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Using compact stars in Globular Clusters to constrain dark matter interactions

In collaboration with N.Raj and R. Garani

Based on arXiv:2303.18009

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Globular Clusters

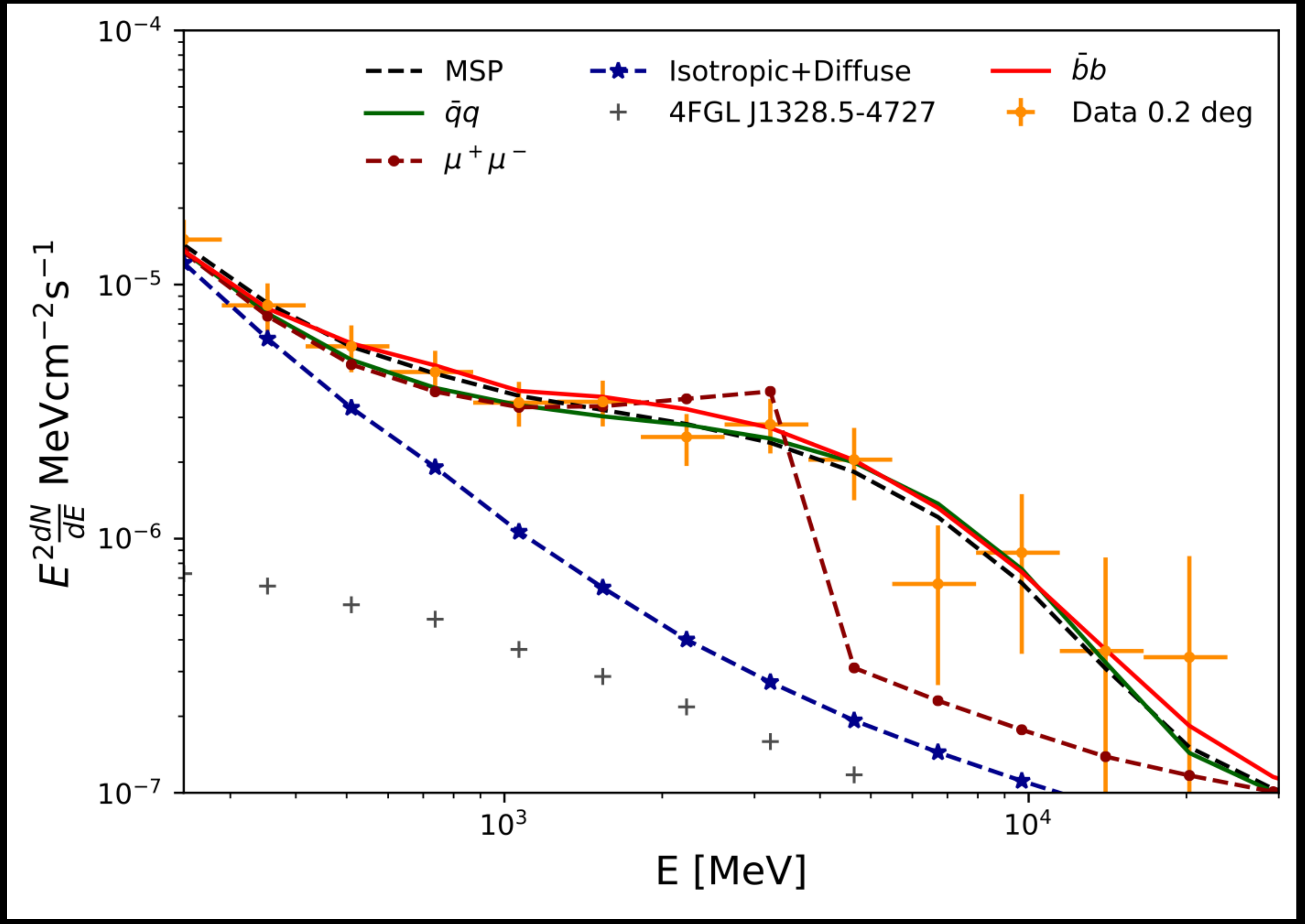
- Compact gravitational bound stellar systems
- Formation history is widely unknown
- Remnants of dark matter disrupted halo?
- Dark matter content? $\Upsilon \simeq O(1) M_\odot / L_\odot$
- Proximity makes them good candidates for ID

Omega Centauri
https://www.eso.org/public/images/eso0844a/

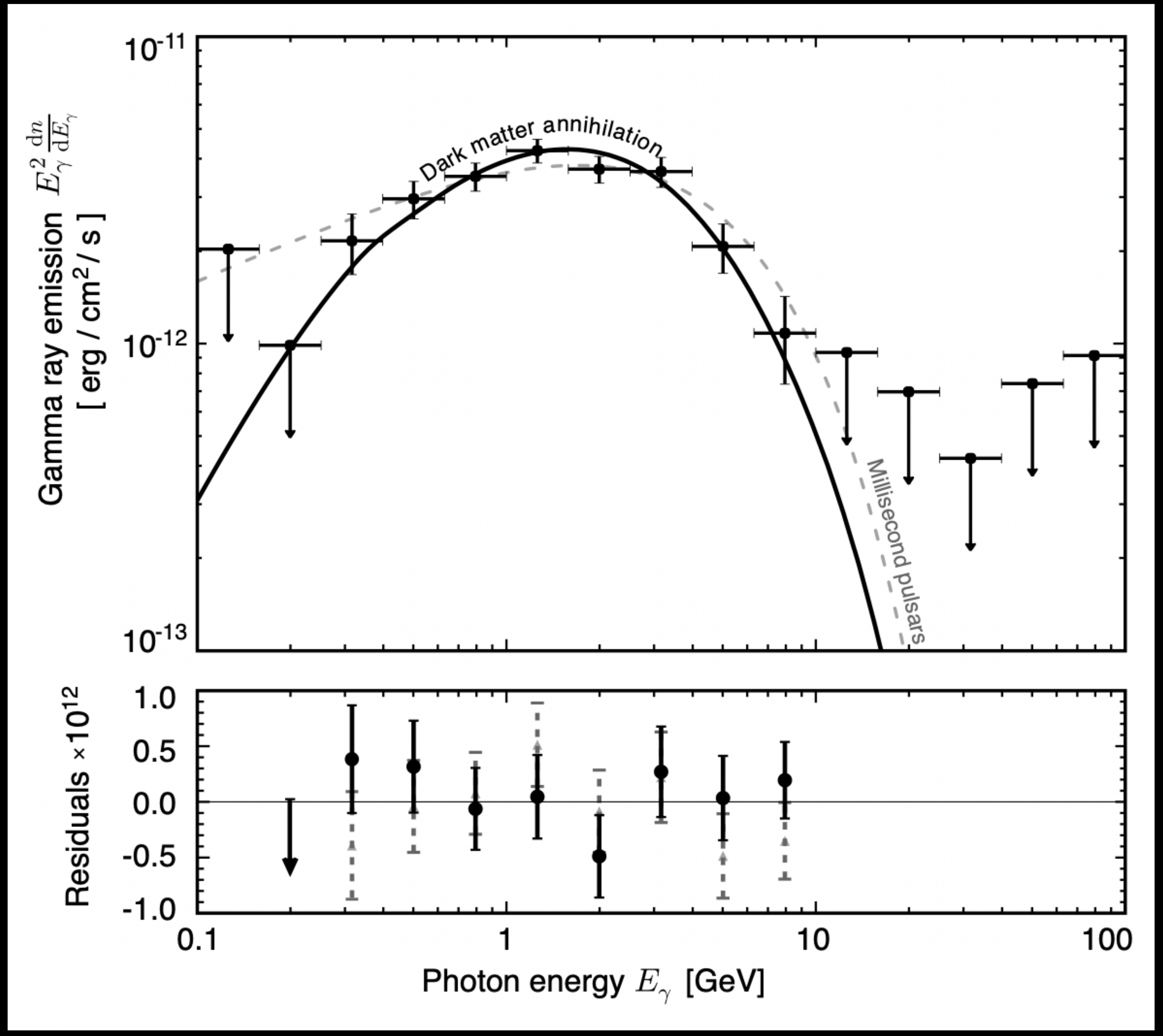
Dark Matter content and implications

It has been discussed the possibility of annihilation products visible on γ-ray experiments (Fermi-LAT) on Omega-cen and Tuc 47

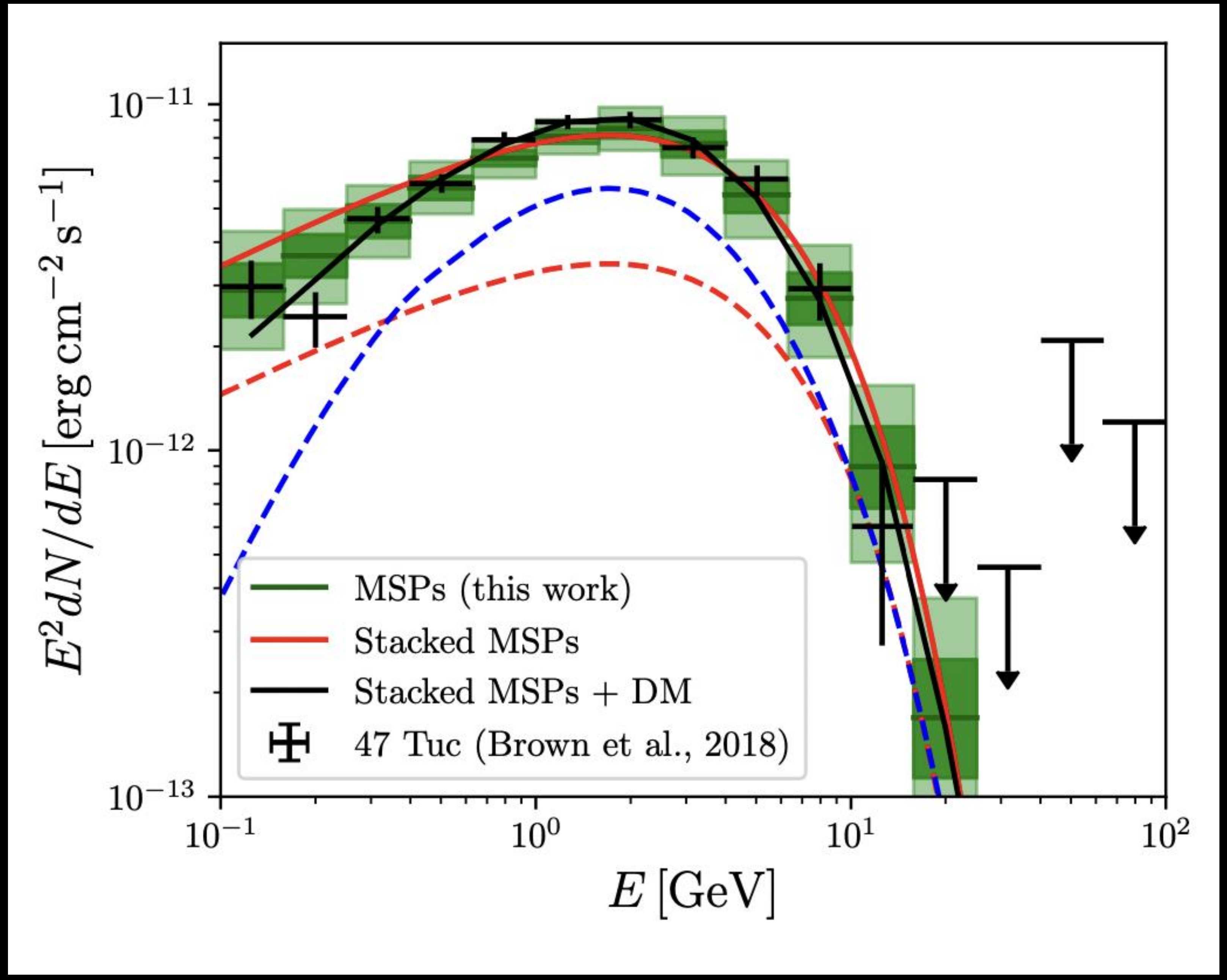
Large J-factor



arXiv:1907.06682



arXiv:1907.08564



arXiv:1807.08800

Uncertain…

Dark Matter content and implications

Furthermore…

In this work we will be focusing on M4 and White Dwarfs;
- previous works have estimated a density of $\sim 10^3 \mathrm{GeV/cm}^3$
1101.2737 based on semi-analytical models

This being the case, such density has implications in dark matter particle models

The capture and subsequent annihilation of Dark Matter by compact stars (White dwarfs) could place constrains on DM-nucleon cross sections (reliable?)

Dark matter content?

Dark Matter content

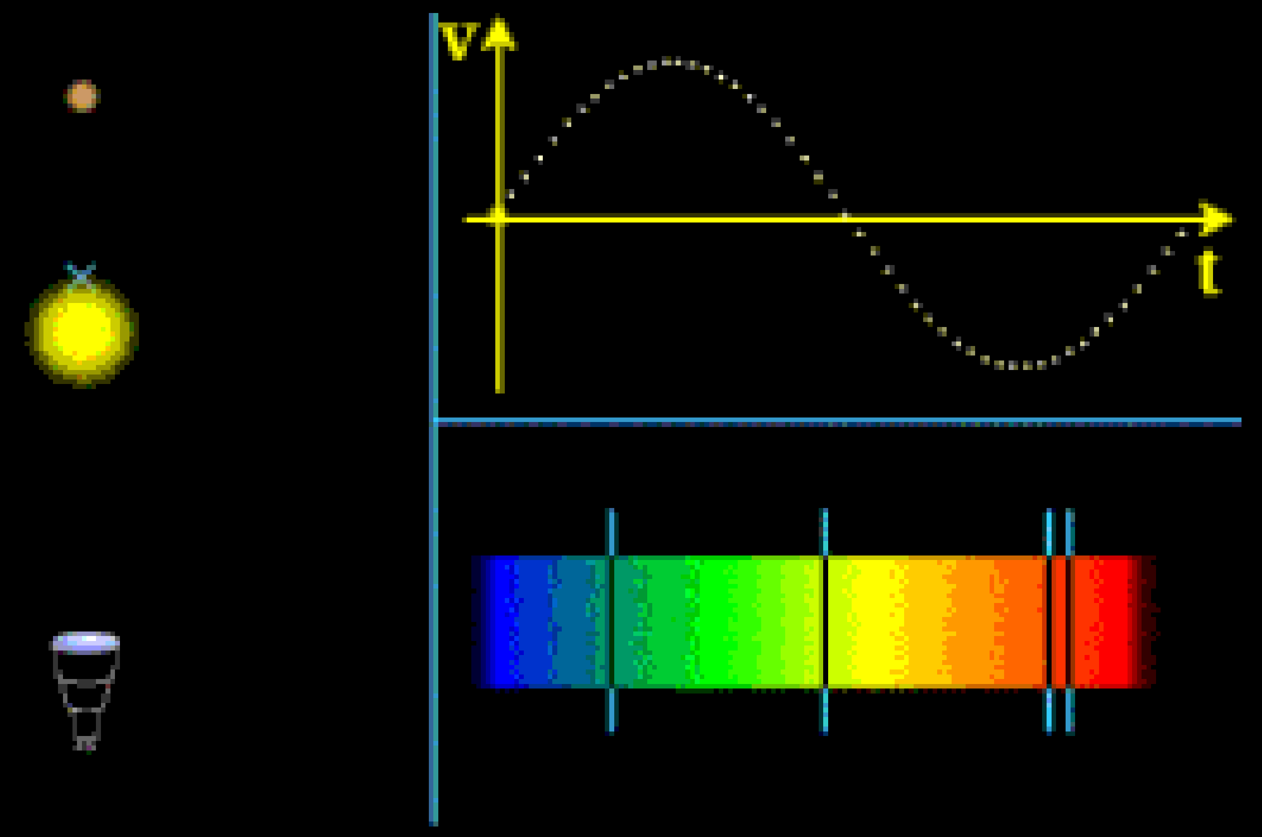
Dark Matter content on M4

We use stellar kinematics to study the mass content of M4 (radial line-of-sight velocities)

$$\frac{1}{\nu(r)}\frac{\partial}{\partial r}\left(\nu(r)\sigma^2(r)\right)+\frac{2\beta(r)\sigma^2(r)}{r}=-\frac{GM(<r)}{r^2}$$ (Spherical non collisional Jeans equation)

Where:

$\nu(r)$ stellar radial density
$\beta(r)$ orbital anisotropy
$\sigma^2(r)$ radial velocity distribution



Line-of-sight (LOS) velocities!

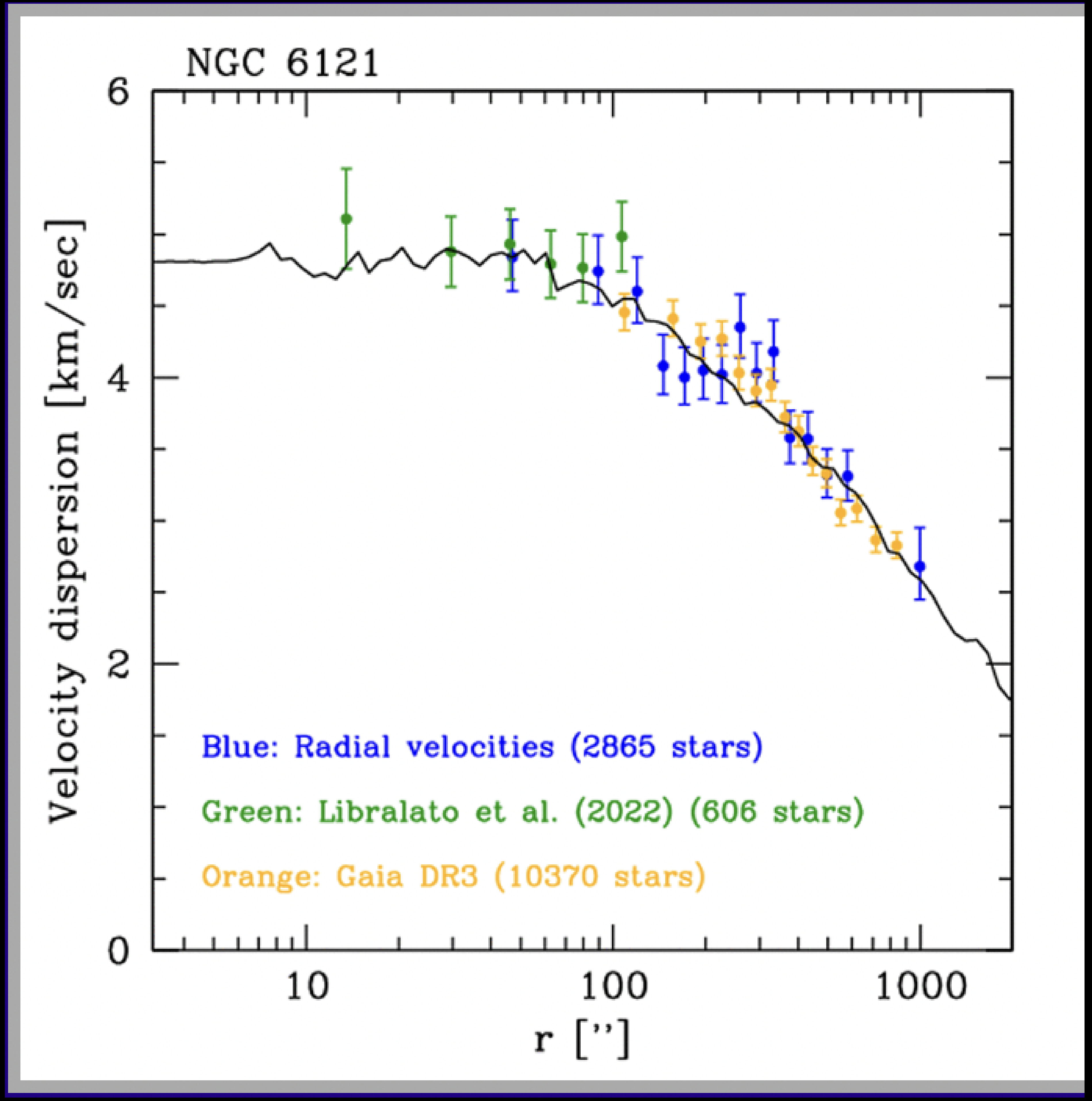
$$\Sigma_*(R)=\sum_j \frac{M_j}{\pi a_j^2}\left(1+\frac{R^2}{a_j^2}\right)^{-2}$$

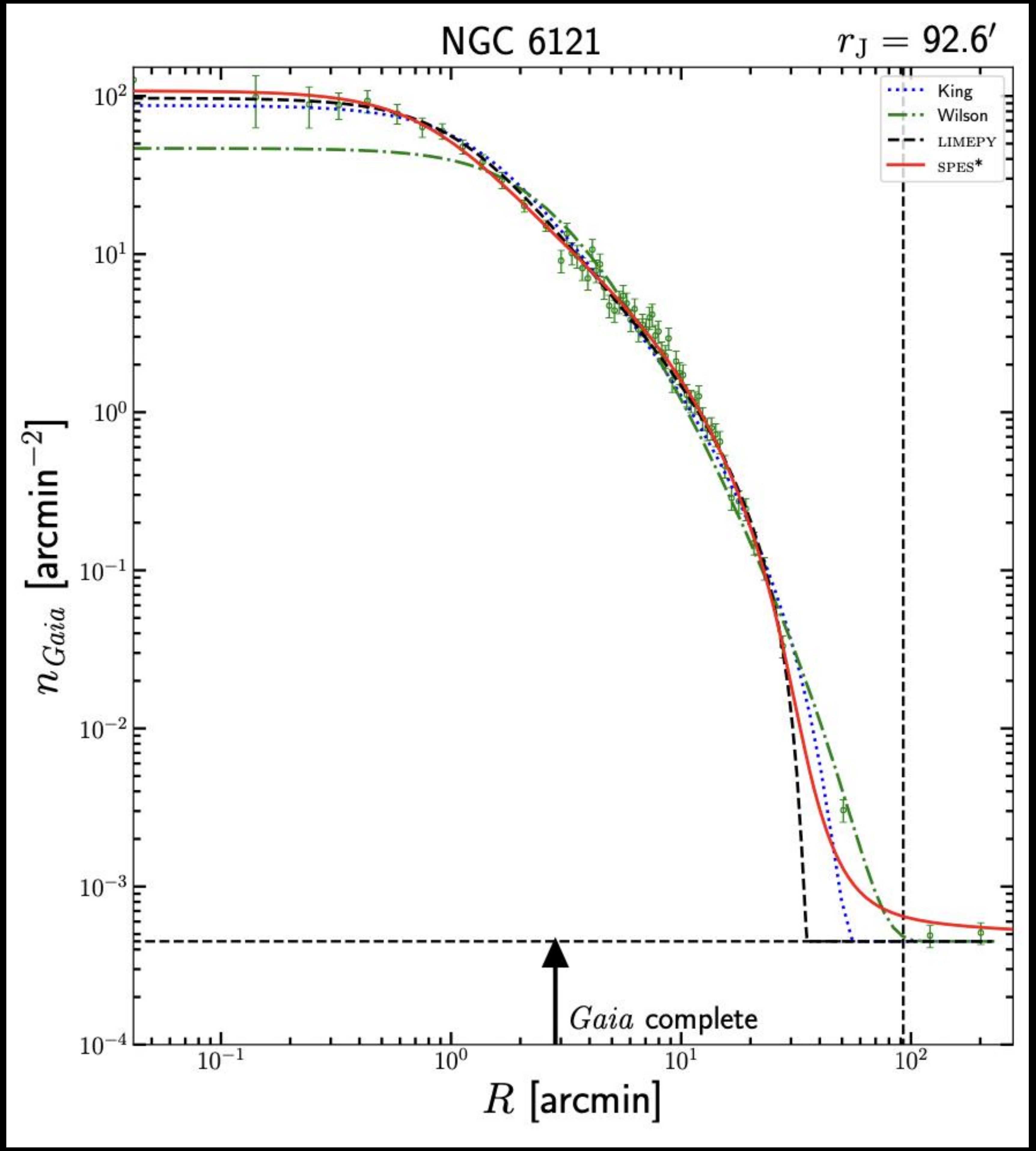
$$\sigma_{\rm LOS}^2(R)=\frac{2}{\Sigma_*(R)}\int_R^\infty\left(1-\beta\frac{R^2}{r^2}\right)\frac{\nu(r)\sigma_r^2(r)r}{\sqrt{r^2-R^2}}$$

Projected surface brightness density

Dark Matter content on M4

Use stellar kinematics to study the mass content of M4 (radial line-of-sight velocities)





Sample collected by: Baumgardt and Hilker. 2018
1804.08359

Surface density: Gaia data
T.J.L. de Boer et al. 2019

Dark Matter content on M4

Model the mass content

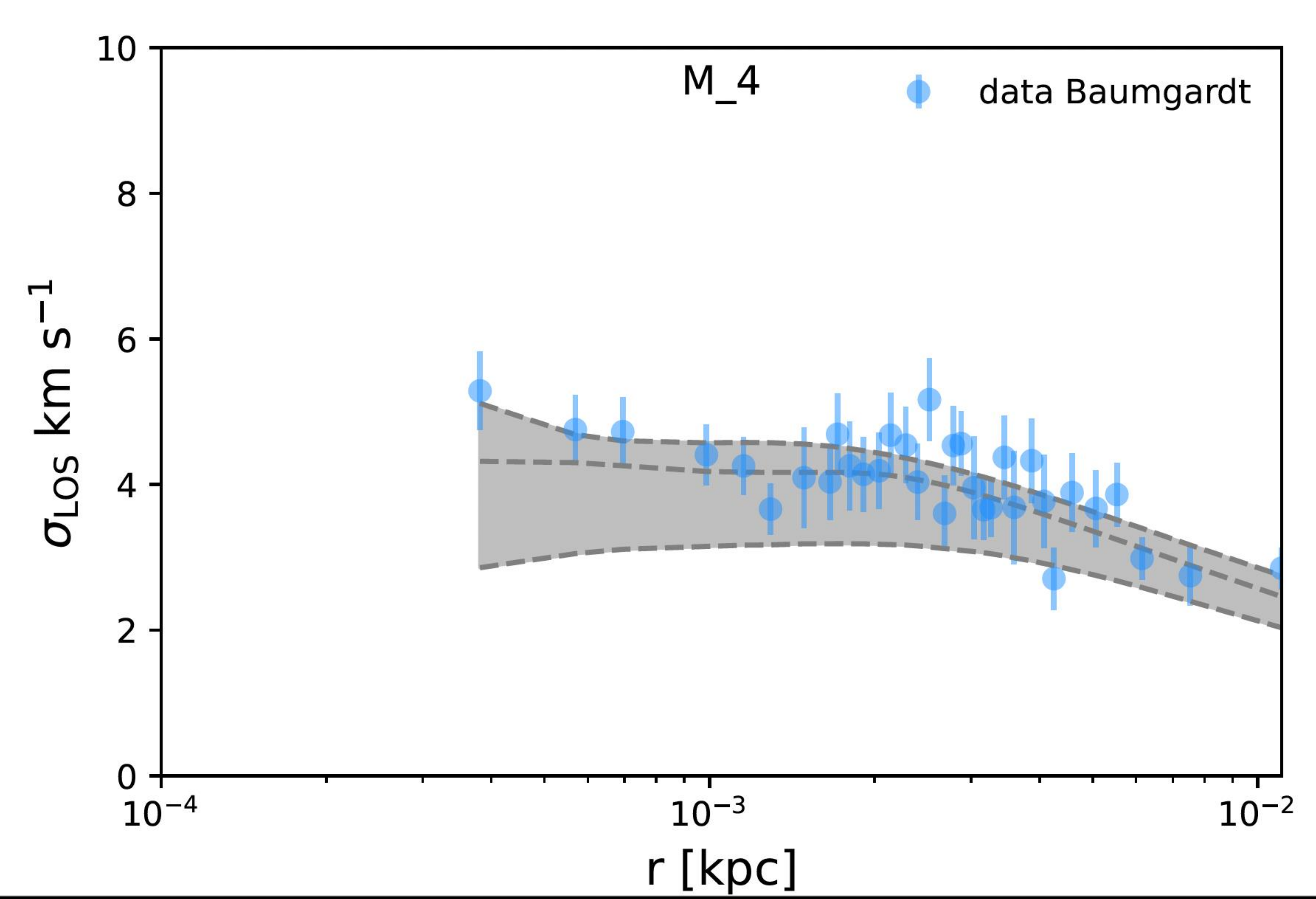
$$M(<r) = M_*(<r) + M_{\rm DM}(<r)$$

Where we have used an NFW and Brukert profiles to model the dark matter density

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2} \qquad \rho_{\rm Burkert}(r) = \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)\left(1+\left(\frac{r}{r_s}\right)^2\right)}$$

Perform an MCMC analysis on the free parameters using non parametric code GravSphere through the python implementation pyGravSphere

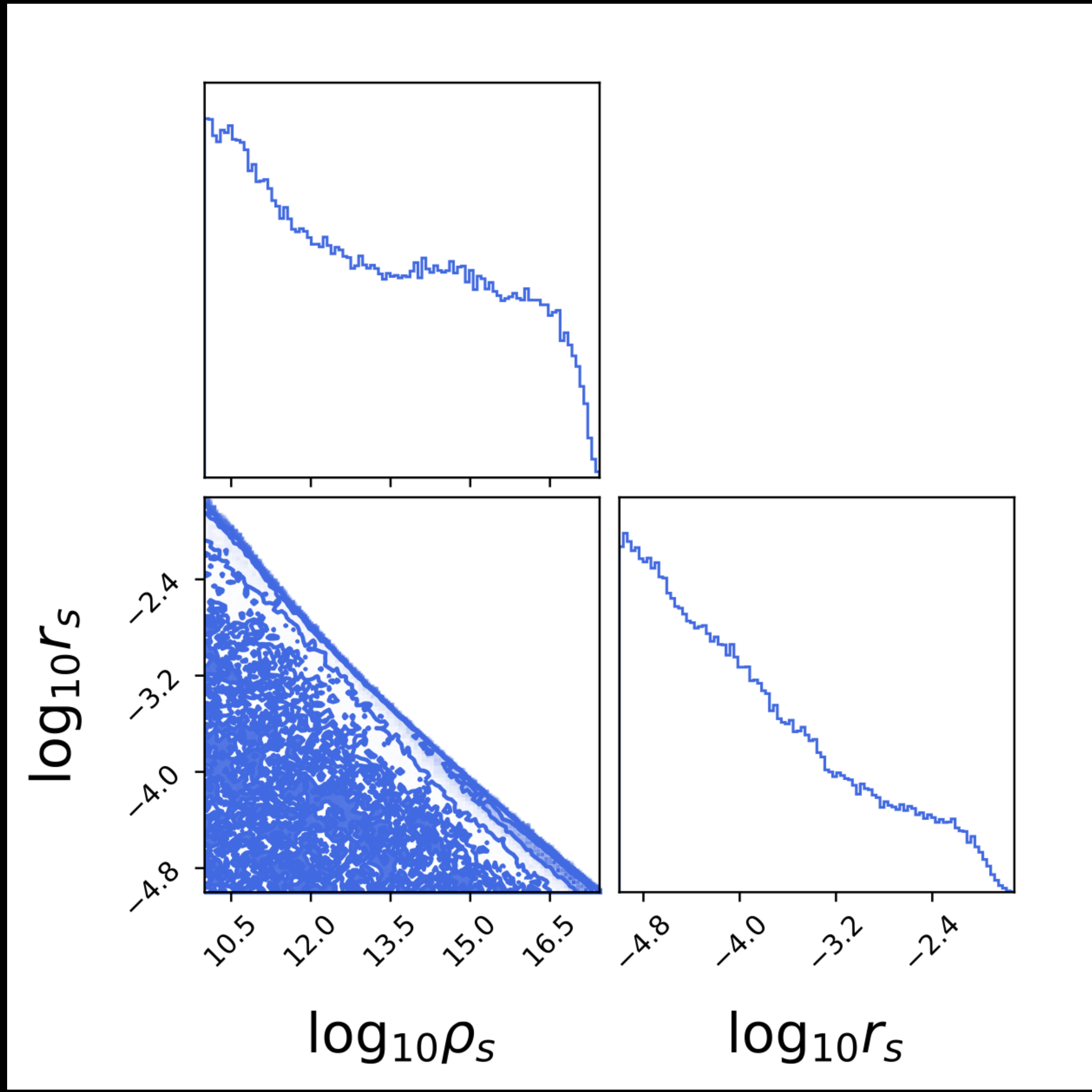
$$\ln\mathcal{L} = \chi^2_{\rm LOS} + \chi^2_{\Sigma_*}$$



No evidence for a DM component

Upper limits!

Implication for DM heating?



White Dwarf heating

Dark Matter content and heating of white dwarfs

White dwarfs: Stars that have depleted their fuel and have no heating mechanism
Capture of dark matter can transfer energy to the star via scatterings

$\dot{Q}_{\mathrm{kin}} = (\gamma - 1) m_\chi C_\chi$ where

$C_\chi = \frac{\rho_\chi}{m_\chi} \pi R_{\mathrm{WD}}^2 \frac{\gamma^2 - 1}{v_*} \mathrm{erf}\left(\sqrt{\frac{3}{2}} \frac{\mathrm{v}_*}{\mathrm{v}_\mathrm{d}}\right) \times \mathrm{p}_\sigma$ is the capture rate of a

dark matter particle with velocity v_d by a WD with speed v_*

$p_\sigma \simeq \tau = \sigma_{\chi T} / \sigma_{\mathrm{geo}}$ is the probability of DM to scatter given a optical depth τ

Being $\sigma_{\chi T}$ the cross section for scattering on target T (nucleus) and σ_{geo} the WD geom. cross section

Dark Matter content and heating of white dwarfs

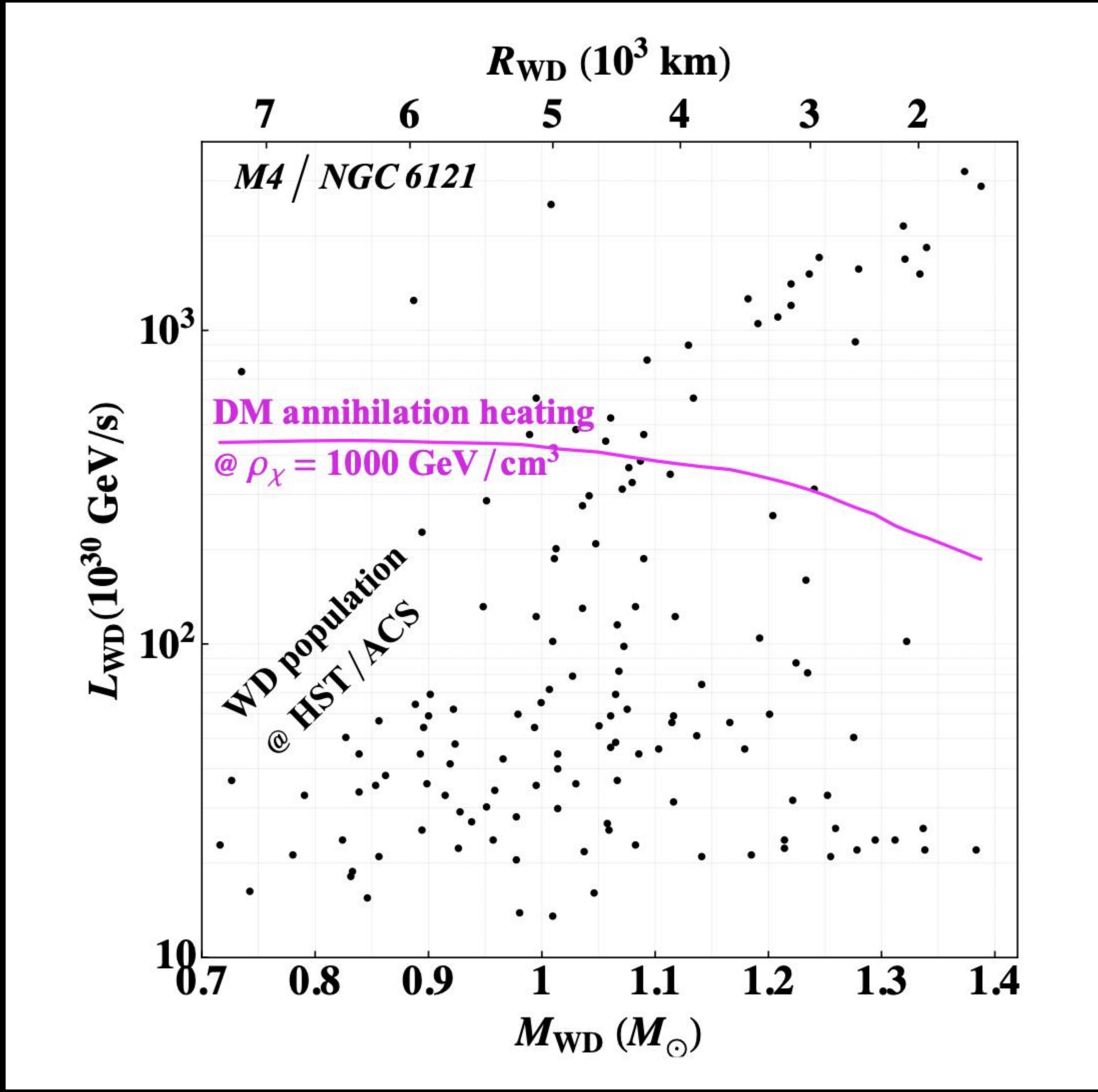
Thermalization and subsequent DM annihilation can further heat the star at rate $Q_{\text{kin+ann}} = \gamma m_\chi C_\chi$

Under thermal equilibrium the WD luminosity equals the DM heating rate $L_{\text{kin(ann)}} = L(M_\odot(\text{WD}))$

Using

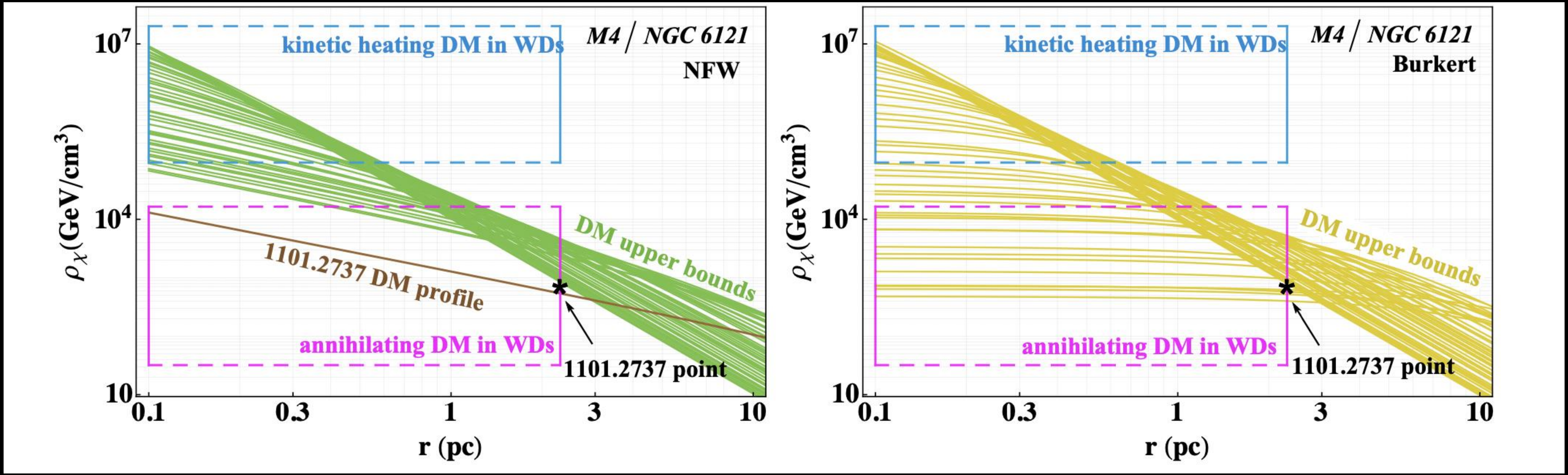
$p_\sigma = 1$

$\rho_\chi = 10^3 \text{GeV/cm}^3$



Sample from 0903.2839

Comparing with our results



$\dot{Q} > L_{\rm WD}$

$r_{\rm max} = 2.3{\rm pc}$ maximum radius at which WD were observed

$r_{min} \sim 0.1{\rm pc}$ radius at which stars can be resolved

Can we use M4 to place constraints on DM interactions?

Conclusions

First empirical limits on the DM density in M4

The upper DM limits cannot invalidate previous claims on annihilation or heating

Due to huge uncertainties these limits are unreliable…

Can future constraints on DM improve ?

Proper motions, multiple stellar populations…

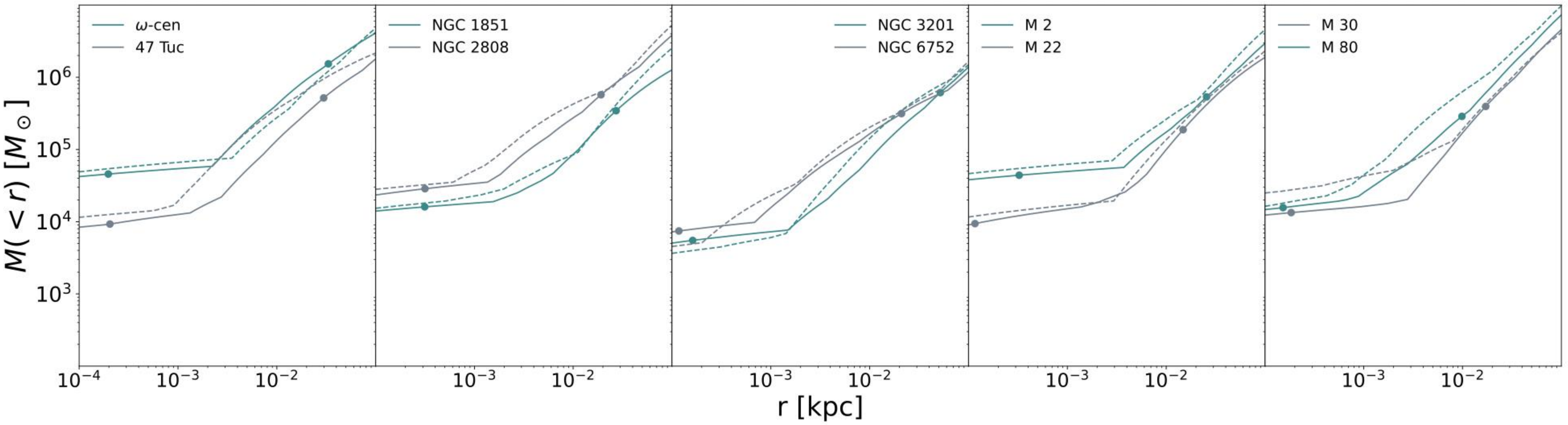
Other Globular Clusters …

Other effects like induced Supernova


insh.world

globular	d (kpc)	M/L_V ($\odot$)	DM hint?	WDs ?
NGC 6121 (M4)	2.2	1.7 ± 0.1	✗ [this work]	[30]
Kron 3	61.0	1.2 ± 0.3	✗ [31]	
NGC 121	64.9	0.9 ± 0.3	✗ [31]	
NGC 1851	12.0	1.3 ± 0.2	✗ [18]	
NGC 2808	10.0	1.4 ± 0.1	✗ [18, 32]	[33, 34]
NGC 3201	4.7	2.6 ± 0.1	✗ [18]	
NGC 4590 (M68)	10.4	1.9 ± 0.1	✗ [35]	
NGC 5024 (M53)	18.5	2.0 ± 0.1	✗ [35]	
NGC 6093 (M80)	10.3	2.0 ± 0.1	✗ [18, 32]	[34]
NGC 6656 (M22)	3.3	2.0 ± 0.1	✗ [35–37]	[38, 39]
NGC 6752	4.1	2.2 ± 0.1	✗ [32, 37]	[40, 41]
NGC 6397	2.3	2.4 ± 0.5	✗ [42–44]	[45–47][a]
NGC 6809 (M55)	5.4	2.1 ± 0.1	✗ [31]	
NGC 6838 (M71)	4.0	1.0 ± 0.05	✗ [48, 49]	[48]
NGC 7078	10.7	1.3 ± 0.1	✗ [32]	[34]
NGC 7089 (M2)	11.7	1.8 ± 0.1	✗ [18]	
NGC 7099 (M30)	8.5	1.6 ± 0.1	✗ [18, 35]	
NGC 104 (47 Tuc)	4.5	1.9 ± 0.1	✗ [31, 37, 49]	[50–52]
			✓ [53]	
NGC 2419	88.5	1.6 ± 0.2	✗ [32, 54, 55]	
			✓ [55]	
NGC 3201	4.7	2.6 ± 0.1	✗ [56]	[4, 57]
			✓ [58]	
NGC 5139 (ω Cen)	5.4	2.8 ± 0.1	✗ [37]	[59, 60]
			✓ [16, 61]	
NGC 6544	2.5	2.3 ± 0.5	? [62]	[63, 64]
NGC 5128 population	3–5 Mpc	> 6 [65]	? [65]	

[a] contains the coldest WD (surface $T \simeq 3700K$) observed [15].



ω-cen
47 Tuc
NGC 1851
NGC 2808
NGC 3201
NGC 6752
M 2
M 22
M 30
M 80
$M(<r)$ $[M_\odot]$
10^3
10^4
10^5
10^6
10^{-4}
10^{-3}
10^{-2}
r [kpc]