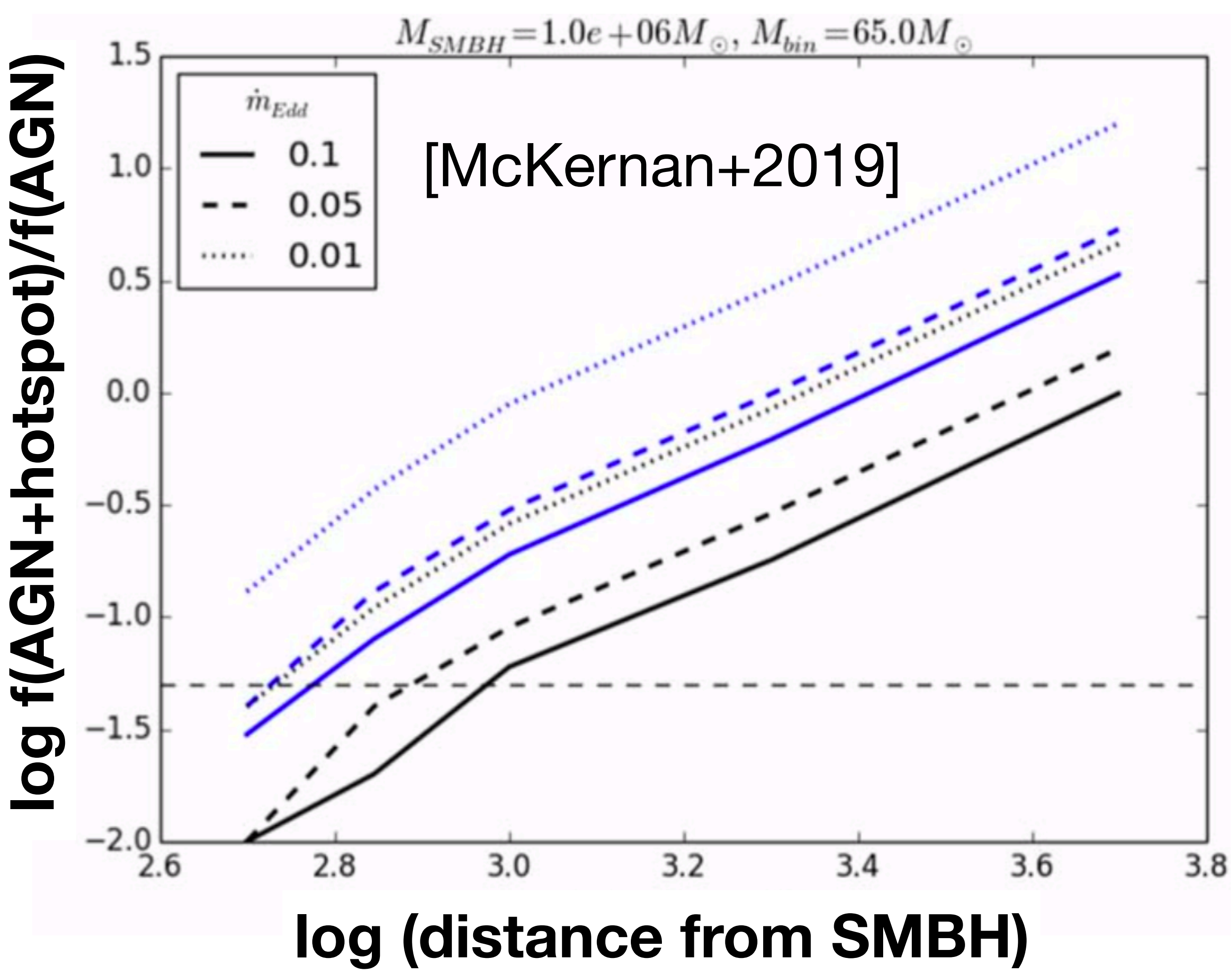
[Perna+2016]

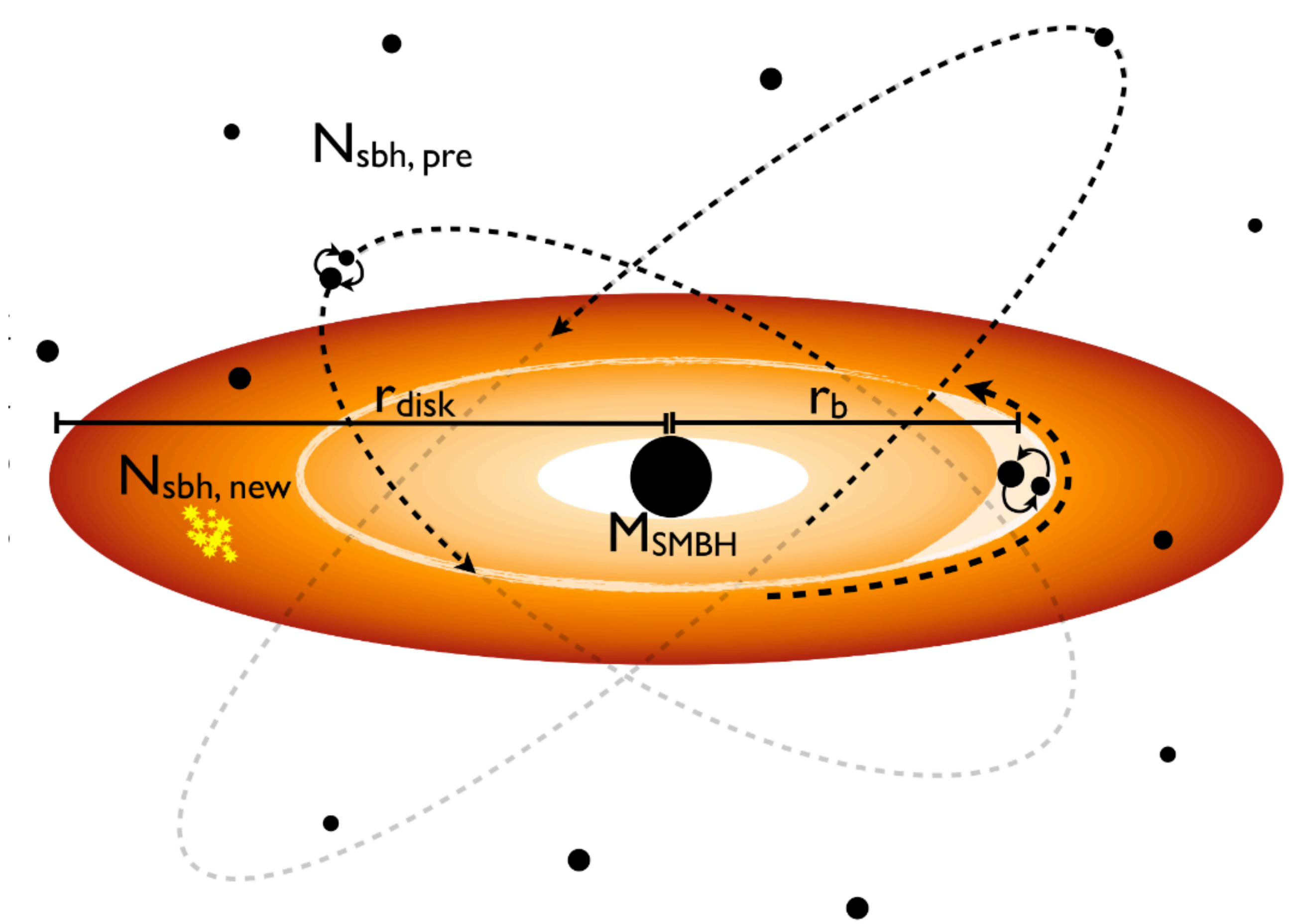
BBH mergers in AGN disks

- AGN + gaseous disk + distribution of BHs
- Some BHs get trapped in the disk
- Torques from gas: BHs migrate within the disk and merge
- BH can grow by gas accretion —> IMBH

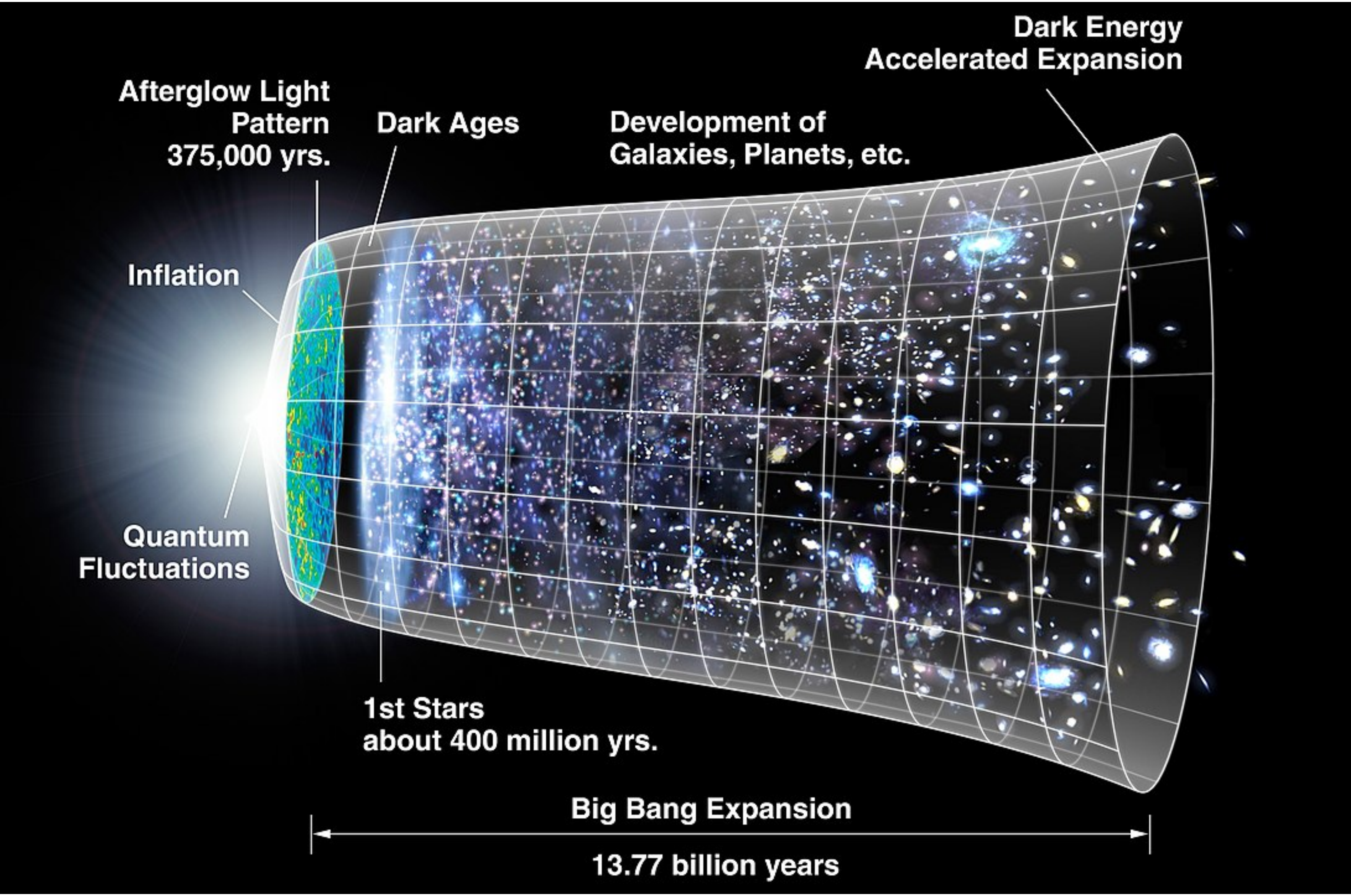
Optical counterpart to GW190521: J124942.3+344929 ? [Graham+2020]

Prompt UV/optical counterpart



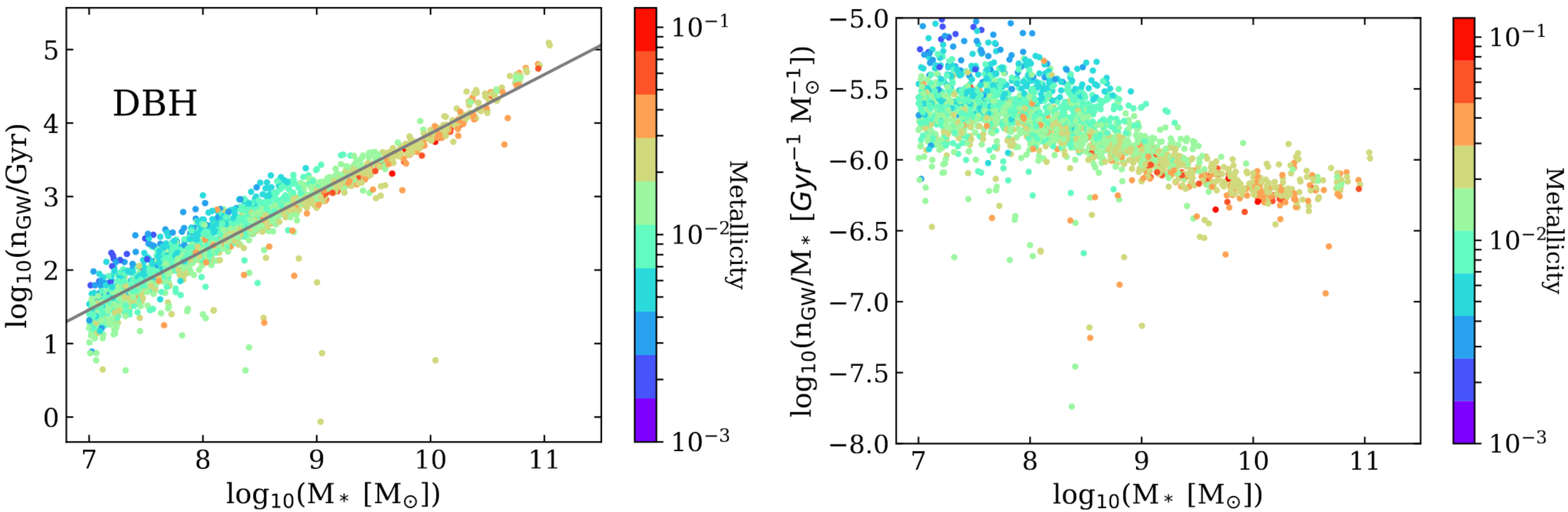


[Saavik Ford+2019: Astro2020 White Paper]



Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

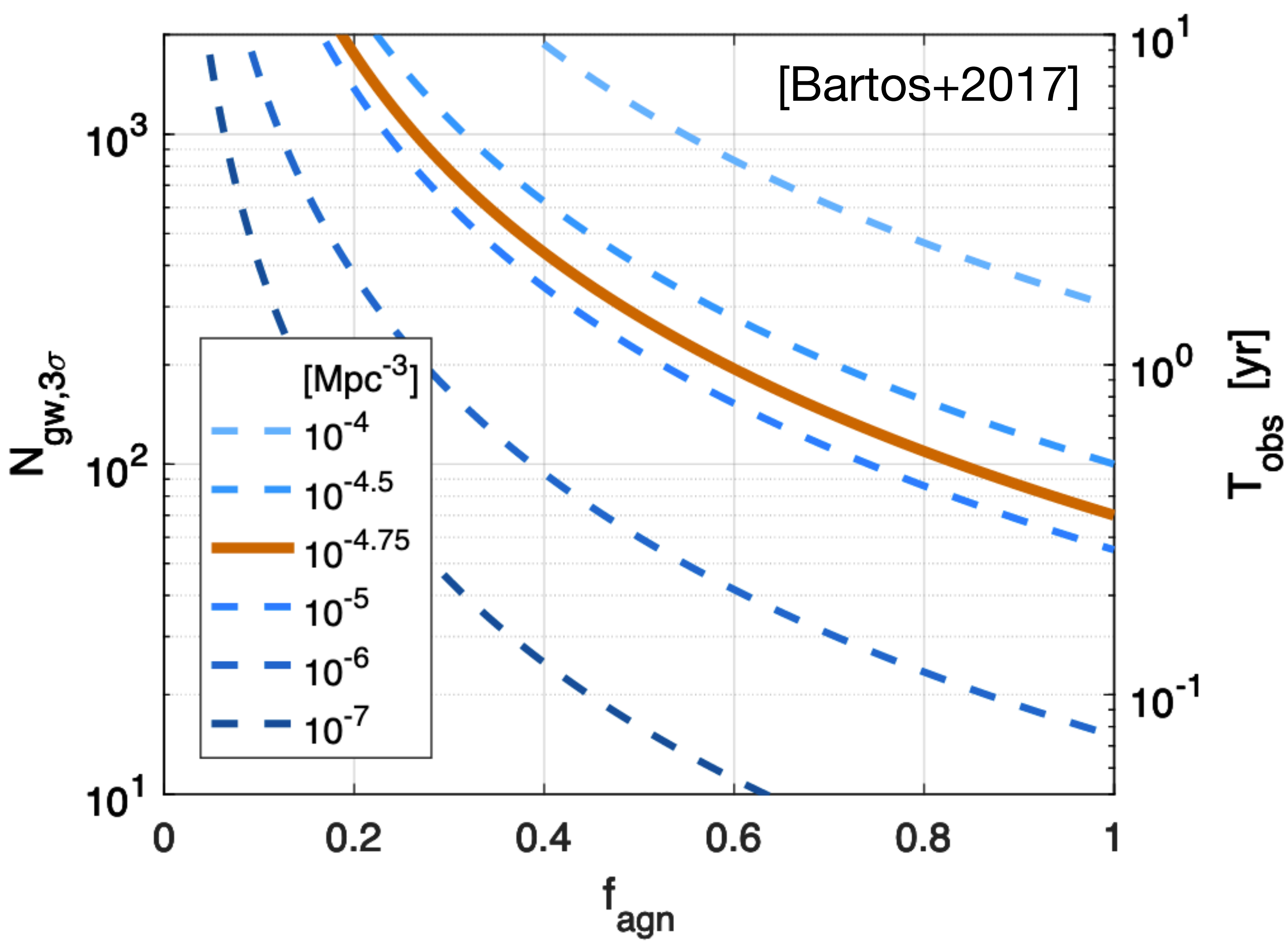
Properties of host galaxies depend on formation channel



[Artale+2019]

BBH mergers in AGN disks: statistical association

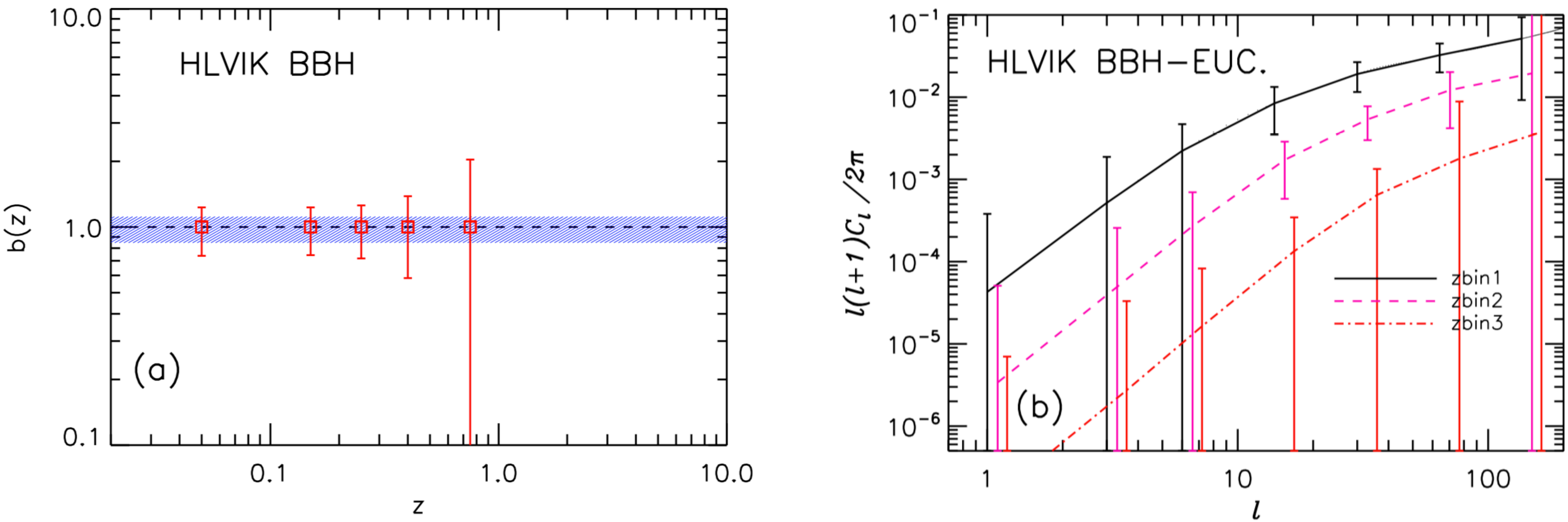
- For GW sources originating in AGN disks, the localisation error box should contain at least 1 AGN
- If fraction of GW sources forming in AGN disks is at least 25%, need 5 years of observations to prove the connection (but depends on AGN number density)



Cross-correlating BBH coalescences and galaxy counts

- Cross-correlate the distribution of GW events and the sky-projected spatial distribution of galaxies
- Constrain the bias of GW events (relative to the underlying matter density)

[Calore+2020]



Multipoles of cross angular power spectrum:
$$C_\ell^{ab} = \frac{2}{\pi}\int k^2 G_{a,\ell}(k) G_{b,\ell}(k) dk$$

$$G_{i,\ell}(k) = \int dz \frac{dN_i}{dz}(z) j_\ell[k\chi(z)]\,\delta_i(k,z)$$

See [Scelfo+2020, Libanore+2021]

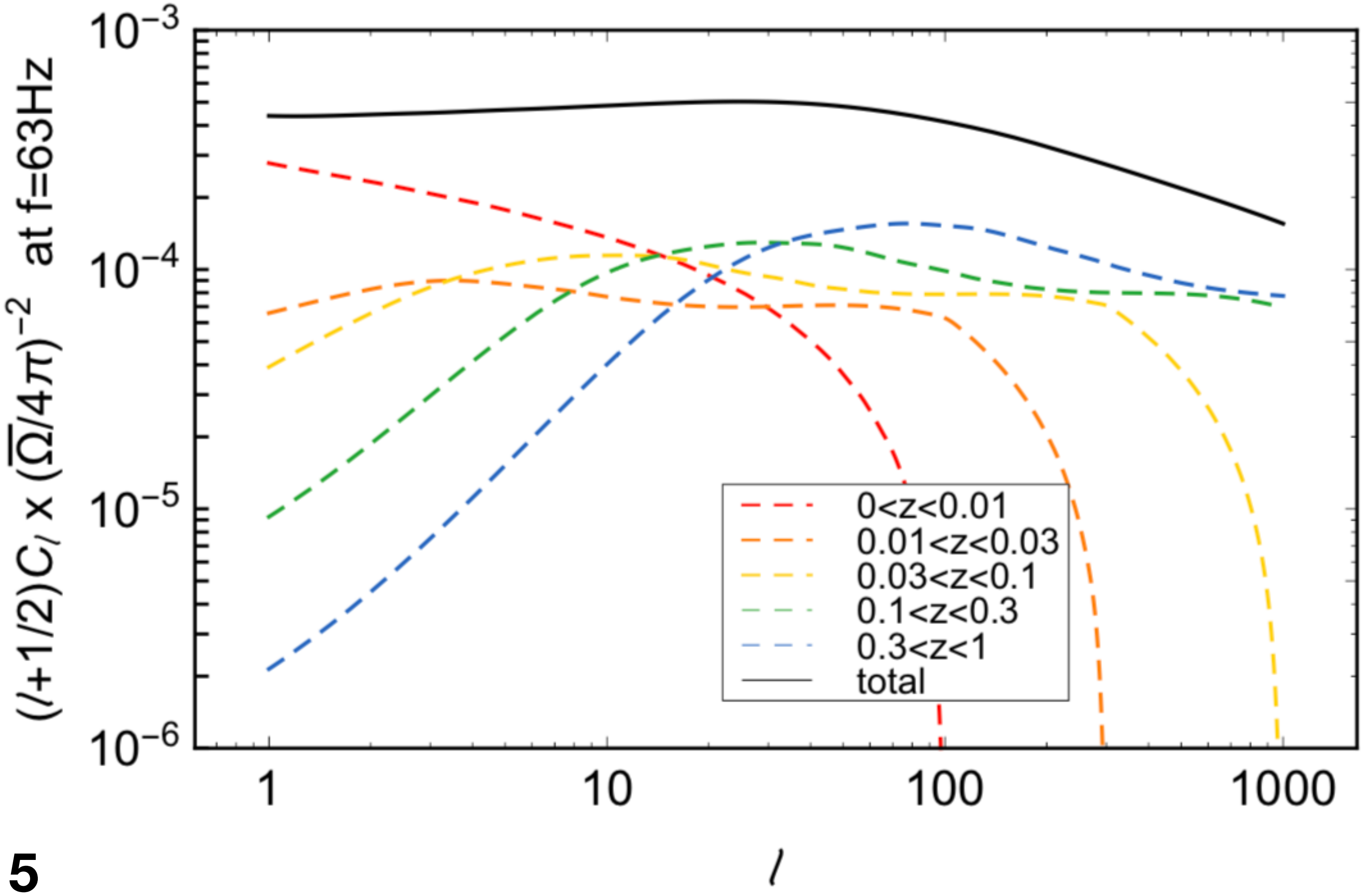
* Incoherent superposition of unresolved sources creates a stochastic signal
* Assume a background that is Gaussian, unpolarized, spatially homogeneous, isotropic

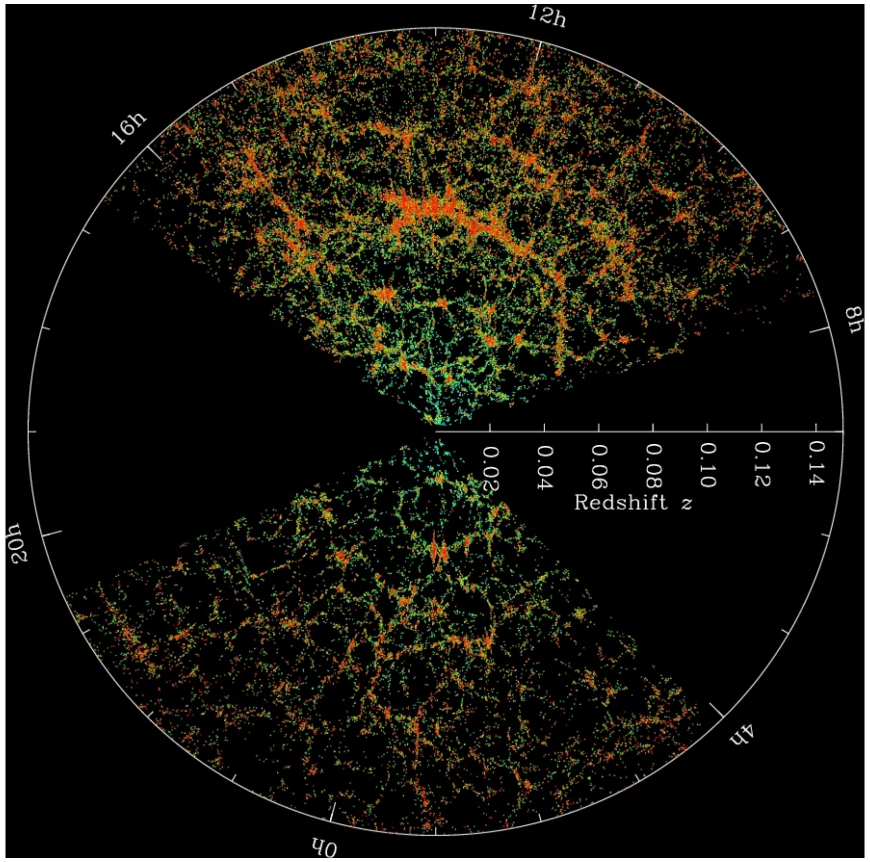
Astrophysical sources are in galaxies

—> GW background is anisotropic

$$\Omega_{\rm gw}(f,\Theta) = \frac{f}{\rho_c}\frac{{\rm d}^3\rho_{GW}}{{\rm d}f{\rm d}^2\Theta}$$

[Cusin, **ID**, Pitrou, Uzan 2019]





SDSS galaxy map

See [Jenkins+2018, Capurri+2021, Bellomo+2022 …]

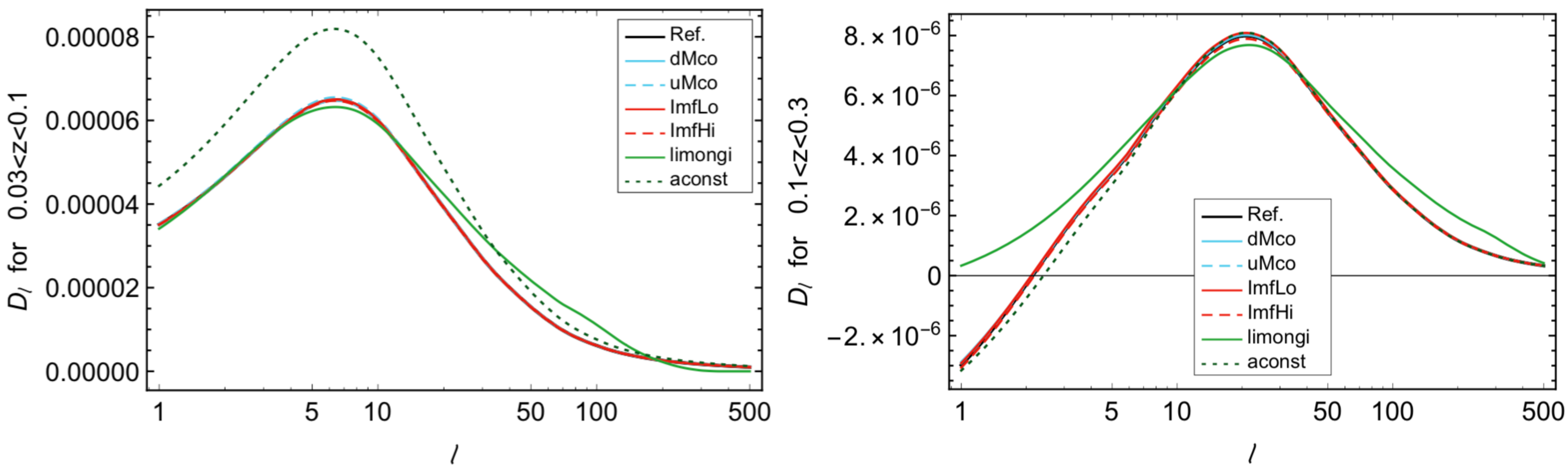
Cross-correlation with galaxy number counts

$$D_\ell(f,z) = \frac{2}{\pi}\int \mathrm{d}k\, k^2 \delta\Omega_\ell^*(k,f)\,\Delta_\ell(k,z)$$

Galaxy number count overdensity

[Cusin, **ID**, Pitrou, Uzan 2019]

0.03<z<0.1 0.1<z<0.3

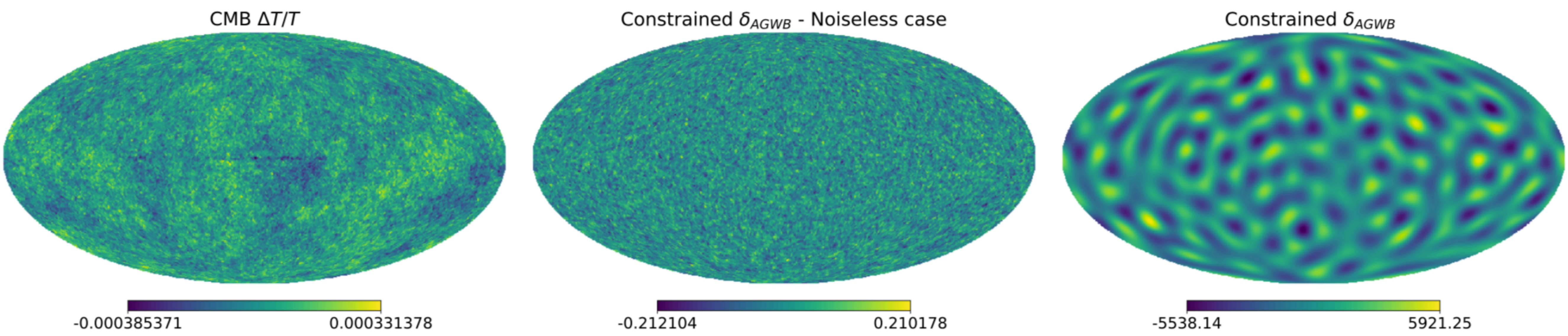


Peak multipole is related to the galaxy redshift range

The GW stochastic anisotropic signal itself may be undetectable
Need correlations with EM tracers!

See [Jenkins+2019; Alonso+2020]

- CMB photons and GW are deviated by intervening LSS
- But: high noise levels in current detectors
- Possible detection with LISA!



[Ricciardone+2021]

See [Capurri+2022]

- ✱ Formation channels of stellar-mass BBH not yet fully understood
- ✱ The massive end of stellar-mass BHs may provide the seeds for MBHs
- ✱ Are there EM counterparts to stellar-mass BBH mergers?
- ✱ Cross-correlating GW and EM observations will bring new information!

Credit: ButterflyLove1

Thank you!