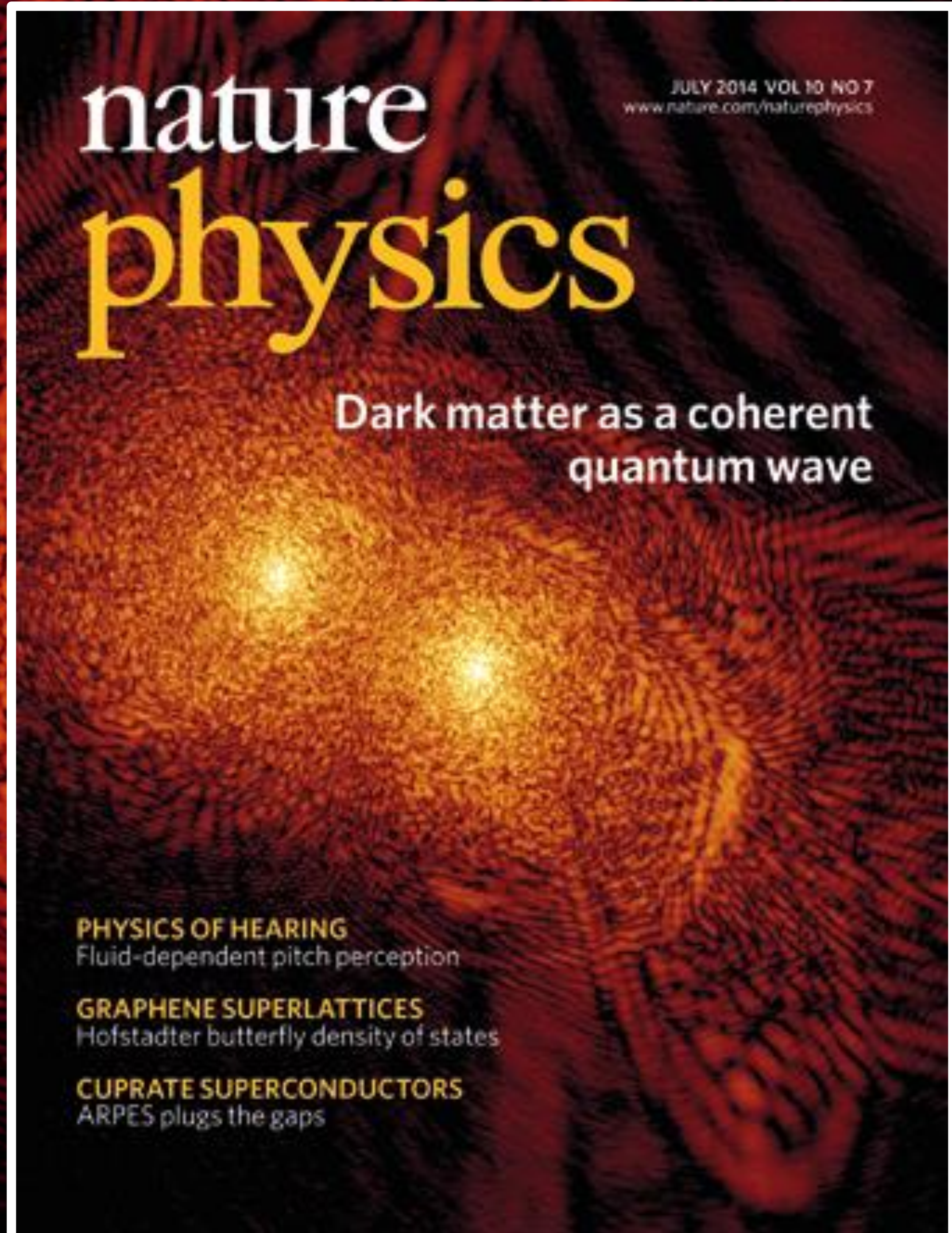

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Outline

- Introduction
  - Cold dark matter (CDM) vs. wave dark matter (ψDM)
- Numerical Methods (GAMER)
  - *Adaptive Mesh Refinement (AMR)*
  - *Graphic Processing Units (GPU)*
- ψDM Simulations
  - Solve the small-scale crises of CDM
- Summary

Introduction

Cold Dark Matter

- **CDM (Cold Dark Matter):**
  - Collisionless particles with self-gravity
  - Relatively heavy (GeV scale)
  - Work very well on large scales (galaxy cluster scale)
  - Controversial on small scales (dwarf galaxy scale)
    - Rely on complicated baryonic feedbacks …

- **Main issues on small scales:**
  - Cusp-core problem
    - → Mass is too concentrated at the center ?
  - Missing satellites problem
    - → Over abundance of dwarf galaxies ?

Wave Dark Matter (ψDM)

- Extremely light particles (~10^{-22} eV → 10^{31} lighter than CDM)
  - de Broglie wavelength becomes astronomical (kpc) scale
  - Wavelike properties (e.g., interference)
- Governing eq.: Schrödinger-Poisson eq. in the comoving frame

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

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

$\eta \equiv m_\psi/\hbar$: particle mass, ψ: wave function

φ: gravitational potential, a: scale factor

Quantum Fluid

- **Schrödinger eq. can be rewritten into conservation laws**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0,$$
$$\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} = \nabla \left(\frac{1}{2\eta^2} \frac{\nabla^2 f}{f} \right) - \nabla \varphi$$

$$\psi = f e^{iS/\hbar},$$
$$\rho = m f^2,$$
$$v = \eta^{-1} \nabla S$$

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

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

quantum stress

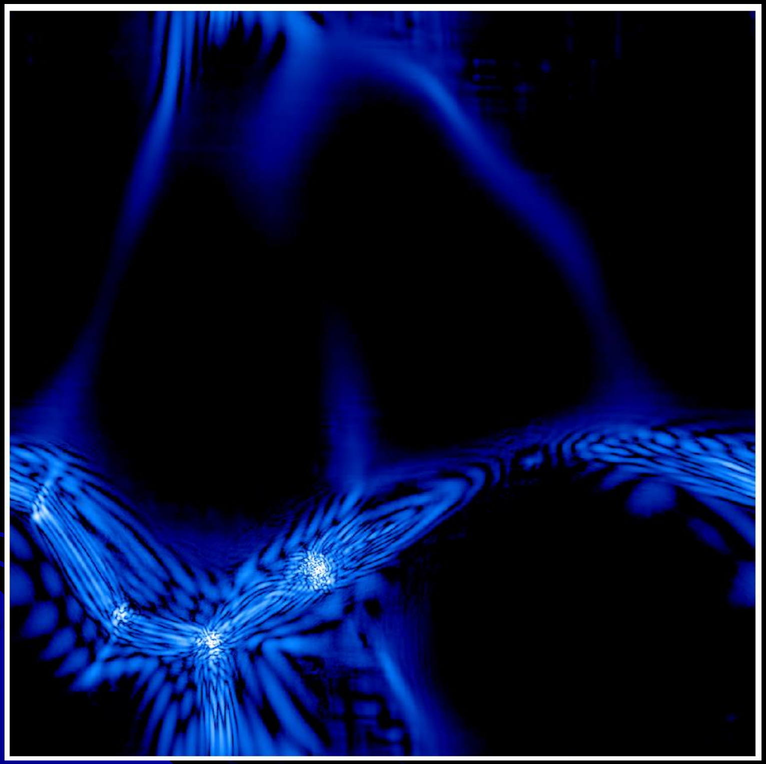
$$k_J = (6a)^{1/4} (H_0 \eta)^{1/2}$$

Jeans wave number in ψDM

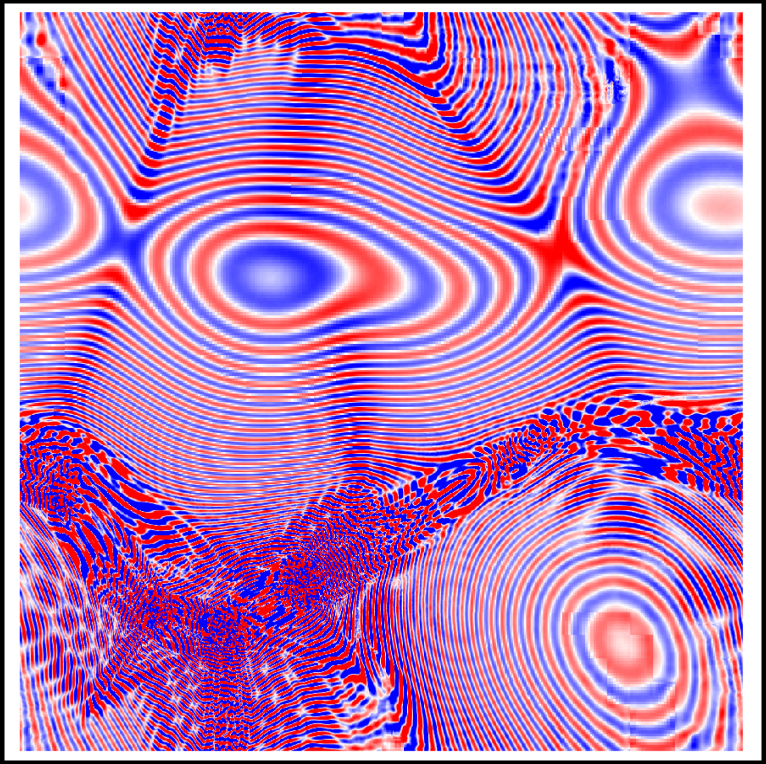
Numerical Methods

Numerical Challenge

Density



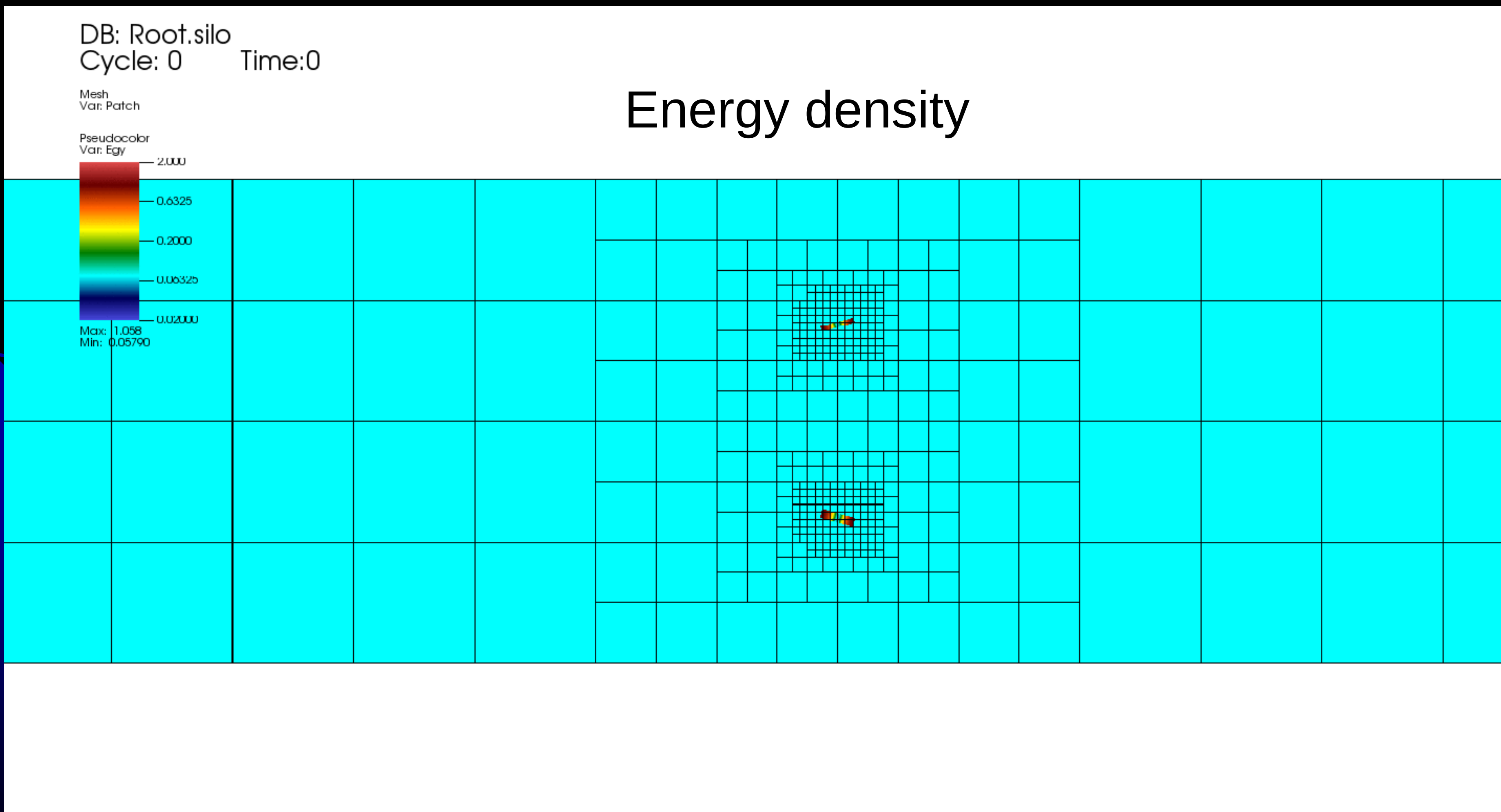
Wave function



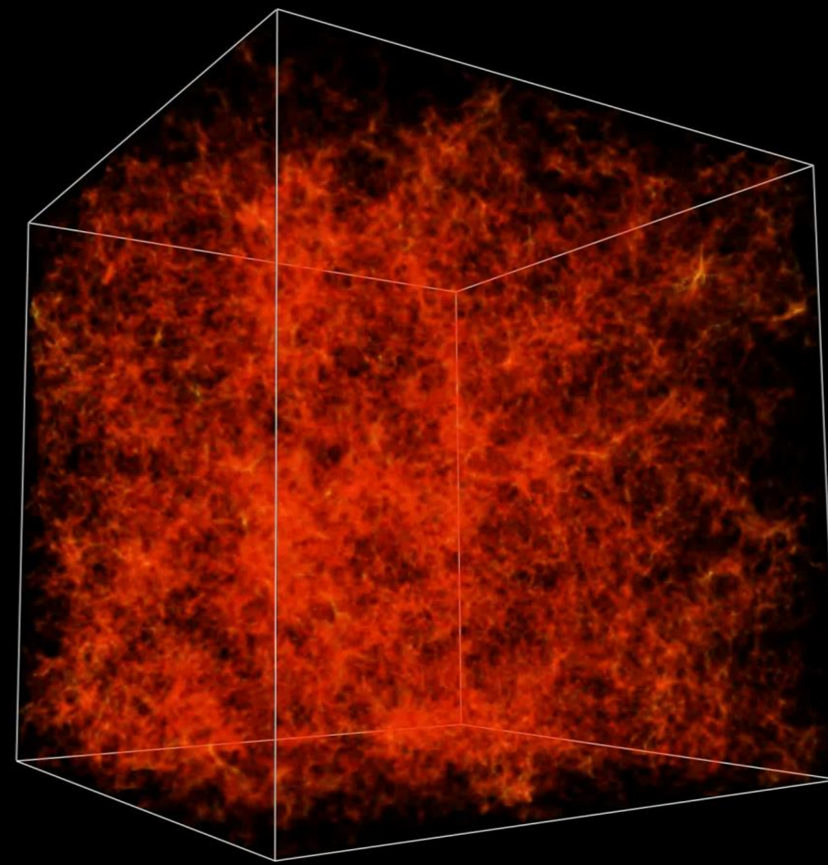
- → **Ultra-high resolution is required**
- → GAMER : *GPU-accelerated Adaptive MEsh Refinement Code*

Adaptive Mesh Refinement (AMR)

- **Example: interaction of active galactic nucleus (AGN) jets**

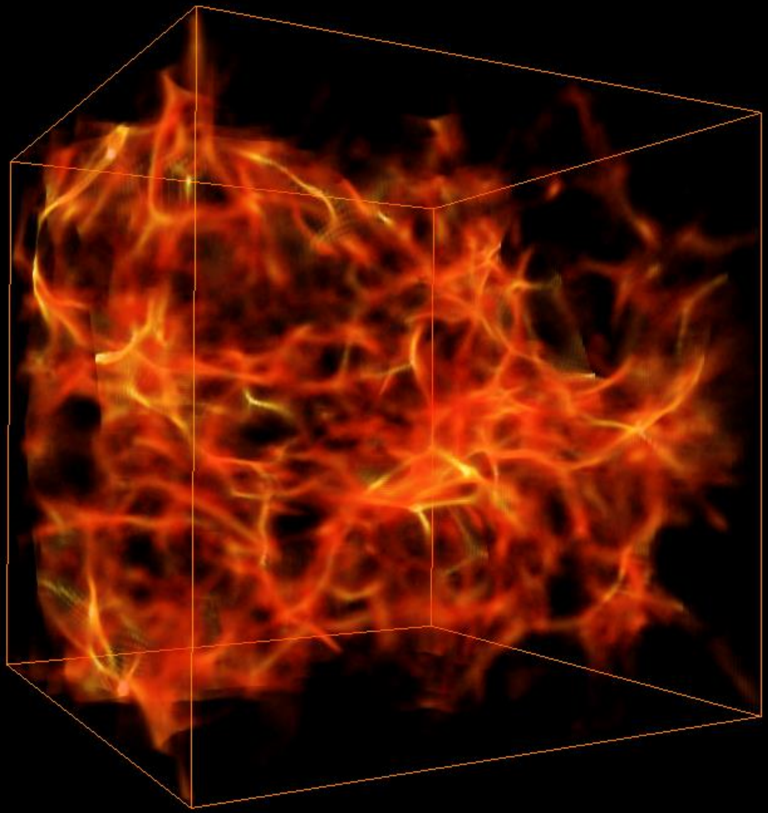


Graphic-Processing-Unit (GPU)



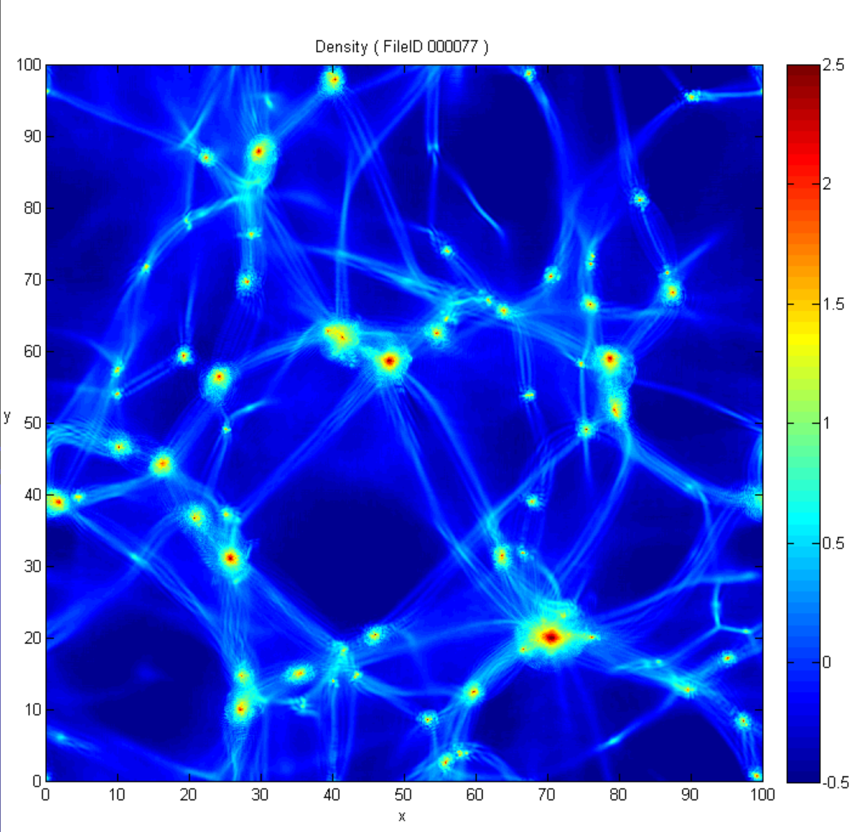
GeForce GTX 680 → Simulation accelerators !

ψDM Simulations

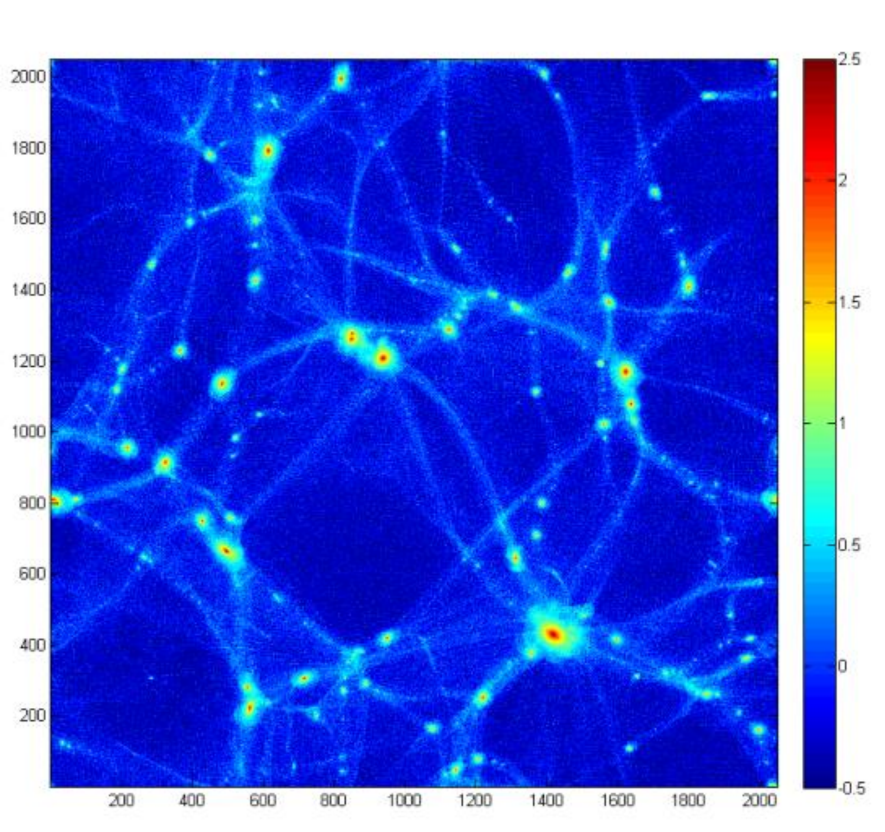


ψDM vs. CDM (Large Scale)

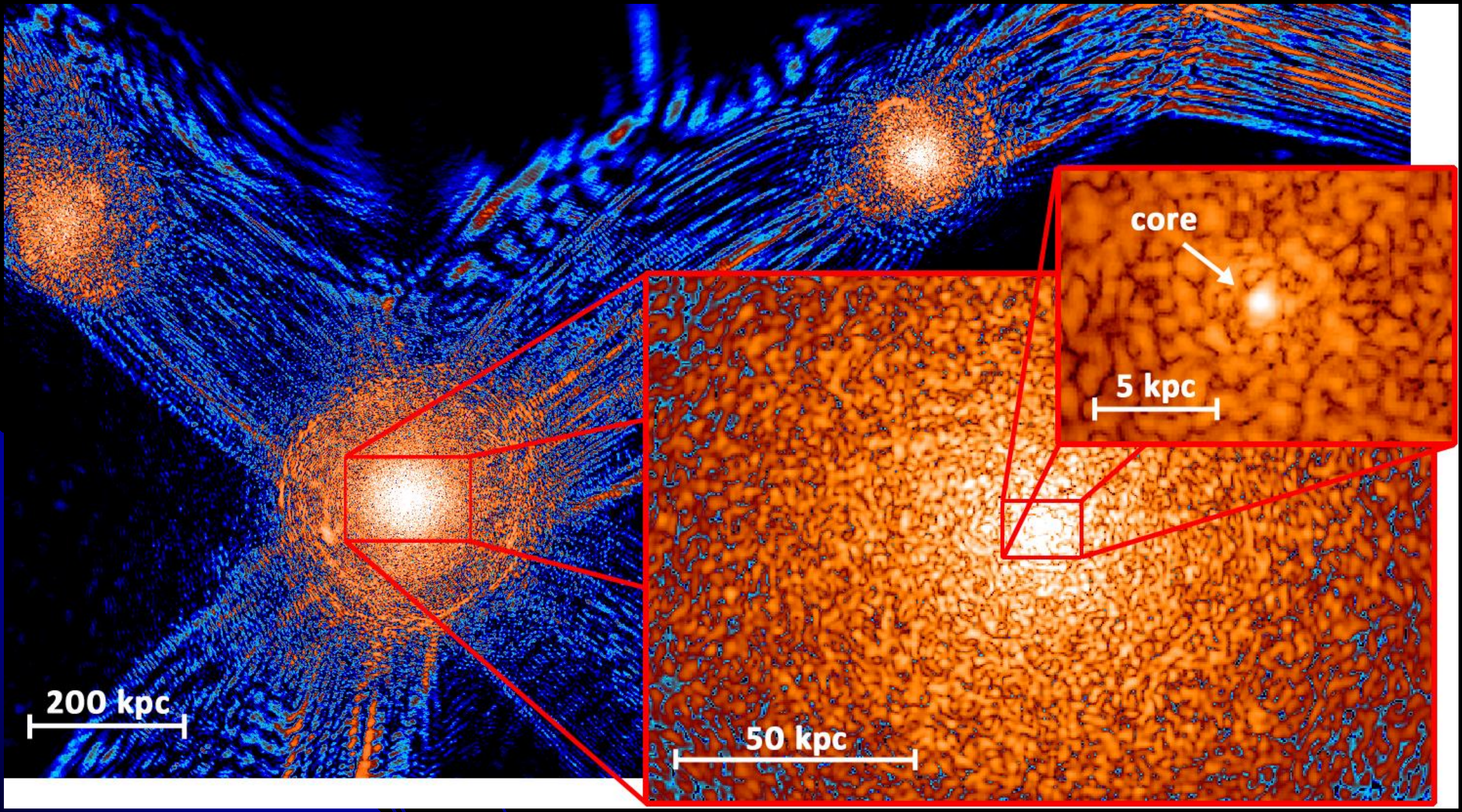
- ψDM (GAMER)



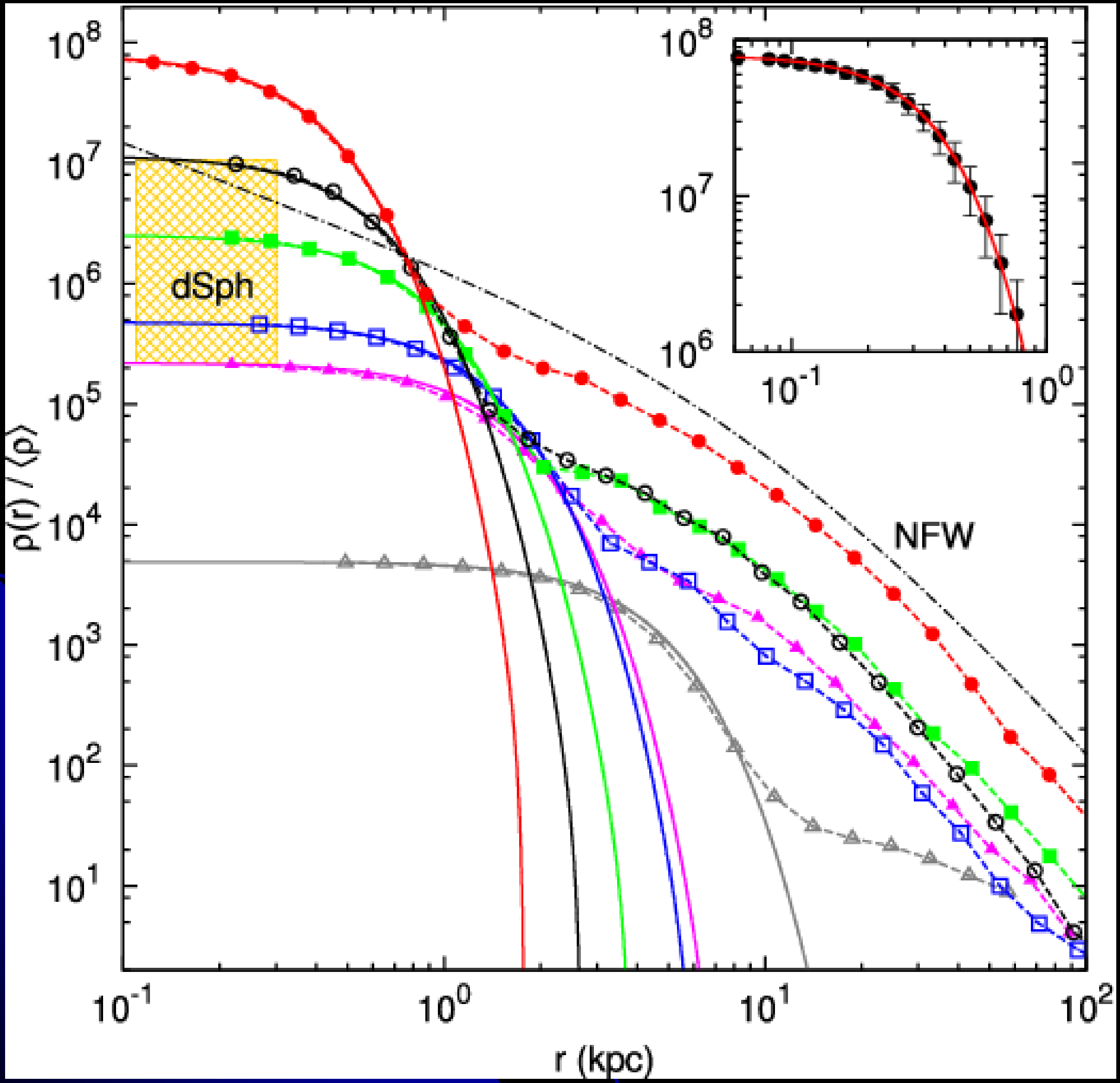
- CDM (GADGET)



ψDM on Small Scale



Halo Density Profile

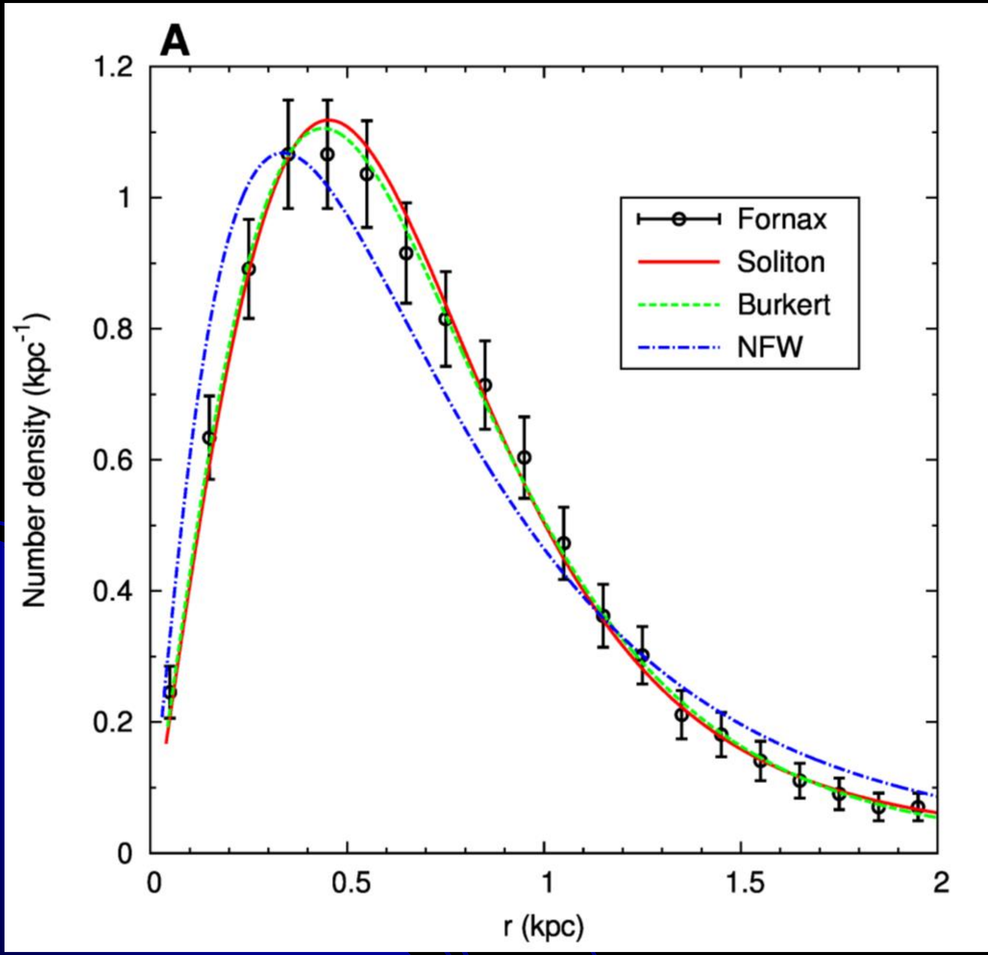


Cored instead of cuspy profiles

Consistent with Milky Way dwarf spheroidal galaxies (dSph)

Cores satisfy the soliton solution

Cusp-core Problem



Jeans Eq.:

$$\frac{d(\rho_\star \sigma_r^2)}{dr} = -\rho_\star \frac{d\Phi}{dr} - \frac{2\beta\rho_\star \sigma_r^2}{r}$$

$\rho_\star$: *star number density*

σ_r : *radial velocity dispersion*

Φ : *gravitational potential*

β : *velocity anisotropy*

Assuming constant and isotropic velocity dispersion

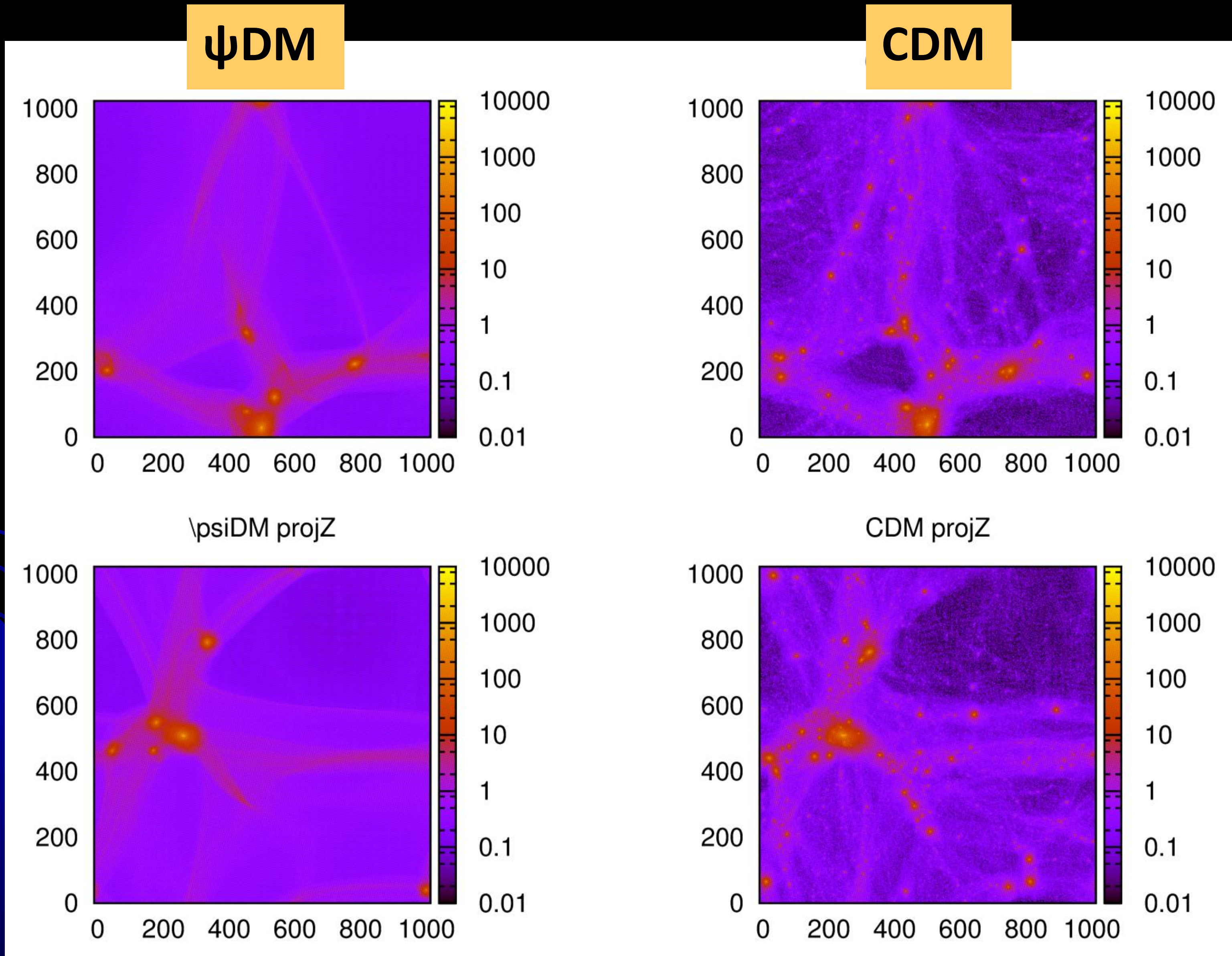
$\rho_\star = \rho_0 exp[-\Phi(r)/\sigma_r^2]$

Find the best-fit m_ψ & r_c

→ $m_\psi \sim 8.1*10^{-23}$ eV

$r_c \sim$ 0.92 kpc

Missing Satellites Problem



Summary

- **Wave Dark Matter (ψDM):**
  - **Extremely light particles ($m_{\psi} \sim 10^{-22}$ eV)**
  - **Governing eq.: Schrödinger-Poisson eq.**
  - **Quantum pressure → suppress structures below the Jeans scale**
  - ***Schive et al., 2014, Nature Physics (cover), 10, 496***
  - ***Schive et al. 2014, submitted to PRL (arXiv:1407.7762)***

- **Numerical Challenges:**
  - **Ultra-high resolution is required due to the wave dispersion relation**
  - **GAMER: *GPU-accelerated Adaptive-MEsh-Refinement***
  - ***Schive et al., 2010, ApJS, 186, 457***

- ψDM Simulations
  - **Solitonic cores within each halo → cusp-core problem !?**
  - **Small halos are highly suppressed → missing satellites problem !?**
  - **By fitting to the Fornax dwarf spheroidal galaxies**
    → $m_{\psi} \sim 8.1 \times 10^{-23}$ eV