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

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Unión Europea
Fondo Europeo de desarrollo Regional
“Una manera de hacer Europa”

(Fornax Dwarf - ESO)

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Based on Various Papers:

- SA+20, A&A, 642, L14
- SA+23, ApJ, 954, 153
- SA 24a, RNAAS, 8, 167
- SA+24b A&A, 690A, 151
- SA+24c, ApJL, 973, L15
- SA+25, A&A, 694A, 283
- SA 25, in prep.

Outline

1.- Motivation & Rationale

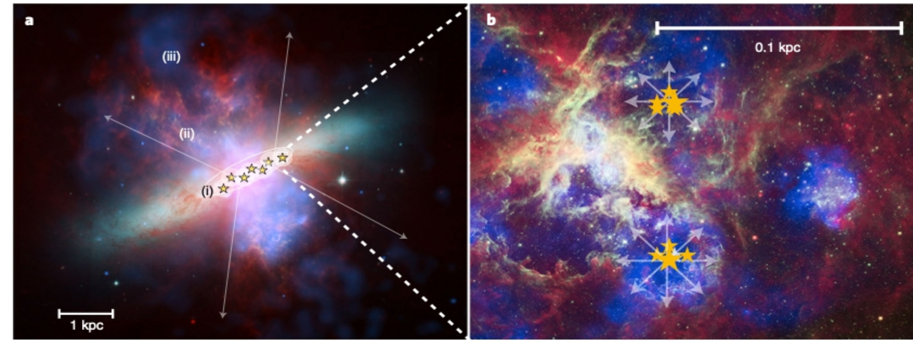
2.- Eddington Inversion Method (EIM) comes to help

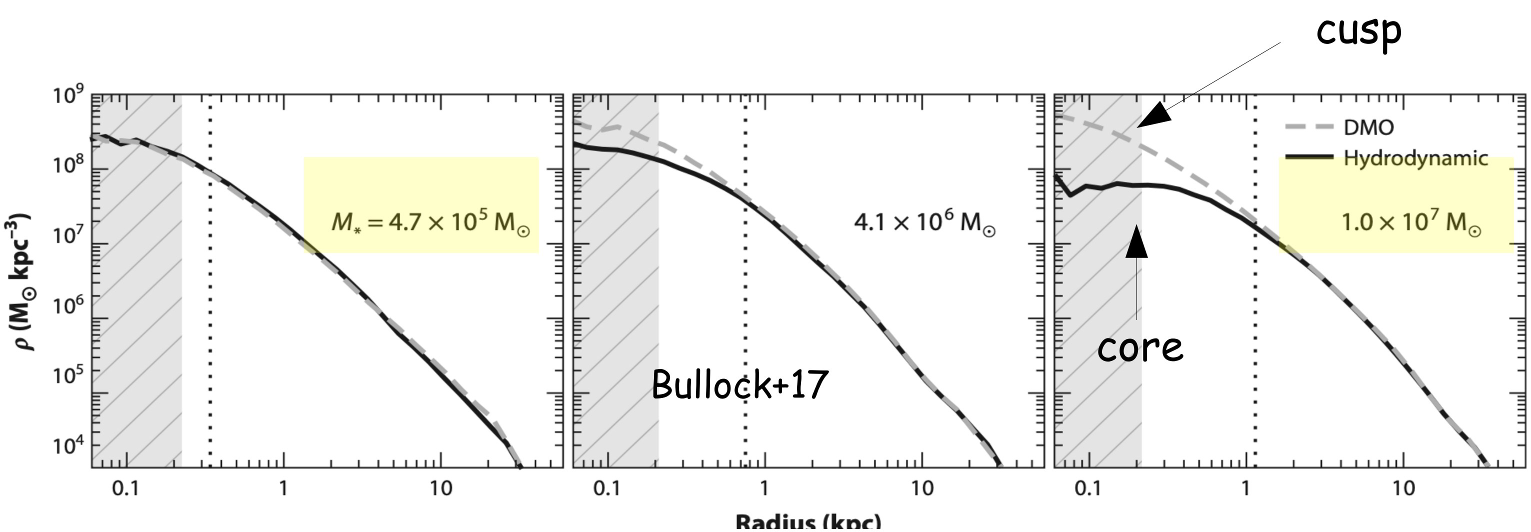
3.- Ultra Faint Dwarfs challenge the Cold Dark Matter paradigm

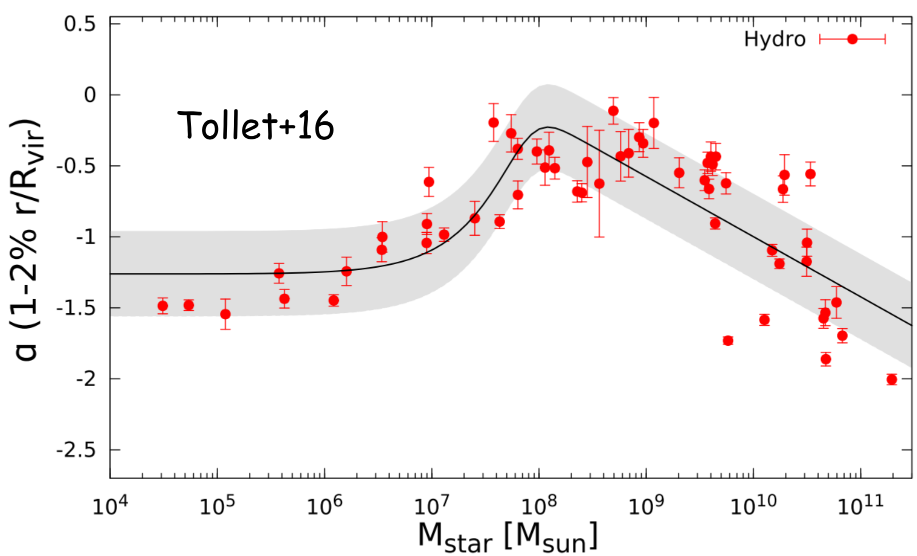
4.- Constraints from UFDs if the DM were SIDM

5.- Take-home message

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., Peñarrubia+12)

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.

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

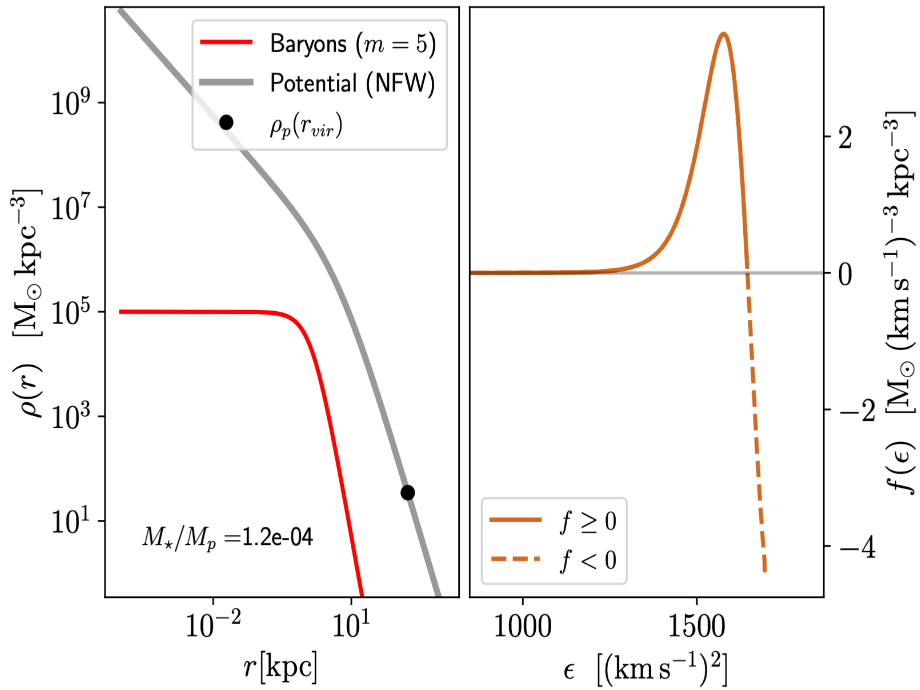
$\epsilon = \Psi - \frac{1}{2}v^2$ is the relative energy

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

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).

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

A cored stellar ρ(r) is inconsistent with a cuspy CDM Ψ(r)



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+24b, SA25):

- holds for quasi-cores embedded in quasi-NFW potentials

- holds for Einasto profiles (not singular as r--> 0)

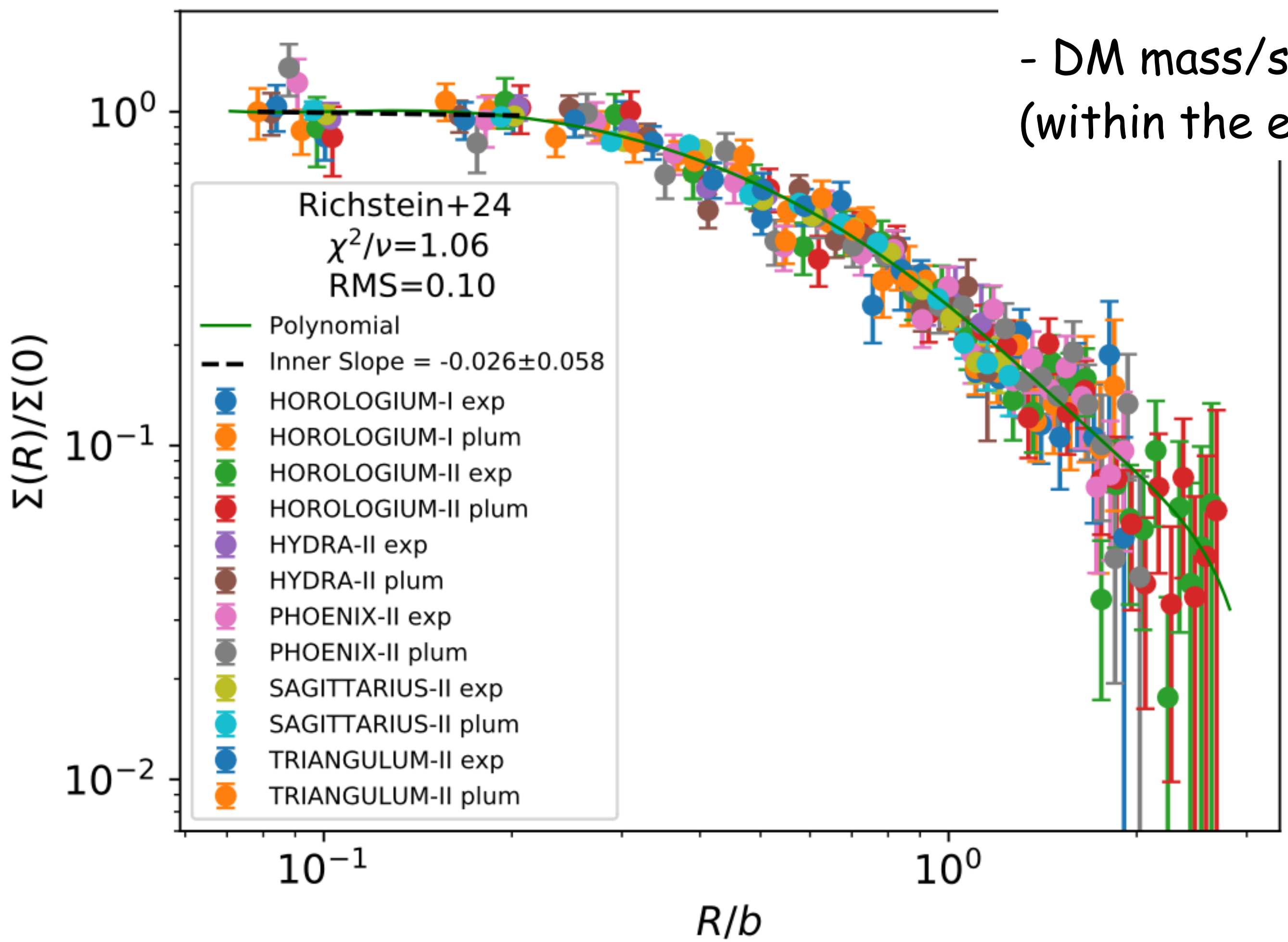
- holds for non-spherical axi-symmetric systems.

- holds for radially biased orbits and Opsikov-Merritt kind of anisotropy (isotropic in the center turning radial in the outskirts)

- consistency requires strongly tangentially biased orbits

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)

3. EDDINGTON INVERSION METHOD APPROACH

SA+25, A&A

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,

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

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

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

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

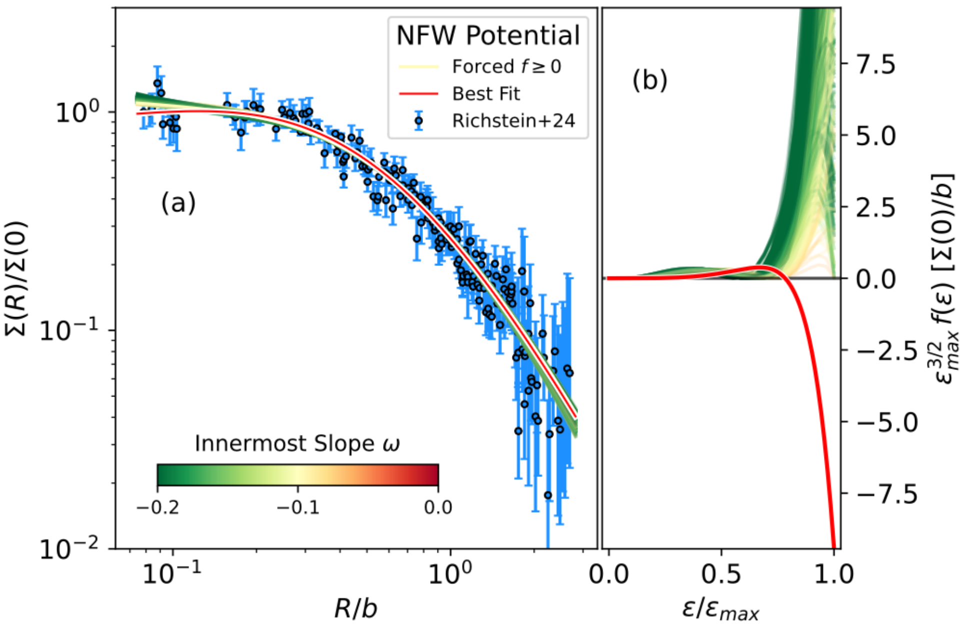
The free parameter of the fit is the shape of the distribution function

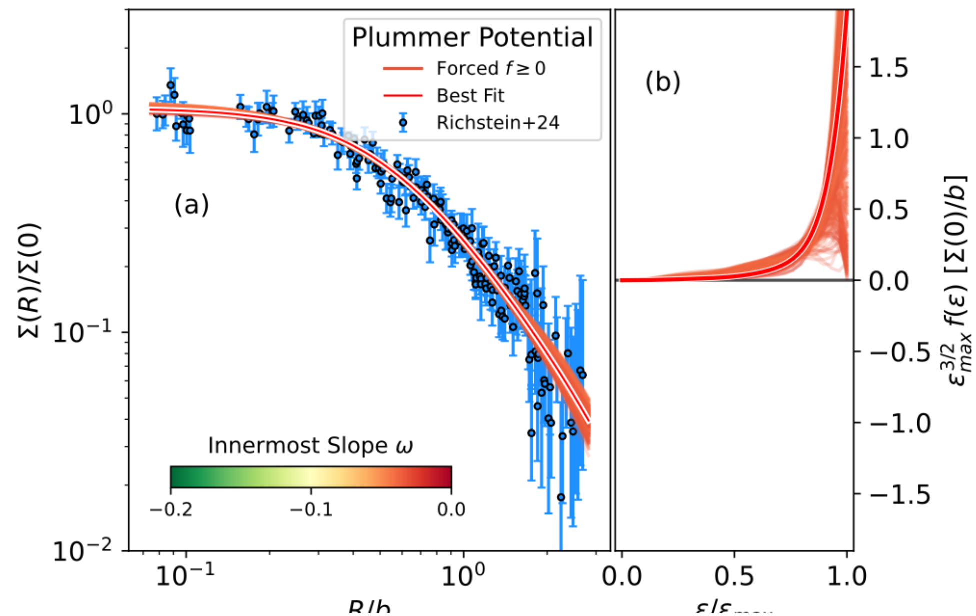
with $\alpha = \epsilon/\epsilon_{max}$. Equation (7) gives a simple expansion of the stellar density $\rho(r)$ in terms of potential-dependent but known functions $F_i(r)$. **The chosen functional form in Eq. (6) is both flexible and, by starting at $i = 3$, it describes a system of finite mass despite** 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.,

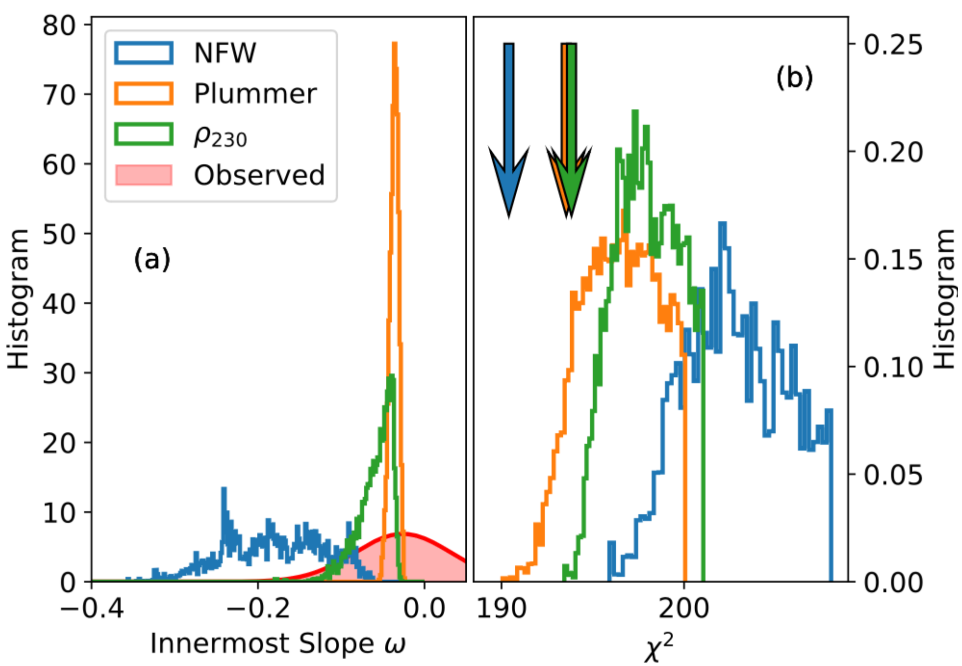
$$\Sigma(R) \simeq \sum_{i=3}^{n} a_i\,S_i(R), \tag{9}$$

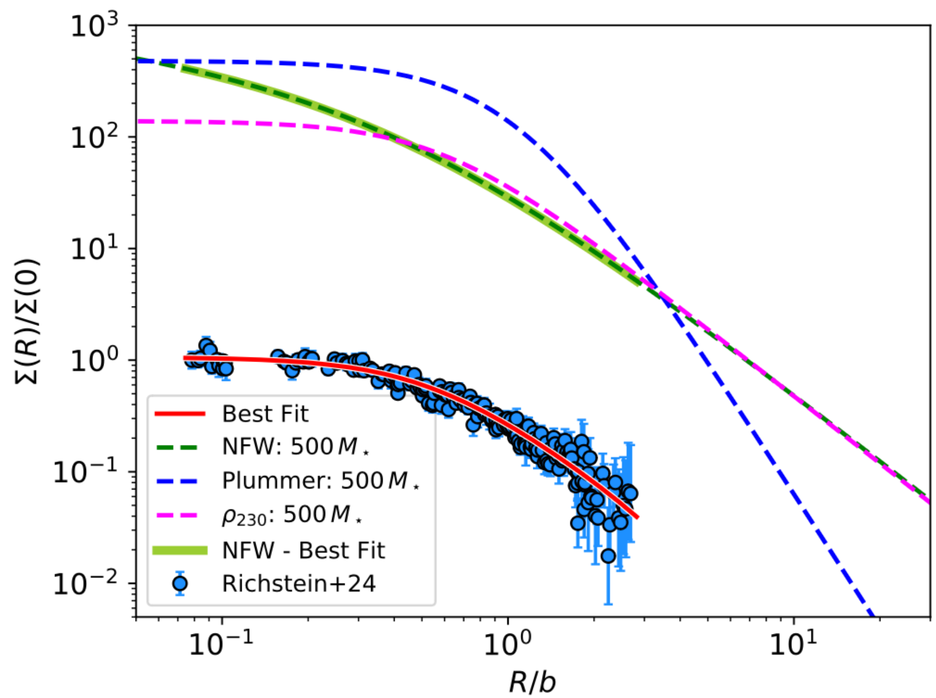
$$S_i(R) = \int_0^1 \alpha^i\,\frac{\xi_\Sigma(\alpha\epsilon_{max}, R)}{\sqrt{\epsilon_{max}}}\,d\alpha, \tag{10}$$

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?

- Spherical symmetry?

- Satellites?

- Shape of the potential?

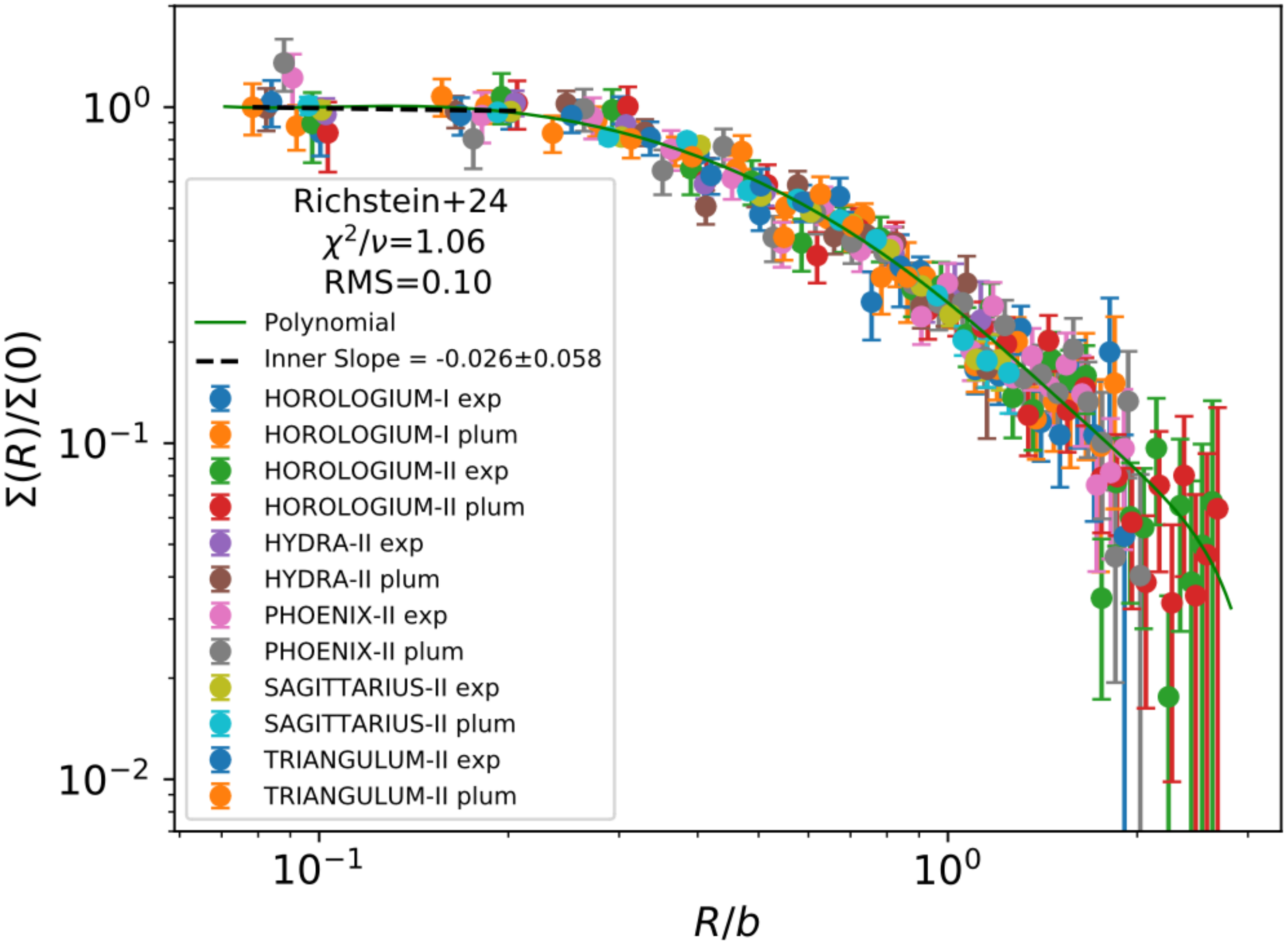
- Stellar feedback irrelevant?

- Is stellar self-gravity negligible?

- Centers and observed ellipticities are a problem?

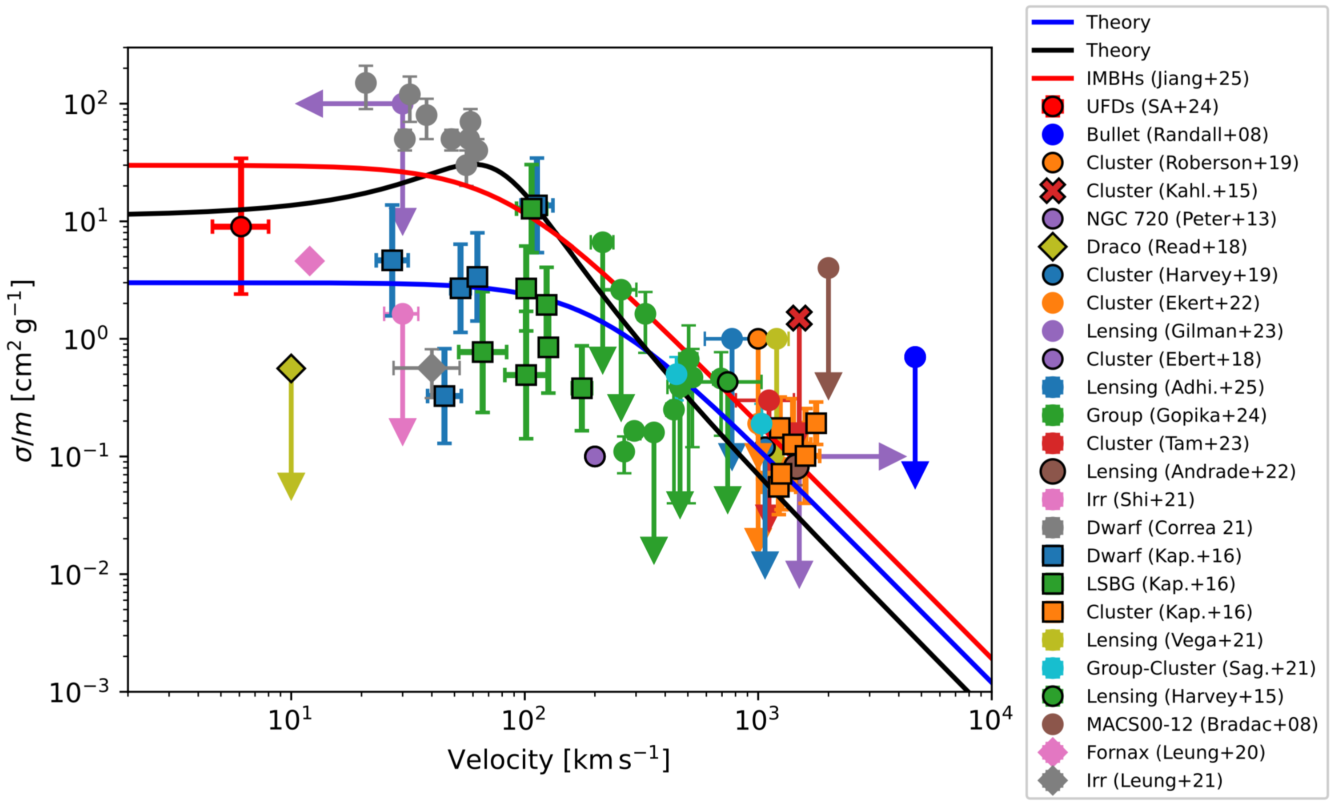
NO PROBLEM

Thus, the stellar distribution in UFDs is incompatible with cuspy CDM potentials and so it suggests the DM to deviate from the Collision-less Cold Dark Matter paradigm … e.g, **SIDM?**



SA+24, ApJL

Constraints from UFDs if the DM were SIDM



core formation timescale < age < core collapse timescale

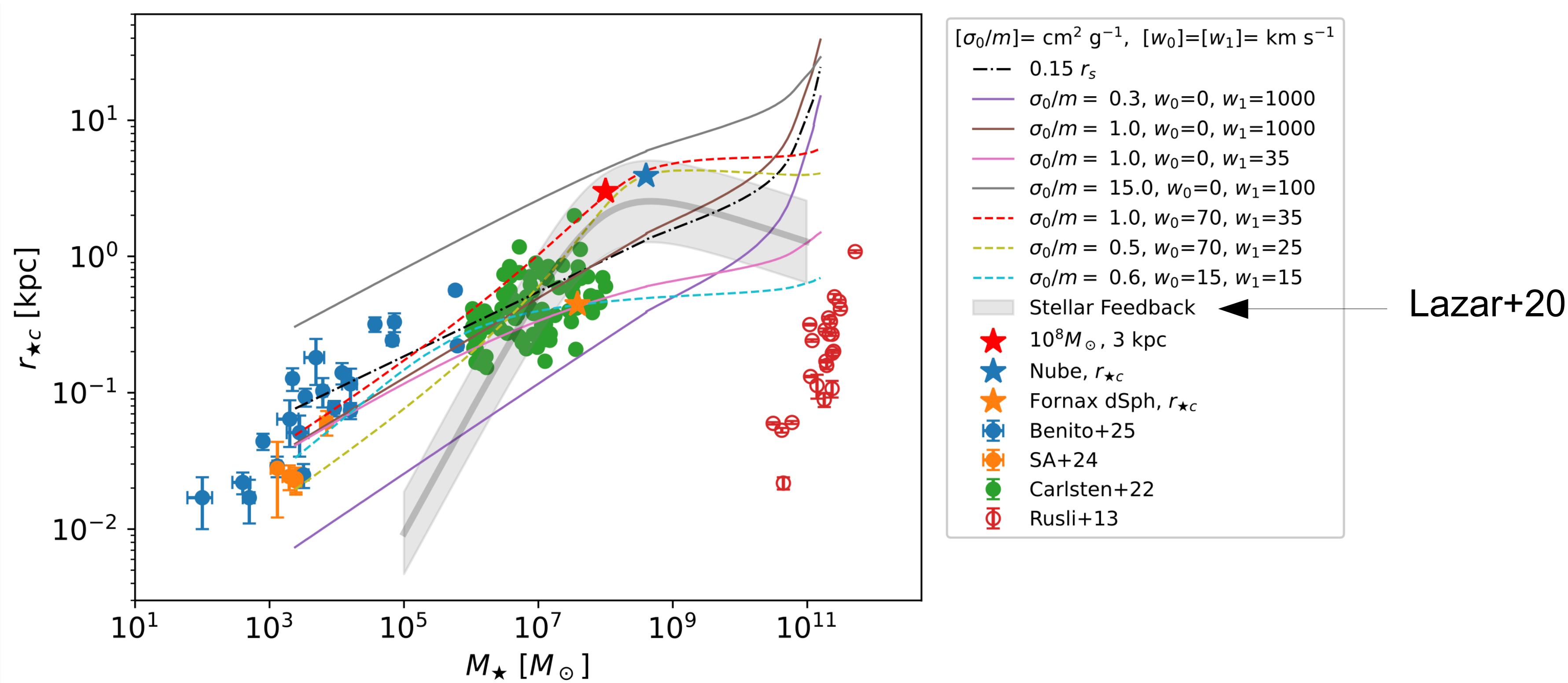
Outmezguine+23, MNRAS

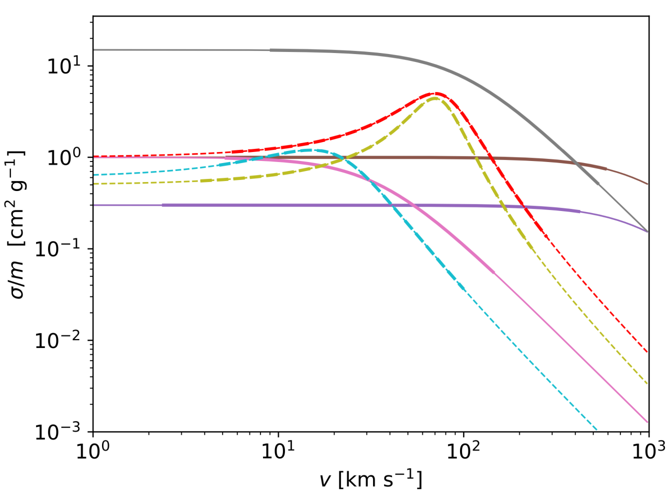
$$t_c \leq \beta_{age}\, t_H \leq t_{cc}, \qquad \sigma_H/m \leq \sigma/m \leq 8.5\, \sigma_H/m,$$

$$\sigma_H/m = 1.84\,\mathrm{cm^2 g^{-1}}\, \frac{t_H}{t_c}\, \frac{0.6}{C} \left[\frac{44\, M_\odot\, \mathrm{pc}^{-2}}{\rho_c(t_c)\, r_c(t_c)}\right]^{3/2} \left[\frac{r_c(t_c)}{50\,\mathrm{pc}}\right]^{1/2},$$

SA+25, in prep

SA+25, in prep





" r_{te} " is the radius where thermalization has been reached

$$t_{age} \simeq \frac{1}{\rho_{\rm NFW}(r_{te})\, v_{\rm NFW}(r_{te})} \frac{1}{[\sigma/m](v_{\rm NFW}(r_{te}))},$$

$$v^2_{\rm NFW}(r) = G M_{\rm NFW}(<r)/r,$$

$$M_{\rm NFW}(<r) = 4\pi\rho_s r_s^3 \left[\ln(1 + r/r_s) - \frac{r/r_s}{1 + r/r_s}\right].$$

$$r_c \simeq r_{te}/2, \qquad M_\star = M_\star(M_h).$$

$$\frac{\sigma}{m}(v) = \frac{\sigma_0}{m} \frac{1 + w_0^2/w_1^2}{1 + [v - w_0]^2/w_1^2},$$

Take-home message

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

2.- Halo shape diagnostic in the HUG regime 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.- Interpreted as produced by SIDM, these cores require

$$\sigma/m \approx 2\ \mathrm{cm}^2/\mathrm{g} \text{ and } 30\ \mathrm{cm}^2/\mathrm{g}.$$

… work in progress, though. Help to improve it welcome!

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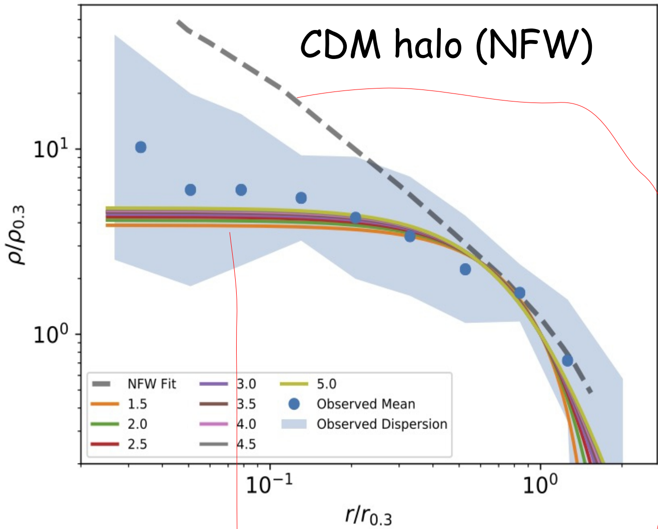
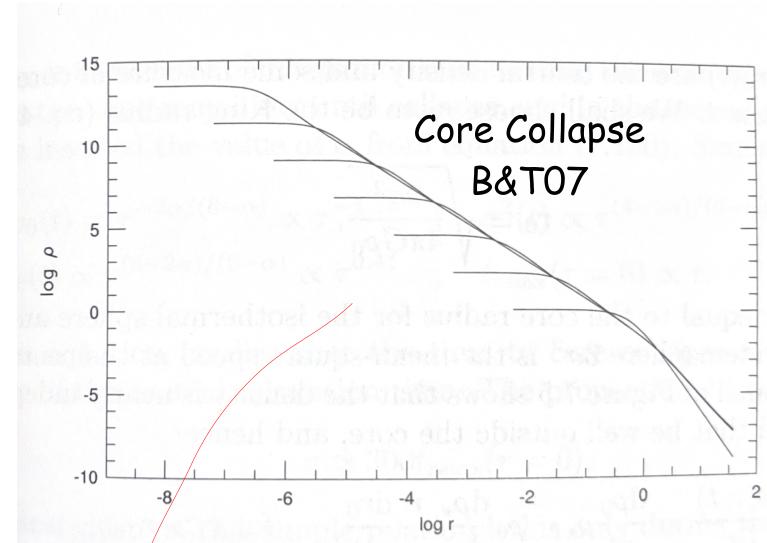
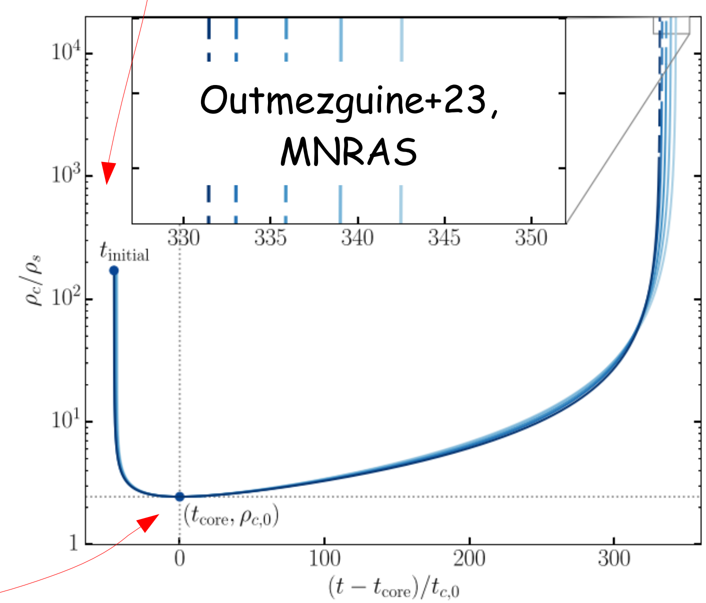
Valencia SIDM, 2025


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







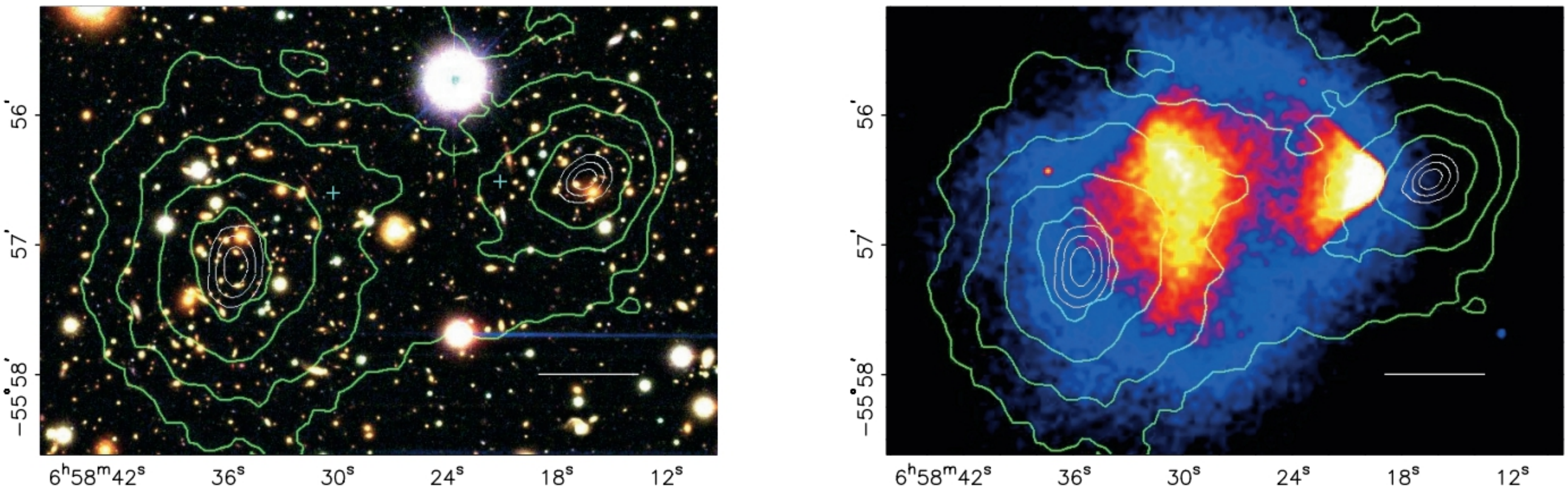
$$14.4\,\mathrm{cm^2g^{-1}} \leq \frac{\sigma_{c,0}}{m_{dm}} \leq 72.1\,\mathrm{cm^2g^{-1}},$$

SA+25, in prep

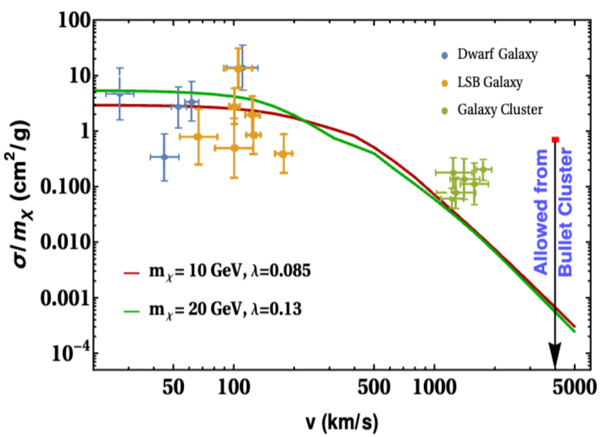
Thermodynamic Equilibrium

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

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



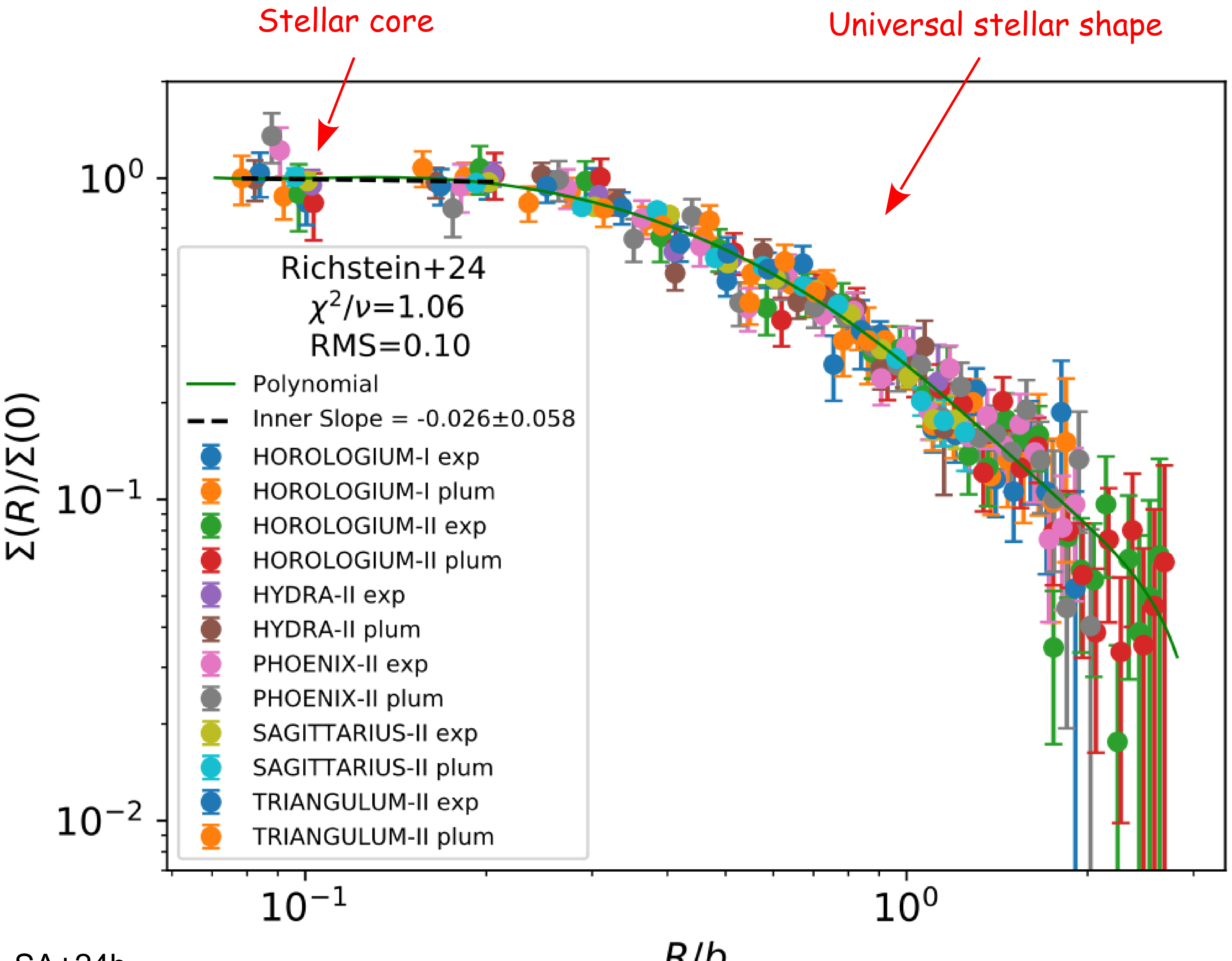
Clowe+06, ApJL



e.g., Ghosh+22, JCAP

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

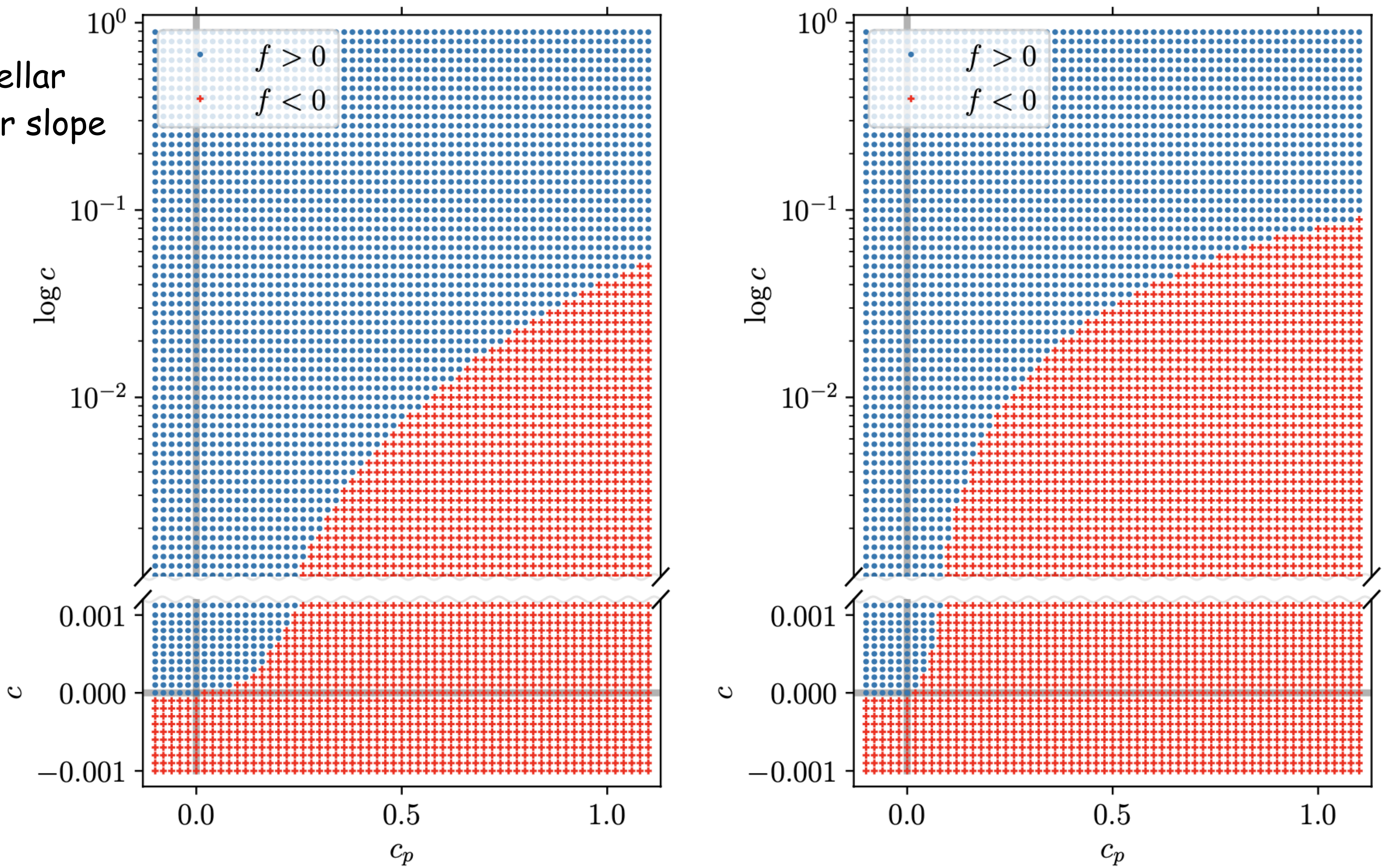
e.g., Correa+22, MNRAS



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
$\Sigma(R)/\Sigma(0)$
10^0
10^{-1}
10^{-2}
R/b

SA+24b

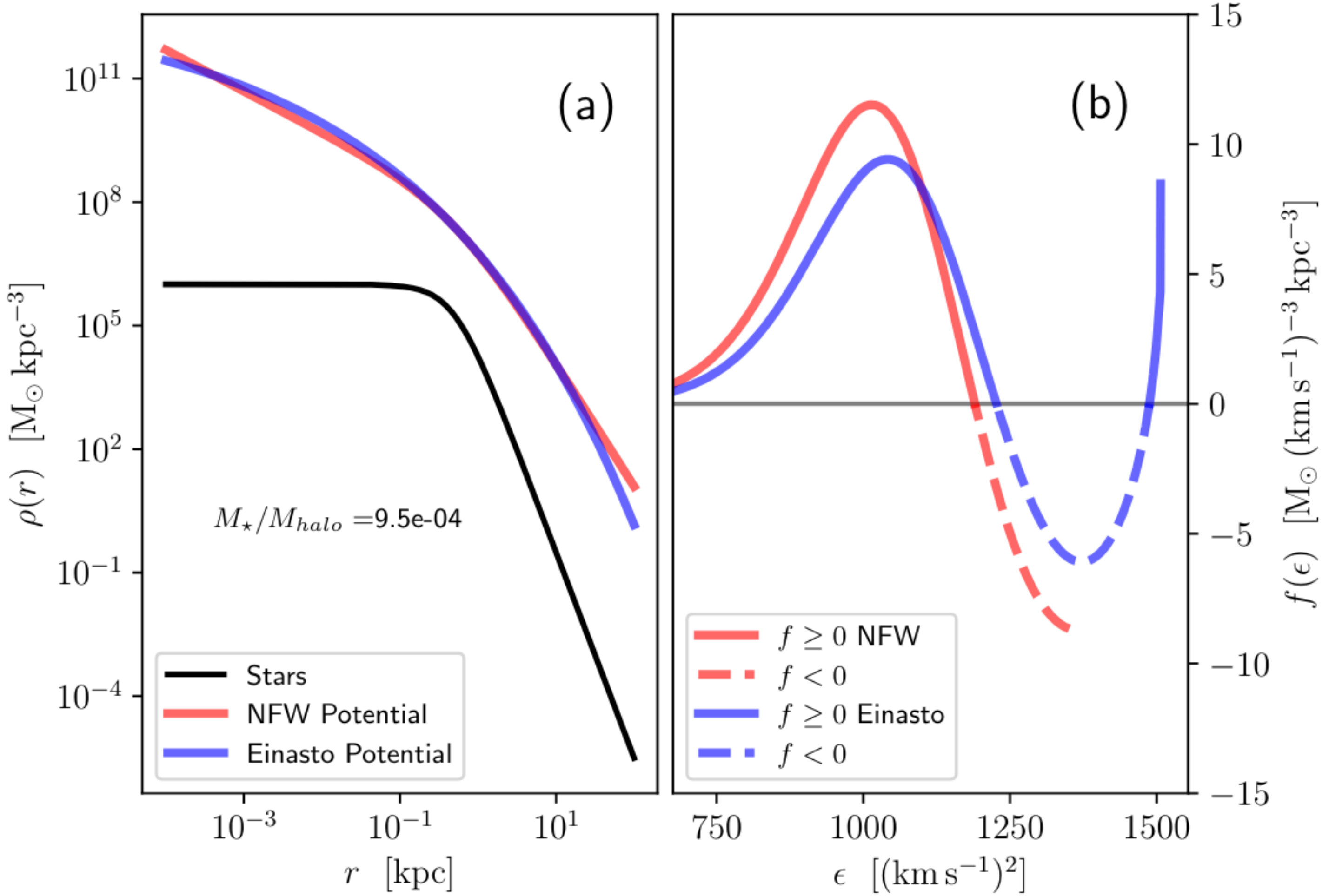
Stellar inner slope



Potential inner slope

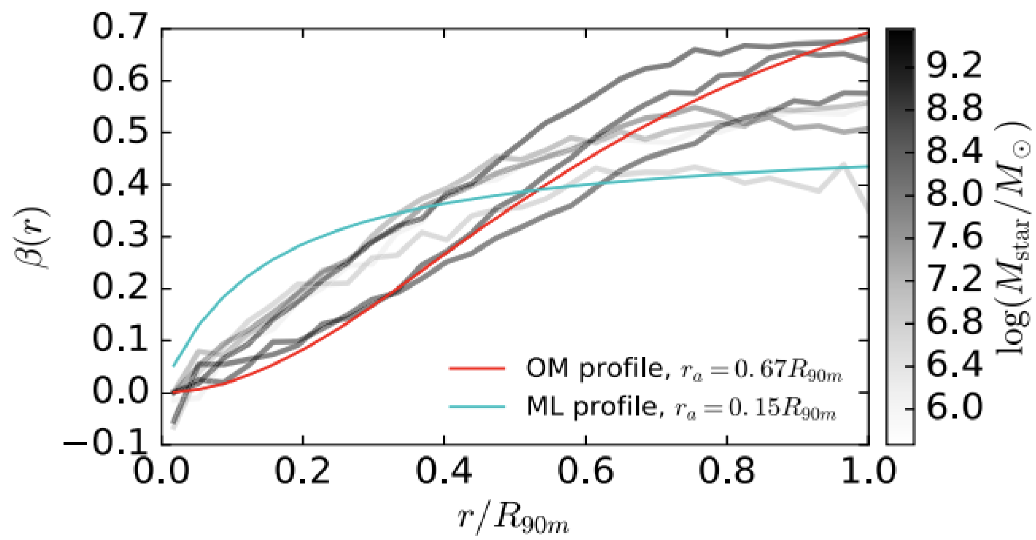
SA+23a, ApJ, 954, 153

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

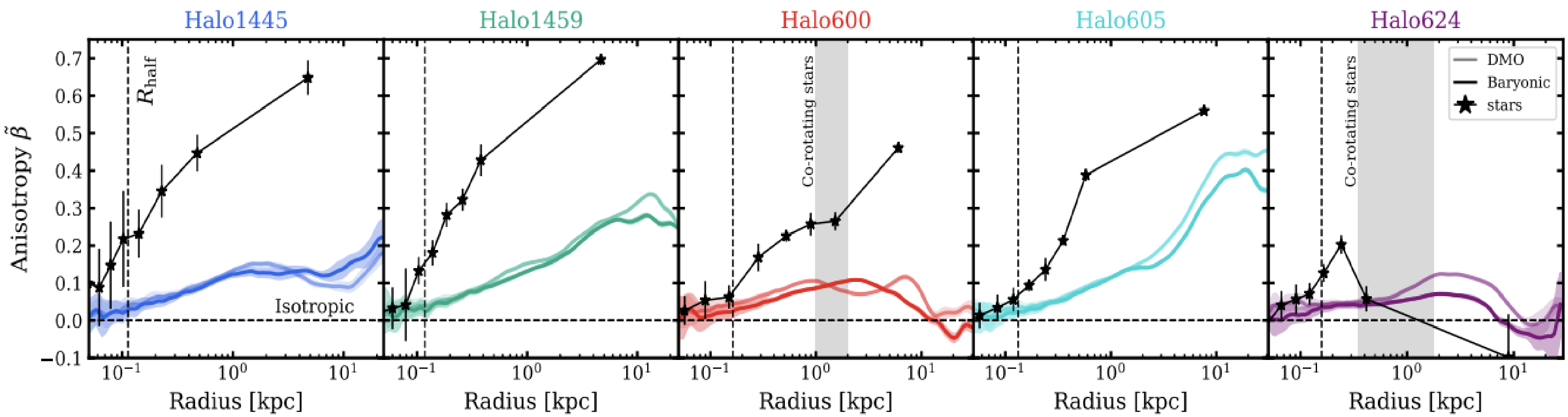


FIRE numerical simulation (El-Badry+17, ApJ)

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

β = 0 Isotropic orbits

β > 0 Radially biased orbits



EDGE numerical simulations (Orkey+23, MNRAS)

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+25)
- 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 maintain the inner NFW shape until disruption … (e.g., Errani+23)

- 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?

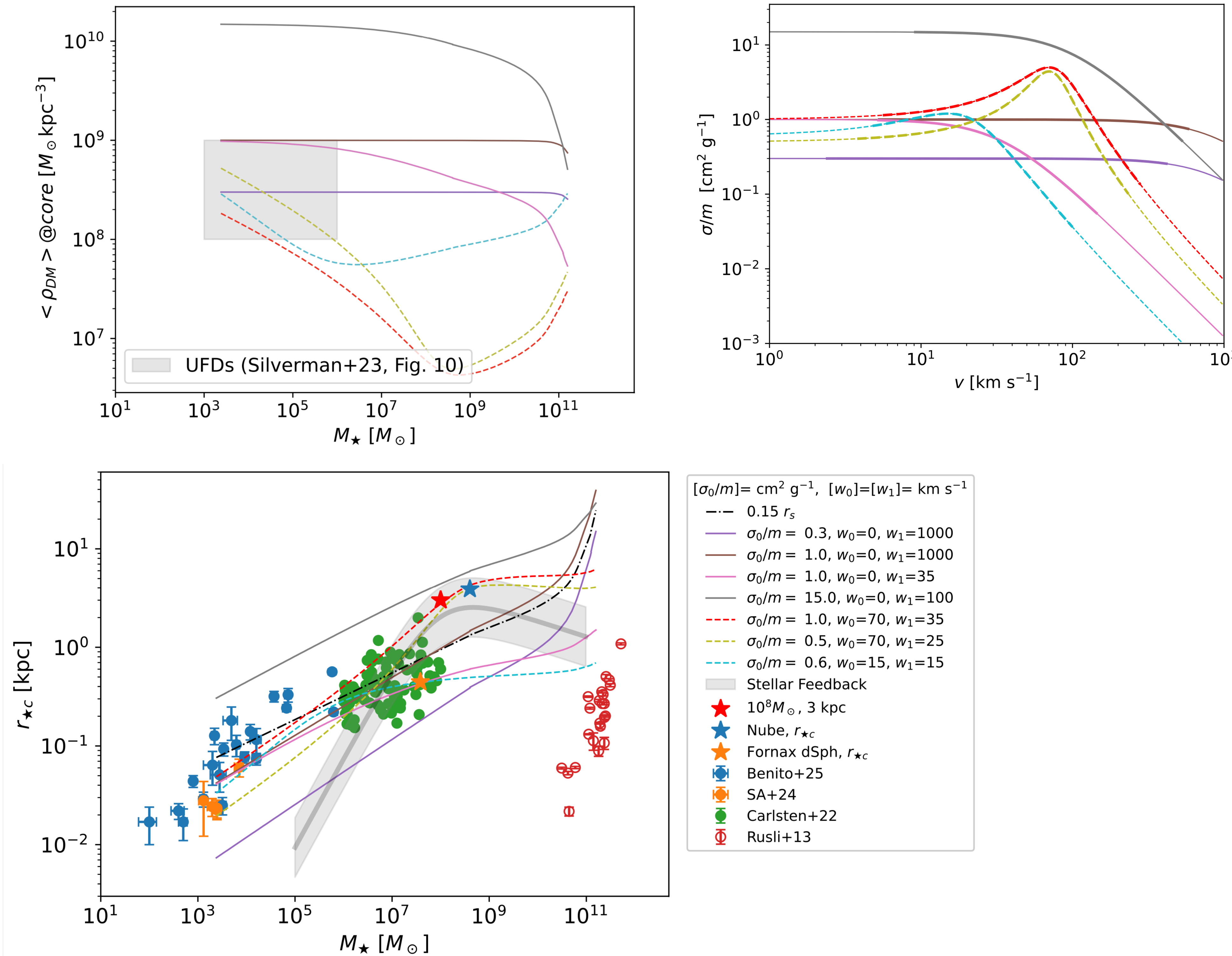
- Yes, at UDFs mass of $\sim 10^3$ - 10^4 $M_\odot$, feedback is unimportant quite independently of the actual modeling (e.g., Peñarubia+12)

- Is stellar self-gravity negligible?

- DM mass/stellar mass ~ 10^3

- Centers and observed ellipticities are a problem?

- Several independent trials



10^{10}
10^{9}
10^{8}
10^{7}
$< \rho_{DM} >$ @core $[M_\odot \, \mathrm{kpc}^{-3}]$
UFDs (Silverman+23, Fig. 10)
10^1
10^3
10^5
10^7
10^9
10^{11}
$M_\star \; [M_\odot]$
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
$\sigma/m \; [\mathrm{cm}^2 \, \mathrm{g}^{-1}]$
10^0
10^1
10^2
10^3
v [km s^{-1}]
10^{1}
10^{0}
10^{-1}
10^{-2}
$r_{\star c}$ [kpc]
10^1
10^3
10^5
10^7
10^9
10^{11}
$M_\star \; [M_\odot]$
$[\sigma_0/m]$= cm^2 g^{-1}, $[w_0]$=$[w_1]$= km s^{-1}
0.15 r_s
σ_0/m = 0.3, w_0=0, w_1=1000
σ_0/m = 1.0, w_0=0, w_1=1000
σ_0/m = 1.0, w_0=0, w_1=35
σ_0/m = 15.0, w_0=0, w_1=100
σ_0/m = 1.0, w_0=70, w_1=35
σ_0/m = 0.5, w_0=70, w_1=25
σ_0/m = 0.6, w_0=15, w_1=15
Stellar Feedback
$10^8 M_\odot$, 3 kpc
Nube, $r_{\star c}$
Fornax dSph, $r_{\star c}$
Benito+25
SA+24
Carlsten+22
Rusli+13