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"Una manera de hacer Europa"
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
Universidad de La Laguna

DM in the Local Group: the kinematic analyses of dwarf spheroidals

José María Arroyo Polonio - Phd Student (IAC)

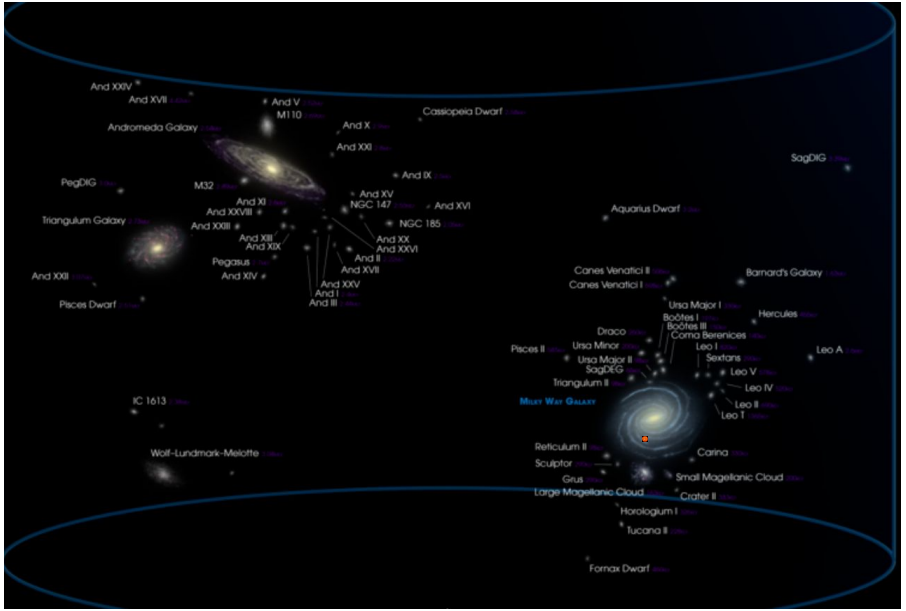
Milky Way and Local Group
- Giuseppina Battaglia
- Guillaume F. Thomas

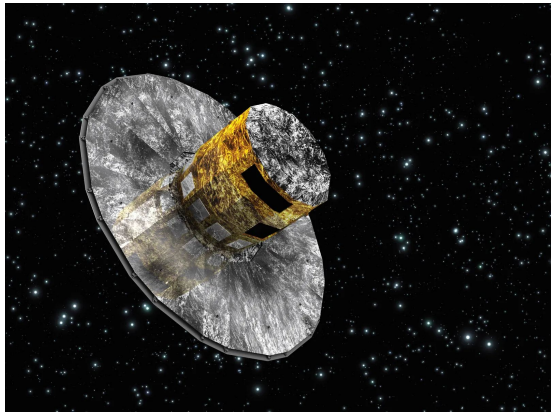
Funded by the European Union

Kick off meeting UNDARK
10/10/2025

Dwarf spheroidals $M_\star \lesssim 10^8 M_\odot$

(a)





Gaia

- Parallaxes
- Proper motions

→ Membership determination

(b)

Ground-based spectroscopy

(c)

VLT/FLAMES

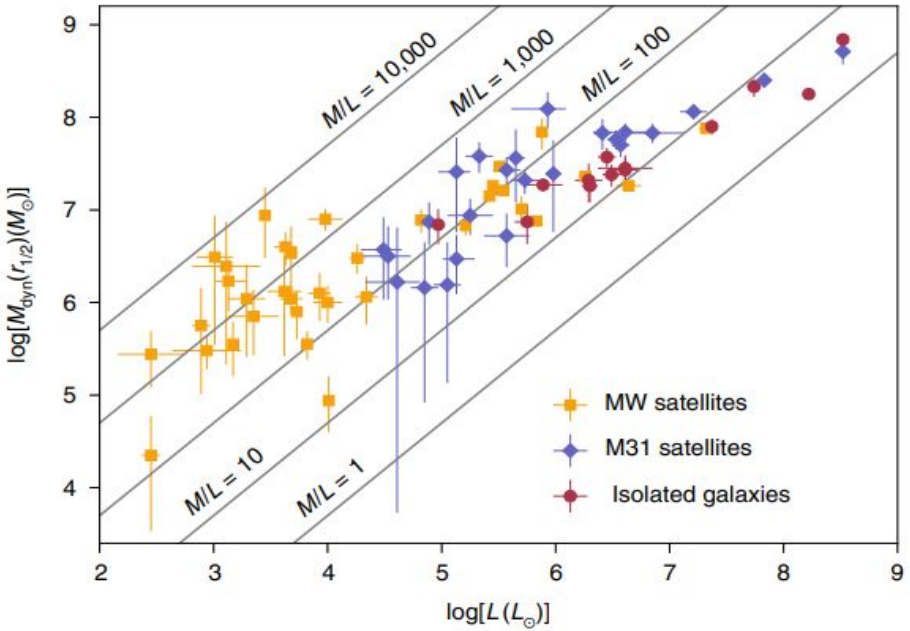
(d)

MAGELLAN/MMFS SURVEY

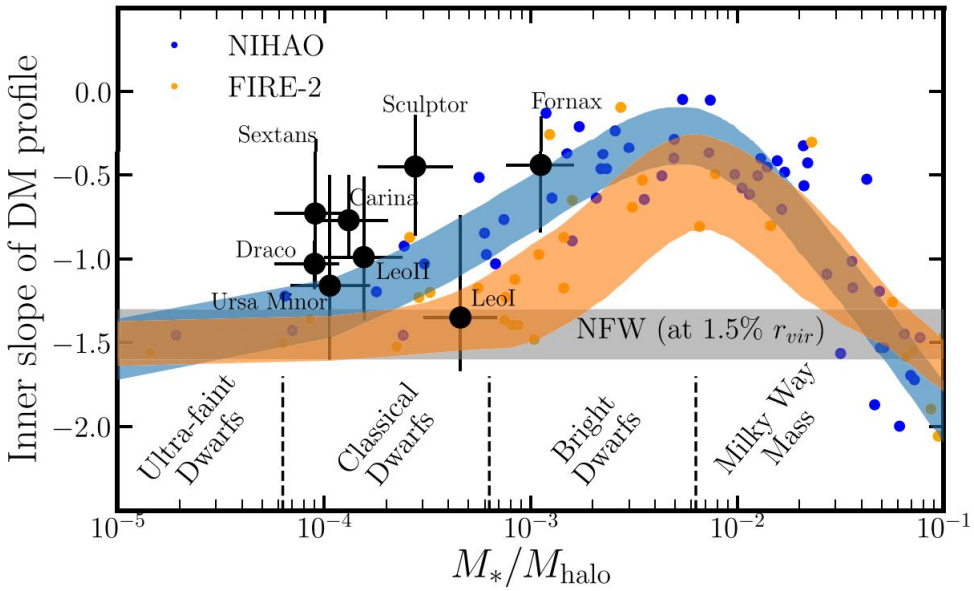
(a) https://es.m.wikipedia.org/wiki/Archivo:06-Local_Group
(b)https://www.britannica.com/topic/Gaia-European-Space-Agency-satellite
(c) https://www.eso.org/public/spain/images/vlt-brunier-nuit/
(d) https://en.wikipedia.org/wiki/Magellan_Telescopes

Dwarf galaxies as dark matter probes

Cusp → -1
Core → 0



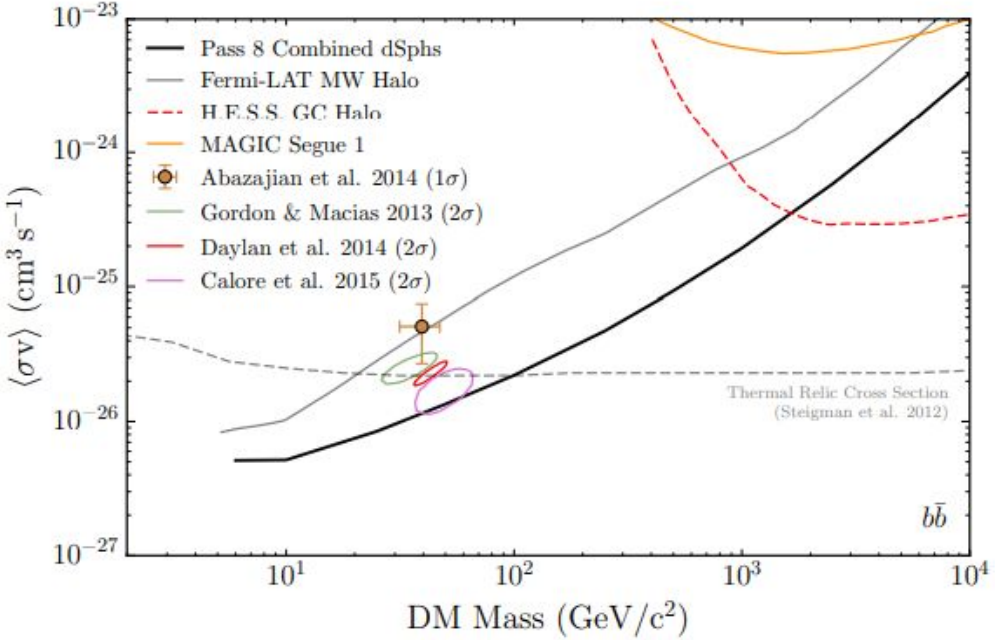
Mateo(1998), Walker(2012), Battaglia & Nipoti (2022)



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

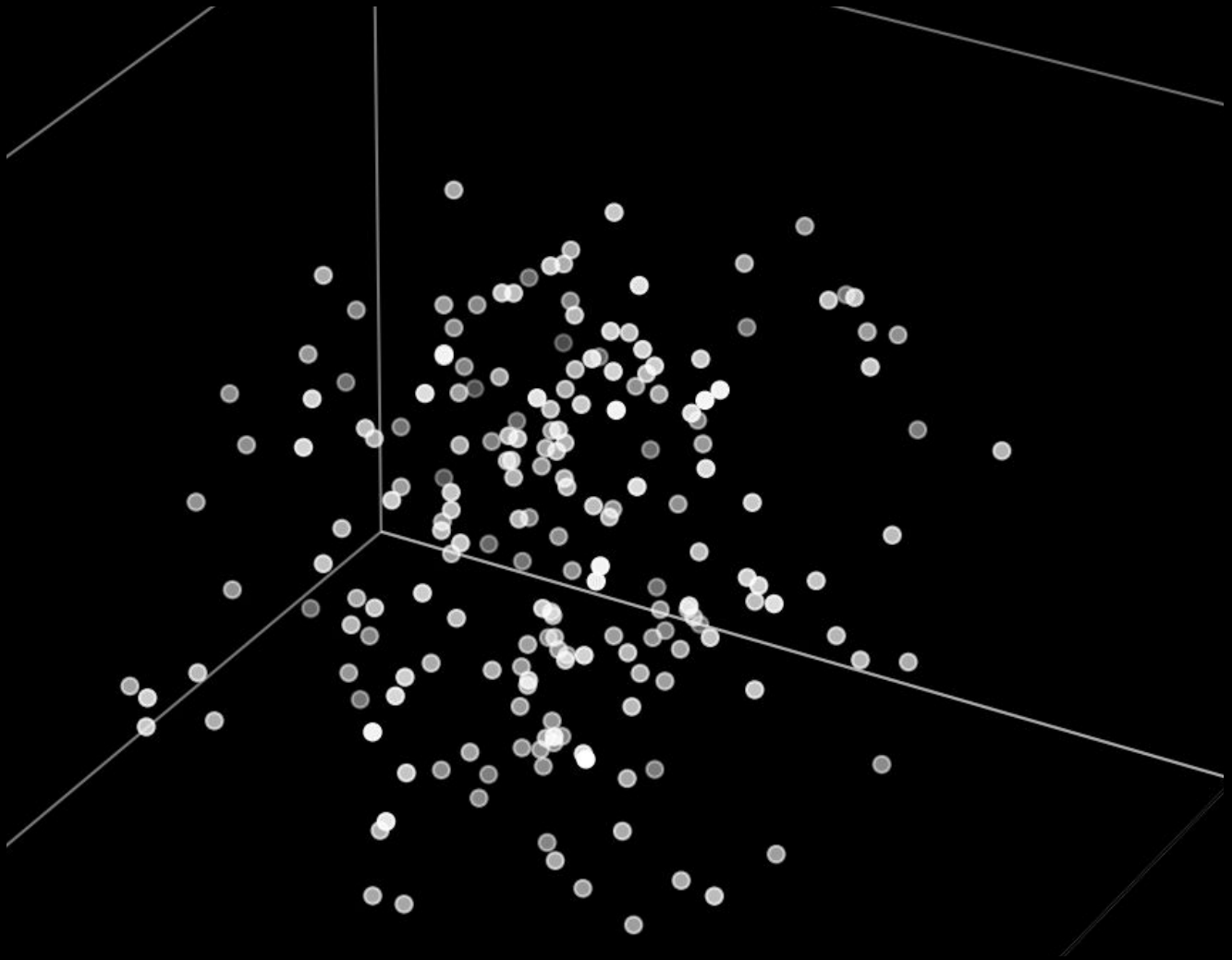
DGs can be used to test DM models in a cosmological framework

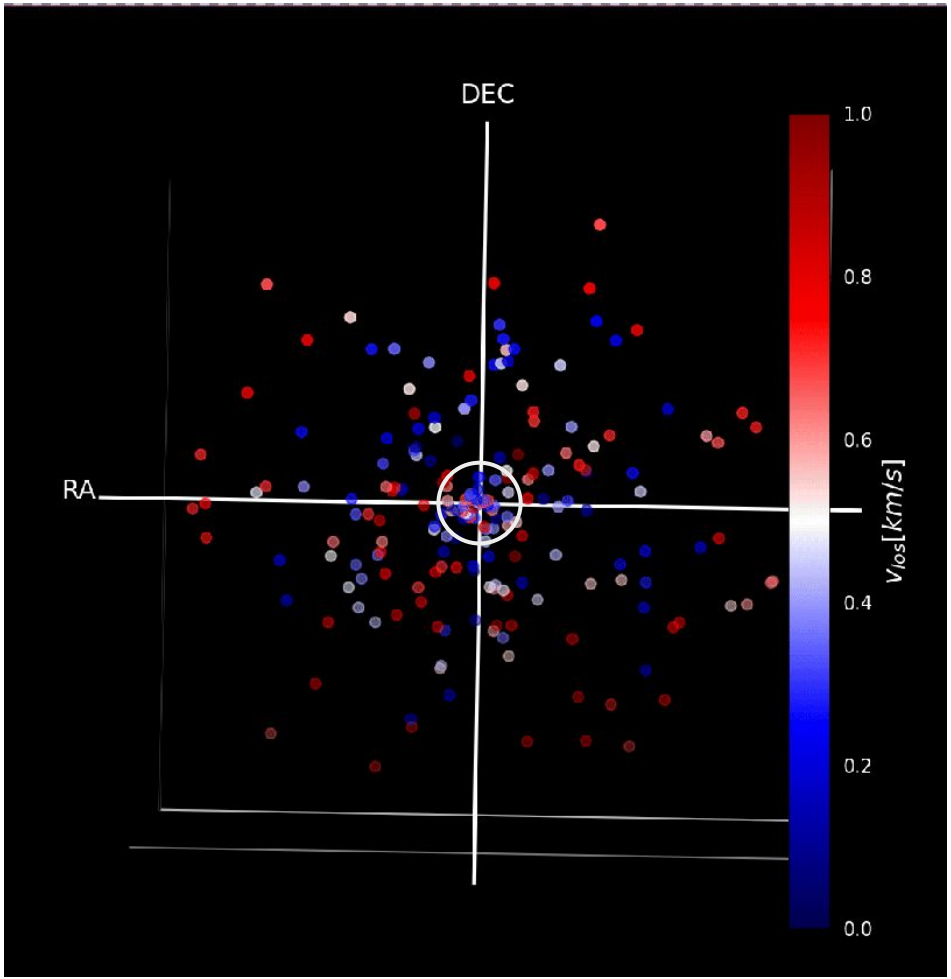
Constraints on DM annihilation cross-section



Ackermann et al. (2015)

Based on FERMI-LAT observations of
15 dwarf spheroidals during 6 years




DEC
RA
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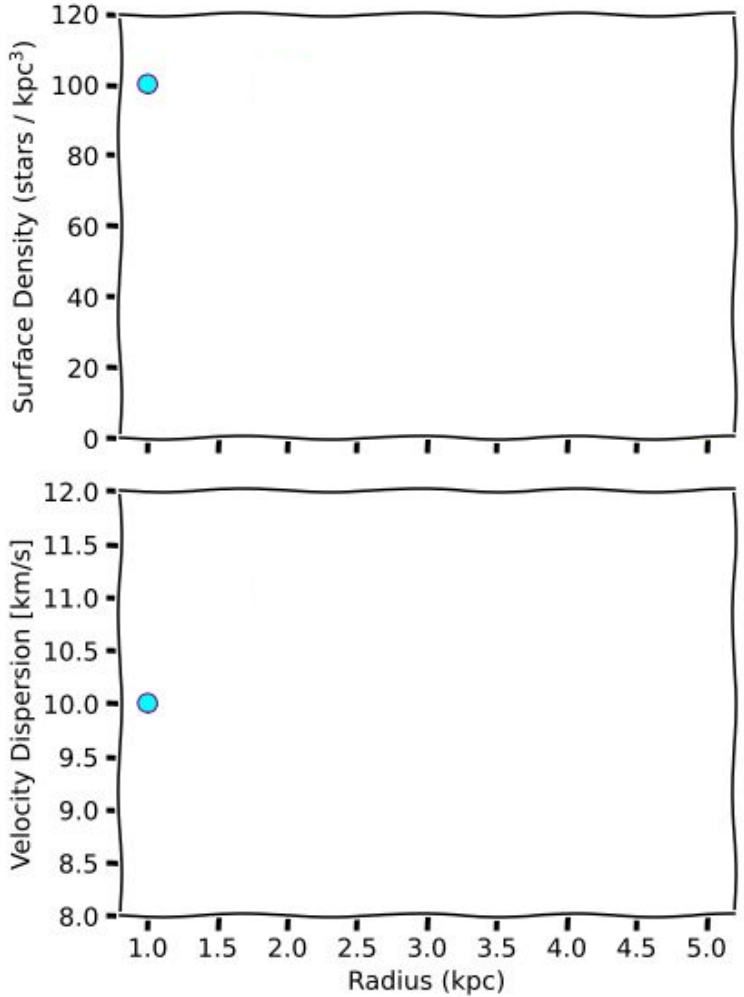
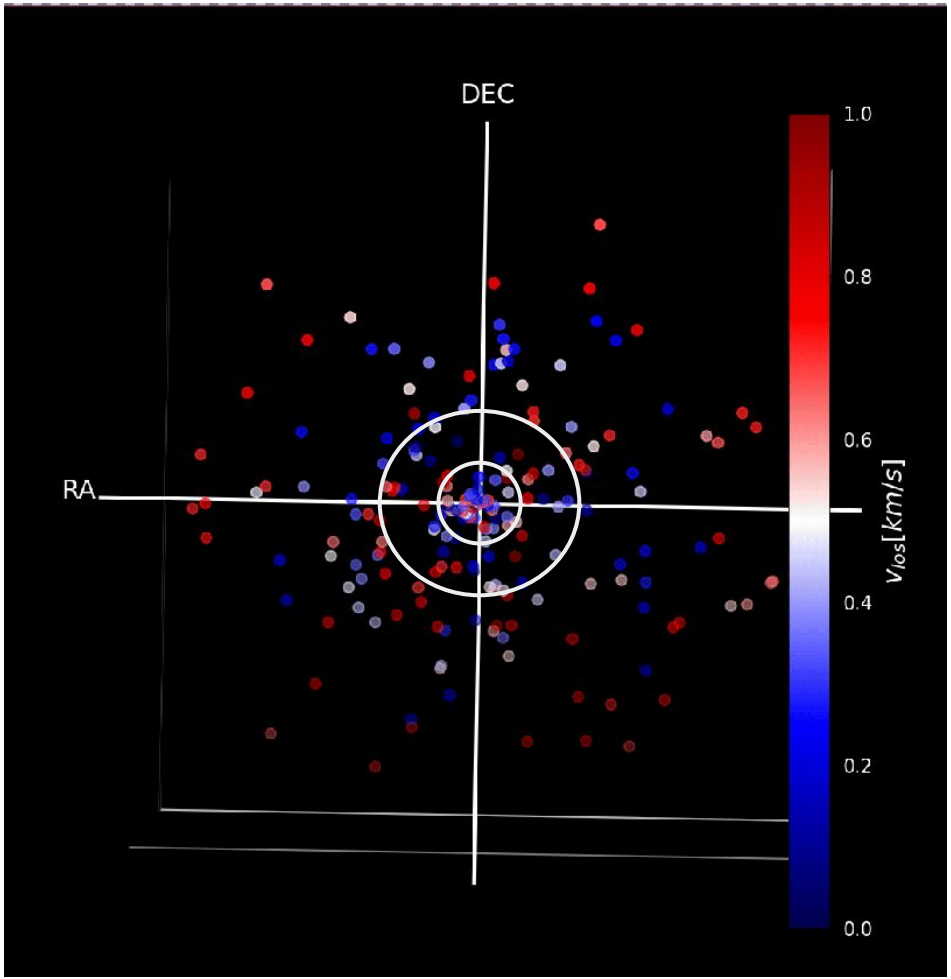
0.8
0.6
0.4
0.2
0.0
$v_{los}[km/s]$


Surface Density (stars / kpc^3)
120
100
80
60
40
20
0
Velocity Dispersion [km/s]
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Radius (kpc)


DEC
RA
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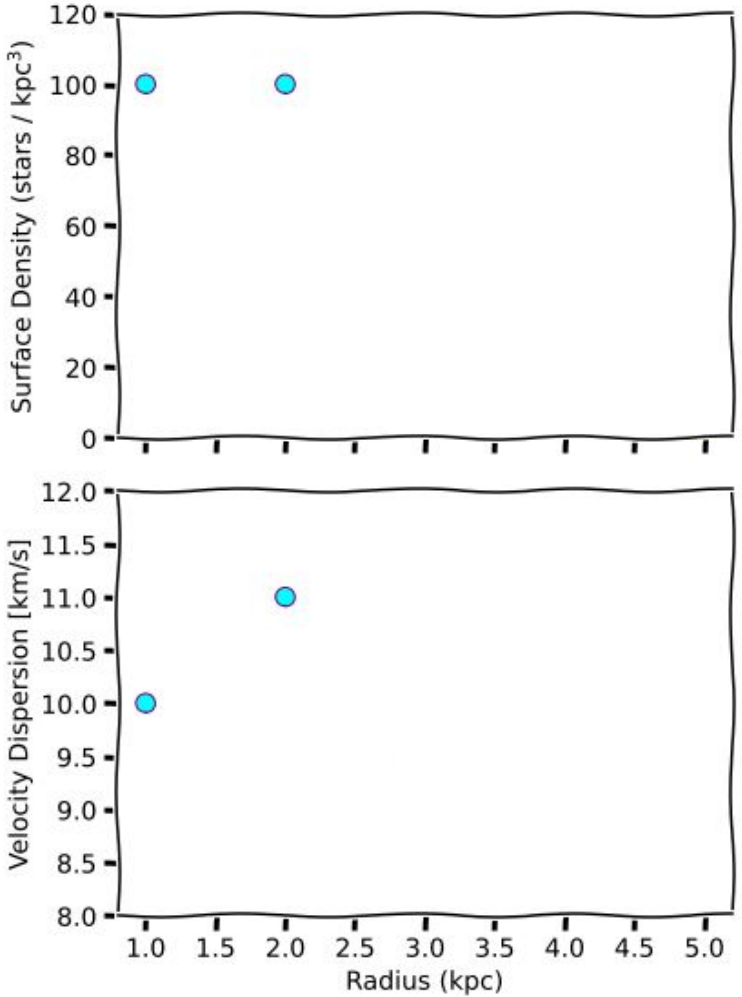
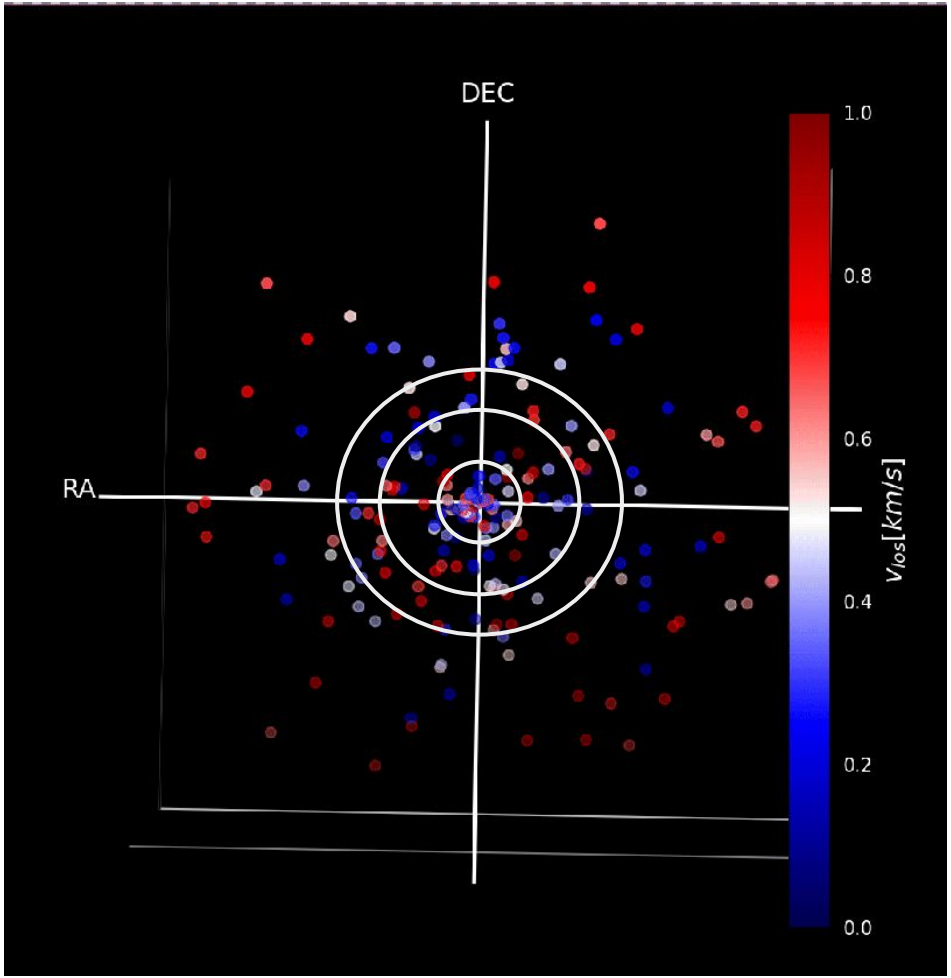
0.6
0.4
0.2
0.0
$v_{los}[km/s]$


Surface Density (stars / kpc^3)
120
100
80
60
40
20
0
Velocity Dispersion [km/s]
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Radius (kpc)


DEC
RA
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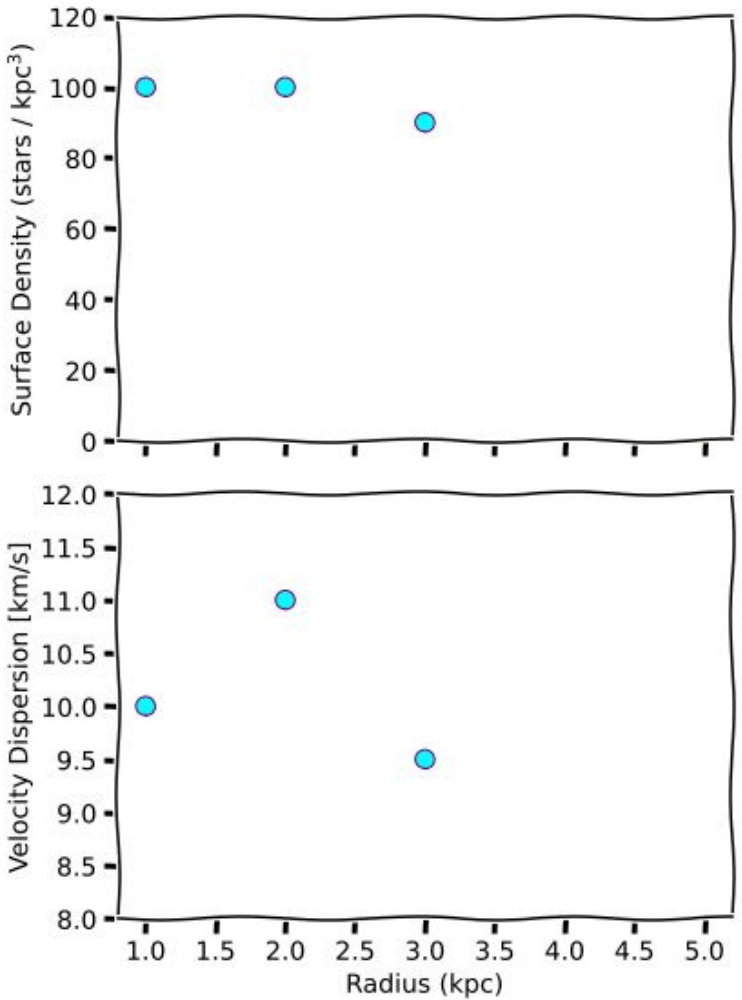
0.8
0.6
0.4
0.2
0.0
$v_{los}[km/s]$


Surface Density (stars / kpc^3)
120
100
80
60
40
20
0
Velocity Dispersion [km/s]
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
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1.0
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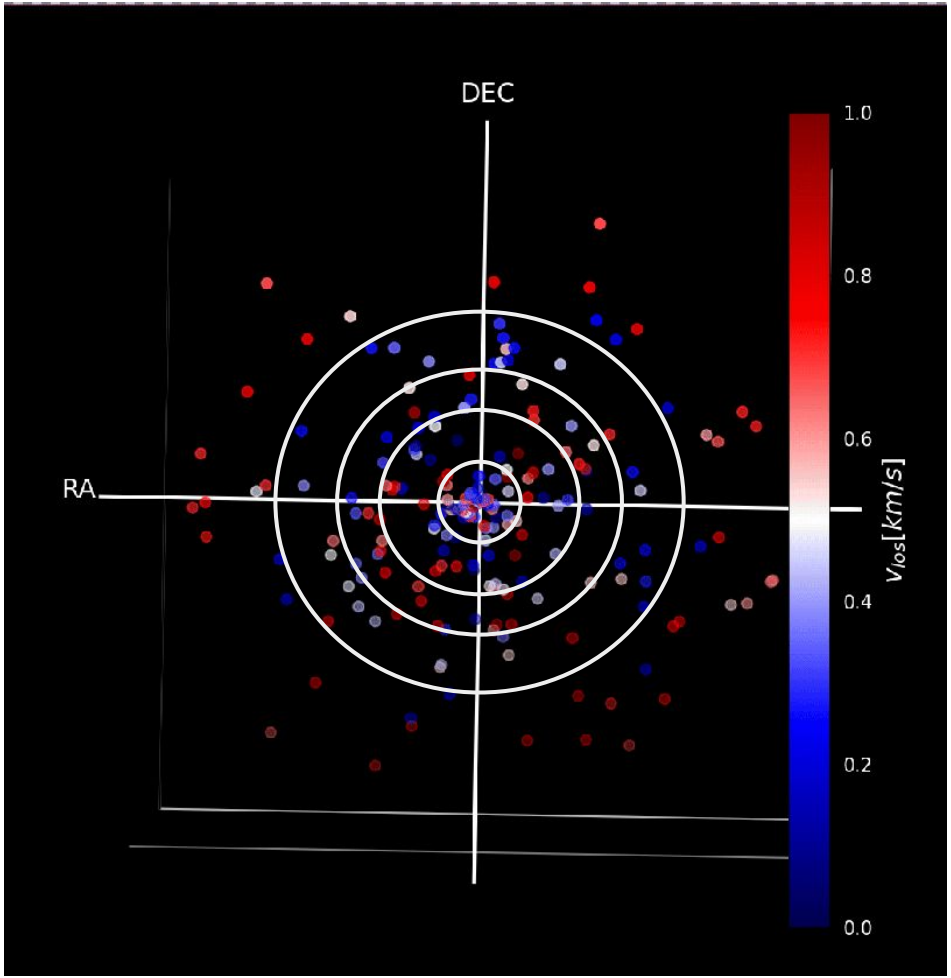
2.5
3.0
3.5
4.0
4.5
5.0
Radius (kpc)


DEC
RA
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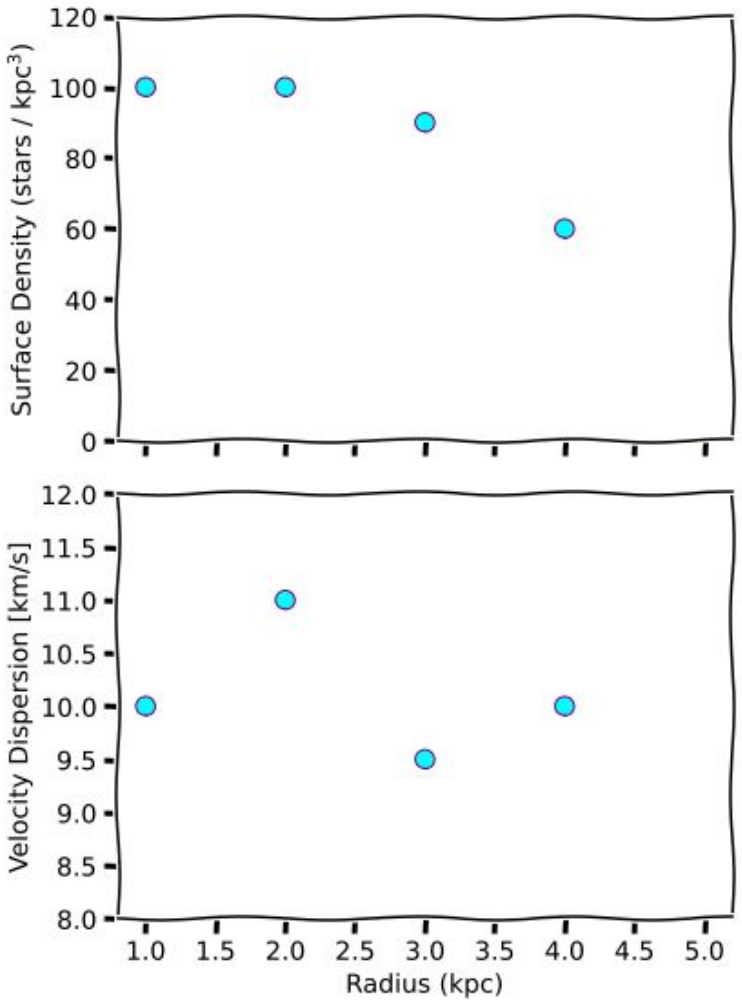
0.8
0.6
0.4
0.2
0.0
$v_{los}[km/s]$


Surface Density (stars / kpc^3)
120
100
80
60
40
20
0
Velocity Dispersion [km/s]
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
1.0
1.5
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2.5
3.0
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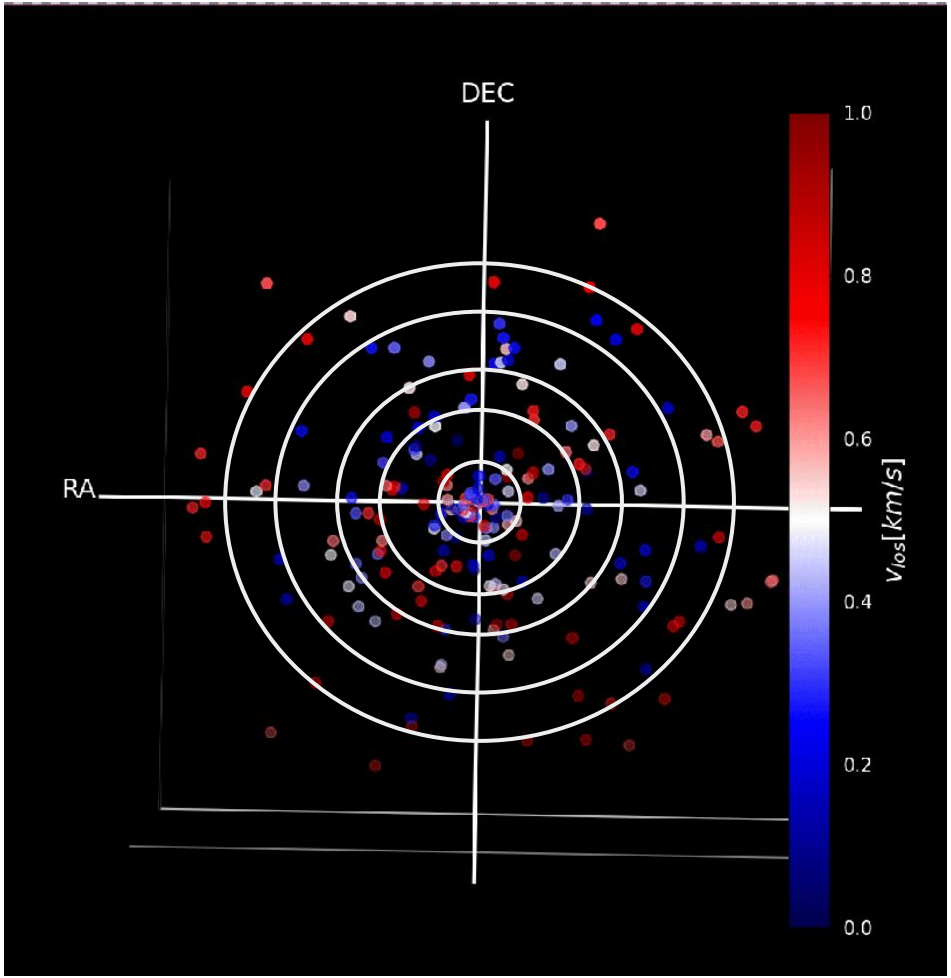
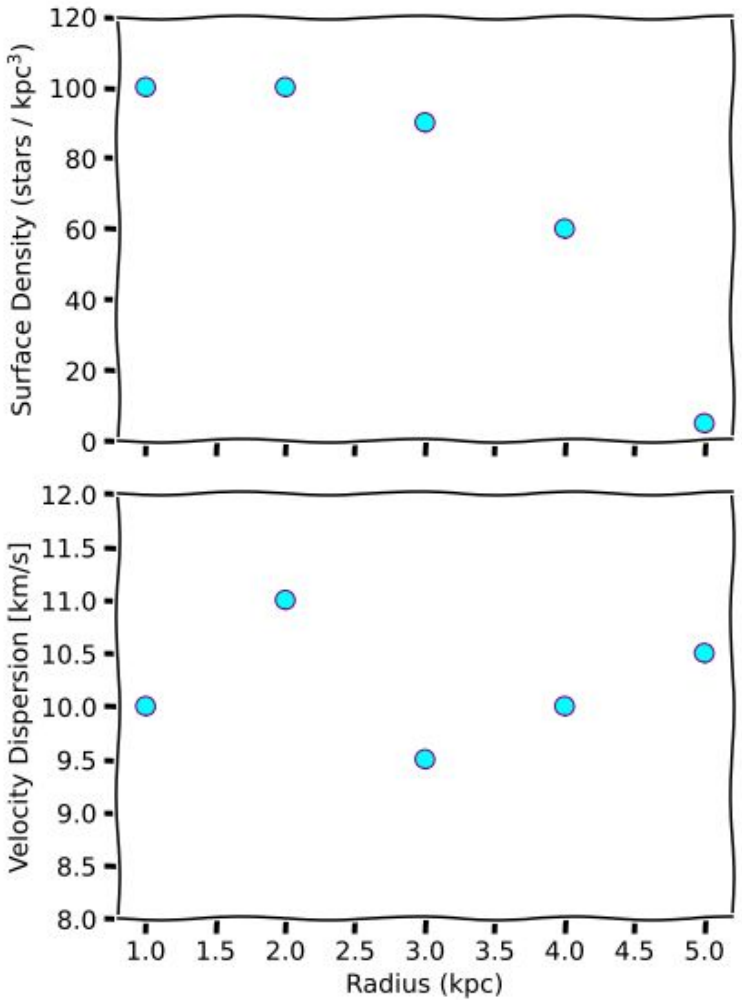
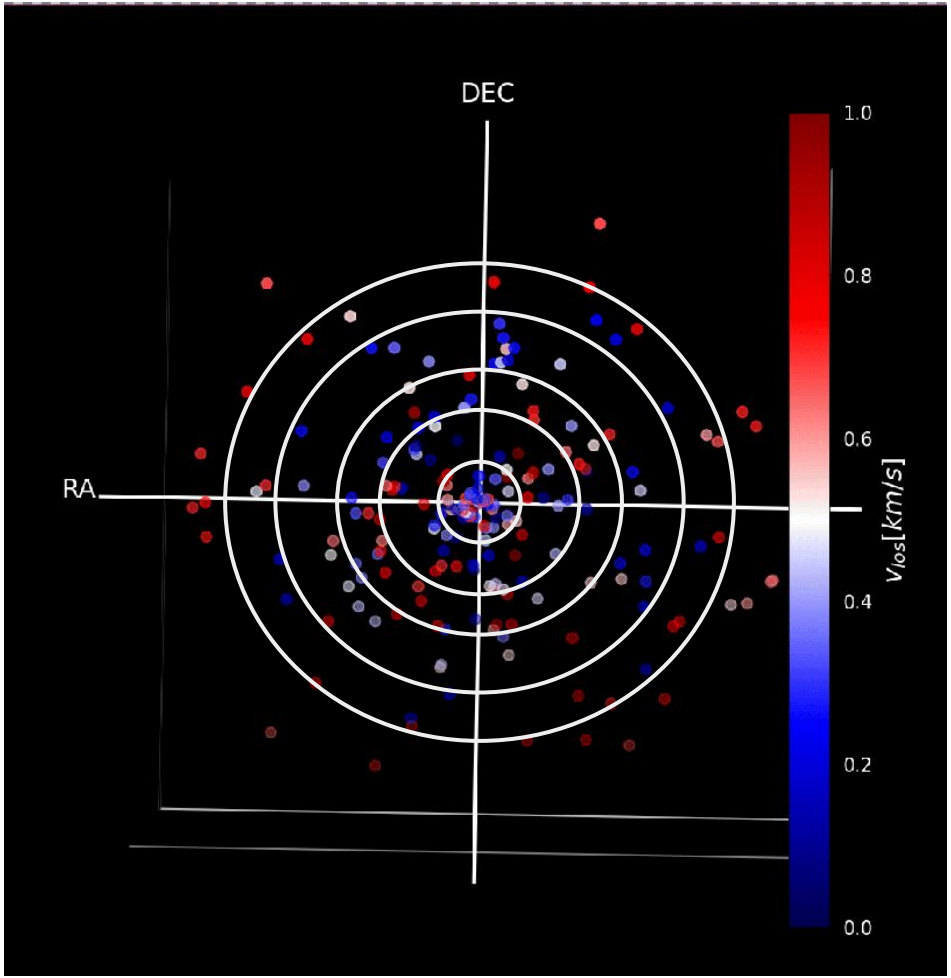
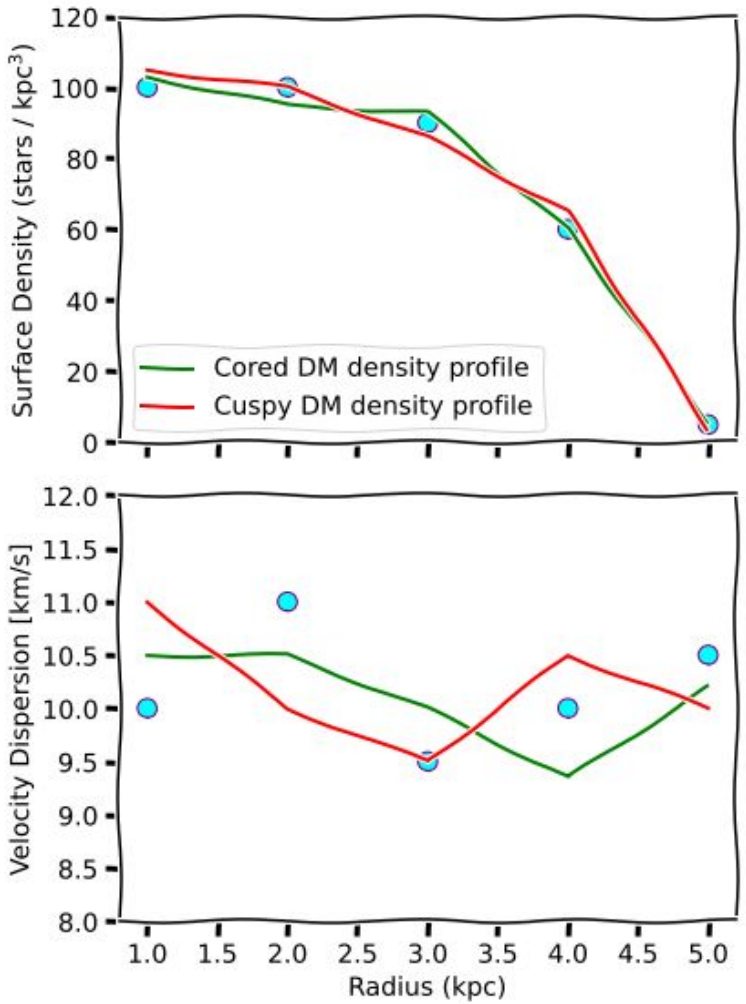
4.0
4.5
5.0
Radius (kpc)


DEC
RA
1.0
0.8
0.6
0.4
0.2
0.0
$v_{los}[km/s]$


Surface Density (stars / kpc^3)
120
100
80
60
40
20
0
Velocity Dispersion [km/s]
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Radius (kpc)


DEC
RA
1.0
0.8
0.6
0.4
0.2
0.0
$v_{los}[km/s]$


Surface Density (stars / kpc^3)
120
100
80
60
40
20
0
Cored DM density profile
Cuspy DM density profile
Velocity Dispersion [km/s]
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Radius (kpc)

Models: Action-based distribution functions

Stellar component:

$$f(\boldsymbol{J}(\boldsymbol{R},\boldsymbol{v})) = \frac{M}{(2\pi J_0)^3}\left[1+\left(\frac{J_0}{h(\boldsymbol{J})}\right)\right]^{\Gamma}\left[1+\left(\frac{g(\boldsymbol{J})}{J_0}\right)\right]^{-\mathrm{B}}$$

$$g(\boldsymbol{J}) \equiv g_r J_r + g_z J_z + (3-g_r-g_z)\left|J_\phi\right|$$

$$h(\boldsymbol{J}) \equiv h_r J_r + h_z J_z + (3-h_r-h_z)\left|J_\phi\right|,$$

Multiple components

(See G. Battaglia's ta

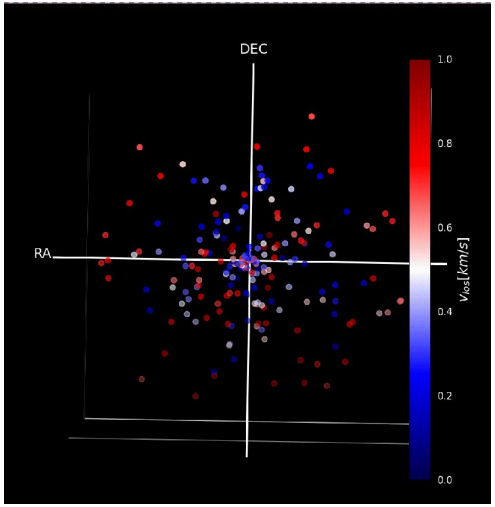
Metallicity distributions

DM component:

$$\rho = \rho_0 \left(\frac{r}{a}\right)^{-\gamma}\left[1+\left(\frac{r}{a}\right)^{\alpha}\right]^{\frac{\gamma-\beta}{\alpha}} \exp\left[-\left(\frac{r}{r_{\mathrm{cut}}}\right)^{\xi}\right]$$

$$P_d(R_i, v_{los,i}) \equiv \int_{-\infty}^{\infty} \mathrm{d}Z \int \mathrm{d}v \mathcal{E}(\mathcal{V}; v, \epsilon_v)\, f(\boldsymbol{J}(\boldsymbol{x},\boldsymbol{v}))S(\boldsymbol{x},\boldsymbol{v}),$$

where $\mathcal{E}(\mathcal{V}; v, \epsilon_v) \equiv \frac{1}{\sqrt{2\pi}\epsilon_v} \exp\left[-\frac{1}{2}\frac{(\mathcal{V}-v)^2}{\epsilon_V^2}\right]$



Target for this work: Sculptor

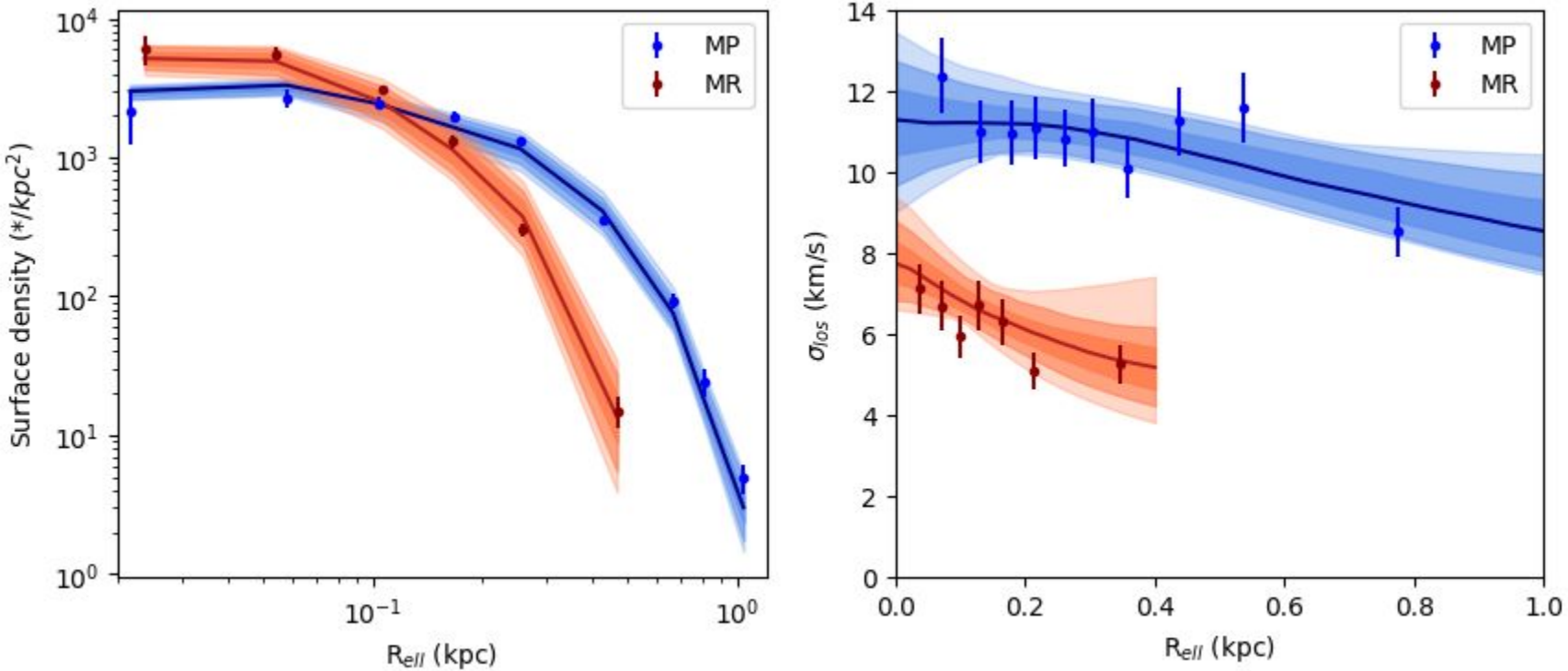
	2-pop	Method	Dataset	DF (par)	Anisotropy	Data	γ flex	result
B08	YES	Jeans	B08	2+1	rad(r)	Binned	NO	Both fit, core preferred
W11	YES	Estimator	W09	3x2	constant	Discrete	-	$0.05^{-0.39}_{-0.51}$
AE12	YES	DF	B08	3x2*	rad(r)	Binned	NO	Both fit, core preferred
B13a	NO	Schwar.	W09 & B08	-	Free	Discrete	YES	Unconstrained
B13b	NO	Schwar.	W09 & B08	-	Free	Discrete	NO	Both fit, cusp preferred
Z16	YES	Axy. Jeans	W09	3x2	Constant	Discrete	YES	0.5±0.3
S17	YES	DF	W09 / B08	8 x 2	Tang/Rad (r)	Discrete	NO	Both fit, core preferred
K19	NO	Jeans	W09	4	Free	Binned	NO	Both fit core preferred
R19	NO	Jeans	W09	5	Free	Binned	YES	$0.83^{0.3}_{-0.25}$
EM19	NO	M.L.	W09	-	-	Discrete	-	Cusp
H20	NO	Axy. Jeans	W09	2	Constant	Binned	YES	0.45±0.35
P22	NO	DF	I19	4	Free	Binned	NO	Core

Core

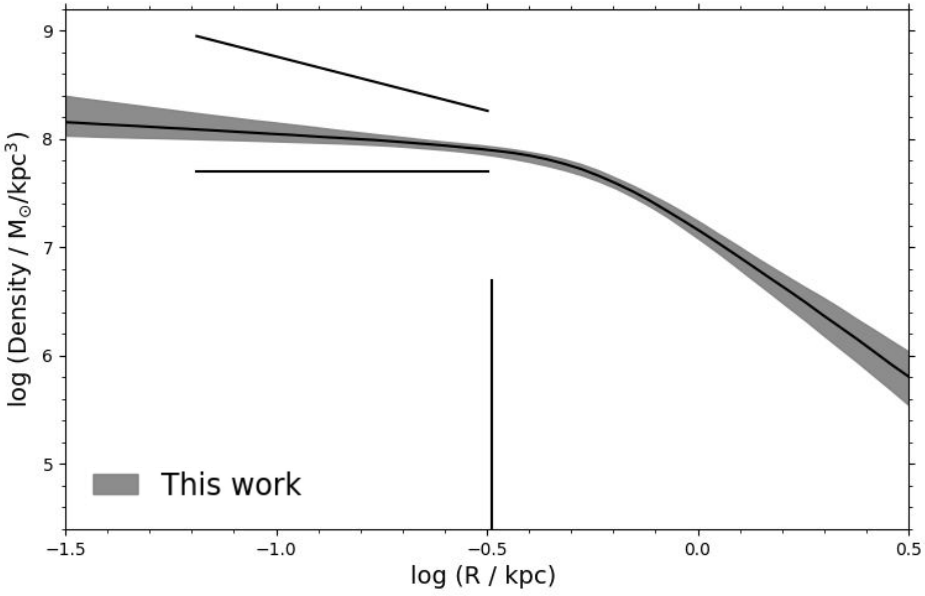
Cusp

Intermediate

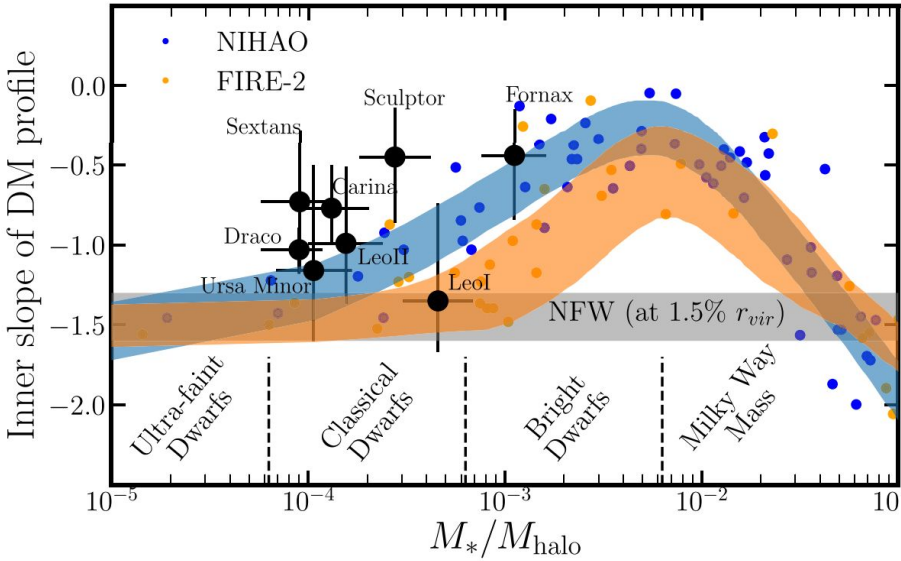
We reproduce the observed characteristics



Dark matter density profile

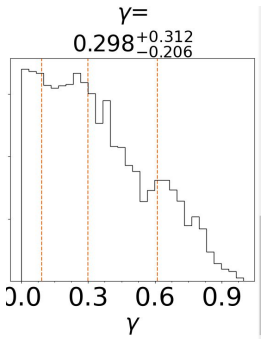


- Very dark-matter dominated
- Short star formation history



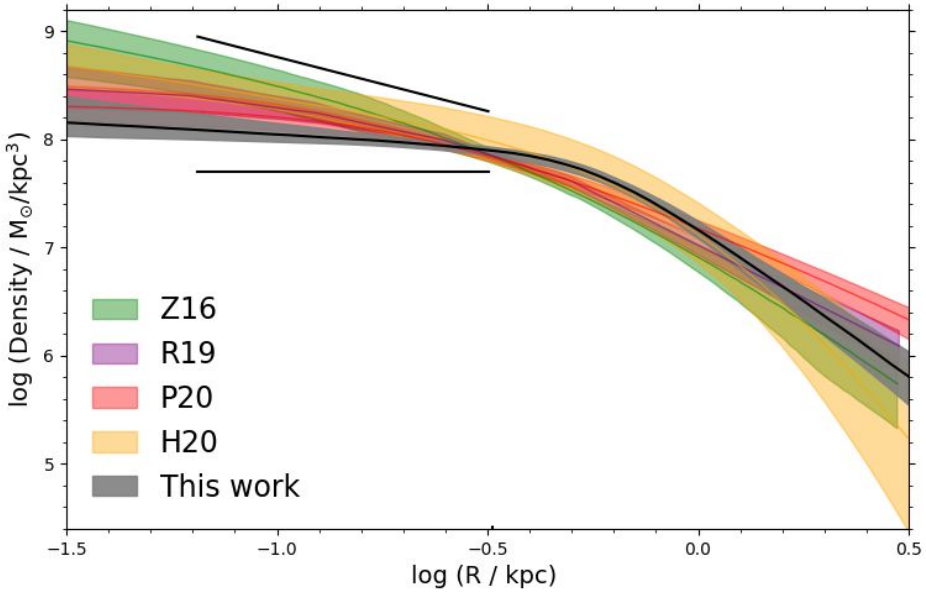
Di Cintio+ (2014), Hayashi, Chiba and Ishiyama (2020)

Inner logarithm slope :



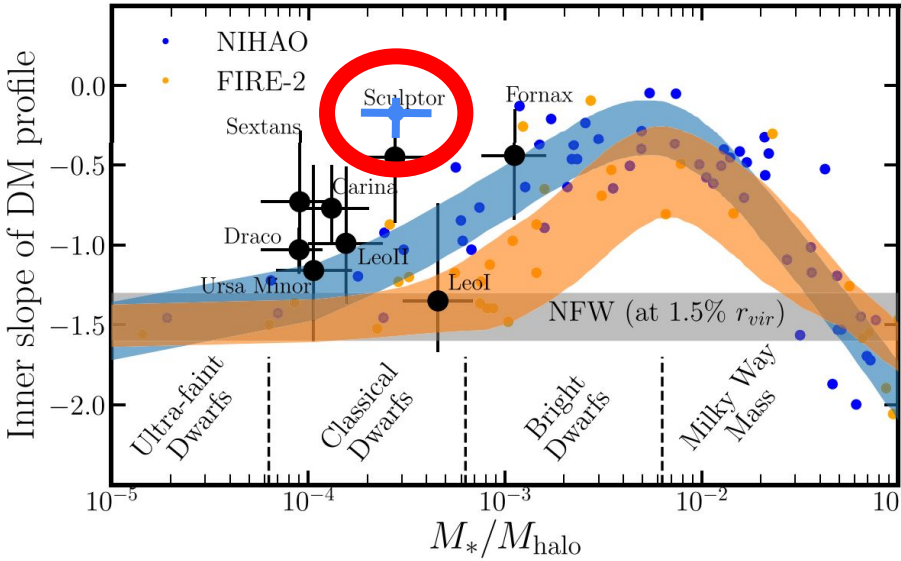
Arroyo-Polonio et al. (in prep.)

Dark matter density profile



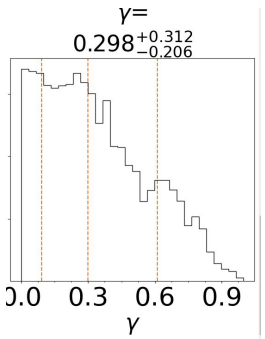
Zhu+ (2016), Read+ (2019),
Pascale (2020), Hayashi+ (2020)

- Very dark-matter dominated
- Short star formation history



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

Inner logarithm slope :



Arroyo-Polonio et al. (in prep.)

Conclusions

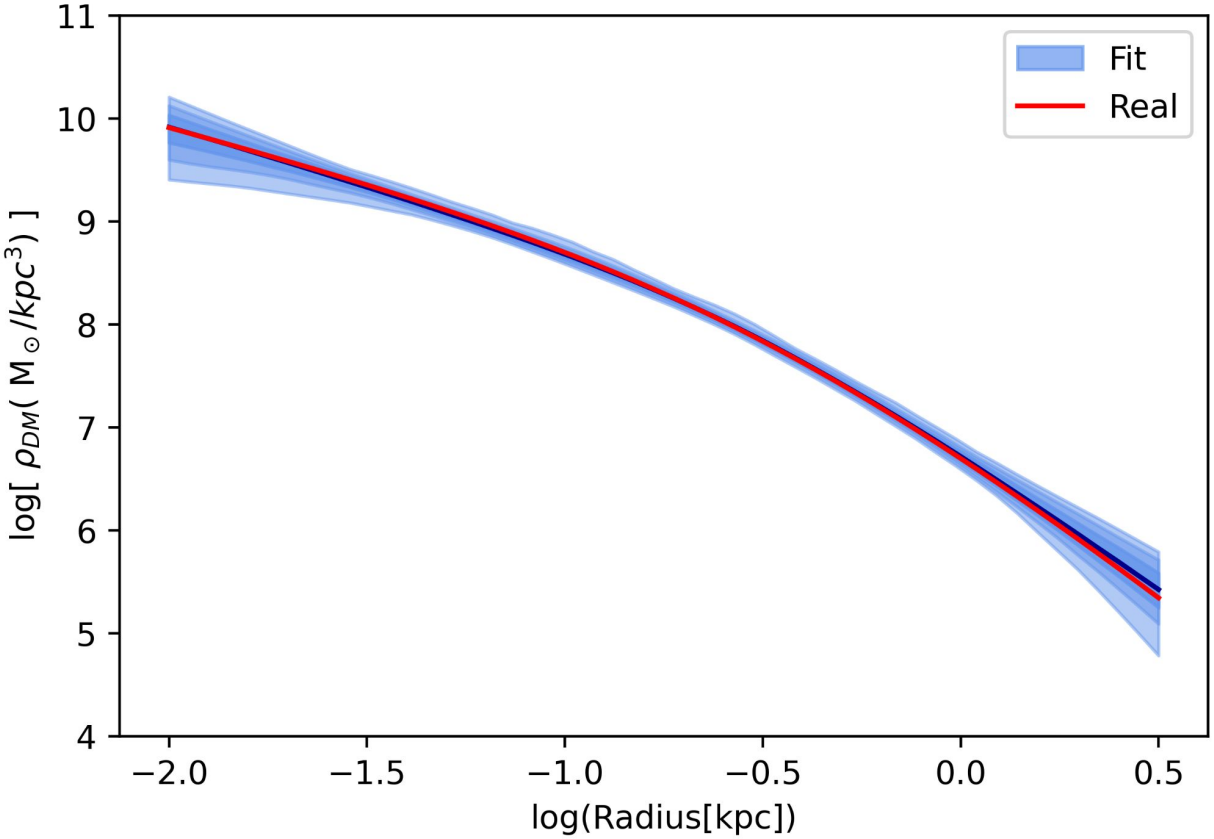
We know that,

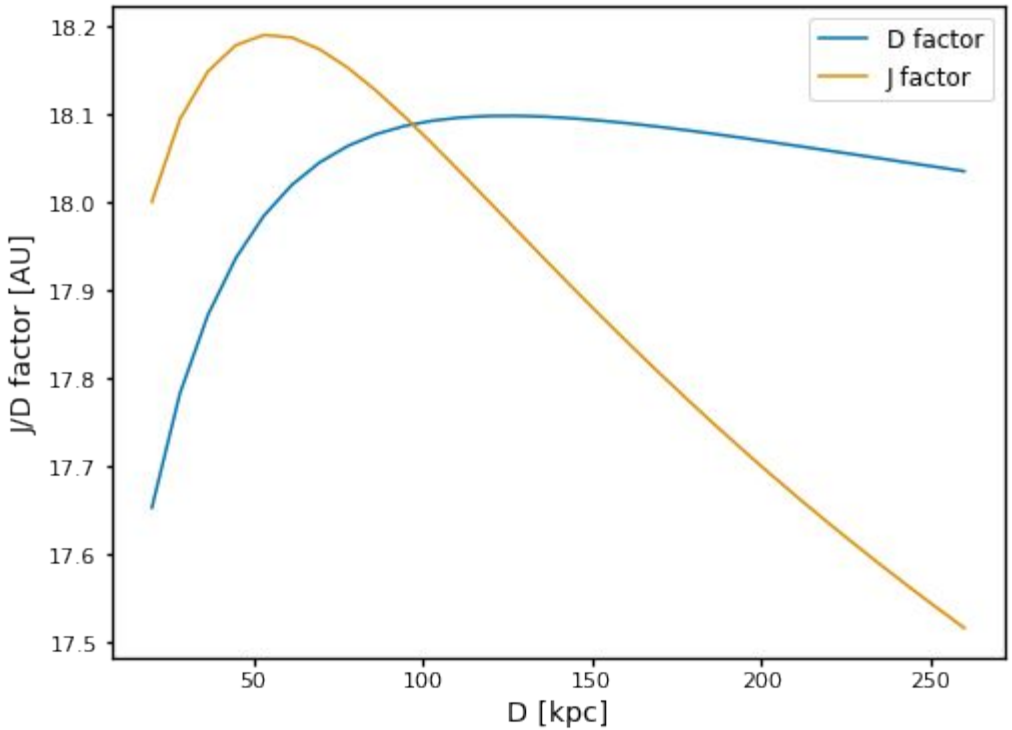
- Dwarf galaxies are excellent **dark-matter probes,**
- There are **tensions between** the expected distribution of DM in simulated dwarf galaxies and the **observed** ones,
- They can be used as targets for **DM decay and annihilation.**

However,

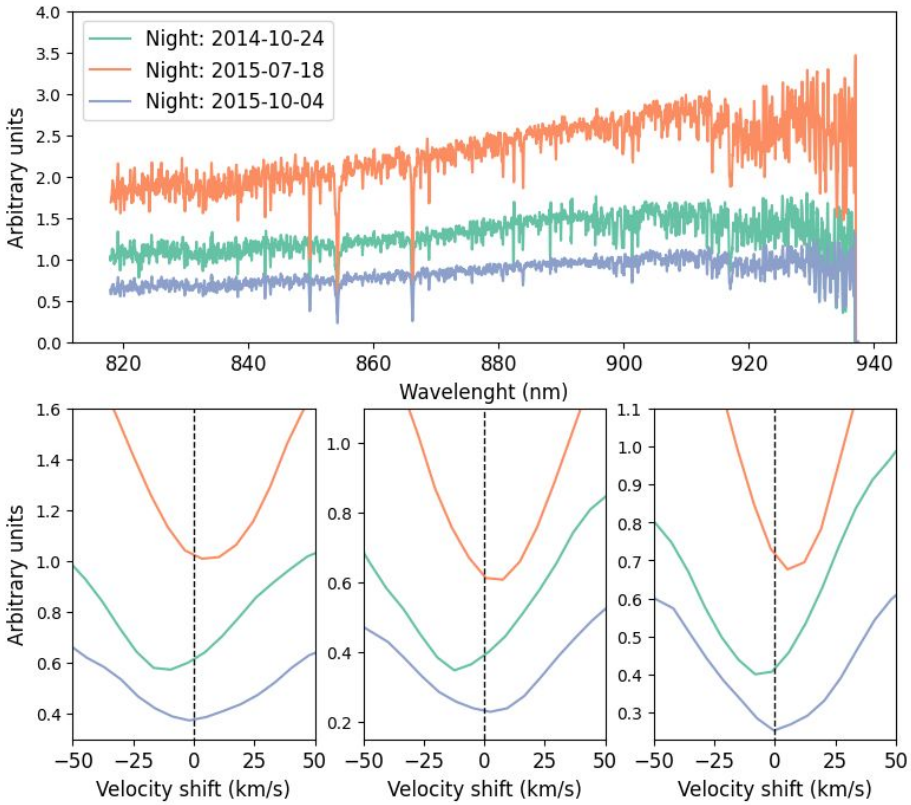
- We need to properly **know the DM density profiles** of dwarf spheroidals to have robust constraints.

Mock test on a cusped dwarf galaxy

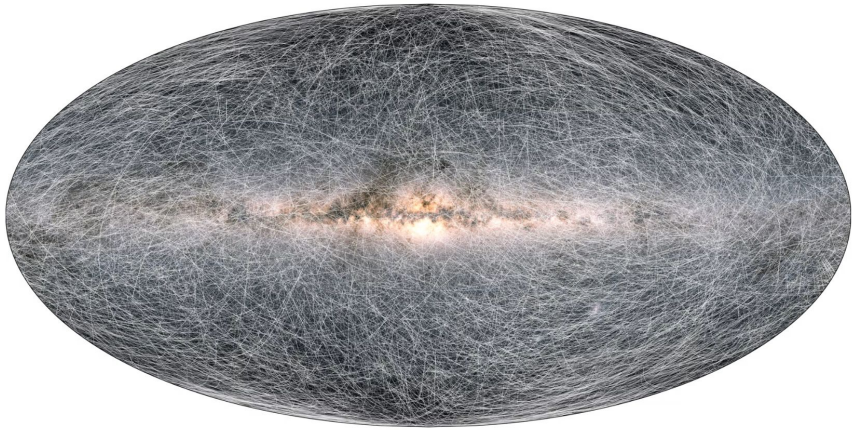



D factor
J factor
J/D factor [AU]
D [kpc]
18.2
18.1
18.0
17.9
17.8
17.7
17.6
17.5
50
100
150
200
250

Observational data



line-of-sight velocity + metallicities (proxy of age)



Tangential velocities + positions