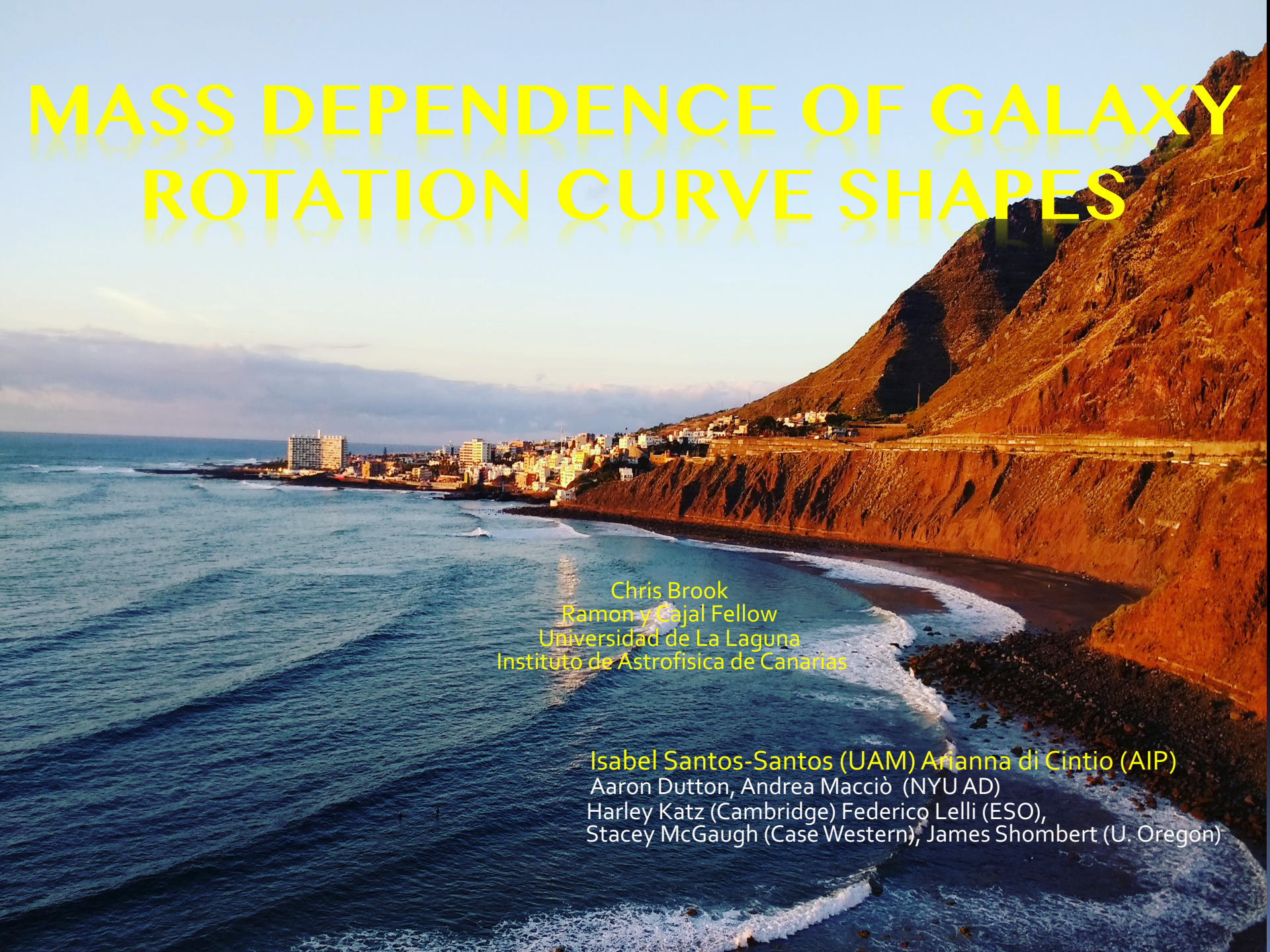
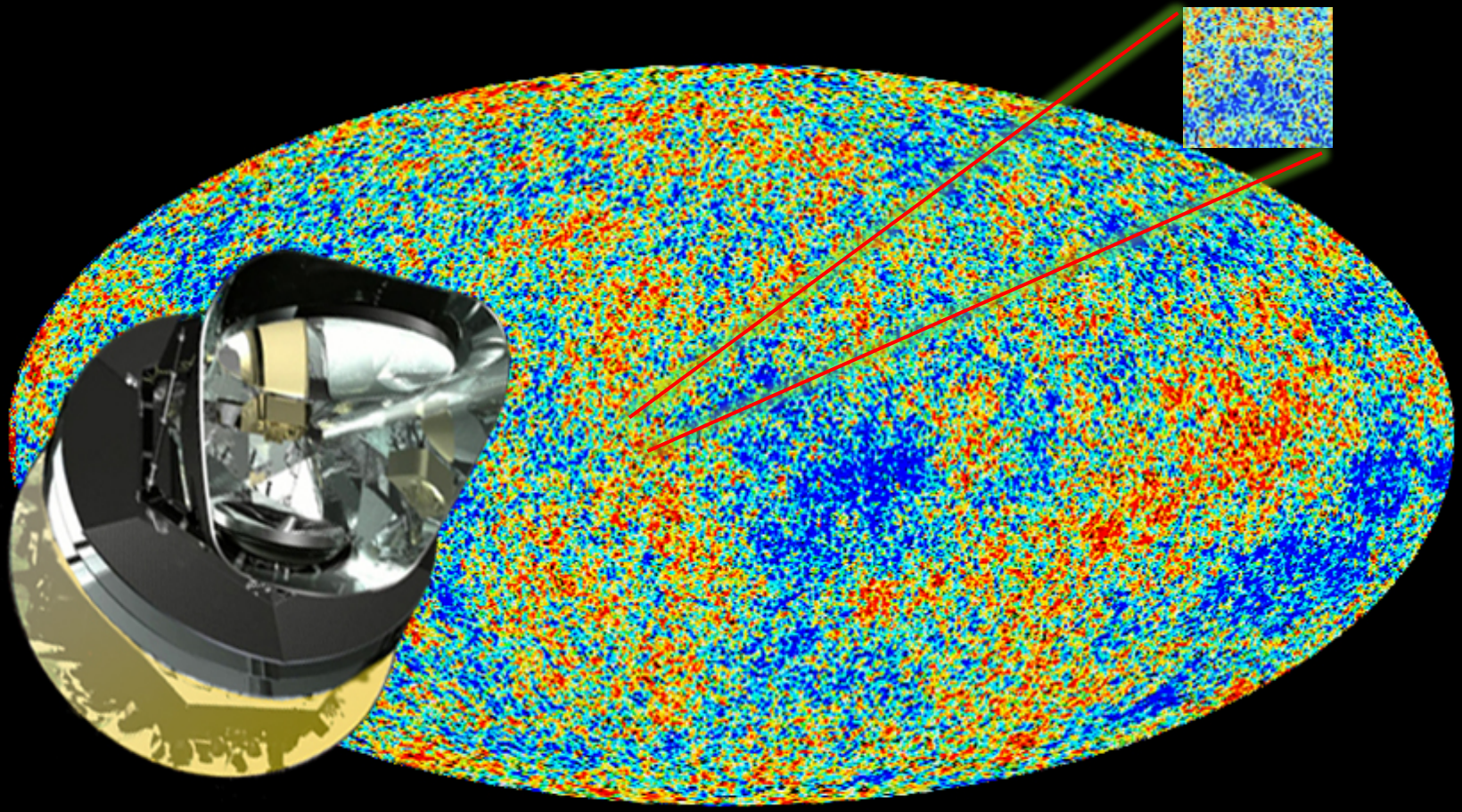
# MASS DEPENDENCE OF GALAXY ROTATION CURVE SHAPES




Chris Brook
Ramon y Cajal Fellow
Universidad de La Laguna
Instituto de Astrofisica de Canarias

Isabel Santos-Santos (UAM) Arianna di Cintio (AIP)
Aaron Dutton, Andrea Macciò (NYU AD)
Harley Katz (Cambridge) Federico Lelli (ESO),
Stacey McGaugh (Case Western), James Shombert (U. Oregon)



# Planck

# Details of the simulations

Parallel chemo-dynamical galaxy evolution code
Tree N-body –Dark Matter & stars:

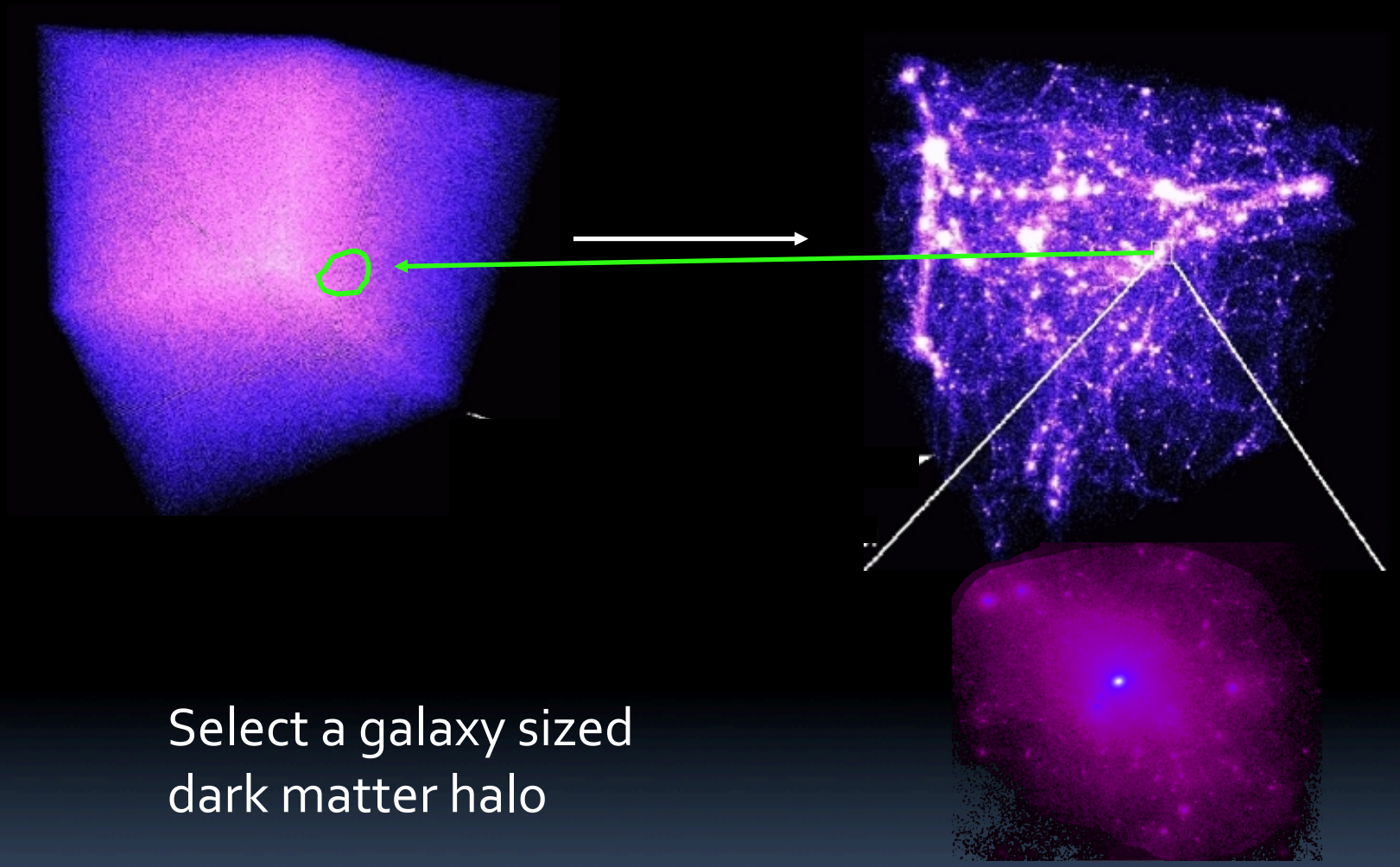
$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f = 0$$

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

potential $\Phi$ is the solution of Poisson's eqn:

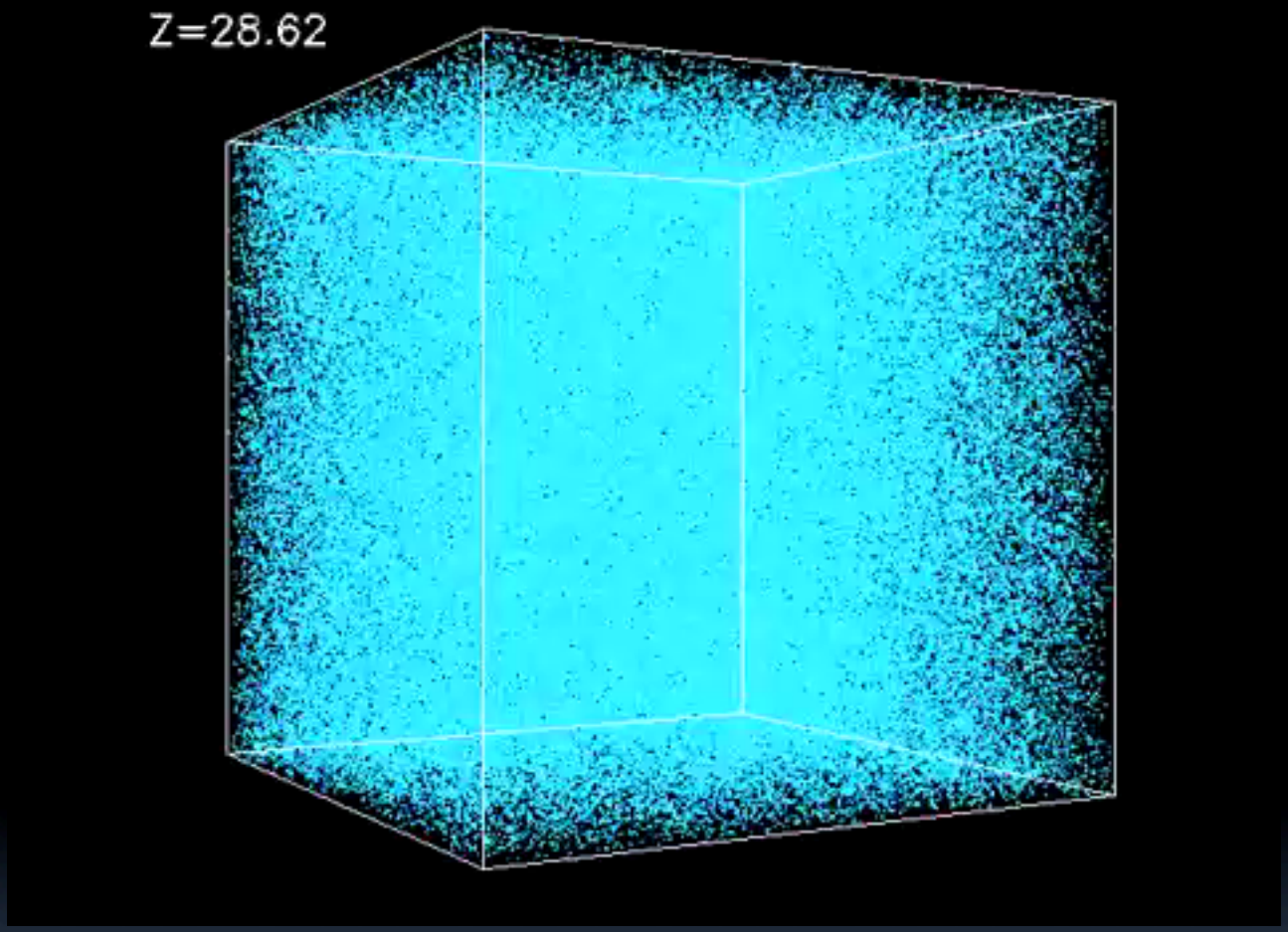
$$\nabla^2 \Phi(\mathbf{r}, t) = 4\pi G \int f(\mathbf{r}, \mathbf{v}, t)\, \mathrm{d}\mathbf{v}$$

# High resolution simulations



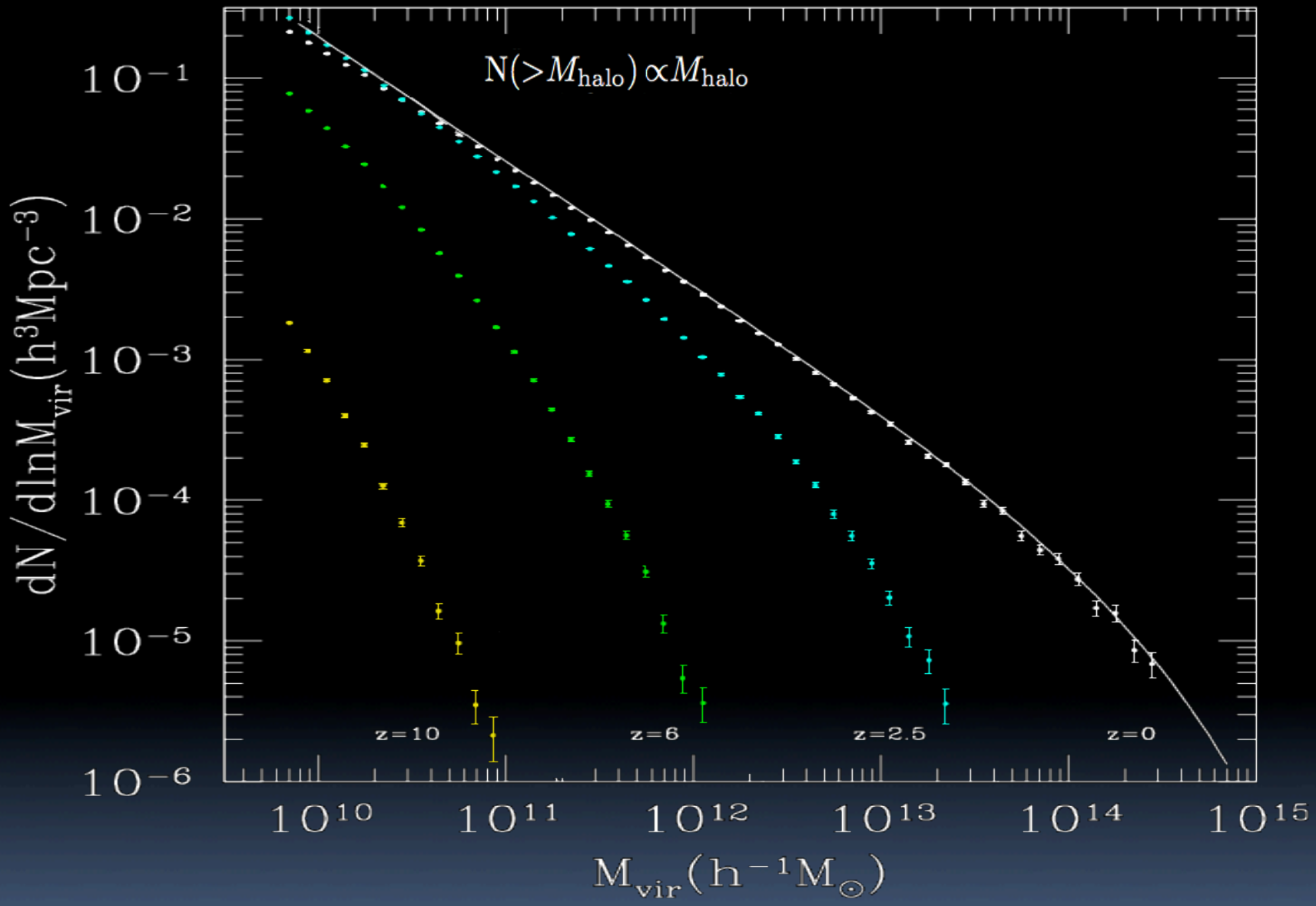
Select a galaxy sized
dark matter halo

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

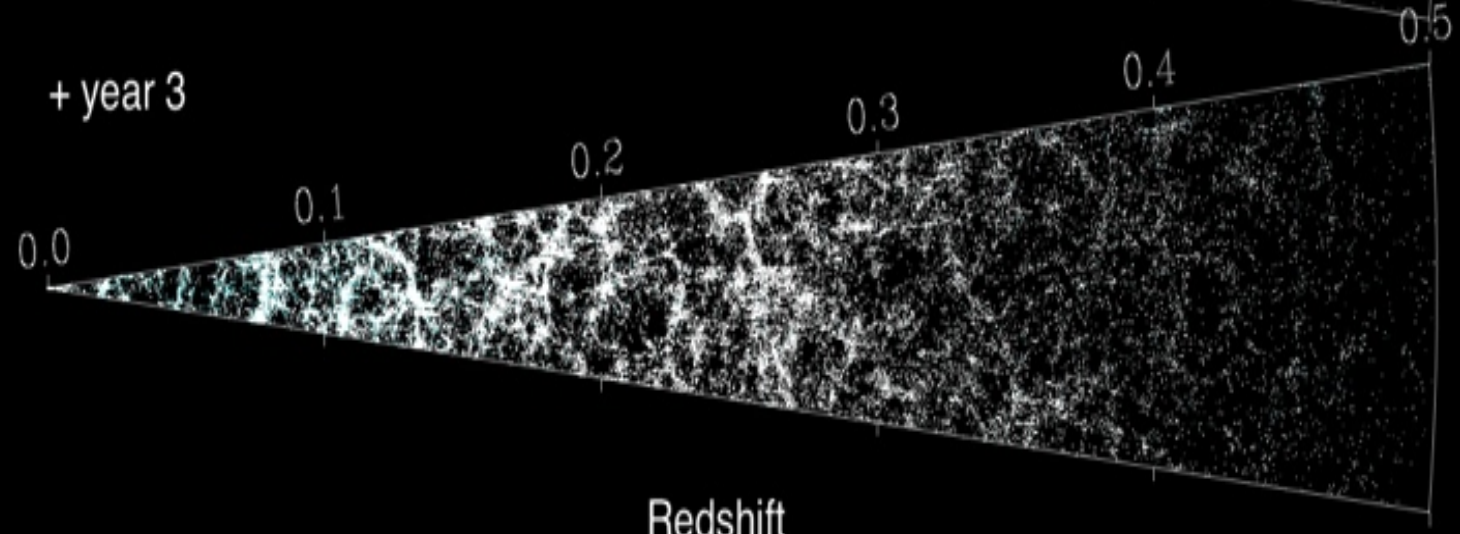


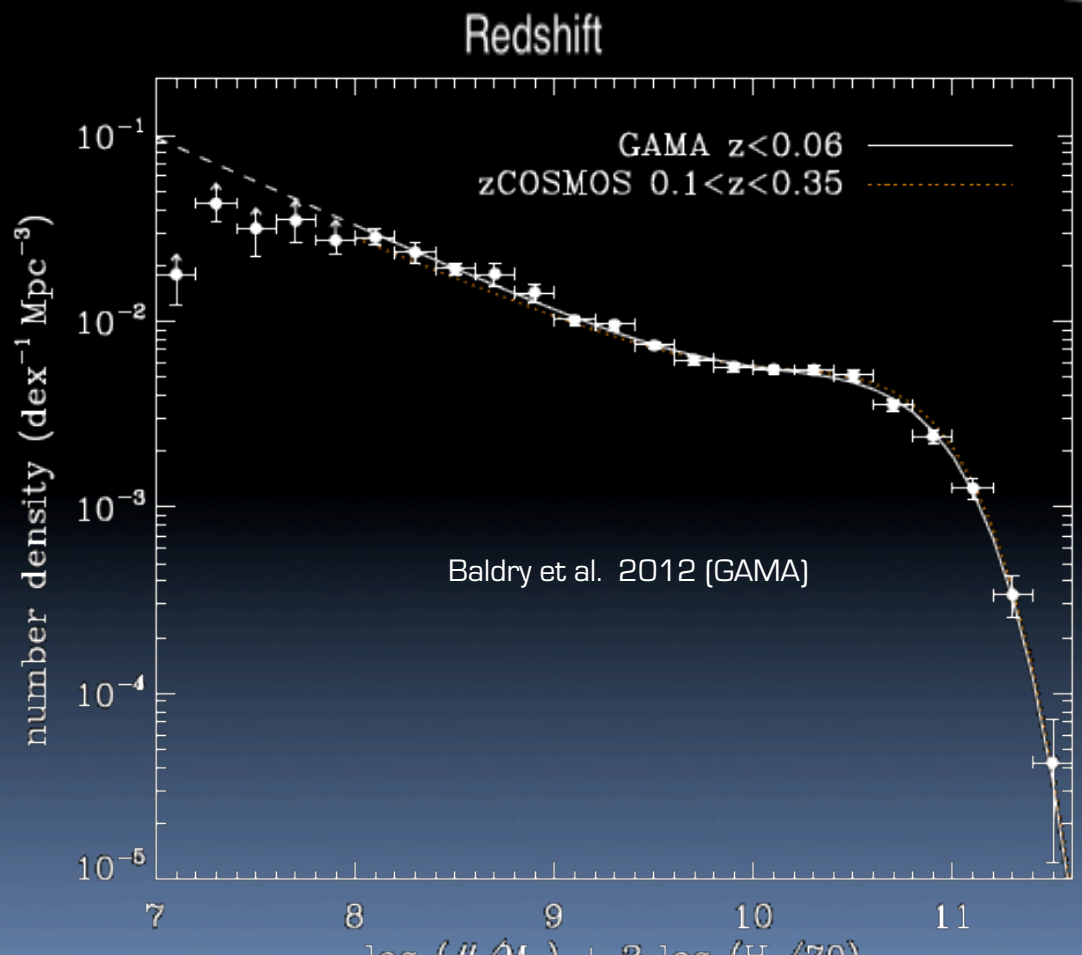

Credit: A.Kravtsov, A. Klypin

# N-body simulations

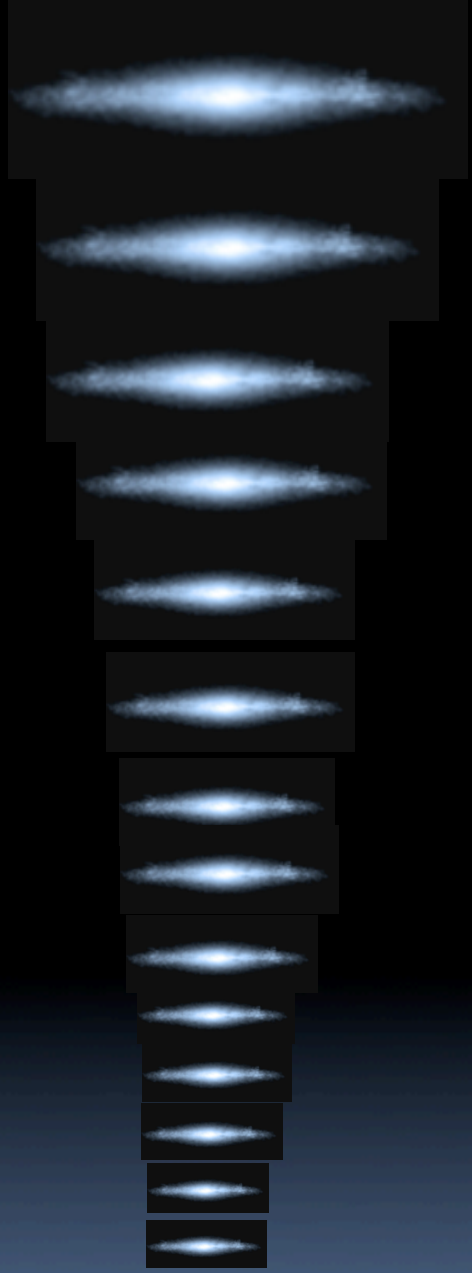


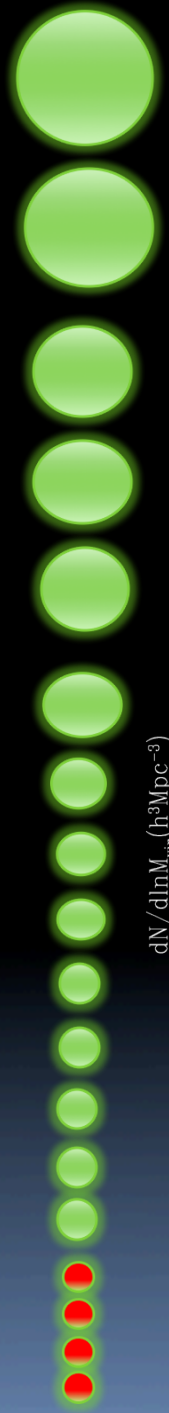

Klypin, Trujillo-Gomez, Primack 2012 (Bolshoi)

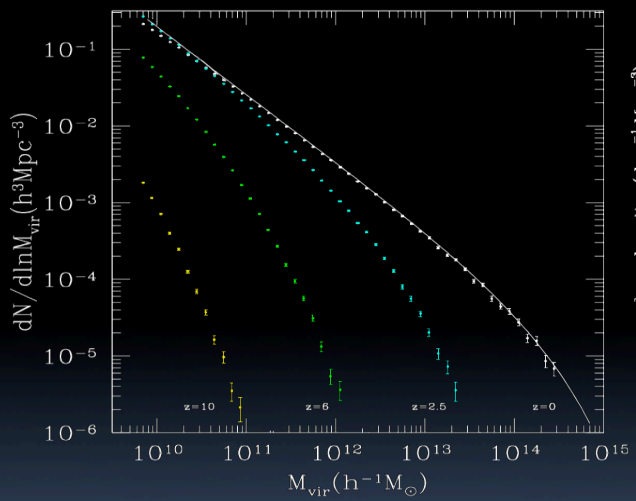


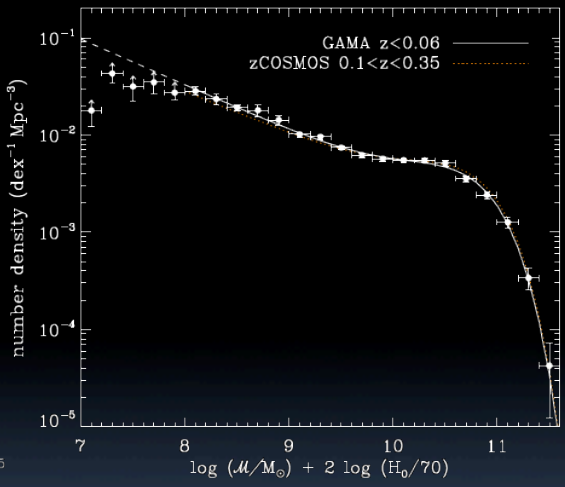

Baldry et al. 2012 (GAMA)





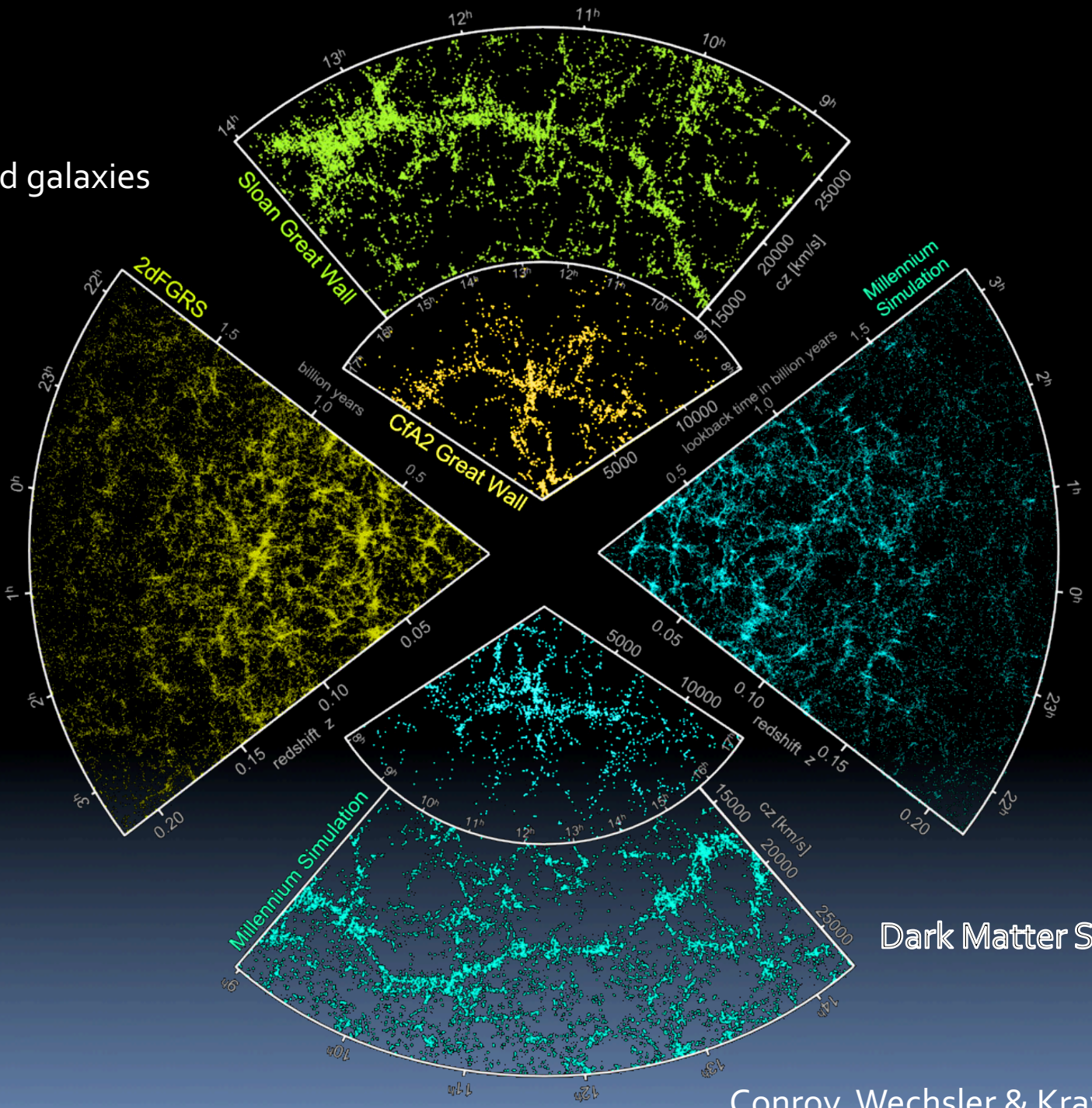



Klypin, Trujillo-Gomez, Primack 2012 (Bolshoi)



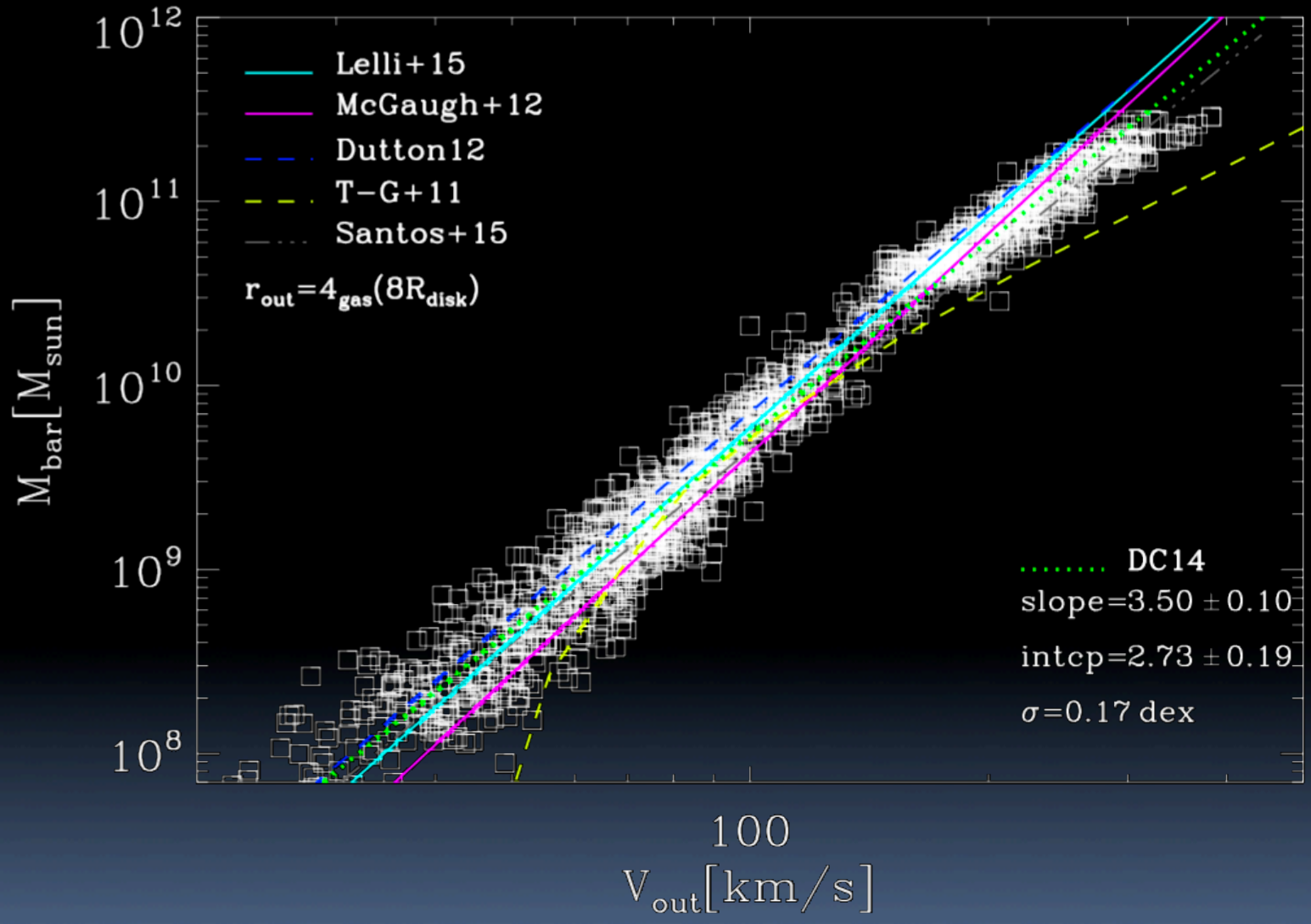

Baldry et al. 2012 (GAMA)

Observed galaxies

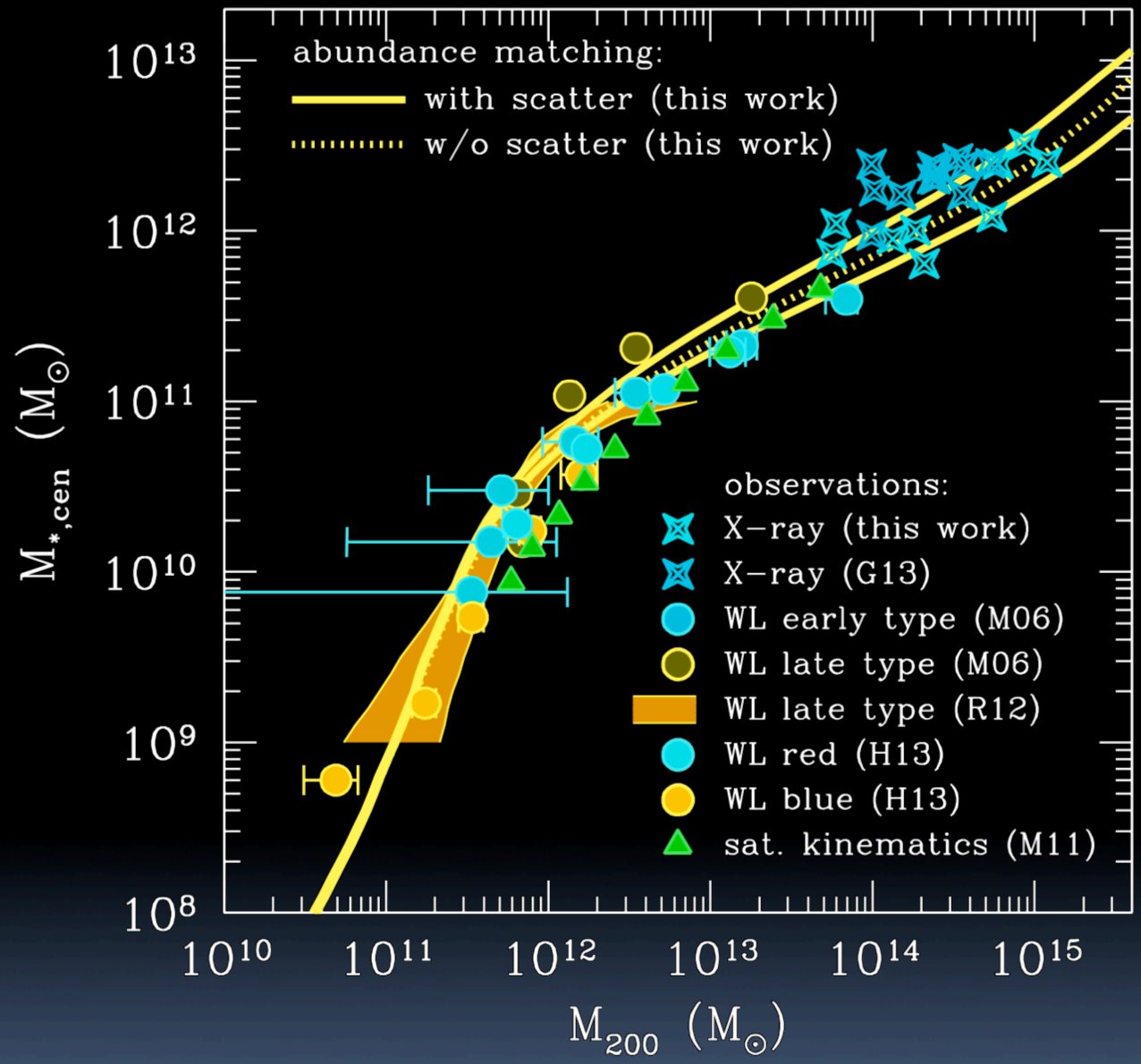



Dark Matter Simulations

Conroy, Wechsler & Kravtsov 2005




Di Cintio & Lelli 2016




Kravtsov+ 2014

# 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

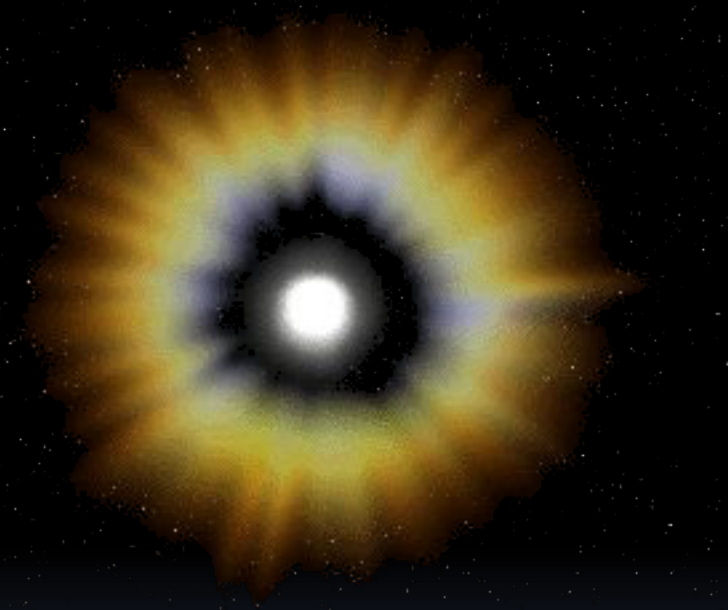
Star Formation Rate- $\propto p^{1.5}$

Kennicut-Schmidt law (empirical)

# Details of the simulations

Parallel chemo-dynamical galaxy evolution code
Energy Feedback

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



# 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

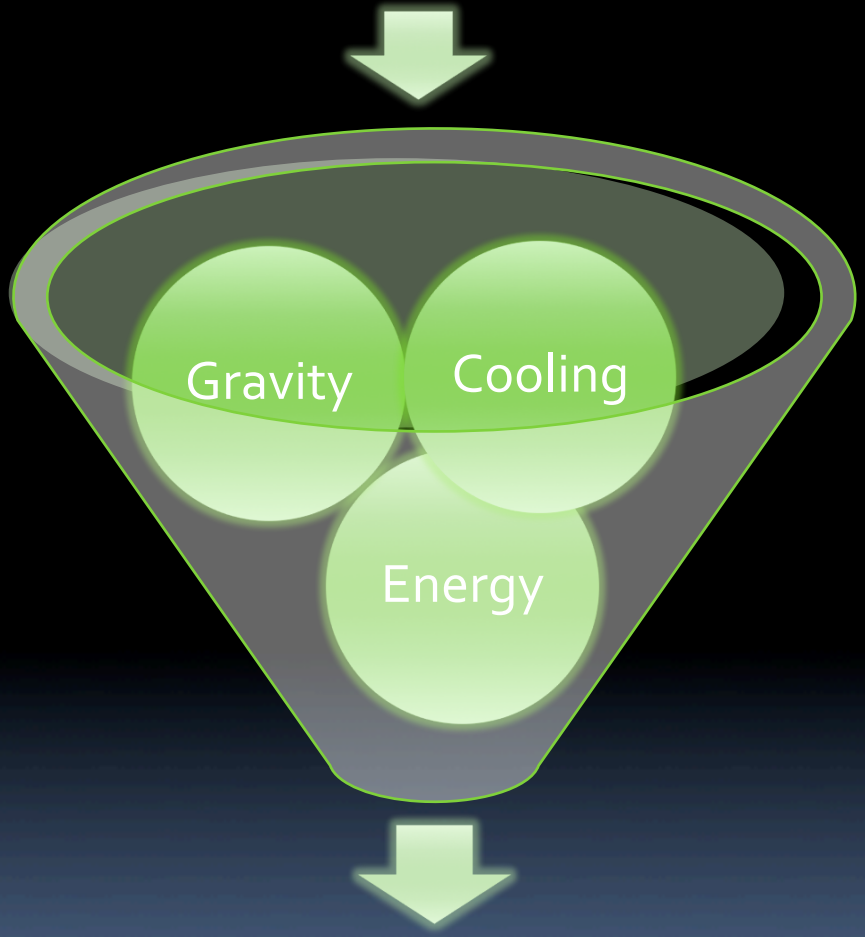
Parallel chemo-dynamical galaxy evolution code
metal enrichment: H,He,O,Fe,C,N,Si,Ne,Mg



Researchers hope to replace silicon microchips with diamonds one day (CNN)

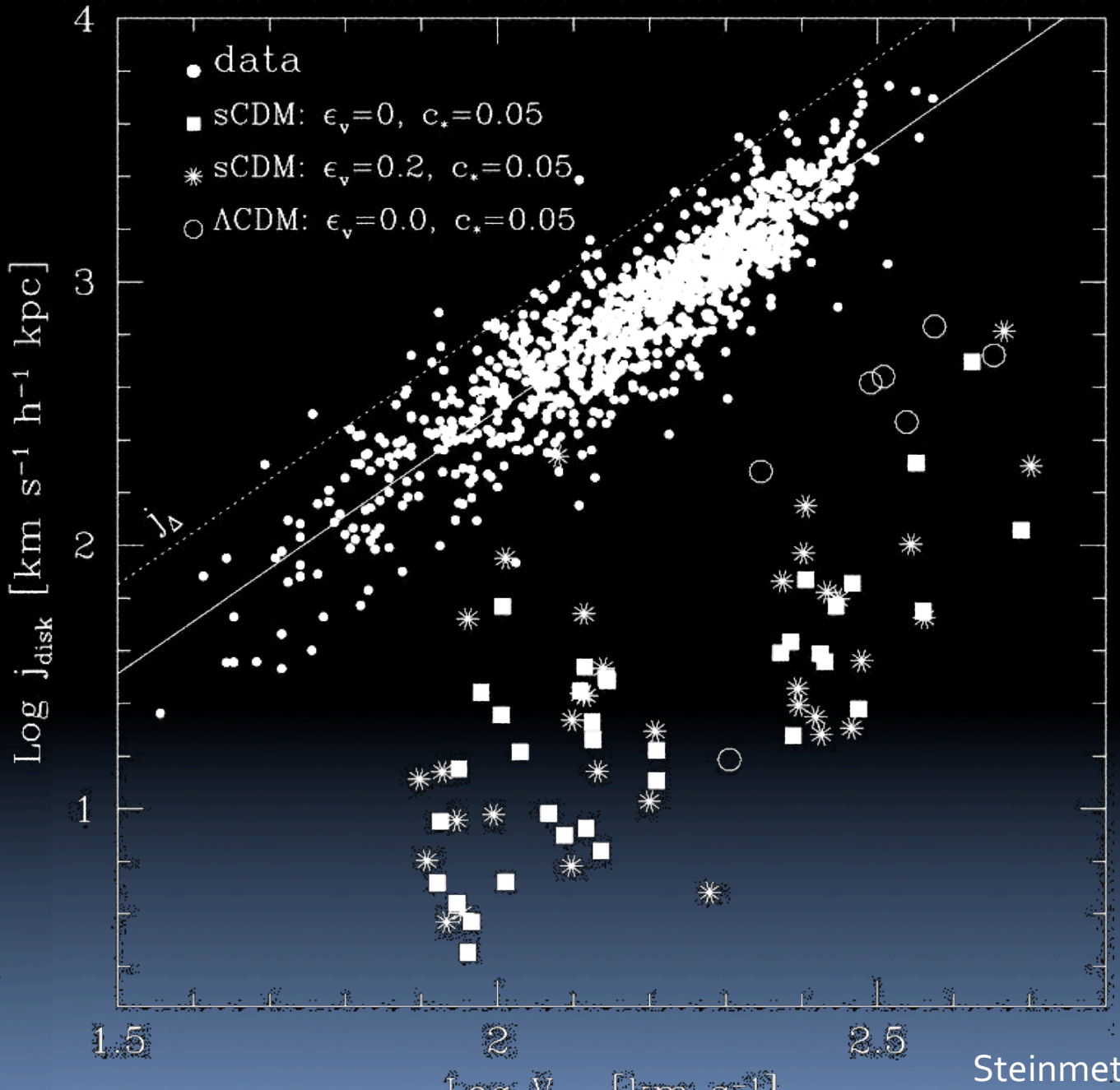
# simulations

10100101100101001100




01101110000011111000

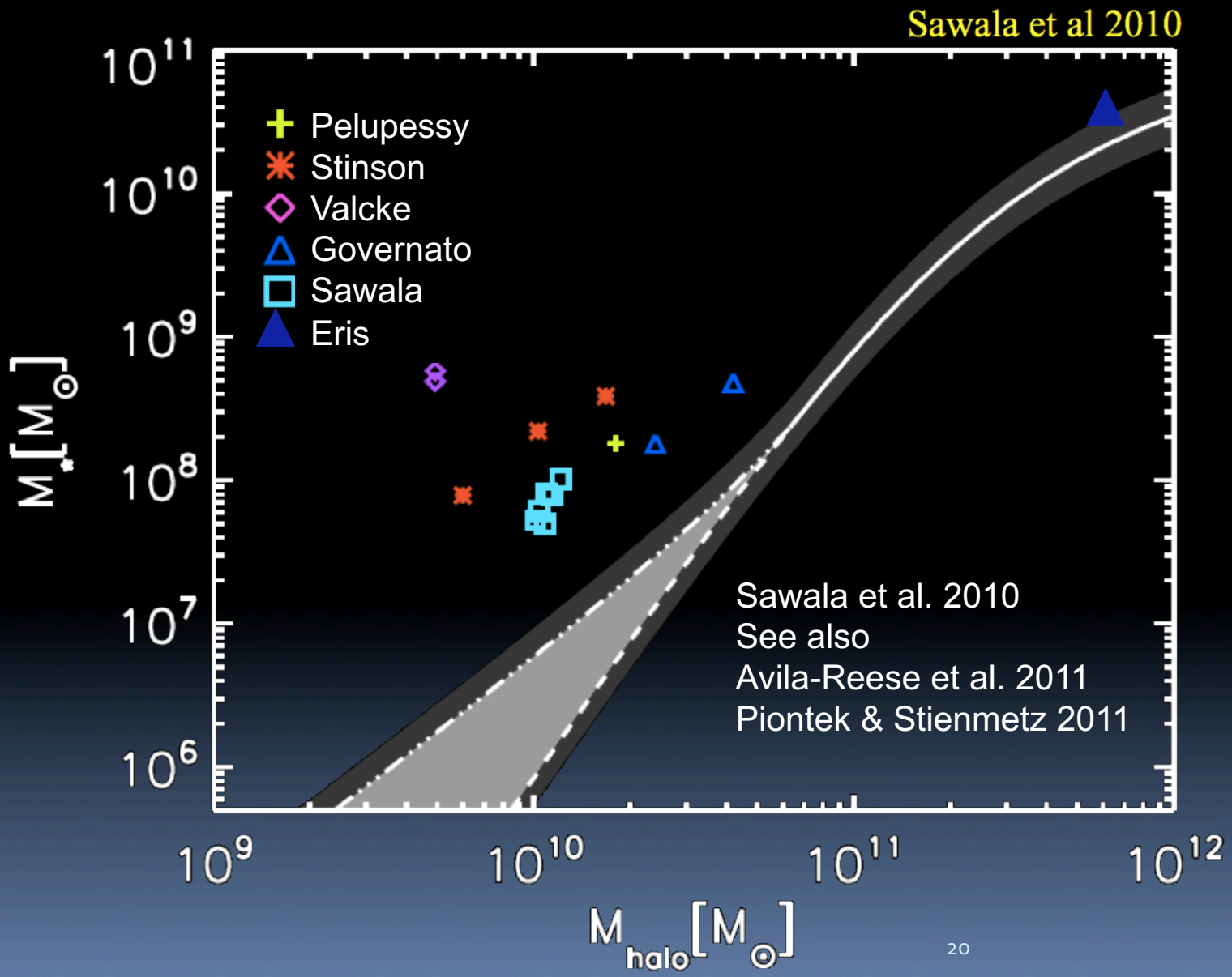
# The angular momentum "problem"



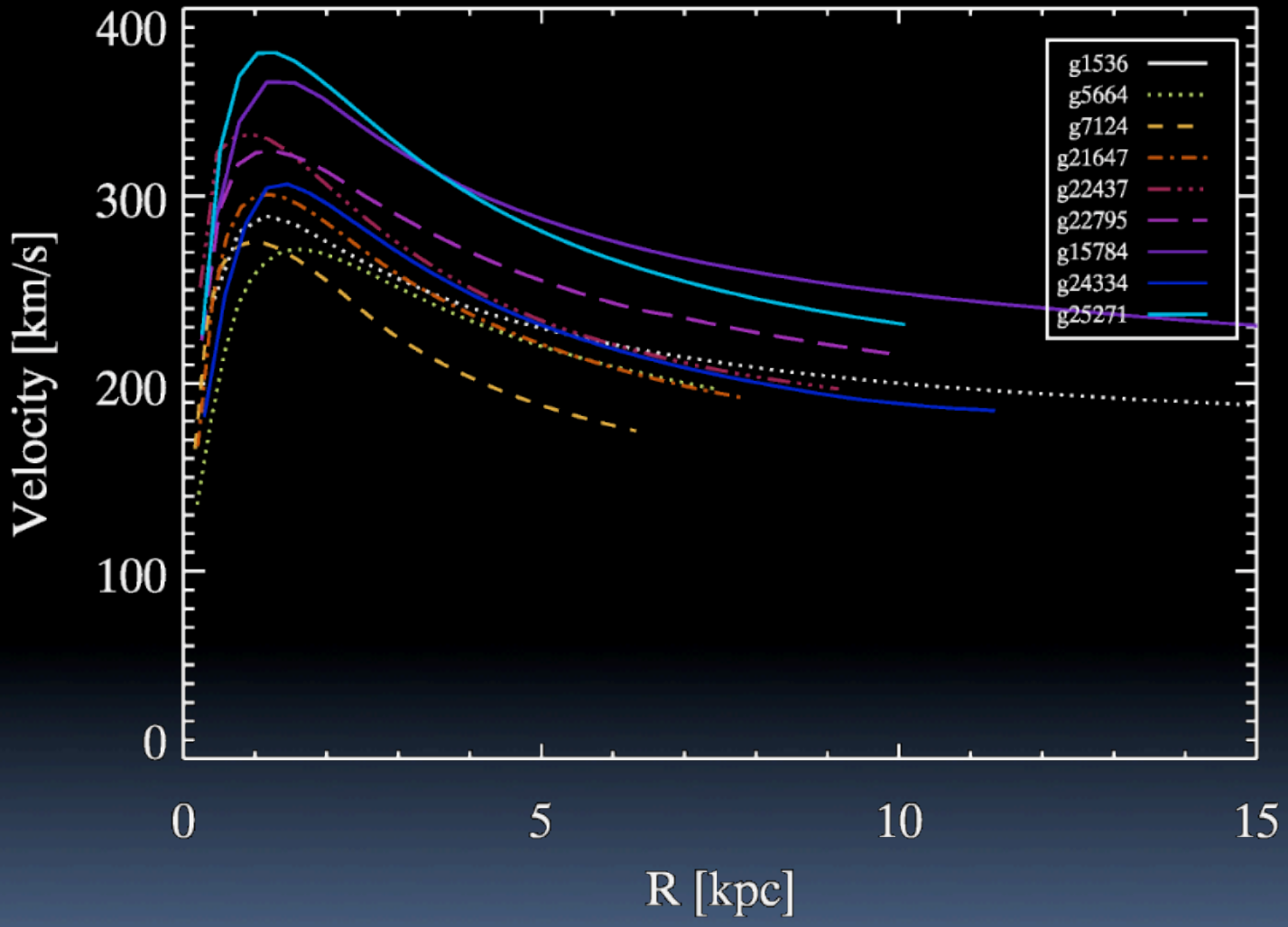

Steinmetz & Navarro 2000

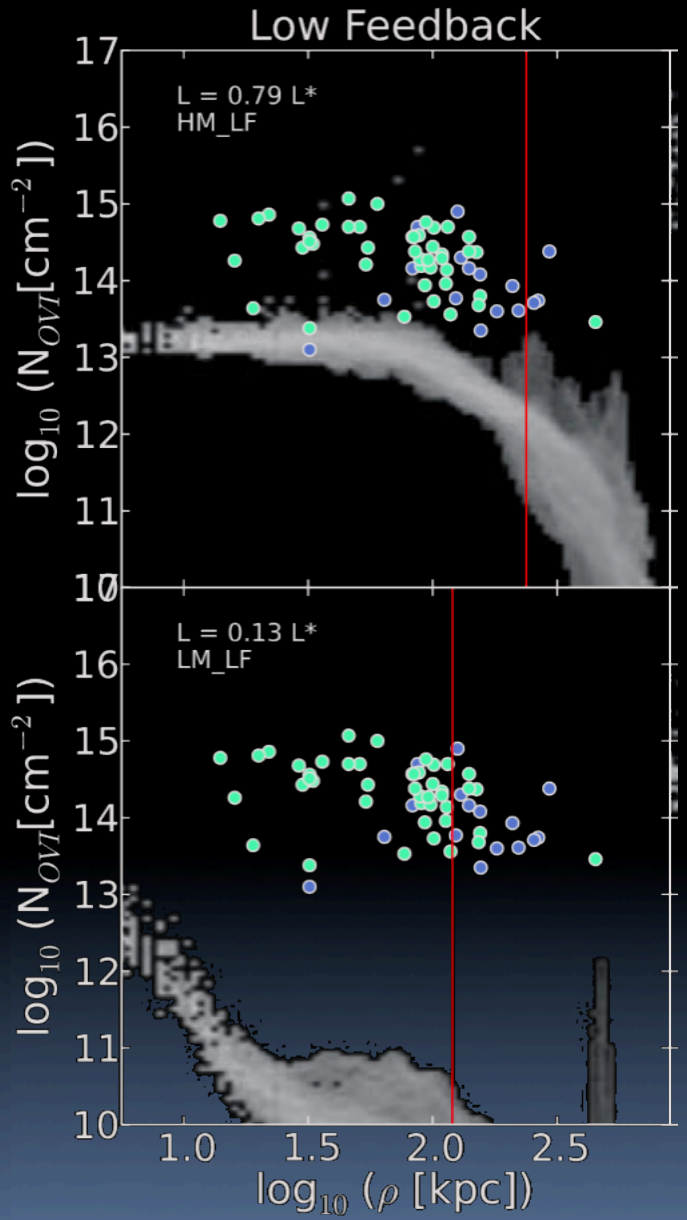
# Stellar Mass-Halo Mass

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



# Simulated rotation curves

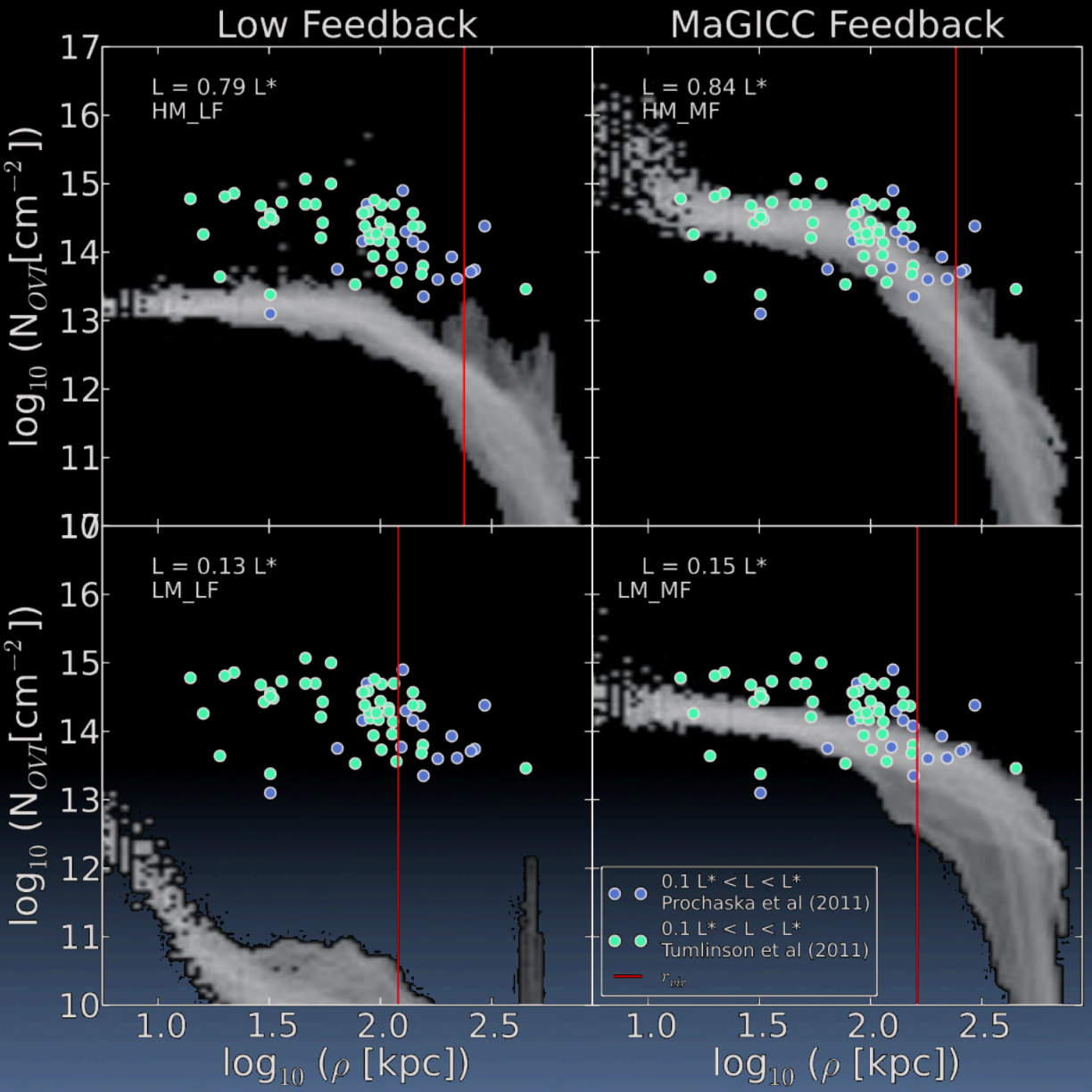





# The "CGM problem"

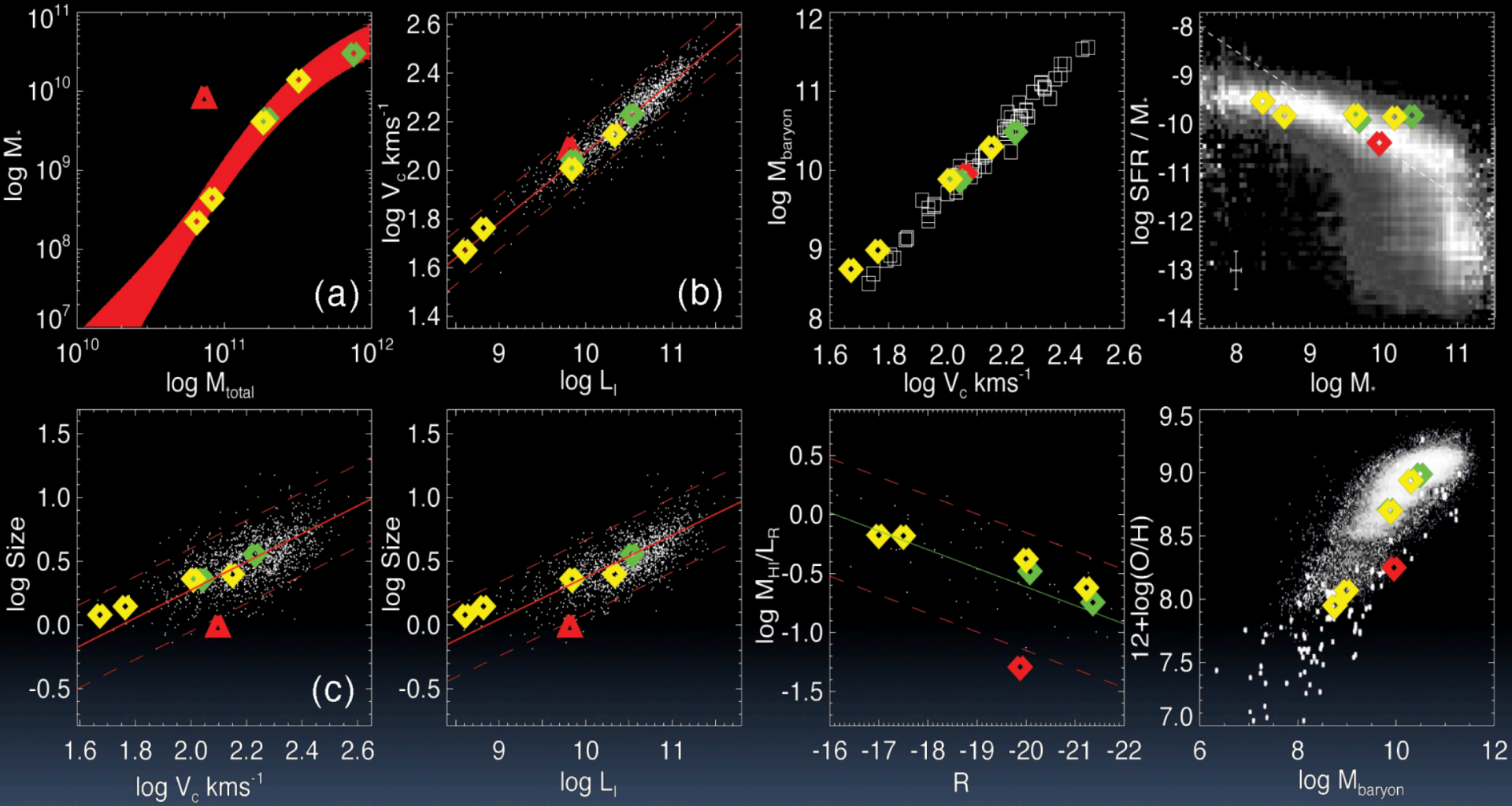
More generally, can the observed metal enrichment of the Universe exist in a CDM model?

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



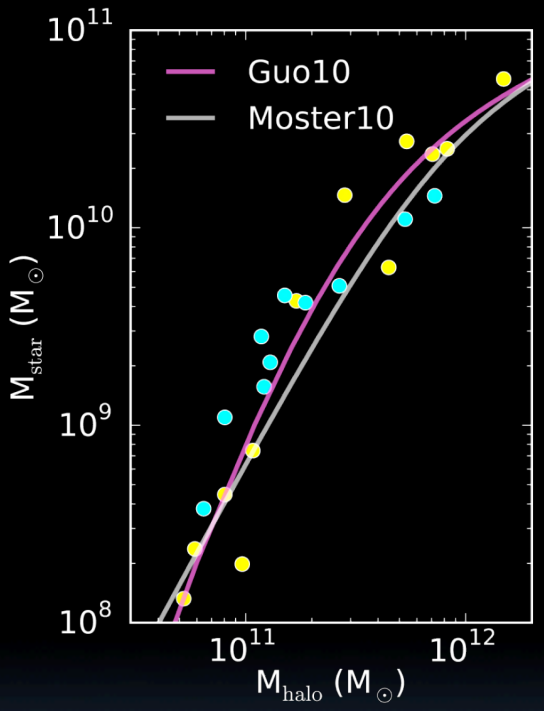

Stinson et al. 2013

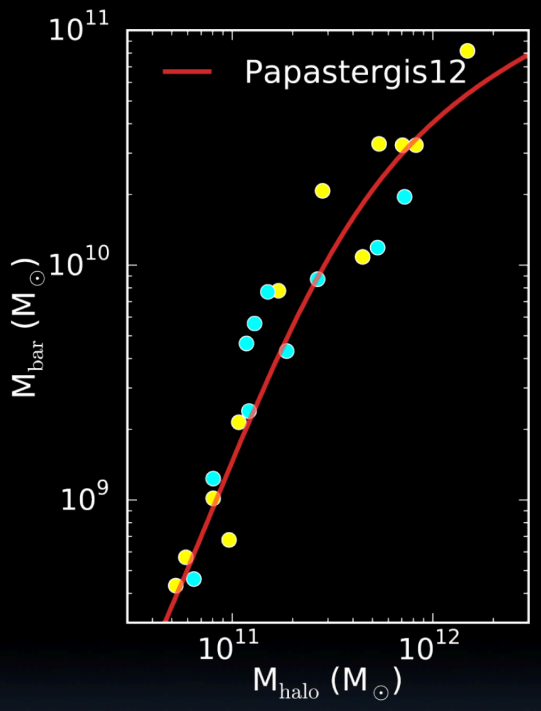
# Matching Observed Scaling Relations

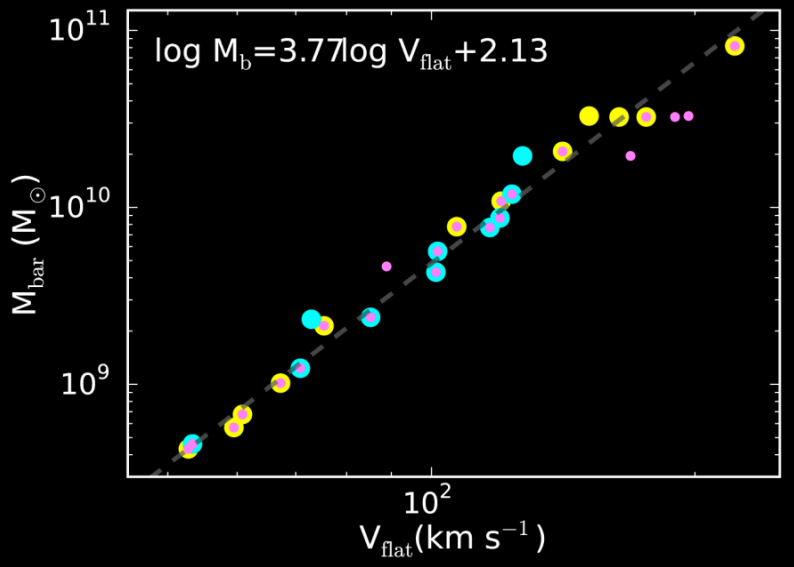



Brook et al. 2012

# Gasoline CLUES



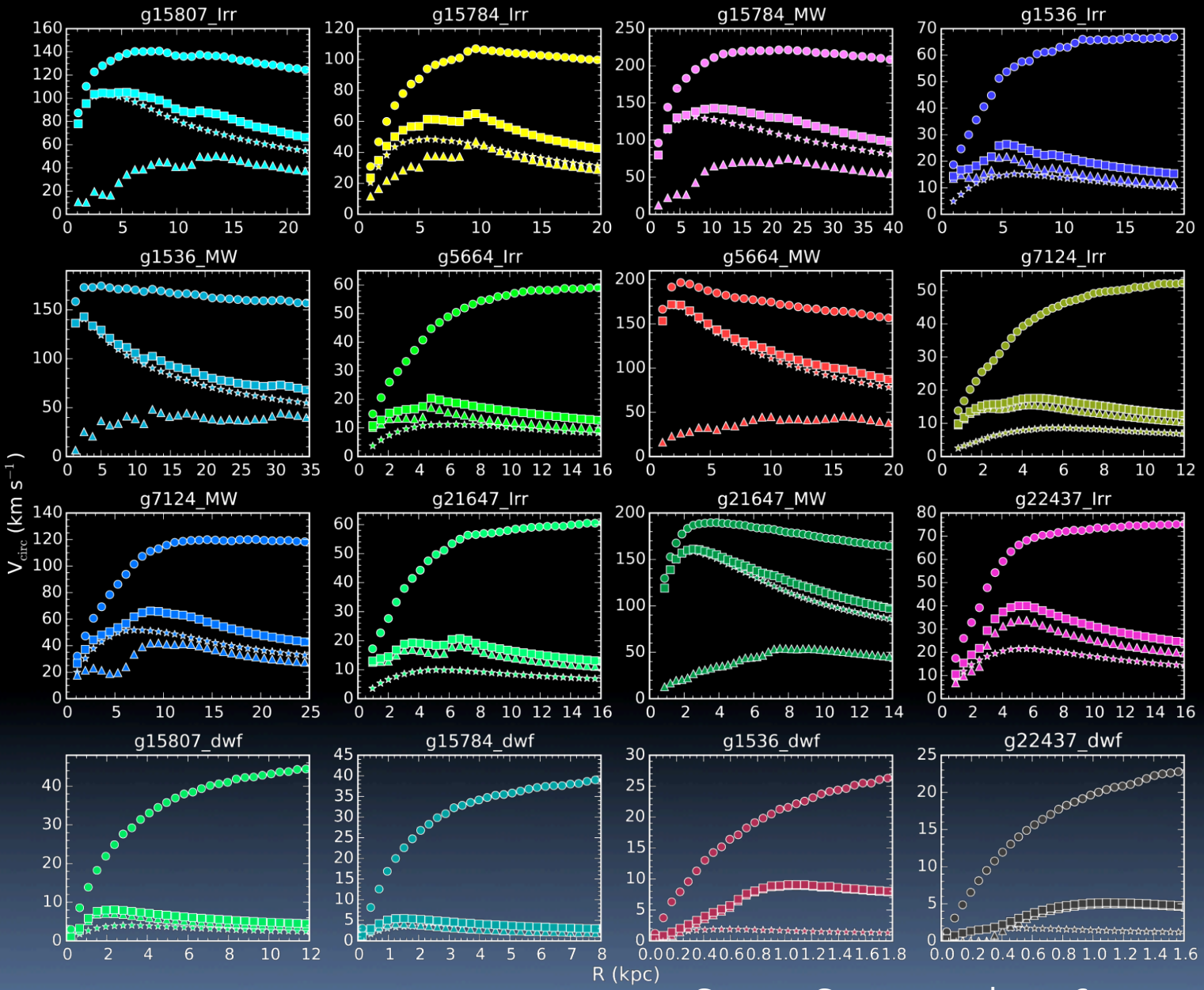




- Magicc simulations (individual isolated galaxies)
- Magicc CLUES simulation WMAP3 4096

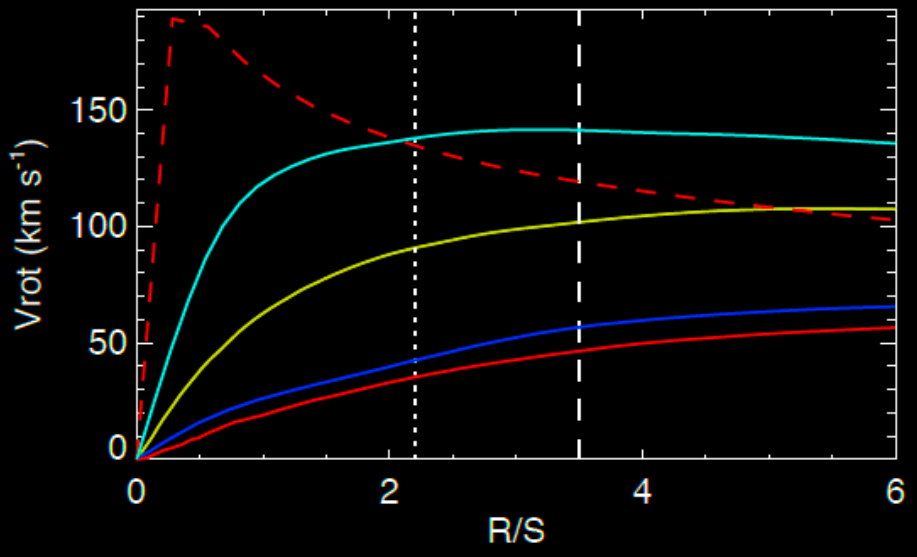
Santos-Santos et al. 2016

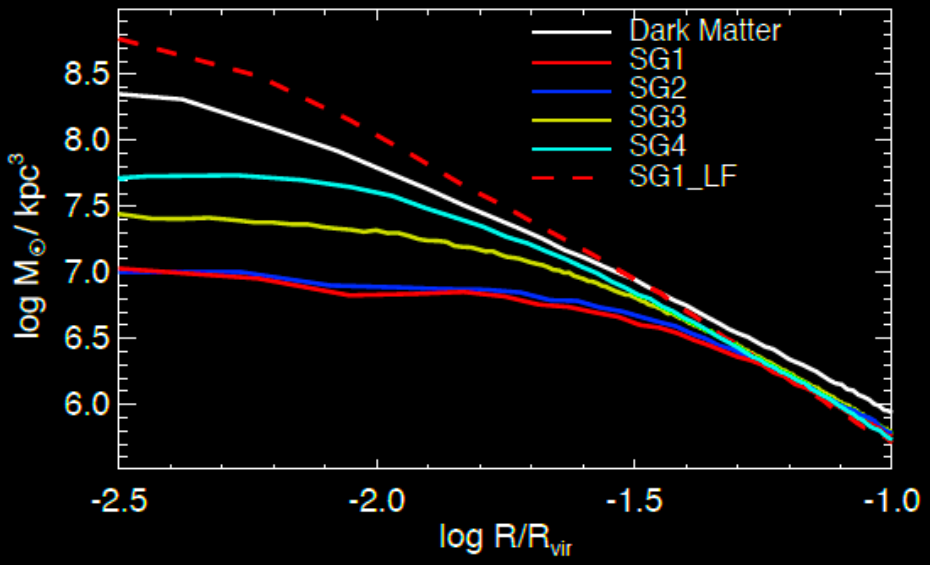
# MaGICC: Mass distribution of all components



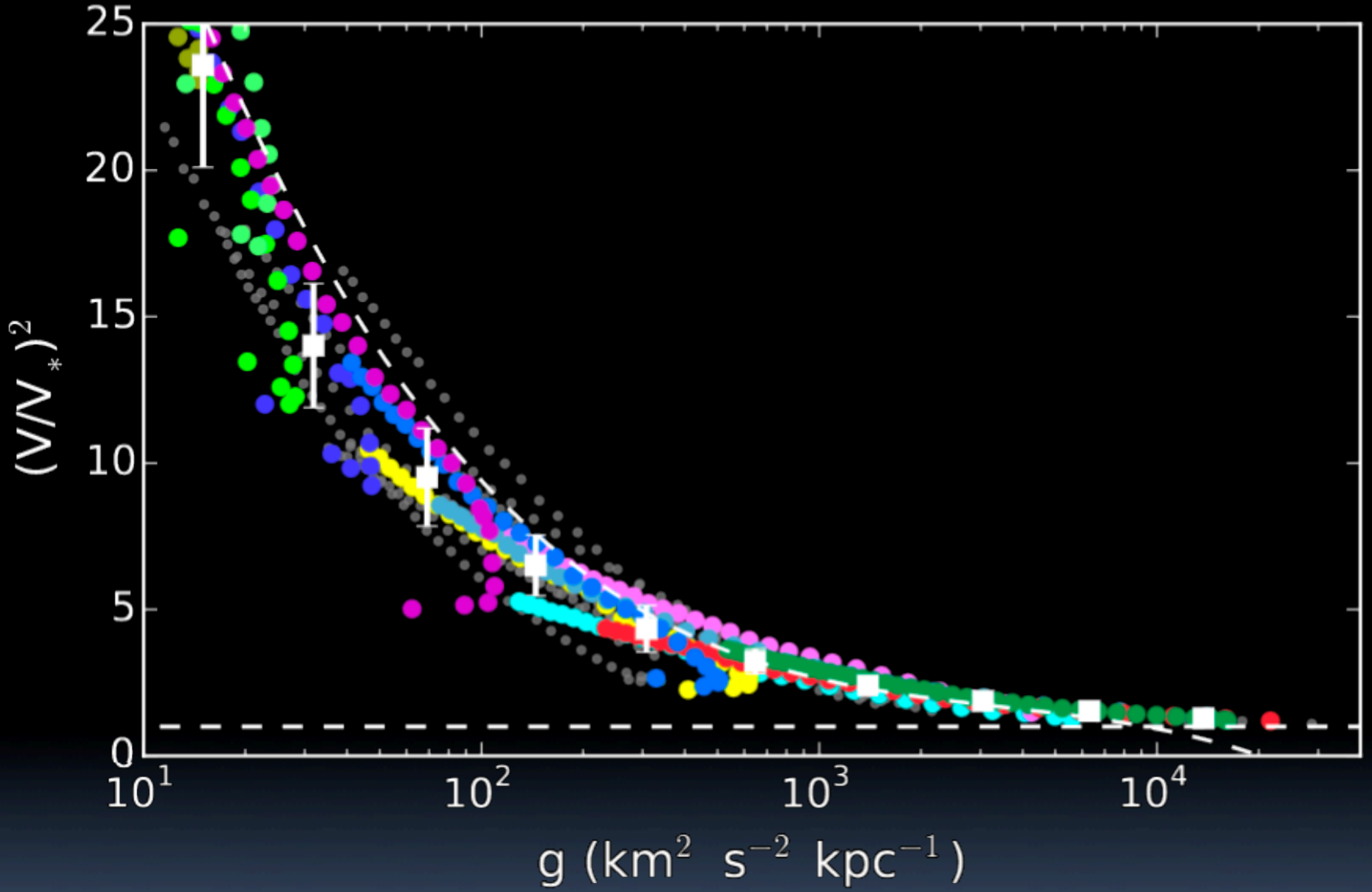

Santos-Santos et al. 2016

# Rotation Curves & Dark Matter Profiles



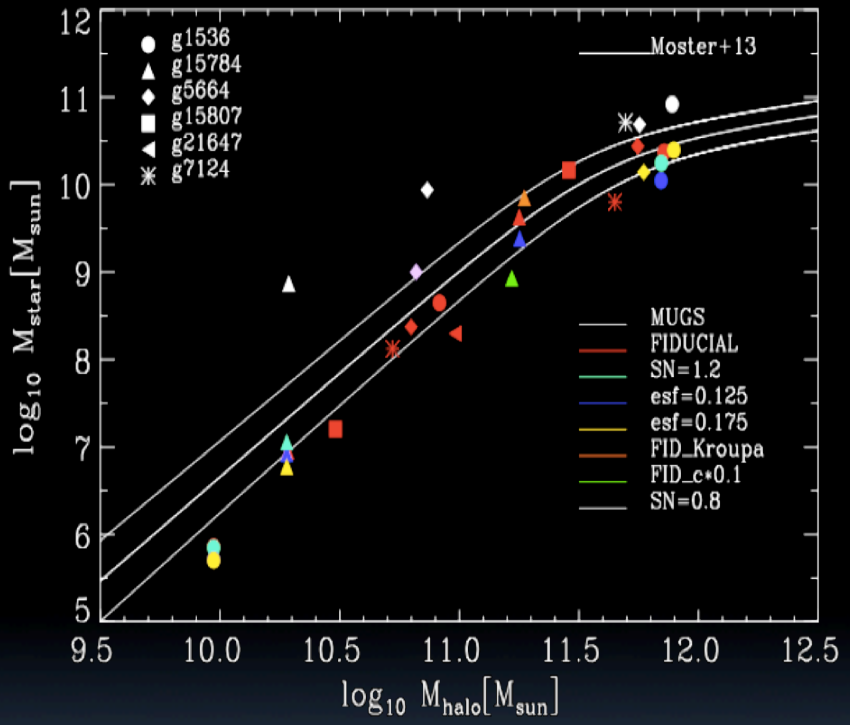



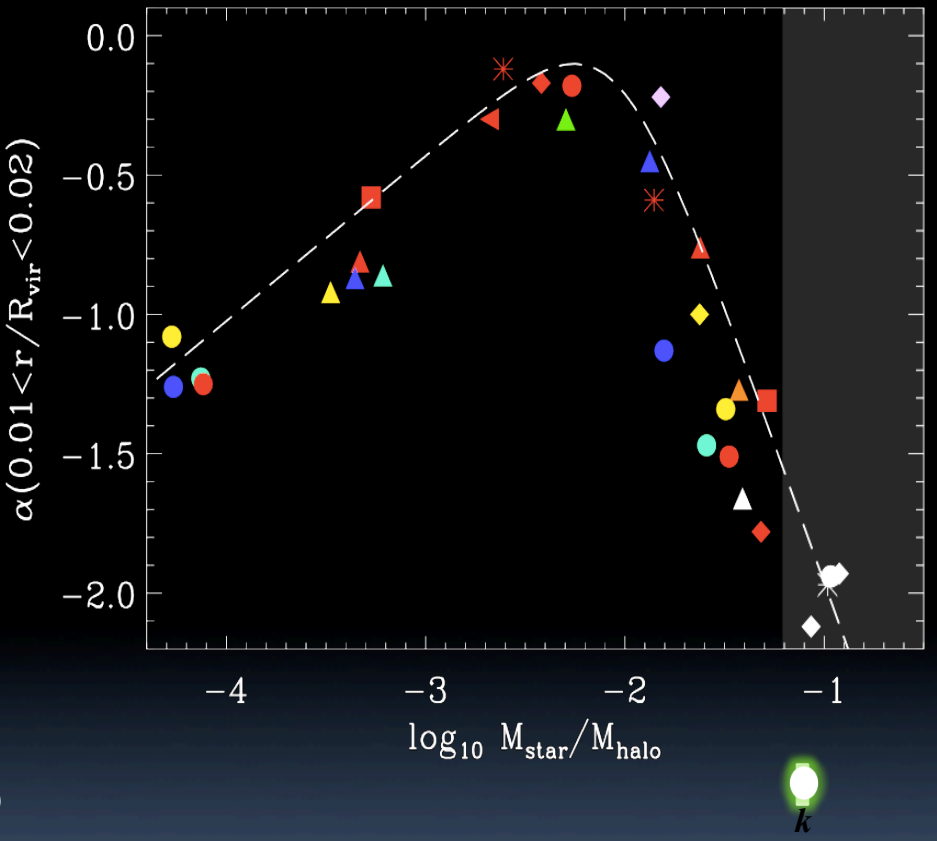

Simulations have slowly rising rotation curves:
Dark matter cores!




Santos-Santos 2016

# Inner slope dependence on $M_\star/M_{halo}$

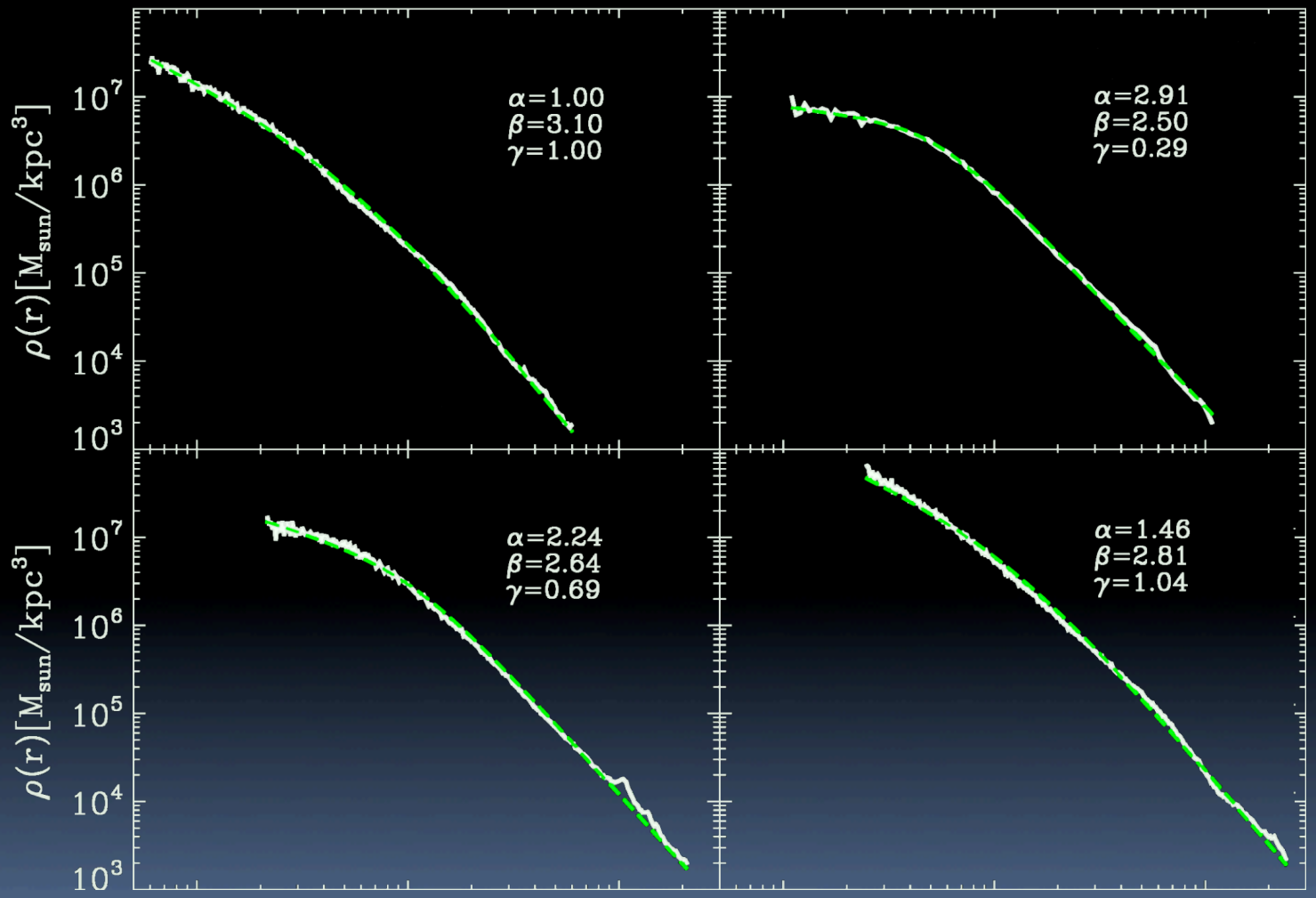



Dark matter profiles determined by two opposite effects: energy from Sne vs Increasing gravitational potential

Di Cintio+14a

# Profile shapes paramatarised by M*/Mhalo



# A double power law profile

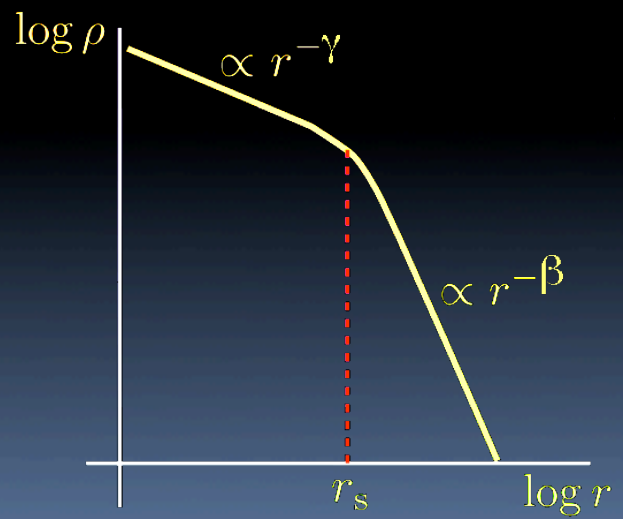
$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

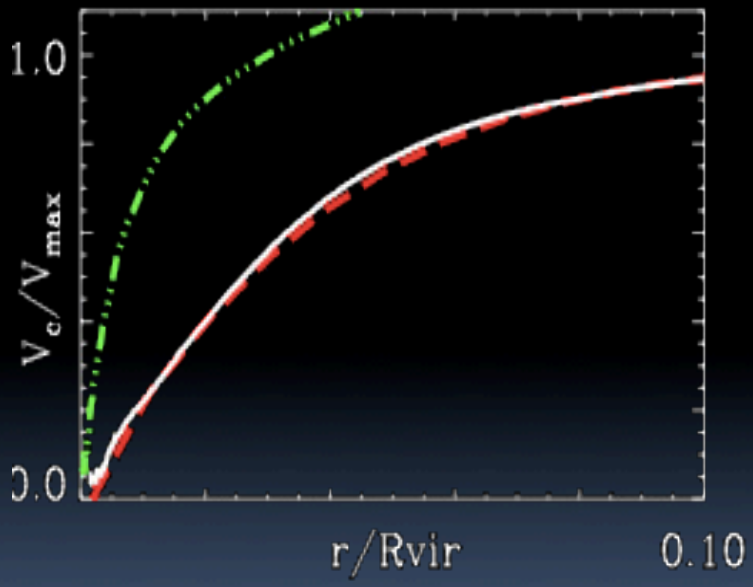
γ inner slope

β outer slope

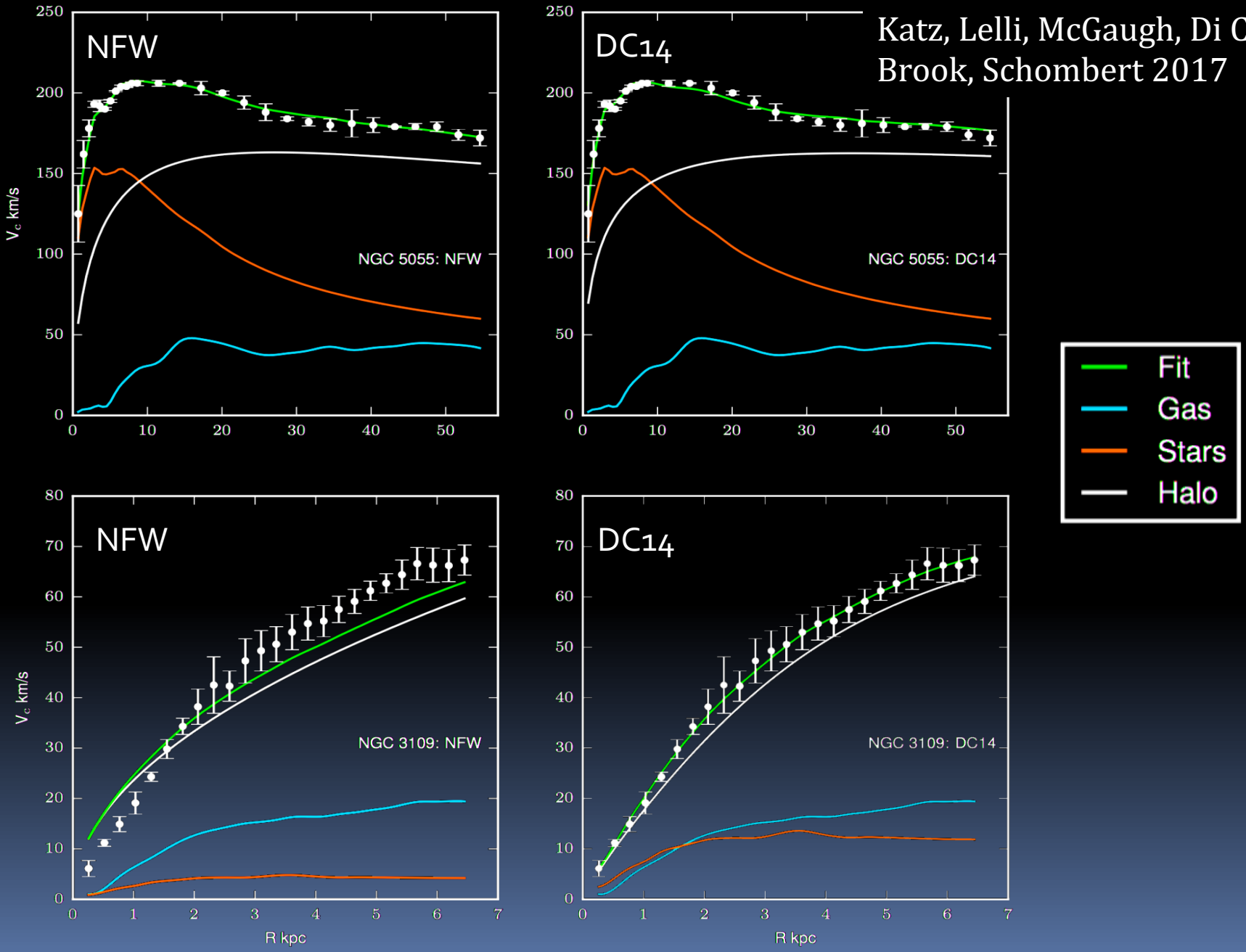
α sharpness of transition

Constrained via $M^*/M_{halo}$



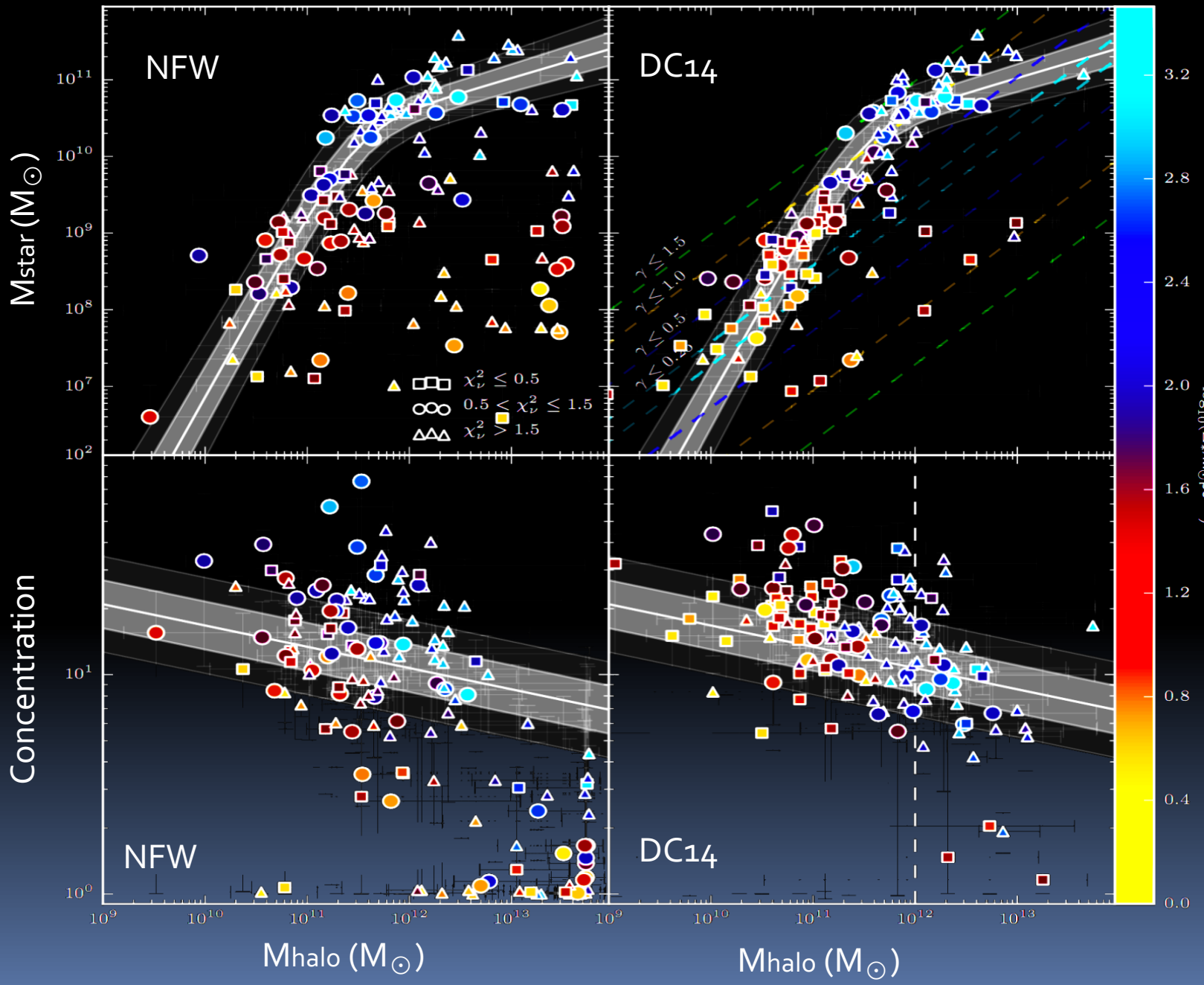



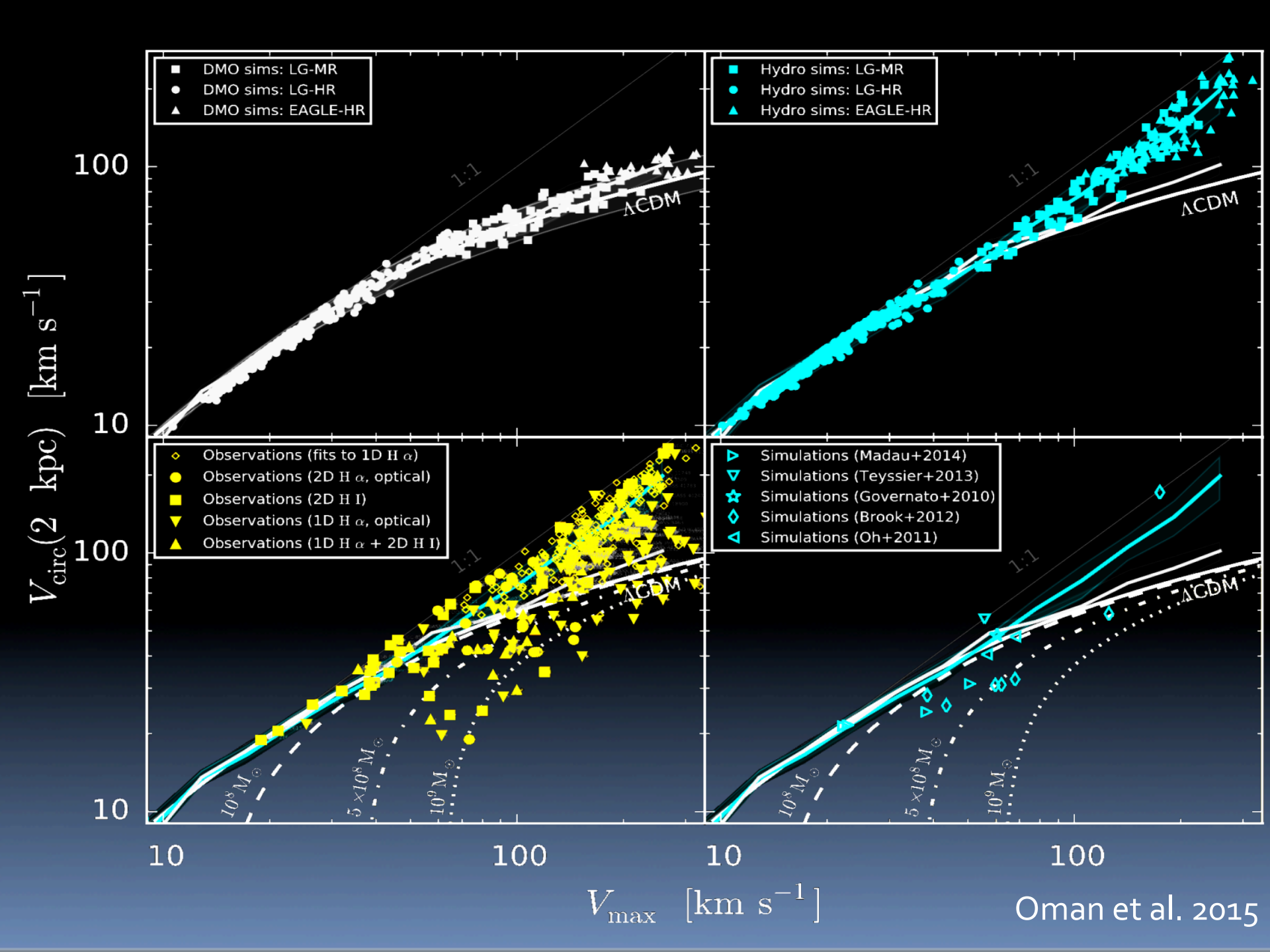

Cores→ slowly rising RCs




Katz, Lelli, McGaugh, Di Cintio, Brook, Schombert 2017

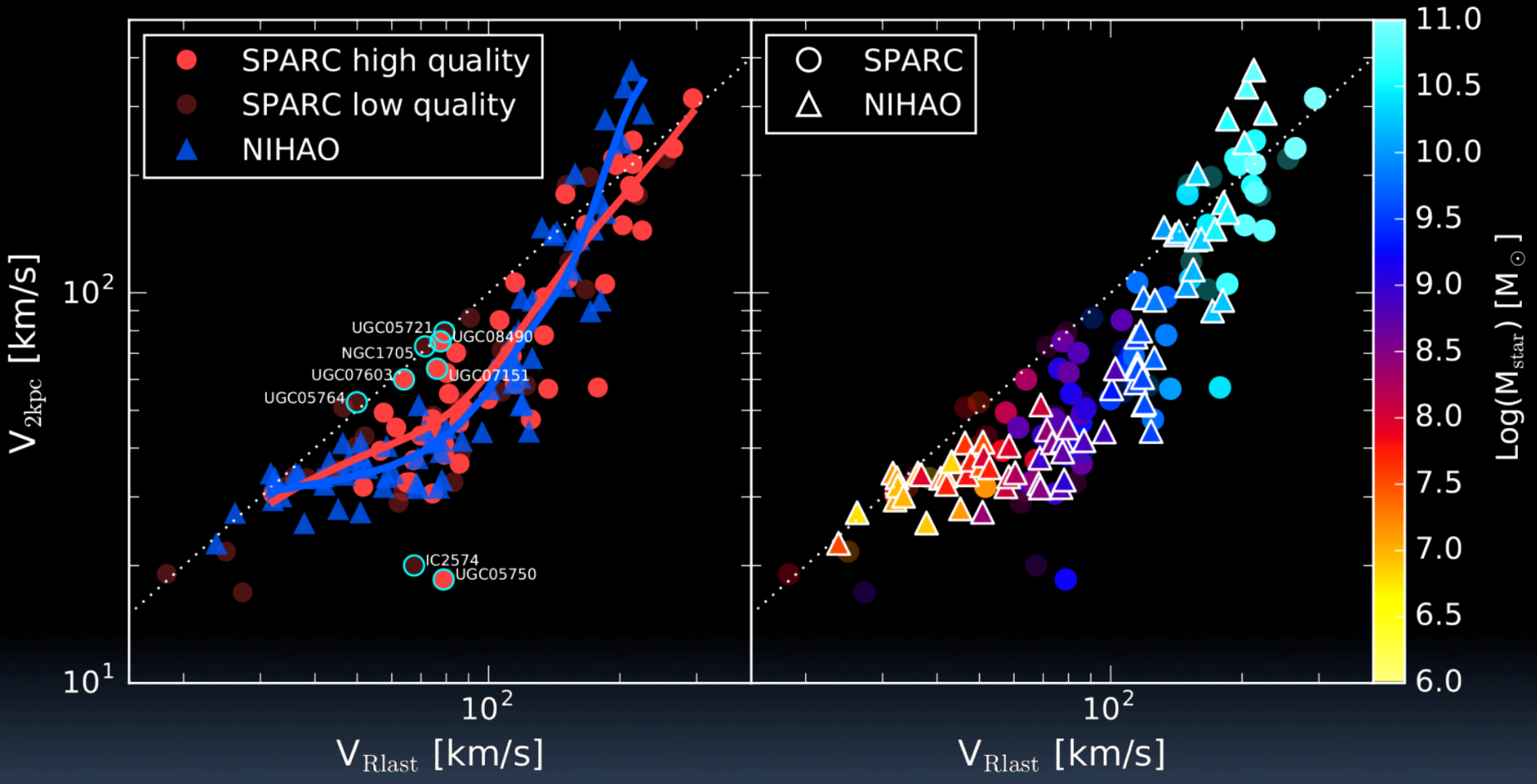
Katz, H et al. 2017





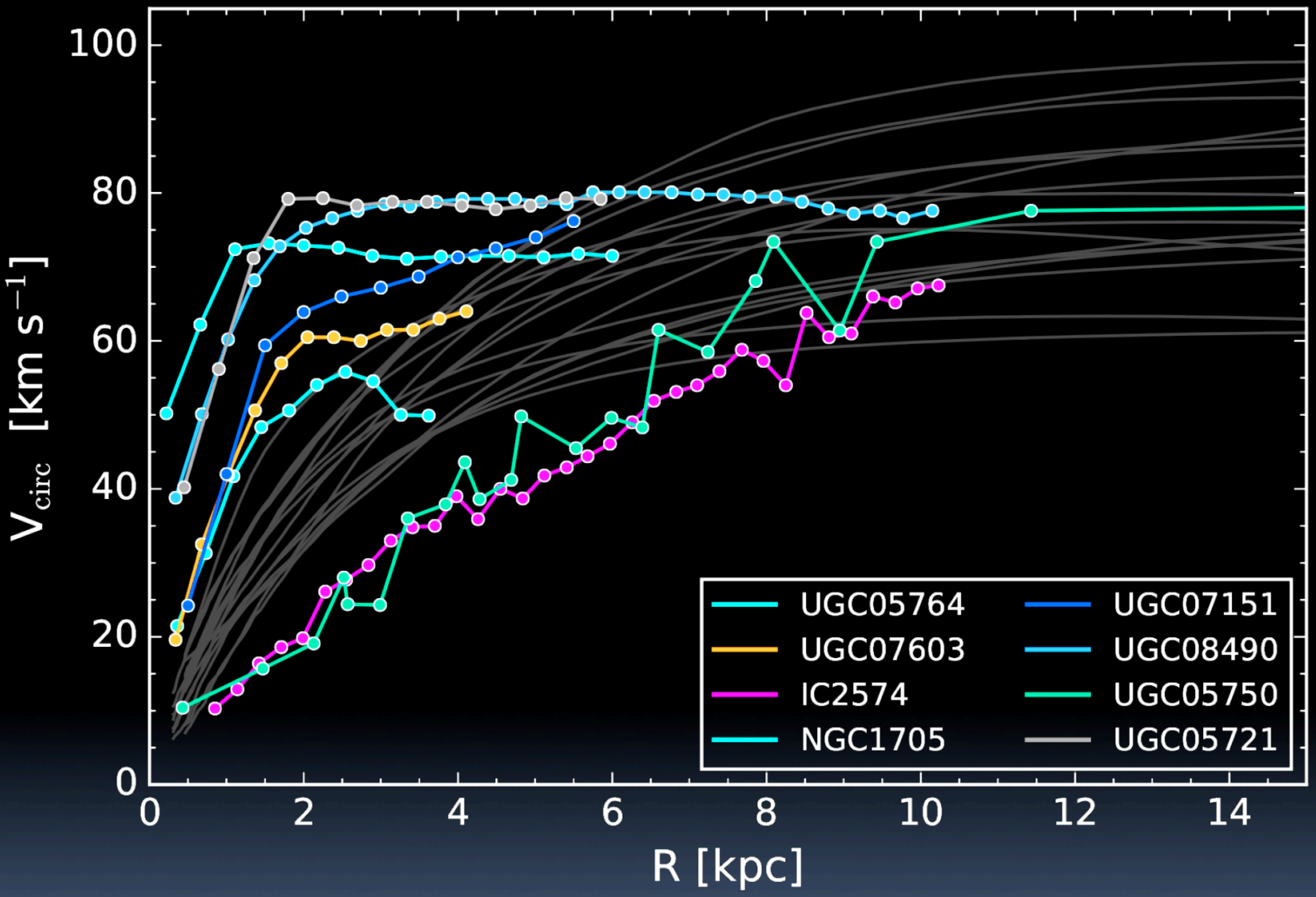

Oman et al. 2015

# Rotation Curve Shapes: Variation




Santos-Santos et al. in prep

# Rotation Curve Shapes: Variation




Santos-Santos et al. in prep

# Conclusions

The allure of CDM is its ability to self-consistently explain a large number of observed galaxy properties, many of which are independent