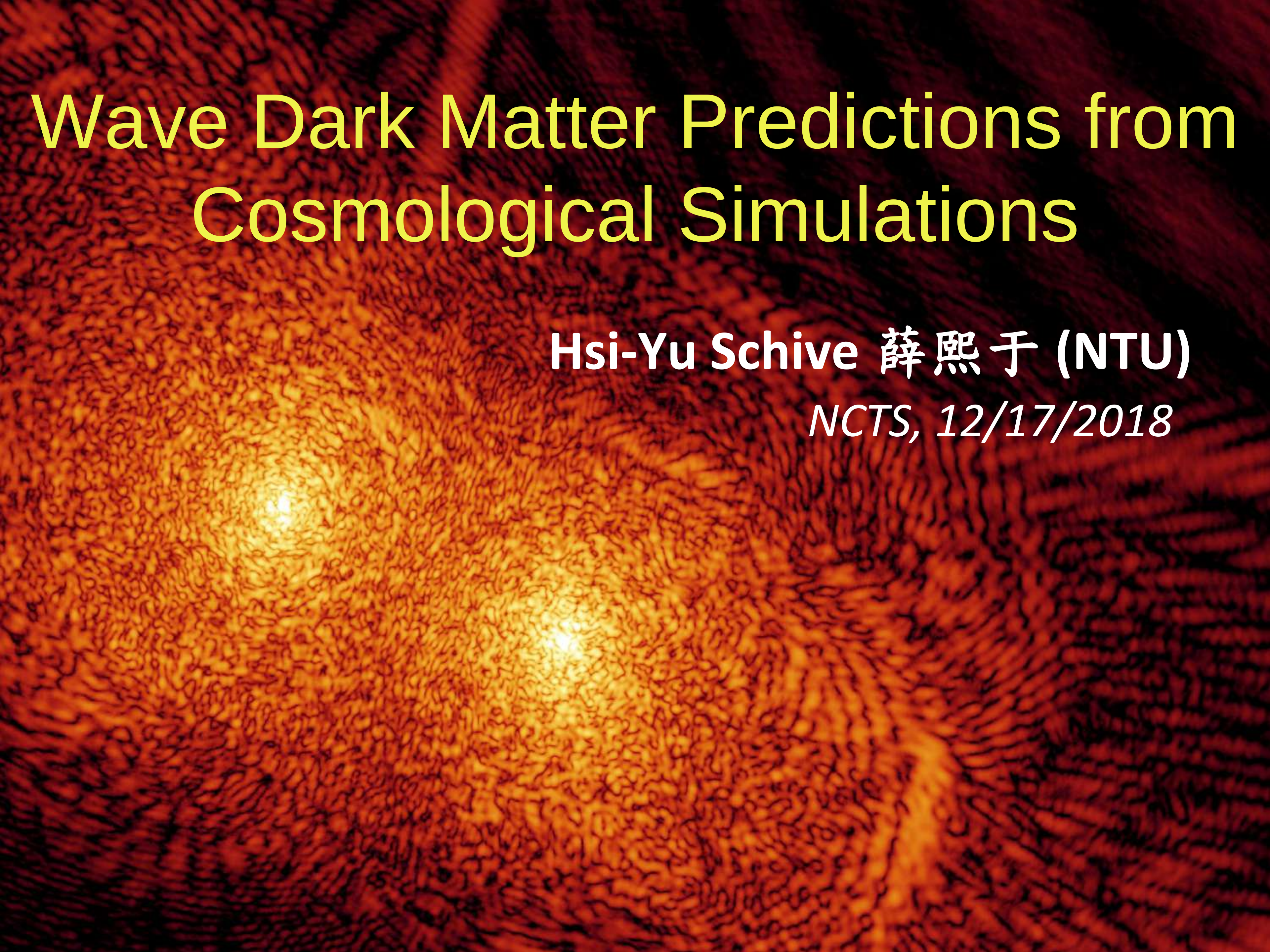
Wave Dark Matter Predictions from Cosmological Simulations



Hsi-Yu Schive 薛熙于 (NTU)

NCTS, 12/17/2018

Outline

- Wave Dark Matter (ψDM)
  - Model Characteristics
  - Cosmological Simulations
  - Comparisons with Observations
  - Ongoing Projects
  - Major Challenges

Outline

- Wave Dark Matter (ψDM)
  - Model Characteristics
  - Cosmological Simulations
  - Comparisons with Observations
  - Ongoing Projects
  - Major Challenges

Wave (Fuzzy) Dark Matter (ψDM)

- 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)
  - Model reviews:
    - L. Hui, J. Ostriker, S. Tremaine, & E. Witten. PRD 95, 043541 (2017)
    - D. Marsh. Physics Reports 643, 1 (2016)
- 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 ψDM

Wave Dark Matter (ψDM)

- 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)
  - Model reviews:
    - ➢ L. Hui, J. Ostriker, S. Tremaine, & E. Witten. PRD 95, 043541 (2017)
    - ➢ D. Marsh. Physics Reports 643, 1 (2016)

- 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

Astrophysics (sim. vs obs.) → Dark Matter ? ← Particle physics (theory vs exp.)

Quantum Fluid

- Schrödinger eq. can be rewritten into conservation laws

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

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

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

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

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

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

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

quantum stress

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

Jeans wave number in ψDM

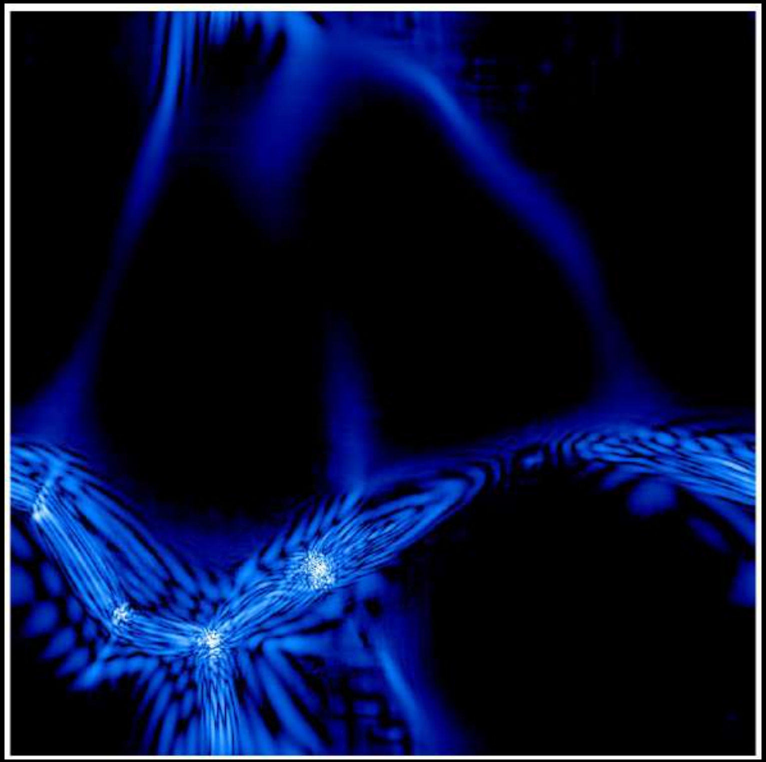
→ Suppressing small-scale structures

Outline

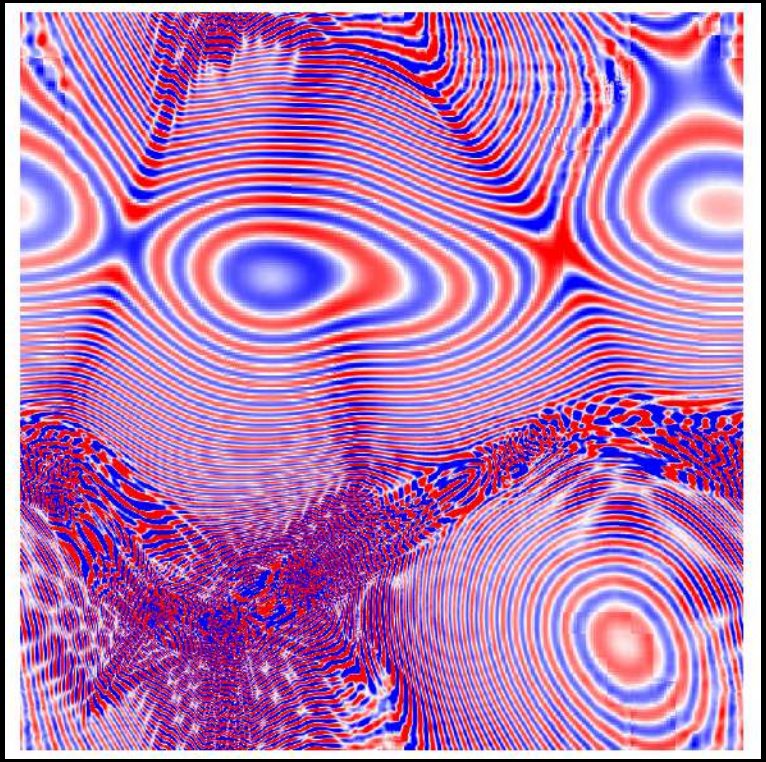
- Wave Dark Matter (ψDM)
  - Model Characteristics
  - Cosmological Simulations
  - Comparisons with Observations
  - Ongoing Projects
  - Major Challenges

Simulation Challenges

Density



Wave function

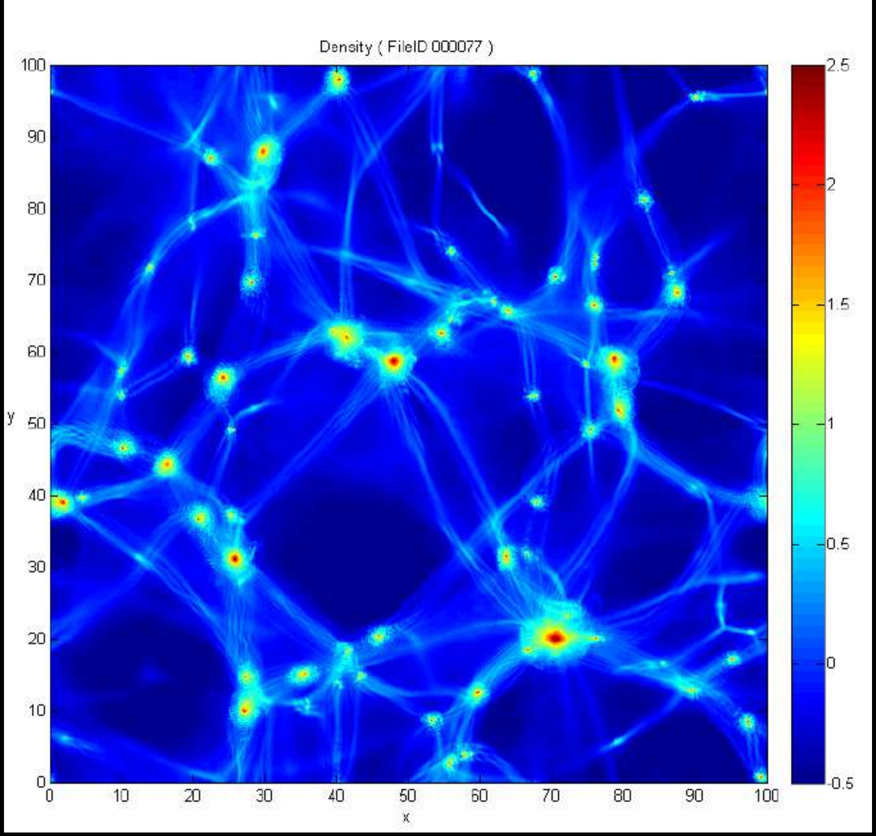


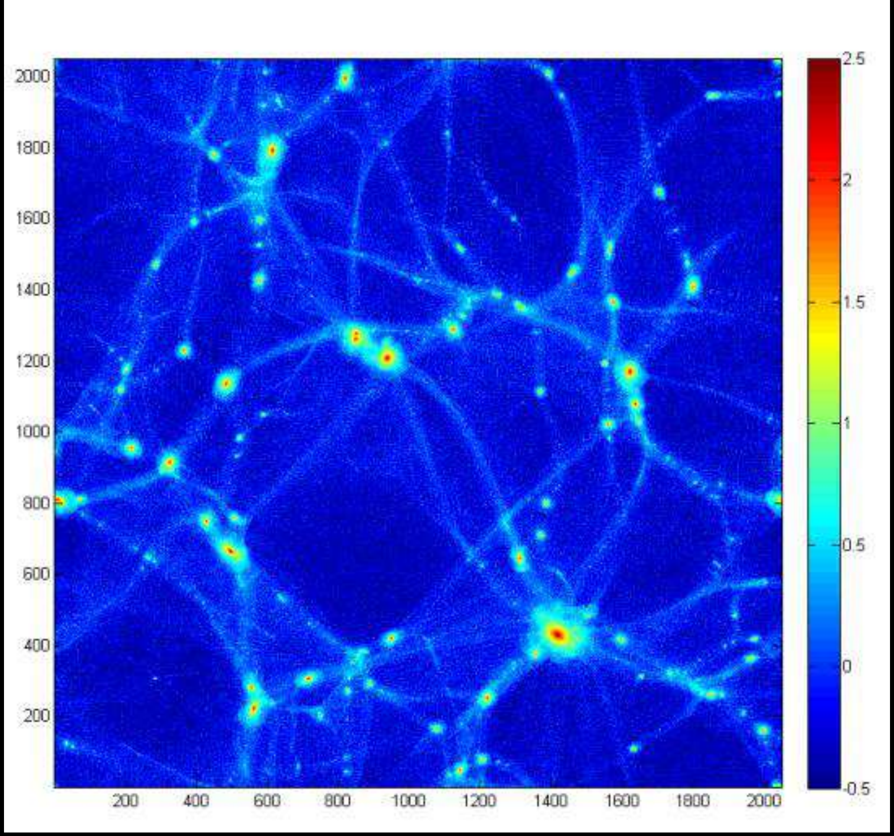
- **Ultra-high resolution is required**
- **GAMER** : ***G**PU-accelerated **A**daptive **ME**sh **R**efinement Code*

→ 10x ~ 100x times faster than other CPU-based codes

ψDM vs. CDM (Large Scales)

ψDM **CDM**

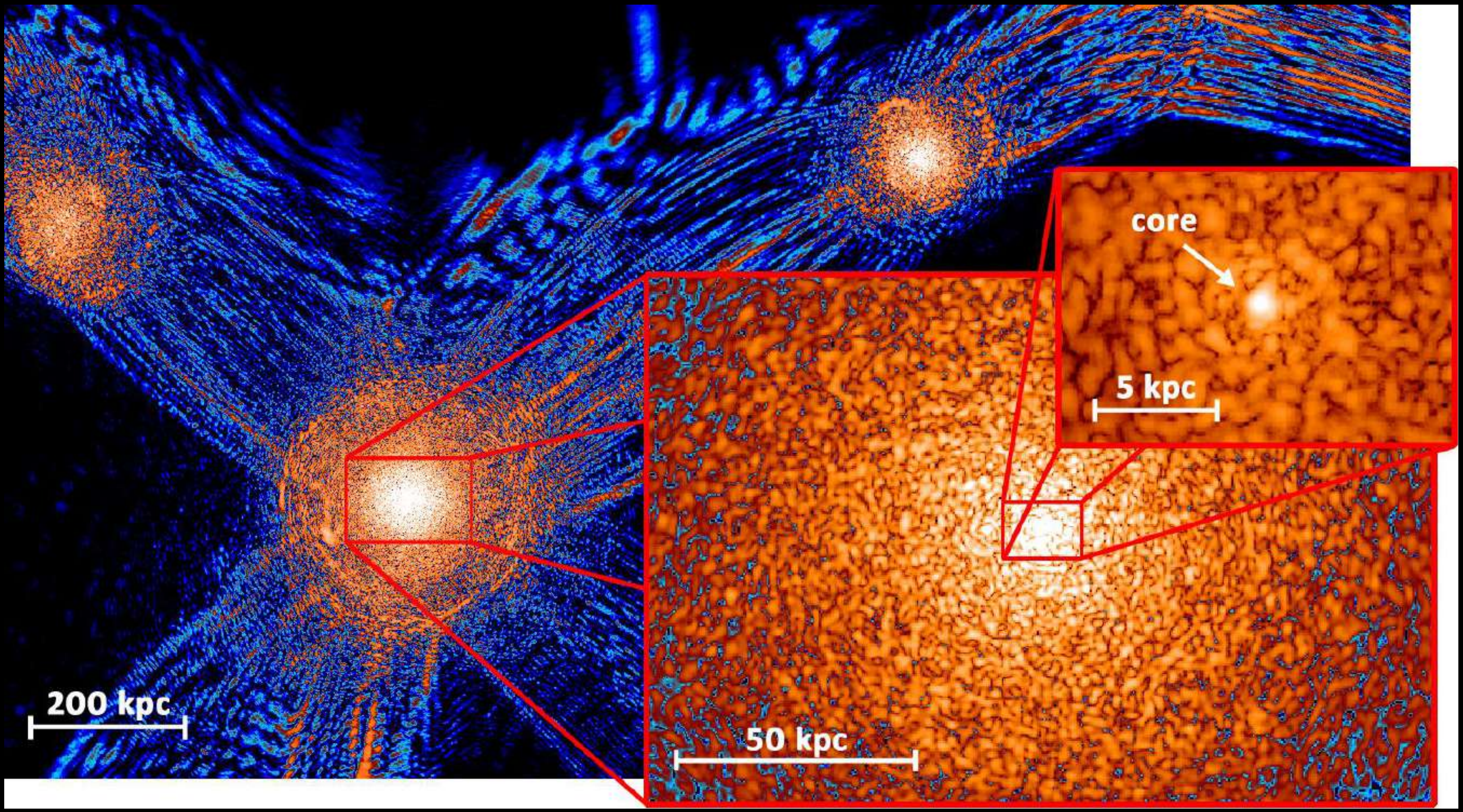




50 Mpc/h box

- **Large-scale structures are indistinguishable**

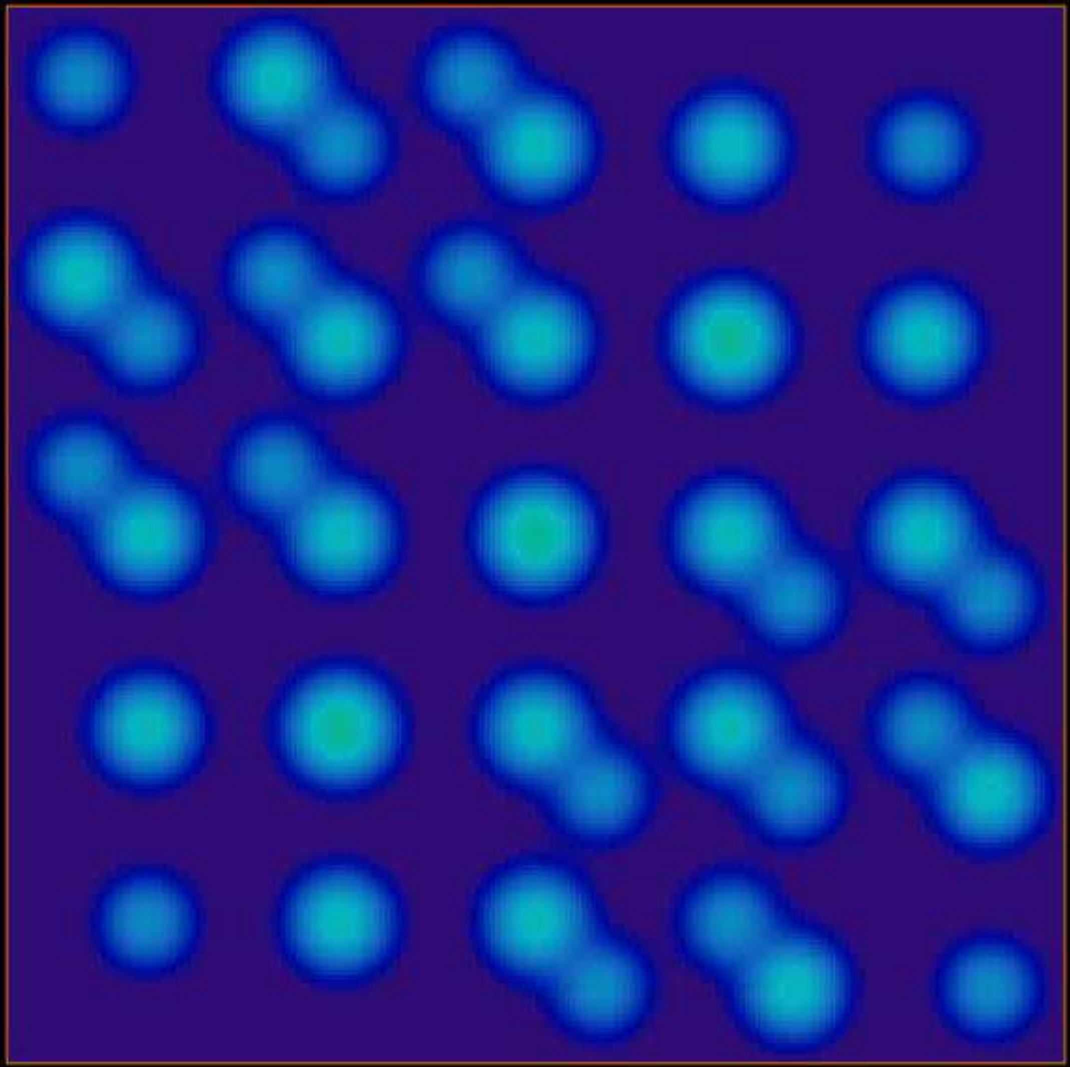
Interference Patterns (Small Scales)



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

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

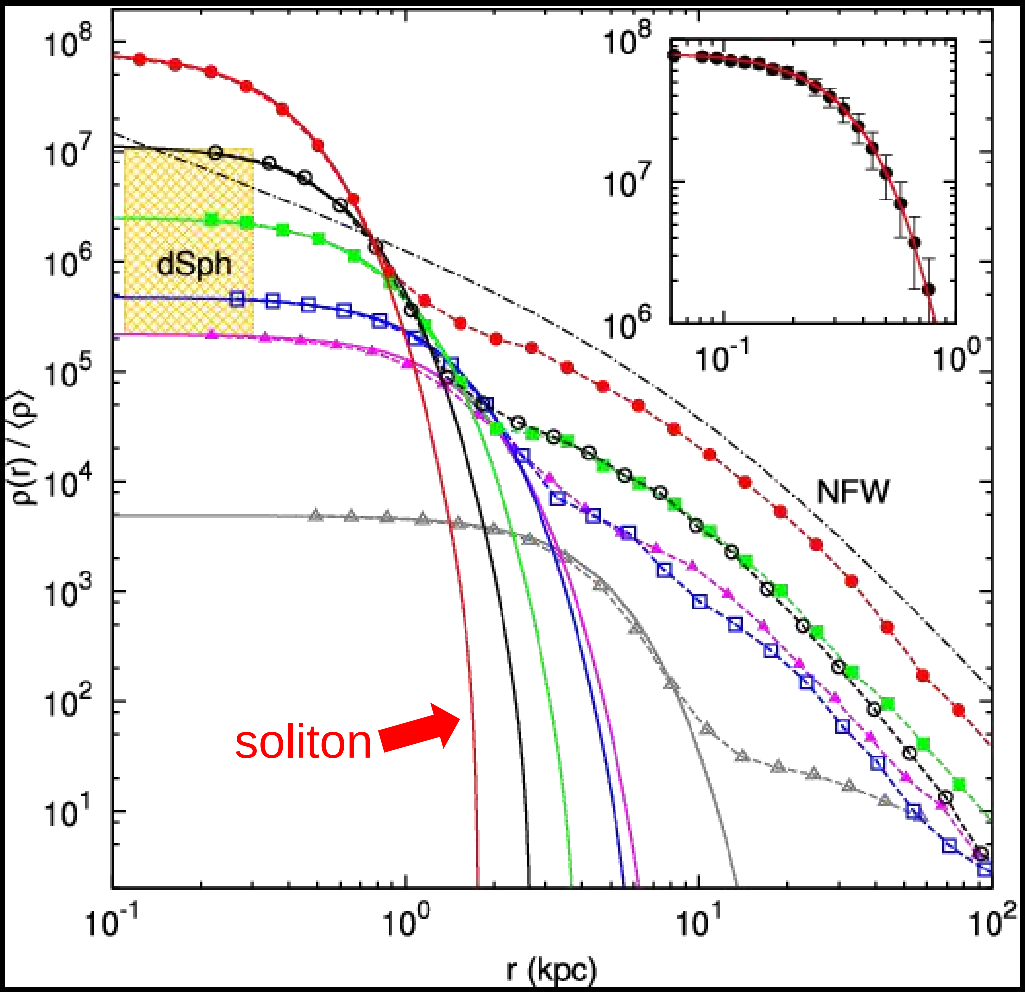
Core-halo Relation



Q1: is there a prominent core in every halo?

Schive et al. 2014, *PRL*, 113, 261302

Core-halo Relation



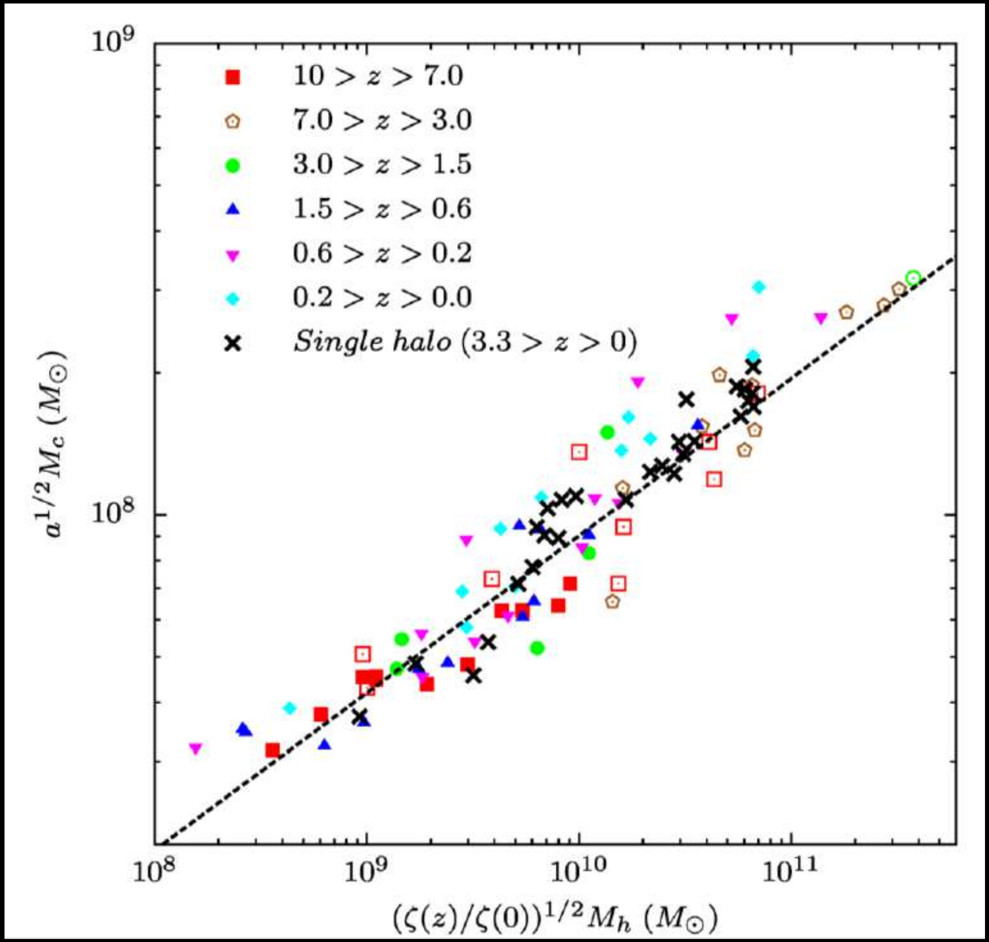
Q1: is there a prominent core in every halo?

YES; core ≈ soliton !!

Q2: for a given halo, can we predict its core properties?

Schive et al. 2014, *PRL*, 113, 261302

Core-halo Relation



- **Core mass (M_c) vs. halo mass (M_h) at different z**
- **Solid line: theoretical prediction**

Schive et al. 2014, *PRL*, 113, 261302

Q1: is there a prominent core in every halo?

YES; core ≈ soliton !!

Q2: for a given halo, can we predict its core properties?

$$M_c \propto r_c^{-1} \propto (1+z)^{1/2} M_h^{1/3}$$

$$M_h \uparrow,\ z \uparrow \ \Rightarrow\ M_c \uparrow,\ r_c \downarrow$$

- **Dwarfs: kpc-scale cores**
- **Minimum halos: $M_h \approx 10^8\ M_\odot$**
- **MW: 100 pc core with $M \approx 10^9\ M_\odot$**
- **More compact cores at higher z**

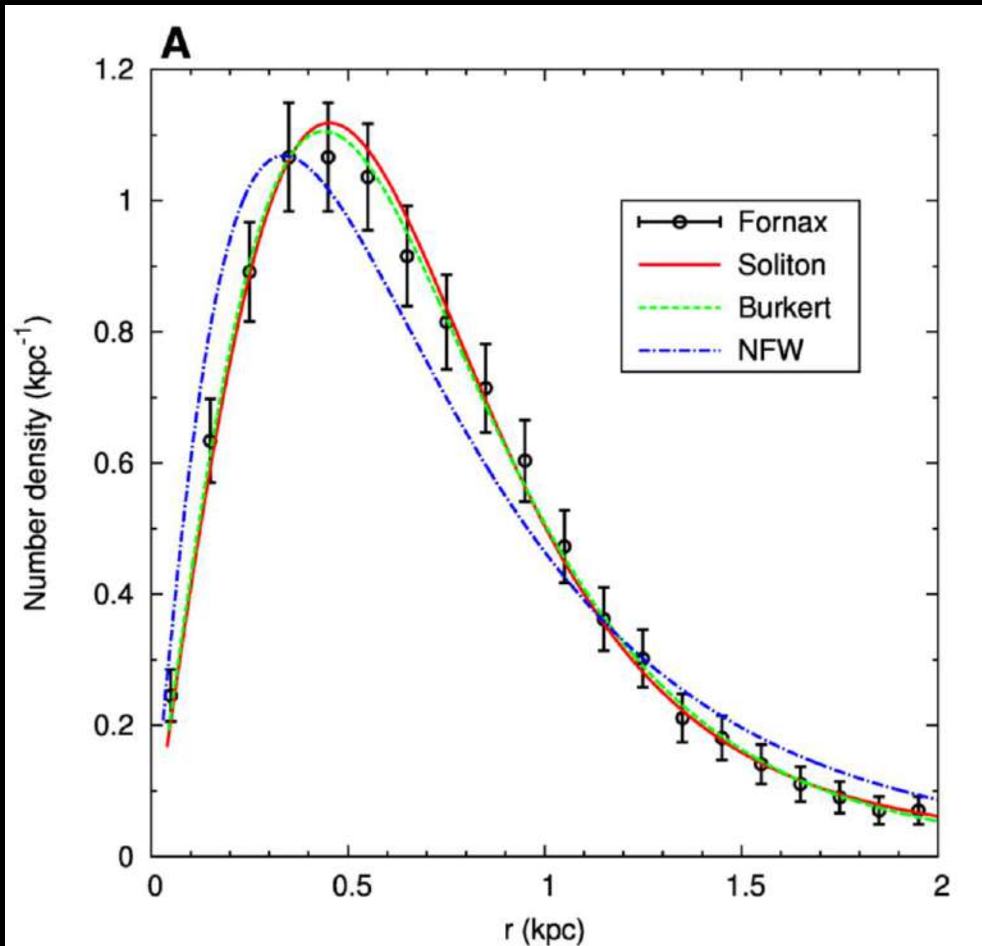
Outline

- Wave Dark Matter (ψDM)
  - Model Characteristics
  - Cosmological Simulations
  - Comparisons with Observations
  - Ongoing Projects
  - Major Challenges

ψDM → Testable Model

- Soliton core
  - Dwarf spheroidal (dSph) galaxies stellar distribution
  - Milky-Way mass within ~100 pc
  - Gravitational lensing
  - Rotation curves of low surface brightness (LSB) galaxies
- Suppress low-mass galaxies
  - High-z luminosity functions
  - Reionization
  - Lyman-alpha forest
  - dwarf galaxy counts
- Density granules
  - Gravitational lensing flux anomalies
  - Stellar streams

Stellar Distribution in Fornax dSph



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

dSph galaxies

- **Dark matter dominated**
- **Dark matter mass profile + stellar velocity dispersion → stellar light profile**

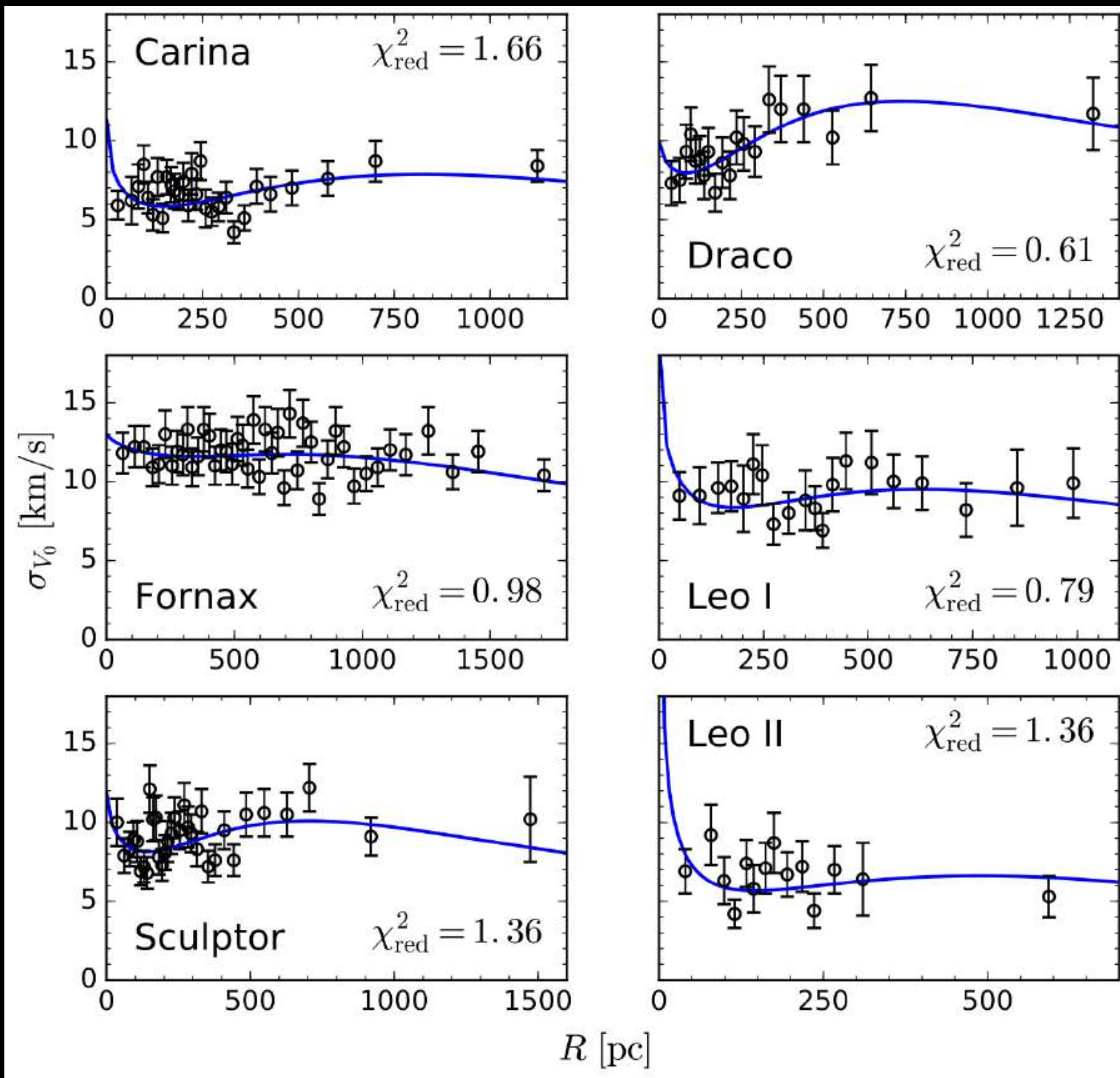
Find the best-fit m_ψ & r_c

→ $m_{22} \equiv m_\psi / 10^{-22}$ eV ~ 0.8 ± 0.4

r_c ~ 0.9 kpc

CDM doesn't fit well due to the <u>cuspy</u> NFW density profile

Jeans Analysis for dSph Galaxies



Soliton mass profile + stellar light profile
→ stellar velocity dispersion

$m_{22} \approx 1.2 \pm 0.3$
→ Consistent with Fornax ($m_{22} \approx 0.8 \pm 0.4$)

Different dSph galaxies ↔ SAME particle mass (m_{22}) !!

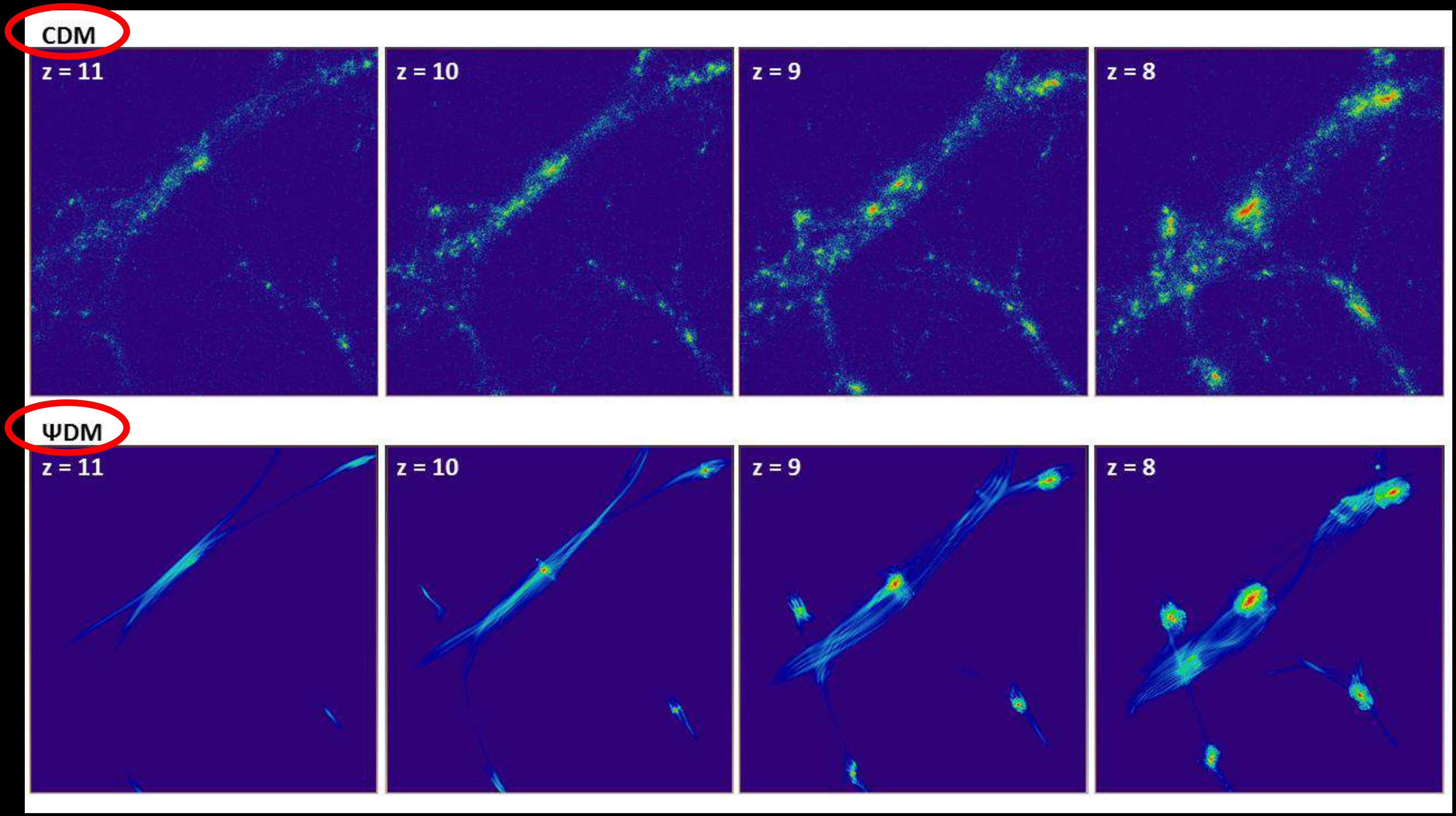
Chen, Schive, & Chiueh 2017, MNRAS

Suppression of High-z Galaxies

- Does ψDM suppress too many high-z galaxies?

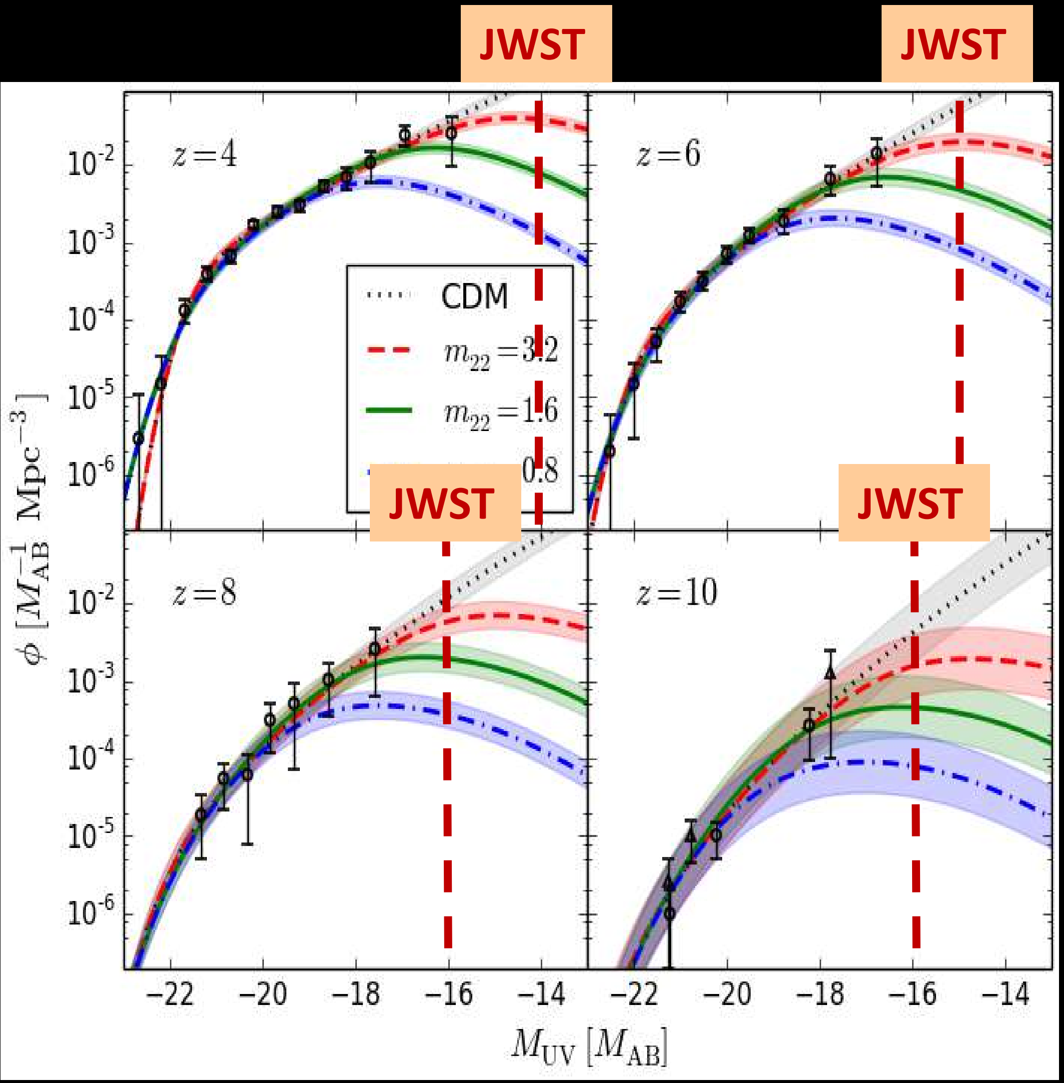
or

- Does CDM produce too many high-z galaxies?



1 Mpc/h

Luminosity Functions



Schive et al. 2016, ApJ

Faintest HST bin: $m_{22} \geq 1.2$ (2σ)

Fitting to dwarfs: $m_{22} = 1.2 \pm 0.3$ (2σ)

Much more consistent than the warm dark matter

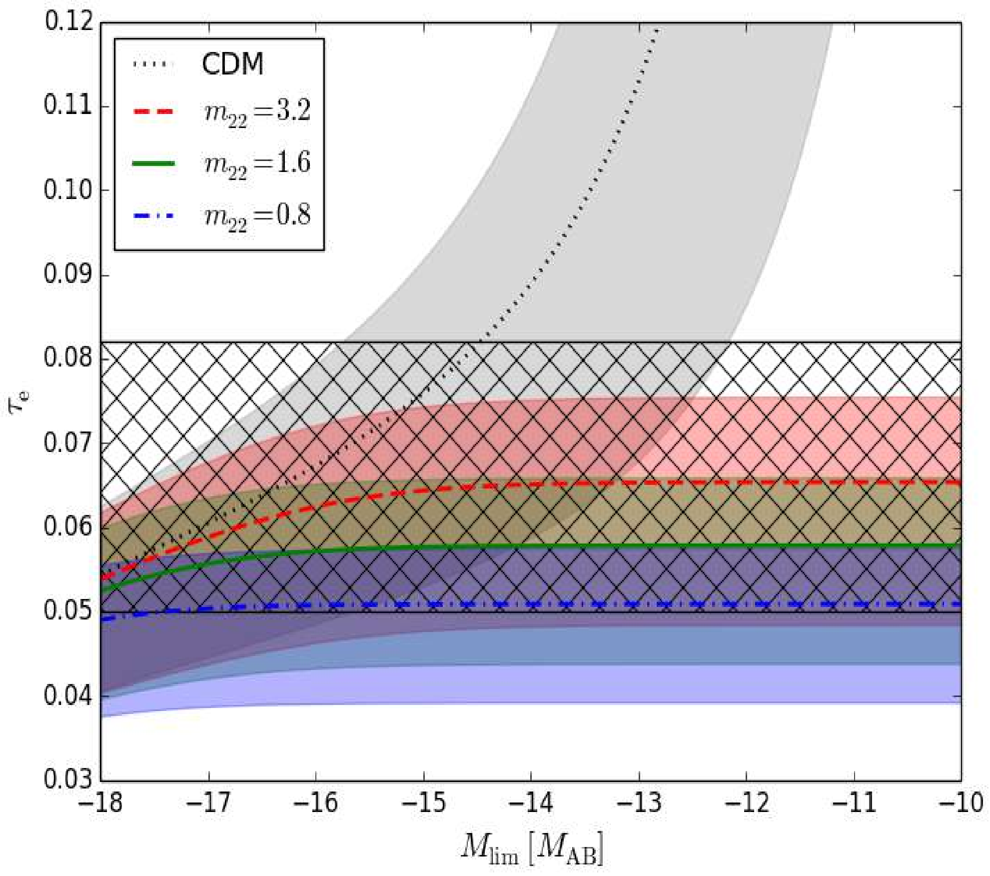
Suppression of low-mass halos

LF turns over slowly around $M_{UV} \geq -16$ at $z \geq 4$

Just beyond the currently detectable range

Directly testable with JWST and highly magnified galaxies in HST

Thomson Optical Depth (τ_e) of CMB



- **Shaded regions: bound by most and least efficient reionization models**

Schive et al. 2016, ApJ

Planck 2015: $\tau_e = 0.066 \pm 0.016$ (1σ)

Both CDM & ψDM can satisfy the observational constraints

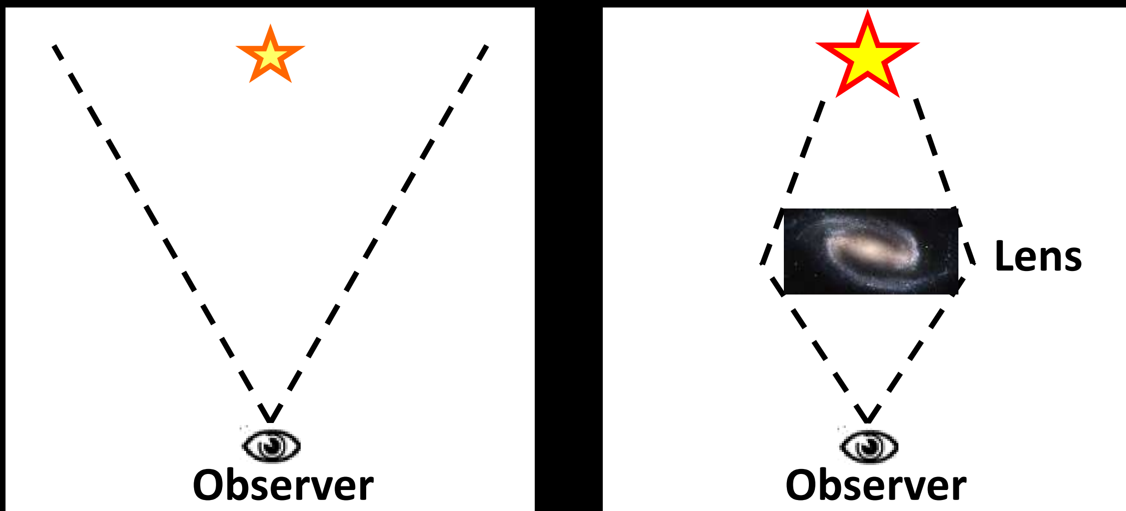
- **$m_{22} \geq 0.7$**
- **Consistent with other constraints**

ψDM: insensitive to M_{lim} (i.e., the faintest galaxies under consideration)

- **Due to strong suppression of faint galaxies**

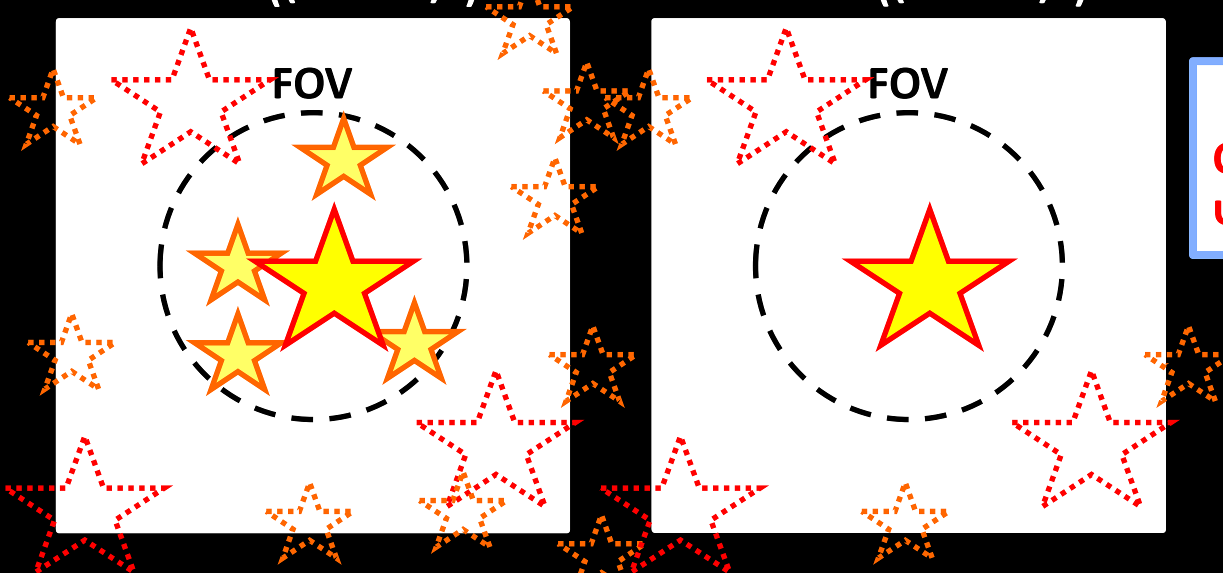
Magnification Bias by Lensing

Unlensed | Lensed



Magnified luminosity
vs.
Reduced field of view

CDM (unlensed) / CDM (lensed) | ΨDM (unlensed) / ΨDM (lensed)



After lensing:
CDM galaxy number density ↑
ΨDM galaxy number density ↓

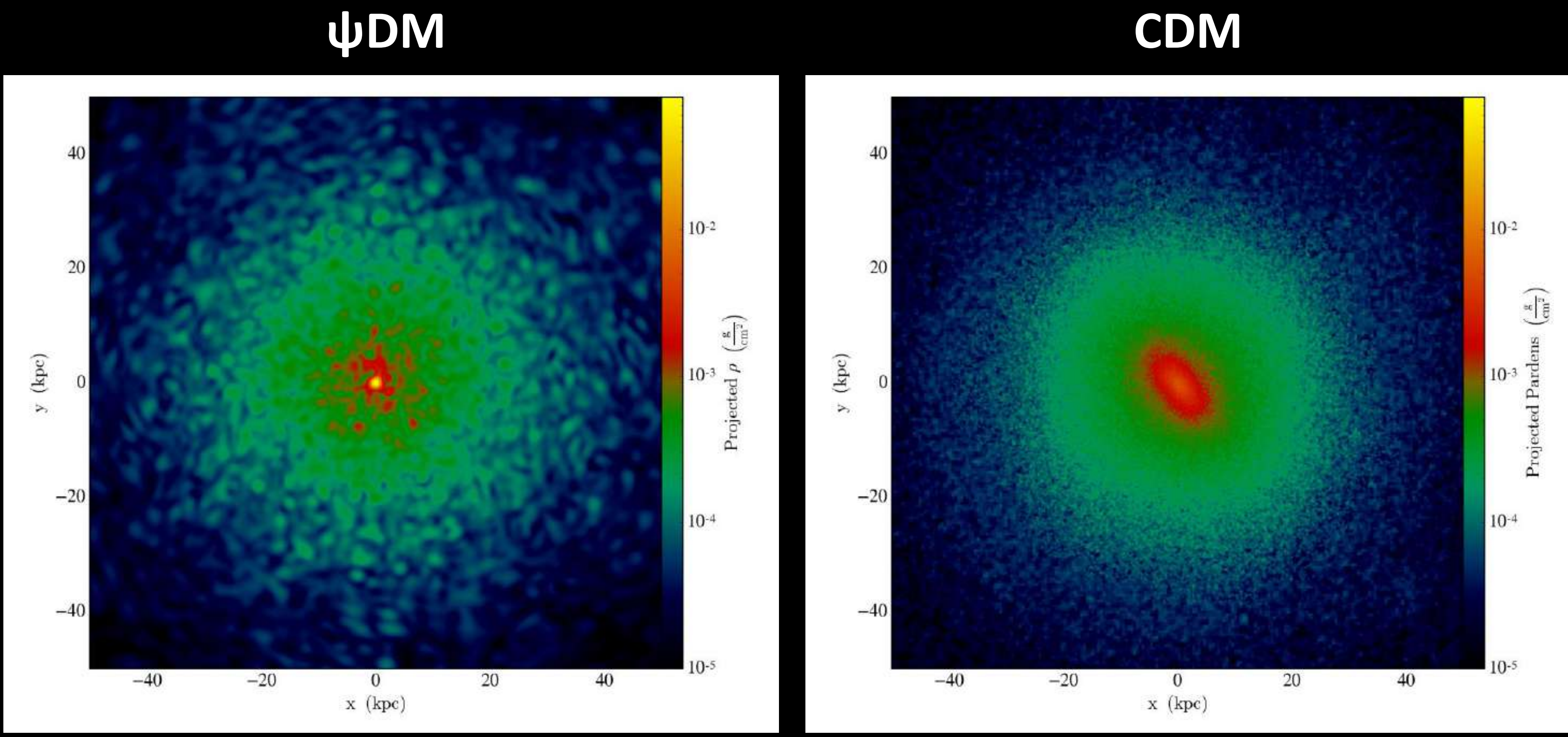
directly testable !!

Leung et al. 2018, ApJ

Outline

- Wave Dark Matter (ψDM)
  - Model Characteristics
  - Cosmological Simulations
  - Comparisons with Observations
  - Ongoing Projects
  - Major Challenges

Density Granules in ψDM



- **Comparable size with the central soliton** → isothermal
- **100% modulated** → density can literally approach zero
- **Throughout the halo** → very different from the CDM substructures

Flux Anomalies in Strong Lensing

- Lensing flux anomalies common for quasars strongly lensed by galaxies: $\mu_1 + \mu_2 + \mu_3 = 0$ for a smooth lens, but usually 10-50% residual (R)
- ψDM granules naturally account for the observed flux anomalies

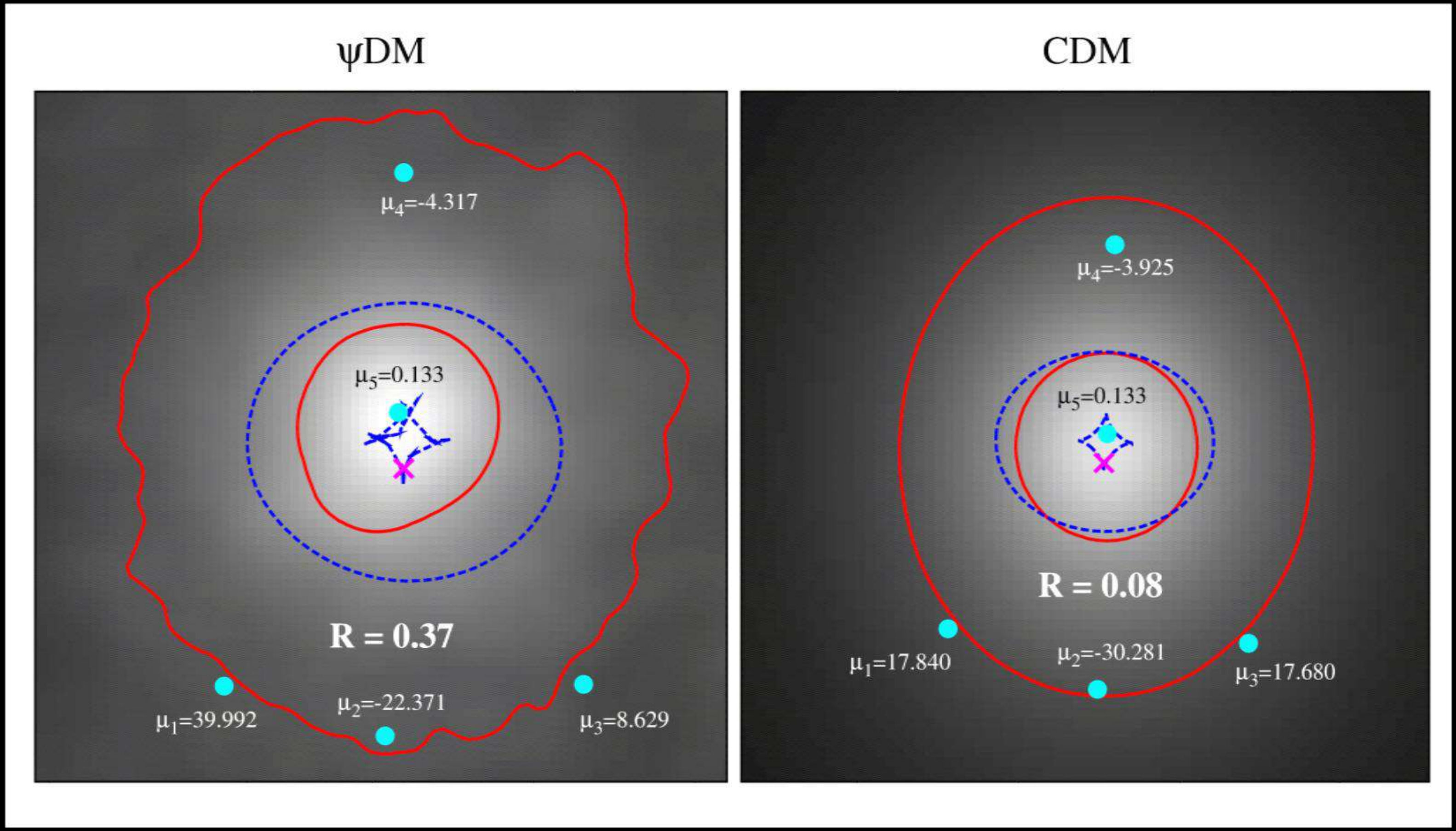
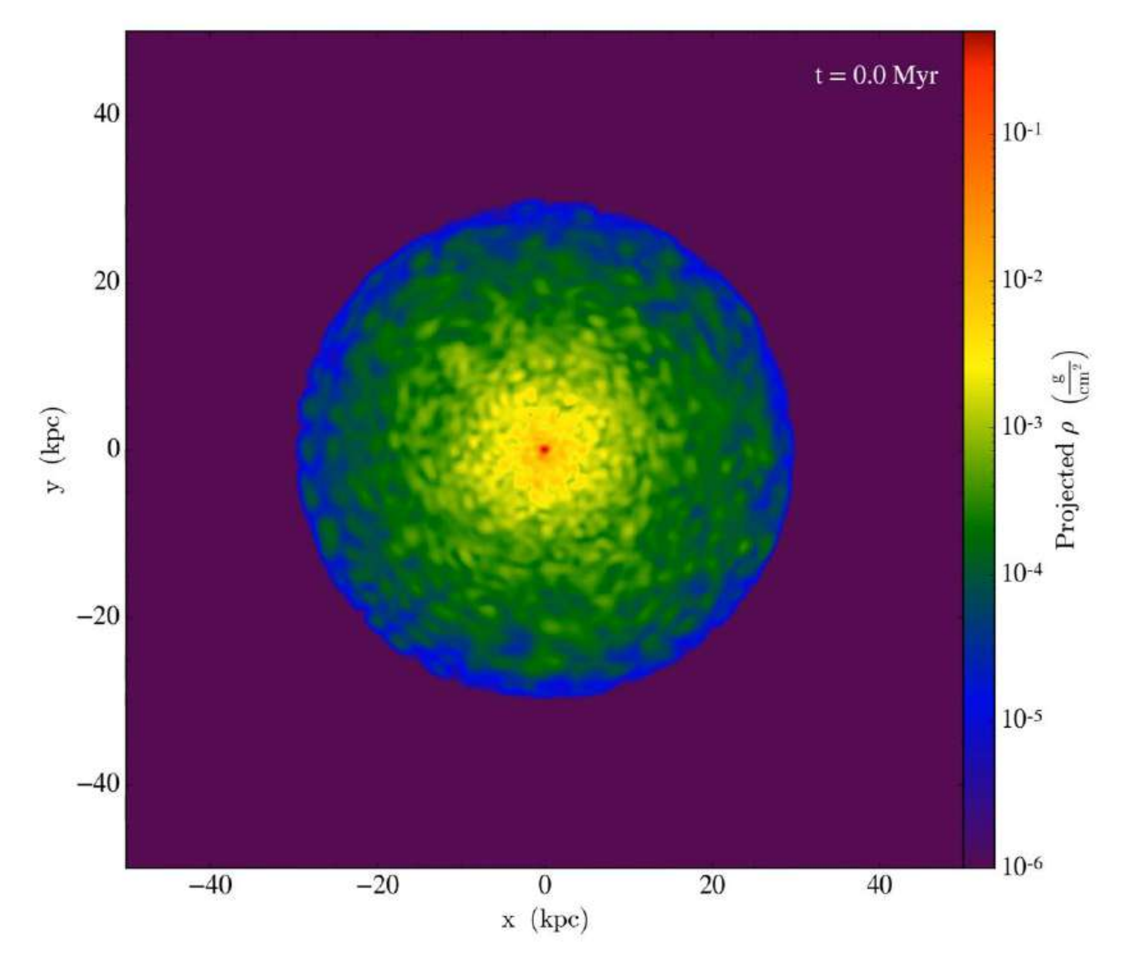


Figure courtesy of James Chan

Tidal Stripping



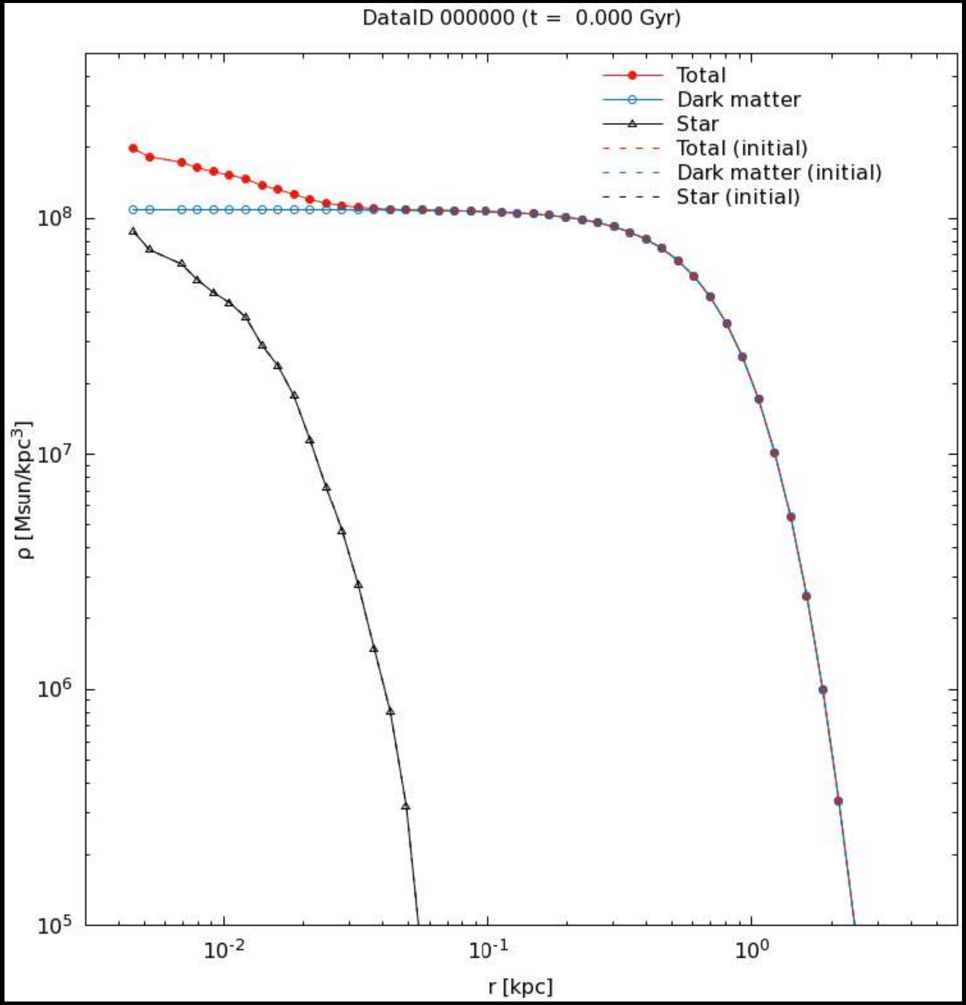
Are ψDM halos more or less vulnerable to tidal disruption?
- **Prominent soliton core**
- **Tunneling effect**

How does it affect the core-halo relation?

Explain the observed high M/L ratios in dSph galaxies?

Heating of Star Cluster

- Soliton actually oscillates in time → may heat up the central star cluster
- Question: can star clusters survive for a Hubble time?



Other Testable Predictions

- Soliton core
  - Milky-Way mass within ~100 pc
    - Is there excessive mass?
  - Gravitational lensing
    - Small galaxies → fall short of critical lensing density → limiting Einstein radii
  - Rotation curves of low surface brightness (LSB) galaxies
    - Any sign of central soliton?
- Suppress low-mass galaxies
  - Dwarf galaxy count
    - Does ψDM predict a correct number?
  - Lyman-alpha forest
    - Probe small-scale structures
- Density granules
  - Stellar streams
    - Density granules may ``heat up” the streams and create gaps

Outline

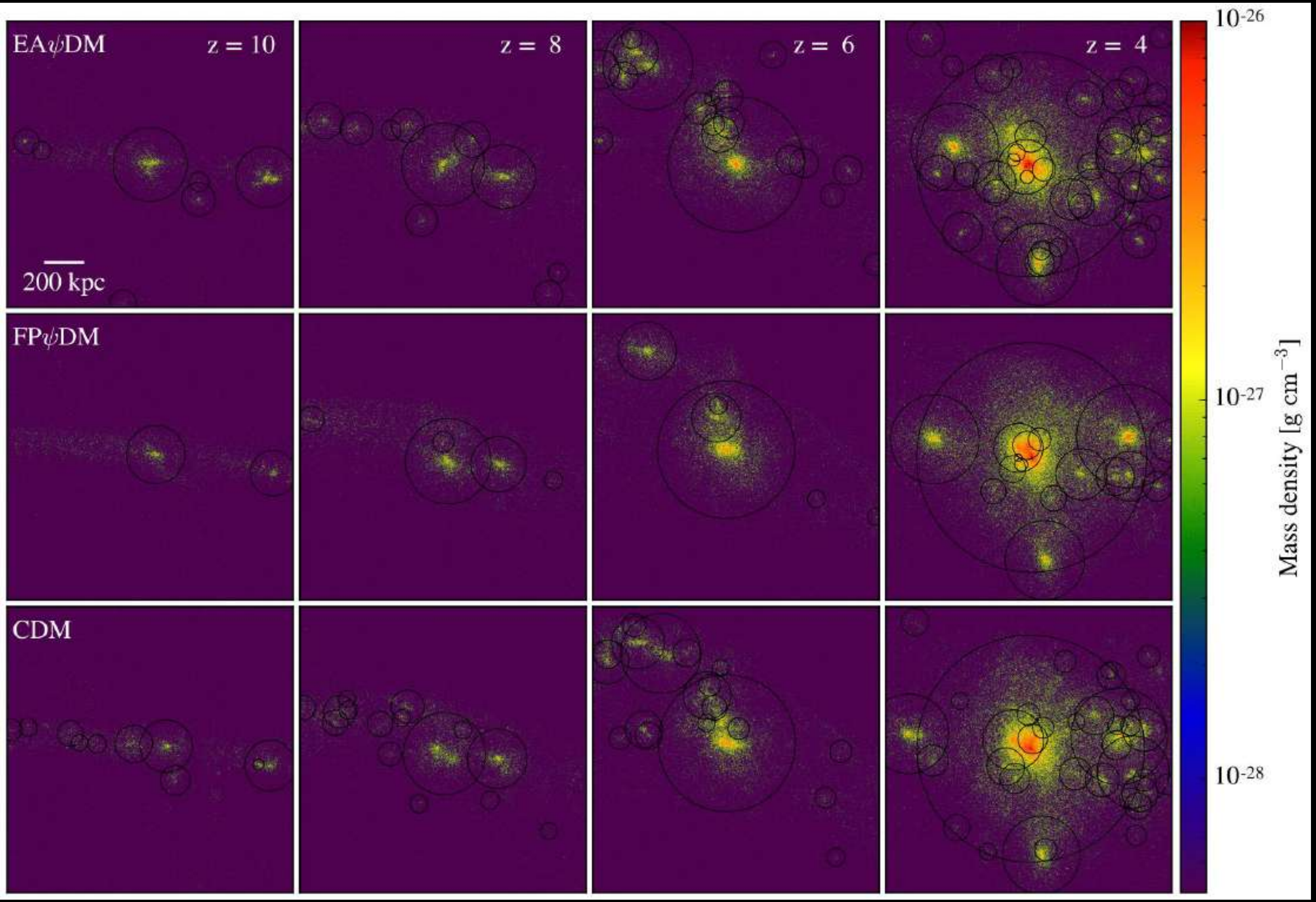
- Wave Dark Matter (ψDM)
  - Model Characteristics
  - Cosmological Simulations
  - Comparisons with Observations
  - Ongoing Projects
  - Major Challenges

Over Suppression of Low-mass Galaxies?

- Quantum pressure $\mathrm{P} \propto m_\psi{}^{-1}$
  - $m_\psi \downarrow \;\Rightarrow\; \mathrm{P} \uparrow$
  - $m_\psi \sim 10^{-22} eV$ fixed by Fornax dSph
  - Strongly suppress halos < 10^9 $M_\odot$
  - Make ψDM halos more vulnerable to tidal disruption?
  - Does $m_\psi \sim 10^{-22} eV$ overly suppress the low-mass galaxies?
- Number of Milky Way Satellite Galaxies
  - 14 → 59 since 2006 (SDSS + DES)
- Lyman-alpha Forest
  - Probe the small-scale power spectrum in the quasi-linear regime
  - Demand $m_\psi \sim 10^{-21} eV$ → 10x larger!
  - Plausible solution: extreme-axion ψDM model
    - Larger cut-off wavenumber in the initial power spectrum
    - More substructures

Extreme Axion

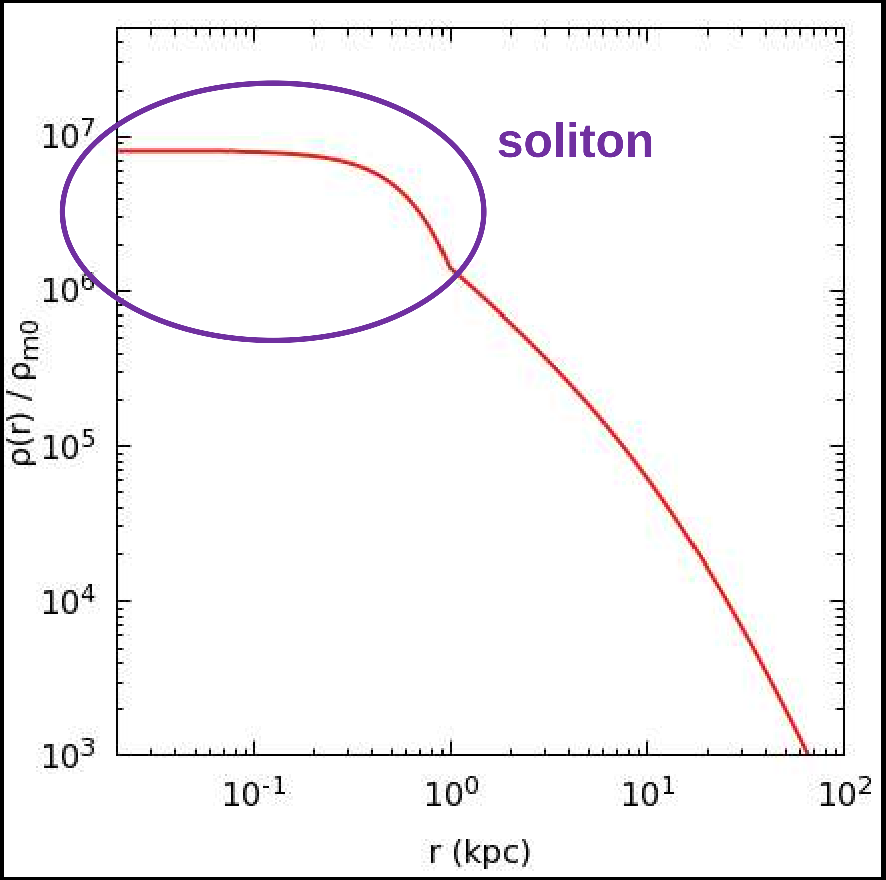
- **Significantly increase the number of low-mass galaxies**
  - **Comparable to CDM for halos > 10^9 $M_\odot$**



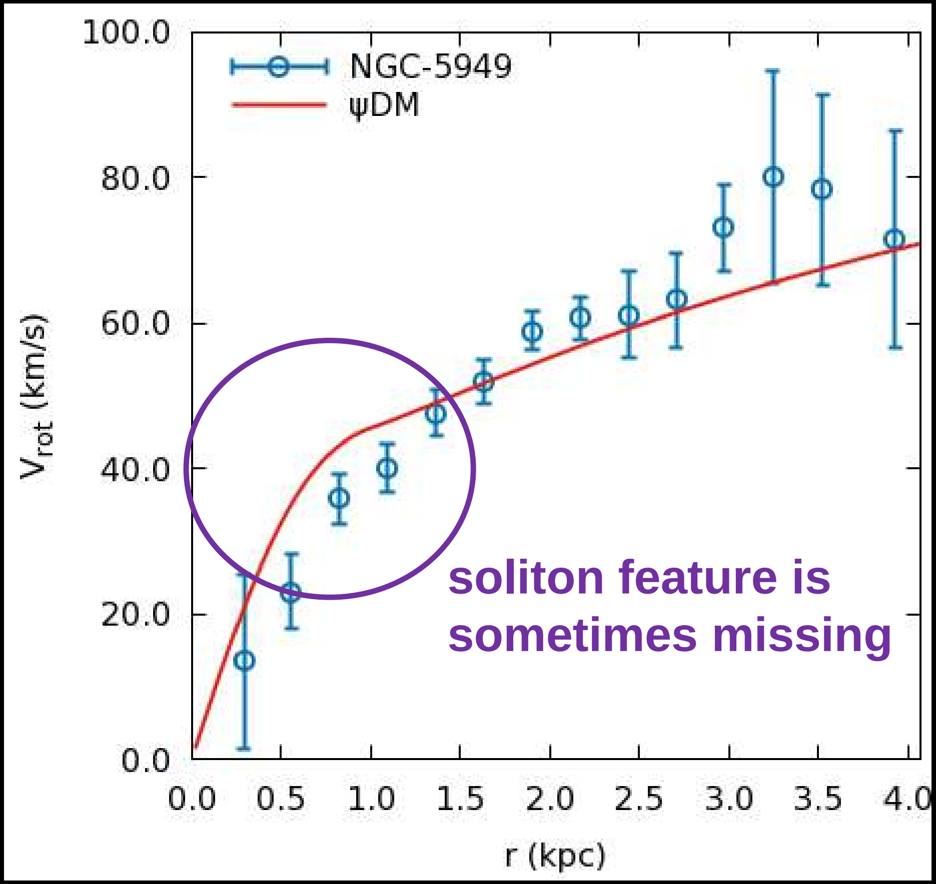
Schive & Chiueh 2017, MNRAS letter

Missing Soliton in Rotation Curve?

Density Profile



Rotation Curve



- Possible solutions:
  - More complicated interaction between soliton, gas, and stars?
  - Soliton jiggling?

Summary

- ψDM (wave dark matter)
  - Interference everywhere → soliton, density granules
  - Quantum pressure → suppress low-mass galaxies
  - Comparisons with observations → $m_\psi \sim 10^{-22}$ eV
  - Core-halo mass relation
  - Major challenges
    - Lyman-alpha forest
    - Missing solitons in rotation curves
- GAMER-2 (GPU-accelerated Adaptive Mesh Refinement)
  - 10 – 100 times faster than other AMR codes
  - Cutting-edge applications that were previously infeasible