The Population of LISA MBHBs: What we have learned from simulations

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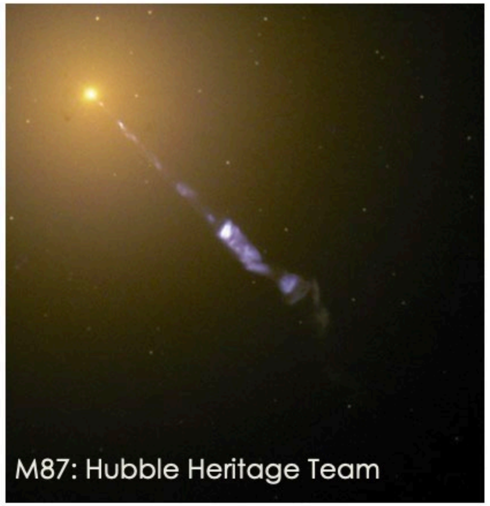
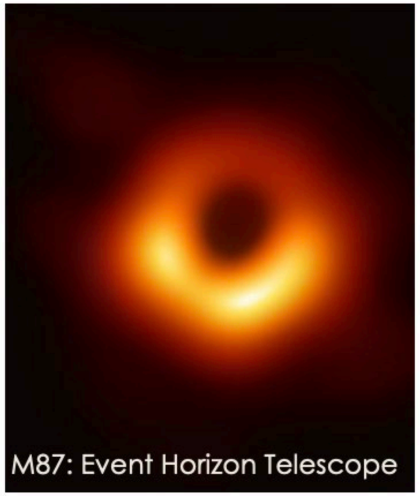
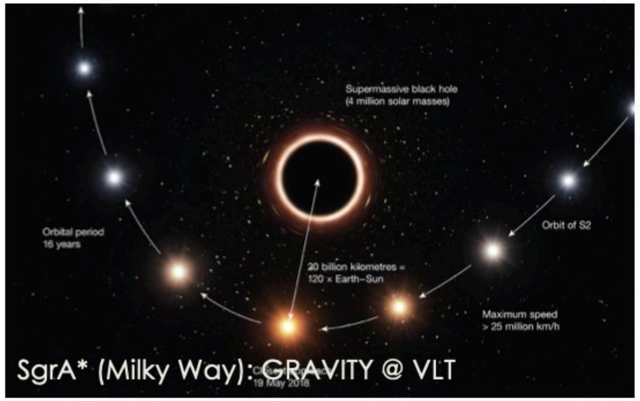
Massive Black Holes



M87: Hubble Heritage Team



M87: Event Horizon Telescope



SgrA* (Milky Way): GRAVITY @ VLT

What we know:

- Inhabit the centres of nearby galaxies, including the Milky Way
- Mass $> 10^4 M_\odot$ up to $\sim 10^{10} M_\odot$
- Power Active Galactic Nuclei (AGN) and quasars when mass falls in

What we want to know:

- What's their origin?
- How do MBH grow in mass?
- How do MBHs pair and merge?

LISA observations will play a key role in addressing these questions.

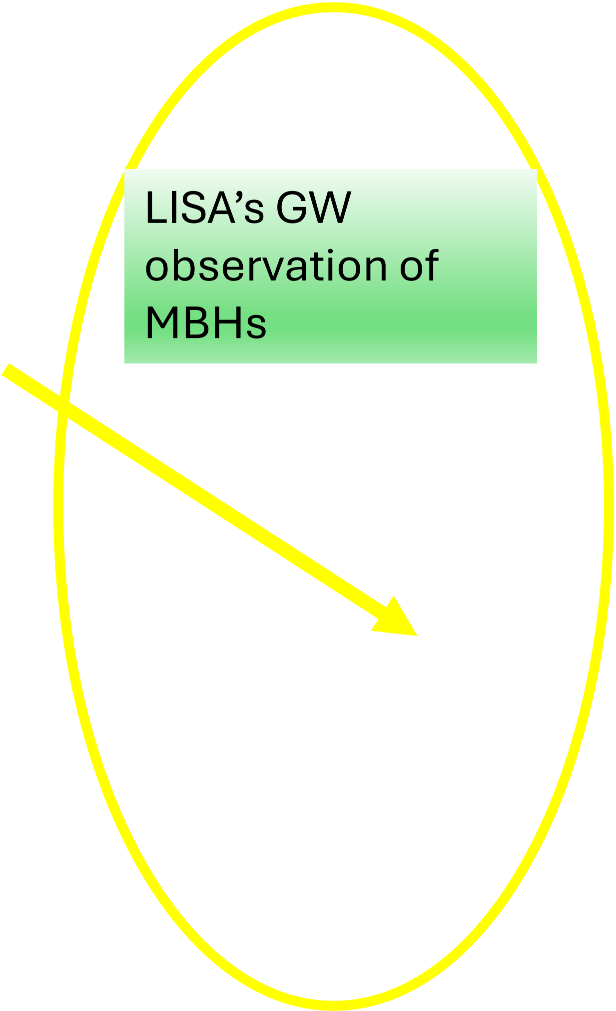
Massive Black Holes & LISA's Discovery Space

Peeks into the "life journey" of MBHs:

- MBHs grow through MBH mergers and accretion

LISA for ESA Cosmic Vision, Amaro Seoane+13; LISA RedBook, Colpi+2024

Massive Black Holes & LISA's Discovery Space



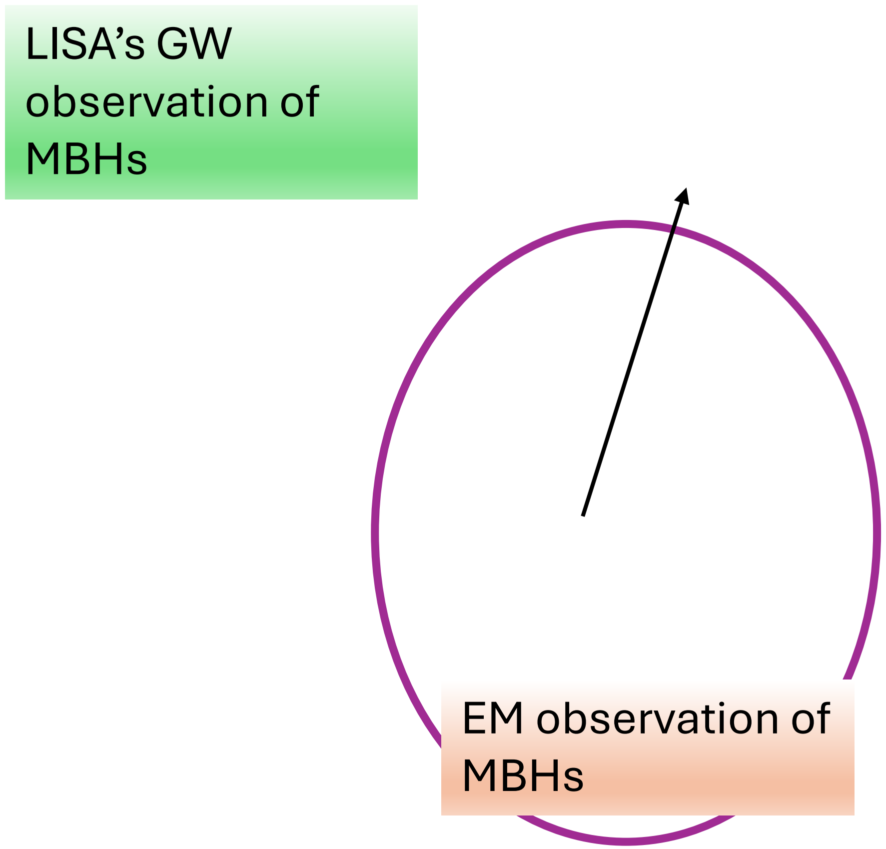
Peeks into the "life journey" of MBHs:

- MBHs grow through MBH mergers and accretion
- Mergers : as MBHs evolve, they sweep through the LISA band frequency

LISA makes observation of high-z and lighter MBHs possible

LISA for ESA Cosmic Vision, Amaro Seoane+13; LISA RedBook, Colpi+2024

Massive Black Holes & LISA's Discovery Space



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- MBHs grow through MBH mergers and accretion
- Mergers : as MBHs evolve, they sweep through the LISA band frequency
- Accretion : complementary EM observations

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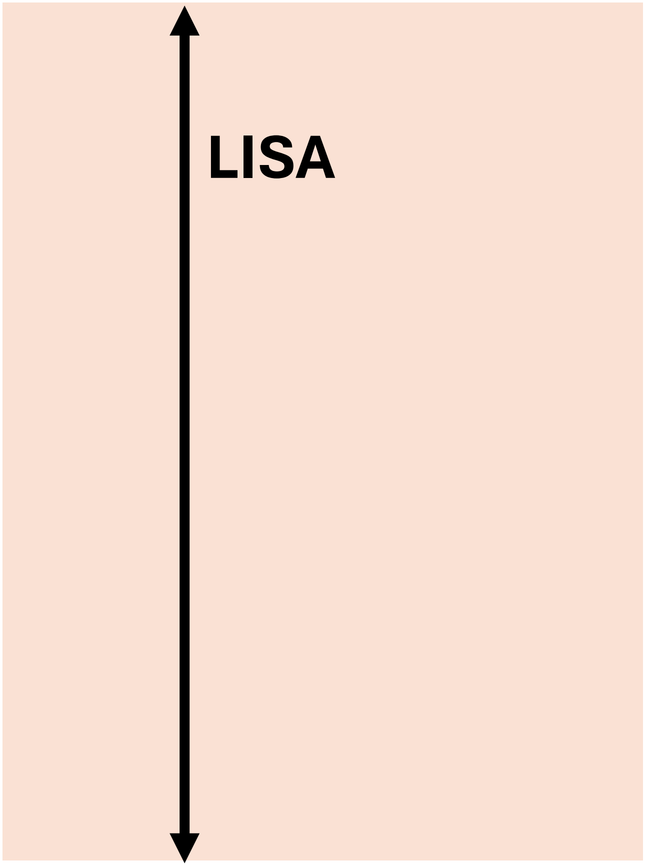
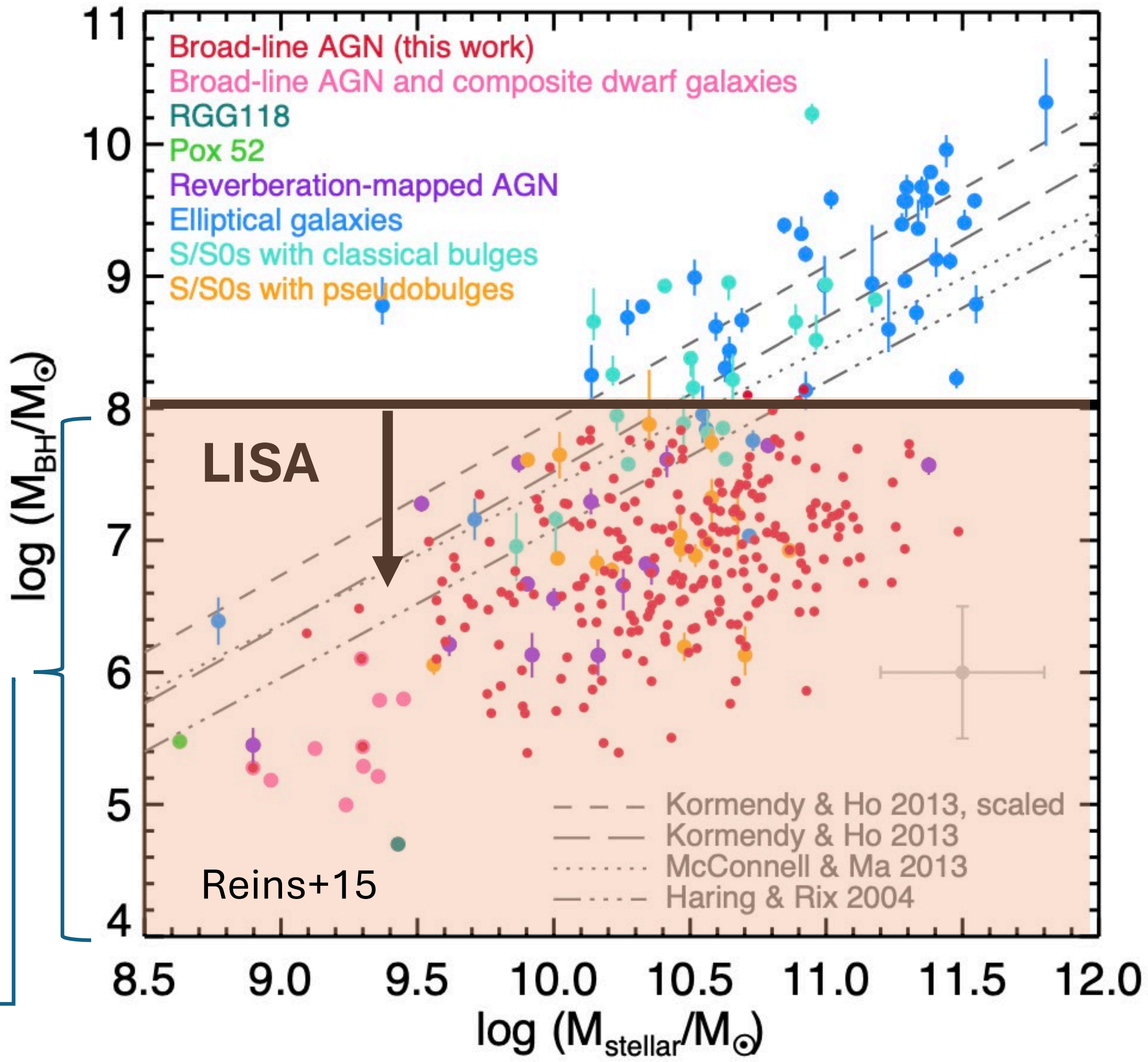
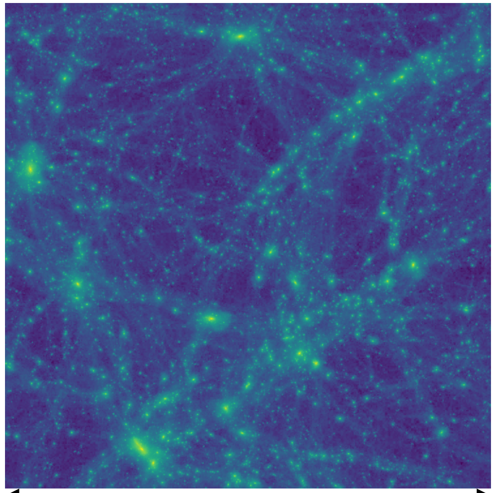
Peeks into the high-z “childhood” of MBHs: Intermediate-mass MBHs in low-z dwarfs :





LISA MBHs

MBH mergers: the journey of two MBHs

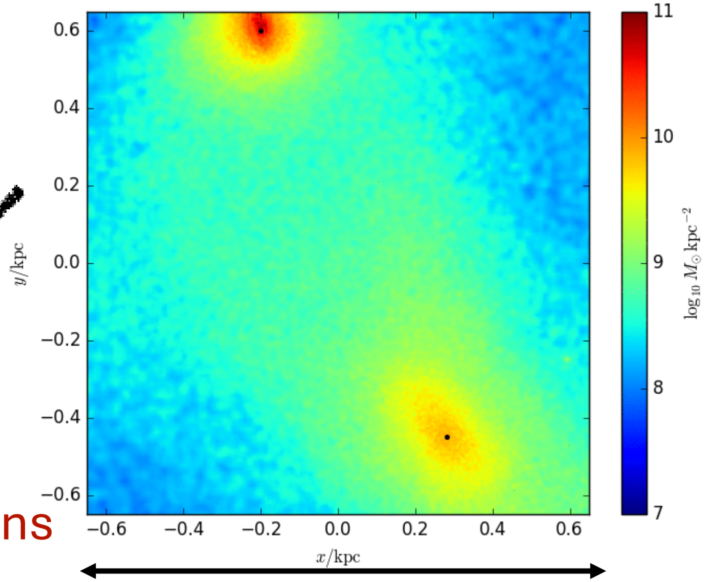


~100 Mpc (cosmology)

Gravity

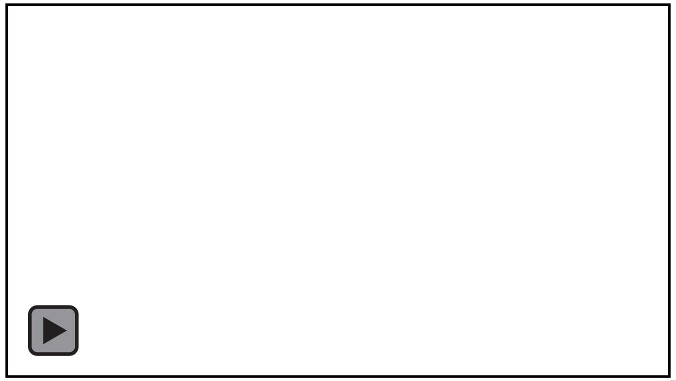
~100 kpc -1 kpc (galaxy mergers)

Dynamical Friction



~1 kpc-1pc (binary formation)

Gas torques
Stellar scattering
Triple-MBH interactions



~1 millipc(BH merger)

Courtesy of Hugo Pfister

Simulating MBH Mergers in the Universe

Theoretical models pros and cons:

Empirical models

- Populate DM halos with galaxies and MBHs
- Ensemble population information compared to (many!) observables to find how population evolves

Haehnelt 94; Padmanabhan & Loeb 20; Zhang + 22; Soltan 1982; Small & Blandford 1992; Cavaliere & Vittorini 2000; Yu & Tremaine 2002; Steed & Weinberg 2003; Marconi et al. 2004; Yu & Lu 2004; Merloni & Heinz 2008; Shankar et al. 2009, 2013; Aversa et al. 2015; Tucci & Volonteri 2017; Conroy & White 2013; Caplar et al. 2015, 2018; Yang et al. 2018; Comparat et al. 2019; Geor- gakakis et al. 2019; Carraro et al. 2020; Shankar et al. 2020a,b; Al- levato et al. 2021, etc etc.

Semi-analytical models

- Make simplified assumptions of baryonic structures evolution in DM halos merger trees assuming analytical expression for evolution
- Fast, cover large parameter space, & able to statistically explore how different physical assumptions affect the global population while losing some self-consistency
- Lack spatial information, can only use simplified analytical functions

Begelman +1980; Izquierdo-Villalba+20; Dayal+19; Trinca+22; Sesana+ 05,11a; Fanidakis+11; Volonteri+03a, 05; Haiman +04; Tanaka & Haiman 09; Enoki +05; Tamanini +16; Croton+06; Lodato & Natarajan 06; Somerville+08; Volonteri +08b; Volonteri & Natarajan 09; Kauffman & Haehnelt +00, Hopkins & Quataert +10; Barausse +12, 20b; Miller & Krolik 13; Bonoli +14; Menci +14; Gatti +15; Gerosa +15b, 20; Klein +16; Ricarte & Natarajan 18a, b; Bonetti +19,21; Inayoshi +19; DeGraf + 20; K.Li +20a, 22; Kauffmann & Haehnelt 20; Marulli + 08; Shirakata + 19; Sayeb +20; Katz +20; Barausse +20b; Valiante +21; etc etc

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Numerical simulations

- Evolve the full hydrodynamics of the DM and baryonic structures simultaneously in a self-consistent way (down to resolution).
- Naturally include spatial information and can reach a high-level of complexity
- High computational costs

Quinlan & Hernquist 97; Teyssier +02; Yu +02; Escala +05; Berczik +06; Dotti +07; Rezzolla +08; Cuadra +09a; Amaro-Seoane +10b; Lousto + 10;Khan +13; Dubois +14b, 15; 20, 21; Taylor & Kobayashi 14; Hirschmann +14; Gerosa +15a; Tremmel +15; Sesana +15; Sijacki +15; Springel +15 ; Schaye +15; Bonoli +16; Khan + 16; Volonteri +16; Salcido +16; Habouzit +17; Tremmel +17; Rantala +17; Kelley +17b; Bortolas +18, 20; ;Dunn +18; Ryu +18; Tremmel +18b; Fiacconi +18; Hopkins +18; Bellovary +19; Bustamante & Springel 19; Pfister +19; Pillepich +19; Davé +19; Cenci +20; Volonteri +20; DeGraf & Sijacki 20; Regan +20a; Chen +21; Sala +21; Zwick +21; Mannerkoski +23; Dong-Páez +23; Liao +24b;K. Li +24 etc etc

Simulating MBH Mergers in the Universe

Theoretical models pros and cons:

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Simulating MBH Mergers in the Universe

- Trade-off due to limited computational resources

  You got to choose between:

  - Cosmological simulations with large volume/ many objects/ low resolution: massive galaxies
  - Cosmological zoom-in simulations with small volume/ few objects/ high resolution: dwarf galaxies

Come on, you got to pick just one!

Large volume

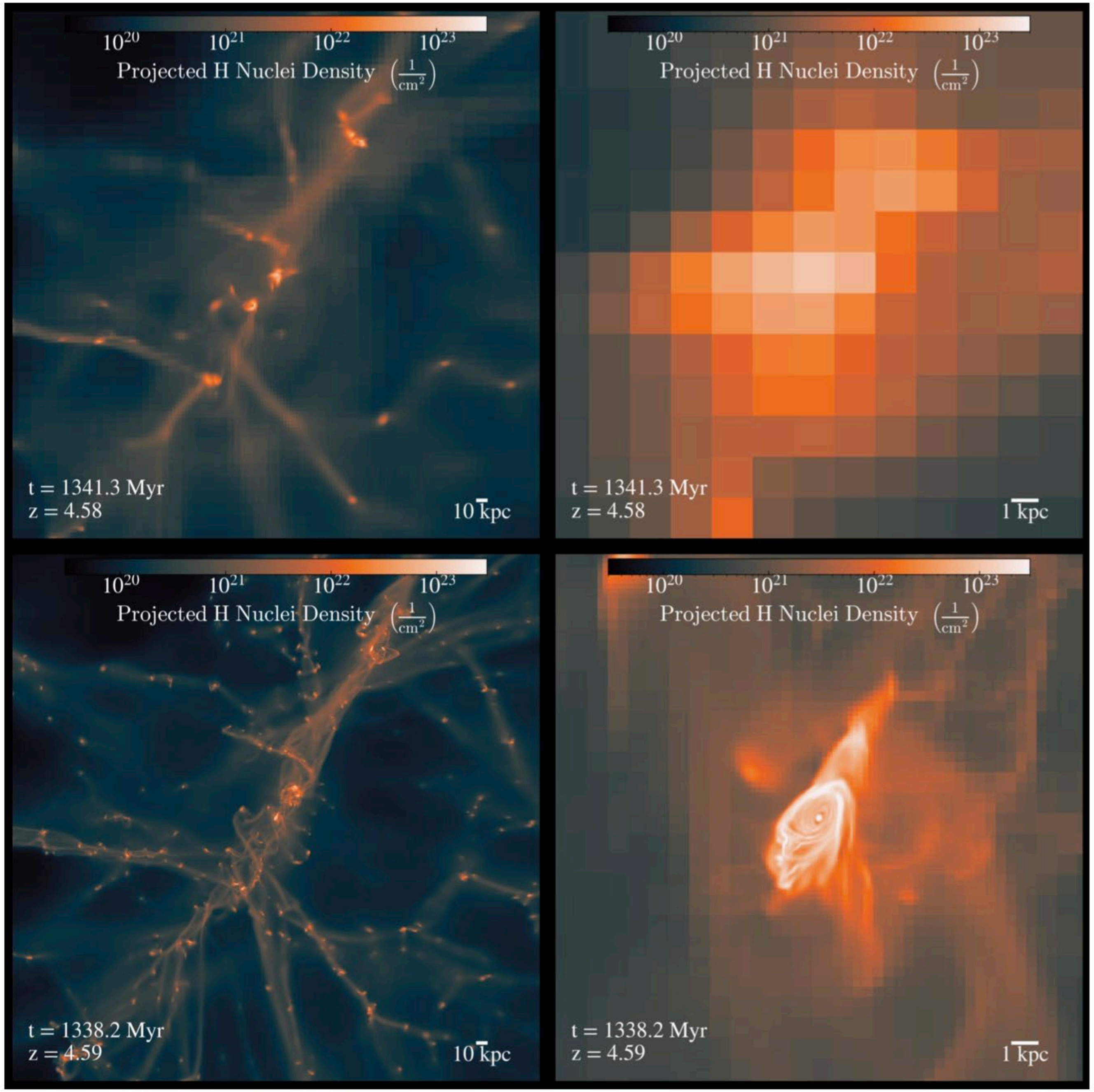
Box: 140 Mpc^3
Resolution: 1 kpc

(HorizonAGN
Dubois +14)

High resolution

Box: 15 Mpc^3
Resolution: 30 pc

(Obelisk
Trebitsch +21)



Trebitsch+21

Simulating MBH Mergers in the Universe

- **Limited computational resources**

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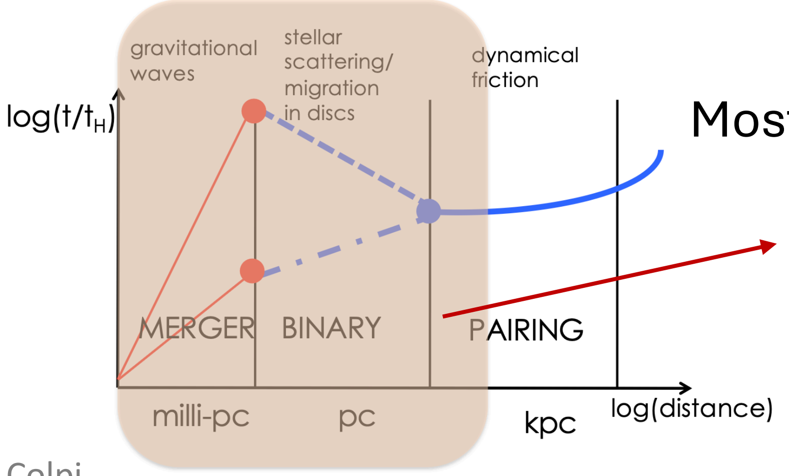
  - Zoom-in simulations with small volume/ few objects/ high resolution: dwarf galaxies

- **Resolution as the bottleneck:**



Most cosmological simulations have a resolution of ~100 pc-1 kpc

Cannot resolve the late evolution of mergers

Numerical mergers + post-processing approach leads to uncertainties.

Credit: Monica Colpi

Dynamics & MBH Mergers

KETJU (e.g., Mannerkoski+19,20,21,23;)

The main idea in KETJU is to add small spherical regions centred on the MBHs, where the dynamics are integrated using a high-accuracy integrator

Tracks the interaction with stars to high-level accuracy

- Dynamical friction and hardening of MBHB from interactions with stellar particles are directly captured.
- Post-Newtonian dynamics of MBHBs, such as orbital decay from GW emission and precession of the orbit.

RAMCOAL (Li, Volonteri+24)

A sub-grid model integrated in adaptive mesh refinement code RAMSES:

Track the orbit of MBHB to coalescence in galaxy simulation on-the-fly

RAMCOAL

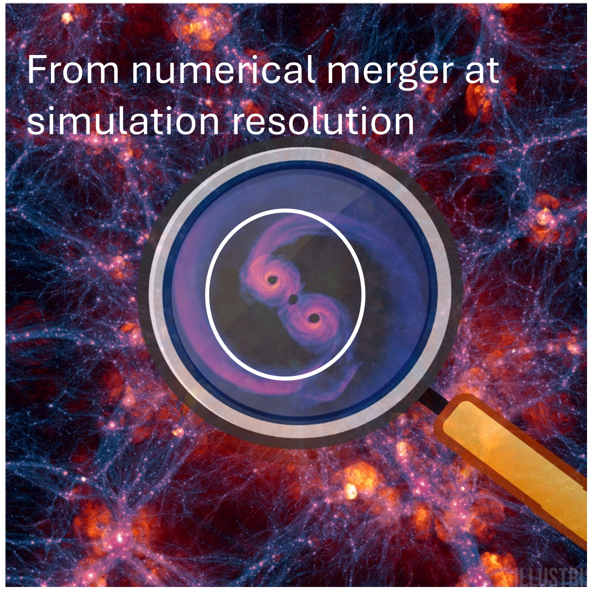
Highly complementary

RAMSES

Brings MBHs to resolution limit

RAMCOAL

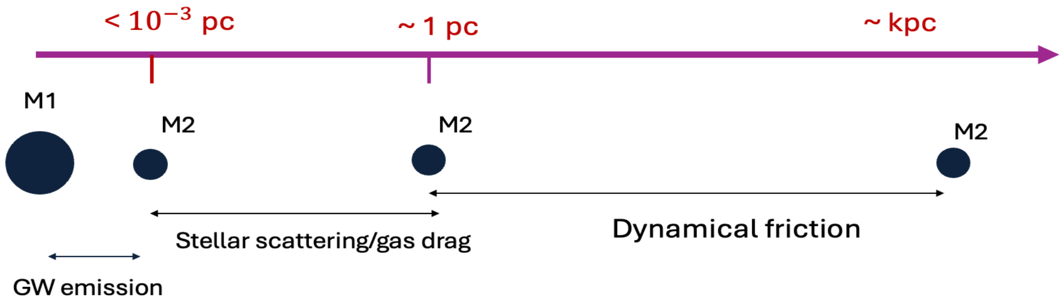
simulates the orbital evolution of MBHBs to coalescence



- Dynamical friction: Gas, star, DM
- Radiation feedback effect on gas dynamical friction
- Loss-cone scattering
- Viscous drag in circumbinary disk
- GW emission
- Binary accretion & AGN feedback
- Spin evolution and recoils
- MBH triplets (coming soon!)

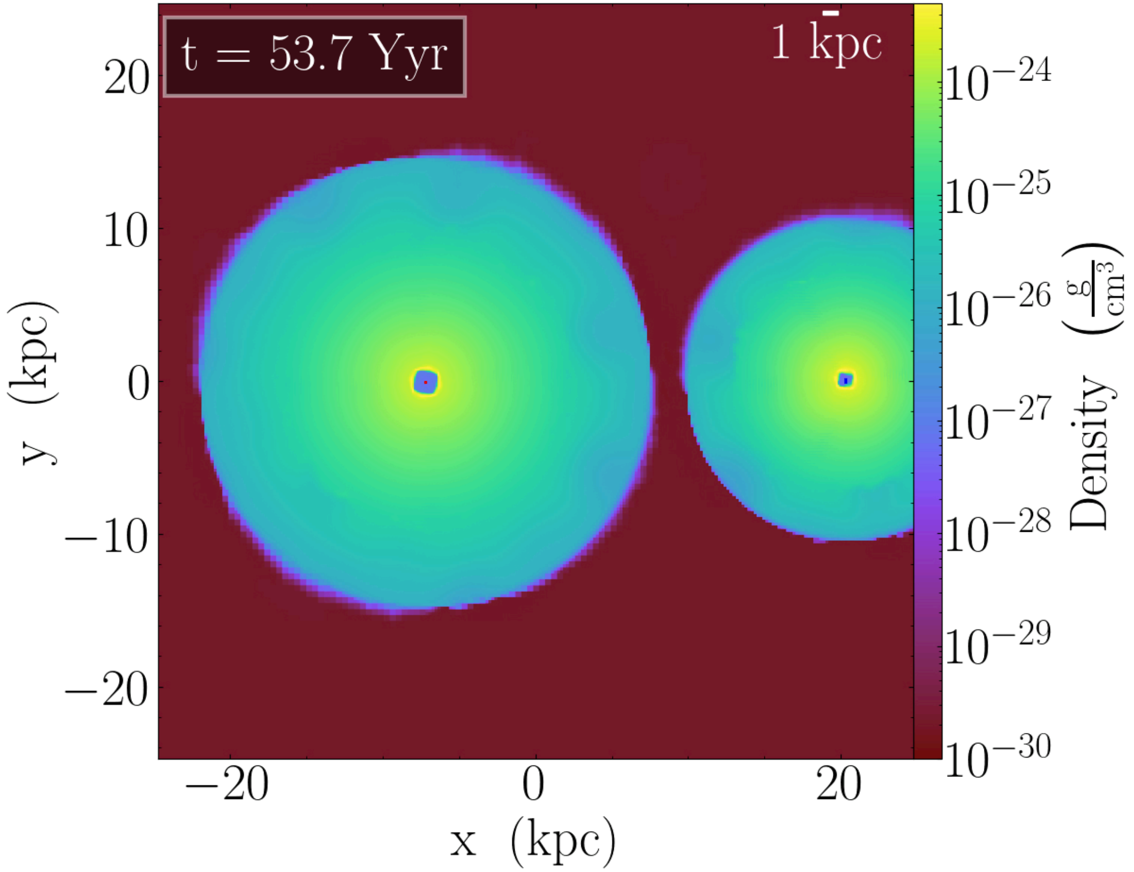
RAMCOAL tracks the real-time evolution of MBHBs in hydrodynamical simulations within their environment in real time to avoid uncertainties in post-processing

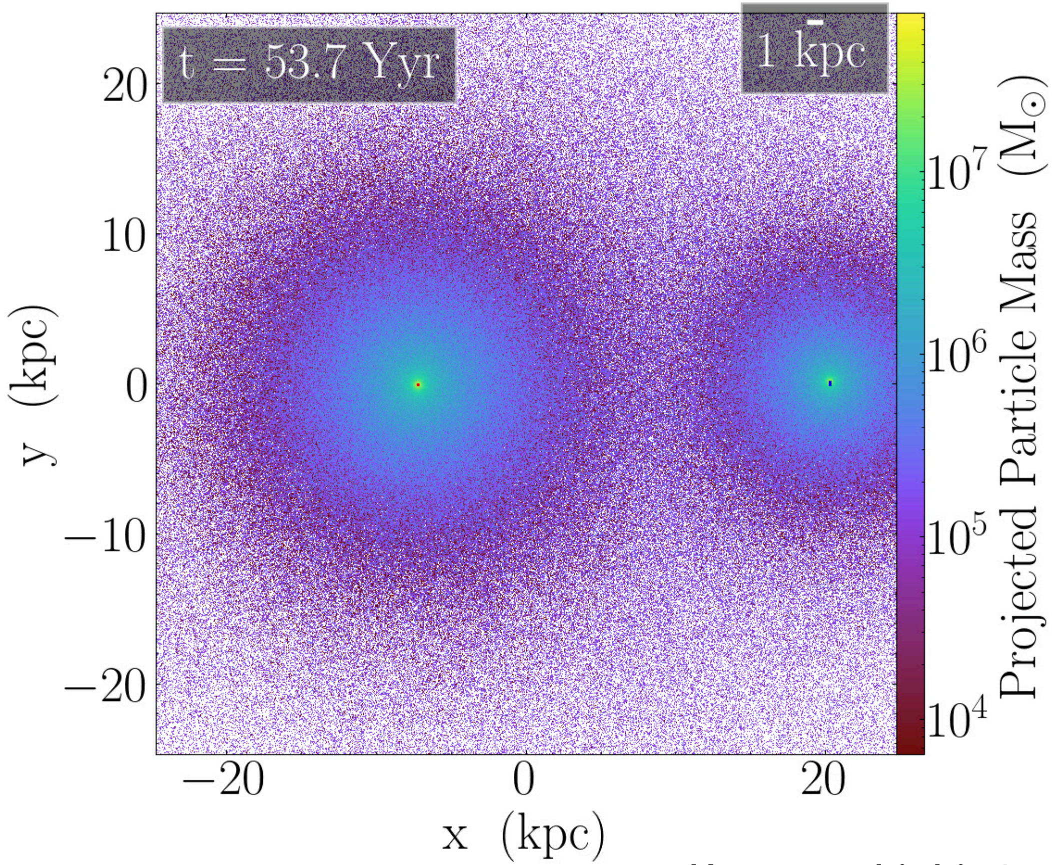
Simulating orbital evolution of MBHB to coalescence on-the-fly!



Example RAMCOAL simulation of galaxy merger at 100pc resolution:

RAMCOAL





Kunyang Li; Li+24, arXiv:2410.07856

The galaxy merger and coalescing trajectory of both MBHs on top of the gas (left) and stellar density (right).

Modelling MBH evolution

Quick overview: the formation of MBHs (aka, seeding/seeds), their early growth, their mergers which will be very important for LISA

Different Lifes of MBH Seeds: seeding mechanisms are still unconstrained

Continuum

Type	Origin	Mass	Frequency	Growth
Small	Remnants of the first stars	~10-100 M_{sun}	Common ~ 0.1-10 Mpc^{-3}	Difficult
Medium	Mergers of stars or stellar BHs/Dynamical heating	~1e3-1e4 M_{sun}	Relatively common ~ 1e-5-0.01 Mpc^{-3}	Intermediate
Large	Supermassive stars/LW>1000 J_{crit}	~1e5-1e6 M_{sun}	Rare: <1e-5 Mpc^{-3}	Easy
Exotic	Primordial Black Holes	Unknown (< 1e6 M_{sun}?)	CMB/XRB: <1e-3 Mpc^{-3} for M>1e4 M_{sun}	Unknown

see MV, Habouzit, Colpi 2021 for a compact review and Regan& MV 2024 for an update

Different Lifes of MBH Seeds:

Key takeaways/points for discussion:

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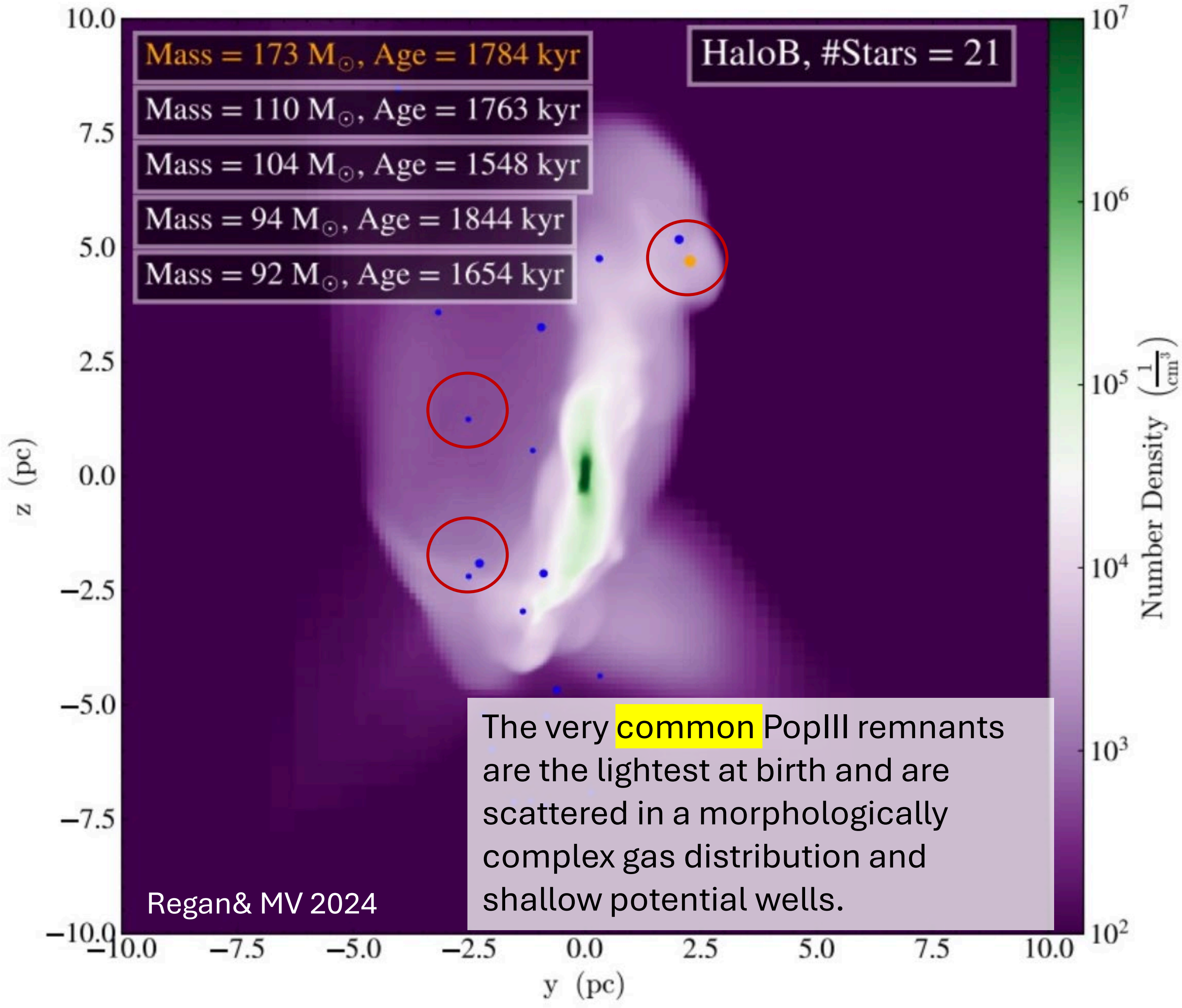

The very common PopIII remnants are the lightest at birth and are scattered in a morphologically complex gas distribution and shallow potential wells.

Growth
Difficult
Intermediate
Easy
Unknown

ın update

Key takeaways/points for discussion:

Natural process
What's their IMF?
Able to grow?

Different Lifes of MBH Seeds:

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Continuum

Natural process
Lots of BHs around
Initial mass function? Able to grow?

see MV, Habouzit, Colpi 2021 for a compact review and Regan& MV 2024 for an update

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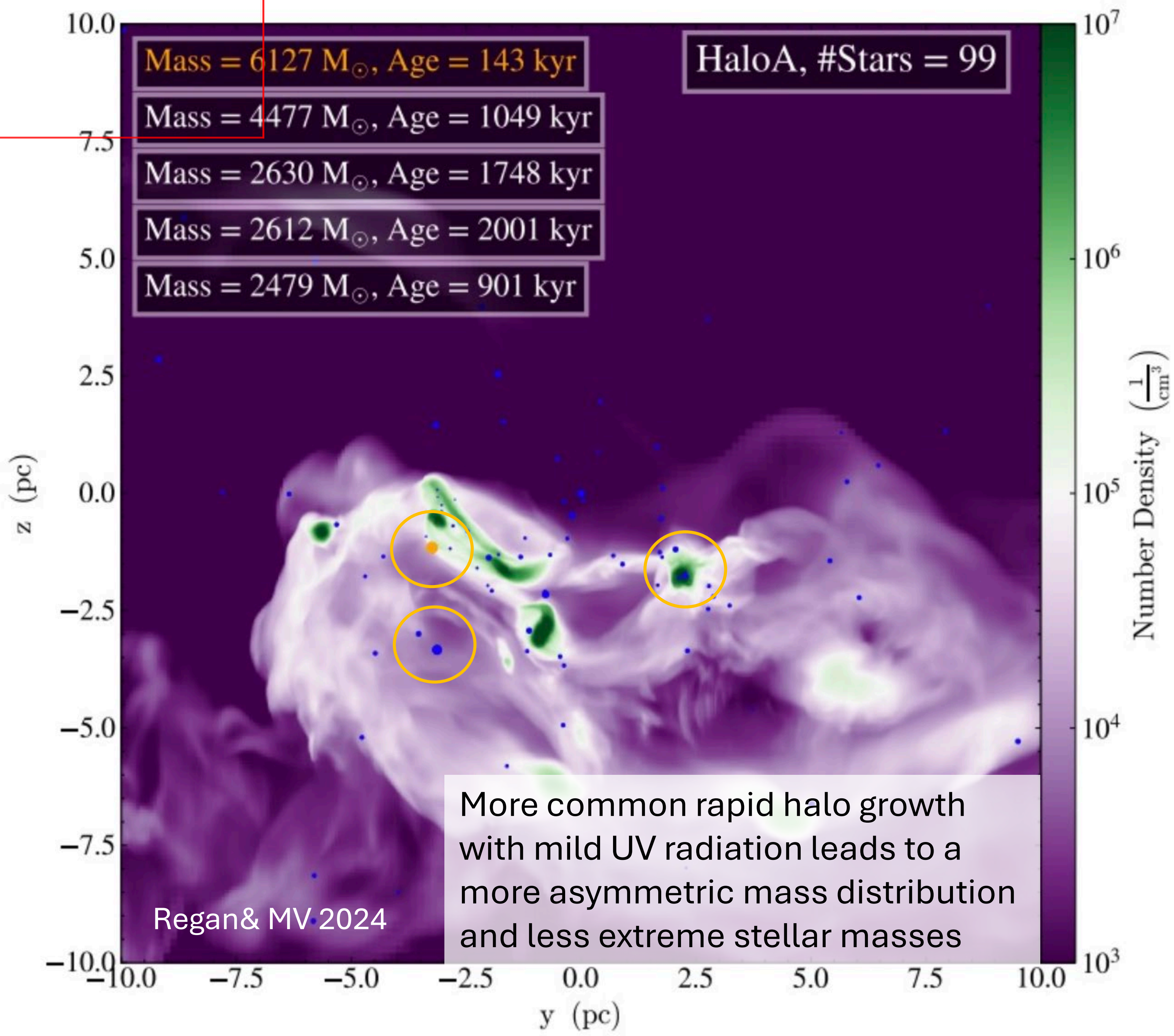
Continuum



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How common?
Few explorations in the cosmological context.

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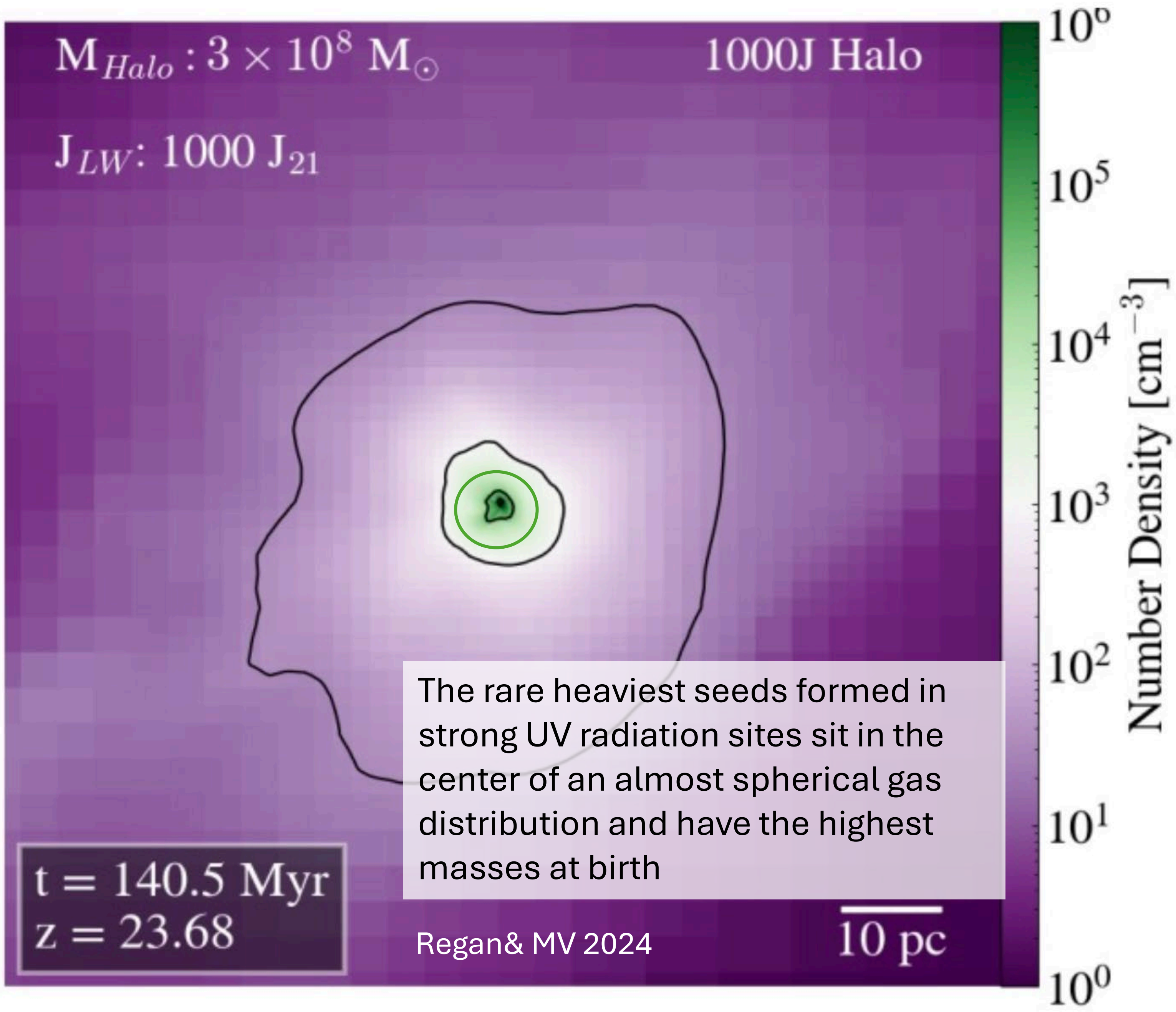


The rare heaviest seeds formed in strong UV radiation sites sit in the center of an almost spherical gas distribution and have the highest masses at birth

Growth
Difficult
Intermediate
Easy ?
Unknown

ın update

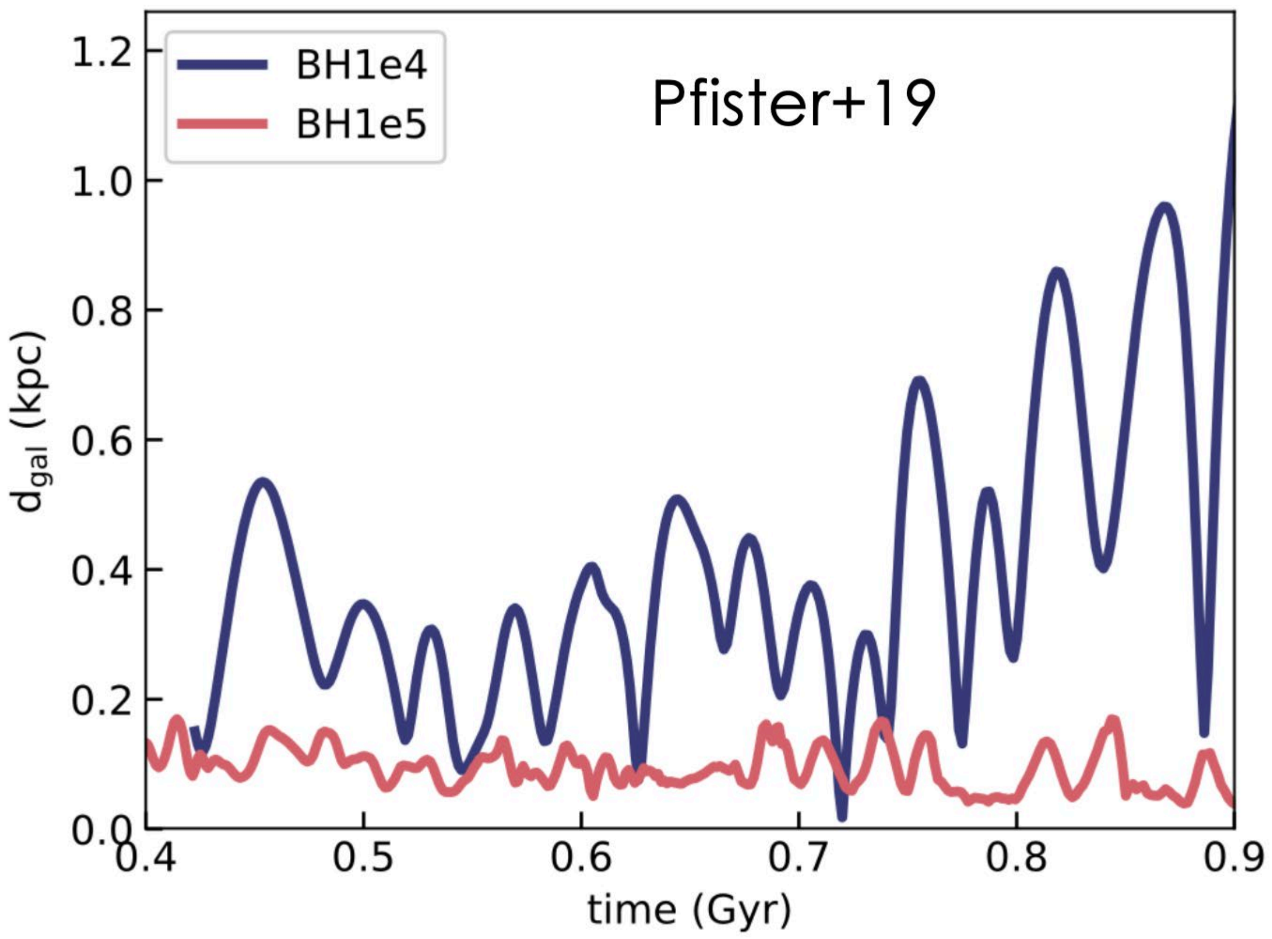
Key takeaways/points for discussion:

Natural process. Lots of BHs around Initial mass function? Able to grow?

Natural process. How common? Few explorations in the cosmological context.

Natural process? Enough BHs around?

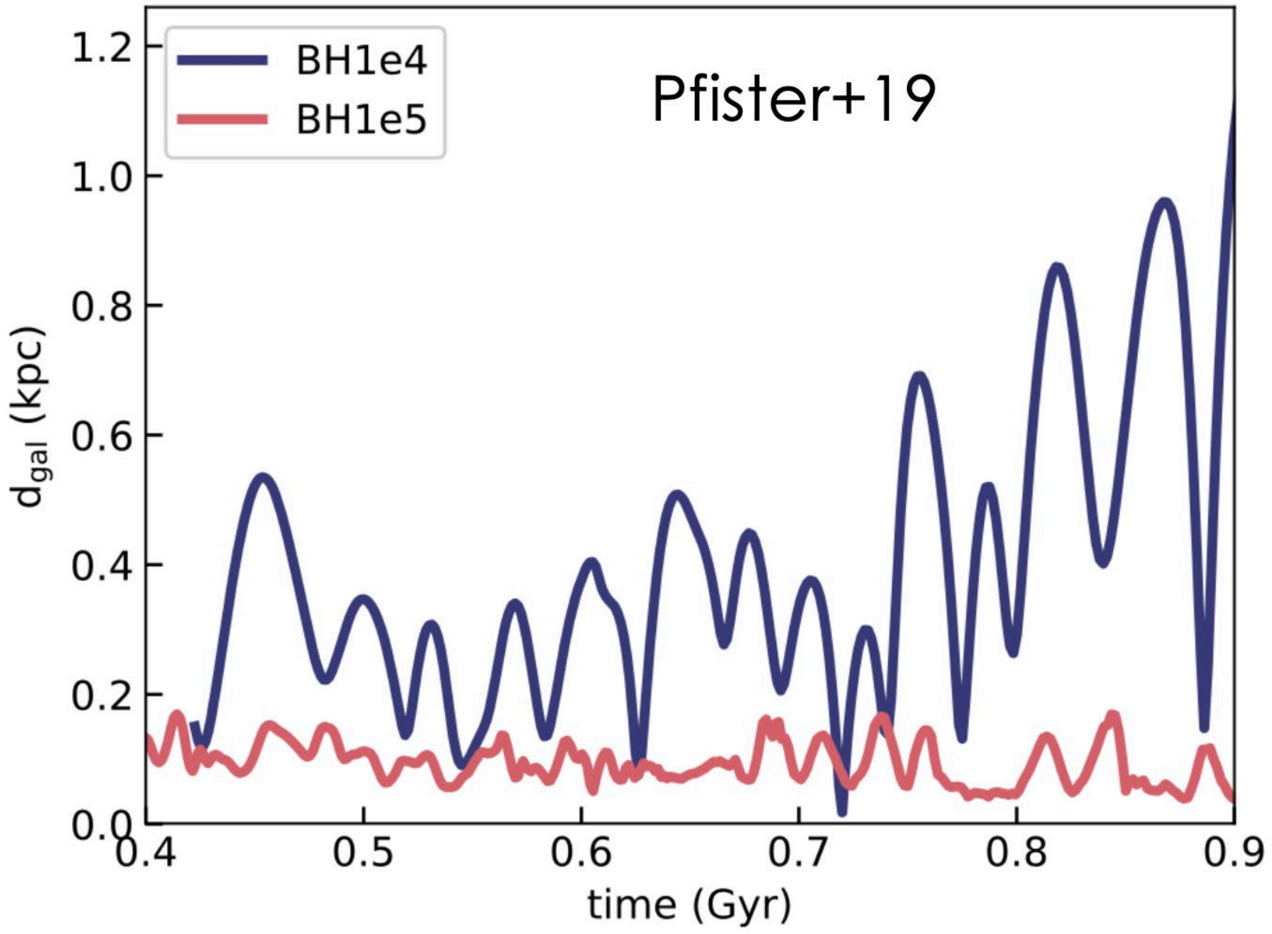
Erratic dynamics in shallow potential wells of high-z galaxies



IMBHs in high-z dwarf galaxies hard to sink via DF due to their messy, shallow, time-variable potentials:

IMBHs not growing

Erratic dynamics in shallow potential wells of high-z galaxies



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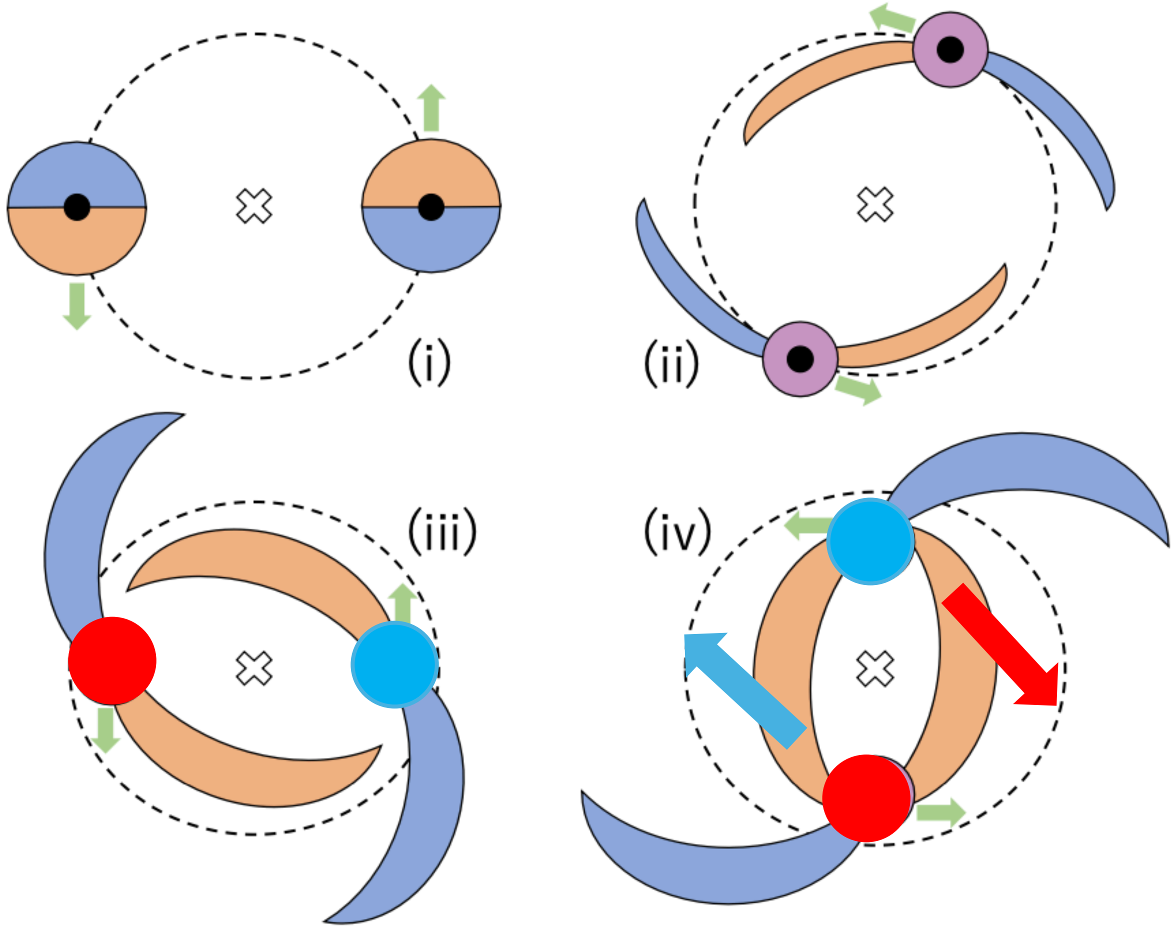
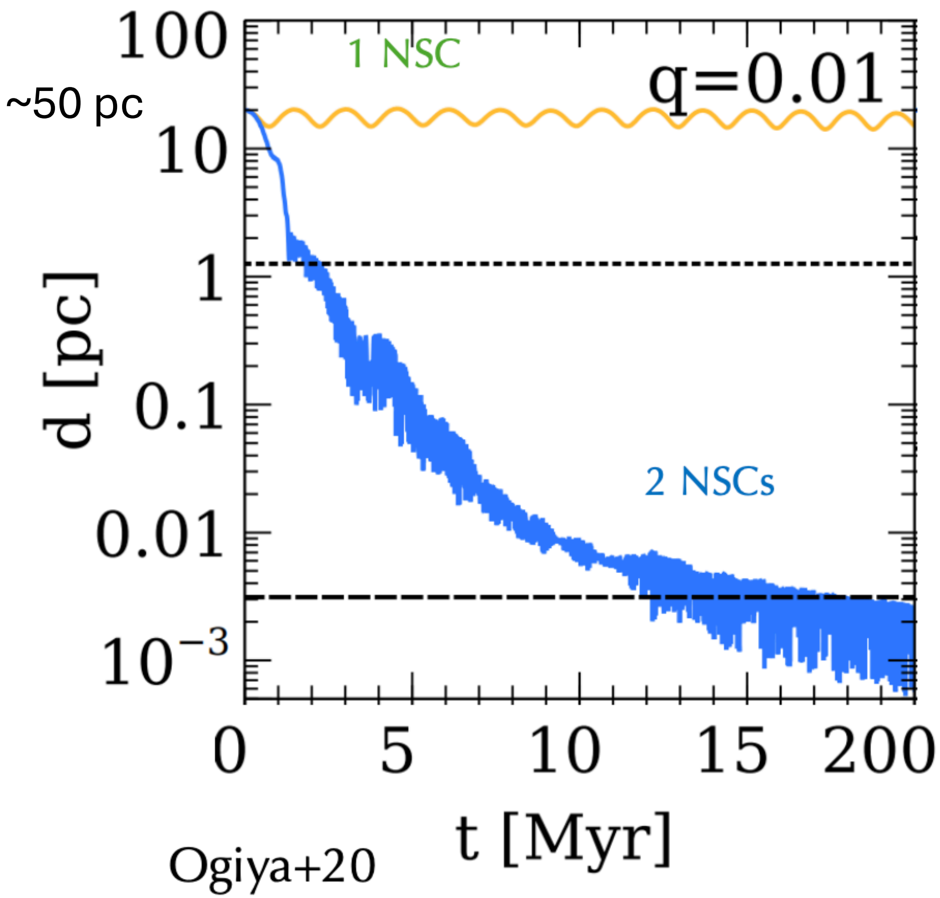
BUT!

Nuclear star clusters at the rescue!

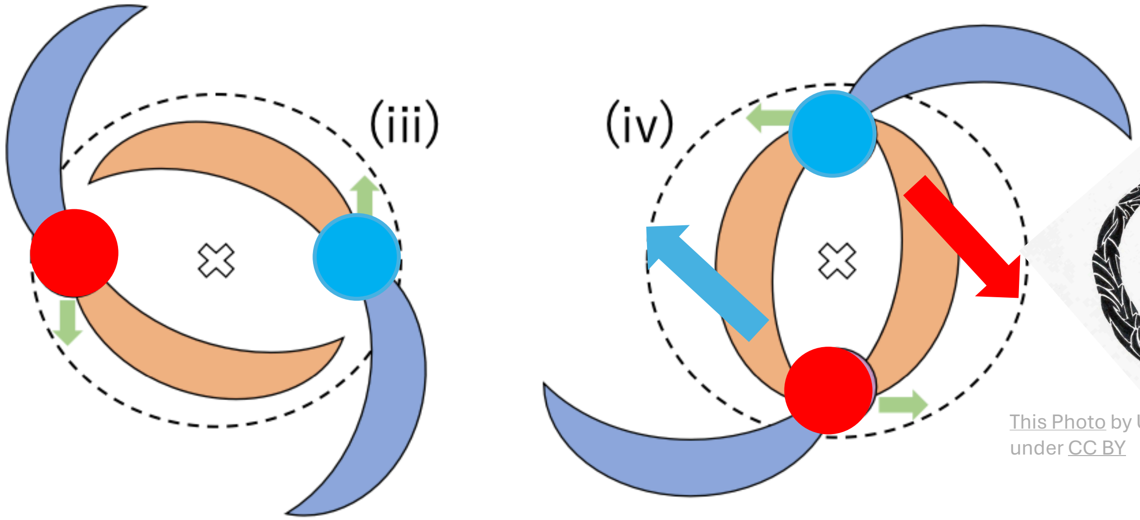


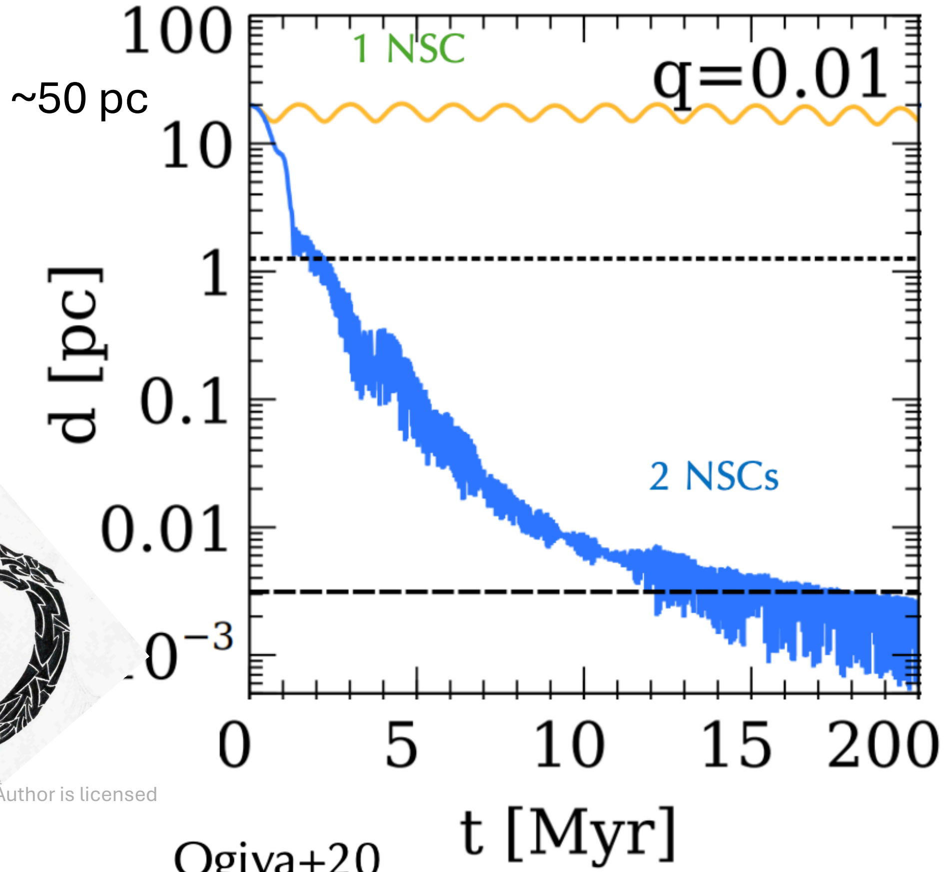


Stars stripped from one nucleus provide additional dynamical friction and speed up subsequent hardening ("Ouroboros Effect", Ogiya+20)

Nuclear star clusters at the rescue!

Stripped stars in leading arm of the NSC attaches to and decelerates the companion NSC's MBH, so that the binary NSCs appear like a pair of snakes biting each other's tail. ("Ouroboros Effect", Ogiya+20)





Ogiya+20

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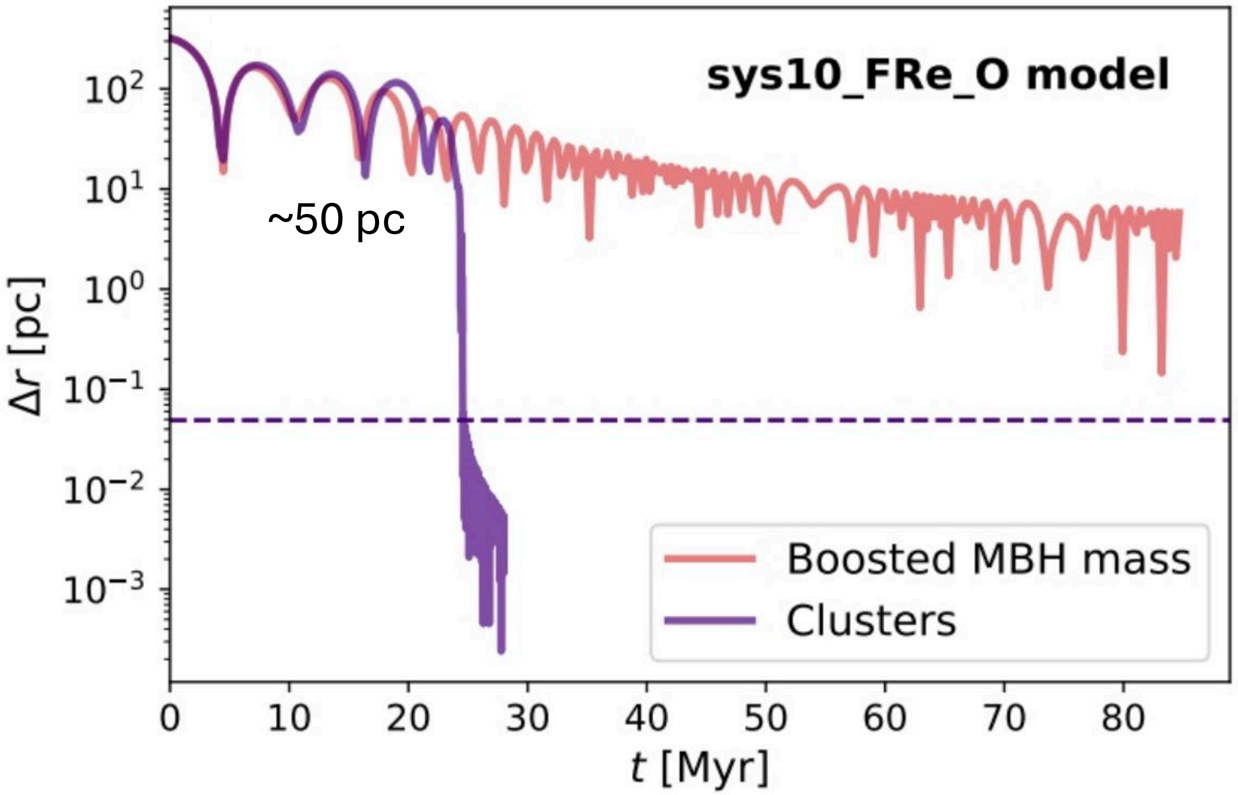
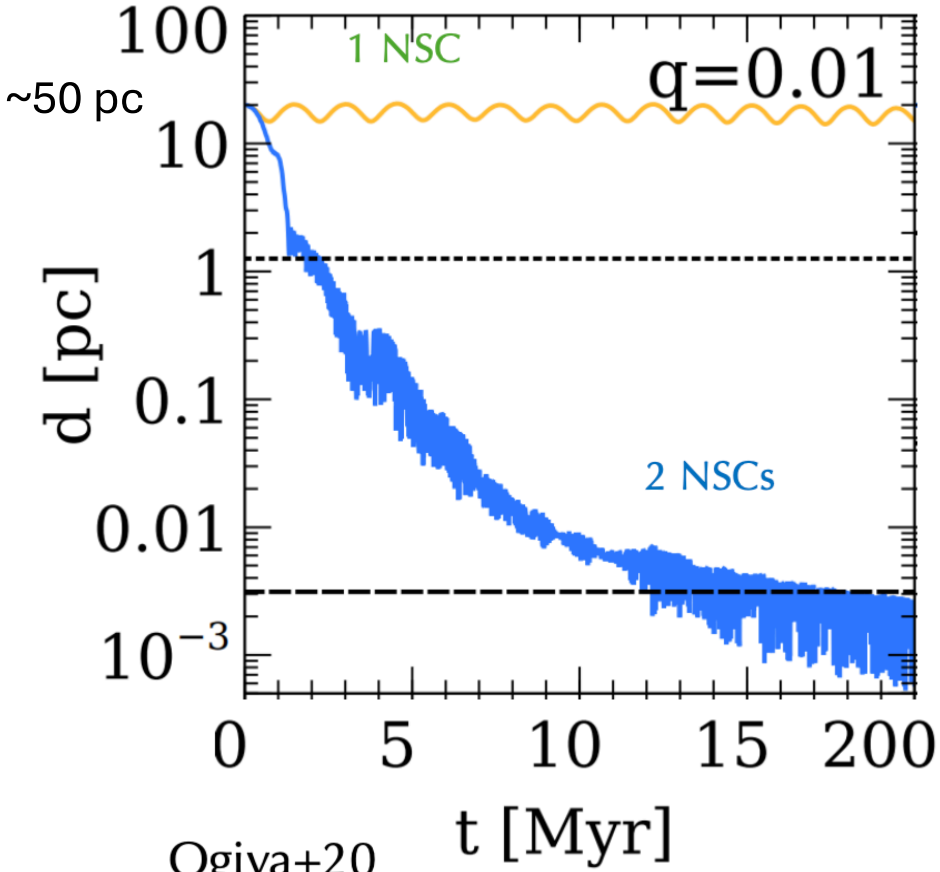


Mukherjee+24

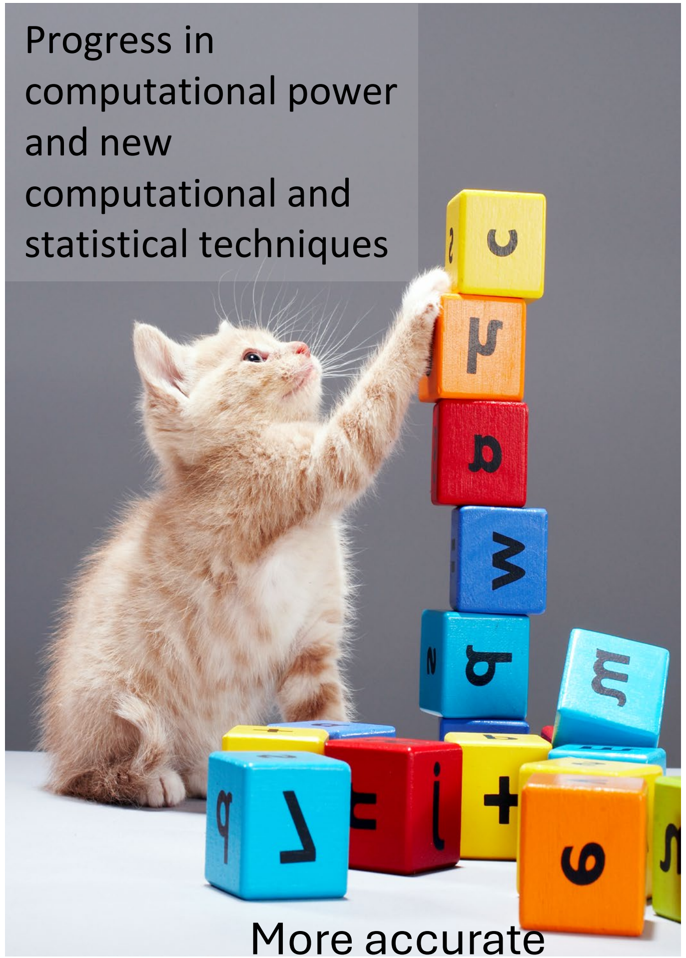


Ogiya+20

The tidal interaction triggered by 2 stellar clusters generates torque and accelerate the sinking of MBHs.

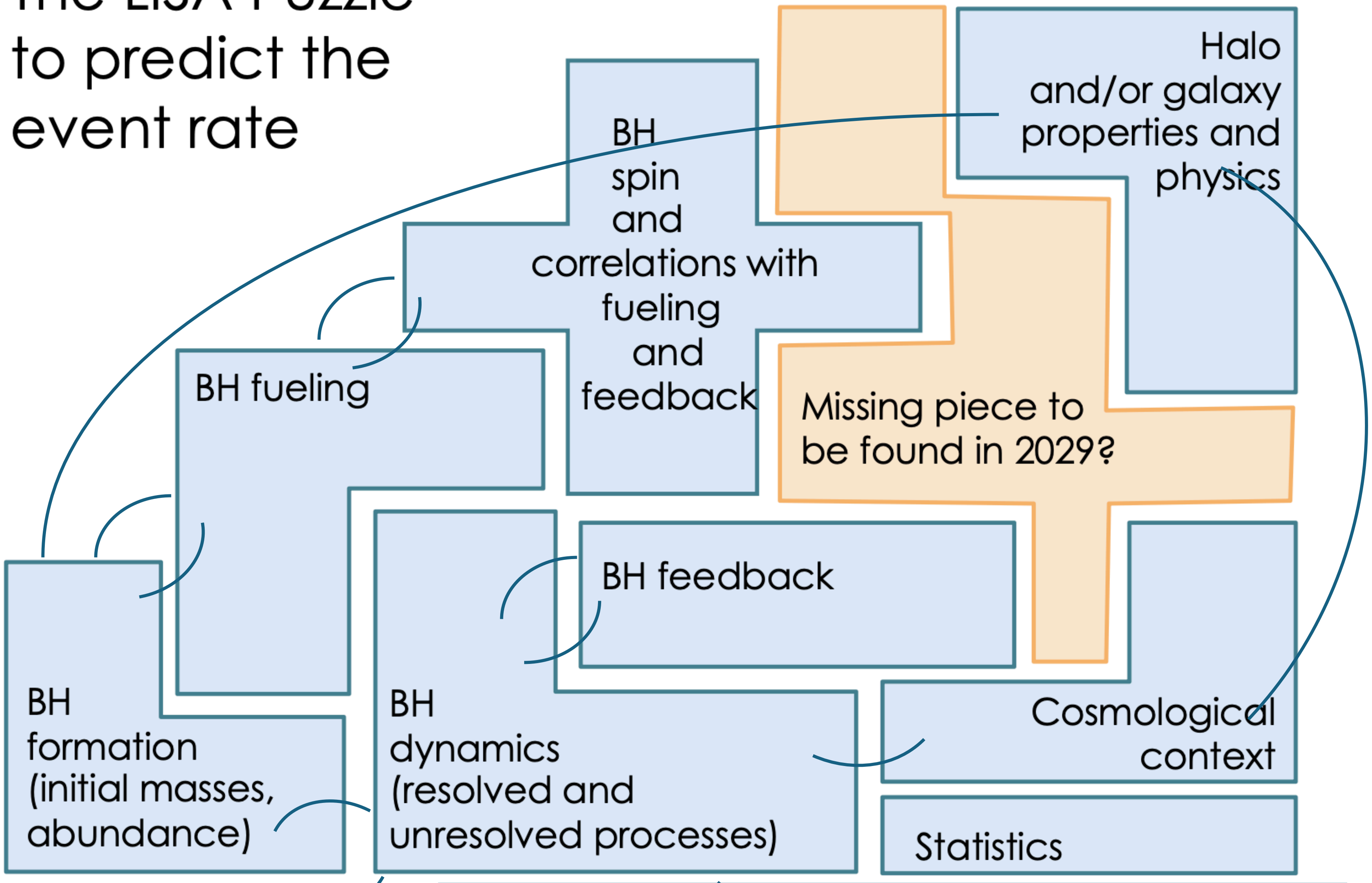
What we leant:

Progress in computational power and new computational and statistical techniques



More accurate and flexible models

The LISA Puzzle to predict the event rate



Slide credit: M. Habouzit

Variety of non-linear physical processes and wide scales & interplay between them results in uncertainties in LISA merger rate predictions

Summary:

- Rich LISA science with MBHBs and mergers
- LISA's MBHs expected (relatively) faint: $10^4 M_\odot \sim 10^7 M_\odot$ MBHs in $10^8 M_\odot \sim 10^{10} M_\odot$ galaxies out to z>>3
- LISA will put more constrains on MBH seeding mechanisms
- A focal point of simulations in the next decade will be to accurately model the assembly of galaxies including modelling the environments, in a cosmological context, in which different MBH seeds can form, and evolve under precise MBH dynamics.
- The use of high-resolution and relatively large-scale numerical simulations with MBH formation and small-scale dynamics prescriptions will be needed to break the current degeneracies between models.

Summary:

Thank you!

- Rich LISA science with MBHBs and mergers
- LISA's MBHs expected (relatively) faint: $10^4 M_\odot \sim 10^7 M_\odot$ MBHs in $10^8 M_\odot \sim 10^{10} M_\odot$ galaxies out to z>>3
- LISA will put more constrains on MBH seeding mechanisms
- A focal point of simulations in the next decade will be to accurately model the assembly of galaxies including modelling the environments, in a cosmological context, in which different MBH seeds can form, and evolve under precise MBH dynamics.
- The use of high-resolution and relatively large-scale numerical simulations with MBH formation and small-scale dynamics prescriptions will be needed to break the current degeneracies between models.

Extra slides

LISA & MBH seeds

Hear the “baby cries” of MBHs:

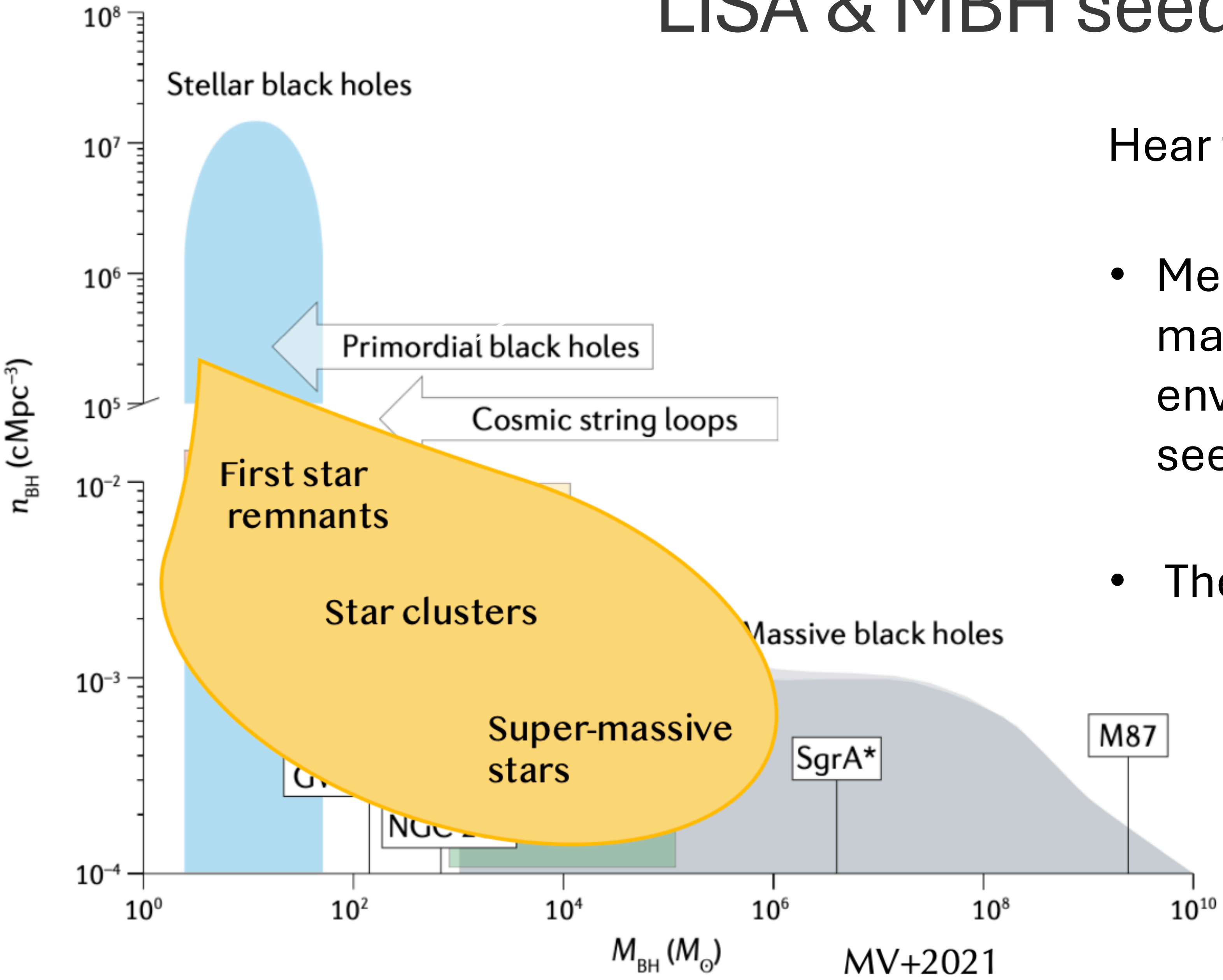
- Mechanisms predict different seed mass, time of formation, environment and abundance of MBH seeds

- Lighter seeds are more ubiquitous

- Heavier seeds are less abundant

*primordial black holes and cosmic string loops are set at arbitrary number densities

LISA & MBH seeds



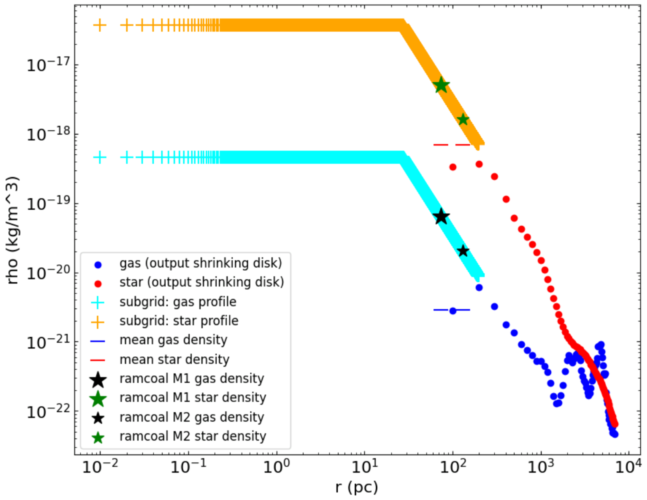
MV+2021

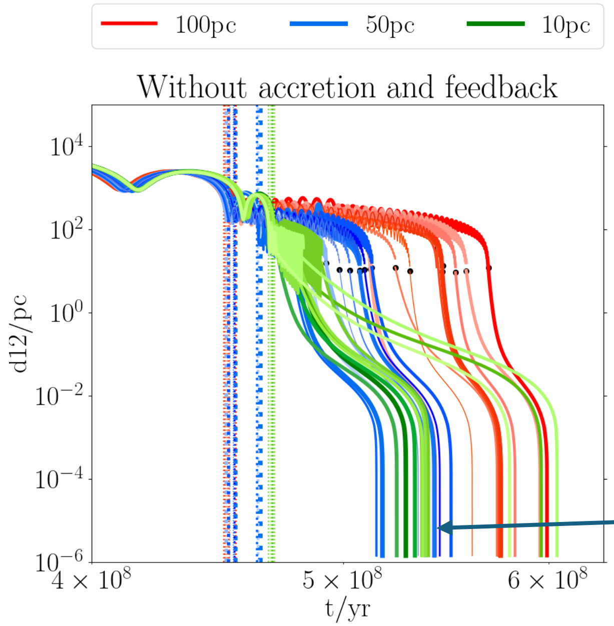
Hear the "baby cries" of MBHs:

- Mechanisms predict different seed mass, time of formation, environment and abundance of MBH seeds
- They're not mutually exclusive!

*primordial black holes and cosmic string loops are set at arbitrary number densities

Dynamics & MBH Mergers





RAMCOAL (Li,Volonteri+24)

Track the orbit of MBHB to coalescence in simulation on-the-fly, a sub-grid model integrated in AMR code RAMSES

- Includes dynamical friction, stellar hardening, migration in circumbinary disc, GW emission, accretion and feedback on each MBH in the binary (in CBD as well), spin evolution and recoil.
- Uses local quantities to calculate local sub-grid potential.
- negligible additional computational overhead (Fast!)
- Sub-grid model of stellar density makes it almost resolution-independent out to 100 pc resolution.