The MUSE-Faint survey
II. The dark matter–density profile of the ultra-faint dwarf galaxy Eridanus 2

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Outline

1. Introduction
2. Methods
3. Results & Conclusions
4. Discussion & Summary
5. Possible questions

Cold dark matter (CDM) paradigm

- Cold -> moving much more slower than light
- Dark -> Only interact through gravity, no electromagnetic interaction

Problems occurs when comes to small-scale (<1Mpc, $<10^{11}M_{sun}$)

Problems

1. Missing satellite & dwarfs
2. Core-cusp problem
3. Too-big-too fail

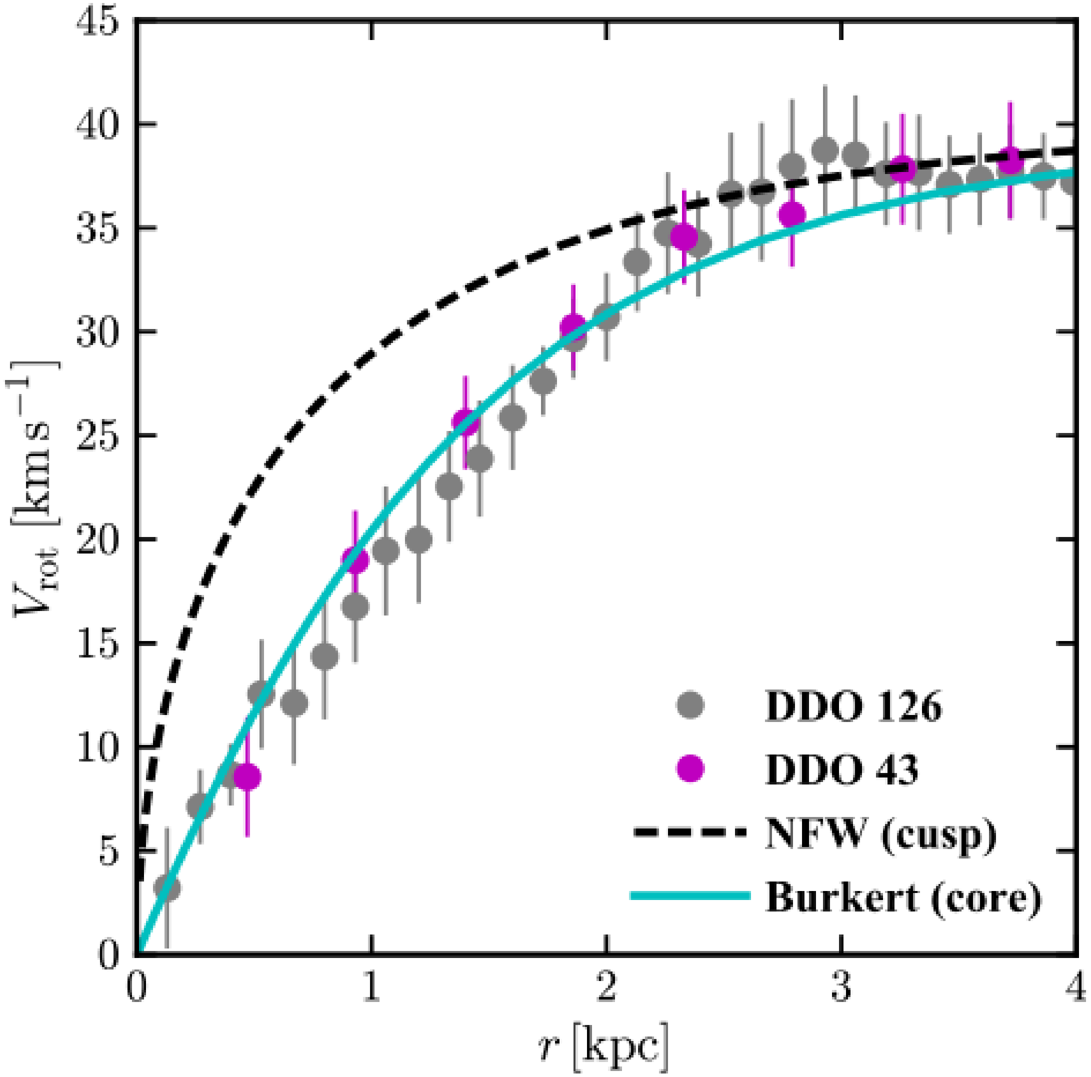
…

Solutions

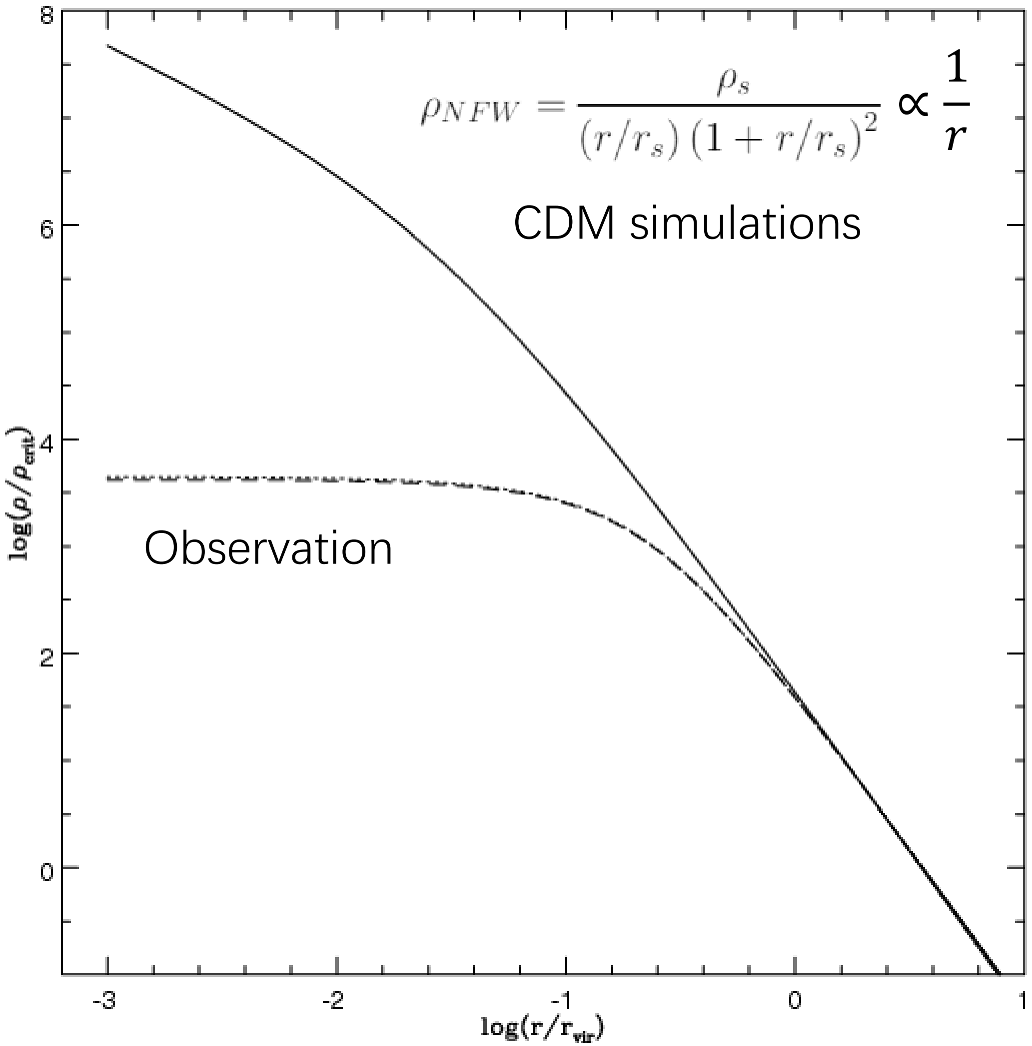
1. Alternative to CDM
2. Modify gravity laws

Bullock et al. 2017

Core-cusp problem: the observed cores of dark-matter dominated galaxies are both less dense and less cuspy than predicted in CDM.



Bullock et al. 2017



Del Popolo, Astrophys.J.698(2009)

- CDM (NFW profile)

$$\rho_{\rm CDM}(r;\rho_0,r_{\rm s}) = \frac{\rho_0}{(r/r_{\rm s})(1+r/r_{\rm s})^2},$$

- Self interacting DM (SIDM): energy & momentum exchange btw DM particles

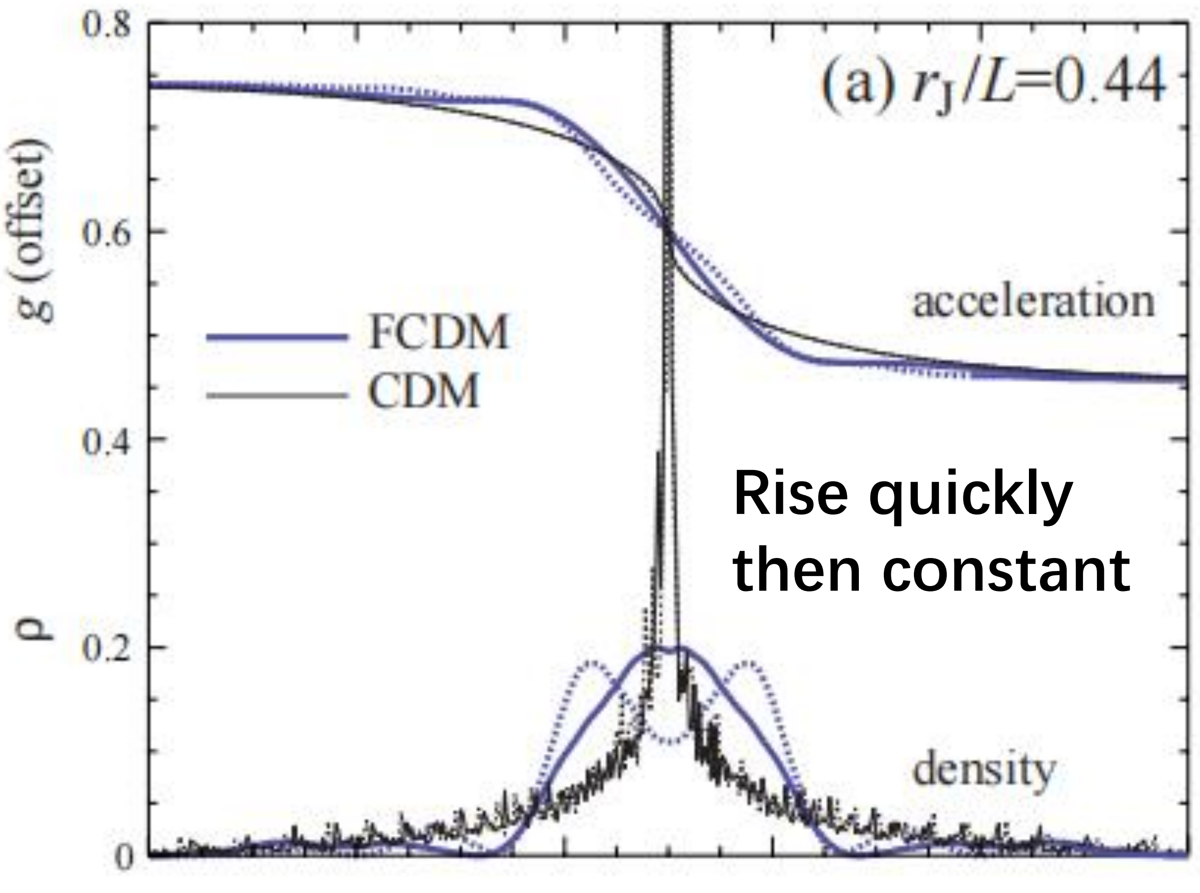
$$\rho_{\rm SIDM}(r;\rho_0,r_{\rm c},r_{\rm s}) = \frac{\rho_0}{r_{\rm c}/r_{\rm s} + (r/r_{\rm s})(1+r/r_{\rm s})^2}$$

- Fuzzy CDM (FCDM): axion, wave-like (quantum-mechanic) at center

$$\rho_{\rm FDM}(r;\rho_{\rm sol,0},r_{\rm sol},\rho_{\rm CDM,0},r_{\rm s}) = \begin{cases}\rho_{\rm sol}(r;\rho_{\rm sol,0},r_{\rm sol}), & (r<r_{\rm t}),\\ \rho_{\rm CDM}(r;\rho_{\rm CDM,0},r_{\rm s}), & (r\geq r_{\rm t}),\end{cases}$$

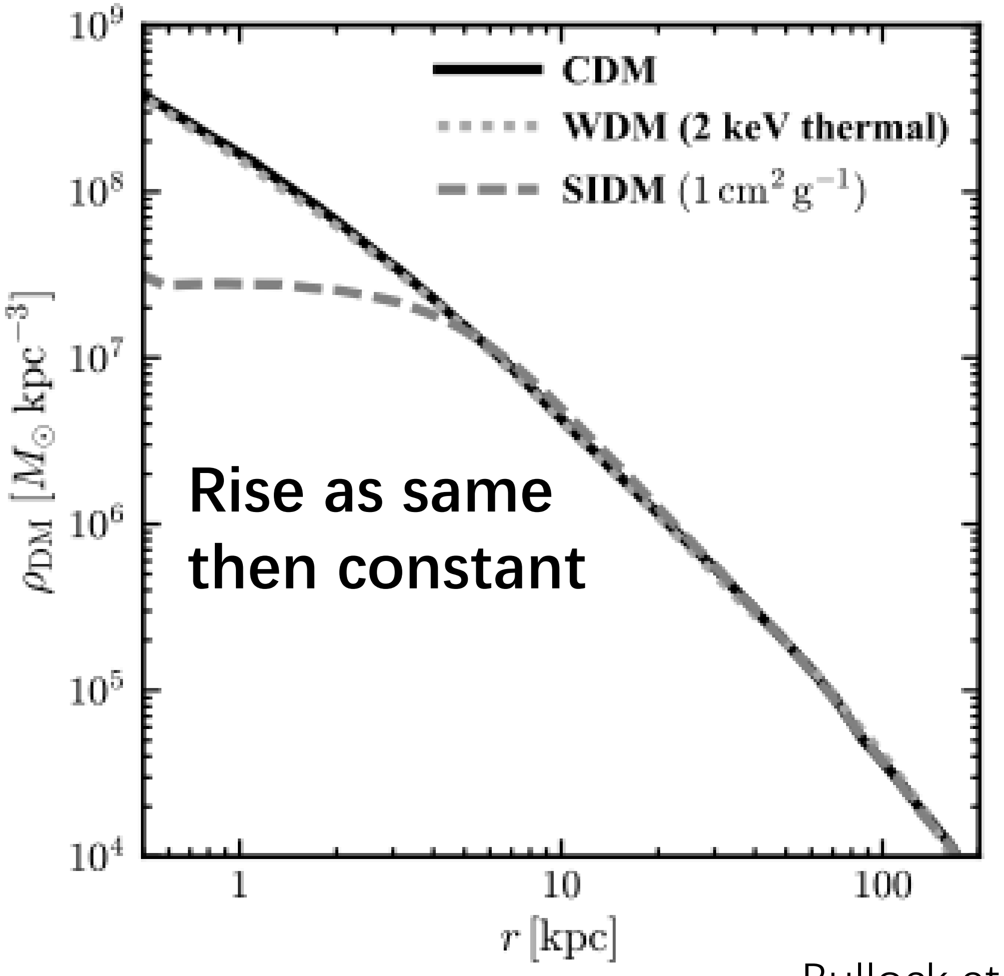
$$\rho_{\rm sol}(r;\rho_{\rm sol,0},r_{\rm sol}) = \frac{\rho_{\rm sol,0}}{(1+(r/r_{\rm sol})^2)^8}.$$

Use alternative DM model to solve the core-cusp problem



Rise quickly then constant

Hu et al. 2000

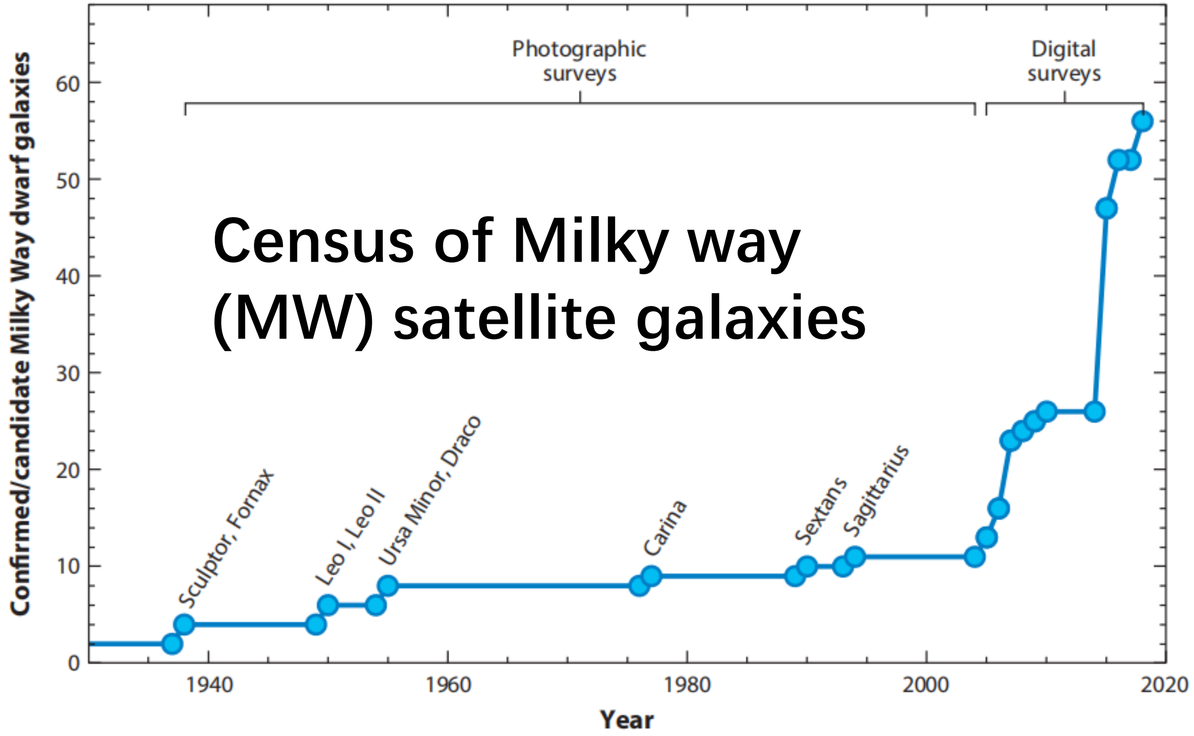


Rise as same then constant

Bullock et al. 2017

Ultra-faint dwarf galaxy (UFDs) as Dark Matter laboratory

- Lowest luminosity $M_V > -7.7$; $M_* < 10^5 M_{sun}$; $L < 10^5 L_{sun}$
- Oldest, most metal-poor, most DM-dominated
- Baryon influence to DM density profile is dynamically negligible
- probes of dark matter on smaller scales (~20–30 pc)

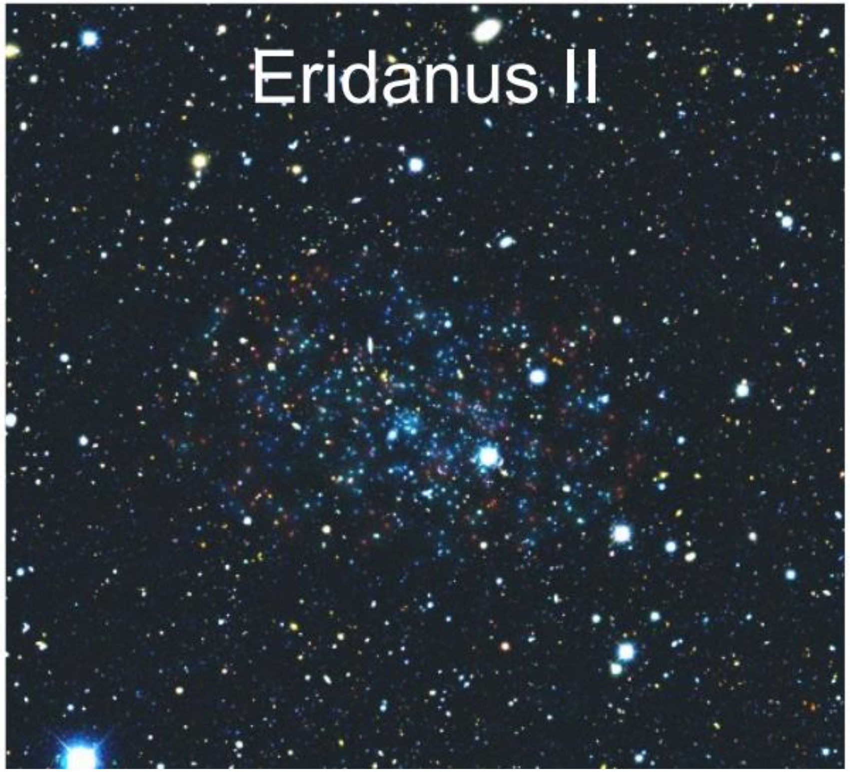


Census of Milky way (MW) satellite galaxies

Simon et al. 2019

Eridanus-2

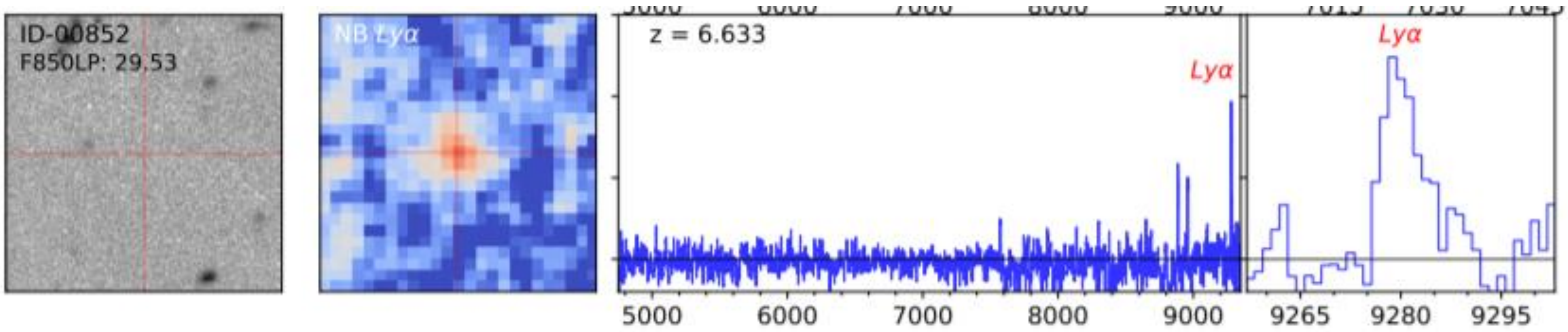
- One of the largest, most luminous, and most distant MW-satellite galaxy
- M_V=-7.1
- $M_* \approx 9 \times 10^4 M_{sun}$
- Small globular star cluster in the center (not supported in this paper)



Li, 2017,Brandt,2016
https://en.wikipedia.org/wiki/Eridanus_II

Deep MUSE-Faint survey is capable of measuring faint star velocity in low-z UFDs

- Mean AB mag > 31



HST broadband image

MUSE-reconstructed
Lyα emission line image

MUSE source spectrum

Roland et al. 2017

Purpose: Constrain parameters of CDM, Self Interacting Dark Matter (SIDM) ,Fuzzy CDM (FCDM) and calculate their possibility

Method

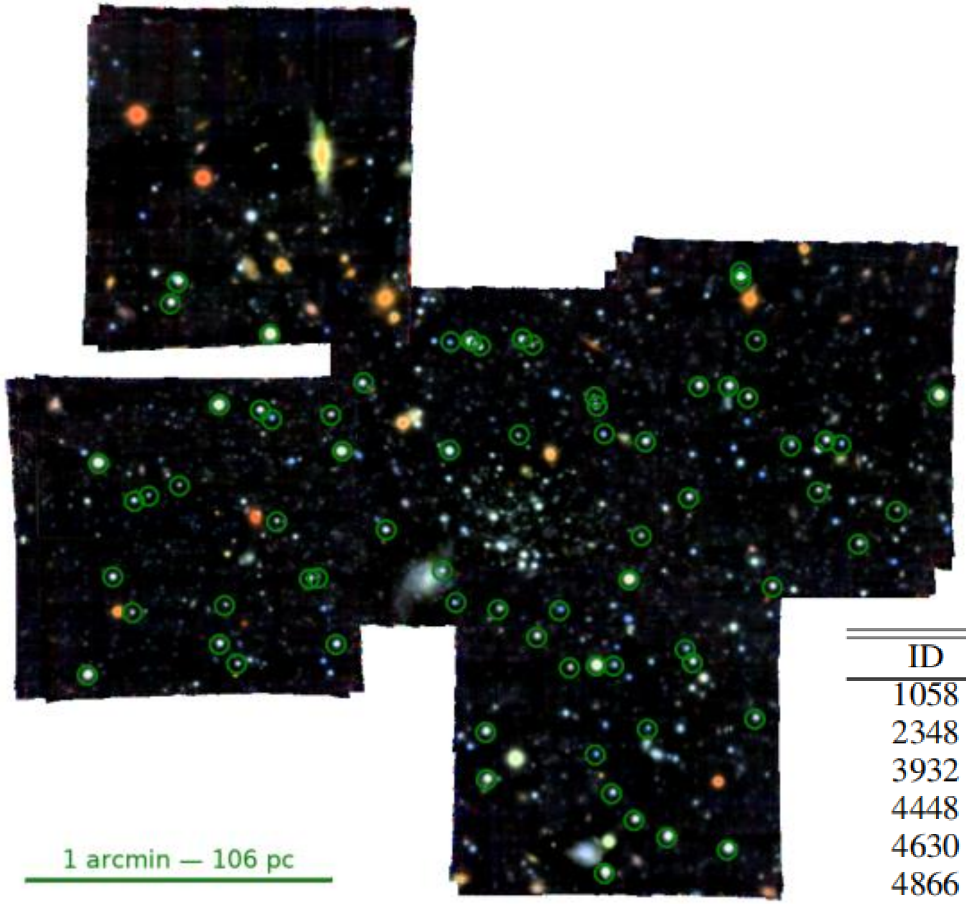
1. Measure the stars' velocity in Eri-2 as input

2. Constrain parameters of 3 models

3. Recover the DM density profile

4. Calculate model evidence

Samples

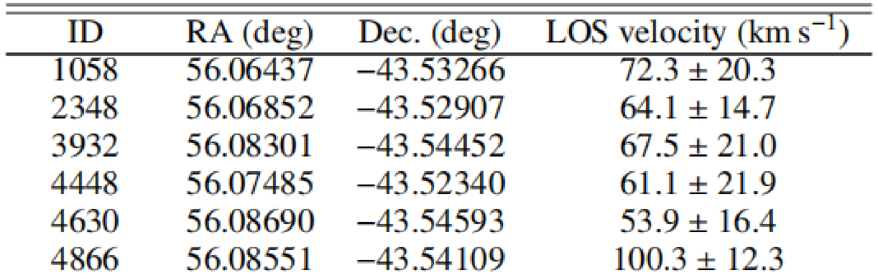


Total 92 stars

MUSE-Faint
64 stars

8
stars

Dark Energy Survey
(DES)
20 stars



ID	RA (deg)	Dec. (deg)	LOS velocity (km s^{-1})
1058	56.06437	−43.53266	72.3 ± 20.3
2348	56.06852	−43.52907	64.1 ± 14.7
3932	56.08301	−43.54452	67.5 ± 21.0
4448	56.07485	−43.52340	61.1 ± 21.9
4630	56.08690	−43.54593	53.9 ± 16.4
4866	56.08551	−43.54109	100.3 ± 12.3

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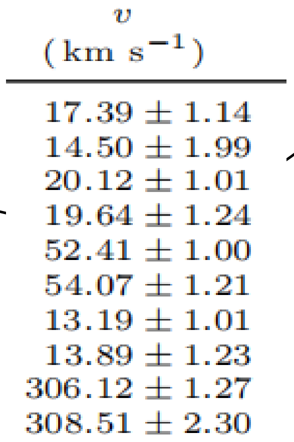


v (km s^{-1})
17.39 ± 1.14
14.50 ± 1.99
20.12 ± 1.01
19.64 ± 1.24
52.41 ± 1.00
54.07 ± 1.21
13.19 ± 1.01
13.89 ± 1.23
306.12 ± 1.27
308.51 ± 2.30

…

72 stars from MUSE-Faint

Zoutendijk et al. 2021

Li et al. 2017

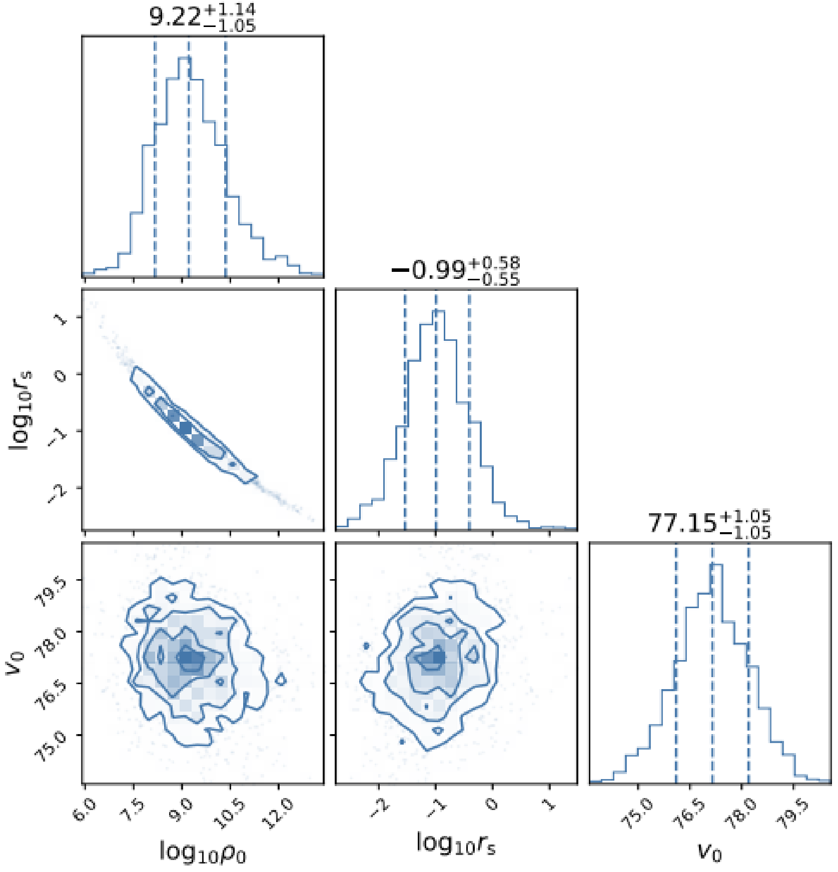
Challenge of converting 2d to 3d

- Only know projected positions & radial velocity of the stars
- So when converting it into 3d, there are velocity anisotropy & mass degeneracy

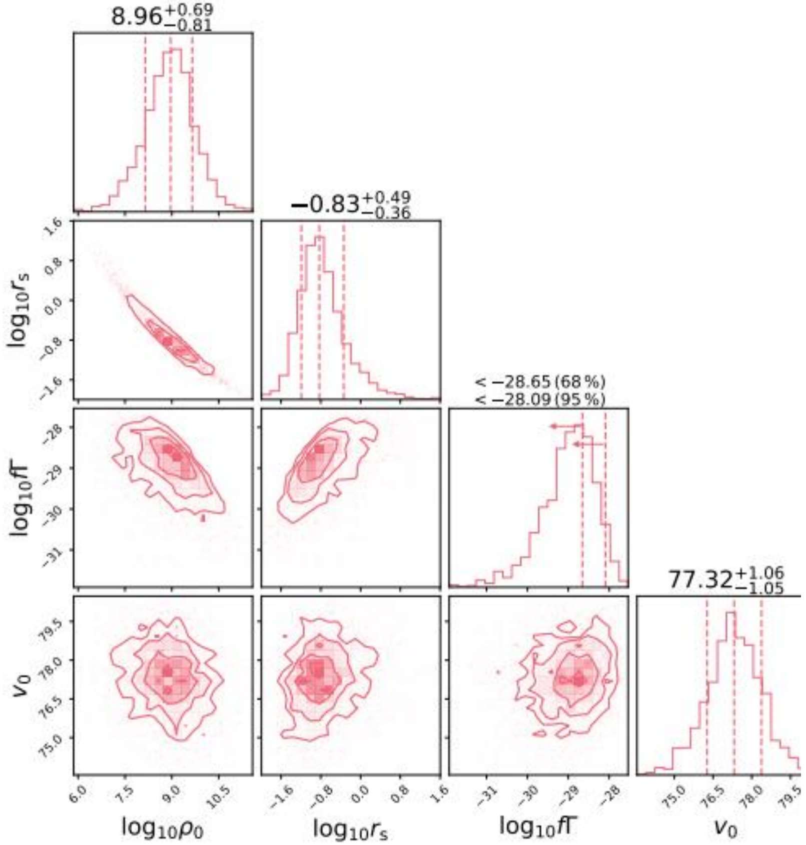
- Use 2 tools to derive density profiles:

1. CJAM
2. PyGravSphere

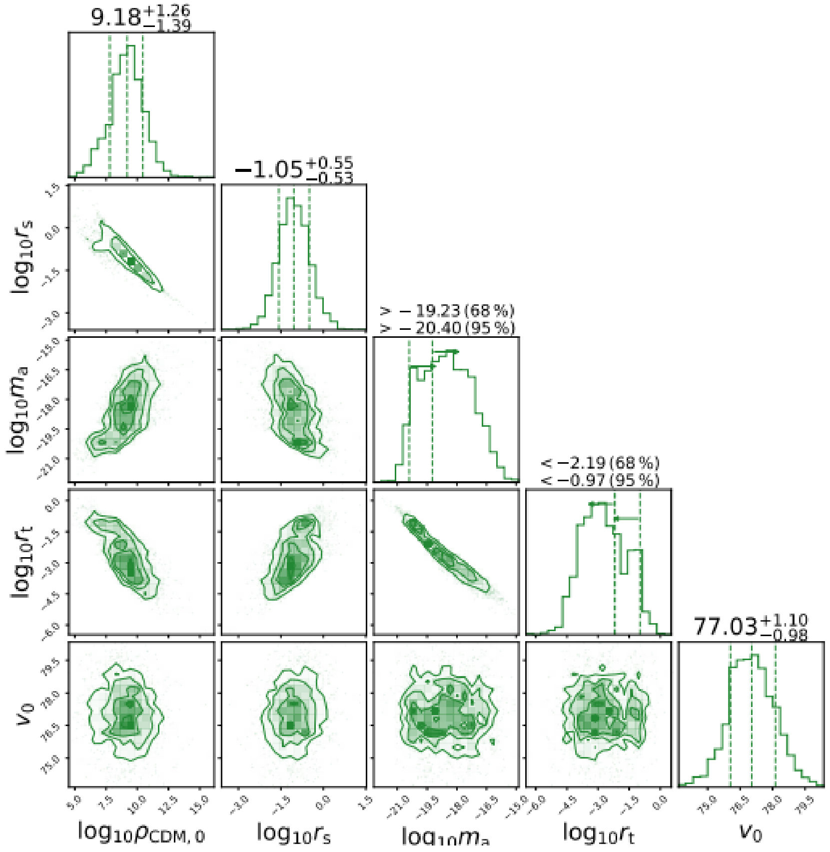
Results
Parameters of alternative DM models



CDM assumption



SIDM assumption



FCDM assumption

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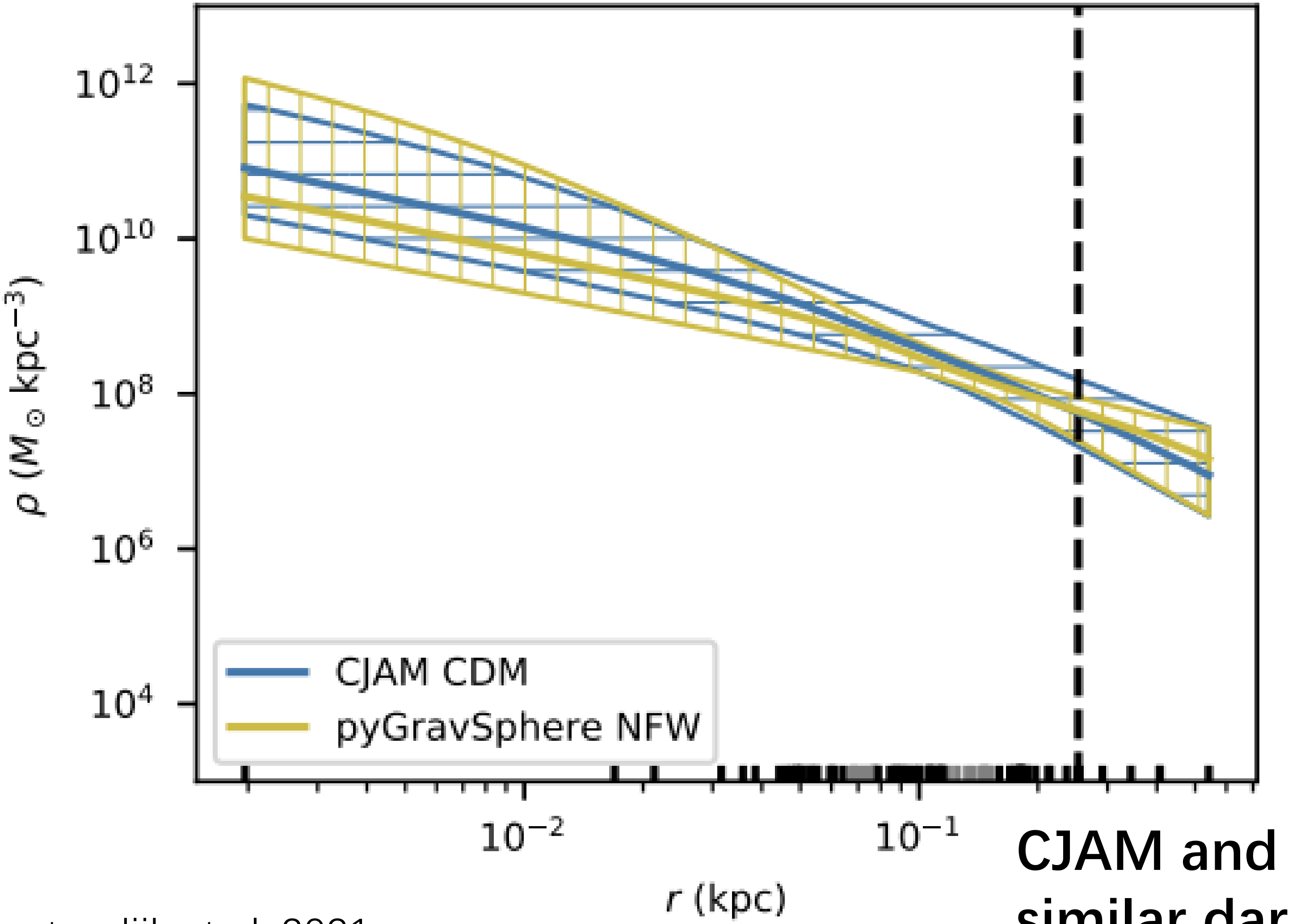
Results
Recovered DM density profile



Virial mass

$M_{200} \sim 10^8\ M_{sun}$

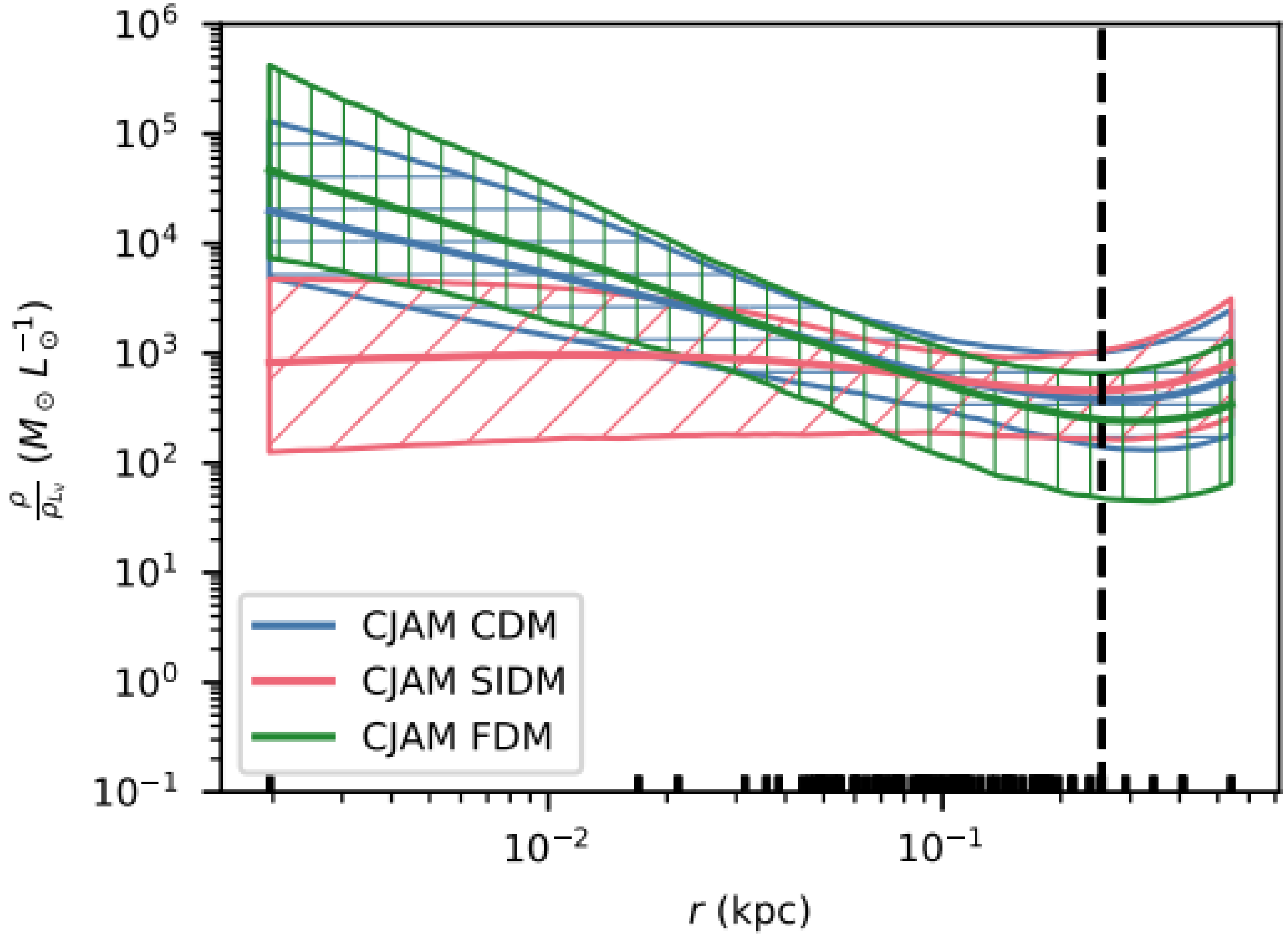
Maximum circular velocities

$V_{\max} \sim 10^{1.2}$–$10^{1.4}$ km s^{-1}

CJAM and pyGravSphere recover similar dark matter–density profiles for CDM

Zoutendijk et al. 2021

Results
Recovered de-projected mass-to-light profiles



FCDM > CDM >> SIDM, FCDM>>SIDM

Summary

- Introduction
  - Core-cusp problem & alternative for CDM
  - **Ultra-faint dwarf galaxies** (UFDs) are **Dark Matter** laboratory & Eri-2 is one of them
  - Deep MUSE-Faint survey is capable of measuring faint star velocity in low-z UFDs
- Methods
  - Using stars' velocity in UFDs to constrain parameters of CDM, Self Interacting Dark Matter (SIDM) ,Fuzzy CDM (FCDM) and calculate their possibility.
- Results
  - Constrain the 3 models' parameters
  - Uncertain about the survival or location of the star cluster
  - CJAM and pyGravSphere recover similar dark matter–density profiles for CDM
  - Not significant to rule out any models

Discussion

- Eri-2’s shape is elliptical (0.45), but pyGravSphere only spherical
- What if DM is made up of several forms, such as mixture of MACHO （MAssive Compact Halo Objects） & WIMP?
- It doesn’t contain proper motion, which means the measurement wouldn’t be accurate enough or the samples may not sufficient to distinguish cusp from core central profile.
- More samples:
  - 1. Deeper observation: current high-resolution spectrographs are not able to reach the spatial resolution required for these crowded systems.
  - 2. Extend study to multiple UFDs

Possible questions

1. What’s the prior probability for the two methods? (How did the Bayes inference conduct?)
2. How will the baryon influence the dark matter density structure?
3. Are there any other method to detect DM via UFDs?

1. What’s the prior probability for the two methods? (How did the Bayes inference conduct?)

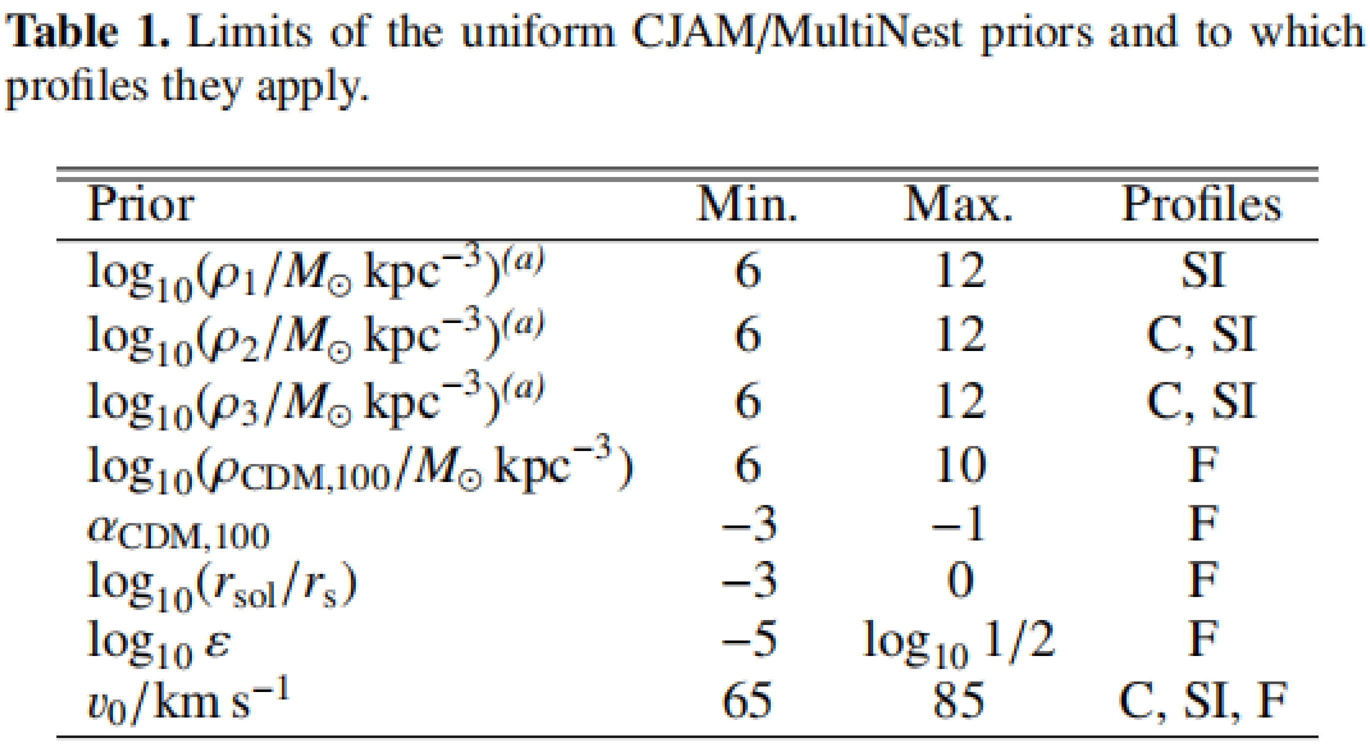


Table 1. Limits of the uniform CJAM/MultiNest priors and to which profiles they apply.

Prior	Min.	Max.	Profiles
$\log_{10}(\rho_1/M_\odot\,\mathrm{kpc}^{-3})^{(a)}$	6	12	SI
$\log_{10}(\rho_2/M_\odot\,\mathrm{kpc}^{-3})^{(a)}$	6	12	C, SI
$\log_{10}(\rho_3/M_\odot\,\mathrm{kpc}^{-3})^{(a)}$	6	12	C, SI
$\log_{10}(\rho_{\mathrm{CDM},100}/M_\odot\,\mathrm{kpc}^{-3})$	6	10	F
$\alpha_{\mathrm{CDM},100}$	−3	−1	F
$\log_{10}(r_{\mathrm{sol}}/r_{\mathrm{s}})$	−3	0	F
$\log_{10}\varepsilon$	−5	$\log_{10}1/2$	F
$v_0/\mathrm{km\,s}^{-1}$	65	85	C, SI, F

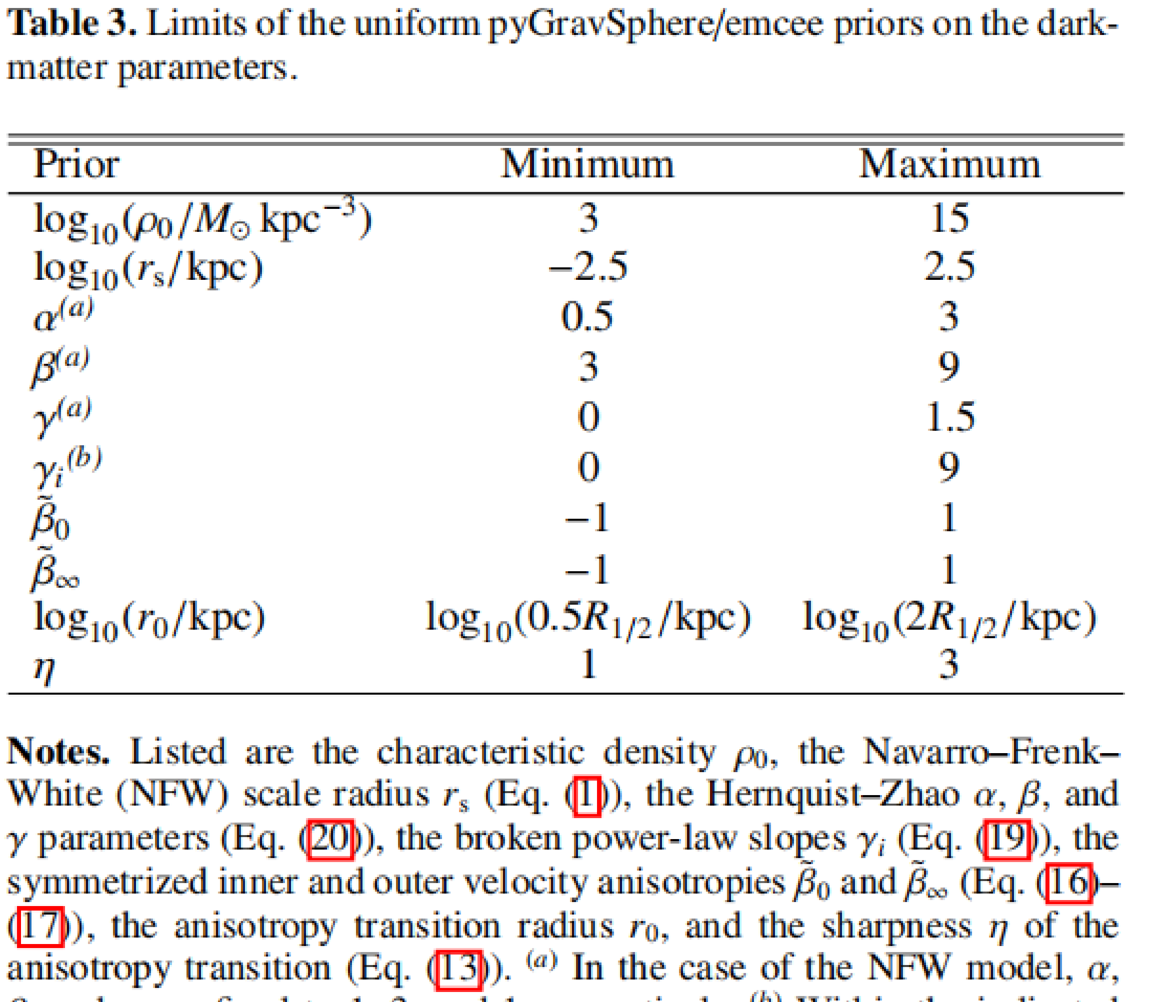


Table 3. Limits of the uniform pyGravSphere/emcee priors on the dark-matter parameters.

Prior	Minimum	Maximum
$\log_{10}(\rho_0/M_\odot\,\mathrm{kpc}^{-3})$	3	15
$\log_{10}(r_{\mathrm{s}}/\mathrm{kpc})$	−2.5	2.5
$\alpha^{(a)}$	0.5	3
$\beta^{(a)}$	3	9
$\gamma^{(a)}$	0	1.5
$\gamma_i{}^{(b)}$	0	9
$\tilde{\beta}_0$	−1	1
$\tilde{\beta}_\infty$	−1	1
$\log_{10}(r_0/\mathrm{kpc})$	$\log_{10}(0.5R_{1/2}/\mathrm{kpc})$	$\log_{10}(2R_{1/2}/\mathrm{kpc})$
η	1	3

Notes. Listed are the characteristic density ρ_0, the Navarro–Frenk–White (NFW) scale radius r_{s} (Eq. (1)), the Hernquist–Zhao α, β, and γ parameters (Eq. (20)), the broken power-law slopes γ_i (Eq. (19)), the symmetrized inner and outer velocity anisotropies $\tilde{\beta}_0$ and $\tilde{\beta}_\infty$ (Eq. (16)–(17)), the anisotropy transition radius r_0, and the sharpness η of the anisotropy transition (Eq. (13)). $^{(a)}$ In the case of the NFW model, α,

2. How will the baryon influence the dark matter density structure?

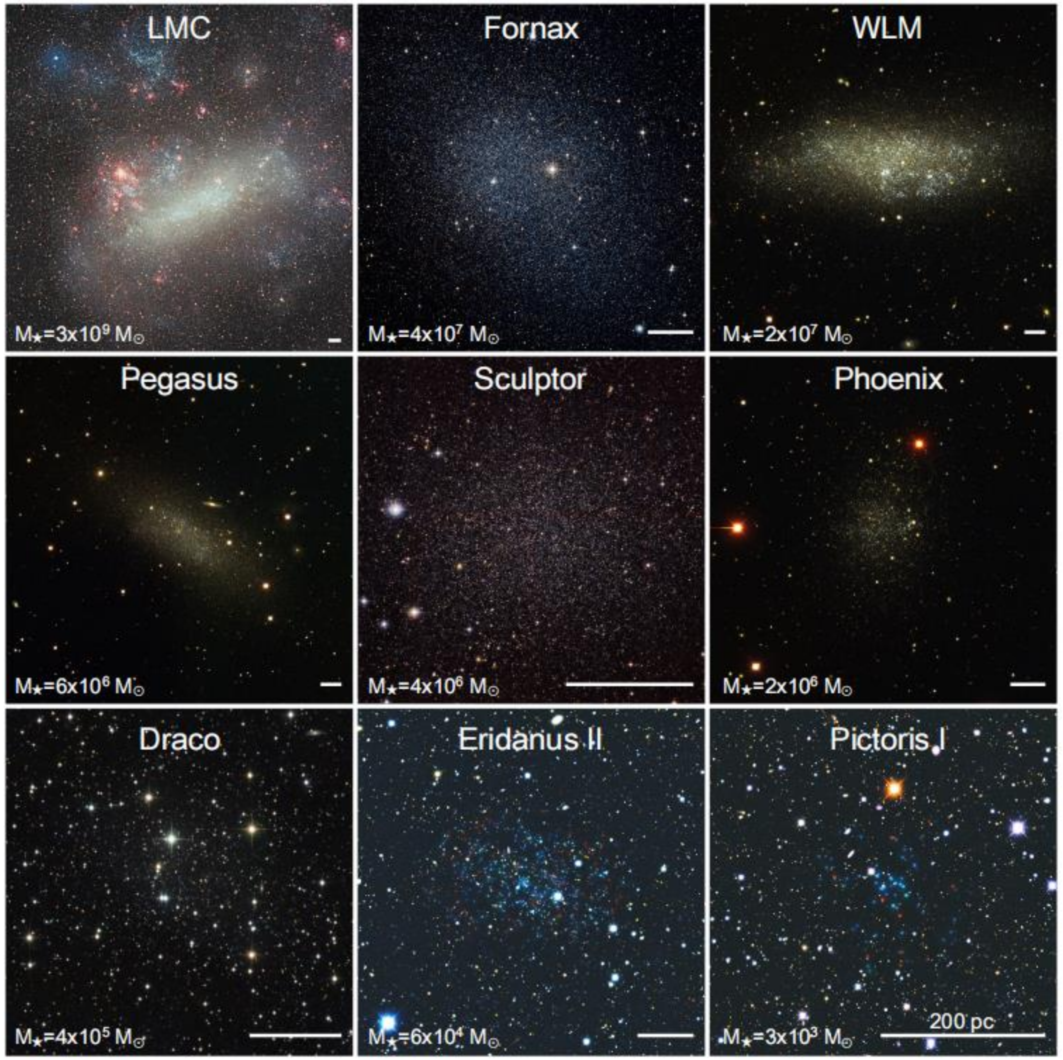
- Low star forming, few Supernovae, less stellar feedback to alter DM density stucture

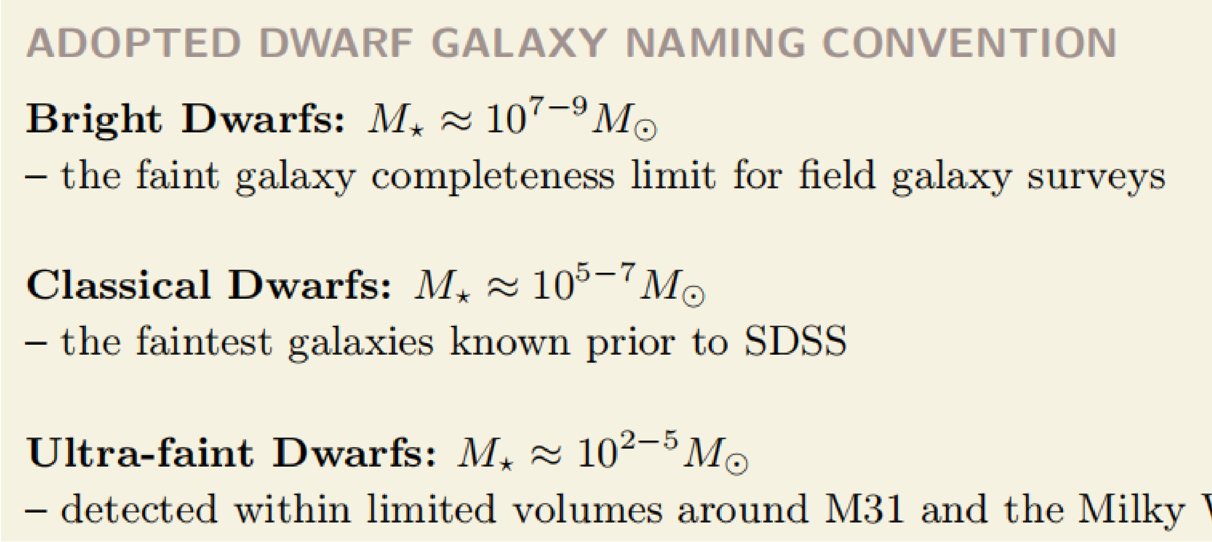
3. Are there any other method to detect DM via UFDs?

- Direct: baryonic matter velocity
- Indirect: DM annihilation generate γ-ray & radio thru synchronous

appendix

Dwarf galaxies





ADOPTED DWARF GALAXY NAMING CONVENTION

Bright Dwarfs: $M_\star \approx 10^{7-9} M_\odot$
– the faint galaxy completeness limit for field galaxy surveys

Classical Dwarfs: $M_\star \approx 10^{5-7} M_\odot$
– the faintest galaxies known prior to SDSS

Ultra-faint Dwarfs: $M_\star \approx 10^{2-5} M_\odot$
– detected within limited volumes around M31 and the Milky