GRAVITATIONAL LENSING

LECTURE 24

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AA 2015-2016

LUMINOUS AND DARK MATTER IN ETGS AND CLUSTERS FROM SL

- do ETGs and clusters live in dark matter halos?
- what is the relative spatial distribution of dark and luminous matter?
- what is the density profile of ETGs and clusters
- what is the nature of DM?
  - are DM density profiles universal?
  - how many substructures do DM halos contain?
  - are the halo shapes consistent with the collision-less picture of DM?

Good reading:

Treu, 2010, Ann. Rev. Astron. & Astrophys., 48, 87

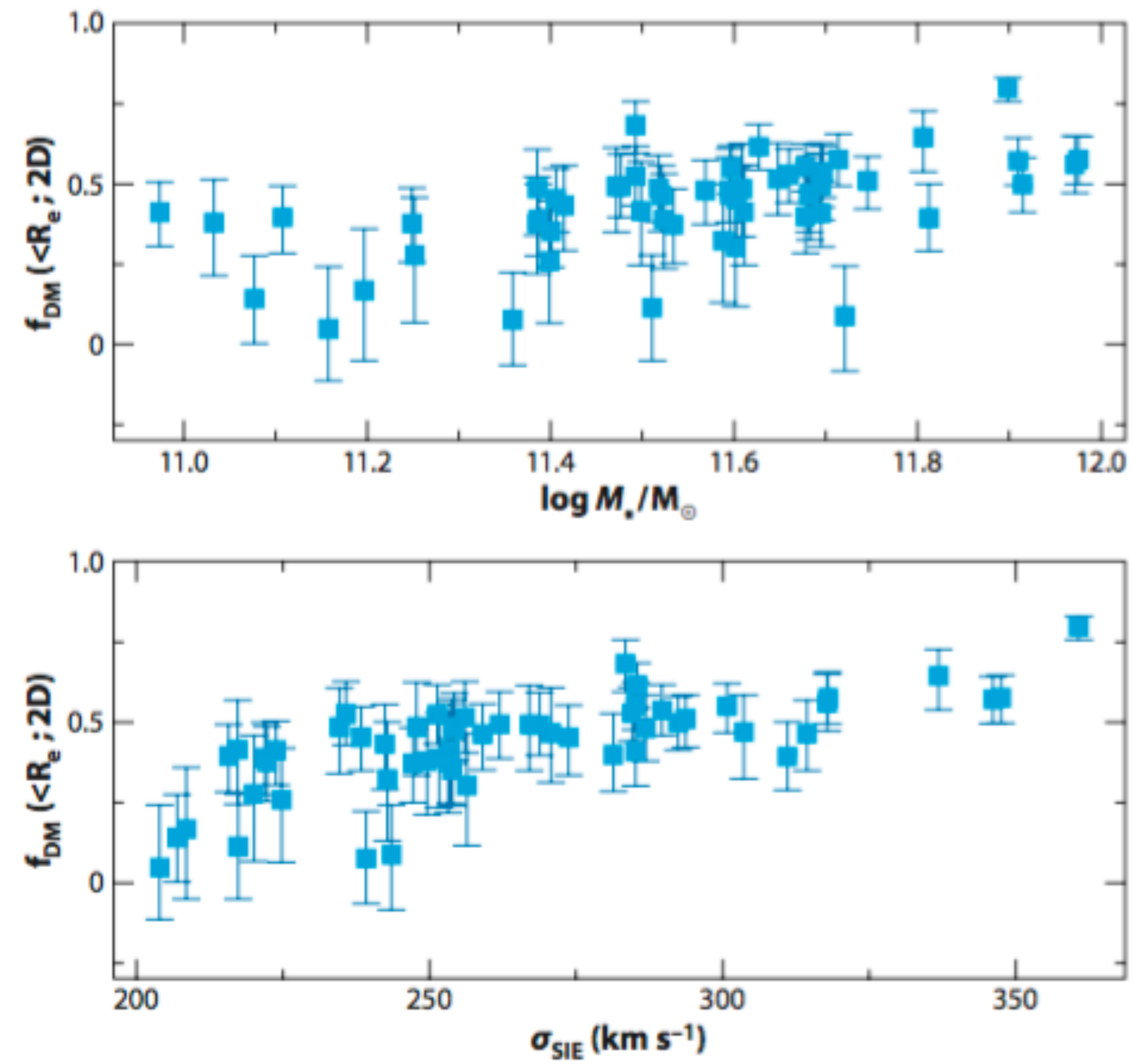
Weinberg et al., 2015, PNAS, 112, 40

DO ETGS AND CLUSTERS LIVE IN DARK MATTER HALOS?

- a much larger amount of matter than the visible one is necessary to explain the observed SL effects.
- the mass inside the Einstein radius is very well determined and can be compared to the stellar mass
- the stellar mass can be derived from photometry and spectra:
  - assume an initial mass function (IMF)
  - apply stellar population synthesis models (SPS) to the photometric or to the spectroscopic data
  - obtain the stellar mass
- the total mass exceeds the stellar mass

WHAT IS THE RELATIVE SPATIAL DISTRIBUTION OF LUMINOUS AND DARK MATTER?

- baryons tend to condense inside halos to form stars
- by condensing to the center of the potential well, they affect the distribution of DM (e.g. by adiabatic contraction)
- however, there are other processes to account for: feedback mechanisms leading to heating of the IGM, which make less efficient such condensation
- with lensing, we can try to understand these processes by measuring the fraction of total mass in DM within a fixed projected radius (a fraction of R_e)
- stellar masses measured as before



WHAT IS THE RELATIVE SPATIAL DISTRIBUTION OF LUMINOUS AND DARK MATTER?

From the virial theorem:

$$\sigma^2 \propto \frac{GM}{R} \qquad \Gamma = \frac{M}{L} \qquad L \propto IR^2$$

$$\sigma^2 \propto G\Gamma IR \qquad R_e = c\frac{\sigma^2}{GI_e\Gamma}$$

If c and M/L do not depend on mass, we expect the fundamental plane:

$$\log R_e = 2\log\sigma - \log I_e + d$$

Observationally:

$$\log R_e = a\log\sigma + b\log I_e + d' \qquad a = [1.1 \div 1.6] \qquad b = [-0.7 \div 0.8]$$

("tilt" of the fundamental plane)

WHAT IS THE RELATIVE SPATIAL DISTRIBUTION OF LUMINOUS AND DARK MATTER?

Lensing allows to measure the mass within a fraction of R_e! Thus we can use it to measure the "mass fundamental plane":

$$\sigma^2 \propto \frac{GM}{R} \qquad \log R_e = a_m \log \sigma + b_m \log \Sigma_e + d_m$$

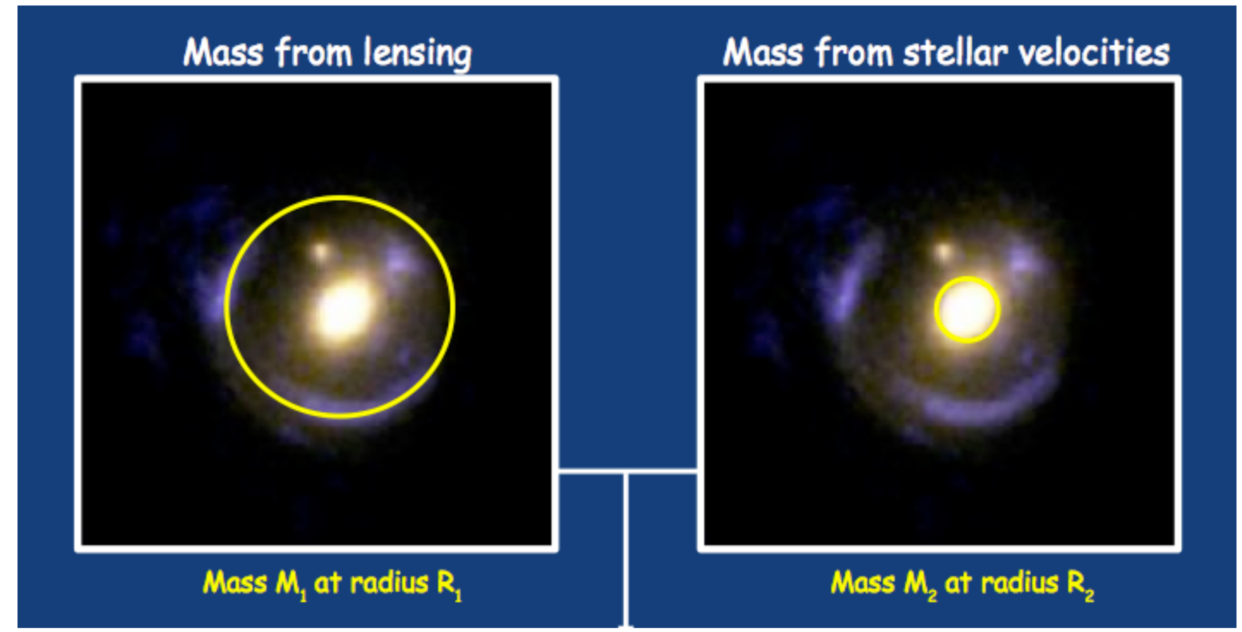
It turns out that the mass fundamental plane is not tilted, indicating that the tilt of the fundamental plane is ascribable to a M/L which is not constant because of the increase in f_{DM} with mass (Bolton et al. 2008 using 53 ETGs from SLAC)

Bolton et al. (2008) also find that the mass distribution of these lenses is not consistent with the assumption that light traces mass.

MASS DENSITY PROFILES

Koopmans & Treu 2002, Treu & Koopmans 2002, Koopmans et al. 2006, 2009, Sonnenfeld et al. 2013, Spiniello et al. 2015

- Since 2005 (LSD survey; Koopmans & Treu), SL and stellar kinematics have been used to probe the mass profiles of ETGs
- Results point into the direction that, at the scales probed by these two methods, the total mass profiles are nearly isothermal
- there seems to be very little evolution with redshift



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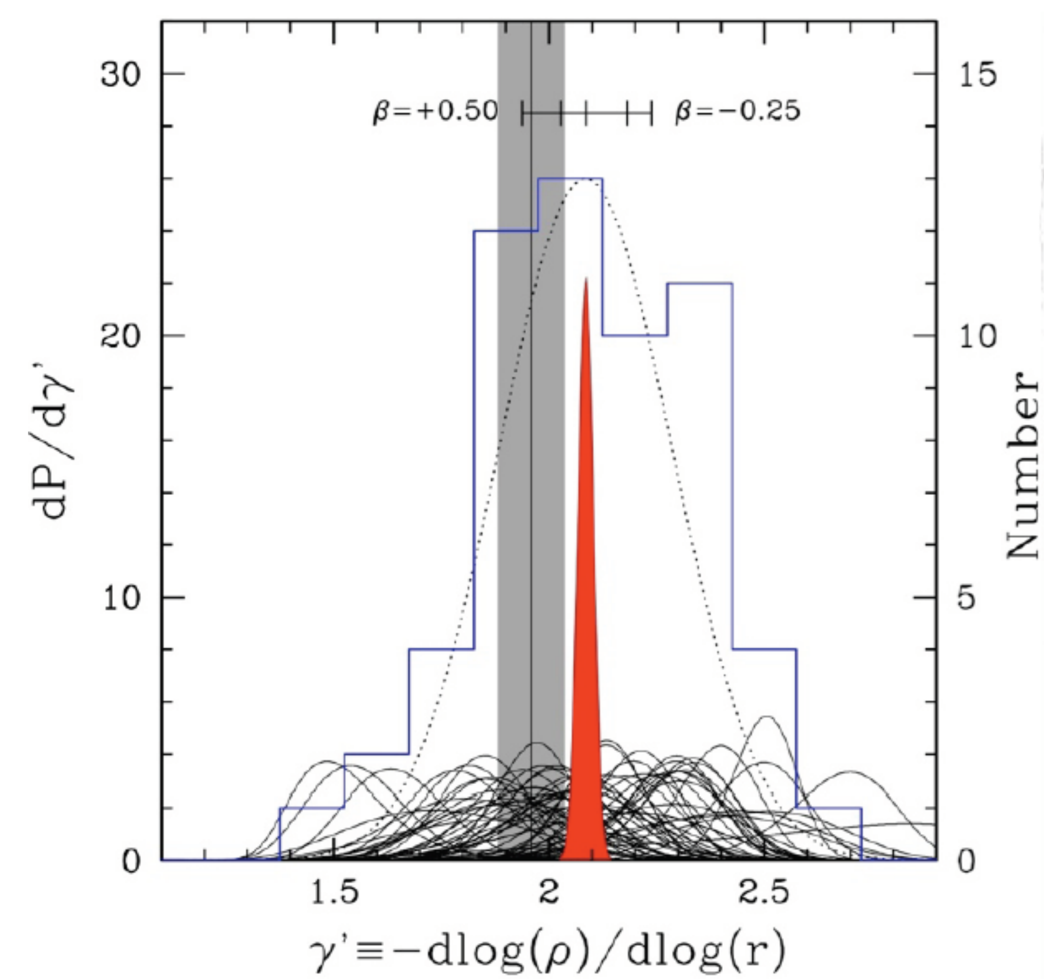

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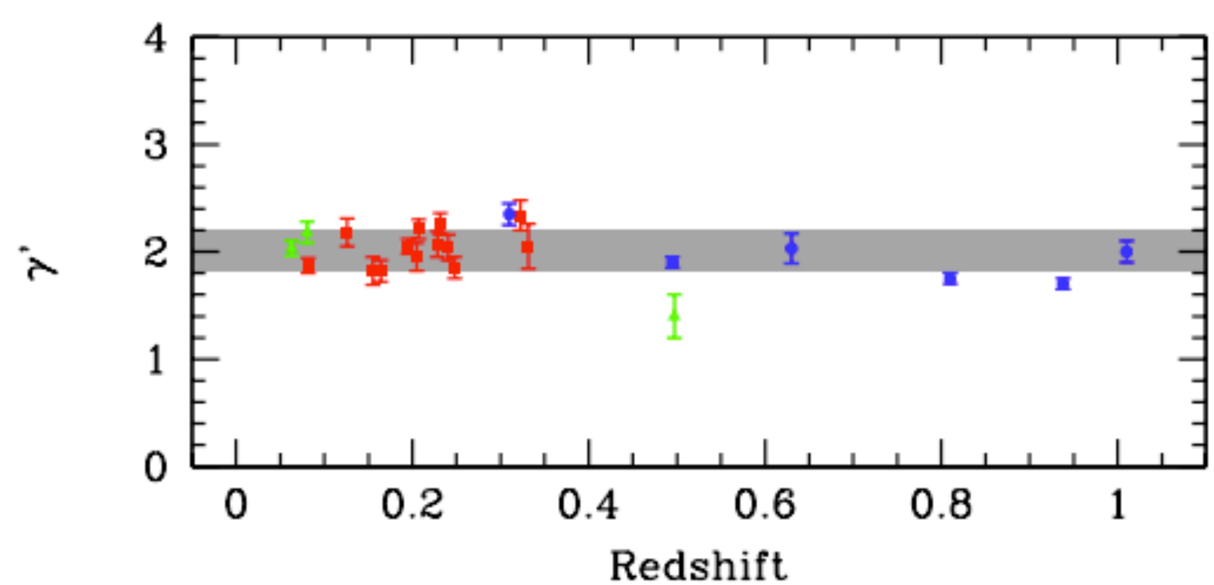
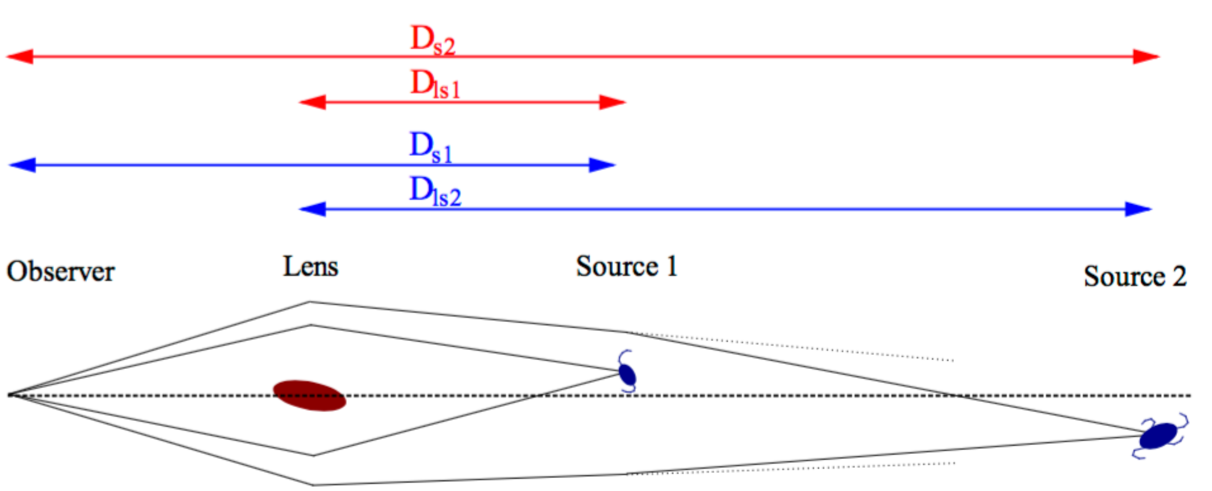


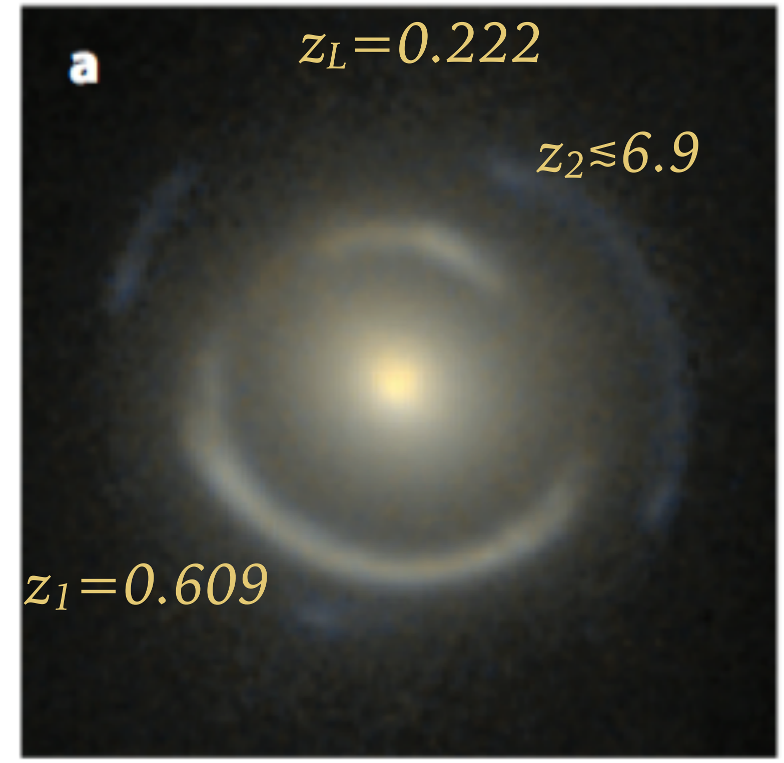
MASS DENSITY PROFILES

- In some rare cases, lensing alone may be sufficient to measure a slope
- this is the case of the so called "compound lenses" (Gavazzi et al. 2008)
- in such cases, two measurements of the mass at two different radii are possible, enabling the measurement of the slope of the mass profile
- the complication: it is a double lens!

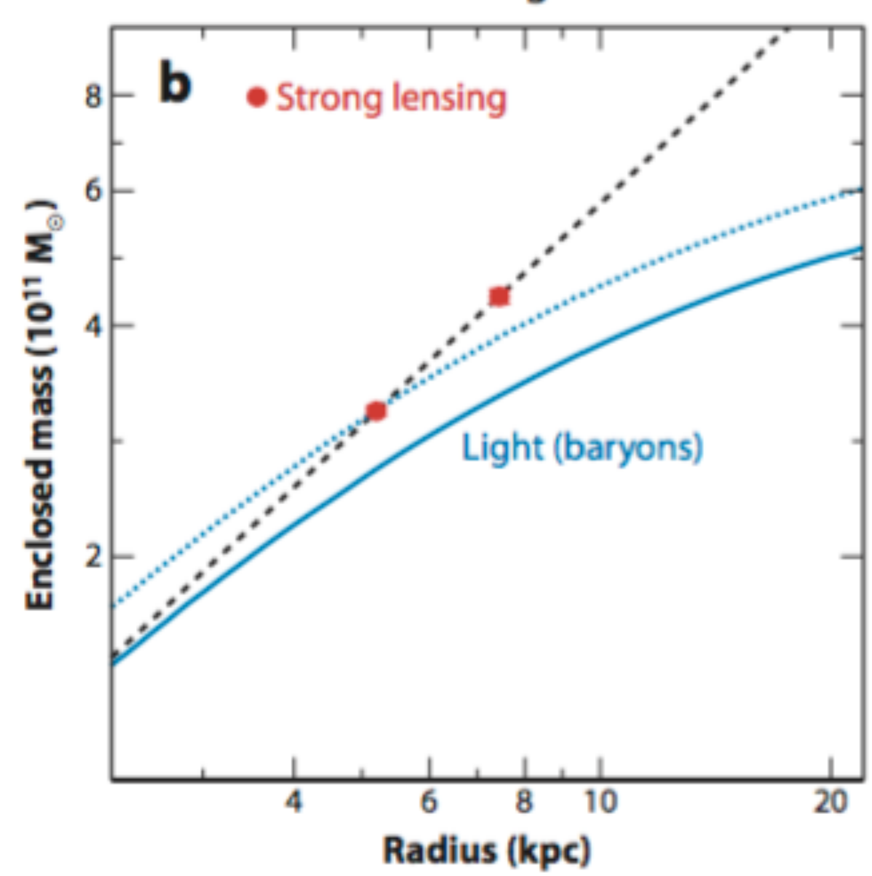


Collett et al. 2014

SDSSJ0946 + 1006



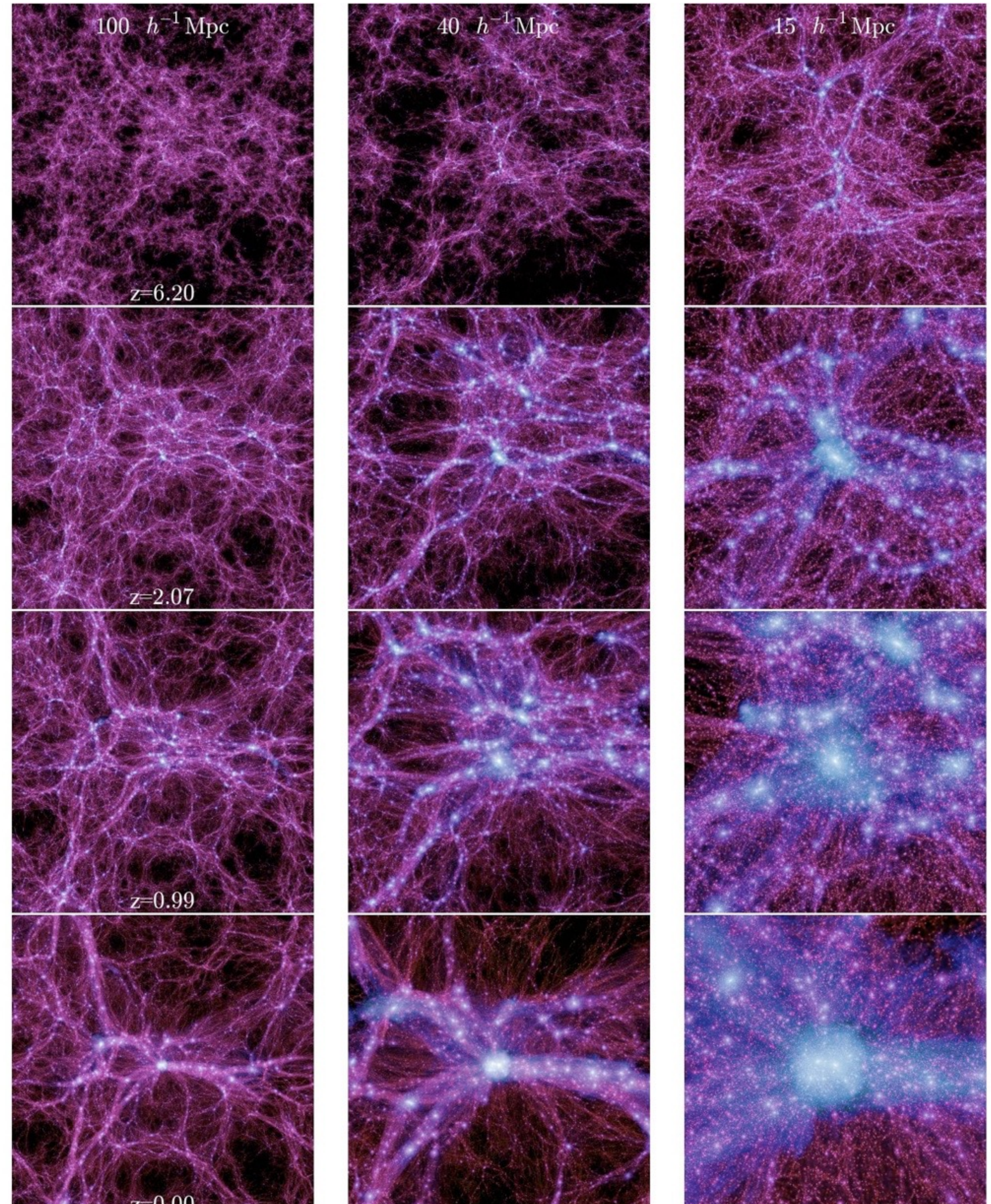
Double Einstein ring J0946 + 1006



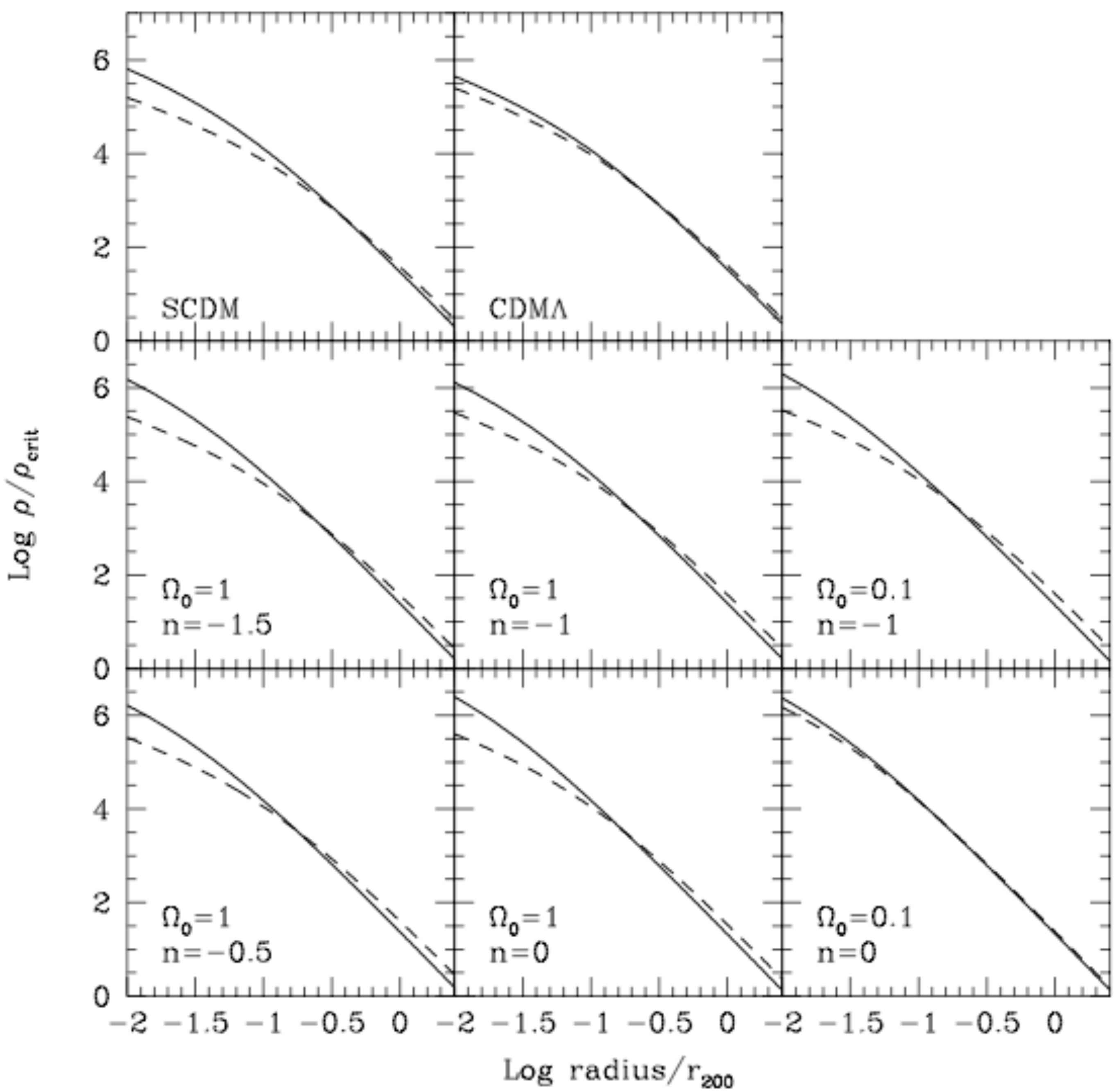
NFW

NAVARRO-FRENK-WHITE, 1997

- This profile was derived by fitting a large number of density profiles of DM halos in cosmological simulations
- Numerical simulations can be used to study the formation of the cosmic structures starting from suitable initial conditions
- The original work of NFW was based on pure N-body, collision less simulations.



NFW



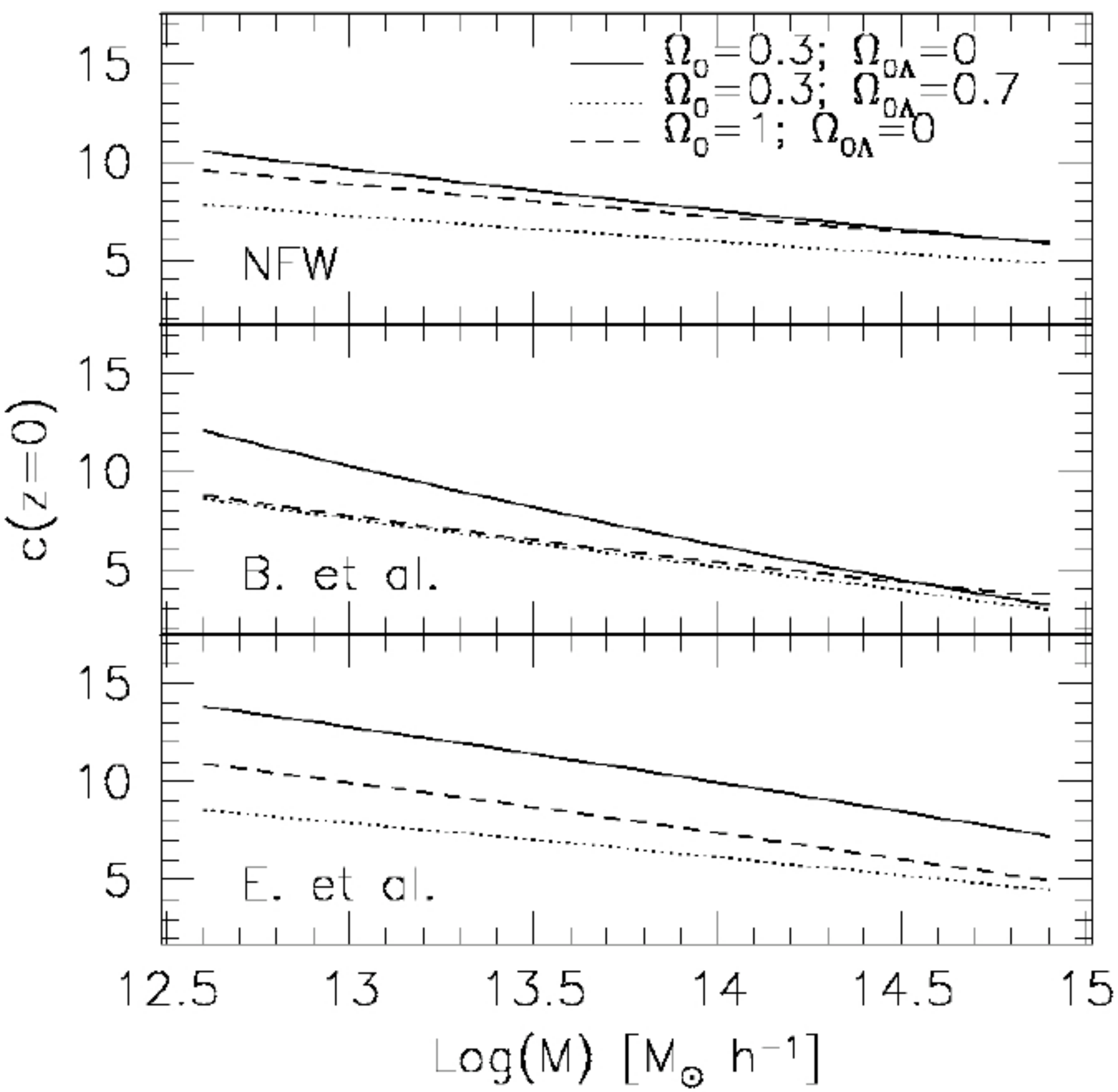
$$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

$$r_{200} = 1.63 \times 10^{-2} \left(\frac{M_{200}}{h^{-1}M_\odot}\right)^{1/3} \left[\frac{\Omega_0}{\Omega(z)}\right]^{-1/3} (1+z)^{-1}h^{-1} \text{ kpc}$$

$$\rho_s = \frac{200}{3}\rho_{\rm cr}\frac{c^3}{[\ln(1+c) - c/(1+c)]}$$

$$c \equiv r_{200}/r_s$$

NFW VS COSMOLOGY



NFW LENSES

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2} \quad \Rightarrow \quad \xi_0 = r_s \quad \Rightarrow \quad \Sigma(x) = \frac{2\rho_s r_s}{x^2 - 1} f(x)$$

$$f(x) = \begin{cases} 1 - \frac{2}{\sqrt{x^2-1}} \operatorname{arctan}\sqrt{\frac{x-1}{x+1}} & (x > 1) \\ 1 - \frac{2}{\sqrt{1-x^2}} \operatorname{arctanh}\sqrt{\frac{1-x}{1+x}} & (x < 1) \\ 0 & (x = 1) \end{cases}$$

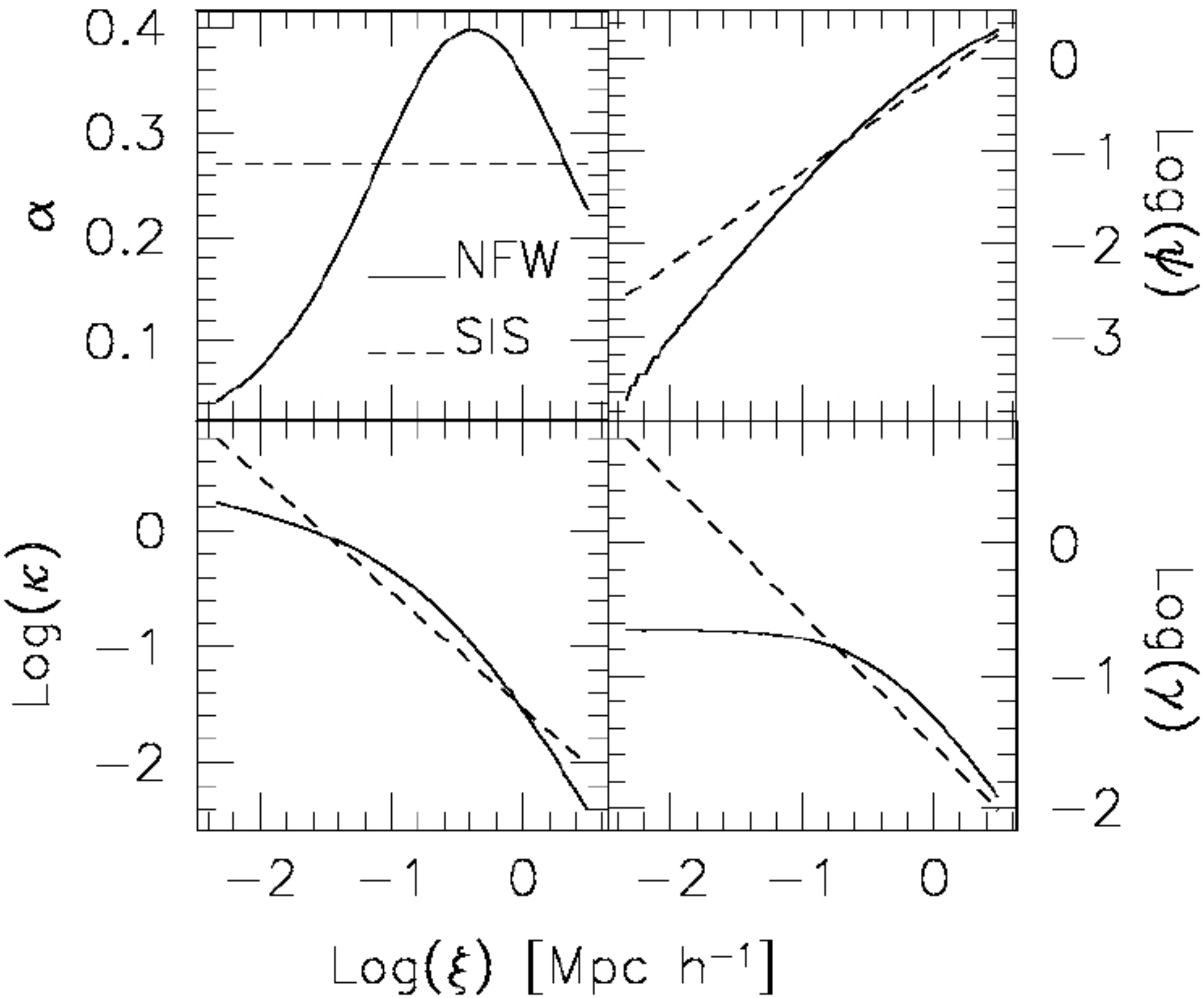
$$\Psi(x) = 4\kappa_s g(x) \qquad \kappa_s \equiv \rho_s r_s \Sigma_{cr}^{-1}$$

$$g(x) = \frac{1}{2}\ln^2\frac{x}{2} + \begin{cases} 2\operatorname{arctan}^2\sqrt{\frac{x-1}{x+1}} & (x > 1) \\ -2\operatorname{arctanh}^2\sqrt{\frac{1-x}{1+x}} & (x < 1) \\ 0 & (x = 1) \end{cases}$$

$$\alpha(x) = \frac{4\kappa_s}{x} h(x)$$

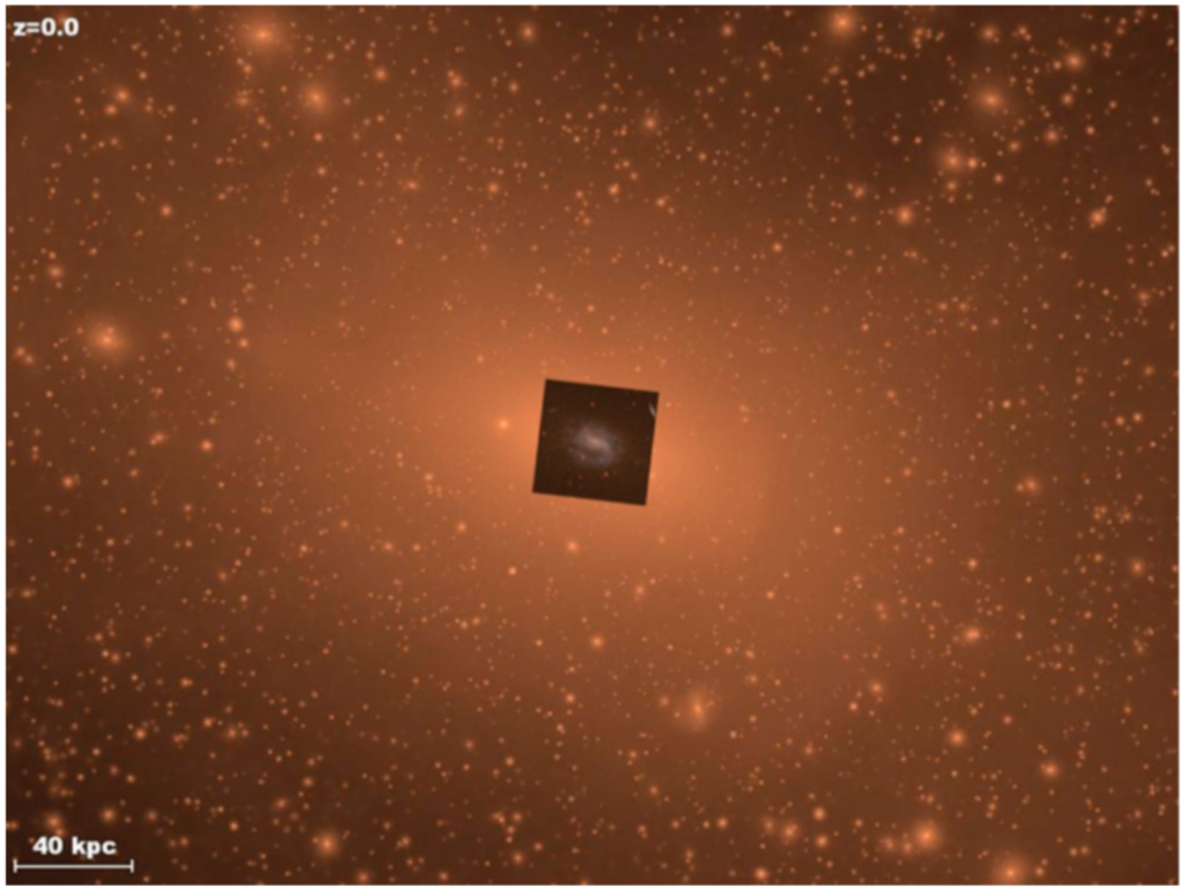
$$h(x) = \ln\frac{x}{2} + \begin{cases} \frac{2}{\sqrt{x^2-1}} \operatorname{arctan}\sqrt{\frac{x-1}{x+1}} & (x > 1) \\ \frac{2}{\sqrt{1-x^2}} \operatorname{arctanh}\sqrt{\frac{1-x}{1+x}} & (x < 1) \\ 1 & (x = 1) \end{cases}$$

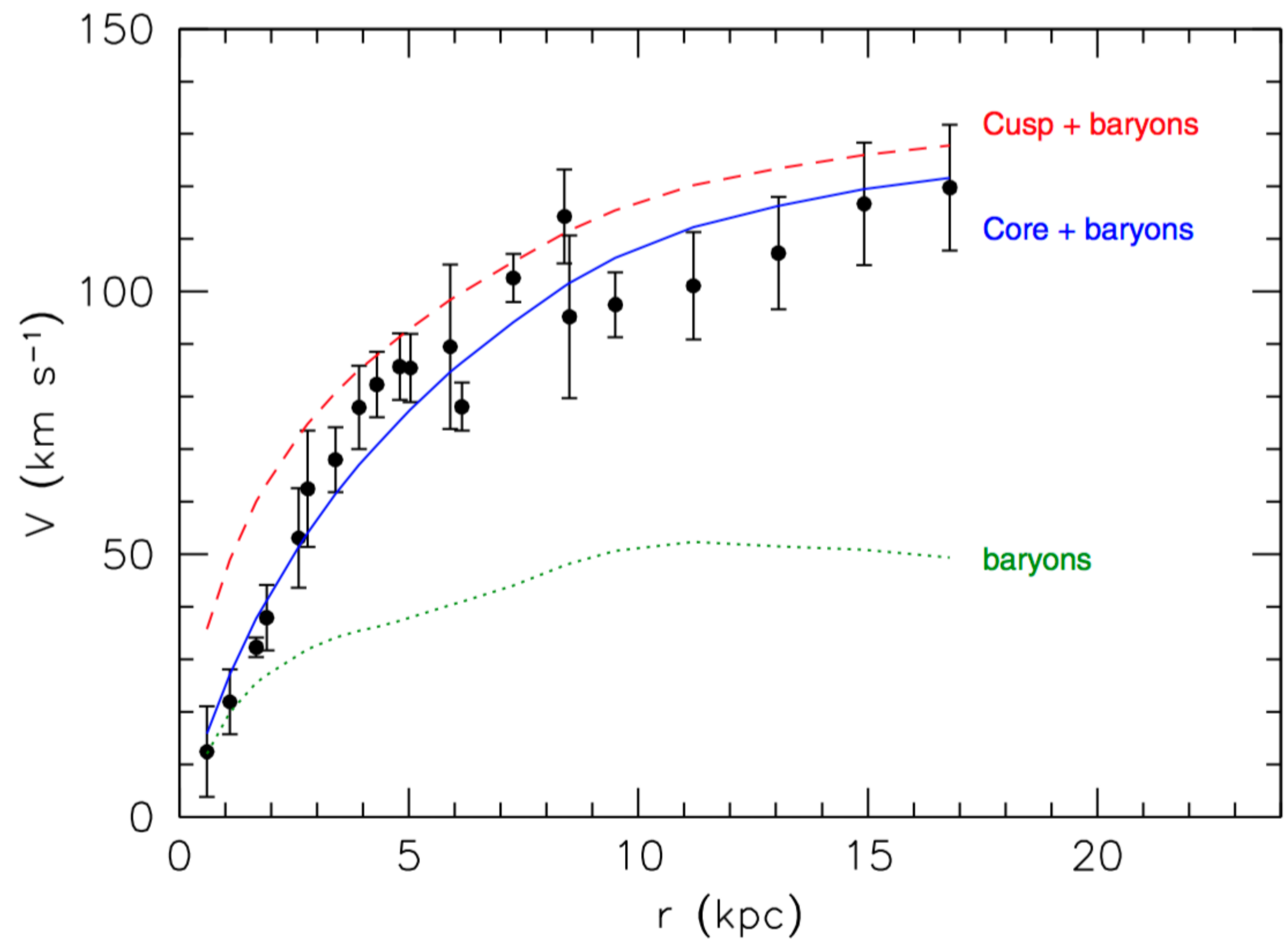
NFW VS SIS



0.4
0.3
0.2
0.1
α
NFW
SIS
0
−1
−2
−3
Log(ψ)
0
−1
−2
Log(κ)
0
−1
−2
Log(γ)
−2
−1
0
−2
−1
0
Log(ξ) [Mpc h⁻¹]

ARE DARK MATTER HALOS UNIVERSAL?

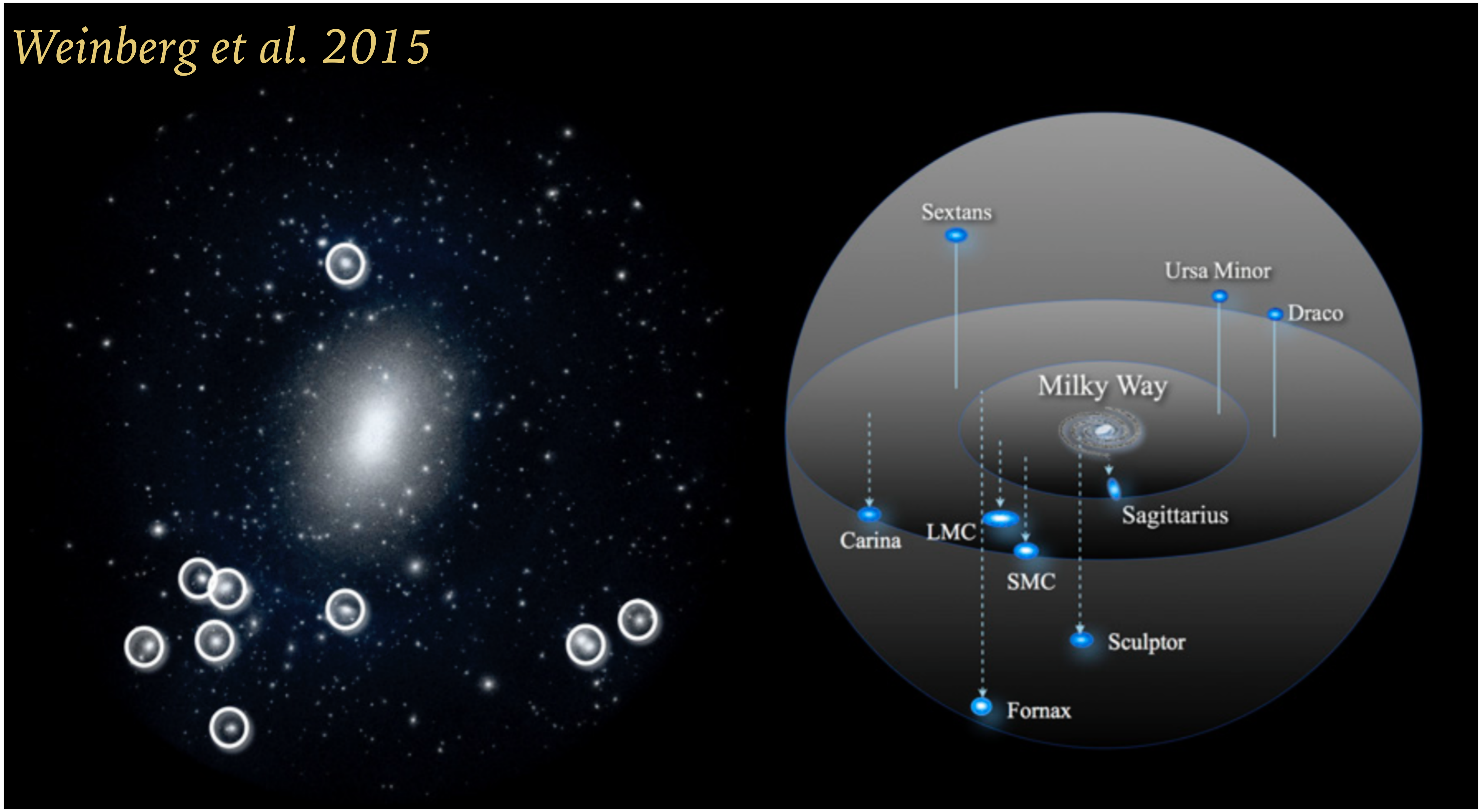




Weinberg et al. 2015

The cusp-core problem: *rotation curves of low-surface brightness galaxies (believed to be dark matter dominated) are inconsistent with cuspy dark-matter profiles (such as the NFW profiles). The circular velocity curve (dots with error-bars refer to the galaxy F568-3)*

SUBSTRUCTURES: THE MISSING SATELLITE AND "THE TOO BIG TO FAIL" PROBLEMS



The missing-satellite problem: *simulations show that CDM forms many more sub-halos than observed around the Milky-Way*

The too-big-to-fail problem: *the biggest sub-halos in simulations are too dense to host dwarf-satellites!*

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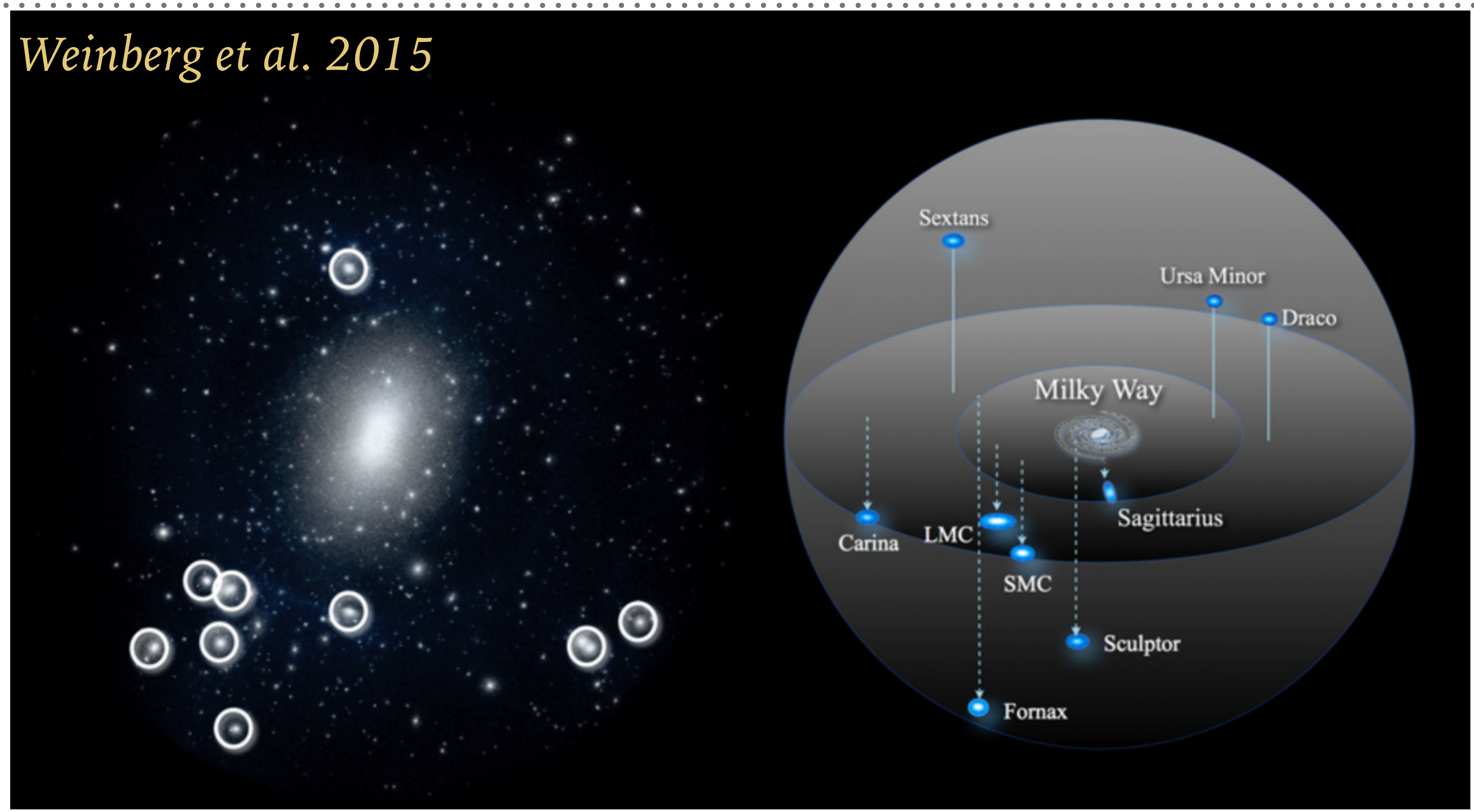

~~***The missing-satellite problem:*** *simulations show that CDM forms many more sub-halos than observed around the Milky-Way*~~

The too-big-to-fail problem: *the biggest sub-halos in simulations are too massive and dense to host the observed dwarf-satellites (x5 in mass)!*

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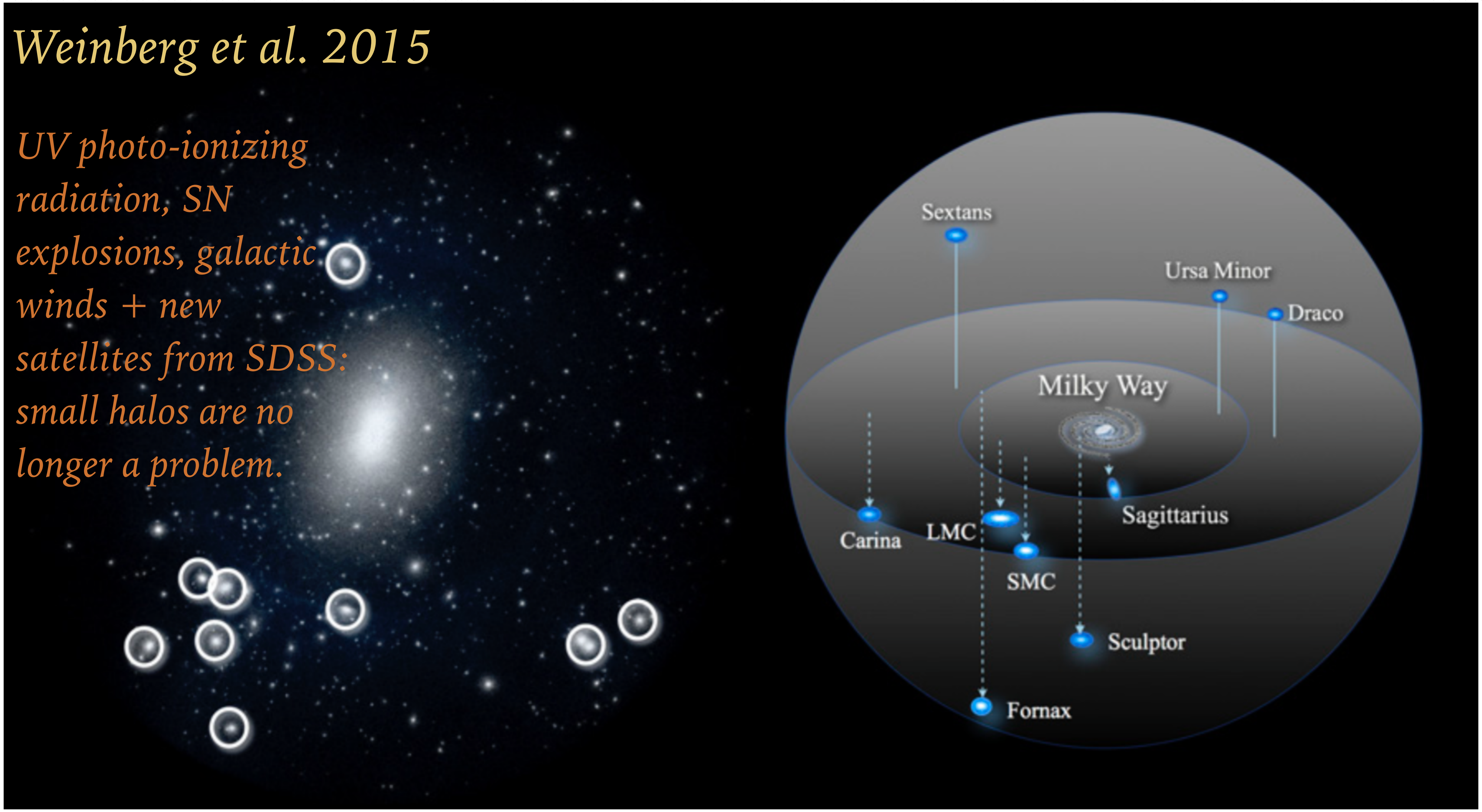

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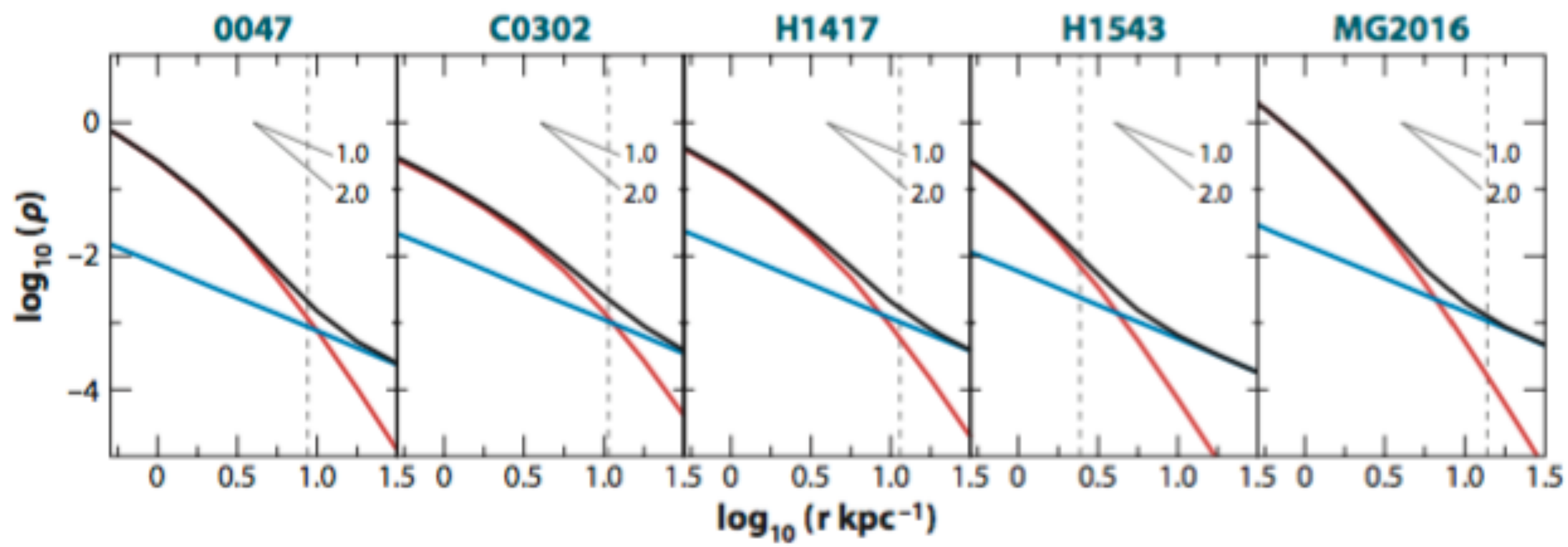
The too-big-to-fail problem: *the biggest sub-halos in simulations are too massive and dense to host the observed dwarf-satellites (x5 in mass)!*

IS THE SOLUTION TO BE FOUND IN BARYONIC PHYSICS?

- The cusp-core and the too-big-to-fail problems both point to the same conclusion: dark matter halos have smaller central densities than expected from CDM
- The are “baryonic” solutions to this problem: feedback episodes from SNe or AGN can create potential instabilities which end up creating a core (Governato et al. 2012)
- Some results, however, seem to indicate that dwarf galaxies are cored (Ferrero et al. 2012)…

ARE DARK MATTER HALOS UNIVERSAL?



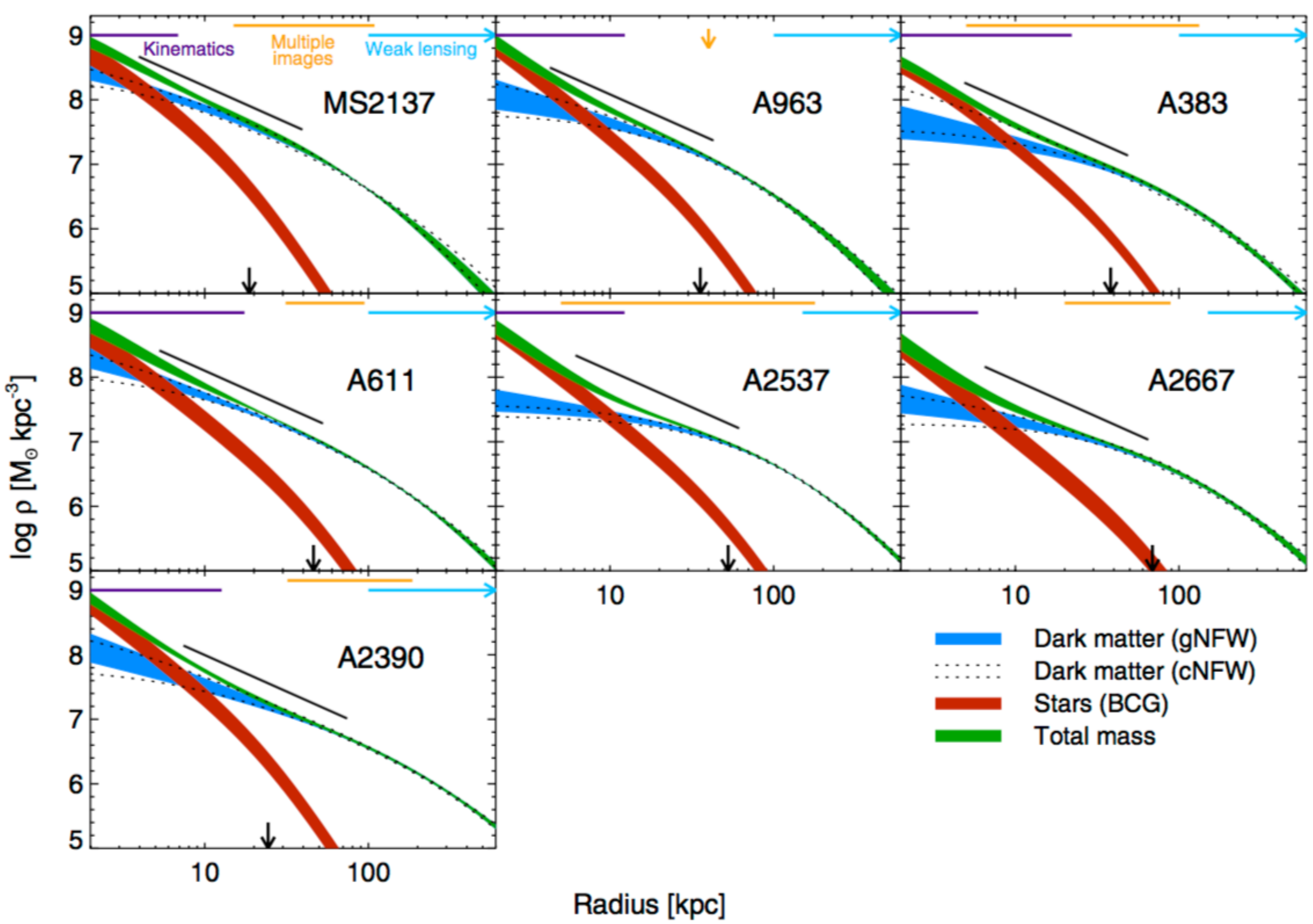
Difficult to say using SL by ETGs, because of the bulge-halo conspiracy…

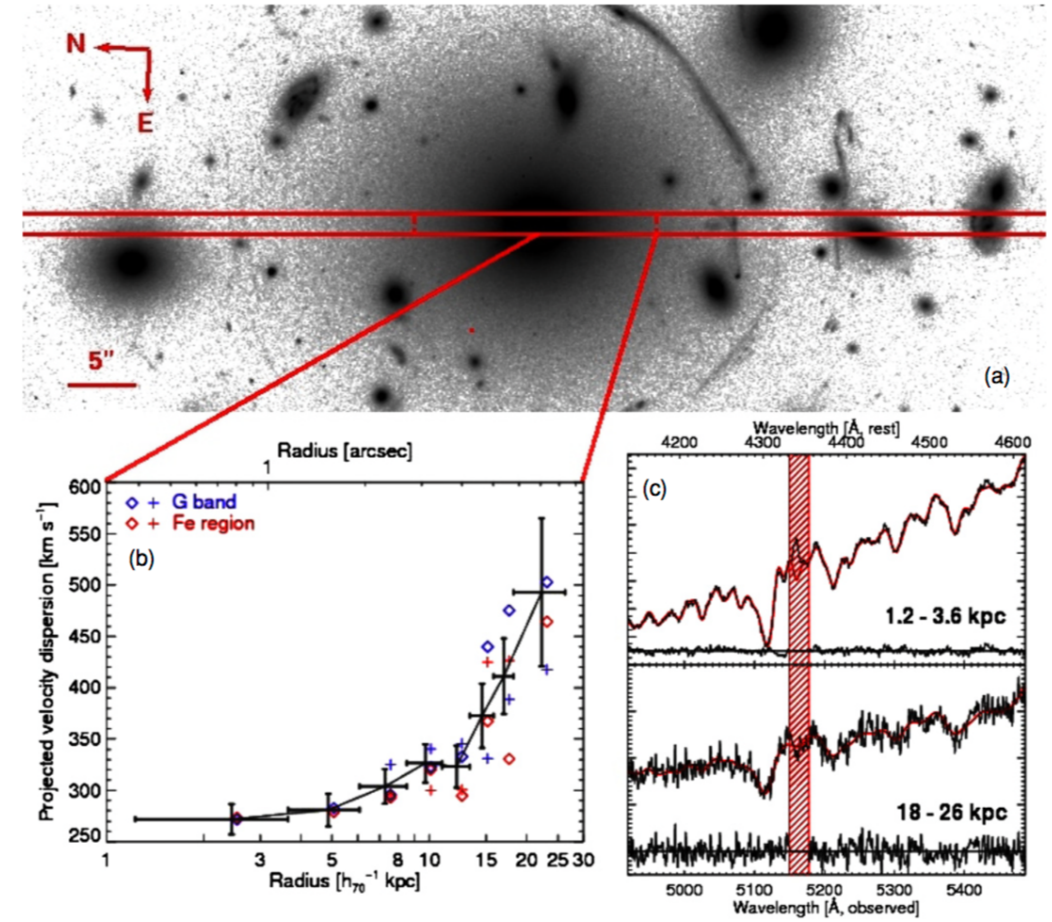
However, imposing the slope of the NFW profile, the assumption of a universal IMF to derive the stellar masses doesn't work (SLACS, Treu et al. 2010).

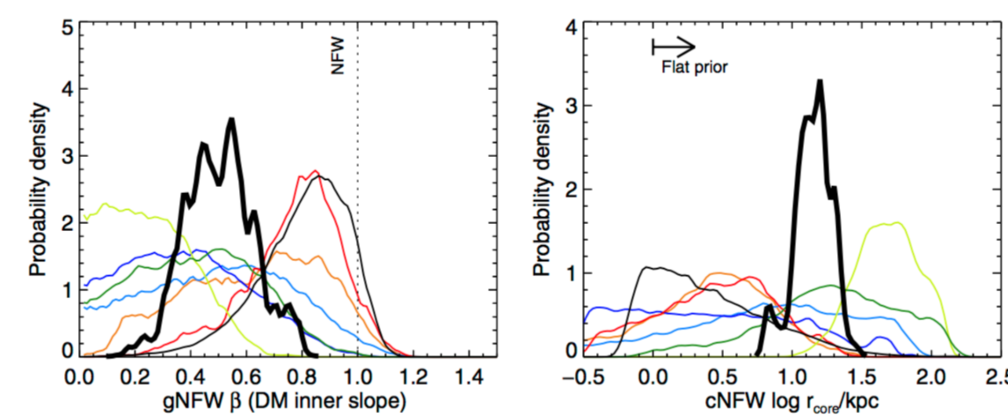
ARE DARK MATTER HALOS UNIVERSAL?

Newman et al. 2012, 2013; see also Sand et al. 2005

On cluster scales: the combination of SL and stellar kinematics in some galaxy clusters seems to point towards profiles that are flatter than NFW on small scales (<30 kpc)



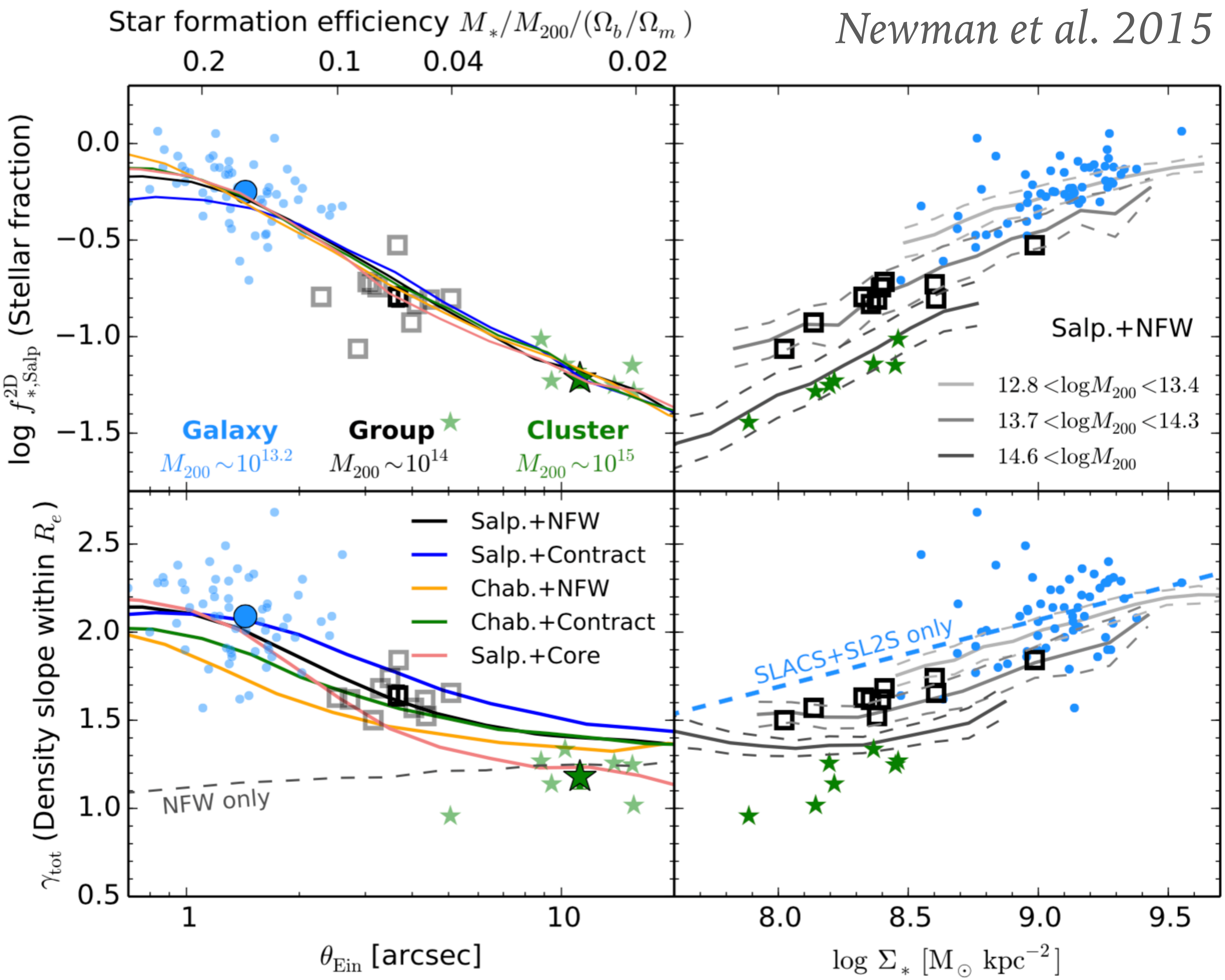




$$\rho_{\rm DM}(r) = \frac{\rho_s}{(r/r_s)^{\beta}(1+r/r_s)^{3-\beta}} \qquad \rho_{\rm DM}(r) = \frac{b\rho_s}{(1+br/r_s)(1+r/r_s)^2}.$$

ARE DARK MATTER HALOS UNIVERSAL?

Newman et al. 2015



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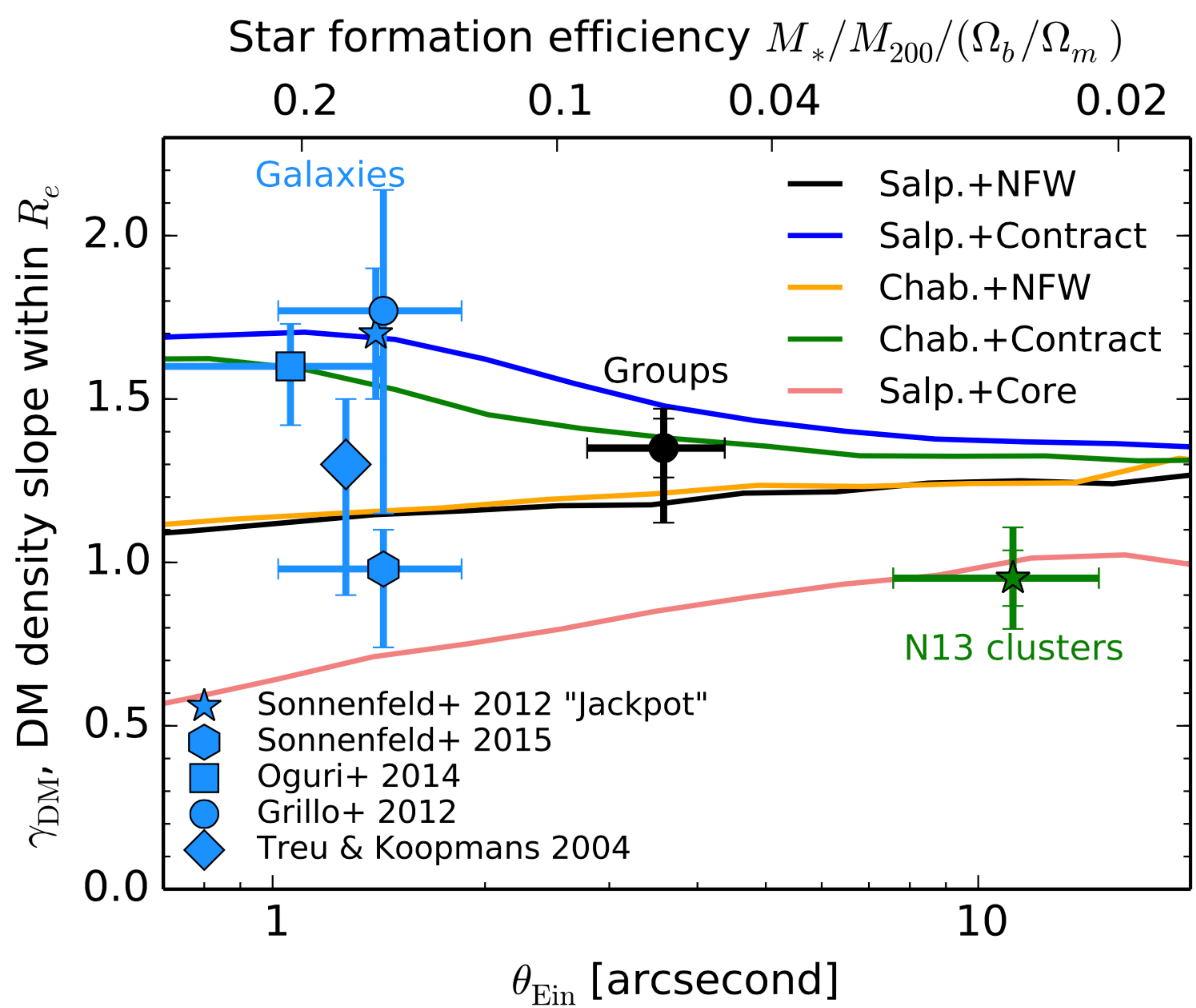
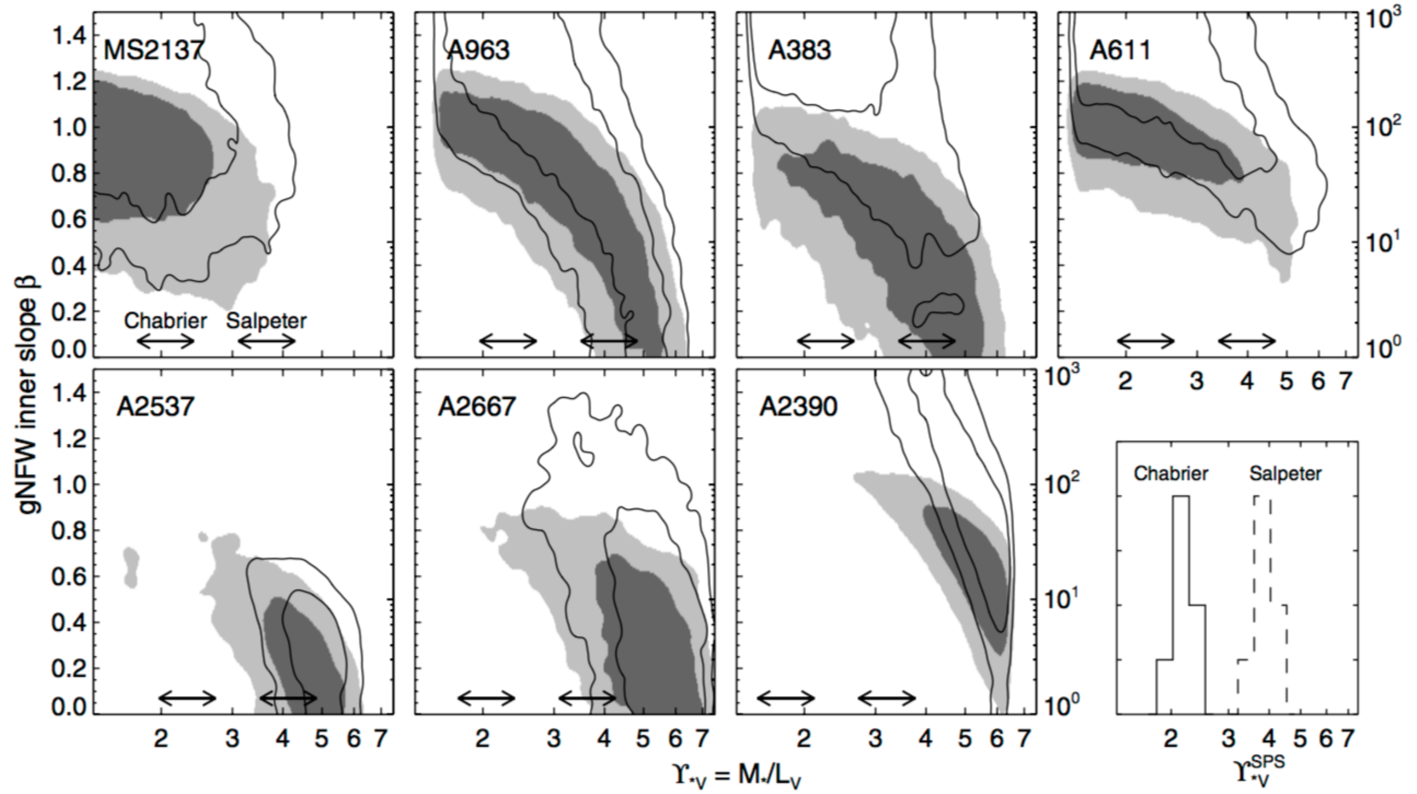
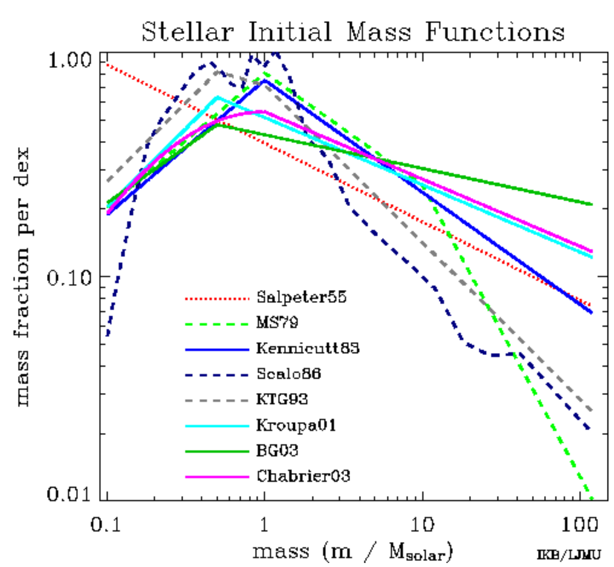
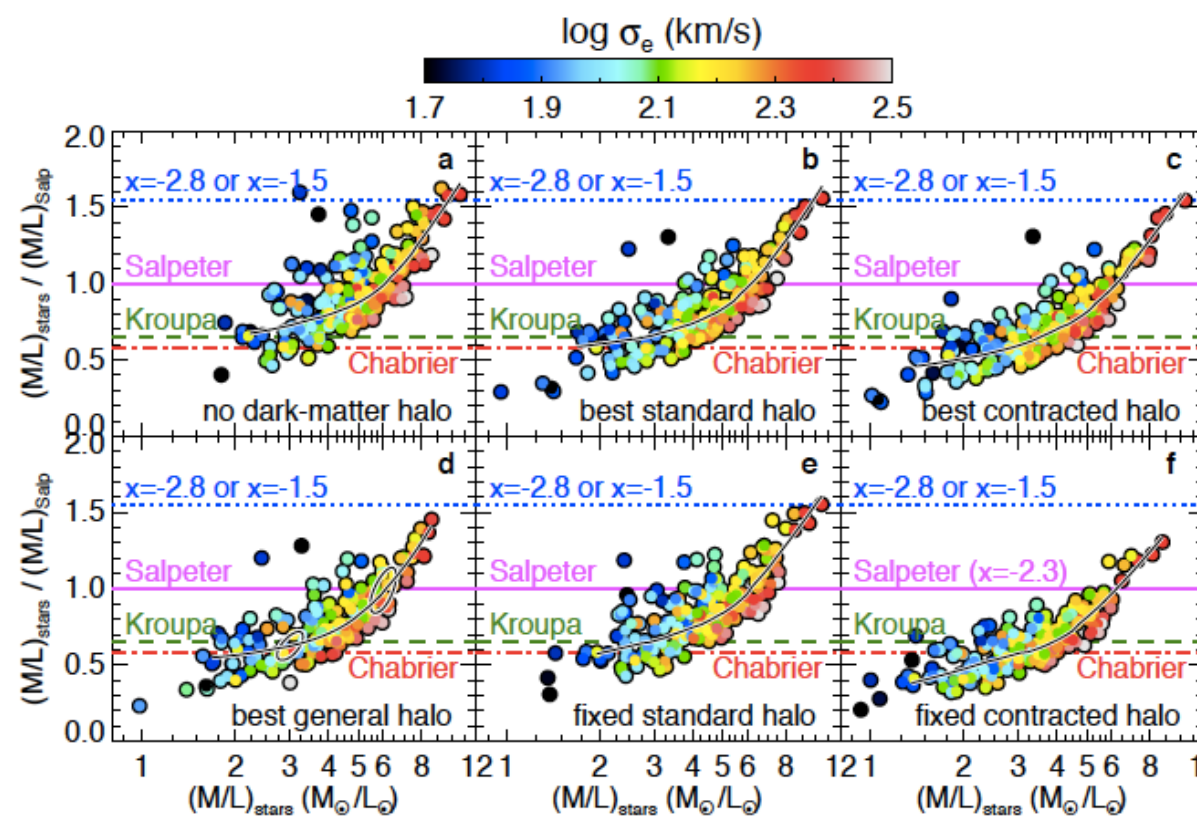


CAVEATS

- lensing probes the projected mass distribution rather than the three dimensional one
- stellar kinematics is affected by its own uncertainties (e.g. mass-anisotropy degeneracy, projection effects, etc)
- lensing is affected by mass-sheet degeneracy, which is not easy to break given the uncertainties on the stellar kinematics mass estimates.
- the IMF is affected by uncertainties too, and it is degenerate with the slope (but massive galaxies seem better described by Salpter IMF)

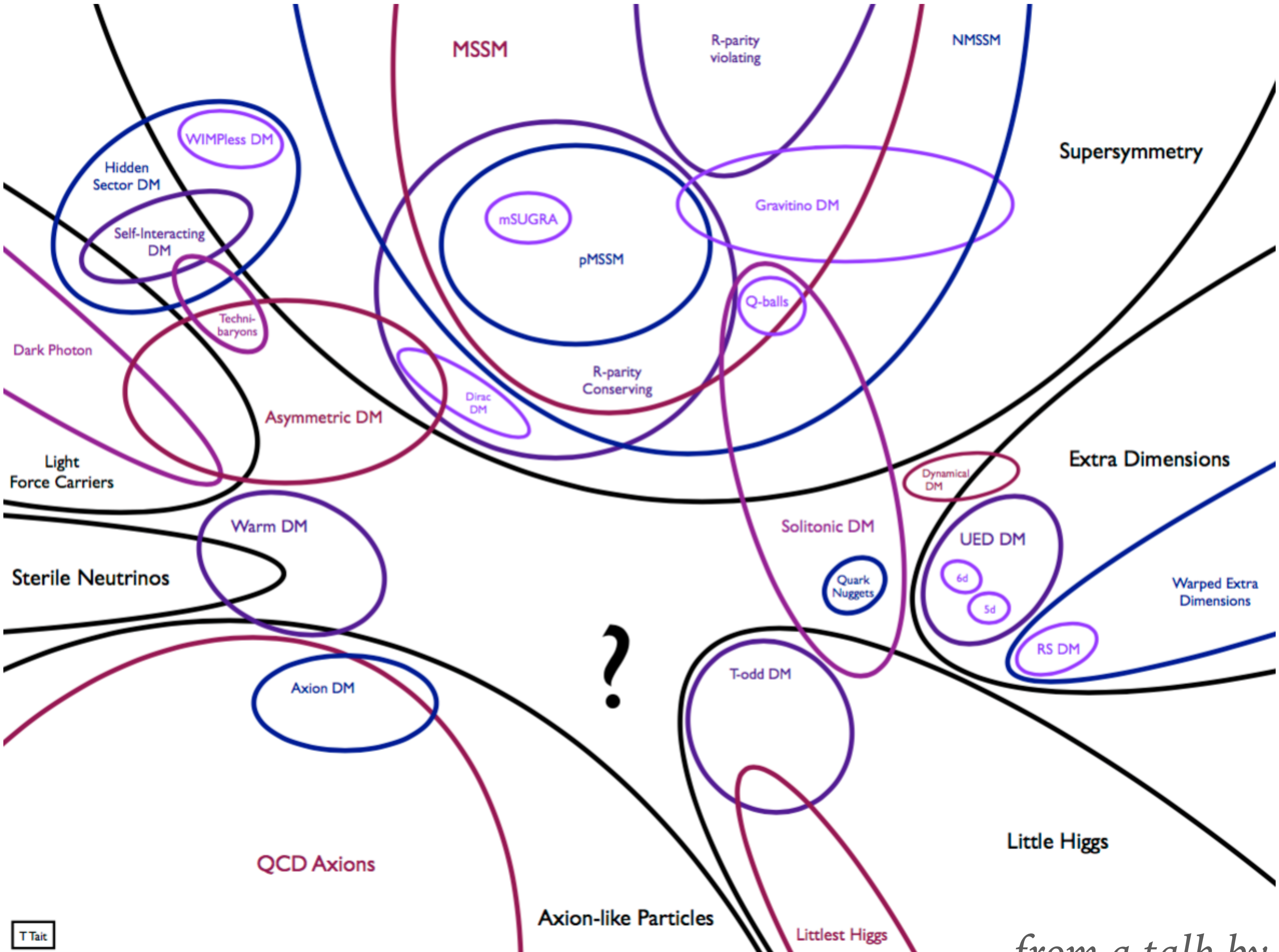






Cappellari et al 2012

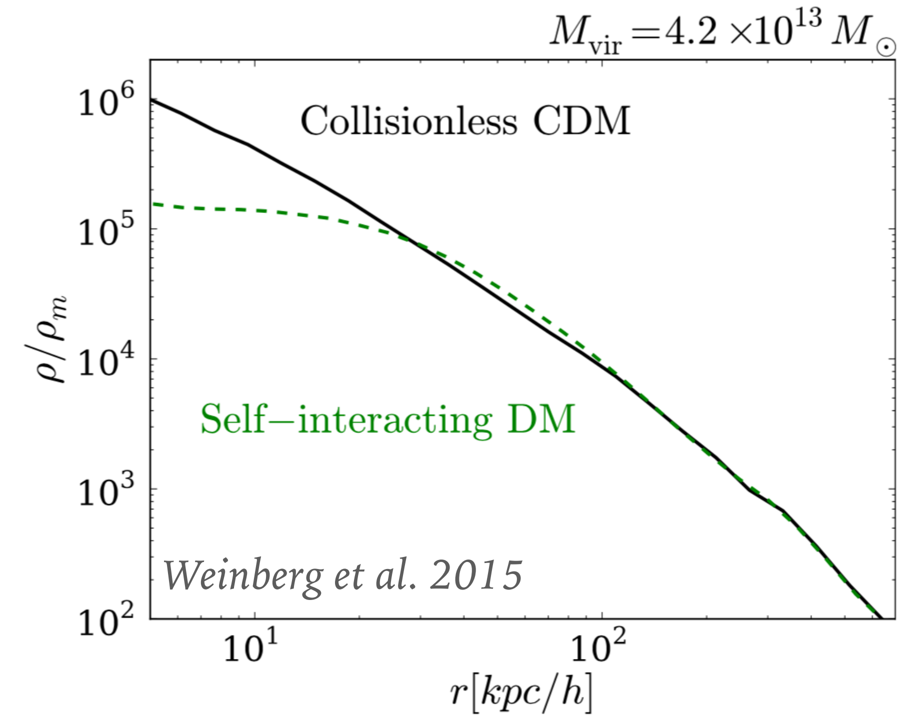
WHAT IS THE NATURE OF DARK MATTER?

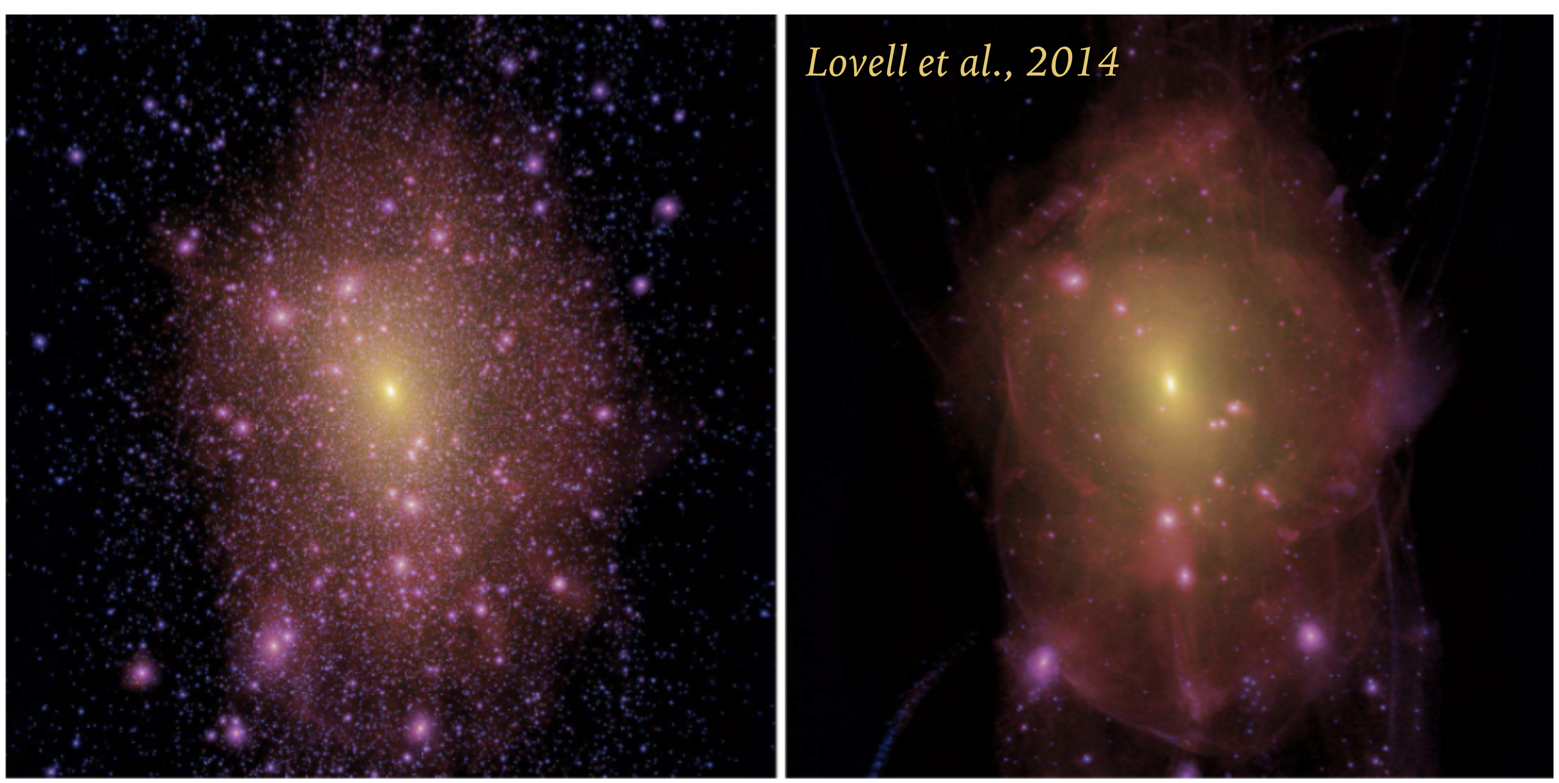


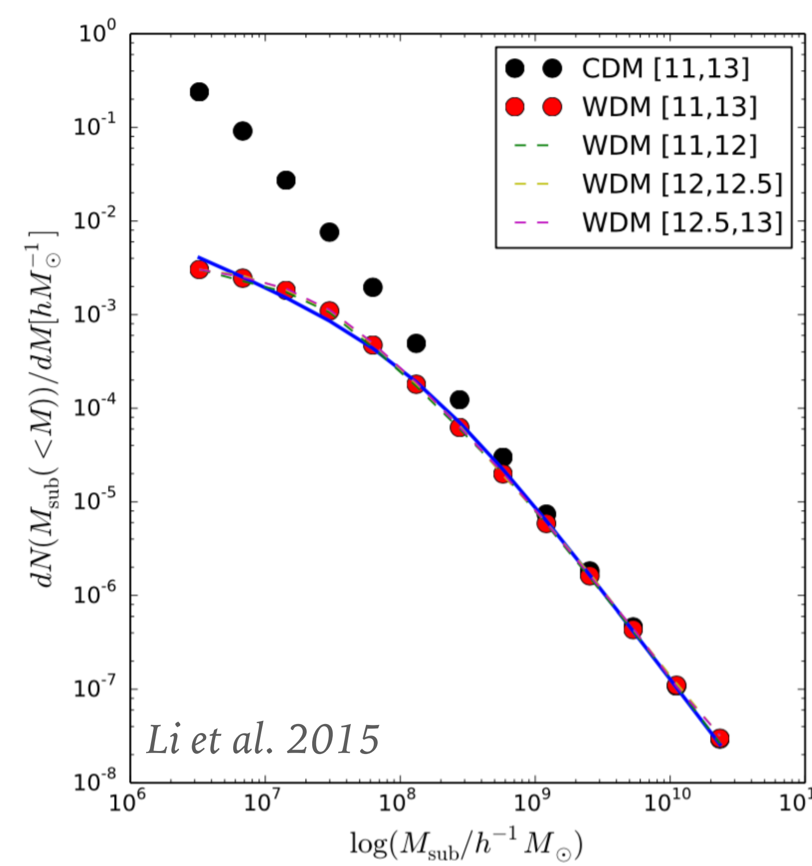
from a talk by T. Tait

IS THE NATURE OF DM INCONSISTENT WITH STANDARD CDM?

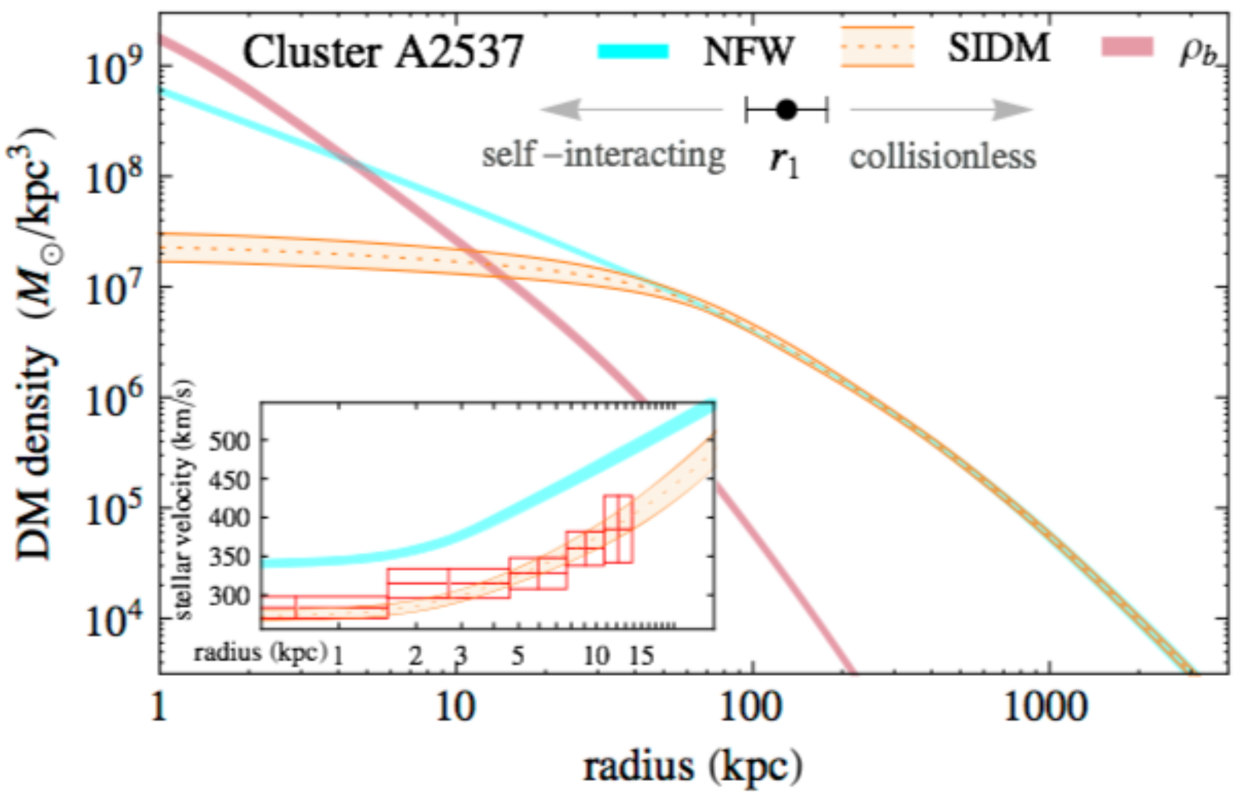
- Self-interacting dark matter? *Wherever density is large, self-interactions become important and erase the cusps (suppressing also the satellites)*
- Warm-dark-matter? *Free-streaming in the early universe suppresses small scales*
- ?



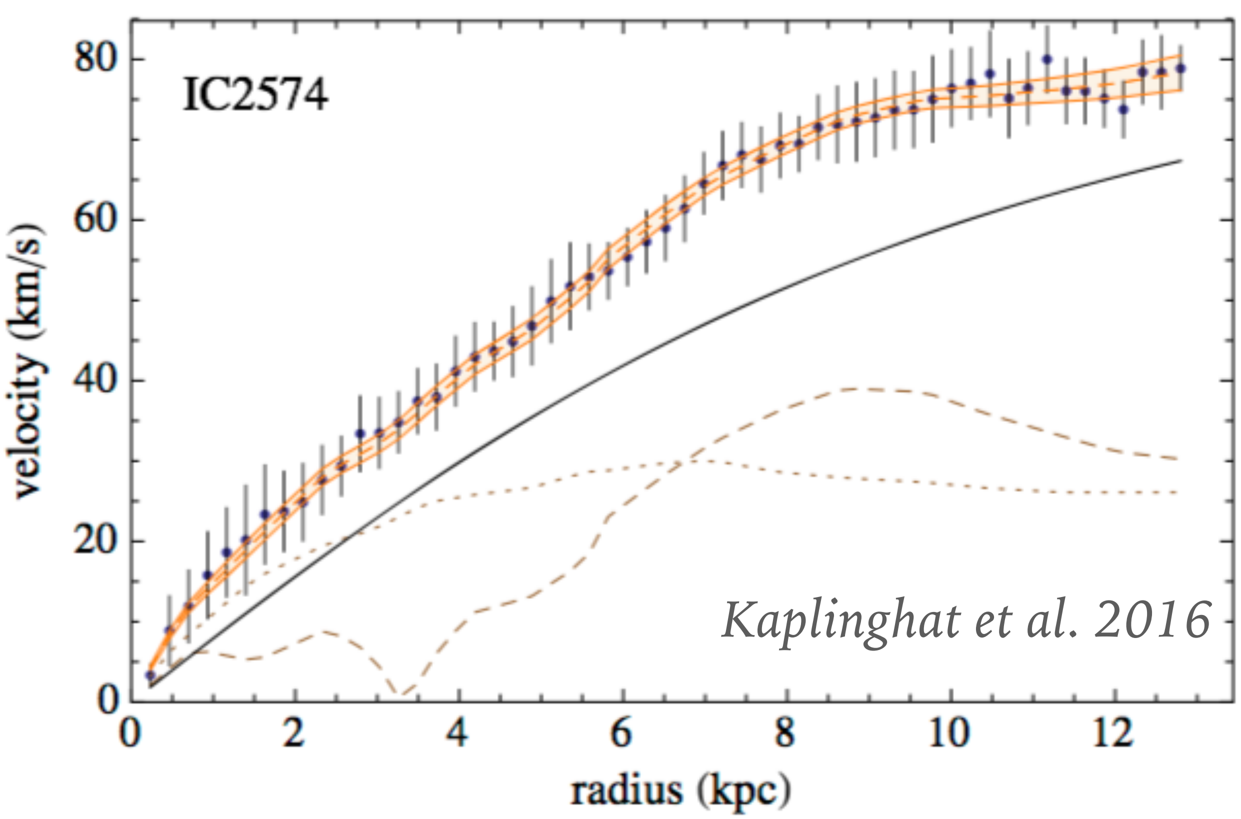


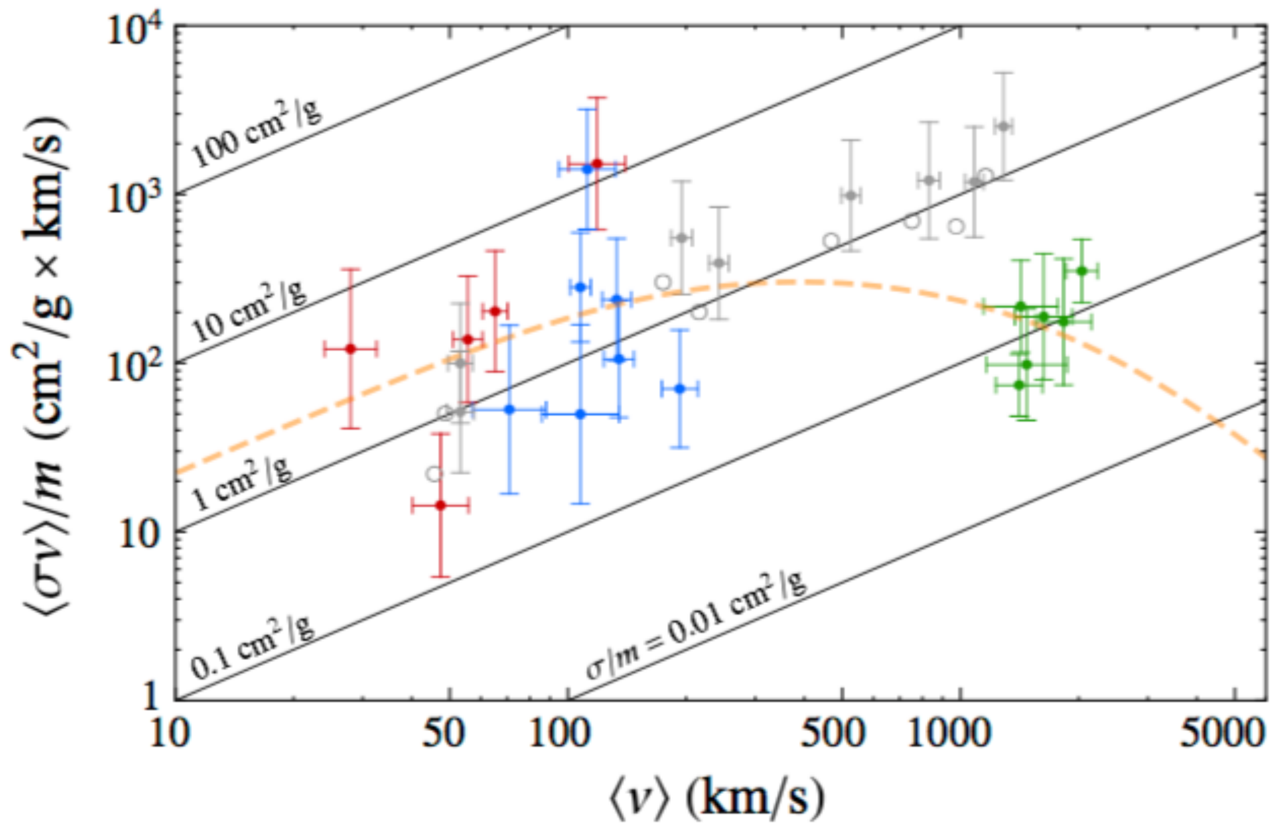


SIDM MODELS PROBED BY SL



- Self-interaction cross sections between 0.1 and 2 cm^2/g may be consistent with observations of dwarf galaxies, LSBs and clusters
- the model of SIDM which is consistent with these data has a velocity dependent cross section
- interactions are more efficient in low velocity regimes, than in high velocity regimes





SIDM MODELS PROBED BY SL

Rocha et al. 2013: numerical simulations of SIDM halos (but with velocity independent SI cross section)

Core circularization (see also Peter et al.2013)

Sub-halo “evaporation” (esp. in the core): trend with mass?