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Upper limits on the dark matter content in Globular Clusters

In collaboration with M. Regis and M. Taoso

Based on arXiv:2203.13735

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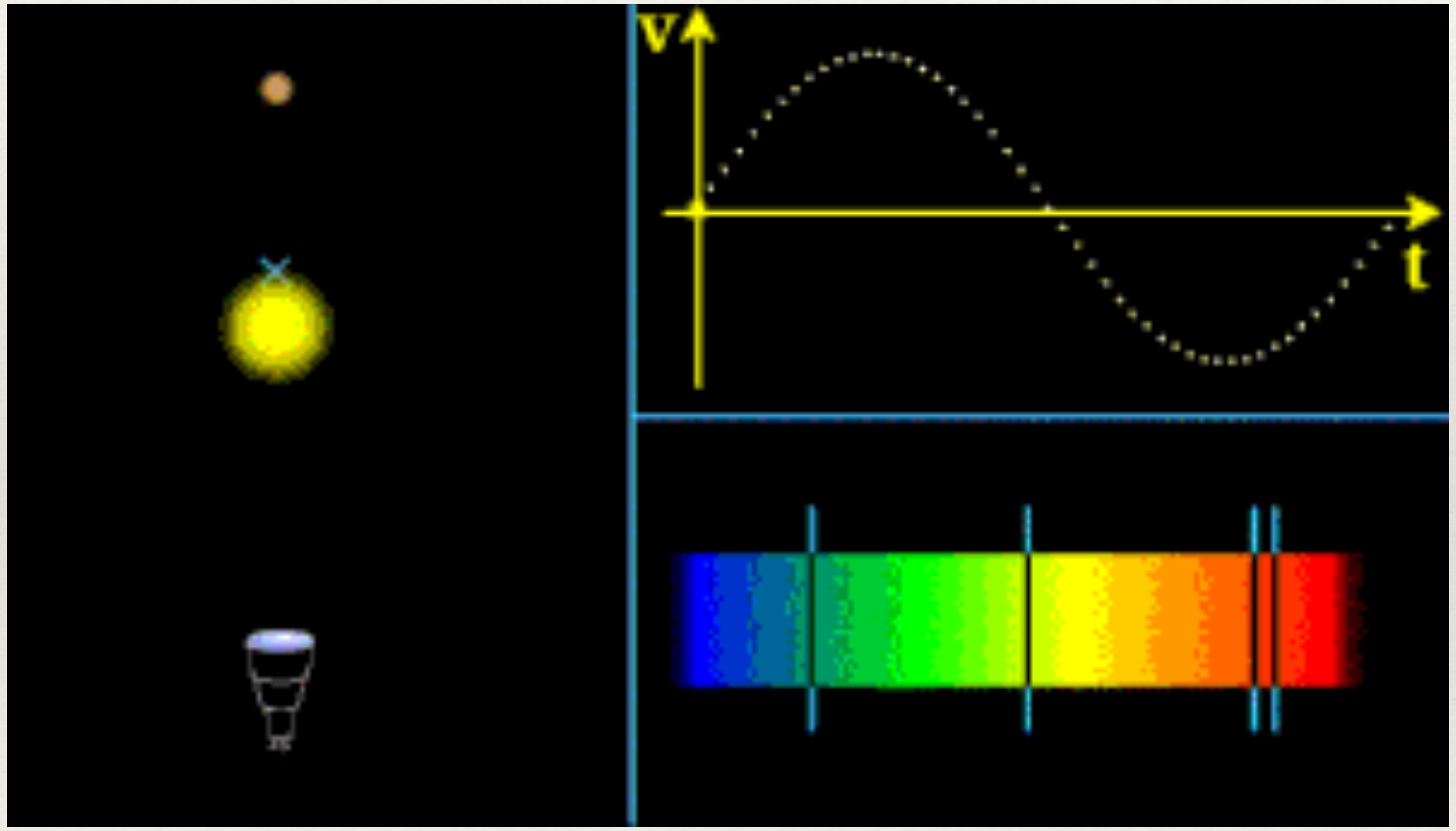
Introduction

- Globular Clusters (GCs) are old, compact, gravitationally bound systems.
- So far there is no compelling evidence of a hosting dark component.
- Formation history?
  - Remnants of a dwarf Galaxy tidally disrupted?
- Due to proximity, they can have a large J-factor, key in Indirect searches
- The content of dark matter is an important question to address

Data and Methods

- We use Stellar dynamics to study the mass content of the Gas

Radial velocities



https://platomission.com/2018/05/20/the-radial-velocity-method/

$$\frac{1}{\nu(r)}\frac{\partial}{\partial r}\left(\nu(r)\sigma_r^2\right) + \frac{2\beta(r)\sigma_r^2}{r} = -\frac{GM(<r)}{r^2}$$

Stellar density Distribution

Radial velocity Distribution

Stellar Orbital Anisotropy

$$\nu(r) = \sum_i \frac{3M_i}{4\pi a_j^2}\left(1+\frac{r^2}{a_i^2}\right)^{-5/2}$$

3 Plummer spheres

Known from Stellar surface density

$$\beta(r) = \beta_0 + (\beta_\infty - \beta_0)\frac{1}{1+(r_a/r)^\eta}$$

Anisotropy profile

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Data and Methods

Line-of-sight velocities data

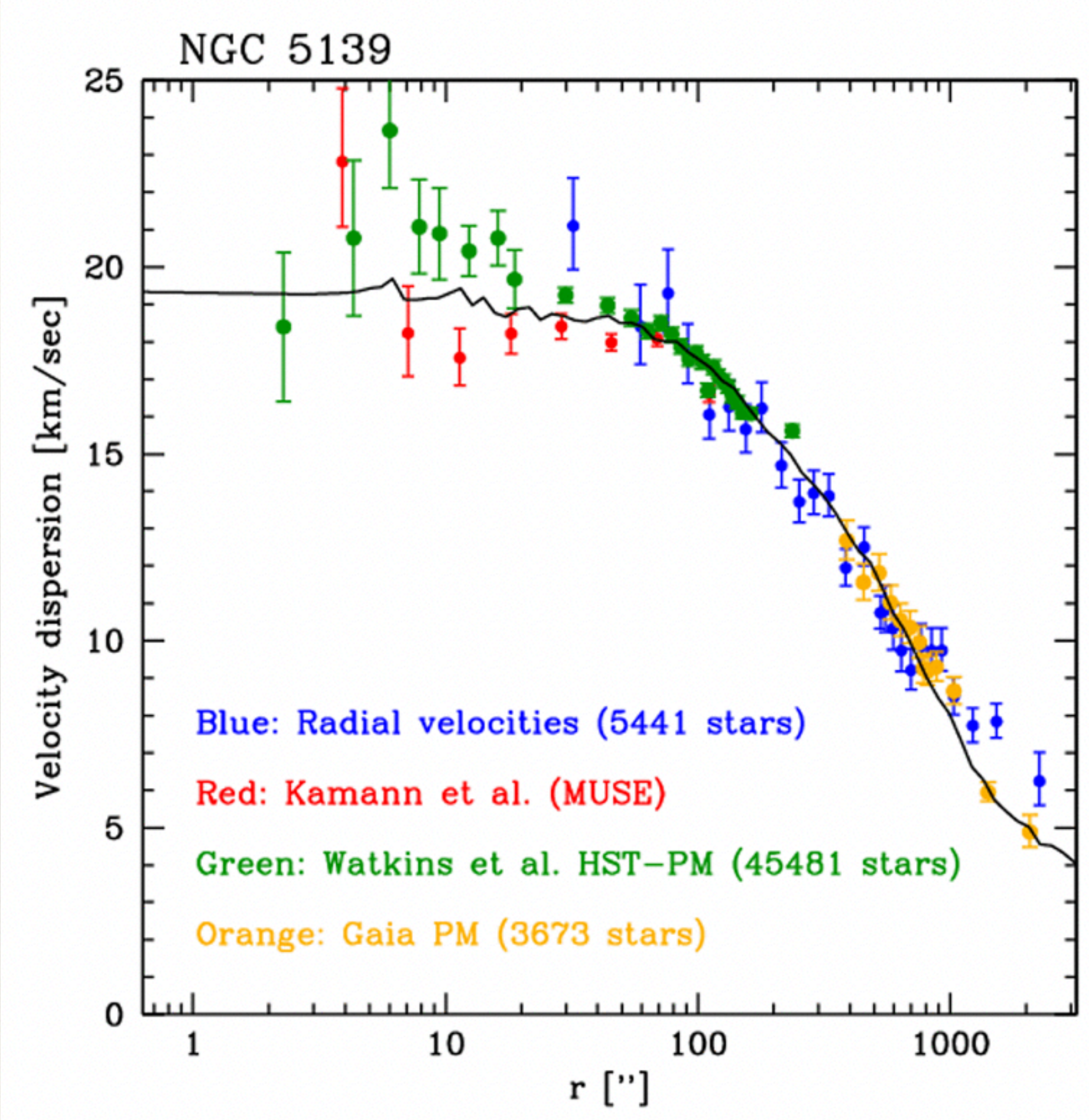
MUSE (Multi-Unit Spectroscopic Explorer)
S. Kamann et al. 2018   1710.07257

Sample collected by: Baumgardt and Hilker. 2018
1804.08359

Exclude binaries!!

Line-of-sight velocity dispersion

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



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Dark matter in GCs

Data and Methods

Surface density / Stellar profile

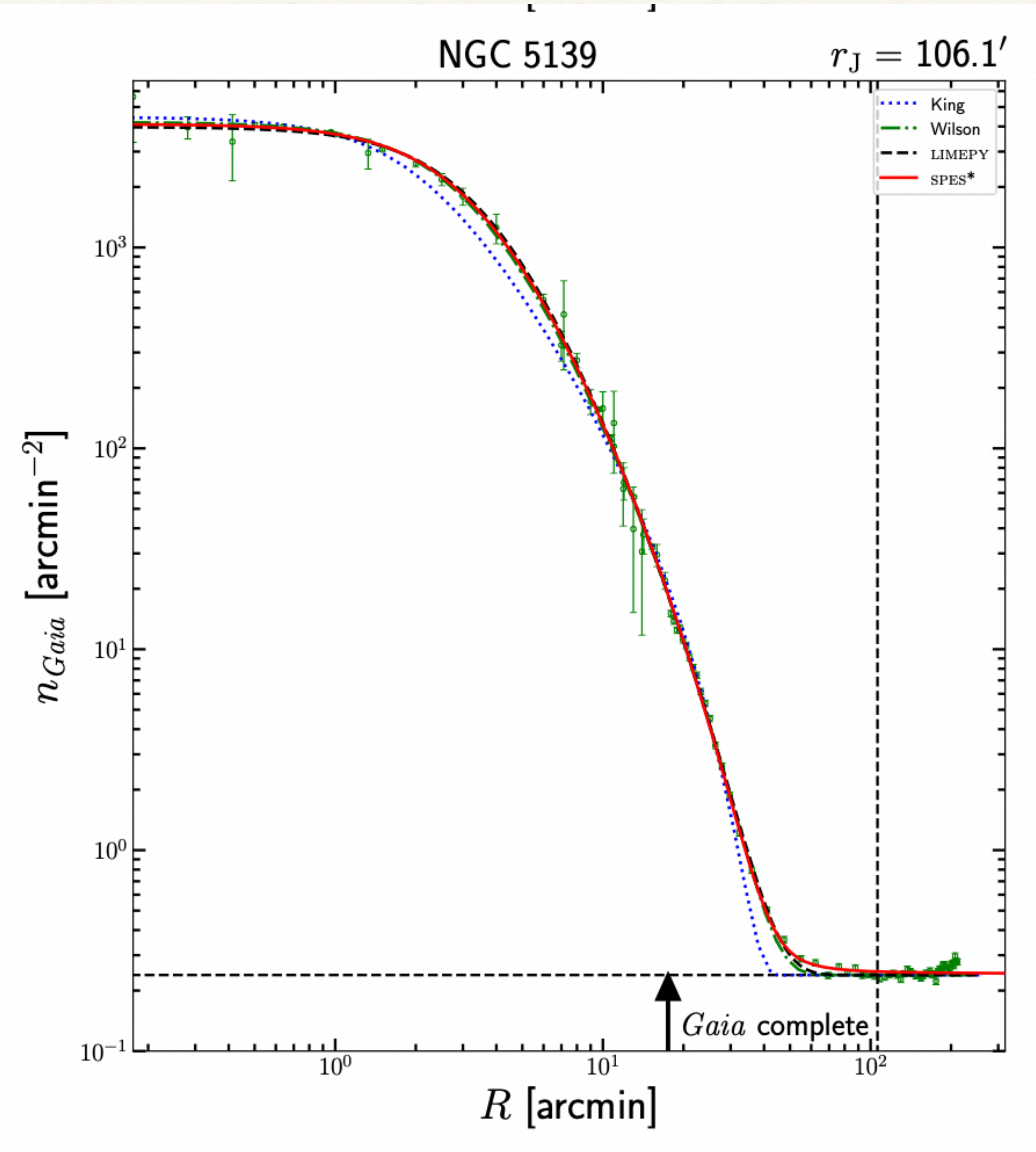
$$\sum_{*}(R) = \frac{M_j}{\pi a_j^2}\left(1 + \frac{R^2}{a_j^2}\right)^{-2}$$

Surface density from radial velocities not a good tracer

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

Fit using minimization: the vary within the fitted values

Specify the stellar density!



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Dark matter in GCs

Models and Analysis

$$M(< r) \qquad M_* + M_{\text{dark}}$$

- Dark matter: NFW profile $$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}$$

Perform an analysis using MCMC!!

- Black Hole: $$M(r) = M_0 \delta(r - r_0)$$

Non-parametric code GravSphere : python implementation pyGravSphere

In addition computes the viral shape parameters

$$v_{s1} = \frac{2}{5}\int_0^\infty GM\nu(r)[5 - 2\beta(r)]\sigma_r^2 r dr = \int_0^\infty \Sigma_*(R)\left\langle v_{\text{los}}^4\right\rangle R dR$$

$$v_{s2} = \frac{4}{35}\int_0^\infty GM\nu(r)[7 - 6\beta(r)]\sigma_r^2 r^3 dr = \int_0^\infty \Sigma_*(R)\left\langle v_{\text{los}}^4\right\rangle R^3 dR$$

Alleviate mass-anisotropy degeneracy

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Dark matter in GCs

Numerical procedure

$$-2\ln\mathcal{L} = \chi^2_{\rm kin} + \chi^2_{\Sigma_*} + \chi^2_{\rm VSP,1} + \chi^2_{\rm VSP,2}$$

- Where the different components are:

$$\chi^2_{\rm los} = \sum_j \frac{(\sigma_{{\rm los},j} - \bar{\sigma}_{{\rm los},j})^2}{\sigma^2_{\sigma_{{\rm los},j}}} \qquad \chi^2_{\Sigma_*} = \sum_j \frac{(\Sigma_{*,j} - \bar{\Sigma}_{*,j})^2}{\sigma^2_{\Sigma_{*,j}}}$$

$$\chi^2_{\rm VSP,1} = \frac{(v_{s1} - \bar{v}_{s1})^2}{\sigma^2_{v_{s1}}} \qquad \chi^2_{\rm VSP,2} = \frac{(v_{s2} - \bar{v}_{s2})^2}{\sigma^2_{v_{s2}}}$$

MCMC Python package: emcee

Stellar profile:
7 parameters

$\{M_j, a_j\}, M_*$

Anisotropy
profile:
4 parameters

$\beta_0, \beta_\infty, r_a, \eta$

DM/BH:
2/1 parameters

$(\rho_s, r_s), \rho_s$

Results

- We have studied 9 GCs, with priors

GCs. >1000 stars in both catalogues

GC	RA	DEC	D	$R_{\rm half}$	Mass	# stars [B]	# stars [M]
47 Tuc	6.02	-72.08	4.52	10.49	8.95	3951	18021
NGC 1851	78.53	-40.05	11.95	10.05	3.18	705	8776
NGC 2808	138.01	-64.86	10.06	6.3	8.64	1602	6399
ω-cen	201.70	-47.48	5.2	12.71	34.4	2994	26387
M 80	244.26	-22.97	10.34	3.07	3.38	469	3853
M 22	279.10	-23.90	3.3	4.4	4.76	1007	9590
NGC 6752	287.71	-59.98	4.13	6.04	2.76	1686	7196
M 2	323.36	-0.82	11.69	13.69	6.2	544	10325
M 30	325.09	-23.18	8.460	6.98	1.4	847	7459

Parameters	min. value	max. value
$\log_{10}(\rho_s/(M_\odot/{\rm kpc}^3))$	0	30
$\log_{10}(r_s/{\rm kpc})$	-8	-1
β_∞	-1	1
β_0	-1	1
η	1.	10.
$r_a/{\rm kpc}$	$R_{\rm half}/10$	$10 \cdot R_{\rm half}$
$M_j/M_\odot$	$0.1(M_{j,{\rm bf}})$	$1.9(M_{j,{\rm bf}})$
$a_j/{\rm kpc}$	$0.1(a_{j,{\rm bf}})$	$1.9(a_{j,{\rm bf}})$
$M_\star/M_\odot$	$M_\star/2.$	$2.5M_\star$

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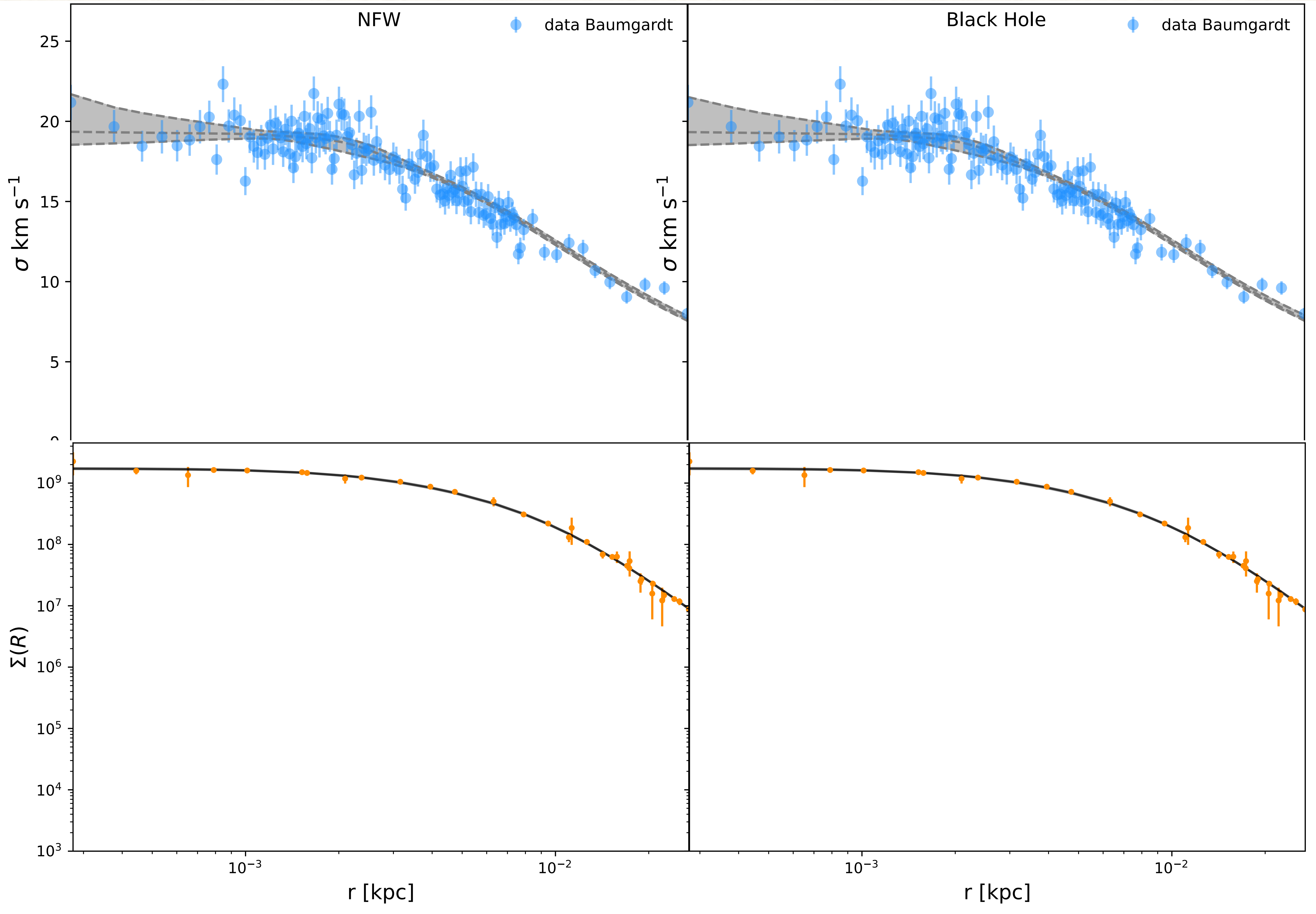
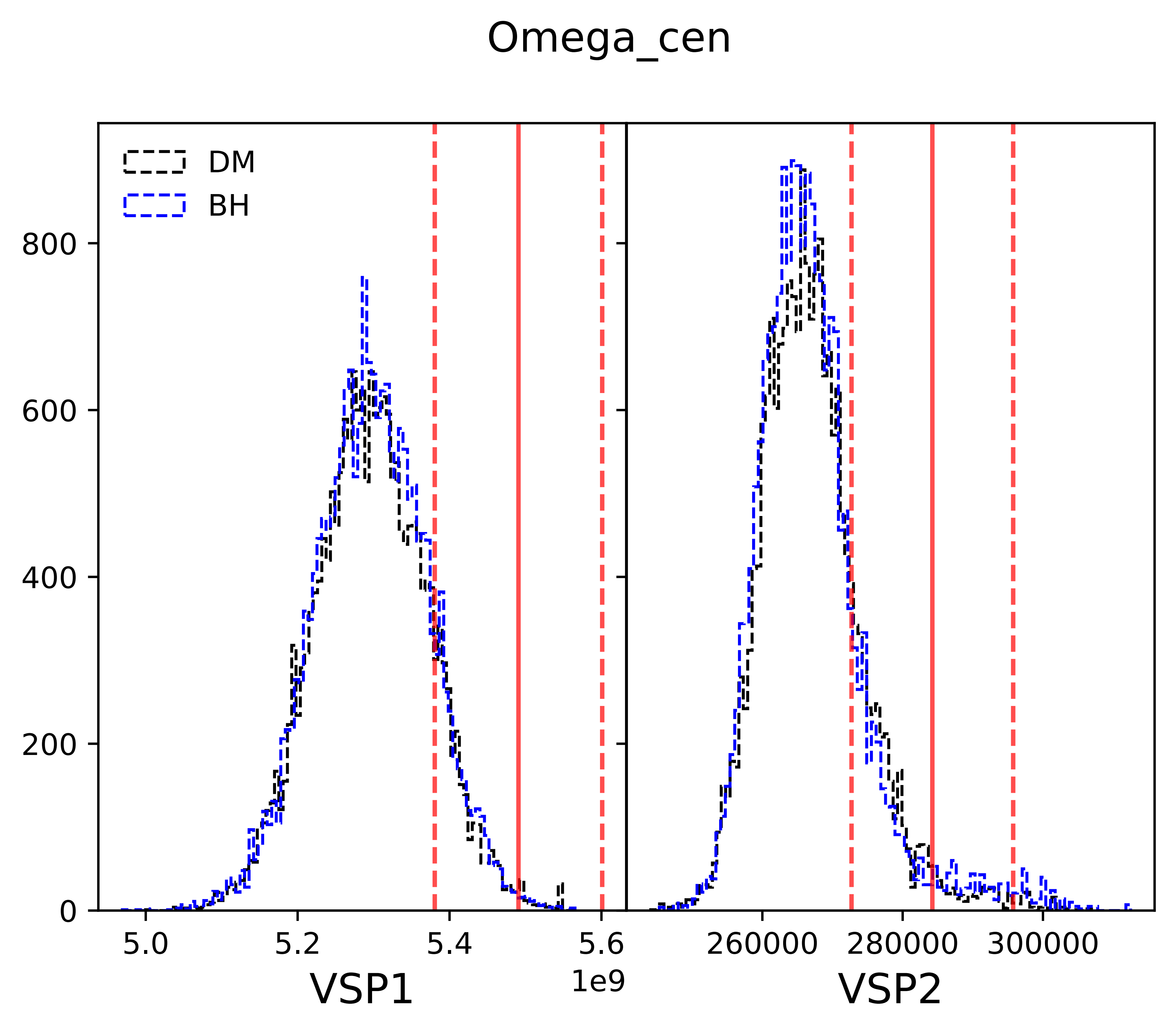
Results





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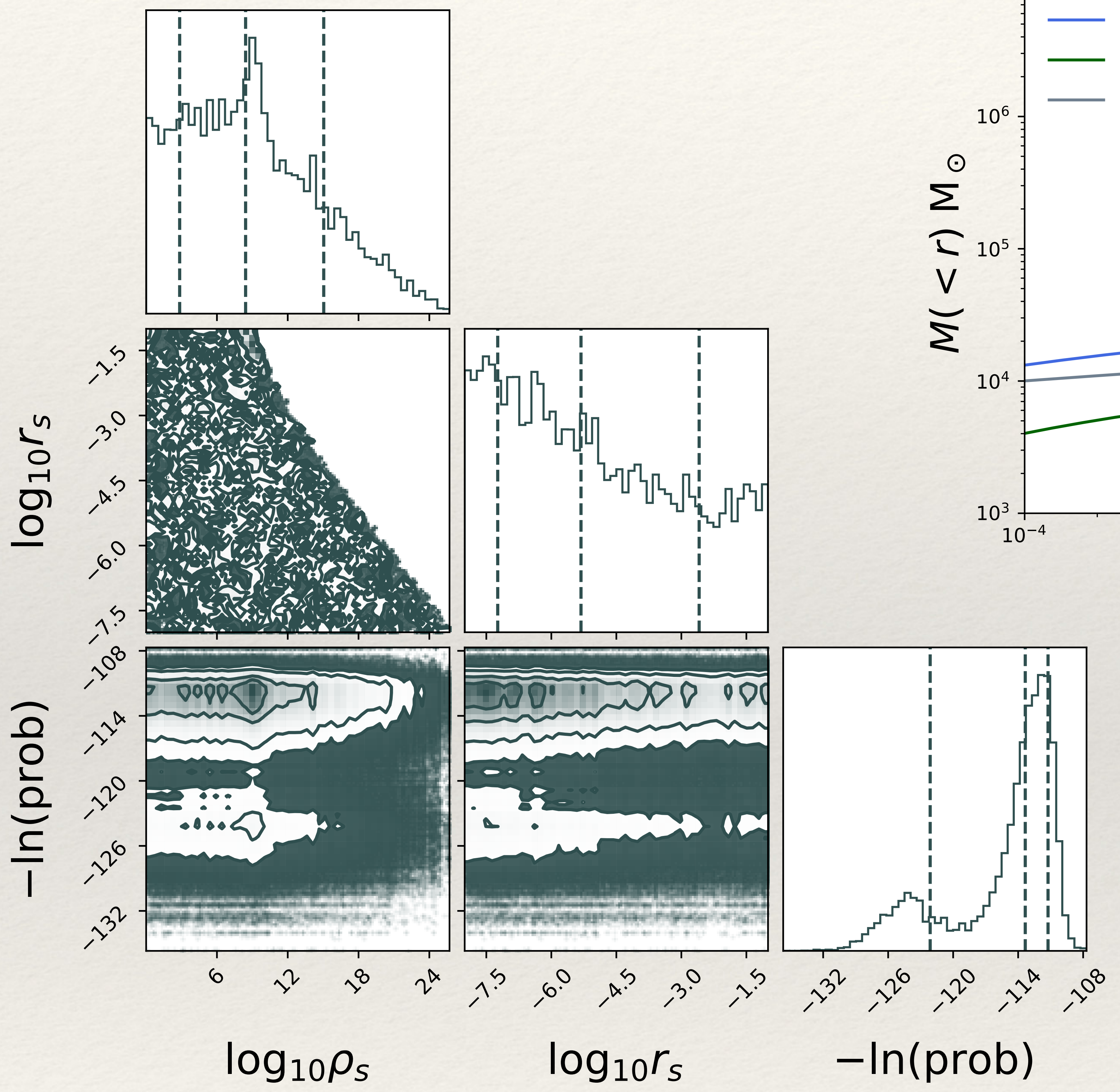
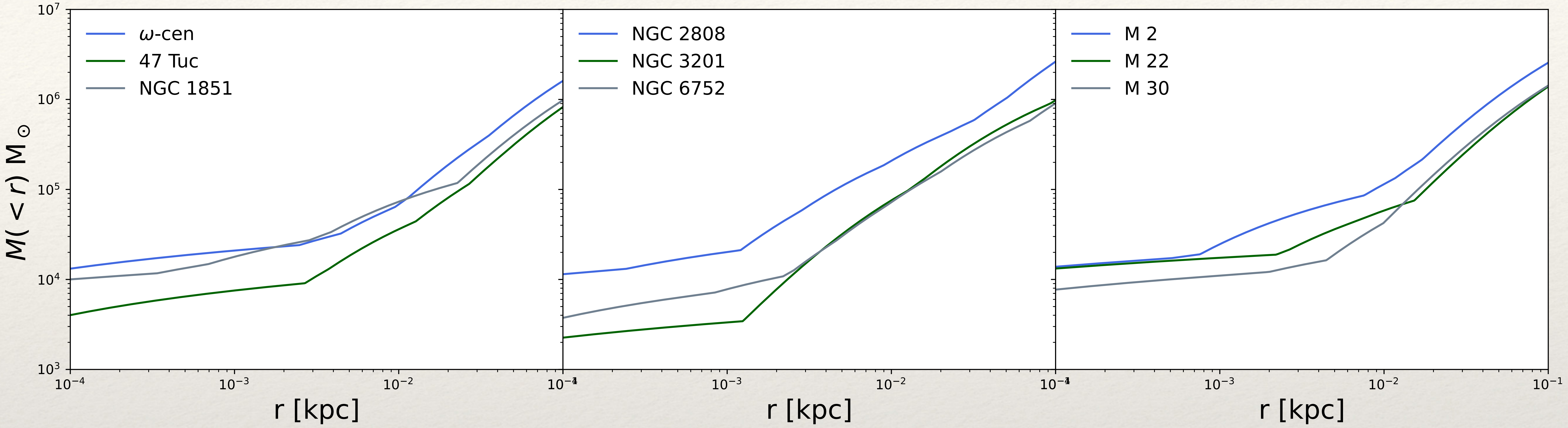
Dark matter in GCs

Limits





GC	N_{points}	$\chi^2_{b.f.}$	$M_{BH}^{\max}$ $[10^4\ M_\odot]$
47 Tuc	128	262	1.2
NGC 1851	150	131	1.7
NGC 2808	155	141	2.3
ω-cen	274	215	3.2
M 80	107	120	1.6

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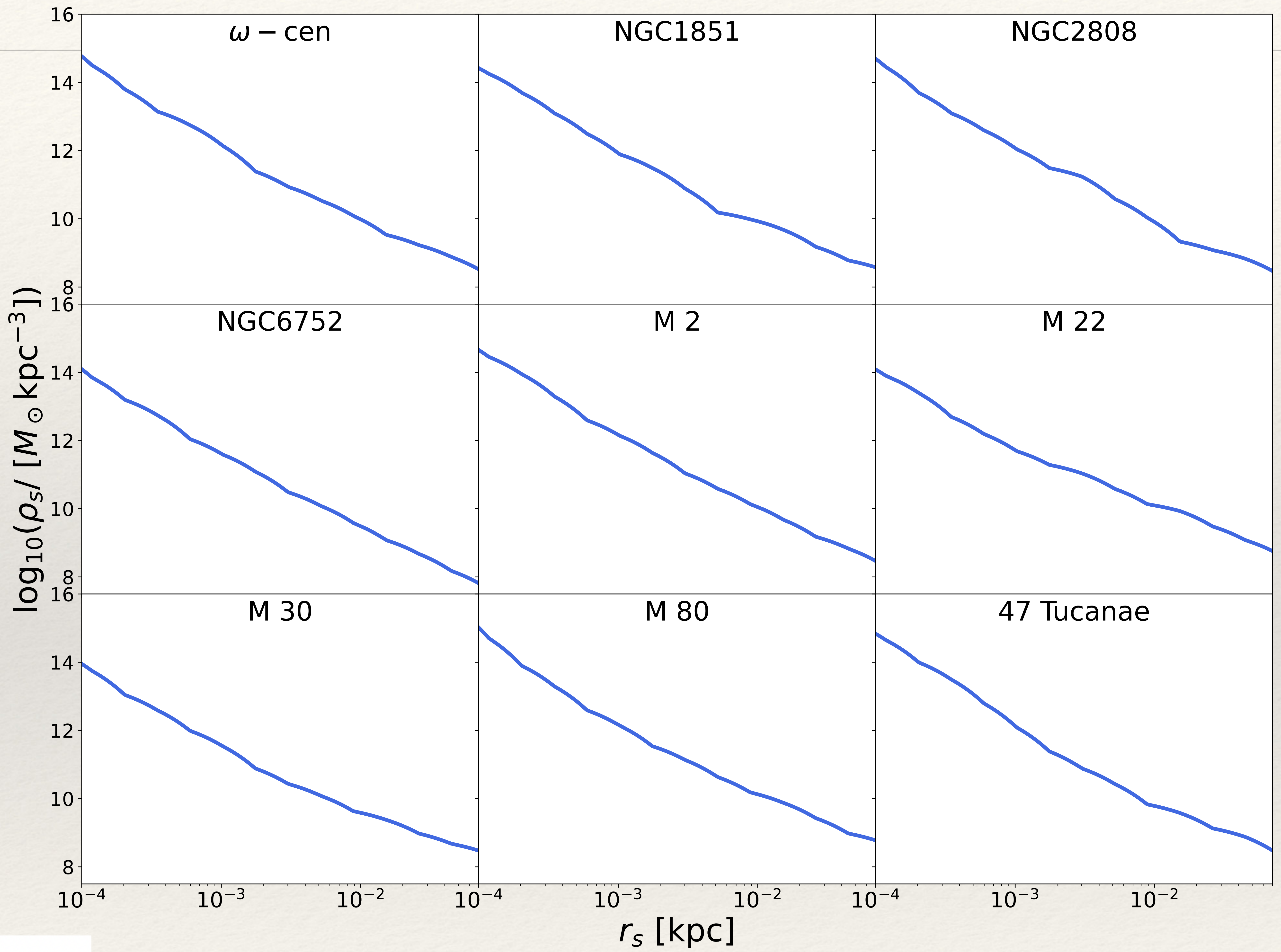
Dark matter in GCs

Limits



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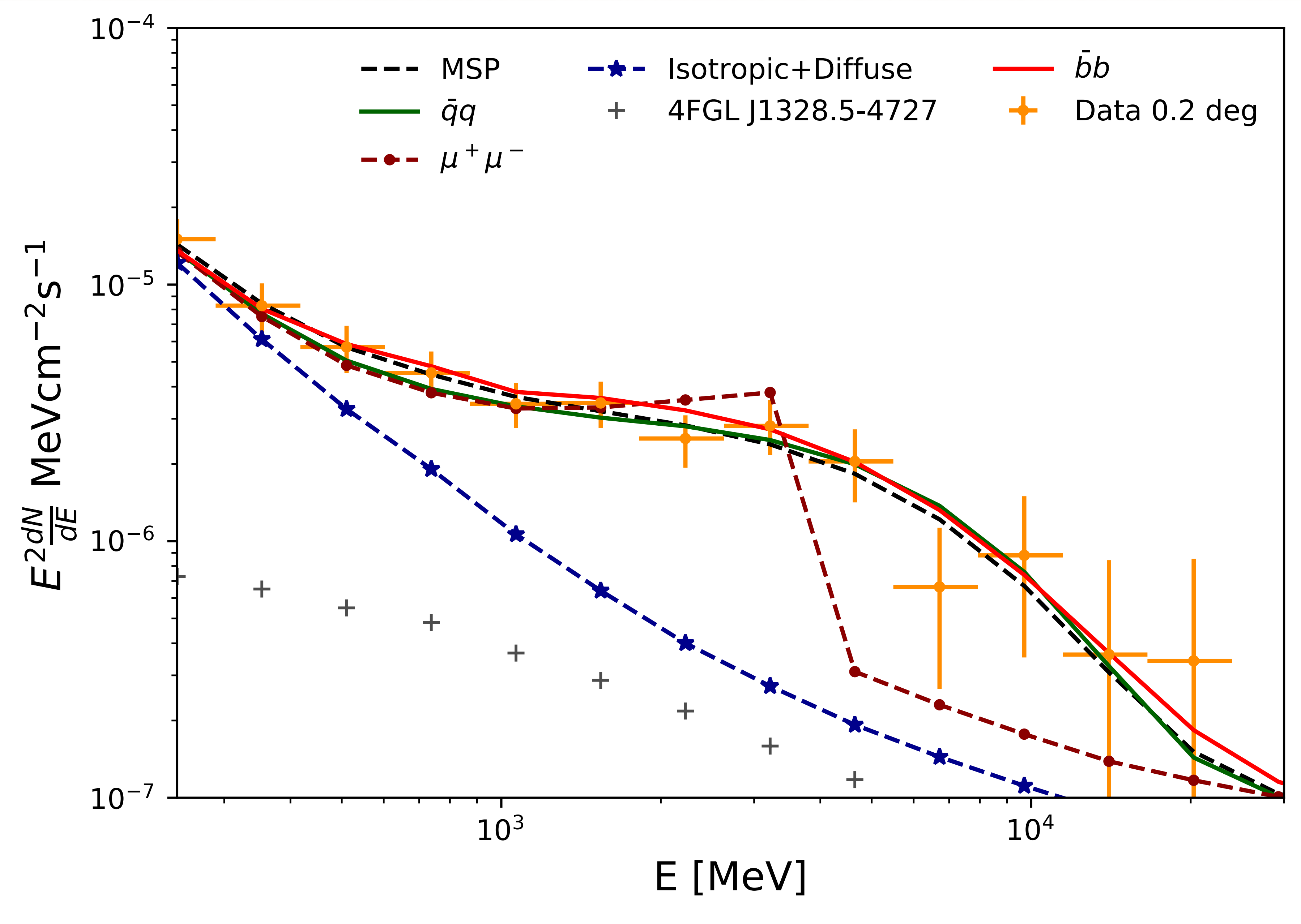
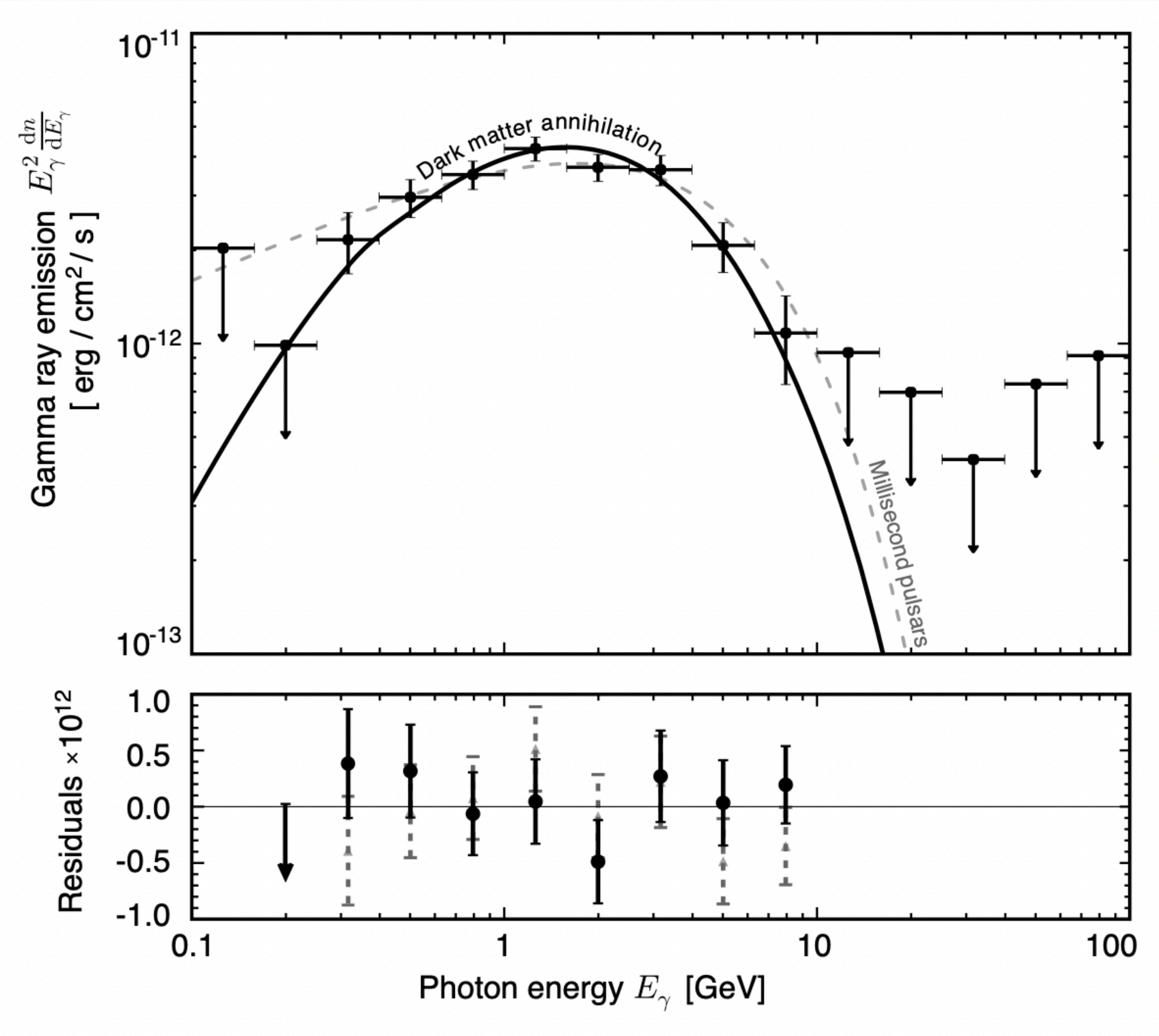
Dark matter in GCs

GCs and Indirect DM detection

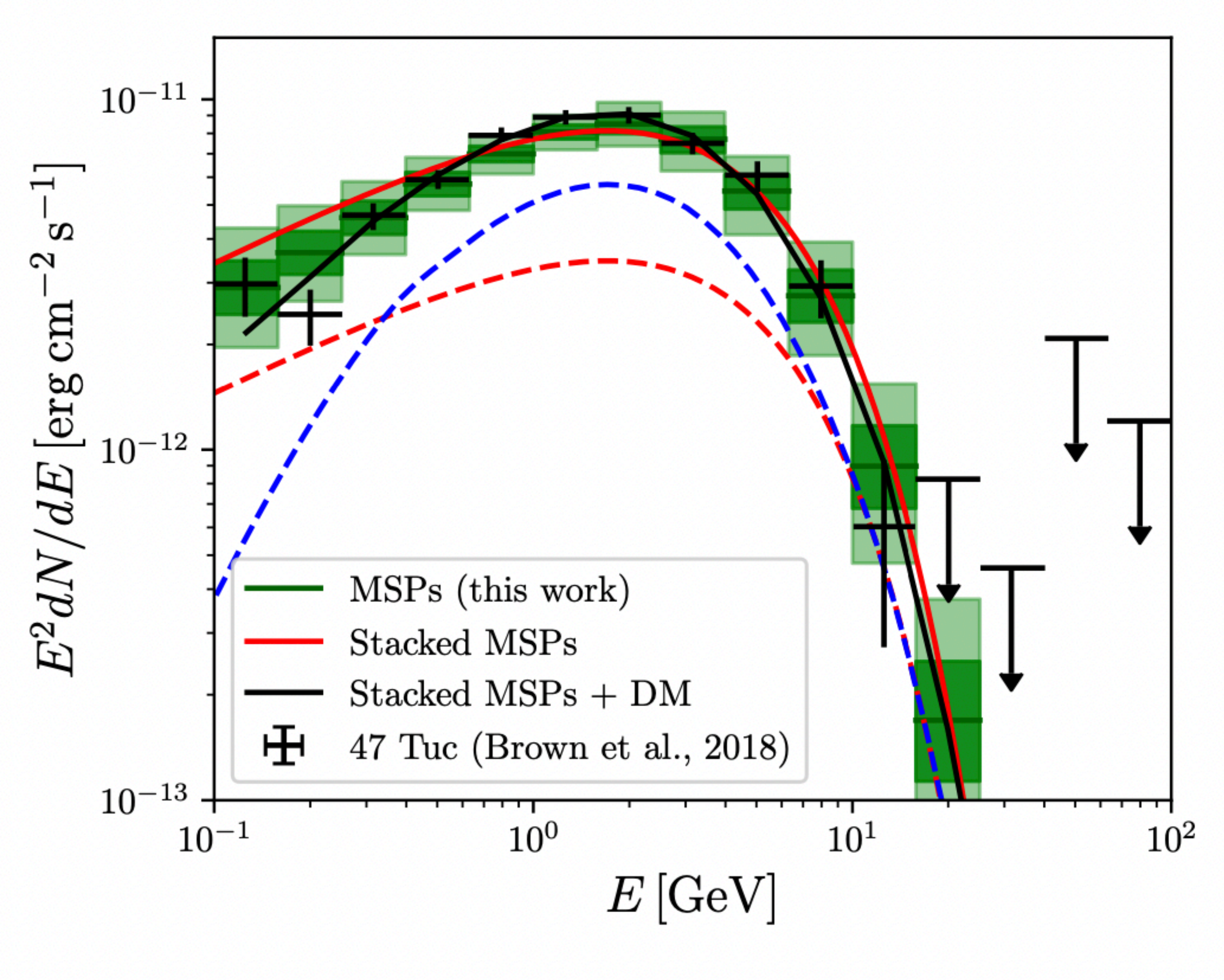
- GCs and DM annihilation



Reynoso-Cordova et al. 2019 arXiv:1907.06682



Brown A. M. Et al. 2019 arXiv:1907.08564



Bartels R. Et al. 2018 arXiv:1807.08800

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Dark matter in GCs

Conclusions

- No evidence for DM or BH component…
- We have derived upper limits on the DM content in GCs
- Proximity means large J-factor, important for indirect dark matter searches
- First attempt on derive constraints for many targets
- Still work to do to improve; proper motions, different DM profiles …

Thanks!

Statistics

No evidence for dark matter: upper limits

Profile likelihood

$$\lambda_b = \frac{\mathcal{L}(\vec{\theta}_{\rm b.f.}, \vec{\Pi}_{\rm b.f.})}{\mathcal{L}(\vec{\theta}, \vec{\Pi}_{\rm b.f.})}$$

$$-2\ \ln \lambda_b = \Delta\chi^2 = \chi^2(\vec{\theta}, \vec{\Pi}'_{\rm b.f.}) - \chi^2(\vec{\theta}_{\rm b.f.}, \vec{\Pi}_{\rm b.f.})$$

$\vec{\theta}$: parameters of interest

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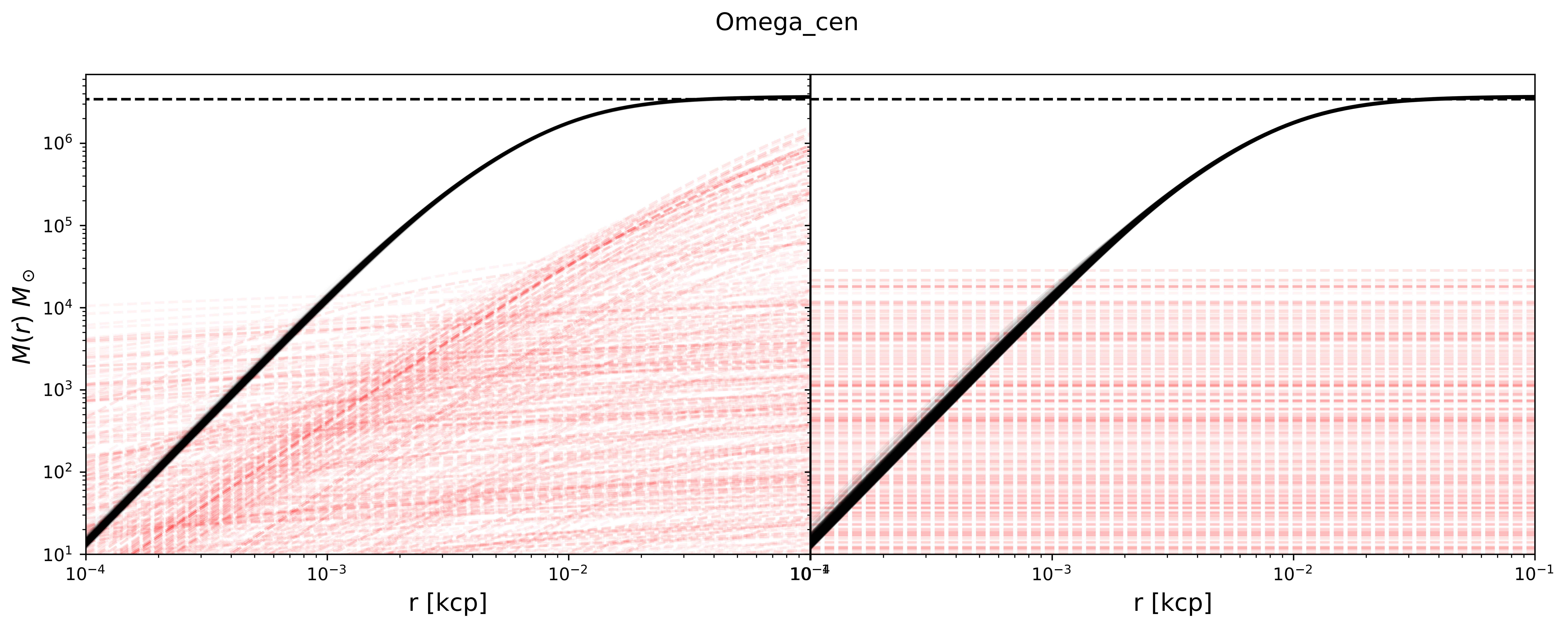
Dark matter in GCs

Total mass



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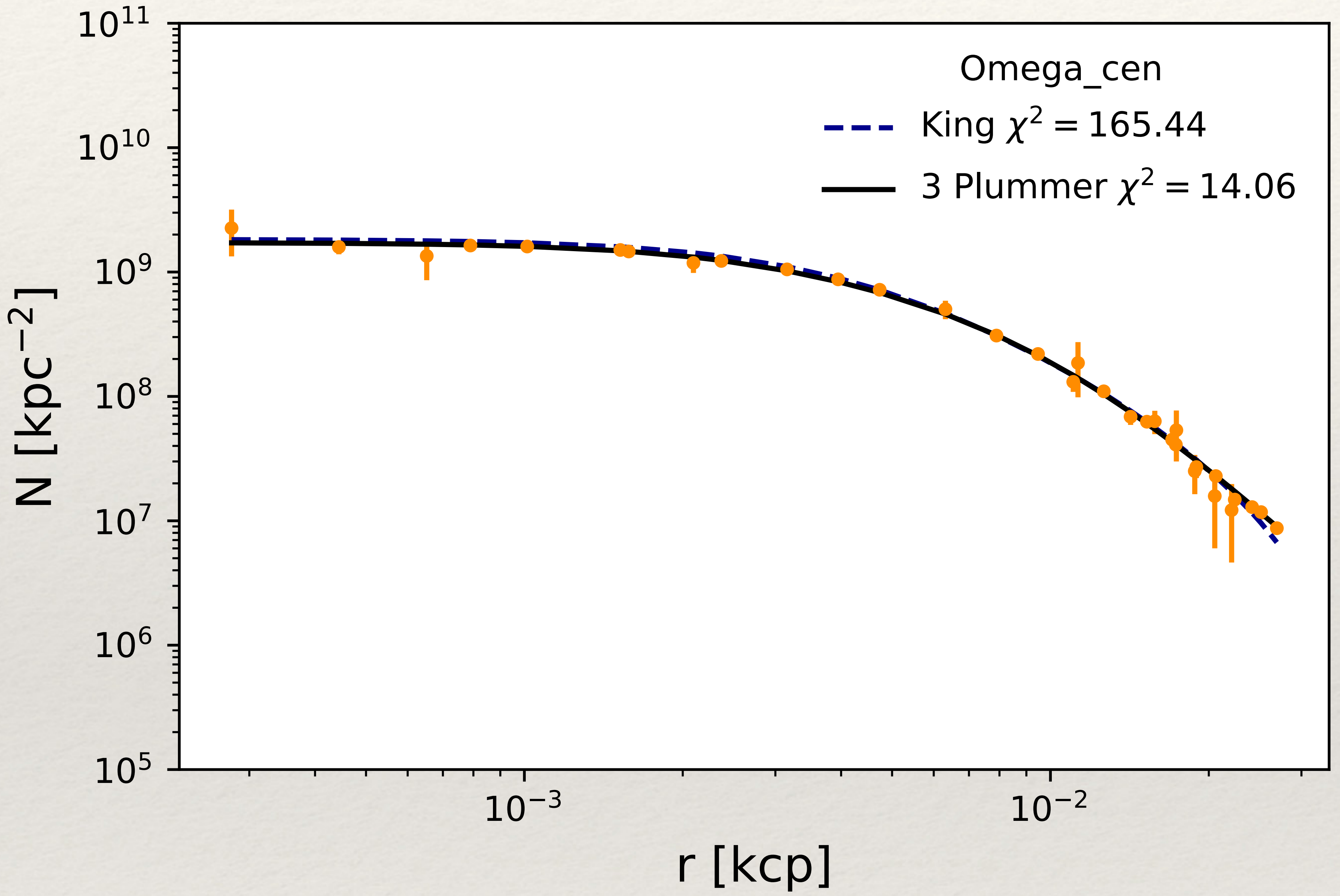
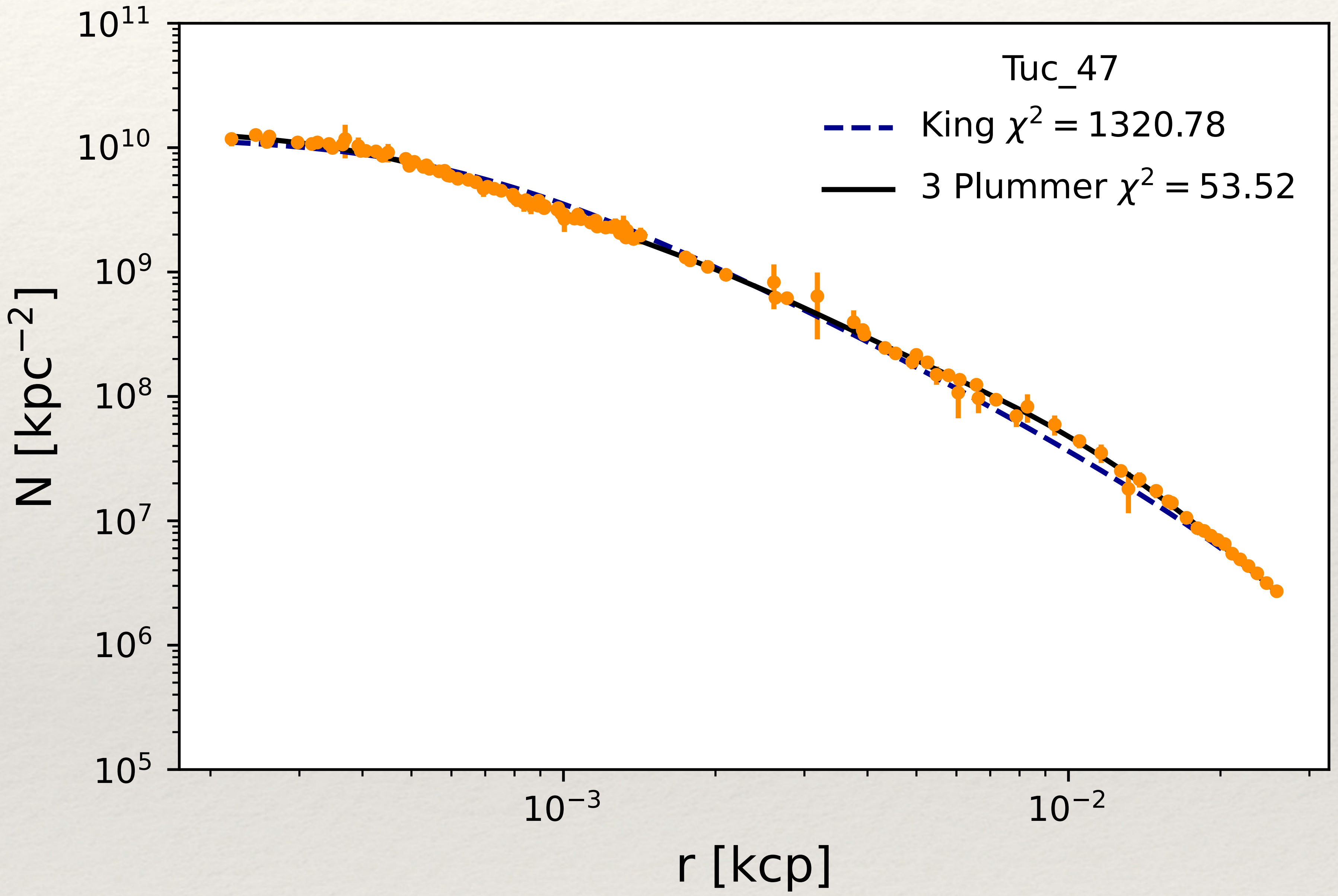
Dark matter in GCs

Stellar profiles





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Dark matter in GCs

Velocity dispersion Binaries vs Singles

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Dark matter in GCs

Line-of-sight velocity

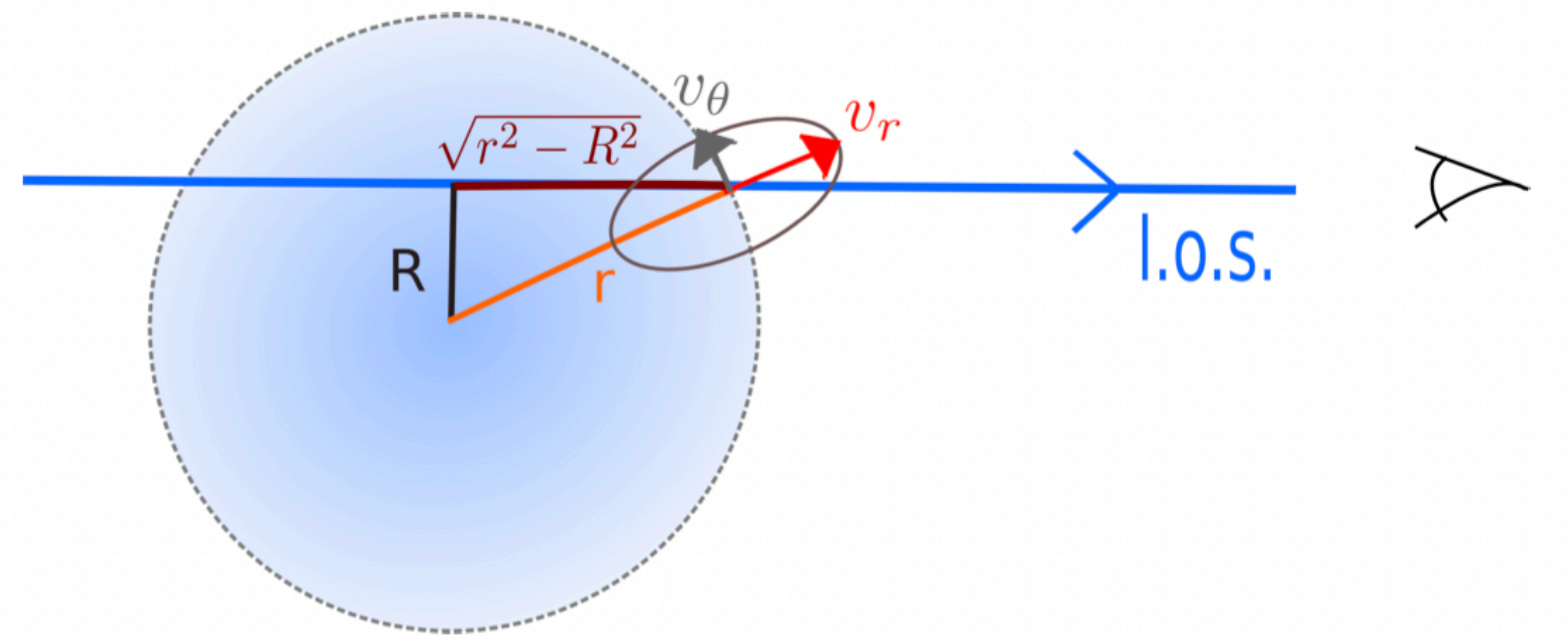

Fig. 1. Cluster geometry (see Binney & Tremaine 1987).

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