SMALL SCALES PREDICTIONS OF THE ΛCDM PARADIGM

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Outline

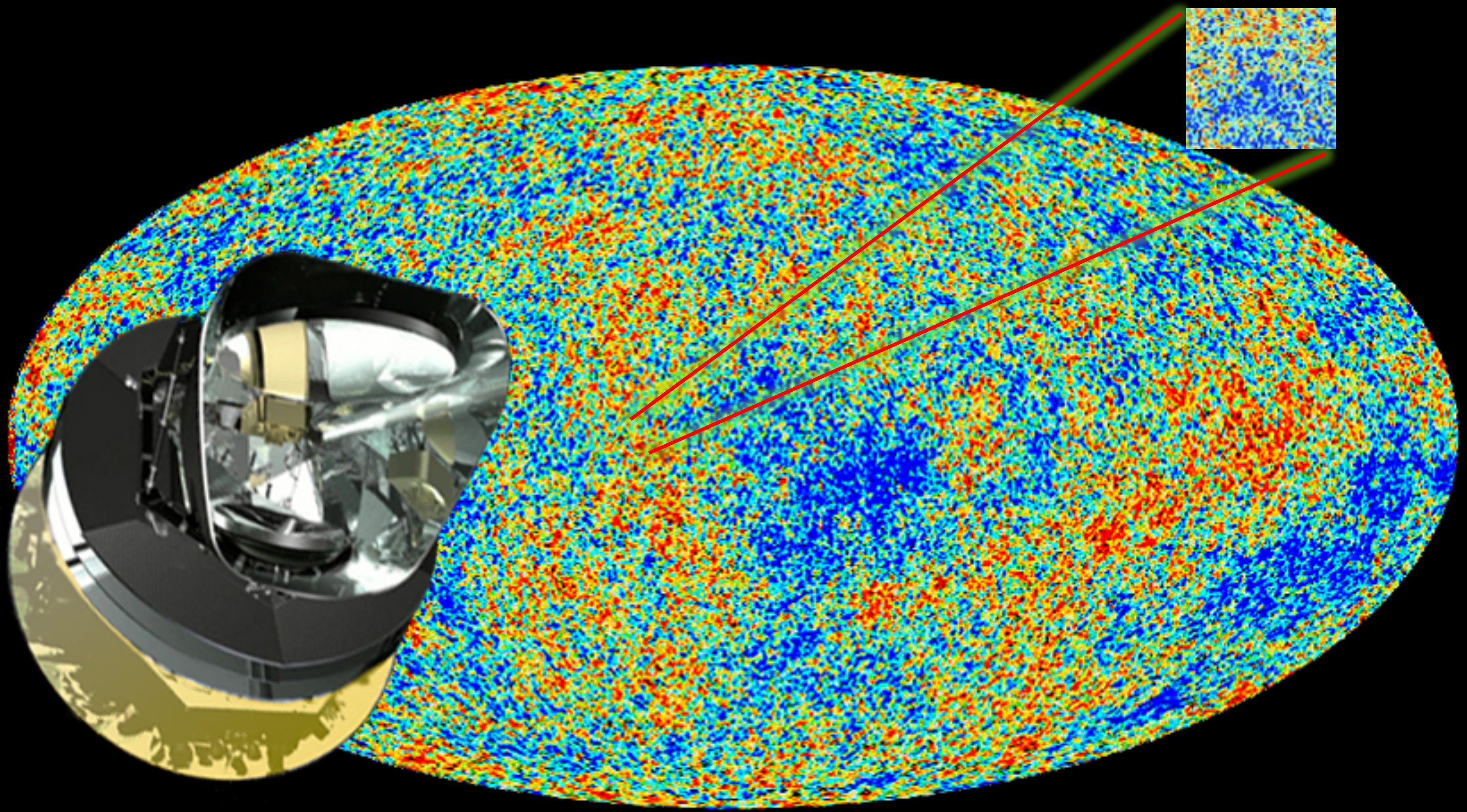
-Abundance Matching

-Missing Satellites

-Too Big to Fail

-Measuring Velocities directly

-Modelling galaxies: feedback



Planck

Details of the simulations

Parallel chemo-dynamical galaxy evolution code

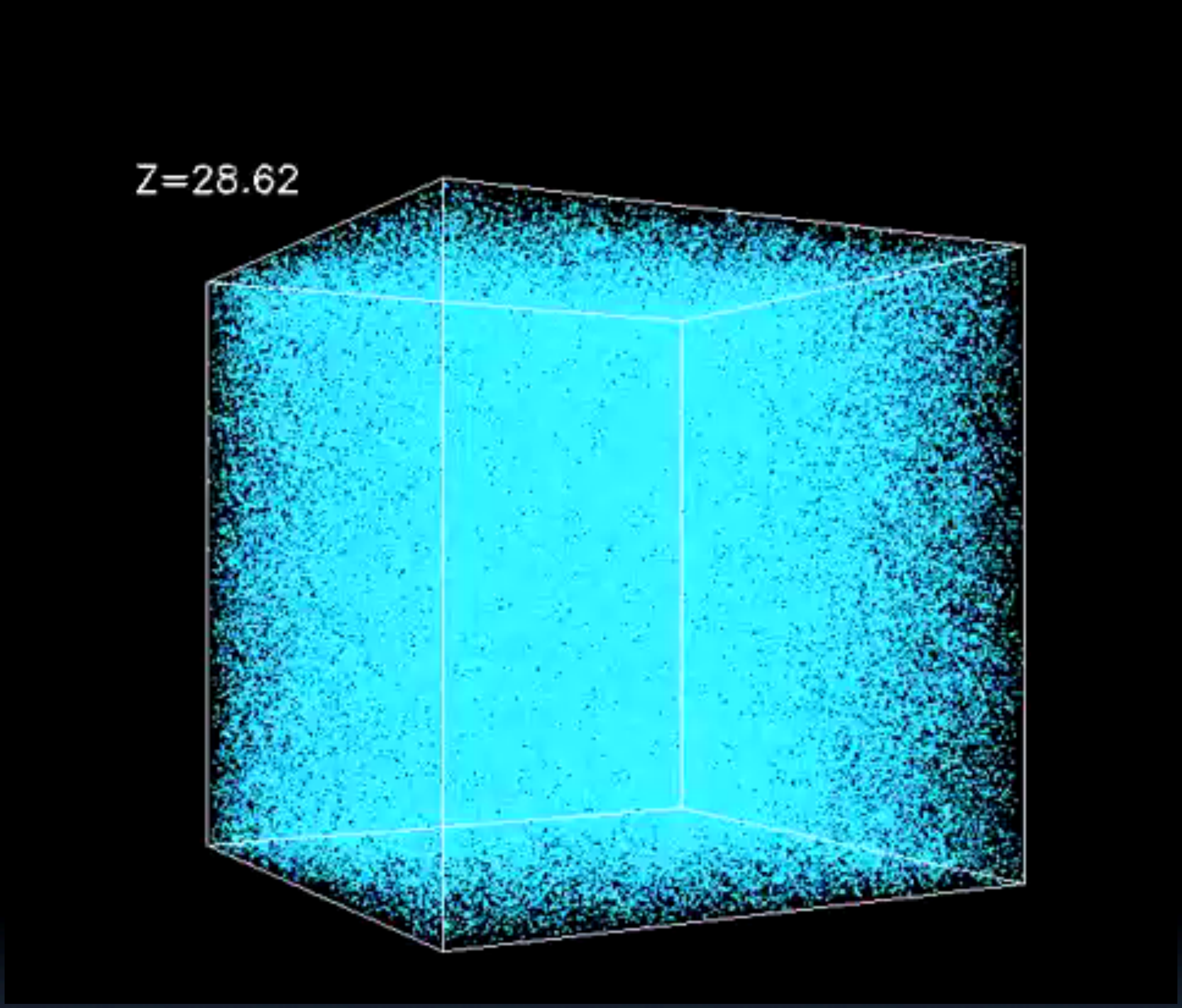
Tree N-body –Dark Matter & stars:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f = 0$$

$$\frac{\mathrm{d}f}{\mathrm{d}t} \equiv \frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{x}} - \frac{\partial \Phi}{\partial \mathbf{r}}\frac{\partial f}{\partial \mathbf{v}} = 0$$

potential Φ is the solution of Poisson's eqn:

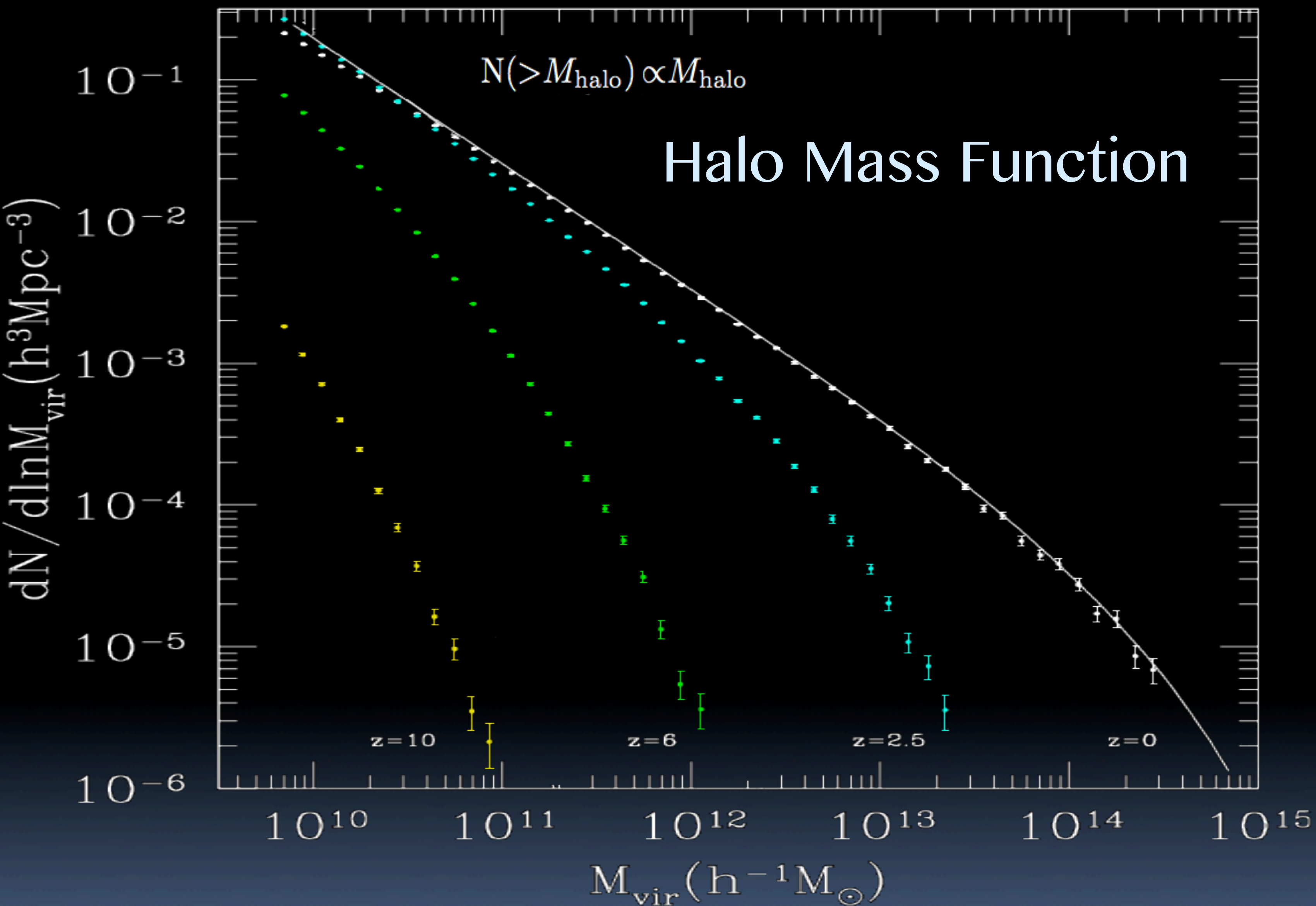
$$\nabla^2 \Phi(\mathbf{r}, t) = 4\pi G \int f(\mathbf{r}, \mathbf{v}, t)\, \mathrm{d}\mathbf{v}$$



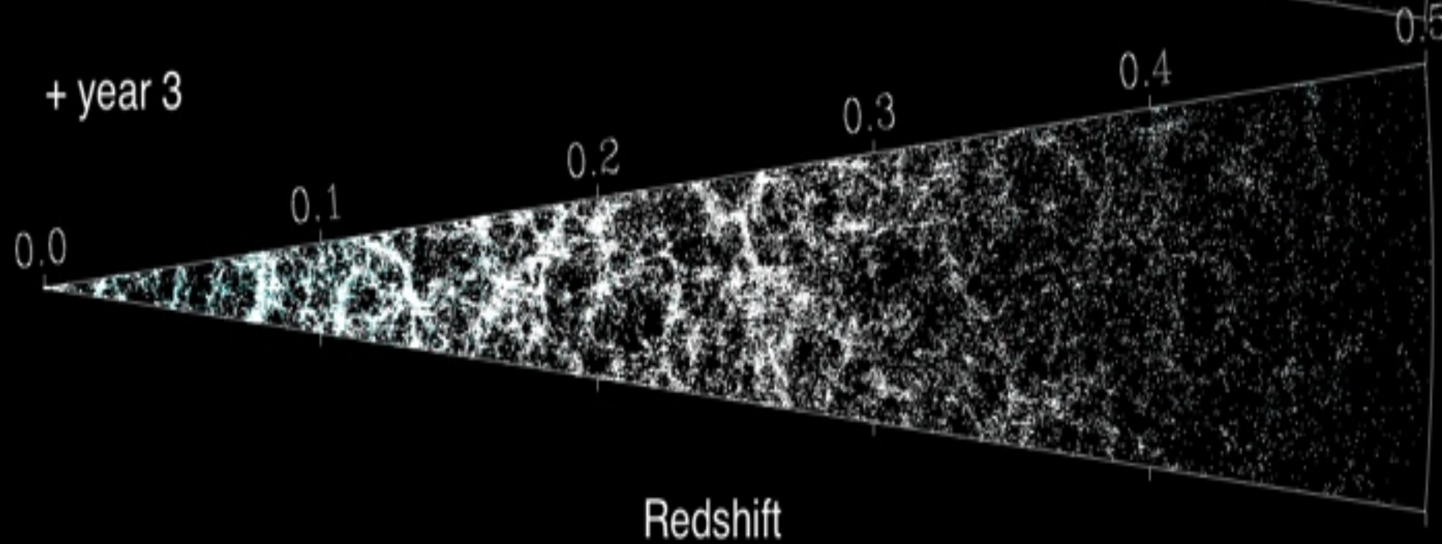
Credit: A.Kravtsov, A. Klypin

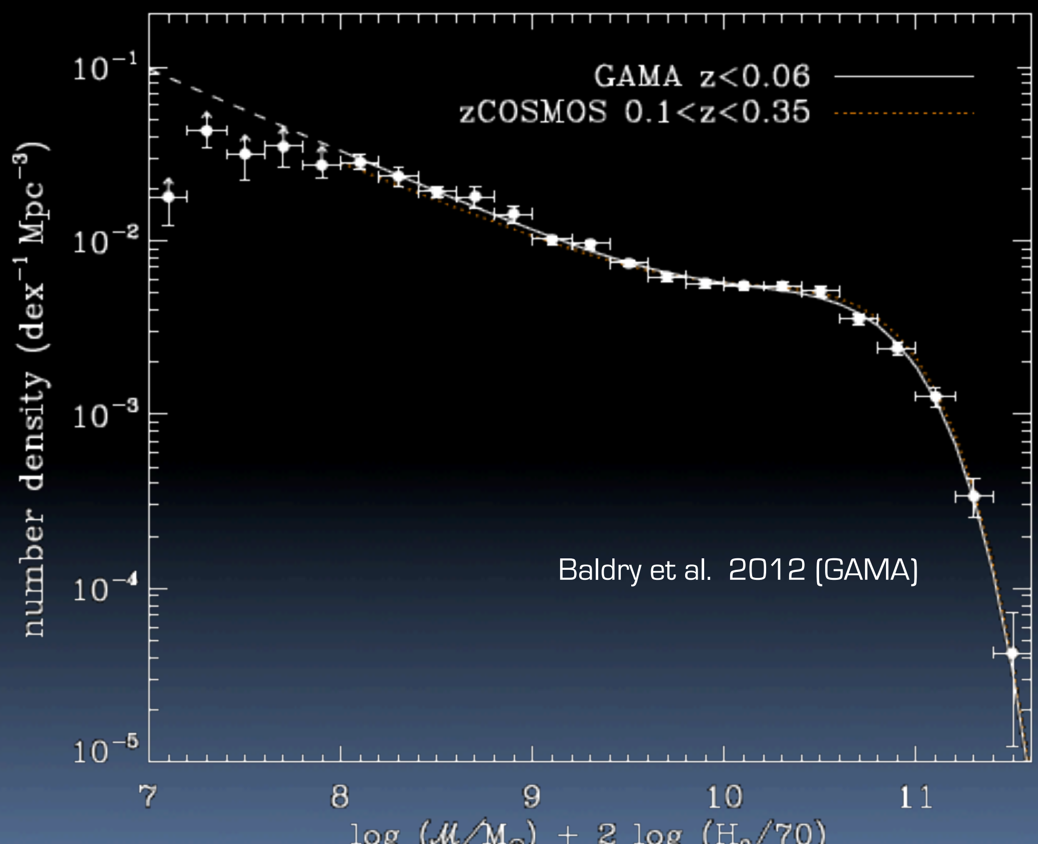
N-body simulations

Halo Mass Function

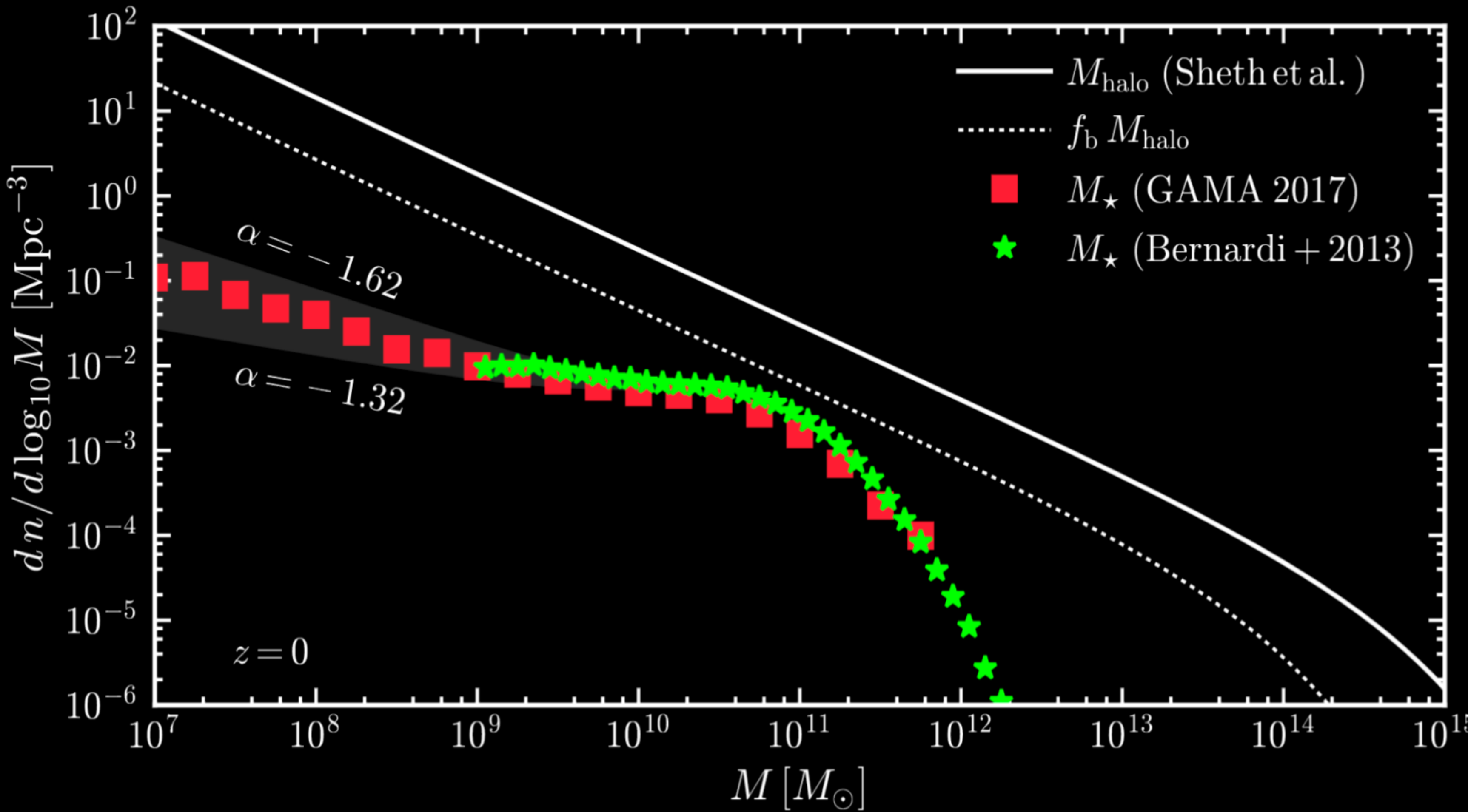


Klypin, Trujillo-Gomez, Primack 2012 (Bolshoi)





Stellar Mass Function



Shape of Stellar Mass Function and Halo Mass Function are very different

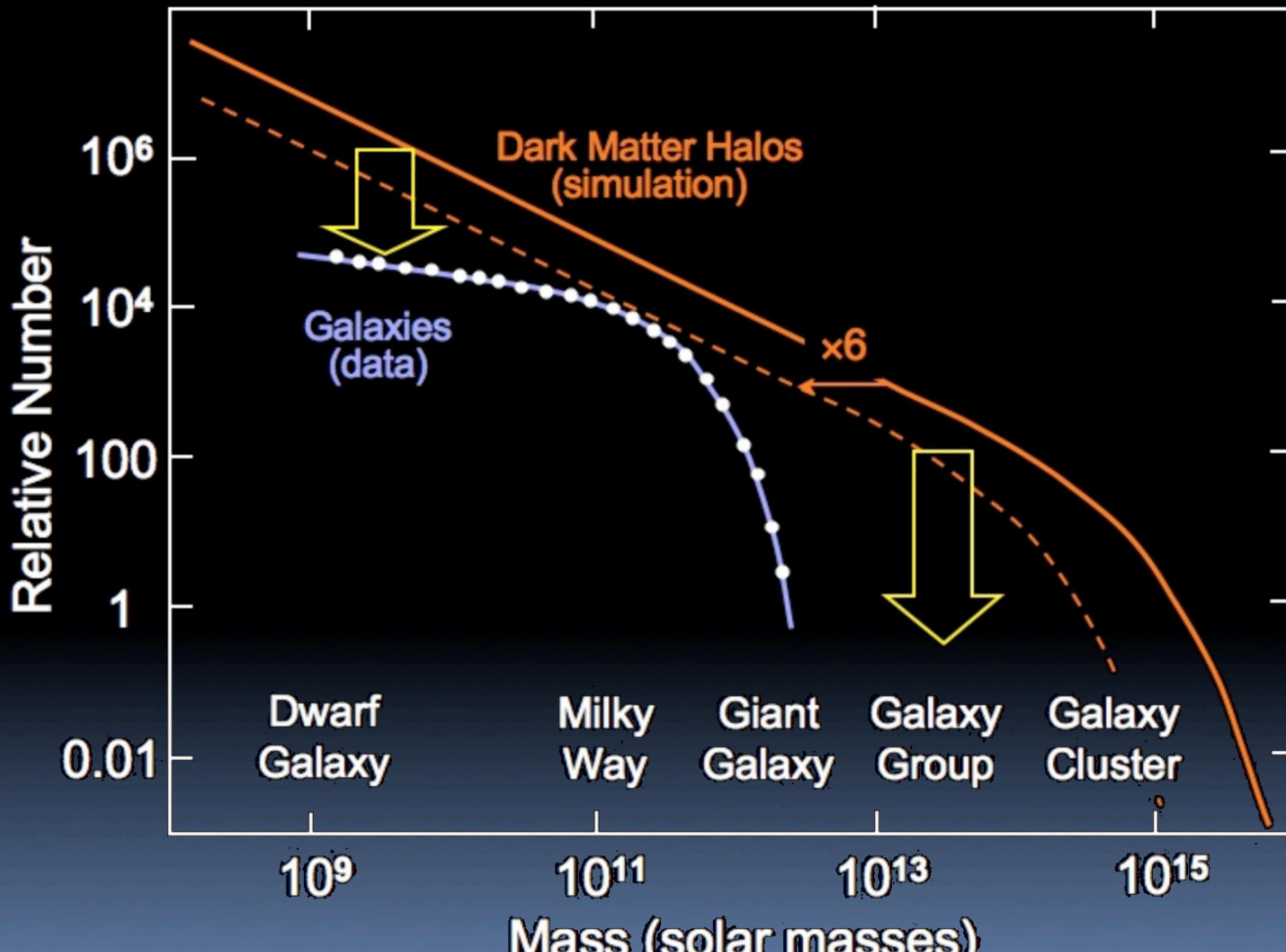
Lets just apply the widely invoked but poorly understood Frenk Principle

the **Frenk Principle**:

"If the Cold Dark Matter Model does not agree with observations, there must be physical processes, no matter how bizarre or unlikely, that can explain the discrepancy."

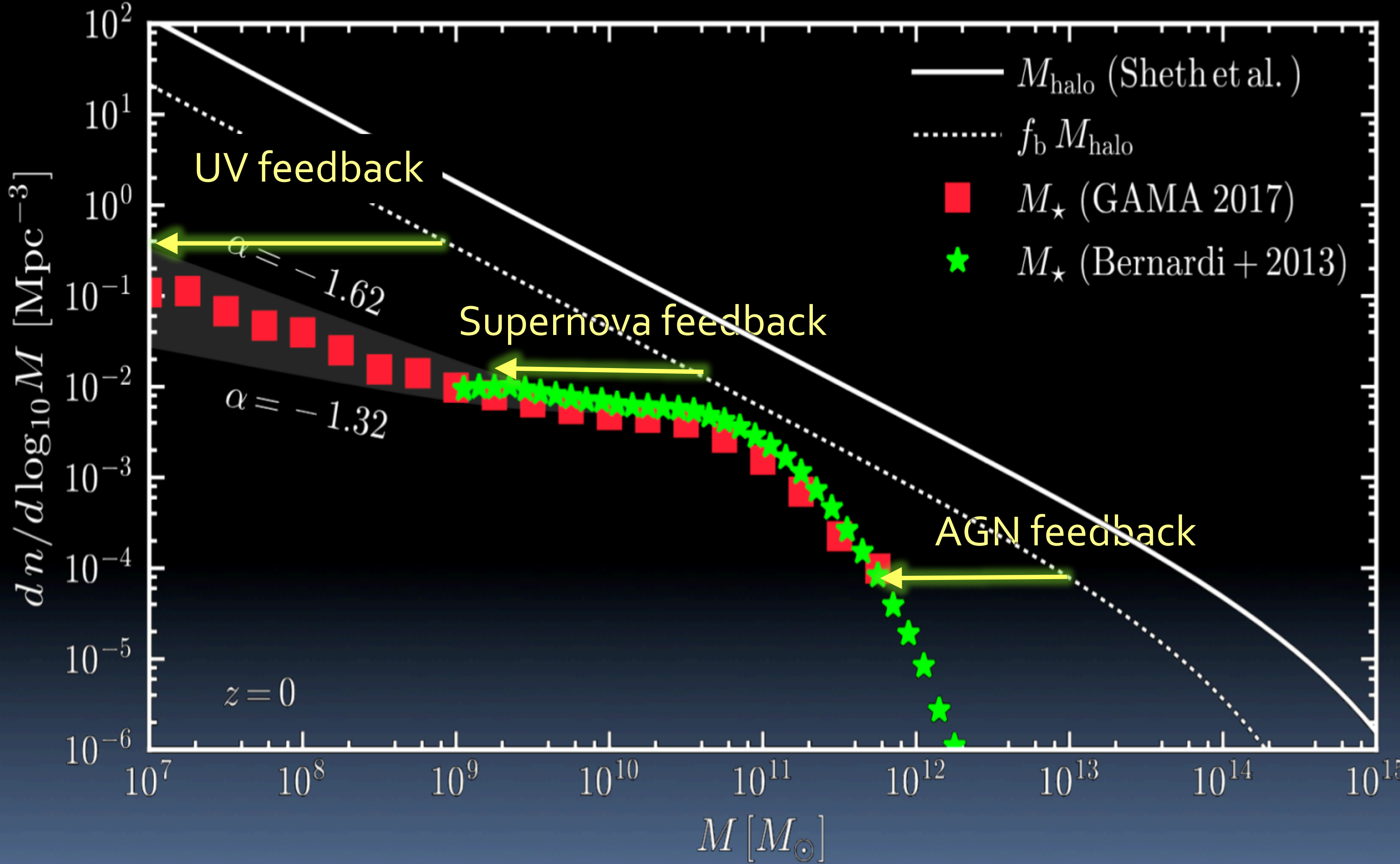
George Efstathiou 1996

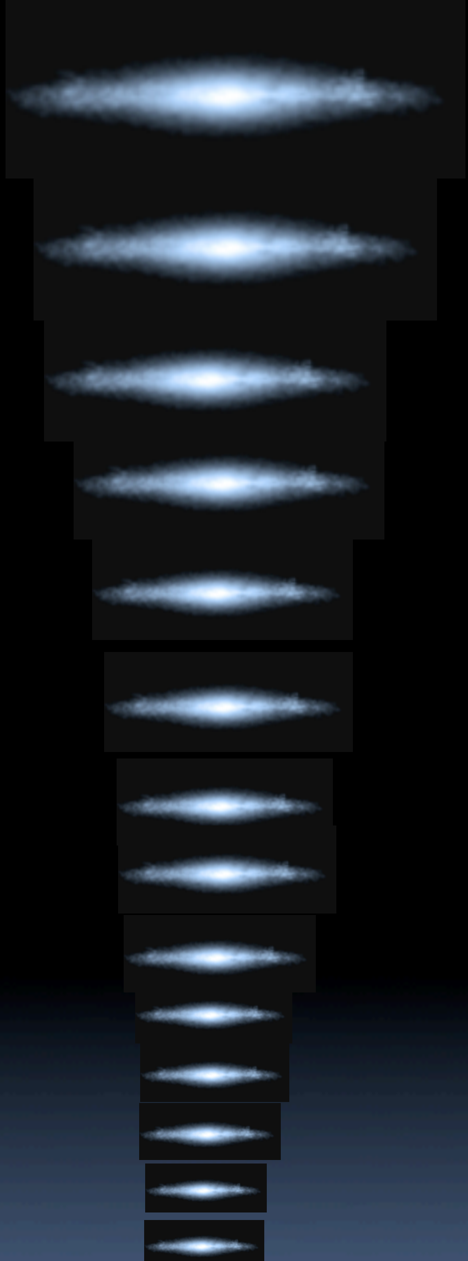
Halo and Galaxy Mass Distributions

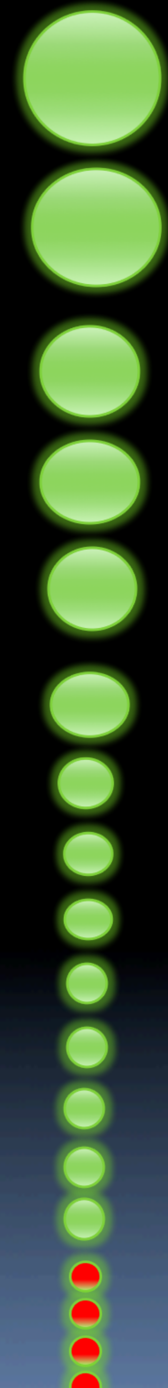


Abundance Matching

an application of the Frenk Principle





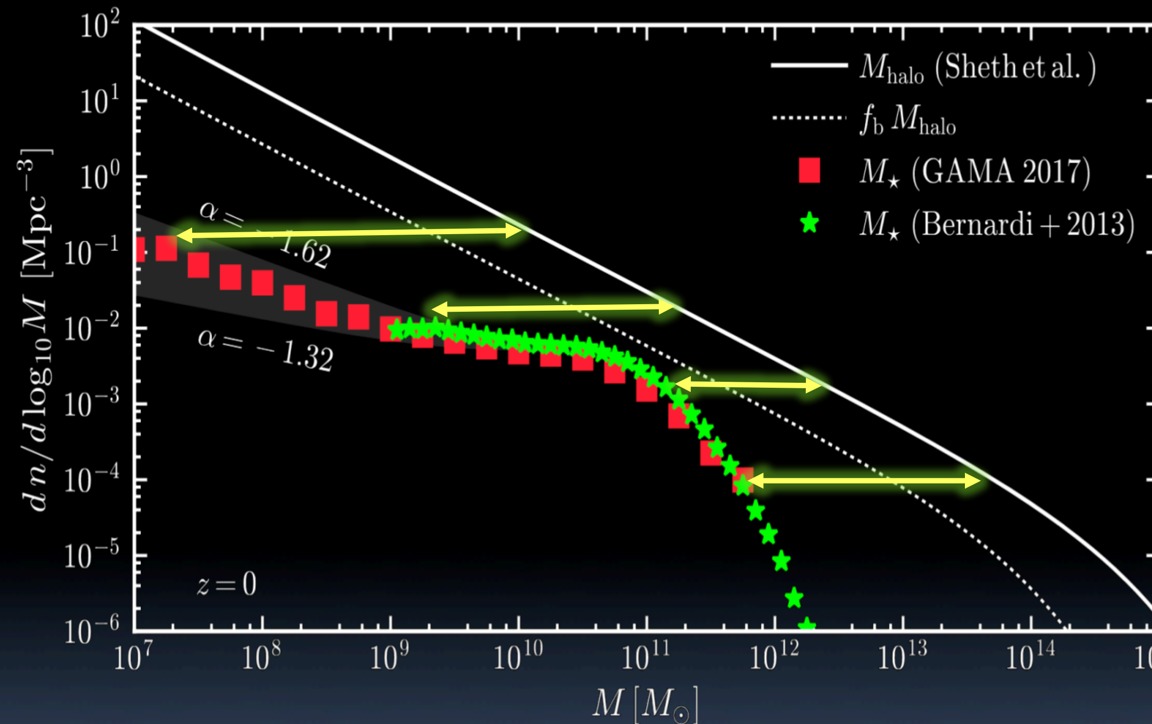


Abundance Matching

chose equal volumes:

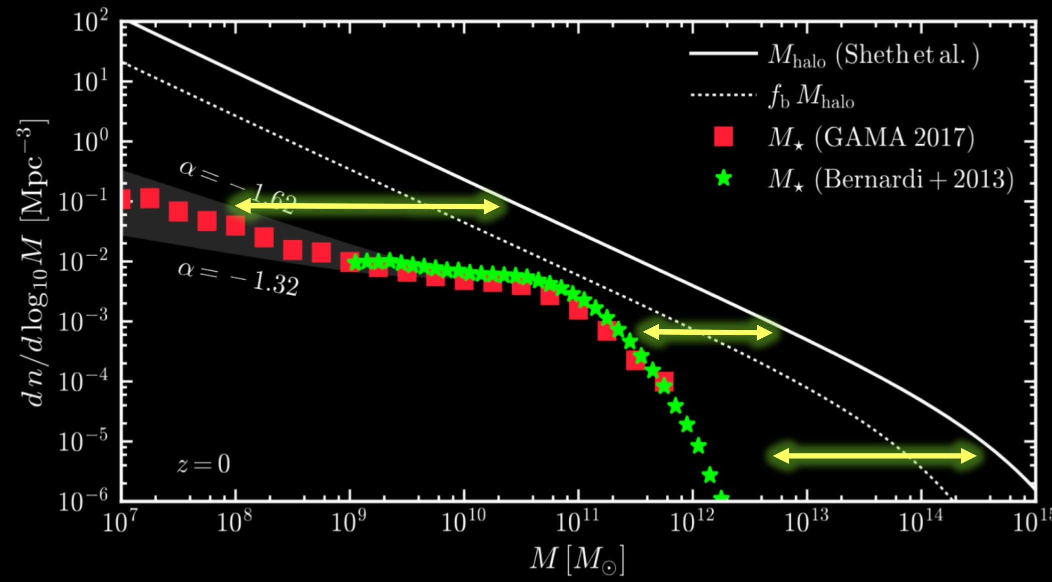
-order galaxies by stellar mass

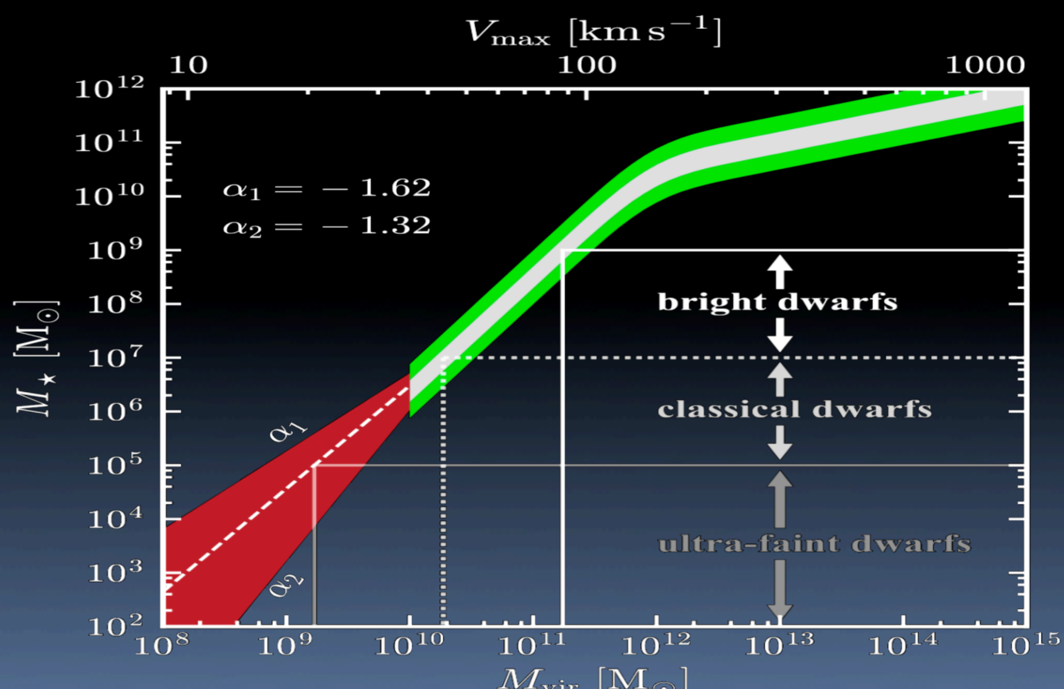
-order halos by halo mass



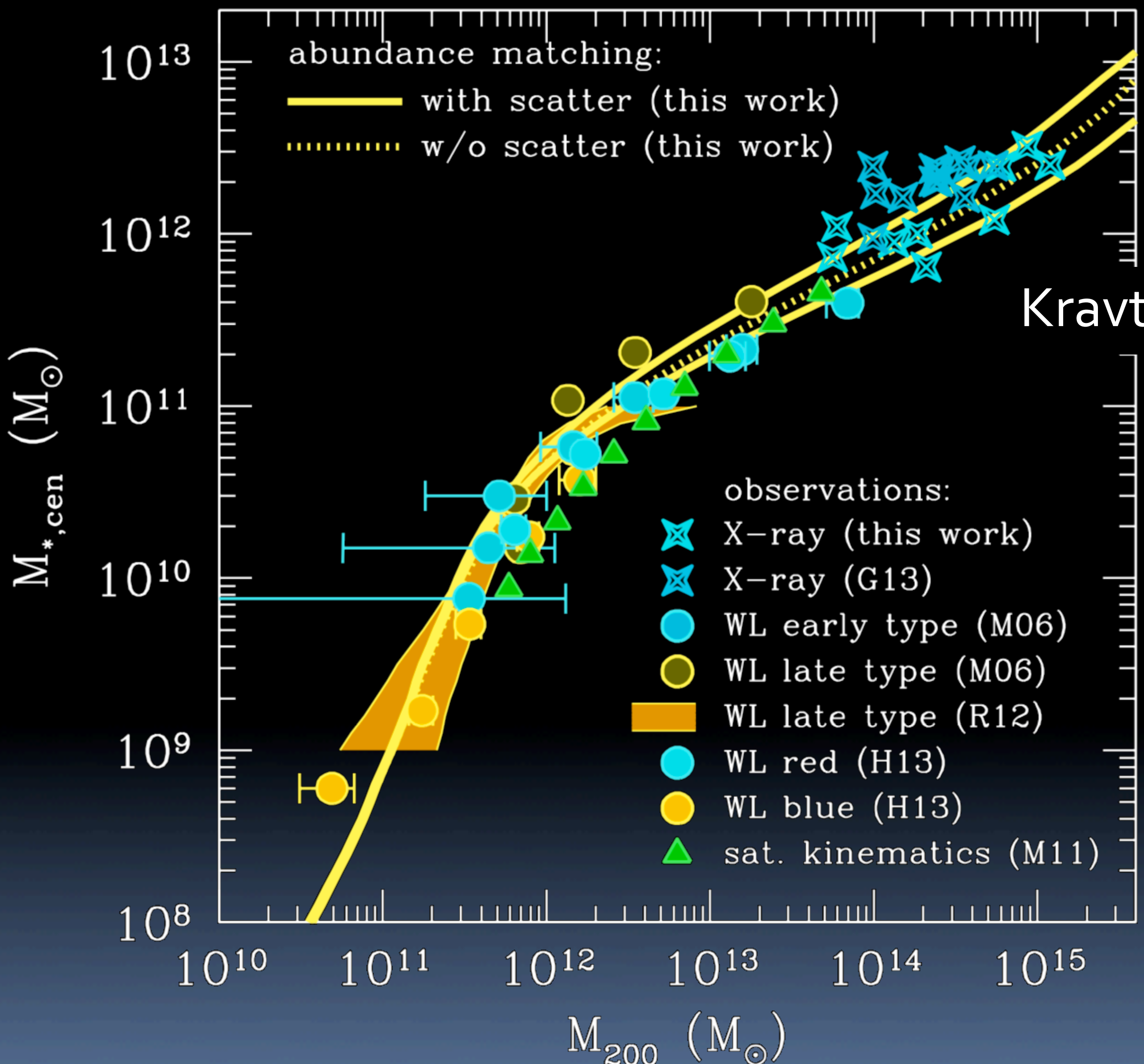
Drawing lines of constant number density

See also HOD, galaxy bias… for other related applications of the Frenk principle


$M_{\rm halo}$ (Sheth et al.)
$f_{\rm b}\, M_{\rm halo}$
$M_\star$ (GAMA 2017)
$M_\star$ (Bernardi + 2013)
$\alpha = -1.62$
$\alpha = -1.32$
$z = 0$
$dn/d\log_{10}M$ [Mpc^{-3}]
M [$M_\odot$]


$V_{\rm max}$ [km s^{-1}]
10
100
1000
$\alpha_1 = -1.62$
$\alpha_2 = -1.32$
bright dwarfs
classical dwarfs
ultra-faint dwarfs
α_1
α_2
$M_\star$ [M$_\odot$]
$M_{\rm vir}$ [M$_\odot$]

Independent mass measurements

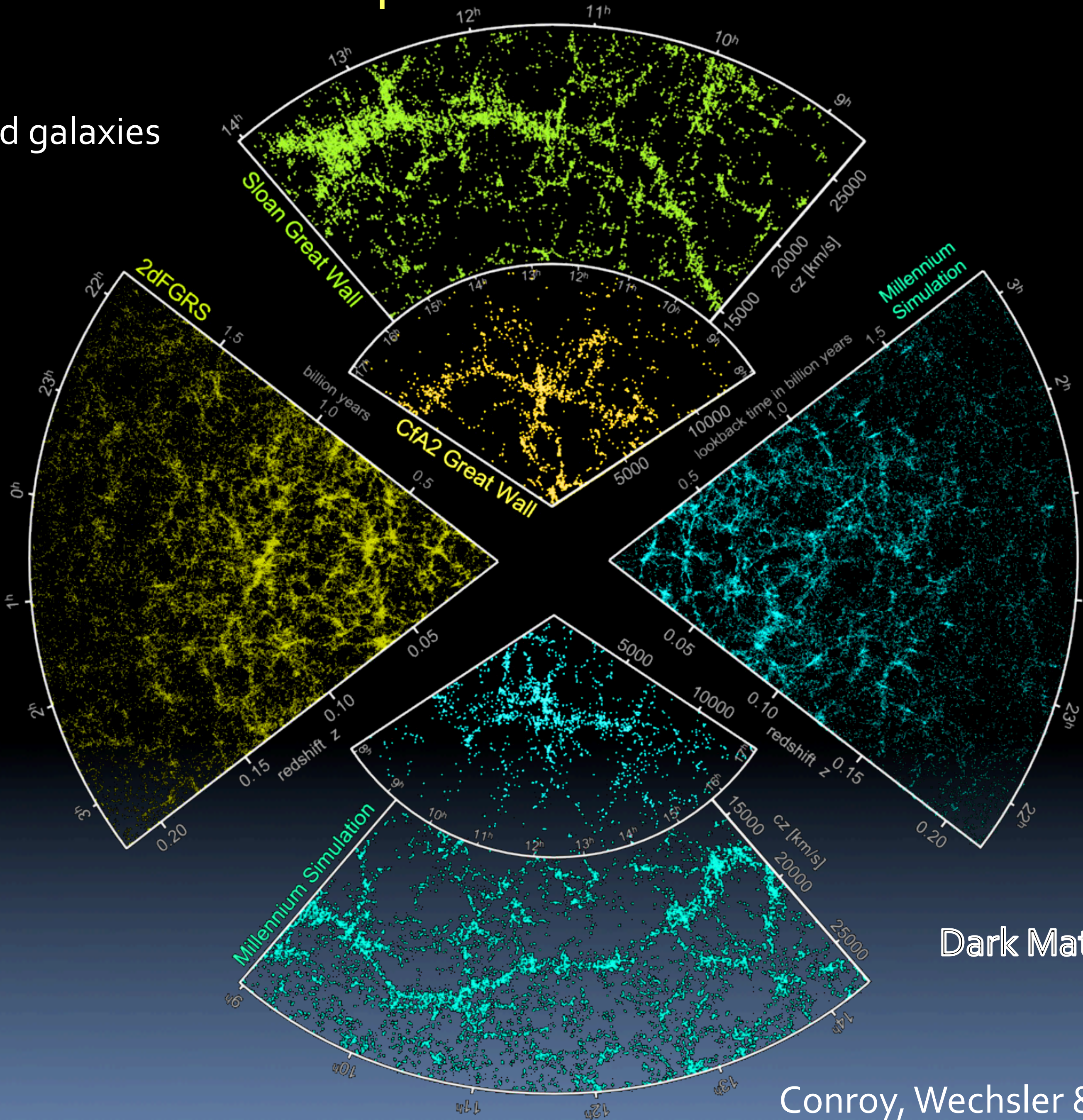


Kravtsov+ 2014

Support for the Frenk principle

Spatial Distribution

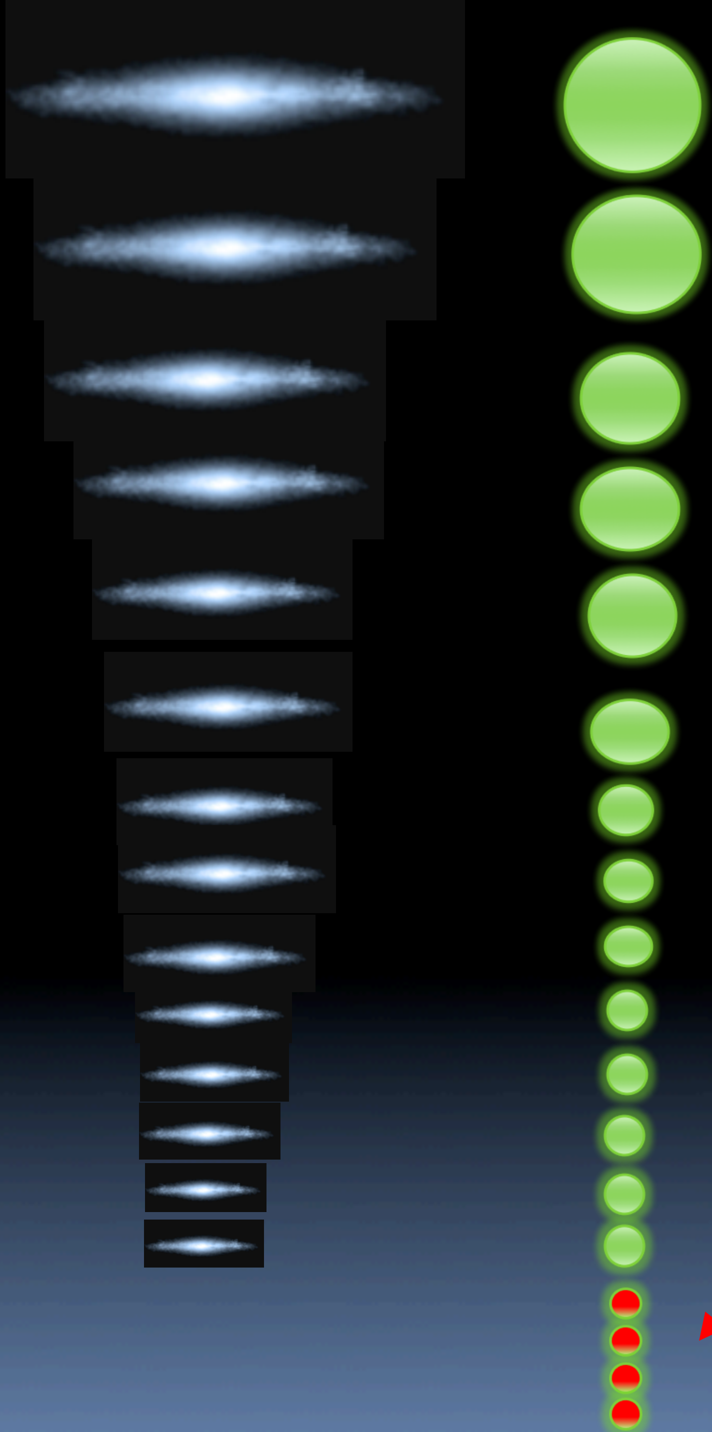
Observed galaxies



Dark Matter Simulations

Conroy, Wechsler & Kravtsov 2006

Missing Satellite Problem



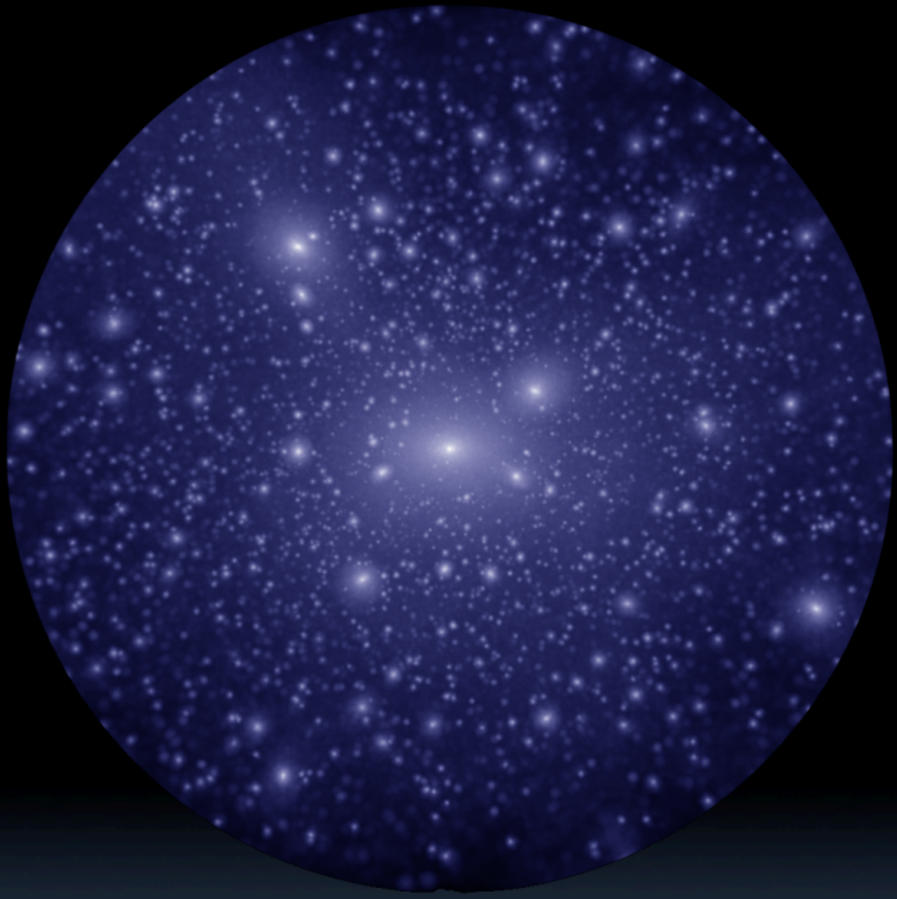
Many more halos than galaxies

Klypin+ 98, Moore+ 98

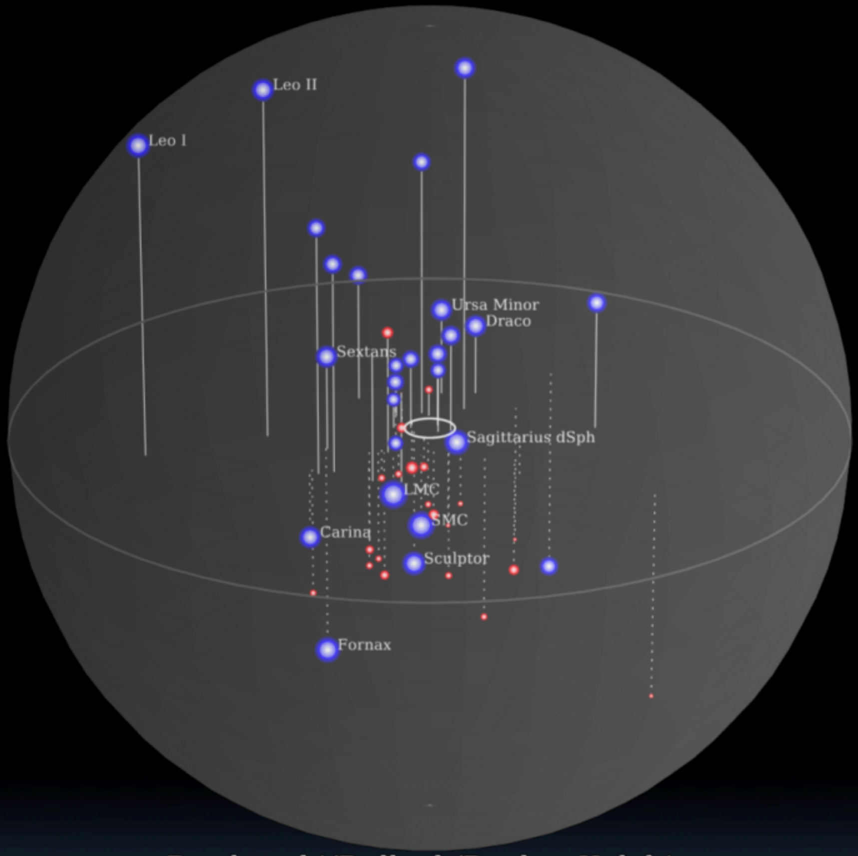
Generalised to larger volumes by blind HI surveys: Not just satellites are missing, also low mass galaxies in the field.

Problem persists in Local Group environments

Missing Satellites

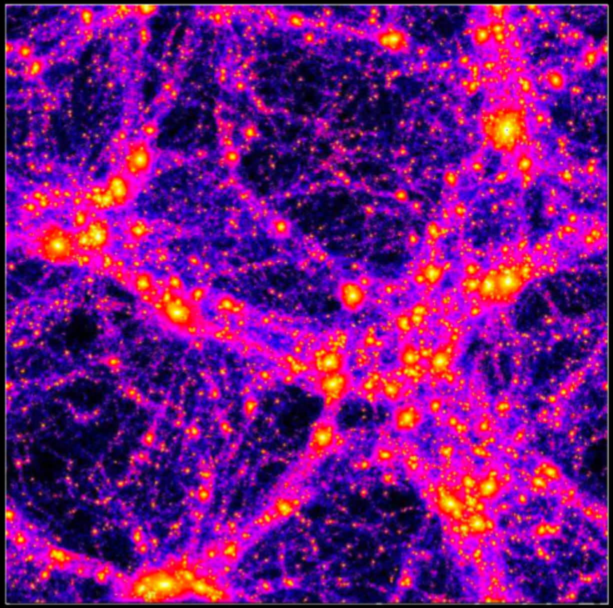


N-body CDM simulation

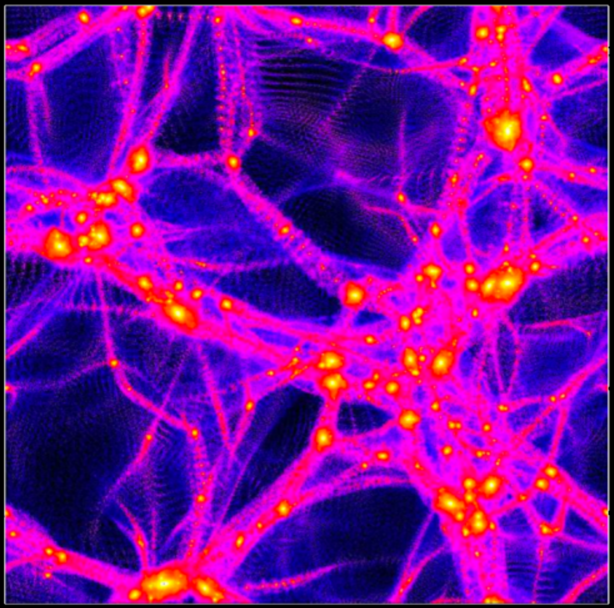


Observed Milky Way Satellite Galaxies

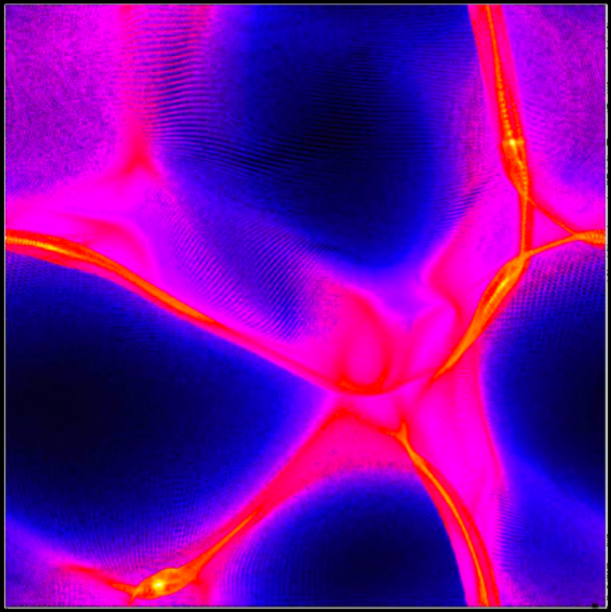
Maccio et al. 2012



CDM



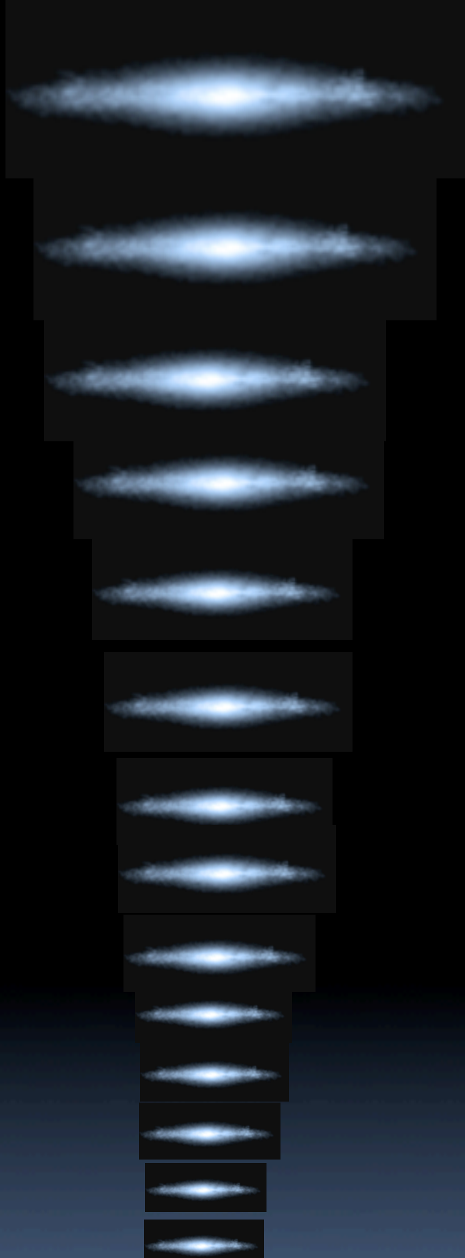
WDM
Mass=2keV

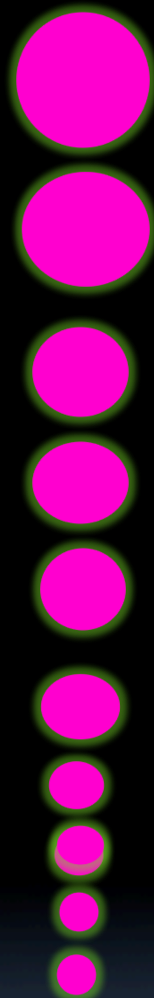


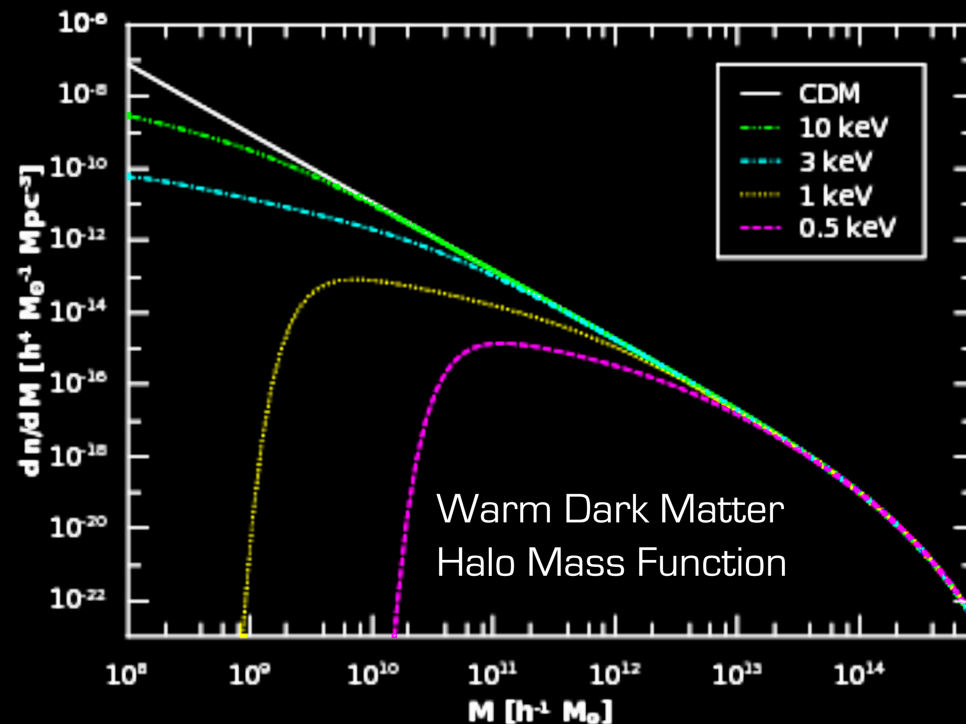
WDM
Mass=0.05keV

Warm Dark Matter dampens the power on small scales

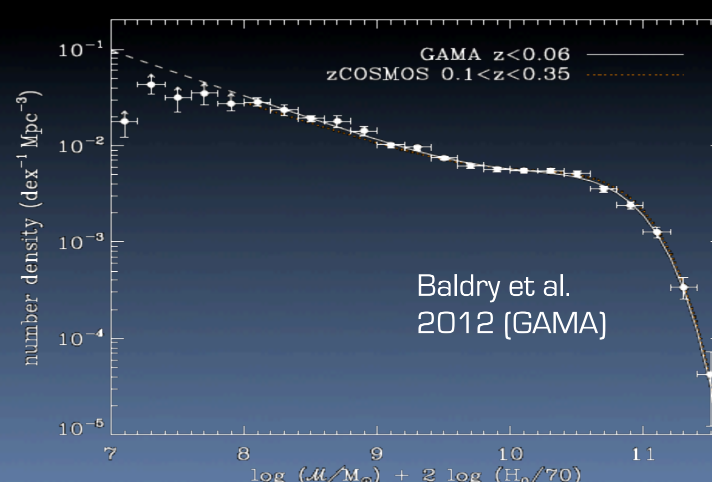
Abundance Matching with warm dark matter



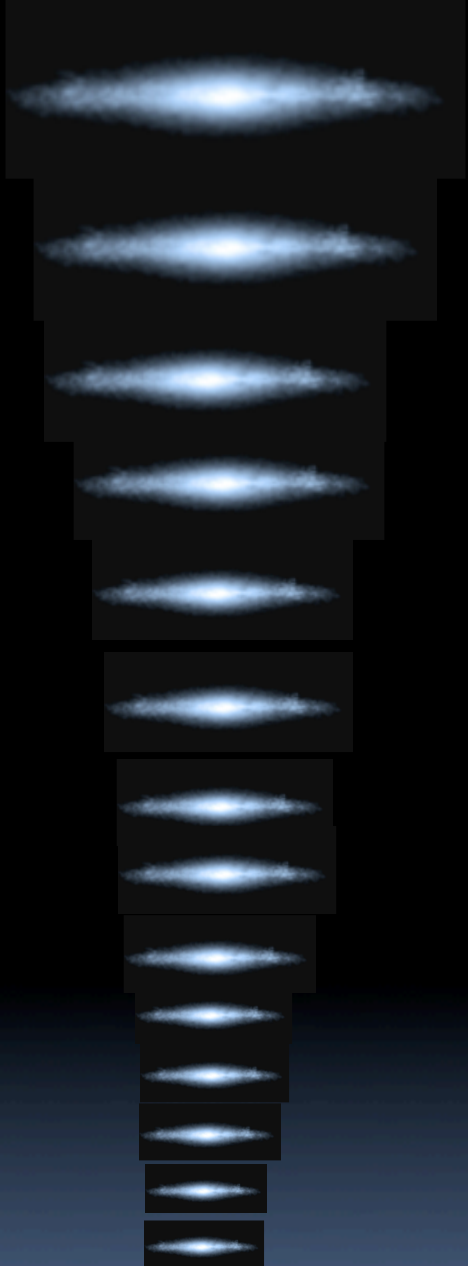


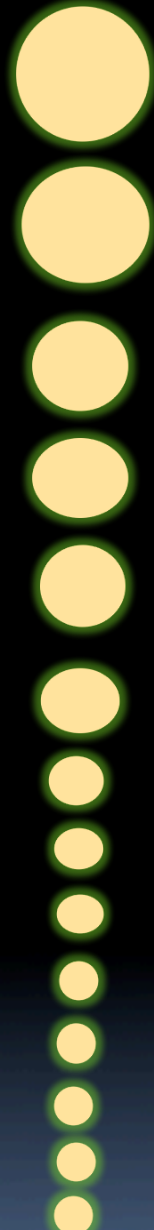


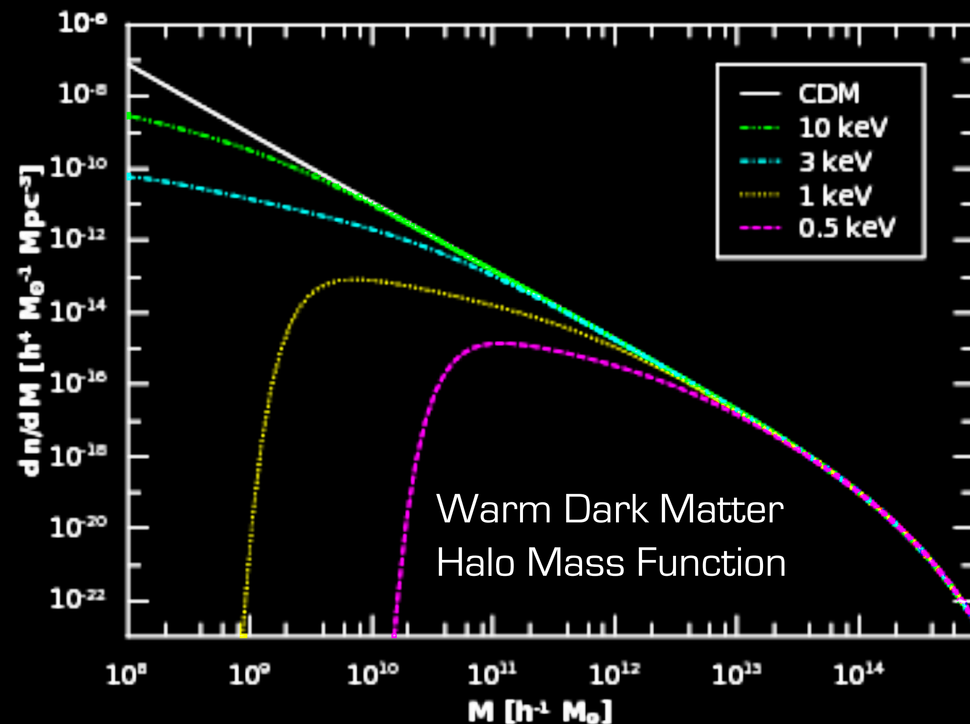
Cant be too warm

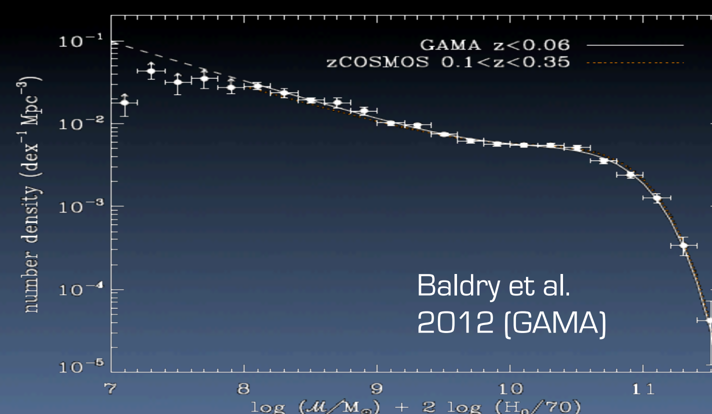


Abundance Matching with warm dark matter





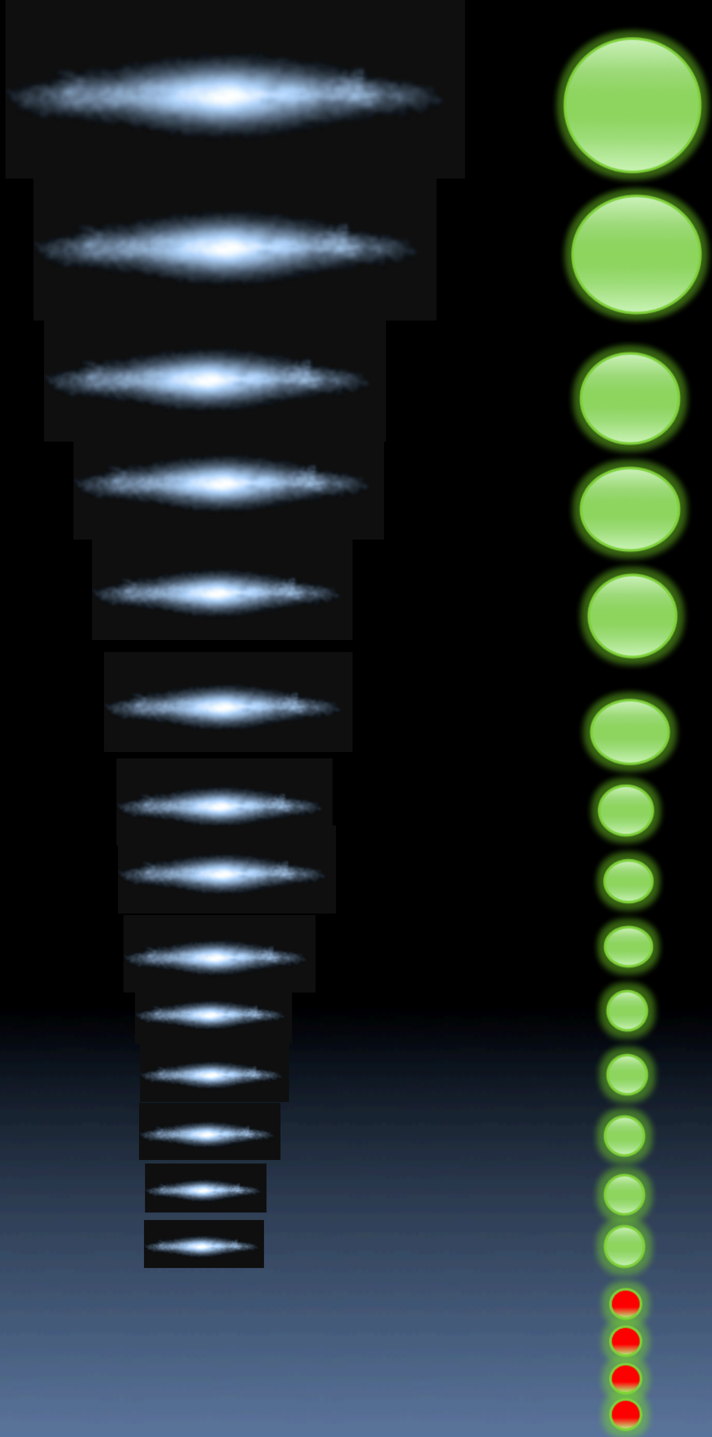




Constrained to be >5.5 KeV

Lovell et al. 2016 (several caveats here)

At such masses, cusp/core issue is not solved (Maccio et al. 2013, see Di Cintio talk)



Missing Satellites

Baryon physics solution within CDM cosmology:

UV background radiation creates a minimum mass for gas to cool on to halos (Bullock+2001)

Many more halos than galaxies

Klypin+ 98, Moore+ 98

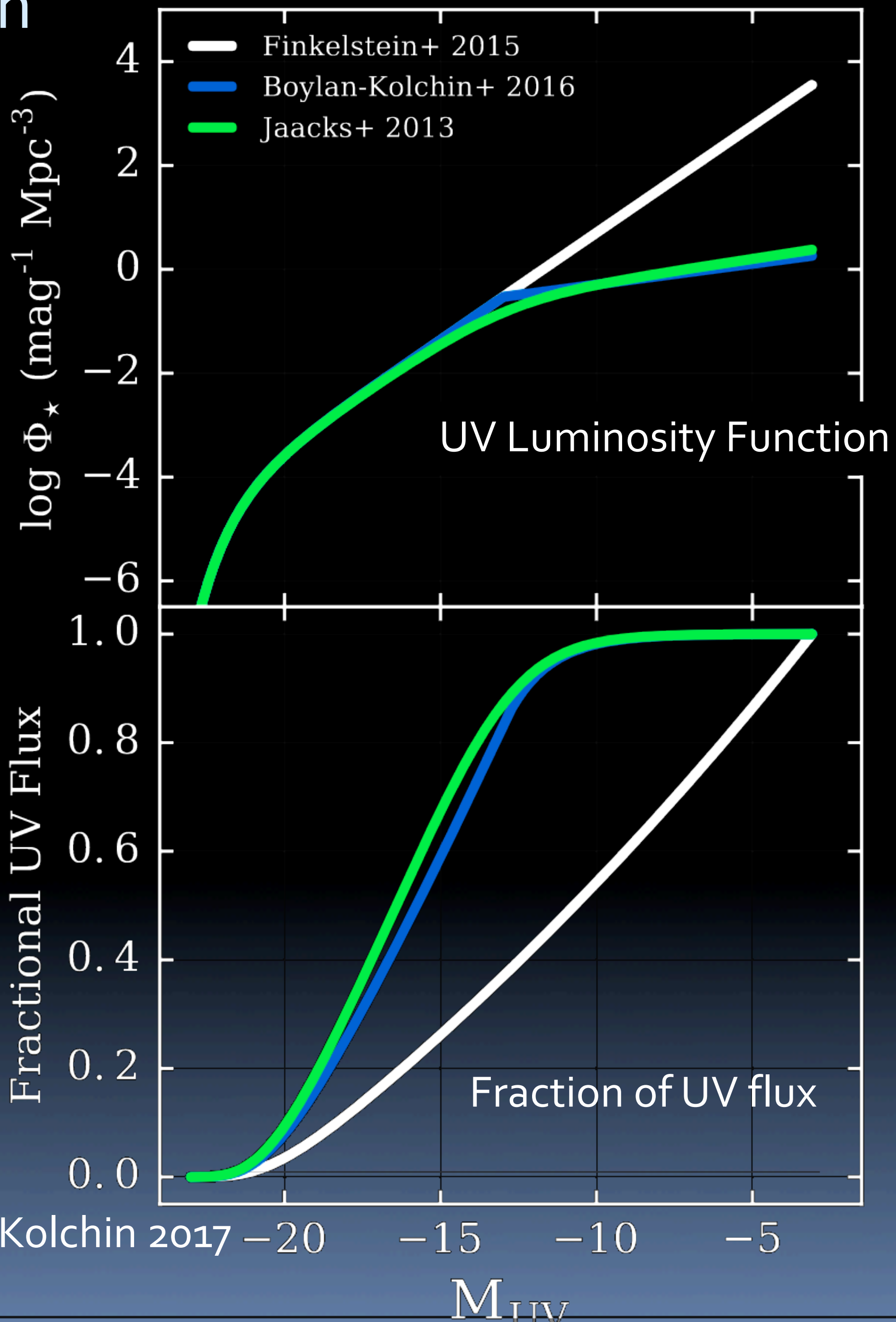
An aside on re-ionisation

UV background radiation (ionization) prevents Star Formation in low mass halos (Bullock et al. 2001)

Low mass galaxies play an important role in re-ionising the Universe

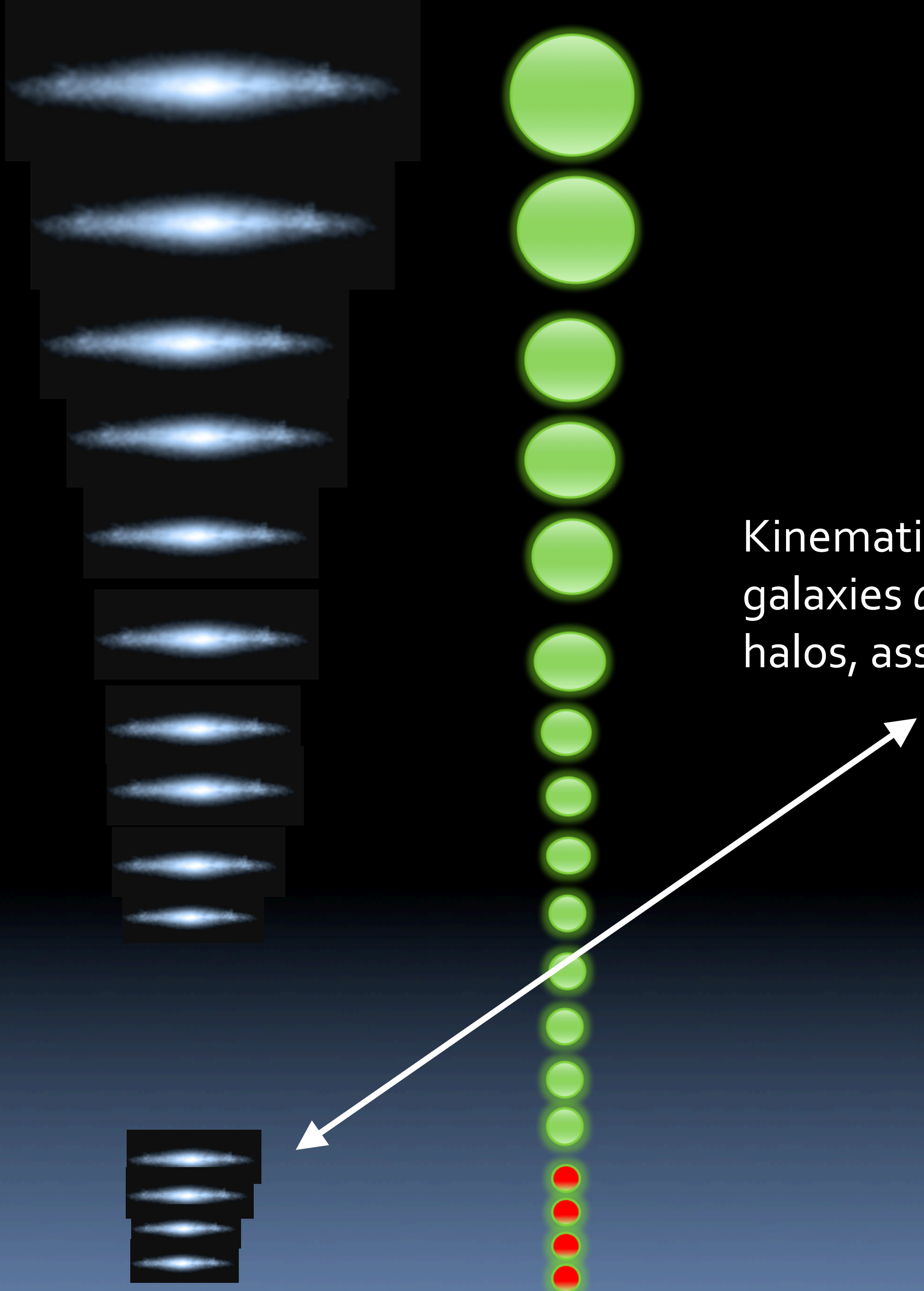
Constraints from Local Universe…
self consistently model star formation and feedback from ionization and invoke observational constraints

Sorce talk: Local Universe simulations including re-ionisation



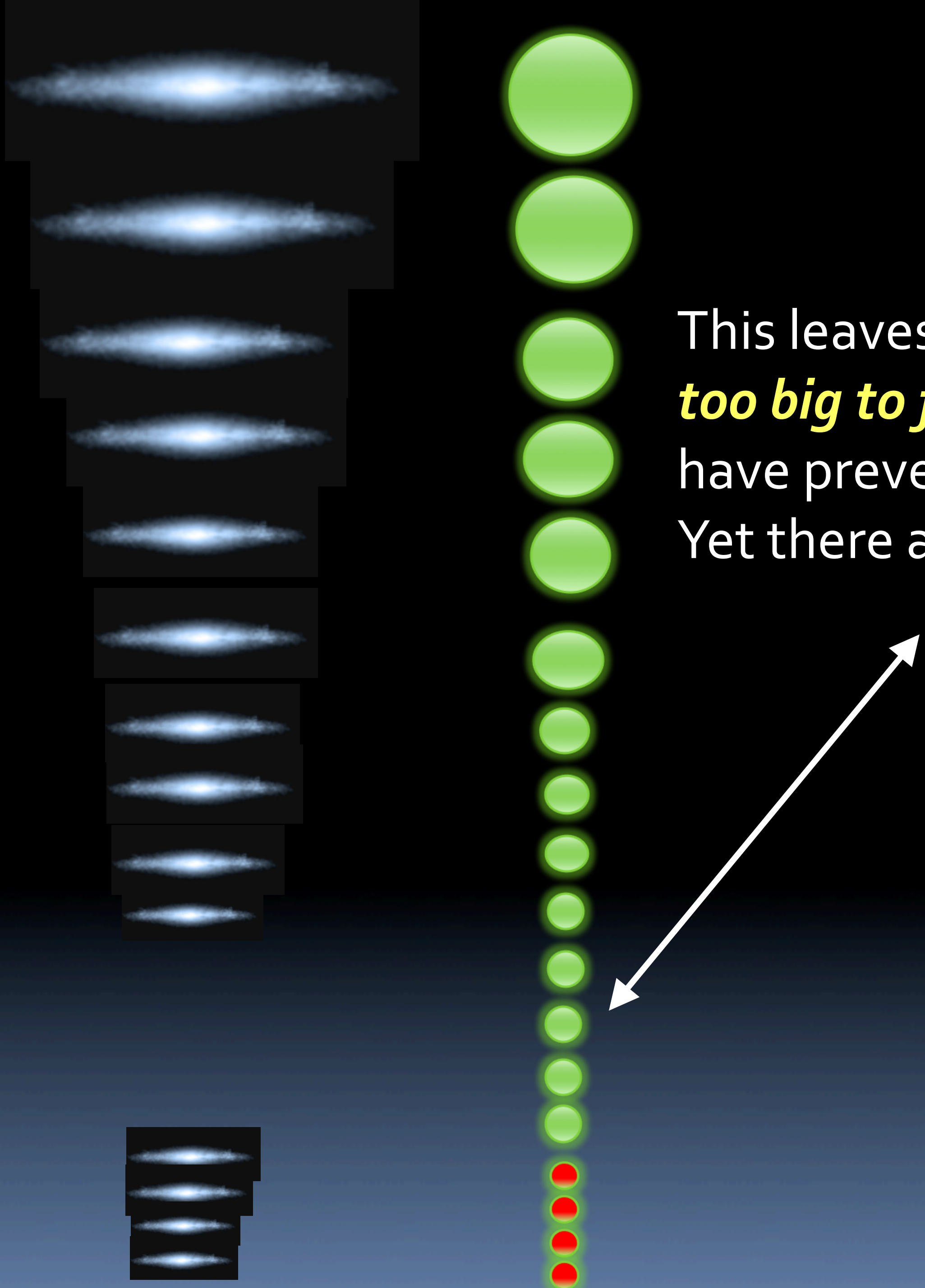
Weisz & Boylan-Kolchin 2017

Too Big to Fail



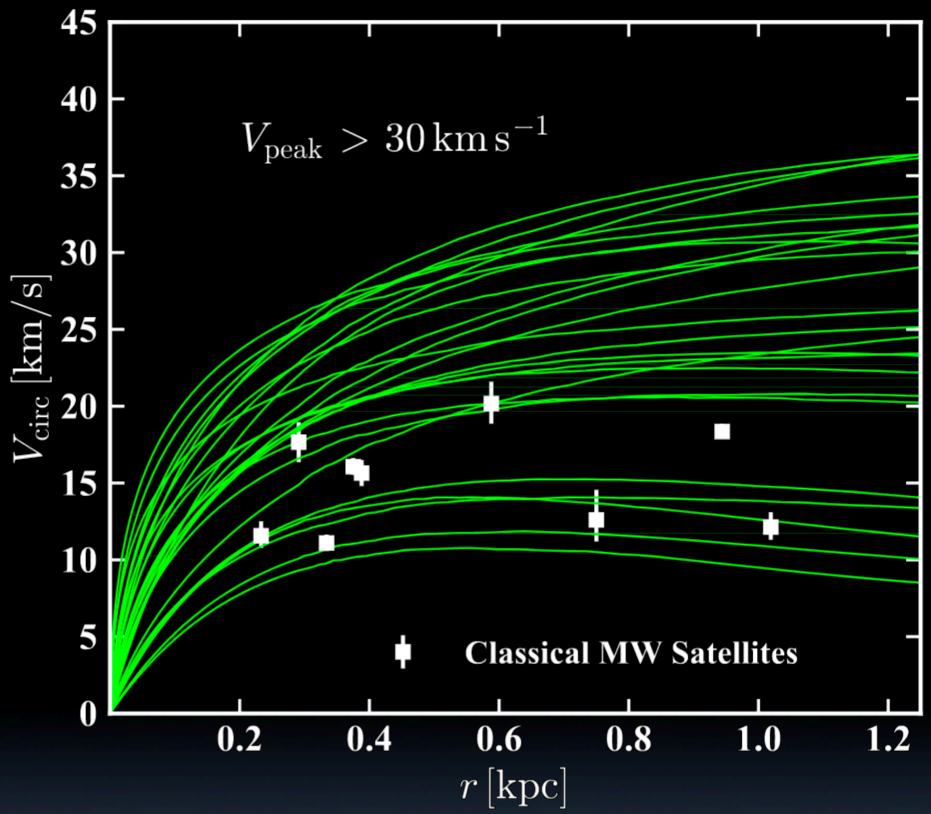
Kinematic measurements indicate that some galaxies *are* associated with these lower mass halos, assuming DM only (NFW) profiles

Too Big to Fail



This leaves some DM halos that are
too big to fail i.e. we do not expect UV to
have prevented star formation…
Yet there are no observational counterpart

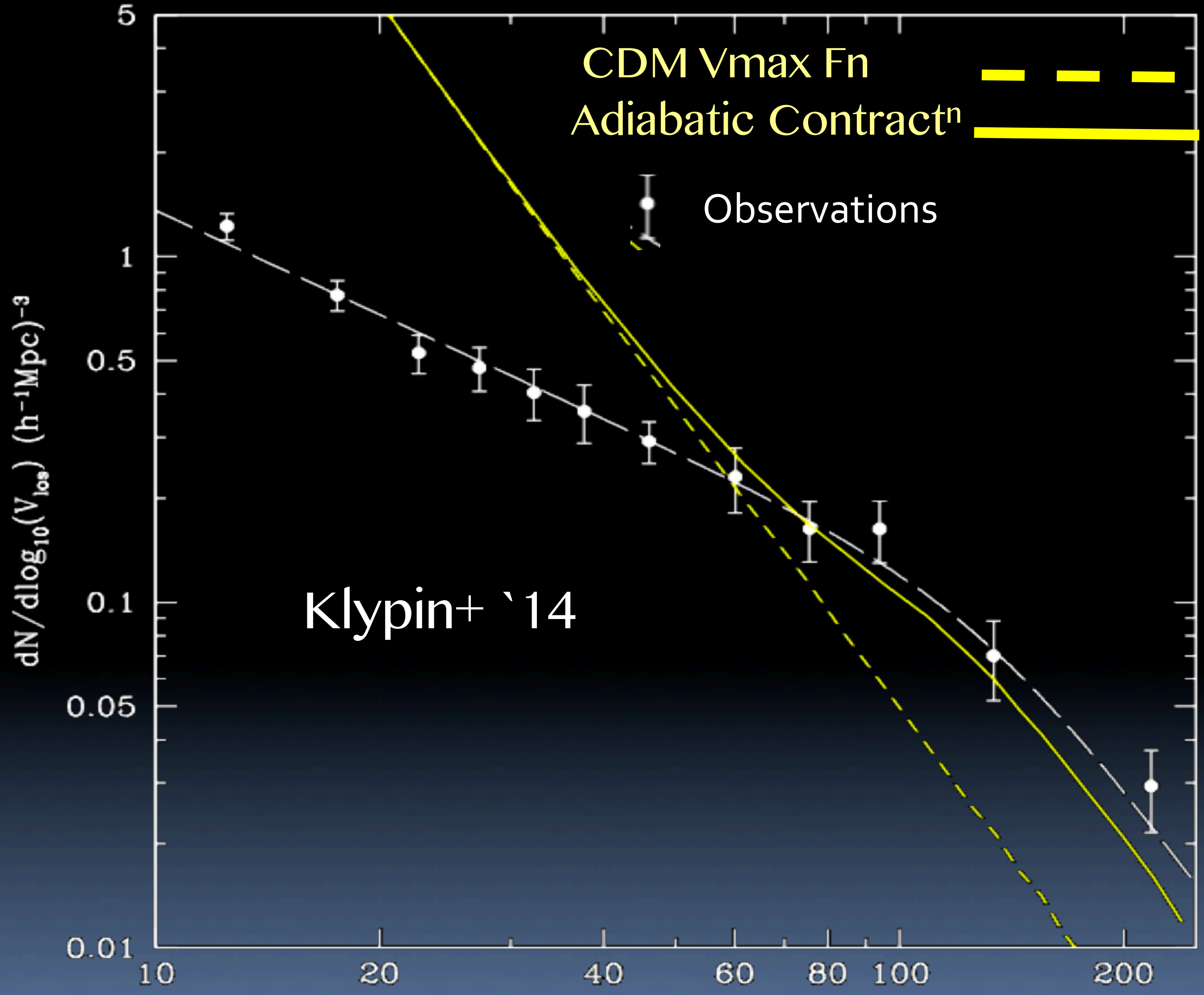
Too Big to Fail



DM halos from simulated Milky Way

Some DM halos are ***too big to fail***
i.e. we do not expect UV to have prevented star formation…
Yet there are no observed counterparts

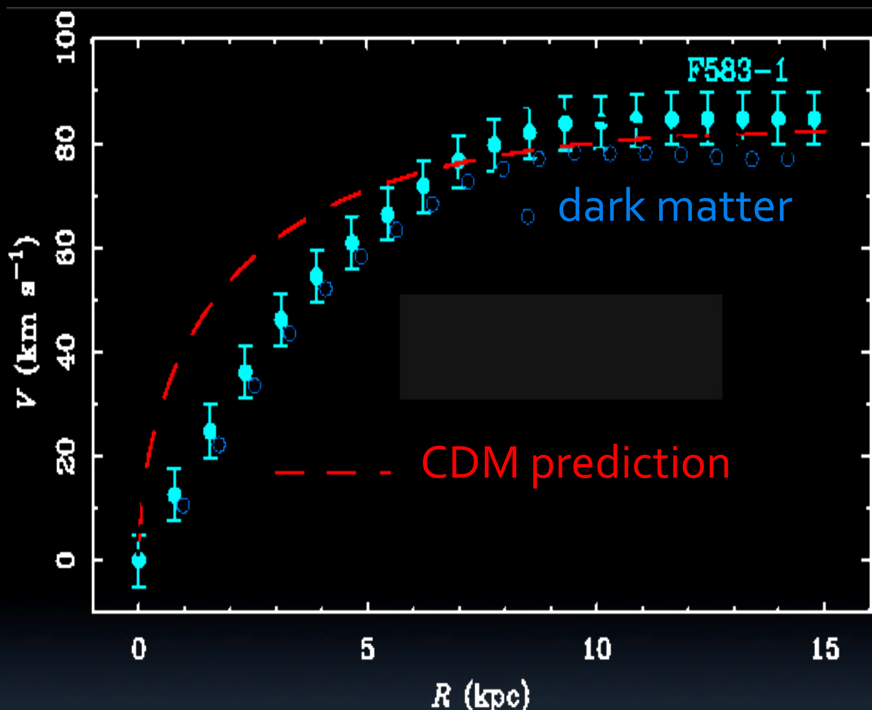
Mismatch between predicted and observed velocity function

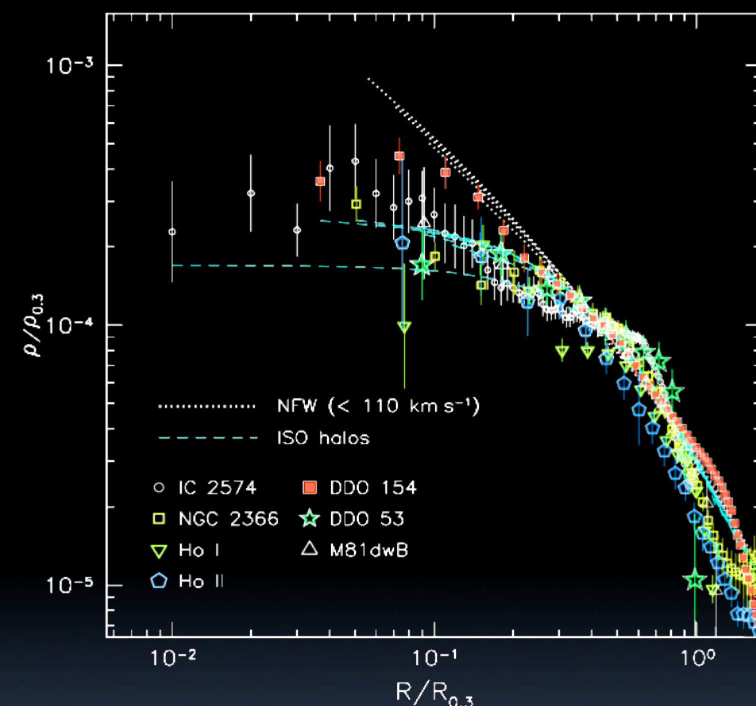


W50/2

See also Zavala+ 09, Papastergis+ 15

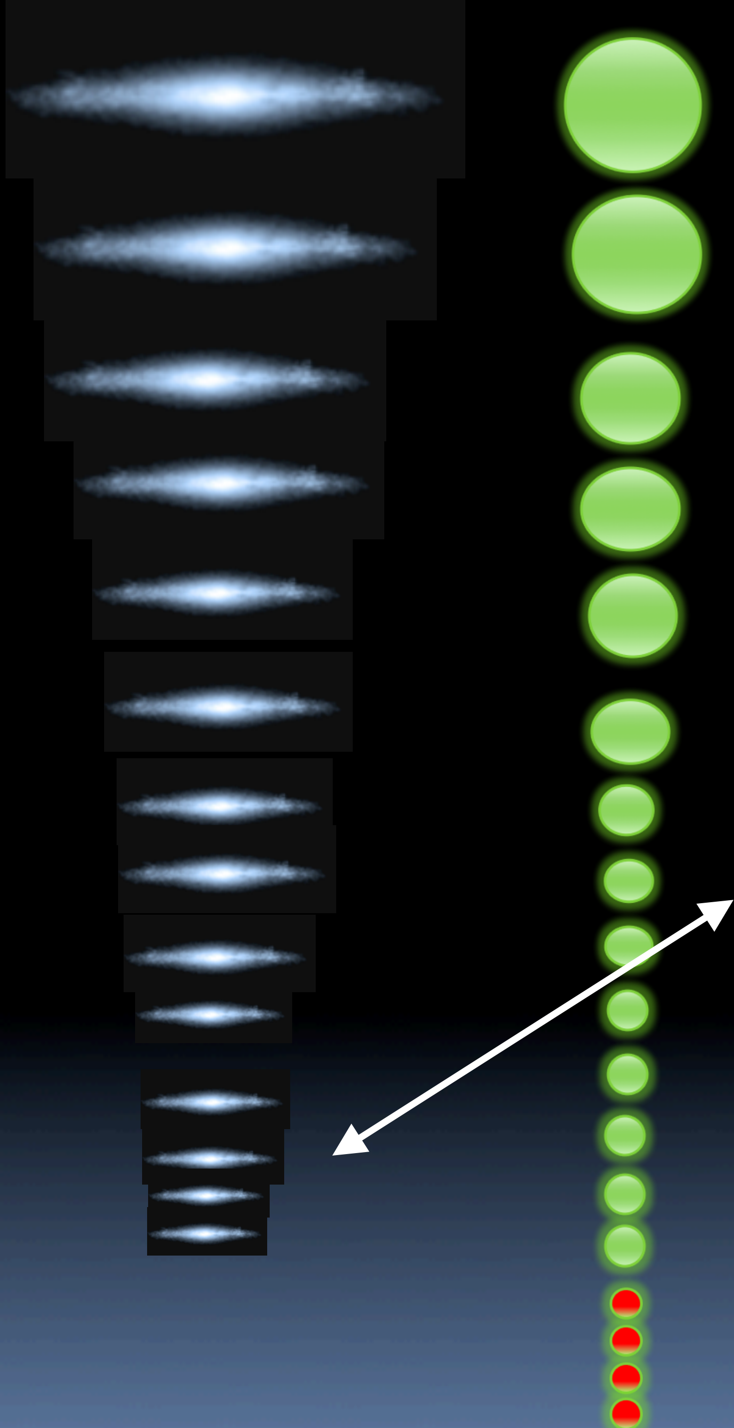
Measuring Mass using Rotation Curves: cusp-core problem   see Di Cintio talk





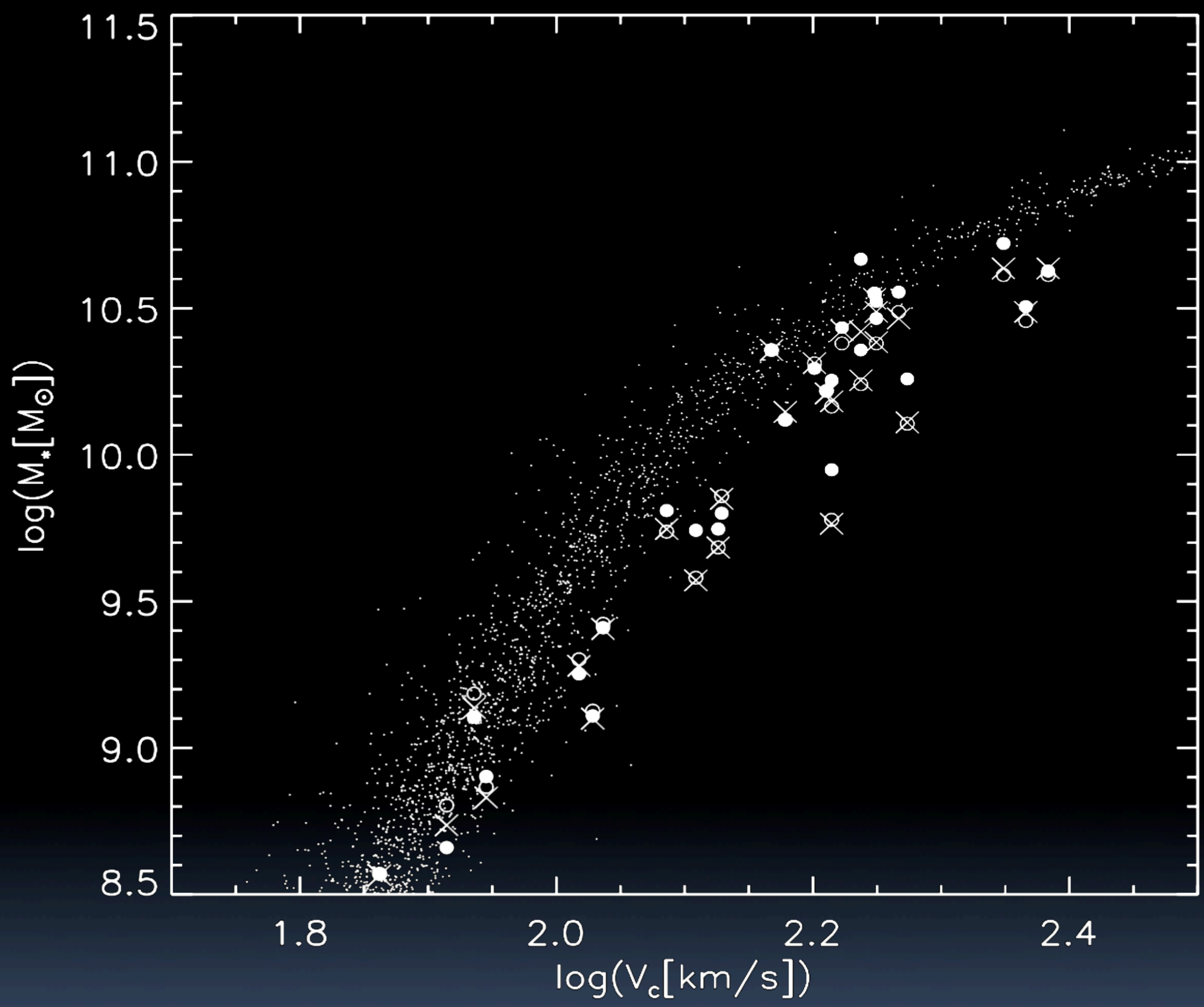
Is *Too Big to Fail* problem just the *Cusp-Core* problem?

Too Big to Fail



If these galaxies have cores, they will have low velocity dispersions but still be massive. So the measured velocities of observed dwarfs may be due to cores rather than low mass halos

Tully-Fisher Relation

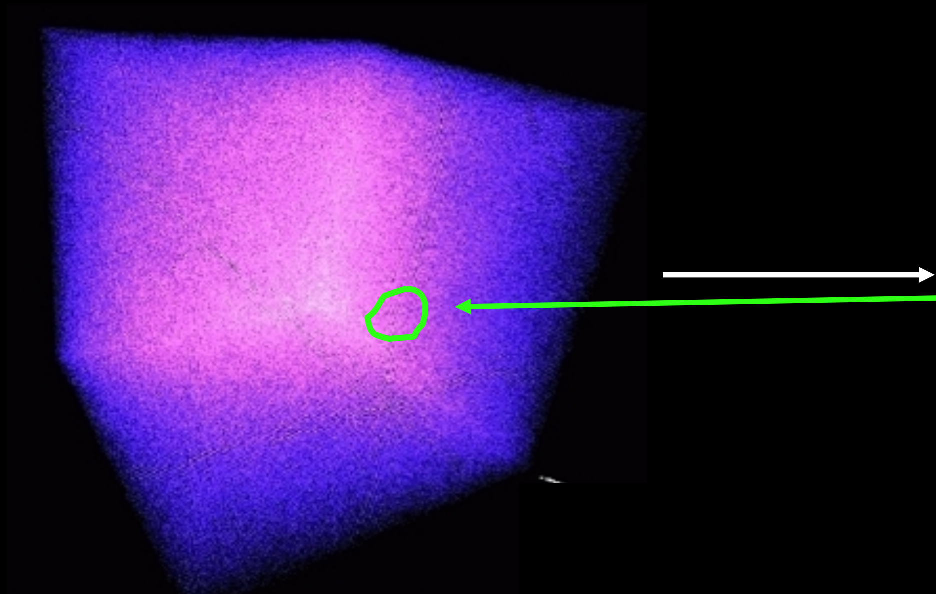


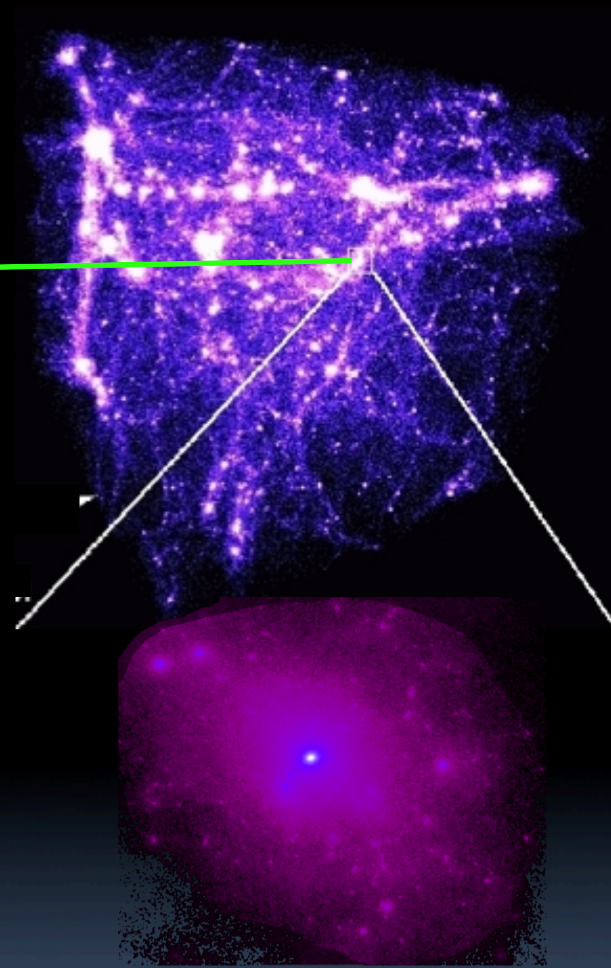
Can ΛCDM simultaneously match Luminosity Function and zero point of T-F relation?

Guo et al. 2010

Can these issues and a multitude of galaxy observations be *self consistently* solved within the Cold Dark Matter paradigm?

High resolution simulations





Select a galaxy sized dark matter halo
Or a Local Group Volume (Sorce talk)

Identify those particles in initial conditions….
The whole box is re-simulated with that region simulated in detail

Hydrodynamical simulations

Parallel chemo-dynamical galaxy evolution code

Gas: Smoothed Particle Hydrodynamics (SPH)

$$\rho(\mathbf{r}) = \sum_{j=1}^{N_{neigh}} m_j W(|\mathbf{r} - \mathbf{r}_j|, h)$$

Details of the simulations

Parallel chemo-dynamical galaxy evolution code

Gas: Cooling Rates

UV background radiation
(Haardt & Madau 96)

From previous generations of massive stars and quasars

Details of the simulations

Parallel chemo-dynamical galaxy evolution code

Gas: Star Formation

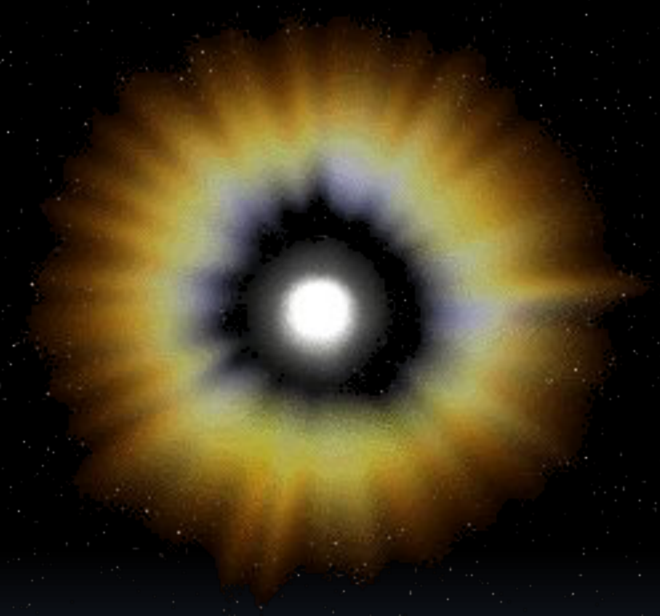
Star Formation Rate- $\propto p^{1.5}$

Kennicut-Schmidt law (empirical)

Details of the simulations

Parallel chemo-dynamical galaxy evolution code

Energy Feedback



$$\Delta E_{s,i} = \frac{m_i W(|\boldsymbol{r}_i - \boldsymbol{r}_\mathrm{s}|, h_\mathrm{s}) \Delta E}{\sum_{j=1}^{N} m_j W(|\boldsymbol{r}_j - \boldsymbol{r}_\mathrm{s}|, h_\mathrm{s})}$$

Details of the simulations

Parallel chemo-dynamical galaxy evolution code

Energy Feedback

Supernova Blastwave McKee & Ostriker 1977 see Stinson et al. 2006

$$\Delta E_{\mathrm{SN},i} = \frac{m_i W(|\boldsymbol{r}_i - \boldsymbol{r}_\mathrm{s}|, h_\mathrm{s}) \Delta E_\mathrm{SN}}{\sum_{j=1}^{N} m_j W(|\boldsymbol{r}_j - \boldsymbol{r}_\mathrm{s}|, h_\mathrm{s})}$$

$$R_E = 10^{1.74} E_{51}^{0.32} n_0^{-0.16} \tilde{P}_{04}^{-0.20} \mathrm{pc}$$

$E_\mathrm{SN} = 10^{51}$ erg, n_0 is the ambient hydrogen density

$\tilde{P}_{04} = 10^{-4} P_0 k^{-1}$ where P_0 is the ambient pressure

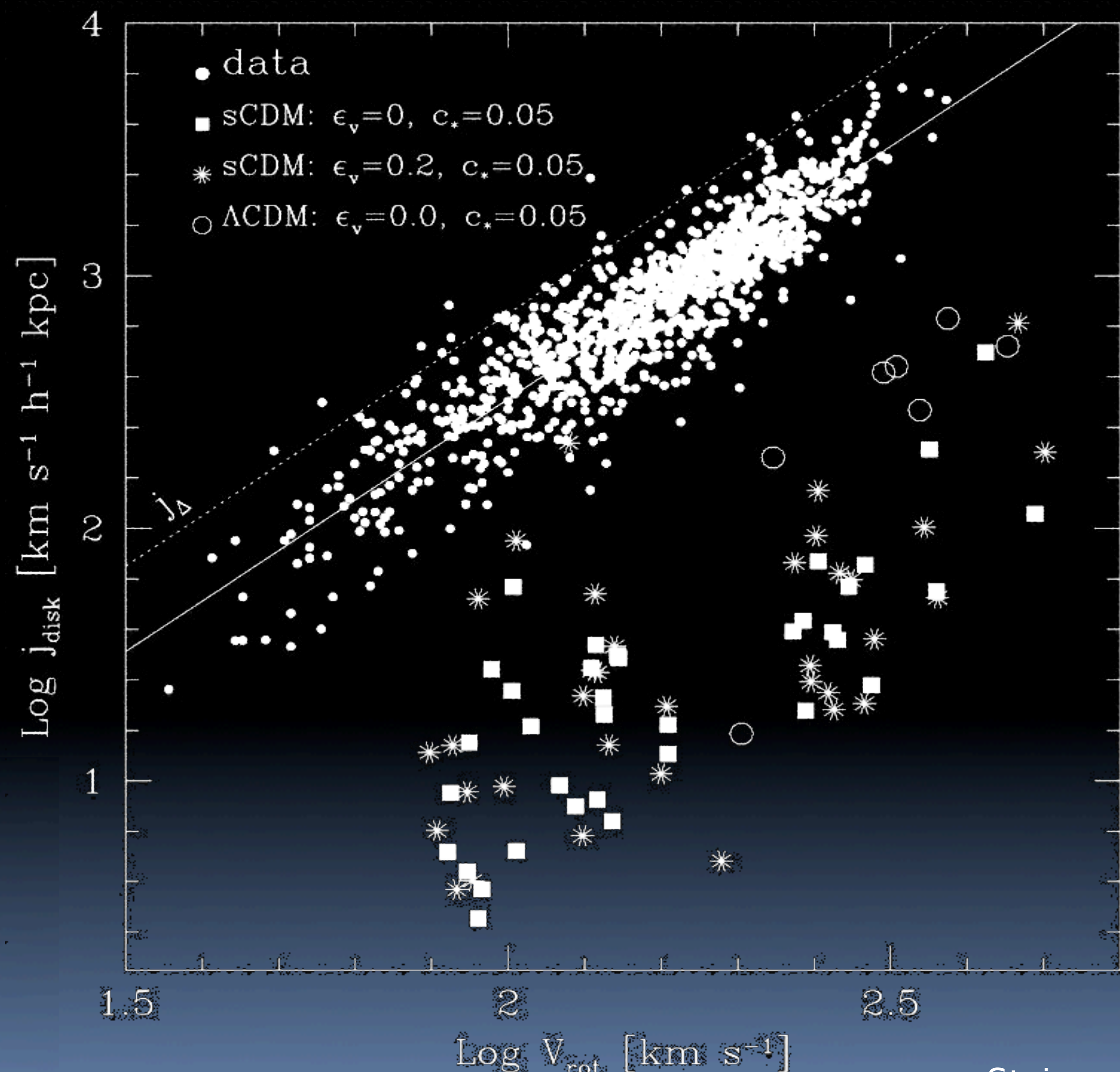
k is the Boltzmann constant

$$t = 10^{6.85} E_{51}^{0.32} n_0^{0.34} \tilde{P}_{04}^{-0.70} \mathrm{yr}$$

Details of the simulations

Parallel chemo-dynamical galaxy evolution code
metal enrichment: H,He,O,Fe,C,N,Si,Ne,Mg

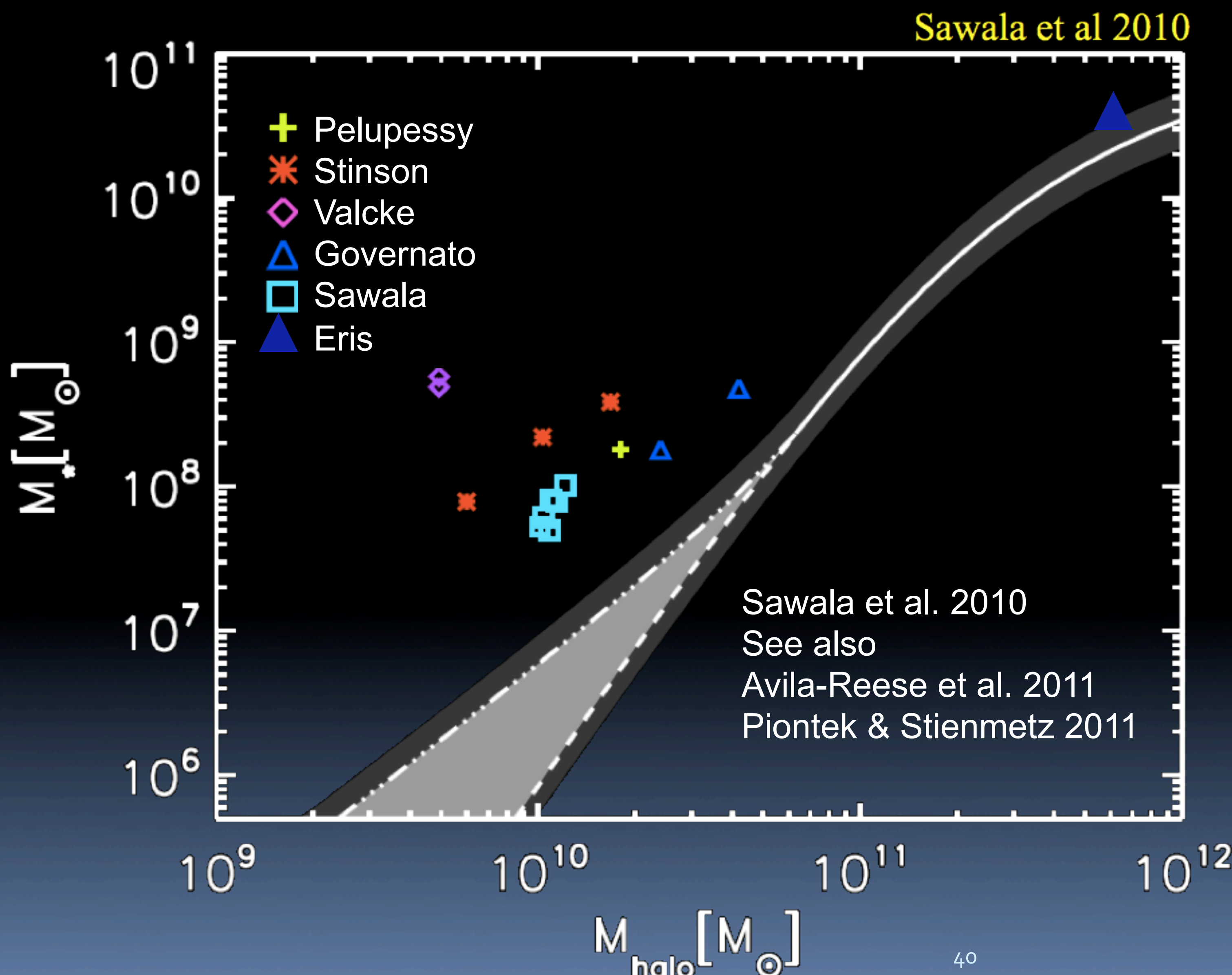
The angular momentum "problem"



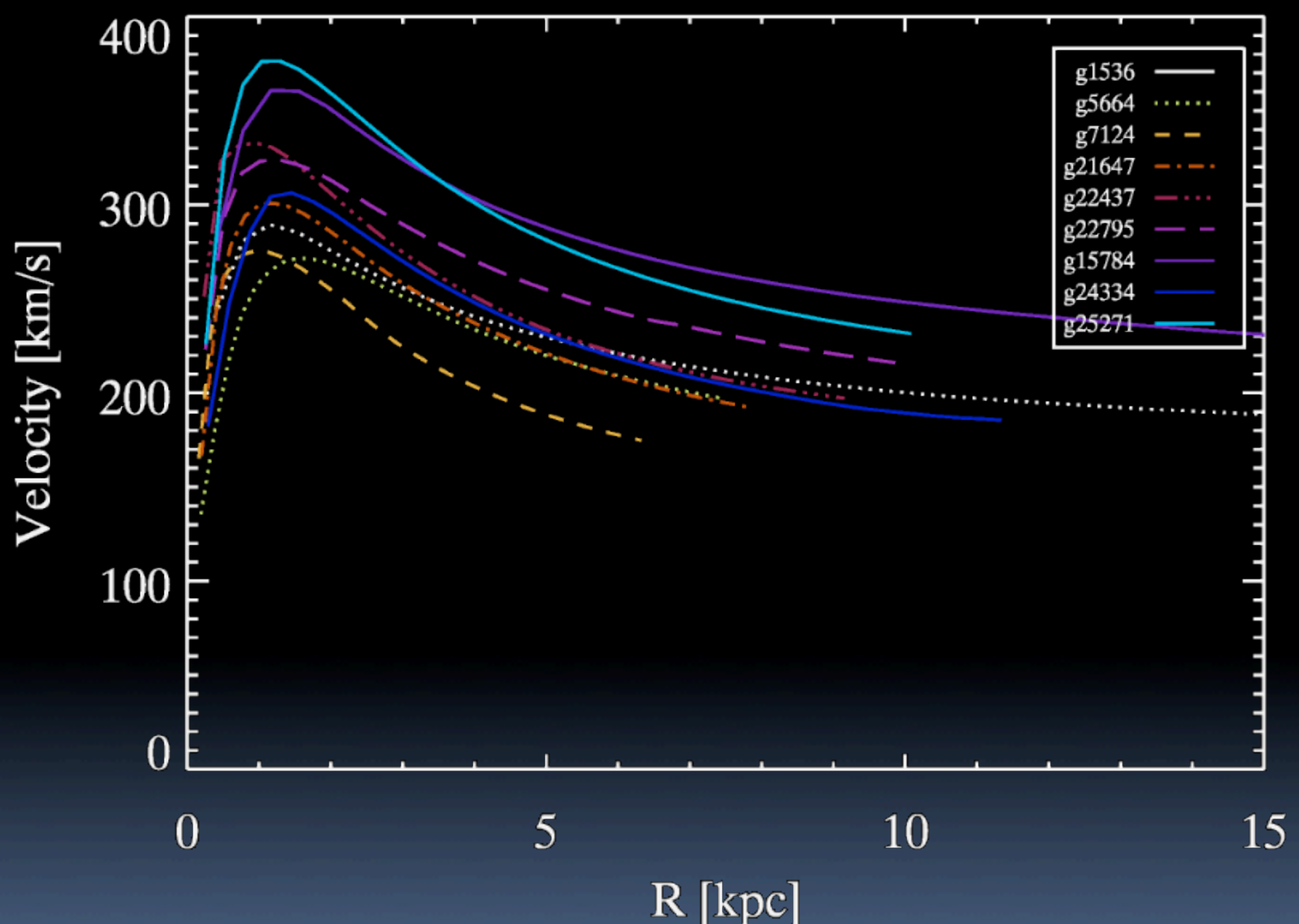
Steinmetz & Navarro 2000

Stellar Mass-Halo Mass

(Moster et al. 2010, Guo et al. 2010)



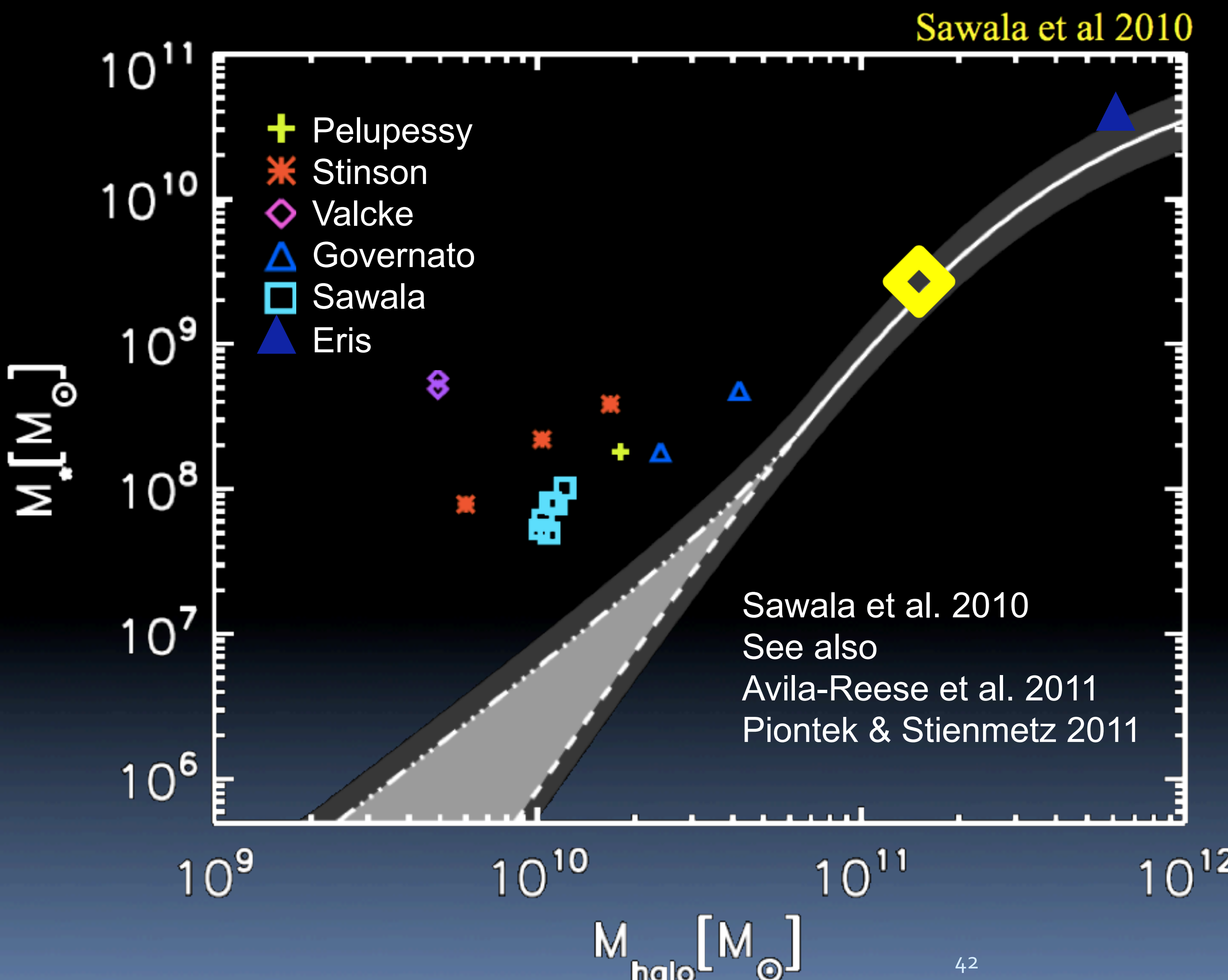
Simulated rotation curves



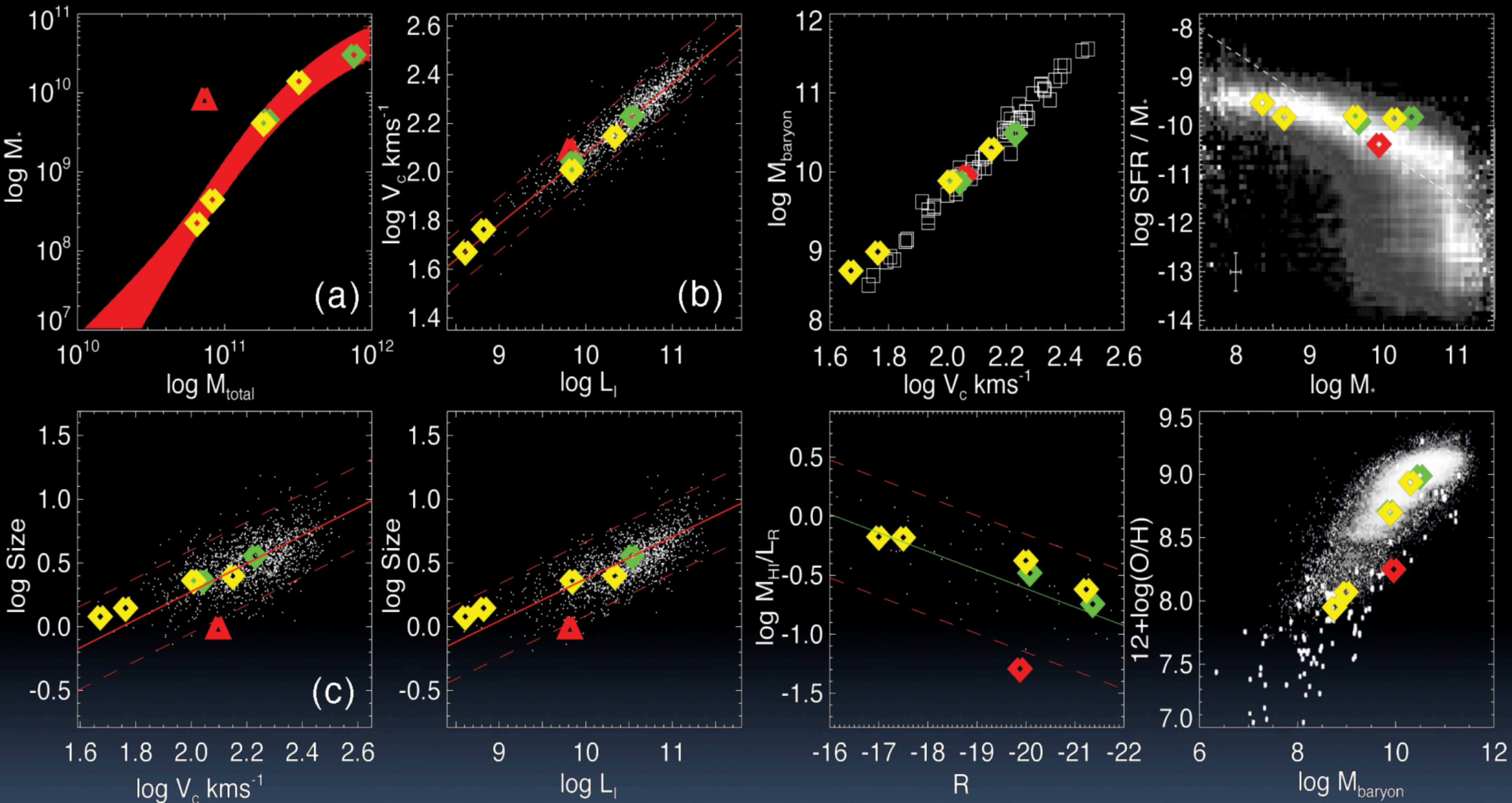
Stinson et al. 2010
See also Scannepieco et al. 2012

Stellar Mass-Halo Mass

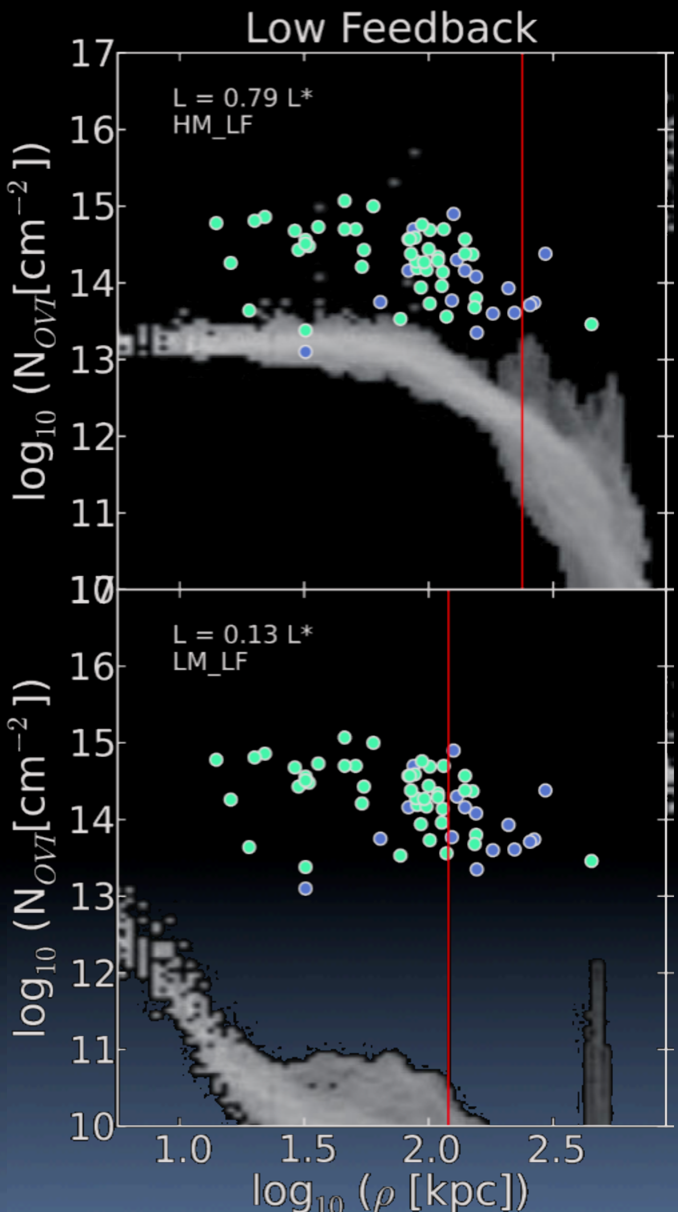
(Moster et al. 2010, Guo et al. 2010)



Matching Observed Scaling Relations



Brook et al. 2012

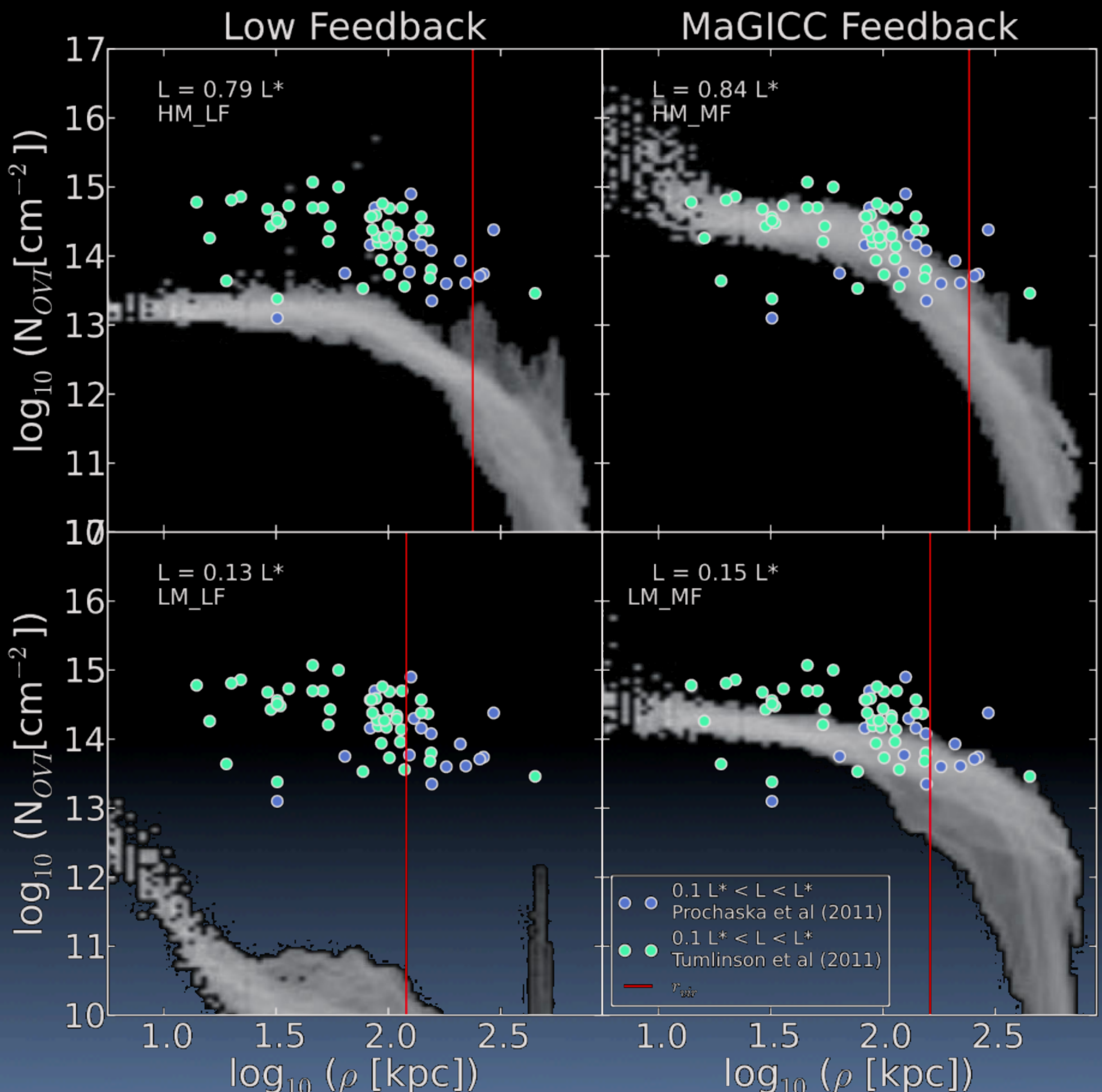


The "CGM problem"

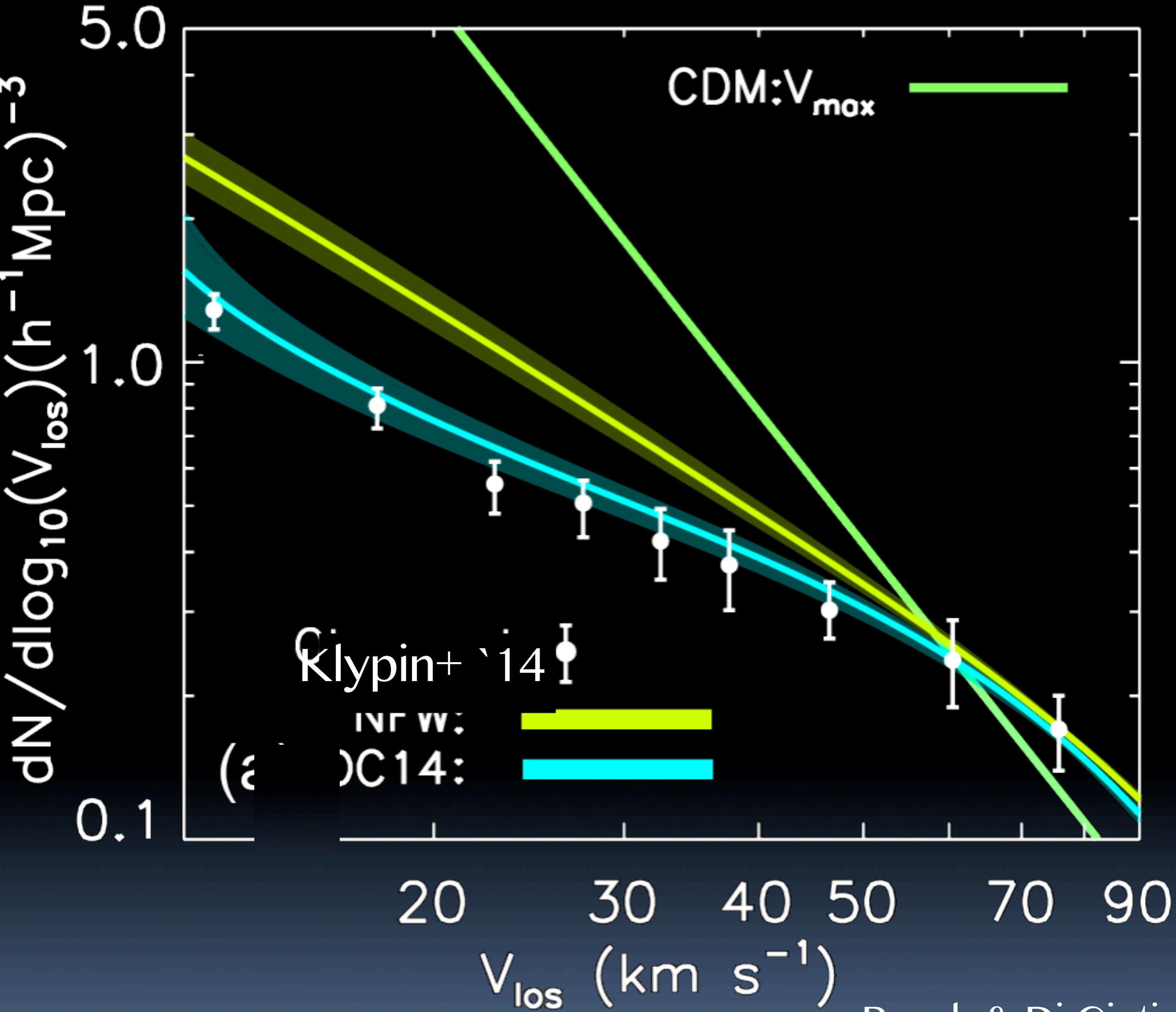
More generally, can the observed metal enrichment of the Universe exist in a CDM model?

Let us "tune" (couple) feedback to match the CGM of observed galaxies

Not a CDM constraint so we are not directly invoking the Frenk principle



Stinson et al. 2013



Brook & Di Cintio 2015
See also Brook & Shankar 2016
Brooks et al. 2017

Conclusions

-When comparing CDM models with observations, it is imperative to model baryons

-Careful comparisons are required, accounting for observational techniques

- Seems that CDM may be able to self-consistently explain range of observed galaxy properties

-No unambiguous contradiction between galaxy properties and CDM paradigm although tensions persist and key processes remain poorly understood/crudely modelled
(tuning parameters to match the luminosity function may be a weak form of the Frenk principle)

Plane of Satellites