

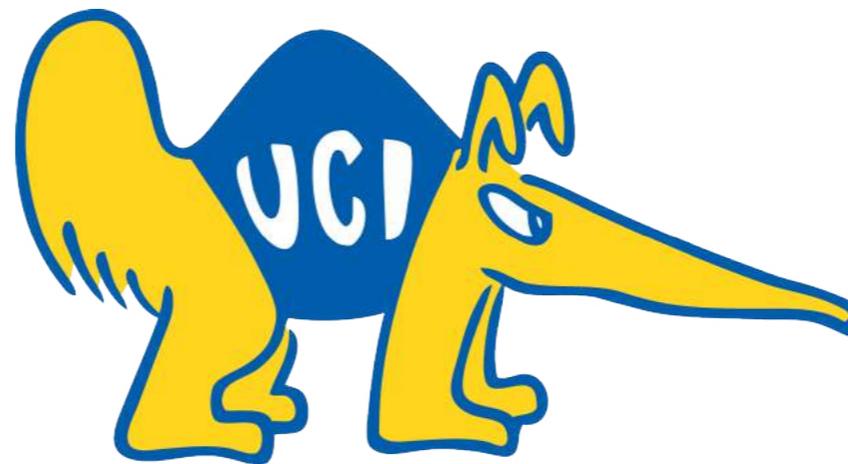
— 22/06/2021 —



Astrophysical Signatures of SIDM

MAURO VALLI

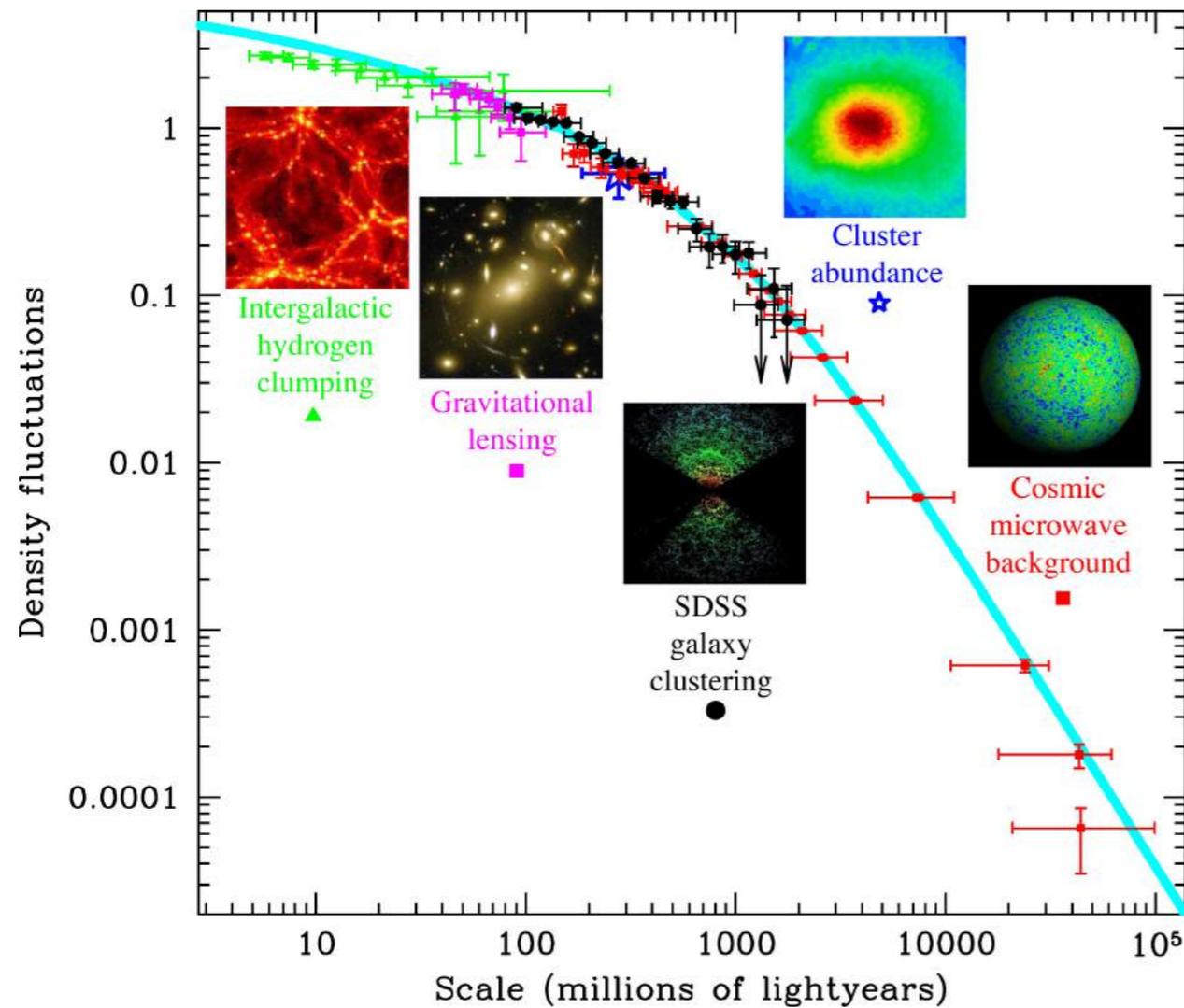
University of California, Irvine



Based on: 1711.03502 , 1904.04939 + work in progress

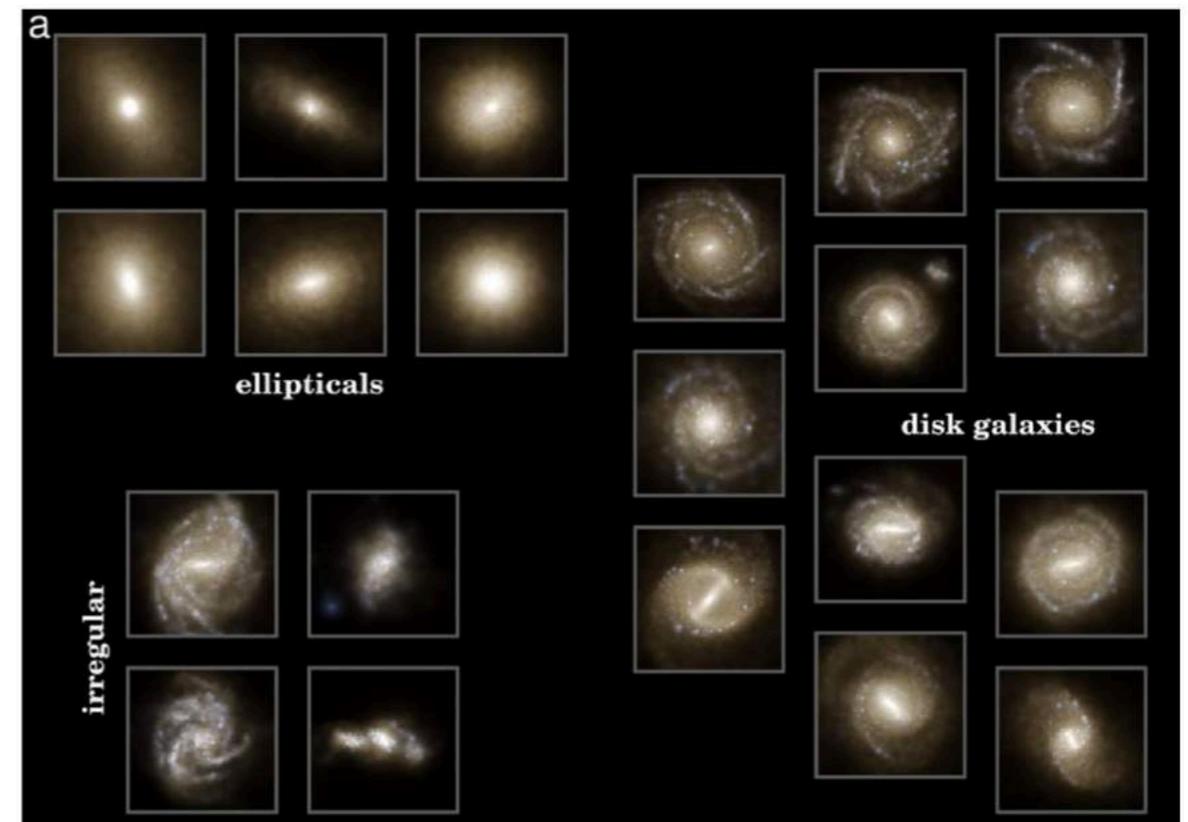
Nature Astron. 2 (2018) 907-912 , MNRAS 490 (2019) 1, 231-242

Cold Dark Matter (CDM)



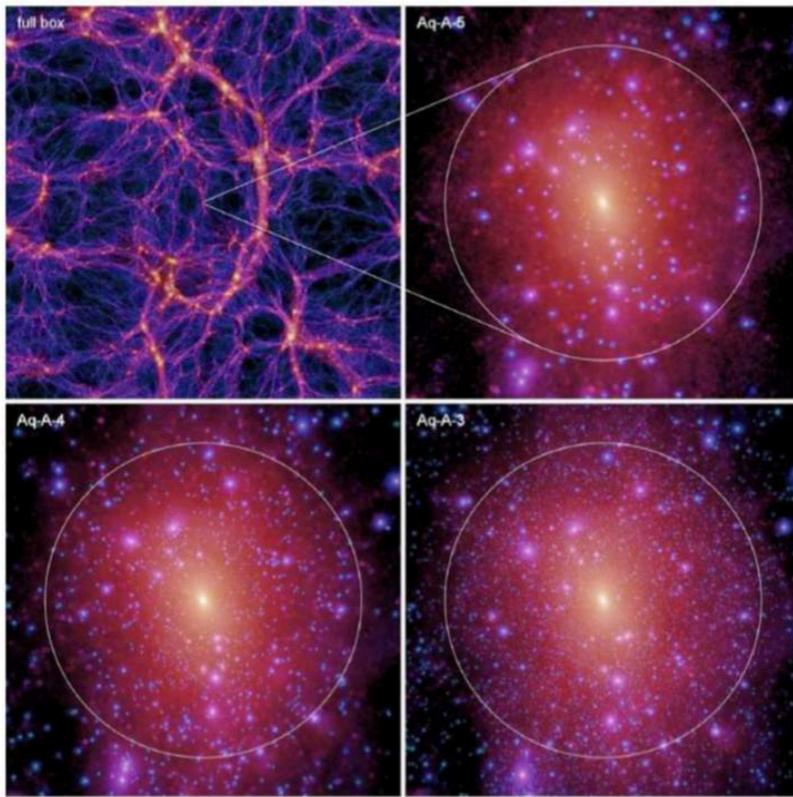
CDM nicely matches observations on typical scales $\approx O(100)$ kpc!

STATE-OF-THE-ART CDM N-BODY SIMULATIONS PROVIDE ACCURATE SNAPSHOT OF OBSERVED GALAXIES.

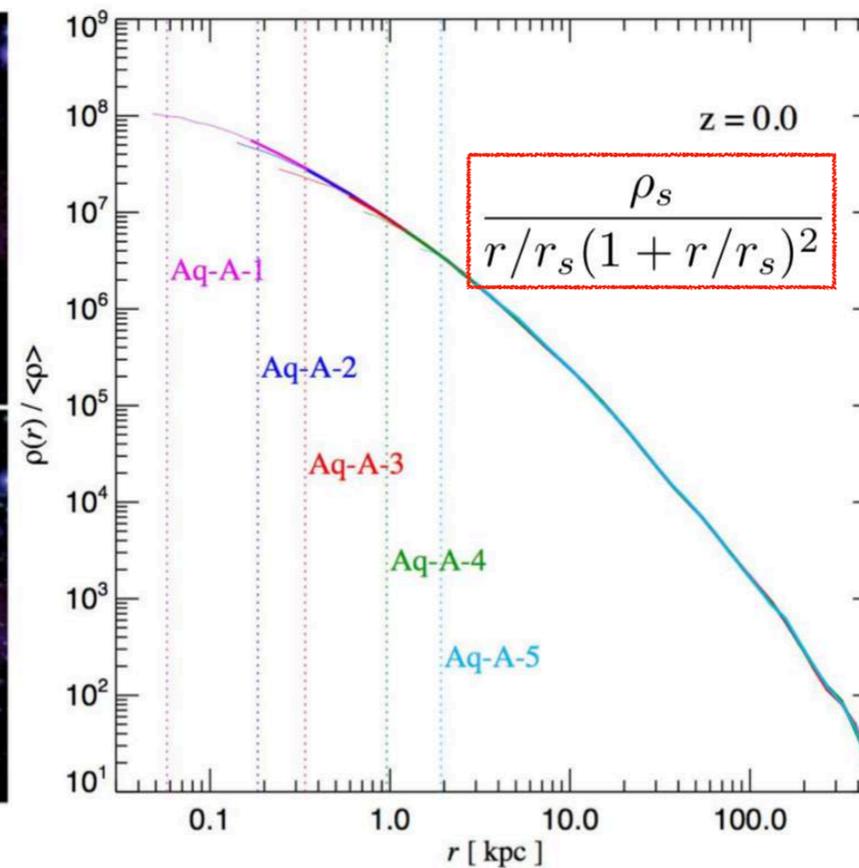


Illustris Project, Vogelsberger et al. (2014)

CDM N-body simulations implementing dedicated recipes for baryonic physics reproduce realistic galaxy morphologies.



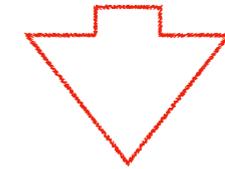
Aquarius Project, Springel et al. (2008)



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

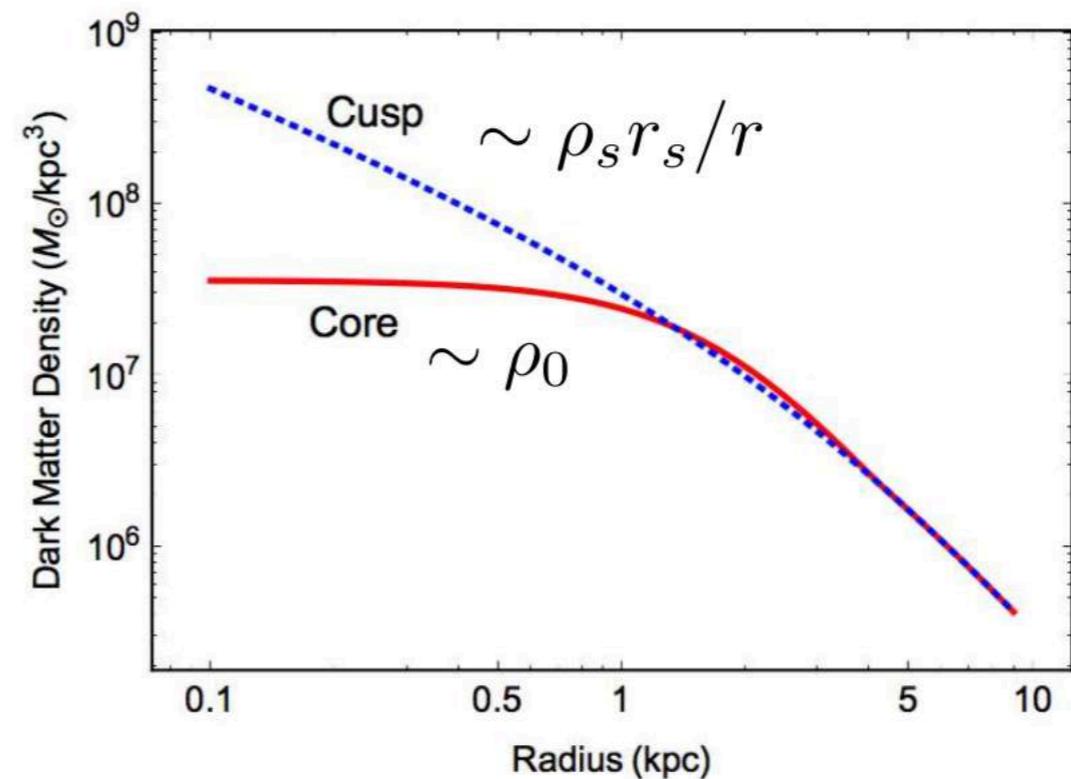
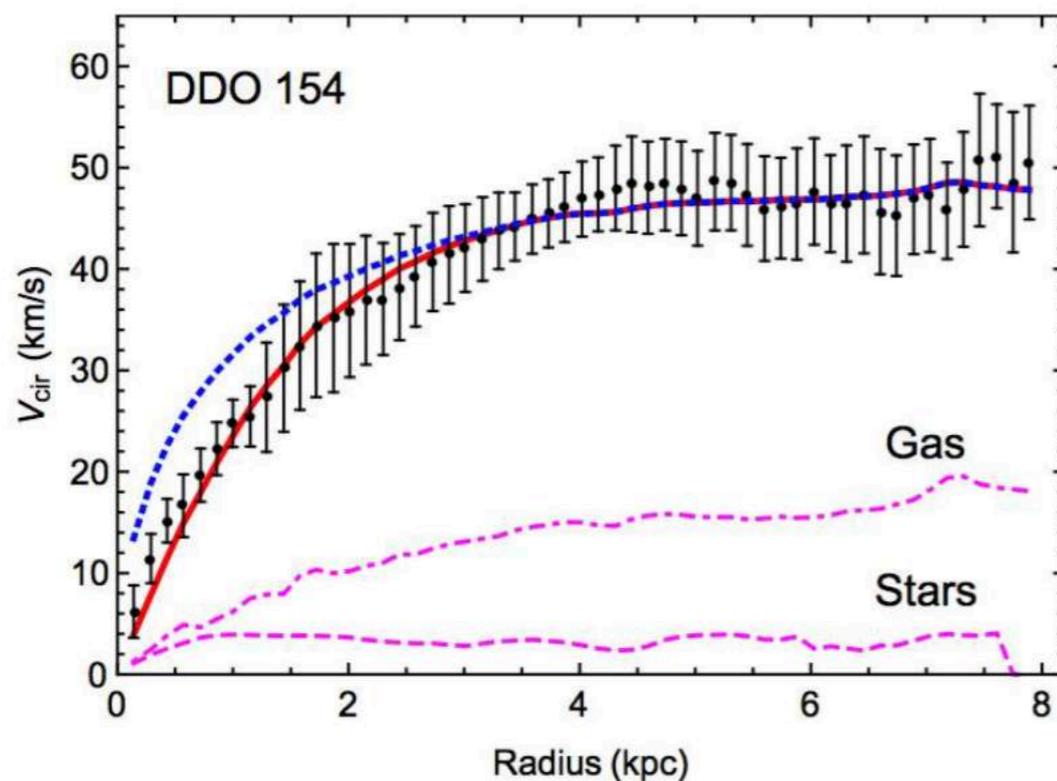
Universal CDM-only prediction:
Navarro-Frenk-White profile.

Central density & scale radius
from N-body are correlated:
mass-concentration relation



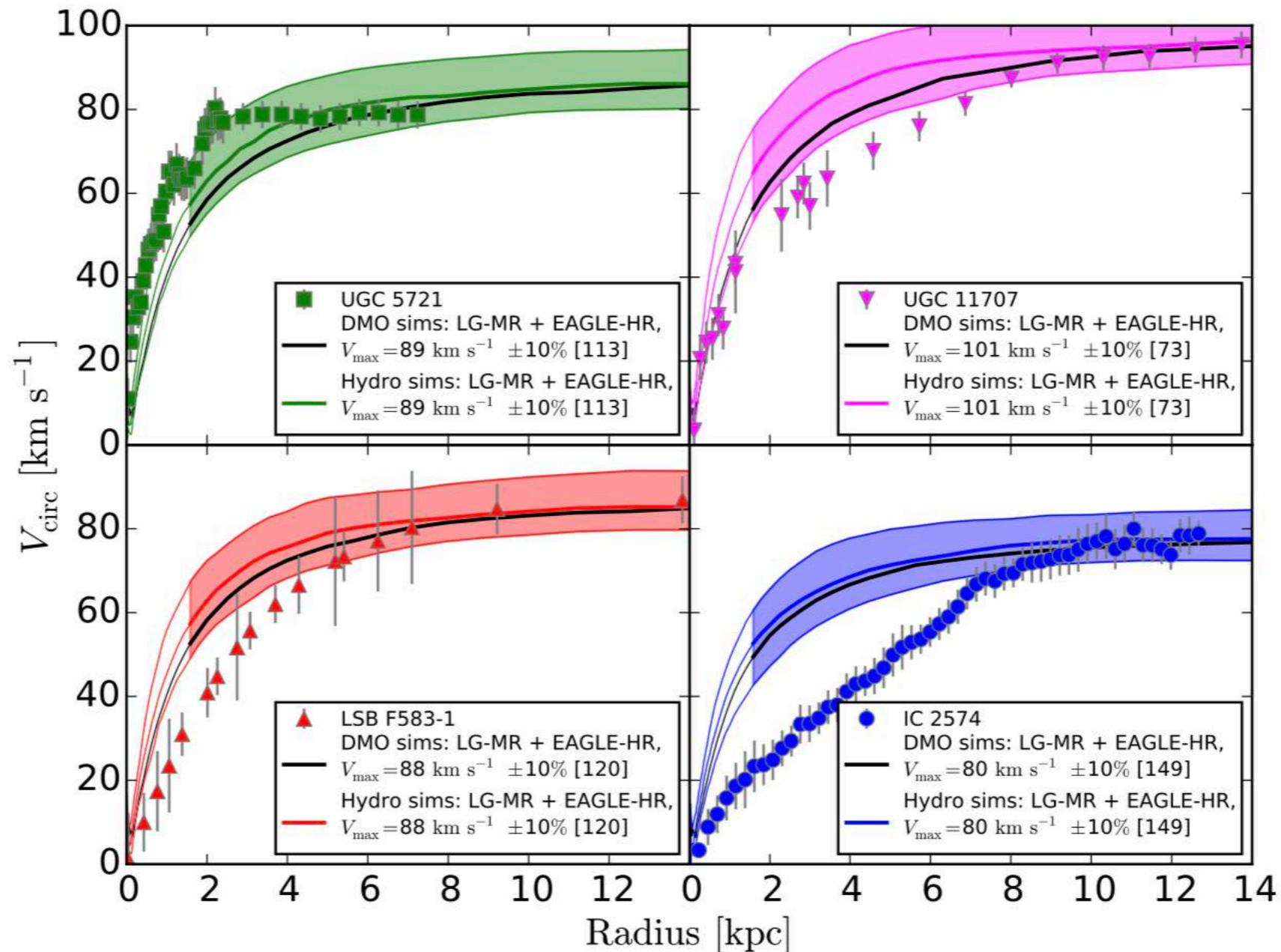
CDM fails in reproducing
many galactic rotation curves
w/o baryonic physics!

1) Core VS Cusp Problem



II) Diversity Problem

While “gastro-physics” does alleviate (or completely solves?) Core VS Cusp ...

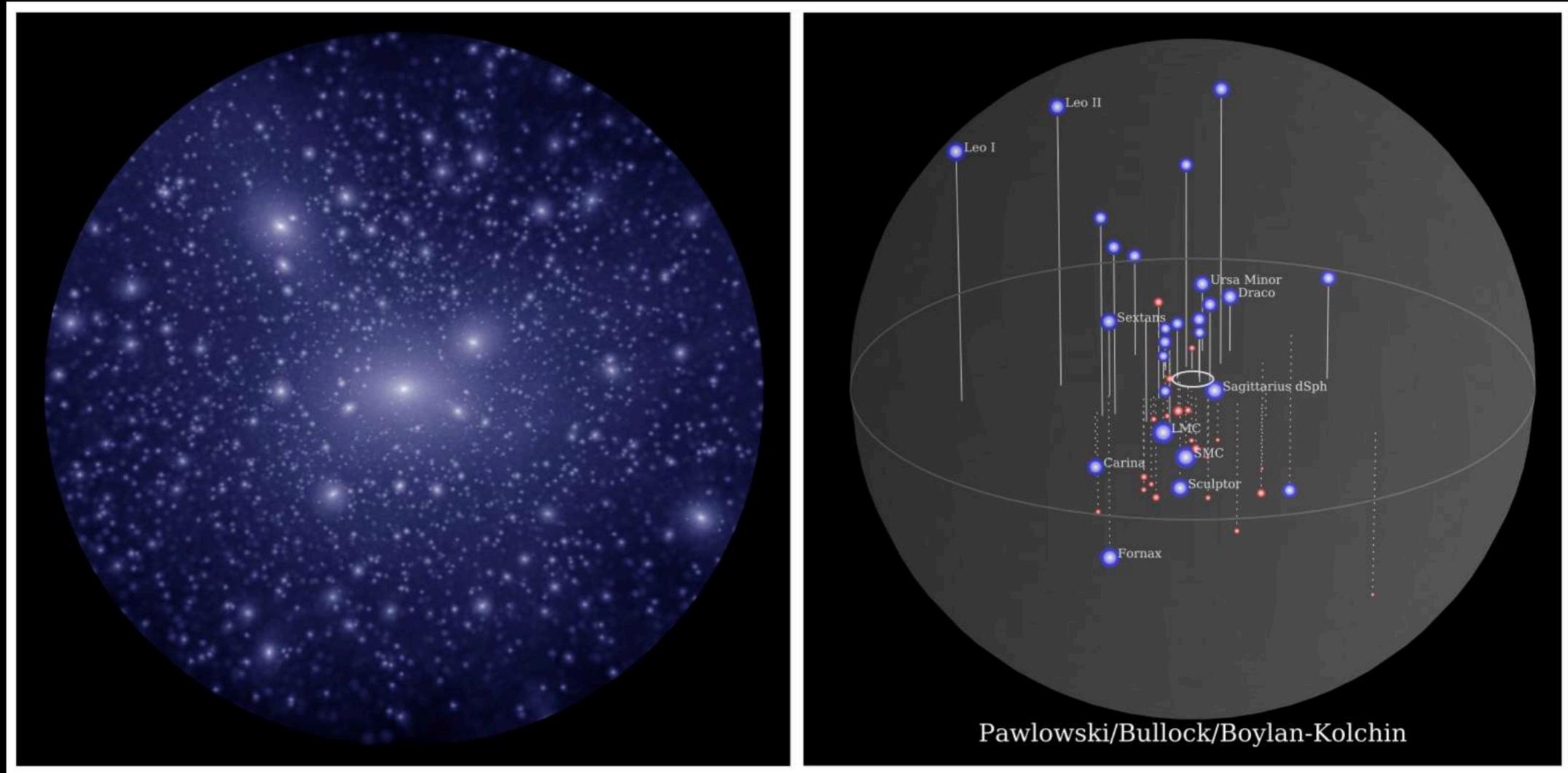


MNRAS 452 (2015) 3650

... Diversity of rotation curves is much harder to address (and digest)!

III) Missing Satellite problem

Ann. Rev. Astron. Astrophys. 55 (2017) 343-387



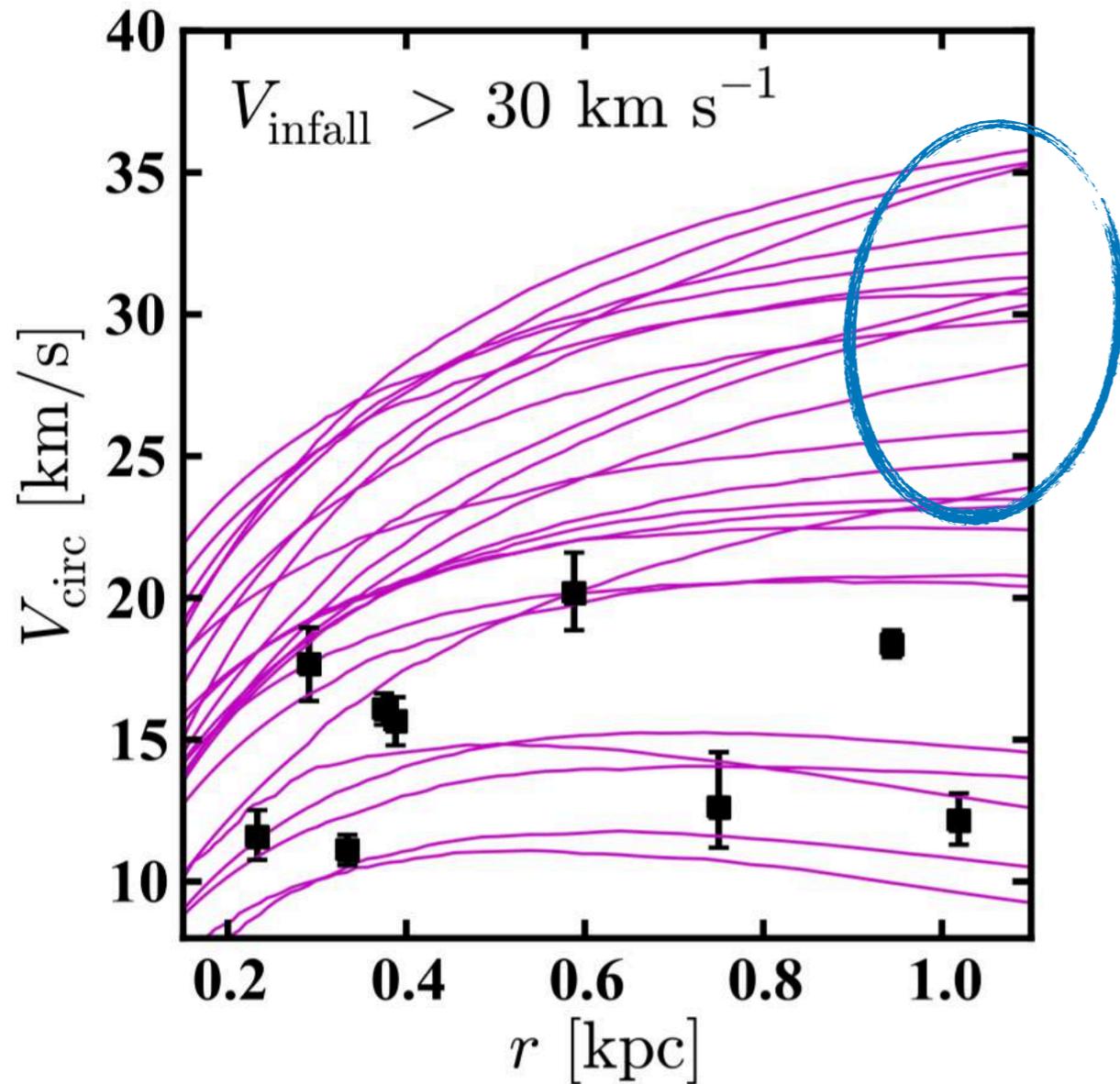
$\sim \mathcal{O}(10^3)$

$\sim \mathcal{O}(10)$

CAVEAT(s): detection efficiency/coverage + abundance-matching scatter,
PRL 121 (2018) 21, 211302, S.Y.Kim et al.

role of Milky Way disk, *MNRAS* 487 (2019) 3, 4409-4423,
T.Kelley et al.

STUDY OF DYNAMICS IN MILKY WAY'S DWARF SPHEROIDAL GALAXIES BRING TO ANOTHER POSSIBLE TENSION.



dSph V_{circ} @ $r_{1/2}$ from stellar kinematics

$$M(r_{1/2}) \Rightarrow V_{\text{circ}}(r_{1/2}) = \sqrt{3\langle\sigma_{los}^2\rangle}$$

IV) Too Big To Fail (TBTf)

Most massive subhalos in CDM seem too dense to host observed brightest satellites ...
... but why they should be dark?

ALLEVIATING FACTORS:

- *Dependence on the mass of host galaxy*
—> *MNRAS 424 (2012) 2715*
- *Host galaxy tidal field + baryonic physics*
—> *MNRAS 457 (2016) 1931*

*MNRAS 415 (2011) L40,
MNRAS 422 (2012) 1203*

M. Boylan-Kolchin, J.S. Bullock
and M. Kaplinghat

SMALL-SCALE RECAP

I) Mechanism for cores

II) Diversity of galaxies

with similar V_{\max}

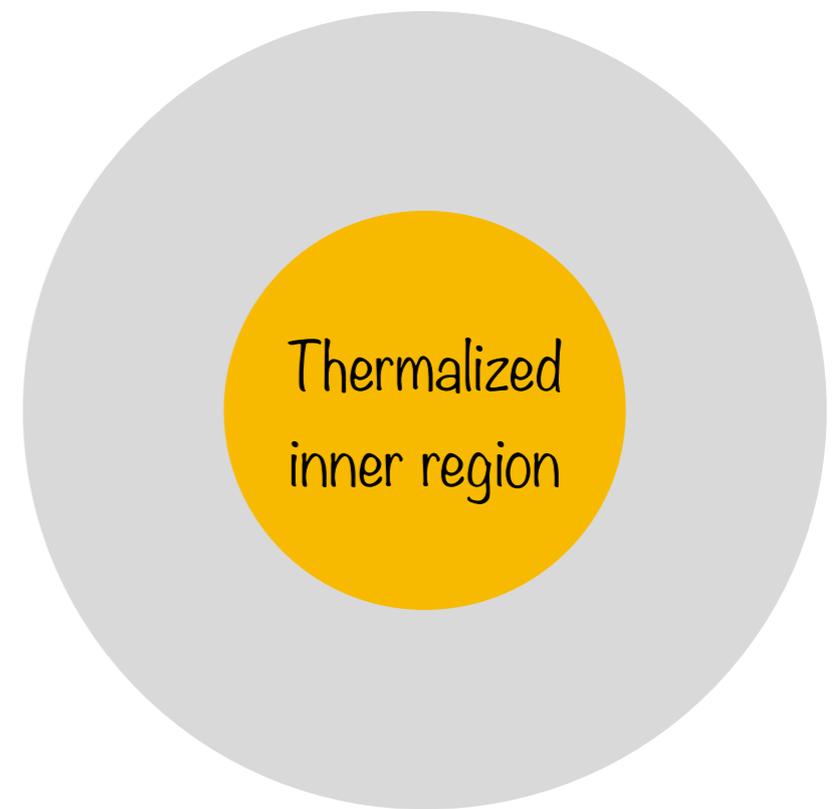
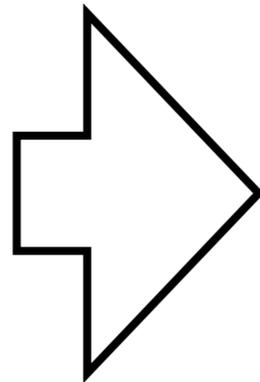
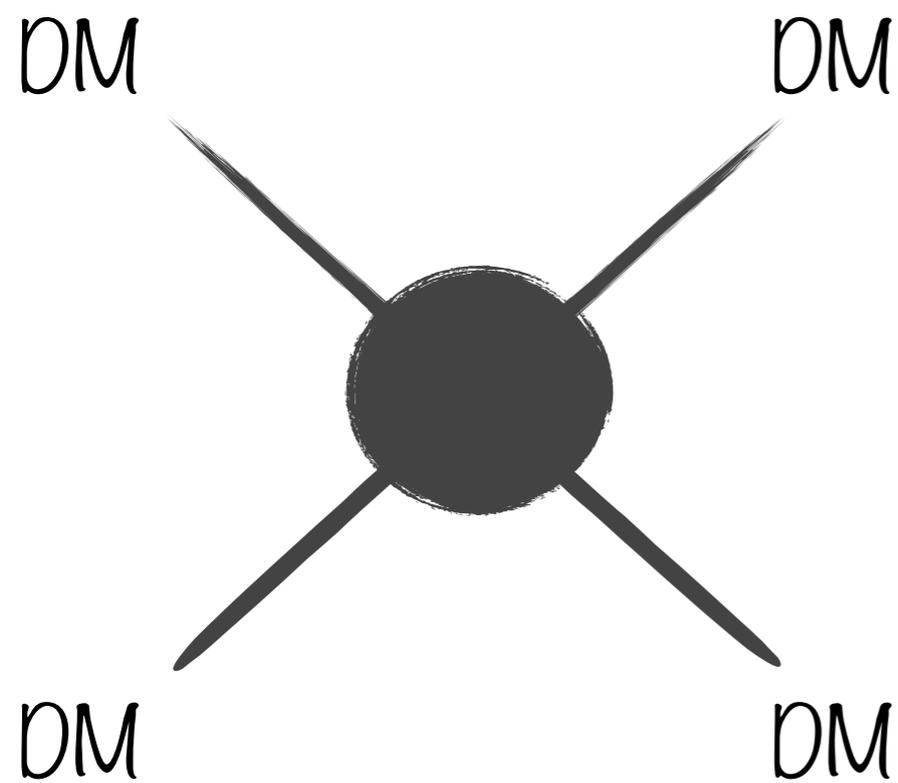
—> related to field galaxies

III) How many satellites ?

IV) Satellite dynamics: TBTF

—> related to satellite galaxies

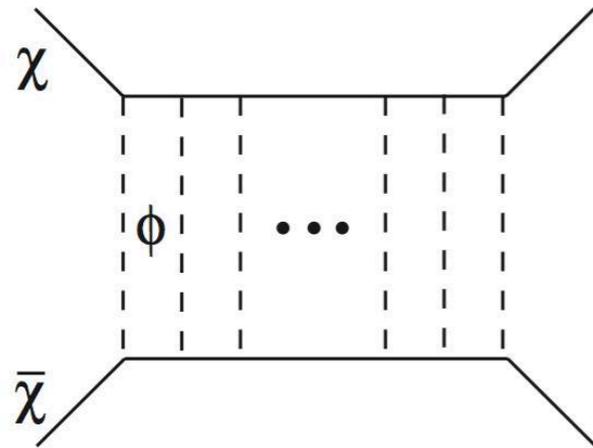
Self-Interacting DM (SIDM)



Galactic DM halo

SIDM: EXAMPLES FROM PARTICLE PHYSICS

Self-Interactions with Light Mediators



PRL 104 (2009) 151301, J. Feng et al.

PRD 81 (2010) 083522, M.R. Buckley & P.J. Fox

PRL 110 (2013) 111301, S. Tulin et al.

LIGHT MEDIATOR MODELS ALLOW FOR DM
V-DEPENDENT SELF-SCATTERING X-SEC

CMB constraints may be very relevant.

→ avoid thermal eq. with SM bath!

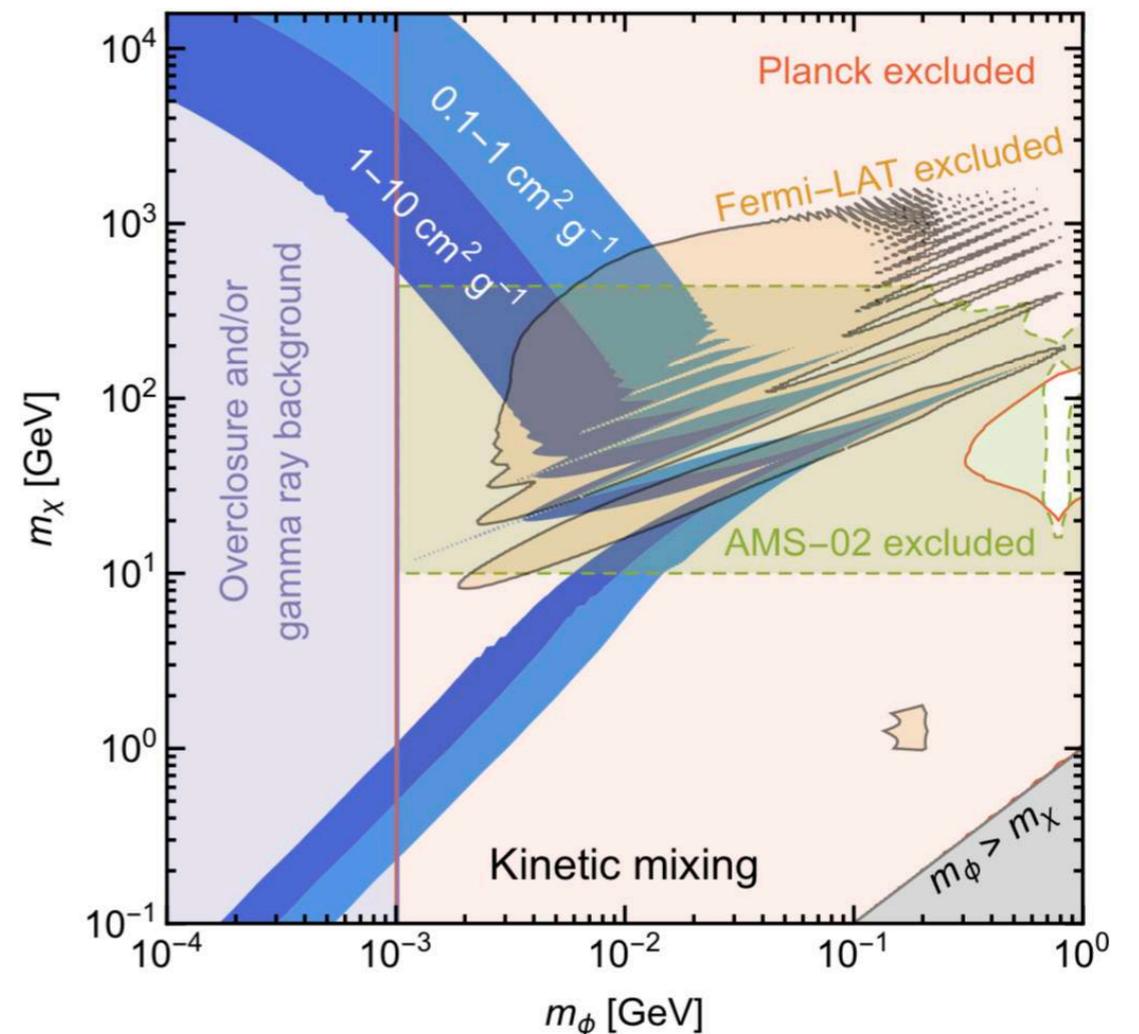
PRL 118 (2017) 14, 141802, T. Bringmann et al.

PRD 101 (2020) 5, 055044, N. Bernal et al.

Large self-scattering points to MeV mediators for weak-scale DM (perturbative regime):

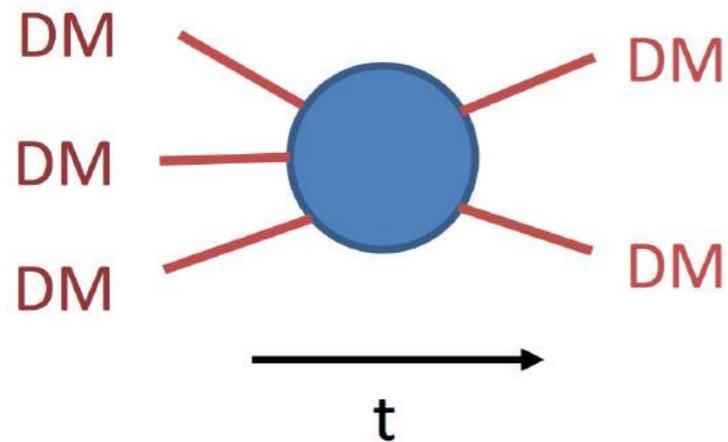
$$g^4 \frac{m_\chi^2}{m_\phi^4} \sim 10^{14} \frac{\alpha_{EW}^2}{m_\chi^2} \Rightarrow \frac{m_\phi}{m_\chi} \sim \left(\frac{g}{0.1}\right)^4 10^{-4}$$

→ $U(1)_D$ coupled to SM via $U(1)_Y$ mixing



SIDM: EXAMPLES FROM PARTICLE PHYSICS

Strongly Interacting Massive Particles



PRL 113 (2014) 171301, Y. Hochberg et al.

PRL 115 (2015) 021301, Y. Hochberg et al.

@ strong coupling, strong scale emerges:

$$m_{DM} \sim \alpha_{eff} (T_{eq}^2 M_{Pl})^{1/3}$$

“Simple” realizations involve non-Abelian dark sector with QCD-like chiral symmetry breaking

Dominant 3, 4 \rightarrow 2 annihilations, dark sector cannot be completely secluded from SM

ApJ 398 (1992) 43, E.D. Carlson et al.

NAIVELY, IN THESE MODELS ONE WOULD NOT EXPECT V-DEPENDENCE IN THE SELF-SCATTERING X-SEC OF DM.

CAVEAT:

QCD-like resonances

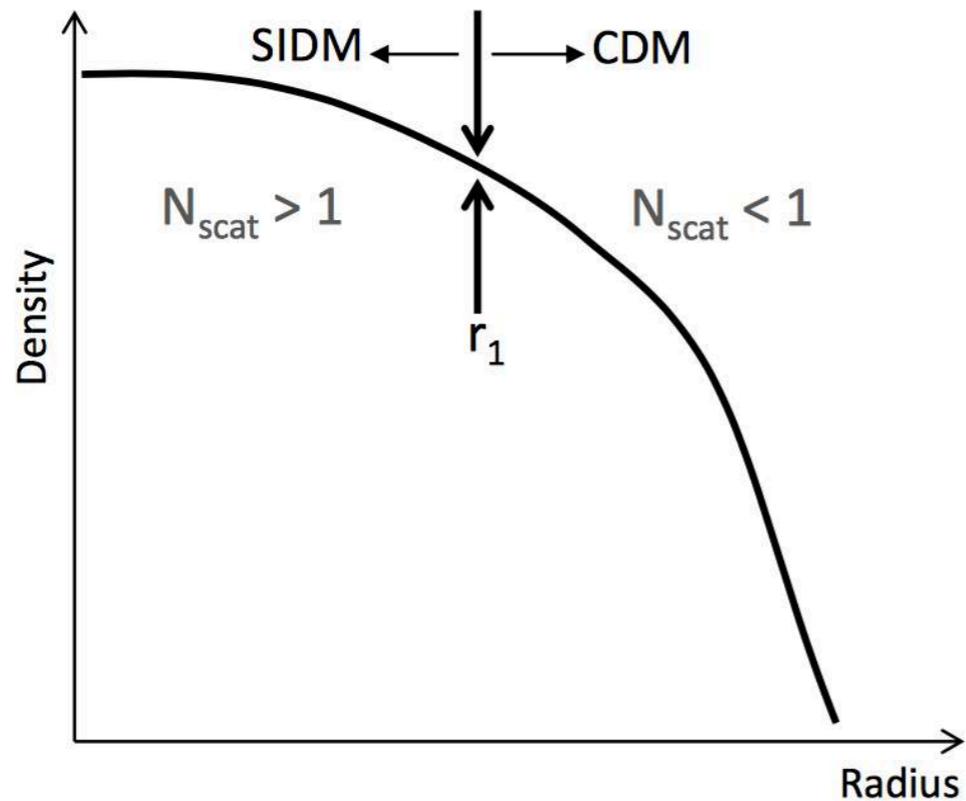
PRL 122 (2019) 7, 071103, X. Chu et al.

JCAP 06 (2020) 043, X. Chu et al.

$$\sigma = \sigma_0 + \frac{4\pi S}{mE(v)} \frac{\Gamma(v)^2/4}{[E(v) - E(v_R)]^2 + \Gamma(v)^2/4}$$

velocity dependence a la Briet-Wigner

Beyond CDM : SIDM galactic halo



$$\Gamma_{\text{scatt.}}|_{r=r_1} \simeq t_{\text{age}}^{-1}, \quad \Gamma_{\text{scatt.}} = \frac{\langle \sigma v \rangle}{m} \rho(r)$$



POINT is **INNER HALO THERMALIZATION**

$$\nabla p = -\rho \nabla \phi_{\text{tot}}, \quad p = \sigma_0^2 \rho.$$

PRL 113 (2014) 021302, PRL 116 (2016) 041302

SEMI-ANALYTIC MODEL

$$\rho_{\text{SIDM}}(r) = \begin{cases} \rho_{\text{ISO}}(r) & \text{if } r \leq r_1 \\ \rho_{\text{NFW}}(r) & \text{if } r \geq r_1 \end{cases}$$

+ same matching on the mass profile.

VALIDATED BY N-BODY SIMULATIONS

See, e.g., recent ***MNRAS 501 (2021) 3***



**CDM success inherited
at cosmological scales**

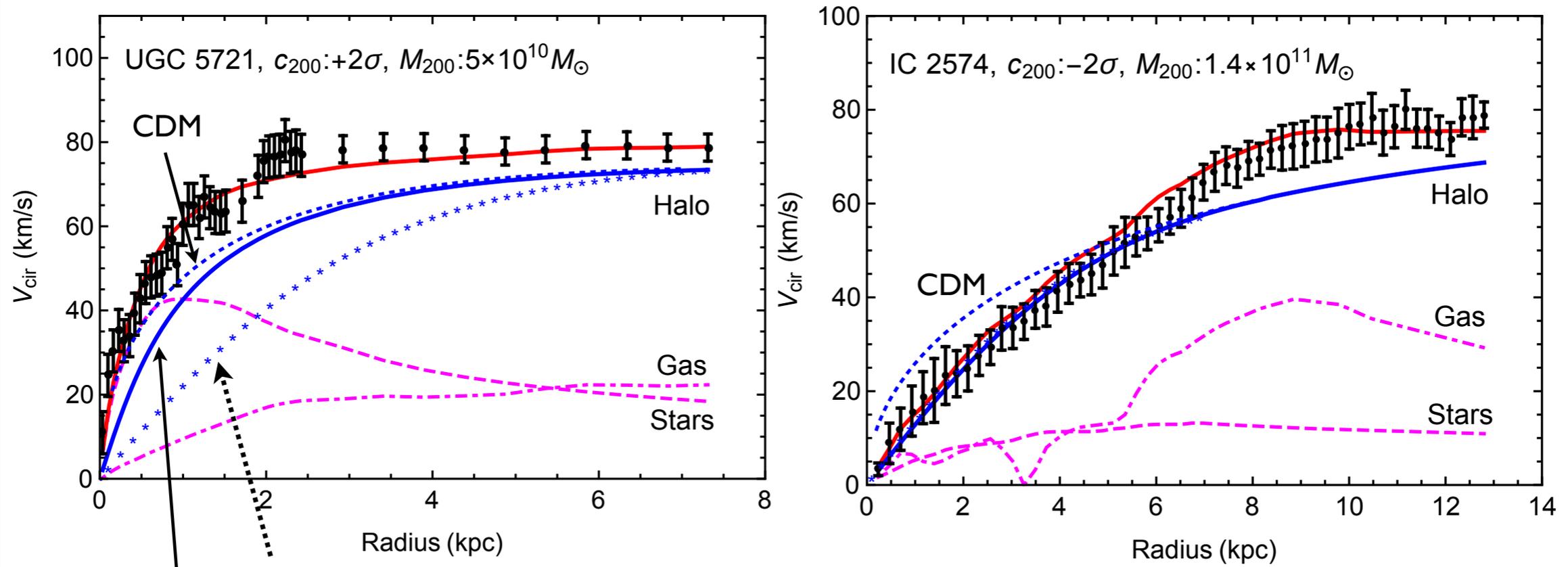
MNRAS 423 (2012) 3740, 430 (2013) 81



**DM & baryon distributions
correlated —> diversity!**

PRL 119 (2017) 111102, JCAP 06 (2020) 027

Solving the Diversity Problem



Isothermal profile without the baryonic influence

True SIDM profile with the baryonic influence

30 galaxies

- Scatter in the halo concentration-mass relation
- Baryon distribution
- DM self-interactions thermalize the inner halo and correlate DM and baryon distributions

$V_{\text{max}} \sim 25\text{-}300$ km/s

with Kamada, Kaplinghat, Pace (2016)



Astrophysical Object \longleftrightarrow Different Collider



Dwarf galaxy

Low energies ($v/c \sim 10^{-4}$)



Spiral galaxy

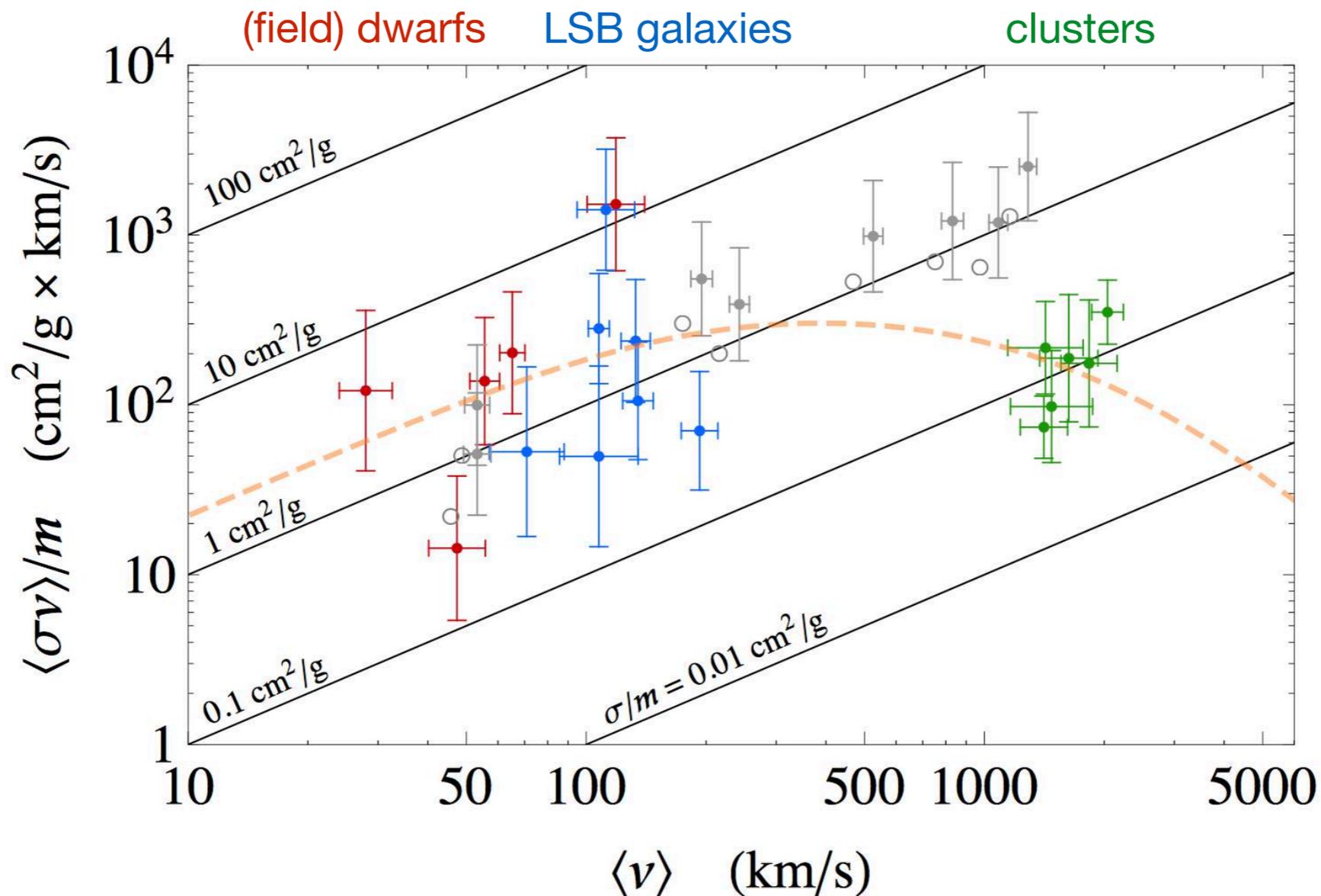
Medium energies ($v/c \sim 10^{-3}$)



Cluster of galaxies

High energies ($v/c \sim 10^{-2}$)

PRL 116 (2016) 041302, M.Kaplinghat, S.Tulin & H.B.Yu





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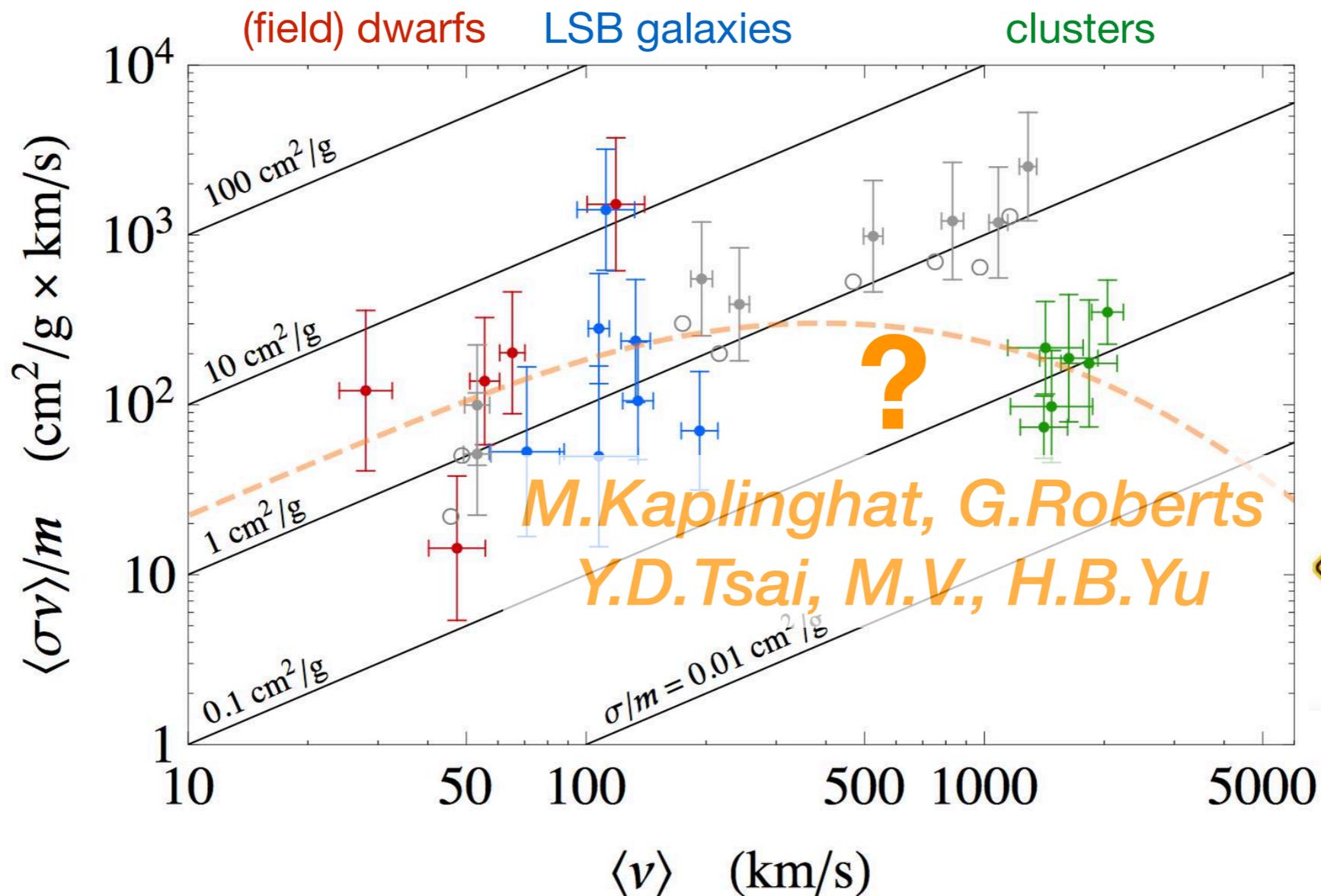
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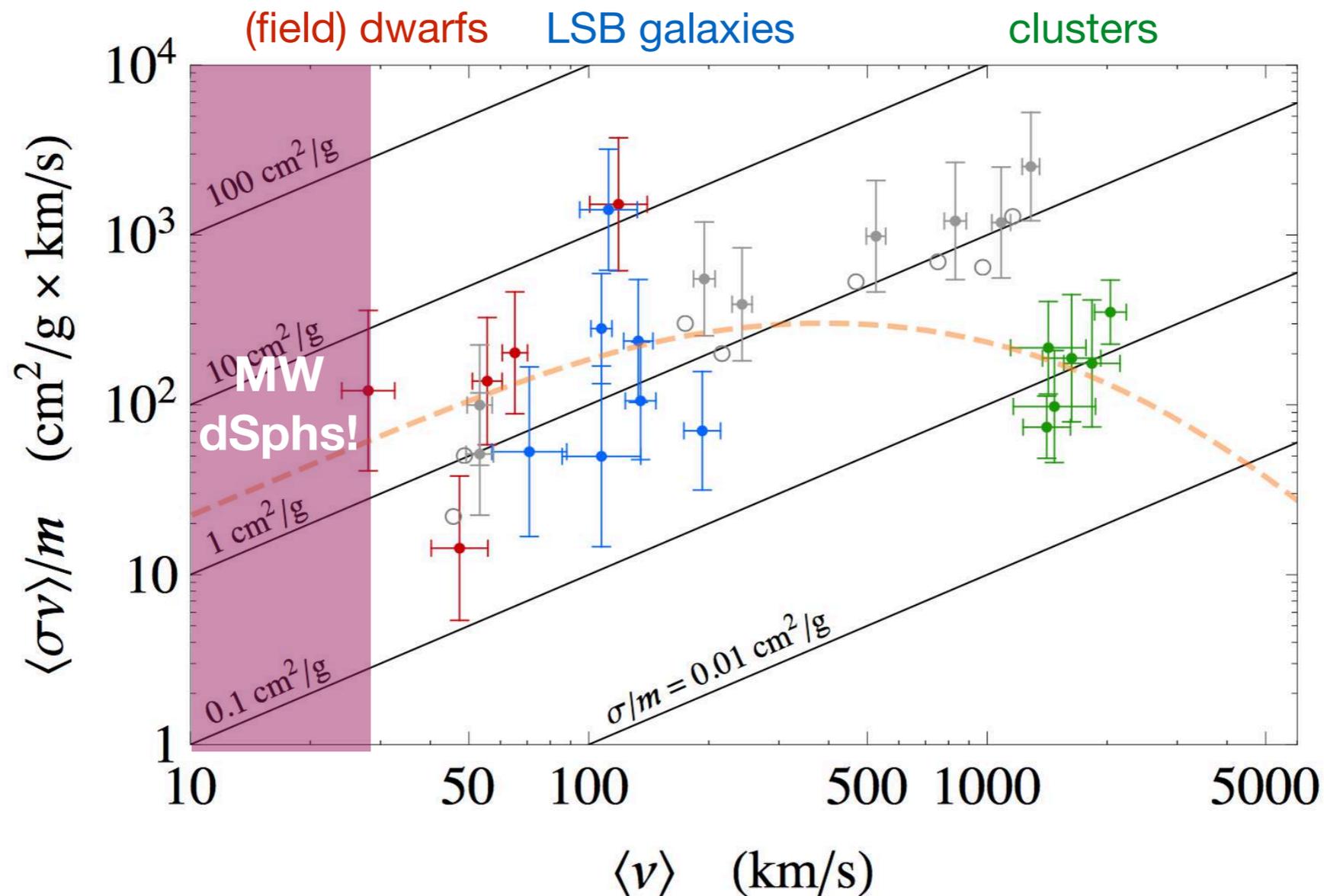
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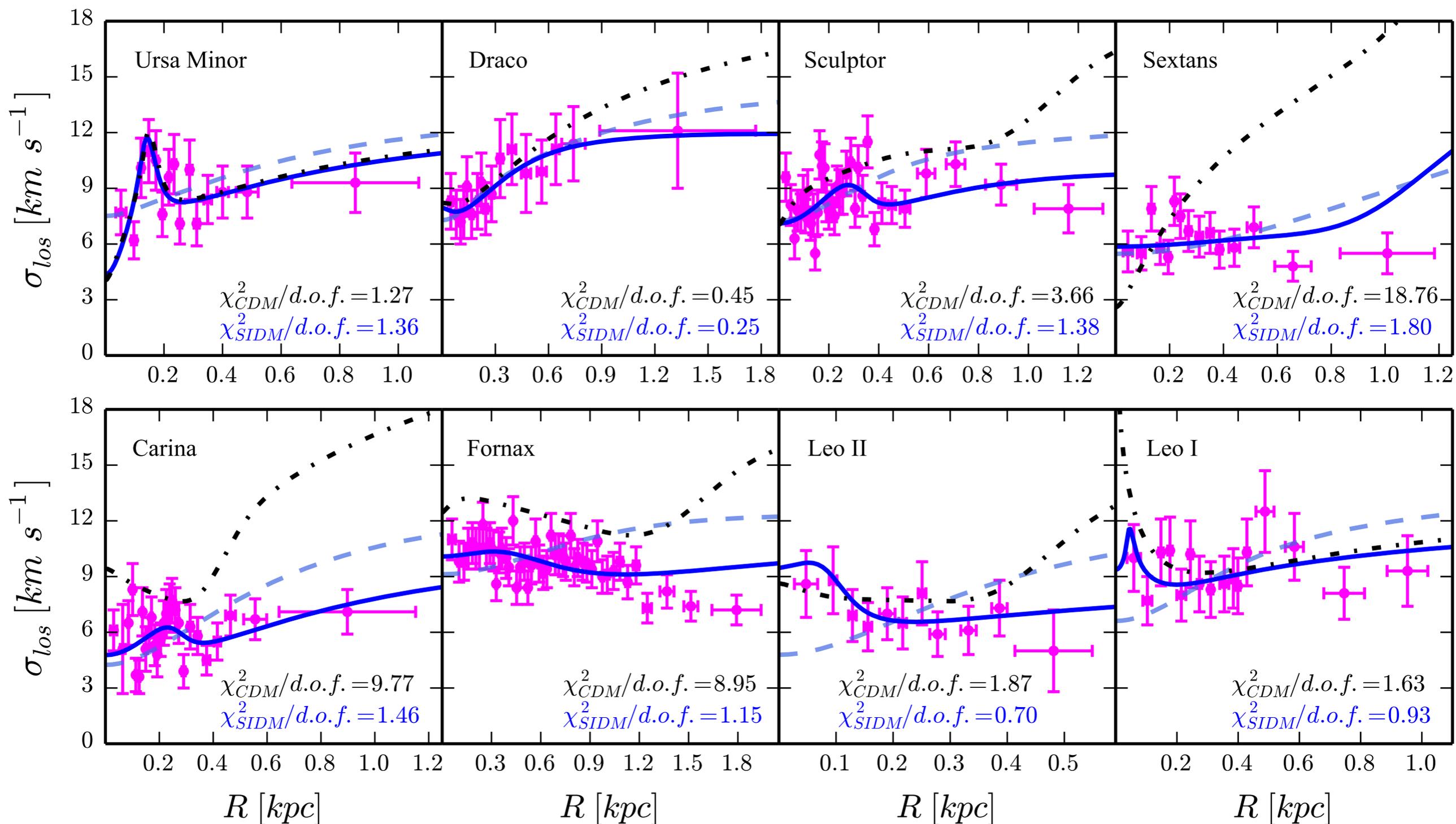


Cluster of galaxies

High energies ($v/c \sim 10^{-2}$)

PRL 116 (2016) 041302, M.Kaplinghat, S.Tulin & H.B.Yu





Dot-Dashed: CDM best fit
(2+4 params)

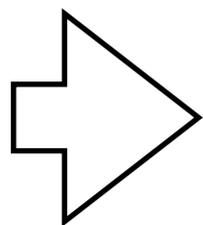
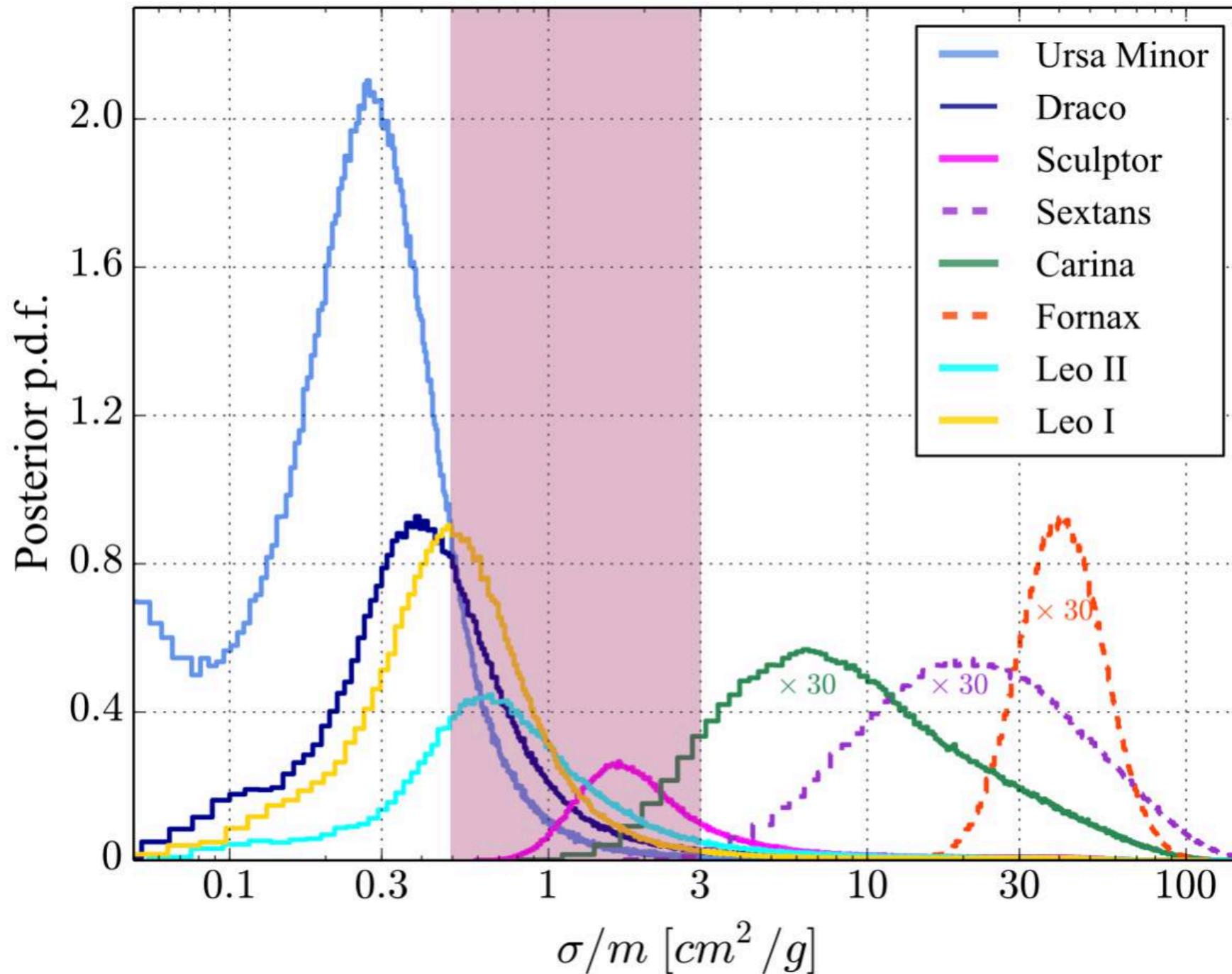
Dashed: SIDM best fit
(3+1 params)

Continuous: SIDM best fit
(3+4 params)

MCMC analysis allows estimate of DM self-scattering x-section

Nature Astronomy 2, 907 - 912 (2018)

M.V. & H.B. Yu



MILKY WAY'S TBTF SHOWS A NEW DIVERSITY PROBLEM !

A “model-independent” approach to characterize TBTF puzzle.

i) Forget about cosmological priors.

Study both cuspy & cored profiles w/o cosmological priors

ii) Focus on best inferred inner-halo density .

Density at 150 pc, ρ_{150} , well-inferred (only) for brightest dSphs

iii) Look for possible interesting correlations ...

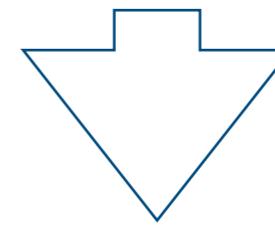
- ✗ *Star-formation shut-off time*
- ✗ *dSph stellar mass content*
- ✗ *dSph distance from MW*
- ✓ *Satellite orbital pericenter*

Astronomy & Astrophysics , 619 (2018)



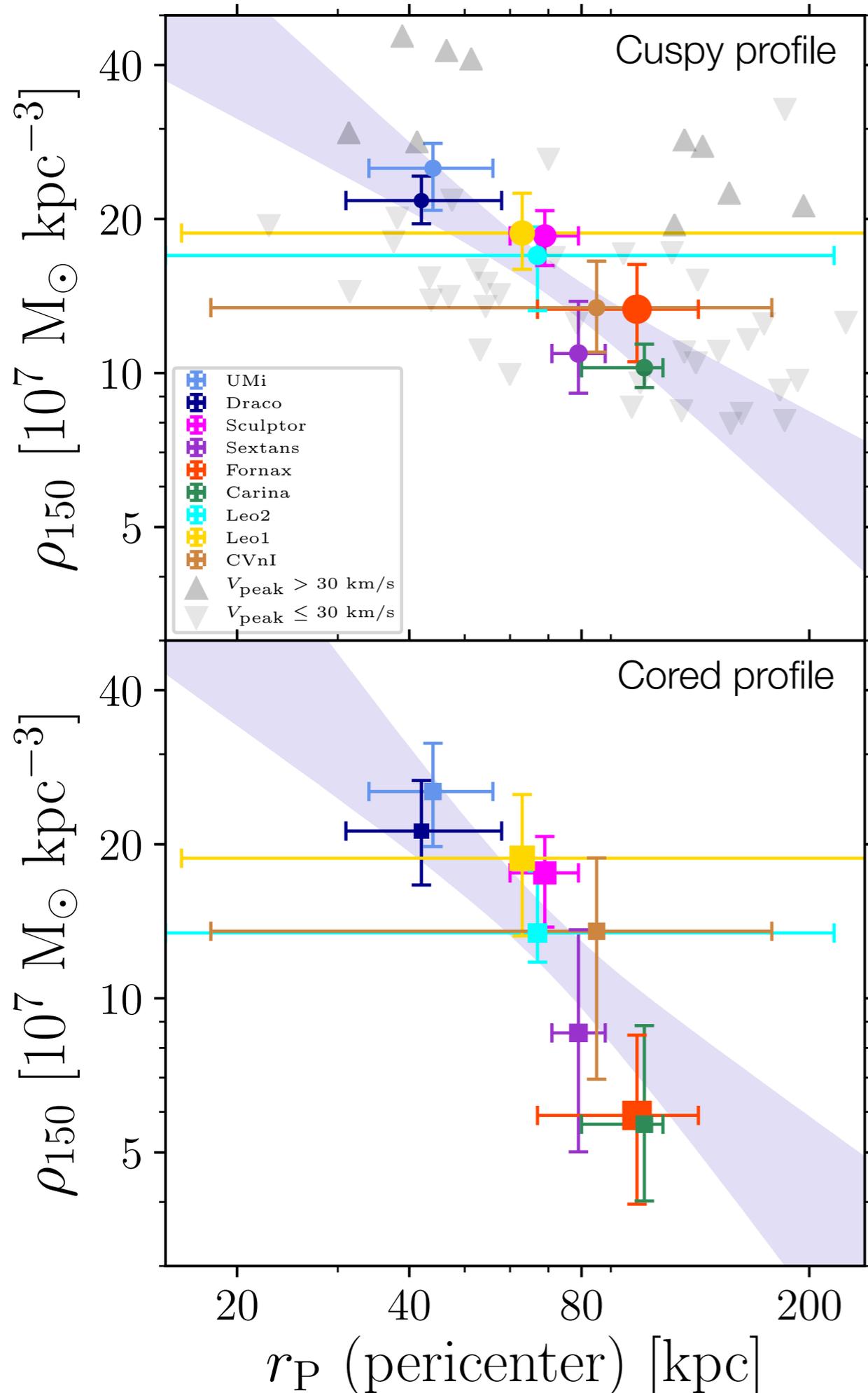
We found an **anti-correlation**
between inner DM density
of MW dSphs **and** their
orbital pericenter.

Triangle points from CDM-only ELVIS
MNRAS 444 (2014) 1, 222-236



Milky Way disk in CDM N-body reduces
subhalo inner densities for $r_P \lesssim 40$ kpc
MNRAS 490 (2019) 2, 2117-2123

... SO, MAYBE IN CDM WE WOULD
EXPECT AN OPPOSITE TREND?



BACK TO SIDM

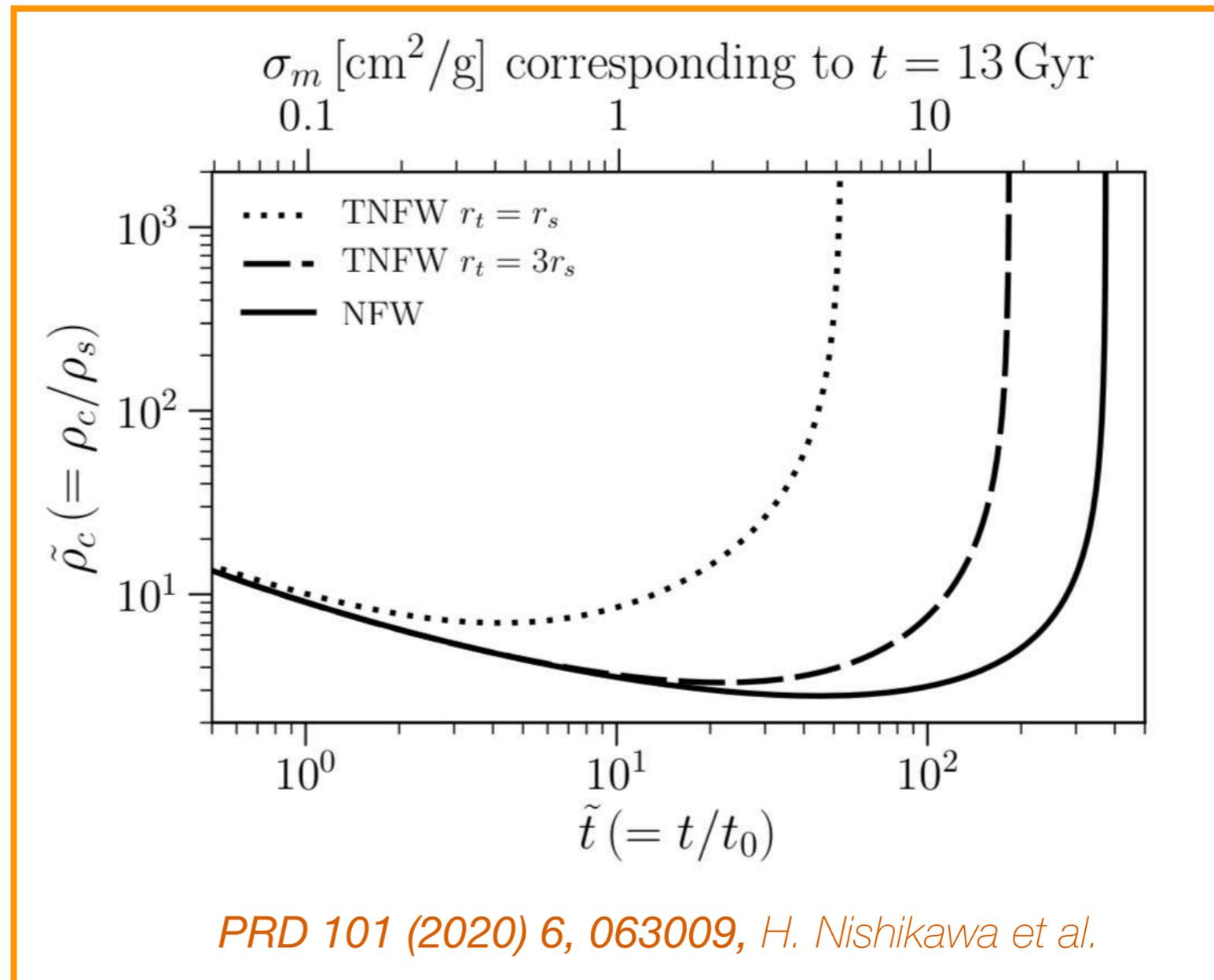
Another signature of SIDM is halo gravothermal collapse.

$$t_c \propto (\sigma/m)^{-1} M_{200}^{-1/3} c_{200}^{-7/2}$$

PRL 123 (2019) 12, 121102, R. Essig et al.



Time scale typically greater than age of Universe for O(1) x-sec!



HOWEVER, CORE-COLLAPSE TIME SCALE CAN BE SHORTENED BY HOST-GALAXY TIDES.

MW dSphs with small pericenter may be in the core-collapse phase.

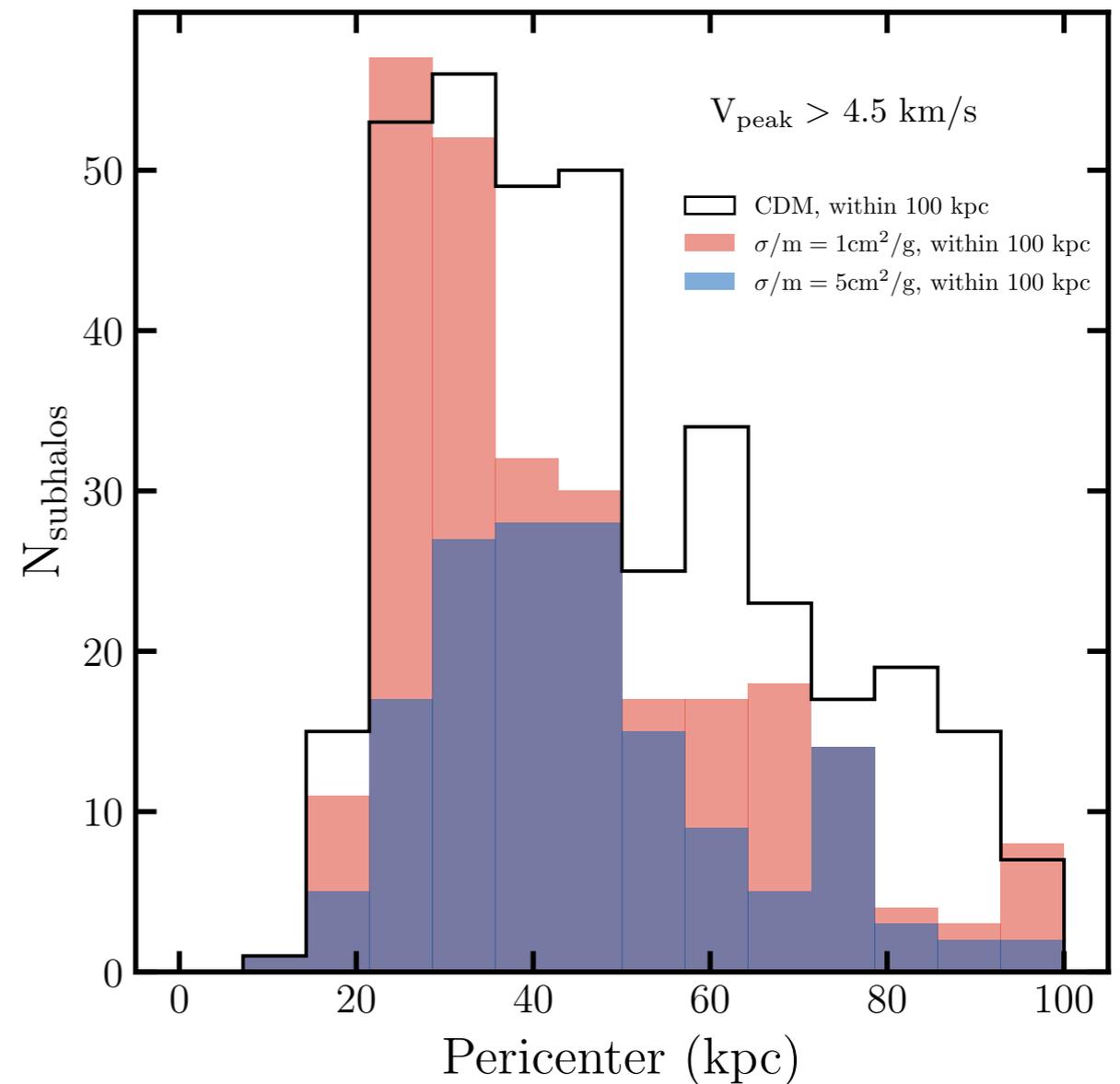
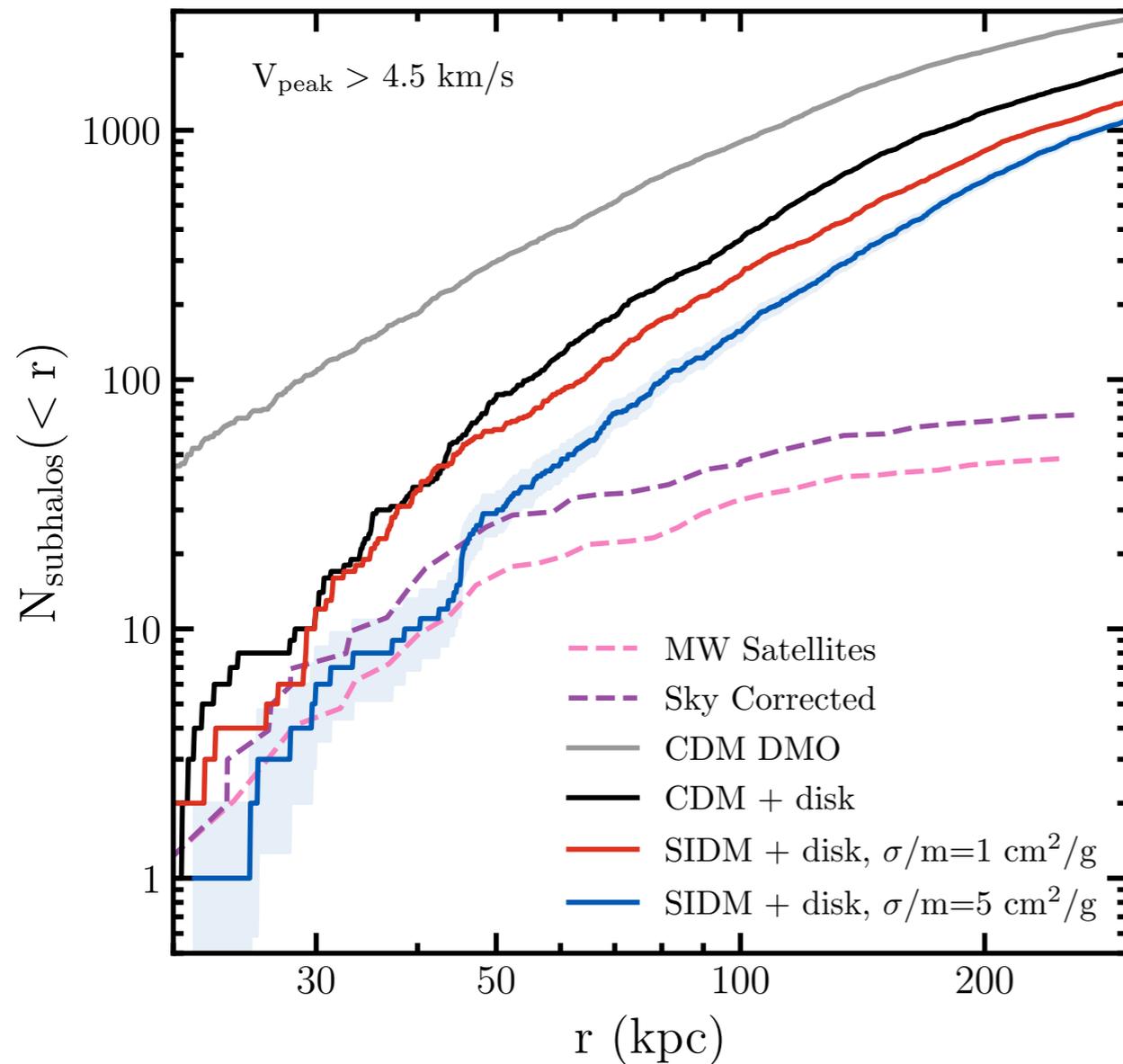
—> their inner density higher than one of dSphs with large pericenter.

Further hints on DM self-scattering x-section from simulations.

M.Silverman, J.S.Bullock, M.Kaplinghat, V.Robles, M.V. (in prep.)



RADIAL & PERICENTER DISTRIBUTIONS: OTHER DISCRIMINANTS?



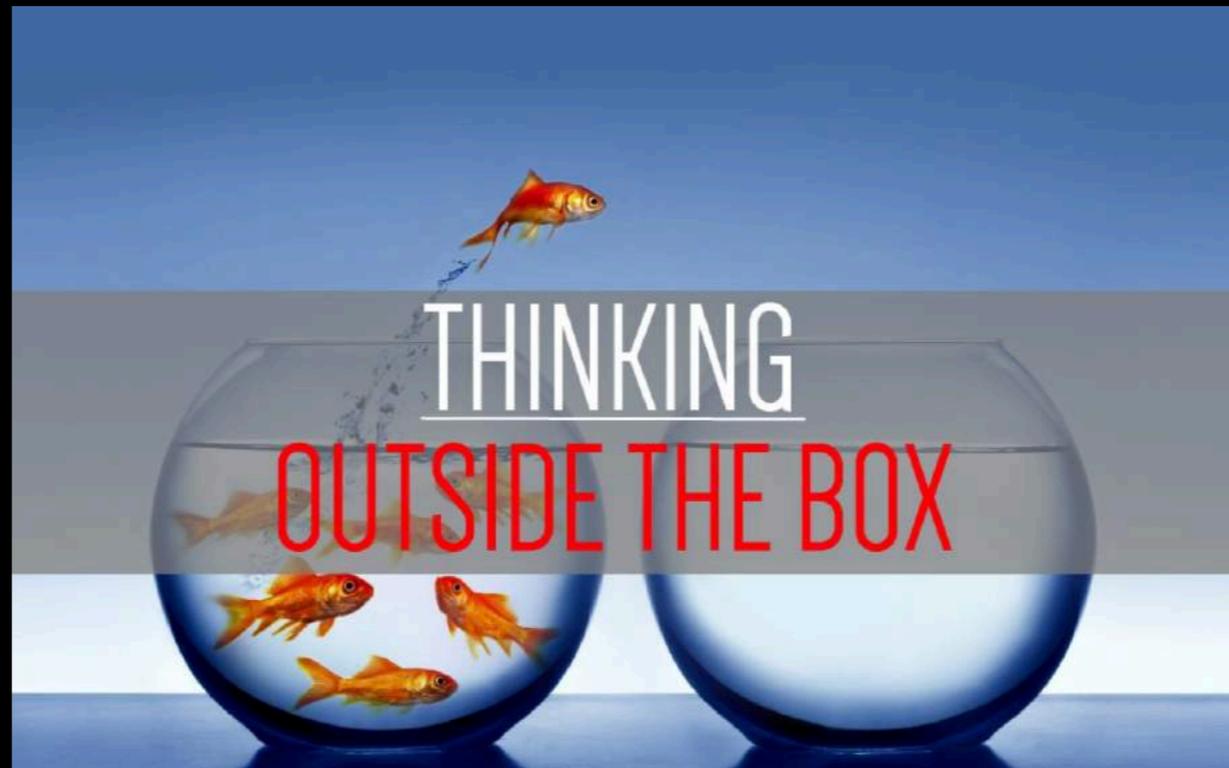


Take Home

- *Small-scale problems could point to fundamental physics*
- *SIDM seems to address present small-scale puzzles*

Key Astrophysical Signatures:

- *phase of halo thermalization*
- *phase of gravothermal collapse*



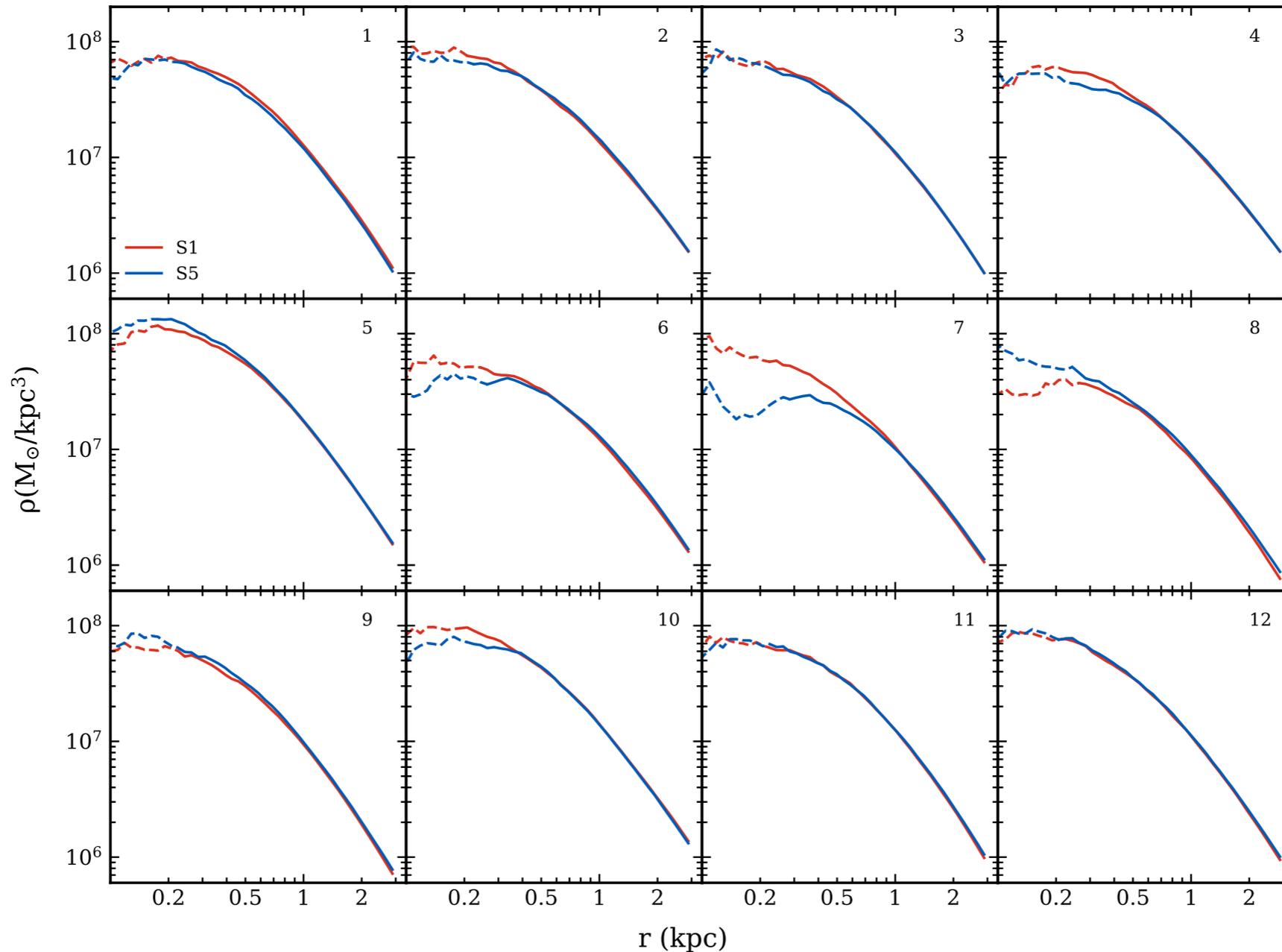
*IF DM INTERACTS WITH THE STANDARD MODEL MAINLY VIA GRAVITY ...
HOW CAN WE PROBE SUCH A “NIGHTMARE SCENARIO” ?*

BACK-UP

Further hints on large DM self-scattering x-section from simulations.

M.Silverman, J.S.Bullock, M.Kaplinghat, V.Robles, M.V. (in prep.)

ANY HINT OF CORE COLLAPSE FOR X-SEC $\sim 5 \text{ cm}^2/\text{g}$?

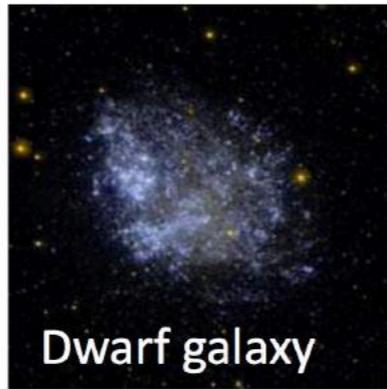


Simulation from **Phat ELVIS** suite: STATE-OF-THE-ART N-BODY FOR THE LOCAL GROUP

MNRAS 487 (2019) 3, 4409-4423



Astrophysical Object \longleftrightarrow Different Collider



Dwarf galaxy

Low energies ($v/c \sim 10^{-4}$)



Spiral galaxy

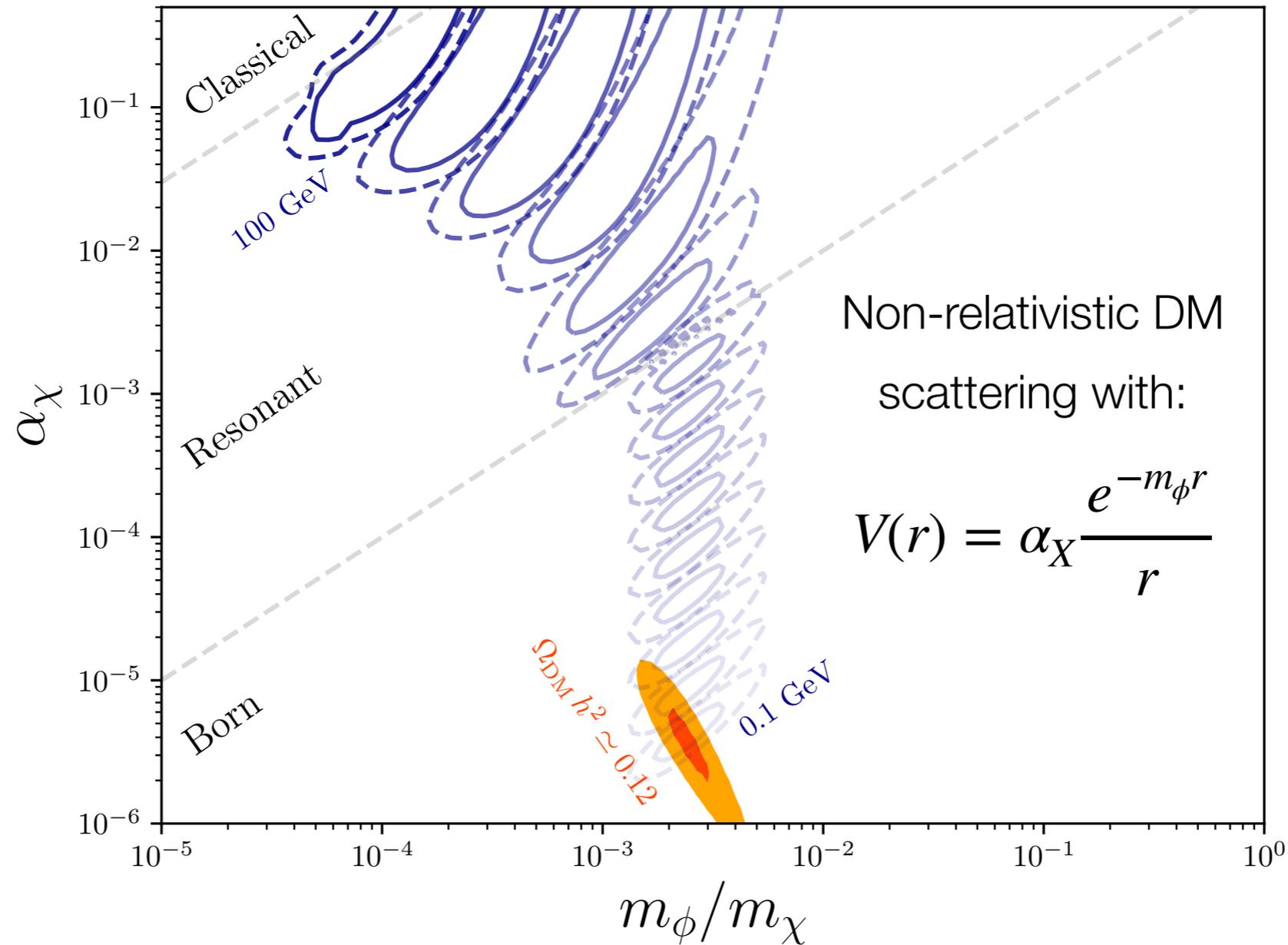
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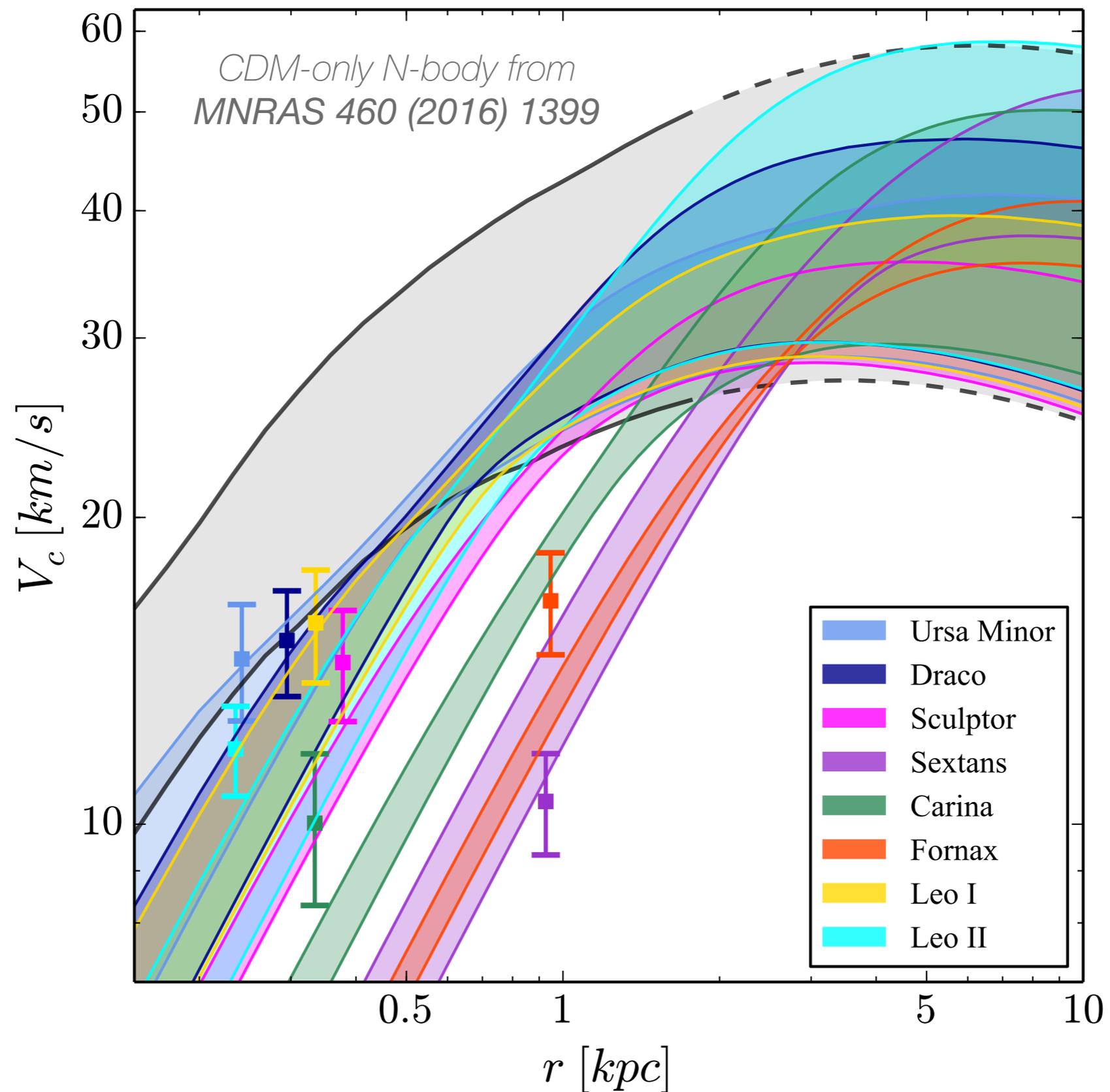
M.Kaplinghat, G.Roberts, Y.D.Tsai, M.V., H.B.Yu (in prep.)



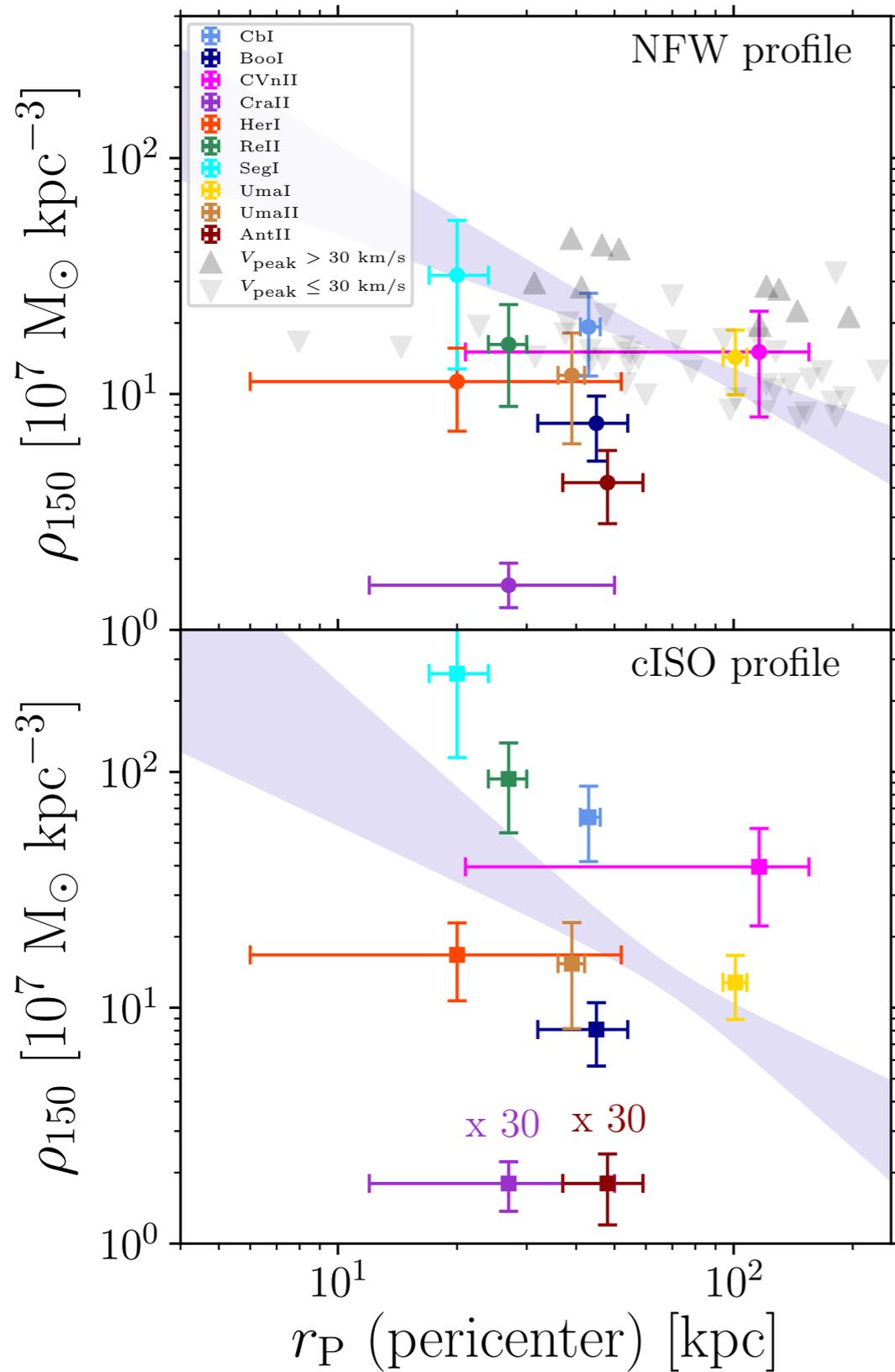
MCMC analysis allows sanity check on
CDM prior: recover CDM above kpc

Nature Astronomy 2, 907 - 912 (2018)

M.V. & H.B. Yu

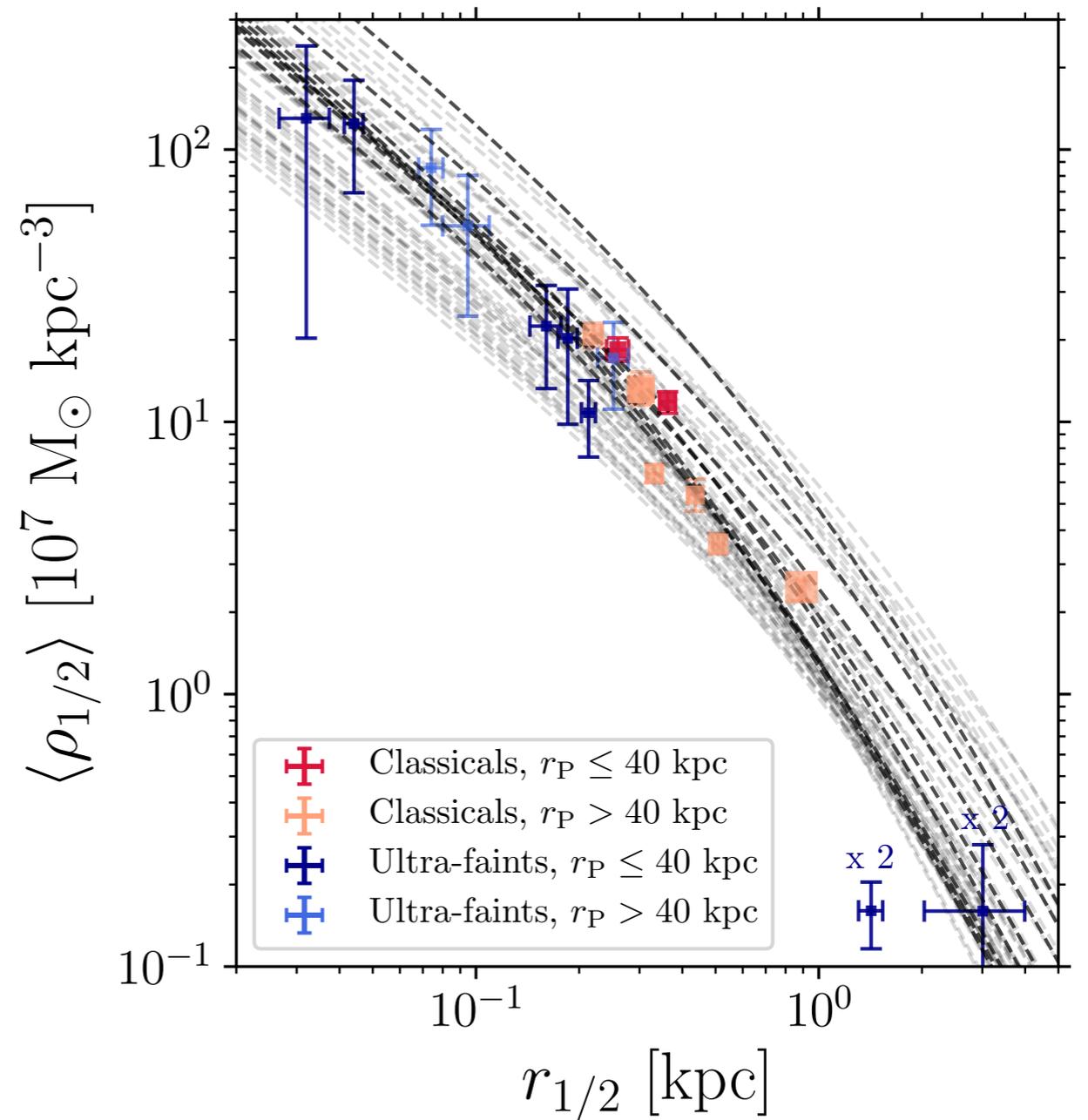


A look at Milky Way ultra-faints



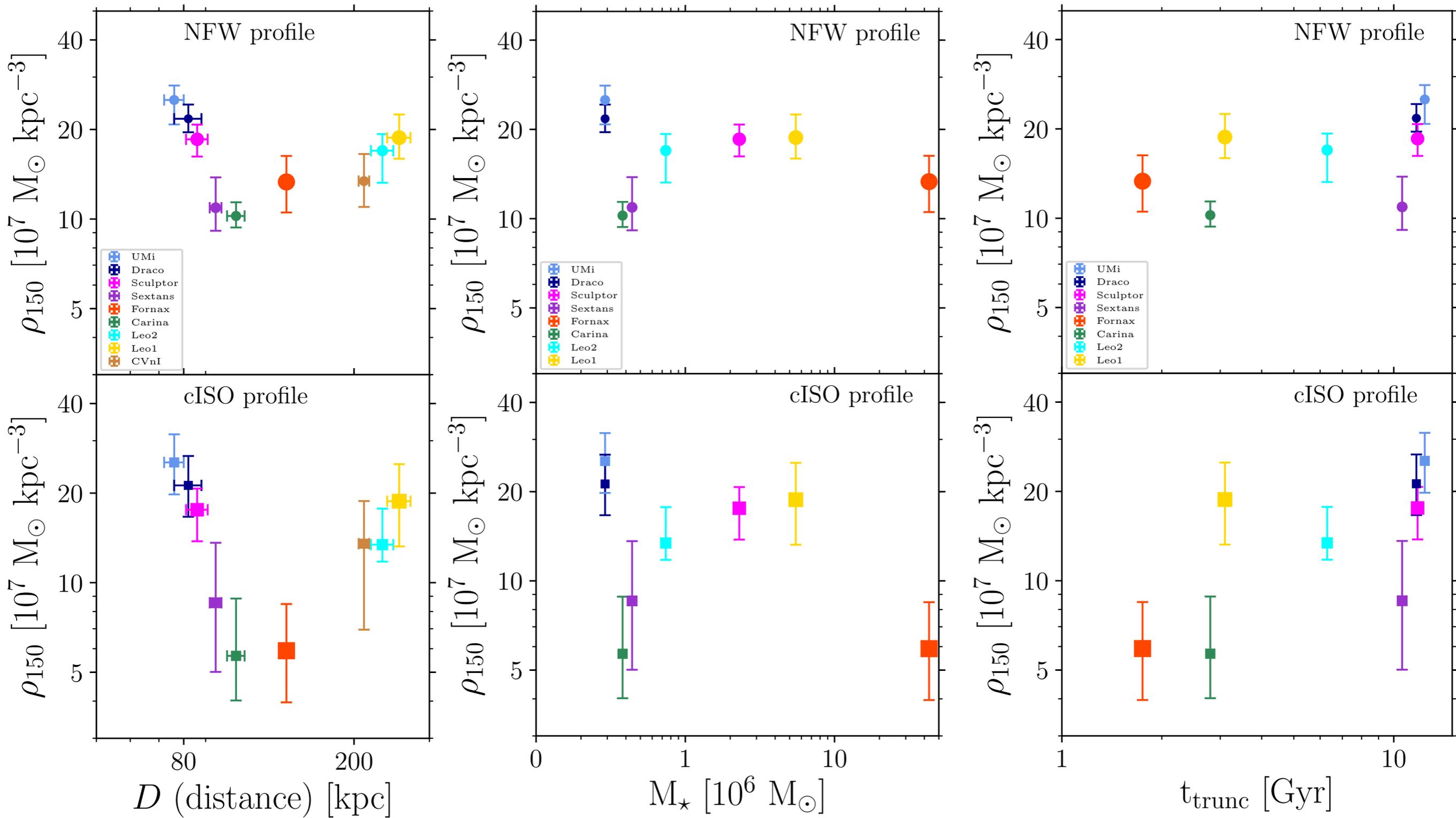
GENERAL TREND OBSERVED WHEN INCLUDING ULTRA-FAINTS:

$$\langle \rho_{1/2} \rangle \equiv M_{1/2} / (4\pi r_{1/2}^3)$$



However, see also: **PRD 103 (2021) 2, 023017, K.Hayashi et al.**

Other correlations investigated

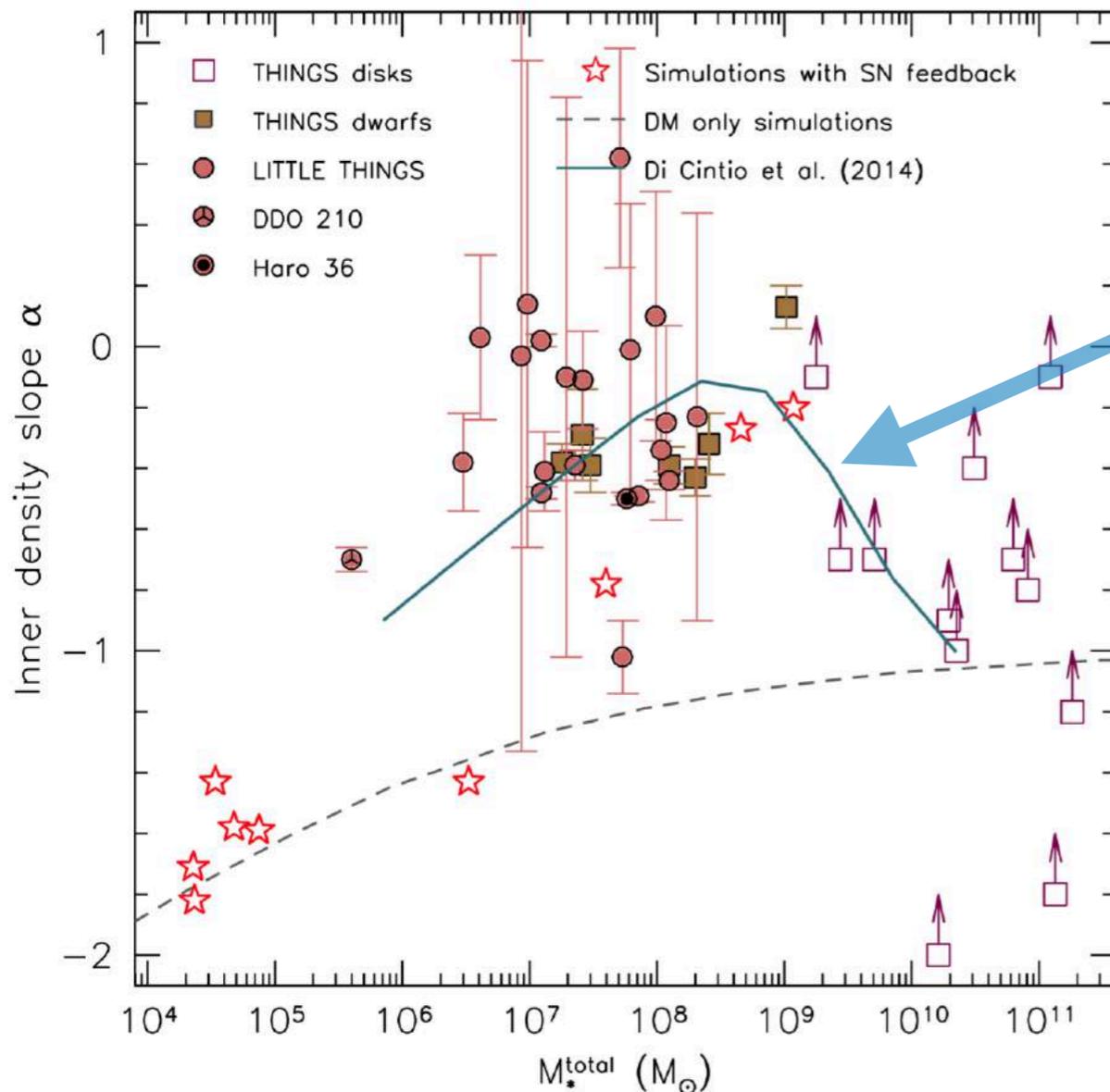
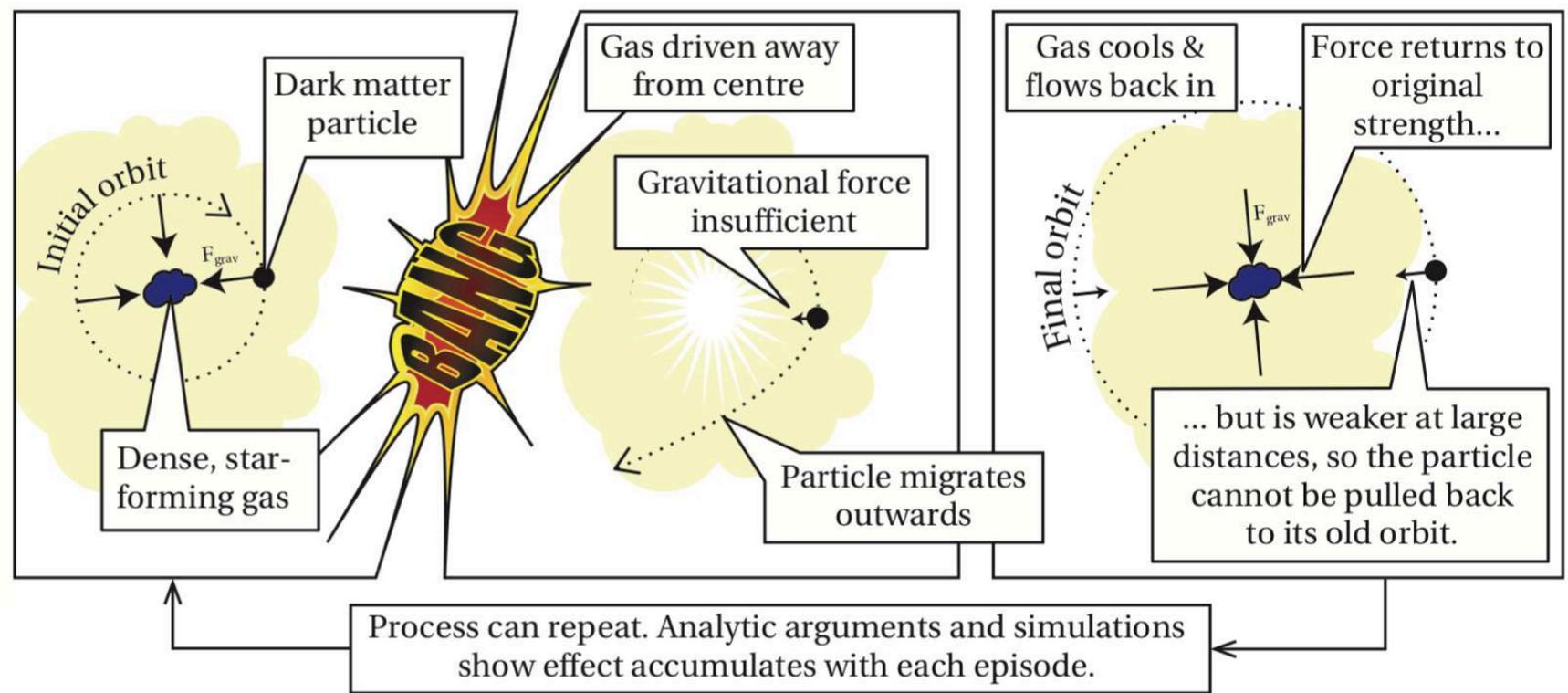


However, see also: ***MNRAS* 484 (2019) 1, 1401-1420, *J.Read et al.***

BARYONIC FEEDBACK

A SKETCHY CARTOON ON WHAT HAPPENS ...

F. Governato & A. Pontzen,
NATURE 506 (2014) 171



BARYONIC PHYSICS AFFECTS
CDM N-BODY INNER HALO

... **HOWEVER:**

- Depends on the stellar mass
Governato, F. et al. '12
- Depends on feedback details
T. K. Chan et al. '15

IT DEPENDS ON SPECIFIC HYDRO RECIPE!

See, e.g., **EAGLE, FIRE, NIHAO** codes ...

MASS MODELING FOR DWARF SPHEROIDALS

Collisionless Boltzmann equation : $\frac{\partial f_{\star}}{\partial t} + \vec{v} \cdot \nabla_{\vec{x}} f_{\star} - \nabla_{\vec{x}} \Phi_{\text{tot}} \cdot \nabla_{\vec{x}} f_{\star} = 0$

1) *DYNAMICAL EQUILIBRIUM*

2) *SPHERICAL SYMMETRY*

Evolution of phase-space density of star in the dSph, tracing distribution of Dark Matter.

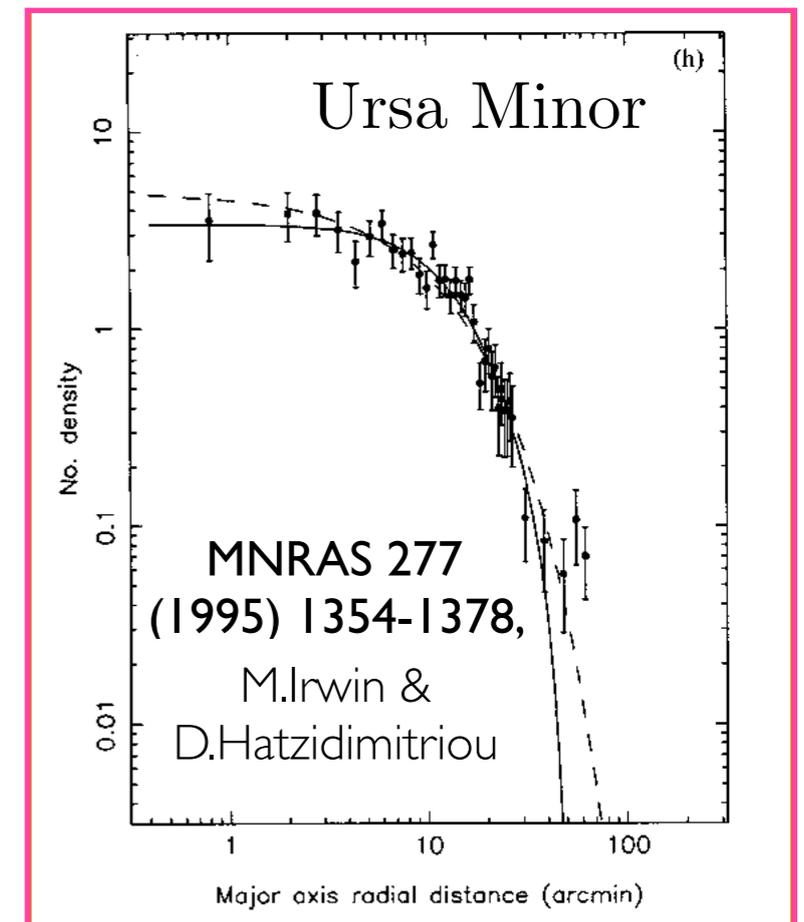
2nd MOMENTS OF BOLTZMANN EQ.: $(\rho_{\star} \sigma_{\star r}^2)' + 2\beta_{\star} \rho_{\star} \sigma_{\star r}^2 = -\rho_{\star} \Phi'_{\text{tot}} \simeq \text{DM}$

HOW ALL THIS CONNECTS TO OBSERVATIONS?

Photometry \rightarrow Surface brightness, i.e.

$$\Sigma_{\star}(R) = \int_{R^2}^{\infty} \frac{dr^2}{\sqrt{r^2 - R^2}} \rho_{\star}$$

(hereafter : $r \equiv$ 3D physical radius, $R \equiv$ 2D projected radius)



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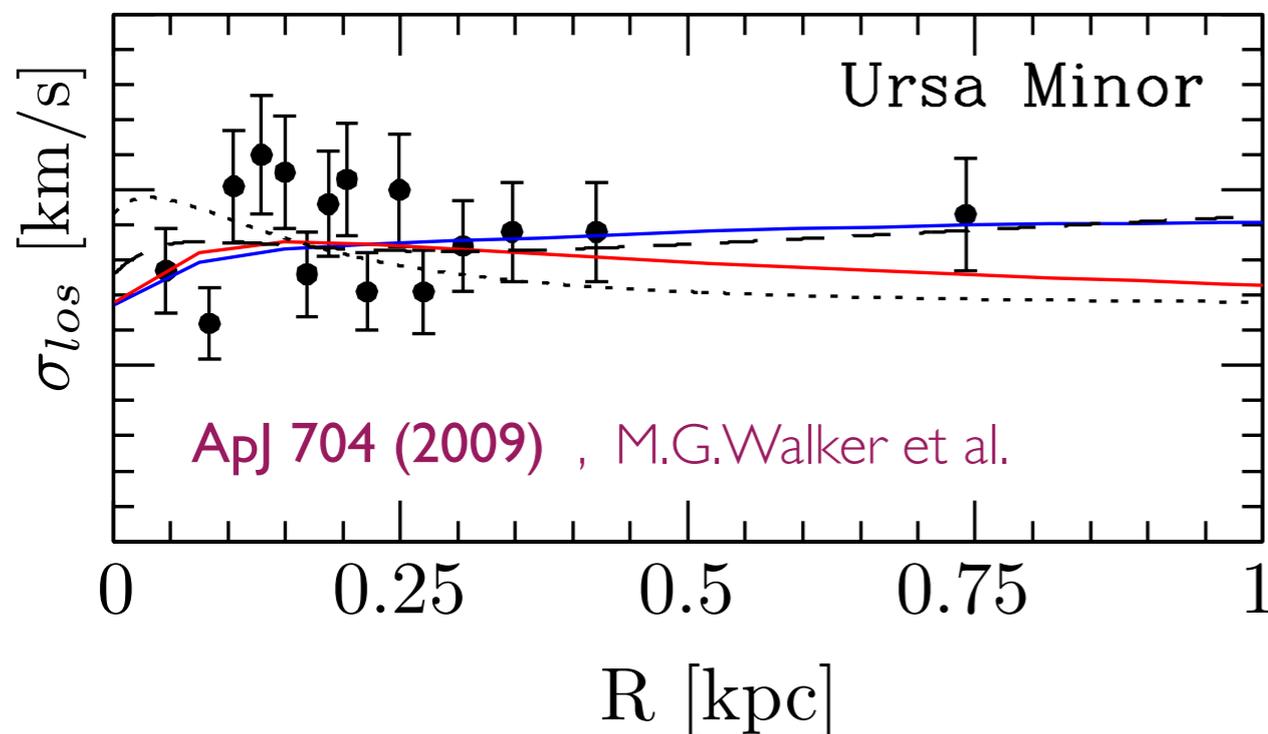
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HOW ALL THIS CONNECTS TO OBSERVATIONS?



**SPECTROSCOPY CONSTRAINTS
VELOCITY DISPERSION**

$$\sigma_{los}(R) \Leftrightarrow \sigma_{los}(\beta_{\star}, \Phi_{\text{DM}})$$

Dark Matter halo must be determined together with the stellar anisotropy profile ...

MASS-ANISOTROPY DEGENERACY

ANY CHANCE TO MINIMIZE THE UNCERTAINTY FROM β_* ?



Accurate masses for dispersion-supported galaxies

Joe Wolf,^{1*} Gregory D. Martinez,¹ James S. Bullock,¹ Manoj Kaplinghat,¹
Marla Geha,² Ricardo R. Muñoz,² Joshua D. Simon³ and Frank F. Avedo¹

¹Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

²Astronomy Department, Yale University, New Haven, CT 06520, USA

³Observatories of the Carnegie Institution of Washington, Pasadena, CA 91101, USA

$$M(r_{1/2}) \simeq 3 \frac{r_{1/2}}{G_N} \langle \sigma_{los}^2 \rangle$$

validated by several N-body studies:

[MNRAS 469 \(2017\) 2, 2335](#)

[MNRAS 472 \(2017\) 1, 4786](#)

[MNRAS 481 \(2018\) 4, 5073](#)

IN RELATION TO THE MASS ESTIMATOR:

Density of Classical dSphs around 150 pc seems to be reasonably constrained by data!

[MNRAS 484 \(2019\) 1, 1401, J.I.Read et al.](#)

