暗物质II

毕效军
中国科学院高能物理研究所

“2017年理论物理前沿暑期讲习班——暗物质、
中微子与粒子物理前沿，
2017/7/25

Outline

- 暗物质profile确定
- Subhalo计算
- Axion简介
- 温暗物质sterile neutrino
- Nonthermal DM
- SIDM
- Fuzzy dm

看什么信号？Gamma，e+,pbar；什么实验探测？

看什么地方？暗物质信号，背景强度，天体环境等

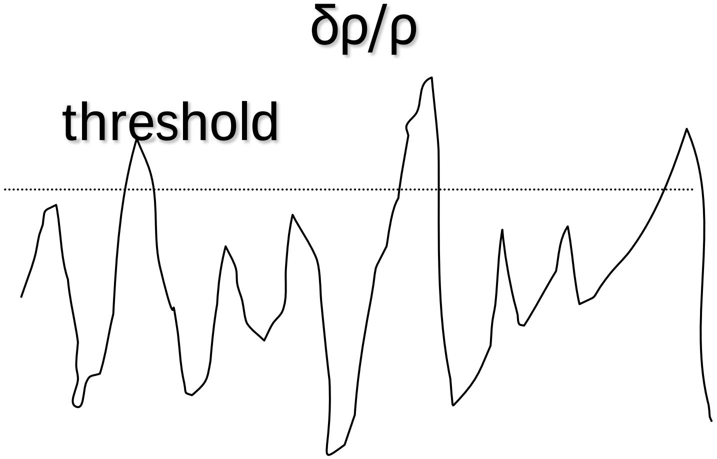
$$\frac{dN}{dE}=\frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_f B_f\,\frac{dN^f}{dE}\,\frac{\int\rho^2 dV}{4\pi d^2}$$

粒子物理模型；相互强度，末态？

暗物质在宇宙空间的分布

How does structure form?

- For CDM, structure form hierarchically bottom up， i.e., smaller object forms earlier (at smaller scale, the fluctuation is larger), they merges to form bigger and bigger structures.
- The smaller object have larger concentration parameter, since earlier epoch has greater density.



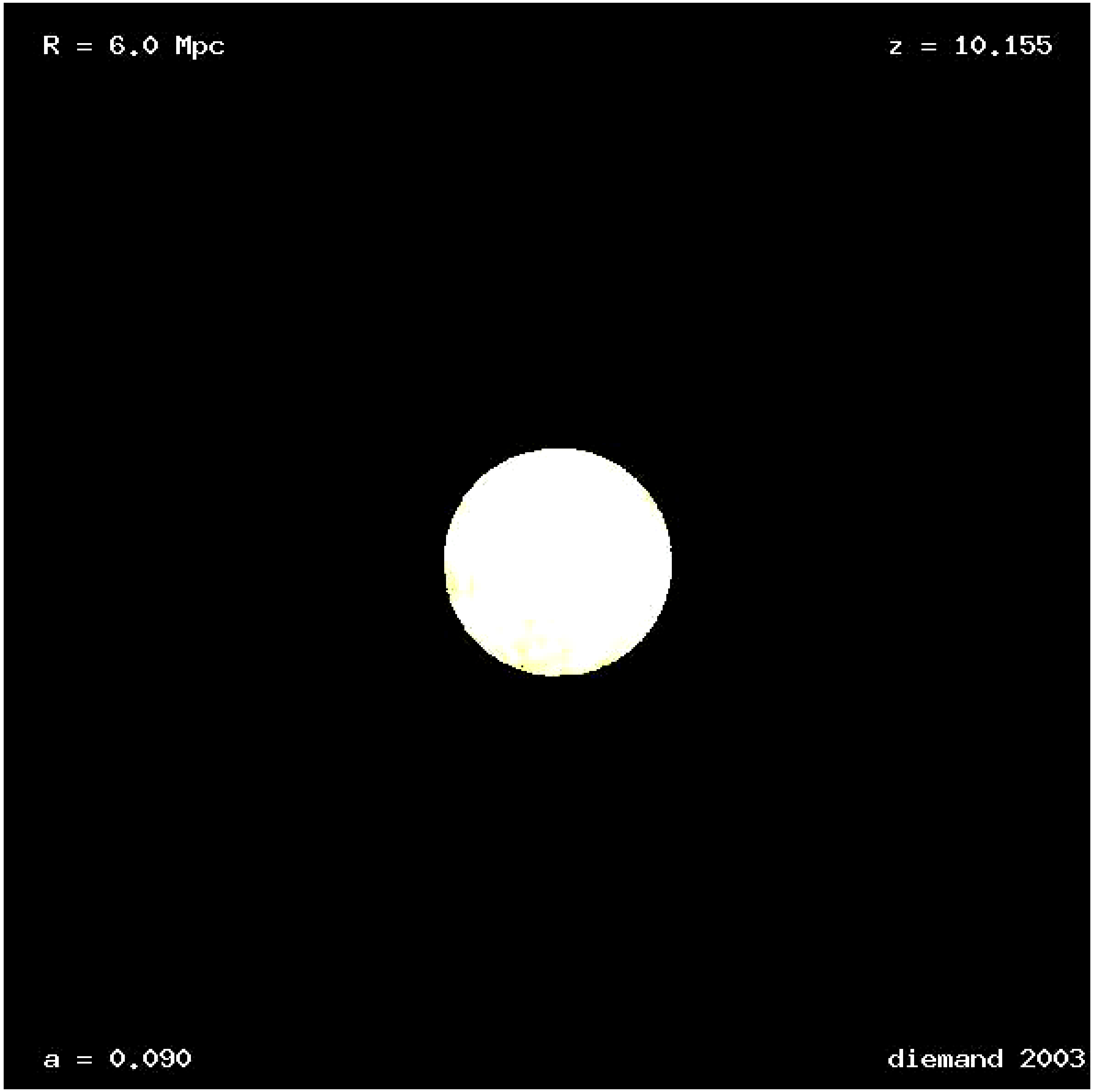
Structure formation – cold dark matter

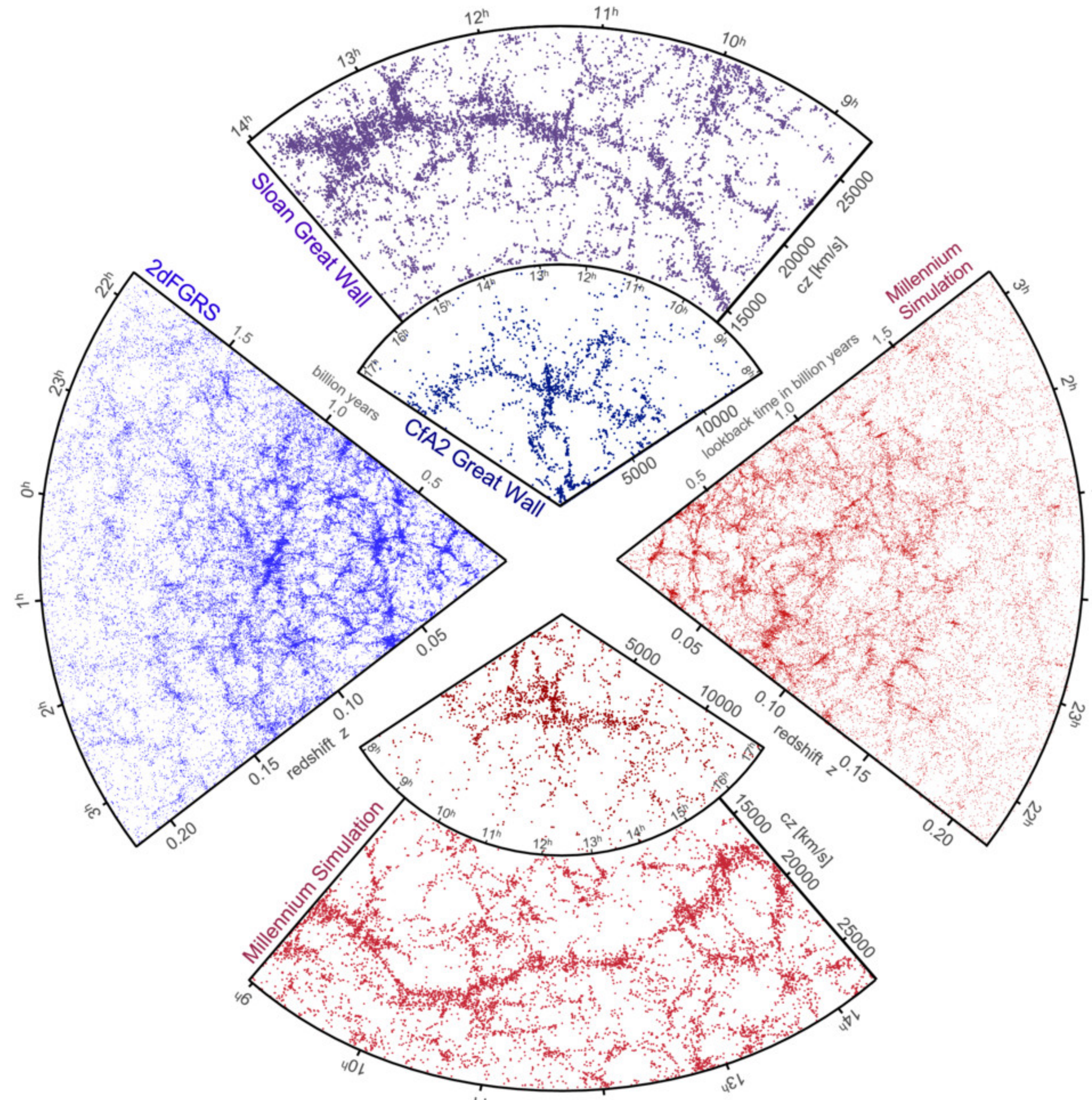
Numerical Simulation VS Observation

→ Cold Dark Matter

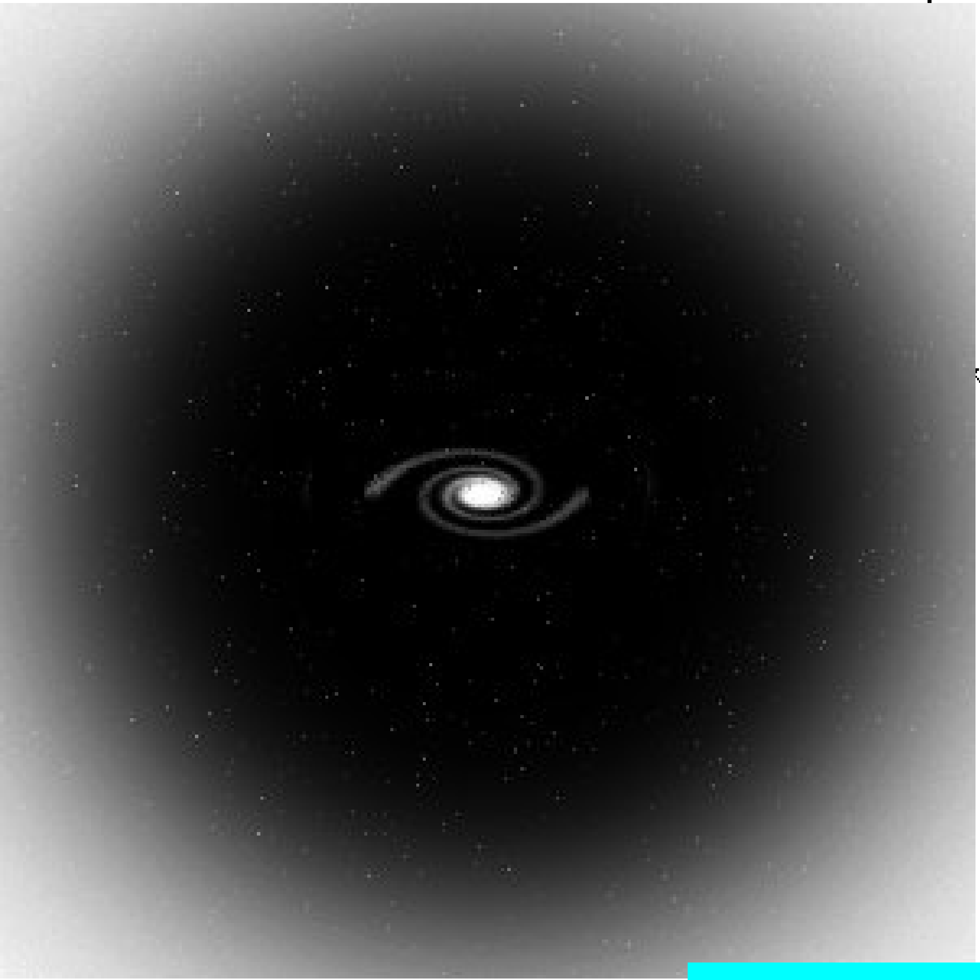
Distribution of the dark matter

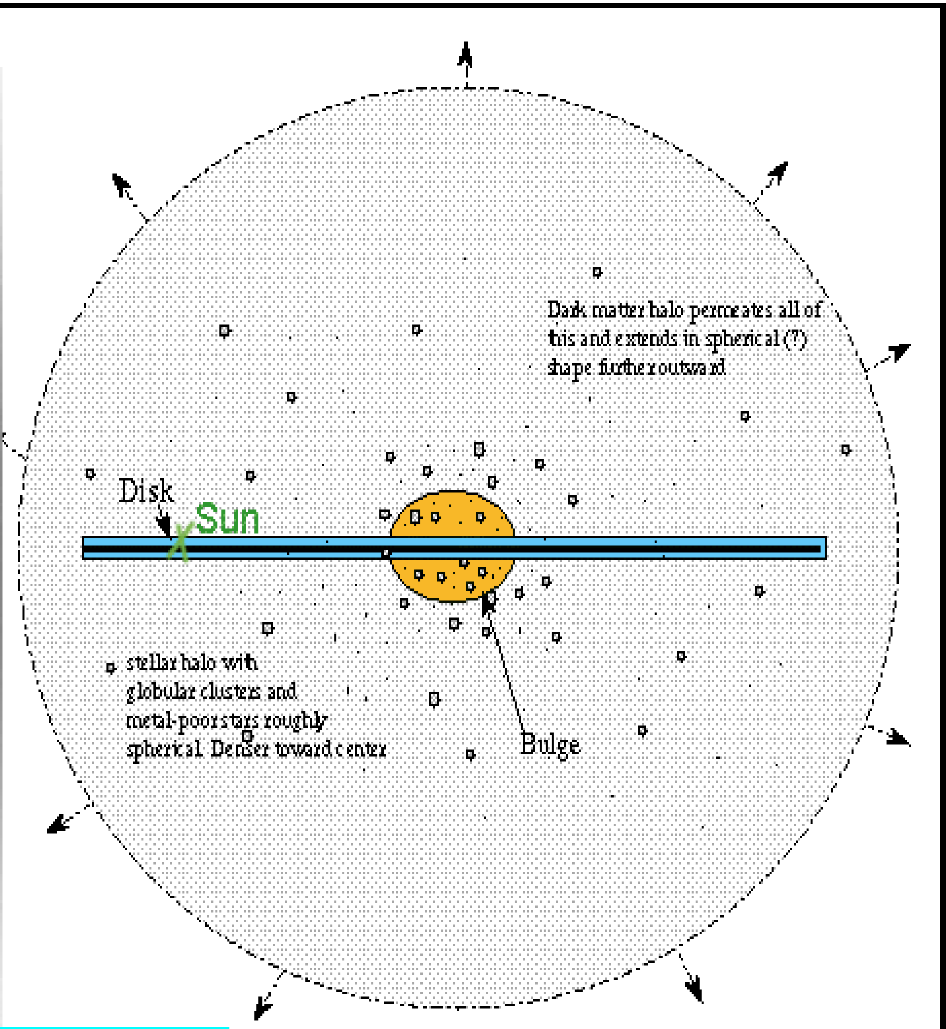
- N-body simulation is extensively adopted to study the evolution of structure with non-linear gravitational clustering from the initial conditions.
- The reliability of an N-body simulation is measured by its mass and force resolution.
- Simulations suggest a ***universal*** dark matter profile, same for *all masses, epochs and initial power spectra.*


R = 6.0 Mpc
z = 10.155
a = 0.090
diemand 2003


Sloan Great Wall
CfA2 Great Wall
2dFGRS
Millennium Simulation
Millennium Simulation
cz [km/s]
5000
10000
15000
20000
25000
redshift z
0.05
0.10
0.15
0.20
billion years
lookback time in billion years
0.5
1.0
1.5
9^h
10^h
11^h
12^h
13^h
14^h
22^h
23^h
0^h
1^h
2^h
3^h

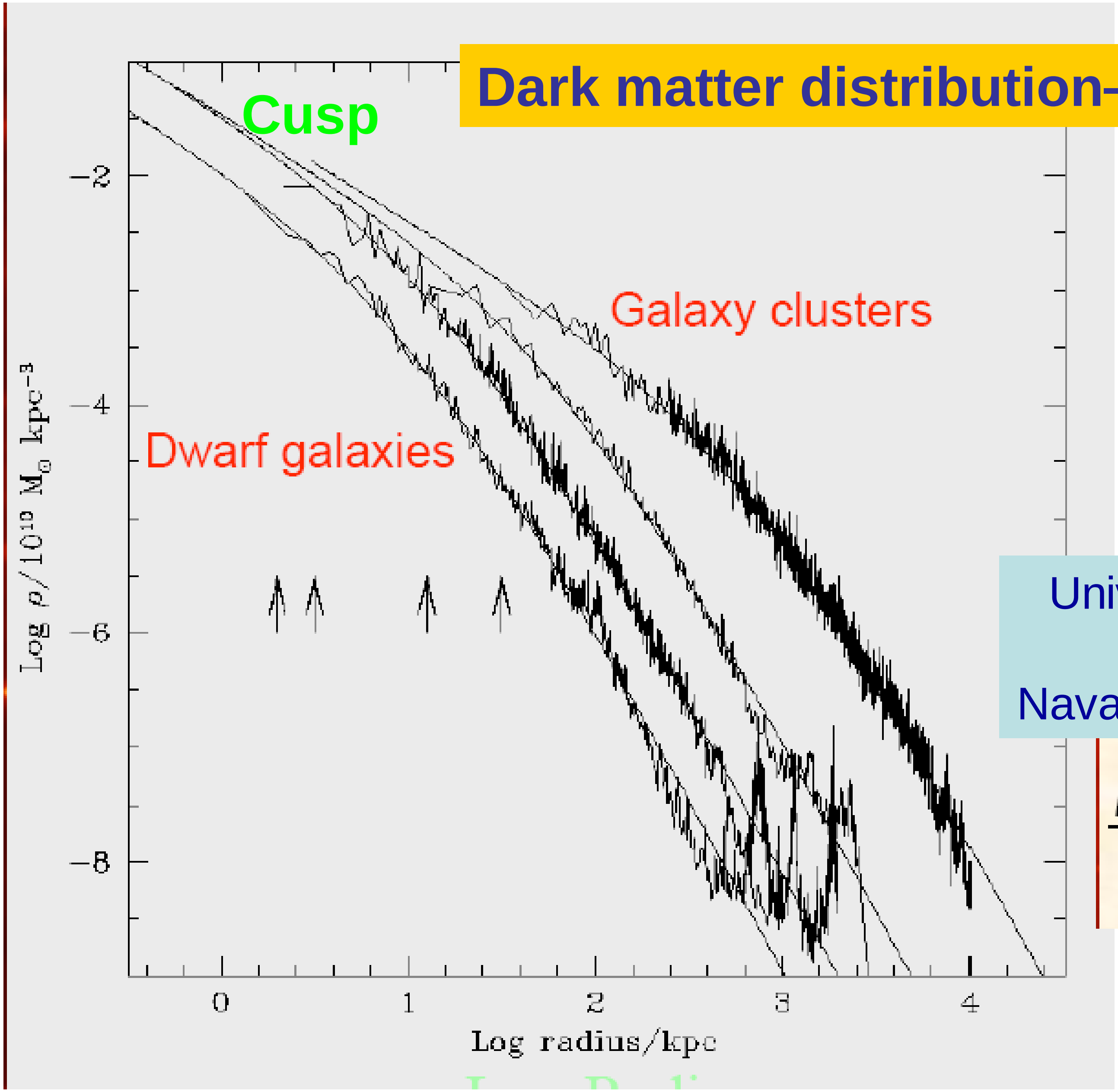
Galaxy configuration





Dark matter halo

Dark matter distribution—Density profile



Universal Density Profile

NFW profile

Navarro, Frenk, White 1997

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

Profiles of dark matter

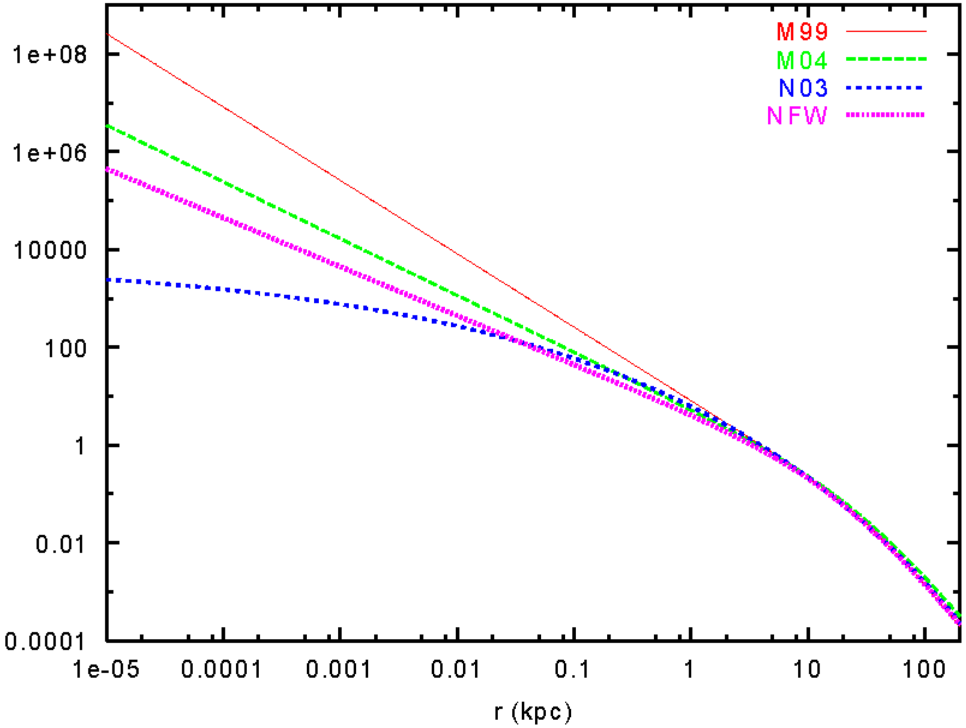
- Two generally adopted DM profiles are the NFW and Einasto profiles
- They have same density at large radius, while different slope as r->0

NFW: $$\rho_\chi(r) = \frac{\rho_s}{\left(r/r_s\right)\left[1+\left(r/r_s\right)\right]^2}$$

$$\rho_{NFW} \xrightarrow{r\to 0} r^{-1}$$

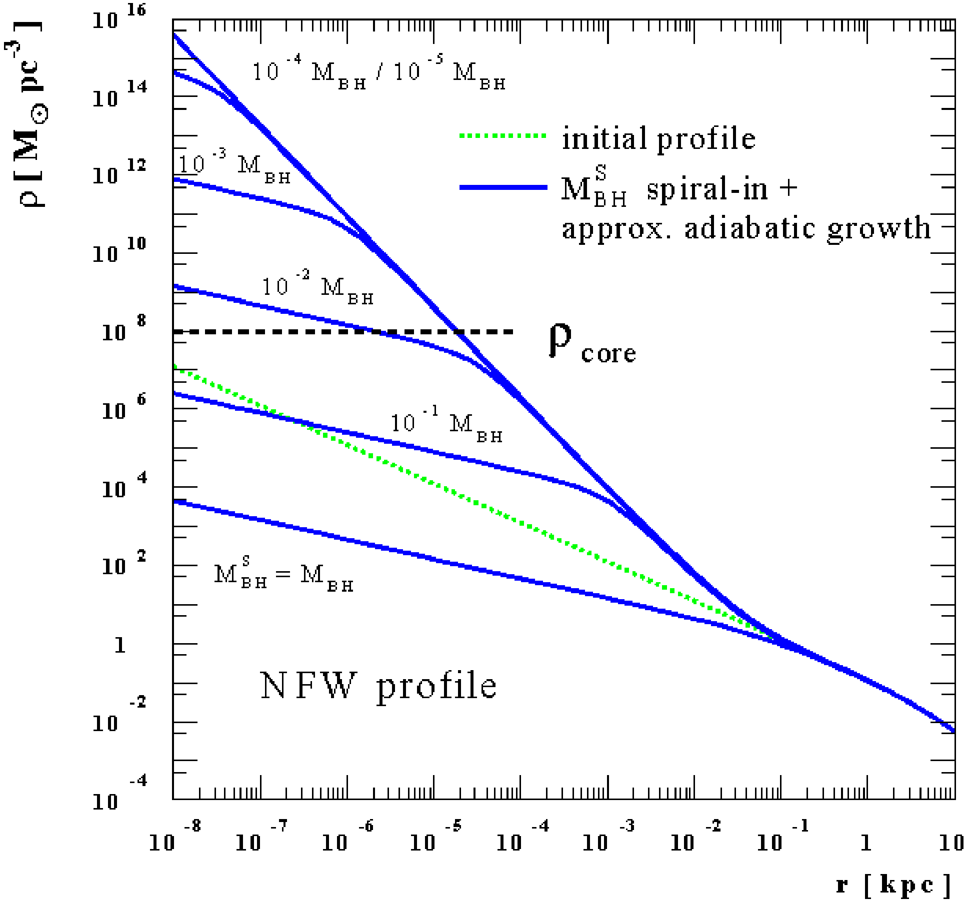
Einasto: $$\rho(r) = \rho_s e^{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^\alpha - 1\right]}$$

Isothermal: $$\rho(r) = \frac{\rho_s}{1+(r/r_s)^2}$$



Some recent developments

- The slope at the inner most radius is under debate. The most recent simulations including baryon matter seem in
between the NFW and
0311231, Reed, 03125
be not universal, depe
[Reed].
- The central super mas
the central cusp heavil
initial mass and adiaba

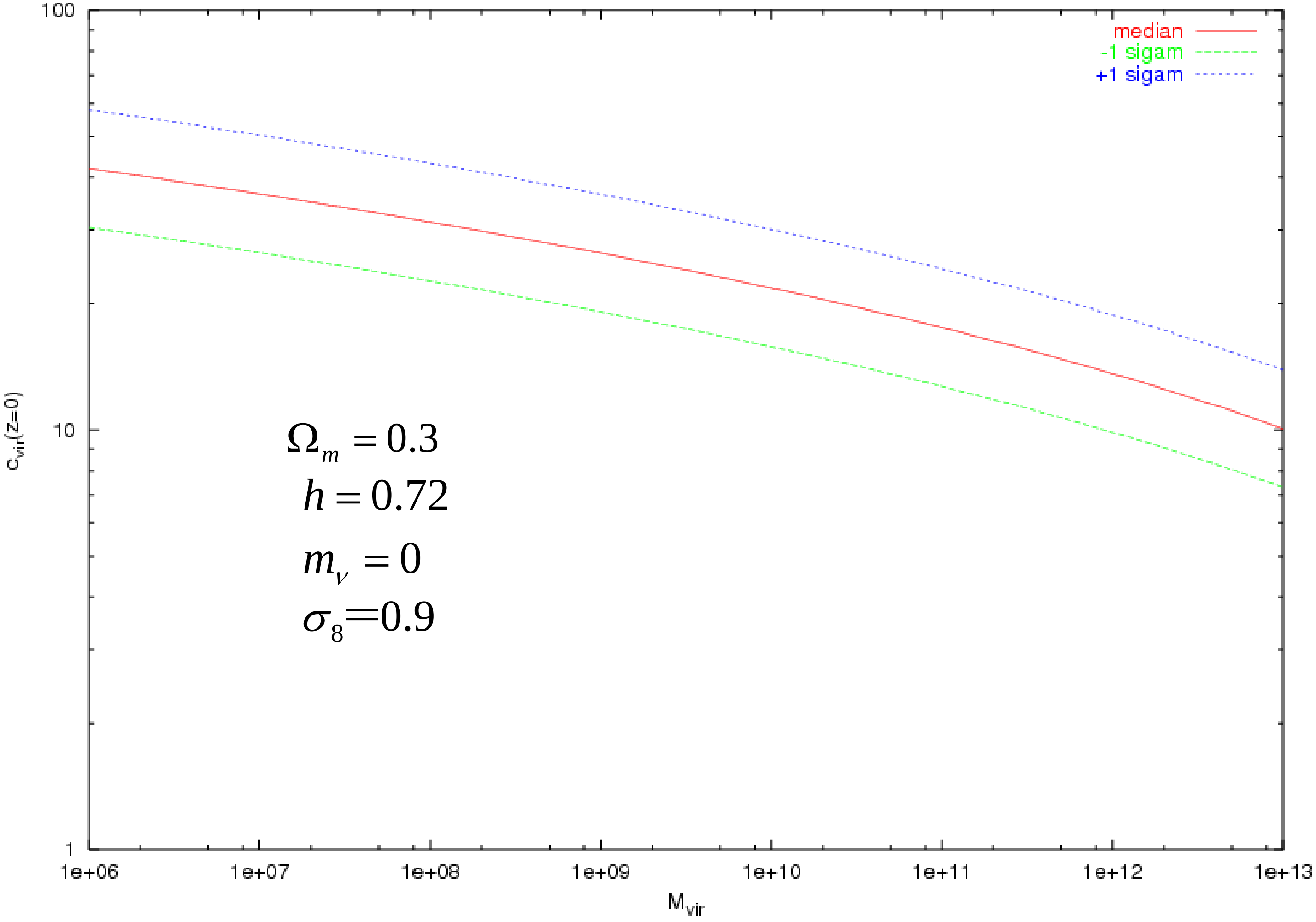


How to determine the dark matter density profile

- The profile is specified by the two scale parameters ρ_s, r_s. They are determined by the virial mass of the structure and the concentration parameter by $c=r_{vir}/r_s$.
- The concentration parameter represents how the dark matter centrally concentrated. The larger concentration the more centrally concentrated.
- The concentration parameter is determined by the evolution of the structure.

Concentration parameter via the virial mass – fitted to N-body simulation

From the figure, the concentration parameter decreases with the virial mass. It is determined once the cosmological parameters are specified.



$\Omega_m = 0.3$

$h = 0.72$

$m_\nu = 0$

$\sigma_8 = 0.9$

Determine the profile parameters

- If a halo viral mass is Mvir at redshift z, we have

and $$r_{\rm vir} = \left(\frac{3M_{\rm vir}}{4\pi\Delta_{\rm vir}(z)\rho_\chi(z)}\right)^{1/3} \qquad \rho_\chi(z) = \rho_\chi(1+z)^3$$

$$\Delta_{\rm vir}(z) = (18\pi^2 + 82y - 39y^2)/(1+y),\ y = \Omega_m(z) - 1 \text{ and } \Omega_m(z) = \frac{\Omega_m(1+z)^3}{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

- Here Δ represents the average density in a viralized halo to the matter density of the universe.
- The concentration parameter is $c_{\rm vir}(z) = c_{\rm vir}(z=0)/(1+z$
- Then we have $r_s = \dfrac{r_{\rm vir}}{c_{\rm vir}(2-\gamma)}$ for a generalized NFW

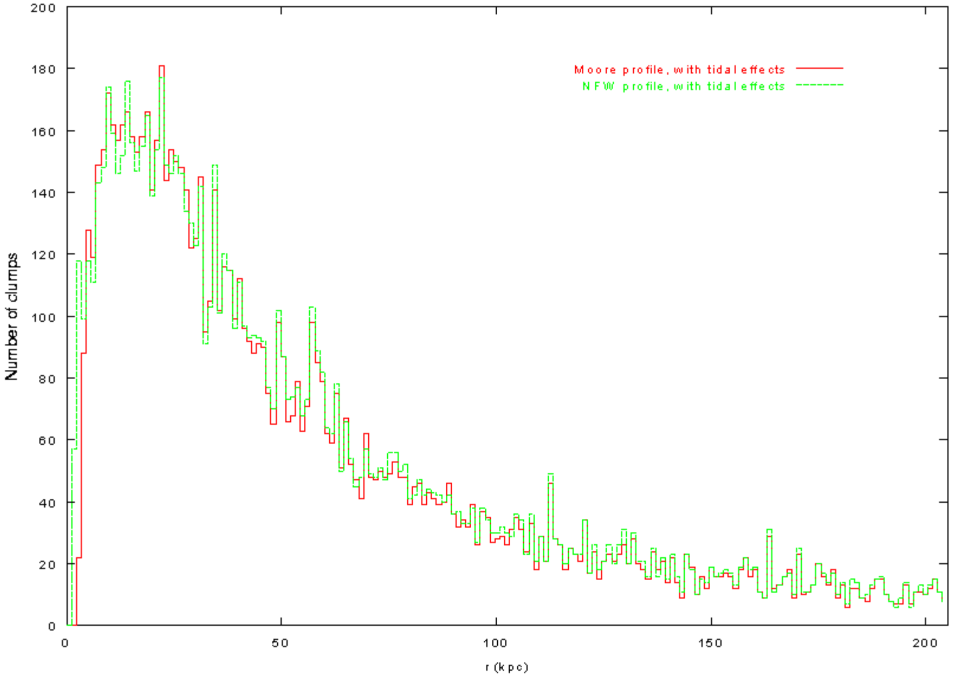
$$\rho(r) = \frac{\rho_s}{(r/r_s)^\gamma(1+r/r_s)^{3-\gamma}}$$

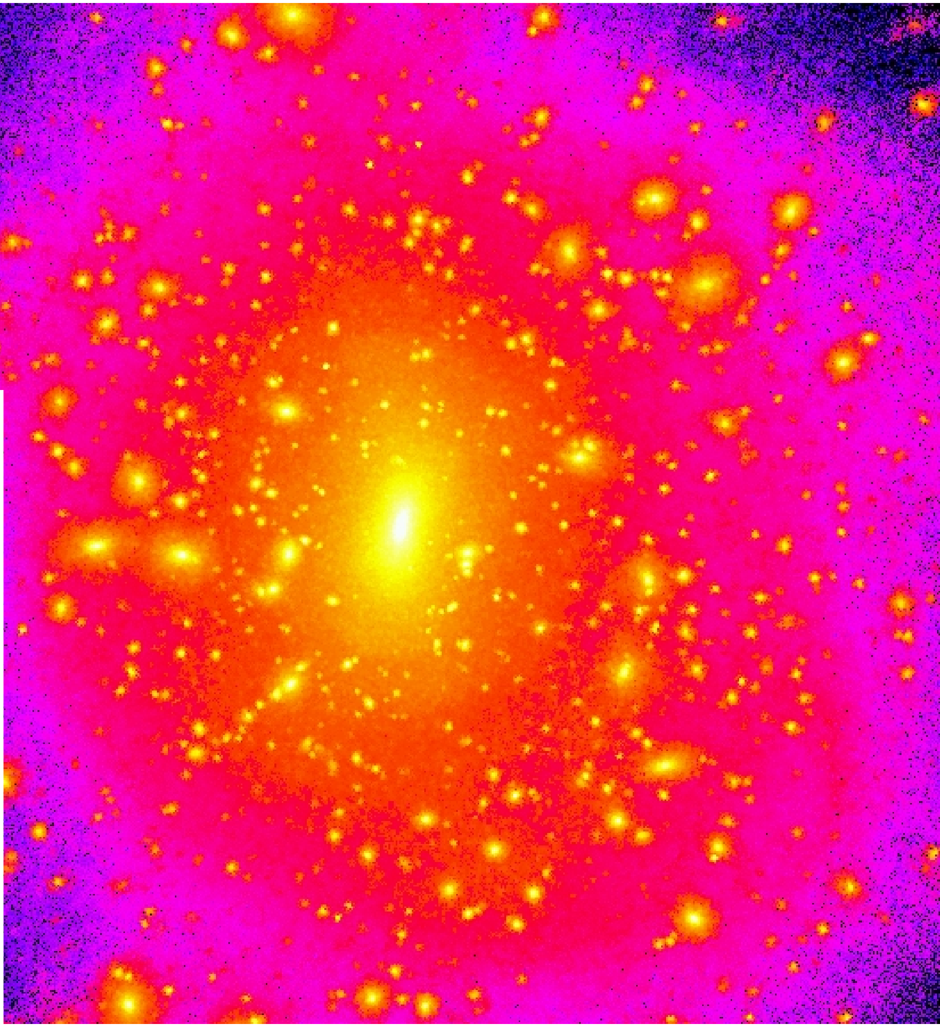
- We have now slightly different models to determine the concentration paramter J. S. Bullock et al 2001, A. V. Macci`o et al. 2008

Substructure

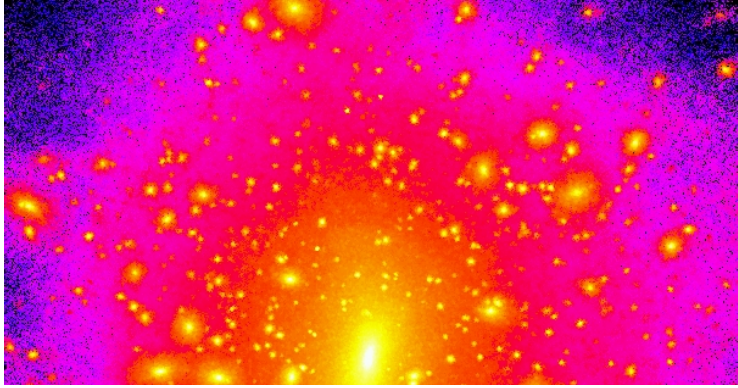
Moore et al

- Will the smaller objects formed earlier survive today in the dark halo?
- A wealth of subhalos exist due to high resolution simulations.
- The number density is as:

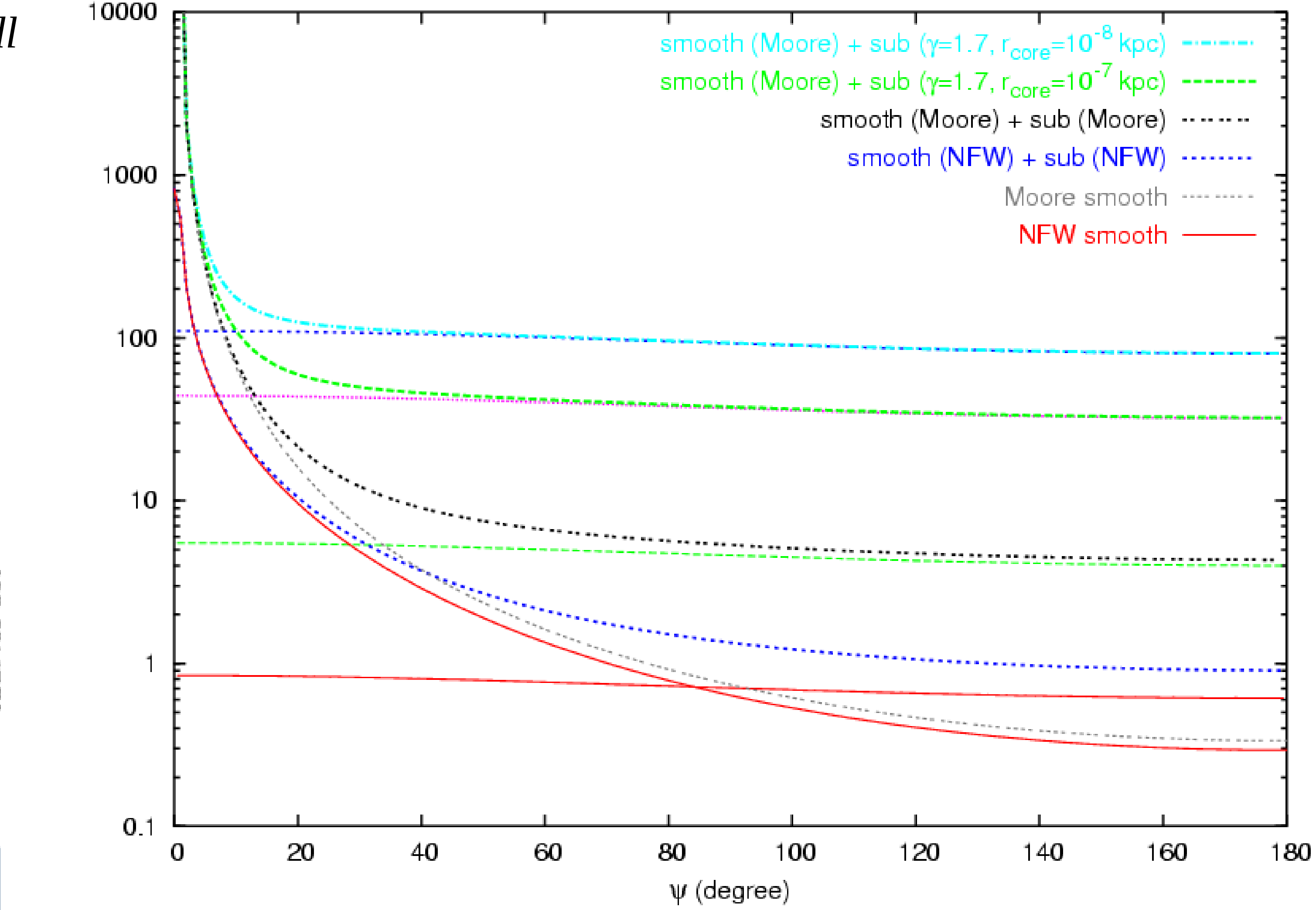


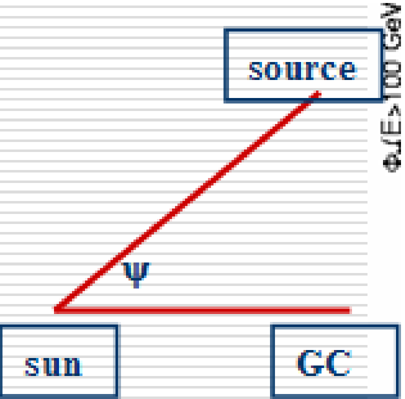


With and without subhalos

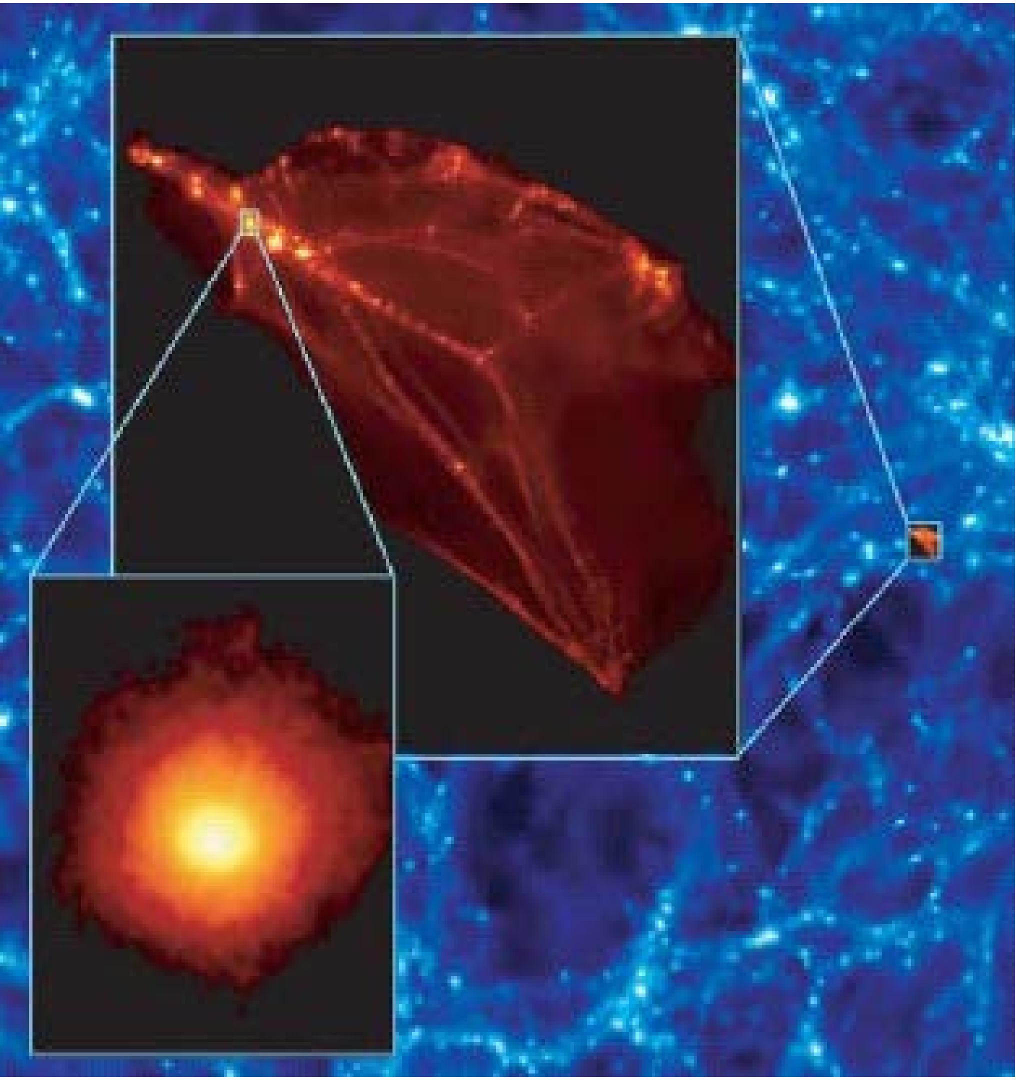


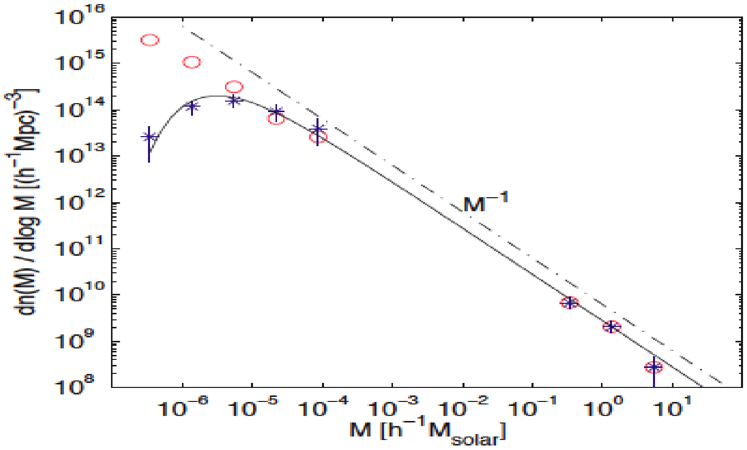
$$\Phi^{cosmo} = \int_{l.o.s} \rho^2(r)\,dl$$





The first generation object

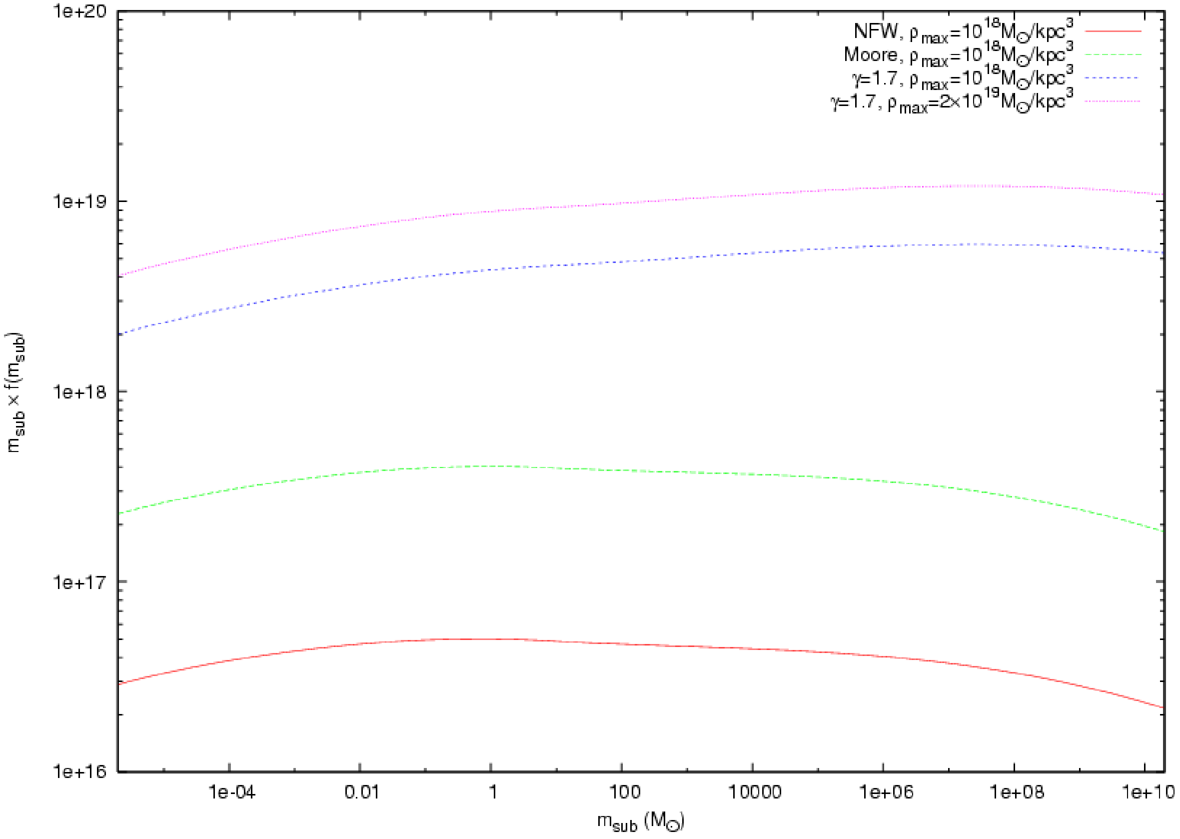




Diemand, Moore & Stadel, 2005:

- **Depending on the nature of the dark matter: for neutralino-like dark matter, the first structures are mini-halos of $10^{-6}\ M_\odot$.**
- **There would be zillions of them surviving and making up a sizeable fraction of the dark matter halo.**
- **The dark matter detection schemes may be quite different!**

Contributions from different mass ranges of subhalos



$$\frac{dN}{dm} \propto m^{-1.9}$$

$$\frac{d\mathcal{P}_V(r)}{4\pi r^2 dr} = K_V \times \left[1 + \left(\frac{r}{r_H}\right)^2\right]^{-1}$$

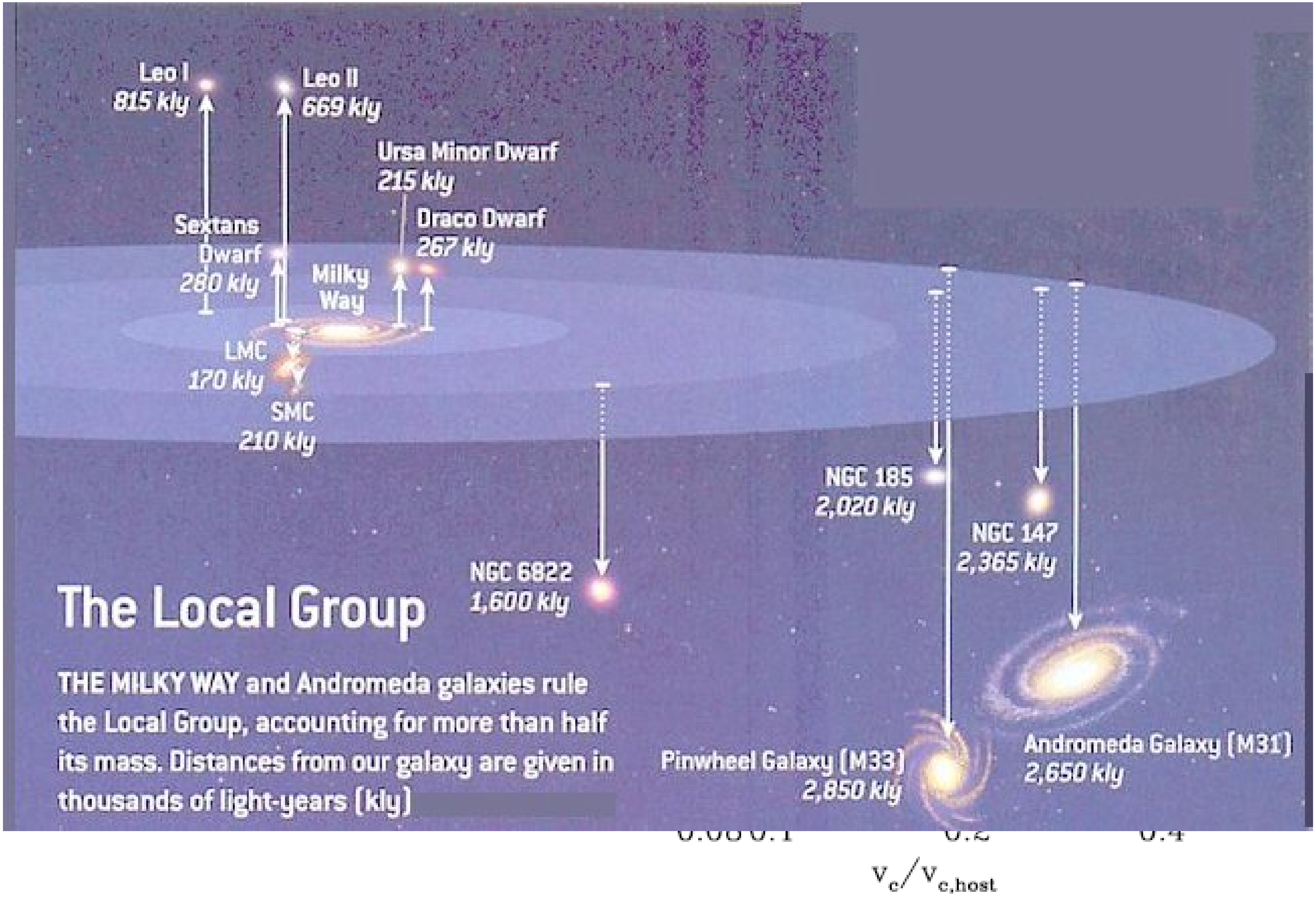
◘ Inconsistencies in ΛCDM paradigm

Scale $<$ 1Mpc

- **Substructure number problem**
  - **DM haloes contain a huge number of subhalos**
  - **the observed number of dwarf galaxies in the voids appears to be far smaller than expected from CDM**
- **Cusp problem**
  - **DM halos have a density profile with sharp slope**
  - **the density profile inferred from galaxy rotation curves are significantly shallower**

Difficulties of CDM: number of satellites

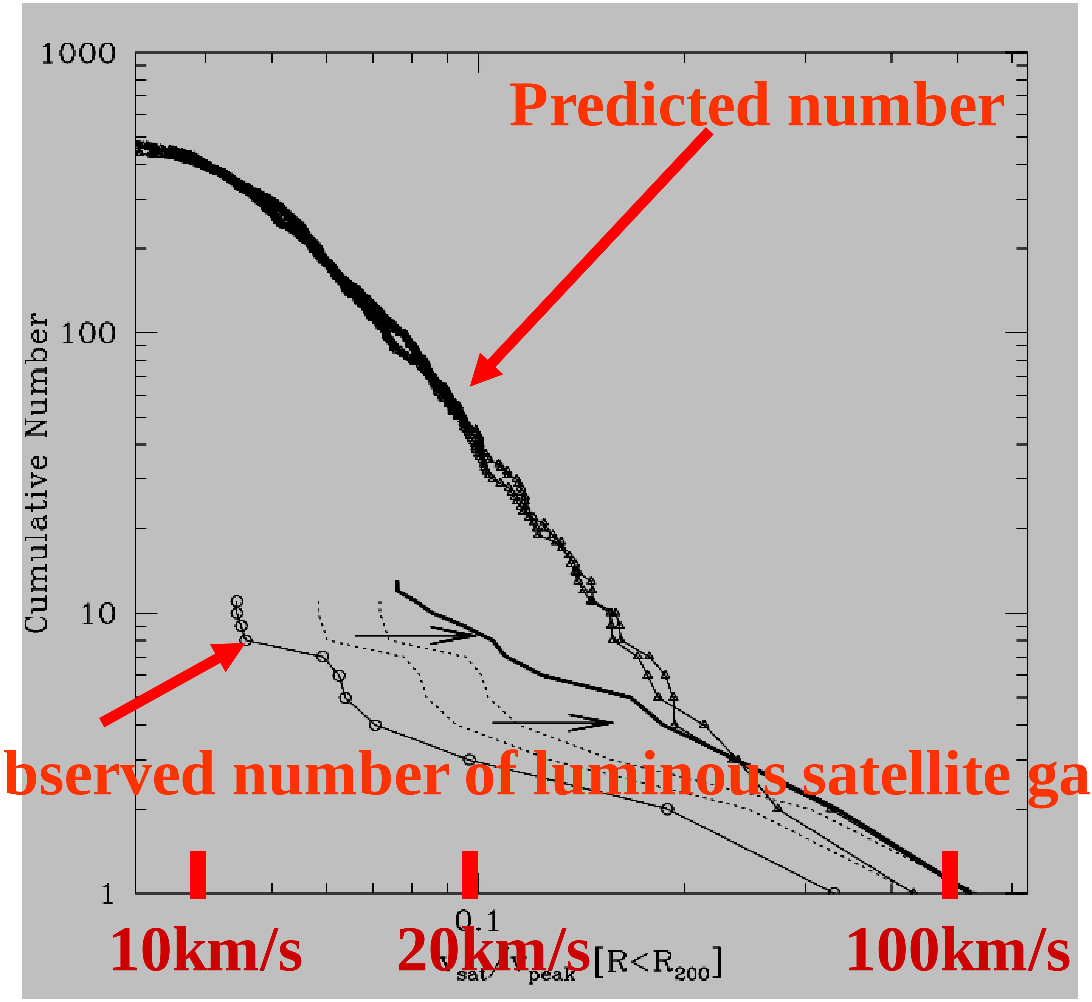
Jing (2001)



The Local Group

THE MILKY WAY and Andromeda galaxies rule the Local Group, accounting for more than half its mass. Distances from our galaxy are given in thousands of light-years (kly)

- Satellite galaxies are seen in Milky Way, e.g. Saggittarius, MCs



Predicted number

Observed number of luminous satellite galaxies

10km/s

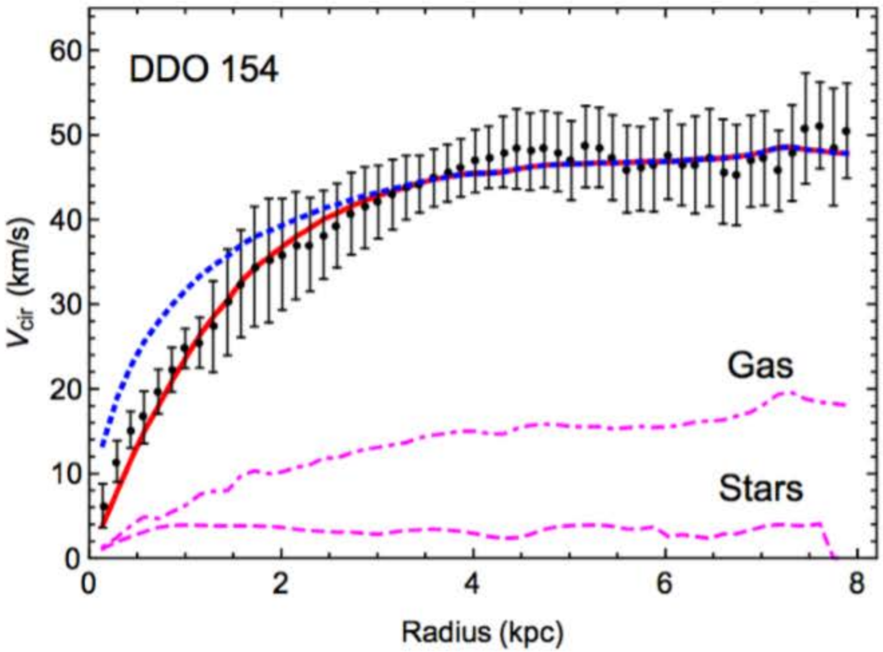
20km/s

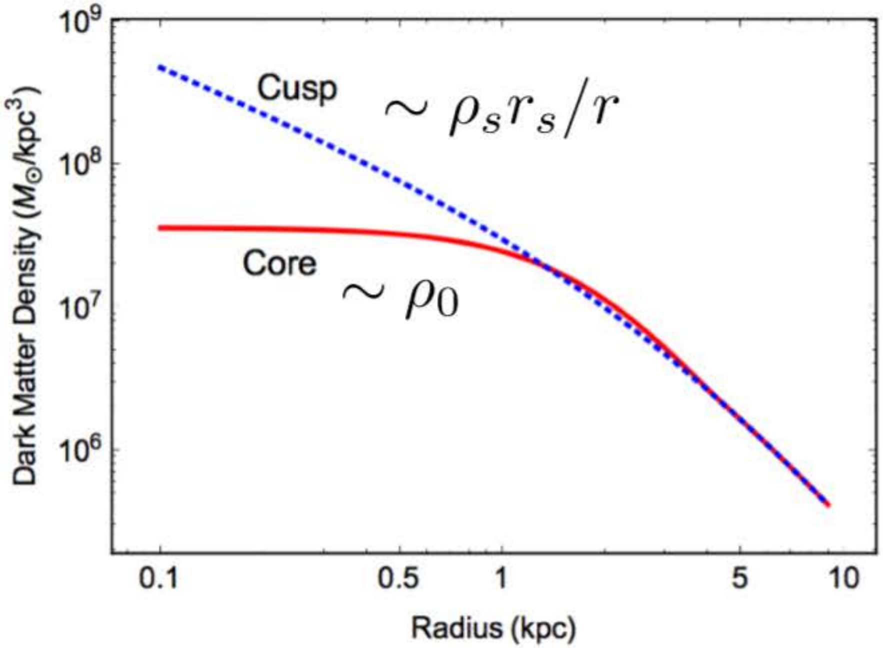
100km/s

- The predicted number of substructures exceeds the luminous satellite galaxies: dark substructures?

Core vs. Cusp Problem

- DM-dominated systems (dwarfs, LSBs)





$$\frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

Navarro, Frenk, White (1996)

universal density profile, NFW profile

ρ_s and r_s are strongly correlated

Problems of CDM on sub-galactic scale

- The simulation over-predicts the number of subhalos. The number of observed dwarf satellites is an order of magnitude smaller than predicted.
- Solutions are proposed, including inflation potential suppressing the small scale fluctuation, star formation suppressed in small subhalos, and new form of dark matter candidates, such as self-interacting dark matter, non-thermal production, warm dark matter, fuzzy dark matter and so on.
- Milli-lensing by halo substructure seems favor the CDM scenario. It is still controversial.

How to define “cold”

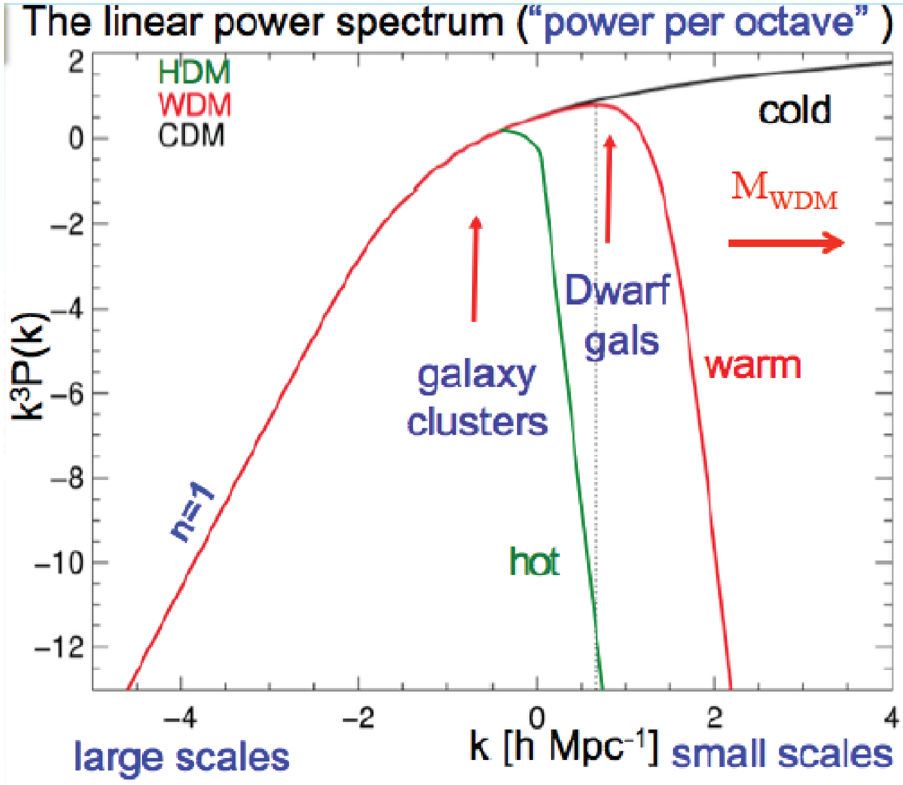
- Definition of cold, warm or hot depends on the effect of their “free-stream” motion on the formation of objects

$$\lambda_{\mathrm{FS}}^{co} = \int_0^t \frac{v(t')dt'}{a(t')}$$

  - Cold dark matter that has effectively zero thermal velocity
  - Hot dark matter (eV neutrinos) that washes out fluctuations on cluster scale (10 Mpc/h);
  - Warm dark matter (sterile neutrinos) that washes out fluctuations on galaxy scale (1 Mpc/h);

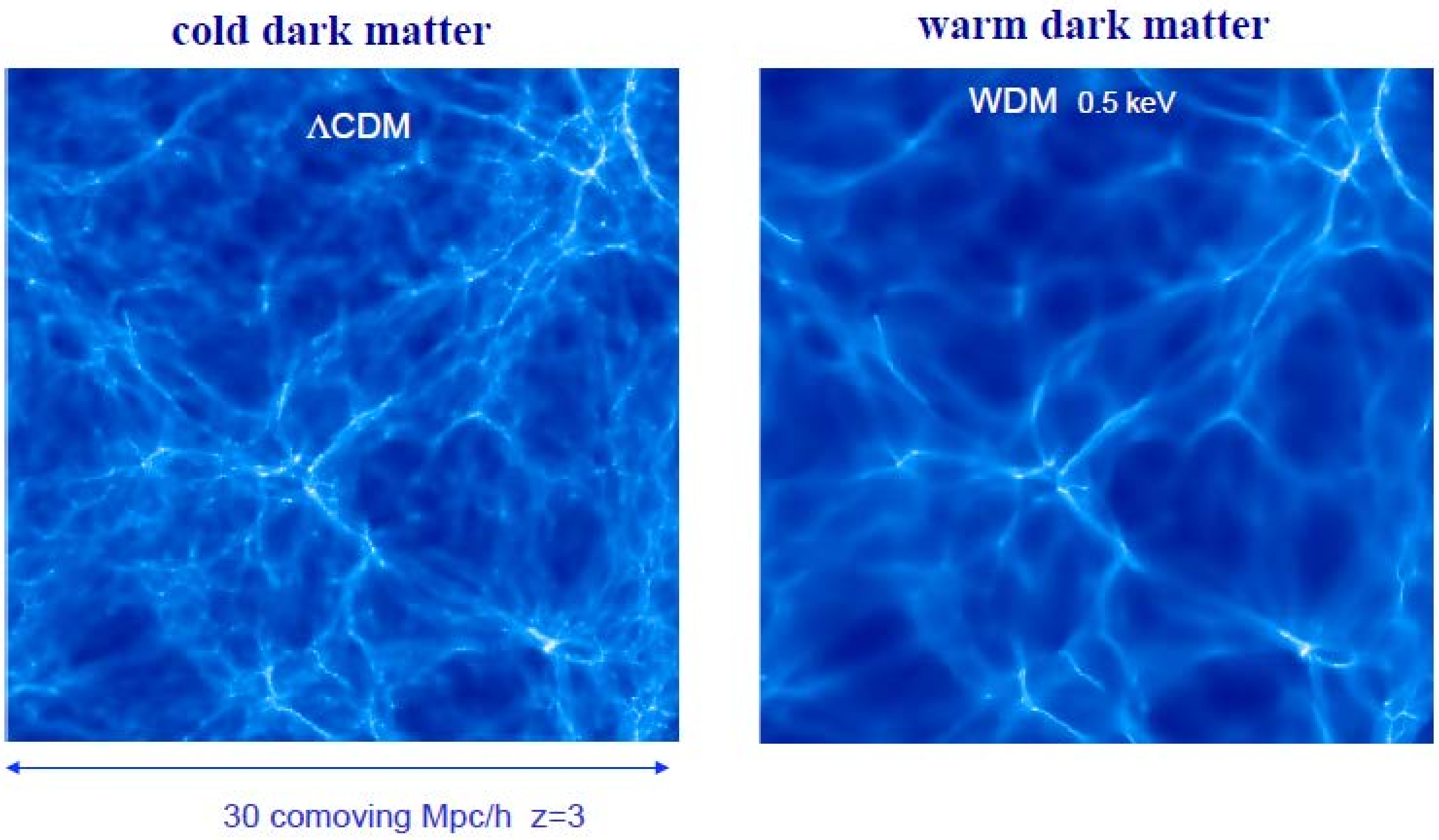
What does warm mean?

Cut-off in the matter power spectrum on astrophysically interesting scales due to free-streaming?

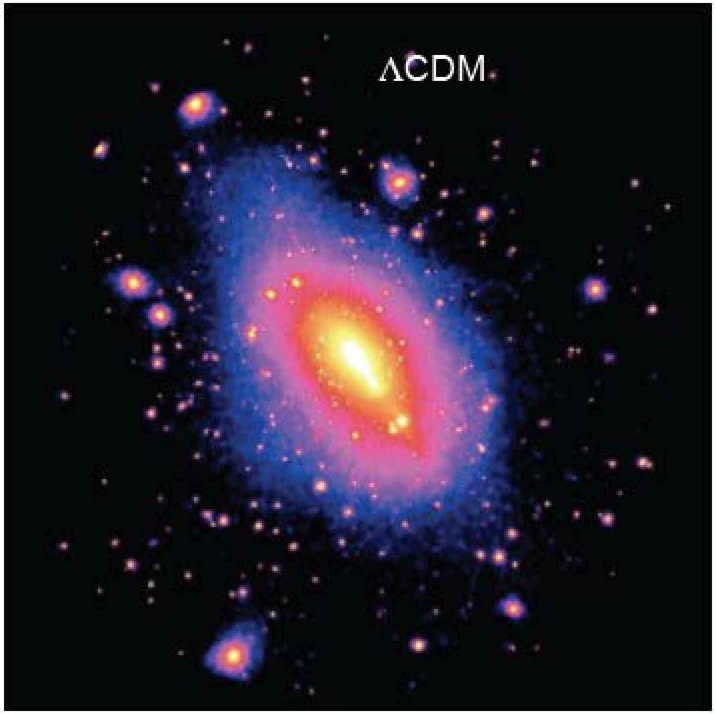


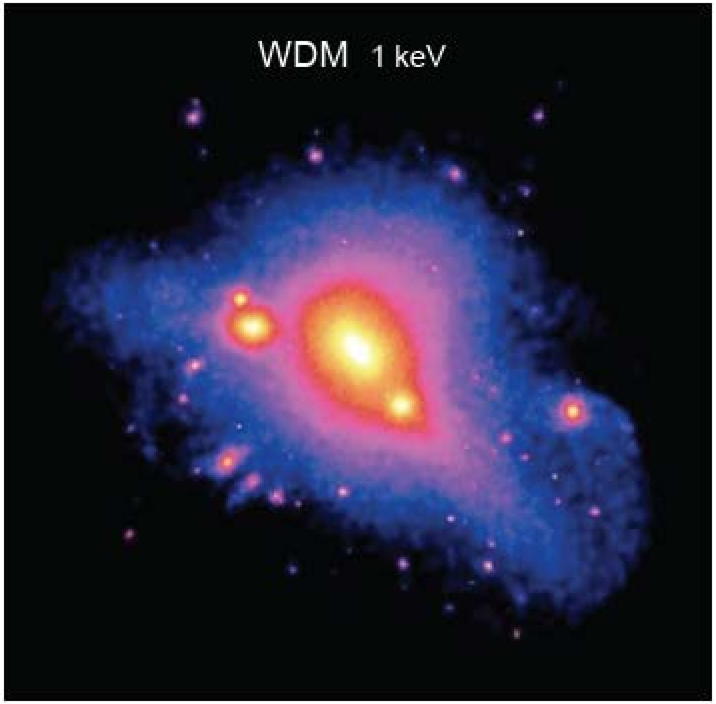
courtesy of
Carlos Frenk

Free-streaming erases structure



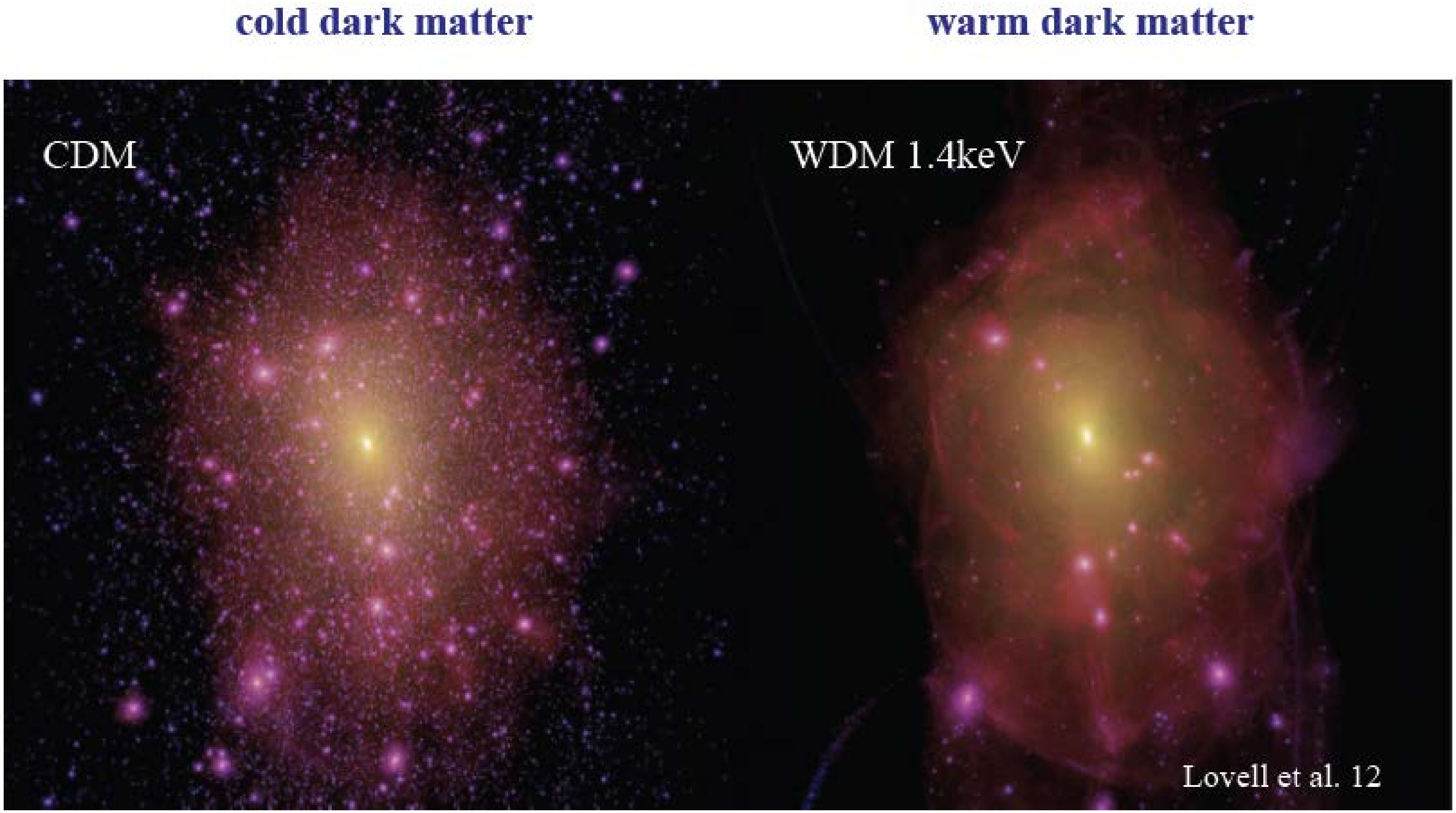
Less subhalos


cold dark matter

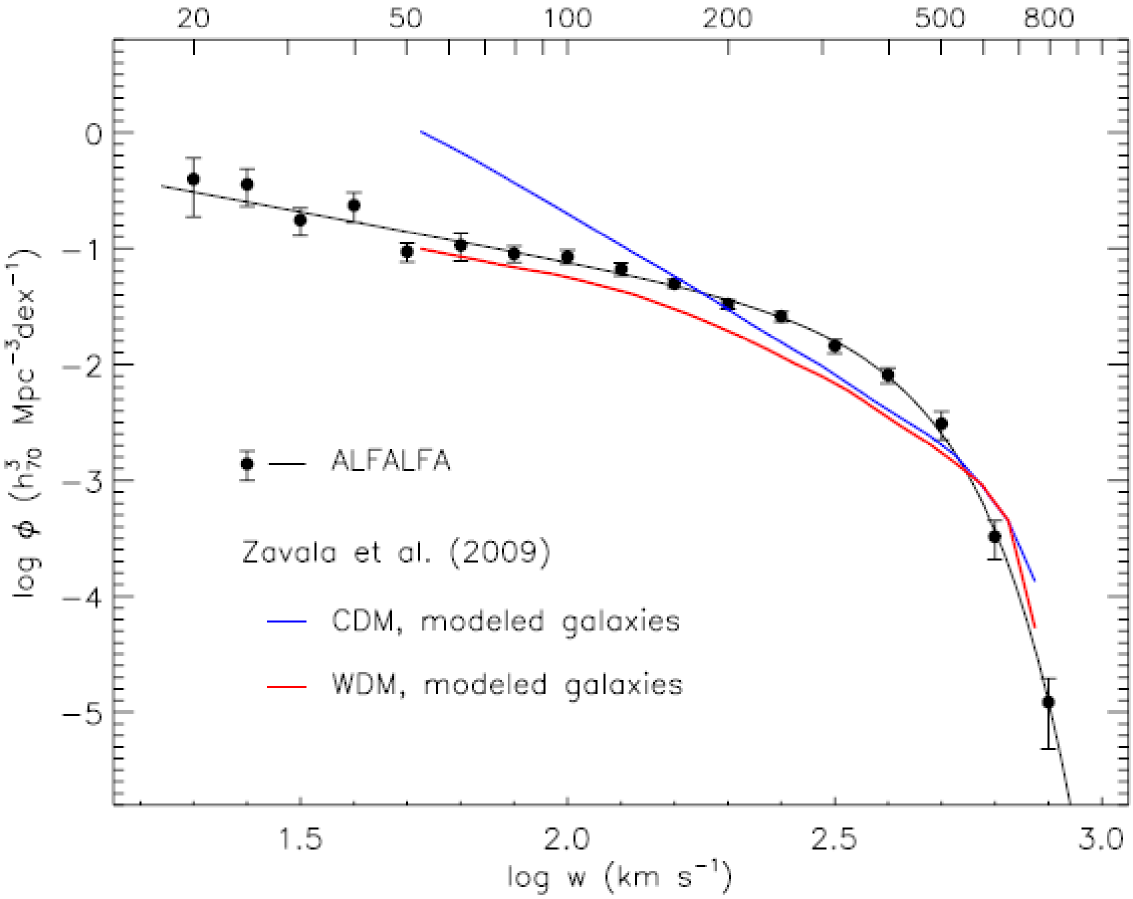

warm dark matter

Maccio & Fontanot 2009

More smaller structures

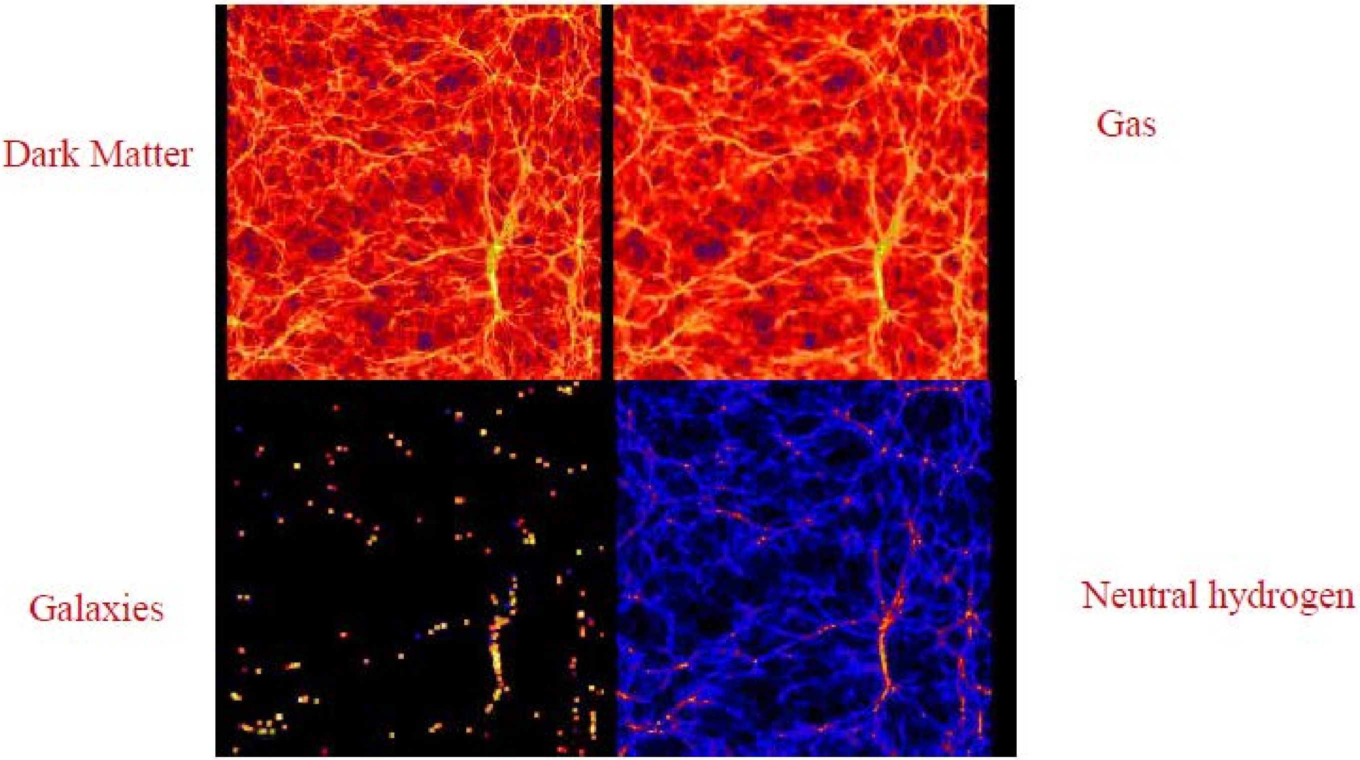


How cold is dark matter: velocity width function of galaxies (ALFALFA survey)



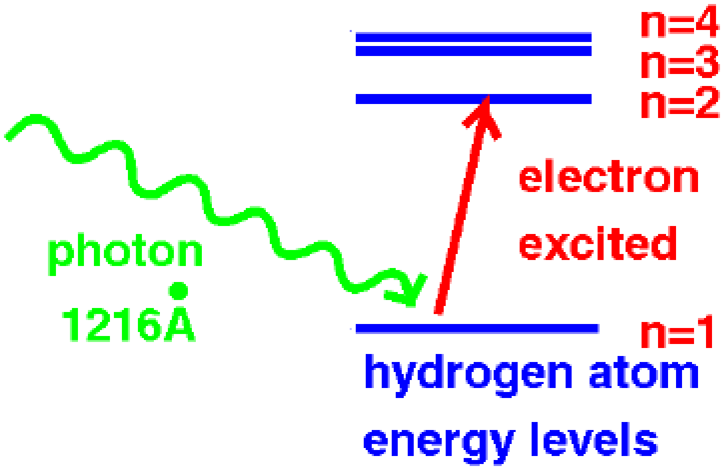
Papastergis et al. (2011)

Observation of the structure

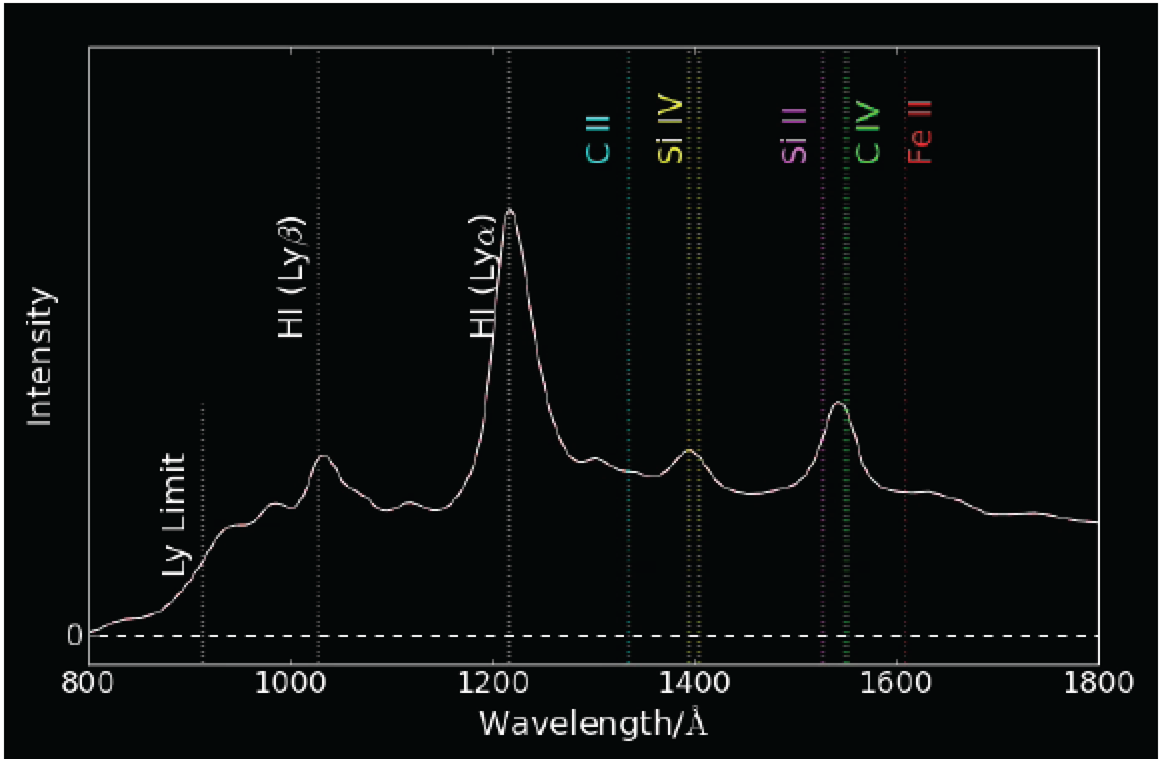


Neutral hydrogen is an excellent tracer of the matter distribution.

Lyα absorption by neutral hydrogen

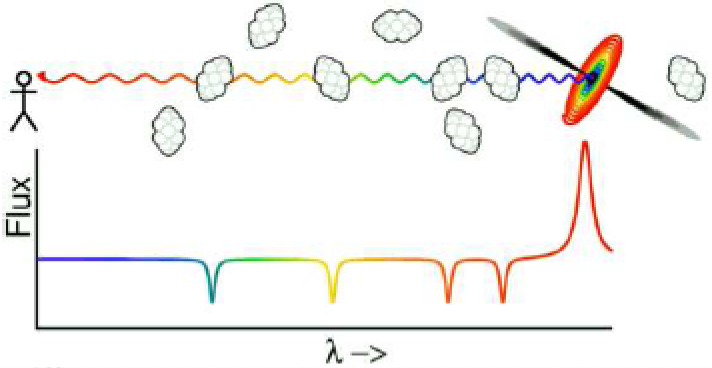


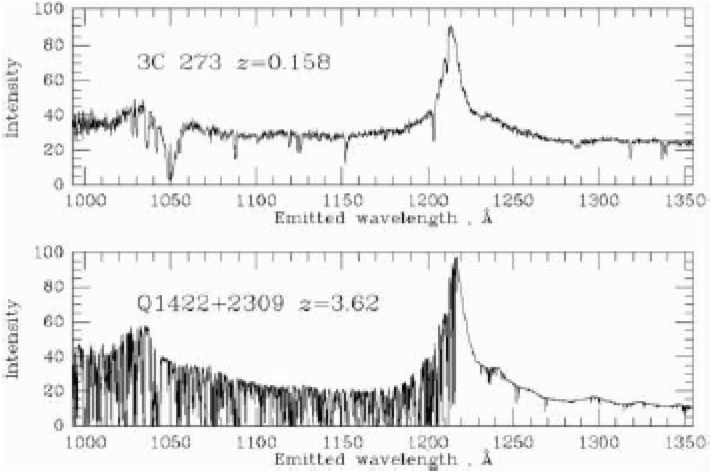
$$\lambda_{obs} = 1216\,(1+z)\ \text{Å}$$



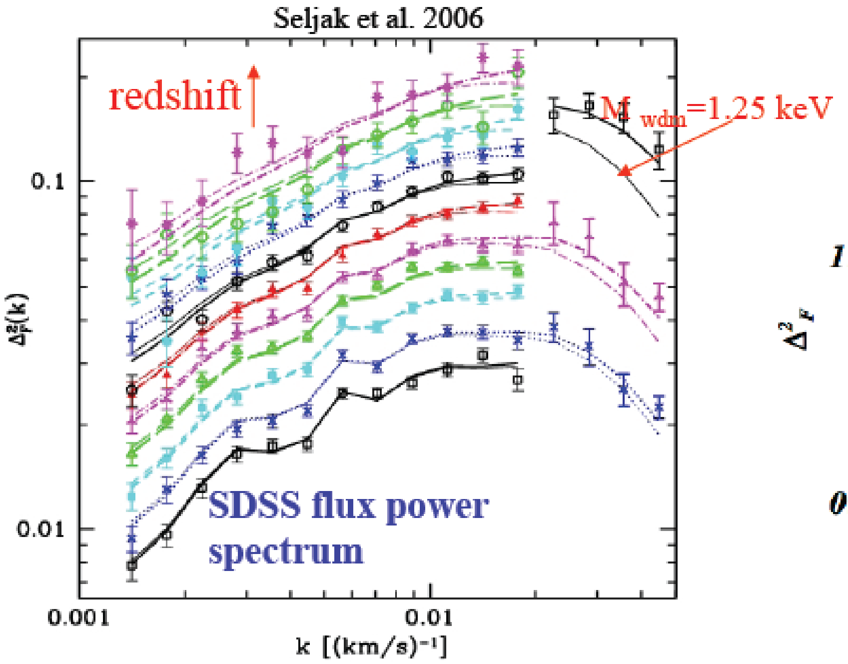
- To probe the DM properties at small scales one can use **Lyman-α** forest data:
- Red-shifted absorption Lyman-α line in the spectra of distant QSOs
- Neutral hydrogen traces DM distribution at red-shifts $z \sim 2 - 4$.
- Allows to measure **one-dimensional** non-linear power spectrum:

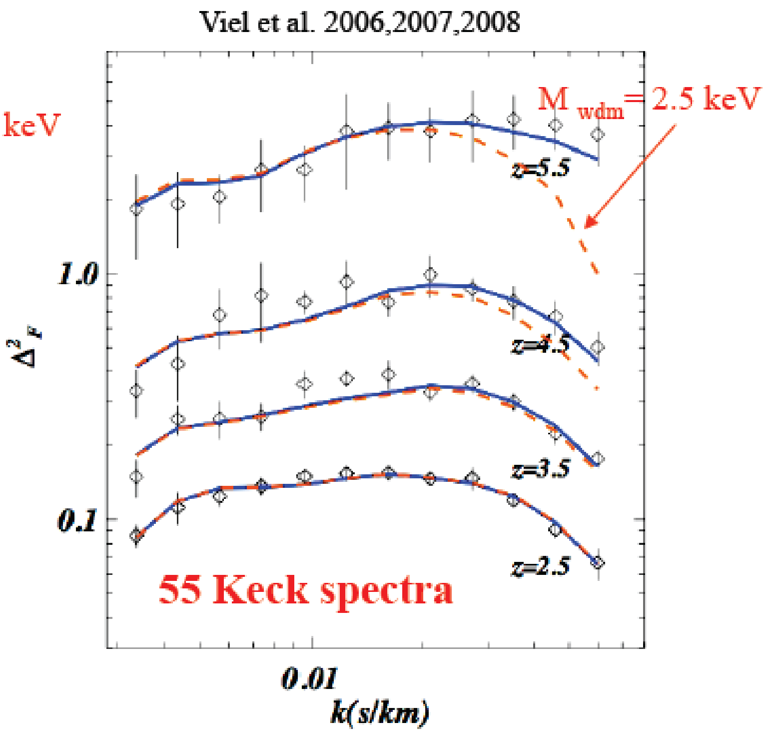
$$P_{1D} = \int_k^\infty P_{3D}(k) \frac{kdk}{2\pi}$$





Observational results


Seljak et al. 2006

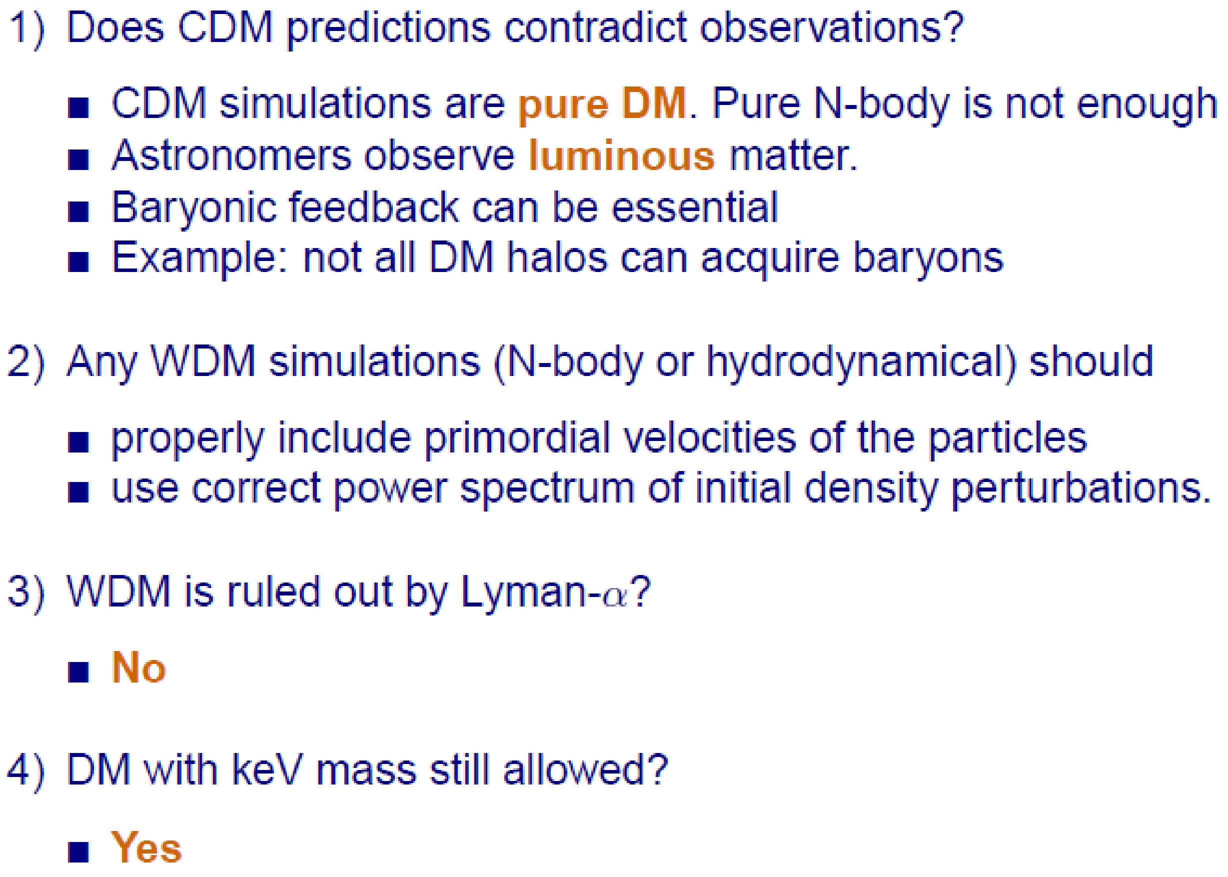

Viel et al. 2006,2007,2008

large scales small scales

M_{wdm} >2.4 keV

M_{wdm} > 4 keV

CDM or WDM? A summary



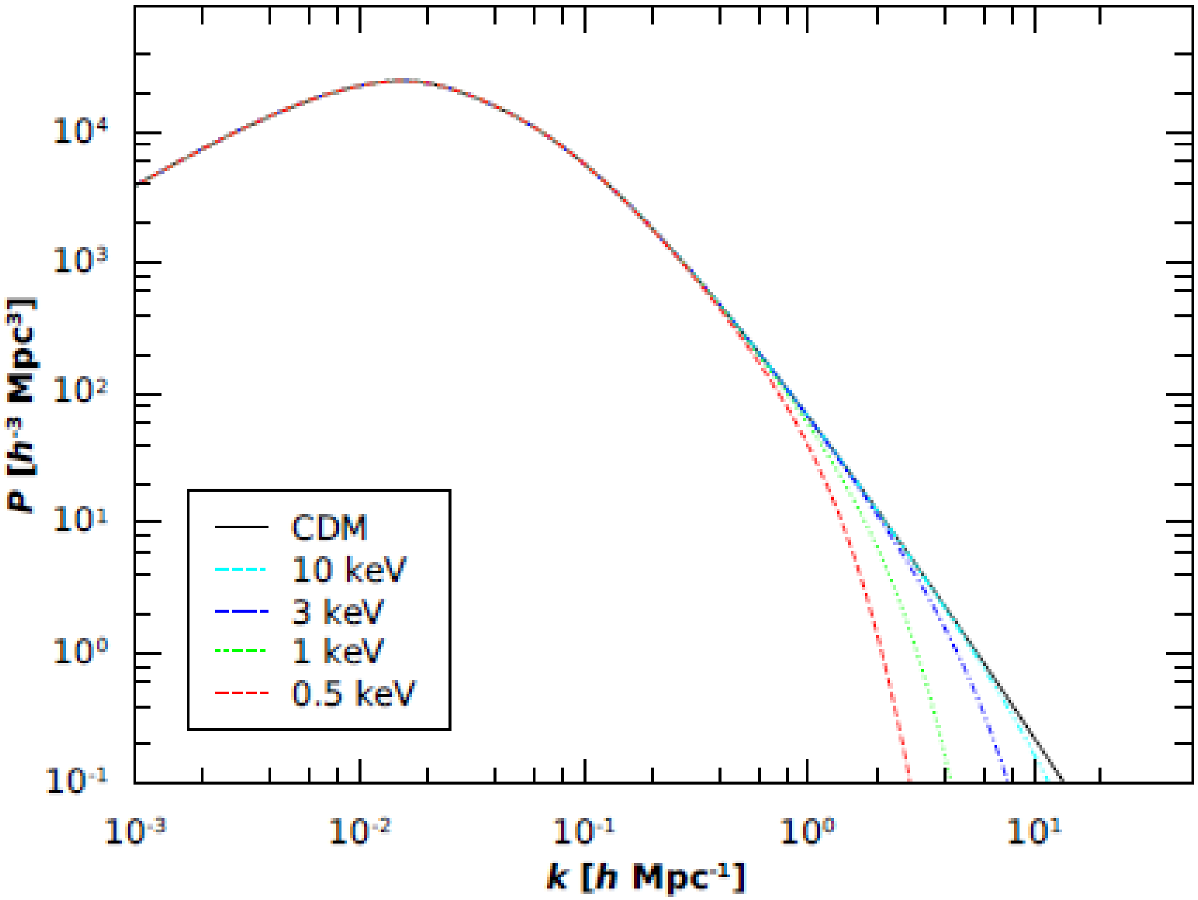
1) Does CDM predictions contradict observations?
   - CDM simulations are **pure DM**. Pure N-body is not enough
   - Astronomers observe **luminous** matter.
   - Baryonic feedback can be essential
   - Example: not all DM halos can acquire baryons

2) Any WDM simulations (N-body or hydrodynamical) should
   - properly include primordial velocities of the particles
   - use correct power spectrum of initial density perturbations.

3) WDM is ruled out by Lyman-α?
   - **No**

4) DM with keV mass still allowed?
   - **Yes**

Sterile Neutrino as WDM

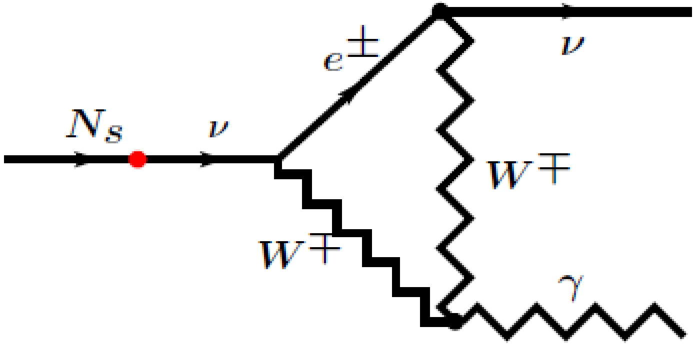


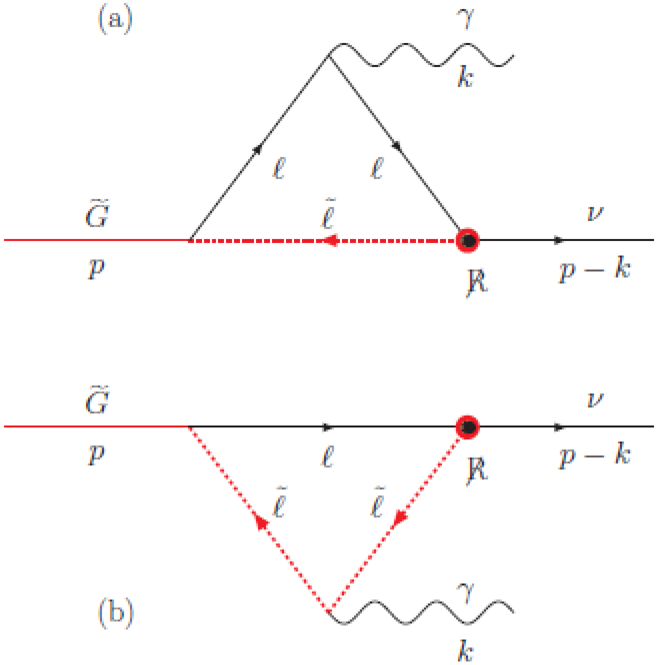
the linear matter power spectrum

Dunstan, et al. (2011)

Decaying DM

DM with **radiative signatures:** DM $\rightarrow \gamma + \nu, \ \gamma + \gamma, \ e^+ + e^- \dots$





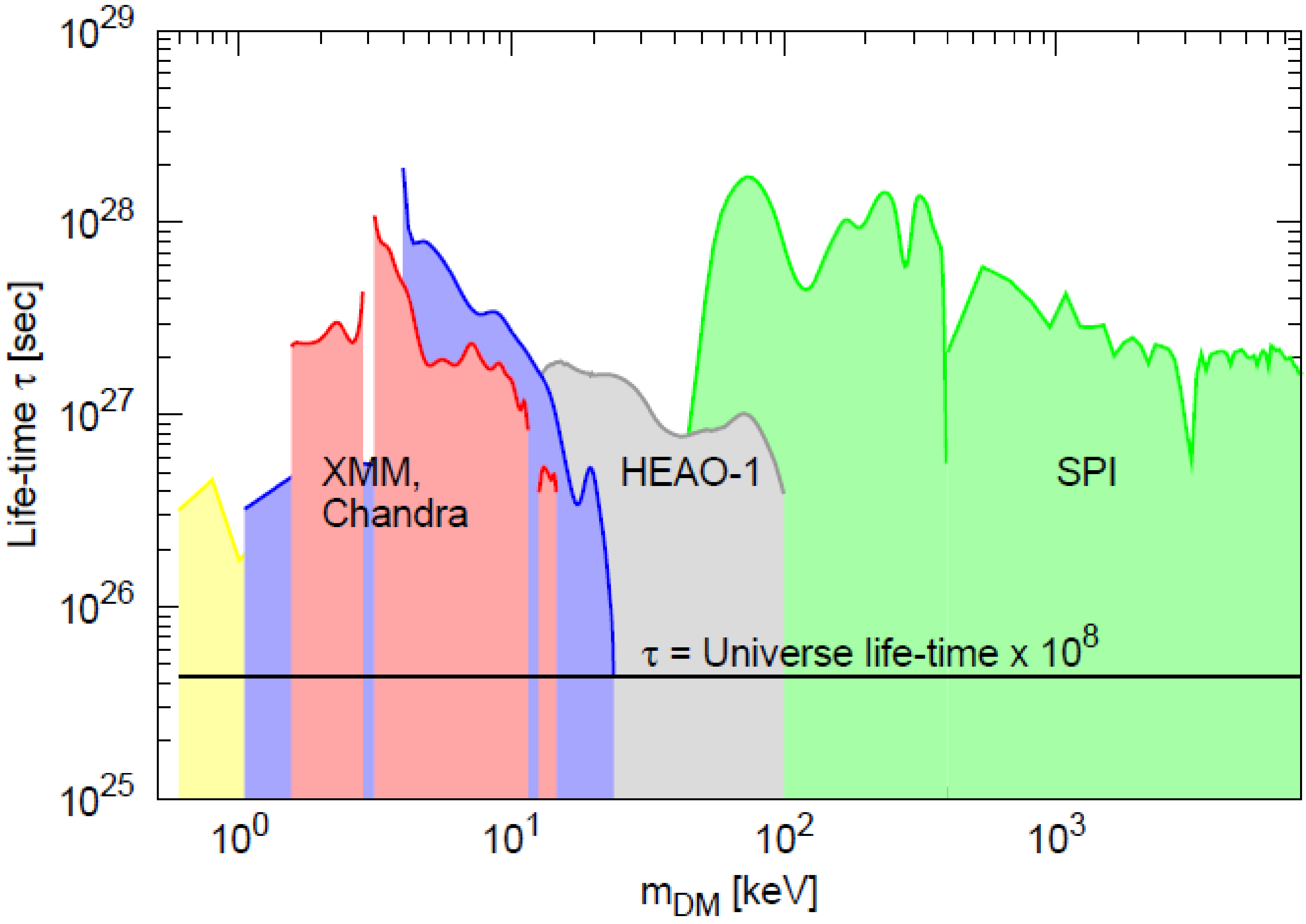
Properties of decaying DM

- Decaying DM should interact **superweakly** $\sim \theta \cdot G_F$ and $\theta \lll 1$
- Radiative decay channel : DM $\rightarrow \gamma + \nu$
- Photon energy $E_\gamma = \frac{m_{\text{DM}}}{2}$
- Life-time $\tau = 1/\Gamma \gg$ life-time of the Universe
- Flux from DM decay:

$$F_{\text{DM}} = \frac{E_\gamma}{m_{\text{DM}}} \frac{\Gamma \mathcal{M}_{\text{DM}}^{\text{fov}}}{4\pi D_L^2} \approx \frac{\Gamma \Omega_{\text{fov}}}{8\pi} \int \rho_{\text{DM}}(r)dr \quad (z \ll 1, \quad \Omega_{\text{fov}} \ll 1)$$

line of sight

Restriction on the life time of sterile neutrino



非热产生暗物质宇宙模型

WIMPs两种产生机制：

1. 热平衡退耦

2. 非热产生

- **Decay of topological defects such as cosmic string**
- **Decay of an unstable heavy particle**
- **produced in the reheating process in a scenario of inflation at low energy scale**

…

Lin, Huang, Zhang, Brandenberger (2001);
Bi, Brandenberger, Gondolo, Li, Yuan, Zhang (2009)

NTDM momentum distribution

$$f(p) = \frac{A}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(p-p_c)^2}{2\sigma^2}\right)$$

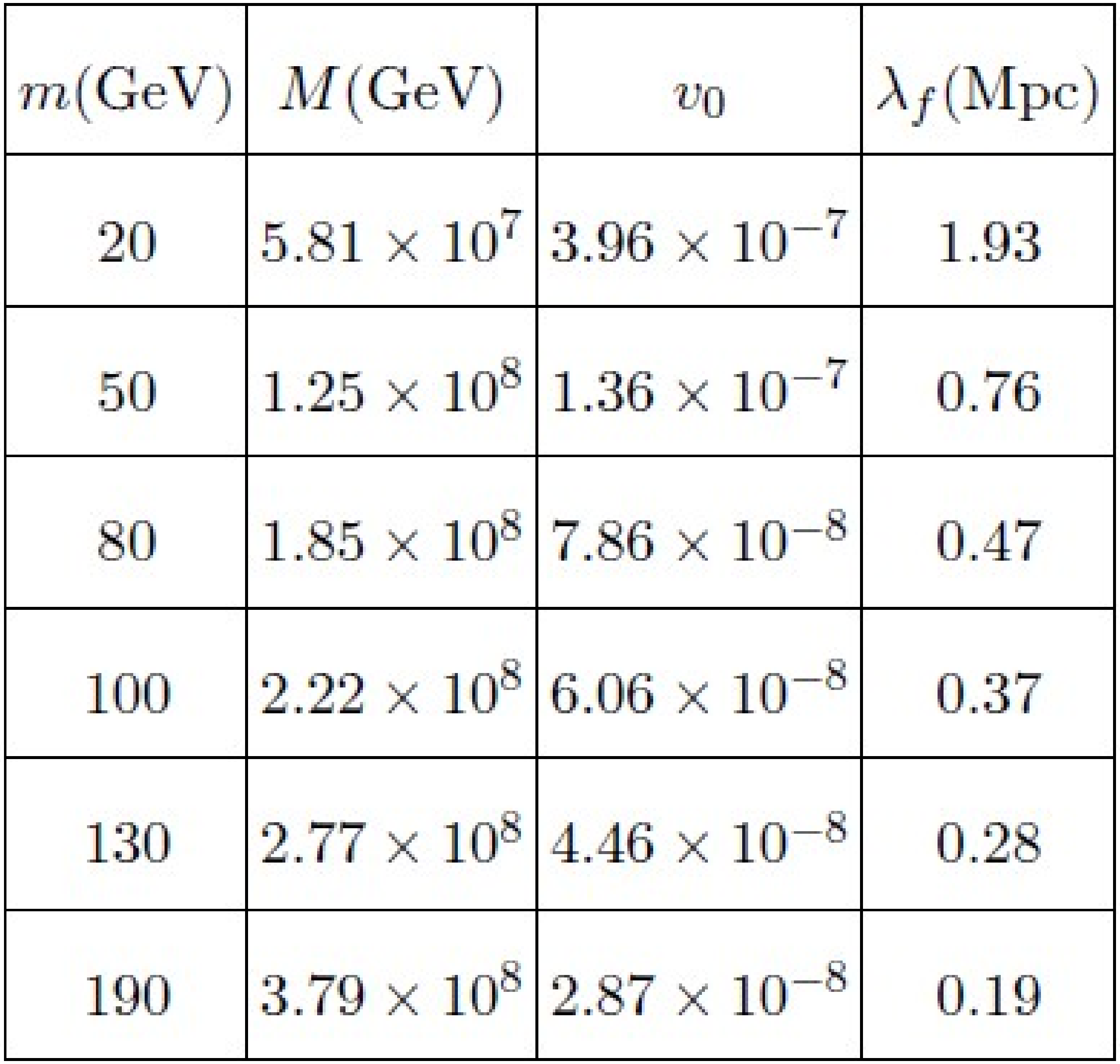
The current velocity of the NTDM particle,

$$v_0 = \frac{T_0}{T_d}\frac{M}{2m}$$

NTDM comoving free-streaming length

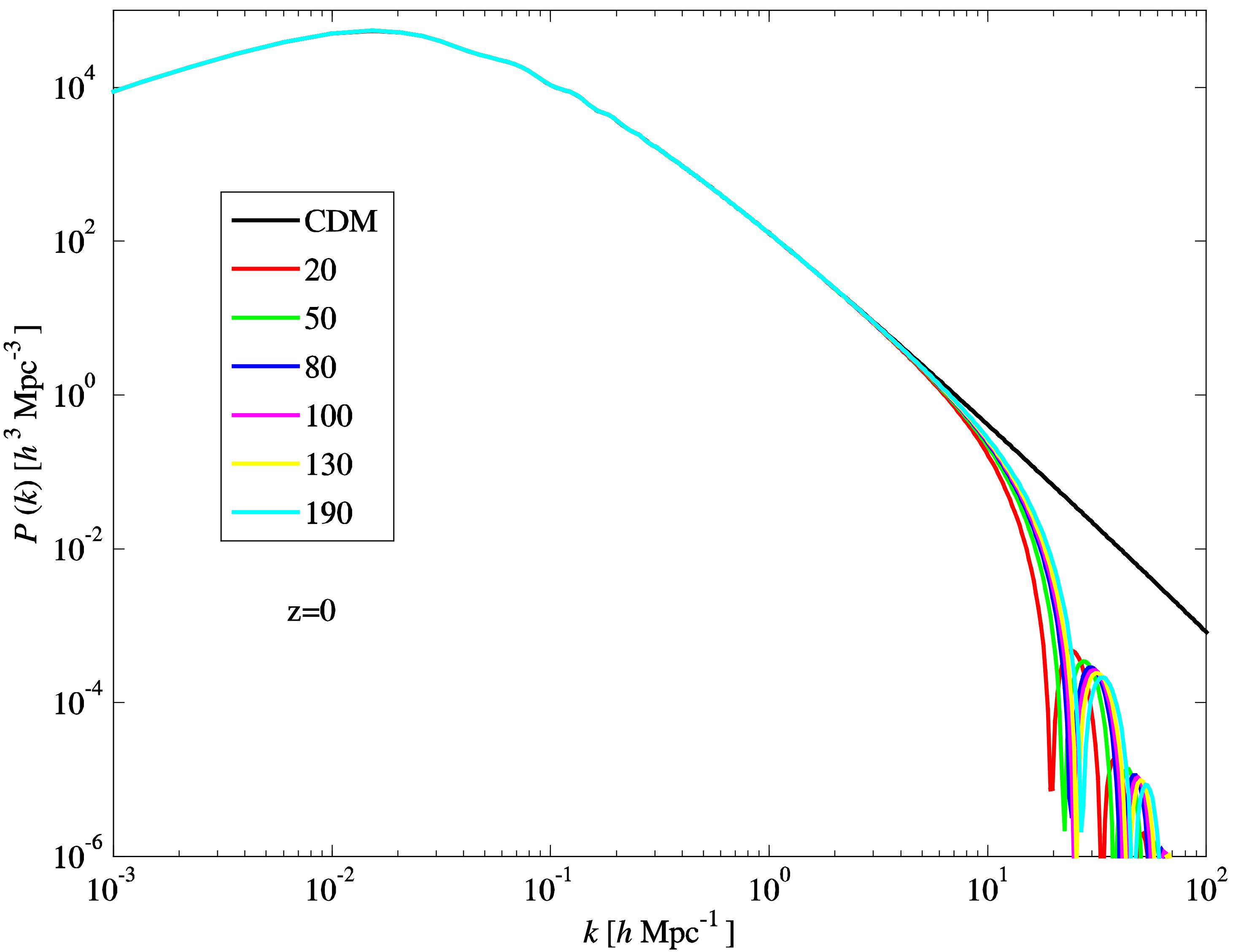
$$\begin{aligned}
\lambda_f &= \int_{t_i}^{t_{EQ}} \frac{v(t')}{a(t')} dt' \simeq \int_0^{t_{EQ}} \frac{v(t')}{a(t')} dt' \\
&\simeq 2v_0 t_{EQ}(1+z_{EQ})^2 \ln\left(\sqrt{1+\frac{1}{v_0^2(1+z_{EQ})^2}} + \frac{1}{v_0(1+z_{EQ})}\right)
\end{aligned}$$

Free streaming length



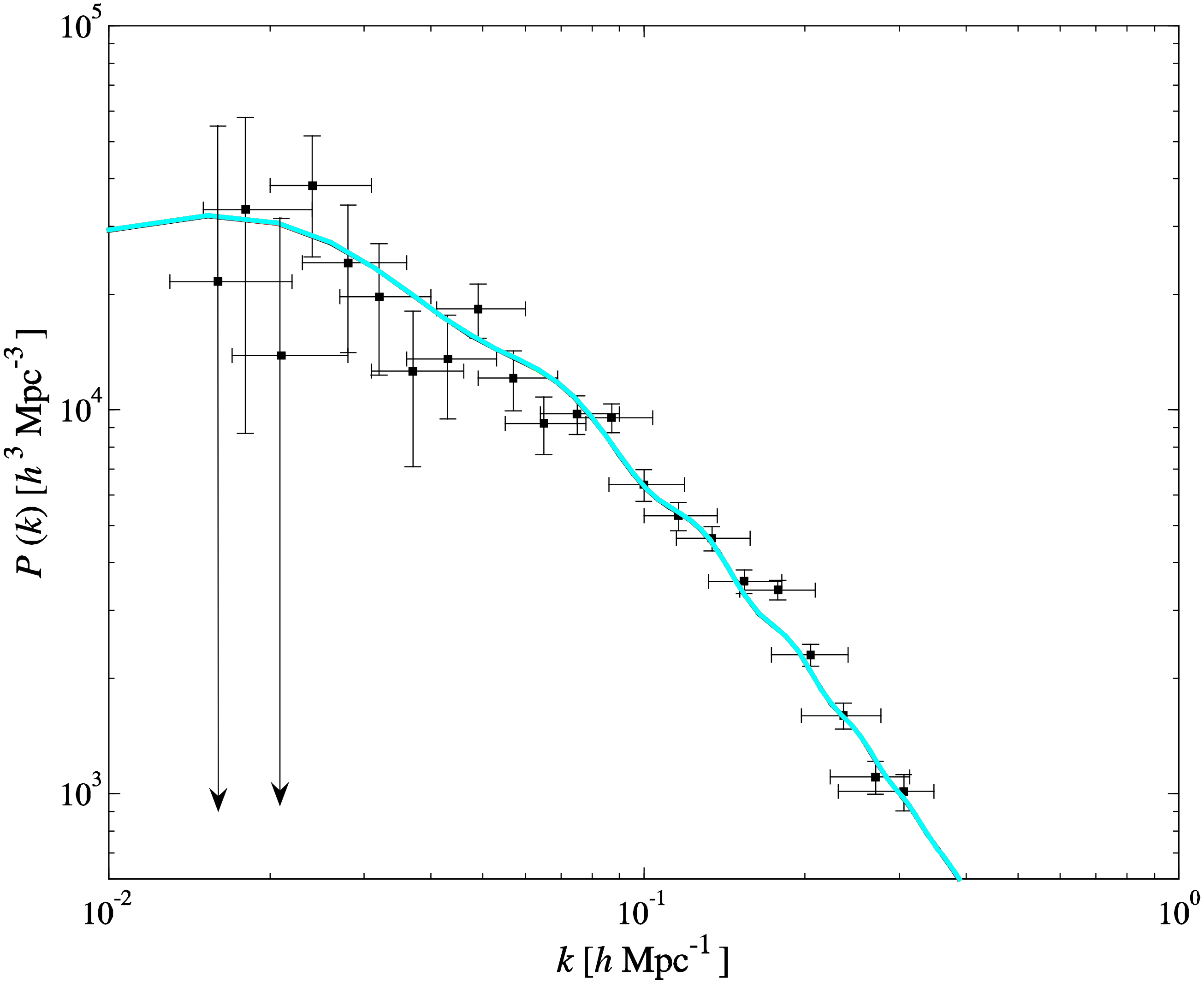
m(GeV)	M(GeV)	v_0	λ_f(Mpc)
20	5.81×10^7	3.96×10^{-7}	1.93
50	1.25×10^8	1.36×10^{-7}	0.76
80	1.85×10^8	7.86×10^{-8}	0.47
100	2.22×10^8	6.06×10^{-8}	0.37
130	2.77×10^8	4.46×10^{-8}	0.28
190	3.79×10^8	2.87×10^{-8}	0.19

PERTURBATION EVOLUTION



不同的m_{NTDM}对应的P（k）

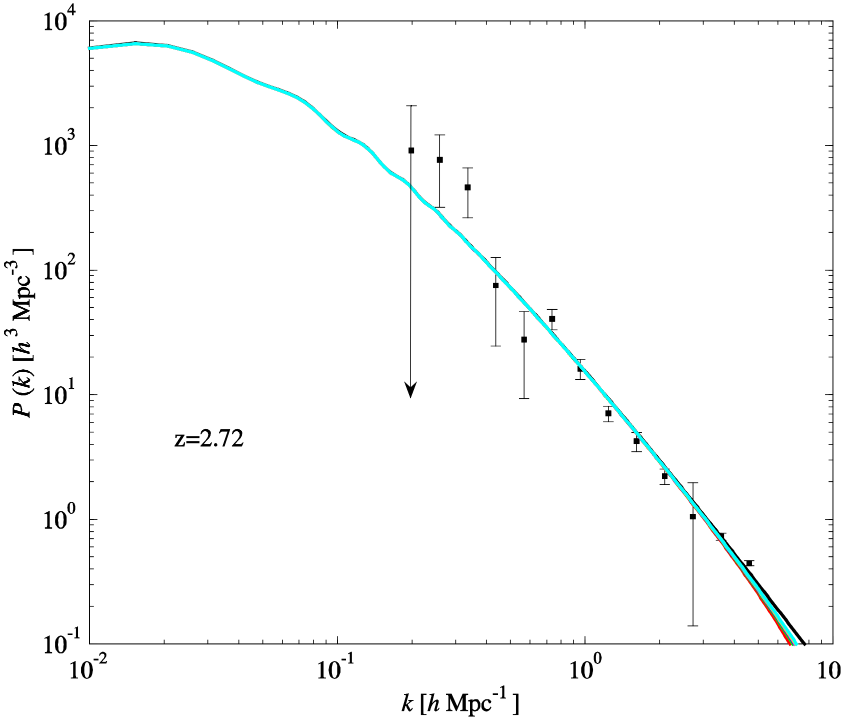
Constraining NTDM with SDSS galaxies



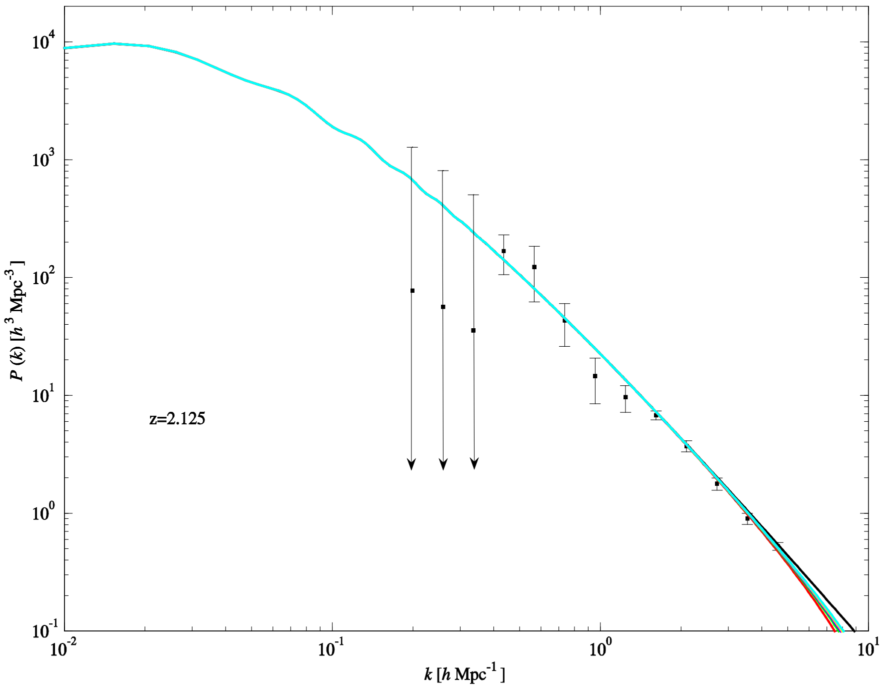
$k < 0.2h^{-1}\mathbf{Mpc}$

$m_\chi > 20\mathbf{GeV}$

Constraining NTDM with LYMAN-α Forest



the sample with median redshift z = 2.72 （Croft et al., 2002)



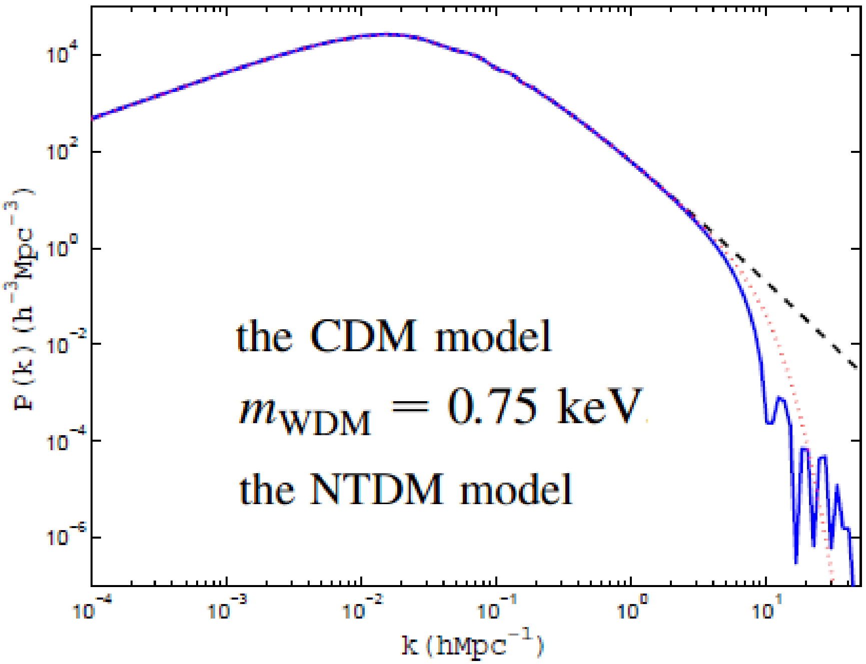
the LUQAS sample with median redshift z = 2.125 (Kim et al.2004)

N-BODY Simulations for NTDM

$$\Omega_m = 0.28 \quad \Omega_\Lambda = 0.72,\ \Omega_b = 0.046,\ h = 0.7,\ n_s = 0.97,\ \sigma_8 = 0.82$$

$$v_0 = 0.66 \times 10^{-7}$$

- **Linear power spectra**



- **N-Body Simulation**

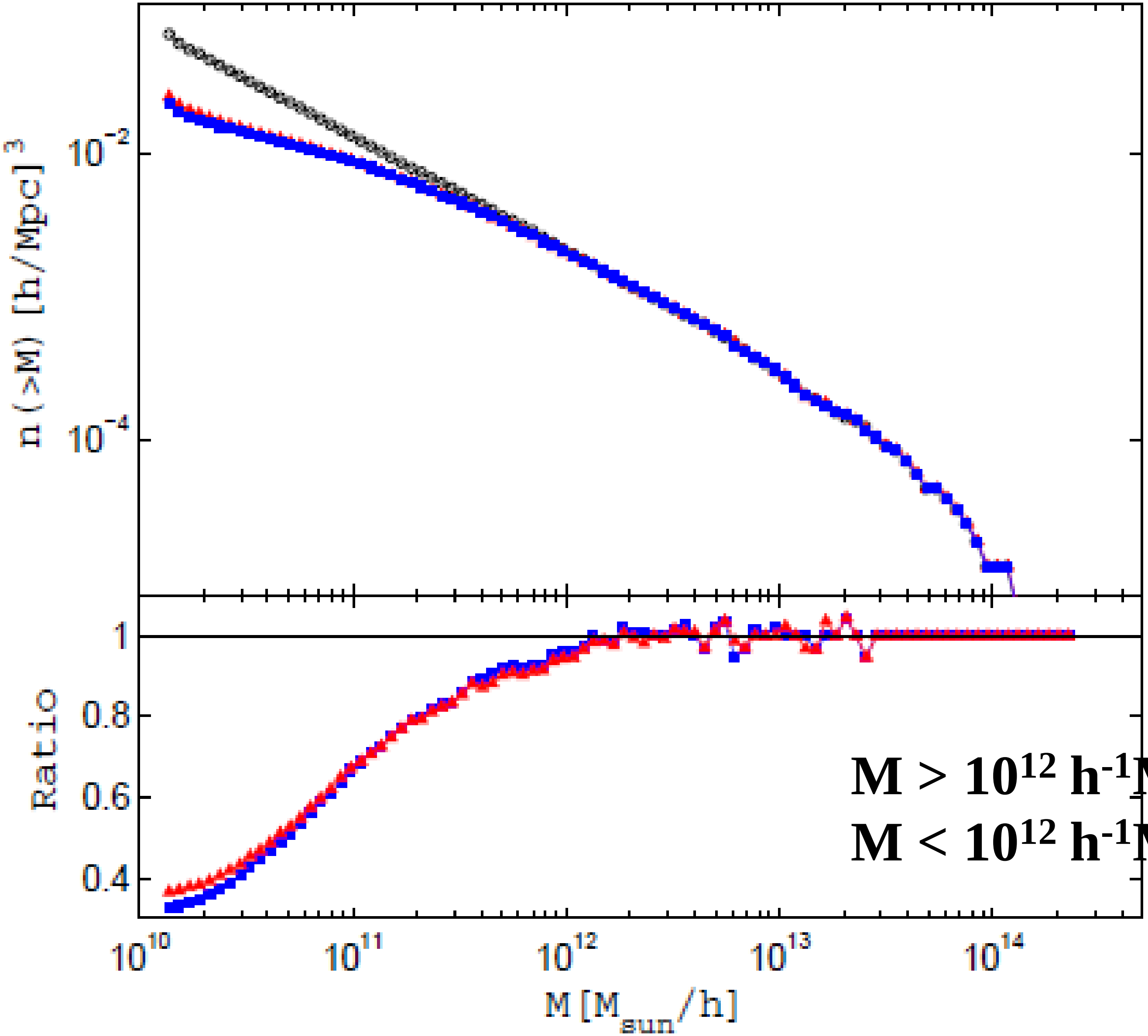
$L_{\mathrm{box}} = 64\ h^{-1}\mathrm{Mpc}$ $\quad N = 256^3$

Generate ICs for N-body simulation

Output particle distribution and velocity at z=49

GADGET-2

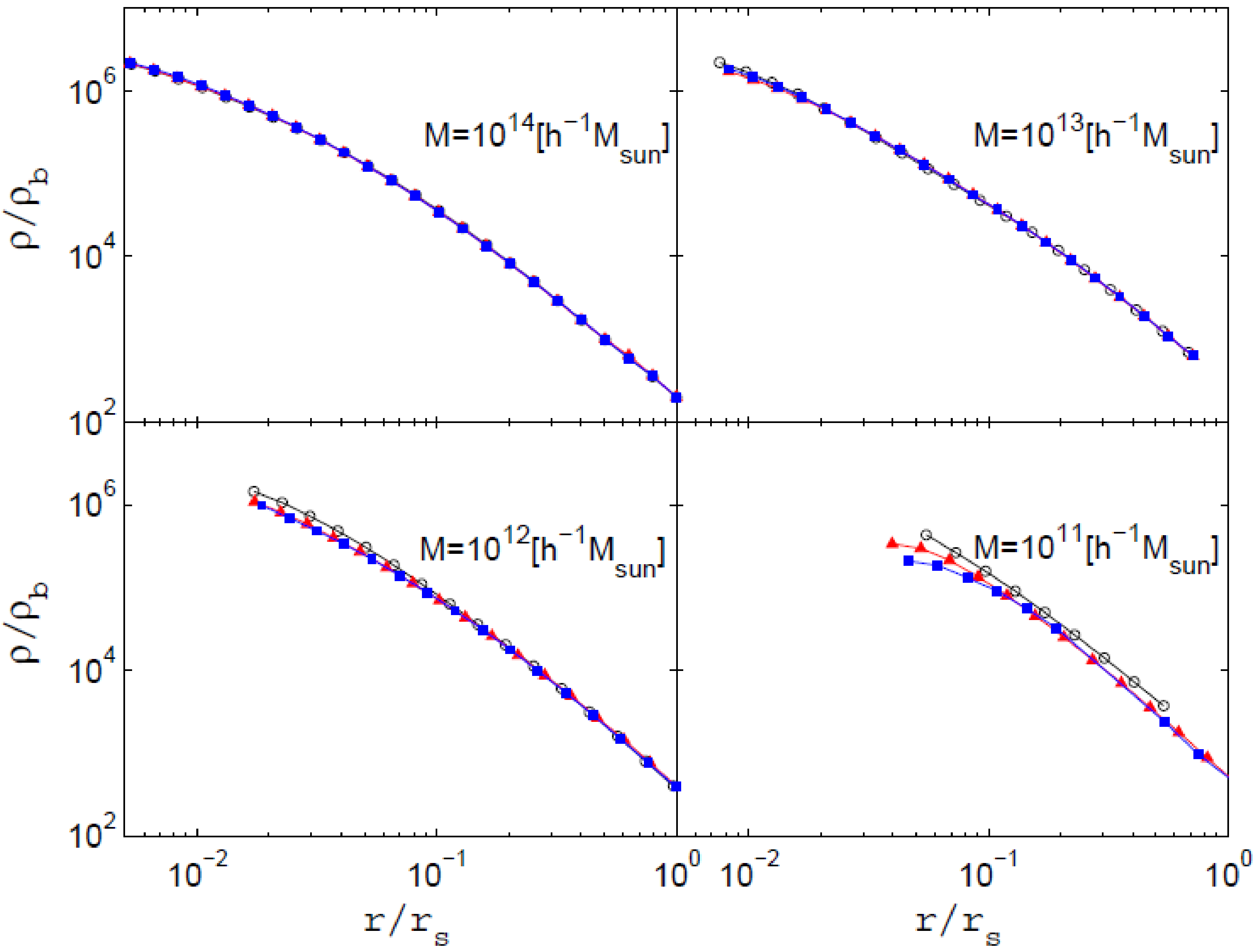
Number Density of Halos



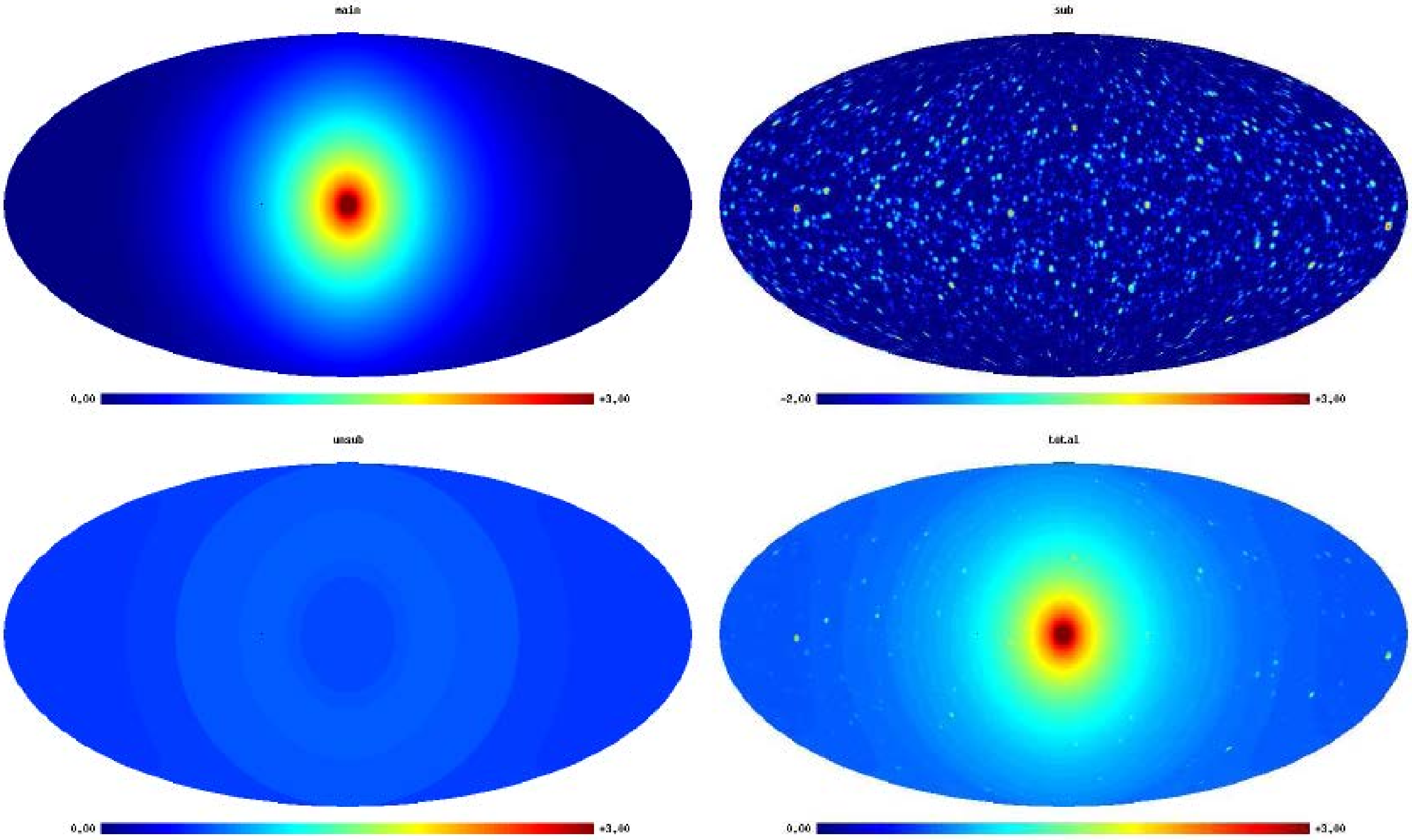
$M > 10^{12}\ h^{-1}M_\odot$, 几乎一致

$M < 10^{12}\ h^{-1}M_\odot$, 差别明显

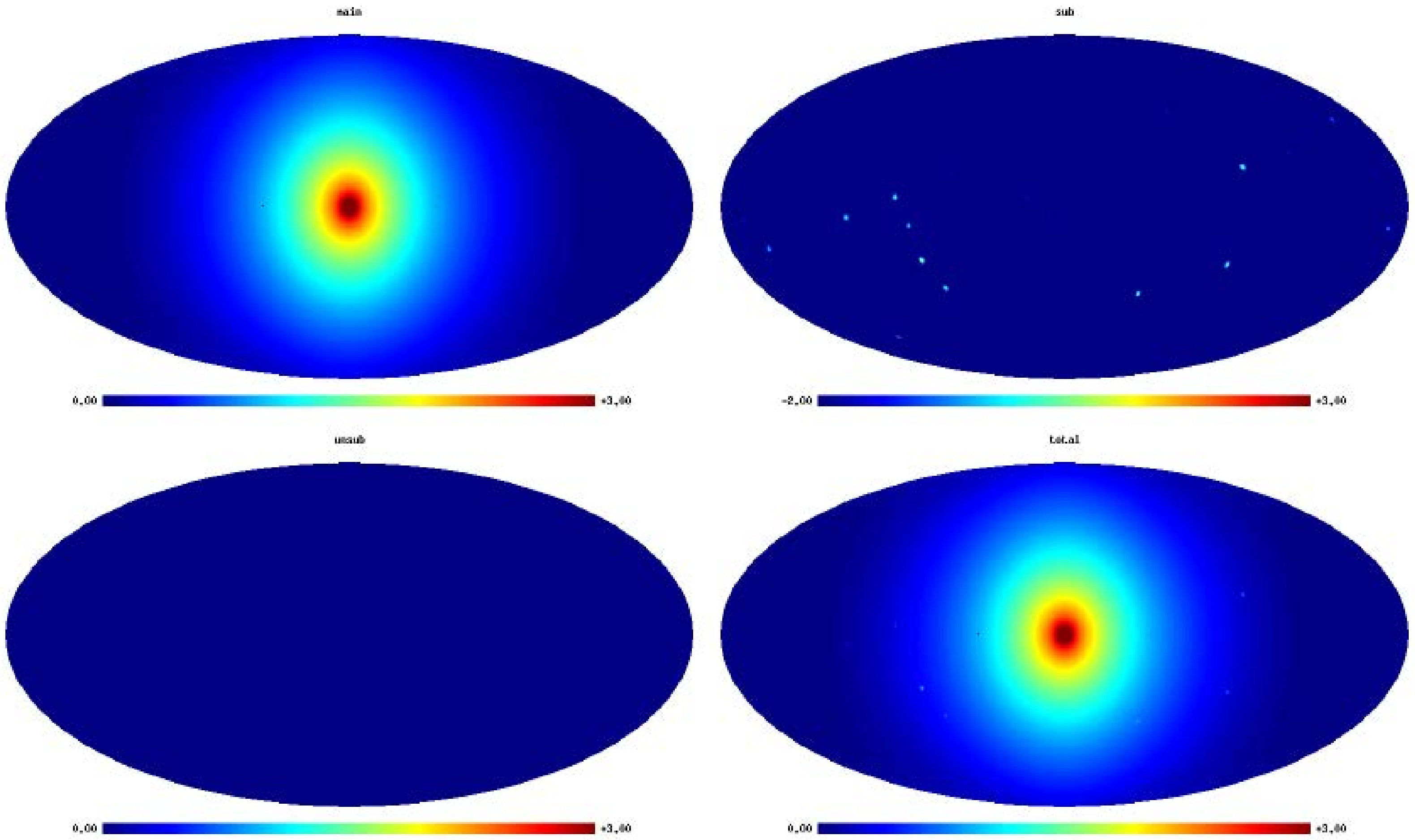
Density profiles



Spatial skymaps: CDM



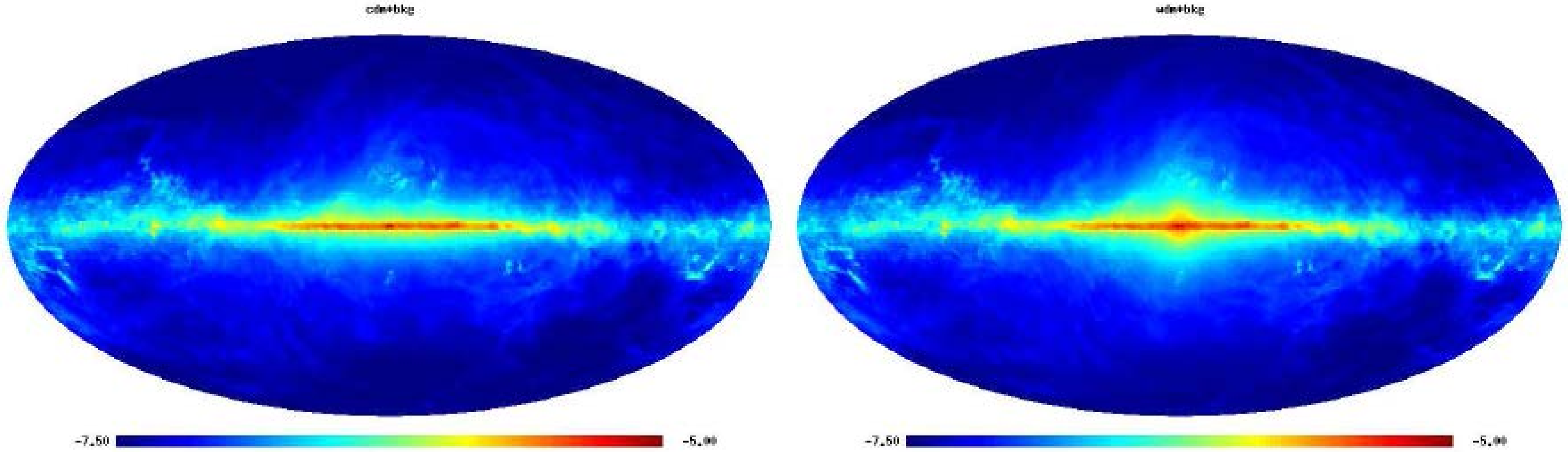
Spatial skymaps: WDM



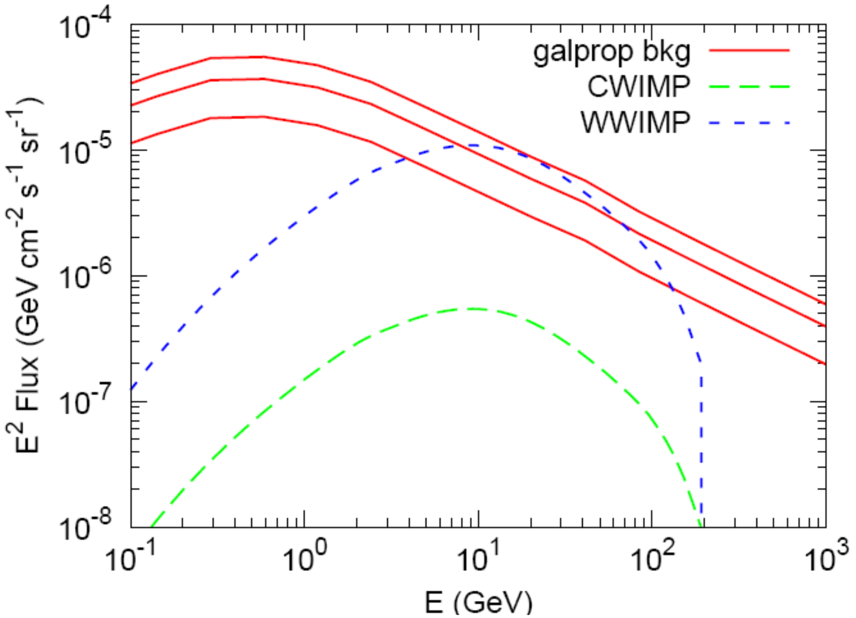
Two supersymmetric benchmark models

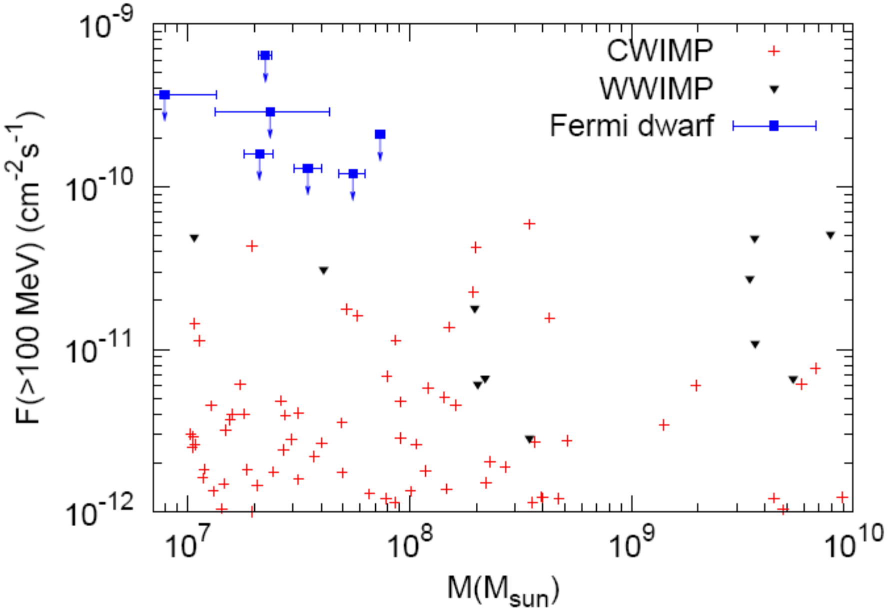
	m_0	m_{H_u}	m_{H_d}	$m_{1/2}$	A_0	$\tan\beta$	$\text{sign}(\mu)$	$m_{\tilde{\chi}_1^0}$	$\langle\sigma v\rangle$
Warm WIMP	1200	1300	788	500	-1000	40	+	211	2.70×10^{-25}
Cold WIMP	1200	1300	824	500	-1000	40	+	211	1.38×10^{-26}

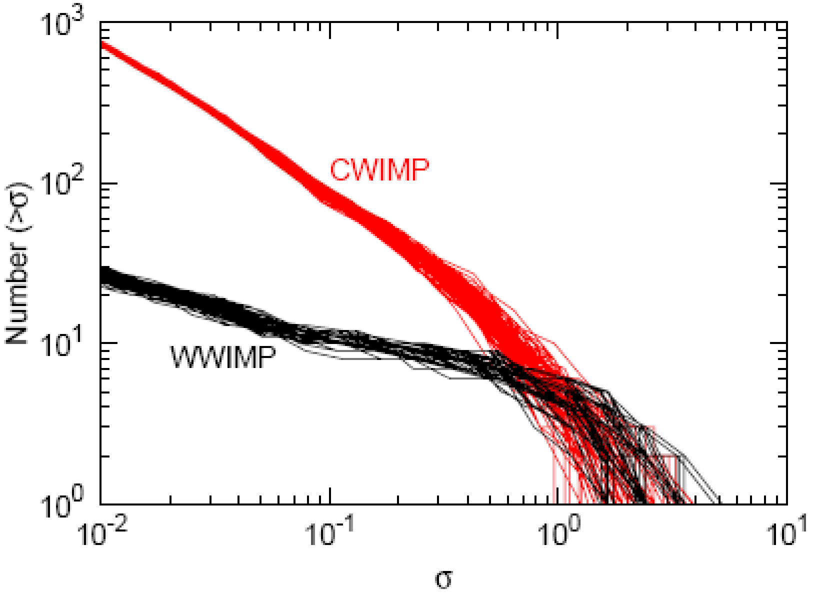
Total skymaps with diffuse background (E>10 GeV)



Detectability comparison

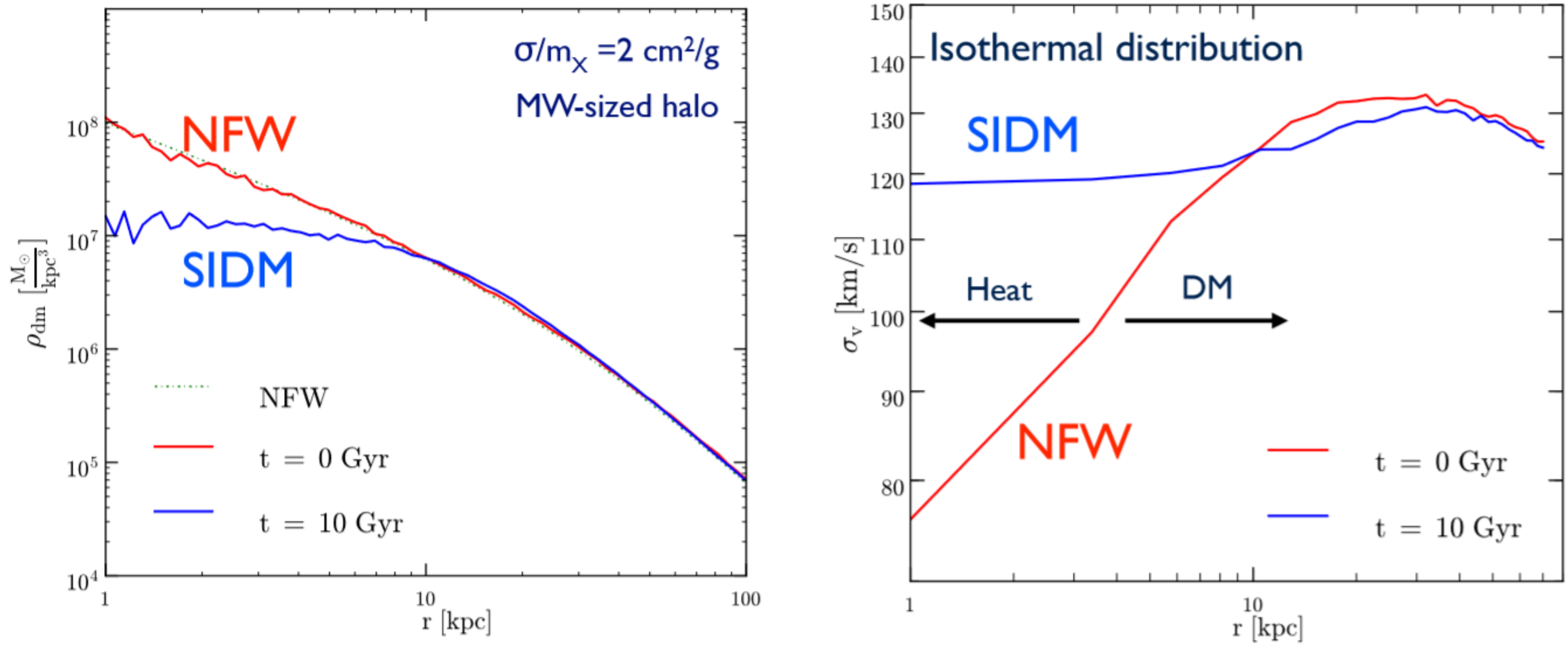






Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo



$\sigma/m_X \sim 1$ cm^2/g

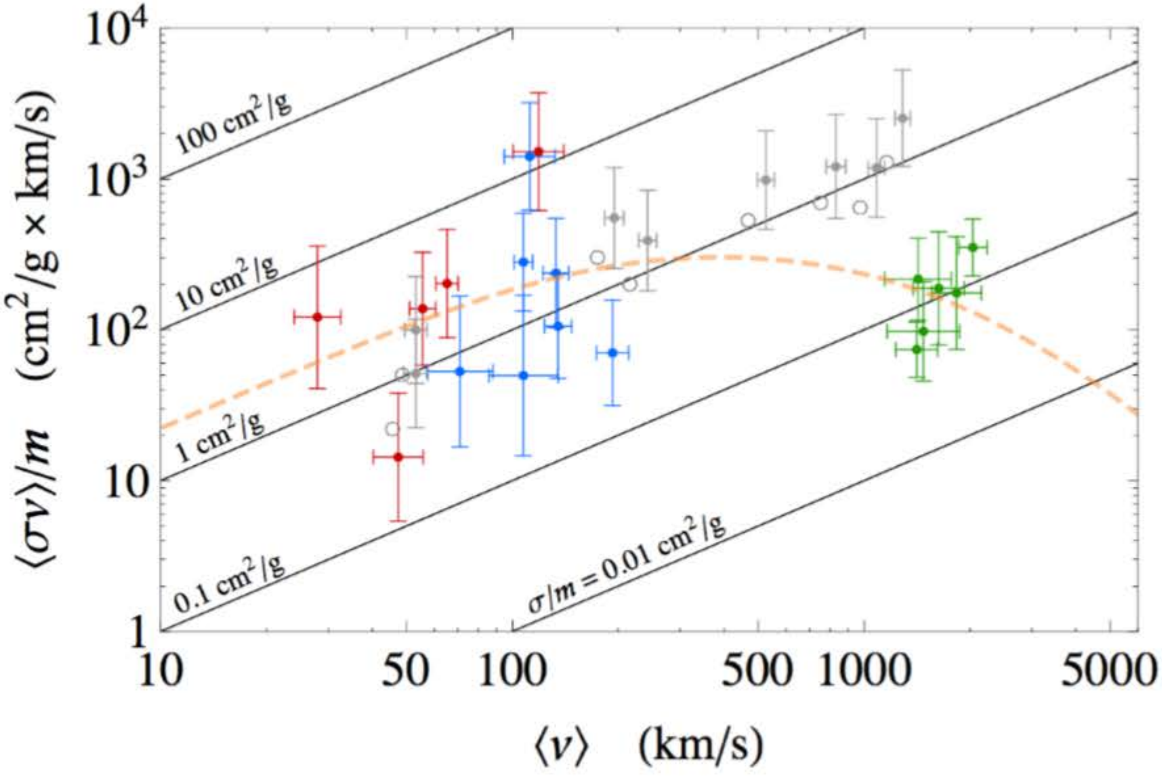
$$\Gamma \simeq n\sigma v = (\rho/m_X)\sigma v \sim H_0$$

with Huo+(UCR SIDM code)

Tulin, HBY (2017) for a review

SIDM from Dwarfs to Clusters

- Consider 5 THINGS dwarfs (red), 7 LSBs (blue), 6 galaxy clusters (green)
- 8 simulated halos with σ/m=1 cm^2/g (gray) for calibration



Galaxies: ~2-3 cm^2/g

Clusters: ~0.1 cm^2/g

Core size in clusters: ~10 kpc

If it were ~1 cm^2/g in clusters,
the core size would be ~100 kpc

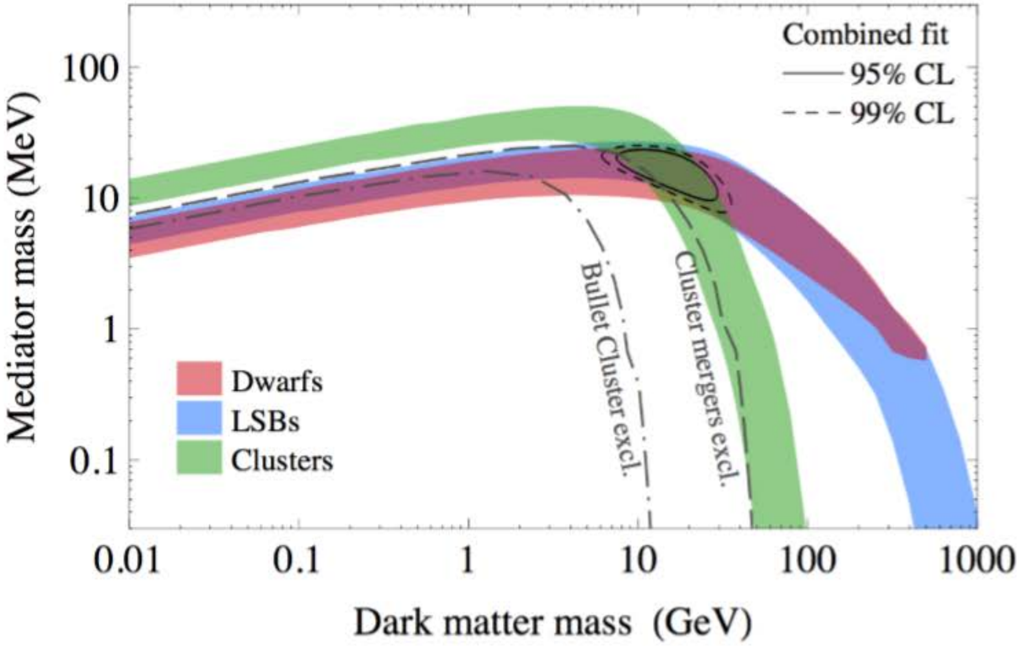
The strongest limit!

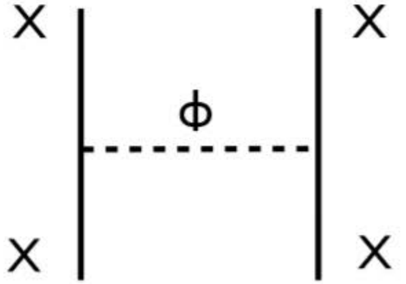
need velocity-dependent cross section

with Kaplinghat, Tulin (PRL 2015)

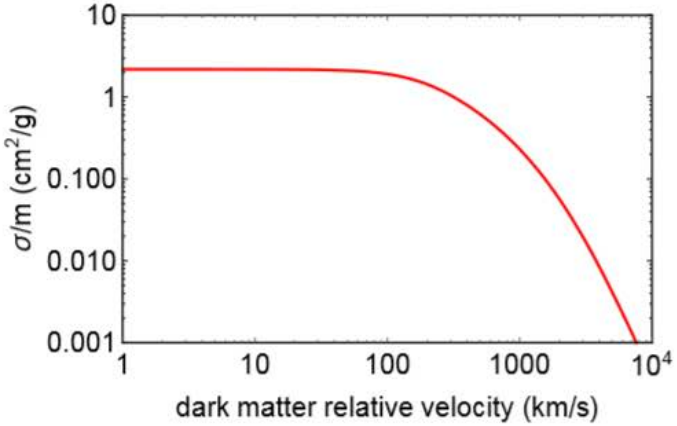
Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass





$$V(r) = \frac{\alpha_X}{r} e^{-m_\phi r}$$



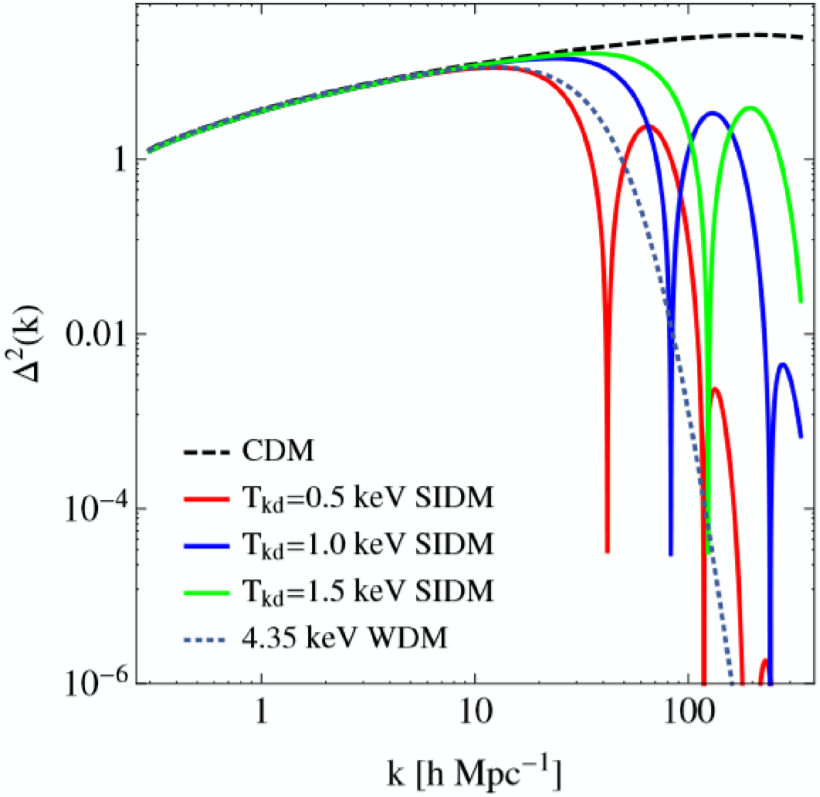
$\alpha_X = 1/137$

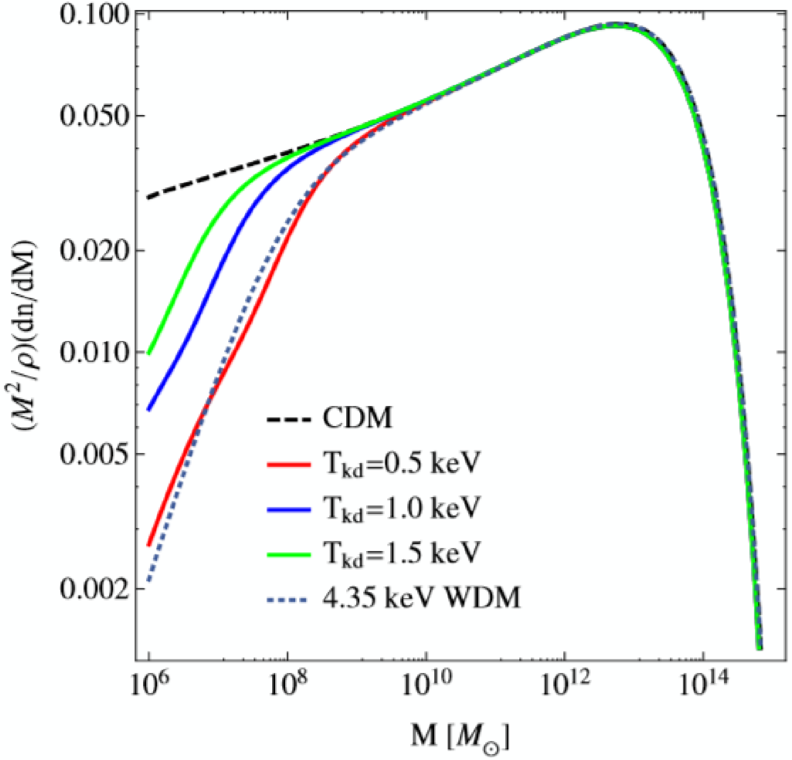
m_X: ~15 GeV, m_ϕ: ~17 MeV

with Kaplinghat, Tulin (PRL 2015)

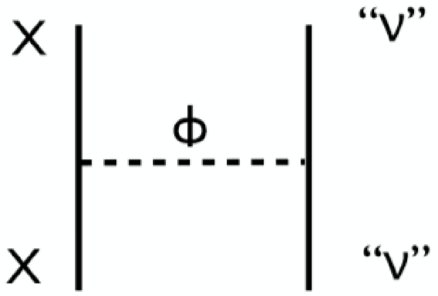
Dark Acoustic Oscillation

- Roles of dark radiation, damped SIDM power spectrum





With Ran, Kaplinghat (in prep)



CDM (WIMP): $m_\phi \sim 1$ TeV, $T_{kd} \sim 30$ MeV
SIDM: $m_\phi \sim 10$ MeV, $T_{kd} \sim 1$ keV

Ultra Light Axion

- T at H~m is 500 eV, z=2e6 (after BBN) behaves like matter, no contribution to Dark Energy.

- It is unnatural for just looking the mass within the order 1e-22 eV but such mass can be natural to have correct relic density. In string theory, some mechanism can generate exponentially small mass.

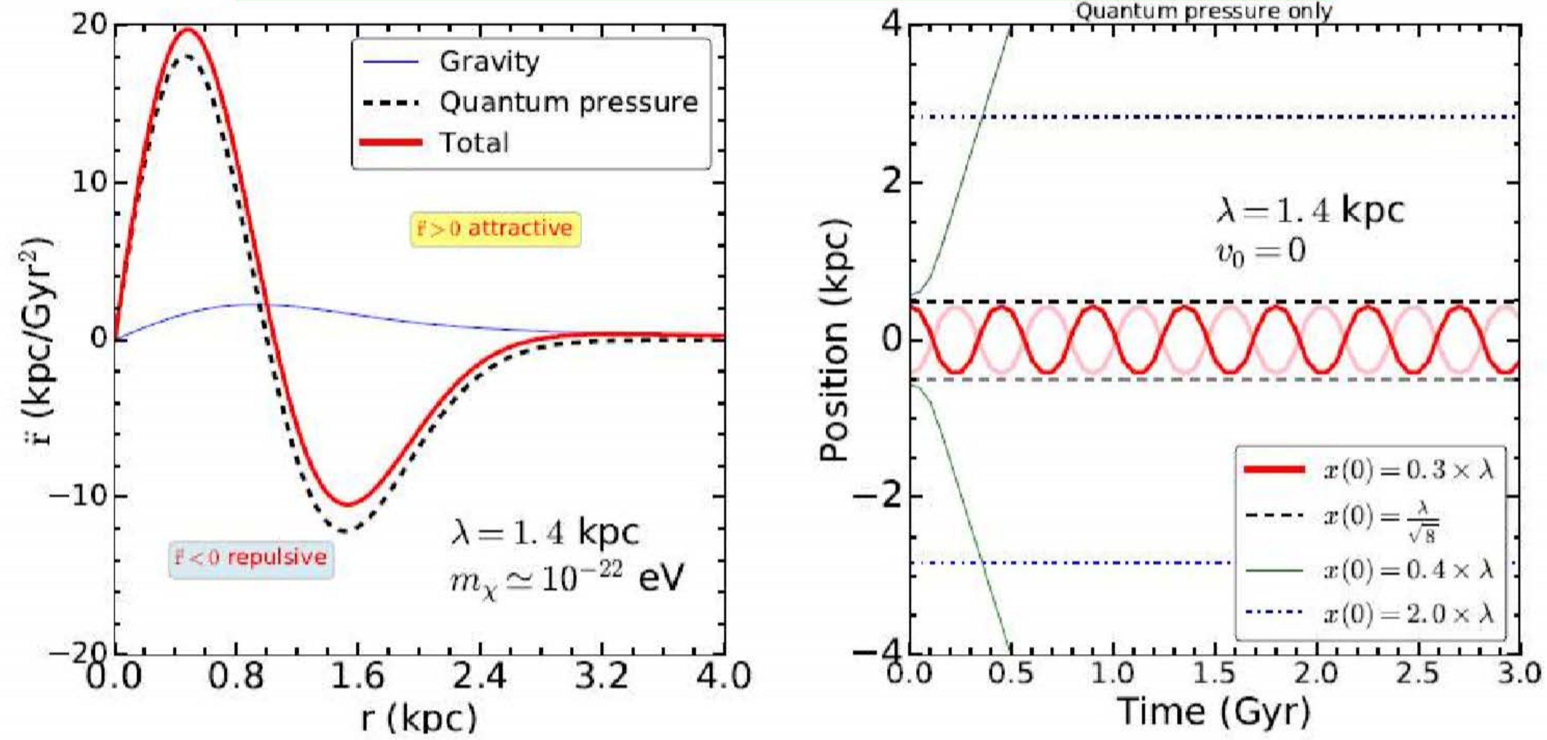
- It is fluid and its mass has some tension with Lyman-alpha forest. (Feedback processes, such as galactic winds or outflows, are assumed to have negligible impact on the forest.)

- The matter wave length ~kpc if the velocity dispersion ~100 kms-1.

$$\frac{\lambda}{2\pi} = \frac{\hbar}{mv} = 1.92\,\mathrm{kpc}\left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)\left(\frac{10\,\mathrm{km\,s^{-1}}}{v}\right)$$

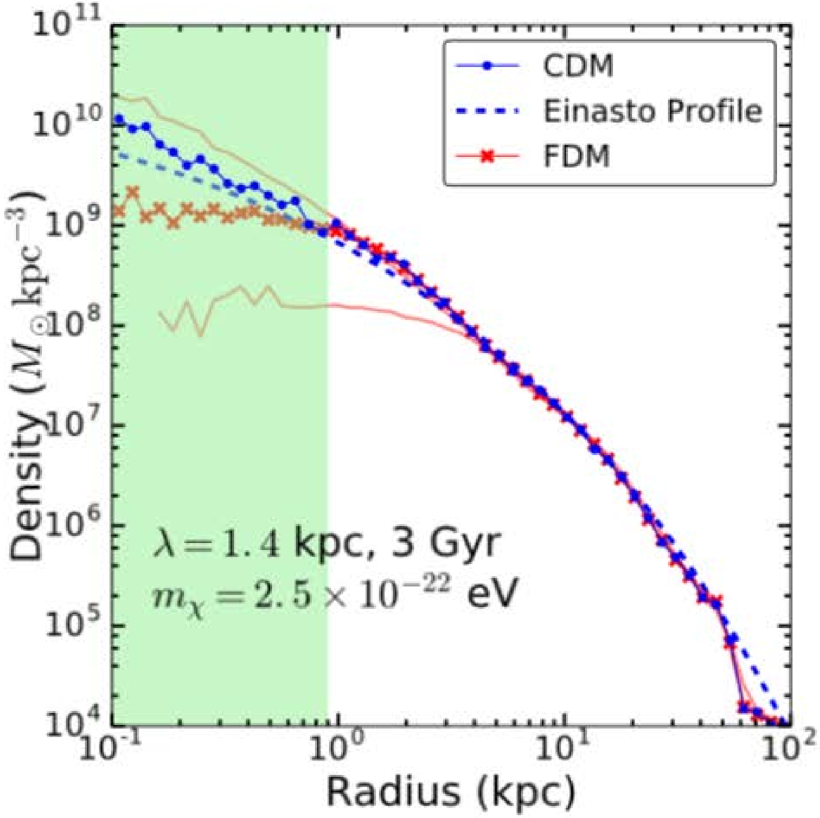
Quantum pressure in the N-body simulation

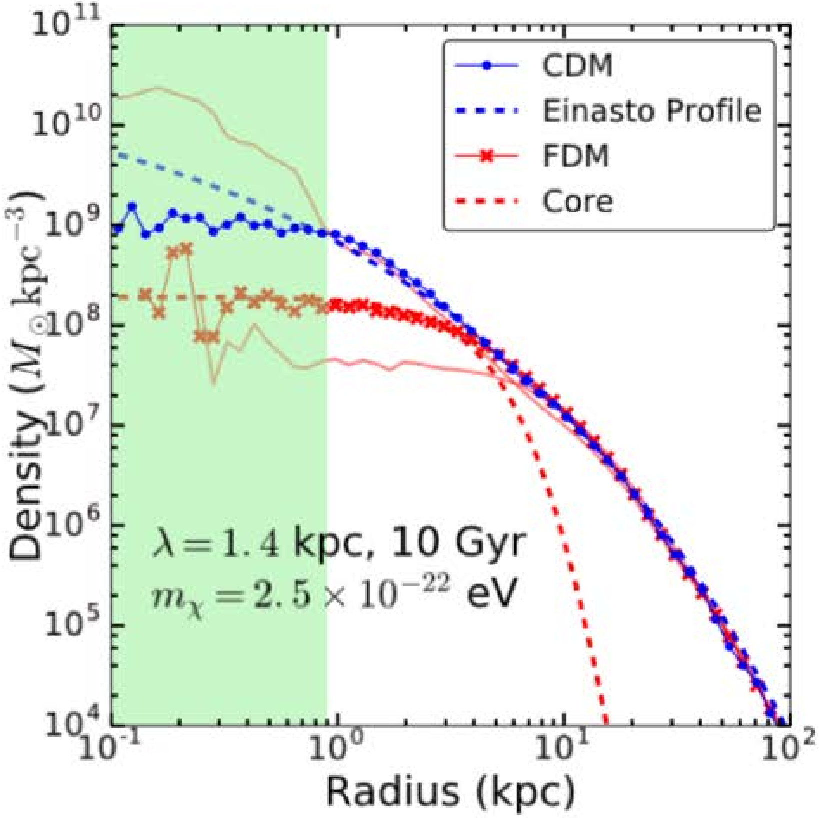
$$\ddot{r} = \frac{4M\hbar^2}{M_0 m_\chi^2\lambda^4}\sum_j \exp\left[-\frac{2|\boldsymbol{r}-\boldsymbol{r}_j|^2}{\lambda^2}\right](1-\frac{2|\boldsymbol{r}-\boldsymbol{r}_j|^2}{\lambda^2})(\boldsymbol{r}_j-\boldsymbol{r}),$$



he quantum pressure as a short-range interaction in the exponentially decay term.

Let's see the N-body simulation Movi


CDM
Einasto Profile
FDM
$\lambda = 1.4$ kpc, 3 Gyr
$m_\chi = 2.5 \times 10^{-22}$ eV
Density ($M_\odot\,\mathrm{kpc}^{-3}$)
Radius (kpc)
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{-1}
10^{0}
10^{1}
10^{2}


CDM
Einasto Profile
FDM
Core
$\lambda = 1.4$ kpc, 10 Gyr
$m_\chi = 2.5 \times 10^{-22}$ eV
Density ($M_\odot\,\mathrm{kpc}^{-3}$)
Radius (kpc)
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{-1}
10^{0}
10^{1}
10^{2}

谢　　谢！