Funded by the European Union

Dark matter halo properties of the Sculptor dwarf spheroidal galaxy.

José María Arroyo-Polonio
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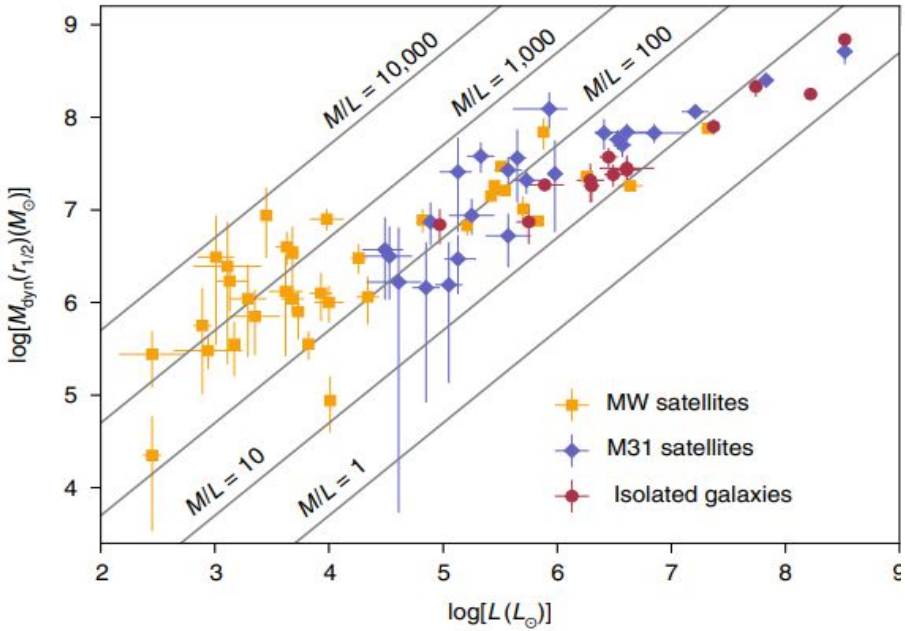
Carlo Nipoti
Eugene Vasiliev
Eline Tolstoy

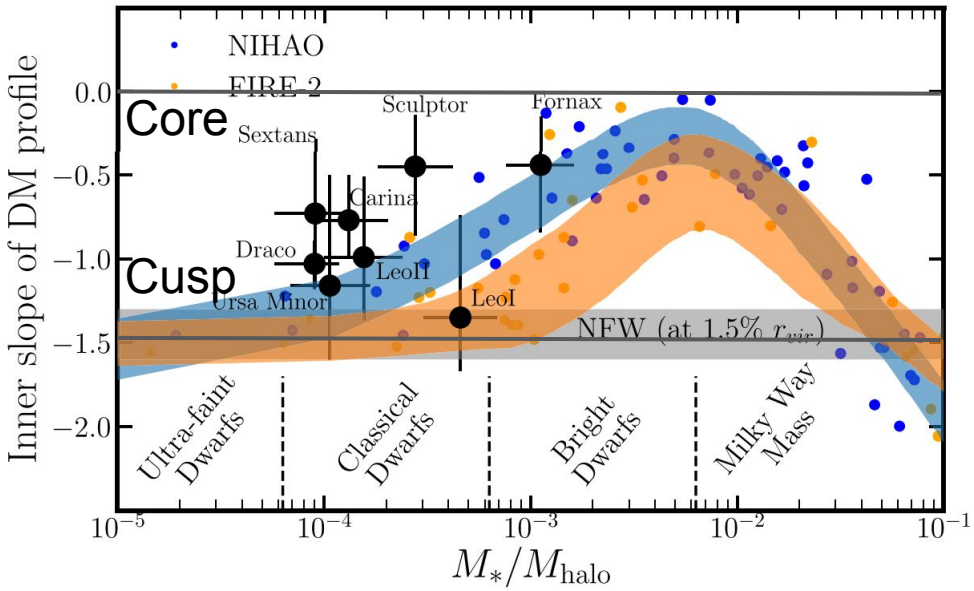
MPG/ESO 2.2. Release no. eso1536

Valencia Workshop on the Small-Scale Structure of the Universe and Self-Interacting Dark matter. (23/06/2025)

Dwarf galaxies as dark matter probes



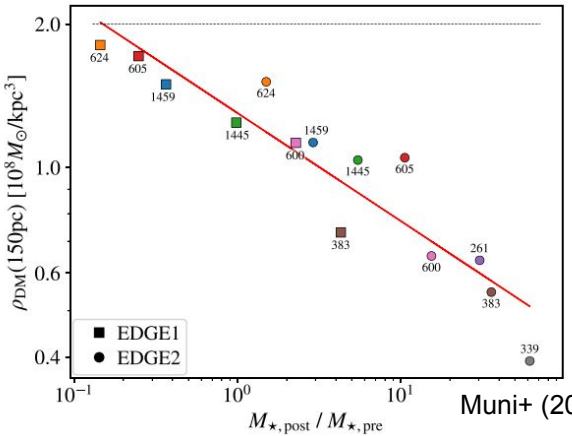
Mateo(1998), Walker(2012), Battaglia & Nipoti (2022)



Di Cintio+ (2014), Hayashi, Chiba and Ishiyama (2020)

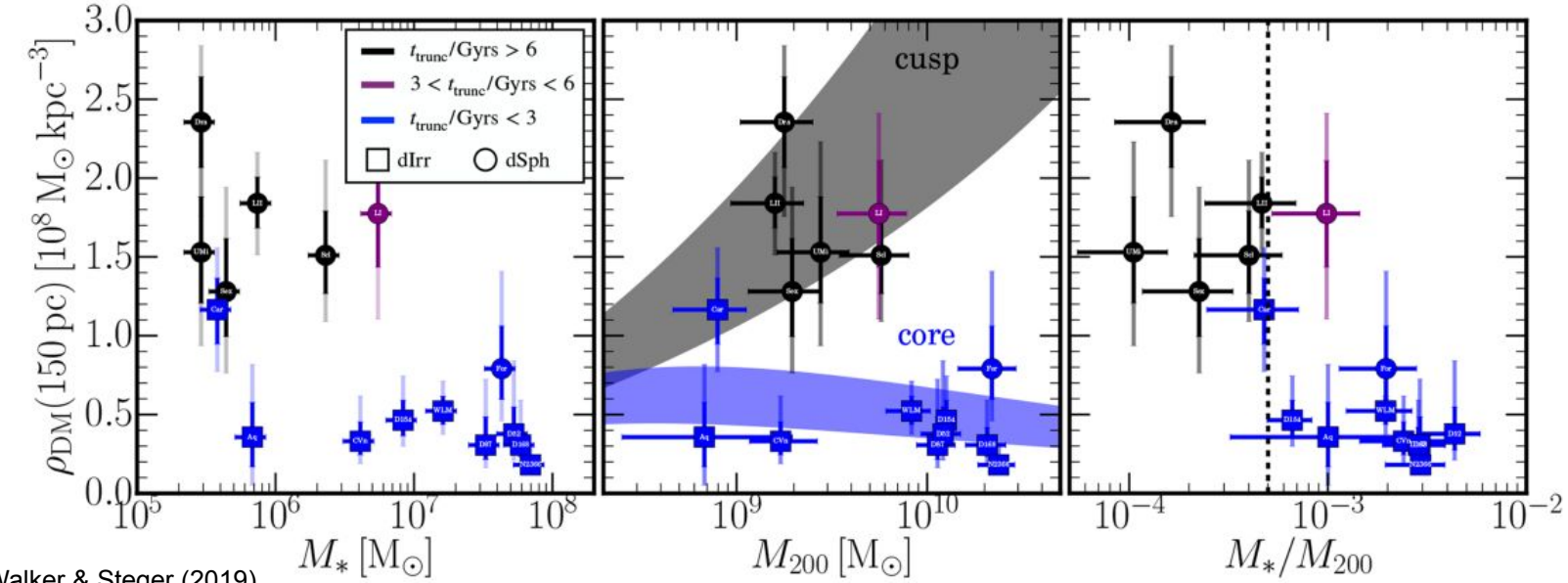
DGs can be used to test DM models / baryonic feedback implementations in a cosmological framework

Central density



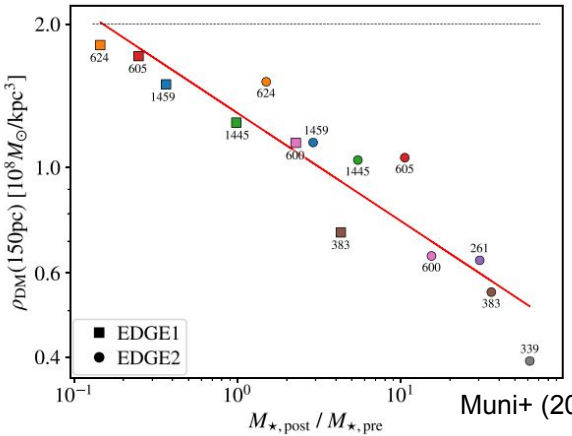
Muni+ (2025)

→ Relation between the central density and the star formation history



Read, Walker & Steger (2019)

Central density



Muni+ (2025)

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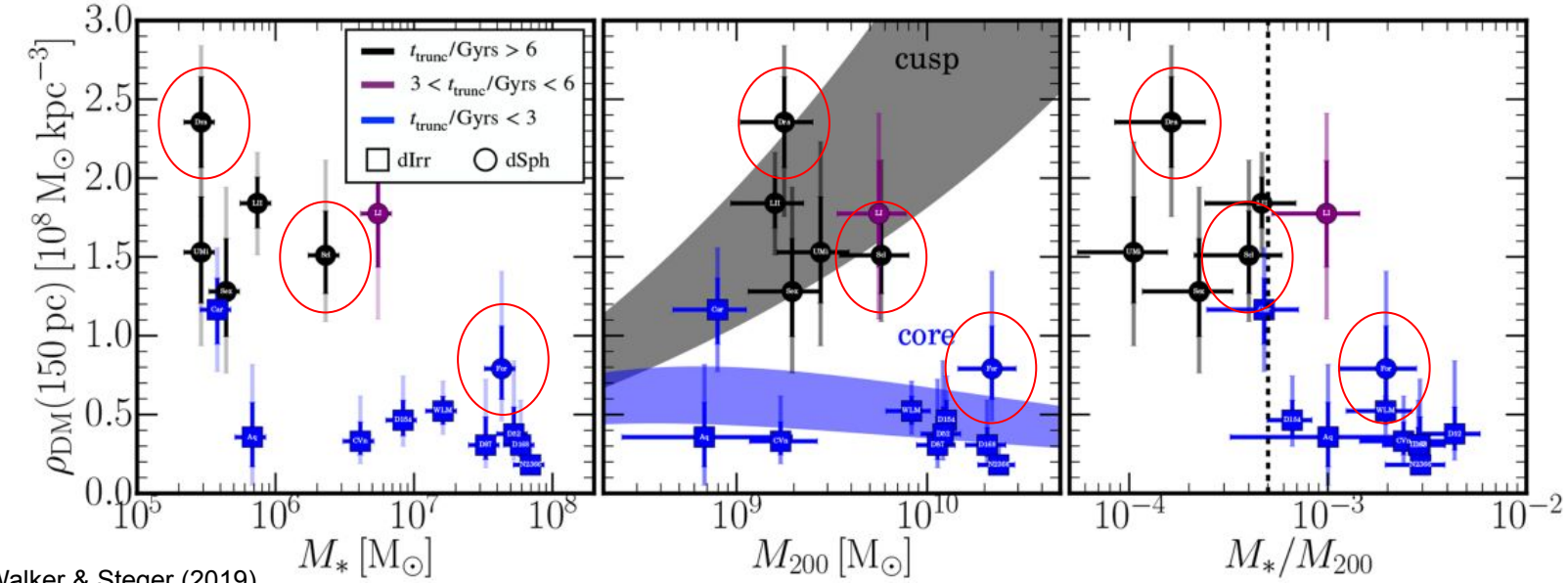
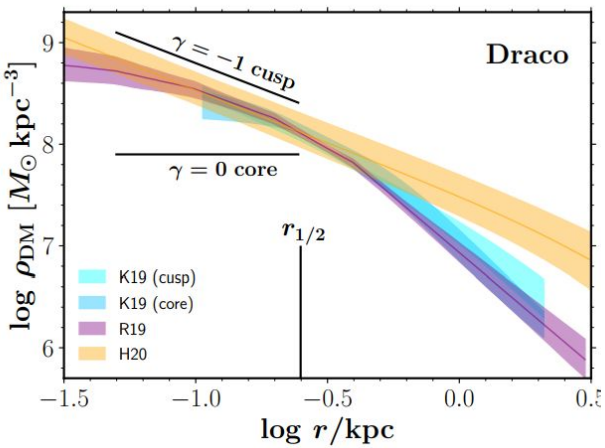


Read, Walker & Steger (2019)

DM density profiles in dwarf galaxies

Draco:

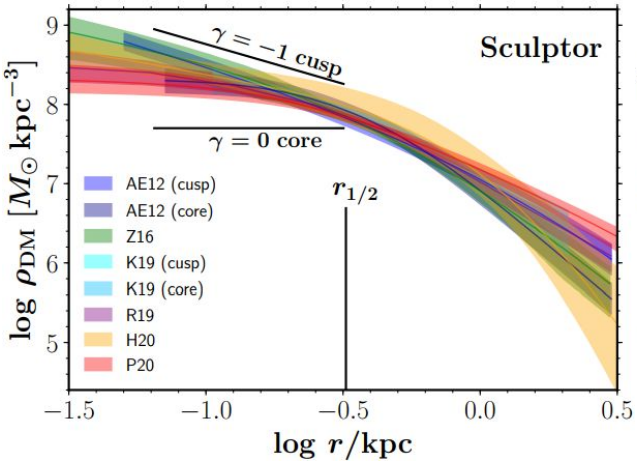
M/L = 53.7 $M_\odot/L_\odot$



Cusp

Sculptor:

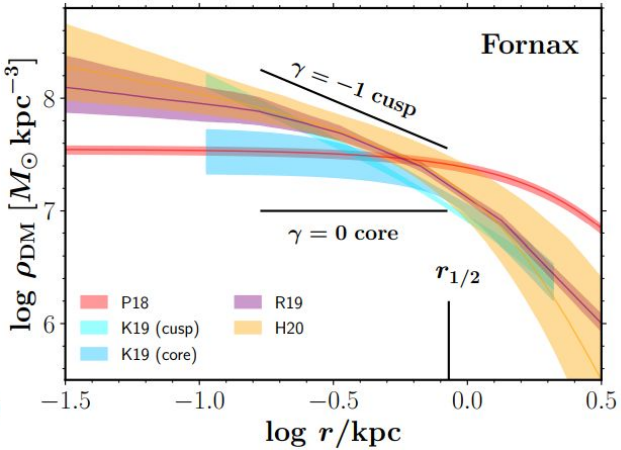
M/L = 12.58 $M_\odot/L_\odot$



?

Fornax:

M/L = 3.63 $M_\odot/L_\odot$



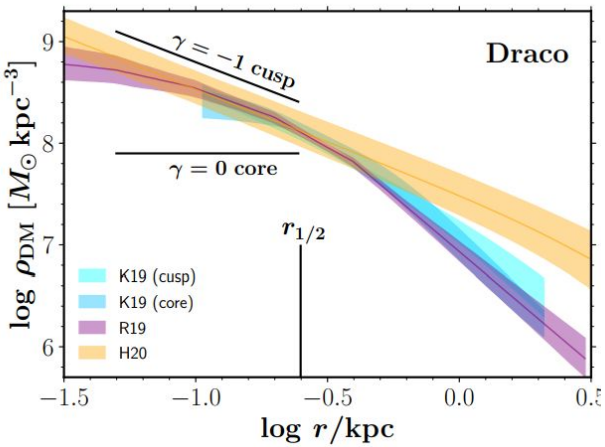
Core

Battaglia & Nipoti (2022)

DM density profiles in dwarf galaxies

Draco:

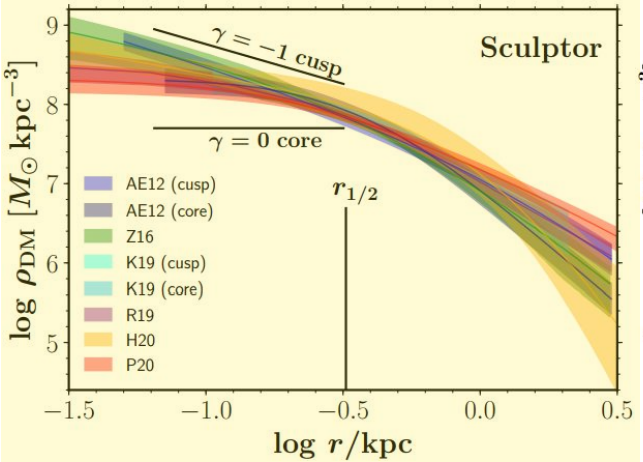
M/L = 53.7 $M_\odot/L_\odot$



Cusp

Sculptor:

M/L = 12.58 $M_\odot/L_\odot$



?

Fornax:

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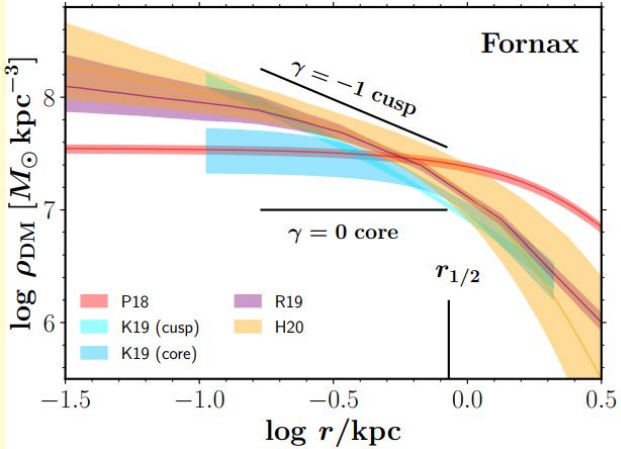


Core

Battaglia & Nipoti (2022)

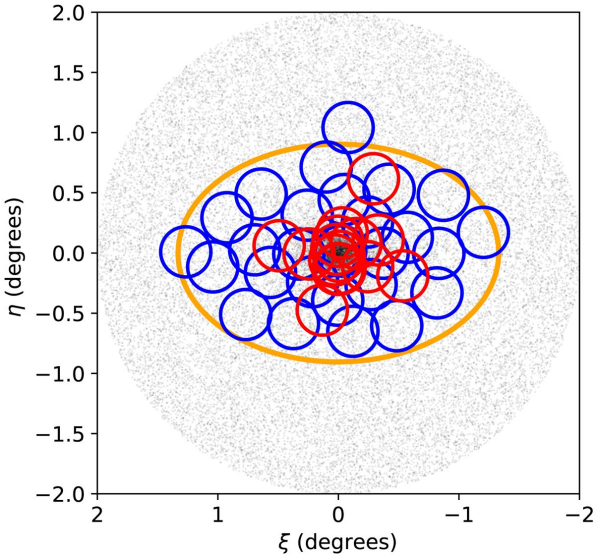
Data

A 3D view of dwarf galaxies with *Gaia* and VLT/FLAMES

I. The Sculptor dwarf spheroidal★,★★

Eline Tolstoy[1], Ása Skúladóttir[2,3], Giuseppina Battaglia[4,5], Anthony G. A. Brown[6], Davide Massari[7,1], Michael J. Irwin[8], Else Starkenburg[1], Stefania Salvadori[2,3], Vanessa Hill[9], Pascale Jablonka[10,11], Maurizio Salaris[12], Thom van Essen[1], Carla Olsthoorn[1], Amina Helmi[1], and John Pritchard[13]

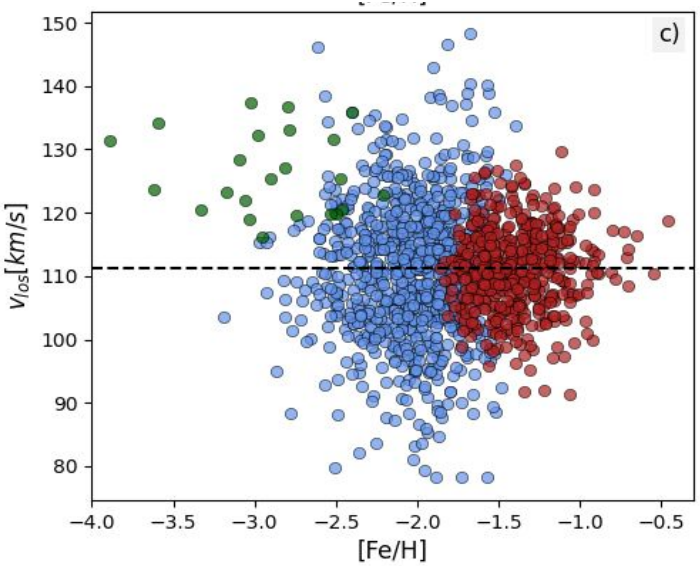
Received 18 December 2022 / Accepted 14 April 2023

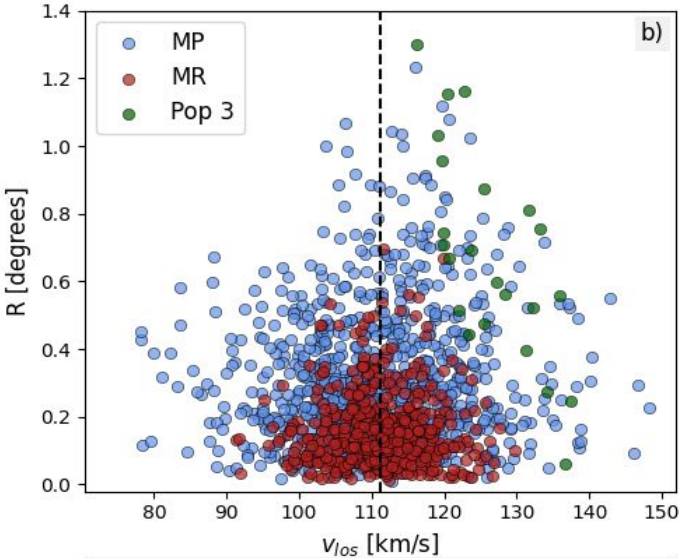


44 VLT/FLAMES pointings

- 1339 member stars
- Δ v_los ~ 1 km/s
- Δ [Fe/H] ~ 0.1 dex

Sculptor dwarf galaxy: stellar components





Tolstoy+(2004), Arroyo-Polonio+ (2024)

Different stellar populations can be used as independent tracers of the DM density profile.

Battaglia+(2008), Walker+(2011), Zhu+(2016), Strigari, Frenk & White(2017)

Dynamical modeling

$$\log(\mathcal{L}) = \sum_{i=1}^{N_{obs}} \log\left(\sum_{p=1}^{N_{pop}} \frac{f_p\, \omega(R_i, G_i)\, \mathcal{L}^p(\zeta_i)}{\int\int\int\int \omega(R, G)\, \mathcal{L}^p(\zeta)\, d^3\zeta dG} \right).$$

Selection function

- We fit individual stars, not binned data.
- Position, metallicity and l.o.s. velocity distributions
- Three populations.

Dark matter density profile inference

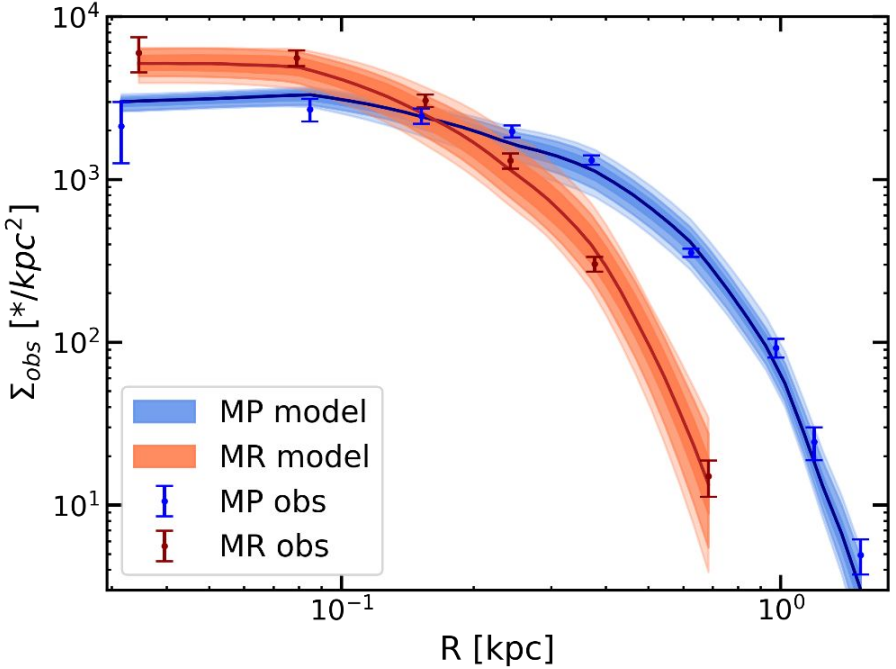
$$\mathcal{L}^p(\zeta_i) = \underbrace{J_p(R_i, v_{los,i})}_{\text{Stellar DF + DM potential}} \underbrace{P_m([Fe/H]_i)}_{\text{Gaussian}}$$

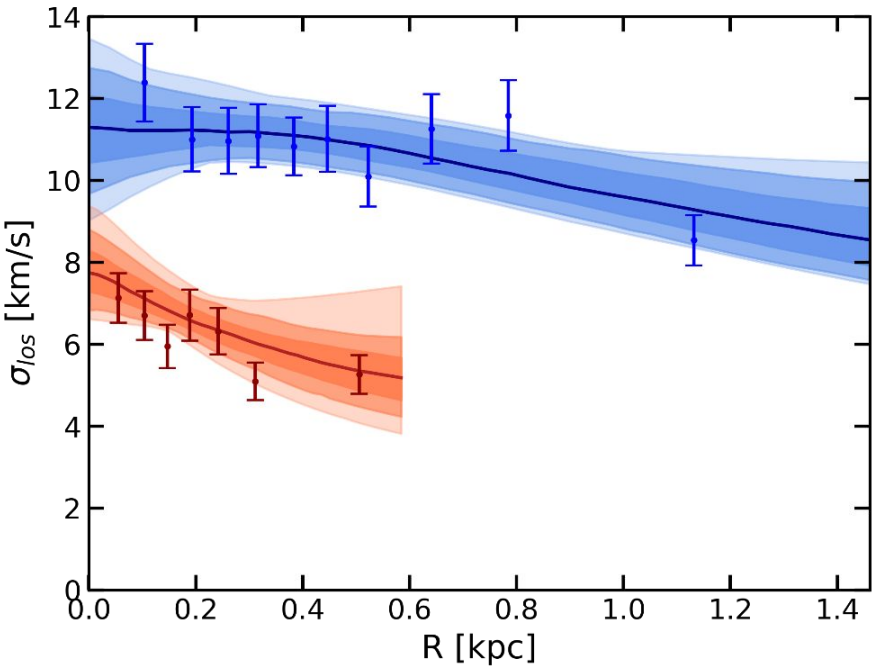
*Spherical models

Vasiliev (2019) AGAMA

25 free parameters

Comparison with the observed data

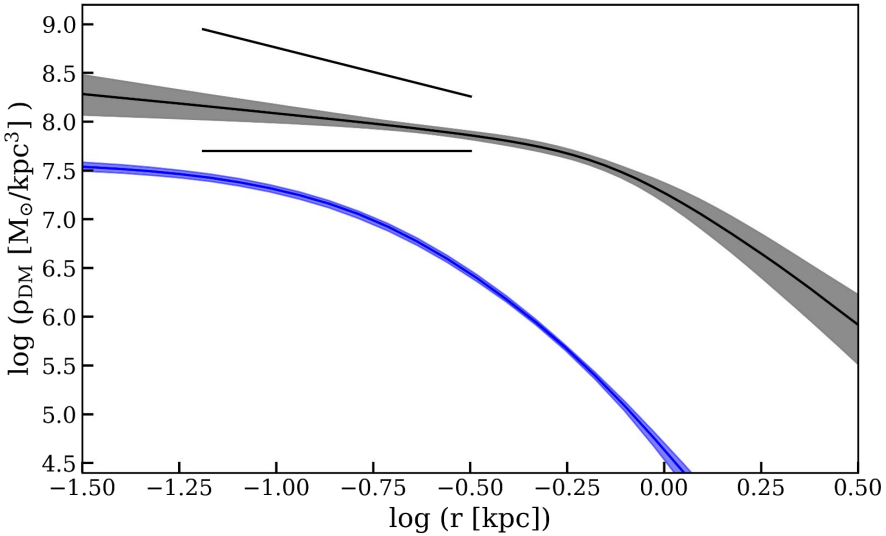




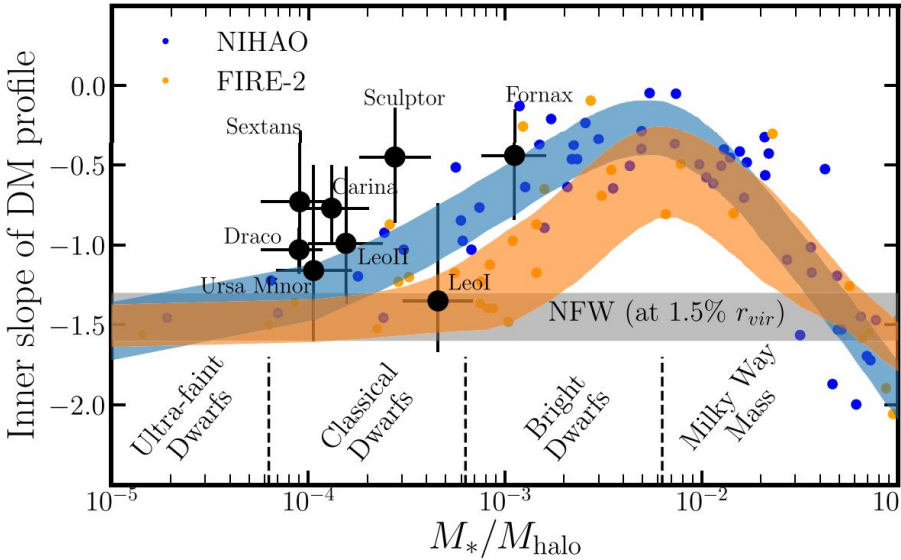
Third stellar component: it still appears with the same properties

Arroyo-Polonio et al. (Accepted)

Dark matter density profile

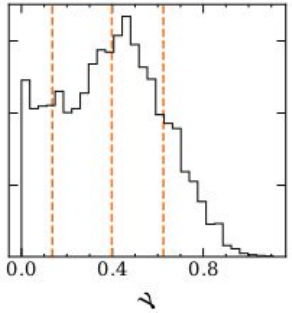


- Very dark-matter dominated
- Short star formation history



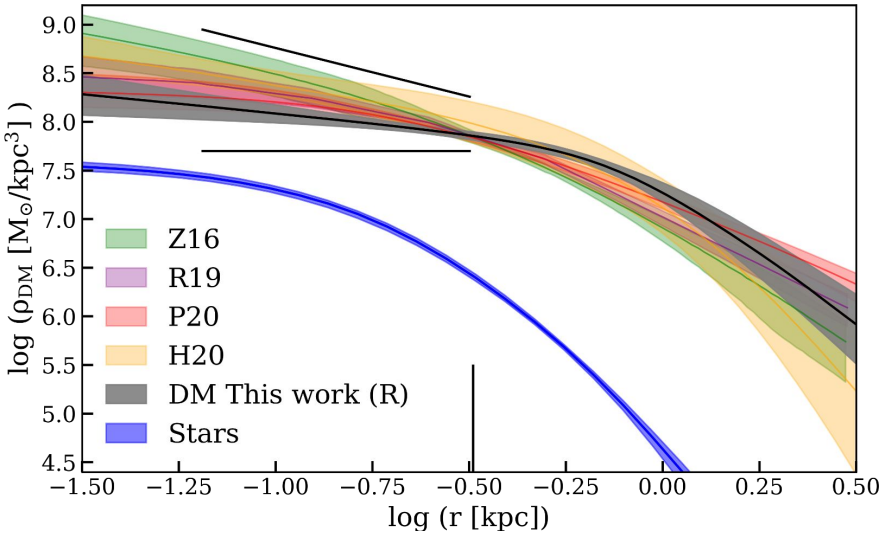
Di Cintio+ (2014), Hayashi, Chiba and Ishiyama (2020)

Inner logarithm slope :



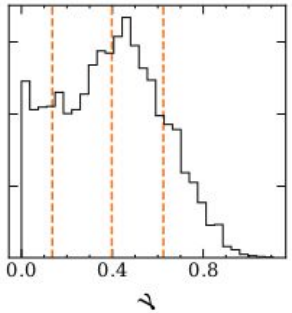
Arroyo-Polonio et al. (Accepted)

Dark matter density profile



Zhu+ (2016), Read+ (2019),
Pascale (2020), Hayashi+ (2020)

Inner logarithm slope :



Arroyo-Polonio et al. (Accepted)

- Very dark-matter dominated
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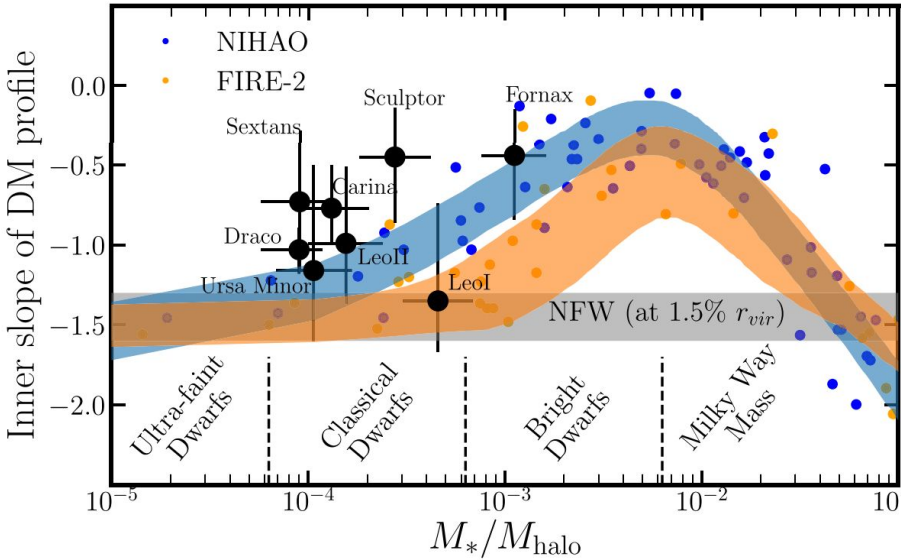
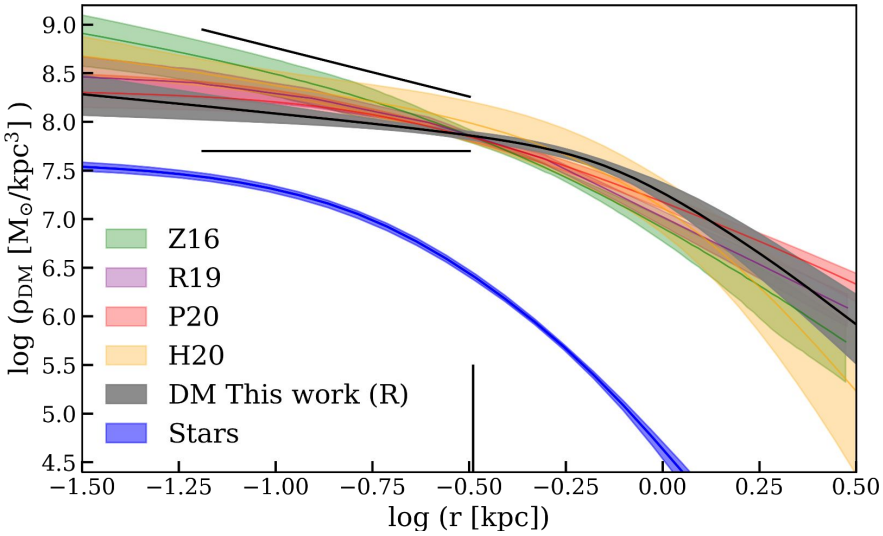


Di Cintio+ (2014), Hayashi, Chiba and Ishiyama (2020)

Dark matter density profile



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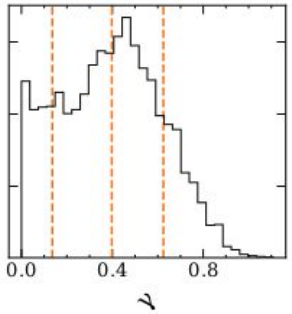

Arroyo-Polonio et al. (Accepted)

- Very dark-matter dominated
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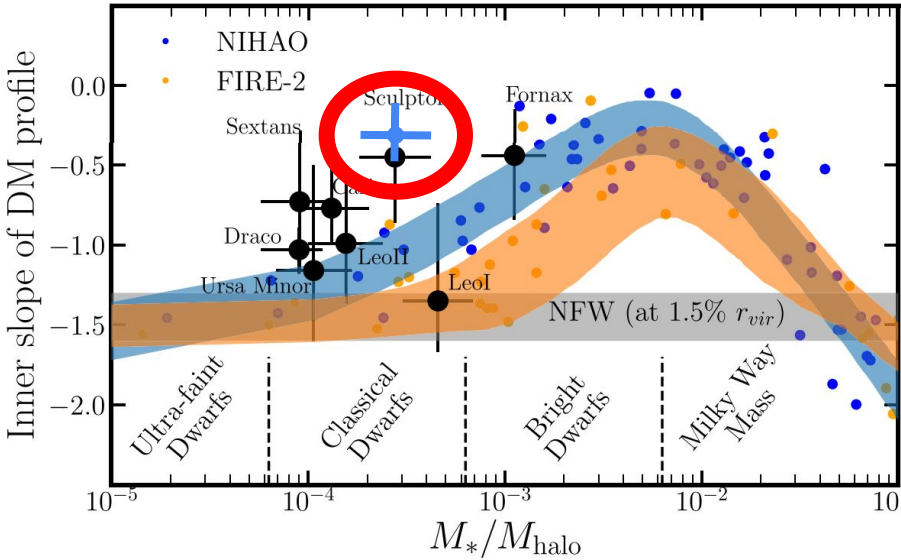
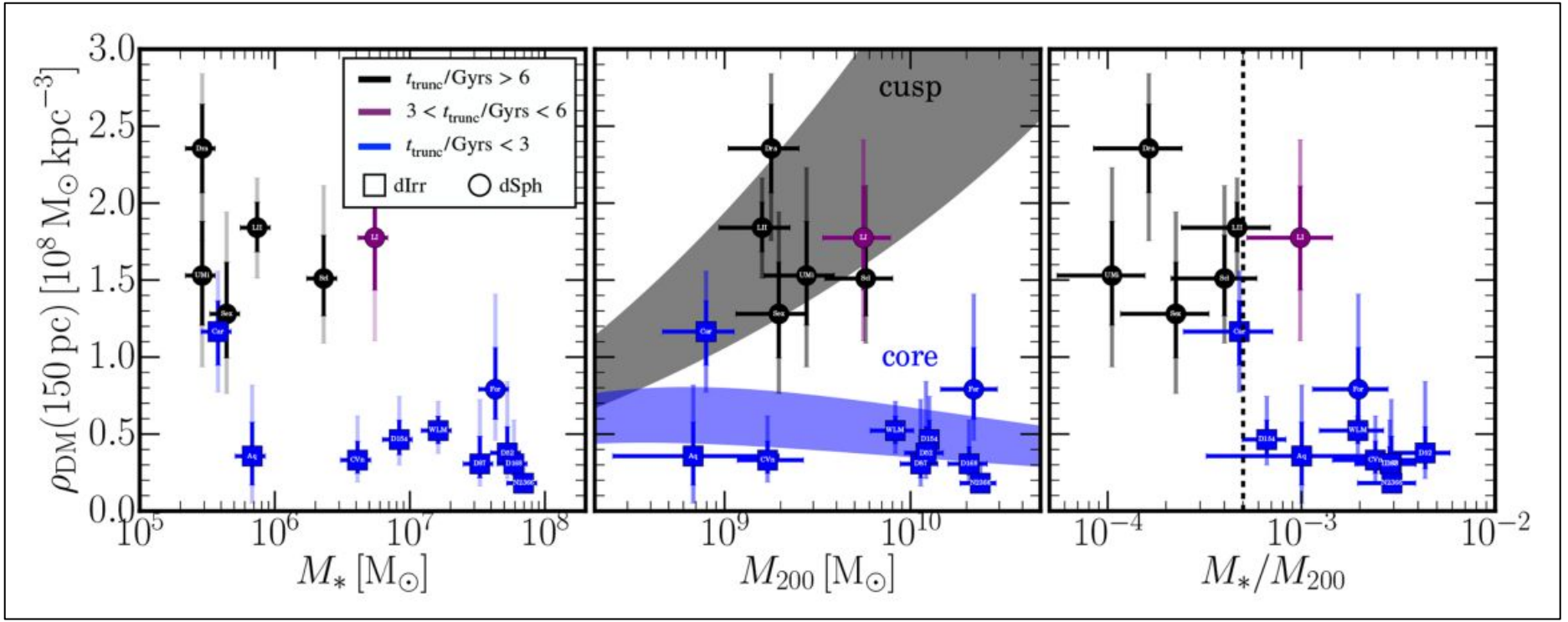


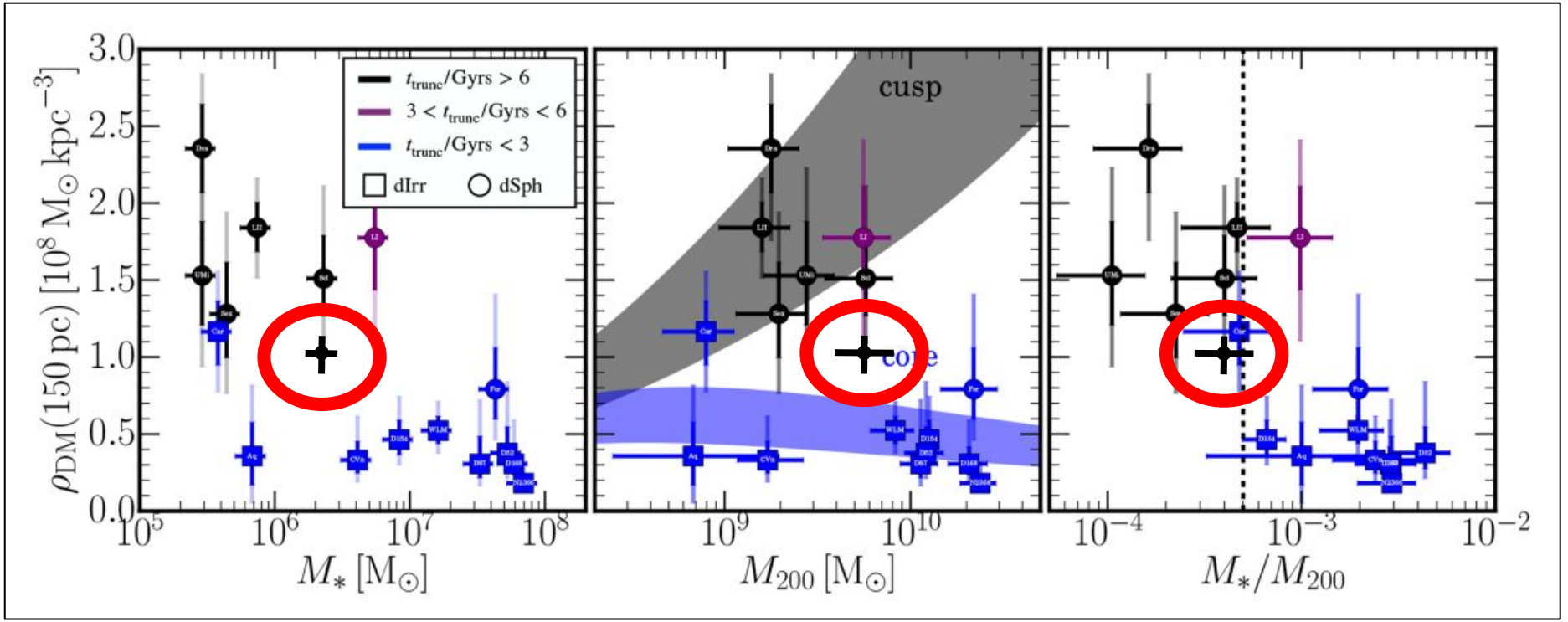
Di Cintio+ (2014), Hayashi, Chiba and Ishiyama (2020)

Central density



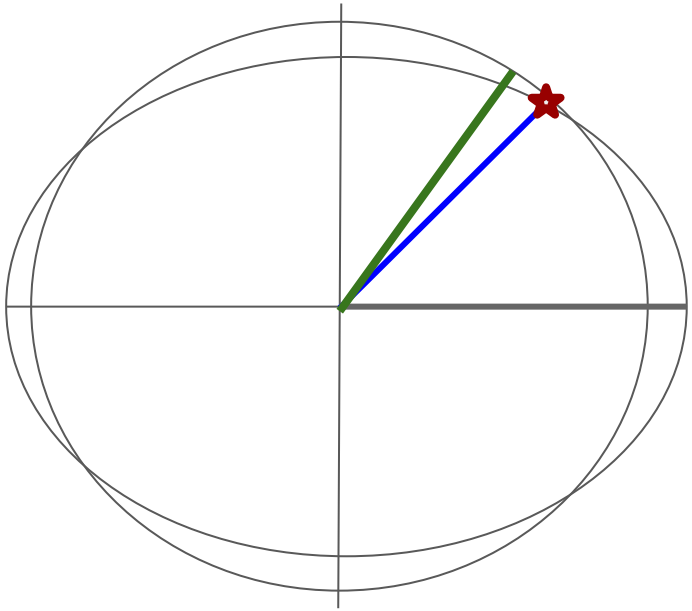
Read, Walker & Steger (2019)

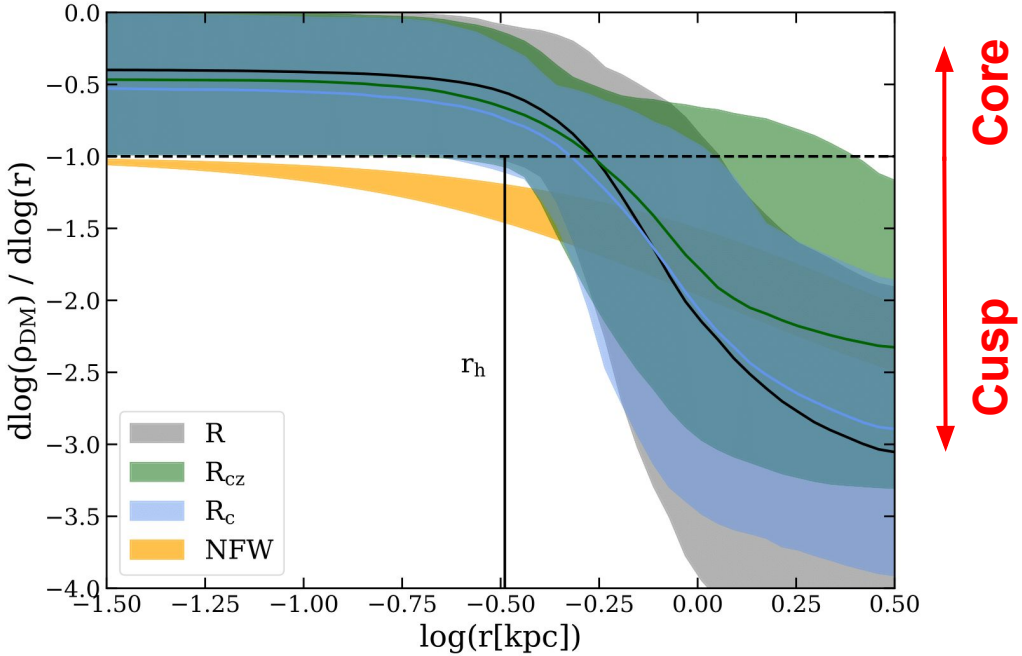
Central density



Read, Walker & Steger (2019)

Different choices of radius



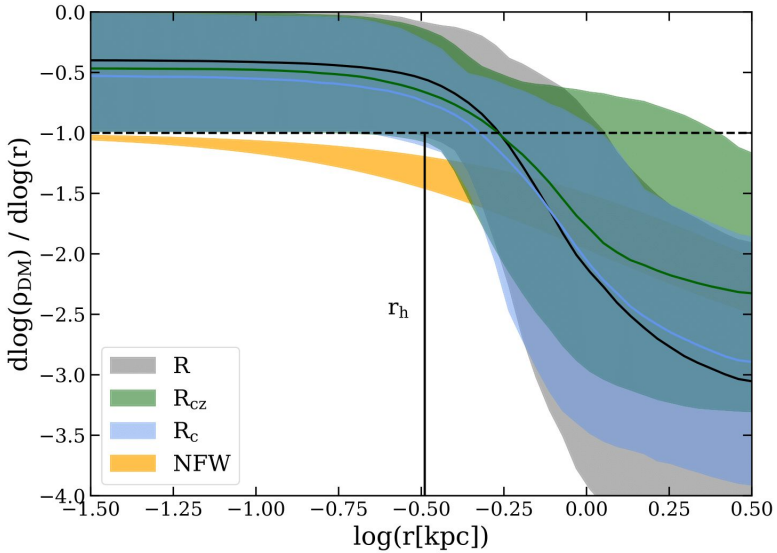


R: Semi-major axis radius
R_c: Circular radius
R_cz: Circularized radius

Arroyo-Polonio et al. (Accepted)

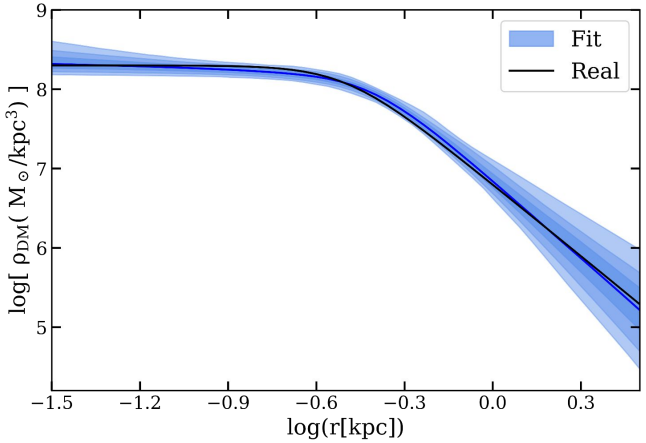
Conclusion

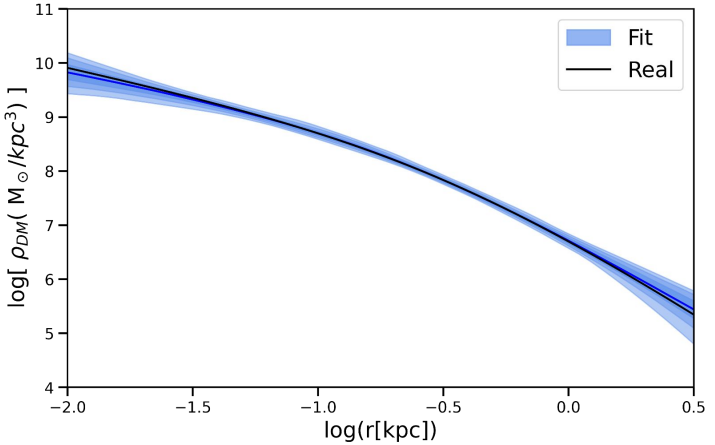
- We find Sculptor, a highly dark matter dominated galaxy with a short star formation history, **inconsistent with hosting a cusped DM halo.**

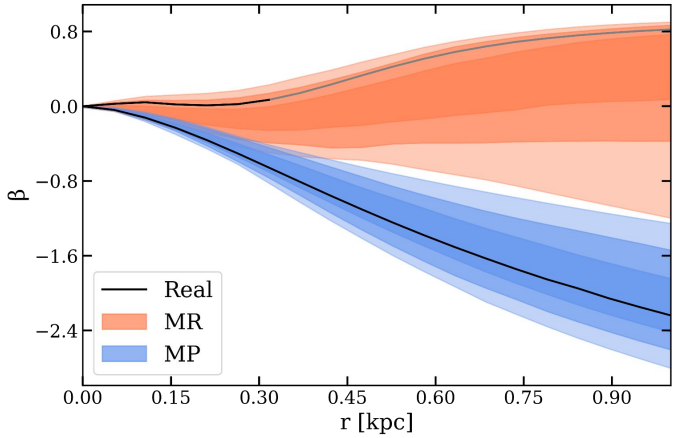


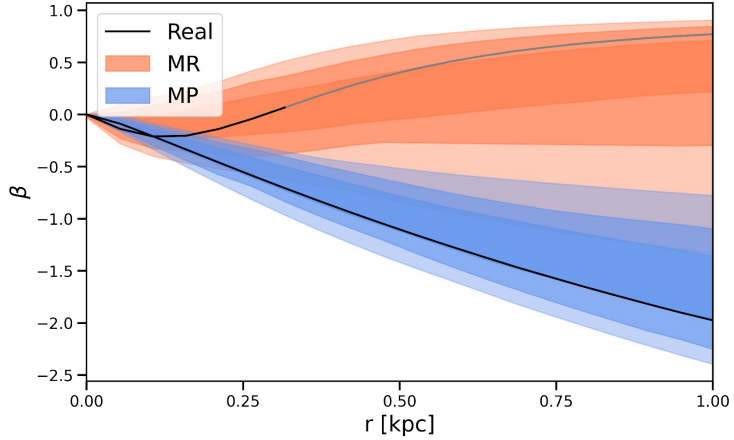
Paper on arXiv today! : https://arxiv.org/abs/2506.11845

Testing the modeling on Sculptor-like mock galaxies







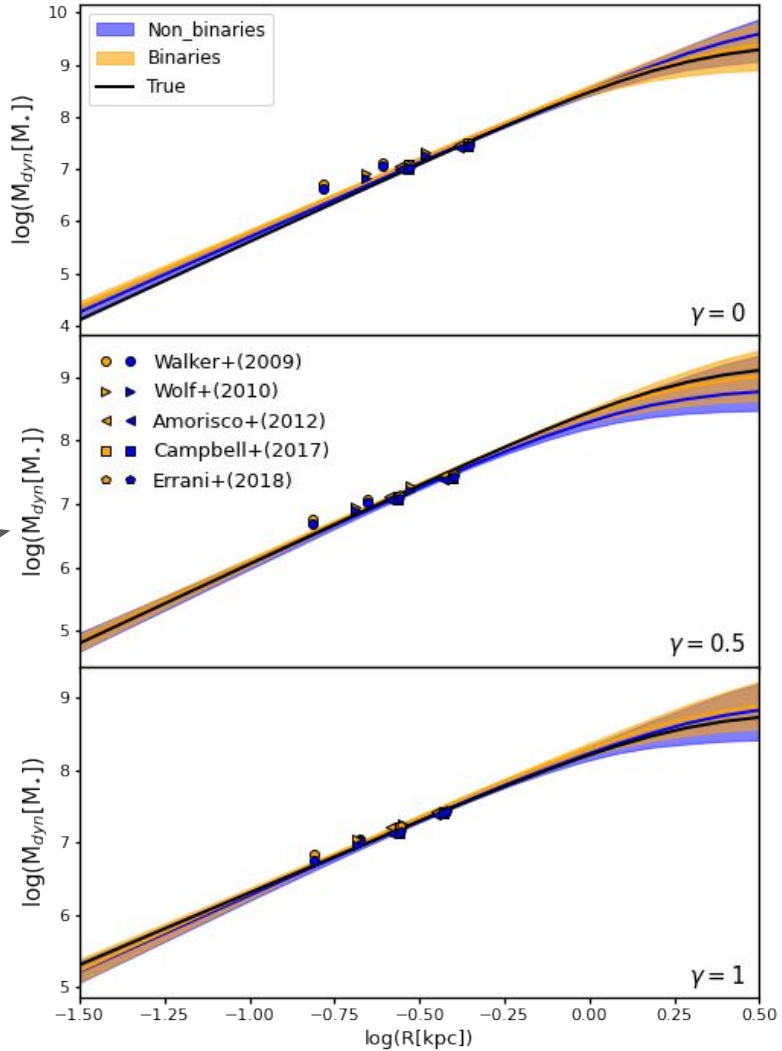


Testing the effect of binaries on Sculptor-like mock galaxies

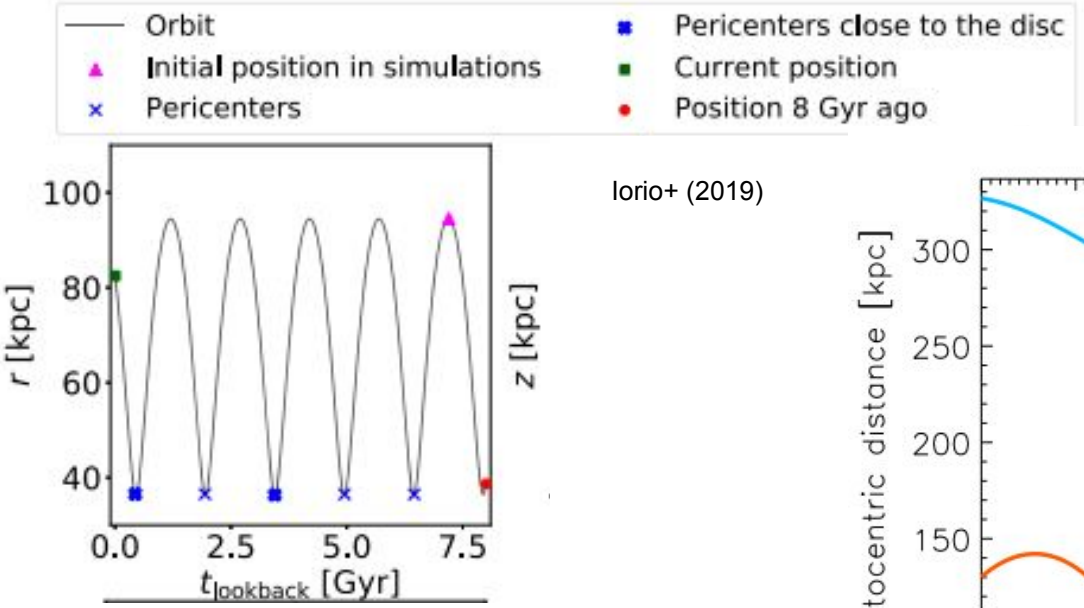
Constant density core (γ = 0)

“Mild cusp” (γ = 0.5)

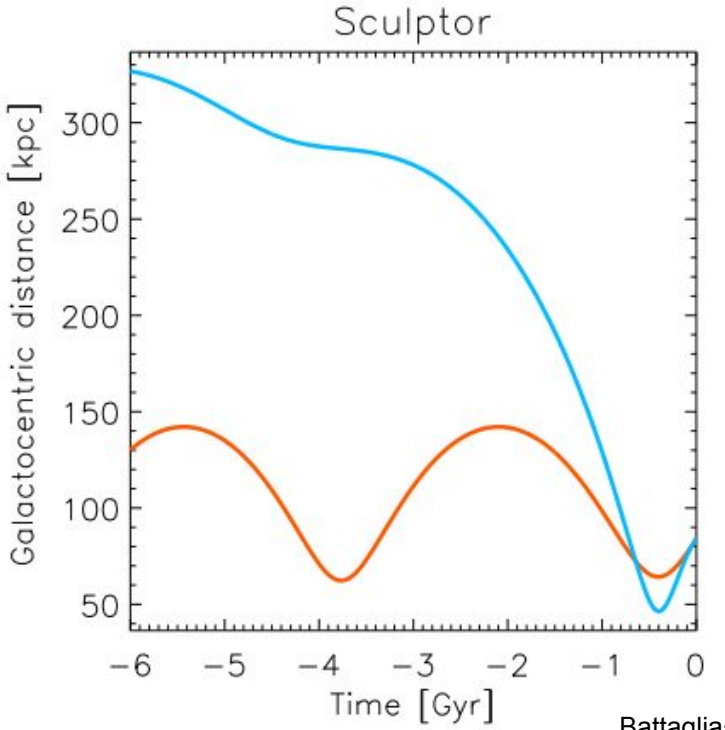
Cusp (γ = 1)



Sculptor dwarf galaxy: Dynamical equilibrium

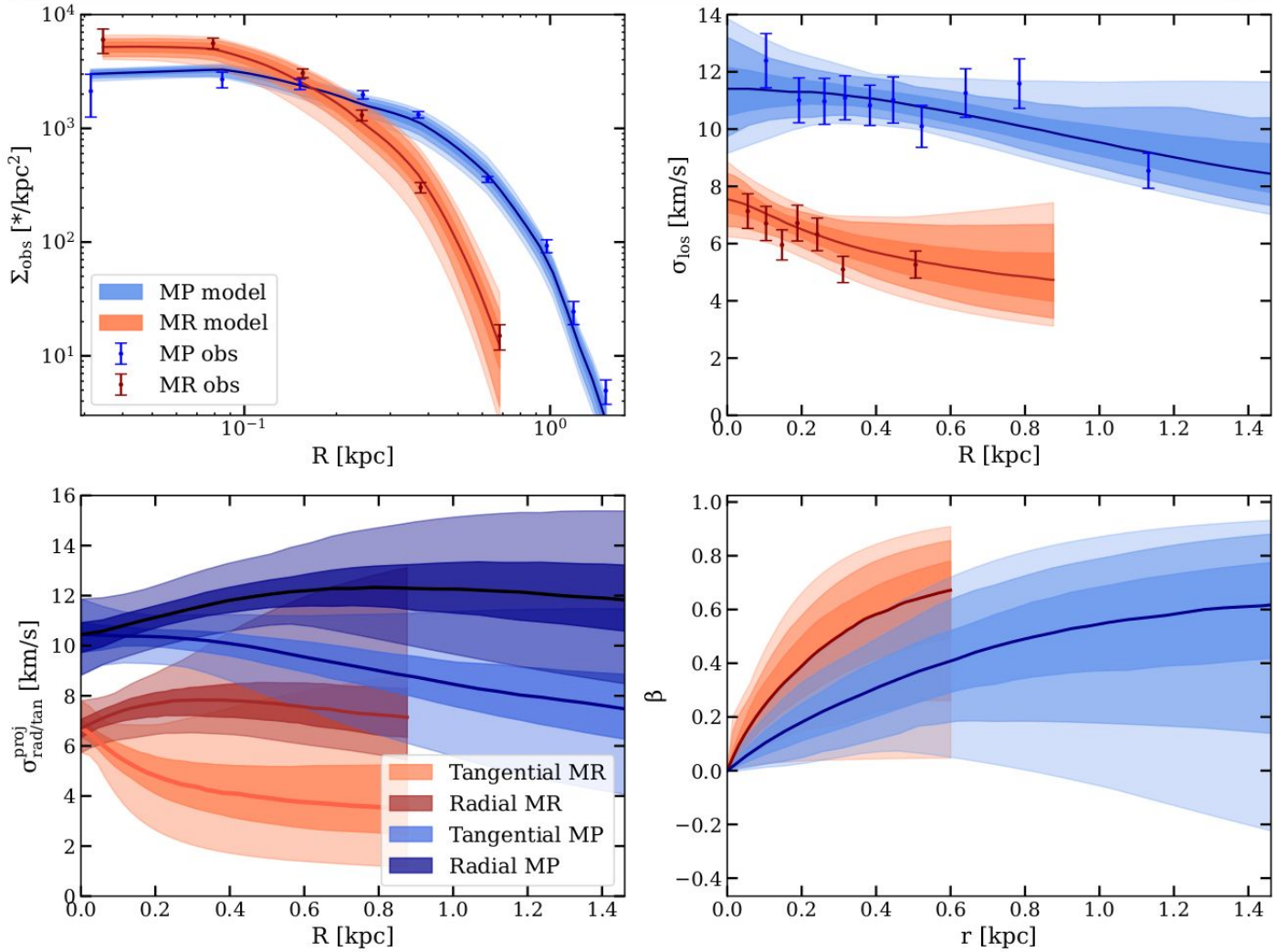


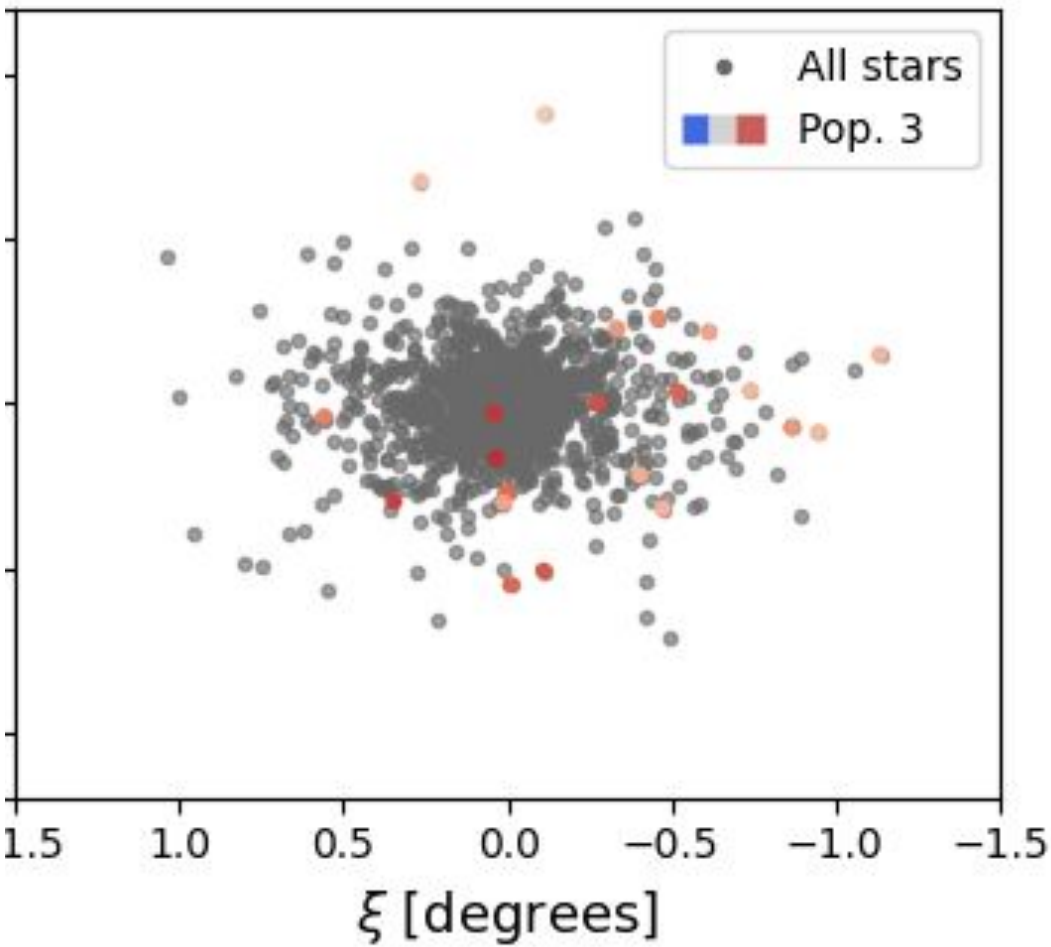
Iorio+ (2019)

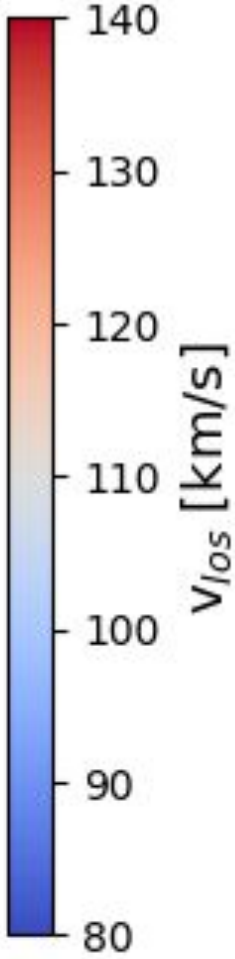


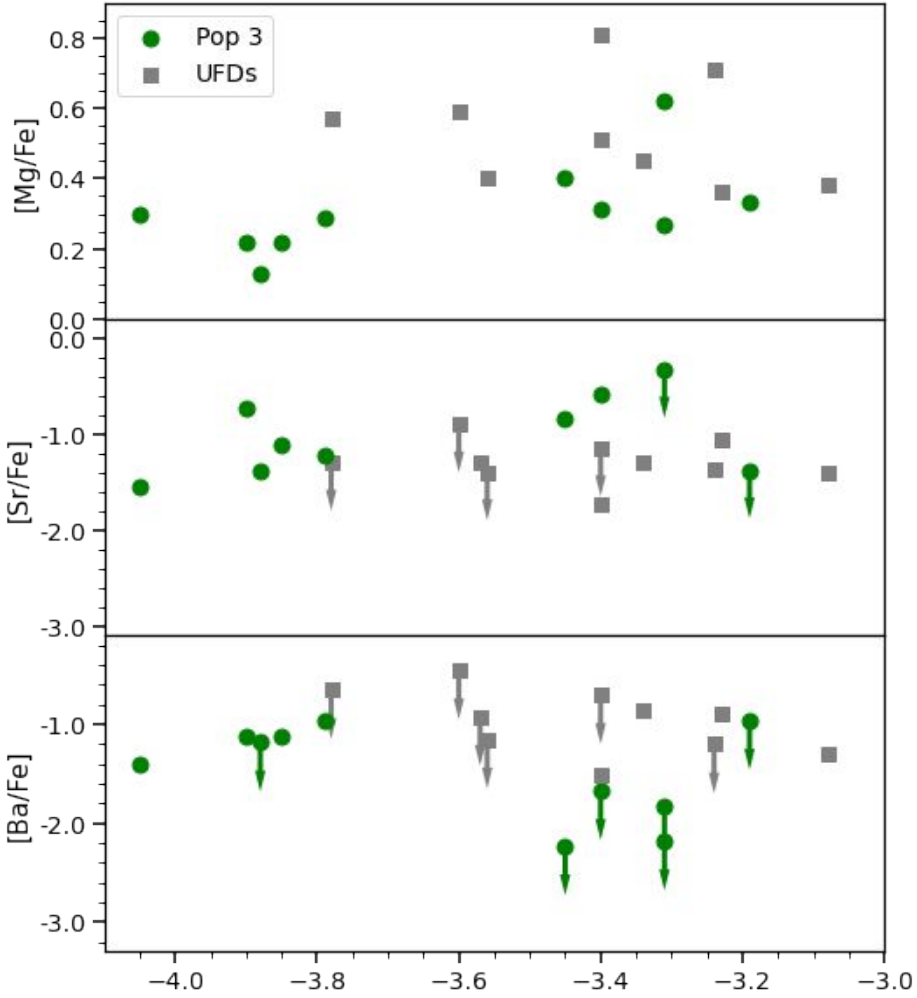
Battaglia+ (2022)

Stellar component is in dynamical equilibrium: Good tracer of DM potential

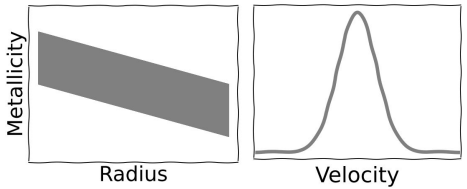

MP model
MR model
MP obs
MR obs
Σ_{obs} [*/kpc^2]
R [kpc]
σ_{los} [km/s]
R [kpc]
$\sigma^{proj}_{rad/tan}$ [km/s]
Tangential MR
Radial MR
Tangential MP
Radial MP
R [kpc]
β
r [kpc]


All stars
Pop. 3
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
ξ [degrees]


140
130
120
110
100
90
80
v_{los} [km/s]

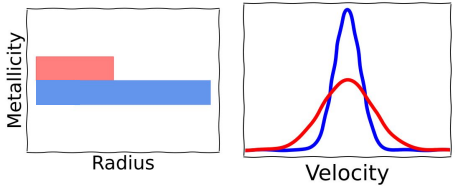

Pop 3
UFDs
[Mg/Fe]
[Sr/Fe]
[Ba/Fe]
0.8
0.6
0.4
0.2
0.0
-1.0
-2.0
-3.0
−4.0
−3.8
−3.6
−3.4
−3.2
−3.0

Two populations vs metallicity gradient



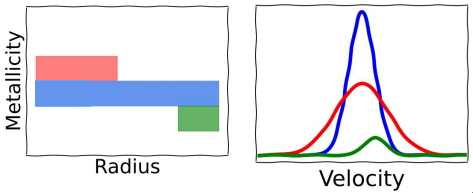
1 pop with metallicity gradient

ΔBIC = 40



2 populations

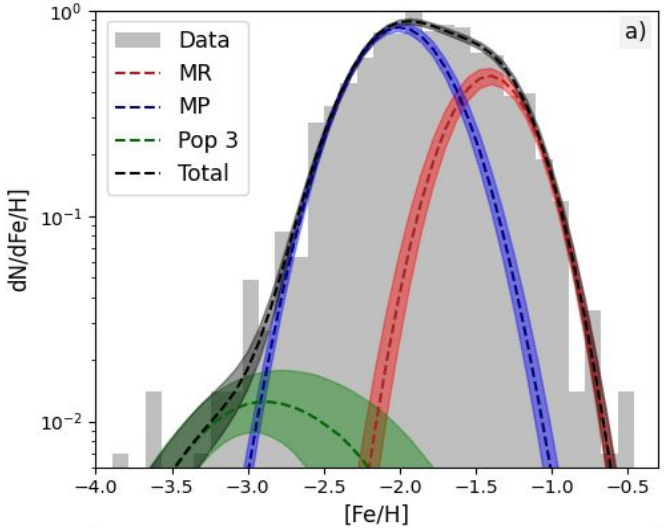
ΔBIC = 29

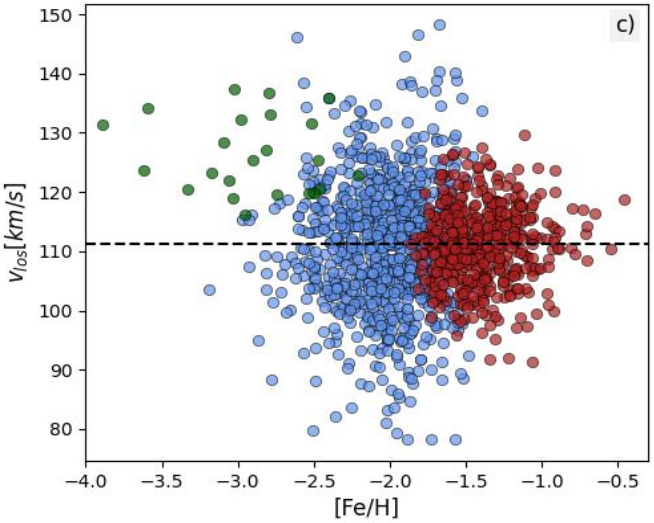


3 populations

ΔBIC = 69

~~Foreground contamination~~
~~Tides~~
~~Streams~~

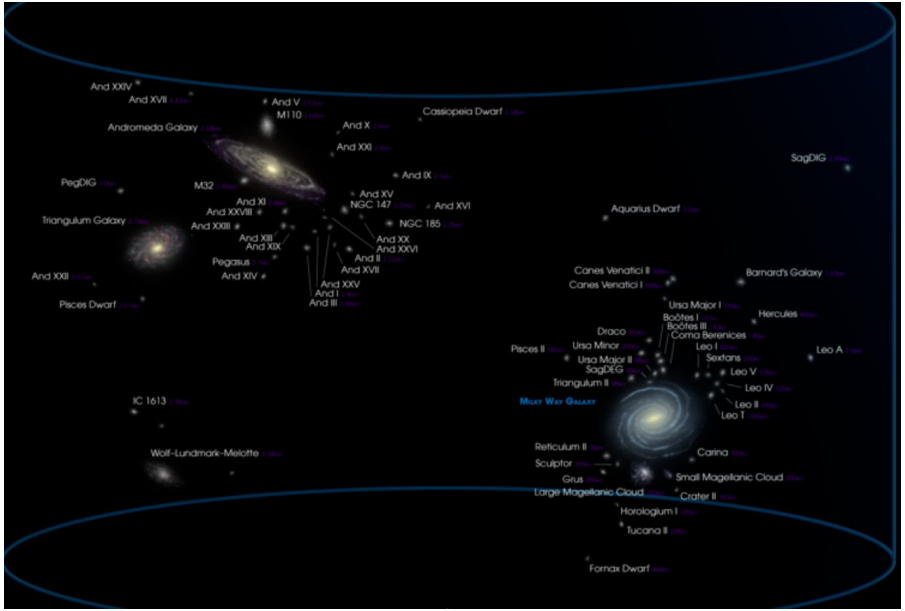




Arroyo-Polonio et al. (2024)

Dwarf galaxies

$$M_\star \lesssim 10^7 M_\odot$$



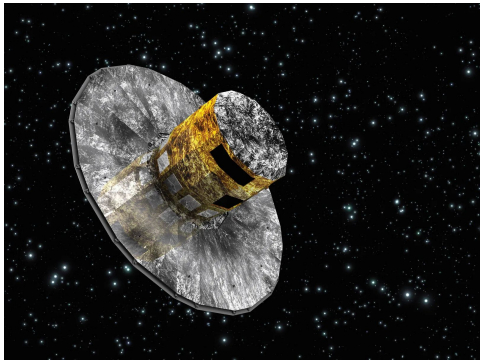
(a)

(b) Ground-based spectroscopy

VLT/FLAMES

(c)

MAGELLAN/MMFS



(d)

Gaia involved

- Parallaxes
- Proper motions

(a) https://es.m.wikipedia.org/wiki/Archivo:06-Local_Group
(b) https://www.eso.org/public/spain/images/vlt-brunier-nuit/
(c) https://en.wikipedia.org/wiki/Magellan_Telescopes
(d)https://www.britannica.com/topic/Gaia-European-Space-Agency-satellite