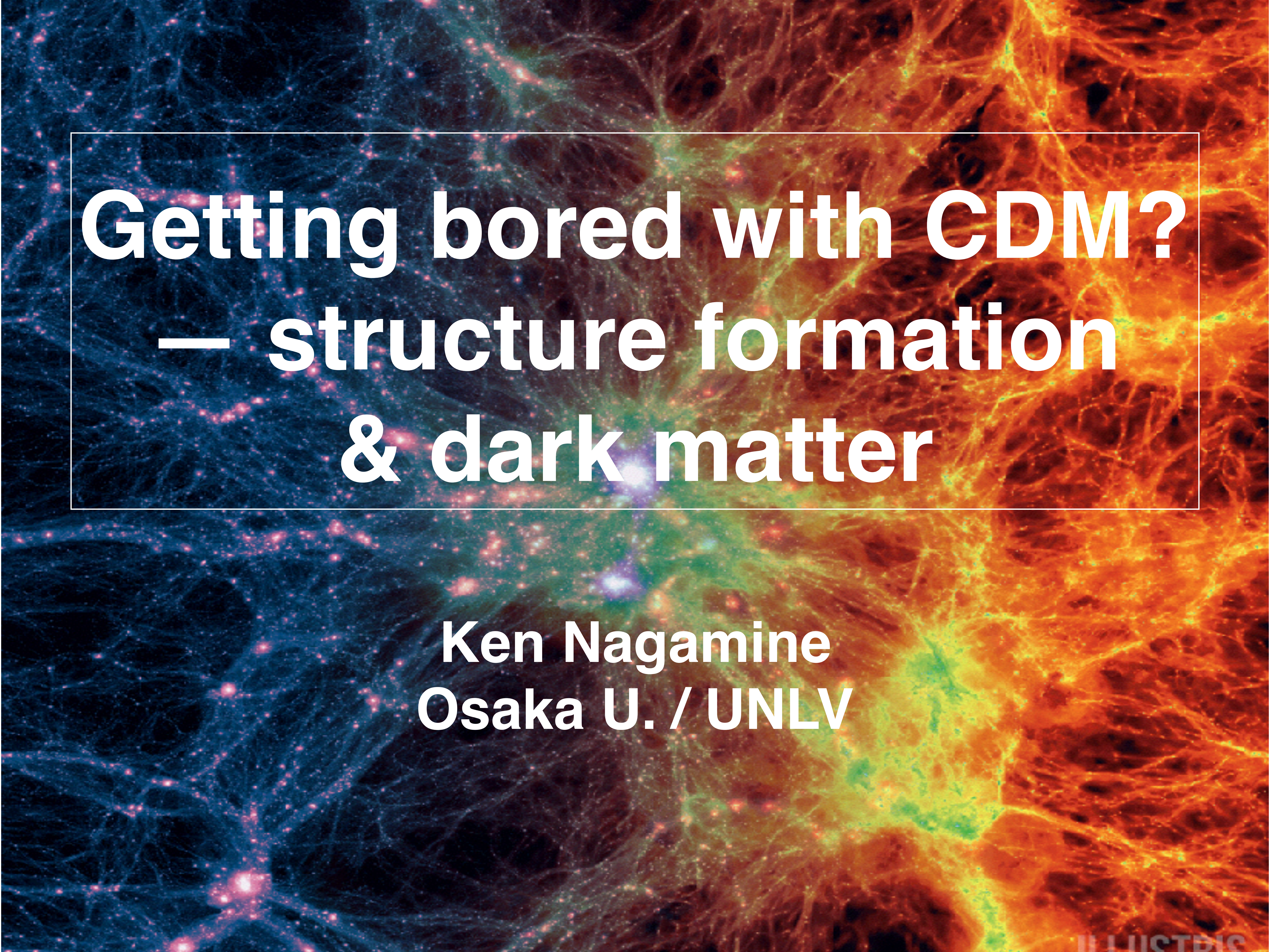


Getting bored with CDM? — structure formation & dark matter

Ken Nagamine
Osaka U. / UNLV

Contents

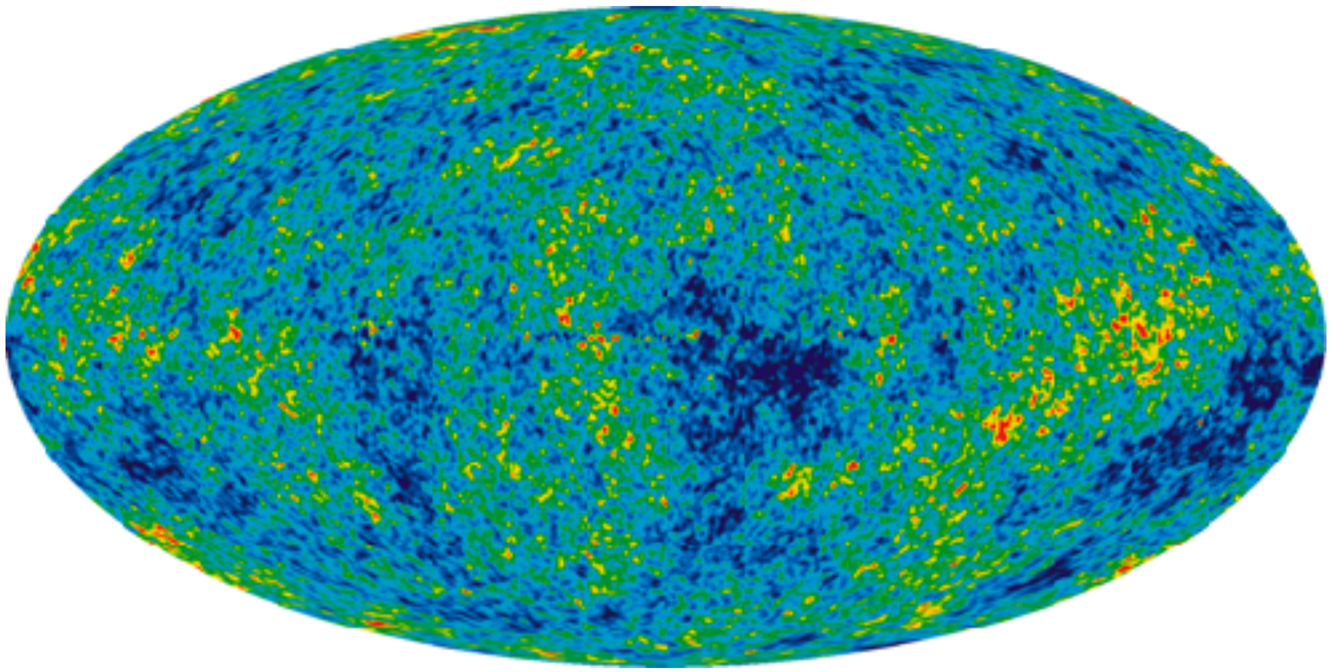
- Successful **ΛCDM** model on **large-scales**
- What about **$\lesssim$10 kpc?** — "**small scale problem**"
- **Alternative models: e.g., WDM, SIDM, FDM, …**
- Complication of **baryonic physics** — do we really need alternative DM ?

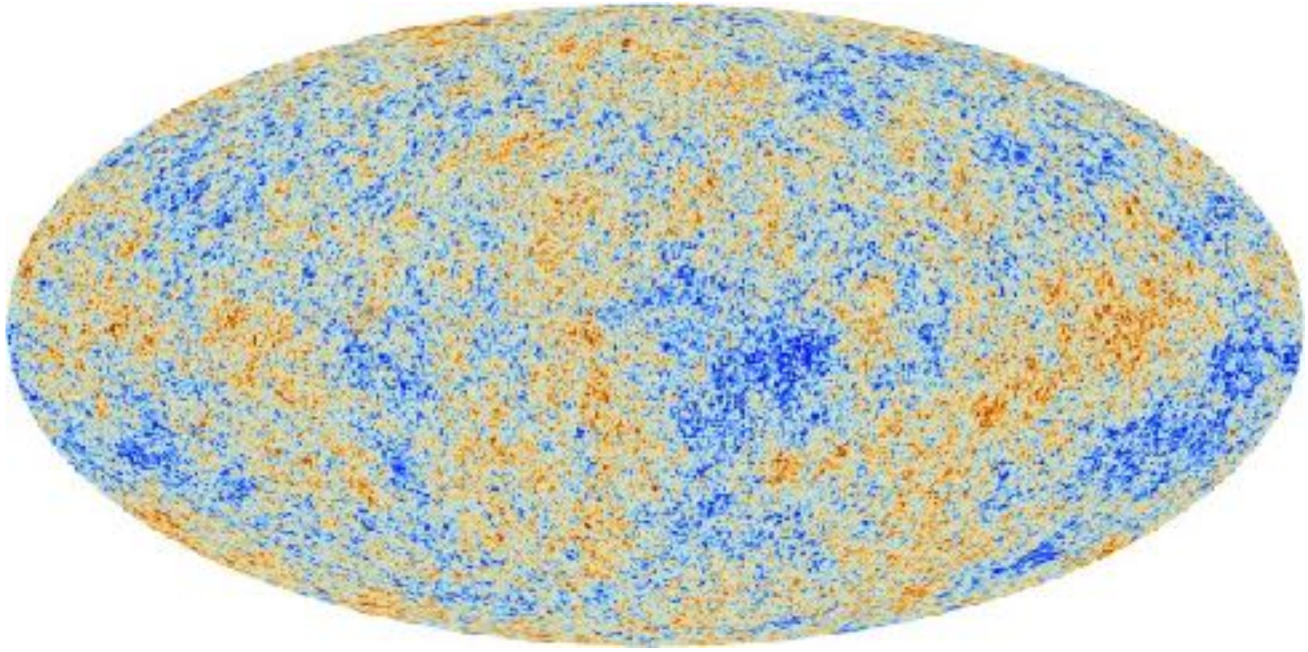
Evidence of Dark Matter

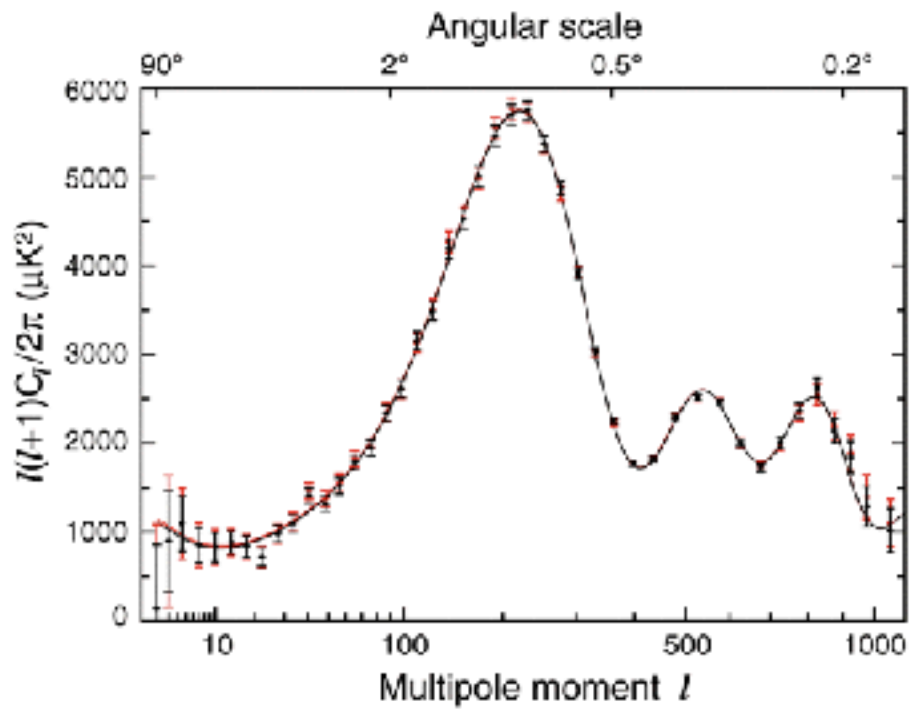
and its success on large scales

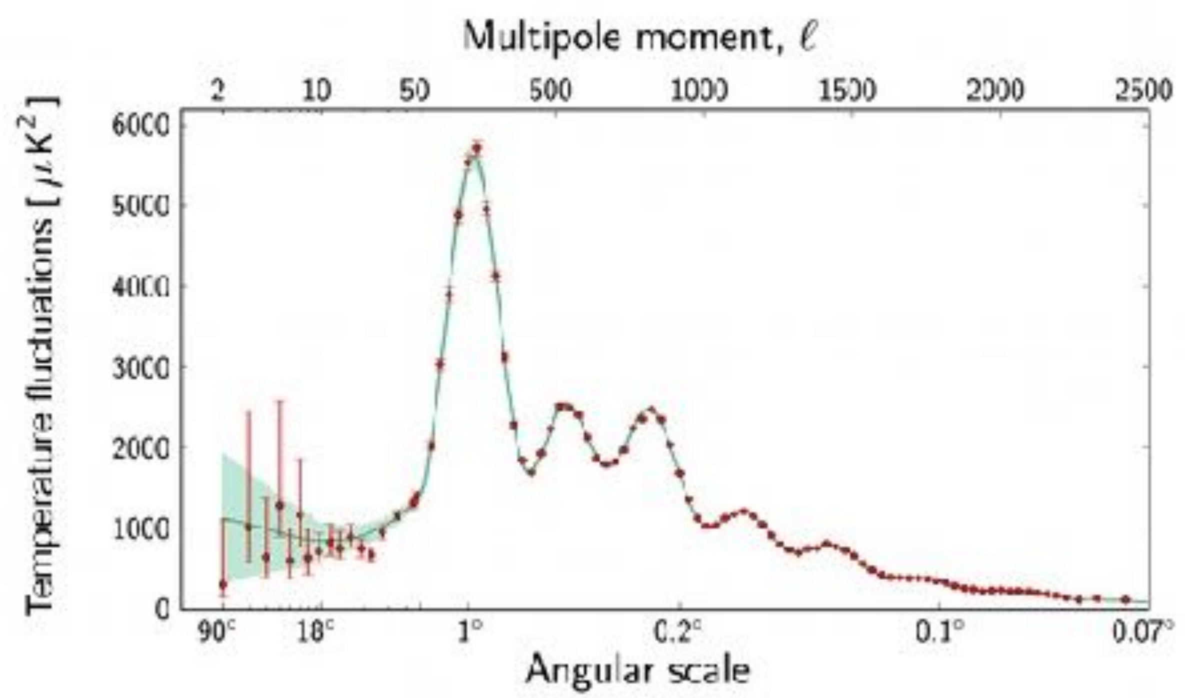
- **Galaxy clusters** — ~80% of mass is dark (Zwicky ’33)
- **Galaxy rotation curves** (Rubin & Ford ‘70)
- **CMB** (angular power spectrum)
- **Structure formation** — P(k), galaxy clustering, Ly-α forest
- **Gravitational lensing** (strong & weak)
- **Bullet Cluster** (Markevich+’02; Clowe+’06)
- ……

WMAP & Planck CMB results







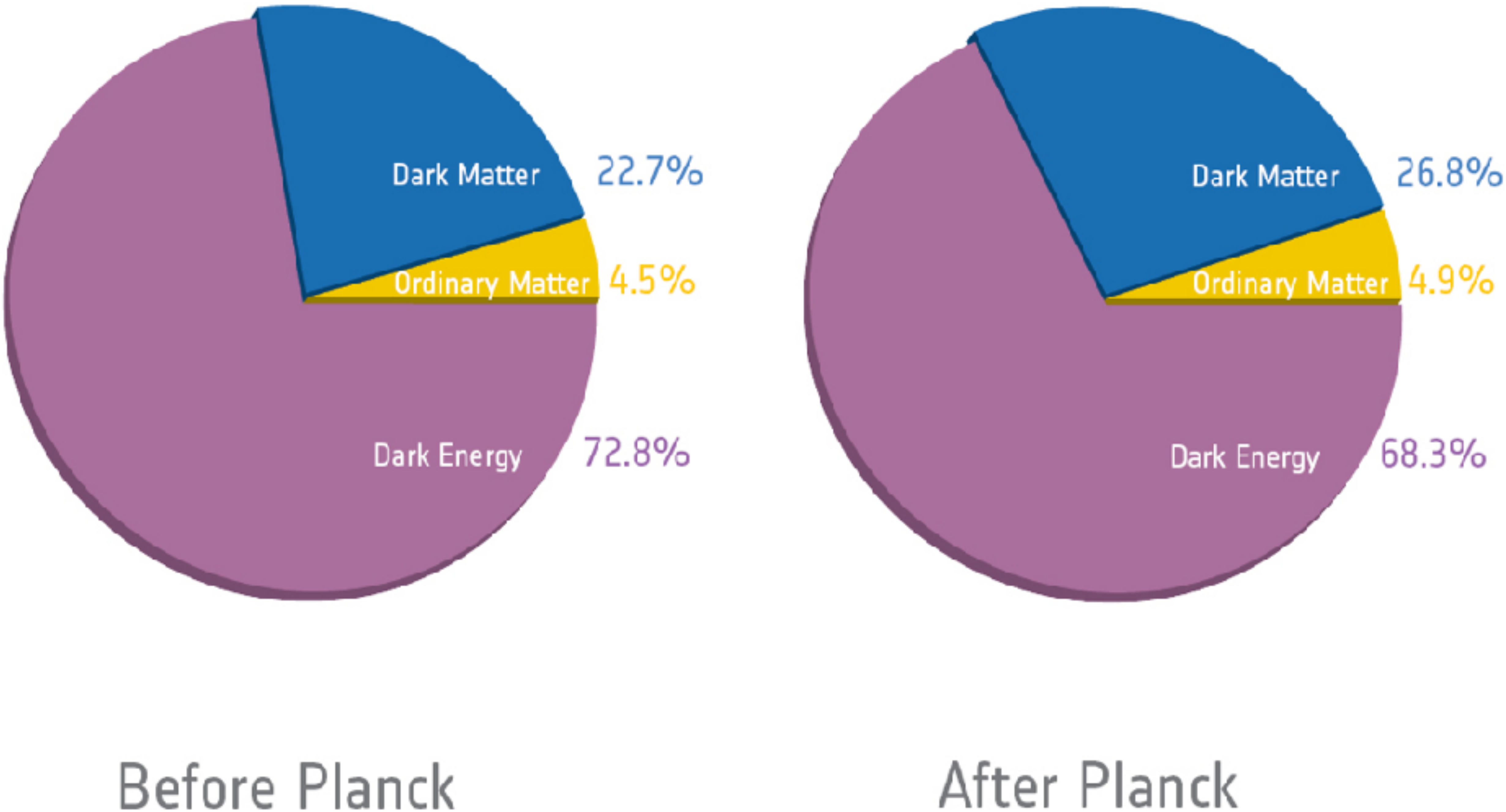


WMAP9; Hinshaw+ '13

(ESA March 2013)

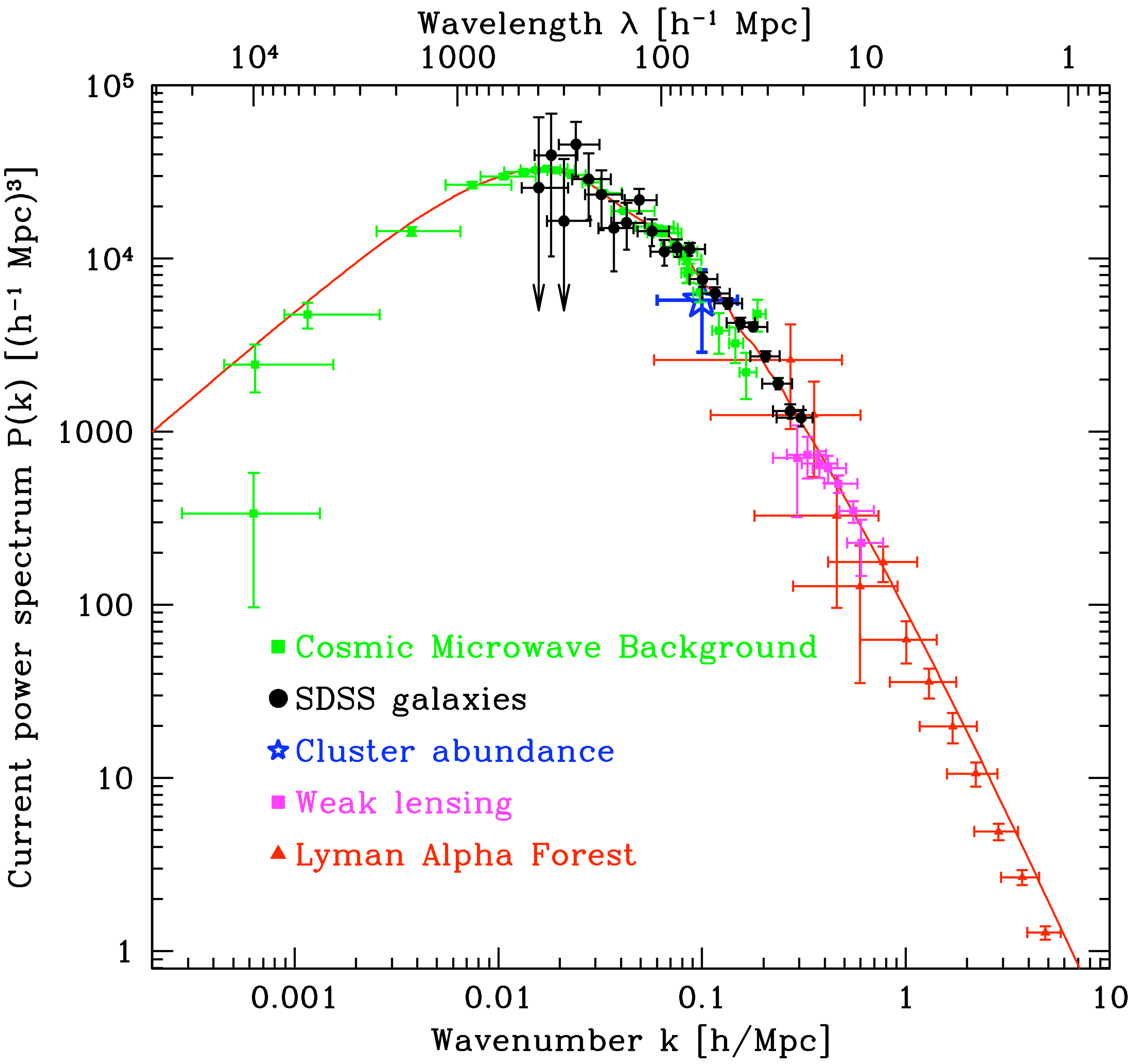
T ~ 2.73K black body with ~10^{-5} fluctuations

Cosmic Energy Budget



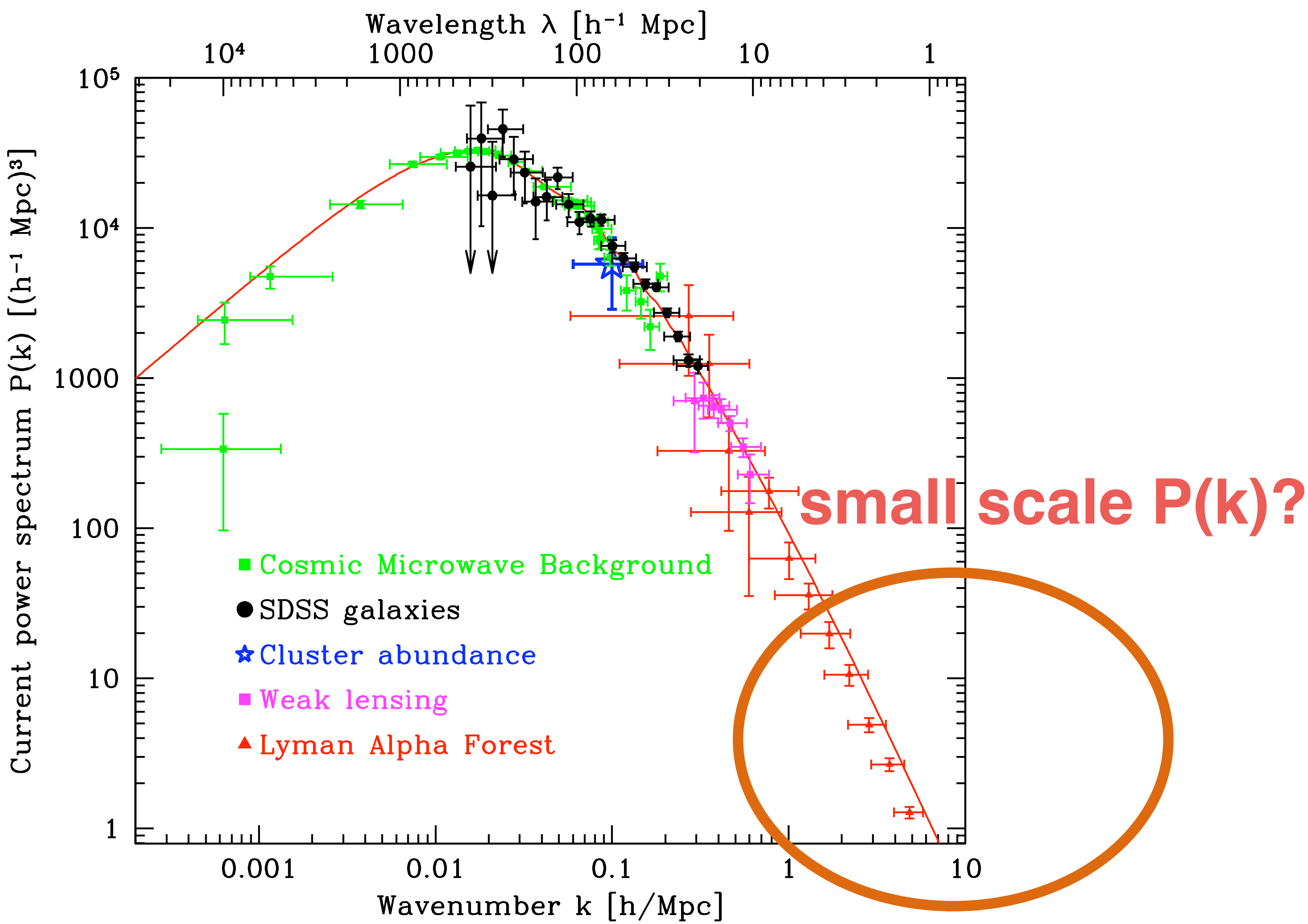
ESA March 2013

Matter Power Spectrum

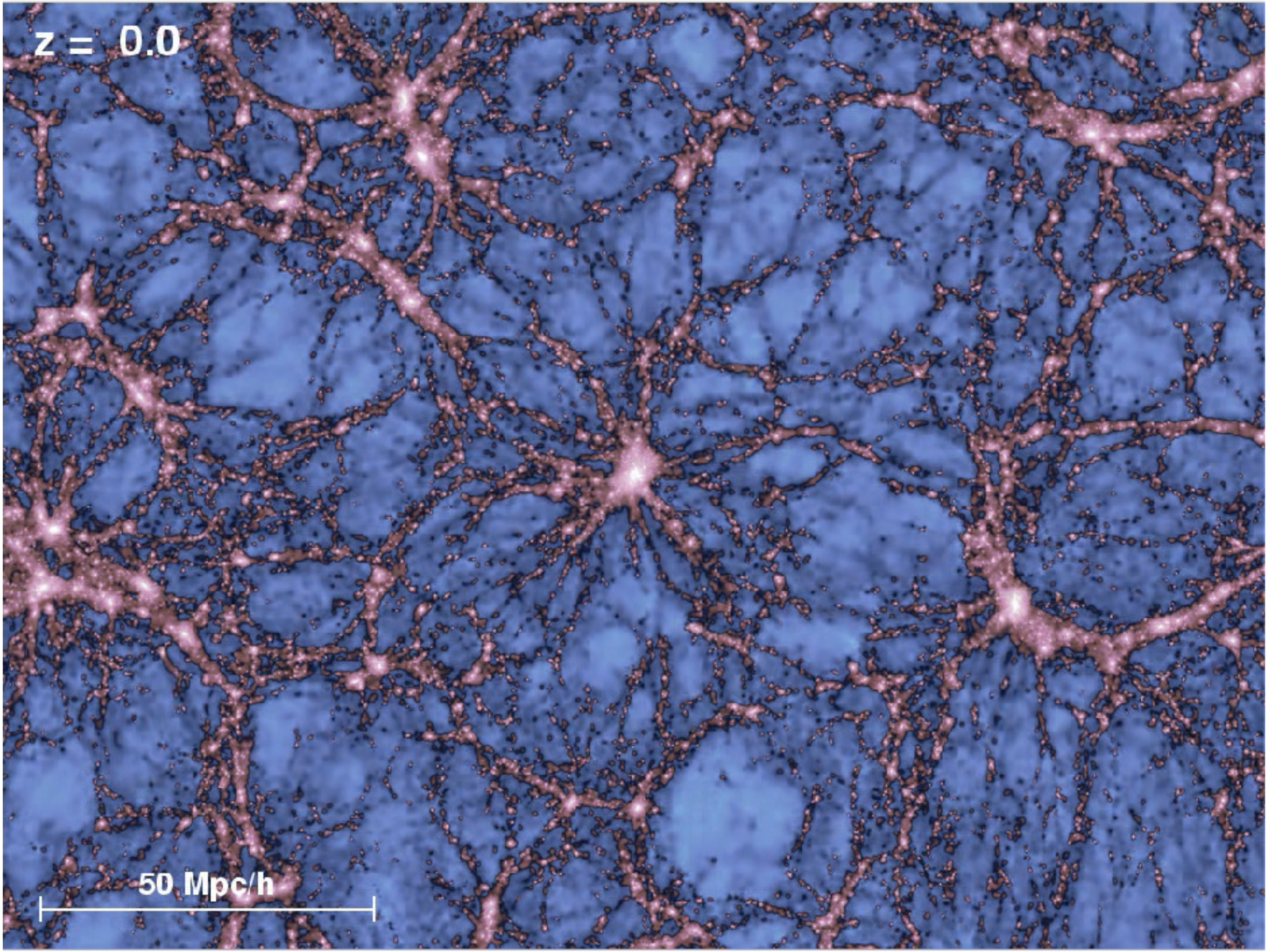


Tegmark 2004

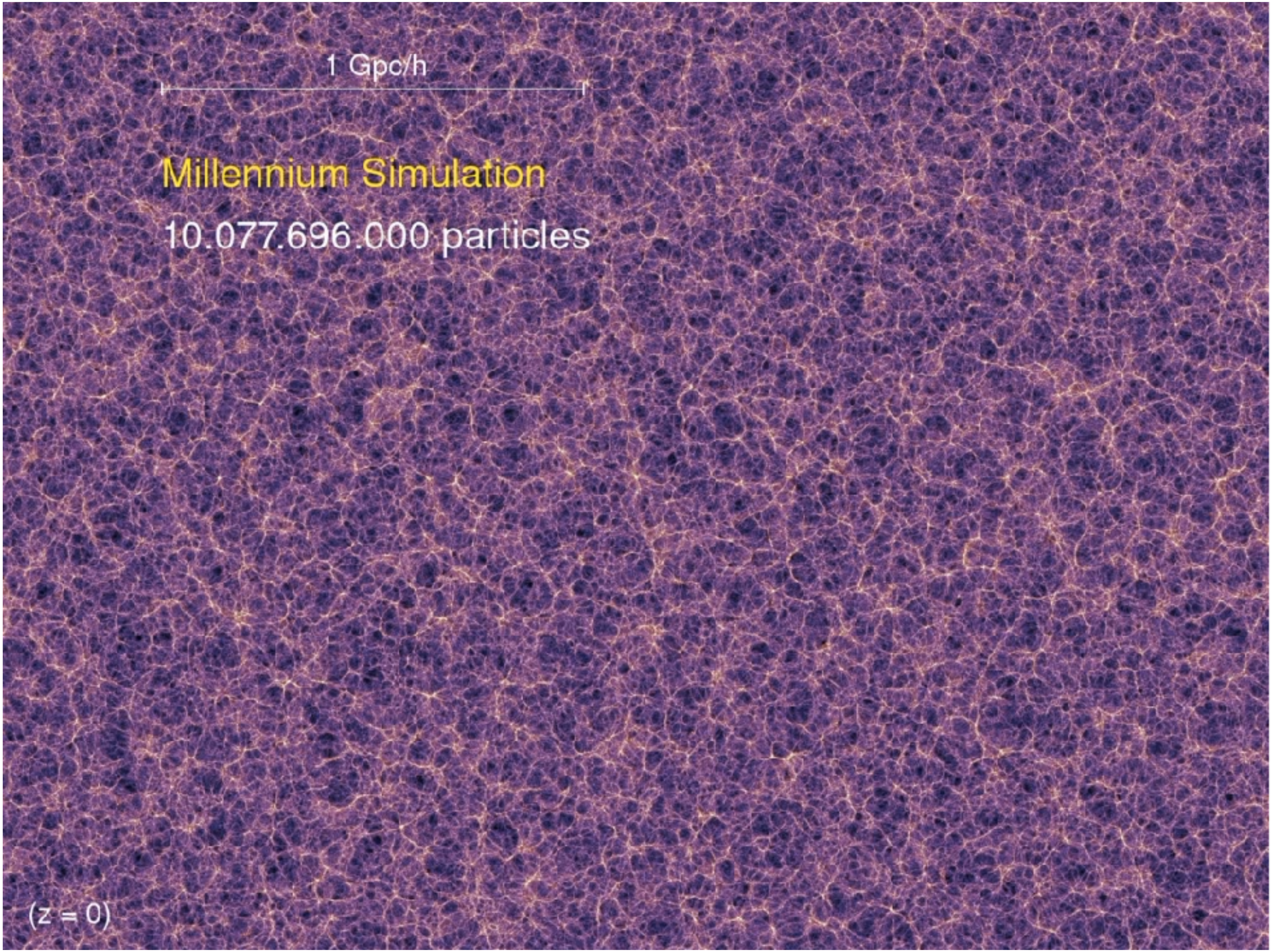
Matter Power Spectrum



Tegmark 2004

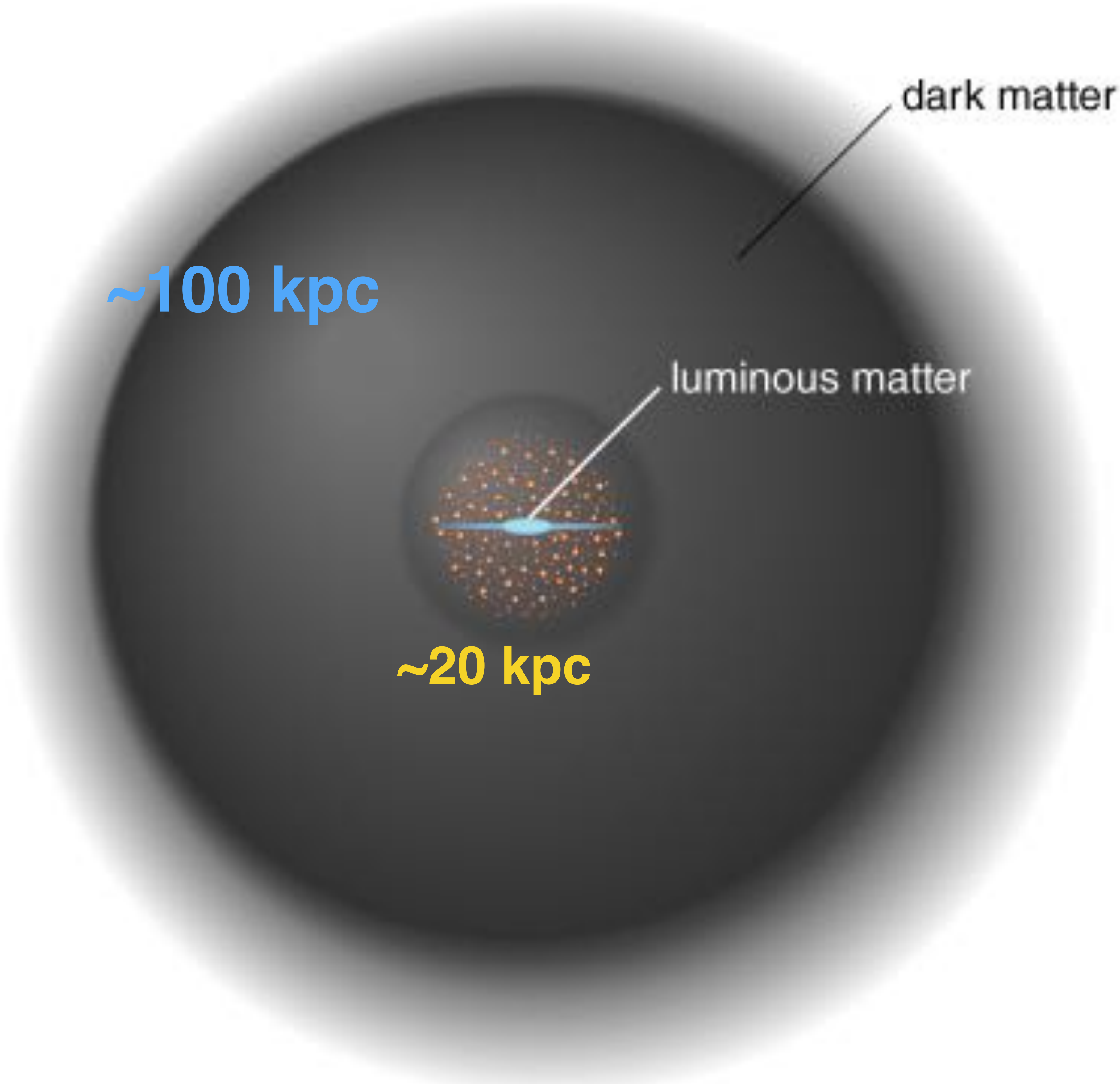


Movie

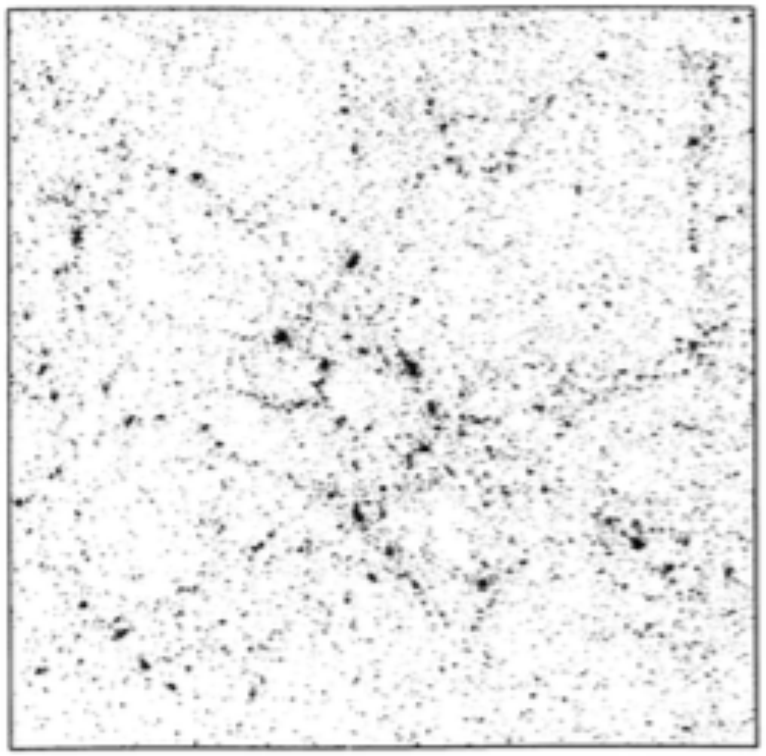


Movie

Current simple picture of DM halo & galaxy

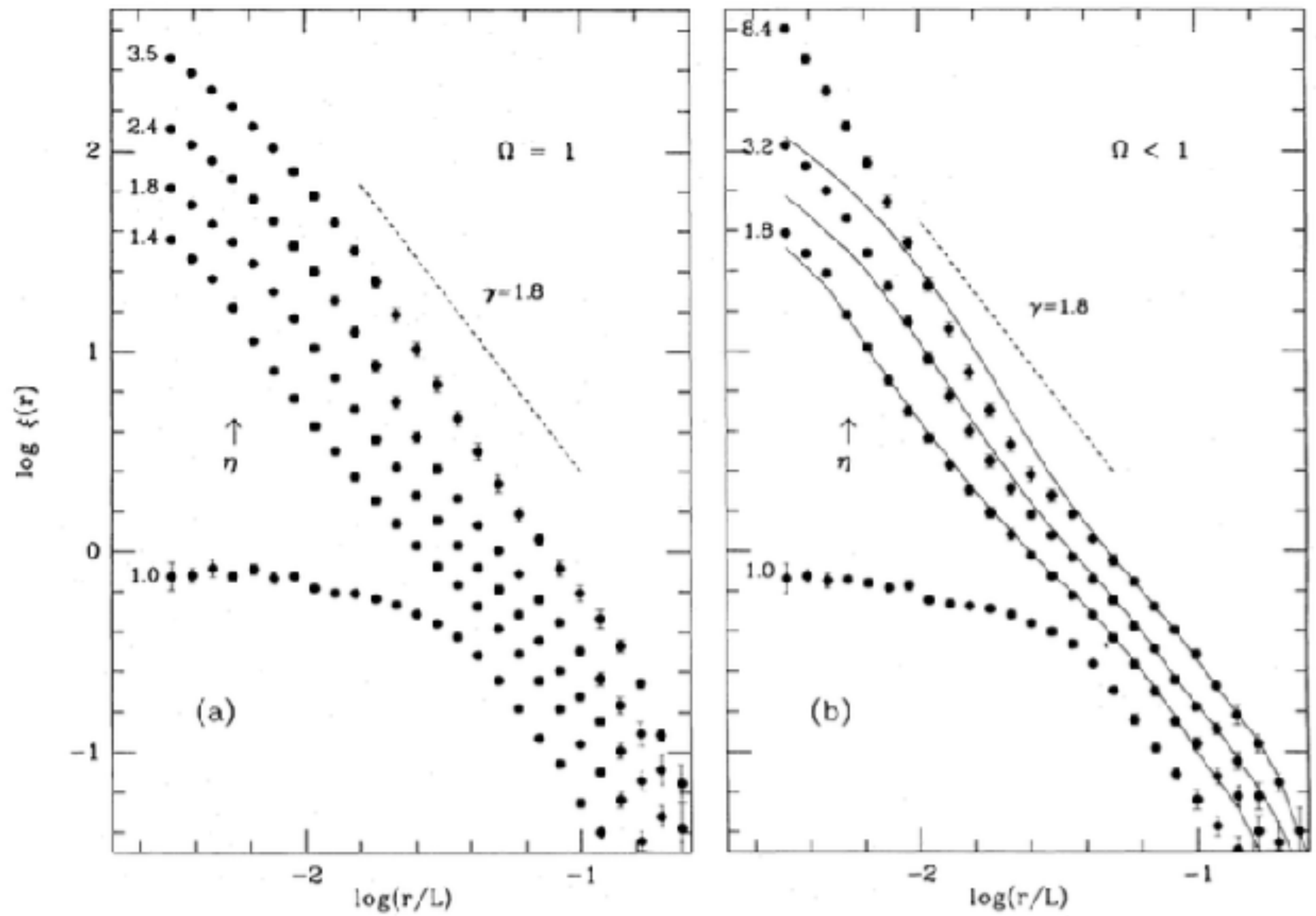


Galaxy Correlation Function & Bias



Davis+'85

only 32^3 ptcl !!
(N-body)



CDM simulation can explain galaxy clustering w/ the idea of "**bias**"

(Some possible)

small-scale problems of ΛCDM

- **Cusp-Core problem:** simulations predicting too steep inner halo profile
- **Missing satellites problem:** too much substructure?
- **Too-big-to-fail problem:** over-abundance of massive substructures that could host gals after reionization (but not observed in MW-satellites)
- **Void phenomenon:** gals in voids are too normal?
- **Satellites plane problem:** satellites aligned in a plane for both MW and Andromeda
- ….

Dark matter halo cusp

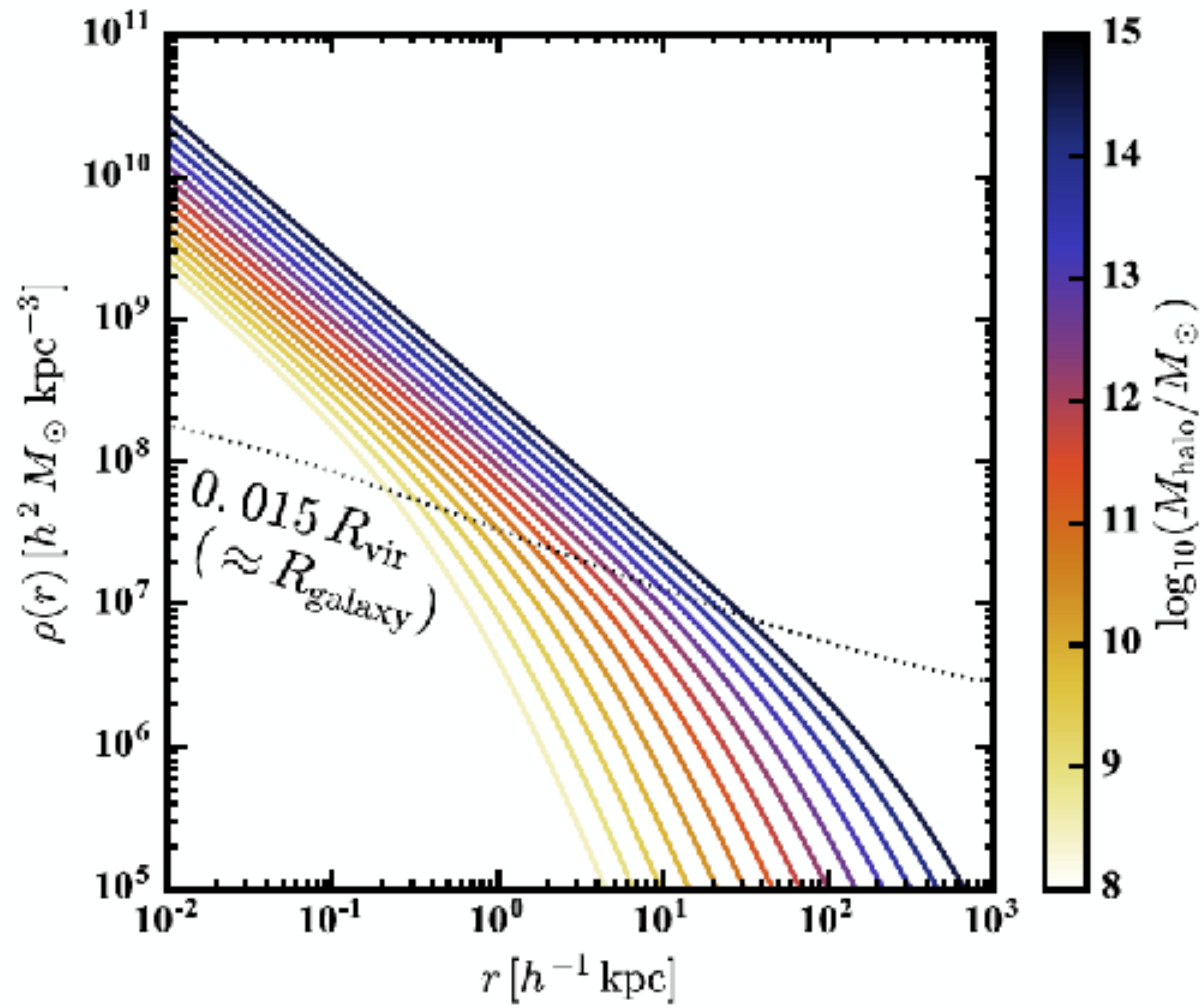
Navarro-Frenk-White (NFW) profile (NFW '96)

$$\rho(r) = \frac{4\rho_{-2}}{(r/r_{-2})(1+r/r_{-2})^2}.$$

$$c = R_{\rm vir}/r_{-2}.$$

$$c \propto M_{\rm vir}^{-a}\,(1+z)^{-1}$$

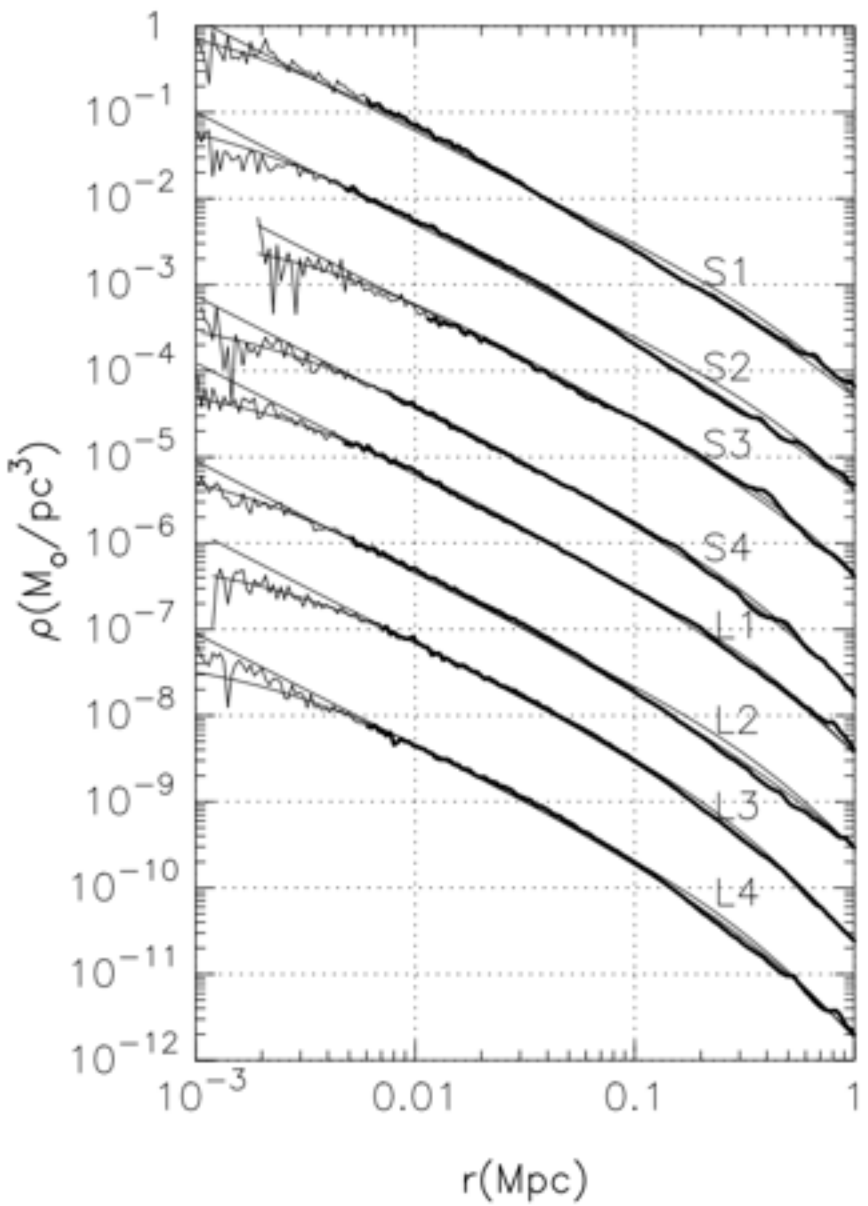
a≃0.1 (Bullock+'01)



Bullock & Boylan-Kolchin '17

But observed dwarf gals tend to have flat cores.

Cuspy profile not universal?



Fukushige+'14

Universal Profile:

NFW: MNRAS 275, 720 (1995): proposed NFW profile for x-ray clusters
NFW: ApJ 462, 563 (1996)
NFW: ApJ 490, 493 (1997): Appendix has useful formulae

Papers supporting NFW profile:

Cole & Lacey, MNRAS 281, 716 (1996)
Tormen, Bouchet, & White MNRAS 286, 865 (1997)
Kravtsov, Klypin, & Khokhlov ApJS, 111, 73 (1997) (Code paper)
Power et al., MNRAS 338, 14 (2003)

Papers finding steeper profiles:

Fukushige & Makino, ApJ 447, J9 (1997)
Moore et al., ApJ 499, L5 (1998)
Moore et Al, MNRAS 310, 1147 (1999)
Ghigna et al, ApJ 544, 616 (2000)
Klypin et al, ApJ 554, 903 (2001)
Fukushige & Makino, ApJ 557, 533 (2001)

Papers finding *shallower* profiles:

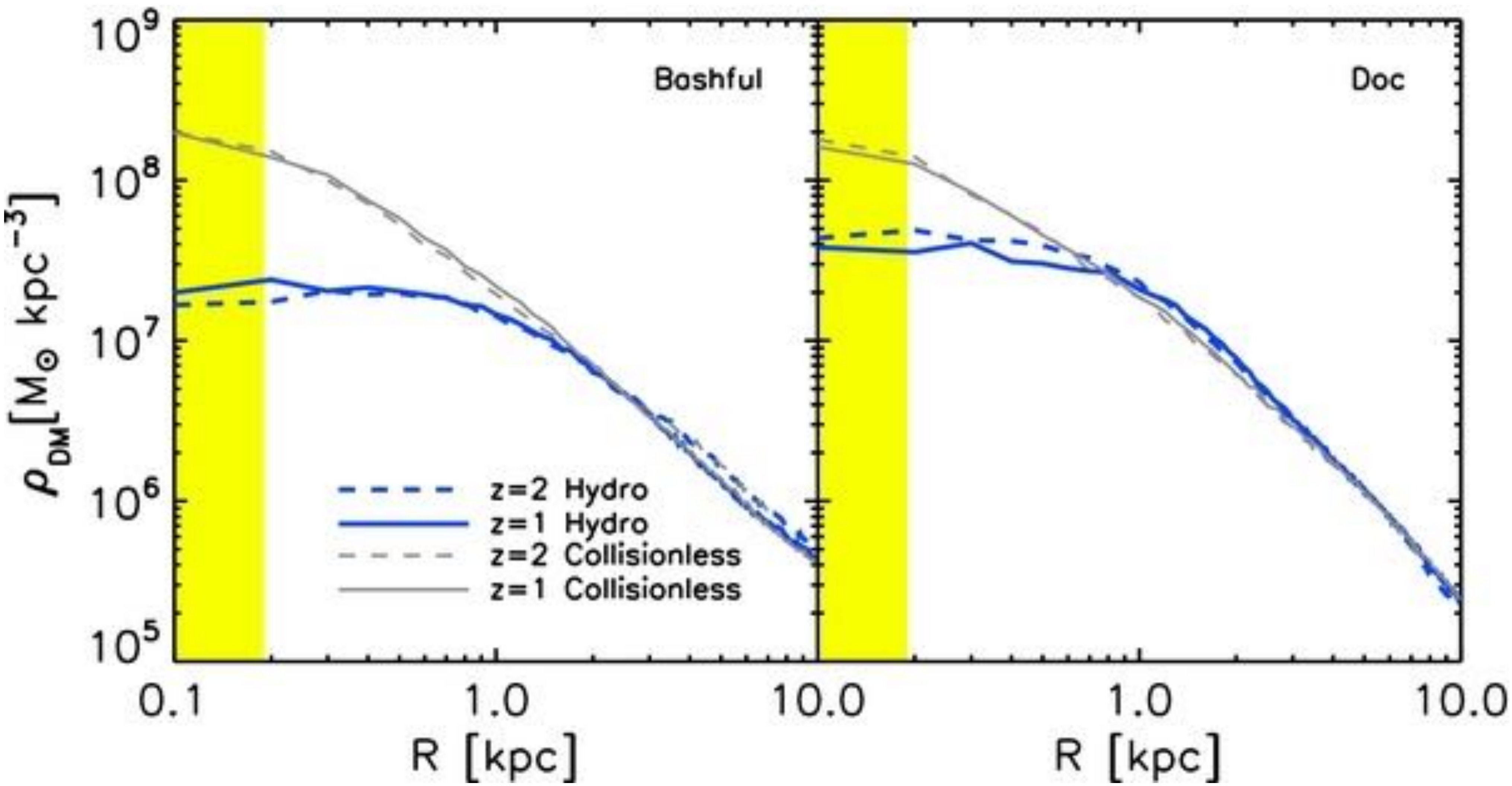
Kravtsov et al., ApJ 502, 48 (1998) (but later "retracted" by Klypin et al 2001)

Papers finding not-so-universal profiles:

Jing & Suto ApJ 529, L69 (2000)
Jing, ApJ 535, 30 (2000)
Fukushige, Kawai, & Makino, astro-ph/0306203 (2003)
Hayashi et al., astro-ph/0310576 (2003)

list by Boylan-Kolchin & Ma

Supernova-driven gas outflows can remove DM cusps and create kpc-size cores

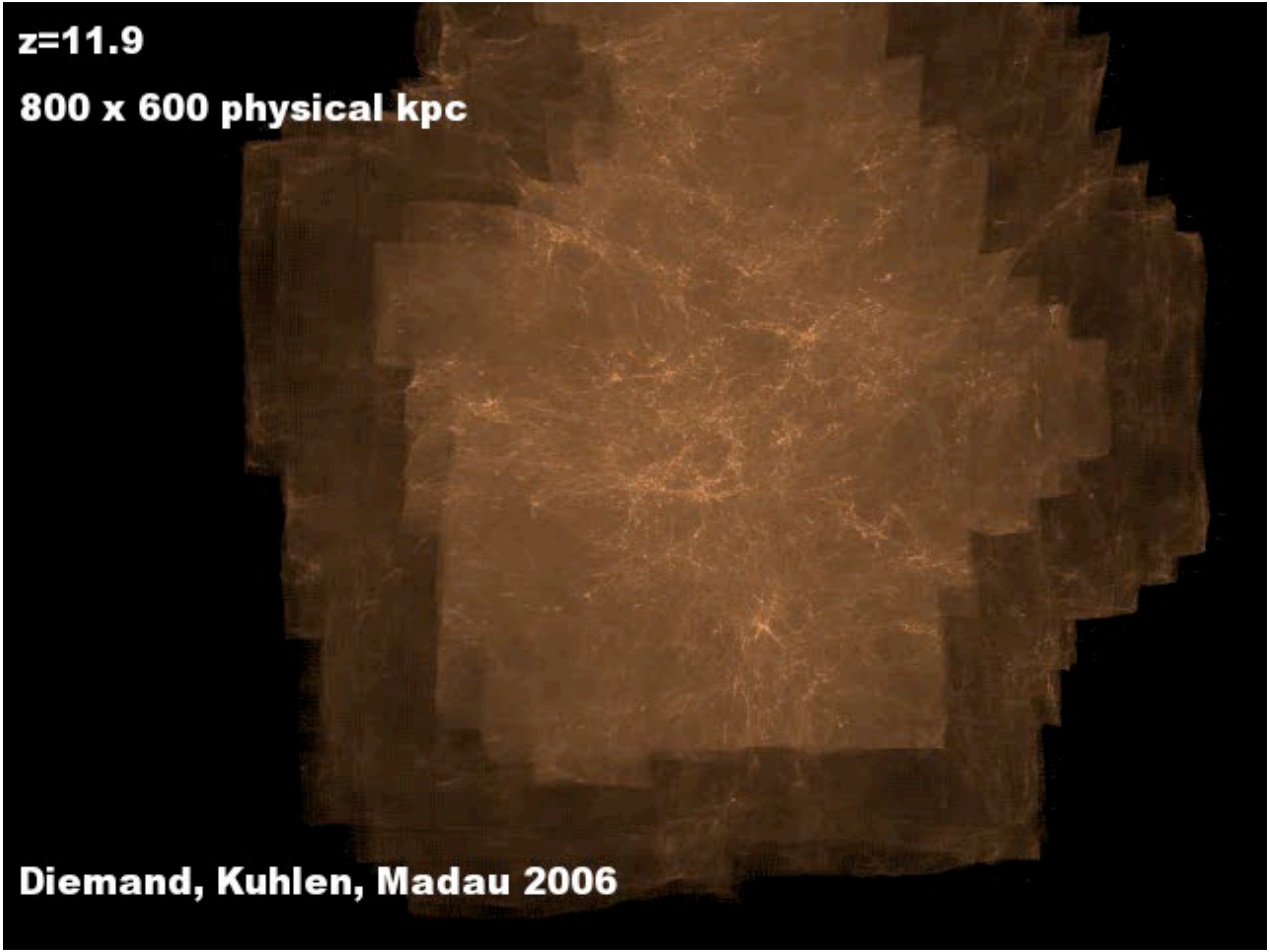


(Results of zoom-in hydro sim.)

So, is CDM just fine?

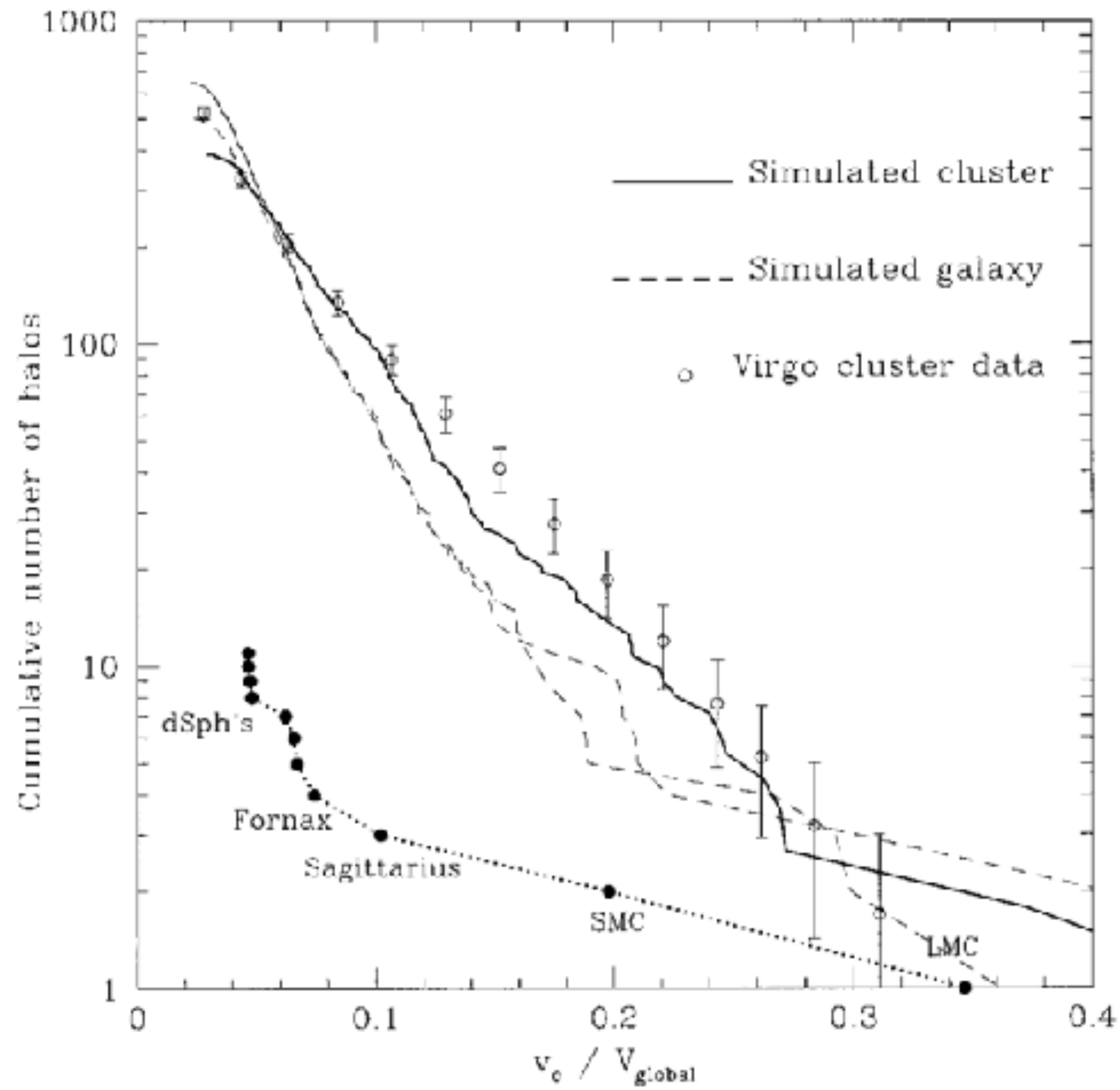
Madau+'14

Substructure problem?

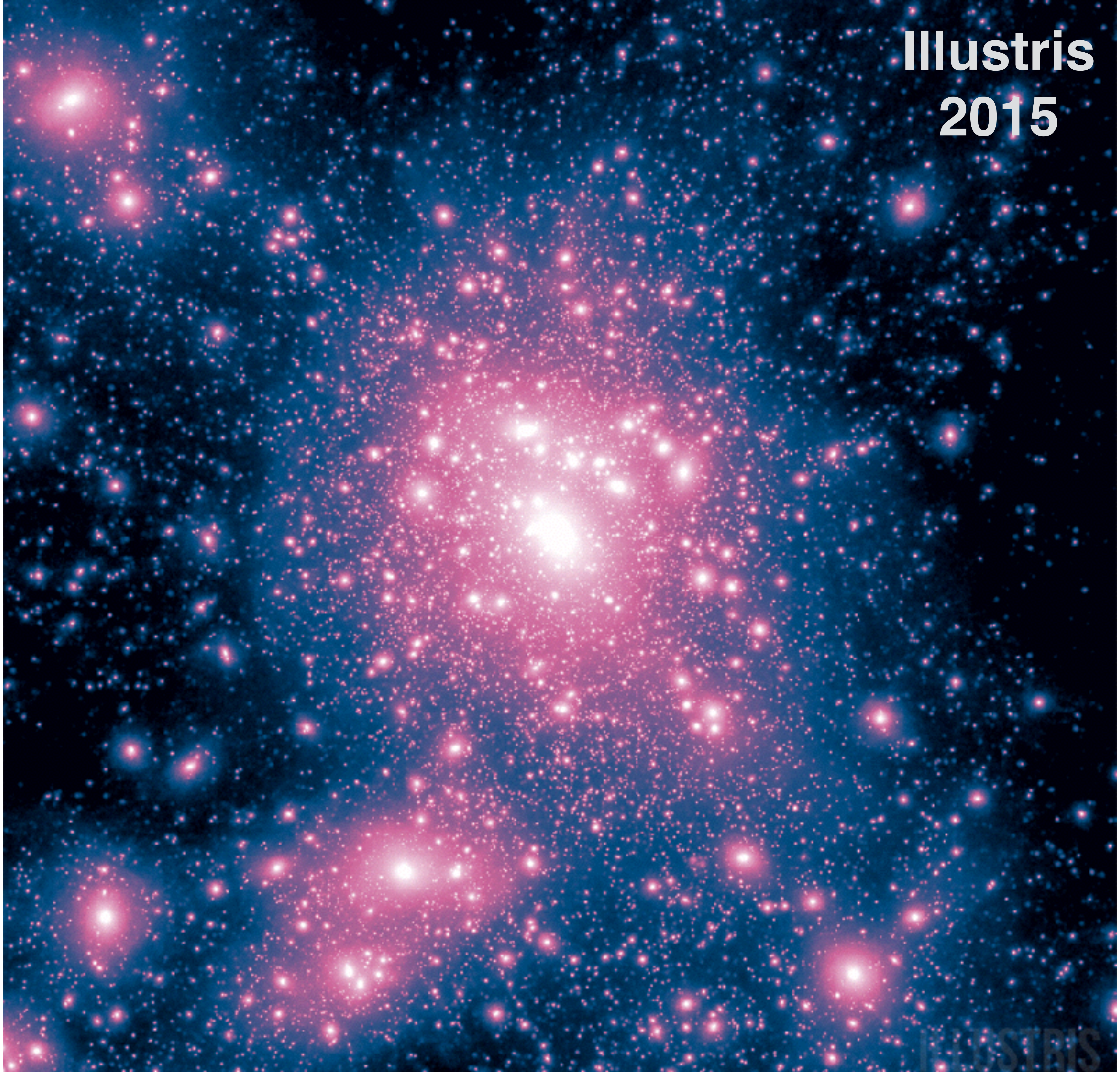


Movie

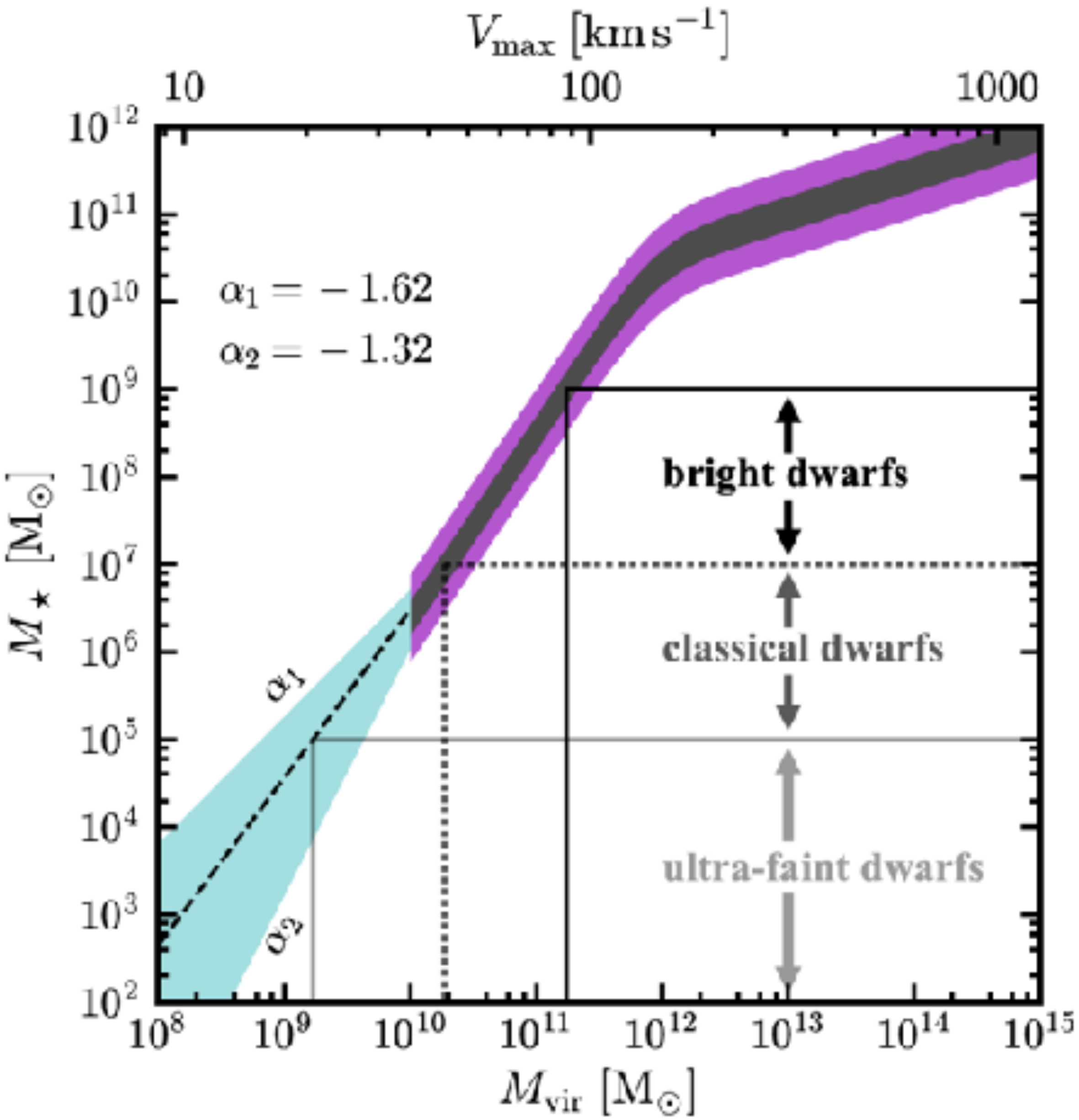
Original Substructure Problem

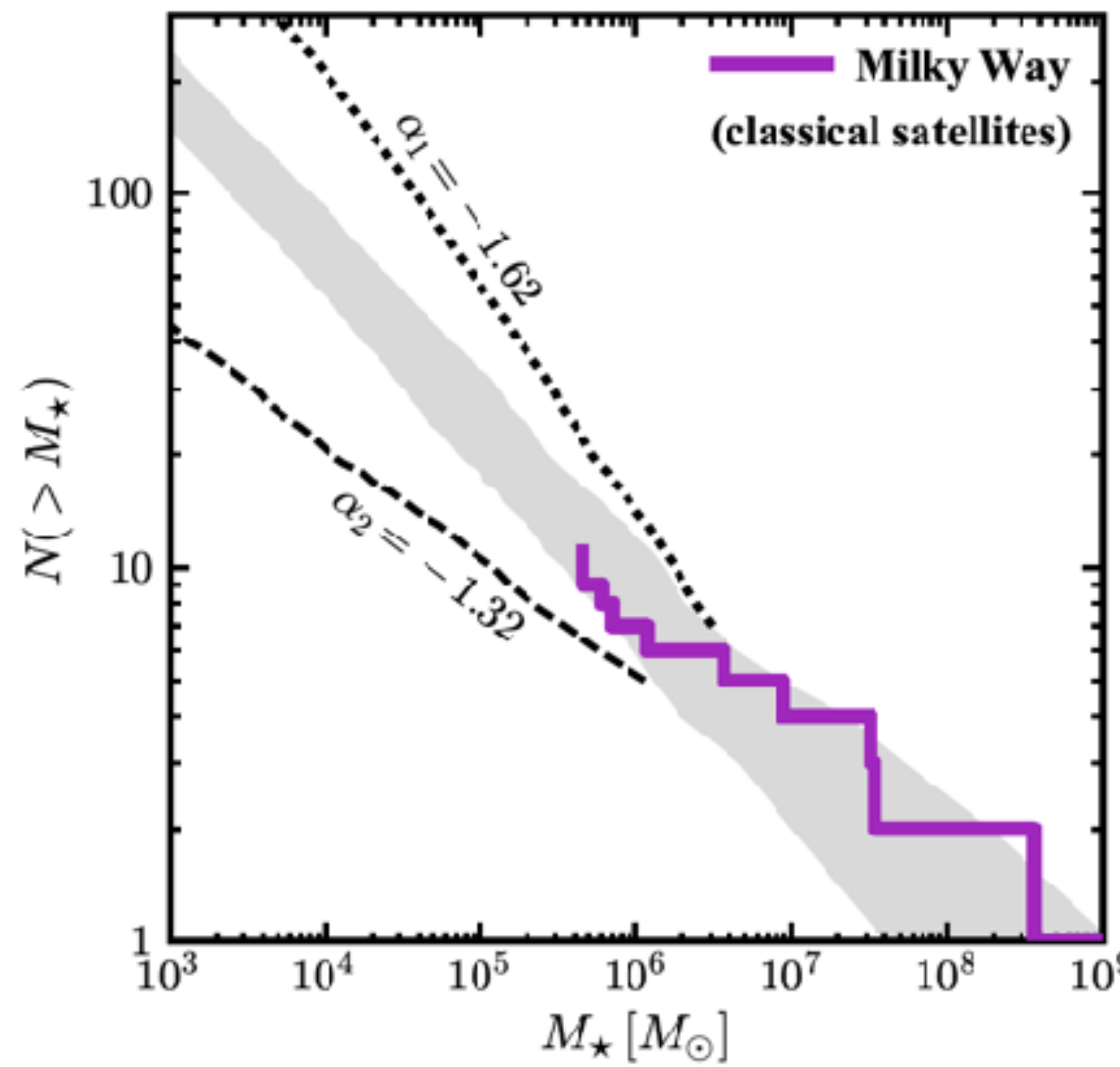


Klypin+'99; Moore+'99


Illustris
2015

Substructure Problem Solved?





Garrison-Kimmel+'17

Bullock & Boylan-Kolchin '17

No Missing Satellite Problem?

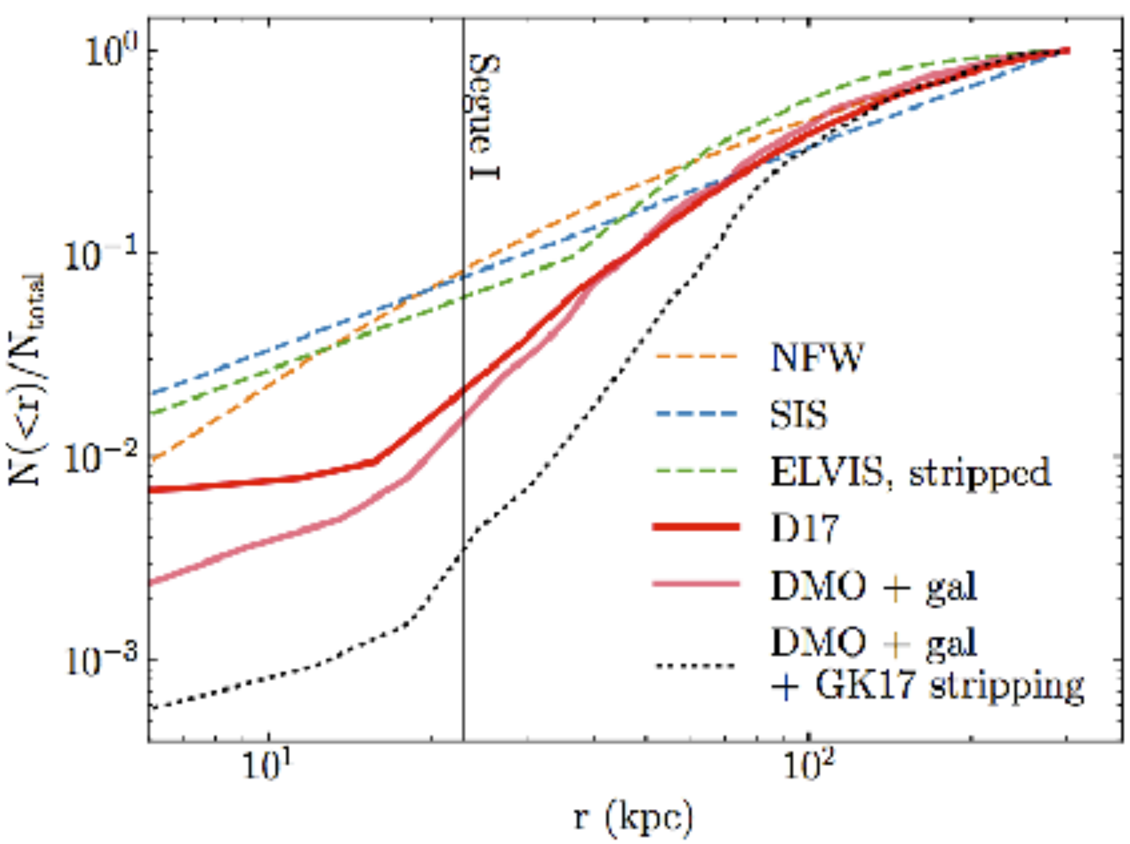
There is No Missing Satellites Problem

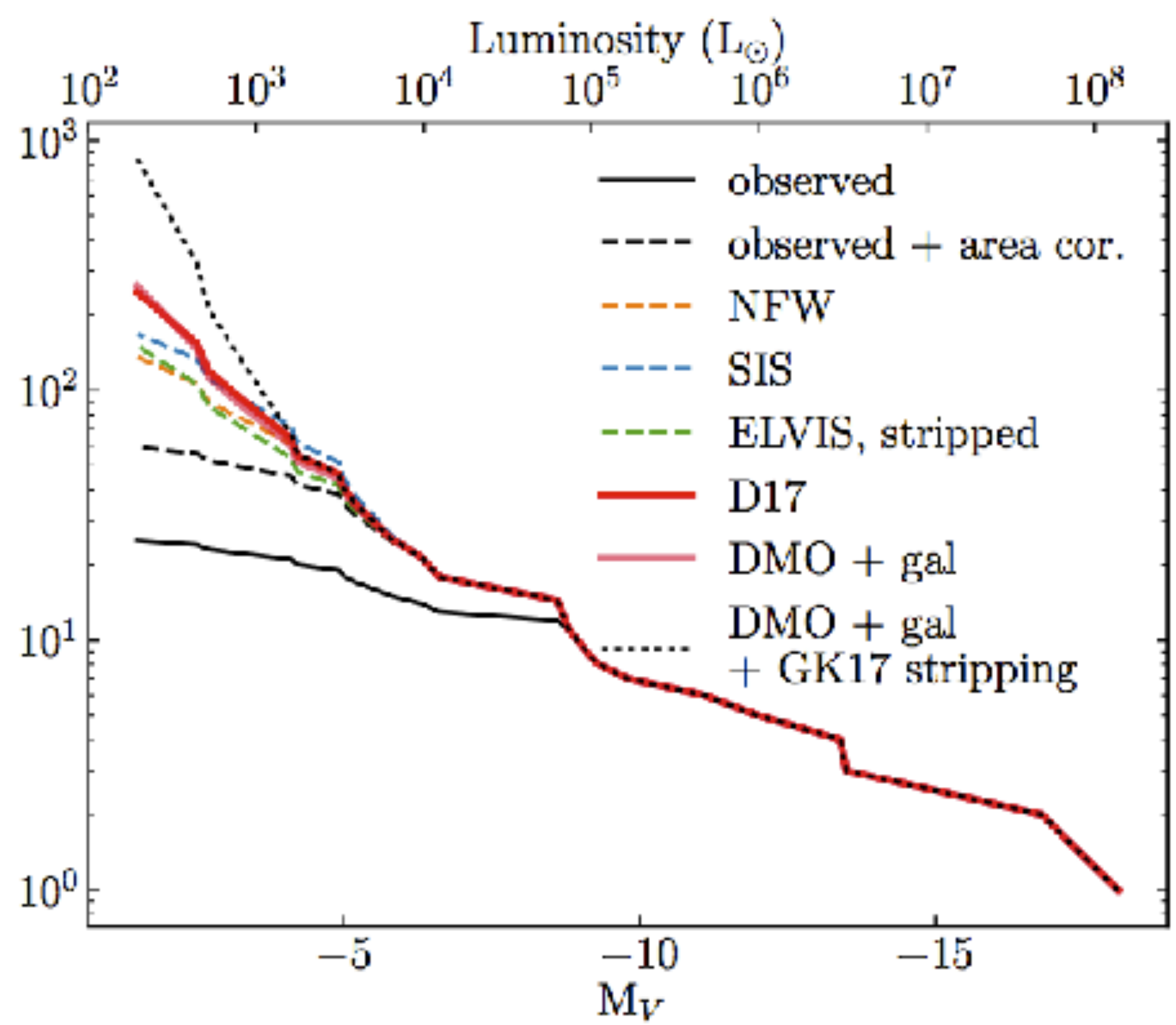
Stacy Y. Kim[1,2,*] Annika H. G. Peter[1,2,3], and Jonathan R. Hargis[4]

arXiv:1711.06267

$$N_{\rm tot} = \int c(L) \frac{dN_{\rm obs}}{dL} dL \approx \sum_{i=1}^{N_{\rm obs}} c(L_i), \qquad c(L) = c_r(L)\, c_\Omega(L)$$

$$c_r(L) = \frac{\int_0^{R_{\rm vir}} \frac{dN}{dr}\, dr}{\int_0^{r_c(L)} \frac{dN}{dr}\, dr} \quad \text{and} \quad c_\Omega = \frac{4\pi}{\int_0^{\Omega_c} d\Omega}$$





Various Dark Matter

Cold Dark Matter (CDM):
$m \sim 100\,\mathrm{GeV}$,
$v_{\mathrm{th}}^{z=0} \approx 0\,\mathrm{km\,s^{-1}}$

Thermal relic
e.g. WIMP (weakly interacting massive ptcl)

Warm Dark Matter (WDM):
$m \sim 1\,\mathrm{keV}$,
$v_{\mathrm{th}}^{z=0} \sim 0.03\,\mathrm{km\,s^{-1}}$

becomes non-relativistic earlier, suppress perturbation at galactic or smaller scales.

(gravitino, steril neutrino,…)

Hot Dark Matter (HDM):
$m \sim 1\,\mathrm{eV}$,
$v_{\mathrm{th}}^{z=0} \sim 30\,\mathrm{km\,s^{-1}}$

remains relativistic until late time, and erase structures at super-galactic scales.

+FDM (axion-like)

So, how about WDM?

e.g.,
gravitino (Kawasaki+'97)
sterile neutrino ~ keV (Boyarski+'09)

Thermal relic; **Streaming velocity $v_S/c \sim T_X/m_X$**

$$R_S \approx 0.31\left(\frac{\Omega_X}{0.3}\right)^{0.15}\left(\frac{h}{0.65}\right)^{1.3}\left(\frac{\mathrm{keV}}{m_X}\right)^{1.15} h^{-1}\ \mathrm{Mpc}$$

m~1.5 keV => Rs~0.3 Mpc/h

Bode+'01

$$T^2_{\rm lin}(k) \equiv P_{\rm WDM}(k)/P_{\Lambda\rm CDM}(k) = [1+(\alpha\, k)^{2\nu}]^{-10/\nu},$$

$$\alpha(m_{\rm WDM}) = 0.049\left(\frac{1\,\mathrm{keV}}{m_{\rm WDM}}\right)^{1.11}\left(\frac{\Omega_{\rm WDM}}{0.25}\right)^{0.11}\left(\frac{h}{0.7}\right)^{1.22}$$

Viel+'12

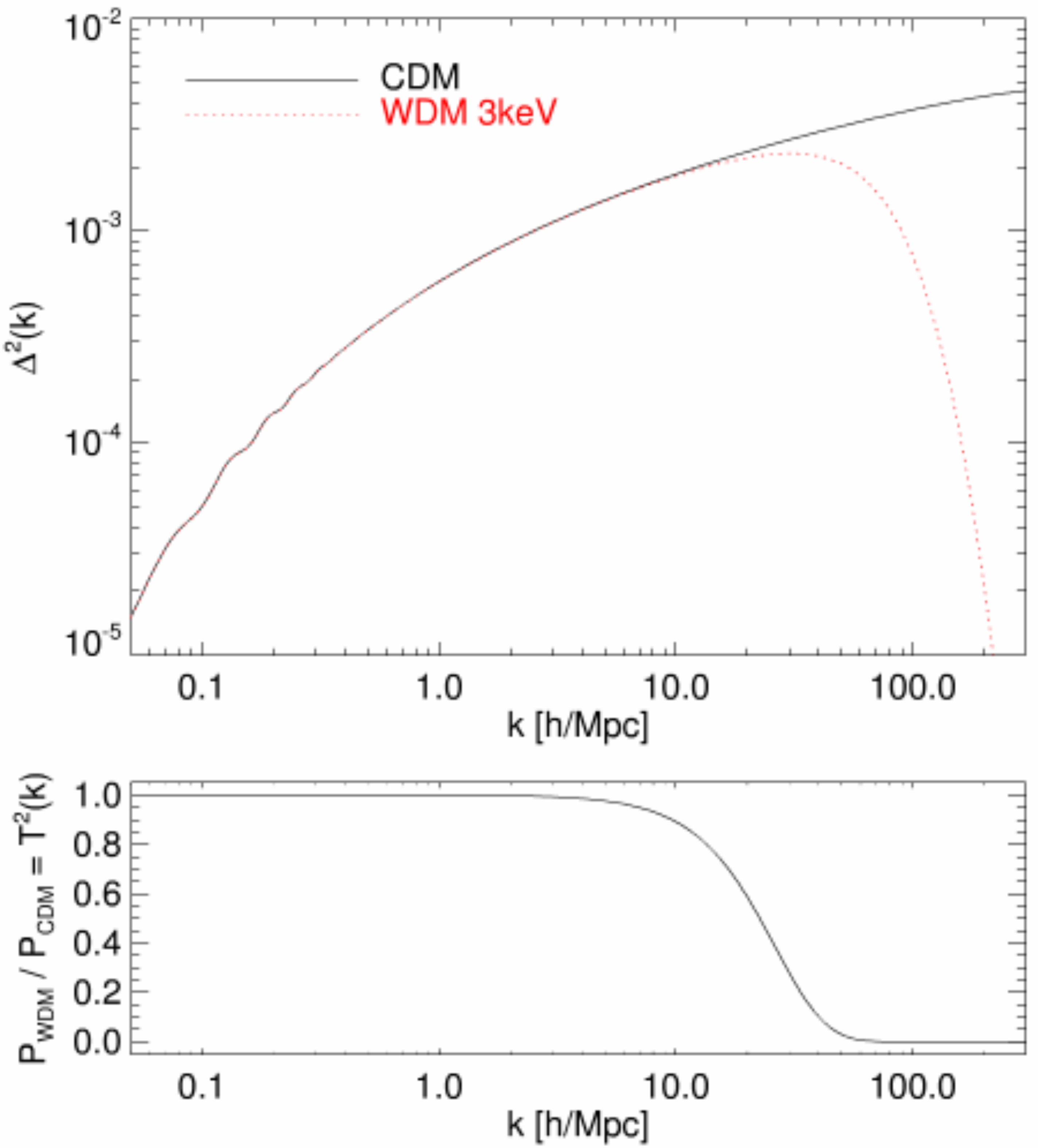
half-mode mass

$$M_{\rm hm} = 5.5\times 10^{10}\left(\frac{m_{\rm WDM}}{1\,\mathrm{keV}}\right)^{-3.33} M_\odot\,.$$

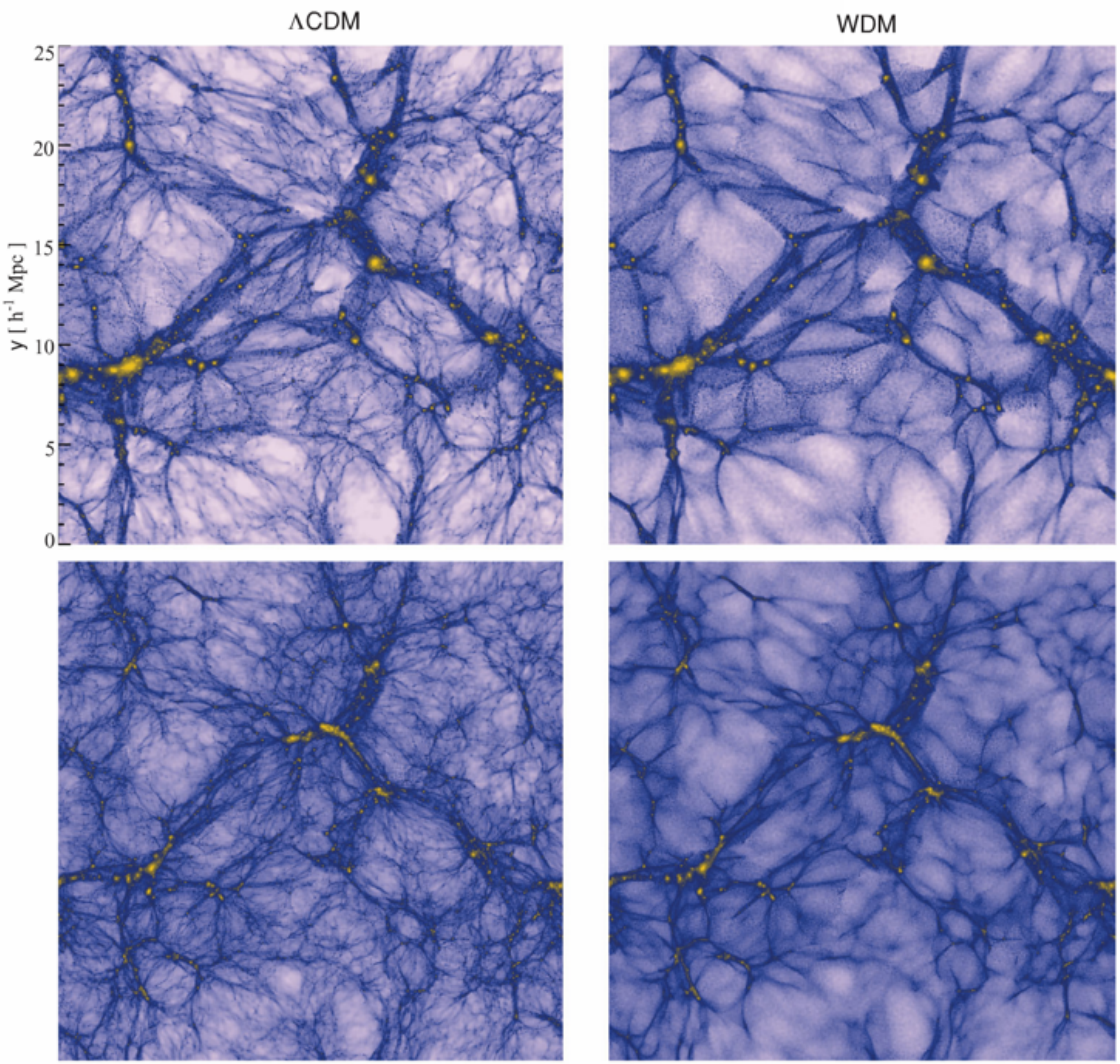
Schneider+'12

Colin+'00; Bode+'01; Viel+'05; Colin+'08; Colombi+'09; Viel+'12; Menci+'17

Suppression of P(k) @ small scales



Maio & Viel '15



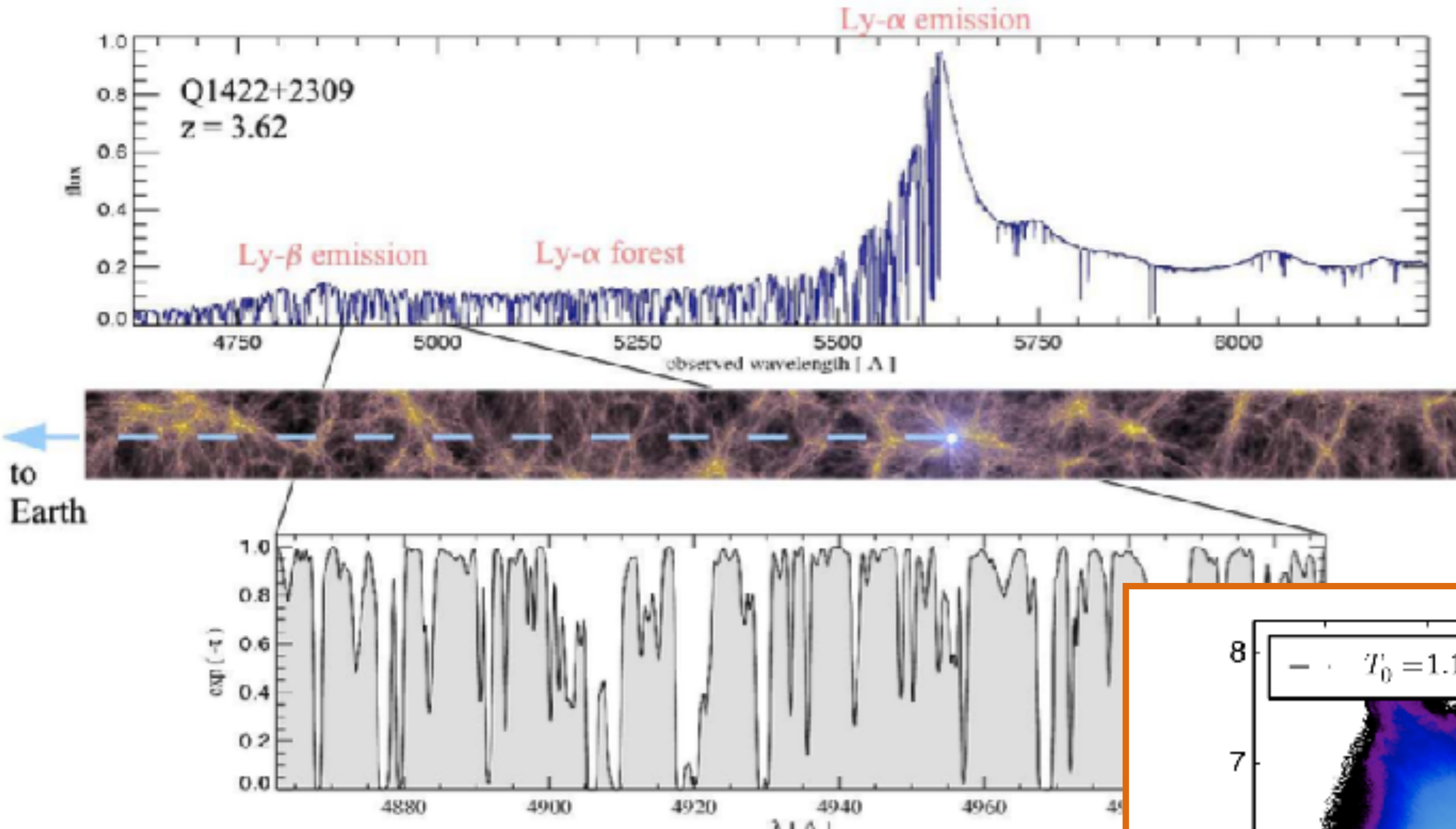
z=0

m=1 keV

z=2

Viel+’12

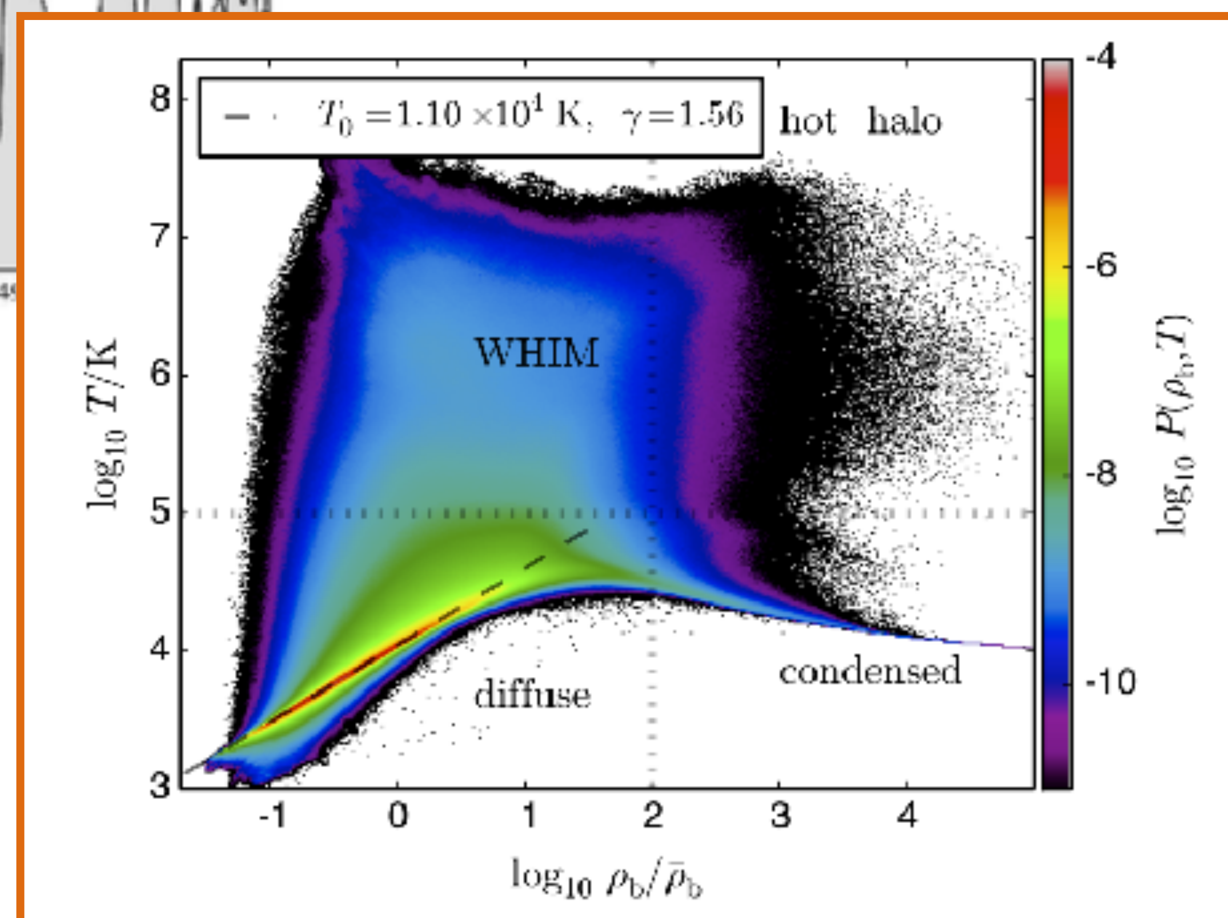
Quasars (QSOs) and Ly-α forest



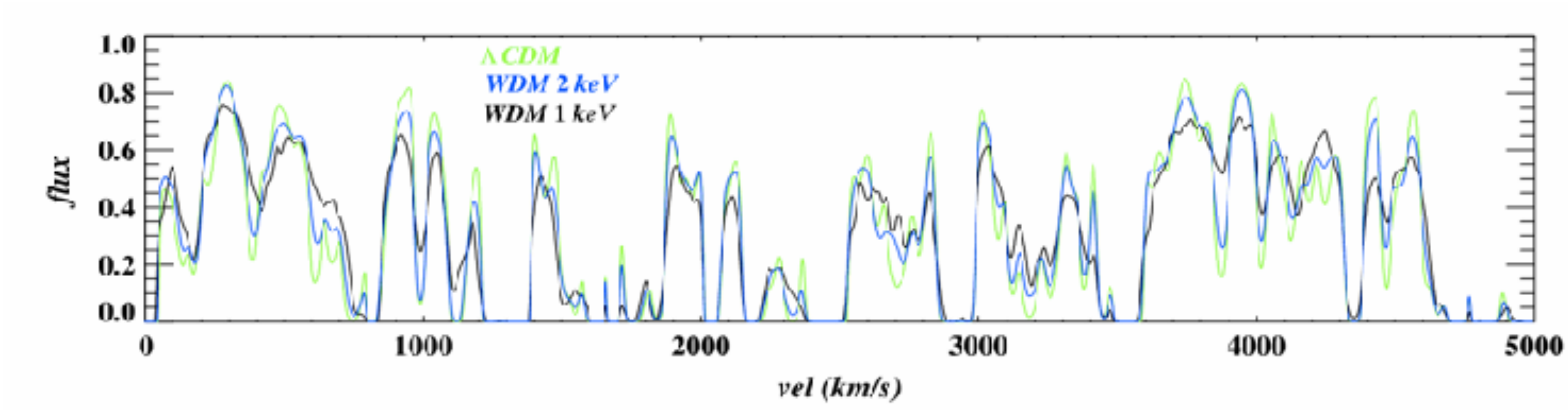
Springel+'05

(cf. Cen+'94)

Lukic+16



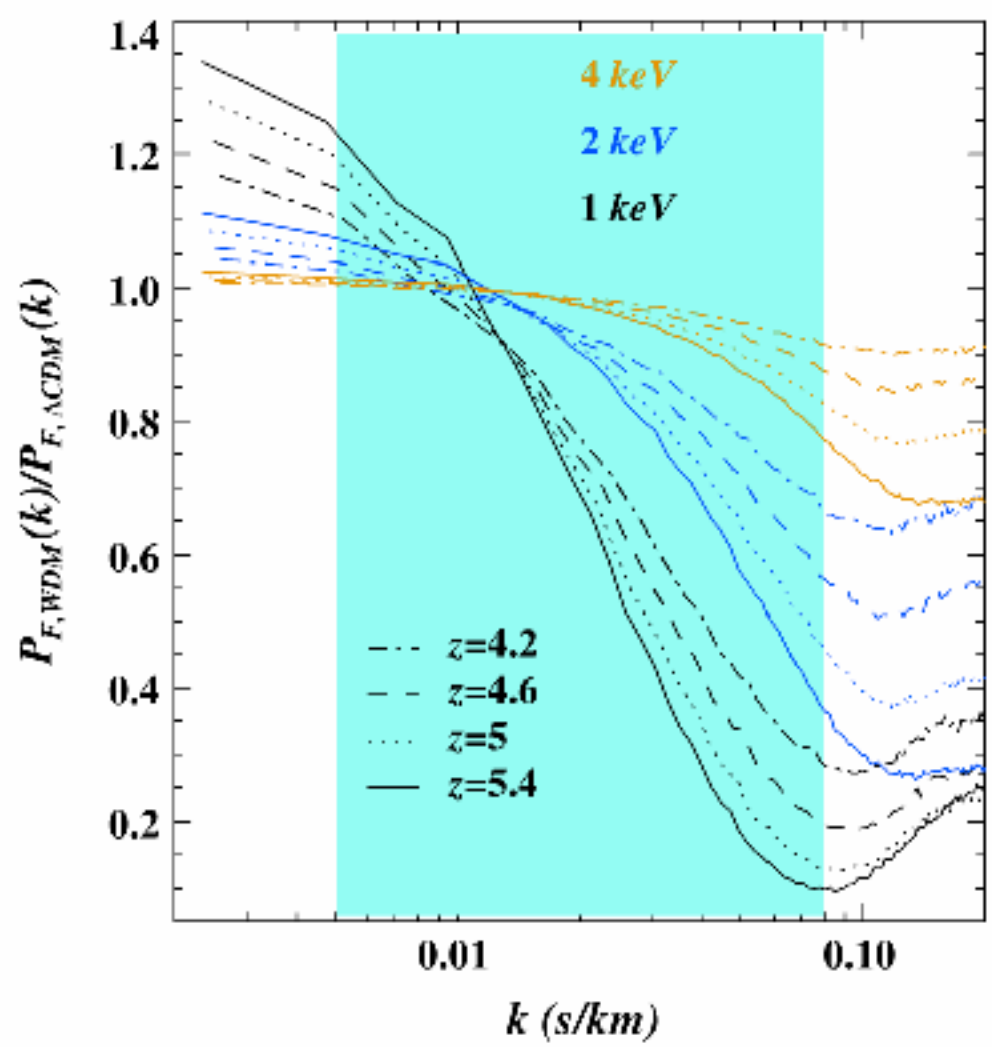
Ly-α forest constraint



$T = T_0(1+\delta)^{\gamma-1}$

1D flux power spec

$\delta_F = F/\langle F \rangle - 1$

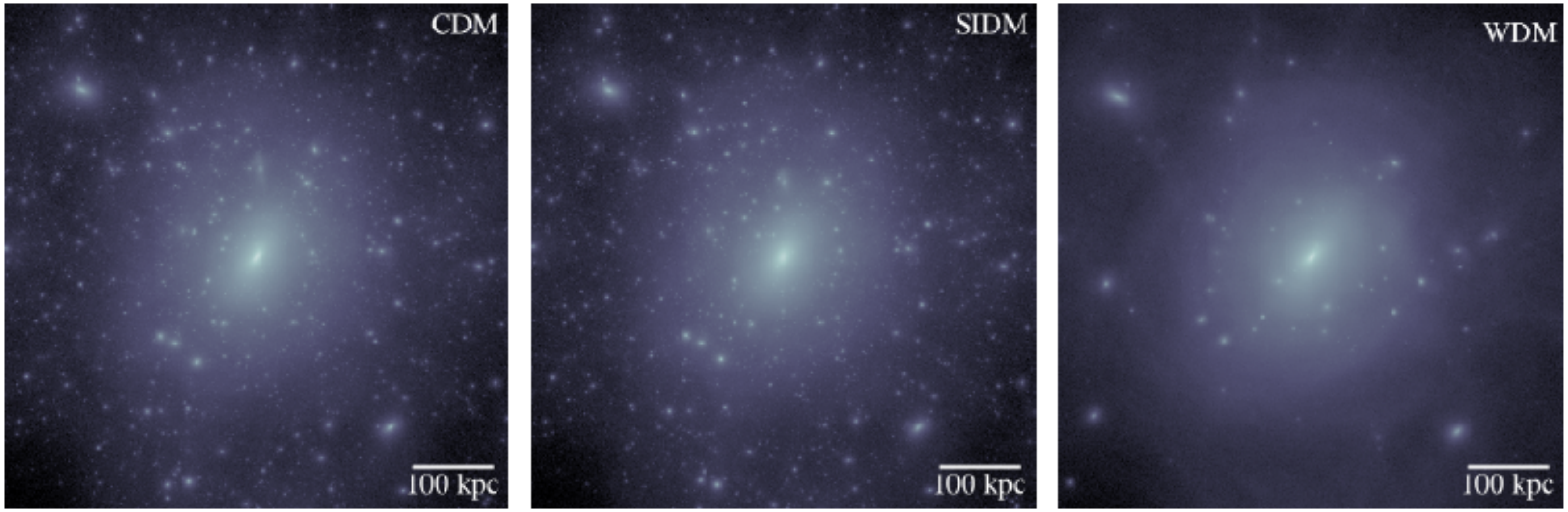


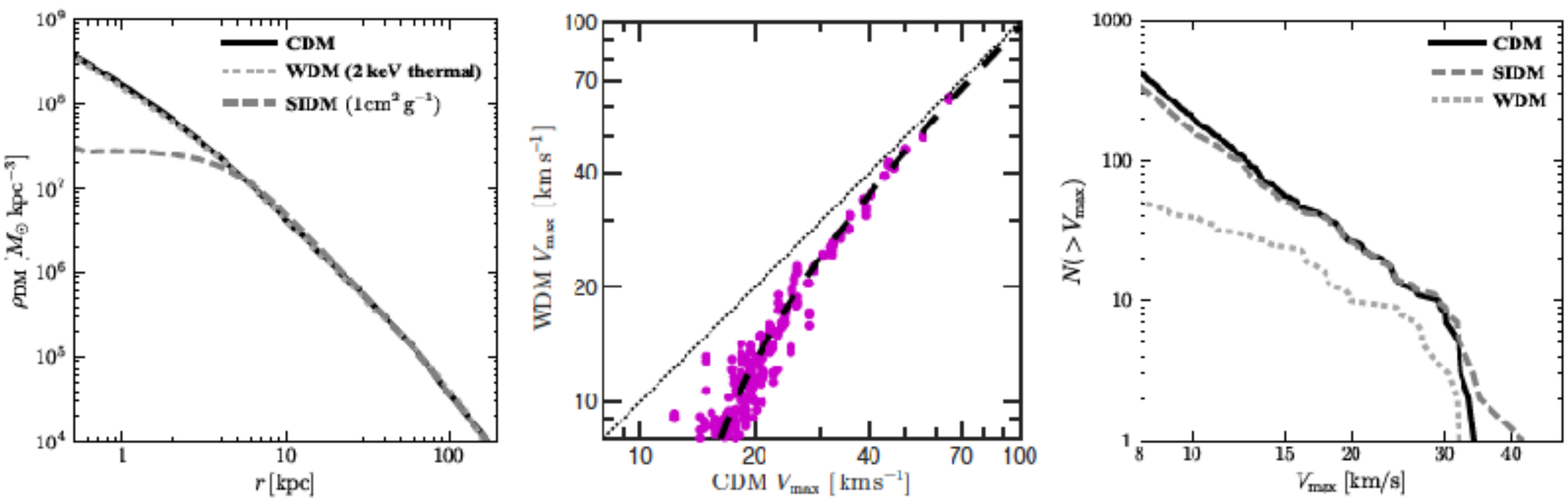
marginalize over
6 cosmo param
& T_0, γ
using COSMOMC
against real obs data

Viel+'13

WDM conclusions

- **WDM** models w/ $\lesssim$ **3keV** have been explored — strong alternative candidate to CDM
- **$m_{dm} \gtrsim$ a few keV** seems more likely than **< 1keV**.
- Viel+13, **Ly-a forest**: **m>3.3 keV** (2-σ), **$M_{h,min}$~2e8 $M_\odot$**
- Further study is needed with high-resolution and realistic SF & feedback models — **e.g. impact of AGN feedback on small-scale power (van Daahlen+'11; Semboloni+'11)**





- **WDM** reduces the substructure, but **keeps the cusp.**
- **SIDM doesn't reduce the abundance of substructure, but produces large const-density core**

Rocha+'13; Bullock & Boylan-Kolchin '17

SIDM (self-interacting DM)

— as a generic consequence of hidden sector extensions to Standard Model

- no couplings to SM particles
- possibly strong self-interaction via dark gauge bosons

(Feng '10; Peter '12 for reviews)

$$\sigma/m \sim 0.1 - 100\ \mathrm{cm}^2/\mathrm{g}$$ **Spergel & Steinhart '00**

$$\sigma/m \simeq 0.1\,\mathrm{cm}^2/\mathrm{g} \simeq 0.2\,\mathrm{barn}/\mathrm{GeV}$$ **Rocha+'13**

can produce results consistent w/ current obs.

LSS & sub halos unchanged.

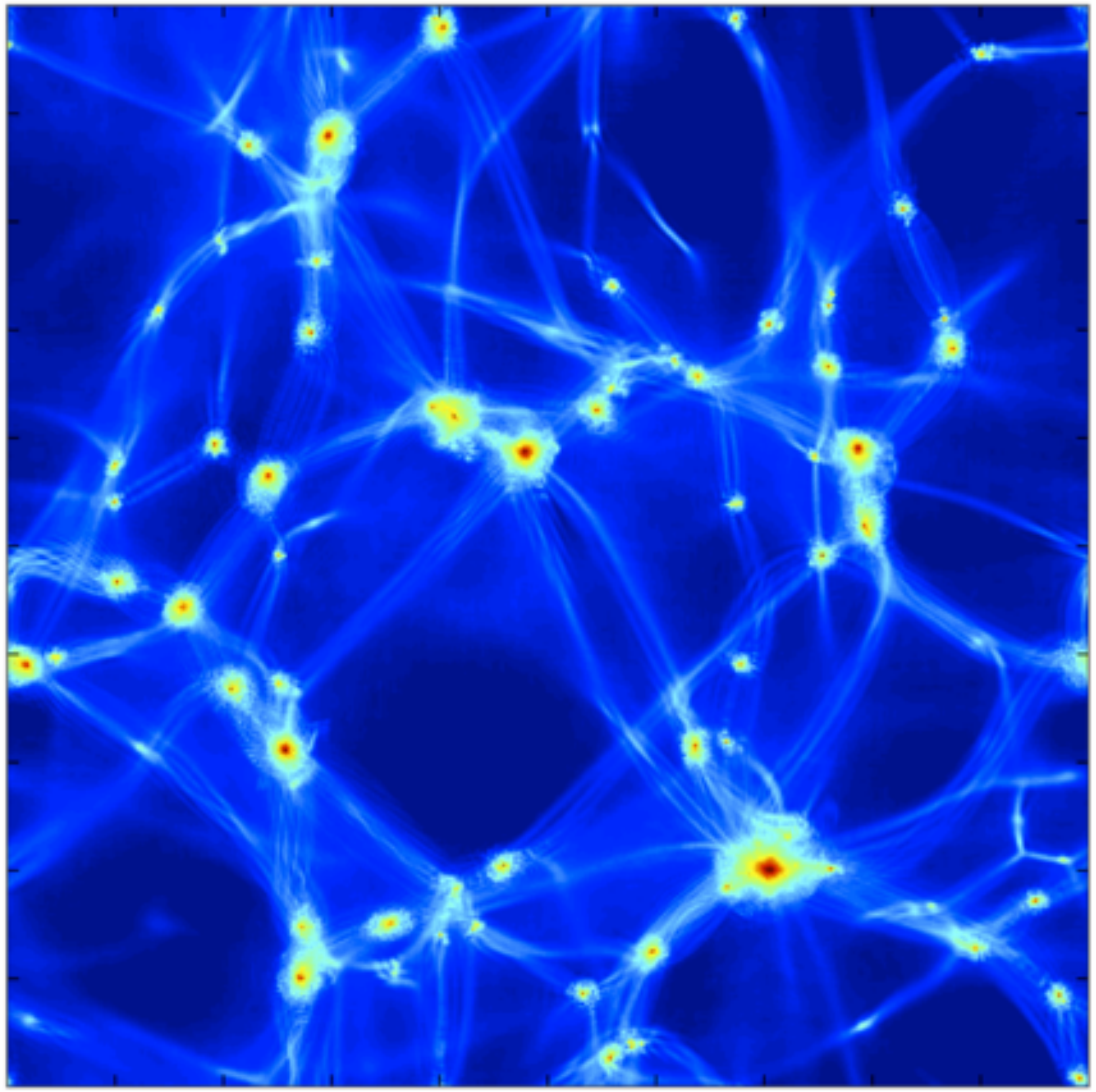
Fuzzy Dark Matter (FDM)

Ultra Light Bosons, Wave-like, Axion-like

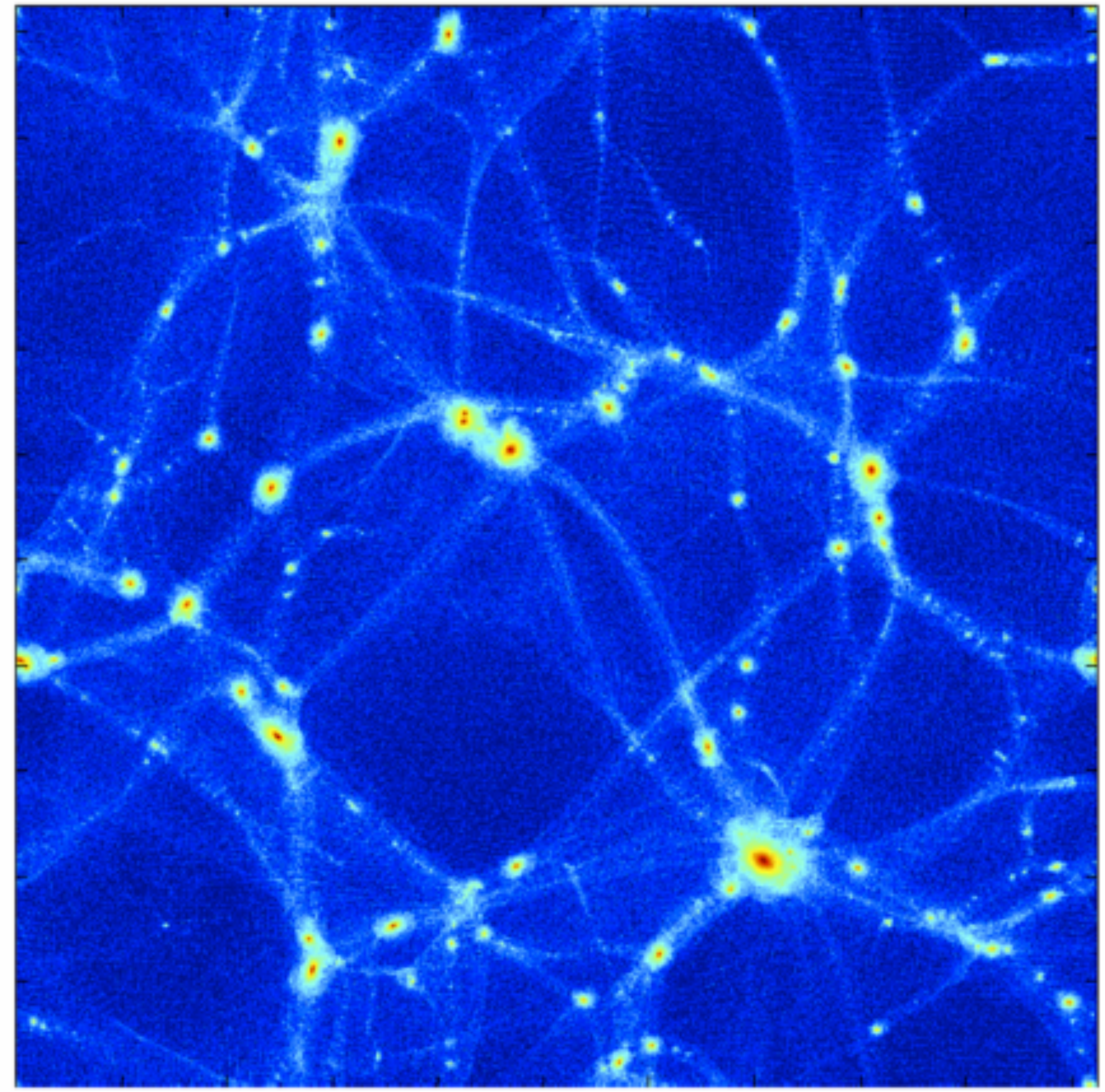
- non-thermal boson field (particularly scalar), non-rela, low-momentum state as a cold BEC
- m~10^{-22} eV, **$\lambda_{\text{de Broglie}}$**~1kpc, $< 10^{7}\left(\frac{m}{10^{-22}eV}\right)^{-3/2} M_{\odot}$
- suppresses halo formation @ $< 10^{10}\left(\frac{m}{10^{-22}eV}\right)^{-4/3} M_{\odot}$
- halo abundance reduced at
- forms a central core as a "**soliton**" (Schrödinger-Poisson eq.)
- on large-scales, $\approx$ CDM

…, Baldeschi+83; Kim '87; Sin+94; Hu+00; Marsh+14; Schive+14; Hui+17; Mocz+17; ….

FDM



≈ CDM (more like WDM)

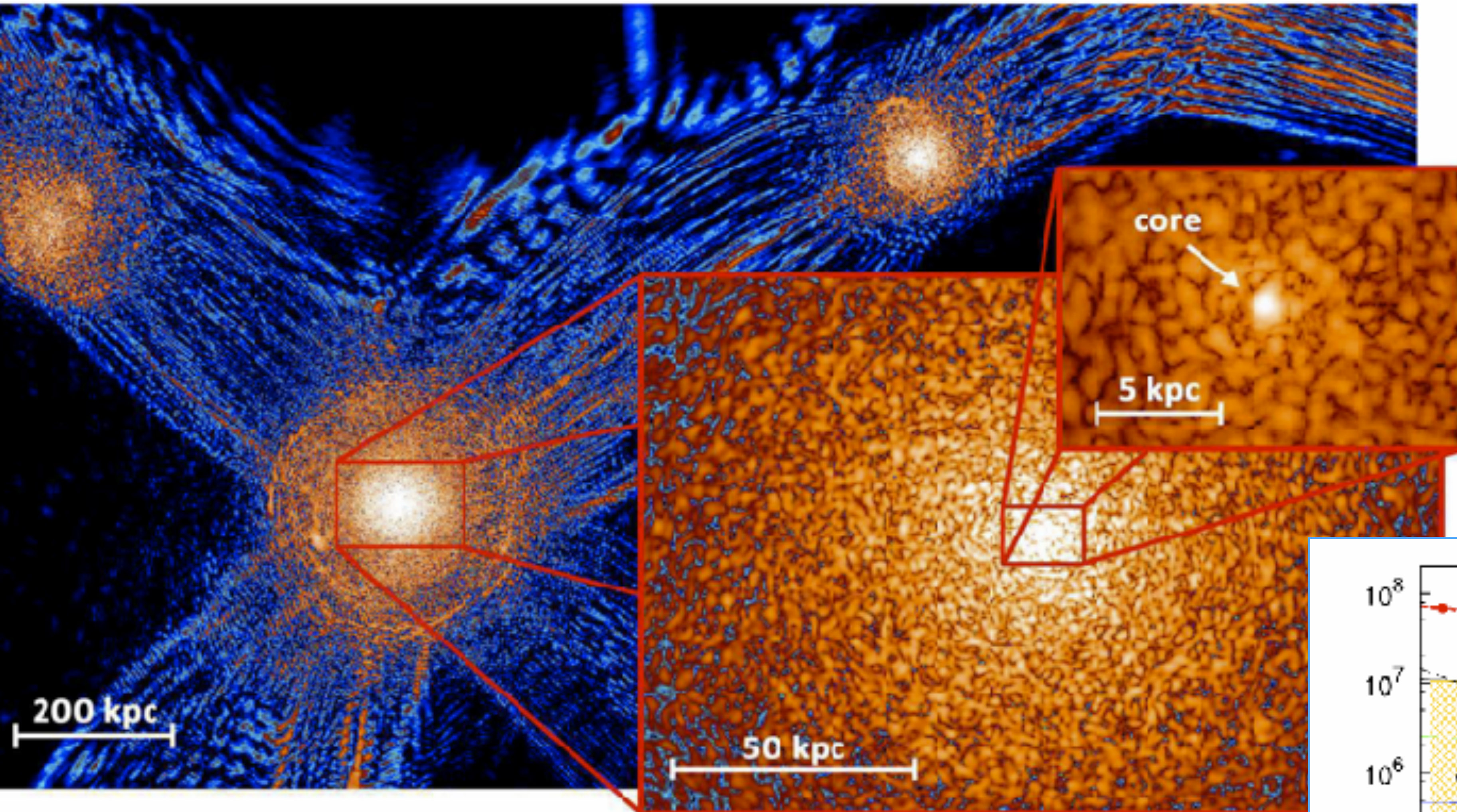


Uncertainty principle counteracts gravity below Jeans scale

Schive+14

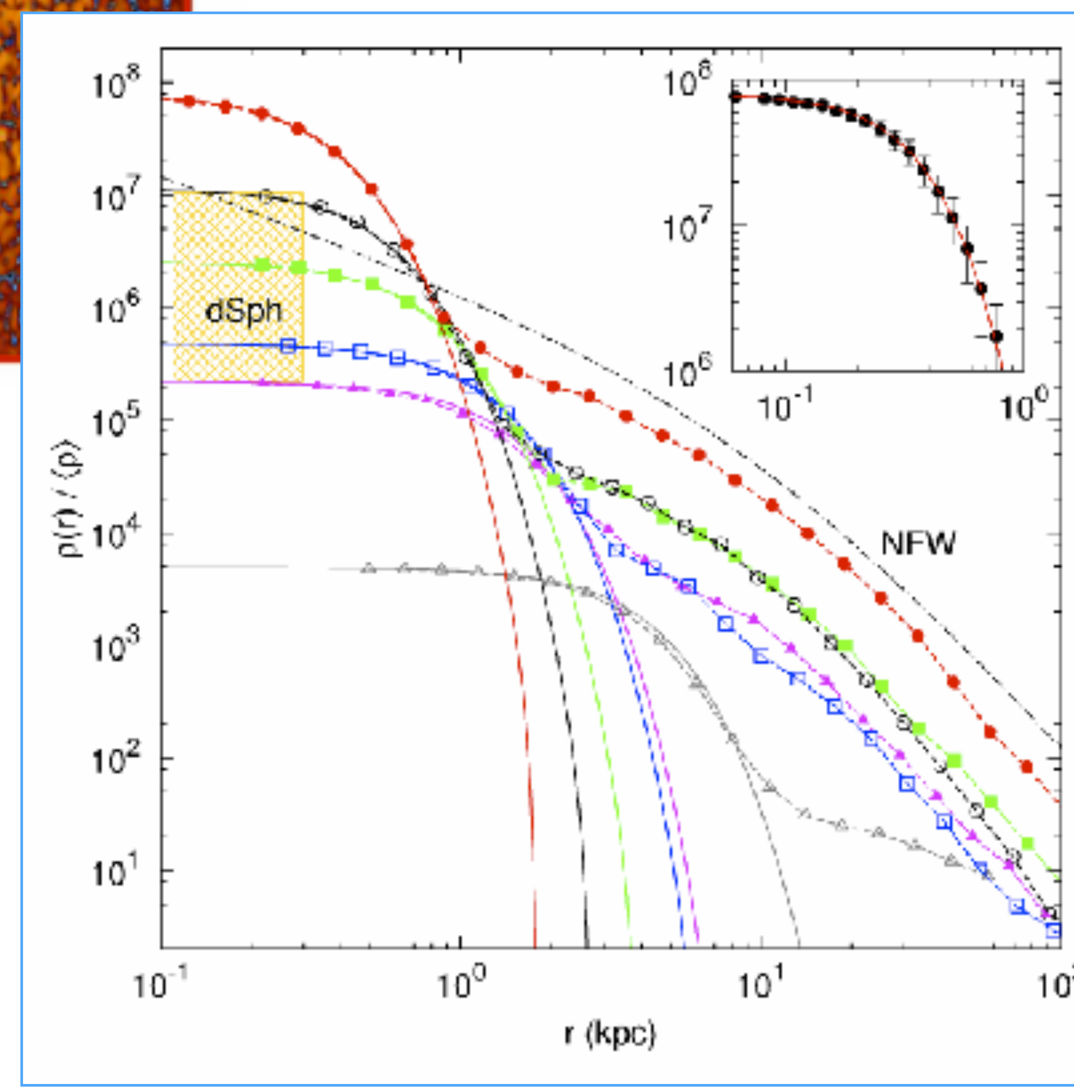
- adds new form of quantum pressure from uncertainty
- comoving Jeans length: $\lambda_J \propto (1+z)^{1/4} m_B^{-1/2}$

Solitonic Core of FDM simulation



Schive+14

gravitationally bound solitonic core



e.g. $m_B = (8.1^{+1.6}_{-1.7}) \times 10^{-23}\ \mathrm{eV}$

for Fornax dSph gal.

$$M_s \propto\!\!\!\!\sim M_{gal}^{1/3}$$

$M_s \simeq 2 \times 10^9\ M_\odot$ for MW core

The impact of ultra-light axion self-interactions on the large scale structure of the Universe

Desjacques+'17 arXiv:1709.07946

- constraints from Lyα P(k): $m > 2 \times 10^{-21}$ eV

cf. Irsic+17; Armengaud+17; but Zhang+17

- **But**, **attractive force due to self-interaction btw ULA**
  - semi-analytic linear stability analysis
  - **cosmic web can be influenced.**

- needs further numerical simulation studies

reconsider Schive+14; Calabrese+16; Zhang+16; Mocz+17; ….

$$\Omega \sim 10^{-1} \left(\frac{f}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{1/2}$$

f: decay const (symmetry-breaking scale)

extremely tiny quartic coupling: $\lambda = \frac{m^2}{f^2} \sim 10^{-96}$;

Various Dark Matter

& Astrophysics

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