Extremely Light Dark Matter Particles: ΨDM

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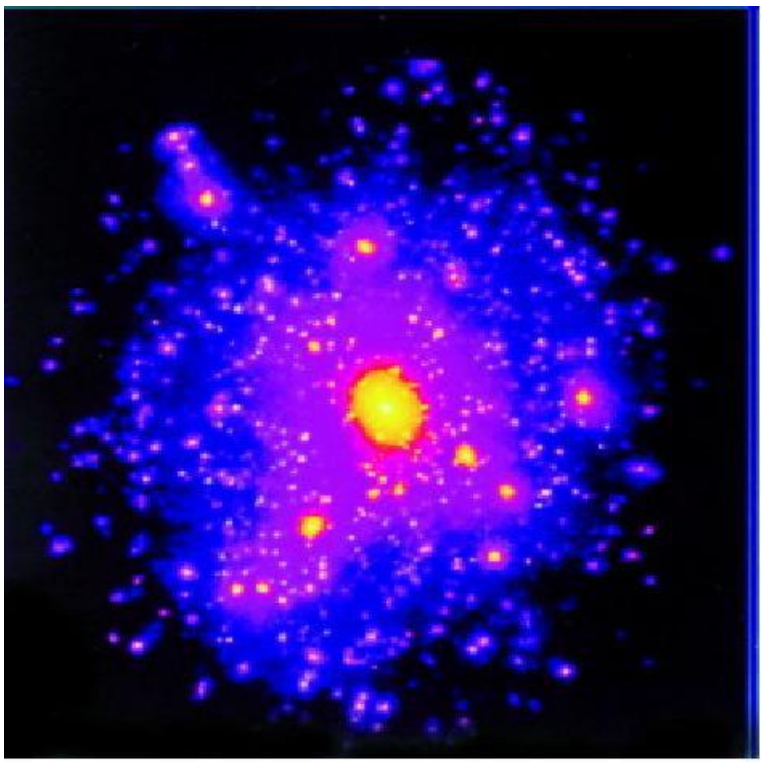
Contents

Cold Dark Matter (CDM)

- Thermally generated non-standard-model particles
- Heavy, e.g. 100 GeV due to WIMPS miracle
- Tiny thermal velocity because of its high mass
- Easy to implement to numerical simulations for investigations of nonlinear large-scale structures
- Fit observations, such as CMB, acoustic oscillations, Lyman-α forests, galaxy clusters, etc.
- The agreements are data of large scale and does not rule out other alternatives
- To really pin down CDM, look for singularity

- CDM is scale-free and forms halos within halos
- CDM simulation consistently shows Narravo-Frenk-White (NFW) radial profile in bound objects



$\rho = a / [r (r+b)^2]$

a & b are object-dependent fitting parameters

Andromeda galaxy (30 kpc)

Three kinds of cosmic objects that have high dark matter concentration

Of the three, galaxies have too much baryon concentration at central 10 kpc

Not suitable for understanding the nature of dark matter

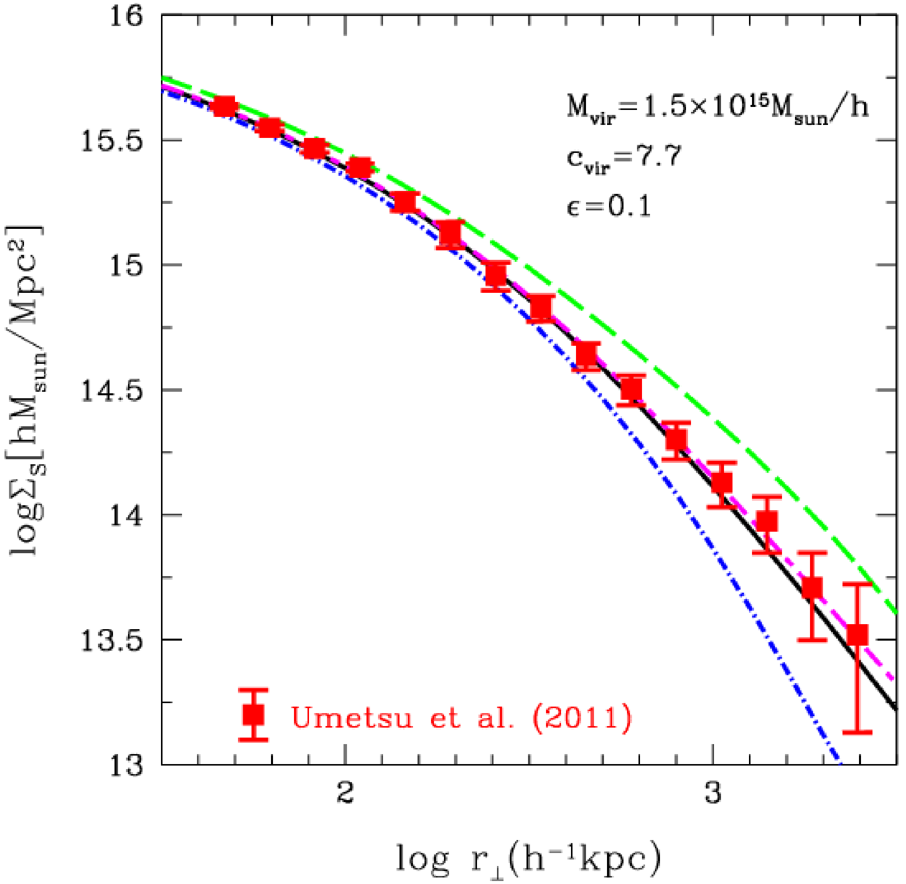
Coma galaxy cluster (1 Mpc)

Fornax dwarf galaxy (1 kpc)

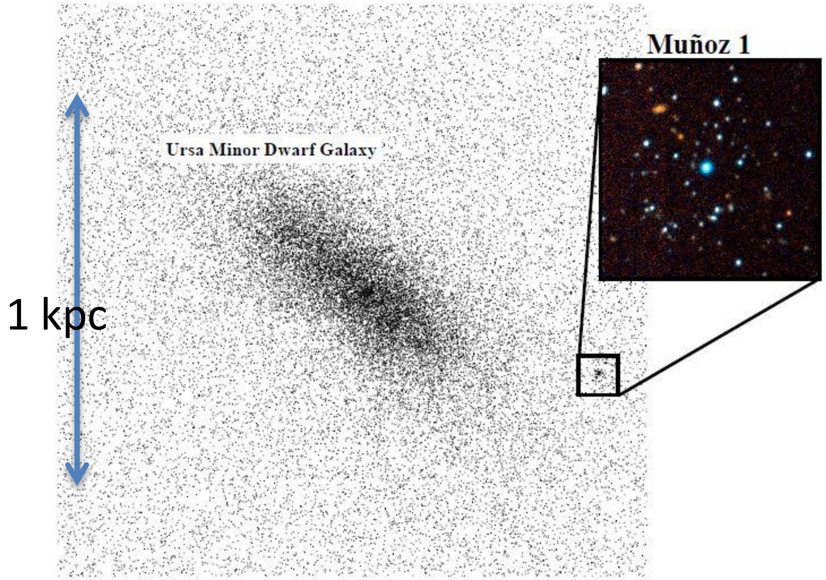
Galaxy Clusters

Observations of galaxy clusters agree with the NFW profile very well

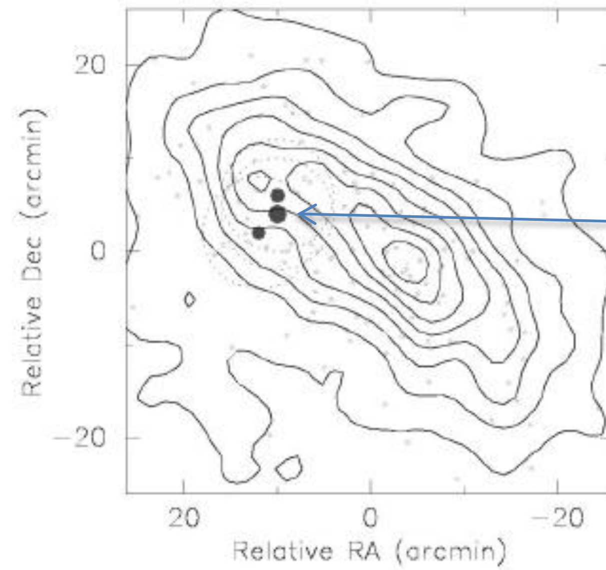
stacked lensing data of 4 rich galaxy clusters of 10^{15} solar mass



Dwarf Galaxies



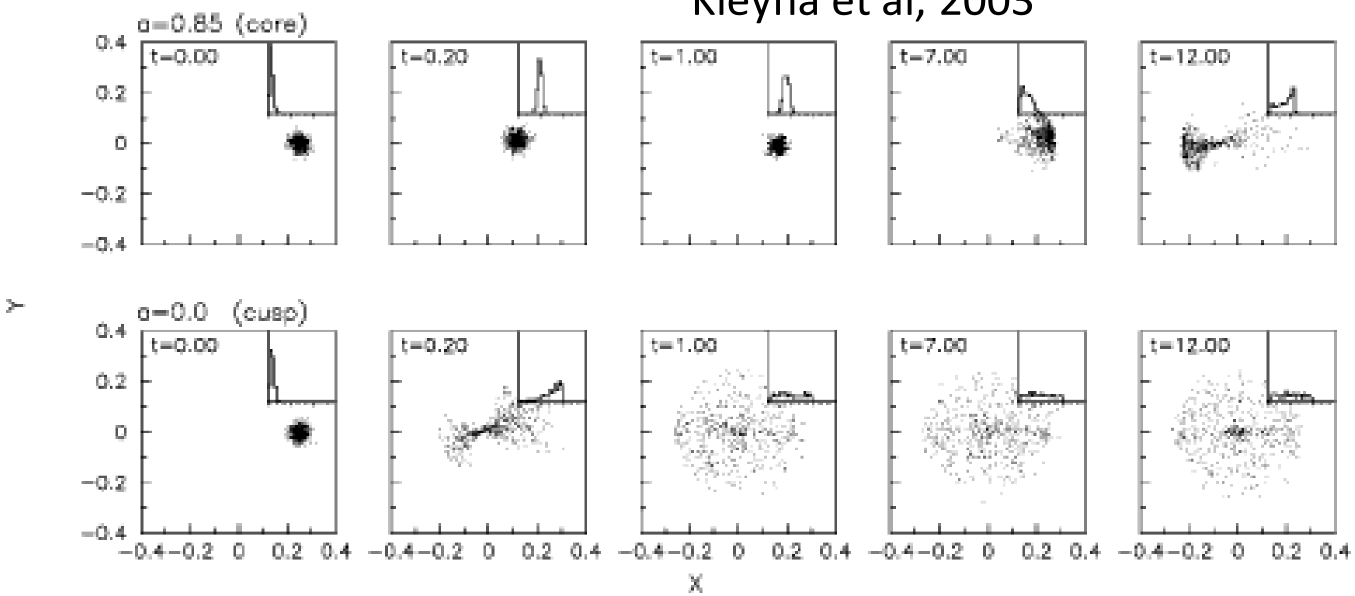
Ursa Minor dwarf galaxy



Old & cold star clump

N=10000 (7% of all stars)

Kleyna et al, 2003



elliptical harmonic potential

elliptical NFW potential

Dwarf galaxies

- Another evidence against CDM is the lack of satellite galaxies near Milky Way, and this becomes more acute after the recent Sloan Digital Sky Survey
- From CDM simulations, there should be hundreds of nearby satellite galaxies around Milky Way, but only few tens (< 10%) are detected.
- Both the galaxy core problem and the abundance problem are associated with dwarf galaxies on the scale < few kpc !!!

Scale symmetry of CDM is broken below few kpc ???

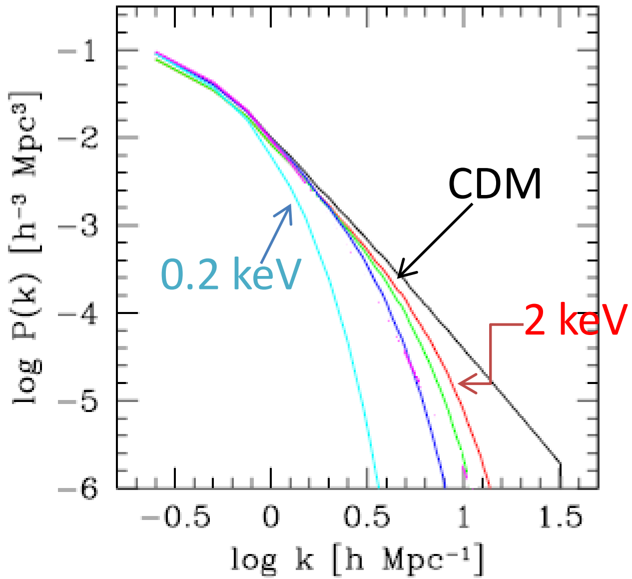
If so, what may be the cause?

Option 1: Warm Dark Matter

- Thermally generated WDM has residual thermal velocity that erases small scale structures due to free stream mixing
- It solves the problem of satellite galaxy deficiency

- Best observational constraint:
  m > 2 keV (via Lyman-α forests)
- Major problem: for this range of mass WDM can not produce a flat core as large as 1 kpc

Linear power spectrum



Option 2: Extremely light particles

- Non-thermally generated bosons, e.g. via axion mechanism, and cold, i.e., BEC condensate

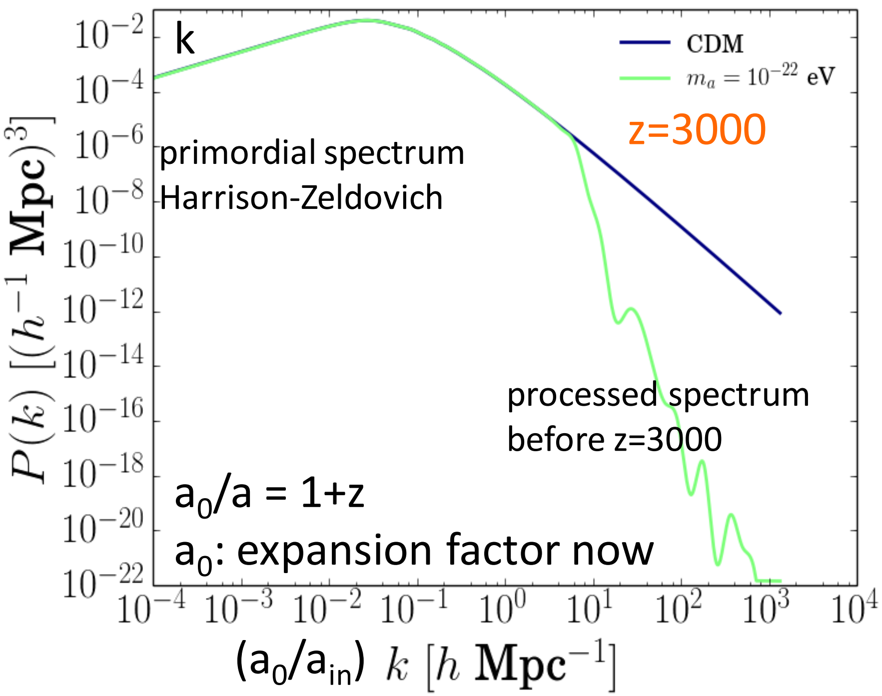
- The universe is described by a single field obeying Klein-Gordon equation, and self-coupled via metric perturbations.
- Breaks the scale symmetry due to a finite mass, or a Compton wavelength λ_{comp}

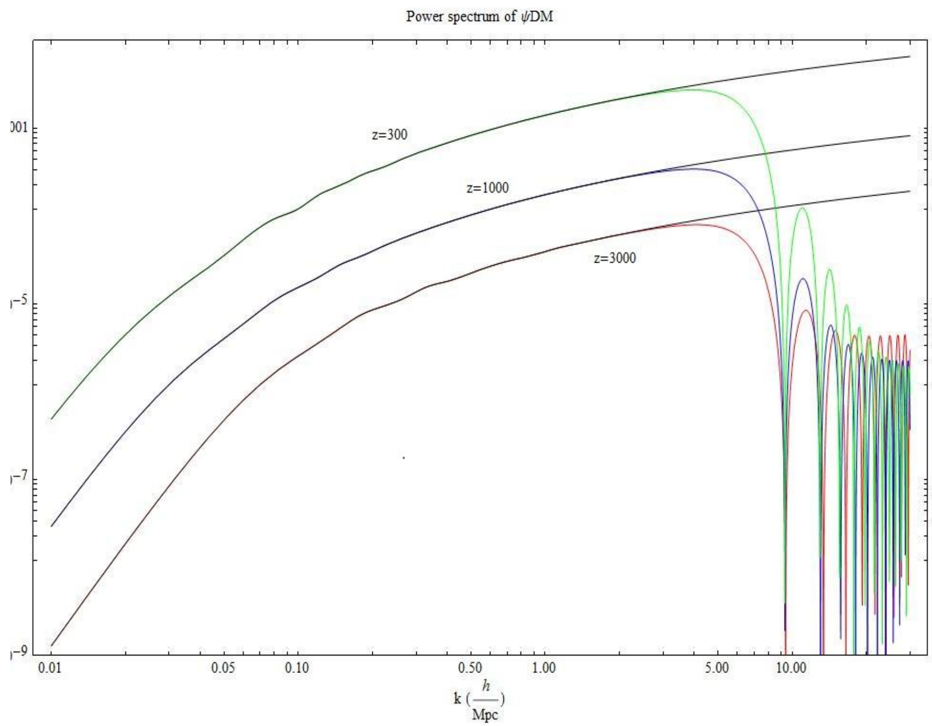
$$\lambda_{comp} = \text{few kpc ???}$$

- Not really! One must take into consideration the evolution of a length scale in an expanding universe.

Linear Evolution of Compton Length

- $\lambda_L(a) = (a/a_{in})\ \lambda_{comp}$
- a_{in}?
- It turns out a_{in} is determined by $\lambda_{comp} = c/H(a_{in})$ = Hubble radius in the radiation era





Nonlinear Evolution

- If $\lambda_L(a_0)$ were few kpc, then m ~ 10^{-20} eV

- Length scale greatly reduced during collapse of a galaxy, i.e.,
  λ_{NL} = few kpc (observed dwarf galaxies size) << λ_L
  Therefore, m << 10^{-20} eV

- One can define $\lambda_{NL}(a)$ = F(a) $\lambda_L(a)$ and ask what F(a) is.
  This nonlinear evolution must be aided by computer simulations.

Nonlinear Evolution in NR regime

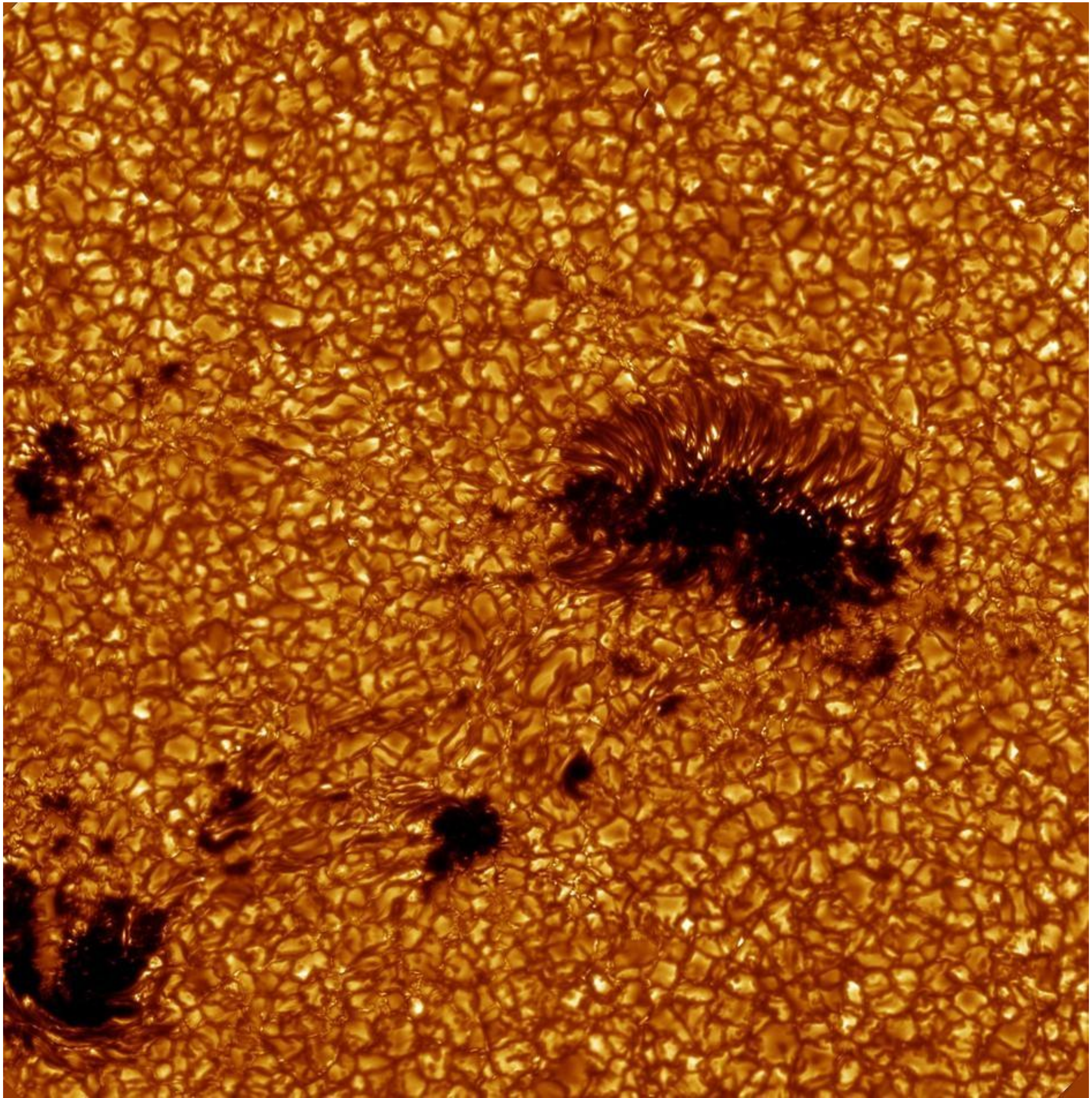
- $\Phi = \Psi_r \cos(mt) - \Psi_i \sin(mt)$ to identify a complex Ψ
  $|\Psi|^2$: normalized number density
- Simulations carried out by solving Poisson-Schroedinger equation

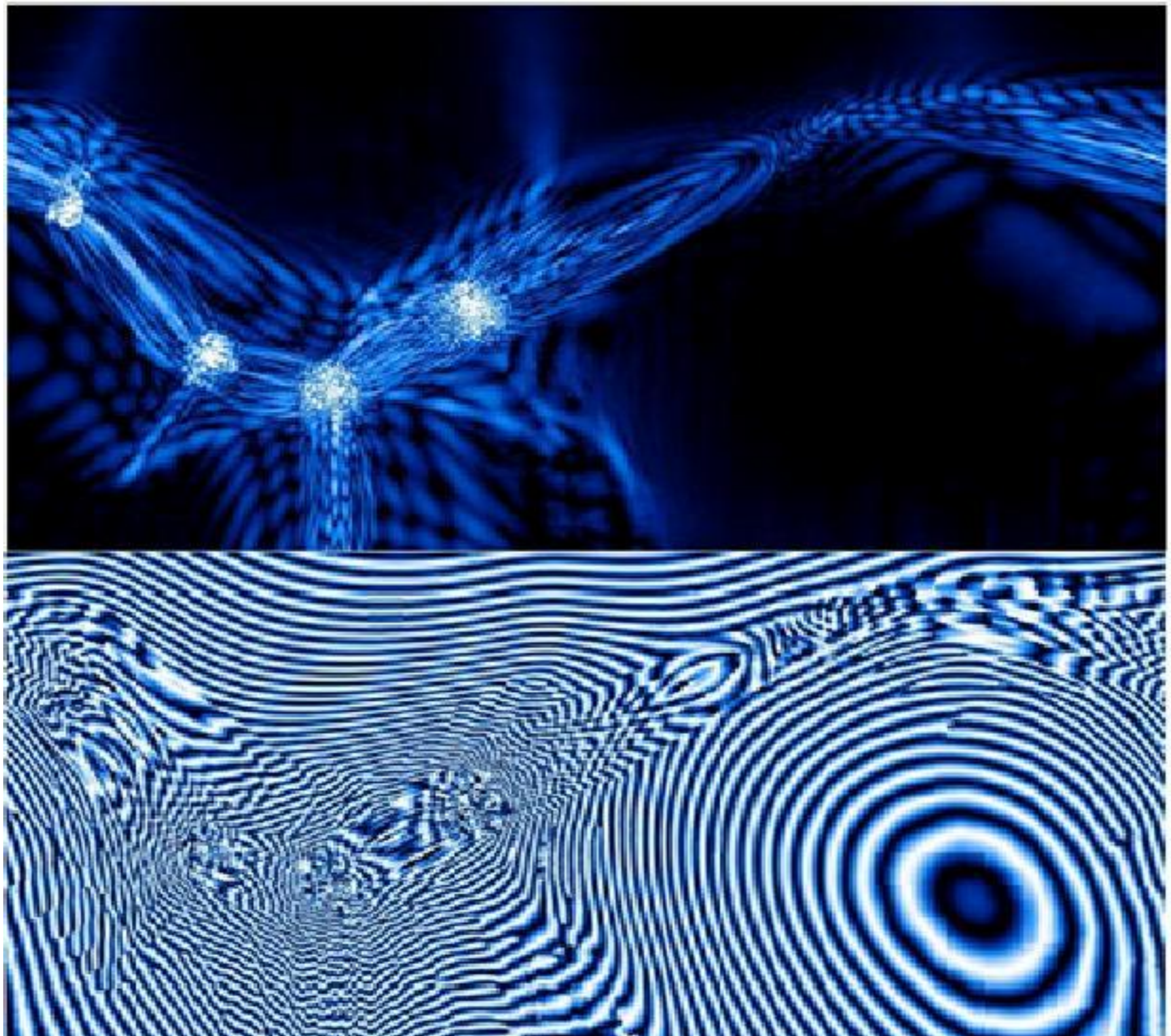
background density

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

- This equation is almost scale free and has an approximate scaling relation
  $x' = \xi^{-1} a^{-1/2} x$, $|\Psi'|^2 = \xi^4 a |\Psi|^2$, $V' = \xi^2 V$, $\tau' = \xi^{-2} a^{-1} \tau$
  In terms of bound objects, $M' = \xi a^{-1/2} M$

AdaptiveMeshRefinement calculations: accurate but time-consuming, $\Delta t \sim \Delta x^2$

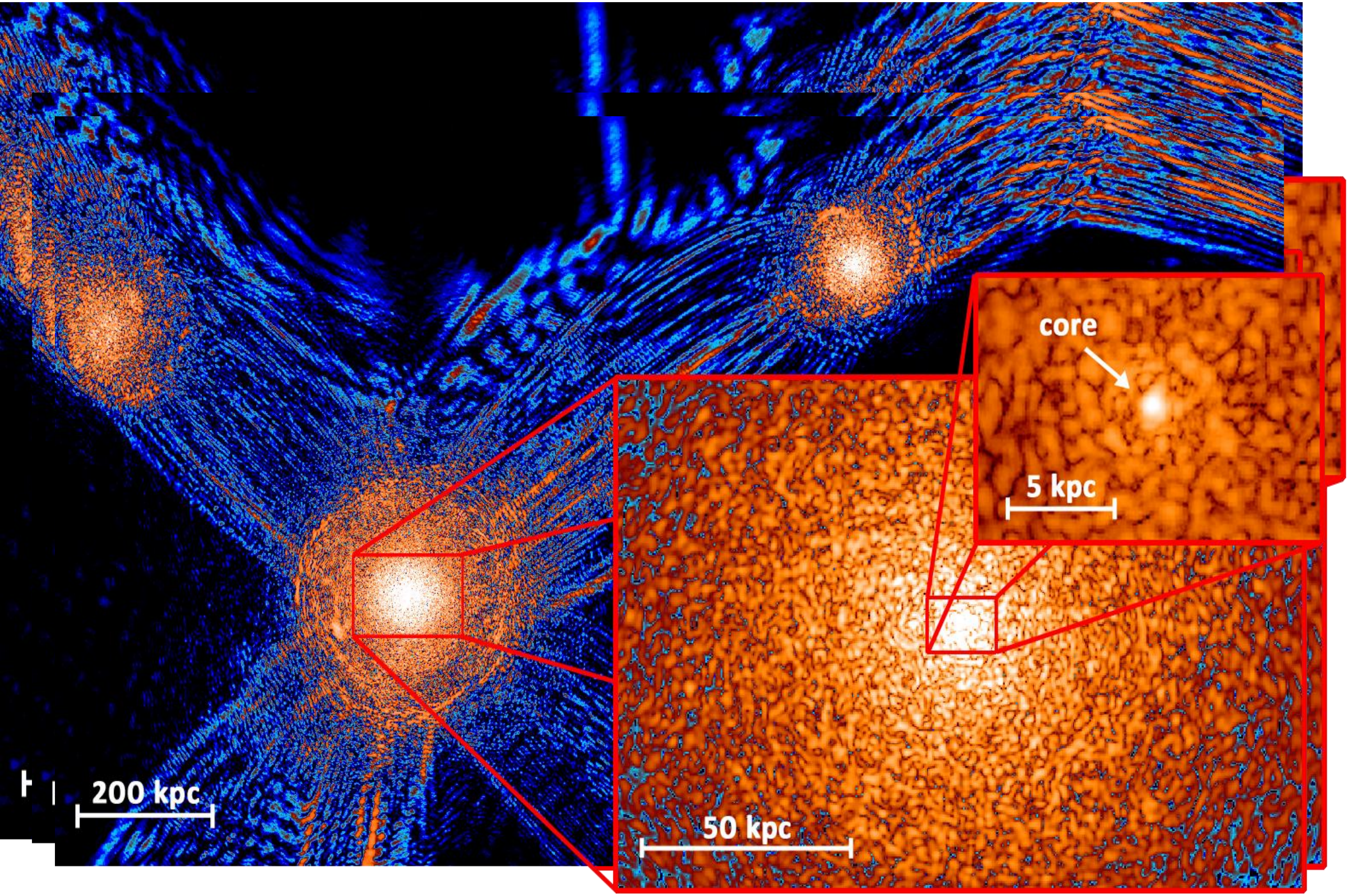




$|\Psi|^2$

ψ_r^2

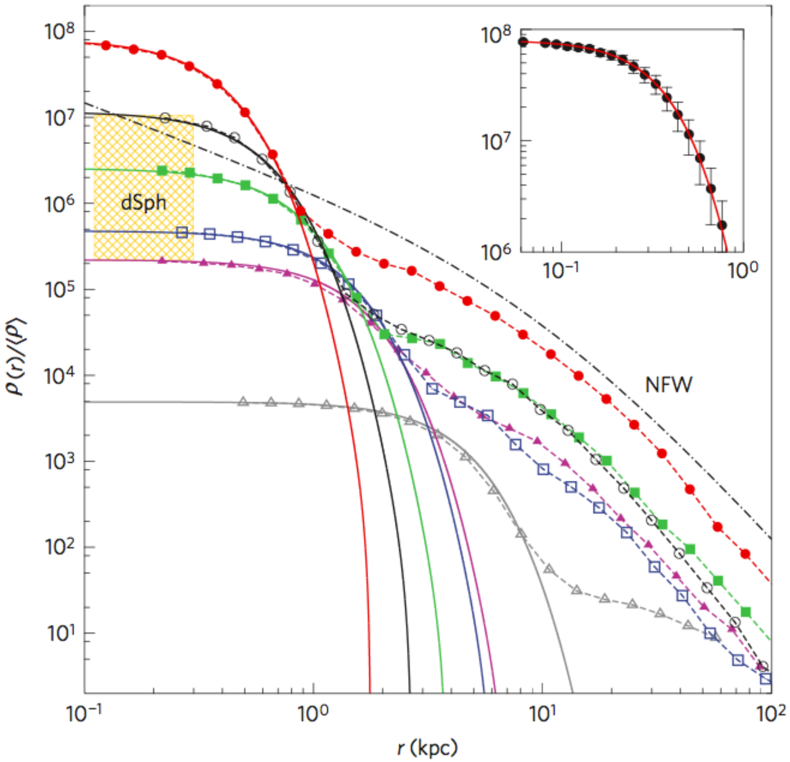
Fuzzy halos & Soliton cores



Soliton core & NFW halo

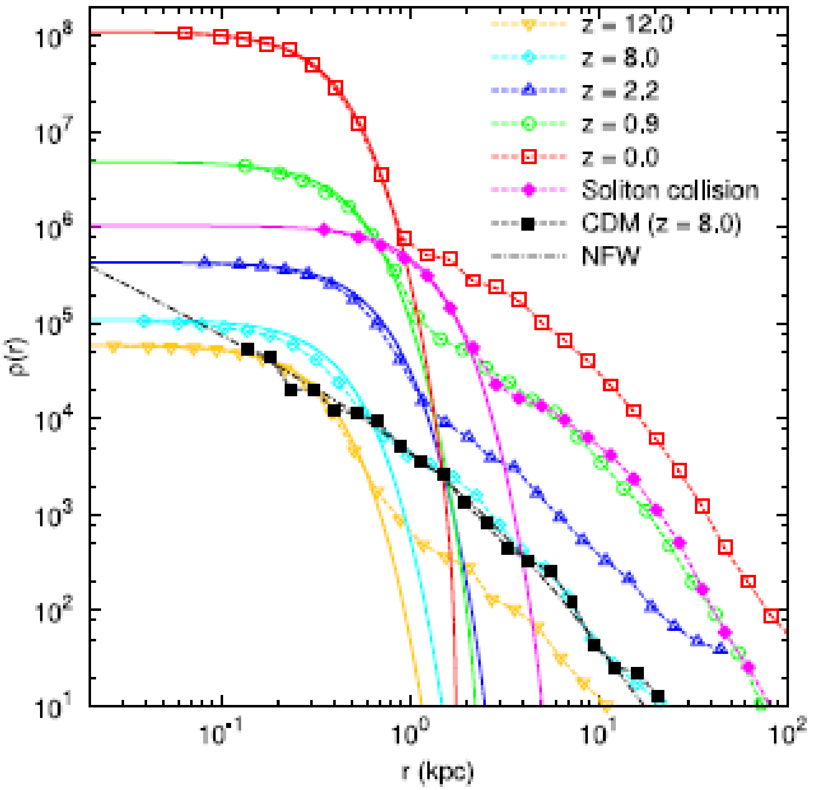
z = 0 dwarf galaxies for any m obey $r_c \sim \rho_c^{-4}$ scaling relation

(Schive, et al 2014,NaturePhys)



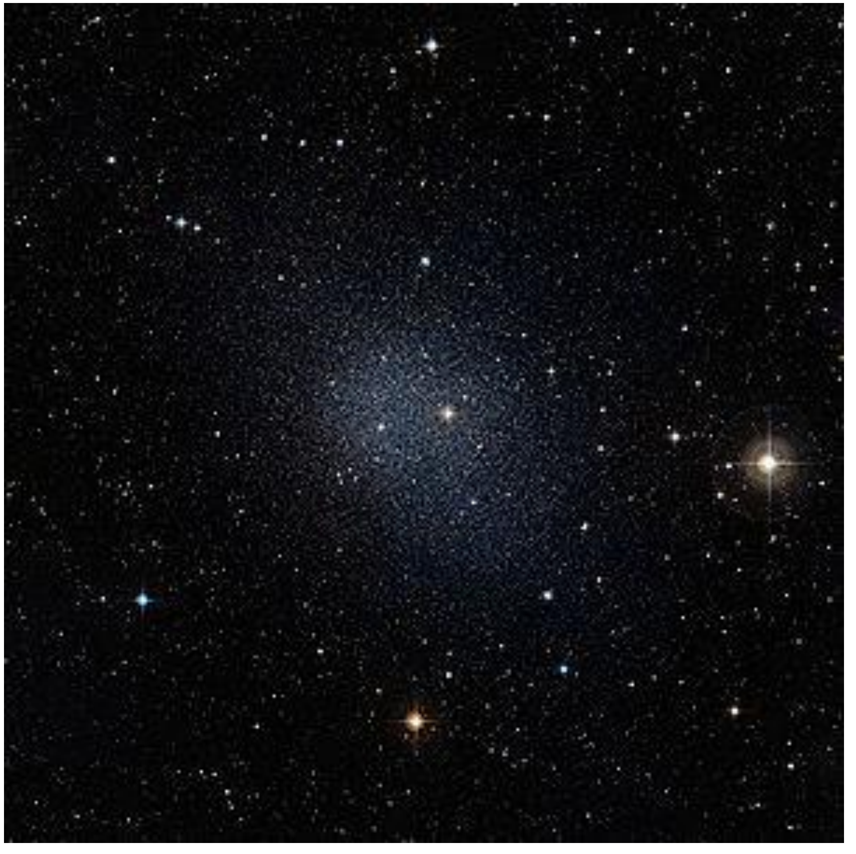
Single halo redshift evolution

(Schive at al. 2014, PRL)



Determination of boson mass

Fornax dwarf spheroidal galaxy



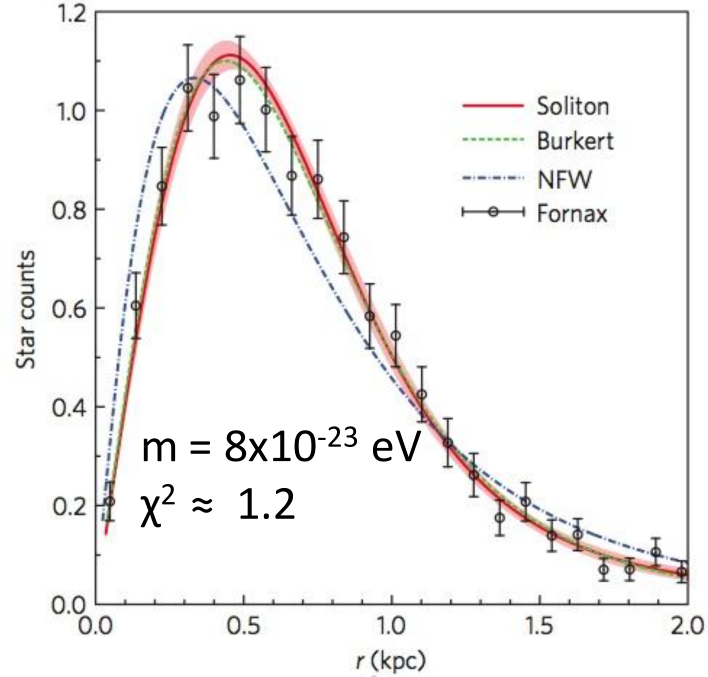
Data:

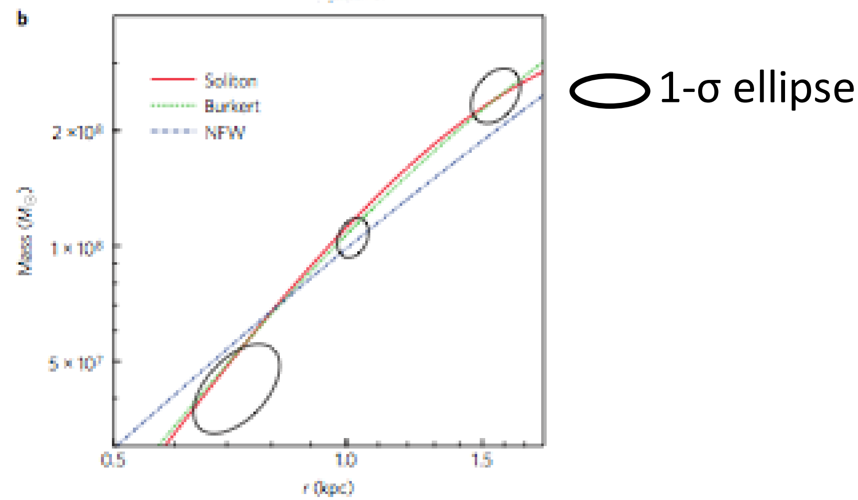
- Fornax dwarf spheroidal galaxy
- good spectral and star count data
- 3 populations of stars

Analysis:

- Choose the richest population
- Solve the Jeans equation for star density, treating stars as test particles in soliton potential
- Adjusting m to yield the least χ^2, and similar approaches apply to opyimize Burkert and NFW
- Check the result with other two populations

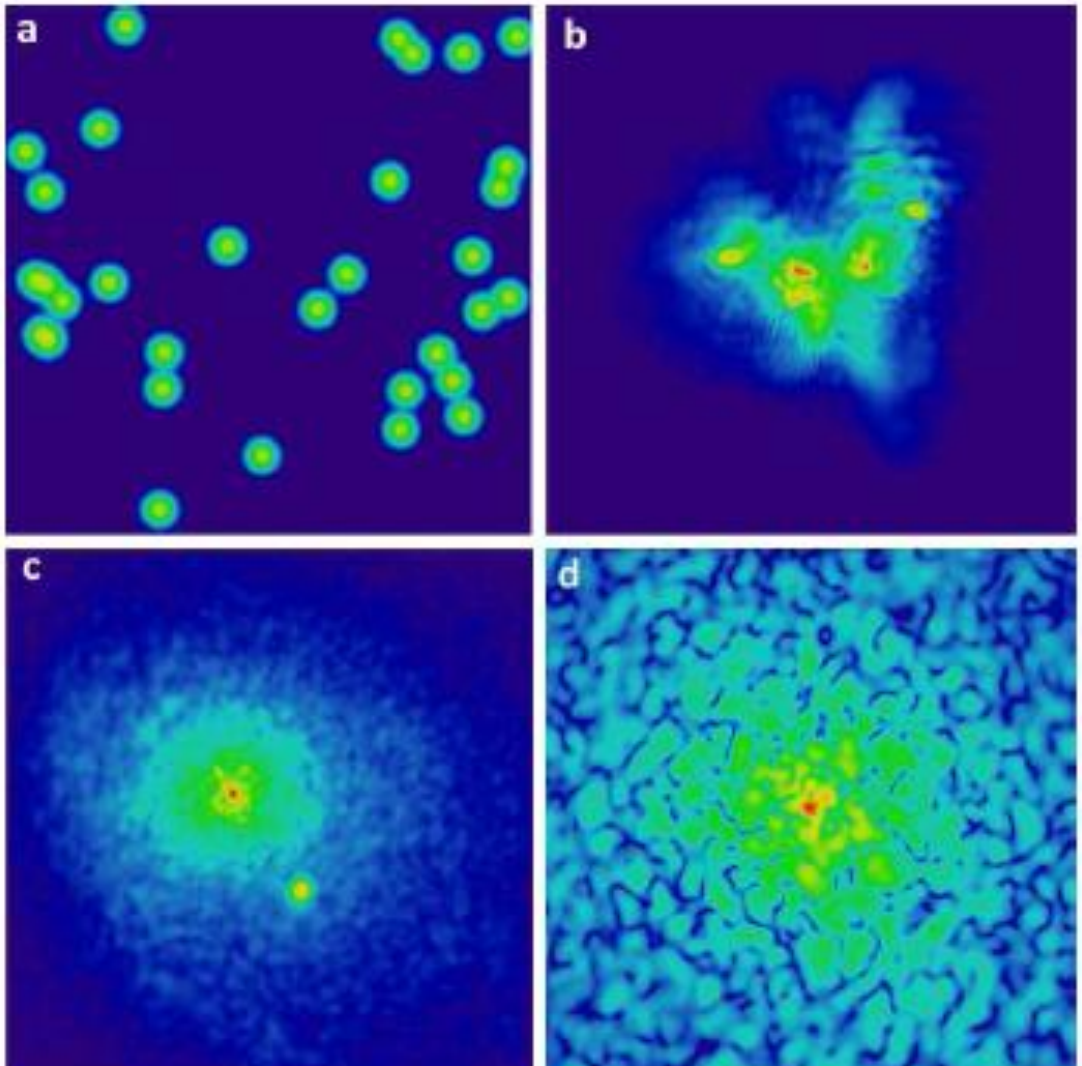
(Schive at al. 2014 Nature Phys)



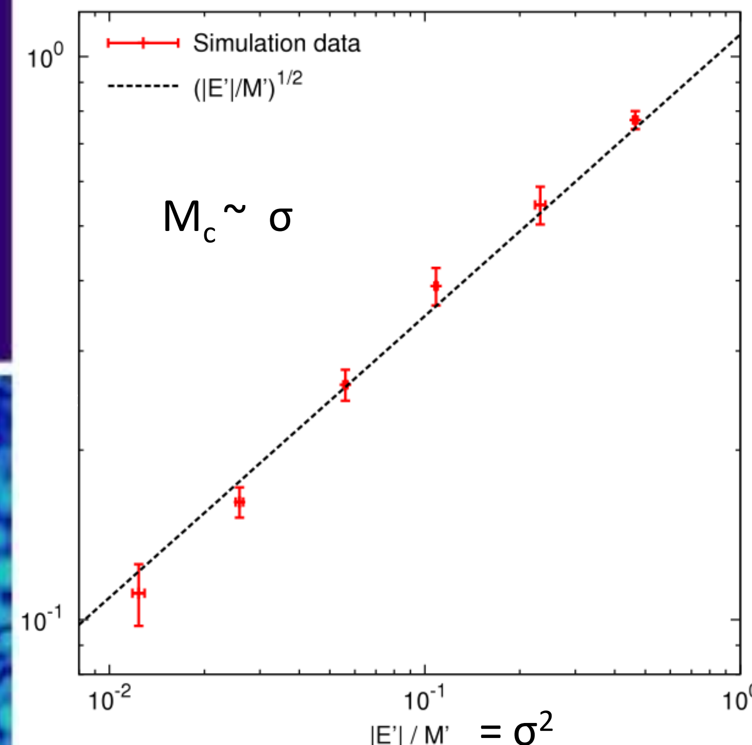


Core-Halo relation:

M_c depends on conserved mass and energy?



A dedicated numerical experiment: soliton collision

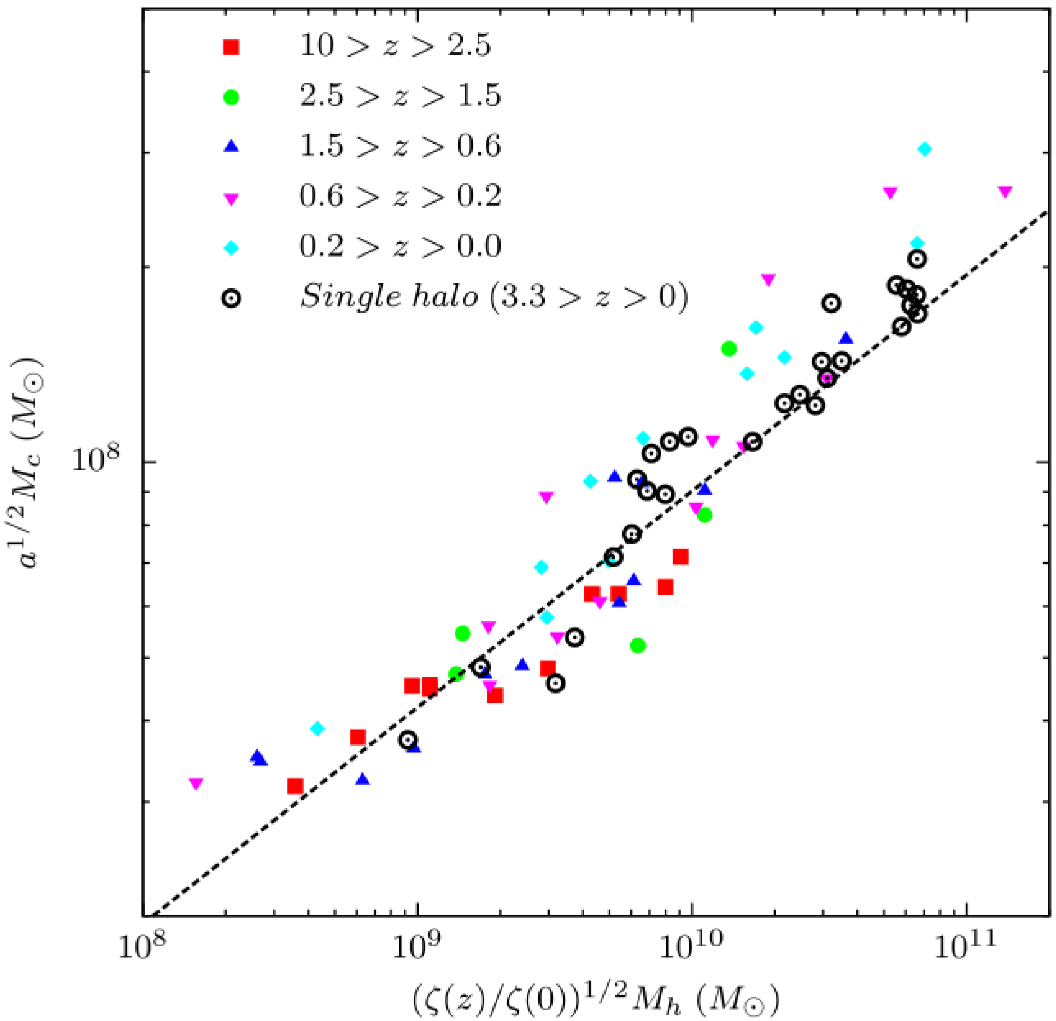


Thermalization of the entire halo!

Core-Halo relation:

$M_c - M_{halo}$-z scaling

((Schive, et al.,PRL (2014))



$M_c \sim M_{halo}^{1/3} (1+z)^{1/2}$

We can predict the core for any redshift and any halo mass !

IMPLICATIONS:

$$M_c \sim M_{halo}^{1/3} (1+z)^{1/2}, \quad r_c \sim M_{halo}^{-1/3} (1+z)^{-1/2}$$

- For the earliest galaxies at z=12, $M_c \sim 5 \times 10^8$ solar mass (determined by λ_{comp}), and gravitational potential

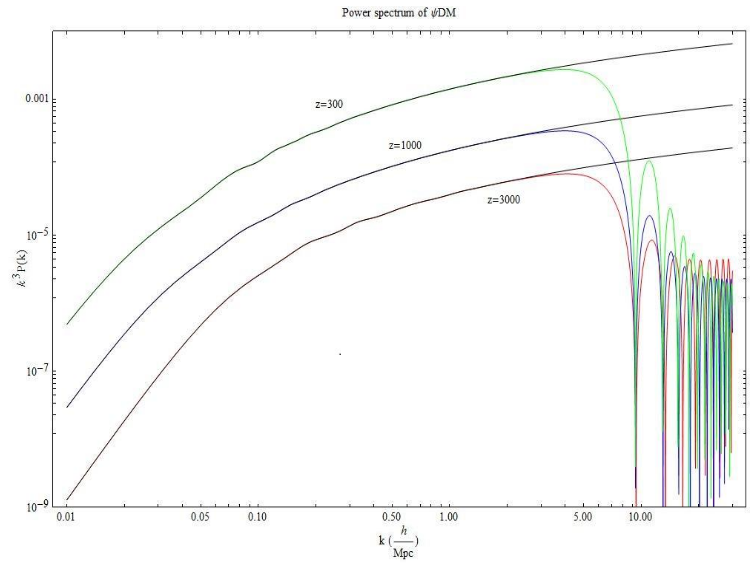
  $(GM_c/r_c)_{z=12} \sim (1+z) \sim 13\,(GM_c/r_c)_{z=0}$

  for the same halo mass.

- The earliest quasar appeared at z=7, for which the age of universe is ~ 8×10^8 yr, requiring formation of supermassive black hole of $M_{BH} \sim 10^9$ solar mass in a short time.
- 13 times deeper potential may help BH formation

Nonlinear Evolution: Summary

- Nonlinearity generates a mass hierarchy of different length scales. Erases the feature of λ_{comp} and replaced by a running length scale $\lambda_{Jeans} \sim \rho_{local}^{-1/4}(a, x_{core})$
- λ_{comp} only important for determining the size of the earliest galaxies at z=12
- After that, galaxies of different masse gradually appear, and λ_{Jeans} of differen ρ_{local} defines core sizes of the galaxies.



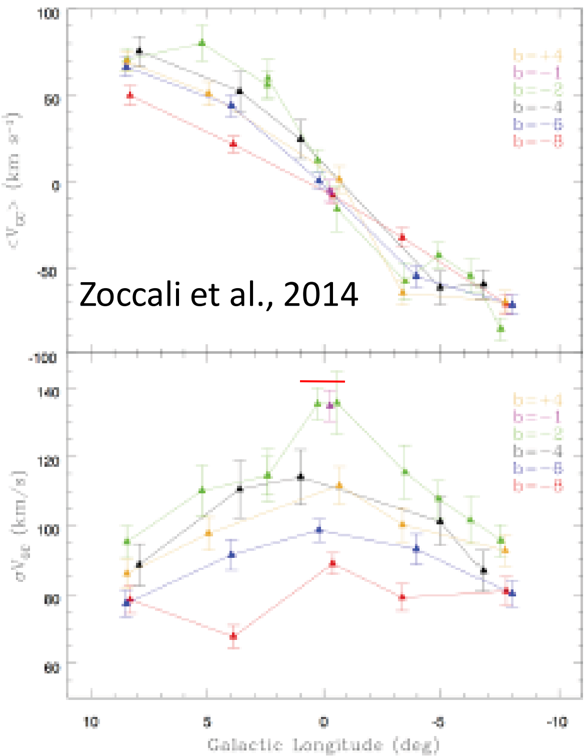
- At every epoch, there is a minimum halo with minimum ρ_{local} and maximum λ_{Jeans} which defines few kpc scale at present epoch.

Hints for soliton core and fuzzy halo:

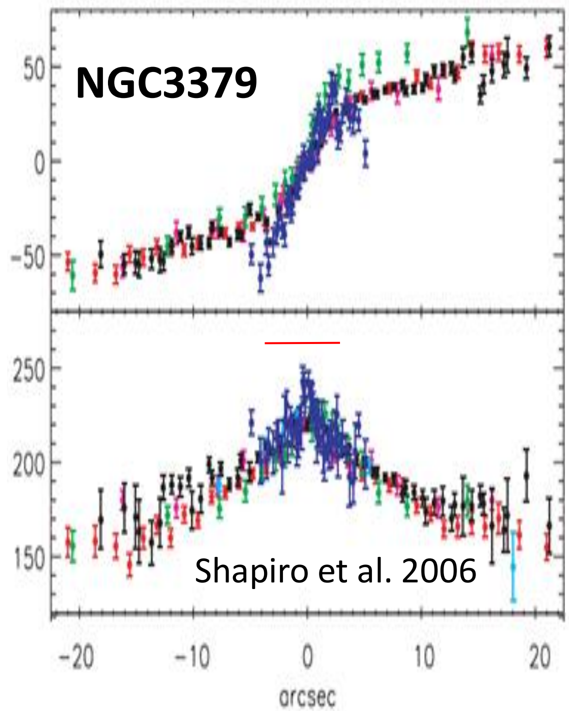
(1) velocity dispersion peaks at central 150 pc

Milky Way bulge

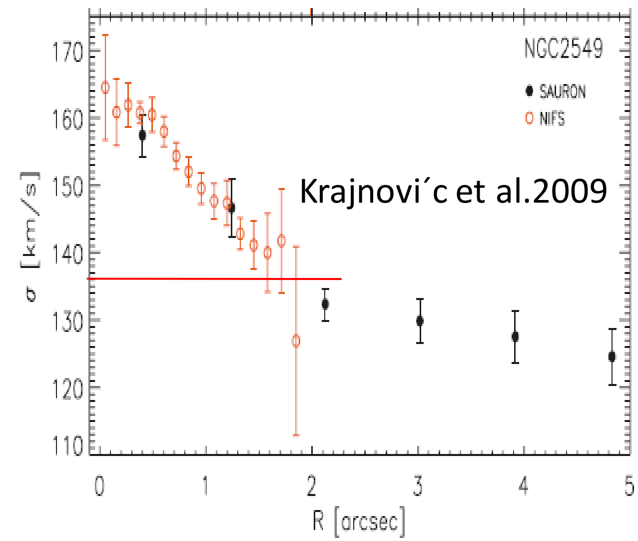
Nearby elliptical galaxies



M_{bh} = 10^6 solar mass



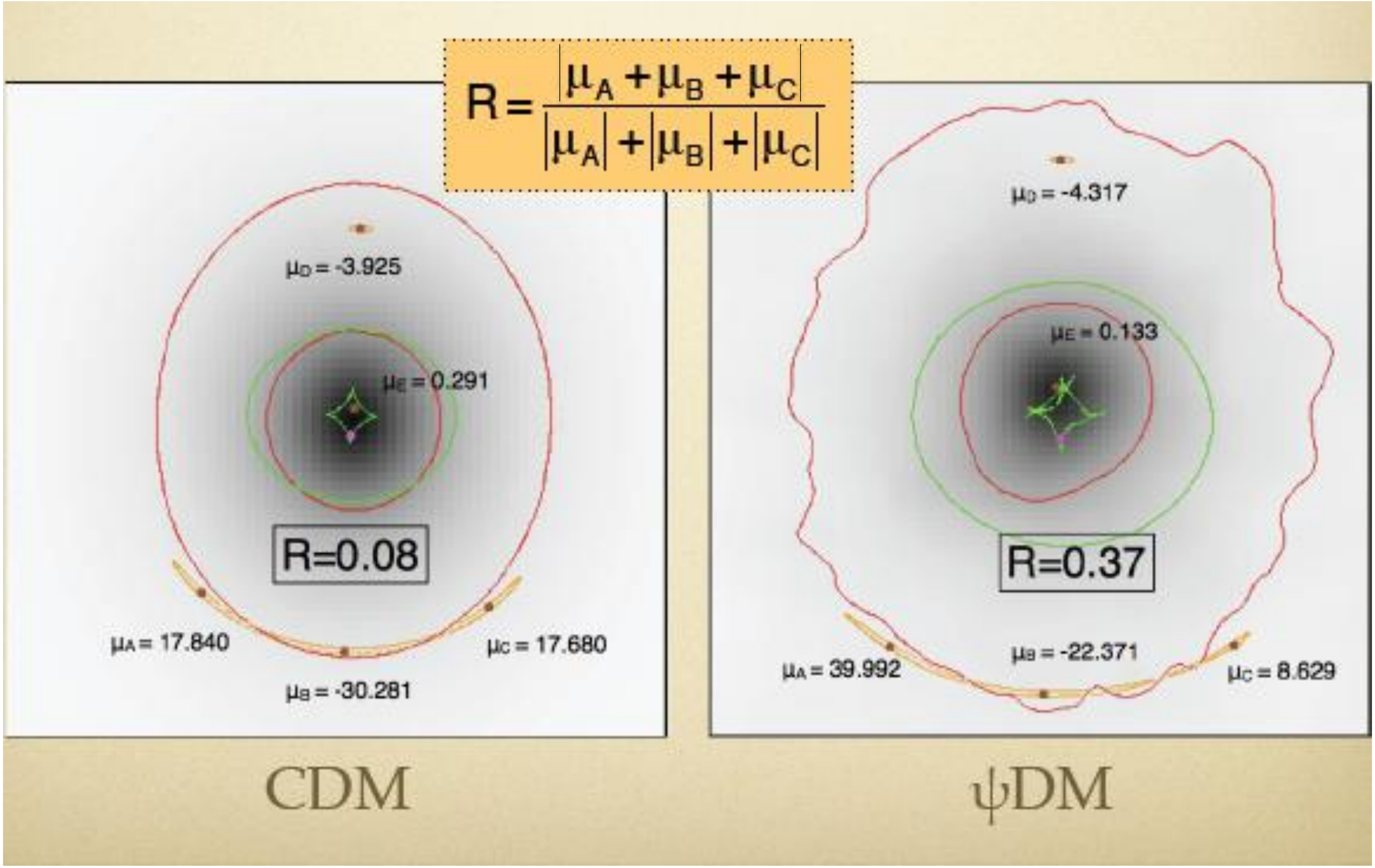
M_{bh} = 1.4 x 10^8 solar mass



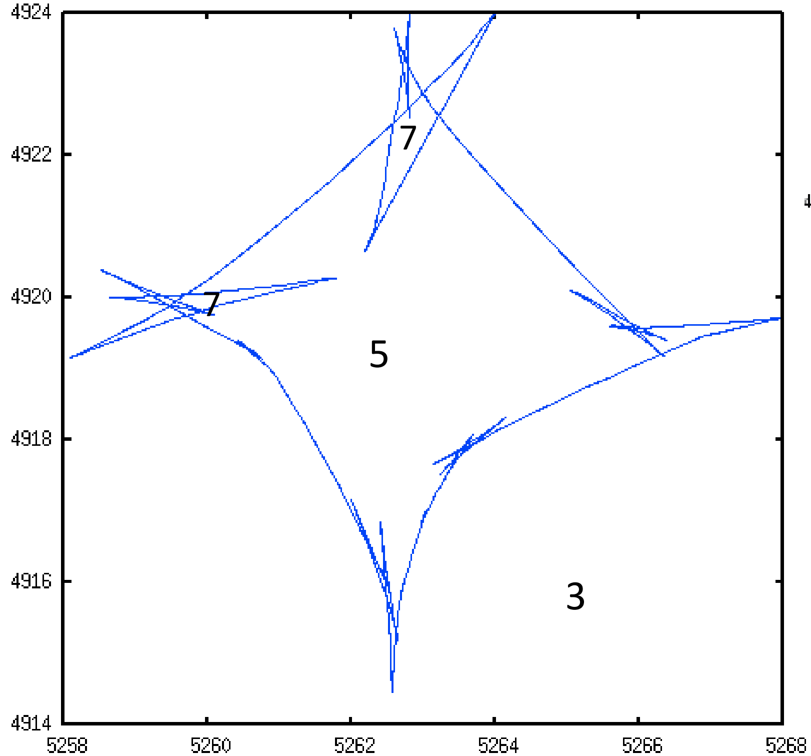
M_{bh}=1.4 x 10^7 solar mass

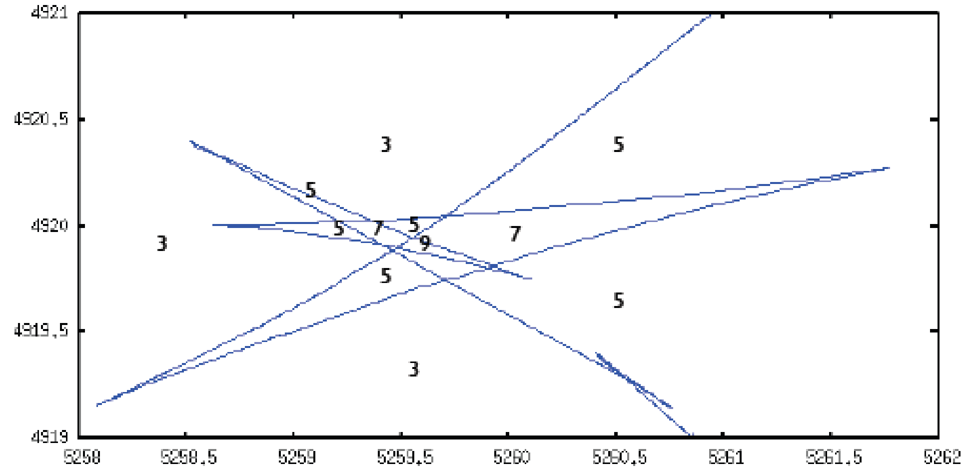
(2) Strong lens quad image flux anomaly

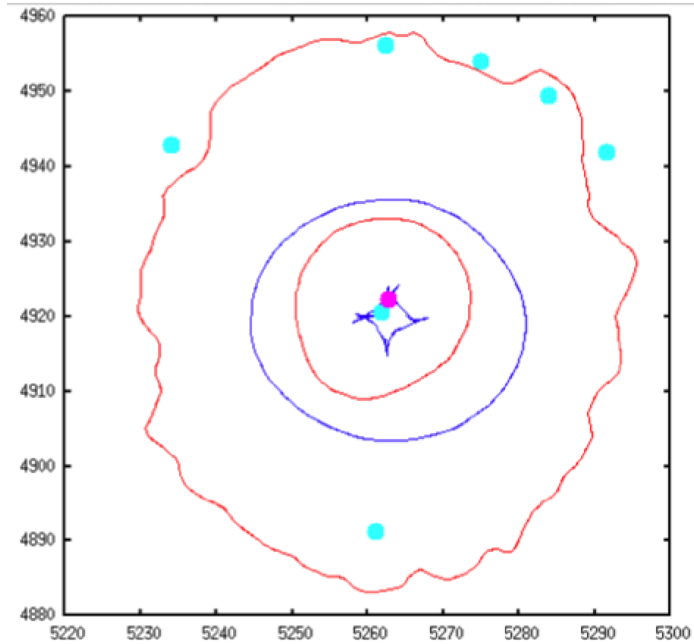
$$R = \frac{|\mu_A + \mu_B + \mu_C|}{|\mu_A| + |\mu_B| + |\mu_C|}$$



Possibility for detecting 7 images





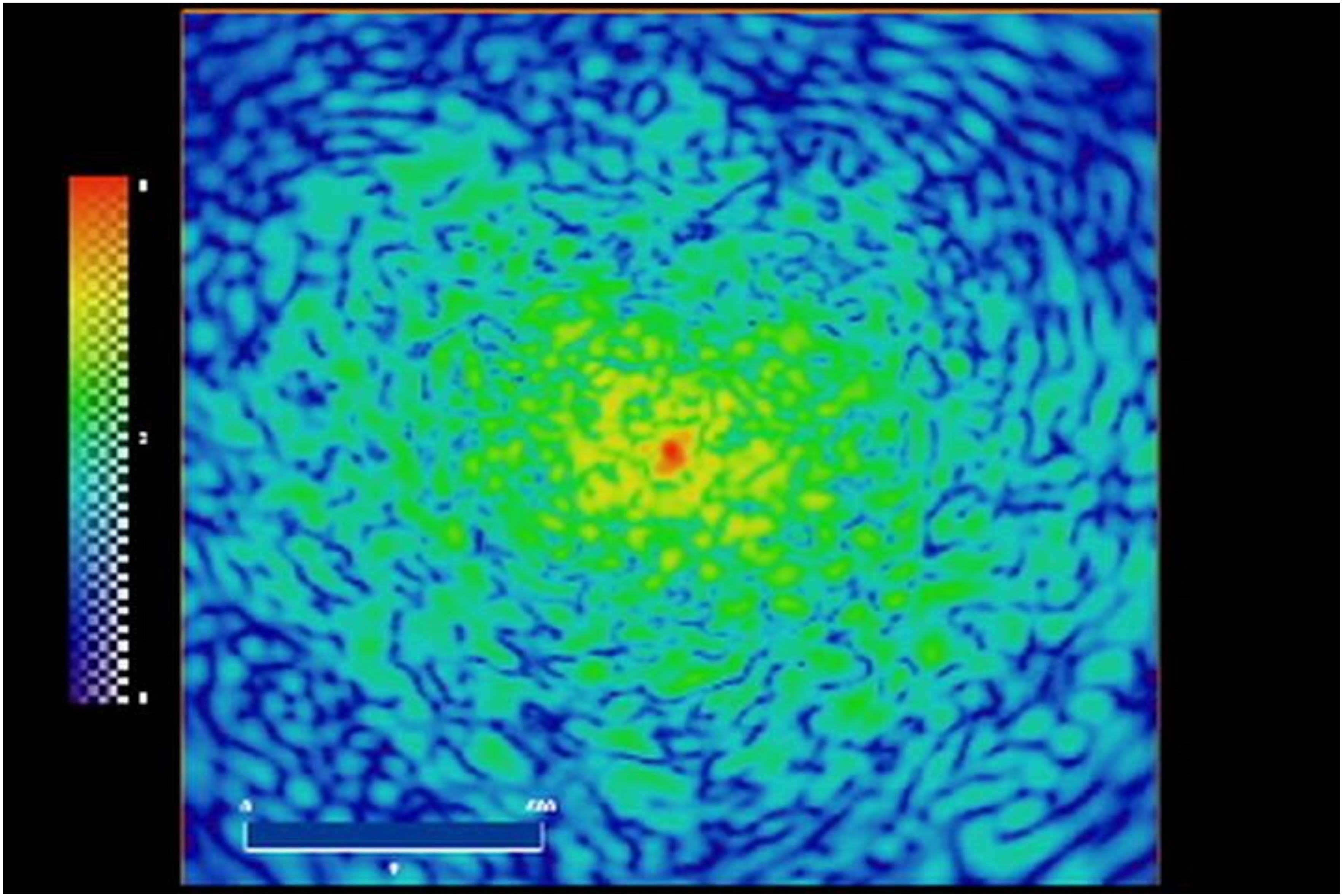


Nonlinear Evolution: Summary

- Soliton is the ground state of this nonlinear Eq. and has a size of $\lambda_{Jeans} \sim (1+z)^{1/4}\, m^{-1/2}\, \rho_{local}{}^{-1/4}$

- Fuzzy halo consists of excitations in the halo potential
- Excitations are random phased, and so granules in the fuzzy halo randomly appear and disappear

- Fuzzy halo & soliton core share the same temperature or squared velocity dispersion $\langle (|\nabla \ln|\Psi||)^2 \rangle$



Conclusions

- ΨDM predicts a soliton core and a fuzzy halo in every galaxy
- ΨDM halos resemble CDM halos by the large, except for minimum halos
- ΨDM is a falsifiable model, having various predictions different from CDM. To name a few, strong lensing, central anomalous velocity peaks, first galaxy forming at z=12 which affects reionization, etc.

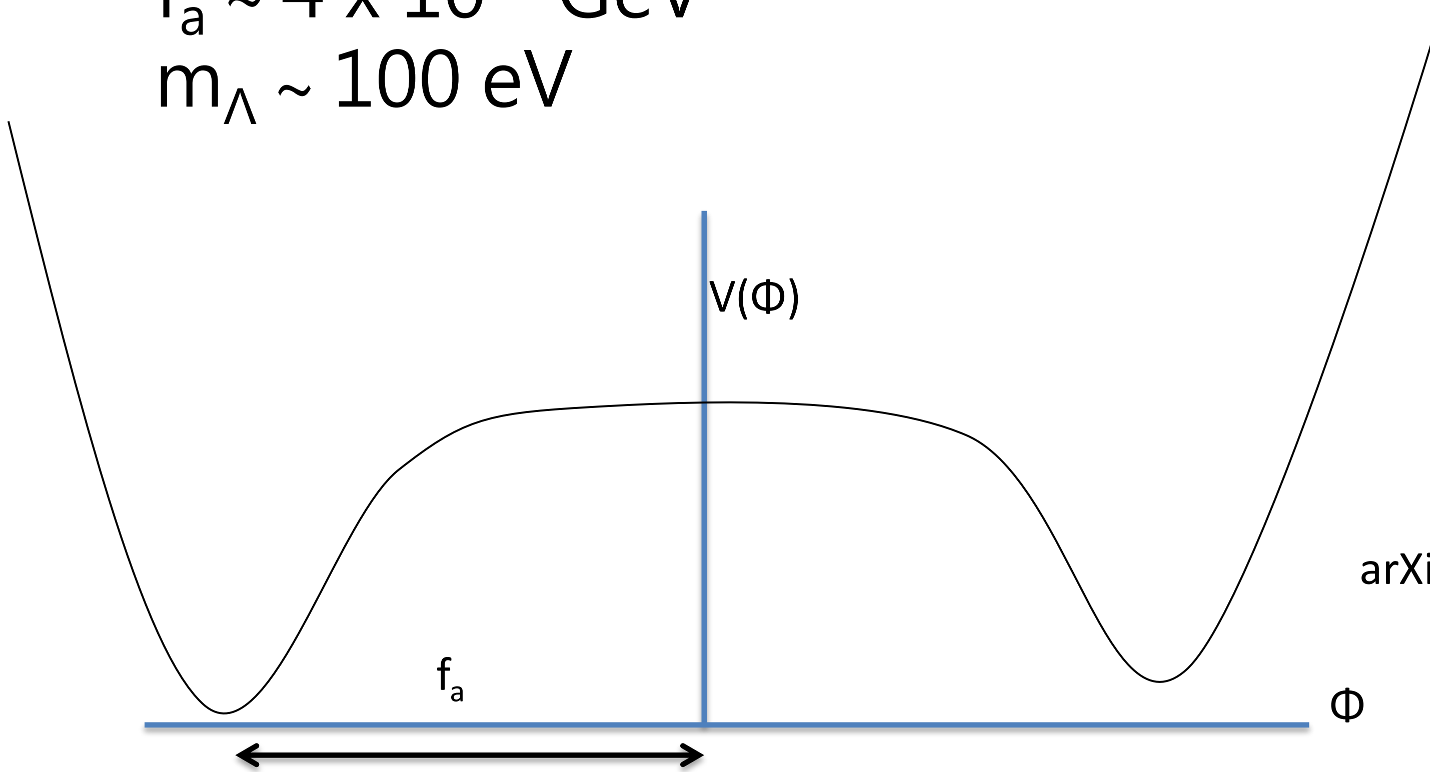
Why is ψDM boson mass 10^{-22} eV?

Tilted wine bottle (axion) model + one general assumption about the dark sector naturally yields

$m_a \sim 10^{-22}$ eV

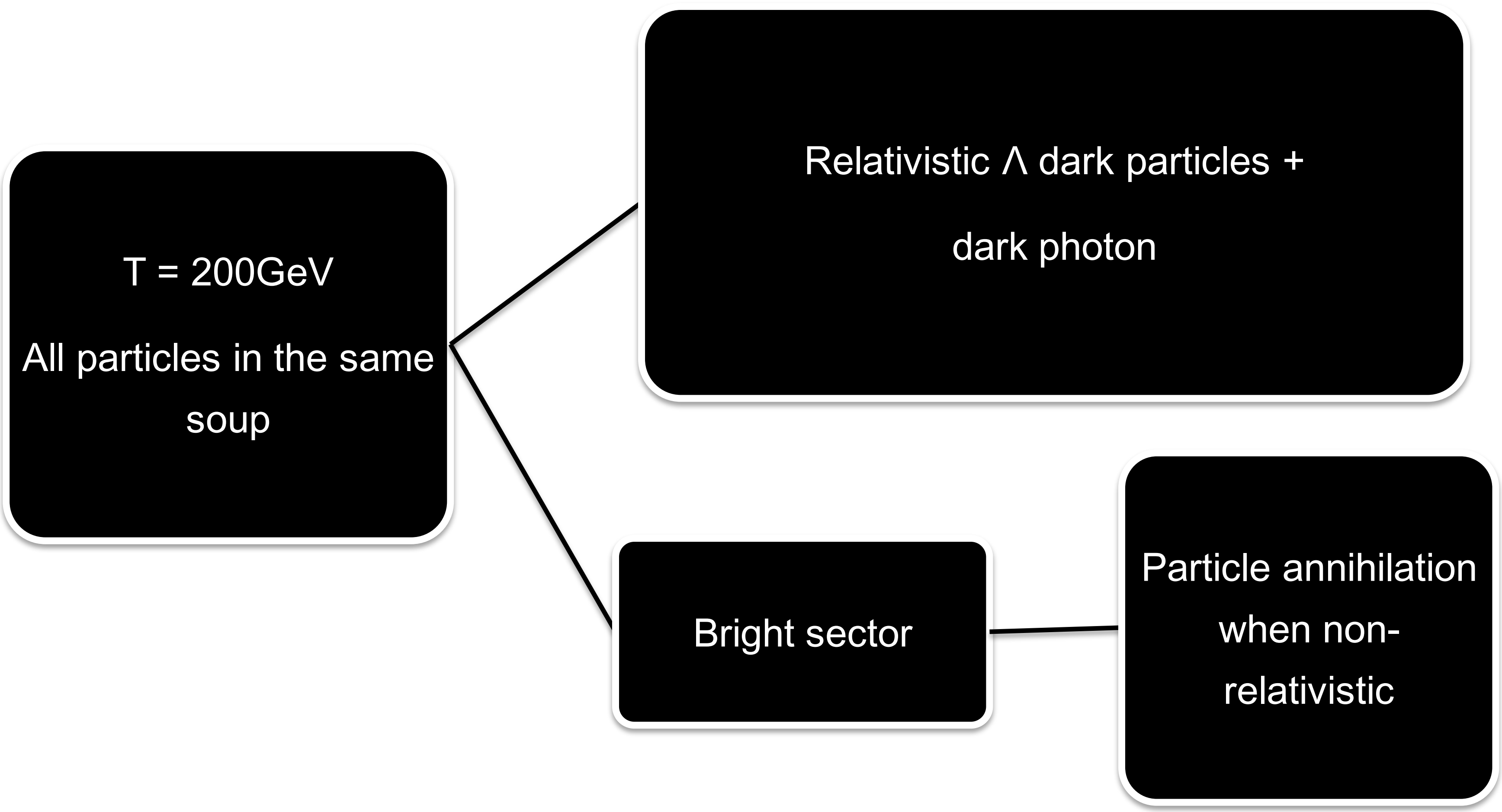
$f_a \sim 4 \times 10^{16}$ GeV

$m_\Lambda \sim 100$ eV



arXiv:1409-0380

Why is ψDM boson mass 10^{-22} eV?



Why is ψDM boson mass 10^{-22} eV?