Dark Matter distribution around galaxies

Andrea V. Macciò

New York University Abu Dhabi

جامعة نيويورك ابوظبي
NYU ABU DHABI

Avignon, April 27th 2017

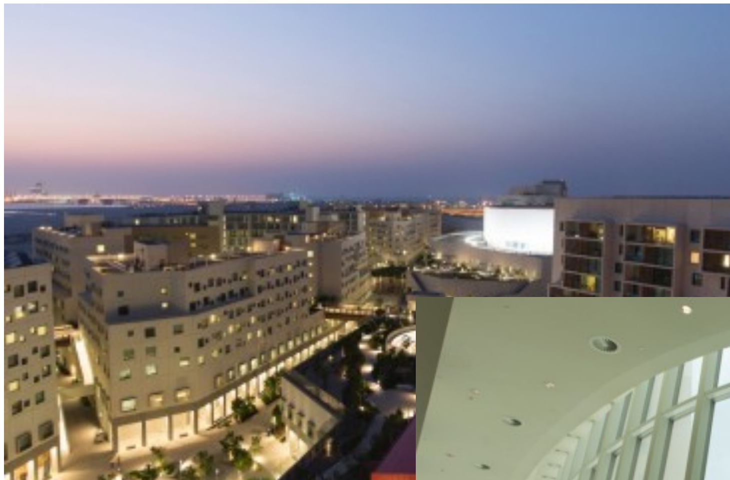
NYU

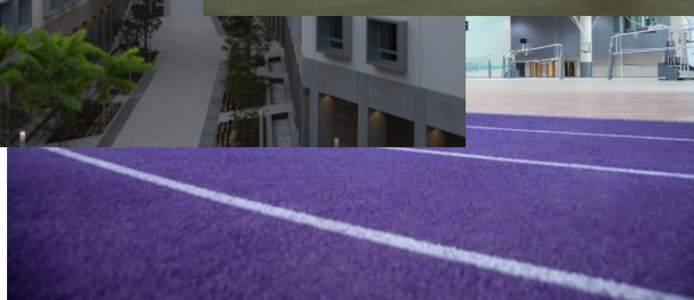
Where?


Denmark
United Kingdom
Ireland
Birmingham
London
Germany
Poland
Belarus
Ukraine
Kazakhstan
Austria
France
Romania
Italy
Caspian Sea
Uzbekistan
Kyrgyzstan
Portugal
Spain
Spain
Portugal
Greece
Turkey
Turkmenistan
Oran
وهران
Casablanca
الدار البيضاء
Tunisia
Syria
Iraq
Iran
Afghanistan
Morocco
Pakistan
Algeria
Libya
Egypt
Western Sahara
Saudi Arabia
India
Oman
Mauritania
Mali
Niger
Sudan
Chad
Yemen
Google
Burkina
Gulf of Aden
Map data ©2015 Google, INEGI
Terms
Privacy
500 km

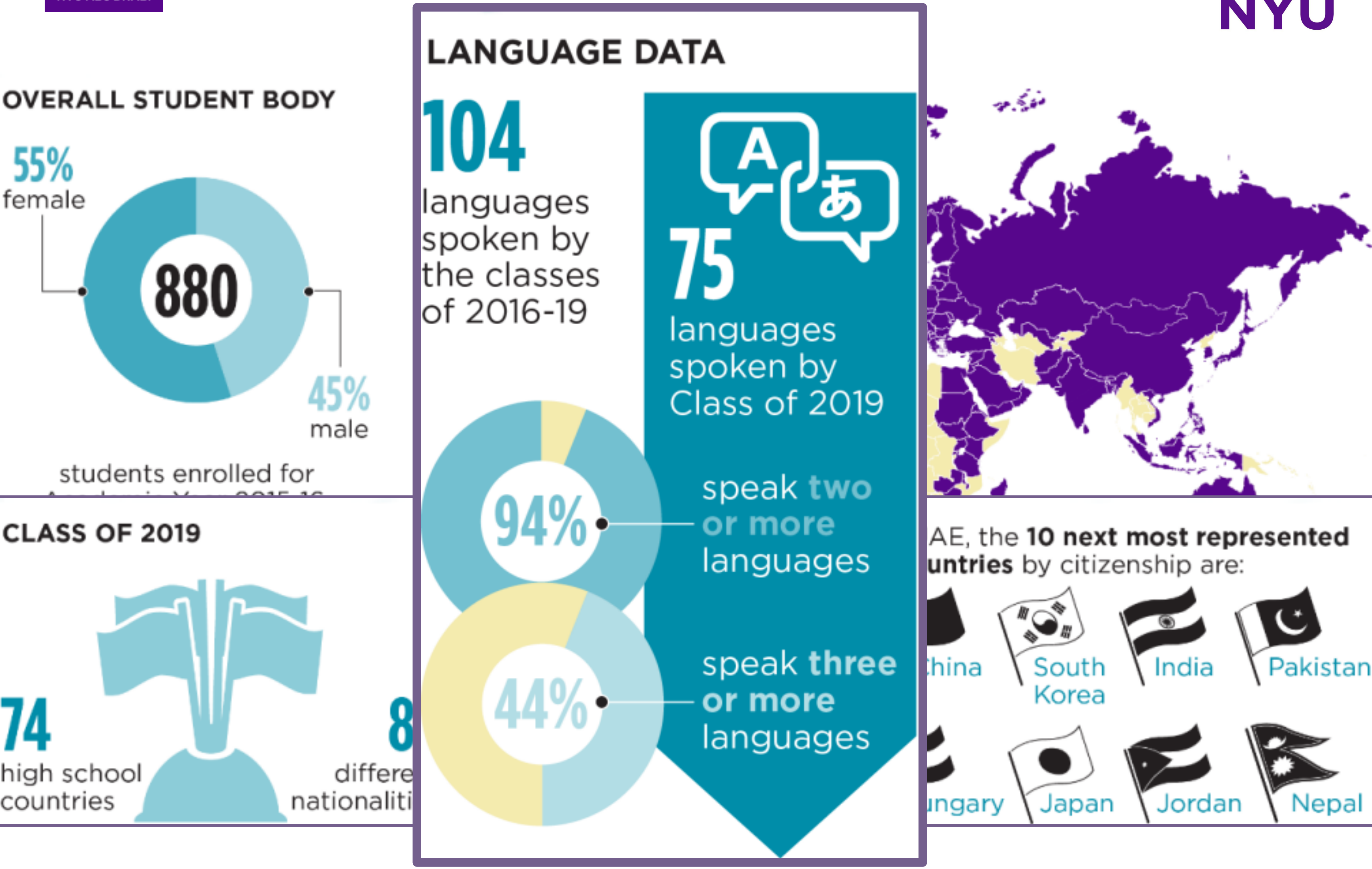
Abu Dhabi

NYU Abu Dhabi

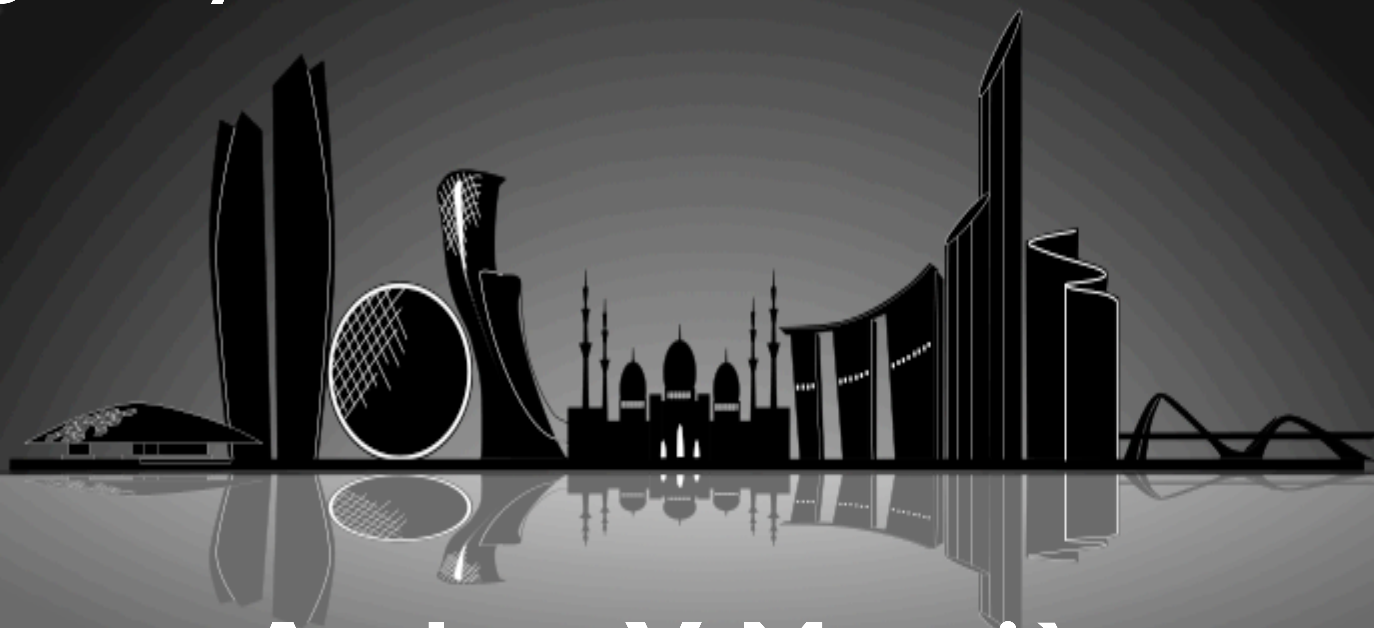




NYU Abu Dhabi



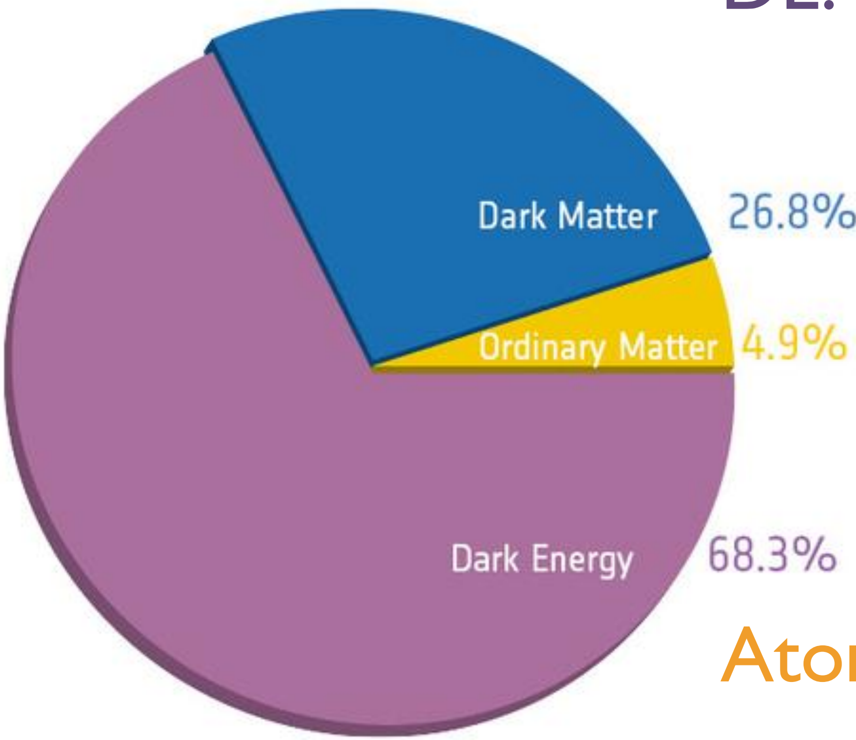
Dark Matter distribution around galaxy: hints from simulations



Andrea V. Macciò

NYUAD – MPIA

The cosmology pie chart



DE: sets the expansion of the Universe.

DM: Sets galaxy potential wells.

Atoms: Ordinary matter, what we can directly observe.

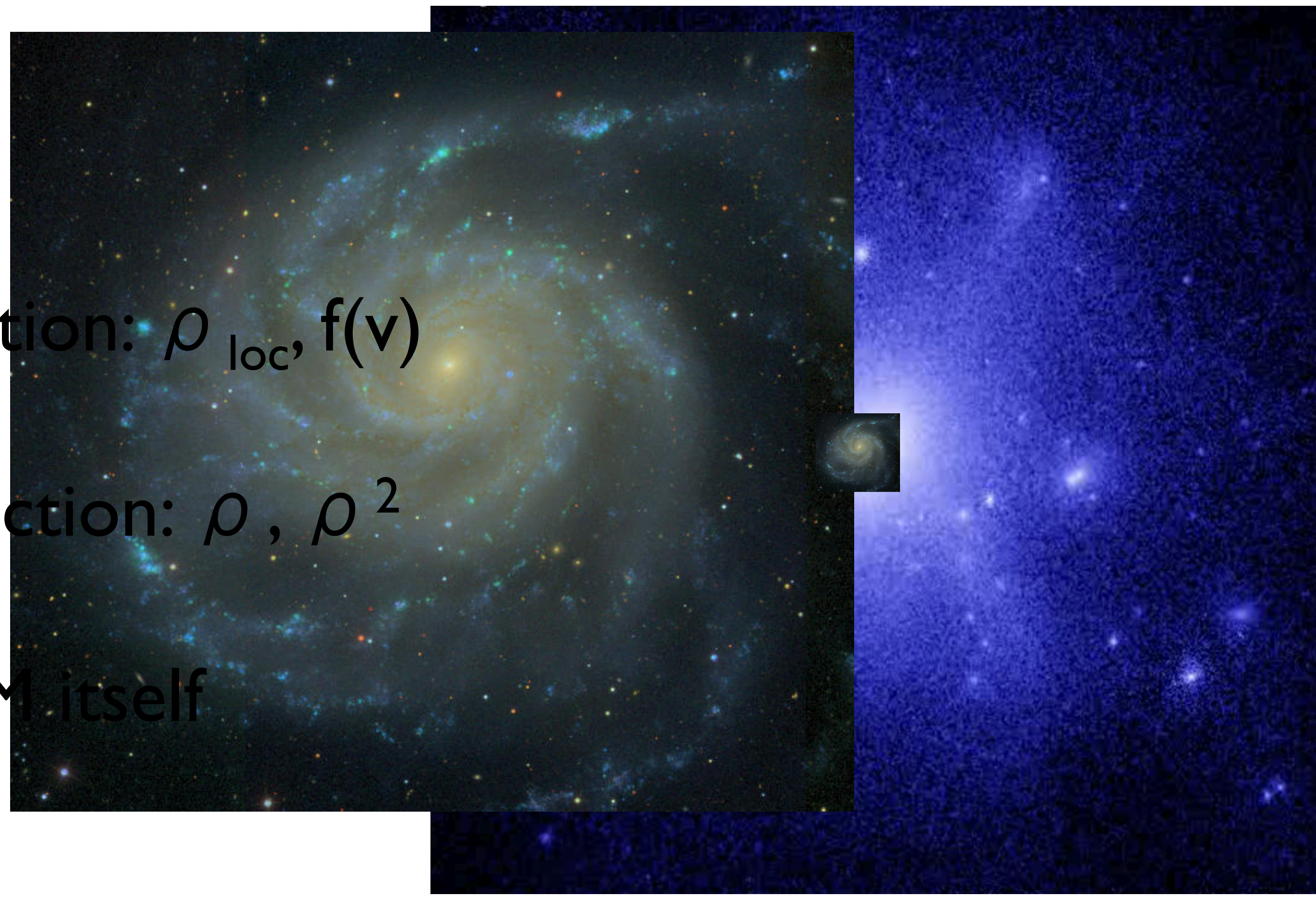
Dark Energy

- Constant in space and time
  $w_0 = P/\rho = -1$, $dw/dt = 0$
  (Lambda or Λ)

Dark Matter

- Negligible thermal velocities at decoupling (Cold)
- Interacts with ordinary matter only via gravitation (Dark)
- Negligible cross section for scattering (Collisionless)

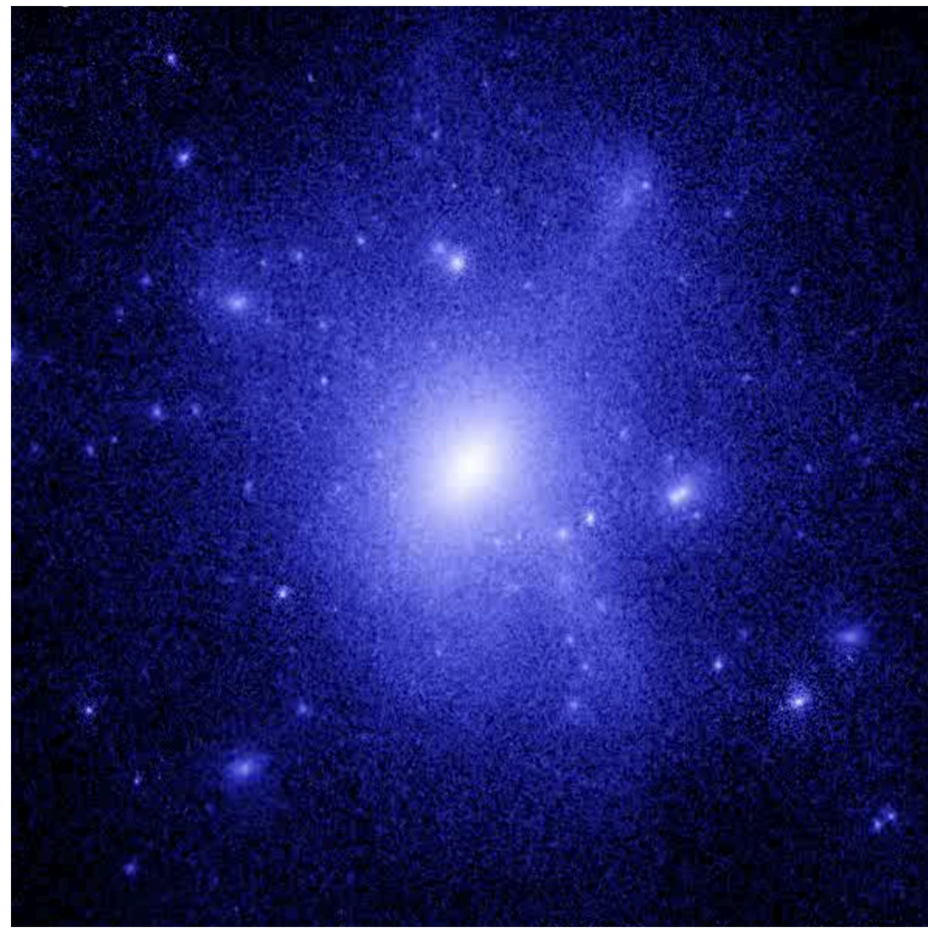
How is Dark Matter distributed around galaxies?



- Direct detection: ρ_{loc}, f(v)
- Indirect detection: ρ , ρ^2
- Test for CDM itself

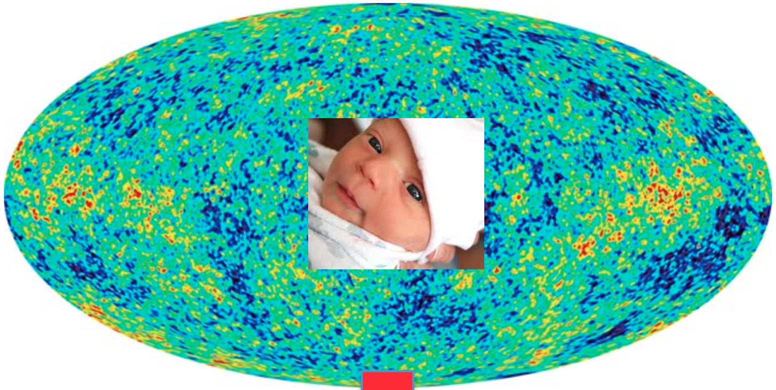
Theory predictions

All predictions come from Cosmological Numerical Simulations. No a priori model for DM distribution in collapsed objects.



Why cosmological numerical simulations?

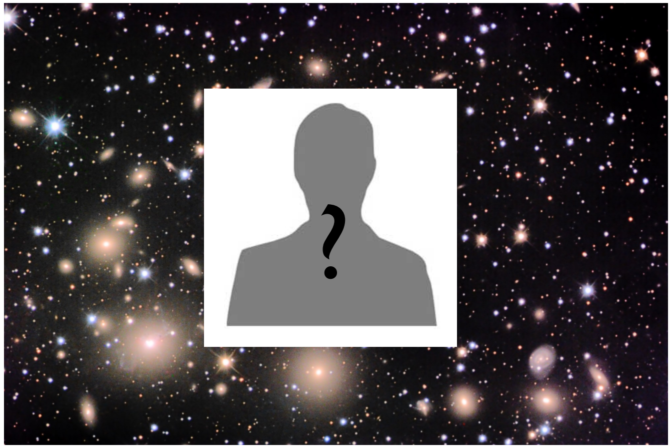
Why cosmological simulations?



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

$$t = 400{,}000 \ yrs$$

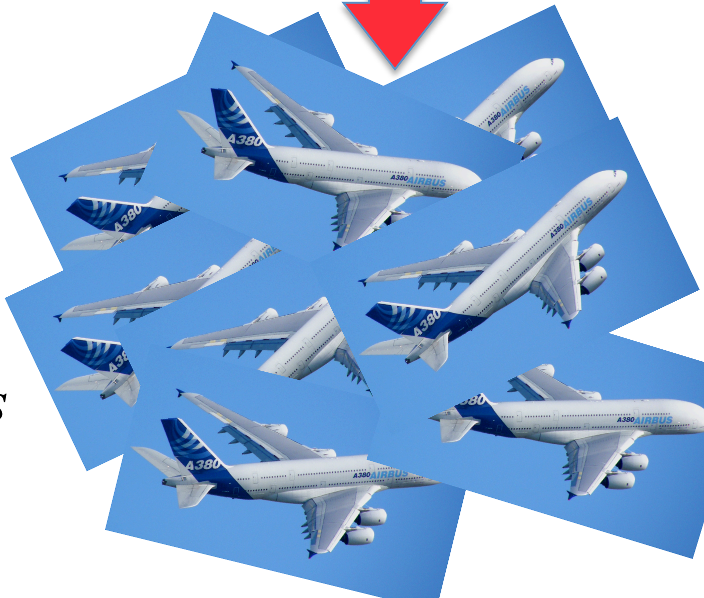
1 day



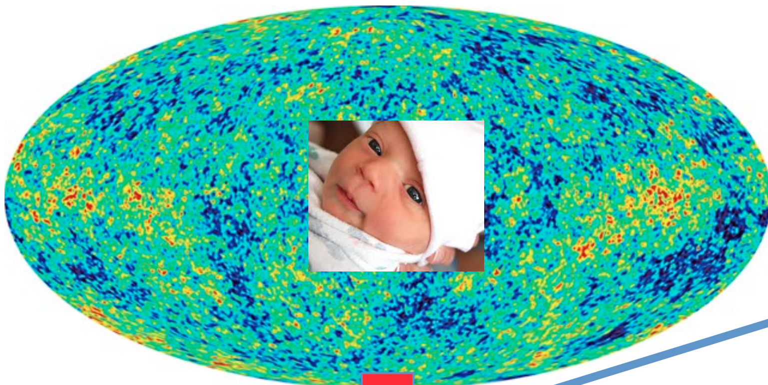
$$\frac{\partial \rho}{\rho} \approx 10^{6}$$

$$t = 13.7 \ 10^{9} \ yrs$$

80 years



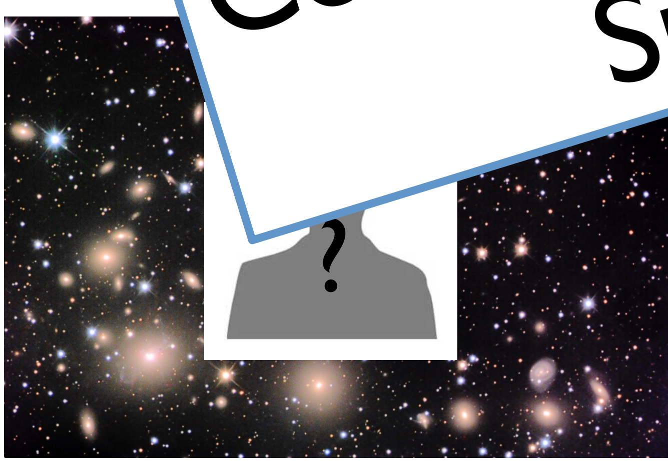
Why cosmological simulations?



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

$t =$

Cosmological Numerical Simulations

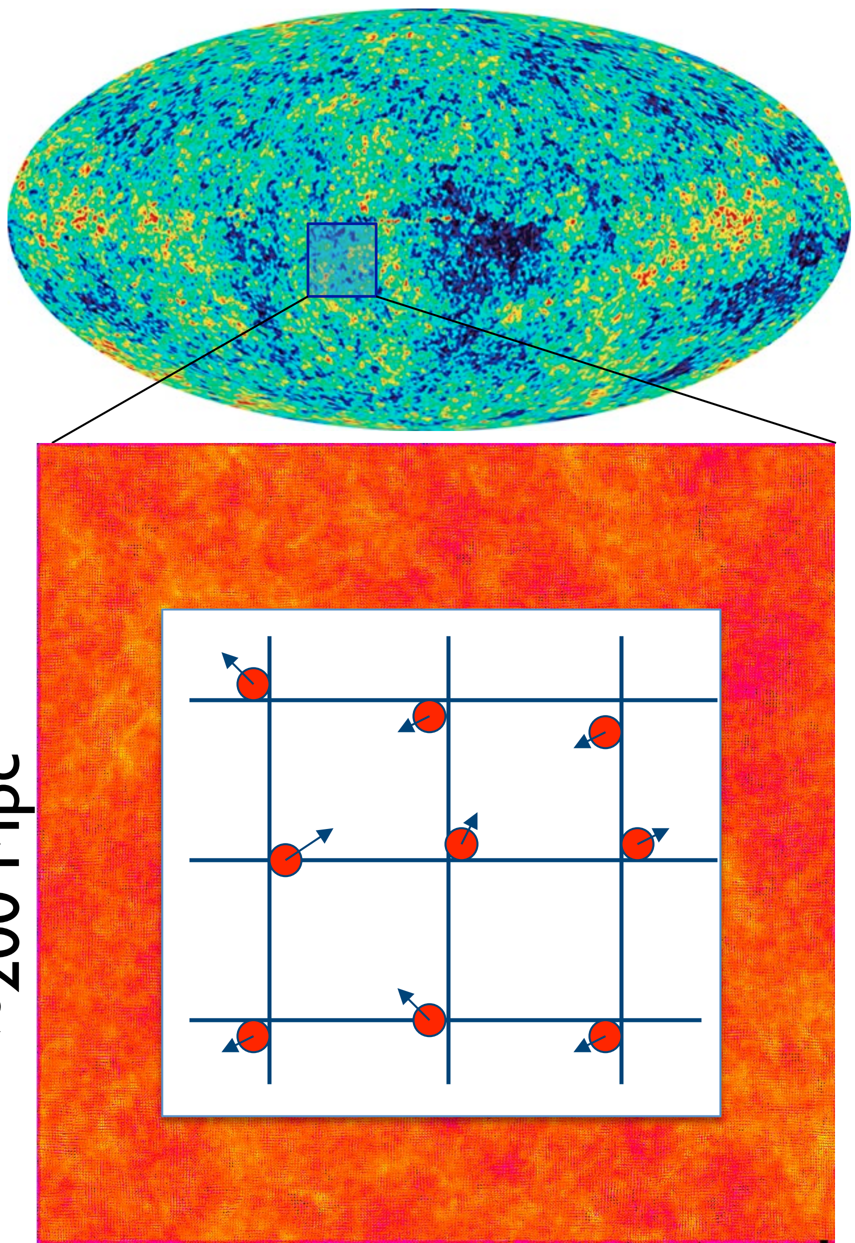


$$\frac{\partial \rho}{\rho} \approx 10^{6}$$

$$t = 13.7\ 10^{9}\ yrs$$

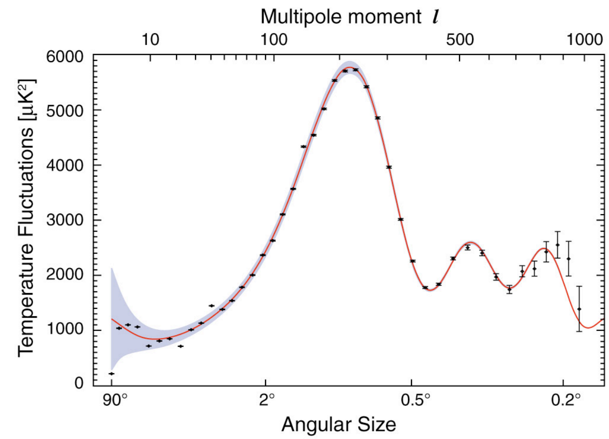
80 years

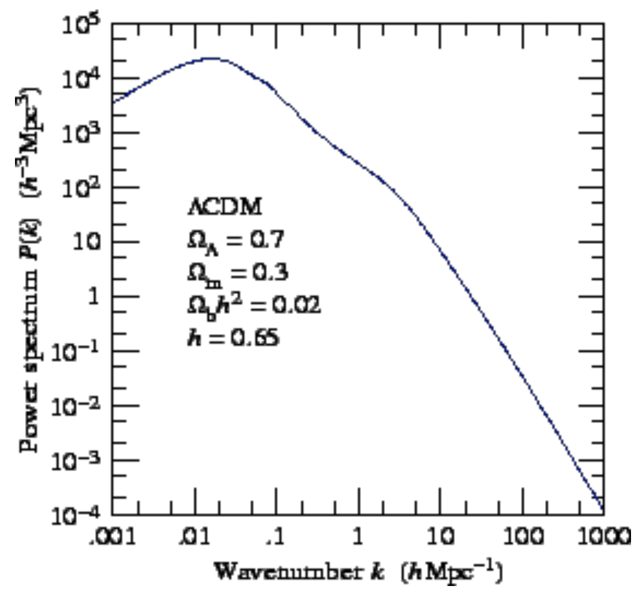
Initial Conditions



~200 Mpc

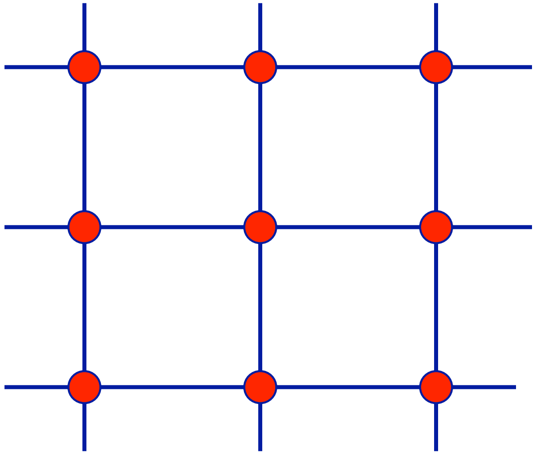
T ⟷ density





Particles in simulations

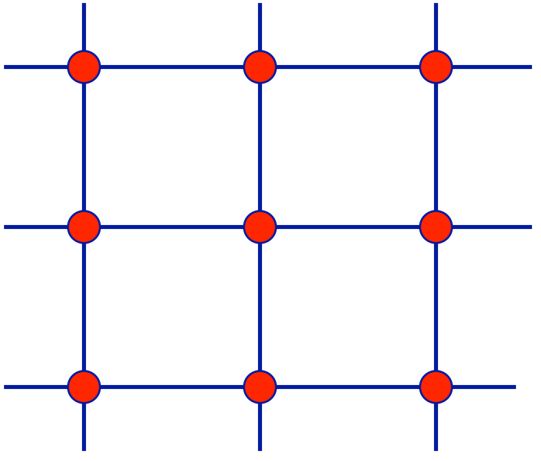
Modern computer can handle more than 10^9 particles/elements



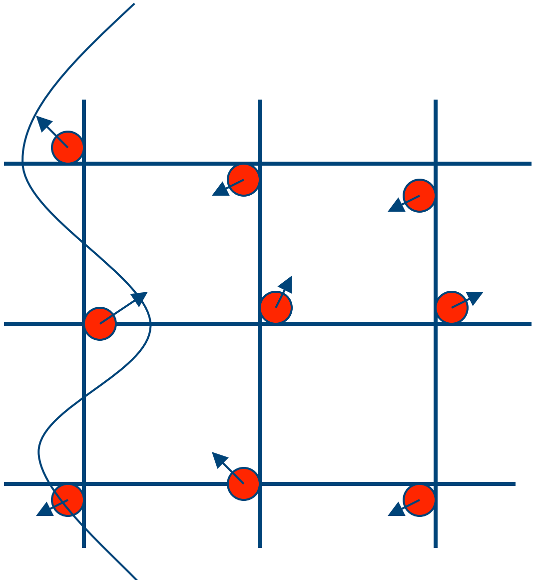
$$V = (200\mathrm{h}^{-1} Mpc)^3$$

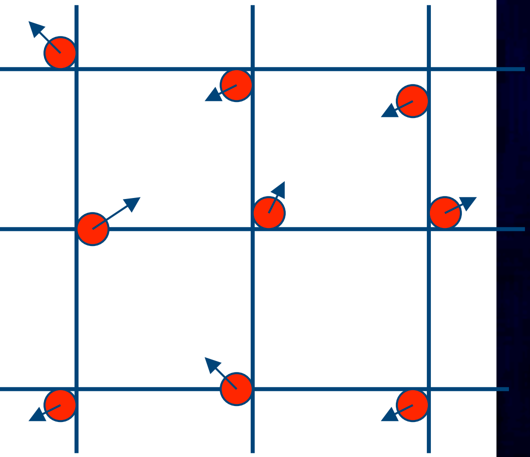
$$\mathrm{m_p} = \frac{V}{N_p} \times \rho_{cr} \times \Omega_m = 6.66 \times 10^8 M_{sun}$$

These particles have the same mass of a dwarf galaxy…

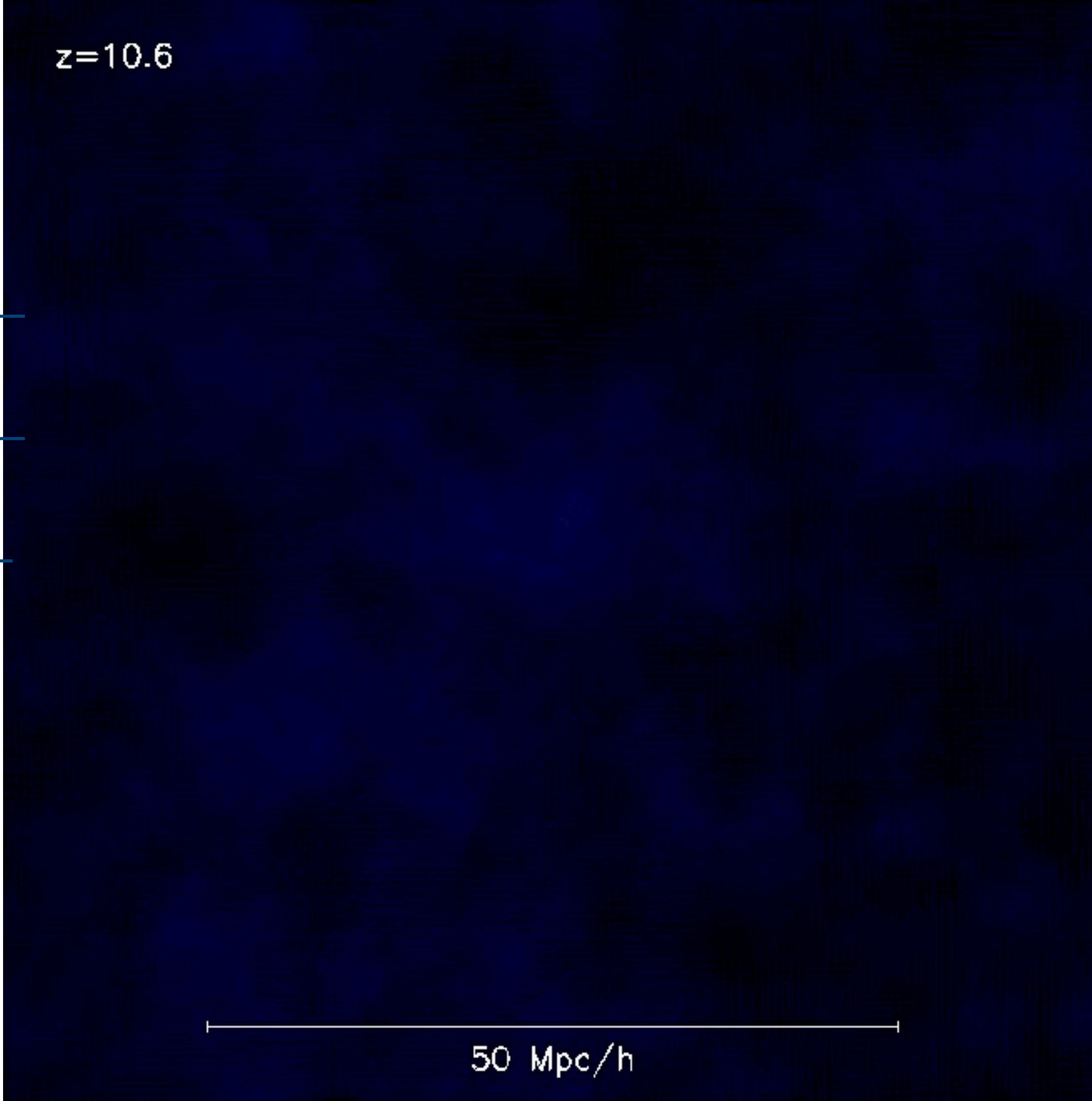


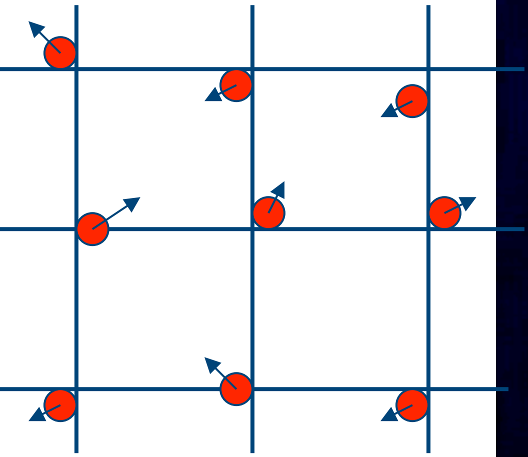
$+ P(k,z) =$





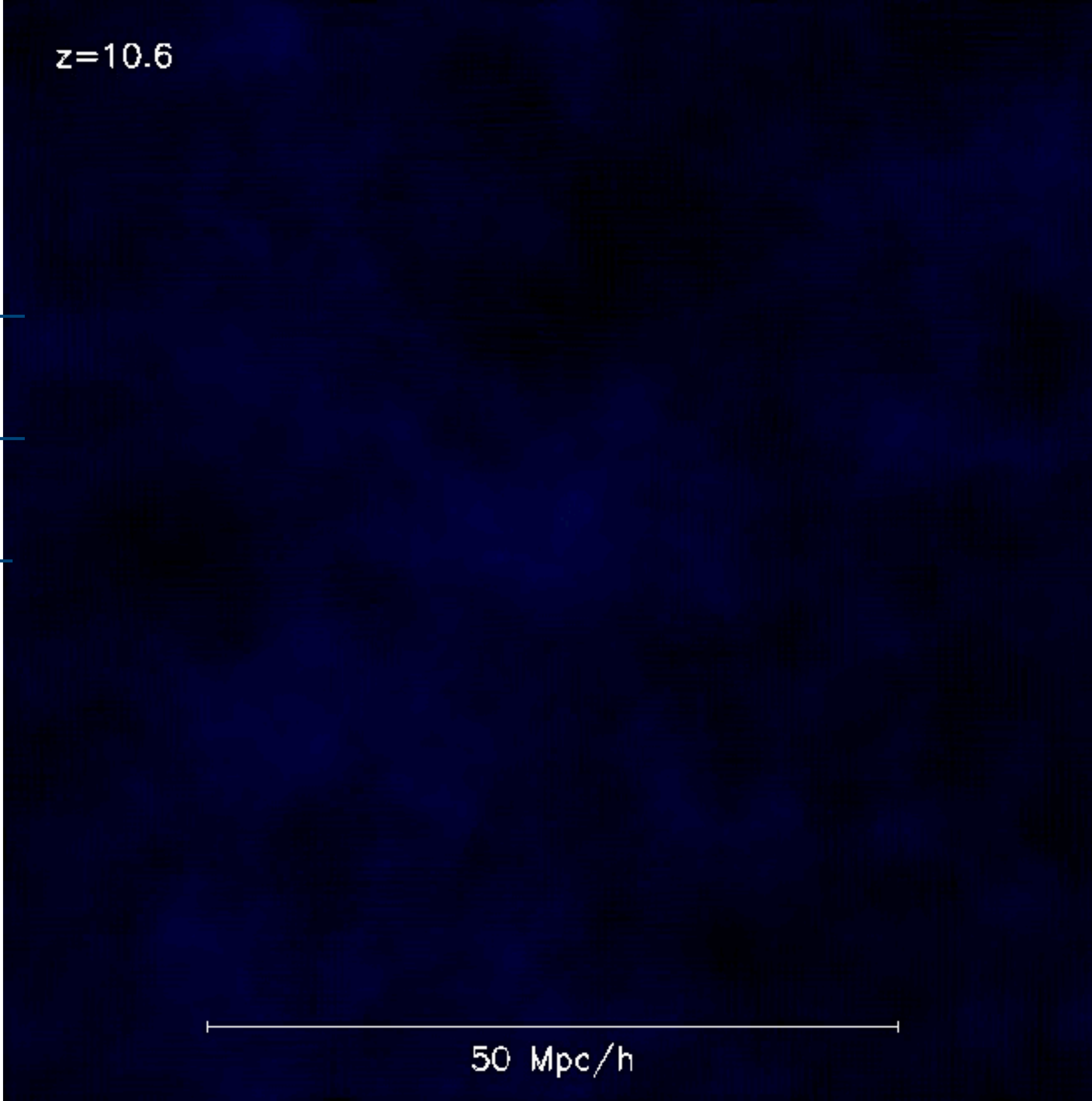
+
GRAVITY



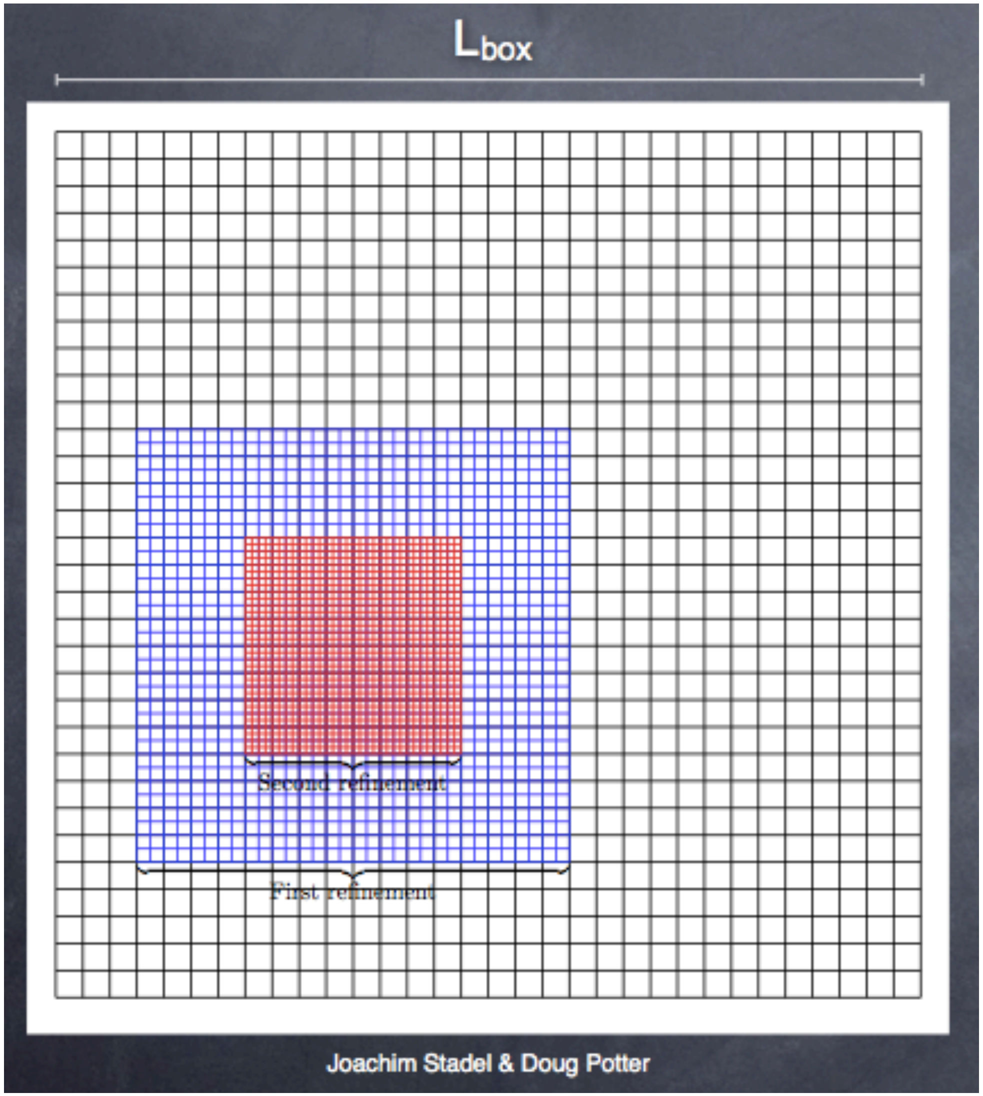


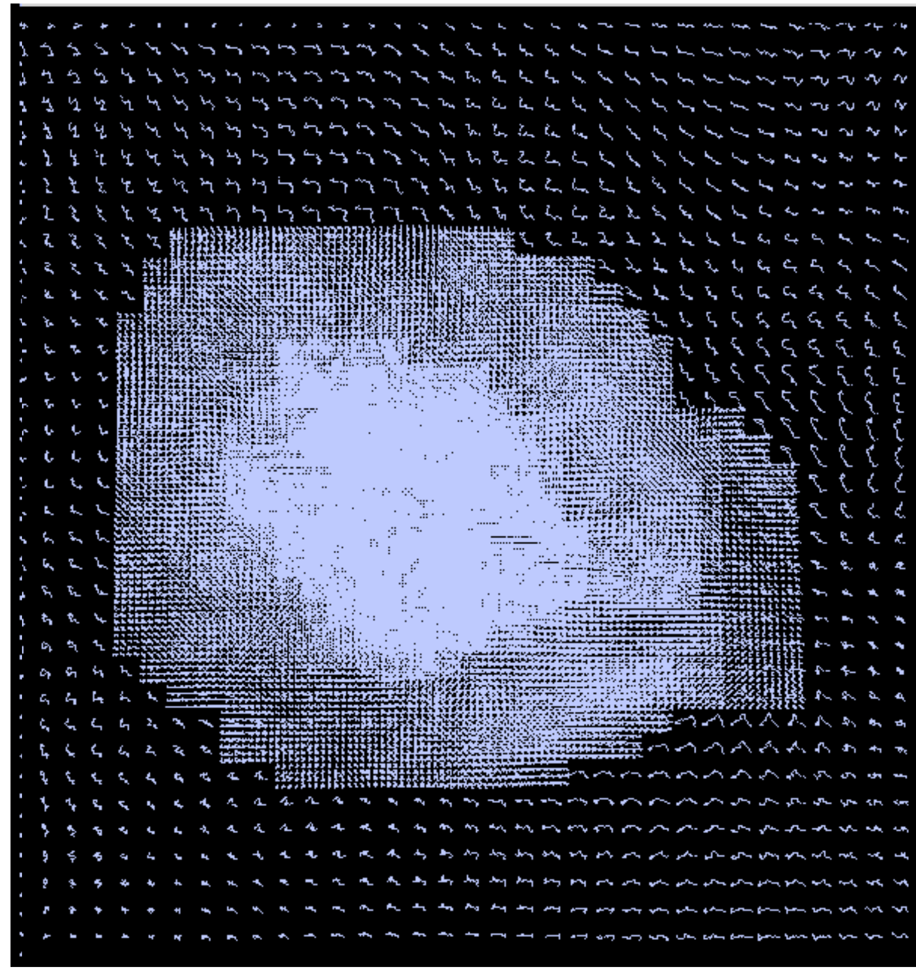
+

GRAVITY

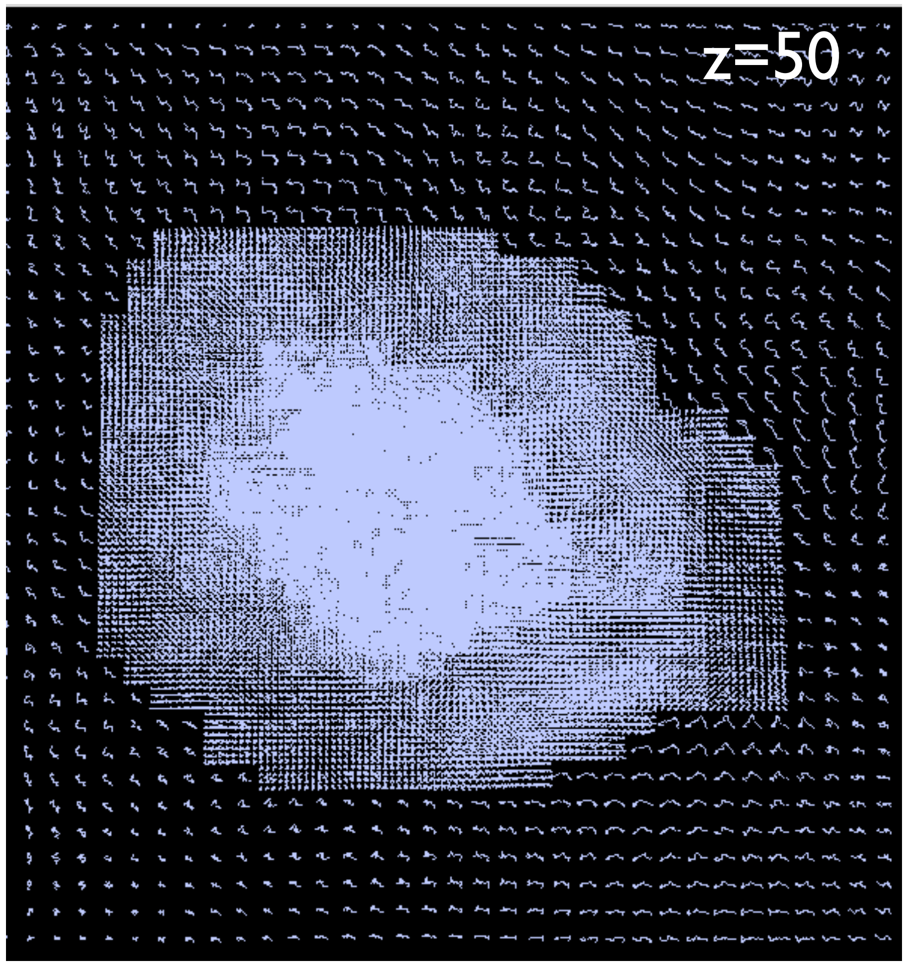


Zoom simulations





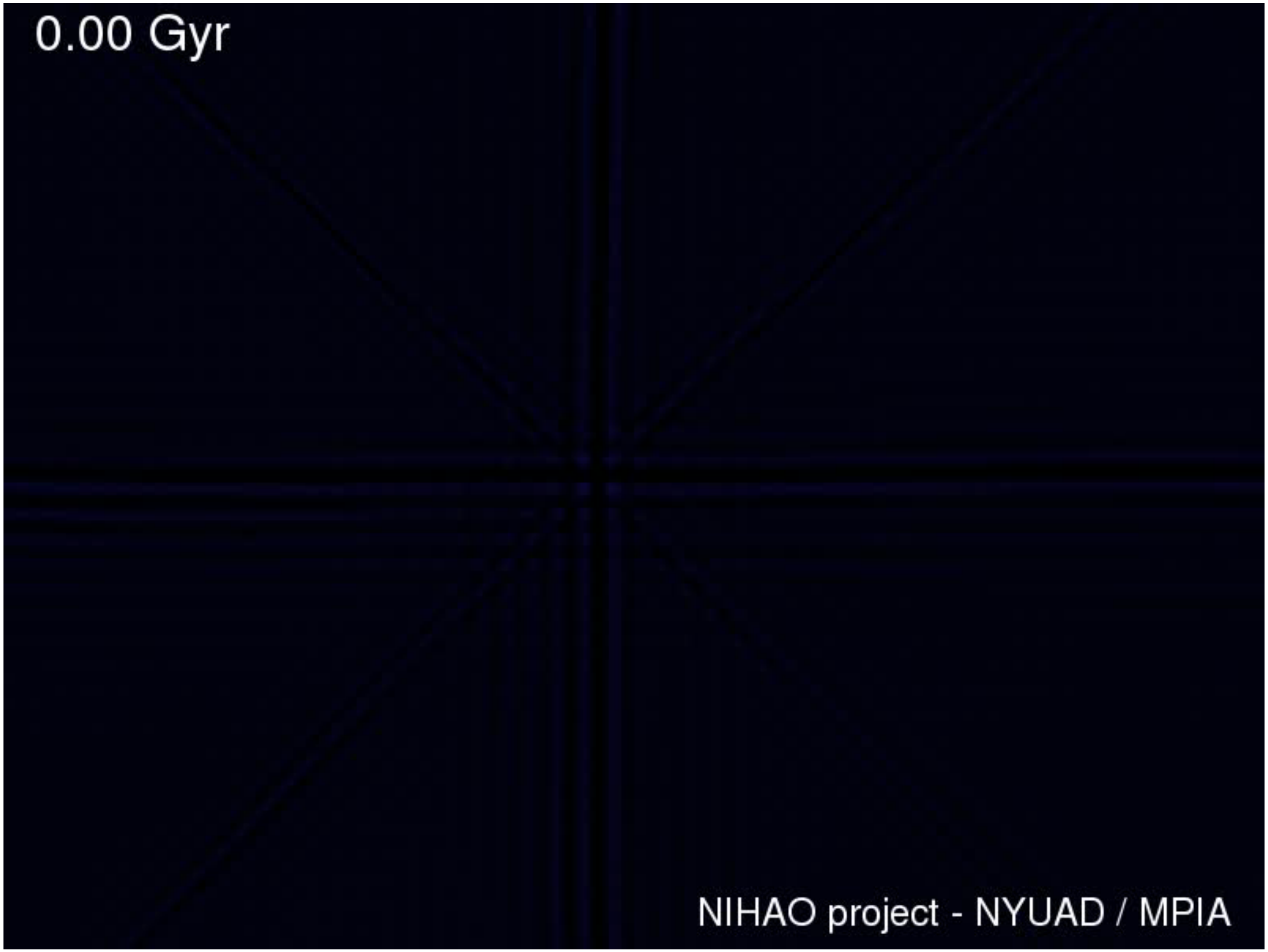
Increasing the resolution



$m_p=10^4$ Msun

400 kpc comoving

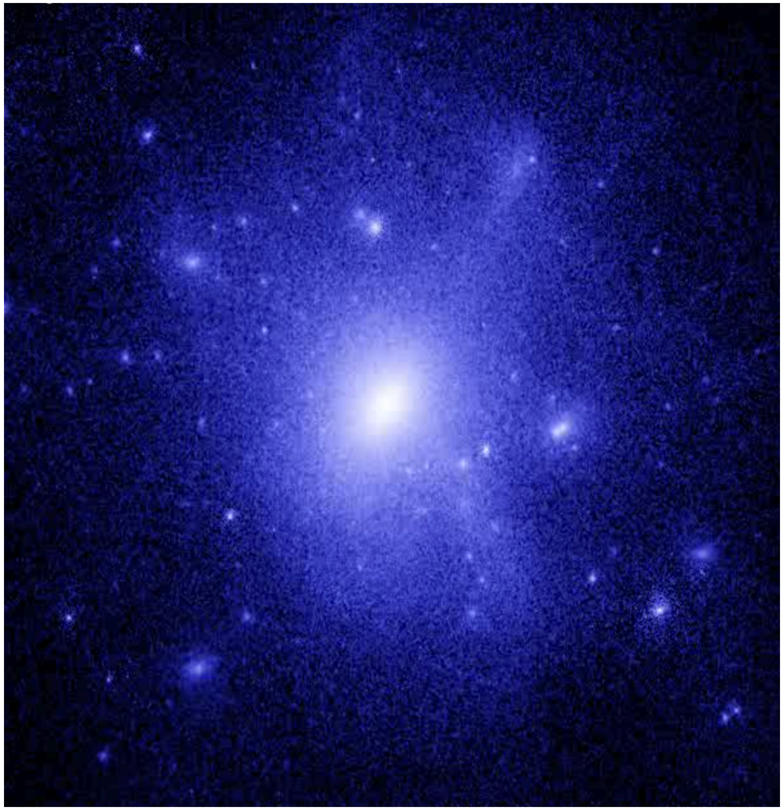
Increasing the resolution



$m_p = 10^6$ Msun

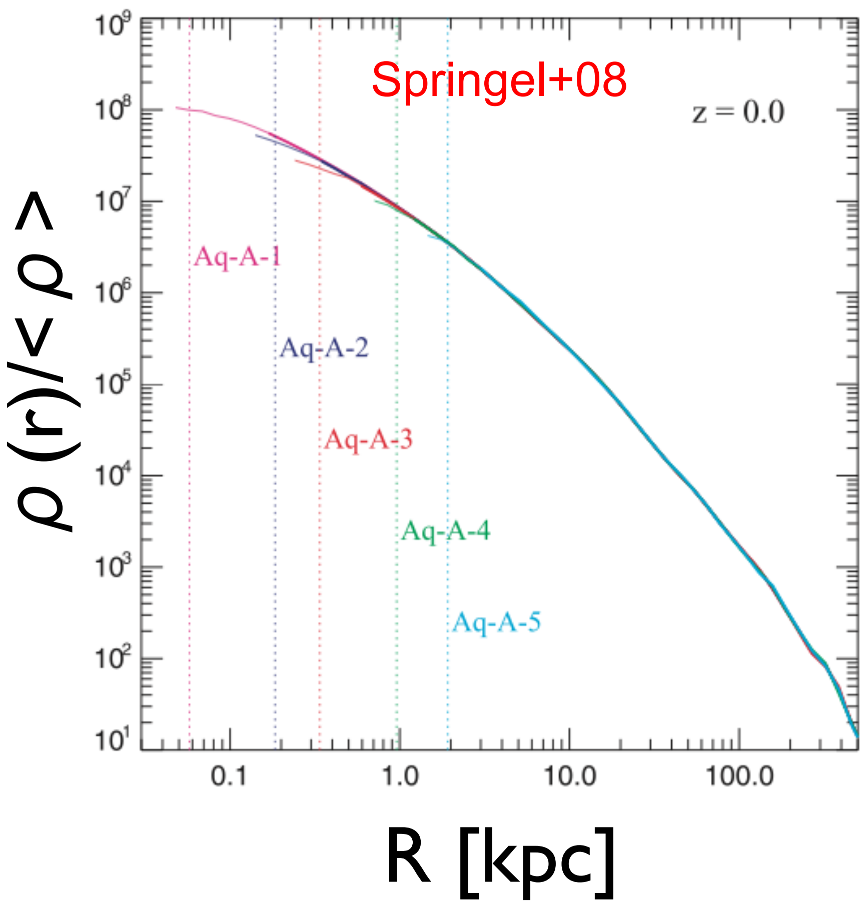
400 kpc comoving

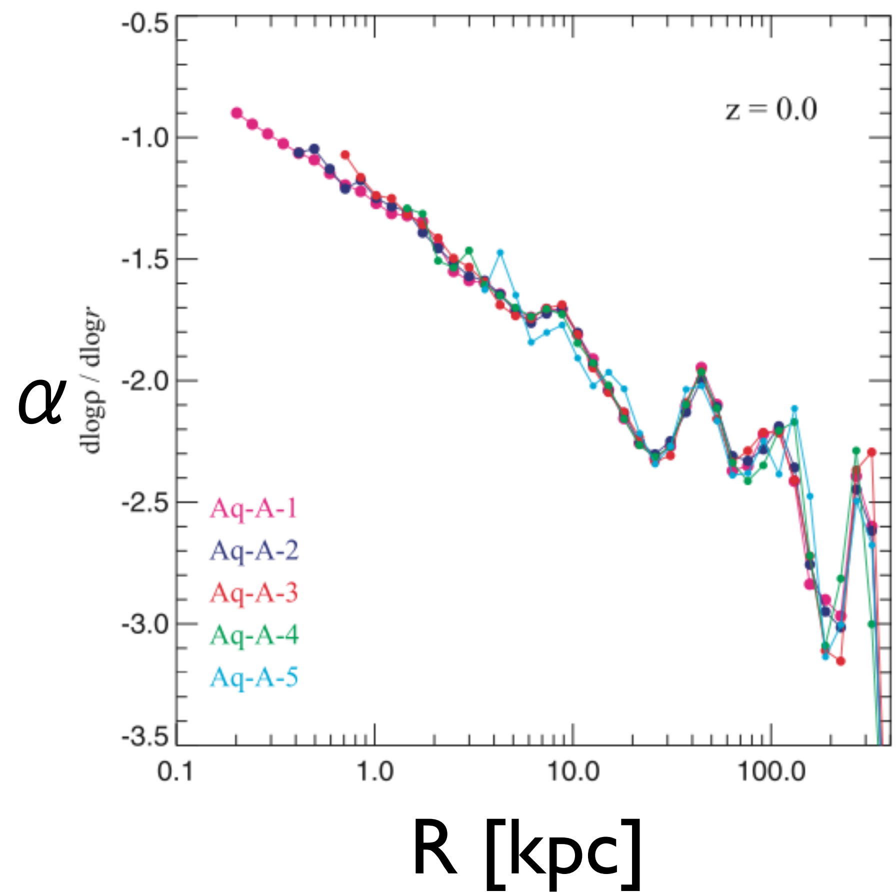
Results from pure gravity simulations



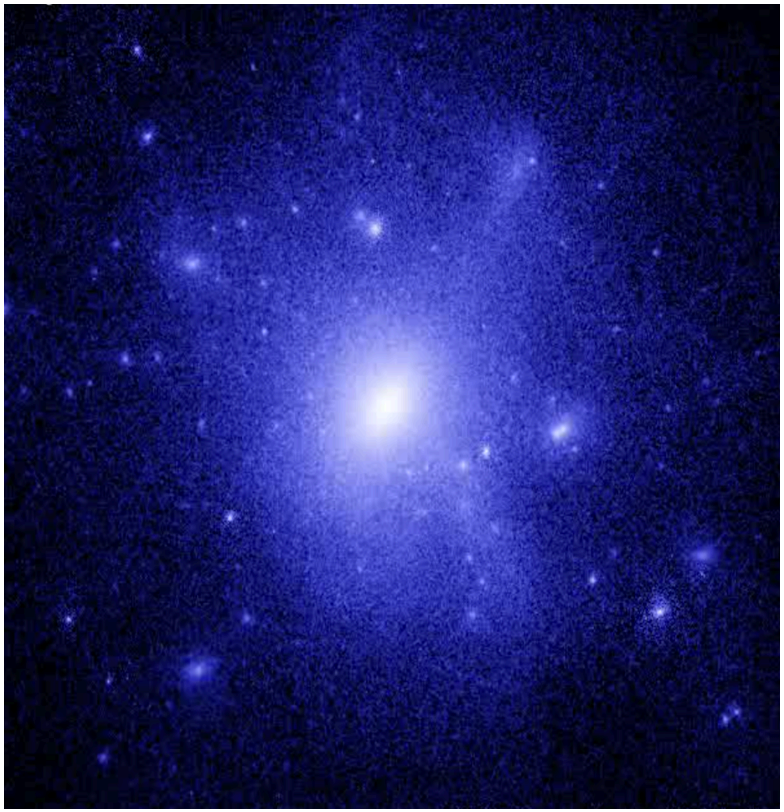
DM has a Universal Profile

DM universal profile





Results from pure gravity simulations



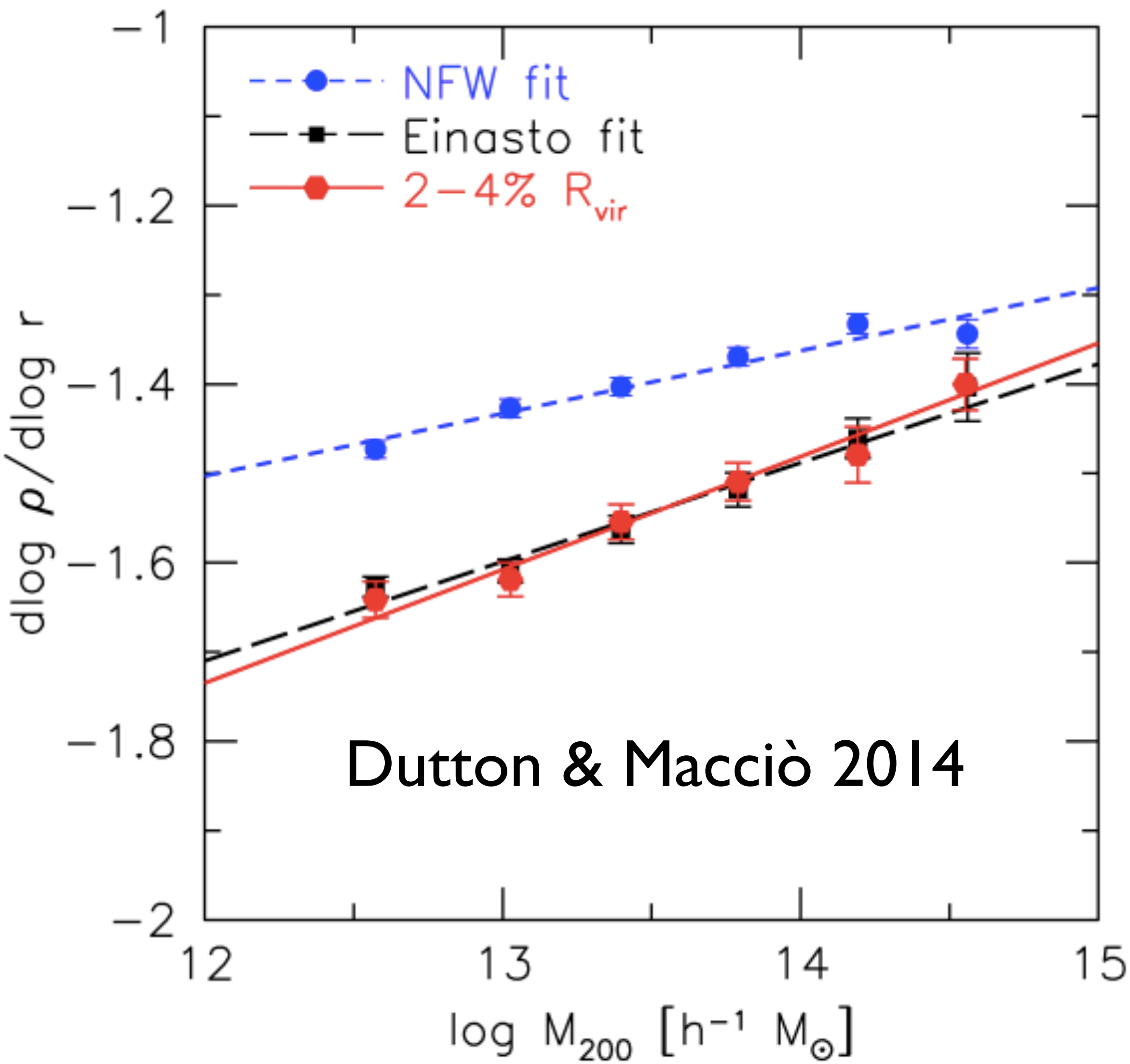
DM has a Universal Profile

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

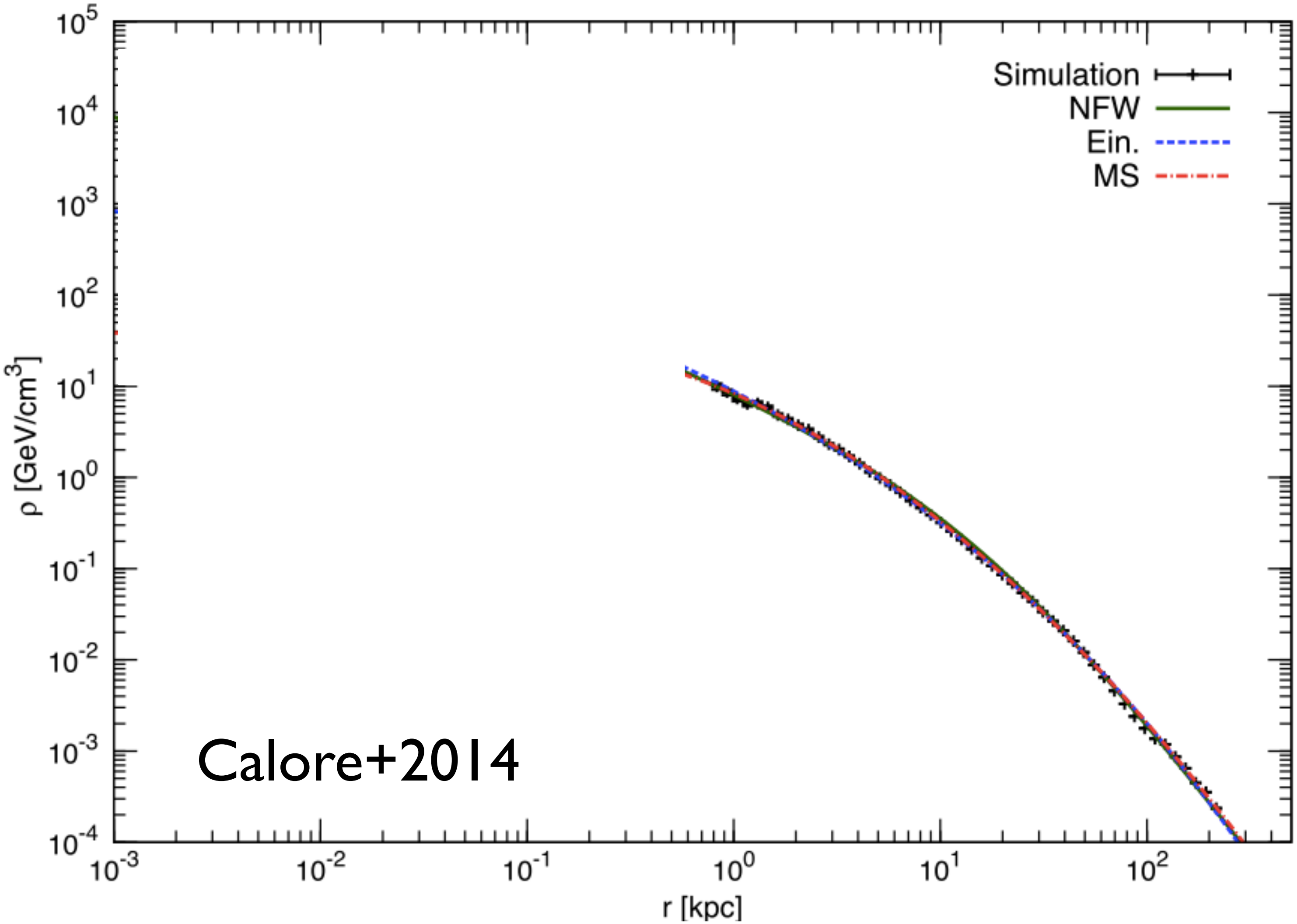
$$\frac{\rho_{\rm EIN}(r)}{\rho_{-2}} = \exp\left\{-\frac{2}{\alpha}\left[(r/r_{-2})^{\alpha}-1\right]\right\}$$

Einasto vs. NFW

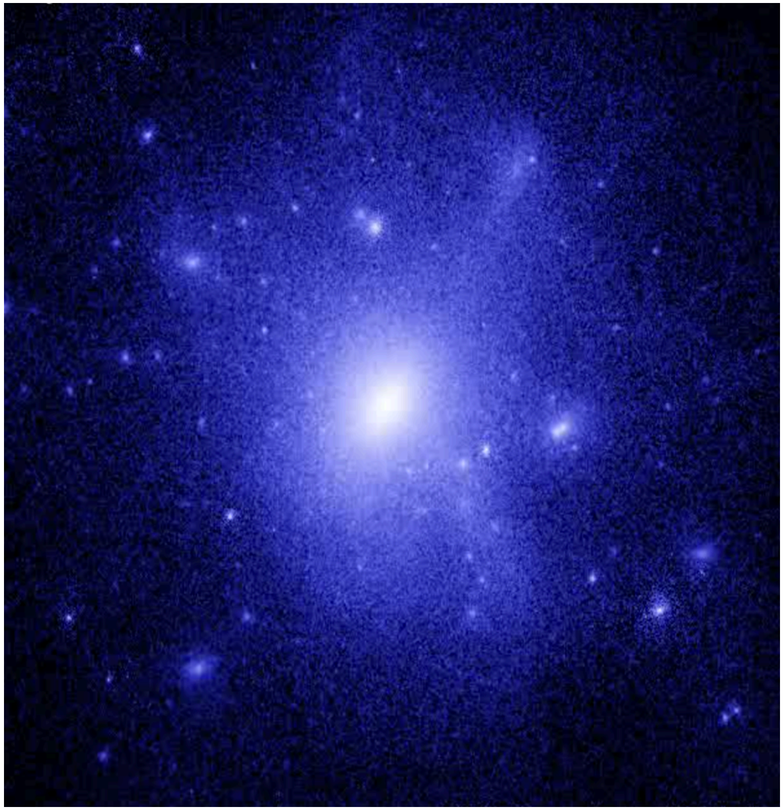
$\boxed{\alpha}$



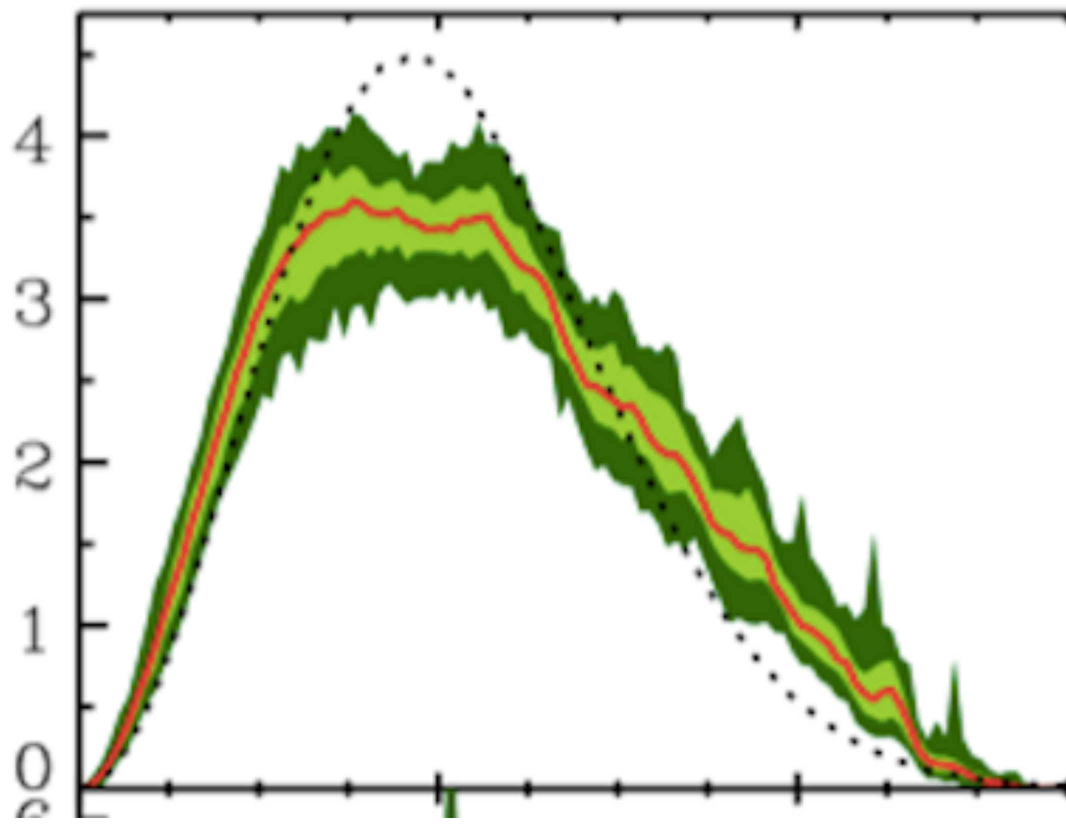
Why should you care?



Results from pure gravity simulations



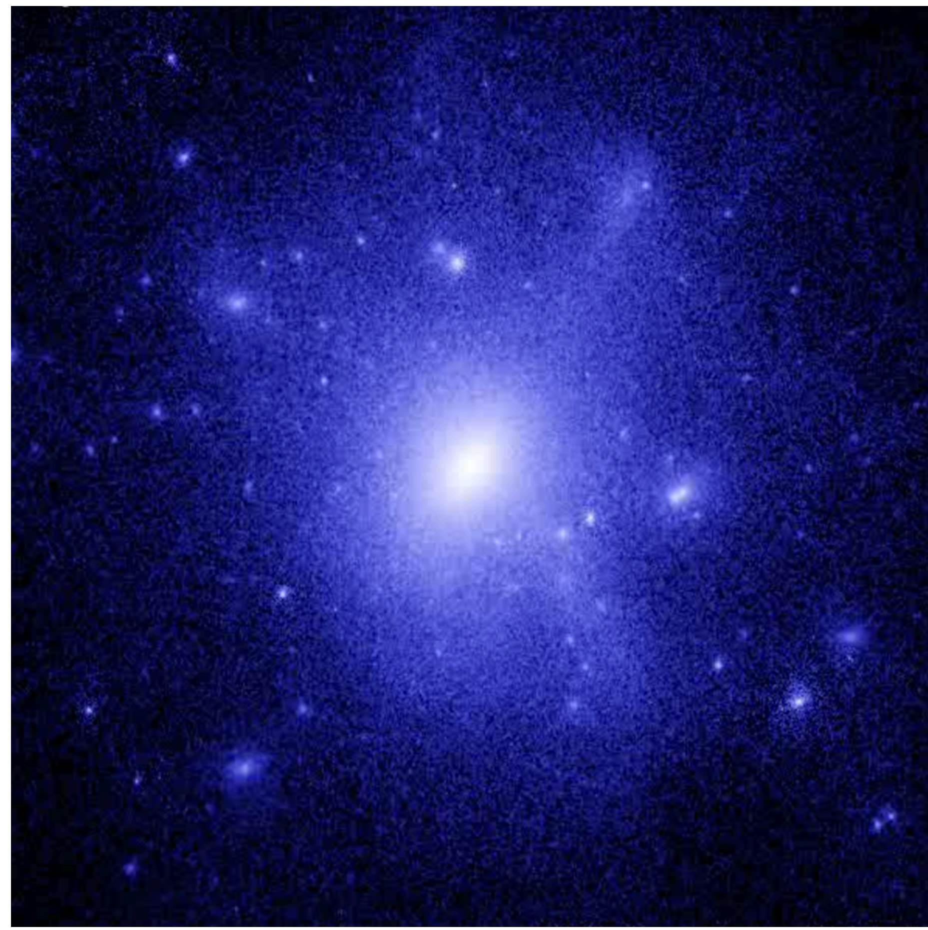
DM has a Universal Profile



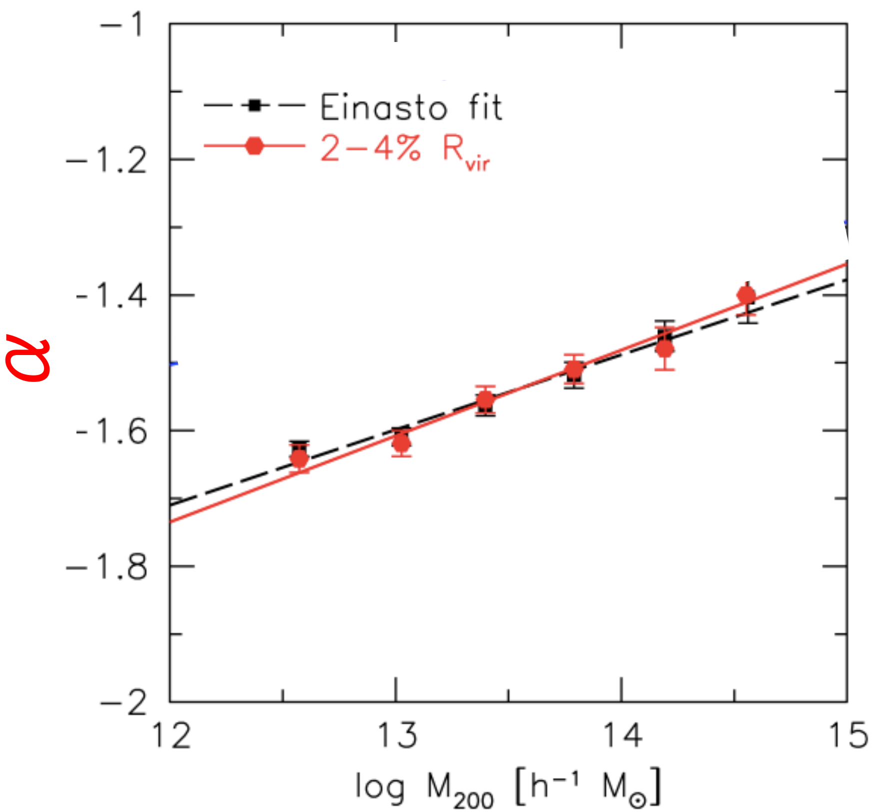
DM velocity distribution is Maxwellian, with a possible excess at high vel. (Kuhlen+10)

How is Dark Matter distributed around galaxies?

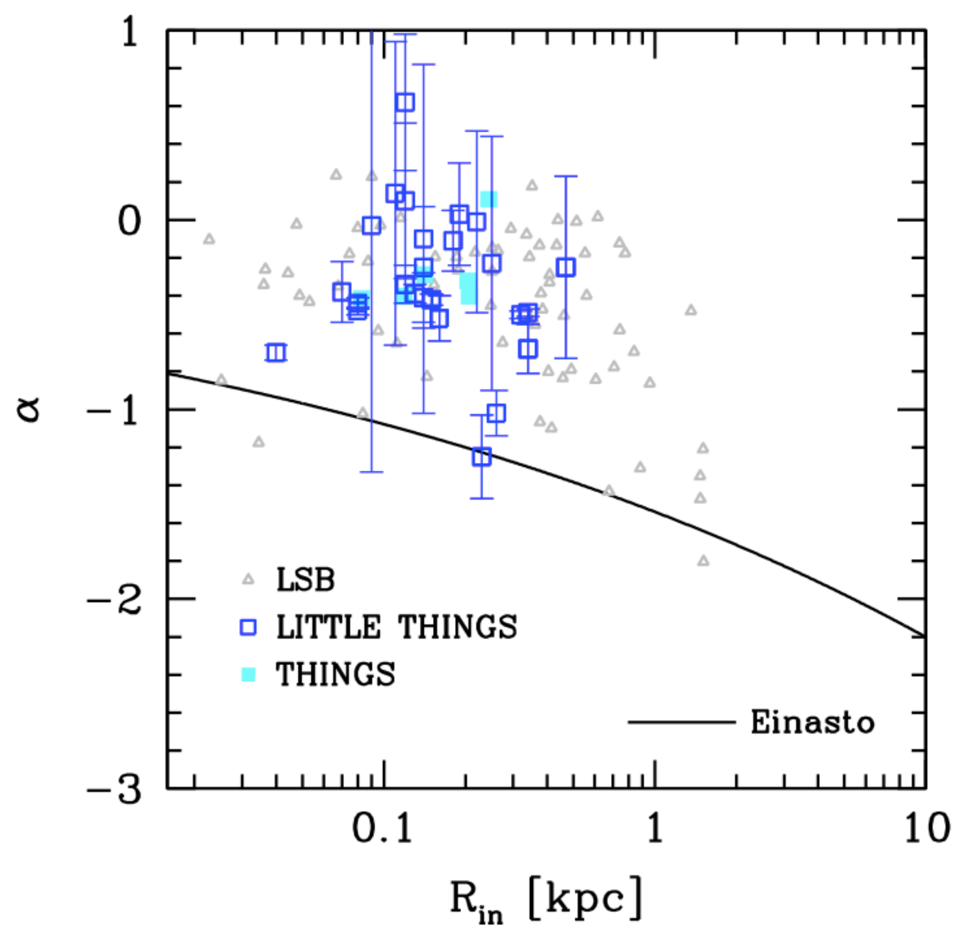
- Direct detection: ρ , f(v)
- Indirect detection: ρ , ρ^2
- Test for CDM itself



Theoretical vs. observed profiles



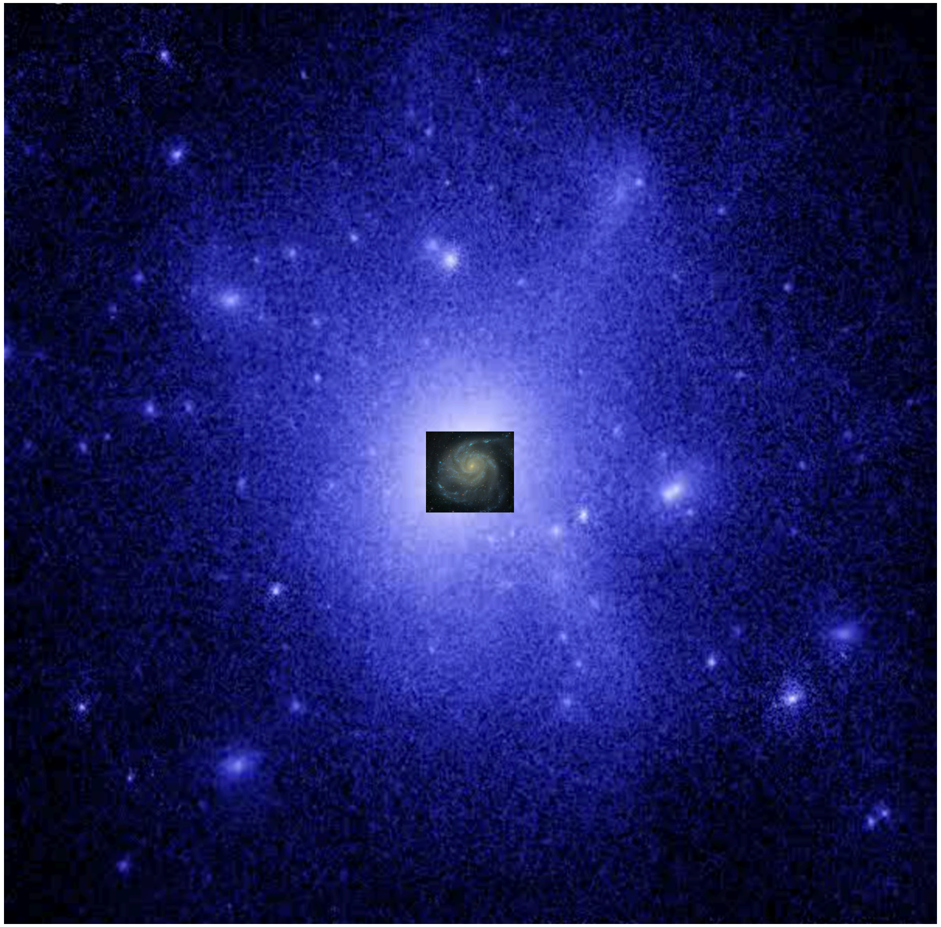
Dutton & Macciò 2014



Tollet, Macciò+2015
data from Oh+2015

Is this the end of the story?
Is CDM dead?

We were lying to you!!!

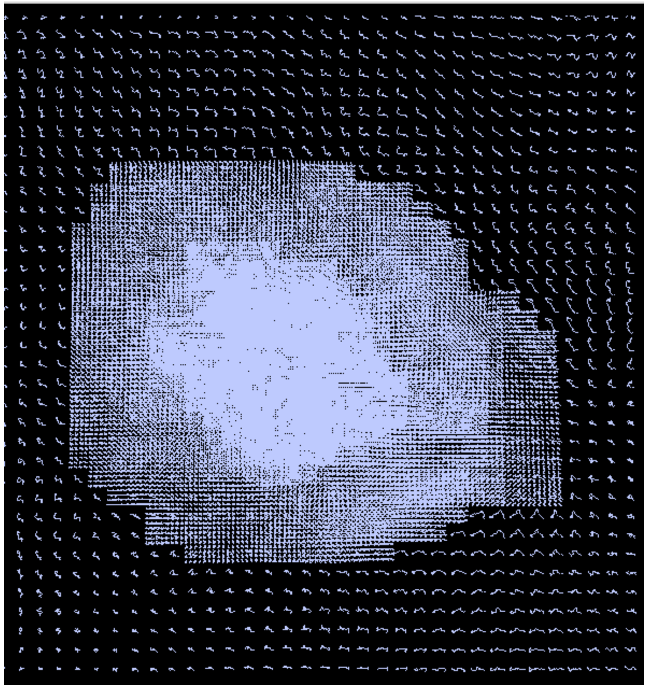


At solar radius more than 50% of the mass is in stars

We canNOT neglect baryons!

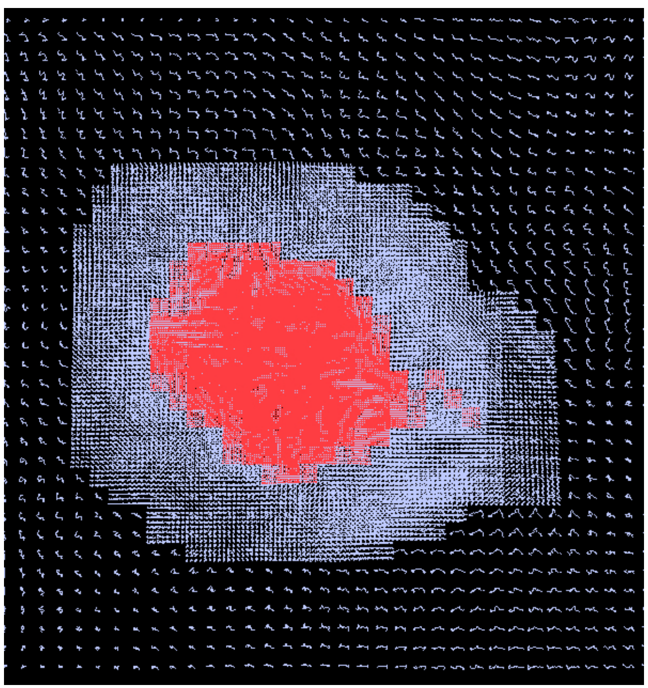
A simple analogy

Adding baryons to the game



Pure Gravity (Nbody)

$$\nabla^2\Phi = 4\pi G a^2 \rho$$



Hydro-dynamical simulations

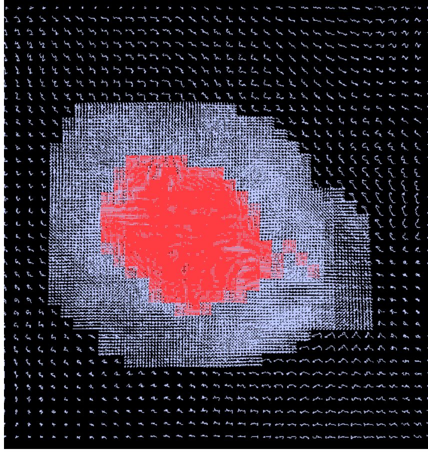
$$\nabla^2\Phi = 4\pi G a^2 \rho$$

$$\frac{\partial}{\partial t}(\rho u) + \frac{1}{a}\nabla(\rho u) = -(\rho u + P)\left(\frac{1}{a}\nabla\cdot v + 3\frac{\dot{a}}{a}\right)$$

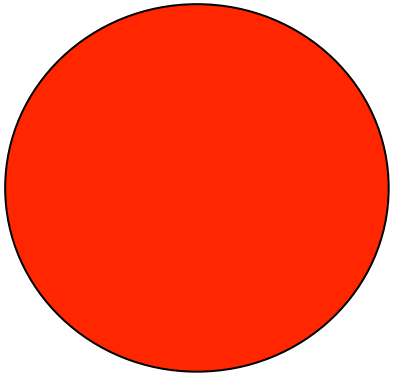
$$\boxed{\frac{du}{dt} = -\frac{P}{\rho}\nabla\cdot v - \frac{\Lambda(u,\rho)}{\rho}}$$

$$\frac{\partial\rho}{\partial t} + \frac{3\dot{a}}{a}\rho + \frac{1}{a}\nabla\cdot(\rho v) = 0$$

Star formation and feedback in a nut shell

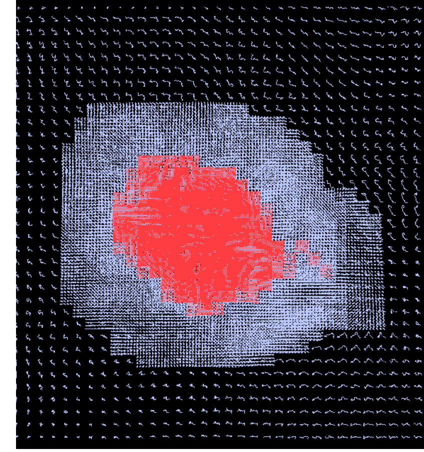


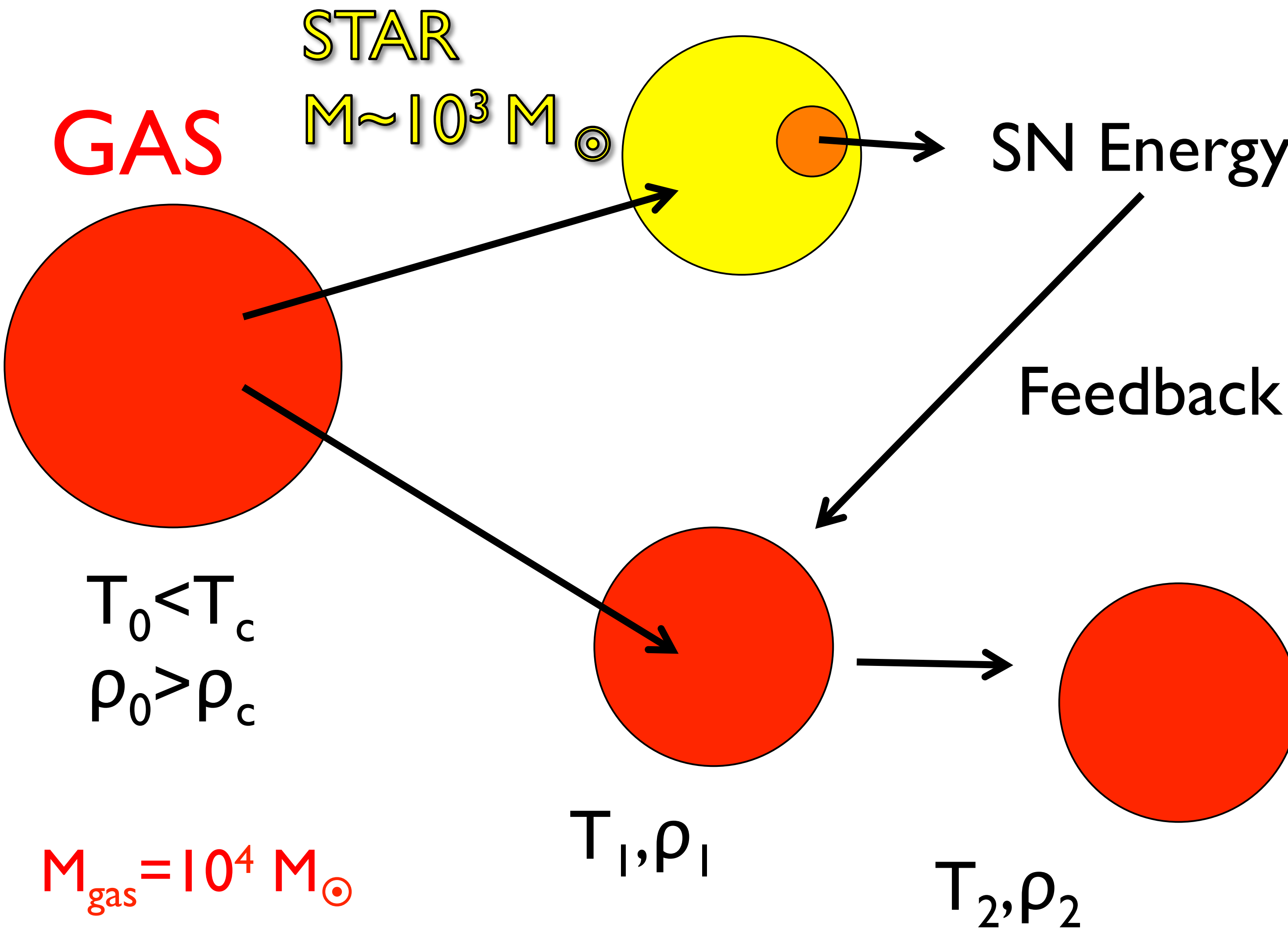
GAS



$M_{gas}=10^4\ M_{\odot}$

Star formation and feedback in a nut shell

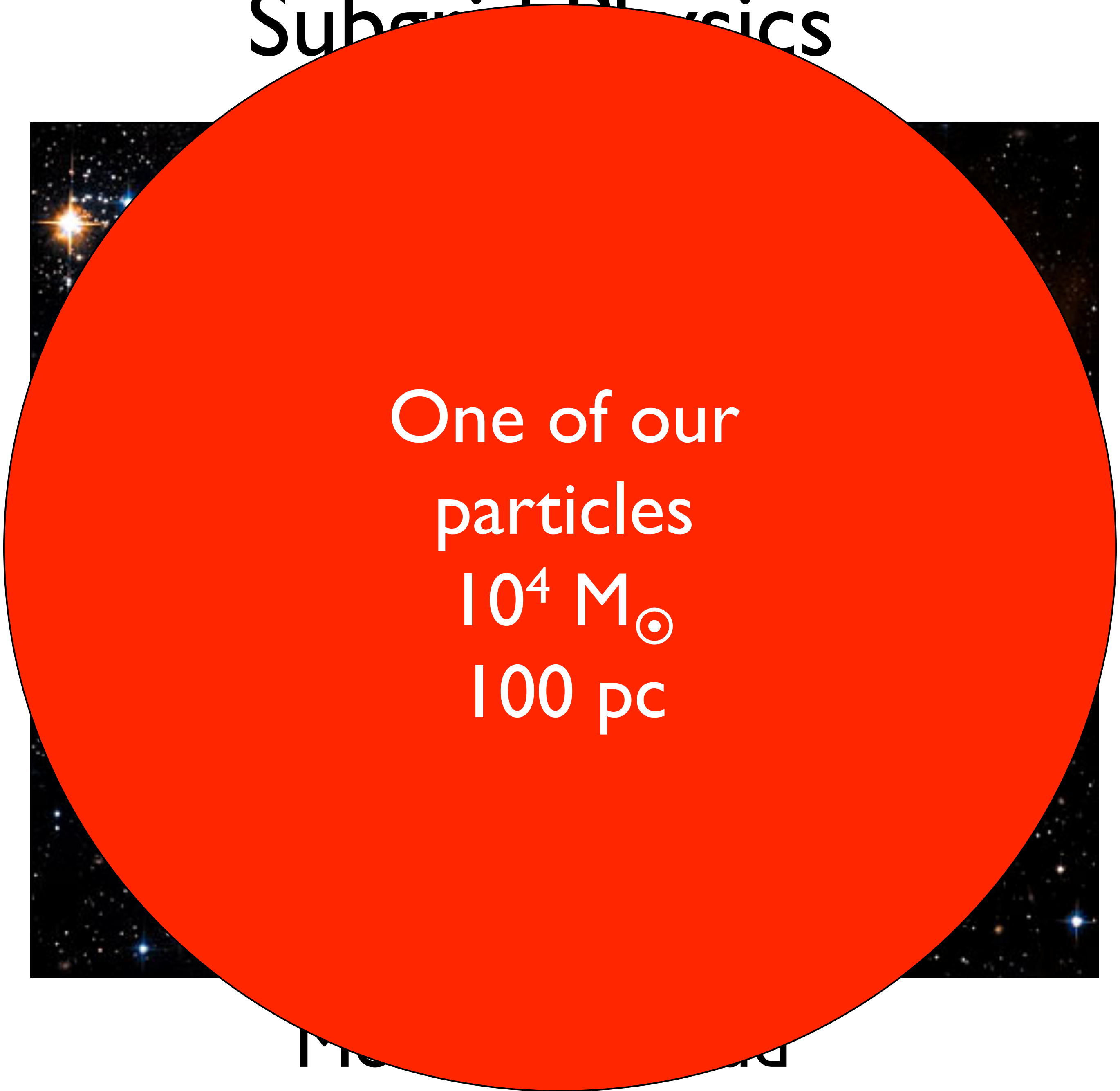


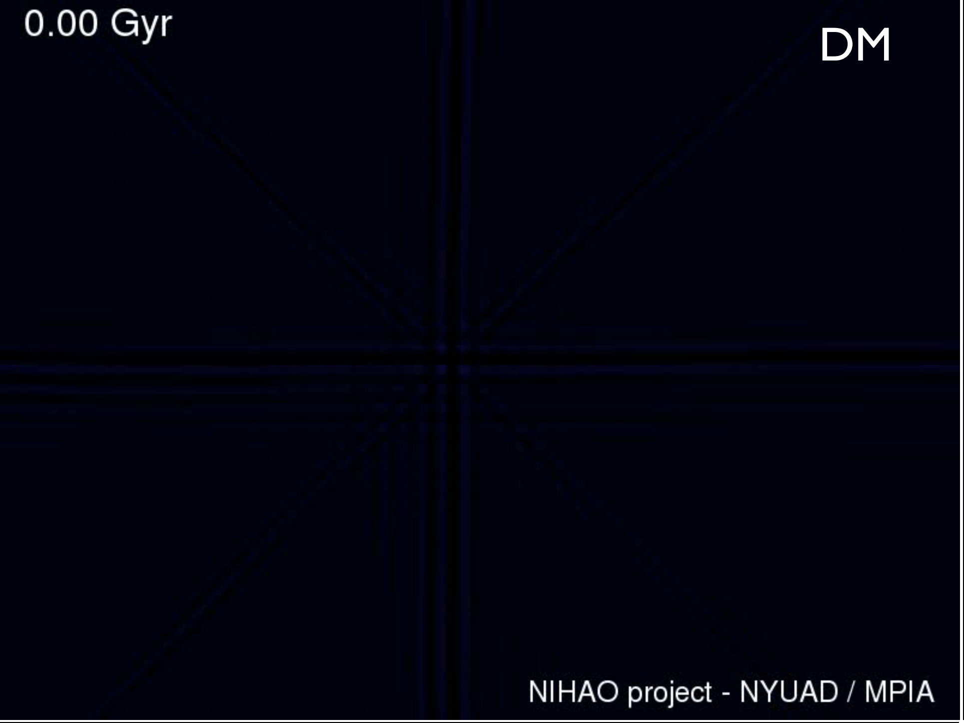


We cannot simulate galaxy formation from first principles

Subgrid Physics

~100 pc





Milky Way like galaxy
200 kpc side
NIHAO project

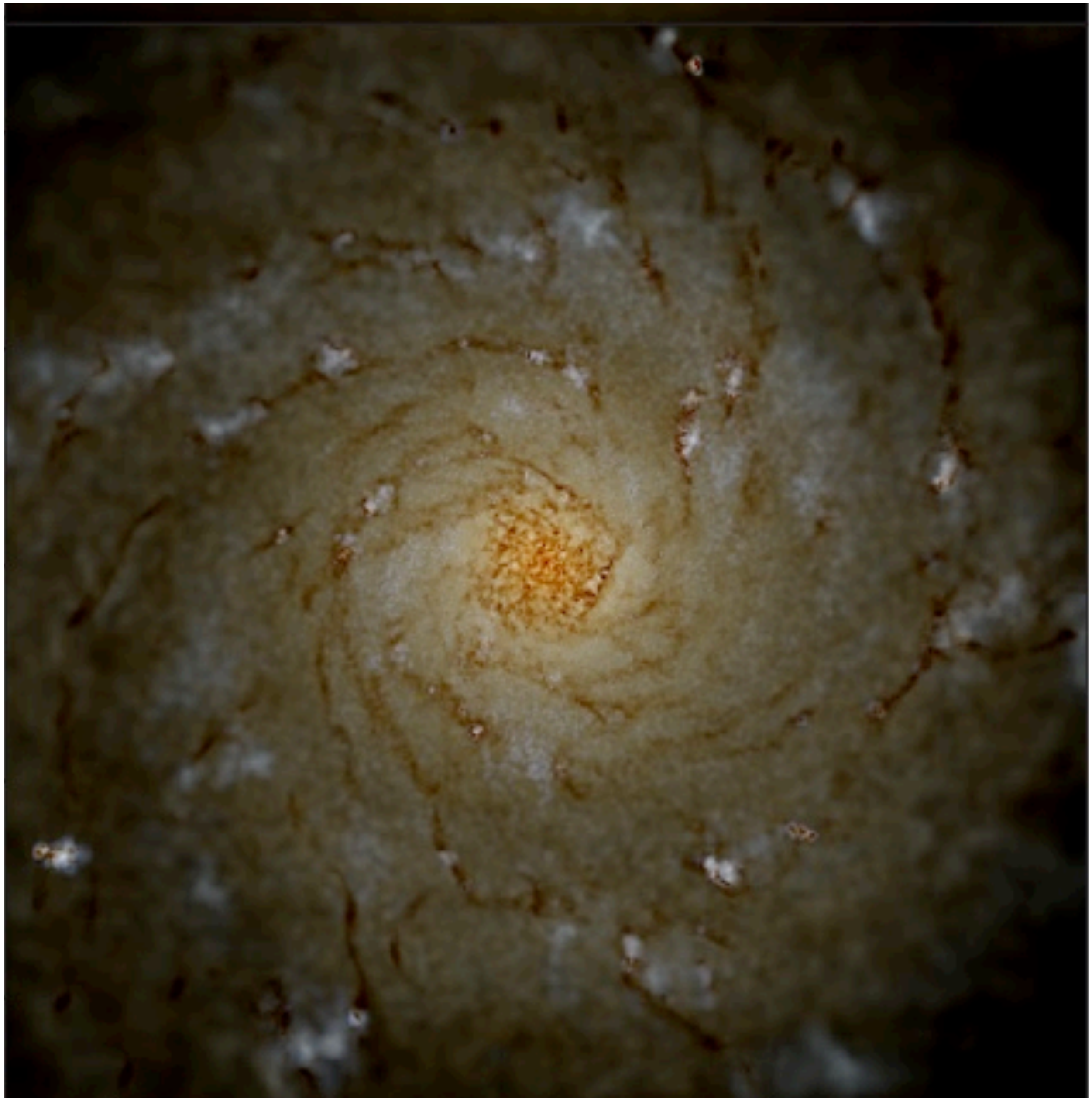
Gasoline 2

- Smoothed Particle Hydrodynamics (SPH) (Wadsley+06)
- New low temperature and Metal Cooling (Shen+ 2010)
- UV heating (Haardt & Madau 2011)
- Metal Diffusion (Wadsley+ 2010)
- Star Formation and SN feedback (Stinson+ 2006)
- *Chabrier IMF & Early Stellar feedback (Stinson, Brook, AM+ 2013)*
- *Dynamical Dark Energy and WDM (Penzo, AM+2014)*
- *New SPH implementation (Keller+14, Stinson+2015)*

Gasoline 2

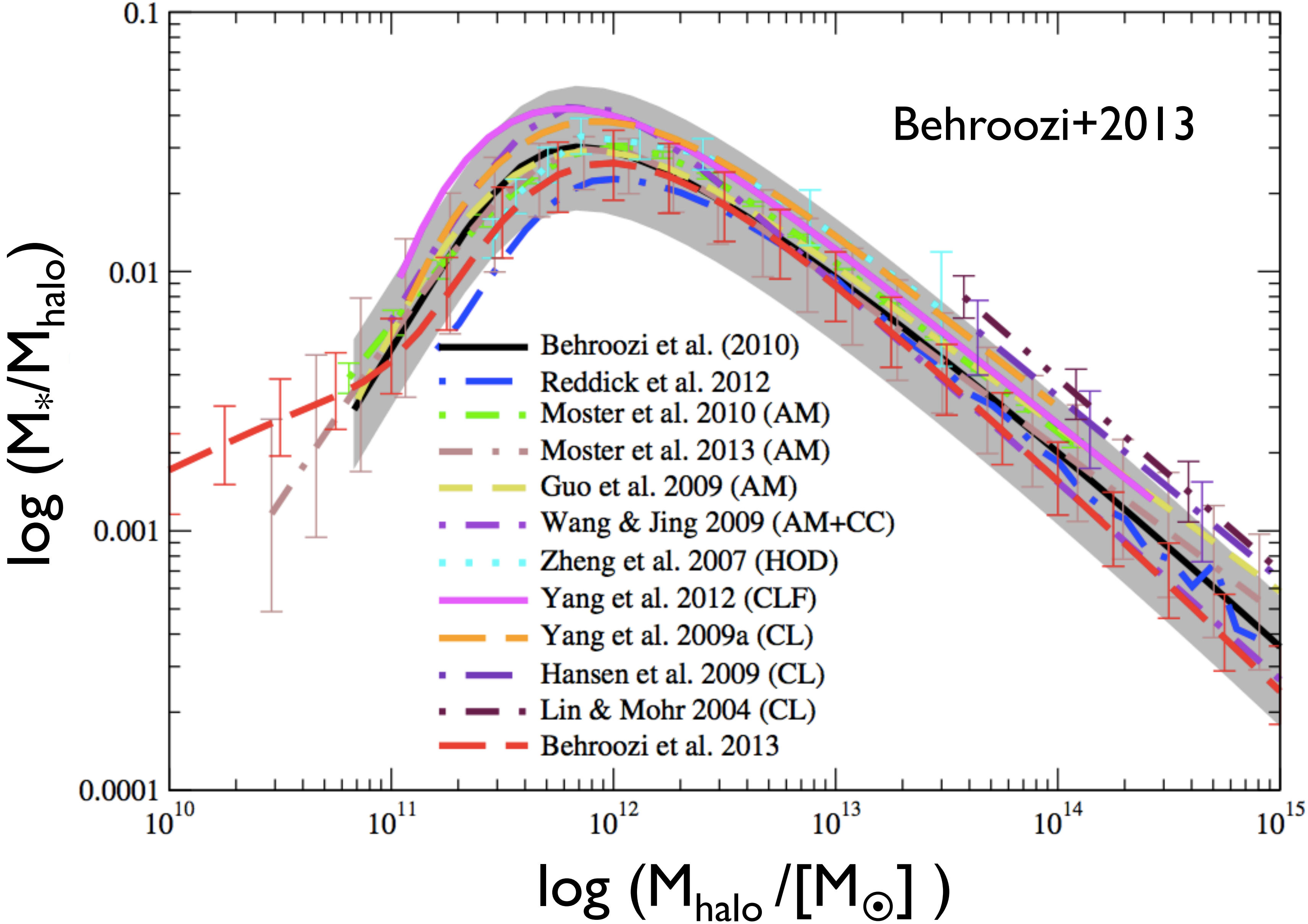
- *Chabrier IMF & Early Stellar feedback* *(Stinson, Brook, AM 2013)*
  - *ESF: Feedback from Massive stars before they explode as SN*
  - *~10% of total luminosity as thermal (energy) FeedBack*
  - *cooling always ON for ESF*

- *New SPH implementation* *(Keller+14, Stinson+2015)*
  - *Ritchie & Thomas (2001) force with pressure smoothing (destruction of blobs)*
  - *Saitoh & Makino (2009) time step limiter (shocks and jumps)*
  - *Larger number of particles in the kernel (60)*

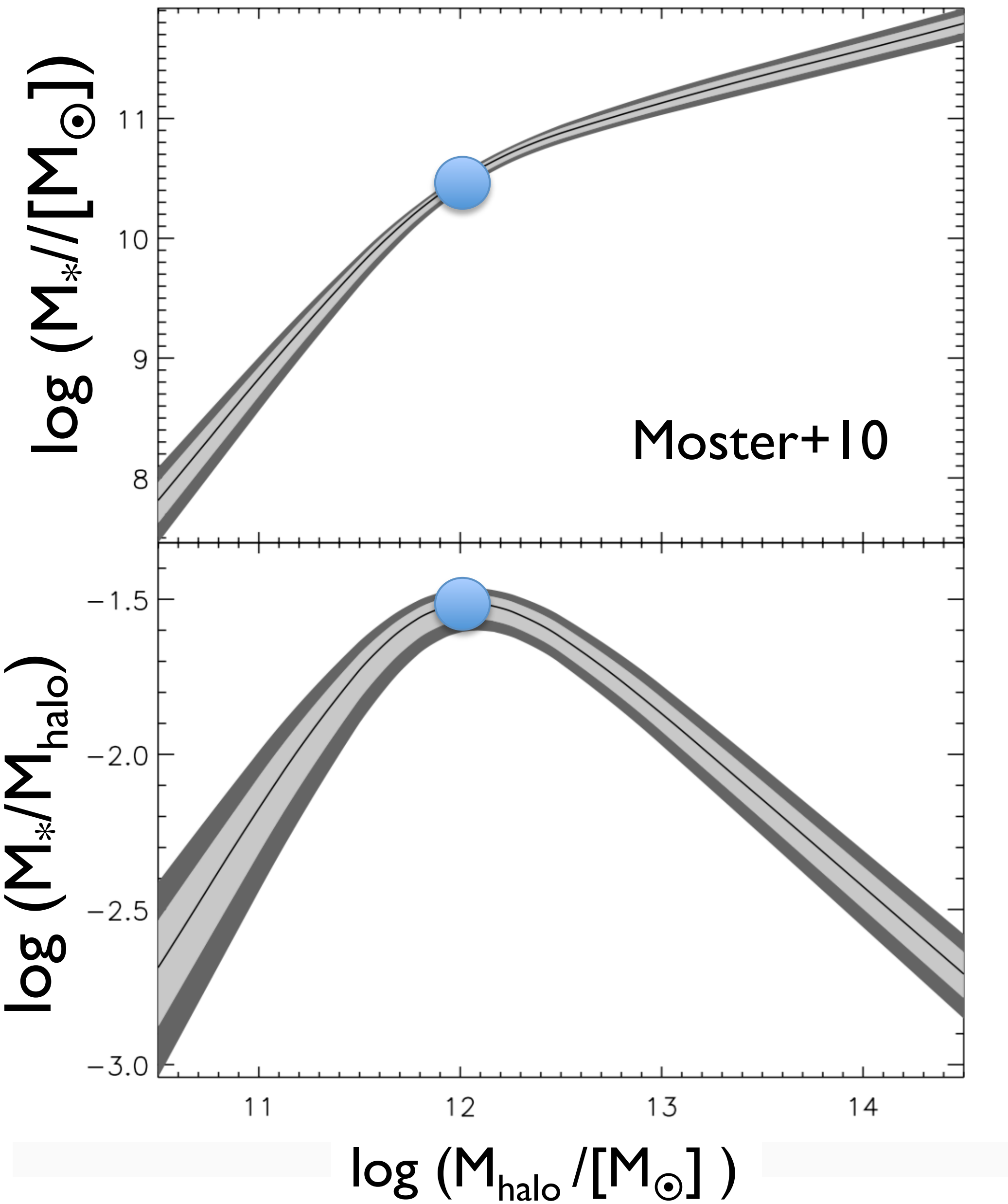


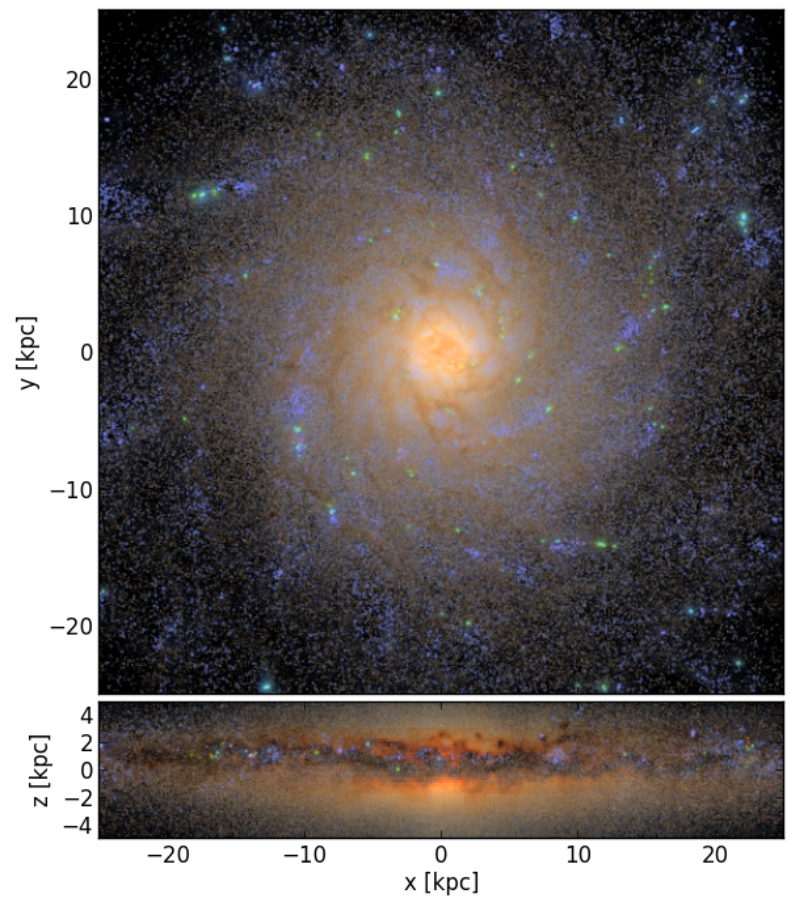
Are simulated galaxies realistic?

Halo mass – stellar mass relation



A realistic galaxy: *MaGICC*

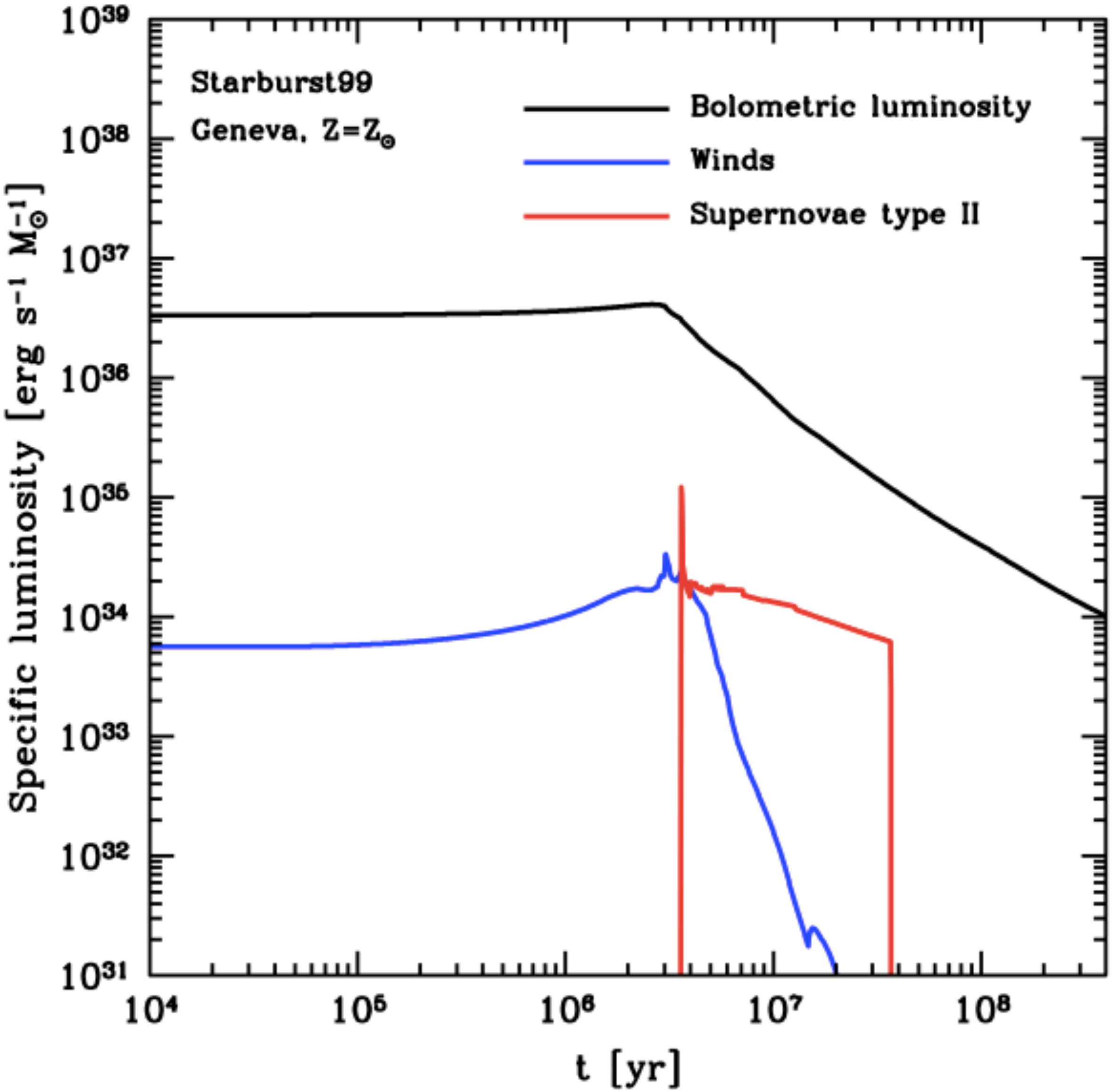


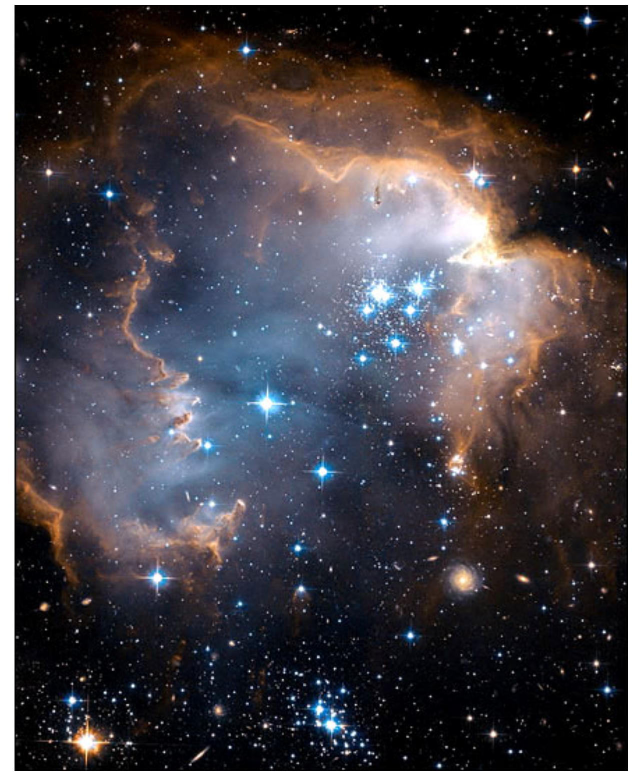


AM+12
Brook+12
Stinson+13, 15

Early stellar feedback

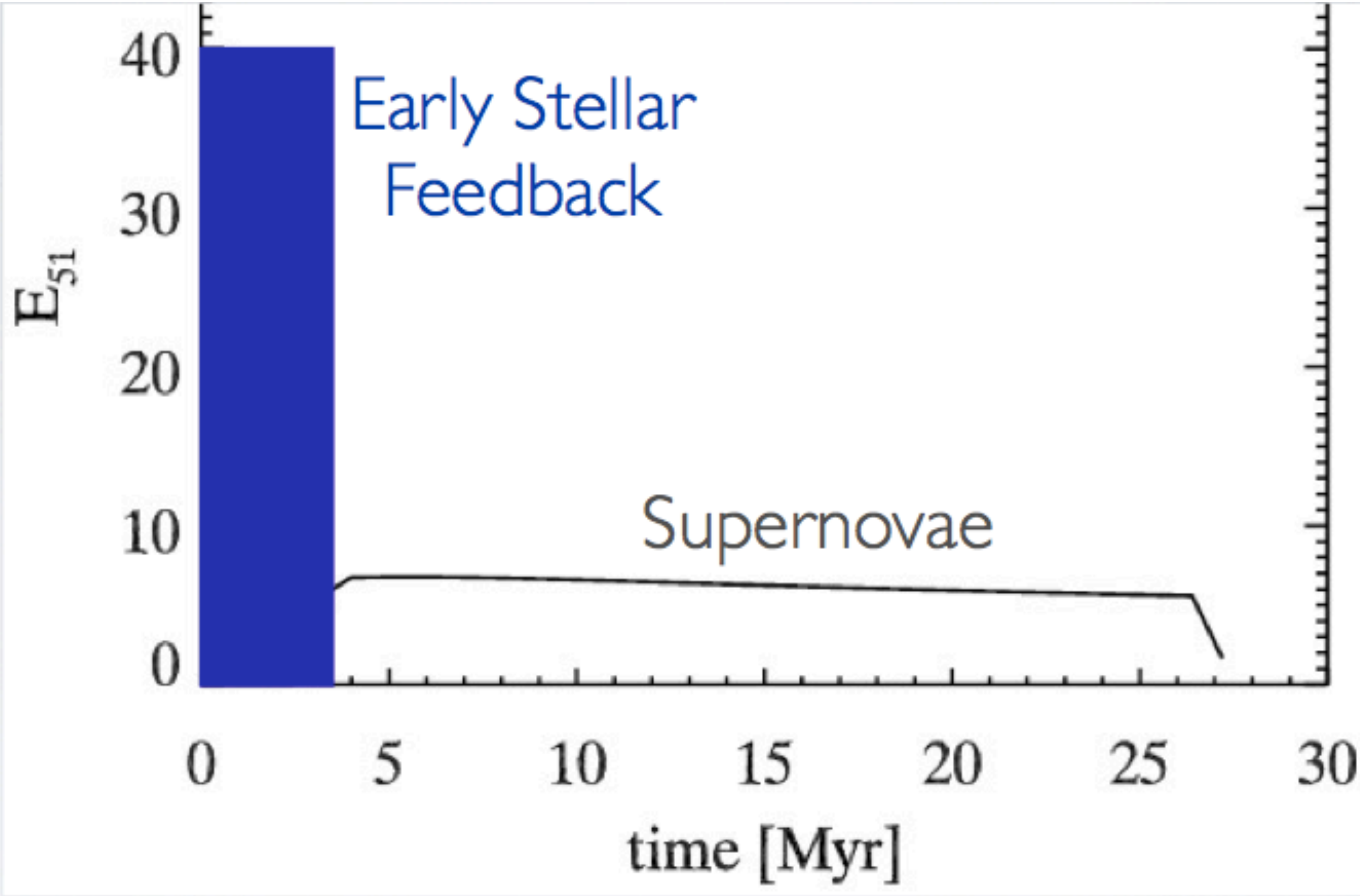
Early stellar feedback





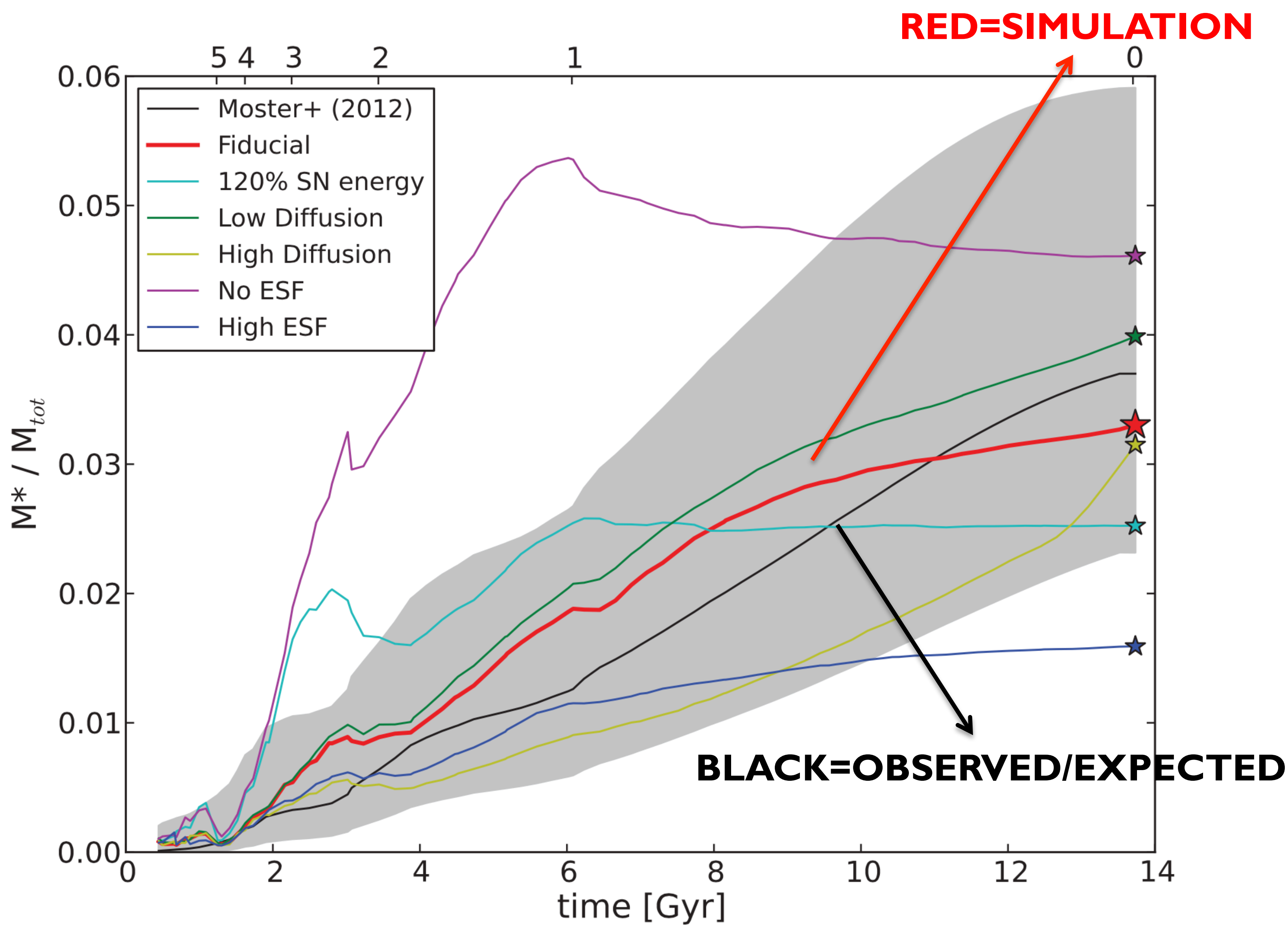
Agertz+13

Early stellar feedback



10% of Luminosity in form of thermal Energy

A realistic galaxy through time

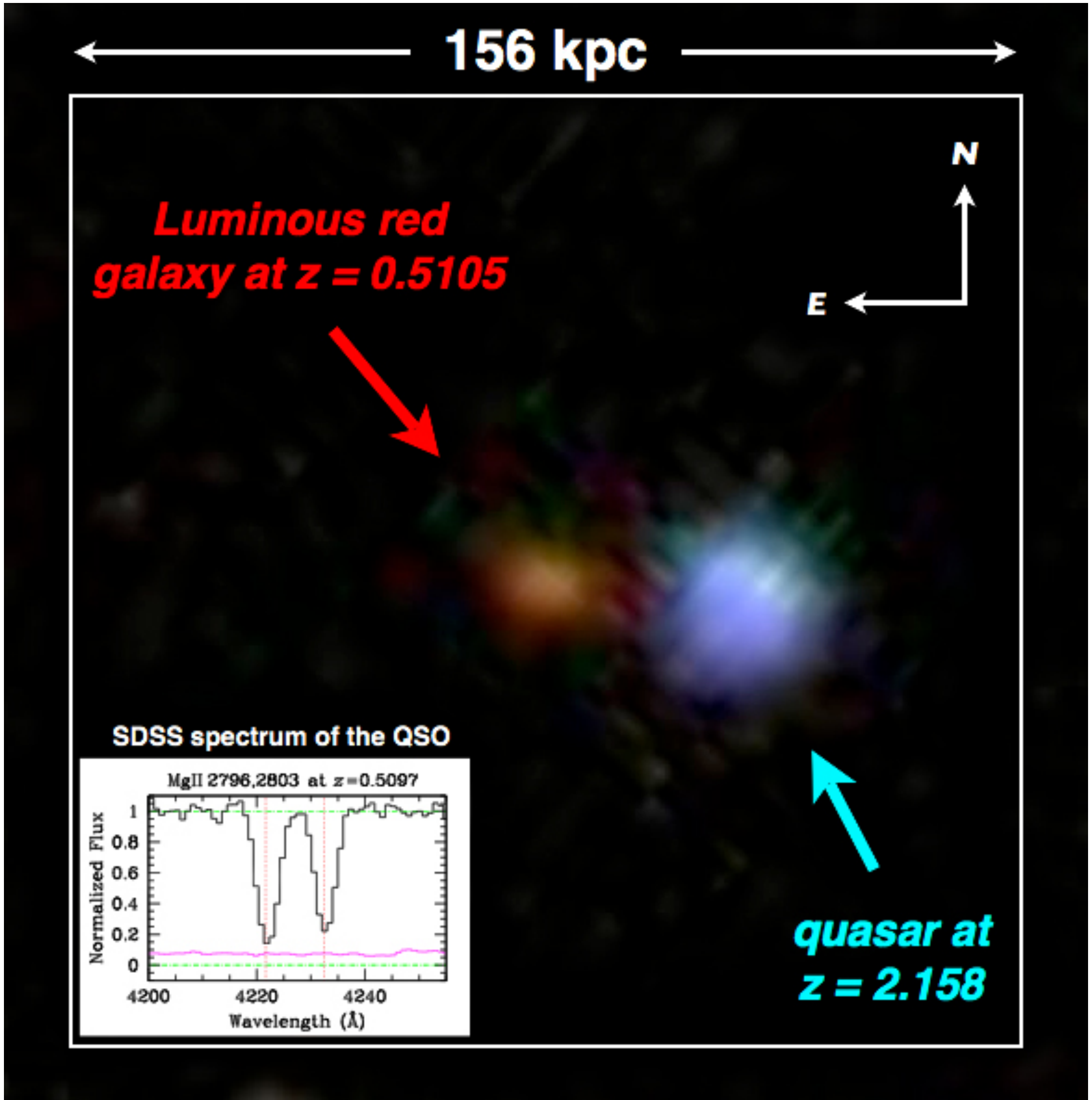


How do we test our Feedback model?

Gas Temperature

Gas Metallicity
(elements heavier than He)

How do we test our Feedback model?

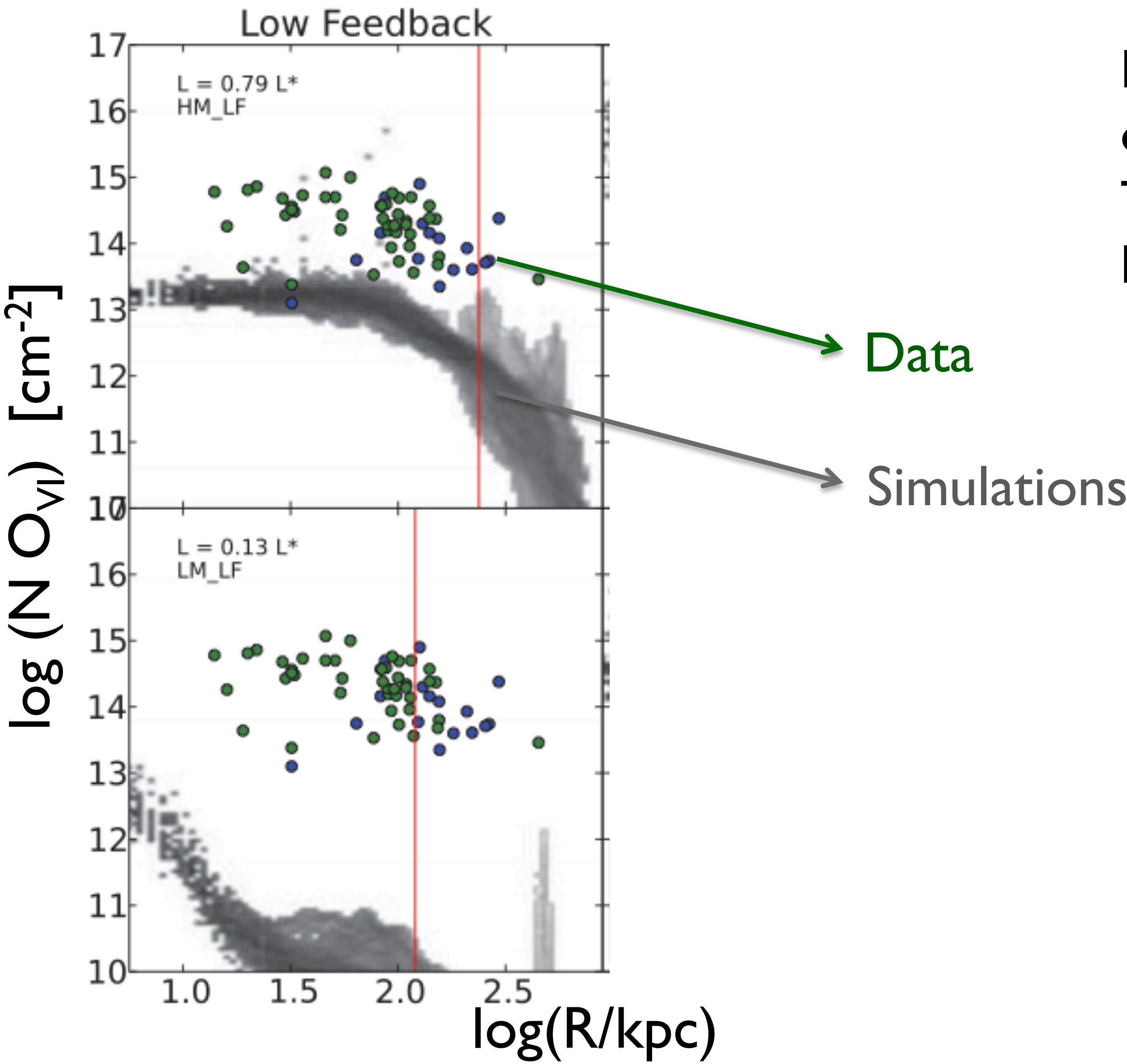


Heavy elements in galaxy outskirts.

Tumlinson+ 2011

Prochaska+ 2011

How do we test our Feedback model?

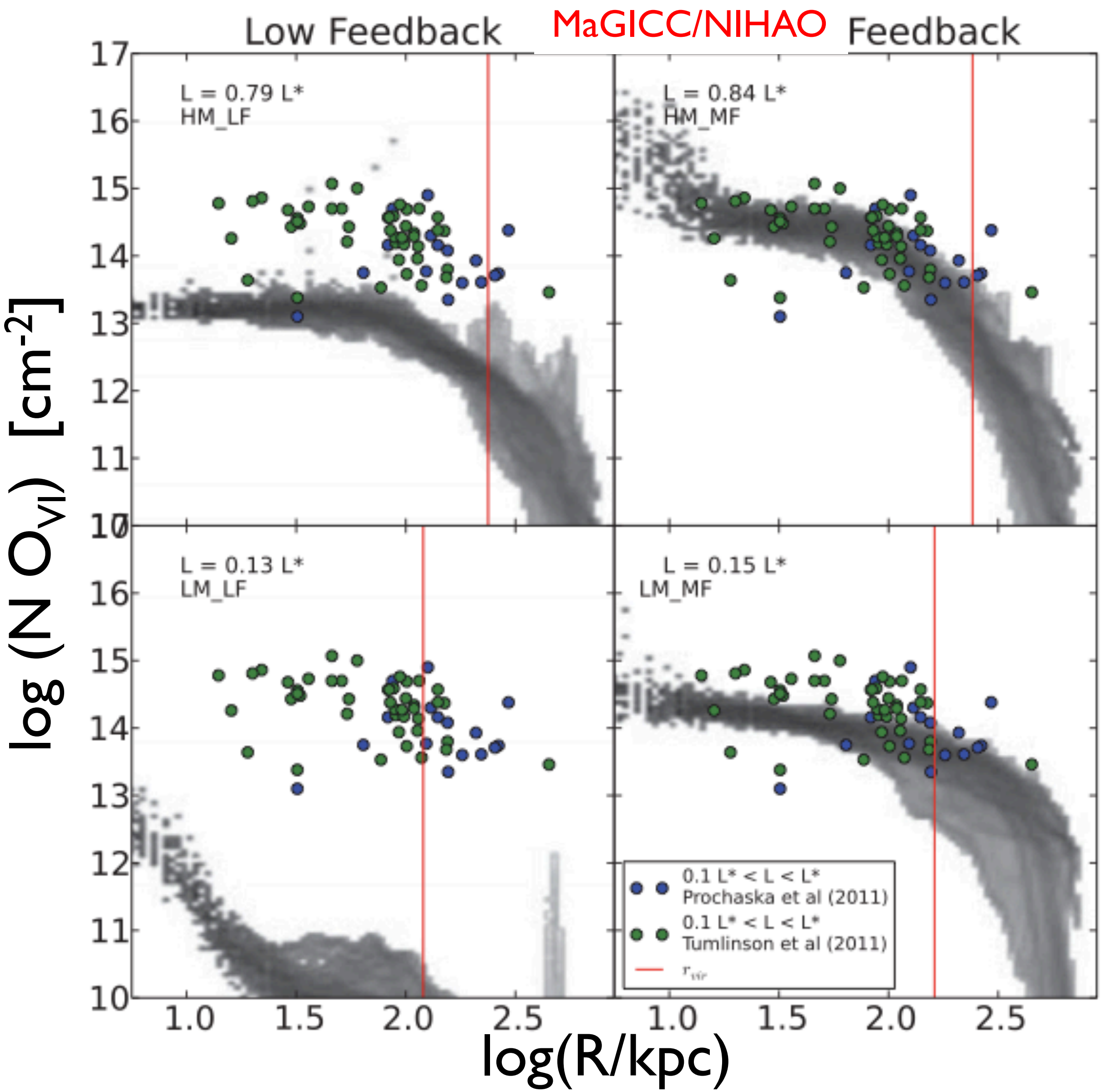


Heavy elements in galaxy outskirts.

Tumlinson+ 2011

Prochaska+ 2011

How do we test our Feedback model?



Heavy elements in galaxy outskirts.

Tumlinson+ 2011

Prochaska+ 2011

Stinson+2013b

From one to many


NIHAO 你好
Galaxy Simulations
NEW YORK UNIVERSITY
ABU DHABI
Max-Planck-Institut für Astronomie Heidelberg
Max Planck Institute for Astronomy Heidelberg
中国科学院紫金山天文台
PURPLE MOUNTAIN OBSERVATORY , CAS

The NIHAO project

Numerical
Investigation (of)
Hundred
Astrophysical
Objects

你好

A.Dutton (NYUAD), T. Buck (MPIA),
A. Obreja (NYUAD), M. Blank (NYUAD),
X Kang (PMO), L. Wang (PMO), J. Frings
(MPIA), A. Di Cintio (AIP), C. Brook (IAC)

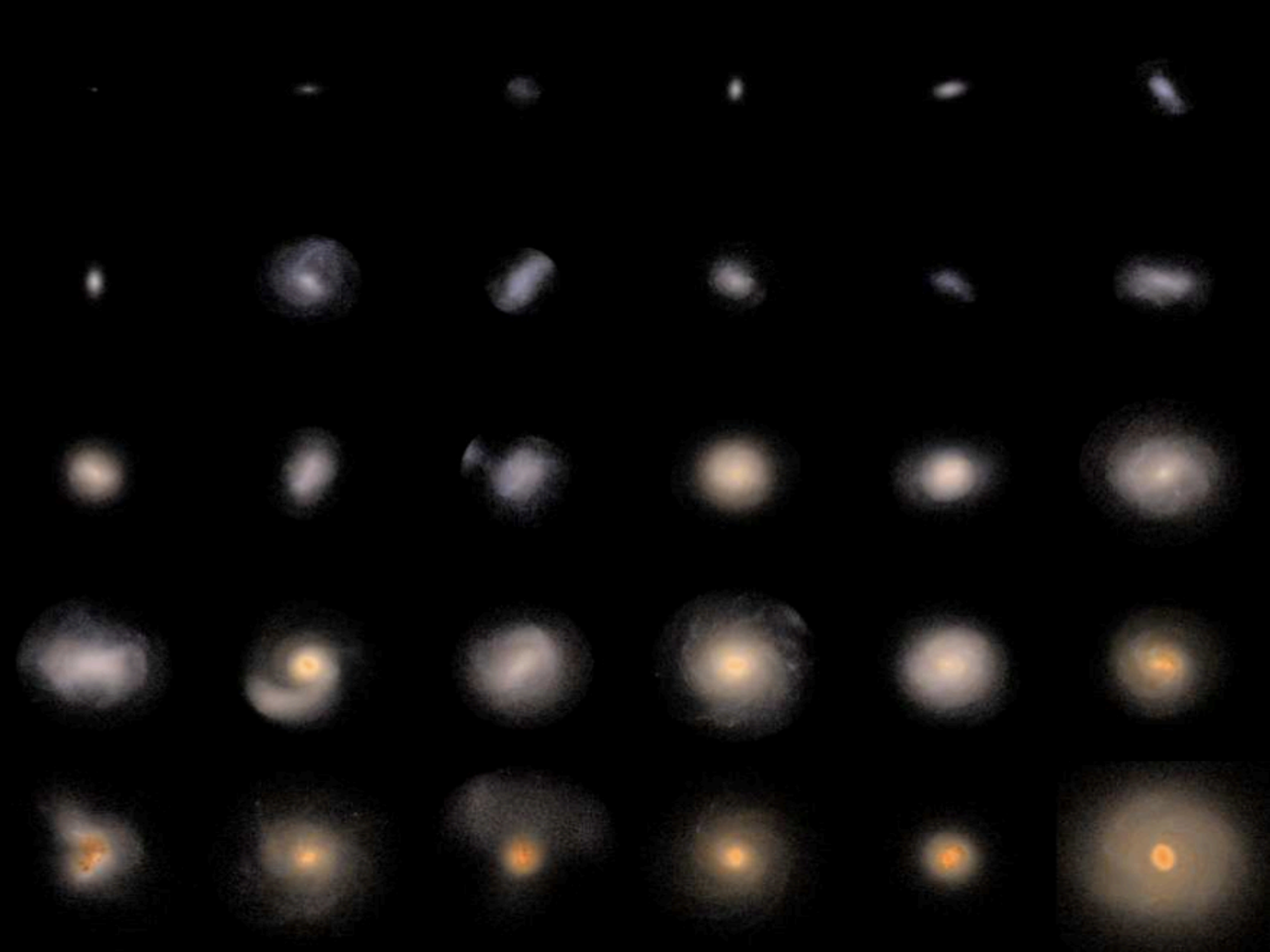
NYU ABU DHABI
جامعة نيويورك ابوظبي

Max-Planck-Institut für Astronomie Heidelberg
Max Planck Institute for Astronomy Heidelberg

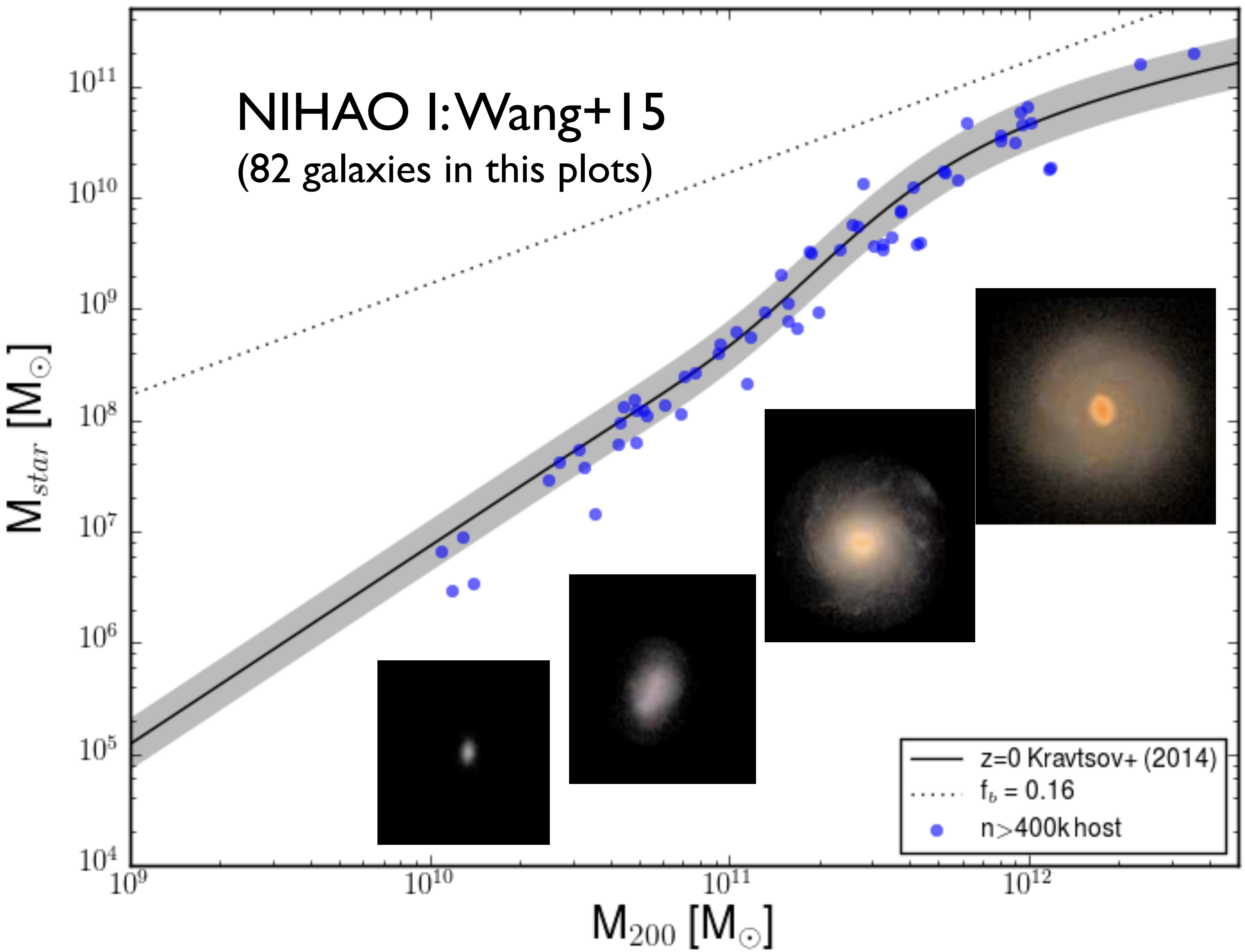
NIHAO 你好
Galaxy Simulations

- Gasoline 2.0 (with SPH fix)
- Planck Cosmology
- ***100 high resolution (zoomed) galaxies***
- **10^6** particles in each halo
- $10^6 - 10^{11}\ M_\odot$ stellar mass range ($5\times10^9 - 5\times10^{12}\ M_\odot$)
- 100 times better than ILLUSTRIS
- 50 times better than EAGLE
- 15 times more galaxies than FIRE (7 vs. 100)

NIHAO I: Wang, Dutton, Stinson, AM et al. 2015



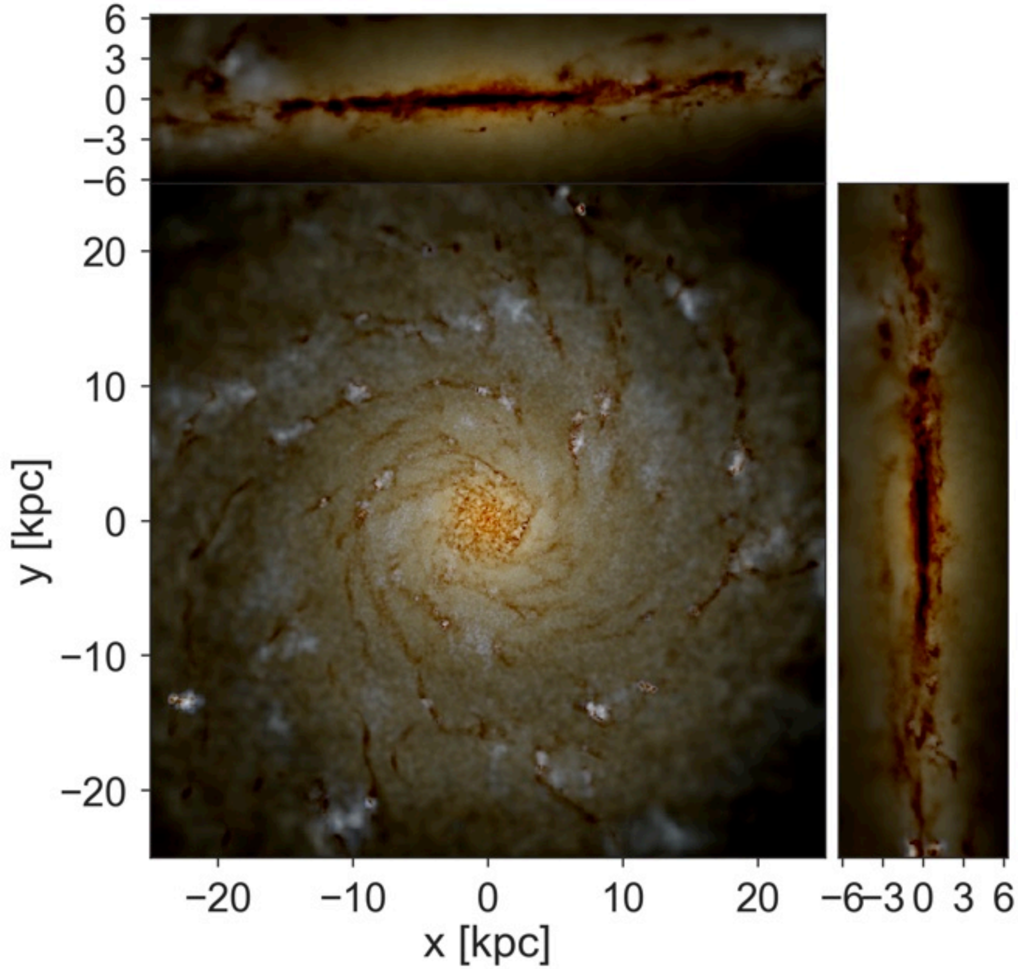
Simulating realistic galaxies



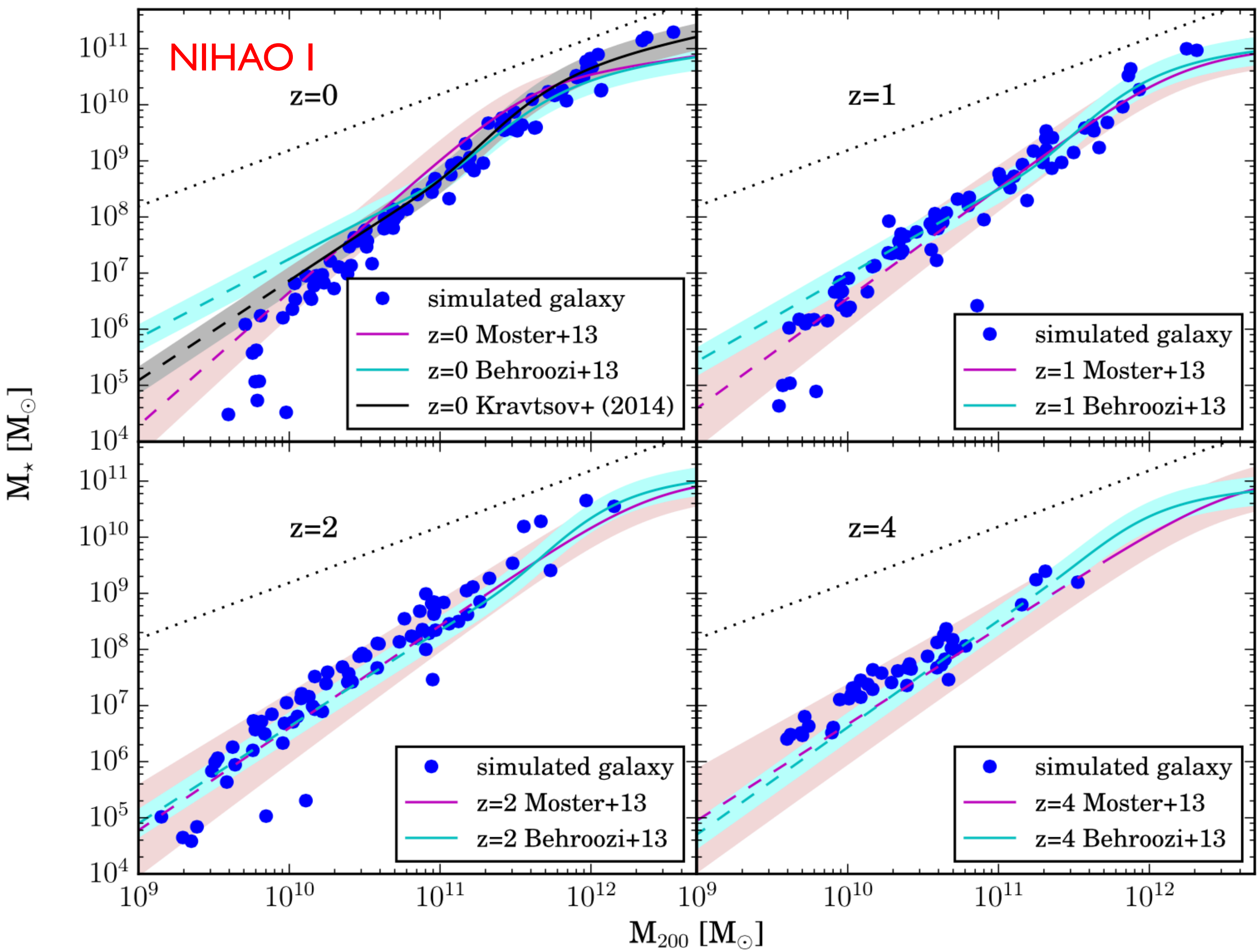
NIHAO vs. Observations

NIHAO vs. Observations

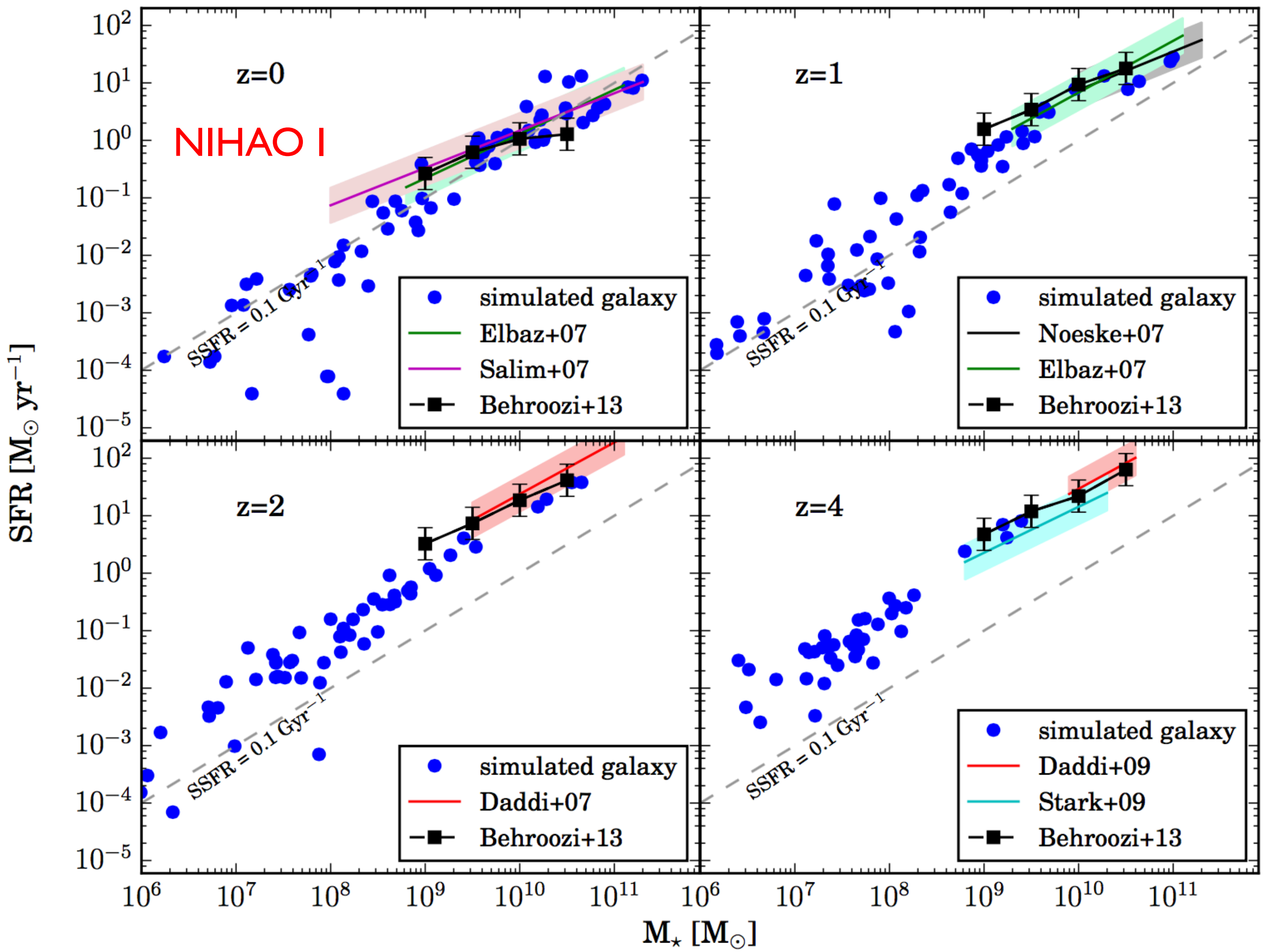
Buck et al in prep.



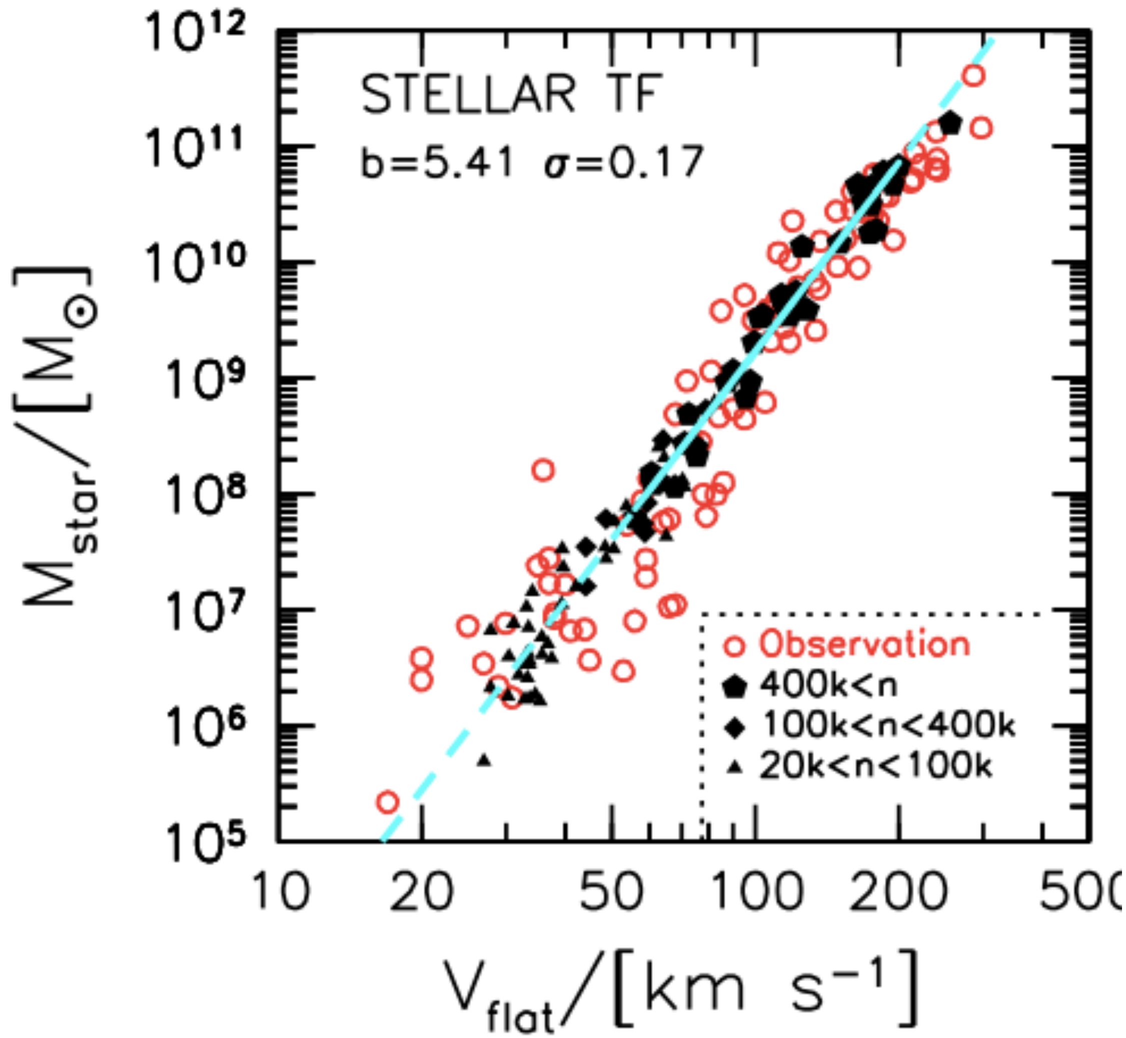
NIHAO vs. Observations



NIHAO vs. Observations

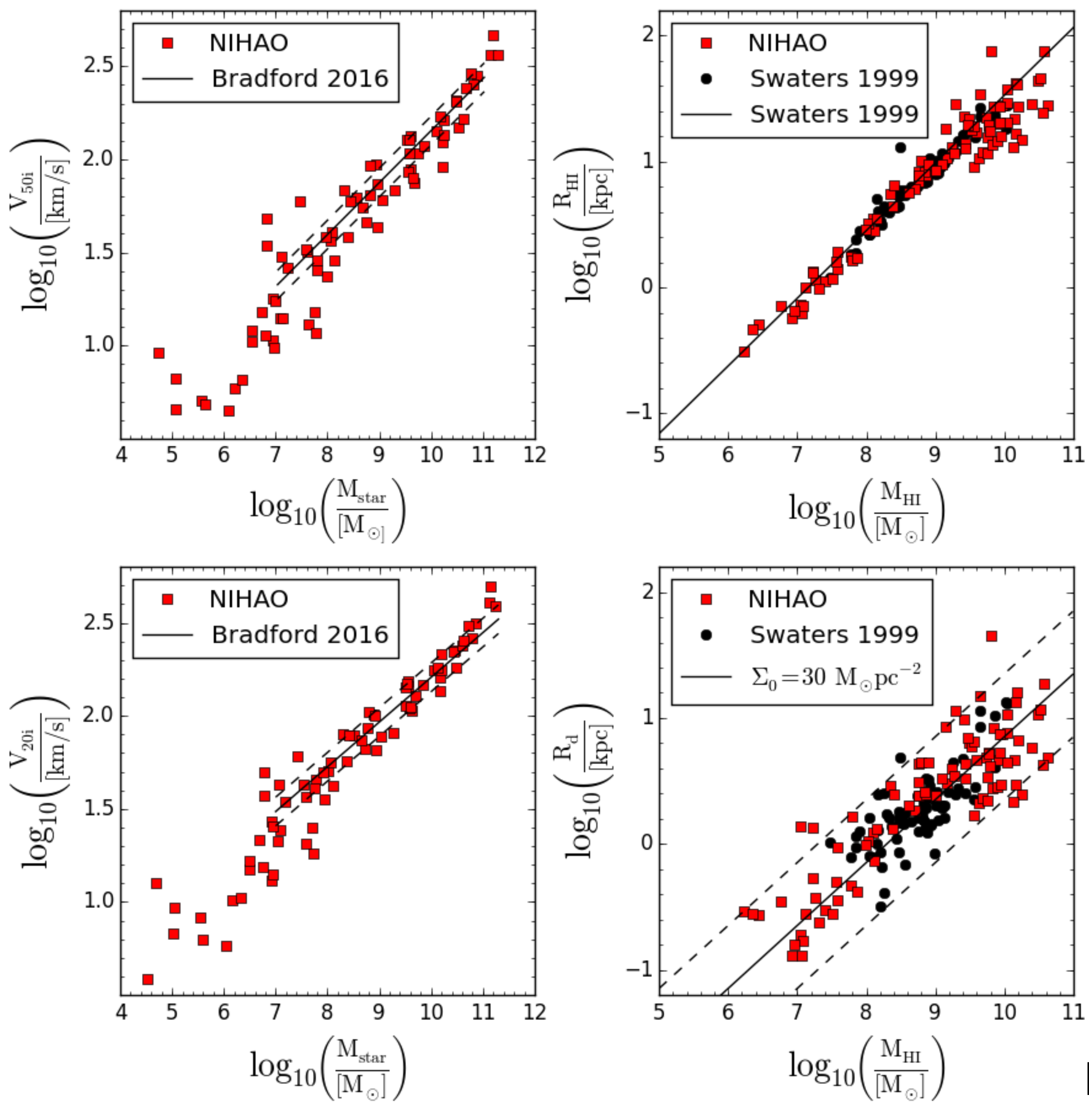


NIHAO vs. Observations



NIHAO XII: Dutton, AM+ 2016

NIHAO vs. Observations



NIHAO X: AM+2016

NIHAO papers

baryon content   galaxy structure   dark matter

I: **Wang+2015** overview + star formation inefficiency

II: **Butsky+2016** dark halo shapes, velocity dist.

III: **Stinson+2015** cold gas content

IV: **Tollet+2016** central dark matter density slopes

V: **Dutton+2016** too big to fail for field dwarfs

VI: **Obreja+2016** kinematic bulge-disk decompositions

VII: **Wang+2017** baryon budget

VIII: **Gutcke+2017** circum galactic medium

IX: **Dutton+2016** dark halo response

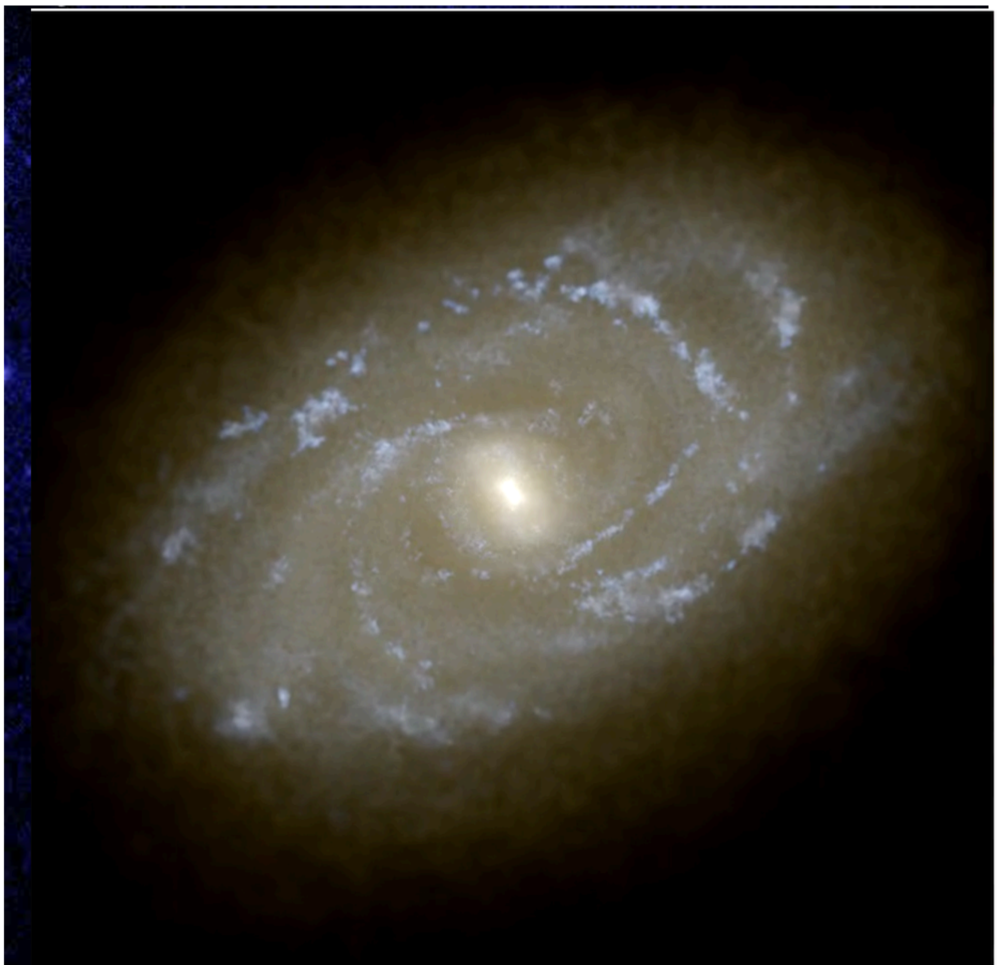
X: **Macciò+2016** HI velocity function

XI: **Di Cintio+2017** Ultra Diffuse Galaxies

XII: Dutton+2017 Tully Fisher relations

XIII: Buck+2017 Clumpy Galaxies at high redshift

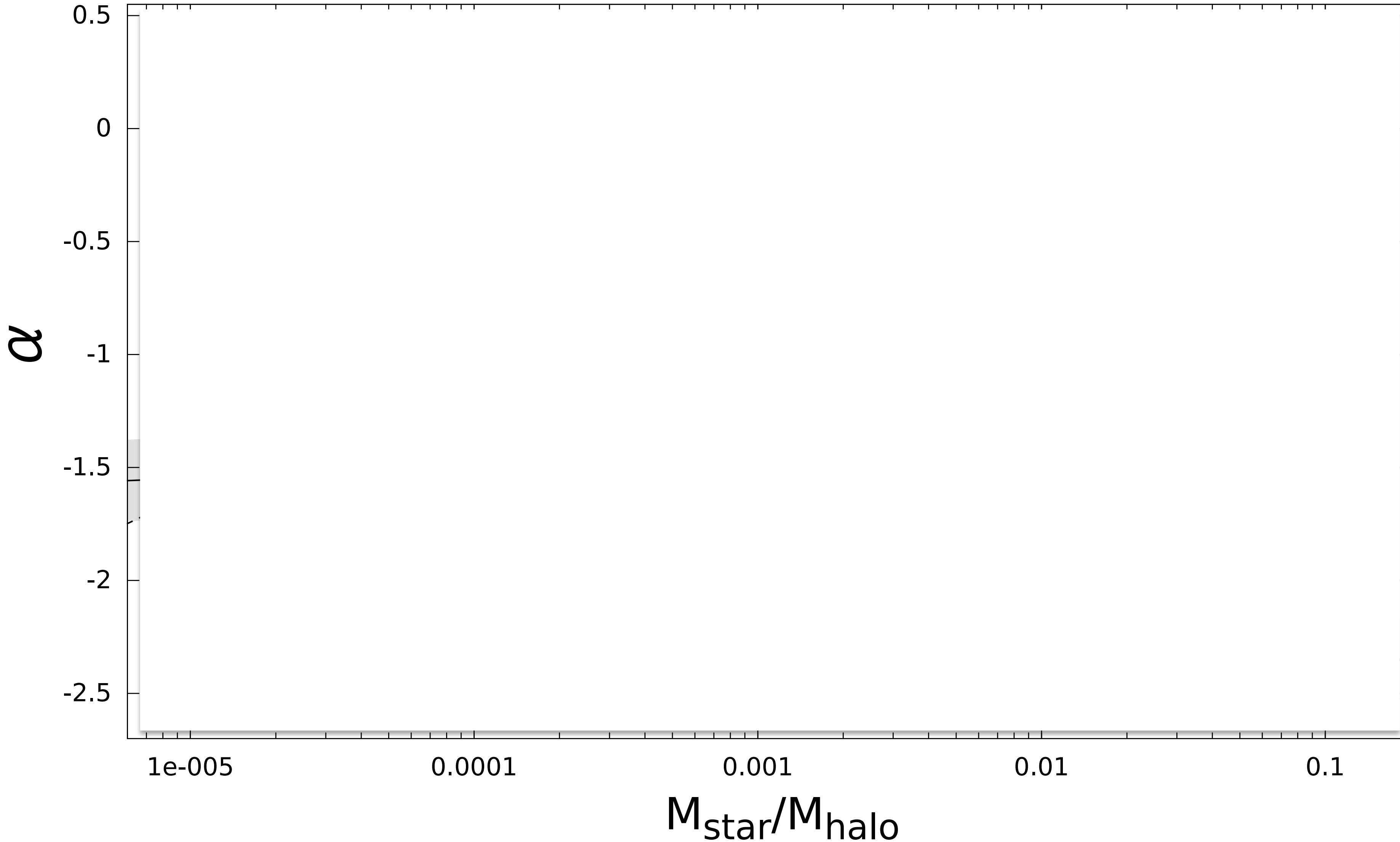
Observations vs. Simulations



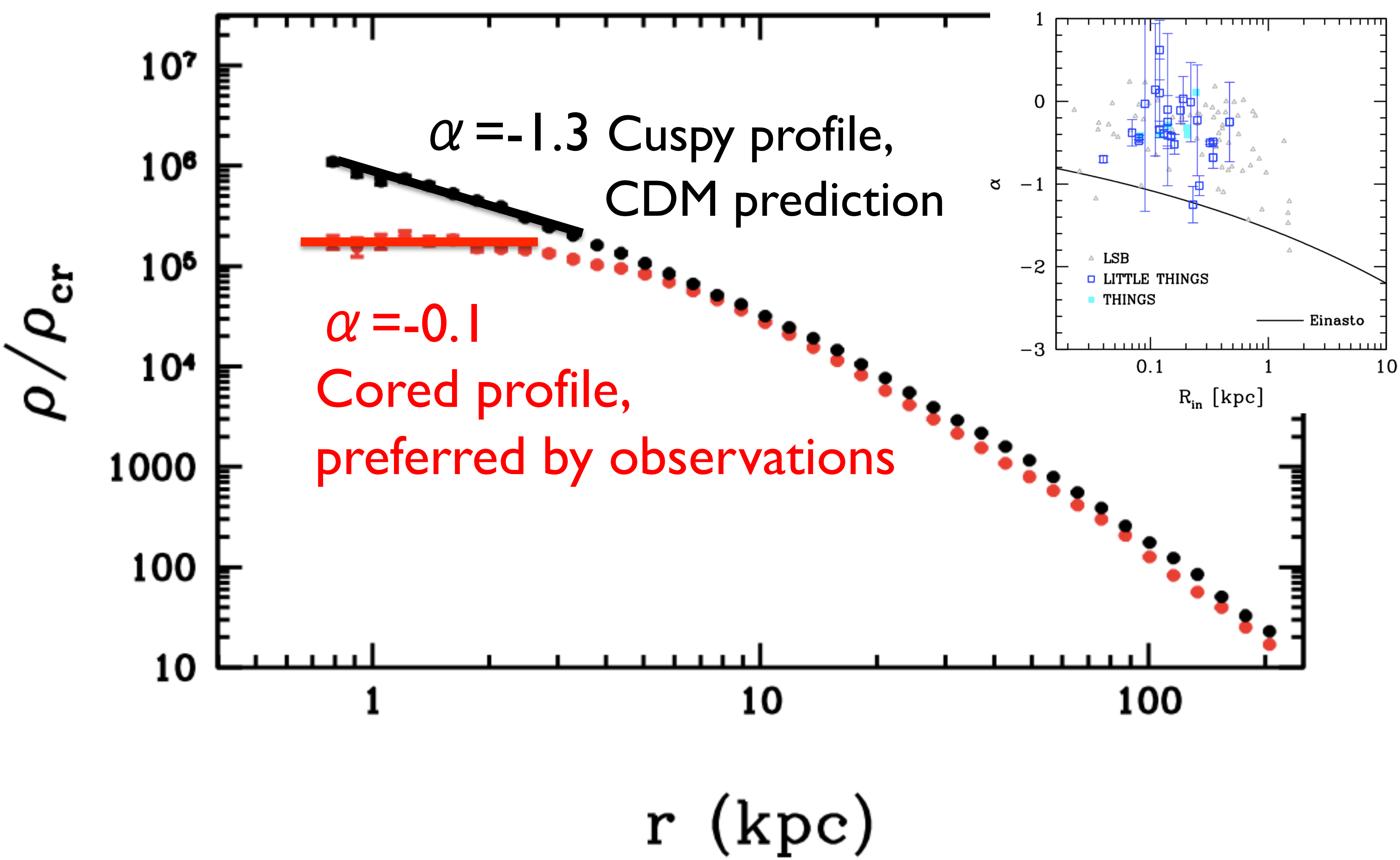
NIHAO XII – Buck+17

NGC4051 @SDSS

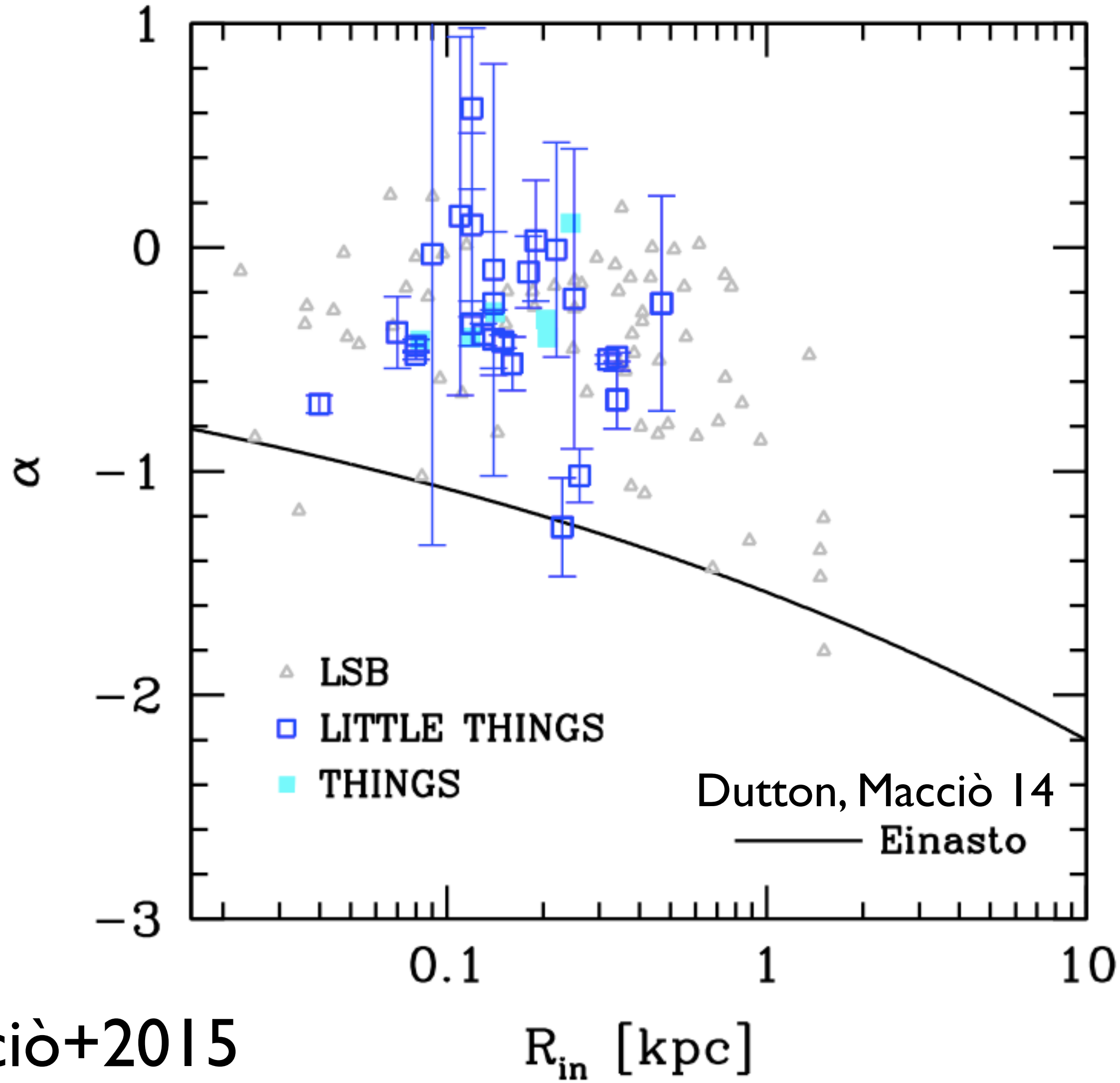
The DM distribution in NIHAO



Dark Matter density profile

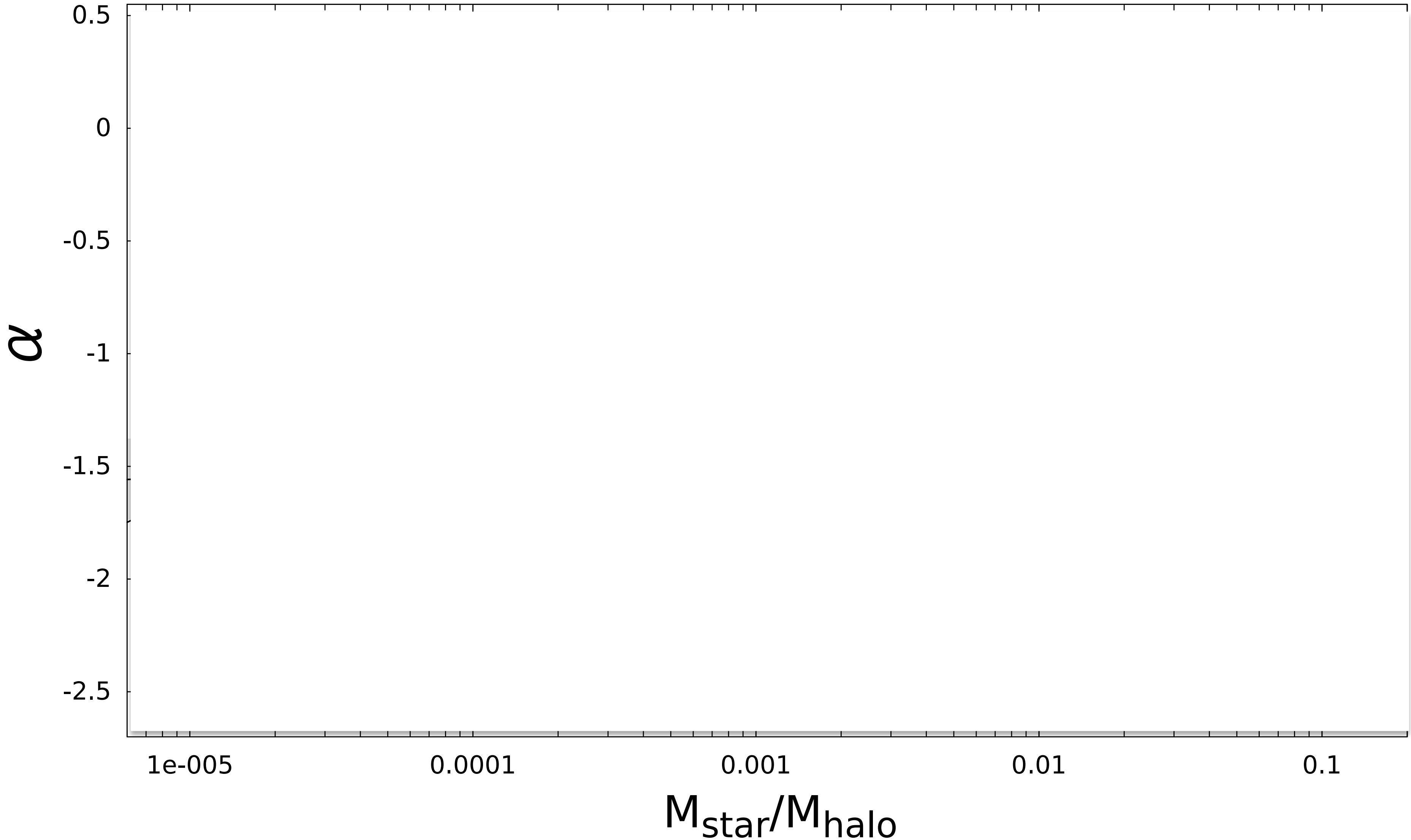


Observations

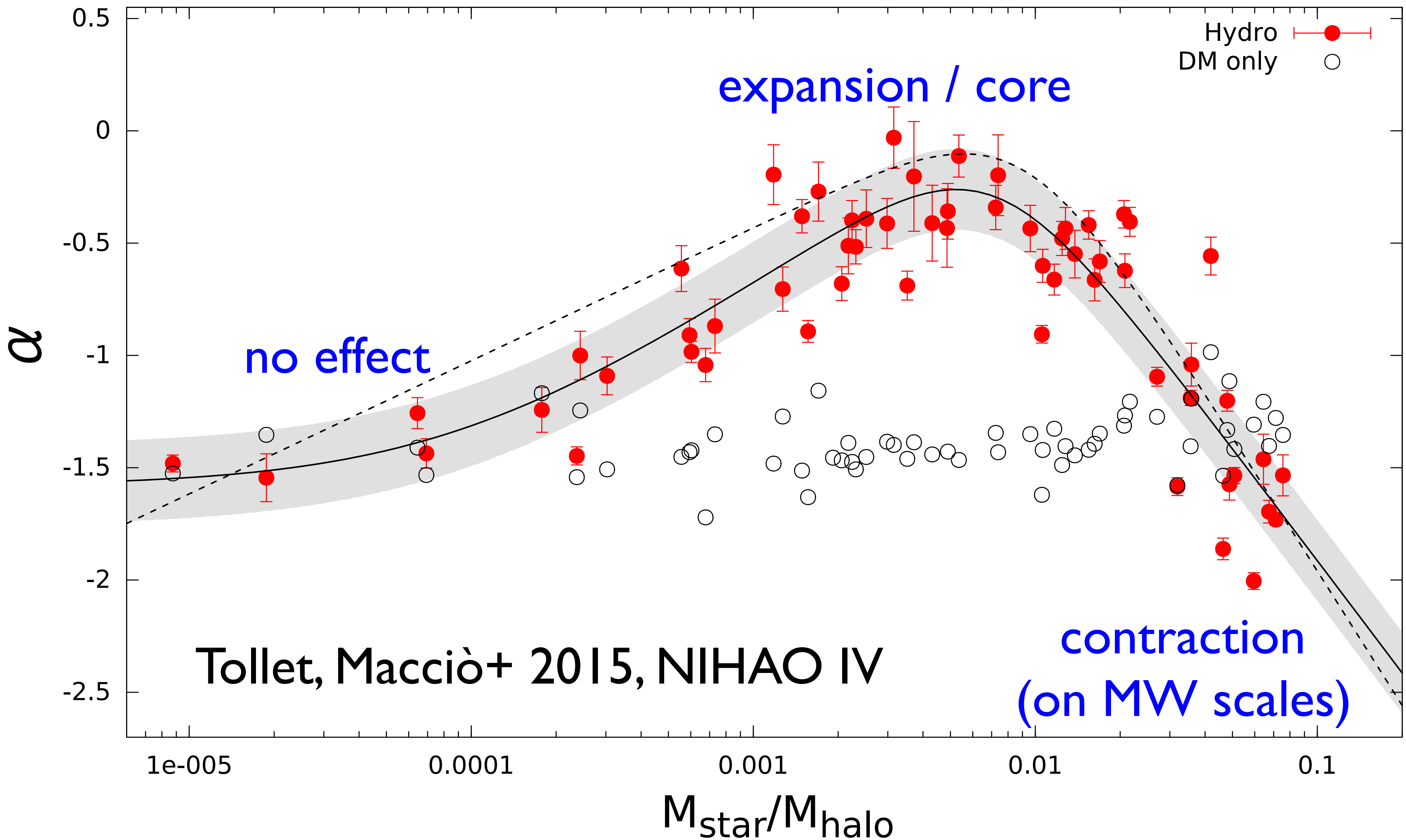


NIHAO IV
Tollet, Macciò+2015

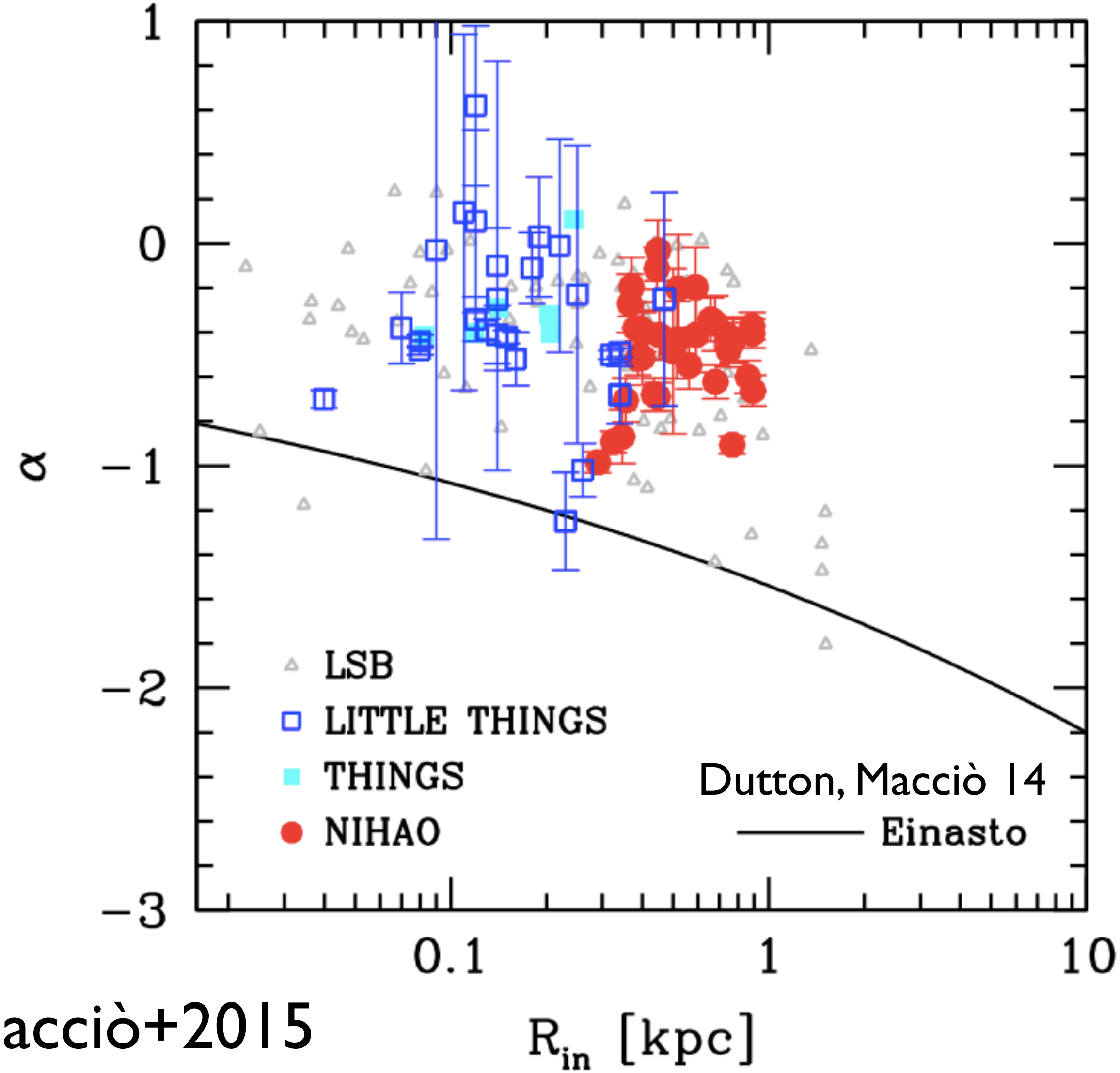
The DM distribution in NIHAO



The DM distribution in NIHAO

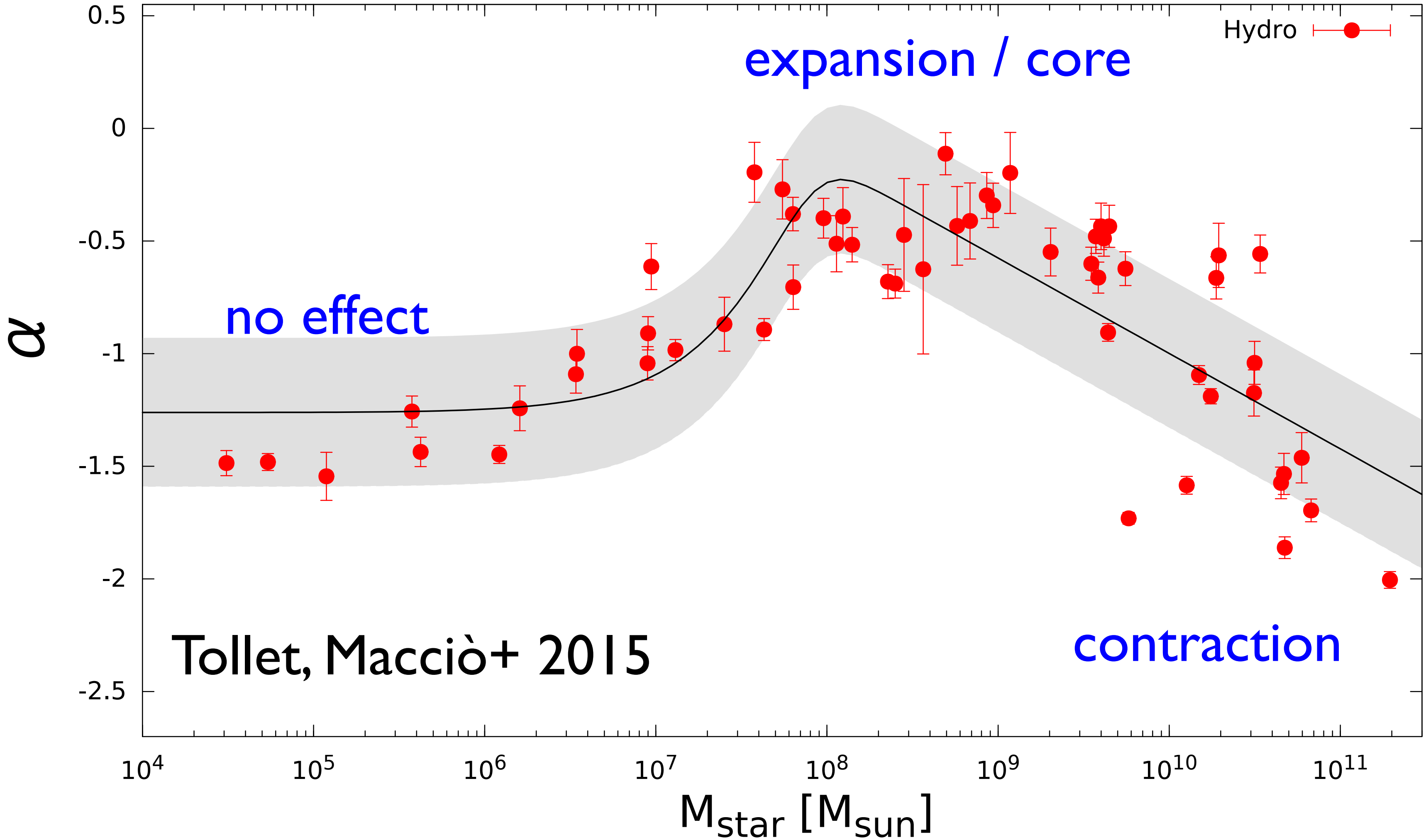


Observations



Tollet, Macciò+2015

The DM distribution in NIHAO

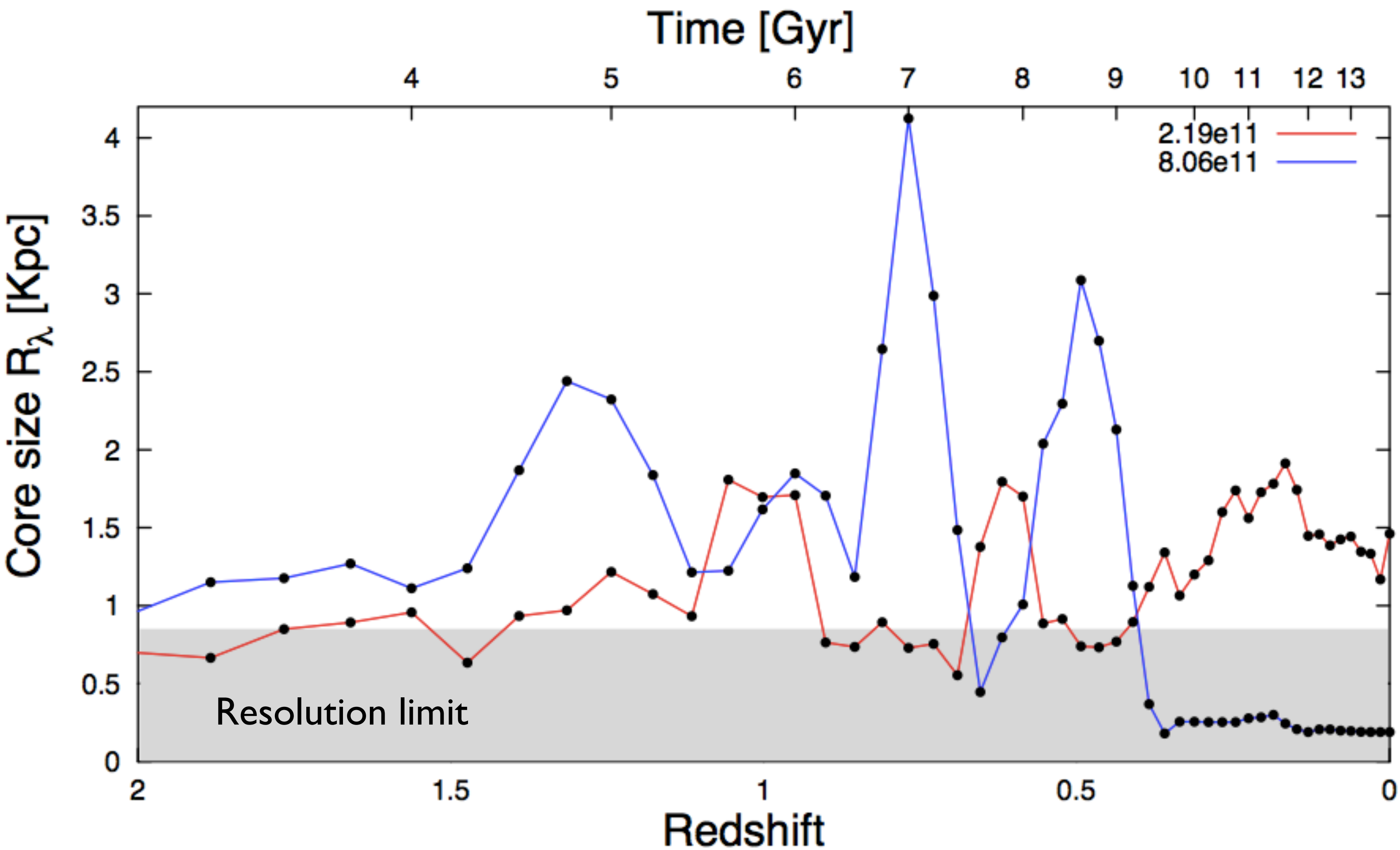


0.00 Gyr

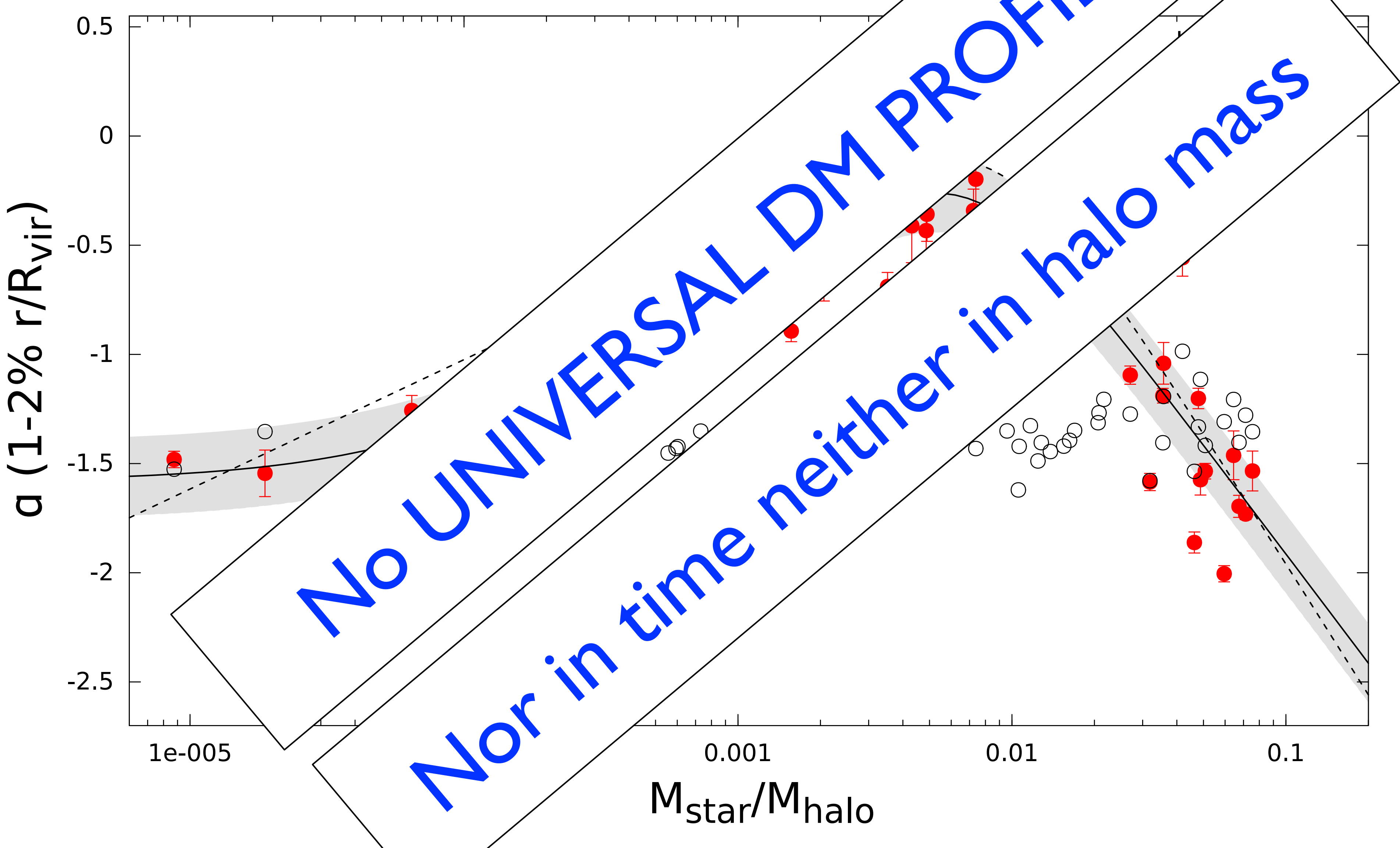
Core creation

NIHAO project - NYUAD / MPIA

Core creation and core destruction

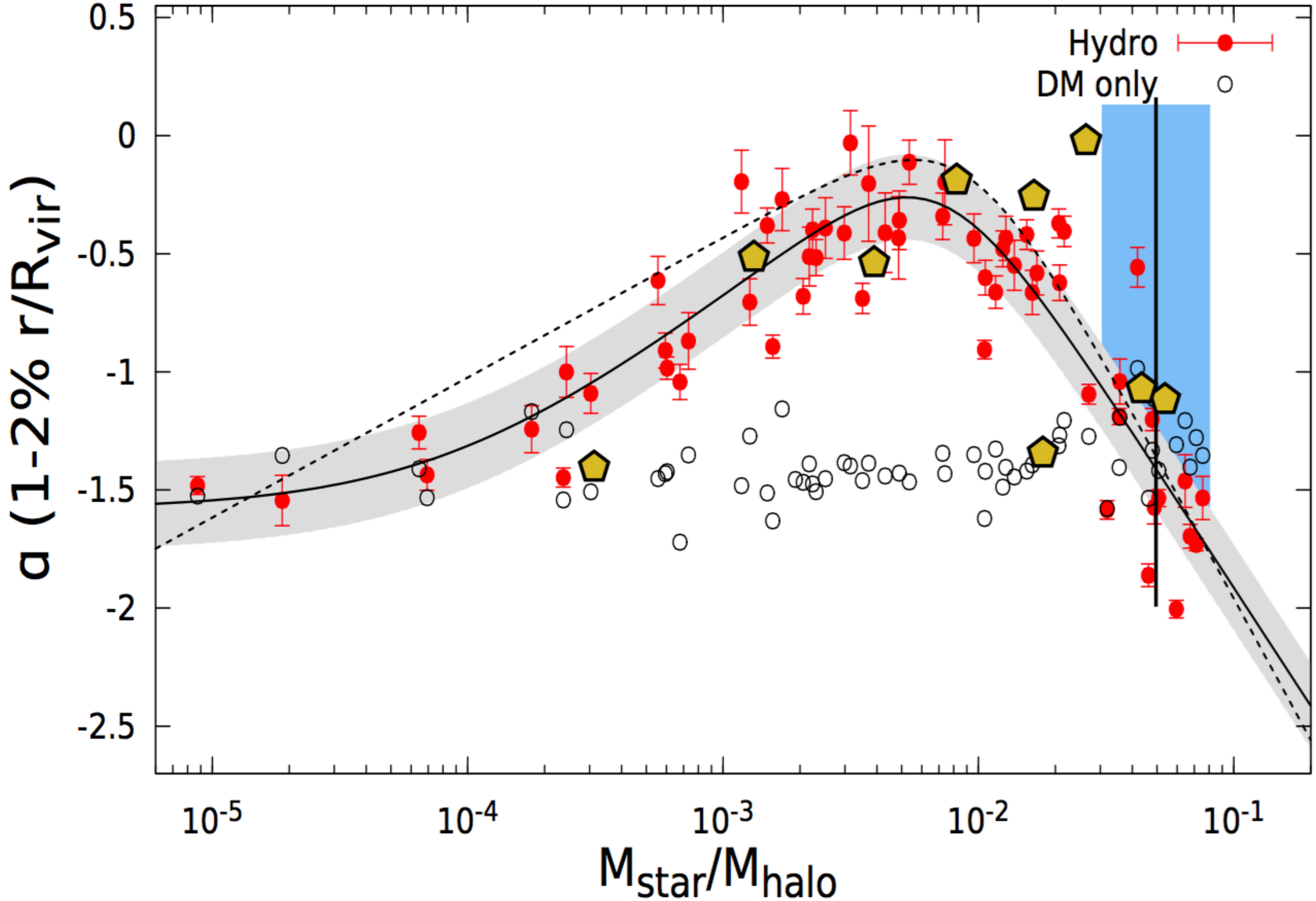


The “*real*” DM distrib



Other codes results

Other code results



FIRE simulations: Chan+15

Expansion on dwarf galaxies scales

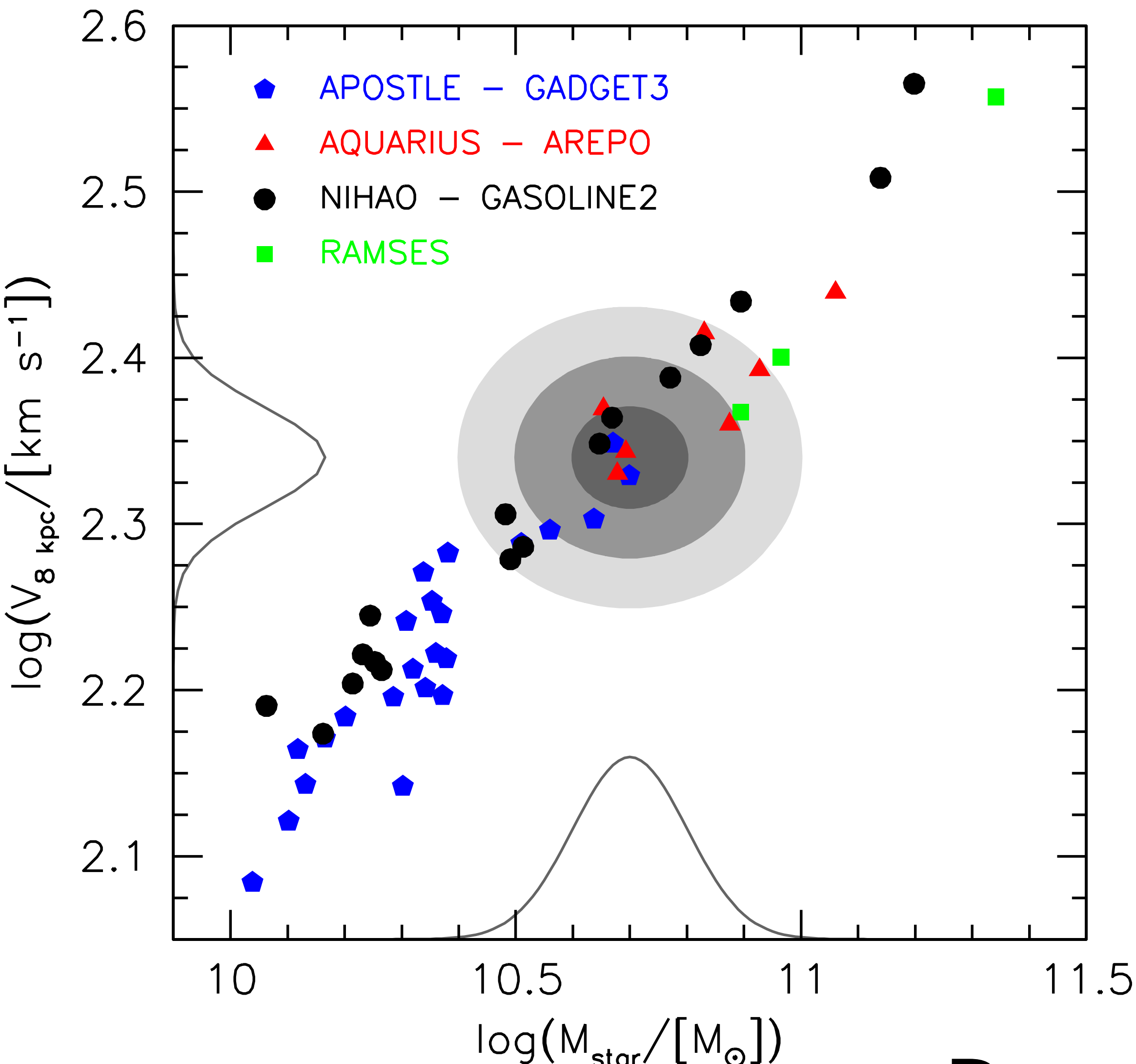
NIHAO (Gasoline2) : expansion (Tollet+15)
FIRE (Gizmo): expansion (Chan+15)

Ramses: expansion (but not cosmological) (Teyssier+13)

EAGLE (Gadget): no effect (but lower resolution)
(Sawala+15, Schaller+15)

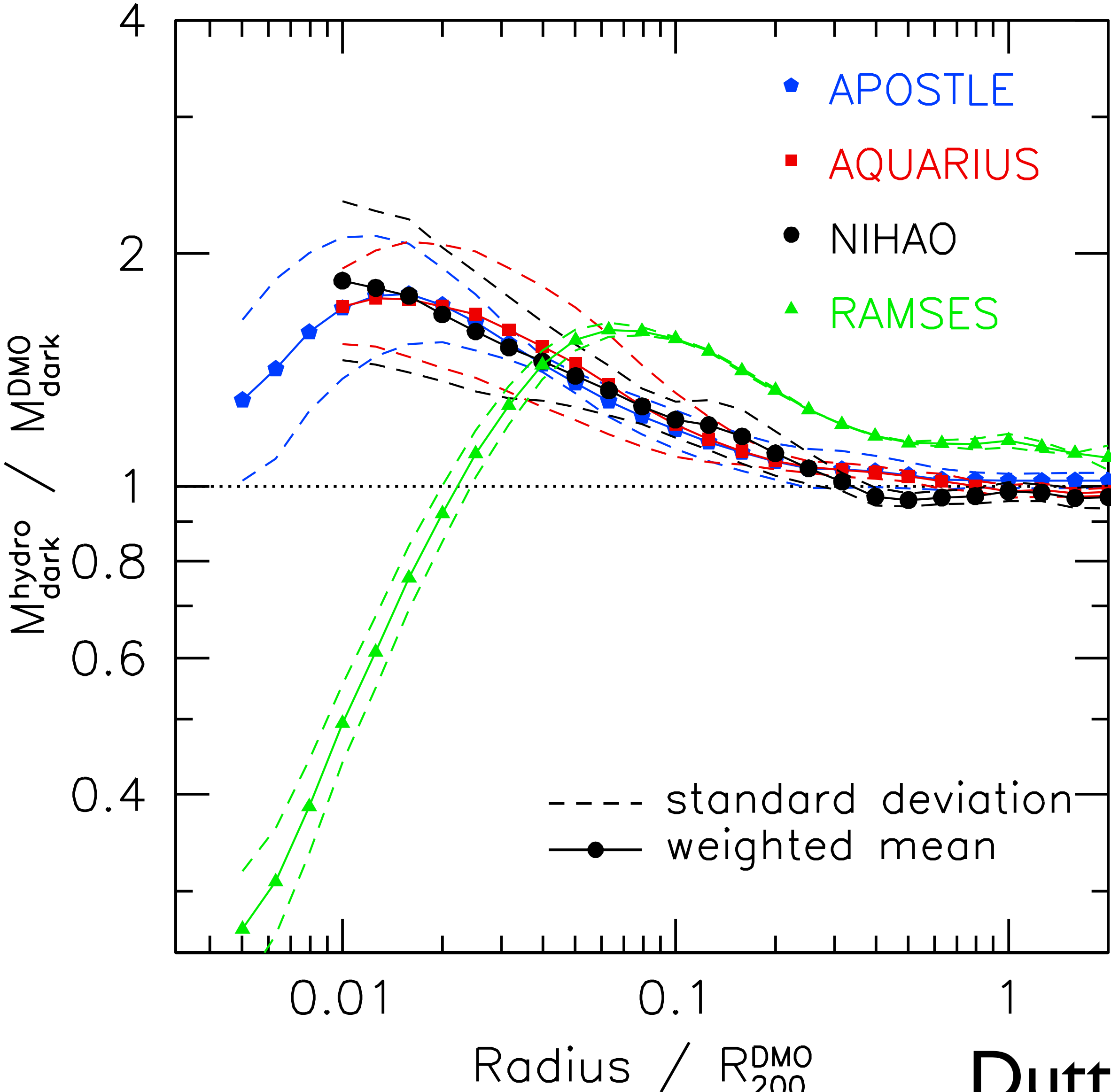
Illustris: no results on these scales

What about the MW?



Dutton+ in prep.

Contraction on MW scale



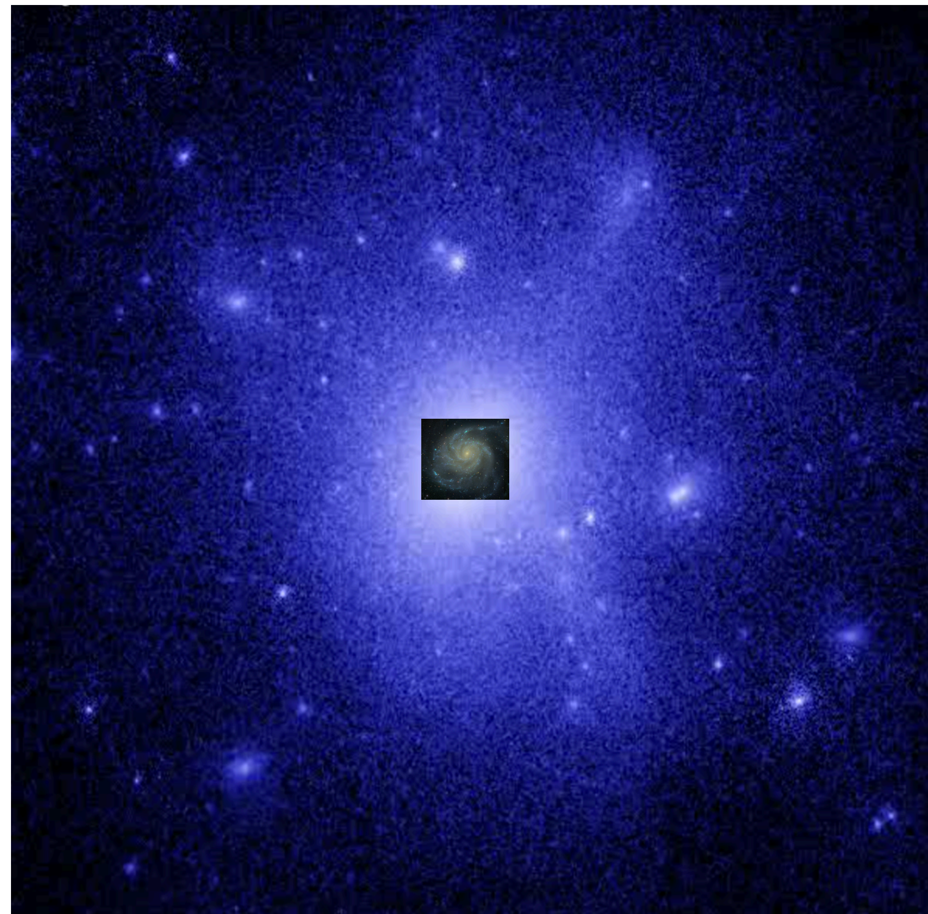
Dutton+ in prep.

Dark Matter velocity distribution

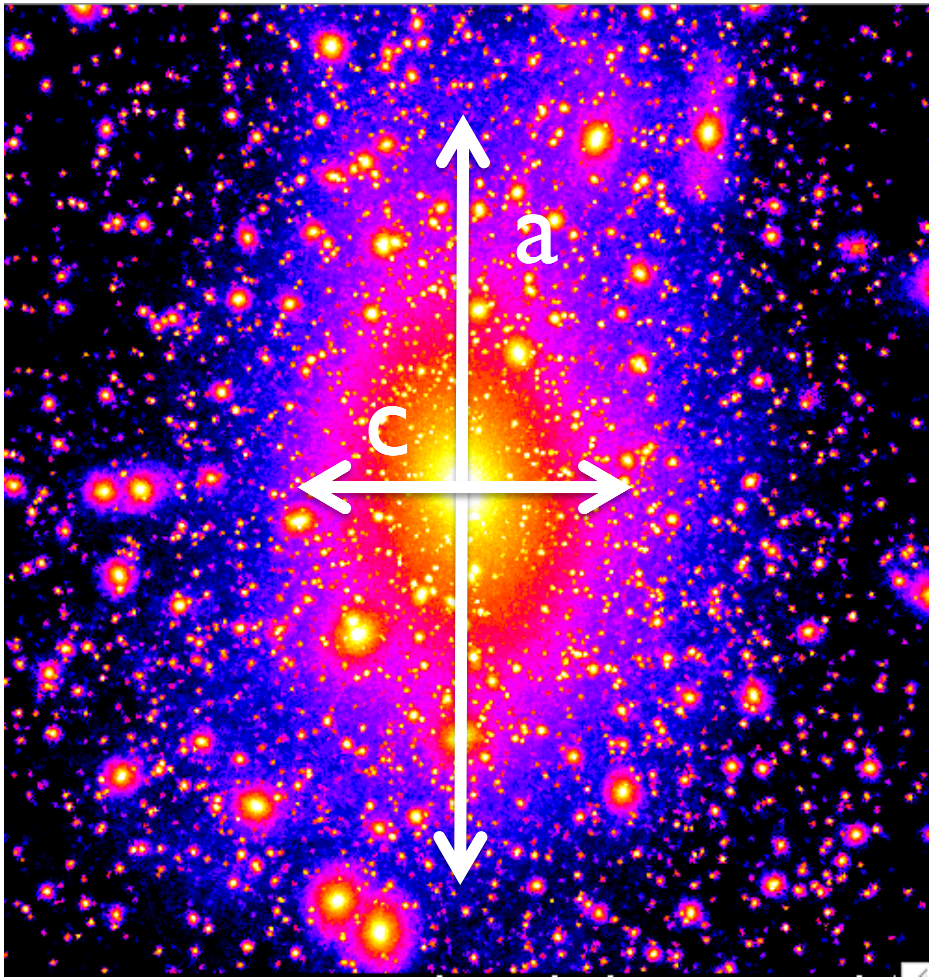
- Direct detection: ρ , f(v)

- Indirect detection: ρ^2

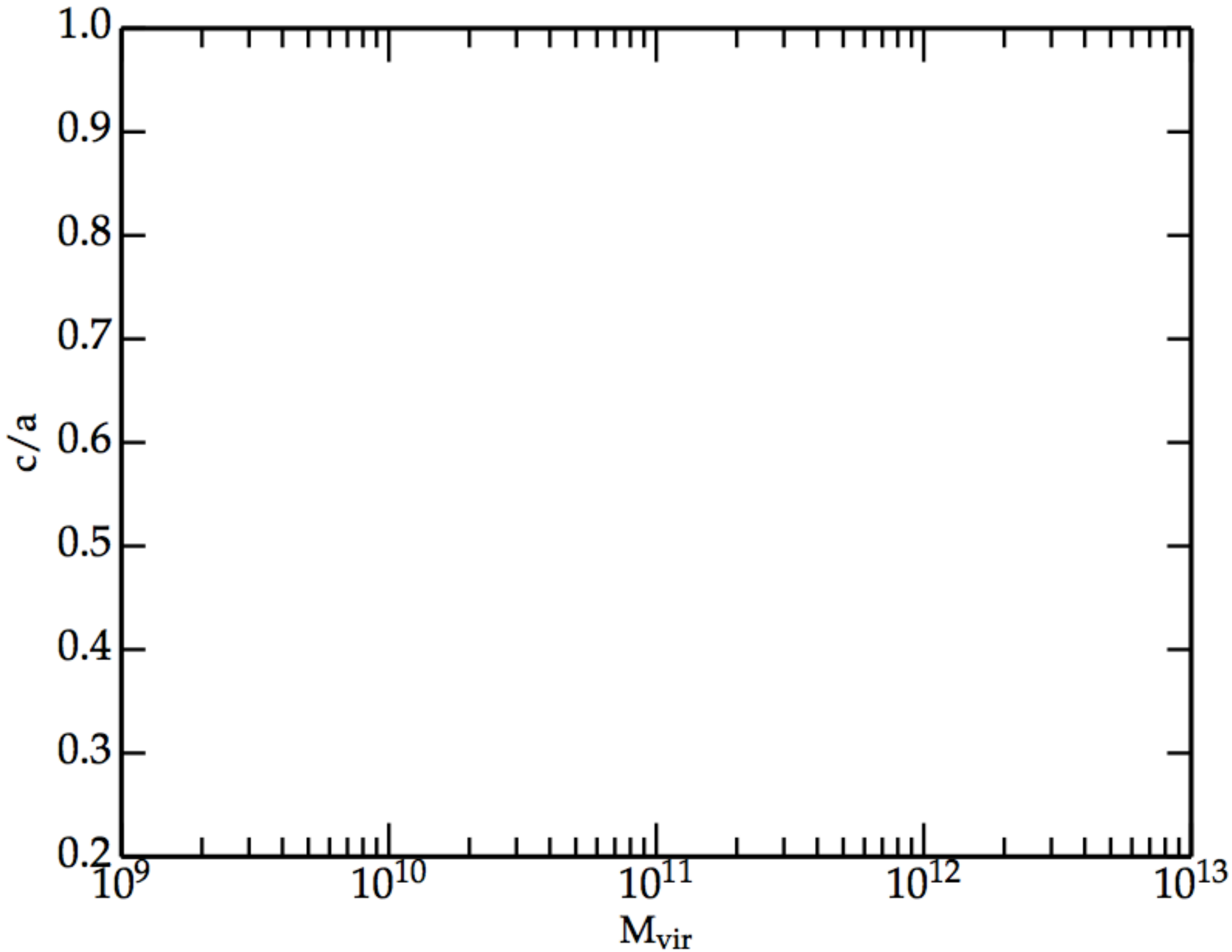
Butsky, Macciò+2016,
NIHAO-II



DM halo shape and f(v)

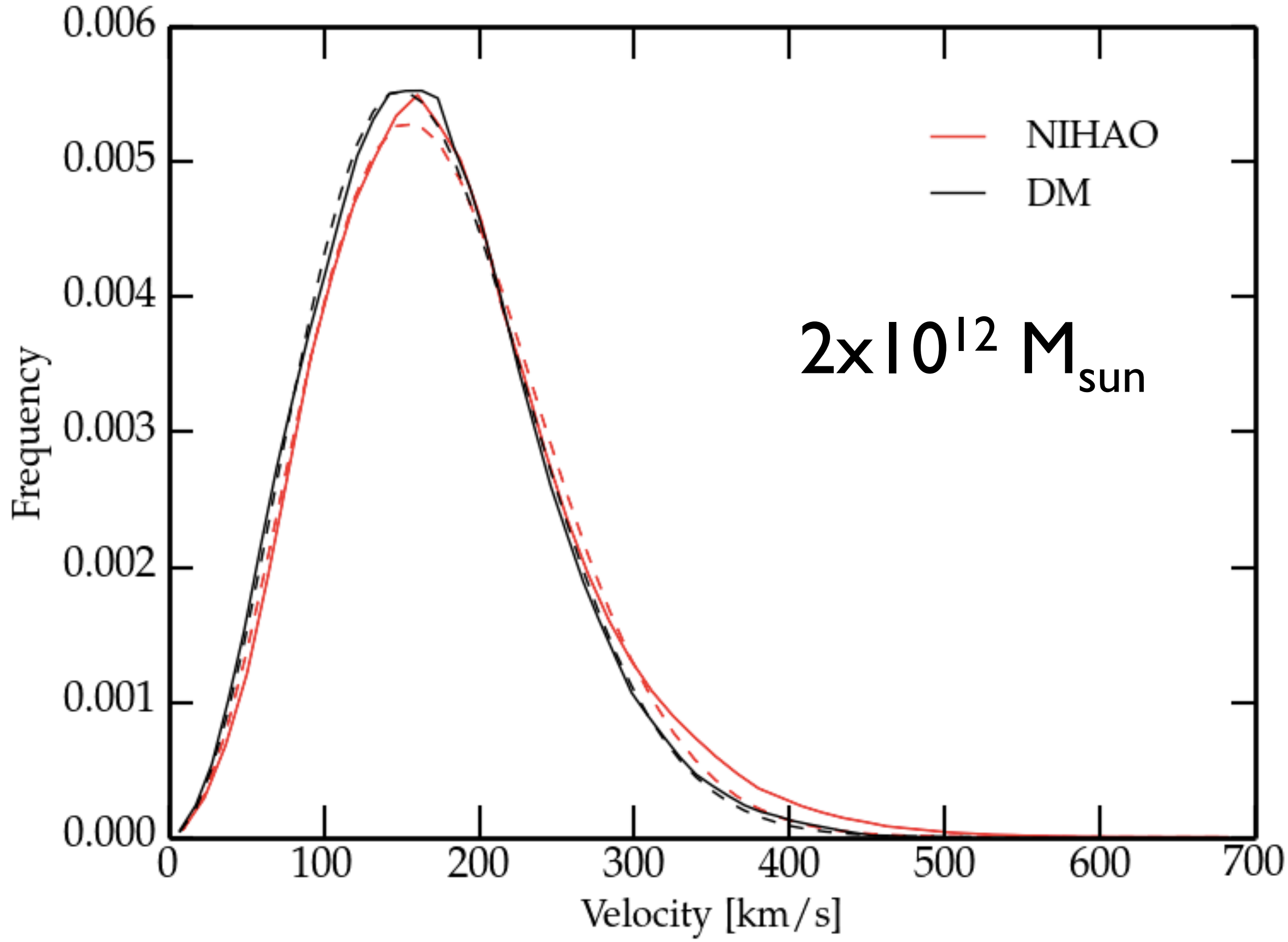


DM halo shape and f(v)

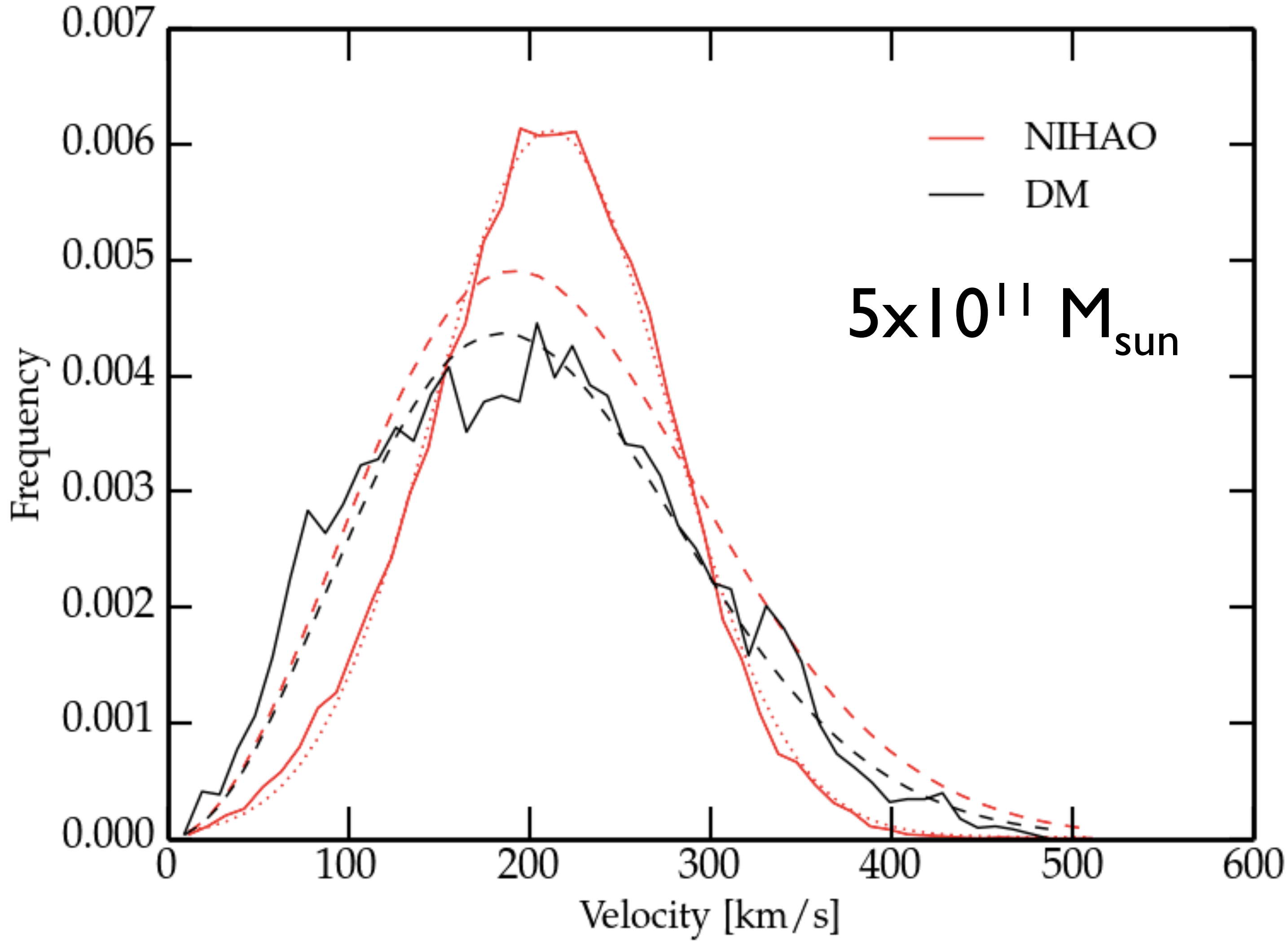


Butsky, Macciò+2016- NIHAO II

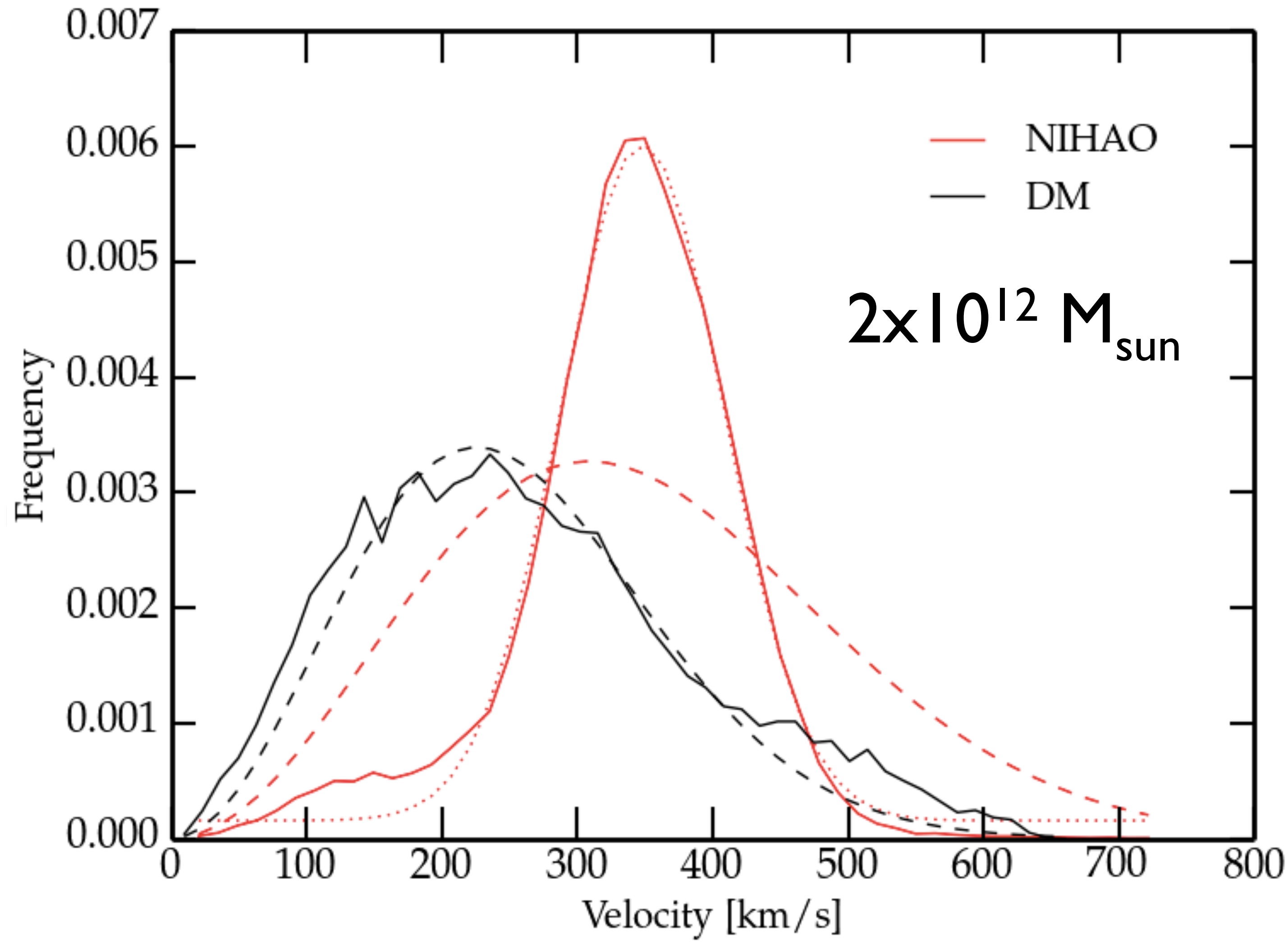
Global velocity distribution



Solar neighbors velocity distribution



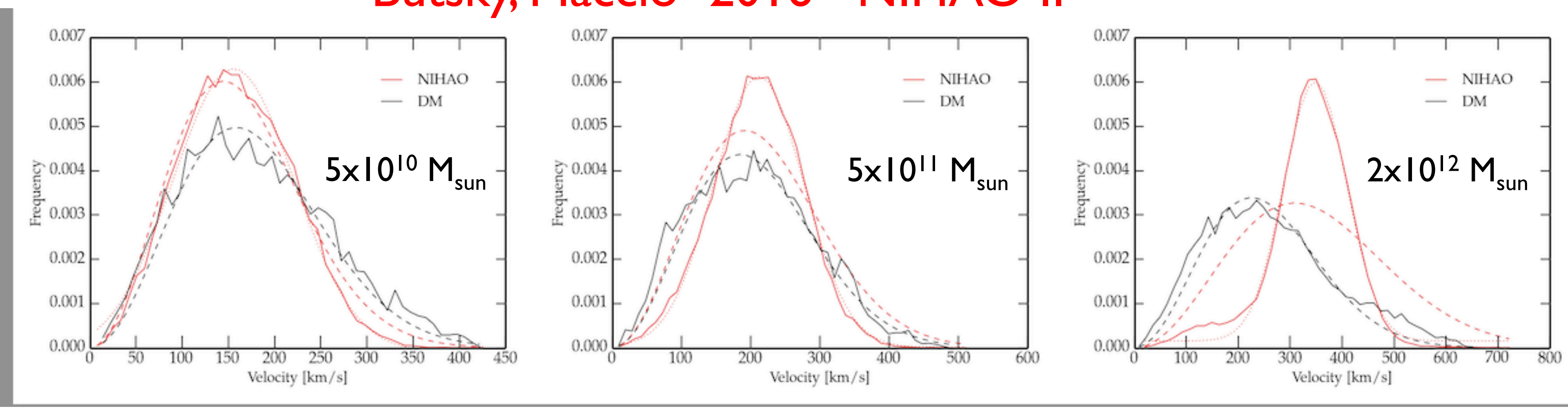
Solar neighbors velocity distribution



DM halo shape and f(v)

- DM Haloes are rounder when galaxy formation is taken into account
- Reshuffling of DM particles orbits (especially in the center)
- Gaussian velocity distribution (central limit theorem)

Butsky, Macciò+2016 NIHAO II



Conclusions

DM distribution in galaxies is strongly affected by baryons

NO universal profiles: cores and cusps are created and destroyed depending on stellar-to-halo mass and star formation history

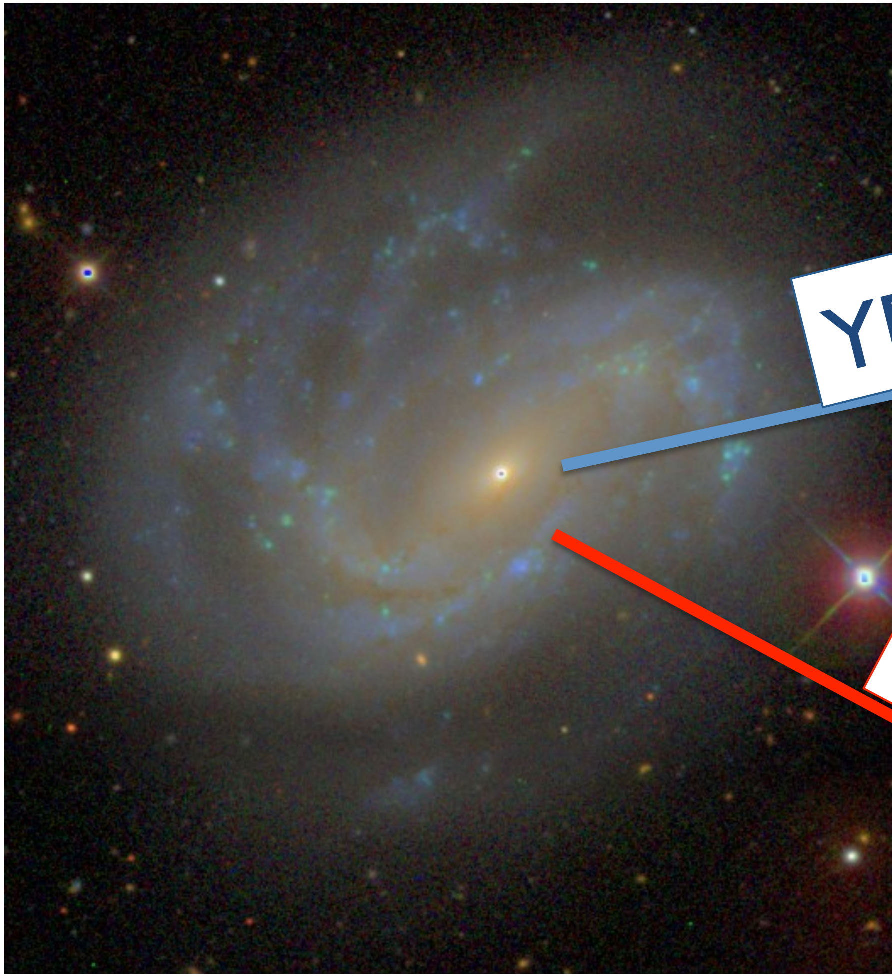
DM velocity distribution is Gaussian and not Maxwellian

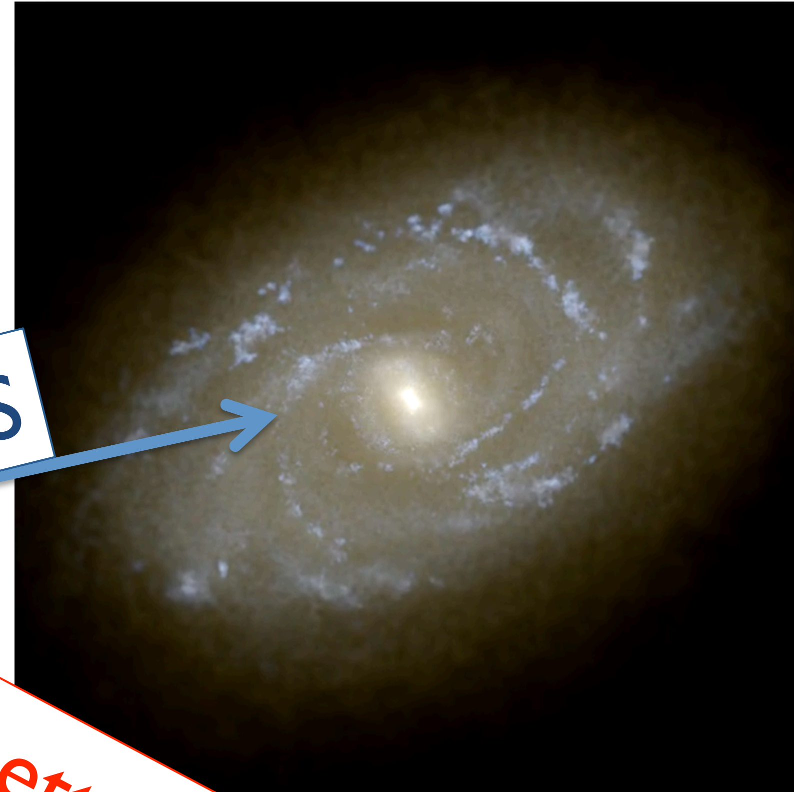
Take home message

Any comparisons of theoretical predictions with observational data can no longer rely on pure collisionless simulations, but must include the effects of visible matter.

Are baryons important at large scales?

Depends on precision!





Baryons Matter!

Thank you