Dark Matter and Structure Formation in the Universe

E01 分担者　長峯健太郎

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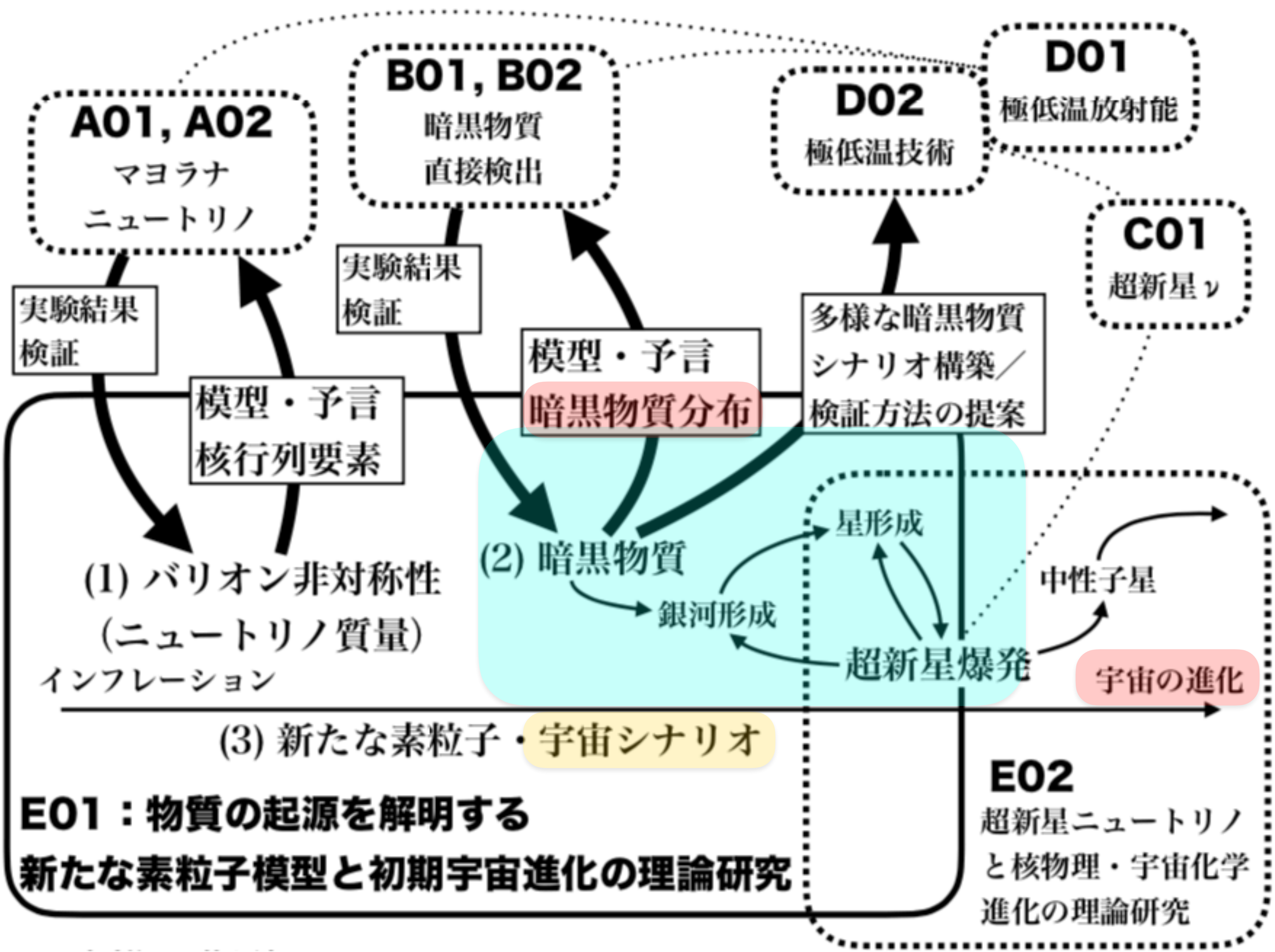


A01, A02
マヨラナ
ニュートリノ
B01, B02
暗黒物質
直接検出
D02
極低温技術
D01
極低温放射能
C01
超新星ν
実験結果
検証
実験結果
検証
模型・予言
暗黒物質分布
多様な暗黒物質
シナリオ構築／
検証方法の提案
模型・予言
核行列要素
(1) バリオン非対称性
(ニュートリノ質量)
インフレーション
(2) 暗黒物質
銀河形成
星形成
超新星爆発
中性子星
宇宙の進化
(3) 新たな素粒子・宇宙シナリオ
E01：物質の起源を解明する
新たな素粒子模型と初期宇宙進化の理論研究
E02
超新星ニュートリノ
と核物理・宇宙化学
進化の理論研究

Various Dark Matter

$m_{\rm DM}$ (self-interacting DM)

GeV-TeV — **CDM** — ***Thermal relic WIMP*** (10GeV ~ 1TeV)

$v_{\rm th} \approx 0\,{\rm km/s}$

keV — **WDM** — becomes non-relativistic earlier; suppress perturbation at galactic or smaller scales

$v_{\rm th} \approx 0.03\,{\rm km/s}$

(gravitino, sterile neutrino,…)

eV — **HDM** — remains relativistic until late time, and erase structures at super-galactic scales. (**ν**,…)

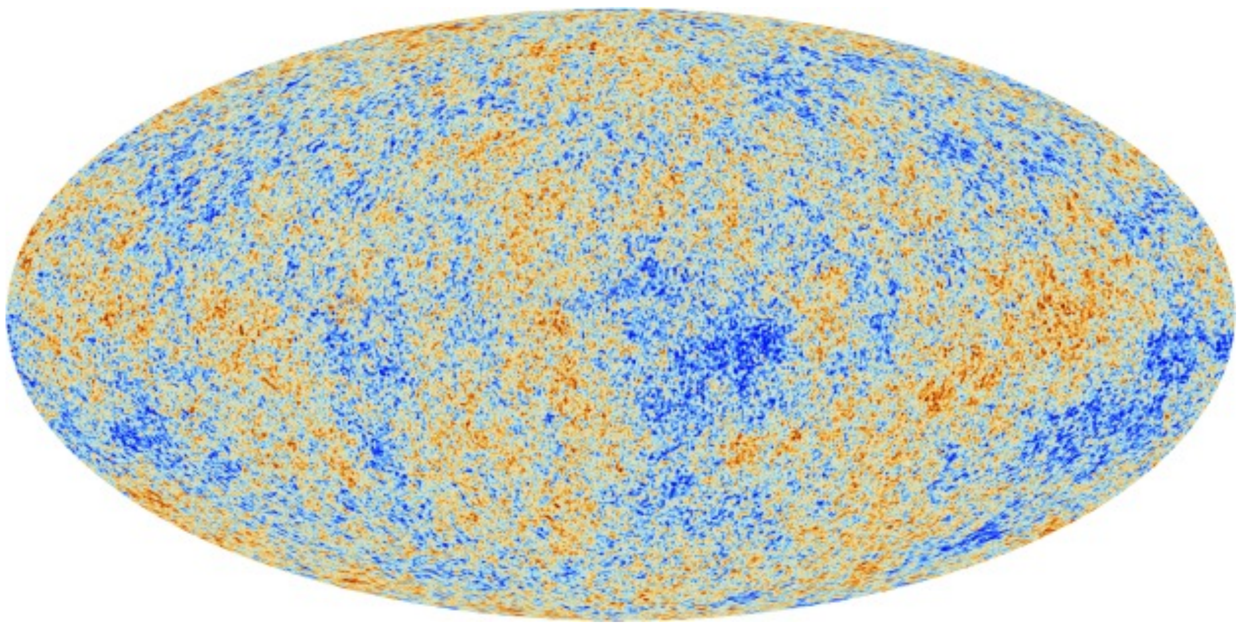
$v_{\rm th} \approx 30\,{\rm km/s}$

meV~μeV — standard QCD-**axion** (1μeV~ 1meV)

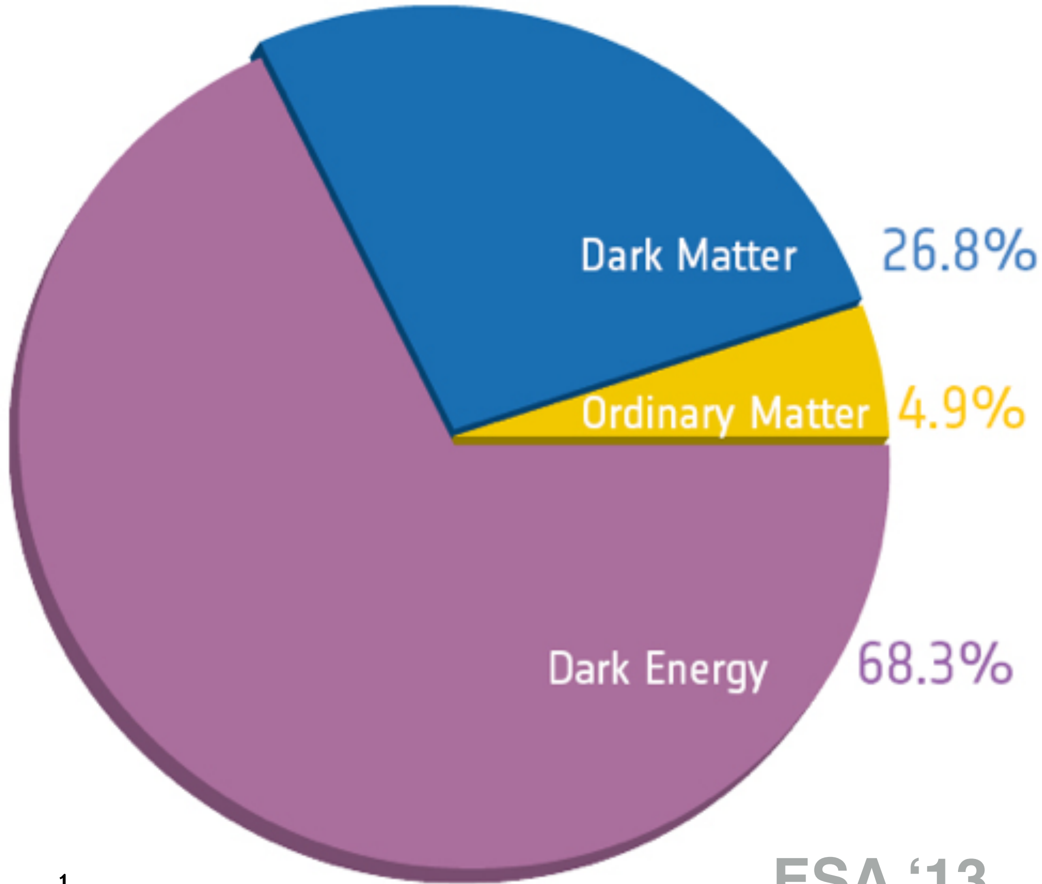
10^{-22} eV — **FDM** (Fuzzy DM; axion-like, ALP, ULA)

quantum pressure

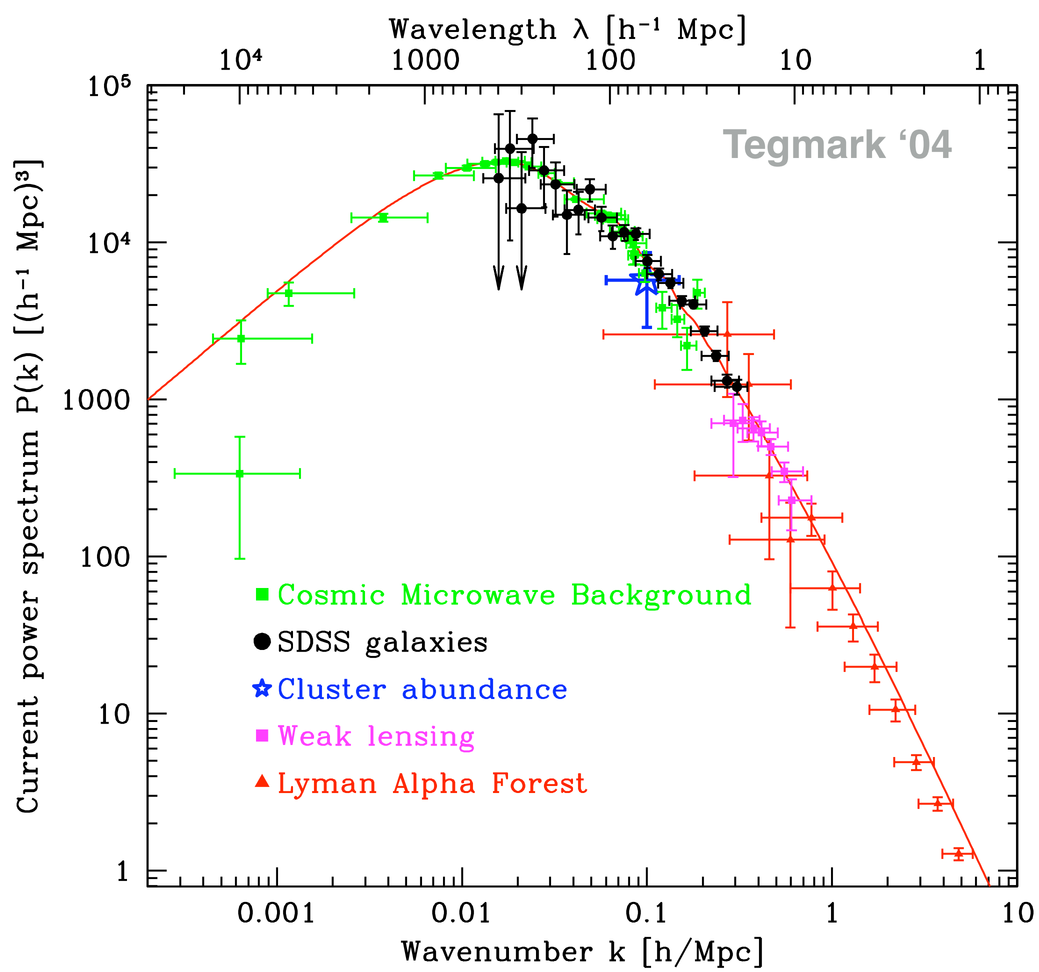
``Era of Precision Cosmology"



Planck



ESA '13

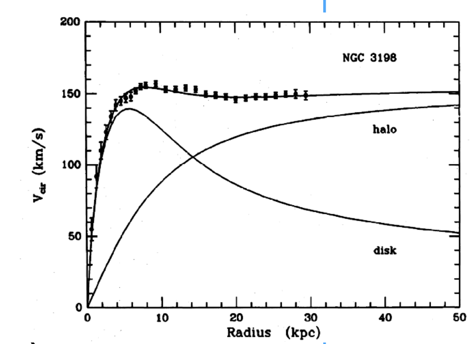


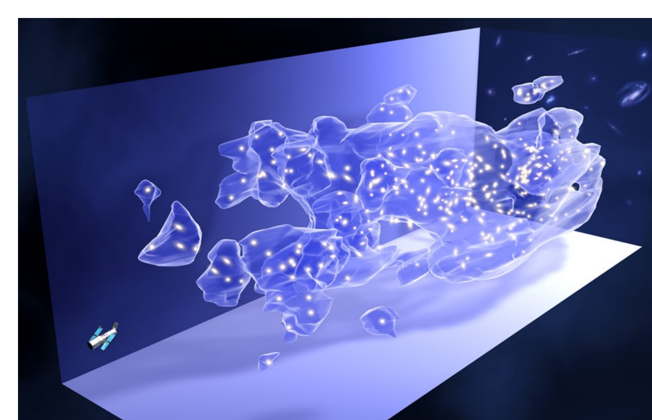
$$\frac{\Omega_{\rm DM}}{\Omega_b} \sim 5$$

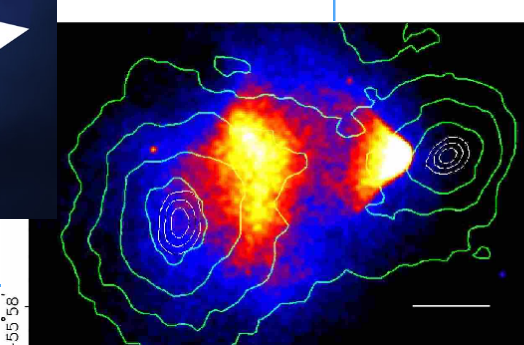
Evidence of Dark Matter

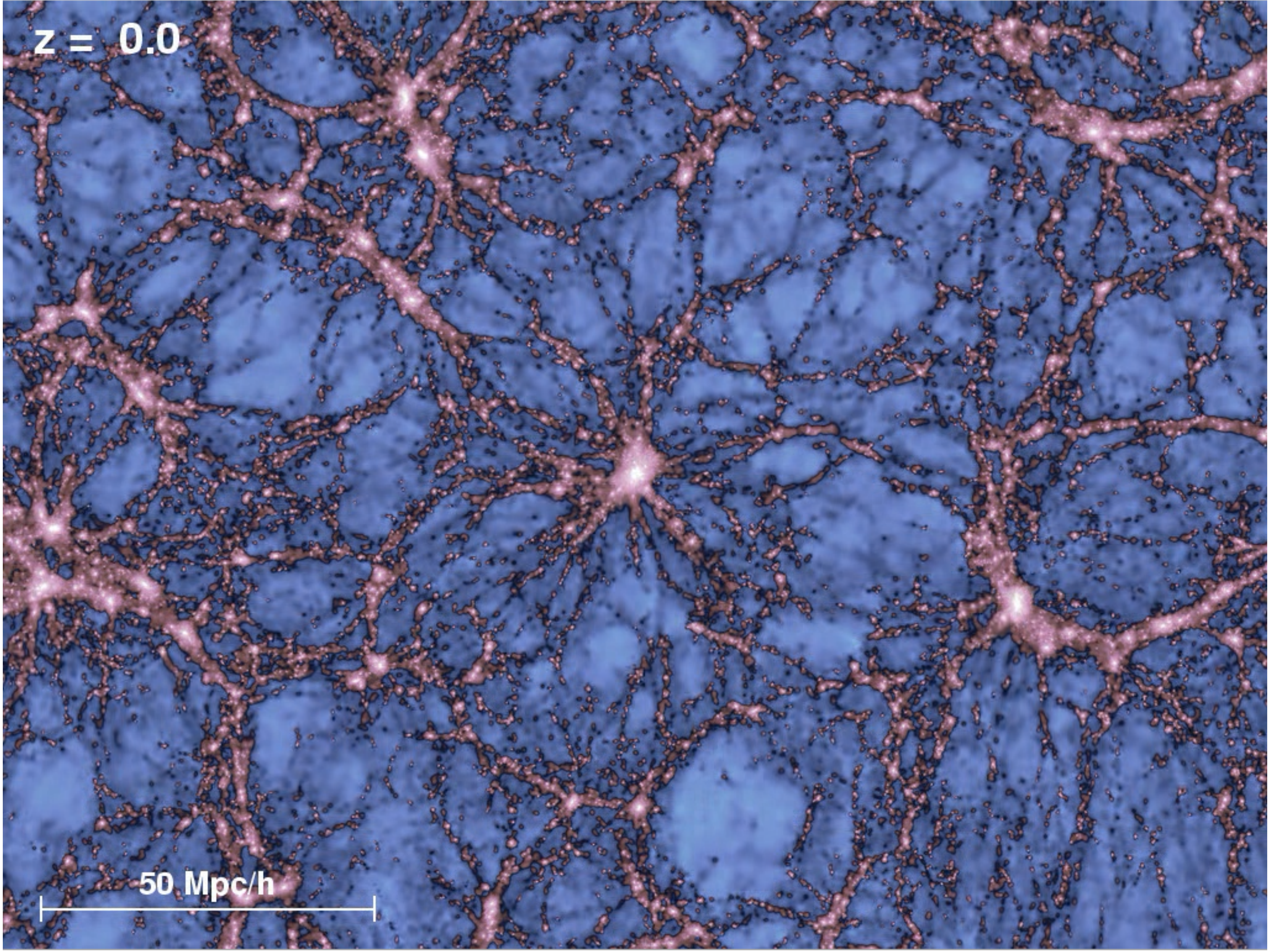
success of CDM on large scales (≳10 kpc)

- stellar motions: Lord Kelvin (1884); Kapteyn '22; Oort '32
- **Galaxy clusters** — ~80% of mass is dark (Zwicky '33)
- **Galaxy rotation curves** (Rubin & Ford '70)
- **Galactic disk stability (stellar kinematics)** (Ostriker & Peebles '74)
- **Cosmic Microwave Background (CMB)** (angular power spec)
- **Structure formation** — P(k), galaxy clustering, Ly-α forest
- **Gravitational lensing** (strong & weak)
- **Bullet Cluster** (Markevich+'02; Clowe+'06)
- ……









galaxy bias: $\delta_{\rm gal} = b\,\delta_{\rm m}$

Millenium Simulation

`Standard Model' of Cosmic Structure Formation

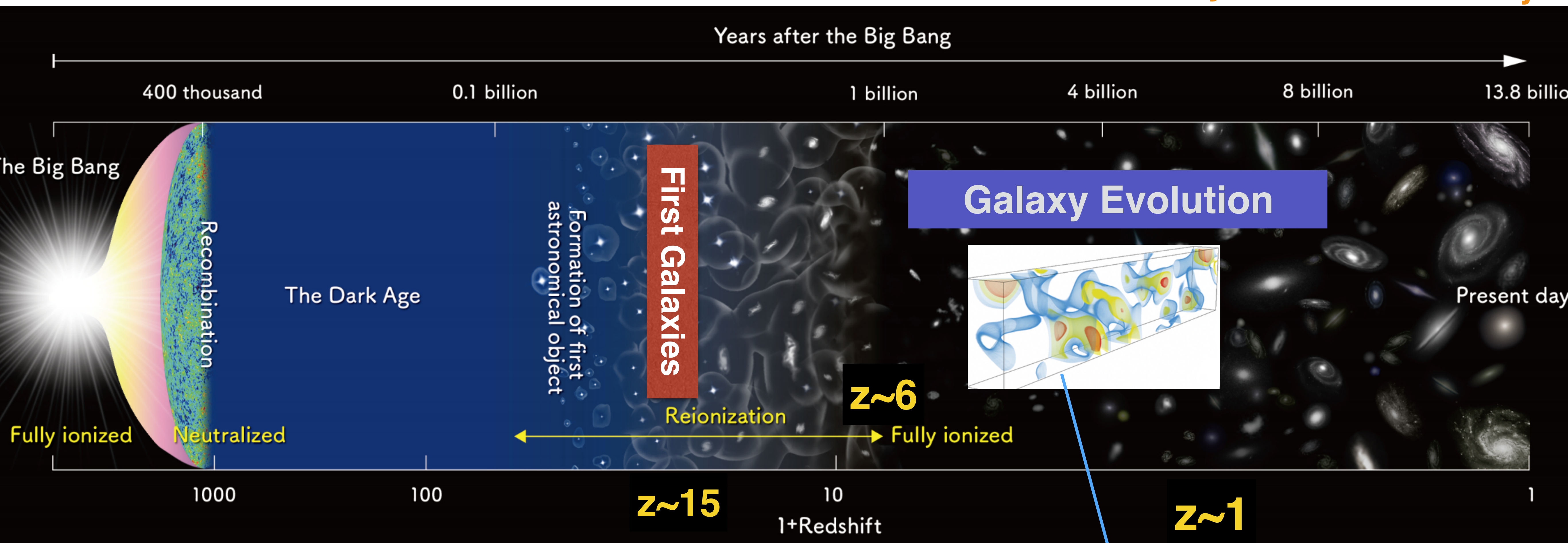
(ΛCDM model)

Cosmic time

1 Gyr

6 Gyr

13.8 Gyr



JWST

HST

SKA

PFS

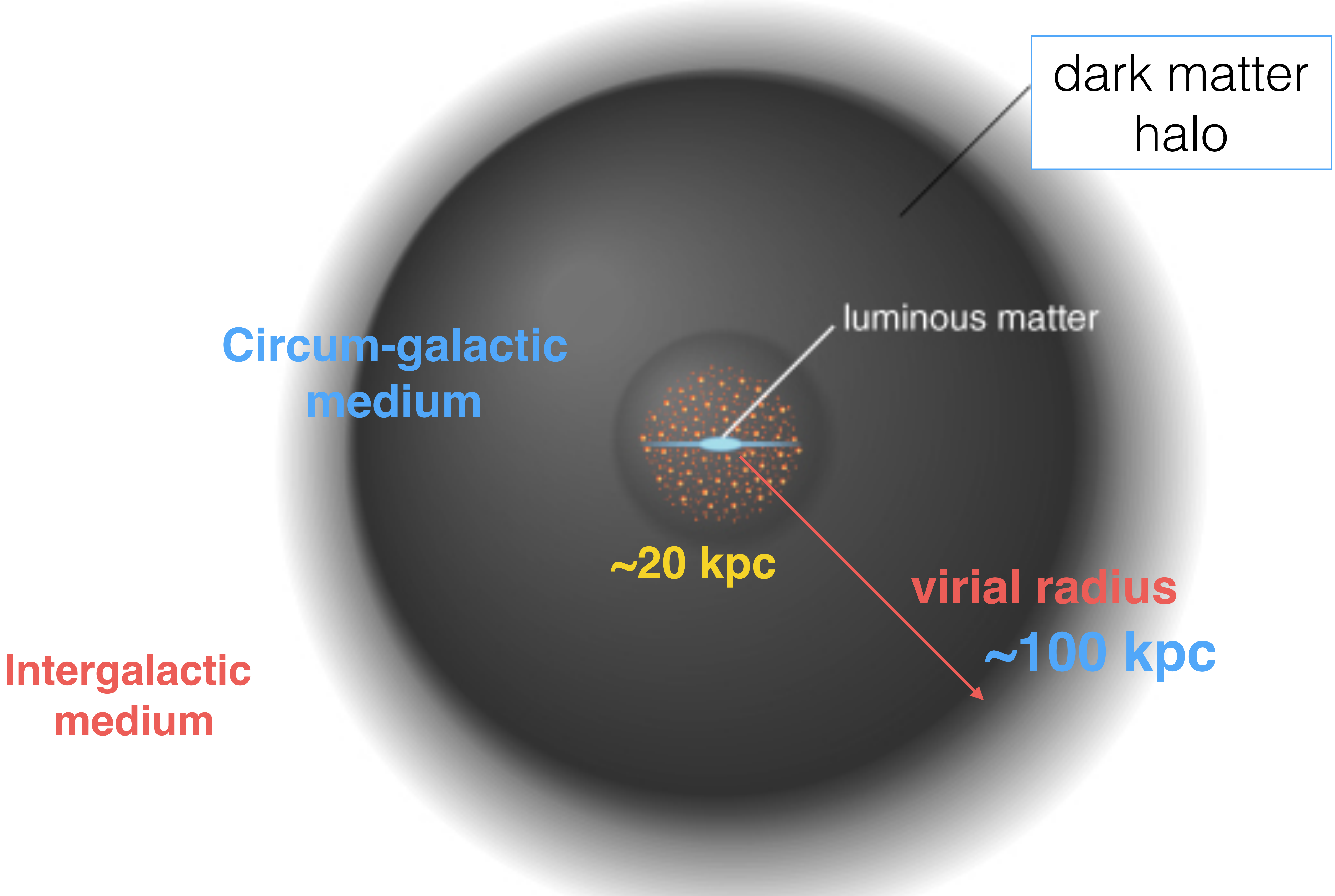
HSC

DES
MOONS
EUCLID…

SDSS, 2dF

Image: NAOJ

DM halo & galaxy



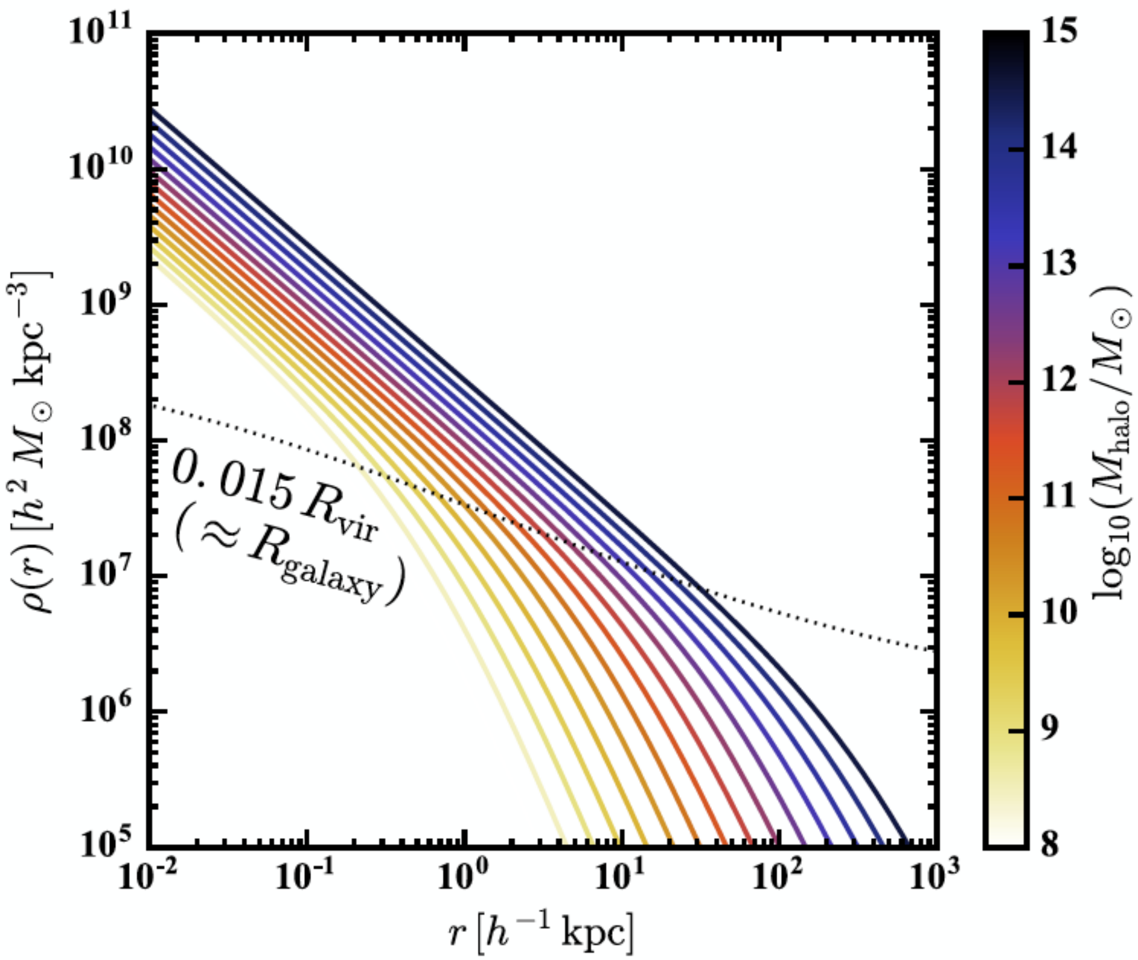
(cf. Spherical collapse model)

Small-scale problems of ΛCDM?

- **Cusp-Core problem:** simulations predicting too steep inner halo profile
  Flores & Primack '94; Moore '94
- **Missing satellites problem:** too much substructure?
  Klypin+'99; Moore+'99
- **Too-big-to-fail problem:** over-abundance of massive & dense substructures (in CDM sim) that could host gals after reionization (but unobserved in MW-satellites)
  Boylan-Kolchin+'11
- **Void phenomenon:** gals in voids are too normal?
  Peebles '01
- **Satellite plane problem:** satellites aligned in a plane for both MW and Andromeda
- ….

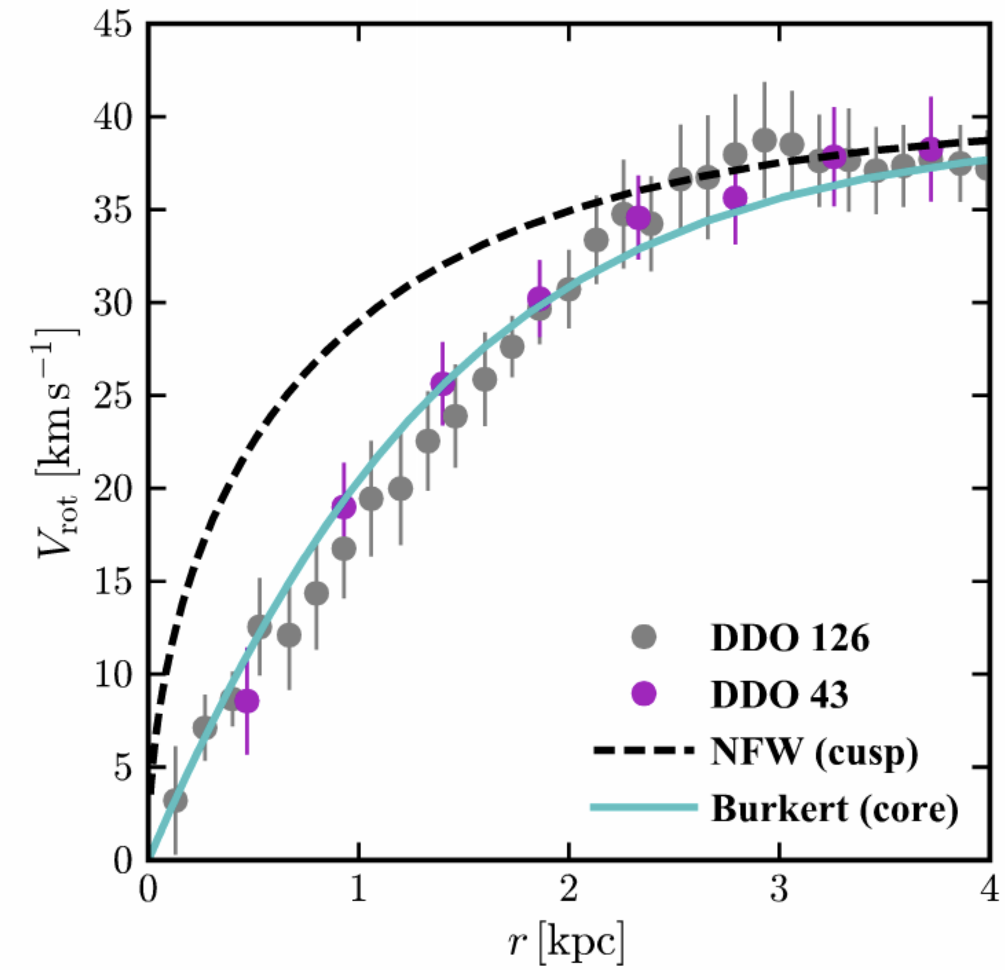
Cusp vs. Core

Navarro-Frenk-White (NFW) profile



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

LITTLE THINGS survey Oh+'15



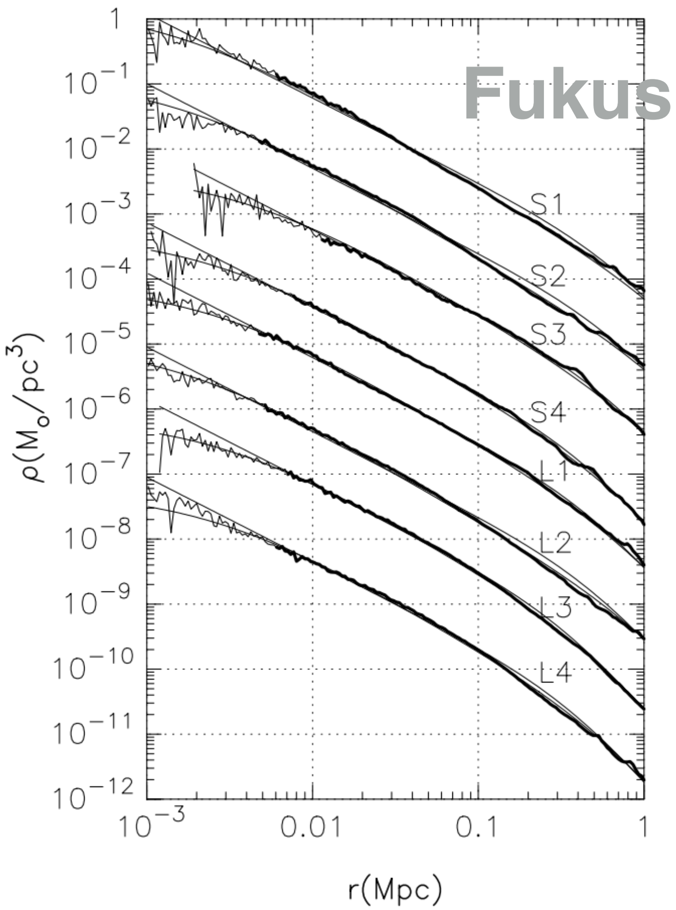
Some observed dwarf gals have flat cores.

review by
Bullock & Boylan-Kolchin '17

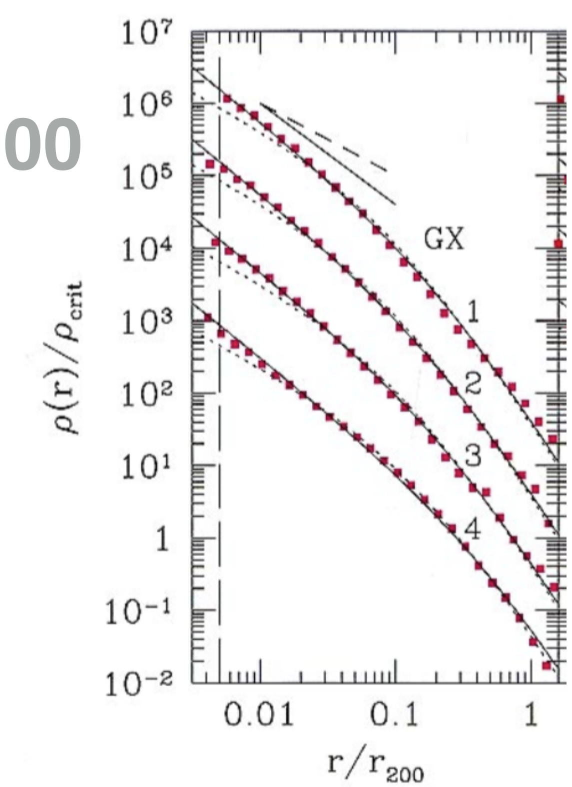
Cuspy profile: non-universal

even with DM-only sims.

Fukushige+'14



Jing & Suto '00



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)

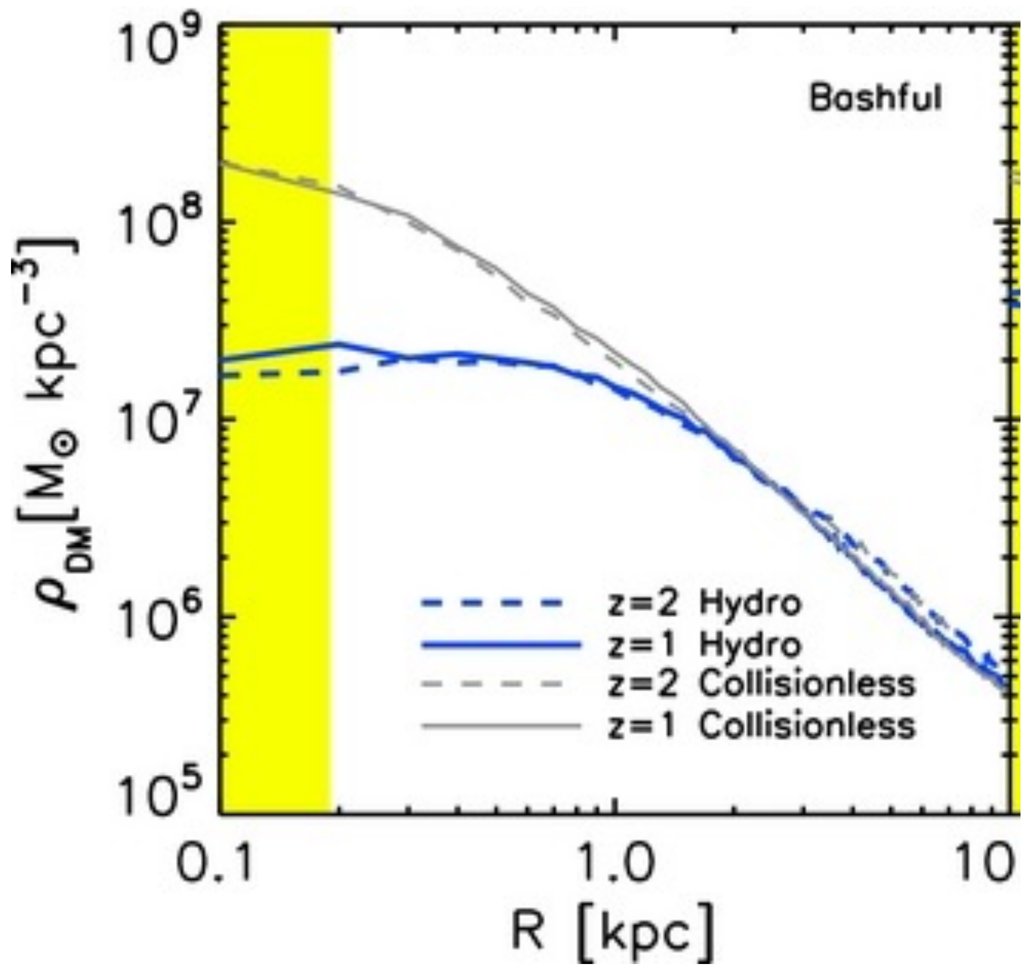
Papers finding not-so-universal profiles:

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: Boylan-Kolchin & Ma

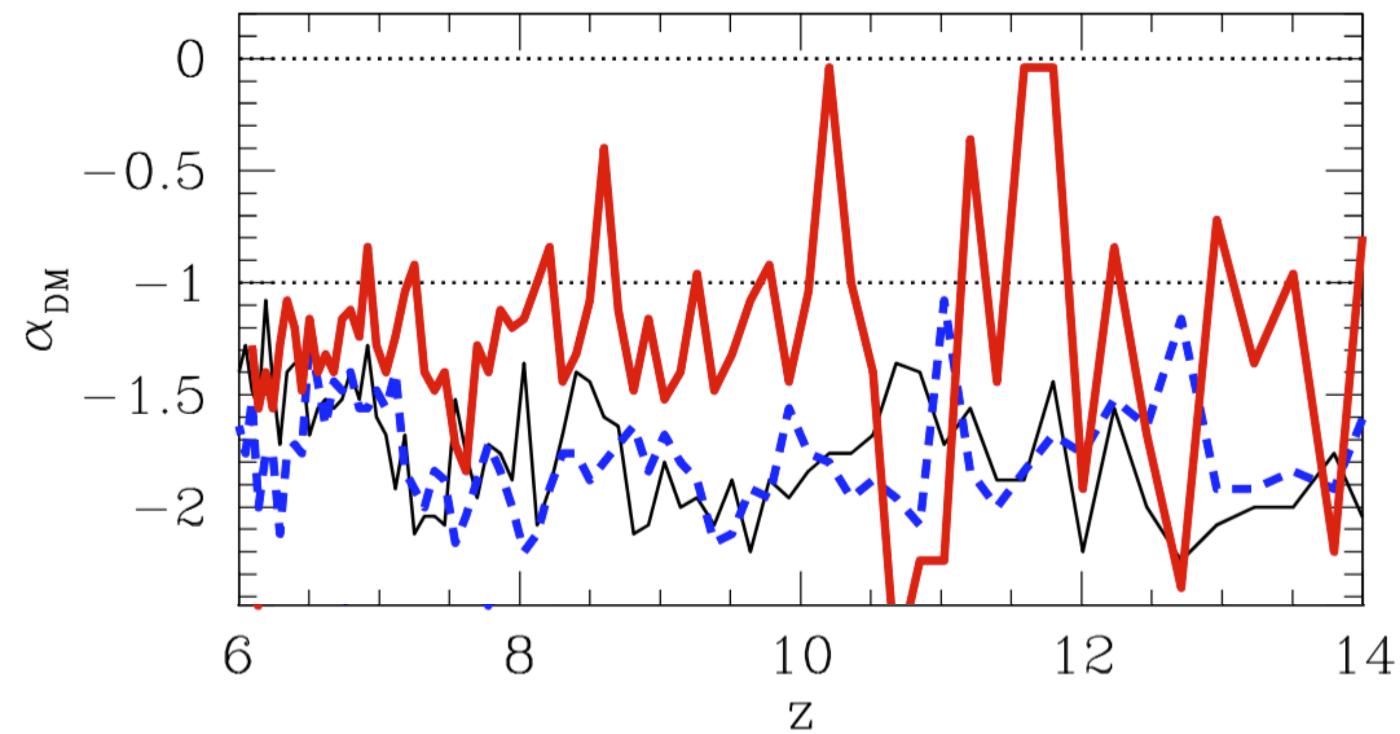
SN-driven outflow creates cores

(zoom-in hydro sim)



Pontzen & Governato '12
Madau+'14

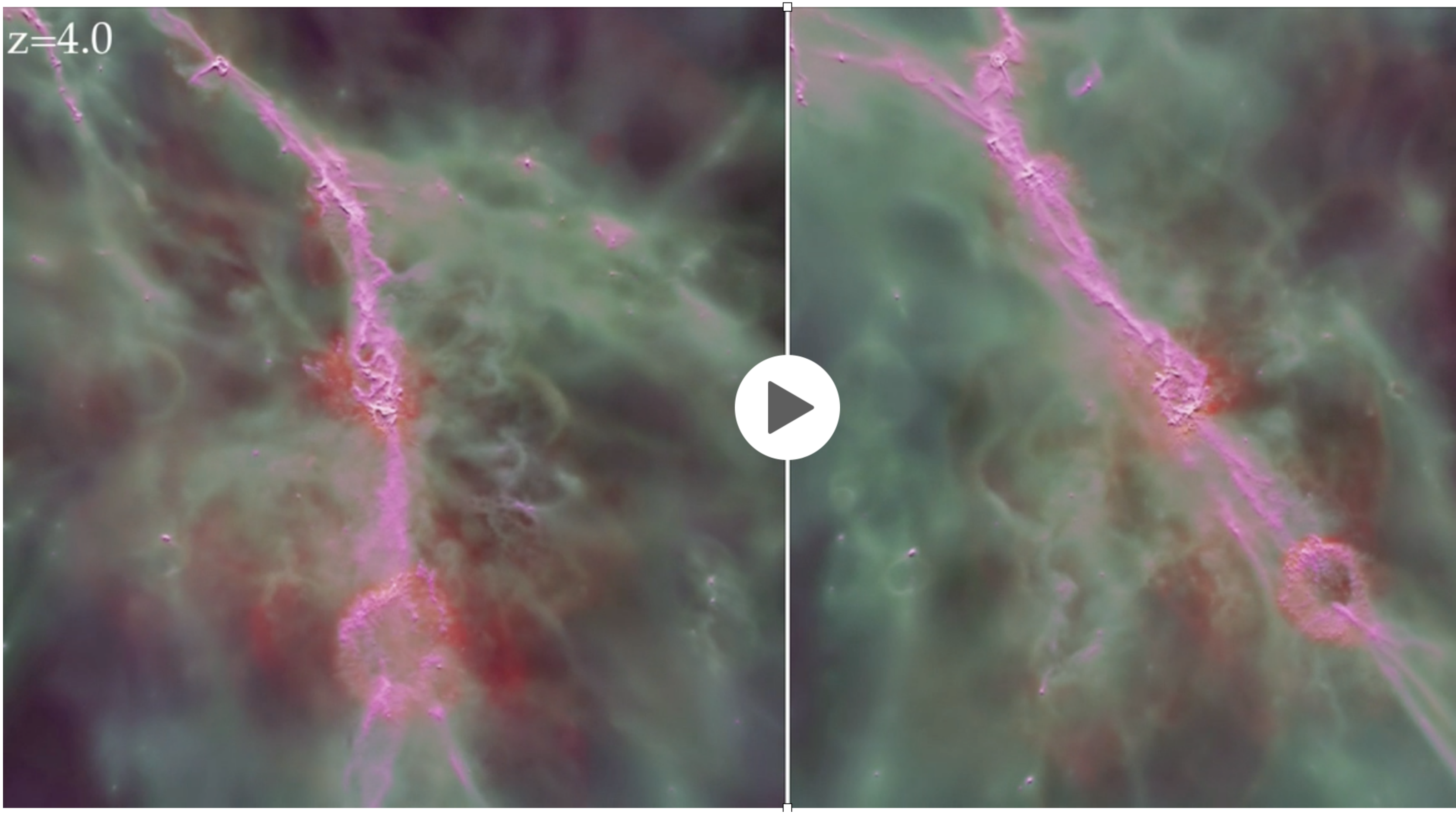
Inner density profile oscillates rapidly.



Yajima, KN+ '17

`Feedback' can remove cusp prob.

Movie



m12q FIRE simulation

m_{dm}~2e5 M⊙/h

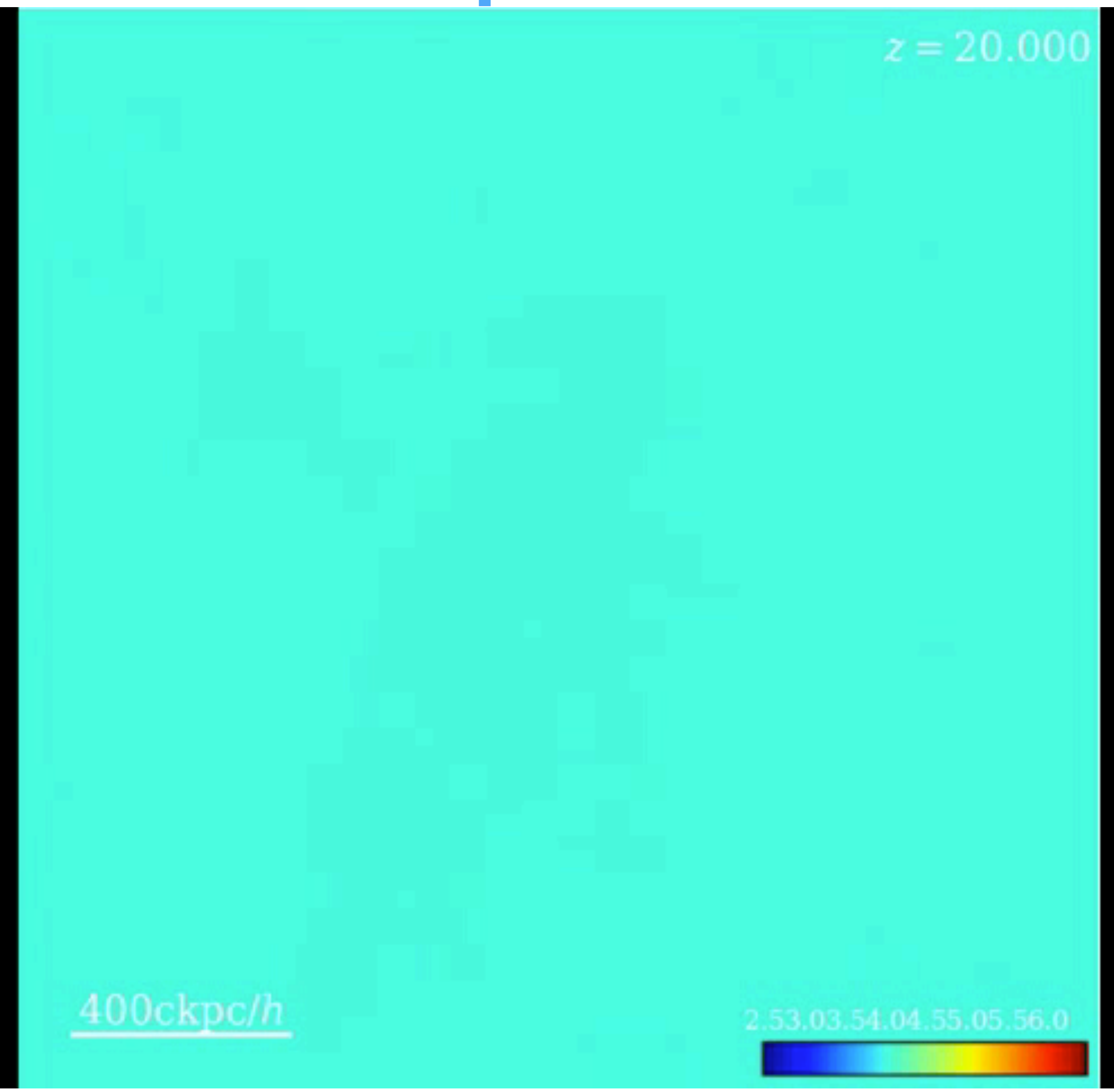
m_b=5e3 M⊙/h

ϵ_{dm}=100 pc/h

ϵ_b=7 pc/h

Gas Density

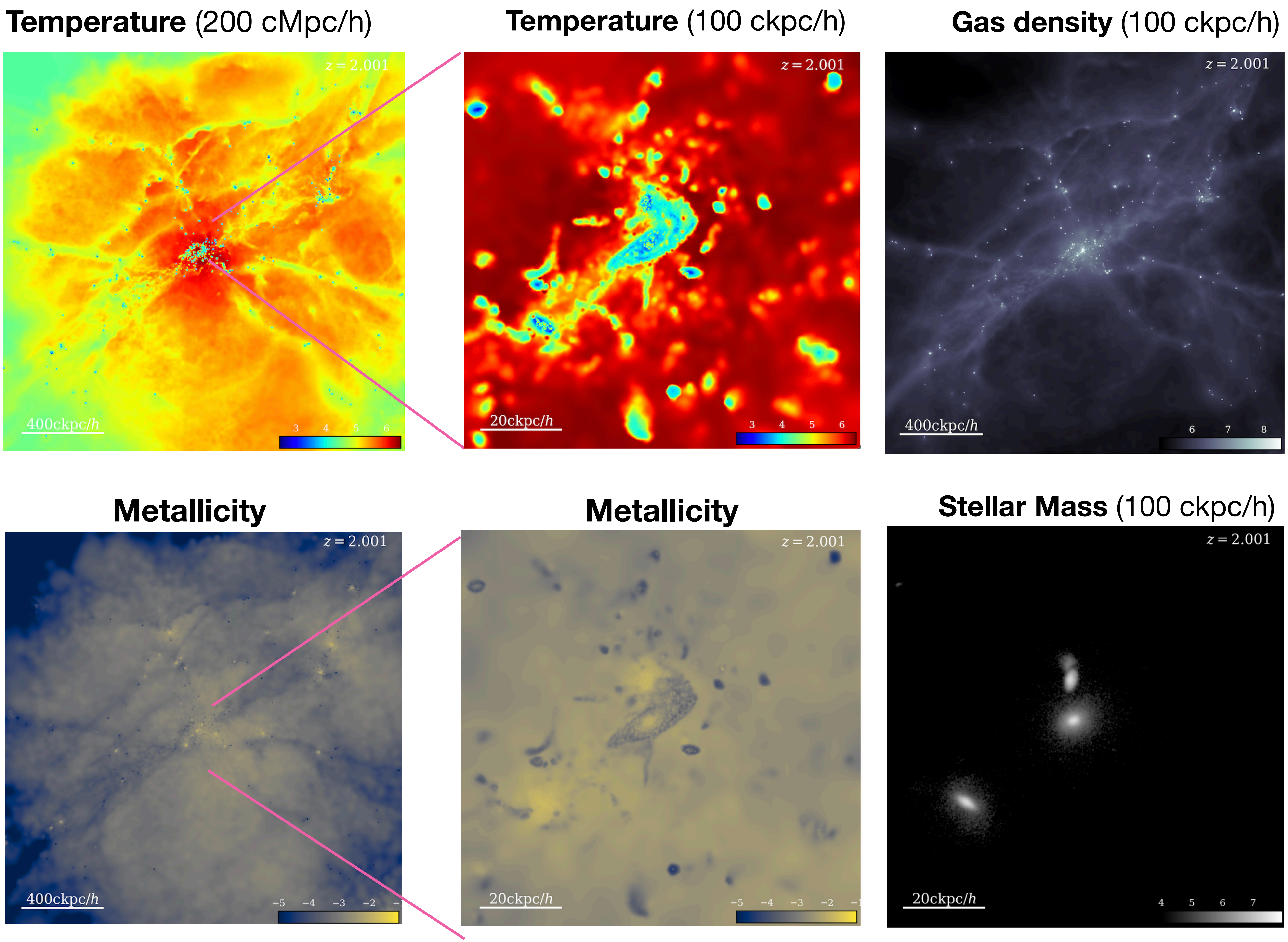
Temperature



AGORA L12 sim.

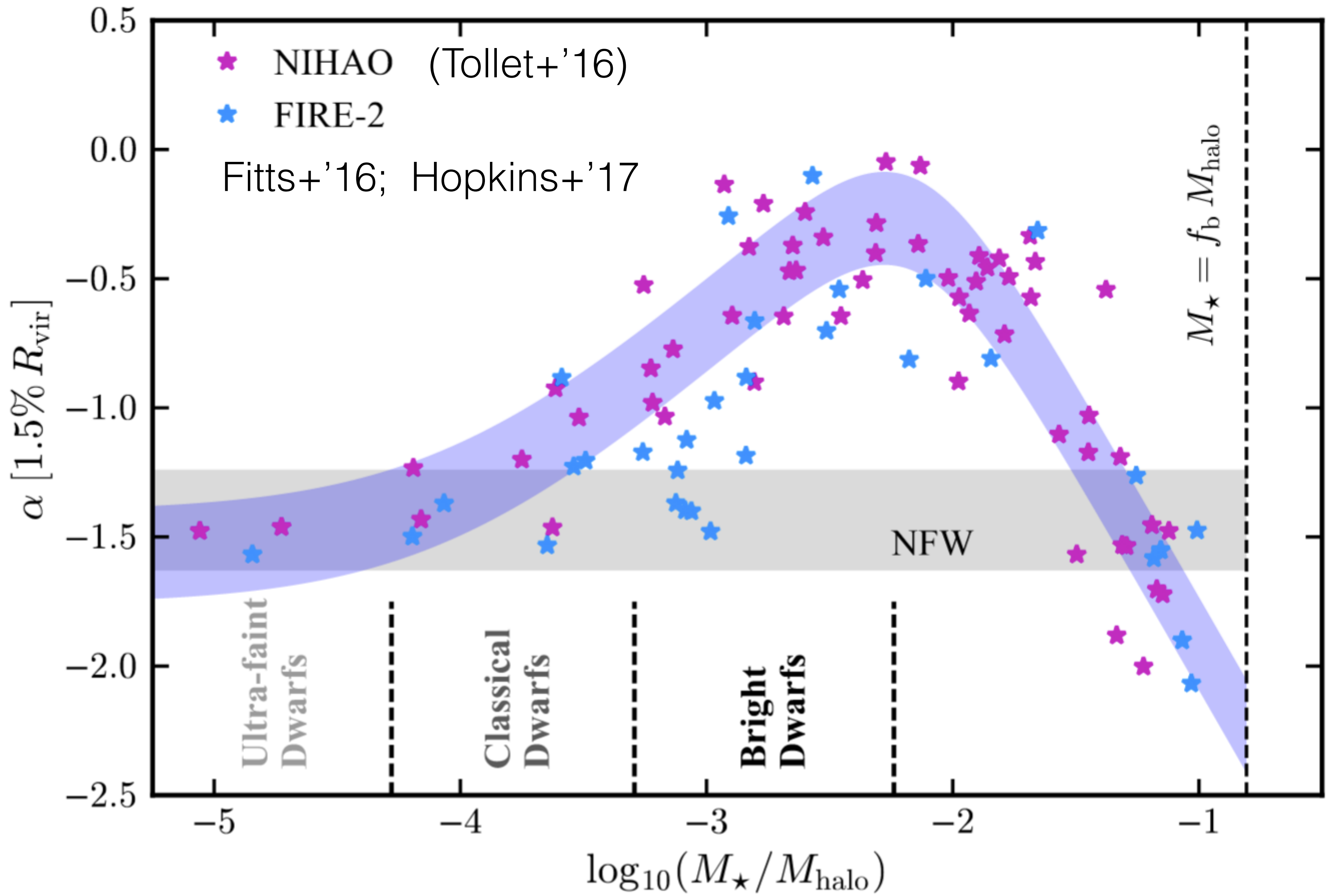
Shimizu & KN'19

Movie



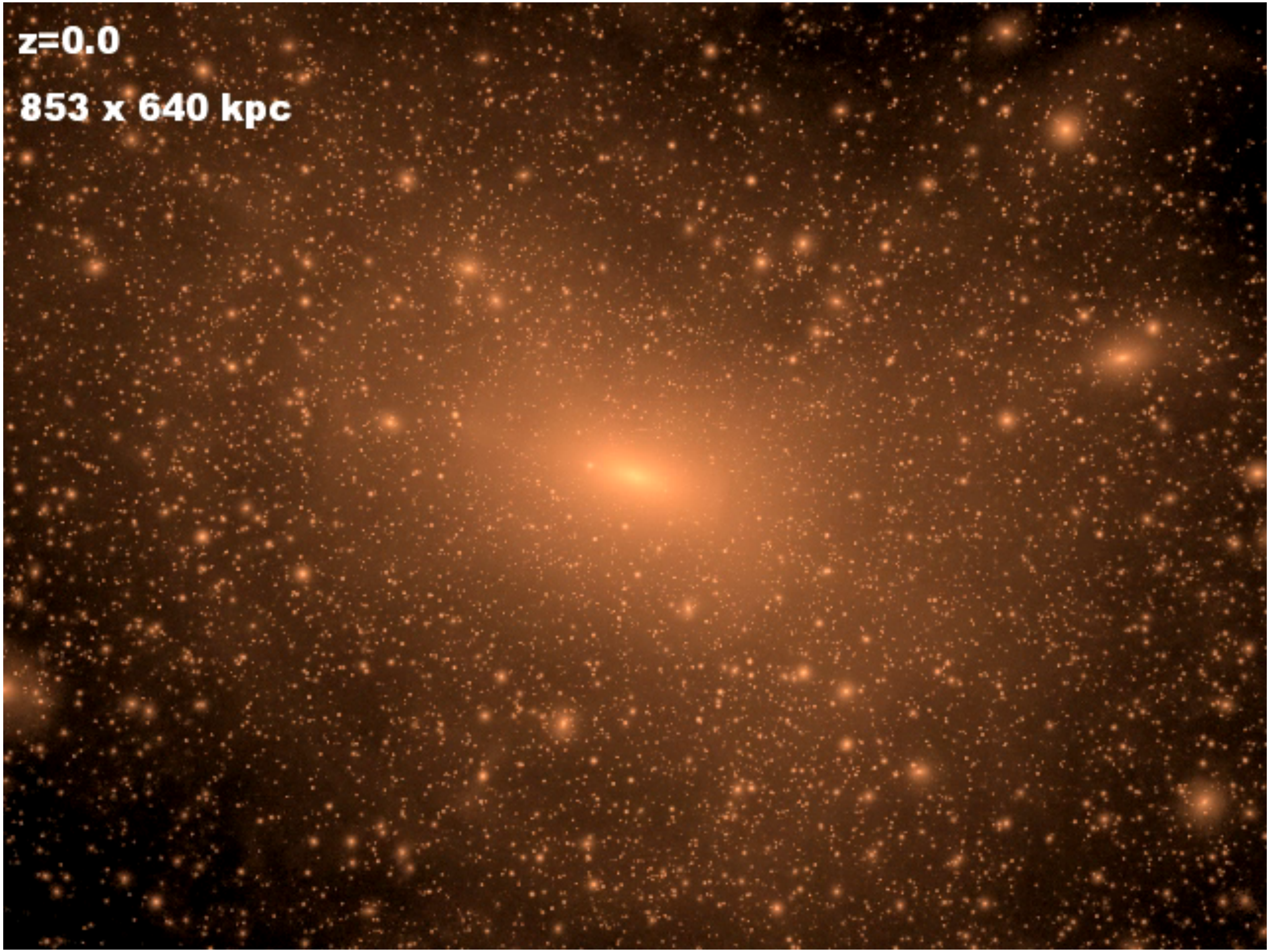
Reference: GADGET3-Osaka simulation (Shimizu et al. 2019); Images: Shimizu & Nagamine (2019, in prep.)

Impact of baryonic feedback on inner density profile



Bullock & Boylan-Kolchin '17

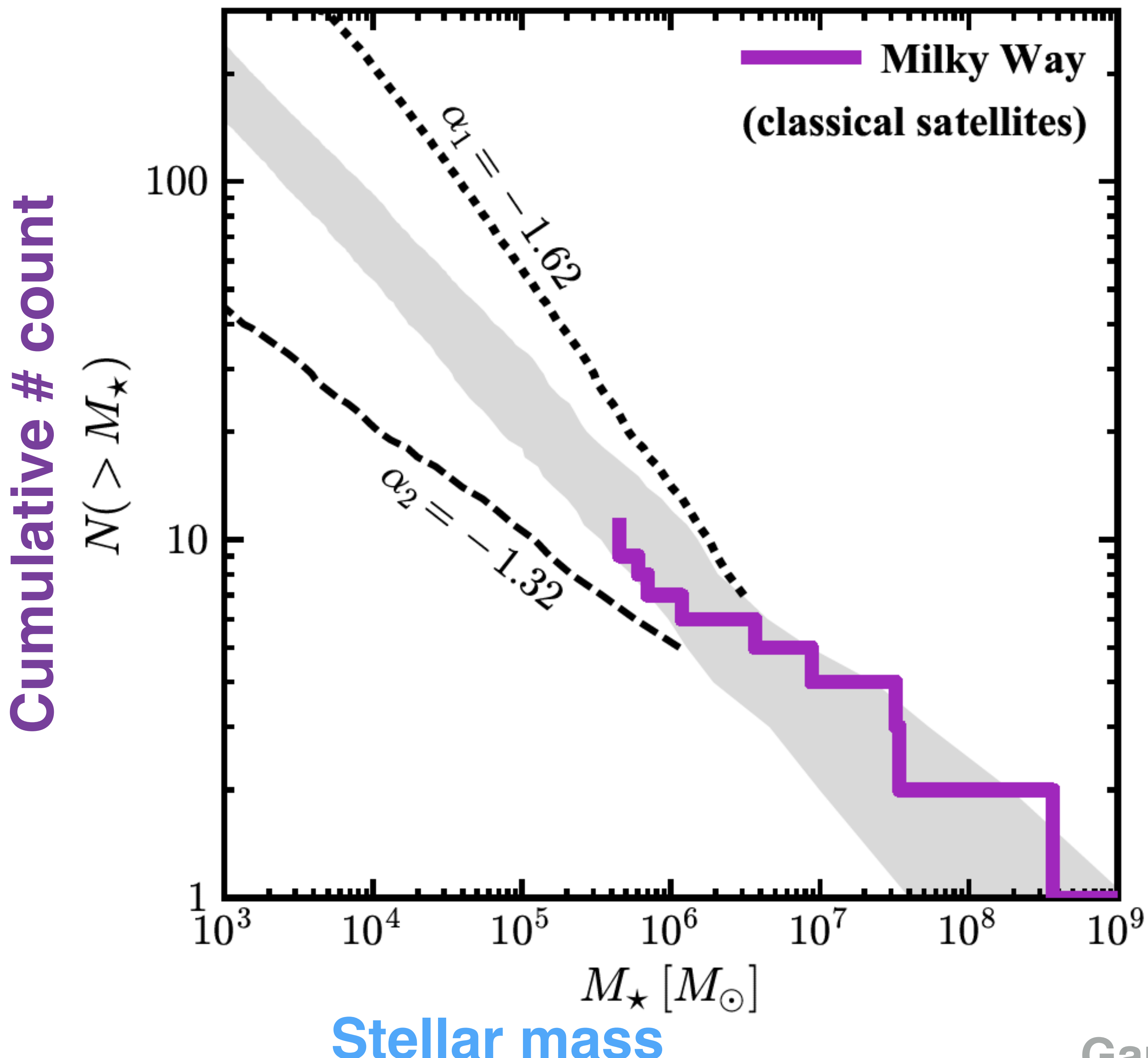
Substructure problem?



Movie

Diemand+'06

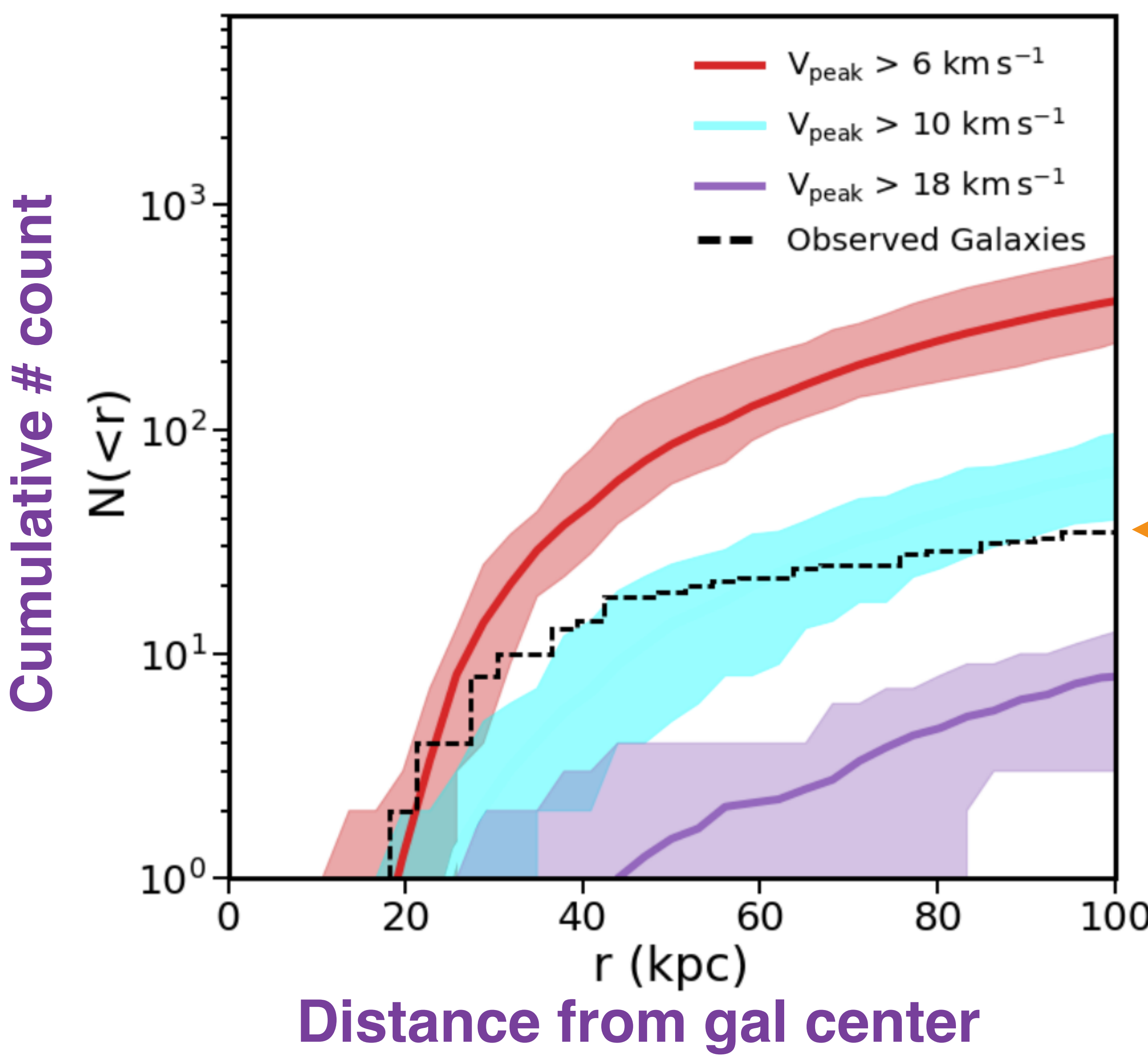
Substructure Problem Solved?



Garrison-Kimmel+'17

Bullock & Boylan-Kolchin '17

No Missing Satellite Problem??



Approaching to reionization suppression scale…

40-50 ultra-faint dwarfs have been discovered

Garrison-Kimmel+'17; Graus+'18

Latest obs by: **SDSS, Pan-STARRS, DES, MagLiteS,…**

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

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

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

Viel+'12

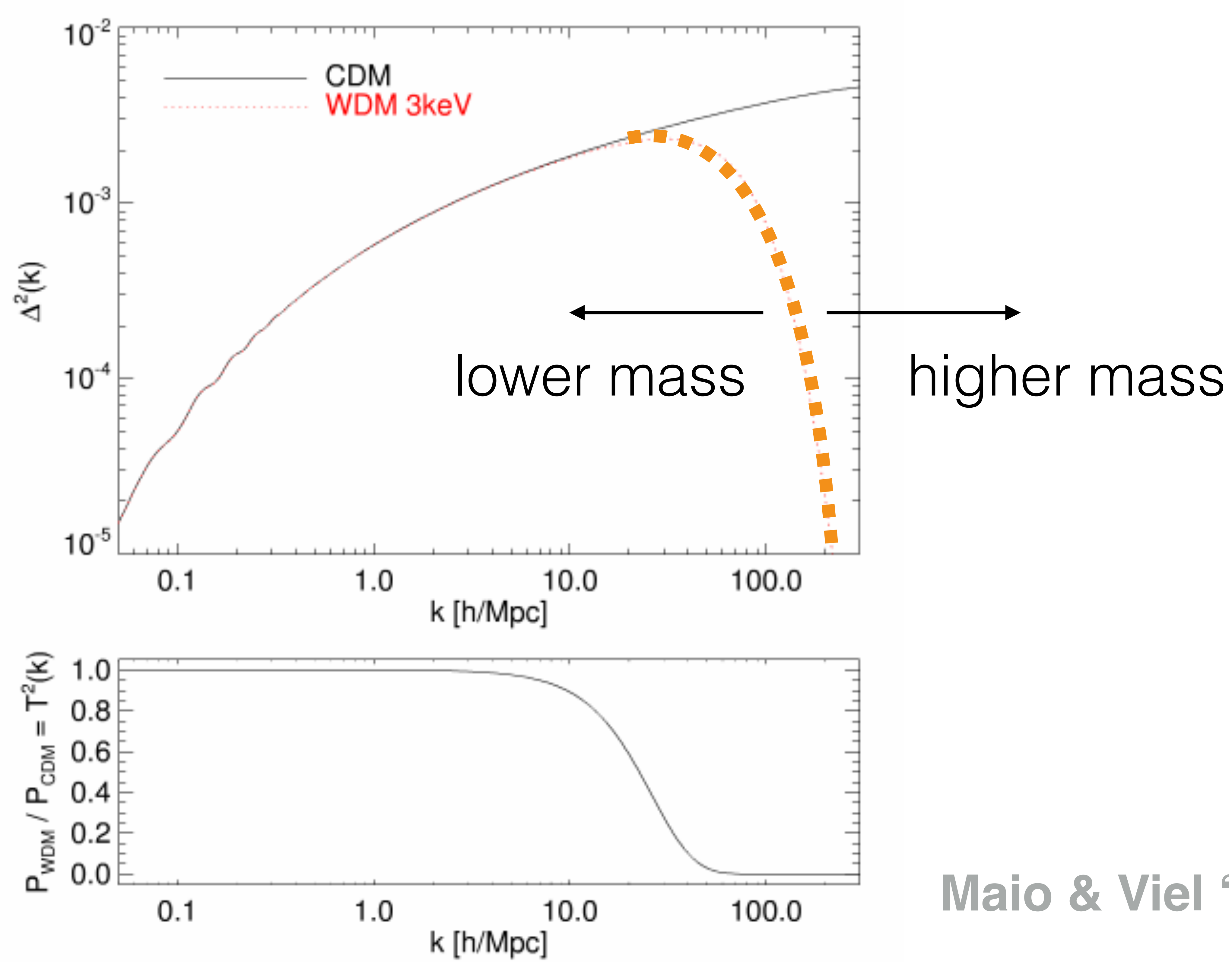
half-mode mass

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

Schneider+'12

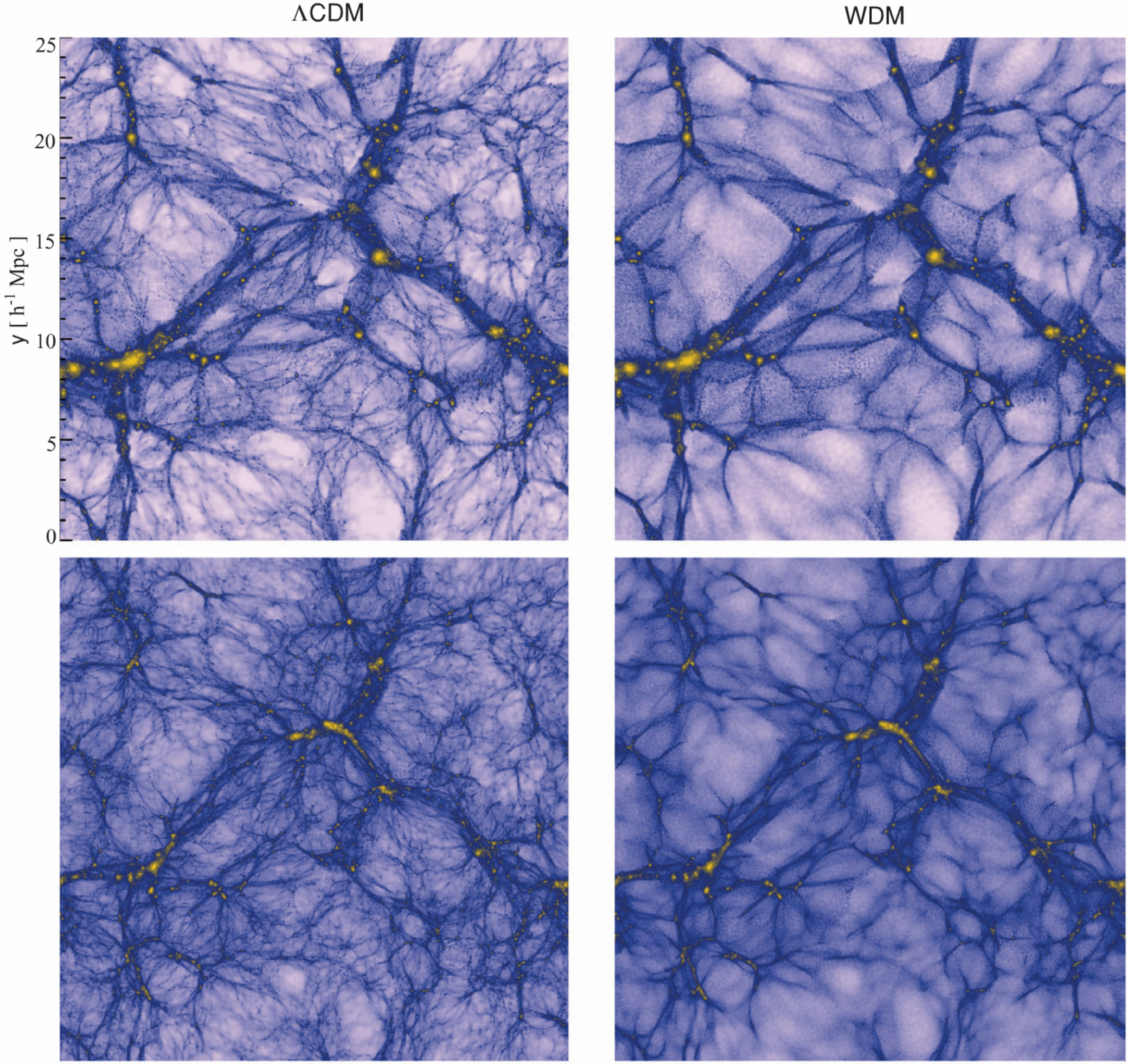
Colin+'00; Bode+'01; Viel+'05; Colin+'08; Colombi+'09; Viel+'12; Menci+'17

WDM
Suppression of P(k) @ small scales



Maio & Viel '15

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



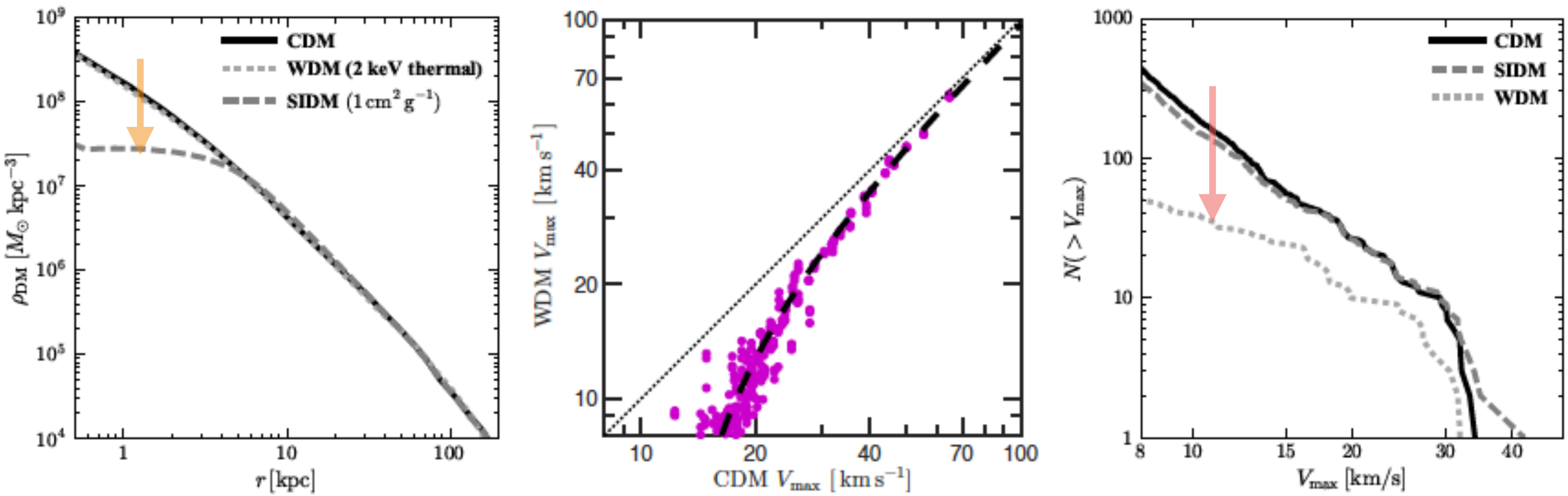
z=0

z=2

m=1 keV

Viel+'12

- $m_{dm} \gtrsim$ a few keV seems more likely



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

$\sigma/m \sim 0.1 - 100\ \mathrm{cm}^2/\mathrm{g}$

Spergel & Steinhart '00

Rocha+'13

Bullock & Boylan-Kolchin '17

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
- $m \sim 10^{-22}$ eV, $\lambda_{\text{de Broglie}} \sim 1$kpc
- expect suppression of halos at 10^{7}-10^{10} $M_{\odot}$
- forms a central core as a "**soliton**" (Schrödinger-Poisson eq.)
- on large-scales, $\approx$ CDM

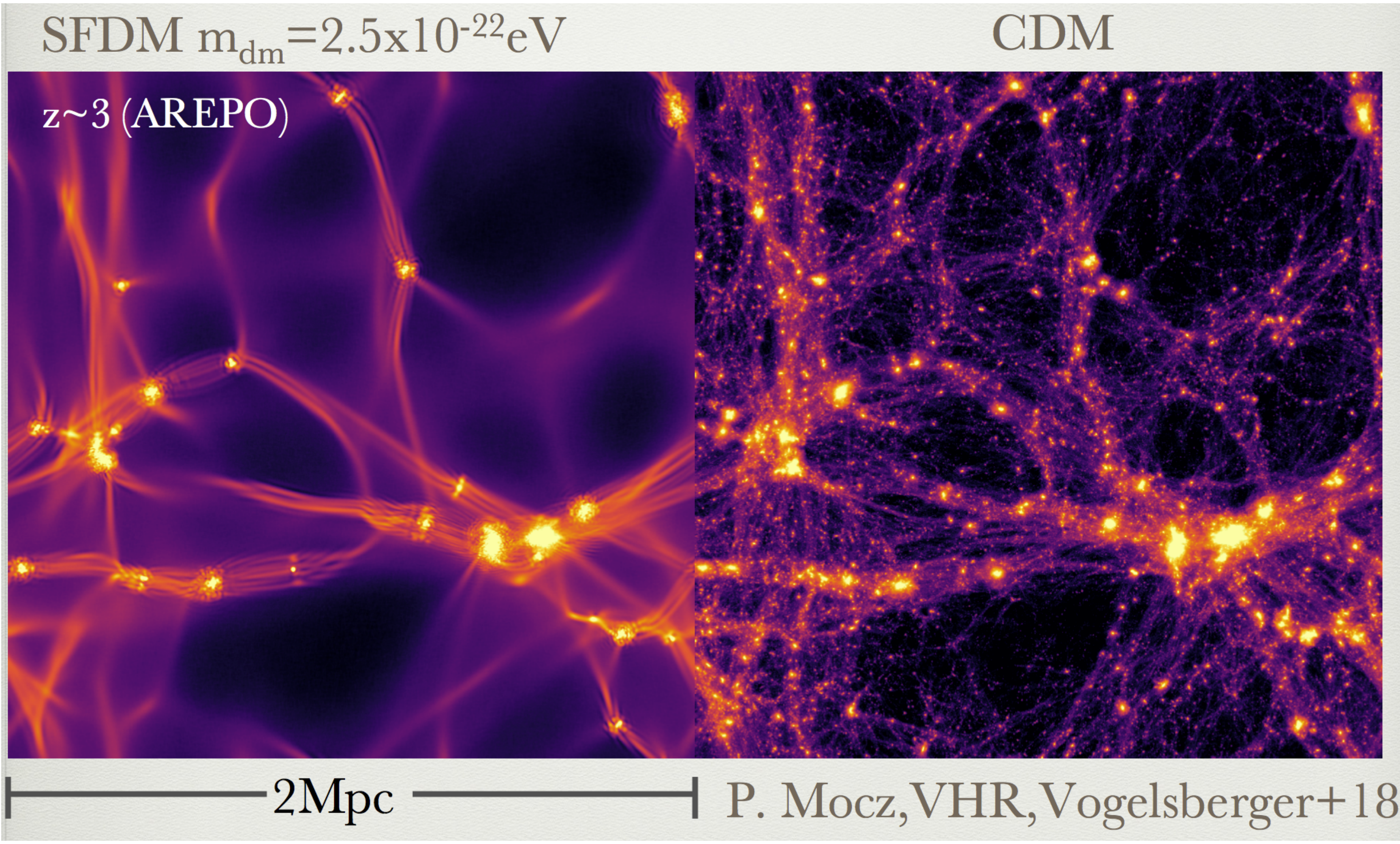
Baldeschi+83; Kim '87; Sin+94; Hu+00; **Marsh+14; Schive+14; Hui+17; Mocz+17; Robles+18; Zhang+18; …..**

Schrödinger-Poisson eq.

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2ma^2}\nabla^2\Psi + Vm\Psi$$

$$\nabla^2 V = \frac{4\pi G}{a}(\rho - \overline{\rho})$$

$$\rho = |\Psi|^2$$

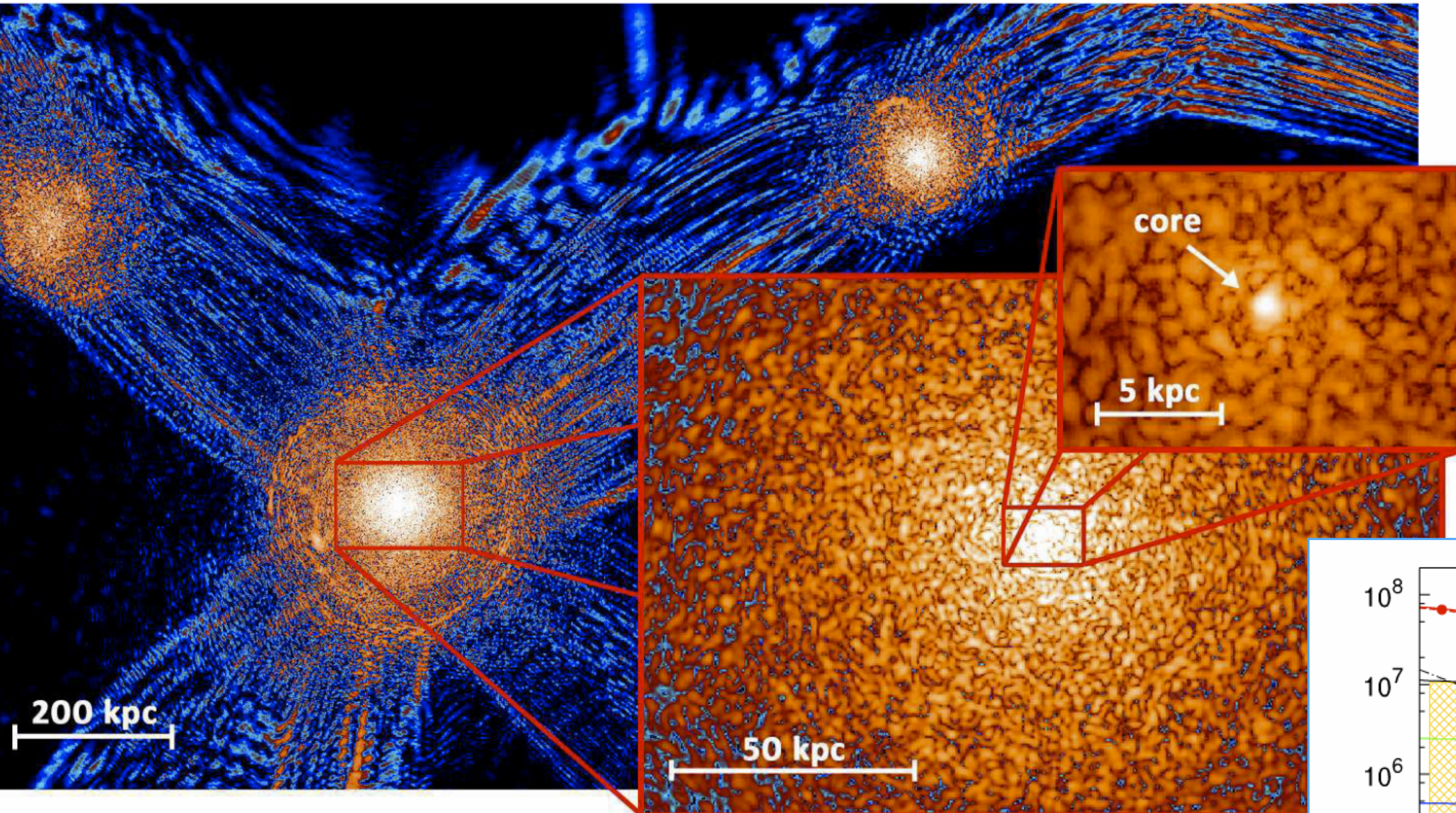


Schive+14; Vertmaat+ '18

- Uncertainty principle counteracts gravity below Jeans scale
- adds new form of **quantum pressure** from uncertainty
- constraints from Lyα P(k): $m > 2 \times 10^{-21}$ eV

cf. Irsic+17; Armengaud+17; Zhang+17
Desjacques+'17

Solitonic Core of FDM simulation



Schive+14

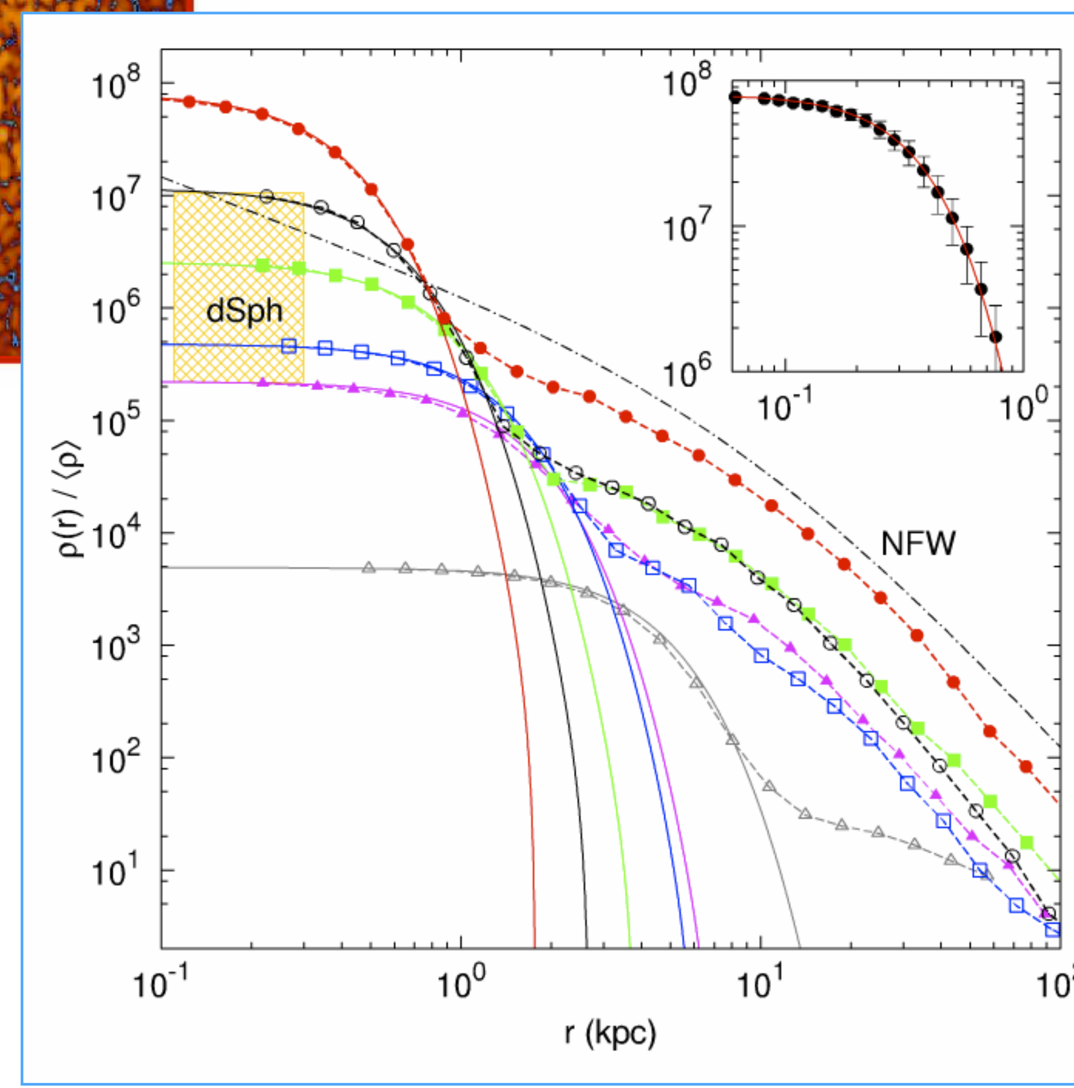
gravitationally bound solitonic core

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

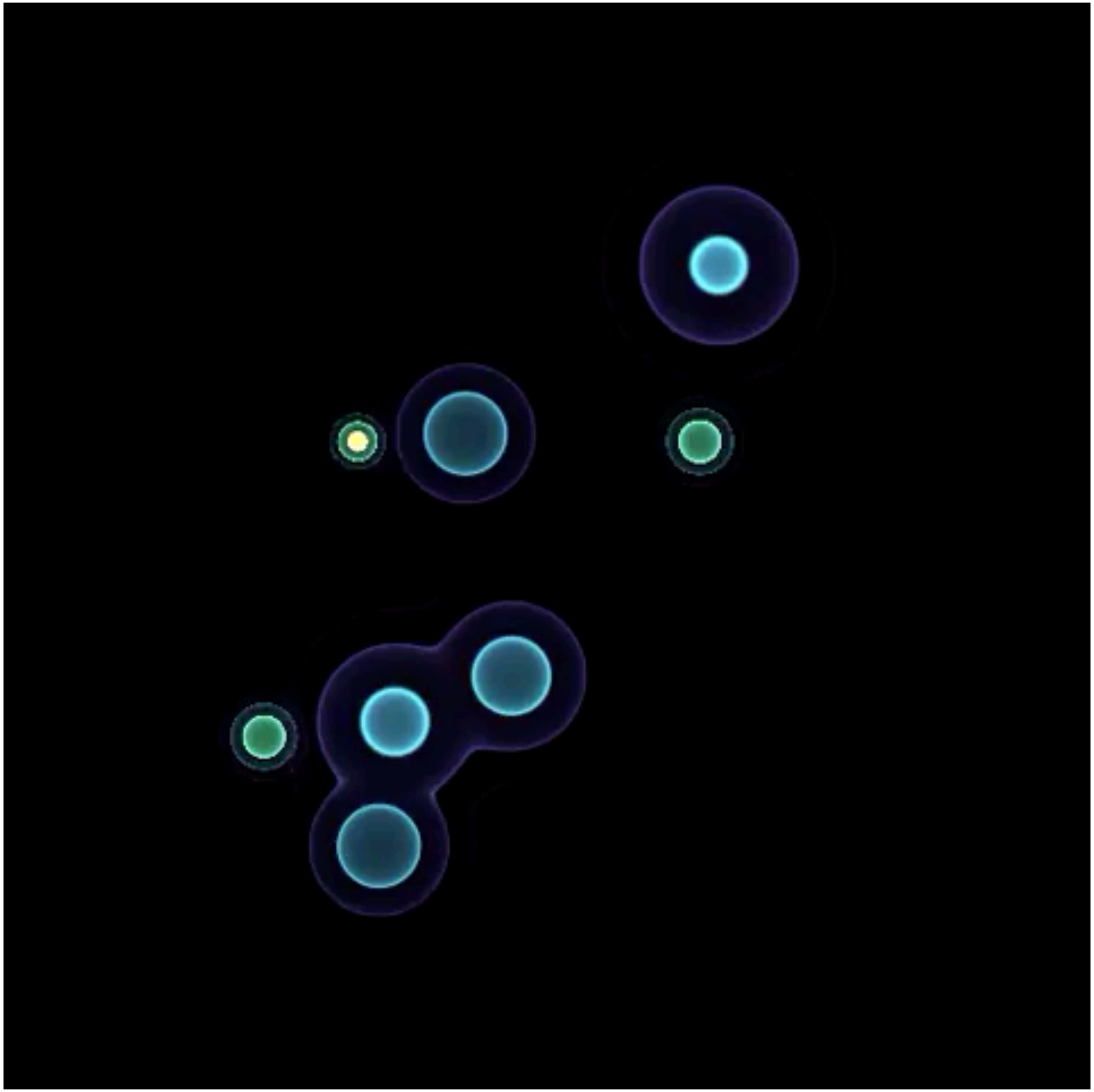
for Fornax dSph gal.

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

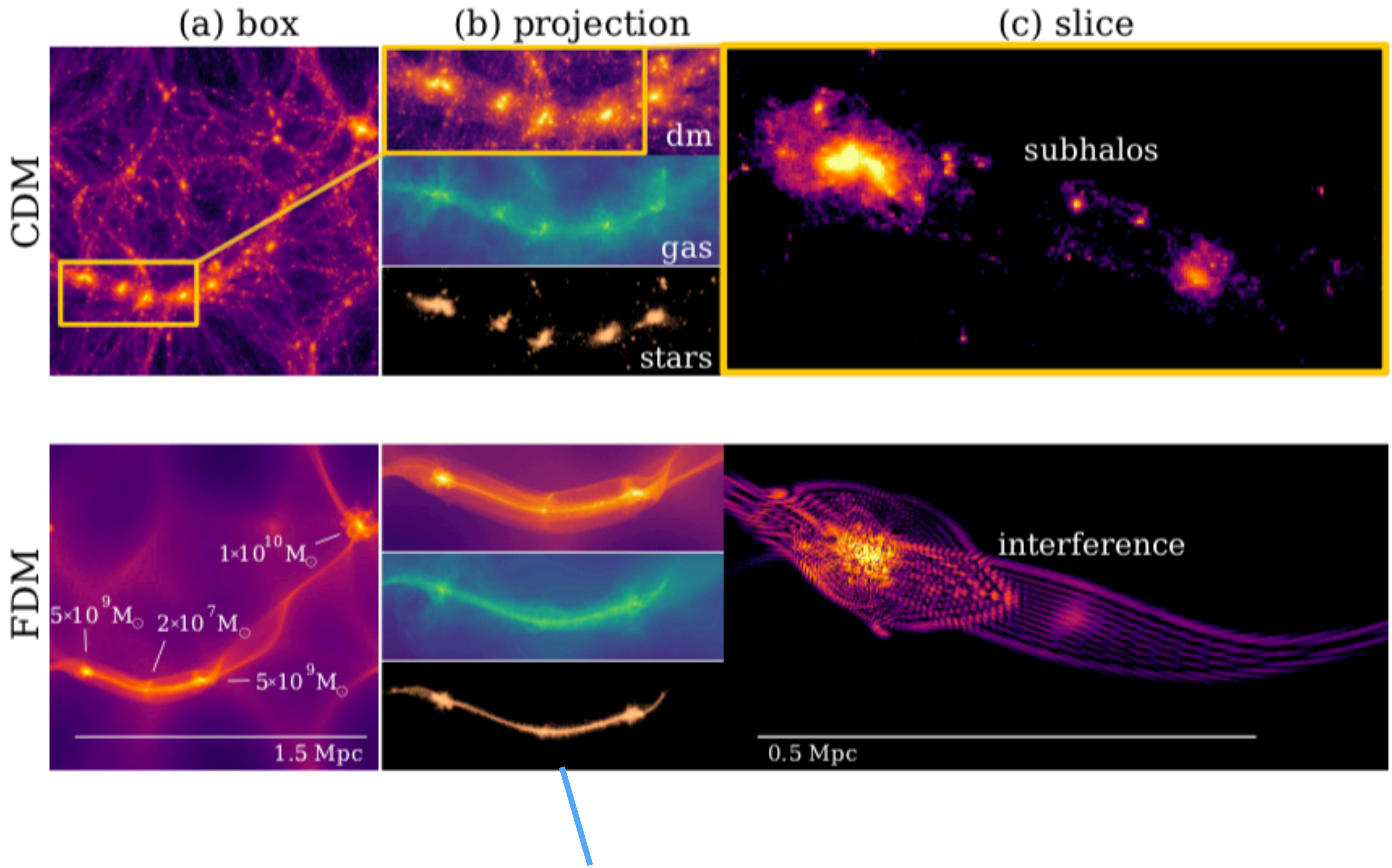
$M_s \simeq 2 \times 10^9\ M_\odot$ for MW core



ULA simulation movie



Mocz+ ‘17



elongated galaxy in FDM ?

Mocz+ '19

— Concluding remarks —

- **"Small-scale problem" —** might exist, but astrophysics can still solve it.
- **"Missing satellite problem" is quickly disappearing** — opposite problem arising?
- **Better understanding of astrophysical effects on various scales w. feedback**
- **How do we reflect the nature of elementary ptcls realistically to numerical simulations?**
- **理想：DM発見時のために要準備（≈ 重力波天文学＋数値相対論）**