The stellar distribution in ultra-faint dwarf galaxies suggests deviations from the collision-less cold dark matter paradigm

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Funded by the European U...

GOBIERNO DE ESPAÑA | MINISTERIO DE CIENCIA E INNOVACIÓN

Unión Europea
Fondo Europeo de desarrollo Regional
"Una manera de hacer Europa"

(Fornax Dwarf - ESO)

Nacho Trujillo (IAC, Spain)

Angel R. Plastino (UNNOBA, Argentina)

Based on Various Papers:

- SA+20, A&A, 642, L14
- SA+23, ApJ, 954, 153
- SA 24, RNAAS, 8, 167
- SA+24a A&A, in press
- SA+24b, ApJL, 973, L15
- SA+24c, ApJ, to be sub.

Outline

1.- Motivation & Rationale

- Galaxies in the HUG regime

2.- Eddington Inversion Method (EIM) comes to help

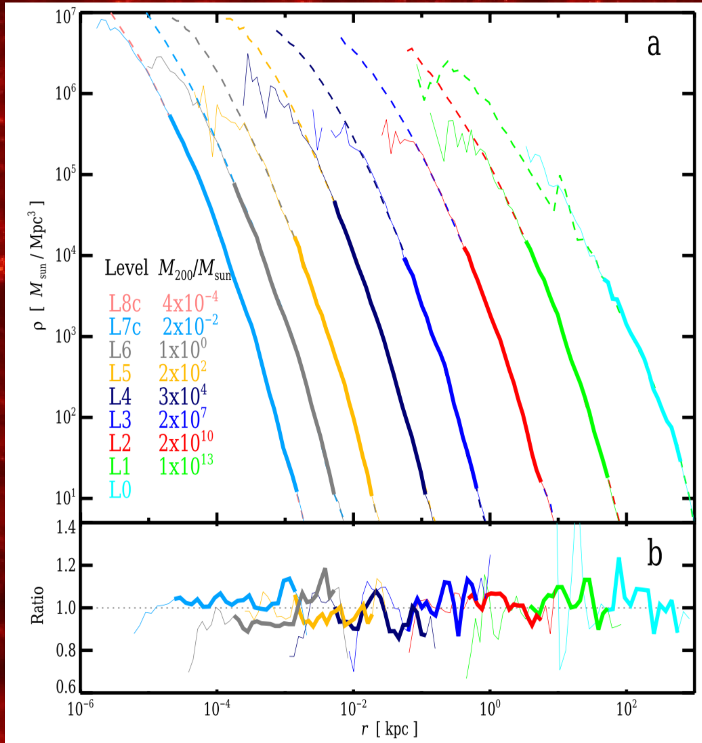
- Stellar cores dislike cuspy CDM potentials

3.- Ultra Faint Dwarfs challenge the Cold Dark Matter paradigm

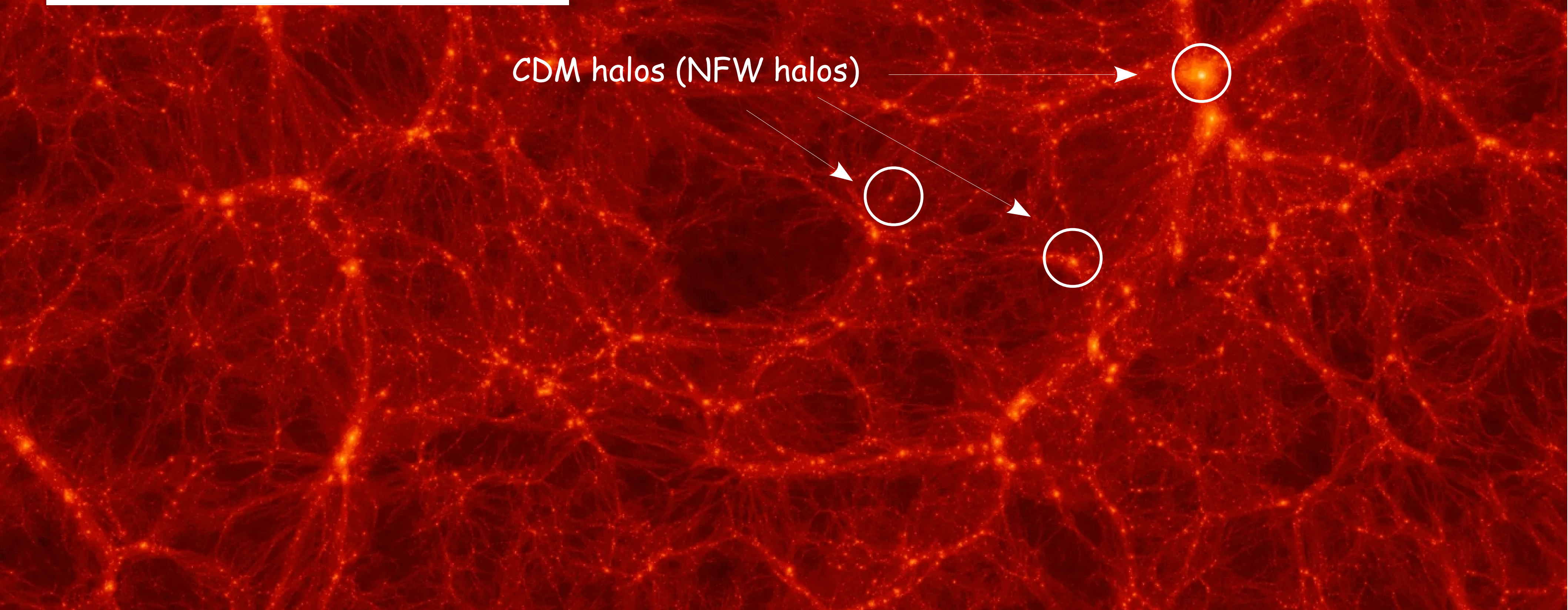
ΛCDM $\rightarrow$ Λ~~C~~DM

4.- Constraints on the Nature of Dark Matter (SIDM, as e.g.)

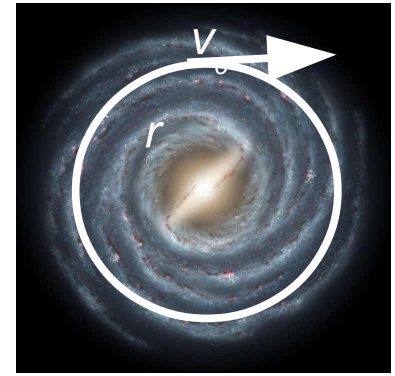
5.- Take-home message



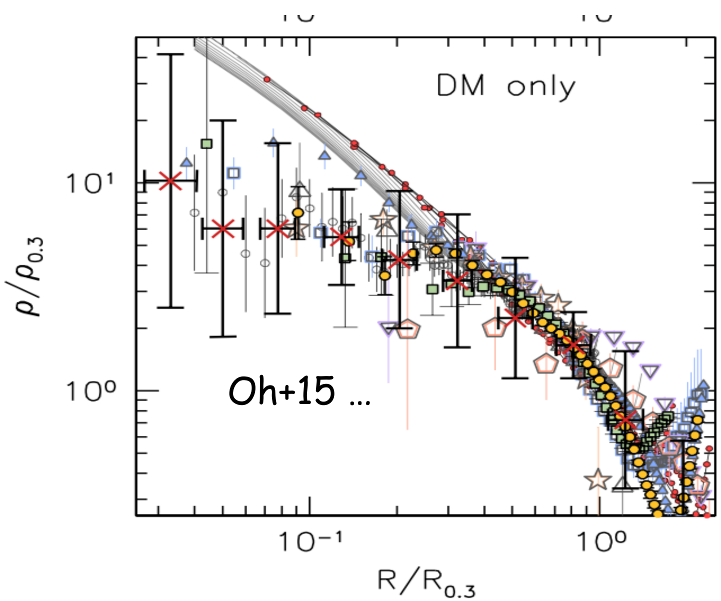
$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$



Small-scale tensions: core – cusp problem

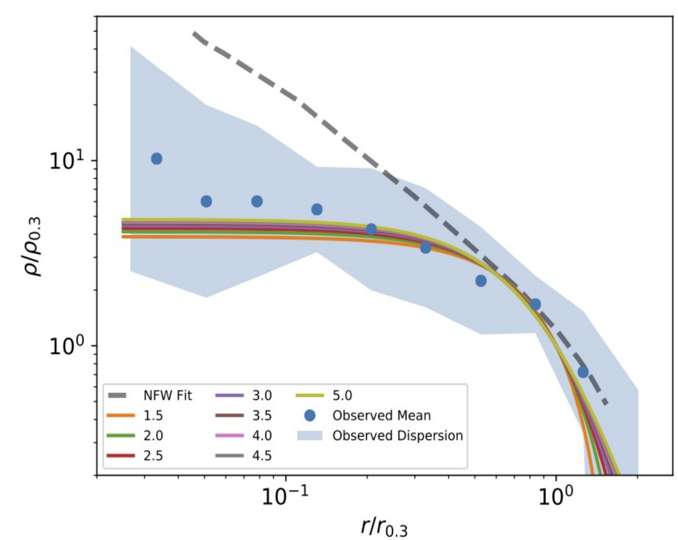


One can measure the DM distribution using kinematic information (e.g. HI rotation curves).

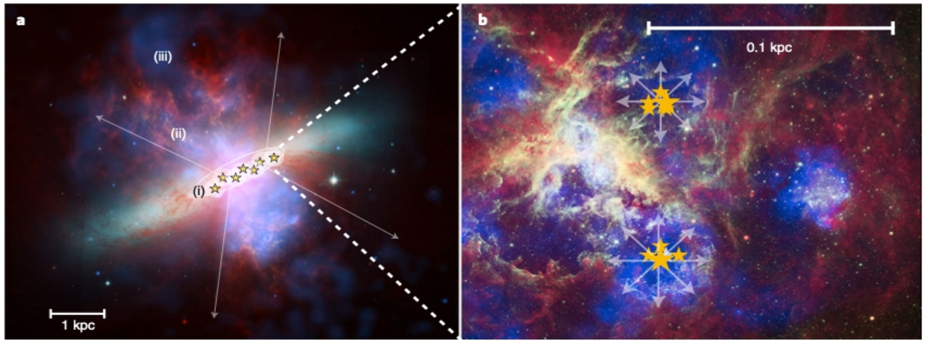


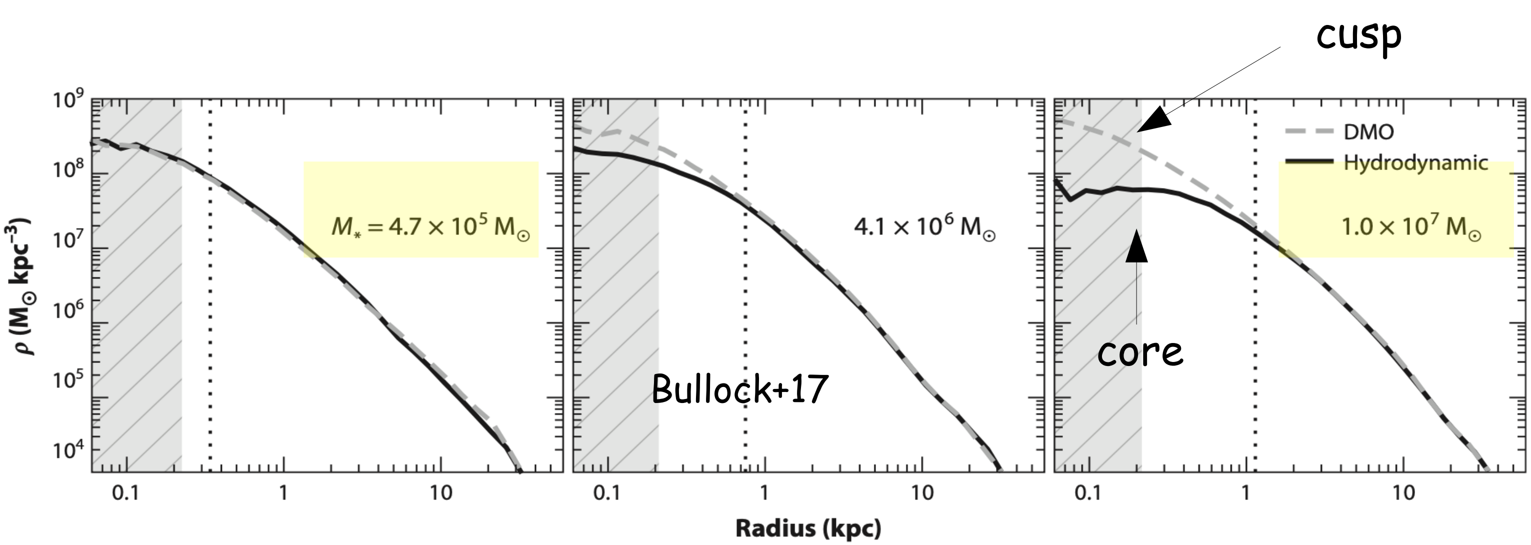
The smallest observed galaxies, M_* >~ 10^6 $M_\odot$, show cores rather than cusps (NFW profile)

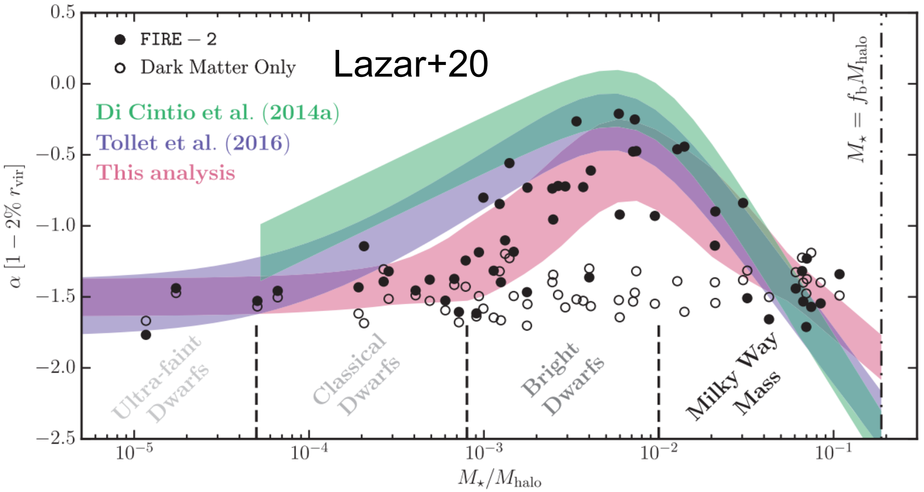
SA+20, cores imply is DM is in thermodynamic equilibrium (Tsallis entropy)



Solution within the CDM paradigm: stellar feedback on the DM distribution Governato+10)







Baryon feedback is unable to modify the CDM profile (NFW profile) for stellar masses smaller than some 10^6 M$_\odot$. (There is not enough energy, e.g., Peñarubia+12)

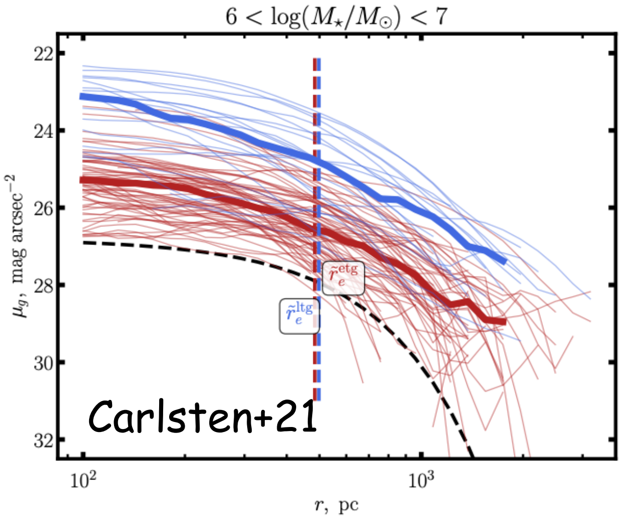

SUPER SIMPLE™
Loading...

- In cores exist for $M_* < \sim 10^6\ M_\odot$ then it cannot

be due to baryon feedback but has to reflect the nature of DM whether is fuzzy, self interacting, warm, or else.

- Kinematic measurements at these masses is technically very challenging (if not impossible), however, photometry is doable. We can measure the mass profile from photometry.

- … and the observed mass profiles tend to show cores …



The question arises as to whether stars trace the DM distribution in these low-mass systems

There is no trivial answer since in general they do not :the distribution of DM and stars do not necessarily have to be the same.

The Eddington inversion method comes to help:

For spherically symmetric systems of particles with isotropic velocity distribution, the phase-space DF f(ε) depends only on the particle energy ε.

$$\rho(r) = 4\pi\sqrt{2}\int_0^{\Psi(r)} f(\epsilon)\sqrt{\Psi(r)-\epsilon}\,d\epsilon.$$

$\epsilon = \Psi - \frac{1}{2}v^2$ is the relative energy

$\Psi(r) = \Phi_0 - \Phi(r)$ is the relative potential

$$f(\epsilon) = \frac{1}{\sqrt{2}\pi^2}\int_0^{\epsilon}\frac{d^3\rho}{d\Psi^3}\sqrt{\epsilon-\Psi}\,d\Psi.$$

Give a stellar mass density profile, ρ(r), and a potential, Ψ(r), the Eddington Inversion Method provides the distribution function consistent with both, f(ε).

- There is no guarantee that two arbitrary ρ(r) and Ψ(r) are physically consistent with each other.
- The absolutely minimum requirement for consistency is f(ε) ≥ 0
- Pairs ρ(r) - Ψ(r) leading to f(ε) < 0 can be discarded, thus, given an observed stellar ρ(r) we can constraint the DM Ψ(r).
- Is a cored estellar ρ(r) consistent with a cuspy CDM Ψ(r)?

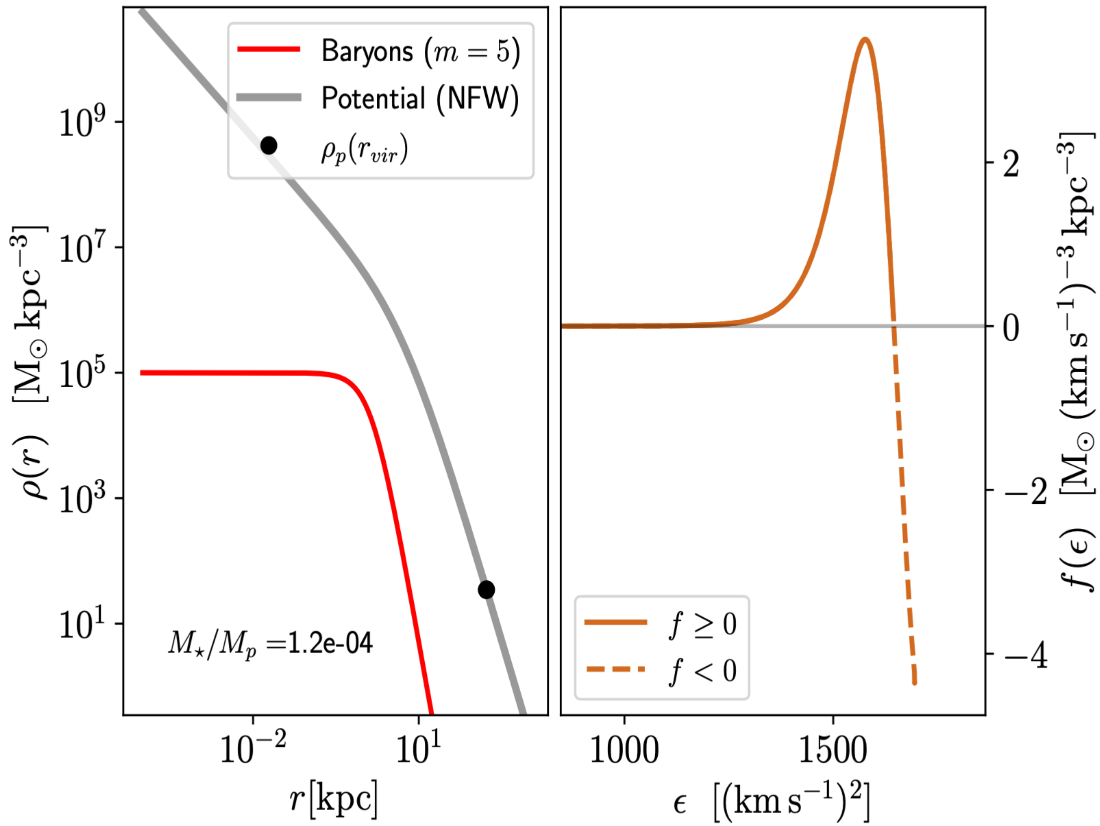
- Is a cored estellar ρ(r) consistent with a cuspy CDM Ψ(r)?

$$\frac{d\rho}{d\Psi} = 2\pi\sqrt{2}\int_0^{\Psi} \frac{f(\epsilon)}{\sqrt{\Psi-\epsilon}}\,d\epsilon.$$ =0 implies f(ε) <0

$$\frac{d\rho}{d\Psi} = \frac{d\rho/dr}{d\Psi/dr},$$

$$\lim_{r\to 0}\frac{d\Psi}{dr} = -\frac{V_c}{2\,r_s^2} \neq 0;$$

$$\lim_{r\to 0}\frac{d\rho}{dr} = 0,$$



NO for spherical systems with isotropic velocities

Table 1. Summary of the compatibility between baryon density profile (ρ) and potential

Baryons & Potential, Velocity	Consistency	Comments	Section
(1)	(2)	(3)	(4)
Core [†] & NFW [‡], isotropic	✗	Eqs. (23) and (24). $\beta = 0^*$. Fig. 1	Sect. 3
Power law [§] & Power law, isotropic	✍	$\alpha > 0$ [§] ✓ $\alpha < 0$ ✗. Eq. (25). $\beta = 0$	Sects. 3, 4.2
Core & Soft-core [#], isotropic	✗	$\beta = 0$. Fig. 4. Fig. 5	Sect. 4.2, App. E
Core & Core, isotropic	✍	$\beta = 0$. $a \leq 2$ ✓ $a > 2$ ✗. Fig. 2. Fig. 7	Sects. 4.1, 4.2, App. E
Soft-core & NFW, isotropic	✍	$\beta = 0$. Figs. 5, 6. $c \gtrsim 0.1$ ✓ $c \lesssim 0.1$ ✗.	Sects. 3, 4.2
Soft-core & Soft-core, isotropic	✍	$\beta = 0$. Figs. 5, 6	Sects. 3, 4.2
		$r_s \gtrsim 2\, r_{sp}$ ✗, $c > c_p$ ✓	Sect. 4.2
Core & NFW, O-M model	✗	$\beta(\neq 0)$ in Eq. (12)	Sect. 3
Core & NFW, radially biased	✗	Constant β. $\beta > 0$	Sect. 3, App. D
Core & Any, radially biased	✗	Constant β. $\beta > 0$	Sect. 3, App. D
Power-law & Any, anisotropic	✍	Constant β. $\alpha > 2\beta$	Sect. 3, App. D
Core & NFW, circular	✓	$\beta = -\infty$	App. C
Any & Any, circular	✓	$\beta = -\infty$	App. C
Any & Any, tangentially biased	✍	$\beta < 0$. Eq. (18). ✗ $f_i < 0$	Sects. 2.3, 3

NOTE—
[†] Core $\equiv d\log\rho/d\log r \to 0$ when $r \to 0$.
[‡] Navarro, Frenk, and White potential (Eq. [A6]) produced by a NFW profile (Eq. [A5]).
[*] Velocity anisotropy parameter β defined in Eq. (11).
[§] $\rho \propto r^{-\alpha}$.
[#] Soft-cores defined in Eqs. (30) and (32), and illustrated in Fig. 3. Power laws [§] are a particular type of those.
(1) Description of the baryon density, the gravitational potential, and the velocity distribution.
(2) The symbols ✓, ✗, and ✍ stand for *compatible*, *incompatible*, and *may or may not*, respectively.
(3) Additional comments and keywords.
(4) Section of the text where the combination described in (1) is discussed.

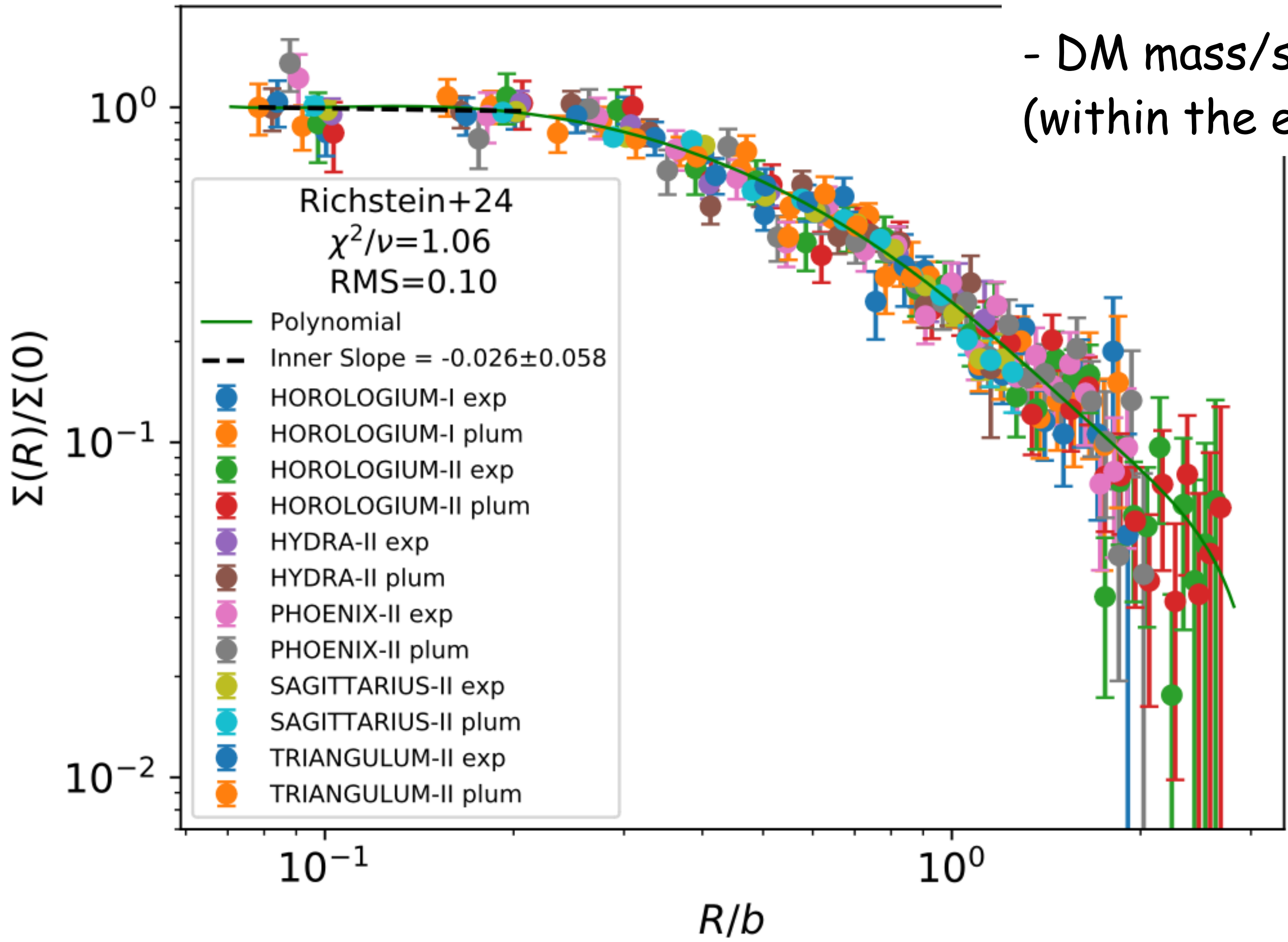
SA+23b, ApJ

The inconsistency between CDM halos and cored stellar distributions goes beyond the assumption of spherical symmetry, isotropic velocities, and NFW potentials (An&Evans06, Ciotti & Morganti 10, SA+23, SA+24, SA24):

- holds for quasi-cores embedded in quasi-NFW potentials
- holds for Einasto profile (not singular as r--> 0)
- holds for non-spherical axi-symmetric systems.
- holds for radially biased orbits and Opsikov-Merritt kind of anisotropy

Ultra Faint Dwarfs challenge the Cold Dark Matter Paradigm

- 6 UFD galaxies from Richstein+24, ApJ
  - stellar mass ~10^3 - 10^4 $M_\odot$
  - DM mass/stellar mass ~ 10^3 (within the effective radius)



1.- All have the same universal shape
2.- All have a core (central plateau)


Horologium-I
stellar mass ~ 10^4 $M_\odot$
DM mass/stellar mass ~ 10^3
(Belokurov & Koposov)

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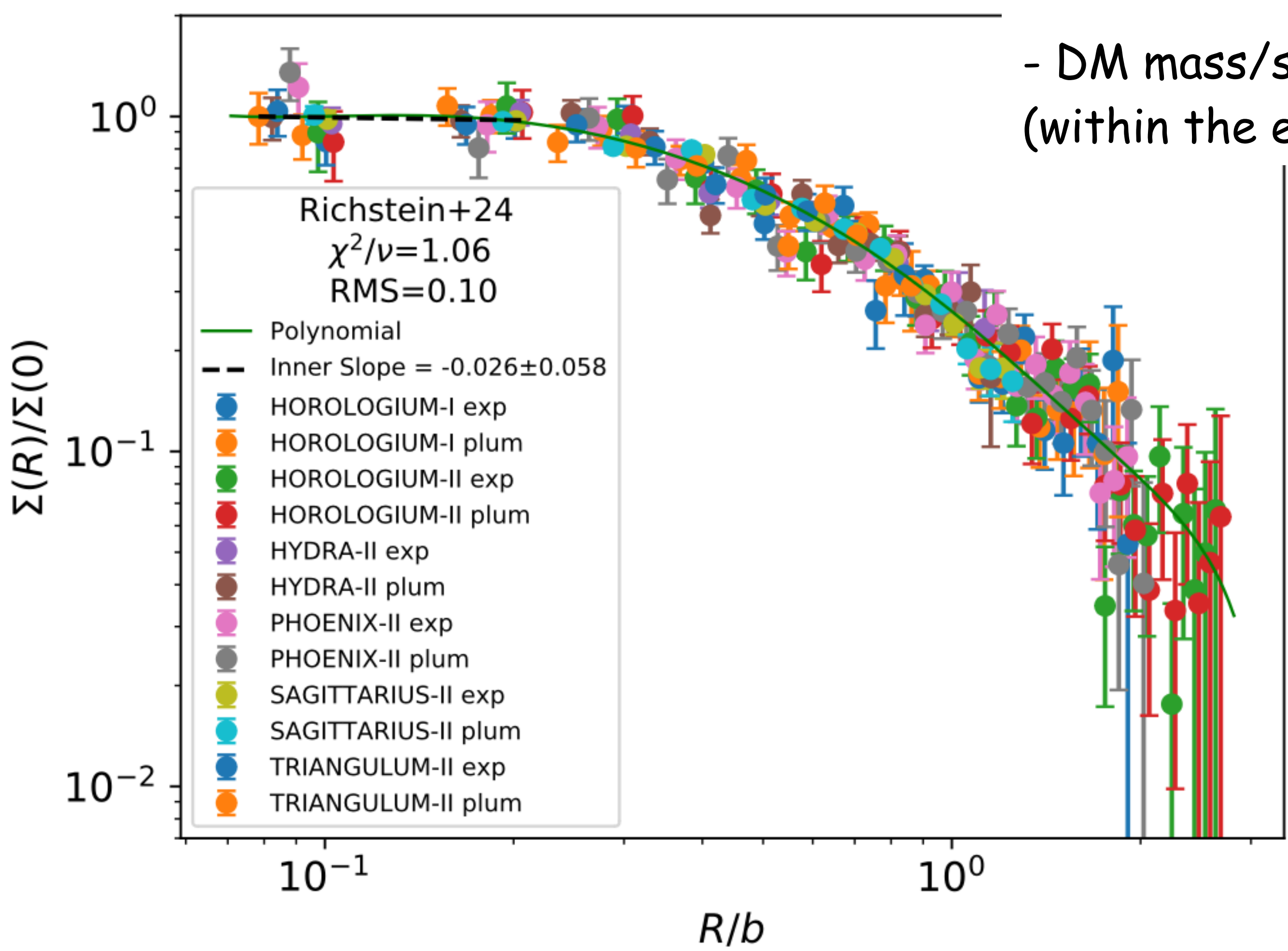

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3. EDDINGTON INVERSION METHOD APPROACH

The details and tests of the technique are given elsewhere (Sánchez Almeida et al. 2024a), but here we summarize the approach used to compute the DF in the phase-space f required for the observed profile (Fig. 1) to reside in a particular potential. For a spherically symmetric system of identical stars with isotropic velocity distribution, $f(\epsilon)$ depends only on the particle energy ϵ. (The impact of relaxing these assumptions is addressed in Sect. 5.) Then, the stellar volume density $\rho(r)$ turns out to be (e.g., Binney & Tremaine 2008, Sect. 4.3),

$$\rho(r) = 4\pi\sqrt{2}\int_0^{\Psi(r)} f(\epsilon)\sqrt{\Psi(r)-\epsilon}\,d\epsilon, \tag{2}$$

with $\epsilon = \Psi - \frac{1}{2}v^2$ the relative energy per unit mass of a star and $\Psi(r) = \Phi_0 - \Phi(r)$ its relative potential energy. The symbol $\Phi(r)$ stands for the gravitational potential energy and Φ_0 is $\Phi(r)$ evaluated at the edge of the system. The previous equation can be rewritten as

$$\rho(r) = \int_0^{\epsilon_{max}} f(\epsilon)\,\xi(\epsilon, r)\,d\epsilon, \tag{3}$$

with

$$\xi(\epsilon, r) = 4\pi\sqrt{2\epsilon_{\rm max}}\sqrt{\left[\frac{\Psi(r)}{\Psi(0)} - \frac{\epsilon}{\epsilon_{max}}\right]}\;\Pi(X - r), \tag{4}$$

$\epsilon_{max} = \Psi(0)$, X the radius implicitly defined as $\Psi(X)/\Psi(0) = \epsilon/\epsilon_{max}$, and $\Pi(x)$ the step function,

$$\Pi(x) = \begin{cases} 0 & x \leq 0, \\ 1 & x > 0. \end{cases} \tag{5}$$

The symbol $\xi(\epsilon, r)$ represents a family of densities that are characteristic of the potential and dependent on the energy ϵ. Then, according to Eq. (3), the stellar density is just the superposition of these characteristic densities with the DF $f(\epsilon)$ giving the contribution of each energy to $\rho(r)$. (The characteristic densities for a Schuster-Plummer potential are shown as an example in Appendix A.) Following Eq. (3), $f(\epsilon_i)$ could be retrieved by fitting the observable $\rho(r)$ with a linear superposition of $\xi(\epsilon_i, r)$ at various ϵ_i. (We will see below that ρ can be replaced with the projected stellar surface density, which is the true observable.) In practice, however, there is no error-proof way to discretize Eq. (3). We approach the practical problem by expanding $f(\epsilon)$ as a polynomial of order n,

$$f(\epsilon) \simeq \epsilon_{max}^{-3/2}\sum_{i=3}^{n} a_i\,(\epsilon/\epsilon_{max})^i, \tag{6}$$

so that

$$\rho(r) \simeq \sum_{i=3}^{n} a_i\,F_i(r),$$

$$F_i(r) = \epsilon_{max}^{-1/2}\int_0^1 \alpha^i\,\xi(\alpha\,\epsilon_{max}, r)\,d\alpha,$$

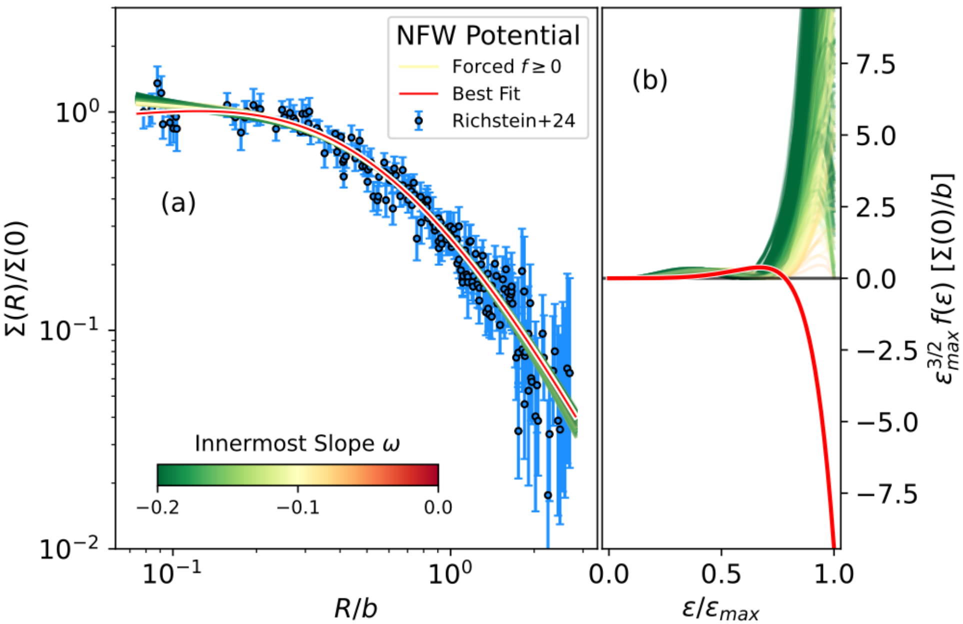
The free parameter of the fit is the shape of the distribution function

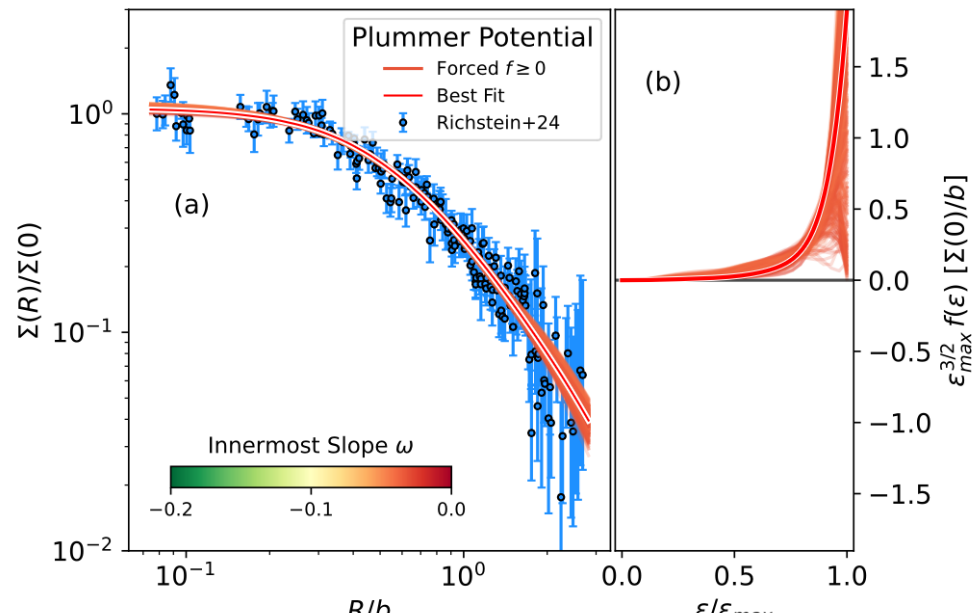
with $\alpha = \epsilon/\epsilon_{max}$. Equation (7) gives a simple expansion of the stellar density $\rho(r)$ in terms of potential-dependent but known functions $F_i(r)$. **The chosen functional form in Eq. (6) is both flexible and, by starting at $i = 3$, it describes a system of finite mass despite** the mass given by $\xi(\epsilon, r)$ diverges as $\epsilon^{-\gamma}$ **when $\epsilon \to 0$,** with $2 < \gamma < 3$ depending on the potential (Sánchez Almeida et al. 2024a). The normalization in Eq. (6) has been chosen so that $F_i(r)$ does not depend on ϵ_{max}. The discretization in Eq. (7) also holds for the projection of the volume density in the plane of the sky, i.e.,

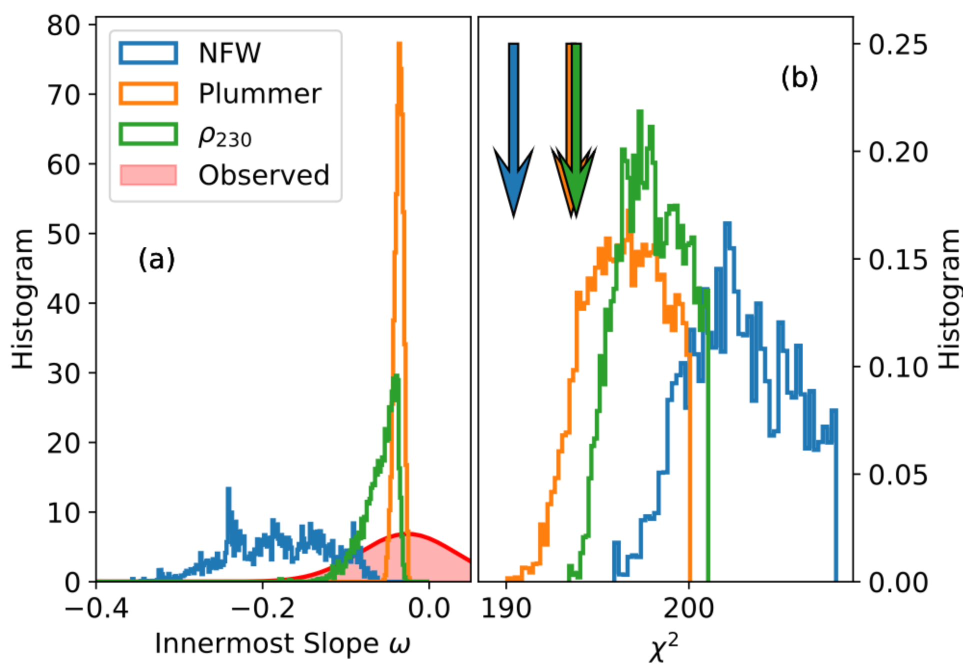
$$\Sigma(R) \simeq \sum_{i=3}^{n} a_i\,S_i(R), \tag{9}$$

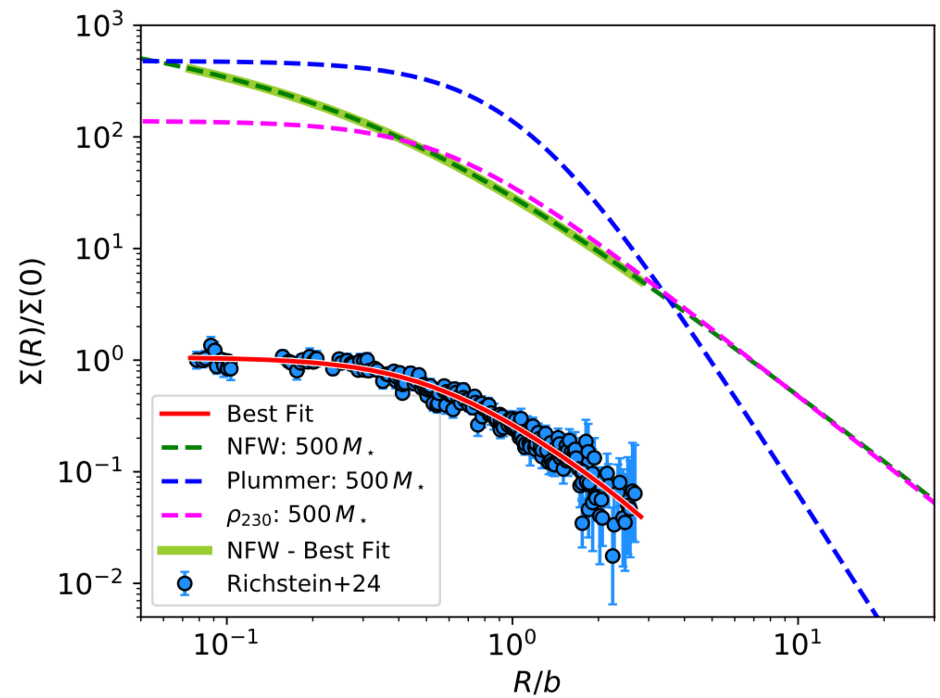
$$S_i(R) = \int_0^1 \alpha^i\,\frac{\xi_\Sigma(\alpha\epsilon_{max}, R)}{\sqrt{\epsilon_{max}}}\,d\alpha, \tag{10}$$

where $\Sigma(R)$ and $\xi_\Sigma(\epsilon_i, R)$ stand the 2D projection (i.e., the Abel transform) of $\rho(r)$ and $\xi(\epsilon_i, r)$, respectively. R represents for the radial coordinate in the plane of the sky projection, as in Sect. 2.









NFW potentials are discarded in favor of cored potentials (≥ 97 % confidence level)

Is any of the assumptions involved in EIM responsible of the conclusion?

- Isotropic velocities?

The incompatibility NFW-cores holds for radially biased orbits and Osipkov-Merrit models

Tangentially biased orbits can fit any stellar distribution … but disfavored from theory and numerical simulations

- Spherical symmetry?

Inconsistency NFW-stellar cores holds for axi-symmetric systems (SA+24a)

Observation of UFDs refer to circular objects … (+ one of the UDFs is round)

- Satellites?

If important, tidal forces do not explain the existence of a single shape

Tidal forces unimportant since the NFW shape remains for tiny satellites (e.g., Wang+20)

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- Shape of the potential?

- The incompatibility holds for Einasto potentials and quasi-NFW, whereas cored potentials and stellar cores are compatible independently of the details of the cored potential.

- Stellar feedback irrelevant?

- Yes, at UDFs mass of $\sim 10^3$ - 10^4 $M_\odot$, feedback is unimportant quite independently of the actual modeling (e.g., Peñarubia+12)

- Is stellar self-gravity negligible?

- DM mass/stellar mass ~ 10^3

- Centers and observed ellipticities are a problem?

- Several independent trials

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NO PROBLEM

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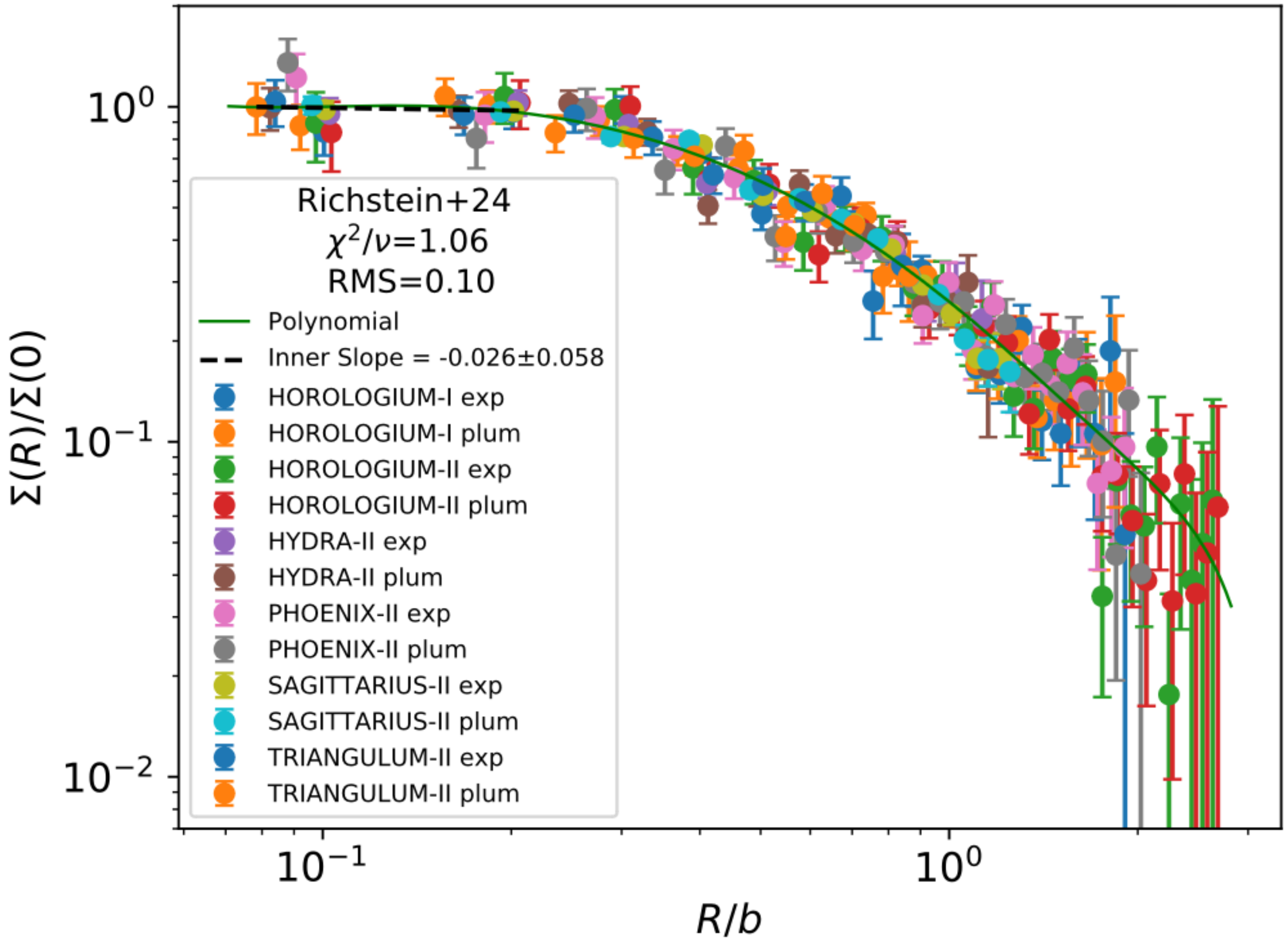
Thus, the stellar distribution in UFDs is incompatible with the Collisionless Cold Dark Matter (CDM) paradigm



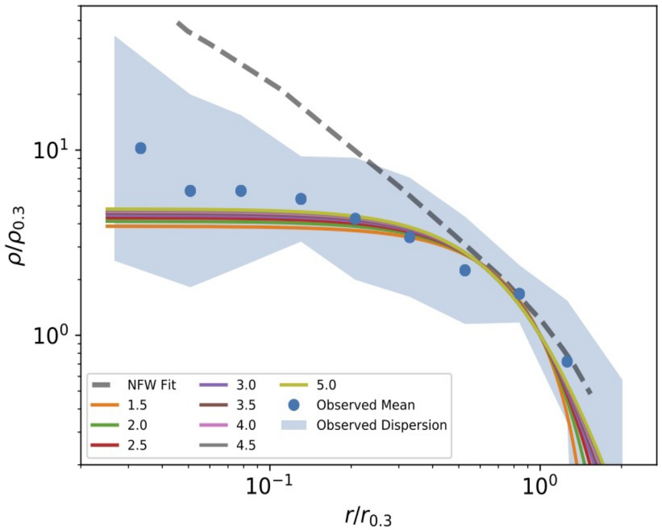
SA+24, ApJL

Constraints on the Nature of Dark Matter

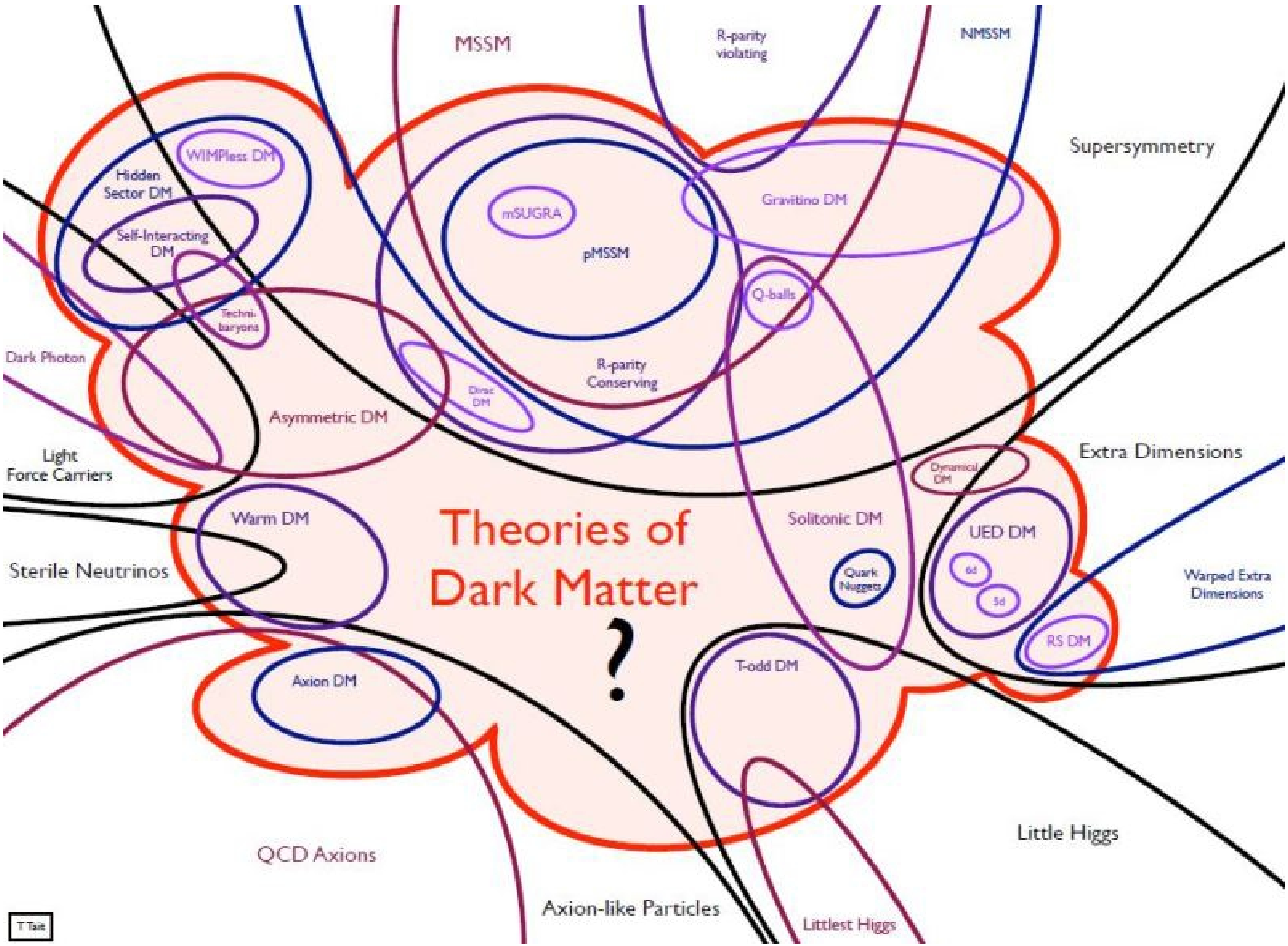
(Example in case DM is made of particles that interact beyond gravity: self interacting dark matter or SIDM)

NFW (or any CDM halos) inherit their shape from the initial conditions (e.g., Braun+22, MNRAS, 509, 5685) since the DM particles do not interact with each other except through gravity. **Gravity alone is unable to thermalize the halo** … (e.g., Binney & Tremaine 07)

If DM particles collide and reach thermodynamic equilibrium, the the DM halos should be polytropes which have cores (Plastino & Plastino 93, Phys. Lett.; SA+20 A&AL)



The cross section should be large enough to thermalize the halo and small enough avoid the core collapse.


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
6d
5d
Sterile Neutrinos
Quark Nuggets
Warped Extra Dimensions
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

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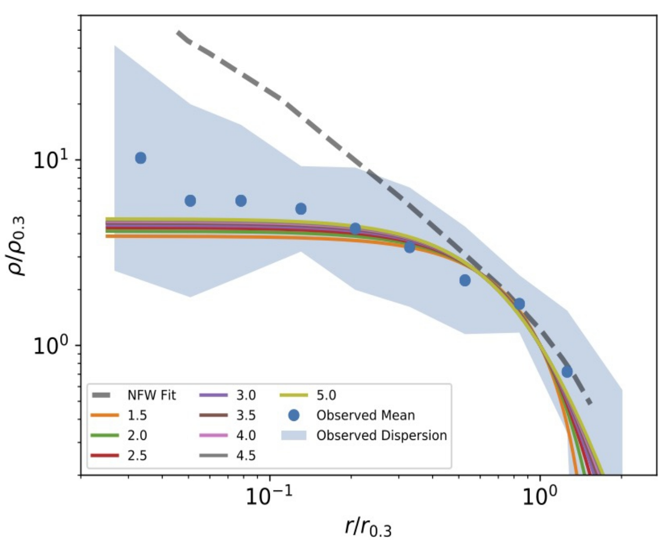

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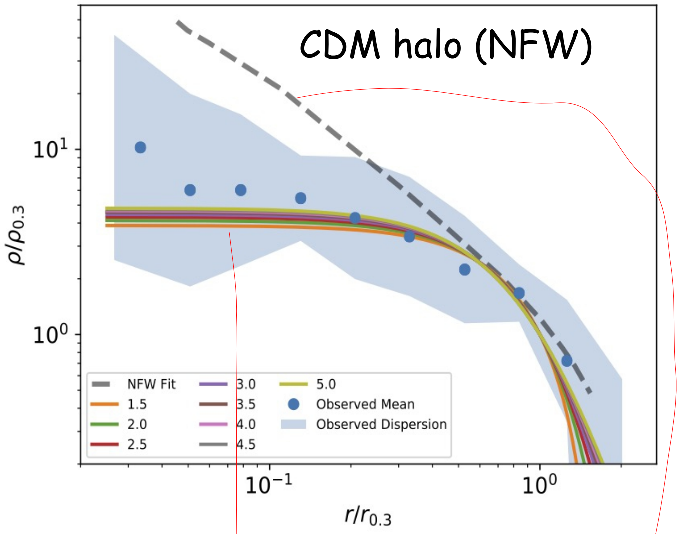
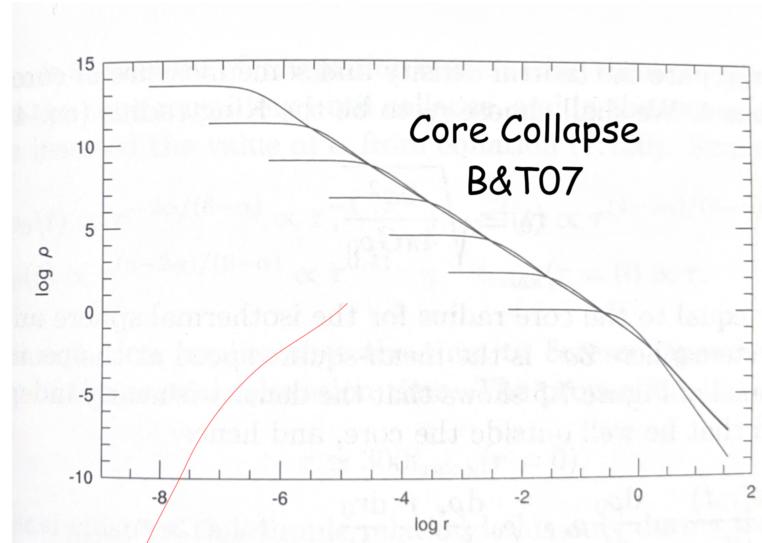
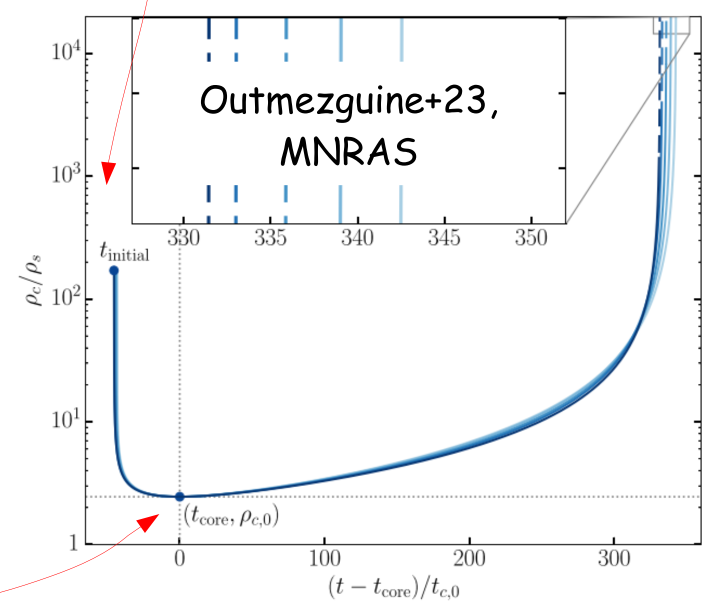






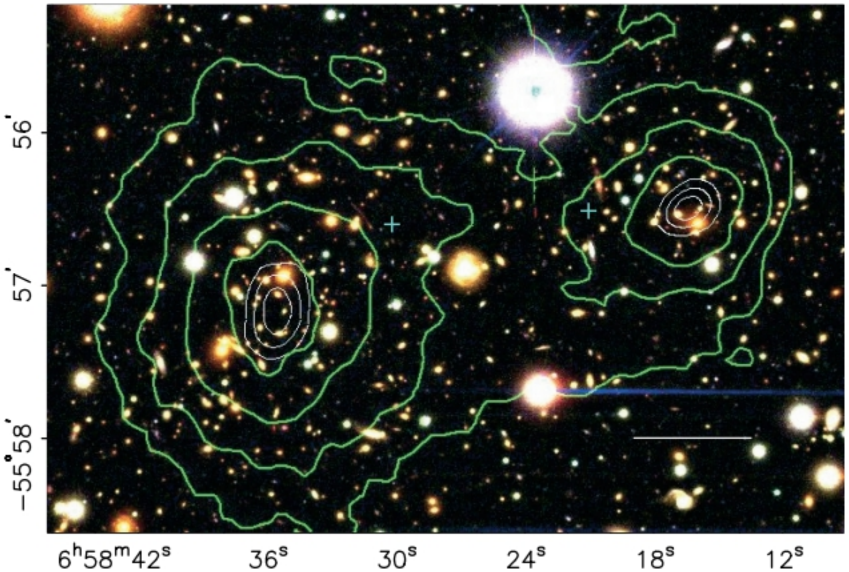
$$14.4\,\mathrm{cm^2g^{-1}} \le \frac{\sigma_{c,0}}{m_{dm}} \le 72.1\,\mathrm{cm^2g^{-1}},$$

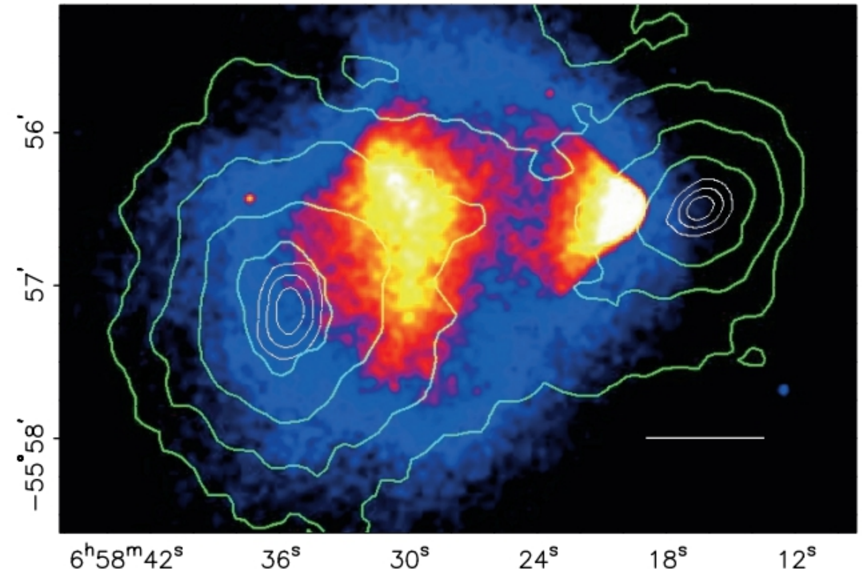
SA+24, in prep

Thermodynamic Equilibrium

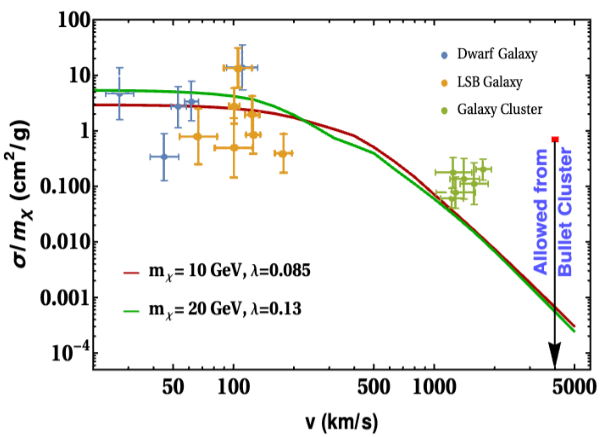
$$t_{c,0} \simeq 1.5\ \mathrm{Gyr}\,\frac{0.6}{C}\,\frac{\mathrm{cm^2g^{-1}}}{\sigma_{c,0}/m_{dm}}\,\frac{100\,\mathrm{km\,s^{-1}}}{V_{max}}\,\frac{10^7 M_\odot\,\mathrm{kpc^{-3}}}{\rho_s}$$

One expects a large dependence on the halo mass, e.g., the Bullet Cluster





Clowe+06, ApJL



$$\sigma \equiv \int \frac{d\sigma}{d\Omega} d\Omega = \frac{4\pi \alpha_\chi^2}{m_\chi^2 (m_\phi^2/m_\chi^2 + v^2)}.$$

e.g., Correa+22, MNRAS

e.g., Ghosh+22, JCAP

Take-home message

$\Lambda CDM \rightarrow \Lambda \not{C} DM$

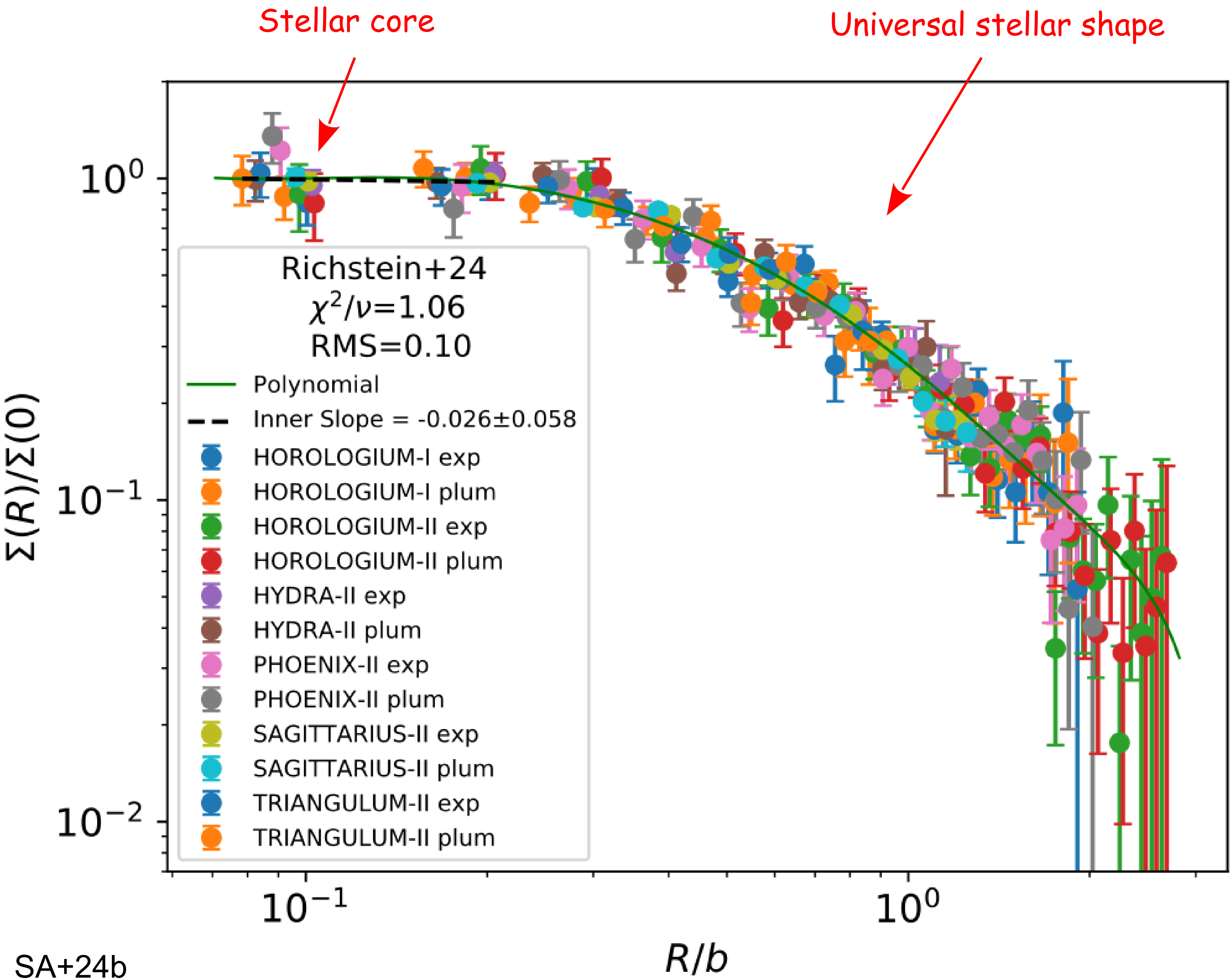
1.- The stellar feedback cannot thermalize DM halos with stellar mass < 10^5 $M_{\odot}$ (HUGs)

2.- Halo shape diagnostic in the HUG regime, nearly impossible from kinematics but doable from photometry using EIM (Eddington Inversion Method)

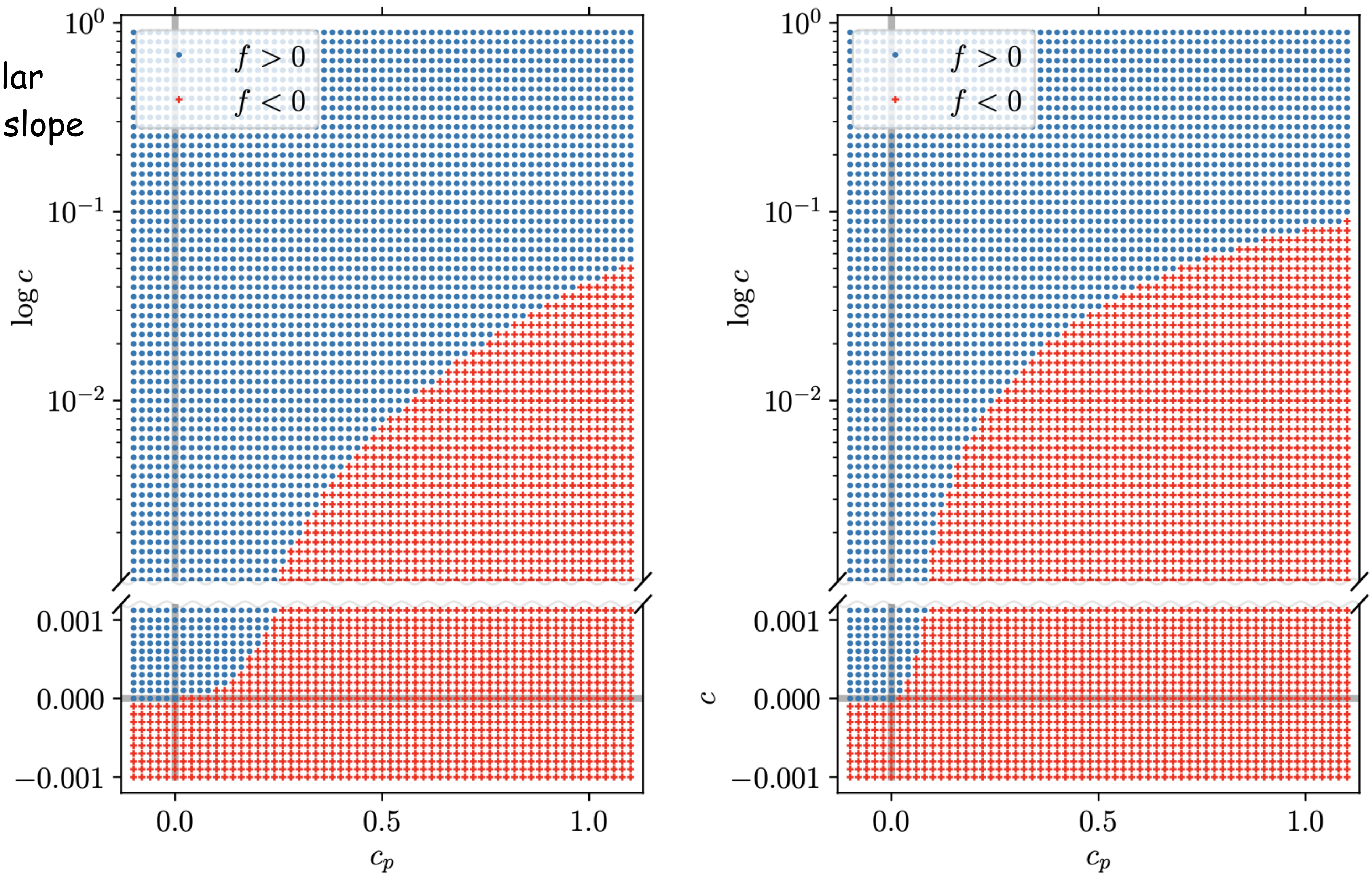
3.- Through the EIM, we know a stellar distribution with a "core" cannot be in a Cold Dark Matter potential (NFW-like).

4.- A number of Ultra Faint Dwarf UFD galaxies have cores, inconsistent with NFW potentials. Since their stellar mass is well within the HUGs range (10^3--10^4 $M_{\odot}$) **the existence of these core suggests the need to go beyond CDM** (SIDM, fermion DM, fuzzy DM, warm ...)

5.- Please, **help up working out** the **actual physical constraints** on the physical models of DM


Stellar core
Universal stellar shape
Richstein+24
χ^2/ν=1.06
RMS=0.10
Polynomial
Inner Slope = -0.026±0.058
HOROLOGIUM-I exp
HOROLOGIUM-I plum
HOROLOGIUM-II exp
HOROLOGIUM-II plum
HYDRA-II exp
HYDRA-II plum
PHOENIX-II exp
PHOENIX-II plum
SAGITTARIUS-II exp
SAGITTARIUS-II plum
TRIANGULUM-II exp
TRIANGULUM-II plum
10^0
10^{-1}
10^{-2}
$\Sigma(R)/\Sigma(0)$
R/b
SA+24b

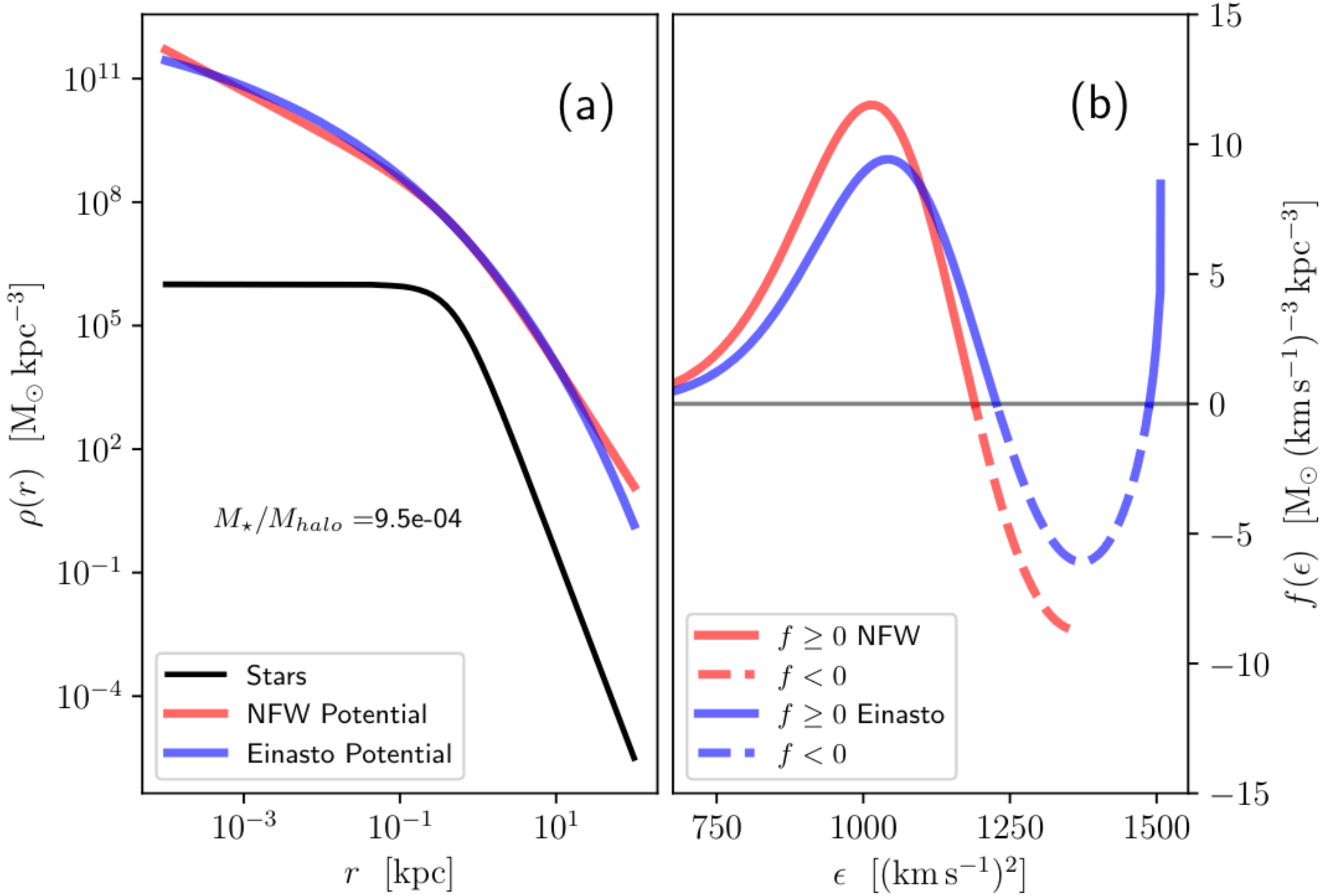
Stellar inner slope



Potential inner slope

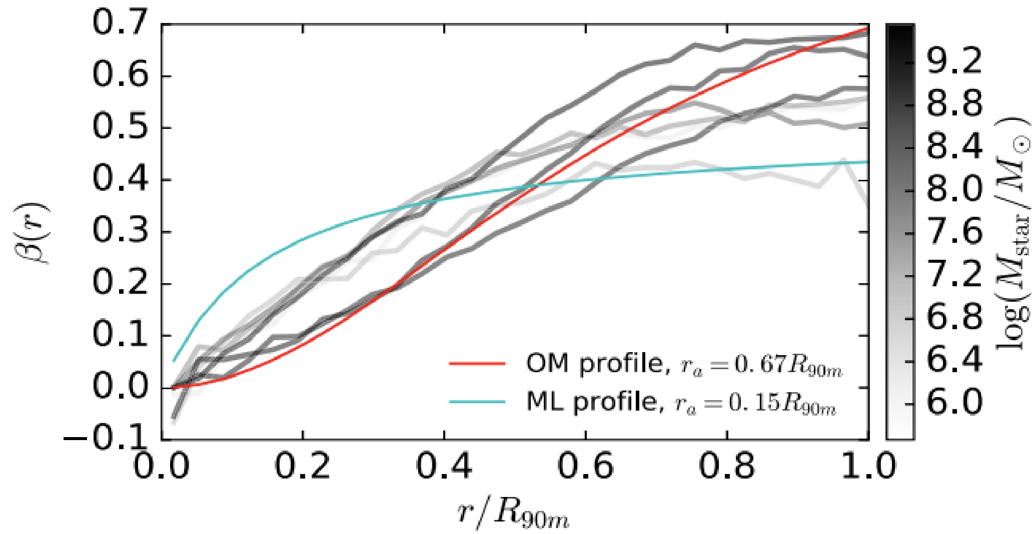
SA+23a, ApJ, 954, 153

SA 24, RNAAS



Einasto potentials are also good representation of CDM halos but they do not diverge when r->0. Cored stellar distributions are inconsistent with Einasto CDM halos.

How good or bad are these assumptions? Isotropic velocities and the like

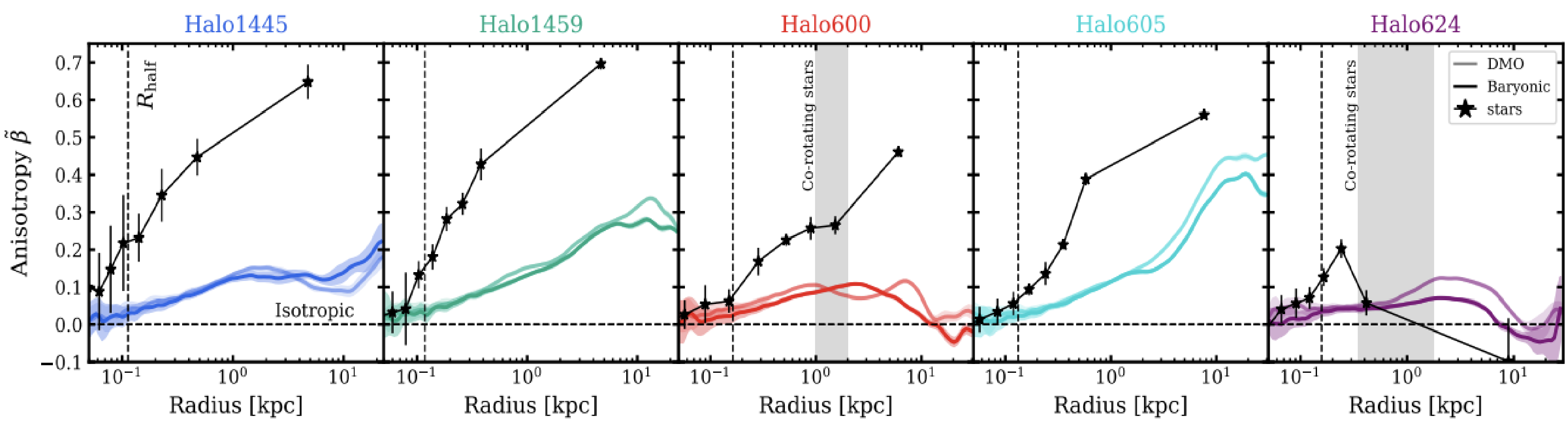


FIRE numerical simulation (El-Badry+17, ApJ)

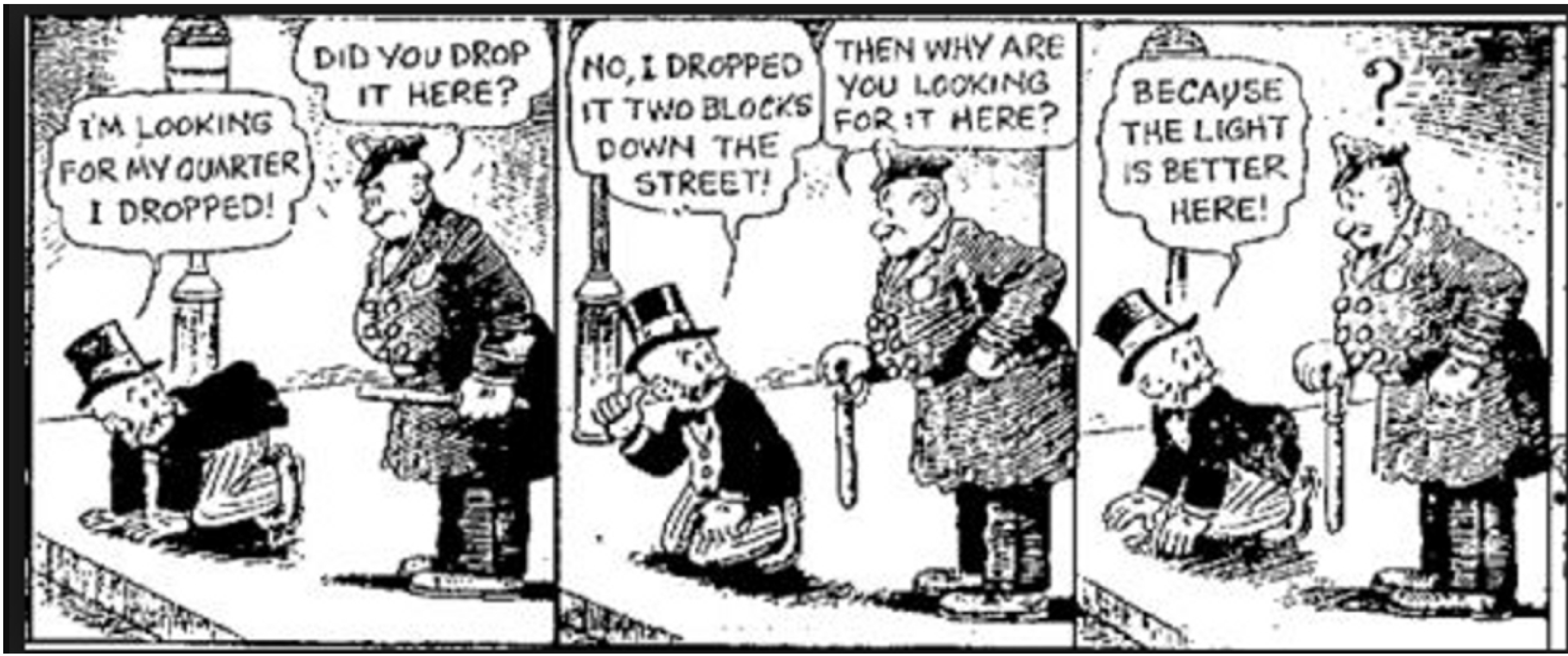
$$\beta(r) = 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2},$$

β = 0 Isotropic orbits

β > 0 Radially biased orbits



EDGE numerical simulations (Orkey+23, MNRAS)



StreetLight effect illustrates our searches for DM …