Arianna Di Cintio
Marie Curie IF @IAC

Challenges to the LCDM paradigm: the internal structure of DM haloes. Can we distinguish CDM from non standard DM models ?

DIGESTIVO Project

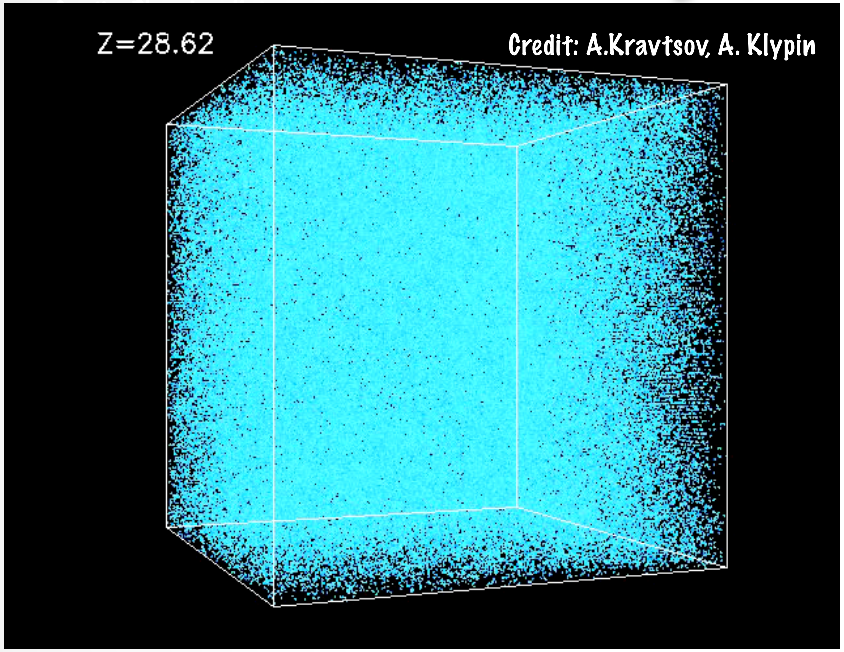
DIffuse **G**alaxy **E**xpansion **S**igna**T**ures **I**n **V**arious **O**bservables project: understanding the emergence of diffuse, low surface brightness galaxies and the link to their dark matter haloes

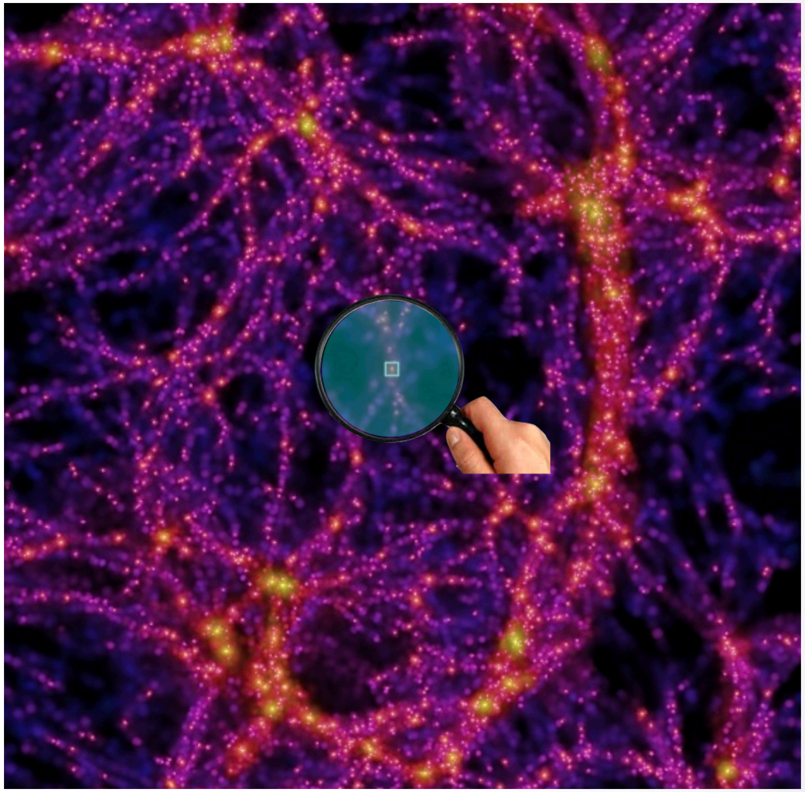
Why is the inner structure of DM haloes so important?

- The distribution of matter within galaxies - AKA their density profile - is a key prediction of galaxy formation within a cosmological framework

- It must agree with observations, and it can potentially provide constraints about the nature of DM itself

Dark matter haloes in N-body (DM only) simulations





$$M_{\rm halo} = \frac{4}{3}\pi R_{vir}^{3}\Delta\rho_{crit}$$

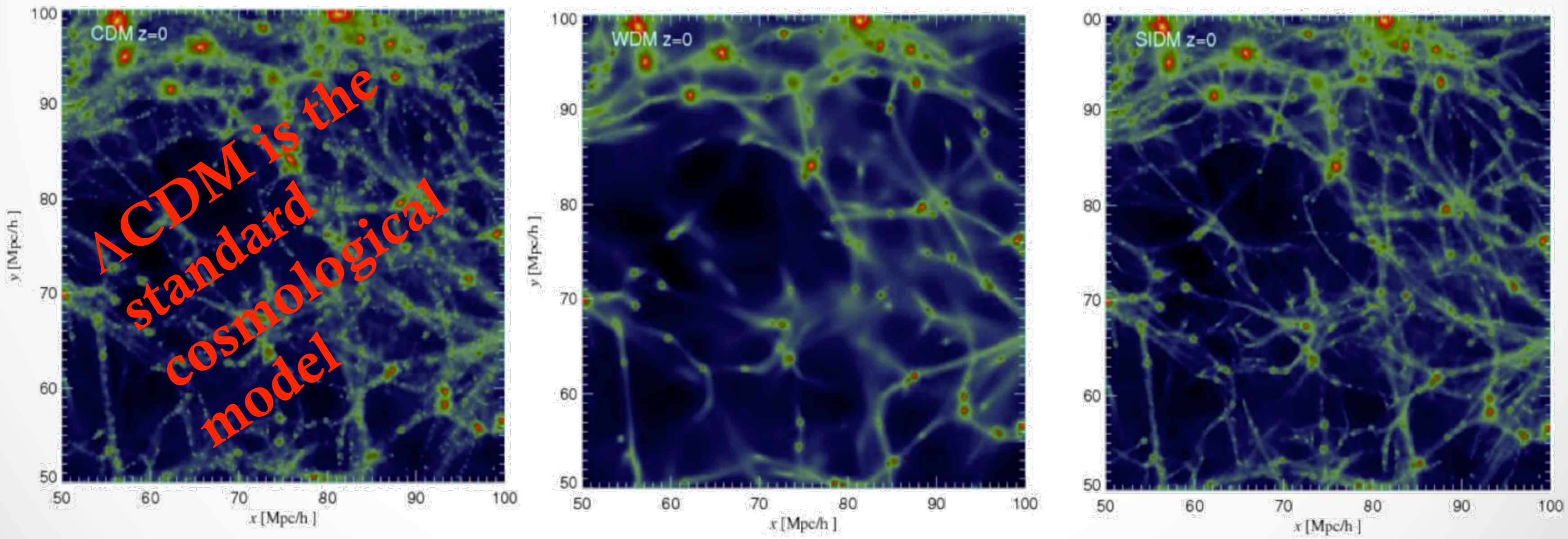
DM halo mass, Mvir=Mhalo, is the mass within a sphere of radius Rvir containing Δ times the critical density of the Universe

The nature of Dark Matter

Cold Dark Matter
(Slow moving)
m~ GeV-TeV
Small structures form first, then merge

Warm Dark Matter
(Fast moving)
m~ keV
Small structures are erased

Self-Interacting Dark Matter
Strongly interact with itself
Large scale similar to CDM,
Small galaxies are different



The ΛCDM small scale crisis

Missing satellite problem

Diversity of RC in dwarf galaxies

RAR relation

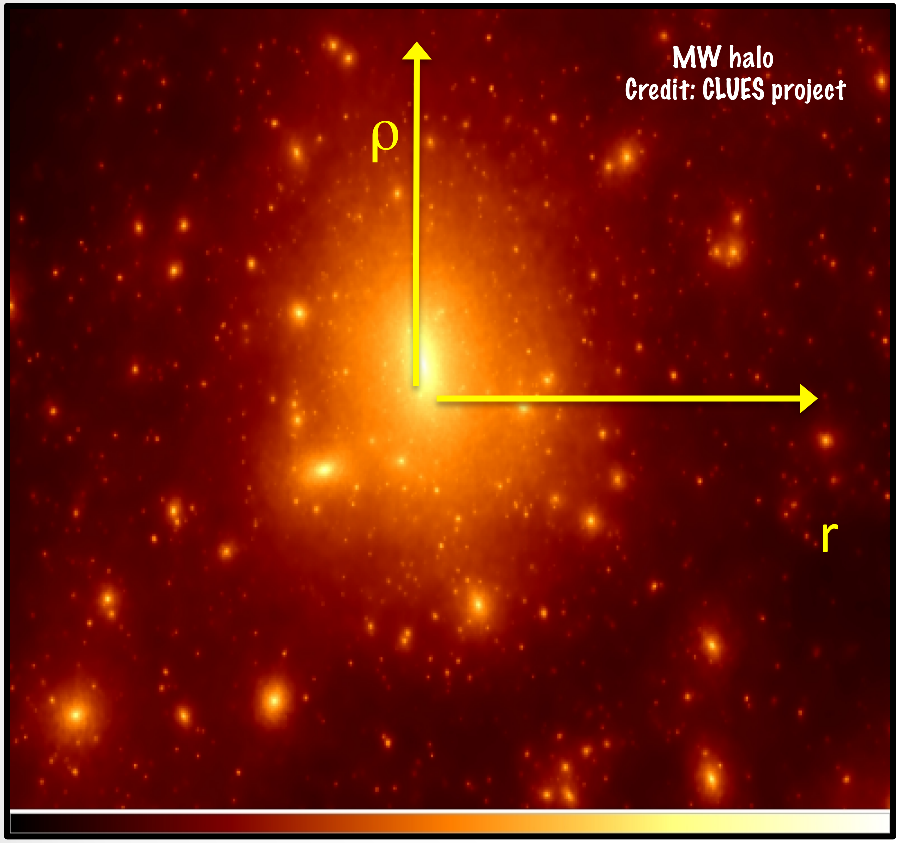
Cusp-core discrepancy in rotation curves of galaxies

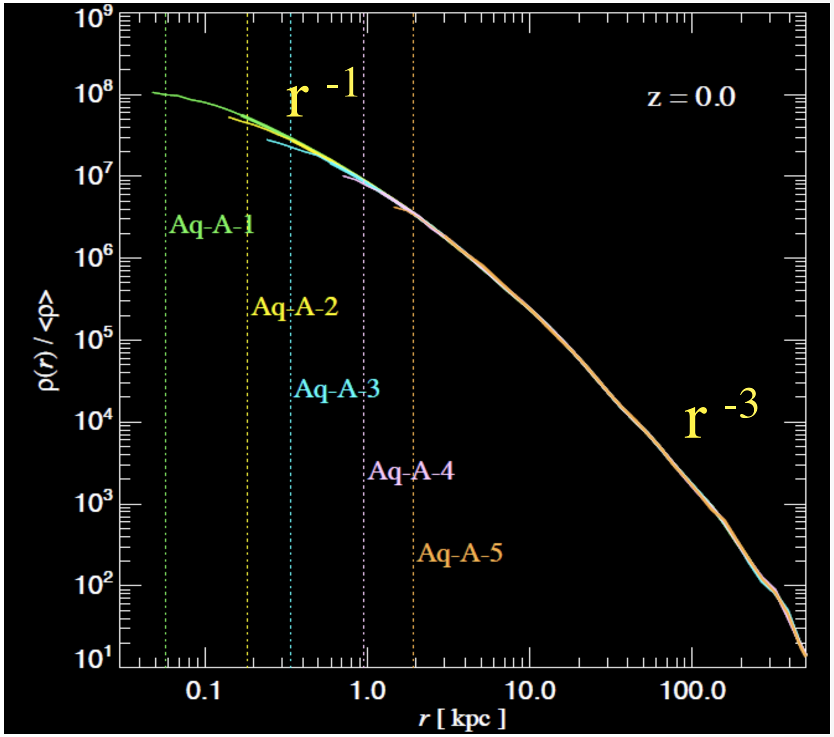
Large size of Ultra-Diffuse galaxies

Velocity function of galaxies

Kinematic of satellite galaxies (TBTF problem)

Density profile of DM haloes





Aquarius simulations

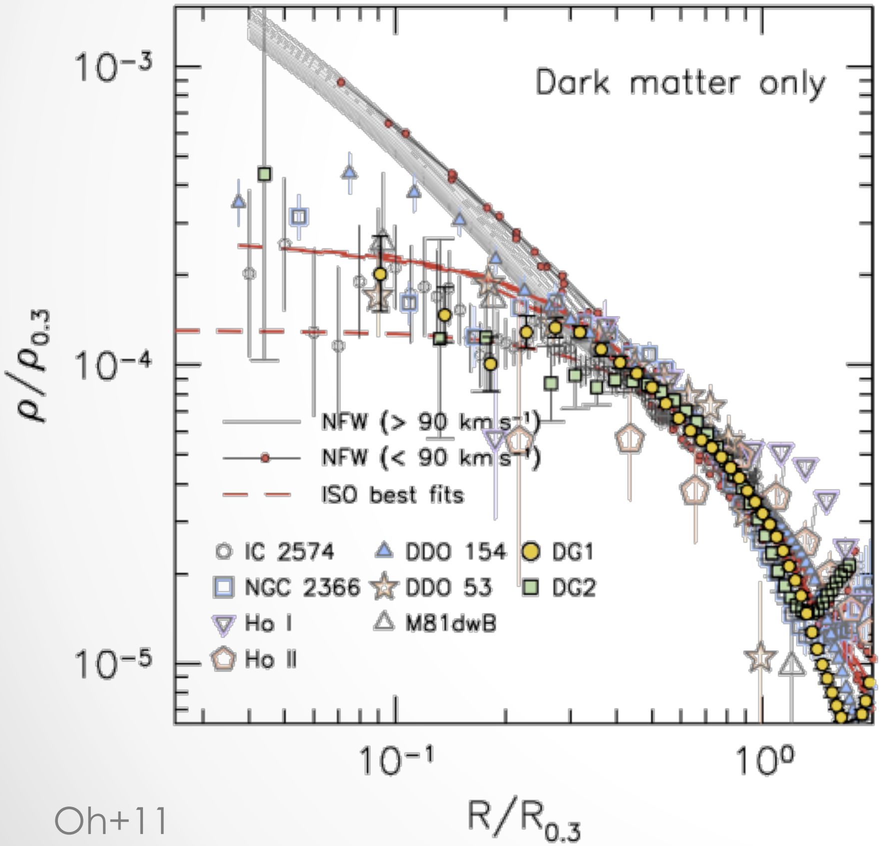
$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

Navarro, Frenk & White 1997 CDM haloes in simulations have a universal density profile

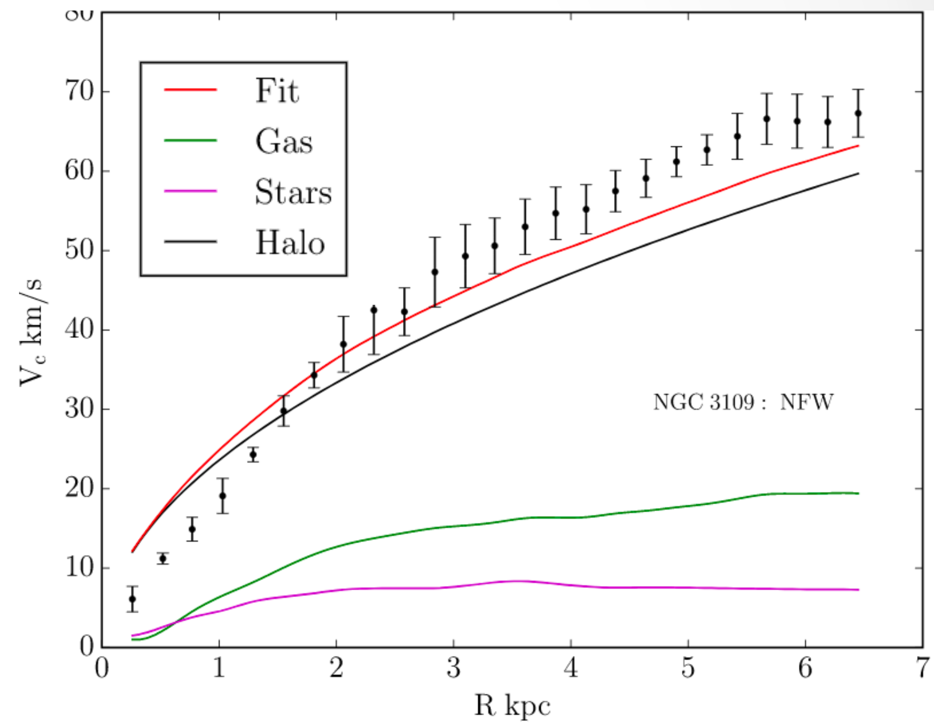
The `cusp-core' discrepancy

Simulations find 'CUSPY' profiles
Inner slope γ <= -1 NFW

Observations of dwarfs and LSB
show 'CORED' profiles
Inner slope 0> γ > -1



Oh+11



Katz ,Lelli,McGaugh,Di Cintio,Brook, Schombert 17

Solution #1: CDM + baryonic physics

Making Galaxies in a Cosmological Context

MaGICC (PIs Stinson-Brook)

&

Numerical Investigation of Hundred Astrophysical Objects (PIs Maccio'-Dutton)

(Brook+12b, Maccio'+12, Penzo+14, Herpich+14, Kannan+14, Obreja+14.Wang+15, Dutton+17,Di Cintio+17 etc)

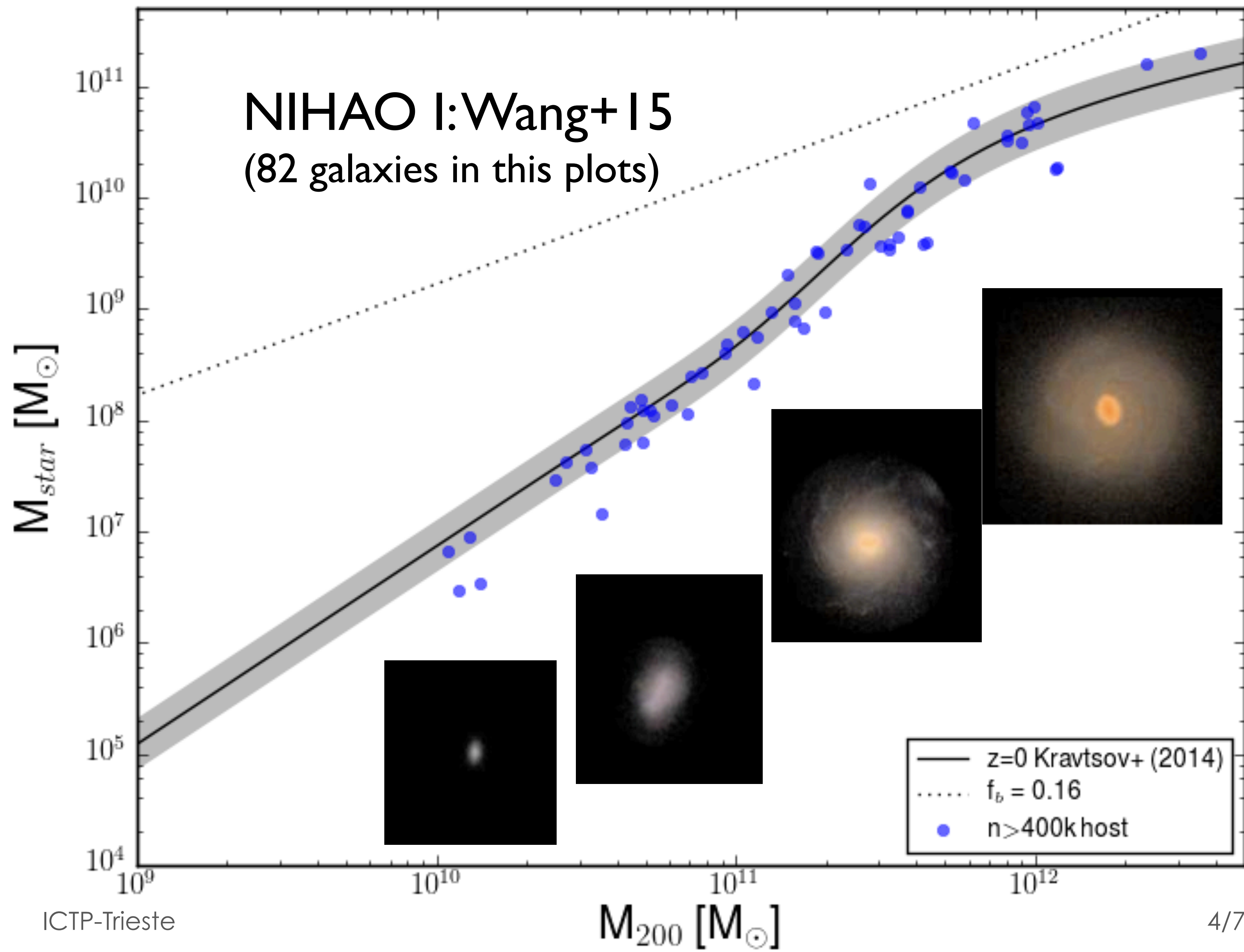
Hydrodynamical simulations of galaxies including dark matter, gas, stars and baryonic feedback

NIHAO 你好 Galaxy Simulations

- Gasoline 2.0
- Planck Cosmology
- ***125 high resolution (zoomed) galaxies***
- more than **10^6** particles in each halo
- $10^5 - 10^{11}\ M_\odot$ stellar mass range ($5\times10^8 - 5\times10^{12}\ M_\odot$)
- 100 times better resolution than ILLUSTRIS
- 50 times better resolution than EAGLE volume
- 10 times more galaxies than FIRE (13 vs. 120)
- 5 galaxies with 3×10^7 elements

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

Halo mass-Stellar mass relation



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 (Wadsley+2017)*

Role of baryons
SNae feedback and outflows

- KEY ingredients:

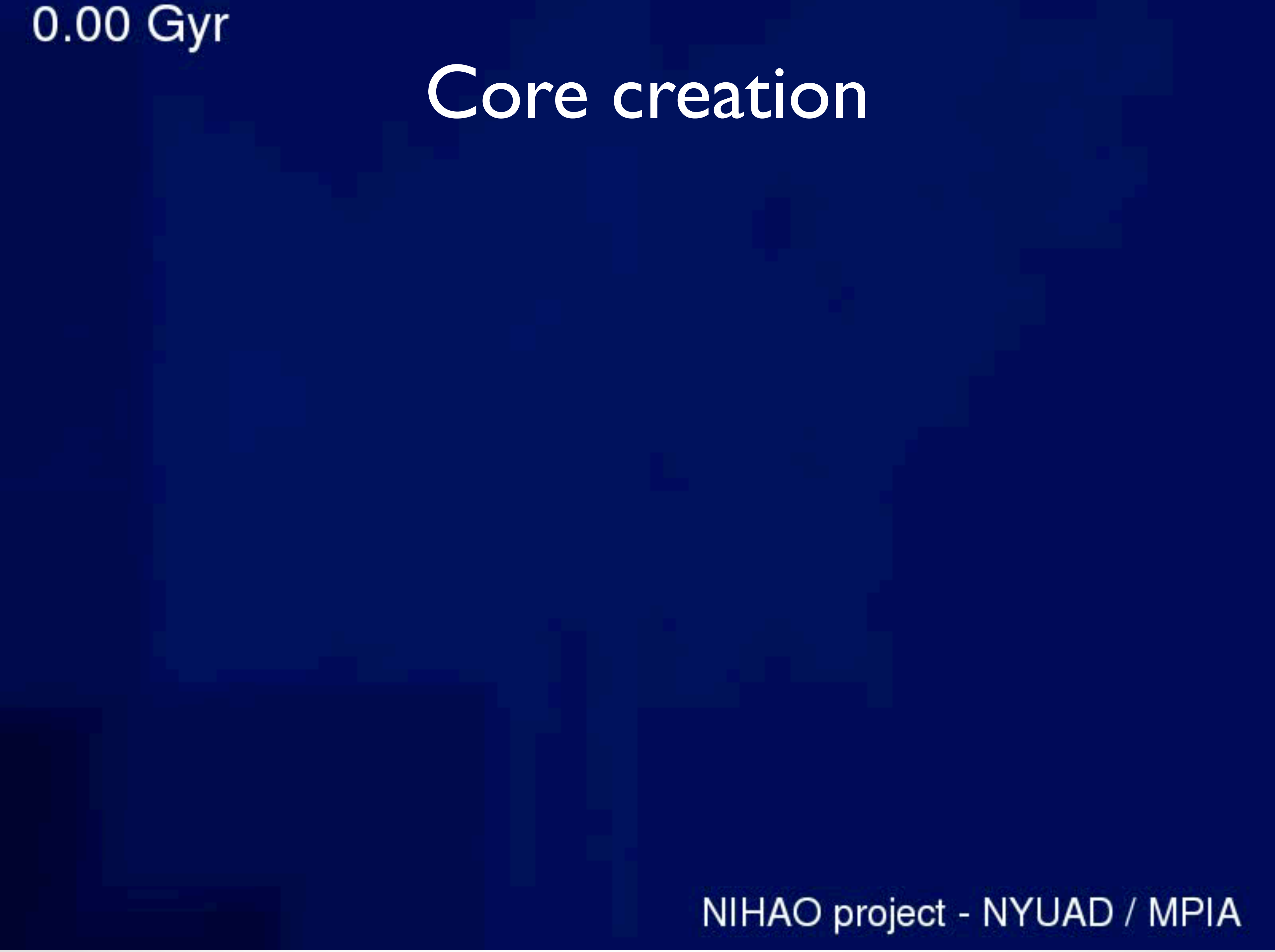
high initial density for star forming gas, similar to molecular cloud formation in our Galaxy n=10-100 mhcm^{-3}

- RESULT:

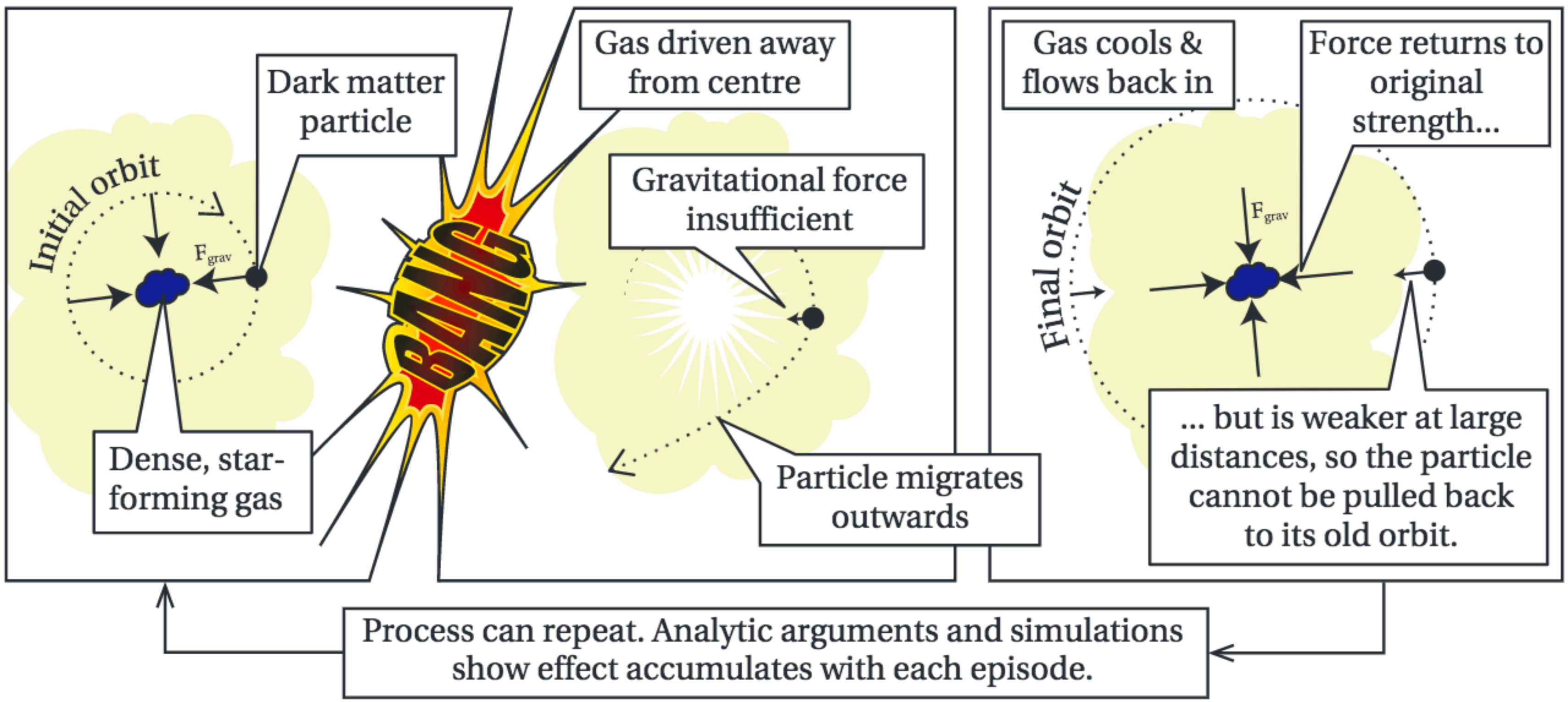
stars form efficiently in small, isolated regions, energy is dumped into the gas which heats to much higher temperatures, gas is overpressurized and expands rapidlly: galactic scales outflows are launched at speeds greater than local circular velocity

- FEATURE: the process is cumulative

Core creation



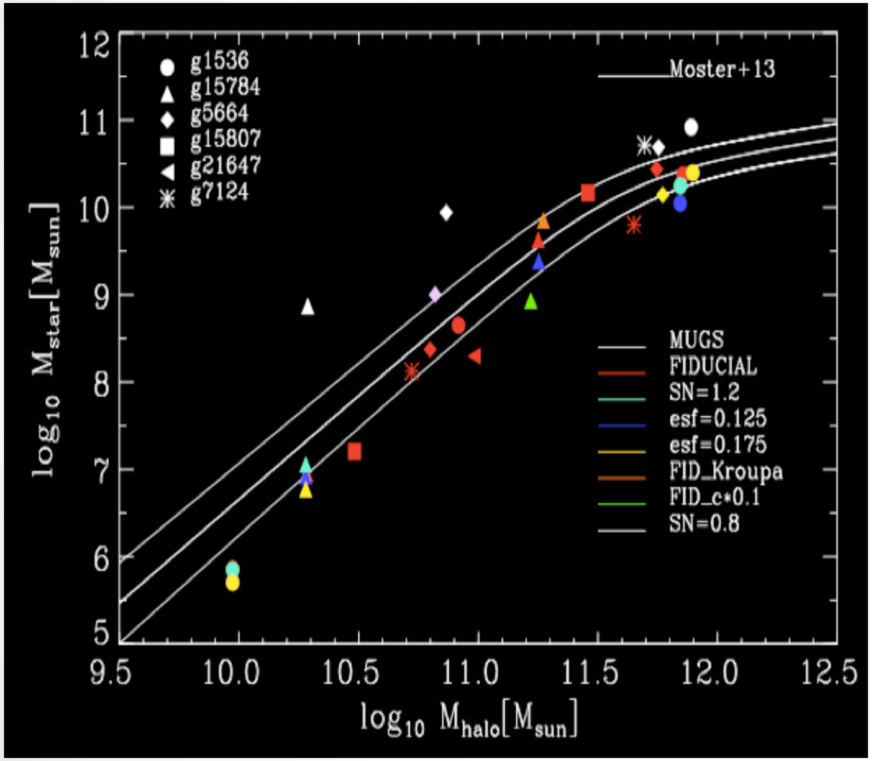
From gas outflows to DM 'cores'

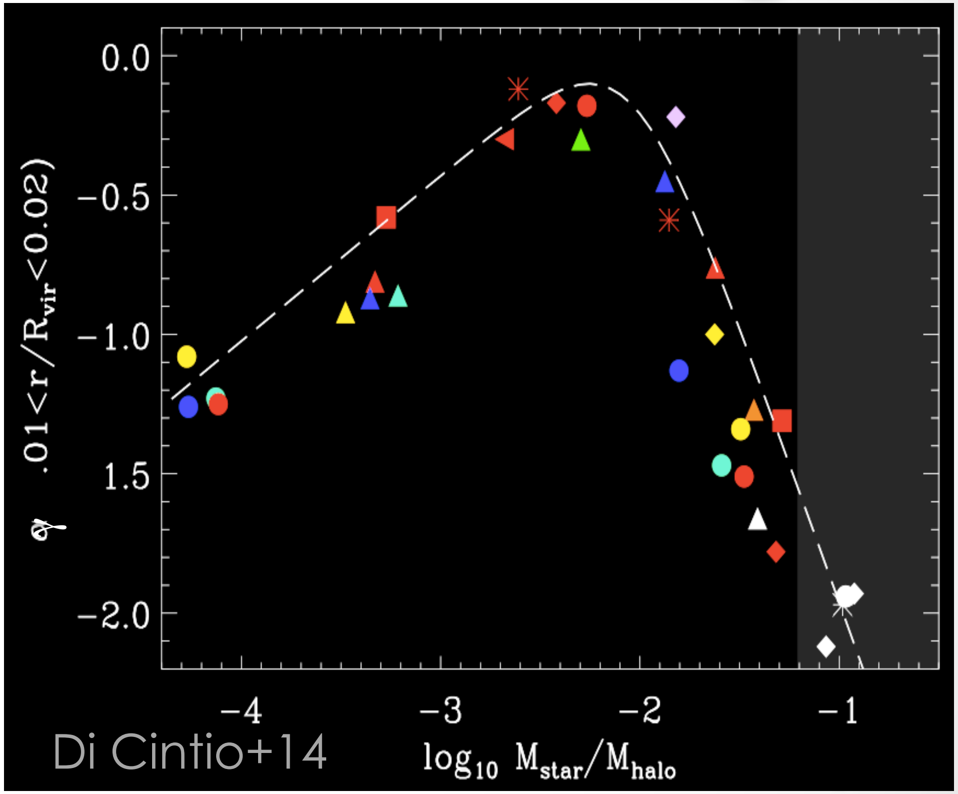


Pontzen & Governatp 14

Core formation mechanism -> outflows driven by SNae feedback
Core created during starburst events that launch powerful gas outflows

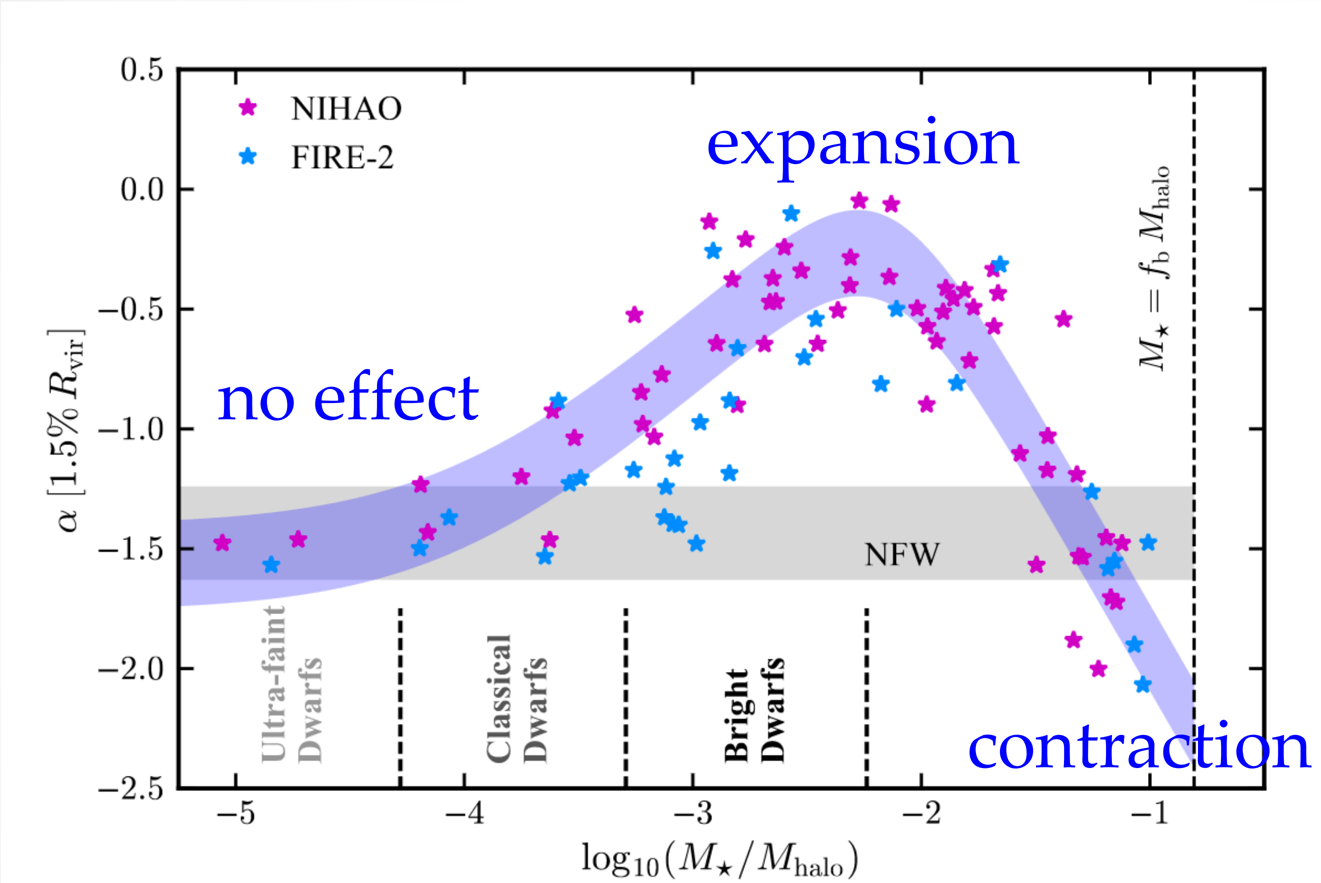
Cores are created in a particular M*/Mhalo range





Peak of core formation at log(M*/Mhalo)~-2.4 → M*~$10^{8.5}$ Msun
Dark matter profiles determined by two opposite effects: energy from Sne vs Increasing gravitational potential (see also Governato+12,Read+16,Onorbe+15,Brooks&Zolotov12)

Sweet spot of core formation



Review by Bullock & MBK 2017

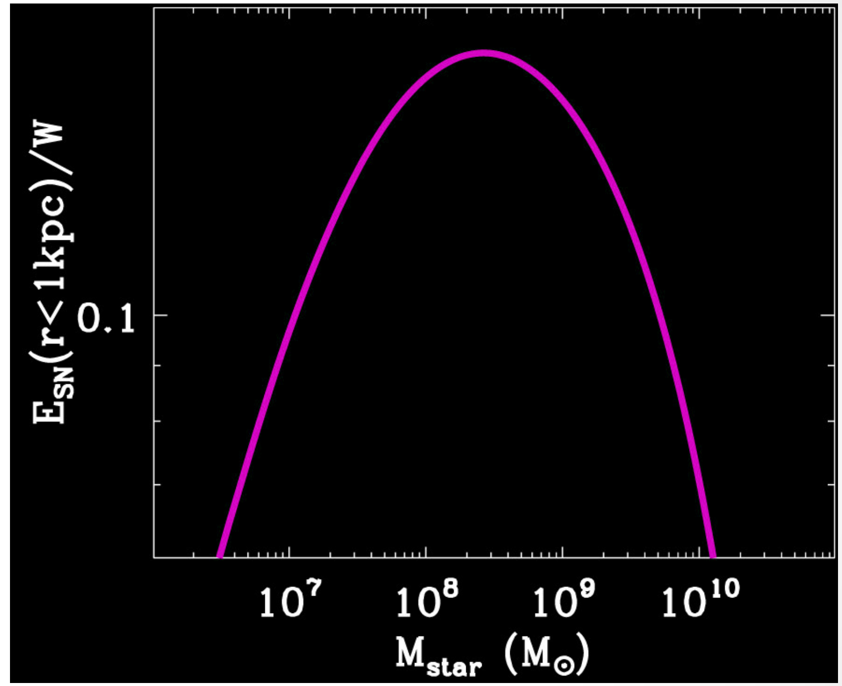
Data from Di Cintio+14, Chan +15, Tollet+16

Small dwarfs not enough energy from stellar feedback to modify NFW halo
Intermediate dwarfs/LSBs correct amount of energy from Snae
Large spirals can not 'win' the large grav potential of 10^{12} halo with SNae alone

Energetic of core formation

$$\frac{E_{SN}}{W} = \frac{M^{\star}(< 1Kpc) \times f_{SN}/\bar{m} \times 10^{51} erg \times \epsilon}{-4\pi G \int_0^{rvir} \rho(r) M(r) r dr}$$

Energy balance between SNe energy and potential energy of NFW halo.
Flattest profiles expected at
$M_* \sim 10^{8.5}\, M_\odot$.



Brook & Di Cintio2015a
(see also Penarrubia +2012)

A mass dependent profile

A mass dependent density profile that takes into account the impact of baryons on DM haloes (Di Cintio, Brook +14a,b)

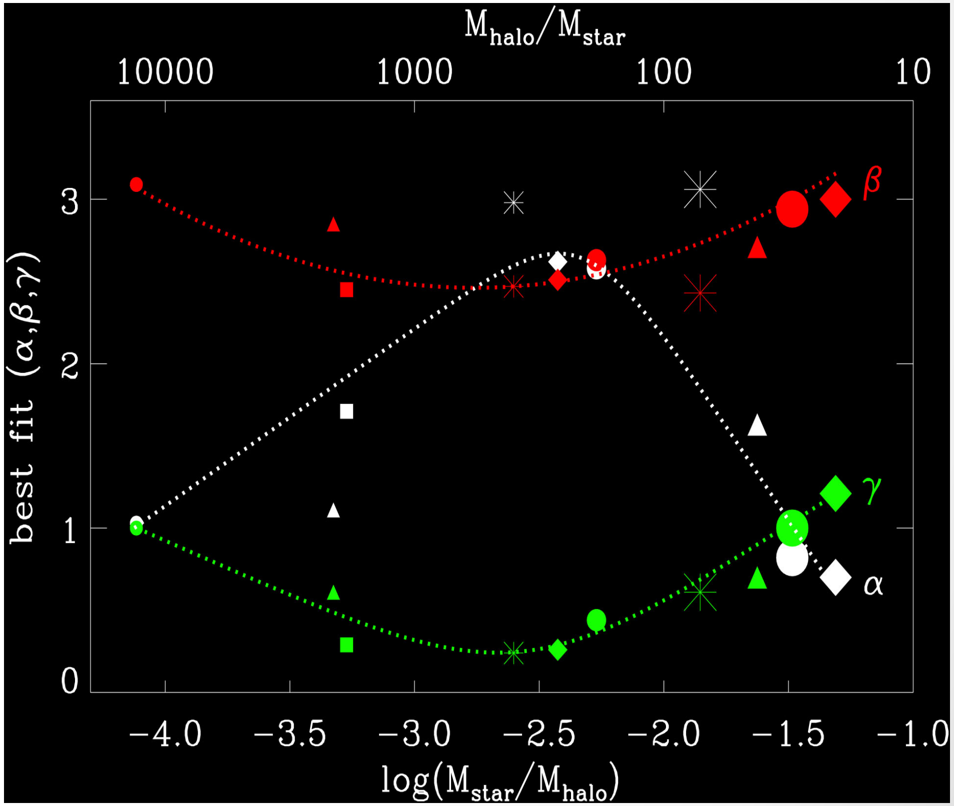
$$\rho_{\mathrm{DC14}}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1+\left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta-\gamma)/\alpha}}$$

γ inner slope

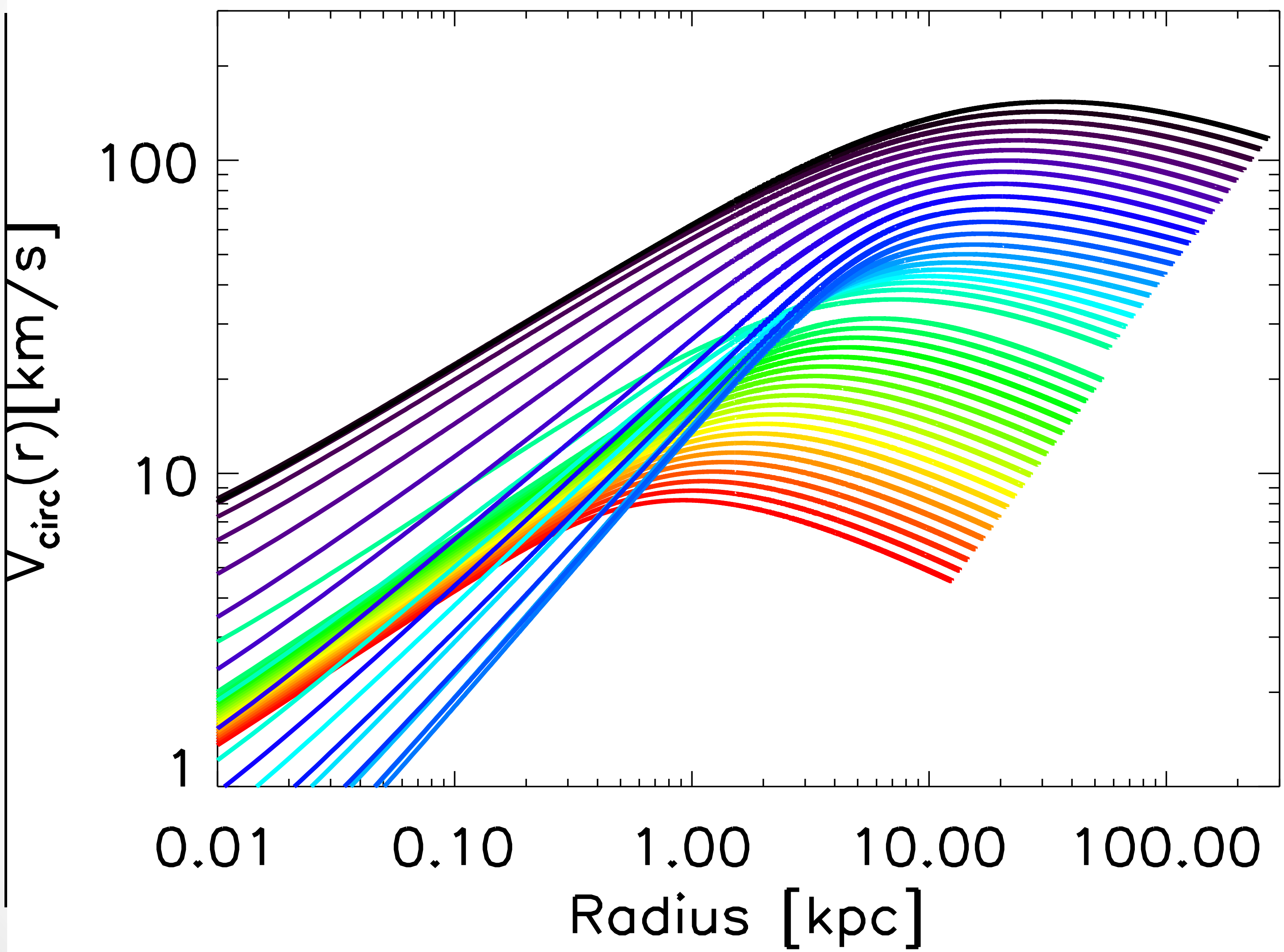
β outer slope

α sharpness of transition

constrained via X=log$_{10}$(M$_\star$/M$_{halo}$)



From cusps to cores to cusps



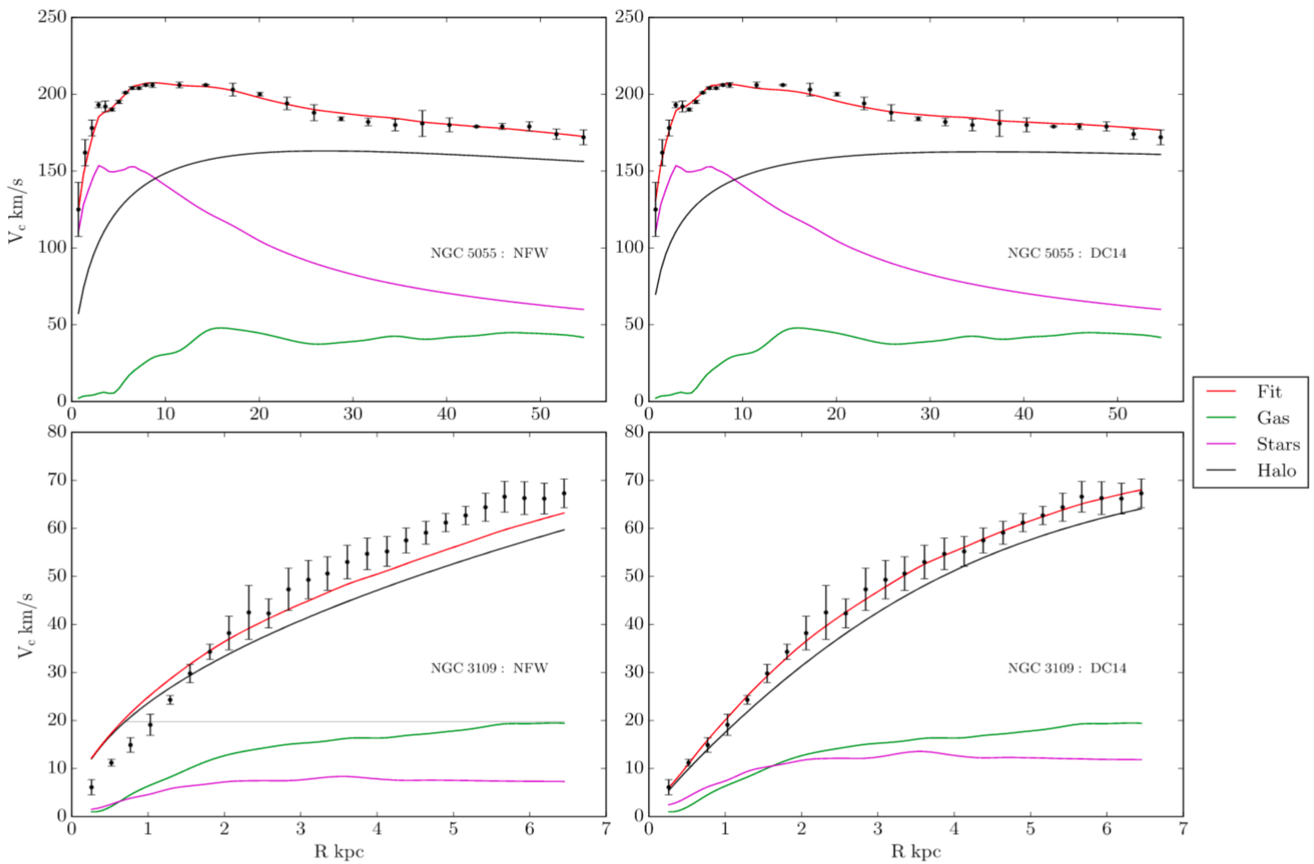
Di Cintio +14

Testing ΛCDM with observed RCs of galaxies

SPARC dataset (Lelli+16)

MCMC fitting $V(r) = (V^2_{dm}(r)+V^2_{gas}(r)+V^2_{star}(r))^{1/2}$ with different profiles for the DM – including or not the effects of baryons

Derive M_{halo} and c and compare it with LCDM expectations



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

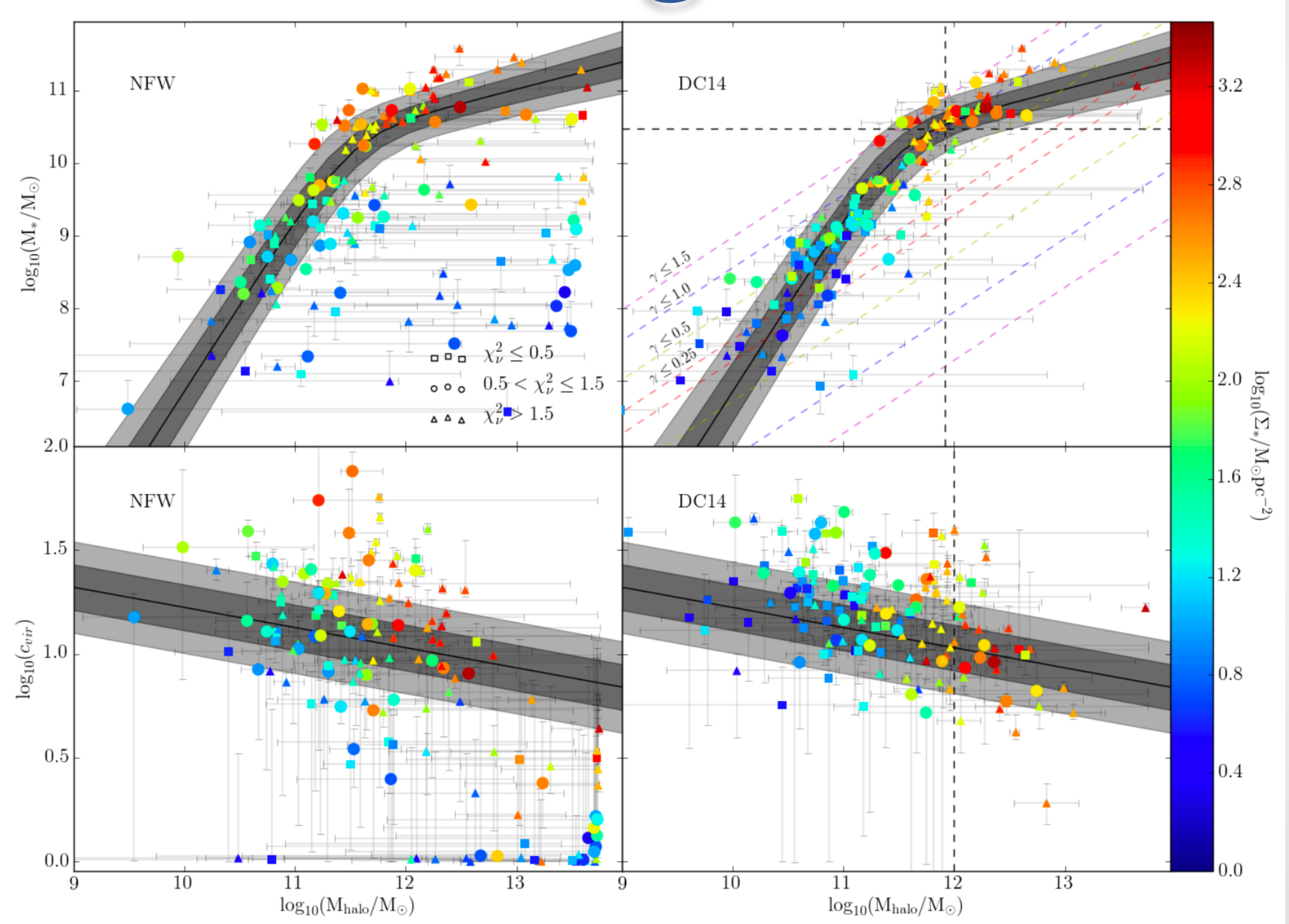
Testing ΛCDM with observed RCs of galaxies

We want to reproduce both observational relations and theoretical predictions :

Rotation curves

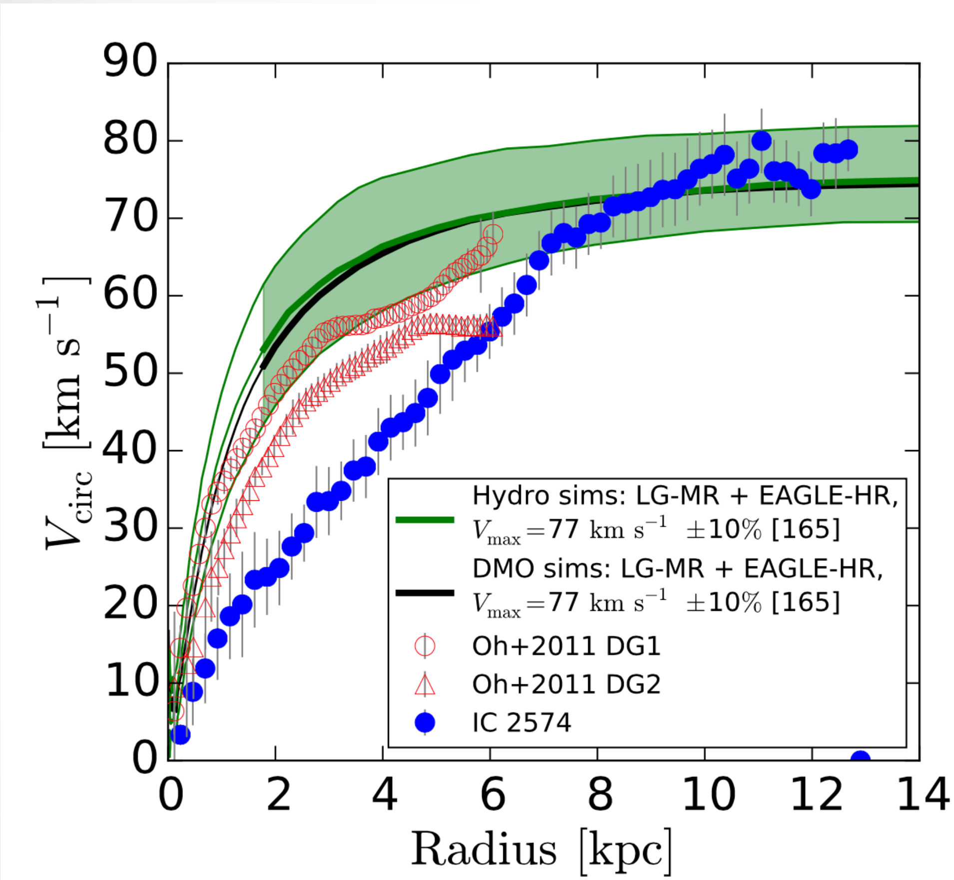
c-Mhalo

Mhalo-M*

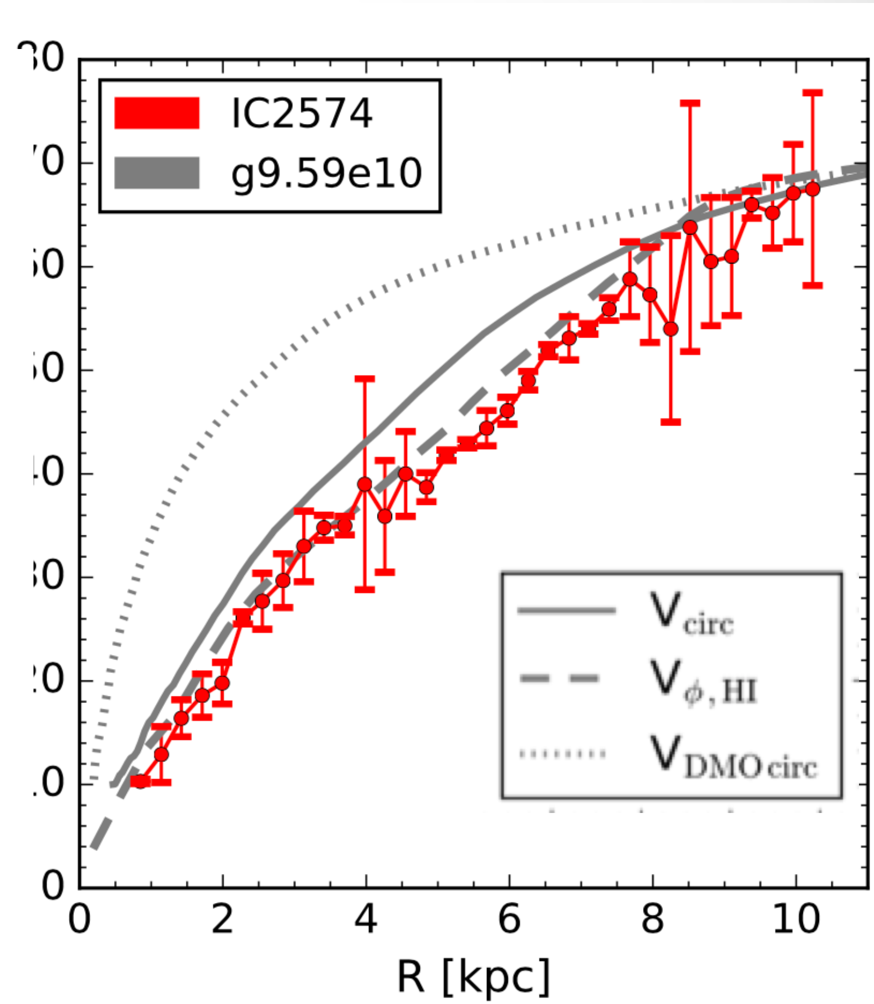


Katz, Lelli, McGaugh,Di Cintio, Brook, Schombert 2017

Diversity of RC shapes explained by cores



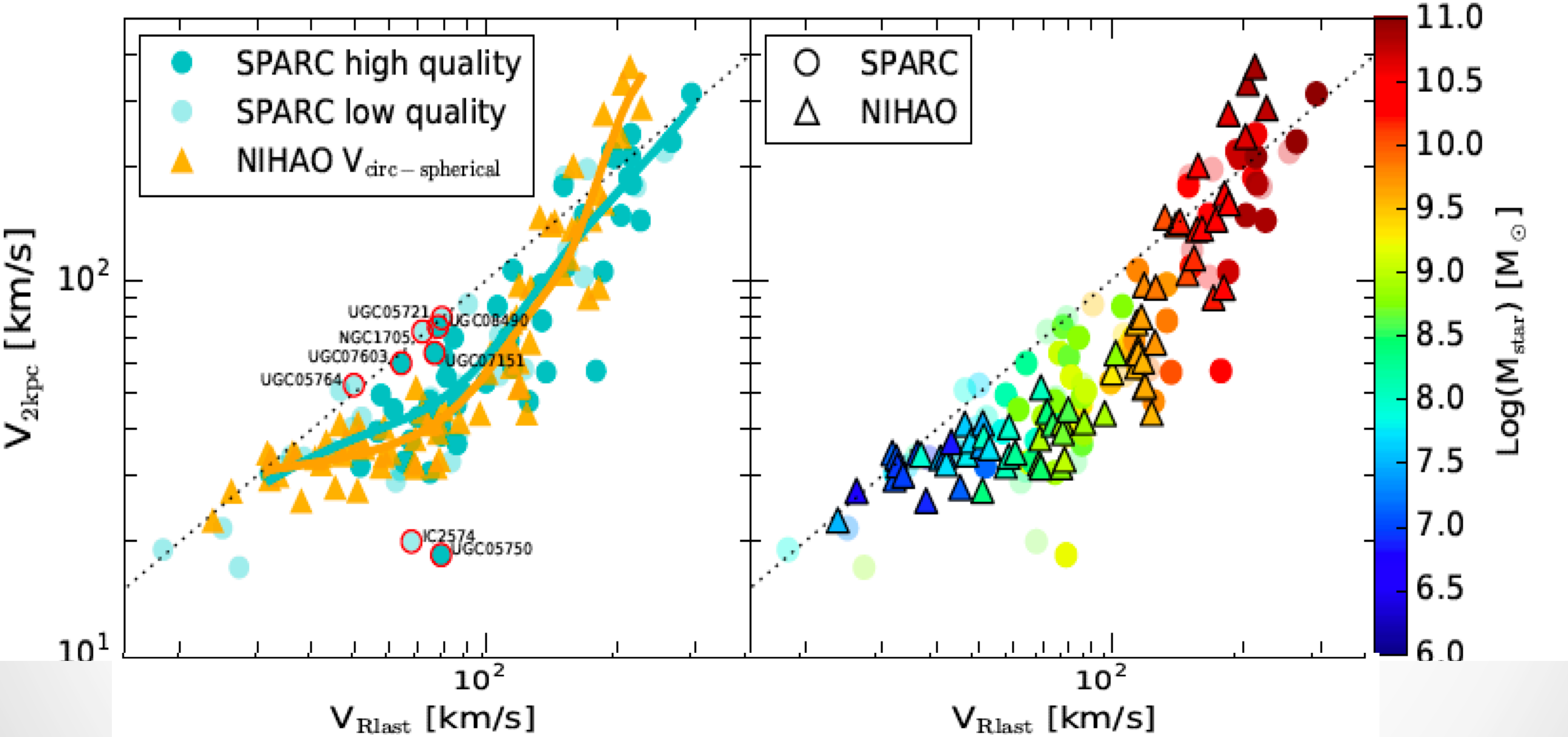
Oman,Navarro +2015
EAGLE simulations



Santos-Santos, Di Cintio +2017
NIHAO simulations

Diversity of RC shapes explained by cores

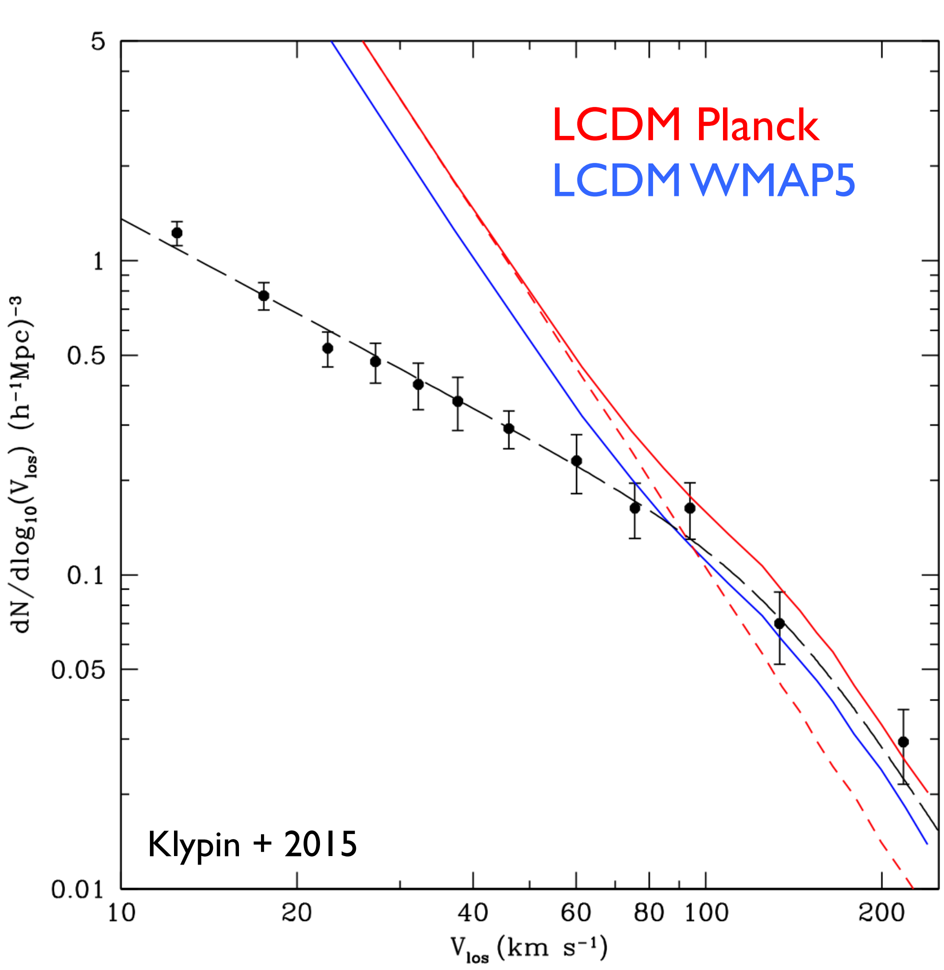
For DM cores not be “real’, there must be some conspiracy for which observational errors mimic the presence of a DM core exactly in the range where we expect DM cores from theoretical models.

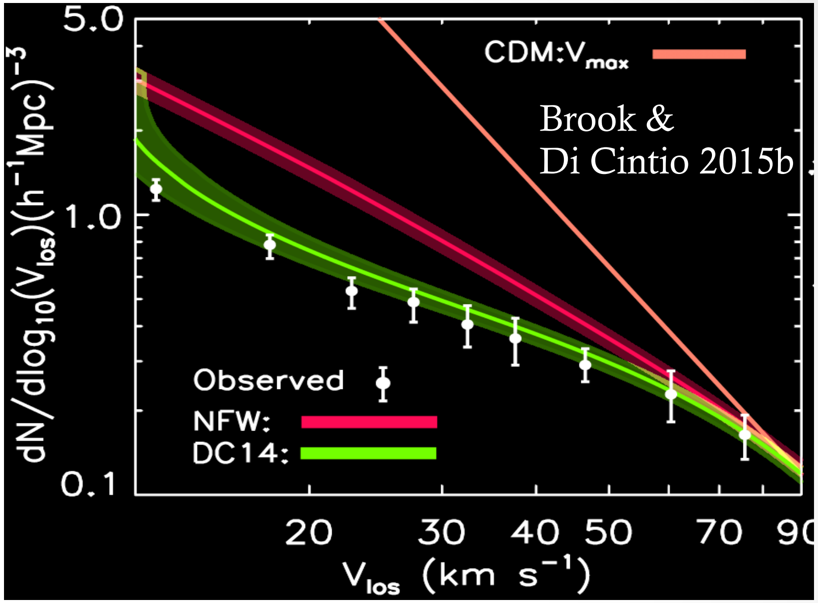


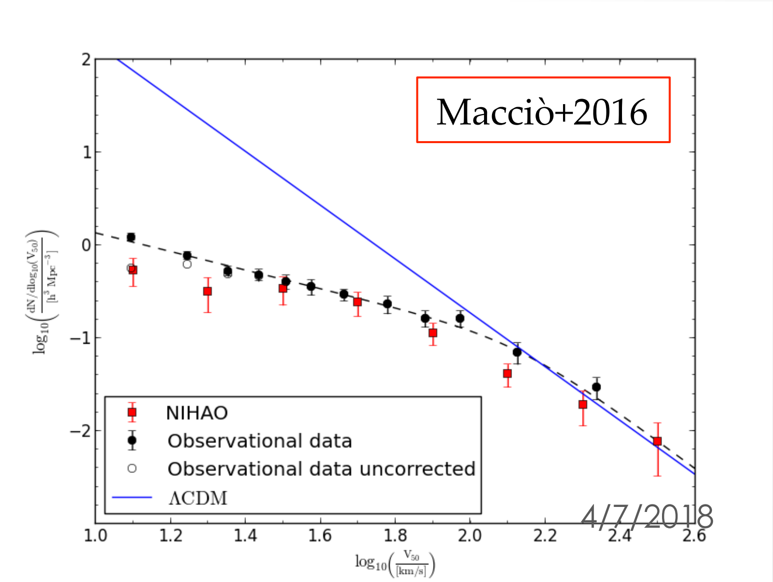
Santos-Santos, Di Cintio et al. 2017

See also Brook 2015, Read+2016

LV Velocity Function



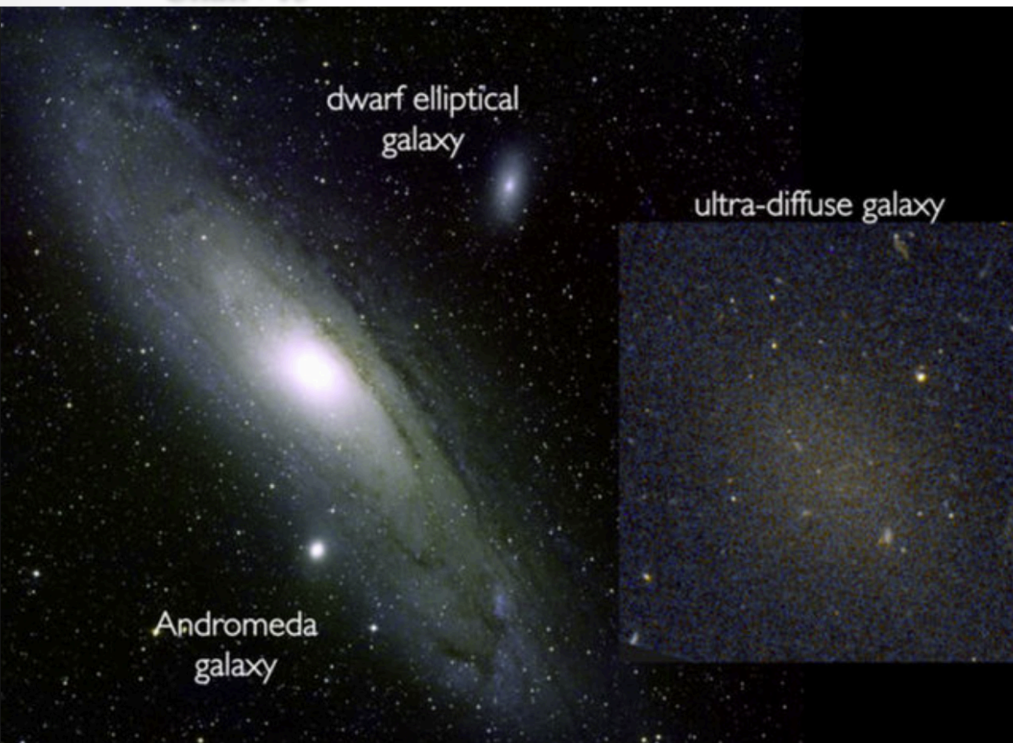


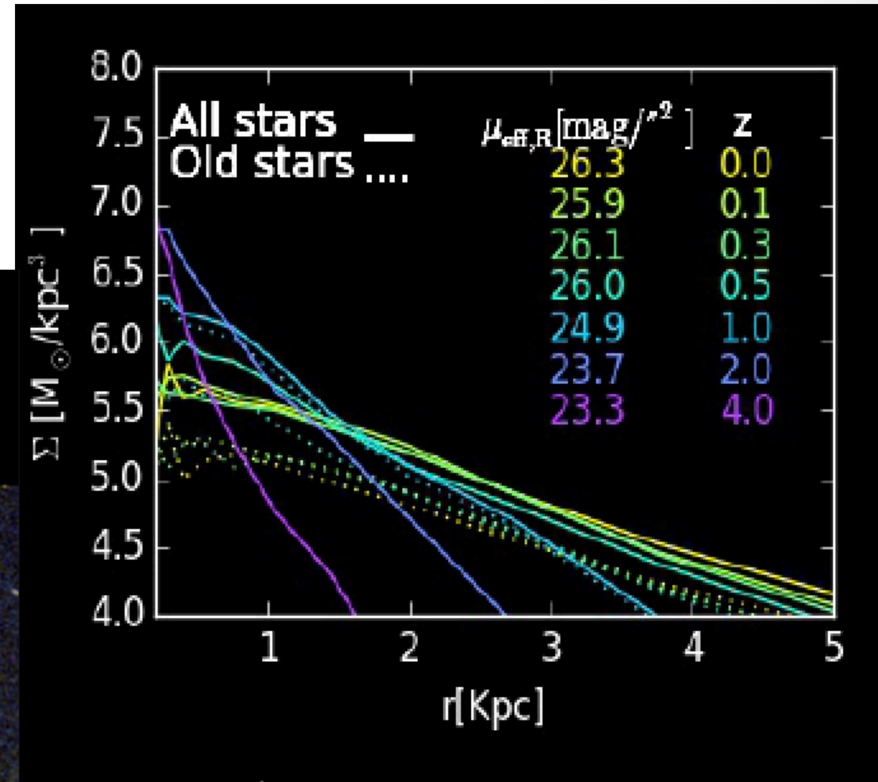


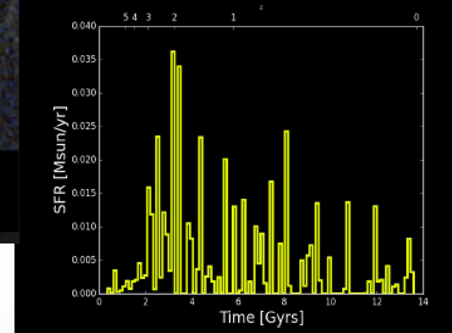
See also Brook & Shankar 2015
Sales+2016 Brooks+17

Ultra diffuse galaxies: outcome of core formation

See Van Dokkum+15
Koda+16, Roman+16,
Amorisco & Loeb 16,
Beasley+16a,b
Chan+15





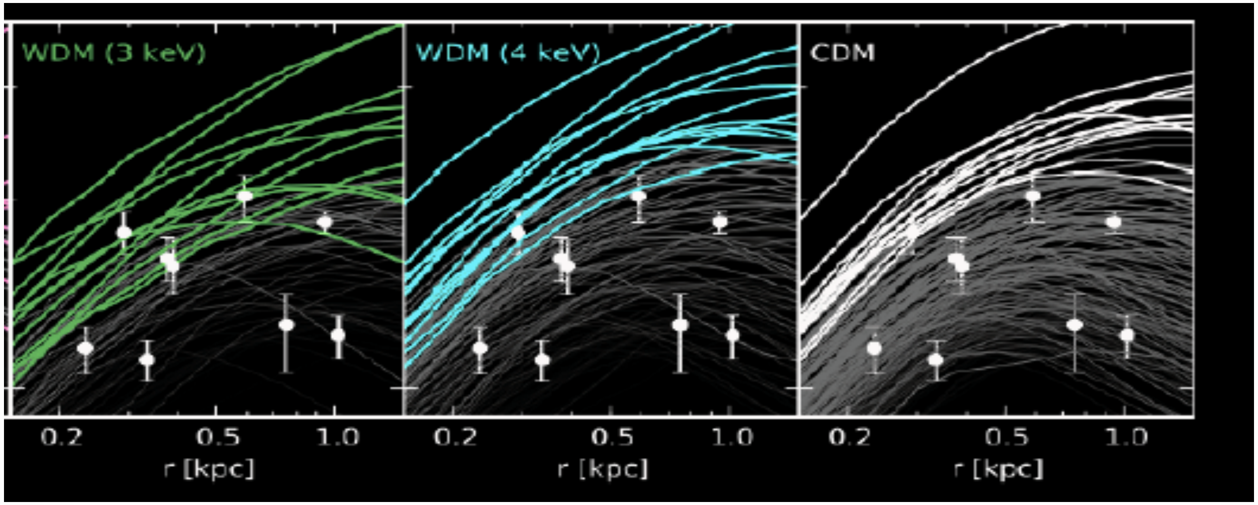


Di Cintio+17

Solution #2: Alternative DM model

TBTF in Warm Dark Matter

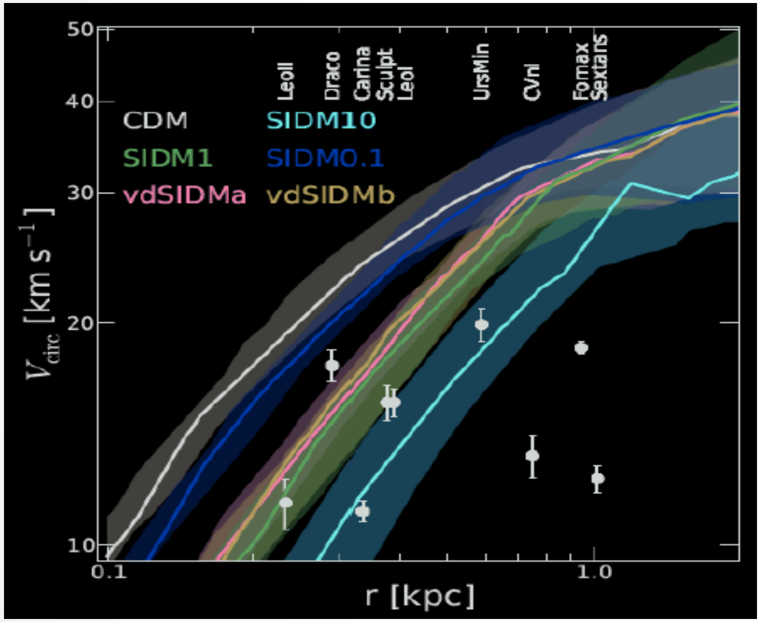
Schneider +15



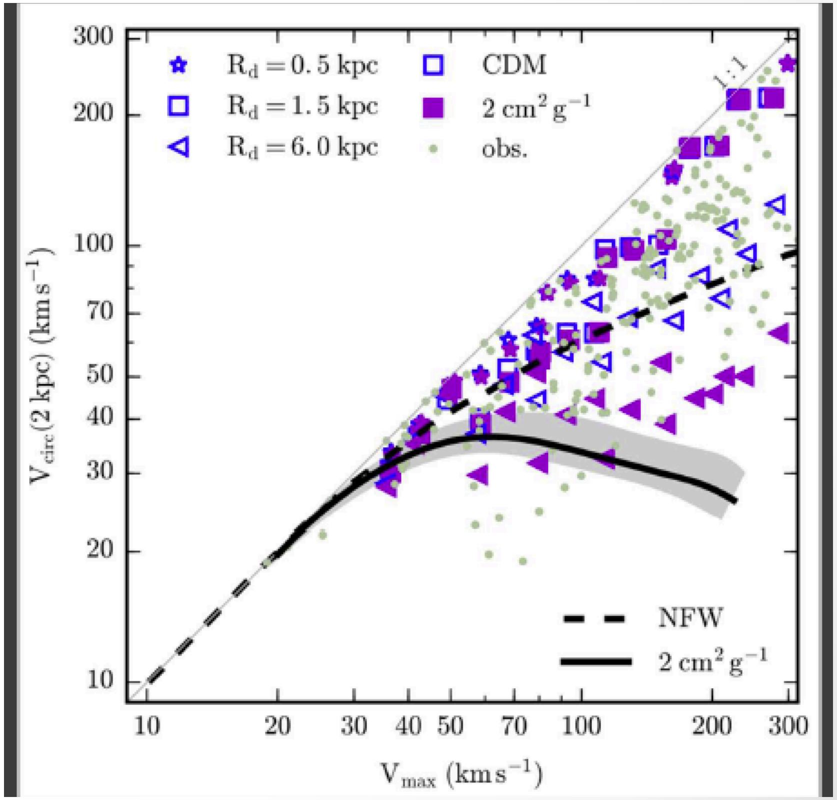
We need to create cores of ~Kpc size to explain the central density of dSphs: in WDM, this requires a thermal candidate with a mass below 0.1 keV, ruled out by all large scale structure constraints (see Schneider+15, Maccio'+15)

Solution #2: Alternative DM model

TBTF in Self Interacting Dark Matter



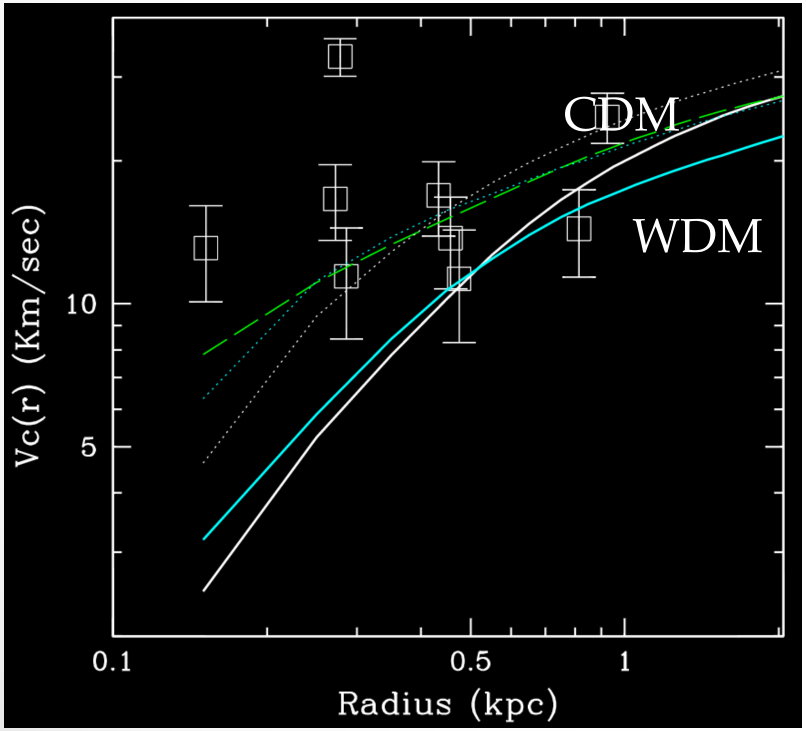
Diversity of RC shapes in SIDM
Creasey +17



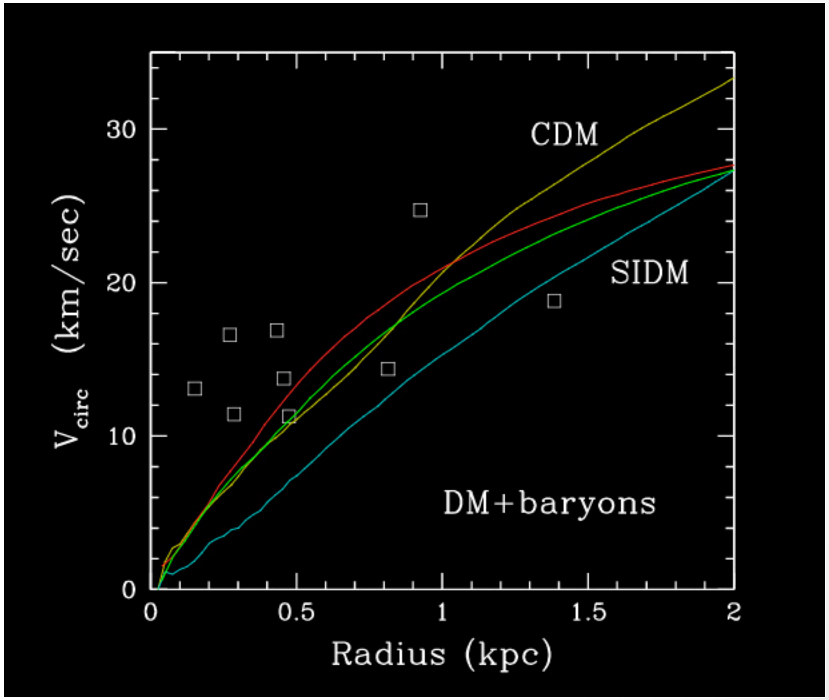
Self-interactions lower the central density alleviating the problem
The cross section must be larger than 0.1 cm^2/gr Vogelsberger+12, Zavala+13, Rocha+12

Solution #3: Alternative DM model + baryonic physics

SF and resulting feedback dominates over SI and WDM physics: dm inner slope, Vcirc SFH, star and gas content are indistinguishable between CDM – WDM – SIDM + baryons in DWARF GALAXIES



Governato +15



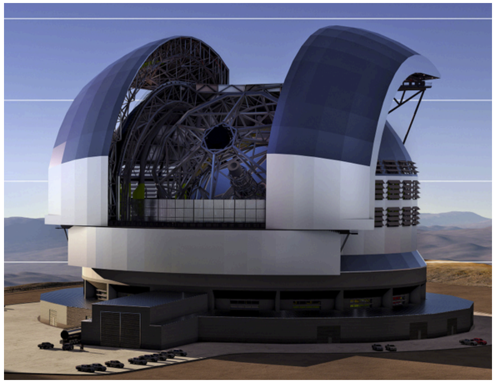
Bastidas-Fry, Governato +15

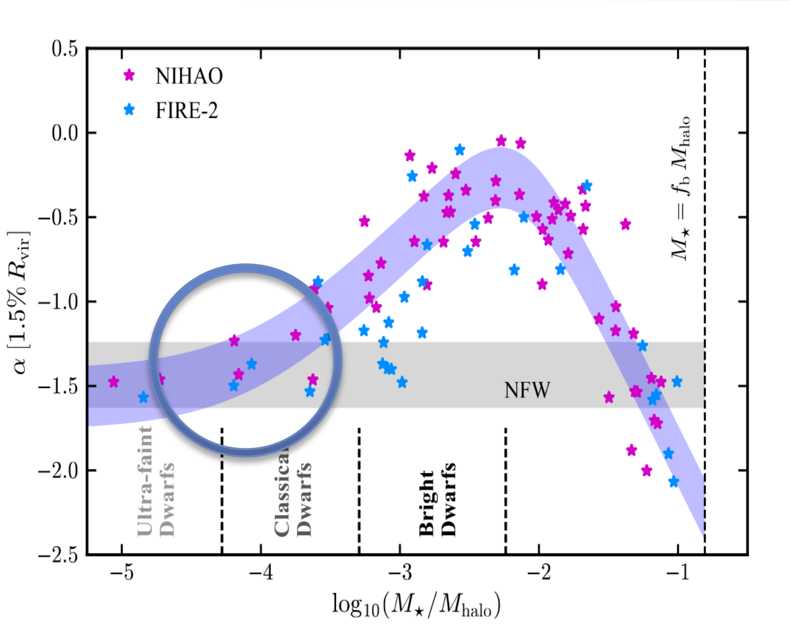
We have too many solutions to the inner DM problem!

- Baryonic physic affects dark matter profiles in galaxies: CDM has a peak in core formation efficiency at $M_* \approx 10^{8.5}\,M_\odot$
- Once the effect of baryonic physics is included, it is hard to distinguish between WDM/SIDM/CDM
- How can we disentangle between different DM models?

Role of ELTs

- We should be looking at "cores" in faint, small dwarf galaxies with $M^* < 10^6 M_{sun}$ => if central "cores" are found, they can not be due to baryonic physics





- Future ELTs useful for this task: they will resolve stellar populations which allows for a better modelization of the inner density in dwarfs
- If kpc size cores are found in faint dwarfs, that would set a minimum cross section on SIDM of $\sigma \sim 2$ cm^2/gr