“ Looking for New Physics in the Satellites of the Milky Way ”

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ALSO SUPPORTED BY

In collaboration with

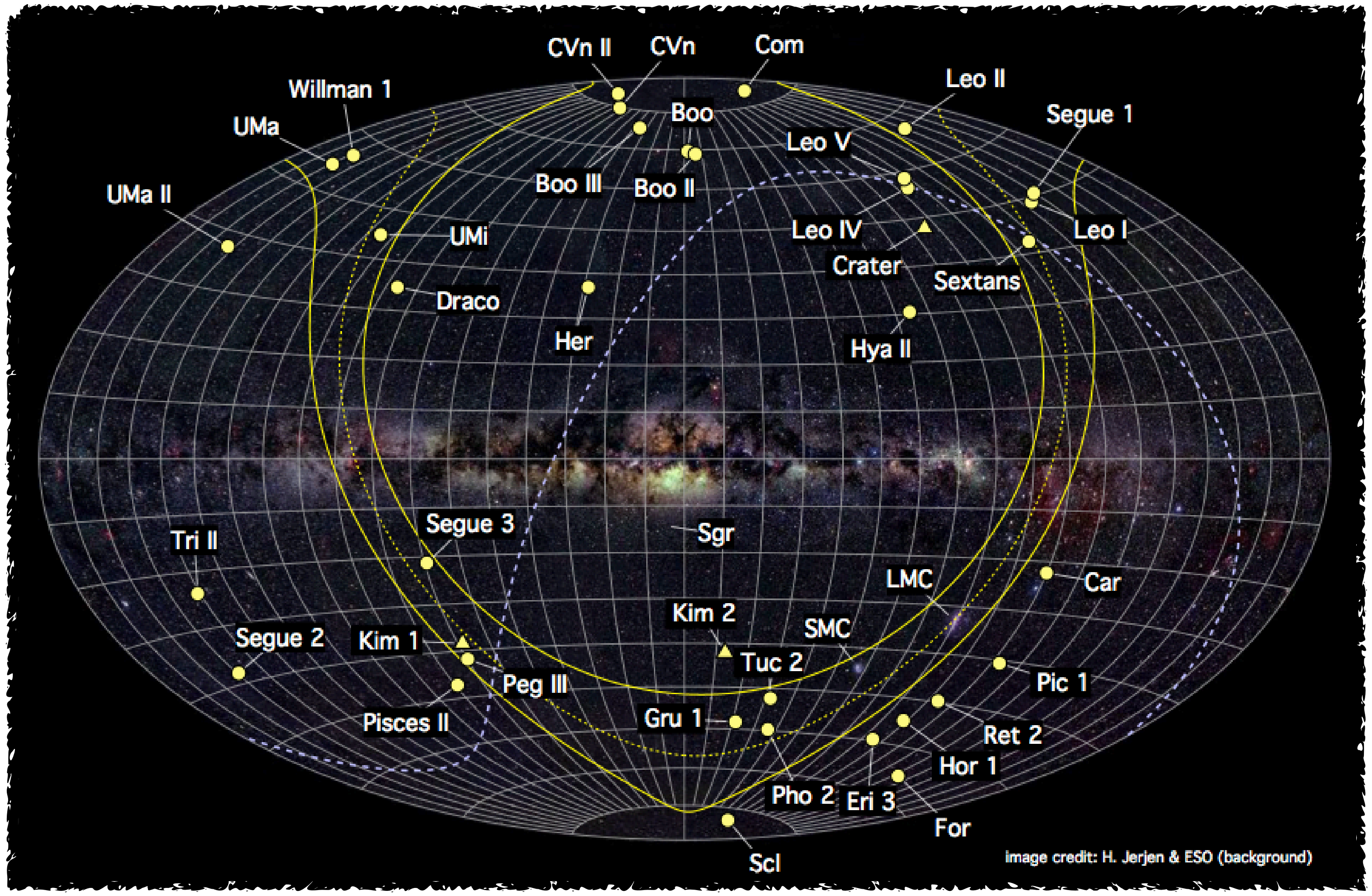
Piero Ullio, Hai-Bo Yu .

NPFlavour
The Flavour of New Physics

erc
European Research Council
Funding for top researchers from anywhere in the world

DWARF SPHEROIDAL GALAXIES (dSphs)

among the Milky Way's (MW) satellites



9 (pre-SSDS) brightest ones (Classicals)

After SDSS and DES surveying the Sky, total of 50 DM dominated MW satellites!

Fairly close to the Sun
(tens to hundreds of kpc)

Low intrinsic background
(below detection sensitivity)

Low Galactic foreground
(intermediate - high latitudes)

Large Mass-to-Light ratios

$$\frac{M}{L} \sim 10^2 - 10^3 \, \frac{M_\odot}{L_\odot}$$

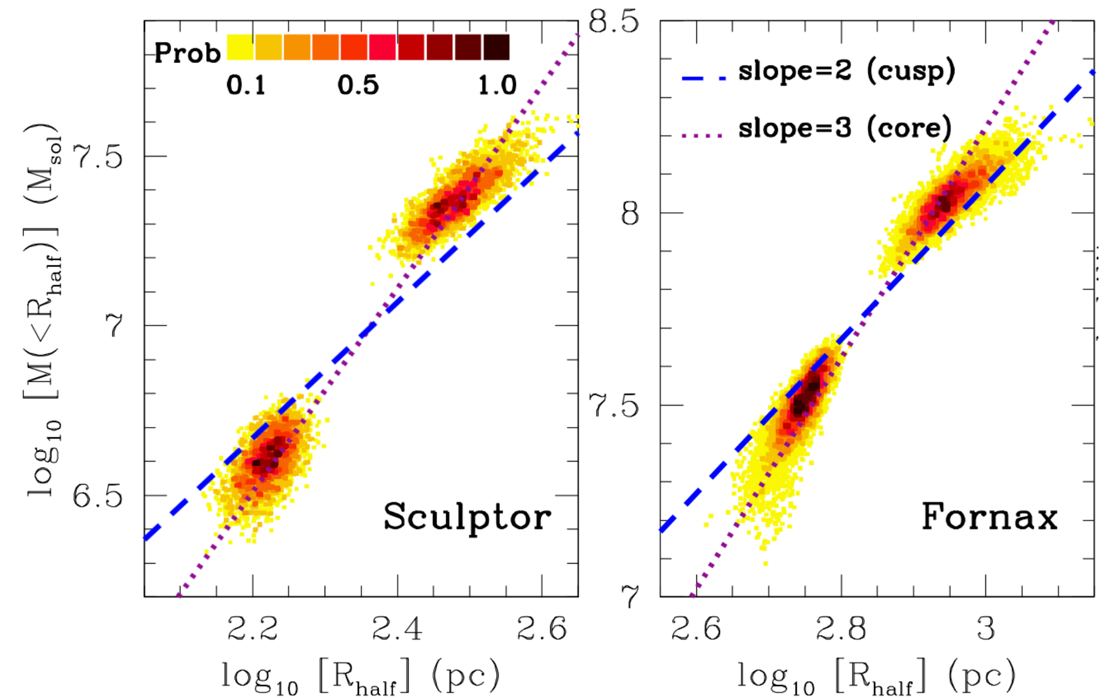
Compelling targets for the quest and the search of Dark Matter (DM)

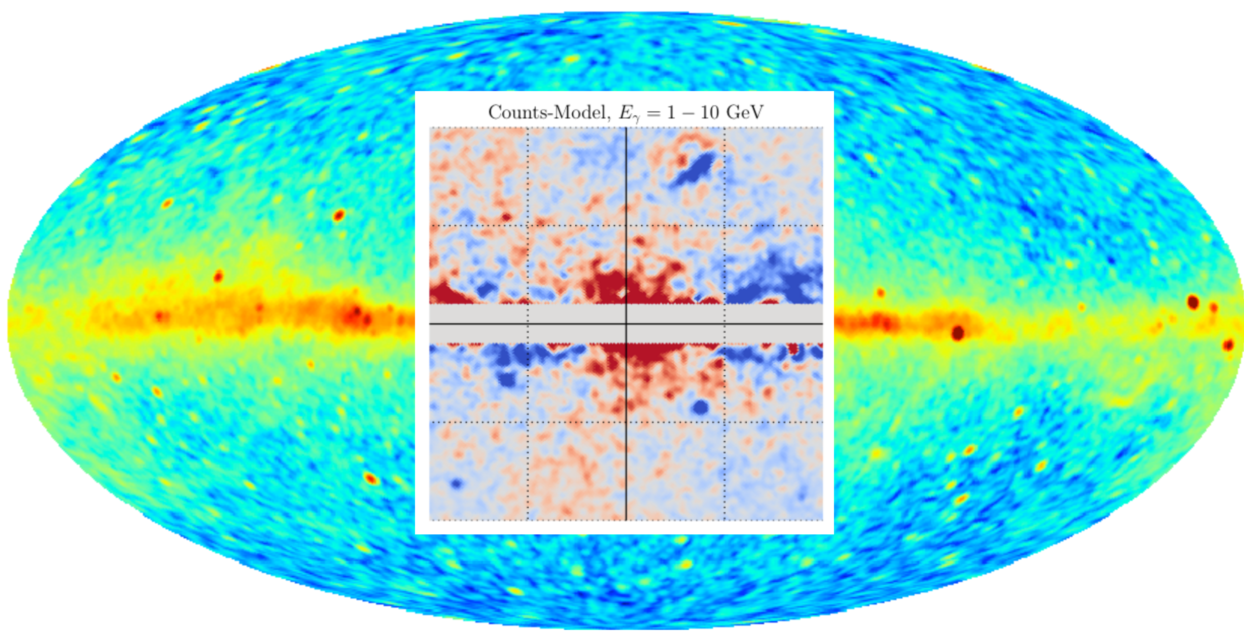
Today, what we can learn from MW dwarfs play a very relevant role in the field .

Astroparticle anomalies

Hints beyond CDM

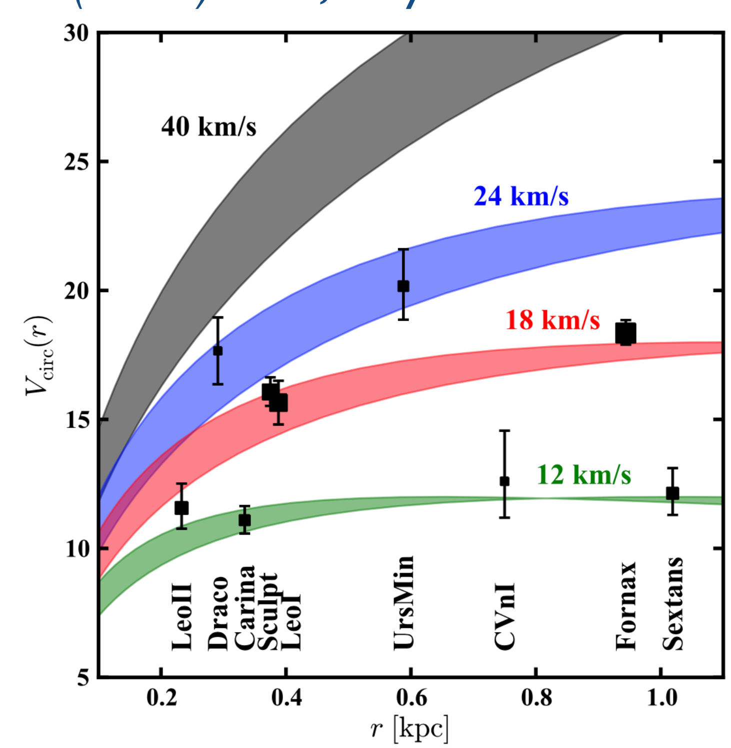
ApJ 742 (2011) 20 , Walker & Penarubbia



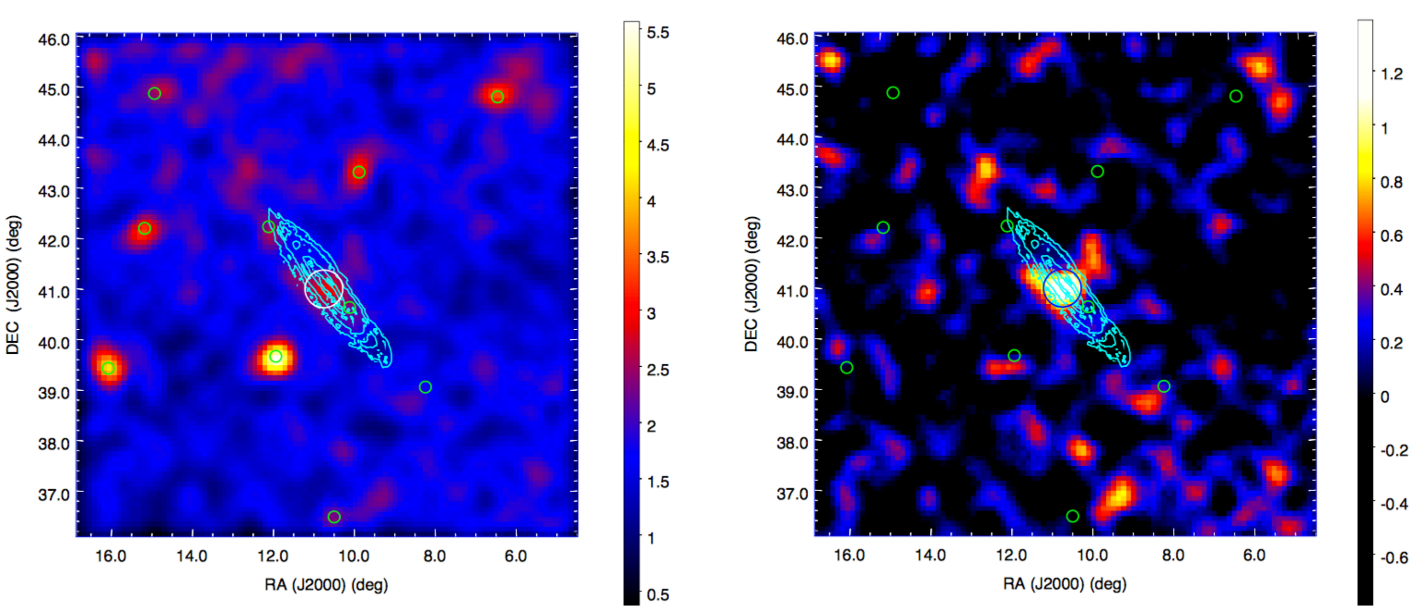


Most recent analysis.: *ApJ 840 (2017) 43 , Ackermann et al.*

MNRAS 415 (2011) L40 , Boylan-Kolchin et al.



ApJ 836 (2017) 208 , Ackermann et al.



Mass models for dwarf spheroidals

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

1) DYNAMICAL EQUILIBRIUM

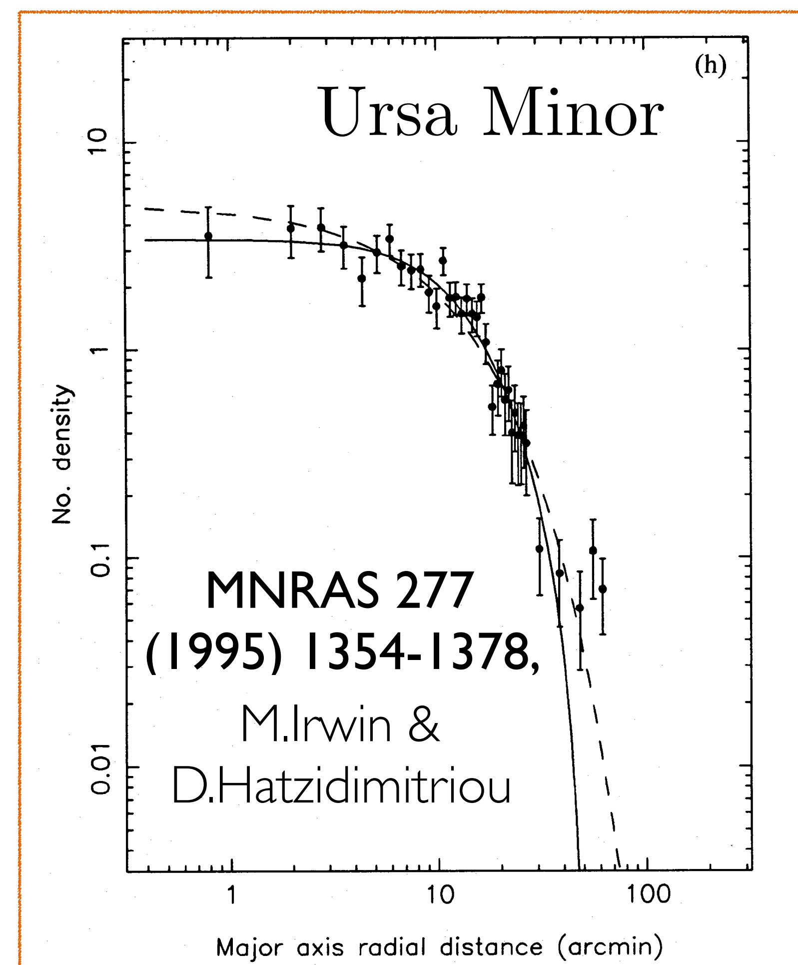
2) SPHERICAL SYMMETRY

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

2nd MOMENT OF THE EQ.:
$$\frac{r}{\nu} \frac{d(\nu \sigma_r^2)}{dr} + 2\beta\, \sigma_r^2 = -G_N \frac{\mathcal{M}}{r}$$

$\nu(r)$ IS THE **STELLAR DENSITY** OF THE SYSTEM,
to be matched to photometric measurements
—> connected to surface brightness, I(R)

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



—> 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

Mass models for dwarf spheroidals

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

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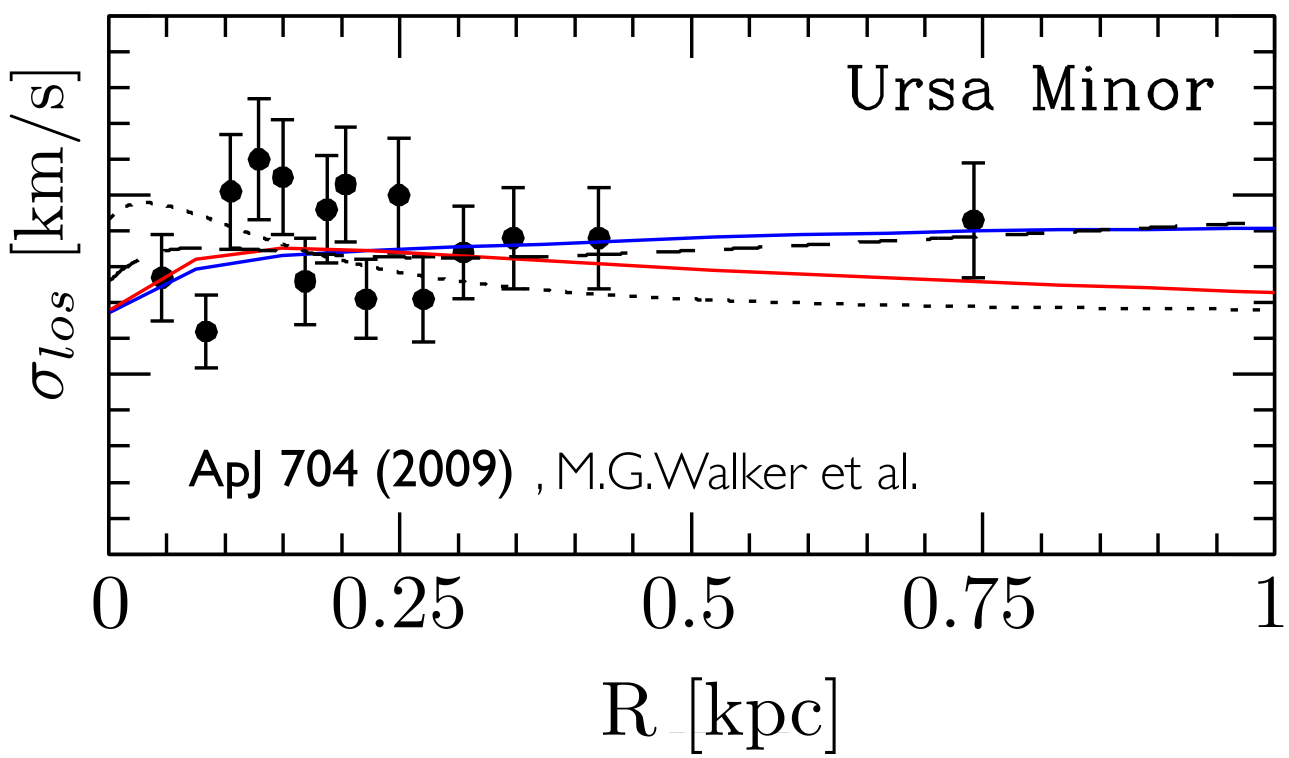
Spectroscopic data give us information along the line-of-sight (l.o.s.).



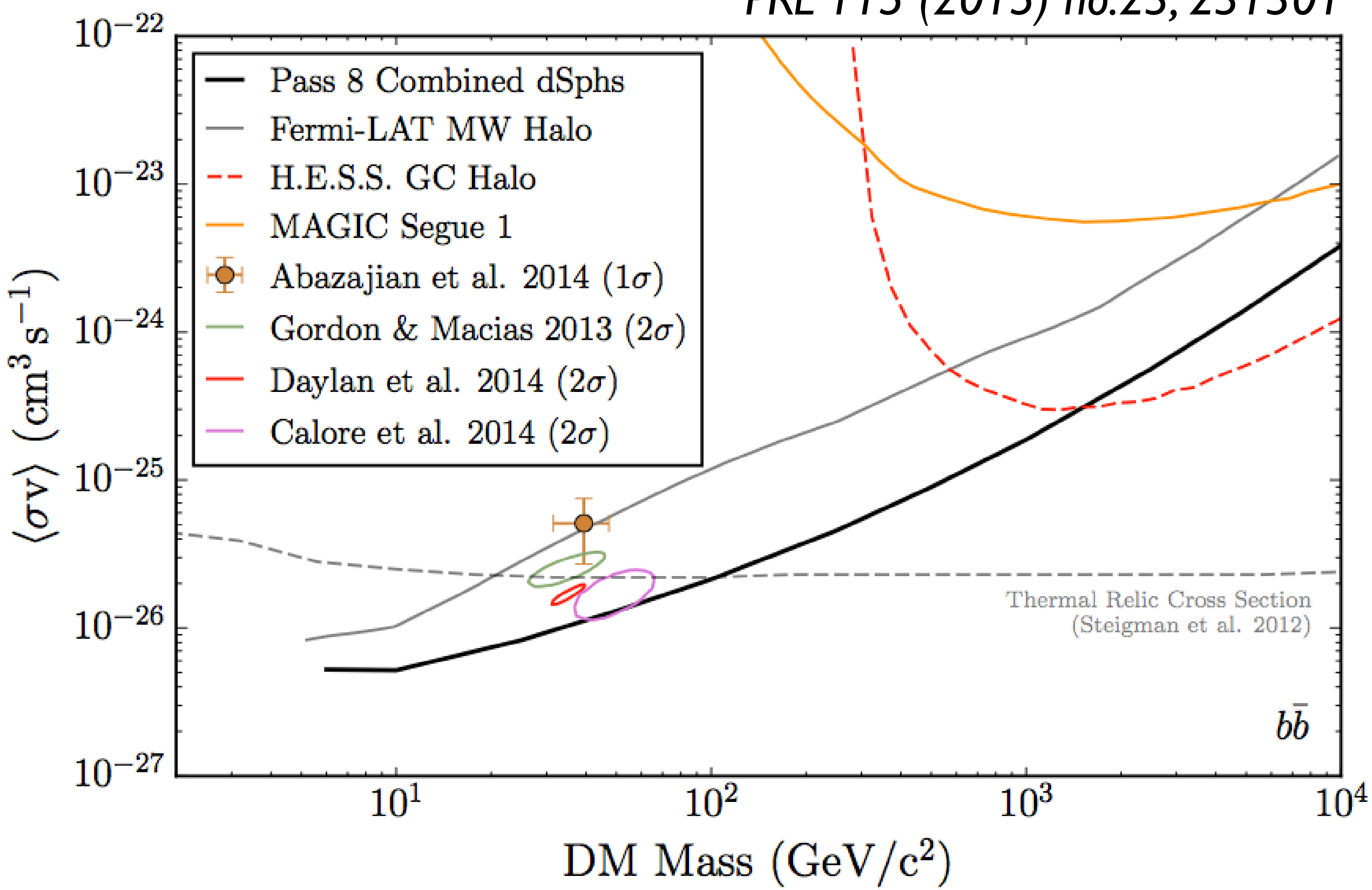
$$\Rightarrow \quad \sigma_{los}(R) = f(\beta, \mathcal{M})(R)$$

DEGENERACY PROBLEM

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

Gamma-ray observation of MW dwarfs set some of the tightest limits at present in the vast literature of indirect searches for DM .

PRL 115 (2015) no.23, 231301



FERMI-LAT BOUNDS ARE CURRENTLY PROBING THE "WIMP MIRACLE" …

… but how much are robust these upper limits ?

$$\frac{d\phi_\chi^{(\gamma)}}{dE_\gamma} = P(E_\gamma, m_\chi) \times J(\Delta\Omega) \propto \int_{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s.}} d\ell\, \rho^2 \left[r(\psi,\ell)\right]$$

$$\sim \frac{\langle \sigma v \rangle}{m_\chi^2} \frac{dN}{dE_\gamma} \times \textit{J-FACTOR}$$

uncertainties on dwarf mass modeling pop up here!

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

WE CAN TEST THIS INVERTING THE SPHERICAL JEANS EQ.!

$$\mathcal{M}_\beta(r) = \frac{1}{G_N\,\nu(r)} \int_{r^2}^{\infty} dR^2 \, \frac{d^2 P}{(dR^2)^2} W_\beta(r^2, R^2)$$

where we have introduced:

$$\boxed{P(R) = I(R)\sigma^2_{los}(R)}$$

l.o.s. projected stellar pressure

product of l.o.s. observables!

Some **physical conditions** must supplement the inversion formula.

$$i) \quad \mathcal{M}_\beta(r) > 0 \;\; , \quad \forall \; r > 0$$

$$ii) \quad \mathcal{M}_\beta(r') \geq \mathcal{M}_\beta(r) \; , \quad \forall \; r' \geq r \; .$$

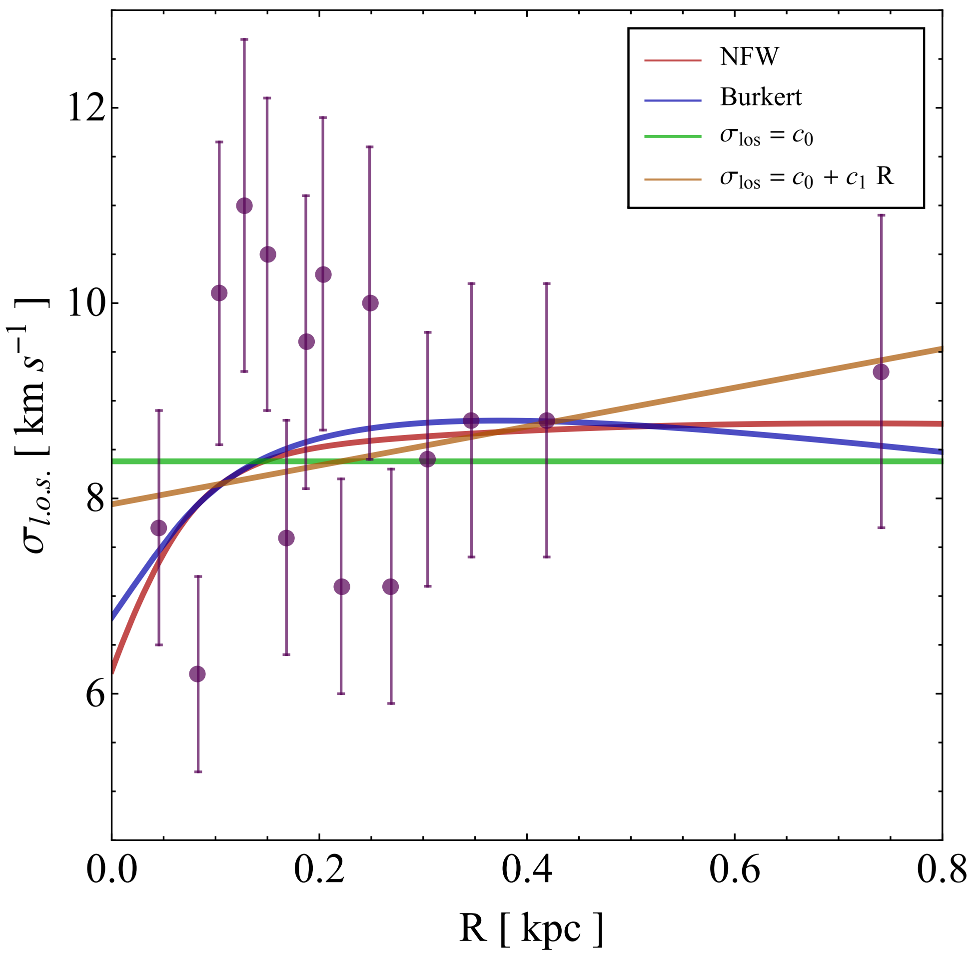
$$\rho_\beta(r) = \frac{1}{4\pi r^2} \frac{d\mathcal{M}_\beta}{dr}$$

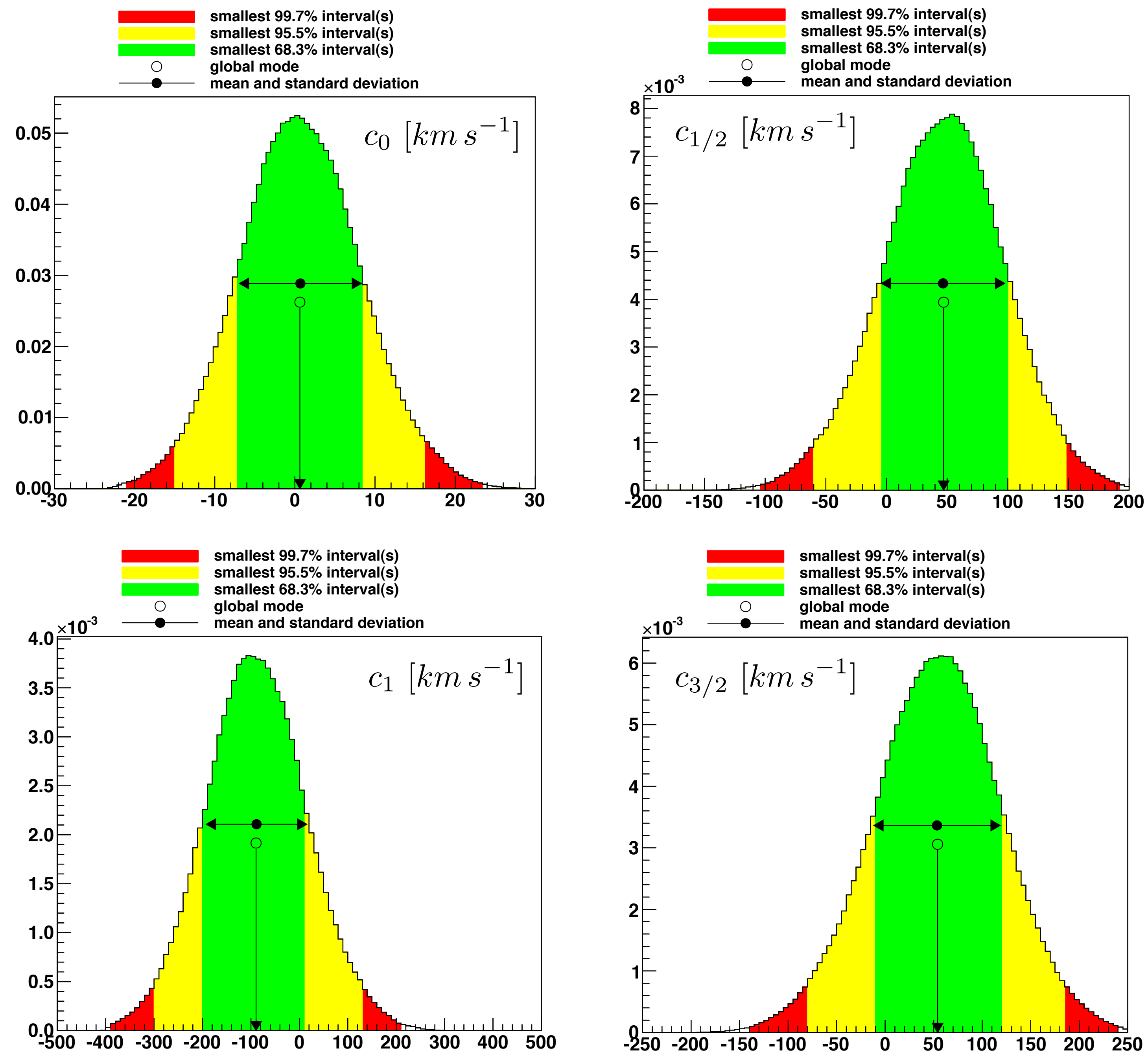
DENSITY PROFILE FOR SPHERICAL SYSTEMS

$$iii) \quad \rho_\beta(r') \leq \rho_\beta(r) \; , \quad \forall \; r' \geq r \; .$$

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

THE STUDY CASE OF URSA MINOR





$$\sigma_{los}(R) = \begin{cases} c_0 + c_1 R \\ \sum_{i=0}^{3} c_{\frac{i}{2}} R^{\frac{i}{2}} \end{cases}$$

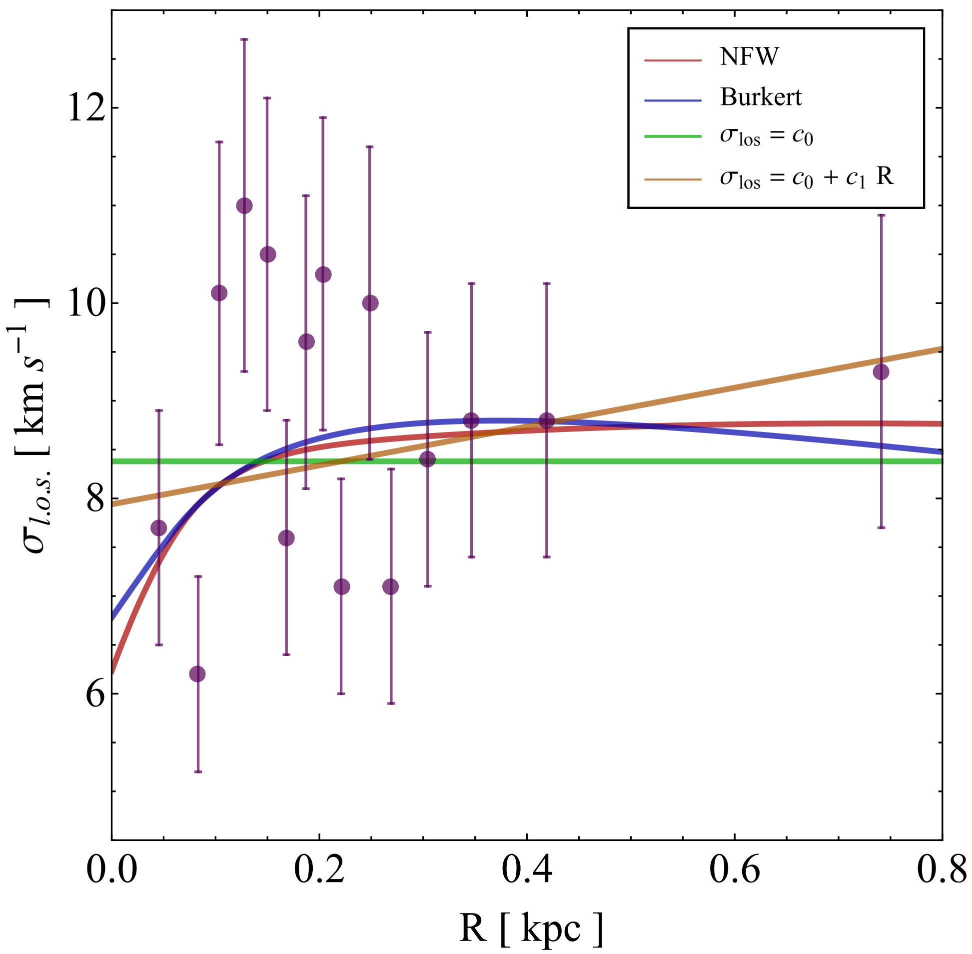
+ Plummer surface brightness

MCMC with BAT

Bayesian **A**nalysis **T**oolkit

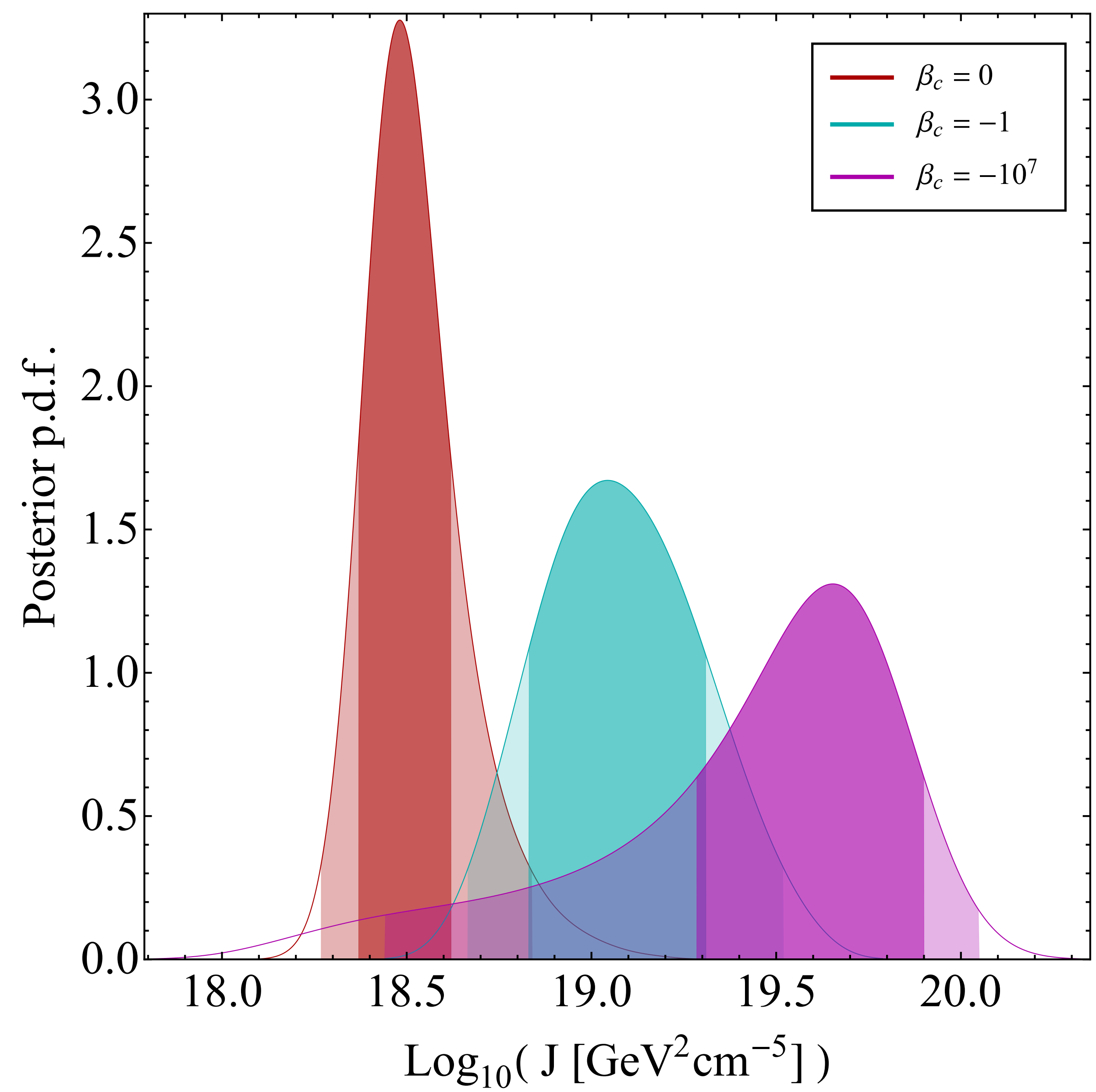
P.Ullio & M.V. *JCAP 1607 (2016) 025*

THE STUDY CASE OF URSA MINOR



AT EVERY STEP IN THE MCMC, CHECK THE PHYSICAL CONDITIONS. IF SATISFIED:

$$\boxed{\mathcal{M}_\beta \Rightarrow \rho_\beta \Rightarrow J_\beta}$$



$$\boxed{\sigma_{los}(R) = \begin{cases} c_0 + c_1 R \\ \sum_{i=0}^{3} c_{\frac{i}{2}} R^{\frac{i}{2}} \end{cases}}$$

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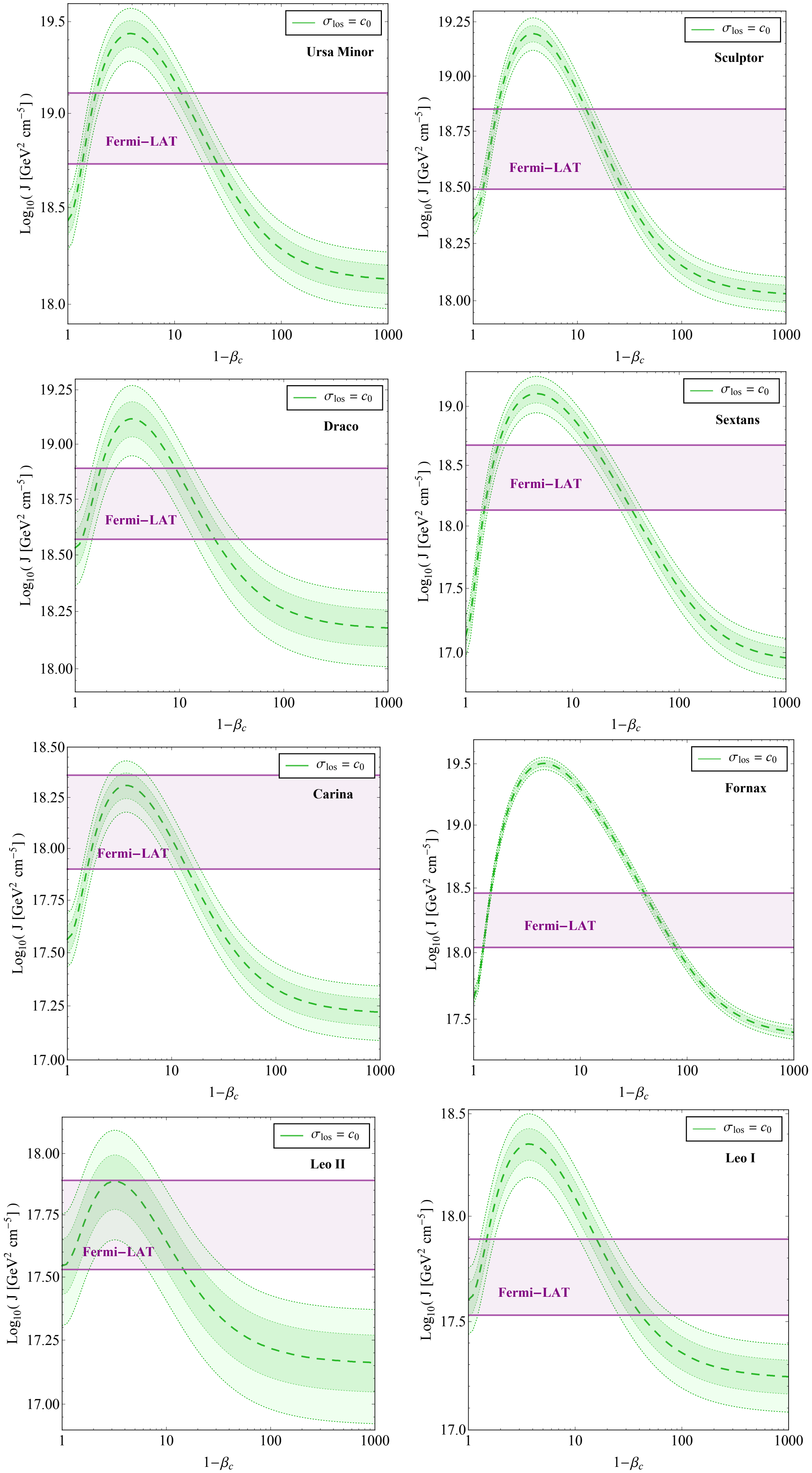


Difficult to relax dSph limits more than a factor of 4 within systematics stemming from mass-anisotropy degeneracy.

http://inspirehep.net/.../Valli_PhdThesis

Classical dSph	$\min J^{\mathrm{Fermi}}_{@\,2\sigma} / \min J_{@\,2\sigma}$	
Ursa Minor	3.80	**3.76**
Sculptor	2.36	**2.64**
Draco	2.59	**3.36**
Sextans	12.88	**1.56**
Carina	3.94	**3.98**
Fornax	3.34	**1.81**
Leo II	2.70	**1.43**
Leo I	1.91	**2.76**

MNRAS 453 (2015) 849 , V.Bonnivard et al.

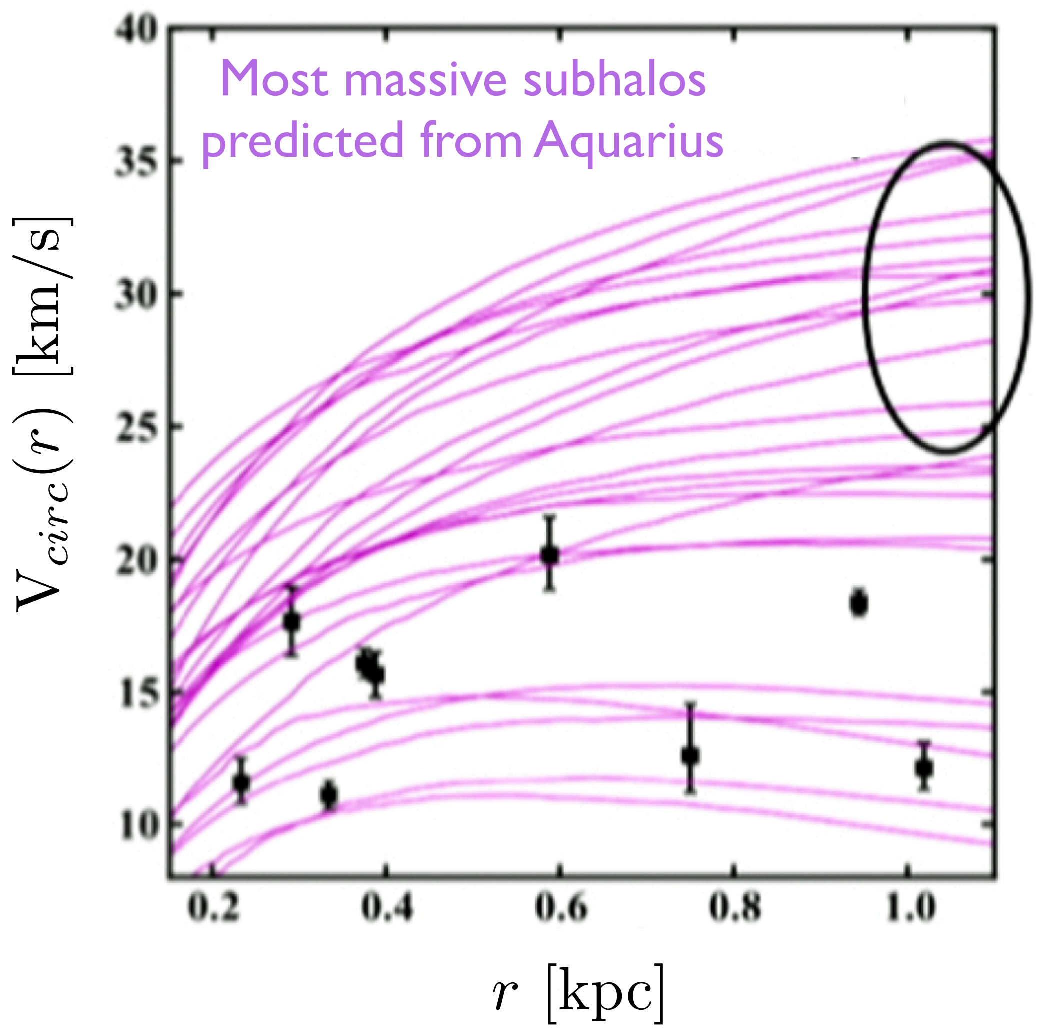
MW dSphs can be considered a DM laboratory where to obtain quite robust particle DM limits.

The inversion of the spherical Jeans equation is also very useful to formally show the existence of a ***mass estimator*** for systems like MW dSphs, namely:

$$\left.\frac{d\log\nu(r)}{d\log r}\right|_{r=r_*} = -3 \quad \Rightarrow \quad \mathcal{M}_\beta(r_*) \simeq 3\,\frac{r_*}{G_N}\,\langle\sigma^2_{los}\rangle\ ,$$

@ $r_* \sim r_{1/2}$ THE ESTIMATE OF THE MASS IS APPROXIMATELY ANISOTROPY FREE.

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



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

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

TOO-BIG-TO-FAIL (TBTF) PROBLEM

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

On other hand, it should be easier for stars to form in deeper potential wells …

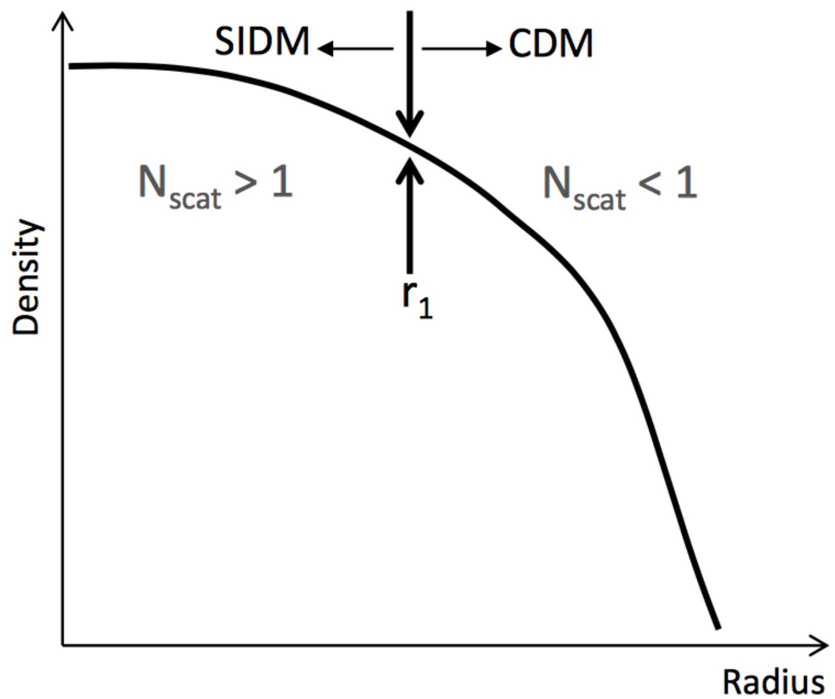
… SO, WHERE ARE THEY?

Possible caveats of the puzzle

- *Abundance matching + baryonic effects*
- *Dependence on the mass of host galaxy*

Sawala, T. et al. [APOSTLE], **MNRAS 457 (2016) 1931**

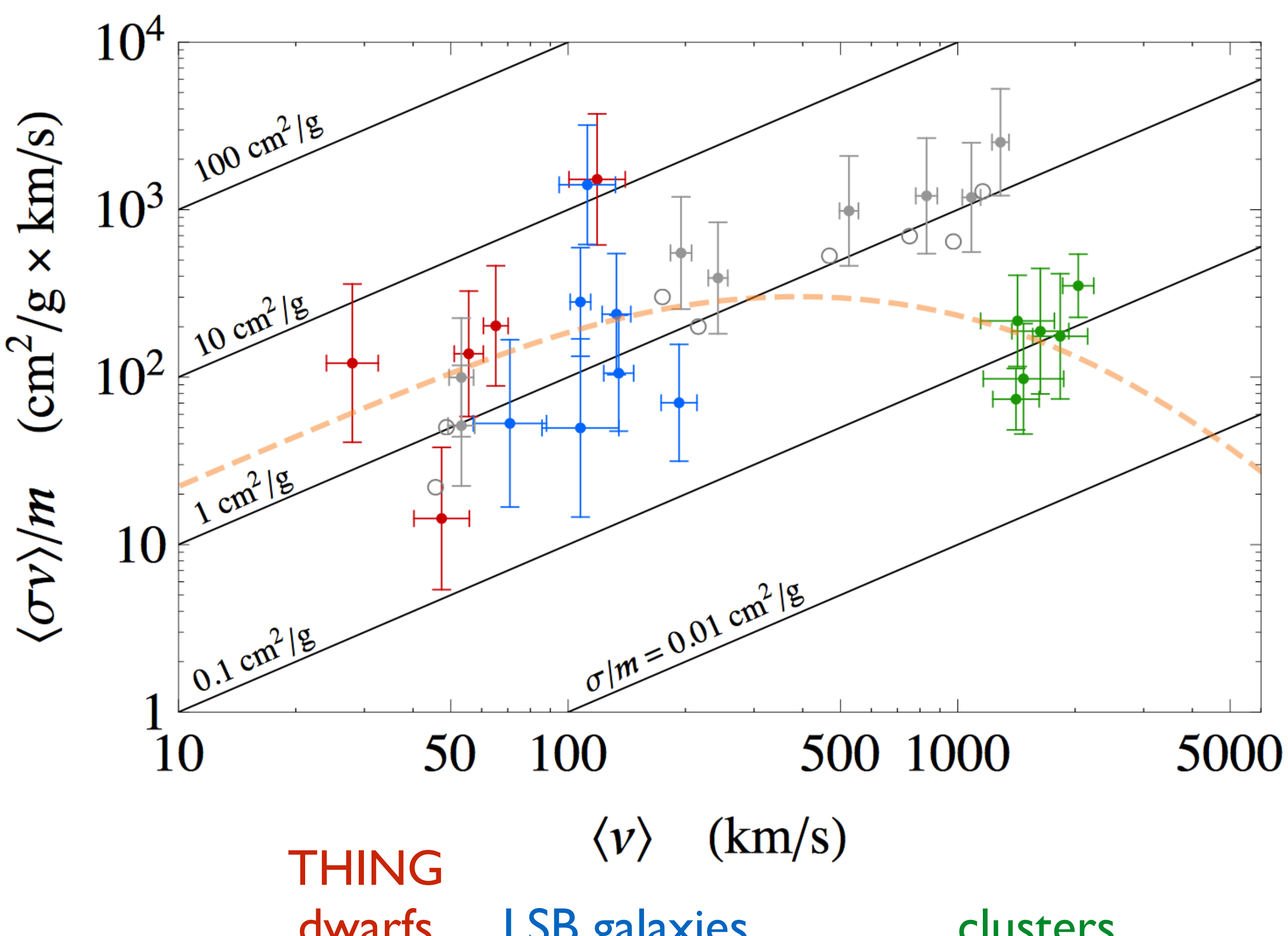
TBTF + "Core VS Cusp" : Hints for New Paradigm beyond CDM ?



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

Self-Interacting DM (SIDM) halo model



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

Self-interactions should keep DM particles in kinetic equilibrium for $r < r_1$, therefore:

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

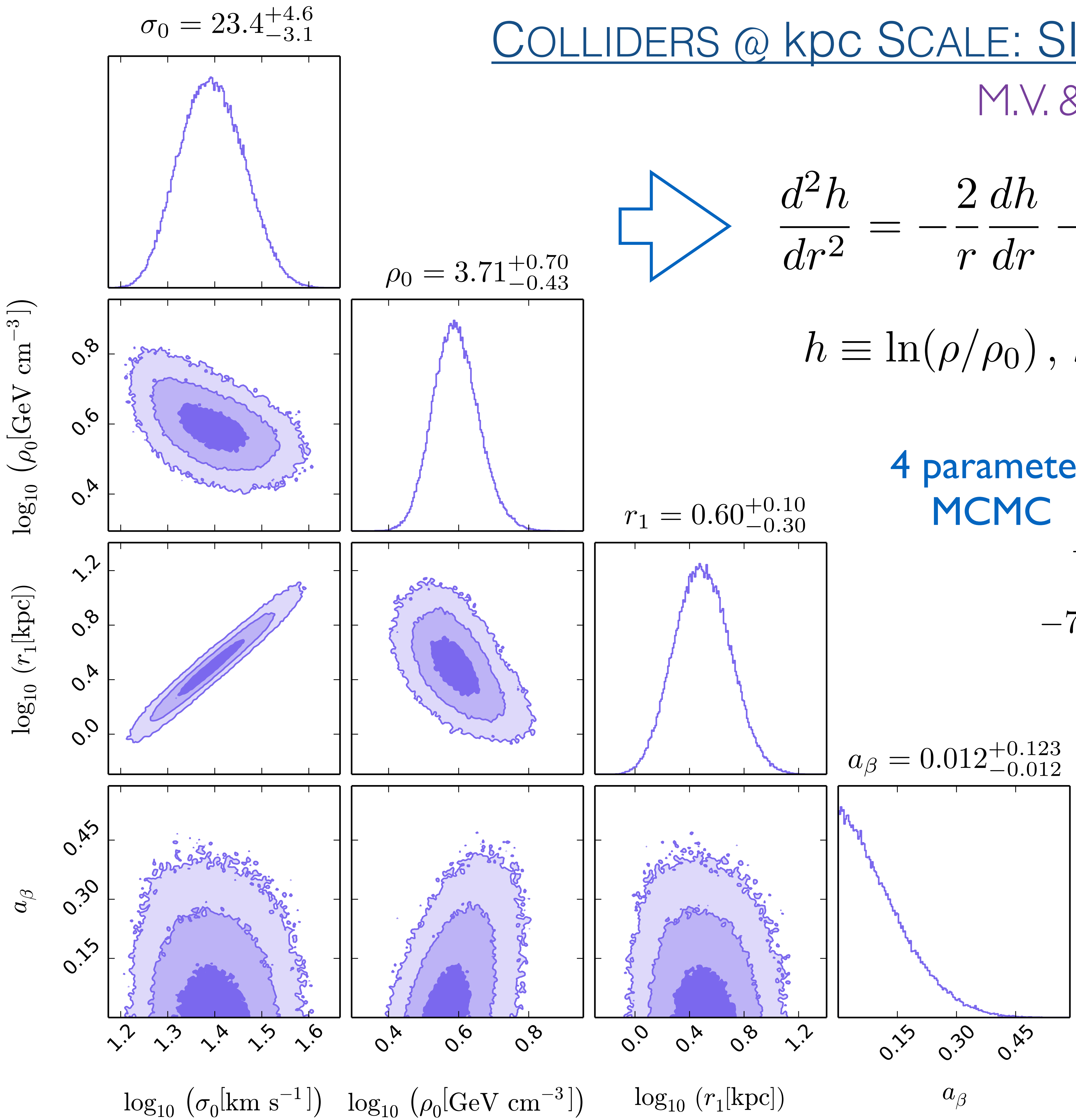
ISOTHERMAL CORED PROFILE

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

+ matching condition on the mass profile.

Colliders @ kpc Scale: SIDM & MW dSphs

M.V. & H.B.Yu (in progress)



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

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

4 parameter MCMC

$$0 \le a_\beta = \frac{\beta}{\beta - 1} \le 1$$

$$-7 \le \log_{10}\left(\frac{\sigma_0}{km\,s^{-1}}\right) \le 7$$

$$-7 \le \log_{10}\left(\frac{\rho_0}{GeV\,cm^{-3}}\right) \le 7$$

$$-2 \le \log_{10}\left(\frac{r_1}{kpc}\right) \le \frac{1}{2}$$

Likelihood including

- dSph kinematics
- match with CDM in the outer region

COLLIDERS @ kpc SCALE: SIDM & MW dSphs

M.V. & H.B.Yu (in progress)

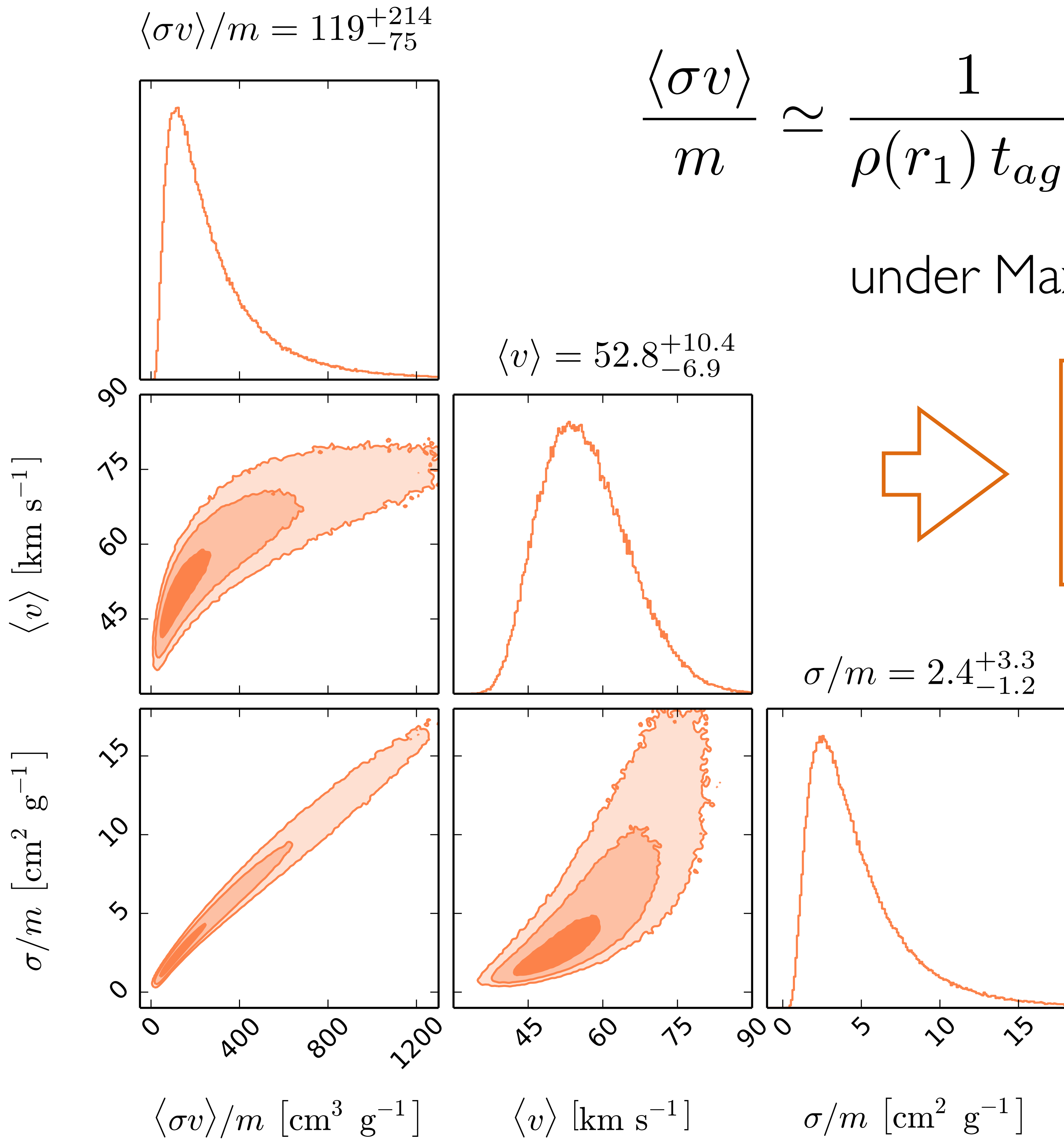
—> typical dSph age:

$5 \leq t_{age}/Gyr \leq 10$

Marginalizing over t_{age}, we extract the SIDM cross-section:

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

under Maxwellian approx (expected to hold).



$$\boxed{\begin{array}{c} 1\mathrm{cm}^2\mathrm{g}^{-1} \lesssim \sigma/m \lesssim 5\,\mathrm{cm}^2\mathrm{g}^{-1} \\ 30\,\mathrm{km\,s}^{-1} \lesssim \langle v \rangle \lesssim 70\,\mathrm{km\,s}^{-1} \end{array}}$$

Range in agreement with available indications from N-body simulations.

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

Same SIDM ballpark for solving "Core VS Cusp" in other kpc-sized systems.

Milky Way dSphs represent today a multidisciplinary DM laboratory where to look for New Physics from several extremely compelling perspectives.

2 specific examples in this talk:

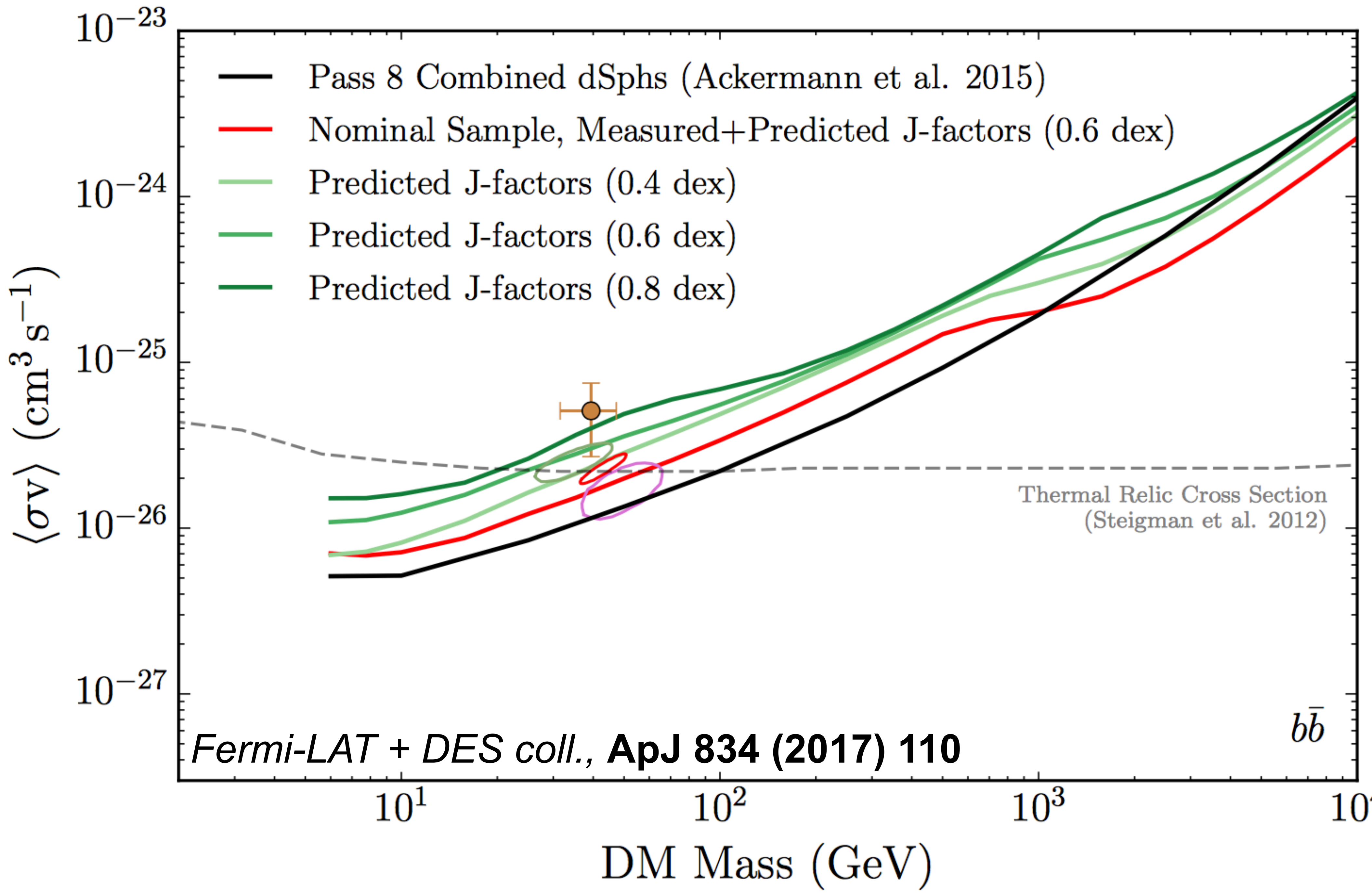
— INDIRECT DM SEARCHES IN GAMMA-RAY BAND

— SOLUTION OF TBTF PROBLEM IN SIDM CONTEXT

Study of dSph dynamics crucial in tracking DM origin!

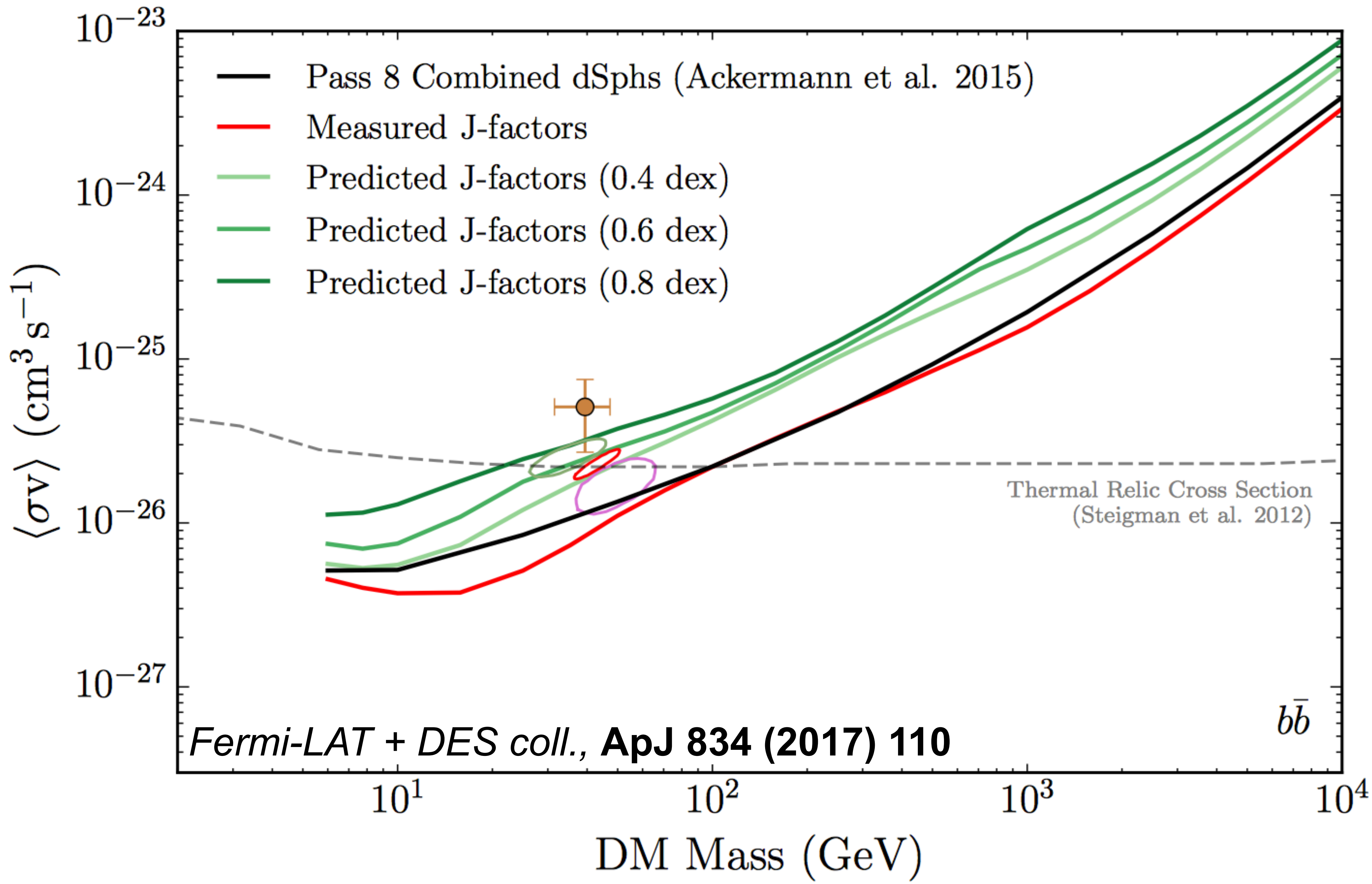
Backup

In light of DES discovery of new ultra-faint dwarfs, new recent reappraisal of DM particle constraints from gamma-ray observation of MW satellites:



WARNING: no available spectroscopic information for some of these newly discovered satellites … J-factors estimated by scaling relations!

In light of DES discovery of new ultra-faint dwarfs, new recent reappraisal of DM particle constraints from gamma-ray observation of MW satellites:



–> … restricting only to objects with "measured" J-factors (obtained from Geringer-Sameth et al. '15), new upper-bounds actually improve !

How much precisely can we determine J in dSphs?

MNRAS 418 (2011) 1526

2011 **Charbonnier, A. et al.**

6 parameter MCMC

uniform priors (linear & $\log_{10}$)

Hernquist-Zhao DM profile

Plummer stellar model

Constant orbital anisotropy
+ phase-space positivity:

$$\beta \leq -\frac{1}{2}\frac{d\log\nu}{d\log r}$$

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

MNRAS 451 (2015) 2524
PRL 115 (2015) 231301

2013 **Martinez, G.D.**
Ackermann, M. et al.

2-level Bayesian hierarchical modeling

7 parameters for Gaussian scatter in log-log rel
motivated by simulations for bottom-level priors

Burkert & NFW DM profiles
+"measured" 1/2-light radius
& mass enclosed within it

Power-law stellar model
+ measured total luminosity

ApJ 801 (2015) 74

2015 **Geringer-Sameth, A. et al.**

6 parameter MCMC

uniform priors (linear & $\log_{10}$)

Hernquist-Zhao DM profile
+ physical outer halo truncation
& cosmological mass function filter

Plummer stellar model

Constant orbital anisotropy

How much precisely can we determine J in dSphs?

MNRAS 453 (2015) 849-867

2015 Bonnivard, V. et al.

Quantity	Profile	Parameter	Prior range
DM density	'Einasto' equation (5)	$\log_{10}(\rho_{-2}/M_\odot\ \mathrm{kpc}^{-3})$	[5, 13]
		$\log_{10}(\mathrm{r}_{-2}/\mathrm{kpc})$	$[\log_{10}(r_s^*), 1]$
		α	[0.12, 1]
Anisotropy	'Baes & van Hese' equation (6)	β_0	[-9, 1]
		β_∞	[-9, 1]
		$\log_{10}(r_a)$	[-3, 1]
		η	[0.1, 4]

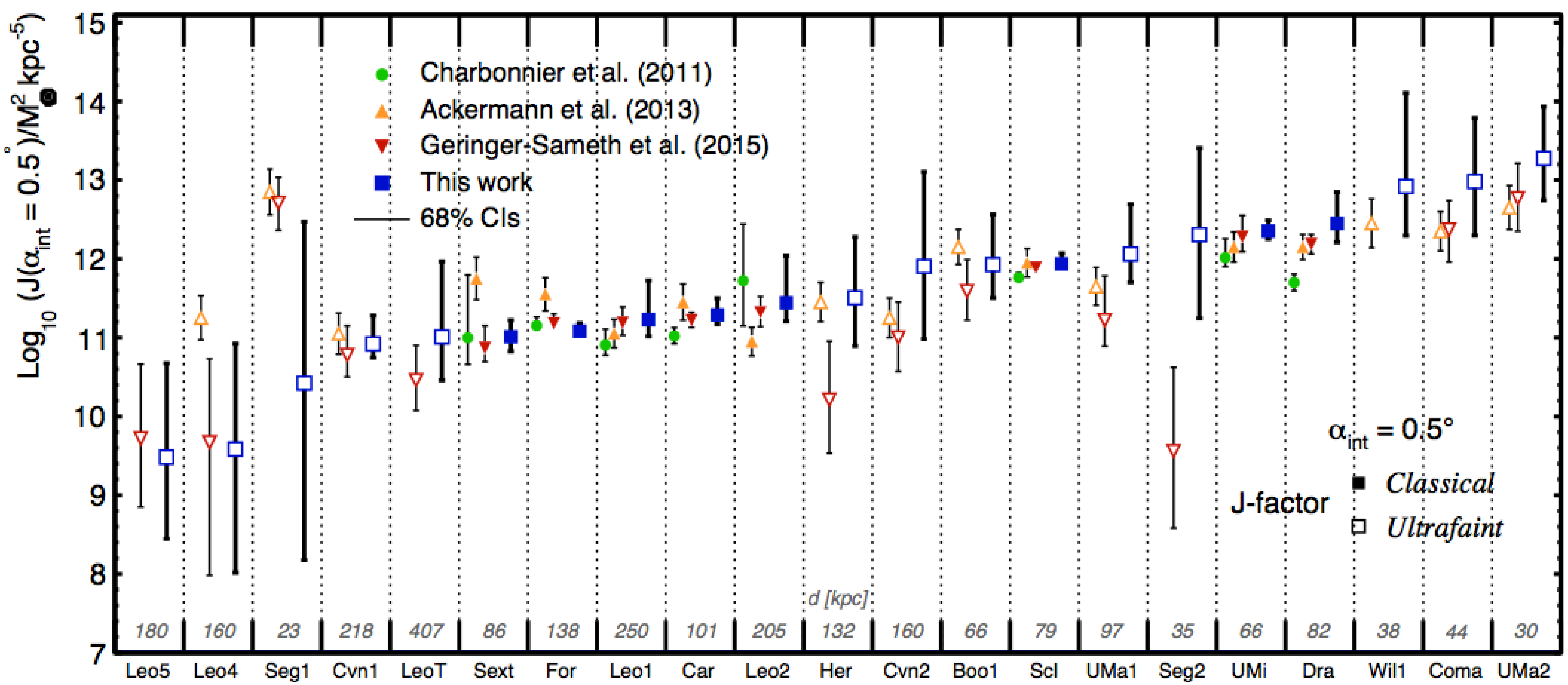
Einasto DM profile

Hernquist-Zhao stellar profile

Baes & van Hese anisotropy

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

+ *phase-space positivity*



Systematics from estimate of structural parameters, analysis of stellar kinematics & modeling w/o approx spherical symmetry turn out to be relevant even for the most well-known MW satellites.

for the Classicals

Optimistically, ***O(10%)*** on normalization of estimated mass enclosed within 1/2-light radius (~***O(1)*** effects on J-factor).

O(1) uncertainty already on $M_{1/2}$ for MW ultra-faint dwarfs.

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MASS ESTIMATOR IN DWARF SPHEROIDALS ?

MINIMAL DEPENDENCE ON ANISOTROPY

Nature 454 (2008) , Strigari, L.E. et al.
MNRAS 406 (2010) , Wolf, J. et al.

$$\boxed{\frac{\mathcal{M}_\beta - \mathcal{M}_{\beta=0}}{\mathcal{M}_{\beta=0}} = \text{const.}}$$

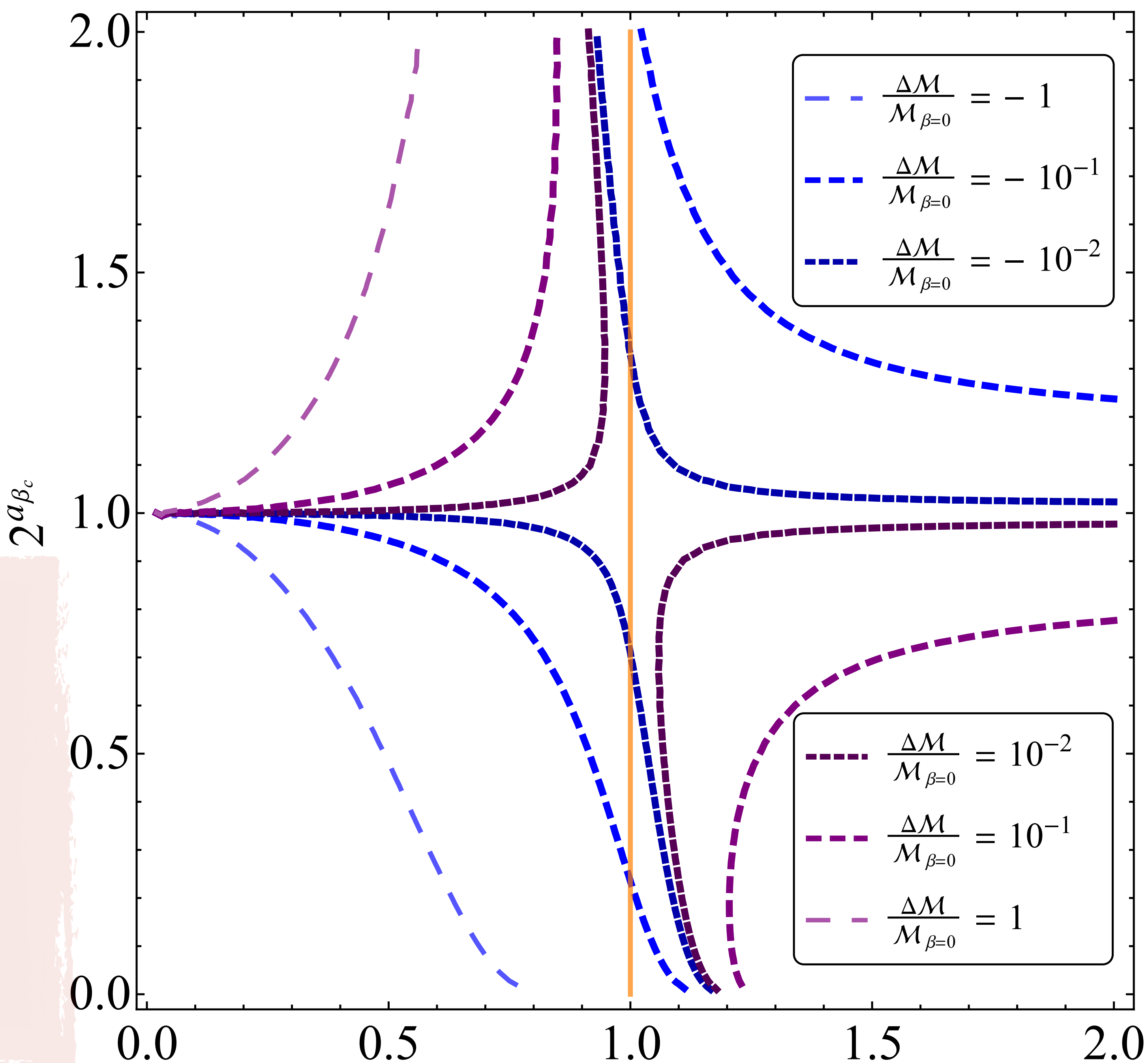
circular limit

10%

isotropic limit

80%

radial limit



CONCLUSIONS STILL HOLD ALSO BEYOND SUCH FIDUCIAL SCENARIO IF ANISOTROPY IS NOT "FASTLY" VARYING @ r_*

TIPICALLY UNPHYSICAL

r/r_* CLOSE TO 2D HALF-LIGHT RADIUS

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

From a well-defined mass estimator we can compute the **minimal J-factor**.

DENSITY AS A SET OF POWER LAWS

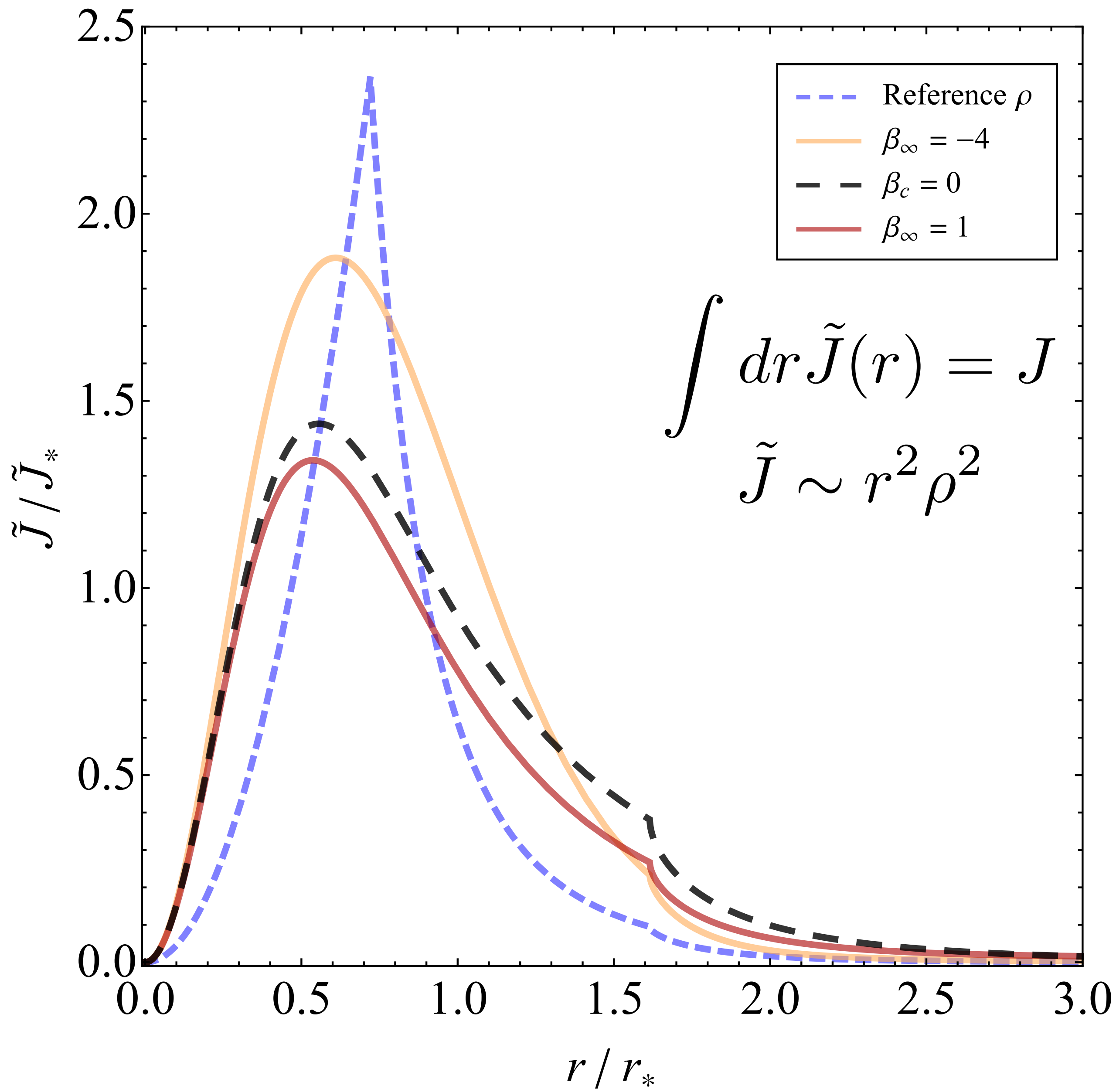
$$\rho \sim r^{-\alpha_i}$$

OVERALL NORMALIZATION FIXED BY

$$4\pi \int_0^{r_*} d\tilde{r}\, \tilde{r}^2 \rho(\tilde{r}) = \mathcal{M}(r_*)$$

MINIMIZE L.O.S. INTEGRAL OF DENSITY²

$$\min_{\alpha_i} J\left[\alpha_i\right]$$



PLUMMER + CONST SIGMA LOS + CONST BETA

WITHIN THE INTRODUCED FIDUCIAL MODEL, ISOTROPIC ORBITS PREFERRED

$$\beta_c \;\rightarrow\; \frac{\beta_0 + \beta_\infty (r/r_a)^\eta}{1+(r/r_a)^\eta}$$ IMPACTS VERY MILDLY THE MINIMAL J-VALUE

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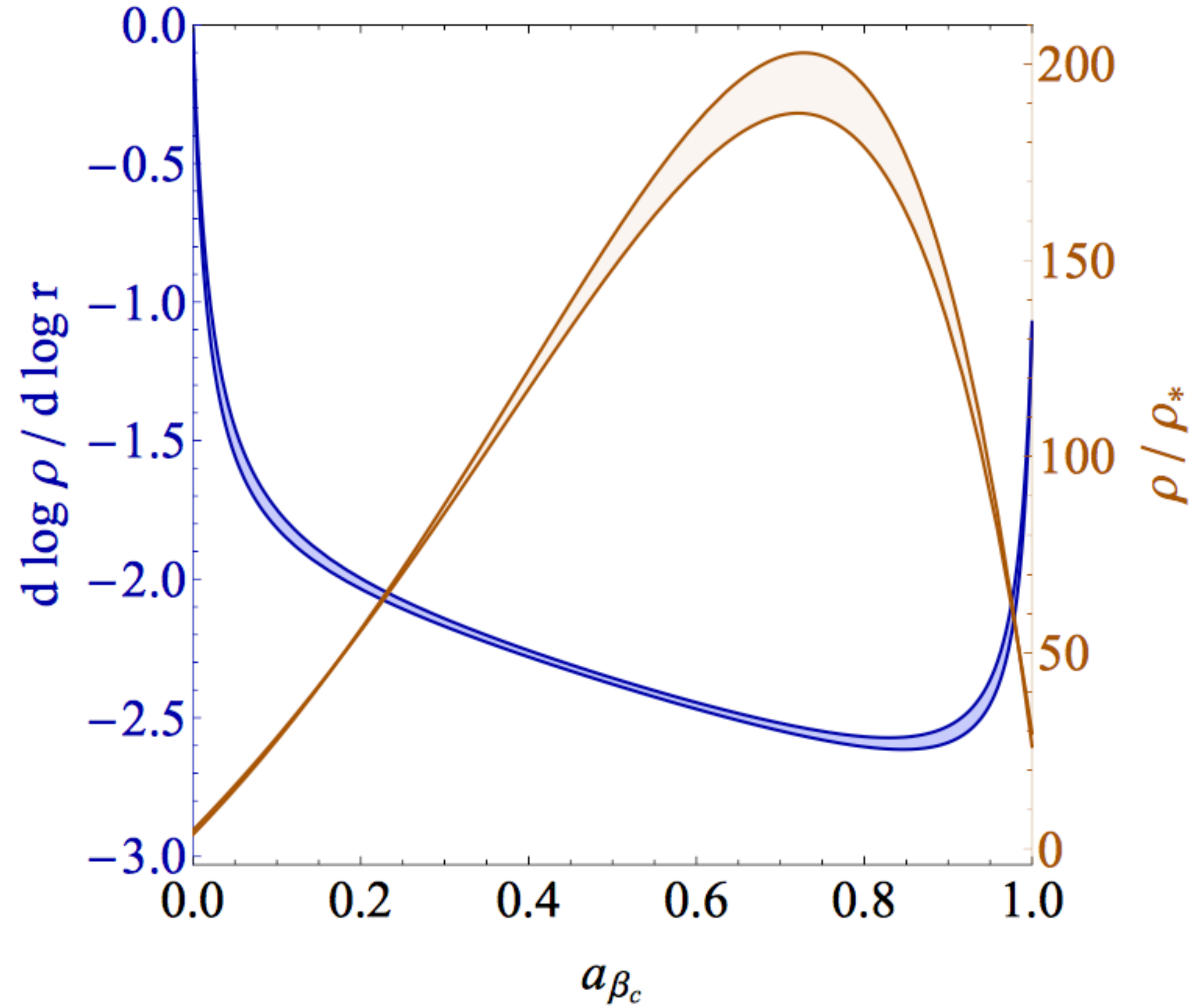
Departure from isotropic limit corresponds to cuspier profiles (therefore, higher J).

<u>BOTTOM LINE FROM FIDUCIAL MODEL</u>

In order to get an inner core in dSph DM density, a cored stellar profile + flattish los sigma require isotropic motion



However, discontinuity of this trend in the limit of perfectly circular stellar orbits:

$$\rho_{a_\beta \to 1}(r=0) \propto r^{-1}$$

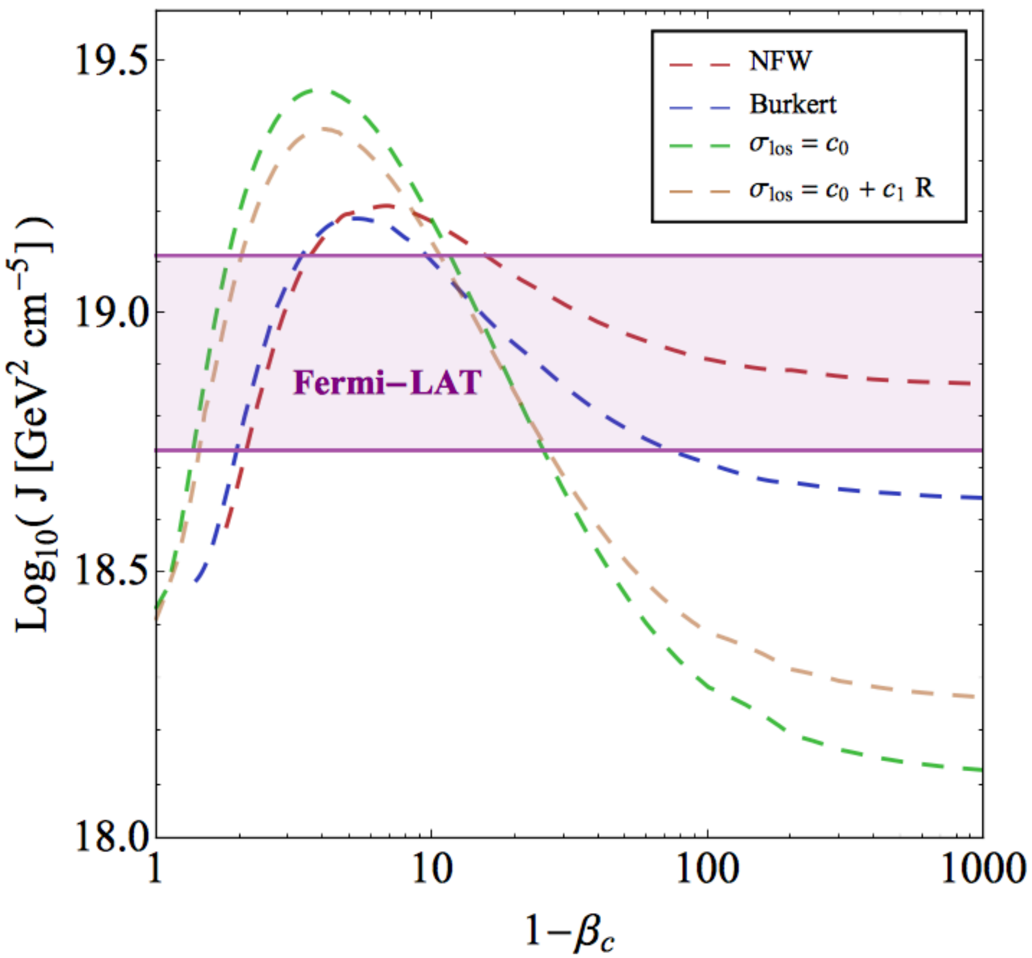
$$\mathcal{M}_{a_\beta \to 1}(r=0) = \frac{4}{3}\frac{\sigma_{los}^2 R_{1/2}}{G_N}$$

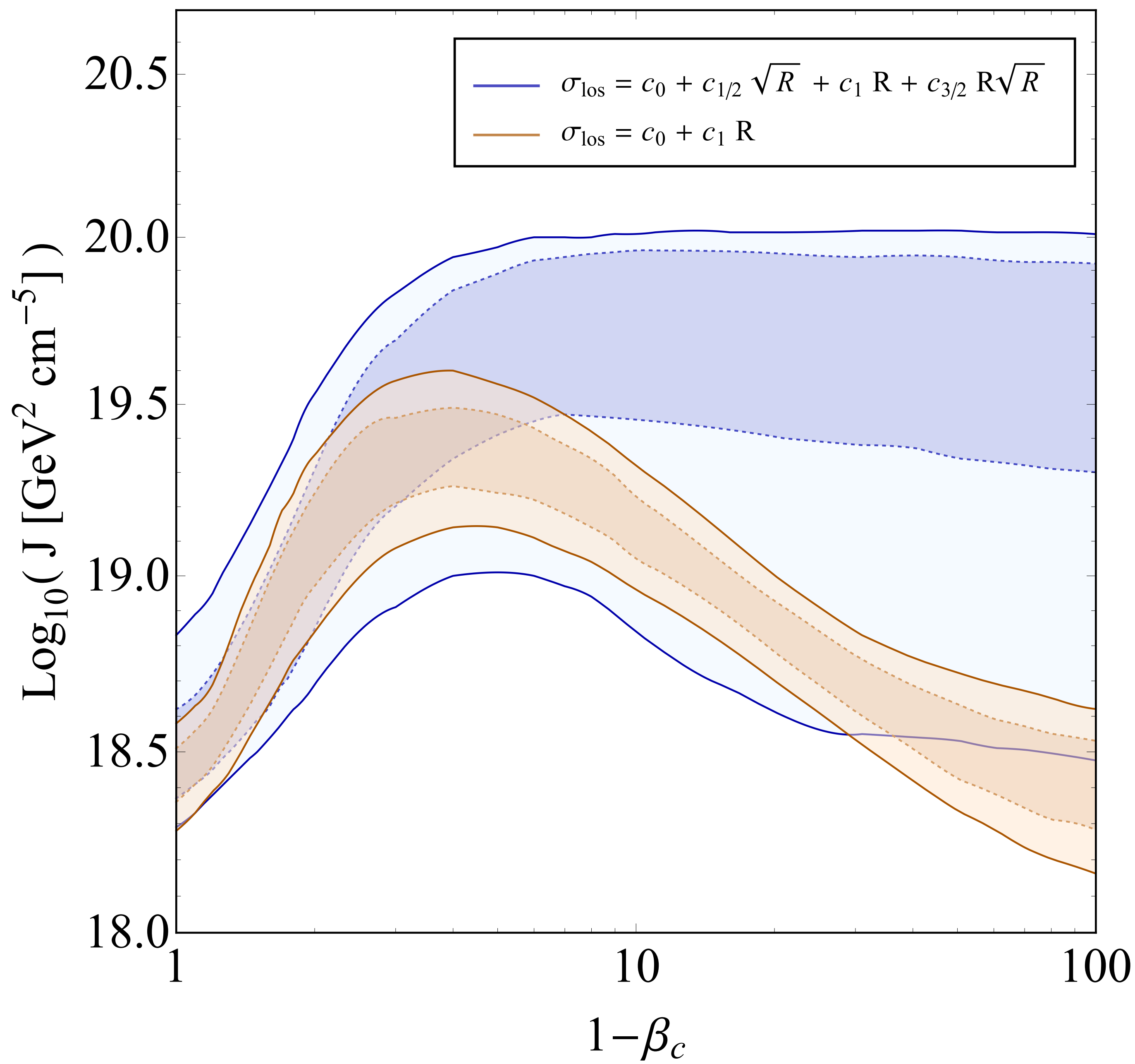
A PHENOMENOLOGICALLY MOTIVATED INNER CUT-OFF ON THE DENSITY SMOOTHES THE DISCONTINUITY WITH THE LIMIT CASE OF NEGATIVE INFINITE ANISOTROPY

IN THIS APPROACH THE MINIMAL J-FACTOR CORRESPONDS NOW TO CIRCULAR-LIKE ORBITS!

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

THE STUDY CASE OF URSA MINOR





$$\sigma_{los}(R) = \begin{cases} c_0 + c_1 R \\ \sum_{i=0}^{3} c_{\frac{i}{2}} R^{\frac{i}{2}} \end{cases}$$

+ Plummer surface brightness

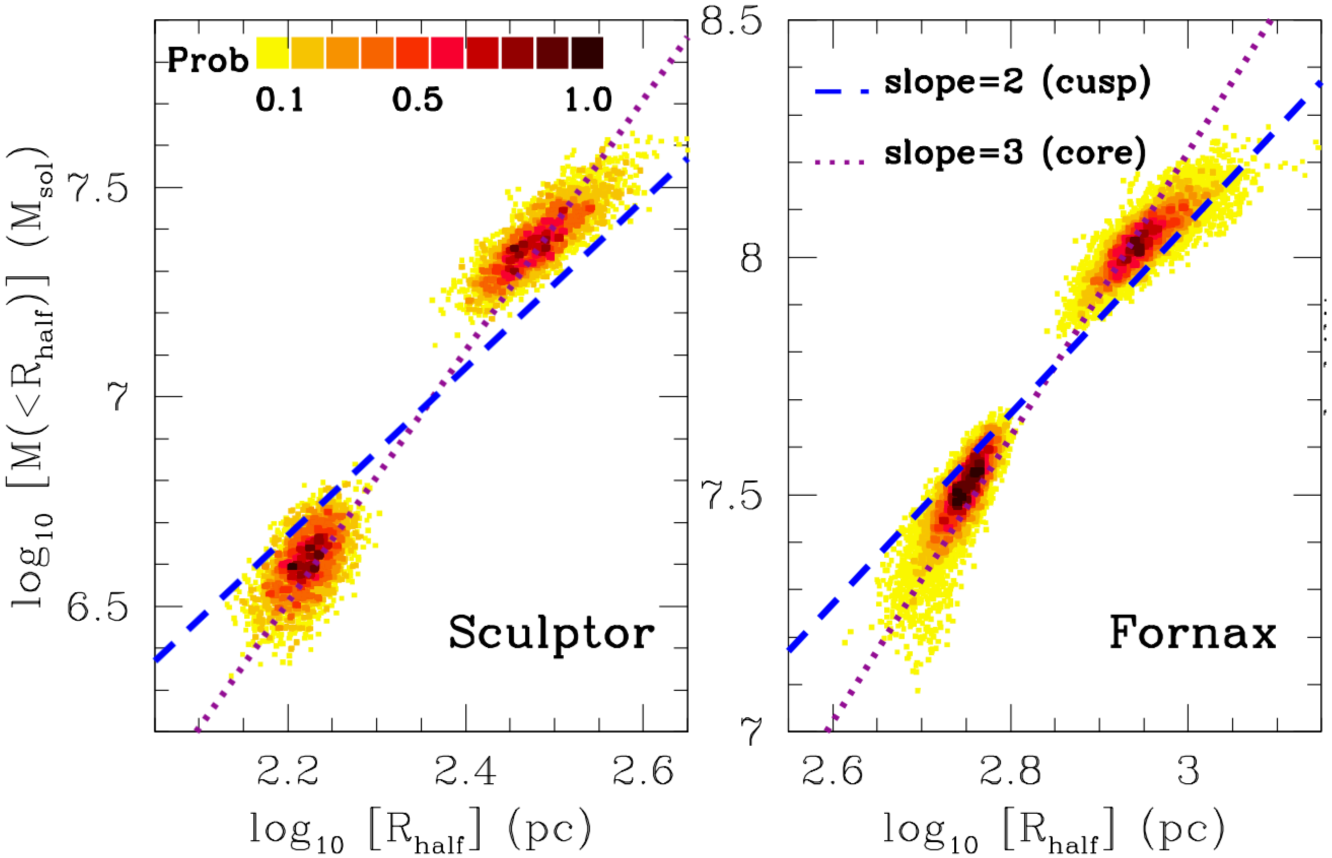
MINIMAL J @ 2 SIGMA AS EXPECTED FROM ANALYTICAL STUDY OF OUR INTIAL FIDUCIAL MODEL

Inner cores in MW satellites ?

"Core VS Cusp" problem seems to be present in many astrophysical systems

Nature 370 (1994) 629, Moore, B.

NEW DM PARADIGM OR EFFECTS FROM BARYONIC PHYSICS ?



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

—> measure of dSph mass slope!

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

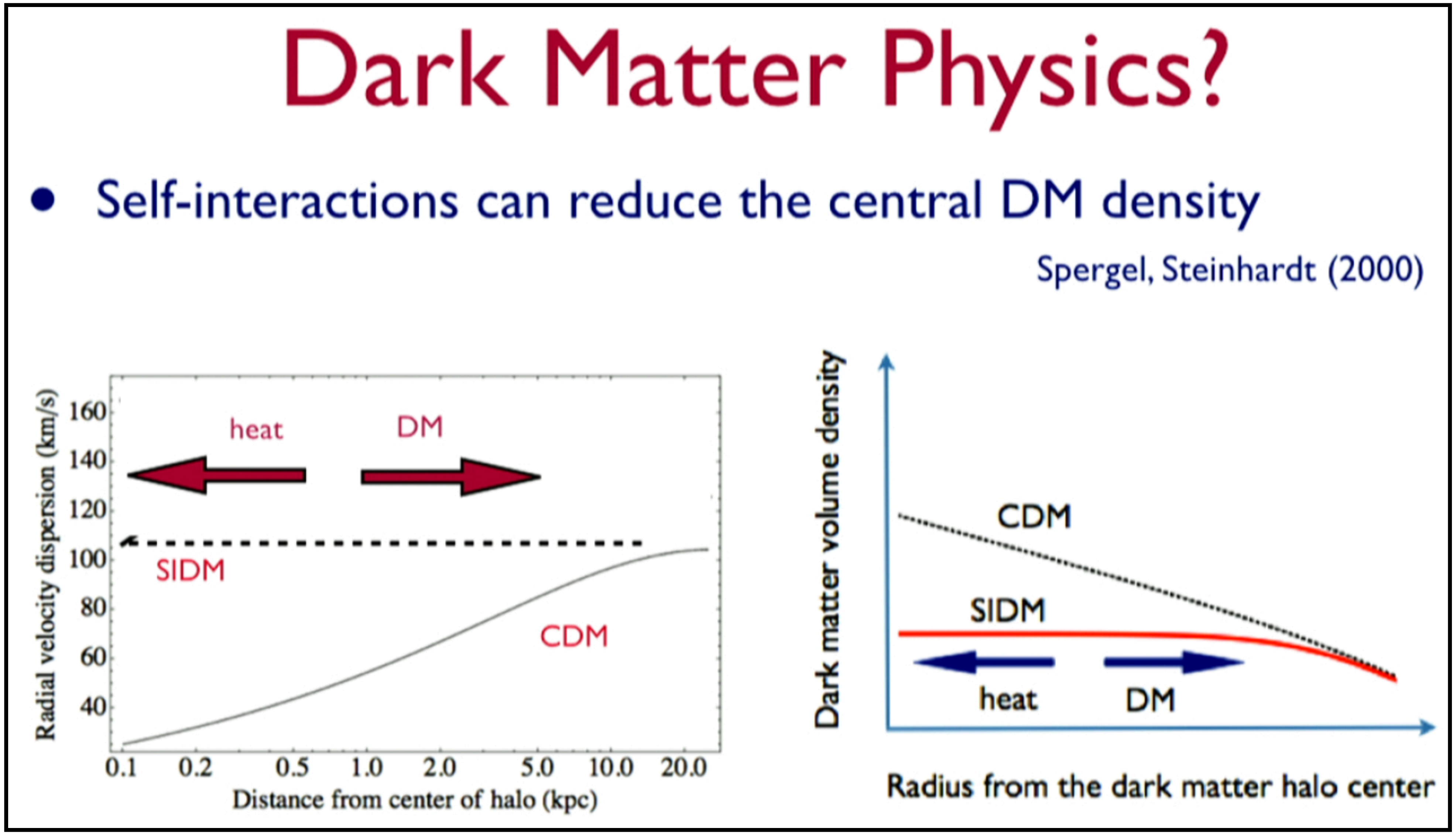
Sculptor & Fornax likely host an inner core

arXiv:1406.6079, Strigari + FW

dSph DM profiles are compatible with NFW

STILL ONGOING DEBATE ...

credit to **H.B.Yu, “The SIDM paradigm”,** Perimeter Institute, 26/04/16



However, stringent upper-limit on self-scattering x-section per unit mass! Recent re-analysis of off-set constraint from merging clusters yields:

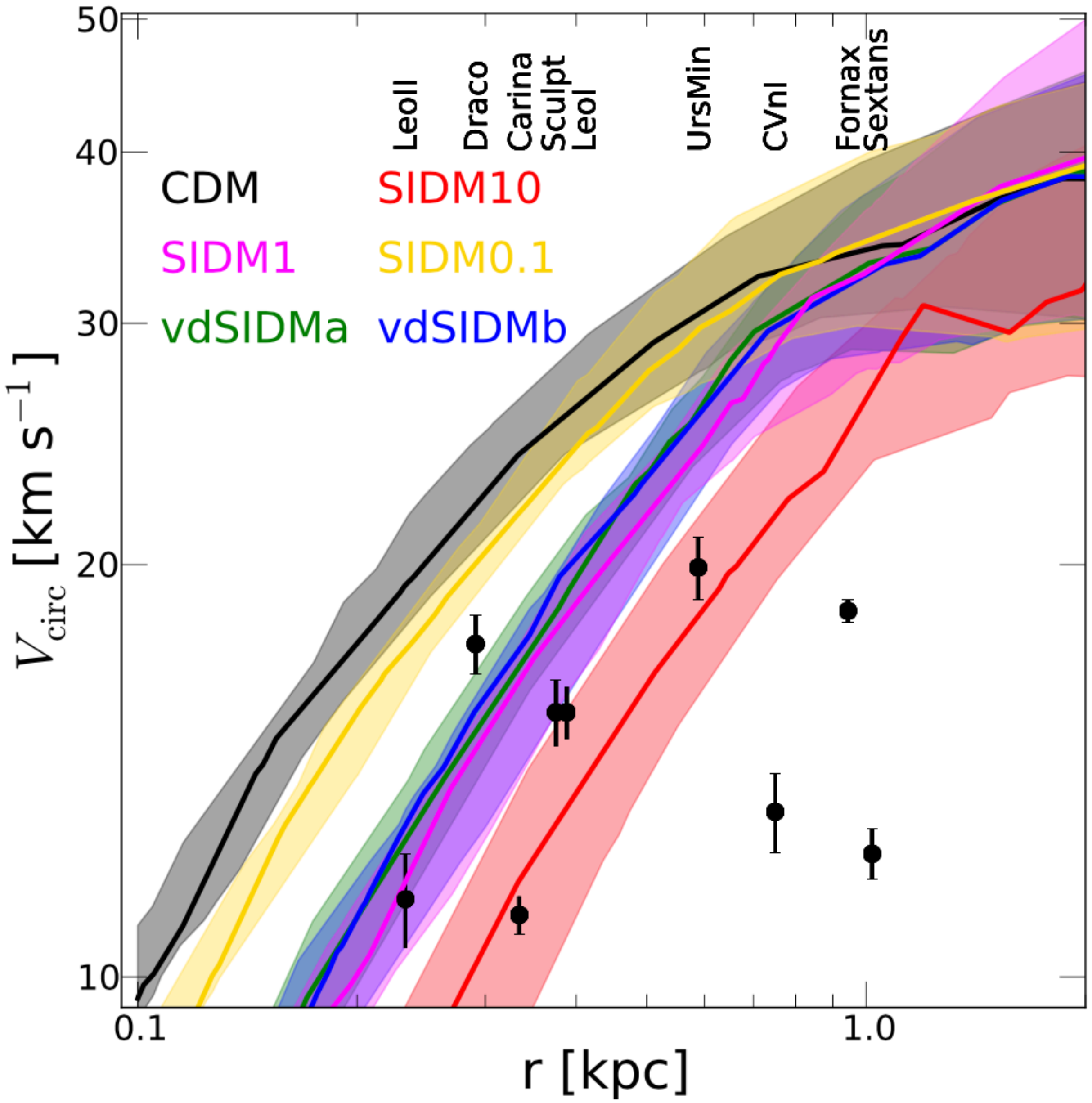
$$\sigma/m \lesssim 2\ cm^2 g^{-1}\ @\ 95\%\,\mathrm{C.L.}$$

arXiv:1701.05877, D.Wittman, N.Golovich & W.A.Dawson

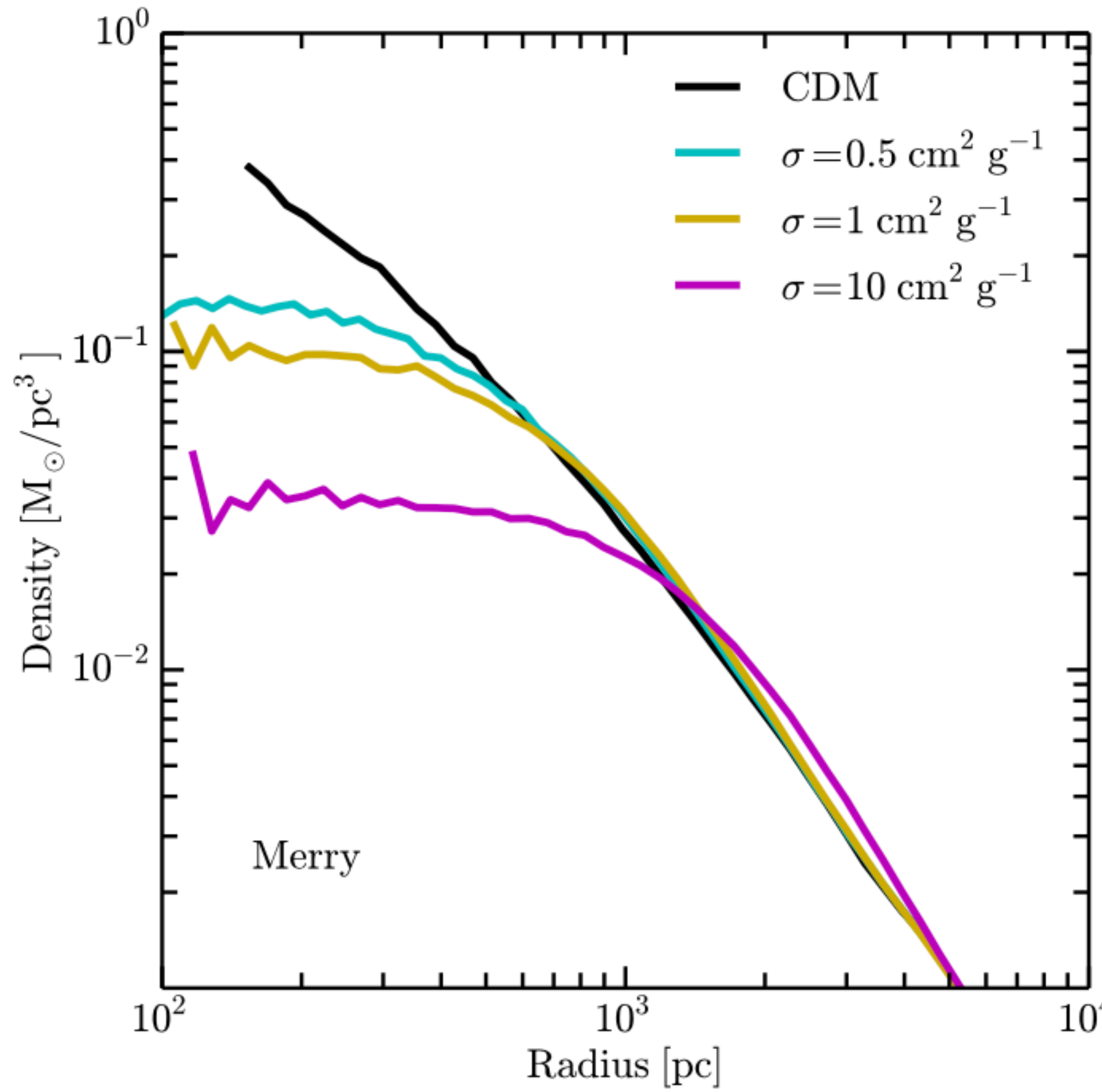
WARNING

In order to have phenomenological implications @ kpc scale of dwarf galaxies, we are looking for a DM self-scattering x-section close to that upper-bound !

$\sigma/m \sim \mathcal{O}(1)\ cm^2 g^{-1}$ ***CAN ALLEVIATE "TBTF" & ADDRESS "CORE VS CUSP"***



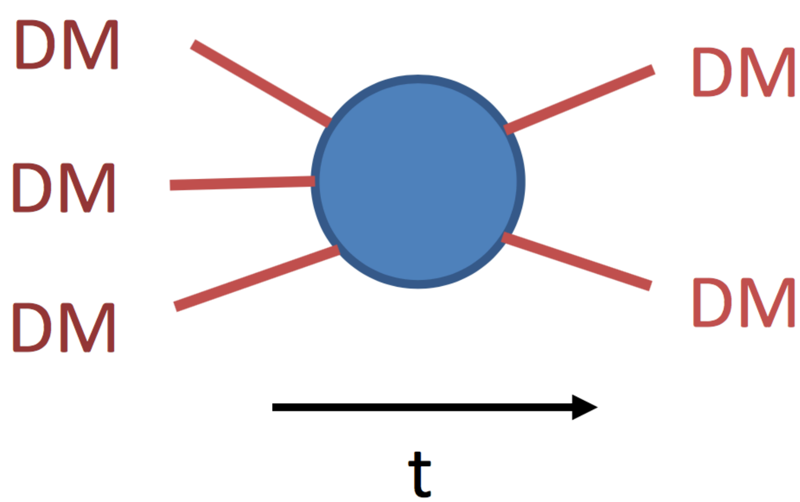
J. Zavala, M. Volgersberger & M. Walker
MNRAS 431 (2013) L20



MNRAS 453 (2015) 29, O. Elbert et al.

IN THE QUEST FOR **DM THERMAL RELICS**, 2 BROAD CLASSES OF MODELING WITH PHENO-RELEVANT SELF-INTERACTIONS + CORRECT RELIC ABUNDANCE .

Strongly Interacting Massive Particles



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

@ strong coupling, strong scale emerges :

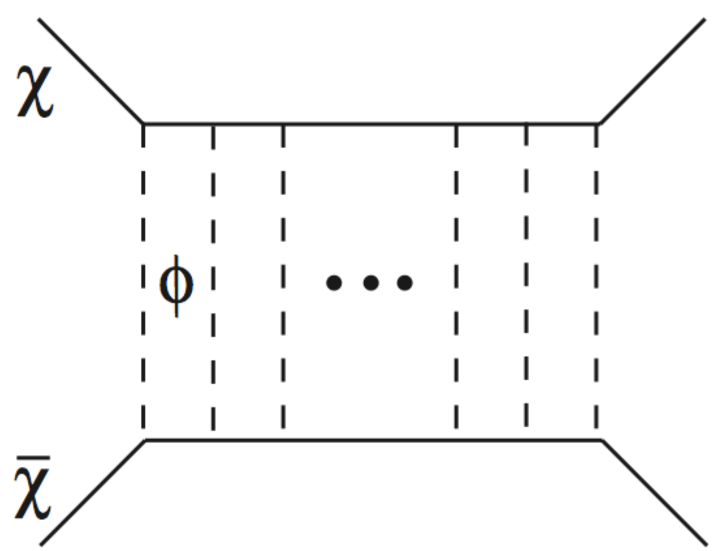
$$m_{DM} \sim \alpha_{eff} (T_{eq}^2 M_{Pl})^{1/3}$$

"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



PRD 81 (2010) 083522 , M.R.Buckley & P.J.Fox
PRL 106 (2011) 171303 , A.Loeb & N.Weiner
PRL 110 (2013) 111301 , S.Tulin, K.Zurek & H.B.Yu

In the perturbative regime, large self-scattering point to MeV mediators for weak-scale DM:

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

Simple realizations include Abelian dark sectors very weakly coupled to SM by $U(1)_D$ mixing with $U(1)_Y$

PRD 89 (2014) 035009 , M.Kaplinghat et al.
arXiv:1612.00845 , T.Bringmann et al.

LIGHT MEDIATORS IMPLY IMPORTANT VELOCITY DEPENDENCE IN SELF-SCATTERING X-SECTION