기초과학연구원
Institute for Basic Science

Galactic Rotation Curves with Dark Matter Self-Interactions

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Based on
AK, M. Kaplinghat, A. B. Pace, H.-B. Yu, arXiv:1611.02716

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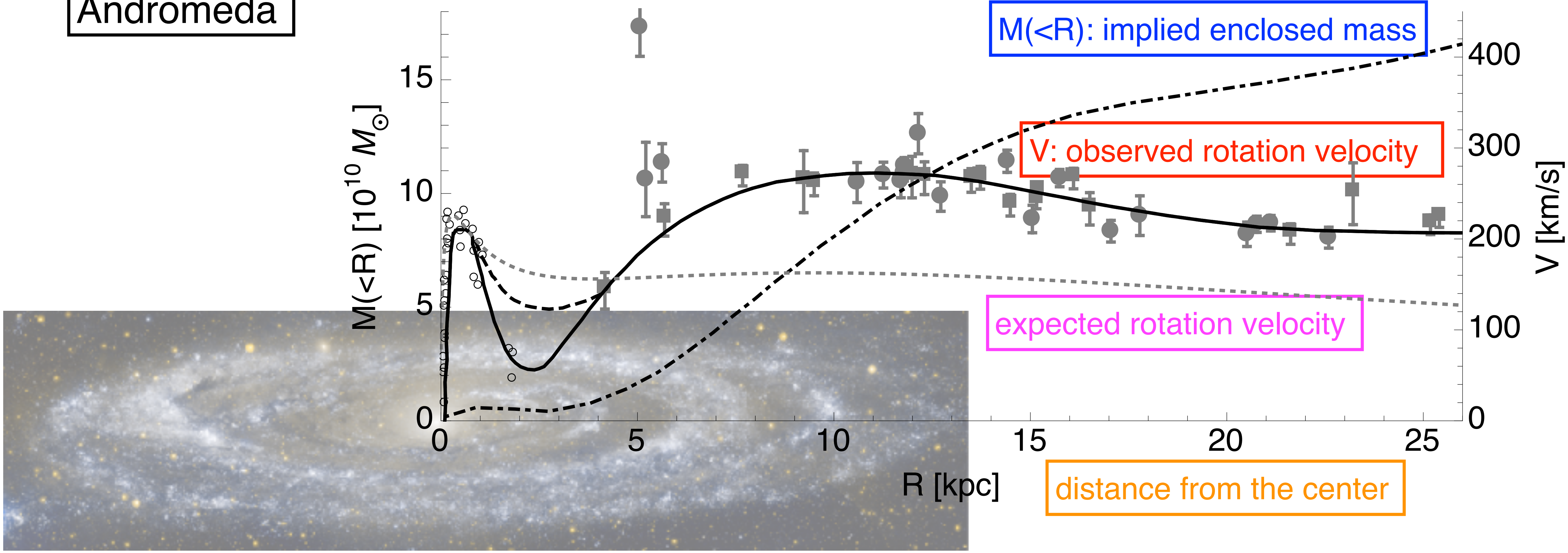
Evidence of Dark Matter

1970 Rubin and Ford
Measurements of Rotation Curves

Enclosed mass increases outside the disk

Andromeda

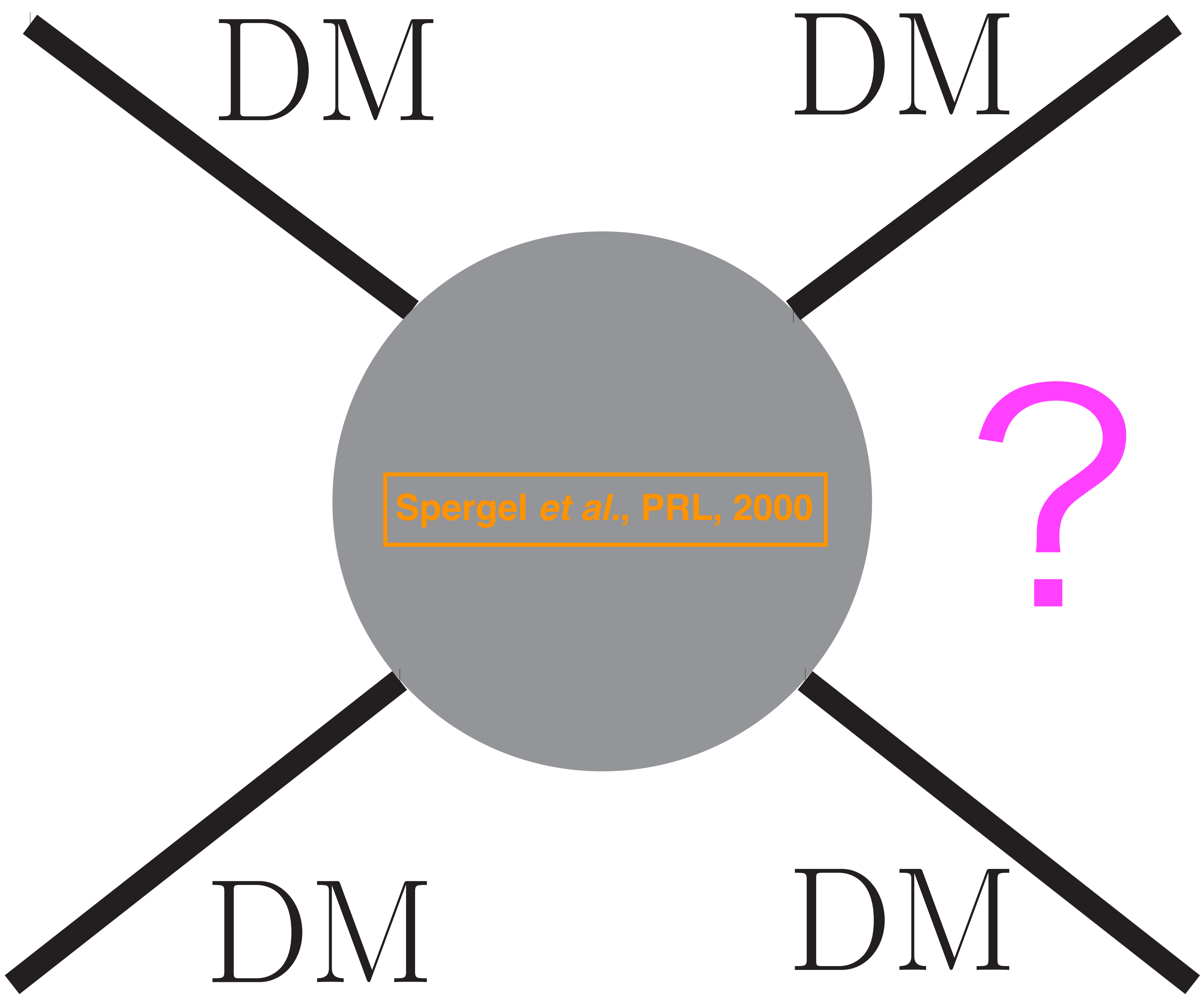


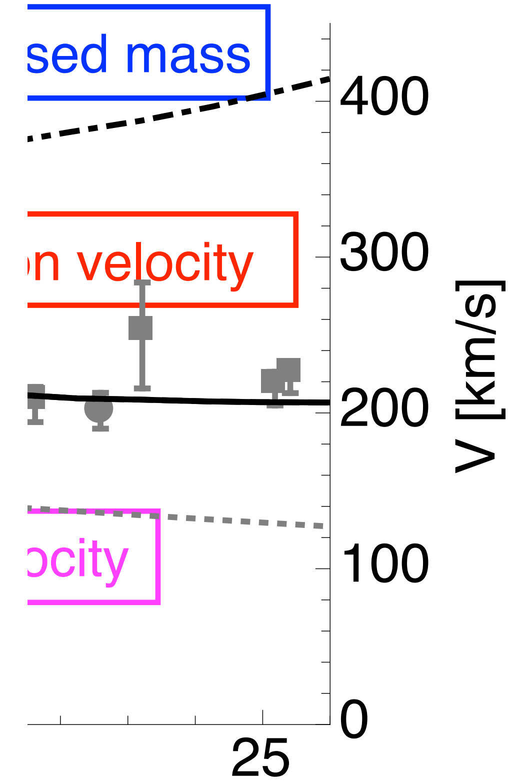
Evidence of Dark Matter

1970 Rubi
Measurem

Andromeda

d mass
ases
the disk

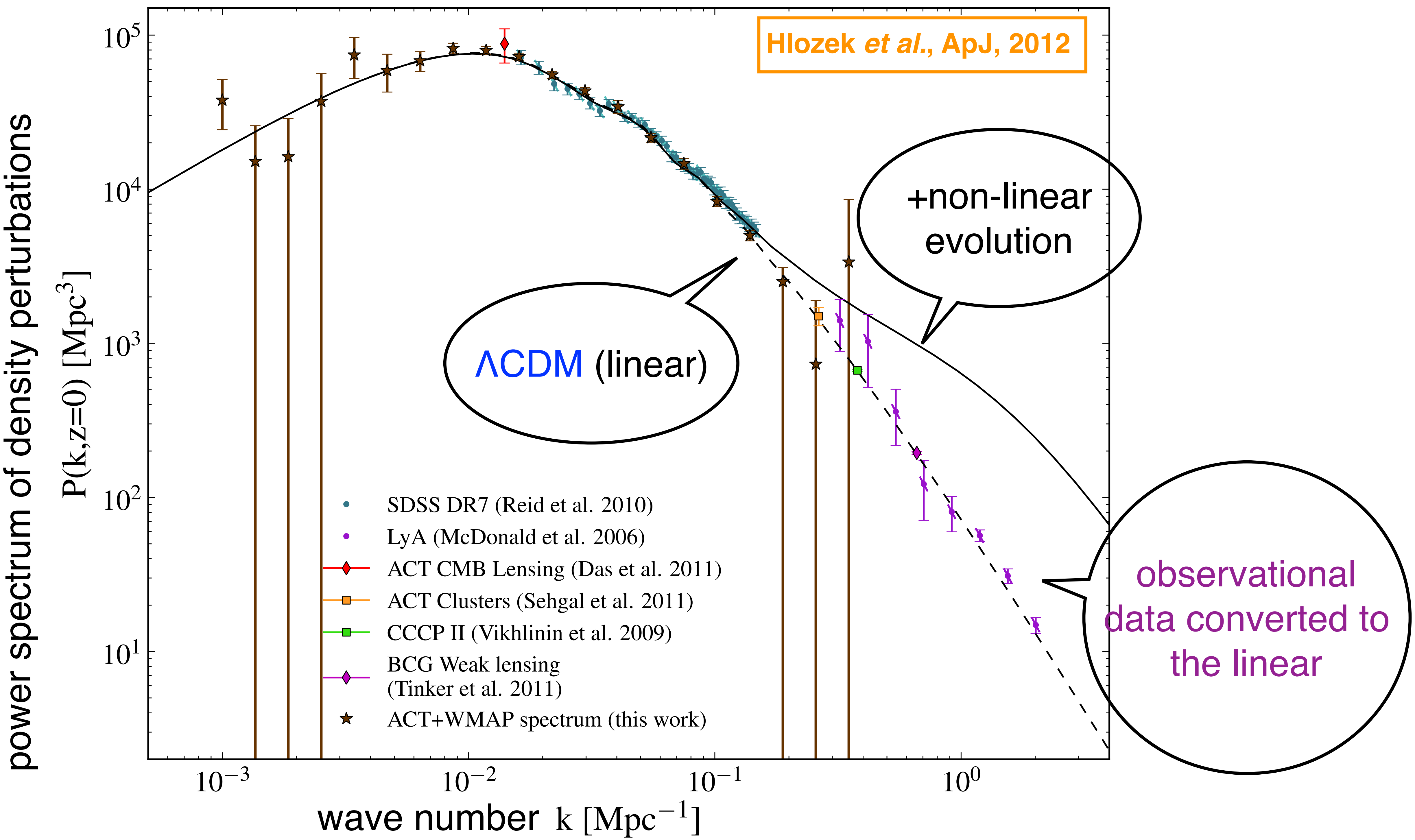




R [kpc]

distance from the center

Large scale structure of the Universe



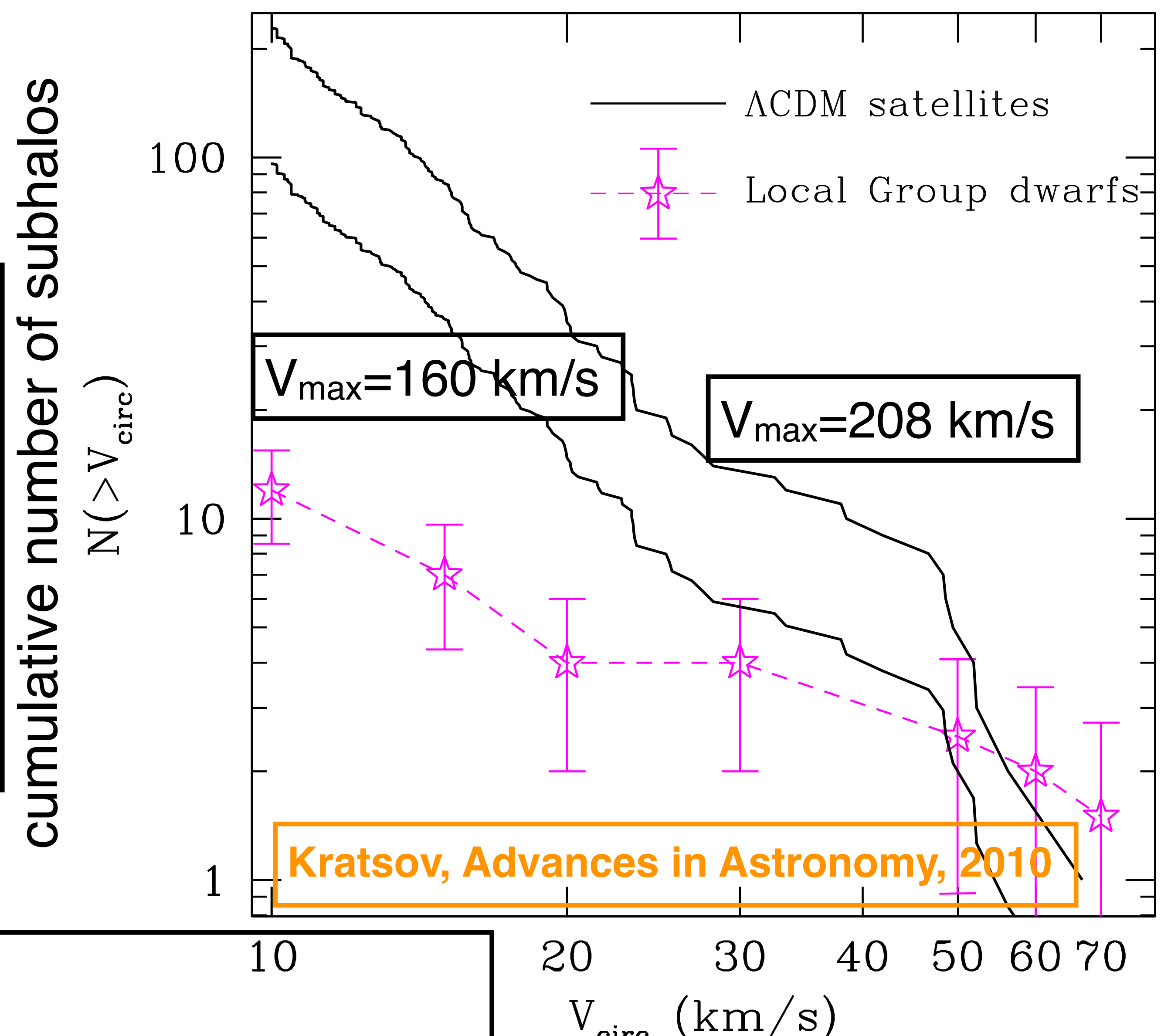
The ΛCDM model reproduces well
the large scale (>Mpc) structure of the Universe

Small scale crisis I

When *N*-body simulations in the ΛCDM model and observations are compared, problems appear at (sub-)galactic scales: **small scale crisis**

missing satellite problem

N-body (DM-only) simulations in the ΛCDM model → Milky Way-size halos host **O(10)** times larger number of subhalos than that of observed dwarf spheroidal galaxies



maximal circular velocity of subhalo

(maximum) circular velocity

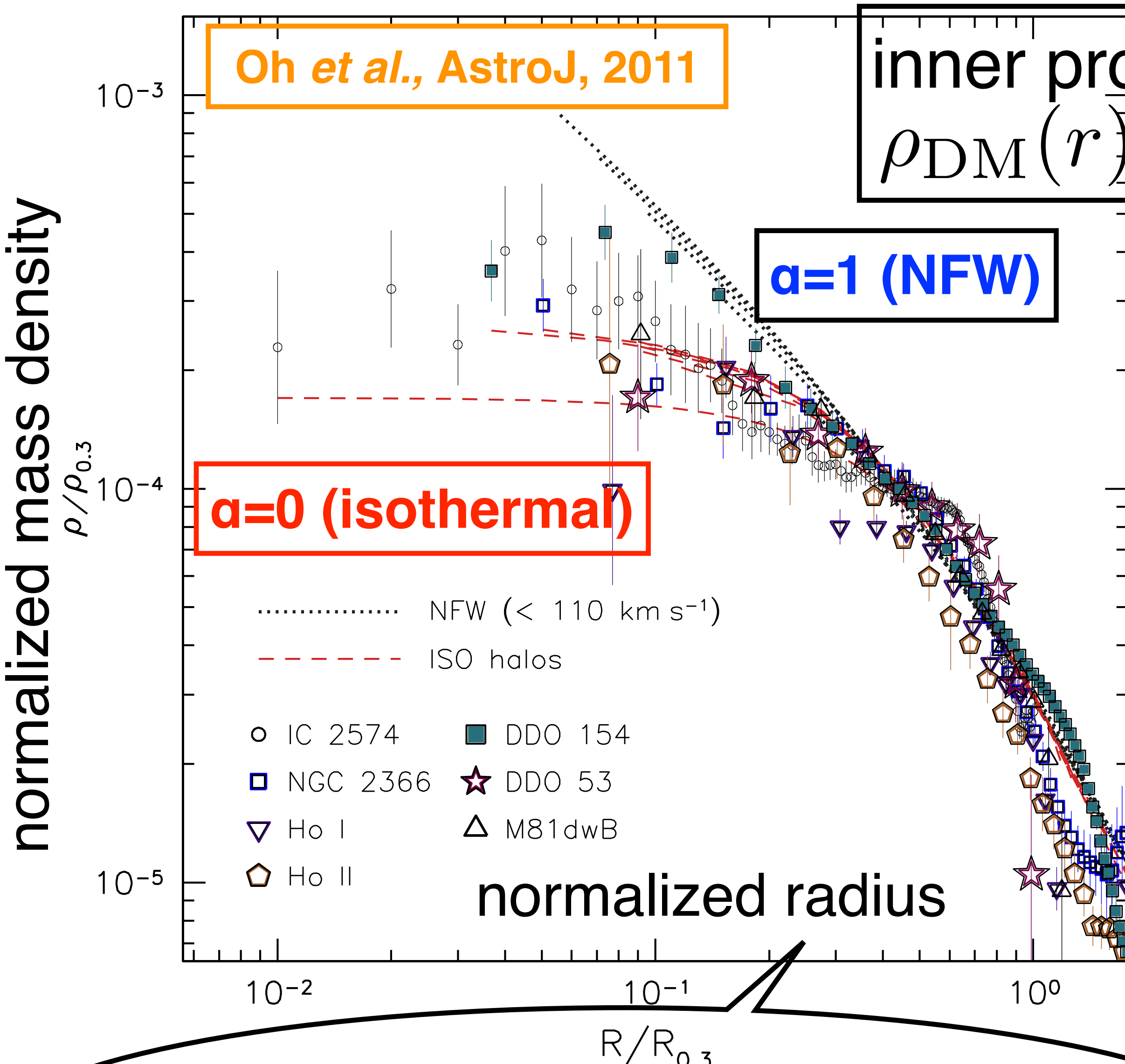
$$V_{\rm circ}^2(r) = \frac{GM(<r)}{r} \qquad V_{\rm max} = \max_r\{V_{\rm circ}(r)\}$$

Small scale crisis II

cusp vs core problem

N-body (DM-only) simulations in ΛCDM model →
UNIVERSAL DM profile independent of halo size**: NFW profile**

inner profile:
$\rho_{\rm DM}(r) \propto r^{-\alpha}$



field dwarf spheroidal galaxies
~10^9 Msun

Observations infer the **CORED** isothermal profile in the inner region rather than the **CUSPY** NFW profile

NFW profile:

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

isothermal profile:

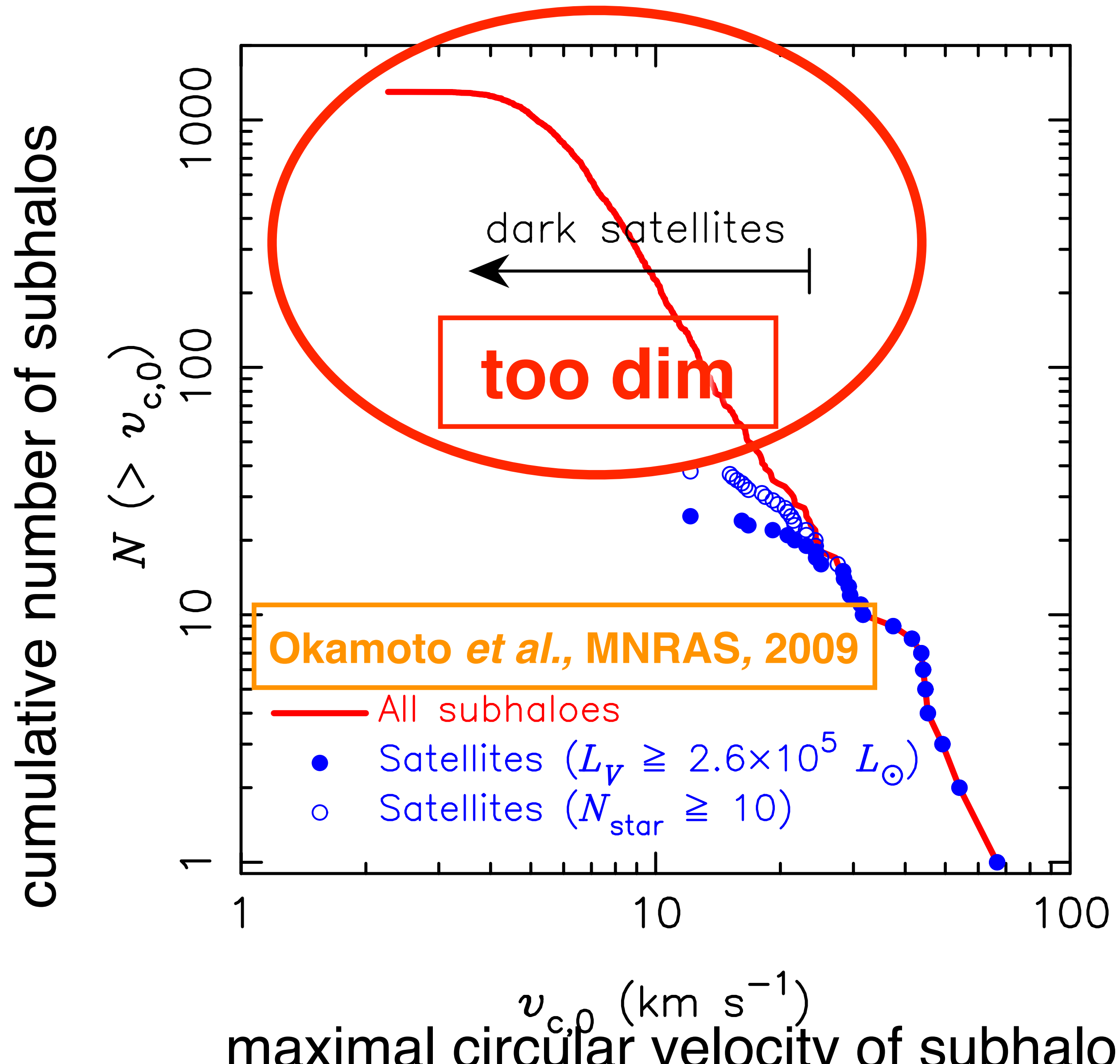
$$\rho_{\rm DM}(r) = \rho^0_{\rm DM}\begin{cases} 1 \ (r \ll r_0) \\ (r_0/r)^2 \ (r \gg r_0) \end{cases}$$

Possible solution I

The above discussions are based on *N*-body (**DM-only**) simulations in the ΛCDM model

↕

Gravitational potentials are shallower at smaller scales → **BARYONIC HEATING** and **COOLING** processes may be important



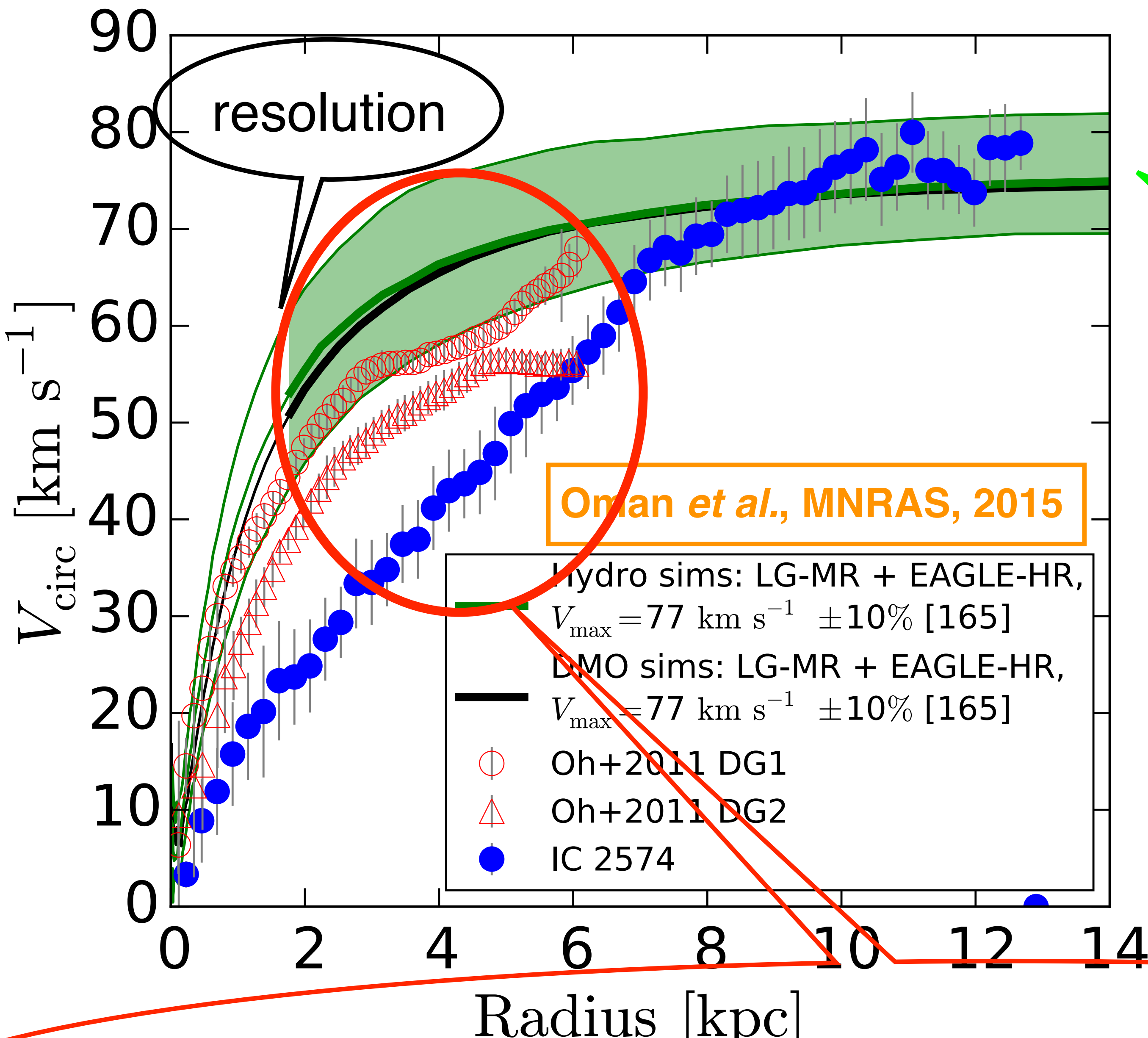
Baryonic processes

- **heating from ionizing photons** - ionizing photons emitted and spread around reionization of the Universe heat and evaporate gases

- **mass loss by supernova explosions** - supernova explosions blow gases from inner region → DM redistribute along shallower potential

Inner mass deficit problem

Rephrasing cusp vs core problem to emphasize that not only the slope but also the **WHOLE MASS DISTRIBUTION** should be examined



10^{th}-90^{th} percentile range from the state-of-the-art hydrodynamical simulations in the ΛCDM model (*EAGLE, Local GROUPS*) with modeled subgrid baryonic physics (radiative cooling, star formation, stellar and chemical enrichment, energetic stellar feedback, black hole accretion and mergers, and AGN feedback)

The simulated enclosed mass is about **FOUR** times higher than the observed!

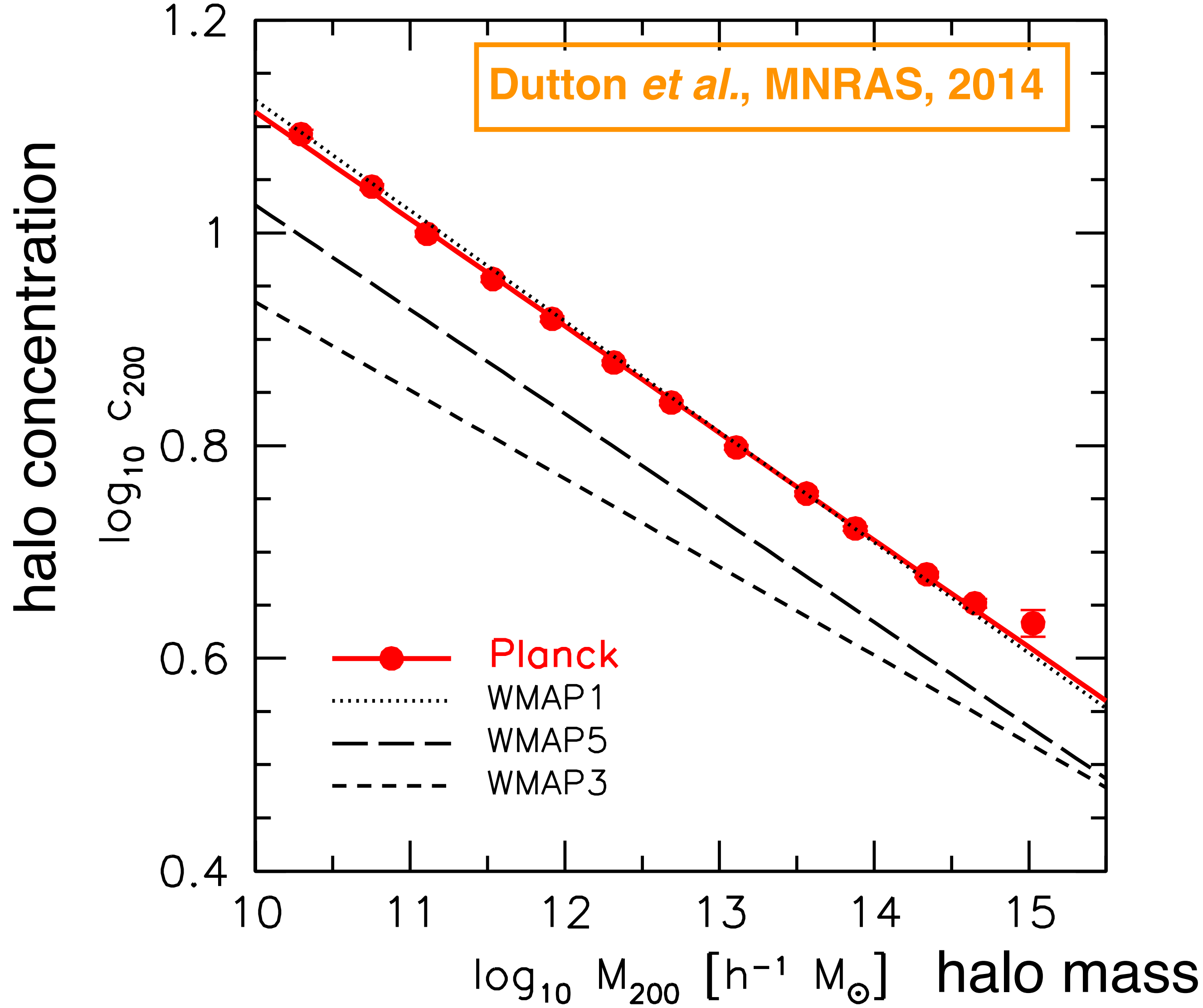
Concentration-mass relation

Why is a simulated rotation curve (almost) **DEFINITE** for a given V_{max}?
Two parameters for the NFW profile

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

A relation between two parameters usually given as the **CONCENTRATION-MASS RELATION**

$$c_{200} = 10^{0.905\pm0.11}(M_{200}/10^{12}h^{-1}M_\odot)$$



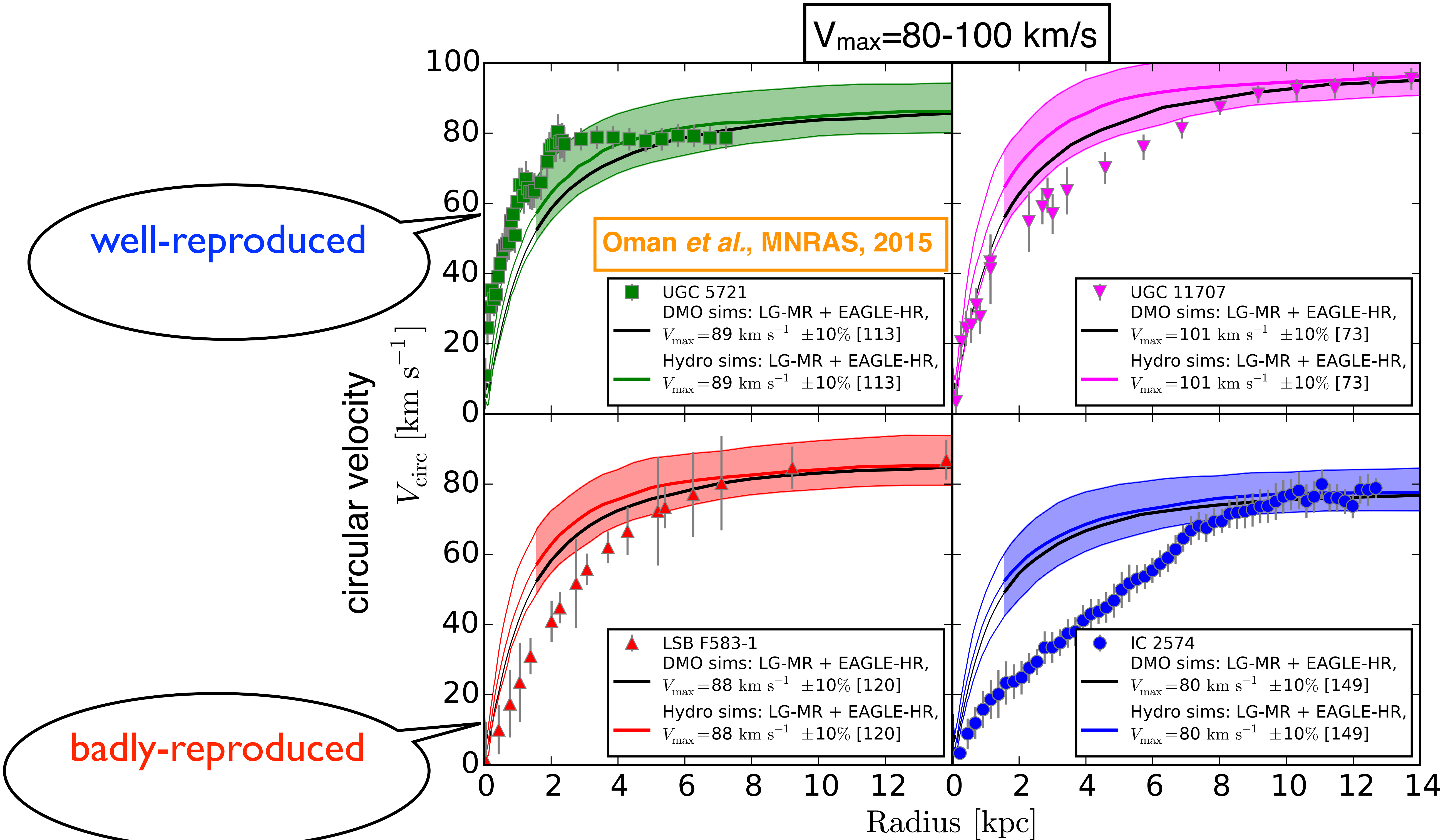
small
intrinsic scatter

$$c_{200} = r_{200}/r_s$$

$$M_{200}(<r_{200}) = \frac{4\pi}{3}\bar{\rho}_{\rm M} r_{200}^3$$

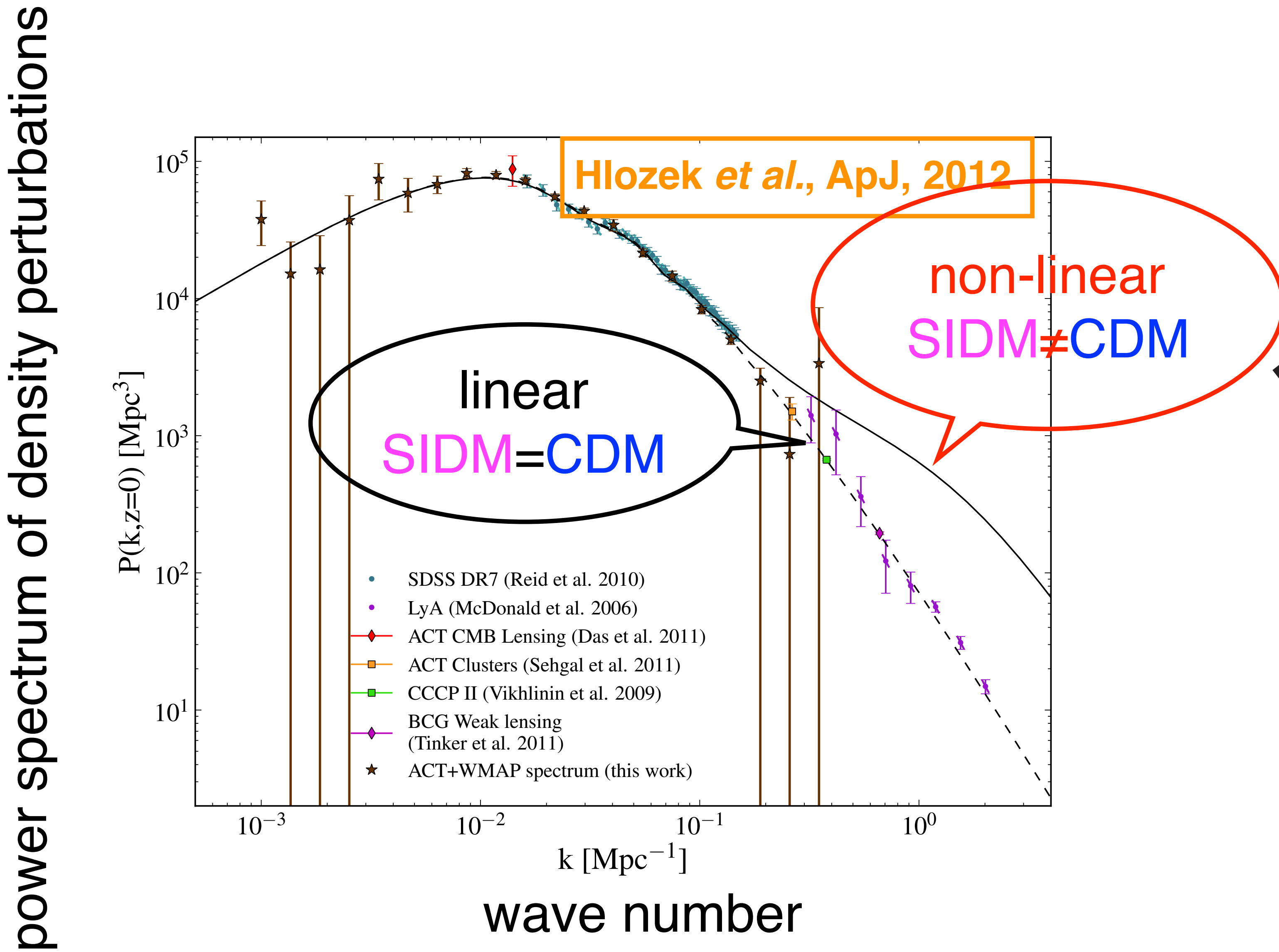
Unexpected diversity problem

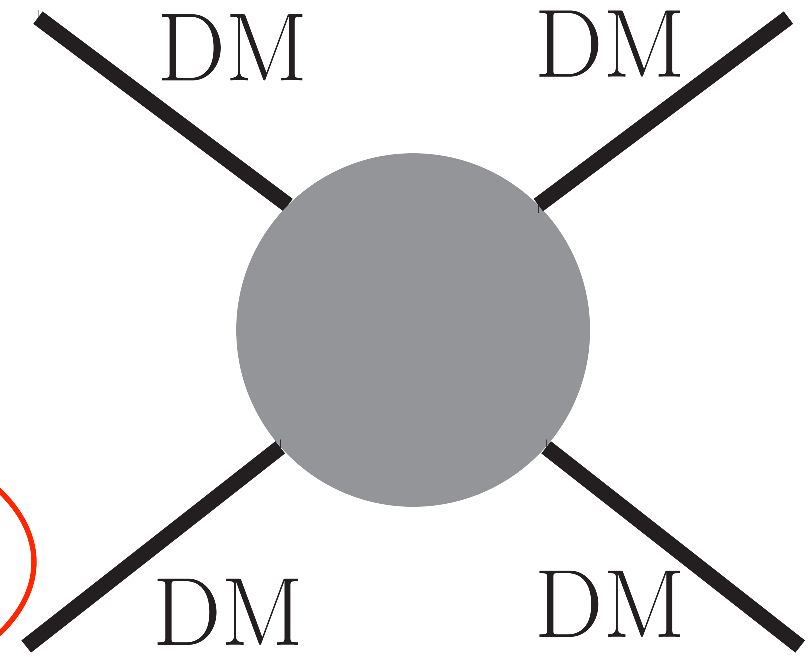
The inner mass deficit is **NOT UNIVERSAL**, but should be elaborated in a **GALAXY-BY-GALAXY** manner even with **V_{max} fixed**



Dark matter self-interaction

Self-Interacting Dark Matter: **SIDM**





Reaction rate $\Gamma=\sigma v \rho/m$

σ: cross section

v: relative velocity

ρ: dark matter mass density

m: dark matter mass

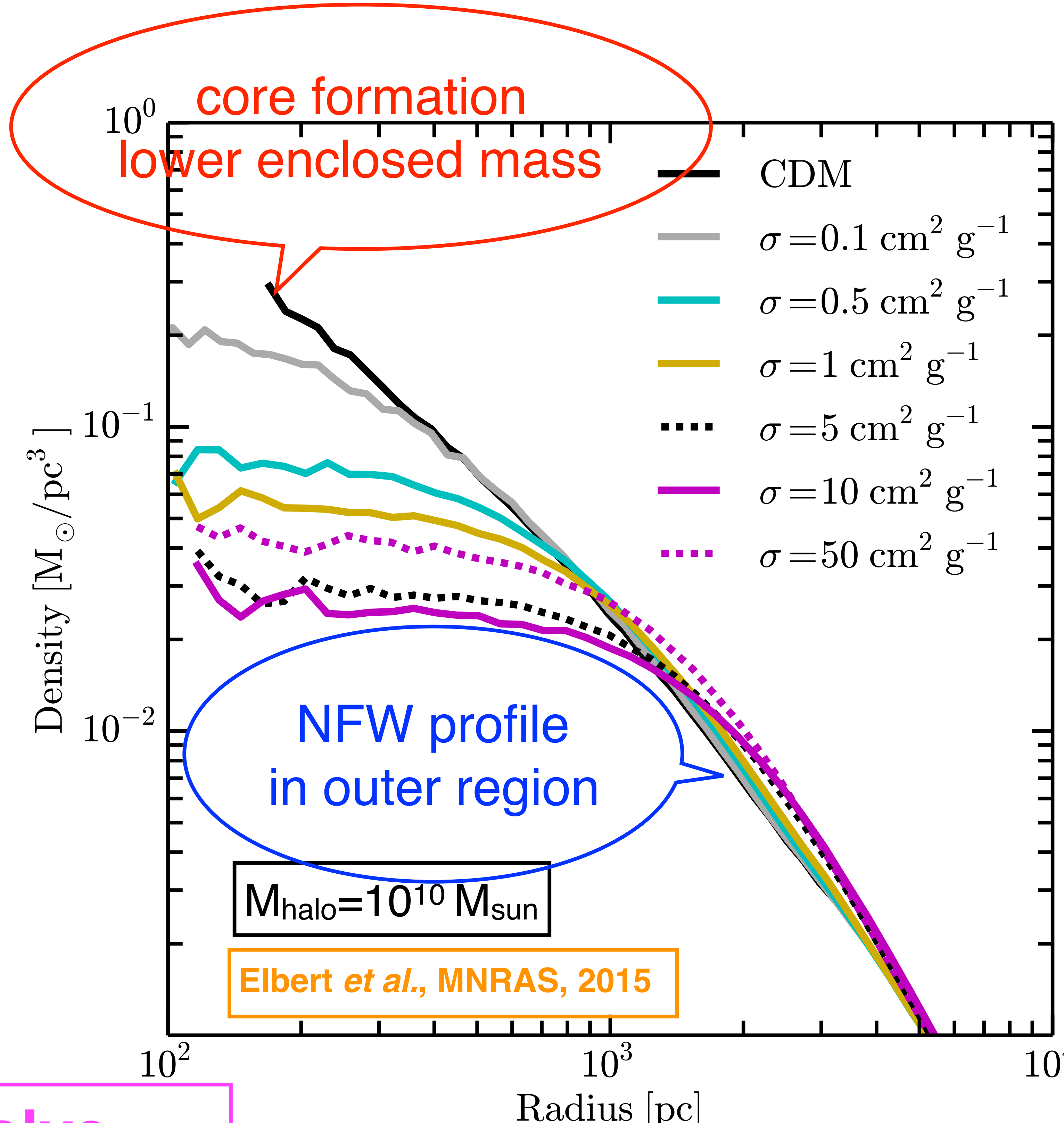
SIDM structure formation starts with the same linear (initial) matter power spectra as ΛCDM, but self-interactions become important as structure formation proceeds ↔ ρ increases

SIDM halo - mass density

SIDM-only simulation

As σ/m increases,
central density decreases

Inverted at some point
← gravo-thermo instability
↔ core-collapse



σ/m=0.5-5 cm^2/g may solve the inner mass deficit problem

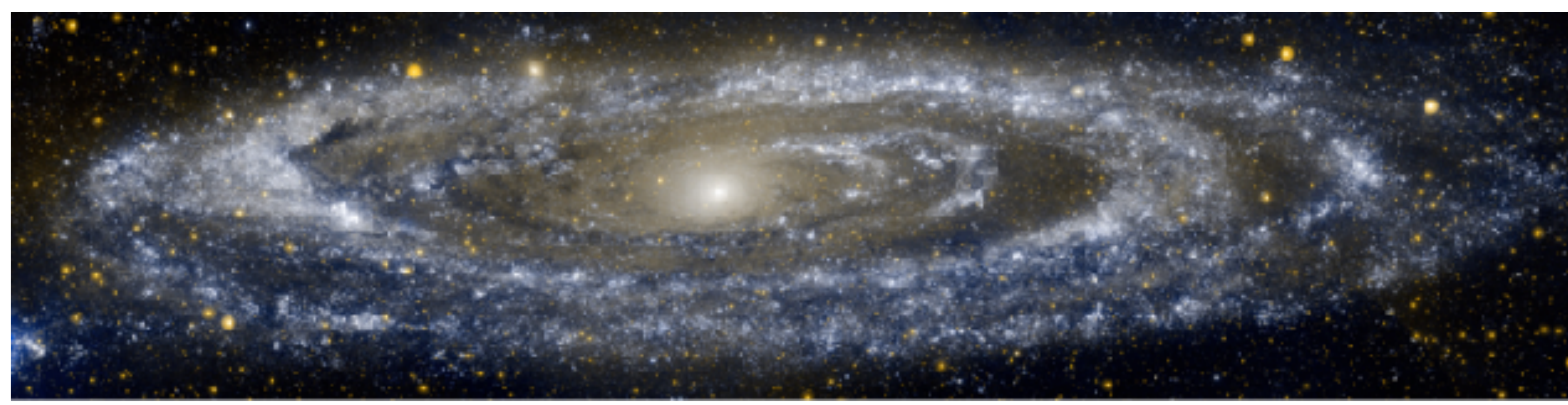
Origin of the diversity

Unexpected diversity problem??

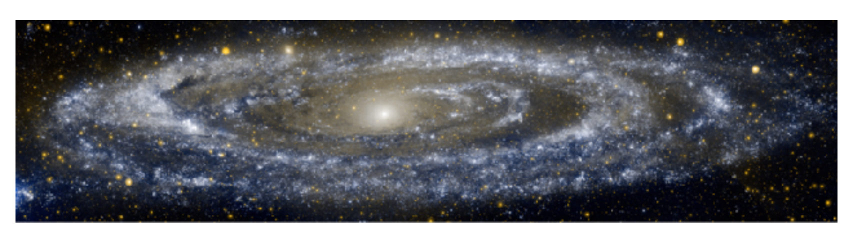
For a given cross section ($\sigma/m=3$ cm^2/g in the following), the SIDM halo profile is still **DEFINITE** and characterized by only one parameter V_{max}

Scatter in distributions of the baryons even in similar-size halos!!

Extended stellar disk



Compact stellar disk



Influence of the baryons

SIDM static distribution with a thin exponential disk potential from the Poisson equation

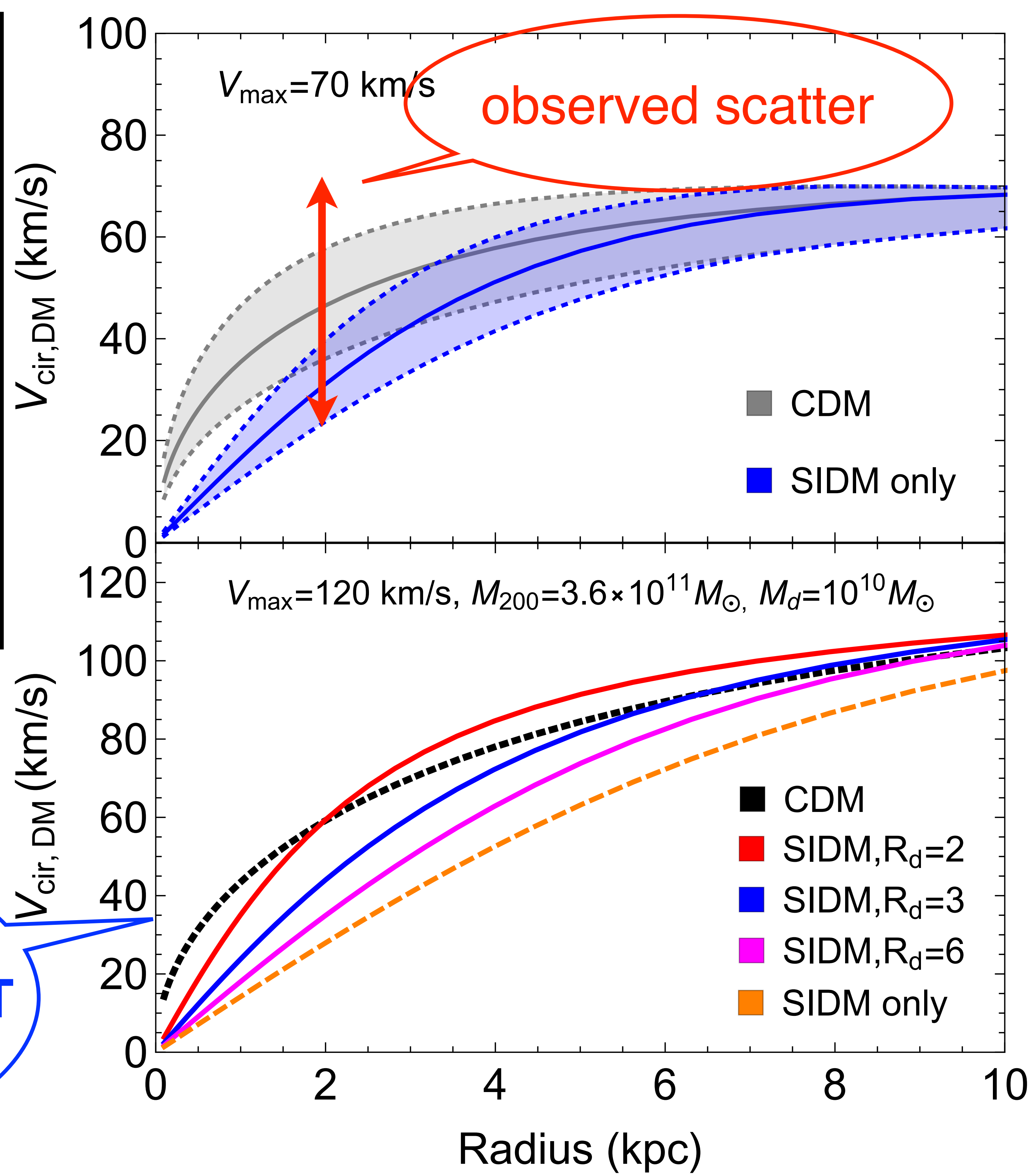
$$\Delta\phi = 4\pi G\rho^0_{\rm DM}\exp(-\phi/\sigma^2)$$

$$\phi(0) = 0$$

$$\phi(\vec{x}) \to V_\infty^2 \ln(r/r_0)$$

$$(r = |\vec{x}| \to \infty)$$

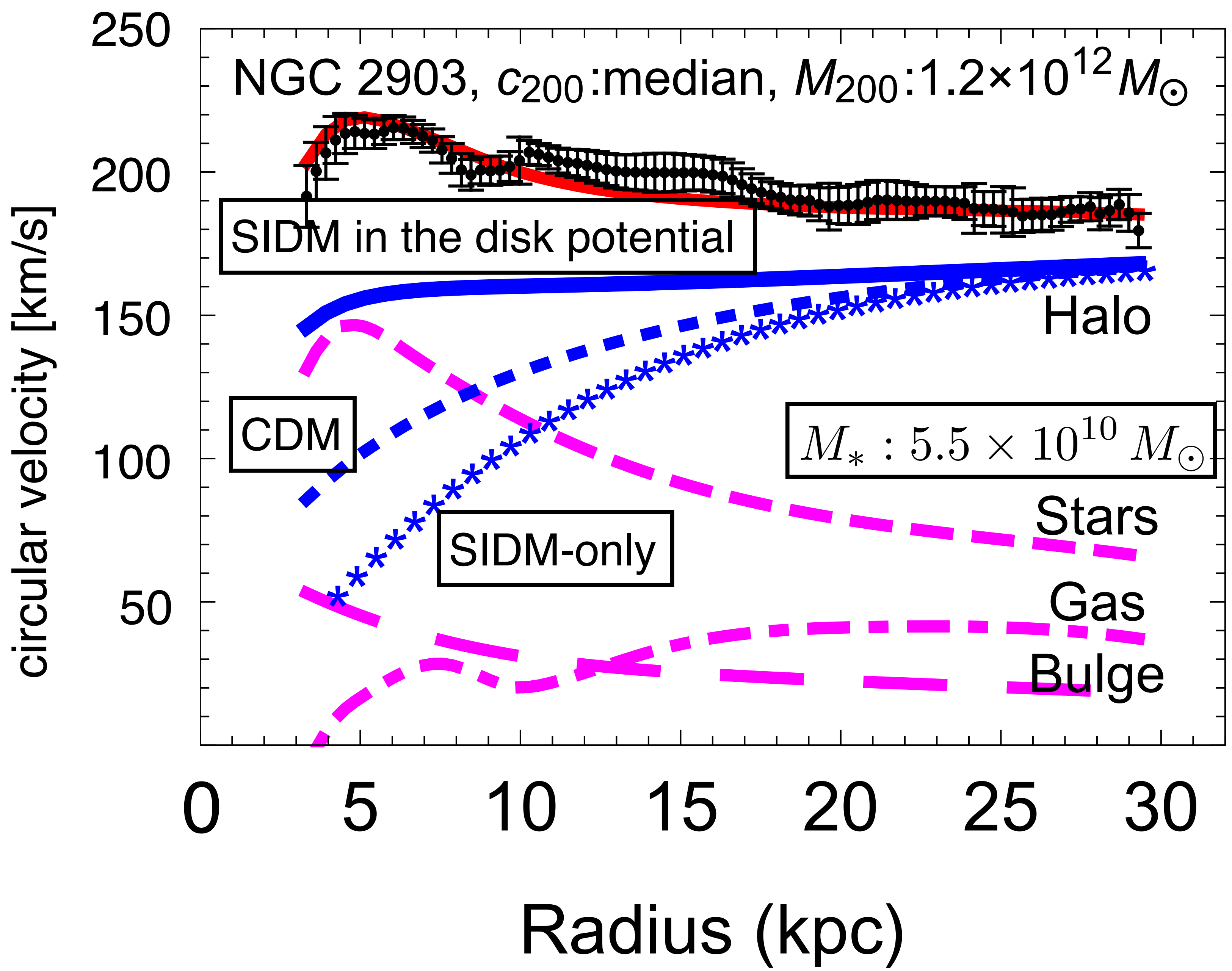
$$V_\infty^2 = 2\sigma^2 = 4\pi G\rho^0_{\rm DM} r_0^2$$



SIDM profile **CONTRACTS** under the presence of a **COMPACT** stellar disk

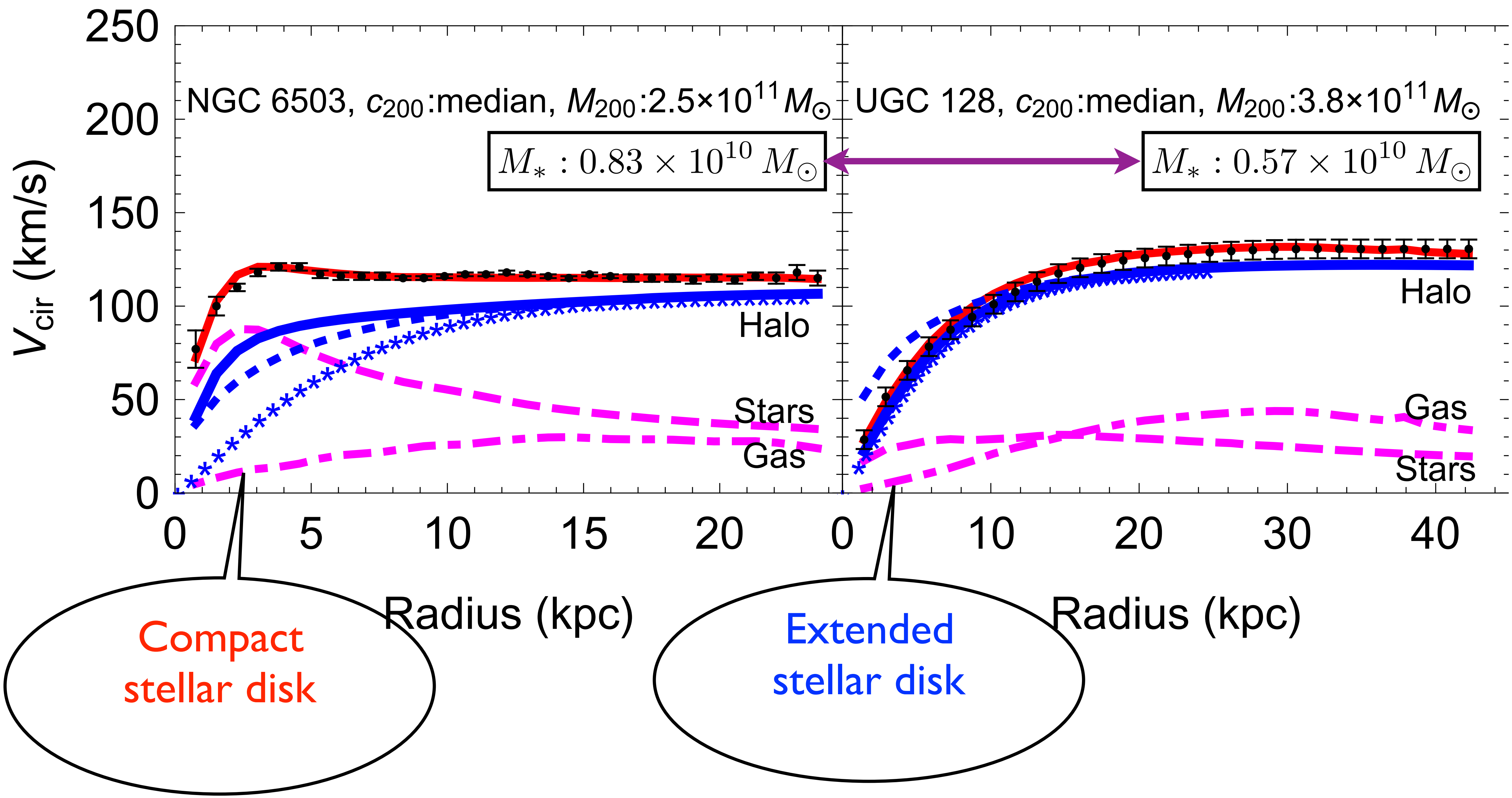
Case study I

In **MASSIVE** spiral galaxies,
stellar disks can change **WHOLE SIDM MASS DISTRIBUTIONS**



Case study II

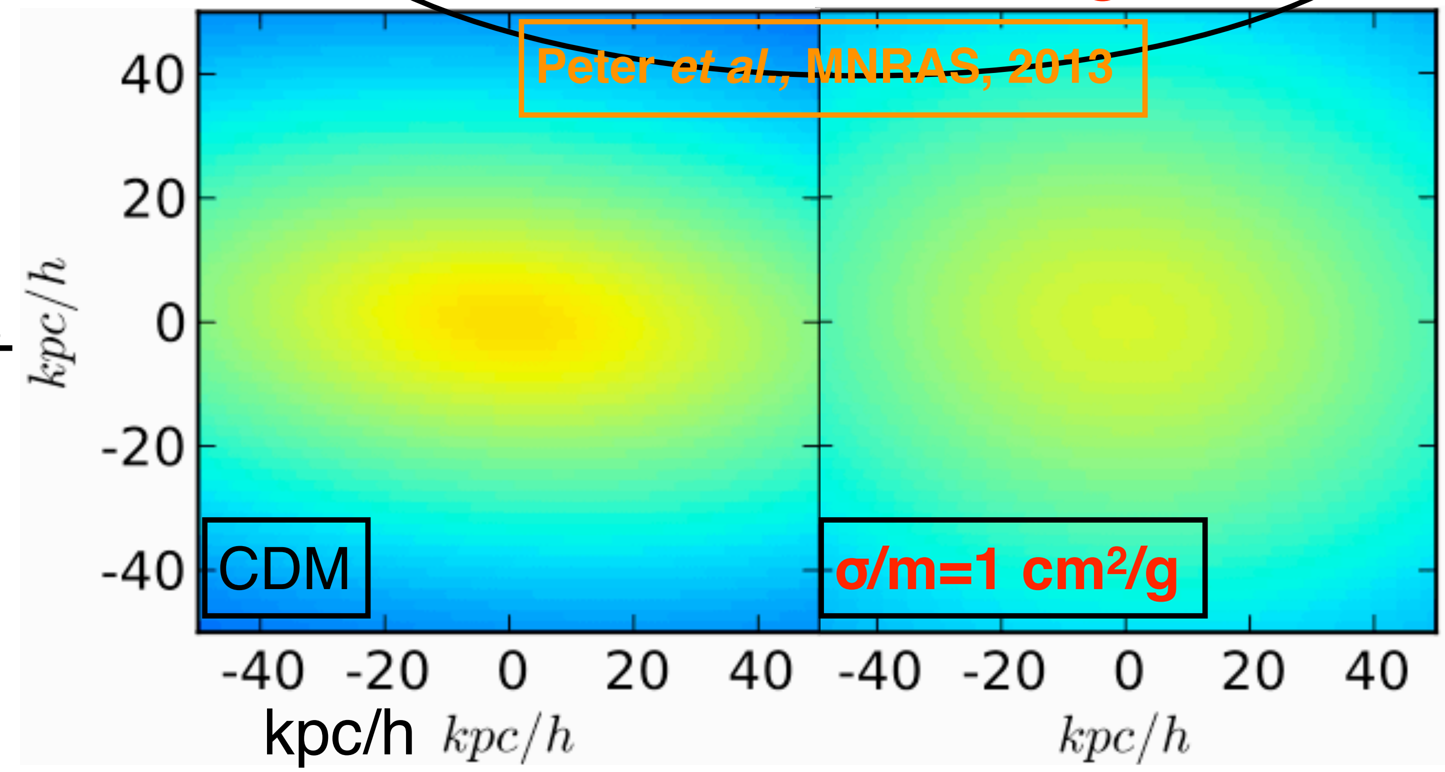
SIDM halo profile reflects **HOW COMPACT** the hosted stellar disk is even with similar **V_{max} AND M_***



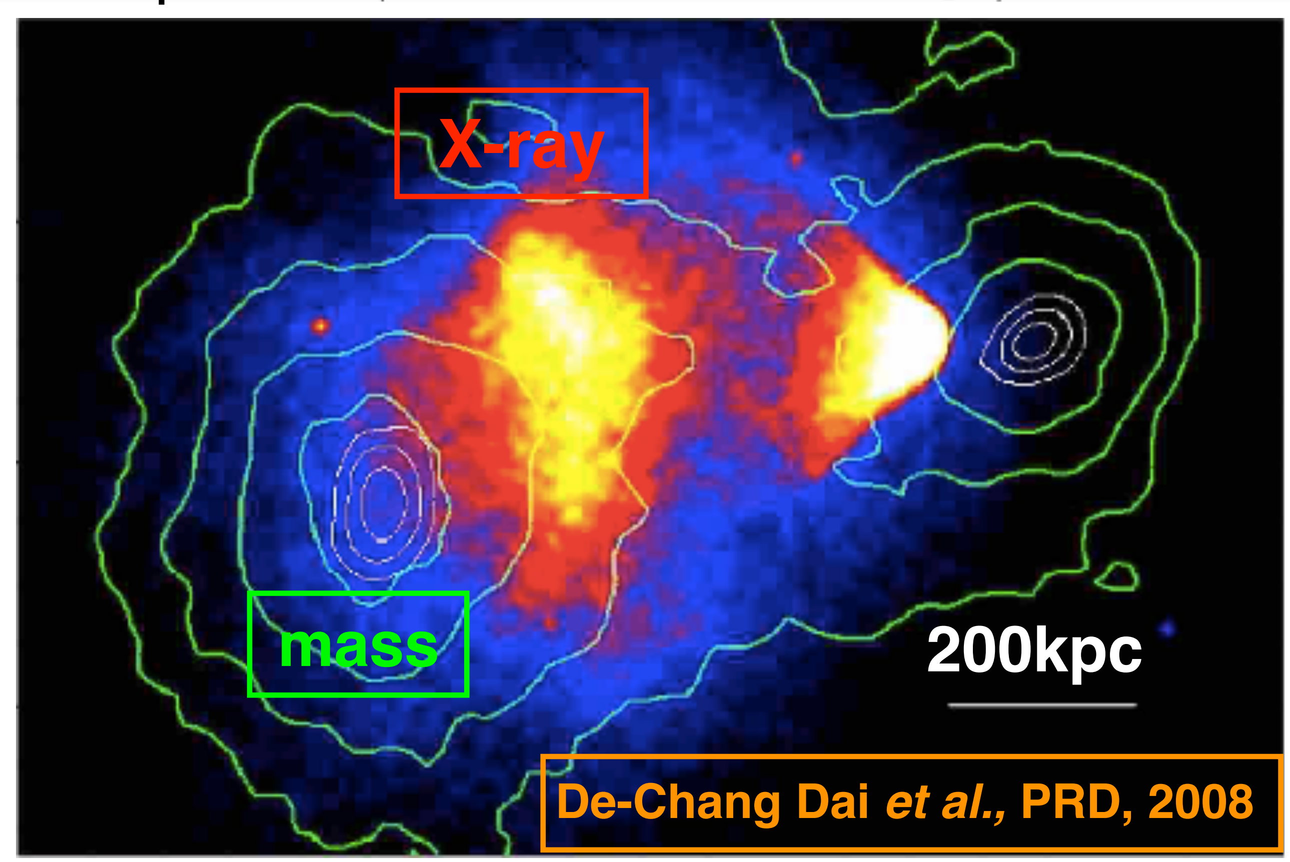
Constraints from galaxy clusters

V_{max}~1000 km/s
↔ galaxy: V_{max}~100 km/s
σ/m=0.5-5 cm^2/g

Halo shape - ellipticity
- galaxy cluster MS 2137–23 (e=0.18@r=70 kpc)
(estimate) σ/m<0.02 cm^2/g
Miralda-Escudé *et al.*, ApJ, 2002
(simulation/l.o.s. effect)
σ/m<1 cm^2/g
Peter *et al.*, MNRAS, 2013



Bullet cluster - transparency
- 1E0657-558
(offset) σ/m<1.25 cm^2/g
(massloss) σ/m<0.7 cm^2/g
Randall *et al.*, ApJ, 2008
- an ensemble (72)
(offset) σ/m<0.47 cm^2/g
Harvey *et al.*, Science, 2015



Particle physics models I

The constraints from galaxy clusters likely imply that dark matter self-interaction should **DIMINISH WITH INCREASING VELOCITY**, even though not necessarily so far

+ interestingly strong lensing of galaxy clusters may support SIDM with a smaller cross section **σ/m=0.1 cm²/g**

Tulin *et al.*, PRL, 2012

velocity-DEPENDENT cross section:

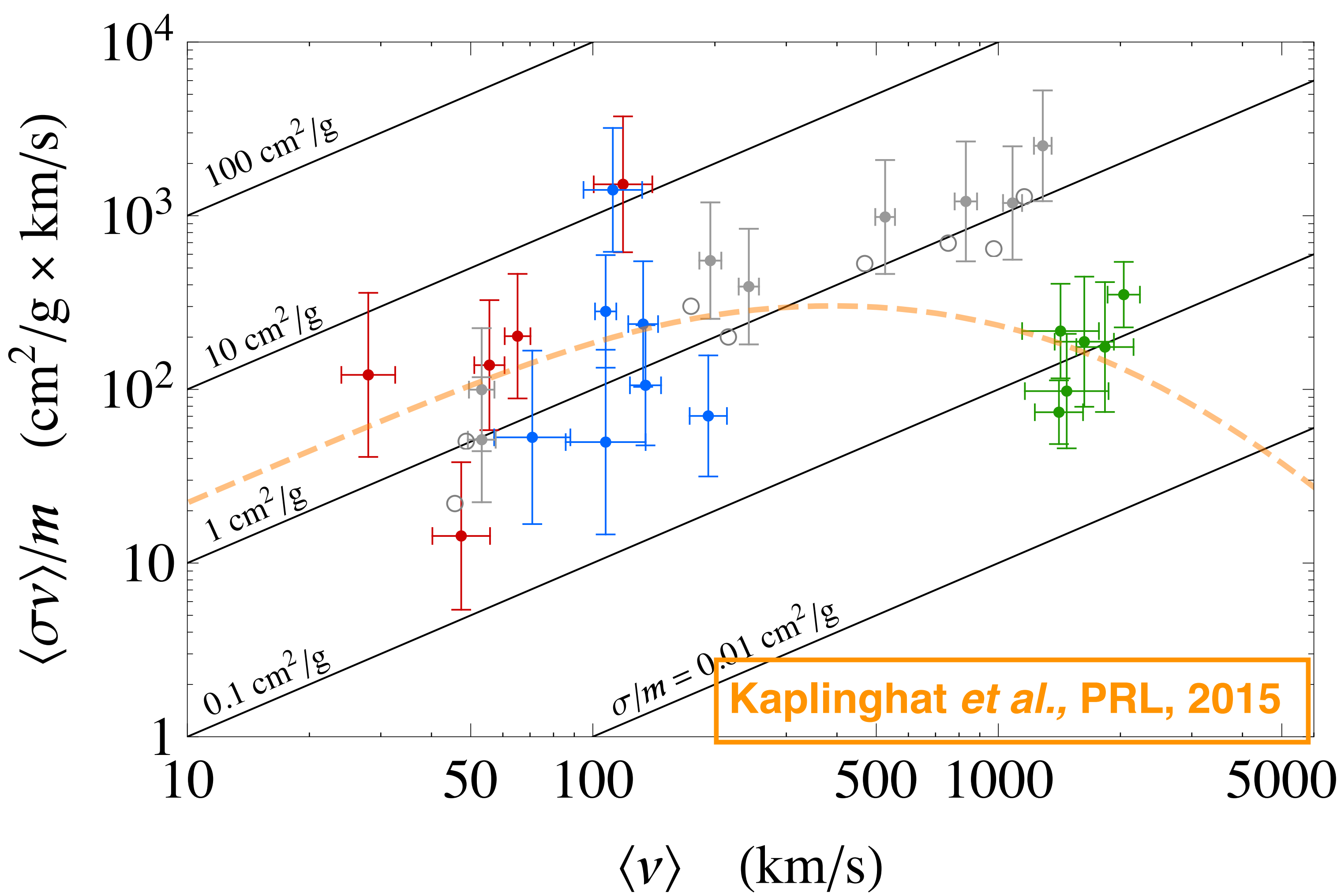
WIMP dark matter

+ light mediator with

$m_{med} \sim m_{DM} v_{gal}/c$

$\sigma \sim 1/m_{med}^2$: const. @(dwarf)galaxies (V_{max}~10-100 km/s)

$\sigma \sim 1/v^4$: suppressed @galaxy cluster (V_{max}~1000 km/s)



Kaplinghat *et al.*, PRL, 2015

Particle physics models II

If a velocity-**INDEPENDENT** cross section is concordant
at both galaxy cluster and galaxy scales,
self-interaction may originate from a **HIDDEN STRONG** interaction
(geometrical cross section of strongly-interacting massive particle:**SIMP**)

Hochberg *et al.*, PRL, 2015

A simple hidden pion theory of $m_\pi \sim f_\pi \sim$ 100-300 MeV
(non-linear sigma model with *CP* symmetry) works well:
Wess-Zumino-Witten term (coefficient may be quantized and/or determined
once a UV theory is specified) $\mathcal{L}_{\mathrm{WZW}} \supset \epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi]$
freeze-out of 3→2 reaction ⇒ correct relic abundance

⇔ If the hidden sector is completely decoupled from the SM sector,
the hidden sector is **HEATED UP** by the rest mass energy of SIMP
through the 3→2 reaction **Carlson *et al.*, ApJ, 1992**
comoving entropy density conservation → $T_h \propto 1/\ln(a)$ $(T \propto 1/a)$

⇒ **KINETIC DECOUPLING** from the SM sector **Kuflik *et al.*, PRL, 2016**
has a big impact on the relic density of dark matter!! (cannibalism)

Summary

- The long-standing cusp vs core problem is now highlighted as an inner mass deficit problem by state-of-the-art hydrodynamical simulations

- The inner mass deficit should be elaborated in a galaxy-by-galaxy basis, in contrast to the concentration-mass relation, which is hold even under the baryonic processes (diversity problem)

- Dark matter self-interaction, which intrinsically makes a mass distribution shallower in inner region, can solve the inner mass deficit problem, and also solve the diversity problem with the help of scatter in baryon distributions