Title: UltraLight Dark Matter Dynamics in the Language of Eigenstates

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Abstract: Self-gravitating quantum matter may exist in a wide range of cosmological and astrophysical settings: from the very early universe through to present-day boson stars. Such quantum matter arises in UltraLight Dark Matter (ULDM): an exciting axion-like particle candidate which keeps the successes of CDM on large scales but alleviates tensions on small scales. This small scale behavior is due to characteristic cores in ULDM called solitons, which also correspond to the ground state of the self-gravitating quantum system governing ULDM. We calculate the full spectrum of eigenstates and decompose simulations of ULDM into these states, allowing us to precisely track the evolution of the tell-tale soliton cores and the surrounding halo "skirt". Using this formalism, we investigate formation of halos through binary soliton collisions and the dependence of the final halo product on initial parameters. We further link characteristic ULDM halo behavior--such as the soliton "breathing mode" and random walk of the center of mass--to the presence of certain modes. Finally, we comment on the relationship between eigenenergies and oscillatory timescales present in the system, as well as future directions for understanding ULDM through the language of its eigenstates.

UltraLight Dark Matter Dynamics in the Language of Eigenstates

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Cosmology & Gravitation Seminar
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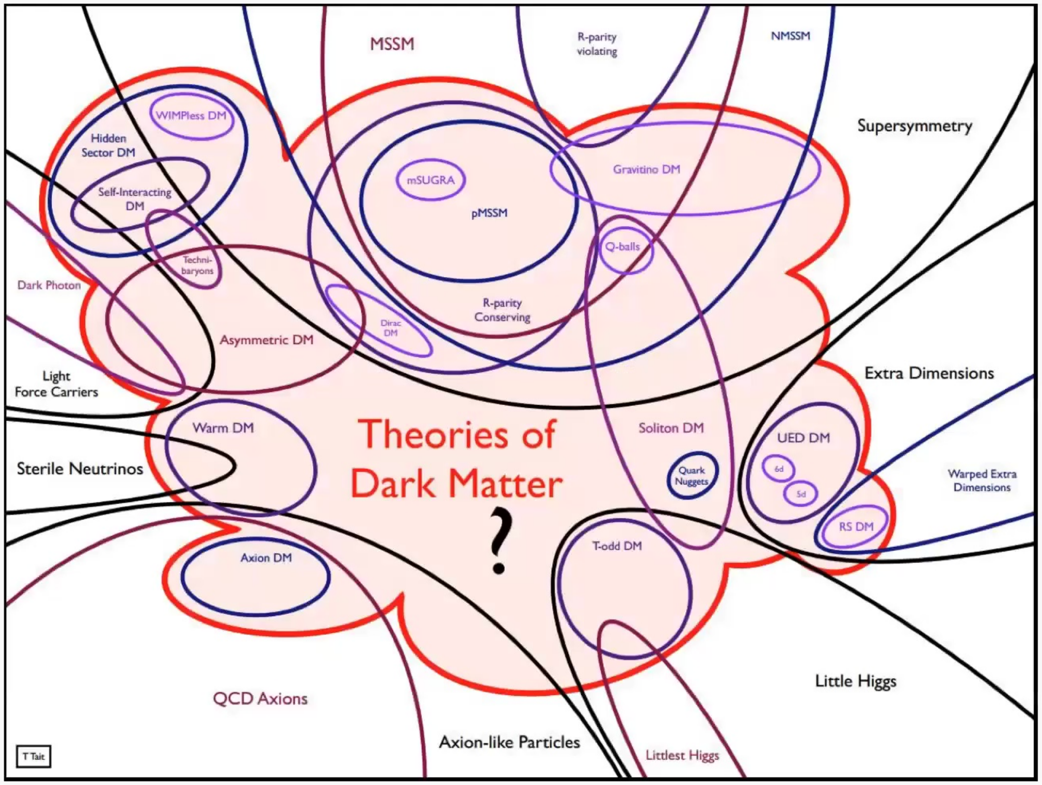
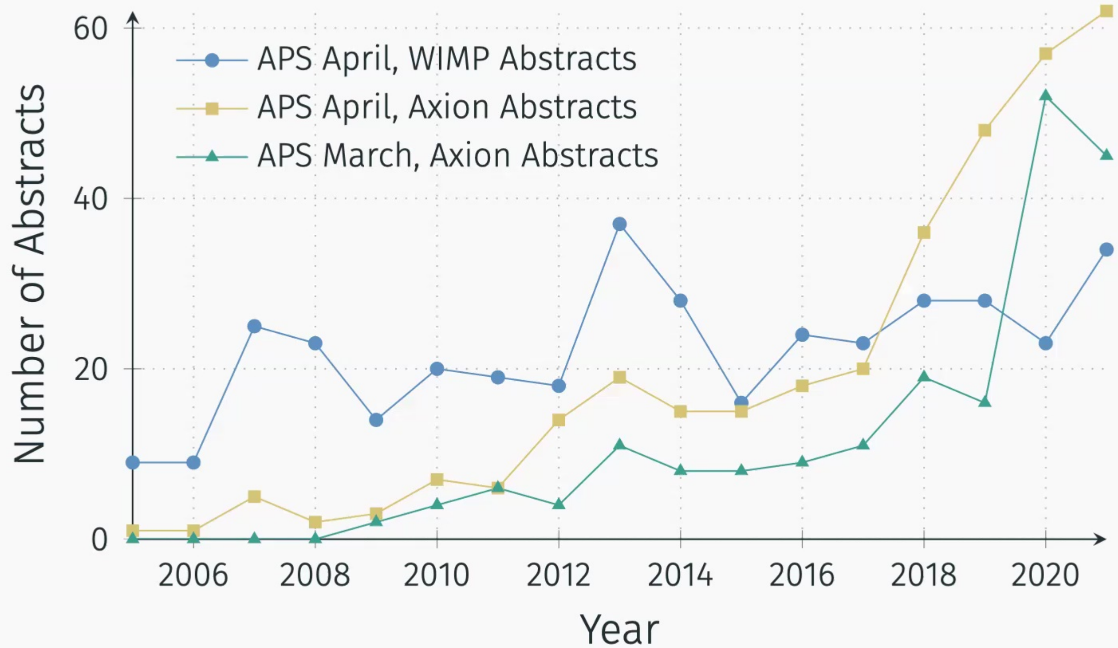
The Many Faces of Dark Matter



Venn diagram of Dark Matter theories circa 2013 from Tim Tait.

Popularity of Axionic Dark Matter



Data courtesy of Dr. Kelly Backes.

UltraLight Dark Matter

UltraLight Dark Matter (ULDM):

- is an axion-like scalar boson
- has low mass: $\sim 10^{-22}\,\mathrm{eV}$
- forms Bose-Einstein condensates
- helps with small-scale problems
  - core-cusp problem *(right)*
  - missing satellites problem
  - too-big-to-fail problem
- cool phenomenology!

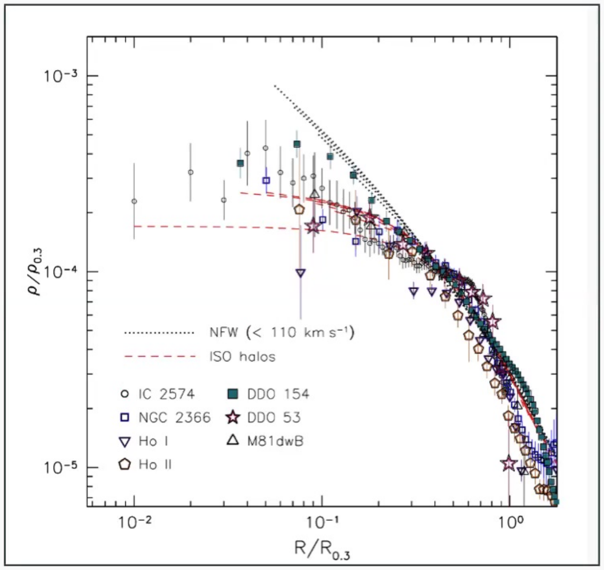


Fig. 7 in Oh, Se-Heon, et al. AJ, 2011.

The Schrödinger-Poisson System

$$i\hbar\dot{\psi} = -\frac{\hbar^2}{2m}\nabla^2\psi + m\Phi\psi$$

$$\nabla^2\Phi = 4\pi G m|\psi|^2$$

$$\rho = m|\psi|^2$$

The Eigenstates

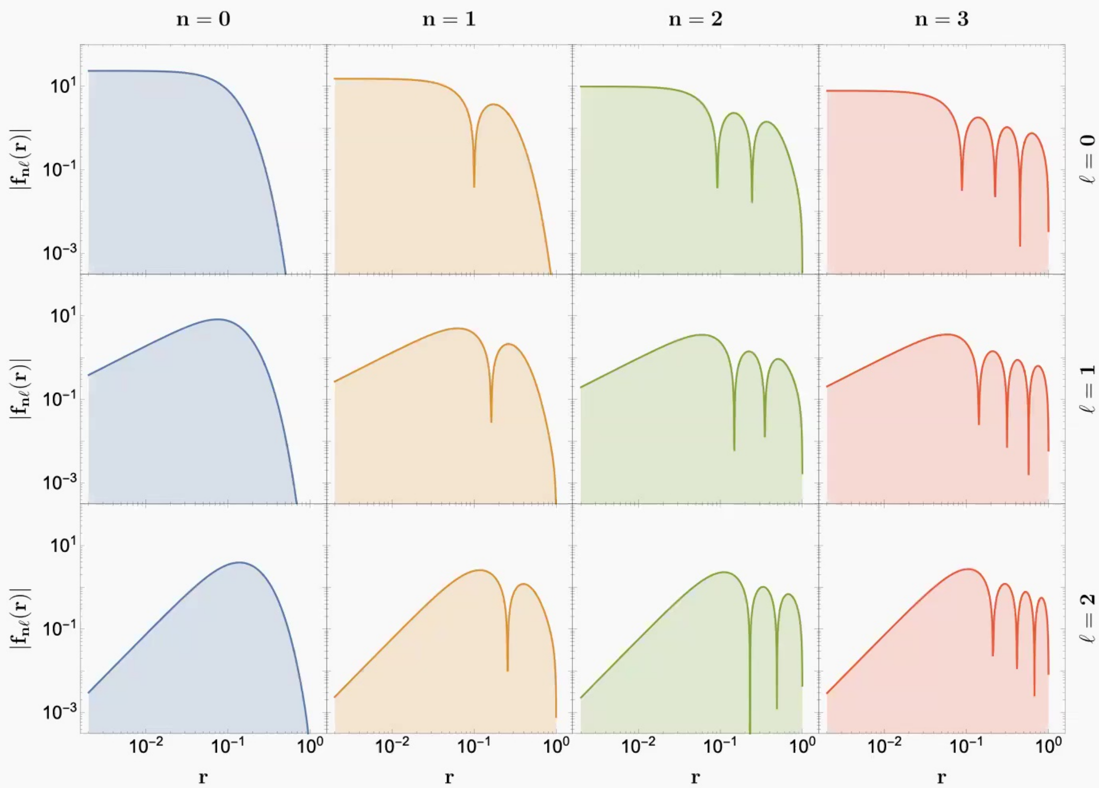
Solving the Eigensystem

$$i\hbar\dot{\psi} = \left(-\frac{\hbar^2}{2m}\nabla^2 + m\langle\Phi\rangle\right)\psi$$

$$\nabla^2\Phi = 4\pi G m|\psi|^2$$

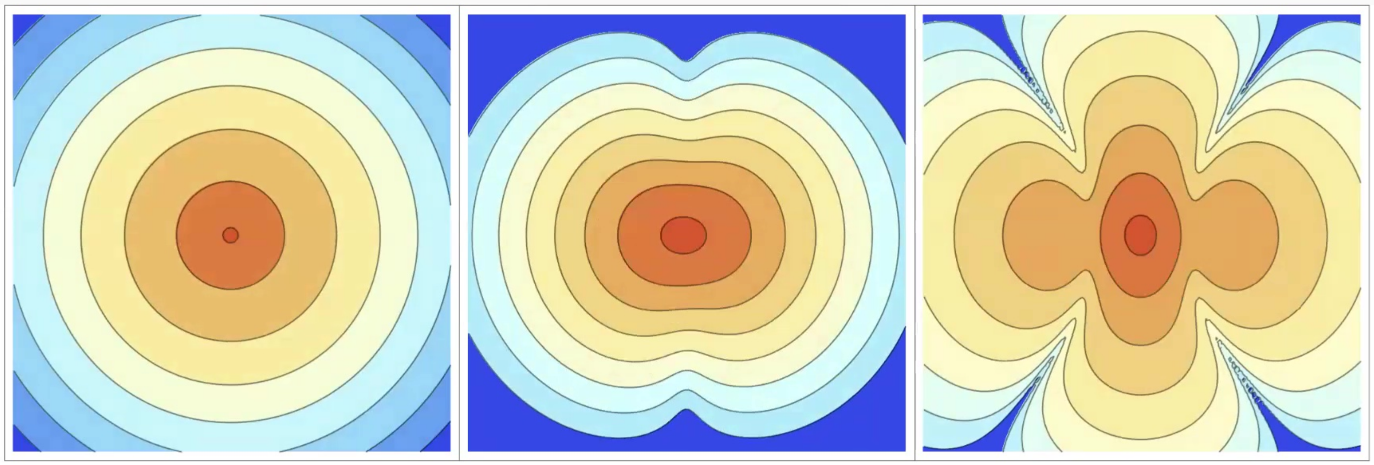
$$\rho = m|\psi|^2$$

The Eigenstates



Note: these eigenstates pop out for both soliton and ULDM potentials!

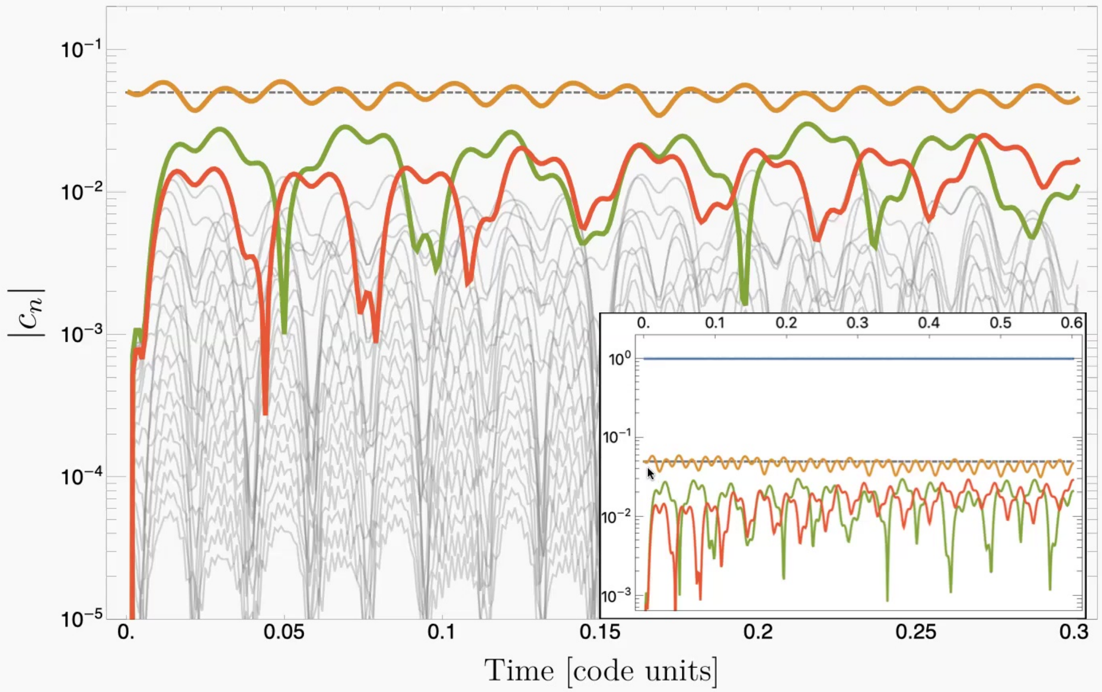
Superposition of Eigenstates



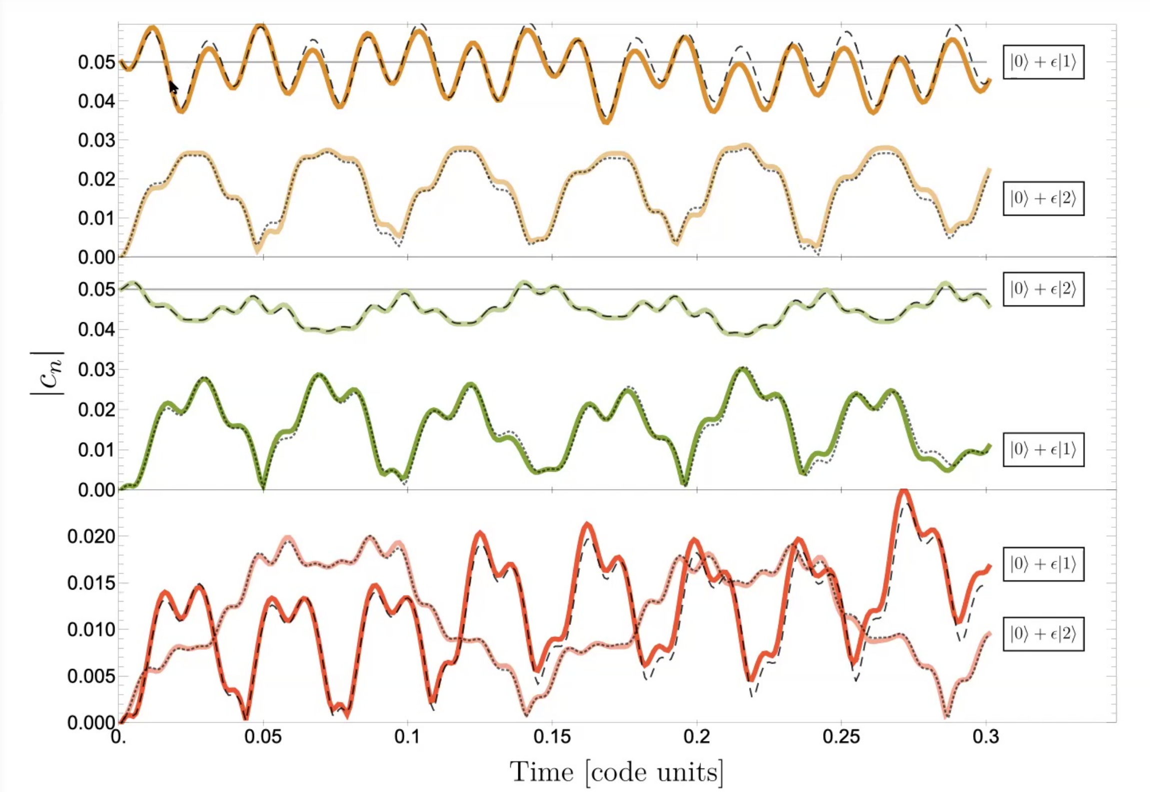
$c_{nl}|\,nl\rangle = \sqrt{0.3}\,|10\rangle$ $c_{nl}|\,nl\rangle = \sqrt{0.3}\,|01\rangle$ $c_{nl}|\,nl\rangle = \sqrt{0.3}\,|02\rangle$

00:13 -00:37

Radially-Symmetric Version: $\ell = 0$

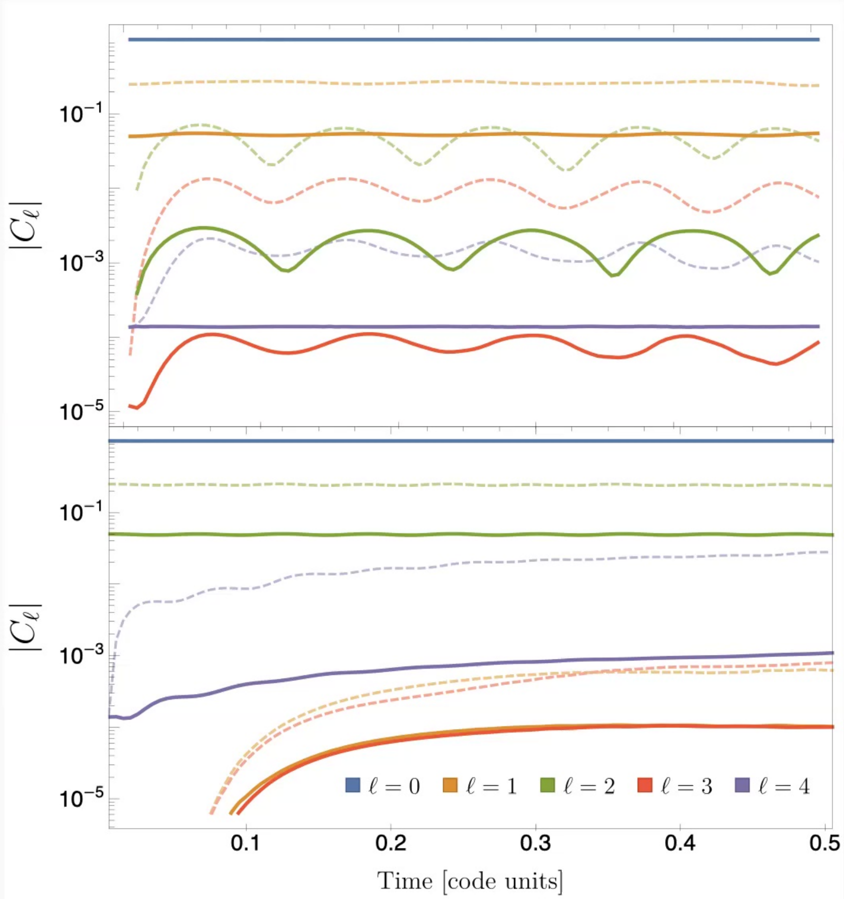


Radially-Symmetric Version: $\ell = 0$

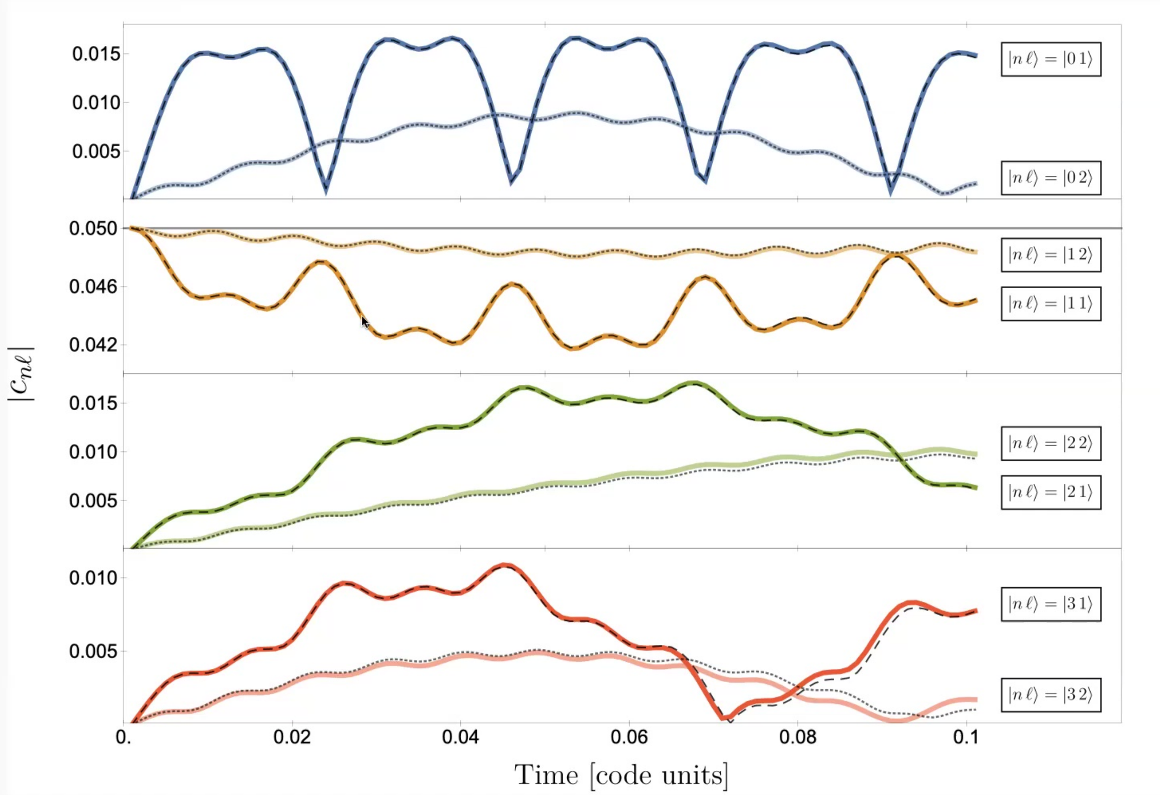


Asymmetric Version: $\ell \neq 0$

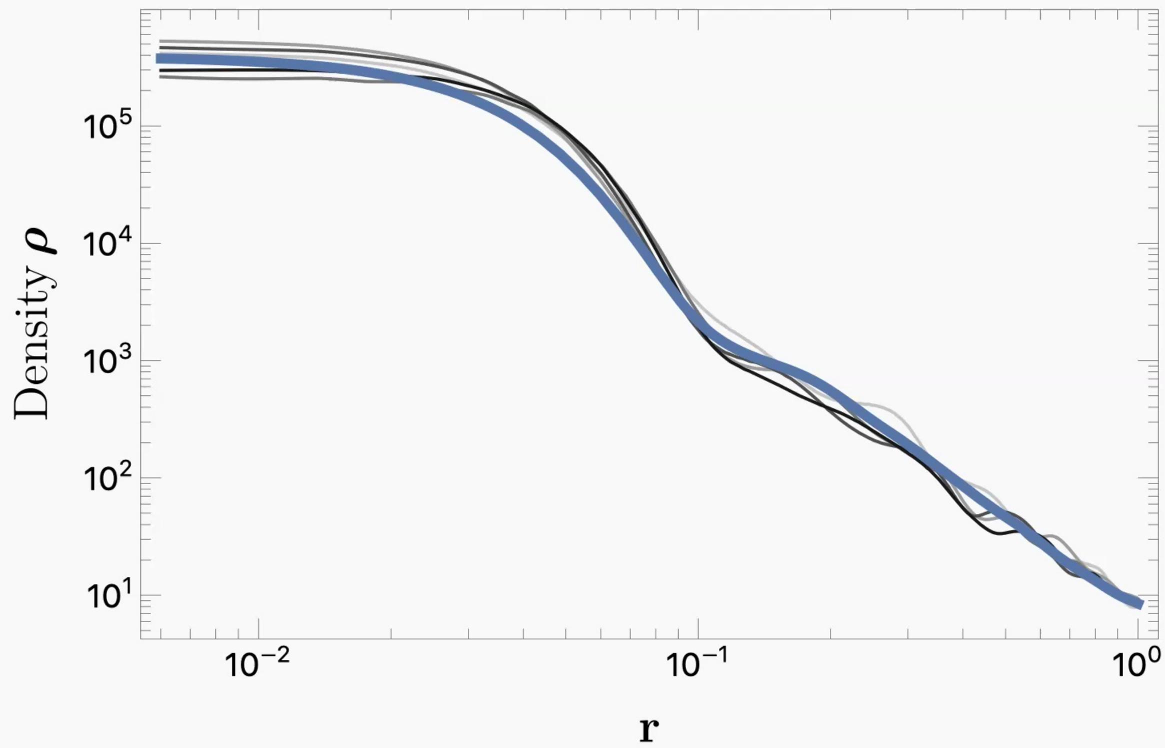
$$|C_\ell| \equiv \sqrt{\sum_n |c_{n,\ell}|^2}$$



Asymmetric Version: $\ell \neq 0$

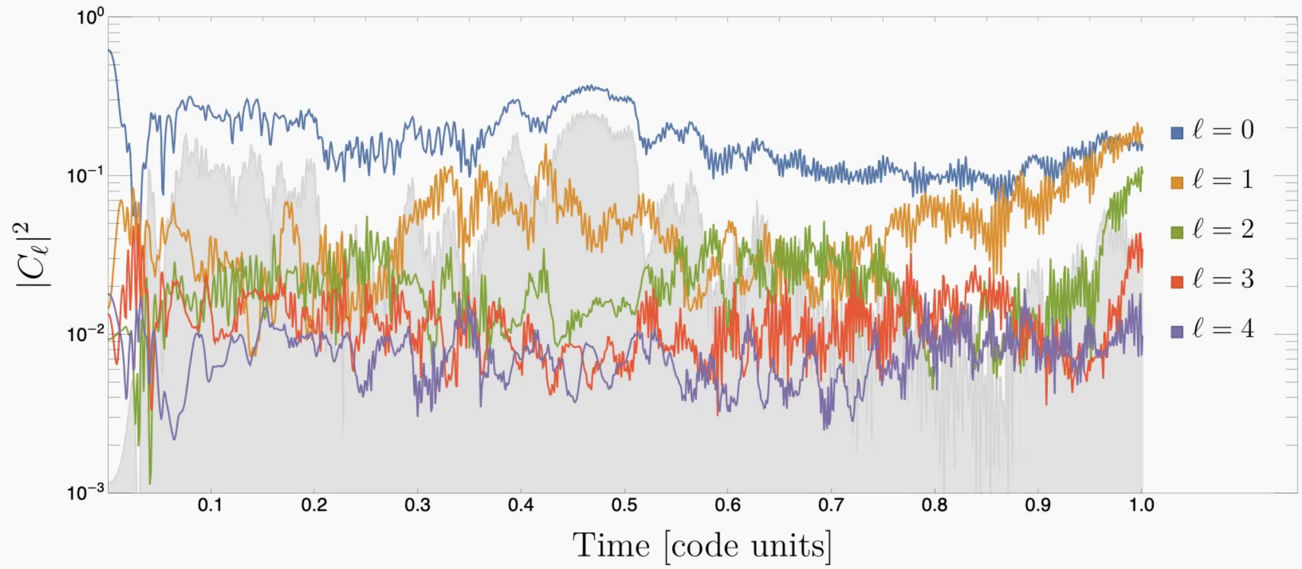


Building Up a Halo: Random Initial Conditions



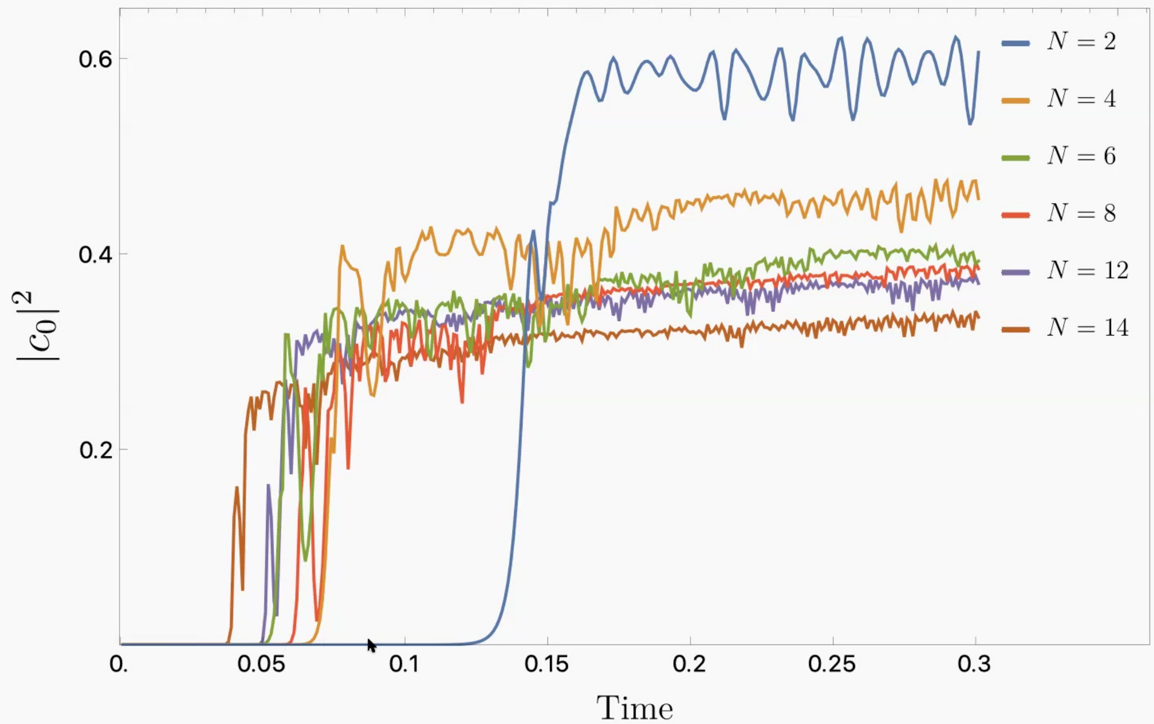
The profile is pretty stable...

Halo Evolution: Random Initial Conditions



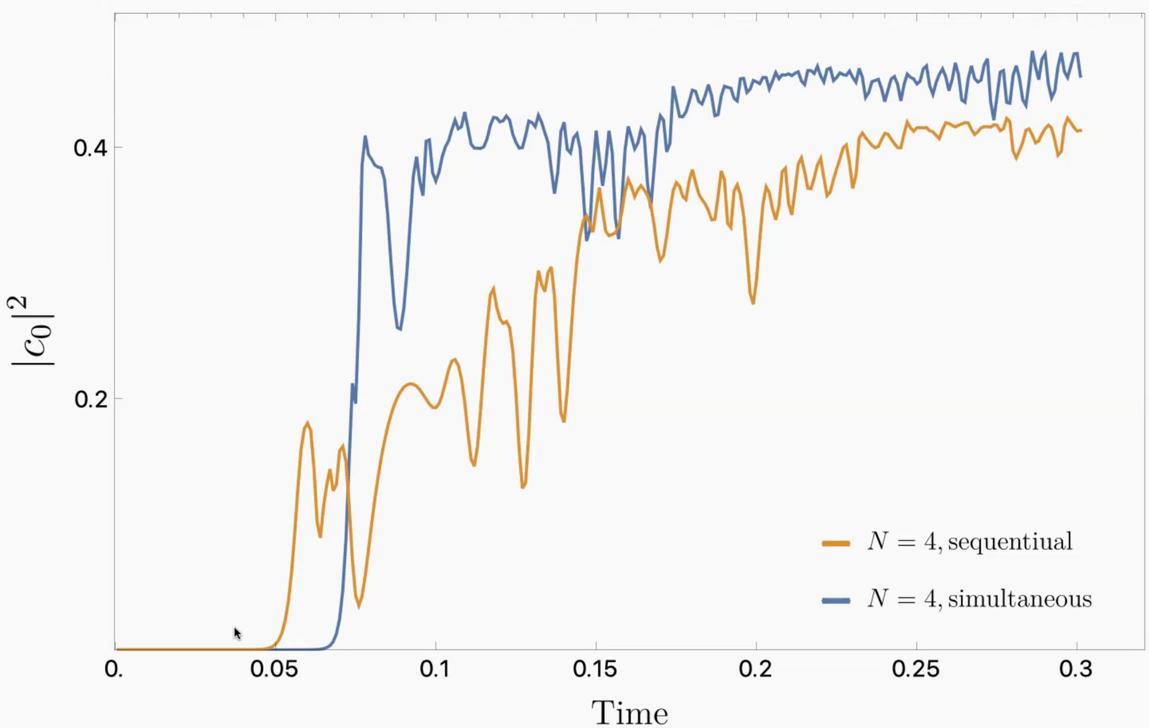
...but the eigenstates vary a lot!

Halo Evolution: Symmetric Initial Conditions



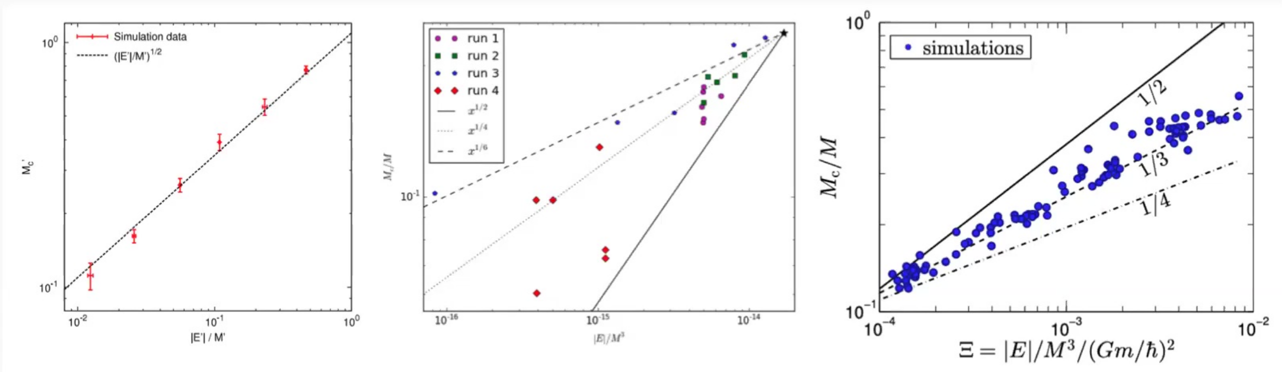
Instead, symmetrically arrange solitons and track just the ground state soliton!

Merger History Matters!



The order of mergers plays a role in the size of the final core!

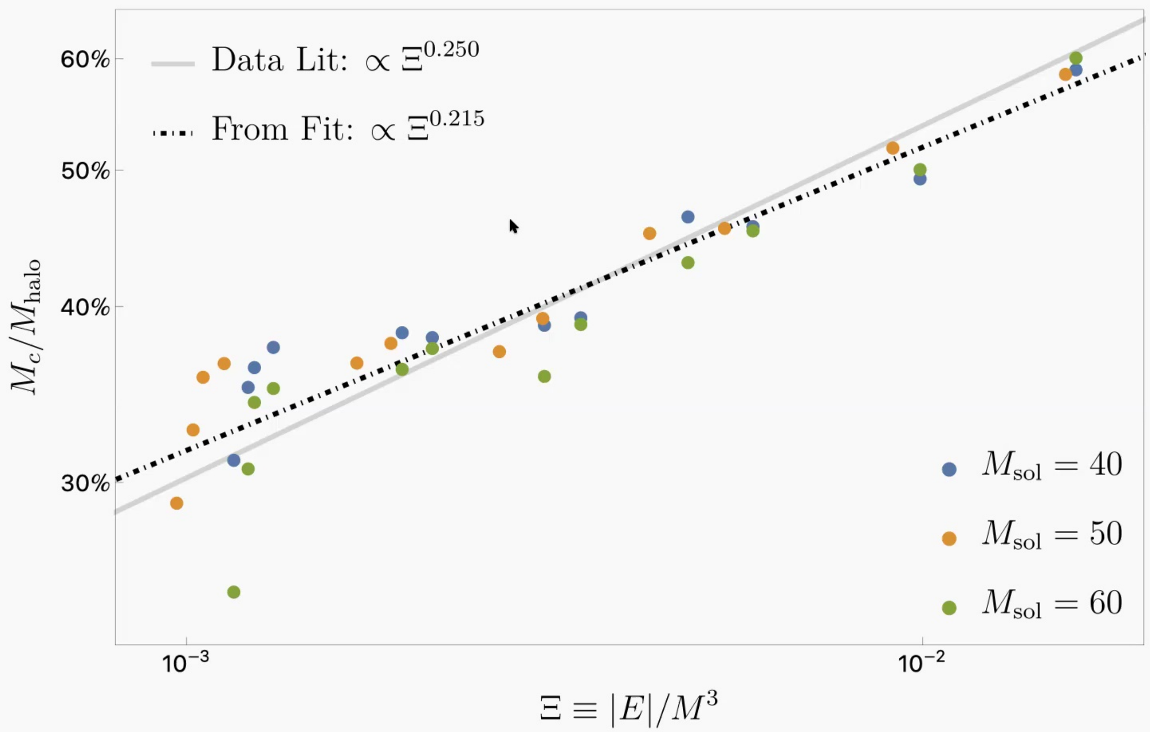
Core-Halo Mass Relation: In the Literature



Schive et al. (2014)	Schwabe et al. (2016)	Mocz et al. (2017)
1407.7762	1606.05151	1705.05845

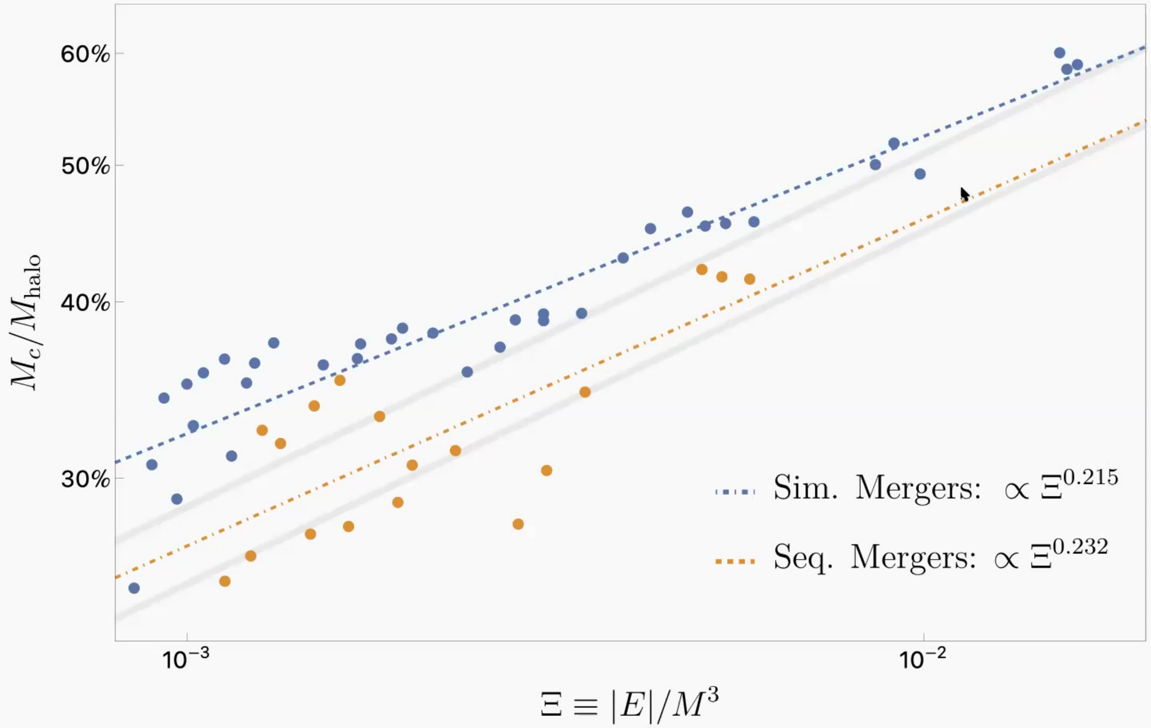
The size of the core relative to the halo is an important prediction but there's no consensus in the literature on the correct scaling!

Core-Halo Mass Relation: Our (Preliminary) Data



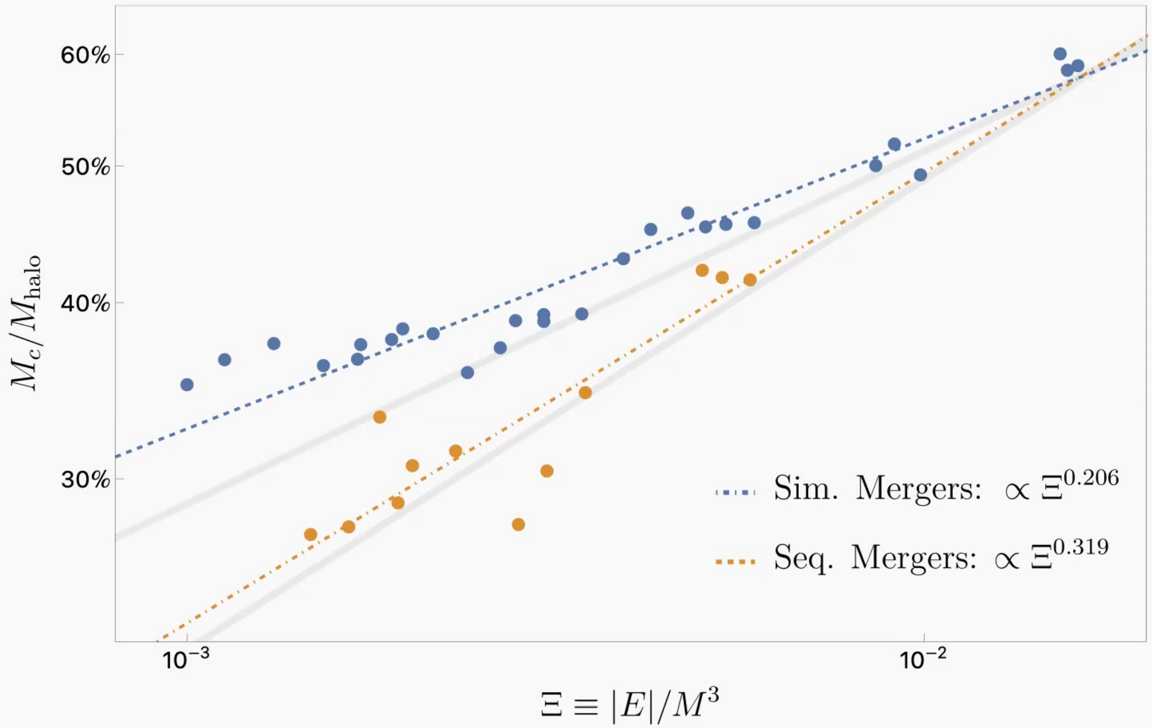
Preliminary results suggest a scaling for equal mass, simultaneous soliton mergers consistent with Schwabe et al. (1606.05151)

Core-Halo Mass Relation: Our (Preliminary) Data



Comparing all data between simultaneous and sequential mergers shows approximately the same slope, but also lots of scatter at small Ξ

Core-Halo Mass Relation: Our (Preliminary) Data



Truncating the data at N < 10 solitons shows a slope more consistent with Mocz et al. (1705.05845)

Takeaways

Perturbed Soliton
Can be modelled with perturbation theory really well!

ULDM Halo with random ICs
Not as simple to model with PT...

...but full simulation box can still be decomposed!

ULDM Halo with symmetric ICs
A cleaner picture in eigenstates!

Conclusions

Soliton formation is quick and evident!

Reveals hierarchical core formation

& the core-halo mass relation!

Future Work

Core Halo Mass Relation
Rounding off the picture with unequal soliton mergers.

Baryonic Effects in ULDM halos
We are modeling baryonic effects with external potentials, including supernova feedback (time-varying Hernquist potential) and baryonic disks (Miyamoto-Nagai disk potential).

Questions?