Self-Interacting Dark Matter & Structure Formation (I)

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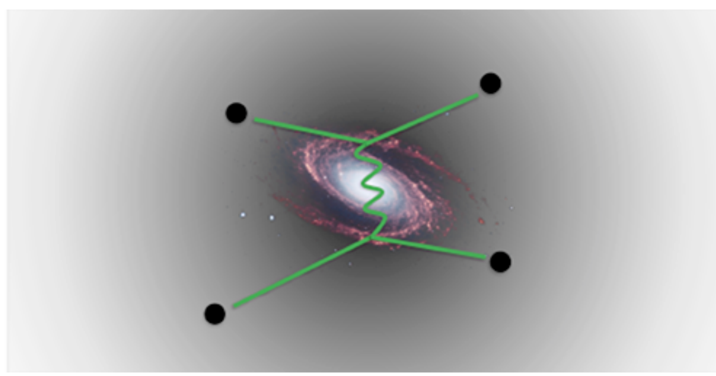
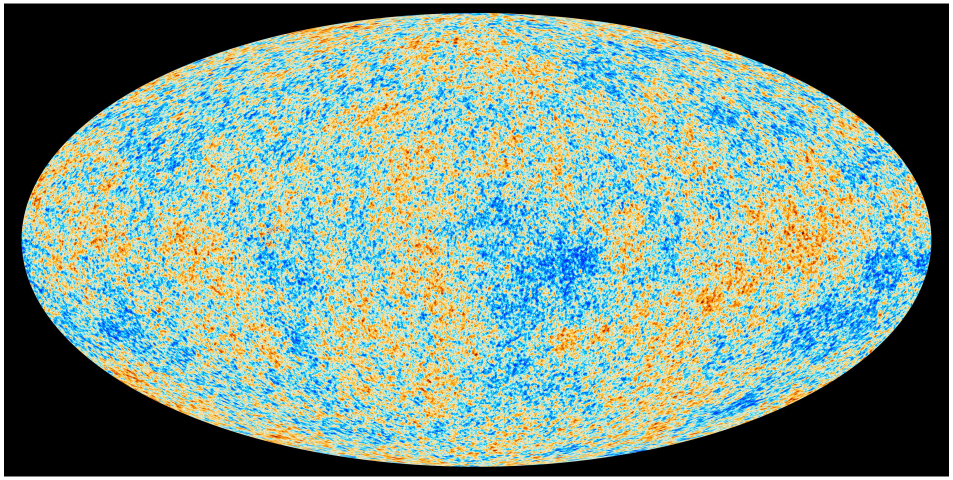
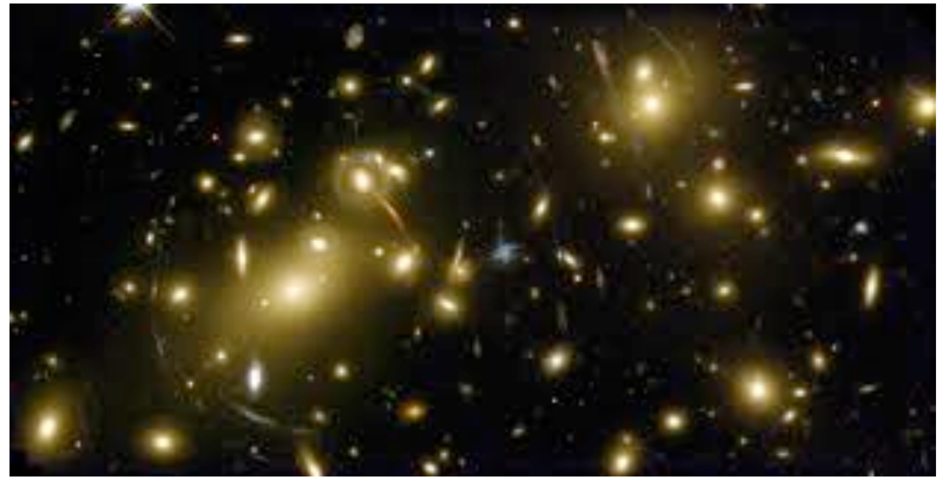


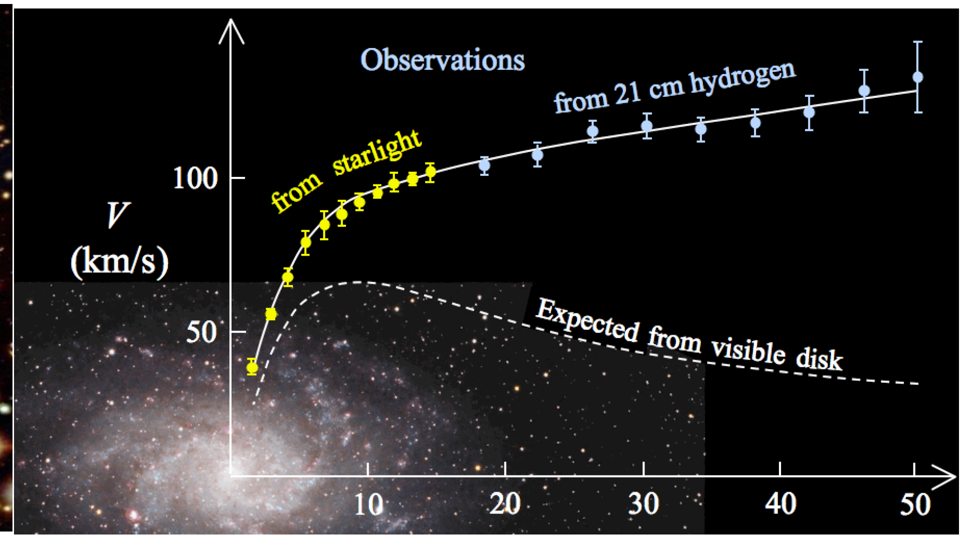
RESCEU Summer School, July 27-30, 2018

Review for Physics Reports: Tulin & HBY (2017)

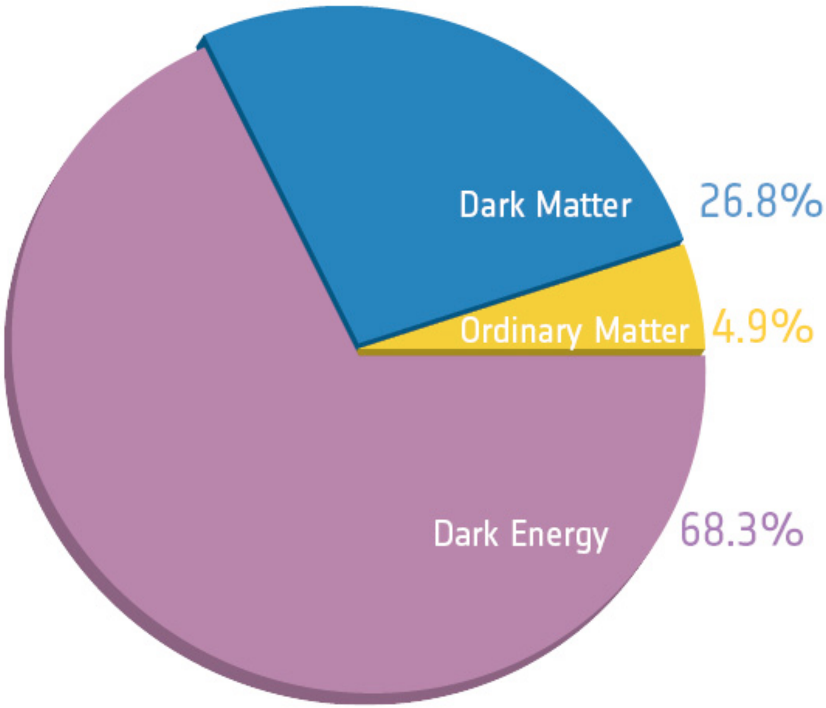
Dark Matter



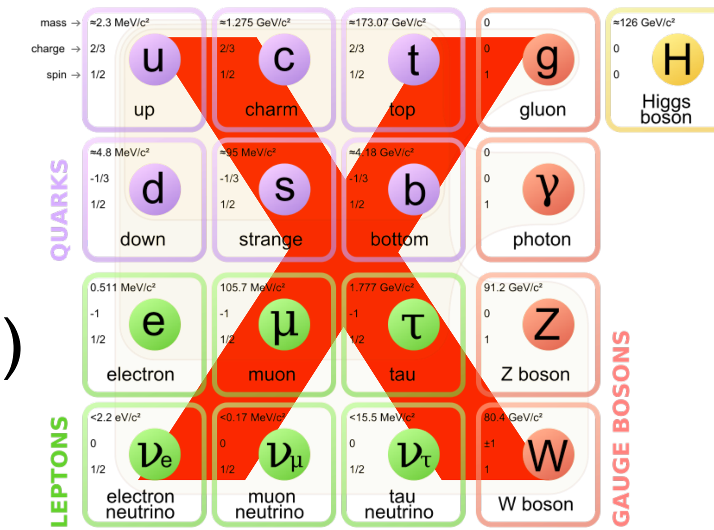


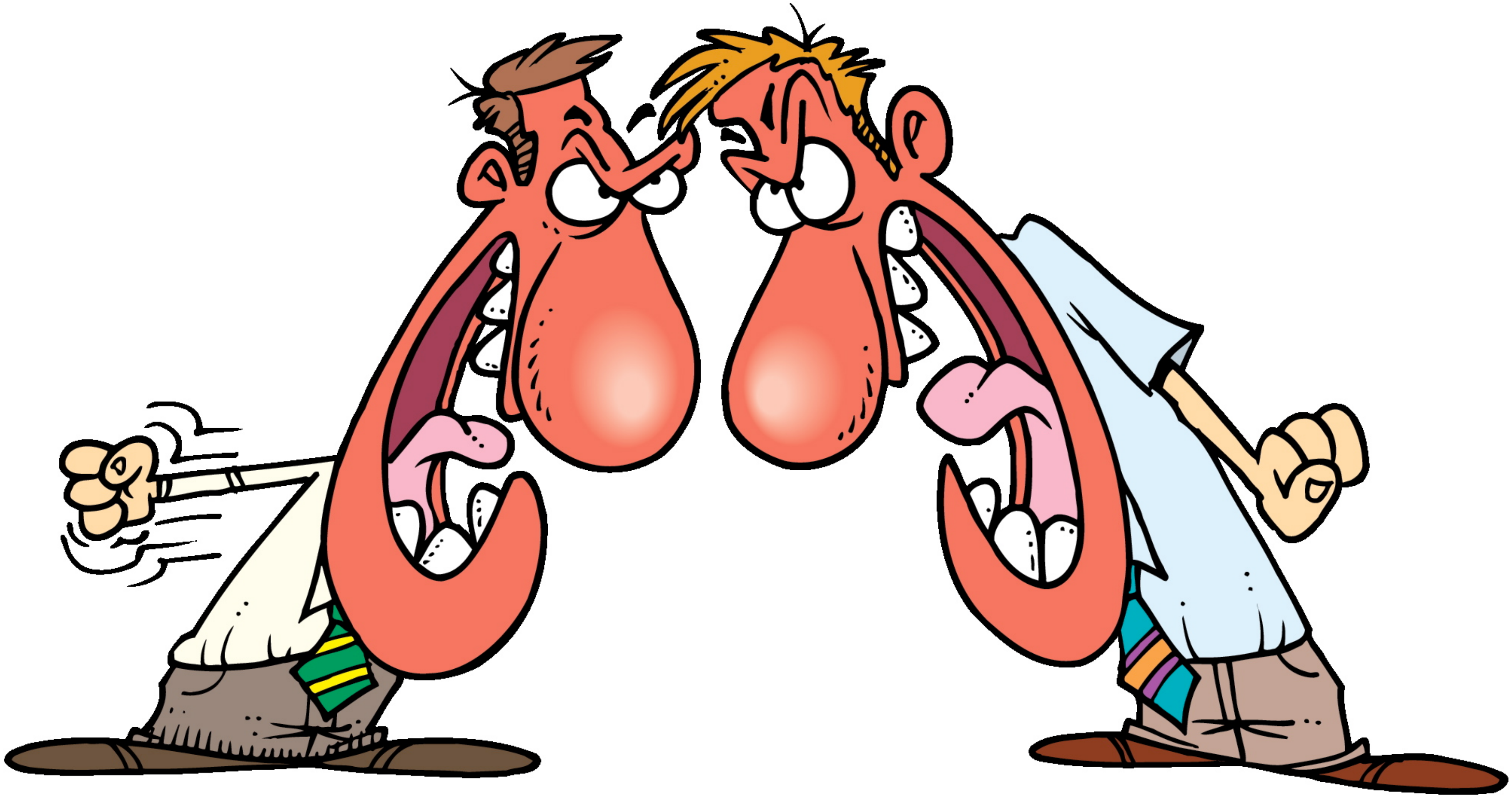

Observations
from 21 cm hydrogen
from starlight
100
V
(km/s)
50
Expected from visible disk
10
20
30
40
50

The Standard Model of Cosmology



dark
cold (warm)
long-lived

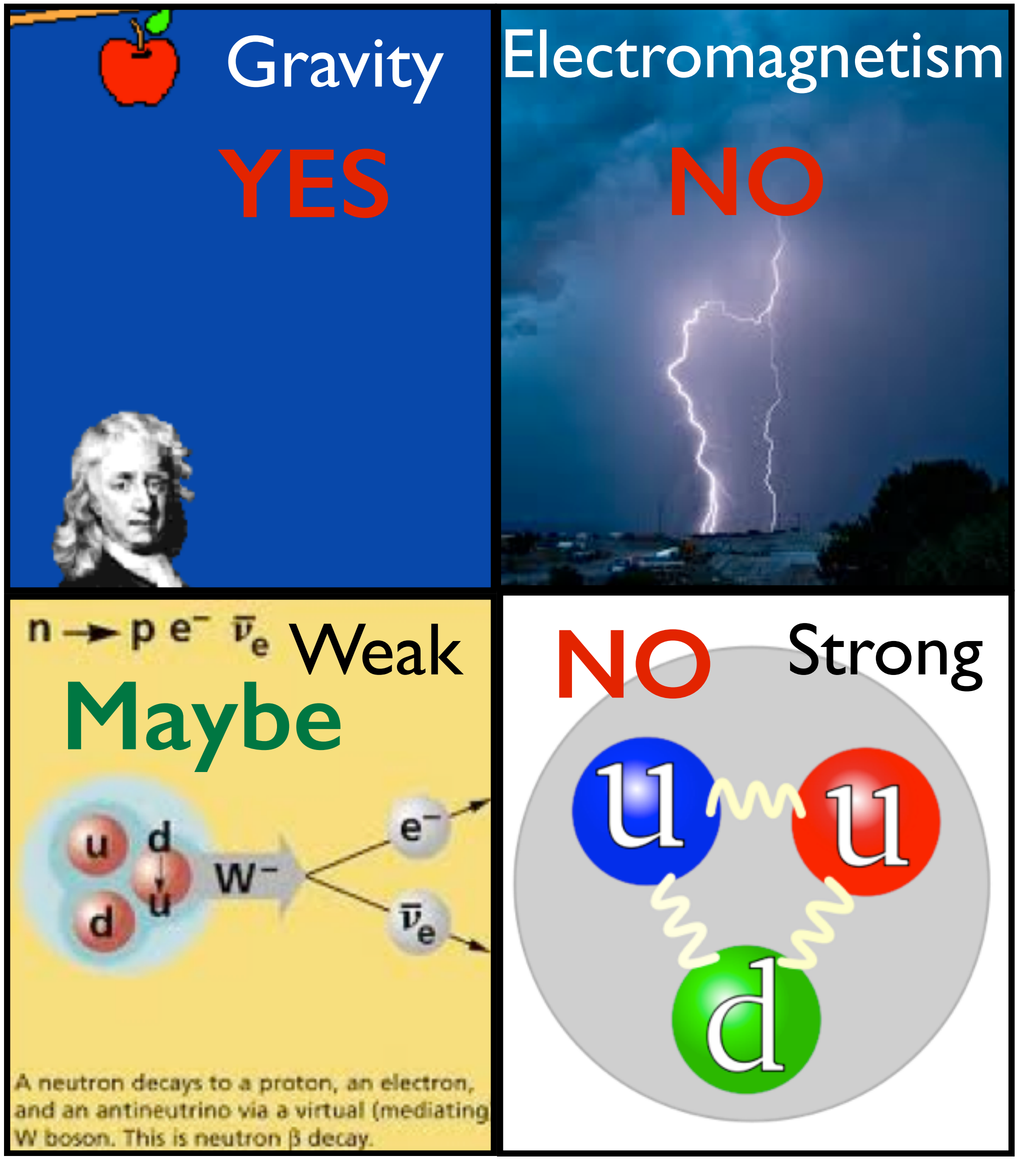




Standard model of modern cosmology

Standard model of modern particle physics

The WIMP Model



Dark matter candidate:

- Add a new massive particle X
- Interacts with us through the weak interaction

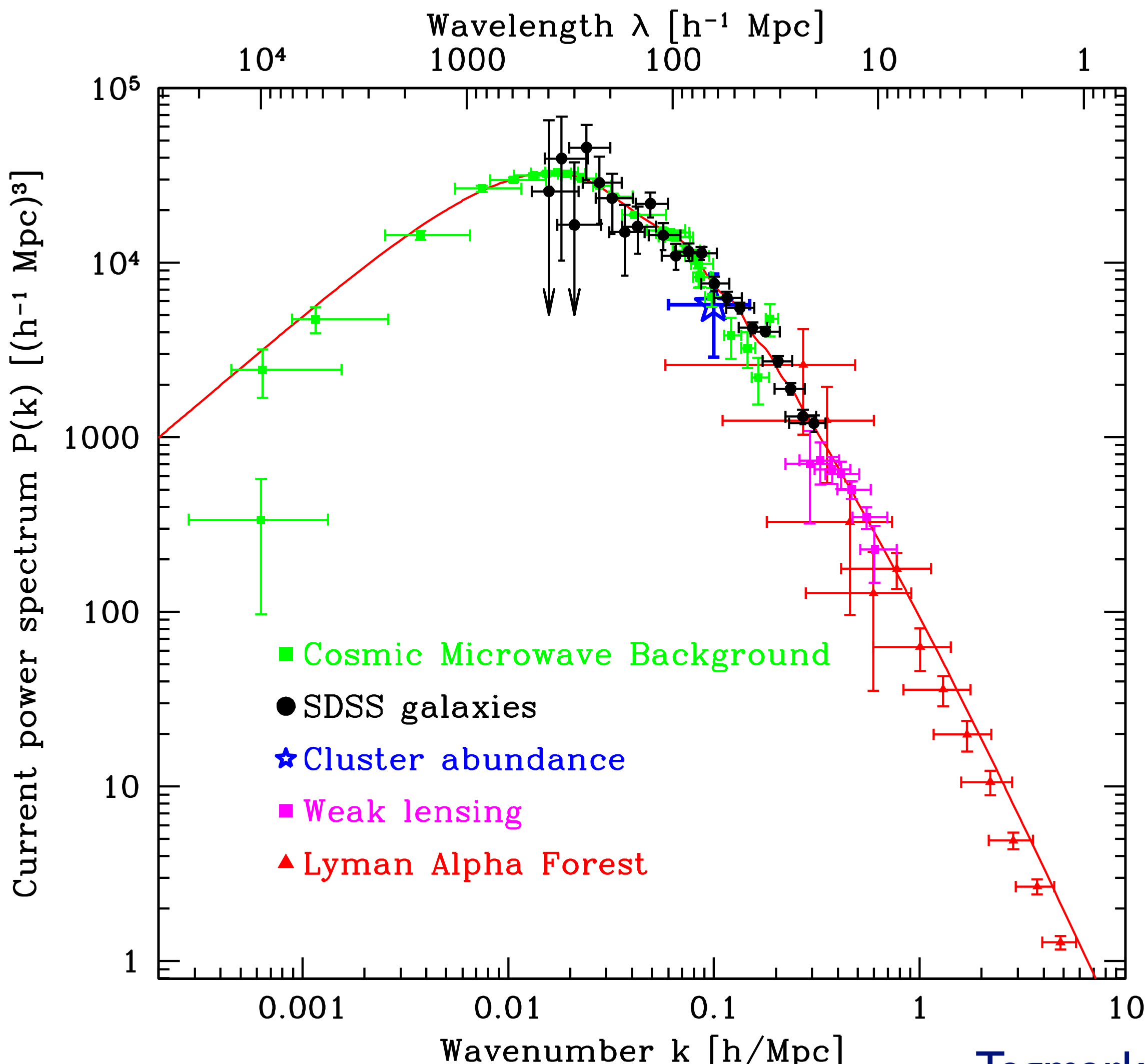
Weakly-Interacting Massive Particle (WIMP)

"WIMP Miracle"

The WIMP is a typical collisionless cold dark matter candidate

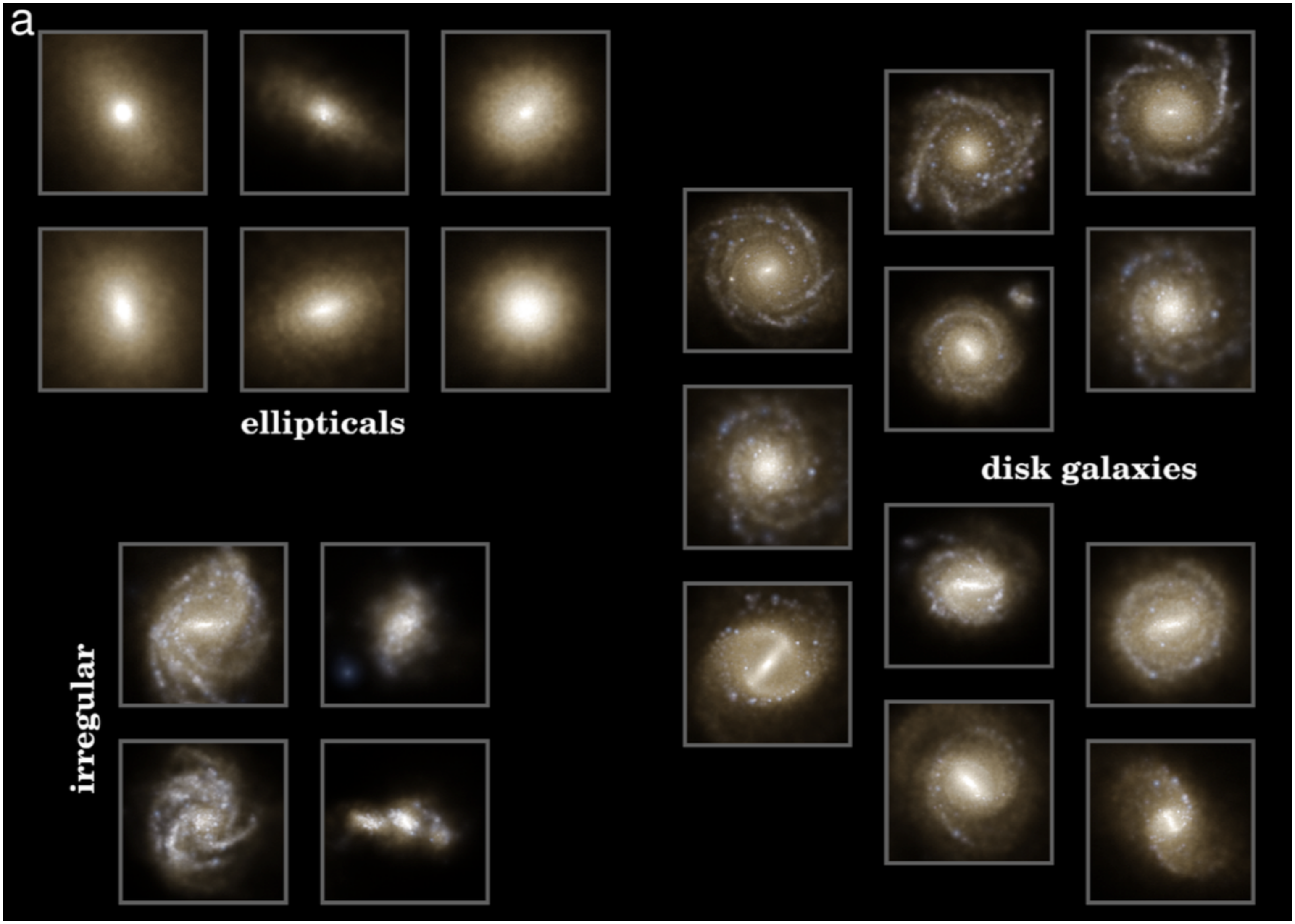
ΛCDM on Large Scales

- works very well, >O(100) kpc



Tegmark et al. (2004)

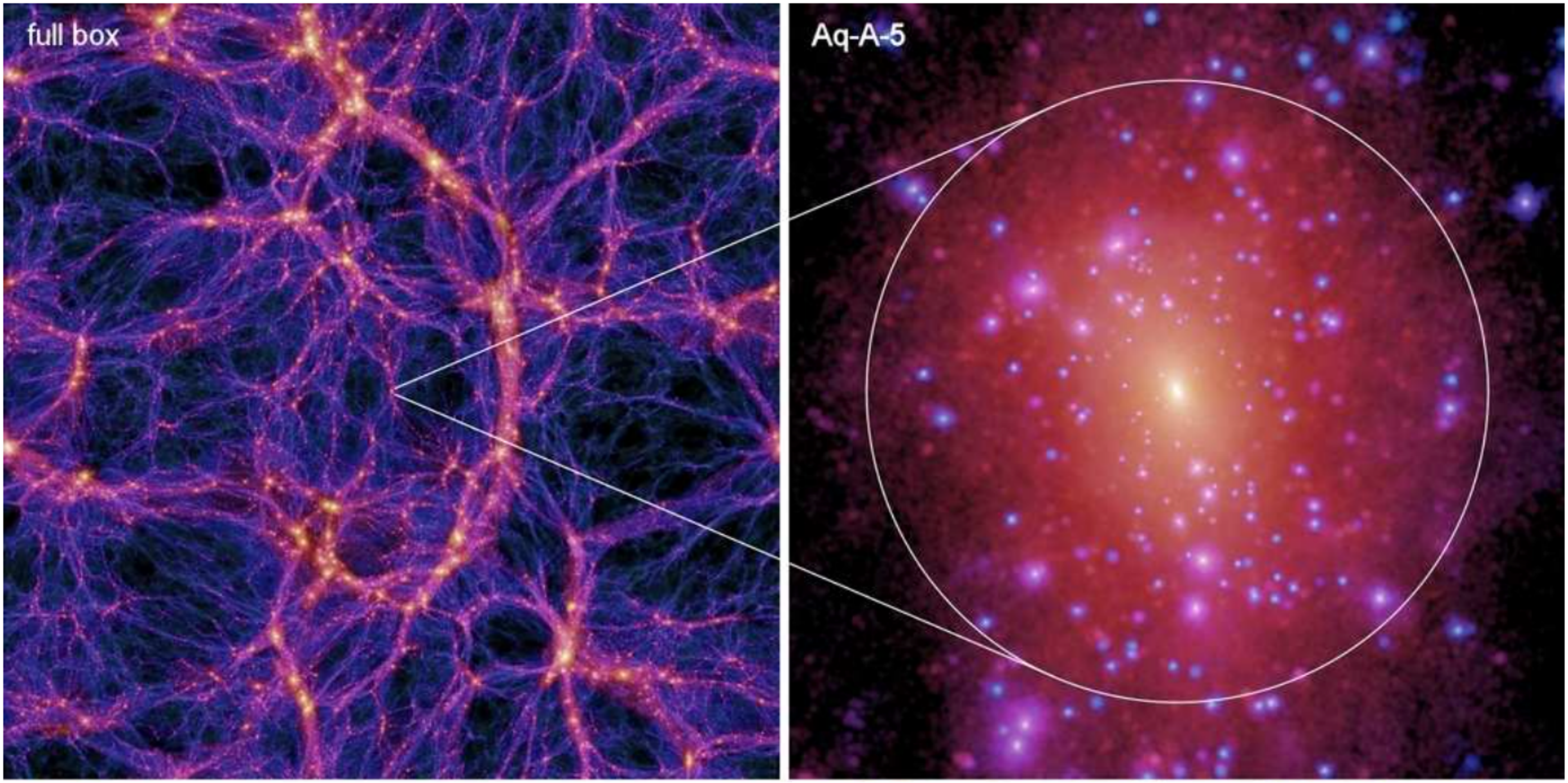
Overall Predictions on Galactic Scales



Illustris Project, Vogelsberger et al. (2014)

Produce a variety of galaxy types consistent with observations

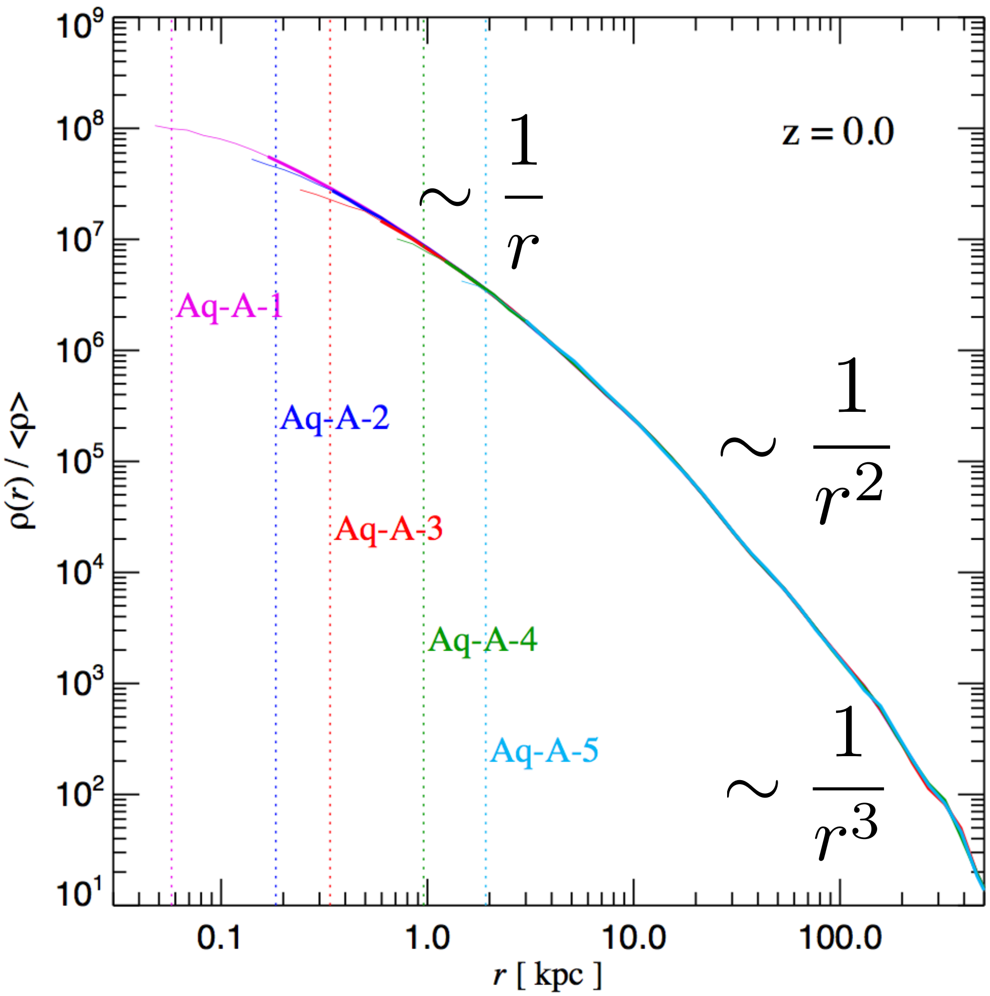
Detailed Predictions on Small Scales



Aquarius Project, Springel et al. (2008)

Rich substructure!

Universal Density Profile



Aquarius Project, Springel et al. (2008)

the Navarro-Frenk-White (NFW) profile (1996)

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

ρ_s and r_s are strong correlated

the concentration-mass relation

Specify a halo with one parameter+scatter

CDM-only cosmological simulations

Small-Scale Issues

- Crisis on small scales: galactic scales, <10-100 kpc

  Core vs. Cusp
  Diversity
  Missing Satellites
  Too-Big-To-Fail

- Solutions

  Observational issues

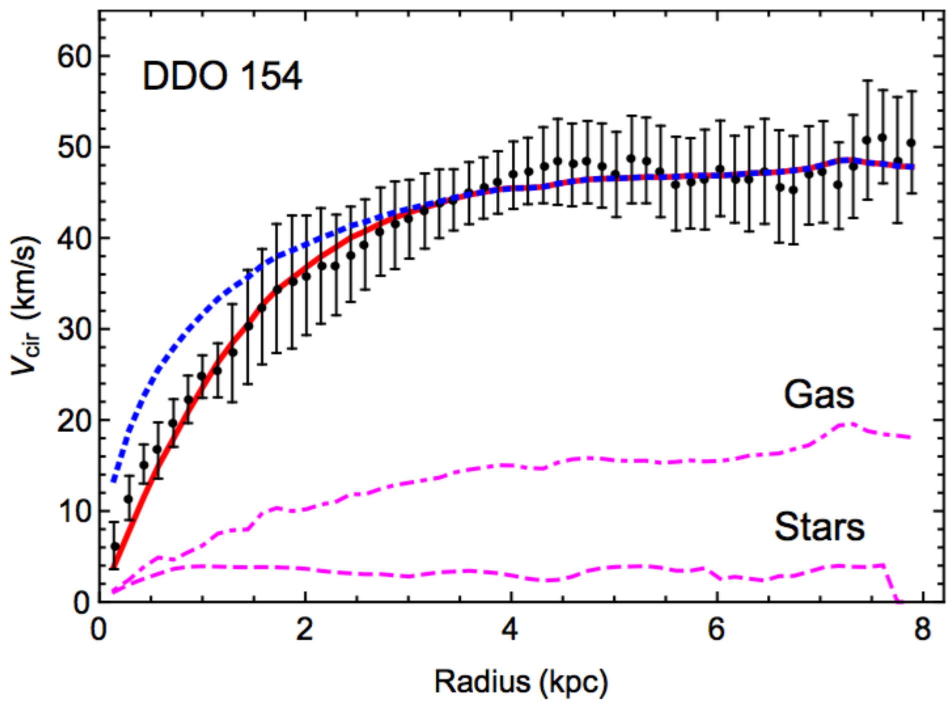
  Baryon physics

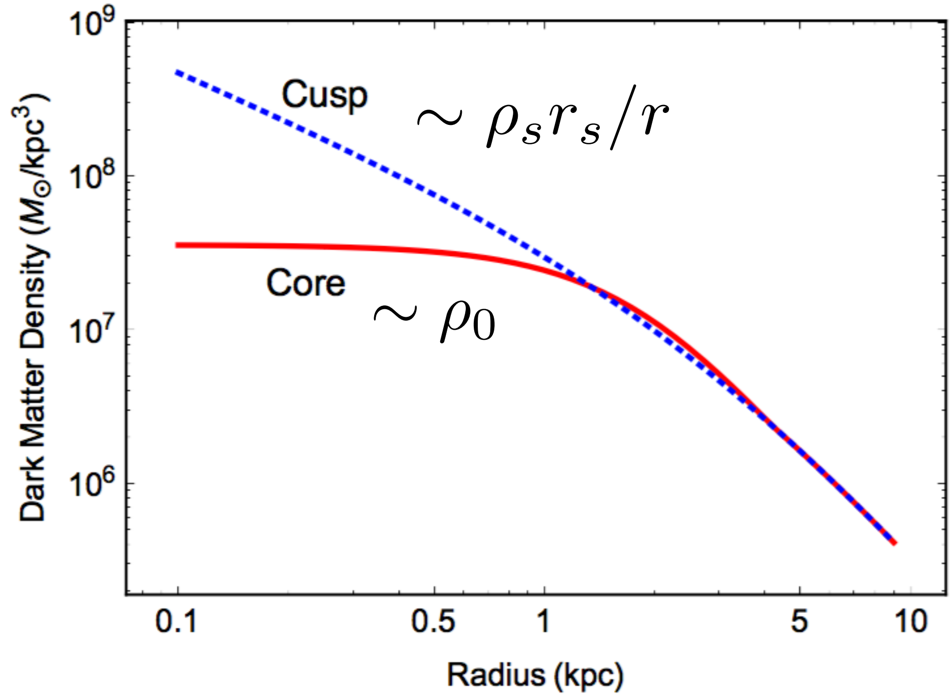
  New physics

see Tulin & HBY (2017) for a review

Core vs Cusp Problem

- DM-dominated systems (dwarfs, LSBs)





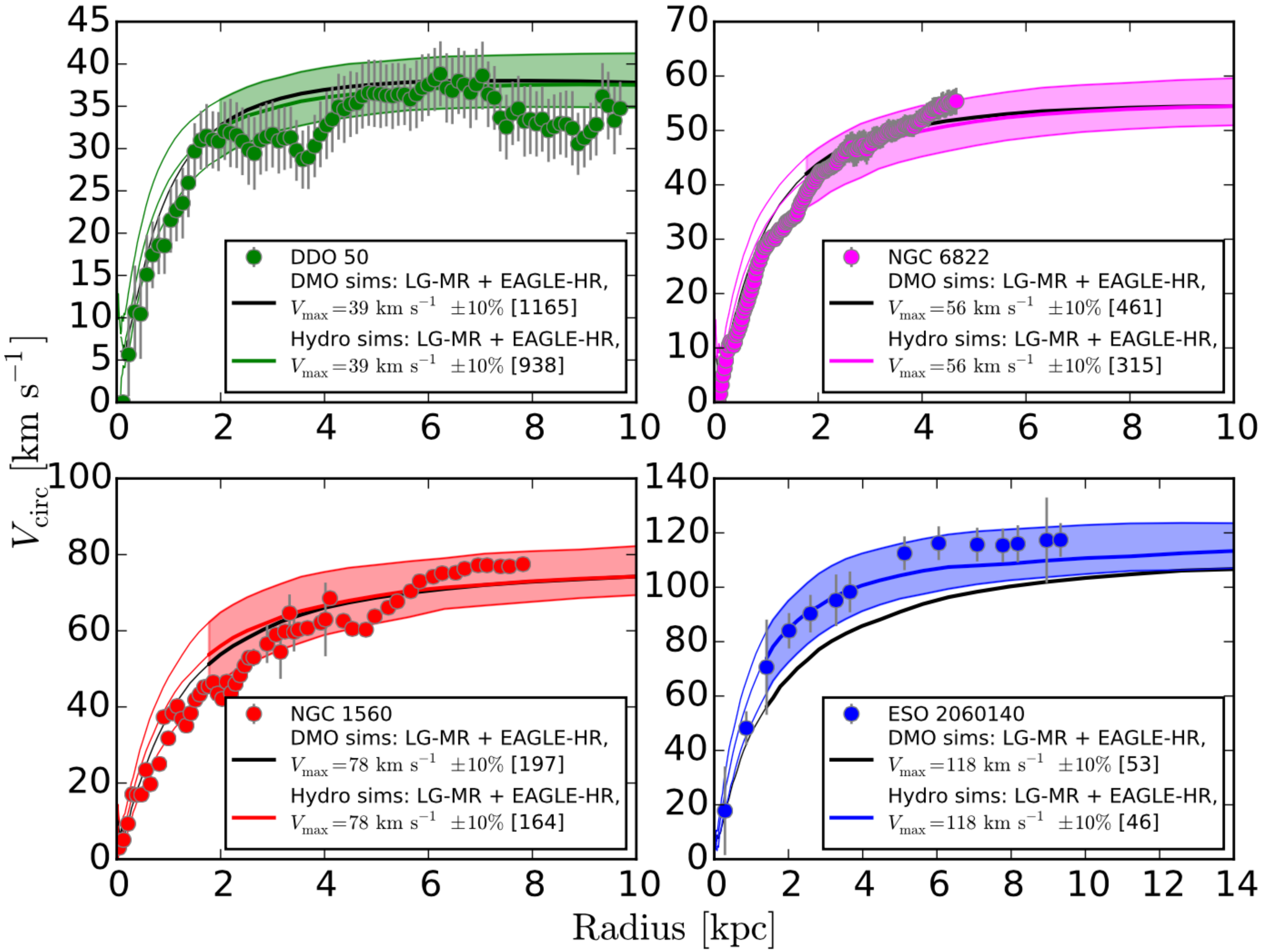
$$V_{\rm circ}(r) = \sqrt{V_{\rm halo}(r)^2 + \Upsilon_* V_{\rm star}(r)^2 + V_{\rm gas}(r)^2}$$

$$V_{\rm halo}(r) = \sqrt{G M_{\rm halo}(r)/r}$$

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

Flores, Primack (1994), Moore (1994)…

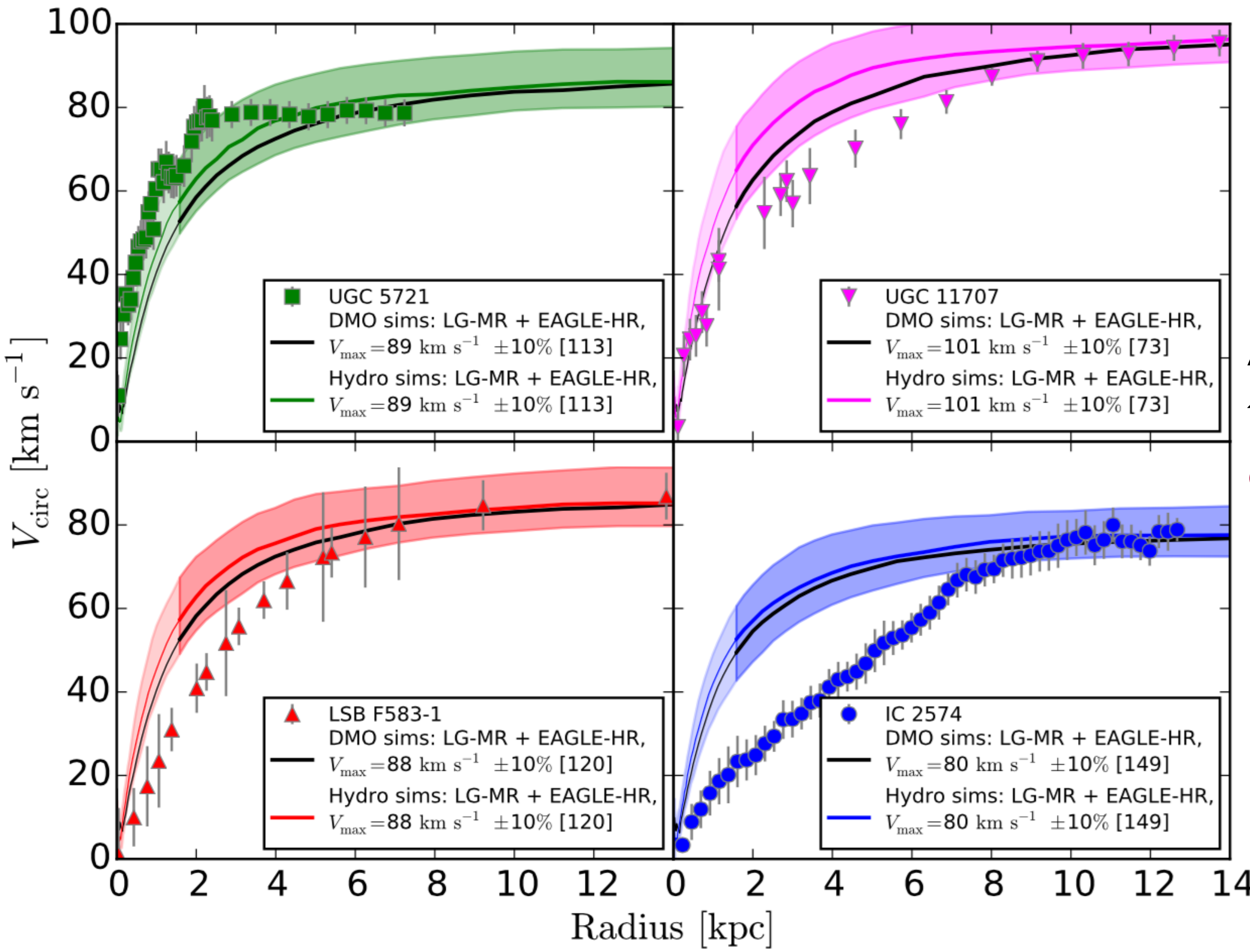
The Diversity Problem



Colored bands: hydrodynamical simulations of ΛCDM, "smooth/weak" baryonic feedback

Oman et al. (2015)

The Diversity Problem

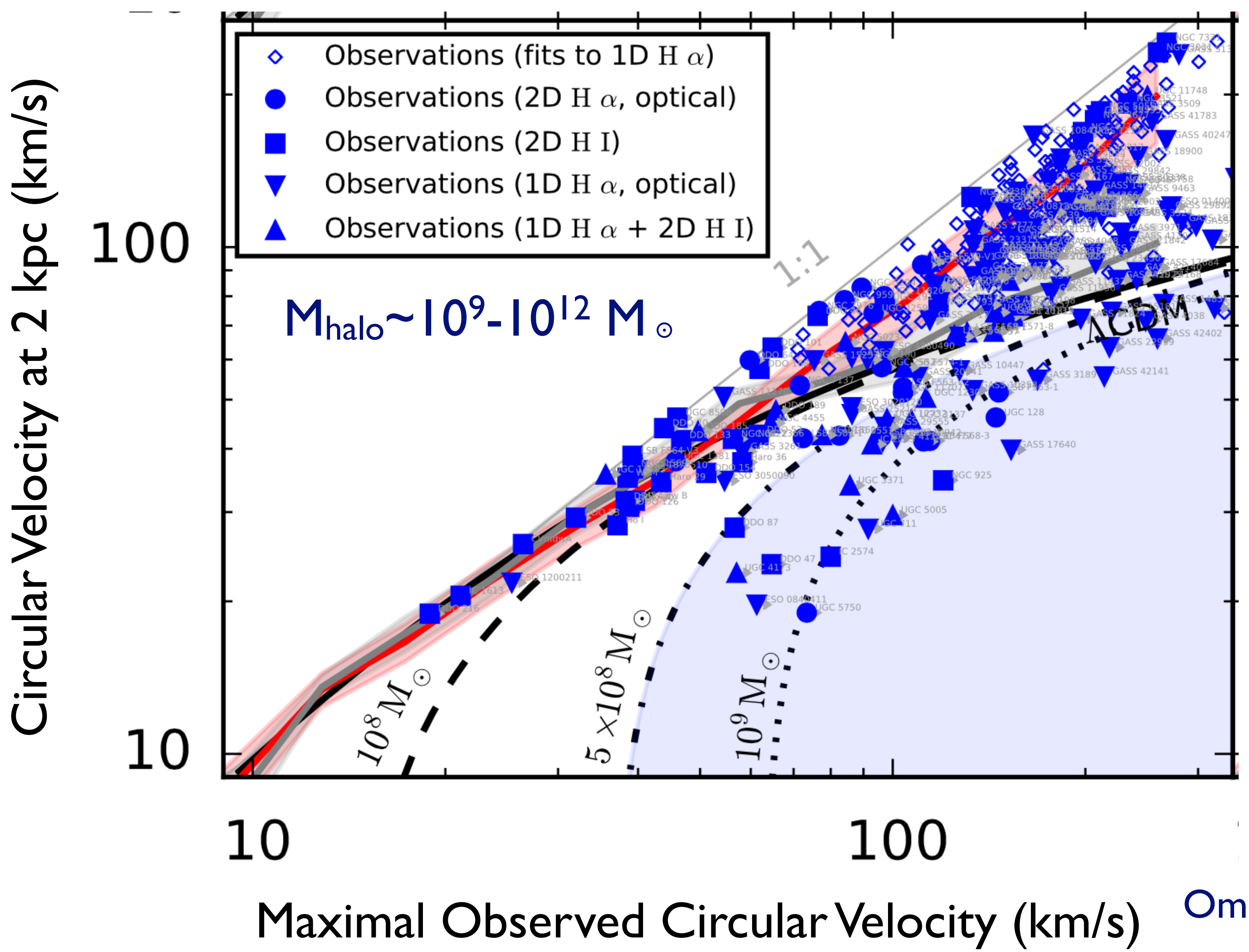


All galaxies have the same observed Vmax!

Oman et al. (2015)

Colored bands: hydrodynamical simulations of ΛCDM

A Big Challenge



Oman et al. (2015)

V_{circ}(2kpc) has a factor of ~4 scatter for fixed V_{max}

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 10 July 2015 (MN LaTeX style file v2.2)

The unexpected diversity of dwarf galaxy rotation curves

Kyle A. Oman[1,⋆], Julio F. Navarro[1,2], Azadeh Fattahi[1], Carlos S. Frenk[3], Till Sawala[3], Simon D. M. White[4], Richard Bower[3], Robert A. Crain[5], Michelle Furlong[3], Matthieu Schaller[3], Joop Schaye[6], Tom Theuns[3]
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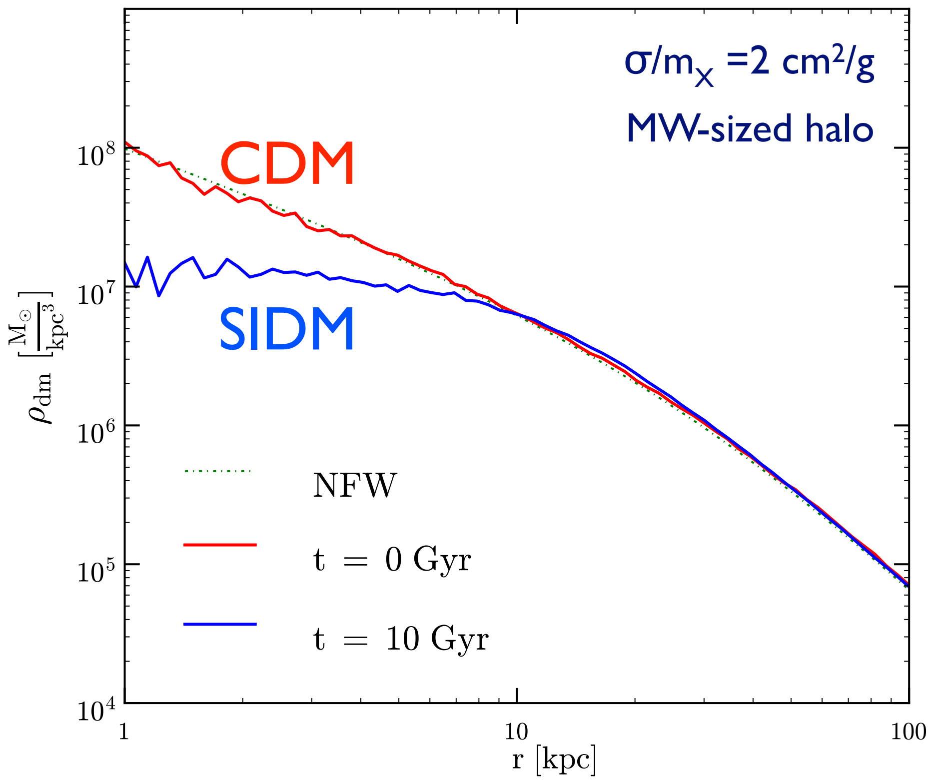
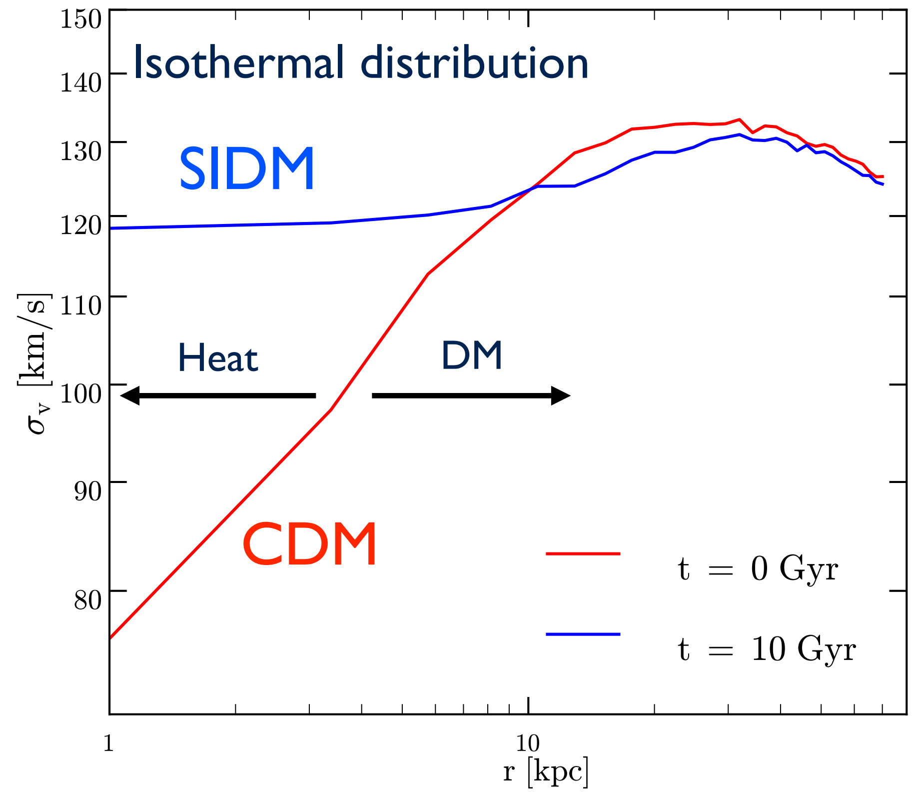
[5] *Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, 146 Brownlow Hill, Liverpool, L3 5RF, United Kingdom*
[6] *Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands*

The diversity is expected if dark matter has strong self-interactions

Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo, not the outer halo





$\sigma/m_X \sim 1\ cm^2/g$ (nuclear scale)

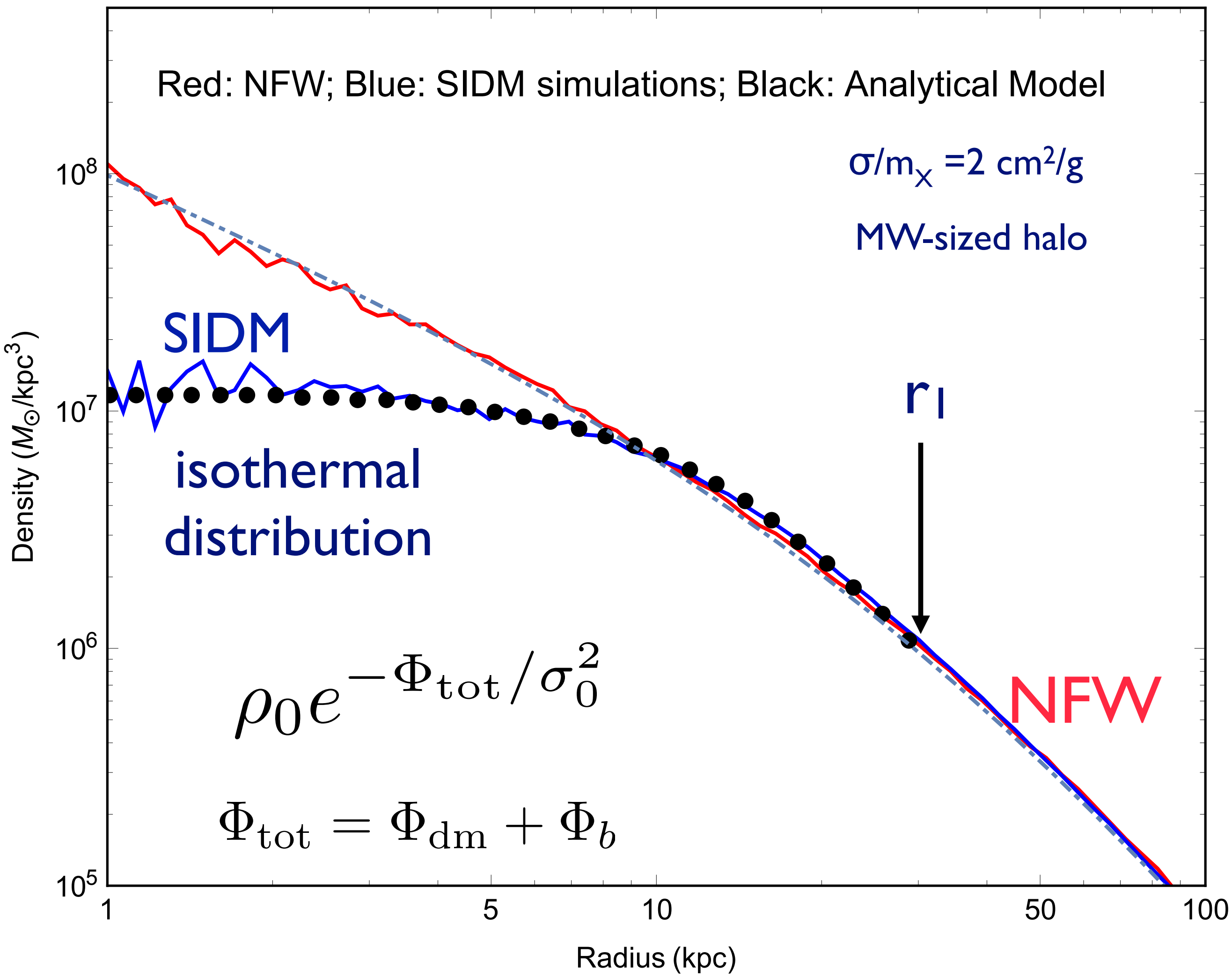
$$\Gamma \simeq n\sigma v = (\rho/m_X)\sigma v \sim H_0$$

Spergel & Steinhardt (PRL 1999)

From Ran Huo

see Tulin & HBY (2017) for a review

Modelling SIDM Halos



$$\nabla^2 \Phi_{\rm tot} = 4\pi G(\rho_{\rm dm} + \rho_b)$$

Ideal gas: PV=nRT

$$\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1)\, t_{\rm age} \approx 1$$

$$\rho(r) = \begin{cases} \rho_{\rm iso}(r)\,, & r < r_1 \\ \rho_{\rm NFW}(r)\,, & r > r_1 \end{cases}$$

Matching conditions:

$$\rho_{\rm iso}(r_1) = \rho_{\rm NFW}(r_1)$$
$$M_{\rm iso}(r_1) = M_{\rm NFW}(r_1)$$

$$(\rho_0, \sigma_0) \leftrightarrow (\rho_s, r_s)$$

with Kaplinghat, Keeley, Linden (PRL 2013)
with Kaplinghat, Tulin (PRL 2015)
with Kamada, Kaplinghat, Pace (PRL 2016)

Modelling SIDM Halos

$$\rho_{\rm iso}(R,z) = \rho_0 \exp\left(\left[\Phi_{\rm tot}(0,0) - \Phi_{\rm tot}(R,z)\right]/\sigma_{\rm v0}^2\right)$$

$$\nabla^2 \Phi_{\rm tot}(R,z) = 4\pi G[\rho_{\rm iso}(R,z) + \rho_{\rm b}(R,z)]$$

$$\rho_{\rm b}(R,z) = \Sigma_0 \exp(-R/R_{\rm d})\delta(z)$$

Scale radius

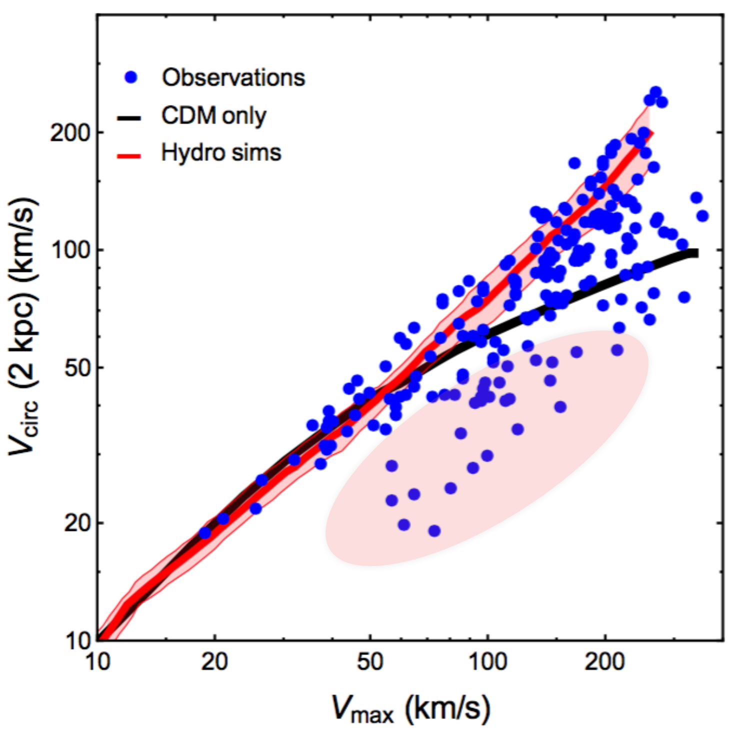
Surface density of the stellar distribution

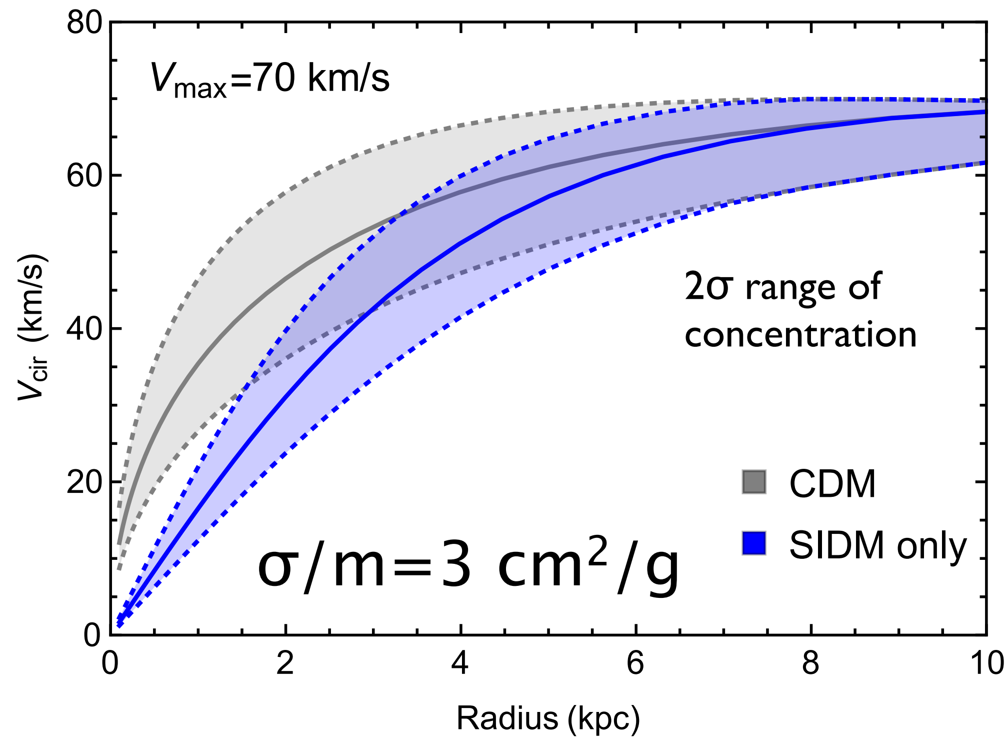
Numerical templates based on the two dimensionless parameters $a \equiv 8\pi G\rho_0 R_{\rm d}^2/(2\sigma_{\rm v0}^2)$ and $b \equiv 8\pi G\Sigma_0 R_{\rm d}/(2\sigma_{\rm v0}^2)$

with Kamada, Kaplinghat, Pace (PRL 2016)

Addressing the Diversity Problem

- DM self-interactions thermalize the inner halo





DM-dominated galaxies: Lower the central density and the circular velocity

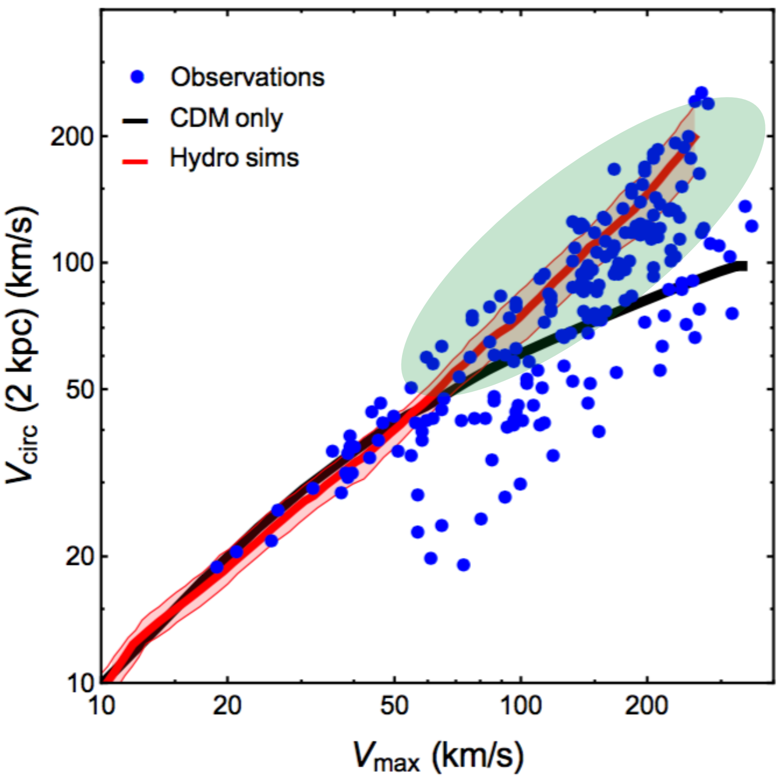
Isothermal distribution

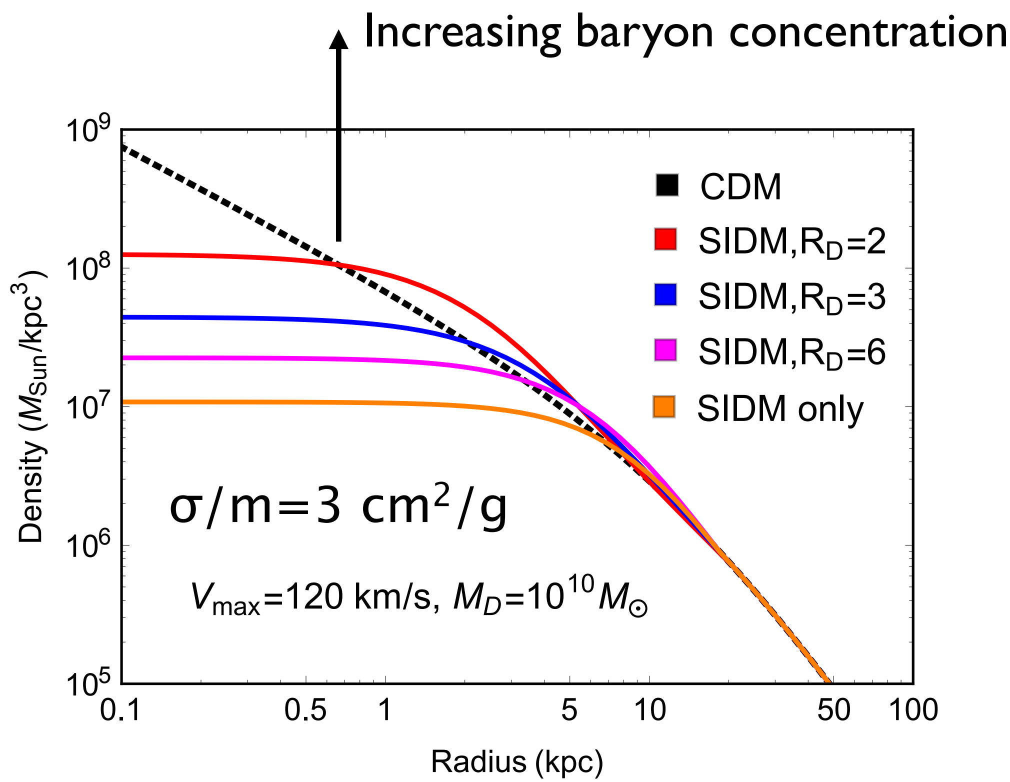
$$\rho_X \sim e^{-\Phi_{tot}/\sigma_0^2} \sim e^{-\Phi_X/\sigma_0^2}$$

with Kamada, Kaplinghat, Pace (PRL 2016)

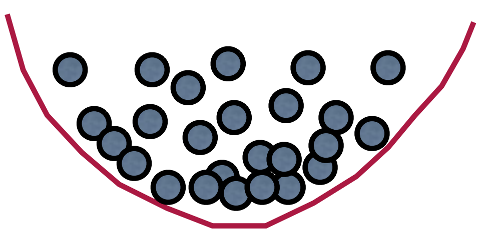
Addressing the Diversity Problem

- DM self-interactions tie DM together with baryons





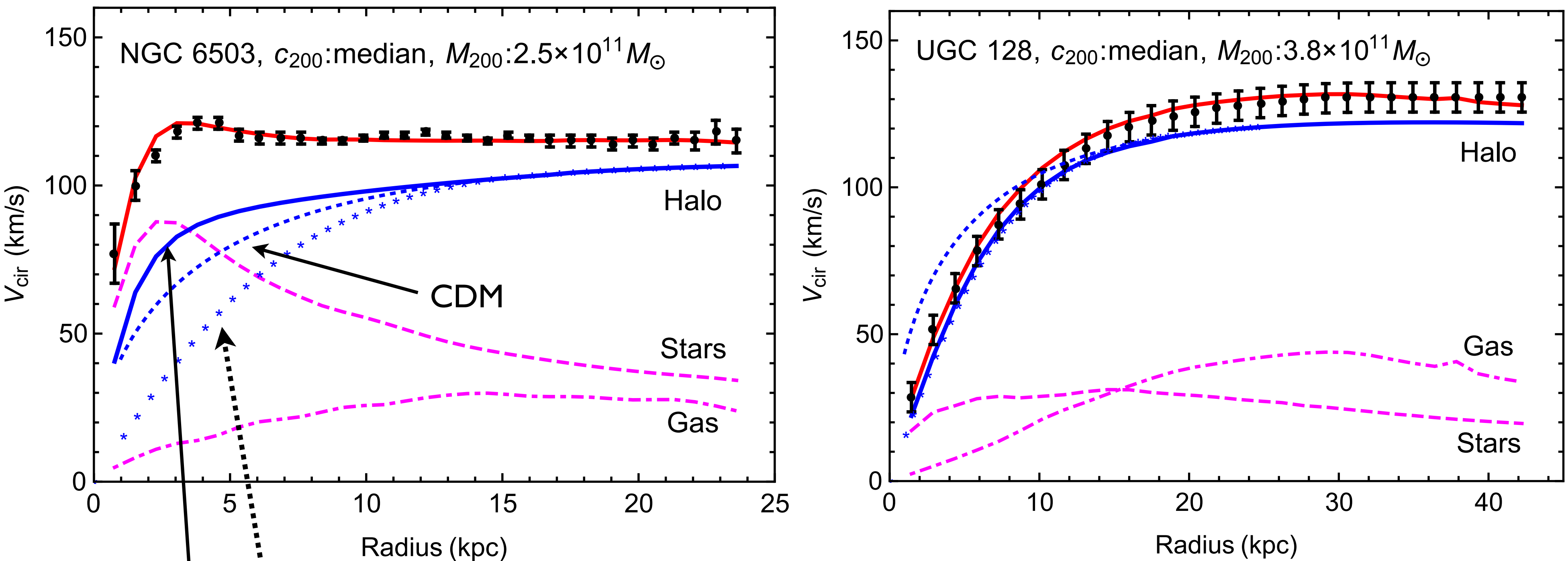
Thermalization leads to higher DM density due to the baryonic influence



$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_0^2} \sim e^{-\Phi_{\rm B}/\sigma_0^2}$$

with Kamada, Kaplinghat, Pace (PRL 2016)

Solving the Diversity Problem



Isothermal profile without the baryonic influence

True SIDM profile with the baryonic influence

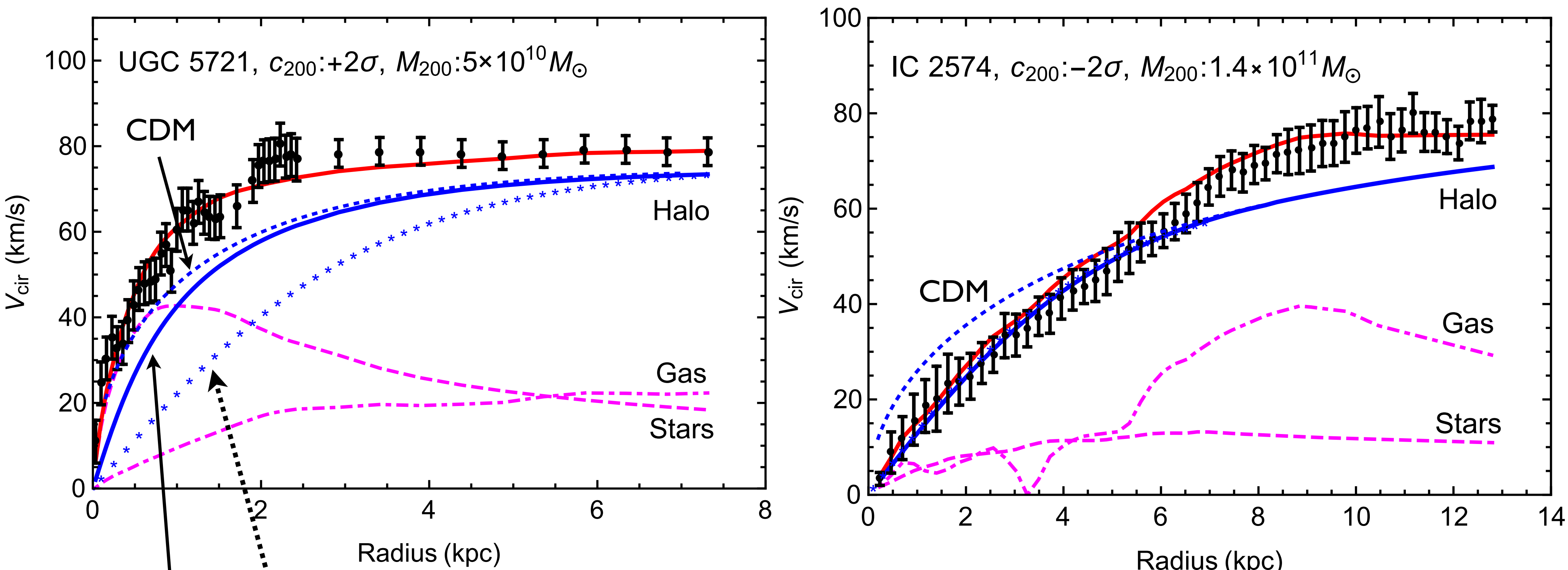
Different baryon distributions, thermalization links DM to baryon distributions

High surface brightness galaxies (NGC 6503): small and dense core
Low surface brightness galaxies (UGC 128): large and shallow core

30 galaxies V_{max}~25-300 km/s

with Kamada, Kaplinghat, Pace (PRL, 2016)

Solving the Diversity Problem

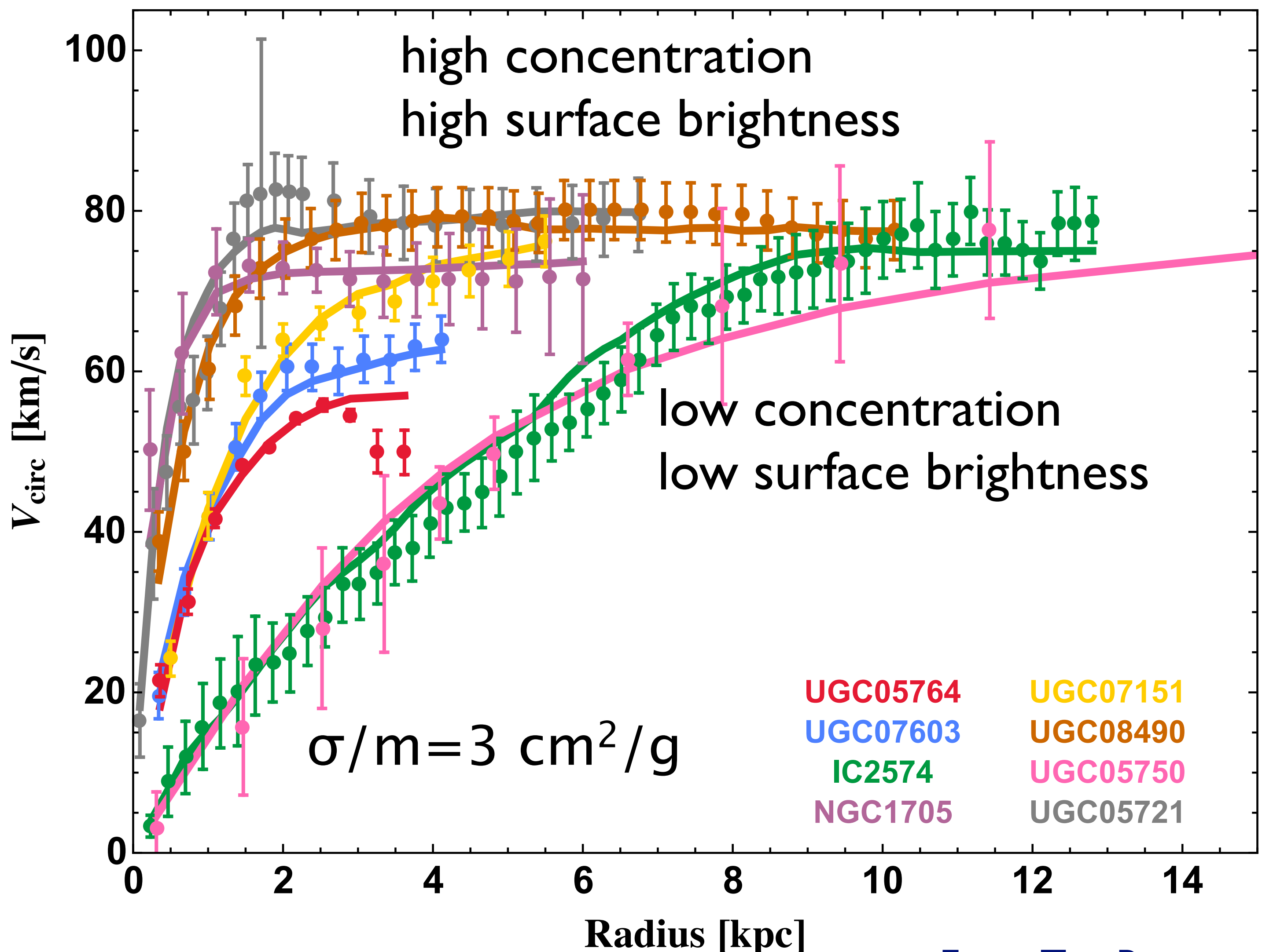


Isothermal profile without the baryonic influence

True SIDM profile with the baryonic influence

Scatter in the halo concentration-mass relation

with Kamada, Kaplinghat, Pace (PRL, 2016)

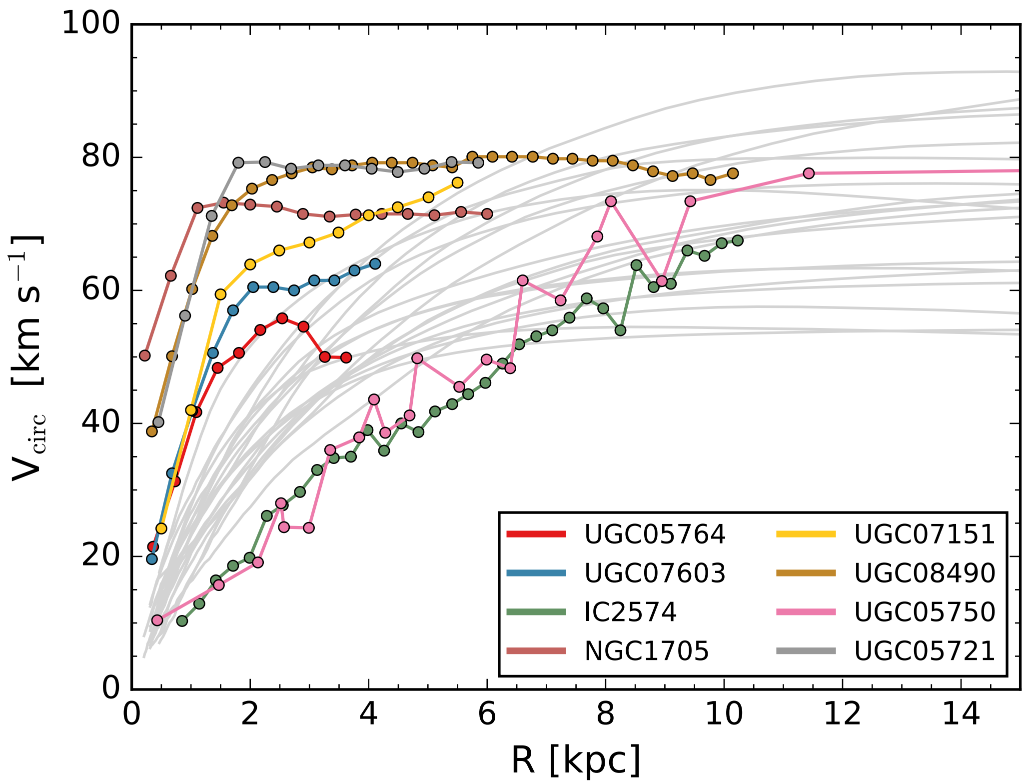


From Tao Ren

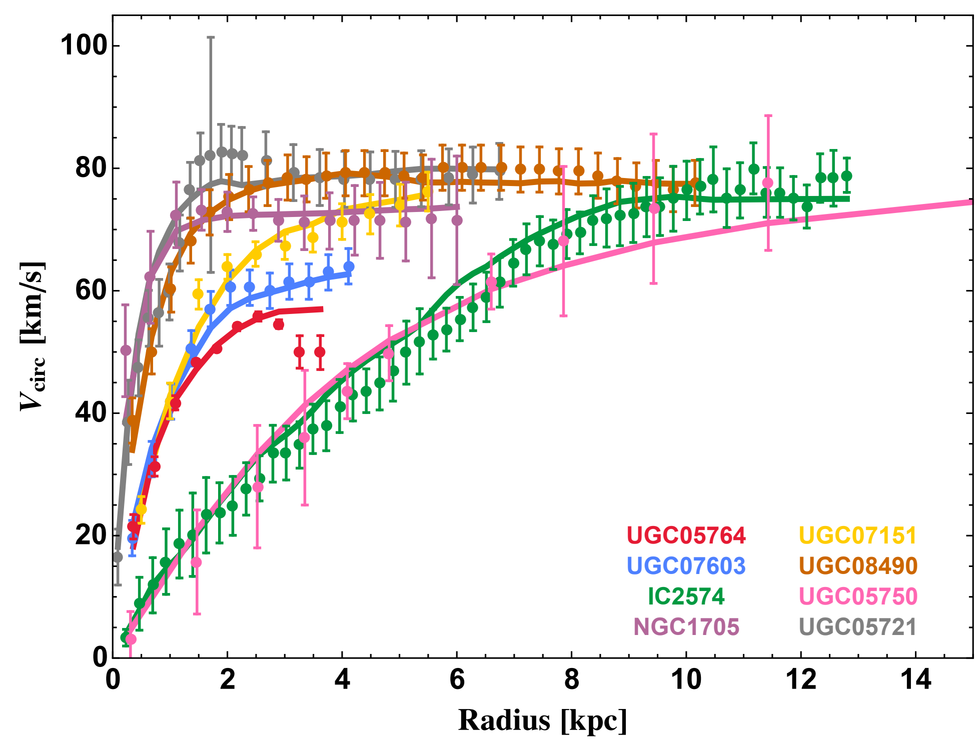
- Scatter in the halo concentration-mass relation (~2σ)
- Baryon distribution
- SIDM thermalization ties DM and baryon distributions

Isolated N-body simulations: with Creasey, Sameie, Sales et al. (MNRAS 2016)

Strong Feedback vs SIDM



Santos-Santos et al. (2017)



From Tao Ren

Gray: NIHAO CDM simulations

"strong/violent" feedback

Observed scatter: ~4 (3σ away)

Simulations: ~2

Solid lines: SIDM fits

(~2σ in the c_{200}-M_{200} relation)


Thank You!