Ultra-Light Axion Dark Matter & Its Astronomical Implications

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in collaboration with
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Woo & Chiueh, ApJ, (2009), Schive et al., Nature Phys. (2014), Schive, et al, PRL (2014), Schive et al. ApJ (2016), Chen et al. MNRAS (2017), De Martino, et al, PRL (2017), Zhang & Chiueh, PRD (2017 a, b), Schive & Chiueh MNRAS (2017), Leong et at., MNRAS (2019)

Outline:

- Axion DM as Bose-Einstein Condensate

  $m_a \sim 10^{-22}$ eV ⇨ $n_0 \sim 10^{25}$/cc, $T_{crit}/(1+z) \sim 10$ keV

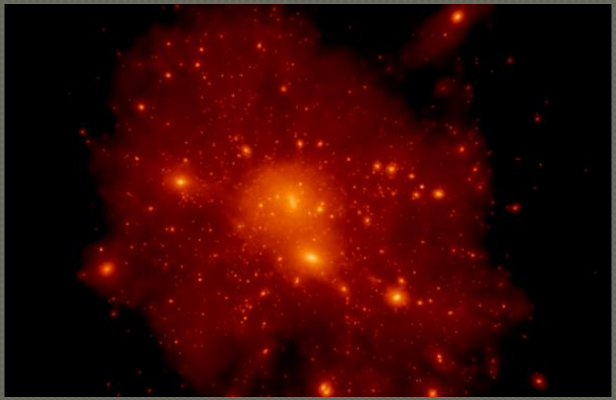
  Axion DM (a<a_{eq}) ⇨ Free-particle wave DM (a>a_{eq})

  Schroedinger Eq. for DM dynamics (ψDM)
- Small-scale astronomical problems
- ψDM halo: dynamical simulation
- Lyα forest Problem (z~2.5-4.5)---Extreme Axion
- Additional observation tests, e.g., pulsar timing, 21cm tomography

Trouble with CDM

- Small-scale (~ kpc) problems:

(a) Missing satellite dwarf galaxies around Milky Way



> 100 satelites for CDM

(b) Flat-cores in dwarf spheroidal galaxies as opposed to CDM bound halo: $\rho\ (r) = \rho_0 / r (1 + c\, r^2)$

Using Jeans Eq. : $d(\rho\sigma^2)/dr = -\rho G M(r)/r^2$

Wave Dark Matter (ψDM) (back of the envelope estimates)

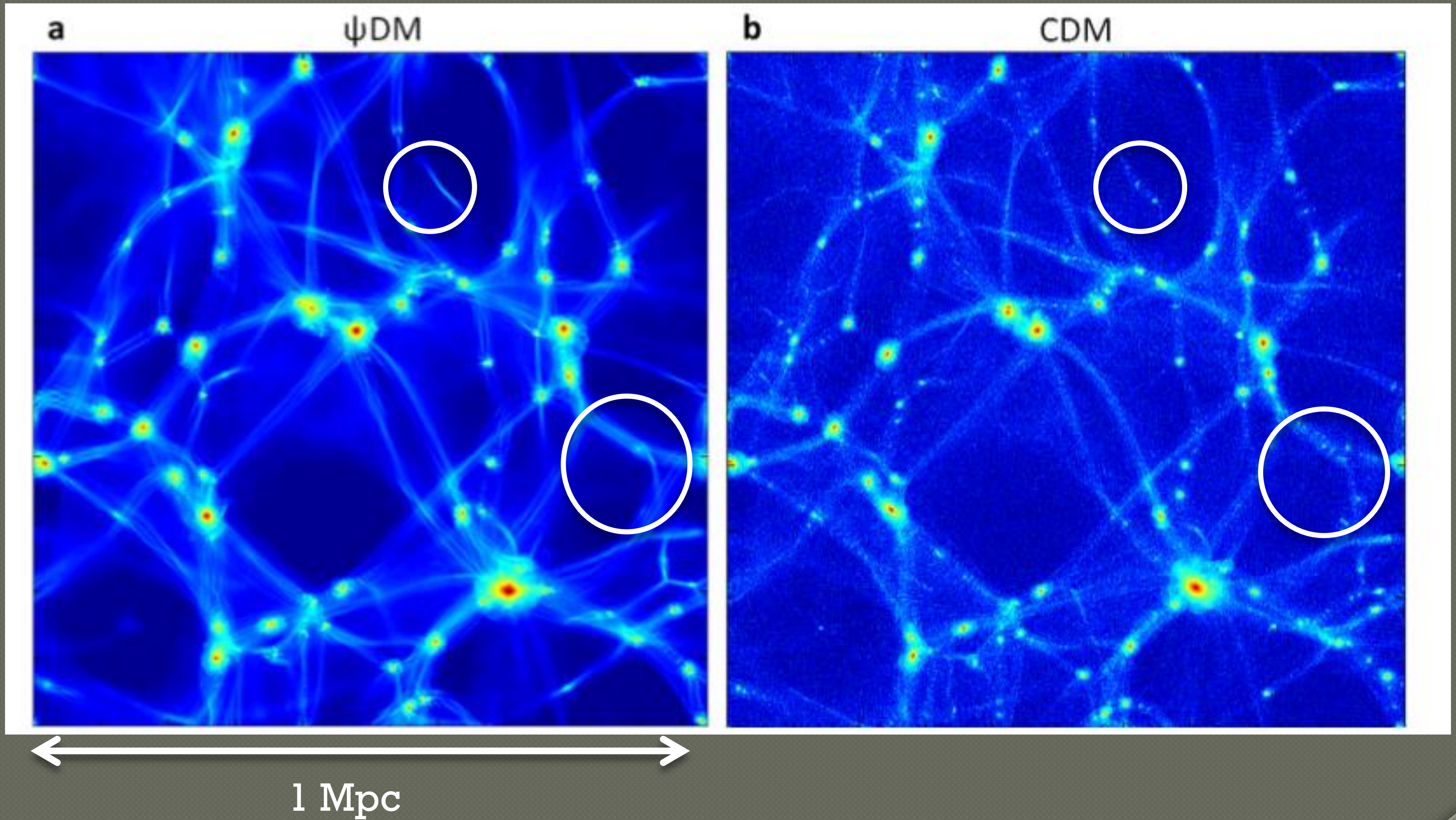
- Dark matter described by a single wave function ψ

$$\left[i\frac{\partial}{\partial\tau} + \frac{\nabla^2}{2} - aV\right]\psi = 0 \qquad \nabla^2 V = 4\pi(|\psi|^2 - 1)$$

- $\Delta x \Delta v = \hbar/m_a \sim (10\text{km/s})\text{kpc}$: astronomical scale
- Expect that the uncertainty principle respected in Milky Way: $\Delta v \sim 200\text{km/s} \longrightarrow \Delta x \sim 0.1\text{kpc}$, small scale!
- However, G & Δv demands large scale ~100kpc!
  $\longrightarrow$ Solution has coexisting small & large scales!

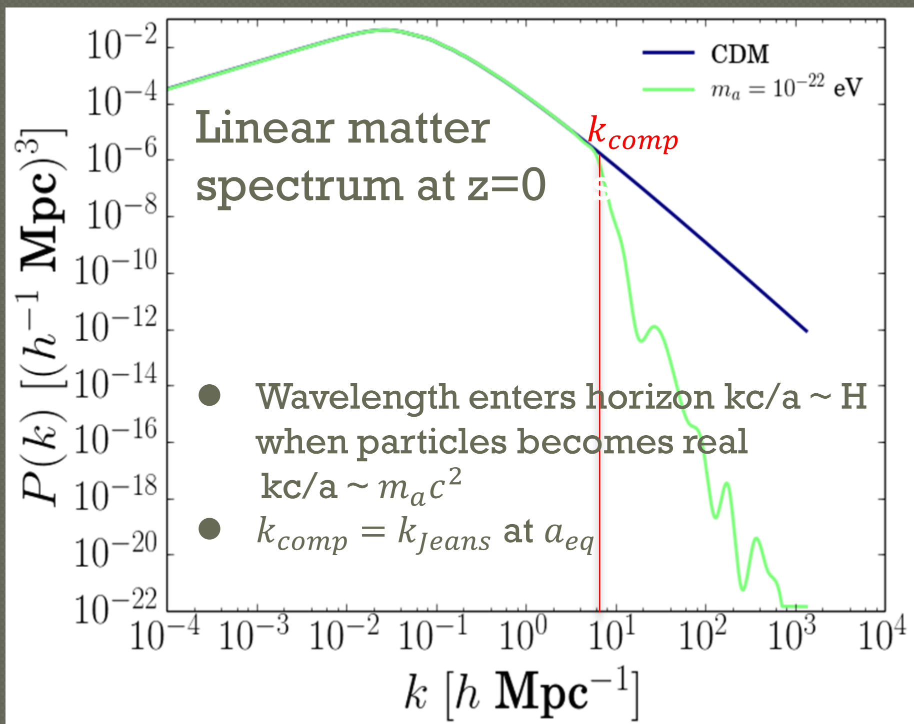
- What if G and $\hbar/m_a$ balance and share the same scale?
  $\Delta x = (\hbar/m_a)^2/GM_s$ for a particular mass M_s
  Black hole analogy, G balances c: $R_{BH} = GM_{BH}/c^2$

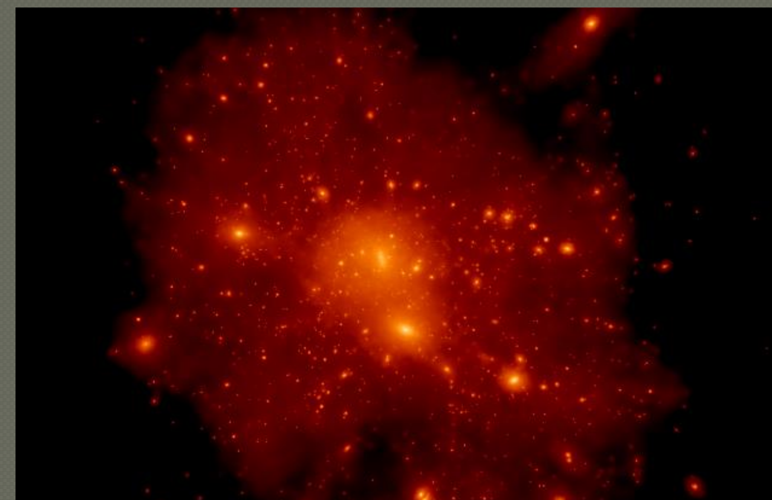
Dynamical simulations:
Reproduce CDM galaxy distribution > 30kpc scale
But small scales ….



Explain Missing Satellite Galaxies

Small-scale linear power suppressed at Compton (Jeans) length





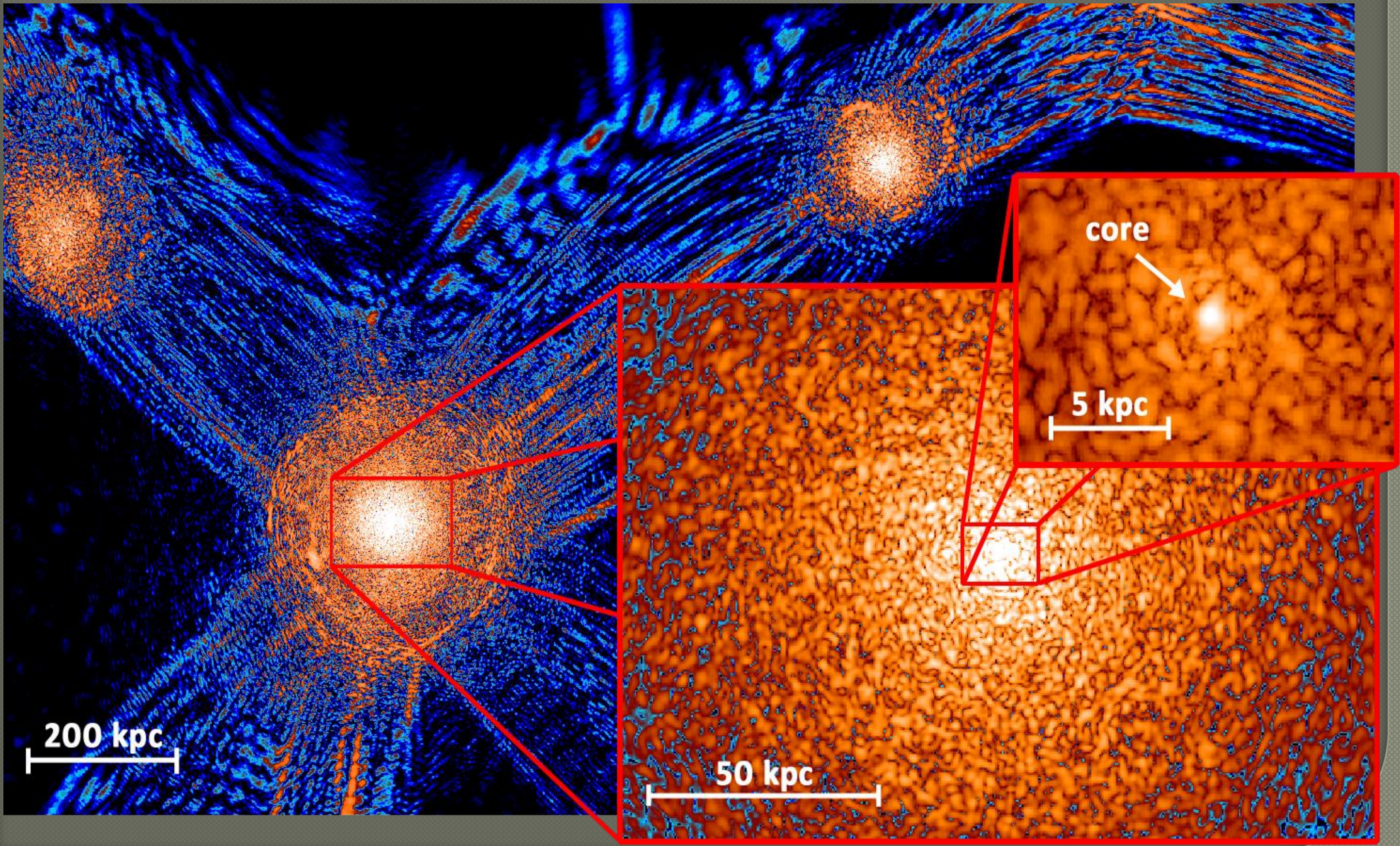
CDM simulation of a major halo several 100s of dwarf galaxies, but only several 10s are detected

Hu et al., PRL, (2000)
Woo & Chiueh, ApJ (2009)
Zhang & Chiueh, PRD (2017a)

Jeans wavenumber $k_J^2 \sim aG/c_s^2 \sim a^{1/2}$
with c_s^2 replaced by $v^2 \sim (\hbar k_J/m_a)^2$

Dynamical Simulations:

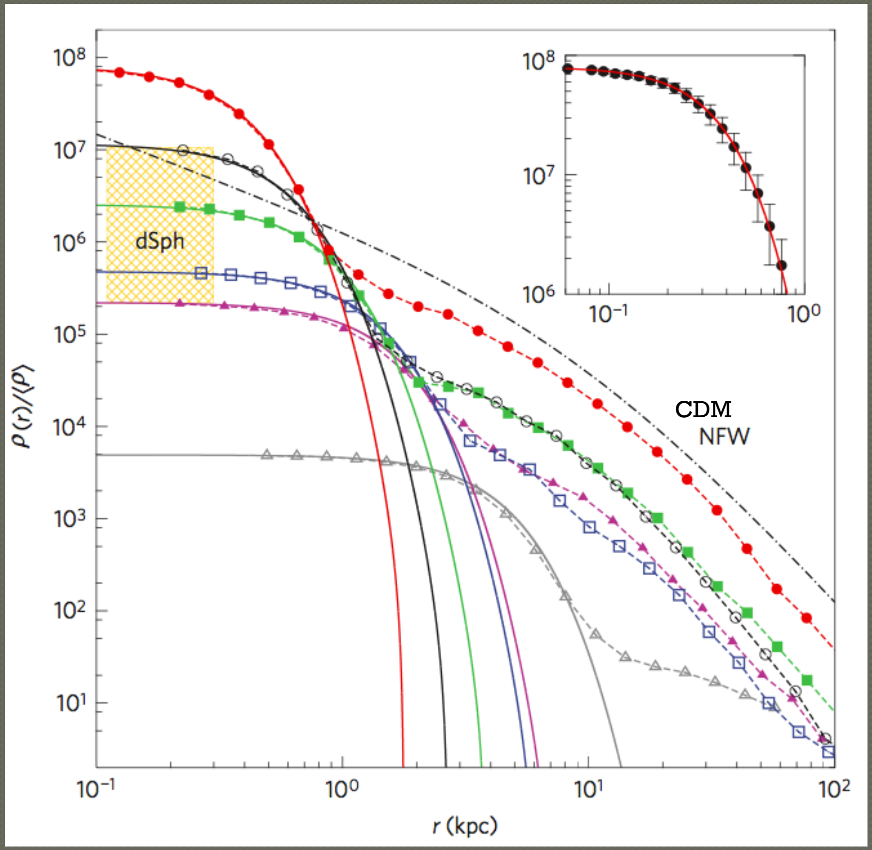
A single soliton core and granular halo in every galaxy



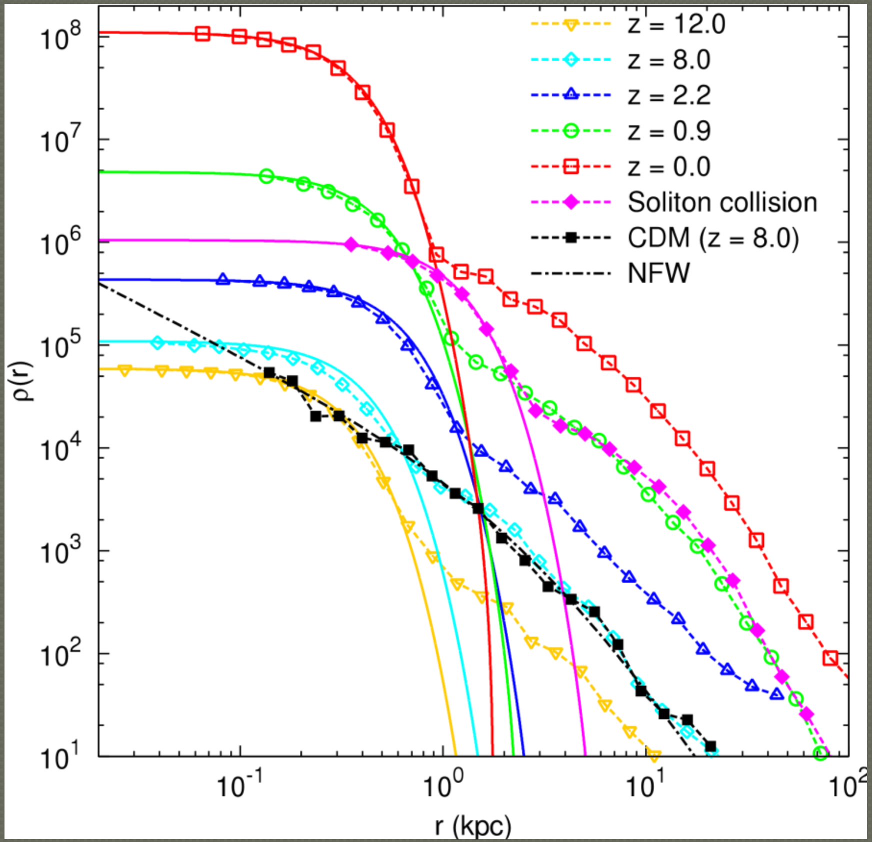
A soliton in a galaxy halo

Schive at al. 2014, PRL

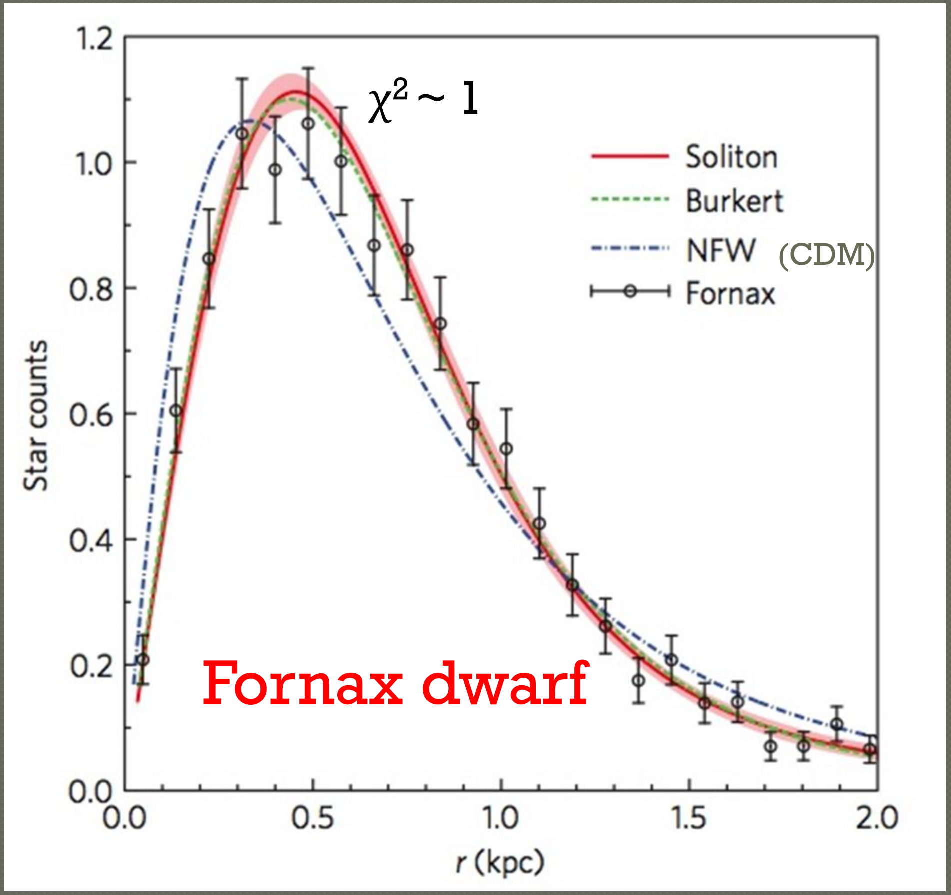
z = 0 dwarf galaxies



Redshift evolution



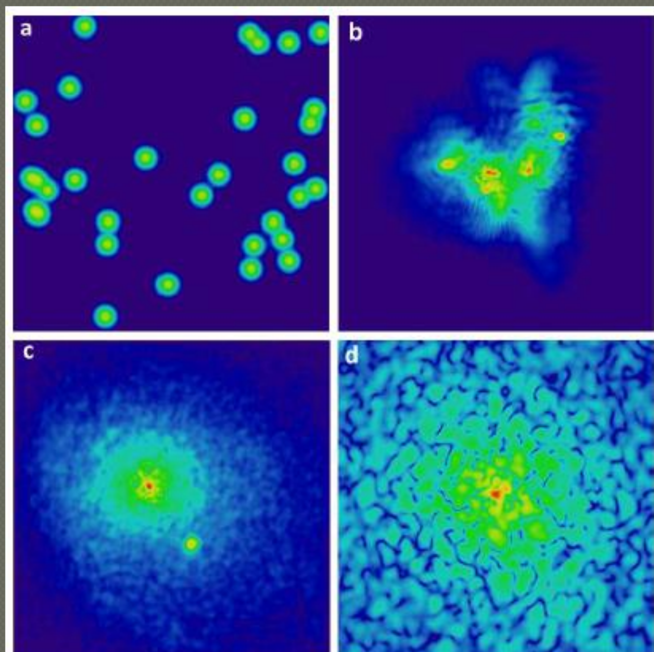
Solution to the flat-core problem:
Stars reside in the soliton core

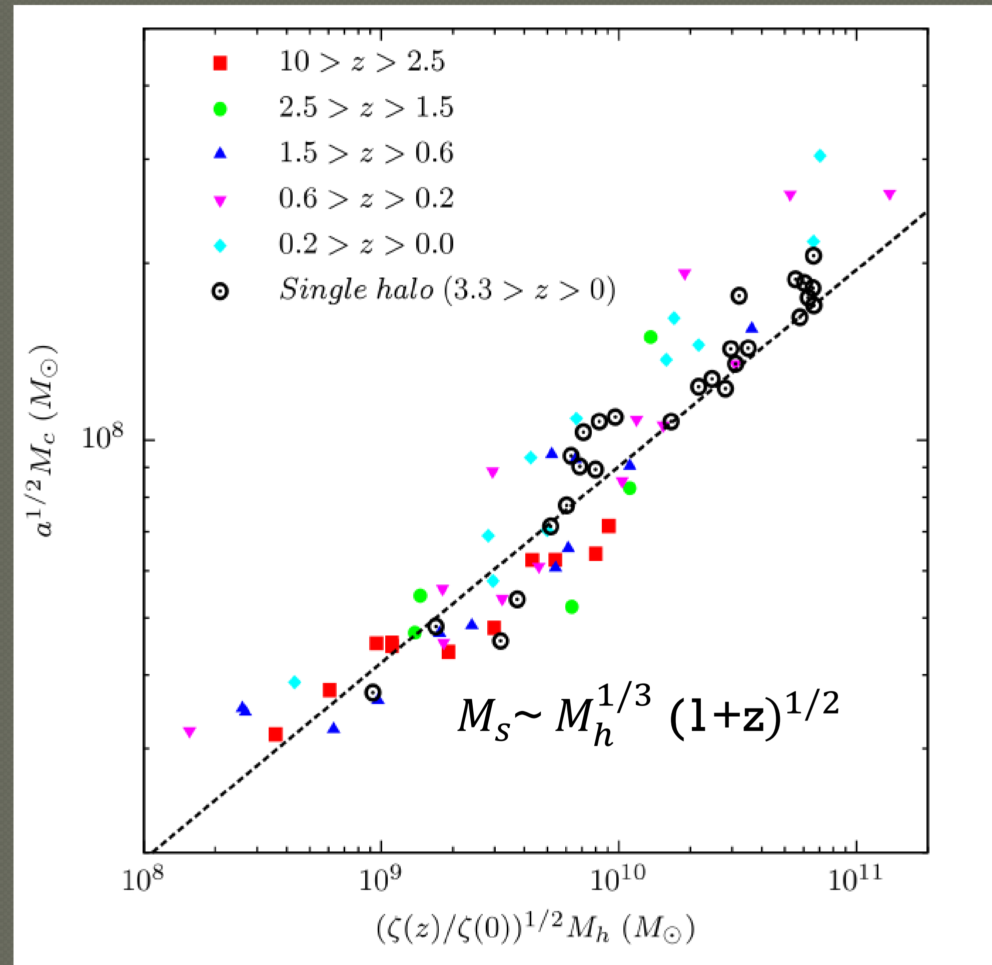


Schive et al. Nature Phys (2014)

- Given observed stars density and velocity profiles, determine $m_a \sim 10^{-22}$ eV using $M_s r_s \sim \hbar/m_a$
- Confirm m_a with 4 more dSphs, Chen et al. (2016)

DM Core-Halo relation:

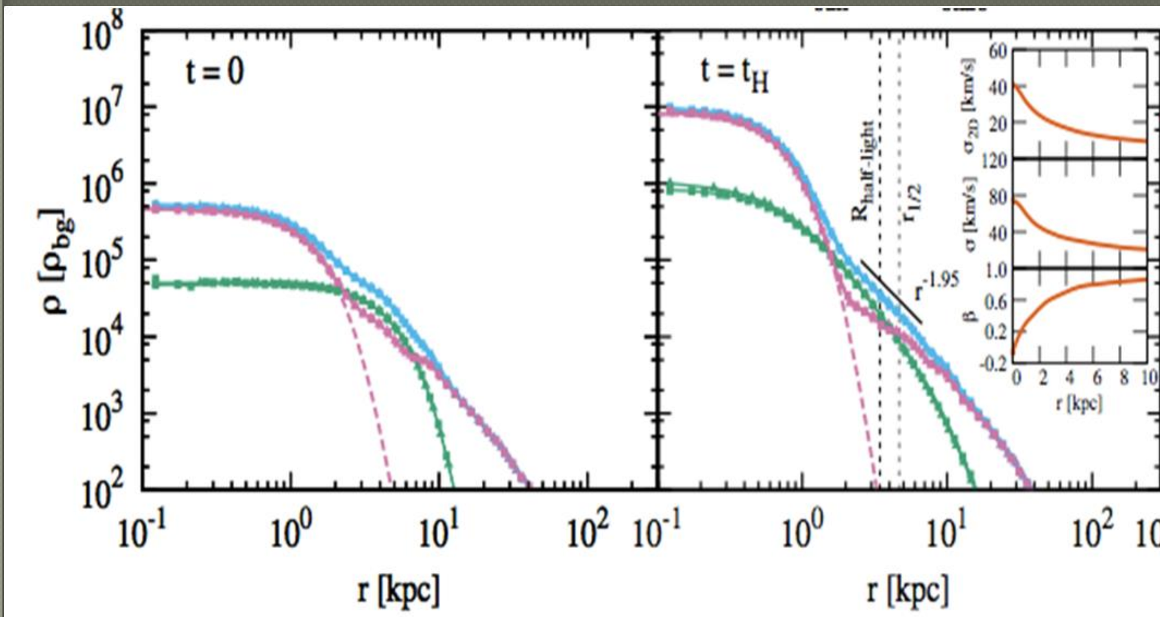




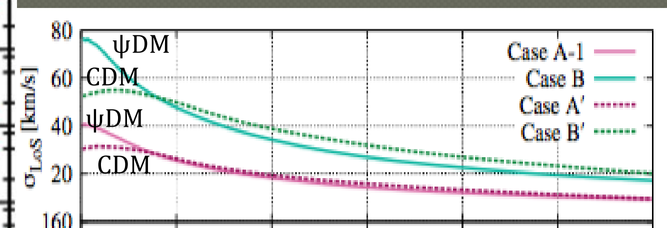
can be explained by equilibration of soliton "temperature" & halo "temperature"

$$\Delta v_{sol} = (\hbar/m_a)/r_{sol} \sim (E_h/M_h)^{1/2} = \Delta v_h$$

DM halo+Stars



Compare ψDM and CDM halos

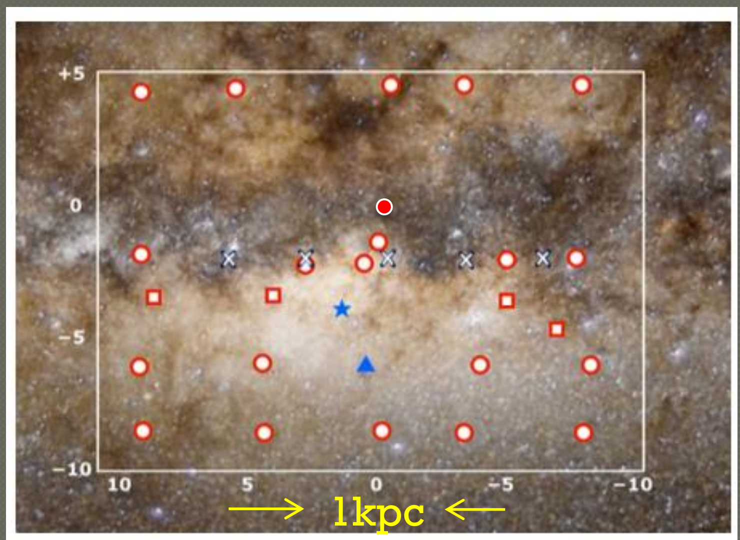


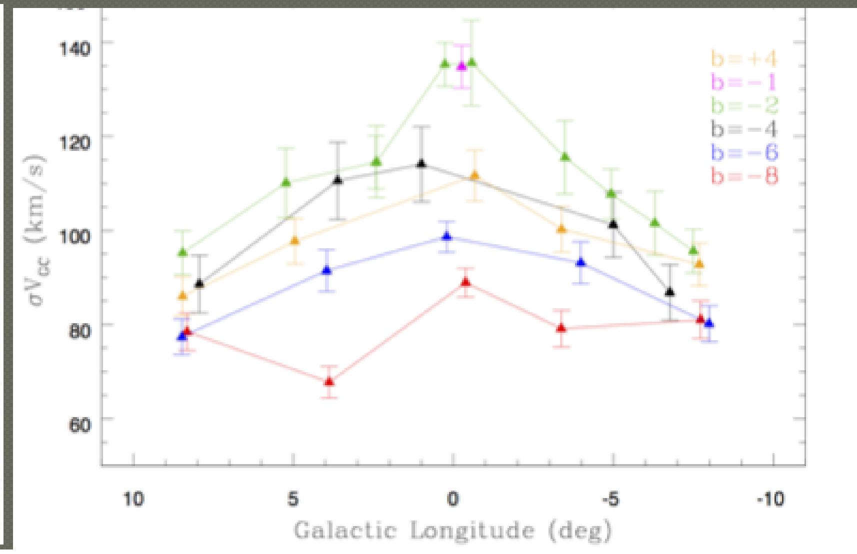
R/R_{HL} = 1 2 3

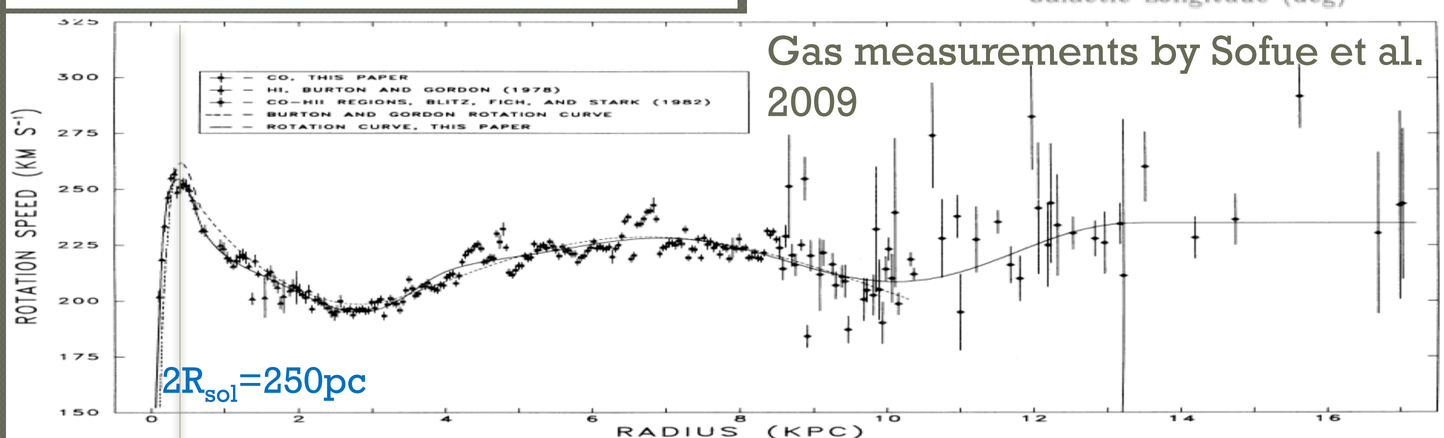
- a stronger soliton with the addition of stars
- velocity dispersion increases by 2 inward from $R=R_{HL}$

Milky Way bulge stars velocity dispersion & rotation curve

Vanlenti et al. A&A (2018), Portail, et al. MNRAS (2017)

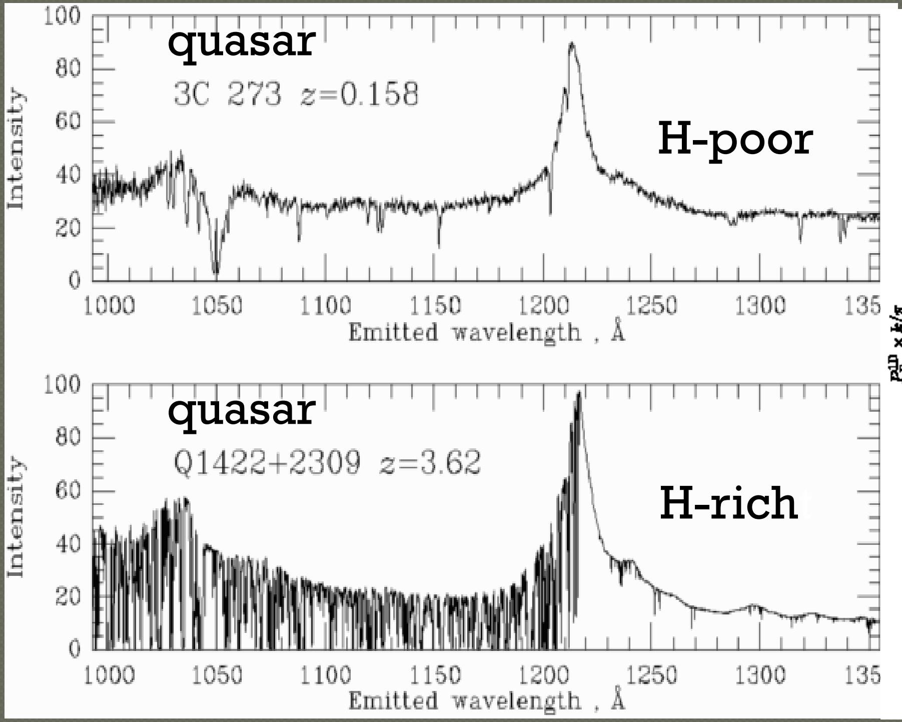


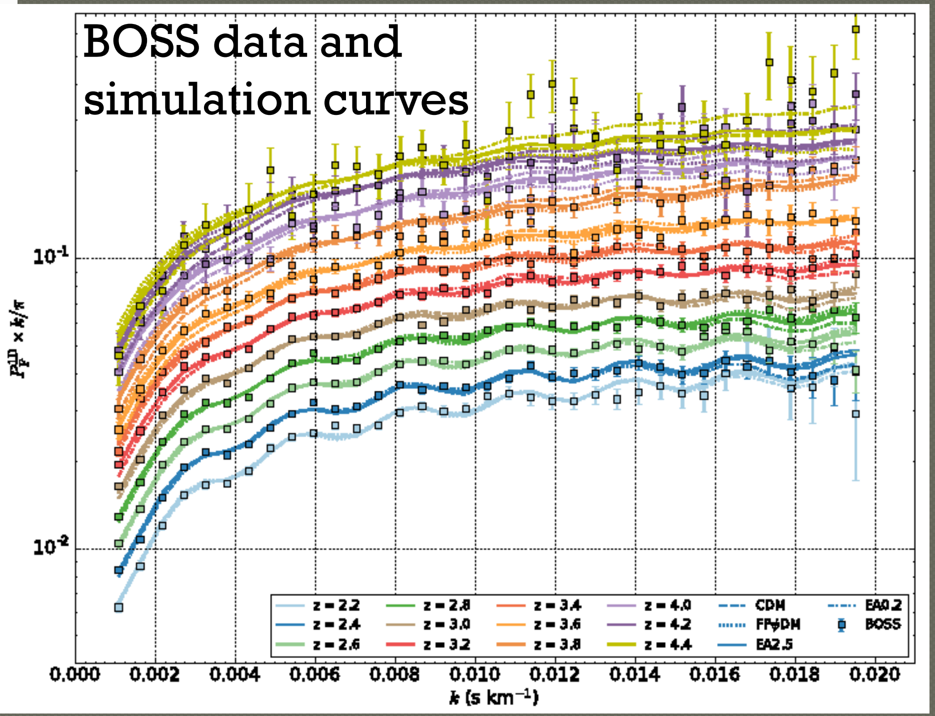




Lyα Forest Problem

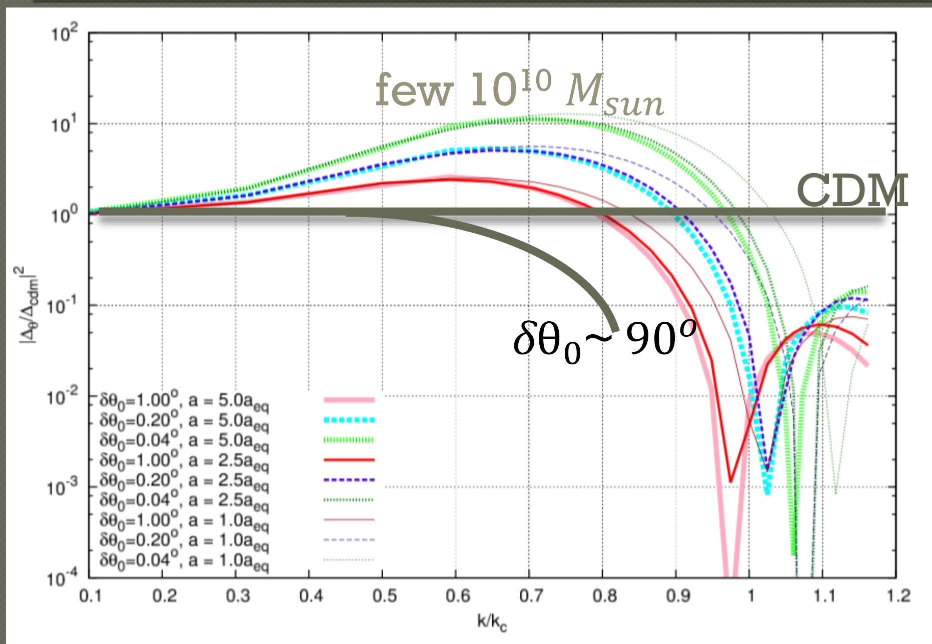
H absorption (Lyα forest) power spectra



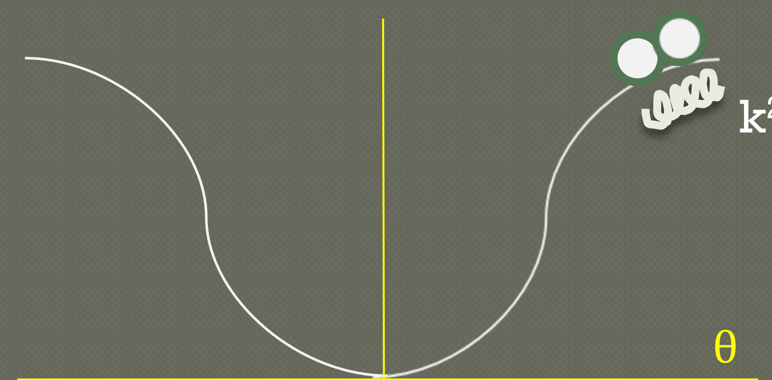


- Free ψDM of $m_a = 10^{-22}$ eV has too little small-scale power! (Armengaud et al. 2017; Irsic et al. 2017)
- Extreme axion DM gives better agreement with the data than CDM

Extreme Axion power spectrum coming out of radiation era



$\delta\theta_0 = 90^o - \theta_0$



Zhang & Chiueh(b), PRD (2017); Schive & Chiueh, MNRAS (2017)

- Parametric instability, δx ↗ with time
- Delayed oscillation avoids Hubble friction
- Growth factor ~ k^2 since long waves enter horizon late
- First galaxies ~ $10^{10}\ M_{sun}$
- Best-fit $\delta\theta_0 \sim 2.5^o$ from Lyman-α forest data (Leong et at. MNRAS 2019)

Pulsar timing observation of ψDM

- $P^{(0)}(t) = \rho^{(0)} \cos(2m\,t + 2S)$
- Poisson gauge, $ds^2 = -(1+2\Phi)\,dt^2 + (1-2\Psi)\,dx^2$

$$\nabla^2\Psi^{(0)} = 4\pi G\rho^{(0)}$$

$$\partial_t^2\Psi^{(1)} = -4\pi G P^{(0)} = -4\pi G\rho^{(0)}\cos(2mt + 2S(x,t))$$

$$\Psi^{(1)} = \frac{\pi G\rho^{(0)}(x,t)}{m^2}\cos(2mt + 2S(x,t))$$

Khmelnitsky & Rubako
JCAP (2014)

$\sim O(v^4/c^4)$

(1) mass oscillation, (2) proportional to local mass density

Photon propagation in G field (Integral Sachs-Wolfe)

$$\frac{d\ln E}{dt} = -\boldsymbol{u}\cdot(\nabla\Phi(x,t)+u^2\nabla\Psi(x,t))+u^2\frac{d\Psi(x,t)}{dt}.$$

$$\ln(E-u^2\Psi)|_{t_0}^{t_1} = -\int_{t_0}^{t_1} dt\boldsymbol{u}\cdot\nabla(\Phi(x,t)+u^2\Psi(x,t))|_{x=ct}$$

O(v/c) smaller

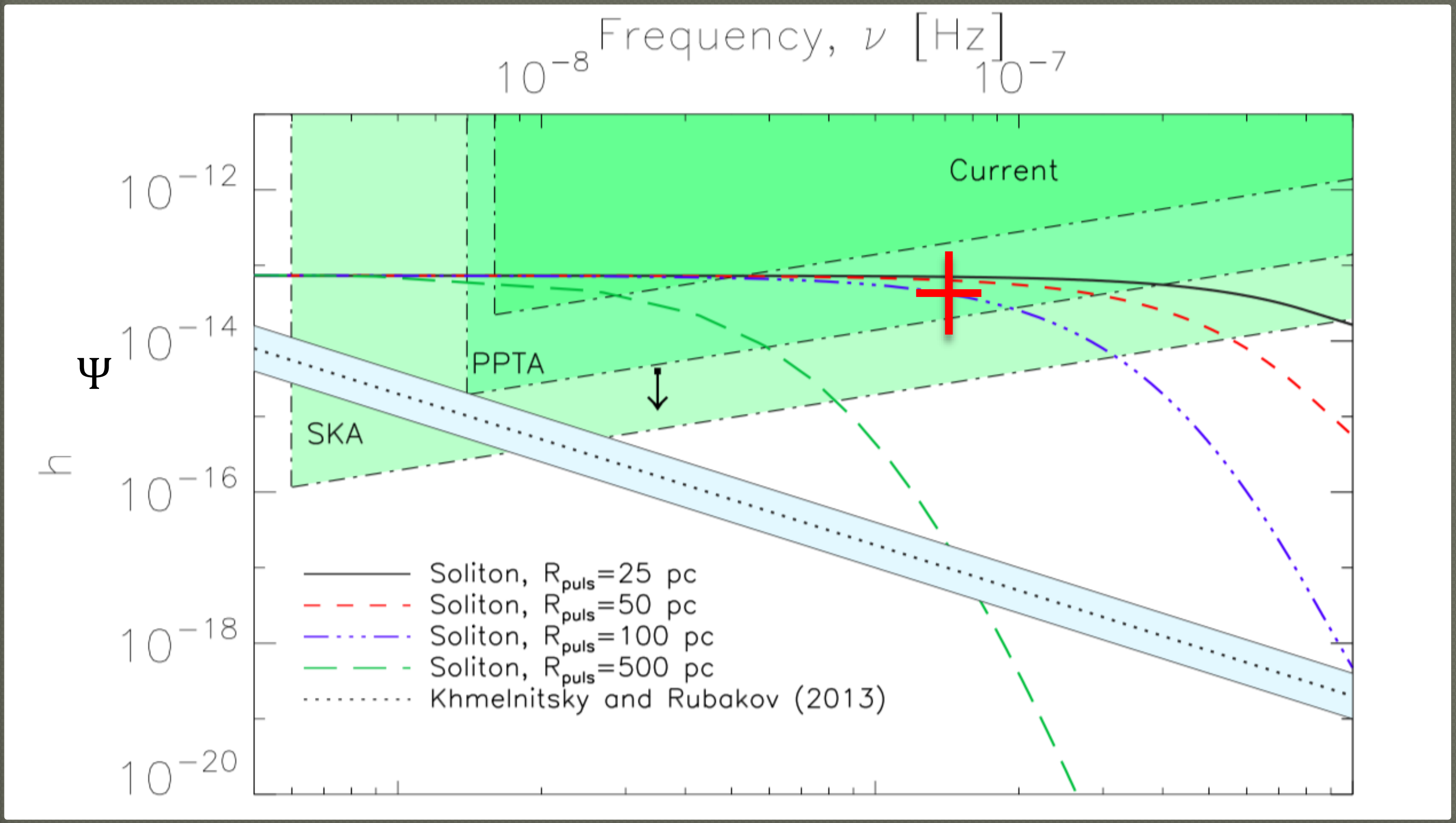
$$\frac{\delta E(t_1)}{E} = -[u^2(\Psi_t^{(1)}(x_0,t_0)-\Psi_t^{(1)}(x_1,t_1))] = \delta\nu/\nu$$

$\sim \rho^{(0)} \cos(2mt+2S)$, $\nu\sim 1\ \mathrm{yr}^{-1}$ for $m \sim 10^{-22}$ eV

Milky Way Pulsar Timing Exp.

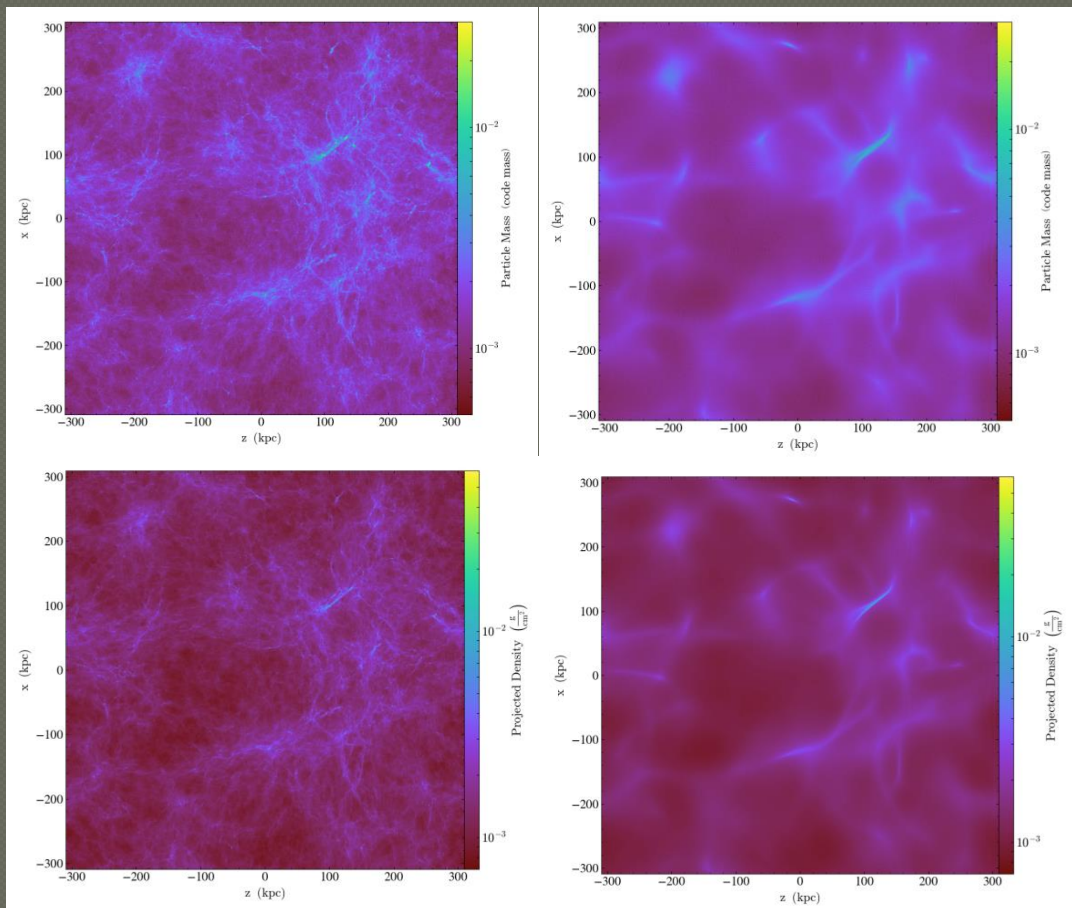
$\Psi^{(1)} \sim 10^{-13}$ at the soliton ($\rho \sim$ 1-2 TeV/cc)

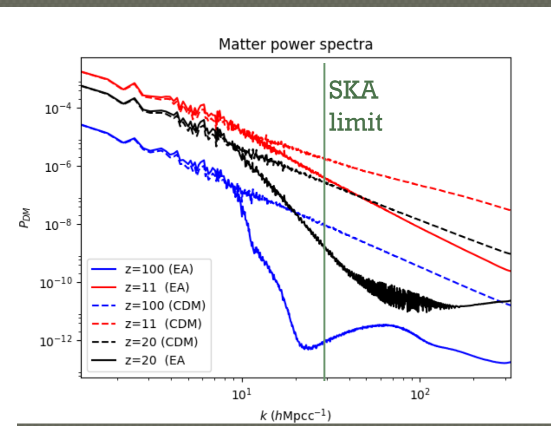
$\sim 10^{-16}$ at 1 kpc inner halo ($\rho \sim$ 1GeV/cc)



De Martino, et al, PRL, 2017

21cm tomography





Conclusion

- Review on basic wave dark matter (ψDM) which solves small-scale problems with matter spectrum and soliton
- Central soliton + granules in any halo: soliton mass & halo mass relation
- Adding stars enhances soliton; cusp in star velocity dispersion due to the central mass lump
- Extreme axion ψDM has enhanced small scale power about $10^{10}\,M_{sun}$, modifying the universe landscape in $z > 4$
- Pulsar timing is within reach to test ψDM
- 21cm tomography probed by SKA

Thank you