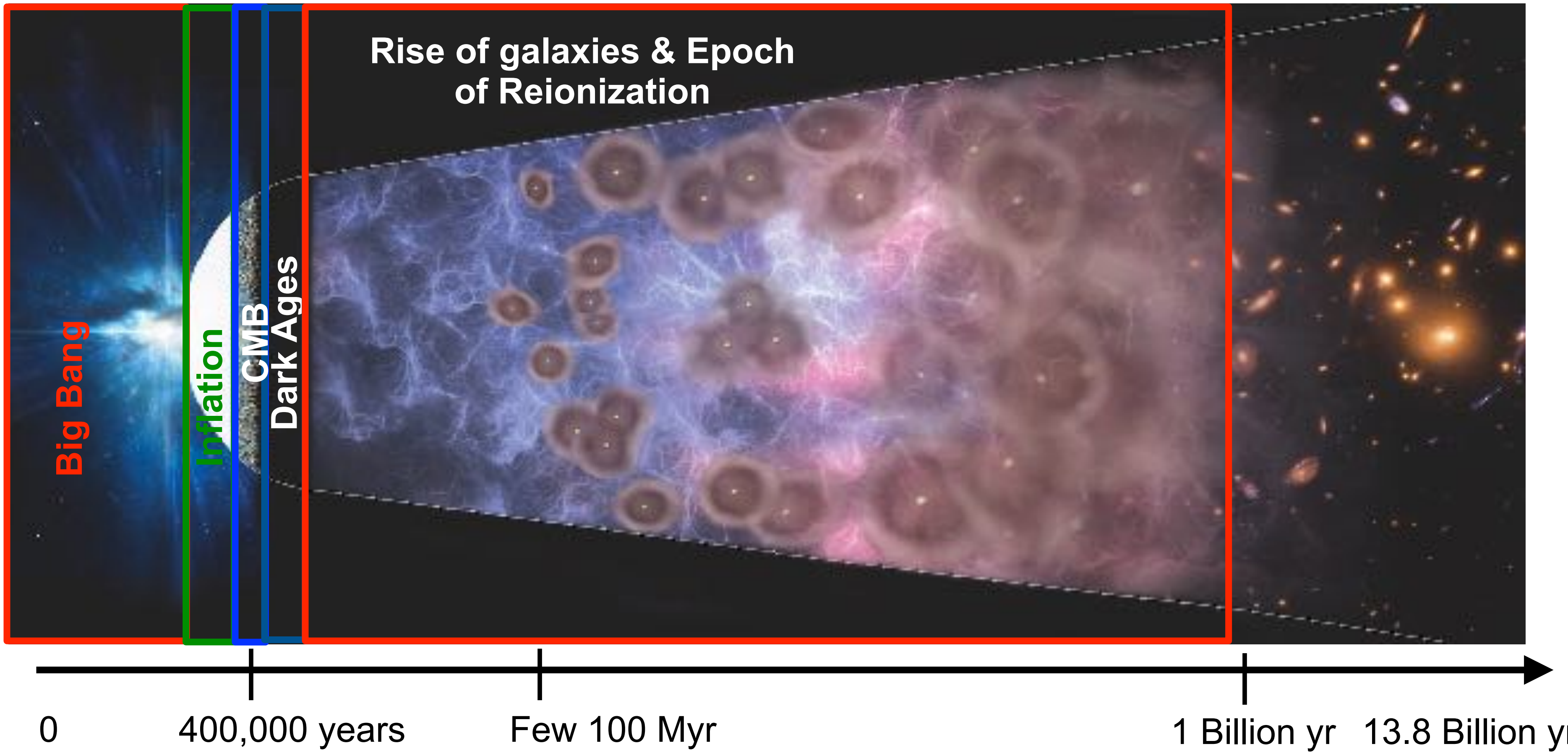
Hunting for gravitational waves in the era of cosmic dawn

Pratika Dayal



rijksuniversiteit groningen

DELPHi erc

ODIN NWO

The team in Groningen

Chris Boettner

Giorgos Nikopoulos

Fernanda Pratama

Paula Caceres-Burgos

Valentin Mauerhofer

Maxime Trebitsch

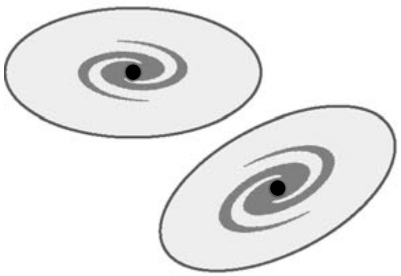
With: the LISA consortium, the SKA and Euclid theory groups, the ALMA (REBELS) team and JWST teams (Panoramic, Primer, CosmicSpring, Uncover)

Some open questions

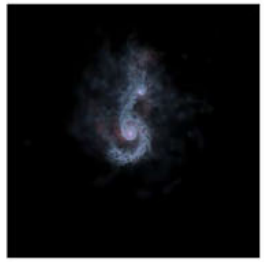
- How many black holes exist and merge in the first billion years?
- Which sort of mergers (in terms of mass and redshift) will LISA see?
- How should we interpret the gravitational wave background seen by LISA?
- What about the electromagnetic counterparts for black hole mergers?

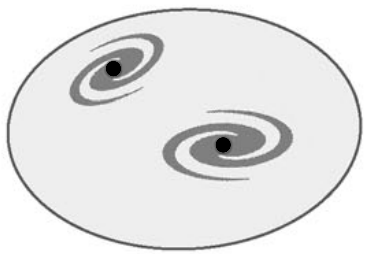
The multi-scale processes determining the formation of a BH binary


Credit: Lupi et al. (2019)

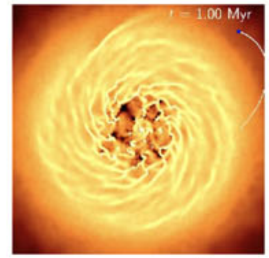


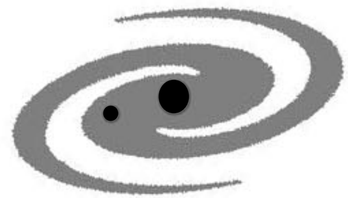
Mpcs:
The large scale structure


Credit: Capelo et al. (2015)

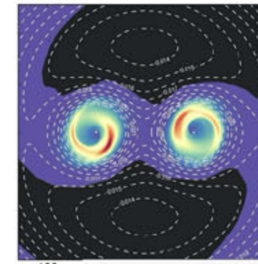


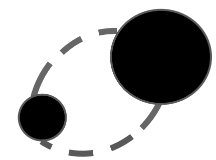
1-100s kpcs:
Galaxy interactions/merger


Credit: Souza Lima et al. (2017)



1-10s pc:
Formation of a bound binary


Credit: Bowen et al. 2017



<1 pc:
Hardening of the binary

The formation, growth and mergers of black holes is intricately tied to the properties of their host galaxies

"Astrophysics with LISA" white paper, 2023, LRR, 26, 2
arXiv:2203.06016

The golden age for observing early galaxies

Number of galaxies/BH of a given luminosity per unit volume as a function of cosmic time (*Luminosity function*)

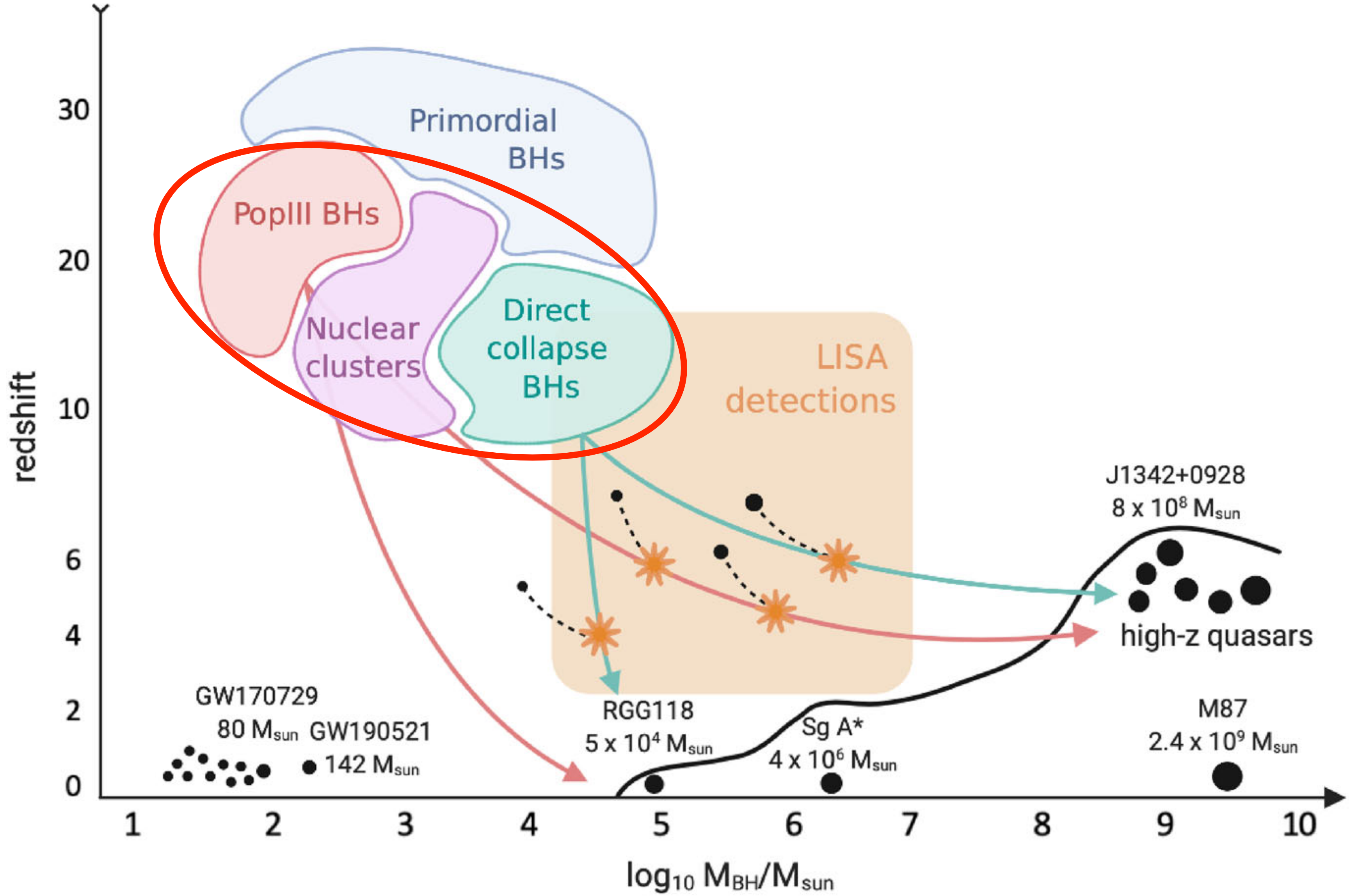
Total rate of star formation per unit volume (*Star formation rate density*)

Total mass bound in stars and BH per unit volume (*Stellar mass and BH mass density*)

The dust masses and metallicities of early galaxies

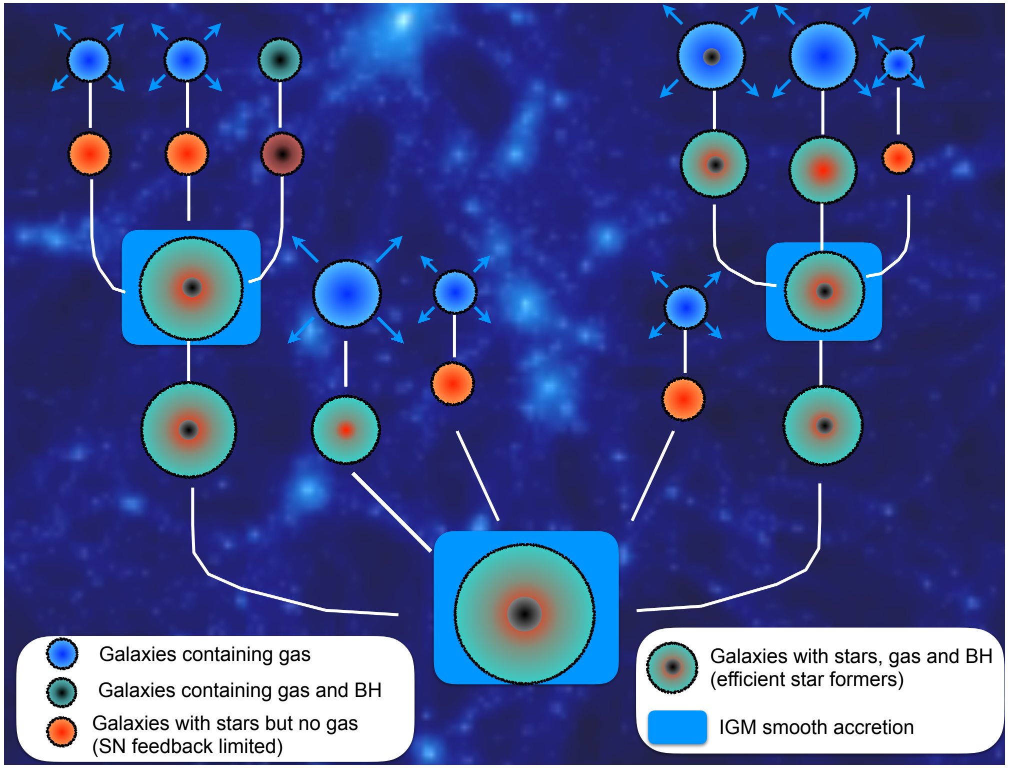
Sizes and mergers of early galaxies; early BH candidates

Numerous pathways for black hole seed formation and growth

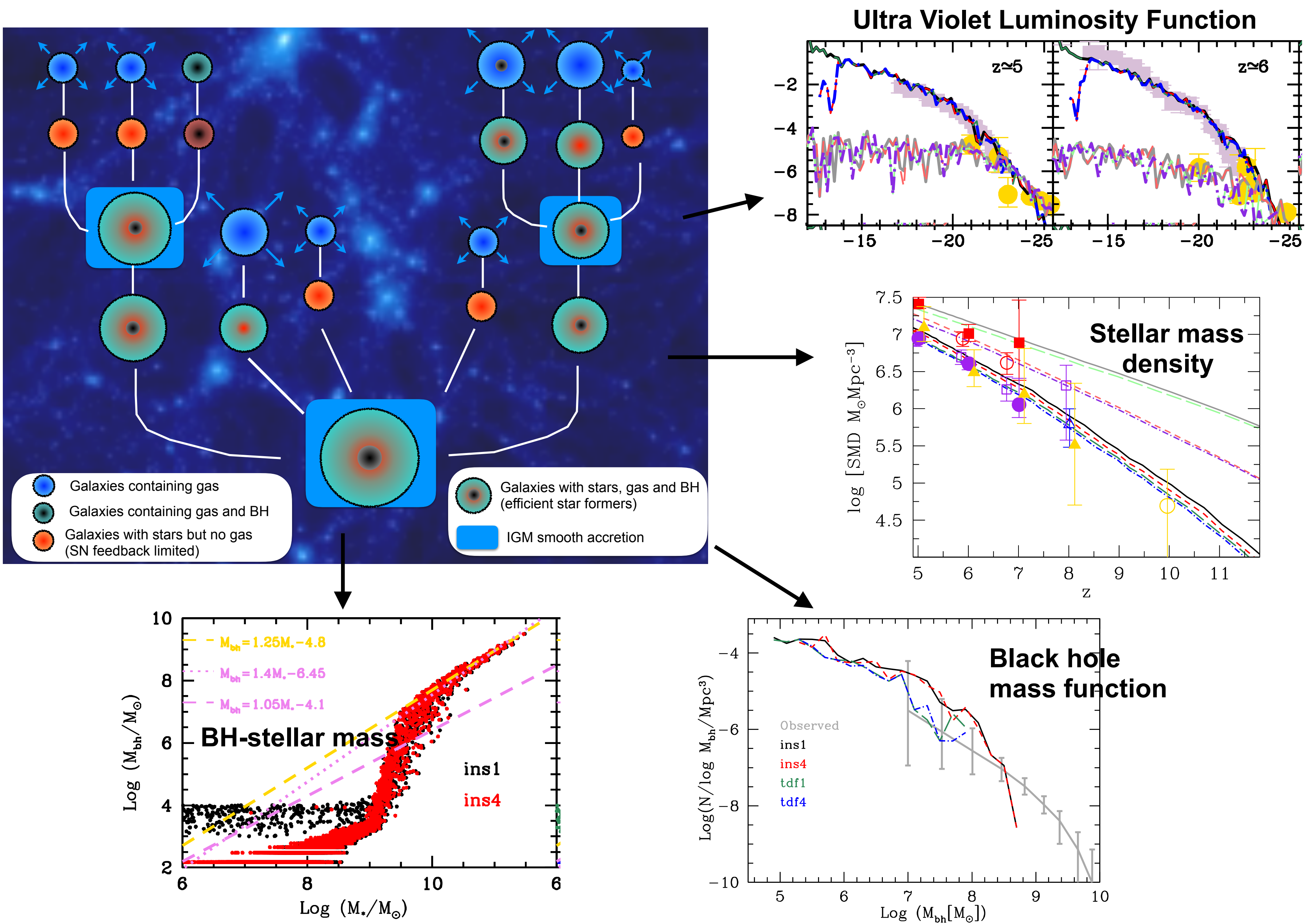


"Astrophysics with LISA" white paper, 2023, LRR, 26, 2
arXiv:2203.06016

Datasets allowing baselined models into unprecedented epochs

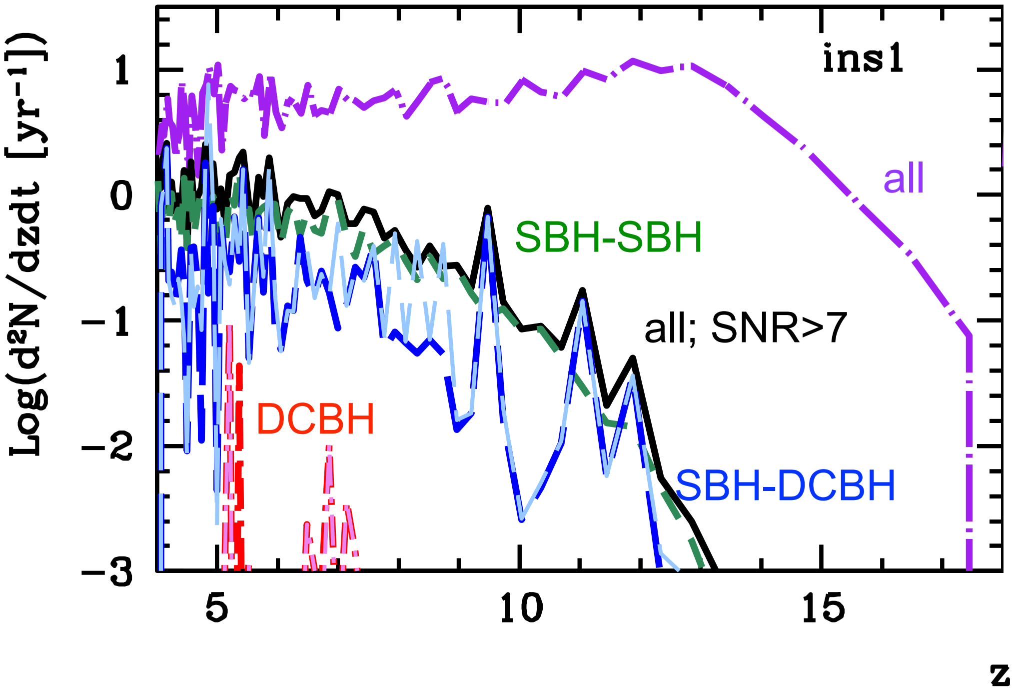


Datasets allowing baselined models into unprecedented epochs



The LISA-detectable GW event rate as function of redshift

Instantaneous merging



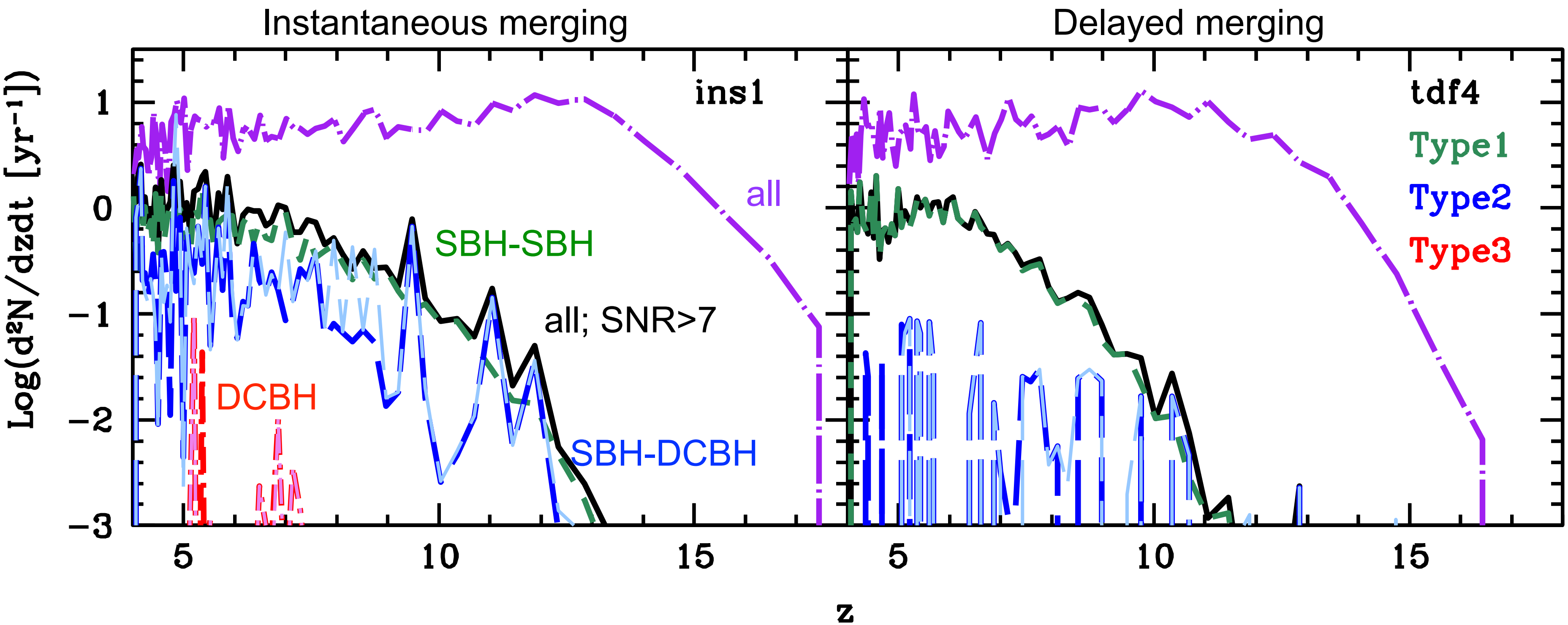
Delayed merging

• In *fiducial case (ins1)* Most detectable mergers (~67%) are those from SBH-SBH, followed by SBH-DCBH mergers (32%). DCBH-DCBH mergers negligible.

• Due to delayed mergers, importance of DCBH-SBH mergers decreases. No detectable DCBH-DCBH mergers (with SNR>7).

DELPHI; PD, Rossi et al. 2019, MNRAS, 486, 2336

The LISA-detectable GW event rate as function of redshift

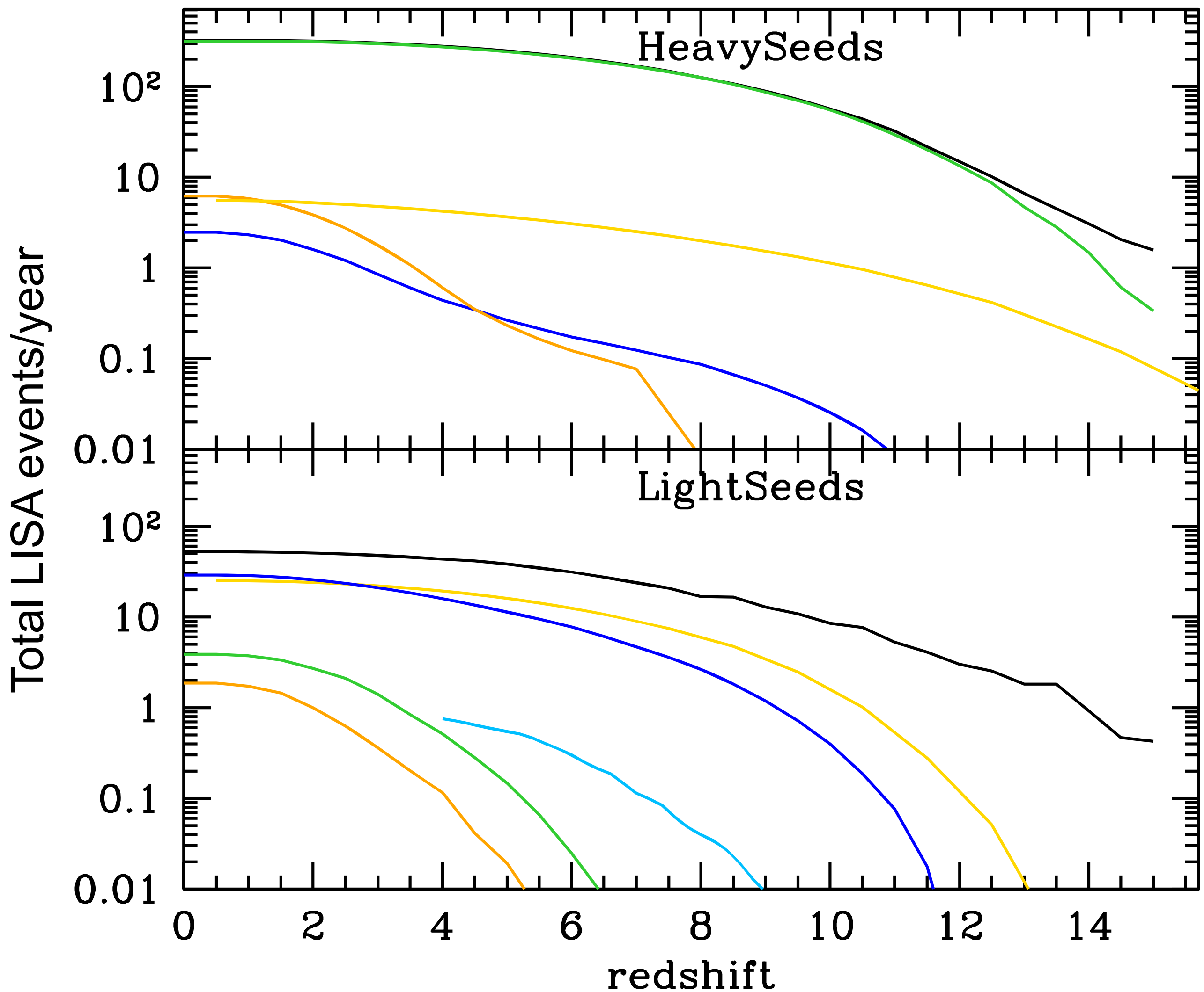


• In *fiducial case (ins1)* Most detectable mergers (~67%) are those from SBH-SBH, followed by SBH-DCBH mergers (32%). DCBH-DCBH mergers negligible.

• Due to delayed mergers, importance of DCBH-SBH mergers decreases. No detectable DCBH-DCBH mergers (with SNR>7).

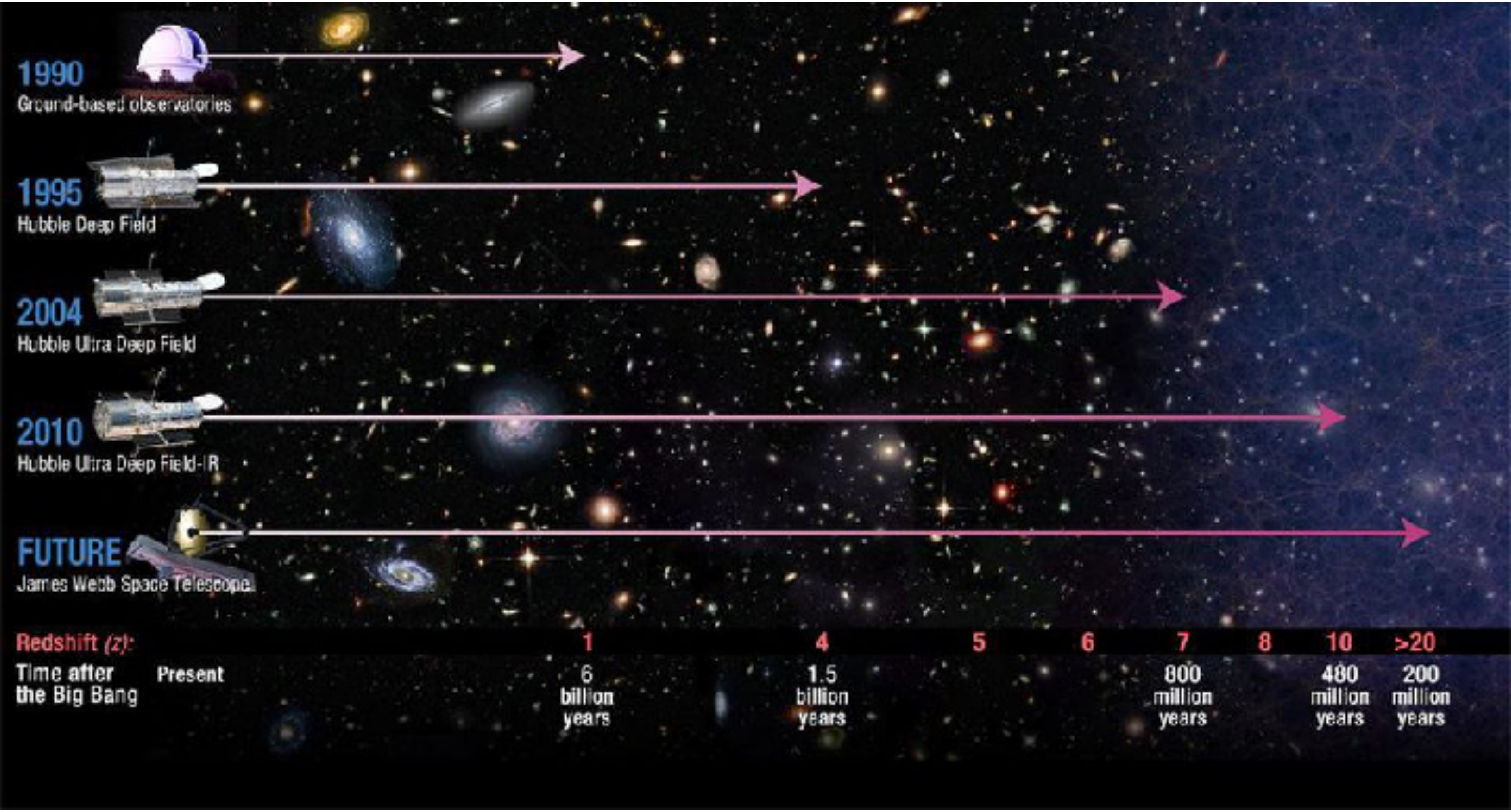
DELPHI; PD, Rossi et al. 2019, MNRAS, 486, 2336

GW event rates crucially dependent on assumptions of BH seeds masses, feedback and merger timescales



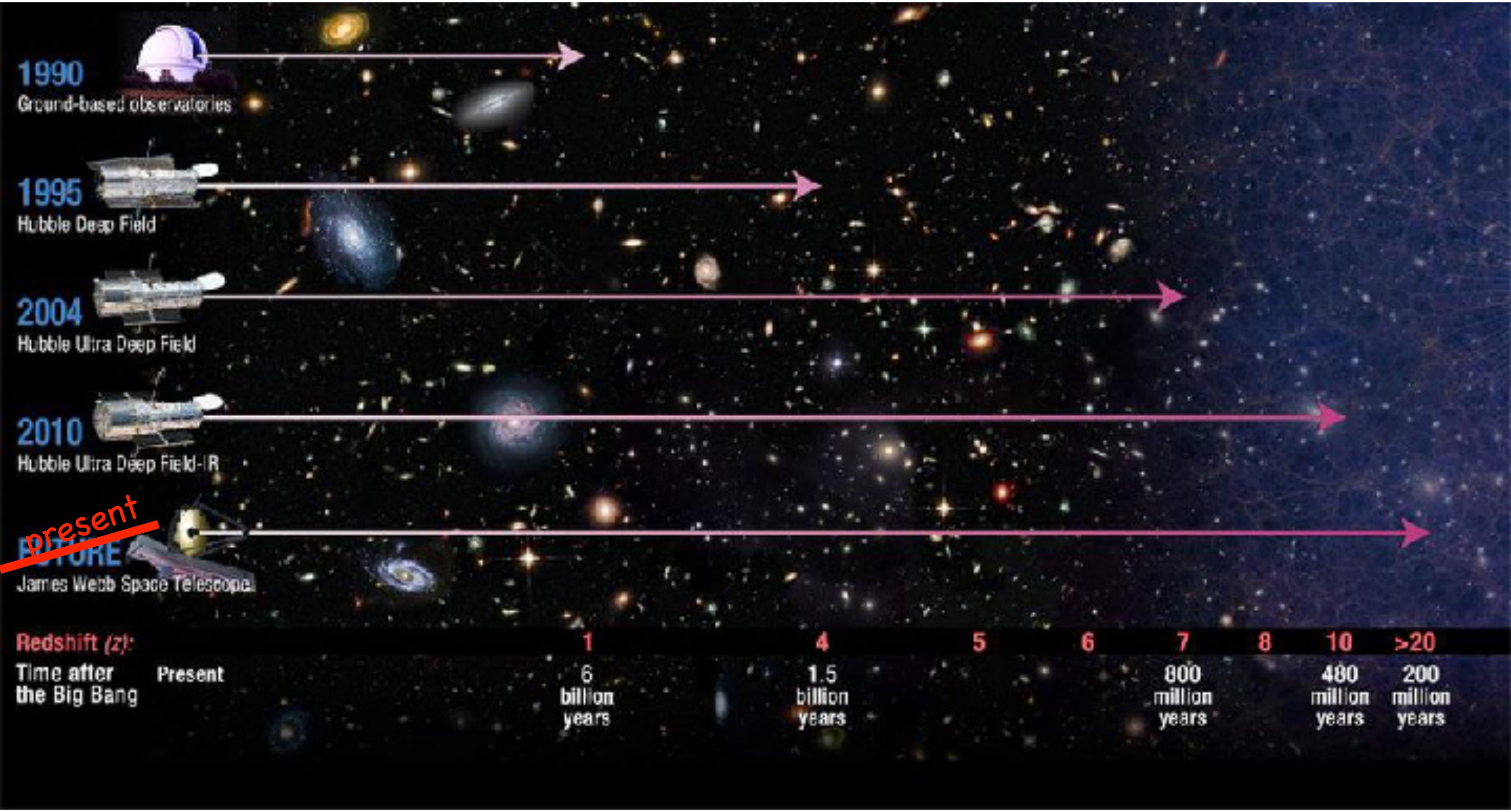
"Astrophysics with LISA" white paper, 2023
arXiv:2203.06016

Breakthroughs in studying galaxies through cosmic time



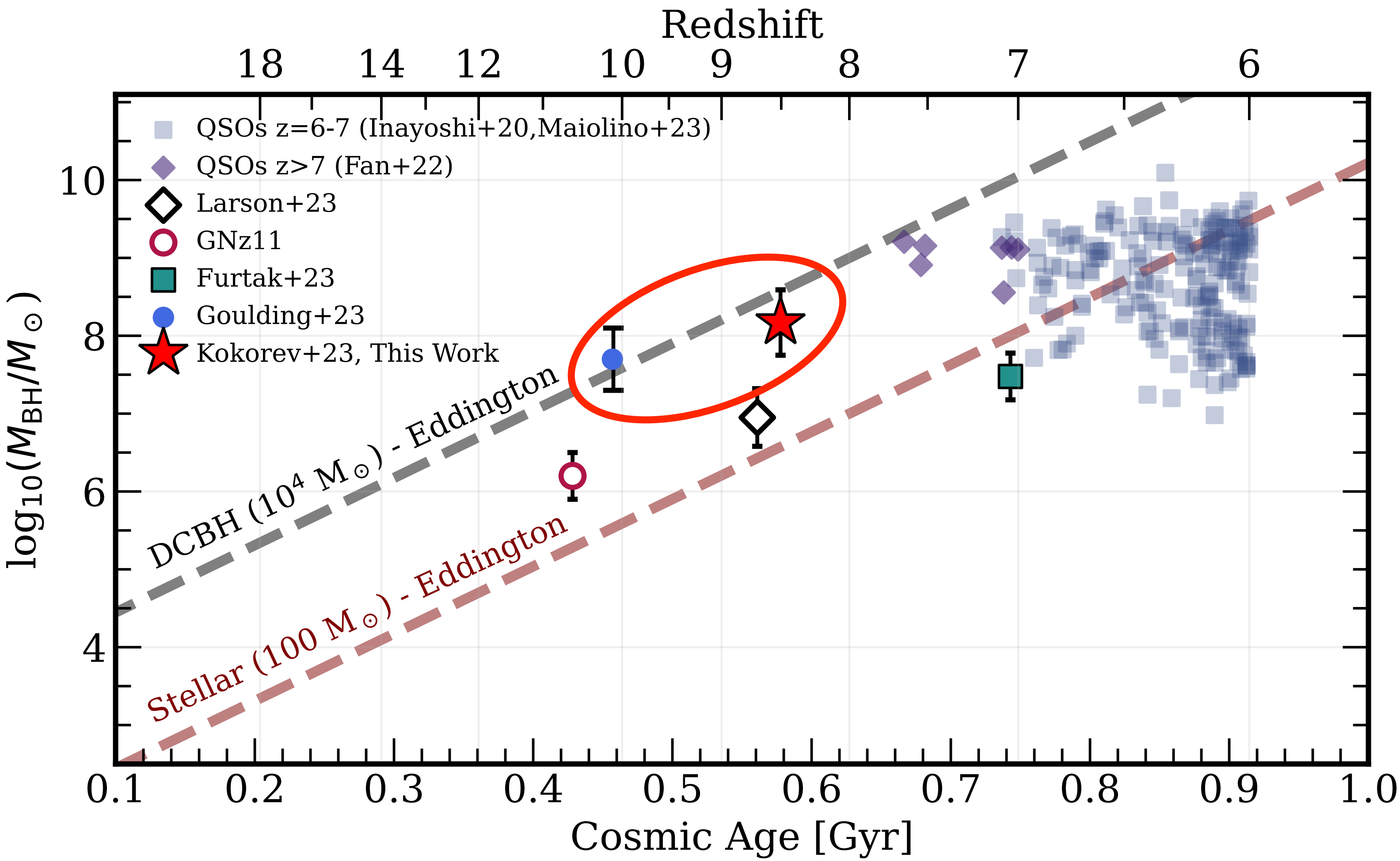
NASA / JWST AND HST TEAMS

Breakthroughs in studying galaxies through cosmic time



NASA / JWST AND HST TEAMS

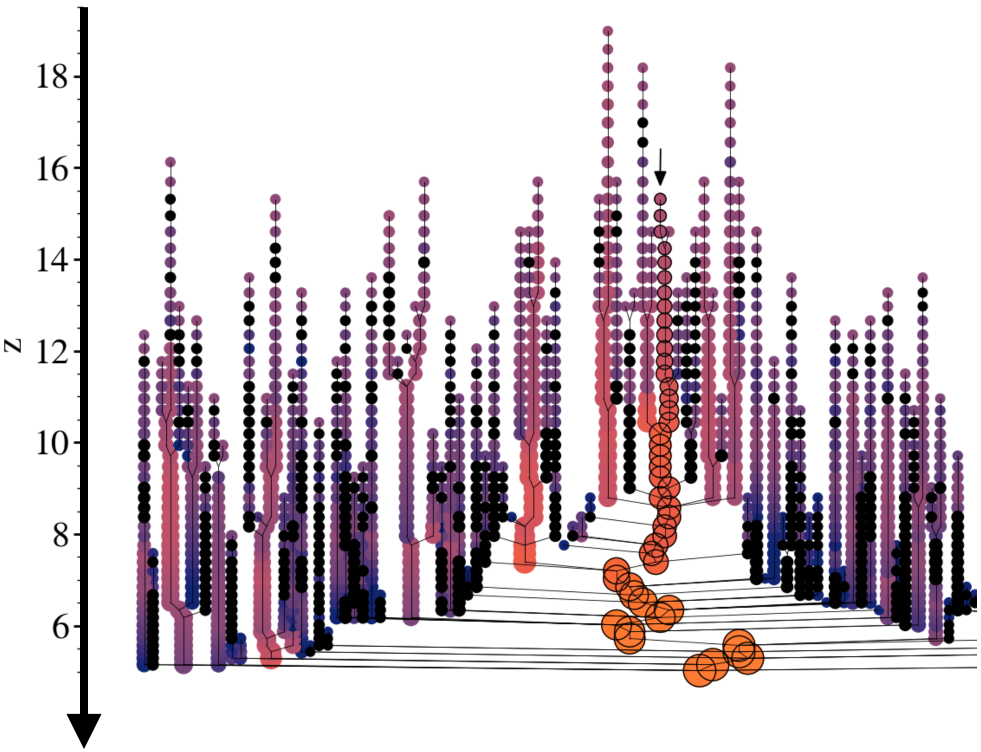
Obese black holes in the first billion years with the JWST



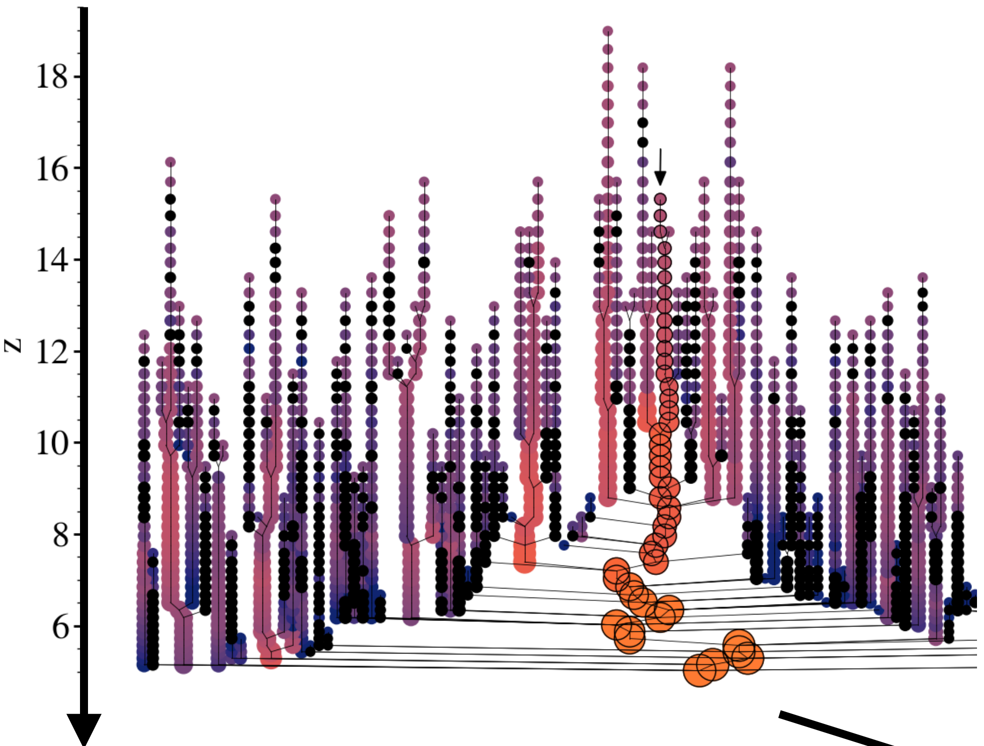
Explaining the supermassive black holes being observed by JWST require unphysical explanations such as super-Eddington accretion onto low-mass seeds or Eddington accretion onto massive (10^4 M$_\odot$) seeds that formed at $z \sim 50$ posing an enormous challenge for all existing theoretical models.

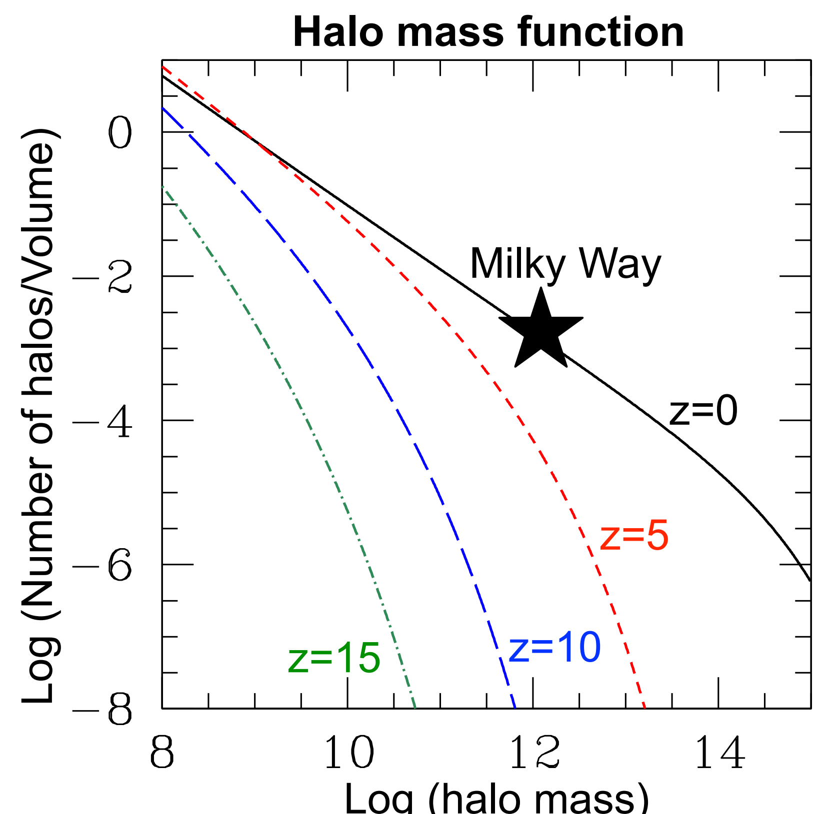
Goulding et al. 2023; Kokorev et al. 2023; Furtak et al. 2023; Greene et al. 2023

JWST black holes in a hierarchical structure formation context

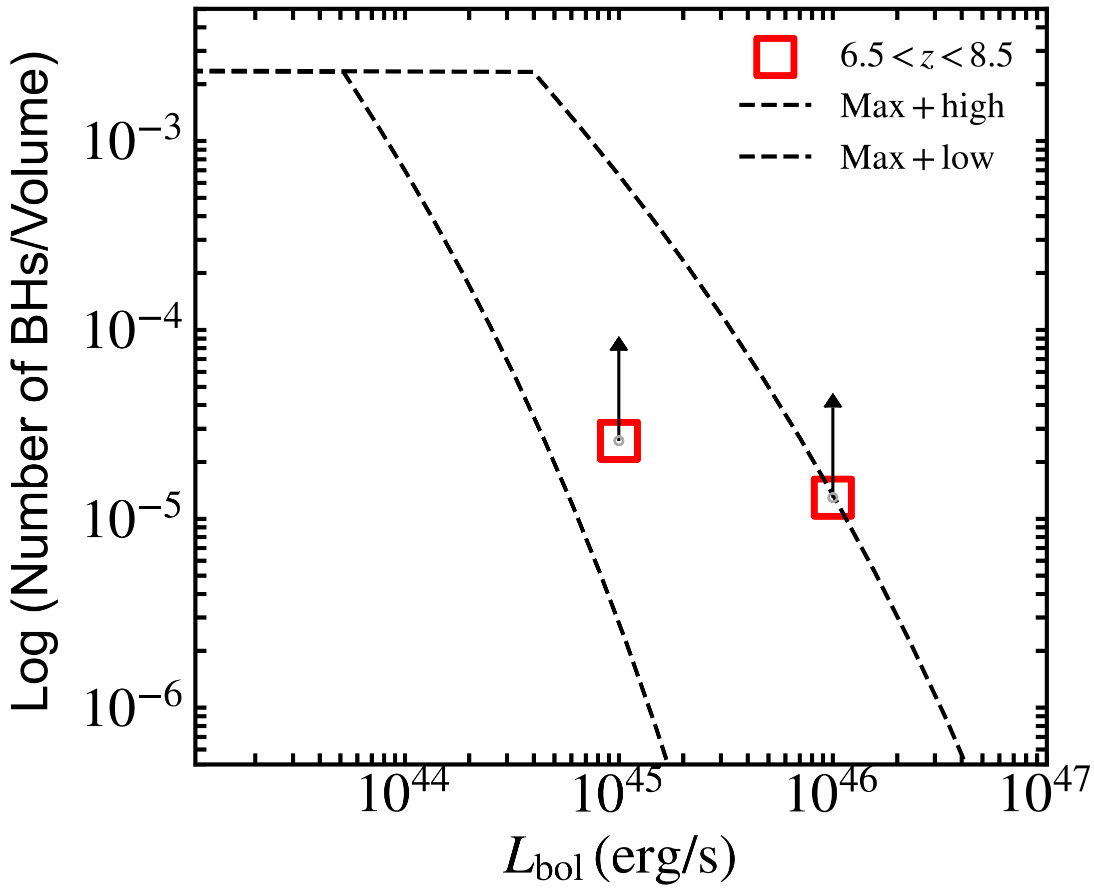


JWST black holes in a hierarchical structure formation context





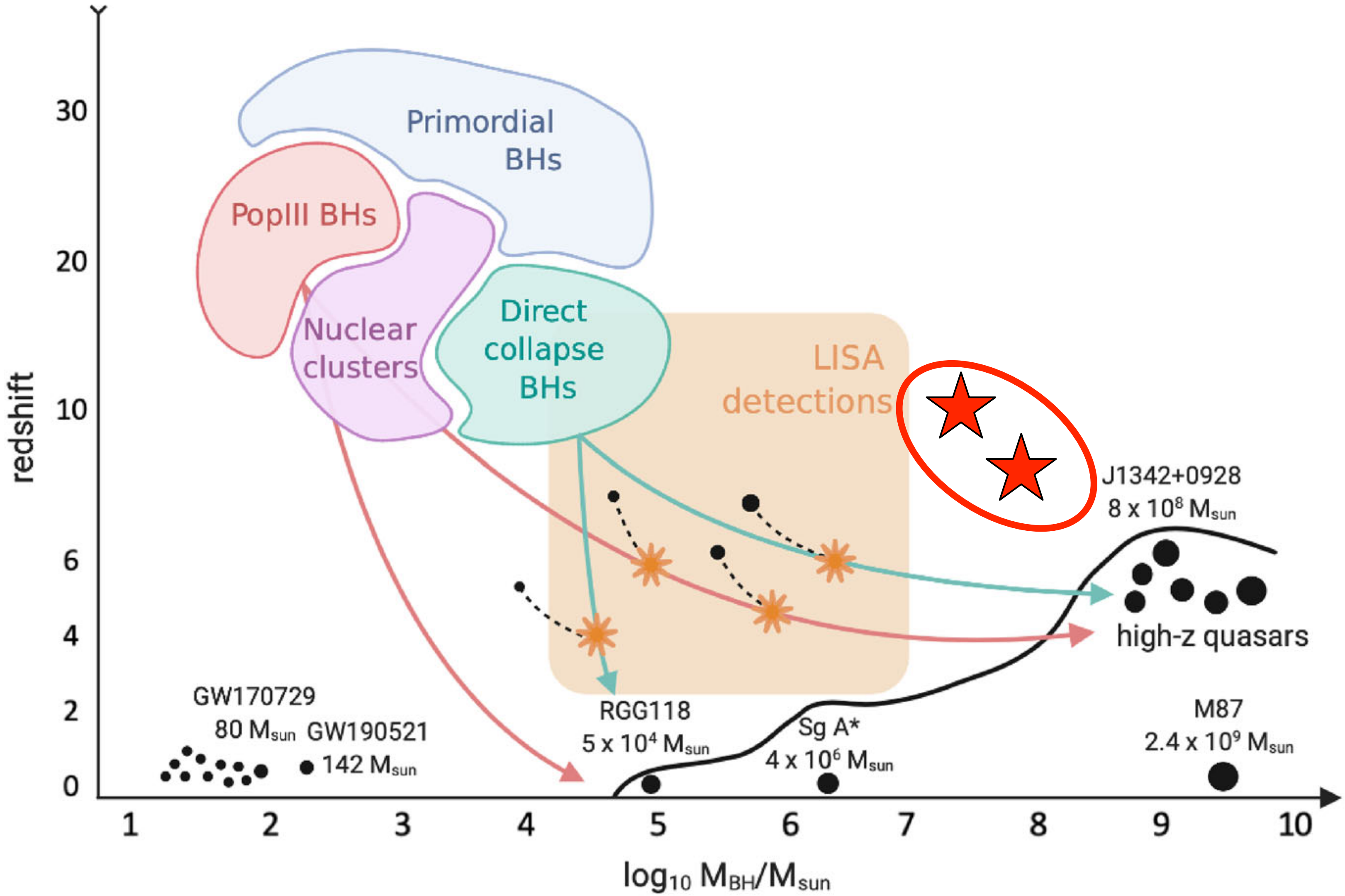
An over-abundance of black holes with the JWST



The JWST indicates at black hole number densities that are at the upper limit of theoretical expectations (each halo has a black hole similar to the local Universe that can accrete at the Eddington rate), specially at $z>6.5$.

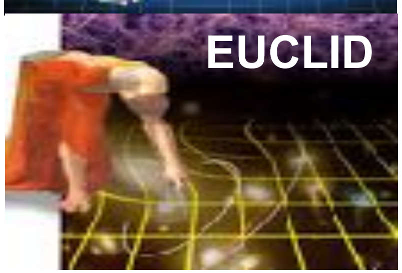
Goulding et al. 2023; Kokorev et al. 2023; Furtak et al. 2023; Greene et al. 2023

A need to revisit black hole seeding and growth pathways



"Astrophysics with LISA" white paper
arXiv:2203.06016

Towards a holistic picture of BHs in the first billion years



<u>Global properties of galaxy populations</u>
Galaxies being probed up to z~13; black holes up to z~10. Indicate an over-abundance of massive galaxies and obese black holes

<u>Individual galaxy properties</u>
constraints on assembly histories, dust formation mechanisms, gas masses, black hole masses, black hole mass-stellar mass relations

<u>Gravitational wave astronomy</u>
LISA will detect mergers from 10^{4-7} solar masses at z~3-15, mostly from low-mass BH mergers. The event rates remain debatable & need revisiting in light of JWST data.