Giornate del Raggruppamento INAF RSN1: Galassie e Cosmologia (2026)

09–11 feb 2026
INAF - Osservatorio Astronomico di Capodimonte

Supermassive black holes formation, evolution and feedback

Theoretical perspective

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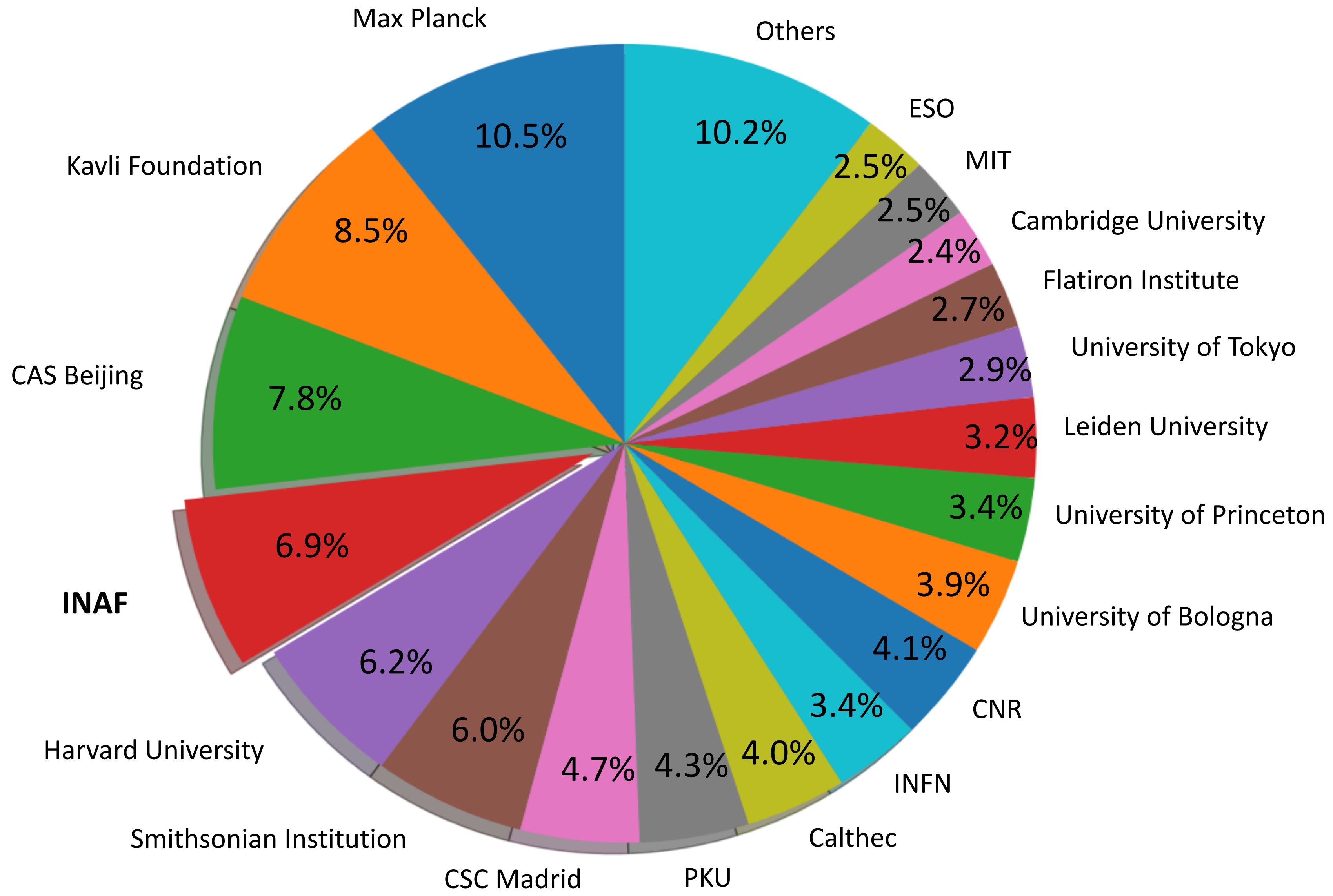
Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani Piano Nazionale di Ripresa e Resilienza | OAR

SMBHs across Institutions

institutional occurrence frequency in refereed SMBH-related Publications
Data source: NASA ADS (Astronomy database, 2020–2026, refereed articles); Selection criterion: “supermassive black holes” in the abstract



NB: The definition of SMBHs varies across the literature, ranging from ≳10^6–10^8 $M_\odot$ and in some cases encompassing massive “stellar” BHs (≳10^2 $M_\odot$)

5423 papers
1188 institutions

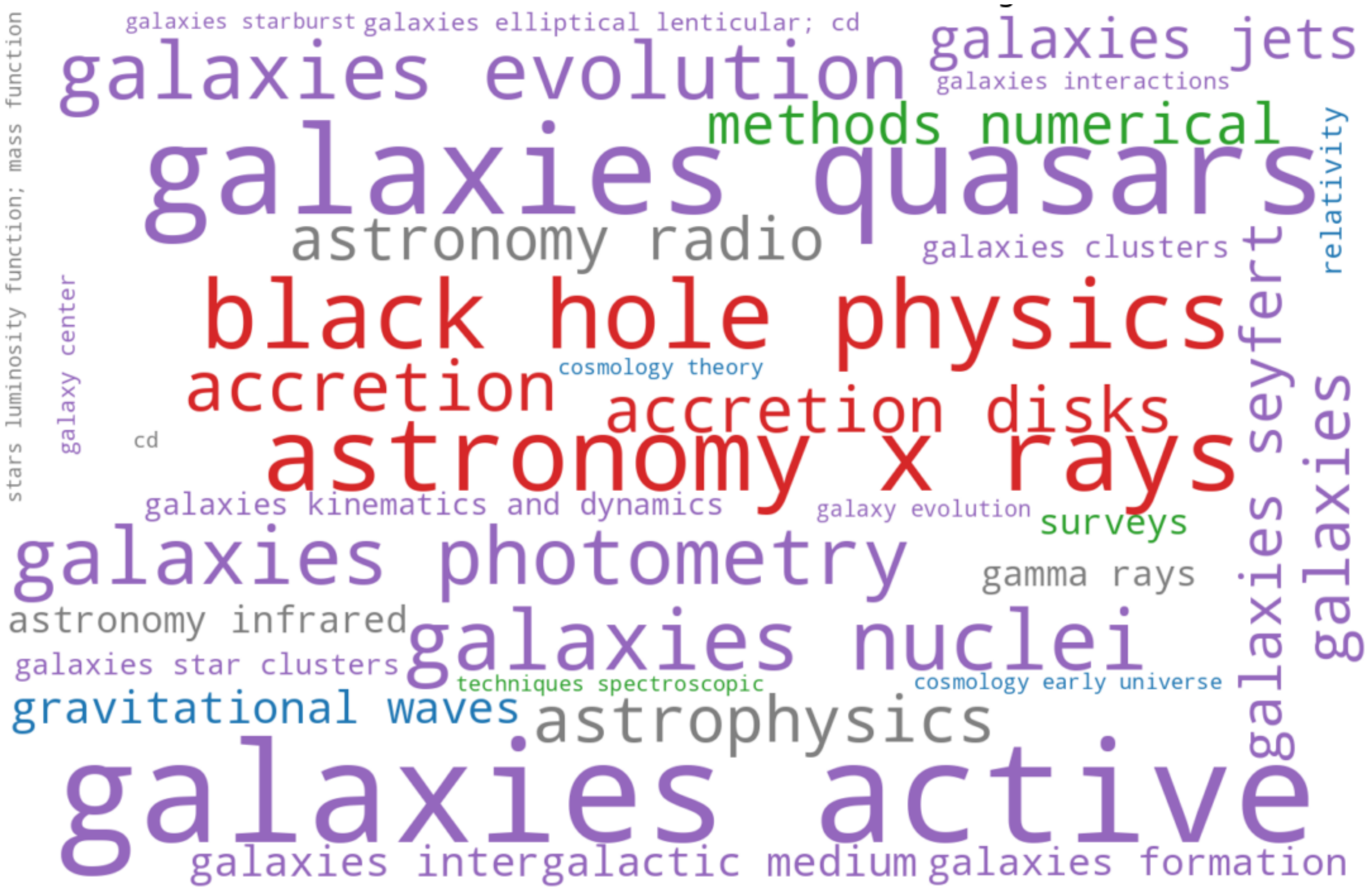
based on institutional affiliations as indexed in ADS
indicative comparison - not an exhaustive census.

SMBHs across INAF Research Themes

Word cloud of **keywords**
from refereed publications
(limited to papers with INAF contribution)

Color-coded by thematic research area

- **AGN & Black Holes**
  Active galaxies, quasars, accretion, jets, X-rays
- **Cosmology & Fundamental Physics**
  Early Universe, relativity, gravitational waves
- **Methods & Surveys**
  Numerical methods, spectroscopy, surveys, photometry
- **Galaxy Physics**
  Galaxy evolution, formation, environment
- **Cross-cutting topics**
  Radio/IR astronomy, gamma rays, general astrophysics



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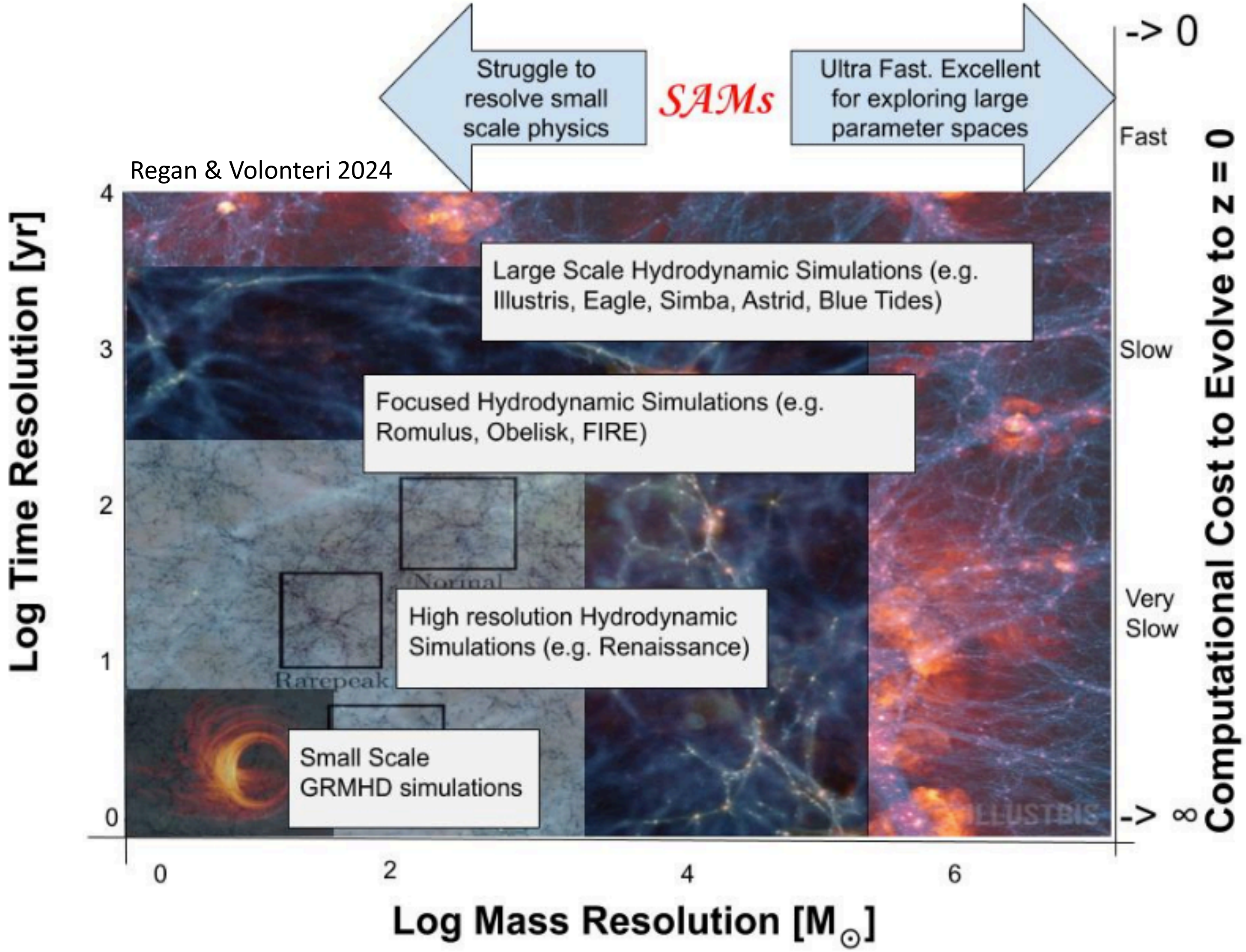
SMBH formation, evolution & feedback: a theoretical challenge

Key question: How do we connect unresolved SMBH physics to observable galaxy properties?

Main Goal: produce **testable predictions**

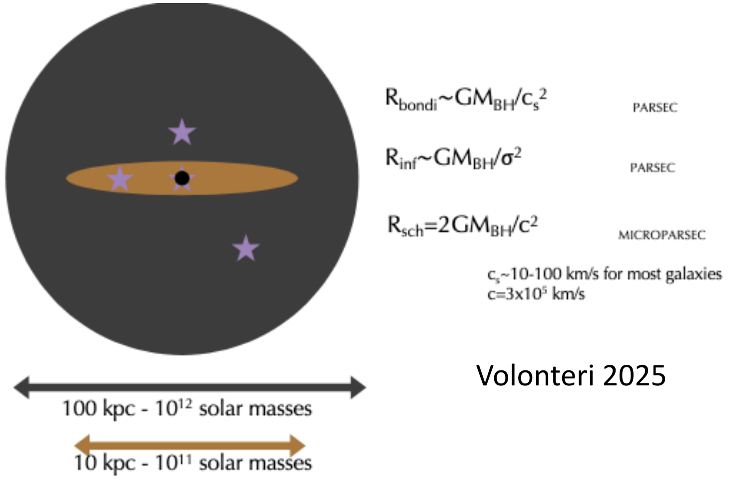


Regan & Volonteri 2024

SMBH/galaxy physics spans **AU → Gpc**

Key processes are **unresolved** observationally

Models link **physical assumptions to observables**



Volonteri 2025

No single simulation, technique or code can cross the entire domain

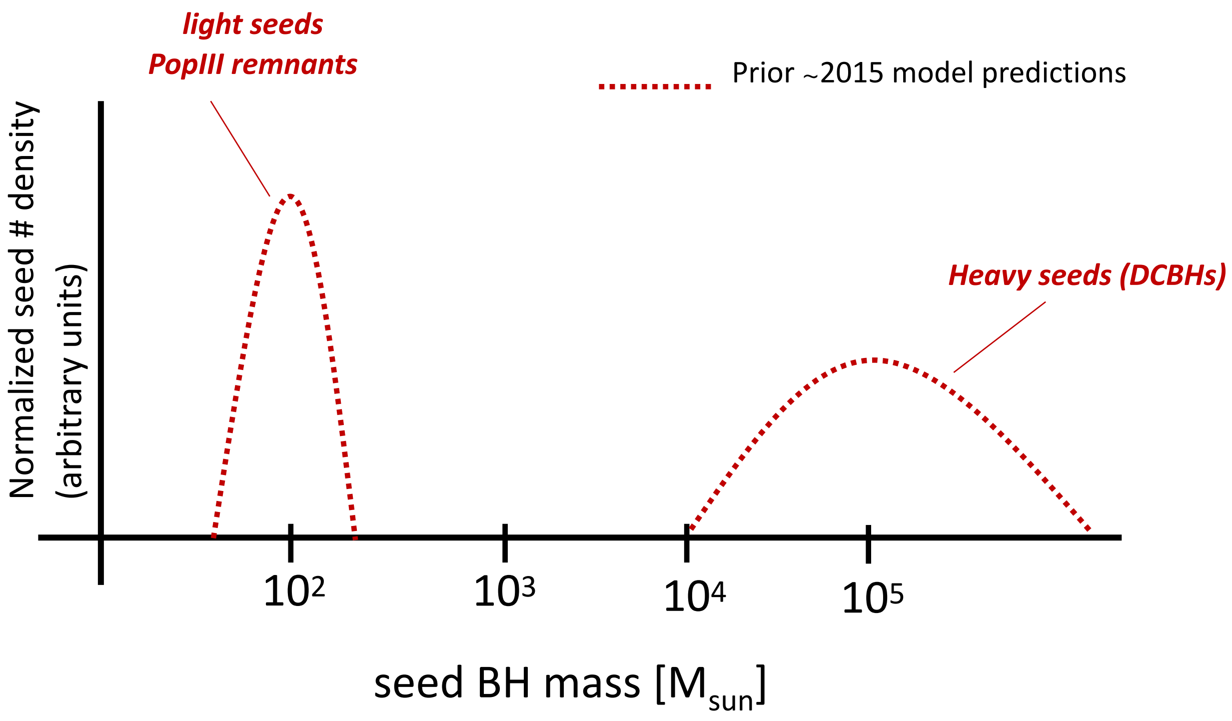
Multiple suites/techniques (SAMs+hydro) are needed

Seeding SMBHs: models and predictions

Key question: what is the mass spectrum and number density of SMBH seeds?

The population of BH seeds is still undetected: their properties are unconstrained and strongly depend on model assumptions

(reviews: Volonteri+2010; Valiante+2017; Greene+2020; Inayoshi+2020; Volonteri+2021; Lusso, Valiante, Vito 2023; Izquierdo-Villalba+2023; Regan & Volonteri 2024)



Historically: two competing seeding channels

light seeds (~100 M_{sun}) → PopIII IMF [10-300] M_{sun}

vs

heavy seeds (~10^5 M_{sun}) → direct collapse scenario

(LW irradiation, Baryonic streaming, galaxy mergers)

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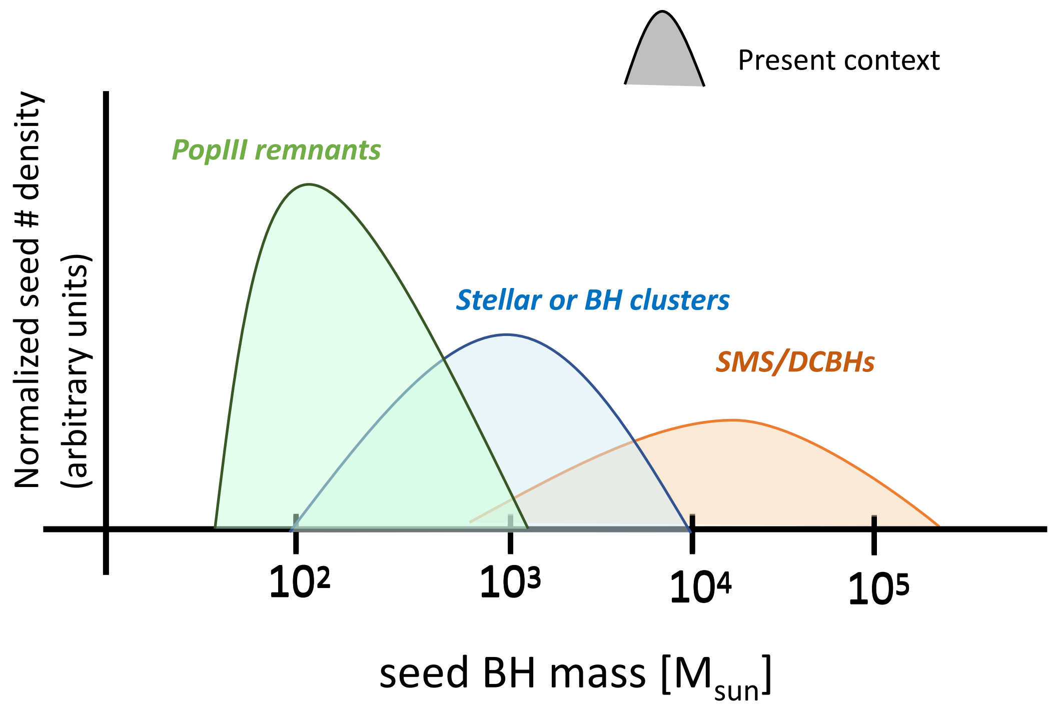
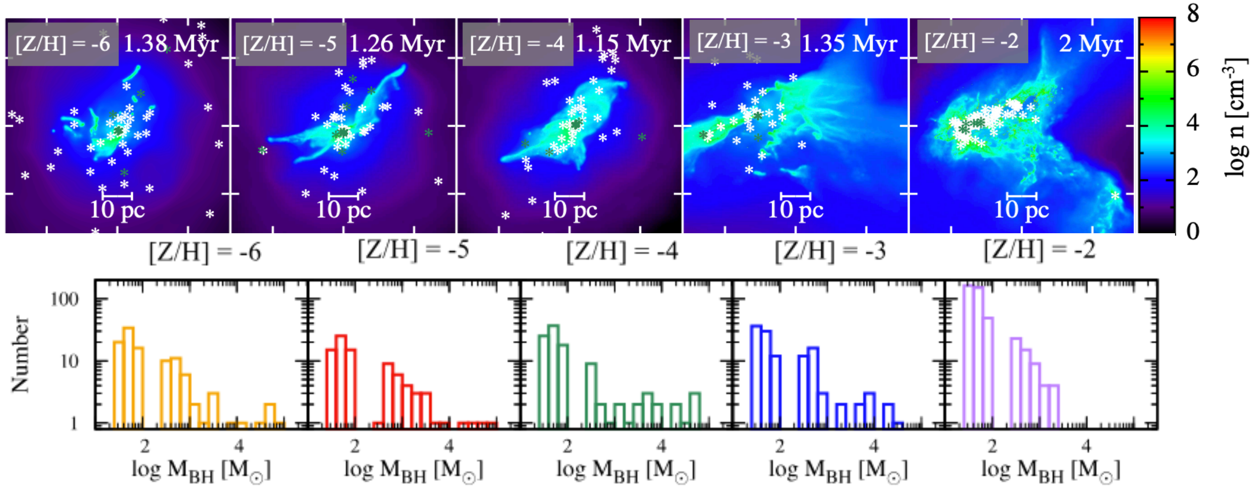




Chon & Omukai 2025

Over the last decade the picture has changed
multiple seed channels likely coexist

light seeds: [10-10^3] M_{sun} → refined/top-heavy PopIII IMF

heavy seeds [10^3 -10^6] M_{sun} → multiple seeds in a single halo

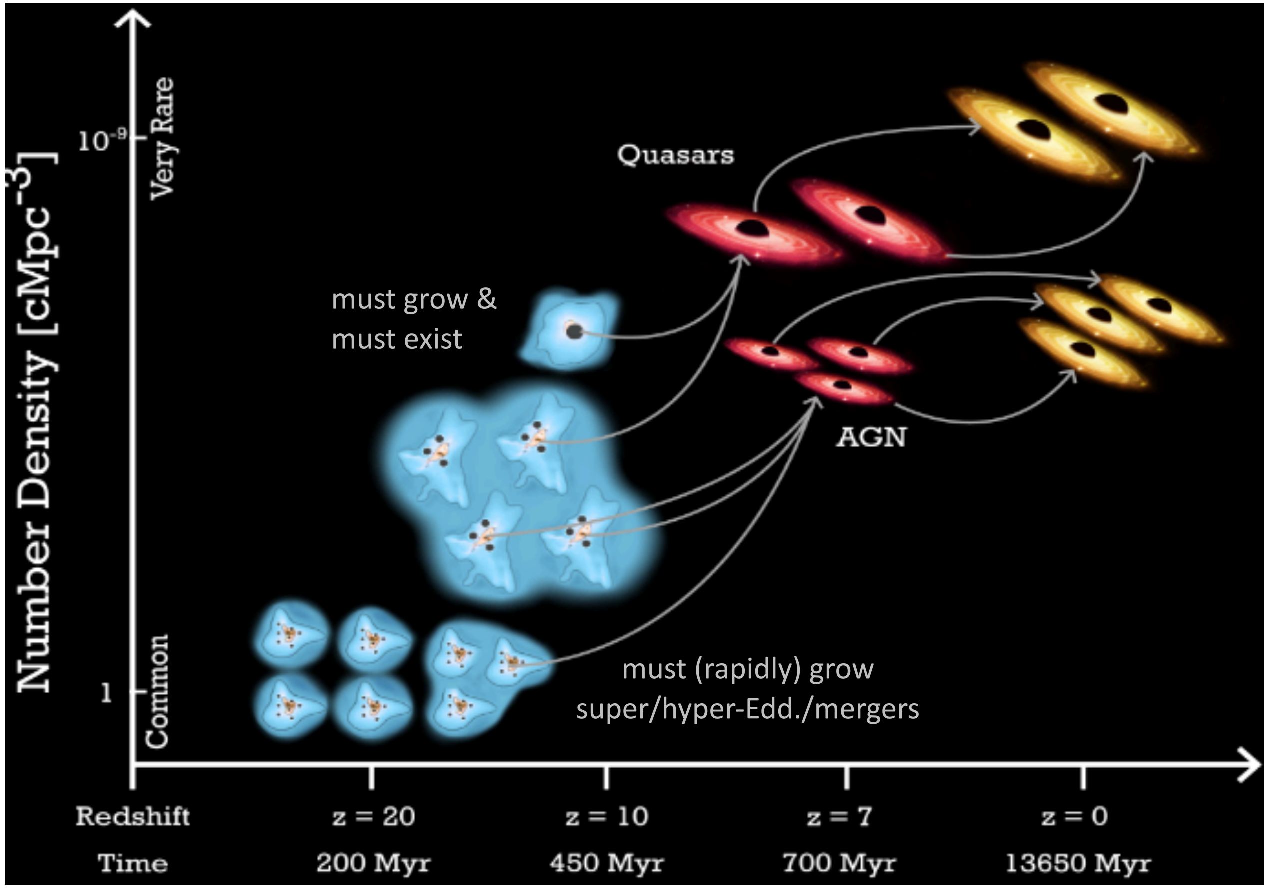
(mergers in dense clusters; competitive accretion/VMS; rapid growth of light seeds; rapid galaxy assembly; Lyman-Werner irradiation; baryonic Streaming; collision/mergers …)

recent progresses includes Regan+2020; Kulkarni+2021; Lupi+2021;2024; Sicilia+2022; Reinoso+2023; Arca-Sedda+2023; Chon+2024;2025; 2026a,b; Rantala+2025…

& alternative channels e.g., **PopIII.1 massive stars** fuelled by dark matter annihilation (Feng+2021; Singh+2023) or **Primordial BHs** (Hasinger 2020; Ziparo+2025)

Growing SMBH seeds is challenging

Key question: How did the first SMBHs form quickly enough to power high-z quasars and AGN and how do the early giants connect to the AGN and quiescent SMBHs we observe across cosmic time, at cosmic noon and in local galaxies?



Gas accretion is inefficient because:

- Bondi radius scales ∝ M_{BH}^2
  (see Pacucci et al. 2017, Trinca et a. 2022, Zhu et al. 2022)
- BHs seeds are easily displaced from the center of the halo
  (see Pfister et al. 2019, Ma et al. 2021; Beckmann et al. 2022; Hazenfratz+2025)
- SN-/BH-driven feedback can evacuate the gas
  (see Dubois+2015, Anges-Alcazar+2017, Habouzit+2017, Prieto+2017, Silk 2017, Smith+2018, Regan+2019, Bhowmick+2022, Koudmani+2022, Lupi+2024; Hazenfratz+2025)

light seeds are generally found not to grow (much)

~ 10^5 M_{sun} seeds grow in sufficiently massive galaxies ($M_* > 10^9$ M_{sun})

Warning: this conclusion is challenged by JWST observations

reviews: Volonteri+2010; Valiante+2017; Greene+2020; Inayoshi+2020; Volonteri+2021; Lusso, Valiante, Vito 2023; Izquierdo-Villalba+2023; DiMatteo+2023; Regan & Volonteri 2024; Volonteri 2025

Seeds grow in favourable environments

When they are embedded in nuclear star clusters or circumnuclear disks

e.g. Alexander & Natarajan 2014, Lupi+2016, Natarajan 2021; Fragione+2022

When they are born in a high density environment:

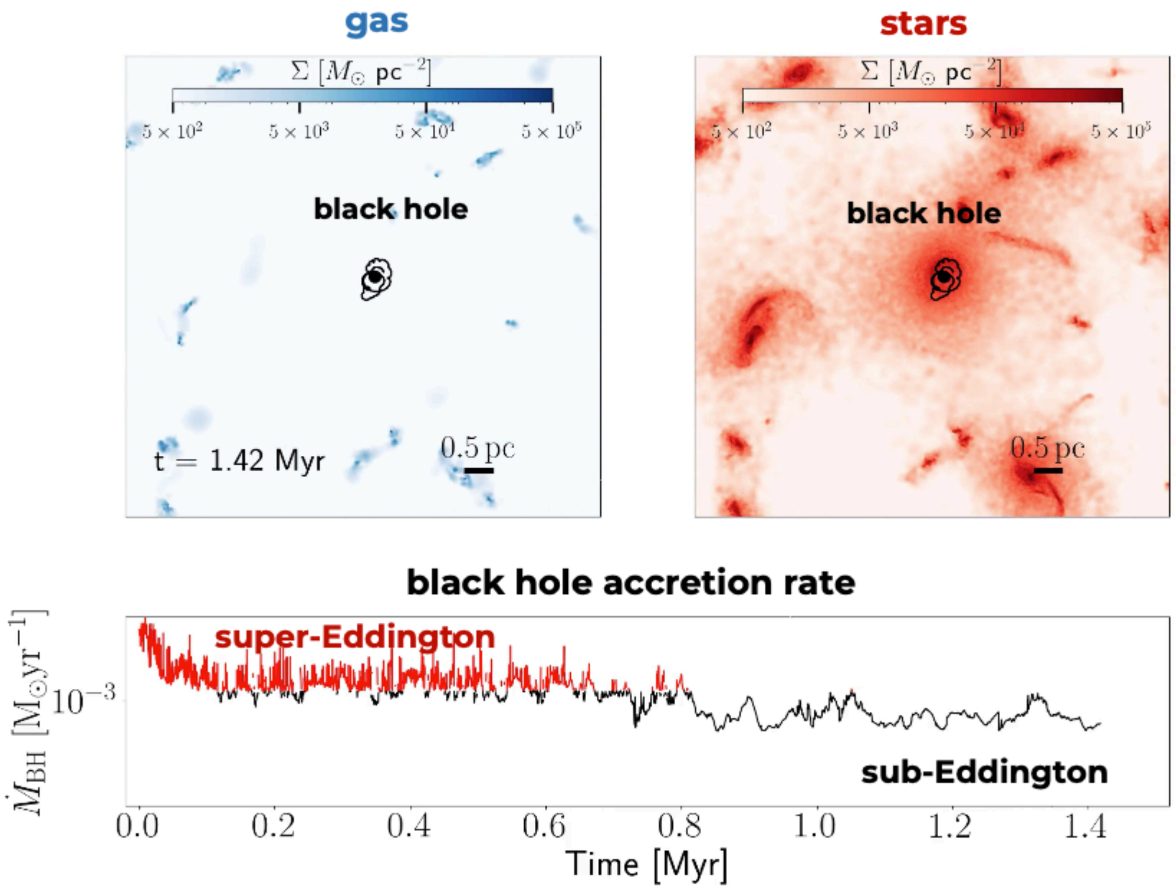
- at the halo center (e.g., Latif & Kochfar 2020)
- in overdense regions of the cosmic web (e.g., Lupi+2024, Quadri+2025)
- in gas-rich protogalactic cores (e.g., Sassano+2023, Shi+2024, Mehta+2024, Zana+2025)

When BH feedback is not very efficient

e.g., Regan+2019; Massonneau+2023, Lupi+2024, Husko+2025

under these conditions, accelerated BH growth can occurr

in short bursts of super-Eddington accretion



Example of super-Eddington accretion in proto-galactic cores

new suites of SPH simulations – modif. GASOLINE2

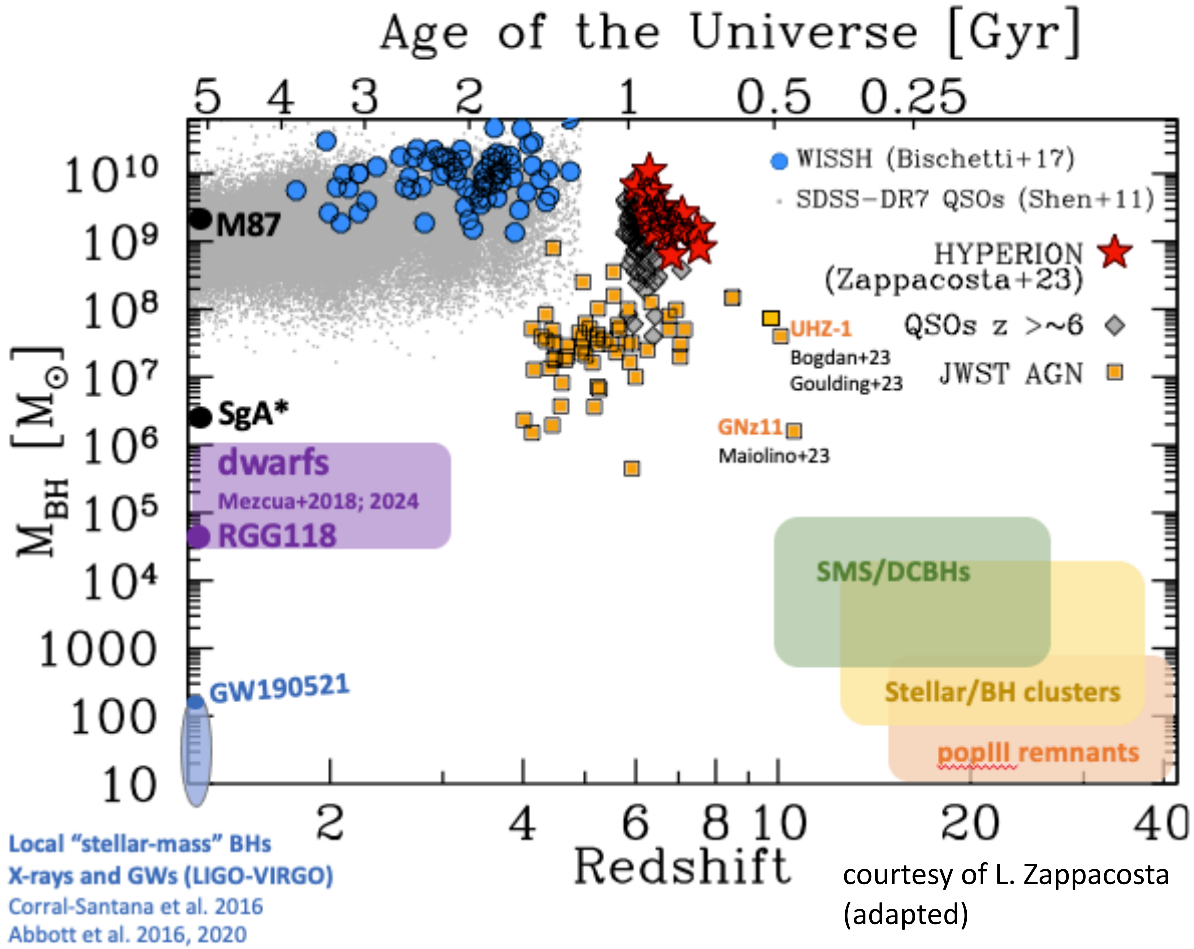
0.18pc resolution, initial BH seed mass 5 x 10^3 M_{sun}

Zana et al. 2025

Pathway(s) to SMBHs

Testing seeding and accretion scenarios in cosmological models/simulations

Main Goal: predicting how to **differentiate seed/accretion models** from observations



courtesy of L. Zappacosta (adapted)

JWST data from: Kocevski+23, Ubler+23, Harikane+23, Larson+23, Maiolino+24, Bogdan+23, Kokorev+24, Kovacs+24; Napolitano+24; Tripodi+24

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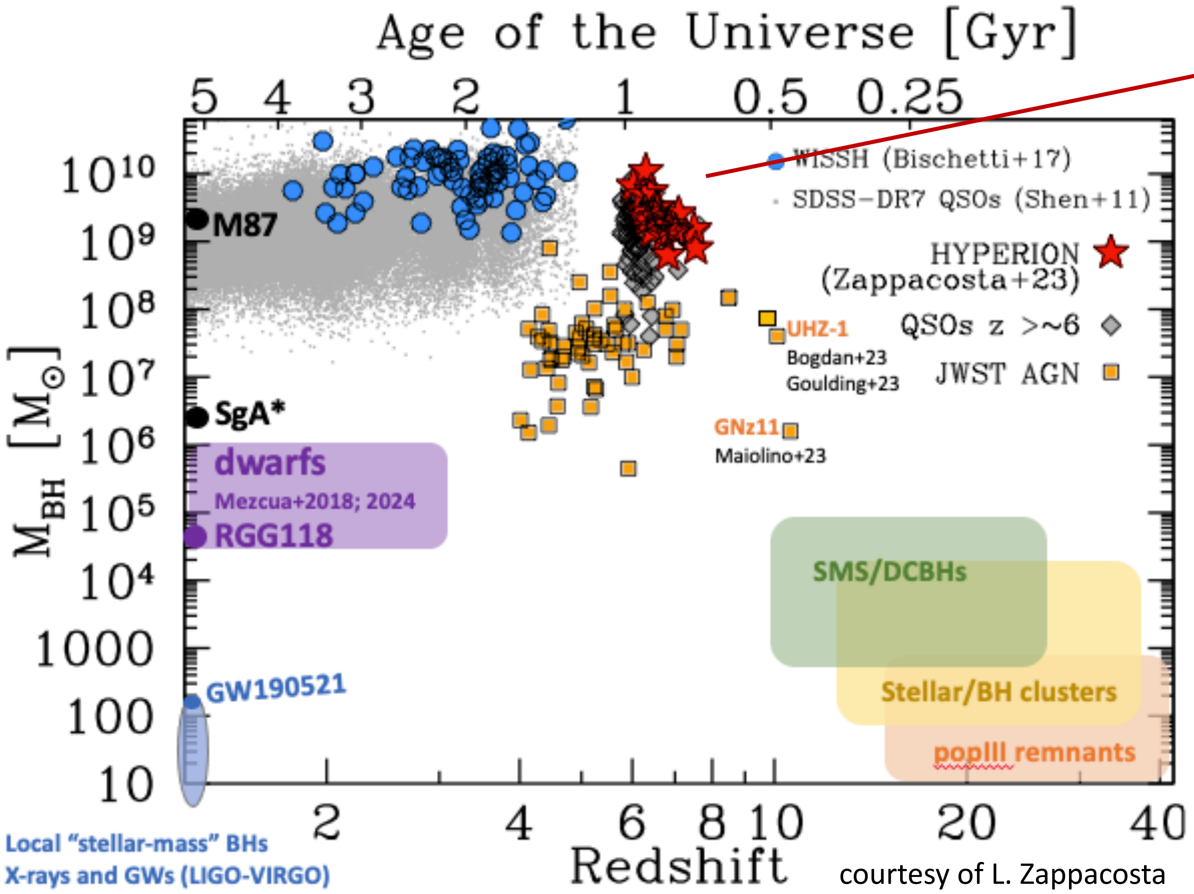
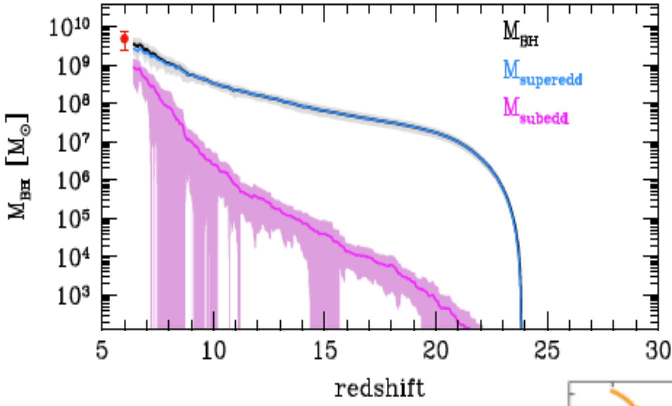


Local “stellar-mass” BHs
X-rays and GWs (LIGO-VIRGO)
Corral-Santana et al. 2016
Abbott et al. 2016, 2020

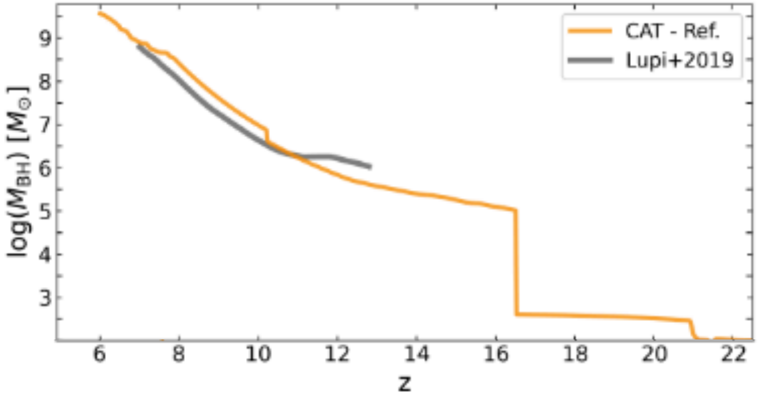
courtesy of L. Zappacosta (adapted)

sustained Eddington/super-Eddington accretion onto light seeds;
or heavy seeds (>10^4 M_{sun}) formation at z>10;

(e.g. …Volonteri+2015; Madau+2014; Valiante+2016;2018; Pezzulli+2016;2017; Dayal+2019; Sassano+2021; Di Matteo+2023; Bhowmick+2024; Trinca+2026…)



LS super-Eddington growth
Pezzulli+2016



Eddington-limited
HS dominated growth
Trinca+2026

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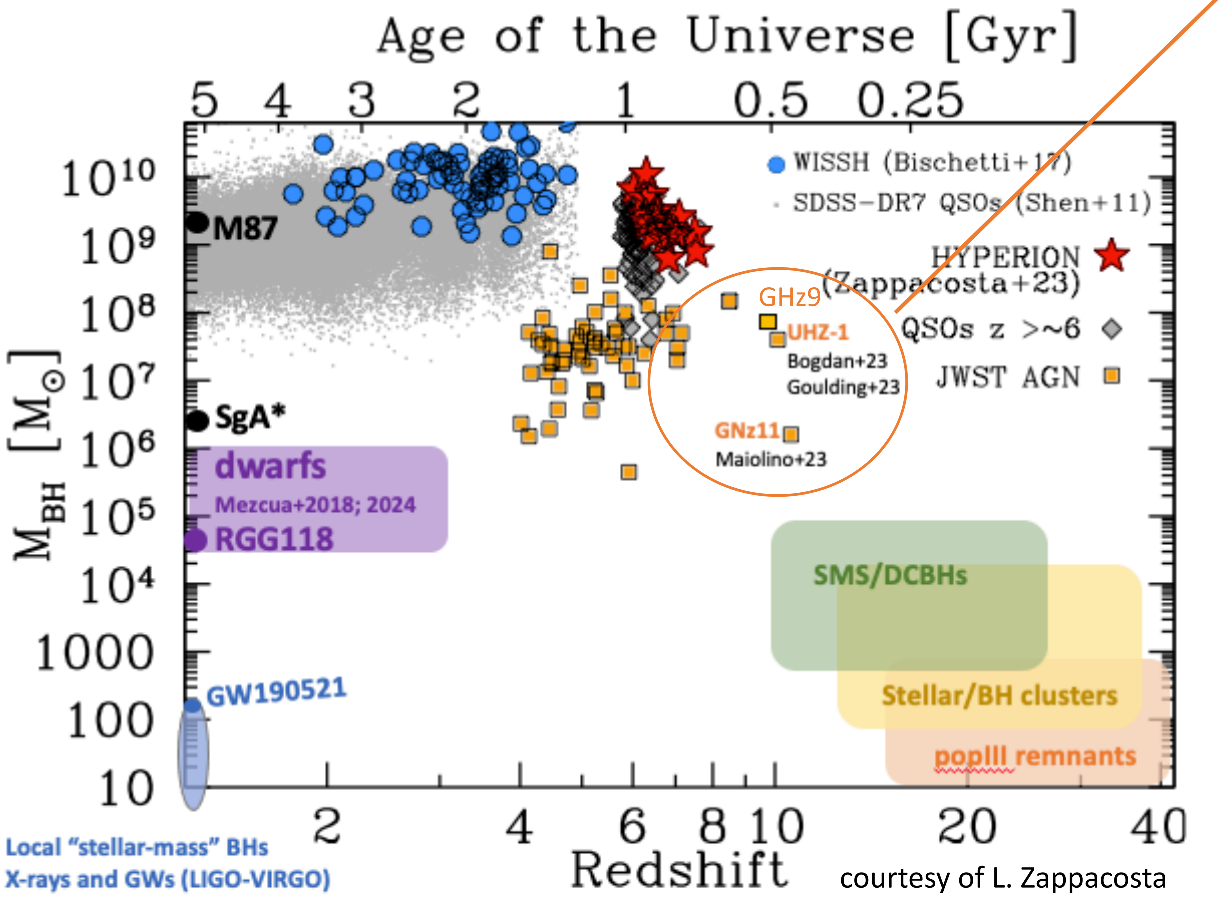
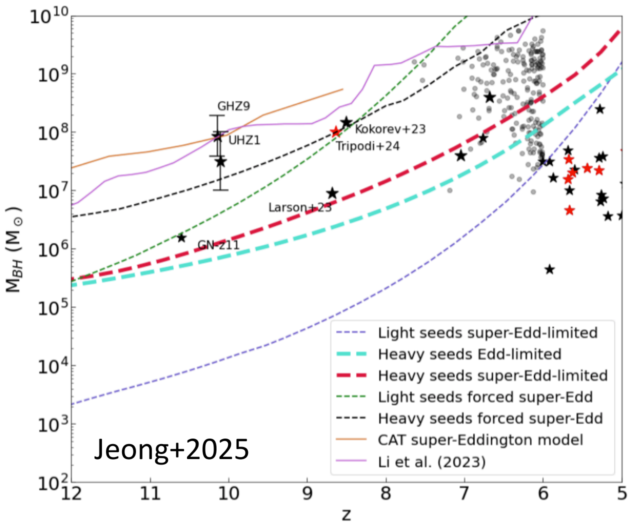


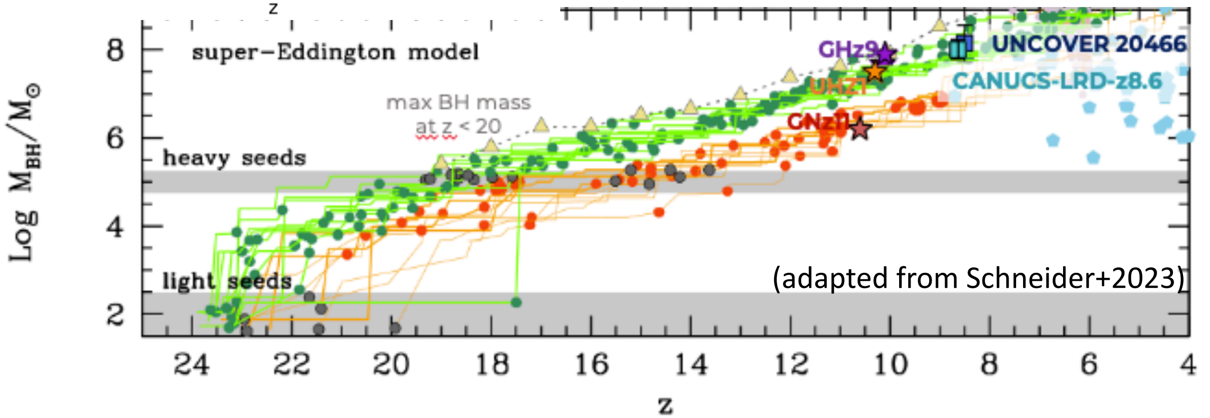
Local "stellar-mass" BHs
X-rays and GWs (LIGO-VIRGO)
Corral-Santana et al. 2016
Abbott et al. 2016, 2020

courtesy of L. Zappacosta (adapted)

short phases of Eddington/super-Eddington accretion onto LS and/or HS

(e.g. Schneider+2023; Natarajan+2024; Trinca+2024;2025; Lupi+2024a,b; Madau+2025; Pacucci+2025, 2026; Chon+2026)





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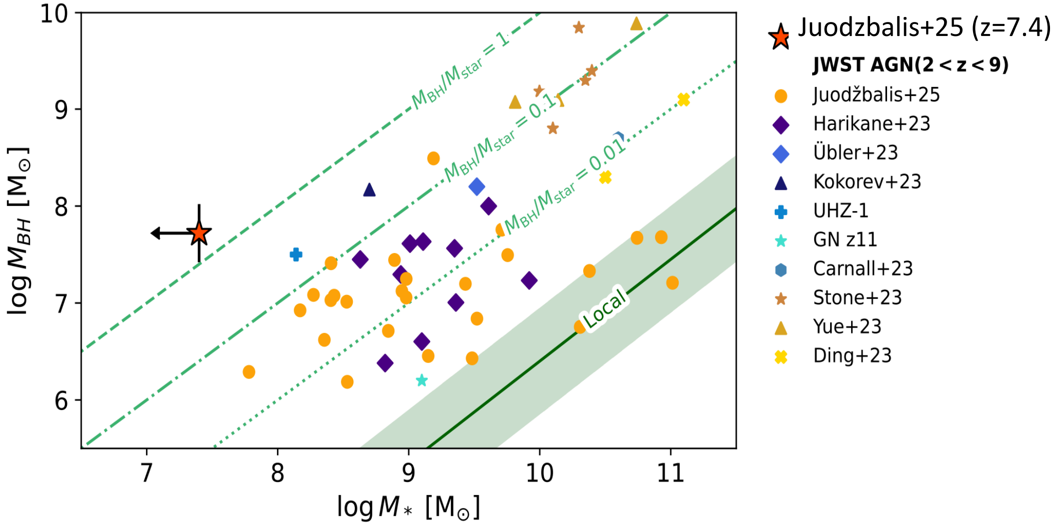
BH mass–galaxy mass relation: the challenge of JWST “overmassive” BHs

Key question: how the ”overmassive” AGN discovered by JWST formed and grew to half (or even twice!) the host galaxy stellar mass and can their evolution can be reconciled with the local scaling relation?

JWST reveals M_{BH}/M_{star}≈0.5–2 at z≳5–7 challenging standard co-evolution models



are they an evidence for HS formation, accelerated (super-Eddington) growth or a combination of the two?

(e.g., Natarajan+2024; Trinca+2024)

Caveat: High-z M_{BH} and M_{star} estimates carry large systematic uncertainties (e.g. Volonteri+2023; Lupi+2024)

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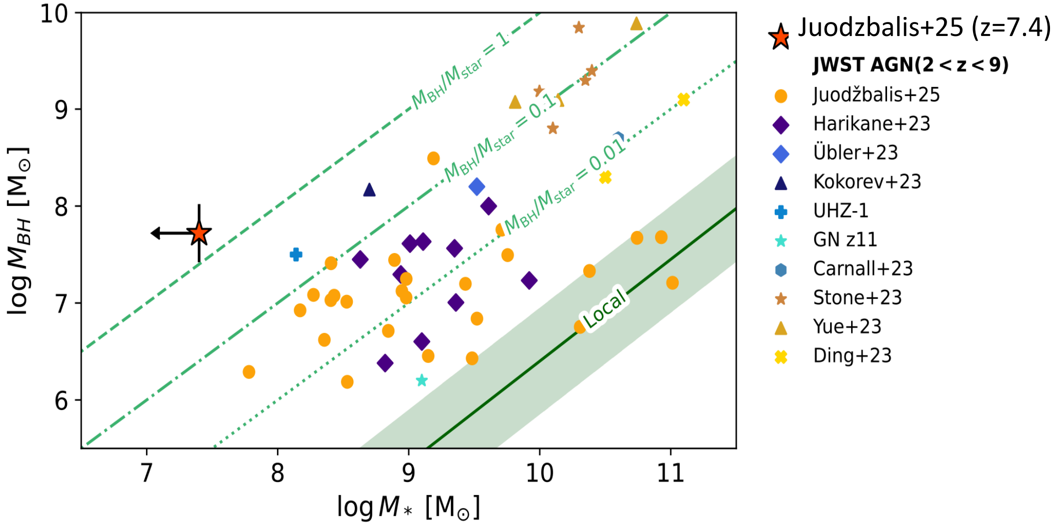

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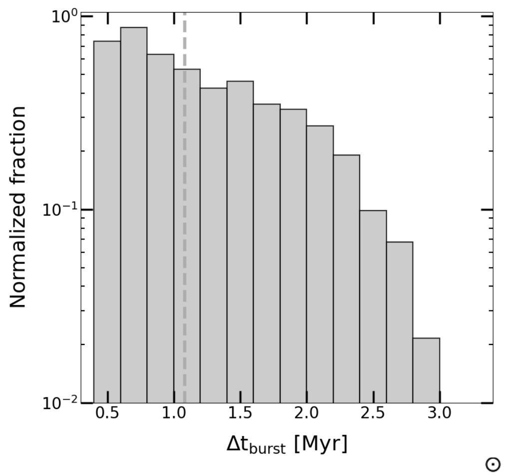
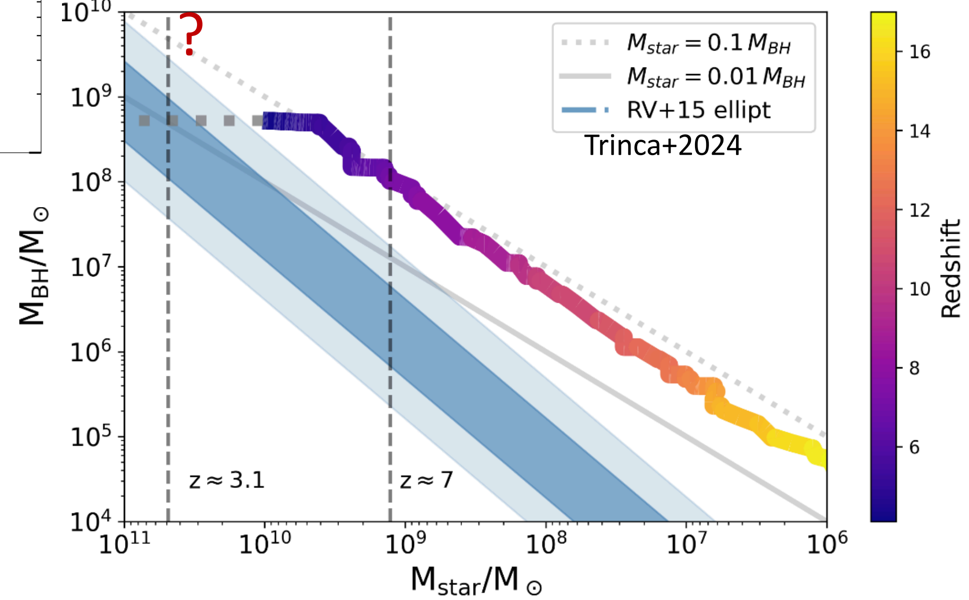


SE burst duration [0.5-3] Myr

(1-6)% duty cycle

Lupi+2014, Sassano+2023, Shi+2024; Trinca+2024



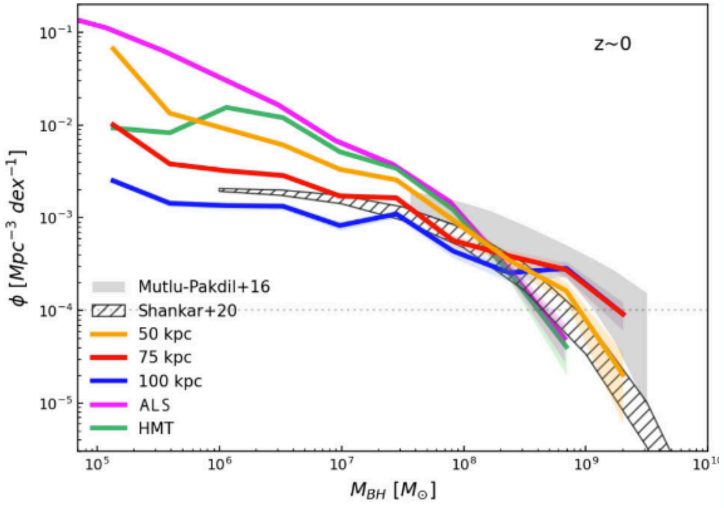
Models predict z>5 overmassive BHs that may be BHs early transient phases of SMBH growth and later converge towards the local relation if BH growth slows. Scatter reflects accretion history, mergers, and duty cycle

(e.g., Barai+18; Habouzit+21; Chon+26; McClymont+26; Hu+25; Weller+23; Volonteri+23; Cammelli+25; Jeong+25; Izquierdo-Villalba+2025)

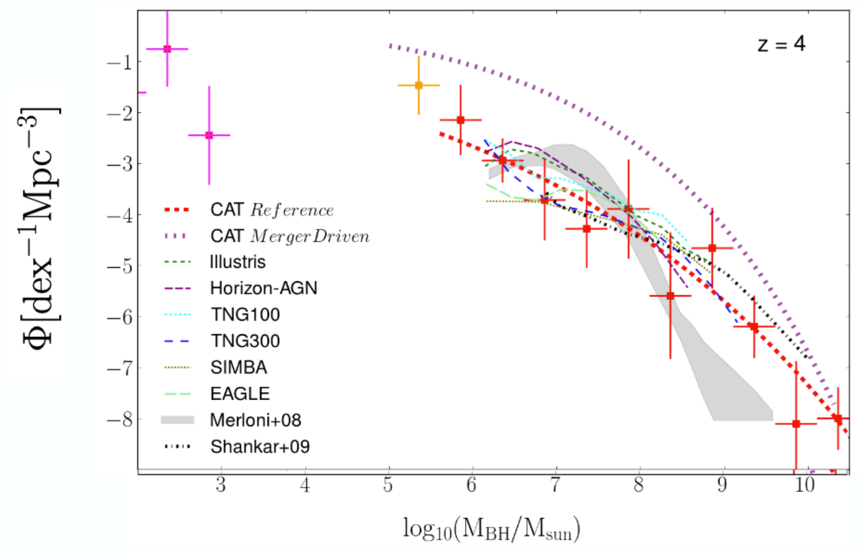
Cosmic evolution of the BH mass spectrum

Key question: How do early SMBHs connect to AGN and quiescent SMBHs we observe across cosmic time, at cosmic noon and in local galaxies?

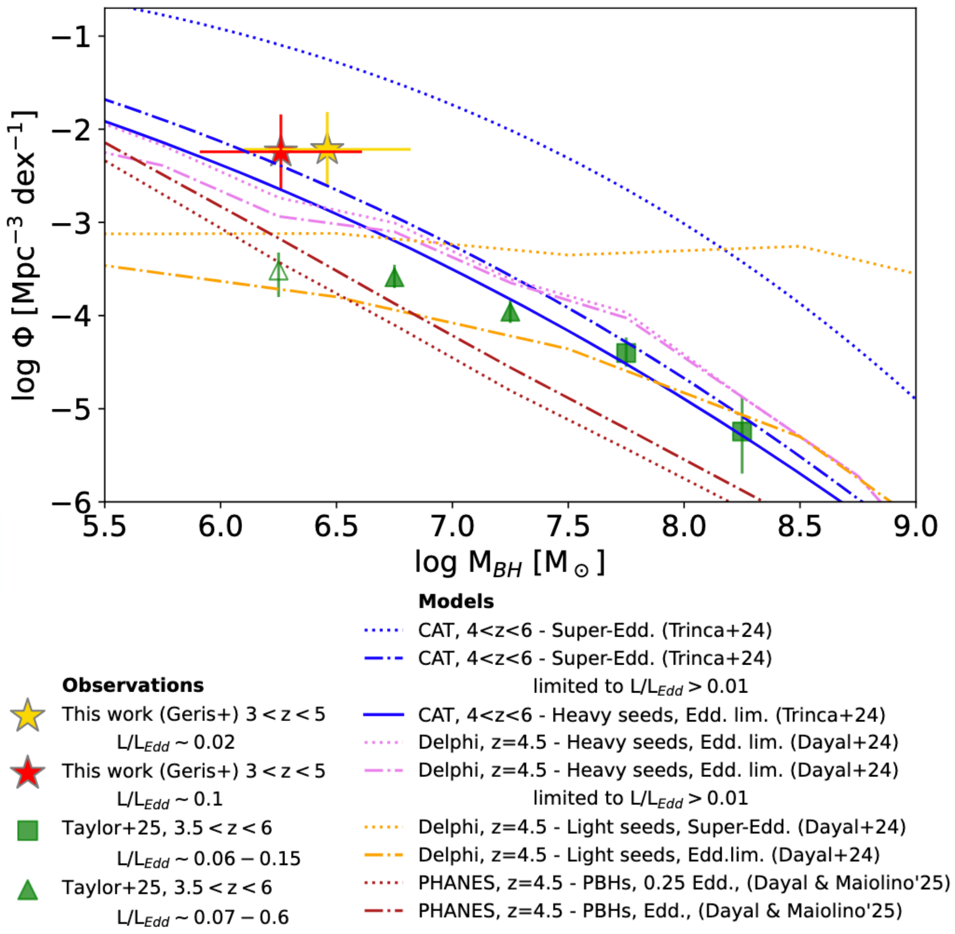
Cammelli+2025



Trinca+2022



Geris+2025



Different seeding schemes and/or accretion modes leave different imprints

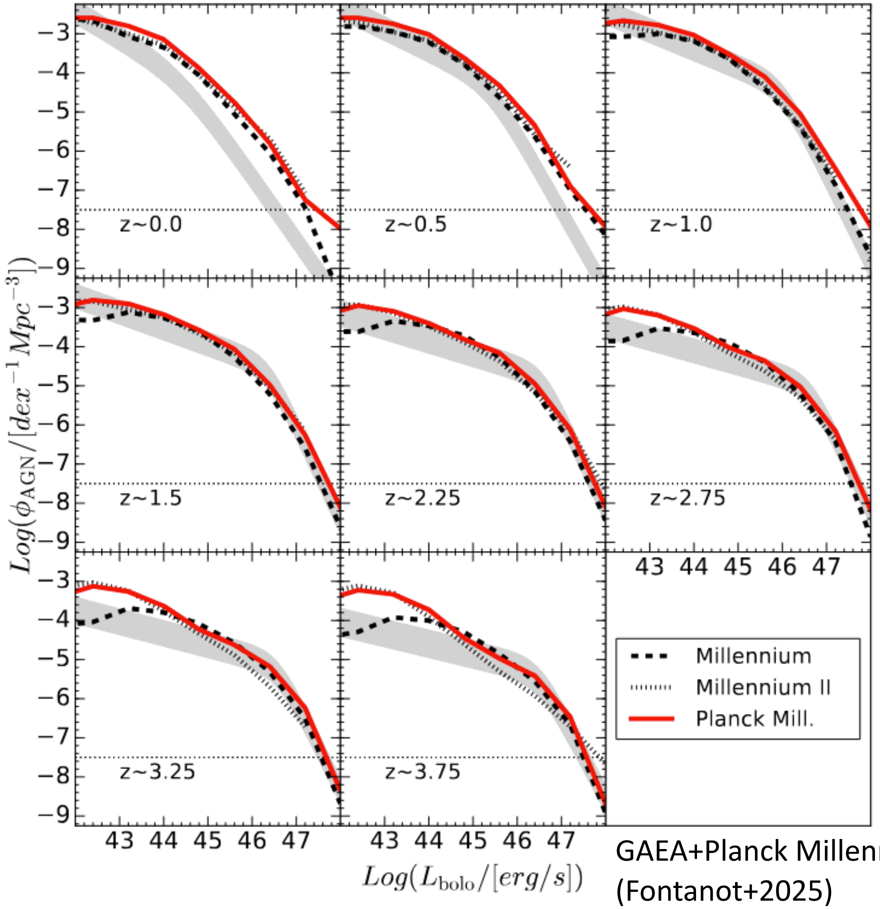
JWST observations now probe the low-mass end of the BHMF at z>4

additional recent models/simulations include:Ricarte&Natarajan 2018; Trinca+2022;2024; Spinoso+2023; Barausse+2023; Porras-Valverde+2025; Roberts+26 Bohwmick+2026; Fontanot+2025

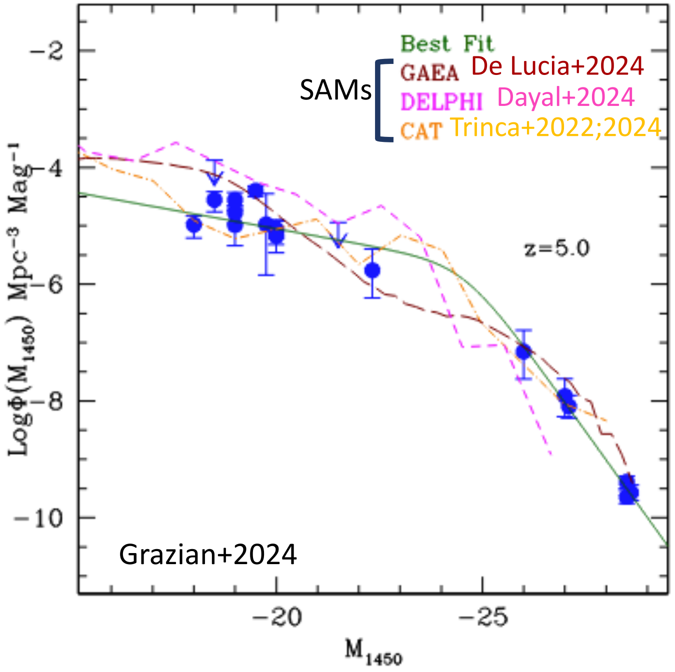
Cosmic evolution of the AGN LF

Key question: What drives the redshift evolution ("downsizing") and the faint-end of the AGN UV/bolometric luminosity function?

SAMs (and simulations) predict the UV and bolometric AGN/QSO LFs from BH accretion histories



GAEA+Planck Millennium (Fontanot+2025)



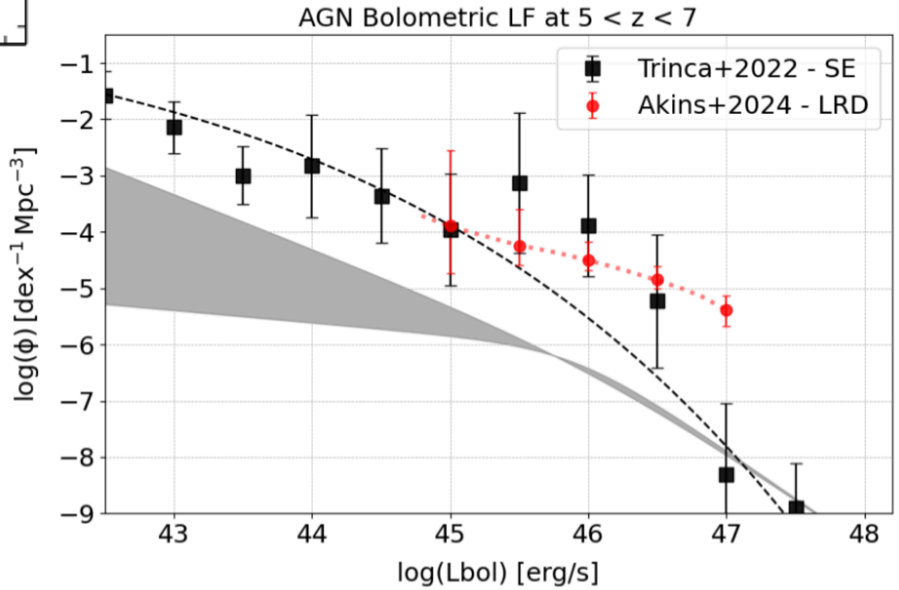
super-Eddington scenarios provides a better agreement with **the estimated BLF of LRDs** (if they are all AGN-dominated systems)

e.g., CAT Trinca+2024

more on LRDs in R. Tripodi's talk!

the faint end at high-z is the key discriminant for early SMBH growth

the large JWST AGN population is consistent with Eddington-limited growth modes where the UV LF is dominated by heavy seeds



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AGN feedback: SMBH–galaxy “coupling”

Models and Simulations require **sub-grid AGN feedback** to match massive-galaxy and halo properties

- Two modes: quasar (winds) & radio (jets)
- Multi-phase outflows with uncertain coupling
- Jets heat CGM/ICM on kpc–Mpc scales
- Quenching: ejective vs preventive
- Efficiency depends on halo mass & accretion

AGN feedback: SMBH–galaxy “coupling”

Key question: How does SMBH feedback regulate gas, star formation, and galaxy growth?

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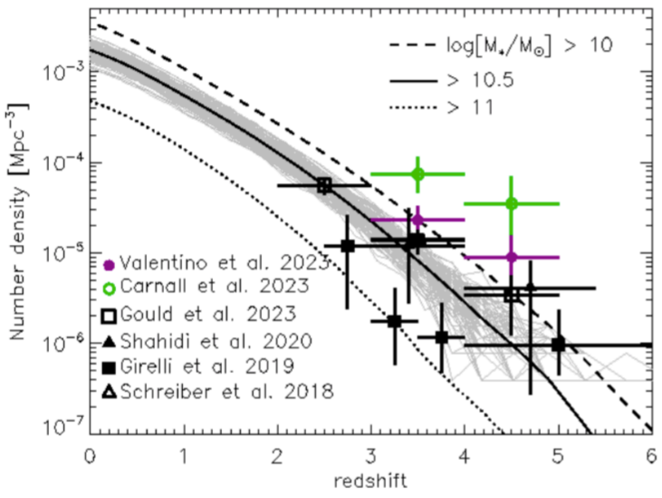
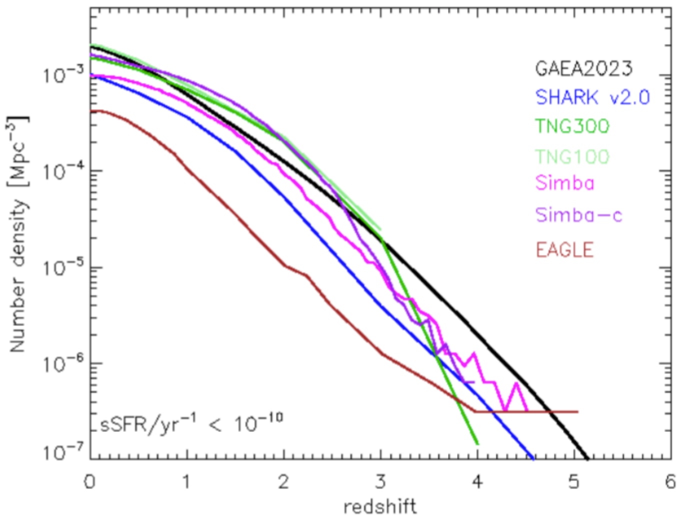
De Lucia+2026

observations



Models/simulations



Different models/simulations reproduce different mass ranges and quenching timescales reflecting the adopted AGN feedback mode (QSO vs radio)

see De Lucia+2024; Fontaton+2025; Lagos+2025; Cammelli+2025…

Other models/simulations: Bassini+2020; Hazenfratz+2025; Zubovs & Kin 2012; Faucher-Giguère & Quataert 2012; Costa+2014, 2020; Ward+2024, Fu+2025…

Jets models: Mignone+2010; Buola+2025; Costa+2026…

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De Lucia+2026

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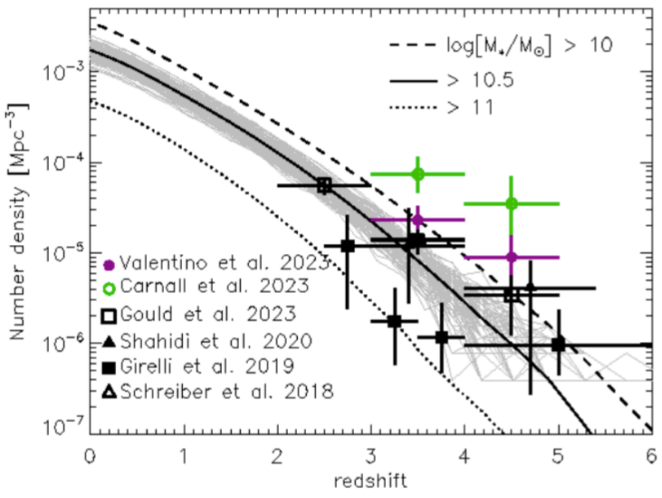

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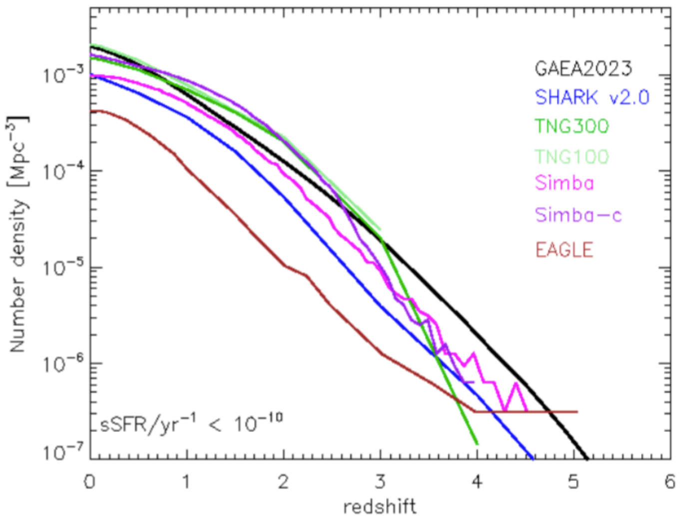
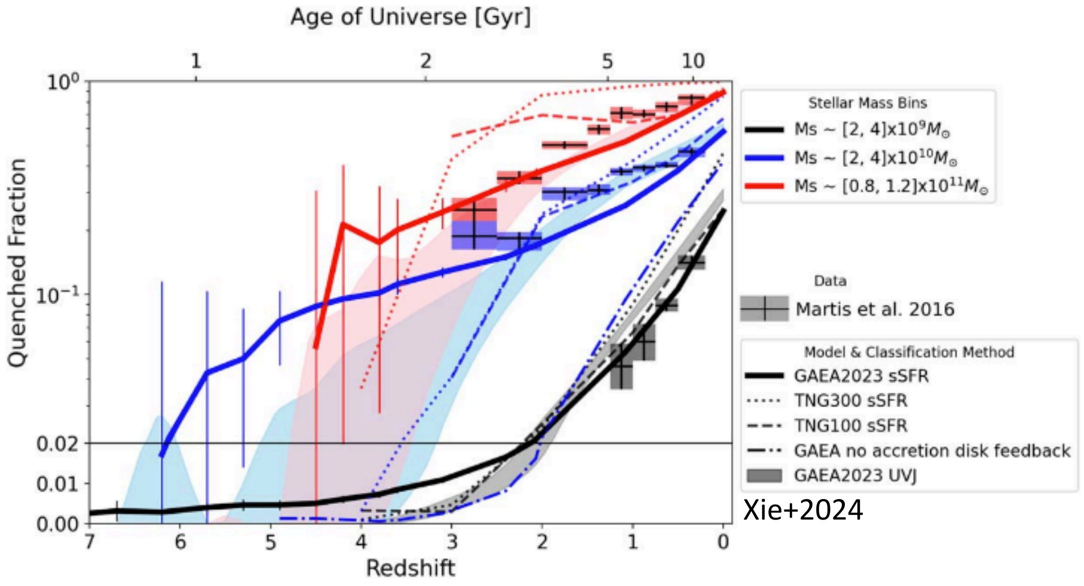




Xie+2024

Different models/simulations reproduce different mass ranges and quenching timescales reflecting the adopted AGN feedback mode (QSO vs radio)

see De Lucia+2024; Fontaton+2025; Lagos+2025; Cammelli+2025…

Quenching starts at high-z (z>6-7) and is dominated by AGN quasar-mode feedback. Most early-quenched galaxies remain passive for > 1Gyr.

Other models/simulations: Bassini+2020; Hazenfratz+2025; Zubovs & Kin 2012; Faucher-Giguère & Quataert 2012; Costa+2014, 2020; Ward+2024, Fu+2025…

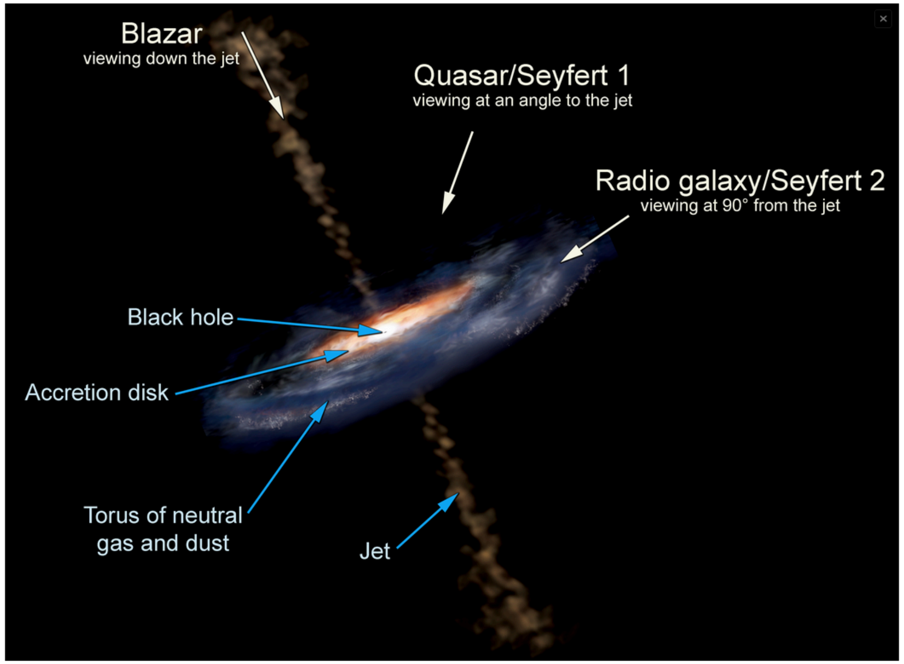
Jets models: Mignone+2010; Buola+2025; Costa+2026…

AGN feedback: SMBH–galaxy "coupling"

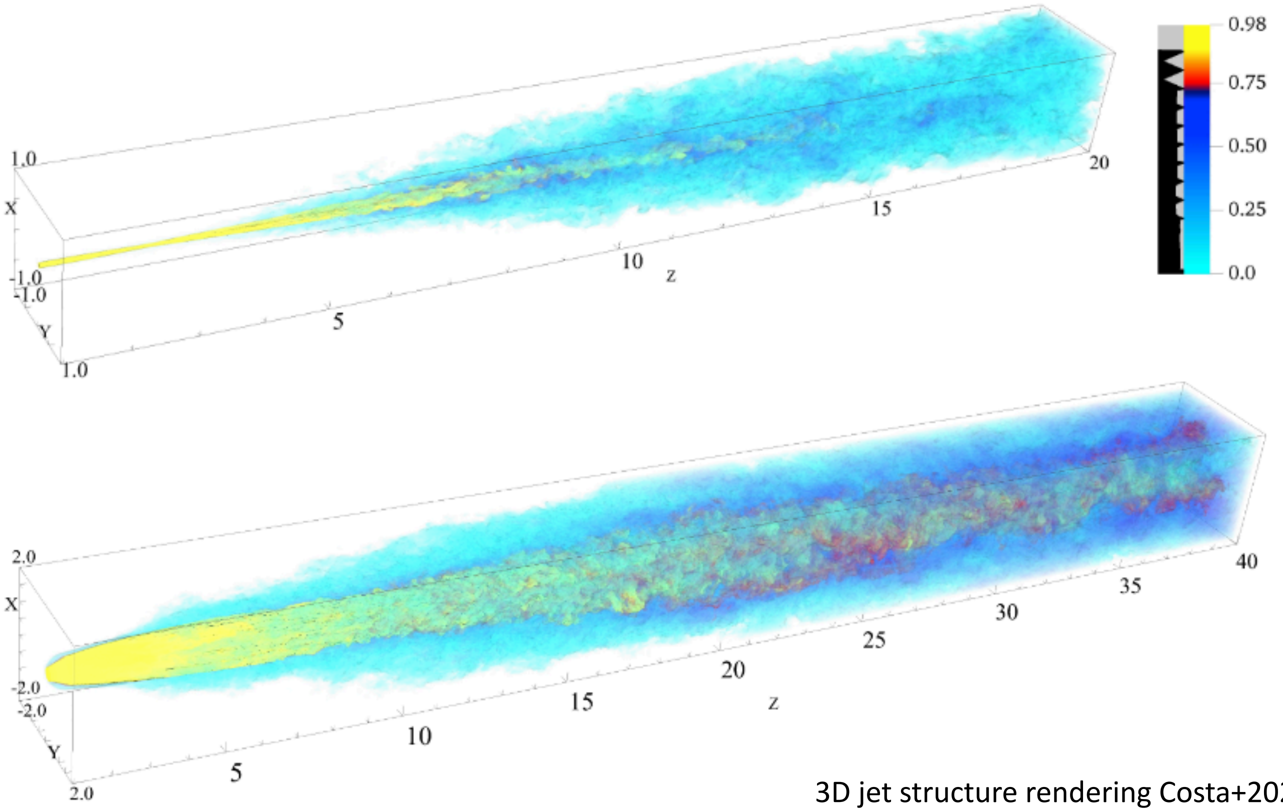
Key question: what is the nature of AGN jets and how do they reshape halos on kpc–Mpc scales?

Models and Simulations require **sub-grid AGN feedback** to match massive-galaxy and halo properties

- Two modes: quasar (winds) & radio (jets)
- Multi-phase outflows with uncertain coupling
- **Jets** heat CGM/ICM on kpc–Mpc scales
- Quenching: ejective vs preventive
- Efficiency depends on halo mass & accretion



Crediti: Gsfc/Nasa



3D jet structure rendering Costa+2026

2D and 3D (magneto) relativistic hydrodynamic simulations - PLUTO

Other models/simulations: Bassini+2020; Hazenfratz+2025; Zubovs & Kin 2012; Faucher-Giguère & Quataert 2012; Costa+2014, 2020; Ward+2024; Fu+2025…

Jets models: Bodo&Tavecchio+2018;Tavecchio+2020; Rossi+2020; Mattia+2023; Boula+2025; Costa+2026…

SMBH mergers: from galaxy encounters to binaries

Key question: How efficiently do galaxy mergers lead to SMBH binaries and coalescence?

Galaxy mergers naturally produce **dual SMBHs** (kpc scales)

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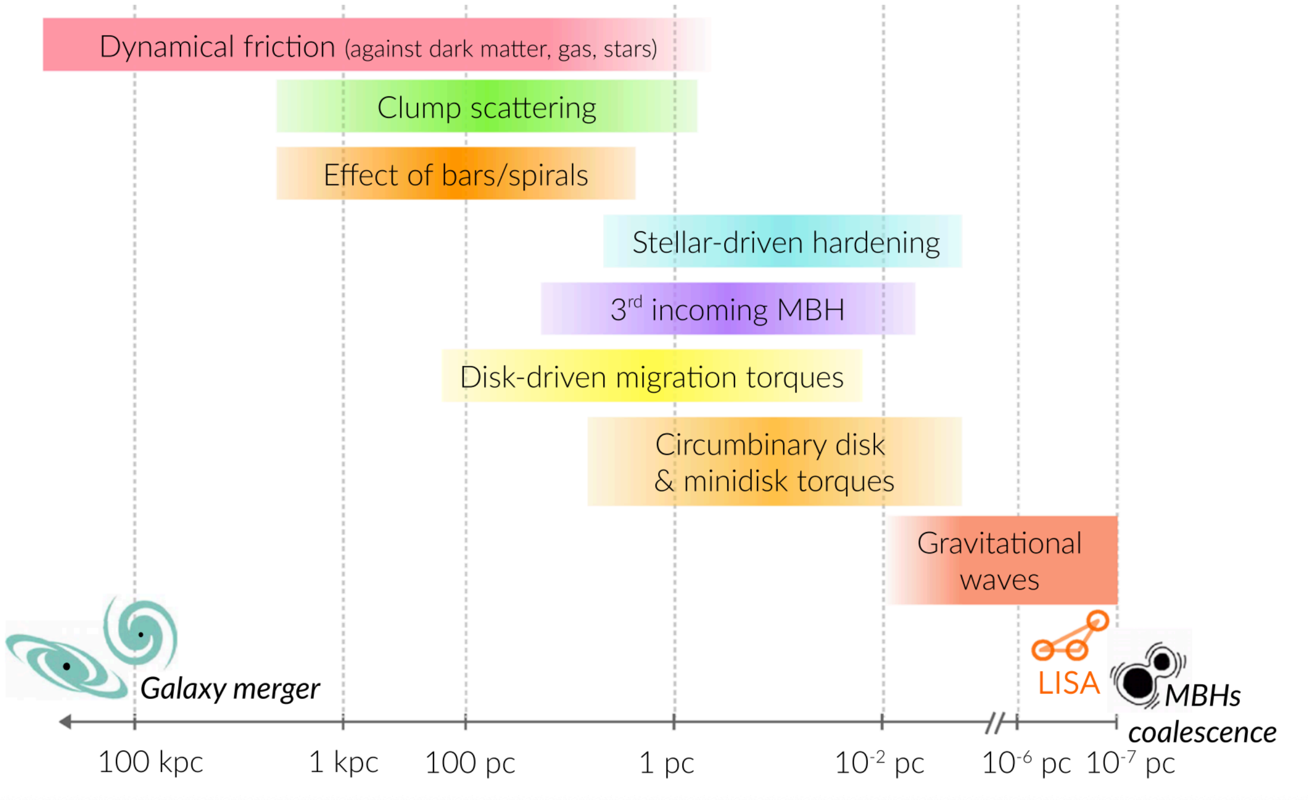

Illustration of the journey of two coalescing MBHs of about 10^6 M_{sun} after the merger of their host galaxies

Image credit E. Bortolas (Amaro-Seoane+2023)

some recent simulations: Bonetti+2018; Pfister+2019; Tremmel+2015; Bortolas+2020;2021; Dubois+2016; Chen+2022; Volonteri+2022; Katx+2020; Bhowmick+2020…

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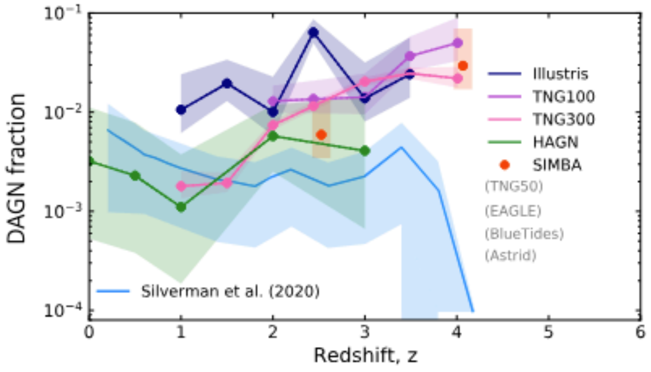
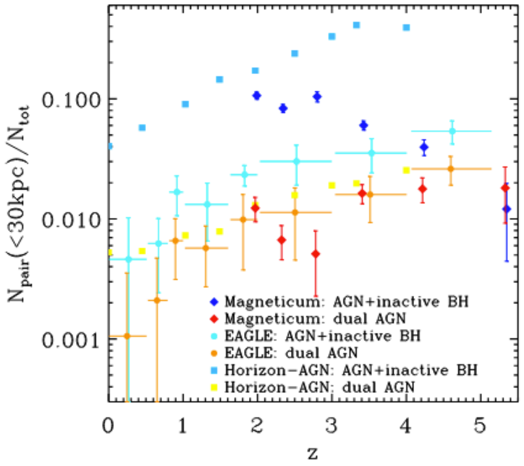
predictions for dual AGN fraction



Puerto-Sanchez+2024

De Rosa+2019



predicted dual AGN fractions and SMBH merger rates span orders of magnitude, reflecting different assumptions on seeding, growth, feedback, and unresolved SMBH dynamics.

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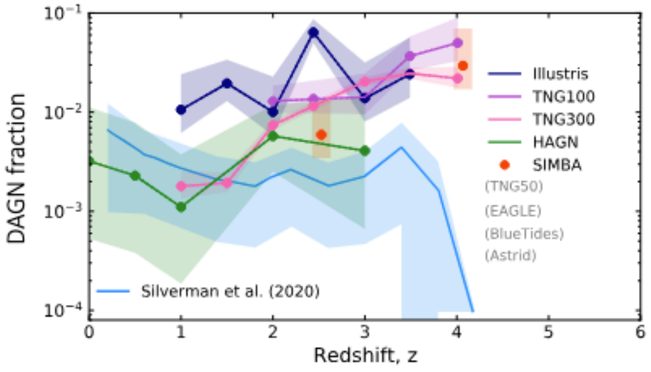

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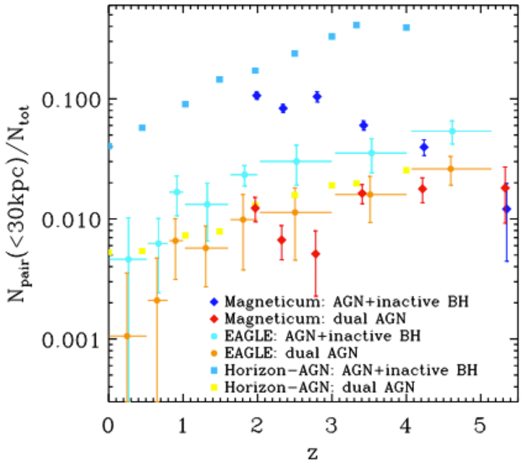

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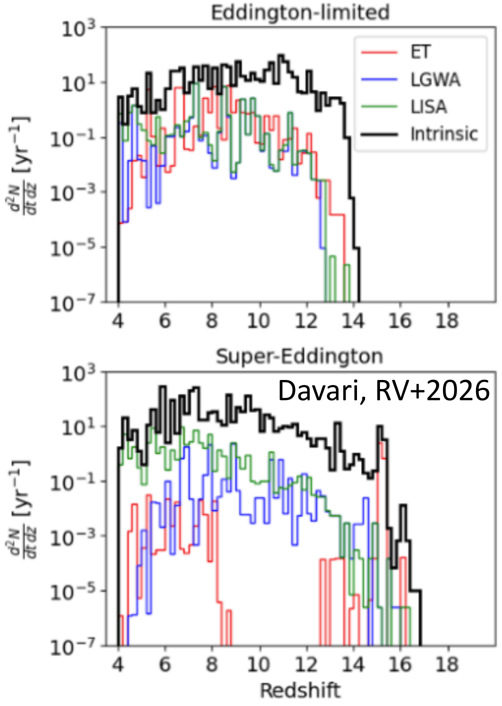

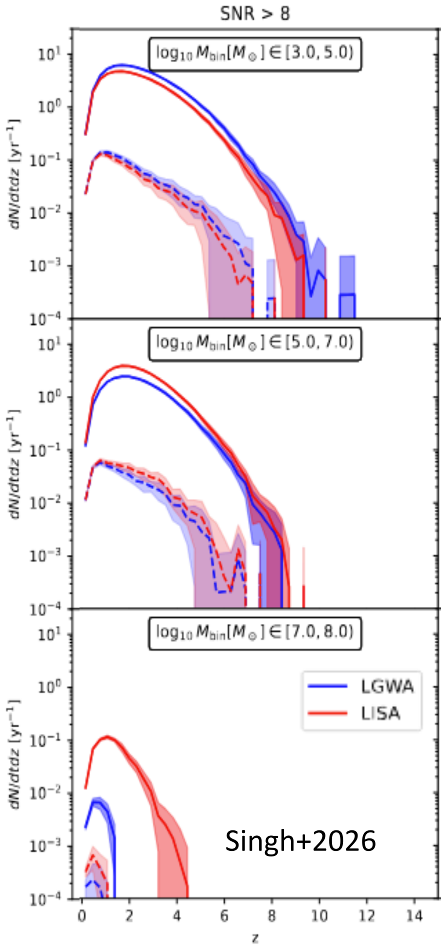

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more on GWs, dual/binary BHs in A. DeRosa's talk!

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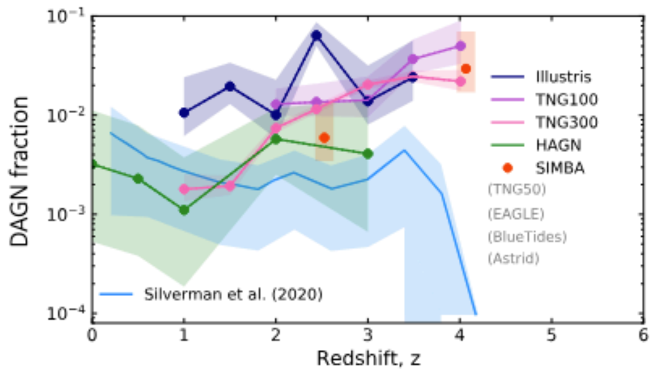

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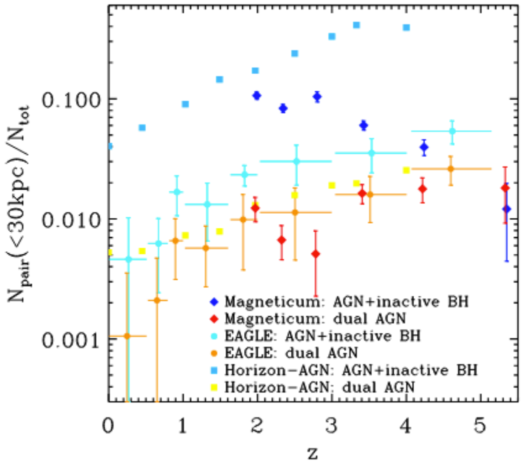

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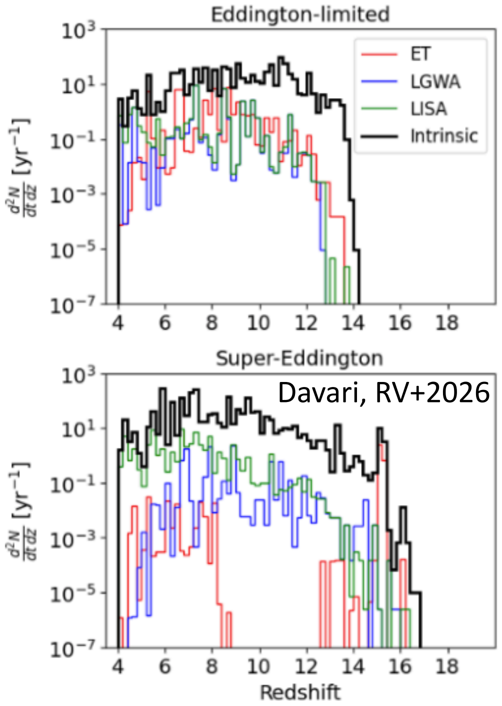
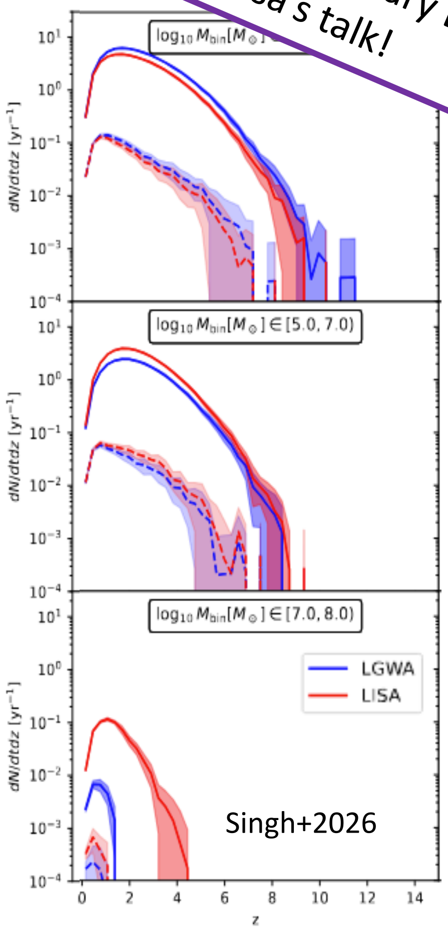


Davari, RV+2026



Singh+2026

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Charting the future: outlook

Open questions

Early SMBH growth & AGN populations

- How do SMBHs grow so fast at high redshift?
- What powers JWST LRDs and X-ray–weak AGN?
- Are we missing AGN due to selection/diagnostic biases?

SMBH–galaxy co-evolution

- Are we missing AGN due to selection/diagnostic biases?
- Are scaling relations statistical outcomes?
- How common are overmassive BH phases?

AGN feedback & quenching

- How does feedback couple to multi-phase gas?
- What sets quenching timescales and efficiencies?
- How do quasar-mode and radio-mode feedback coexist across cosmic time?

Dual AGN, mergers & GW sources

- How efficient is the kpc → sub-pc transition?
- What controls dual/binary AGN observability?
- How do seeding/growth/feedback models affect GW rates?

What theory needs

Advanced physical modelling (small scales)

- Physically realistic simulations of stellar and seed BH initial mass functions
- Zoom-in radiation-(M)HD of early BH growth and feedback
- High-res simulations of BH dynamics from low- to high-mass binaries (orbital decay, merger probability and timescales)

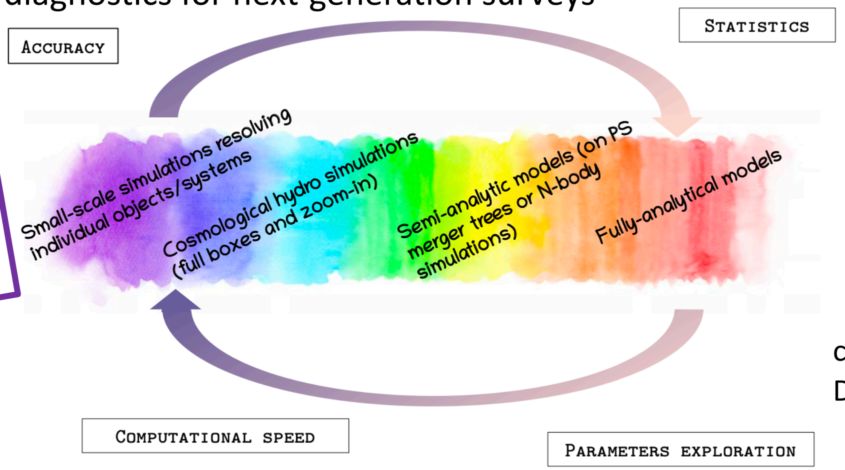
Next-generation cosmological simulations

- Higher spatial, temporal, and mass resolution
- Improved treatment of SMBH dynamics and feedback coupling
- Multi-scale frameworks: embedding small scale physics in cosmological models

Multi-wavelength & multi-messenger integration

- Direct model-data comparison through forward modelling of EM+GW observables (luminosities, SEDs, variability, GW signals…)
- Time-dependent SED models, tailored to X-ray week AGN and LRDs
- New AGN diagnostics for next-generation surveys

The future of modelling: “gaining from diversity”
unify/combine the wide spectrum of theoretical approaches
direct connection to observations
acceleration by HPC, ML and AI



courtesy of
Dr. Silvia Bonoli