Arianna Di Cintio
Marie Curie IF @IAC

The internal structure of DM haloes in the presence of baryons: 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

Annecy-Le-Vieux

28/6/2018

Why is the inner structure of DM haloes so important?

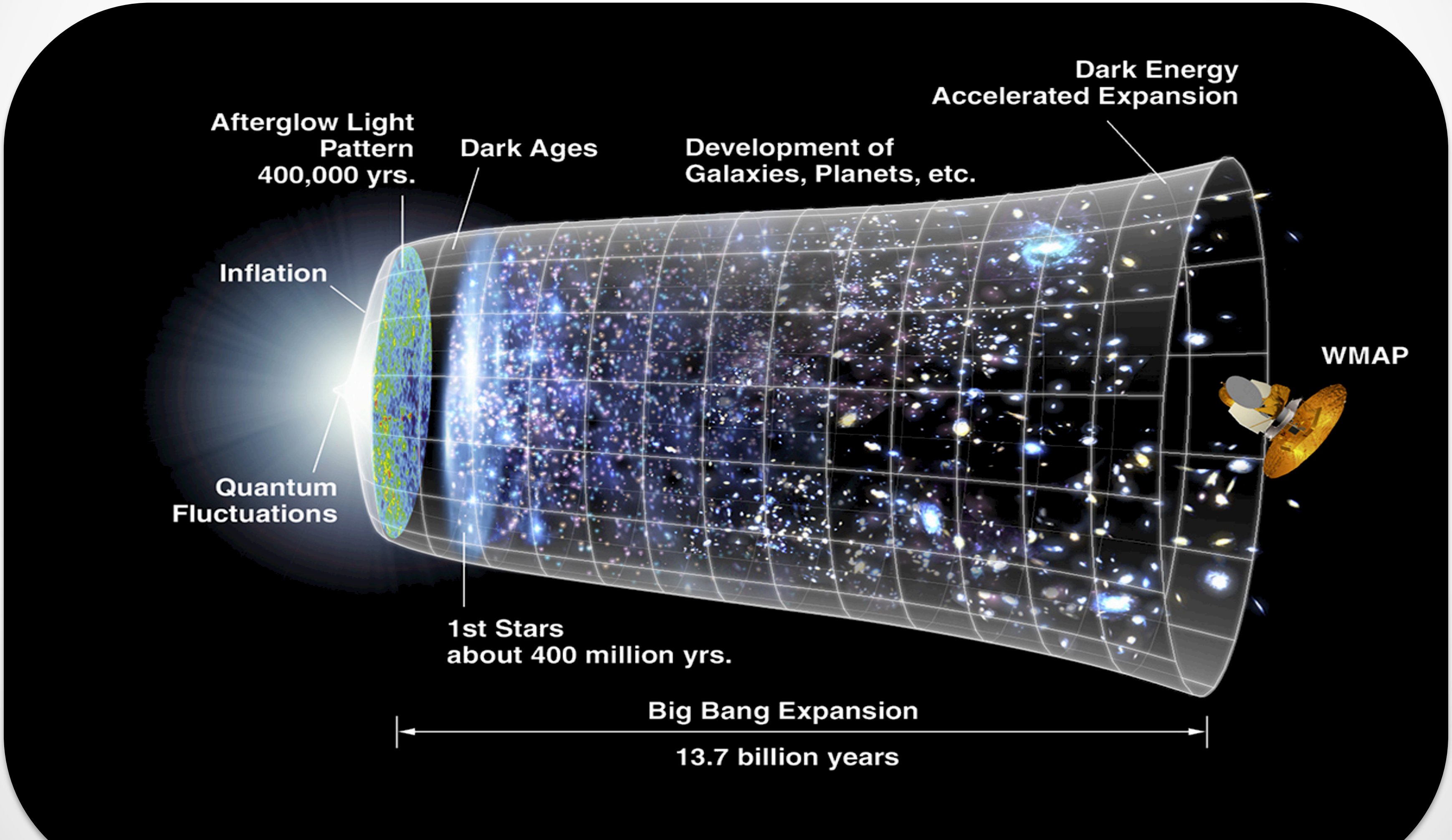
- The distribution of matter within galaxies - AKA their density profile - is a key prediction of galaxy formation happening within a cosmological framework!

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

Outline

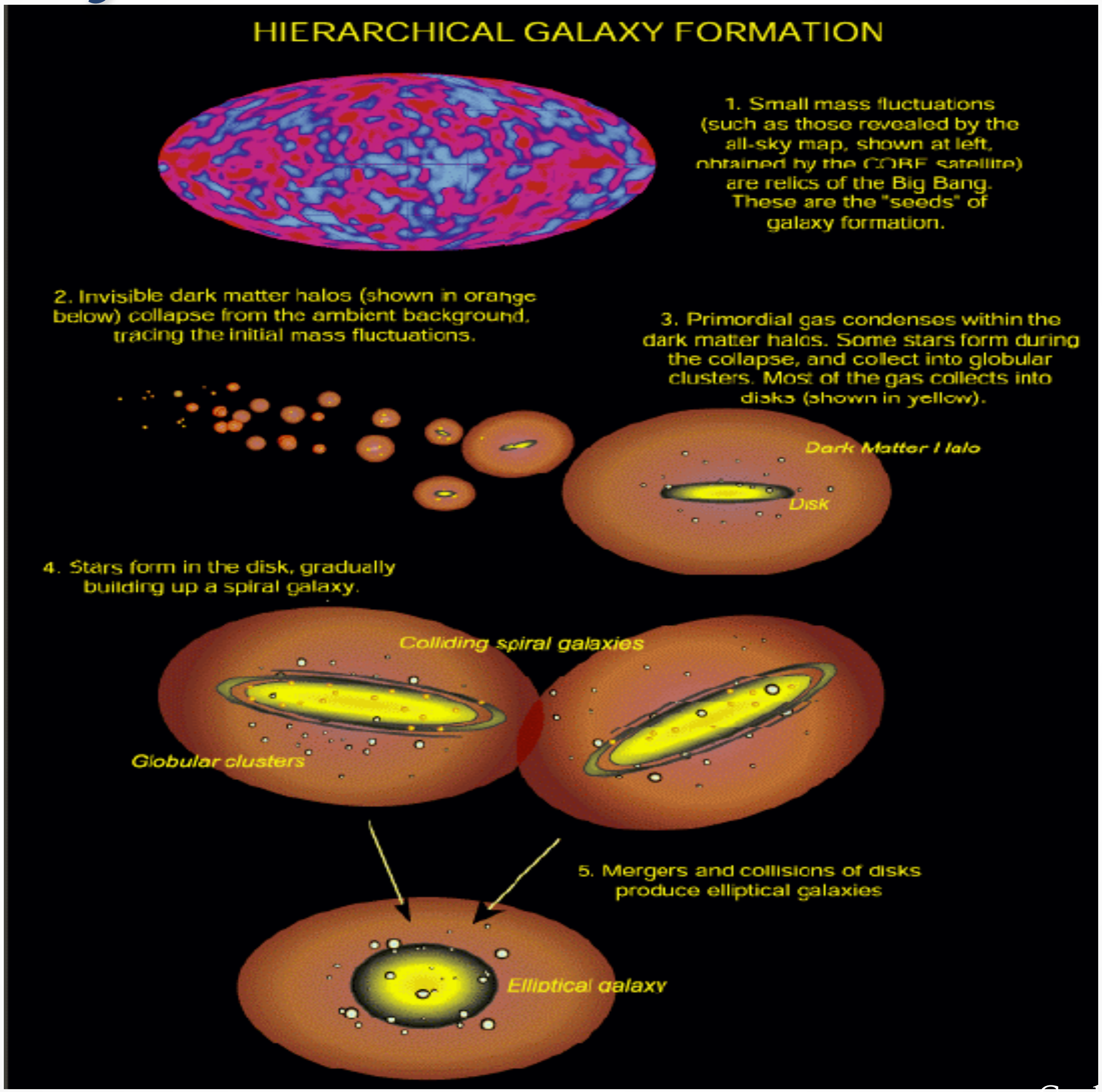
- ΛCDM→Galaxy formation with simulations
- Inner structure of DM halos => “cusp-core” issue
- Solution #1: CDM + baryonic physics
- Solution #2: SIDM/WDM (+ baryonic physics)

Galaxy Formation



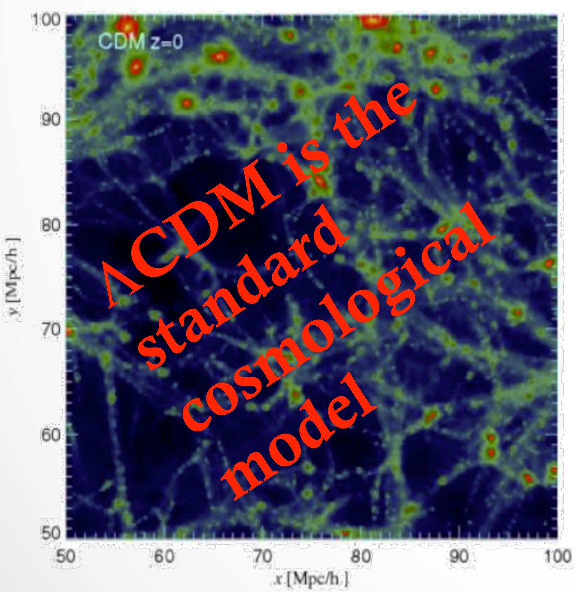
Cradit:NASA-WMAP science team

Galaxy Formation in LCDM

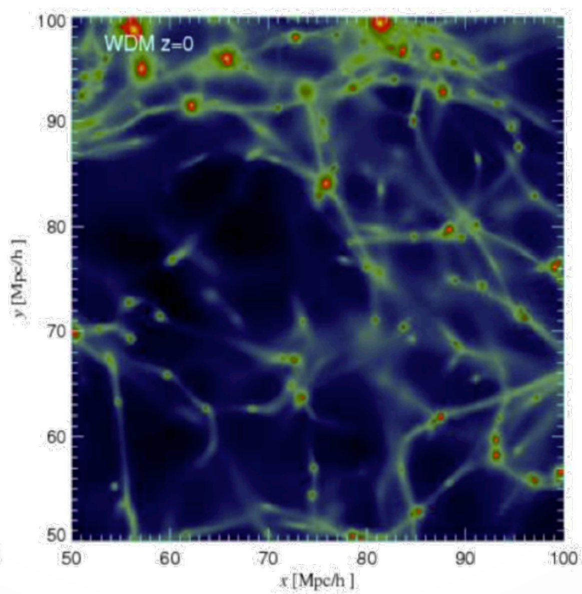


The nature of Dark Matter

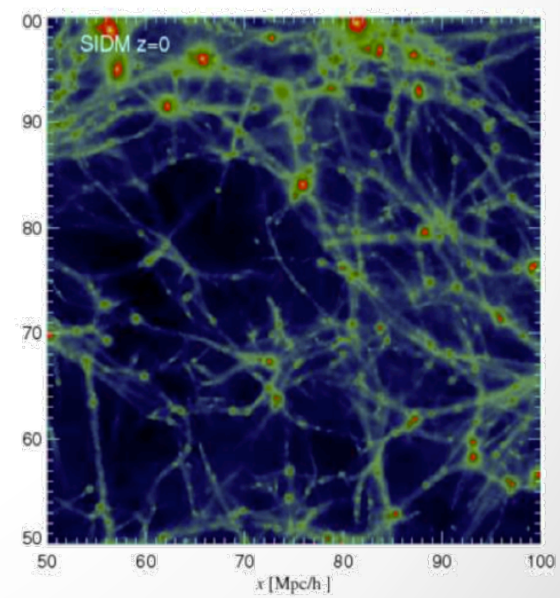
Cold Dark Matter
(Slow moving)
m~ GeV-TeV
Small structures form first, then merge



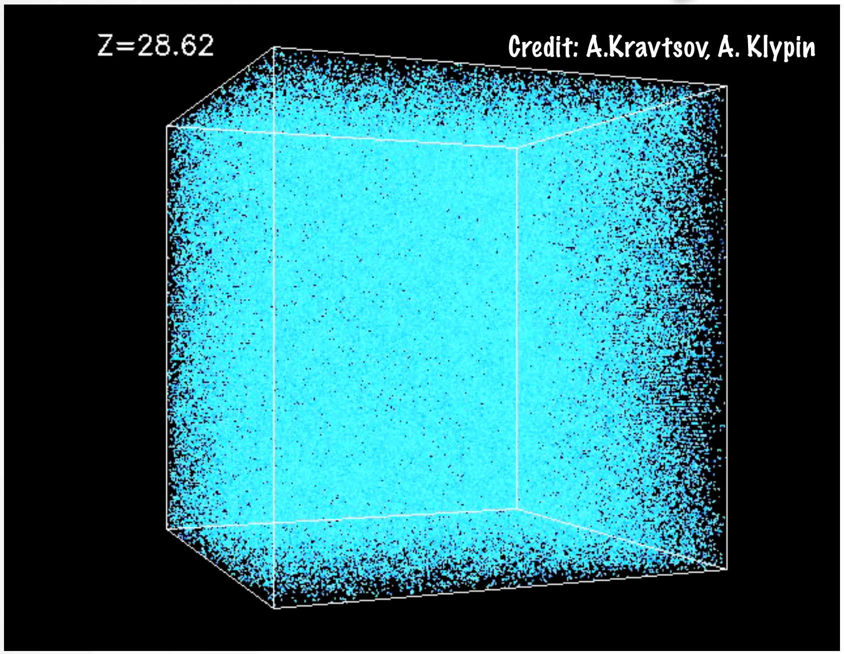
Warm Dark Matter
(Fast moving)
m~ keV
Small structures are erased

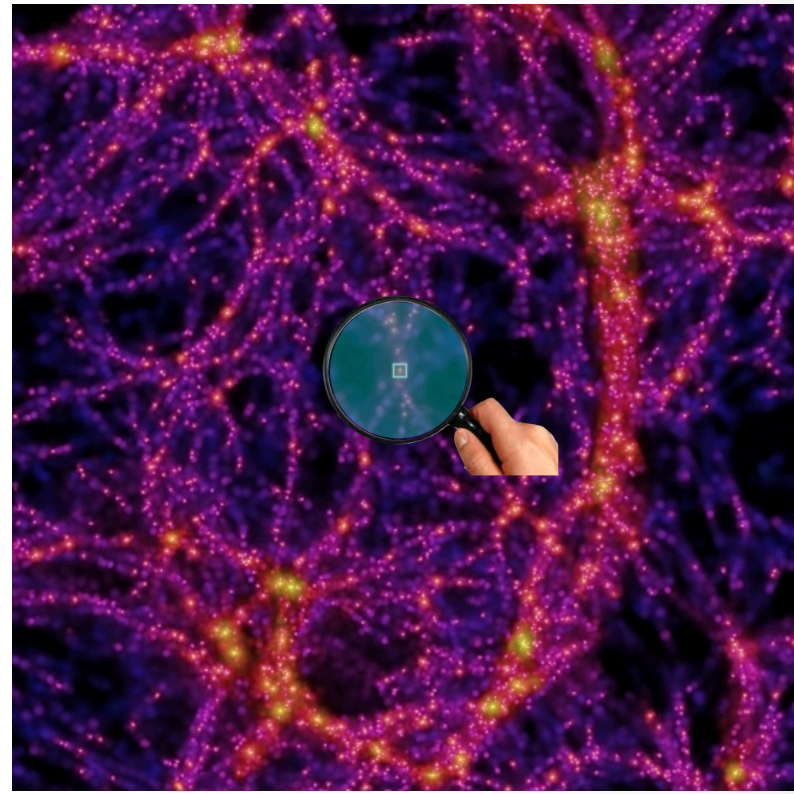


Self-Interacting Dark Matter
Strongly interact with itself
Large scale similar to CDM,
Small galaxies are different



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

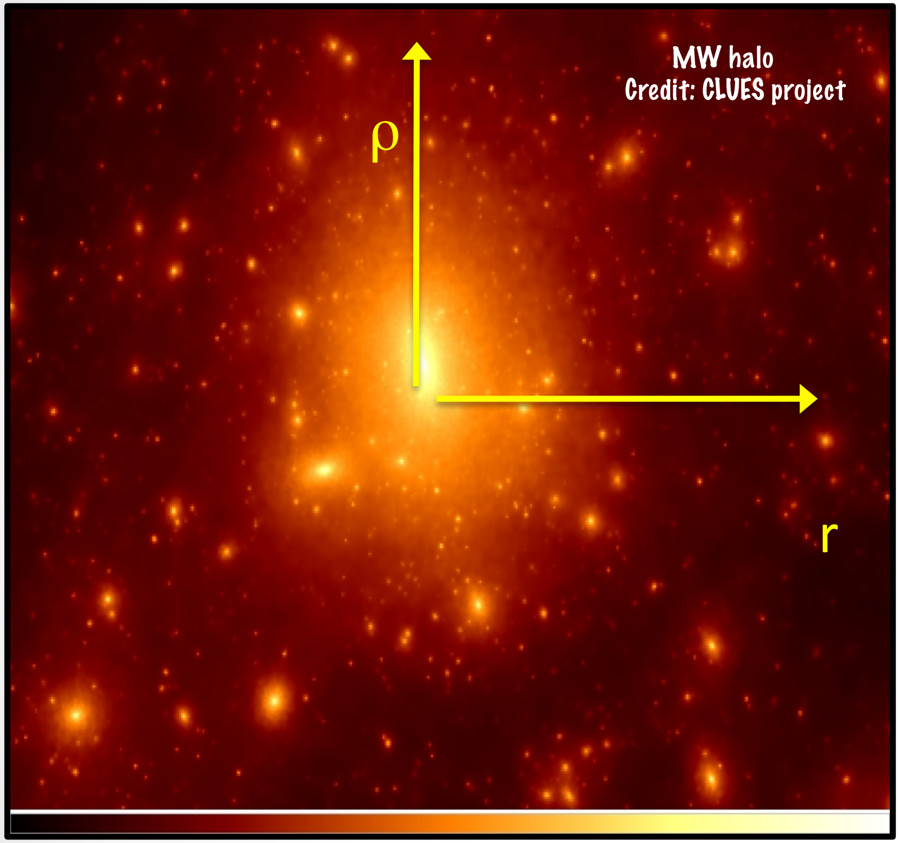


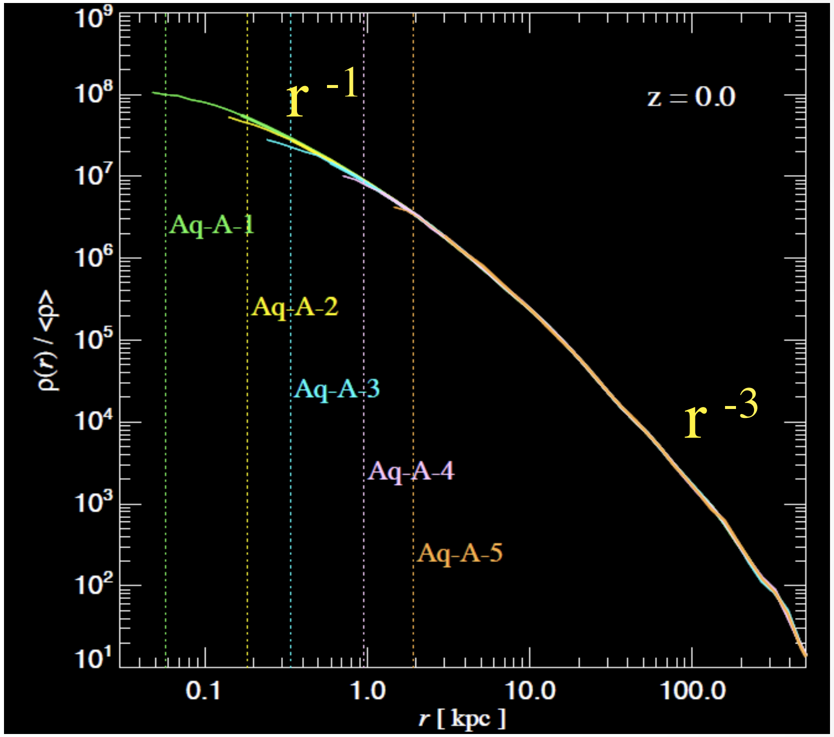


$$M_{\rm halo} = \frac{4}{3}\pi R_{vir}^3 \Delta \rho_{crit}$$

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

Density profile of DM haloes





Aquarius simulations

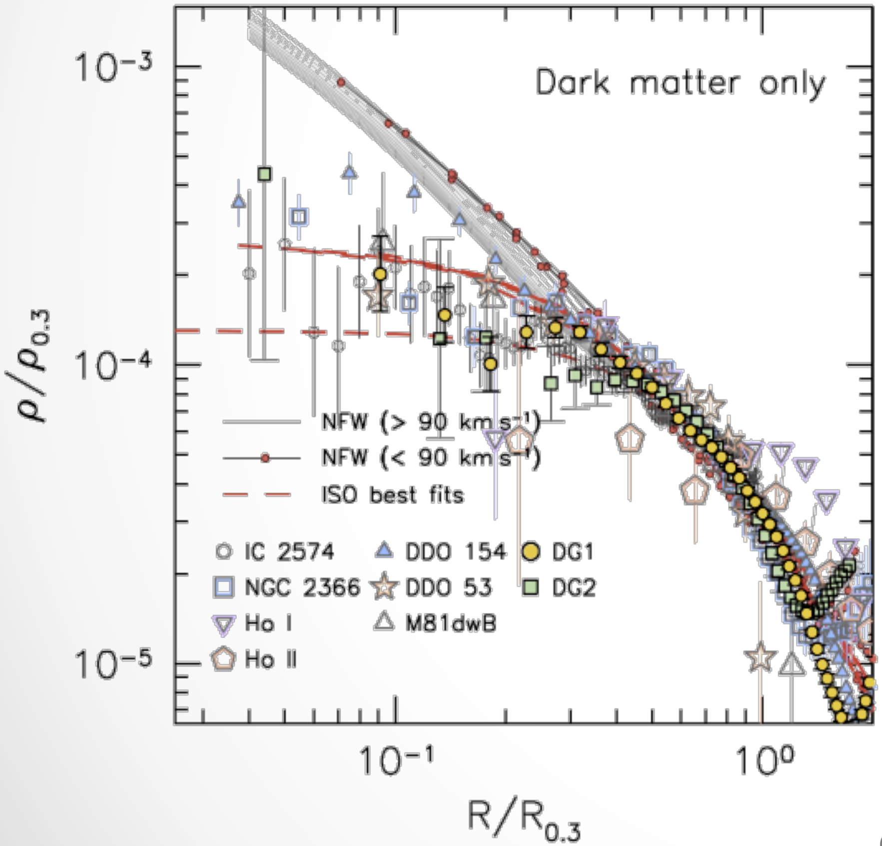
$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

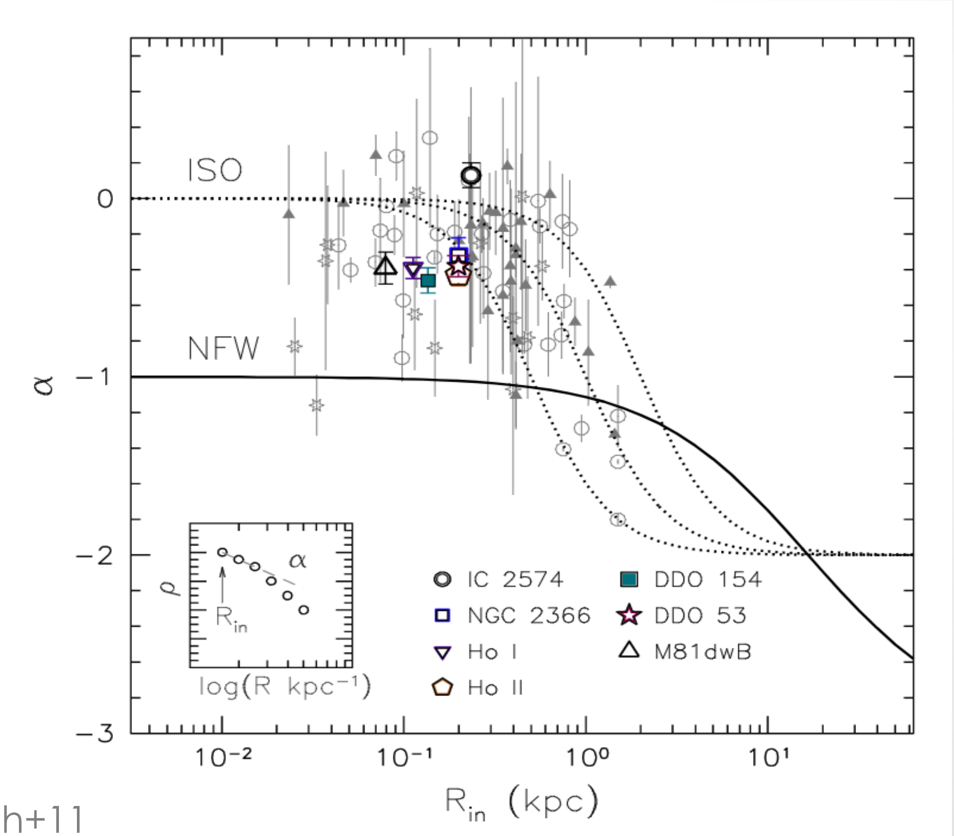
Navarro, Frenk & White 1997 CDM haloes in simulations have a universal density profile

The `cusp-core' discrepancy

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

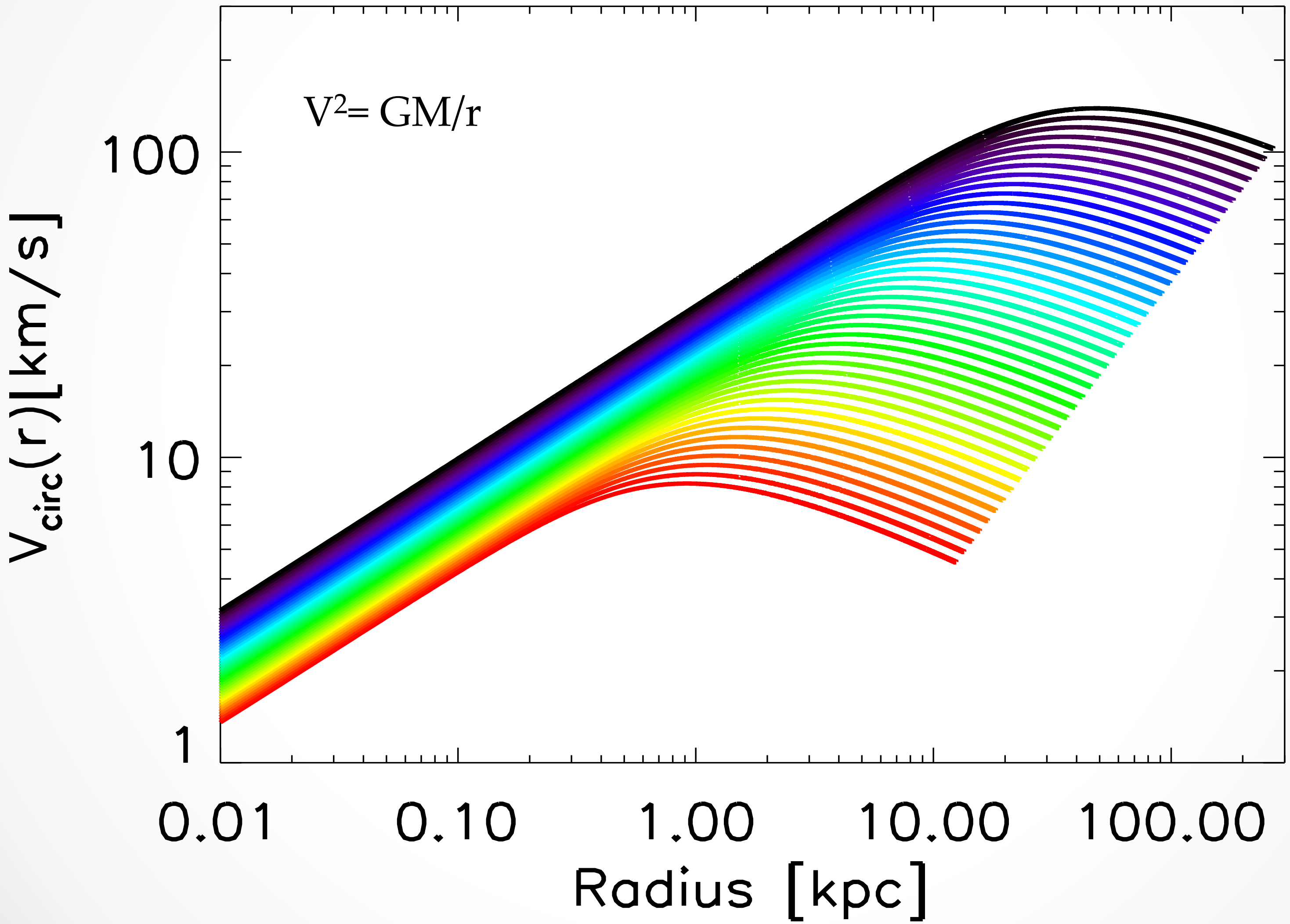
Observations of dwarfs and LSB
show 'CORED' profiles
Inner slope 0> γ > -1





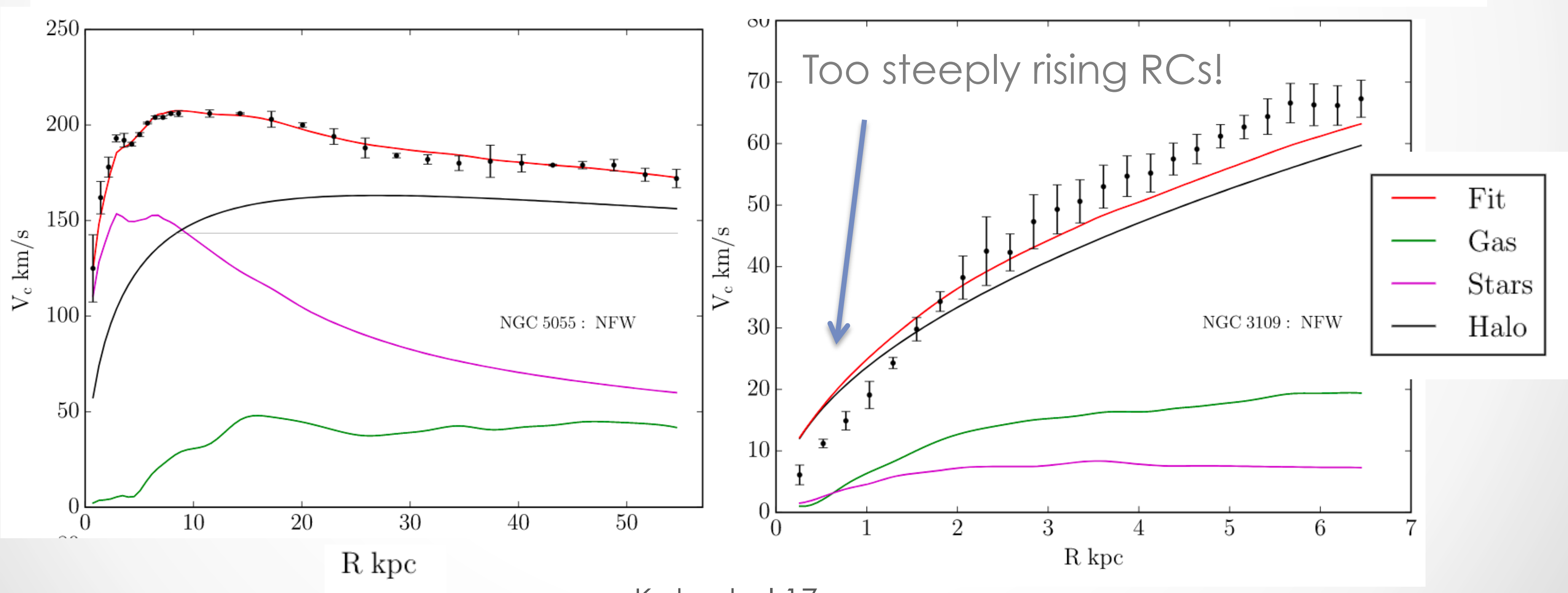
Oh+11

The NFW profile: cusps



Cusp-core issue arising in galaxy rotation curves

$$V_c(r) = \sqrt{V_{DM}(r)^2 + V_{gas}(r)^2 + (M_*/L)V_{stars}(r)^2}$$



Katz et al.17

Solution #1: CDM + baryonic physics

Making Galaxies in a Cosmological Context
MaGICC (PIs Stinson-Brook)

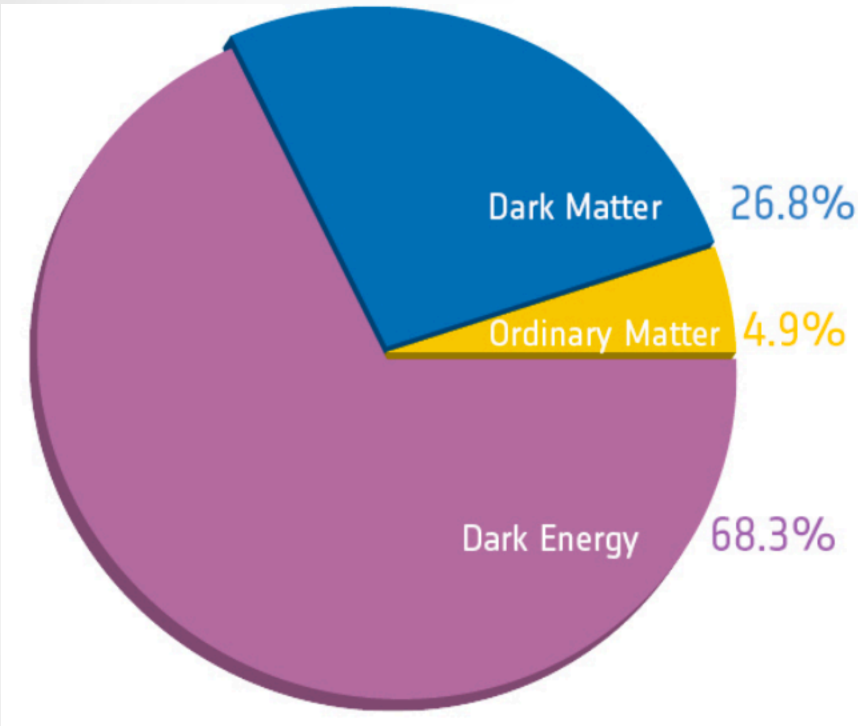
&

Numerical Investigation of Hundred Astrophysical Objects
NIHAO (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

Role of baryonic physics



baryons for astrophysicists

Baryonic physics processes modeled in hydrodynamical simulations:

- Gas inflowing and cooling
- Star formation
- Feedback (mechanical, thermal, kinetic, radiation pressure) from SNae, massive stars, AGNs

MaGICC & NIHAO simulations

Stinson+13, Brook+12
Wang+15,Buck+17

GASOLINE N-body + SPH code from Wadsley + 04
SN feedback with blastwave formalism Stinson+06
Early-stellar feedback from massive stars

=> Reproducing realistic galaxies

Credit: Dominguez-Tenreiro, Obreja+16

Credit: Sawala +10

Role of baryons
SNae feedback and outflows

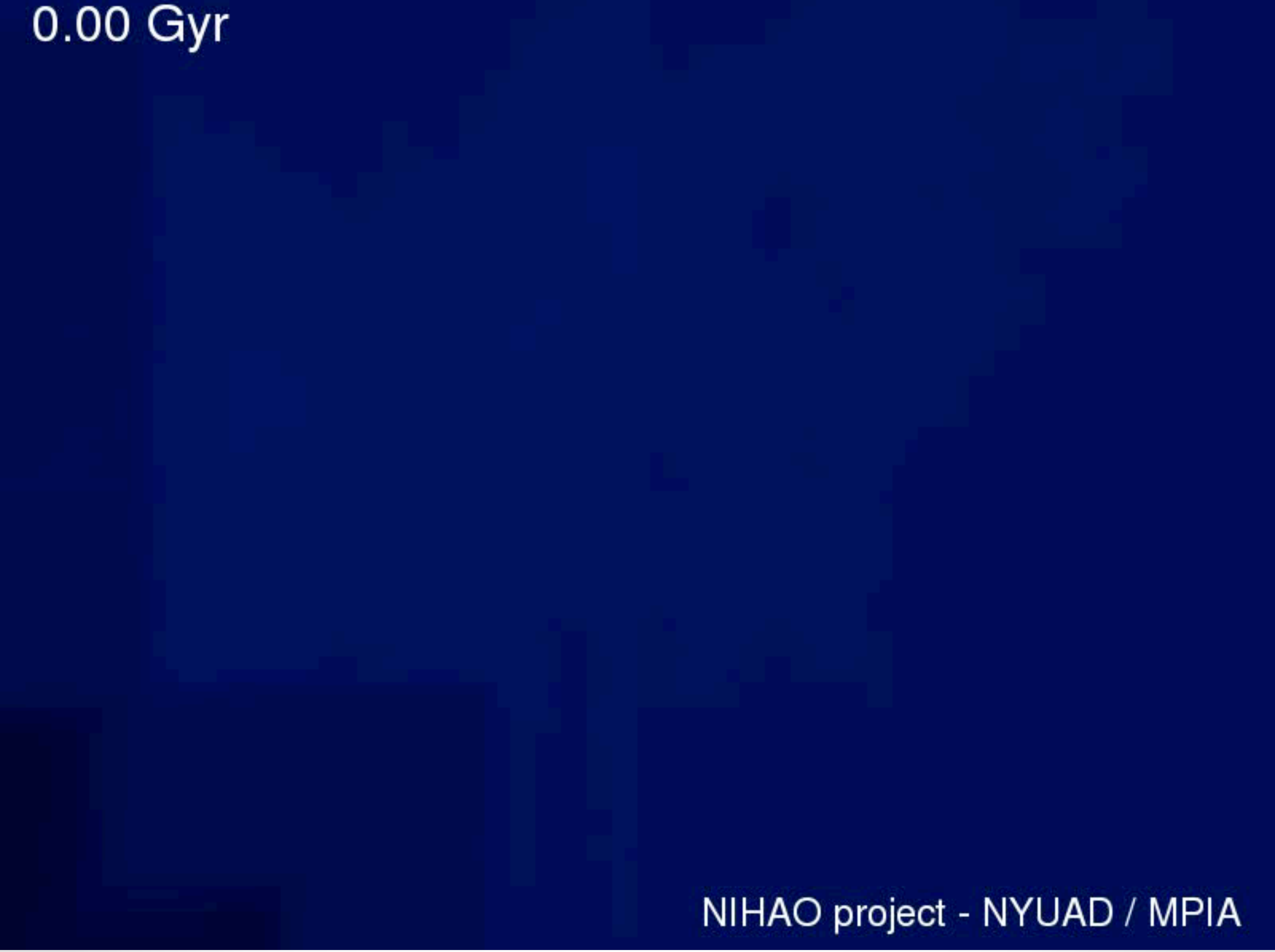
- KEY ingredients:

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

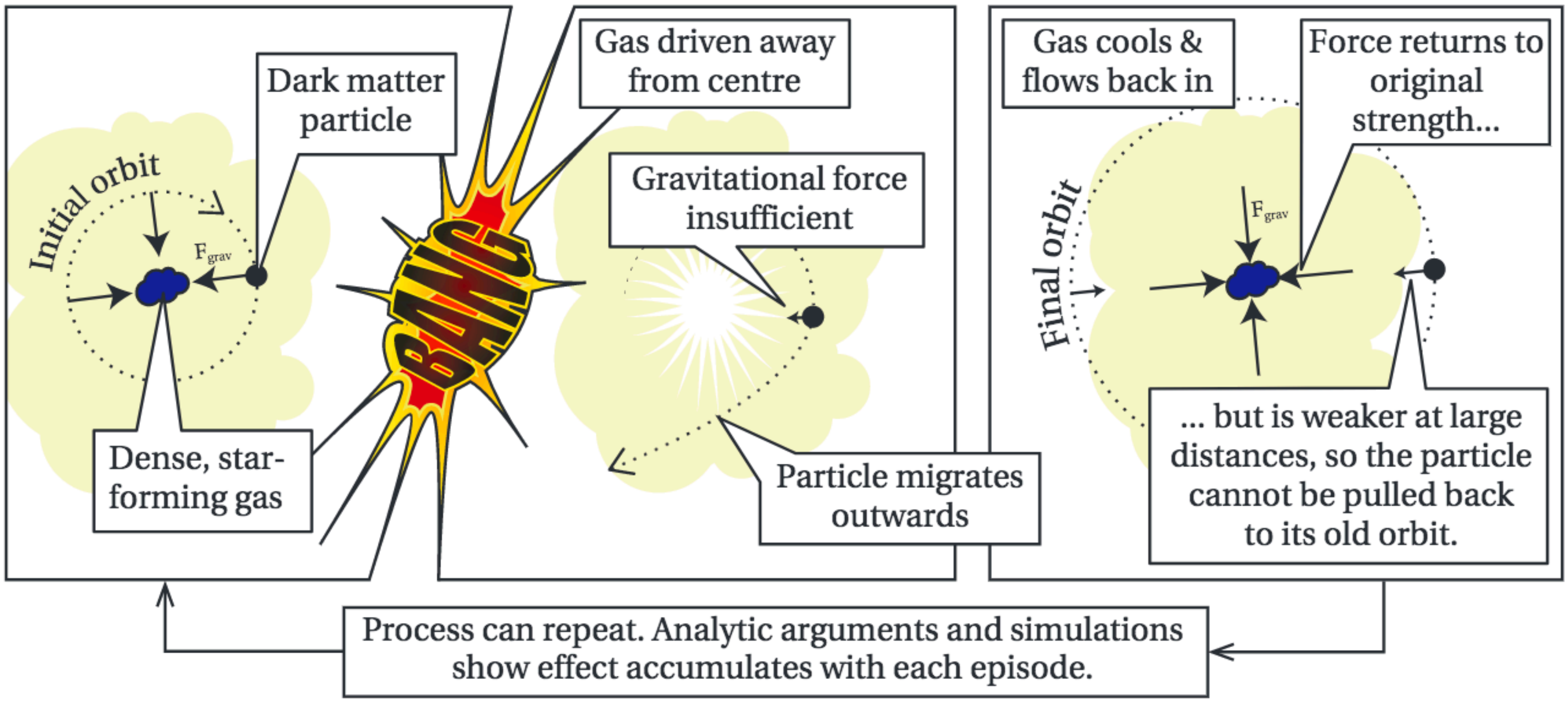
- RESULT:

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


0.00 Gyr
NIHAO project - NYUAD / MPIA

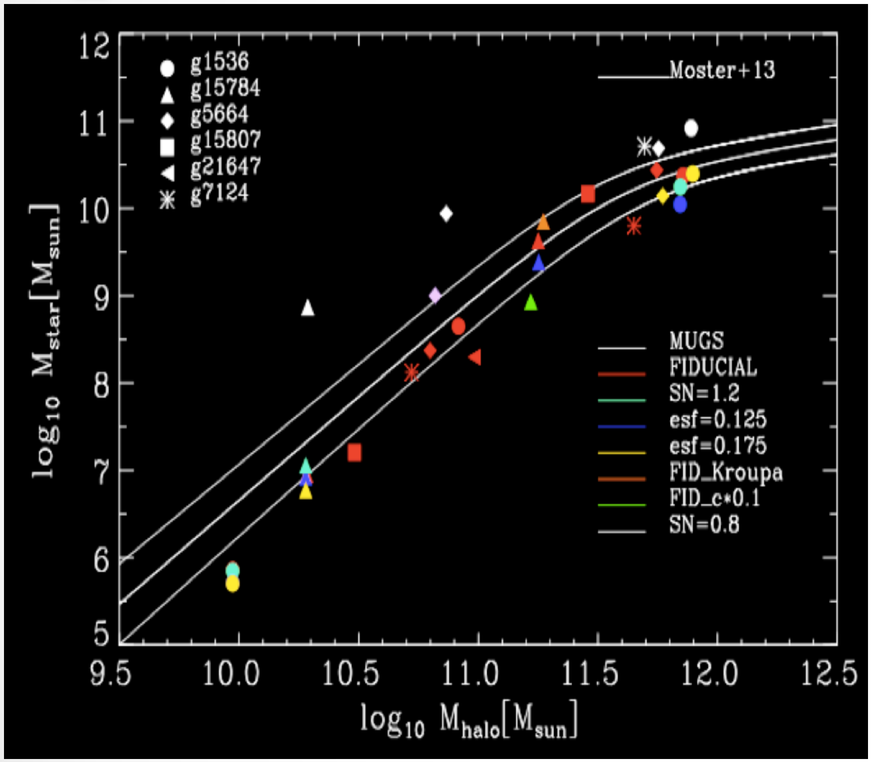
From gas outflows to DM 'cores'

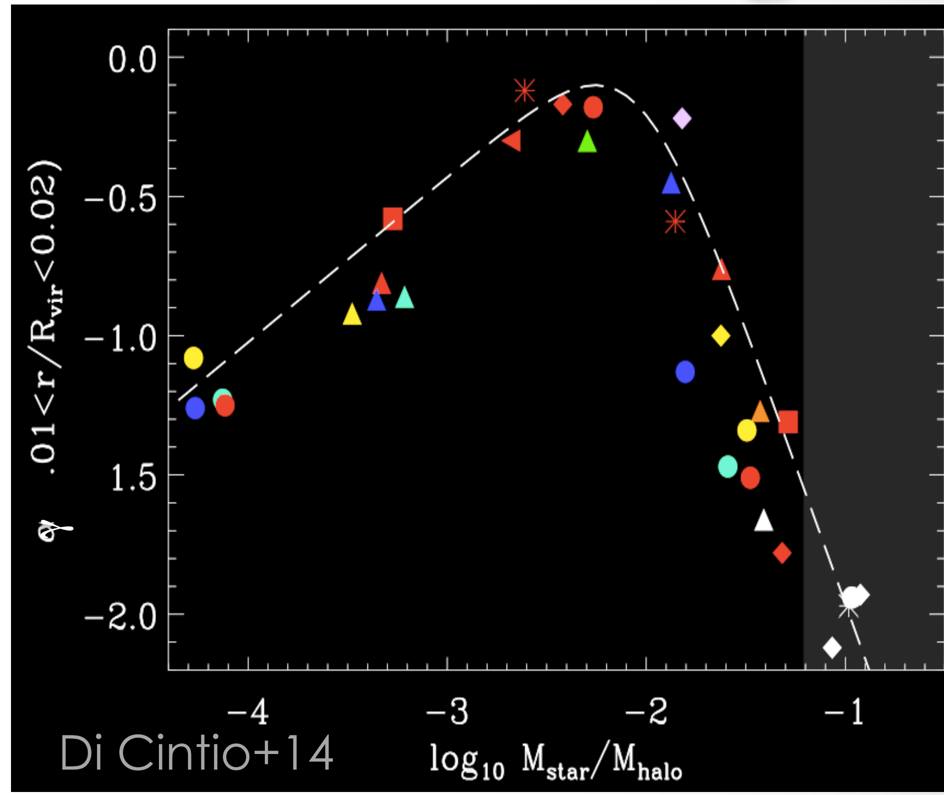


Pontzen & Governatp 14

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

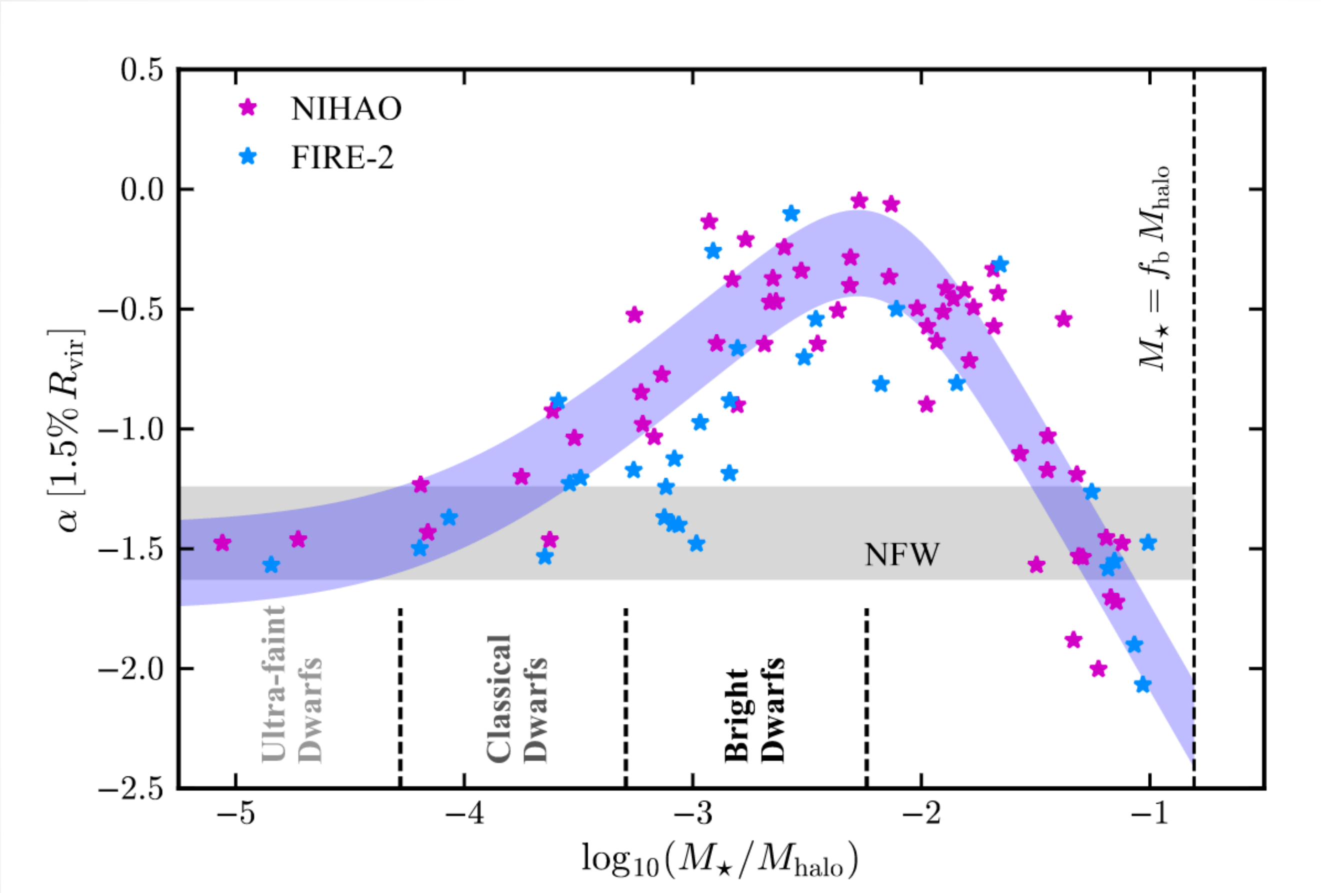




Peak of core formation at log(M*/Mhalo)~-2.4 → M*~$10^{8.5}$ Msun

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



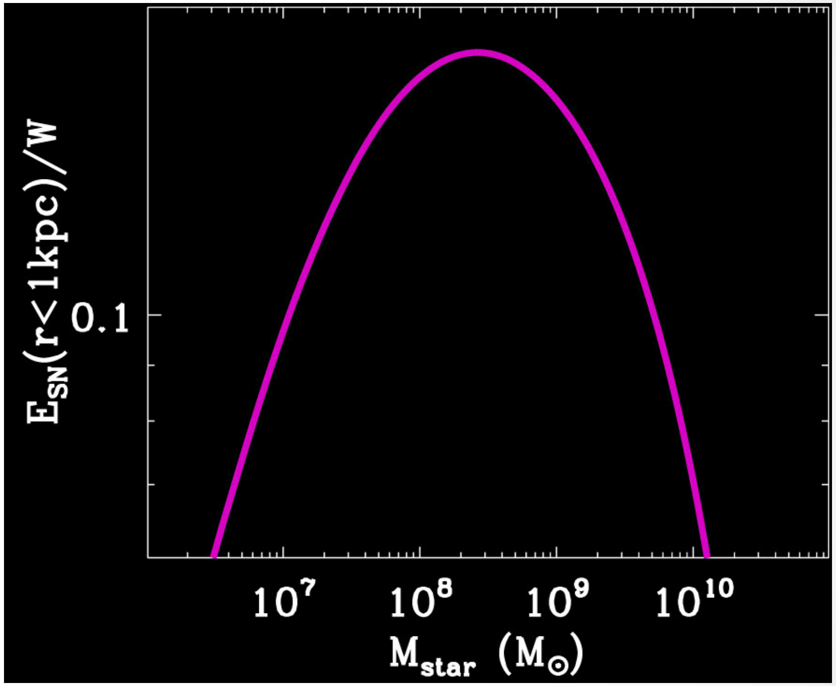
Review by
Bullock & MBK 2017

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

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



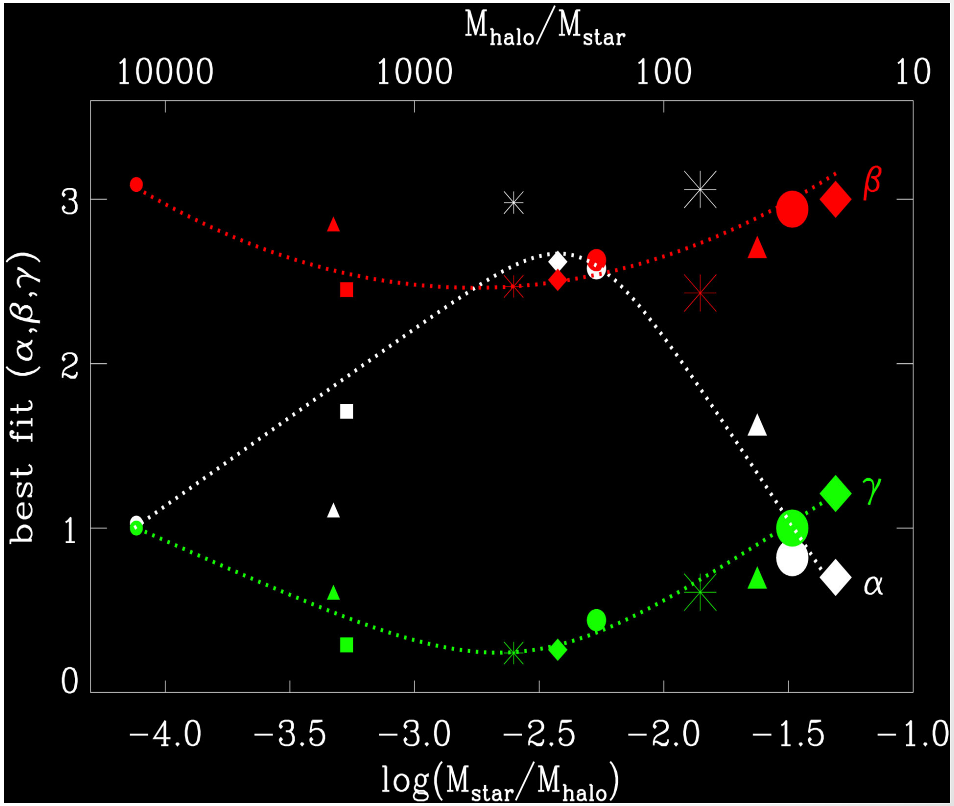
Energy balance between SNe energy and potential energy of NFW halo.
Flattest profiles expected at $M_{*} \sim 10^{8.5} M_{\odot}$.

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)

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



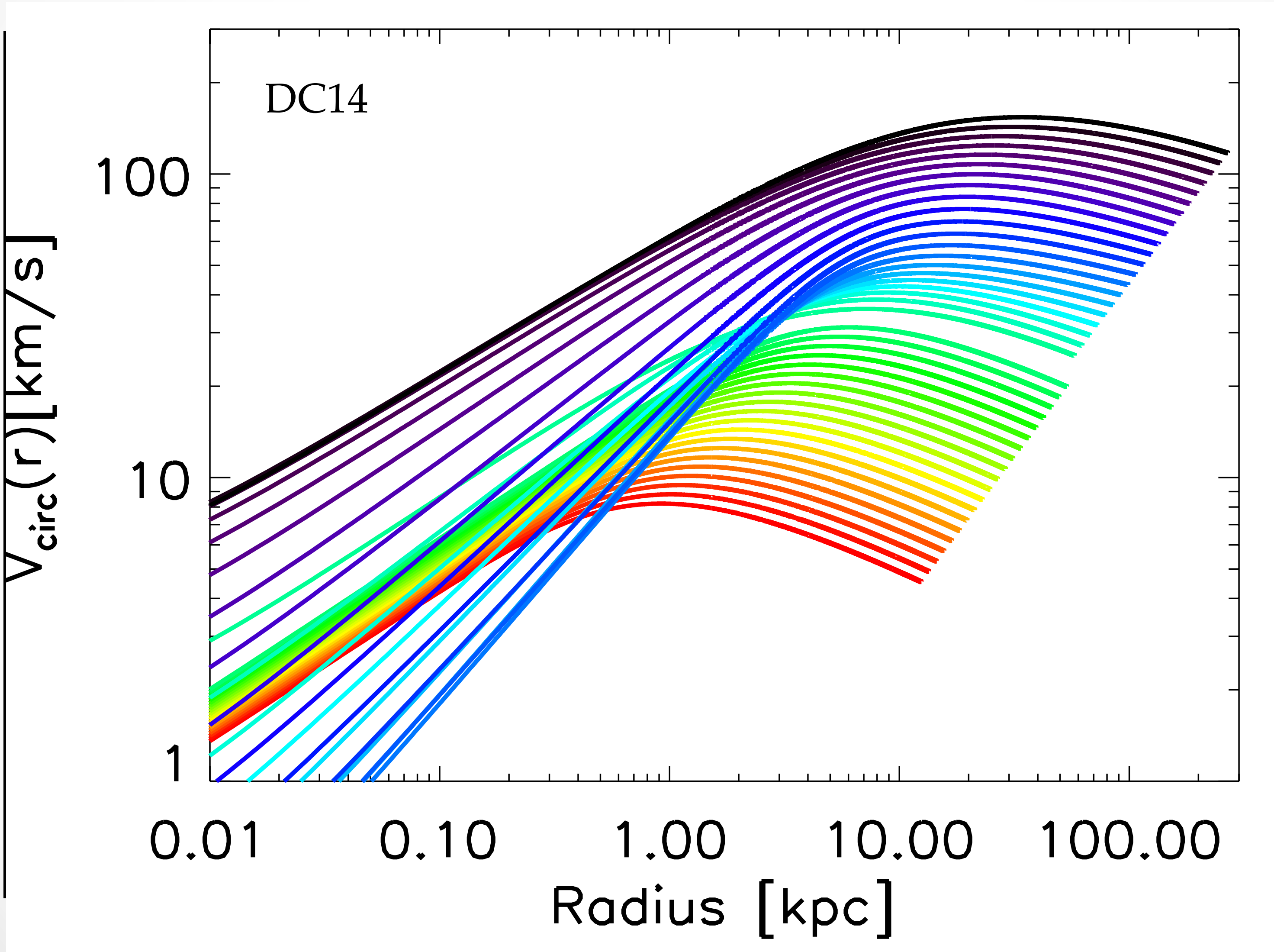
γ inner slope

β outer slope

α sharpness of transition

constrained via $X=\log_{10}(M_{\star}/M_{halo})$

From cusps to cores to cusps



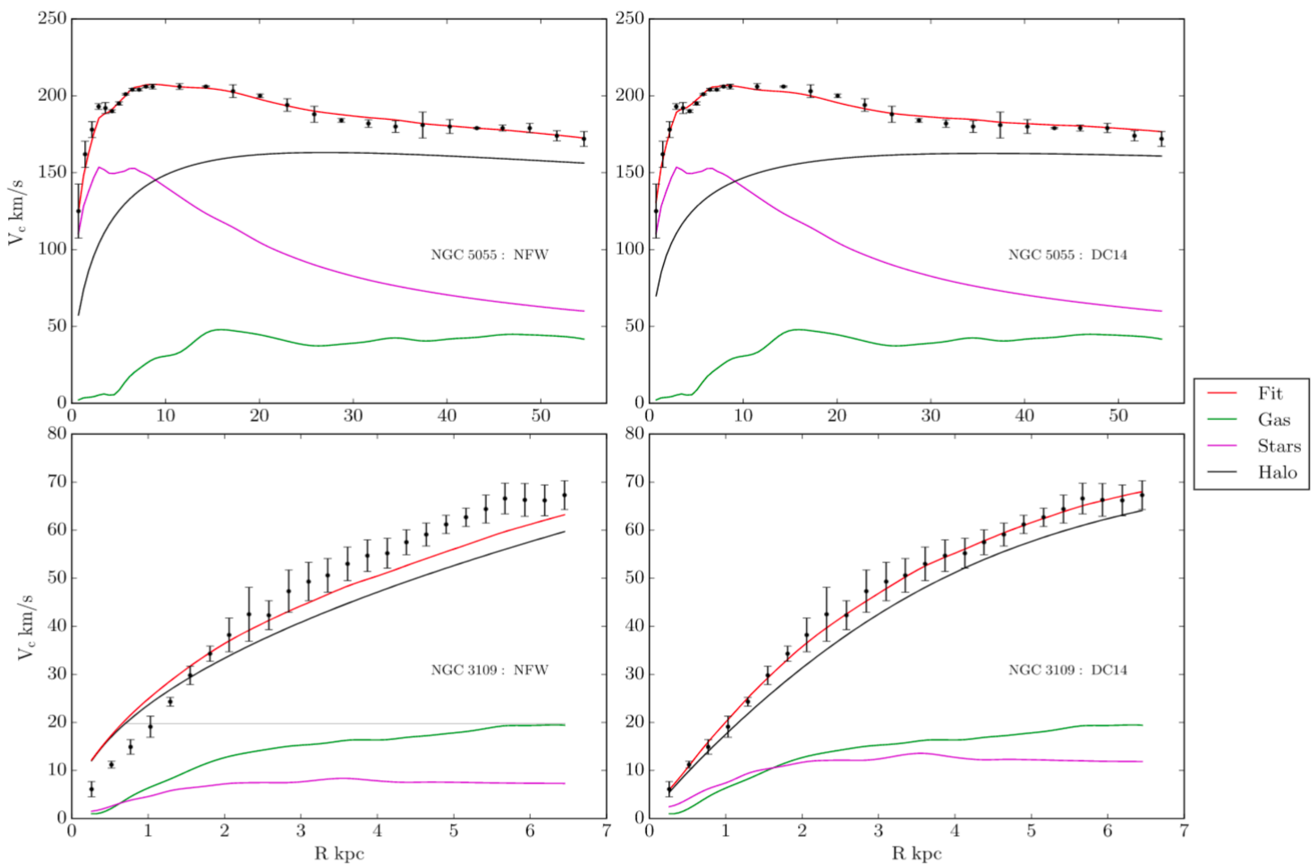
Di Cintio +14

Testing ΛCDM with observed RCs of galaxies

Take M* and V(r) from observations

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

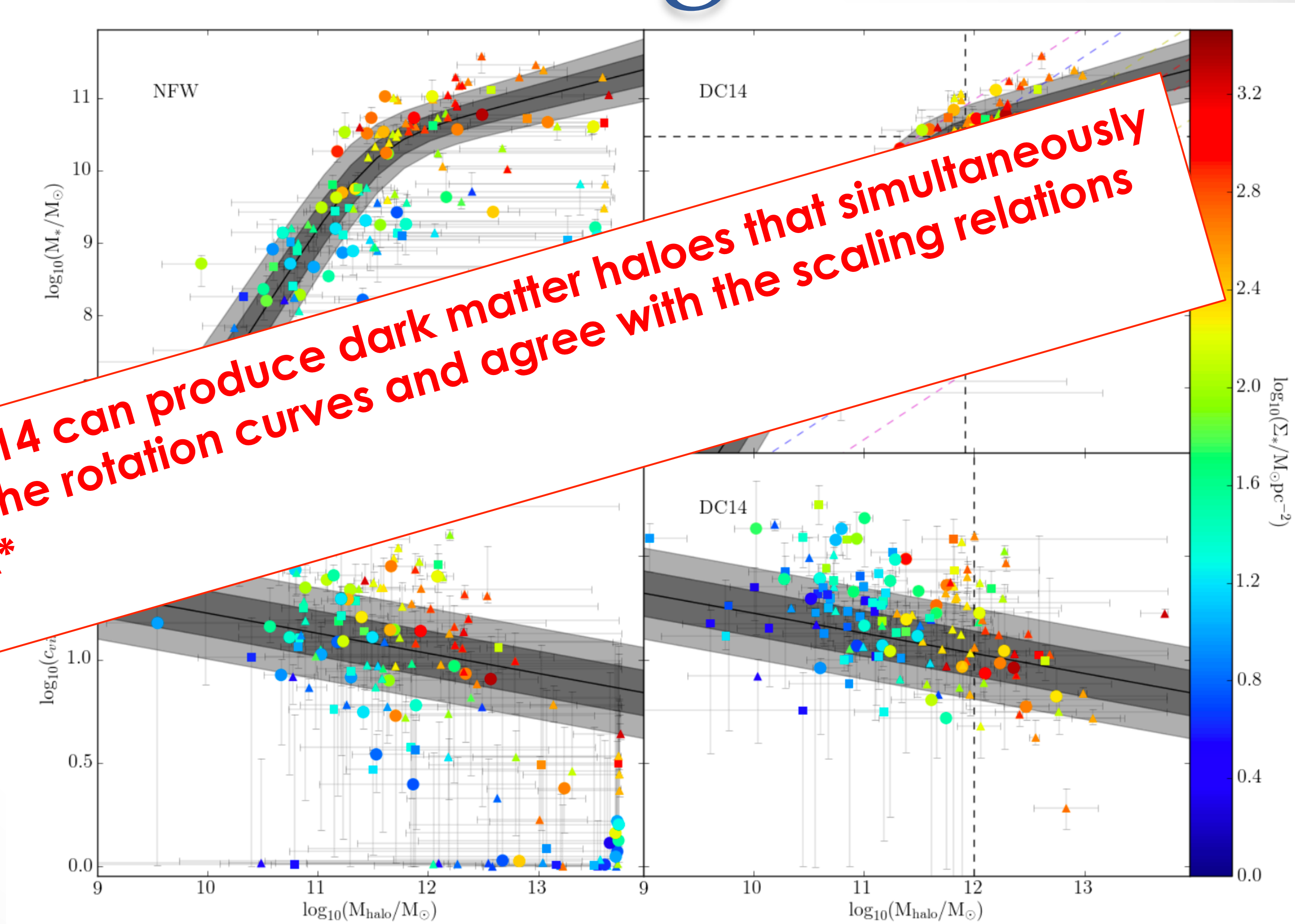


Katz, Lelli, McGaugh,Di Cintio, Brook, Schombert 2017

Testing ΛCDM with observed RCs of galaxies

We want to reproduce both observational relations and theoretical predictions :

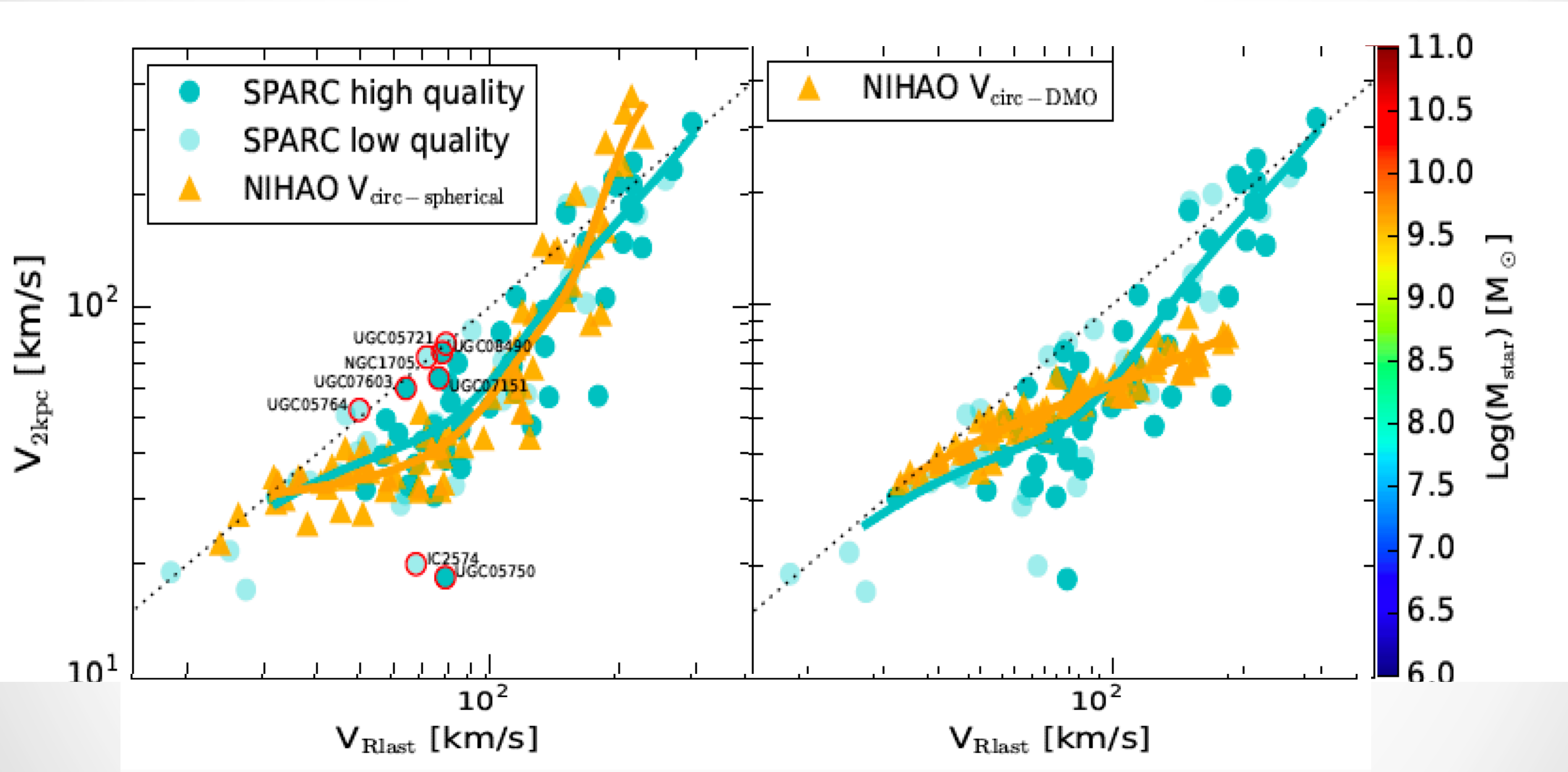
Take home point: DC14 can produce dark matter haloes that simultaneously provide good fits to the rotation curves and agree with the scaling relations C-M_{halo} and M_{halo}-M*



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

Mhalo-M*

Diversity of RC shapes explained by cores

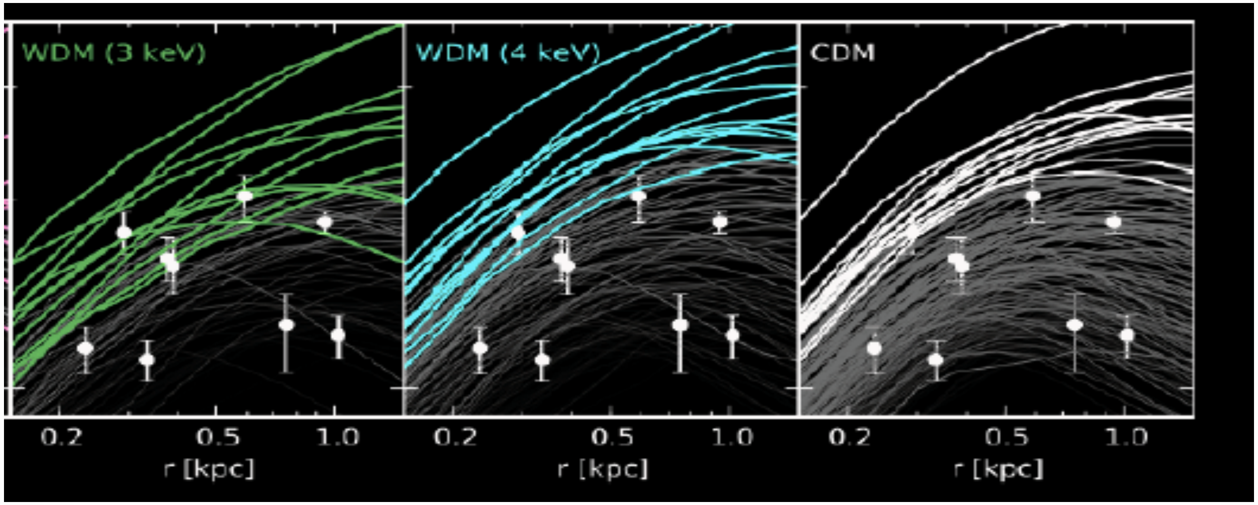


For DM cores not be "real', there must be some conspiracy for which observational errors mimic the presence of a DM core exactly in the range where we expect DM cores from theoretical models.

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)

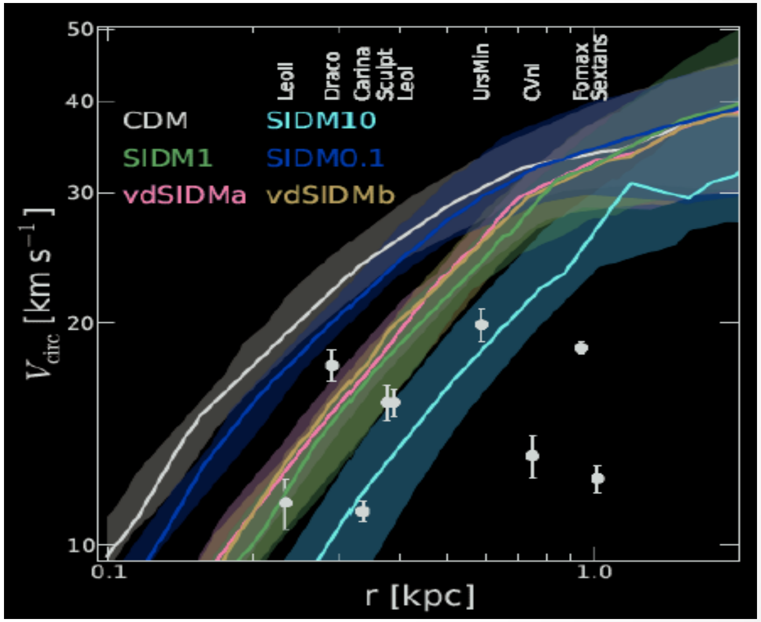
Solution #2: Alternative DM model

TBTF in Self Interacting Dark Matter

Self-interactions lower the central density alleviating the problem

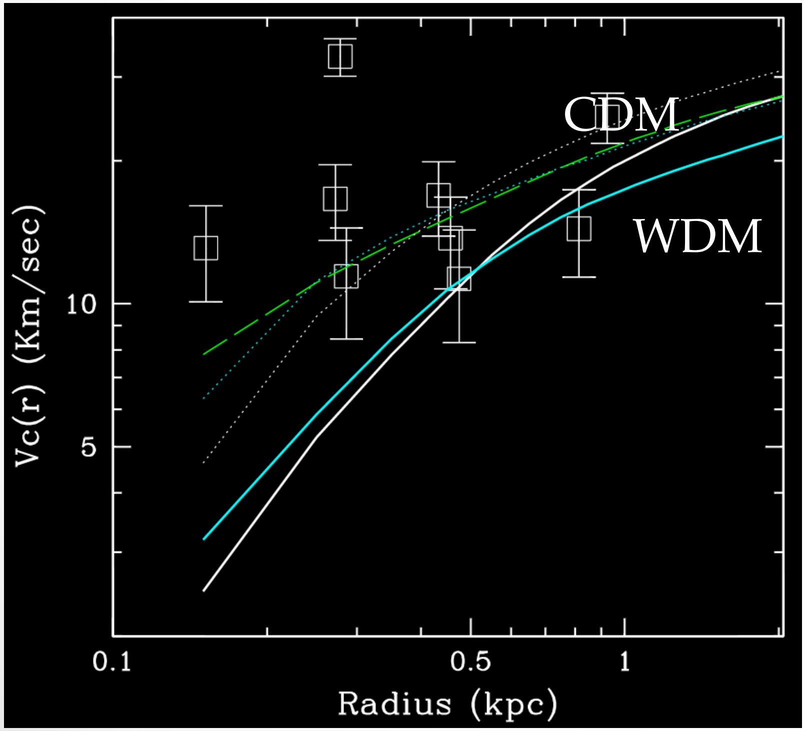
The cross section must be larger than 0.1 cm^2/gr

Vogelsberger+12, Zavala+13, Rocha+12

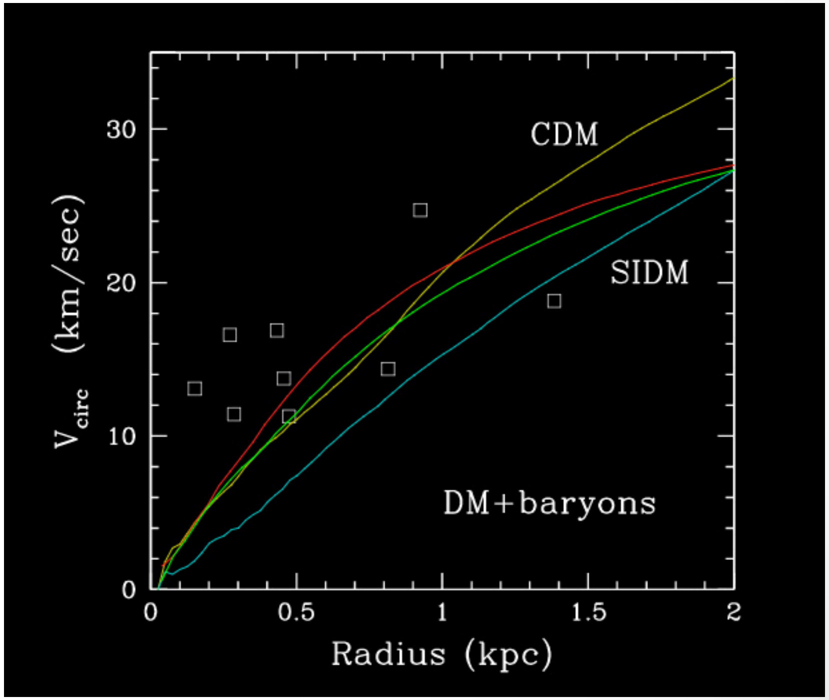


Solution #3: Alternative DM model + baryonic physics

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!

- How can we disentangle between different DM models?
- 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
- That would set a minimum cross section on SIDM of $\sigma \sim 2\ cm^2/gr$

Conclusions and future prospect

- 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
- Looking for cores in small dwarfs can help disentangle CDM from other DM types. Future Extremely Large Telescopes useful for this task: they will resolve stellar populations which allows for a better modelization of the inner density in dwarfs

Stay tuned..

Thanks for your attention!