Soliton Random Walk and Oscillations in Fuzzy Dark Matter

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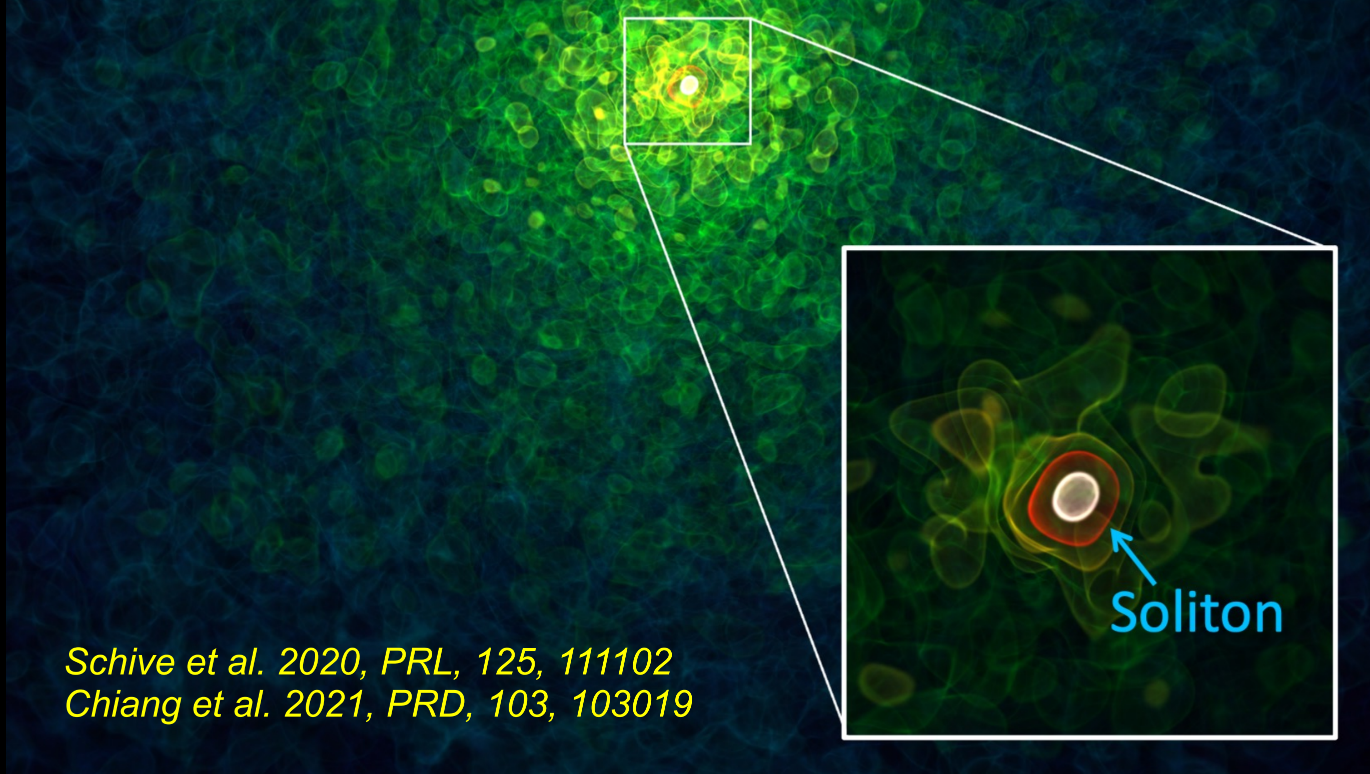

Schive et al. 2020, PRL, 125, 111102
Chiang et al. 2021, PRD, 103, 103019

Outline

- Fuzzy/Wave Dark Matter (FDM/ψDM)
- Simulations
- Soliton Random Walk
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Fuzzy Dark Matter (FDM)

- Extremely light particles
  - $m_{22} \equiv m_\psi$ / 10^{-22} eV ~ 1.0 → 10^{31} lighter than cold dark matter (CDM)
  - de Broglie wavelength becomes astronomical (kpc) scale
  - Wavelike properties (e.g., interference)
  - References:
    - D. Marsh. Physics Reports 643, 1 (2016)
    - L. Hui, J. Ostriker, S. Tremaine, & E. Witten. PRD 95, 043541 (2017)
    - E. Ferreira. The Astronomy and Astrophysics Review; arXiv:2005.03254 (2020)
    - L. Hui. Annual Review of Astronomy and Astrophysics; arXiv:2101.11735 (2021)

- Governing eq.: Schrödinger-Poisson eq.

$$i\frac{\partial \psi(x)}{\partial t} = -\frac{1}{2m_\psi}\nabla^2\psi(x) + m_\psi \varphi(x)\psi(x)$$

$$\nabla^2\varphi(x) = 4\pi G a(t)\left(|\psi(x)|^2 - 1\right)$$

ψ: wave function

ϕ: Newton potential

a: scale factor

ħ: 1

Particle mass (m_ψ) → the ONLY free parameter in FDM

Quantum Fluid

- **Rewrite Schrödinger eq. into conservation laws**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0,$$

$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} = \nabla \left(\frac{1}{2 m_\psi^{2}} \frac{\nabla^2 f}{f} \right) - \nabla \varphi$$

$$\psi = f e^{iS}$$

$$\rho = m_\psi f^2$$

$$v = m_\psi^{-1} \nabla S$$

$$\text{Hydro}: \frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} = -\frac{1}{\rho} \nabla P - \nabla \varphi$$

$$\tilde{P}_{ij} = \frac{1}{m_\psi} \left(\partial_i f \partial_j f - \frac{1}{4} \delta_{ij} \nabla^2 f^2 \right)$$

quantum stress

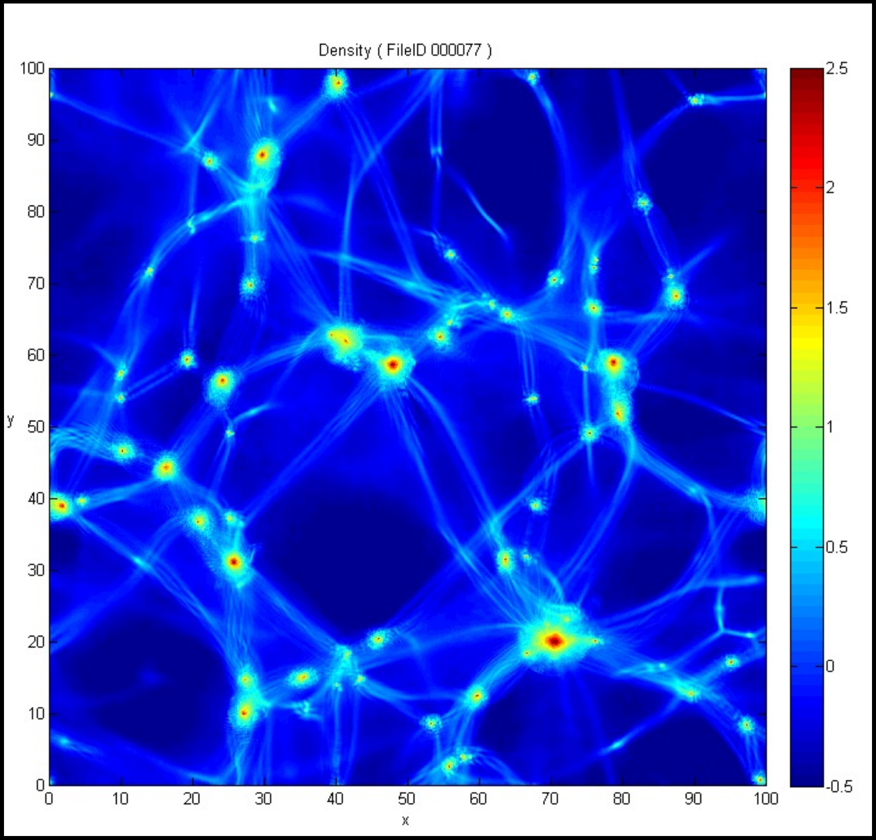
$$k_J = (6a)^{1/4} (H_0 m_\psi)^{1/2}$$

Jeans wave number in FDM

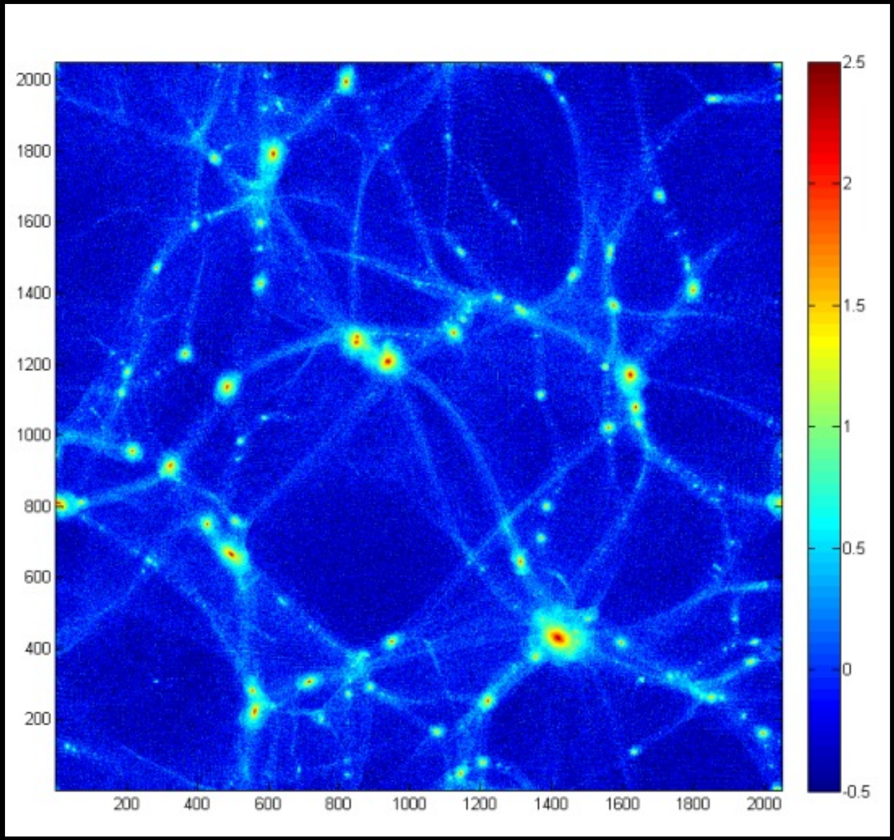
→ Suppressing small-scale structures

FDM vs. CDM (Large Scales)

FDM



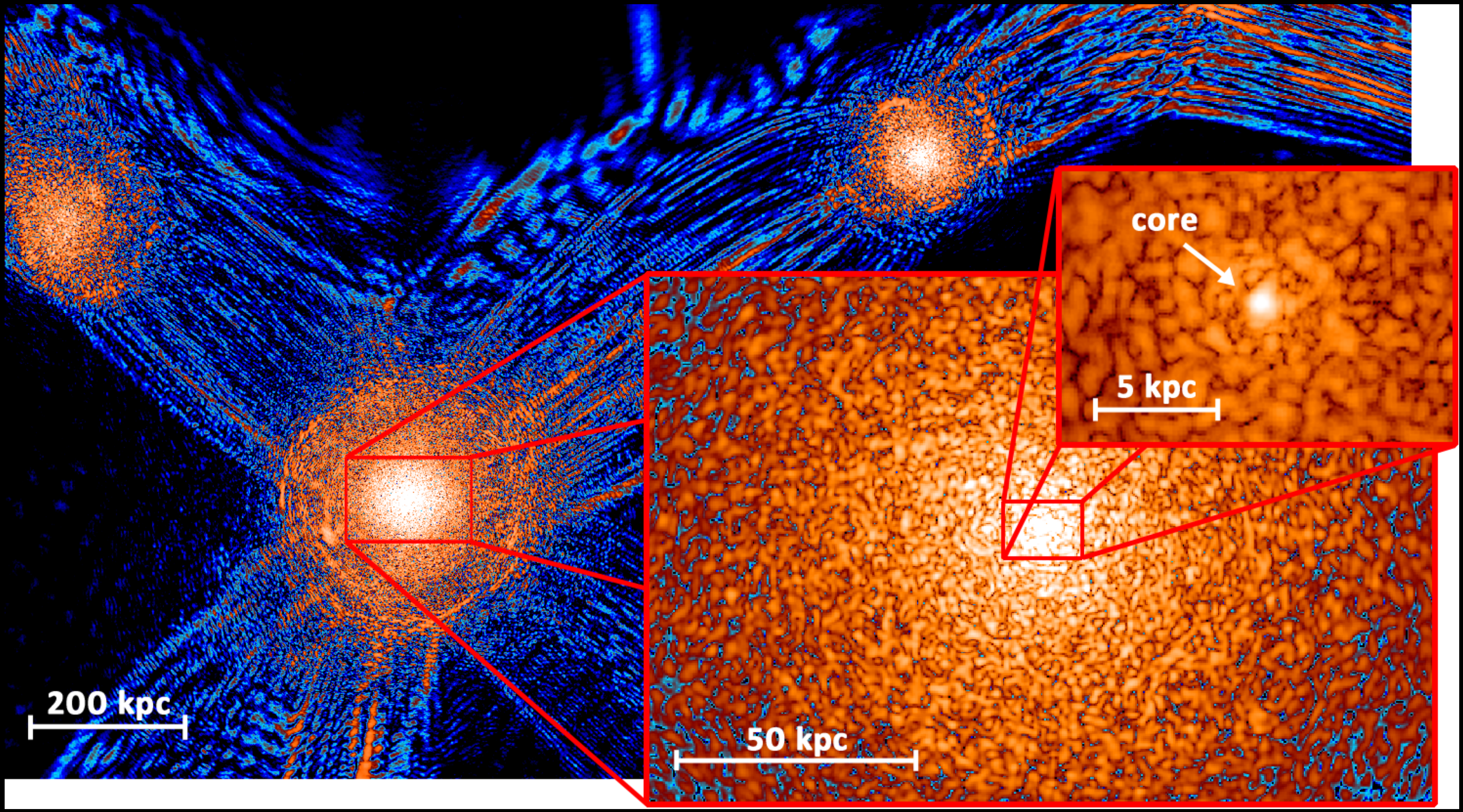
CDM



50 Mpc/h box

- **Large-scale structures are indistinguishable**

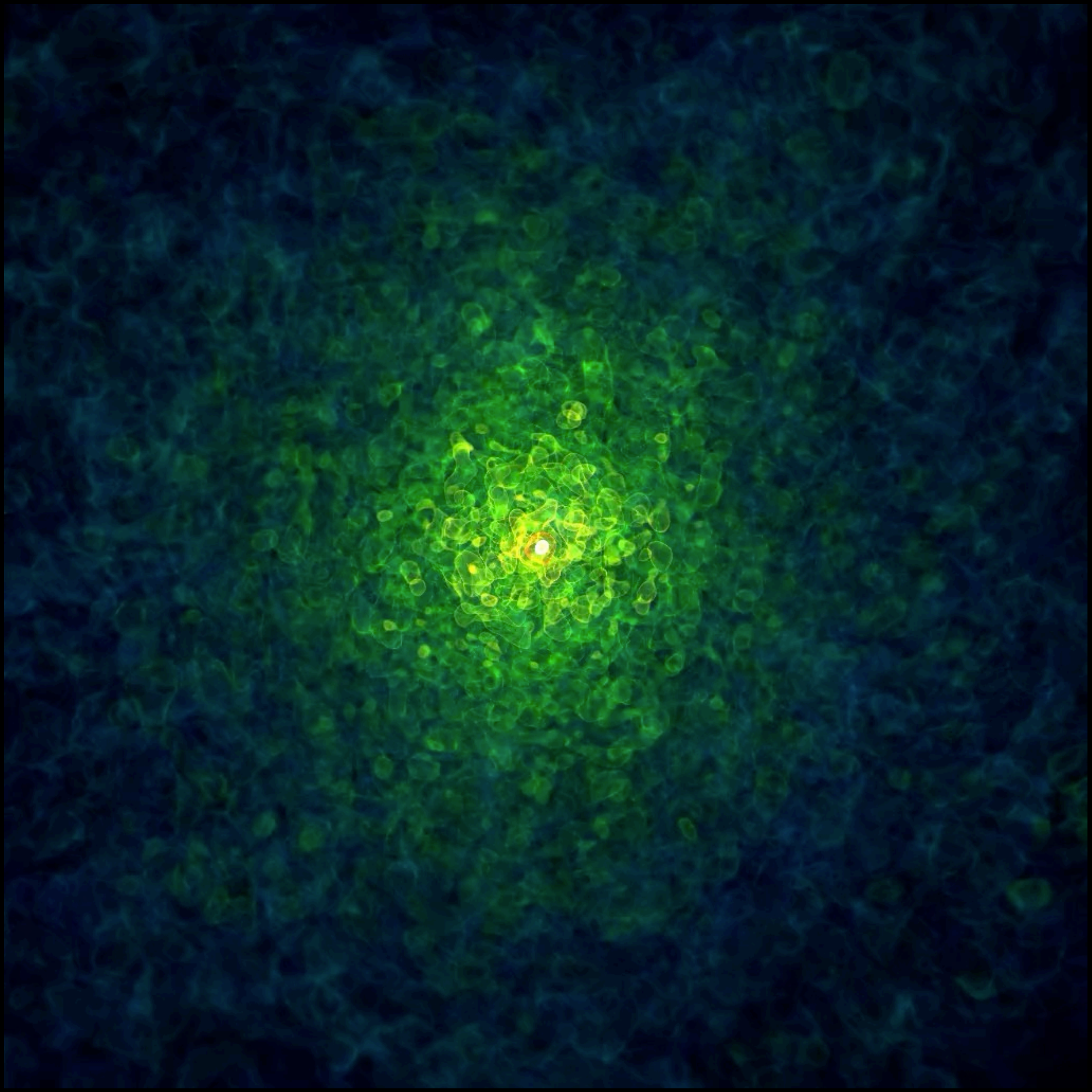
Interference Patterns (Small Scales)



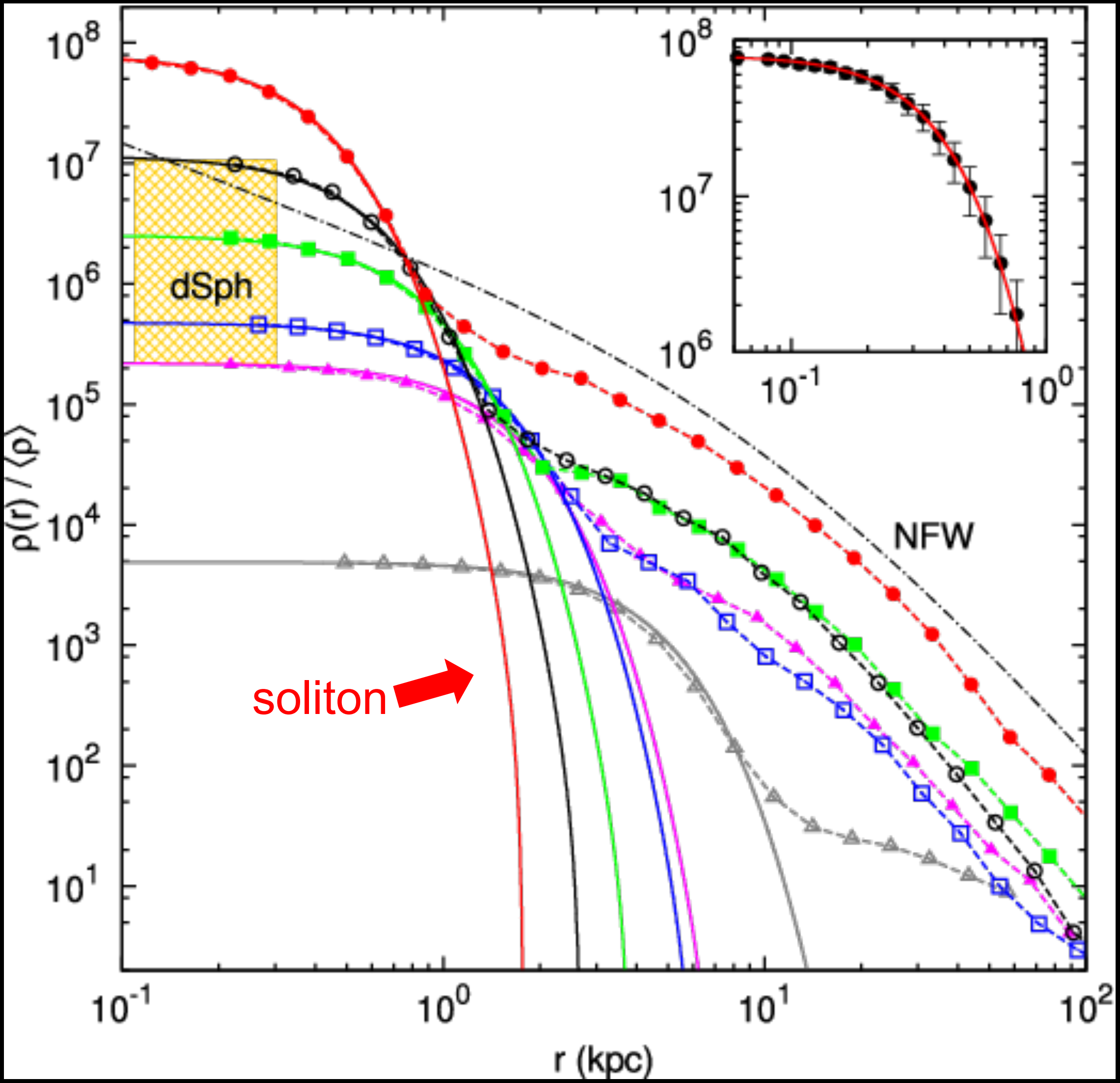
- Interference is everywhere: filaments, density granules, and central cores ↔ CDM predicts cuspy profiles

Schive, Chiueh, & Broadhurst 2014, Nature Physics, 10, 496

Soliton-Halo Pair



Soliton-Halo Pair



Schive et al. 2014, PRL, 113, 261302

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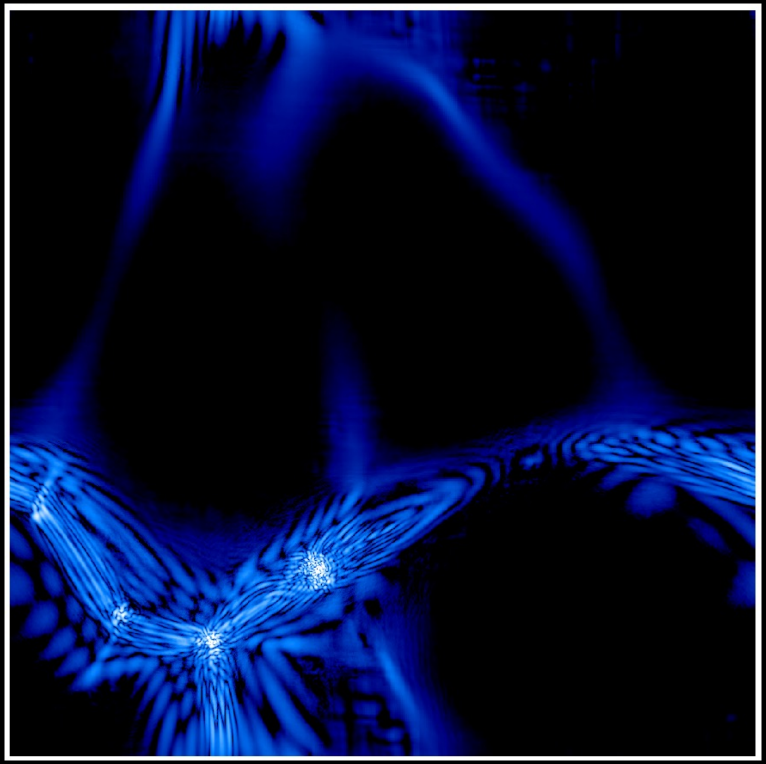
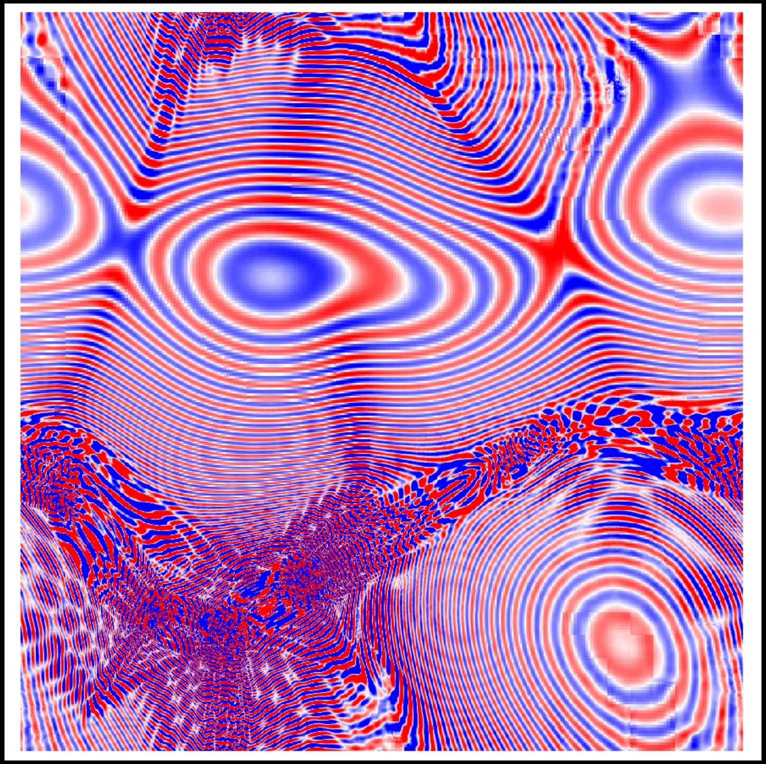
Simulation Challenges

Density



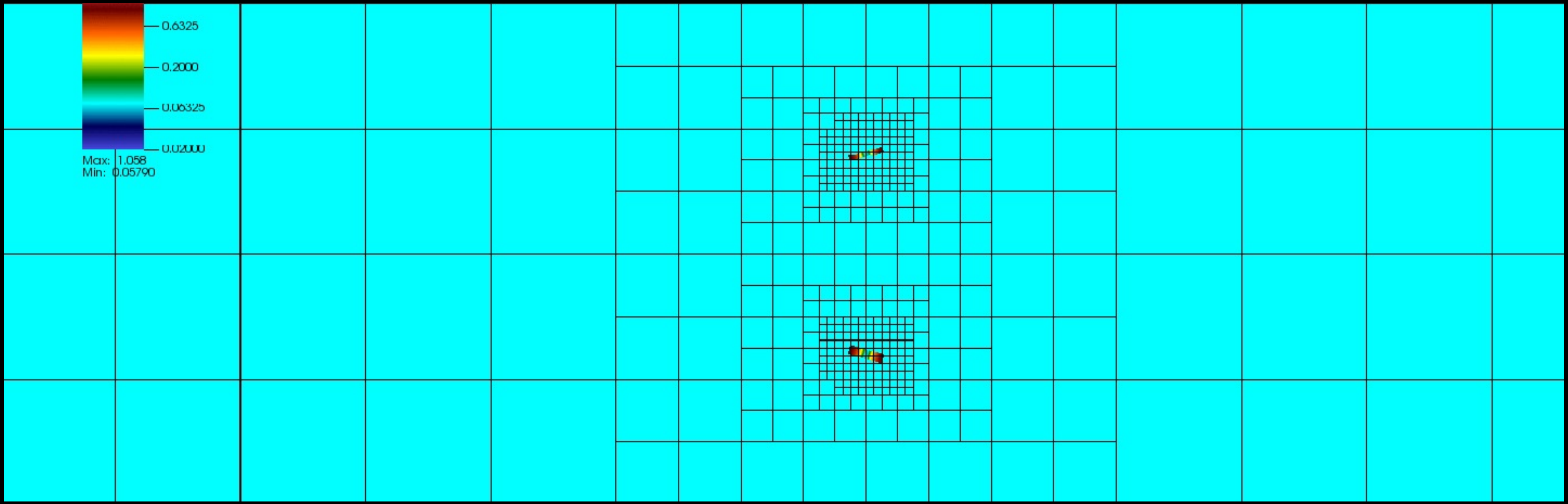
Wave function



- **Ultra-high resolution is required**
- **GAMER : *GPU-accelerated Adaptive MEsh Refinement Code***

Adaptive Mesh Refinement (AMR)

- Astrophysical simulations require a large dynamic range
  - $10^4 – 10^9$ spatial scales
  - Uniform-resolution simulations become impractical
- AMR: allow resolution to adjust locally and automatically
  - Problem-specific refinement criteria



Colliding active galactic nucleus jets using the GAMER code (*Molnar, Schive, et al. 2017, ApJ*)

GAMER → GPU-accelerated AMR

- Physics modules
  - FDM
  - (SR-)Hydrodynamics
  - Magnetohydrodynamics
  - General equation of state
  - Self-gravity
  - Particles
  - Star formation
  - Chemistry
  - Radiative cooling/heating
- Features
  - AMR (no external library)
  - Adaptive time-step
  - Hybrid MPI/OpenMP/GPU
  - Load balance by Hilbert curve
  - Data analysis with *yt*
  - Bitwise reproducibility
  - Open source
    - github.com/gamer-project/gamer
    - FDM module will be released soon
  - Designed from scratch
    - 177,488 code lines as of Mar. 2018

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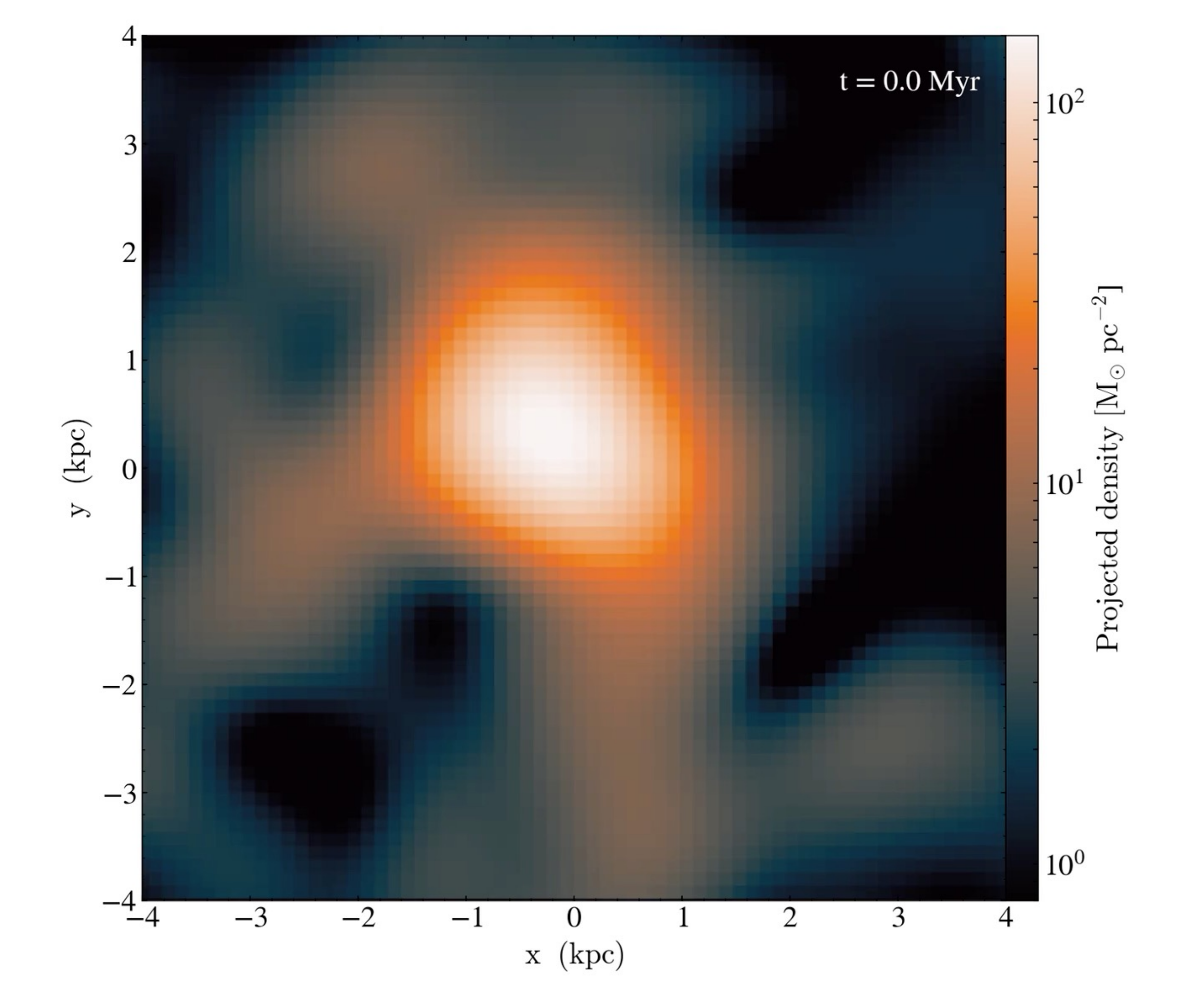
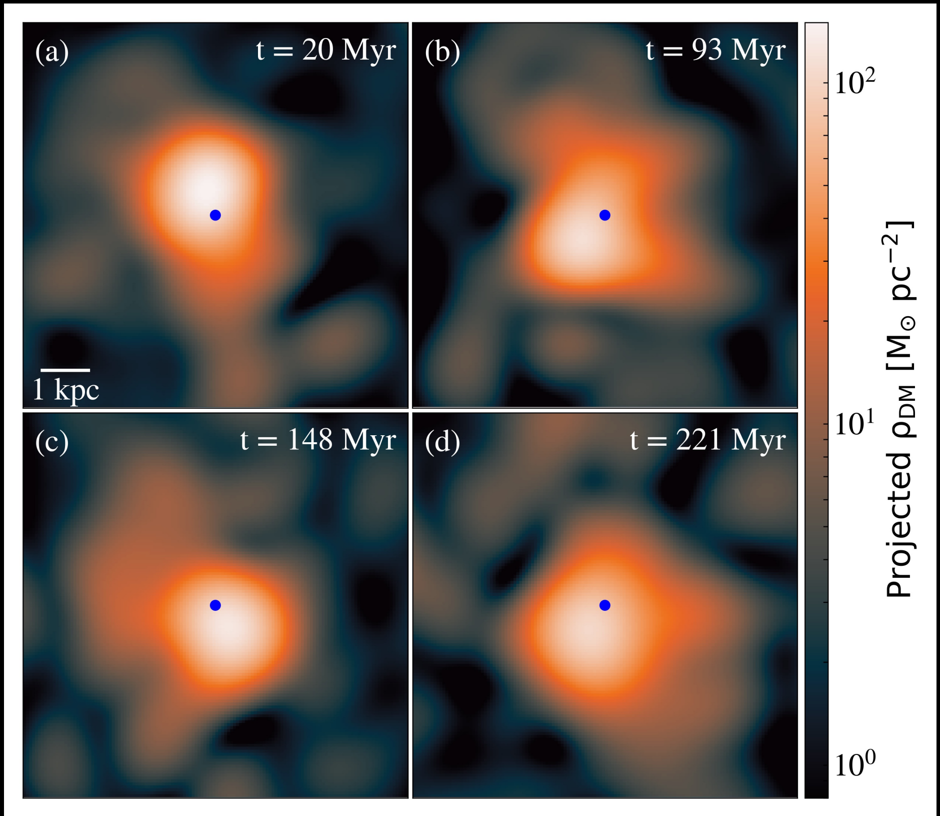
Soliton Random Walk



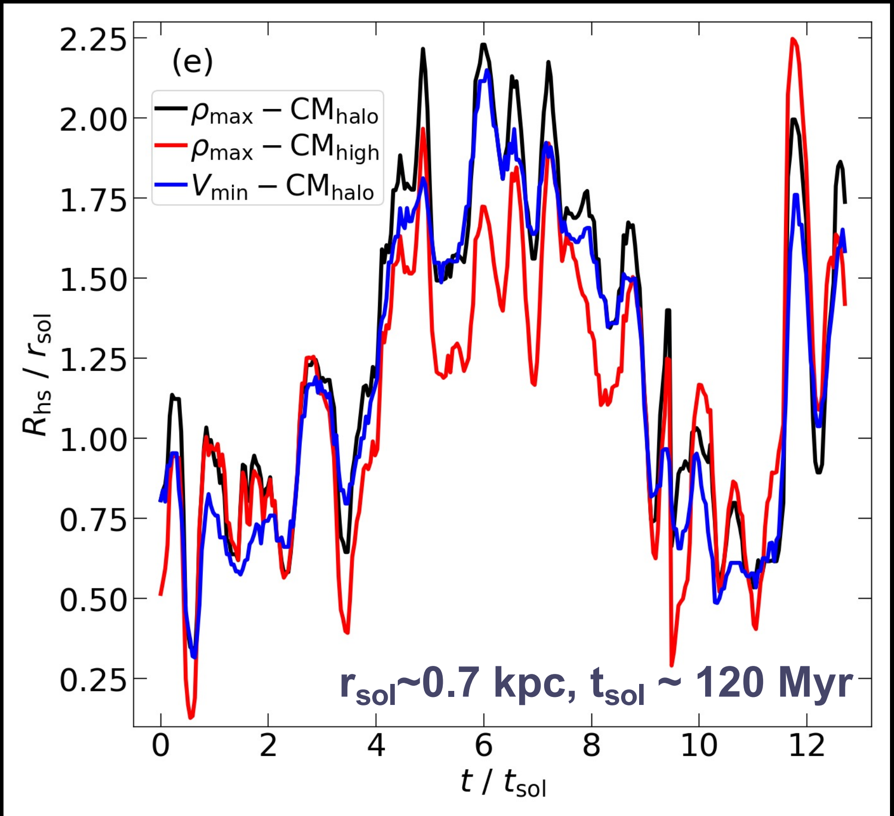
Schive et al. 2020, PRL, 125, 111102

Soliton Random Walk

Projected dark matter density

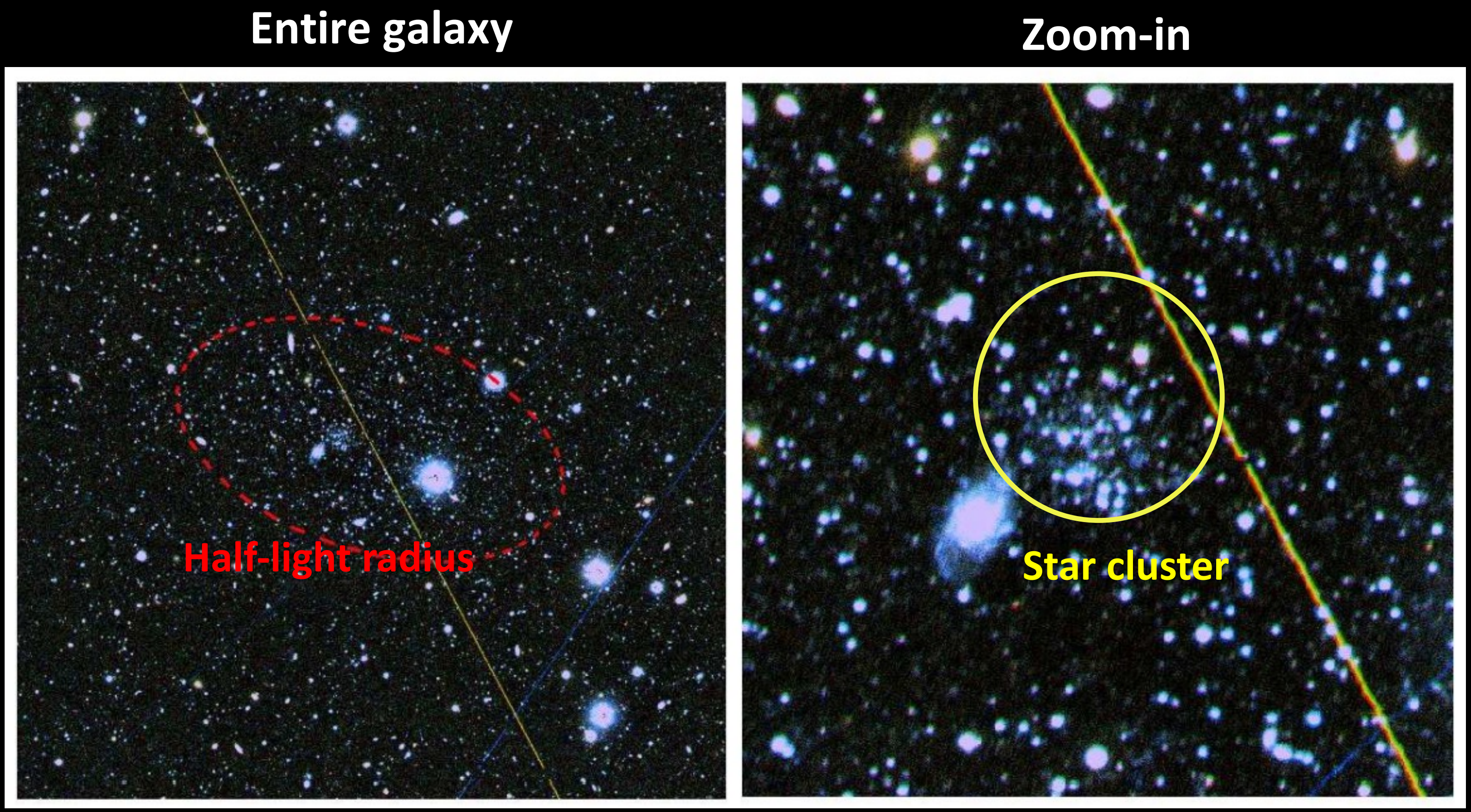


Offset between soliton and halo



- **Feature**: confined random walk at the base of the halo potential
- **Characteristic scales**: close to the length and time scales of soliton itself
- **Numerical robustness**: results are insensitive to the definitions of centers

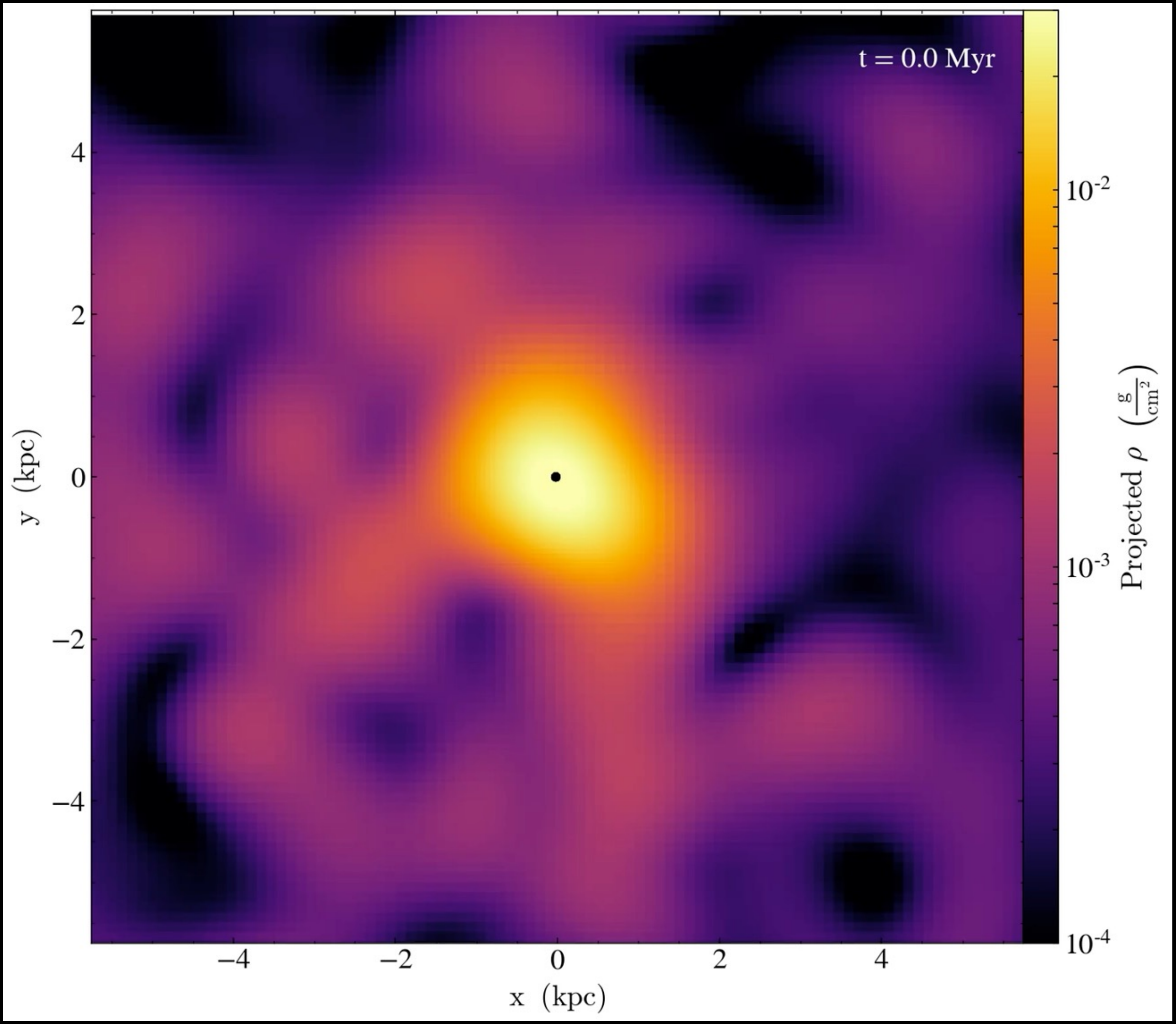
Central Star Cluster in Eridanus II



Crnojevic et al. (2016)

- **Key questions:**
  - **Can this star cluster survive in an FDM halo?**
  - **How does soliton random walk affect its survival?**

Tidal Disruption of Star Cluster



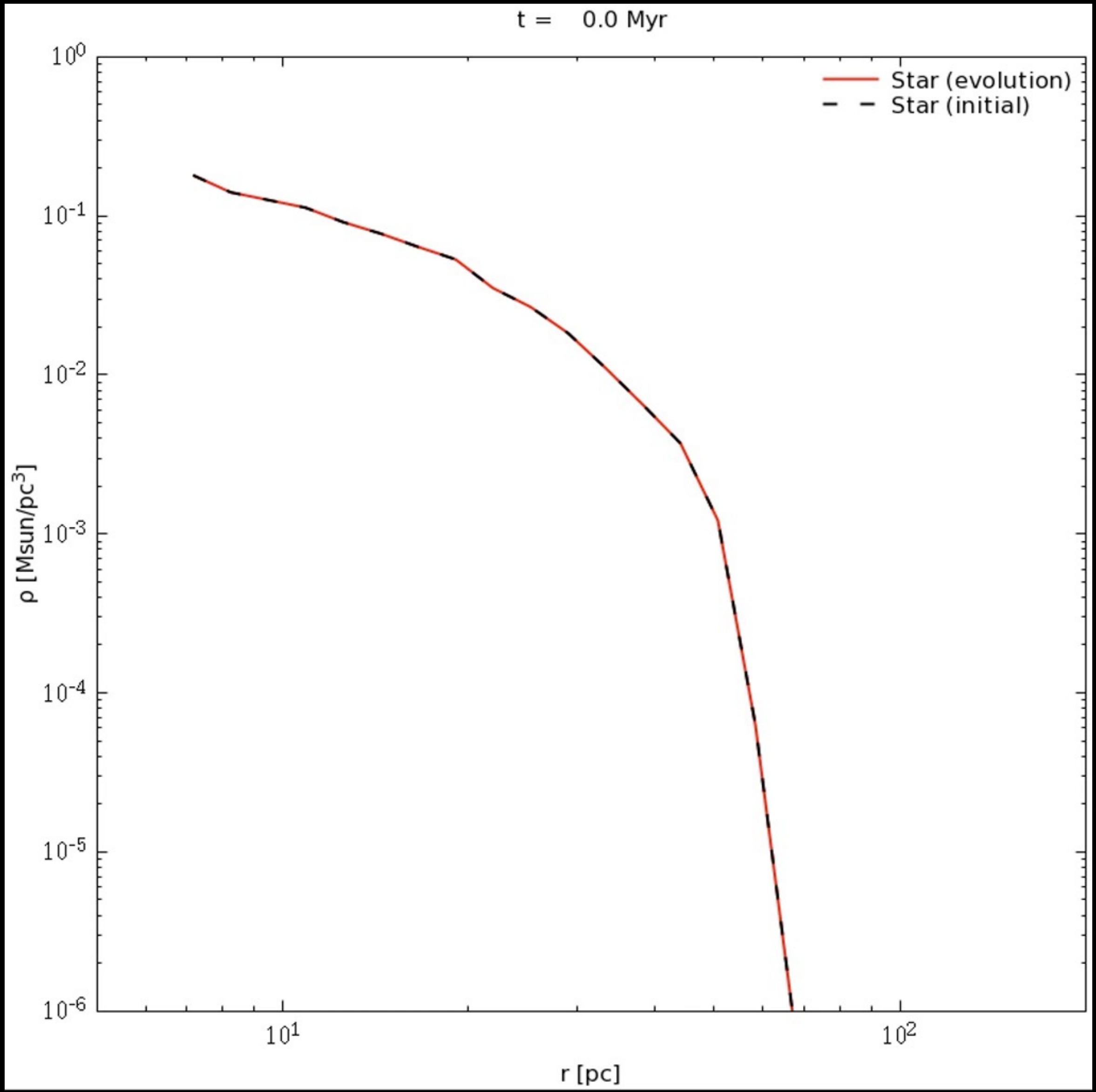
Star cluster traces soliton

Clear separation between star cluster and soliton caused by soliton random walk

Maximum separation ~ r_{sol}

Star cluster is disrupted by the tidal field of soliton within 1 Gyr

Tidal Disruption of Star Cluster



Star cluster traces soliton

Clear separation between star cluster and soliton caused by soliton random walk

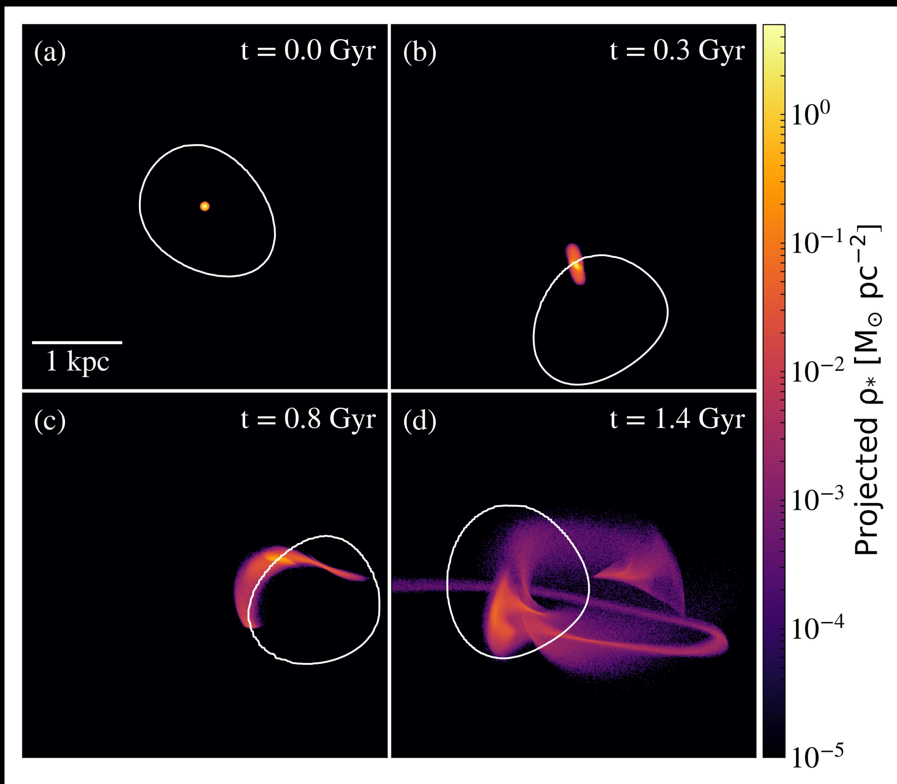
Maximum separation ~ r_{sol}

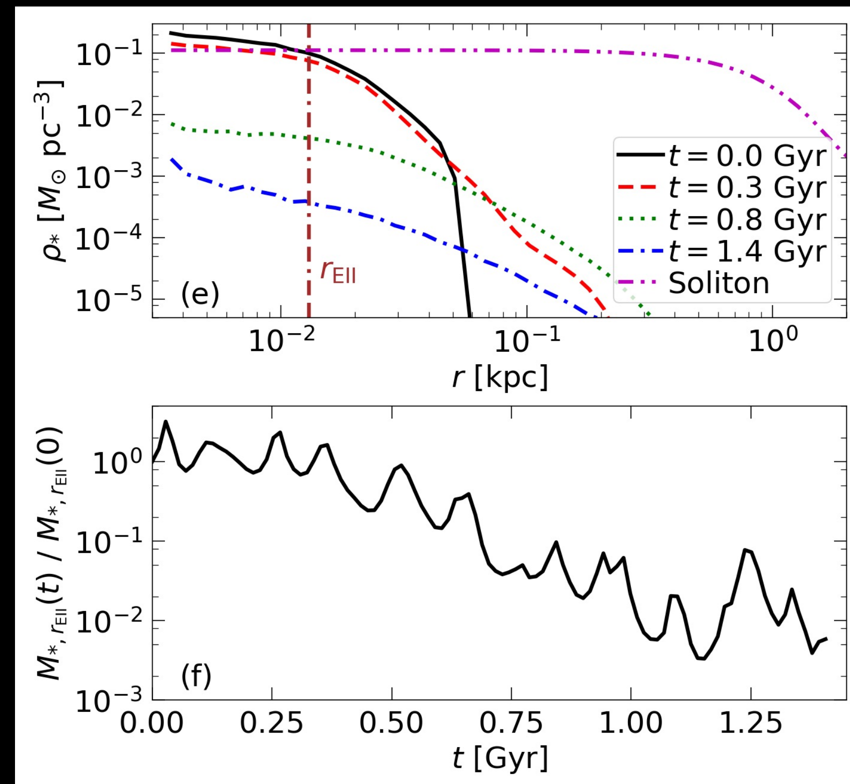
Star cluster is disrupted by the tidal field of soliton within 1 Gyr

Tidal Disruption of Star Cluster

COLOR: Projected stellar mass density
CONTOUR: Soliton

UPPER: Stellar density profiles
LOWER: Enclosed stellar mass fraction

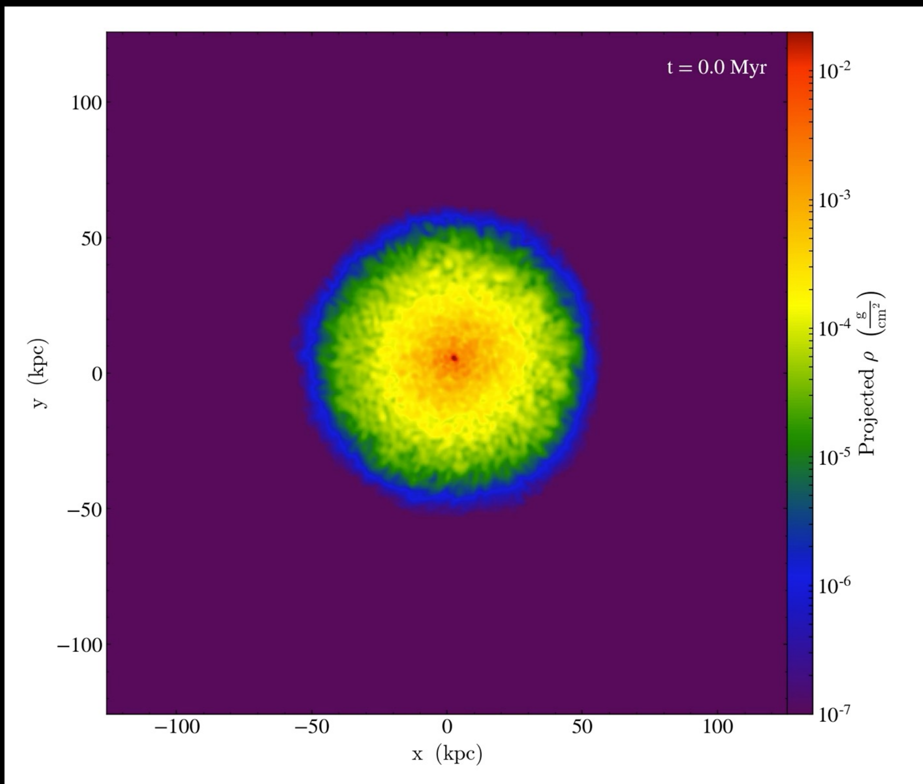




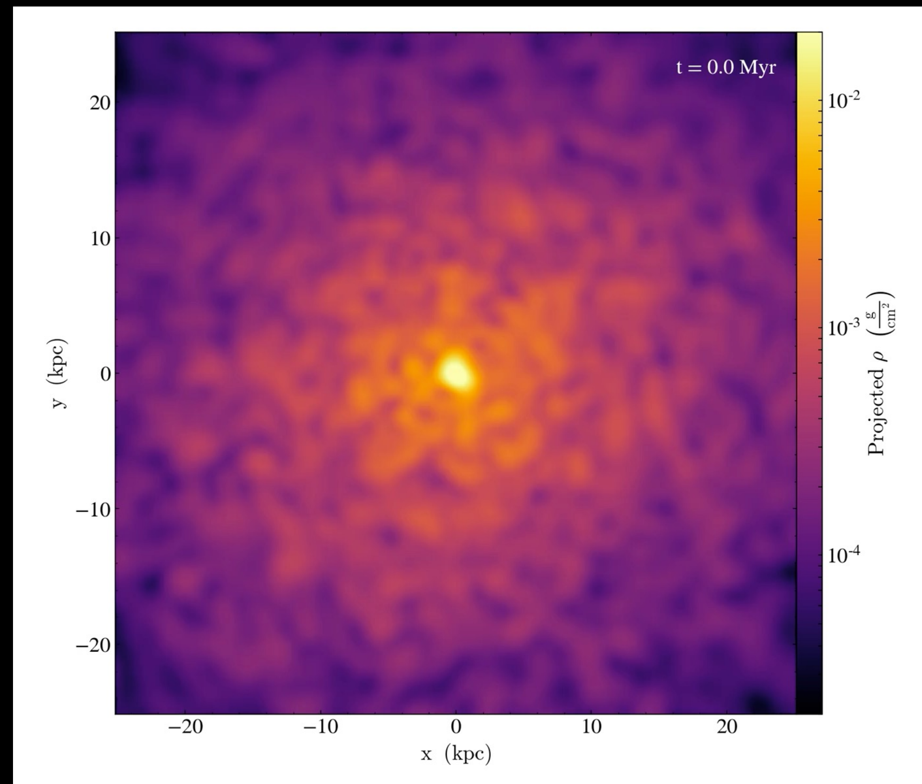
- Flat core → Tidal stripping is most effective at the soliton edge (F_{tidal} ~ F_*)
- Star cluster loses ~99% of mass after ~1 Gyr → Shorter than the estimated minimum age of the star cluster (3 Gyr) → Crisis for FDM !?

Tidal Stripping of Eri II's Halo

Entire halo



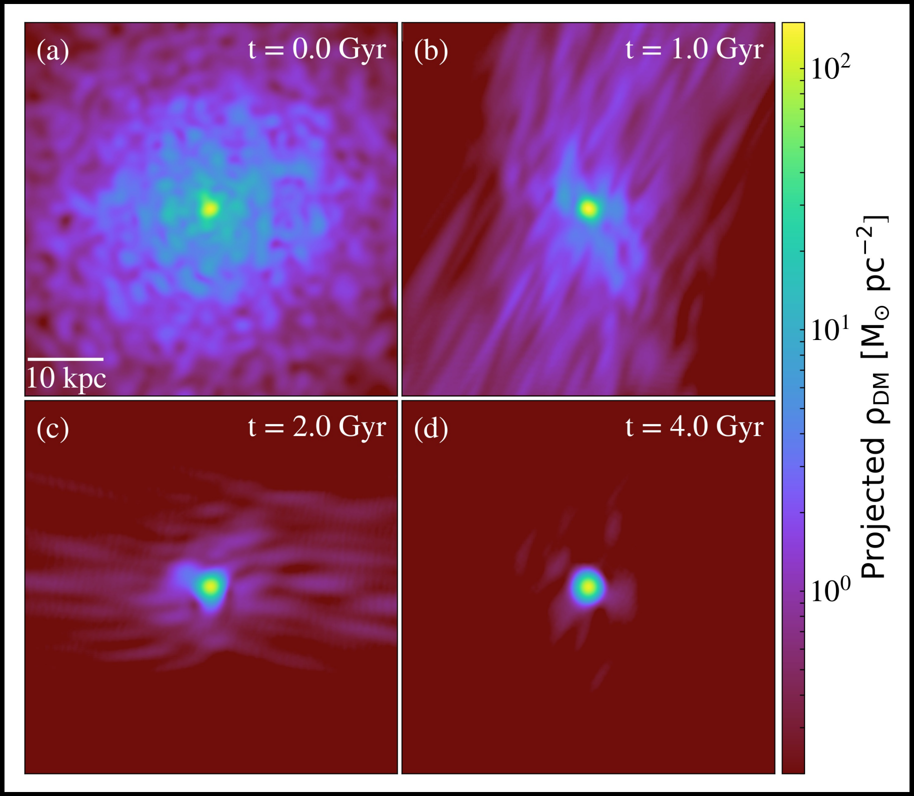
Zoom-in



- **Question**: whether the **Milky Way tides** can affect the soliton random motion?
- **Simulation setup**:
  - Adding a Milky Way tidal field
  - Circular orbit of radius 100 kpc for Eri II
  - Simulation coordinates move together with Eri II (so Milky Way is orbiting)

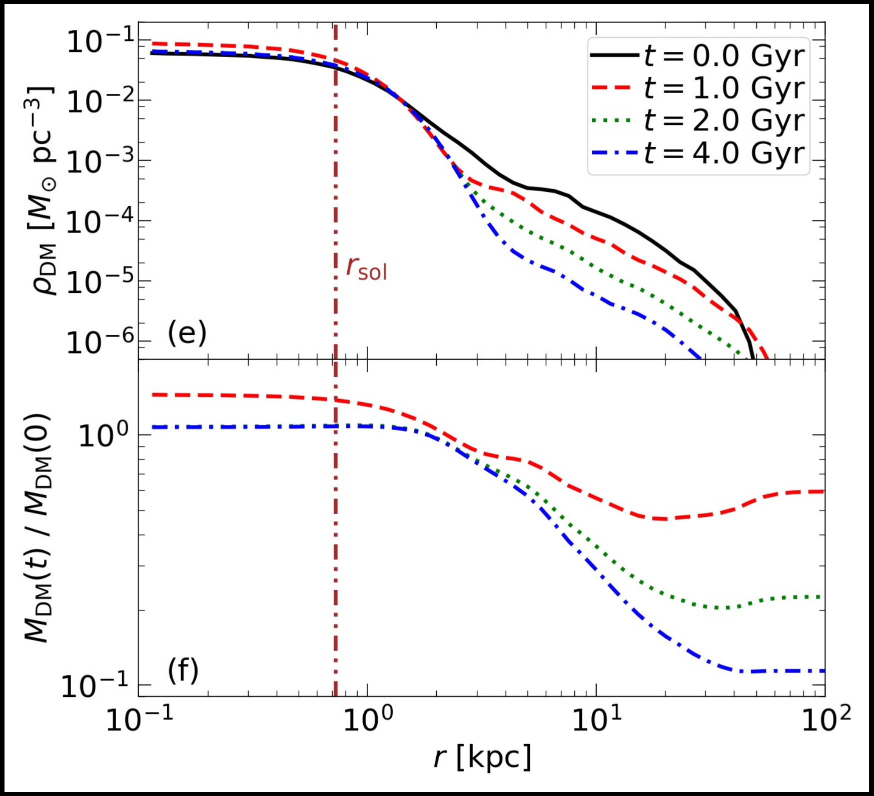
Tidal Stripping of Eri II's Halo

Projected dark matter (DM) density



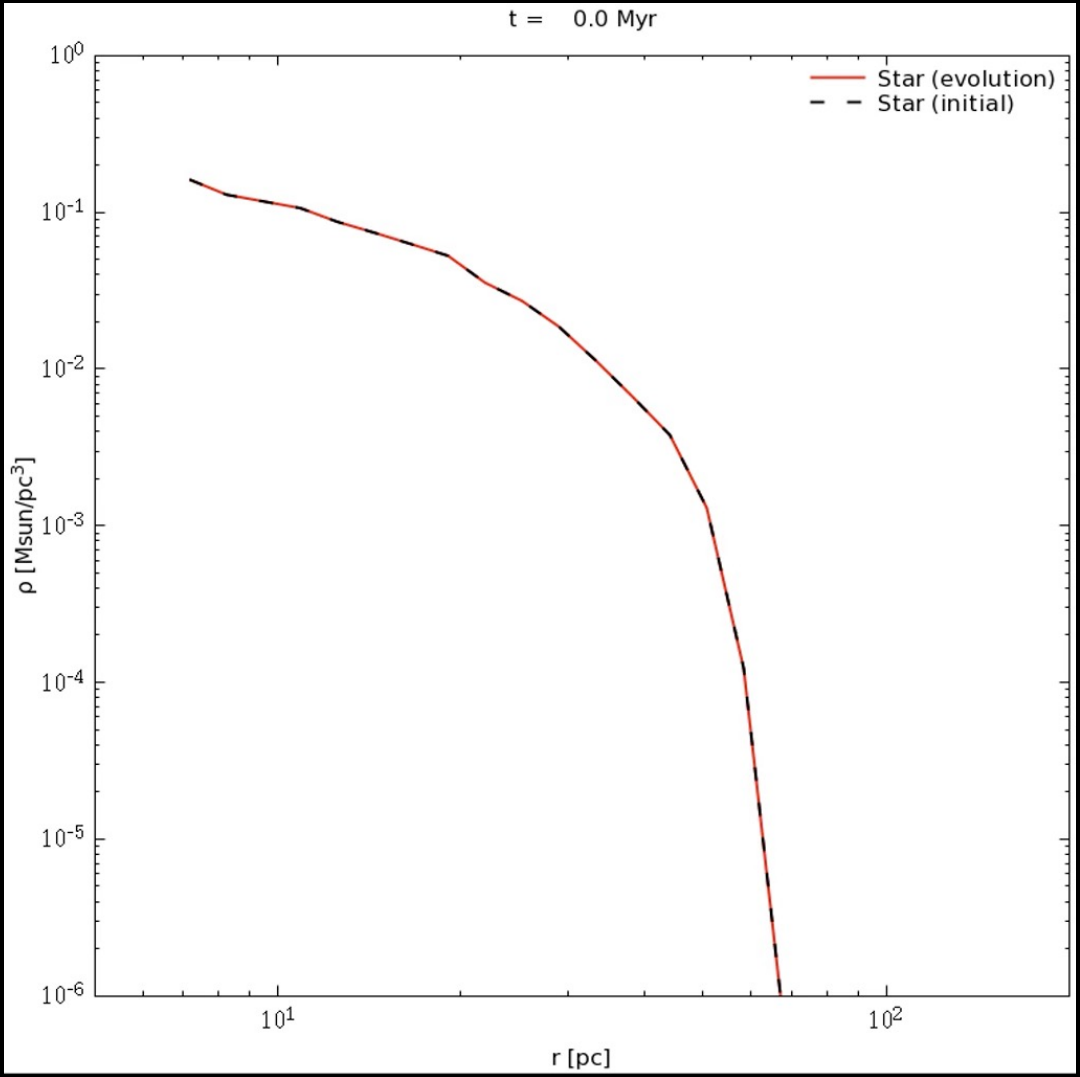
UPPER: DM density profiles

LOWER: Enclosed DM mass fraction



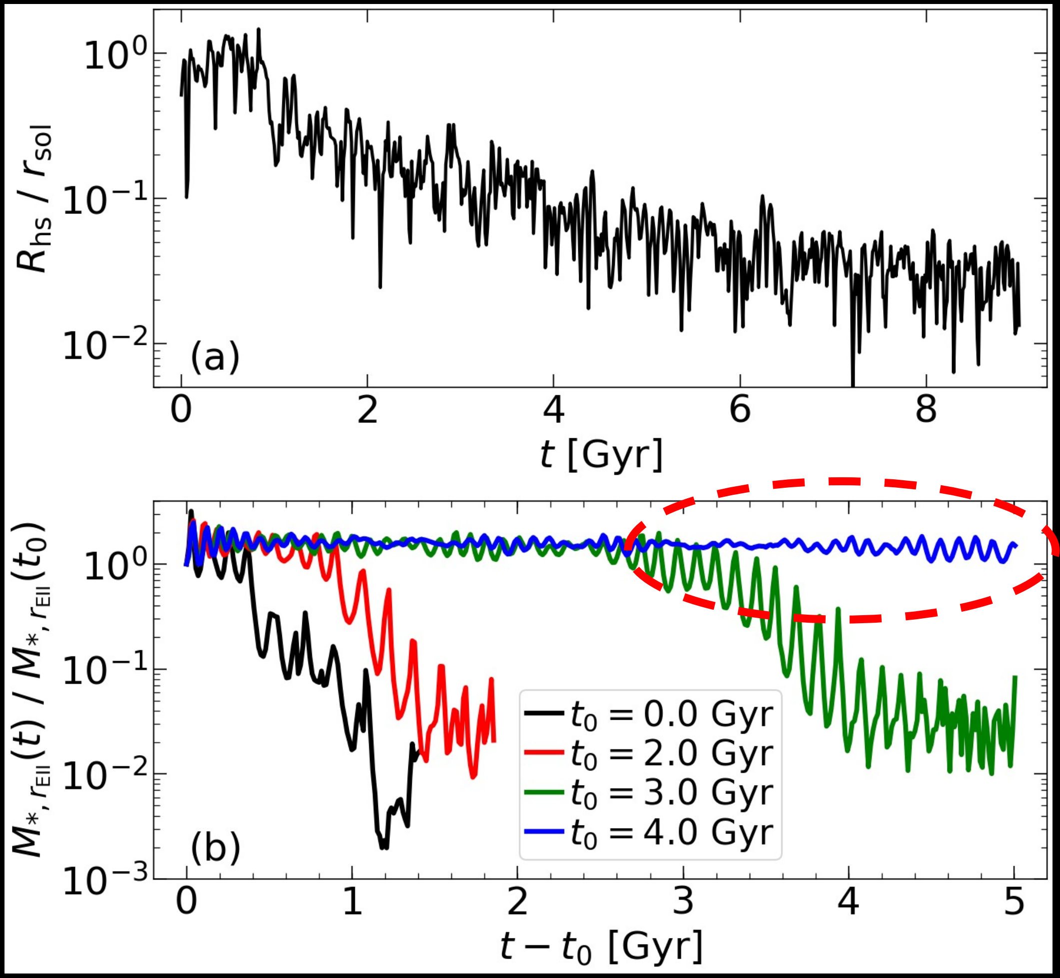
- **Soliton remains intact ($\gtrsim$ 9 Gyr)**
- **FDM halo ($r \gtrsim 3\, r_{sol}$) is tidally stripped after a few Gyr**
- **Without the interplay between halo and soliton:**
  - **Soliton random motion is significantly diminished**
  - **Star cluster and soliton can coexist!**

Star Cluster in a Tidally Stripped Halo



- Star cluster **can survive** longer than 5 Gyr in a tidally stripped FDM halo

Star Cluster in a Tidally Stripped Halo



Soliton random motion becomes smaller over time as the halo being tidally stripped

The later the star cluster is added, the more stable it is

For t_0 = 4 Gyr, the star cluster can remain intact for more than 5 Gyr

Avoid the aforementioned FDM crisis!

- **UPPER**: Offset between soliton and halo
- **LOWER**: Enclosed stellar mass fraction (adding a star cluster at four different time t_0)

Open Questions

- More accurate orbital parameters of Eridanus II
  - Is it on its second or third orbit around the Milky Way?
- How does soliton random walk depend on other parameters?
  - FDM particle mass
  - Halo mass
  - Baryonic components
- How does it affect the observational predictions of FDM?
  - Dynamical friction and core stalling in dwarf galaxies
  - Galactic rotation curve
  - Excess mass in the Milky Way center (e.g., central molecular zone)
  - Black hole formation and evolution

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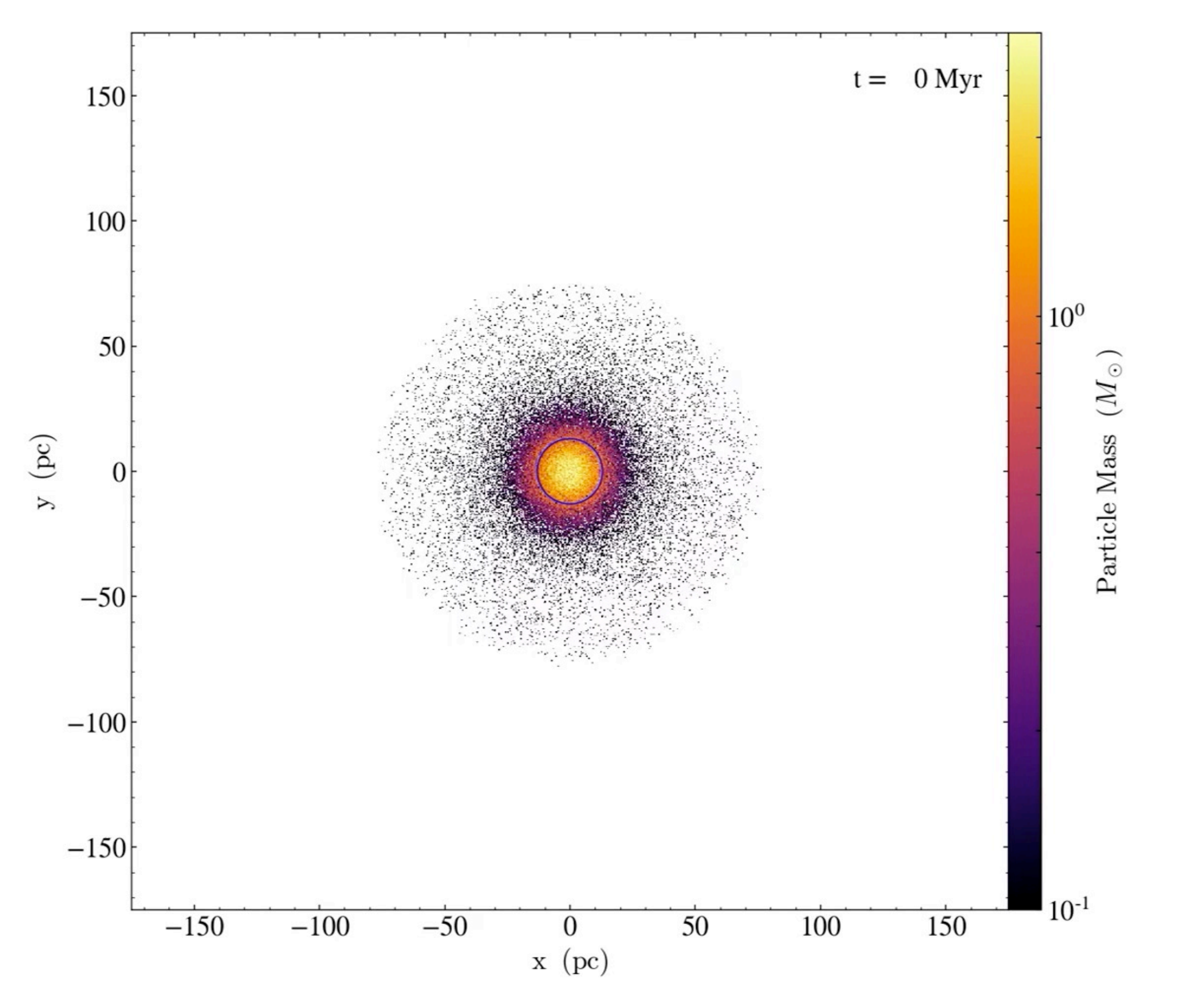
Gravitational Heating by an Oscillating External Field



External field oscillation period: τ_{osc}

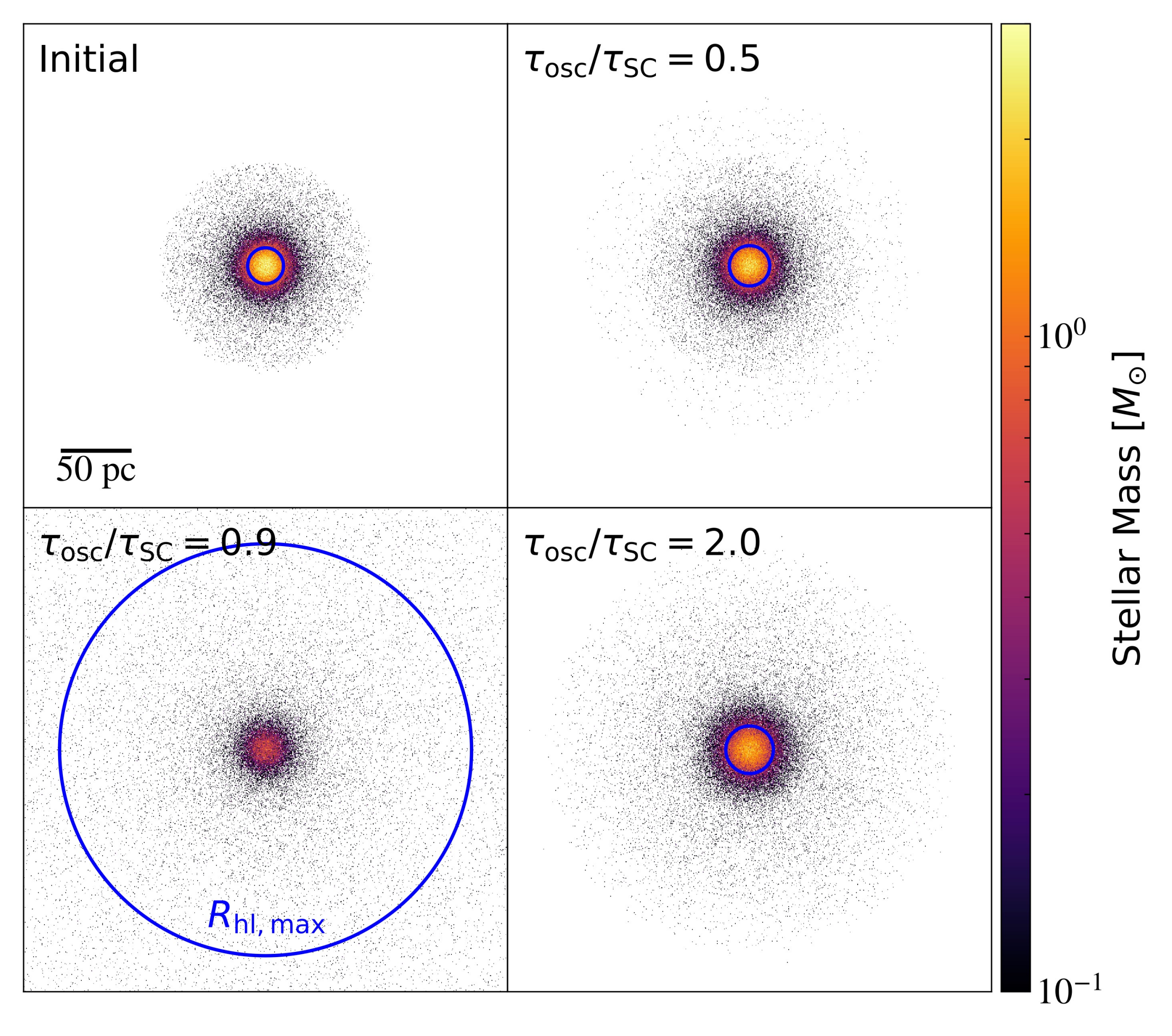
Star cluster characteristic timescale: τ_{SC}

$\tau_{osc} \approx \tau_{SC}$ in this example

Efficient heating due to resonance

Chiang et al. 2021, PRD, 103, 103019

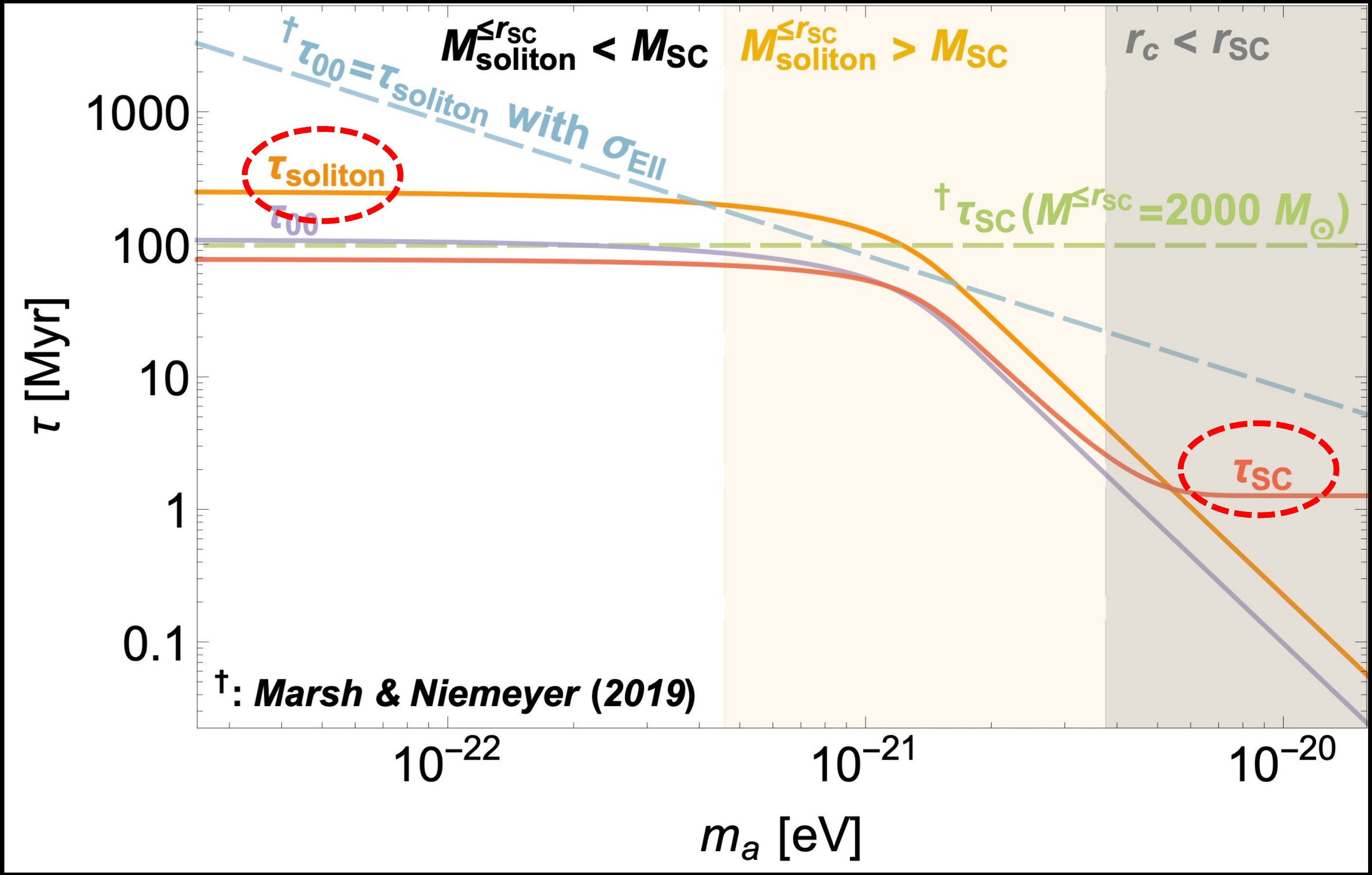
Gravitational Heating by an Oscillating External Field



Heating is efficient only when $\tau_{osc} \approx \tau_{SC}$

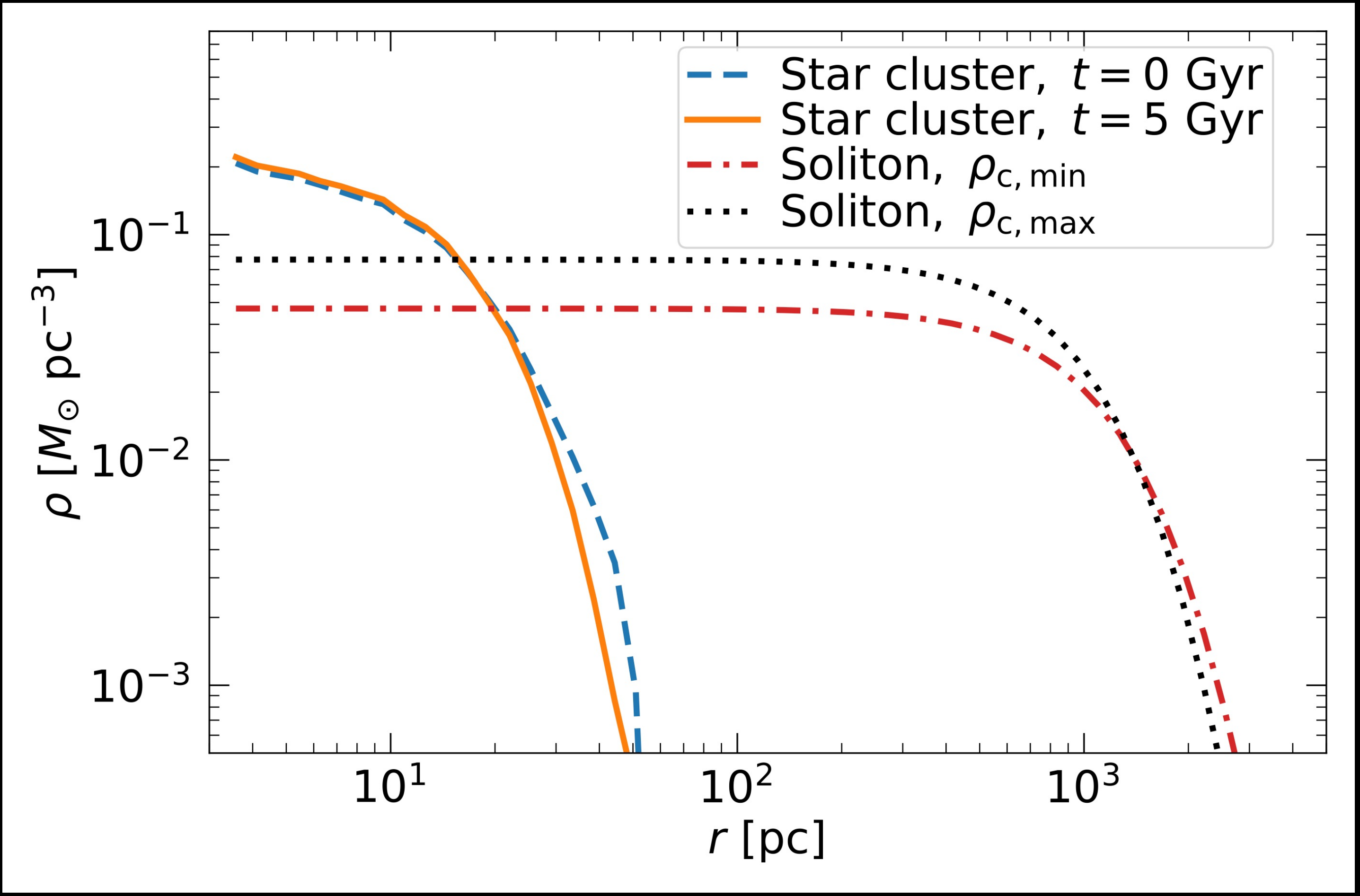
What is the oscillation period of a real soliton?

How about Soliton Oscillations?



$\tau_{soliton} \approx 2 - 3\ \tau_{SC}$ for $m \leq 3\times10^{-21} eV$

How about Soliton Oscillations?



Gravitational heating from soliton oscillations is very inefficient (adiabatic)!

Summary

- FDM Simulations are challenging
- Soliton random walk
  - Caused by soliton-halo interaction
  - Characteristic length and time scales close to the soliton itself
- FDM crisis?
  - Soliton random walk can displace the central star cluster in Eri II slightly outside the soliton

  → Lead to efficient tidal disruption of the star cluster
- Possible solution
  - Milky Way tides can disrupt the halo of Eri II (but soliton remains intact)
  - Without the interplay between soliton and halo, the soliton random motion is significantly diminished

  → Star cluster and soliton can coexist
- Soliton oscillations cannot heat star clusters in dwarfs efficiently