Massive Black Holes formation and evolution in cosmological environments

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Collaborators:

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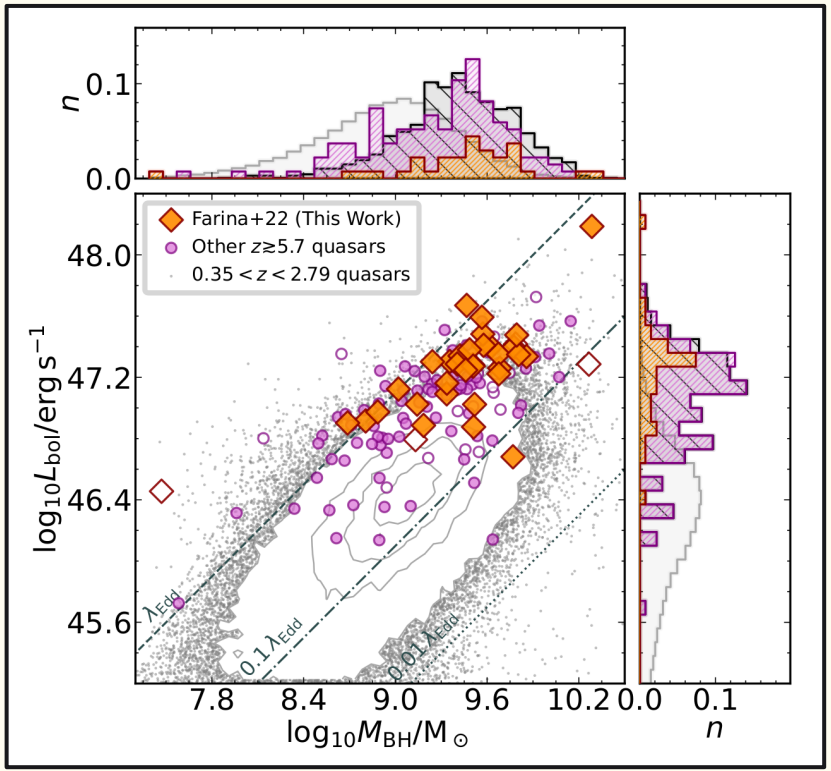
1st BiCoQ conference

- from gravity to particles -

15th - 19th June 2026

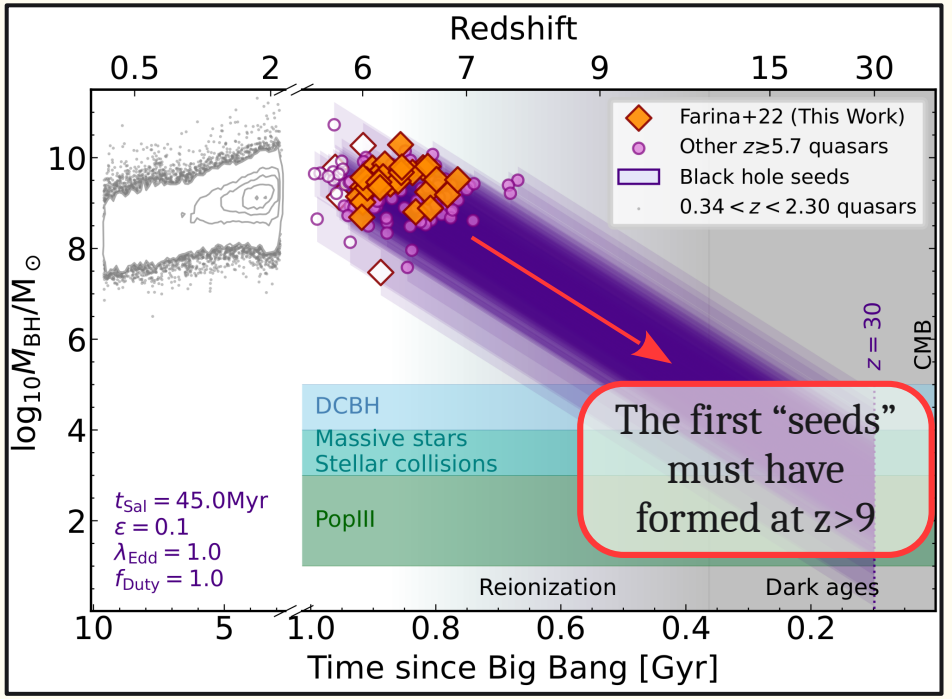
The first Super-Massive Black Holes

$L_{bol} > 10^{47}$ erg s^{-1} ; $M_{BH} > 10^{8}$ $M_\odot$



Farina et al. 2022

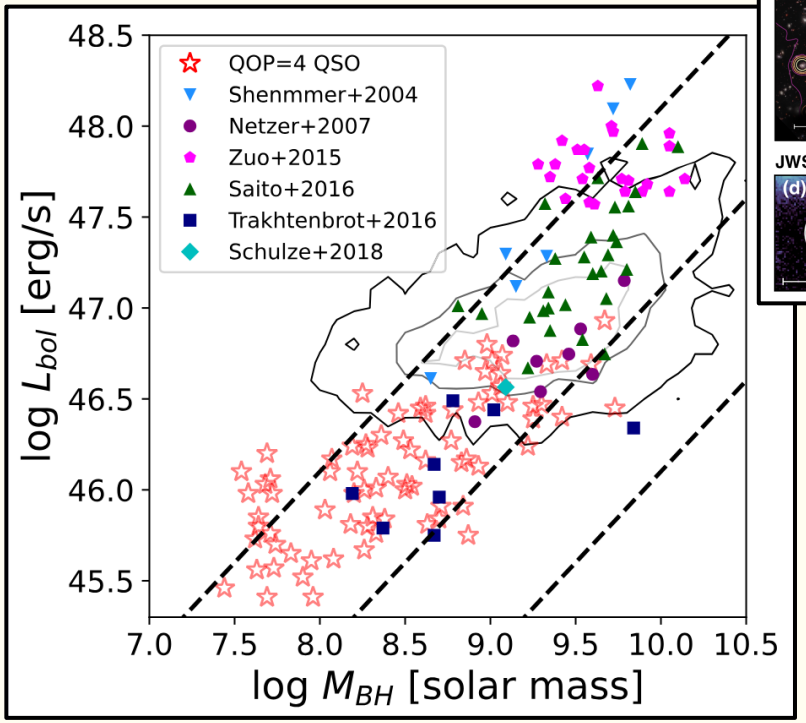
Farina et al. 2022

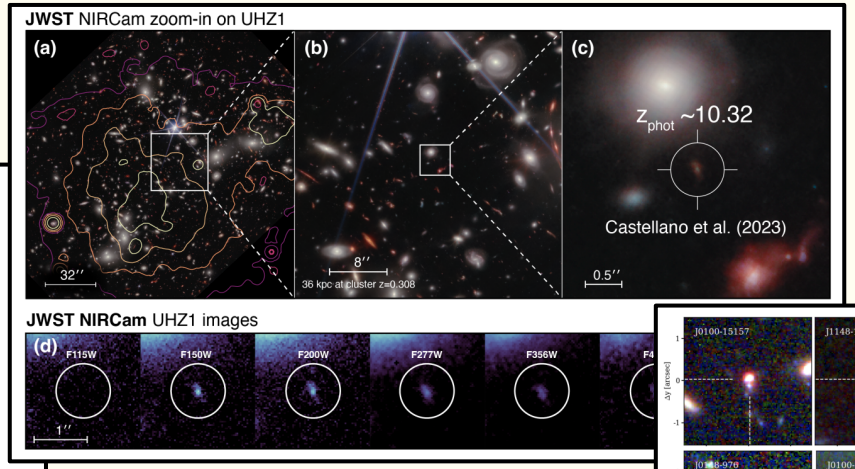


Observed at $z > 6$-7 ($t_H < 800$ Myr)

"Common" AGN populations at $z > 4$

He et al. 2025

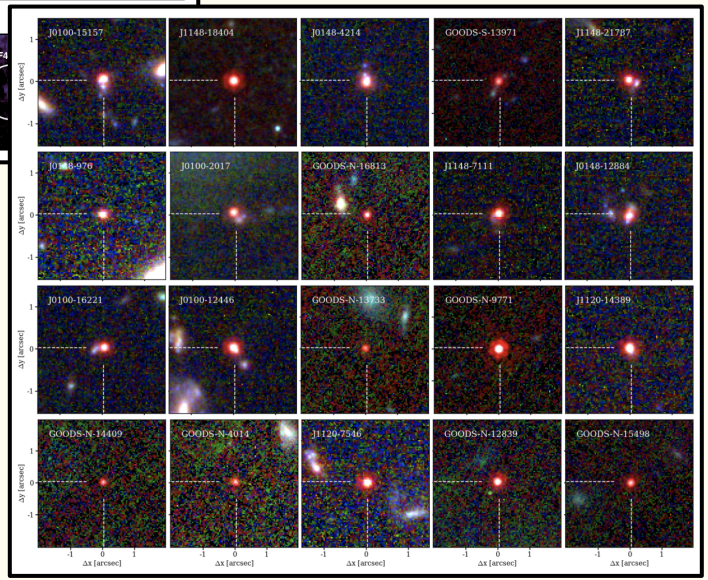




Bogdan et al. 2023

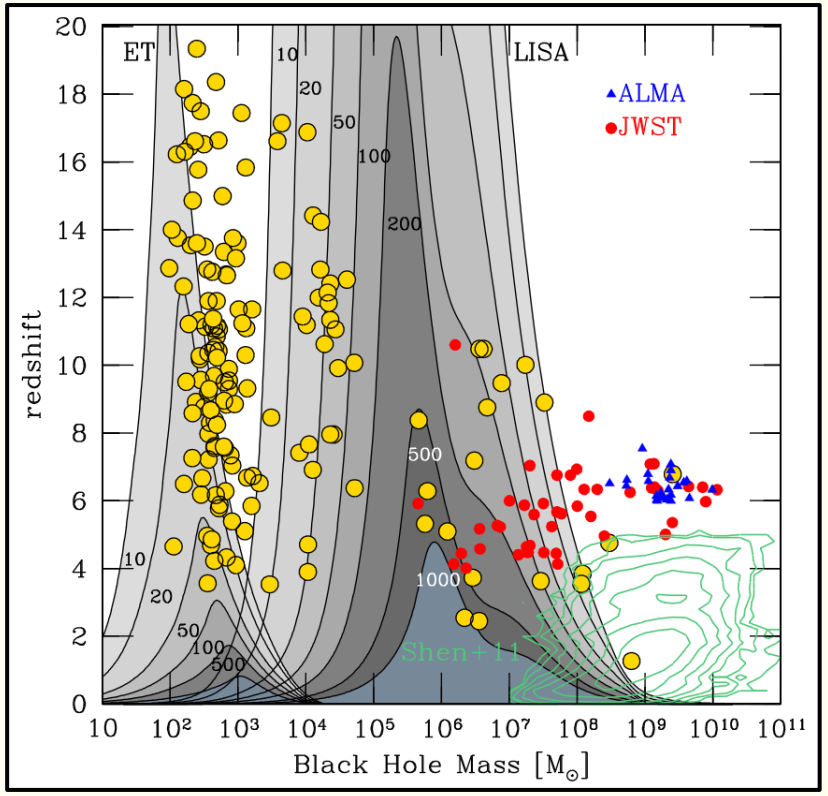
Abundant classes of objects unveiled by JWST and Subaru HSC (& LSST...)

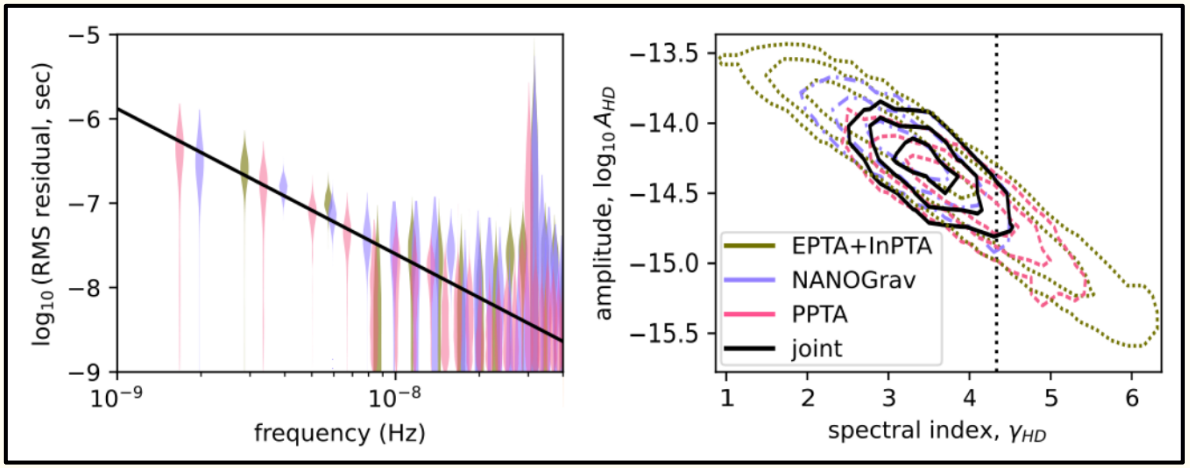
Matthee et al. 2023



New GW constraints and predictions

Abac et al. 2025, Valiante et al. 2020





Sesana & Figueroa 2025

Evidence for a stochastic GW background at $z = 0$

- possible MBH binaries signal -

Predictions for future GW observatories at $0 < z < 100$

(e.g. LISA, Einstein Telescope, Cosmic Explorer...)

Simulating Massive Black Holes

QUESTIONS

- How did “early monsters” form?
- How did common MBHs form?

→ MBH-seeding model

- Do all MBHs only form at high-z?
- Can we tell apart seeding and growth?
- What is the mass distribution of MBHs?

- How do MBHs evolve in their hosts?
- What will the GW sky look like?

→ MBHs evolution model

REQUIREMENTS

- Mass resolution ($M_{halo} \sim 10^6 M_\odot$)
- Formation environment
- Large volumes ($L_{box} \sim$ Gpc)

- Wide dynamic ranges
- Cosmological environments
- Physics of spin and mass growth
- MBH binaries and GW emission
- Merger history down to $z = 0$
- Co-evolution with host galaxies

Simulating Massive Black Holes

Detailed MBH physics
- Formation / seeding
- BH spin evolution
- BH mass growth
- Dynamics & GW emission

Galaxy and MBH evolution tool

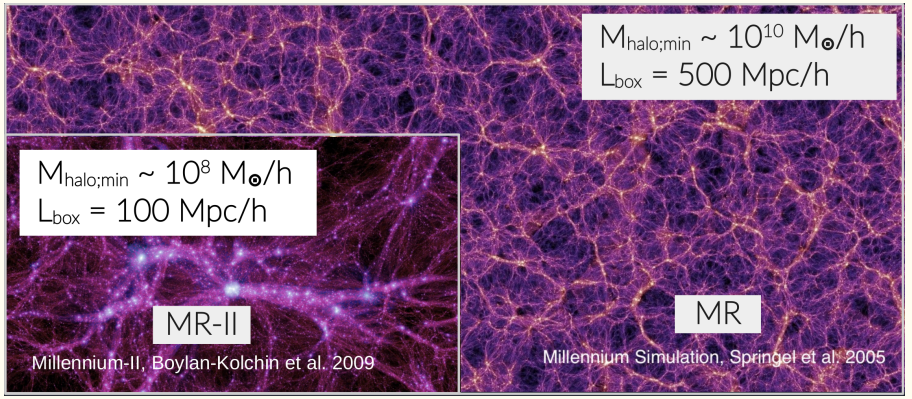
Wide dynamic ranges
- High resolution
- Large volumes
- Diverse environments

Galaxy Evolution model
- Star formation & feedback
- Galaxy mergers & secular evolution
- Environmental effects (e.g. stripping)

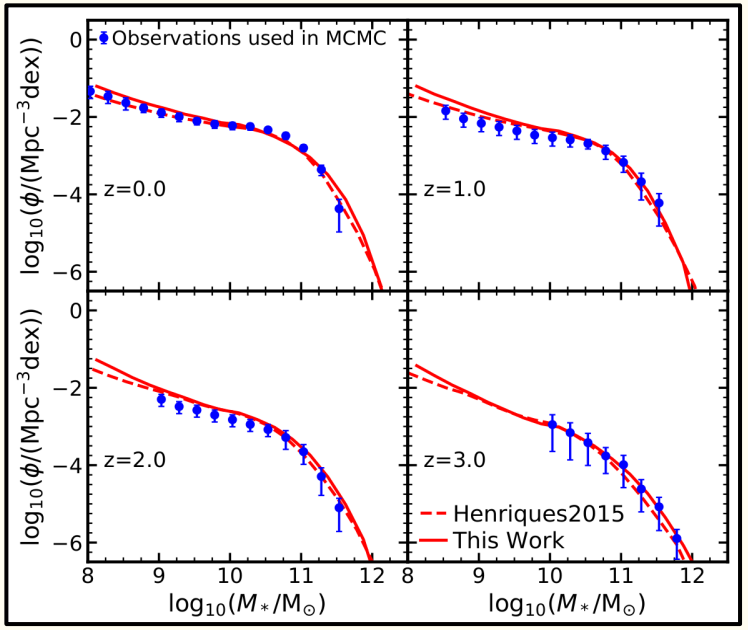
L-GALAXIES

Henriques et al. 2015, 2020 ; Yates et al. 2021, 2024 ; Ayromlou et al. 2021

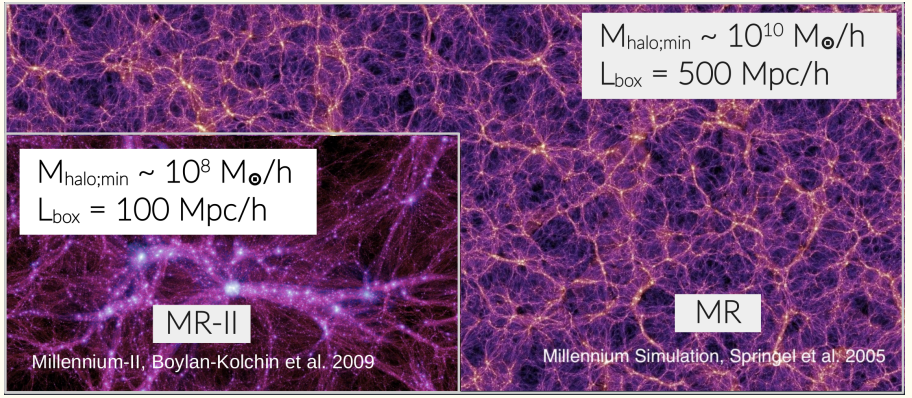
- Semi-analytical, galaxy formation model
- Designed on merger trees from wide, N-body cosmological simulations (Millennium suite)
- Wide dynamic range
- Detailed physical models
  - Gas cooling / heating
  - Star formation / SNe feedback
  - Galaxy mergers and disruptions
  - Secular evolution / Chemical enrichment



L-GALAXIES

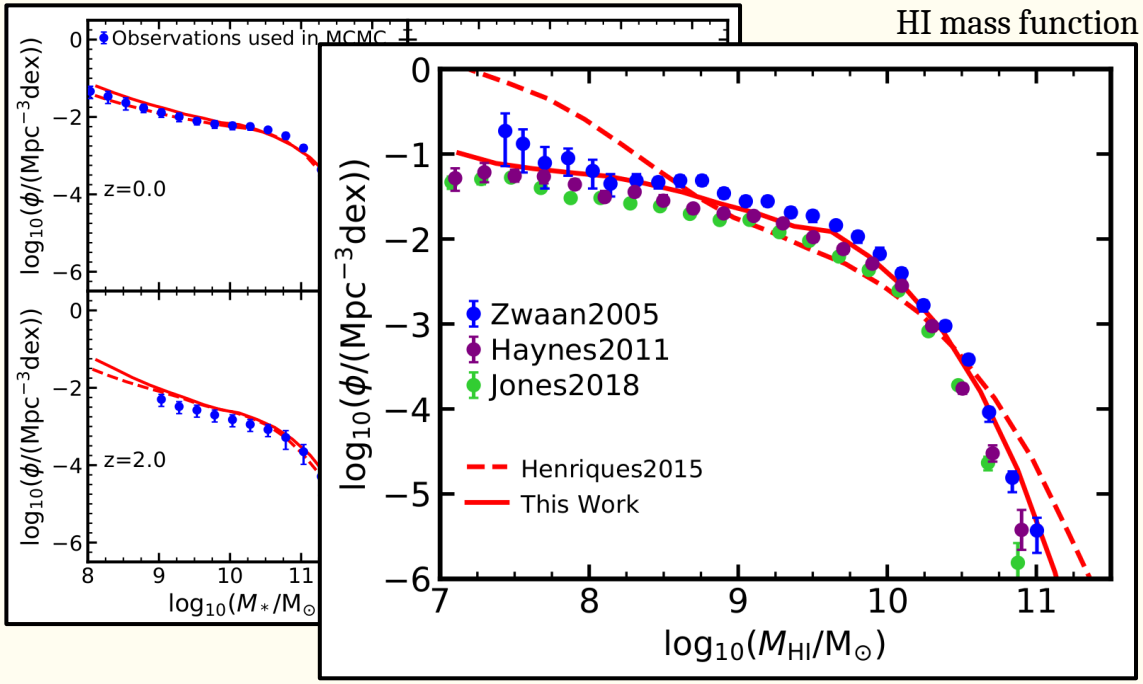


Stellar mass function

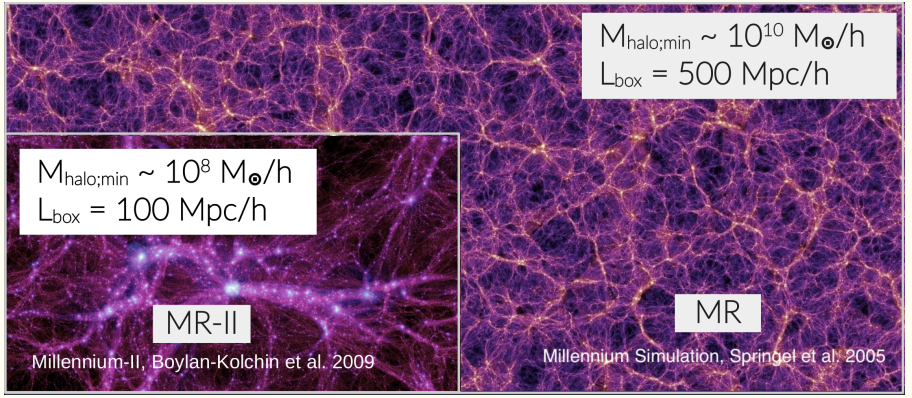


Good agreement with galaxy-evolution constraints

L-GALAXIES

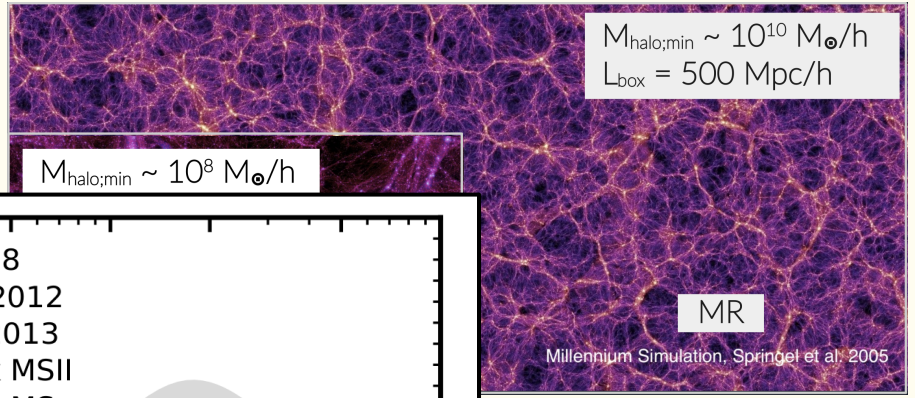


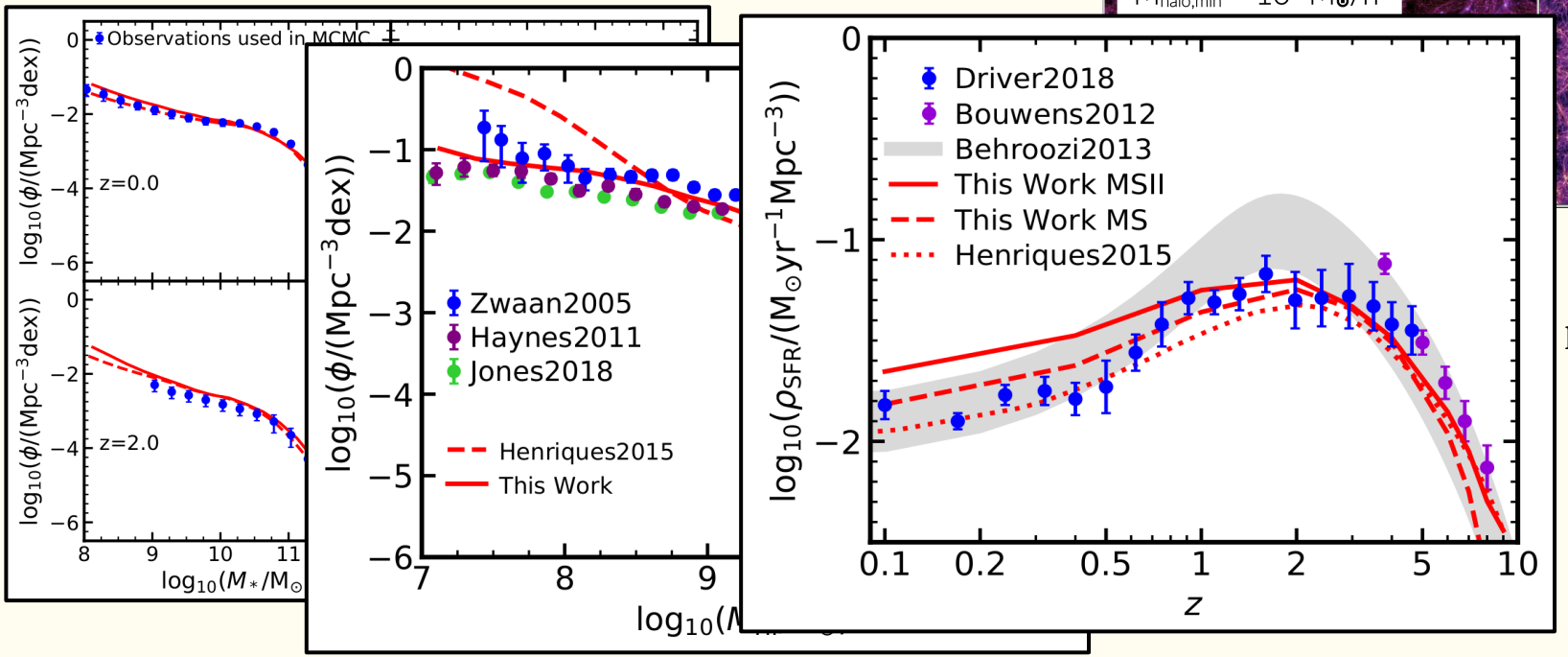
HI mass function



Good agreement with galaxy-evolution constraints

L - GALAXIES

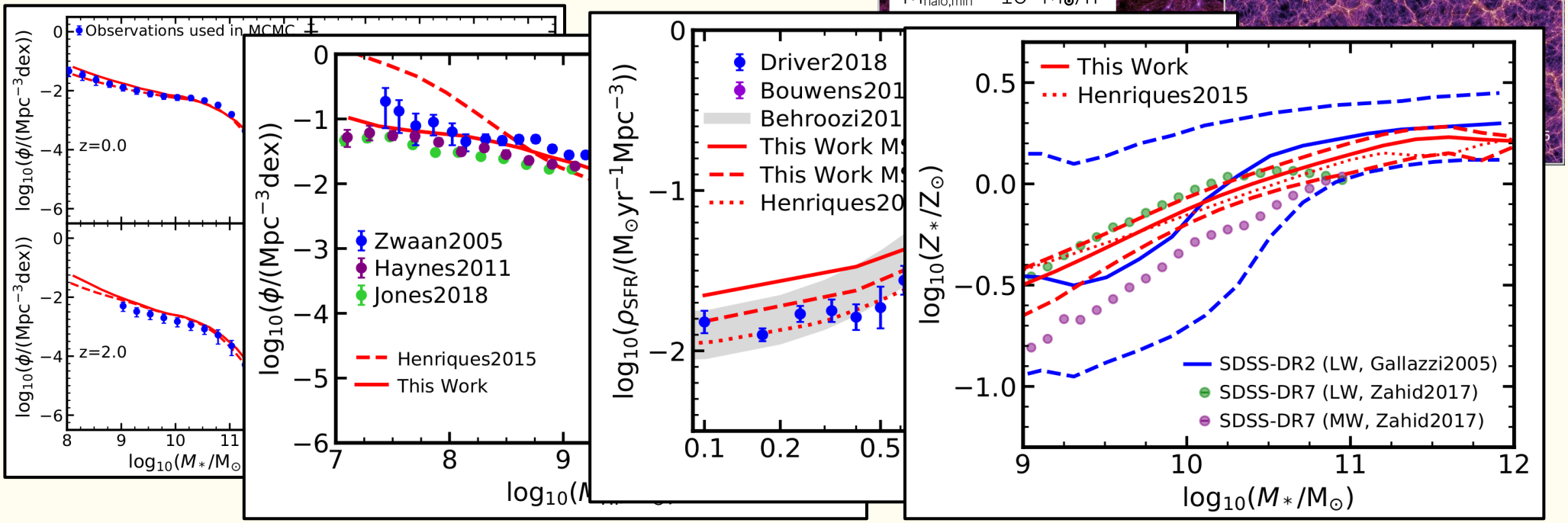




SFR history

Good agreement with galaxy-evolution constraints

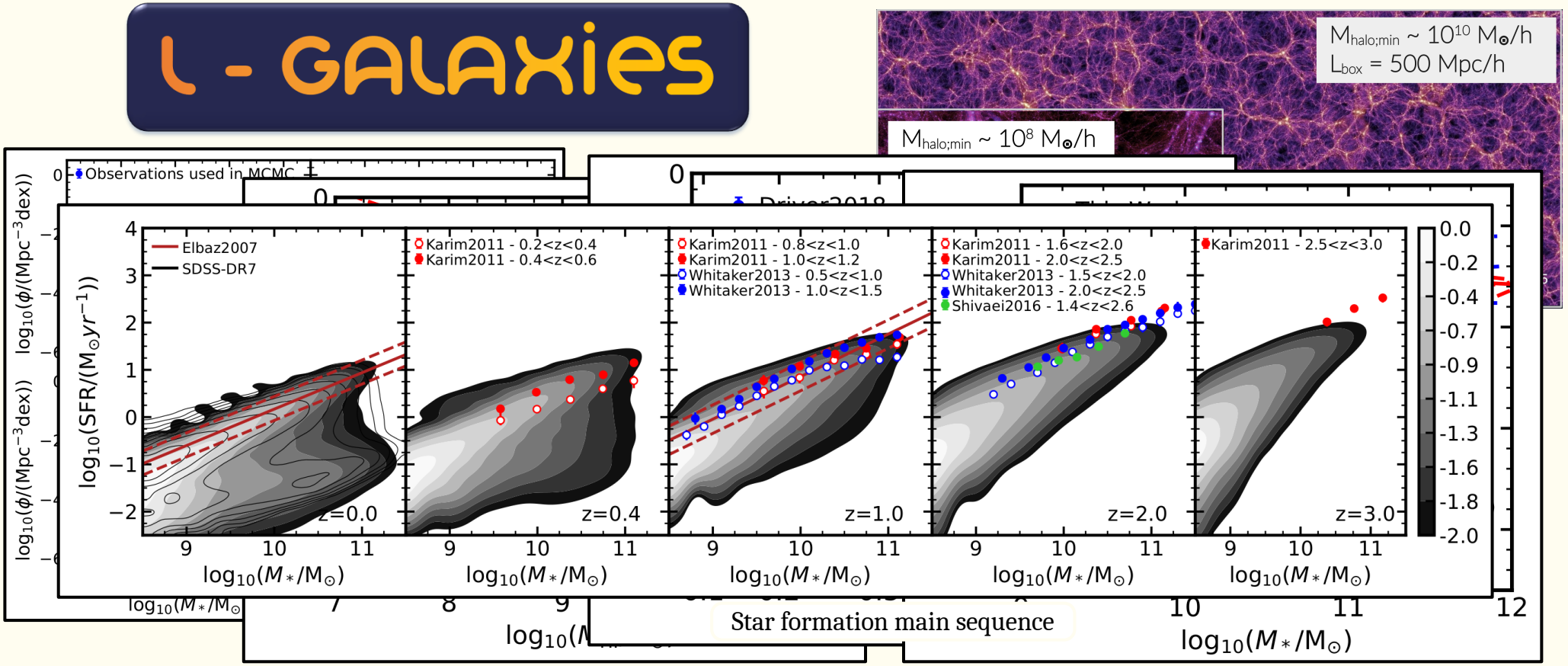
L-GALAXIES



Mass-Metallicity relation

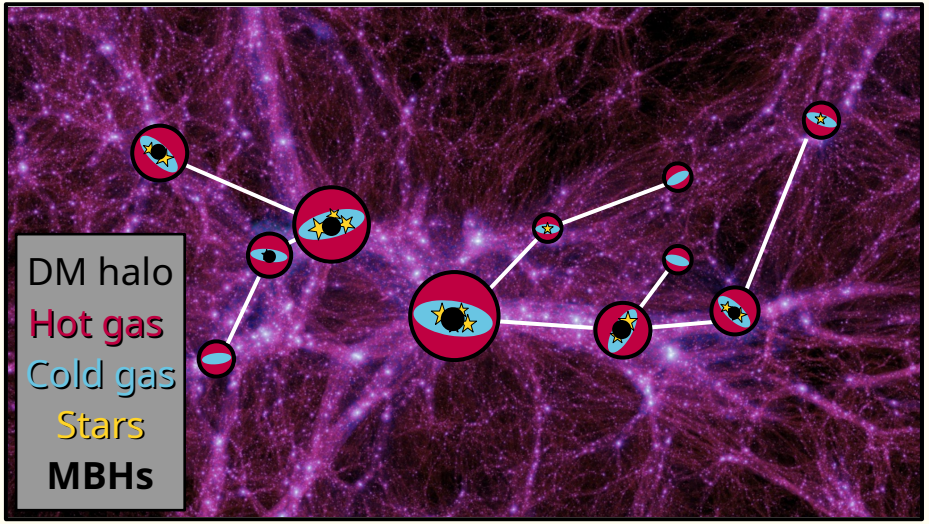
Good agreement with galaxy-evolution constraints

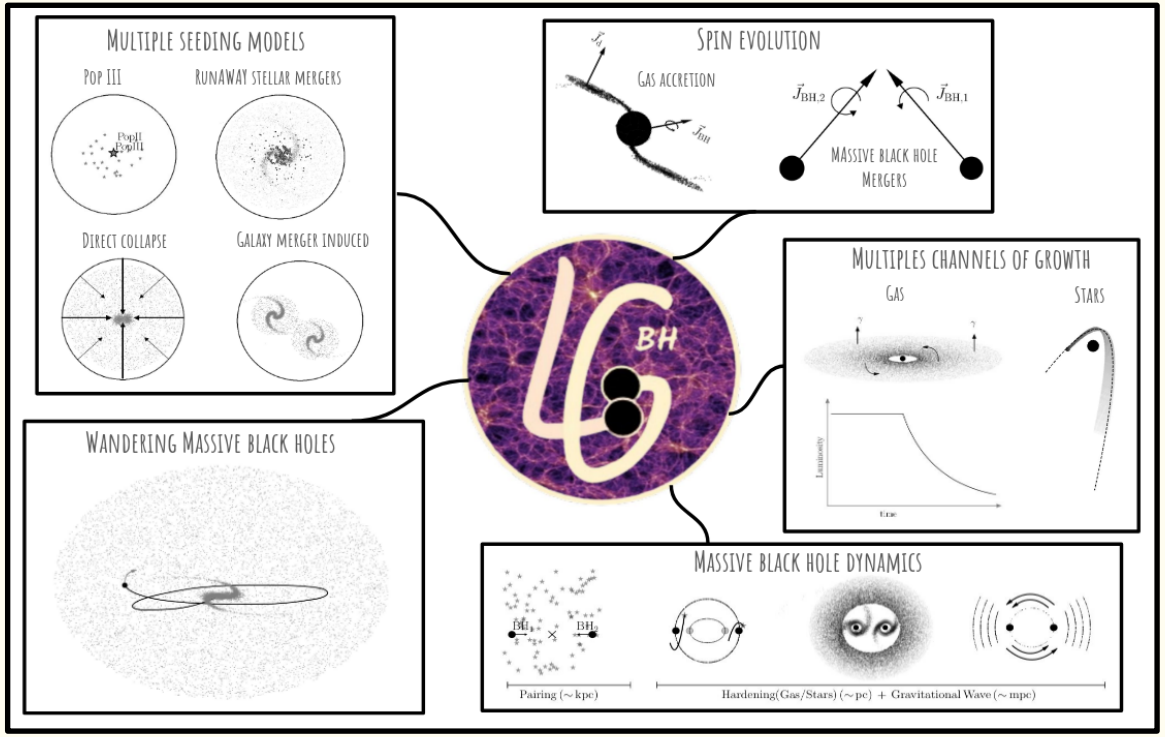
L-GALAXIES



Good agreement with galaxy-evolution constraints – MBH physics missing

- Addition of MBHs physics to L-Galaxies
- Detailed physical models for MBHs
  - BH seeding coupled to environment
  - MBH growth (gas accretion & mergers)
  - MBH binaries (formation & coalescence)
  - GW emission and recoils after BH-BH mergers
  - MBH-star interactions (TDEs)





Izquierdo-Villalba+ 2020, 2022, 2023 ; Spinoso+ 2023 ; Polkas+ 2024 ; Bonoli+ 2025

MBH seeding scenarios

Light	RSM	DCBHs	miDCBHs
First stars	Stellar clusters	Gas clouds	Galaxy mergers

PopIII stellar remnants

- Unresolved
- Probabilistic model

Runaway Stellar Mergers

- Resolved (H-cooling halos)
- Constrained by environment
- Weak UV illumination
- Low chemical enrichment

Direct Collapse BHs

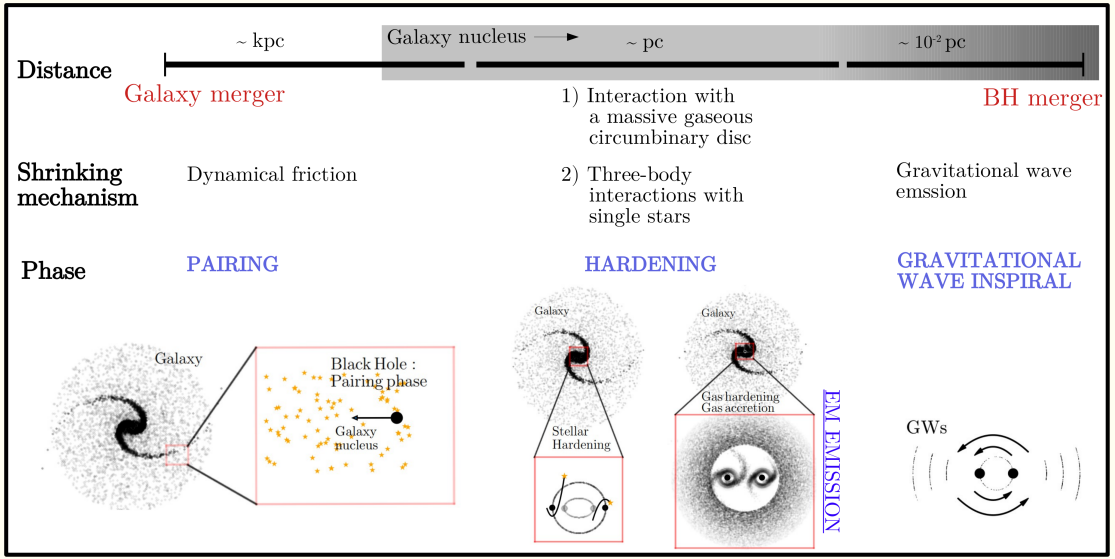
- Resolved (H-cooling halos)
- Constrained by environment
- Strong UV illumination
- Chemically pristine halos

Merger-induced Direct Collapse BHs

- Resolved
- Gas-rich mergers
- Milky way-like galaxies

Developed on Millennium-II (Boylan-Kolchin et al. 2009) – Access to H-cooling halos

L-GalaxiesBH



MBH binaries

- BH-BH mergers
- Triple-body interactions
- GW emission

(Izquierdo-Villalba et al. 2022)

Mass growth

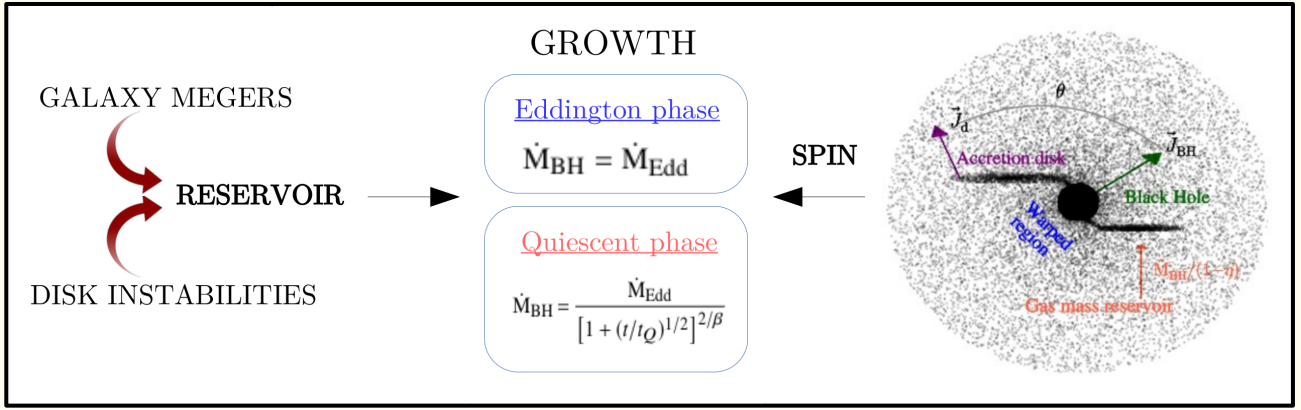
- hot and cold gas
- galaxy mergers / DIs
- Super-Eddington

(Izquierdo-Villalba et al. 2020)

MBH growth & dynamics

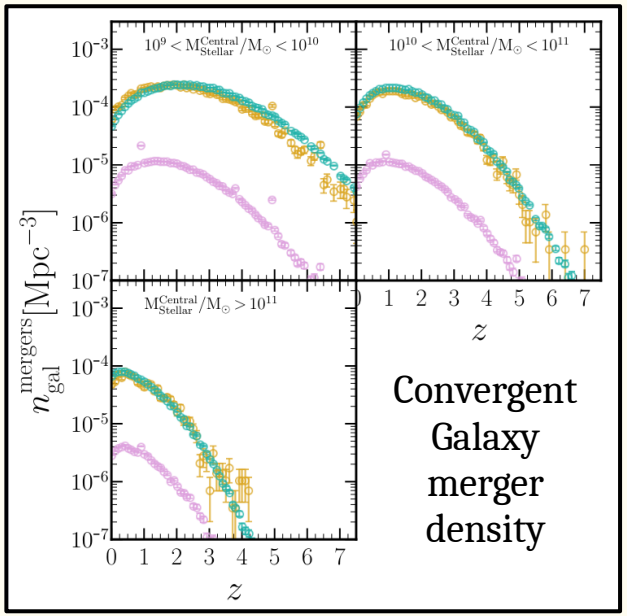
- Comprehensive model
- BH spin coupled to mass growth
- GW recoils and wandering BHs

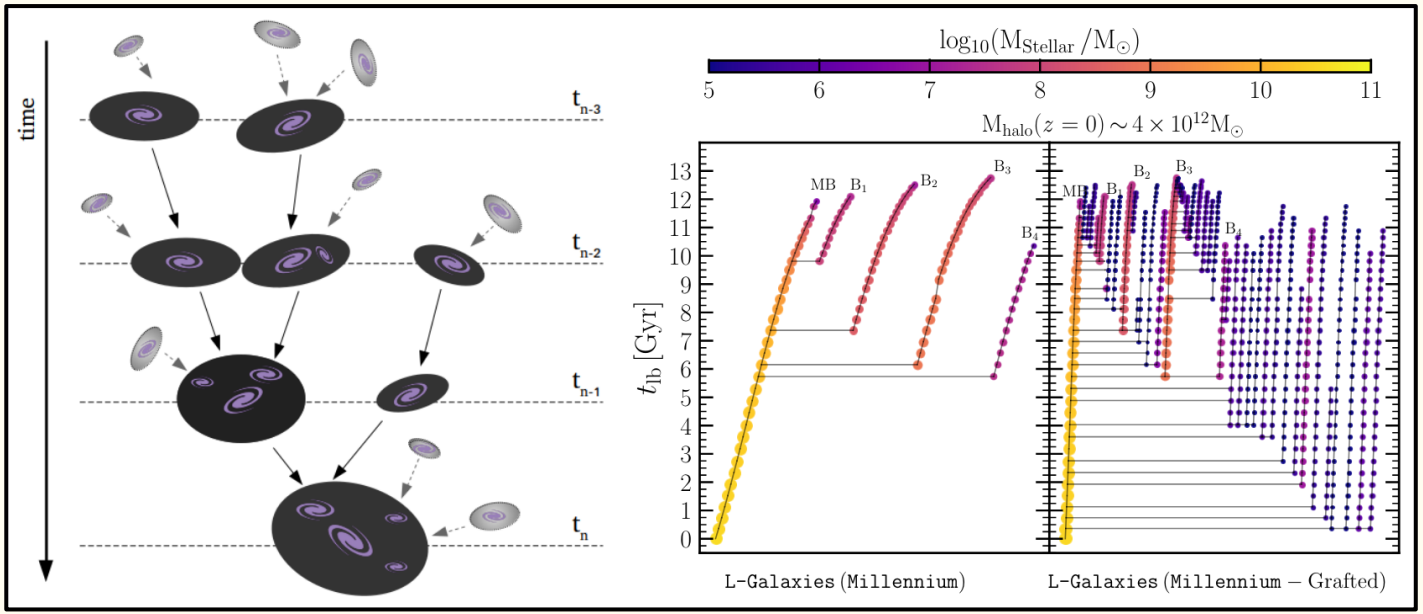
(Izquierdo-Villalba et al. 2020, 2022,2023,2024)



"Grafting" technique
(Bonoli et al. 2025)

- Initialization of larger simulations with inputs from smaller ones
- Combination of large volumes and high-resolution





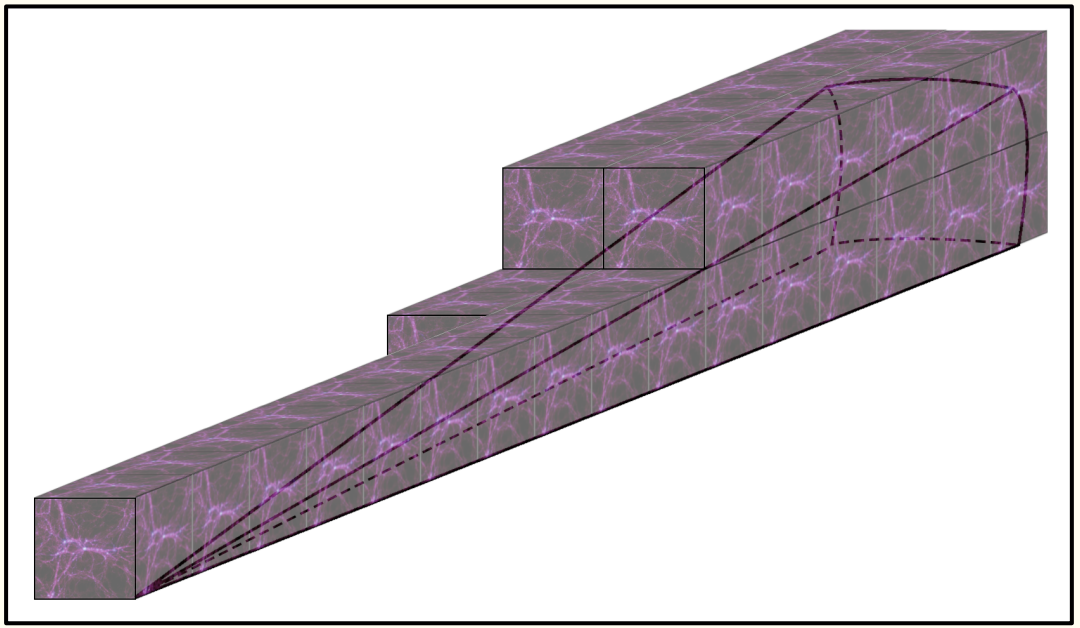
Mock surveys
(Izquierdo-Villalba et al. 2019)

Realistic multi-messenger simulated skies

- Galaxy photometry with emission lines
- MBHs and MBHBs populations

Simulated “light-cones”

- Built from N-body, cosmological simulations
- Box is replicated on each direction
- Line of sight chosen to minimize box repetitions (Kitzbichler & White 2007)



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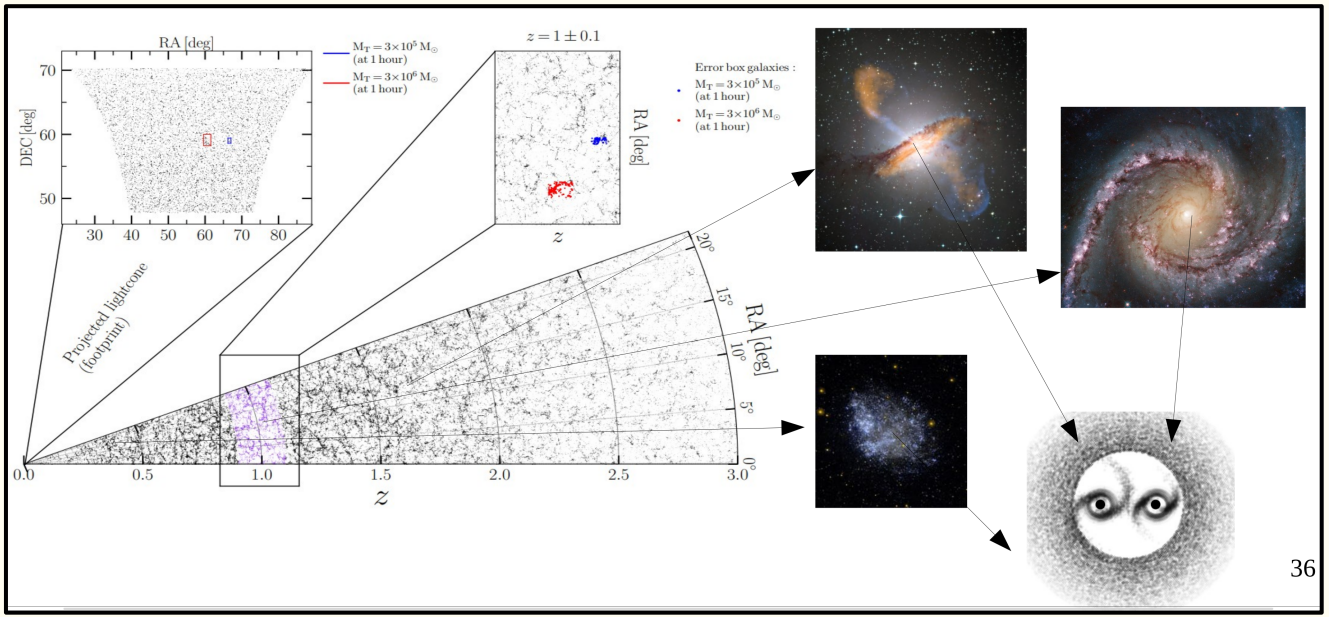
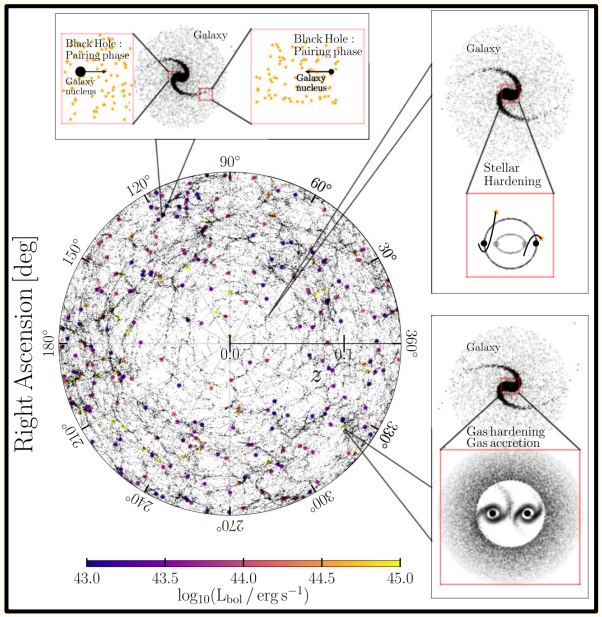
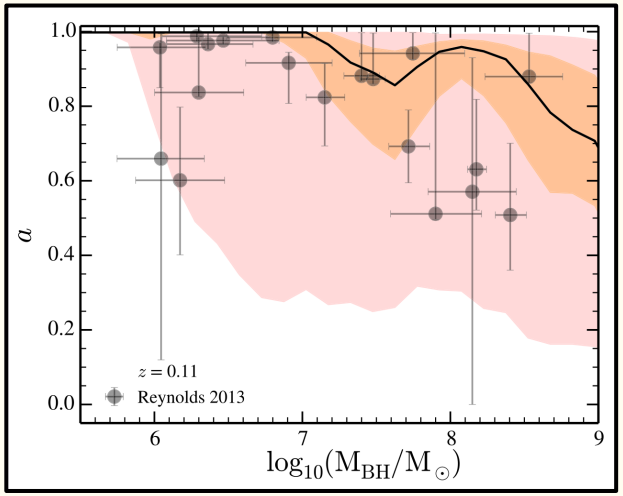
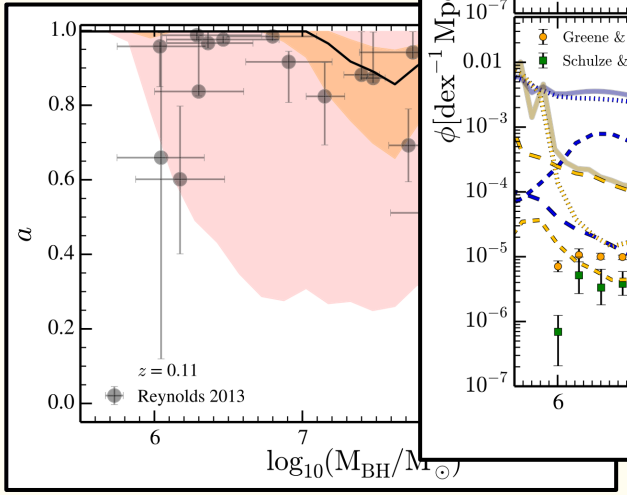




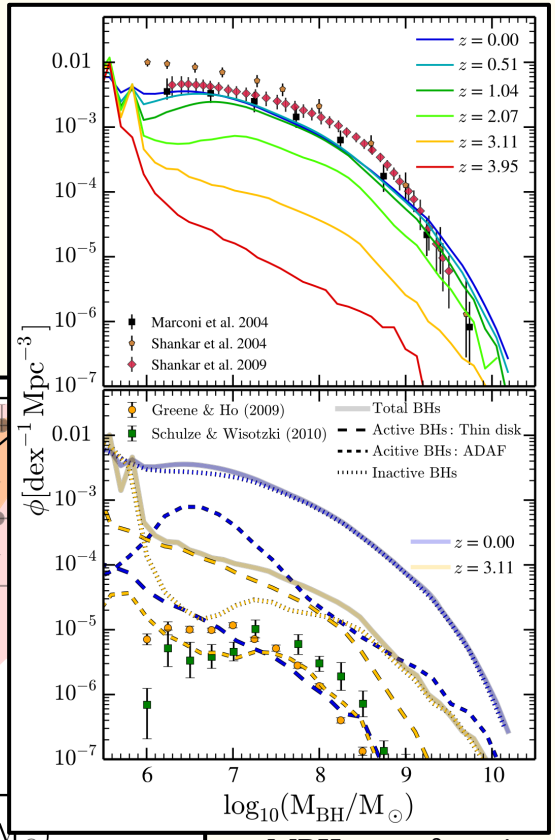


Spin distribution

Good agreement with MBH-evolution constraints

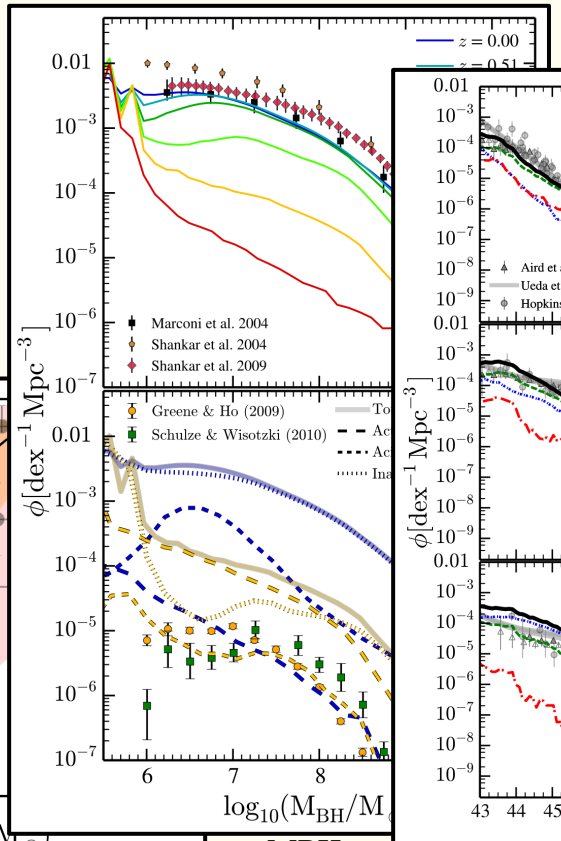


Spin distribution

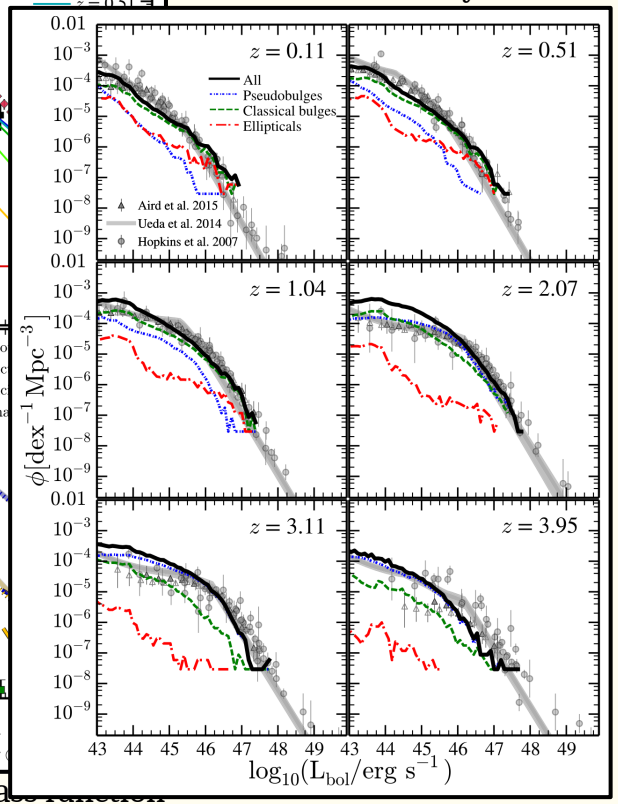


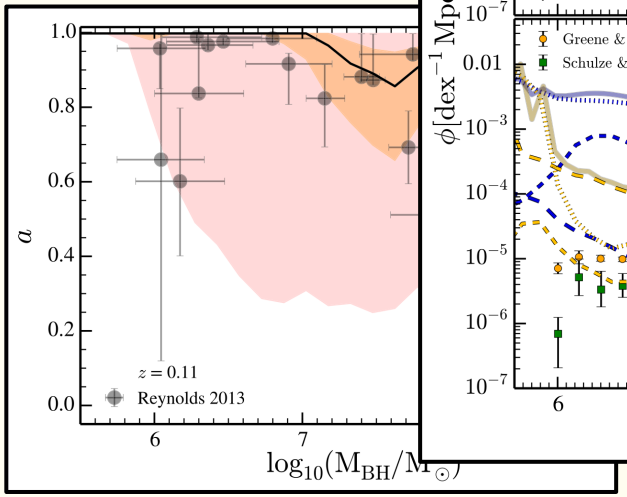
MBH mass function

Good agreement with MBH-evolution constraints



AGN luminosity function

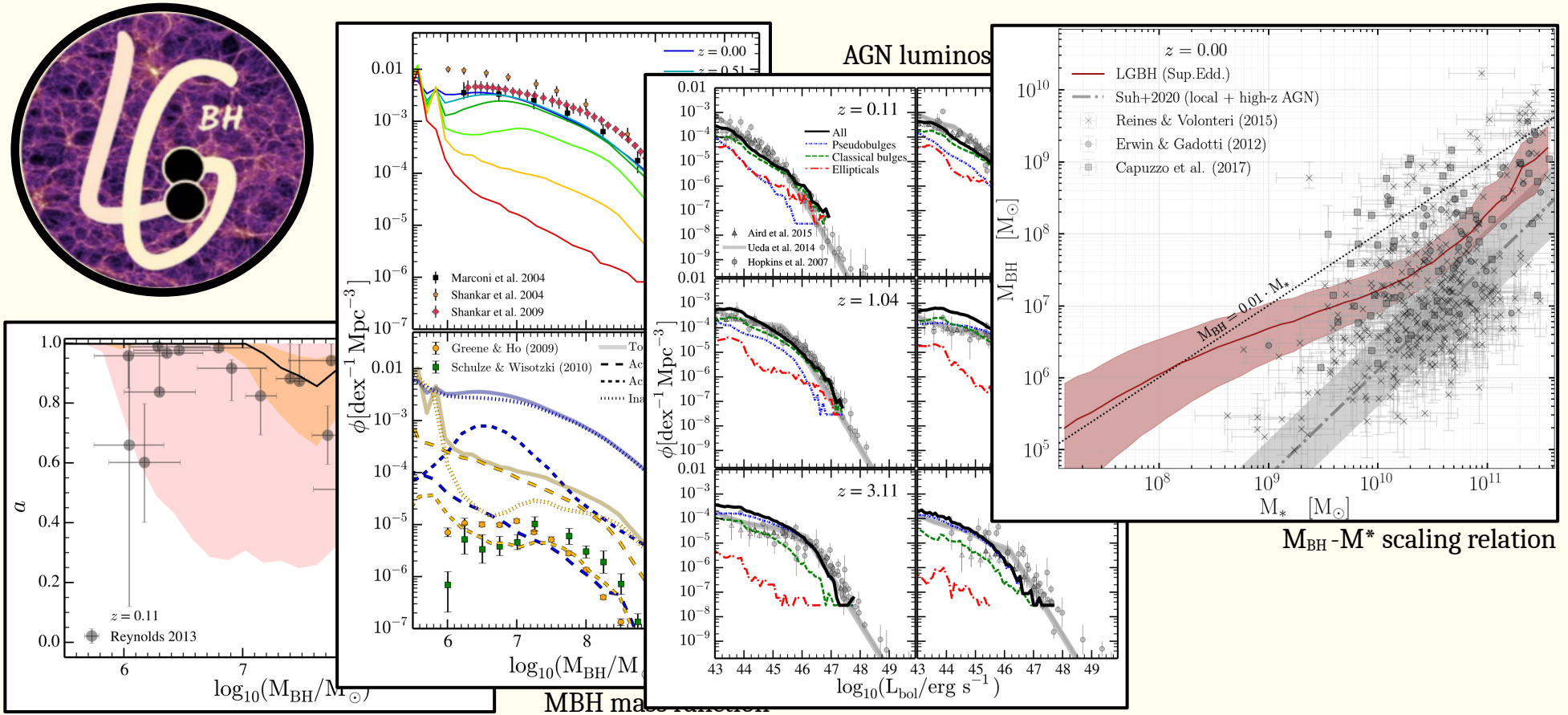




Spin distribution

MBH mass function

Good agreement with MBH-evolution constraints



Spin distribution

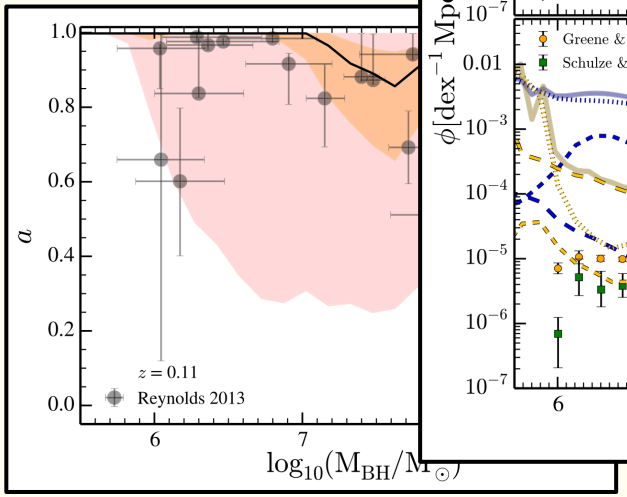
MBH mass function

AGN luminos

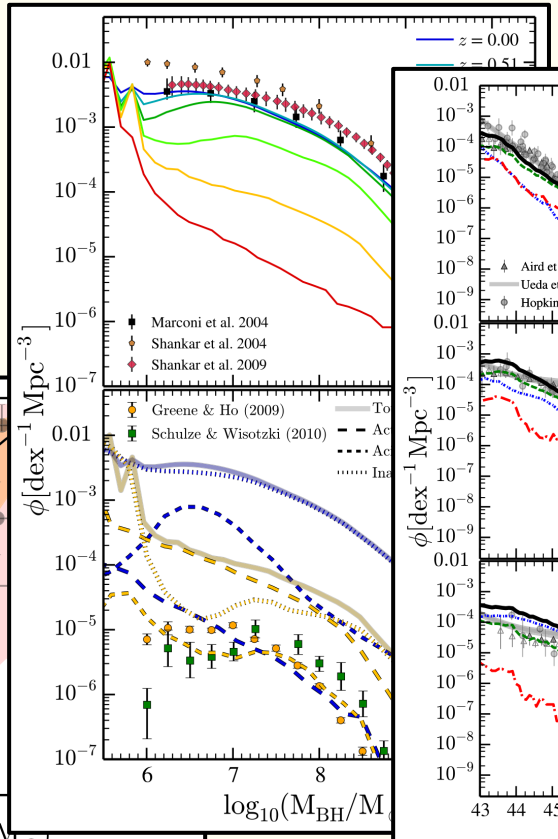
M_{BH} -M* scaling relation

Good agreement with MBH-evolution constraints

L-GalaxiesBH

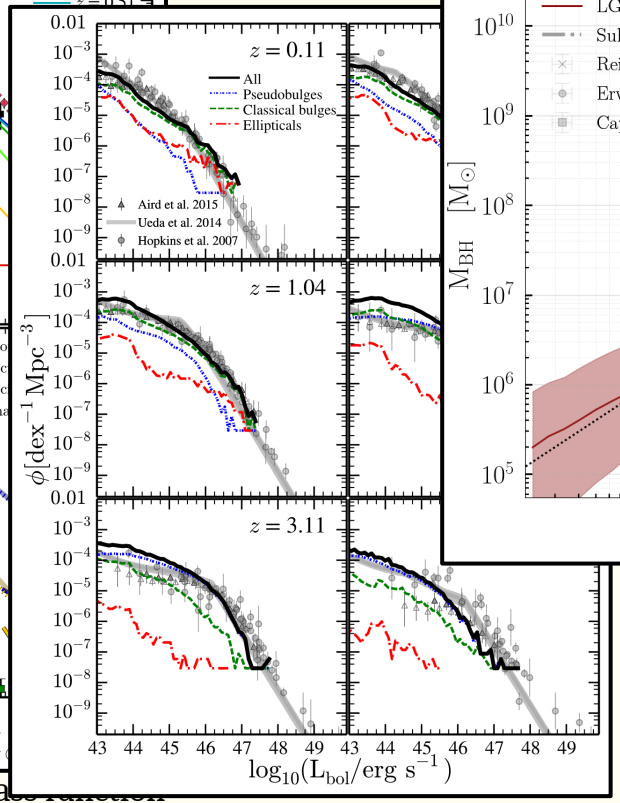


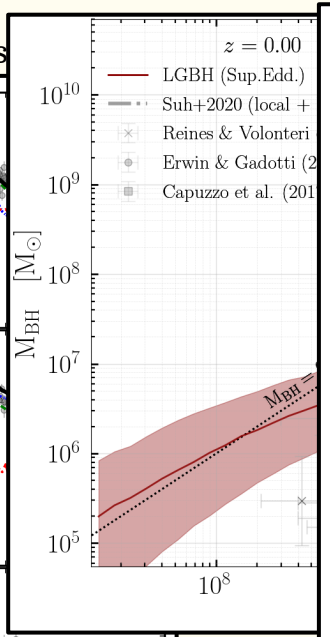
Spin distribution

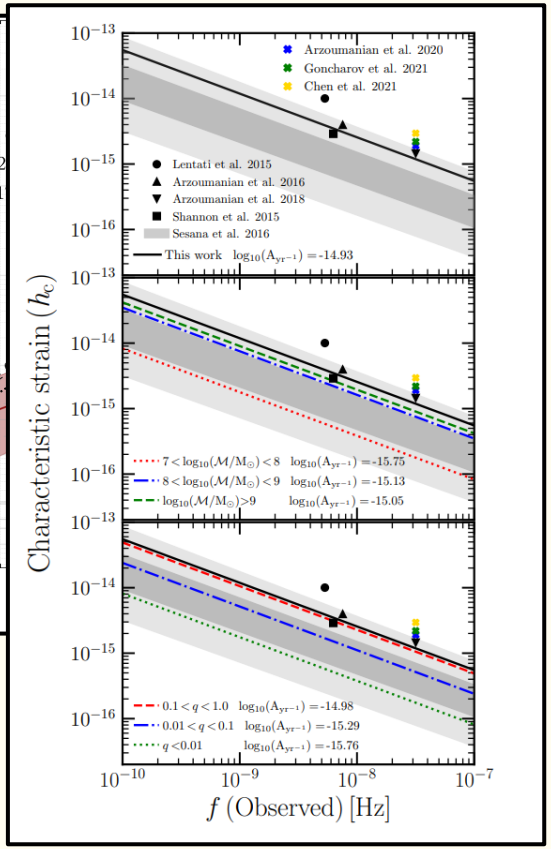


MBH mass function

AGN luminos





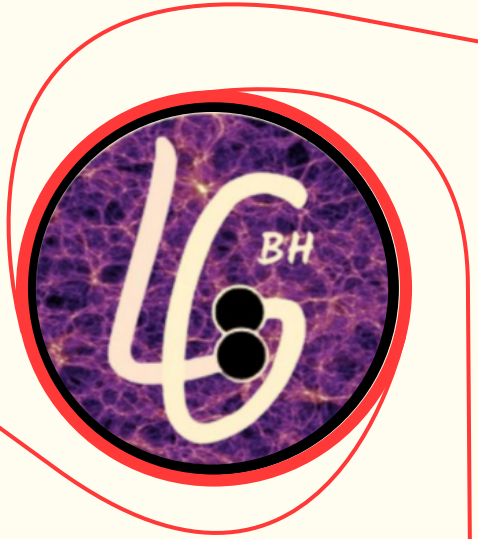


Stochastic GW background

Good agreement with MBH-evolution constraints

Detailed MBH physics

- Formation / seeding
- BH spin evolution
- BH mass growth
- Dynamics & GW emission



Wide dynamic ranges

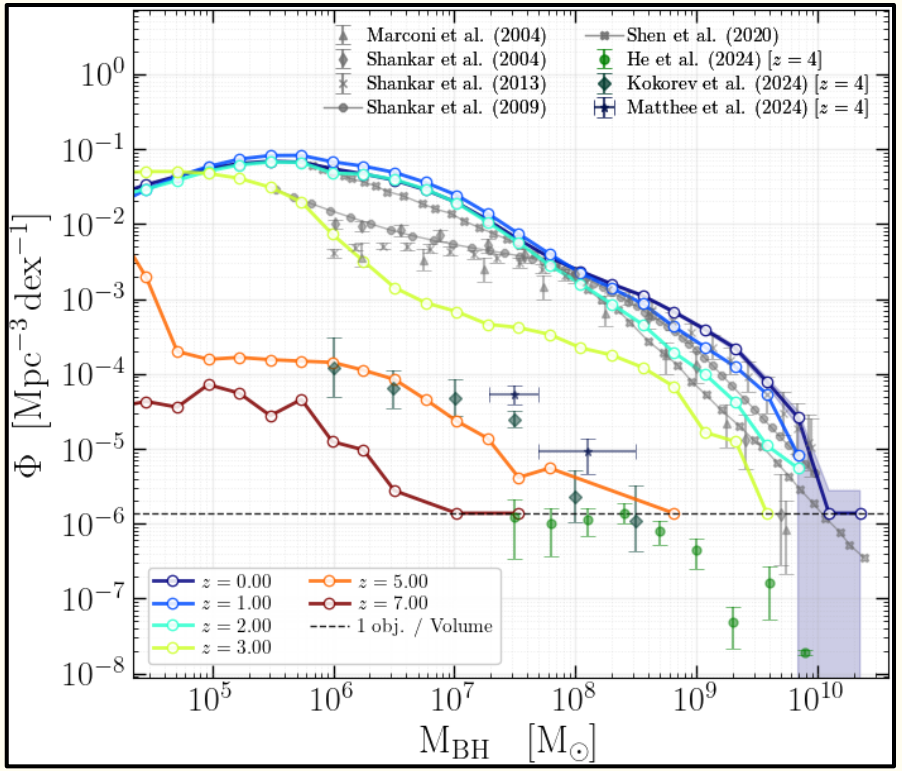
- High resolution
- Large volumes
- Diverse environments

Galaxy Evolution model

- Star formation & feedback
- Galaxy mergers & secular evolution
- Environmental effects (e.g. stripping)

State-of-the-art, comprehensive model for galaxy and MBH formation and evolution

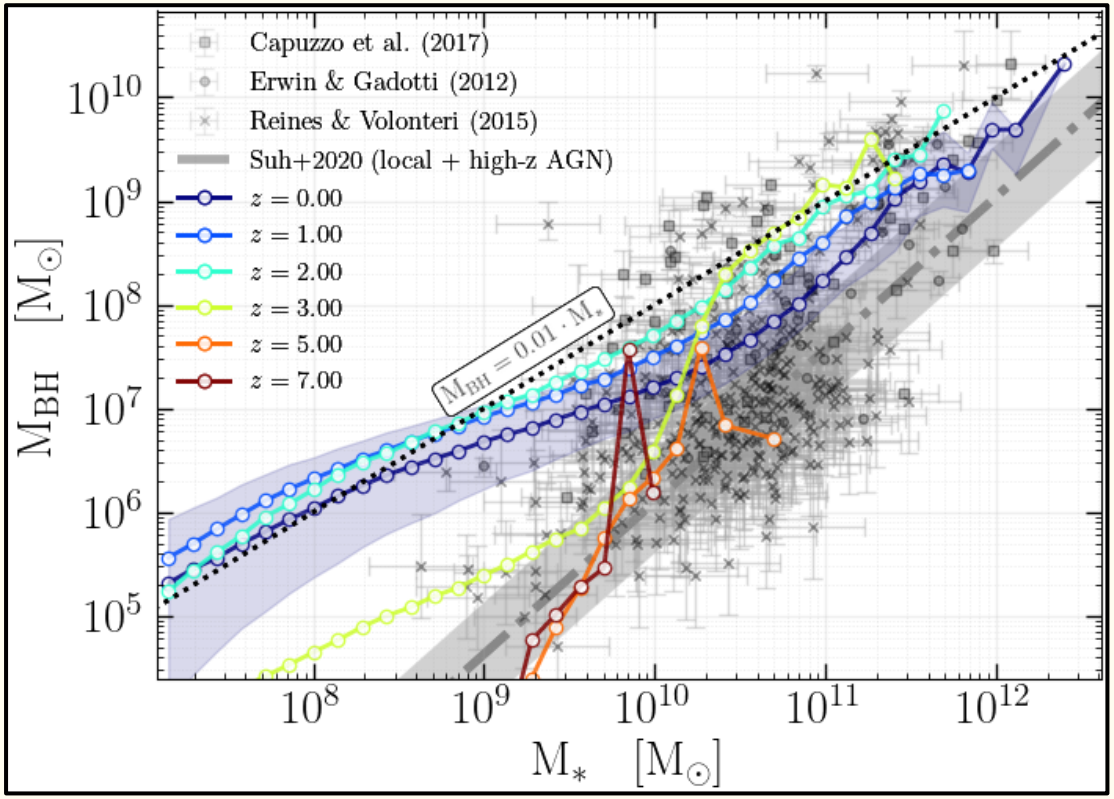
Results



- M_{BH} function in place at $z \sim 2$
- M* tends to "lag" behind M_{BH}

MBH populations from BH-seeds

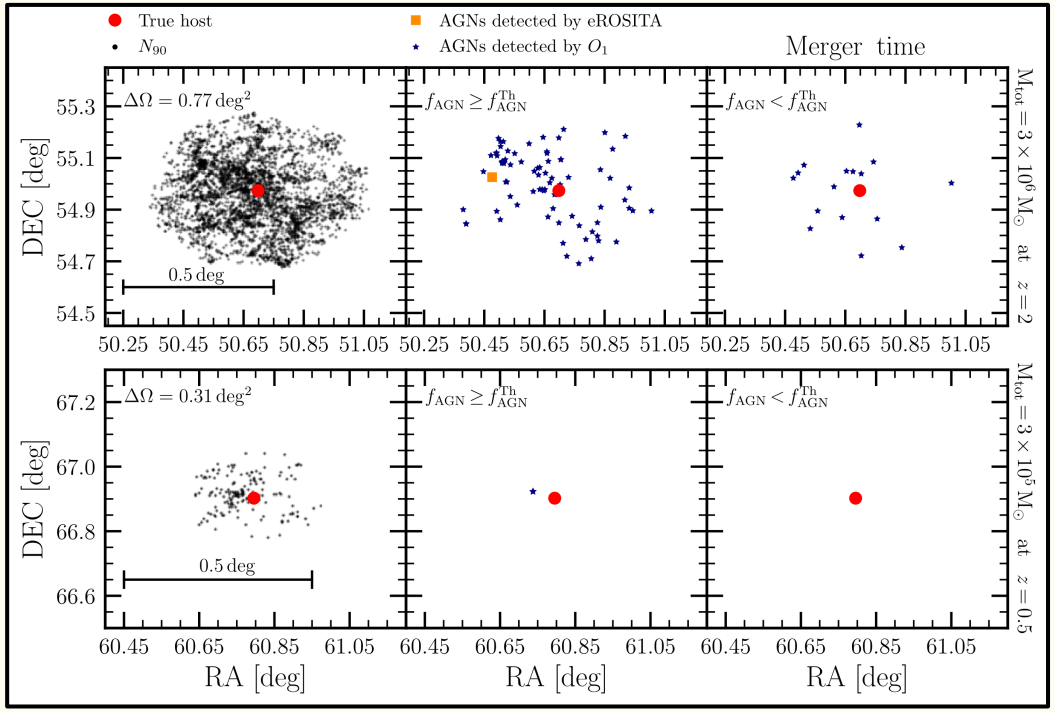
Spinoso et al. 2023



Results

GW predictions with MBH populations

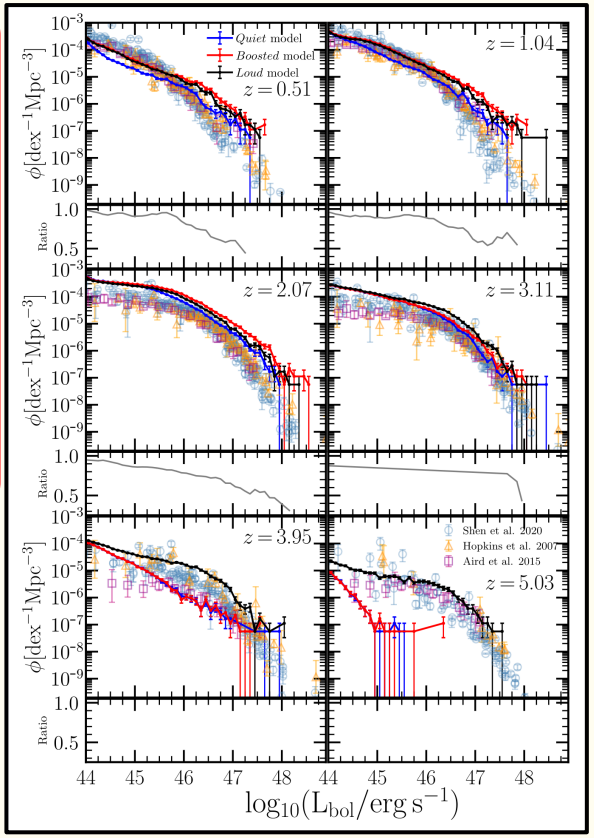
Lops et al. 2023 ; Izquierdo-Villalba et al. 2024



Hosts of LISA MBHB will be difficult to observe

The high sGWB from PTAs favors fast MBHs growth (Super-Eddington) at high-z while leaving unaffected the LISA event rates

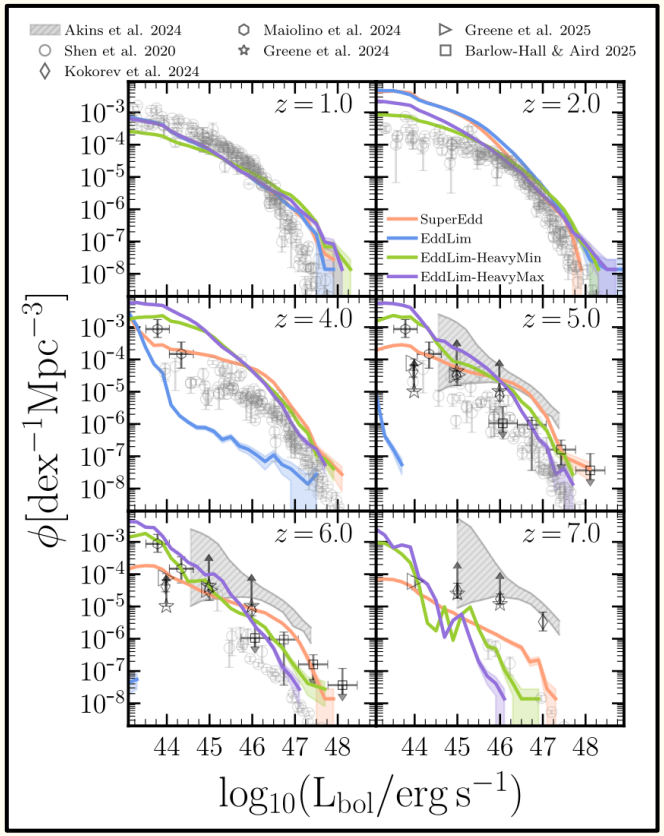
Loud: A = 1.8 x 10^{-15}



Results

Multi-messenger constraints on MBH populations

Bonoli et al. 2025



- Confronting BH-seeding and MBH growth:
  - Super-Eddington + “Physical” BH-seeding
  - Edd.-limited + “Physical” BH-seeding
  - Edd.-limited + Probabilistic BH-seeding (only heavy seeds)
  - Edd.-limited + Probabilistic BH-seeding (only heavy seeds ; low occ. fraction)
- Using recent PTA constraints (sGWB amplitude at $z = 0$) together with JWST ones at $z > 4$ (AGN LF ; BHMF)

Results

Multi-messenger constraints on MBH populations

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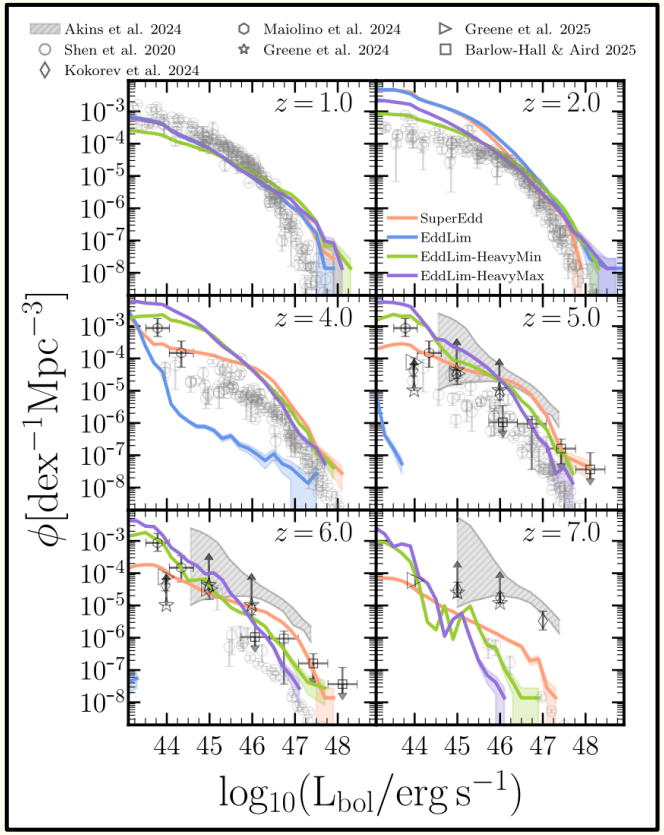
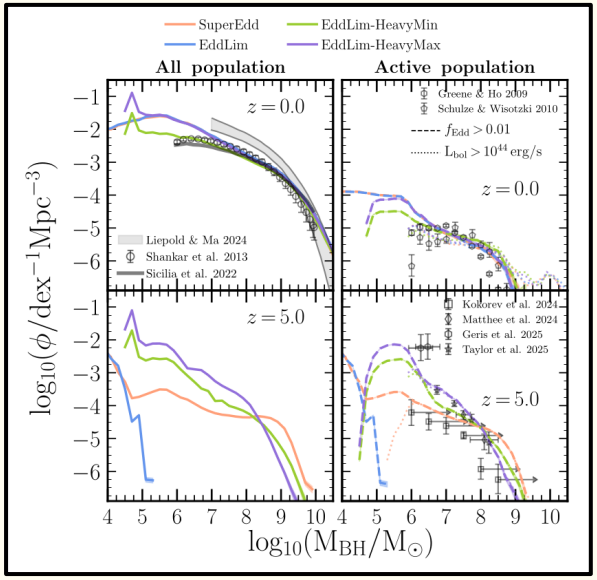
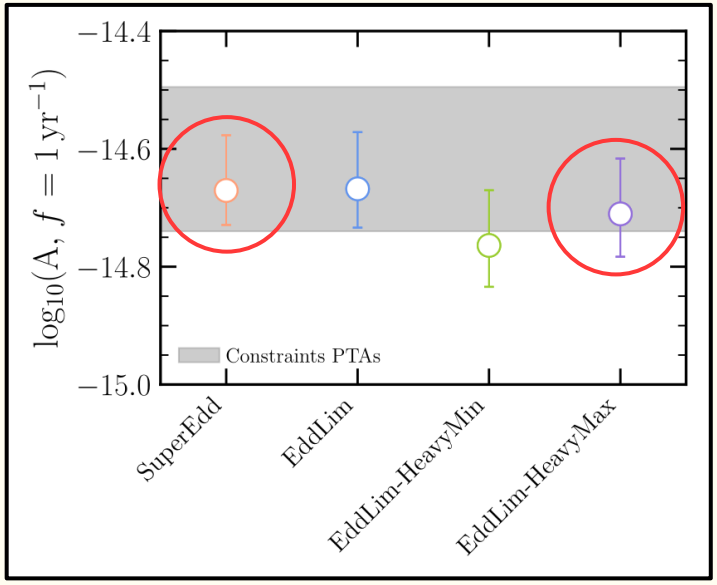




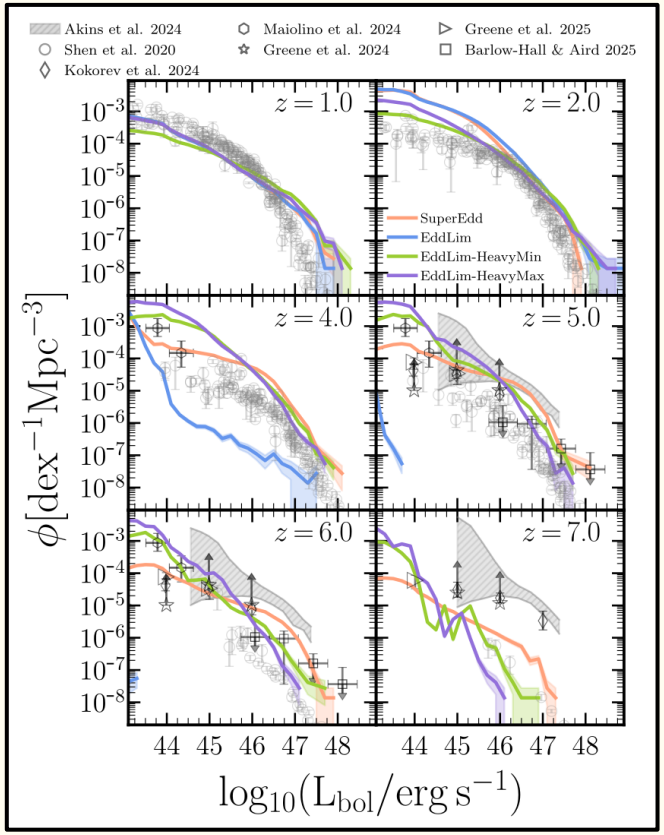


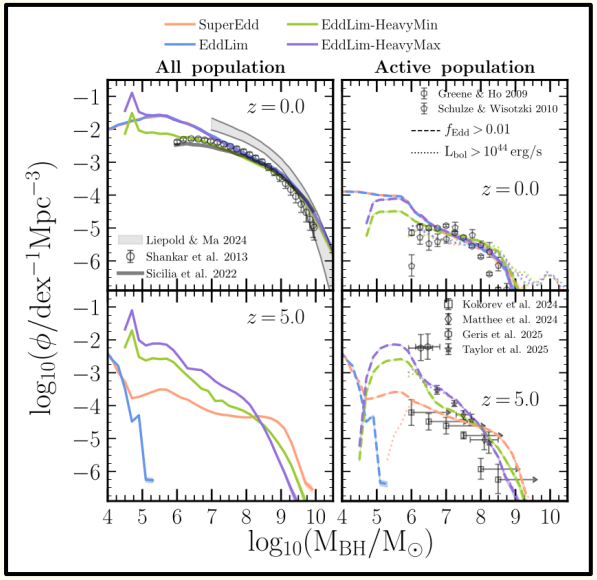
- Super-Eddington mildly favored by matching PTA and JWST observations

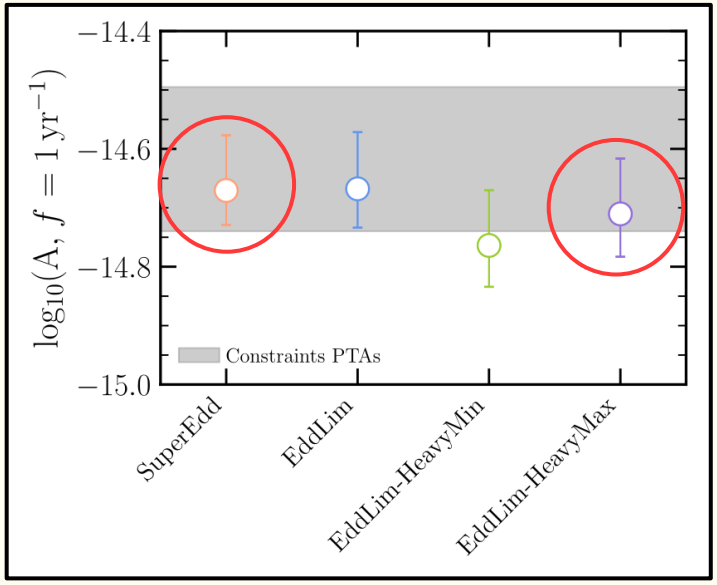
Results

Multi-messenger constraints on MBH populations

Bonoli et al. 2025







- Super-Eddington mildly favored by matching PTA and JWST observations
- Disentangling the strong degeneracy between BH-seeding and MBH growth is still difficult

Conclusions

- L-GalaxiesBH : comprehensive tool to study MBH formation and evolution
  - Physically-motivated MBH and MBHB populations
- Grafting technique + lightcones : simulated multi-messenger skies with MBHBs
- Physical interpretation of current GW / multi-messenger data (PTA + JWST):
  - Super-Eddington accretion onto light seeds mildly favored w.r.t heavy seeding
  - Strong degeneracy between BH seeding and growth
- Predictions for future GW experiments (e.g. LISA)
  - Sky-localization of LISA-binaries hosts may be (very) difficult

Thank you!

Outline

- High-redshift Massive Black Holes
  - Early monsters and “common” Black Holes in observations
  - Current and future GW constraints
- Simulating Massive Black Holes across cosmic times
  - The L-GalaxiesBH semi-analytic model
  - MBH populations from light, intermediate and heavy BH seeds
  - Multi-messenger constraints on MBH populations
- Forming the first Black Holes
  - The Millennium-*seeds* simulation
  - Bridging the gap between ET and LISA events
- Conclusions and future perspectives

MBH seeding scenarios

- **Light** — First stars
- **RSM** — Stellar clusters
- **DCBHs** — Gas clouds
- **miDCBHs** — Galaxy mergers

PopIII stellar remnants

- Unresolved
- Probabilistic model

Runaway Stellar Mergers

- Resolved (H-cooling halos)
- Constrained by environment
- Weak UV illumination
- Low chemical enrichment

Direct Collapse BHs

- Resolved (H-cooling halos)
- Constrained by environment
- Strong UV illumination
- Chemically pristine halos

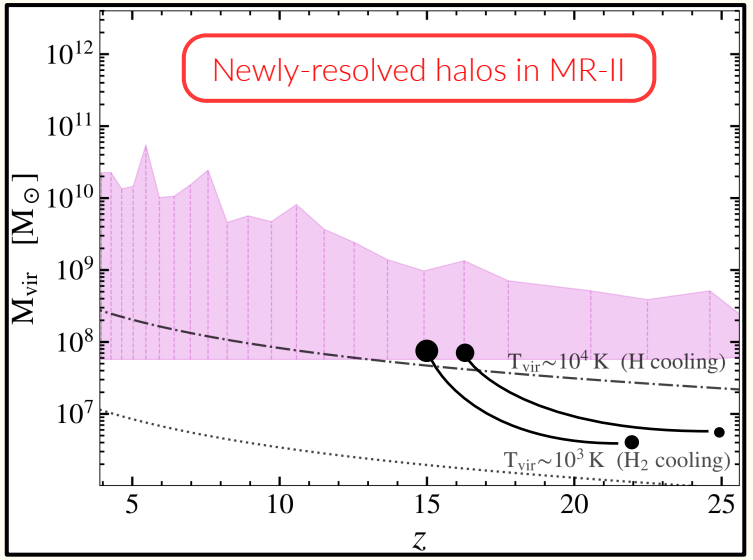
Merger-induced Direct Collapse BHs

- Resolved
- Gas-rich mergers
- Milky way-like galaxies

Developed on Millennium-II (Boylan-Kolchin et al. 2009) – Access to H-cooling halos

MBH seeding scenarios

Light	RSM	DCBHs	miDCBHs
First stars	Stellar clusters	Gas clouds	Galaxy mergers



"Sub-grid" model for light BH-seeds

- Random formation redshift
  - $z_{init} < z_{form} < 35$; until $Z_{IGM} < Z_{crit} = 10^{-3} Z_\odot$
  - Larson IMF (e.g. Valiante et al. 2016)
- Unresolved BH-mass evolution
  - Eddington-limited growth from cold-gas
  - Typical initialization mass $\sim 10^3 M_\odot$

Single central remnants

Multiple off-center remnants

MBH seeding scenarios

Light

First stars

RSM

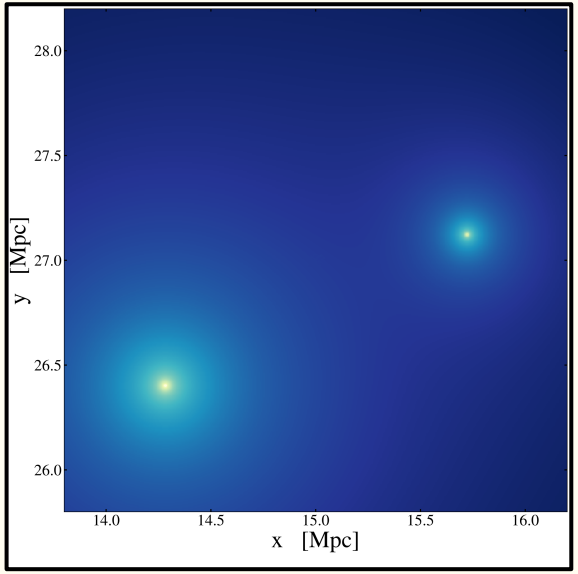
Stellar clusters

DCBHs

Gas clouds

miDCBHs

Galaxy mergers



Local IGM conditions

$$J_{LW}(x,t) = J_{bg} + J(x,t)$$

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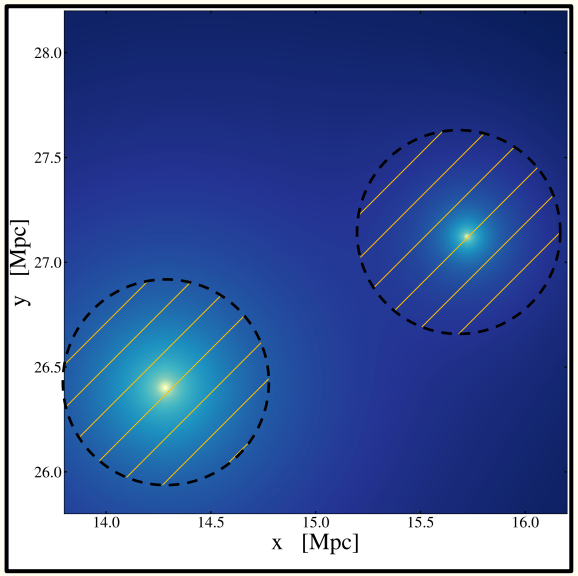

Local IGM conditions

$$J_{LW}(x,t) = J_{bg} + J(x,t) \quad ; \quad Z_{IGM}(x,t) = Z_{bg} \oplus Z(x,t)$$

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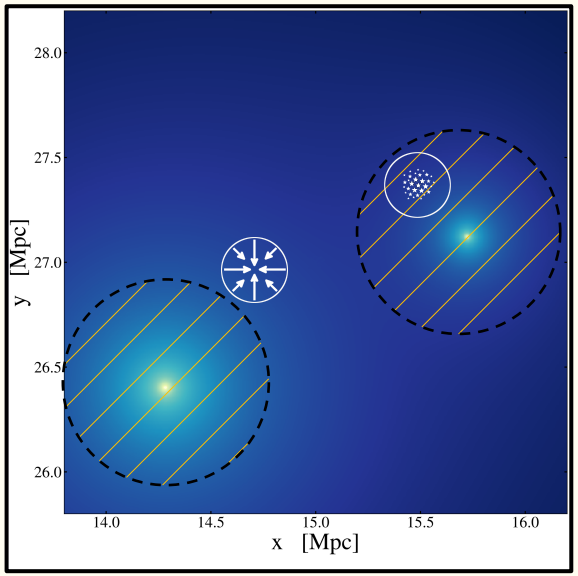

Local IGM conditions

$$J_{LW}(x,t) = J_{bg} + J(x,t) \quad ; \quad Z_{IGM}(x,t) = Z_{bg} \oplus Z(x,t)$$

DCBHs : $J_{LW}(x,t) > J_{crit,DCBH}$ and $Z_{IGM}(x,t) < Z_{crit,DCBH}$

RSMs : $J_{LW}(x,t) > J_{crit,RSM}$ and $Z_{IGM}(x,t) < Z_{crit,RSM}$

MBH seeding scenarios

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RSM

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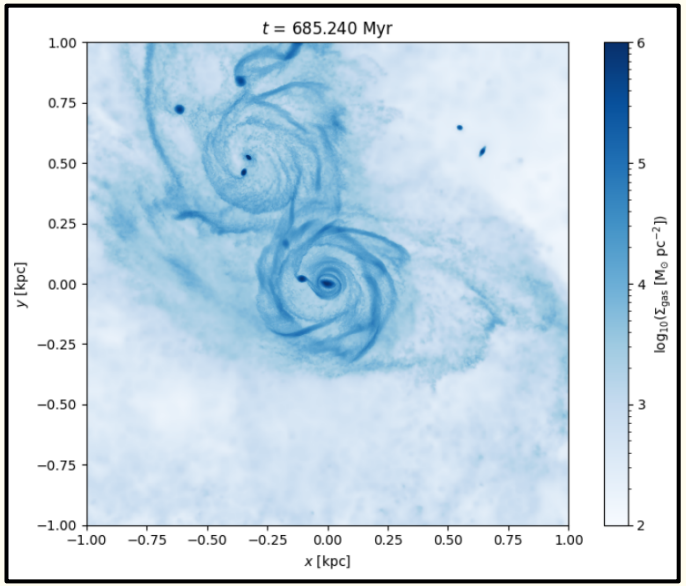
Gas clouds

miDCBHs

Galaxy mergers



Gas-rich galaxy mergers

(Mayer et al. 2015, 2024 ; Bonoli et al. 2014)

- Super Massive Disk formation (Mayer et al.2024)
- Inflow rate > 100 $M_\odot$/yr
- Inflow mass > $3 \times 10^8 M_\odot$
- BH seed mass ~$10^{6\text{-}8} M_\odot$ (Zwick et al. 2023)

MBH seeding scenarios

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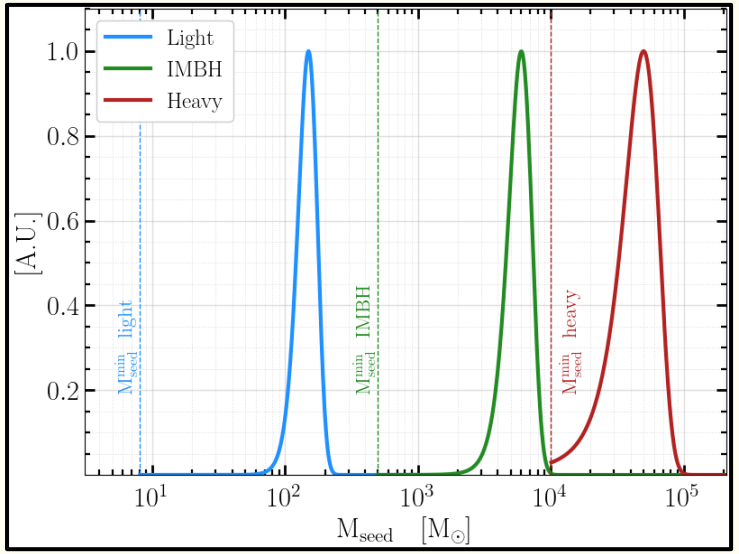
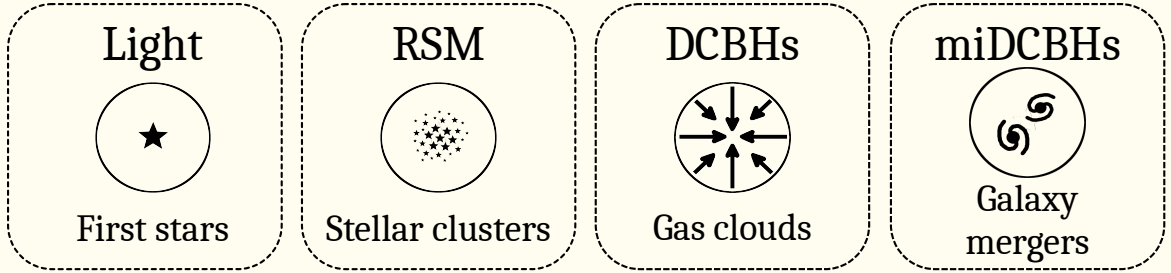
Galaxy mergers



"Parametric" multi-flavor BH-seeding model

- BH-seeding probability according to M_{halo} and z
- Light, intermediate and heavy BH-seeds
- BH masses extracted from gaussian distributions
- Unresolved BH-mass evolution

MBH seeding scenarios



Multi-flavor BH seeding

- All channels can be activated
- BH-seeds descendants down to z=0
- Mixing of different types

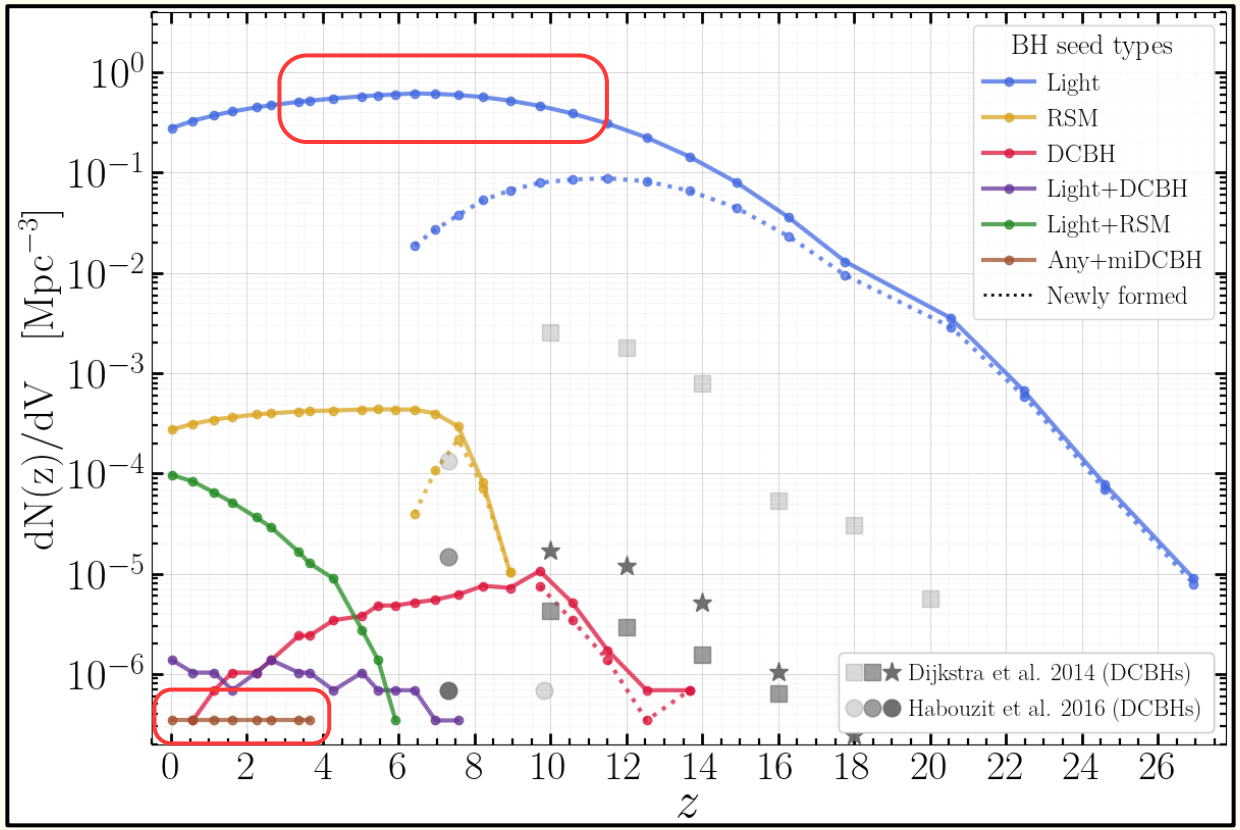
(Spinoso et al. 2023; Spinoso et al. in prep)

Results

MBH populations from BH-seeds

Spinoso et al. 2023

- Light seeds largely prevail
- miDCBHs extremely rare in the Millennium-II volume



Results

MBH populations from BH-seeds

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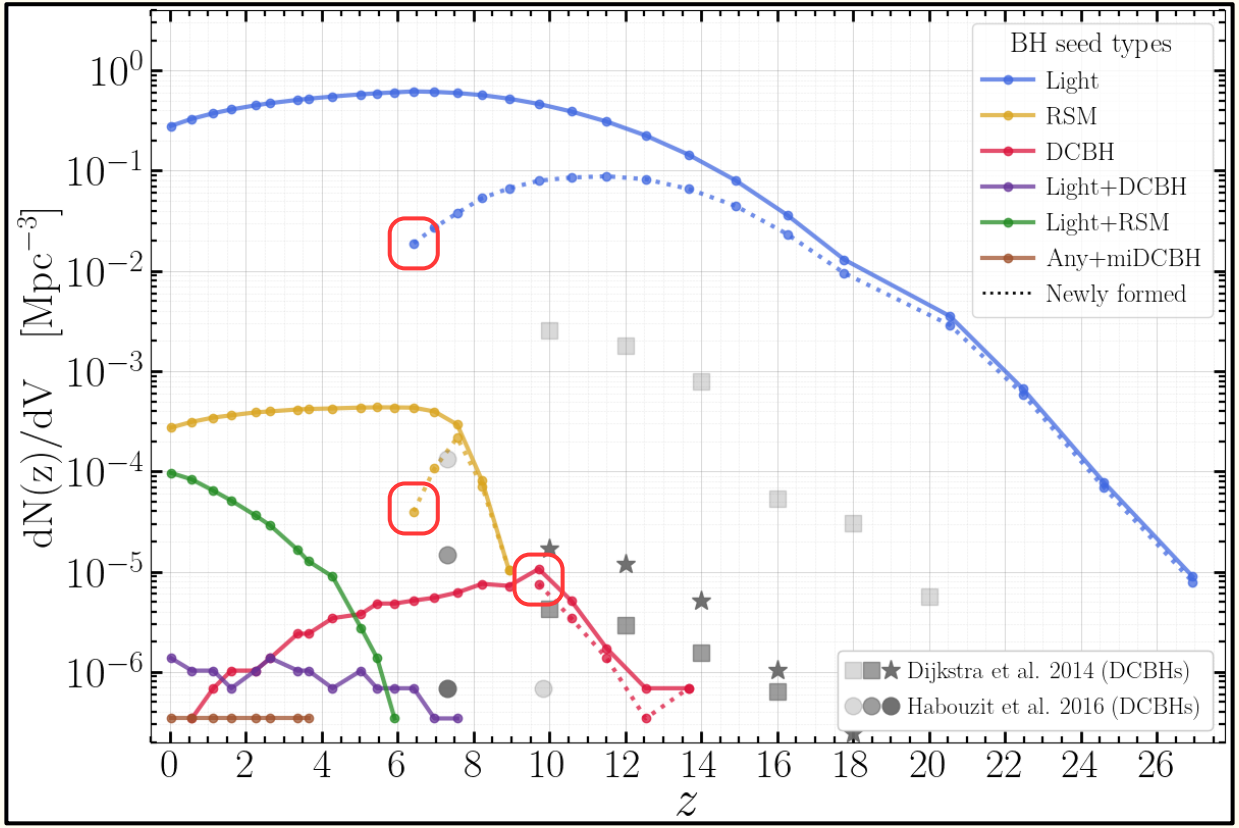
- Light, RSM and DCBH only form until favorable conditions are verified

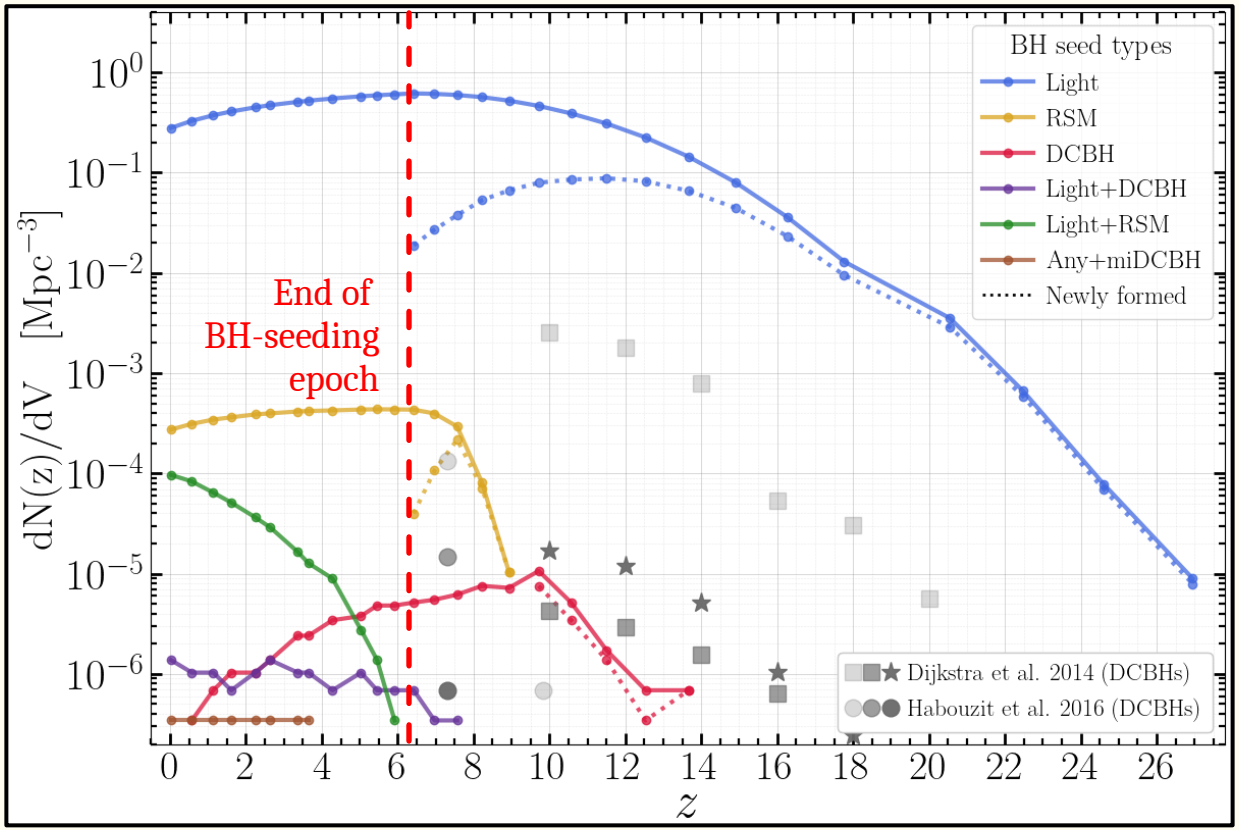


Results

MBH populations from BH-seeds

Spinoso et al. 2023

- Light seeds largely prevail
- miDCBHs extremely rare on the Millennium-II volume
- Light, RSM and DCBH only form until favorable conditions are verified
- Natural end of BH-seeding epoch (z<6 evolution driven by accretion and mergers)



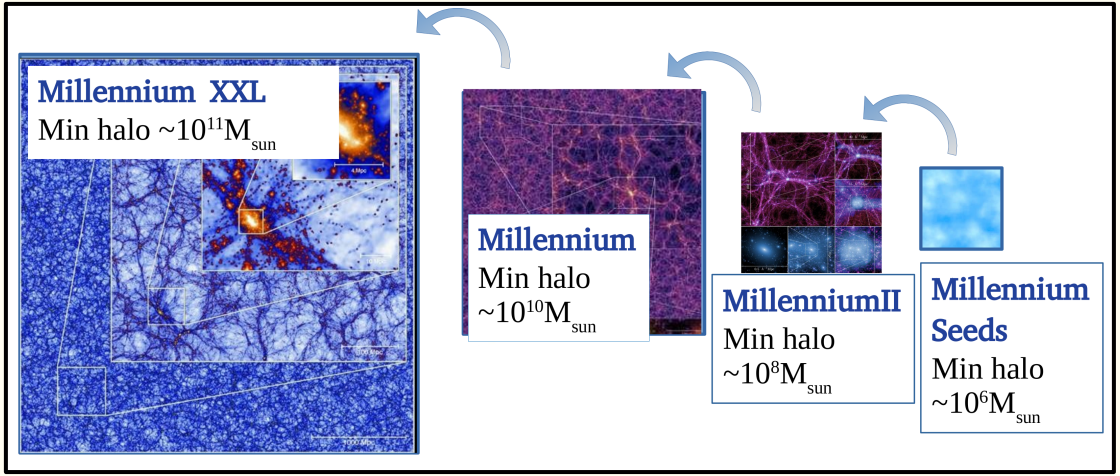
Millennium-*seeds*

I. Flores et al. – in prep.

I. Flores – Ph.D. student @ DIPC

- Resolving PopIII stars / remnants in cosmological contexts
- Developing a detailed model for light BH-seeds
- Binaries of massive PopIII remnants ($M_{BH} > 100\ M_{\odot}$)
- Tracking populations of stellar-BHs binaries

- High-resolution inputs for “grafting”
- Detailed model of the high-z IGM
  - Spatial variations of J_{LW} and Z_{IGM}
  - Resolving IMBH and DCBH formation

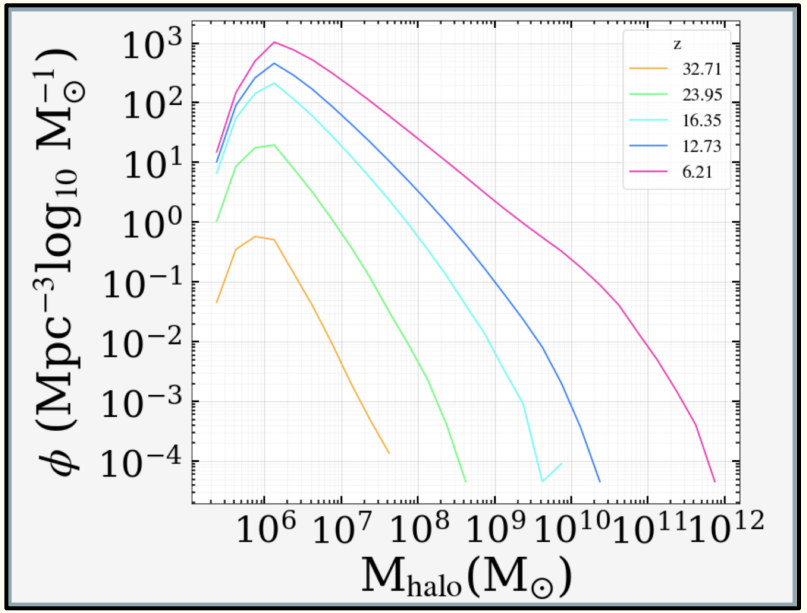


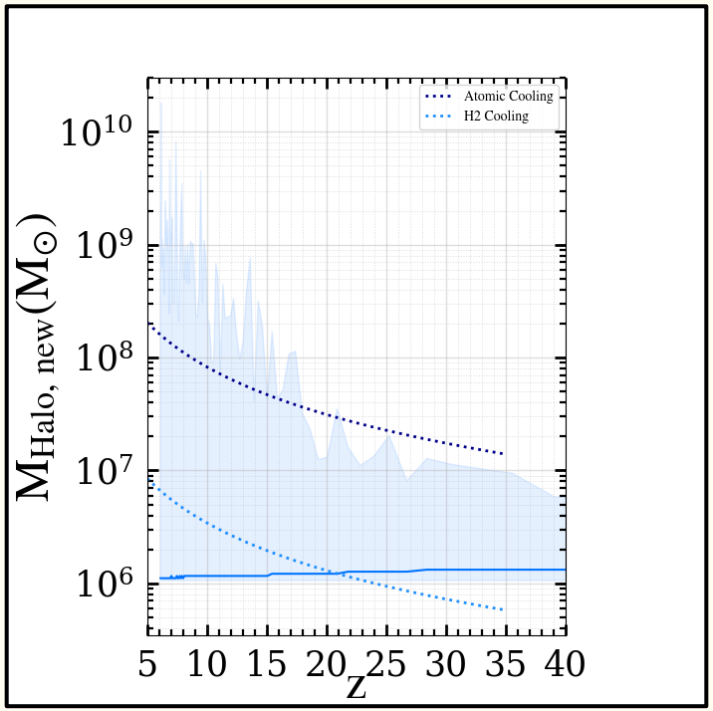
Millennium-*seeds*

I. Flores et al. – in prep.

- $M_{halo;min} = 10^6\ M_\odot$ (H2-cooling mini-halos)
- $6 < z < 127$
- $L_{box} = 32$ Mpc / h

Ideal to study PopIII star formation, light BH-seeds and early BH binaries





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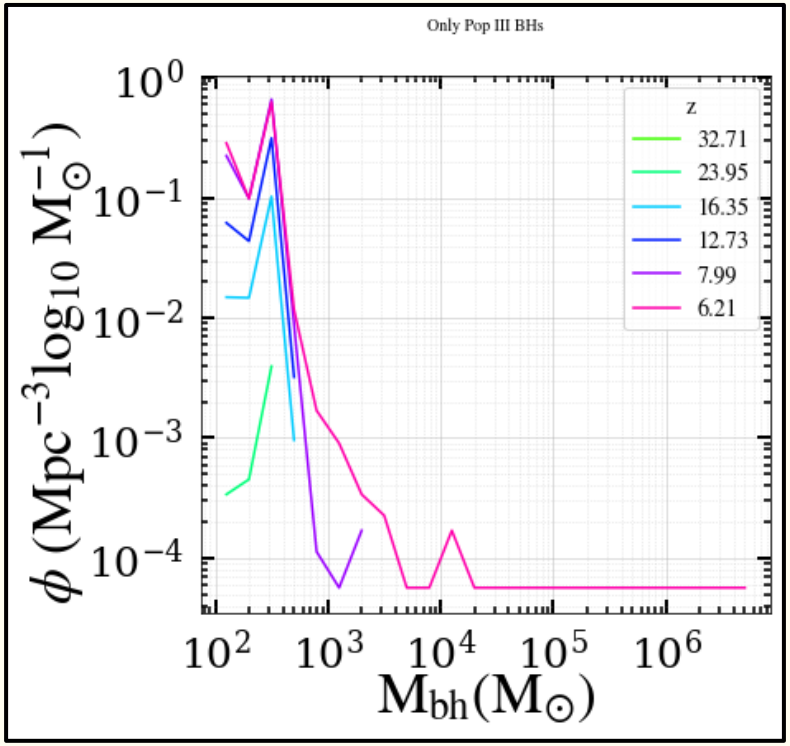
PRELIMINARY



- Larson IMF sampling for PopIII (with binaries…)
- M_{BH} up to ~10^6 $M_\odot$ at z~6 : high-z SMBHs may be difficult to explain only with light seeds
- Abundant population of MBHs at $z > 15$
- Possibility to track stellar BHs and binaries (i.e. possible ET sources) as they grow to become IMBHs and SMBHs (e.g. possible LISA sources)

Millennium-*seeds*

I. Flores et al. – in prep.

Potential applications to ET + LISA synergies

- Track BHs and their hots as they evolve at $z > 6$
- Explore the possibility that LISA events at "low" z originated from the same BH population which produced ET events at $z > 20$
- Predictions from contemporary, multi-band measurements of ET and LISA
- Breaking the degeneracy between BH-seeding and early growth
- Predictions for MBH spin distributions and the low-mass end of the MBH mass function