

Excited states of wave dark matter after a sudden disturbance

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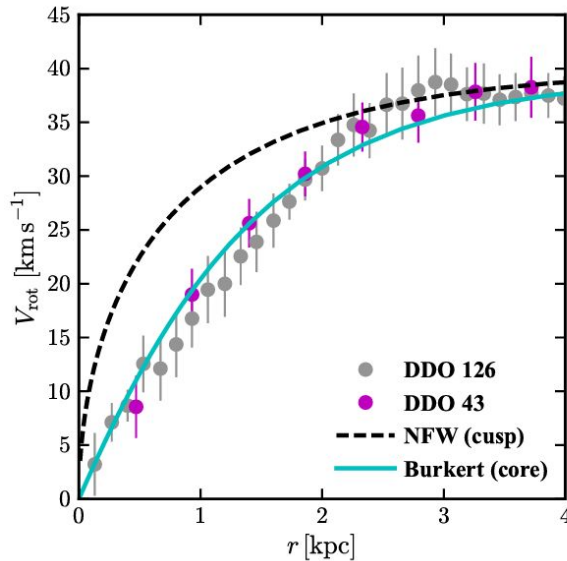
Fuzzy Dark Matter : a quick overview

- CDM has some known limitations :
 - Cusp/Core Problem,
 - Missing Satellites and Dwarfs,
 - Too big to fail.

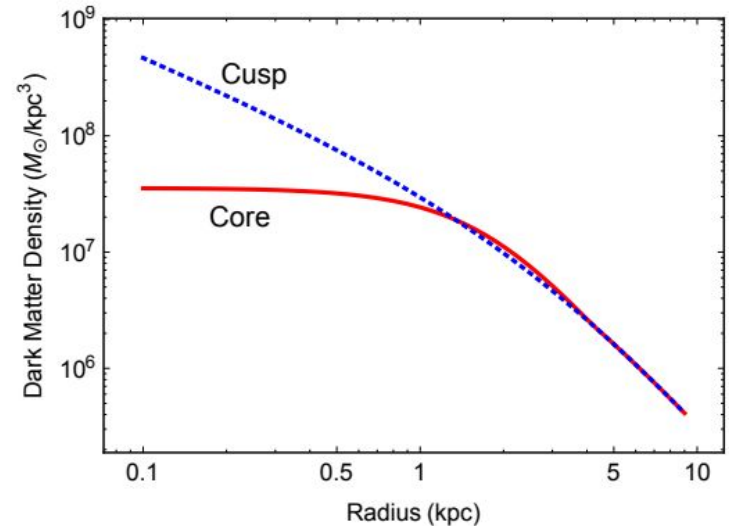
Bullock & Boylan-Kolchin (2017), arXiv:1707.04256.
- In particular: Cusp/Core Problem → an issue on small (galaxy-size) scales.

Fuzzy Dark Matter : a quick overview

Illustration of Cusp/ Core Problem



Bullock & Boylan-Kolchin (2017), arXiv:1707.04256.



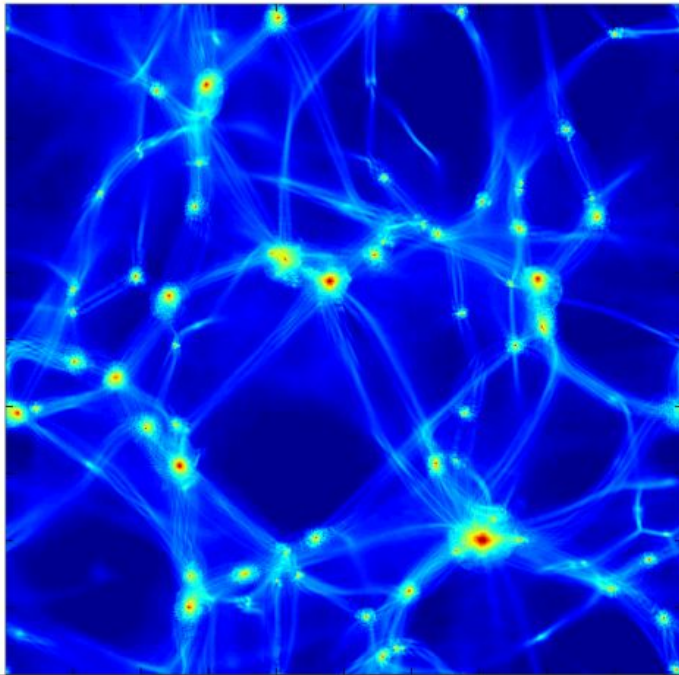
Tulin et al, 2018, Physics Reports 730:1–57

Fuzzy Dark Matter : a quick overview

- Fuzzy Dark Matter studies began around 2000;
early seminal paper:
W. Hu, R. Barkana & A. Gruzinov, arXiv:astro-ph/0003365 (2000)
- Core Idea: If DM was a ultralight scalar particle(ALPs), forms a Bose Einstein Condensate
- The Pros: quantum effects can prevent formation of the cusp.
- The Cons: Needs $m > \sim 10^{-22} - 10^{-23} \text{ eV}$
which may or may not be compatible with observed properties

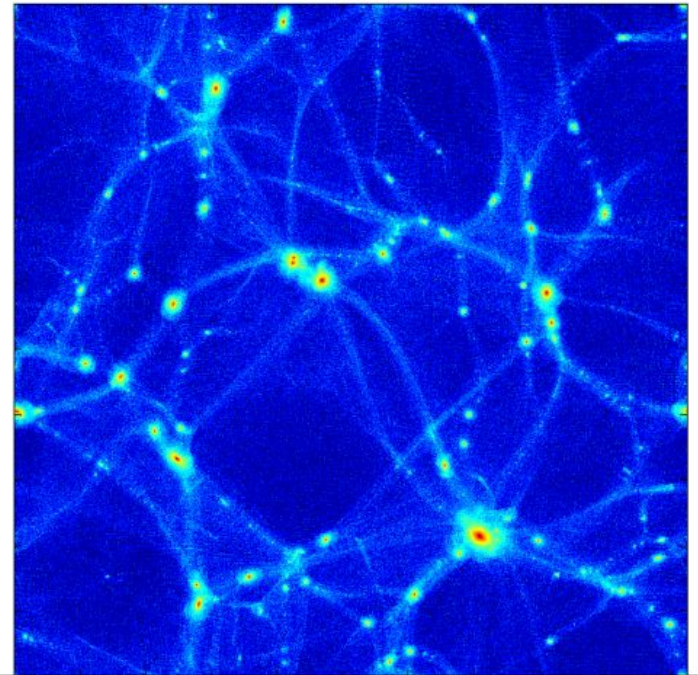
Fuzzy Dark Matter : a quick overview

- Major paper : [Schive, Chiueh & Broadhurst \(2014\), *Nature Phys.* 10, 496.](#)
→ Showed equivalence with CDM at large scales



← FDM Sim

N-body CDM sim →



Aims of our preliminary work:

- The majority of FDM simulations and work on the small (galaxy) scale has looked primarily at the properties of:
 - long-time virialised haloes
 - Full 3d simulations with small simulation boxes (periodic boundary conditions)
- Want to move towards an understanding of the superfluid dynamics that goes on to tackle a number of questions such as:
 - are existing halos likely to be in a stable/virialized phase, or in an initial transient?
 - what happens during the transient?
 - how important are high velocity (small scale) phenomena and the possibility of escape (bigger simulation boxes or absorbers)

Current status

- preliminary work, looking at qualitative information about what dynamics is occurring in a variety of situations
- We desire to include very high velocity/small scale components which are expensive to resolve in 3D
- Therefore running spherically symmetric simulations that allow higher resolution and bigger boxes

Terminology Interlude

- The ultralight scalar particles obey the Gross-Pitaevskii equation

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + V\psi + g|\psi|^2$$

- Fuzzy $\rightarrow$ No self interaction(g).
For self interacting dark matter see [Poster #37]

Dynamics – what we simulate

- Schrödinger-Poisson Equations(SPE)

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V \psi$$

$$\nabla^2 V = 4\pi \rho |\psi|^2$$

- Spherically symmetric 3D equations $\rightarrow$ 1D equations (radial)

$$i \frac{d\phi}{dt} = \left[-\frac{1}{2} \frac{d^2}{dr^2} + V_G \right] \phi;$$

$$\frac{d^2 \mathcal{V}}{dr^2} = 4\pi r |\psi|^2.$$

$$V_G = \mathcal{V}/r$$

$$\phi = r\psi$$

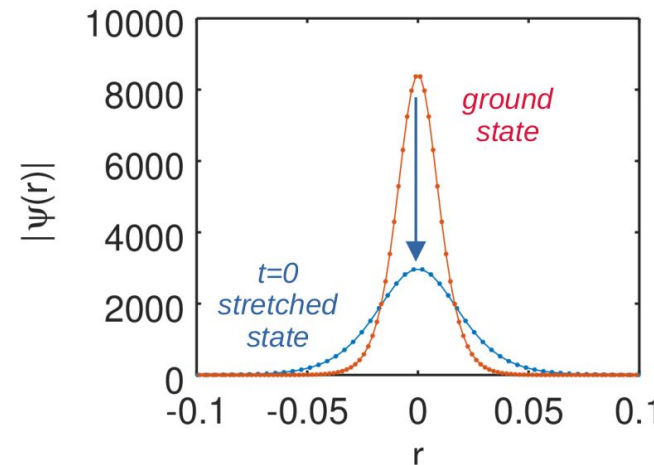
Numerics-what we simulate

- Imaginary Time Propagation
→ Groundstate of the SPE

- Introduce scaling :

$$r = \tilde{r}/\sigma; \quad \phi = \tilde{\phi}/\sqrt{\sigma};$$

- Single control parameter to introduce a family of systematic initial conditions

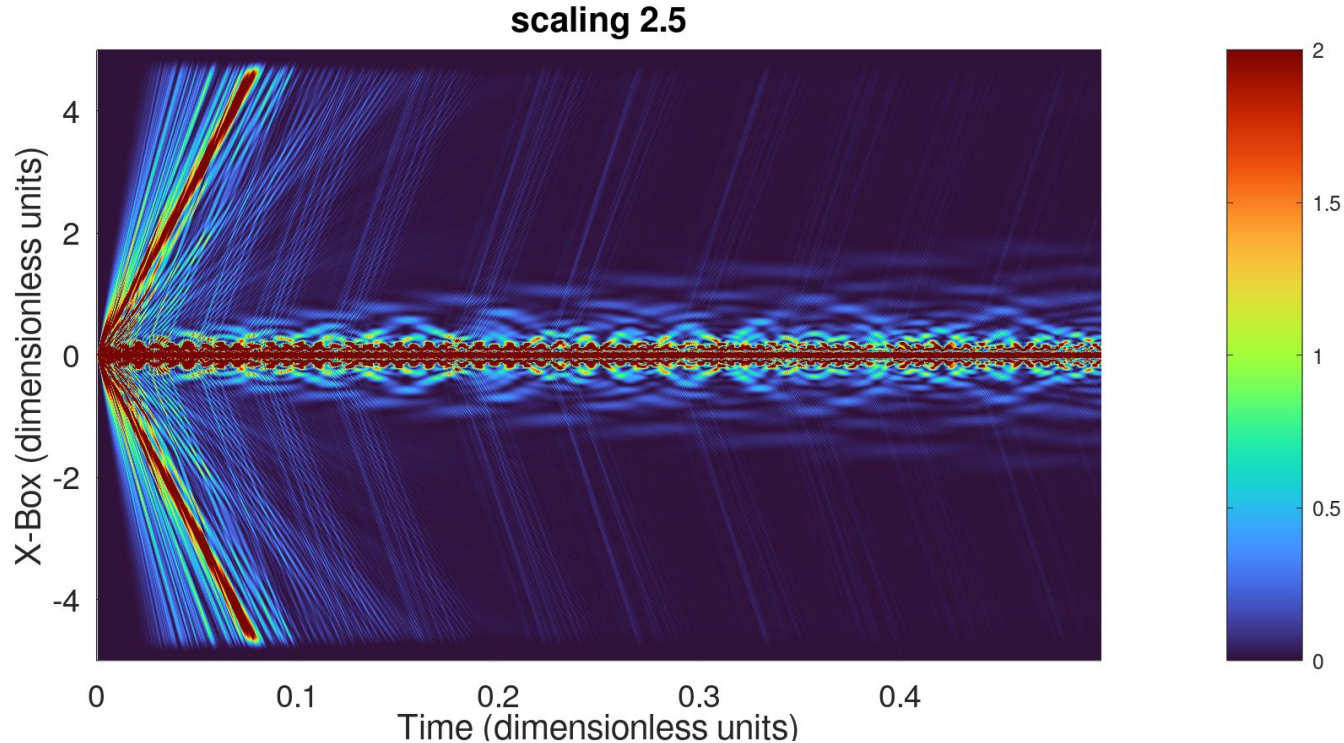


Numerics-what we simulate

- radial spherically symmetric equation allows high resolution to resolve small scale fluctuations, in big boxes (e.g. $2^{14} = 16384$ points), without supercomputer time.
- Absorbing boundary conditions allow for unbound mass to leave, No potential wrap around.
- At time=0 we scale the ground state halo to produce excitations
 - Scaling > 1 stretching
 - Scaling < 1 compression

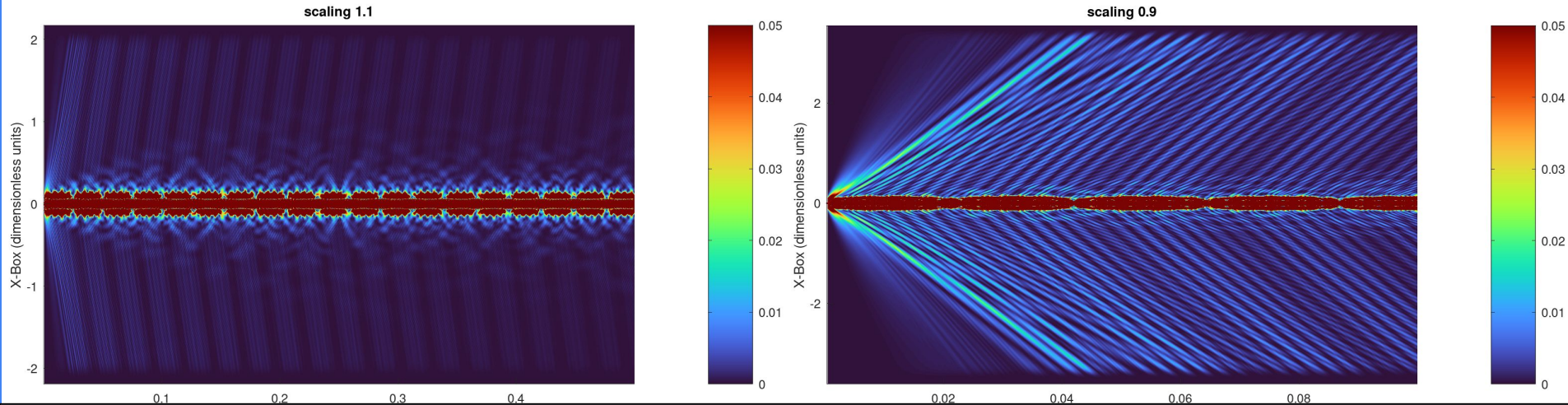
Vanilla evolution after a disturbance

- E.g. Expansion at $t=0$ by a factor of $\sigma = 2.5$



Preliminary Results-Beats and Bursts

- Both scaling >1 and <1 show emissions, referred to in literature as scalar field bursts. Guzmán & Ureña-López (2006), *ApJ* 645, 814.
- The core shows clear signs of oscillations.

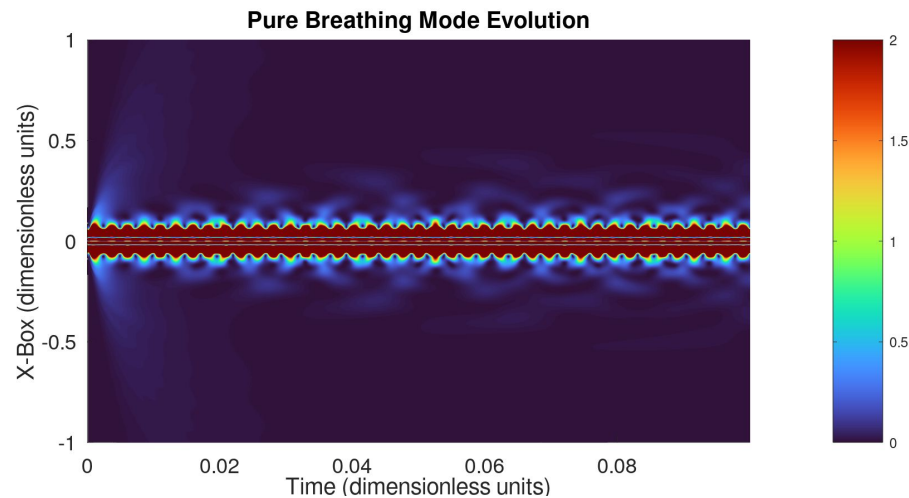
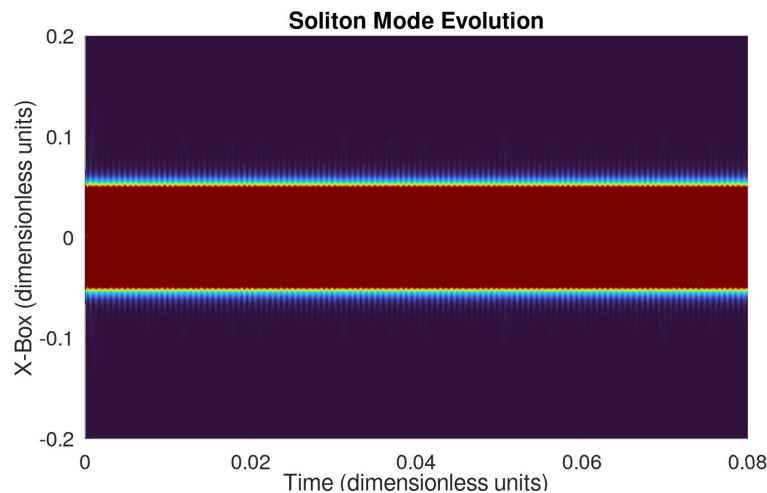


Preliminary Results–Density Matrix Analysis

- How do we recover soliton and excited modes of the system?
 - One body density matrix constructed from snapshots of the wavefunction in time.
- Isolate the soliton and breathing mode. Evolve and observe

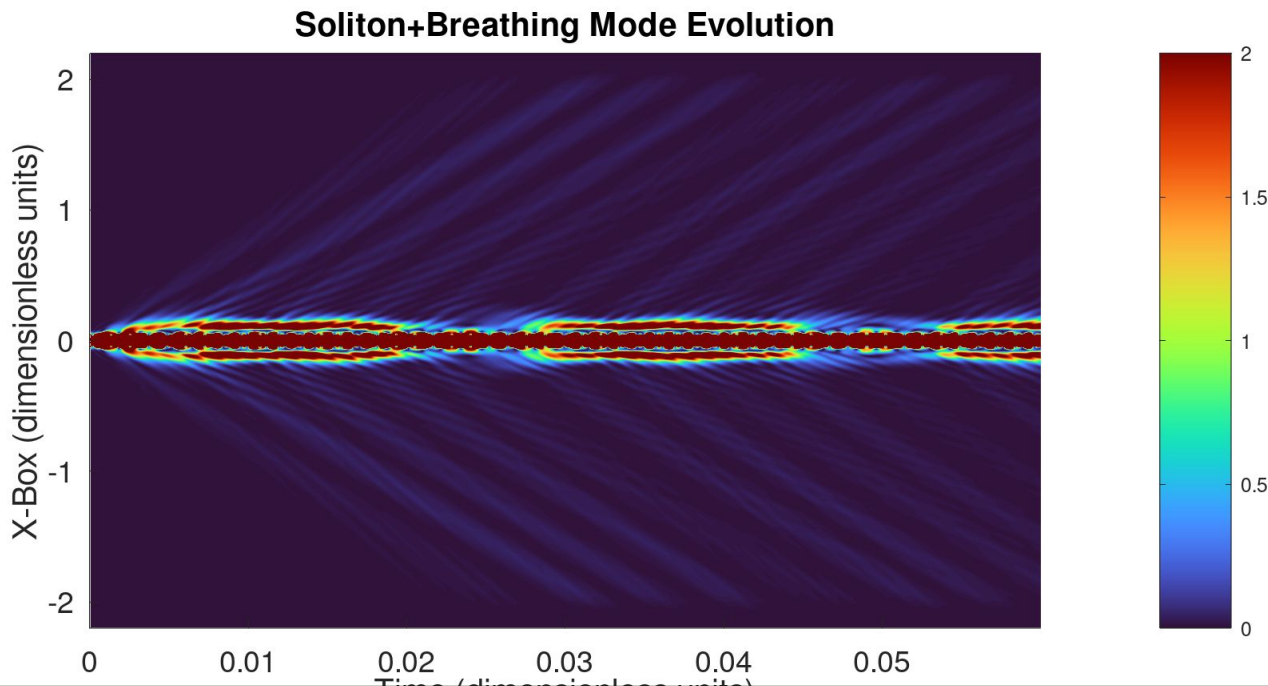
Preliminary Results–Density Matrix Analysis

- Reconstruct a partial wavefunction then evolve with SPE equation to better understand mechanisms
- Soliton evolved in its self potential....does nothing. Good!
- Breathing evolved in the average potential by itself also does..not much?



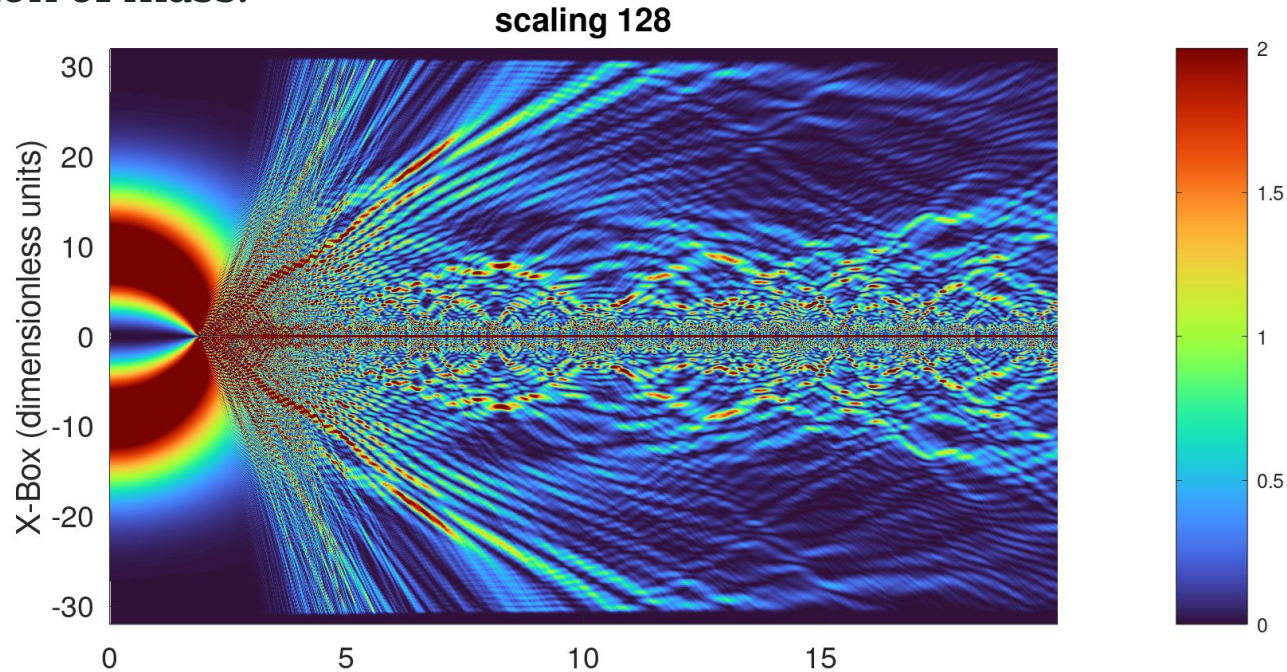
Preliminary Results–Density Matrix Analysis

- Soliton+Breathing mode in their self potential ...does stuff!?
- In particular – bursts appear again



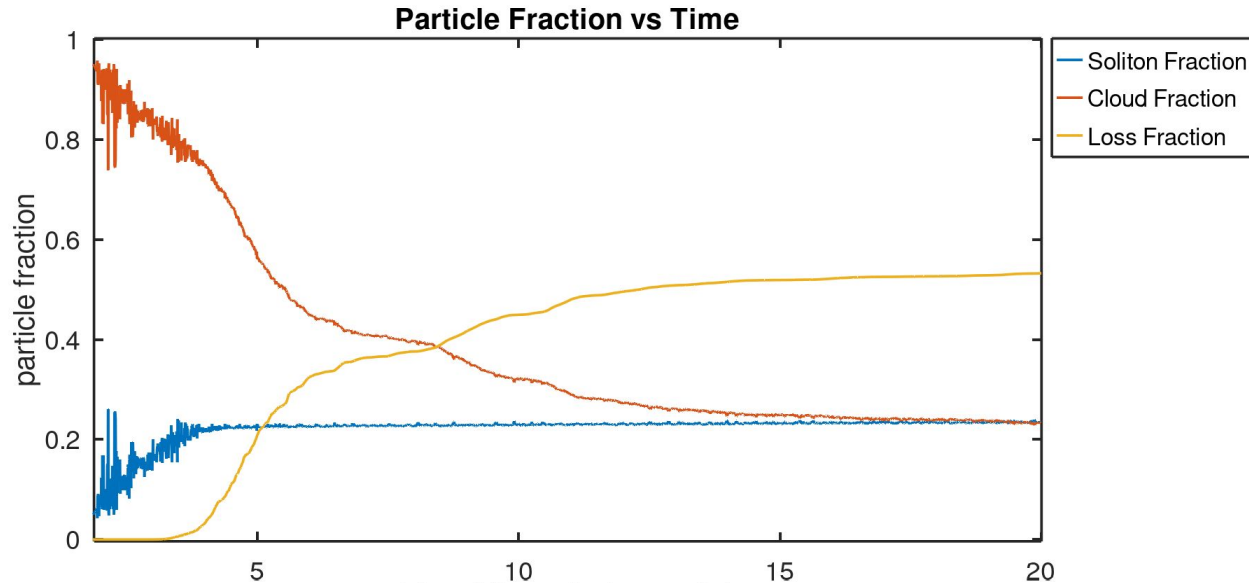
Preliminary Results–A more plausible halo

- Potential problem: most simulations produce very high soliton to halo fraction.
- Goal: Try to generate a soliton-halo system which has a more reasonable distribution of mass.



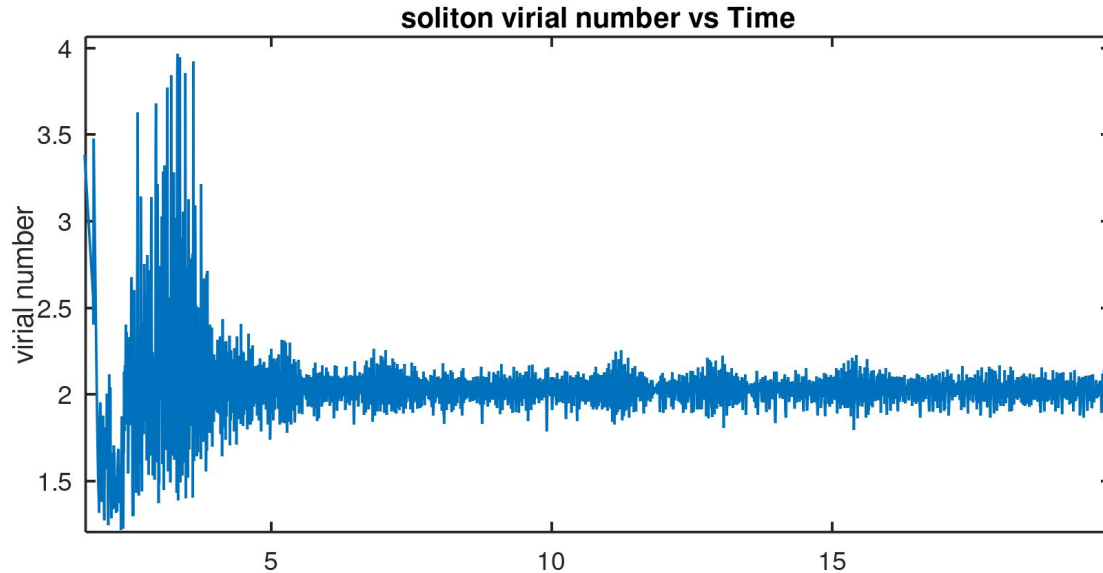
Preliminary Results–A more plausible halo

- Diagnostics: How do we know this resulted in something reasonable ?
- Clue 1: Particle Fraction



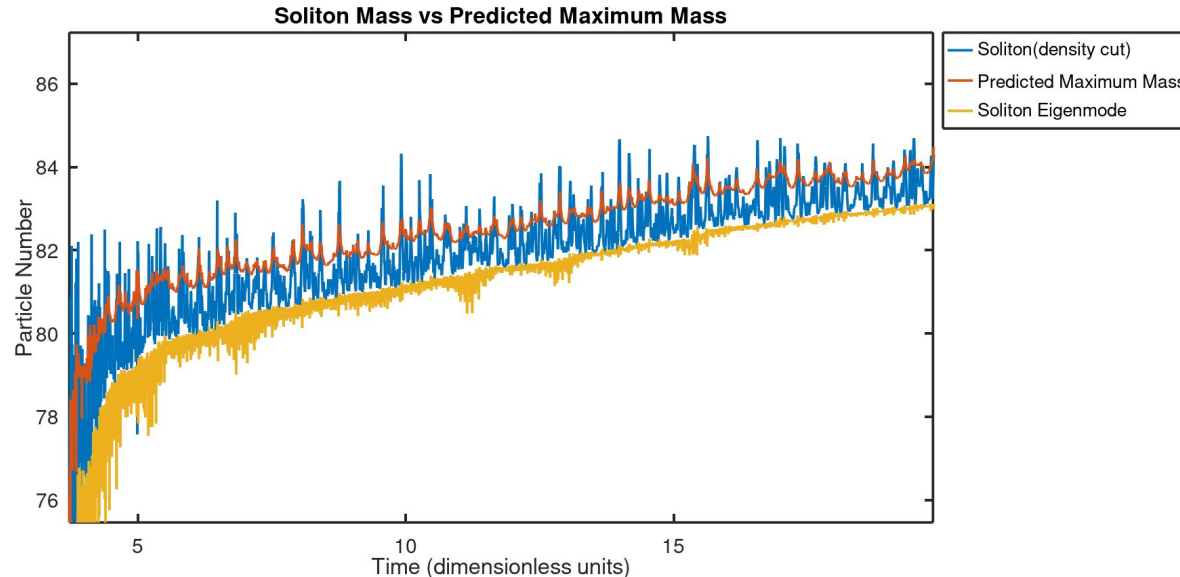
Preliminary Results–A more plausible halo

- Diagnostics: How do we know this resulted in something reasonable ?
- Clue 2: Virialization



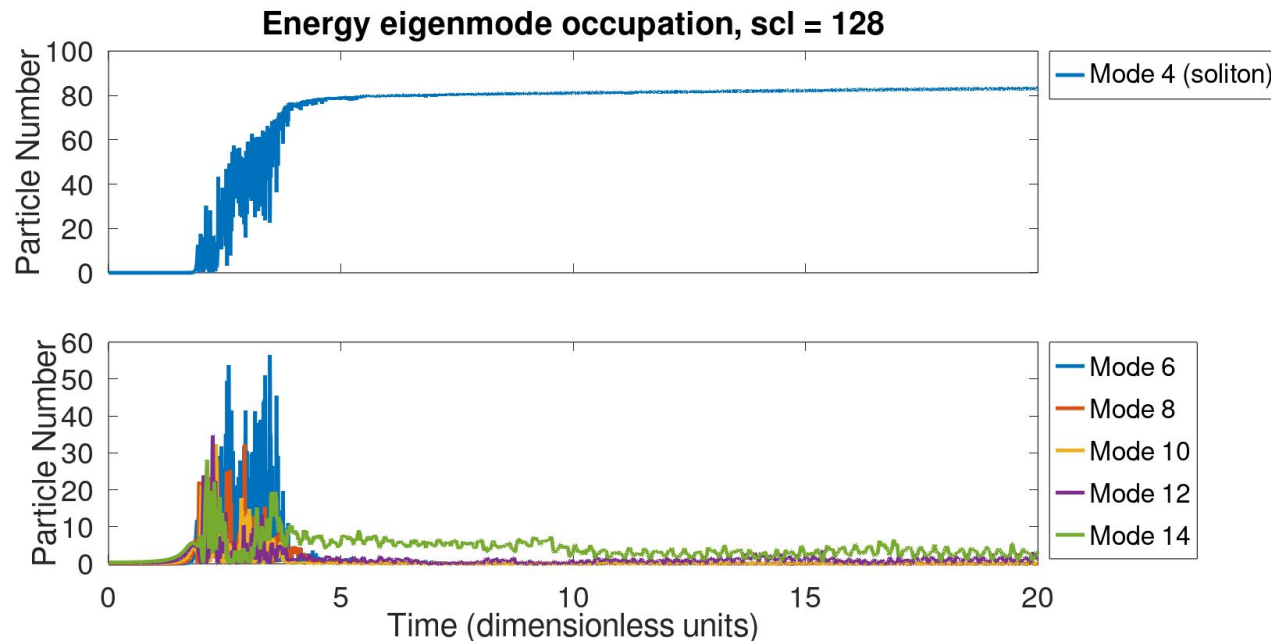
Preliminary Results–A more plausible halo

- Diagnostics: How do we know this resulted in something reasonable ?
- Clue 3: Maximum soliton mass (“ $1/3$ relation”). [Blum et al. \(2025\), JCAP 06, 050.](#)



Preliminary Results–A more plausible halo

- Soliton Density cut: Soliton + Bound modes



Future Outlook

- Work in progress:
validation of spherical vs full 3d cartesian simulations (in smaller boxes).
- Mechanism behind scalar field bursts
- Core-Halo mass relations from the perspective of using a single parameter to generate various regimes
- Work in Progress:
Extension to cylindrical filament modeling(2D), poster #36