arXiv:2410.01876

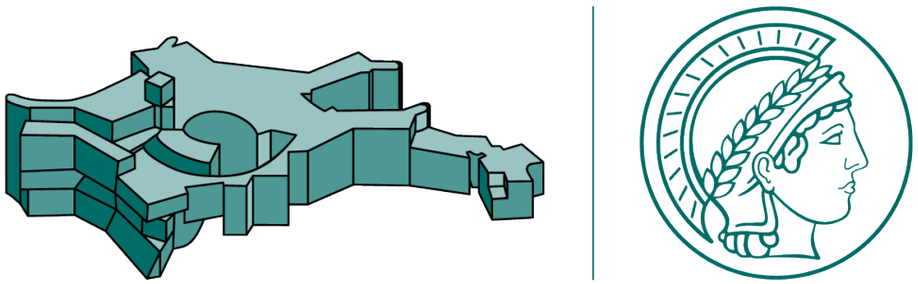
Structure formation with primordial black holes:

M. Sten Delos, Antti Rantala, Sam Young, Fabian Schmidt

collisional dynamics, binaries, and gravitational waves

Fabian Schmidt (MPA)

KIAS Workshop Gyeongju, 10/28/24

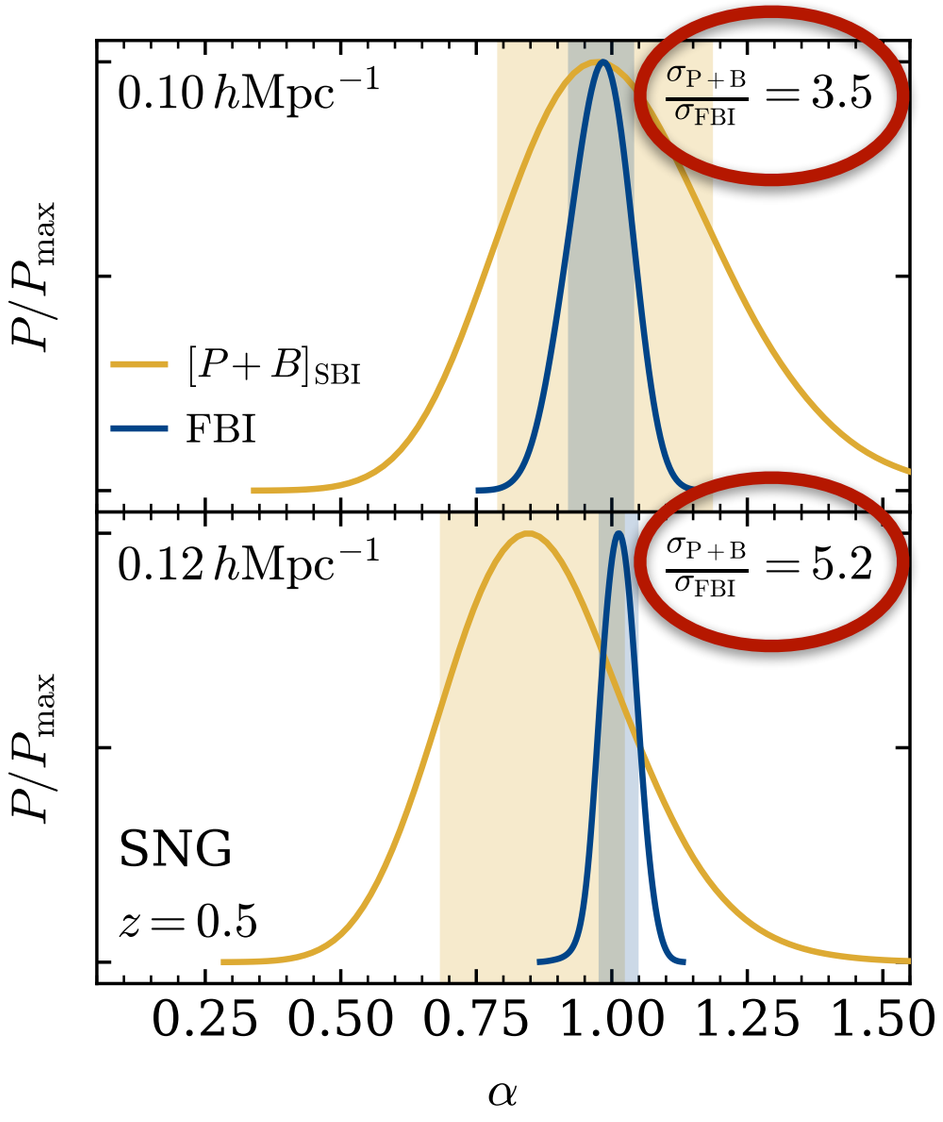


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arXiv:2403.03220 arXiv:2407.01524

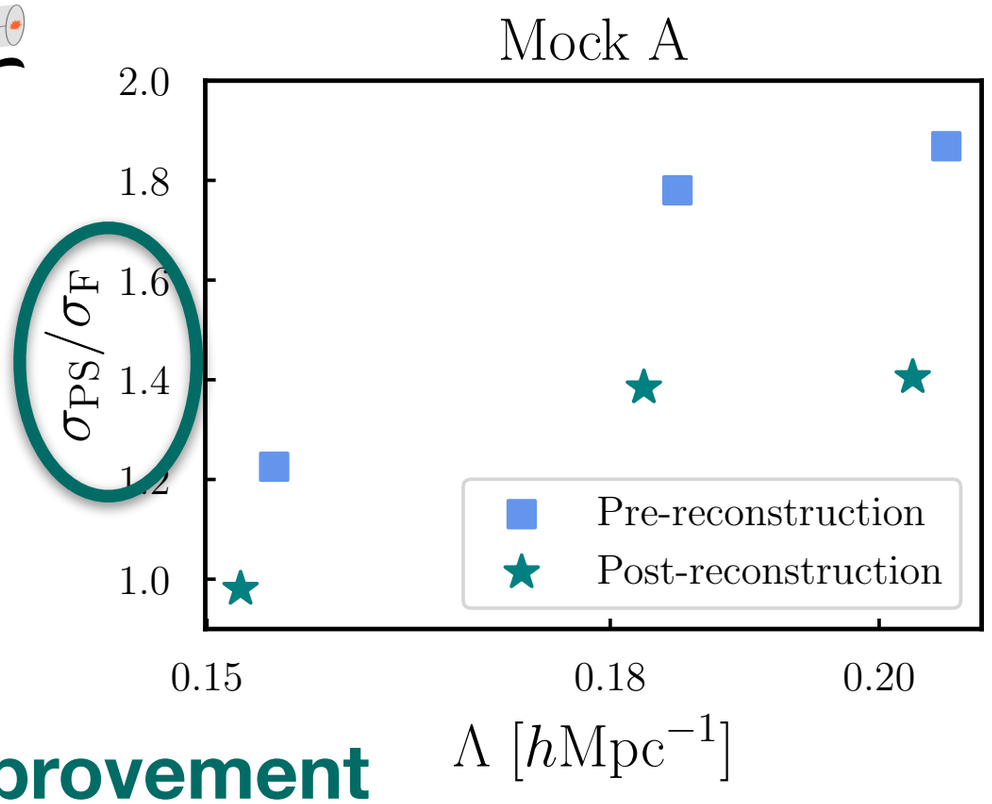
What my original talk title was about

- Field-level inference of σ_8 (left) and BAO scale (right)



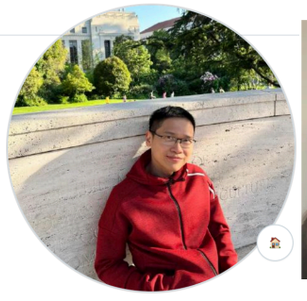
LEFTfield

Improvement in field-level over power- and bispectrum



Improvement in field-level over post-reconstruction power spectrum







arXiv:2410.01876

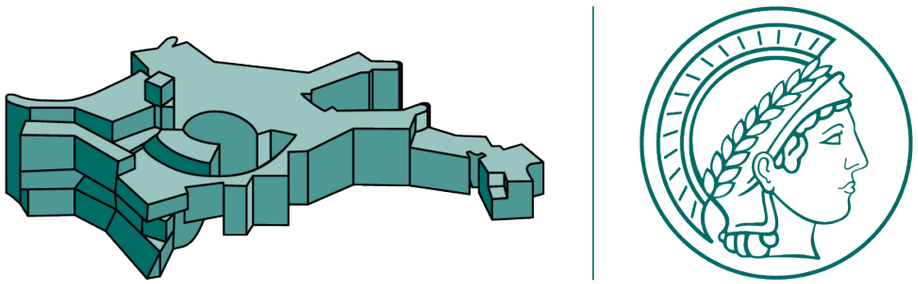
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Protagonists



- Sten Delos
  - Fellow, Carnegie Observatories



- Antti Rantala
  - MPA fellow



- Sam Young
  - Marie Curie Fellow, Leiden University

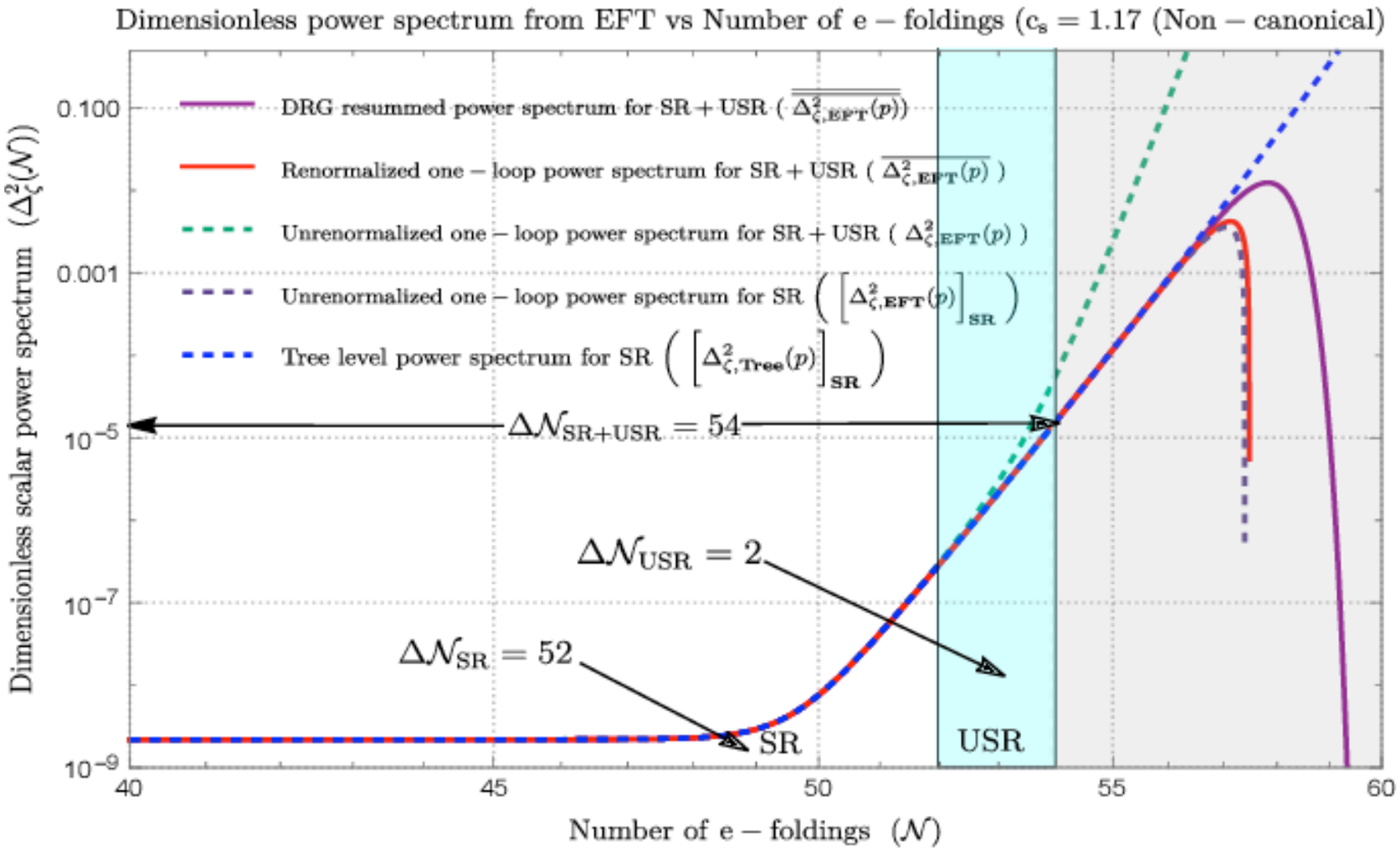
Primordial black holes (PBH)

- Rapid slowdown in single-field inflation can lead to enhanced curvature perturbations ζ on very small scales

- If ζ >~ 0.5 over a given Hubble volume, that volume is expected to collapse to a PBH

- Collection of such PBH behaves as cold dark matter (but see later)

- Alternative / addition to WIMPs



Choudhury, Panda, Sami (2023)

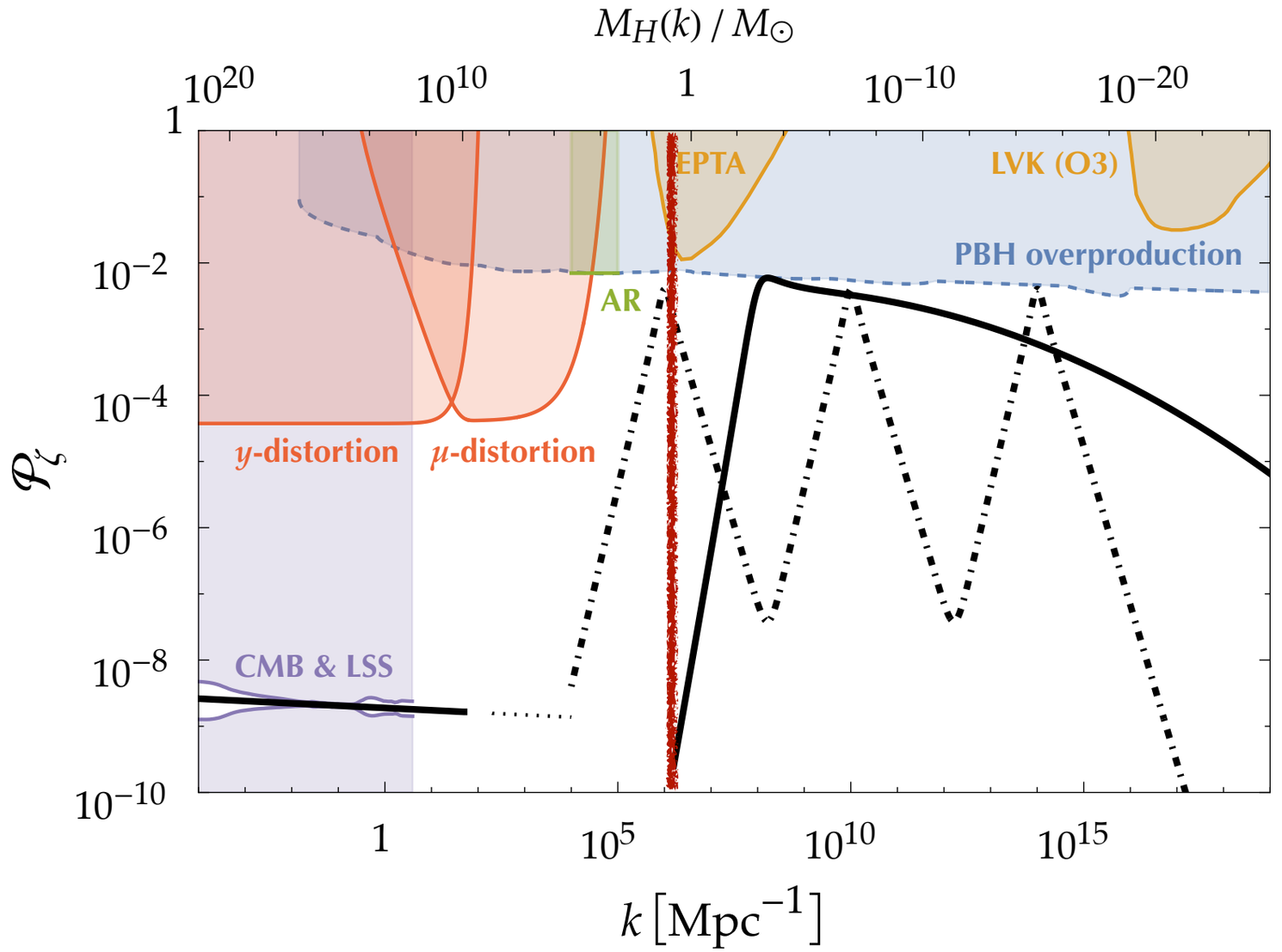
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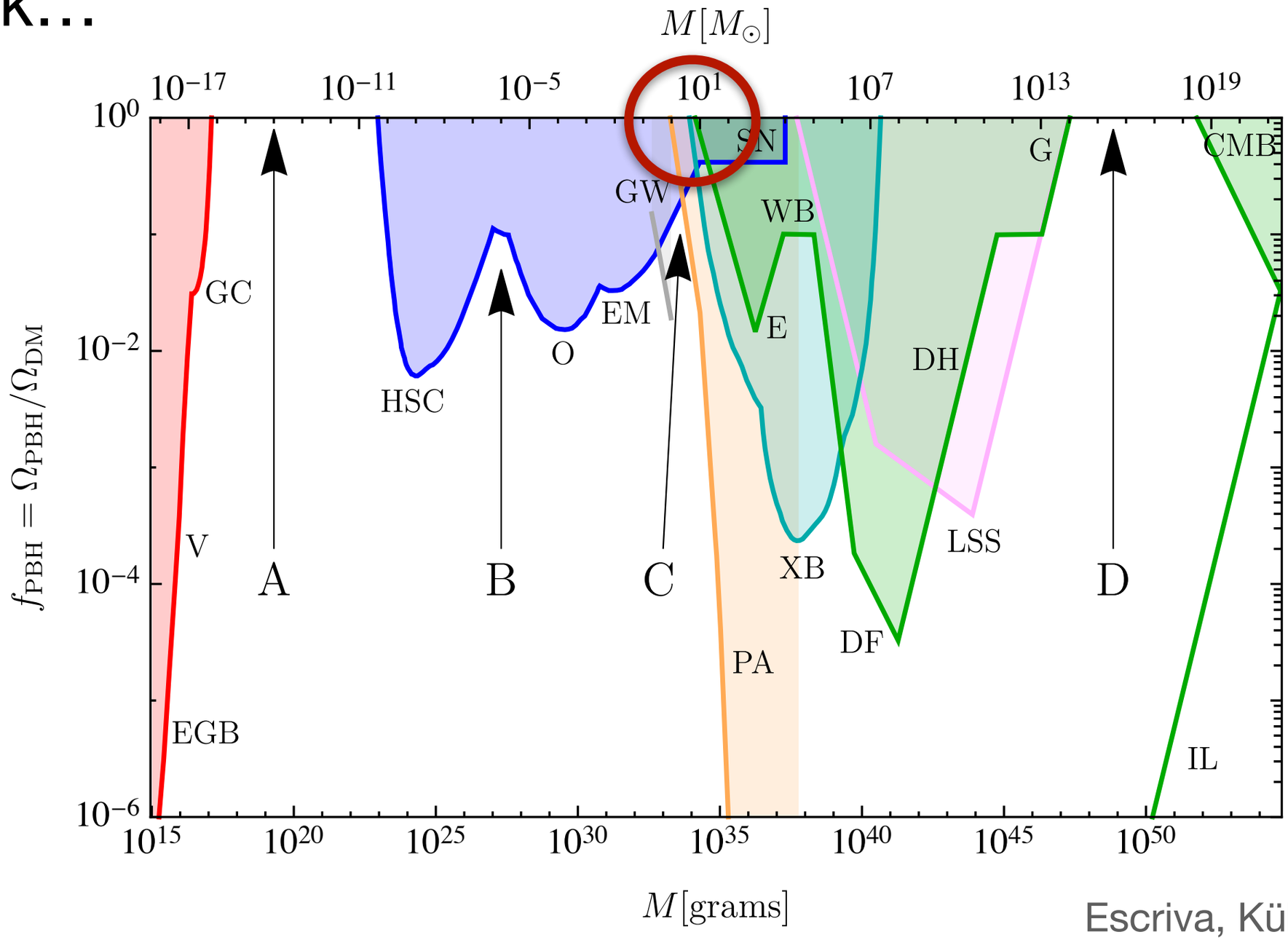
- Alternative / addition to WIMPs



Escriva, Kühnel, Tada (2022)

Constraints on PBH abundance

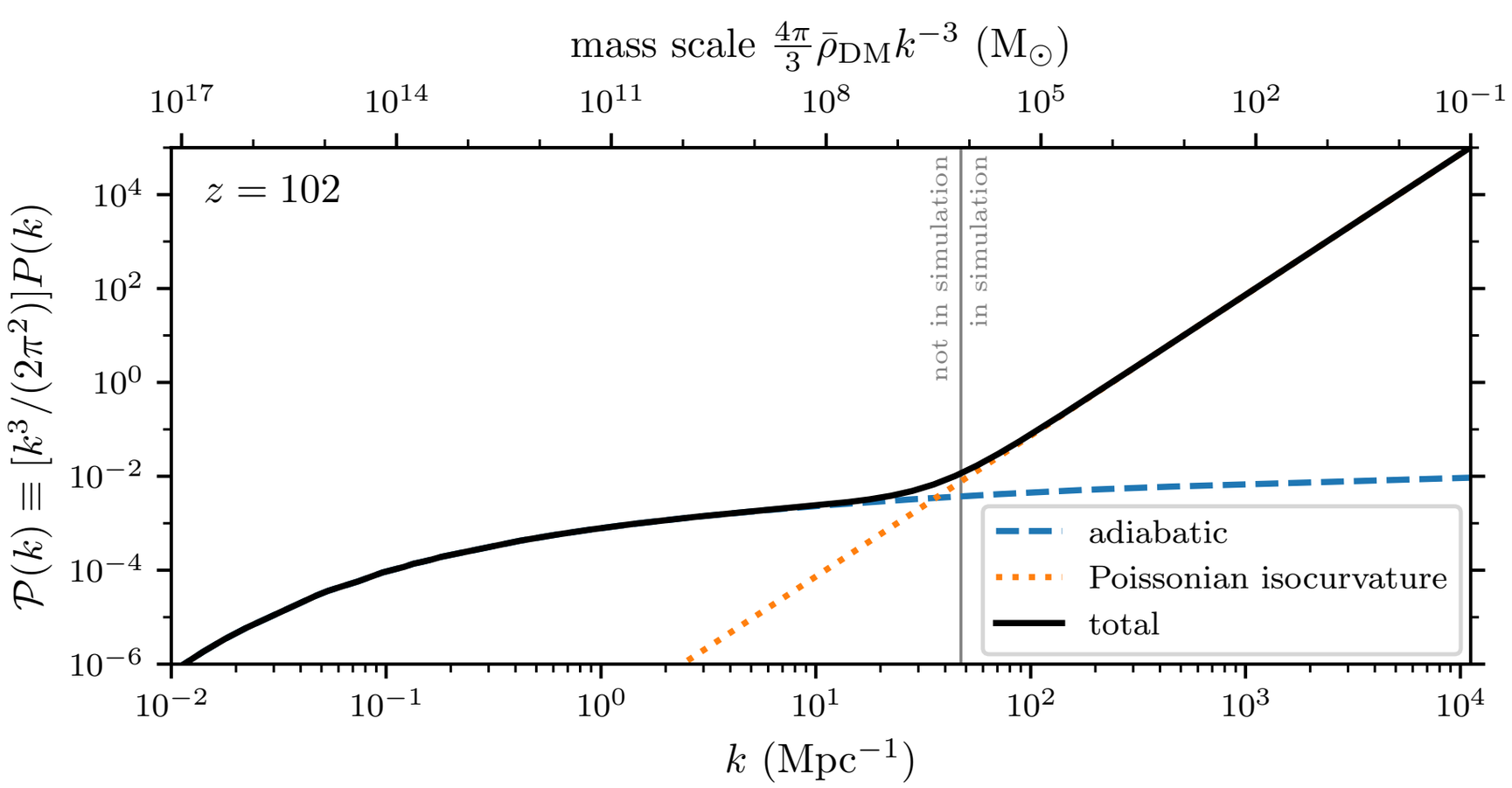
- I don’t know about any of these, so please don’t ask…



Escriva, Kühnel, Tada (2022)

Structure formation with PBH

- We start with a radiation-dominated epoch of the Universe, where the subdominant CDM component is made up of discrete PBH with M ~ 10 Msun
  - PBH are locally Poisson-distributed, modulated by large-scale adiabatic density perturbations



Structure formation with PBH

- We start with a radiation-dominated epoch of the Universe, where the subdominant CDM component is made up of discrete PBH with M ~ 10 Msun
    - PBH are locally Poisson-distributed, modulated by large-scale adiabatic density perturbations
- Subsequent evolution is just gravity!
- Goal: fully solve for evolution of structure from a collection of PBH
    - *"Full UV theory" of CDM*: no effective fluid treatment or softening

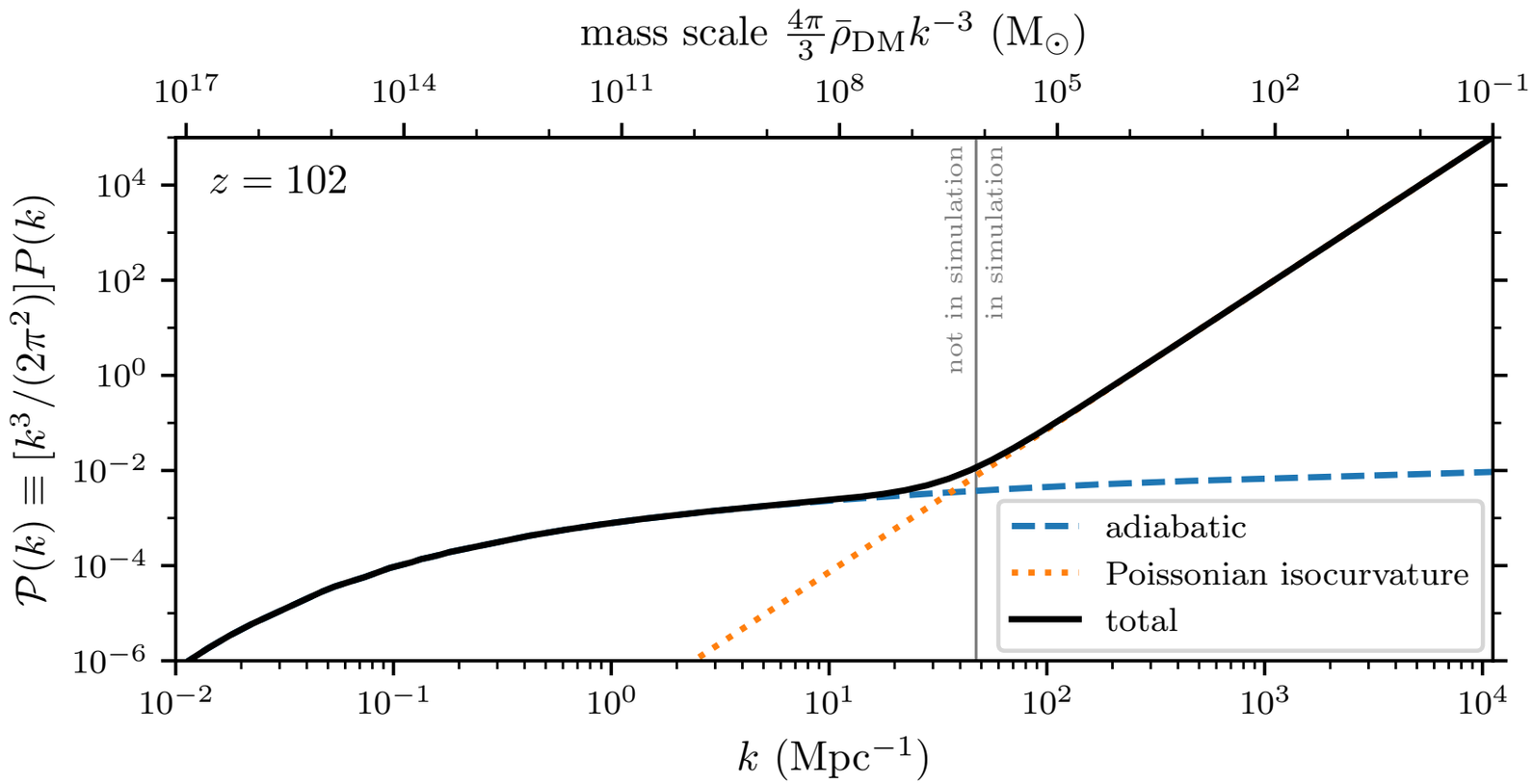
Structure formation with PBH

- *"Full UV theory" of CDM*: no effective fluid treatment or softening
- Difference to particle CDM (WIMPs, axions, …):
  - Collisional effects due to finite *N* in N-body
  - Formation of binary, triple, … systems
  - Mergers of PBH: BH kicks and gravitational-wave emission
  - Accretion onto PBH

arXiv:2410.01876

Initial conditions

- Consider slightly overdense spherical region within volume of ~100 kpc (comoving)
- This region contains ~10^6 PBH drawn from a lognormal mass function ($\langle M \rangle = 16\ M_{sun}$)
- Initialize at *a=3*10^{-12}*, *actual formation time*
- Evolution through radiation domination with high-precision-tuned Gadget4 (no softening)



arXiv:2410.01876

Three simulations

- **Particle dark matter simulation**
- Standard CDM ICs from same adiabatic realization
- **Collisionless PBH simulation**
- Gadget4 (softened) from PBH ICs
- **Collisional PBH simulation**
- Bifrost code

Bifrost

[20] A. Rantala, T. Naab, F.P. Rizzuto, M. Mannerkoski, C. Partmann and K. Lautenschütz, *BIFROST: simulating compact subsystems in star clusters using a hierarchical fourth-order forward symplectic integrator code*, *Monthly Notices of the Royal Astronomical Society* **522** (2023) 5180 [2210.02472].

- Direct-summation N-body code written by Antti Rantala
- 4th-order symplectic integrator,
- regularization for close encounters and hard bound systems (LogH)
- BH spin is followed
- including post-Newtonian corrections (in regularized regime) up to order 3.5 (v^7), including GW radiation reaction
- Out-state of binary BH mergers described by fitting formulae derived from numerical-relativity simulations

Bifrost

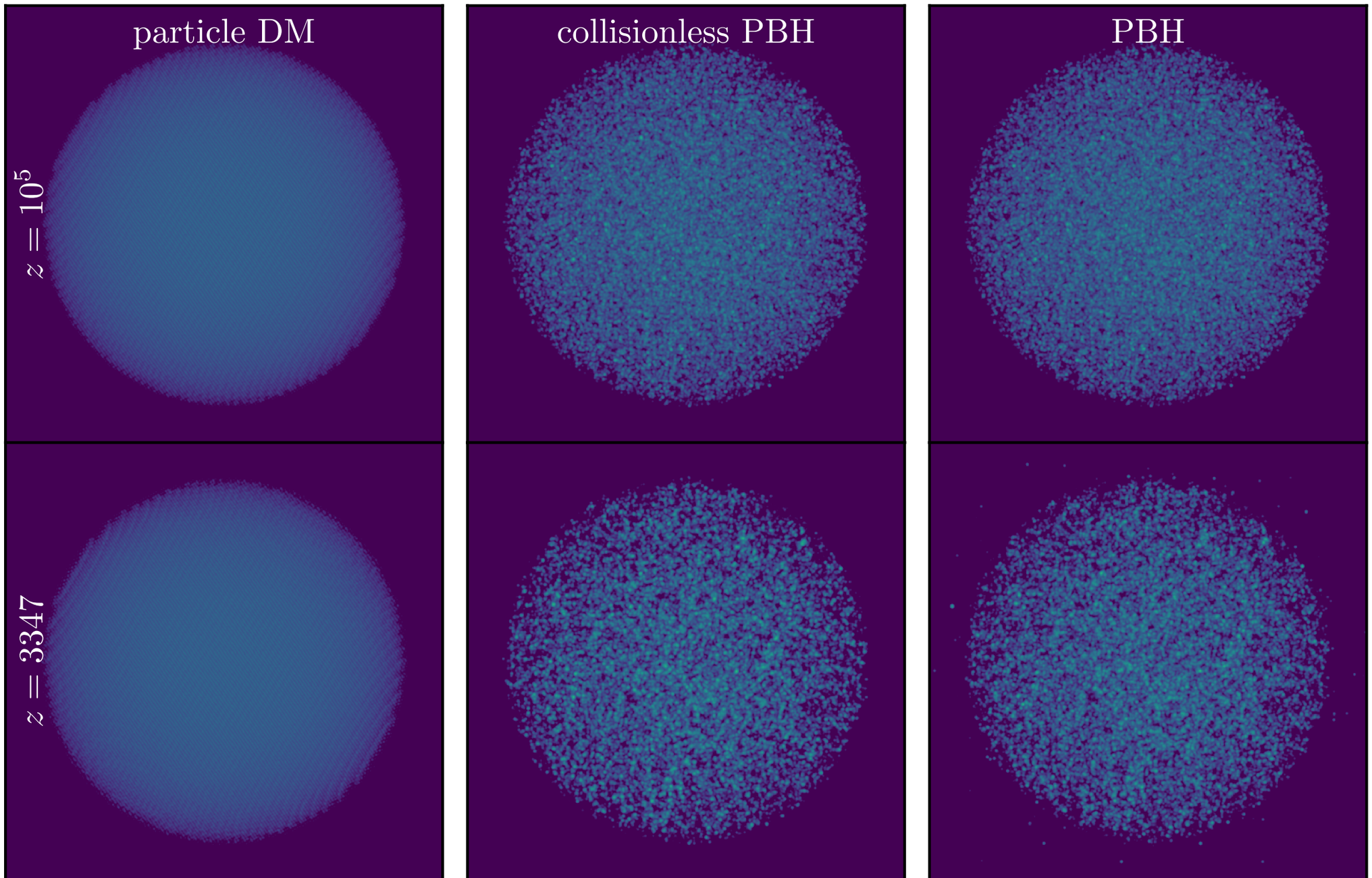
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- But:
  - Bifrost uses physical coordinates
  - Vacuum boundary conditions
- Hence, choice of isolated overdense region for our simulation

arXiv:2410.01876

Three simulations

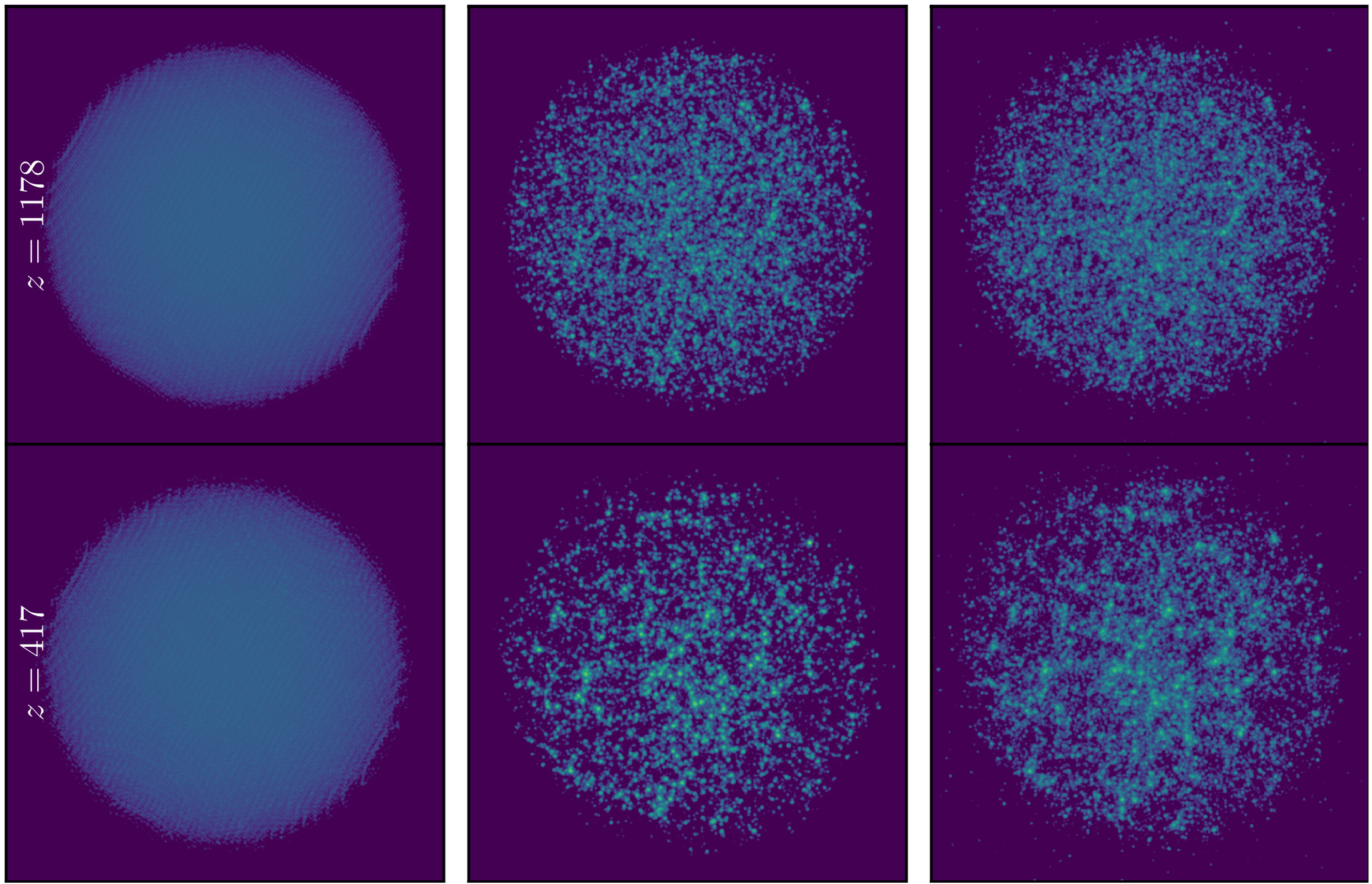
- **Particle dark matter simulation**
- **Collisionless PBH simulation**
- **Collisional PBH simulation**



arXiv:2410.01876

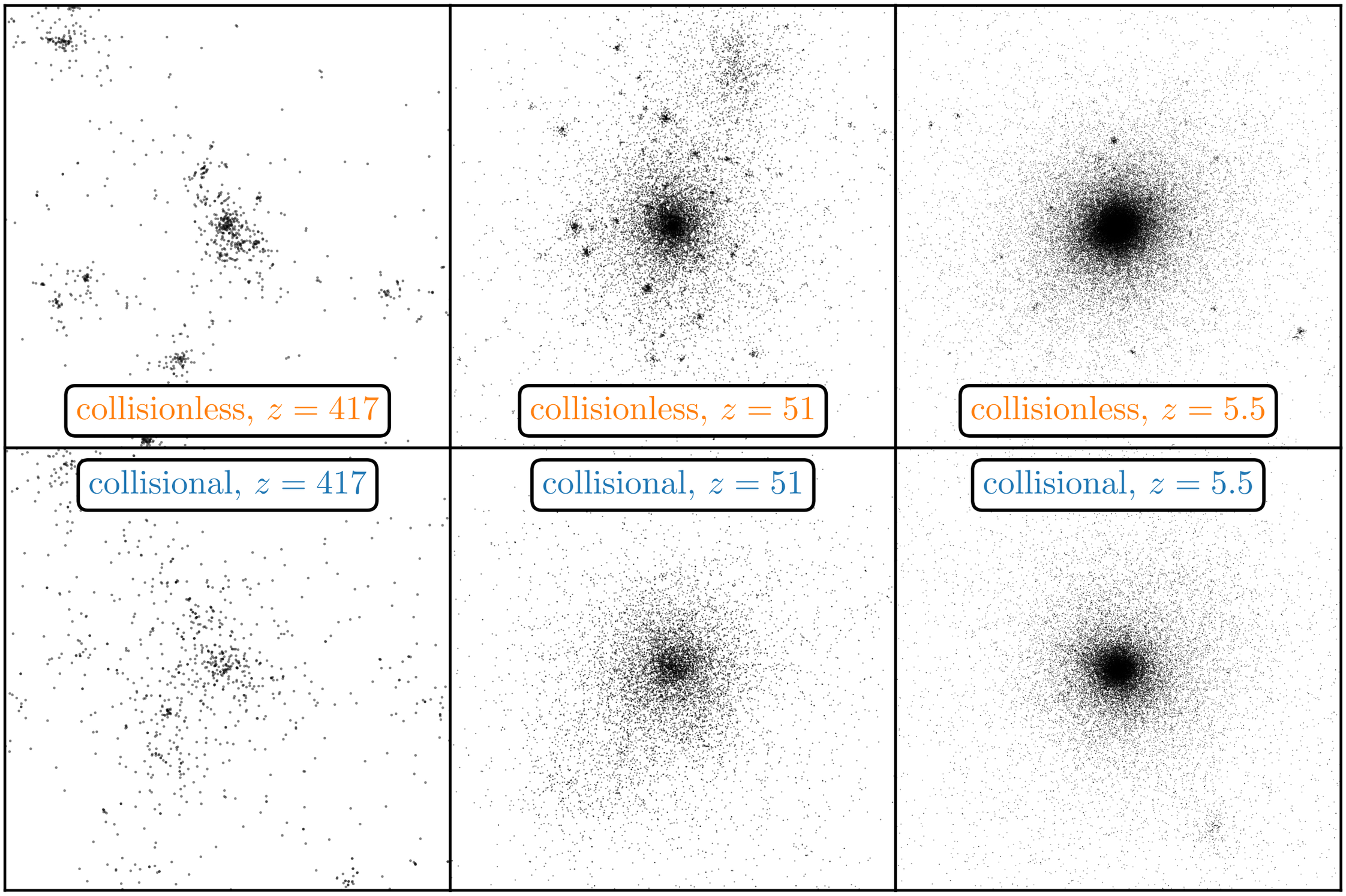
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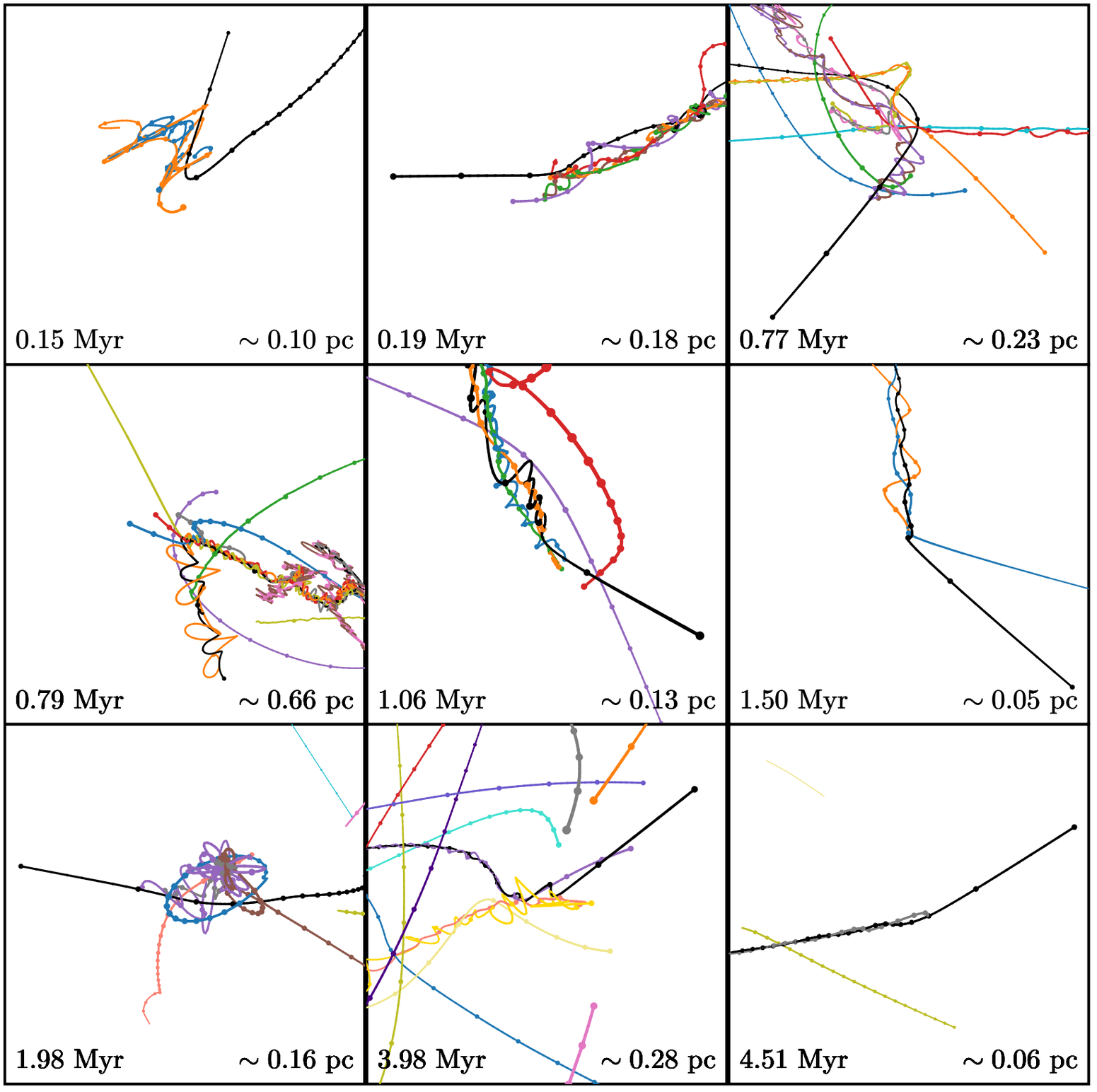


arXiv:2410.01876

Collisional vs collisionless PBH simulations

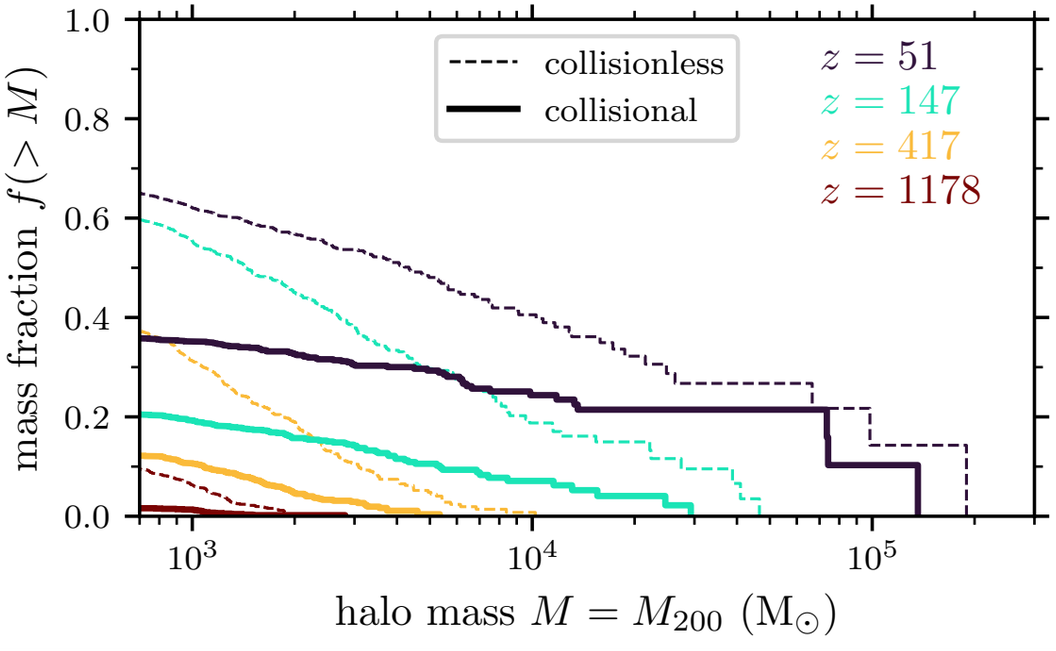


A plethora of multi-body interactions

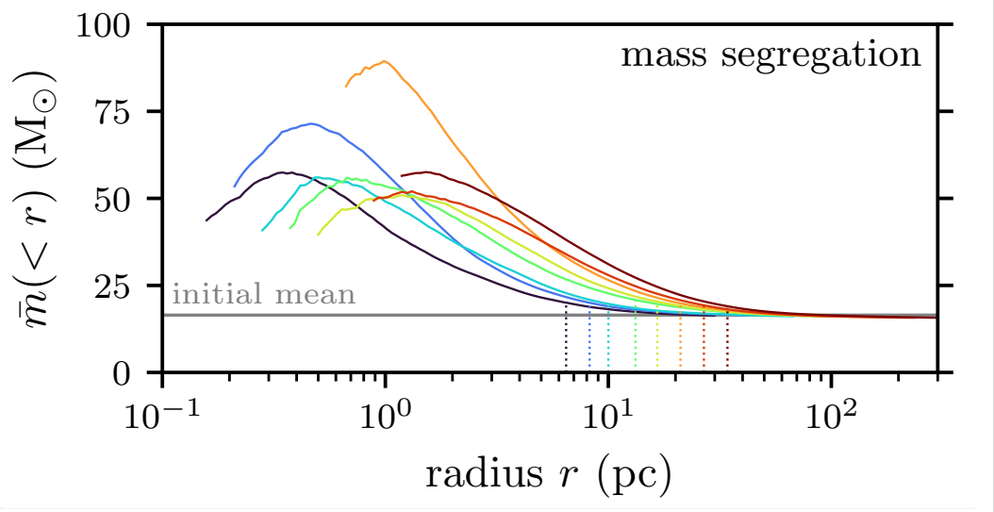


Dynamical effects on halo formation

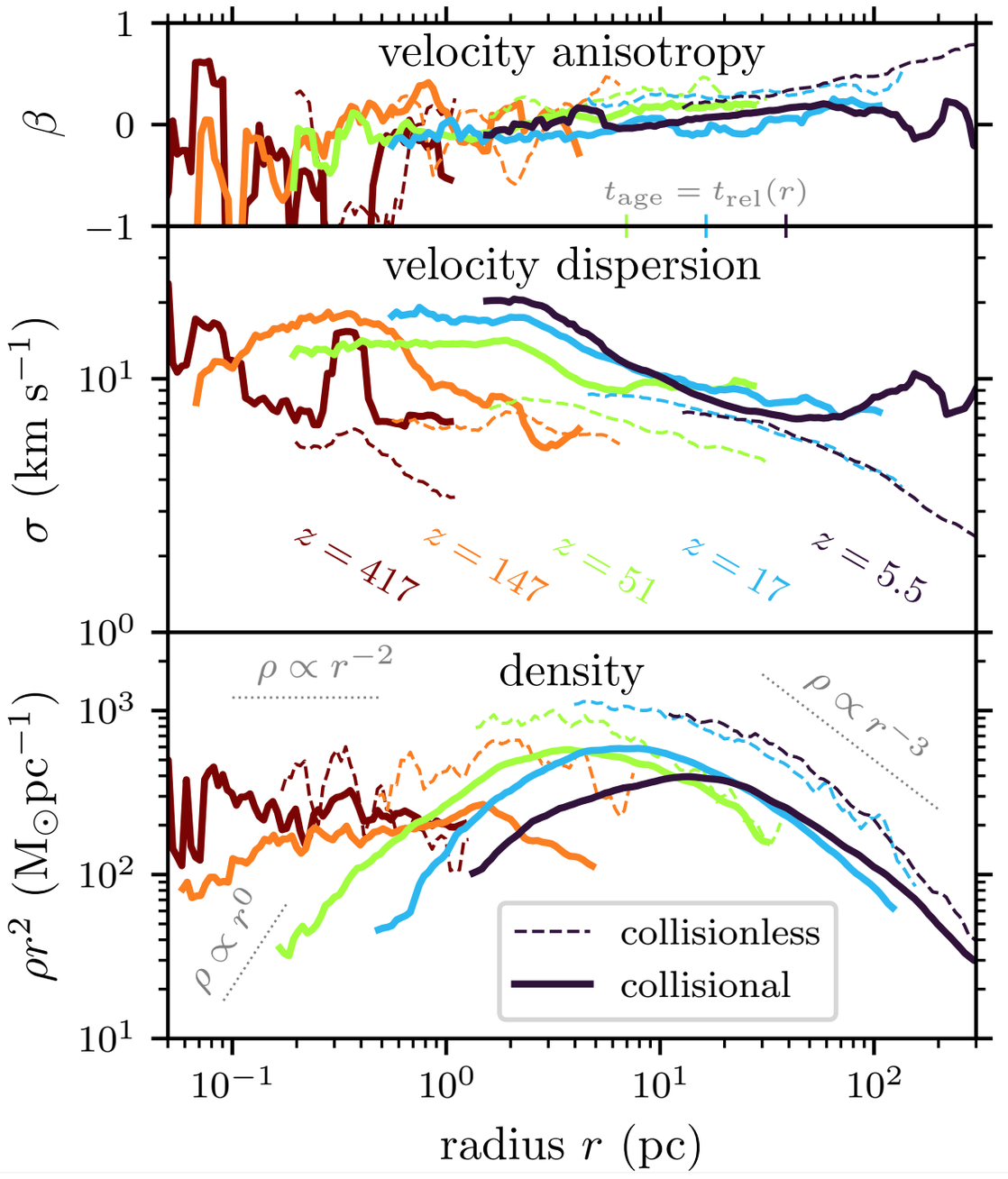
Suppression of substructure



Mass segregation among PBH



Formation of core, erasure of velocity anisotropy



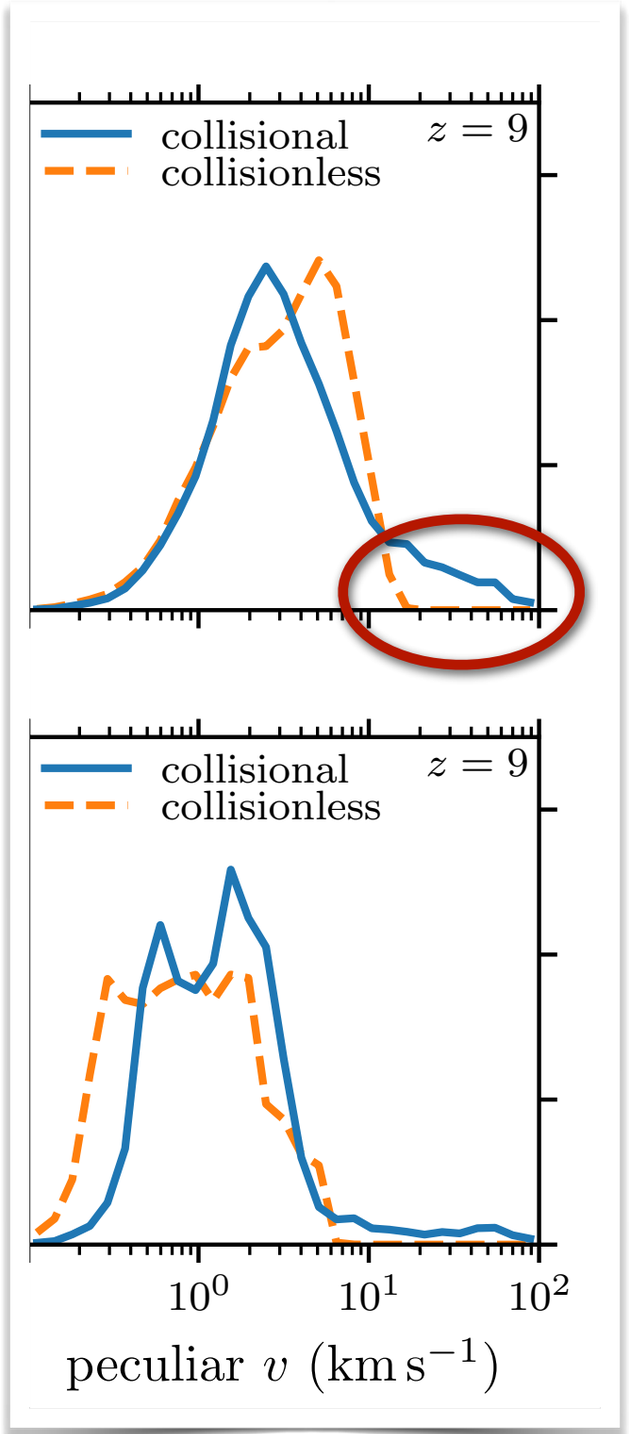
Dynamical effects on halo formation

High-velocity tail from 3-body interactions & kicks

-> W/HDM component is generated dynamically!

Lower panel:

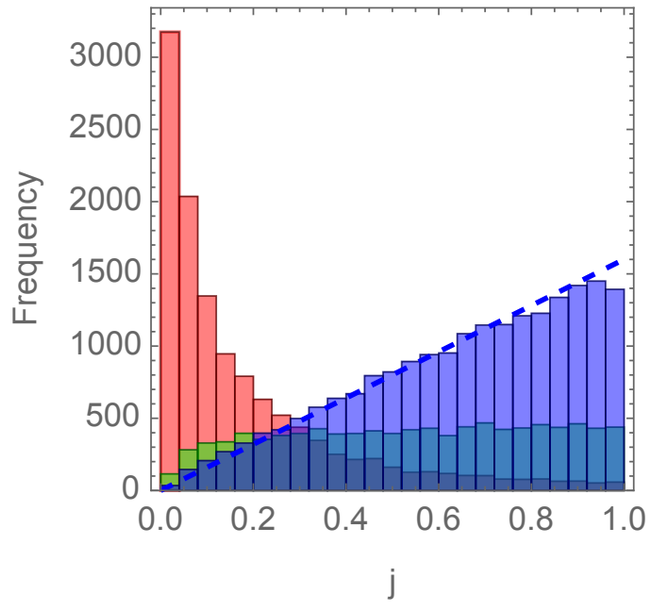
Attempt to remove binary velocities

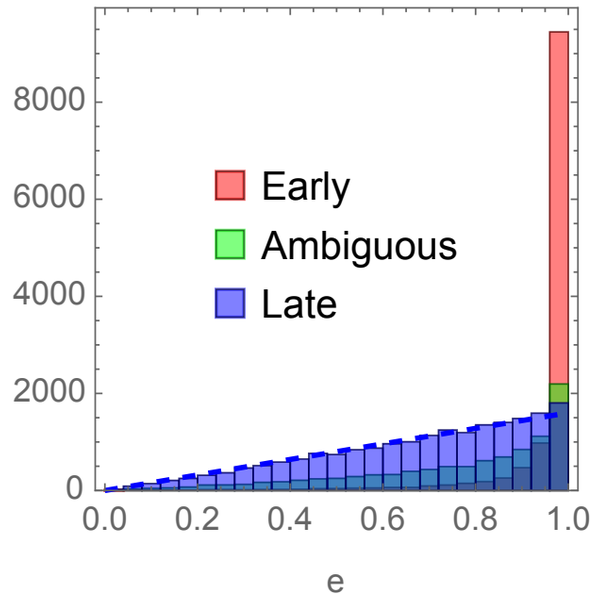


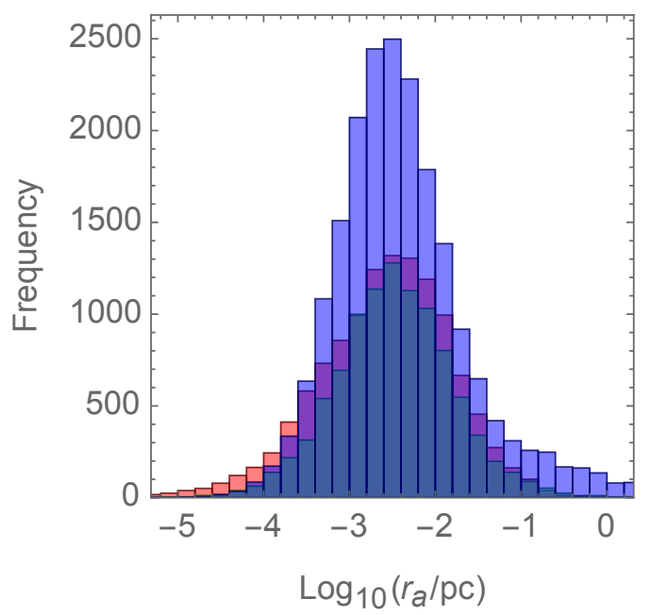
Properties of binary PBH population

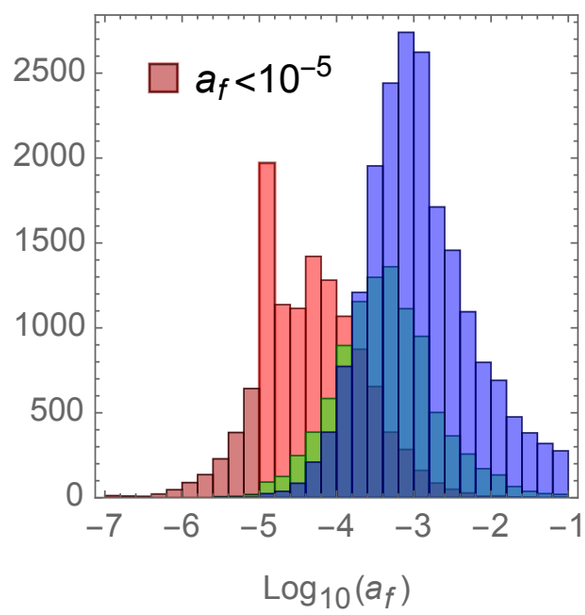
- Distinguish between binaries formed during radiation domination (early) and during nonlinear structure formation (late)

Angular momentum	Eccentricity
Semi-major axis	Formation time









Generation of gravitational background

- Current LIGO/Virgo/Kagra limit: $\Omega_{\rm GW} \lesssim 10^{-8}$ per e-fold
- Apparently provides very tight constraint on PBH mass fraction, but needs a more careful calculation…

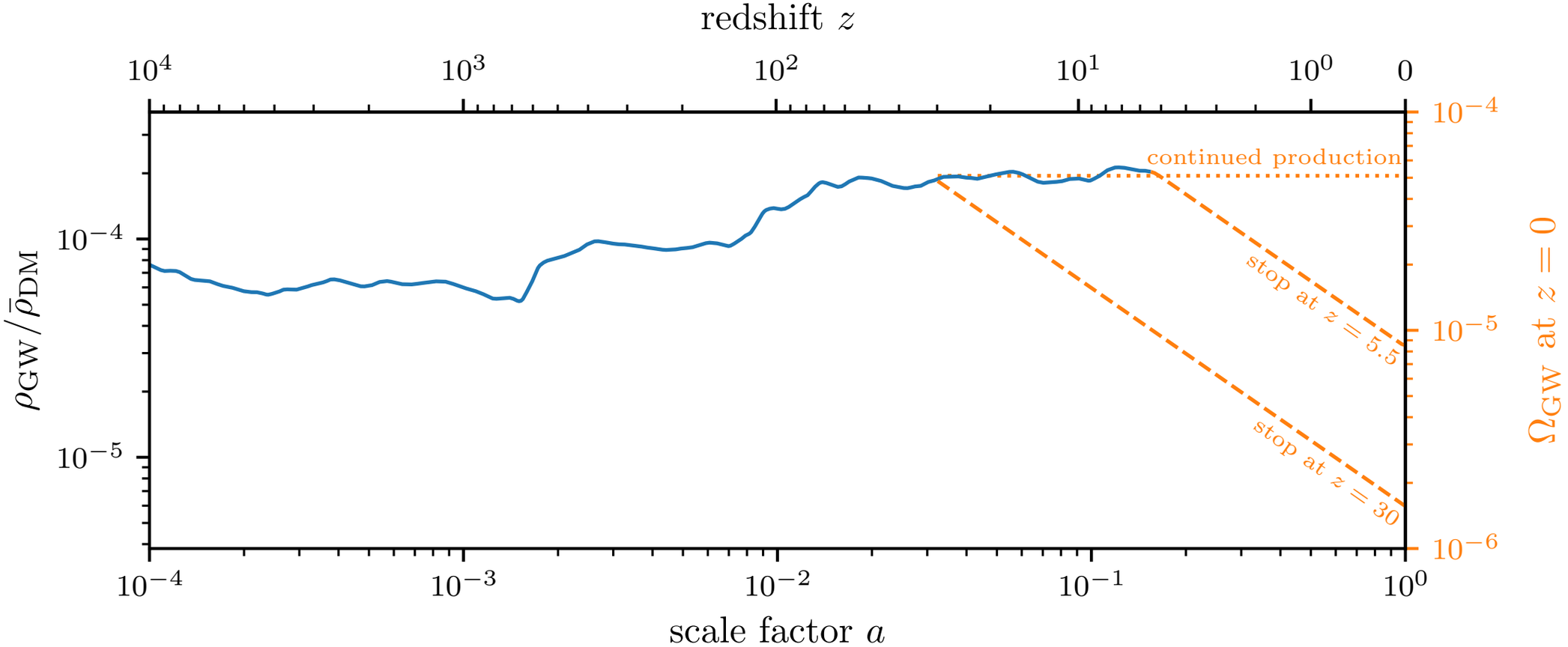


Figure 21: Energy density $\rho_{\rm GW}$ in gravitational radiation compared to the mass density $\bar{\rho}_{\rm DM}$ of the PBHs. At late times, the ratio is steady at about $\rho_{\rm GW}/\bar{\rho}_{\rm DM} \simeq 2 \times 10^{-4}$.

arXiv:2410.01876

Conclusions

- The universe might well contain a population of primordially formed BH
  - Constraints on PBH <=> constraints on primordial curvature perturbations on scales ($k \sim 10^6$ Mpc^{-1}) that cannot be probed directly otherwise
- *First fully consistent simulations of structure formation with PBH* yield a multitude of interesting dynamical effects and observational consequences
- Expect tight constraint from GW background limits!
- Future: consider mixture of PBH and particle DM