UiO : Department of Physics

The Faculty of Mathematics and Natural Sciences

# “ Bayesian inference of Self-Interactions in the Dark Matter Halos of Milky Way Dwarfs ”


INFN

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Sezione di Roma



ALSO SUPPORTED BY:

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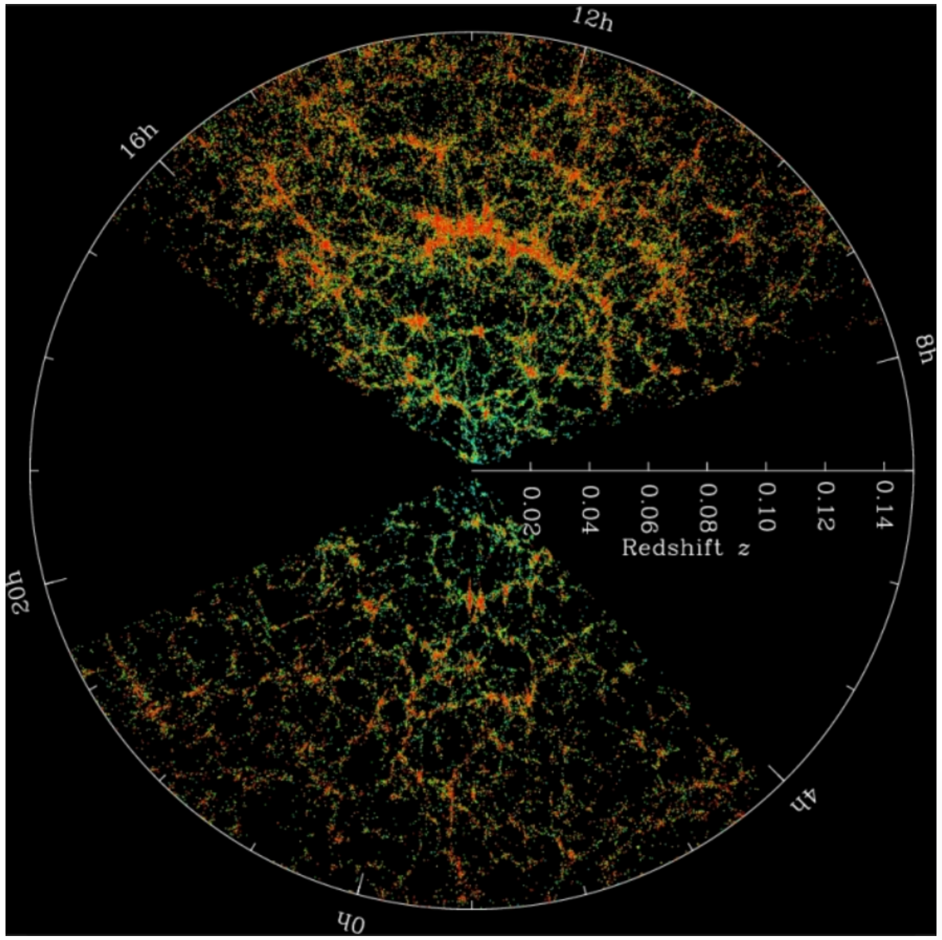
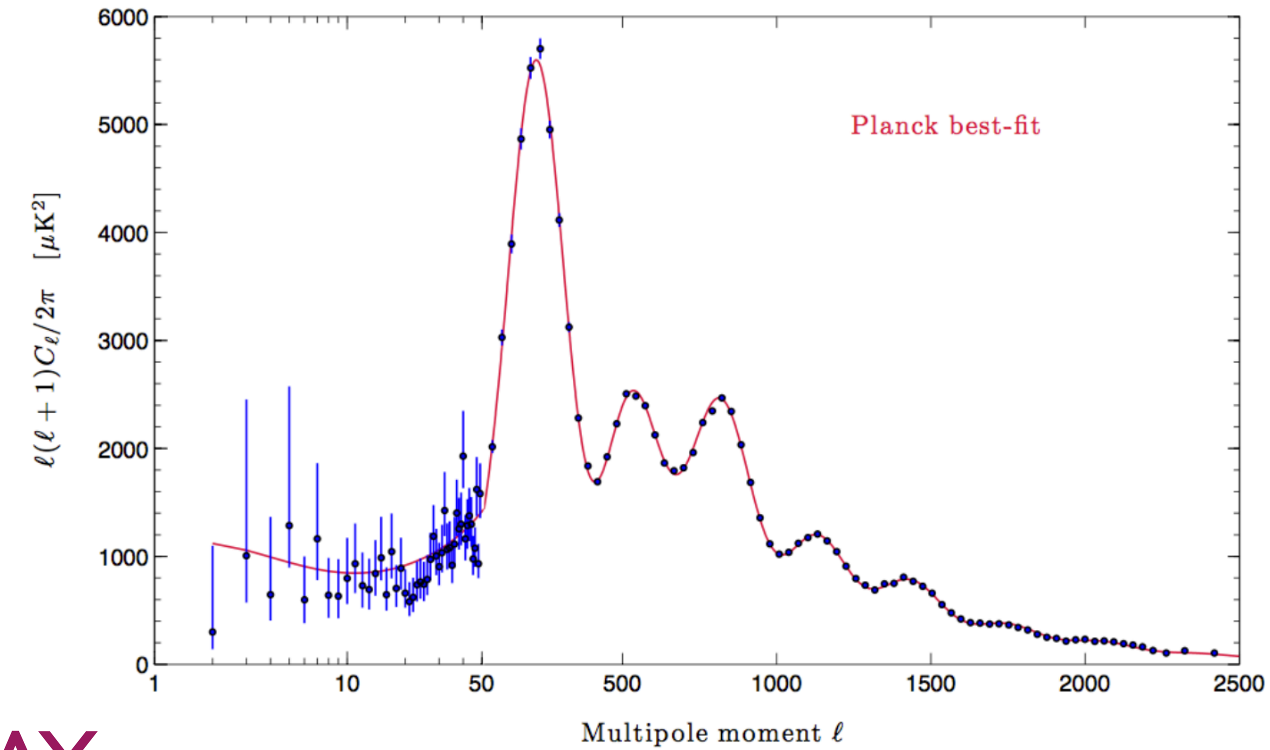


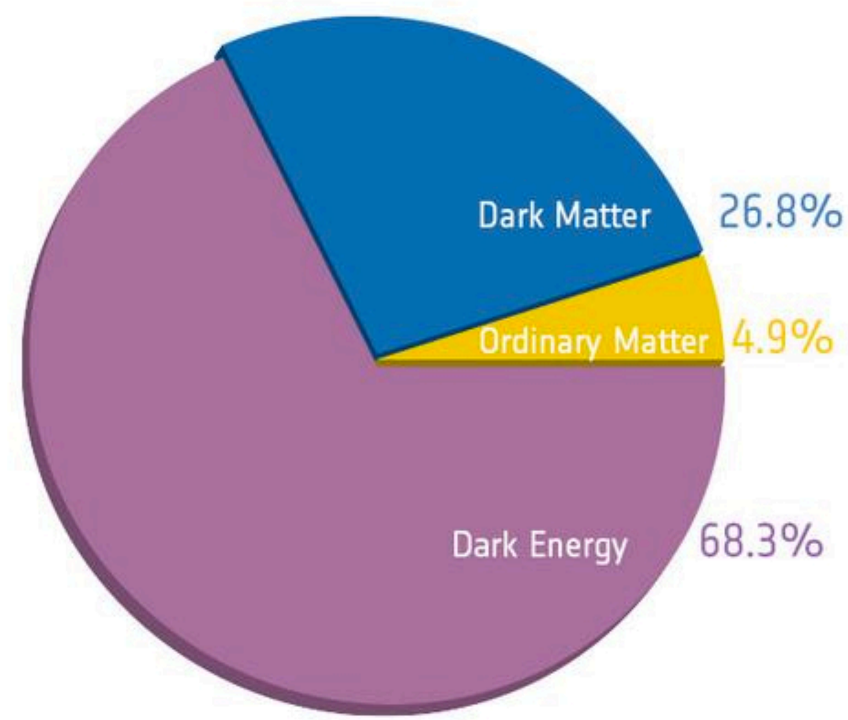

## TODAY

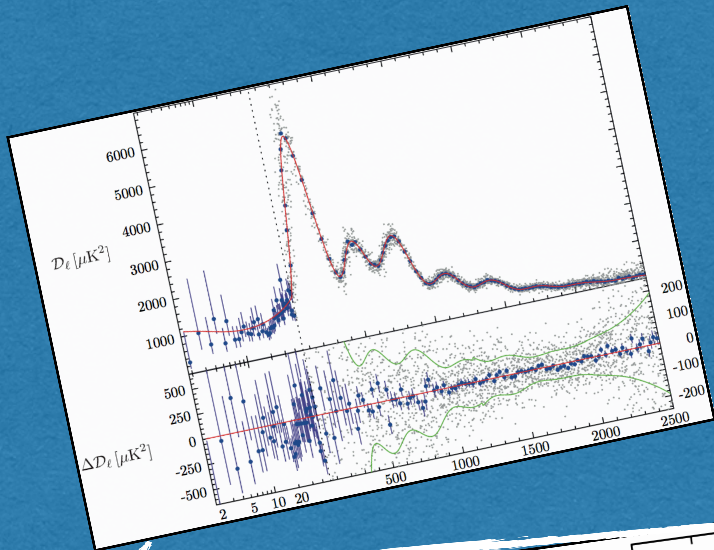
We live in the "Cosmological Precision Era"

—> compelling questions intimately related to **NP** !

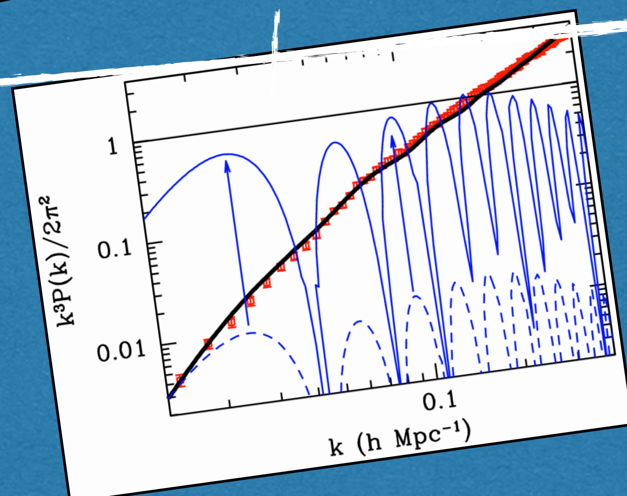
E.g.:

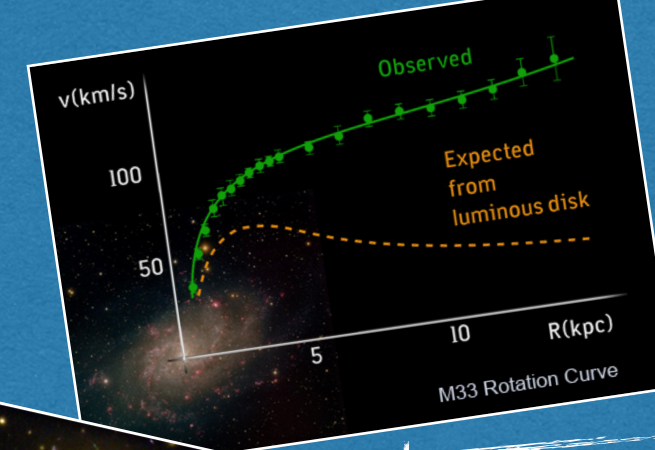
- $\Omega_{DM} \sim 5 \times \Omega_b$ , $O(\Omega_{DM+b}) \sim O(\Omega_\Lambda)$
  ... just parametric coincidences ?
- Why today anti-matter/matter << 1 ?
- The (small) Cosmological Constant: a (huge) hierarchy problem ?
- Origin about non-baryonic matter?






Mpc




kpc

(DM)
Dark Matter —> BSM opportunity!

## Available mass window

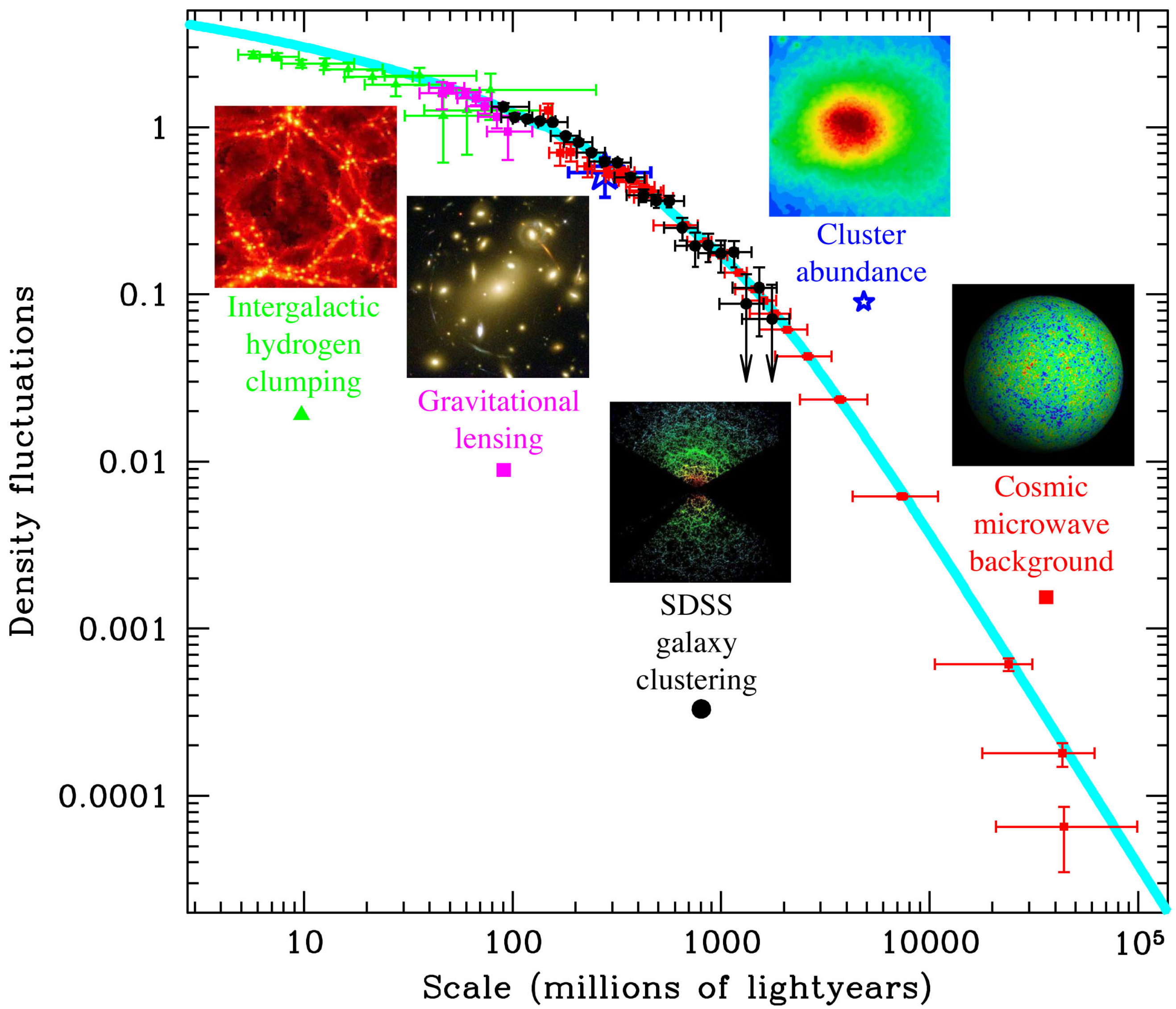
$m_{DM}$

$10^{-23} eV$ $10^{67} eV$

## DM self-interaction range

$\sigma_{DM}/m_{DM}$

$\mathcal{O}(M_{Pl}^{-2} m_{DM}^{-1})$ $\mathcal{O}(cm^2 g^{-1})$



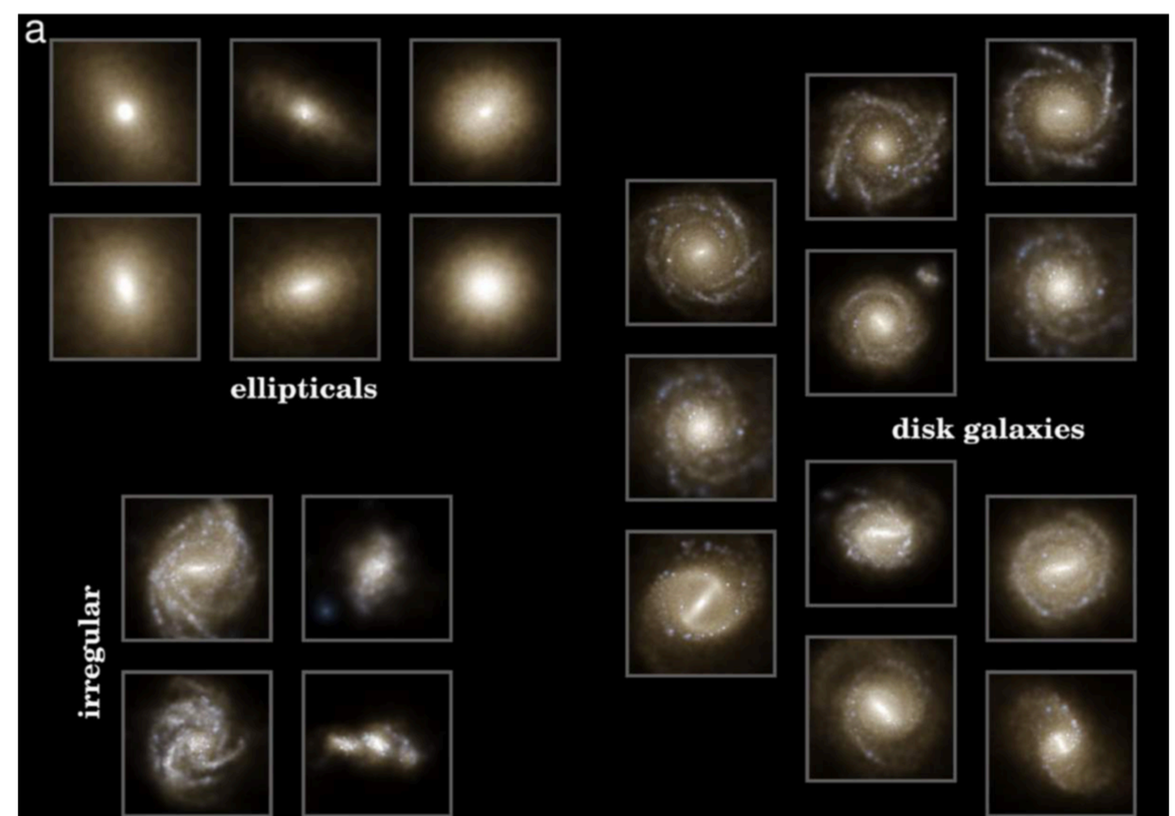

# Cold Dark Matter (CDM)

A cosmologically cold and collisionless particle species beyond the Standard Model well describes all observations we have on large-scale structures of the Universe.

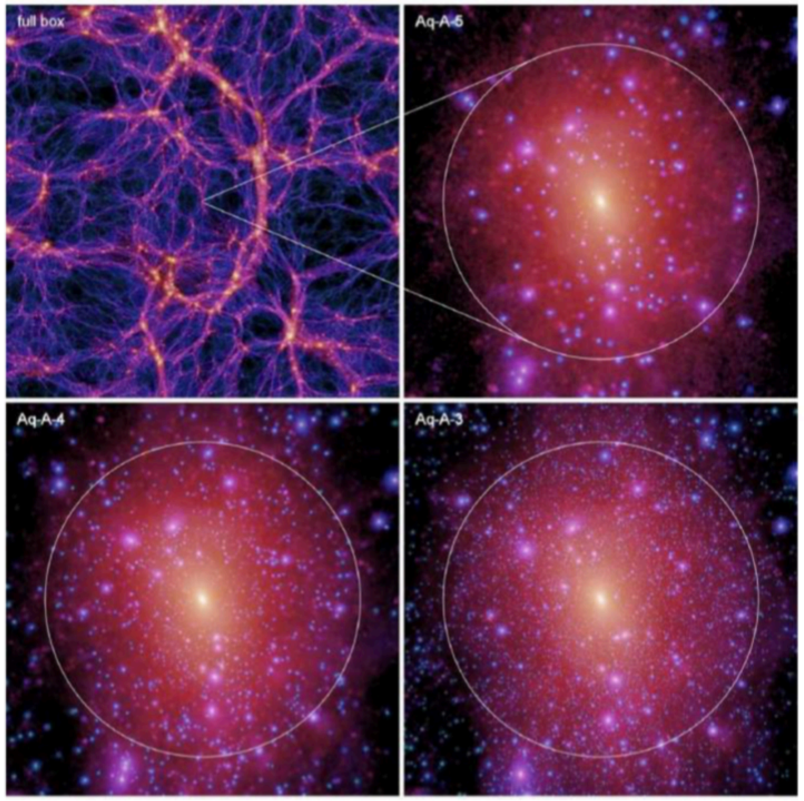
CDM nicely match observations on typical scales ≳ O(100) kpc !

**STATE-OF-THE-ART CDM SIMULATIONS ABLE TO PROVIDE ACCURATE SNAPSHOTS OF KNOWN OBSERVED GALAXIES.**

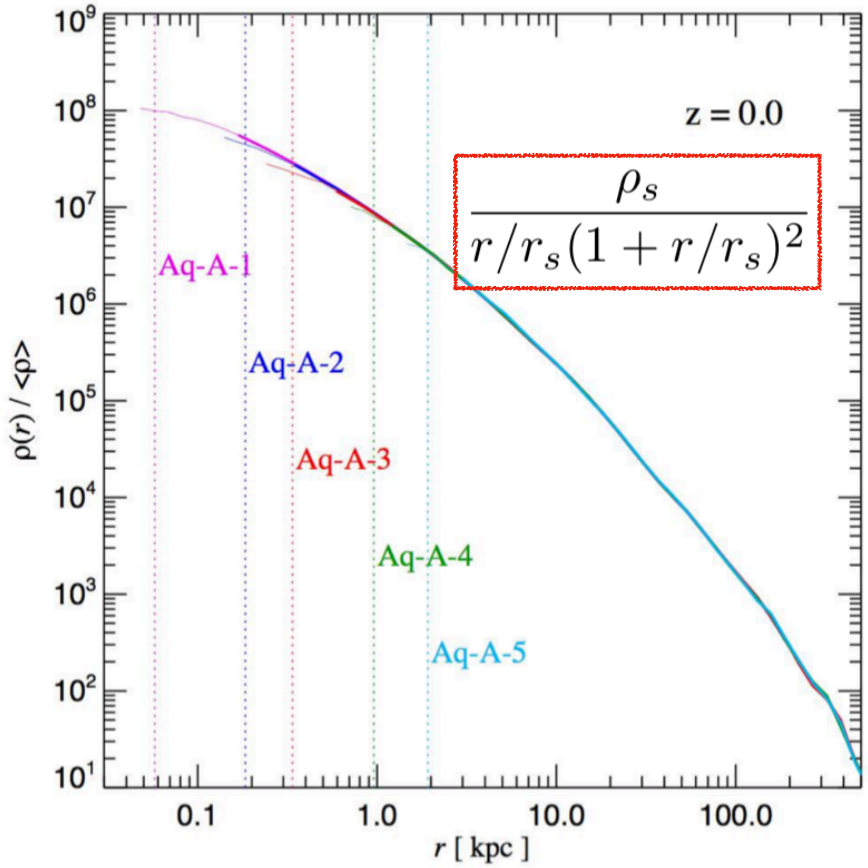
N-body simulations implementing CDM idea + dedicated recipes for baryonic physics reproduce realistic galaxy morphologies.




Illustris Project, Vogelsberger et al. (2014)




Aquarius Project, Springel et al. (2008)




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

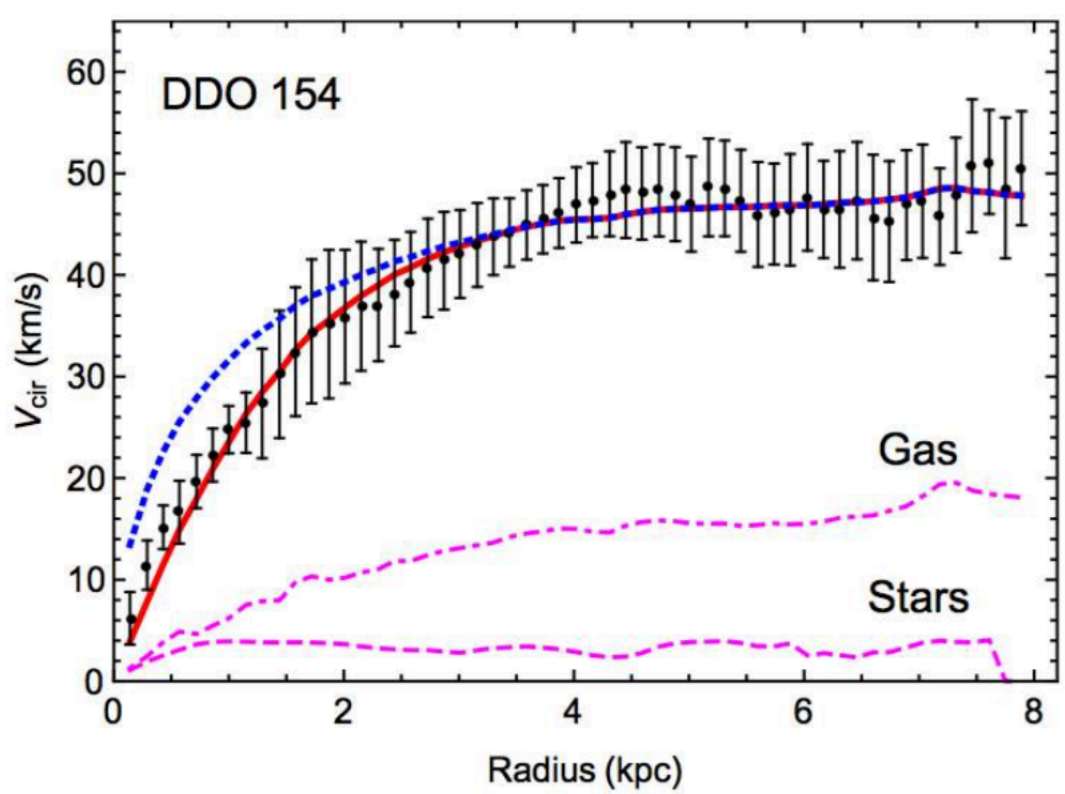
# HOWEVER ...

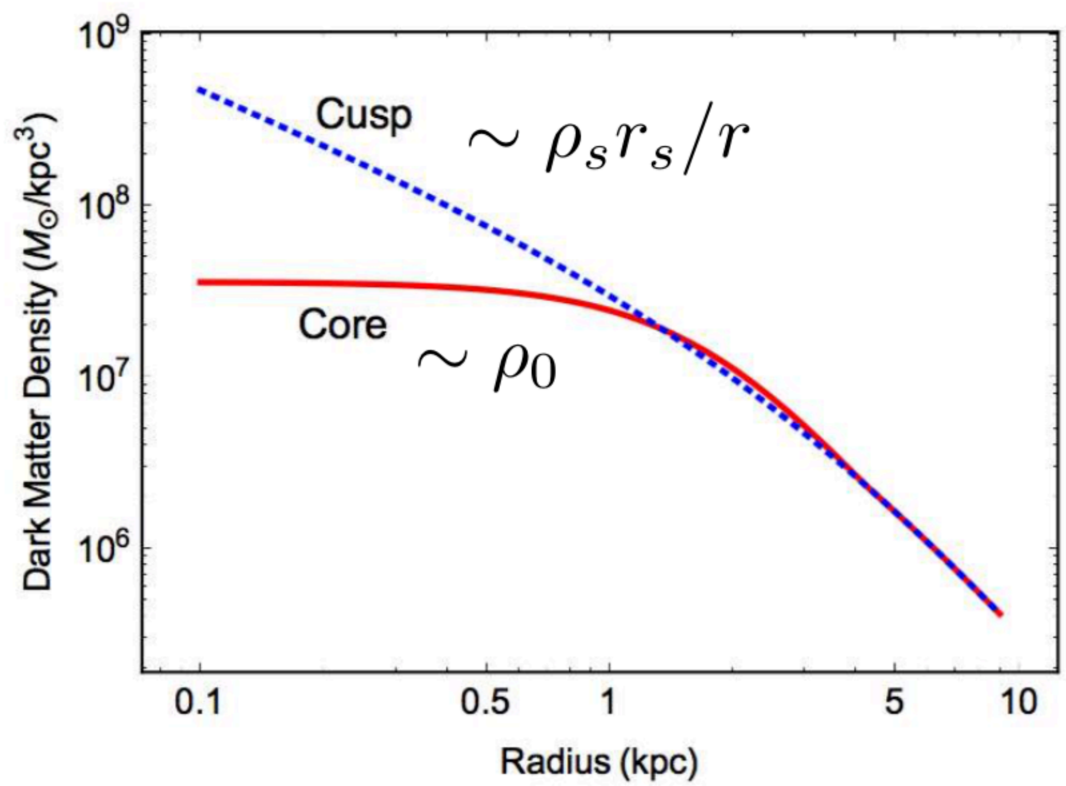
Standalone CDM framework FAILS IN REPRODUCING MEASURED ROTATION CURVES for many spiral galaxies.

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

Central density & scale radius from N-body are correlated!
**—> mass-concentration relation**

## —> " CORE VS CUSP " PROBLEM ... TO GET AN IDEA:

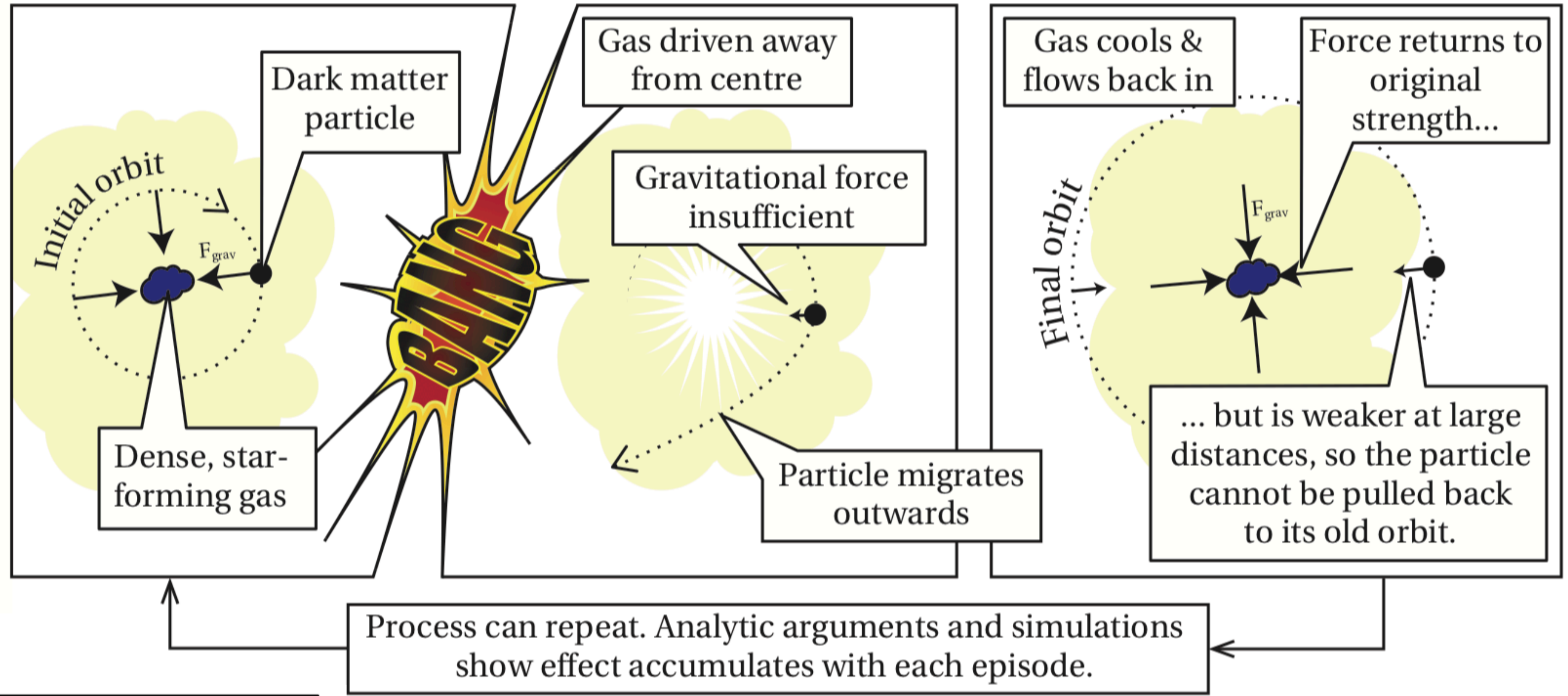


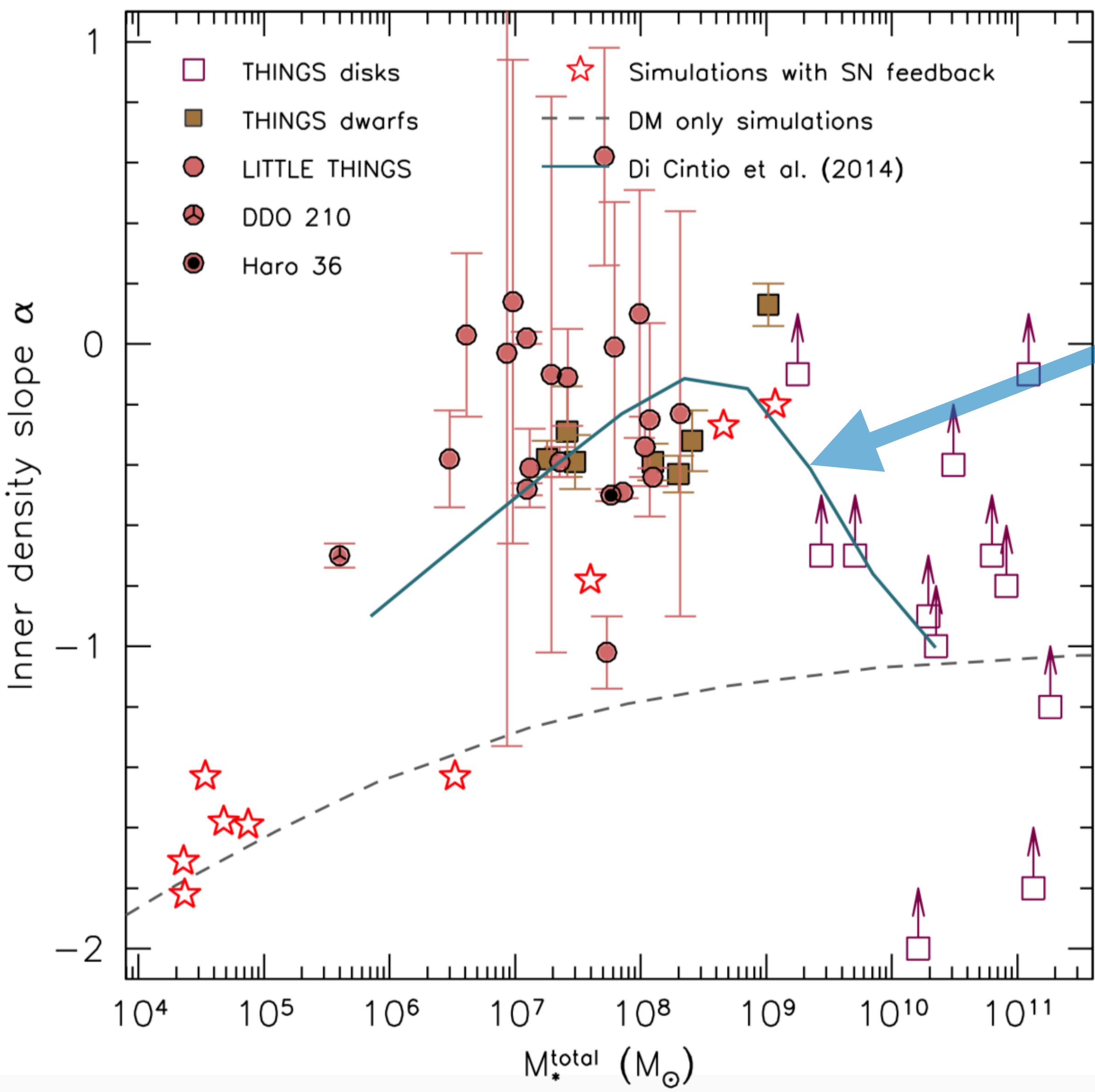



# BARYONIC FEEDBACK

A SKETCHY CARTOON ON WHAT HAPPENS …

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




BARYONIC PHYSICS MAY CERTAINLY AFFECT CDM N-BODY INNER HALO !

**… HOWEVER :**

- **Depends on the stellar mass content**
  ***Governato, F. et al. ‘12***
- **Depends on feedback time-scale**
  ***T. K. Chan et al. ‘15***

—> IT DEPENDS ON THE SPECIFIC RECIPE ADOPTED IN HYDRO-SIMULATIONS !

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

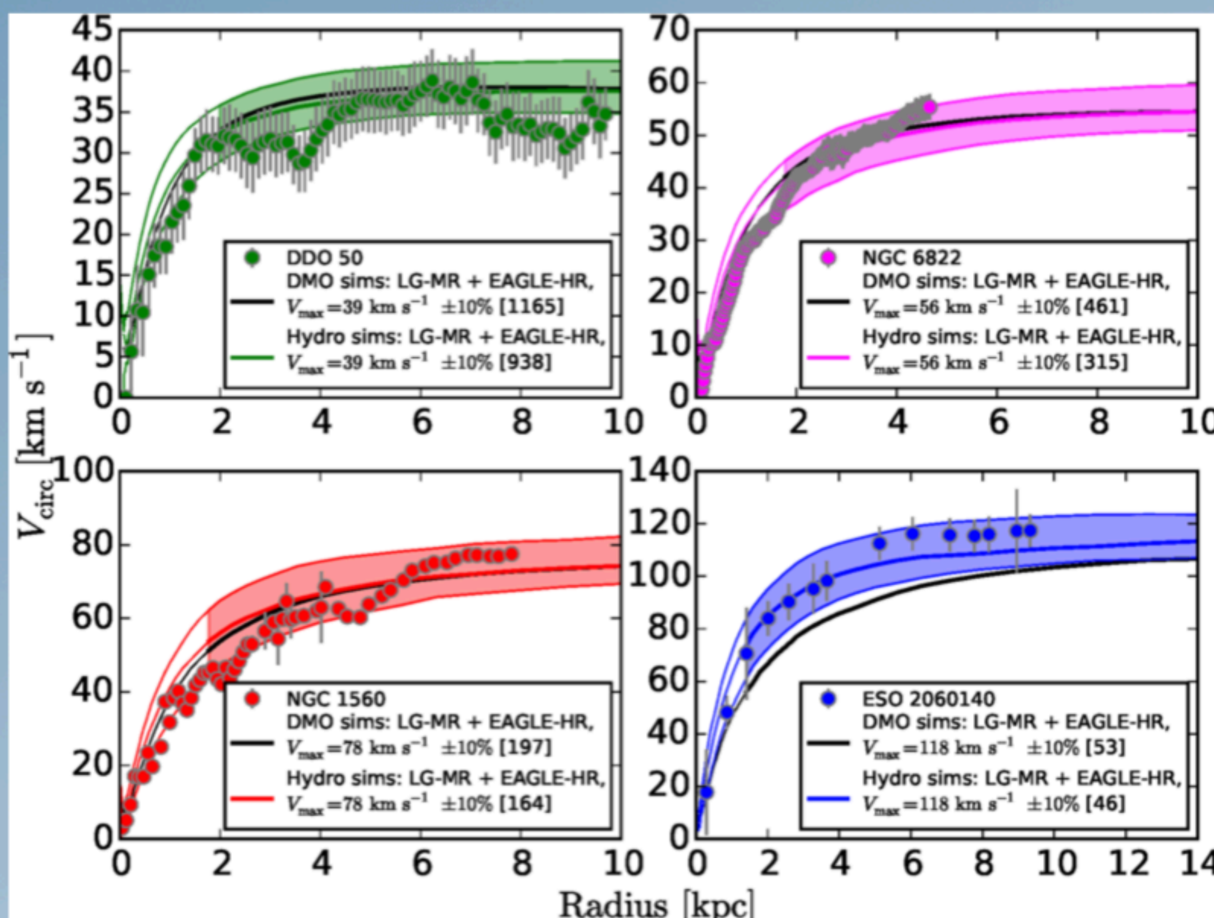
# 4. The diversity problem

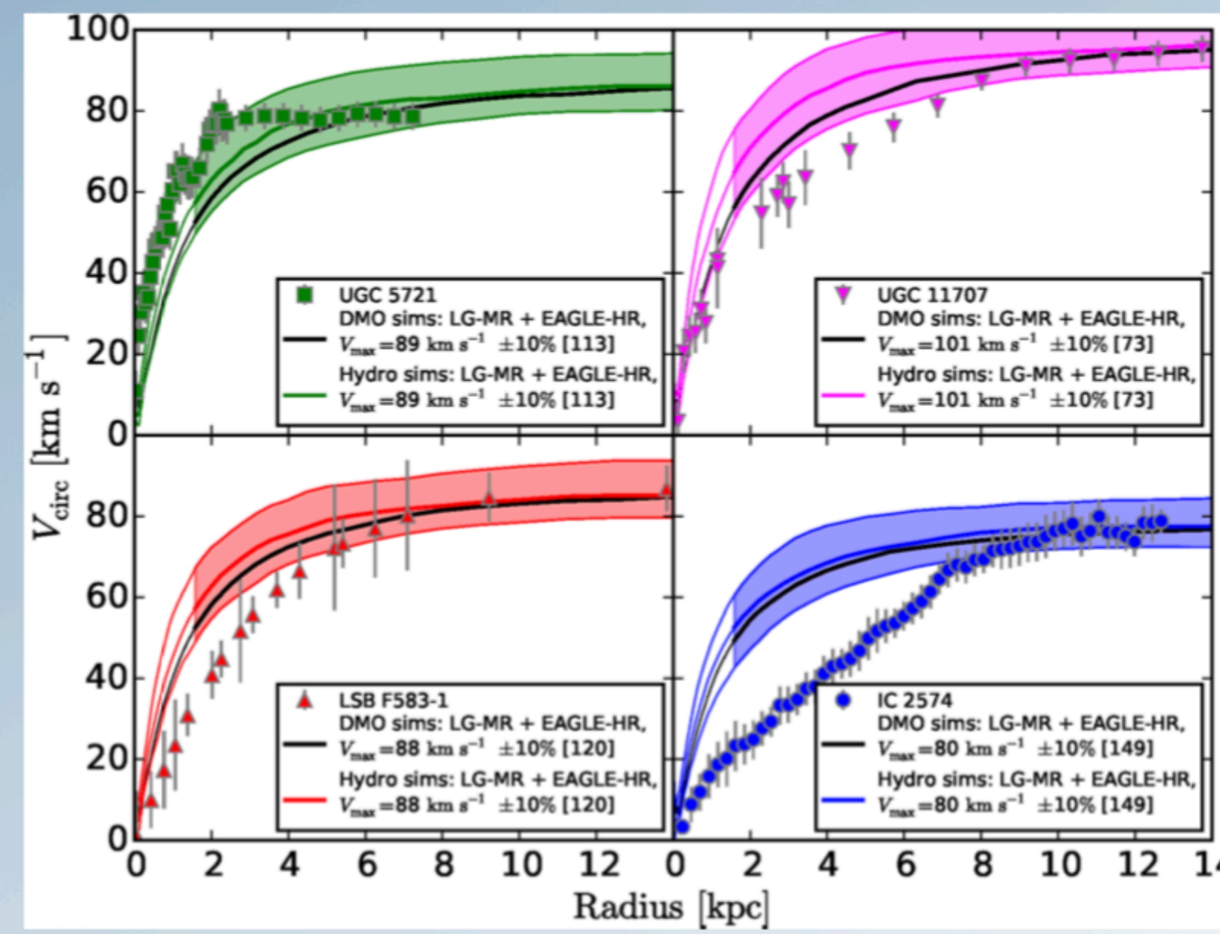
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **452**, 3650–3665 (2015)

**The unexpected diversity of dwarf galaxy* rotation curves**

Kyle A. Oman,[1★] Julio F. Navarro,[1†] Azadeh Fattahi,[1] Carlos S. Frenk,[2] Till Sawala,[2] Simon D. M. White,[3] Richard Bower,[2] Robert A. Crain,[4] Michelle Furlong,[2] Matthieu Schaller,[2] Joop Schaye[5] and Tom Theuns[2]

***) not dSph!**



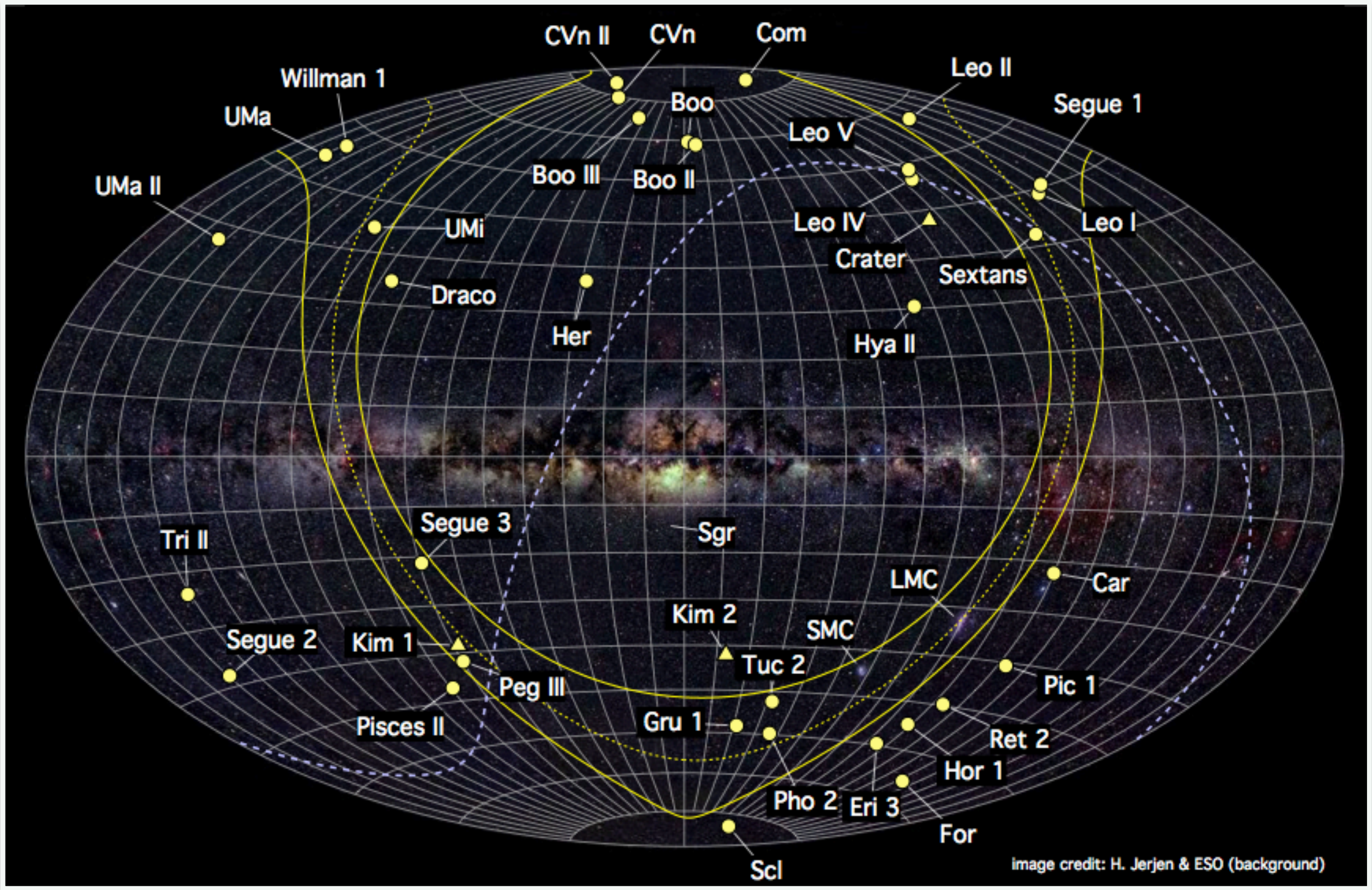

**Adding baryons significantly improves agreement with *some* observations**
(*also* by increasing the scatter…)

**But cannot explain the diversity of observed rotation curves!**



**BORROWED** FROM A WAY-BETTER SPEAKER :)

# DWARF SPHEROIDAL GALAXIES (dSphs) among the Milky Way's (MW) satellites




Fairly close to Us
(tens - 100s kpc from Sun)

No ongoing star formation
(old stellar populations)

Faint stellar component
(gas below exp sensitivity)

Large Mass-to-Light ratios

$$M/L \sim \mathcal{O}(10^{2-3})\, M_\odot/L_\odot$$

~10 (pre-SDSS) brightest ones (Classicals)

After SDSS and DES surveying the Sky,
~ **50** DM dominated MW satellites found.

CLOSE TO IDEAL DM ASTRO-LABORATORY!

CDM-only predicts many more … A “MISSING SATELLITES” (MS) PROBLEM ?!

***Moore et al. ‘99, Klypin et al. ‘99 …*** but see, e.g., ***Kim et al.’17*** for a recent criticism

# MASS MODELING FOR DWARF SPHEROIDALS

Collisionless Boltzmann equation:

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \nabla_{\vec{x}} f - \nabla_{\vec{x}} \phi \cdot \nabla_{\vec{v}} f = 0$$

Evolution of phase space density of star in the galaxy, tracing the total gravitational potential.

*1) DYNAMICAL EQUILIBRIUM*

*2) SPHERICAL SYMMETRY*

**2nd MOMENT OF THE EQ.:**

$$(\rho_\star \sigma_r^2)' + 2\,\beta\,\rho_\star \sigma_r^2 = -\rho_\star \Phi'_{\rm tot}$$

where $' \equiv d/d \log r$ .

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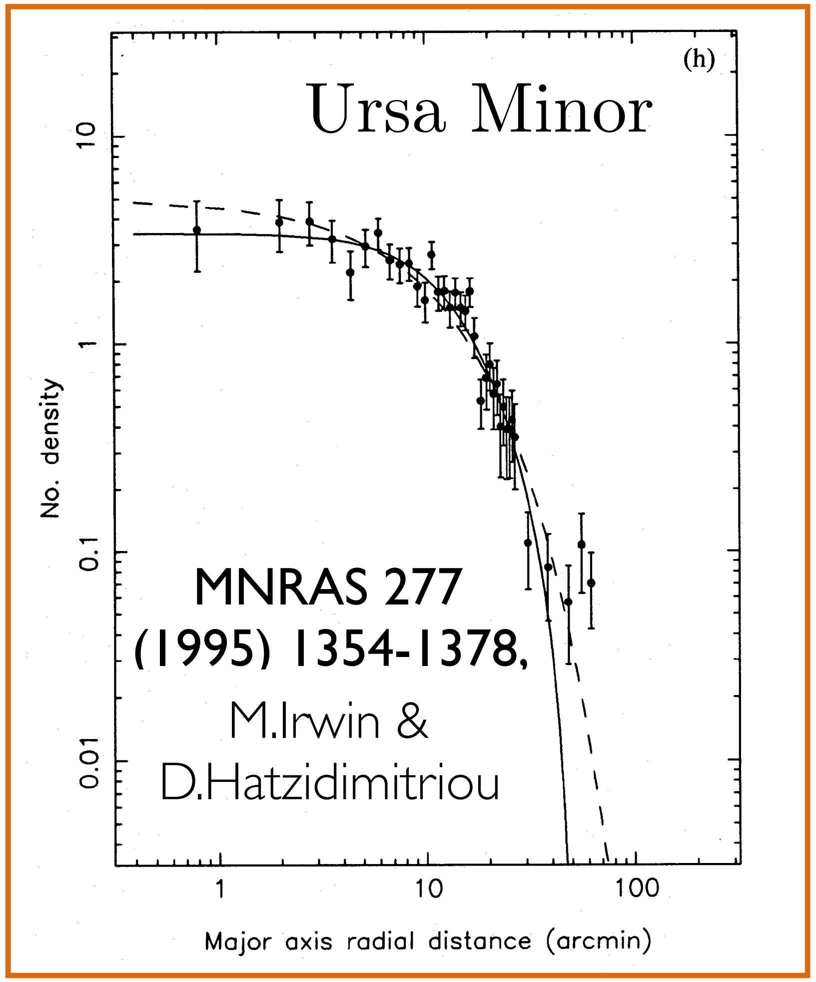
$\rho_\star(r)$ IS THE **STELLAR DENSITY** OF THE SYSTEM,

to be matched to photometric measurements —> connected to surface brightness, i.e.

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

(hereafter : **r ≡ 3D physical radius, R ≡ 2D projected radius**)



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$\sigma_{r(t)}(r)$ IS THE **RADIAL (TANGENTIAL)** COMPONENT OF THE STELLAR **VELOCITY DISPERSION**.

THE STELLAR **ORBITAL ANISOTROPY** IS DEFINED AS :

$$-\infty < \beta(r) \equiv 1 - \sigma_t^2 / \sigma_r^2 \leq 1$$

circular limit — β = 0 : isotropic motion — radial orbits

*Observational info on the stellar velocity dispersions only along line of sight (l.o.s.) from spectroscopy.*

$$\Rightarrow \quad \sigma_{los}^2(R) = \Sigma_\star^{-1} \int_{R^2}^{\infty} \frac{dr^2}{\sqrt{r^2 - R^2}} \left(1 - \beta \frac{R^2}{r^2}\right) \rho_\star \sigma_r^2$$

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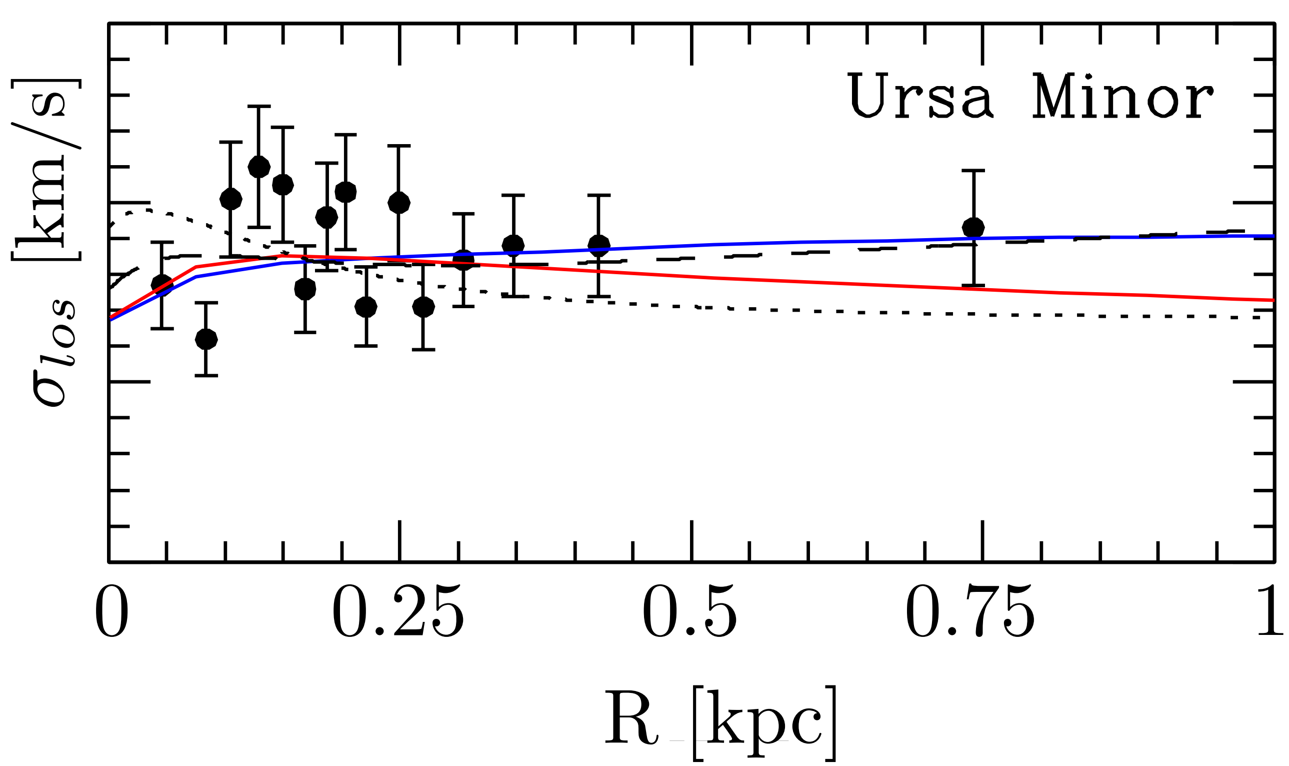
**Obs.** tot ~ DM

**L.o.s. projection + Poisson's eq. leave us with 2 unknowns for 1 observable!**

**ApJ 704 (2009)** , M.G.Walker et al.




$$\Rightarrow \quad \sigma_{los}(R) = f(\beta, \mathcal{M})(R)$$

DEGENERACY PROBLEM

In the spherical Jeans analysis, the total mass profile must be determined together with the orbital anisotropy function.

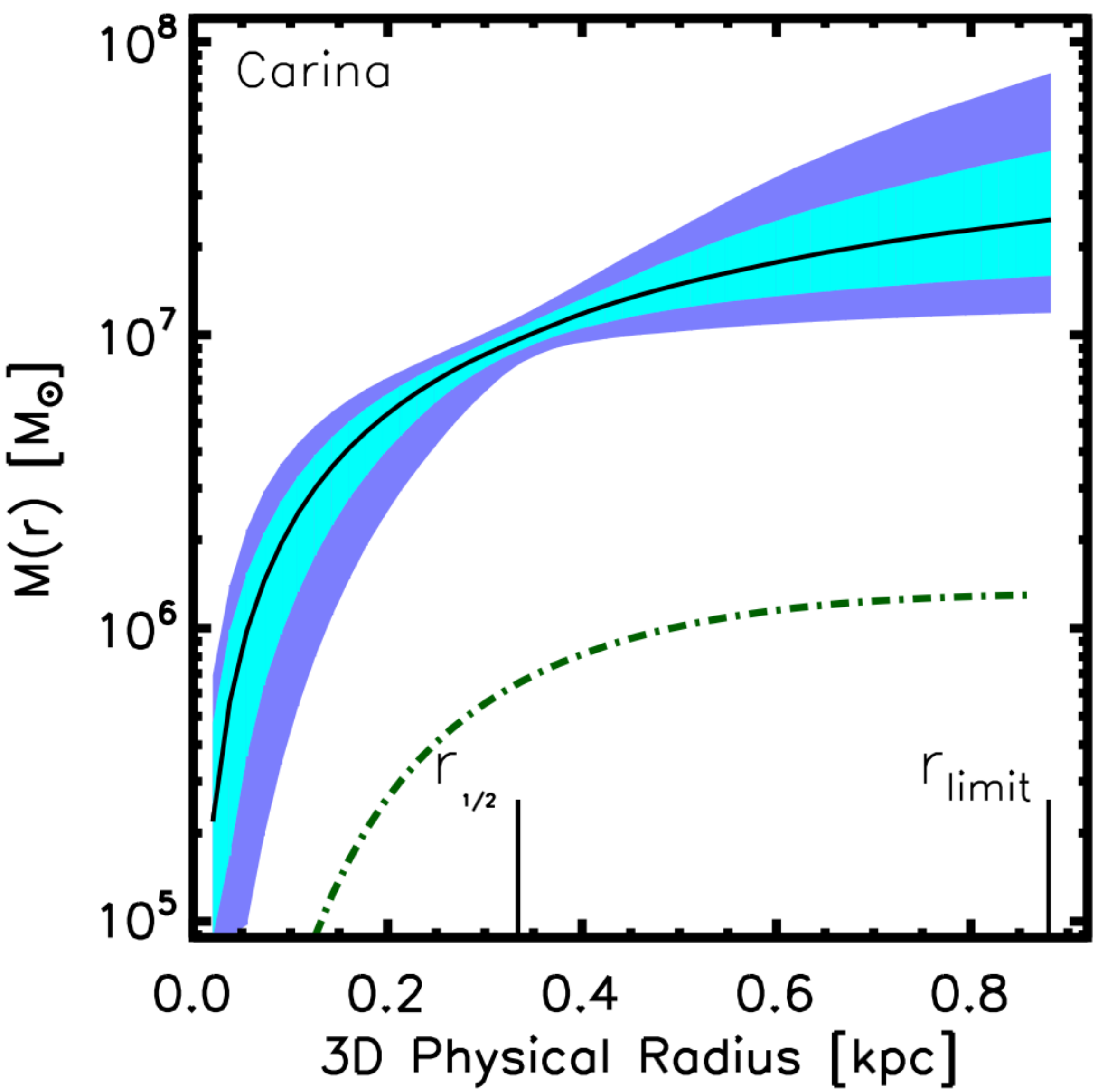
# EXISTENCE OF A "MASS ESTIMATOR"

I.E., APPROXIMATELY W/O DEGENERACY !

There is a ***mass estimator*** for dispersion-supported systems like MW dSphs.

FROM THE JEANS EQ.: $\mathcal{M}(r;\beta) - \mathcal{M}(r;\beta=0) \propto \gamma_{\rho_\star} + \gamma_{\sigma_r^2} + \gamma_\beta - 3$

where $\gamma_O \equiv -O'/O\,.$




*MNRAS 406 (2010) 1220* , Wolf, J. et al.

Numerical evidence for mass difference to be 0 close by **3D half-light radius**, i.e. when density slope approaches 3.

$$\mathcal{M}(r_{1/2};\beta) \simeq \mathcal{M}(r_{1/2};\beta=0)$$

$$\mathcal{M}_{1/2} \simeq 3\, r_{1/2} \langle \sigma_{los}^2 \rangle / G_N$$

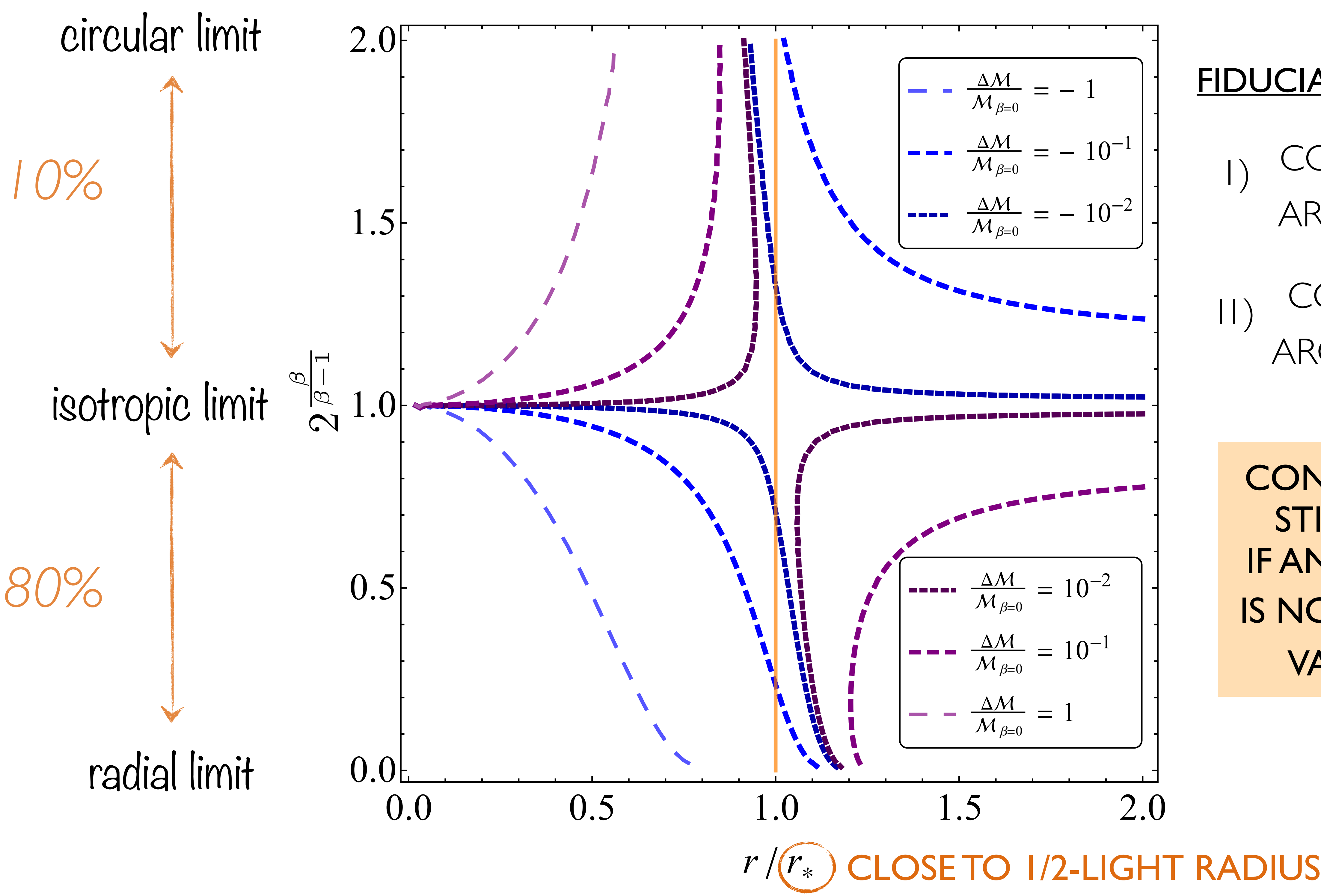
Similar formula, but w/o analytical insights, originally proposed in ***Walker et al. '09***.

P.Ullio & M.V. *JCAP 1607 (2016) 025*

# THEORY BIAS ON THE MASS ESTIMATOR

*ApJ 704 (2009)* , *Walker, G.M. et al.*
*MNRAS 406 (2010)* , *Wolf, J. et al.*

$$\mathcal{M}(r;\beta)/\mathcal{M}(r;\beta=0) - 1 = \text{const}$$




<u>FIDUCIAL SCENARIO</u>

I) CONST $\sigma_{los}$ AROUND $r_*$

II) CONST $\beta$ AROUND $r_*$

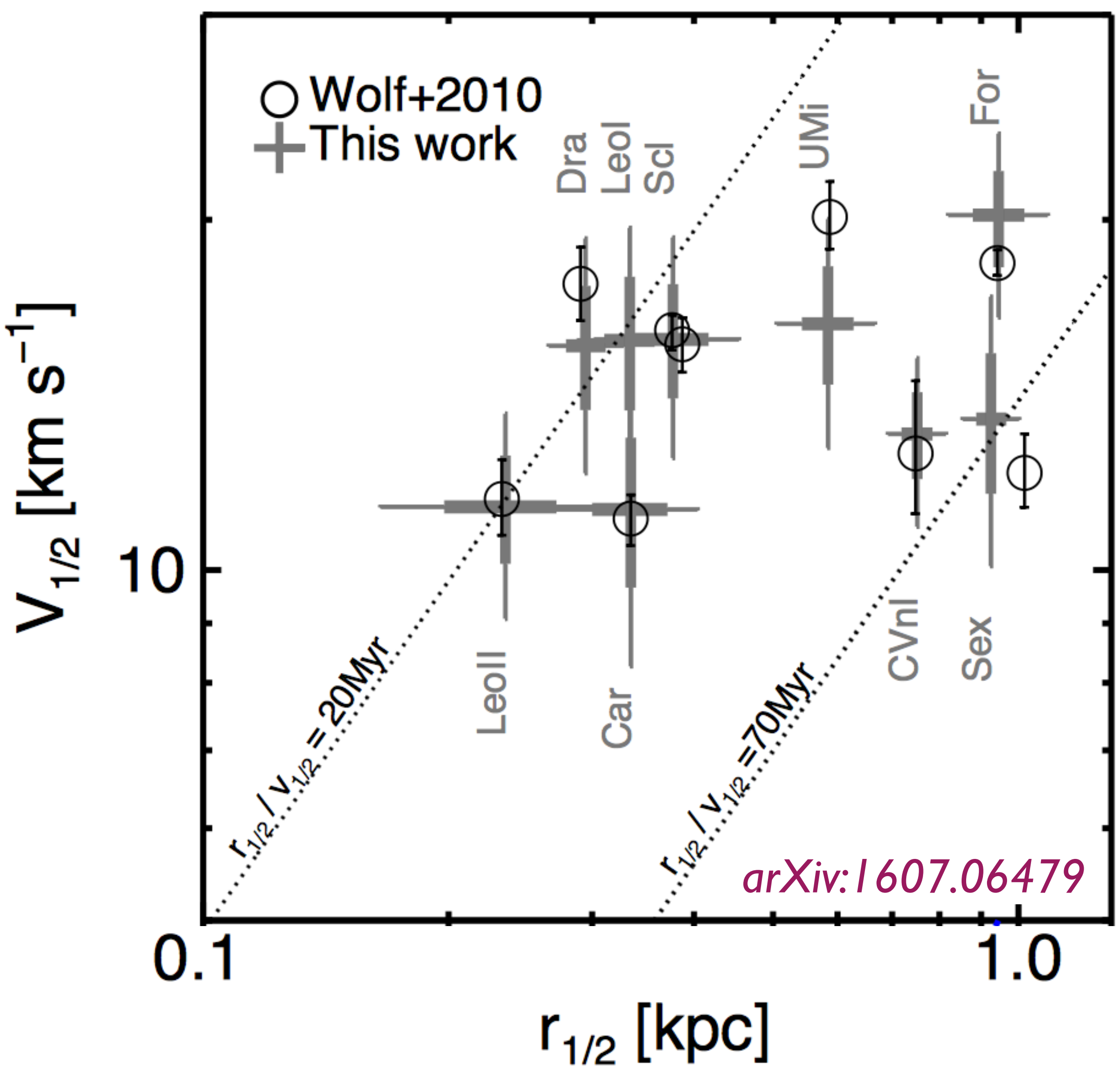
CONCLUSIONS STILL HOLD IF ANISOTROPY IS NOT "FASTLY" VARYING @

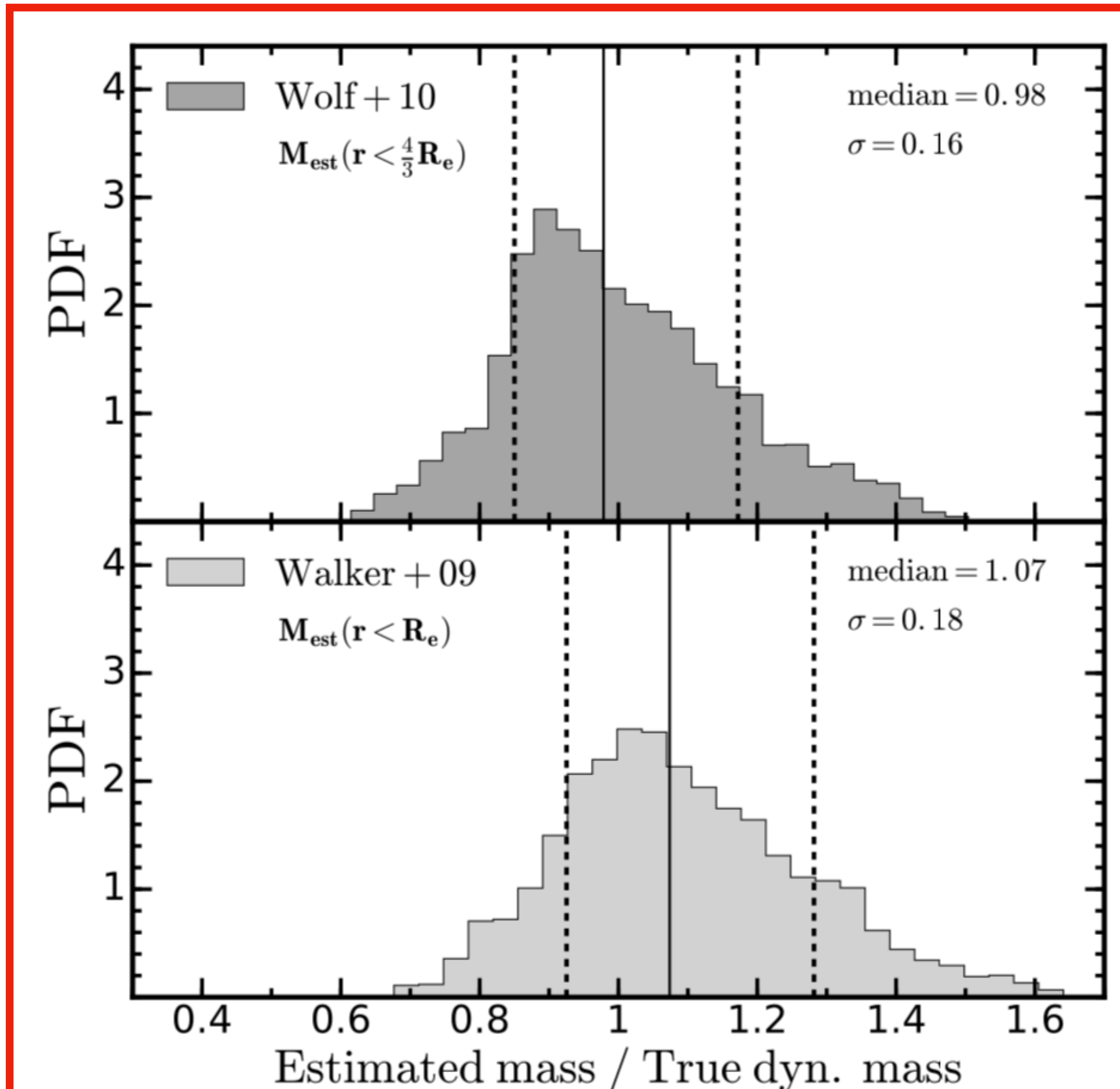
# EXISTENCE OF A "MASS ESTIMATOR"

## I.E., APPROXIMATELY W/O DEGENERACY !

Recently, dedicated simulations for dSph-like systems confirm estimator.

*Campbell et al.'16, Gonzalez-Samaniego et al.'17*

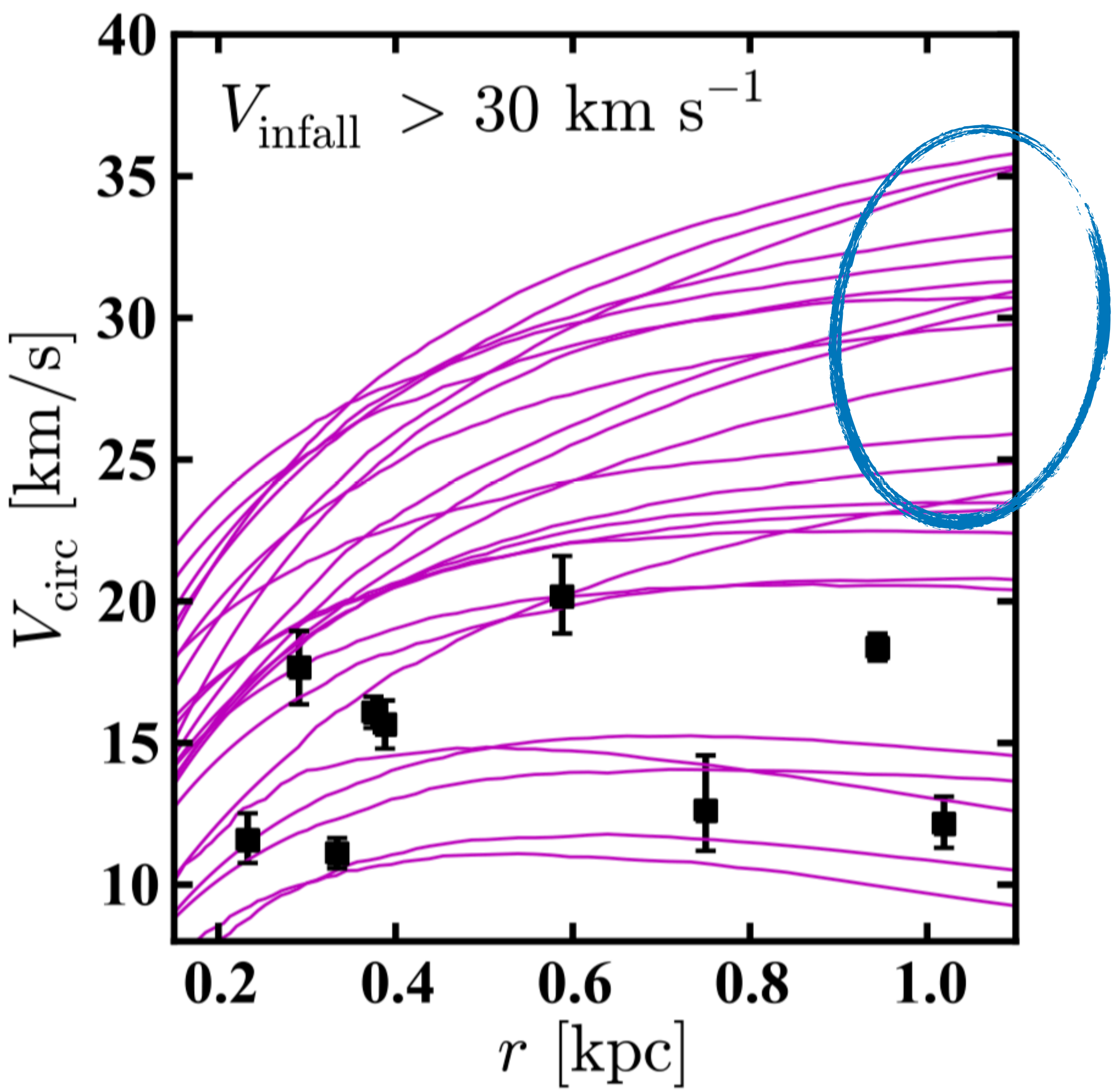



… BUT OBSERVATIONAL ERRORS MAY NOT BE WELL UNDER CONTROL !!!

**See, e.g.,** *Fattahi, A. et al. '16*

# MW DWARFS INTERNAL DYNAMICS IN TENSION WITH CDM PREDICTIONS !




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

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

## TOO-BIG-TO-FAIL (TBTF) PARADOX

Most massive subhalos in CDM seem to be too dense to host the observed brightest MW satellites.

On other hand, typically easier to trigger star formation in deep potential wells …

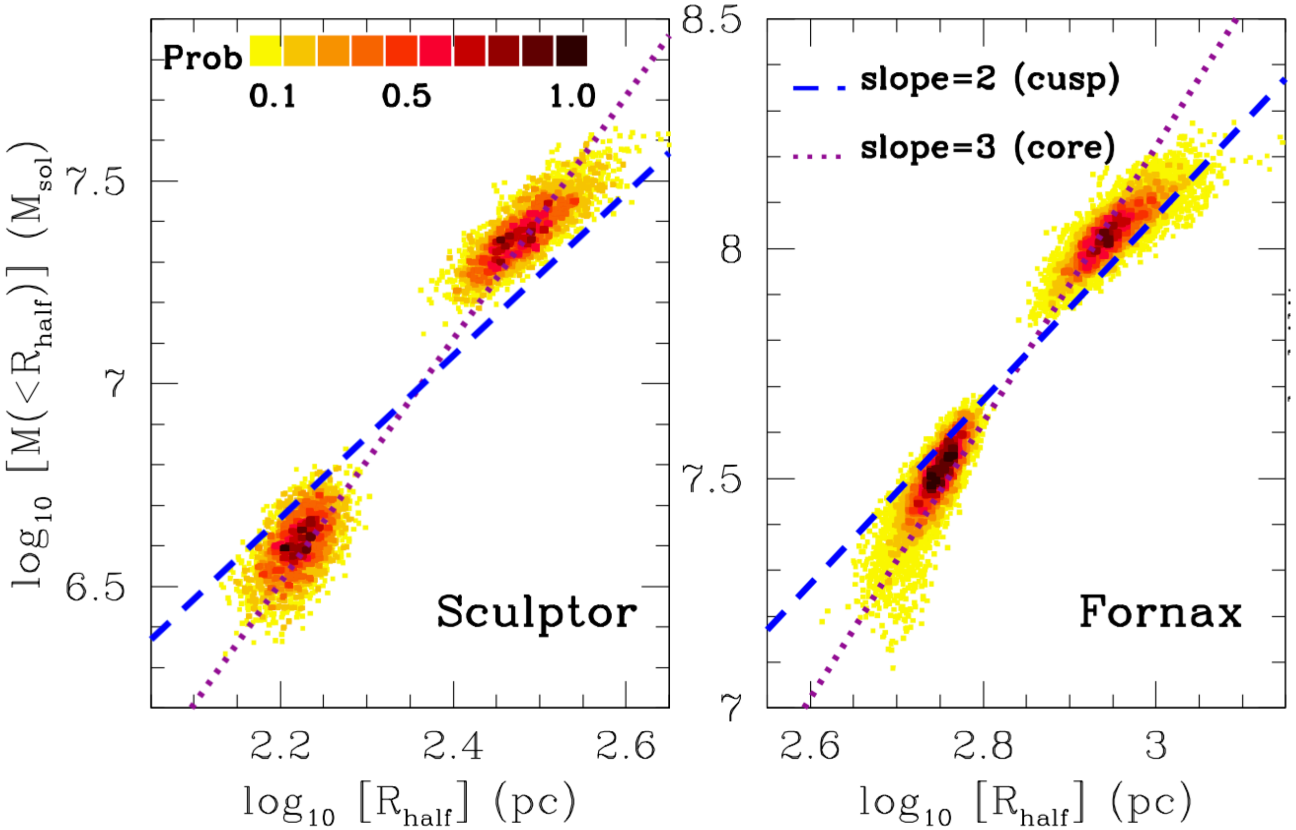
… SO, WHERE ARE THEY?

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

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

- *Dependence on the mass of host galaxy*
  —> Wang, J. et al., *MNRAS 424 (2012) 2715*
- *MW tidal field effects + Baryonic physics*
  —> Sawala, T. et al., *MNRAS 457 (2016) 1931*

# INNER CORES IN MW DWARFS PROFILES?

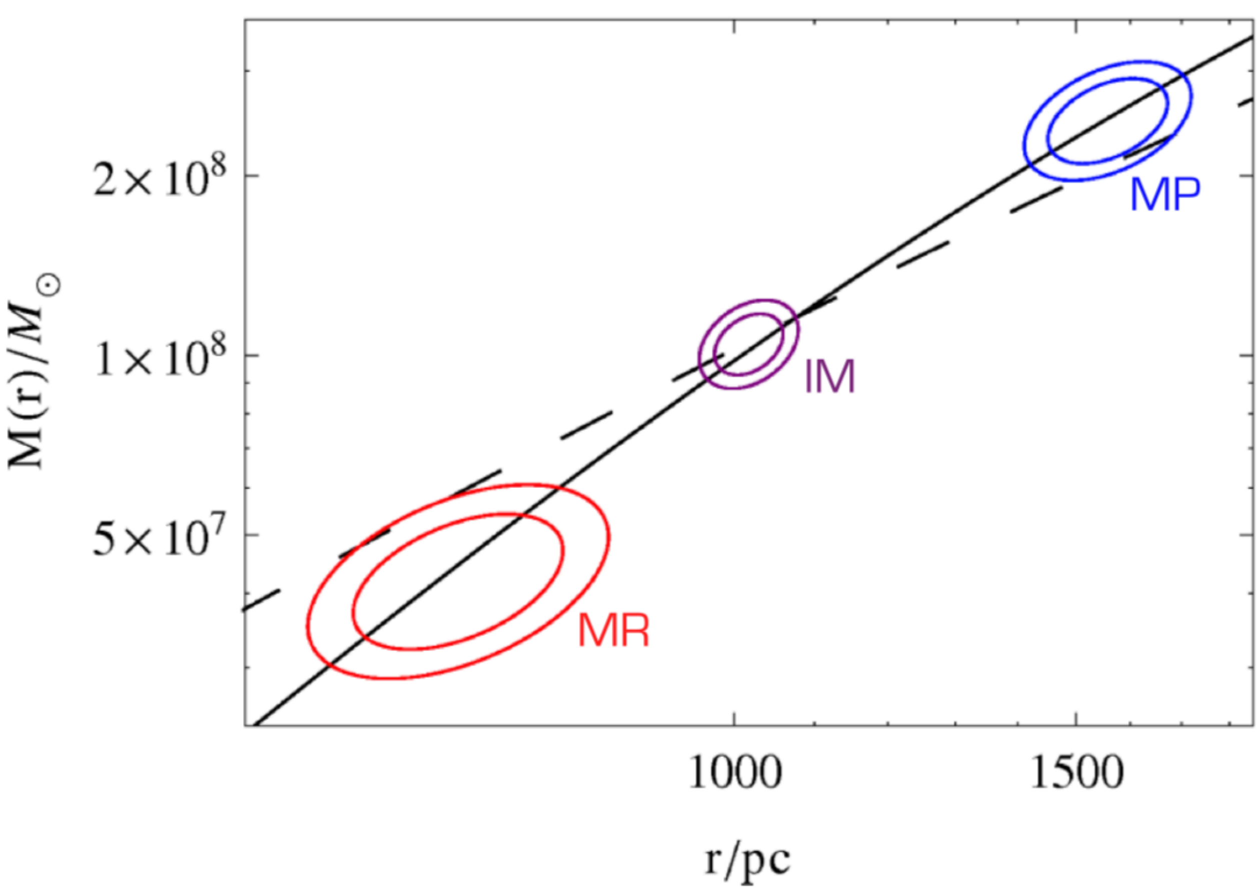



Chemo-distinct stellar populations can trace reliably the same gravity potential well, but @ different $r_{1/2}$.

—> MEASURE dSph MASS SLOPE!

*ApJ 681 (2008) L13* , Battaglia, G. et al.
*MNRAS 406 (2010) 1220* , Amorisco & Evans
*ApJ 742 (2011) 20* , Walker & Penarubbia

Sculptor & Fornax host inner core




*MNRAS 429 (2013) L89* , Amorisco, N. et al.

Fornax core is large, of order kpc

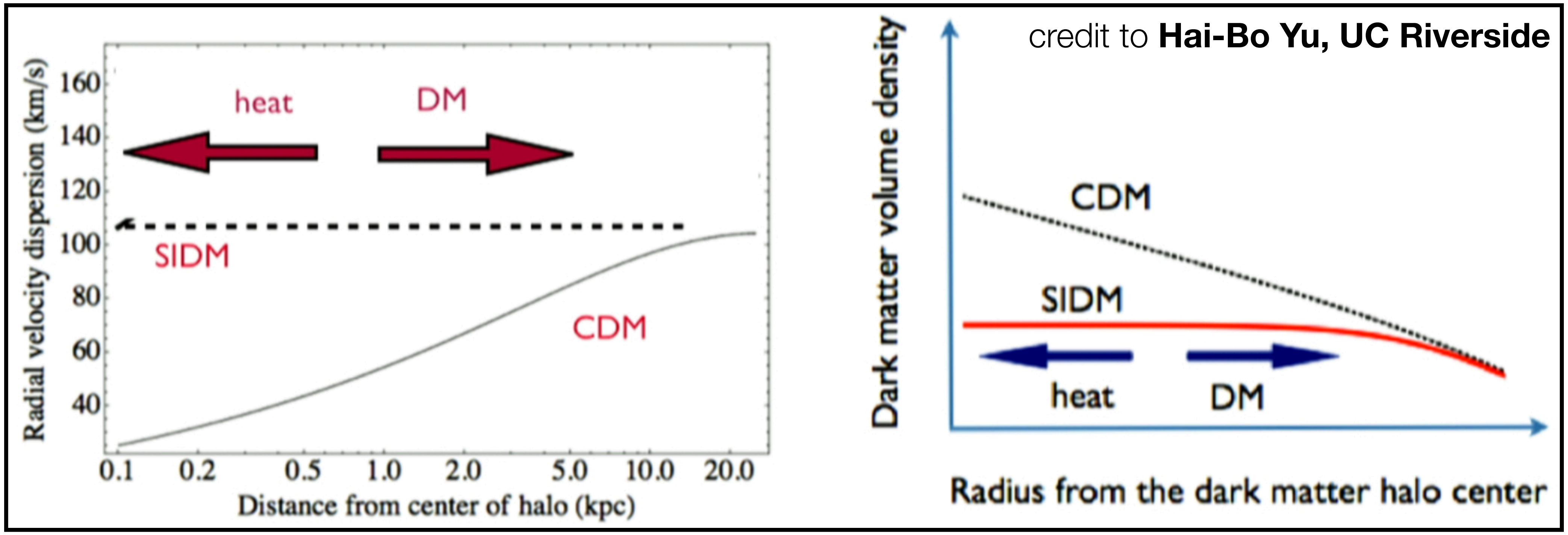
*ApJ 838 (2017) 123*, Strigari + FW

Generalized PSDF approach showing Sculptor may be fine also with NFW

Consensus not completely unanimous …
… ANSWER MAY (LIKELY) BE “YES”!

# CORE VS CUSP + DIVERSITY + TBTF : NEW PARADIGM BEYOND CDM ?

## Self-Interacting Dark Matter (SIDM) , *D.Spergel & P.Steinhardt '00*




SELF-INTERACTIONS SHARED BY DM PARTICLES ALLOW FOR HEAT TRANSPORT. THIS ESTABLISHES A THERMALIZATION REGIME IN THE INNER GALACTIC HALO.

**FORMATION OF INNER DENSITY CORES !**

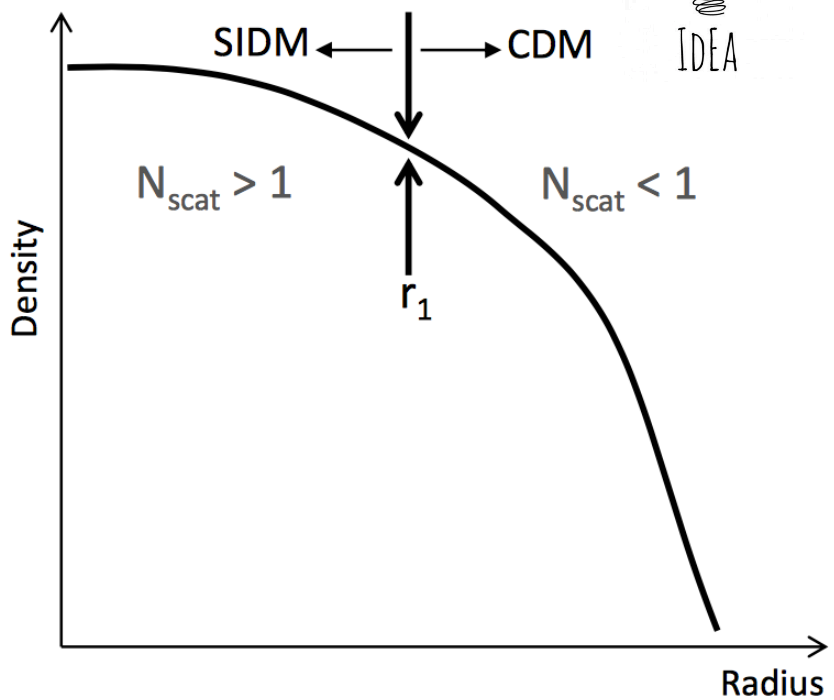
WARNING: upper-limit on self-scattering x-section per unit mass do exist !

Most recent merging cluster analyses typically agree on: $\sigma/m \lesssim cm^2/g$

Stellar kinematics of cluster brightest central galaxies gives even stronger limit.

**See. e.g.,** S.Tulin & H.B.Yu `17 for an extensive discussion!


# Astro-Object Size <—> Different Collider Energy



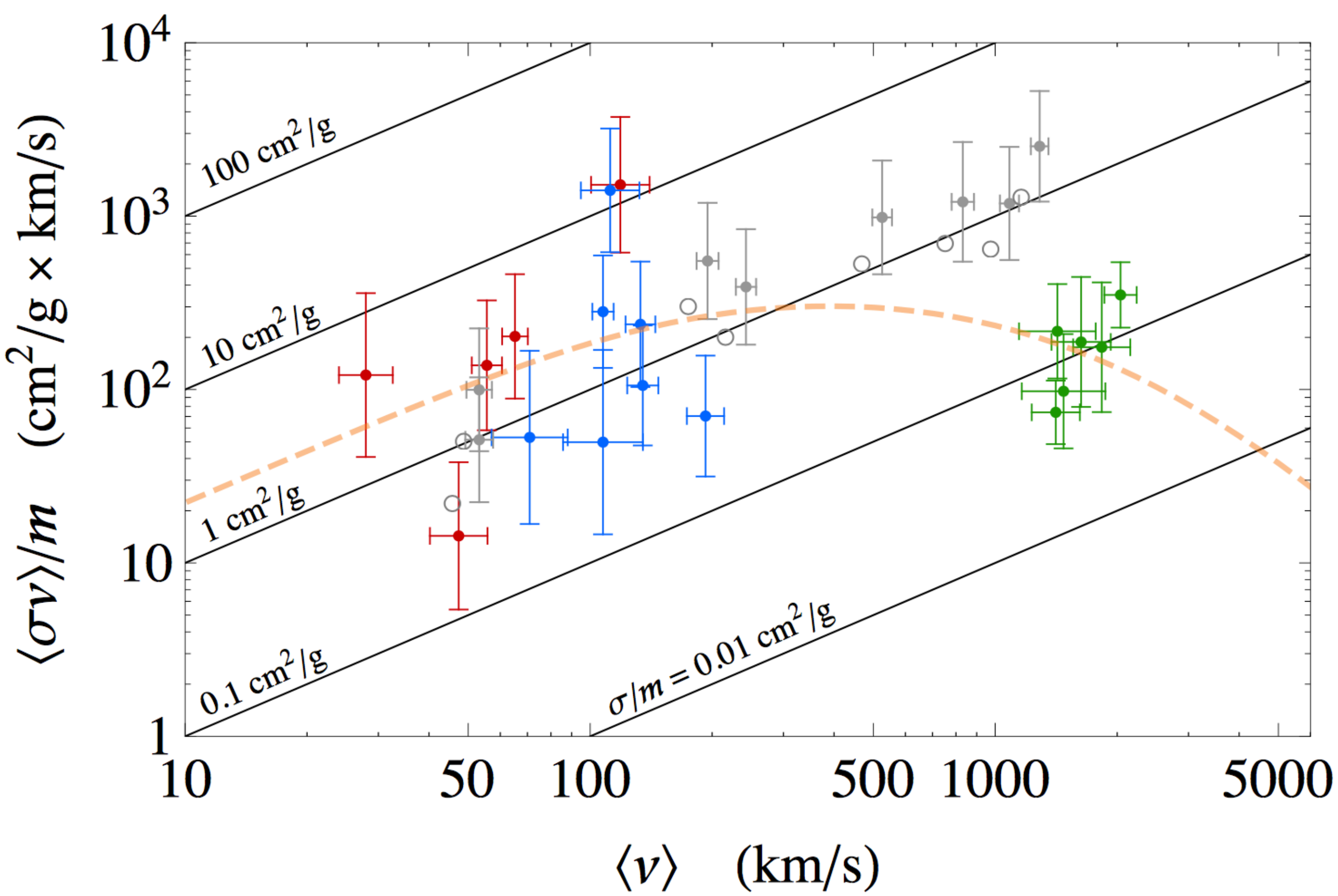


Low energies (v/c ~ $10^{-4}$)


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


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

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




THING dwarfs

LSB

cluster

## SEMI-ANALYTIC SIDM HALO MODEL

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

SIDM —> kinetic eq. for $r < r_1$. Therefore:

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

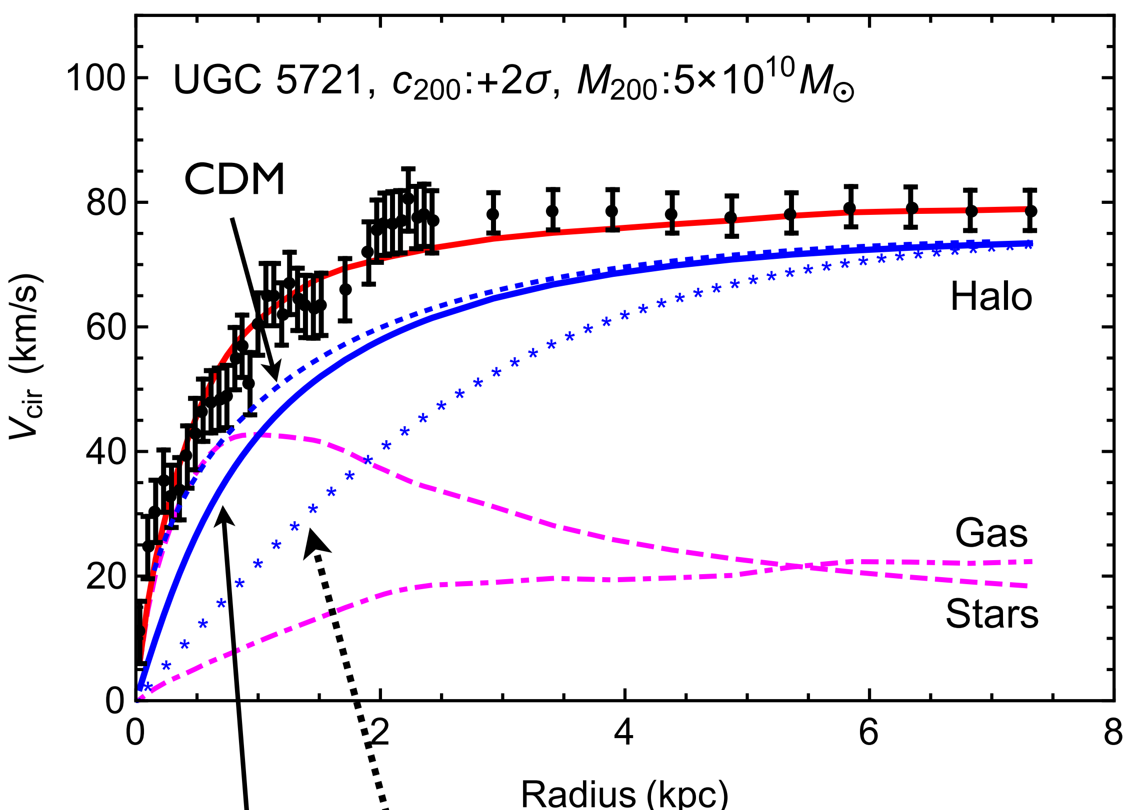
ISOTHERMAL CORED PROFILE

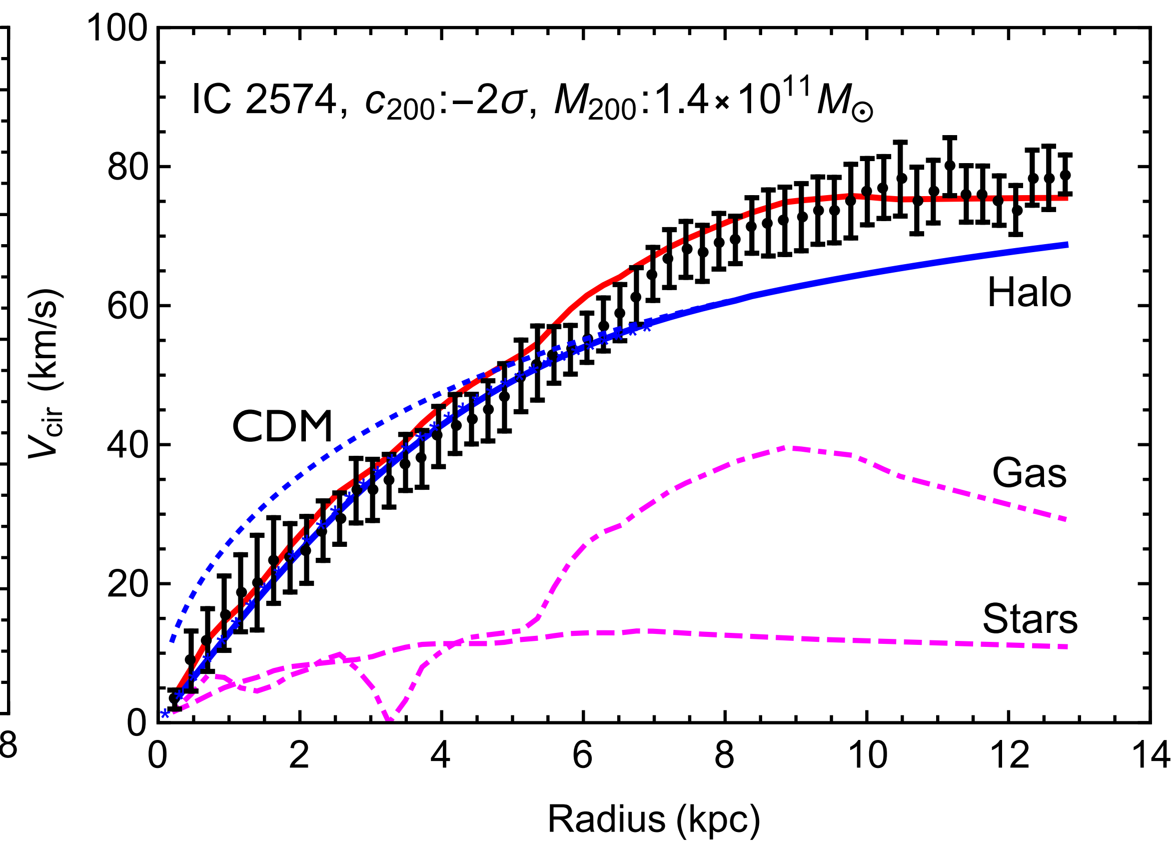
$$\rho_{\rm SIDM}(r) = \begin{cases} \rho_{\rm ISO}(r) & \text{if } \ r \le r_1 \\ \rho_{\rm NFW}(r) & \text{if } \ r \ge r_1 \end{cases}$$

+ same matching on the mass profile.

credit to **Hai-Bo Yu, UC Riverside**

# Solving the Diversity Problem




Isothermal profile without the baryonic influence

True SIDM profile with the baryonic influence

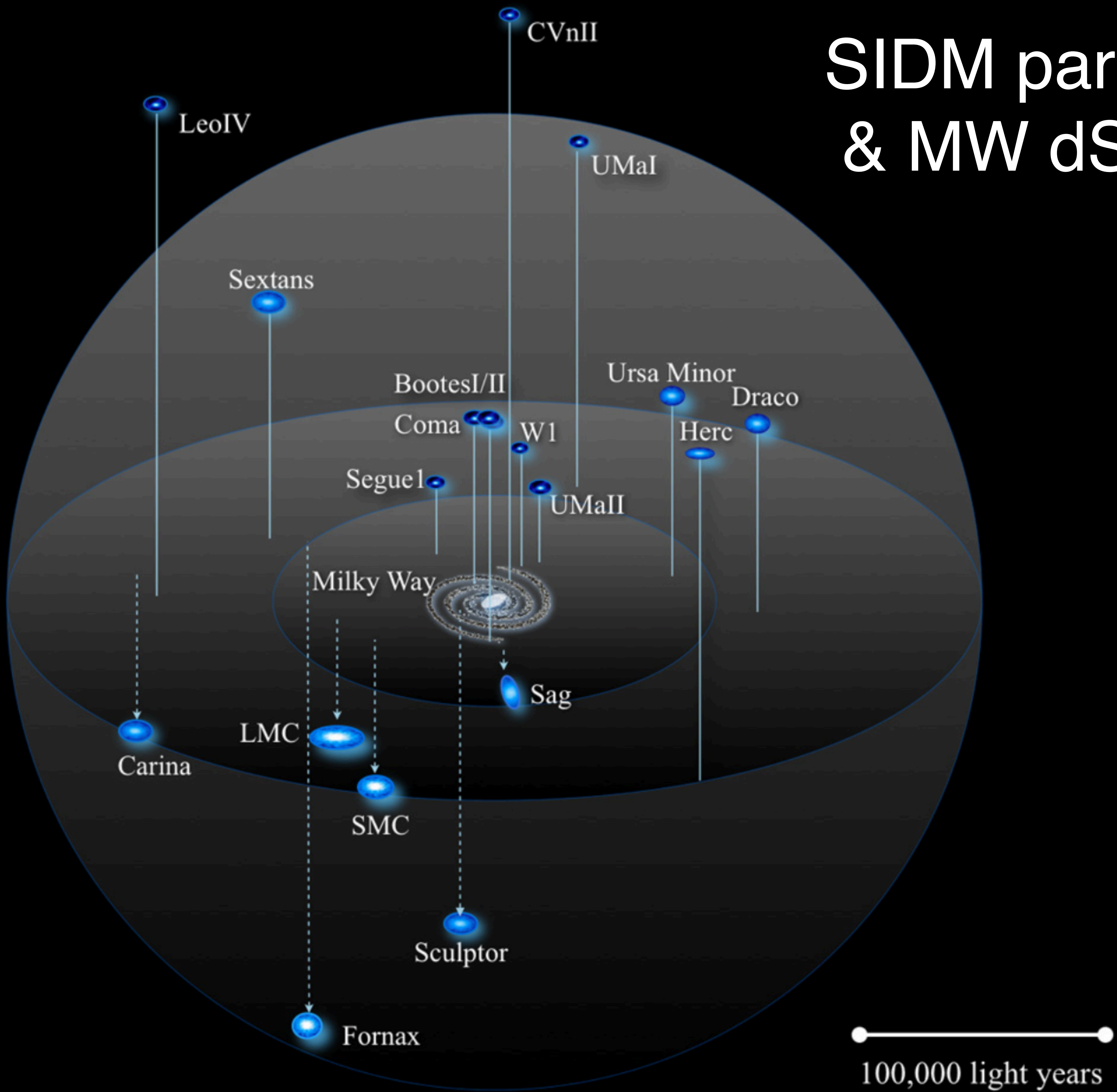
30 galaxies

$V_{max}$~25-300 km/s

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

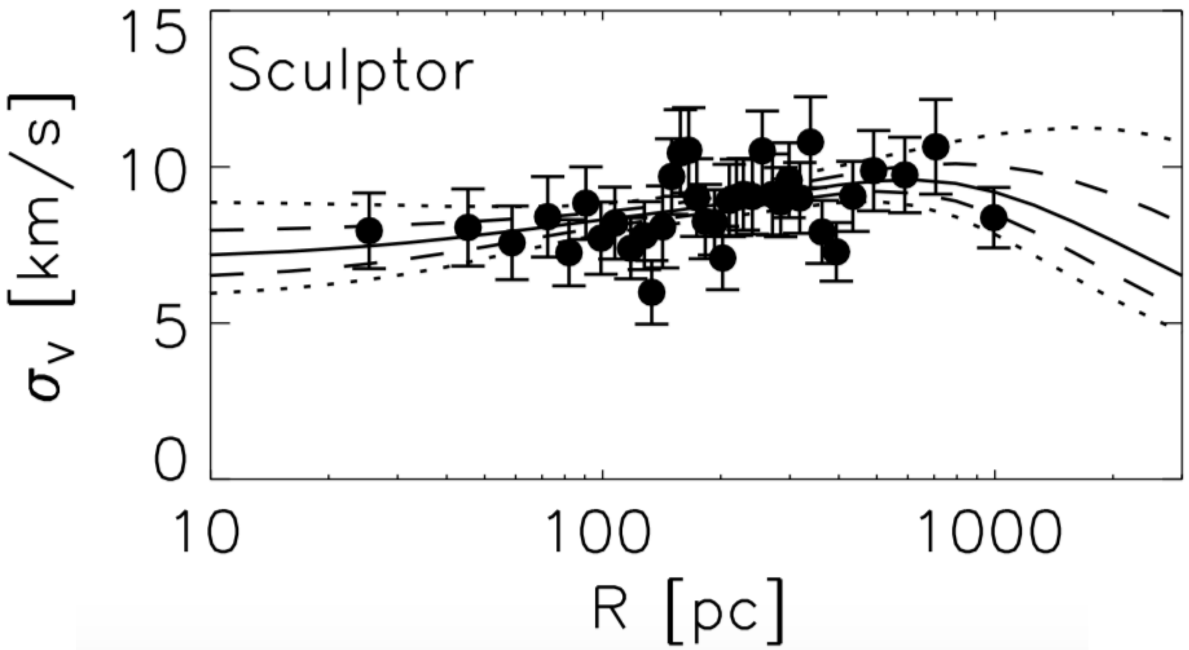
with Kamada, Kaplinghat, Pace (2016)

# SIDM paradigm & MW dSphs?



# COLLIDERS @ kpc: SIDM IN MW dSphs

M.V. & H.B.Yu, **1711.03502**




We exploit the kinematic data available for the 8 MW classical dwarf spheroidals, presented in *Geringer-Sameth et al.'15*.

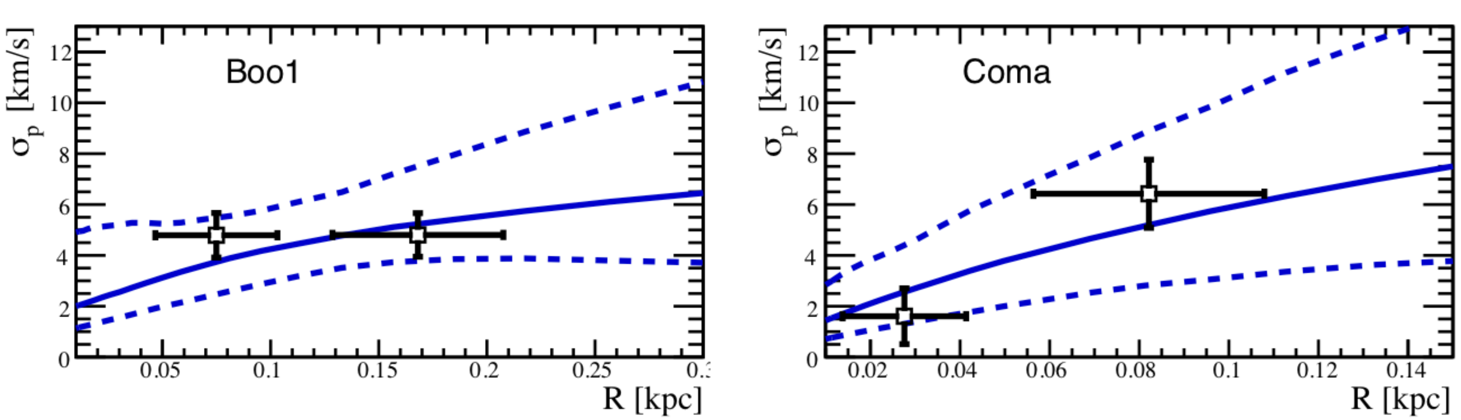
**TEST STATISTICS IN OUR ANALYSIS FOR KINEMATIC DATA.**

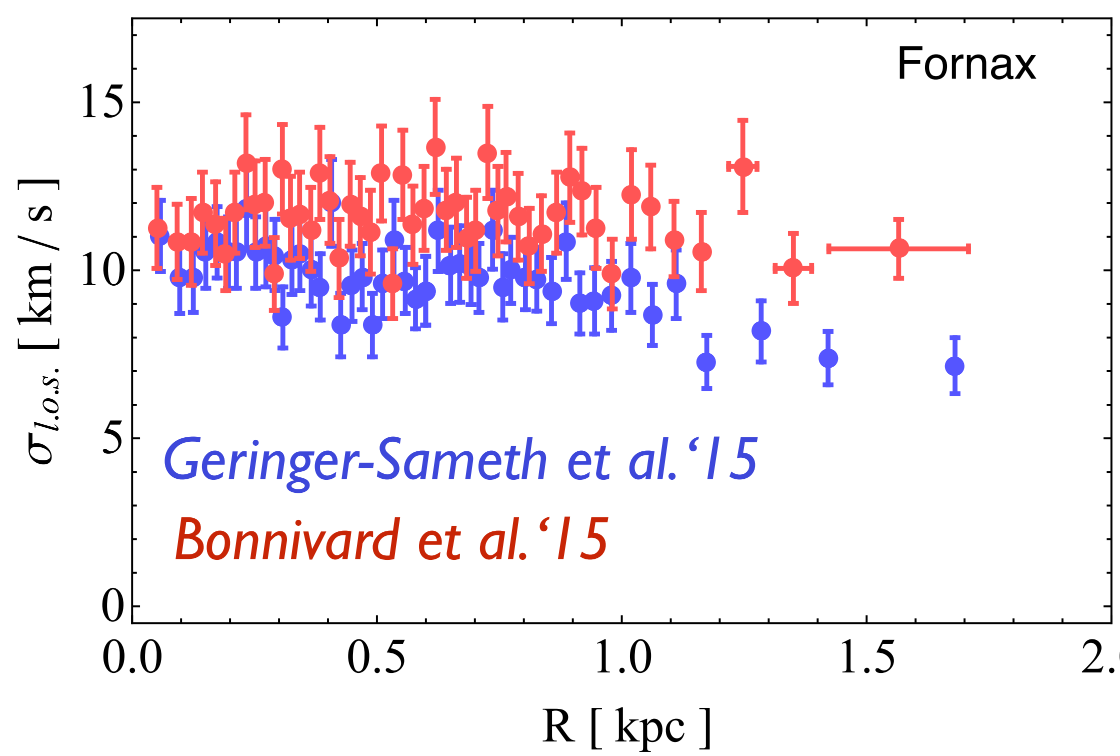
$$\mathcal{L}^{\rm bin} = \prod_{i=1}^{N_{\rm bins}} \frac{(2\pi)^{-1/2}}{\Delta\sigma_i(R_i)} \exp\left[-\frac{1}{2}\left(\frac{\sigma_{\rm obs}(R_i)-\sigma_{\rm p}(R_i)}{\Delta\sigma_i(R_i)}\right)^2\right],$$

where

$$\Delta^2\sigma_i = \Delta^2\sigma_{\rm obs}(R_i) + \left(\frac{1}{2}\left[\sigma_{\rm p}(R_i+\Delta R_i)-\sigma_{\rm p}(R_i-\Delta R_i)\right]\right)^2.$$

More recent Ultra-faint dSphs not included …
… already not-easy life with Classicals' data!



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M.V. & H.B.Yu, 1711.03502


**Cauchy problem for SIDM profile in dSphs:**

$$\frac{d^2h}{dr^2} = -\frac{2}{r}\frac{dh}{dr} - \frac{4\pi G_N \rho_0}{\sigma_0^2}\exp(h)\,,$$

$$h \equiv \ln(\rho/\rho_0)\,,\ h(0) = 1\,,\ h'(0) = 0\,.$$

**NFW matching at $r_1$ :** $\begin{cases} \mathcal{M}_{\rm NFW}(r_1) = \mathcal{M}_{\rm ISO}(r_1)\,, \\ \rho_{\rm NFW}(r_1) = \rho_{\rm ISO}(r_1)\,. \end{cases}$

$$\rho_\star(r) \propto \frac{3}{4\,R_{1/2}}\left(1 + (r/R_{1/2})^2\right)^{-5/2}$$

Plummer model provides good fit of available photometry (see, e.g., *Irwin & Hatzidimitriou '95*).

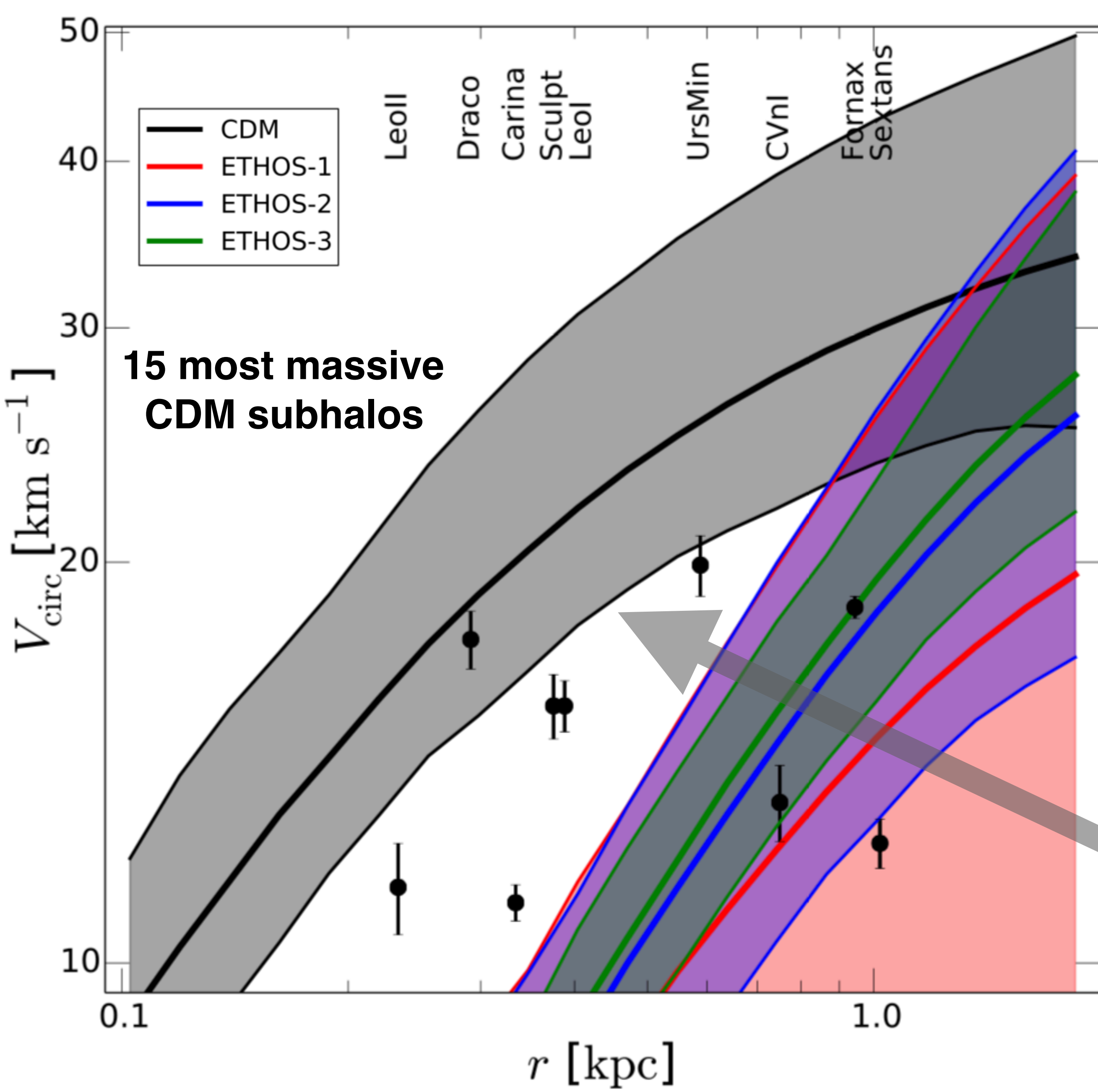
Orbital anisotropy from *Baes & Van Hese '07*,

$$\beta(r) = \frac{\beta_0 + \beta_\infty (r/r_\beta)^\eta}{1 + (r/r_\beta)^\eta}$$

# COLLIDERS @ kpc: SIDM IN MW dSphs

M.V. & H.B.Yu, **1711.03502**

**IN OUR ANALYSIS FURTHER CONSTRAINTS FROM CDM-ONLY N-BODY SIMULATIONS.**




*Vogelsberger, M. et al., MNRAS 460 (2016) 1399*

Matching conditions @ $r_1$ allows for:

$$(\rho_0, \sigma_0) \leftrightarrow (V_{max}, R_{max})$$

$$R_{max} = 2.16\, r_s$$

$$V_{max} = 0.465\sqrt{4\pi G_N \rho_n r_s^2}$$

To get the "right cosmology" at large scales, we implement the CDM-only mass-concentration relation:

$$\log_{10}\left(\frac{R_{max}}{\rm kpc}\right) = A + B\,\log_{10}\left(\frac{V_{max}}{km/s}\right)$$

$$A = 0.48,\ B = 0.18$$
$$\sigma_{\log_{10}(R_{max})} = 0.2$$
$$30 \lesssim V_{max} \lesssim 60$$

# COLLIDERS @ kpc: SIDM IN MW dSphs

M.V. & H.B.Yu, **1711.03502**

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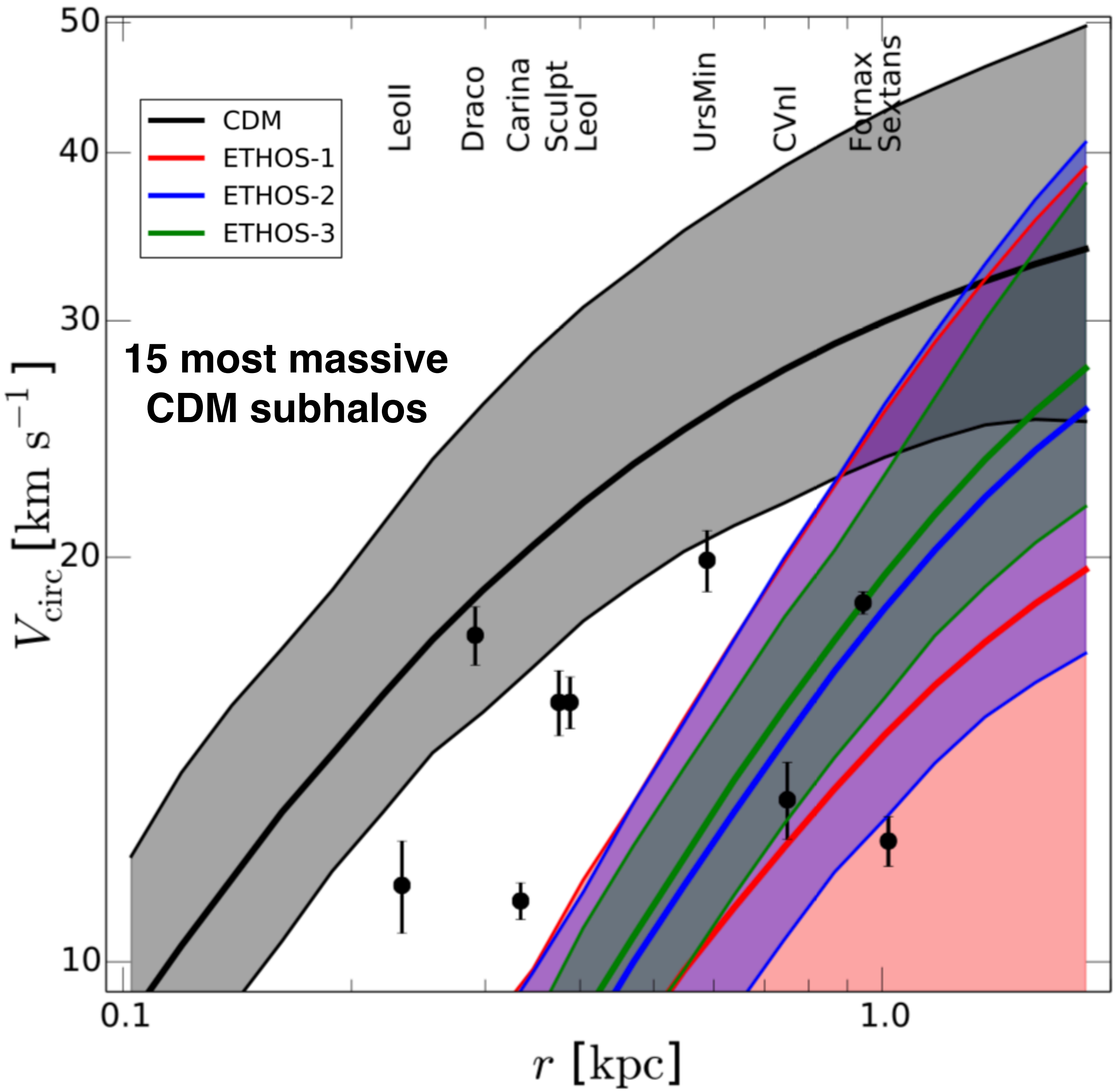


*Vogelsberger, M. et al., MNRAS 460 (2016) 1399*

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$$R_{max} = 2.16\, r_s$$

$$V_{max} = 0.465\sqrt{4\pi G_N \rho_n r_s^2}$$

**PRACTICALLY, USE OF GAUSSIAN WEIGHT:**

$$\chi^2_{\rm CDM} = \frac{1}{2}\left(\frac{\log_{10}(R_{max}) - 0.48 - 0.18\,\log_{10}(V_{max})}{0.2}\right)^2$$

WE ASSUME SUCH RELATION TO BE VALID UP TO HALO SIZE ~ $\mathcal{O}$ (10 kpc)

**+ PENALTY FACTORS FOR $V_{MAX}$ RANGE:**

$$V_{\rm circ}(r = 10\,{\rm kpc}) < 25\ ,\ > 60\ {\rm km/s}$$

$$V^{\rm NFW}_{\rm circ}(r = 0.5\,{\rm kpc}) < 19\ {\rm km/s}$$

# COLLIDERS @ kpc: SIDM IN MW dSphs

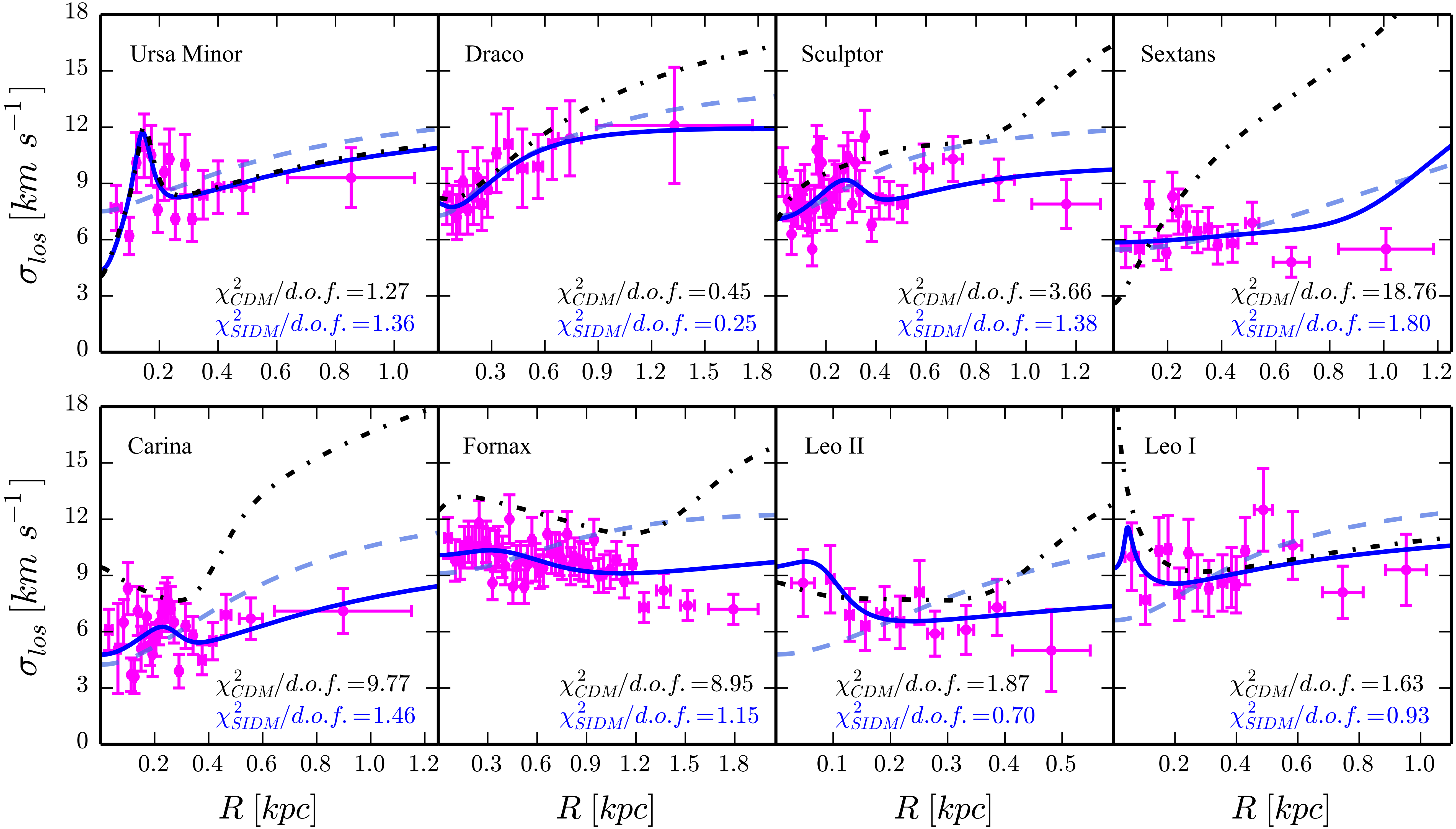
M.V. & H.B.Yu, **1711.03502**

**Dot-Dashed: CDM fit (6 params)**

**Dashed: SIDM fit (4 params)**

**Continuous: SIDM fit (7 params)**

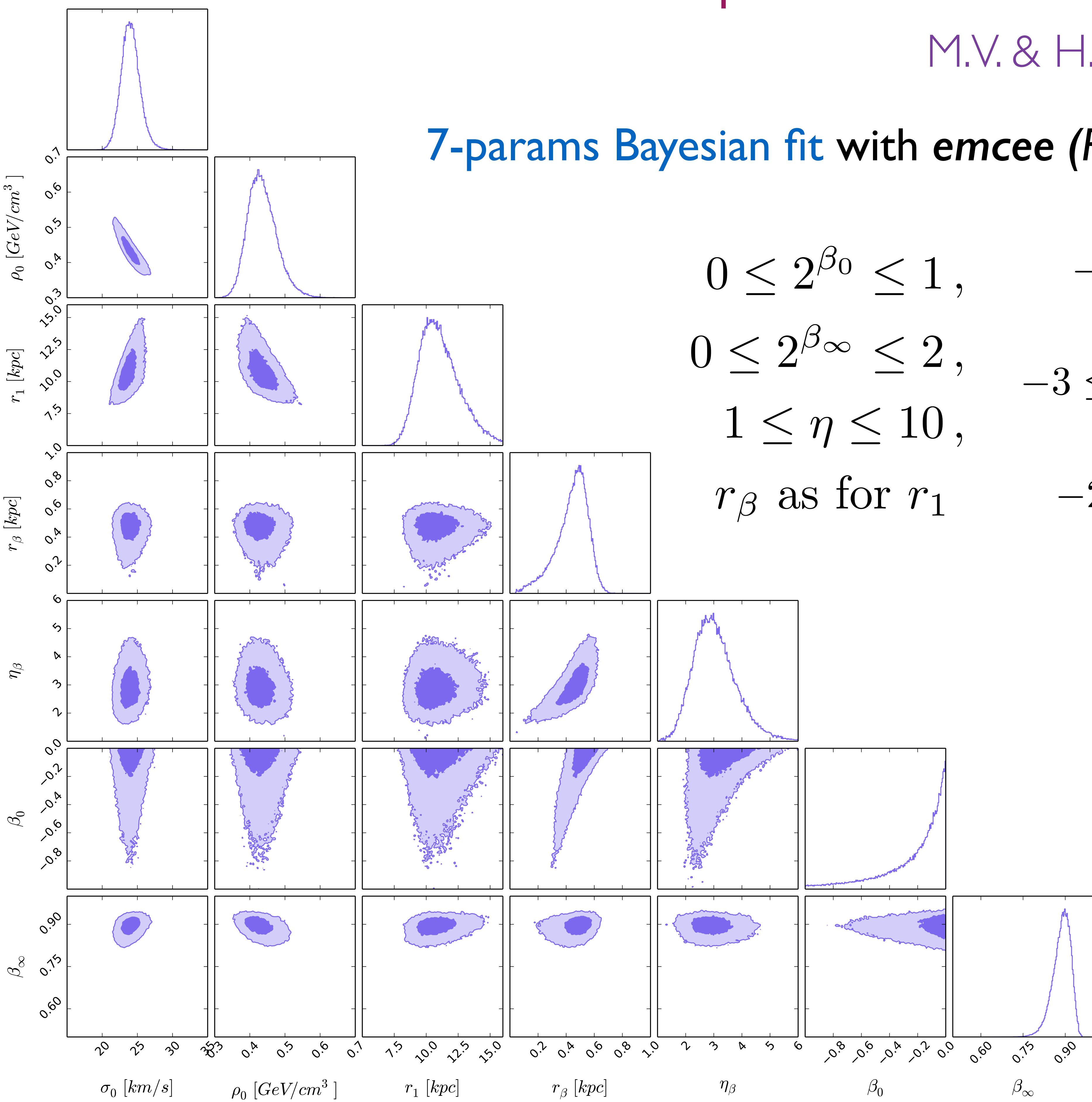
**Good fit of kinematic data while respecting cosmo-constraint!**



# COLLIDERS @ kpc: SIDM IN MW dSphs

M.V. & H.B.Yu, **1711.03502**

**Fornax**




7-params Bayesian fit with *emcee (Foreman-Mackey et al.'13)*

$$0 \leq 2^{\beta_0} \leq 1\,, \qquad -2 \leq \log_{10}\left(\frac{\sigma_0}{[\mathrm{km/s}]}\right) \leq 2\,,$$

$$0 \leq 2^{\beta_\infty} \leq 2\,, \qquad -3 \leq \log_{10}\left(\frac{\rho_0}{[\mathrm{GeV/cm^3}]}\right) \leq 3\,,$$

$$1 \leq \eta \leq 10\,, \qquad -2.5 \leq \log_{10}\left(\frac{r_1}{[\mathrm{kpc}]}\right) \leq 1.5$$

$$r_\beta \text{ as for } r_1$$

Obs.

Theory condition from the stellar phase-space density non-negativity:

$$\gamma_{\rho_\star}\Big|_{r\to 0} \geq 2\beta\Big|_{r\to 0}$$

*J. An & N.W.Evans*
**ApJ 642 (2006) 752**

# COLLIDERS @ kpc: SIDM IN MW dSphs

M.V. & H.B.Yu, **1711.03502**

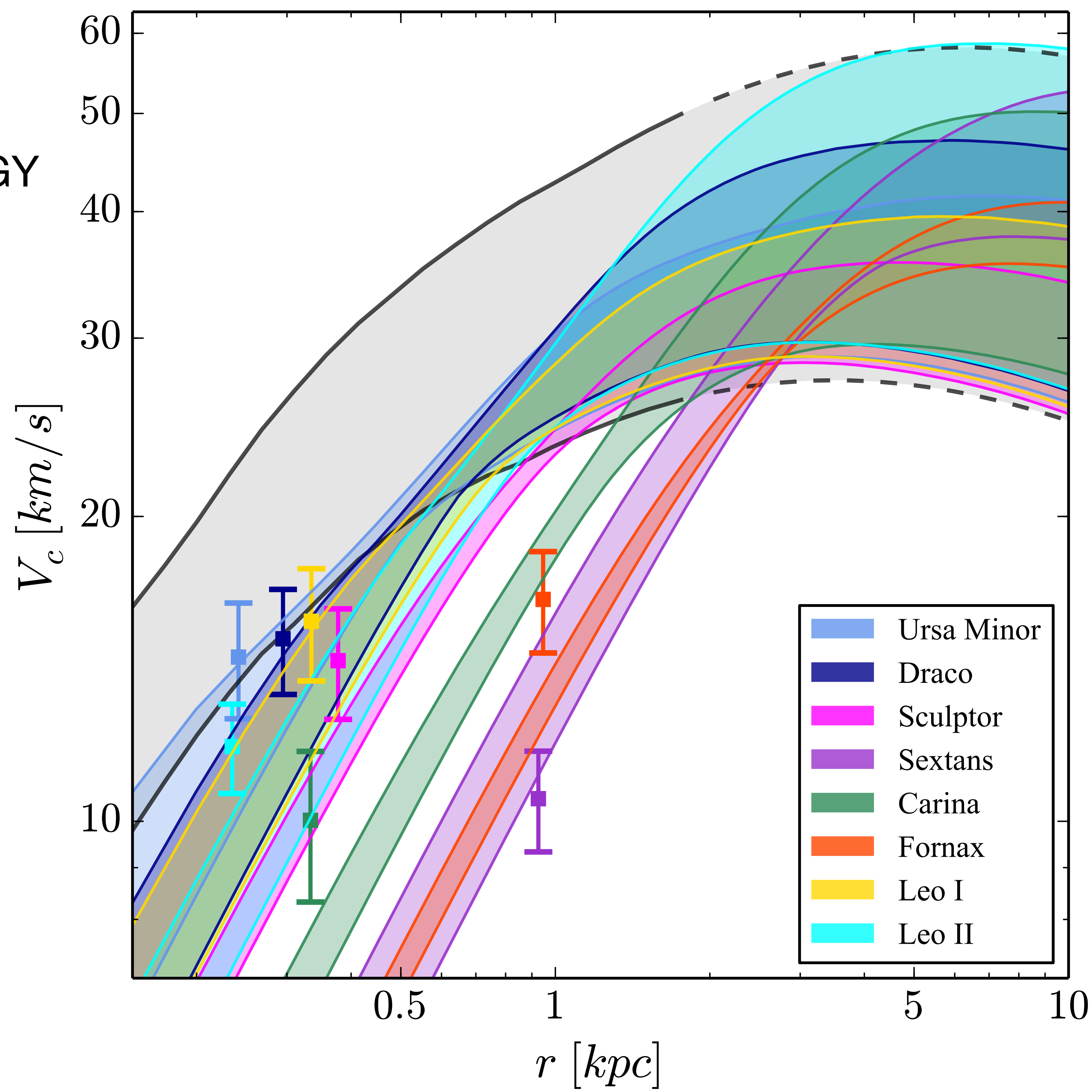
**TBTF & SIDM FROM MCMC ANALYSIS**

- NICE MATCH TO CDM COSMOLOGY ROUGHLY AT SCALES $\gtrsim$ kpc.

- MATCH ENCLOSED MASS @ $r_{1/2}$ WITHIN ~2 SIGMA LEVEL

- MASS ESTIMATOR SHOWN WITH QUITE "CONSERVATIVE" ERRORS

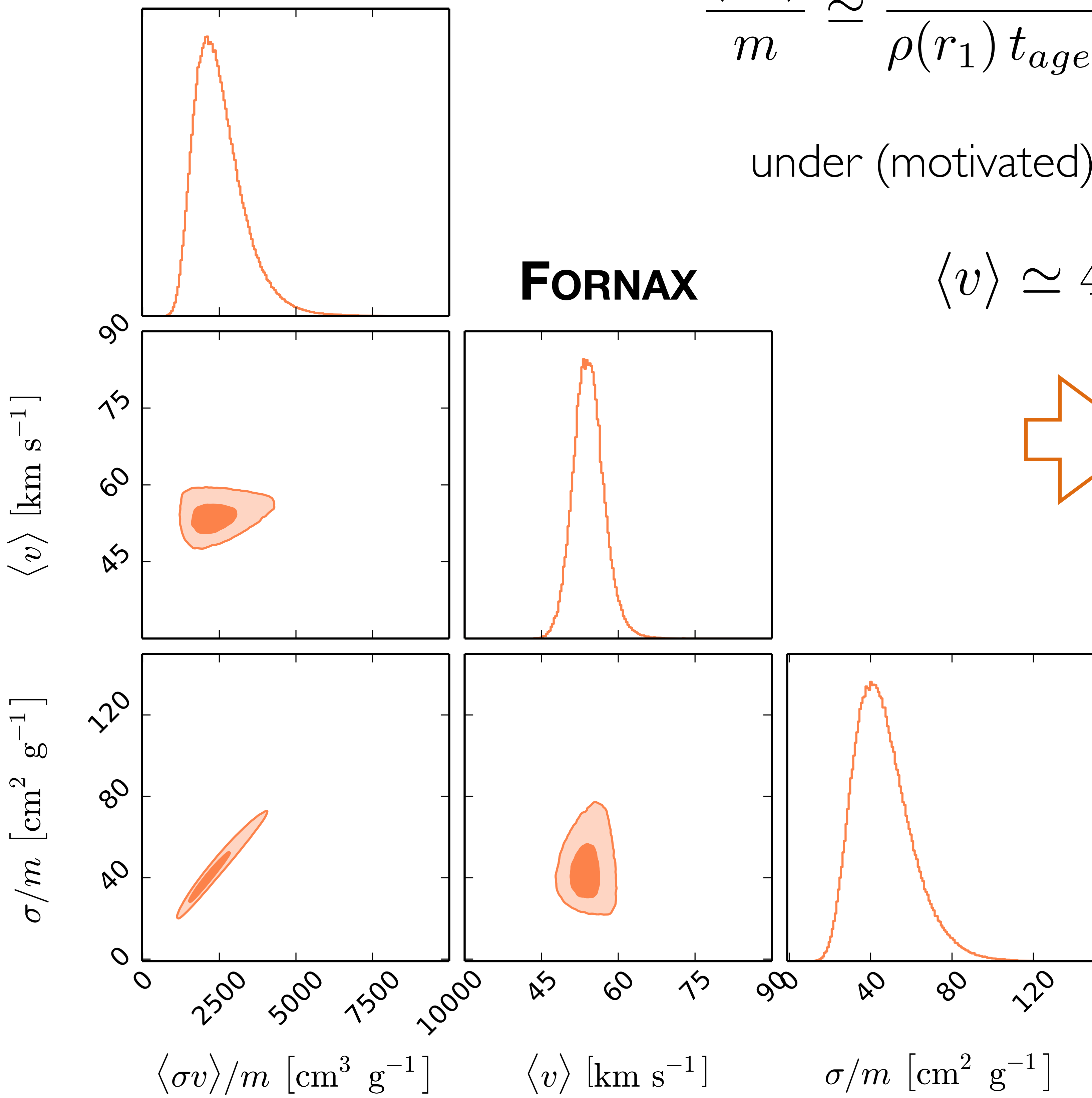
- **FIT TO FULL DATASET USEFUL**: MASS ESTIMATOR INDUCE SOME BIAS, DUE TO ANISOTROPY!



# COLLIDERS @ kpc: SIDM IN MW dSphs

**ABOUT SIDM X-SEC:**
A DATA-DRIVEN ESTIMATE

M.V. & H.B.Yu, **1711.03502**




$$\frac{\langle \sigma v \rangle}{m} \simeq \frac{1}{\rho(r_1)\, t_{age}} \;\Rightarrow\; \frac{\sigma}{m} \simeq \frac{\sqrt{\pi}}{4\sigma_0} \frac{1}{\rho(r_1)\, t_{age}} \,,$$

under (motivated) Maxwellian approximation, i.e.:

$$\langle v \rangle \simeq 4\sigma_0/\sqrt{\pi} \;,\;\; \langle \sigma v \rangle \simeq \sigma \langle v \rangle \;.$$

$$? \lesssim \sigma/m \lesssim ?$$

Marginalization over the age of the system using the flat prior:

$$8 \lesssim t_{\rm age}\ [\rm Gyr] \lesssim 12$$

*A. W. McConnachie* **ApJ 144 (2012) 4**

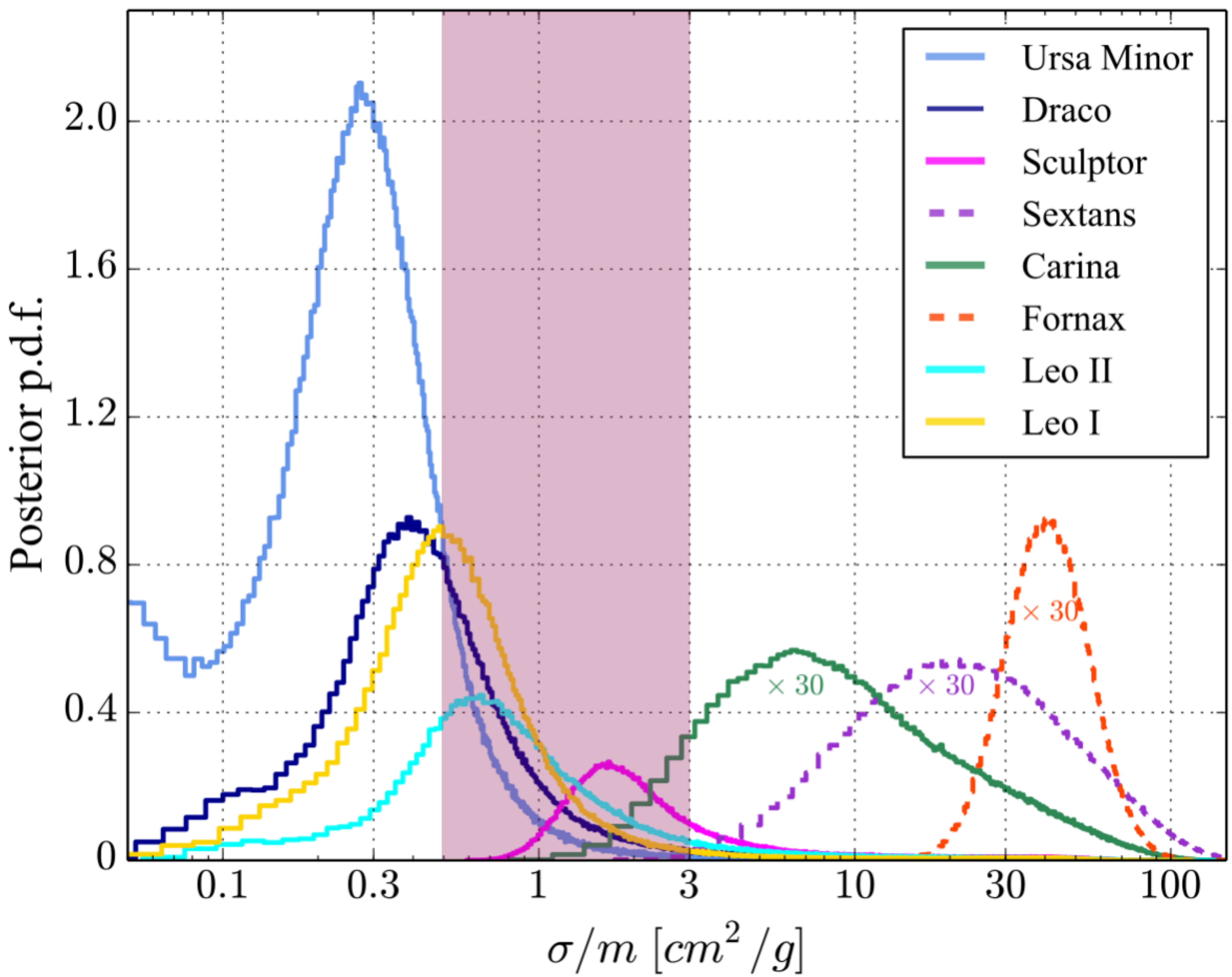
—> estimate of SIDM x-sec from data!

# COLLIDERS @ kpc: SIDM IN MW dSphs

M.V. & H.B.Yu, **1711.03502**

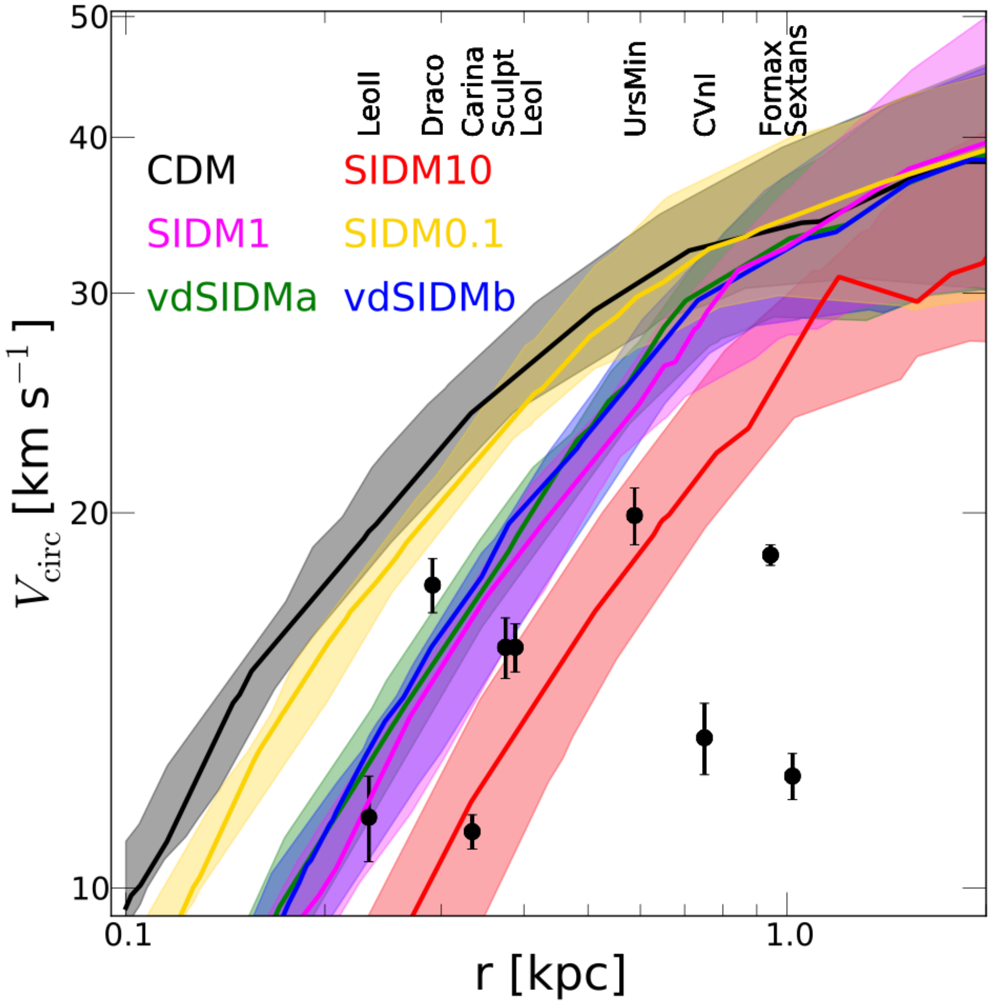
**X-SEC PROBED BY MW DWARF SATELLITES SPANS 2 ORDERS OF MAGNITUDE !**

**HOWEVER,** 6 OUT OF 8 GALAXIES CAN BE CONSISTENT @ 68% WITH 0.5 — 3 $cm^2\,g^{-1}$.



# COLLIDERS @ kpc: SIDM IN MW dSphs

M.V. & H.B.Yu, **1711.03502**

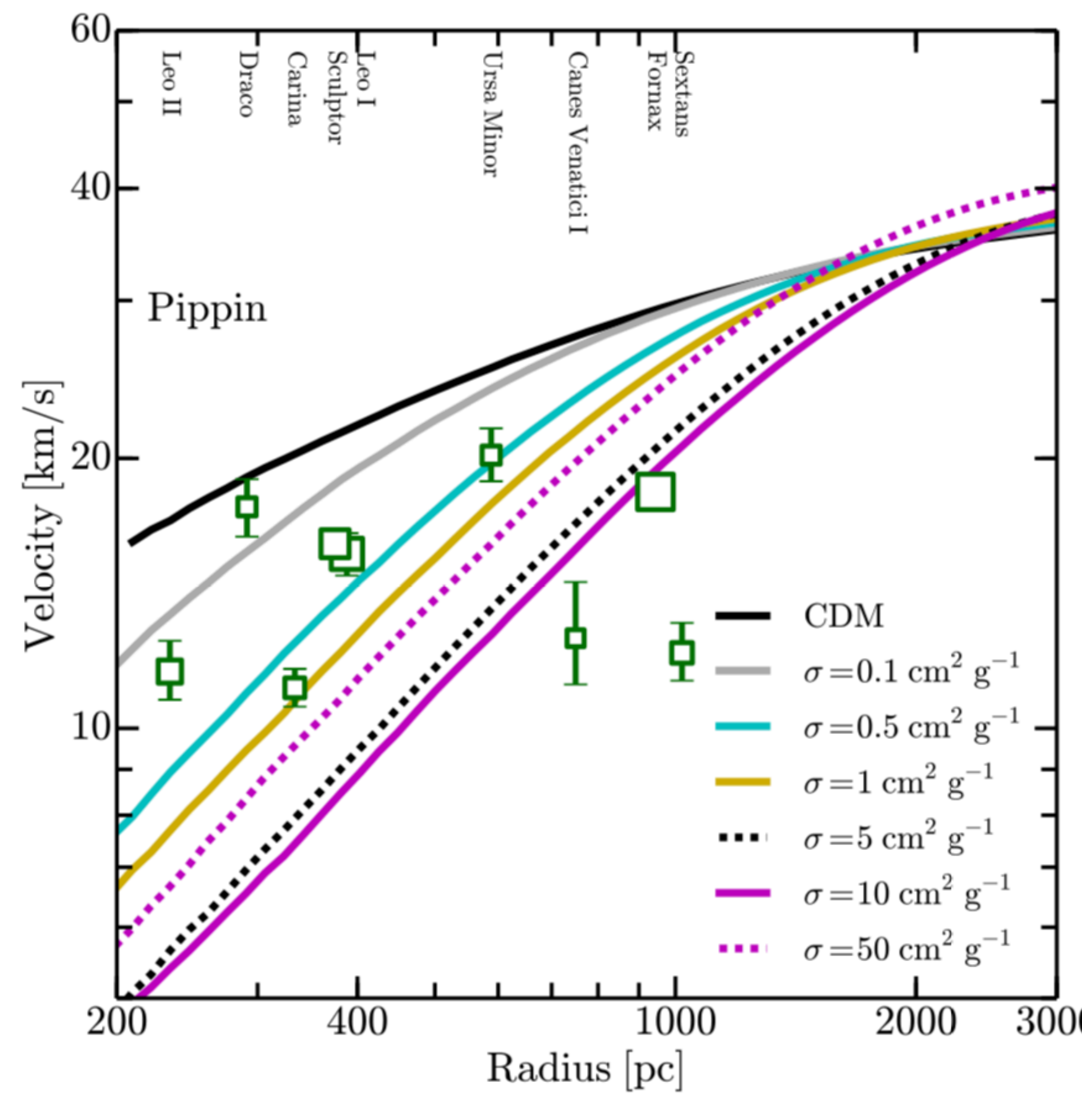



**Our study on SIDM halo in MW dSphs shows:**

I) X-sec range in agreement with current indications from N-body simulations.

*Zavala, J. et al. '13, Elbert, O. et al. '15*

**N.B.** We did not account for core collapse …




II) Same SIDM ballpark to address "Core VS Cusp" in other kpc-sized systems.

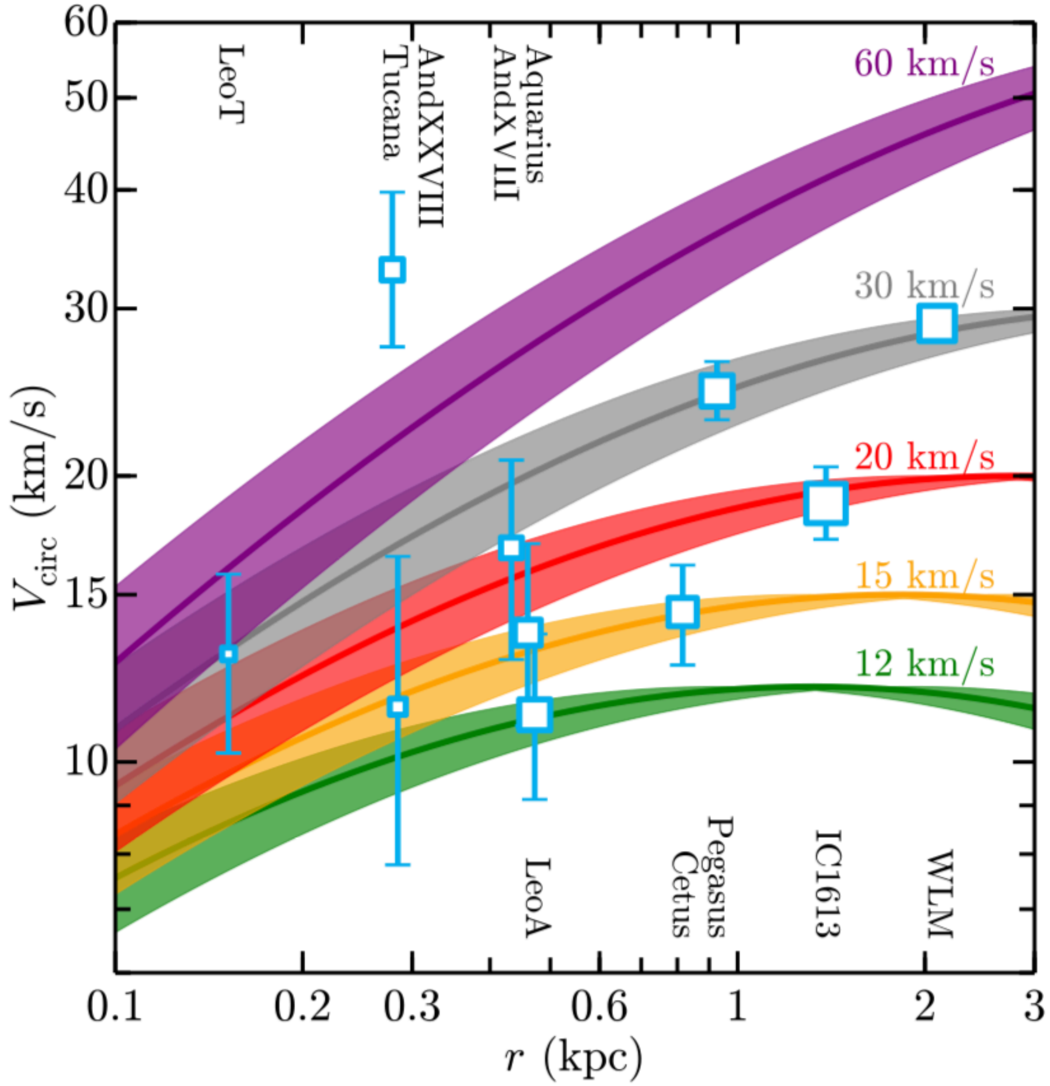
*Kaplinghat, M. et al. '16, Kamada, A. et al. '17*

III) Two main "outliers" pointing to possible importance of environmental effects.

**—> SIDM ameliorates TBTF problem!**

*Vogelsberger, M. et al. '16 (ETHOS)*

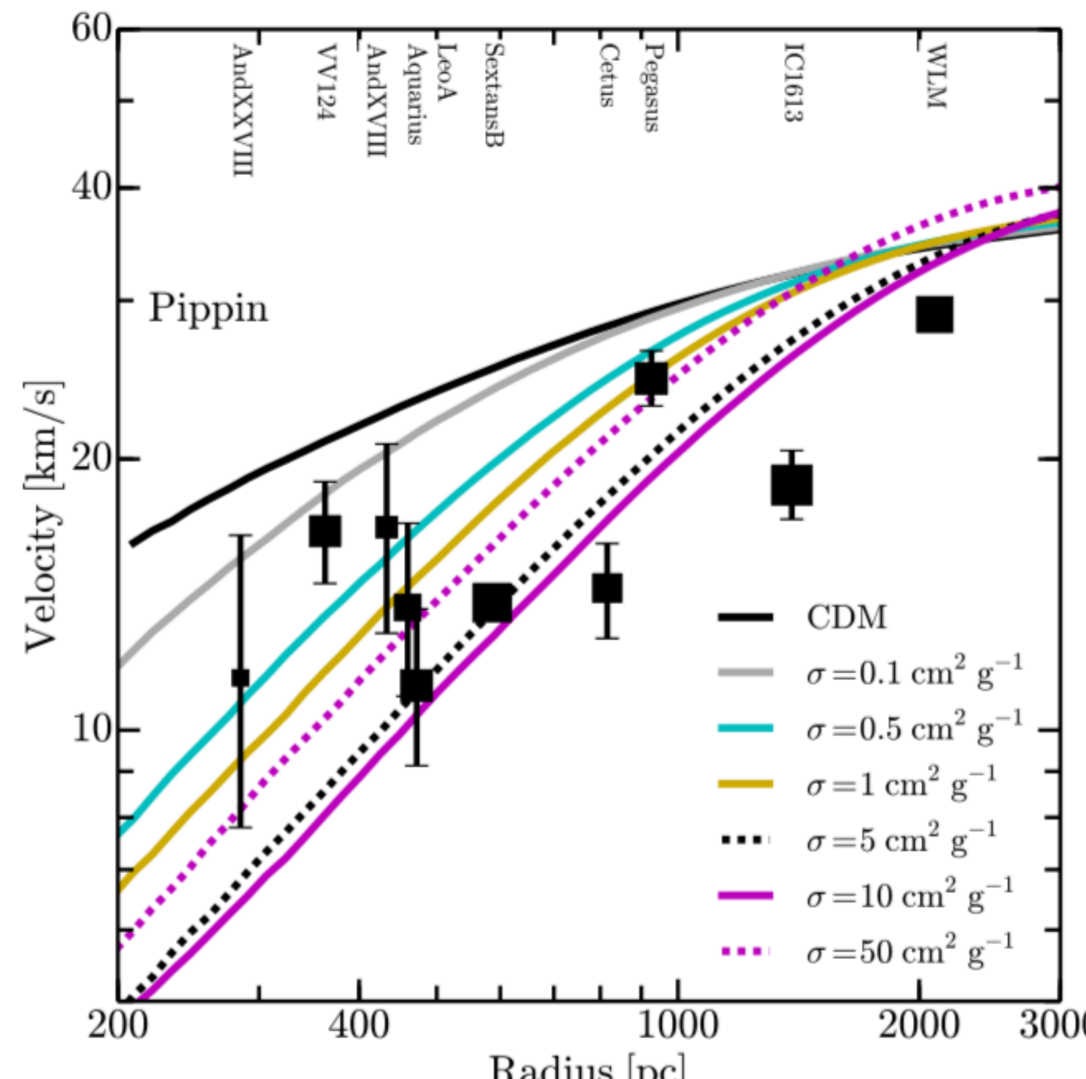
# NEXT STEPS: A TBTF PROBLEM IN THE FIELD !




Measured kinematics for field galaxies near MW & M31, in the Local Group, point once again to less massive subhalos than in CDM studies.

*Garrison-Kimmel et al. '14 , Papastergis et al. '14*

"field galaxies" should not be influenced by (otherwise possibly relevant) external tides!




**dSph FIELD GALAXIES** MAY REPRESENT EXTREMELY IMPORTANT TESTS!

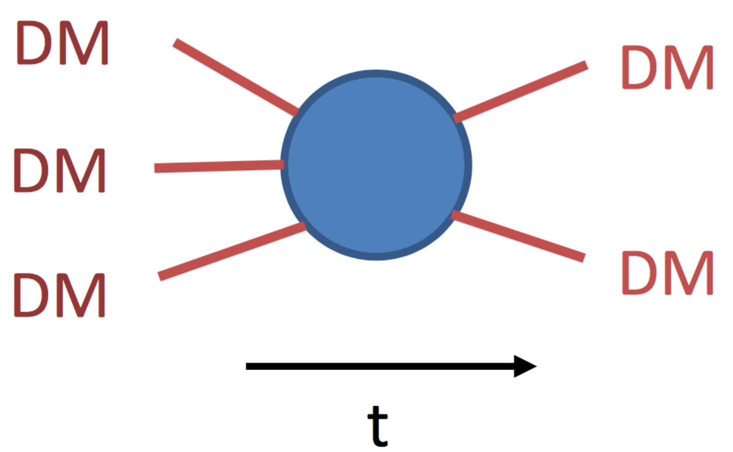
SIDM SIMULATIONS FOR FIELD DWARFS CONFIRM TREND SEEN FOR MW ONES …

*—> see, for instance,* ***Elbert et al. '14***

**… DEEPER INVESTIGATION NEEDED!**

# NEXT STEPS: MODEL-BUILDING NEED GUIDELINES…

## Strongly Interacting Massive Particles




*PRL 113 (2014) 171301, Hochberg, Y. et al.*
*PRL 115 (2015) 021301, Hochberg, Y. et al.*

@ strong coupling, strong scale emerges:

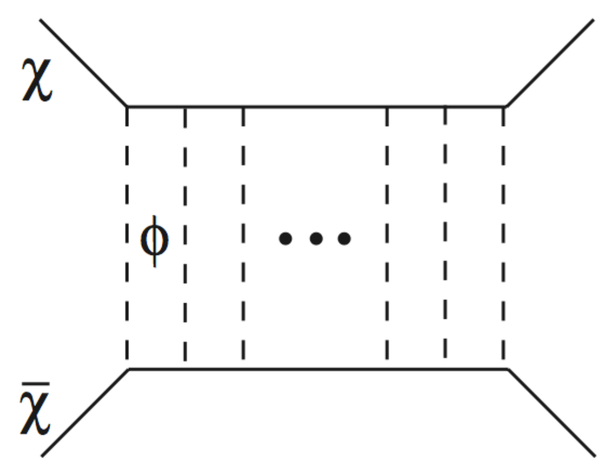
$$m_{DM} \sim \alpha_{eff}(T_{eq}^2 M_{Pl})^{1/3}$$

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

Dominant 3, 4 —> 2 annihilations, dark sector cannot be completely secluded from SM

*ApJ 398 (1992) 43, E.D. Carlson, M. E. Machacek & L.J.Hall*

## Self-Interactions with Light Mediators




*PRL 104 (2009) 151301, J. Feng et al.*
*PRD 81 (2010) 083522, M.R.Buckley & P.J.Fox*
*PRL 106 (2011) 171303, A.Loeb & N.Weiner*
*PRL 110 (2013) 111301, S.Tulin 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 through $U(1)_Y$ small mixing

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

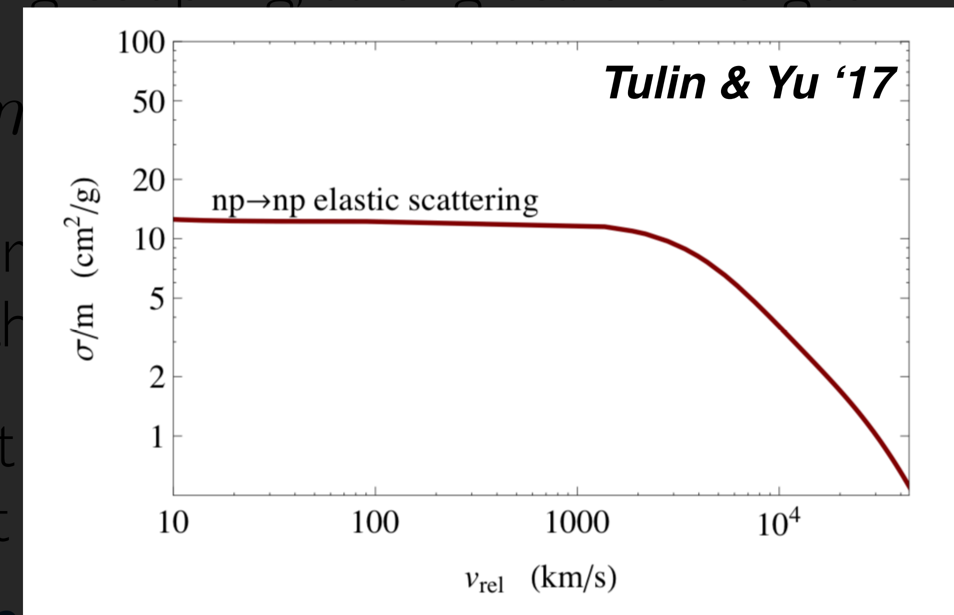
# NEXT STEPS: MODEL-BUILDING NEED GUIDELINES…

Strongly Interacting Massive Particles

@ strong coupling, strong scale emerges:

**IF VELOCITY DEPENDENCE IS IMPORTANT, FORGET IT !**

**( but actually, nucleon-nucleon scatt. x-sec is velocity-dependent… )**




"Simple" r…

sector with…

Dominant…

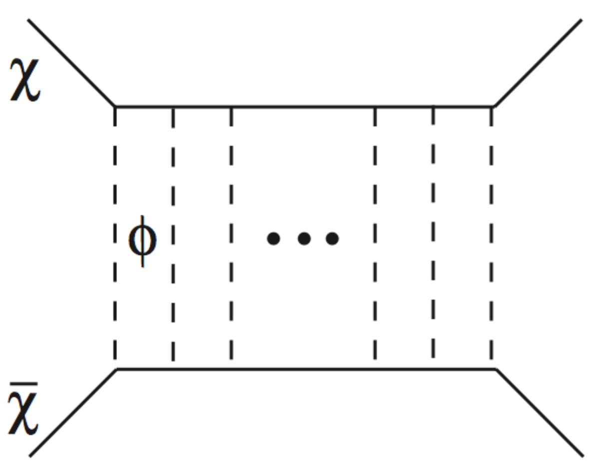
cannot…

PRL 113 (2014) 171301, Hochberg et al.

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

ApJ 398 (1992) 43 , E.D. Carlson, M. E. Machacek & L.J.Hall

## Self-Interactions with Light Mediators




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

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

*PRL 106 (2011) 171303 , A.Loeb & N.Weiner*

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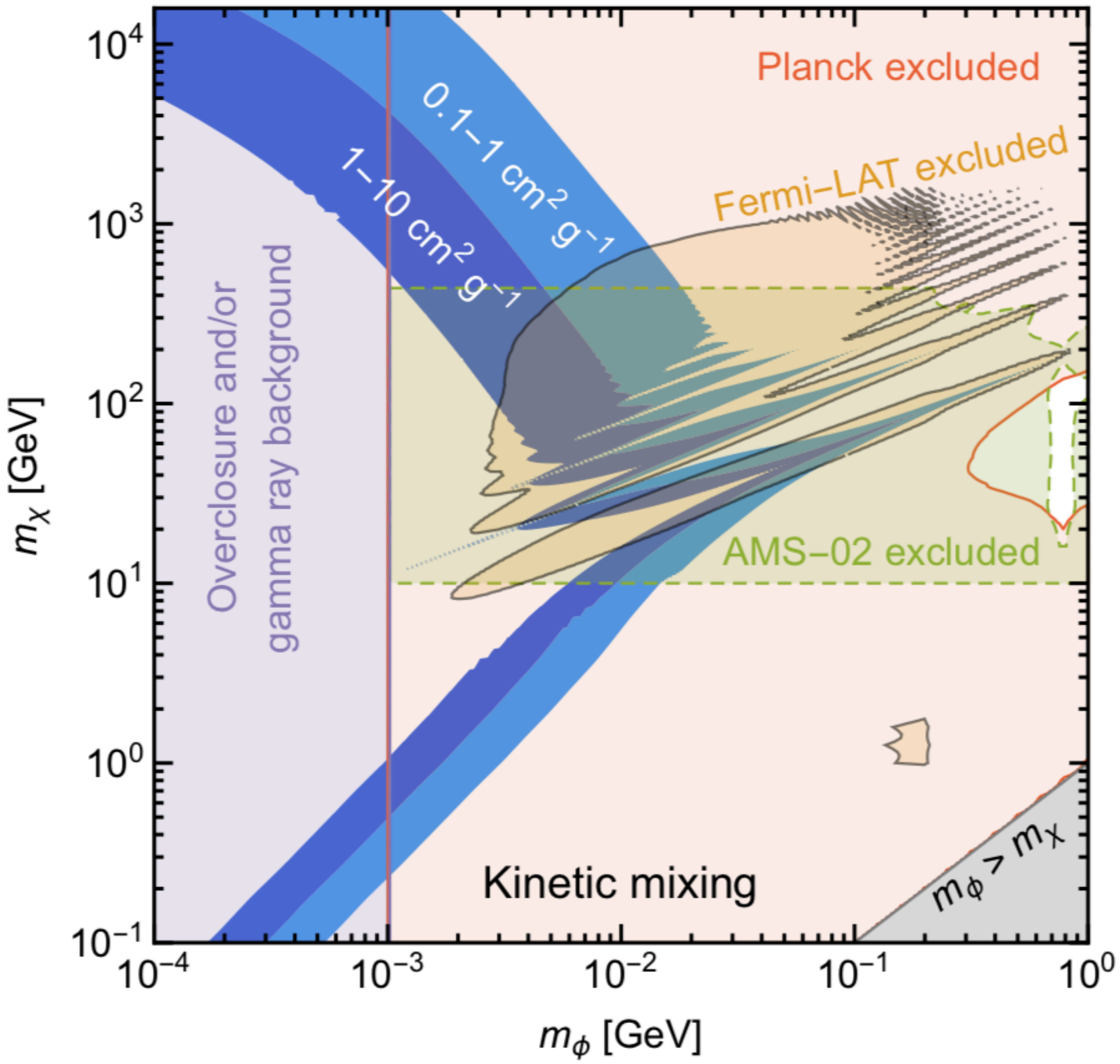
—> $U(1)_D$ coupled to SM through $U(1)_Y$ small mixing

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

# … ESPECIALLY IN LIGHT OF PRESENT CONSTRAINTS…

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

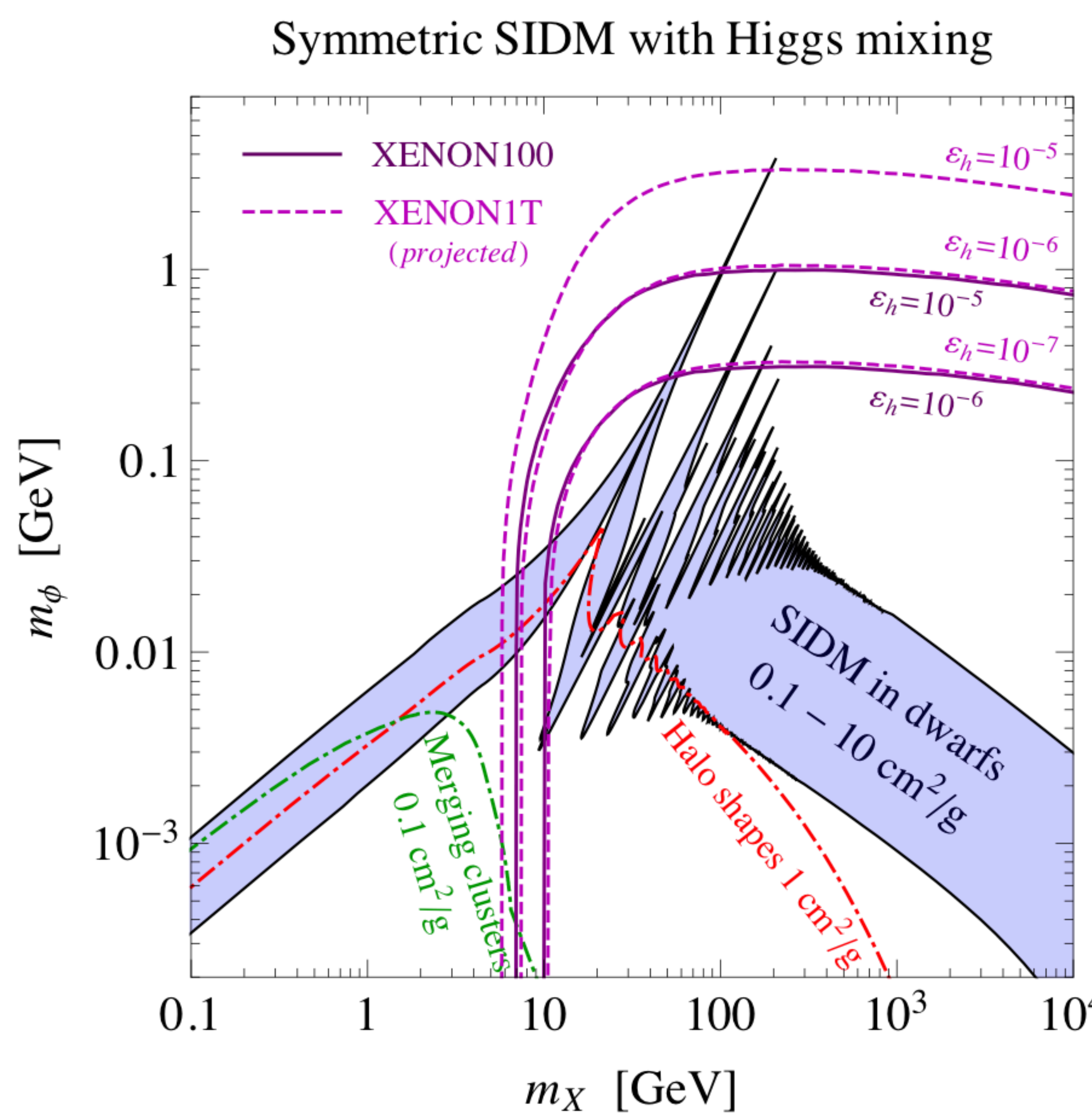



$$\mathcal{L} \supset -g_\chi^{\rm V}\phi^\mu\bar{\chi}\gamma_\mu\chi - \frac{1}{2}\sin\epsilon\, B_{\mu\nu}\phi^{\mu\nu} - \delta m^2\phi^\mu Z_\mu$$

**—> s-wave thermal production assumed**

p-wave available with scalar mediators, but excluded by direct detection !

*PRD 89 (2014) 035009 , M.Kaplinghat et al.*

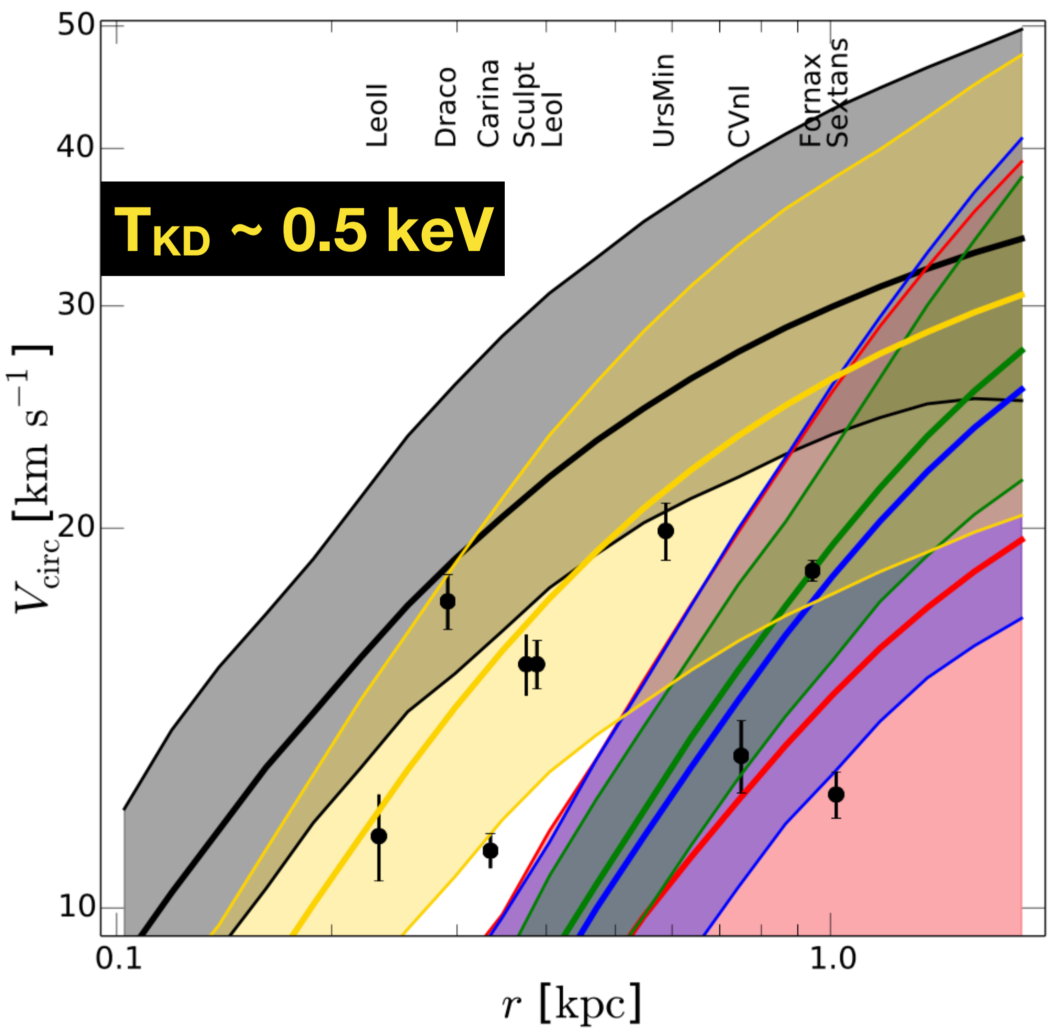



INTERPLAY BETWEEN INDIRECT & DIRECT SEARCHES DSIFAVORS THERMAL PRODUCTION MECHANISM

NON-THERMAL —?> NO PREDICTIVITY

# … BUT "NIGHTMARE SCENARIOS" MAY BE (STILL) INTERESTING!

*Vogelsberger, M. et al., **MNRAS '16***



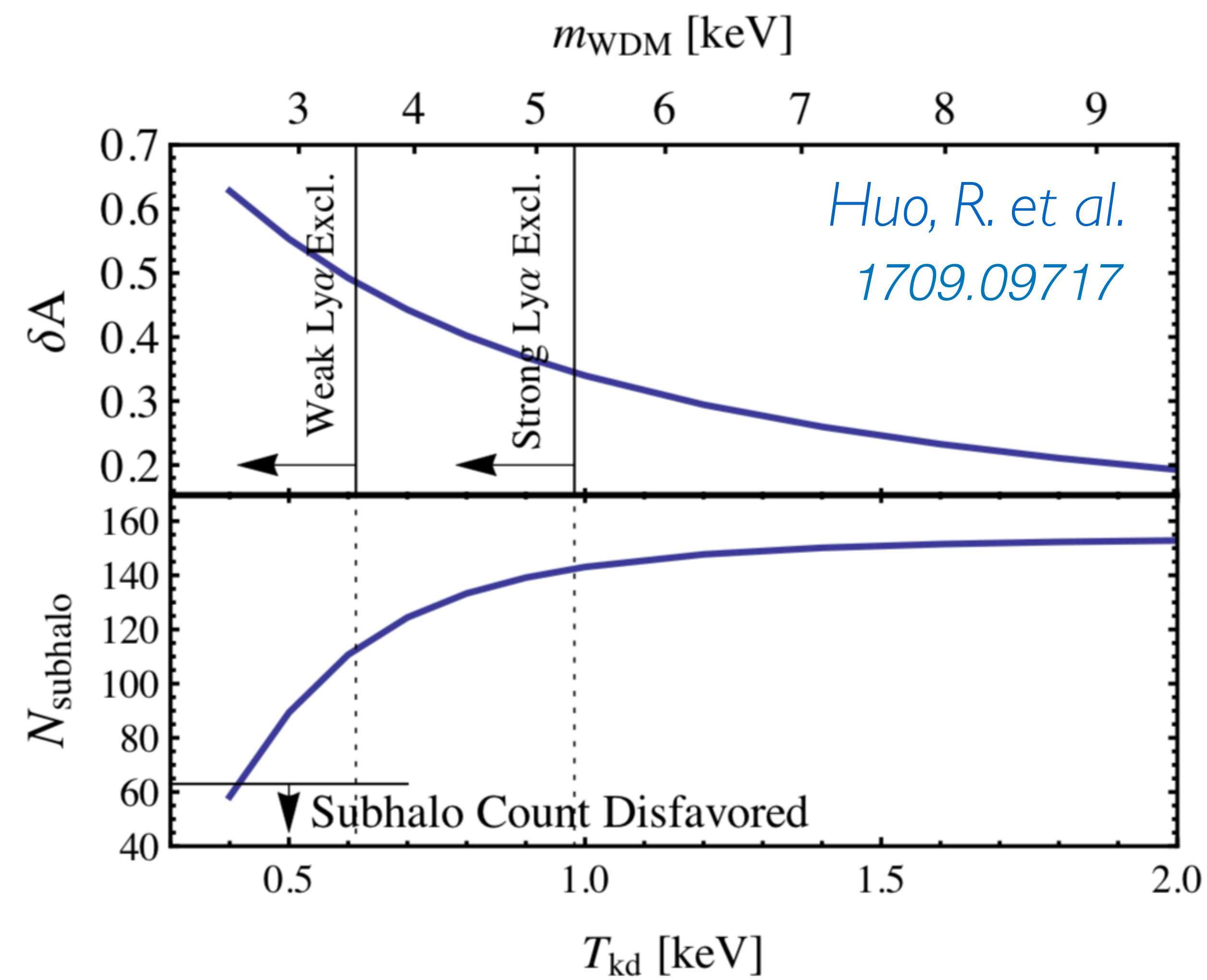

$$\mathcal{L}_{\rm int} = -ig_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu + m_\chi \bar{\chi}\chi + \frac{1}{2} m_\phi^2 \phi^\mu \phi_\mu - ig_f \bar{f}\gamma^\mu f \phi_\mu$$

I.E. ADD DARK RADIATION SPECIES (E.G. STERILE ν)

**LATE KINETIC DECOUPL. —> TBTF + MS IN 1 SHOT!**

*van den Aarsen et al., PRL ' 12, Bringmann et al., PRD '14*

**UPDATED LYMAN-α** CONSTRAINTS **MAY POINT TO $T_{KD}$ > 1 keV** … IF SO, NOT GOOD NEWS FOR MS!




"NIGHTMARE SCENARIO" STILL PROVIDES X-SEC GOOD FOR TBTF PROBLEM!

—> INTERESTING SIGNATURES FOR NEXT-GEN COSMO-SURVEYS

—> NEED MORE PRECISE SCRUTINY ON ITS GALACTIC PREDICTIONS

# NEXT STEPS: SIDM VS NP SMALL-SCALE ALTERNATIVES

*L.Hui, J.Ostriker, S.Tremaine & E.Witten '17*

*Fuzzy DM = Wave DM = Ultra-light Axion DM*

*W.Hu, R.Barkana & A.Gruzinov '00*

SEVERAL STUDIES ON MW DSPH KINEMATICS !

*D.Marsh & A.Pop '15 , S.-R.Chen, H.-Y.Schive & T.Chiueh '16 , L.Urena-Lopez, V.Robles & T.Matos '17*

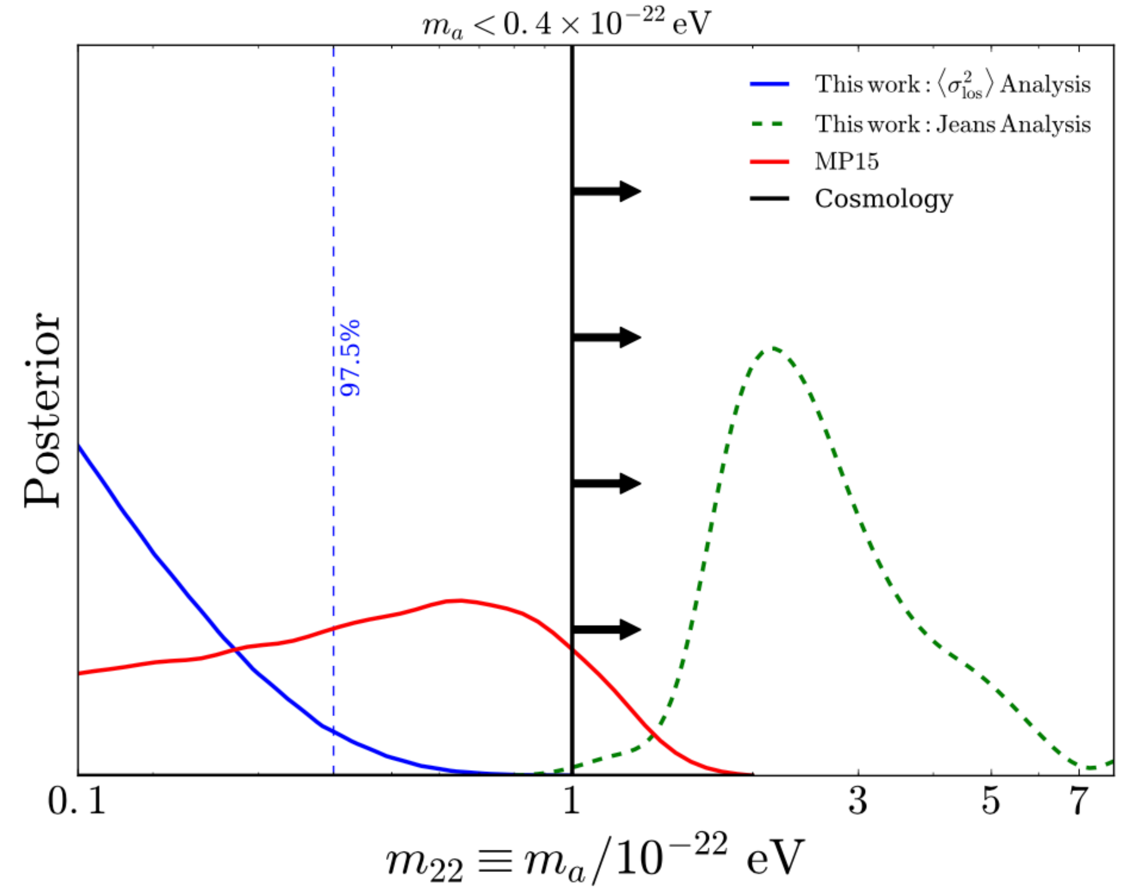
—> tension with current cosmological bounds ?

*A.Gonzalez-Morales et al. '16*

LYMAN-α ! *Irsic, V et al., PRL 119 (2017) 10*

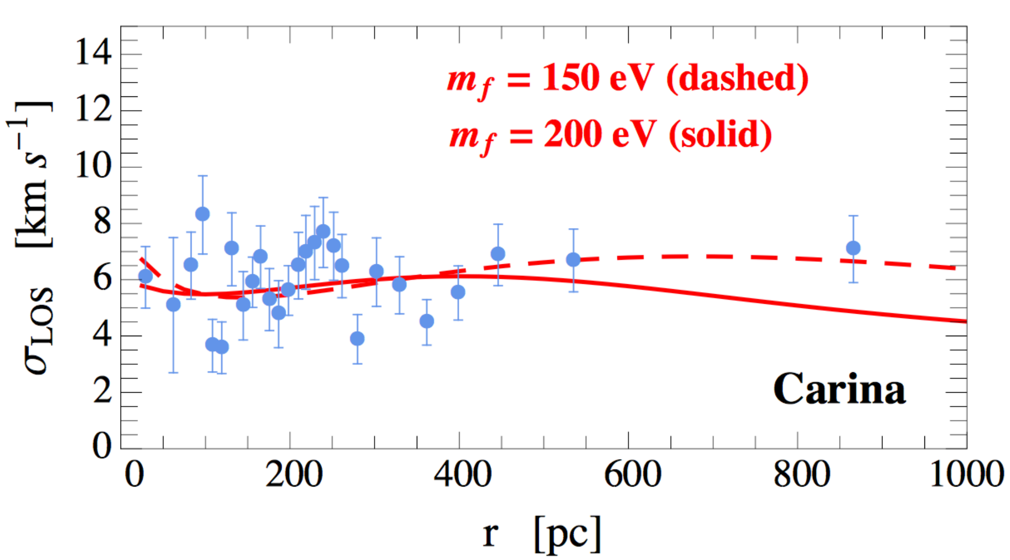
Similar proposals based on BEC / Superfluidity.

*T.Harko '11 , L. Berezhiani & J.Khoury et al. '15*




Few N-body simulation studies so far …

*H.-Y.Schive et al. '14 , P.Mocz et al. '17*




NOT ONLY BOSONS: *Degenerate Fermi gas*

*V. Domcke & A.Urbano '15 , L.Randall, J.Scholtz & J.Unwin '17*

$$f_{FD} = \begin{cases} 1 & p \leqslant p_F \\ 0 & p > p_F \end{cases}$$

Fermi quantum pressure can balance gravity, yielding cored density profiles.

# PERSONAL RECAP ...

The SIDM proposal offers a very compelling DM paradigm :

— TO SOLVE CORE VS CUSP (LIKELY PRESENT ALSO IN DSPHS)

— TO ADDRESS (ELEGANTLY) THE DIVERSITY PROBLEM

( TO LOOSE MEMORY ON BARYONIC FEEDBACK !!! )

— TO PARTIALLY ADDRESS "TBTF PROBLEMS" AS THE ONE SHOWN BY THE INTERNAL DYNAMICS IN MW DSPHS


—> NEW MODEL-BUILDING AVENUES TO BE FURTHER EXPLORED IN RELATION TO CORE VS CUSP, DIVERSITY, TBTF, MS & "NIGHTMARE SCENARIOS"

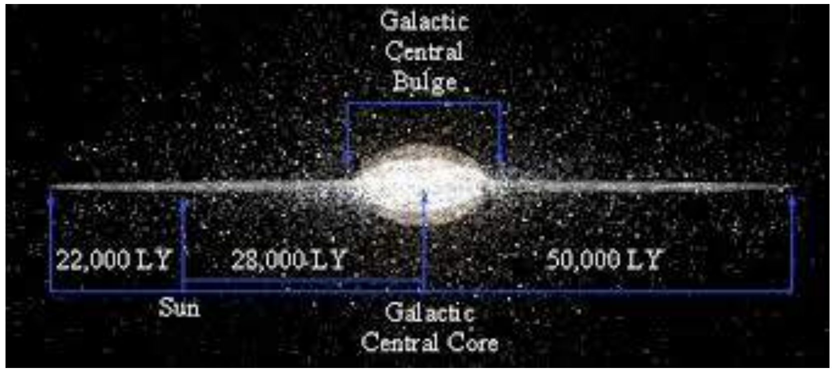
—> CLOSE COMPARISON WITH OTHER SMALL-SCALE NP SOLUTIONS MISSING !

# Backup

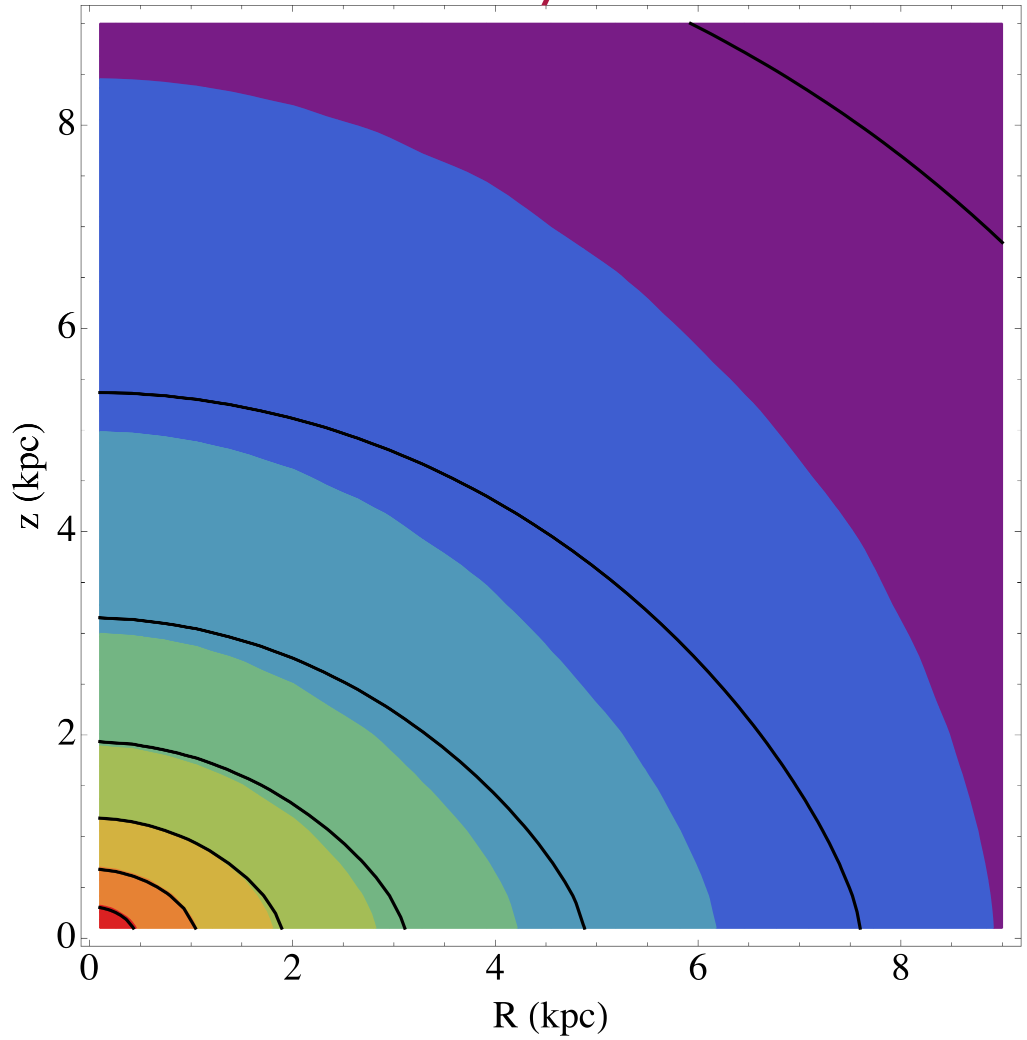
credit to **Hai-Bo Yu, UC Riverside**

# Tying SIDM to Baryons

- SIDM may follow the stellar distribution; halo morphology




SIDM density contour

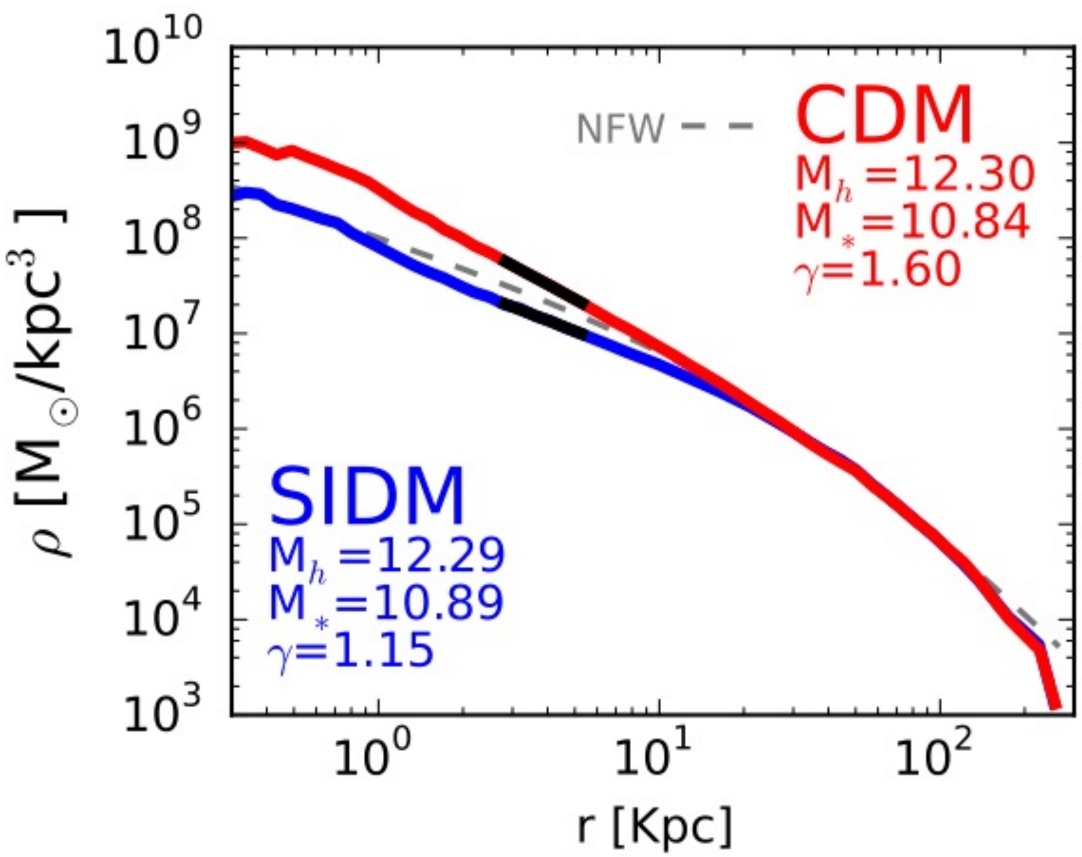



with Kaplinghat, Keeley, Linden (2013)

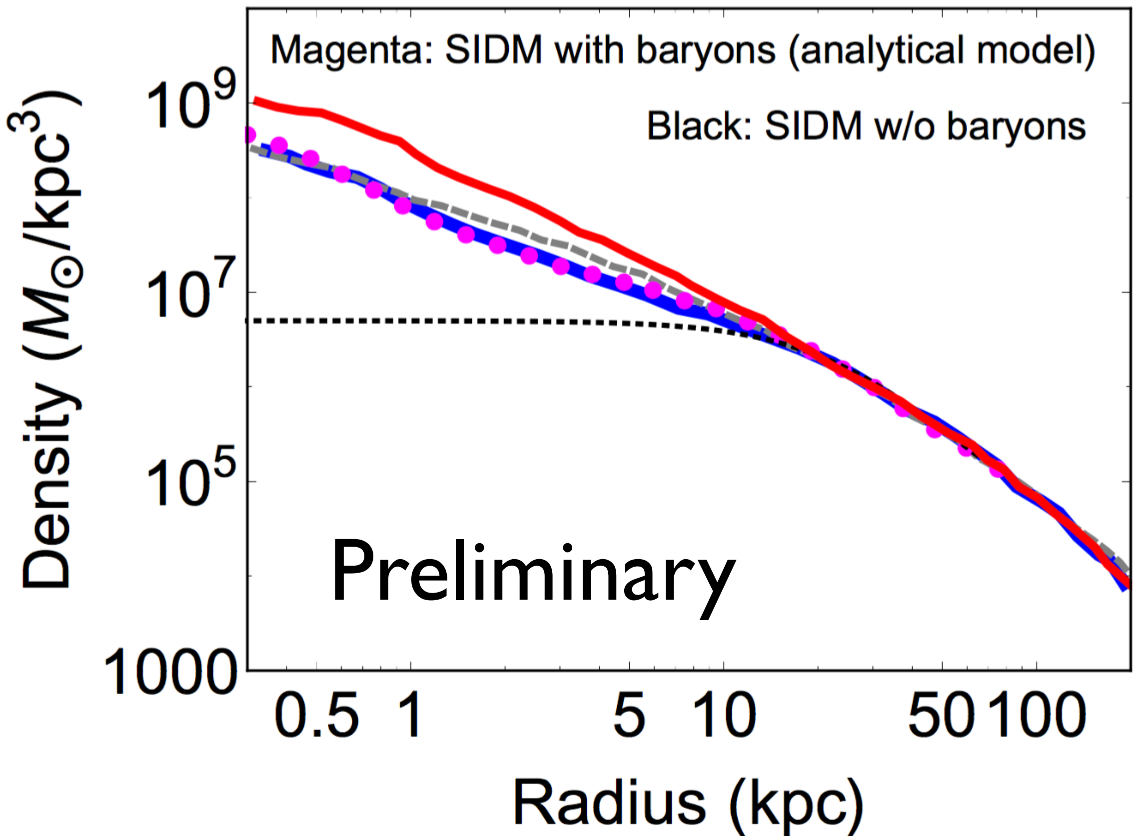
Correlation between the stellar distribution and the SIDM distribution

credit to **Hai-Bo Yu, UC Riverside**

# SIDM with Strong Feedback




Di Cintio et al. (2017)

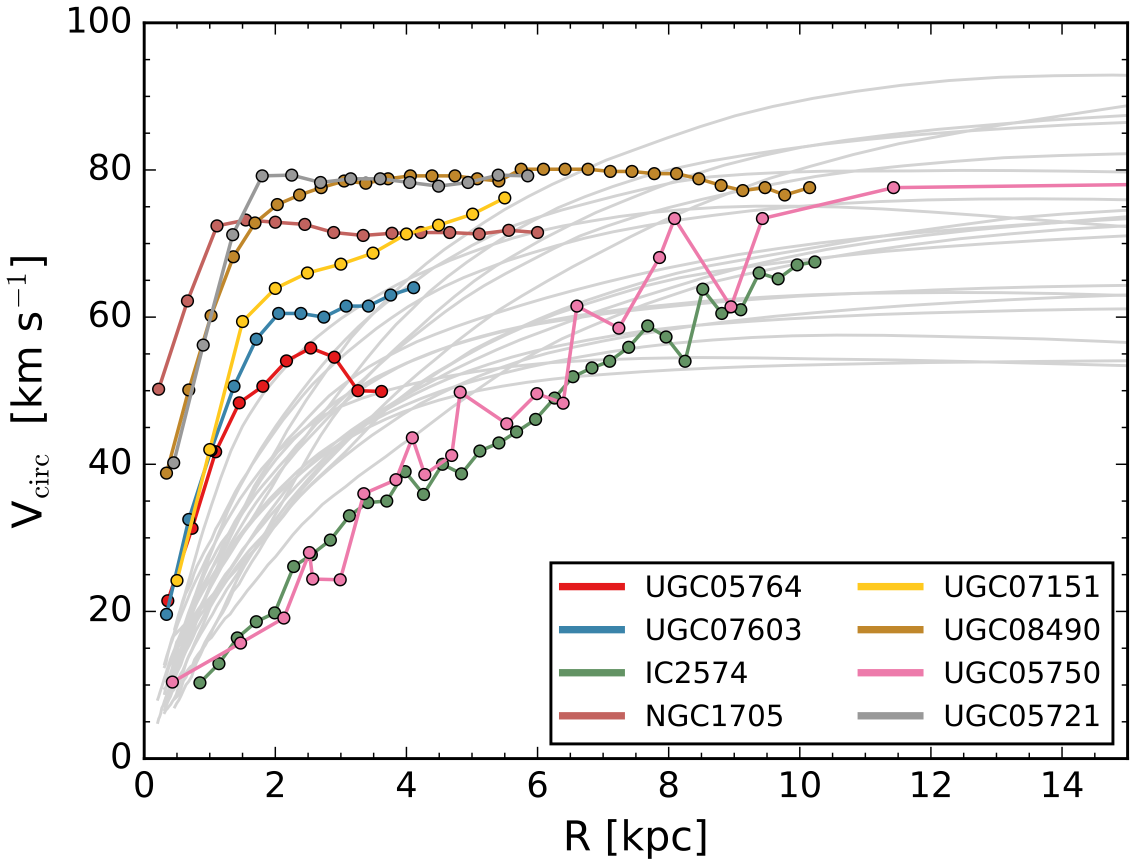



Magenta: predicted using the analytical SIDM halo model in Kaplinghat, Keeley, Linden, Yu (PRL 2014)

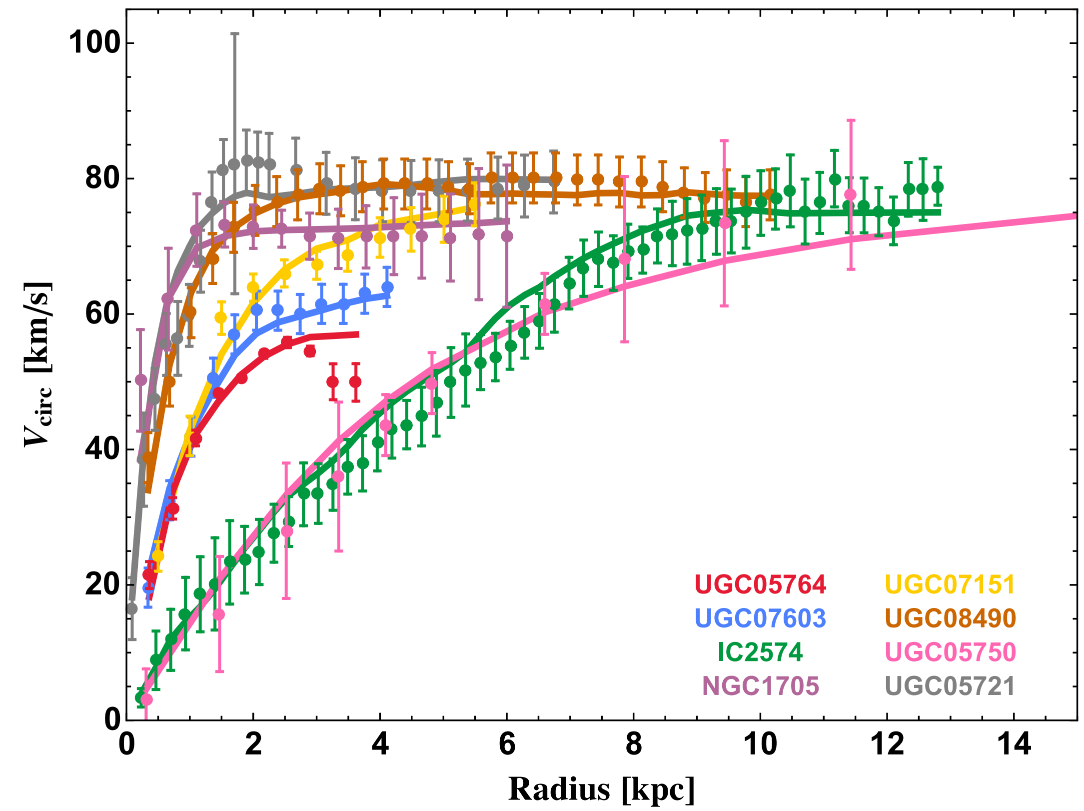
- The SIDM distribution is sensitive to the final baryon distribution
- But, it is not sensitive to the formation history

credit to **Hai-Bo Yu, UC Riverside**

# Strong Feedback vs. SIDM




Santos-Santos et al. (2017)




with Kamada, Kaplinghat, Pace (PRL 2017)
with Kaplinghat, Kwa, Ren (in prep)

Gray lines: NIHAO simulations of CDM (3σ band)

"strong/violent" feedback

Observed scatter: ~4
Simulations: ~2

Solid lines: SIDM fits

(2σ in the $c_{200}$-$M_{200}$ relation)

Vogelsberger, M. et al., *MNRAS 460 (2016) 1399*

| Name | $\alpha_\chi$ | $\alpha_\nu$ | $m_\phi$ [MeV c$^{-2}$] | $m_\chi$ [GeV c$^{-2}$] | $r_{\rm DAO}$ [$h^{-1}$ Mpc] | $r_{\rm SD}$ [$h^{-1}$ Mpc] | $a_4$ [$h$ Mpc$^{-1}$] | $\langle\sigma_T\rangle_{30}/m_\chi$ [cm$^2$ g$^{-1}$] | $\langle\sigma_T\rangle_{200}/m_\chi$ [cm$^2$ g$^{-1}$] | $\langle\sigma_T\rangle_{1000}/m_\chi$ [cm$^2$ g$^{-1}$] |
|---|---|---|---|---|---|---|---|---|---|---|
| CDM | – | – | – | – | – | – | – | – | – | |
| ETHOS-1 | 0.071 | 0.123 | 0.723 | 2000 | 0.362 | 0.225 | 14095.65 | 4.98 | 0.072 | 0.0030 |
| ETHOS-2 | 0.016 | 0.03 | 0.83 | 500 | 0.217 | 0.113 | 1784.05 | 9.0 | 0.197 | 0.00097 |
| ETHOS-3 | 0.006 | 0.018 | 1.15 | 178 | 0.141 | 0.063 | 305.94 | 16.9 | 0.48 | 0.0028 |
| ETHOS-4 (tuned) | 0.5 | 1.5 | 5.0 | 3700 | 0.138 | 0.0615 | 286.09 | 0.16 | 0.022 | 0.00075 |

CDM: has MS and TBTF problems
ETHOS-1: over-solves MS and TBTF problems
ETHOS-2: over-solves TBTF problem
ETHOS-3: over-solves TBTF problem
ETHOS-4 (tuned): alleviates MS and TBTF problems