

Goals

- Study galaxy evolution in the Ultralight Dark Matter (ULDM) framework.
- Develop numerical methods for the Poisson–Schrödinger system:
 - Poisson solvers
 - Symplectic/conservative Schrödinger schemes
 - Mass and unitarity preservation
- Investigate isolated ULDM halos formed through idealized subhalo mergers:
 - Compare standard ULDM halos with self-interacting scenarios.
- Simulate cosmological ULDM initial conditions using Gaussian random fields.
- Identify halo formation through massless tracer particles evolved with adaptive mesh refinement (AMR).

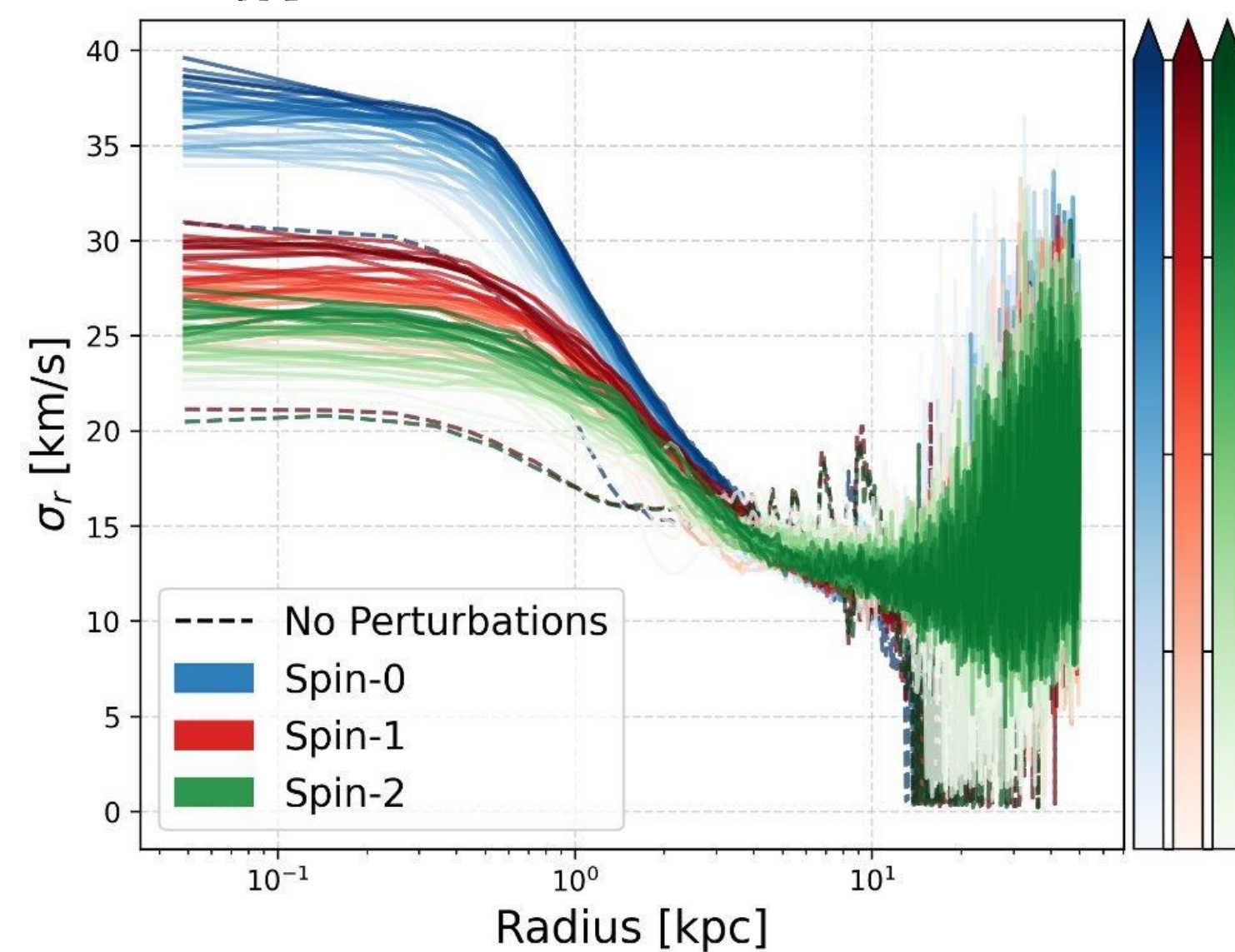
Dynamical Heating

For generalized spin- s [1] and self-interacting [2] ULDM we solve the multi-component SP system

$$i\hbar\partial_t\Psi = -\frac{\hbar^2}{2m_s}\nabla^2\Psi + m_s\Phi\Psi, \quad \nabla^2\Phi = 4\pi G\rho_0(\text{Tr}[\Psi^\dagger\Psi] - 1).$$

$$i\hbar\partial_t\psi = -\frac{\hbar^2}{2m}\nabla^2\psi + m\Phi\psi + \frac{4\pi\hbar^2\rho_0 a_s}{m^2}|\psi|^2\psi + \mathcal{O}(|\psi|^4\psi),$$

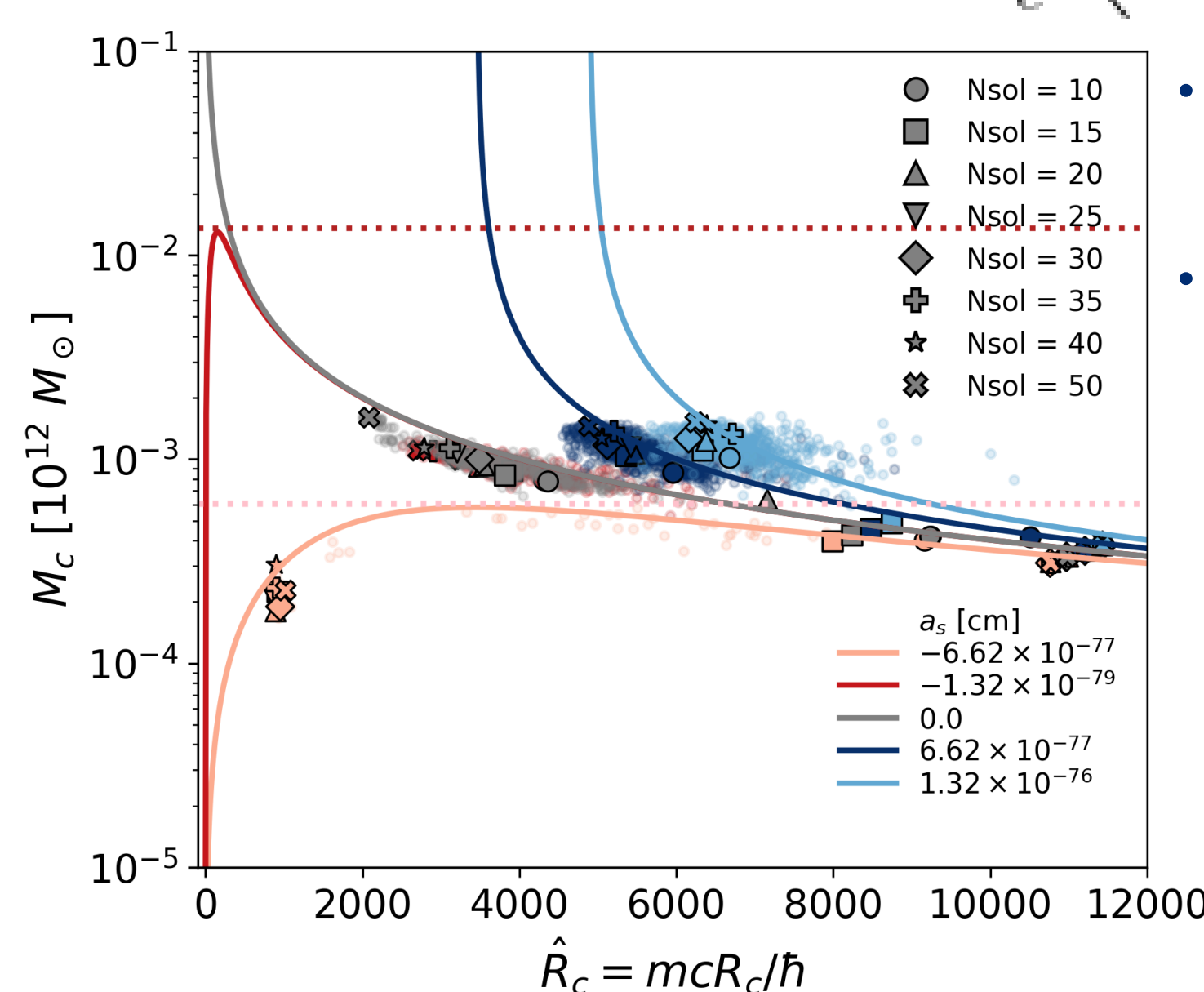
- A CUDA/C++ timestep evolution algorithm was developed for the Poisson–Schrödinger system.
- Simulations were executed on NVIDIA Tesla A100 GPUs available on the Phoebe cluster at FZU.
- Galactic-scale initial conditions were implemented on a fixed grid and evolved for several dynamical times.
- The resulting halos were analyzed to study the impact of each ULDM model on the dynamical heating of stellar populations.



Self-Interacting

- The code was extended to include non-zero self-interactions for spin-0 ULDM.
- Minimum-energy configurations of composite ULDM halos were studied by considering:
 - Kinetic energy
 - Gravitational potential energy
 - Quantum pressure
- The resulting analytical model predicts the core–size scaling relation:

$$M_c = 3\sqrt{2\pi}\frac{\hbar^2}{Gm^2r_c}\left(\sqrt{2\pi} - \frac{6\hbar^2 a_s}{Gm^3 r_c^2}\right)^{-1}$$



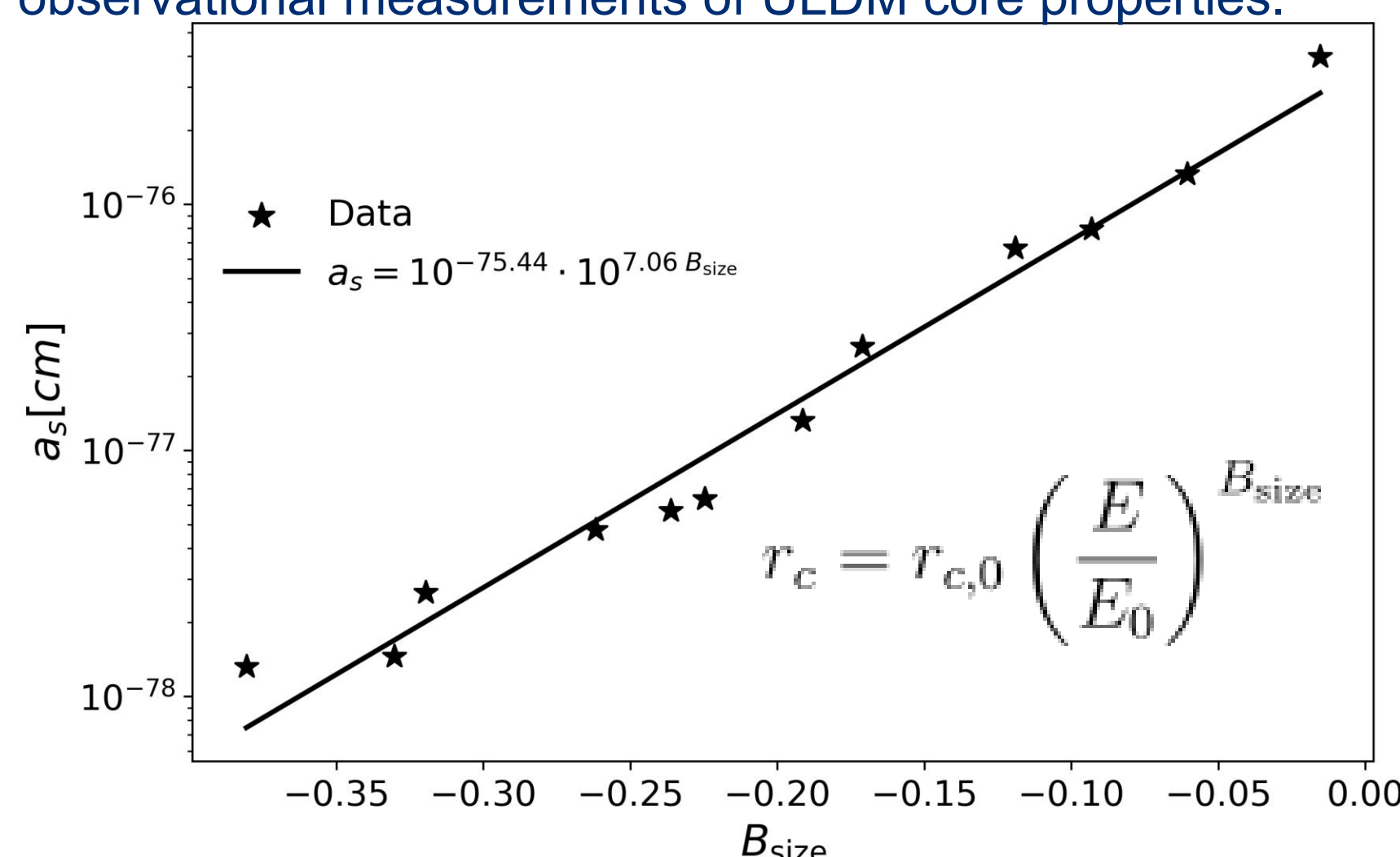
- This analytical framework provides insight into the limitations and predictive power of the numerical code.
- Assuming the core–halo relation depends on the invariant

$$\Xi = \frac{|E|}{M^3(Gm/\hbar^2)}$$

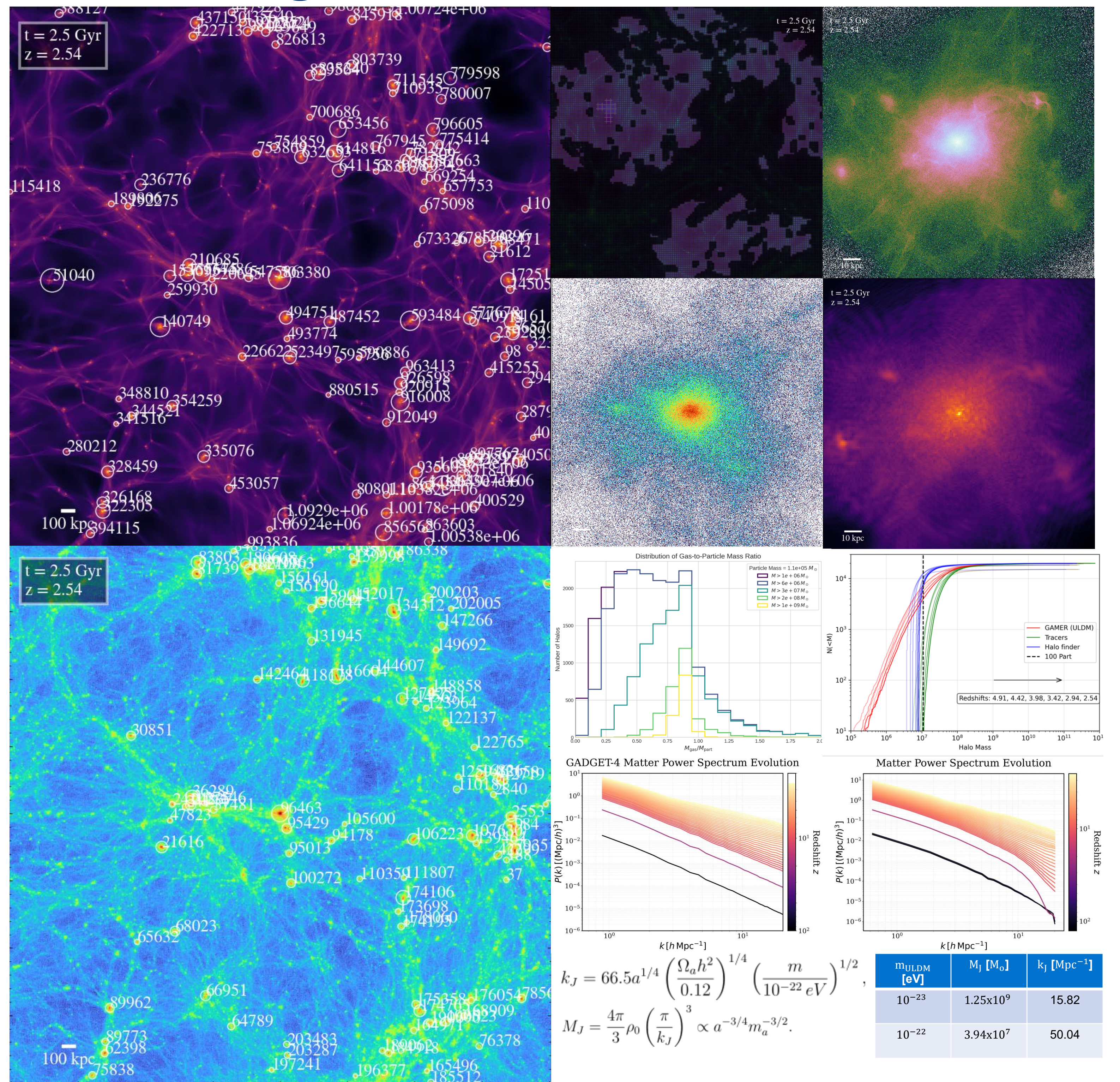
$$\frac{M_c}{M} = A_{\text{mass}}\Xi^{B_{\text{mass}}}$$

we obtain B close to $(1/3)$, consistent with current literature.

- We also identified a new scaling relation for positive self-interactions: the size–energy relation.
- By considering the total halo energy (up to the virial radius), we obtained an accurate description of the relation as a function of the self-interaction strength.
- In principle, this relation could be used to constrain the self-interaction strength from observational measurements of ULDM core properties.



Cosmological simulations



- Cosmological ULDM initial conditions were generated from Gaussian random fields and evolved using the Schrödinger–Poisson system with adaptive mesh refinement [3] (AMR) along with massless particles depositing density using Triangular Shaped Cloud (TSC).
- Cosmological CDM simulations were carried out with a specialized code for Nbody simulations Gadget-4.
- Halo formation and evolution were tracked through massless tracer particles coupled to gravity sourced by ULDM.
- We further investigate the reliability of tracer-particle methods for reconstructing halo evolution and merger dynamics in wave-like dark matter simulations.
- Future developments include:
 - Mixed dark matter (MDM) models (CDM+ULDM)
 - Baryonic components
 - Galaxy formation across different ULDM particle masses (m_{ULDM}) and Self-Interaction strength (a_s).

Conclusions

- Stable CUDA-accelerated ULDM simulations were successfully developed.
- Self-interacting ULDM halos reproduce core–halo scaling relations consistent with previous literature.
- Preliminary cosmological simulations demonstrate stable multiscale halo evolution and merger tracking.
- Larger m_{ULDM} values require higher tracer resolution for halos with $M_{\text{Halo}} < M_J$ [4].
- Future work will explore mixed dark matter and baryonic galaxy formation scenarios.

References

- [1] E. Munive-Villa, et al., “Core-halo scaling relations in self-interacting scalar field dark matter”, <https://doi.org/10.1093/mnras/stag583>, arXiv:2512.07020 (2025).
- [2] E. Munive-Villa, et al., “Scaling relations and tidal disruption in spin- s ULDM”, <https://doi.org/10.1093/mnras/staf1616>, arXiv:2502.03561 (2025).
- [3] Hsi-Yu Schive, “Fuzzy dark matter simulations”, Living Reviews in Computational Astrophysics, arXiv:2509.23231 (2025).
- [4] M. Kulkarni and J. P. Ostriker, “What is the Halo Mass Function in a Fuzzy Dark Matter Cosmology?”, arXiv:2011.02116 (2020).