Galaxy Formation & Dark Matter

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Dark Matter

Dark Energy

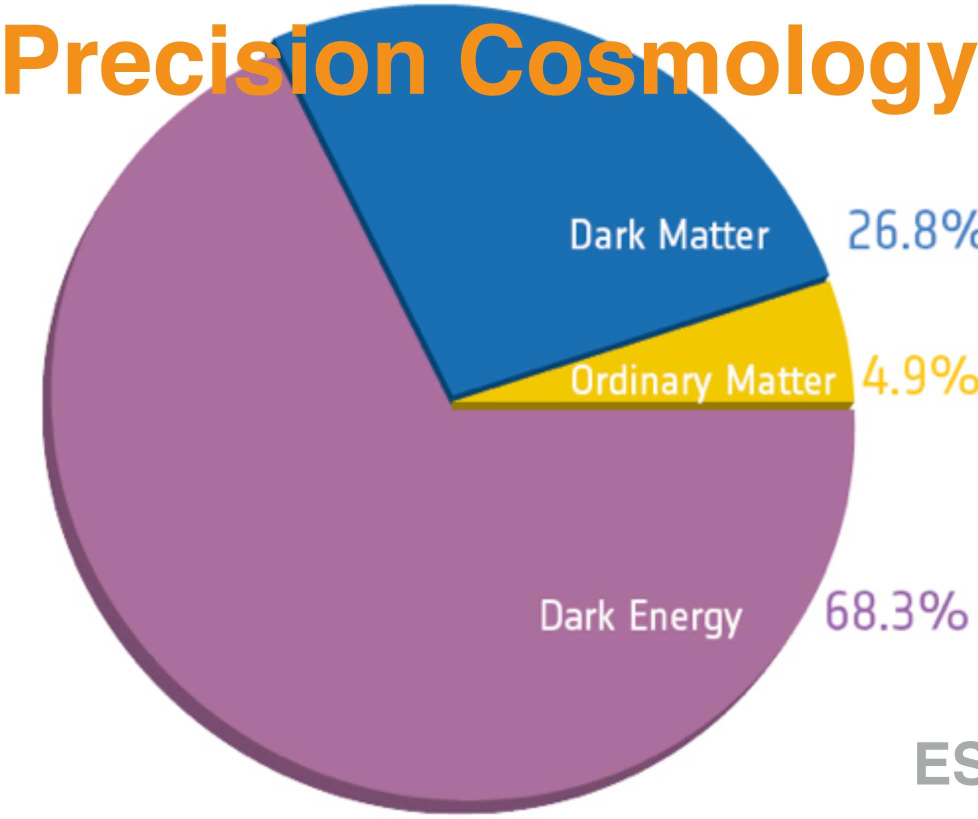
Summary of Observations

- **Various obs suggest the existence of DM.**

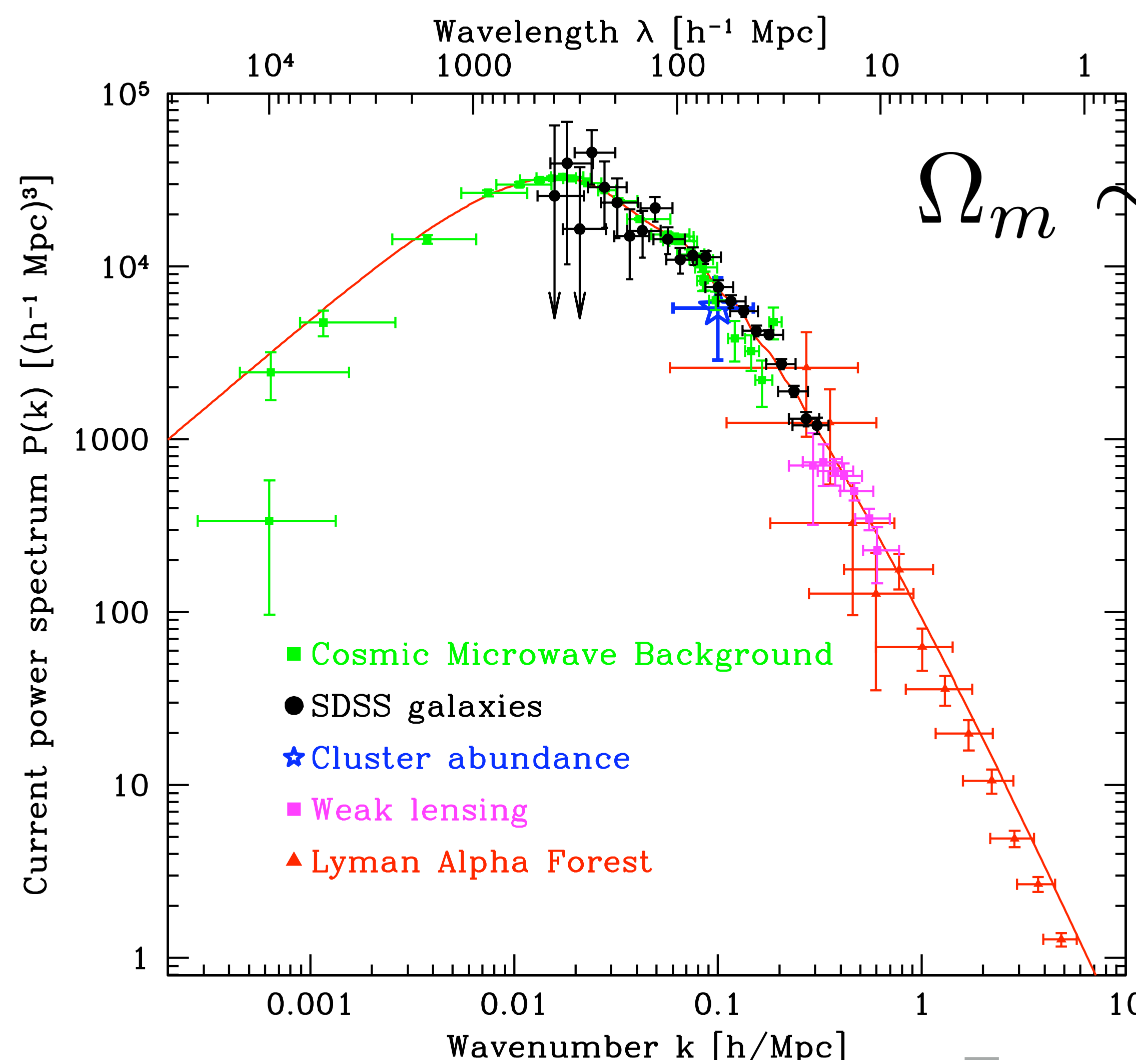
$$\frac{\Omega_{\rm DM}}{\Omega_b} \sim 5$$

`737' Concordance ΛCDM model

`Precision Cosmology'



ESA 2013



$\Omega_m \sim 0.3$

Tegmark 2004

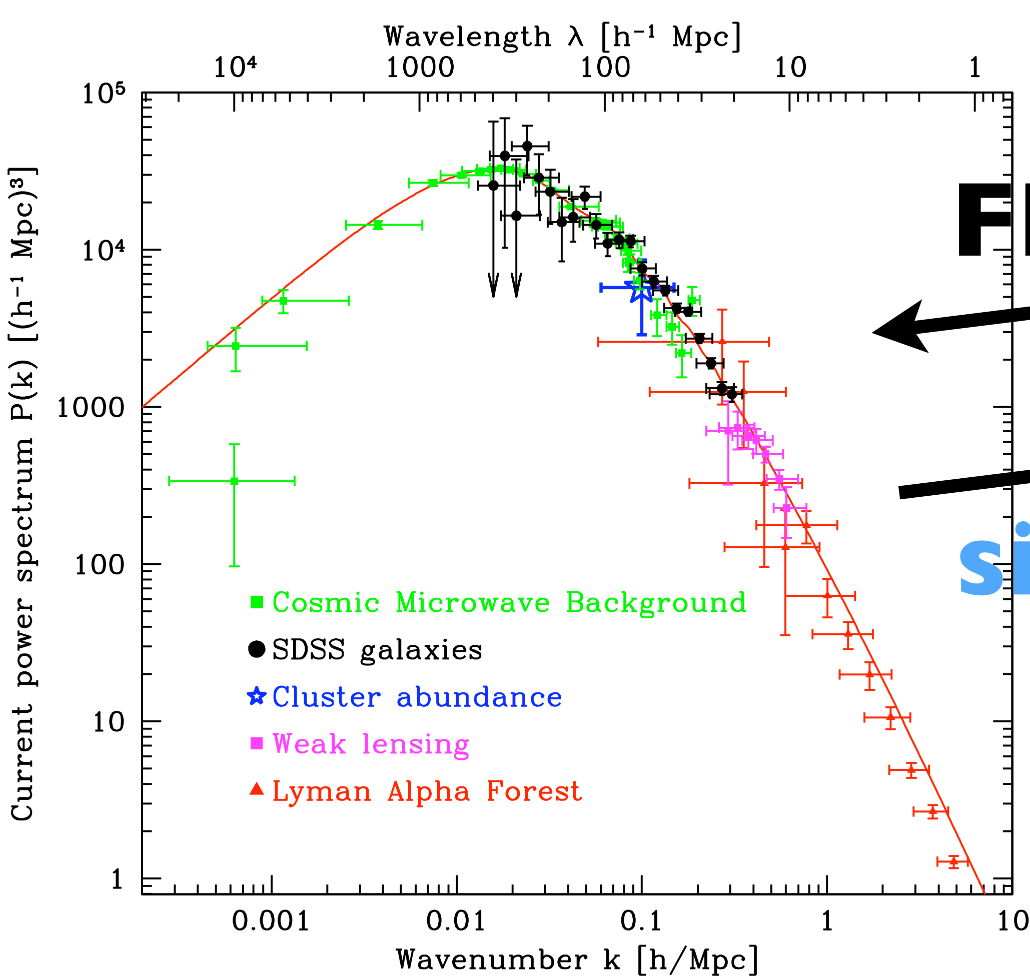
Concordance ΛCDM model

WMAP, Planck
SN Ia

$$(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_8, n_s) \approx (0.3, 0.7, 0.04, 0.7, 0.8, 0.96)$$

$$\Omega_{DM} \approx 0.26$$

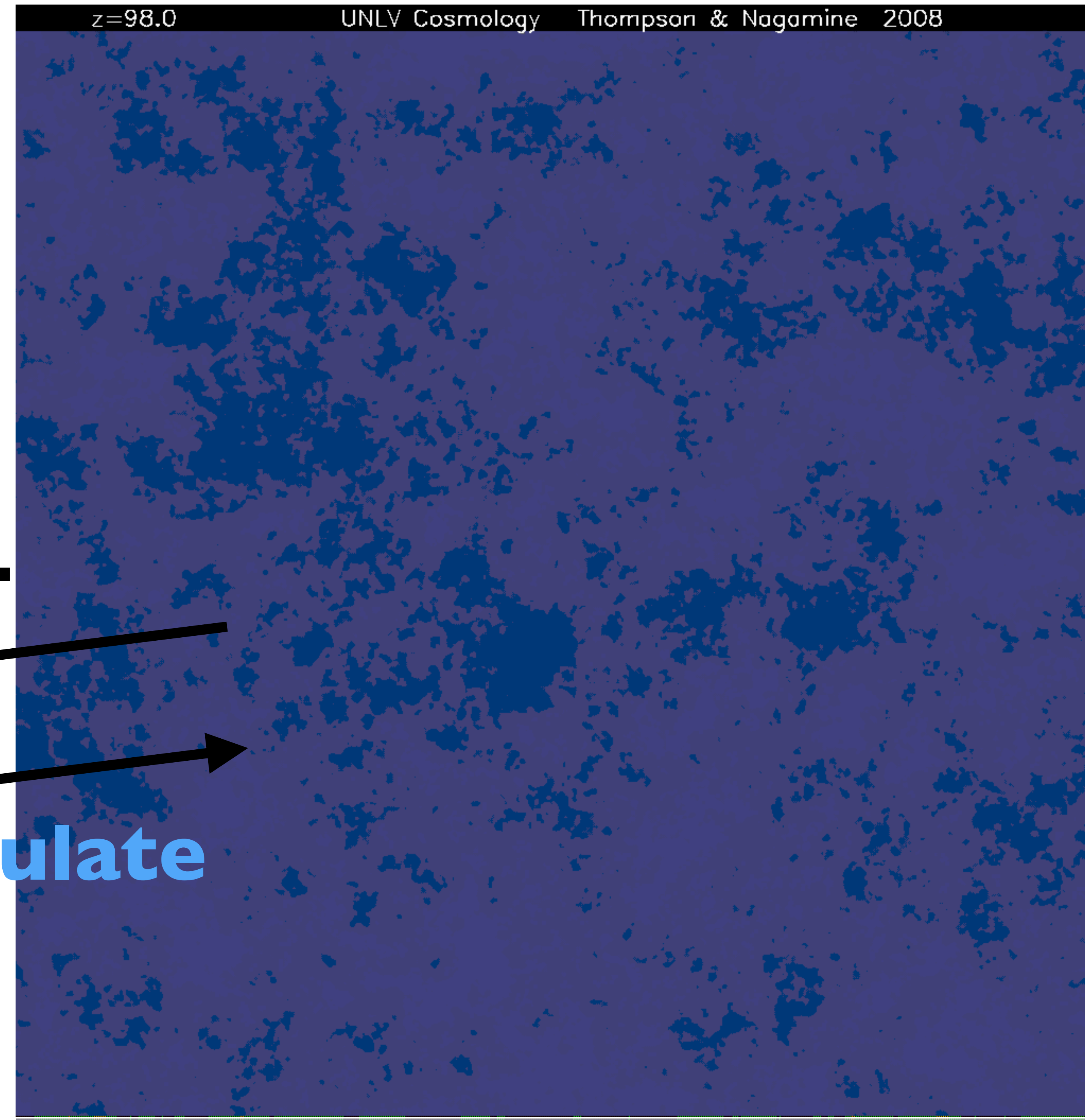
- Successful on large-scales (>1Mpc)
- Can we understand galaxy formation in this context?



Tegmark+ (2004)

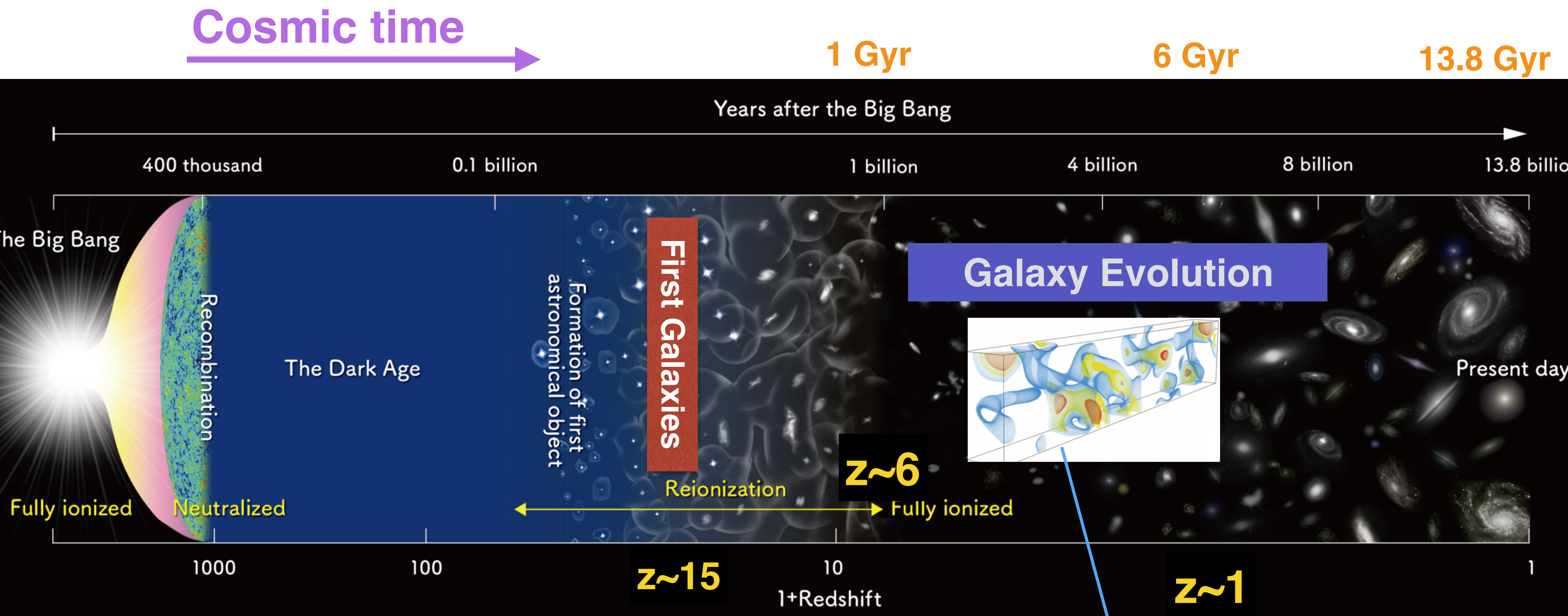
FFT

simulate



"Back-bone of structure"

History of Cosmic Structure Formation in ΛCDM Universe



JWST

HST

SKA

PFS

HSC

DES
MOONS
EUCLID…

SDSS, 2dF

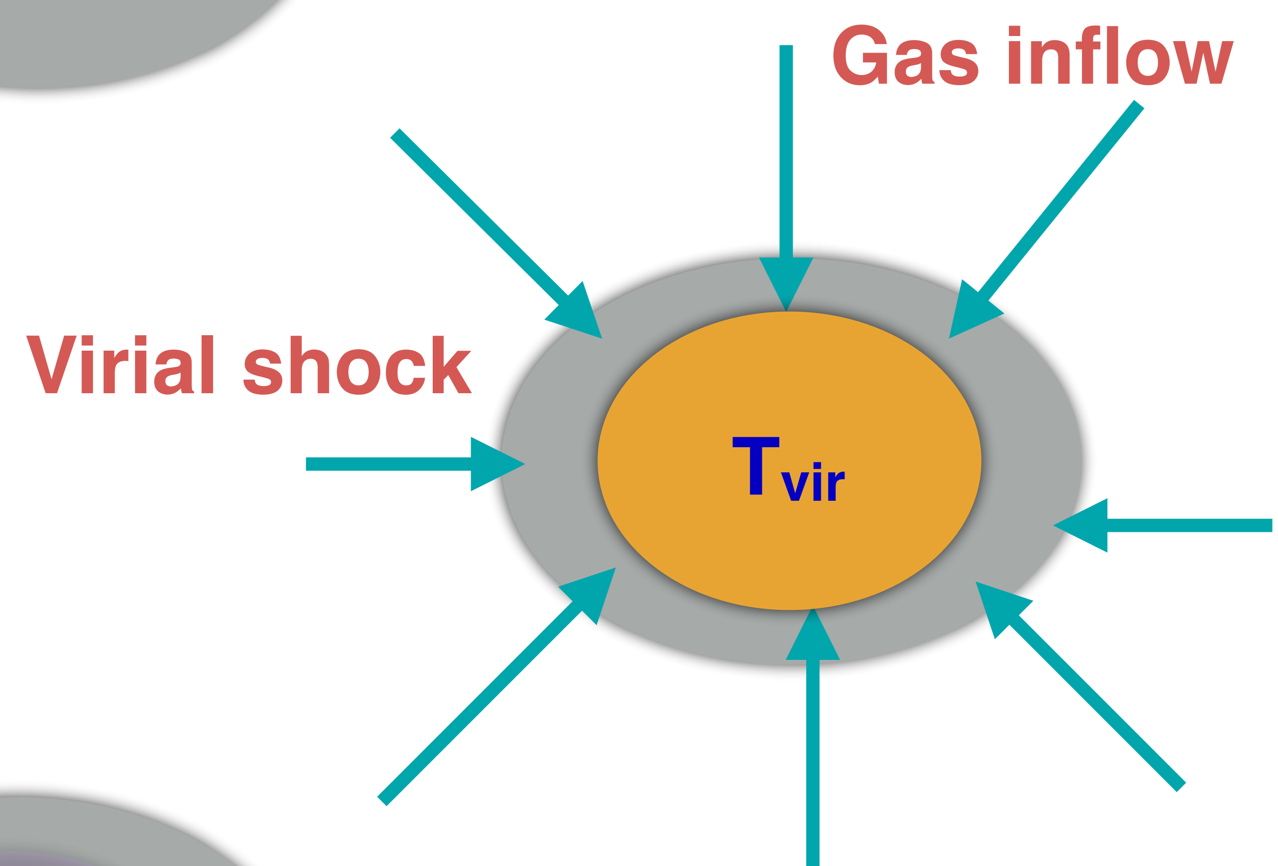
Image: NAOJ

1st-order Galaxy Formation

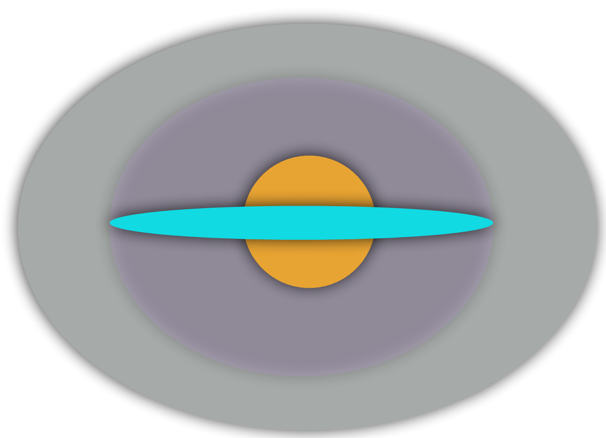
DM halo forms.

“spherical cow”

Gas infall
& shock heating



Gas dissipates,
cools,
& forms a disk.



Star, Galaxy Formation

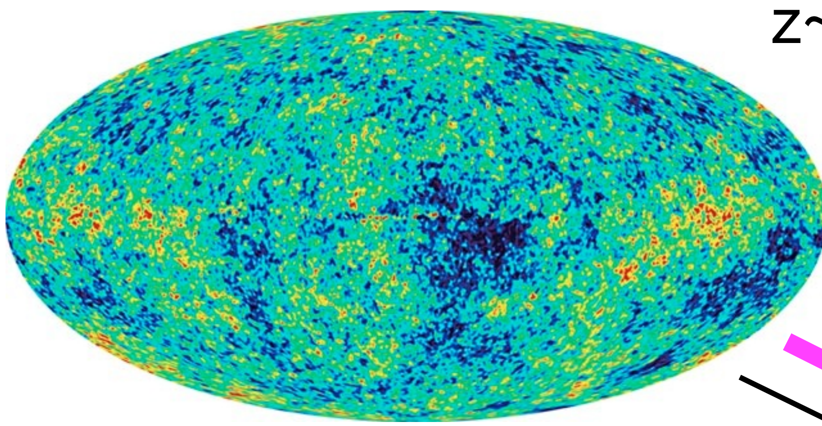
$$R_{\mathrm{d}} = \frac{1}{\sqrt{2}}\left(\frac{j_{\mathrm{d}}}{m_{\mathrm{d}}}\right)\lambda r_{200}$$

Rees & Ostriker ’77
White & Rees ’78
Fall & Efstathiou ’80
White & Frenk ‘91
Mo, Mao & White ‘98

Computational Cosmology

Self-consistent galaxy formation scenario from first principles (as much as possible)

z~1100



Initial conditions

Cosmological params,
Dark energy, Dark matter,
Baryons
(+expanding universe)

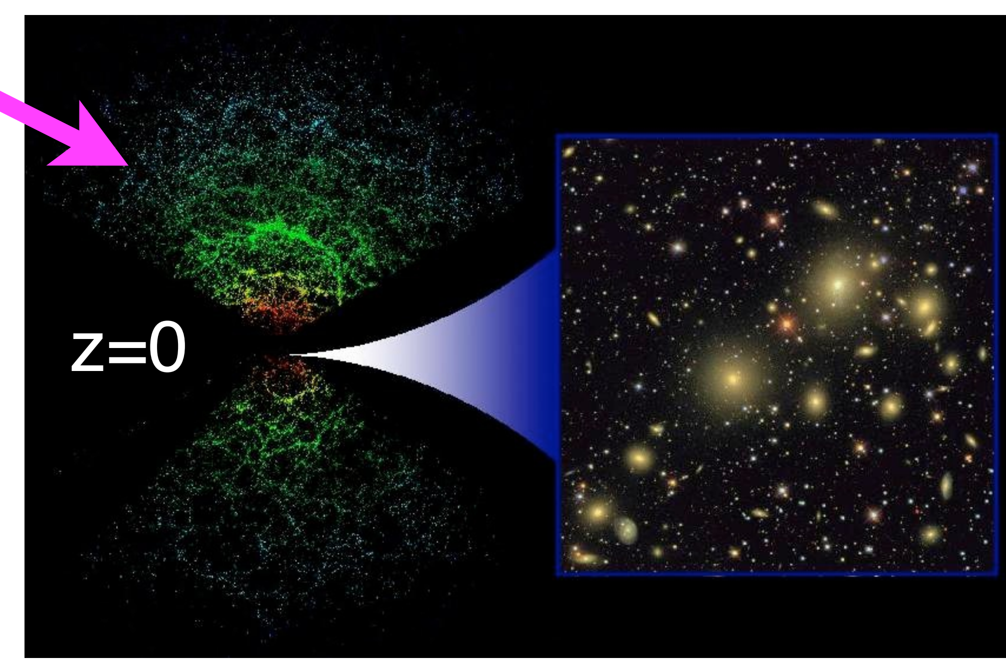
z=100

z=10

z=3

Baryonic physics

Radiative heating/cooling,
Star formation,
& Feedback



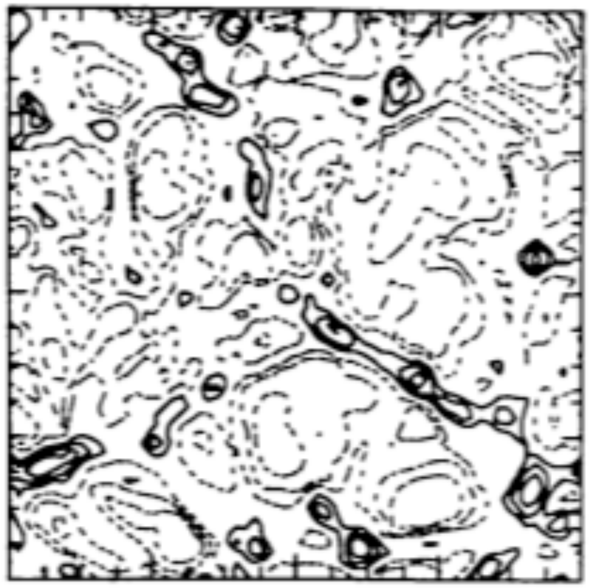
Gravity + Hydrodynamics

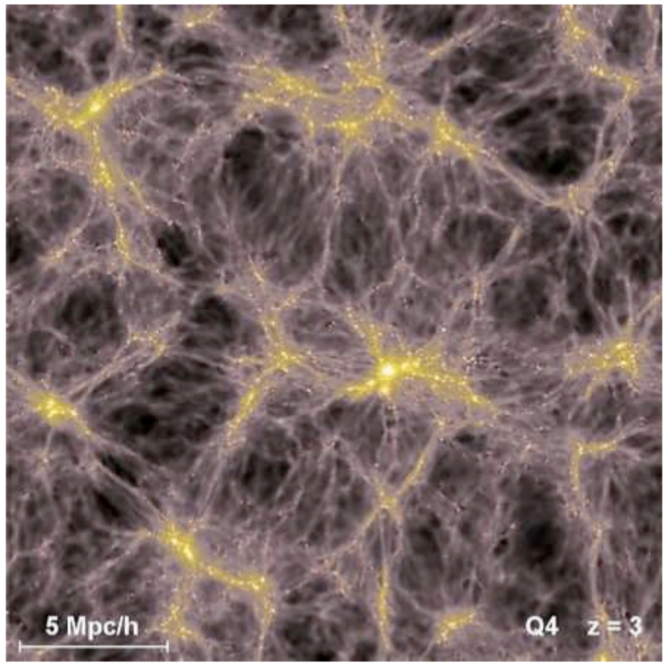
Three Revolutions in Cosmological Hydro Simulations

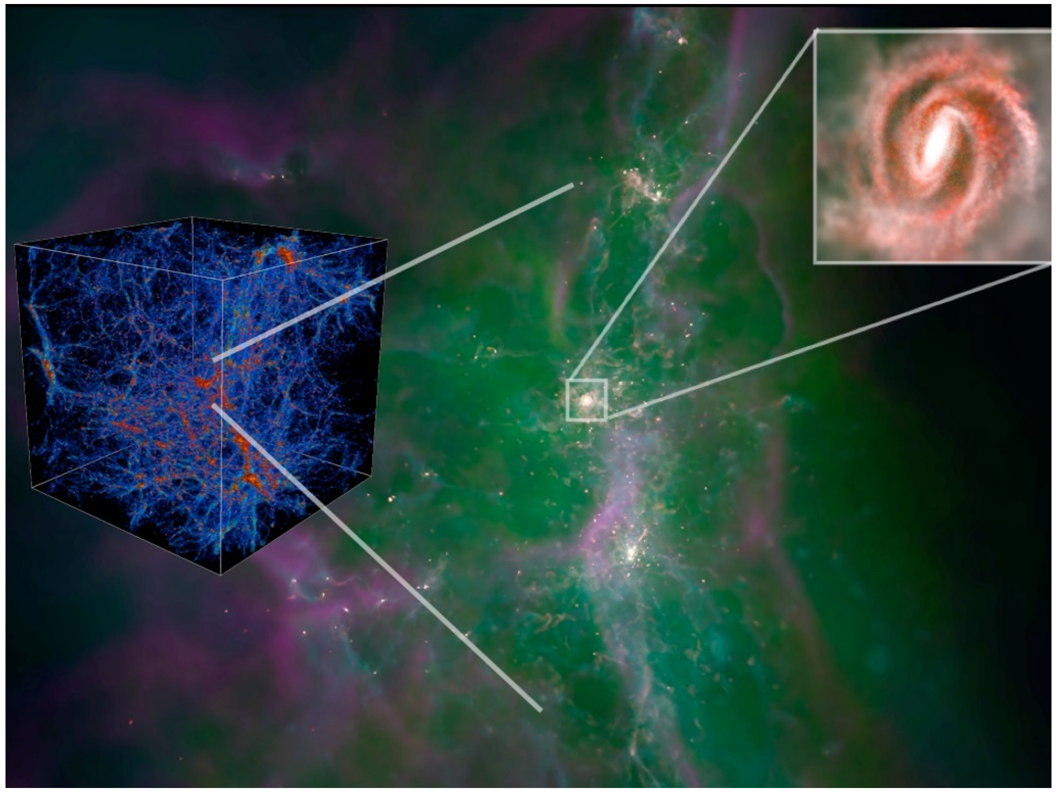
1990': 1st Revolution

2001-2011 2nd Rev.

2012~ 3rd Rev.







First cosmological, but coarse calculation

Resolution~100 kpc

e.g. Cen, Ostriker '92-'93
Katz+ '96

Larger scale, medium resolution **w. subgrid models**

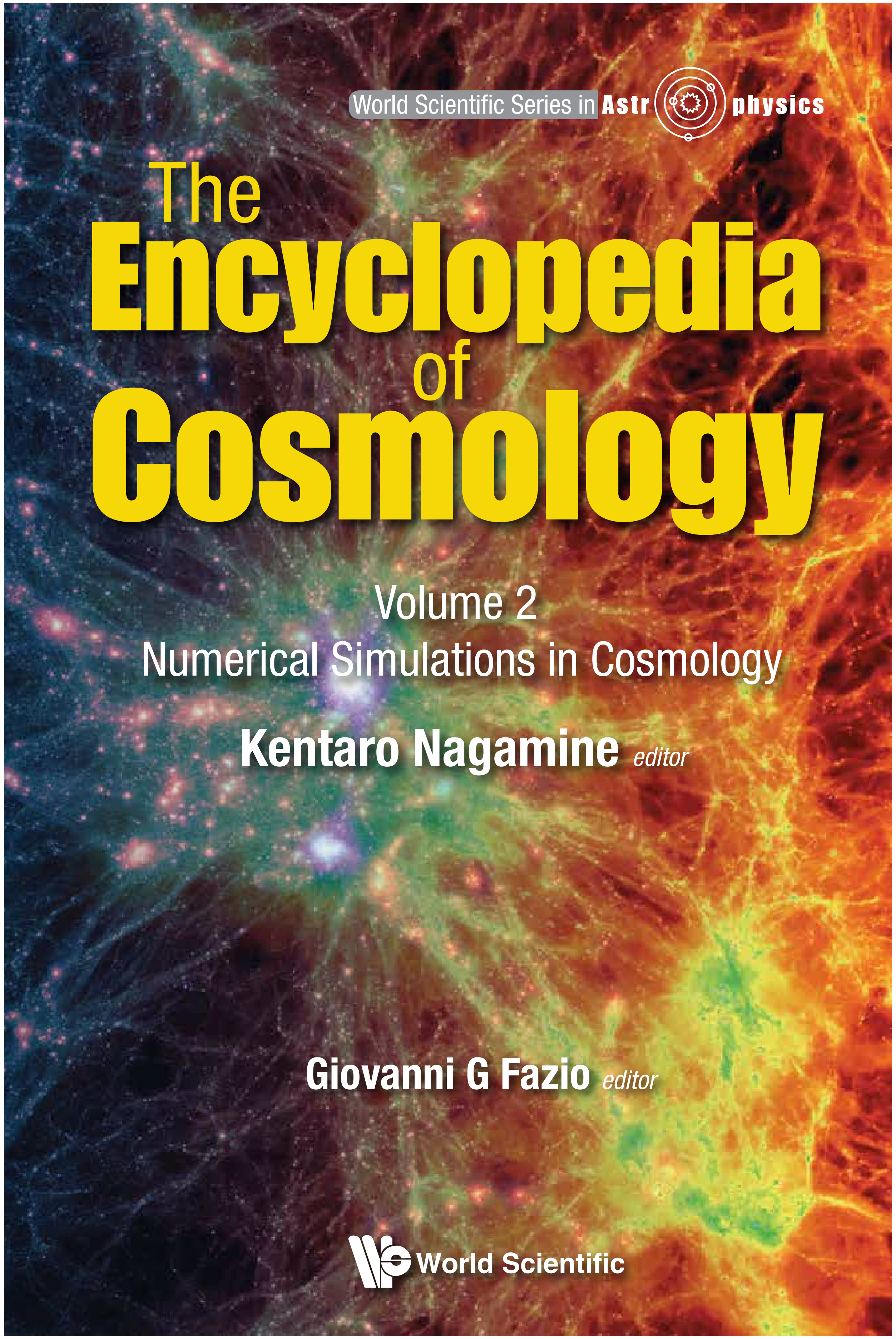
Resolution ~ kpc

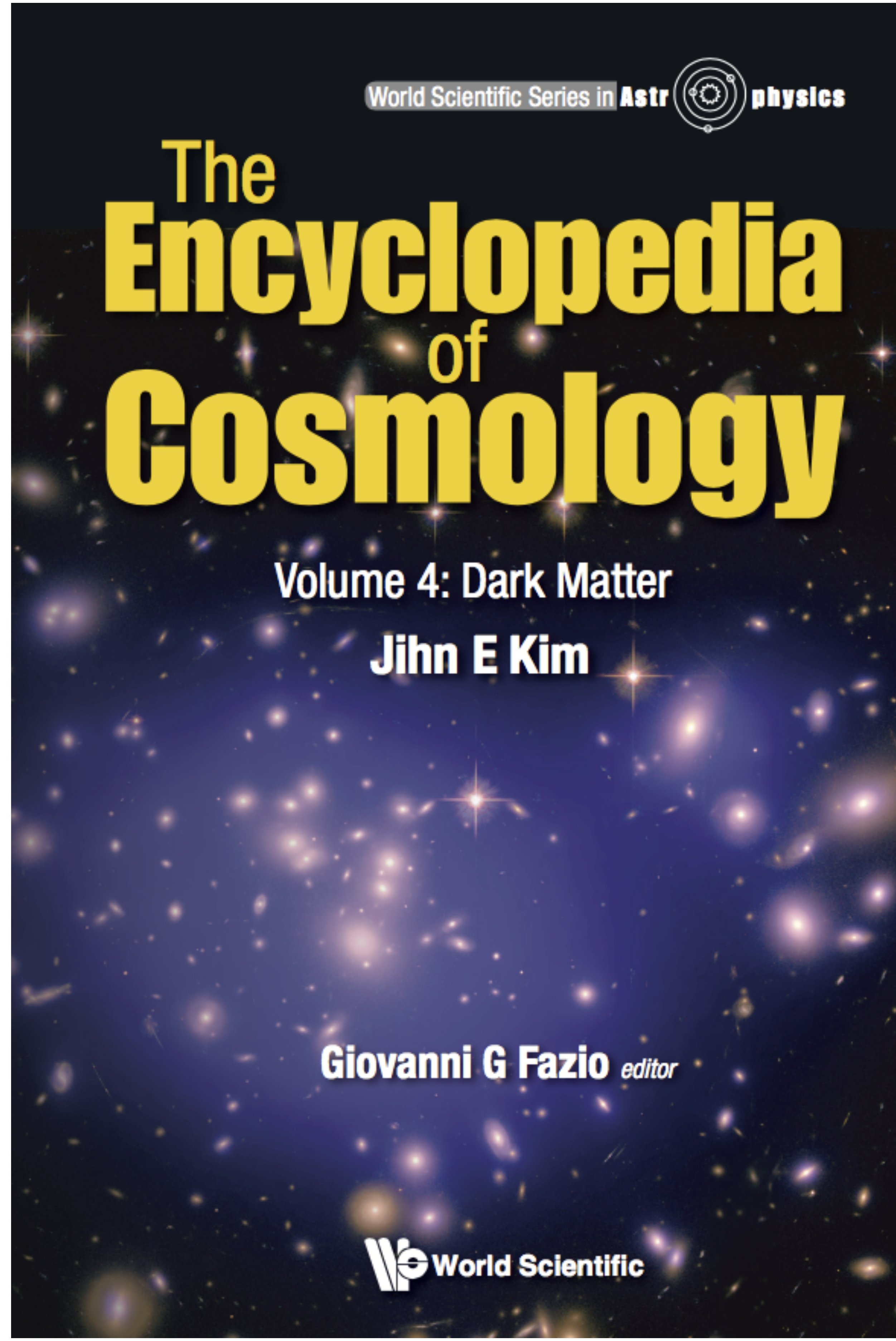
e.g. KN+ '01, 04, 06
Springel & Hernquist '03

Zoom-in method allows much higher res.

Resolution~ 10-100pc

IC code: GRAFIC (Bertschinger)
MUSIC (Hahn & Abel '11)



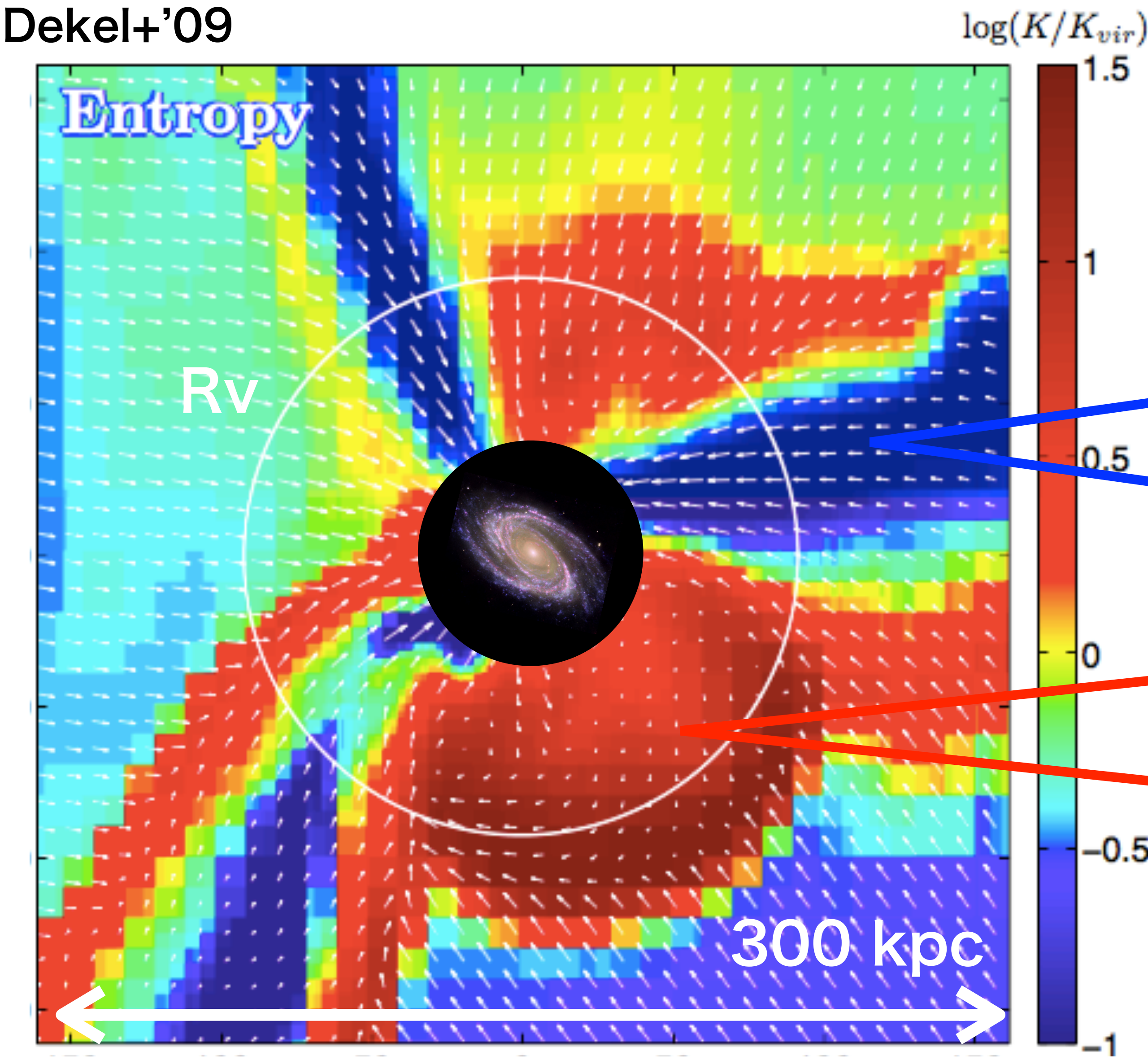


Amazon, or https://www.worldscientific.com/worldscibooks/10.1142/9496#t=toc

How do galaxies acquire gas?

Cold Flow & Virial Shock

Dekel+'09



Cold Flow

Efficient inflow of cold gas

Promotes SF

Gas Accretion & **Virial Shock**

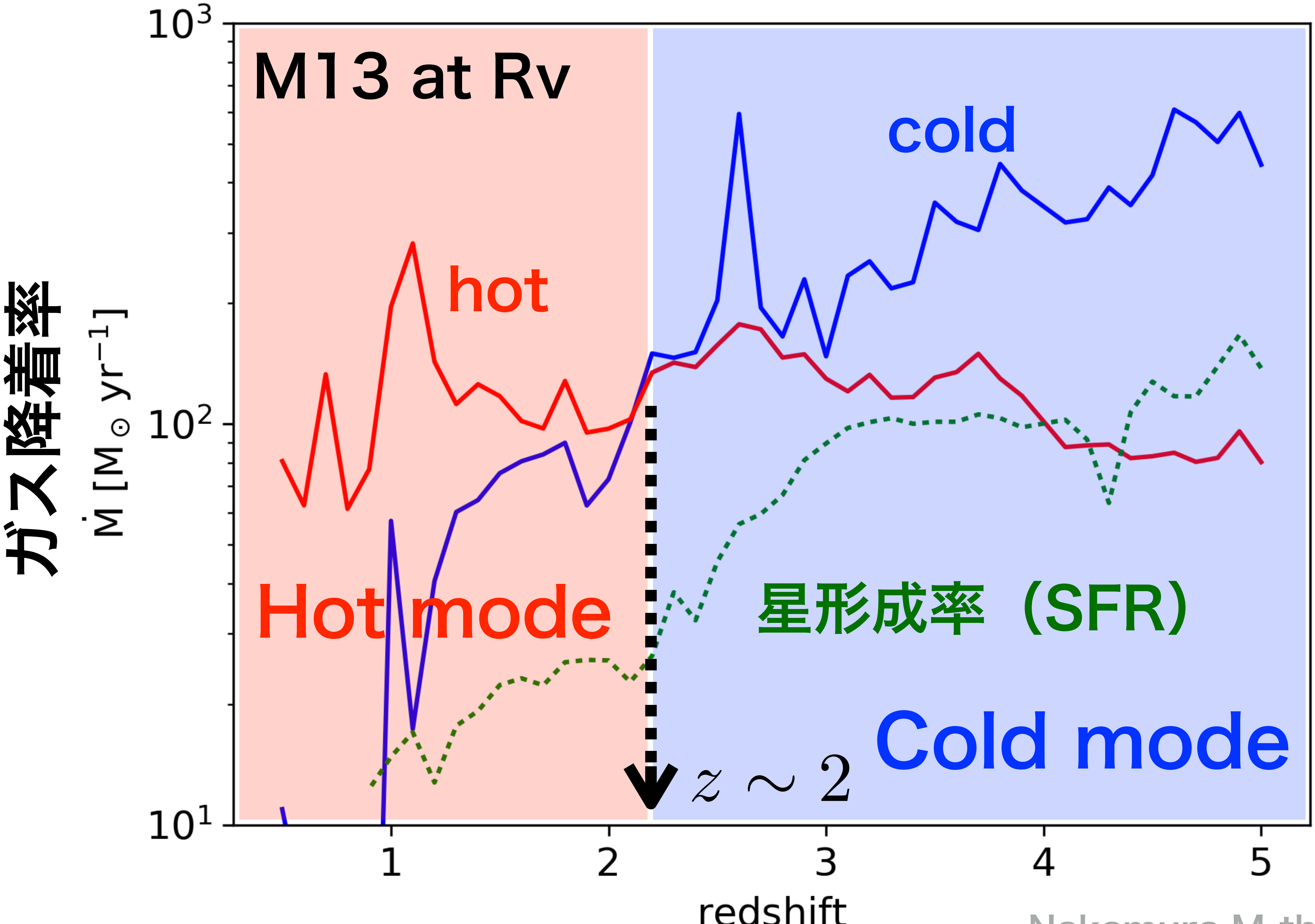
Heating to T_{vir}

Prohibit SF

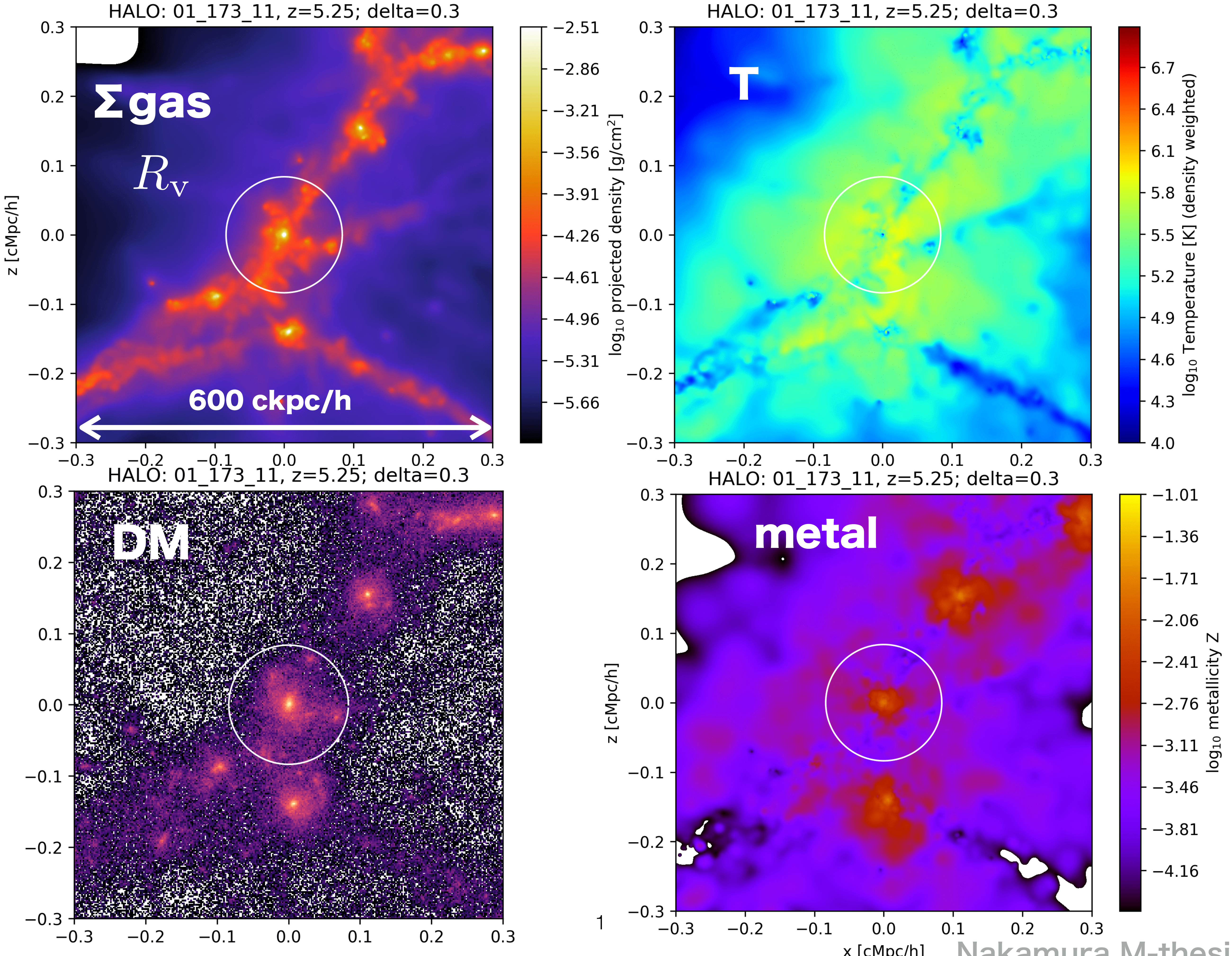
Birnboim & Dekel '03 :
Keres+'05

t_compression vs. **t_cool**
controls the thermal state of gas.

Transition from Cold to Hot mode



Nakamura M-thesis

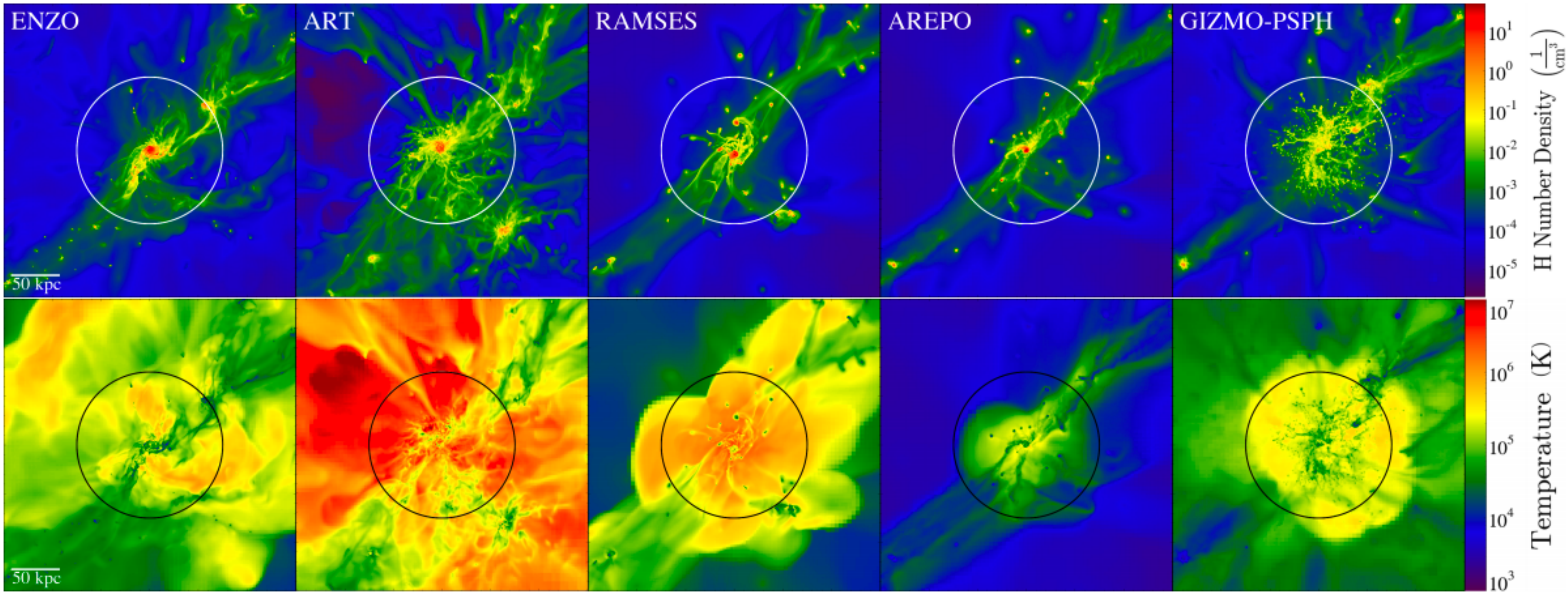


HALO: 01_173_11, z=5.25; delta=0.3
Σgas
R_v
600 ckpc/h
log10 projected density [g/cm2]
T
log10 Temperature [K] (density weighted)
DM
metal
log10 metallicity Z
z [cMpc/h]
x [cMpc/h]

1

Cold flow: generic feature of ΛCDM

Enzo ART RAMSES AREPO GIZMO-PSPH

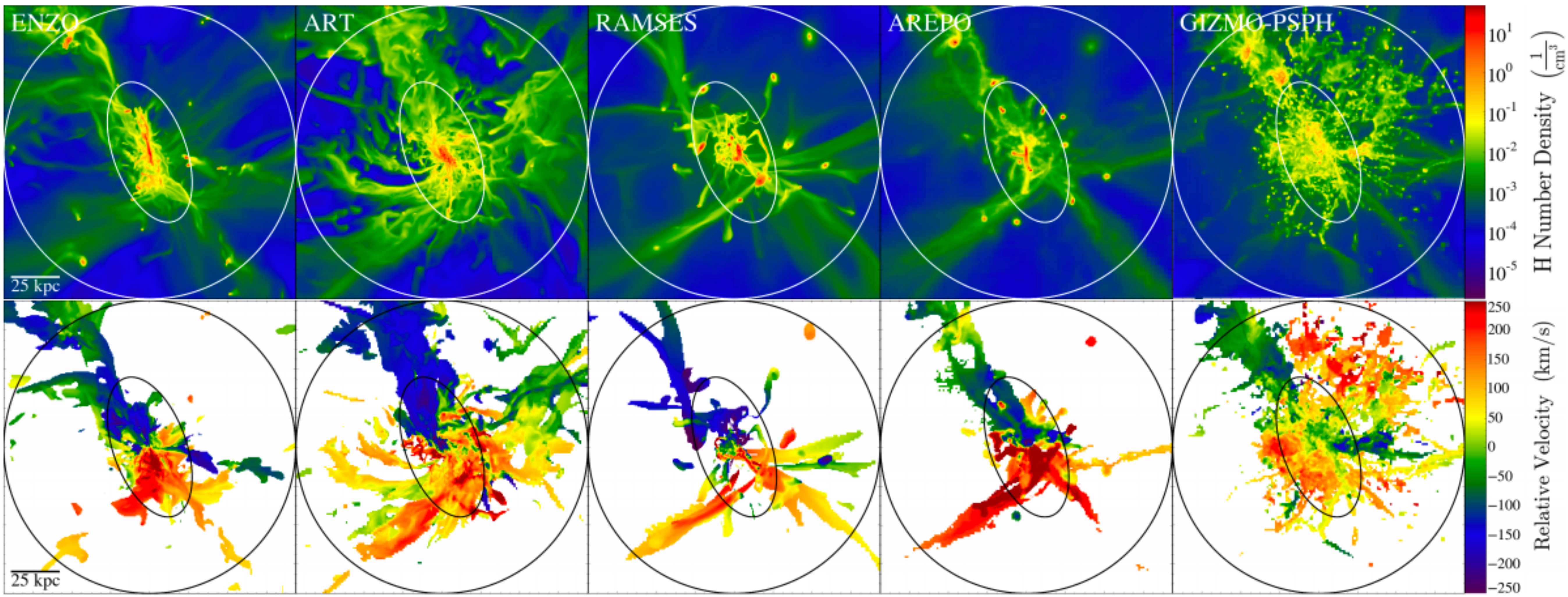


(details of SF & feedback are different in each code)

Stewart+'17

“Cold Flow Disk”

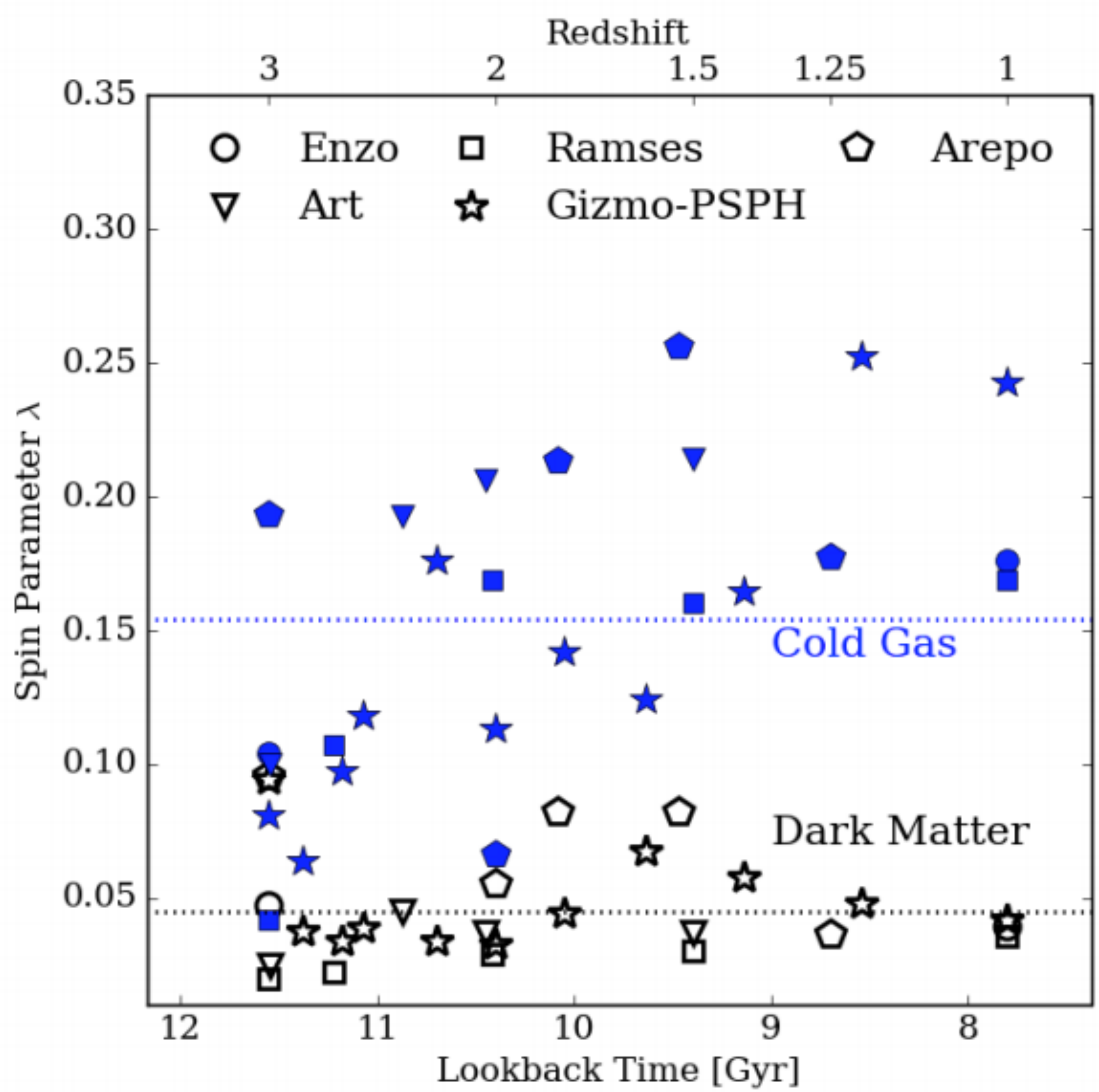
z~3



Extended, flattened rotating structures of high–*J* material.

Stewart+’17

Cold gas in halos have 4x *J* than dark matter



spin param.

$\lambda_x \equiv j_x / 2V\,R$

$\boxed{\lambda_{cold} \simeq 0.15}$

$\lambda_{DM} \simeq 0.04$

Stewart+'17

Historical Flow Chart of SN Feedback Treatment

1st phase
'90s

Simple thermal feedback

Overcooling problem

2nd phase
'00-'10

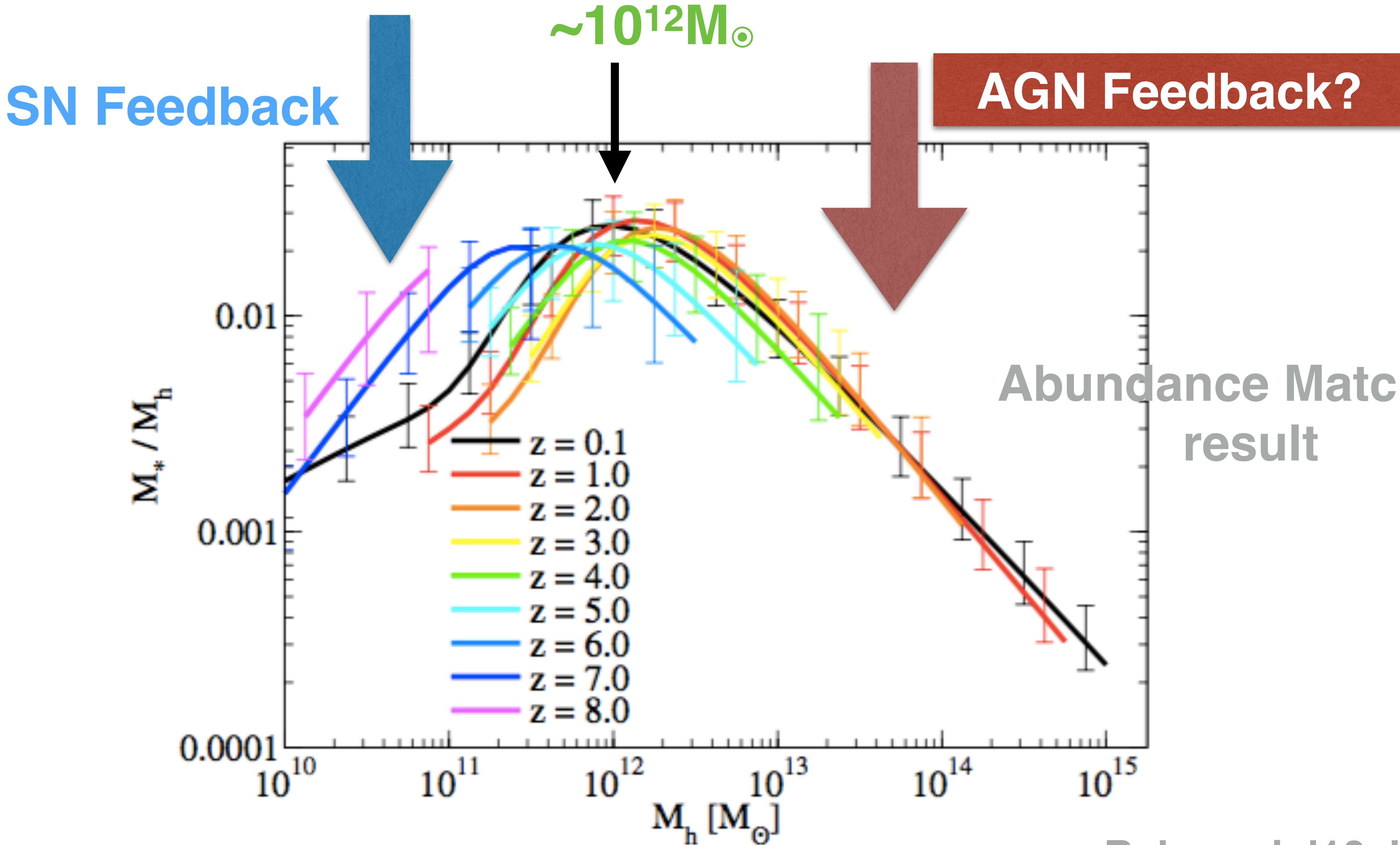
Phenomenological subgrid model (thermal + kinetic) based on galactic properties (SFR, M_{star}, M_{halo})

Multi-phase ISM model

3rd phase
'10~
(w/ zoom sim)

More direct, local, thermal+kinetic+radiative feedback

Stellar-to-Halo Mass Ratio (SHMR)

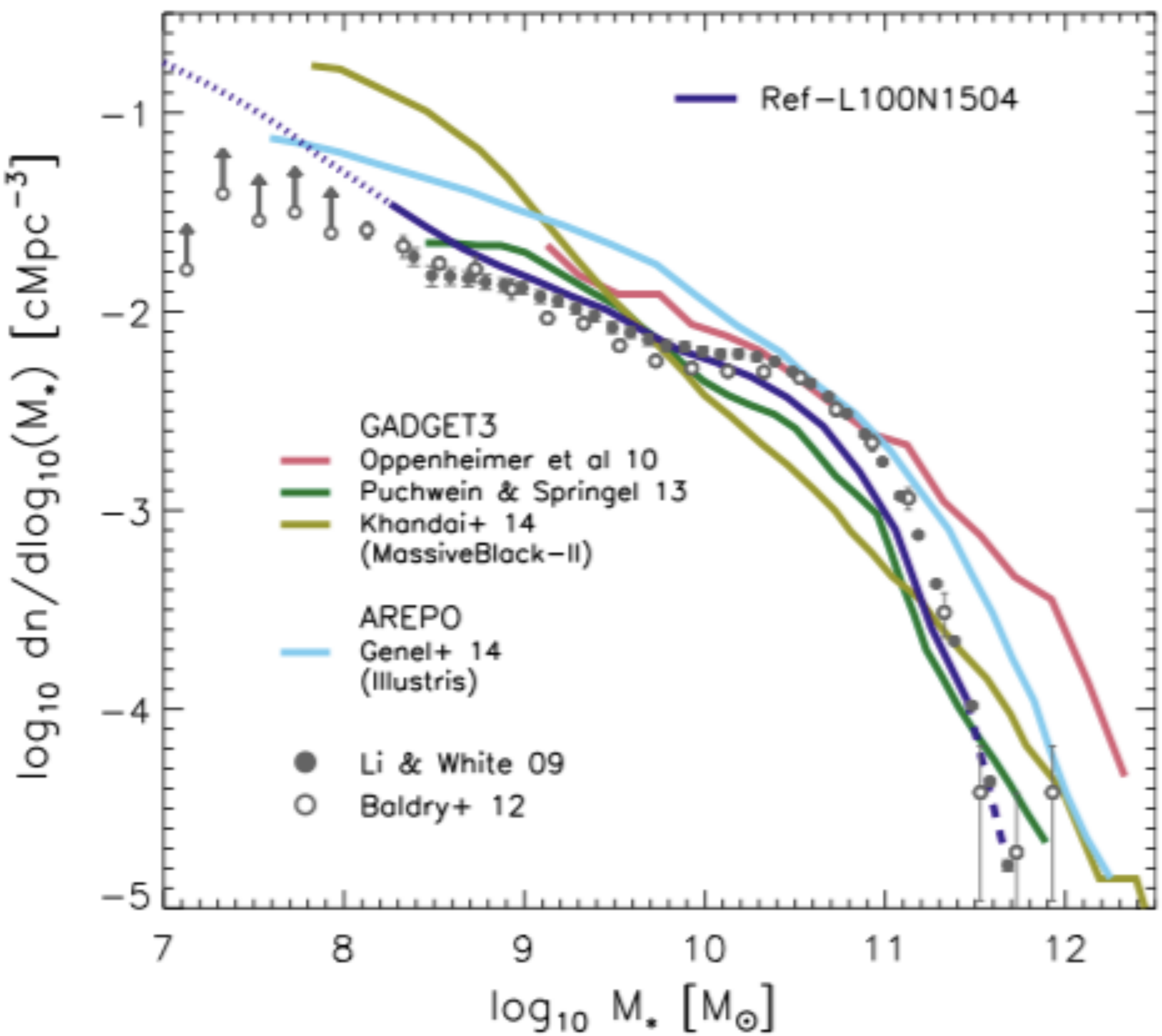


Abundance Matching result

Behroozi+'10, '13, '18

(cf. Ilbert+'10; George+'11; Leauthaud+'12)

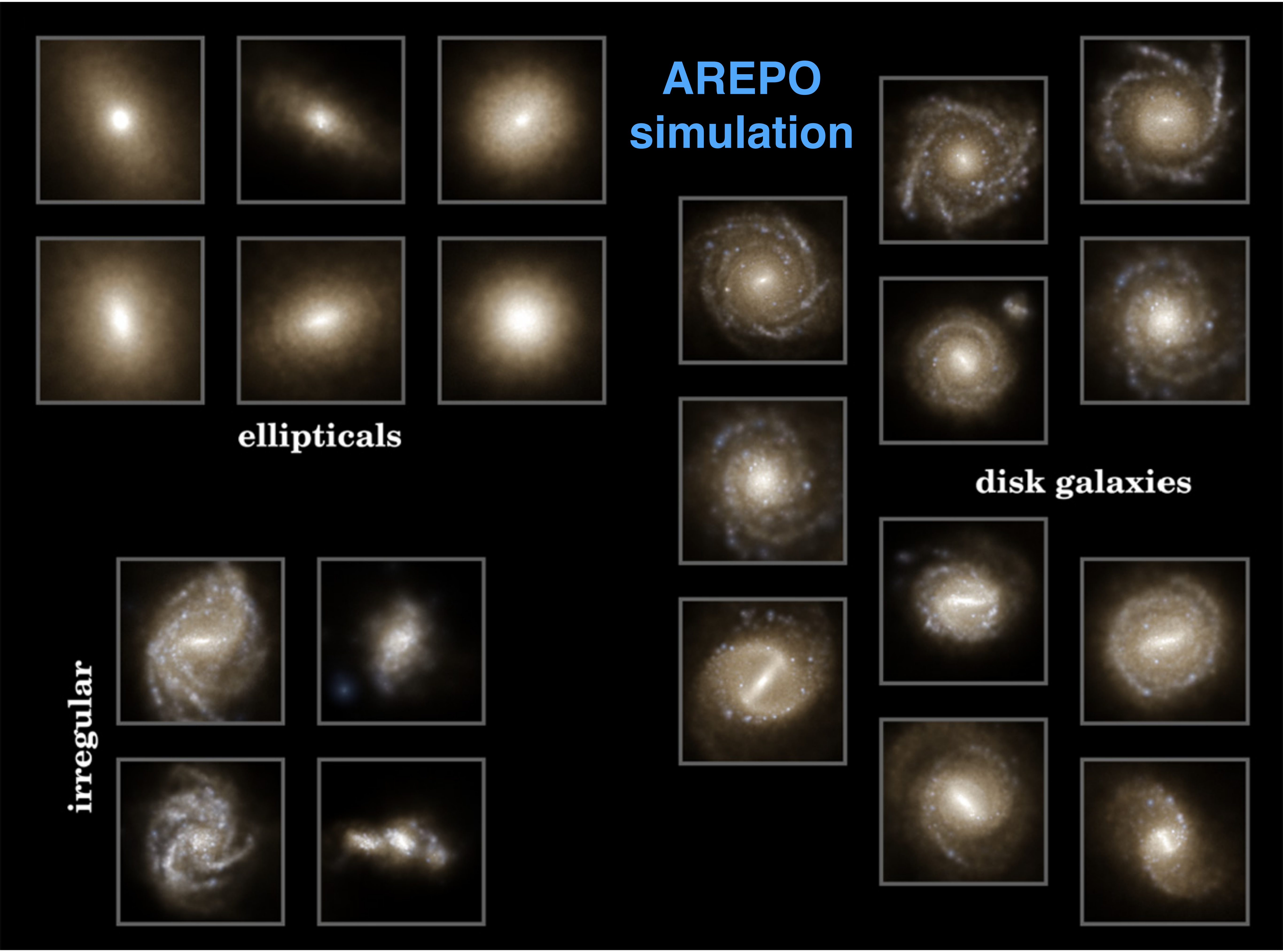
Galaxy Stellar Mass Function (z=0)



Still much variations among sims remain.

Some FB param tuning is necessary for each resolution.

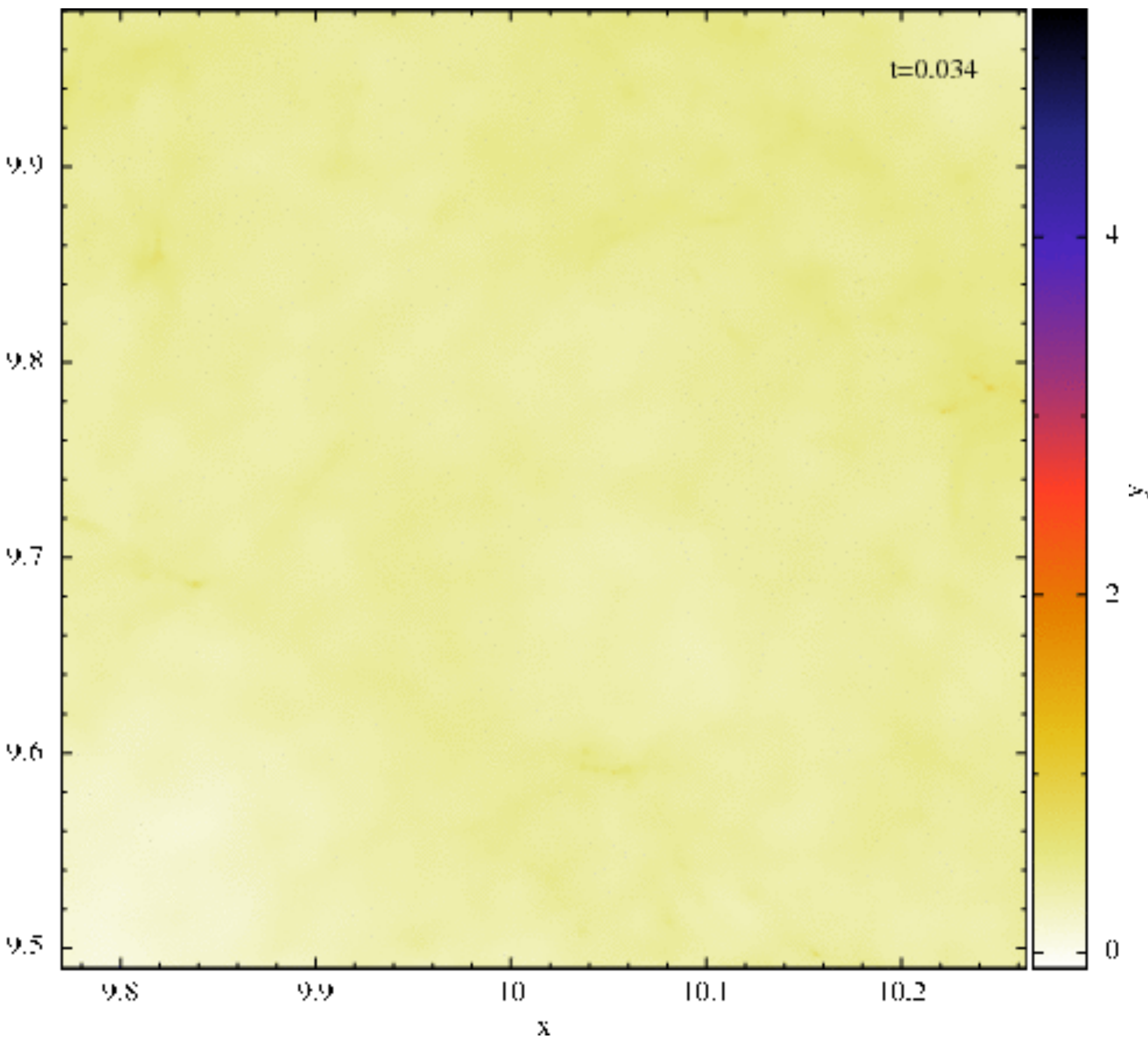
Schaye+ '15
Crain+ '15


AREPO
simulation
ellipticals
disk galaxies
irregular

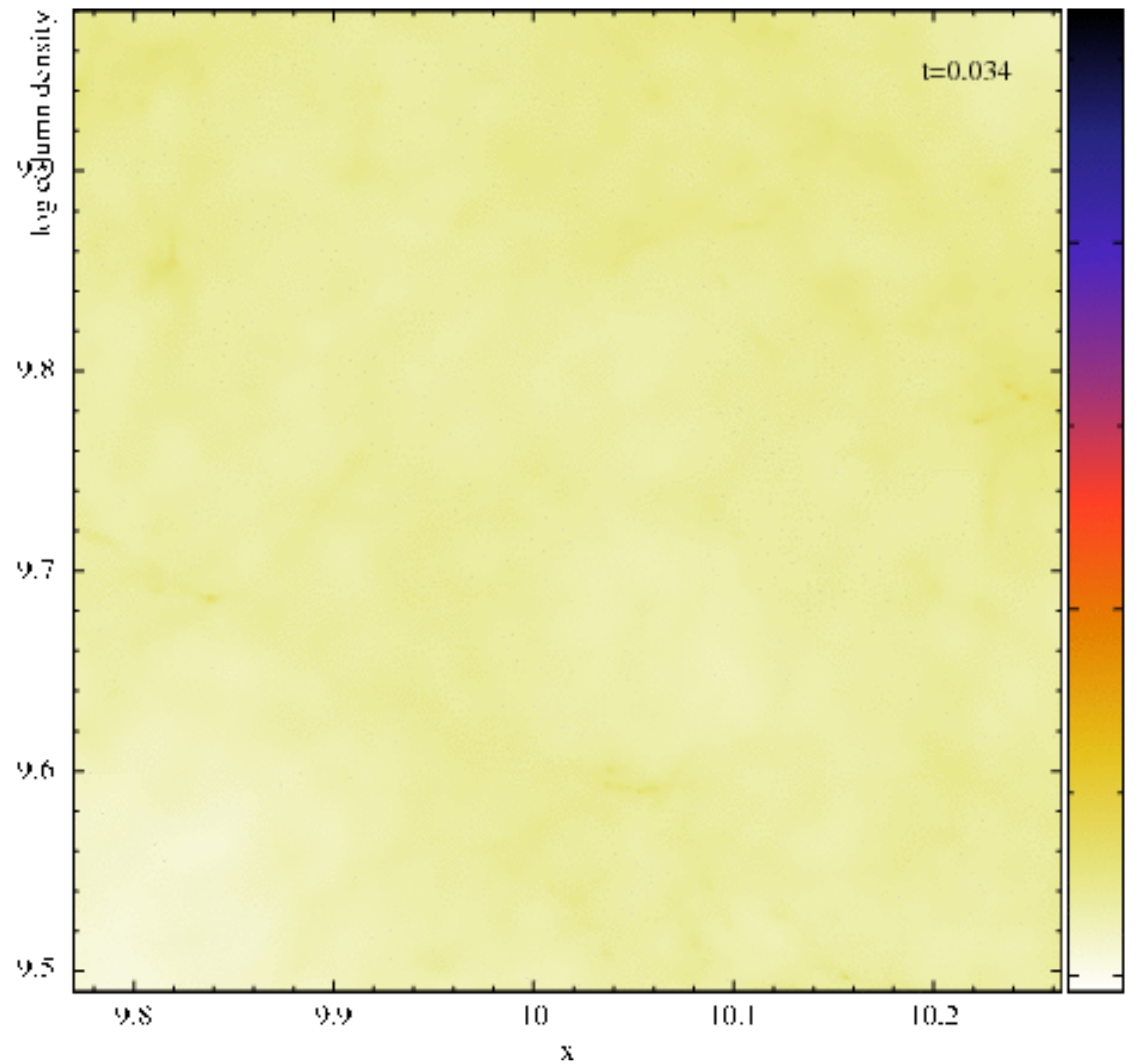
Impact of SN feedback on Gas

zoom-in sim: from z=20 to 6, resol. ~ 30 pc @ z~6

No SN feedback



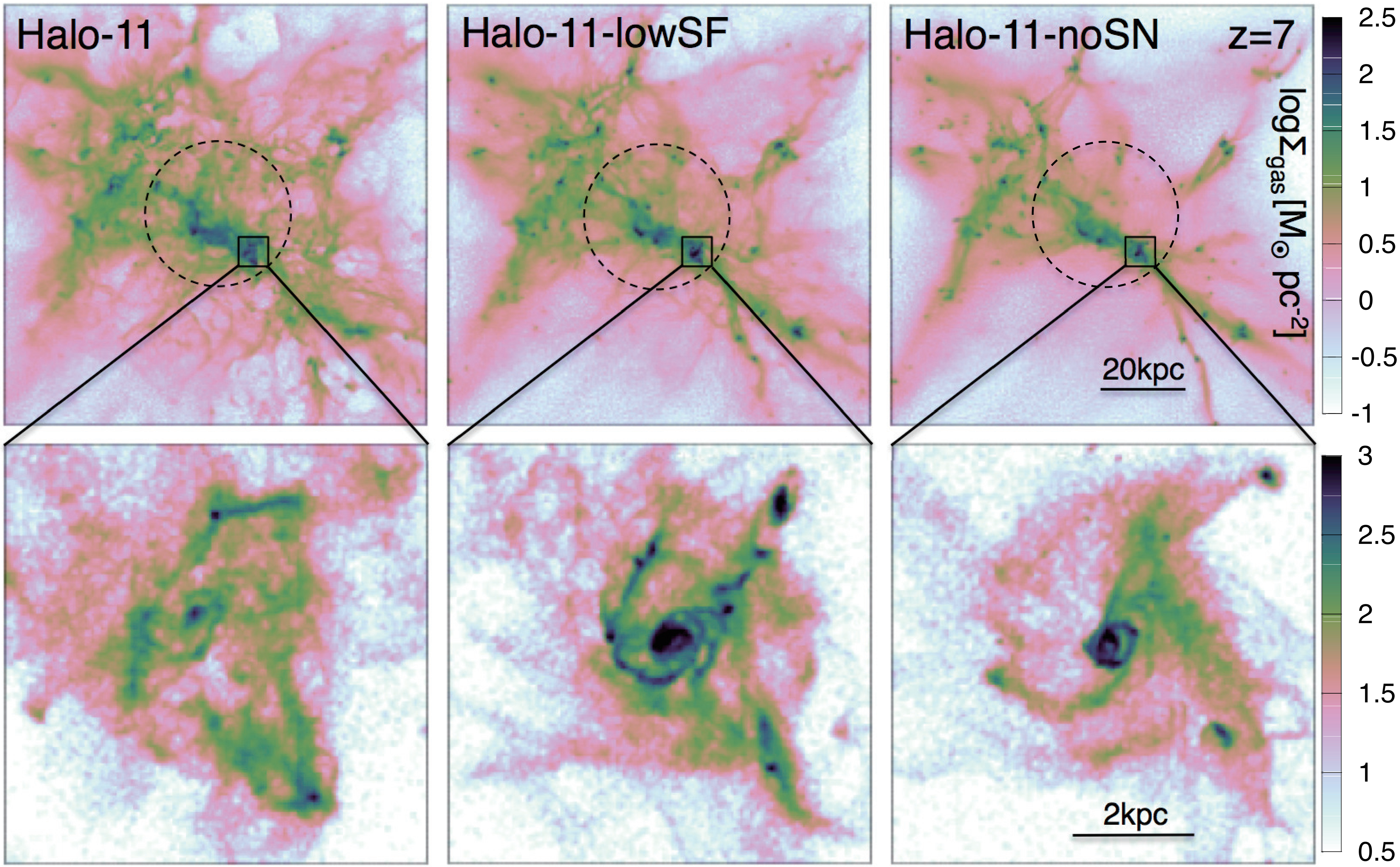
w. SN feedback



500 kpc (com)

Yajima, KN+ '17

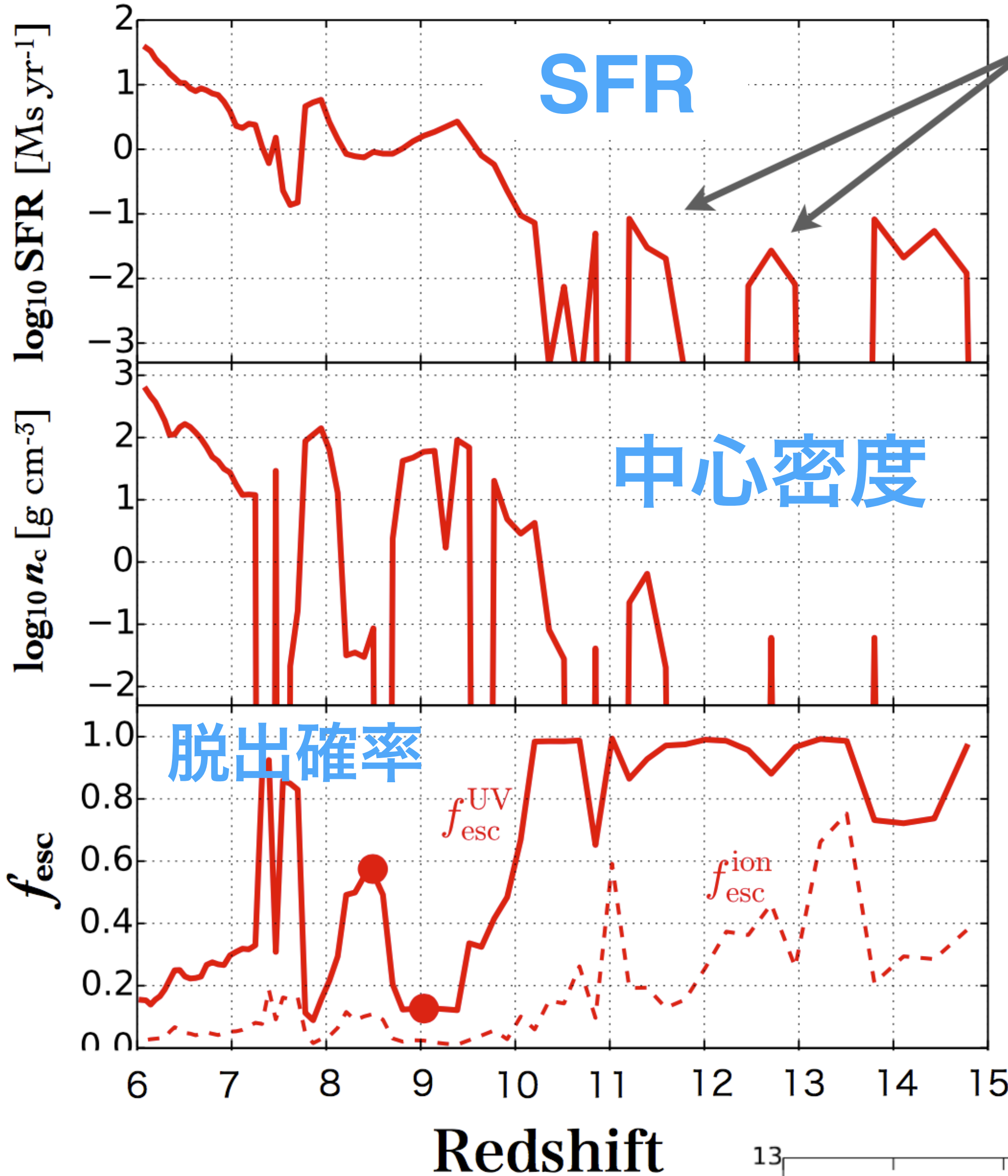
Different morphologies @ z~7 w/ diff. SF & FB models



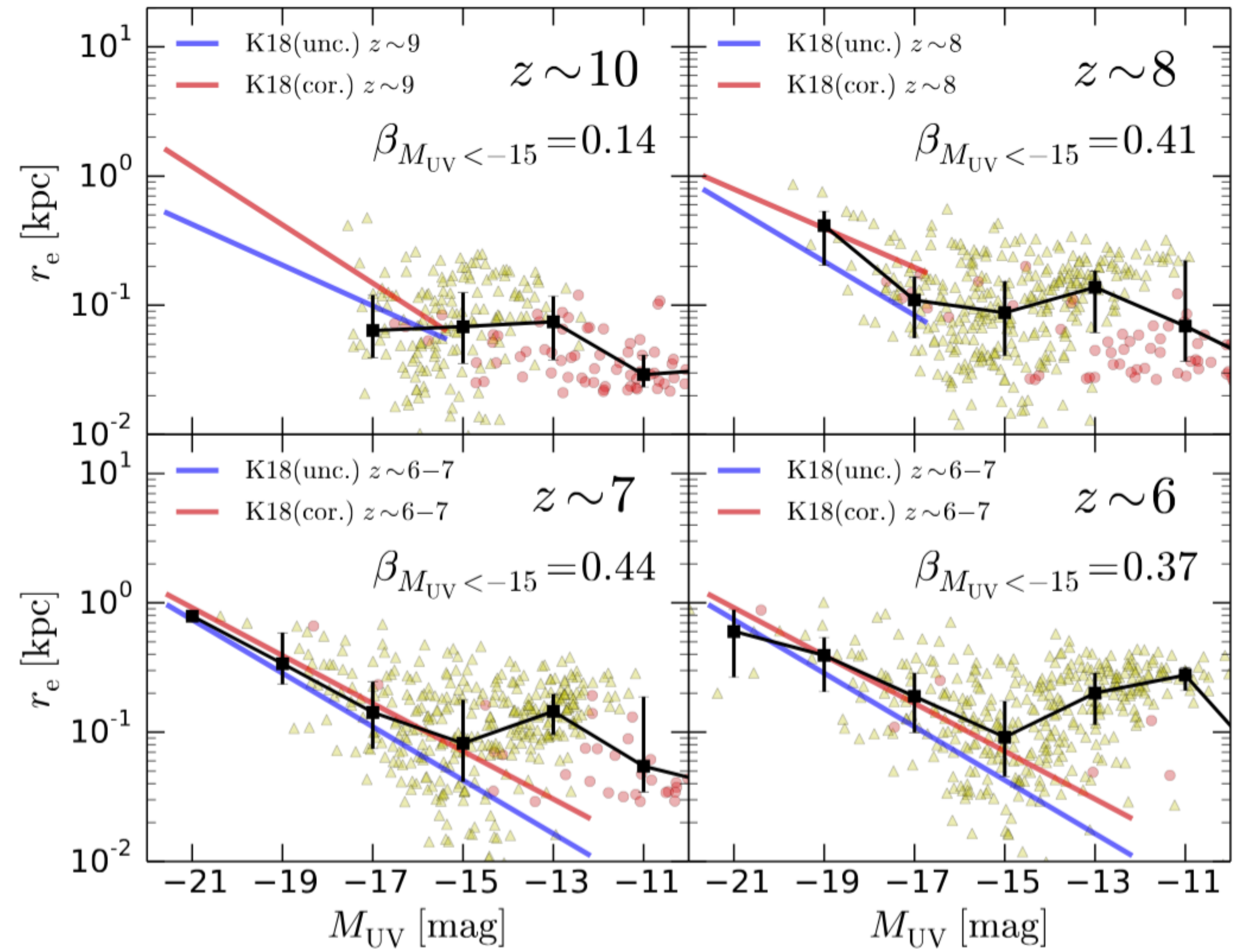
(zoom-in sim)

Yajima, KN+ '17

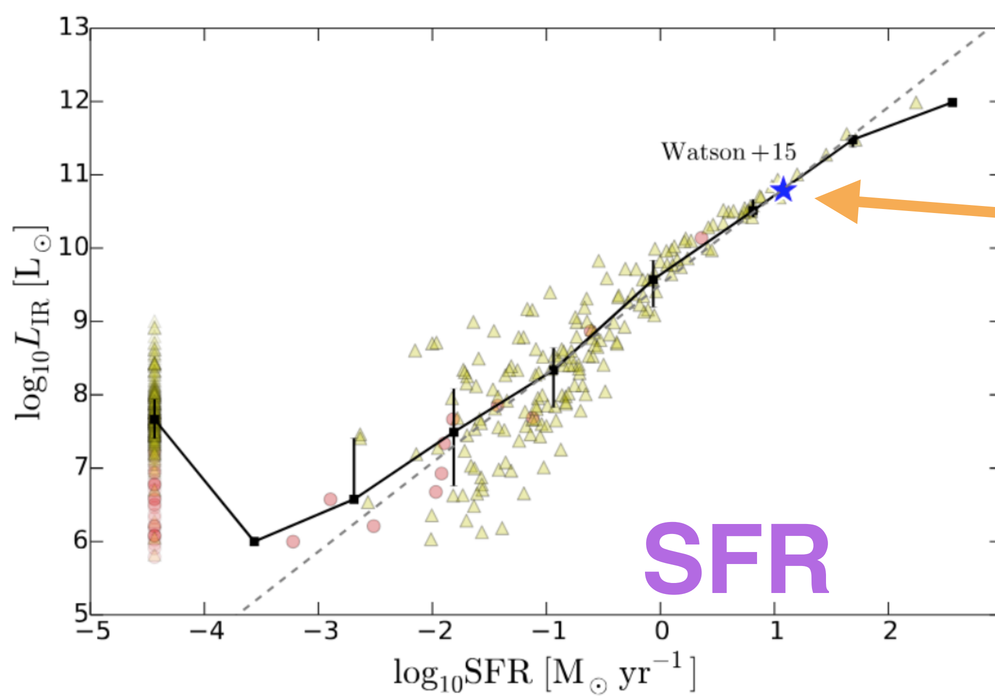
Intermittent SFR



Size — L relation

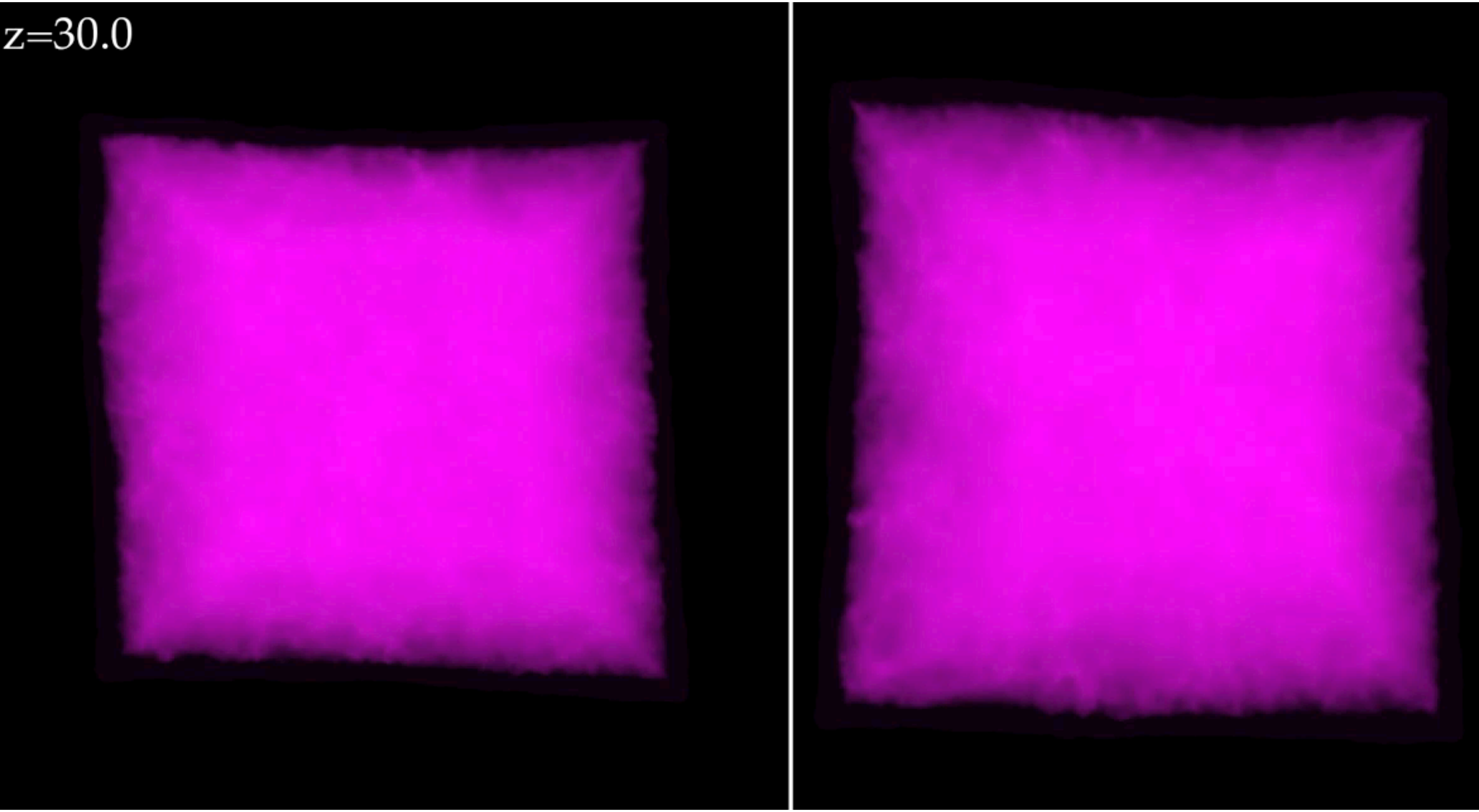


IR luminosity



obs data

Arata, Yajima, KN+ '18
Yajima, KN+ '17



m12q FIRE simulation

m_{dm}~2e5 M⊙/h

m_b=5e3 M⊙/h

ϵ_{dm}=100 pc/h

ϵ_b=7 pc/h

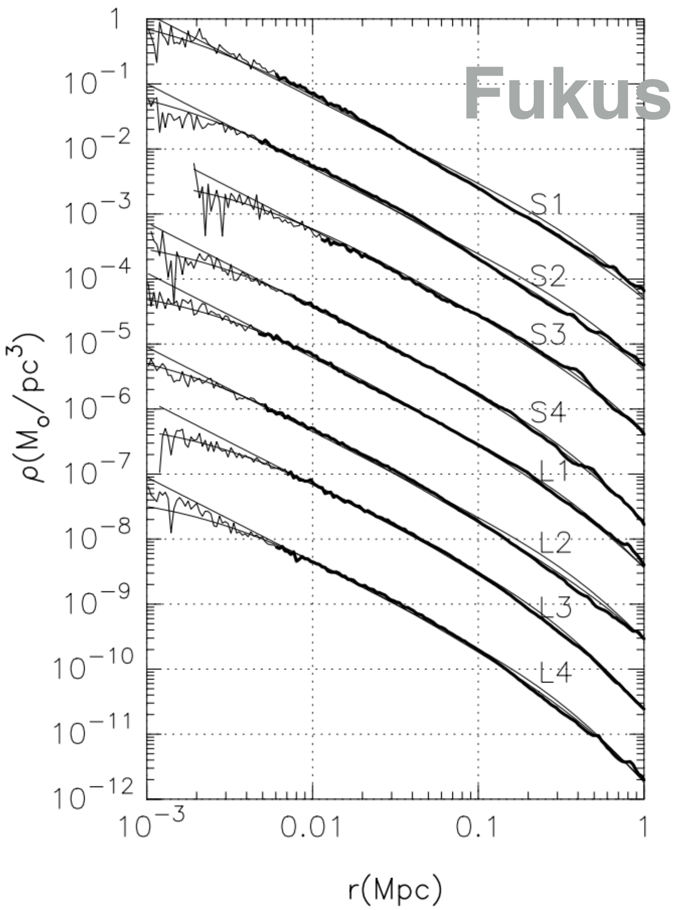
II. Small-scale crisis for CDM?

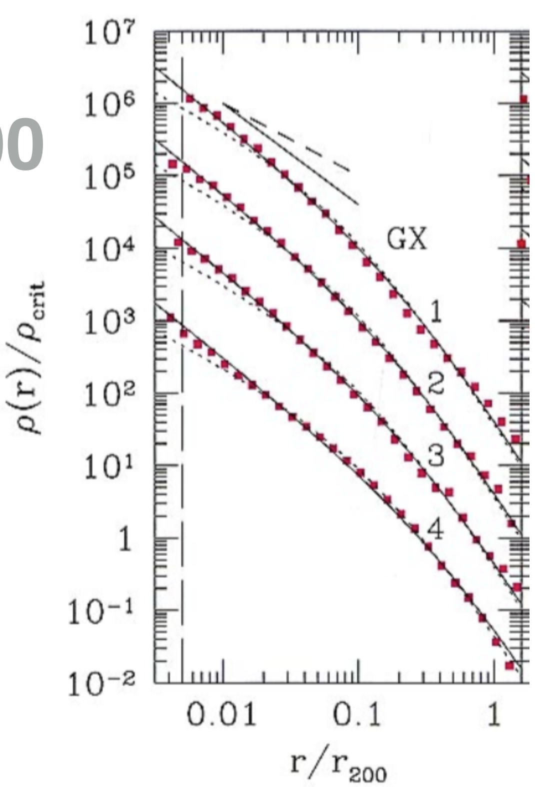
Small-scale problems of ΛCDM?

- **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?
- **Satellites plane problem:** satellites aligned in a plane for both MW and Andromeda
- ….

Cusspy profile not universal

even with DM-only sims.





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)

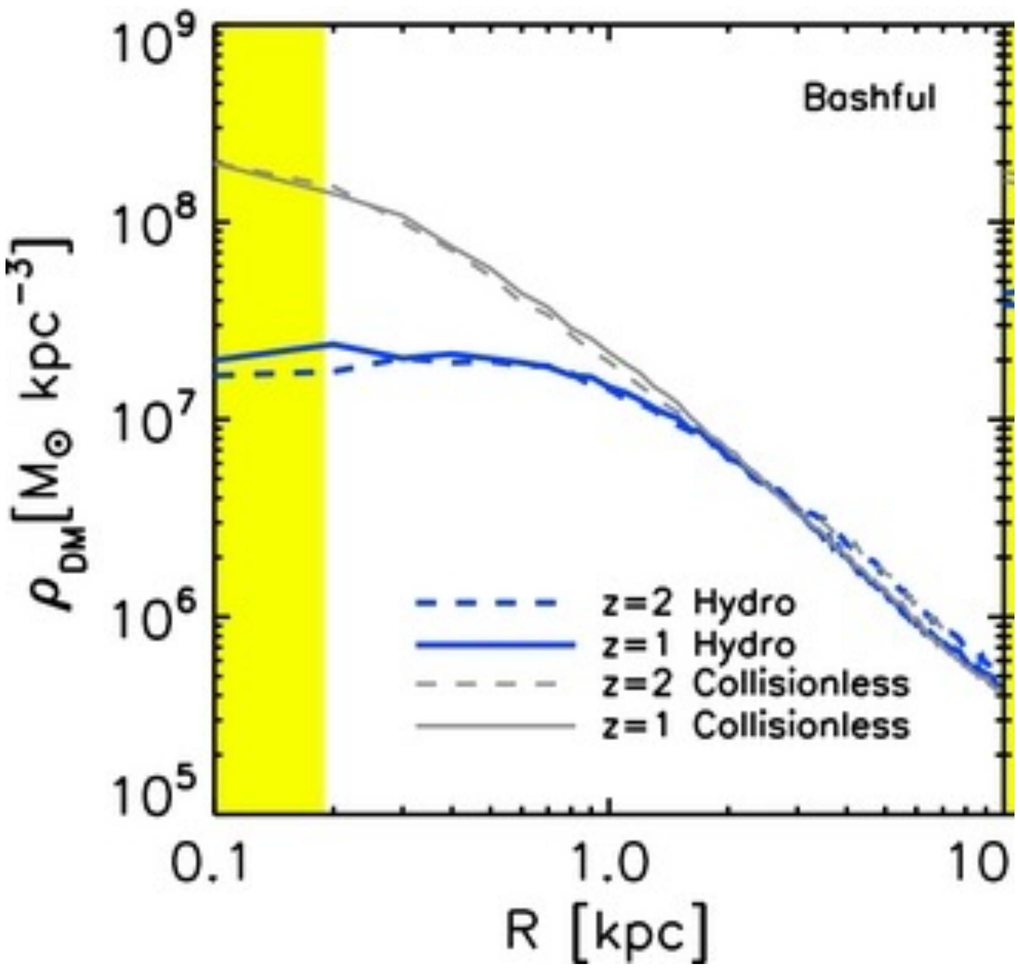
Papers finding not-so-universal profiles:

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)

Boylan-Kolchin & Ma

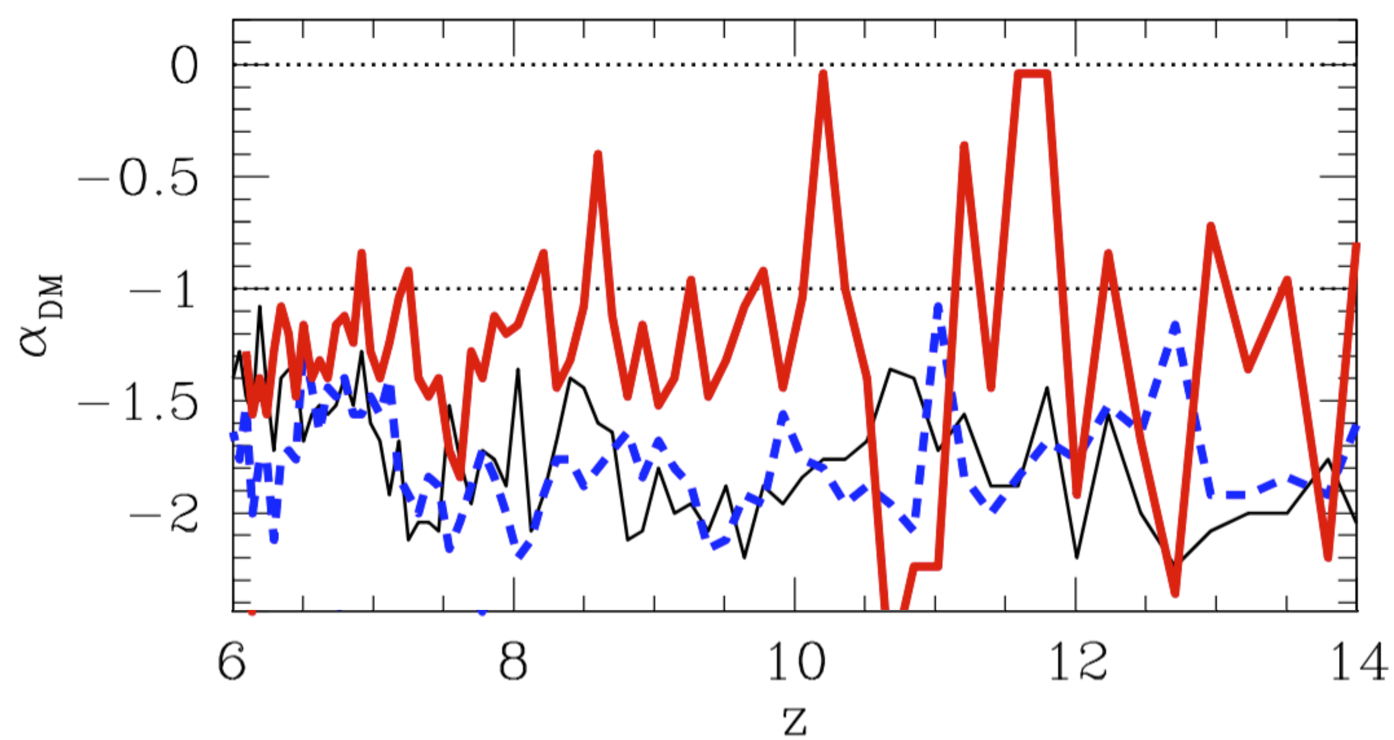
SN-driven gas outflow erases DM cusp and create cores

(zoom-in hydro sim)



Pontzen & Governato '12
Madau+'14

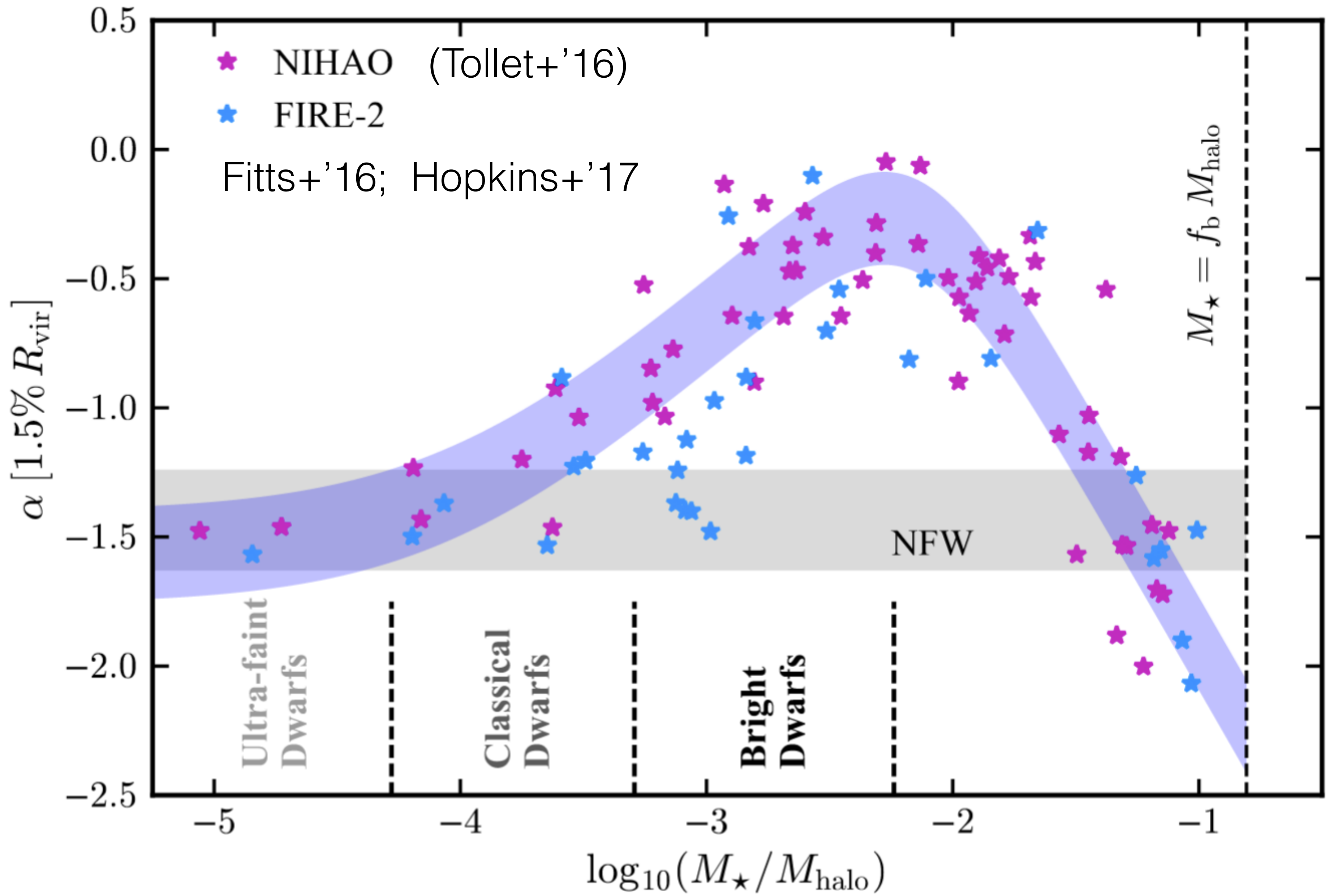
Inner density profile oscillates rapidly.



Yajima, KN+ '17

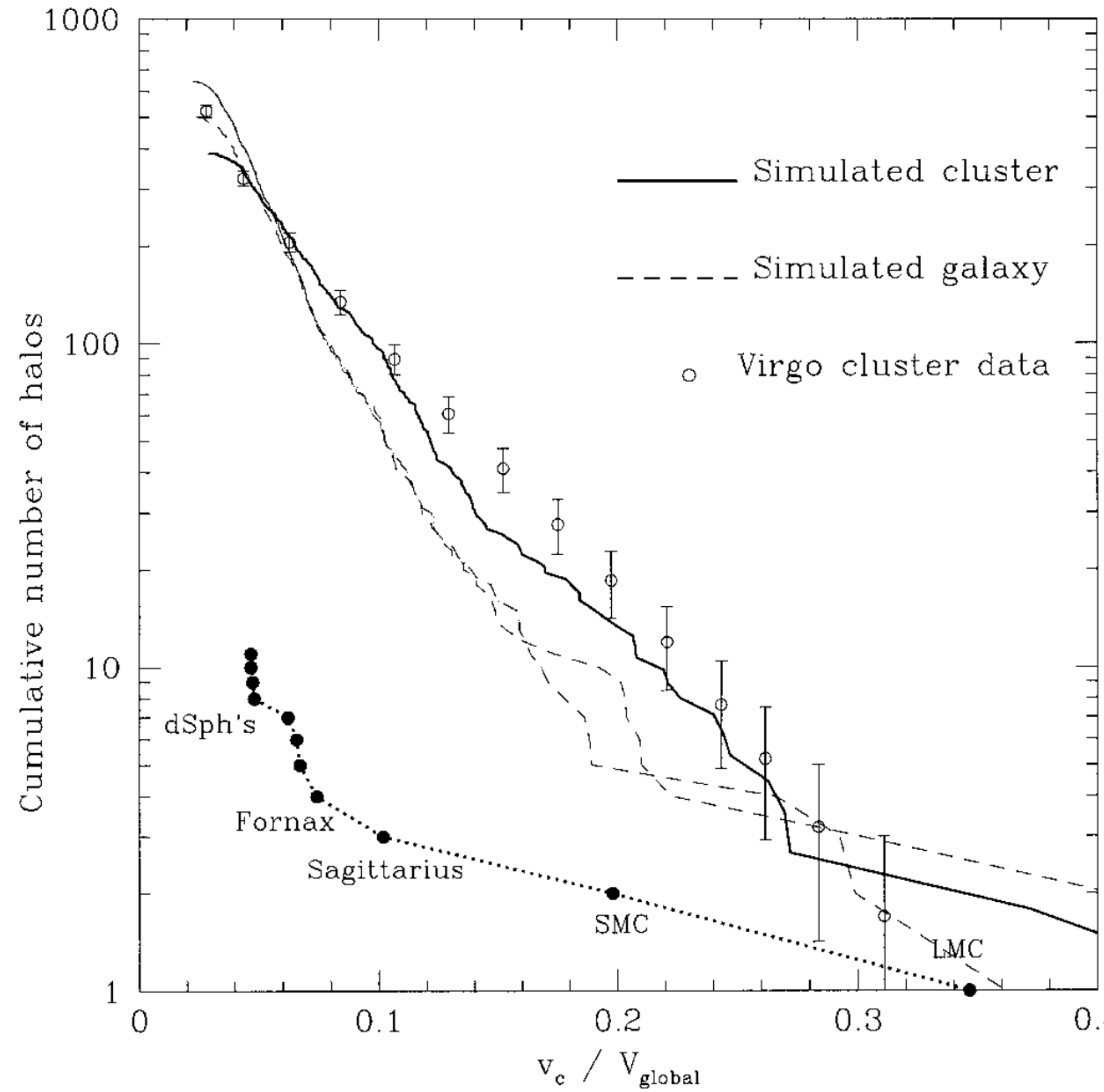
`Gastrophysics' can remove cusp prob.

Impact of baryonic feedback on inner density profile



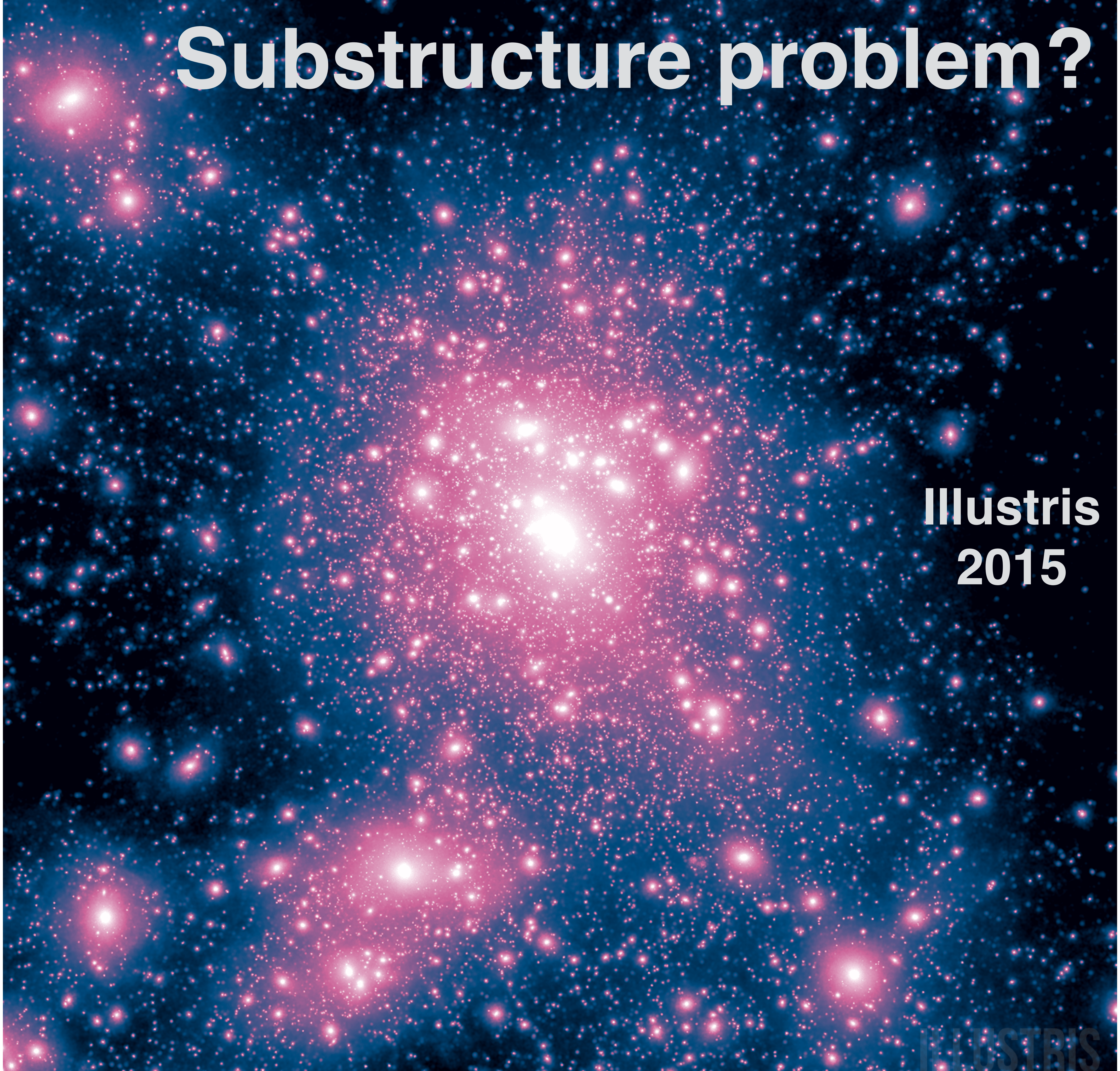
Bullock & Boylan-Kolchin '17

Original Substructure Problem



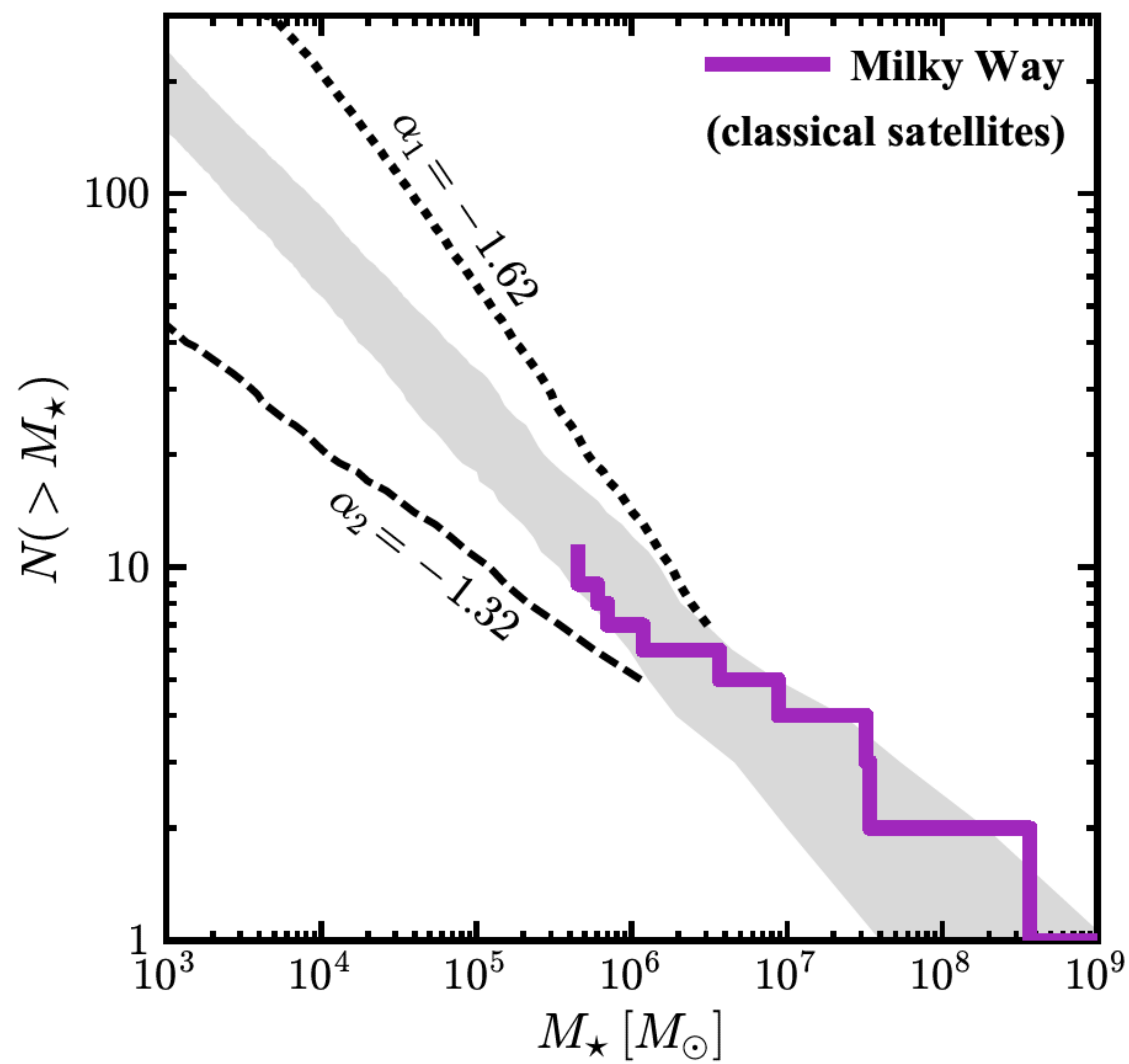
Klypin+'99; Moore+'99

Substructure problem?



Substructure Problem Solved?

Cumulative # count

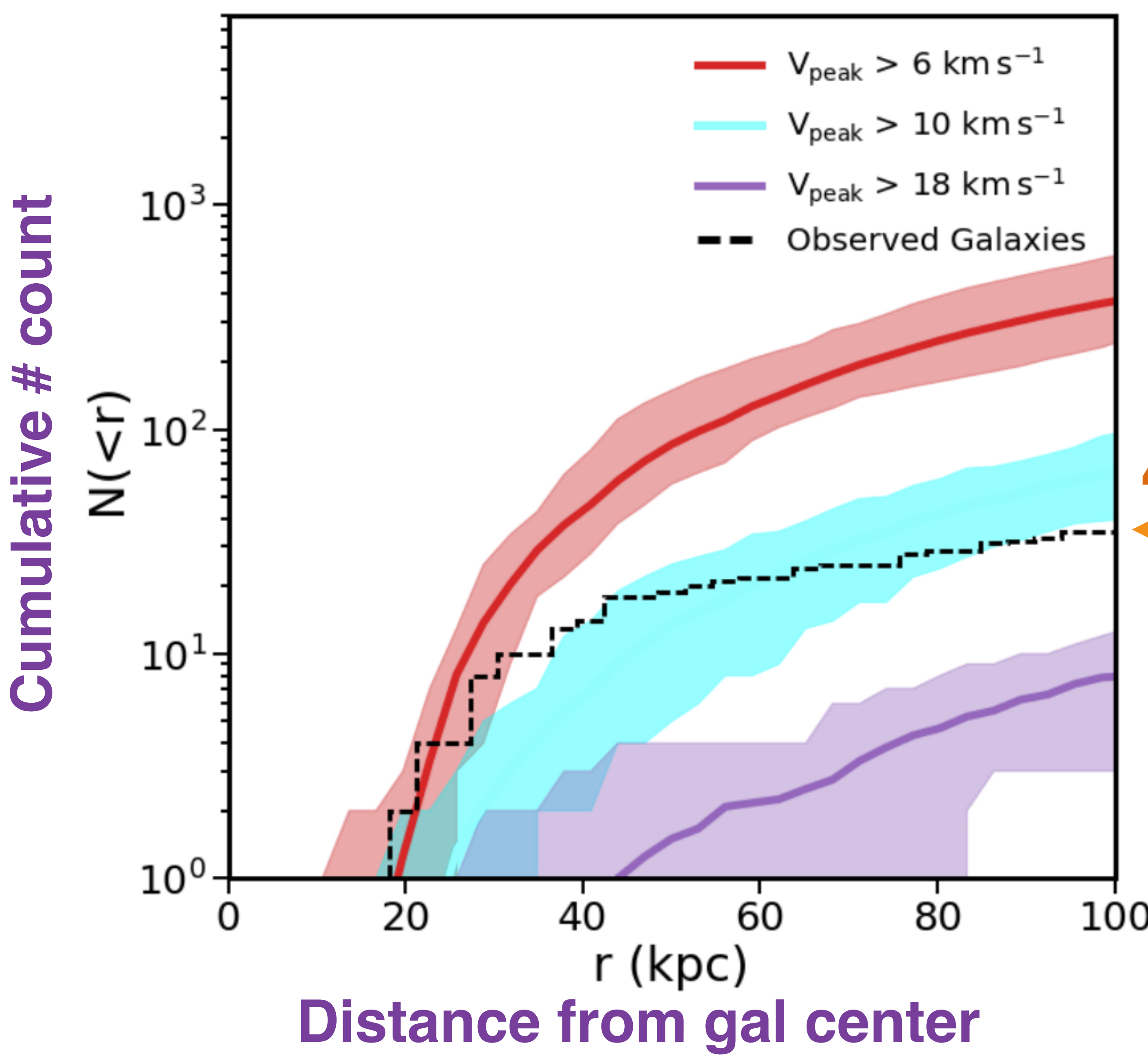


Stellar mass

Garrison-Kimmel+'17

Bullock & Boylan-Kolchin '17

No Missing Satellite Problem??



Approaching to reionization suppression scale

40-50 ultra-faint dwarfs have been newly discovered

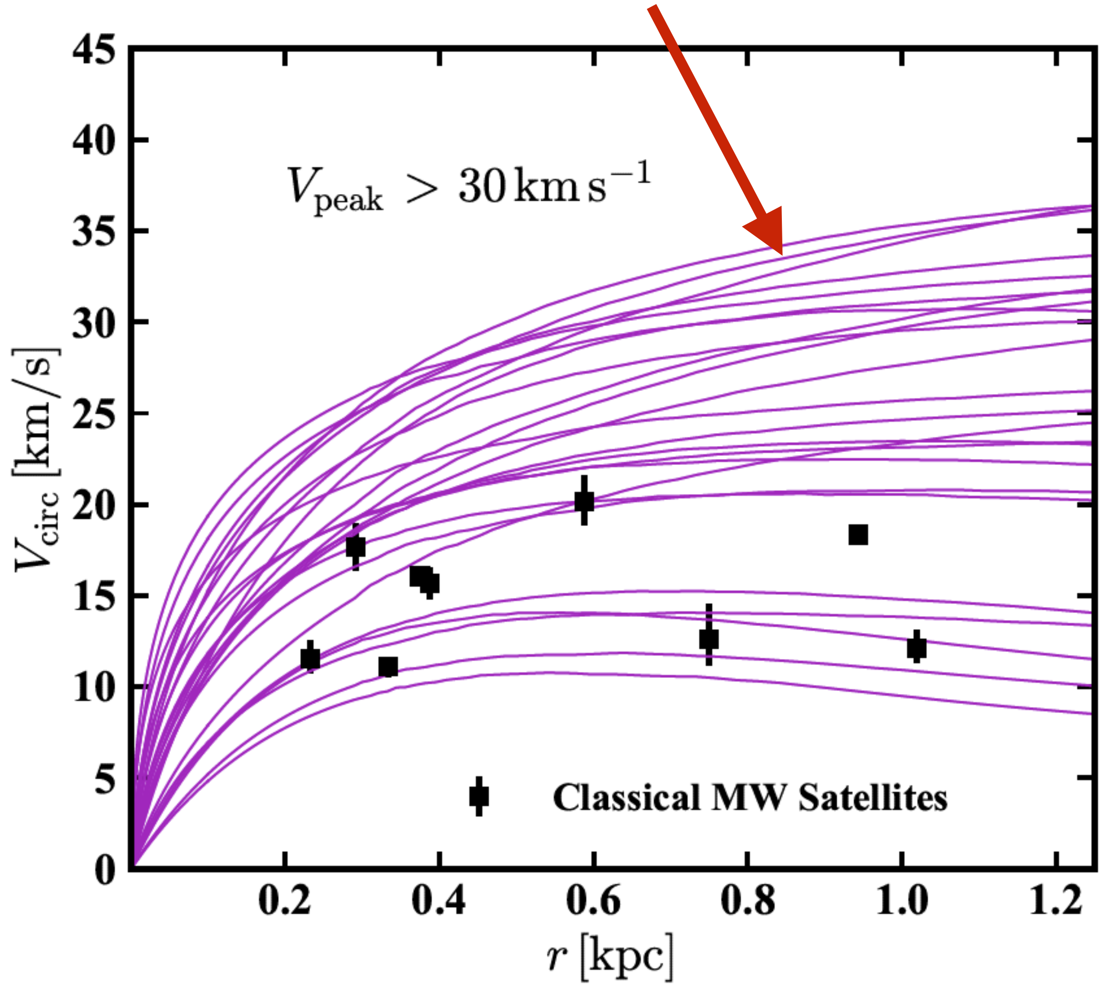
Garrison-Kimmel+'17; Graus+'18

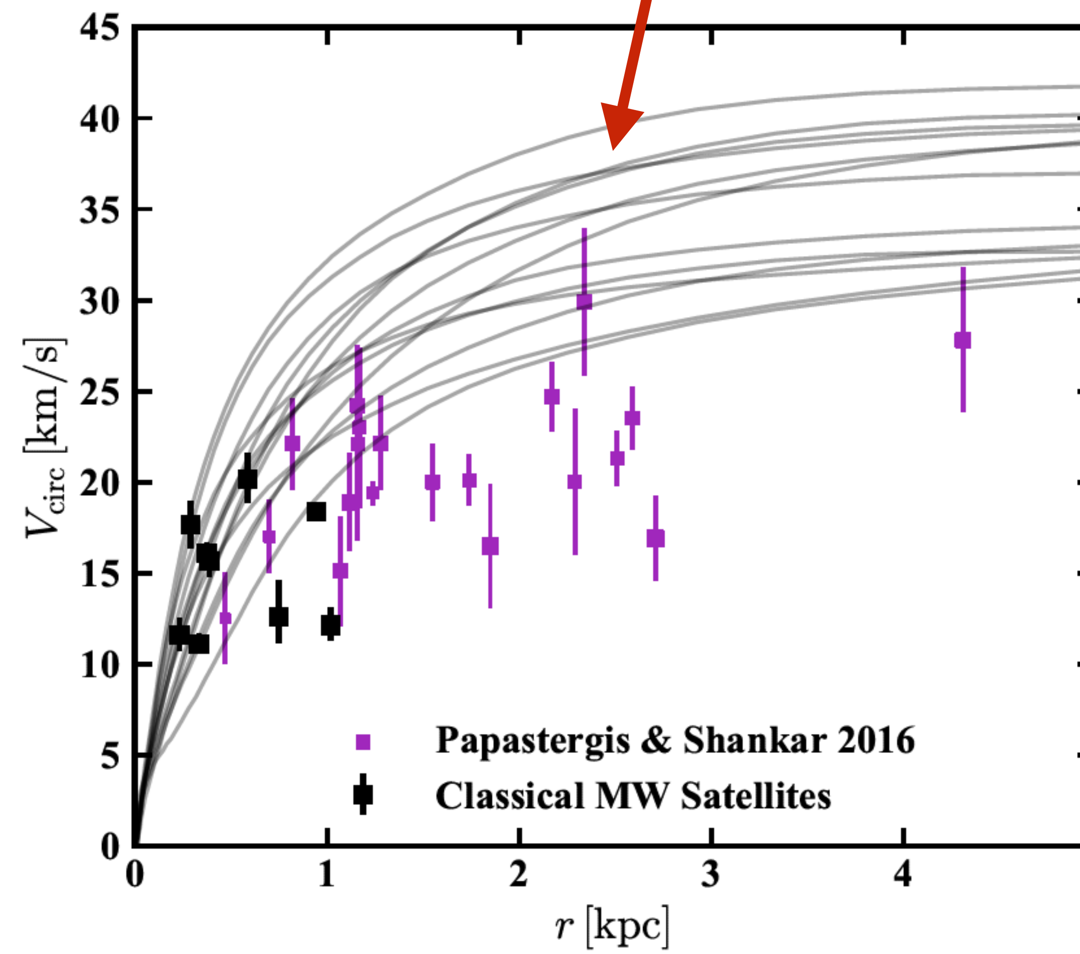
Latest obs by: **SDSS, Pan-STARRS, DES, MagLiteS,…**

Too-big-to-fail problem

N-body simulation

hydro sims (Fitts+'16)





Boylan-Kolchin+ '11

`too big' to have failed to form stars…

Various Dark Matter

1. 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** (10GeV ~ 1TeV)
standard QCD-**axion**(1μeV ~ 1meV)

2. 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, sterile neutrino,…)

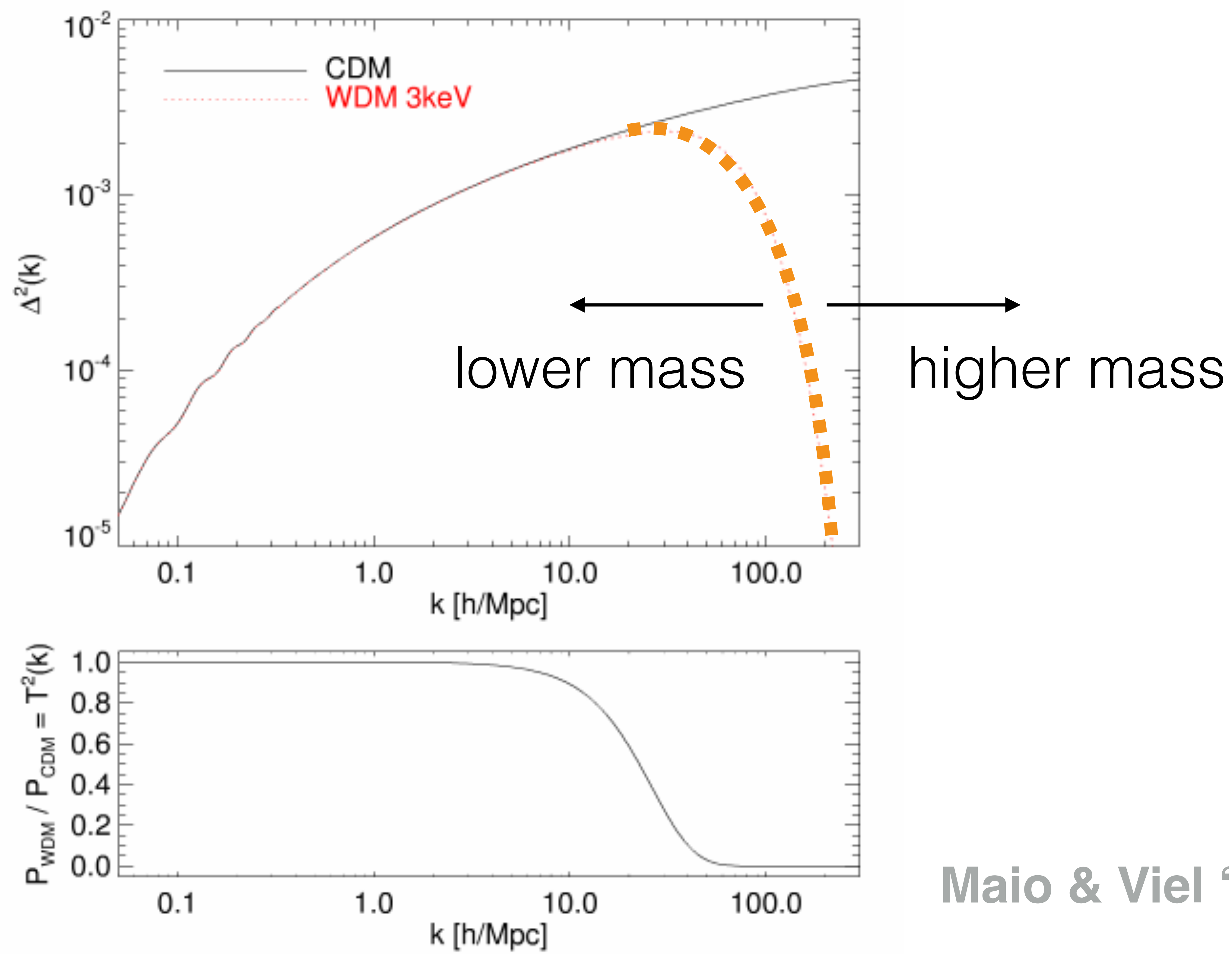
3. Hot Dark Matter (HDM):
$m \sim 1\,\mathrm{eV}$,
$v_{\mathrm{th}}^{z=0} \sim 30\,\mathrm{km\,s^{-1}}$

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

(**ν**,…)

4+ **Fuzzy** *(axion-like)*, **Self-interacting DM**
ALP

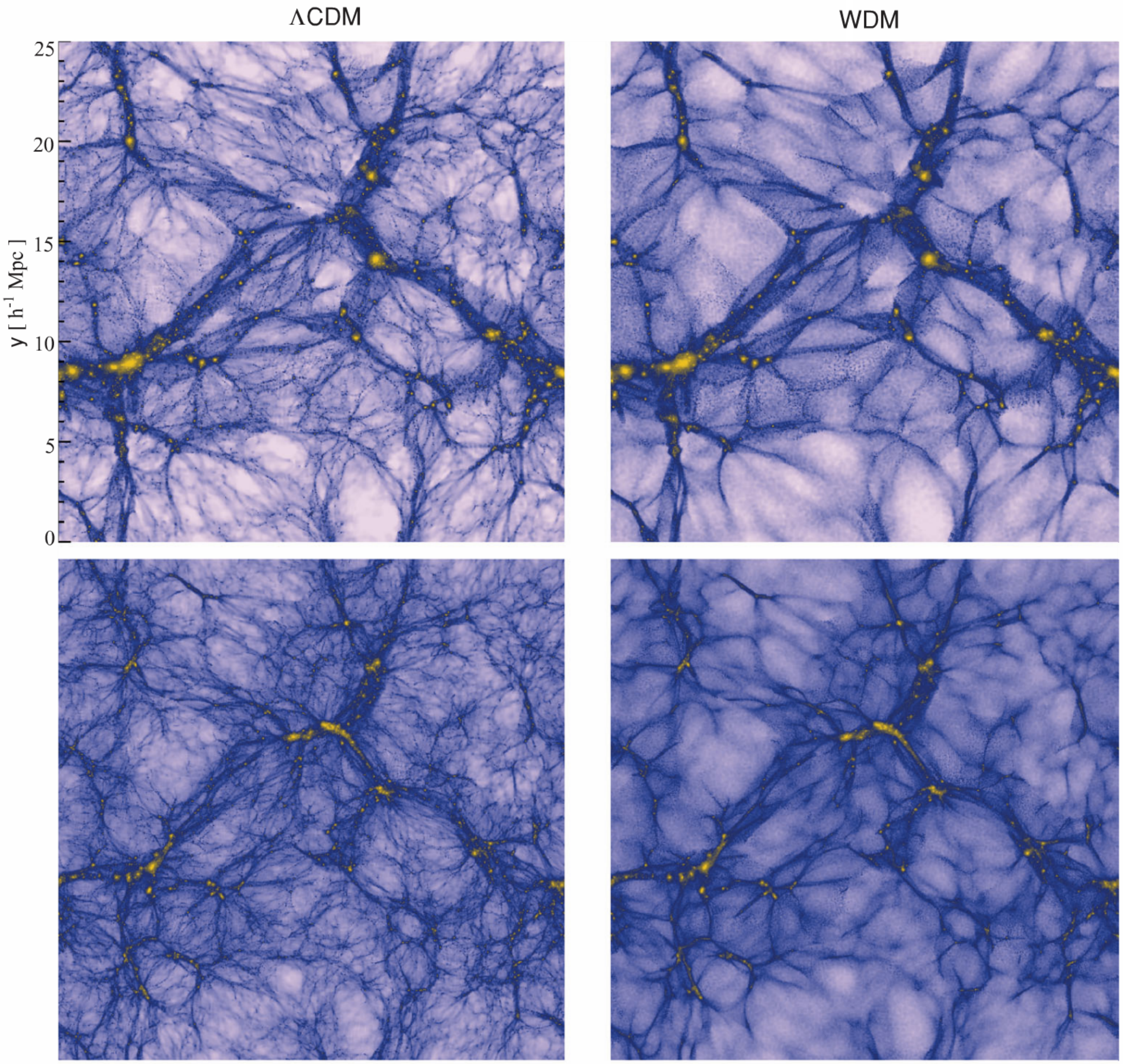
WDM
Suppression of P(k) @ small scales



Maio & Viel ‘15

Colin+’00; Bode+’01; Viel+’05; Colin+’08; Colombi+’09; Viel+’12; Menci+’17 z=0

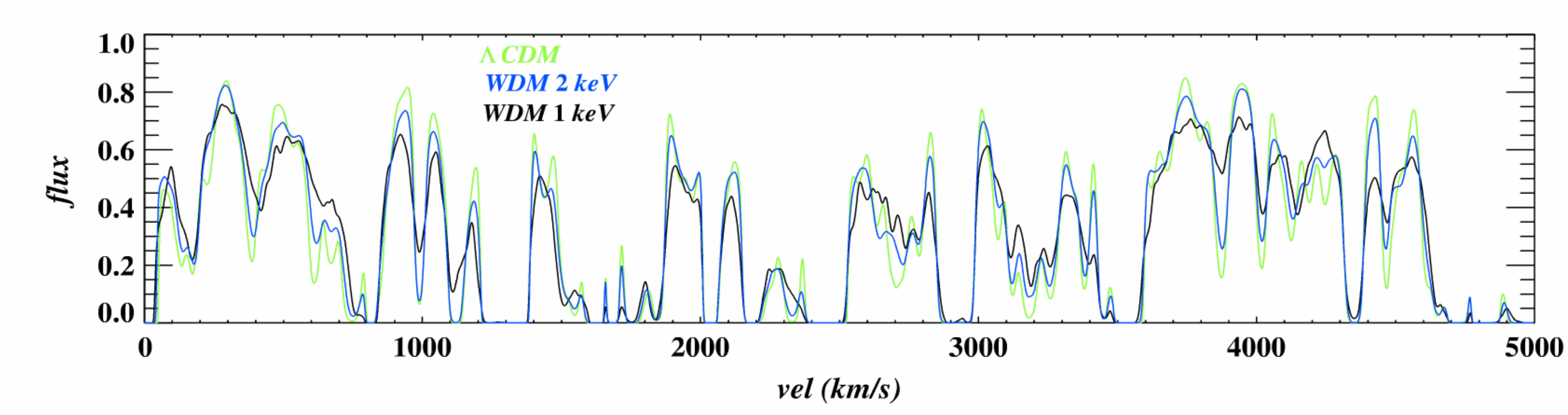
z=2



m=1 keV

Viel+'12

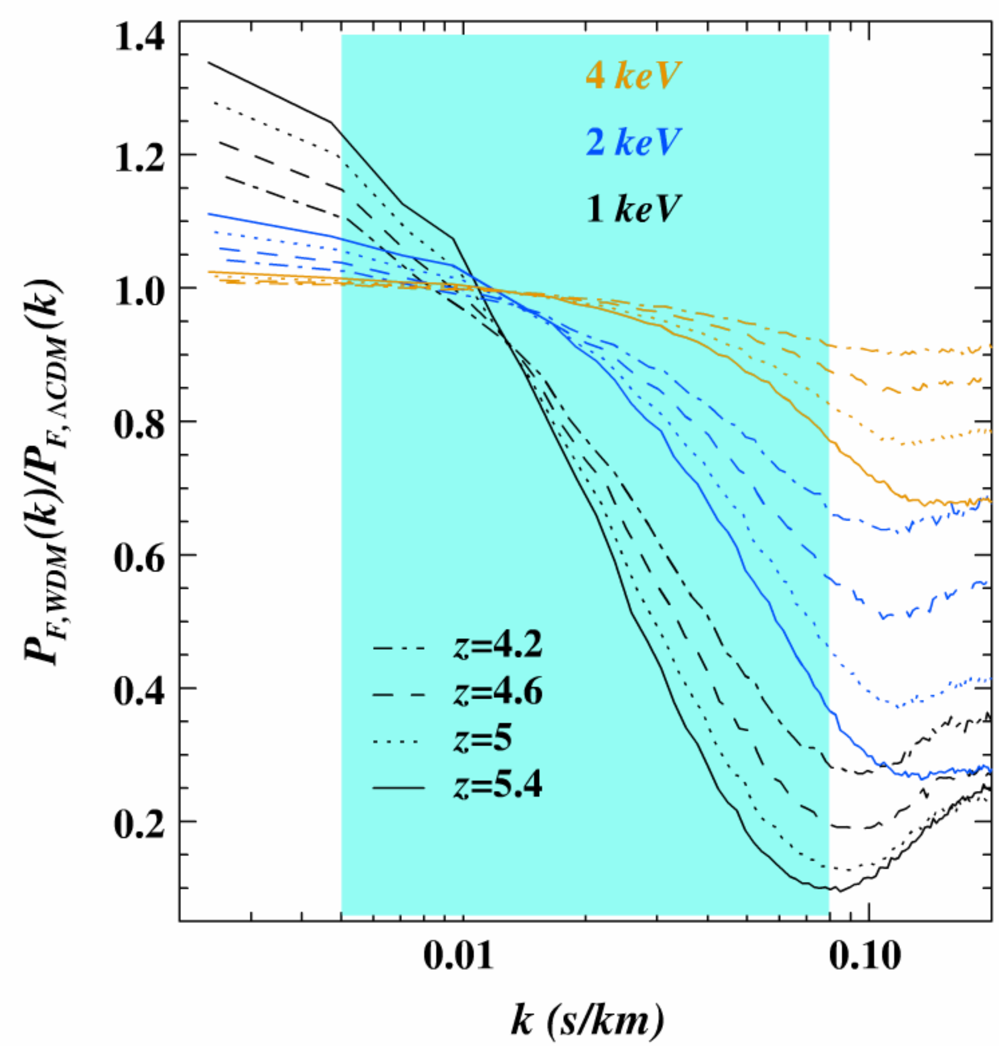
Ly-α forest constraint



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

1D flux power spec

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



marginalize over cosmo params & T_0, γ using COSMOMC against obs data

Viel+'13
Baur+'16

WDM conclusions

- **WDM** models w/ $\lesssim$ **3keV** have been explored — strong alternative candidate to CDM

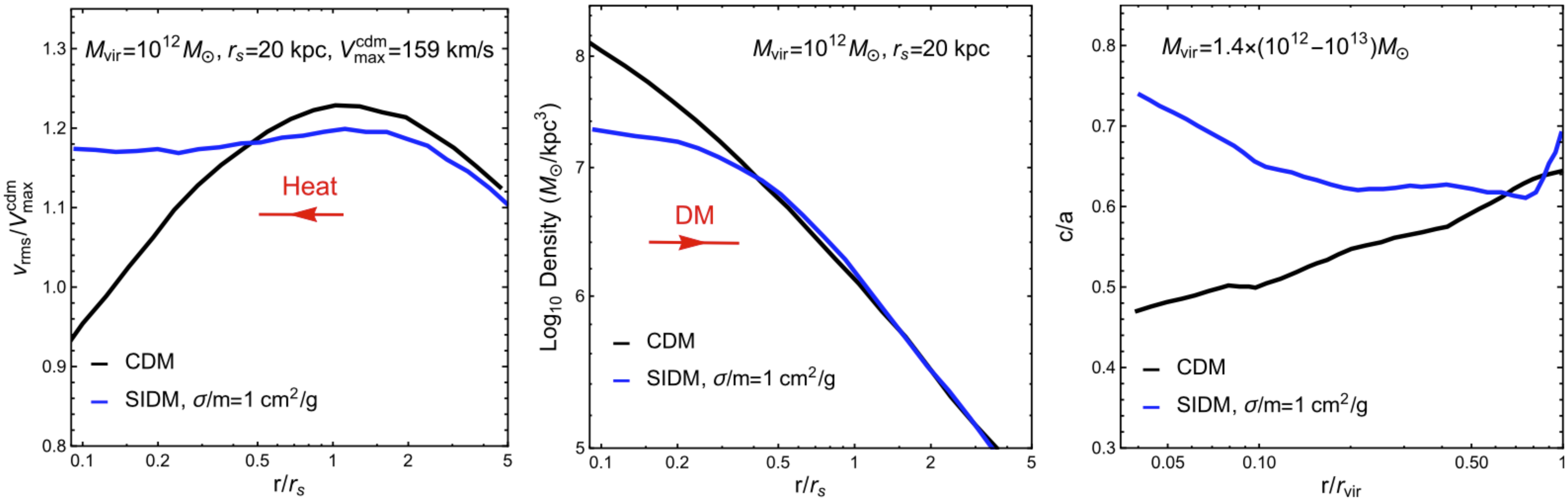
- **$m_{dm} \gtrsim$ a few keV** seems more likely than **< 1keV**.

- **Viel+13, Ly-a forest: m>3.3 keV** (2-σ), **$M_{h,min}$~2e8 $M_\odot$**

  Baur+16: m>2.96 eV (for thermal relic)

- Further study is needed with high-resol. and realistic SF & feedback models — **e.g. impact of AGN feedback on small-scale power (van Daahlen+’11; Semboloni+’11)**

Impact of Self-interaction



`Heat' transfer from outside to inside

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

Spergel & Steinhart '00

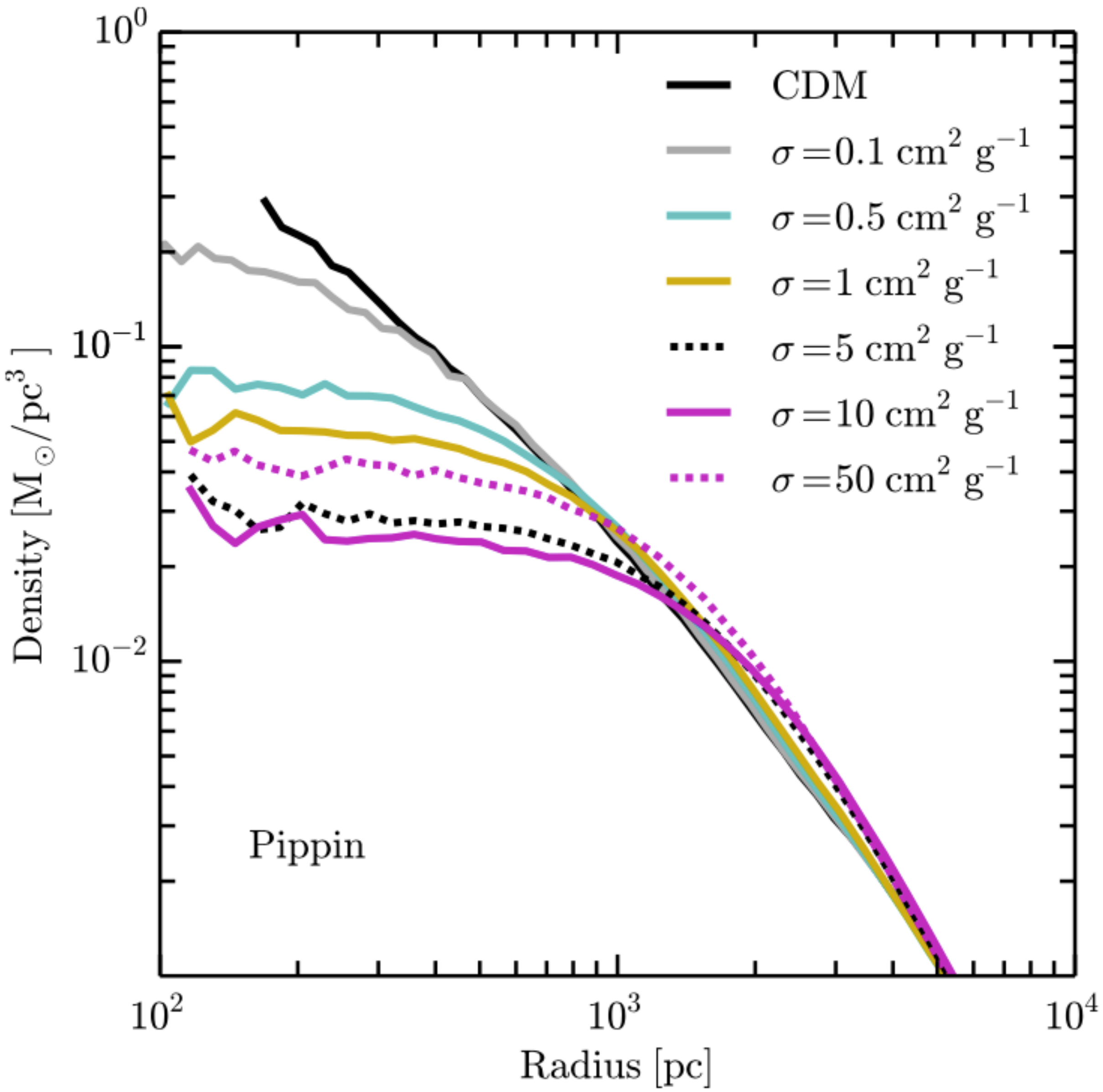
Rocha+'13

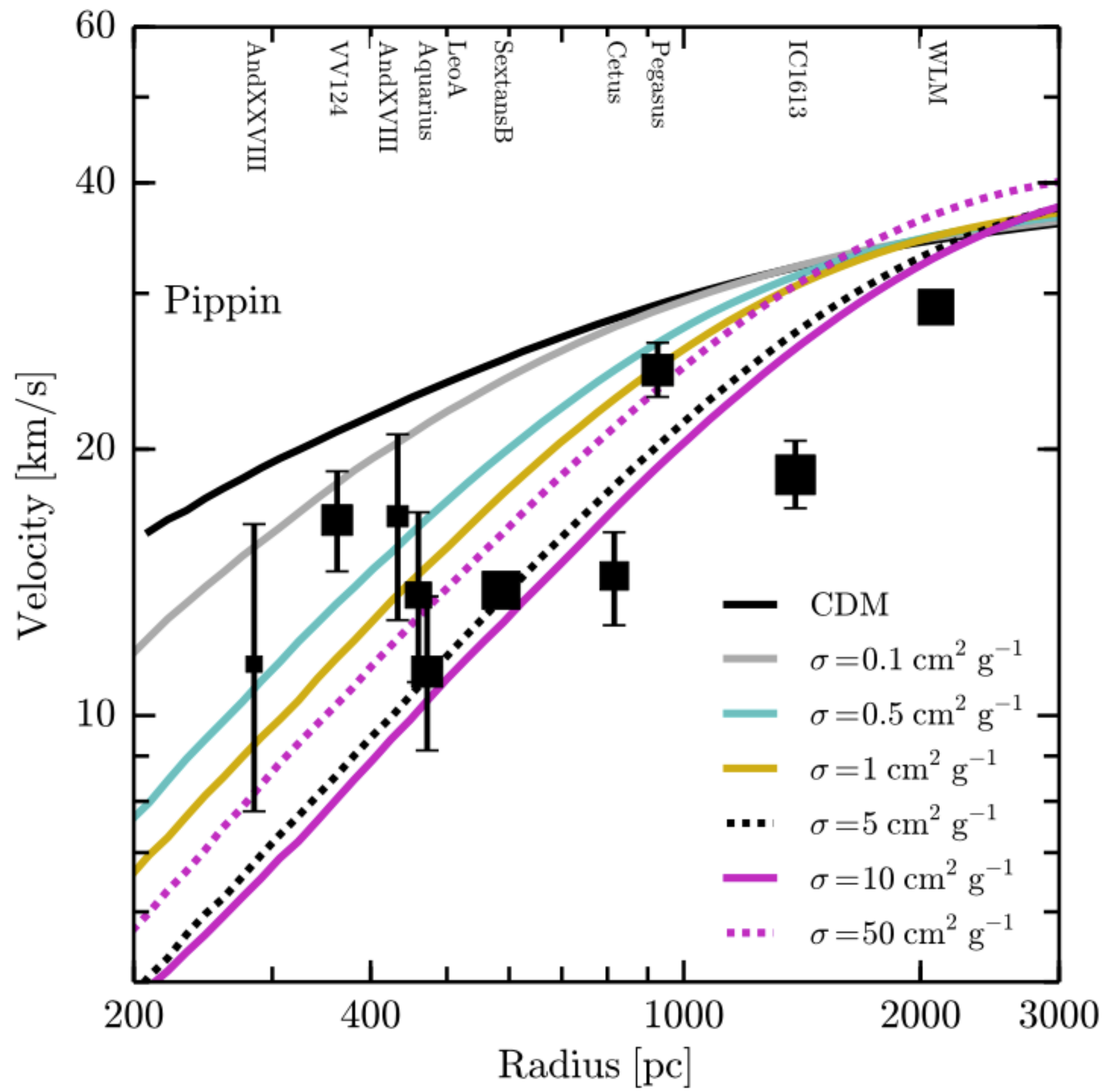
cf. WIMP

$$\sigma/m \sim 10^{-38}\,\mathrm{cm}^2/\mathrm{g}$$

Tulin & Yu '18

SIDM

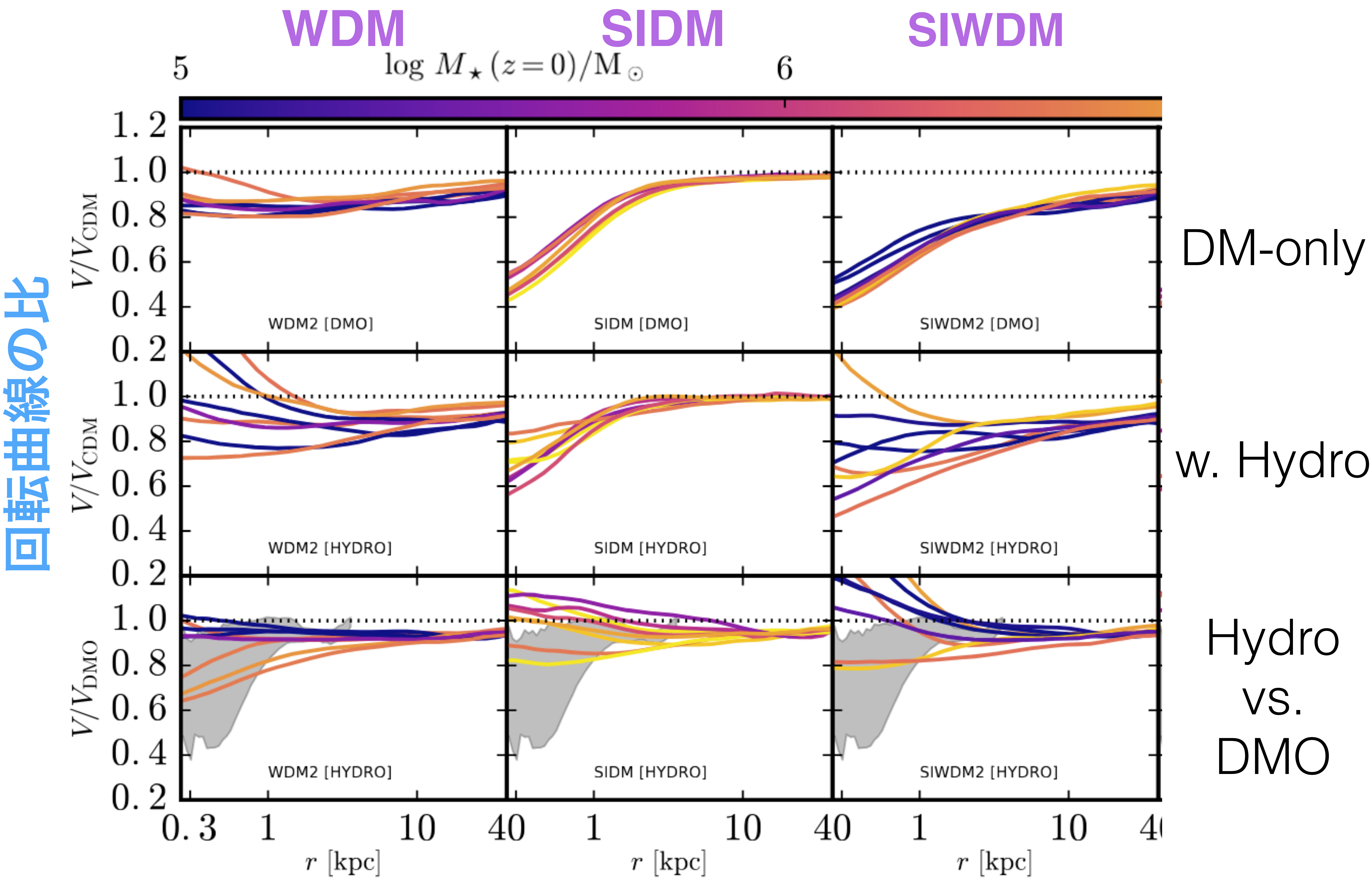




Elbert+'15

Tulin & Yu '18

Impact of Baryons on Rotation Curves



Fitts+ '18

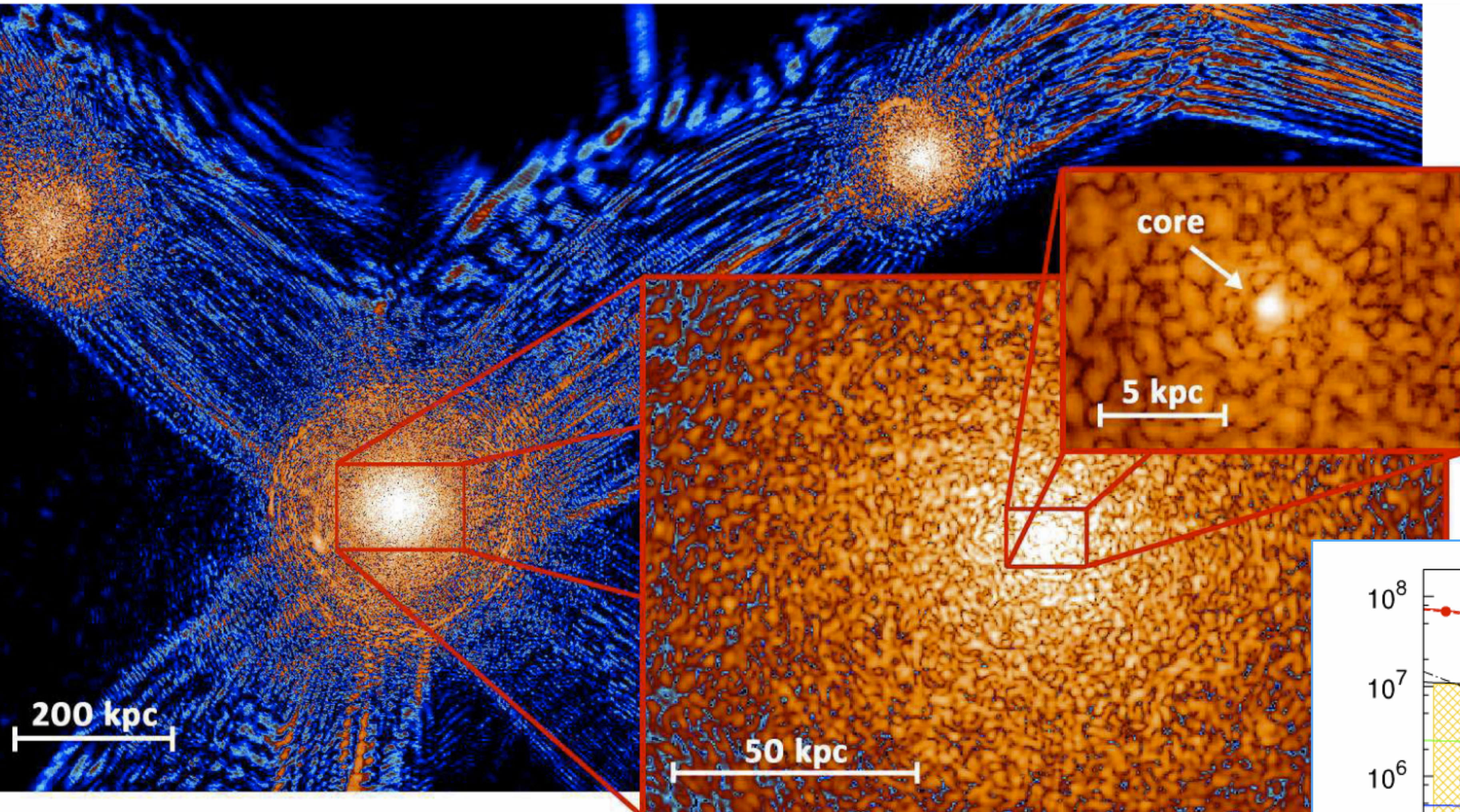
Fuzzy Dark Matter (FDM)

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
- expect suppression of halos at 10^{7}-10^{10} $M_{\odot}$
- forms a central core as a "**soliton**" (Schrödinger-Poisson eq.)
- on large-scales, ≈ CDM

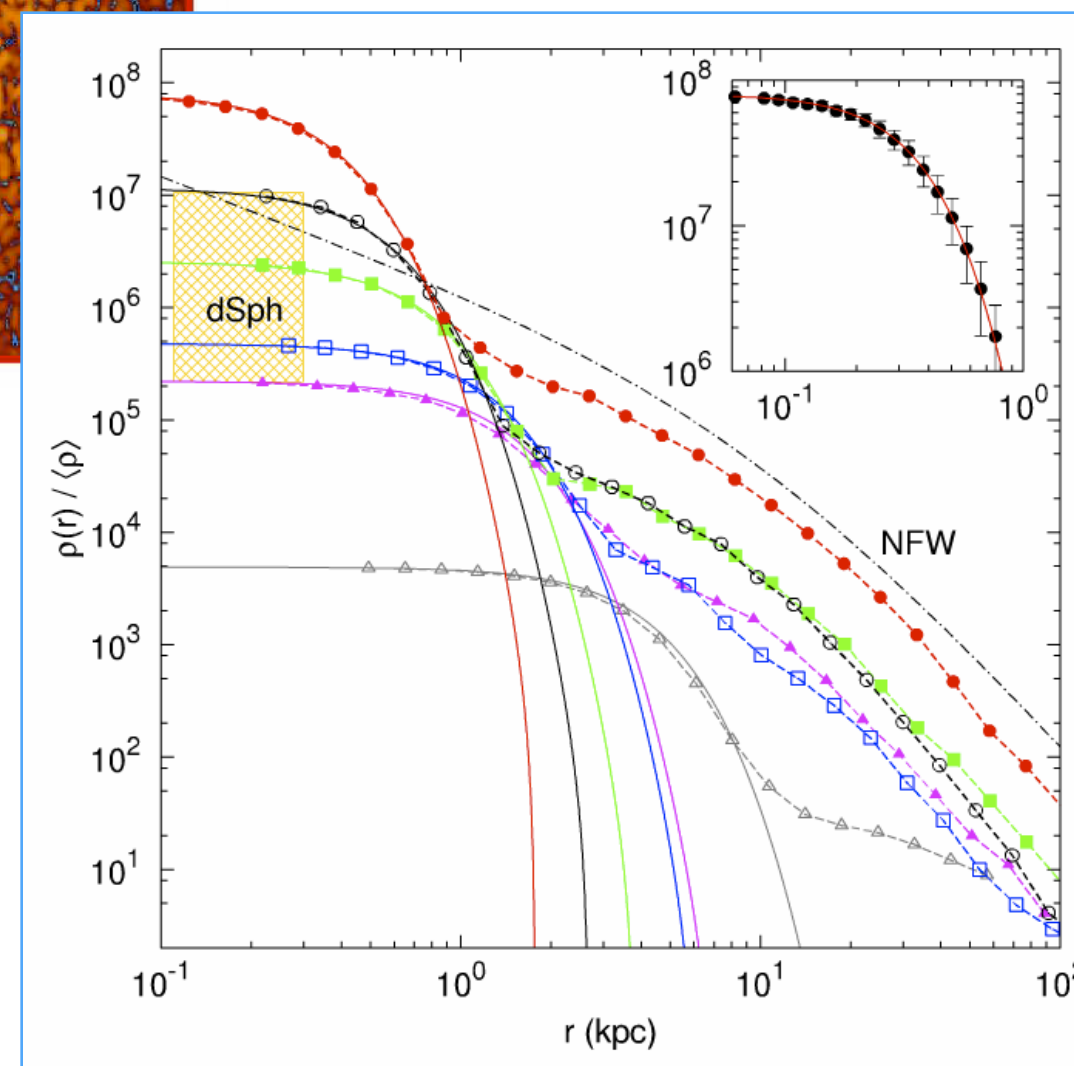
Baldeschi+83; Kim '87; Sin+94; Hu+00; **Marsh+14; Schive+14; Hui+17; Mocz+17; Robles+18; Zhang+18; …..**

Solitonic Core of FDM simulation



Schive+14

gravitationally bound solitonic core



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

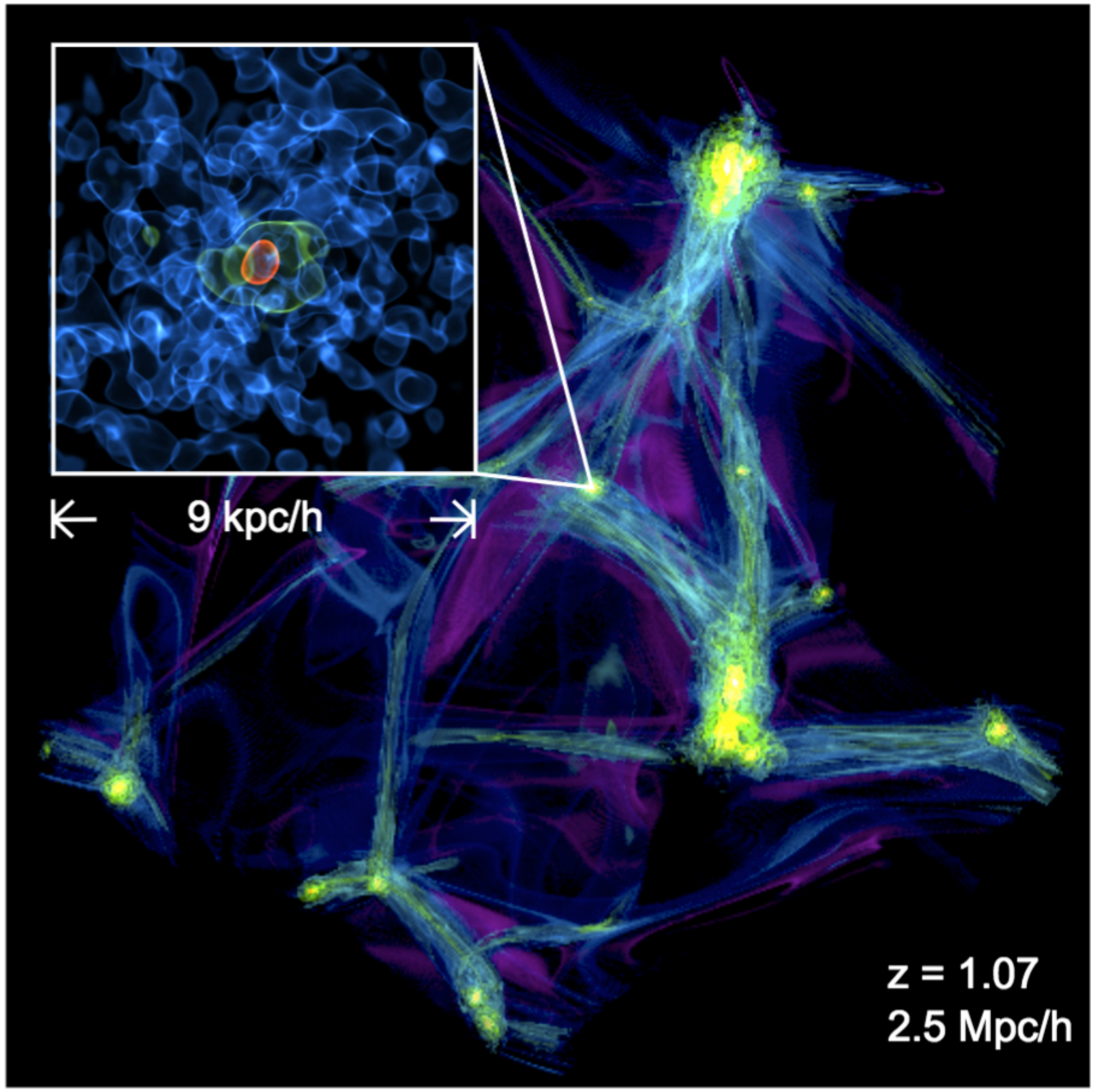
for Fornax dSph gal.

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

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

Formation and structure of ultralight bosonic dark matter halos

Vertmaat+ '18



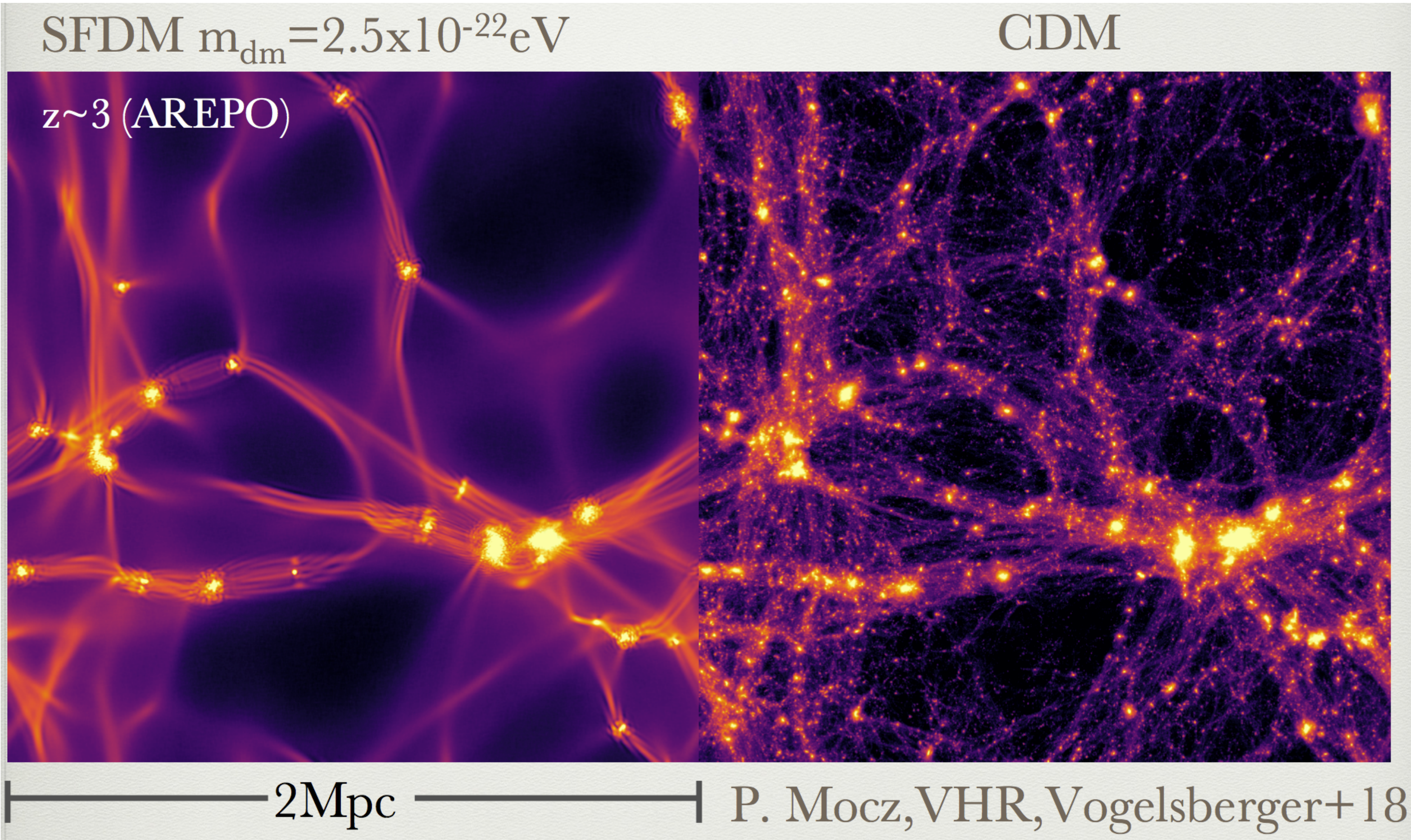
- zoom sim. w/ ***Enzo*** code
  - outside: N-body
- inside halo: Schrödinger-Poisson eq.
- solitonic core:
  - core-halo mass relation
    — consistent w. Schive+'14
  - quasi-periodic oscillation
- difficulty of boundary conditions

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

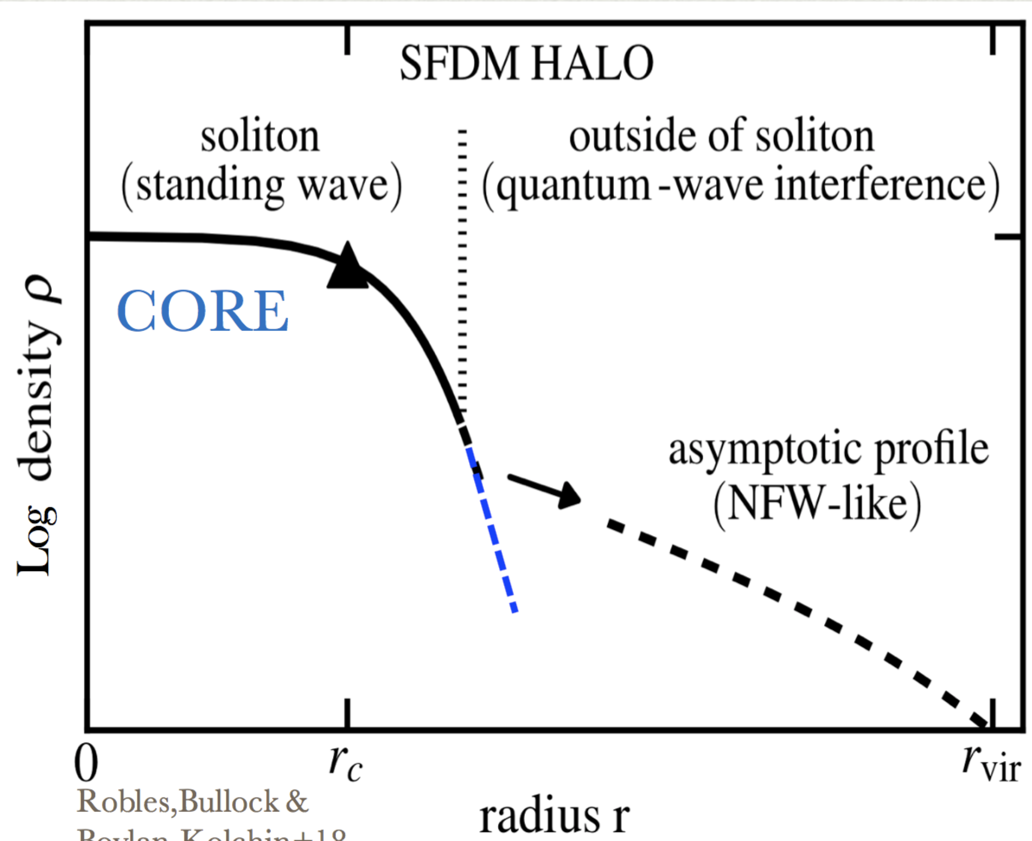
$$\nabla^2 V = \frac{4\pi G}{a}(\rho - \bar{\rho})$$

$\rho = |\Psi|^2$: FDM density

comoving S-P eq.

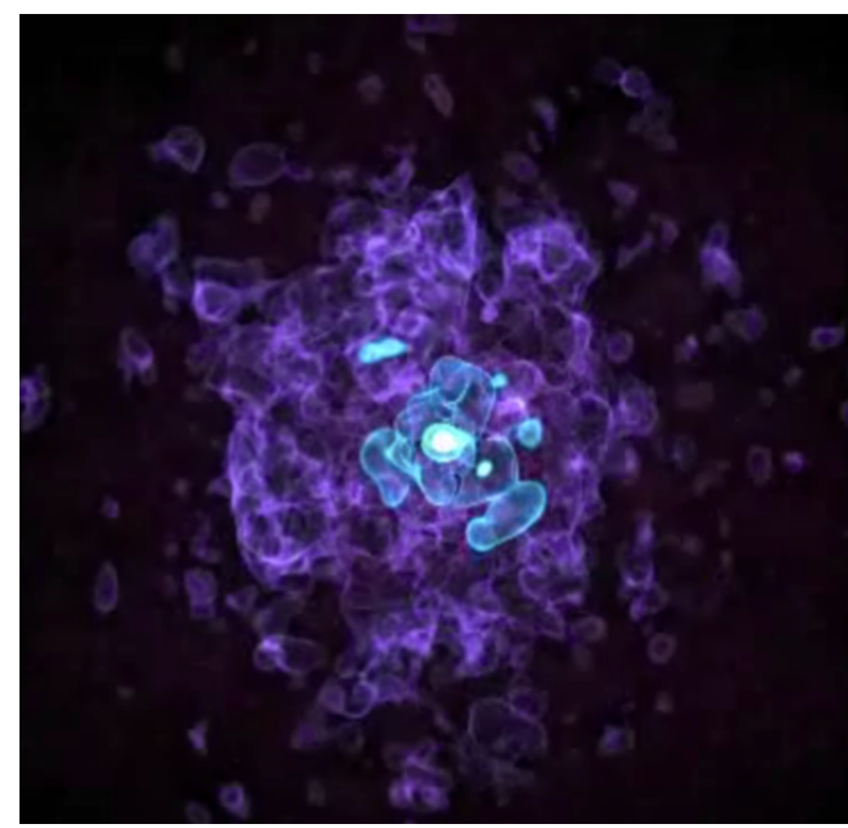


SFDM m_{dm}=2.5x10^{-22}eV
CDM
z~3 (AREPO)
2Mpc
P. Mocz,VHR,Vogelsberger+18



SFDM HALO
soliton
(standing wave)
outside of soliton
(quantum-wave interference)
CORE
asymptotic profile
(NFW-like)
Log density ρ
0
r_c
$r_{\rm vir}$
radius r
Robles,Bullock &
Boylan-Kolchin+18

Robles+18



— Concluding remarks —

- **Feedback !!** — thermal, kinetic, radiative
- **Cold flow** — how gals acquire gas & J
- **Small-scale prob.** might exist — but at the level that can be resolved by `**gastrophysics**'
- Missing satellite prob. — quickly disappearing; opposite prob.?
- Better understanding of **WDM, SIDM, FDM, …** **w. hydro & feedback**
- **How do we reflect the nature of elementary particles realistically to the sims?**
- **DM発見時のために準備が必要（〜 重力波天文学＋数値相対論）**