Decays and annihilation of galactic dark matter: determine D-, J_s-, J_p- and J_d factors with dark matter profiles inferred from GravSphere fit to stellar observations

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Motivation

- Indirect searches: Measurements of the annihilation and/or decay products of dark matter
- Dwarf spheroidal galaxies provide excellent targets for gamma-ray searches
- Many newly-discovered dSphs lack measured stellar kinematics, previous studies have appealed to scaling relations between the J-factor and observable quantities

J-factor: annihilation rate

The gamma-ray flux from DM self-annihilation: $\Phi_\gamma = \frac{1}{8\pi m_\chi^2}\int_{E_1}^{E_2}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma < \sigma_A v_{12} >$

$$< \sigma_A v_{12} > = \int_{\Delta\Omega}\mathrm{d}\Omega\int_{\mathrm{los}}\mathrm{d}l\int \mathrm{d}^3 v_1 \mathrm{d}^3 v_2 f(\vec{r}, v_1) f(\vec{r}, v_2)(\sigma_A v_{12})$$

dSphs approximately have Maxwell-Boltzmann distribution:

$$f(r,v) = \frac{\rho(r)}{(2\pi)^{\frac{3}{2}} m^4 \sigma_r(r)\sigma_\perp^2(r)} \exp\left(-\frac{1}{2}\left(\frac{v_r^2}{\sigma_r^2(r)} + \frac{v_\perp^2}{\sigma_\perp^2(r)}\right)\right) \qquad (1)$$

where we introduce the velocity anisotropy parameter: $\beta(r) = 1 - \frac{\sigma_\perp^2(r)}{\sigma_r^2(r)}$

J-factor: annihilation rate

The non-relativistic expansion ($v \to 0$): $\sigma_A v_{12} = a + b v_{12}^2 + \underline{O}(v_{12}^4)$

s-wave J-factor: $$J \equiv \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \mathrm{d}l \times \rho^2(r) \Longrightarrow \Phi_\gamma = \frac{a}{8\pi m_\chi^2} \int_{E_1}^{E_2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \mathrm{d}E_\gamma \times J$$

p-wave J-factor: $$J_p \equiv \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \mathrm{d}l \int \mathrm{d}^3 v_1 \mathrm{d}^3 v_2 f(\vec{r}, v_1) f(\vec{r}, v_2) v_{12}^2 = [f = (1)] = \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \mathrm{d}l \times \rho^2(r)\, P(r)$$

where $P(r) = 2\sigma_r^2(r)(3 - 2\beta(r))$

d-wave J-factor: $$J_d \equiv \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \mathrm{d}l \int \mathrm{d}^3 v_1 \mathrm{d}^3 v_2 f(\vec{r}, v_1) f(\vec{r}, v_2) v_{12}^4 = [f = (1)] = \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \mathrm{d}l \times \rho^2(r)\, P(r)$$

where $P(r) = 4\sigma_r^4(r)(15 - 20\beta(r) + 8\beta^2(r))$

D-factor: decay rate

The gamma-ray flux from DM decay: $$\Phi_\gamma = \frac{\Gamma}{4\pi m_\chi^2} \int_{E_1}^{E_2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \mathrm{d}E_\gamma \times D$$

where: $$D \equiv \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \mathrm{d}l \times \rho(r)$$

Numerical analysis

Radial Jeans equation:

$$\frac{1}{\rho_*}\frac{\partial}{\partial r}\left(\rho_*(r)\sigma_{r*}^2(r)\right)+\frac{2\beta_*(r)}{r}\sigma_{r*}^2(r)=-G\,\frac{M_{tot}\,(<r)}{r^2}$$

$$\frac{1}{\rho}\frac{\partial}{\partial r}\left(\rho(r)\sigma_r^2(r)\right)+\frac{2\beta(r)}{r}\sigma_r^2(r)=-G\,\frac{M_{tot}(<r)}{r^2}$$

where $\sigma_{r*}^2(r)$ and $\rho_*(r)$ must fit the observed parameters $\sigma_{LOS}^2(R)$ and $\Sigma_*(R)$

$$\sigma_{LOS}^2(R)=\frac{2}{\Sigma_*(R)}\int_R^\infty\left(1-\beta\,\frac{R^2}{r^2}\right)\frac{\rho_*(r)\sigma_{r*}^2(r)r}{\sqrt{r^2-R^2}}\,\mathrm{d}\,r$$

$$\beta=\beta_0+\frac{\beta_\infty-\beta_0}{1+\left(\frac{r_0}{r}\right)^n}$$

Numerical analysis

Stellar density:

$$\rho_* = \sum_{i=1}^{3} \frac{3N_i}{4\pi a_i^3}\left(1 + \frac{r^2}{a_i^2}\right)^{-5/3}$$

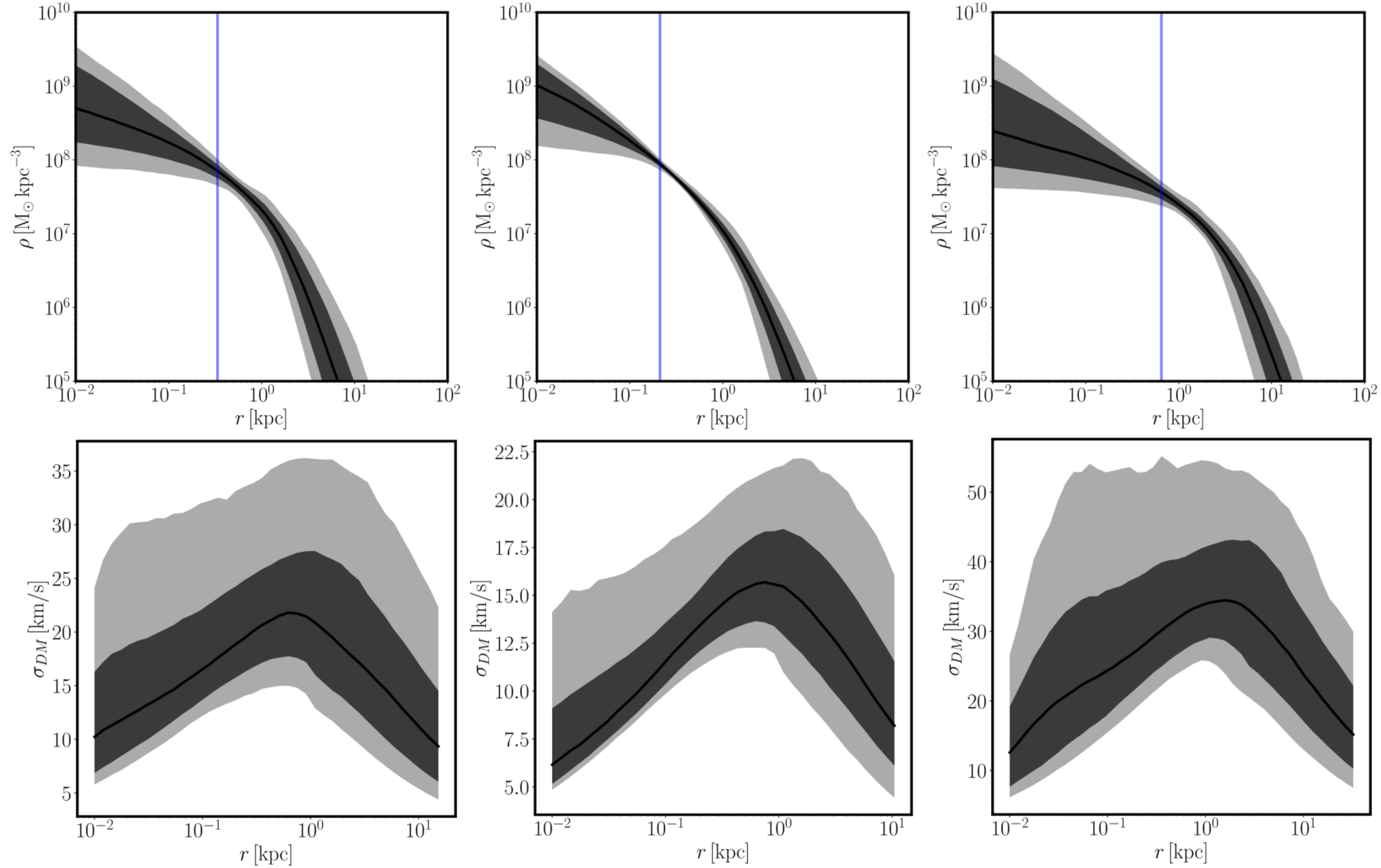
DM density:

$$M_{cNFWt} = M_{NFW}(r < r_t)f^n + 4\pi\rho_{cNFW}(r_t)\frac{r_t^3}{3-\delta}\left[\left(\frac{r}{r_t}\right)^{3-\delta} - 1\right]$$

$$\rho_{cNFW} = \rho_{NFW}f^n + \frac{nf^{n-1}(1-f^2)}{2\pi r^2 r_c} \qquad f = \tanh\left(\frac{r}{r_c}\right)$$

Equations above can be solved using *GravSphere* code.

Numerical analysis



GravSphere numerical approximation to $\rho(r)$ and $\sigma(r)$ for Aquarius Dwarf (left), Sculptor Dwarf Galaxy (middle) and WLM Galaxy (right). The dark blue vertical lines indicate the position of half-light radius.

Results

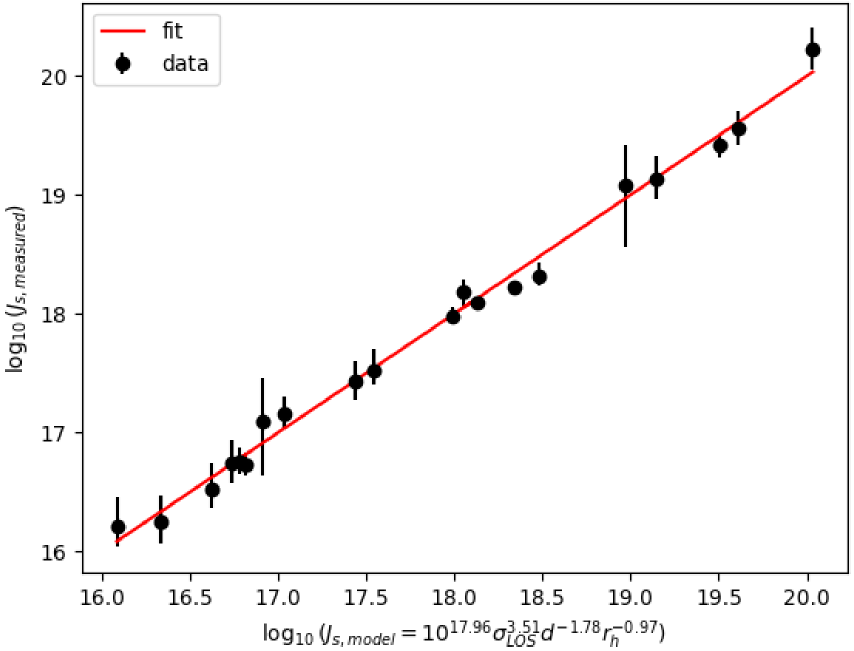
J, J_p, J_d and D-factors calculated in this work:

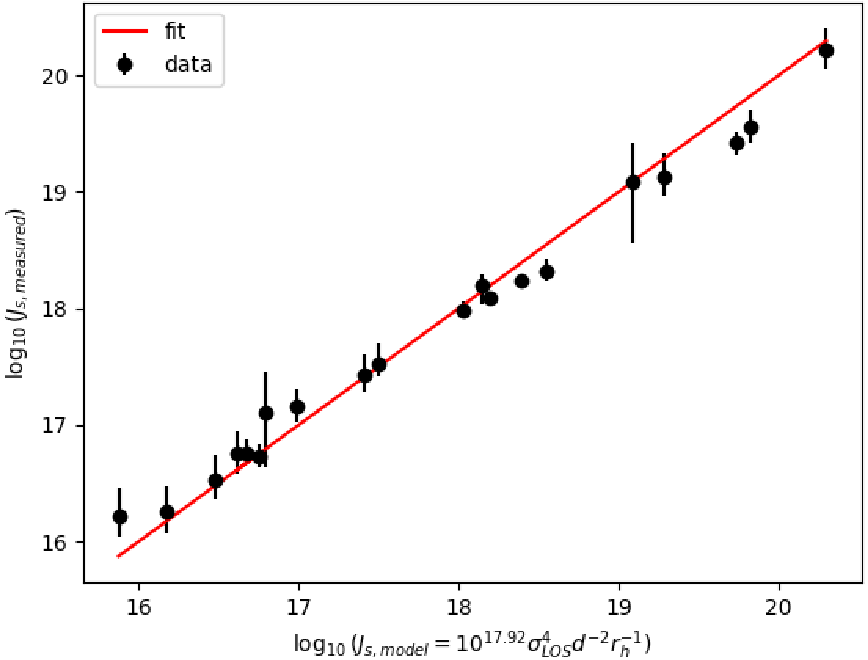
Name	$\log_{10}\frac{J}{\mathrm{GeV^5cm^{-2}}}$	$\log_{10}\frac{J_p}{\mathrm{GeV^5cm^{-2}}}$	$\log_{10}\frac{J_d}{\mathrm{GeV^5cm^{-2}}}$	$\log_{10}\frac{D}{\mathrm{GeV\ cm^{-2}}}$
Andromeda V	$16.76^{+0.11}_{-0.10}$	$14.90^{+0.30}_{-0.23}$	$13.46^{+0.40}_{-0.35}$	$17.21^{+0.24}_{-0.20}$
Aquarius	$16.75^{+0.19}_{-0.17}$	$15.18^{+0.39}_{-0.43}$	$13.82^{+0.53}_{-0.58}$	$17.19^{+0.34}_{-0.32}$
Bootes	$20.22^{+0.18}_{-0.16}$	$18.83^{+0.47}_{-0.41}$	$18.07^{+0.62}_{-0.54}$	$19.14^{+0.14}_{-0.11}$
Carina	$18.32^{+0.11}_{-0.08}$	$16.92^{+0.25}_{-0.24}$	$15.77^{+0.40}_{-0.36}$	$18.44^{+0.09}_{-0.07}$
Cetus	$16.25^{+0.22}_{-0.18}$	$13.70^{+0.37}_{-0.38}$	$11.81^{+0.54}_{-0.46}$	$16.67^{+0.28}_{-0.22}$
Coma	$19.08^{+0.34}_{-0.52}$	$16.22^{+0.30}_{-0.32}$	$14.48^{+0.38}_{-0.40}$	$18.42^{+0.10}_{-0.13}$
CVn I	$17.43^{+0.17}_{-0.15}$	$15.74^{+0.27}_{-0.22}$	$14.30^{+0.37}_{-0.34}$	$17.98^{+0.10}_{-0.09}$
Draco	$19.56^{+0.14}_{-0.14}$	$18.51^{+0.25}_{-0.32}$	$17.70^{+0.49}_{-0.43}$	$18.97^{+0.10}_{-0.10}$
Fornax	$18.09^{+0.03}_{-0.03}$	$16.63^{+0.08}_{-0.07}$	$13.46^{+0.40}_{-0.35}$	$18.33^{+0.02}_{-0.02}$

J-factor: scaling relation

Assuming fitting relation: $$J_s = 10^{J_{s,0}} \left(\frac{\sigma_{los}}{5\ \mathrm{km/s}}\right)^{\gamma_\sigma} \left(\frac{d}{100\ \mathrm{kpc}}\right)^{\gamma_d} \left(\frac{r_h}{100\ \mathrm{pc}}\right)^{\gamma_r}$$

J_0	γ_σ	γ_d	γ_r
17.96±0.07	3.35±0.26	−1.76 ±0.13	-1.07±0.26
17.92±0.04	4	-2	-1

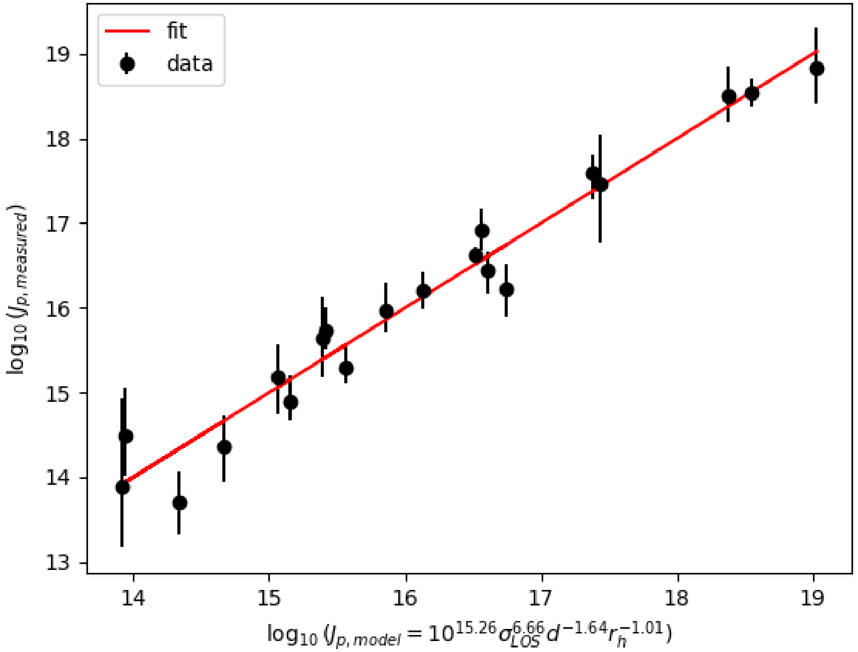


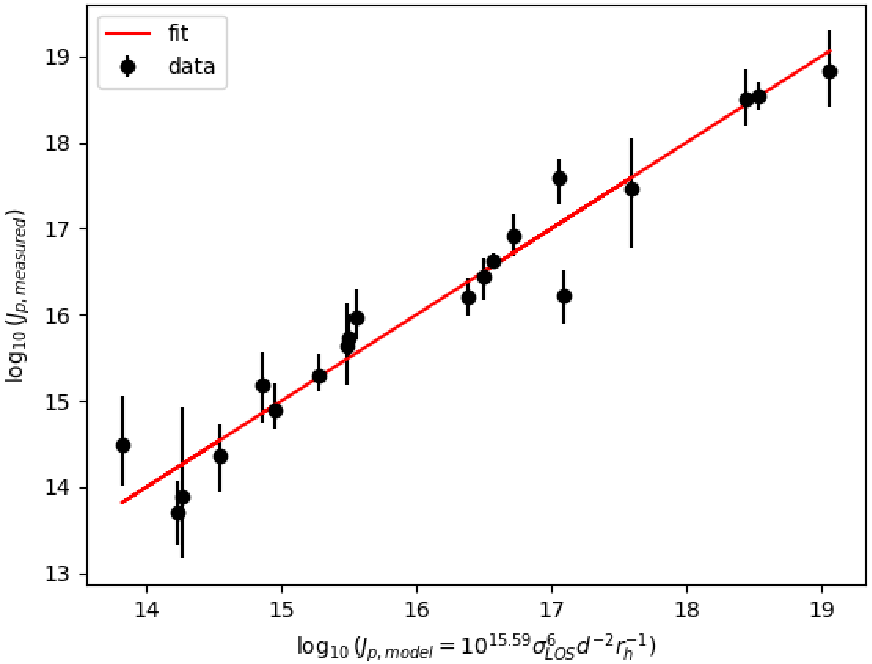


J-factor: scaling relation

Assuming fitting relation: $J_p = 10^{J_{p,0}} \left(\frac{\sigma_{los}}{5\ \mathrm{km/s}}\right)^{\gamma_\sigma} \left(\frac{d}{100\ \mathrm{kpc}}\right)^{\gamma_d} \left(\frac{r_h}{100\ \mathrm{pc}}\right)^{\gamma_r}$

J_0	γ_σ	γ_d	γ_r
15.26 ± 0.21	6.66 ± 0.44	-1.64 ± 0.22	-1.01 ± 0.44
15.59 ± 0.11	6	-2	-1

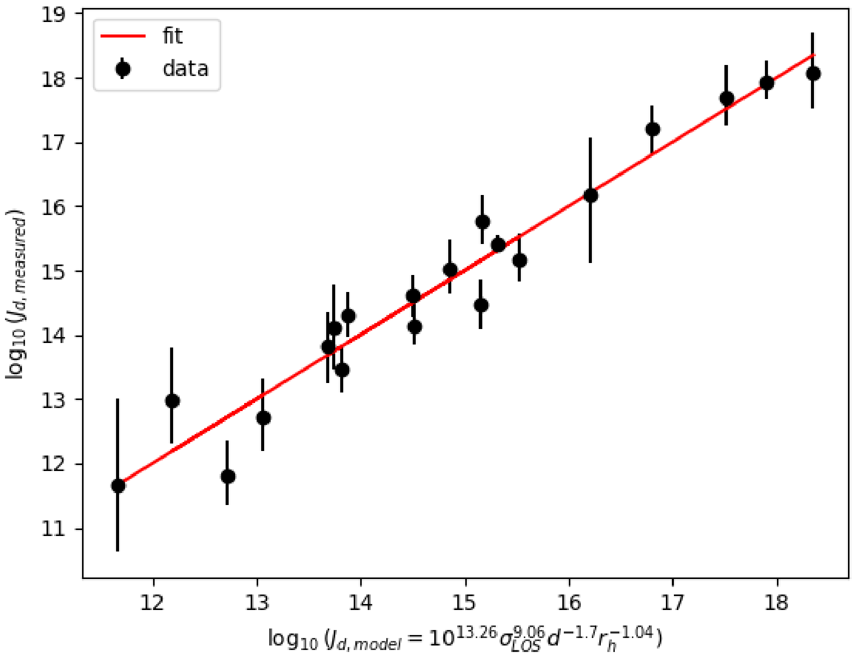


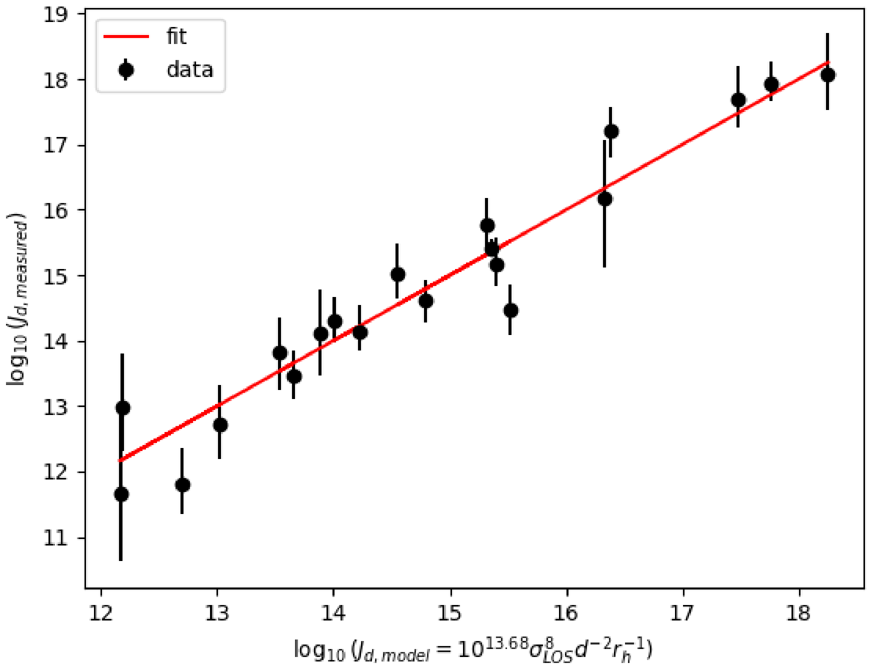


J-factor: scaling relation

Assuming fitting relation: $$J_d = 10^{J_{d,0}} \left(\frac{\sigma_{los}}{5\ \mathrm{km/s}}\right)^{\gamma_\sigma} \left(\frac{d}{100\ \mathrm{kpc}}\right)^{\gamma_d} \left(\frac{r_h}{100\ \mathrm{pc}}\right)^{\gamma_r}$$

J_0	γ_σ	γ_d	γ_r
13.26 ± 0.30	9.06±0.64	-1.70 ± 0.32	-1.04±0.64
13.68±0.11	8	-2	-1

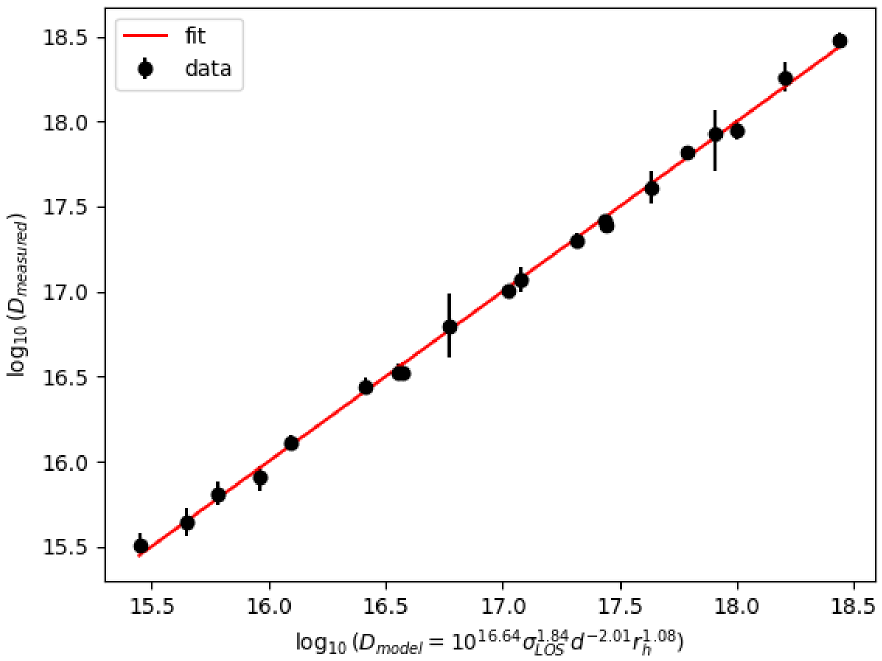


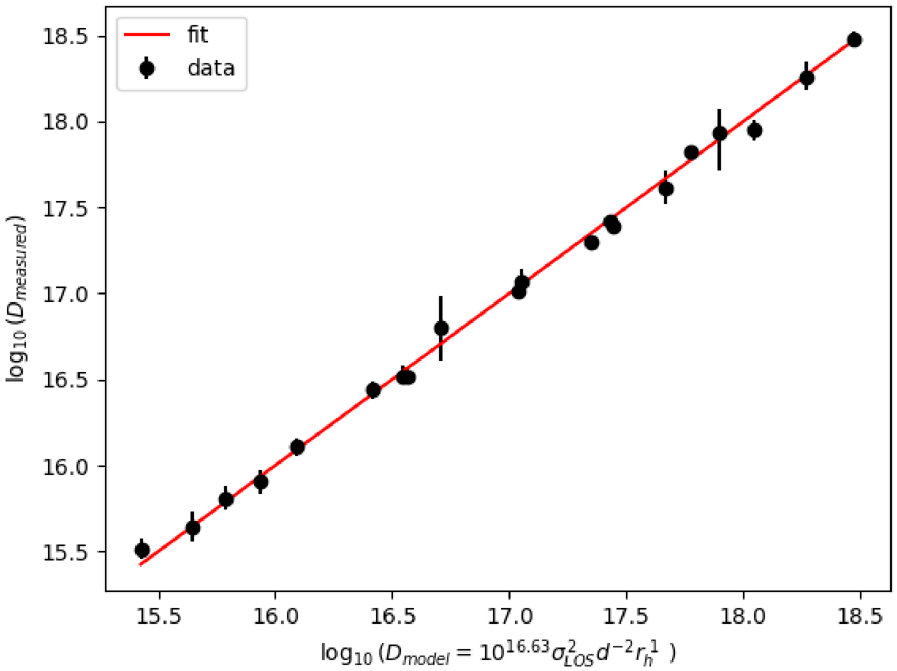


D-factor: scaling relation

Assuming fitting relation: $$D = 10^{D_0}\left(\frac{\sigma_{los}}{5\ \mathrm{km/s}}\right)^{\gamma_\sigma}\left(\frac{d}{100\ \mathrm{kpc}}\right)^{\gamma_d}\left(\frac{r_h}{100\ \mathrm{pc}}\right)^{\gamma_r}$$

D	γ_σ	γ_d	γ_r
16.64 ± 0.03	1.84 ± 0.06	-2.01 ± 0.03	-1.08 ± 0.06
15.63 ± 0.01	2	-2	1





Thank you for attention