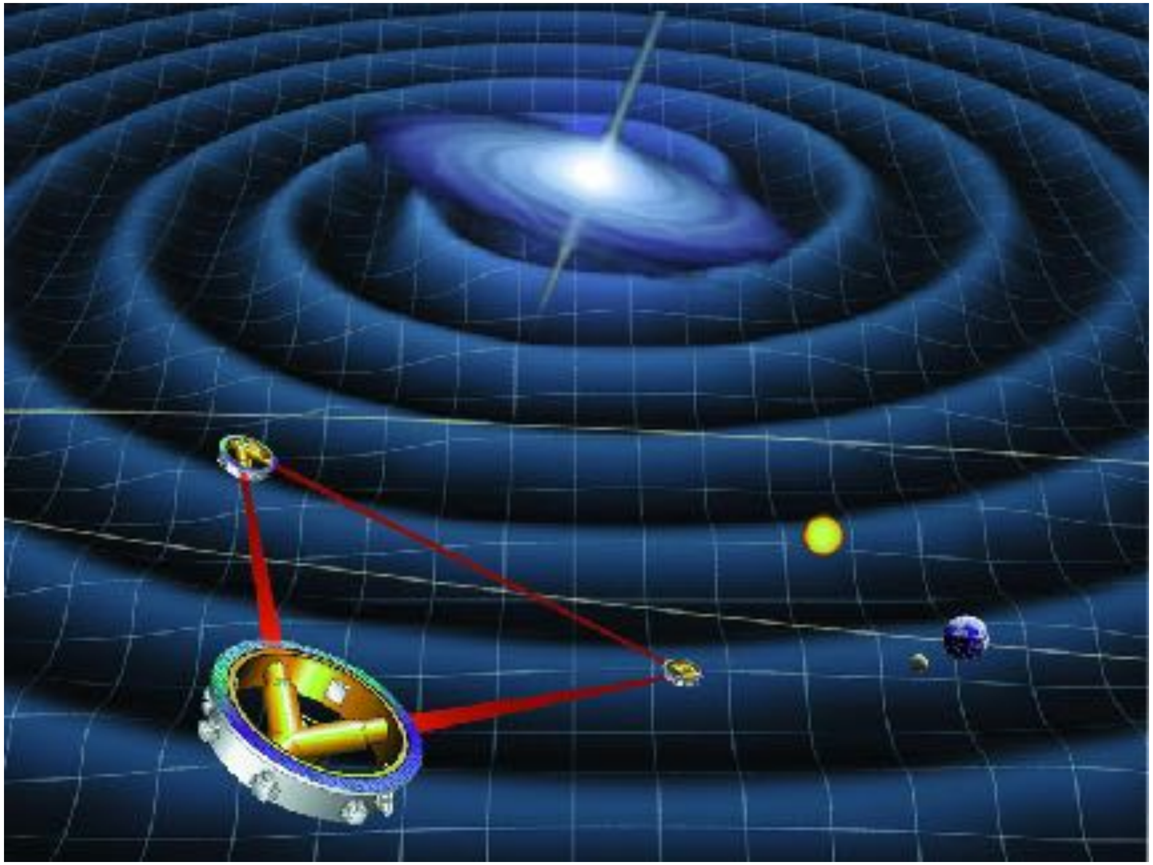
The hierarchical assembly of galaxies and black holes: predictions for LISA

Pratika Dayal



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DELPHi erc

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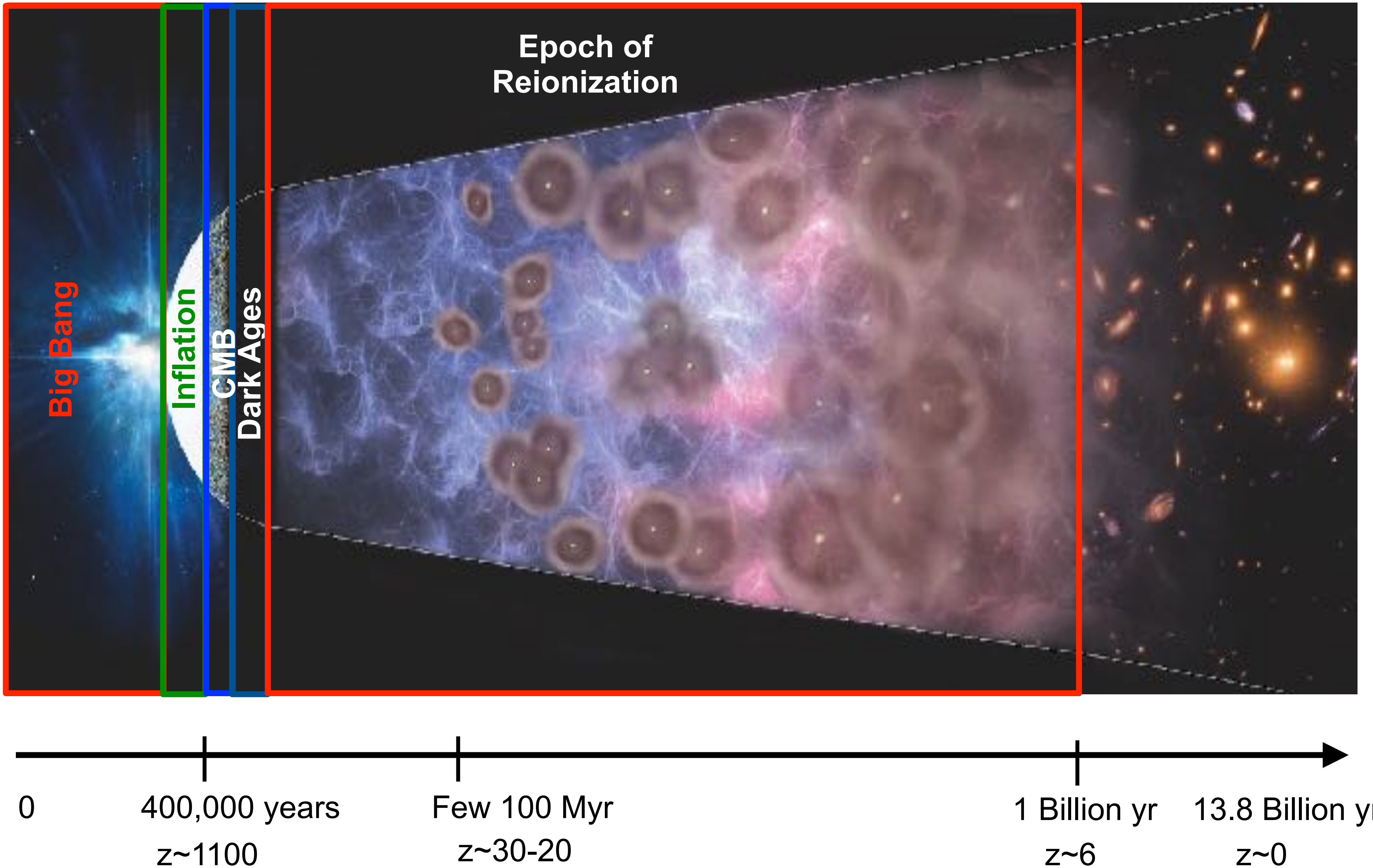
The cosmic timeline



Some open questions

- **How many black holes exist and merge through cosmic time?**
- **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?**

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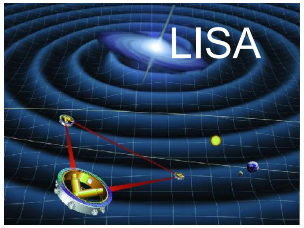
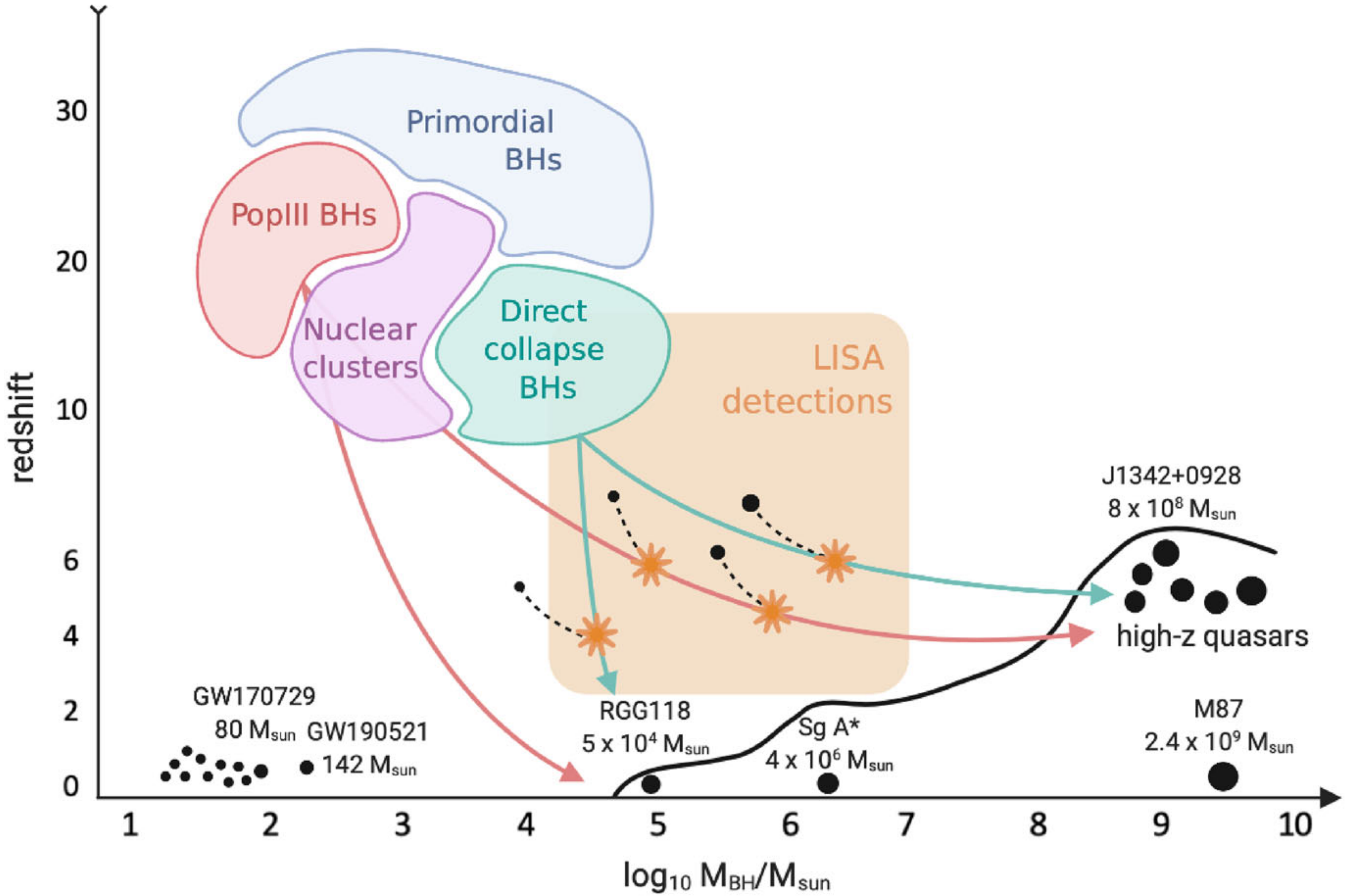
ALMA

SKA

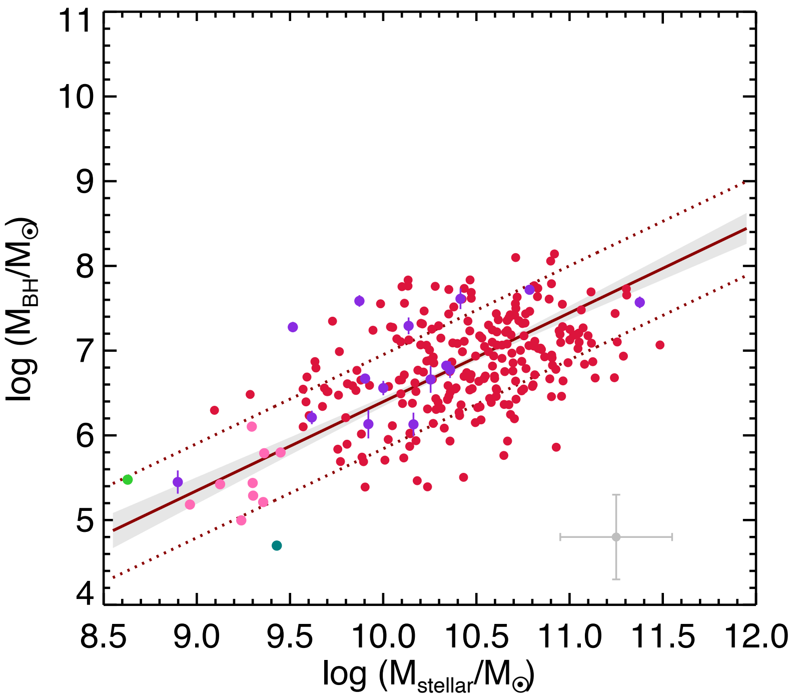


Numerous pathways for black hole seed formation and growth

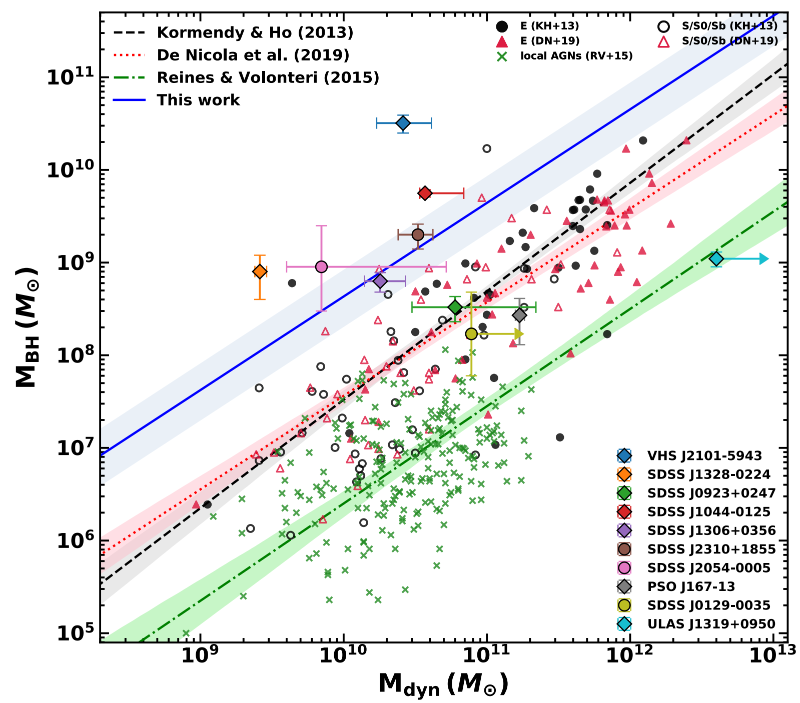


“Astrophysics with LISA” white paper, 2023, LRR, 26, 2
arXiv:2203.06016

Black hole masses correlate with galaxy mass at all z



z~0
Reines & Volonteri, 2015, ApJ, 813, 82

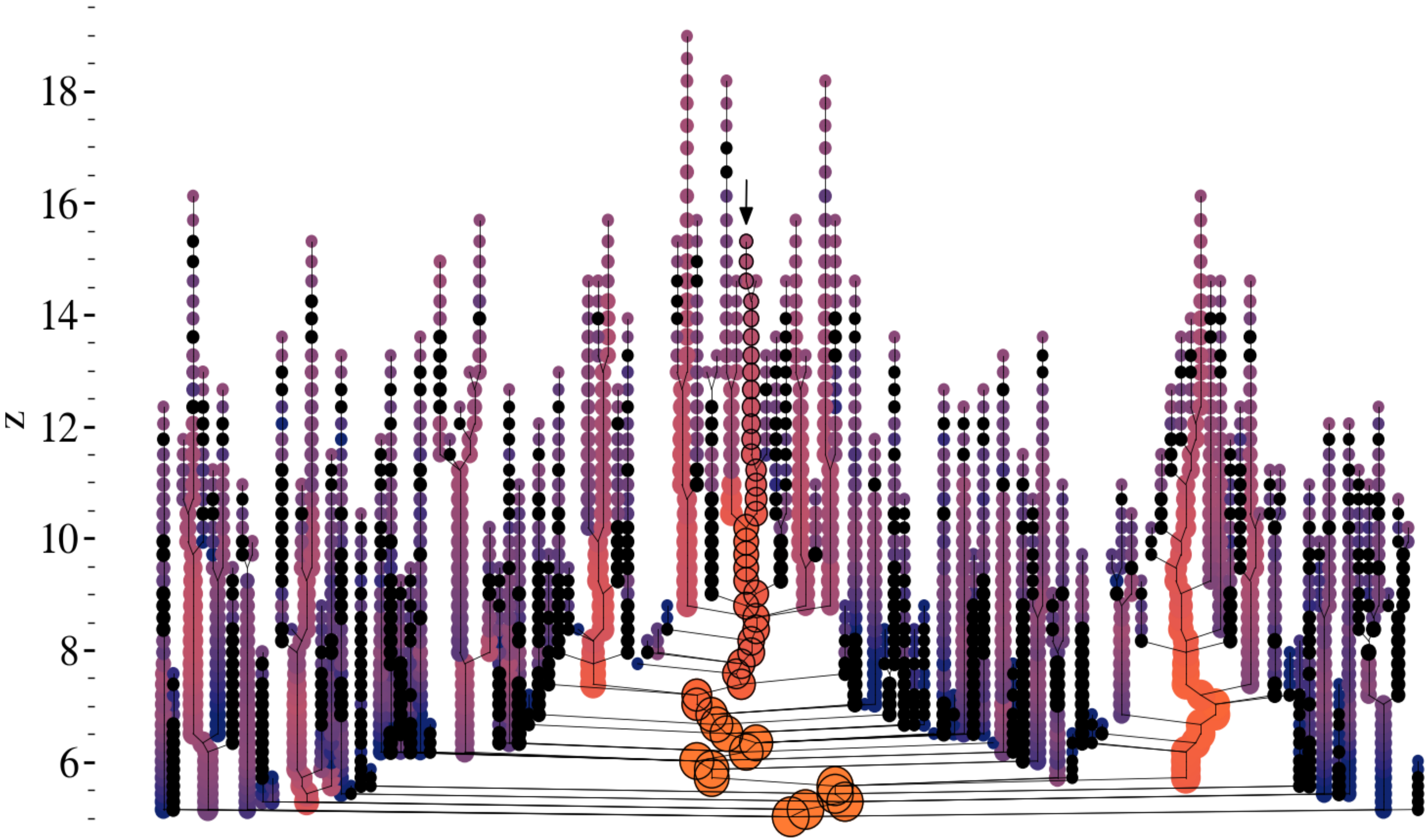


z~2-7
Pensabene et al., 2020, A&A, 637, 84

Growth and mergers of black holes are intricately tied to the hierarchical assembly of their host galaxies

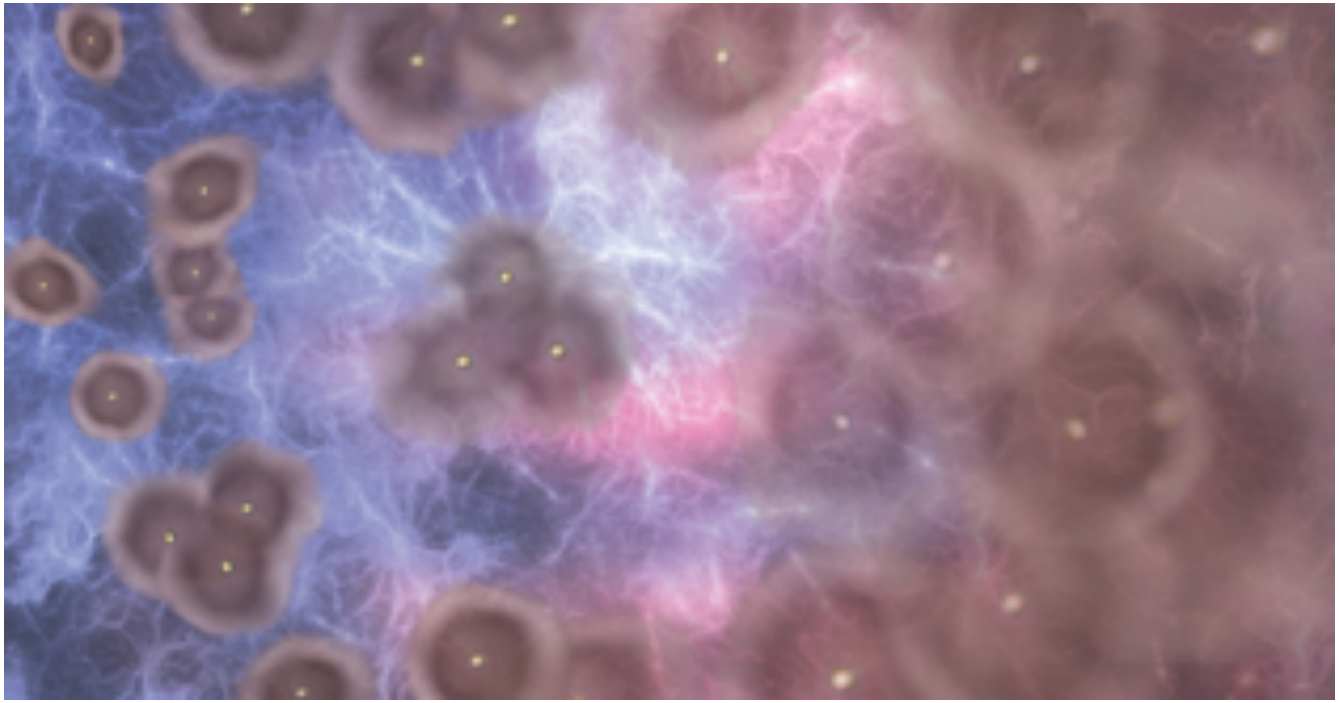
- DM assembly
- Gas/stellar mass from accretion & mergers
- Star formation
- Impact of supernovae in ejecting gas

- BH seeding
- BH growth
- Impact of BH feedback in ejecting gas
- Impact of reionization feedback



A complication: impact of reionization feedback on galaxy formation

Neutral hydrogen :
T = T(CMB)



Ionized hydrogen :
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A complication: impact of reionization feedback on galaxy formation

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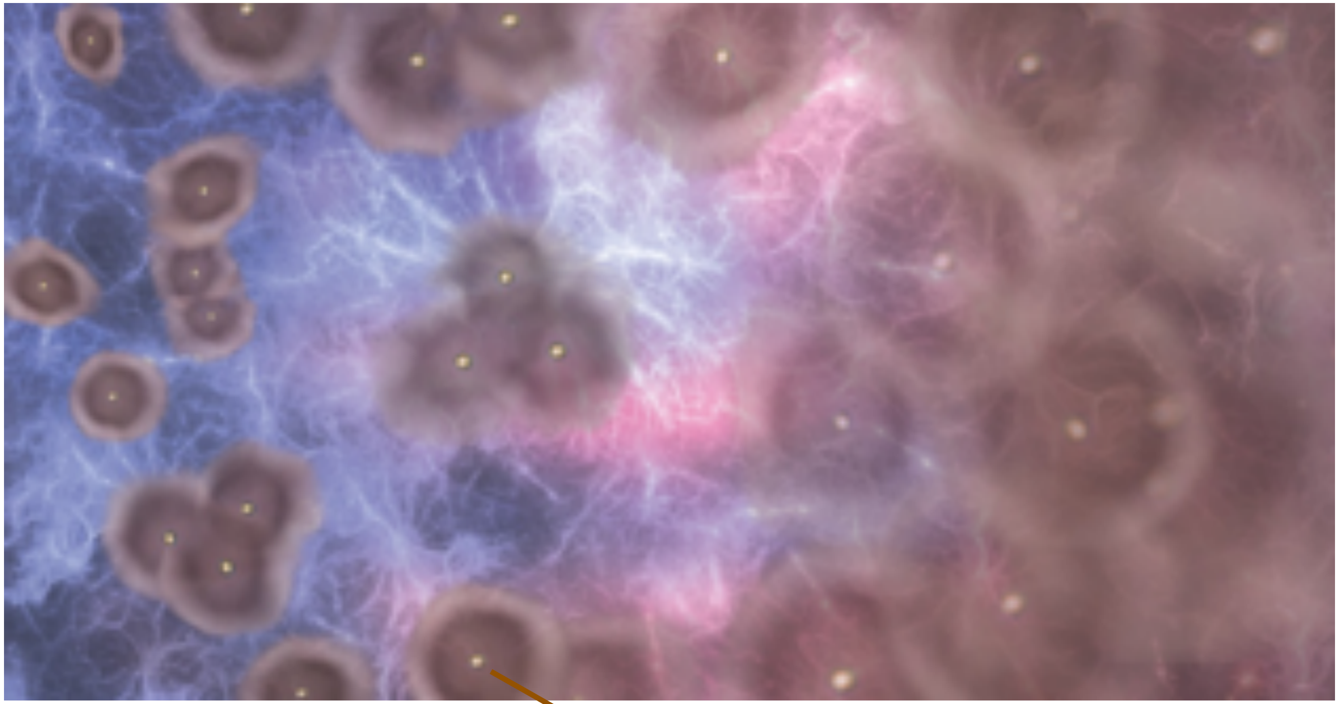

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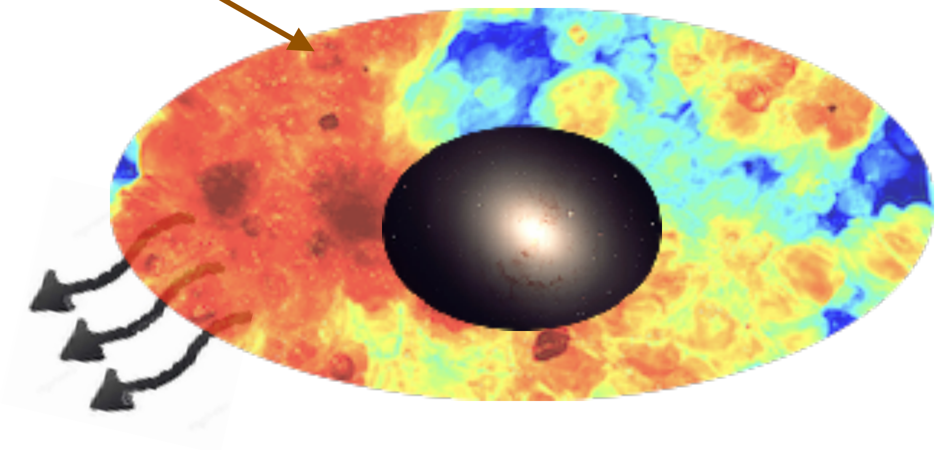
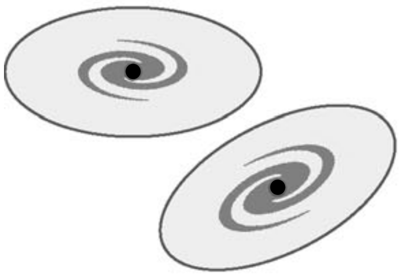


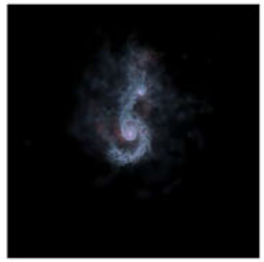
Low-mass halos in ionized (hot) regions can lose some/all of their gas mass limiting both star formation and black hole growth.

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

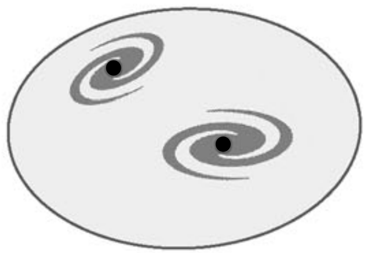
Credit: Lupi et al. (2019)



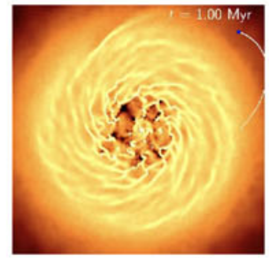
Mpcs:
The large scale structure



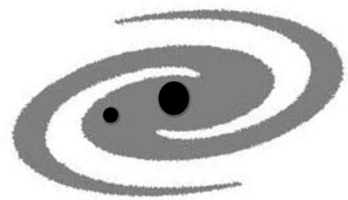
Credit: Capelo et al. (2015)



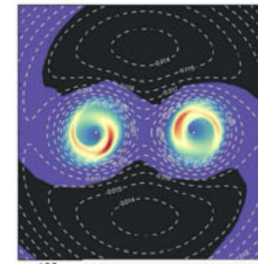
1-100s kpcs:
Galaxy interactions/merger



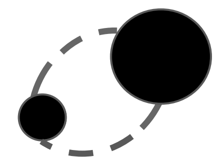
Credit: Souza Lima et al. (2017)



1-10s pc:
Formation of a bound binary



Credit: Bowen et al. 2017

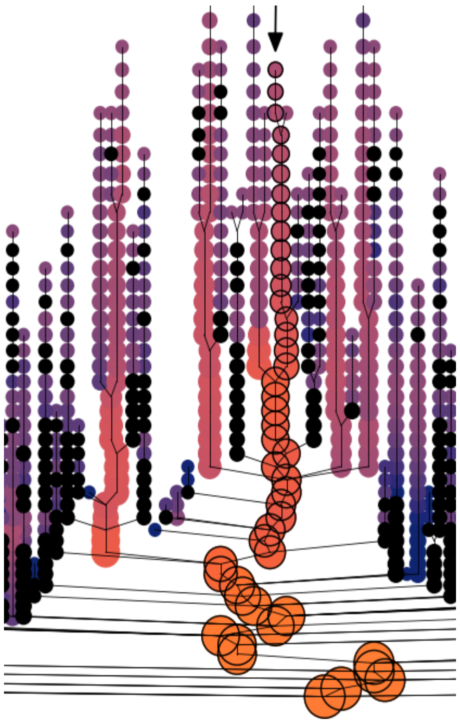


<1 pc:
Hardening of the binary

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

Complexity necessitates multitude of modelling techniques

Semi-analytics



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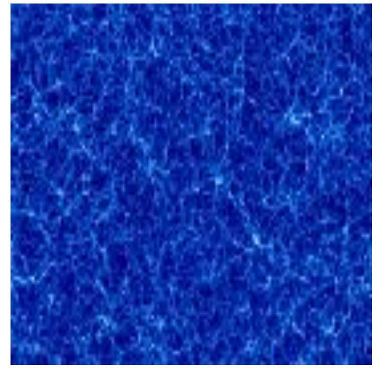
Key physical processes of galaxy formation

Semi-numerics



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Key physical processes of galaxy formation

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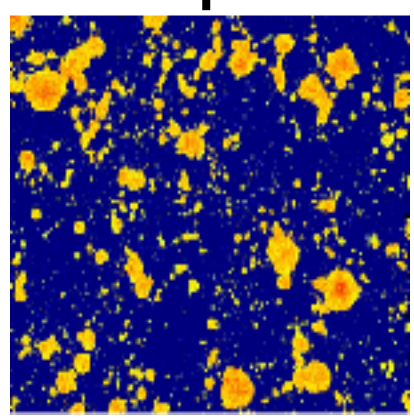
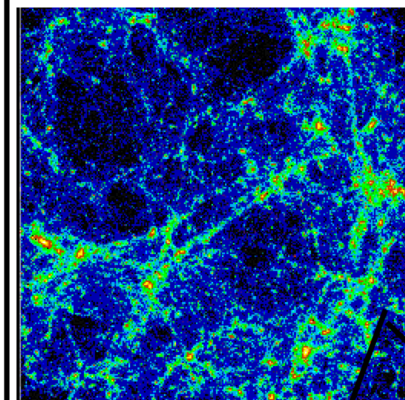
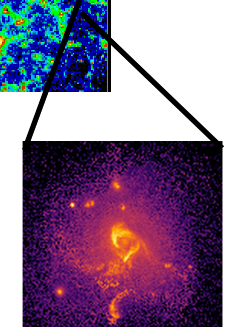


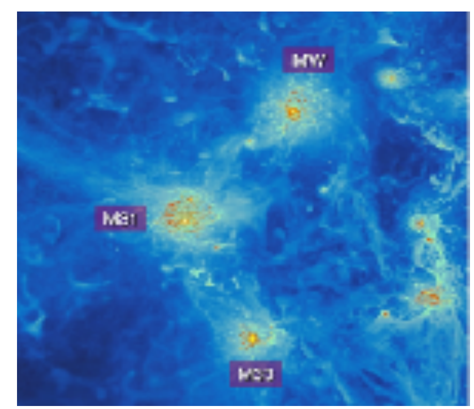
Hydrodynamics



Large-scale



Small-scale



Enormous ongoing theoretical effort to model galaxy formation

No.	Main aim	Technique	box size [cMpc]	M_{DM} [$M_\odot$]	Key Physics	Code [reference]
				Small-scale models		
1	SF in GMC	Resimulated	1–10 R_{vir}	$\sim 10^2$–10^6	AIKO	FIRE [136]
2	SF, GF, EoR	AMR	1	1840	DIKO	[137]
3	GF, EoR	AMR+RT	4 h^{-1}	4×10^6	EO	EMMA [138]
4	UV fb	SPH+RT	5	2.5×10^5	EIO	[139]
5	UV fb, GF	SPH+RT	3-6 h^{-1}	0.18–1.4×10^6	GIKO	[140]
6	ISM,CGM	AMR	9.7 h^{-1} kpc	9.5×10^4	AIKL	[141]
7	UV fb, GF	SPH+RT	10 h^{-1}	4.3×10^7	GIO	[142]
8	GF, EoR	Eulerian+RT	20	4.8×10^5	EIKO	[143]
9	GF, EoR	AMR	40	3×10^4	diko	Renaissance [144,145]
10	GF, EoR	AMR+RT	20–40 h^{-1}	7×10^6	AIO	CROC [146]
				Intermediate-scale models		
1	GF, EoR	N-body+semi-numerical RT	100	3.9×10^6	DIKO	DRAGONS [147]
2	GF	SAM	–	$M_{min} = 10^8$	CIP	DELPHI [148]
3	EoR (LG)	Eulerian+RT	91	3.5×10^5	EIO	CoDA [149]
4	GF, EoR	SPH+ RT	12.5–100 h^{-1}	10^6–8×10^7	EIKO	Aurora [150]
5	f_{esc}	SPH	10–100 h^{-1}	6×10^6–9×10^8	GIKLM	[151]
6	GF	SPH	25–100 h^{-1}	1.2–9.7×10^6	FIJKM	EAGLE [133]
7	GF	Unstructured mesh	106	6.2×10^6	GIJK	Illustrus [152]
				Large-scale models		
1	EoR	N-body+RT	114–425 h^{-1}	0.55–5×10^7	HO	[134]
2	GF	SPH	400 h^{-1}	1.7×10^7	GIJKM	BlueTides [153]
3	GF	SAM	500 h^{-1}	1.3×10^9	BIJKP	GALFORM [154]

+Atraeus, Thesan, Obelisk, Sphinx, Astrid, Romulus, Horizon-AGN..

PD & Ferrara, 2018, Physics Reports,780, 1

Unprecedented datasets from cutting-edge instruments instruments

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

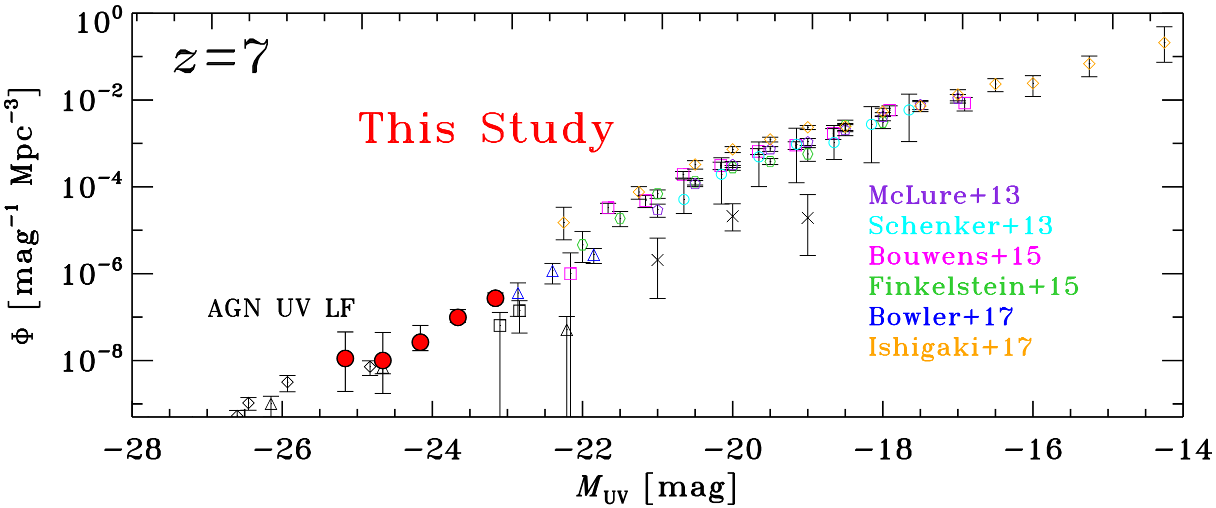
Total rate of star formation per unit volume (*Star formation rate density*)

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

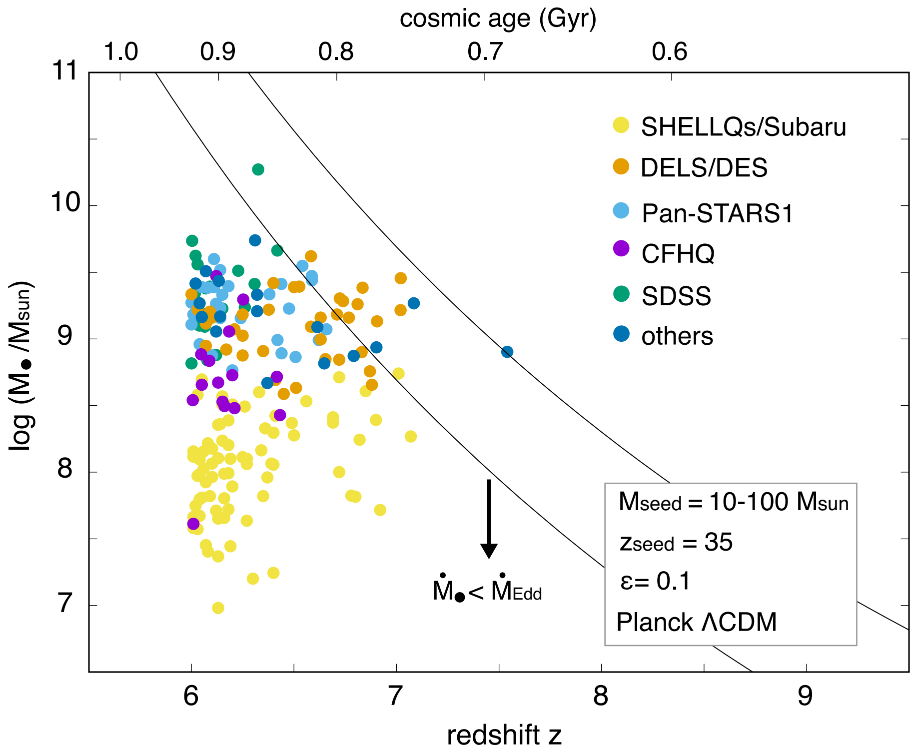
The dust masses and metallicities of early galaxies

Sizes and mergers of early galaxies; early BH candidates

A continually expanding frontier for black hole detection

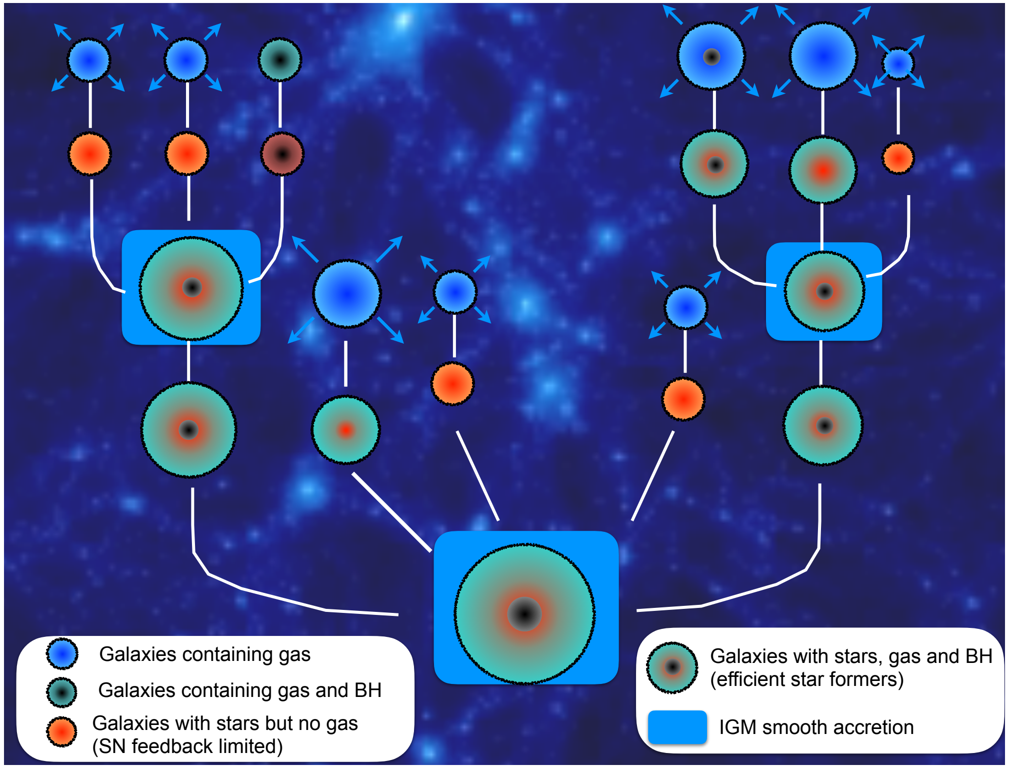


Ono et al., 2018, PASJ, 70, 10



Inayoshi & Haiman, 2020, ARAA, 58, 27

Datasets allowing unprecedented opportunity to baseline models



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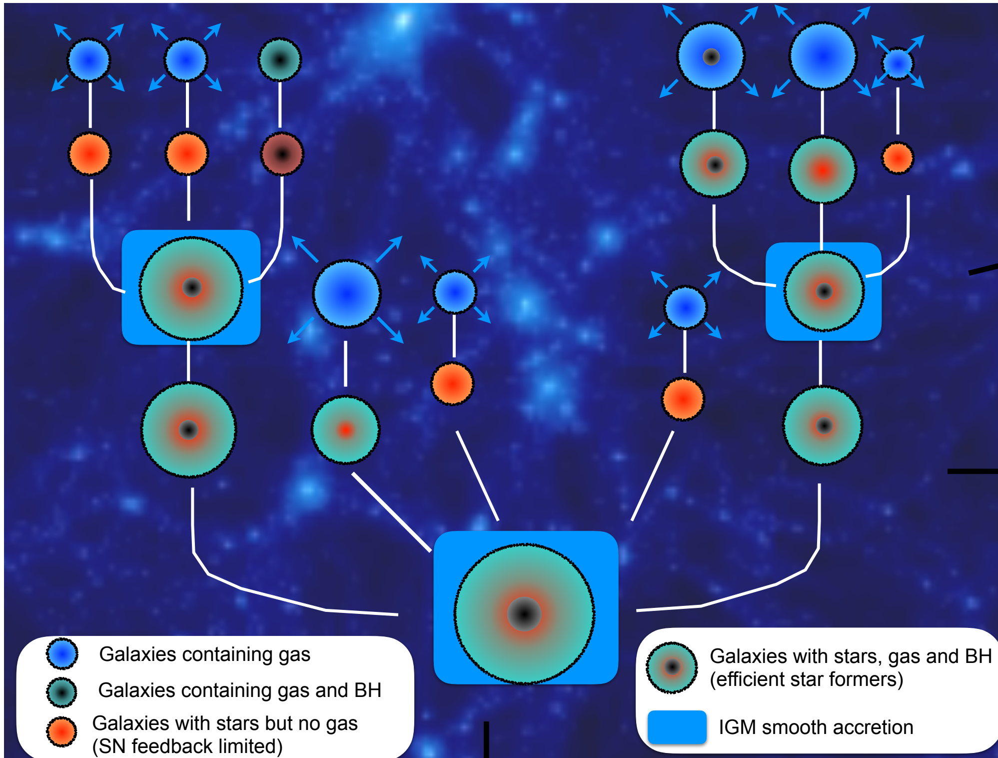
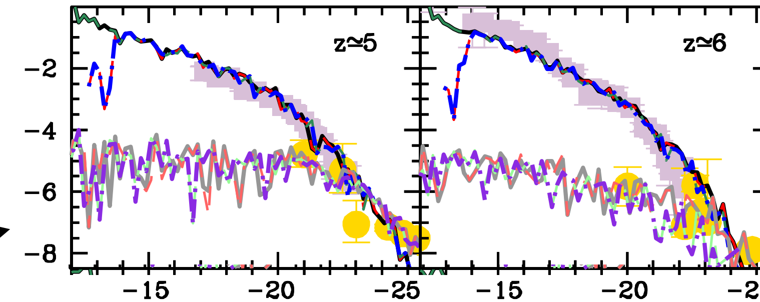
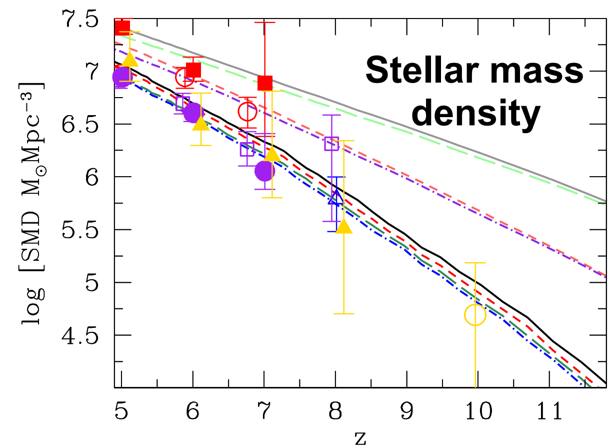
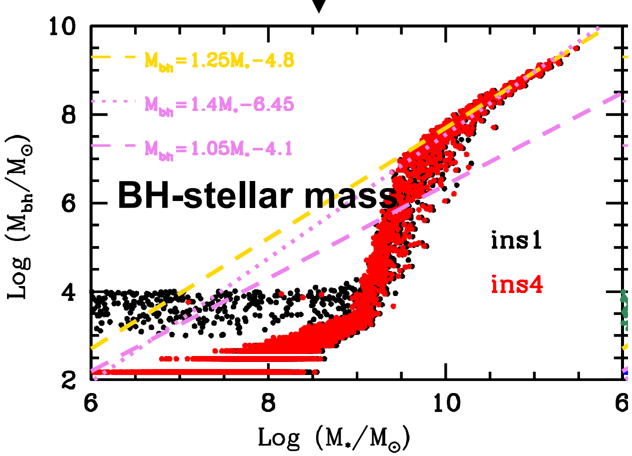
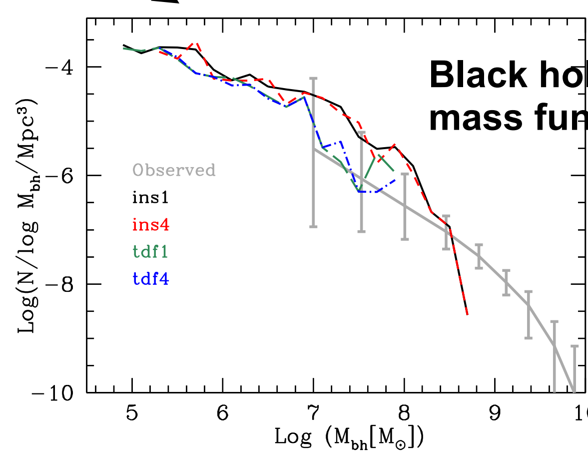


Ultra Violet Luminosity Function









The key physics required

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

The key physics required

Different types of BH seeds - stellar (PopulationIII) and direct collapse black holes (based on strength of Lyman alpha background)

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

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Different types of BH seeds
- stellar (PopulationIII) and direct collapse black holes (based on strength of Lyman alpha background)

Impact of reionization feedback in photo-evaporating gas from low-mass halos and slowing black hole growth

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

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Black hole growth regulated by both halo mass and gas availability (due to the impact of Supernova and reionization feedback)

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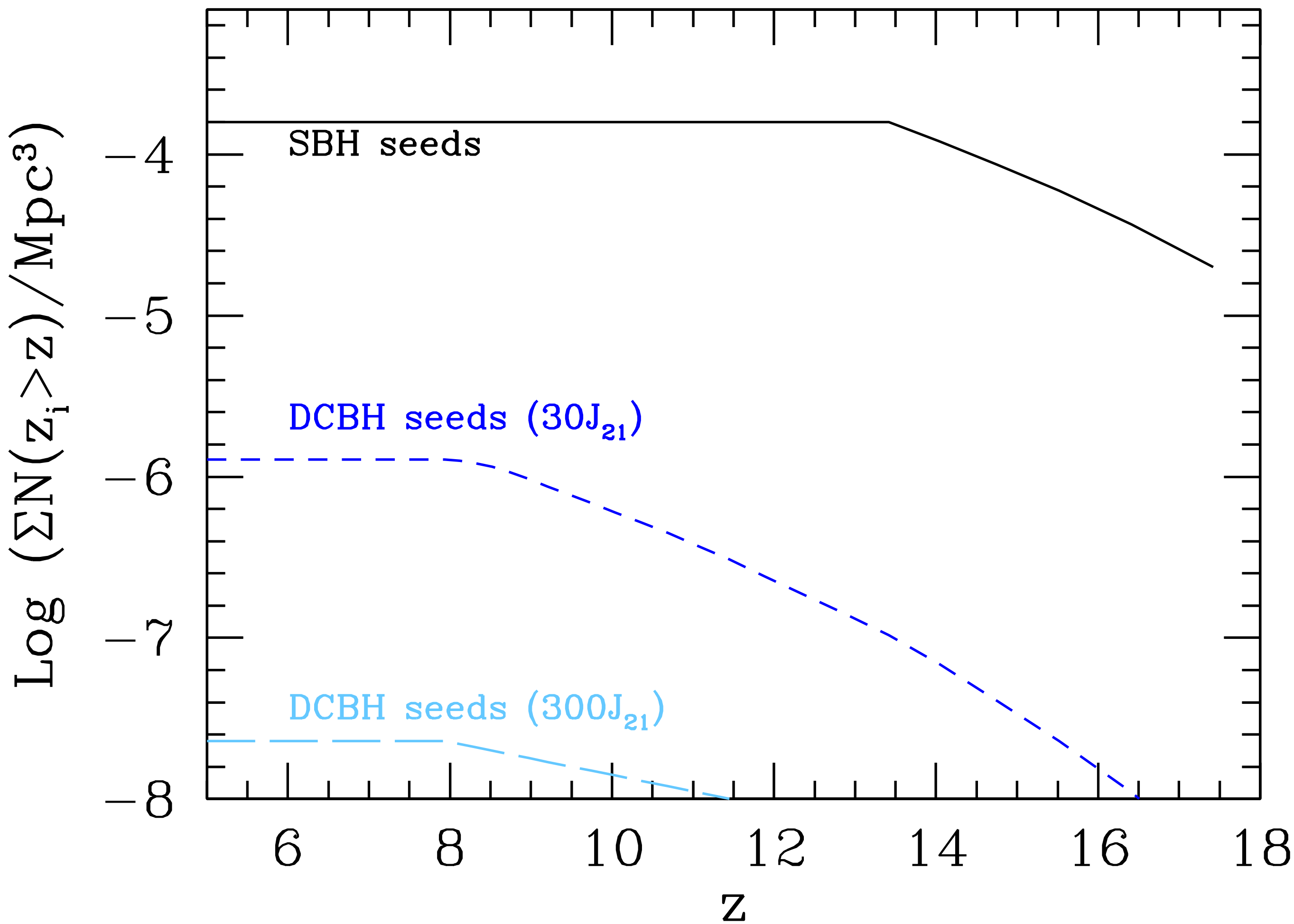
Black hole growth regulated by both halo mass and gas availability (due to the impact of Supernova and reionization feedback)

Impact of instantaneous versus (dynamically) delayed galaxy mergers on the black hole merger rate

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

Number densities of seed black holes

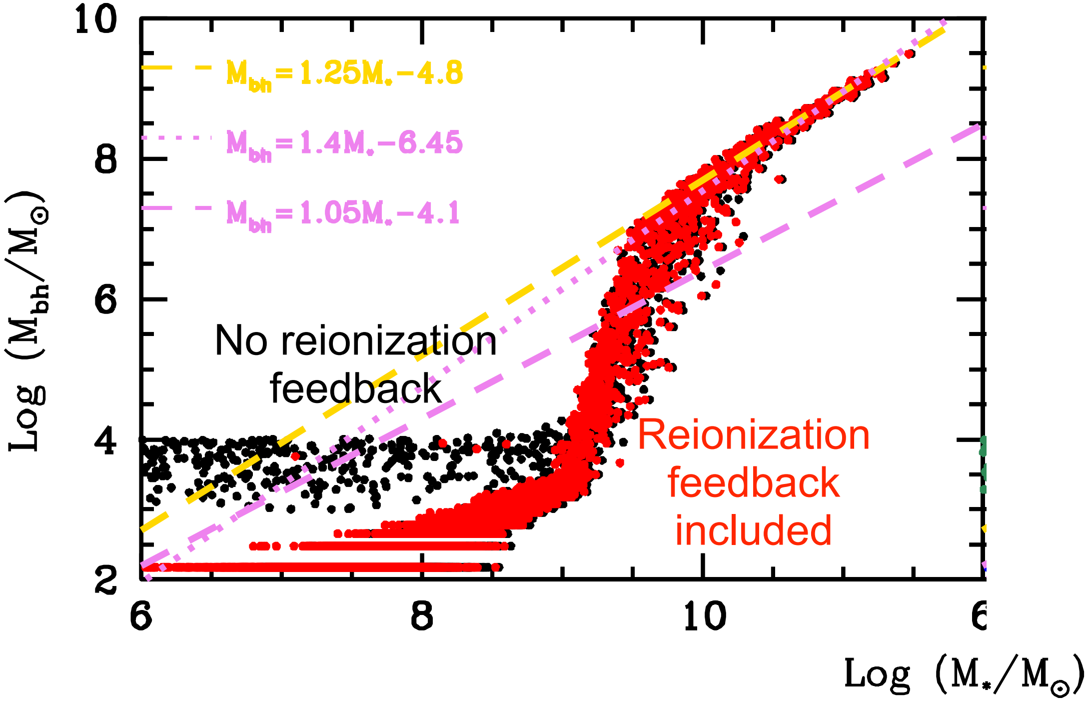


- Stellar BH seeds dominate DCBH seeds by about two-4 orders of magnitude.
- DCBH seeds can grow into QSOs at z~6 but *only if* they are seeded into the progenitors of the most massive halos by construction.

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

What shapes the black hole mass- stellar mass relation?

Instantaneous merging $z \simeq 5$ Delayed merging



• In instantaneous merging (*black*), BH mass-stellar mass correlated for $M_* \geq 10^{9.5} M_\odot$.

• Adding the effects of reionization (*red*) result in a “stalling” of BH growth for $M_* \leq 10^9 M_\odot$ galaxies.

• Delayed BH mergers introduce larger scatter in relation although still consistent with average *fiducial* trend.

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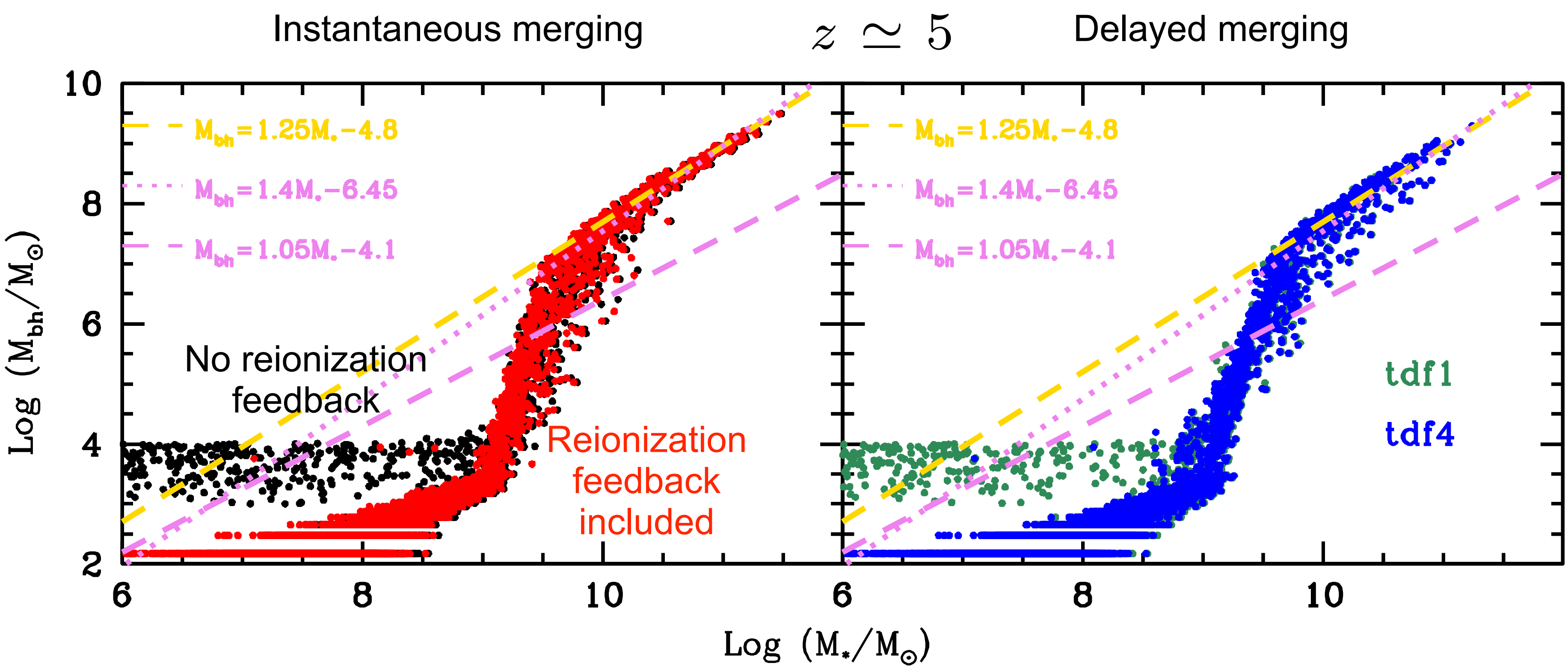

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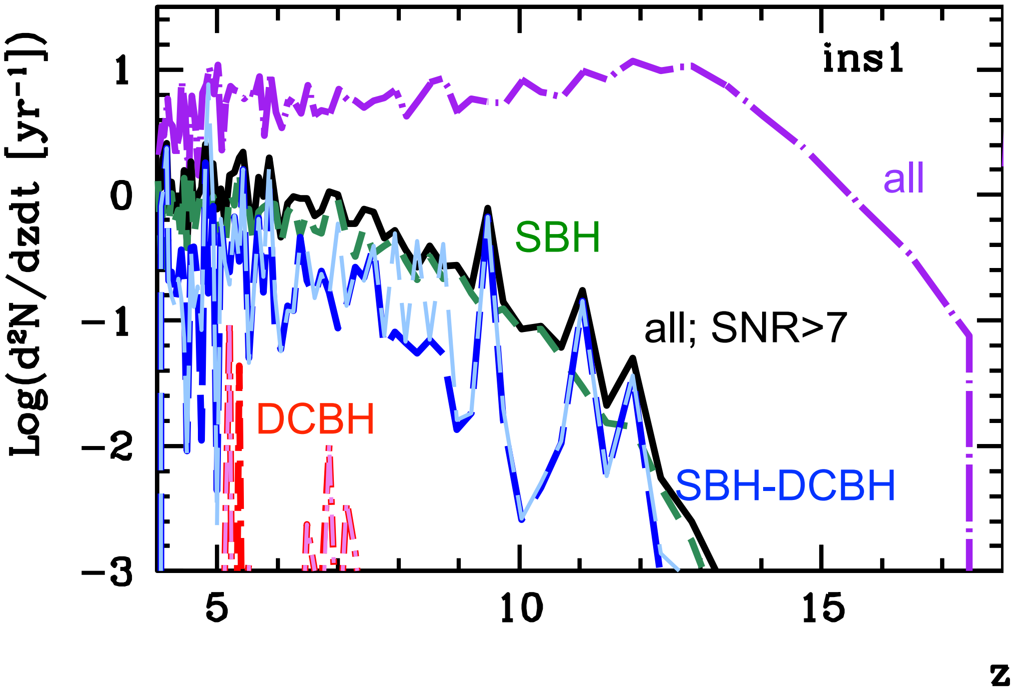
The LISA-detectable GW event rate as function of redshift

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 + reionization feedback, importance of DCBH-SBH mergers decreases. No detectable DCBH-DCBH mergers (with SNR>7).

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

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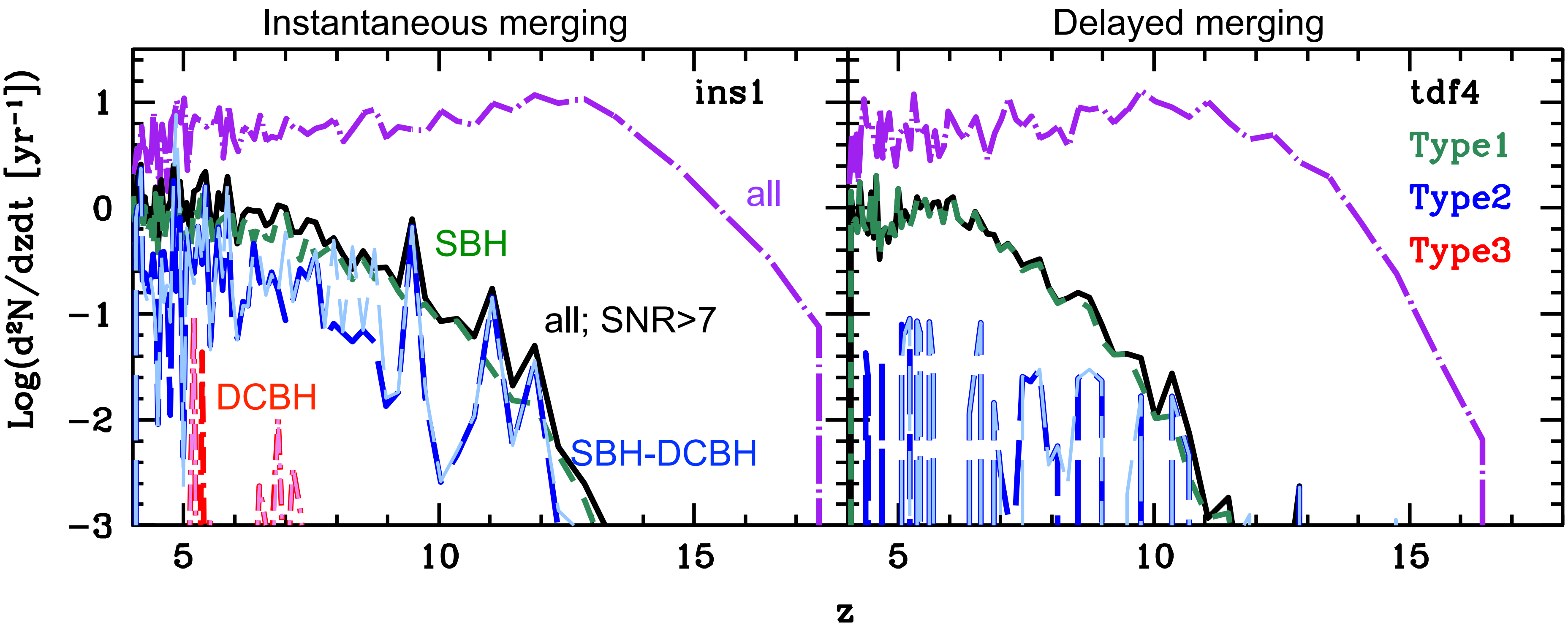

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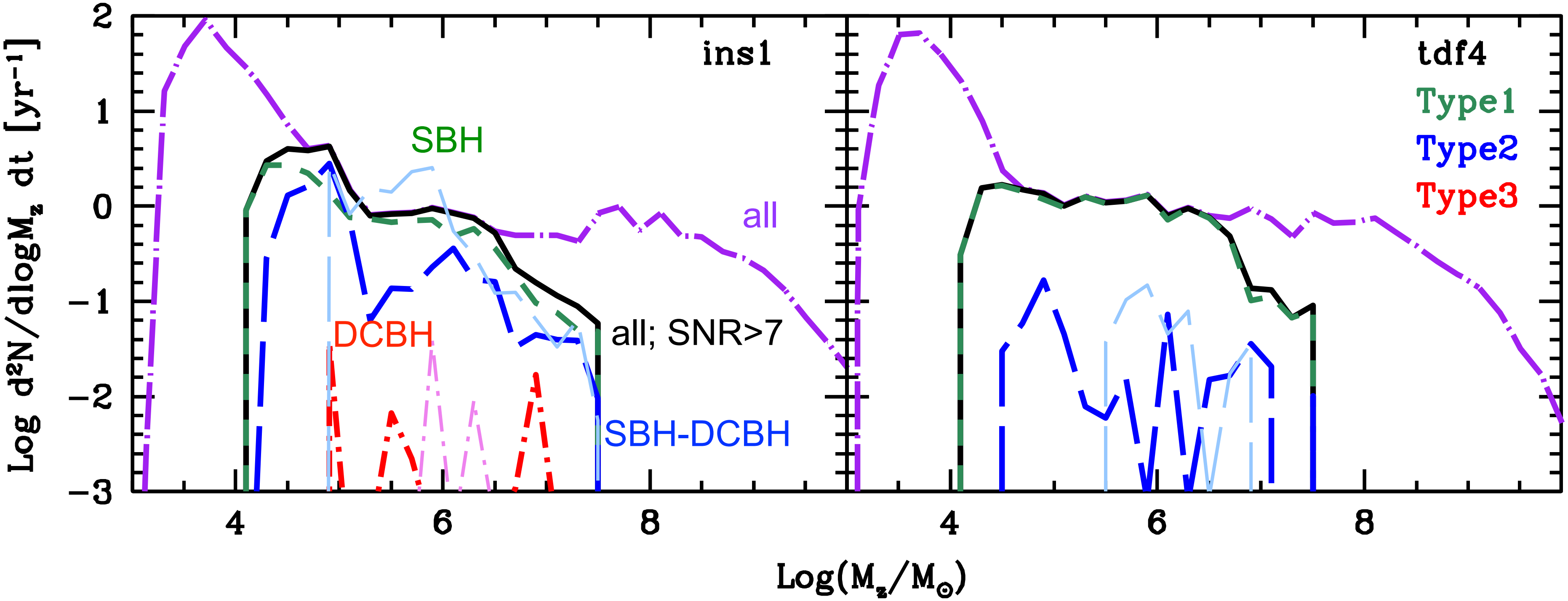
DELPHI; PD, Rossi et al. 2019, MNRAS, 486, 2336

The LISA-detectable GW event rate as function of mass



• LISA will preferentially detect BHs with mass $M_{BH} \sim 10^{4-7} M_{\odot}$. In *fiducial case (ins1)* most detectable mergers are those from SBH-SBH, followed by SBH-DCBH mergers. DCBH-DCBH mergers negligible.

• Although same mass range true for the *tdf4 model, d*ue to delayed mergers + reionization feedback, importance of DCBH-SBH mergers decreases. No detectable DCBH-DCBH mergers (with SNR>7).

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

LISA detectability of early BH mergers

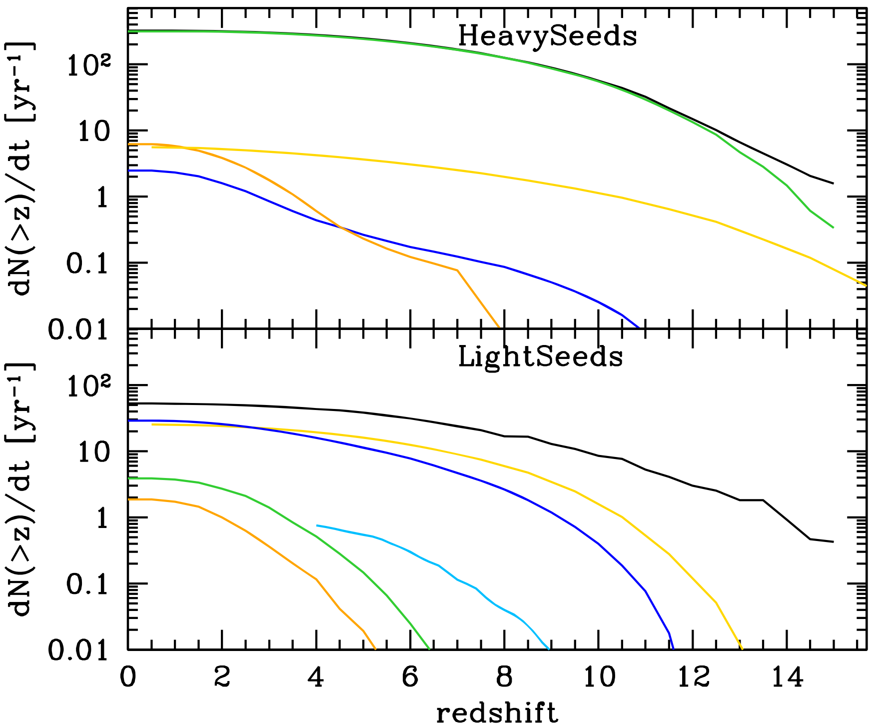
LISA detectability of high-z BH mergers over a 4-year duration using a SNR>7.

Model	All_7	Type 1_7	Type 2_7	Type 3_7
ins1	19.8	13	6.8	0.05
tdf4	12.5	12.1	0.4	0
ins1 (heavy)	23.3	13	10.3	0.04
tdf4 (heavy)	12.5	12.1	0.4	0

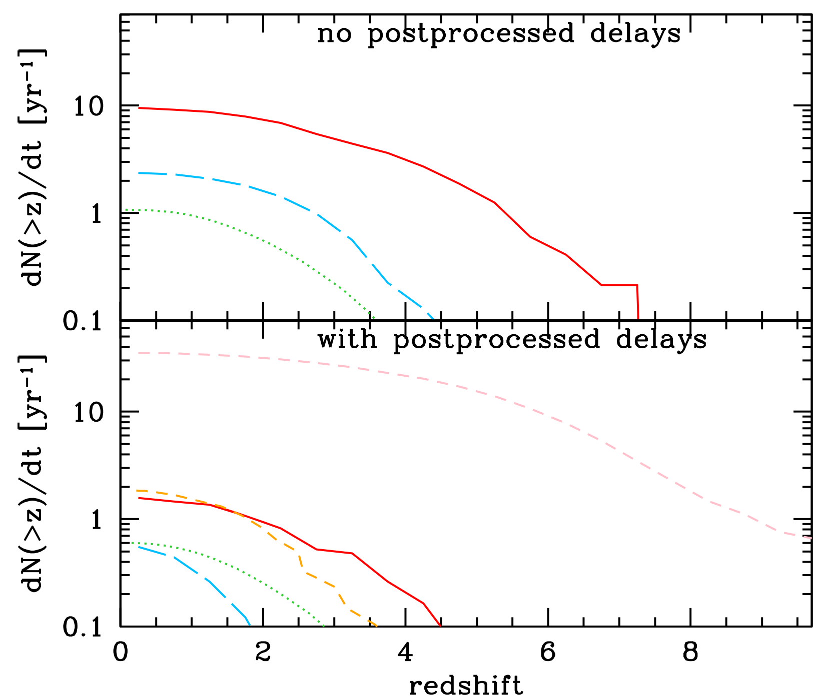
- SBH-SBH mergers dominate the detectable event rate followed by SBH-DCBH mergers.
- DCBH-DCBH mergers extremely rare.
- Changing seed mass of DCBH changes numbers slightly for detectable SBH-DCBH mergers.

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

Assumptions on BH seeds masses, feedback and merger timescales crucially determine event rates



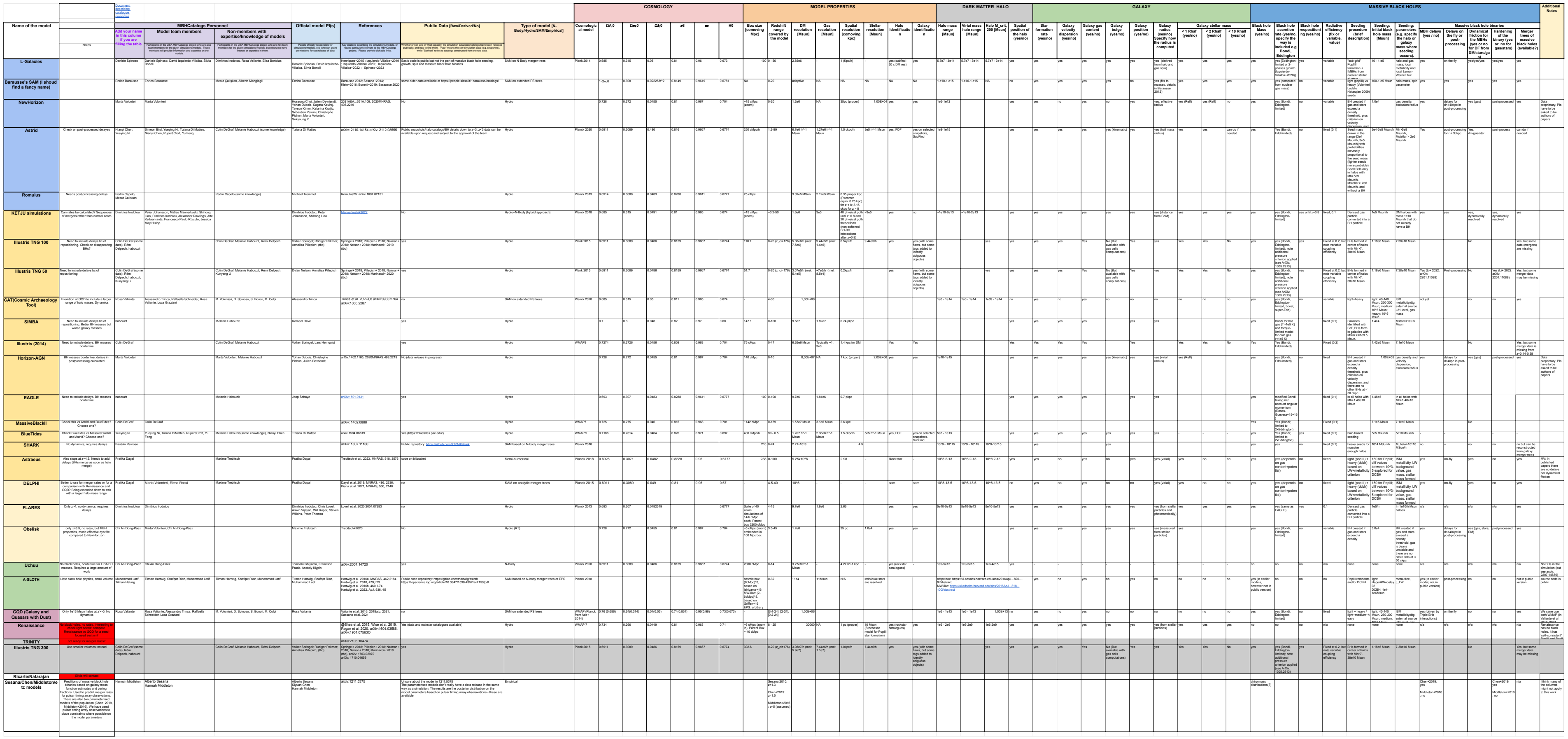
Semi-analytic models



Numerical simulations

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

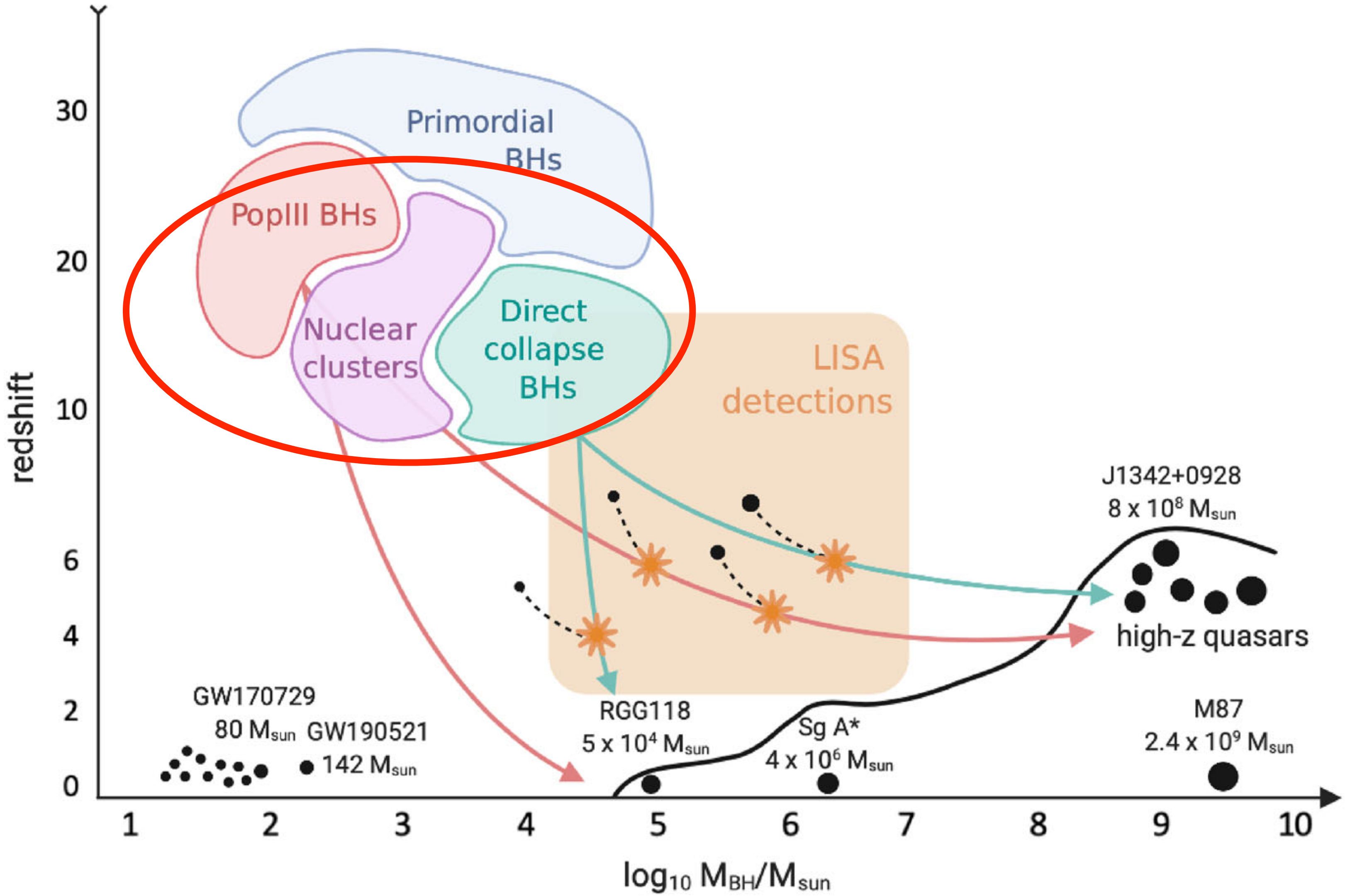
The need for a physical-results comparison project



- As of now, 35 models under study

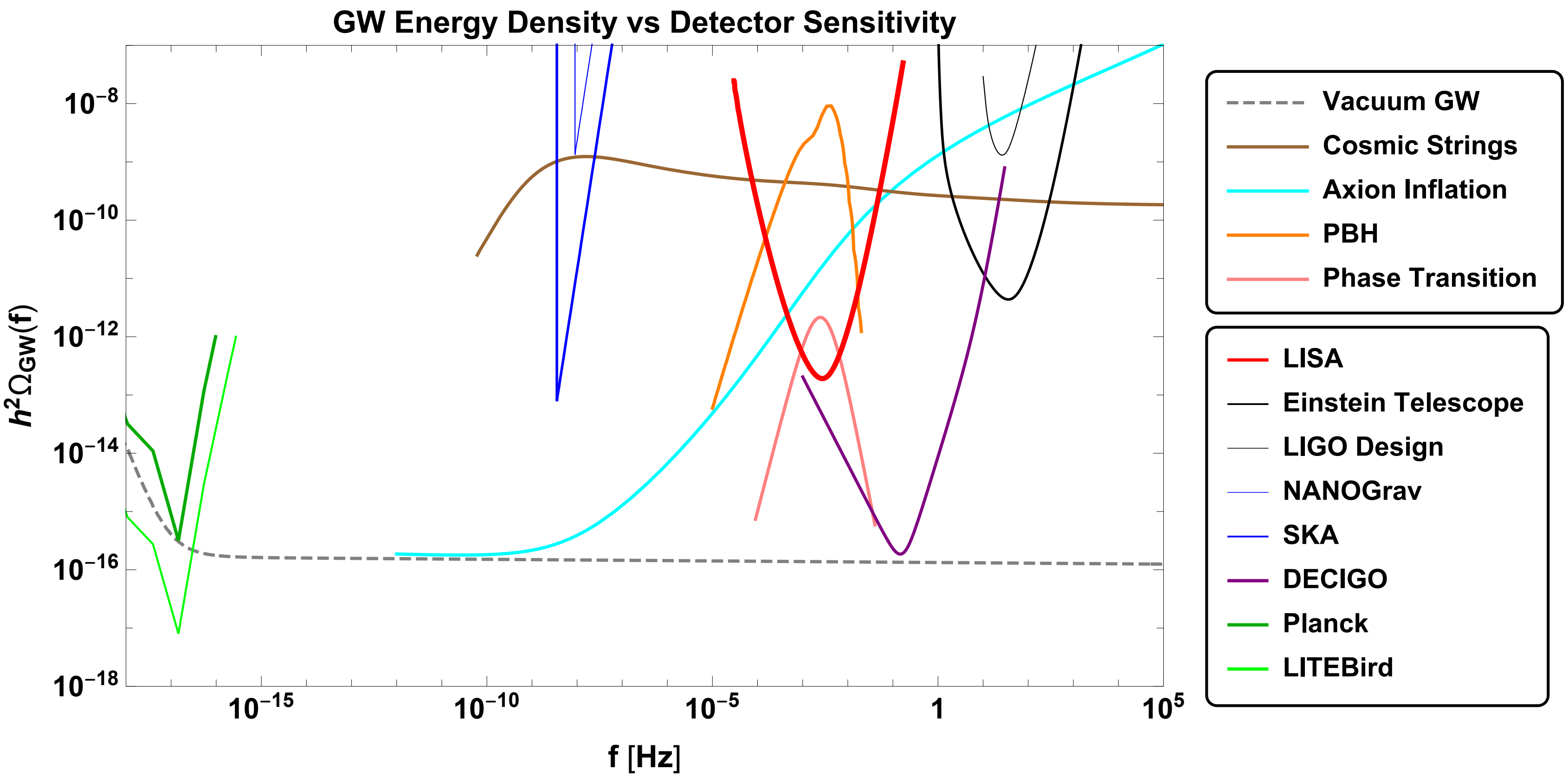
- Key properties for comparison include: cosmological model, galaxy properties (masses, sizes, star formation rates) and BH properties (seeding prescriptions, accretion models, merger timescales implemented, feedback..)

Outstanding issues 1: BH seeding mechanisms



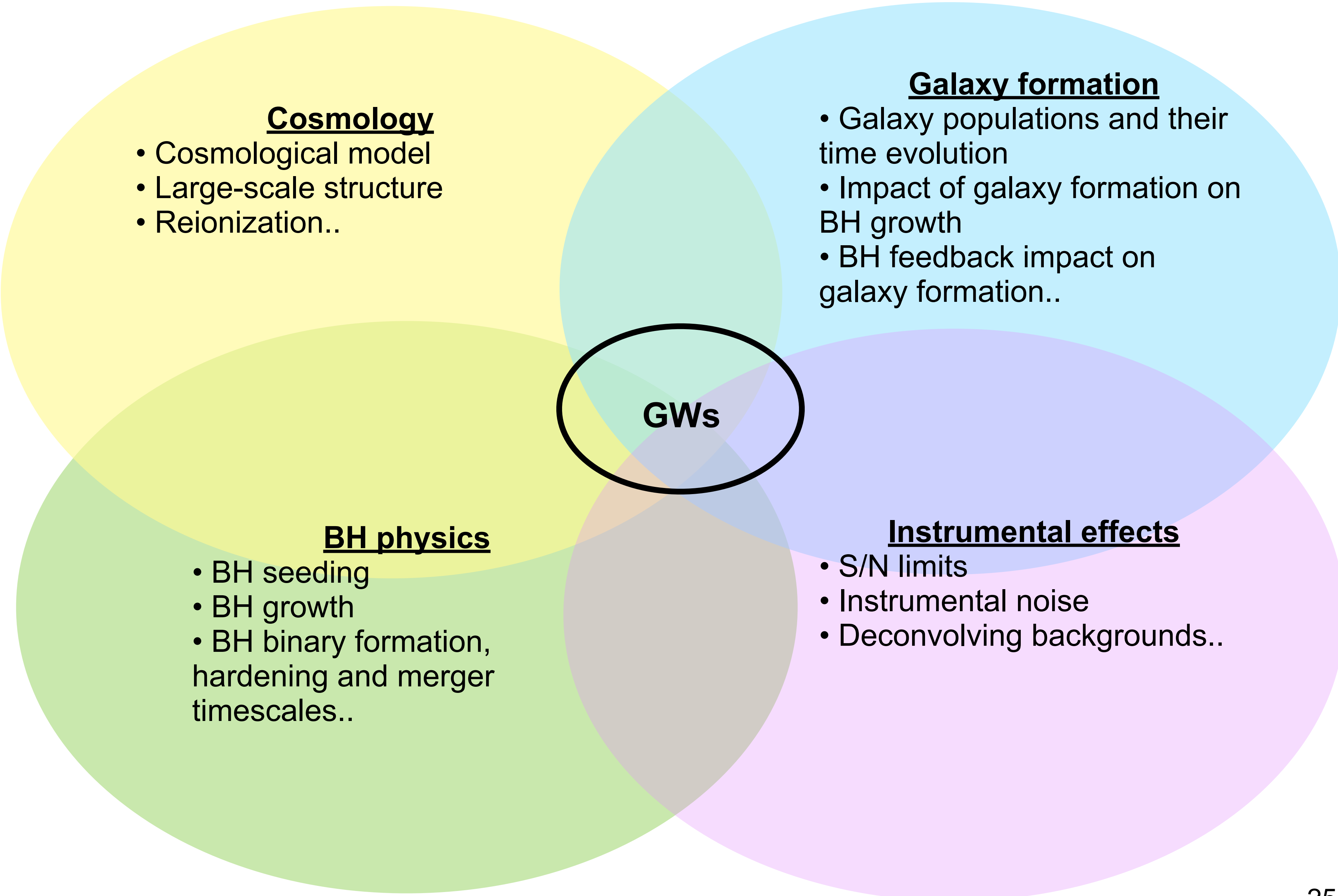
"Astrophysics with LISA" white paper, 2023, LRR, 26, 2
arXiv:2203.06016

Outstanding issues 2: sources of the stochastic background

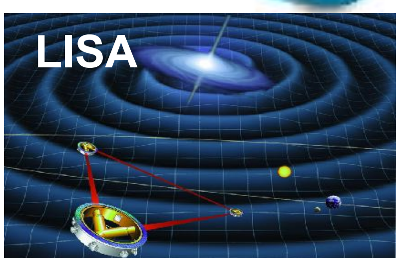


"Cosmology with LISA" white paper
arXiv:2204.05434

GWs: interface of cosmology, astrophysics and BH physics



Towards a holistic picture of BHs in the first billion years



Global properties of galaxy populations
link between halos and their baryons, constraints on efficiency of star formation and feedback

Individual galaxy properties
constraints on assembly histories, dust formation mechanisms, gas masses

21cm cosmology
constraints on source population and its redshift evolution, constraints on topology and history of reionization

Gravitational wave astronomy
constraints on black hole masses, abundances; constraints on black hole seeding and growth channels