Dark Matter Cosmological simulations

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Outline

- Numerical simulations in cosmology

- Results from pure DM simulations

- Comparison with observations

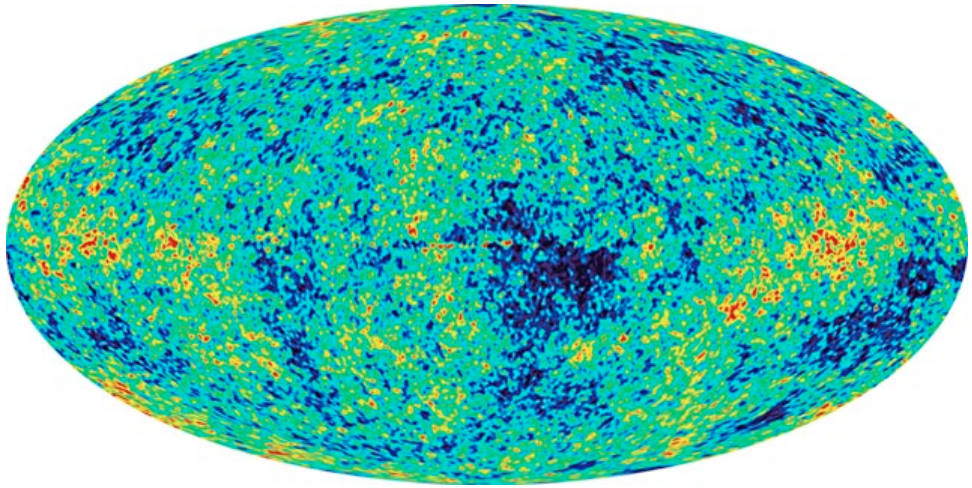
- Playing with DE and DM properties

- The role of Baryons

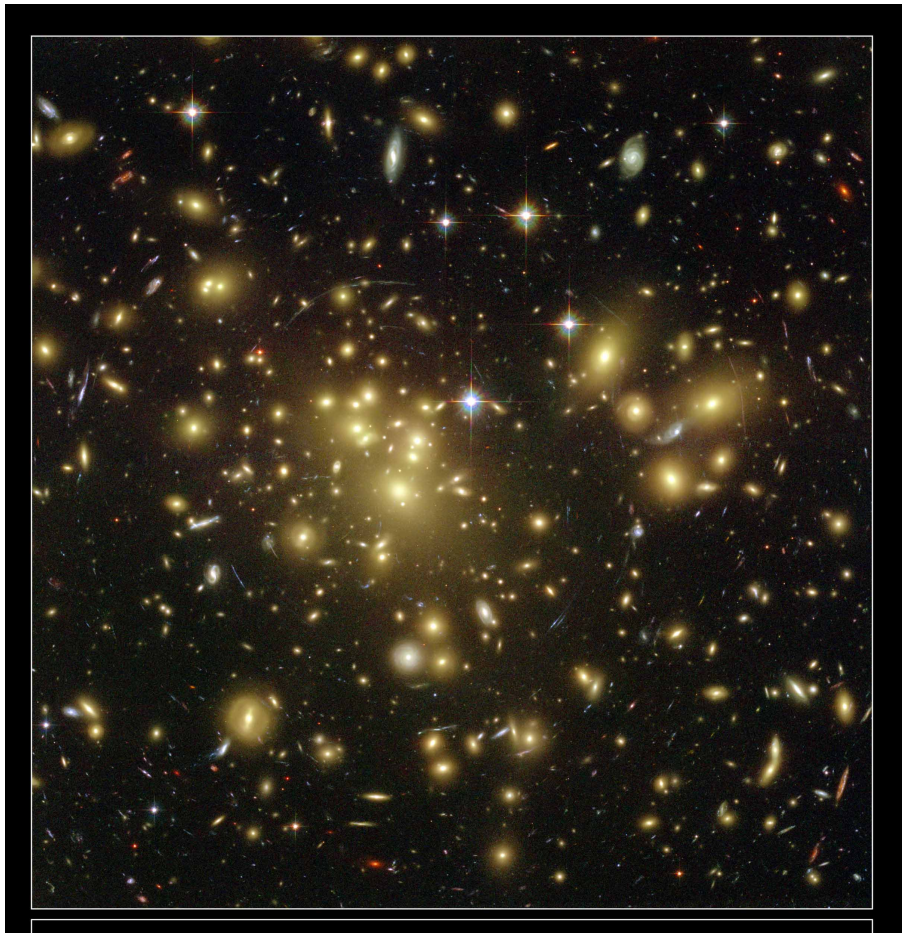
- Conclusions

How to study the evolution of the Universe

Evolution is highly non linear: initial conditions from the CMB



$$\frac{\partial T}{T} \approx \frac{\partial \rho}{\rho} \approx 10^{-5}$$



$$\frac{\partial \rho}{\rho}(cluster\ center) \approx 10^{5}$$

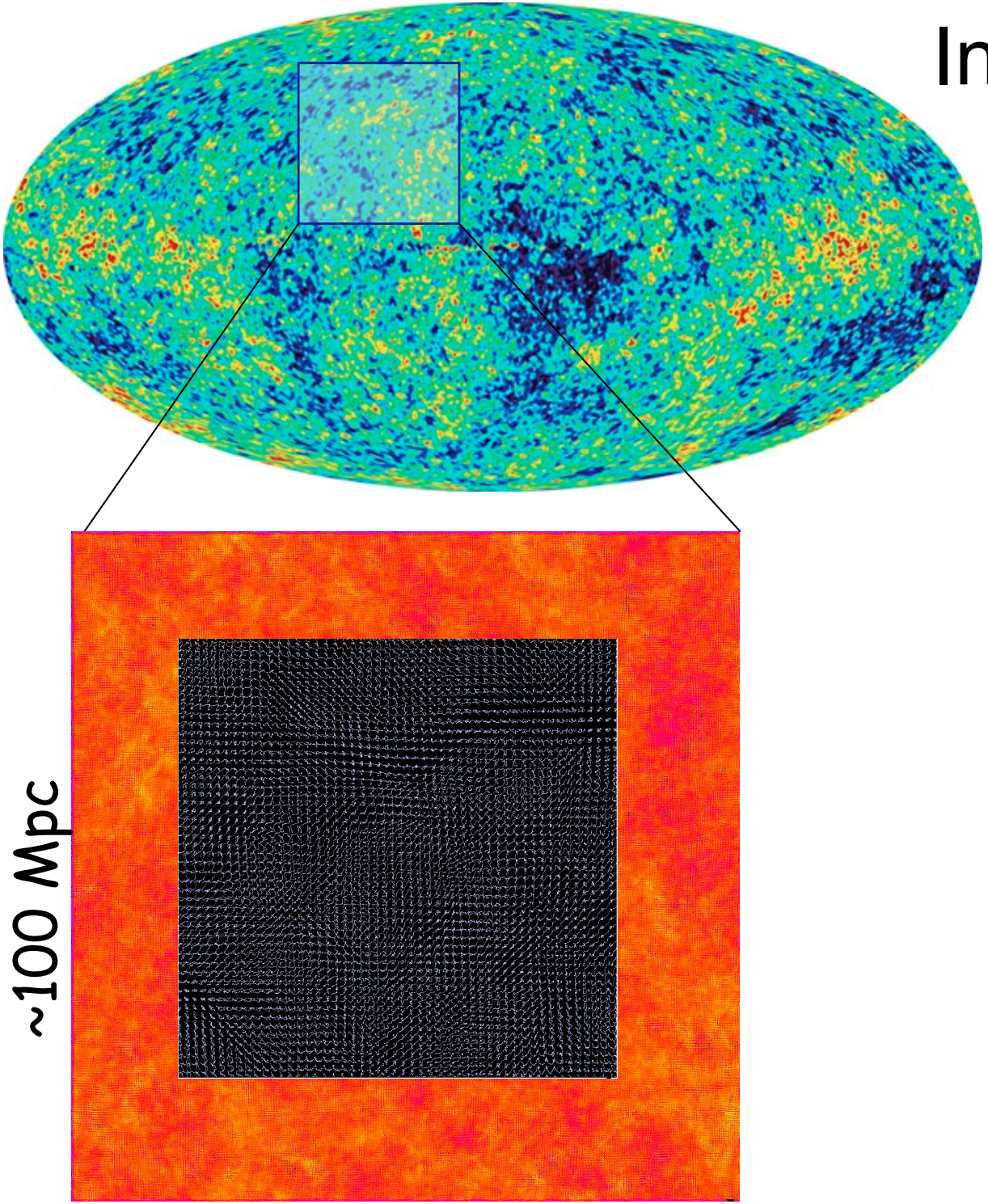
10 orders of magnitude

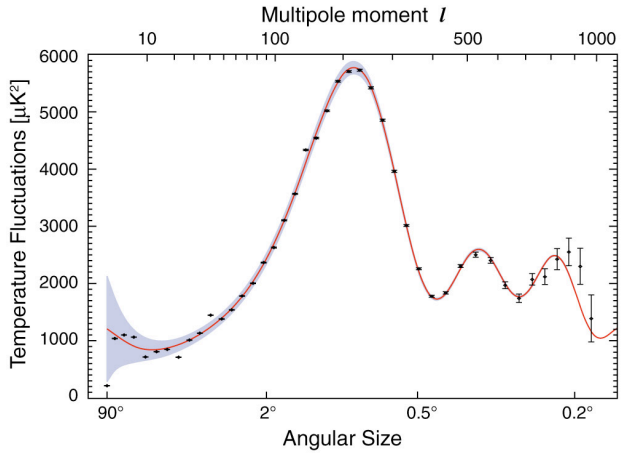
(break down of linear theory)

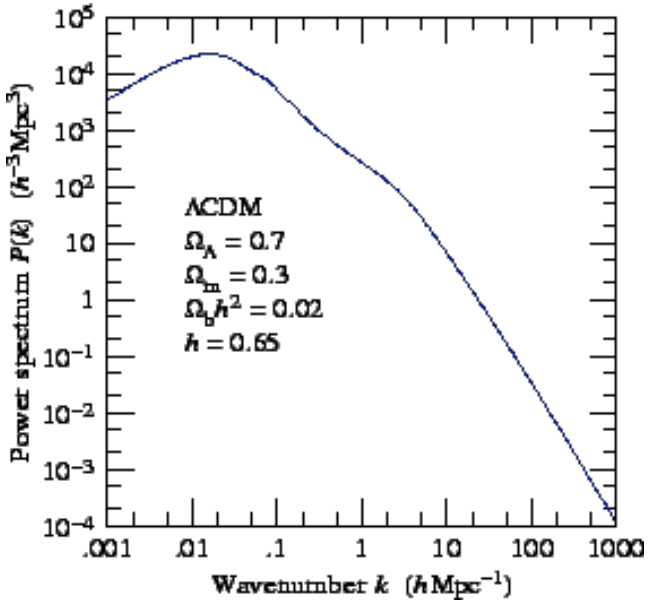
→Numerical techniques

Initial Conditions

T ⟺ density







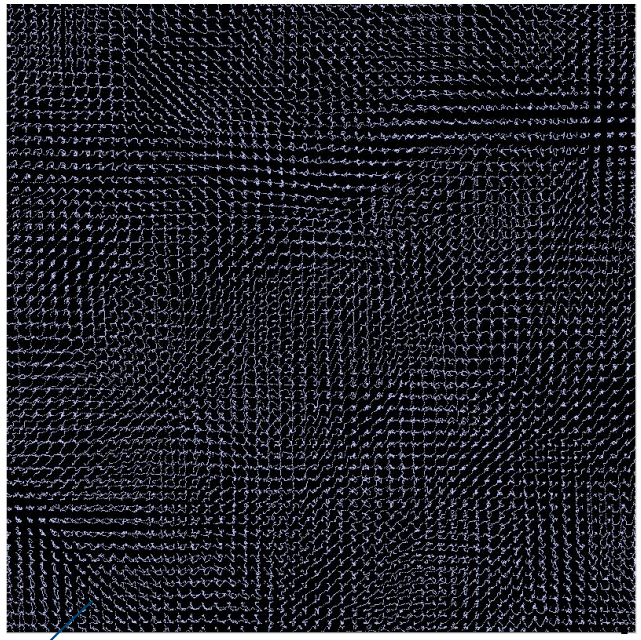
Particles for a numerical cosmologist

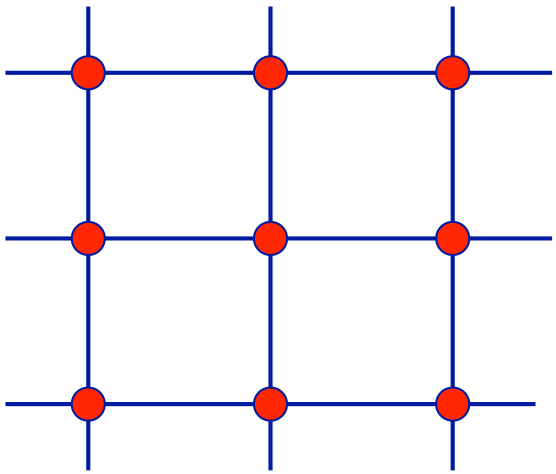
Modern computer can handle more than 10^9 particles/elements

$$V = (200\mathrm{h}^{-1} Mpc)^3$$

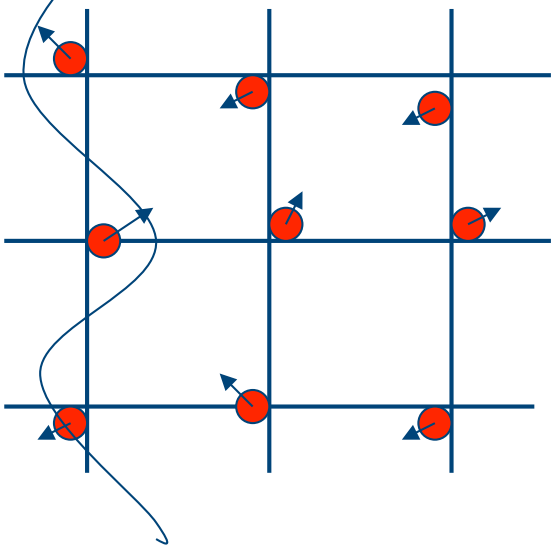
$$\mathrm{m_p} = \frac{V}{N_p} \times \rho_{cr} \times \Omega_m = 6.66 \times 10^8 M_{sun}$$

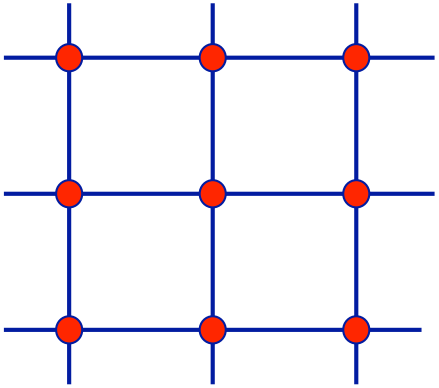
Our particles have the same mass of a dwarf galaxy…

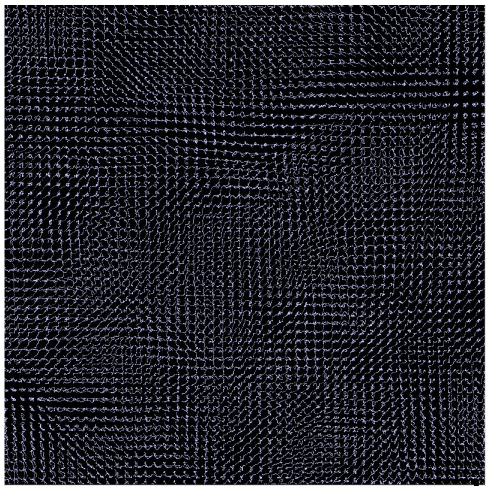




+ P(k,z) =

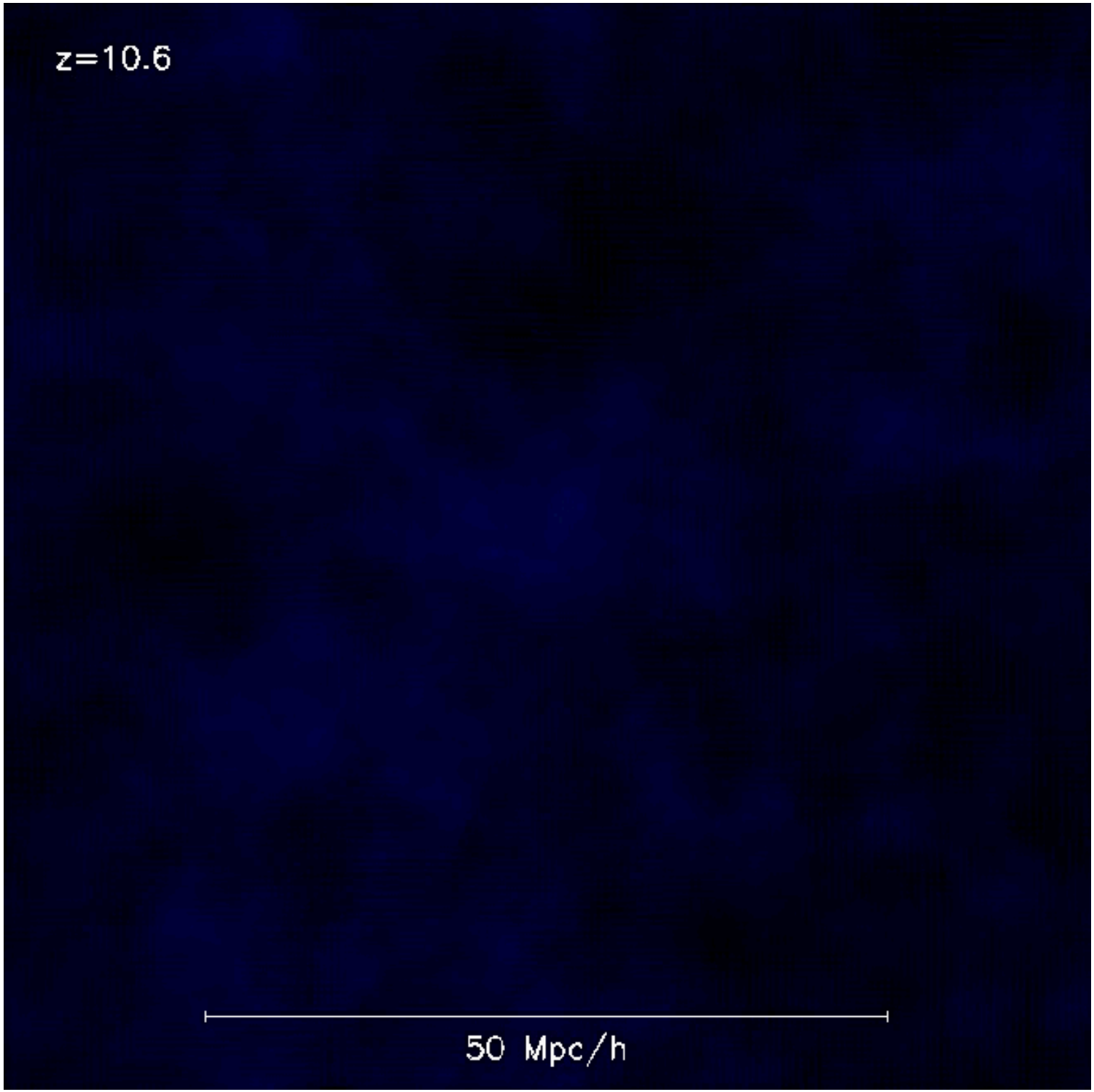






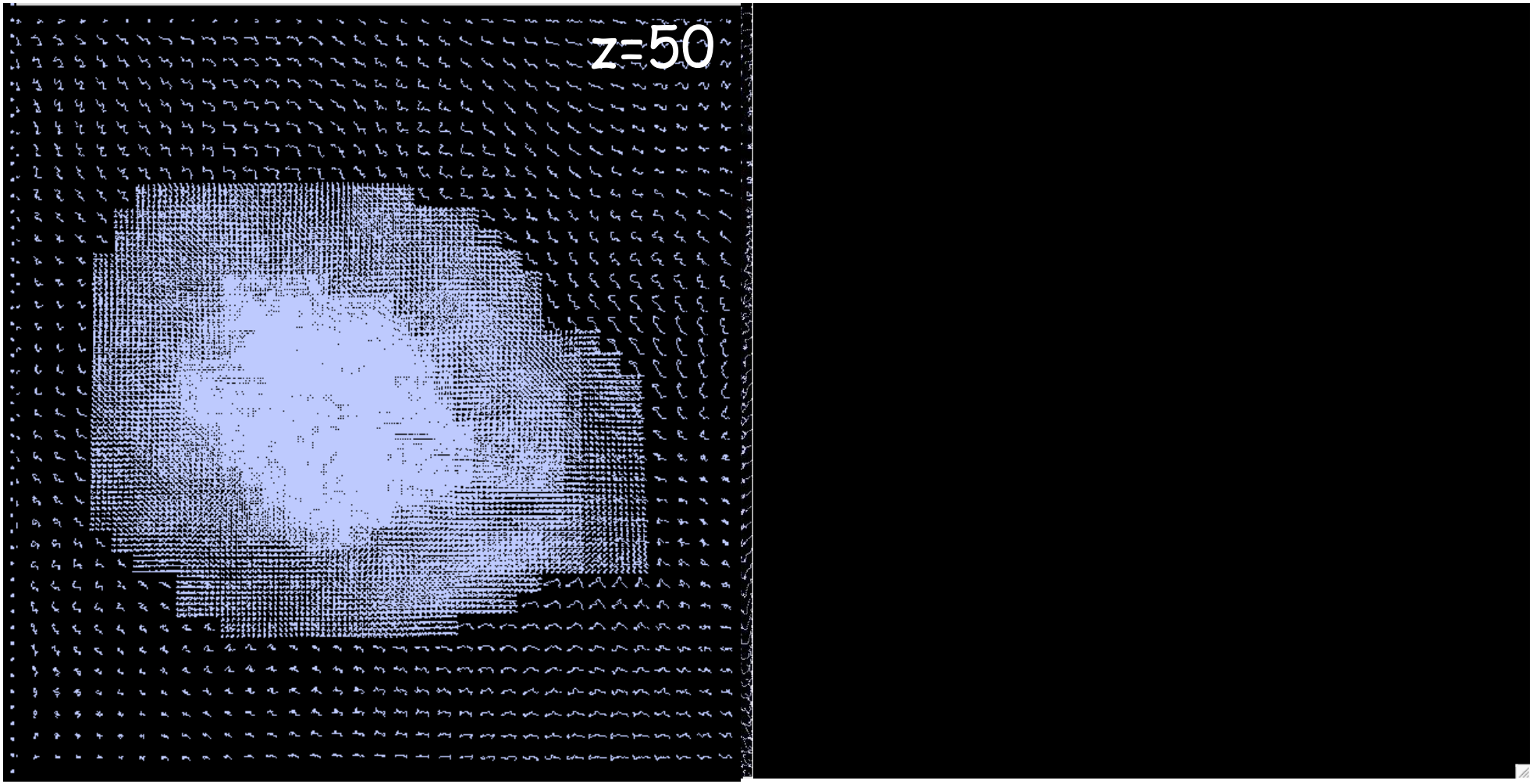
+

GRAVITY

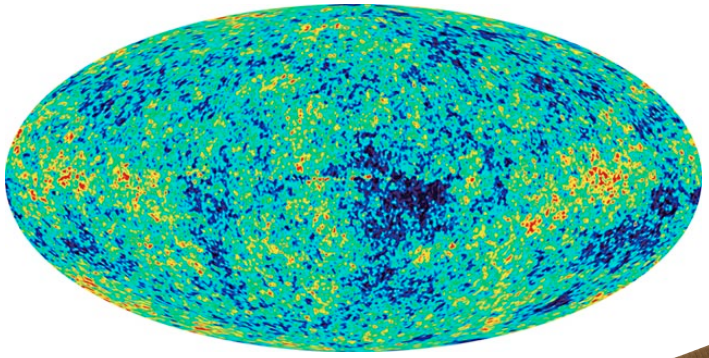


High resolution Cosmological Nbody simulations

$m_p=10^4$ Msun



400 kpc comoving



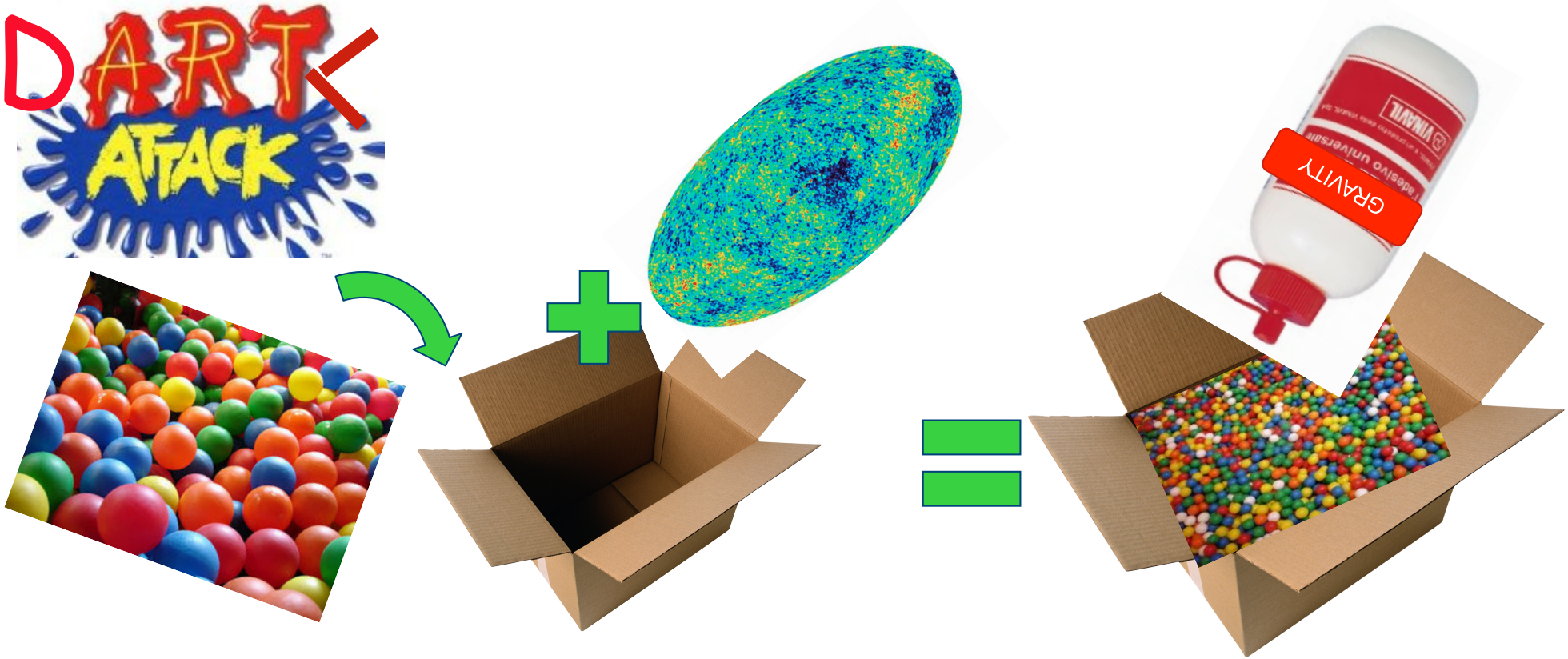
Some initial conditions

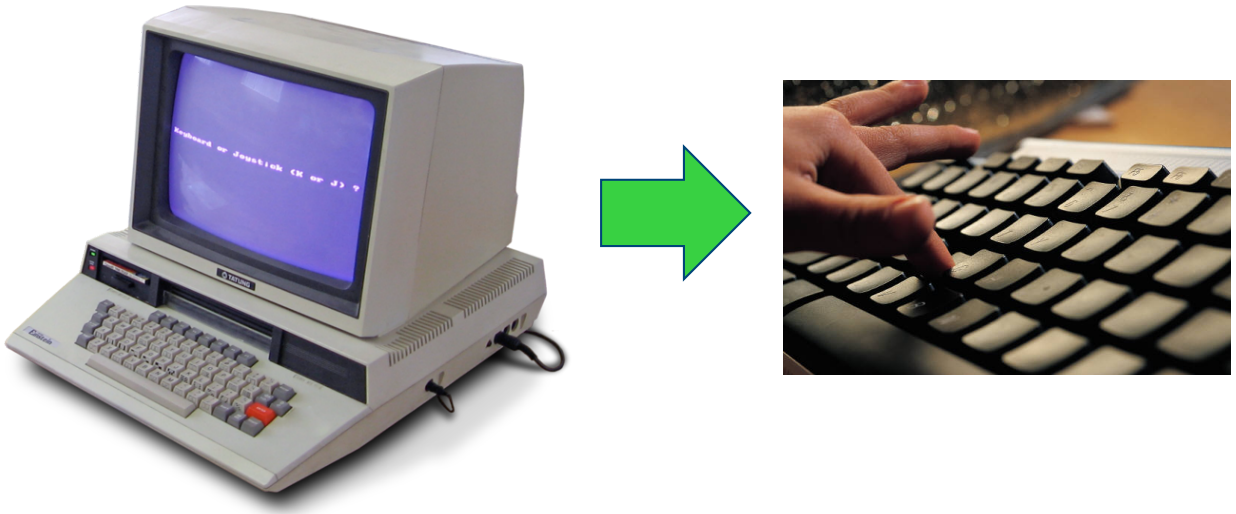
(fatto? fatto!)

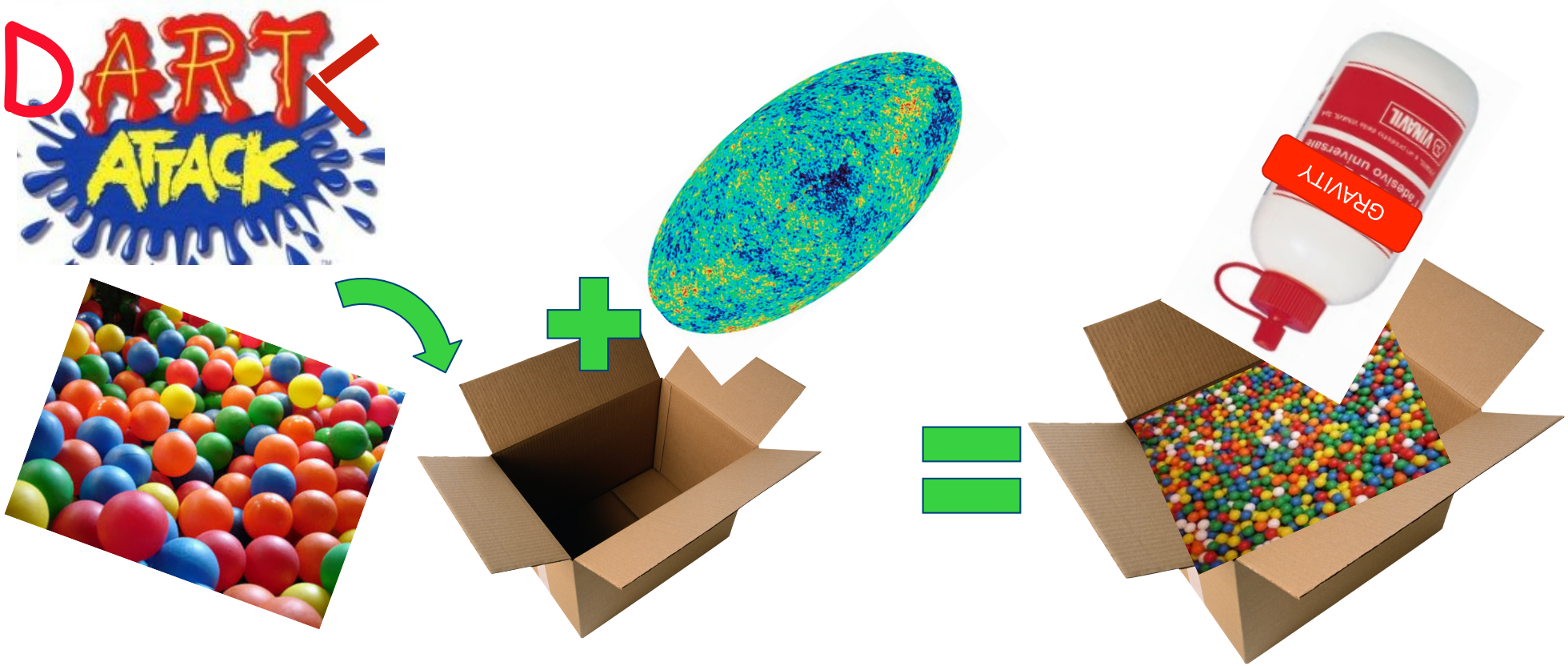
A large Box (>100 Mpc)

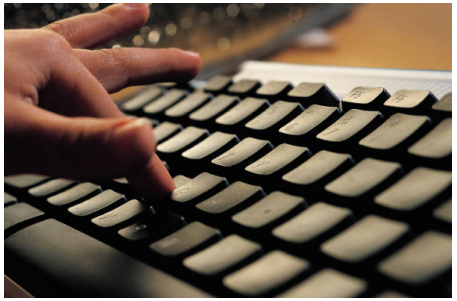
A bunch of colorful particles

Something to keep them together


DARK
ATTACK
GRAVITY

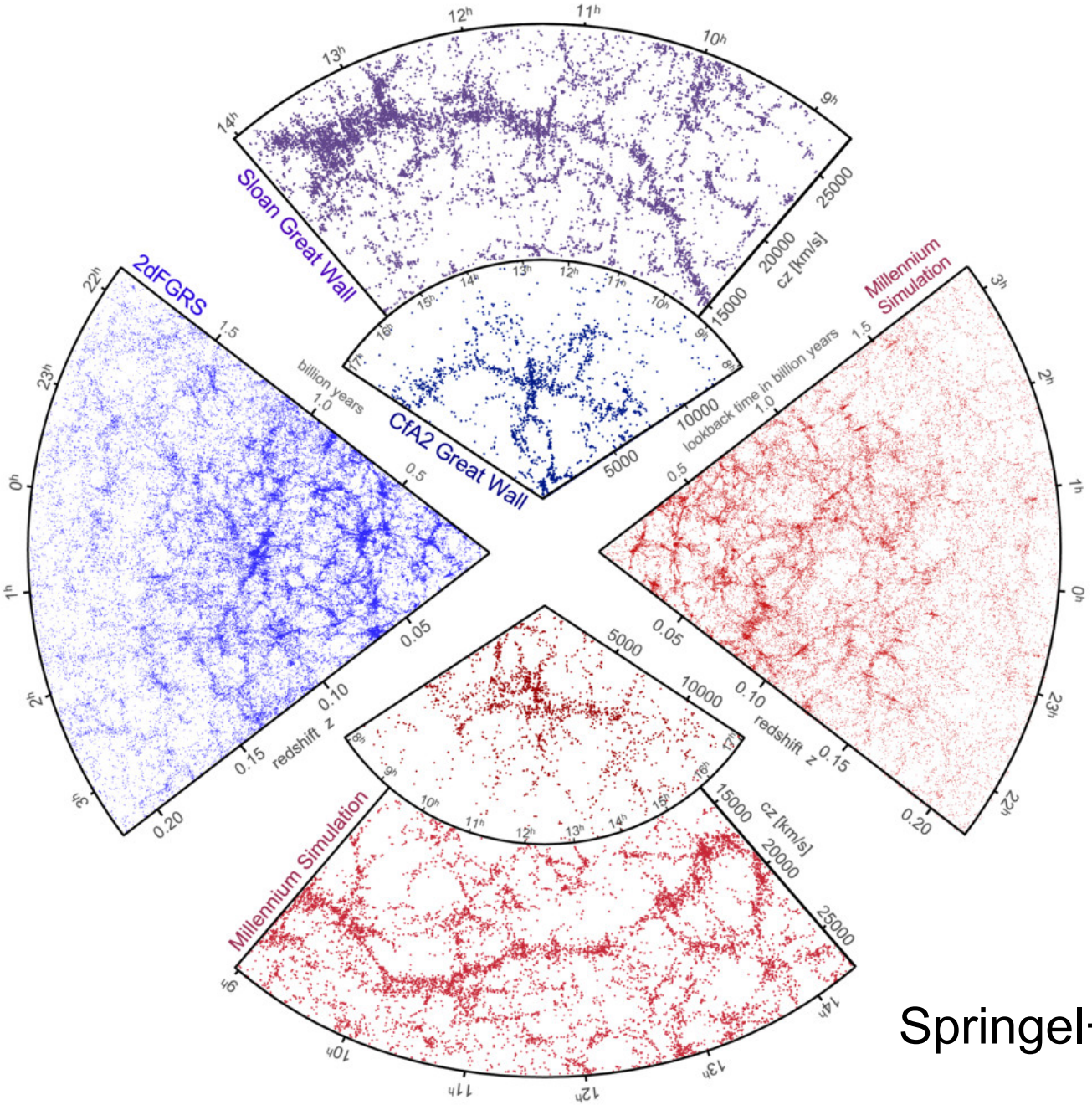






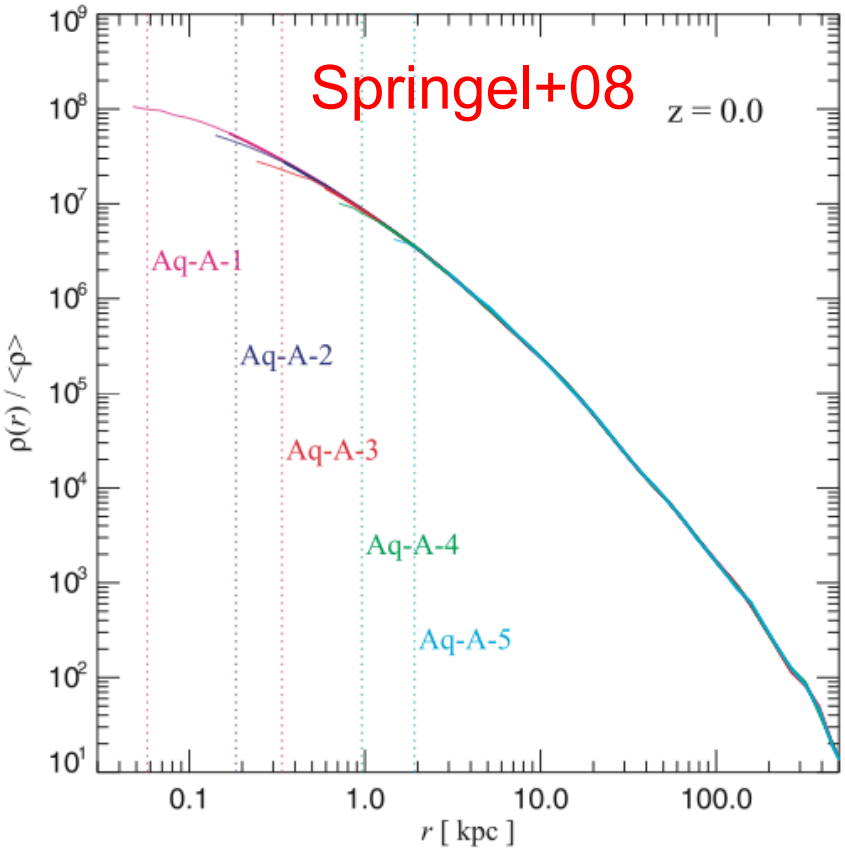
Use Gravity only under adult supervision!

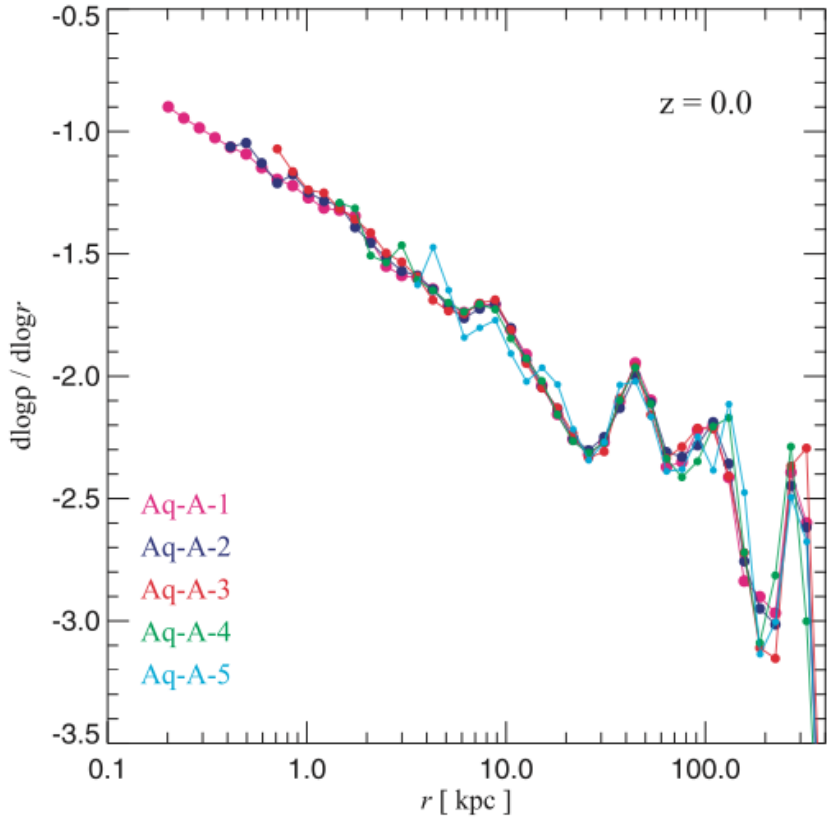
Pure gravity predictions at ***large*** scales



Springel+06

Pure gravity predictions at ***small*** scales



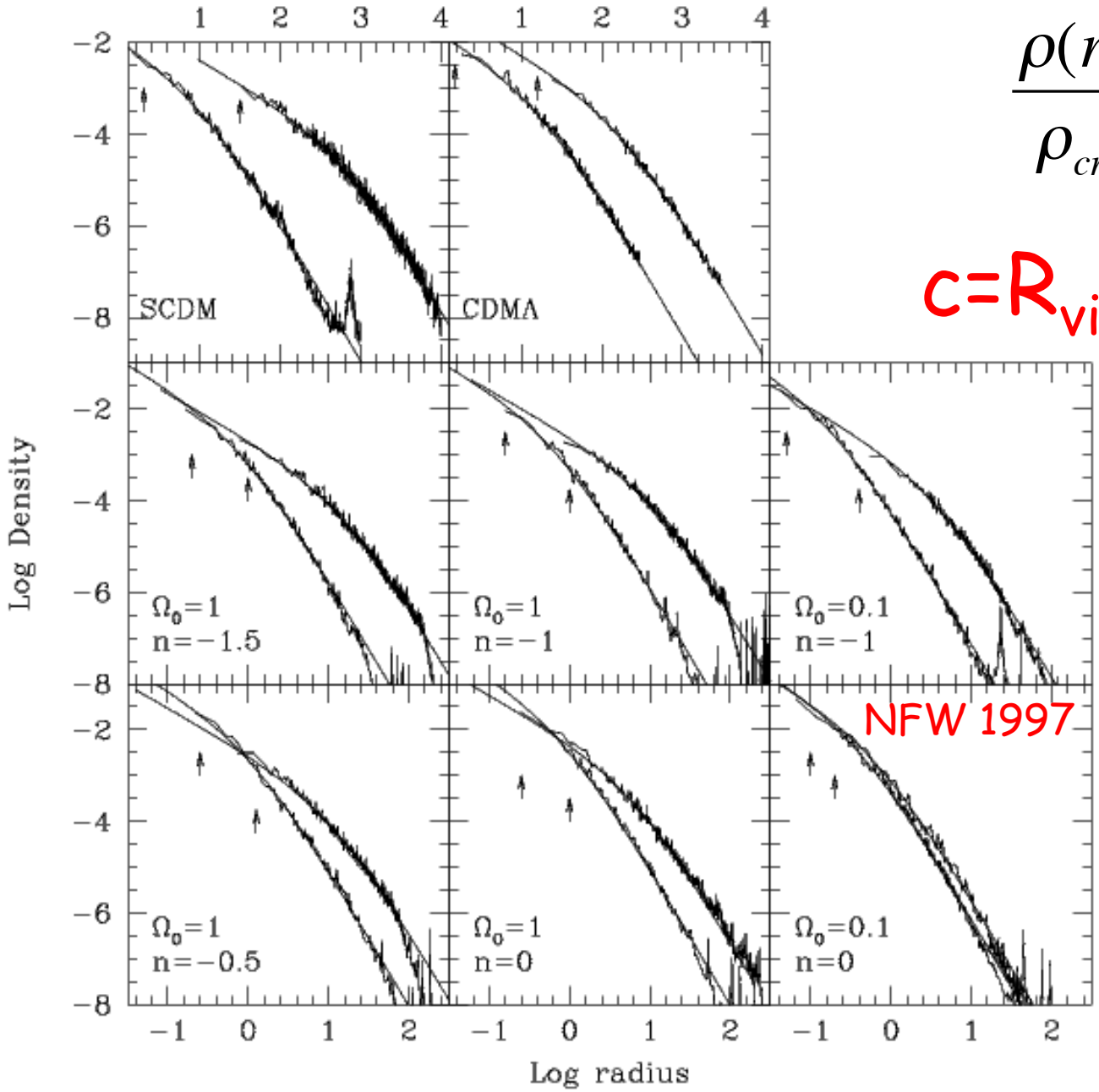


Cuspy density profiles

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

Navarro, Frenk, White 97

Statistic of DM Density profiles



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

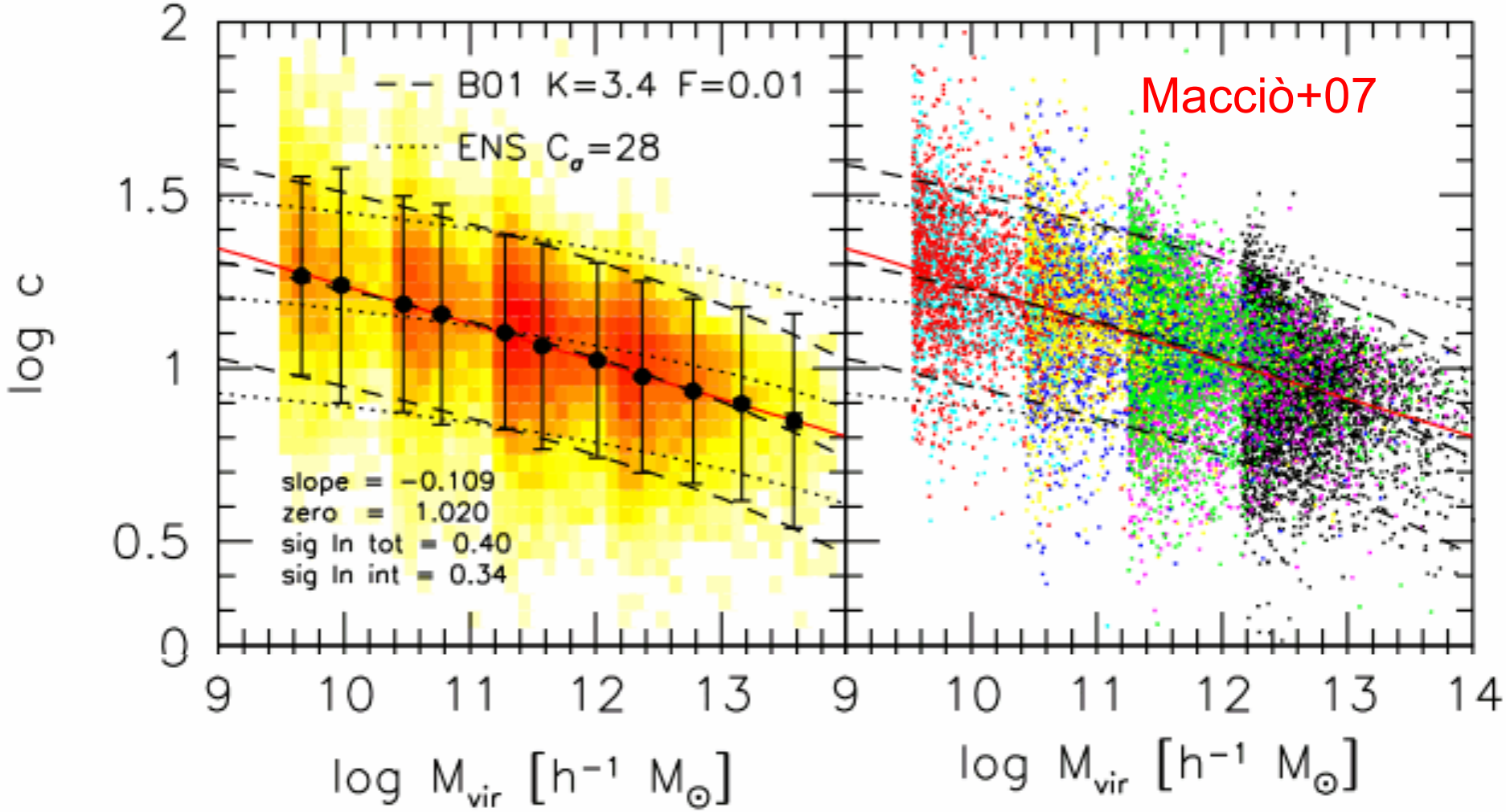
$c = R_{vir}/r_s$

NFW 1997

Two free parameters:
- r_s (or c) and δ_c
or
- c and M_{vir}.

DM density profile II

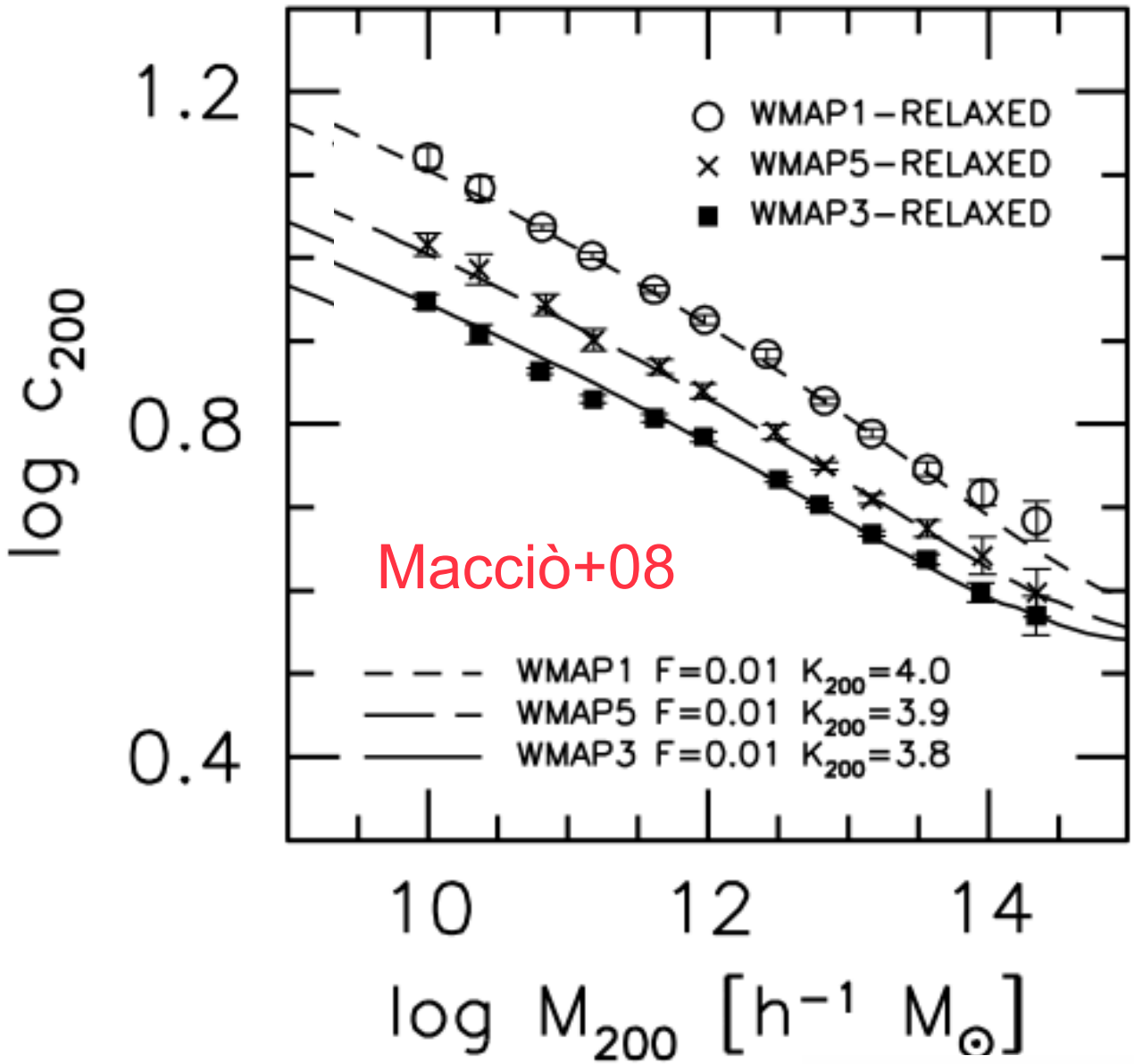
$$\frac{\rho(r)}{\rho_{cr}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$



Concentration
$c=R_{vir}/r_s$

Small haloes form earlier
-> the universe was denser at high z
-> small haloes are more concentrated

Concentration and Cosmological model

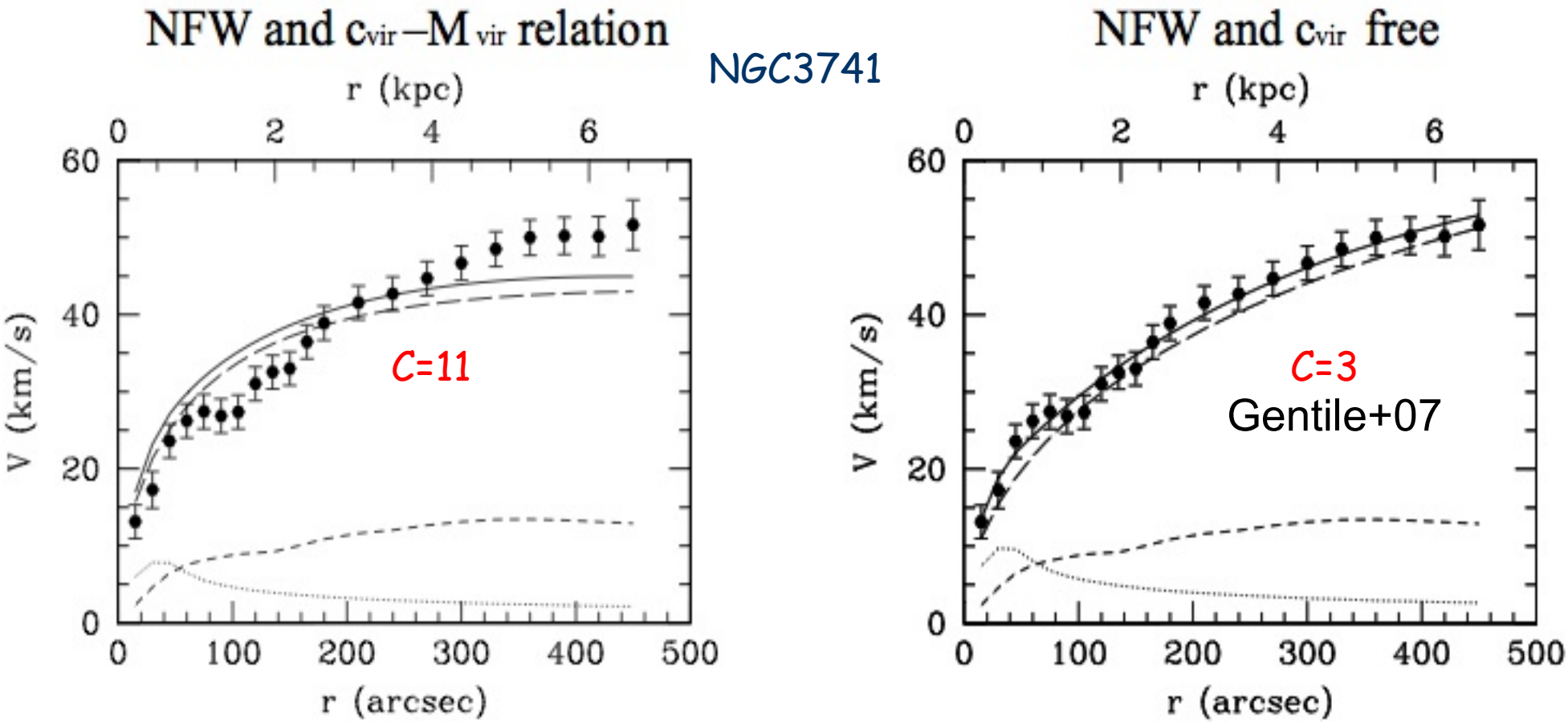


C depends on
Omega matter,
σ_8 and spectral index n

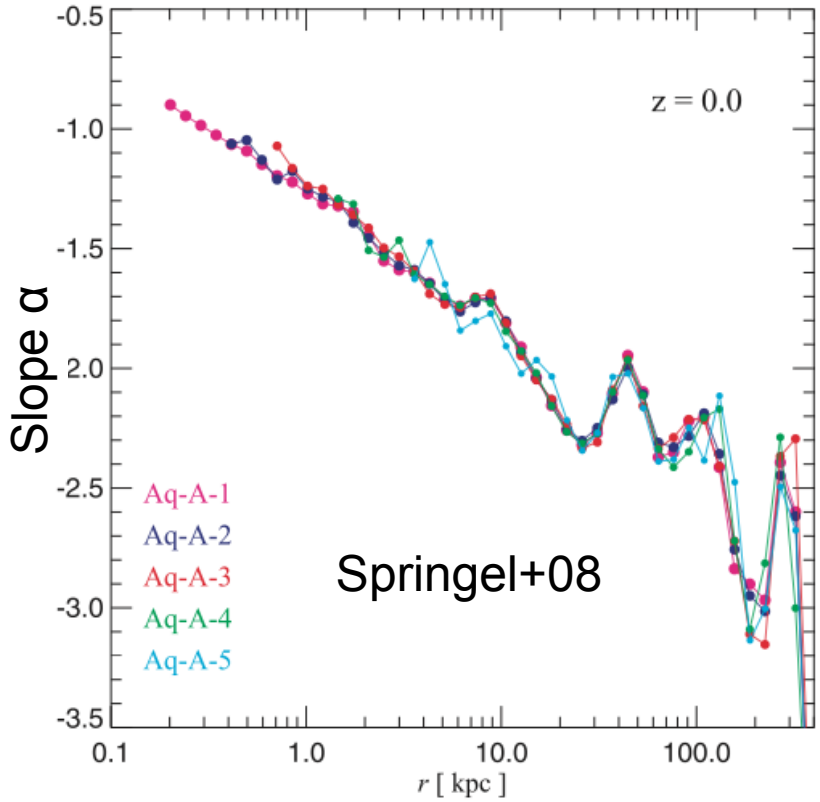
Name	$\Omega_\Lambda + \Omega_m$	Ω_m	h	σ_8	n	Ω_b
WMAP1	1.0	0.268	0.71	0.90	1.00	0.044
WMAP3	1.0	0.238	0.73	0.75	0.95	0.042
WMAP5	1.0	0.258	0.72	0.796	0.963	0.0438

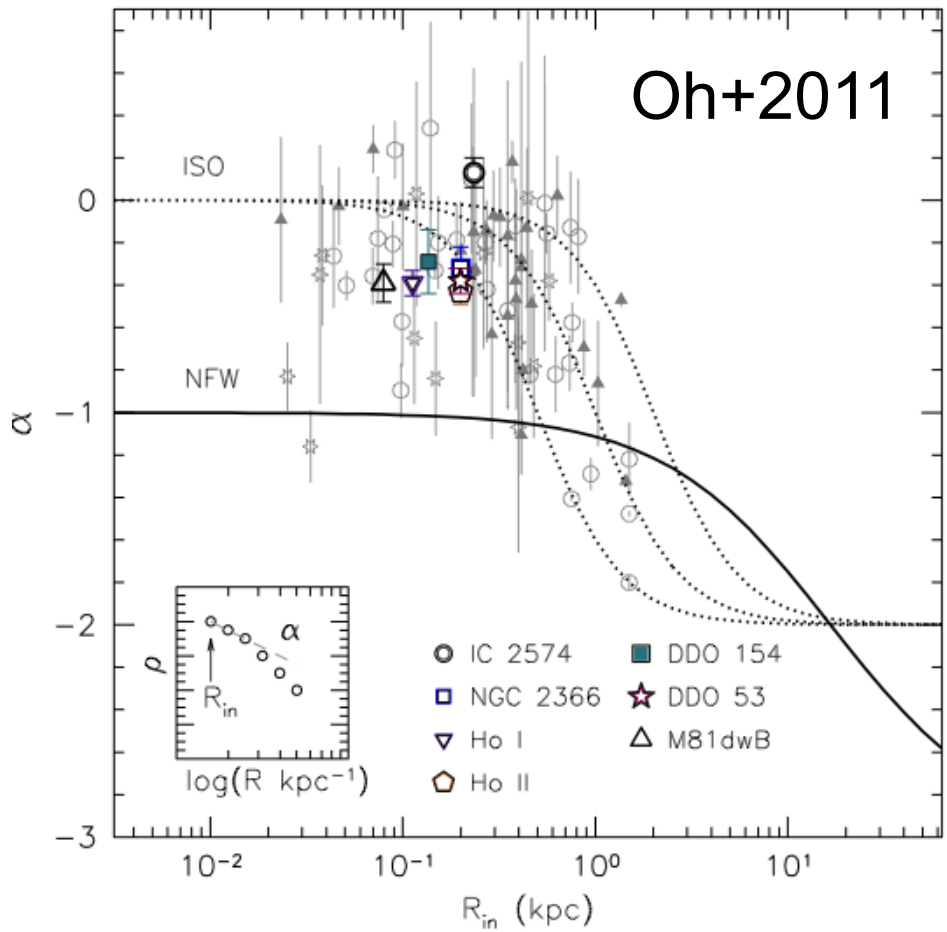
Comparison with observations

Circular velocity $$V_c(<R) = \sqrt{\frac{GM(<R)}{R}}$$



Comparison with observations



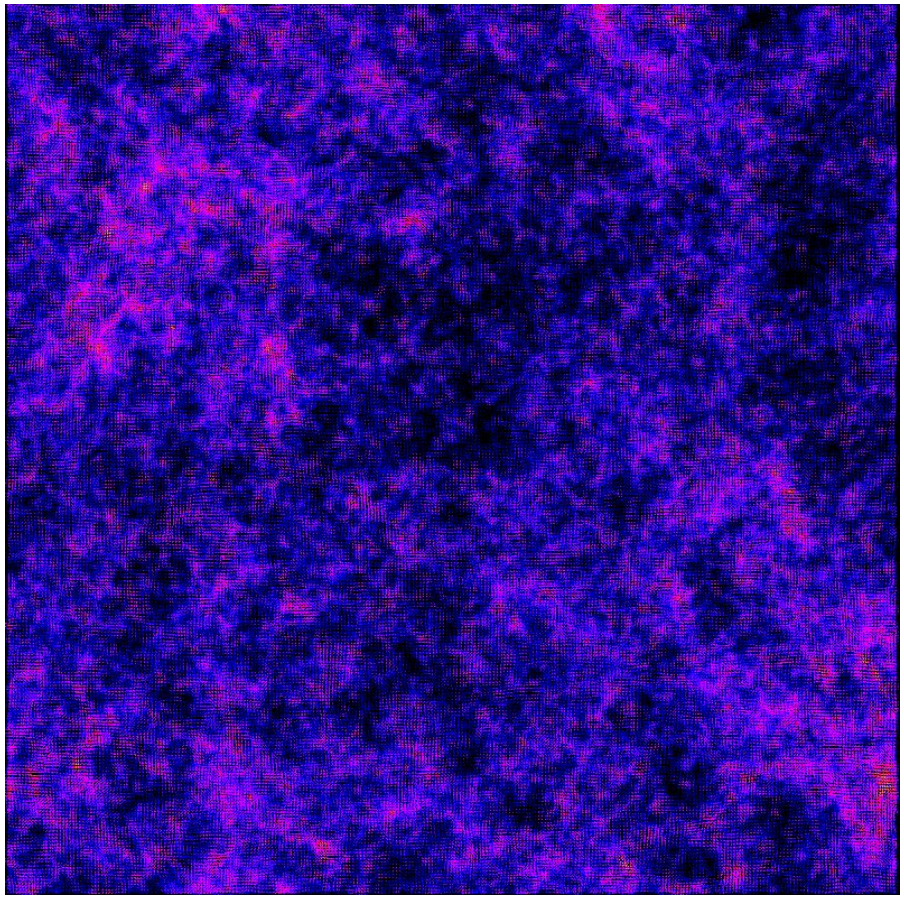


$$\frac{\rho(r)}{\rho_{cr}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

$$\rho(r \to 0) \propto r^{\alpha}$$

$$\rho(r \to 0) \propto r^{0} = \text{const.}$$

Where are Cosmology and Dark Energy?

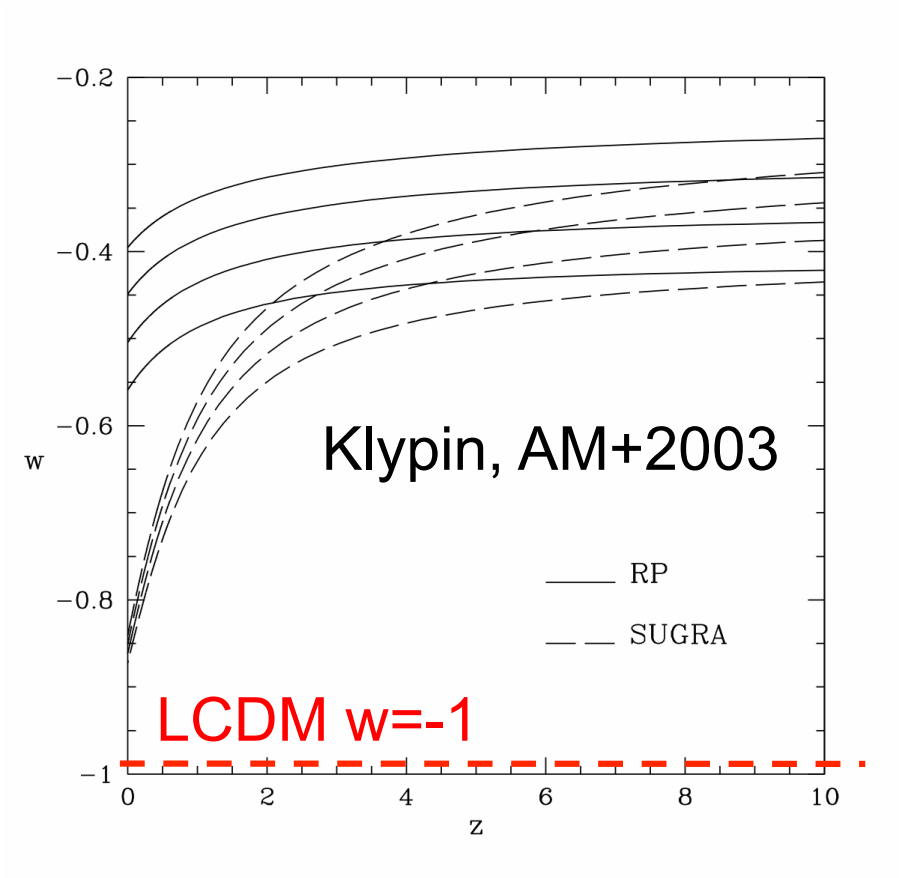


$$P(k) = A\, k^n\, T^2(k,z)$$

$$\nabla^2 \Phi(x,t) = 4\pi G a^2 [\rho(x,t) - \bar{\rho}(t)]$$

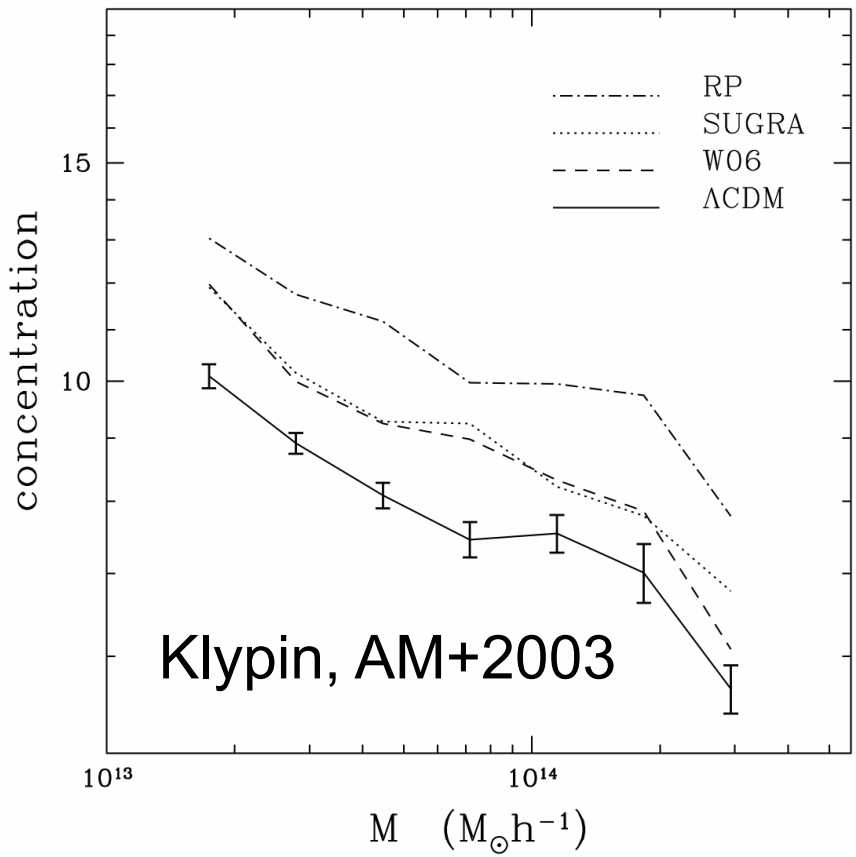
1) Initial conditions: Power Spectrum
2) Background evolution: a(t)

Dynamical DE: beyond a simple cosmological constant

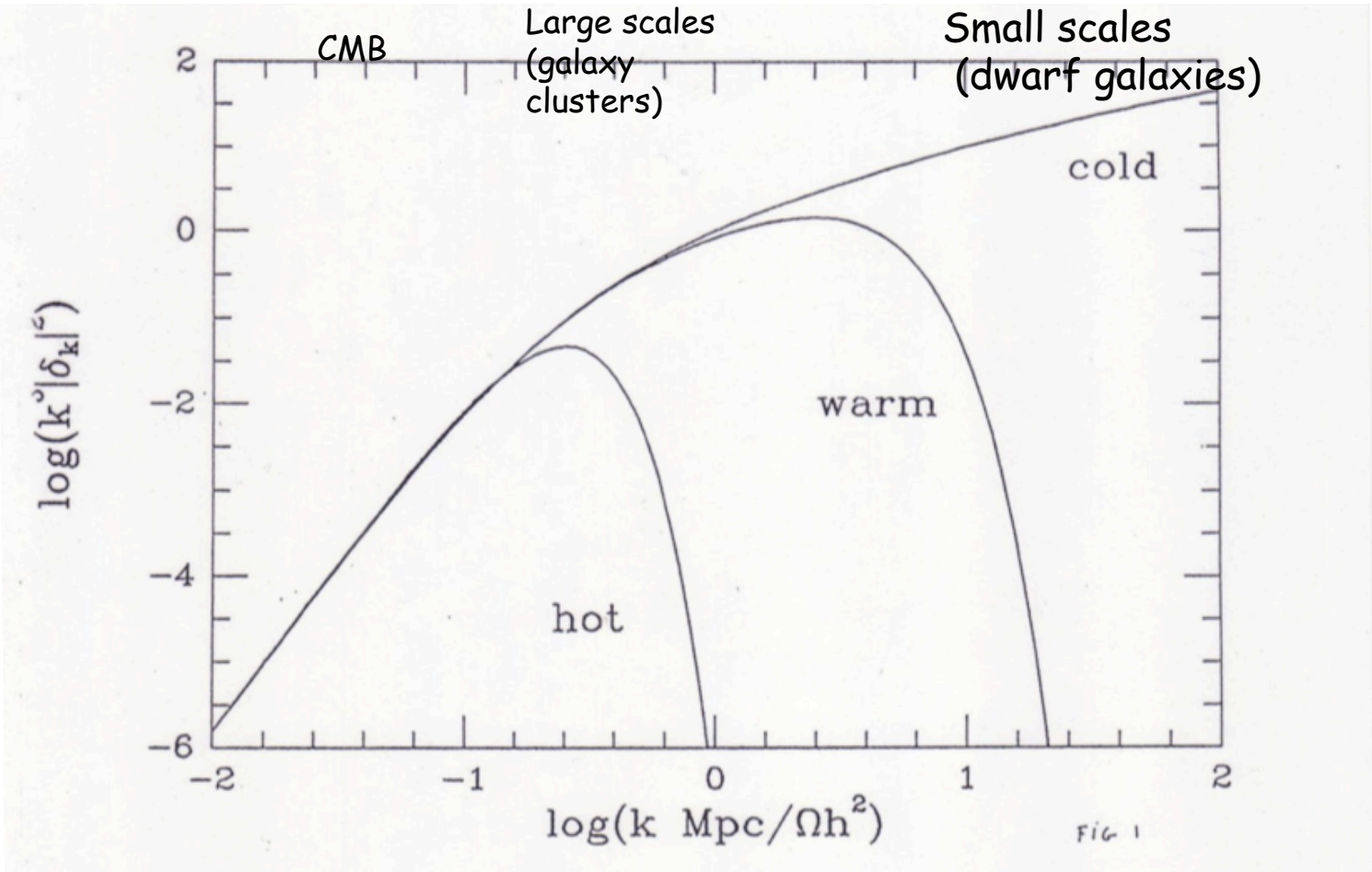


$$P = -\rho$$ LCDM

$$P = w(t) \times \rho$$



Early DE models predict
higher concentration
for a given Halo Mass



$$m_{HDM} \sim eV$$

$$m_{WDM} \sim keV$$

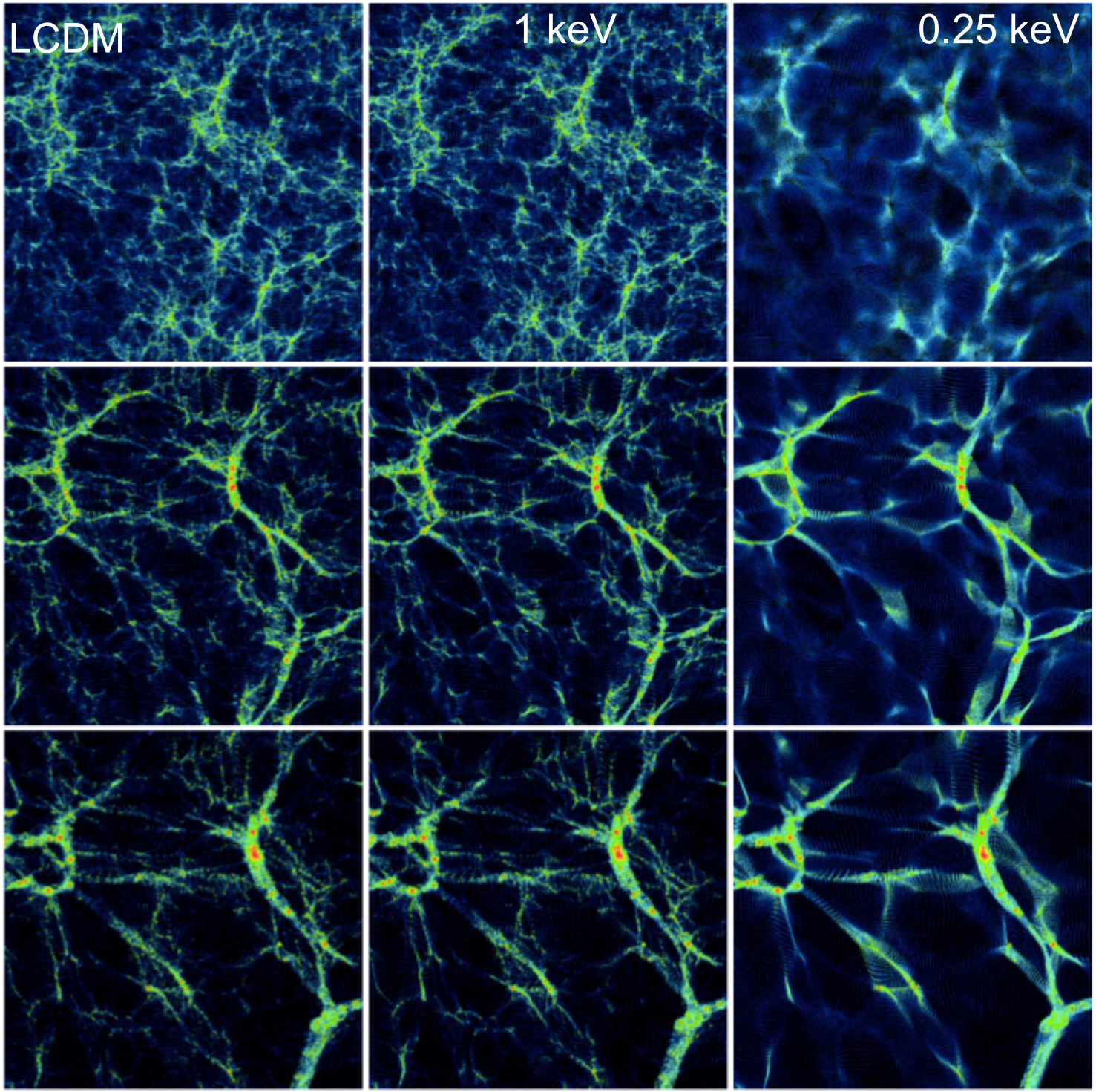
$$m_{CDM} > GeV$$

$$v_0(z) \propto (1+z)\left(\frac{keV}{m_x}\right)^{4/3} km/s$$

$$k_S \approx \left(\frac{0.3}{\Omega_X}\right)^{0.15}\left(\frac{m_X}{keV}\right)^{1.15} Mpc^{-1}$$

$$M_{\min} = 10^{-9} M_{sun} \quad \text{CDM}$$

$$M_{\min} = 10^{9} M_{sun} \quad m_X = 0.1\, keV$$



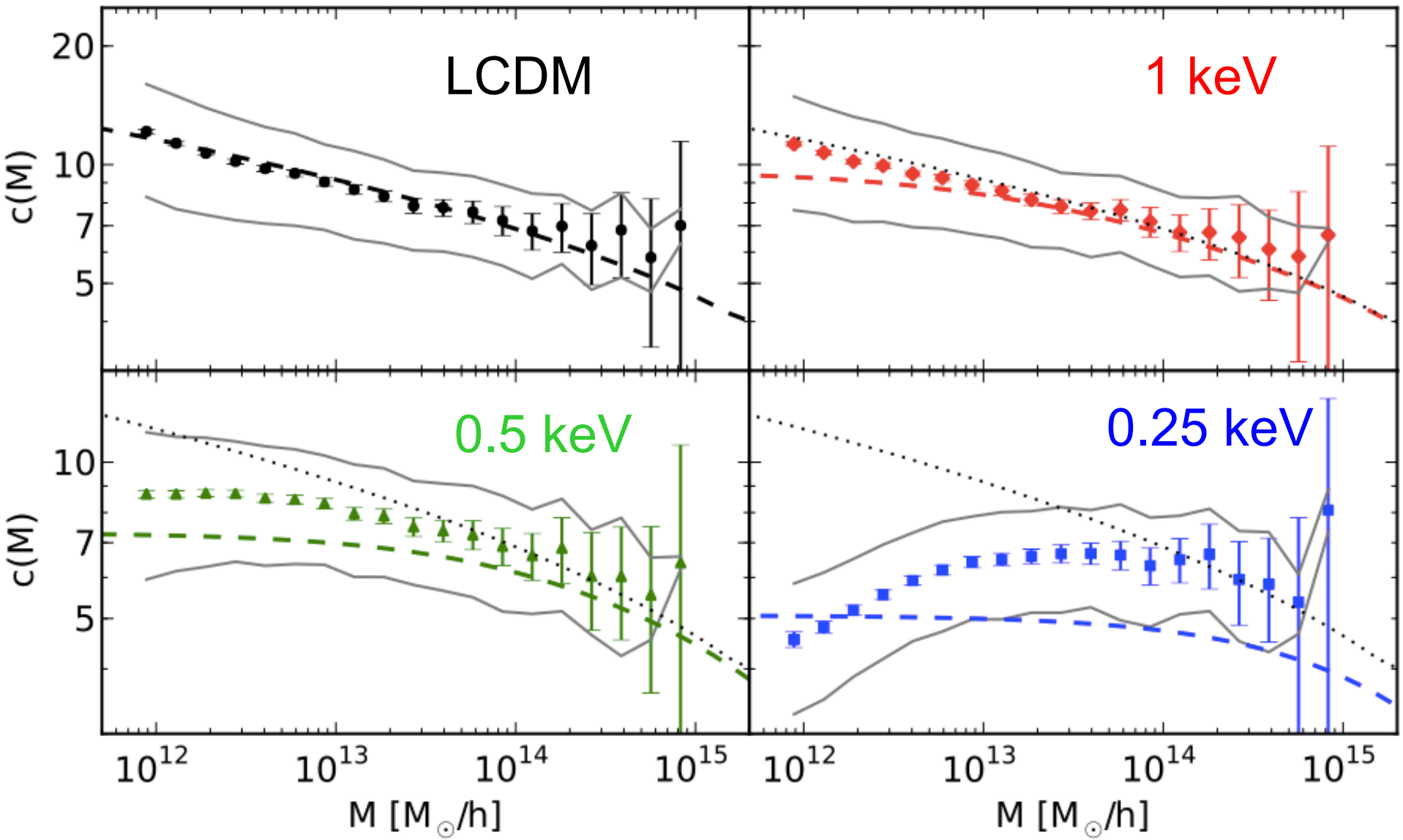
z=4.5

z=1

z=0

Schneider, Smith, AM+ 2012

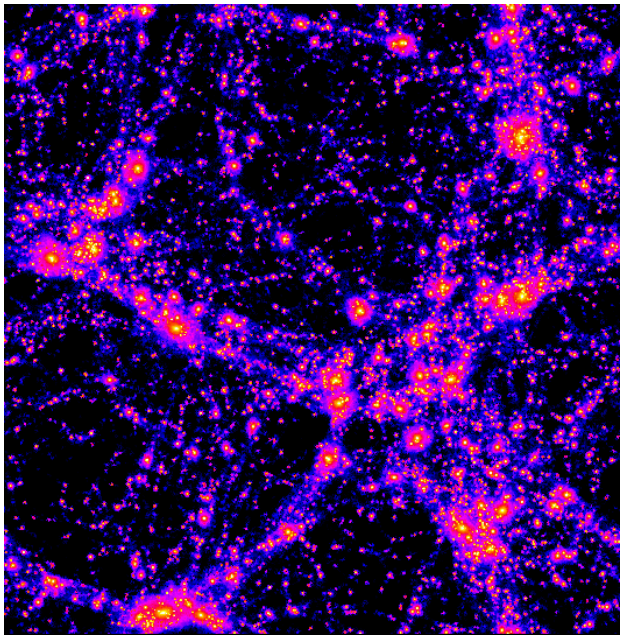
Concentration Mass relation in WDM

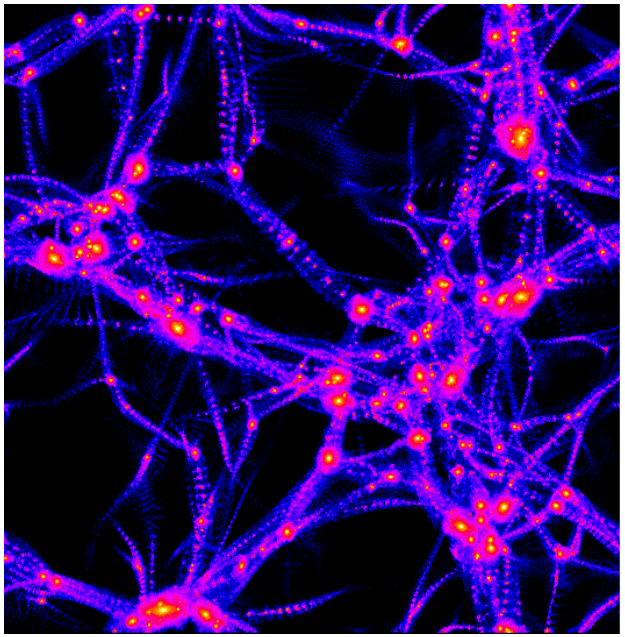


Schneider, Smith, AM+2012

WDM “effects” on structure formation:

- Reduction of overall number of low mass haloes
- Suppression of the number of low mass satellites in high mass halos
- Delayed structure formation (lower DM halo concentration)
- Upper limit in the density profile of dark matter haloes v_0 + Luiville Theorem ($PS \sim \rho/\sigma^3$)





Schneider, Smith, AM+2011

Density profile and WDM

- For a collisionless and dissipationless gas the *fine-grained* value of the phase space density (Q) is conserved.
- Deformation of "phase sheet": the *coarse-grained* phase space density can only decrease

$$f(\vec{x},\vec{v}) \approx Q \equiv \frac{\rho}{\sigma^3}$$

$$v_{thermal}(z) \propto (1+z)\left(\frac{keV}{m_x}\right)^{4/3} km/s$$

$$Q(z=100) = \frac{\Omega_m \rho_{cr}}{\sigma^3_{thermal}} \geq Q(z=0) = \frac{\rho_{central}}{\sigma^3_{central}}$$

Cold $m_x > 10^7 keV \rightarrow \sigma_{th} \sim 0$ $\quad Q \rightarrow \infty,\ \rho_{central} \rightarrow \infty$ Cuspy profile

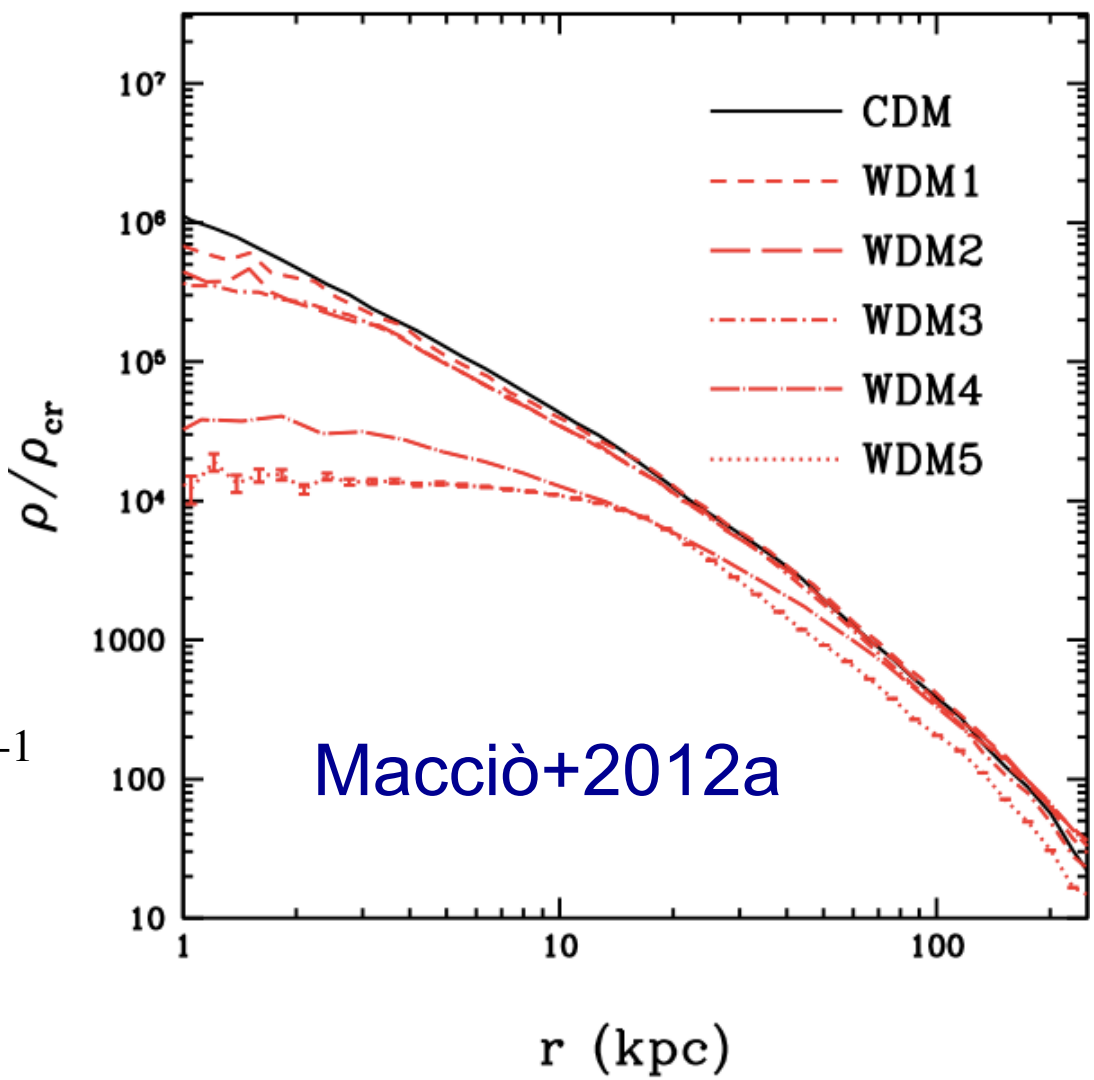
Warm $m_x \sim keV \rightarrow \sigma_{th} \sim km/s$ $\quad Q \rightarrow Q_{\max},\ \rho_{central} \rightarrow \rho_0$ Cored profile

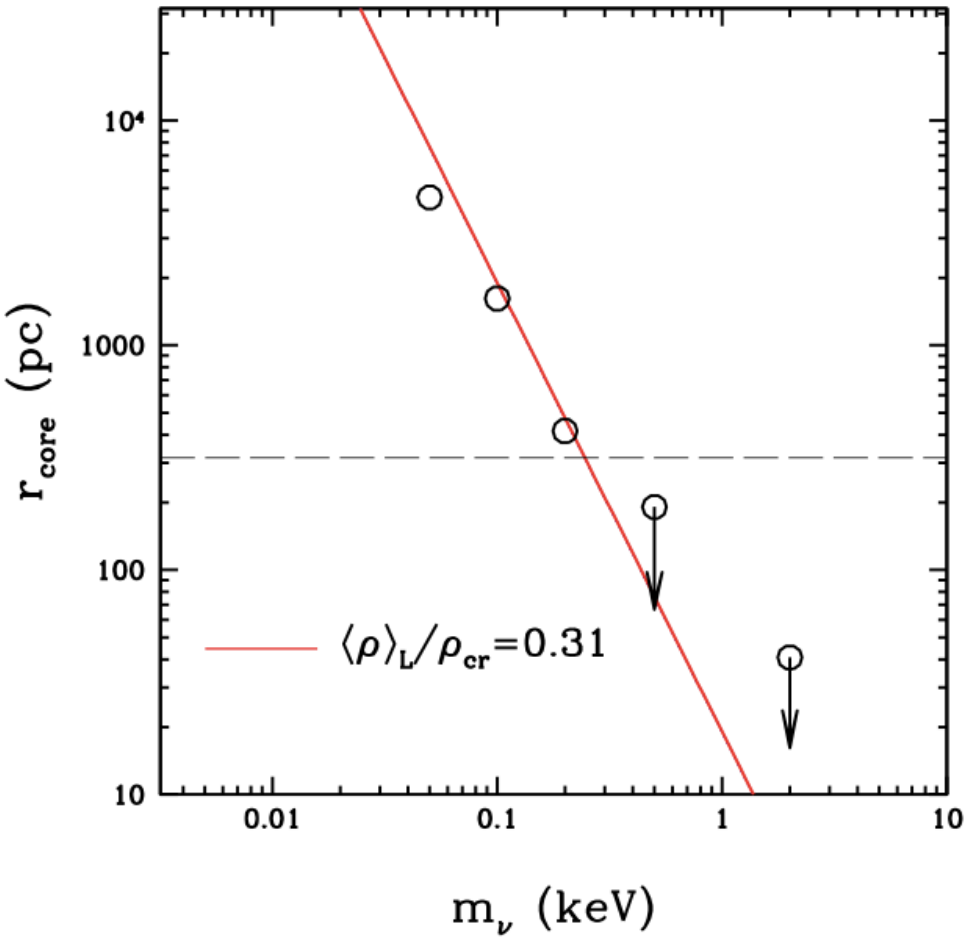
WDM & halo profile

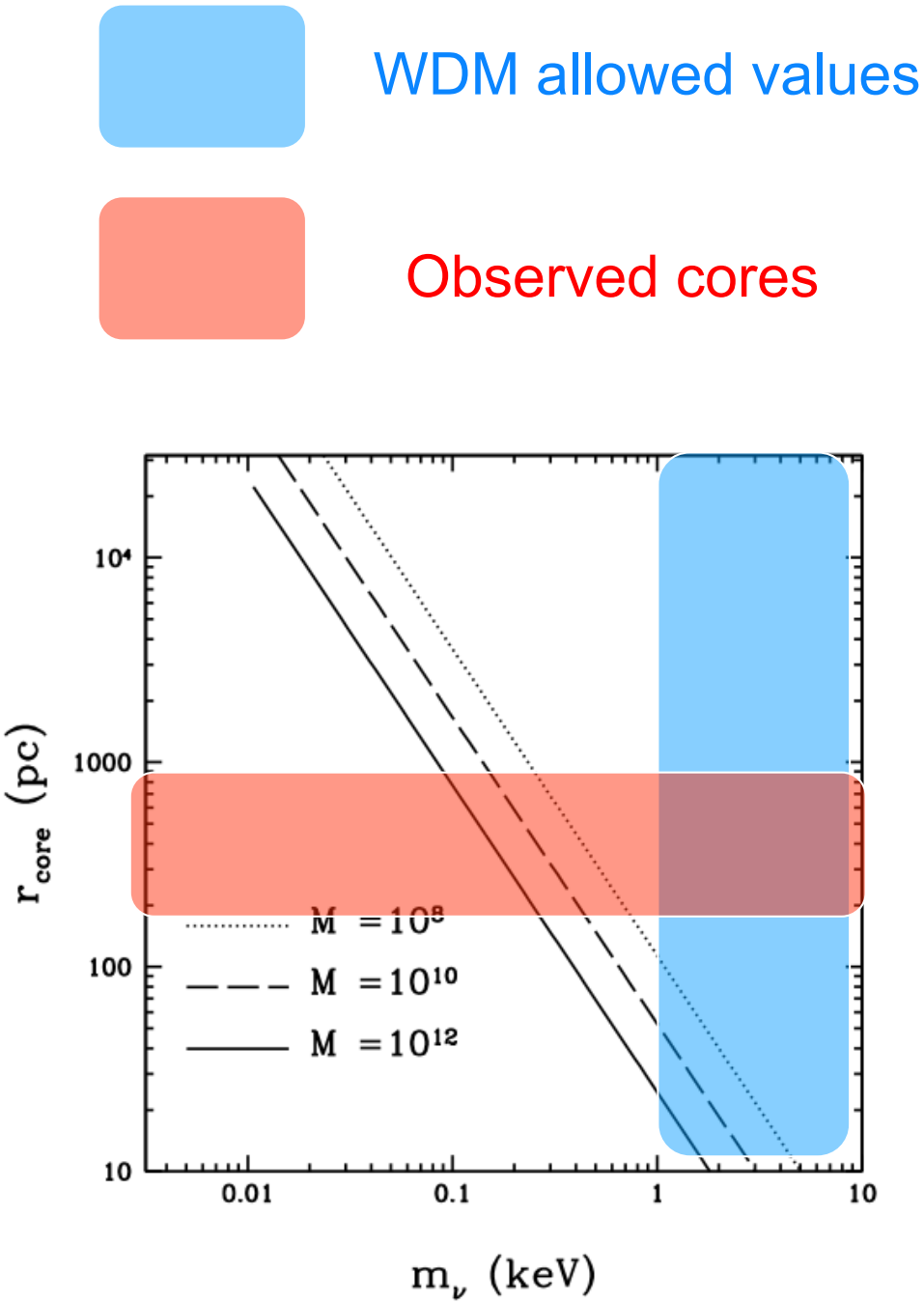
Label	m_ν (keV)	$m_{\nu,\mathrm{vel}}$ (keV)
CDM	∞	–
WDM1	2.0	2.0
WDM2	2.0	0.5
WDM3	2.0	0.2
WDM4	2.0	0.1
WDM5	2.0	0.05

$$v_0(z) \propto (1+z)\left(\frac{keV}{m_{\nu,vel}}\right)^{4/3} \frac{km}{s}$$

$$k_S \approx \left(\frac{0.3}{\Omega_X}\right)^{0.15} \left(\frac{m_\nu}{keV}\right)^{1.15} Mpc^{-1}$$



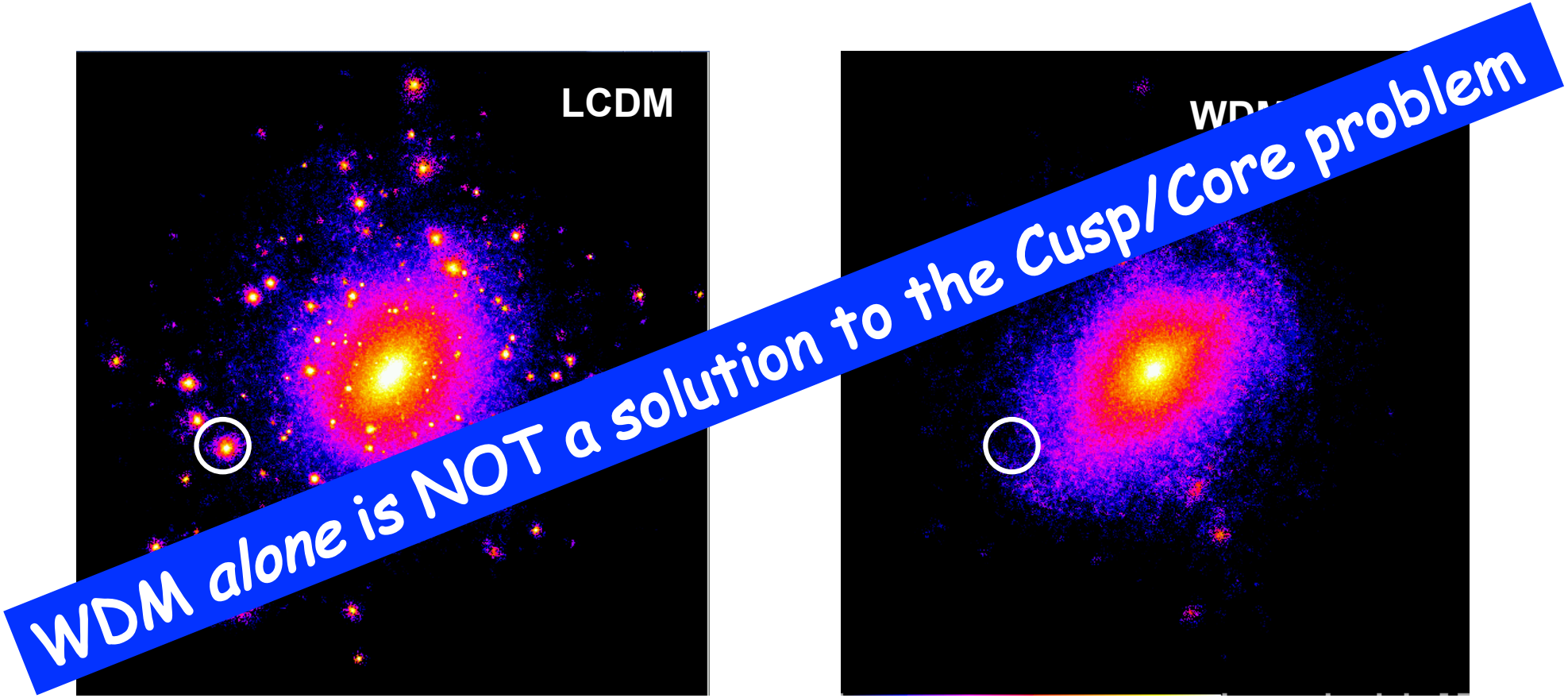




Lyman-α forest
Lensing:
m_ν>1-2 keV

Rcore (Fornax) ~ 0.5 kpc → m_v=0.2 keV

How does the host galaxy (MW like) of Fornax look like if m_v=0.2 keV?



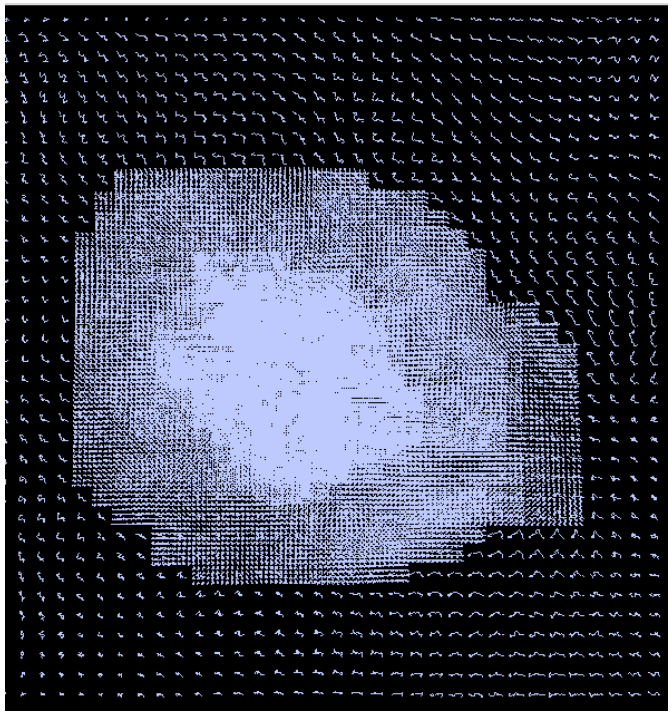
Catch 22 problem:

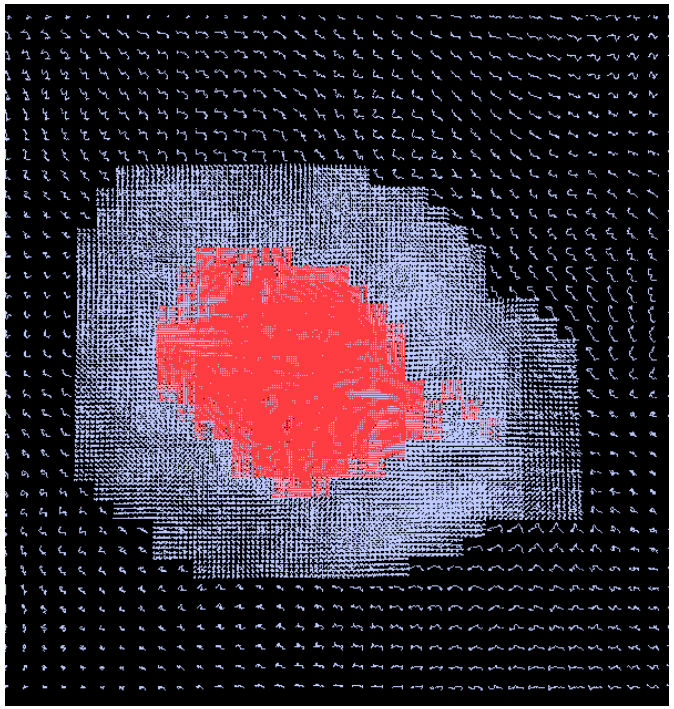
If you want a large core you won't get the dwarf galaxy

If you get the dwarf galaxy it won't have a large core

Macciò et al 2012a, MNRAS, 458, 34

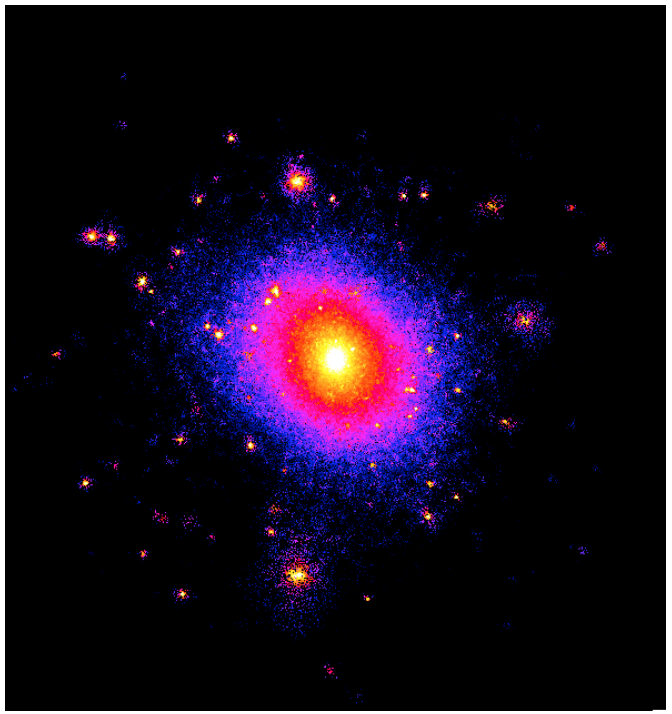
What is the effect of baryons?

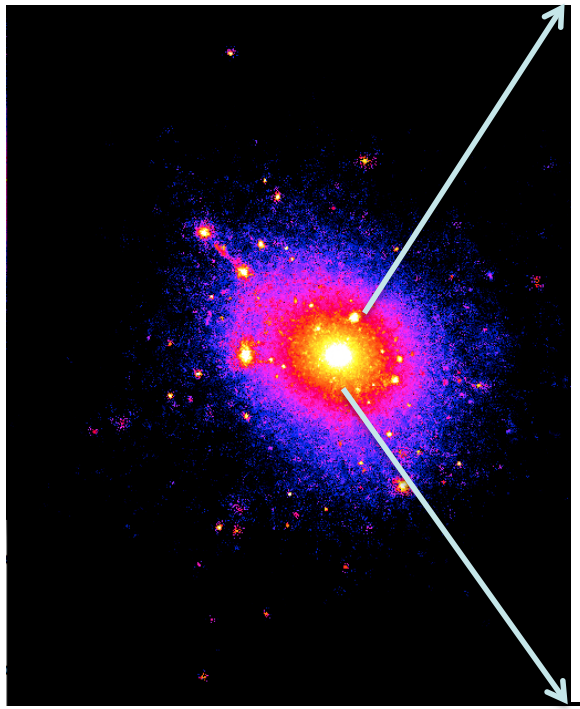


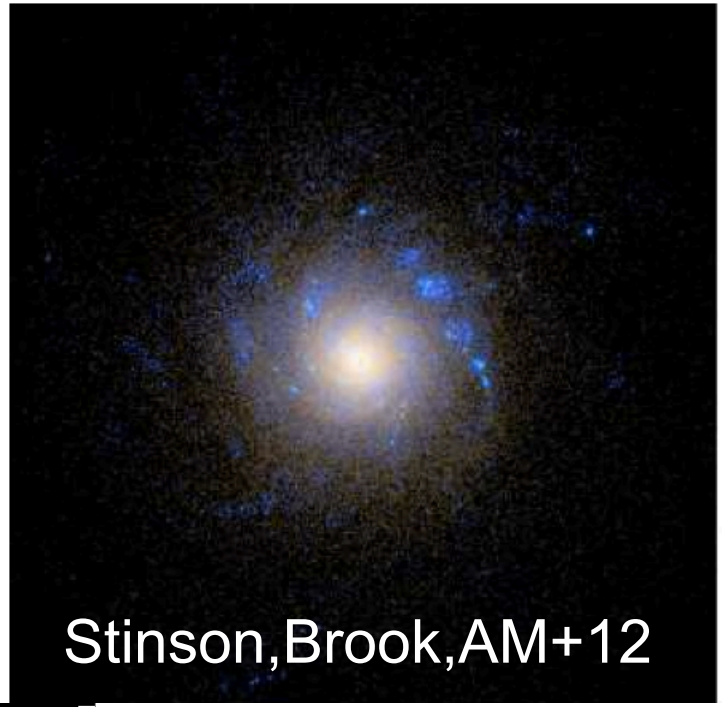


DM
GAS
Nbody= gravity

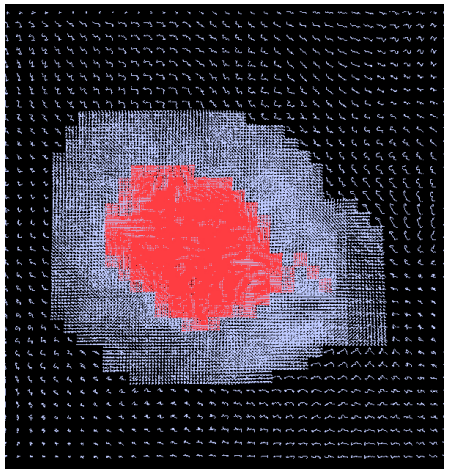
Hydro + cooling
+ Star Formation
+ feedback

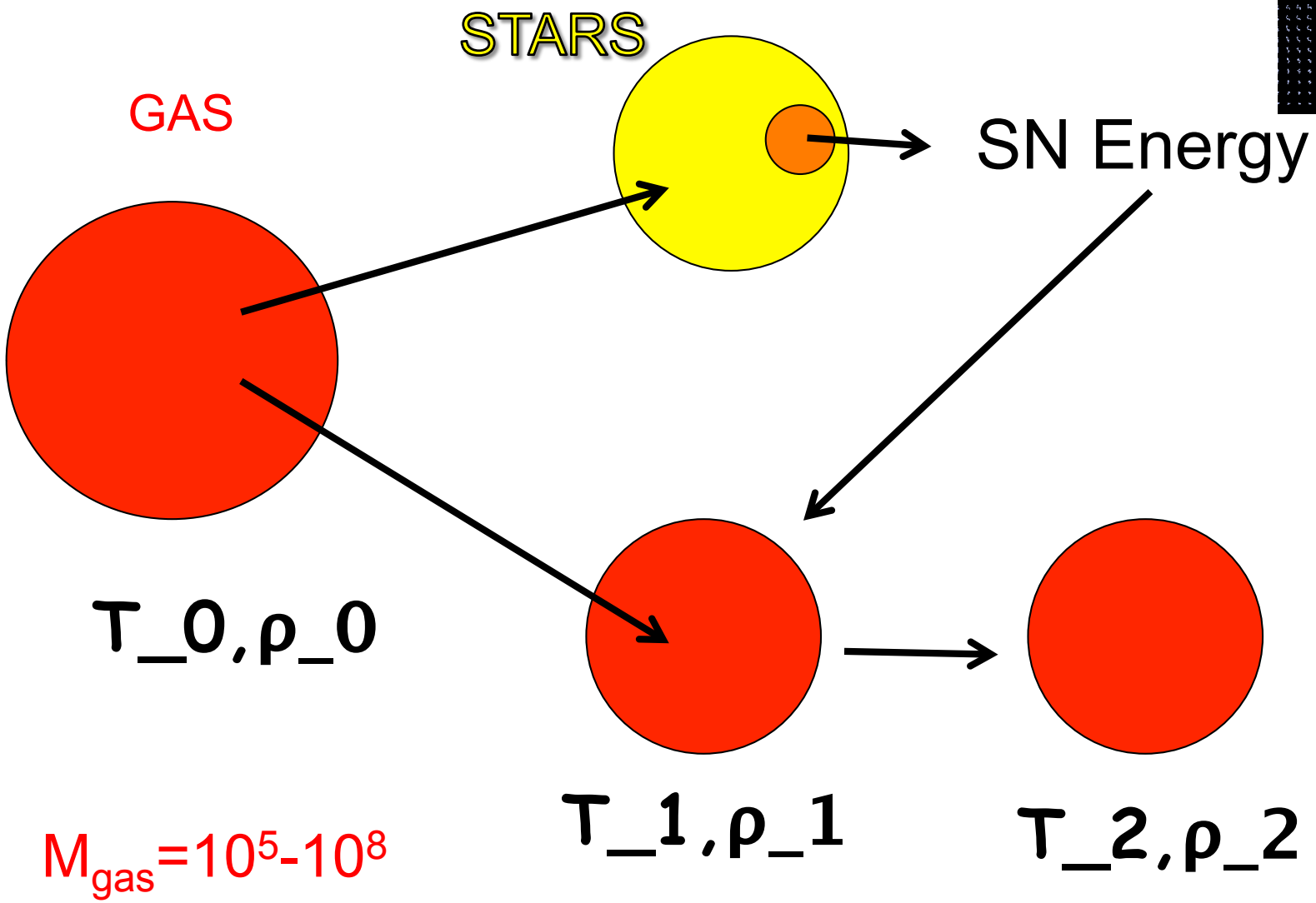




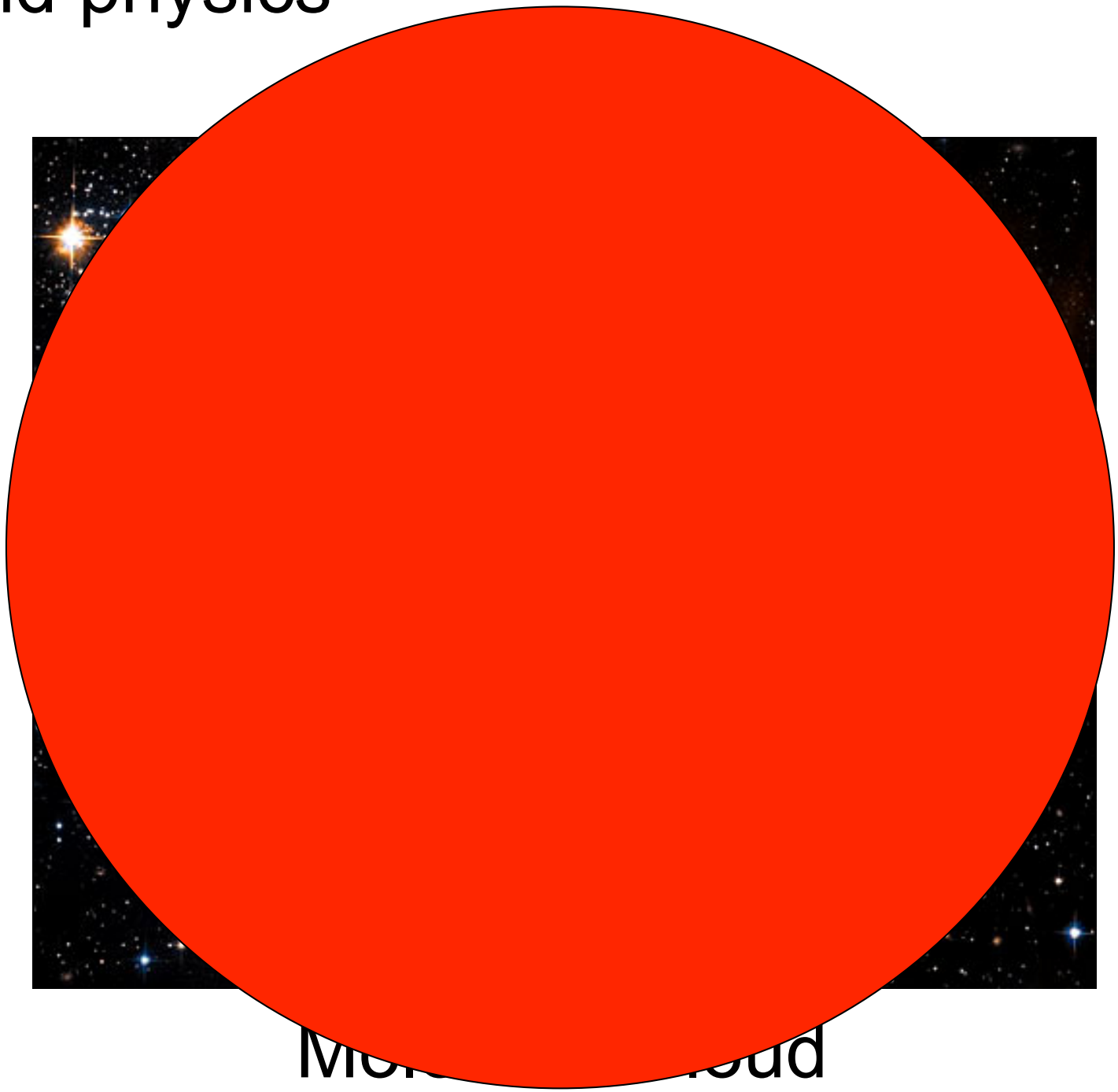


Star formation and feedback in a nut shell



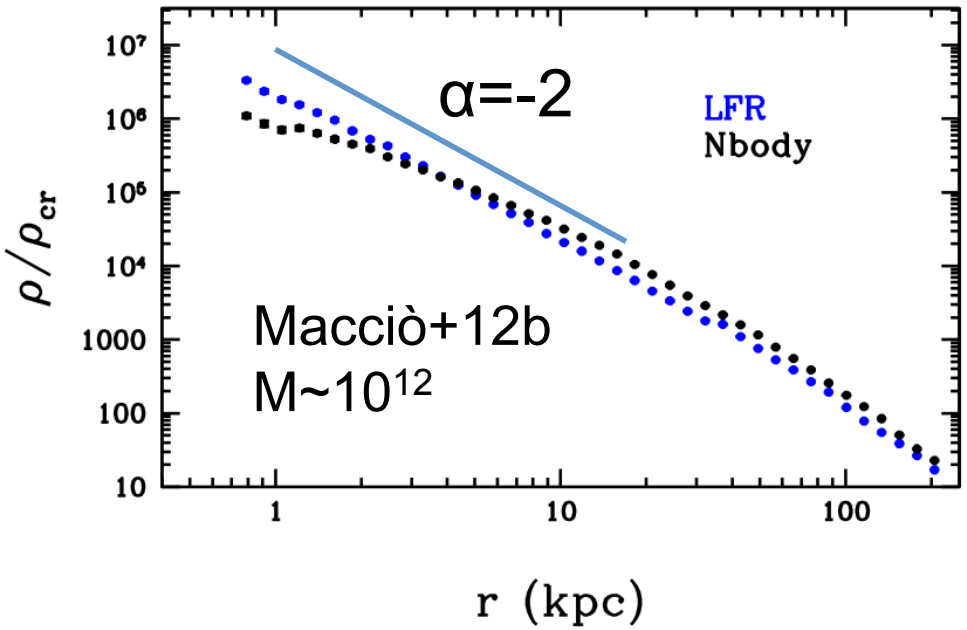


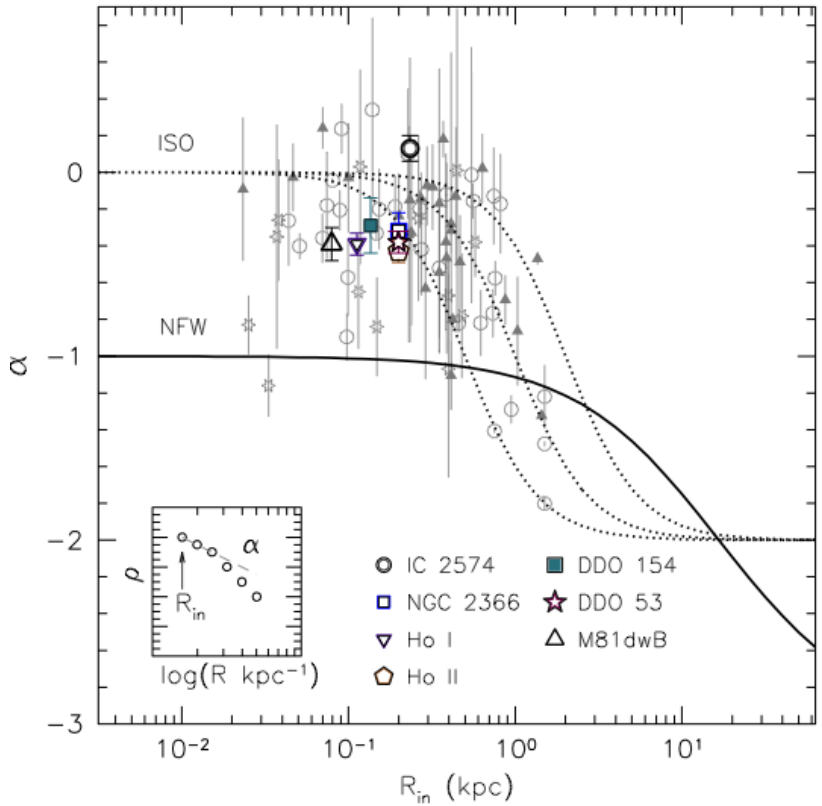
Sub grid physics



300 pc

What is the effect of baryons?





With no or low feedback:

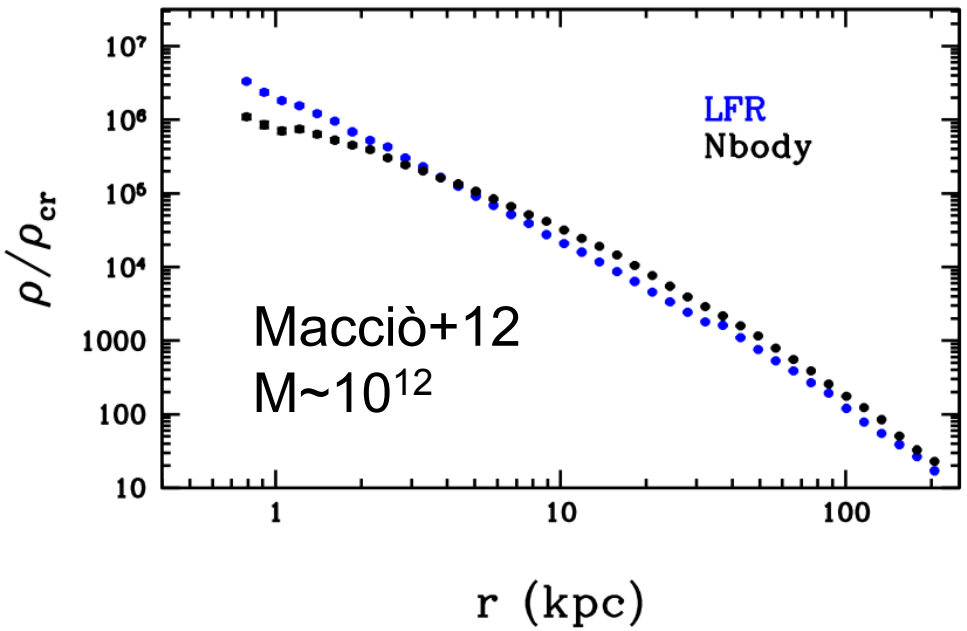
➡ Halo contraction

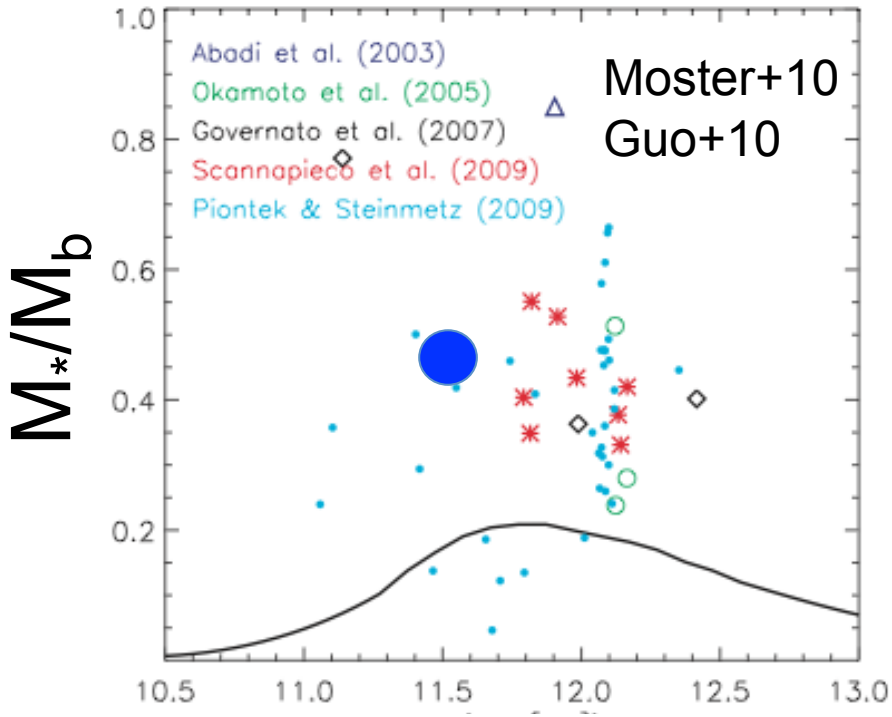
(Gnedin+04, Gnedin+11)

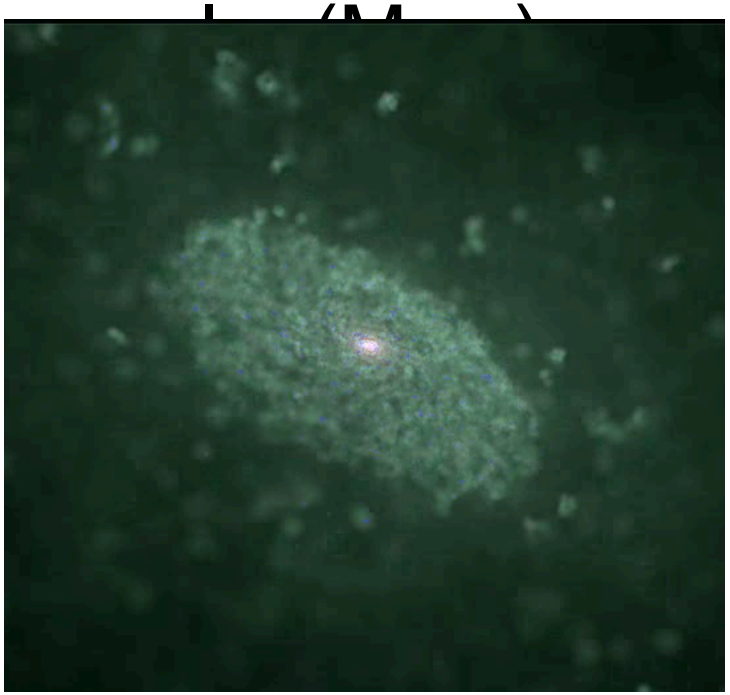
"The halo contraction effect is real and must be included in modeling of the mass distribution of galaxies…"

BUT CONTRACTION IS BAD!

We need realistic disc galaxies



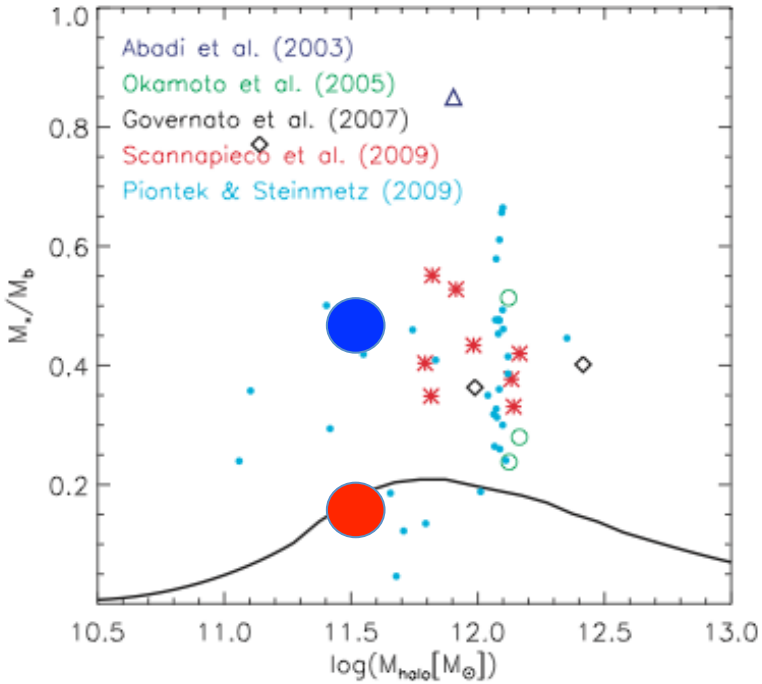




- Gasoline SPH code
- SN feedback
- Chabrier IMF
- Massive stars rad. pressure
- Higher resolution

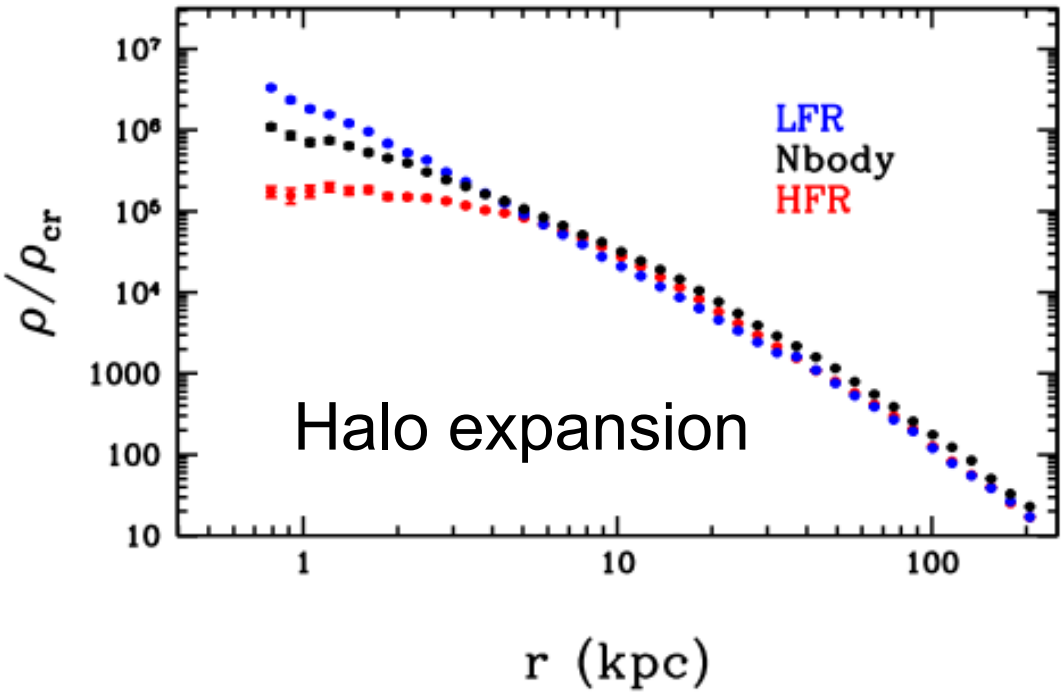
(Stinson, Brook, AM+12)

New simulations with increased feedback (HFR)

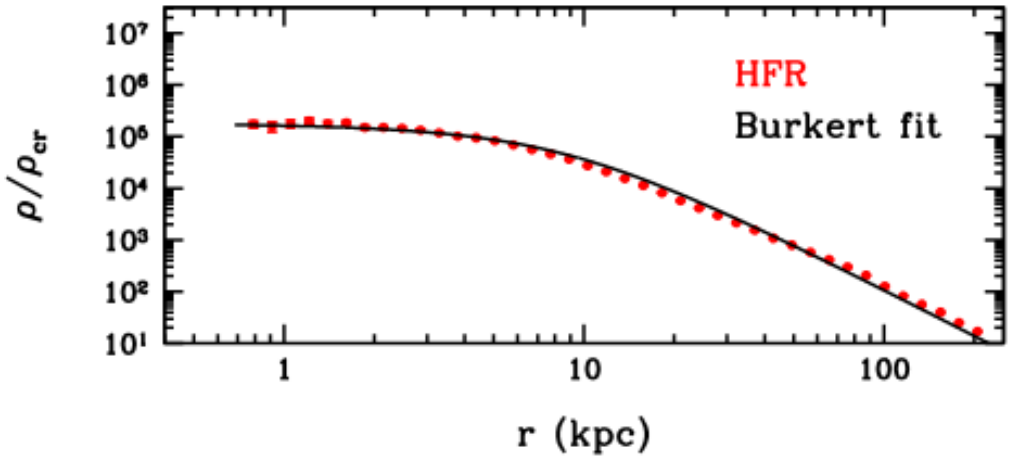


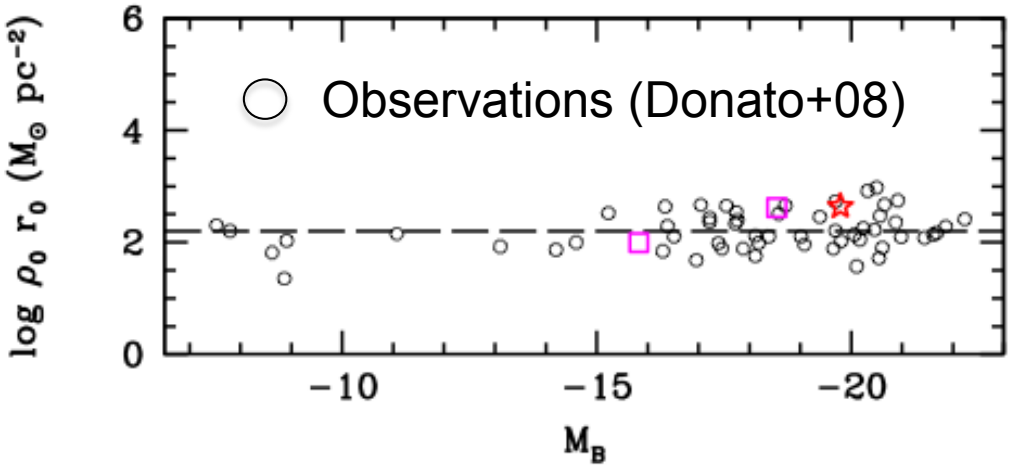
Right amount of baryons
Exponential disc
Flat rotation curve
…
…
and the DM profile?

Cored DM profile in a LCDM cosmological simulation of a massive disc galaxy (M~7e11 Msun)

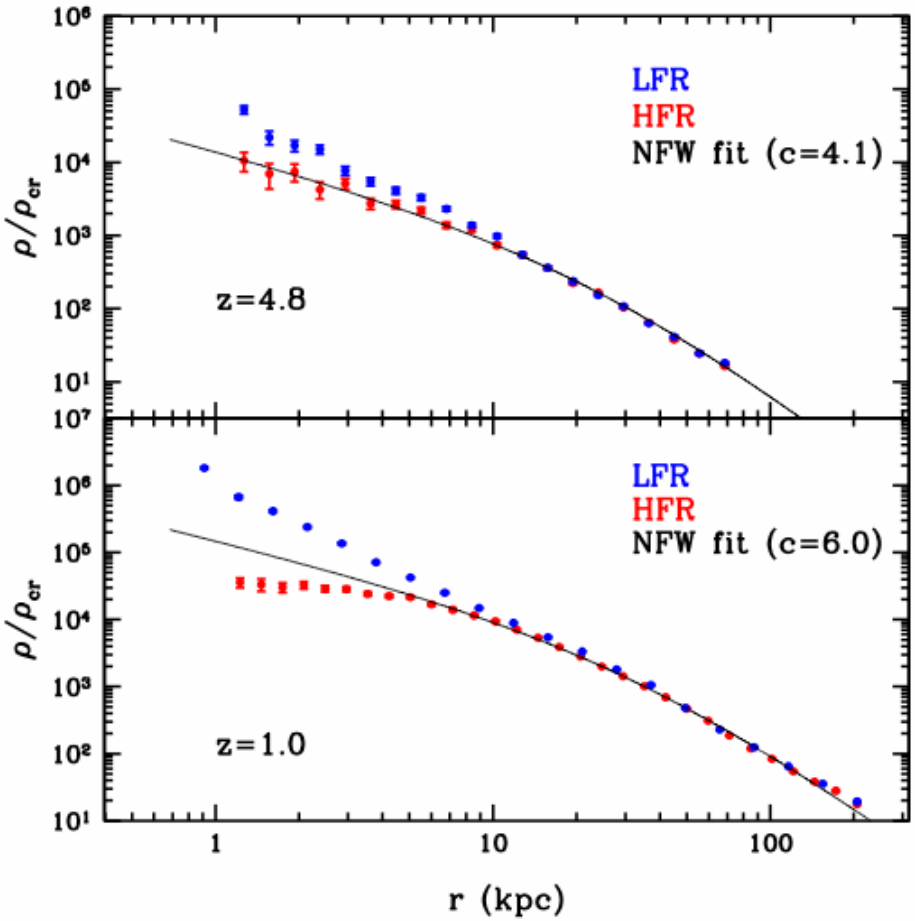


As flat as observed





Profile flattens with time



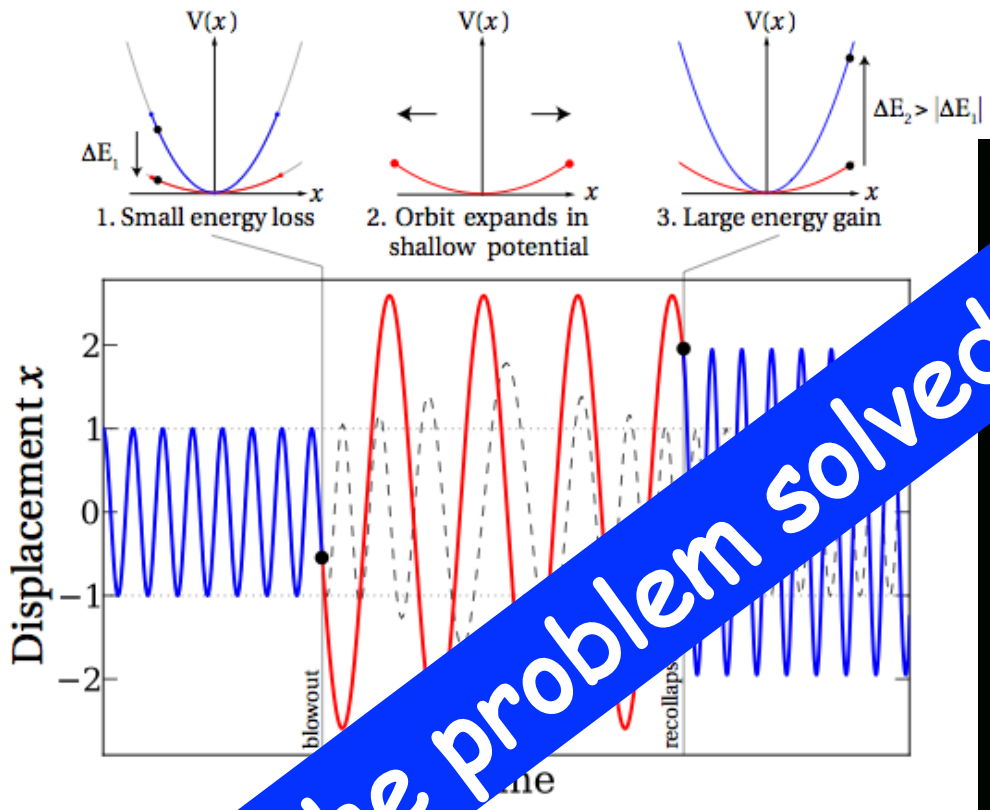
Burkert profile

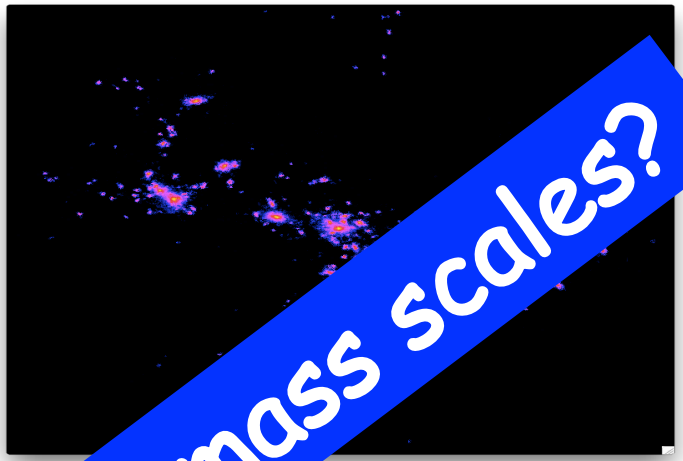
$$\rho(r) = \frac{\rho_0 r^3}{(r + r_0)\left(r^2 + r_0^2\right)}$$

WHY?

Main mechanism:

1) Strong and quick energy injection
Pontzen & Governato 2011





Is the problem solved on ALL mass scales?

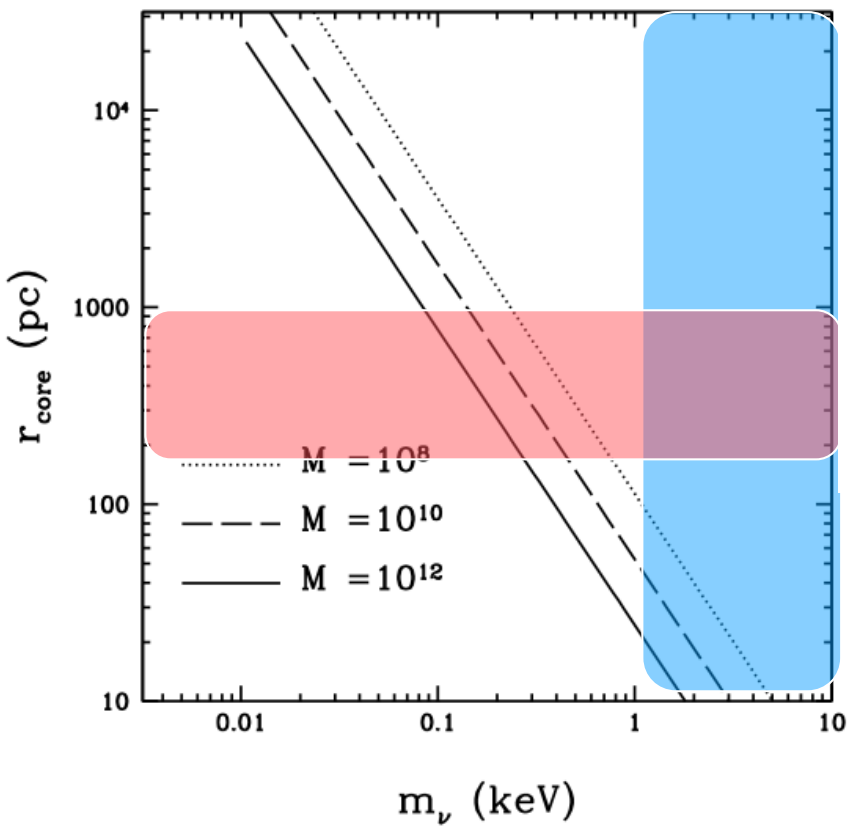
adiabatic expansion

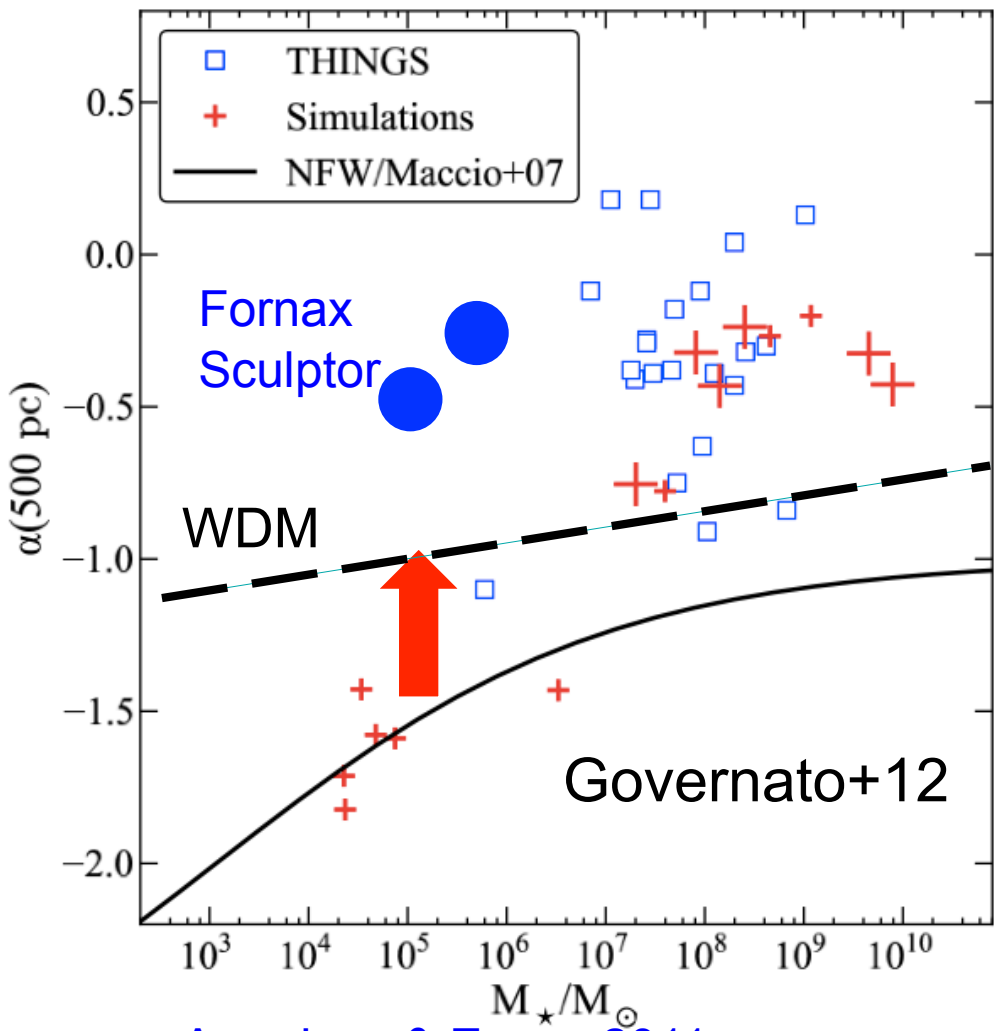
MaGICC project
(Stinson, Brook, Macciò+2012)

Dwarfs and Baryons

$$\frac{M_b}{M_{dm}} \rightarrow 0$$

$$\alpha \rightarrow -1$$

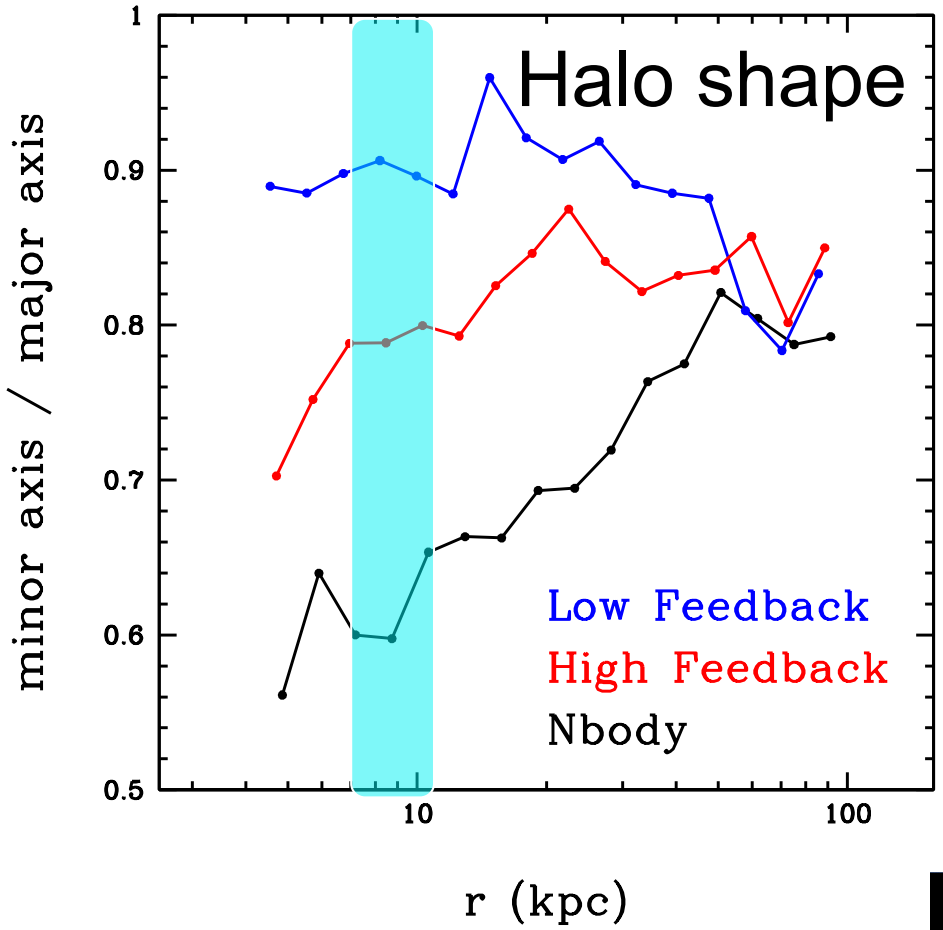


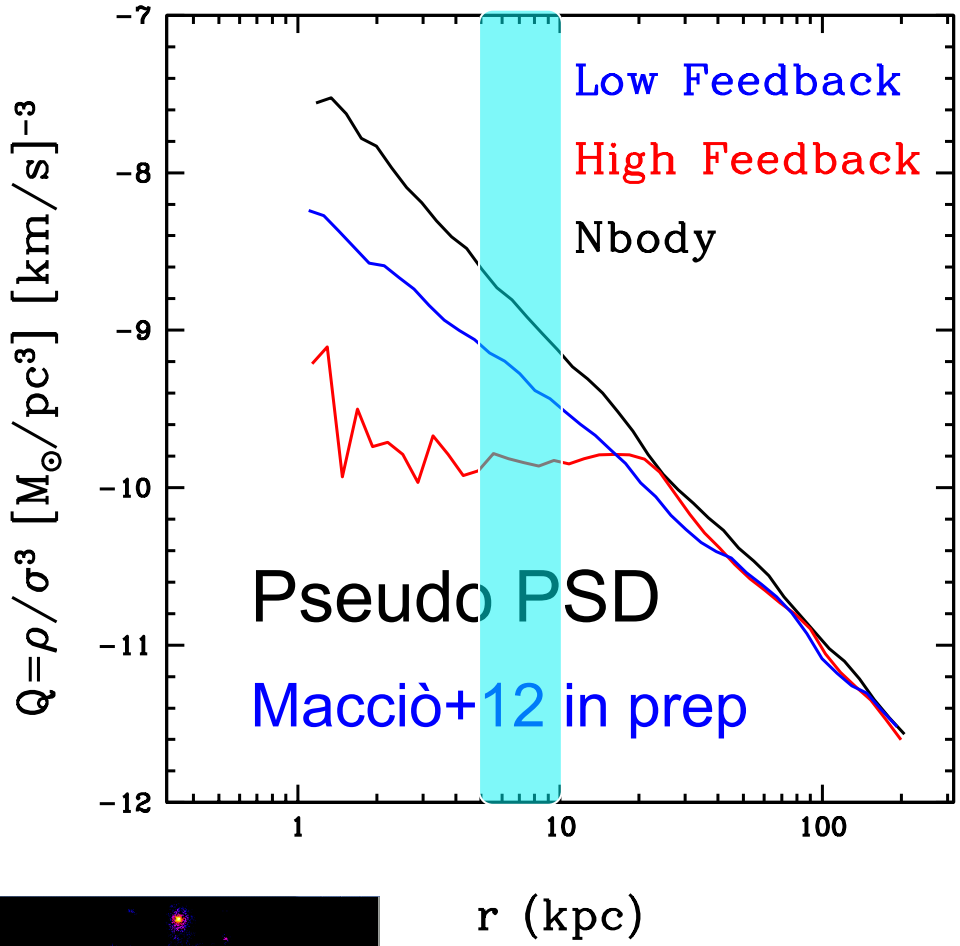


Amorisco & Evans 2011
Walker & Penarrubia 2011

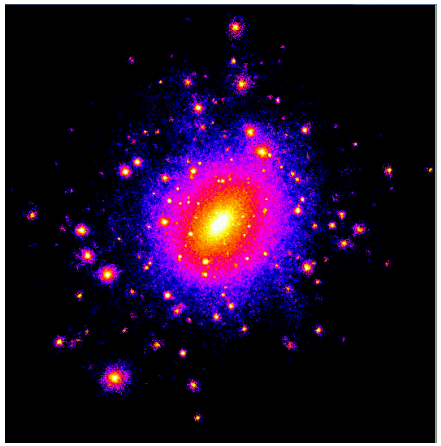
Possibly not enough baryons (feedback) in local dwarf galaxies to remove the CDM cusp (but see Zolotov+12)

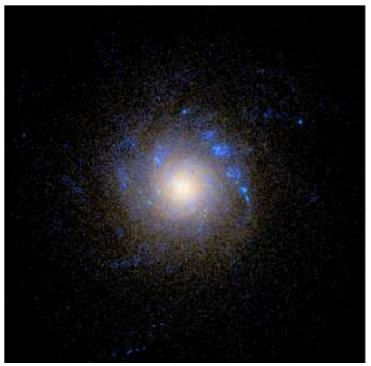
More Baryonic effects





Anisotropy distribution β
Local DM density/velocity
etc





Conclusions

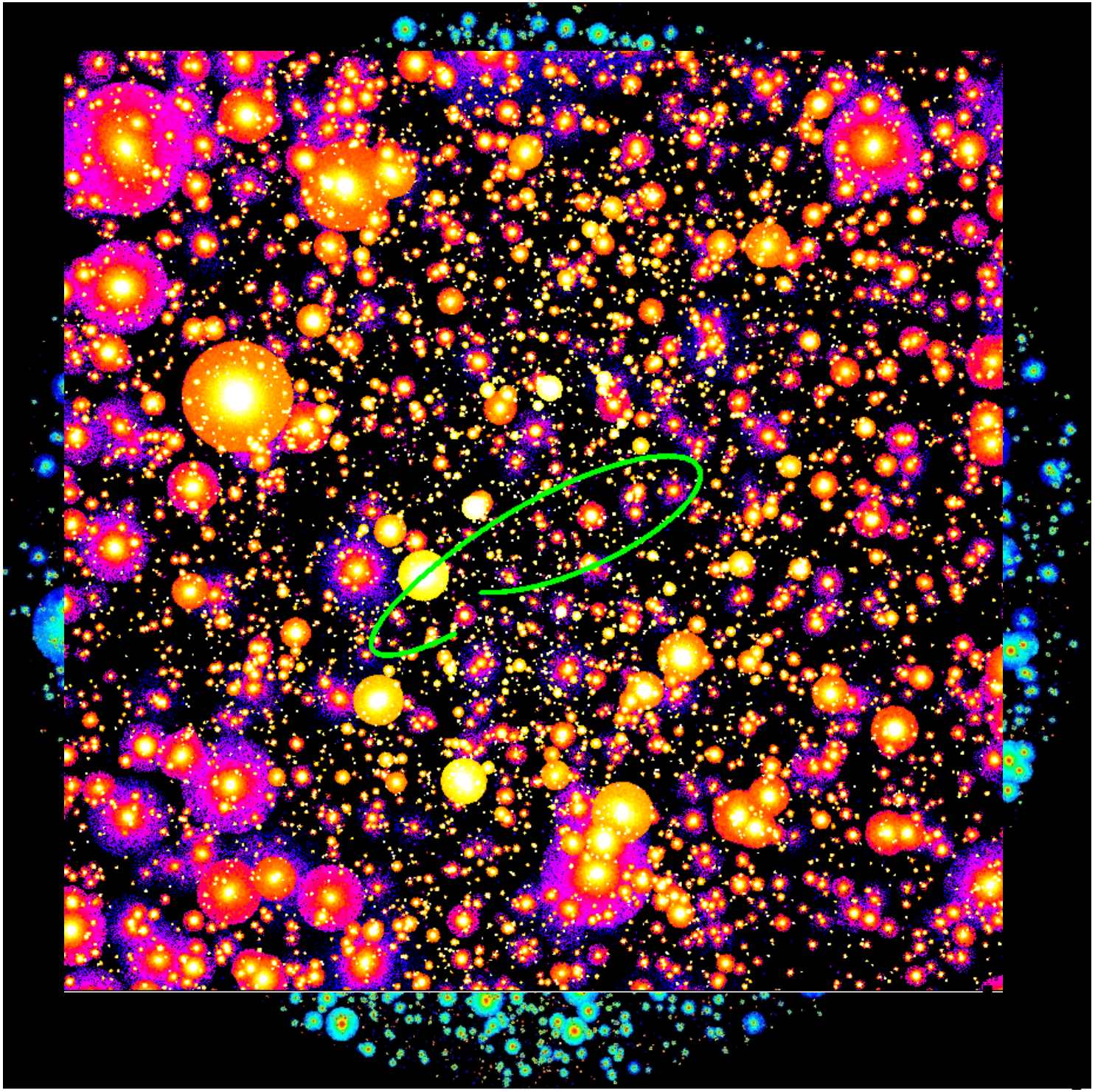
Pure DM simulations very useful to study properties of matter distribution on large scales

On small scales baryons must be taken into account:
-shallower (cored) density profiles
-rounder haloes etc…

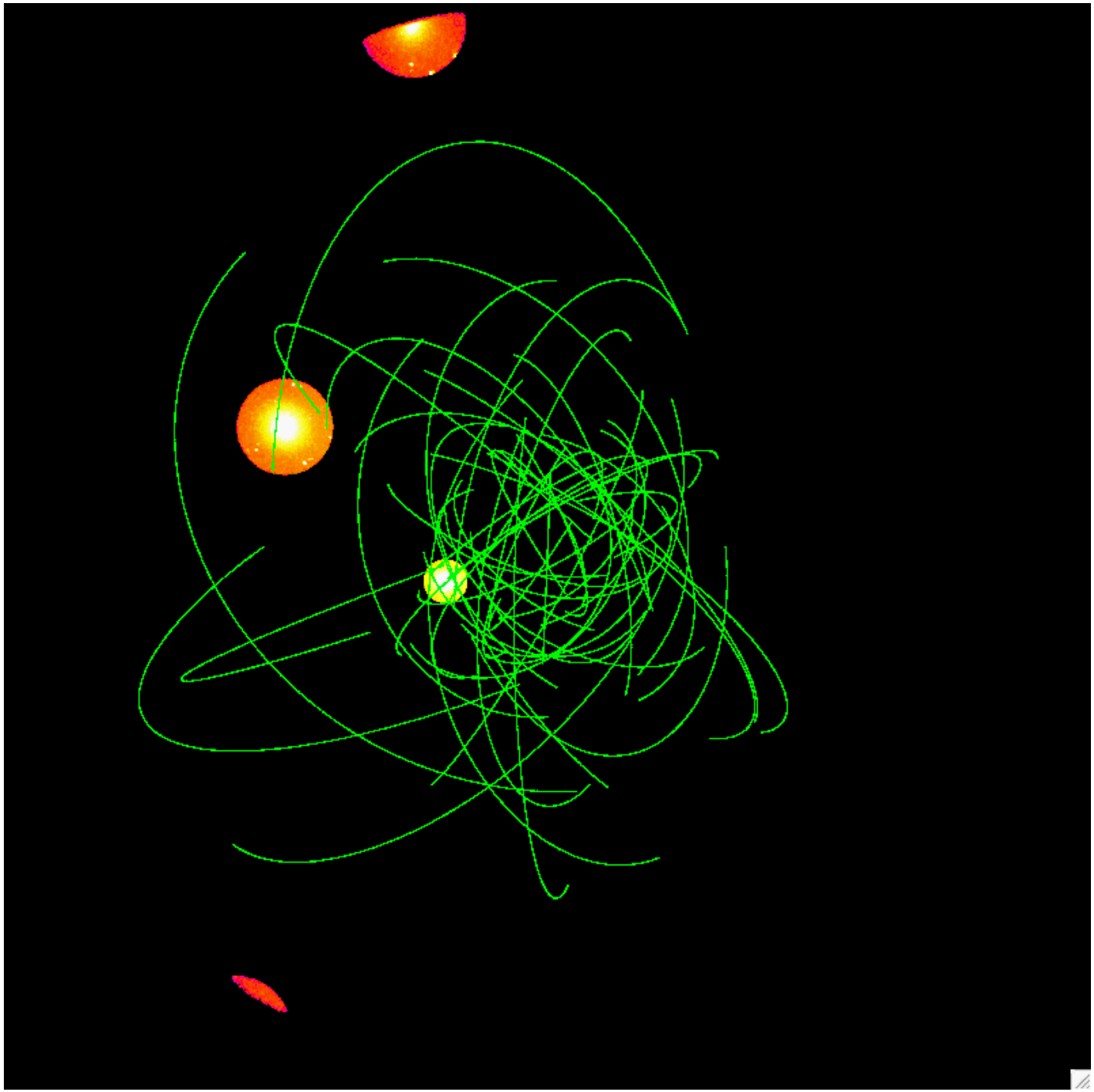
Baryonic physics highly unconstrained in simulations
No ‘state-of-the-art’ code or model
Don’t trust anyone (including me!)

Open question
Cores in very faint MW satellites could require WDM & baryons acting together.

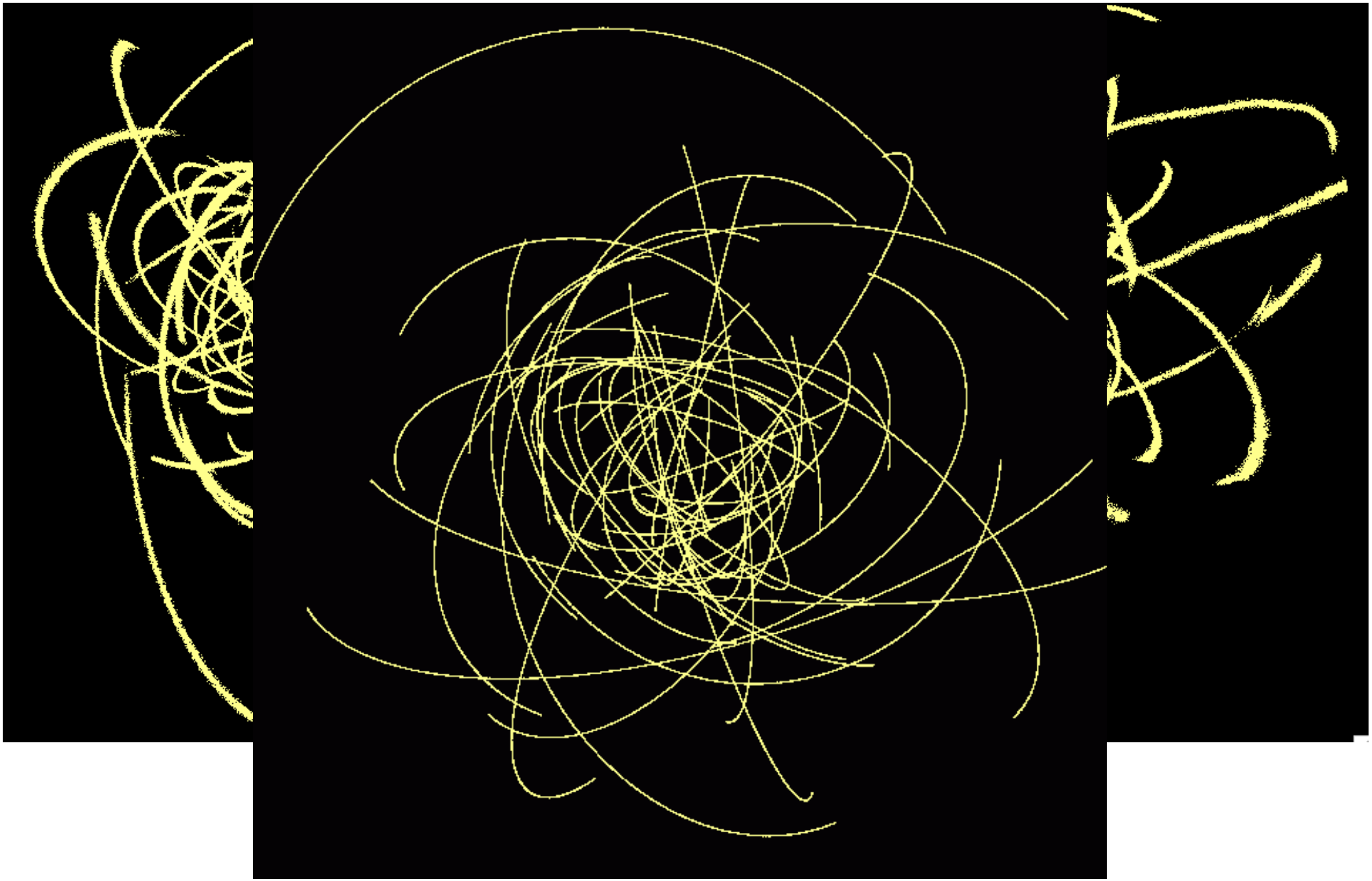
THANK YOU



Macciò, Koposov
in preparation

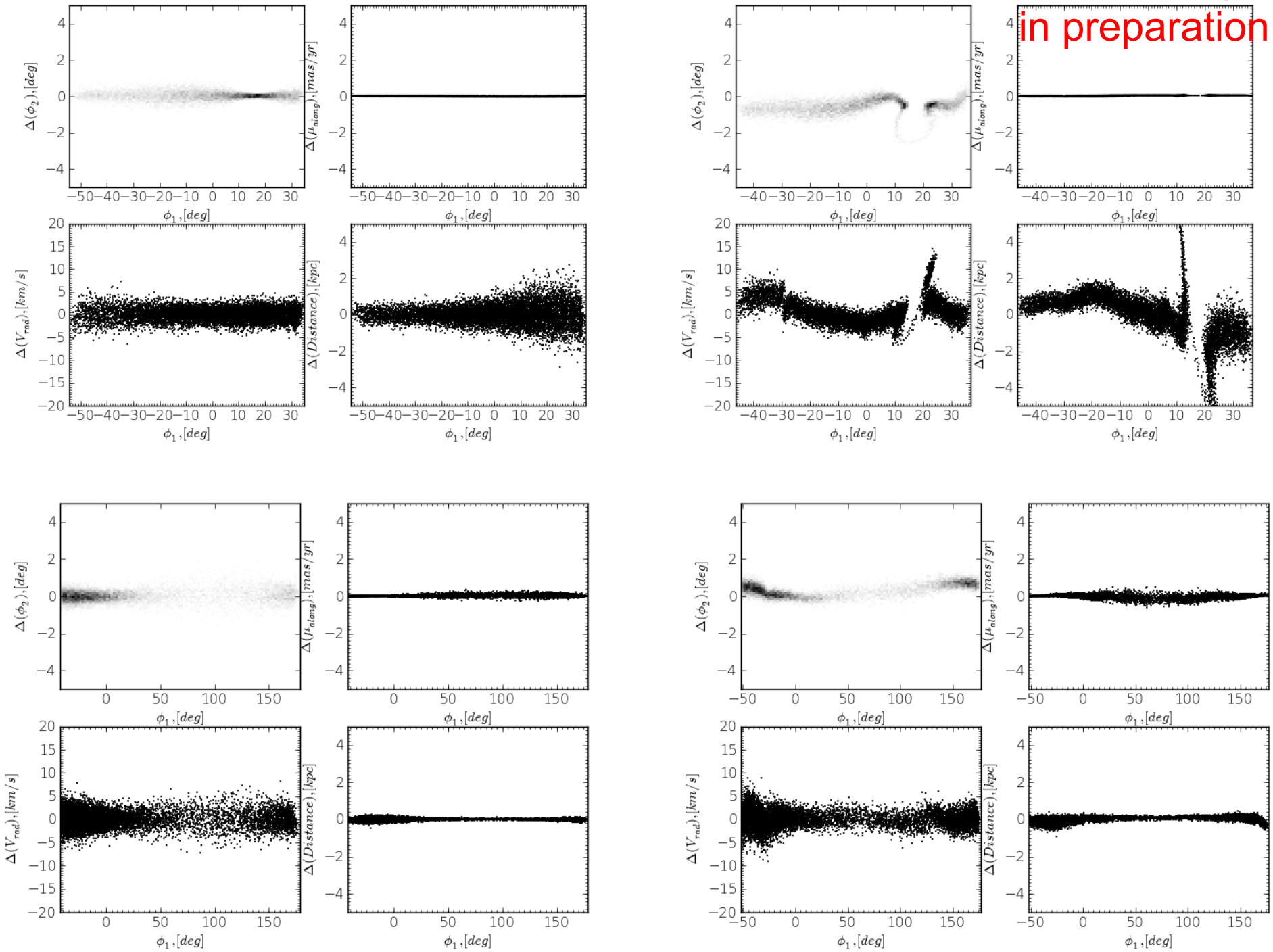


Macciò, Koposov
in preparation

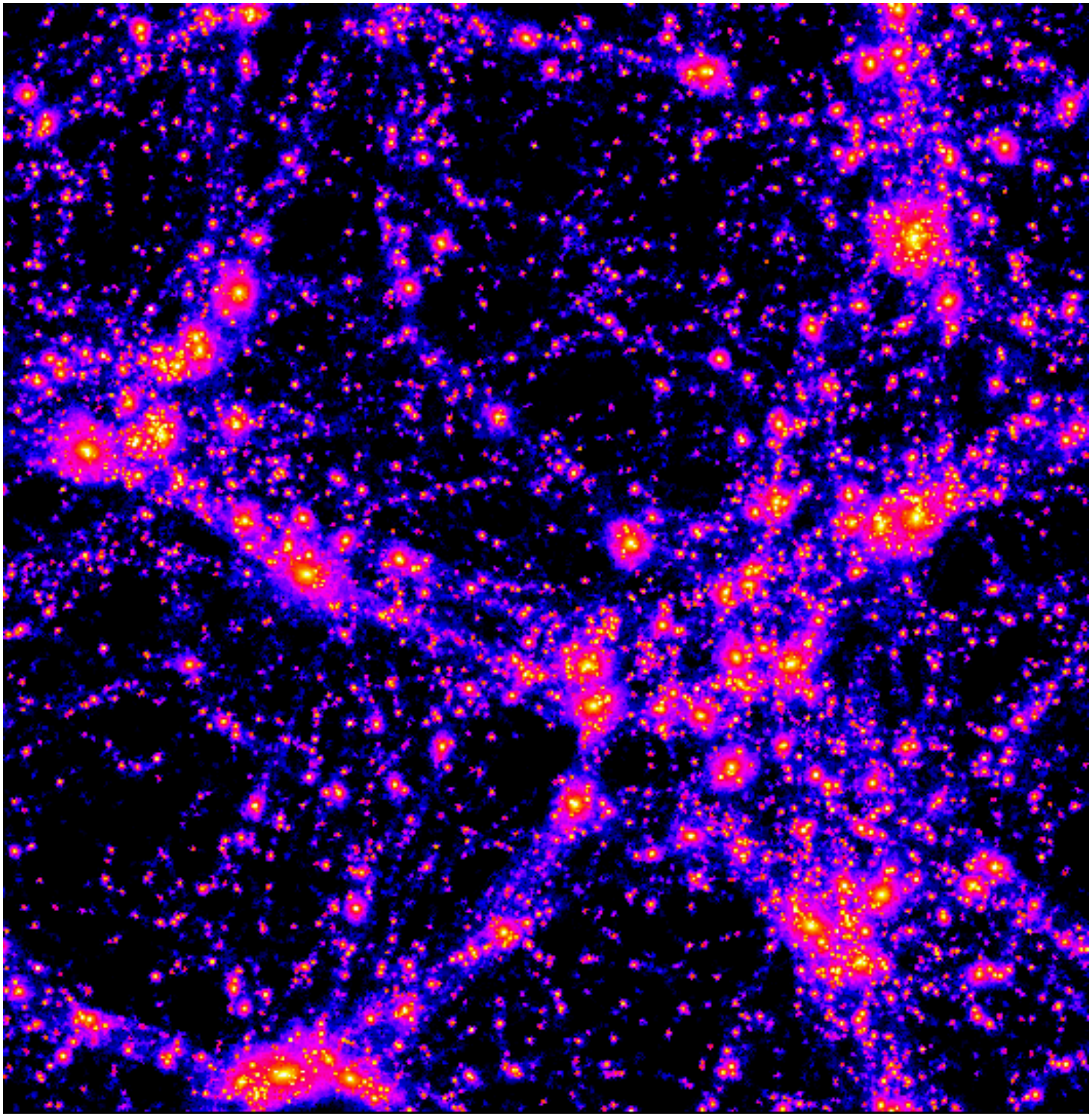


Macciò, Koposov
in preparation

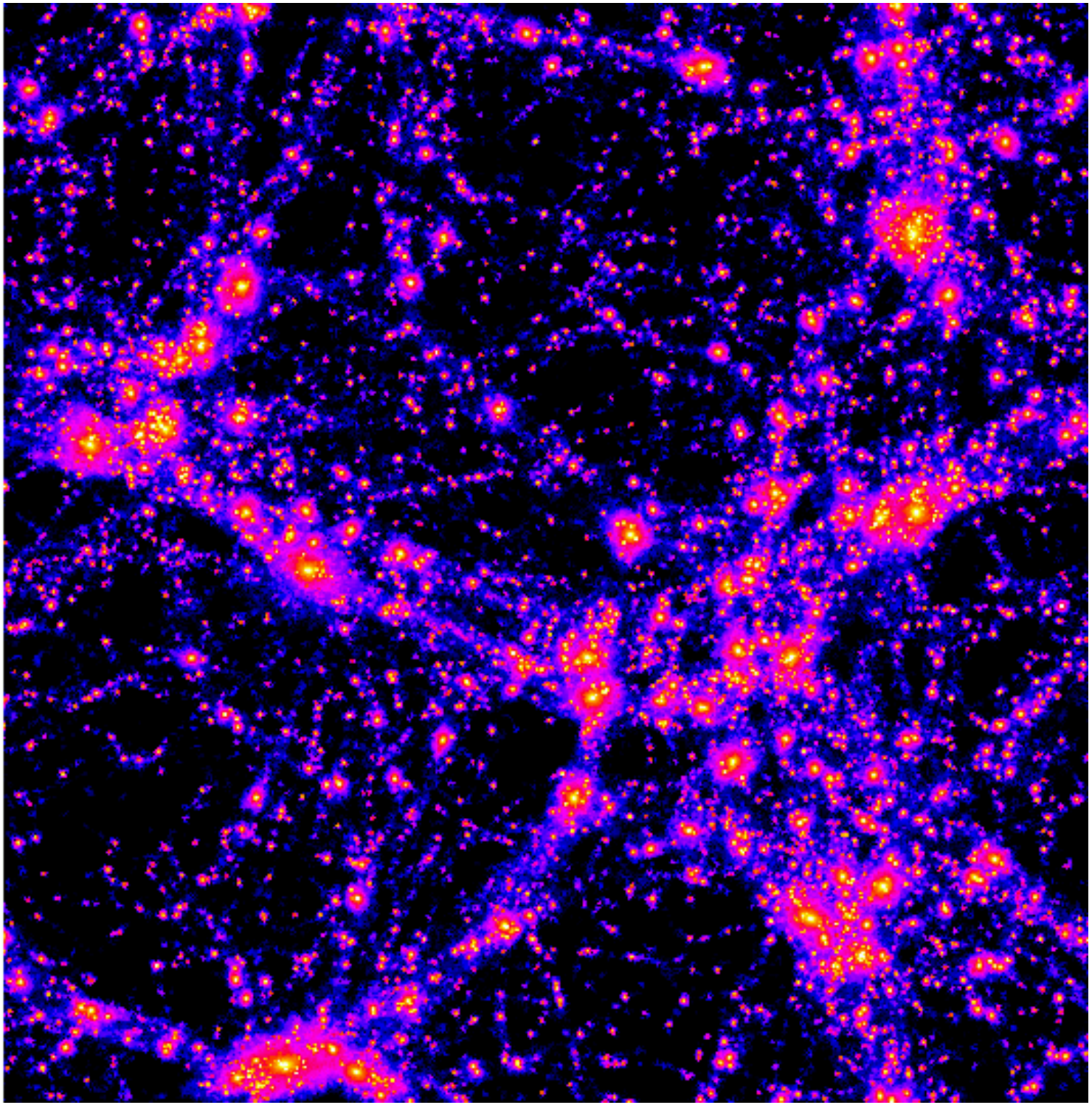
Macciò, Koposov
in preparation



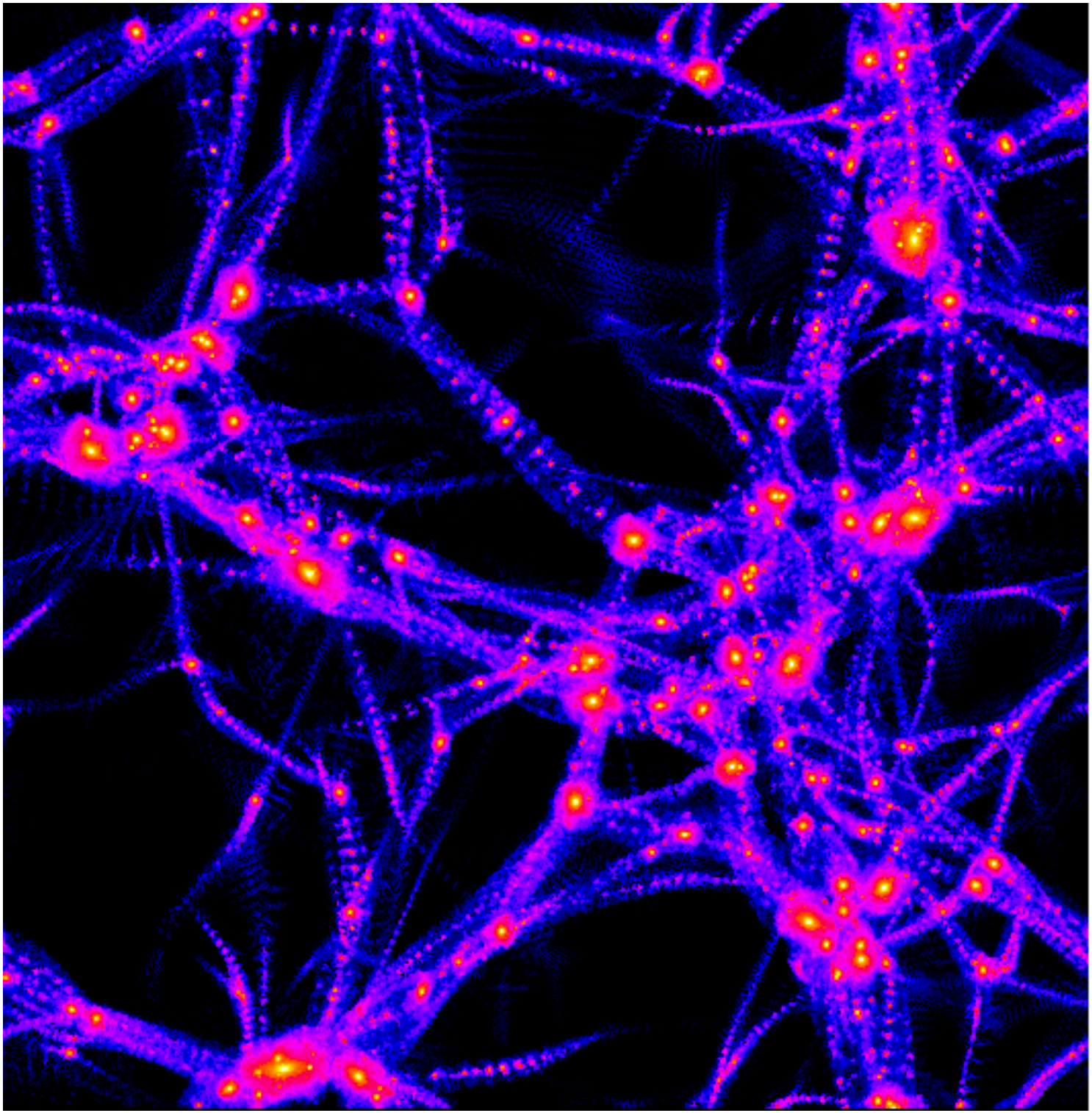
THANK YOU
AGAIN



LCDM
L=40 Mpc
N=300^3



WDM
L=40 Mpc
N=300^3
m=2 keV



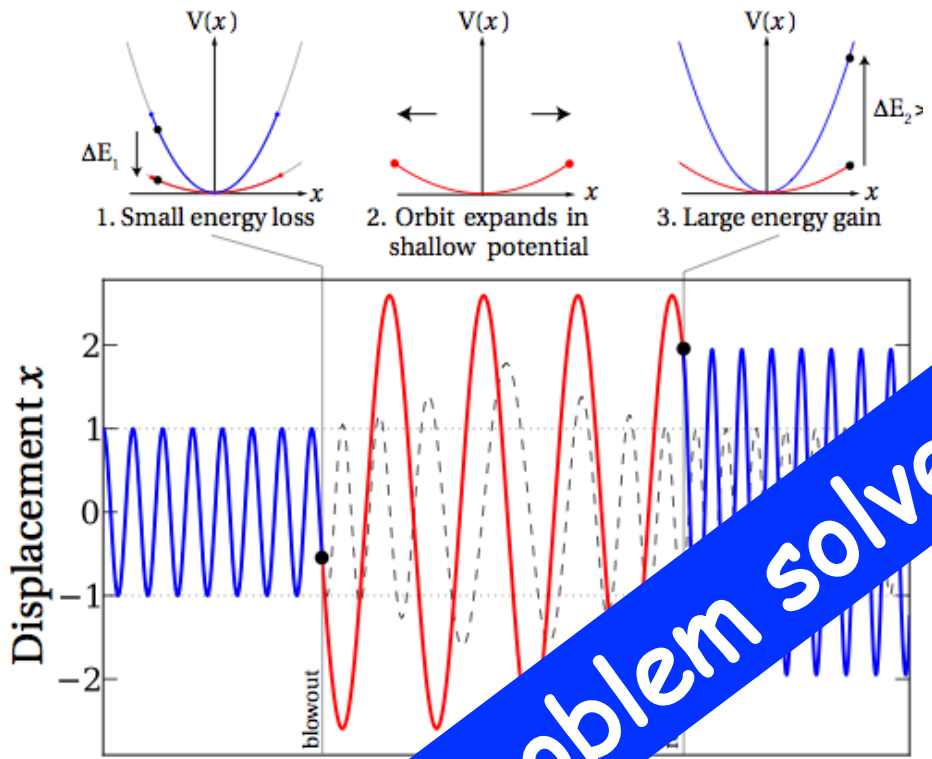
WDM - LSS

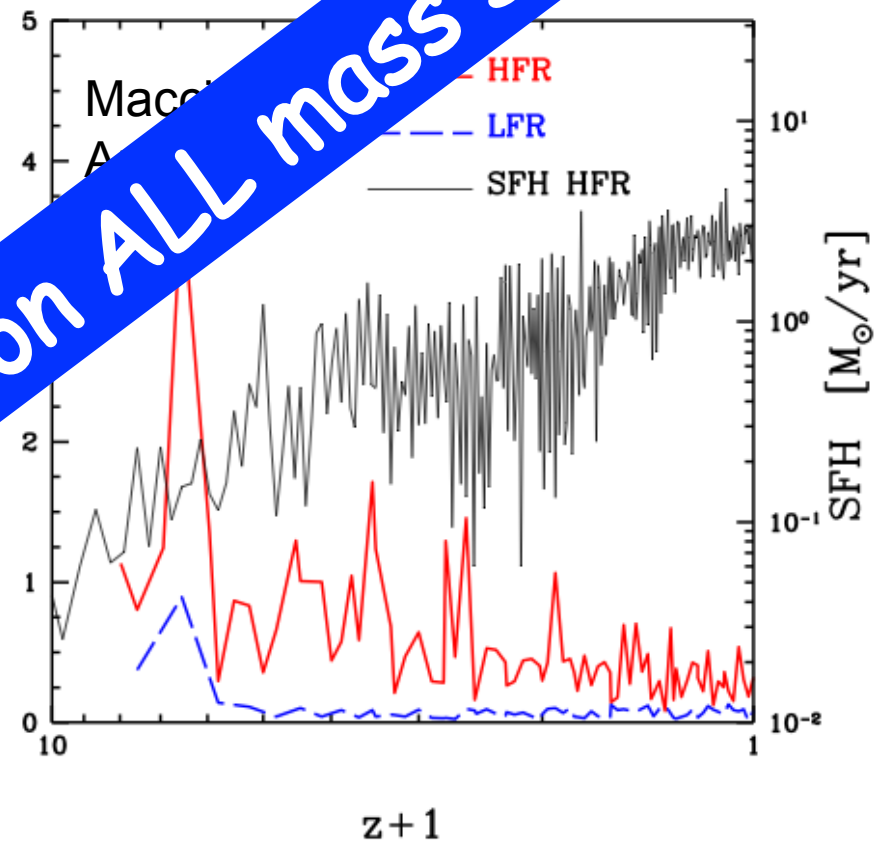
WDM
L=40 Mpc
N=300^3
m=0.5 keV

Two main mechanisms:

1) Strong and quick energy injection

2) Fluctuation of the p



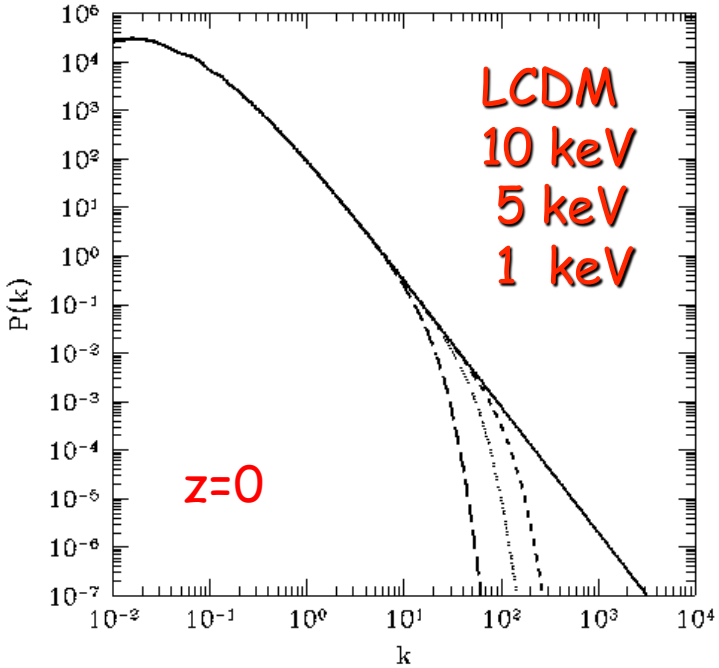


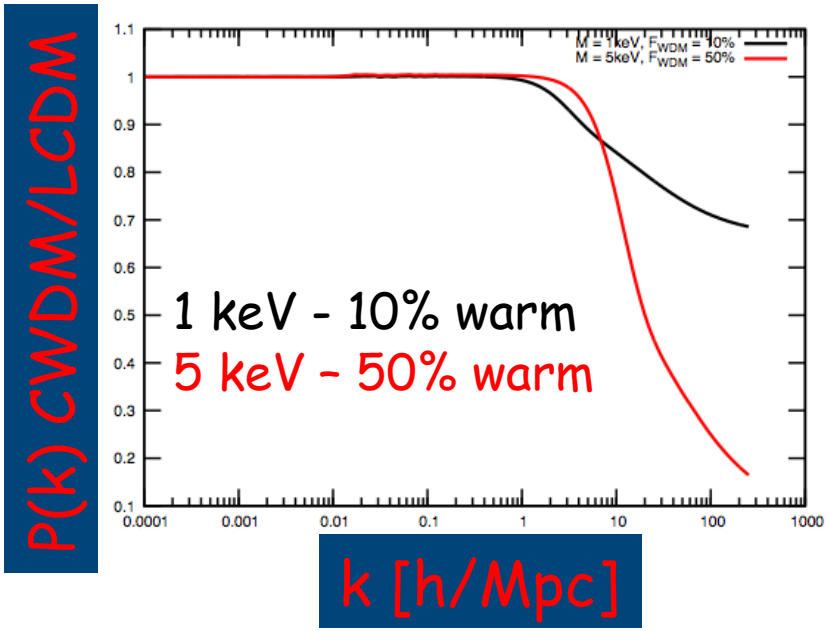
NO
batic expansion
en & Governato 2011

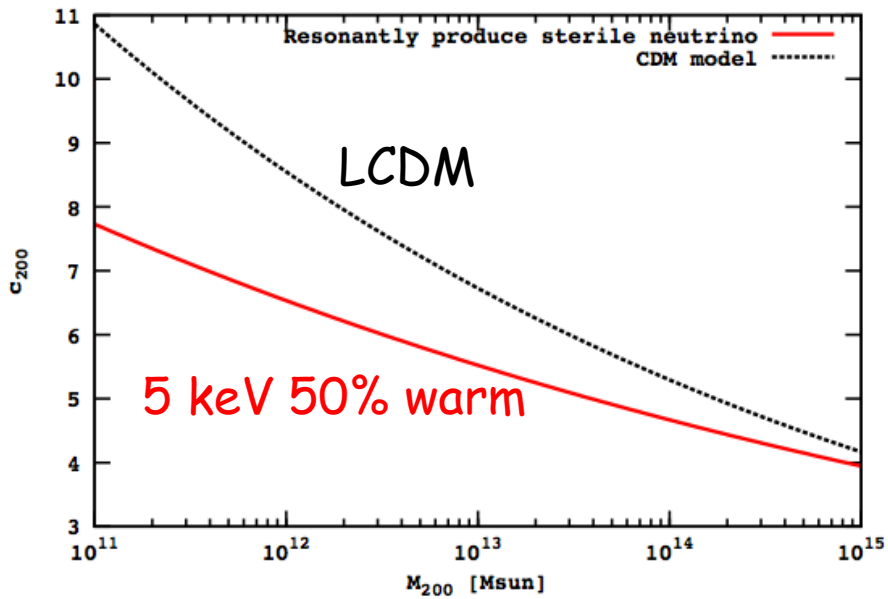
Strong feedback shakes the DM potential well
Macciò, Stinson+2012

Is the problem solved on ALL mass scales?

Mixed models: Cold+Warm Dark Matter (CWDM)

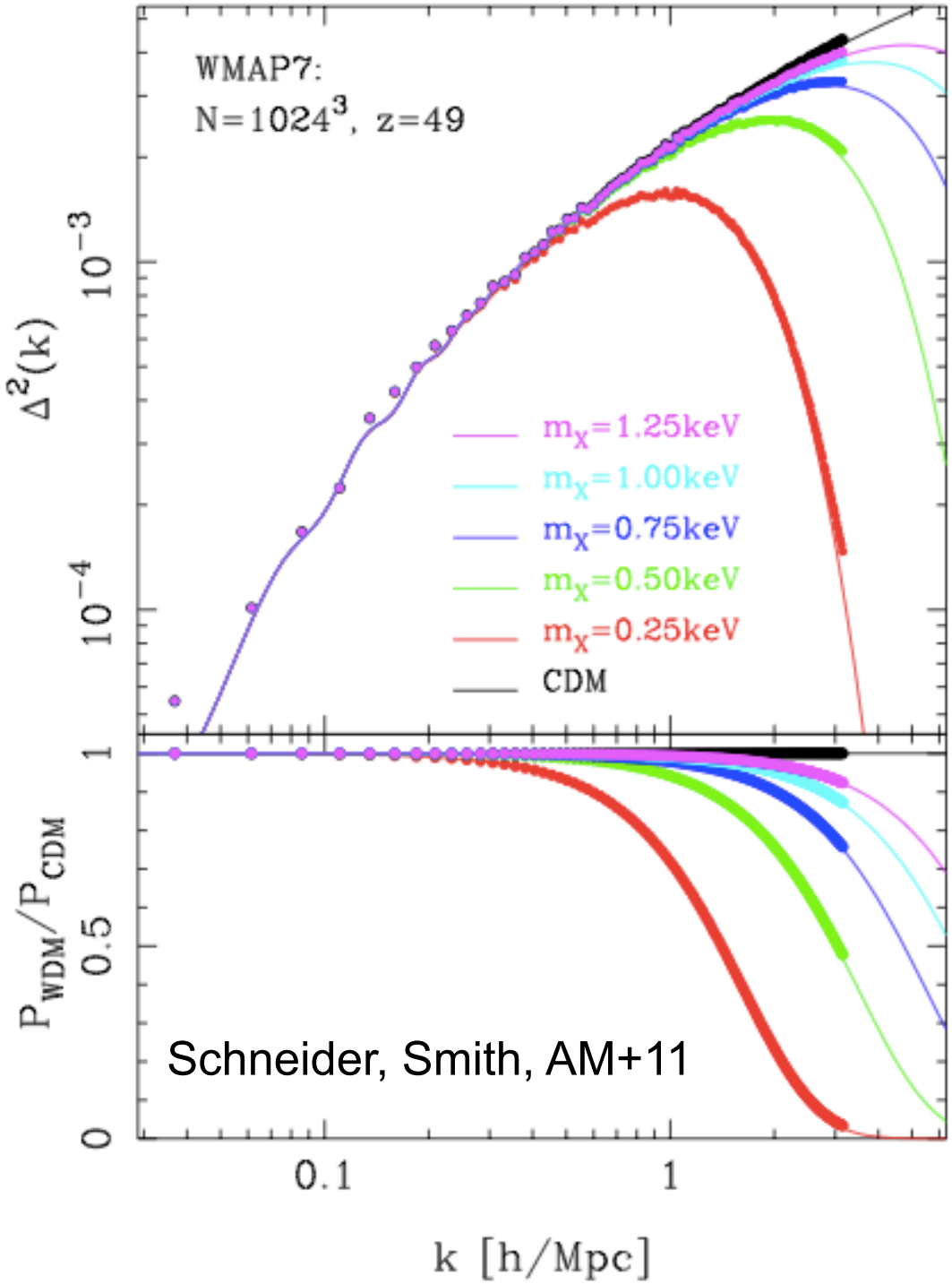






Lower concentration at all masses.

Maccio', Ruchayrskyi & Boyarsky in preparation


WMAP7:
N=1024^3, z=49
m_X=1.25keV
m_X=1.00keV
m_X=0.75keV
m_X=0.50keV
m_X=0.25keV
CDM
$\Delta^2(k)$
10^{-3}
10^{-4}
P_{WDM}/P_{CDM}
1
0.5
0
0.1
1
k [h/Mpc]
Schneider, Smith, AM+11