XXXIII Canary Islands Winter School of Astrophysics

Fundamental Physics with Galaxies

Kfir Blum | Weizmann Institute of Science

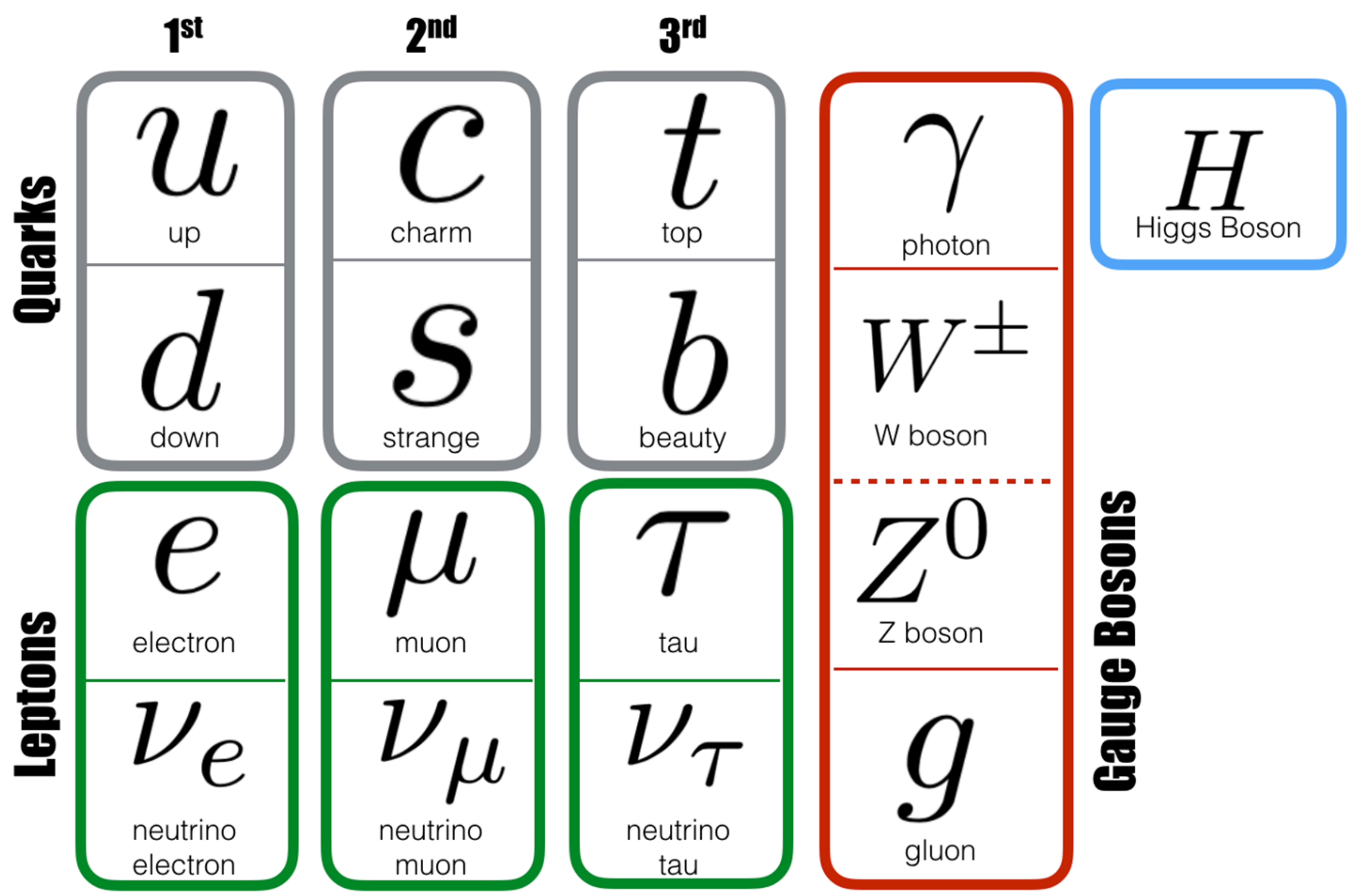
The Standard Model of Particle Physics

No gravity

Does not include neutrino mass
Does not include dark matter

Cosmic inflation (origin of Universe)
Baryon asymmetry (origin of matter)

Why vacuum energy *just (not)* zero?
Why weak scale << Planck scale?
Why no strong CP violation?
Almost grand unification?
Why Higgs vacuum *just* metastable?



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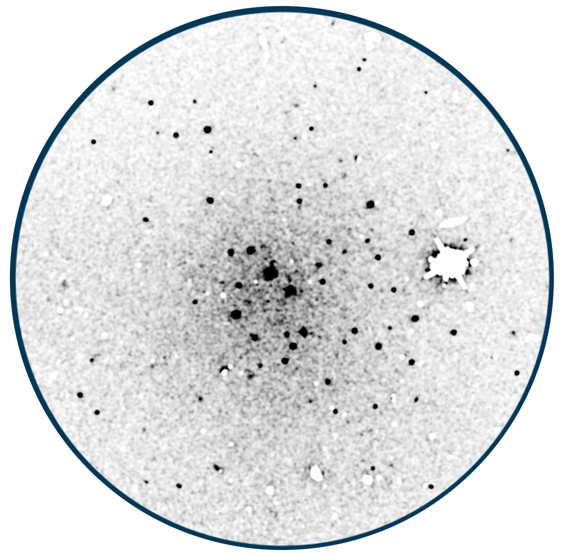
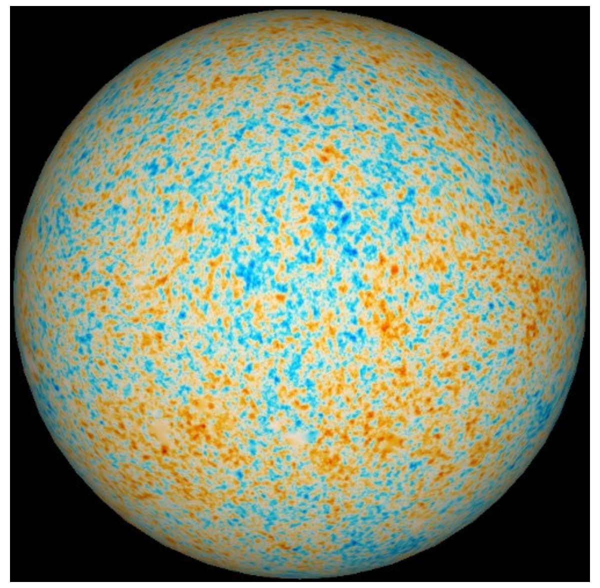
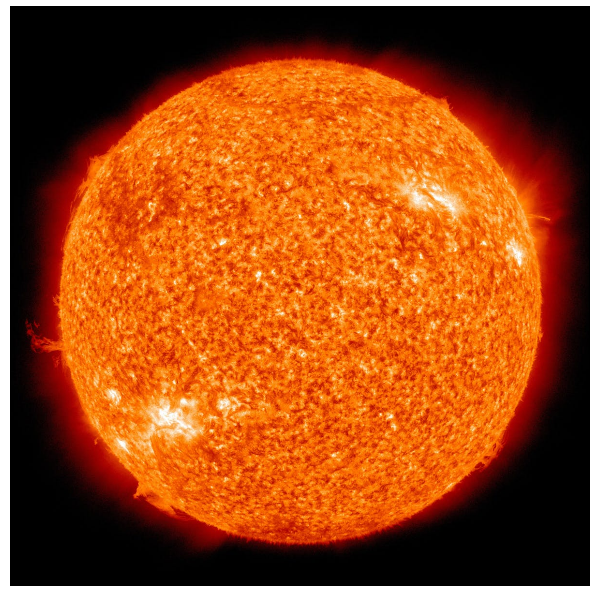
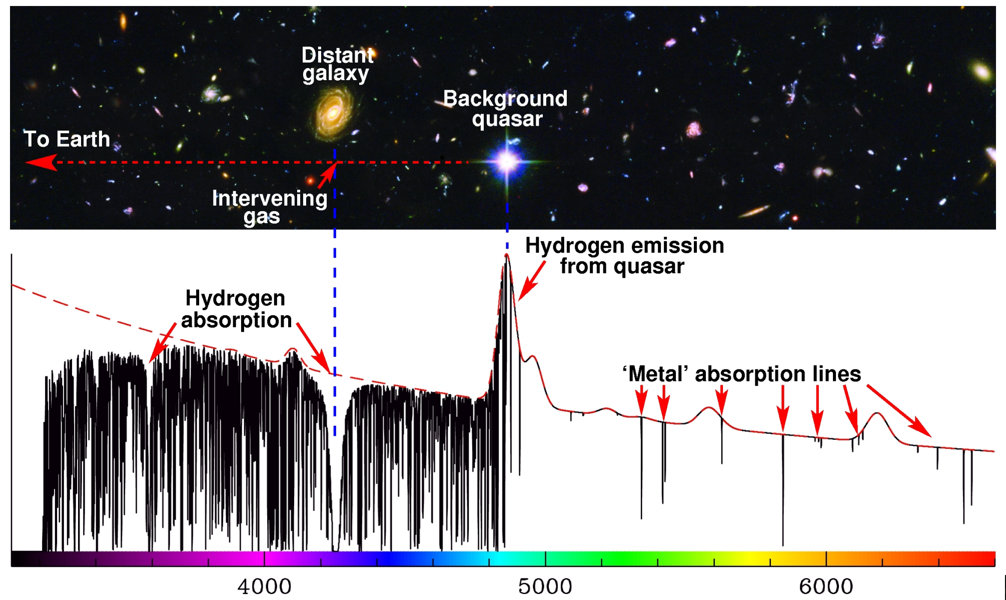
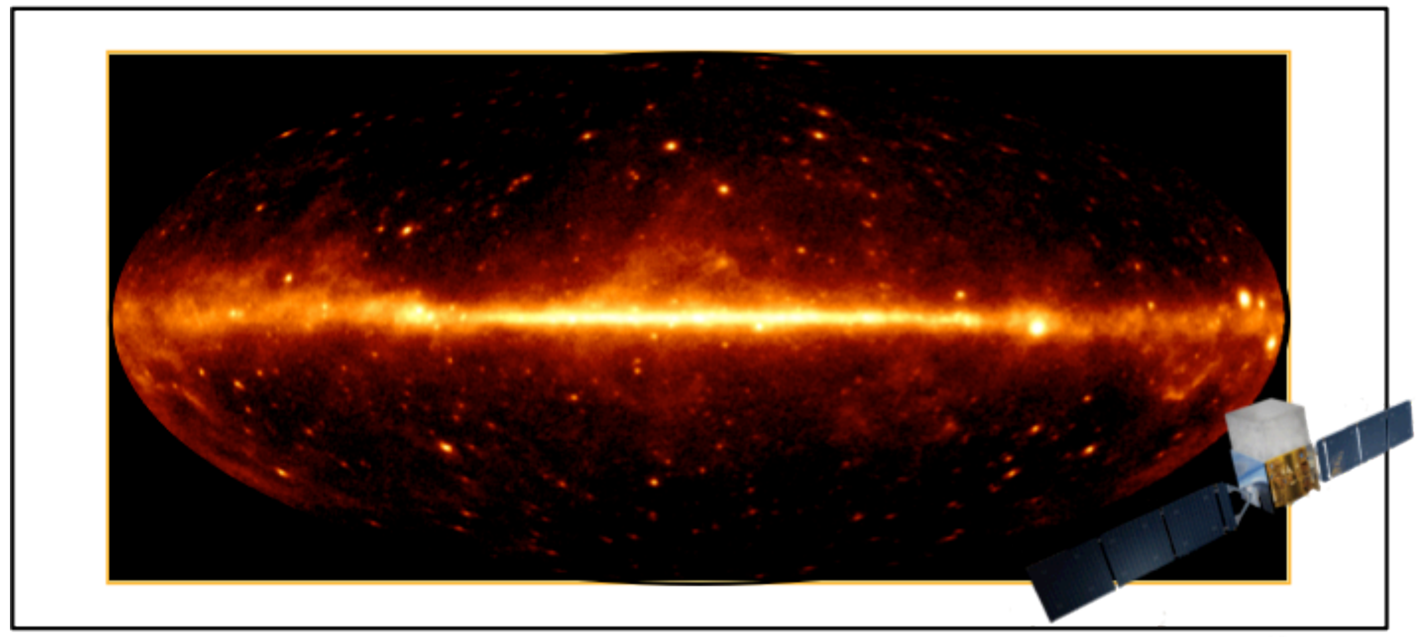
- Observed first in astrophysics
- Observed only in astrophysics
- Constrained by astrophysics

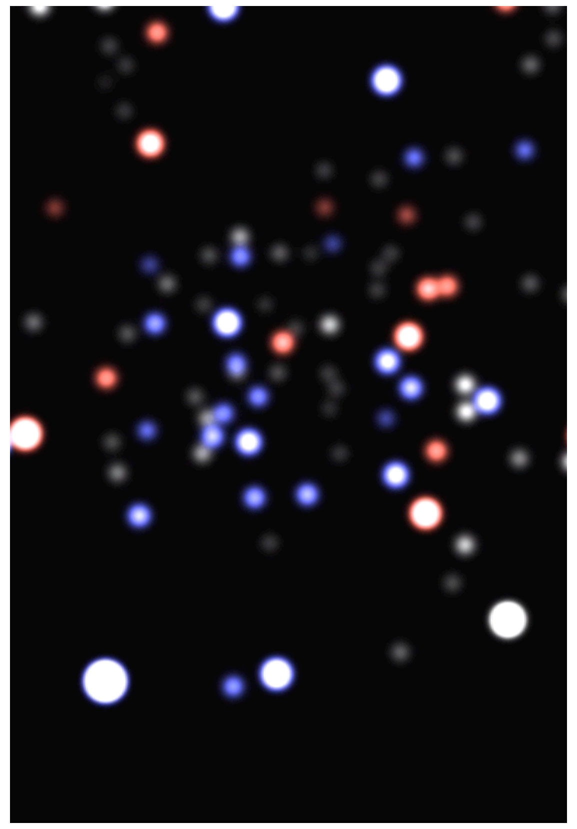


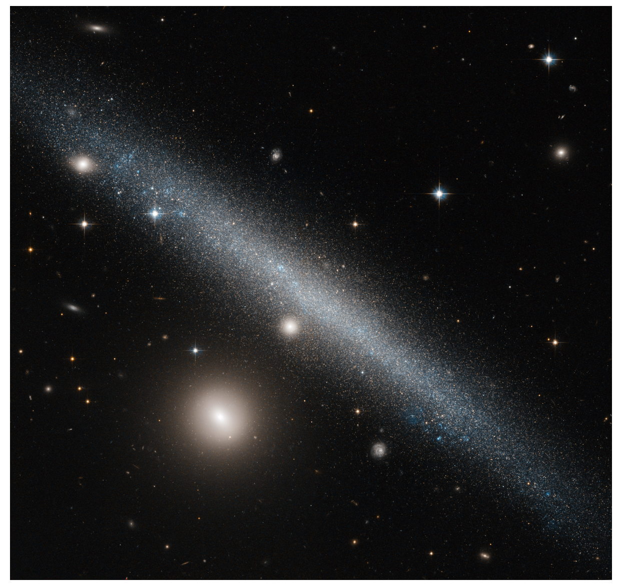


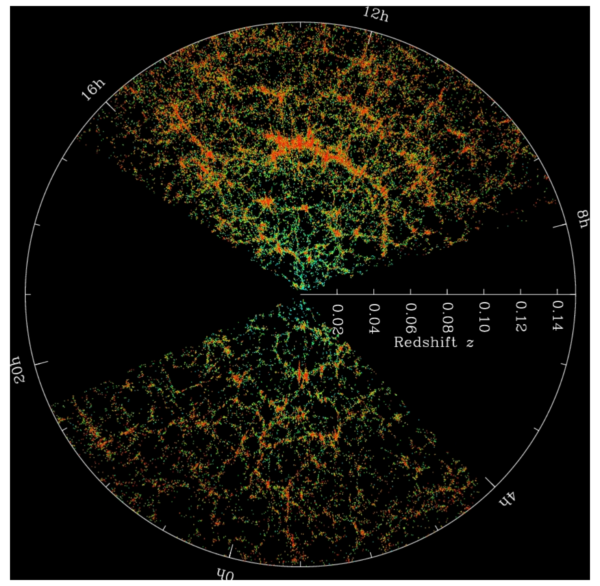


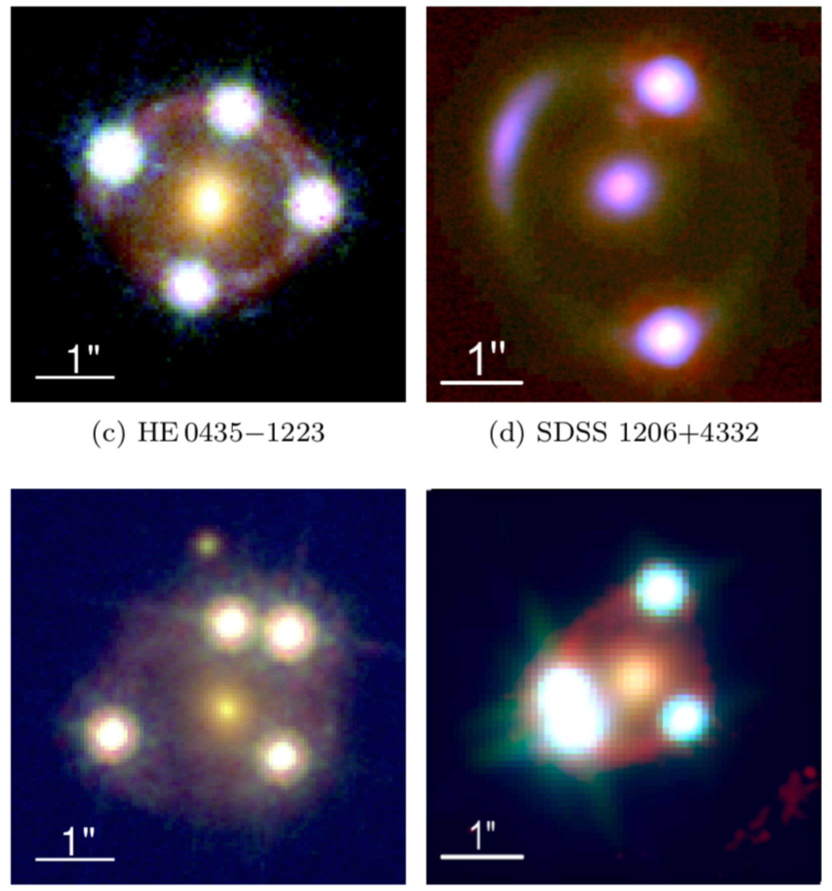






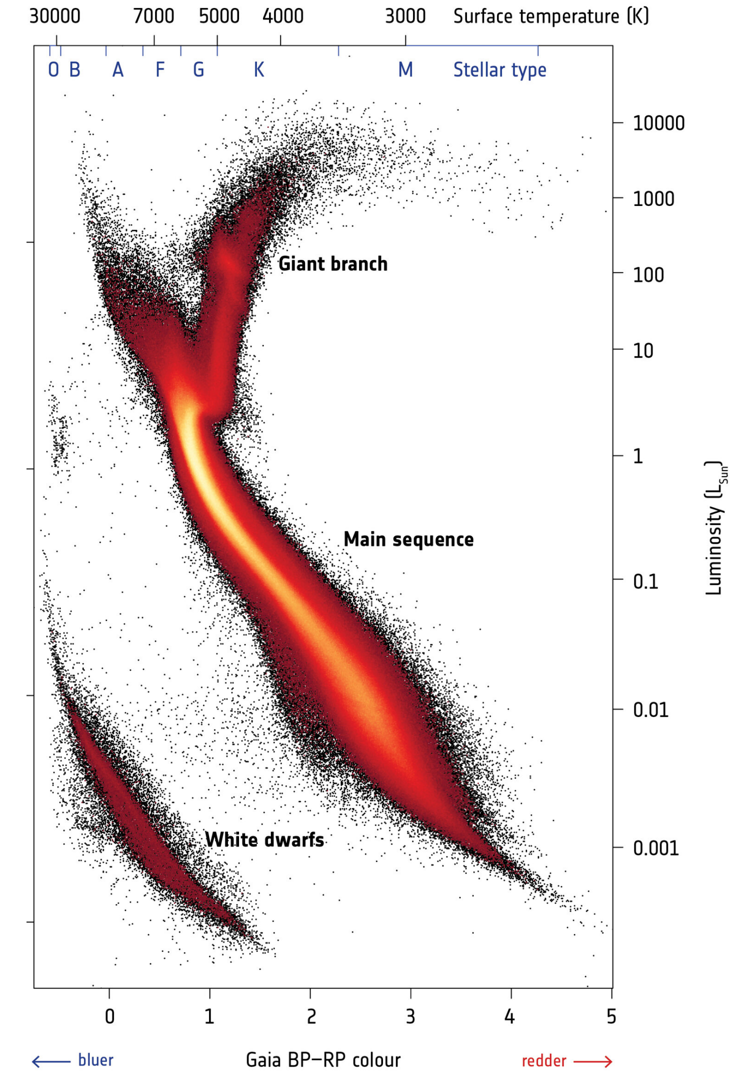


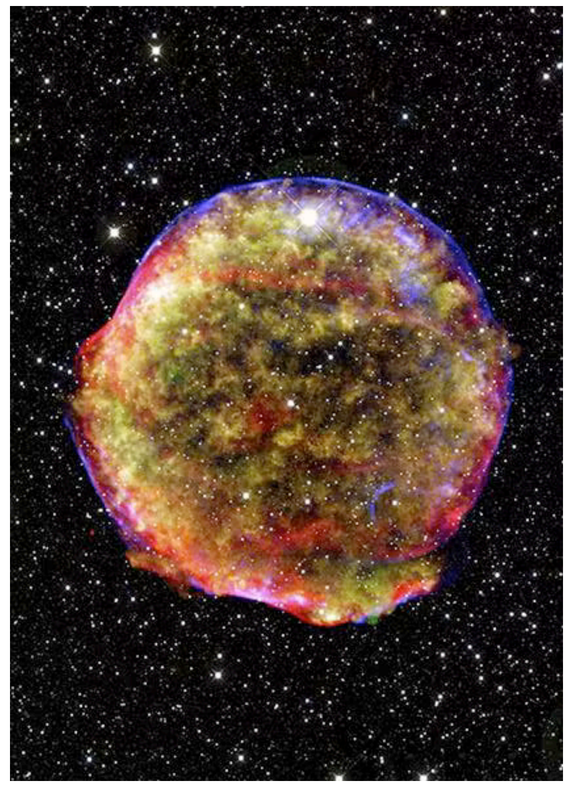


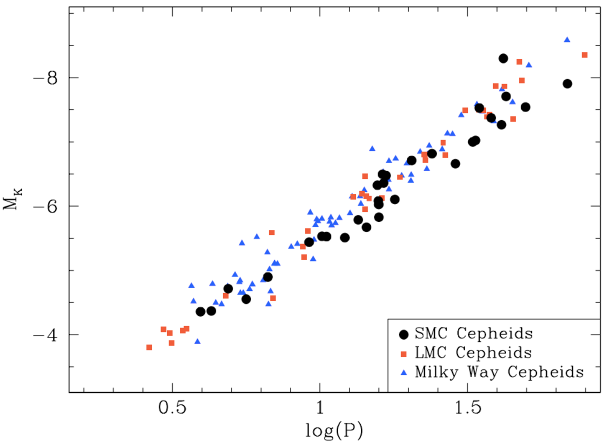


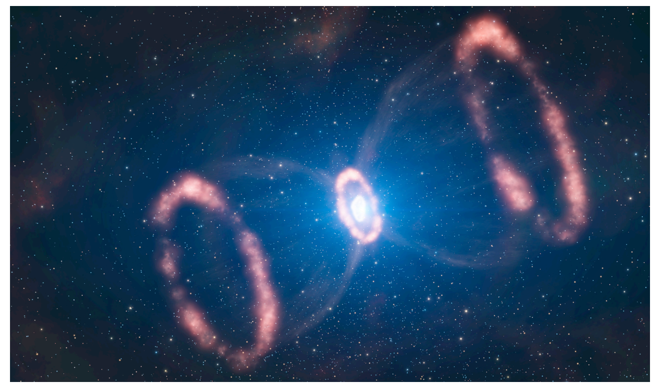
(c) HE 0435−1223 (d) SDSS 1206+4332

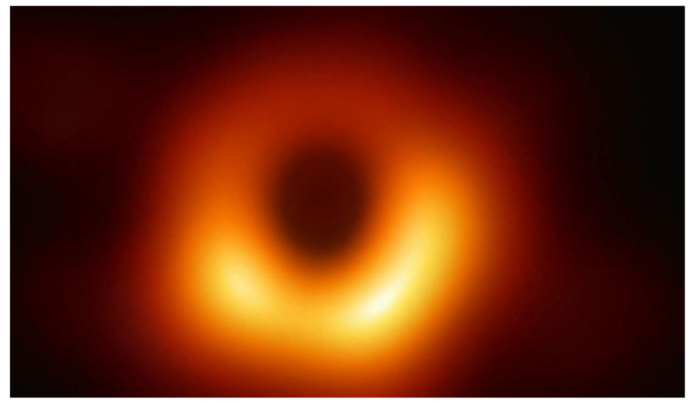
(e) WFI2033−4723 (f) PG 1115+080



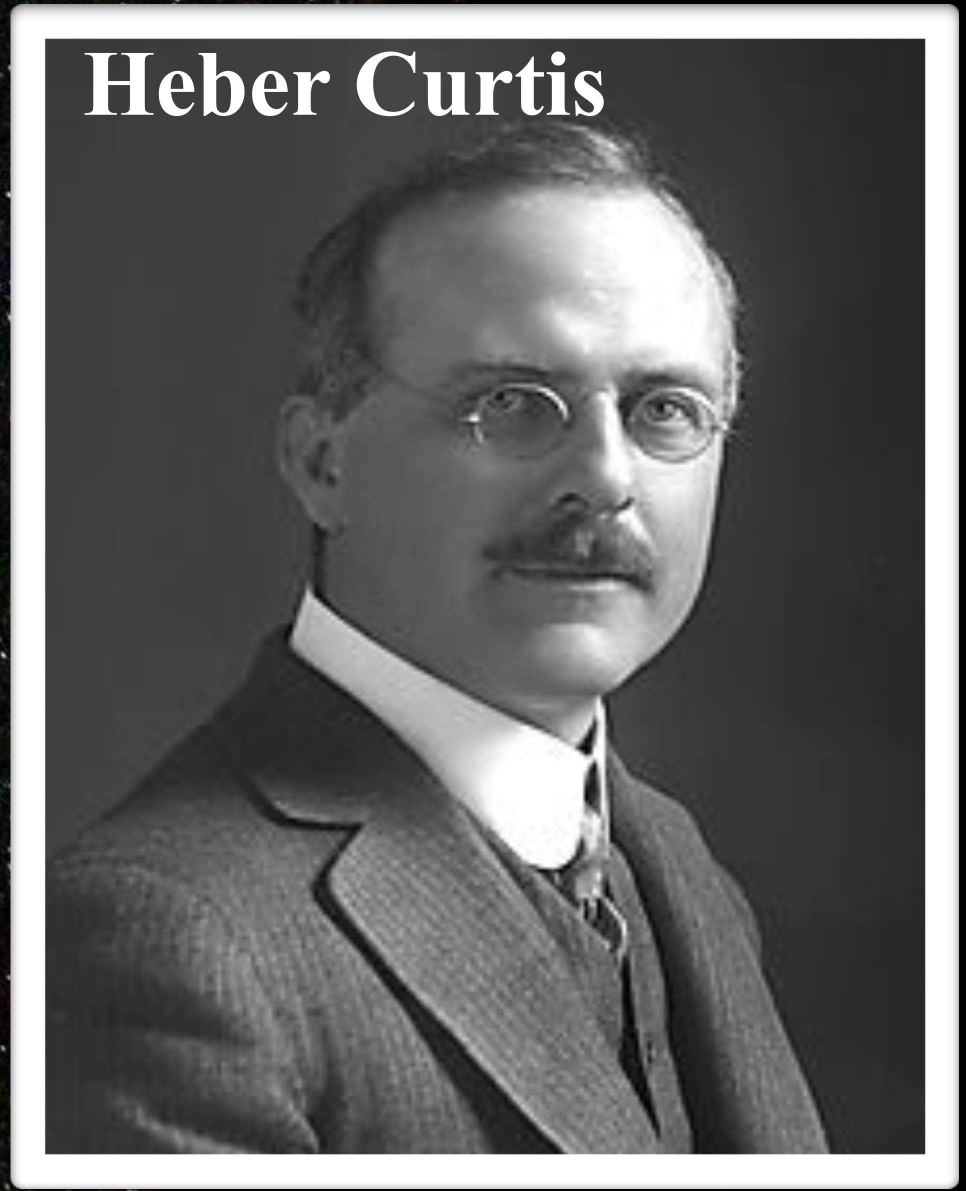




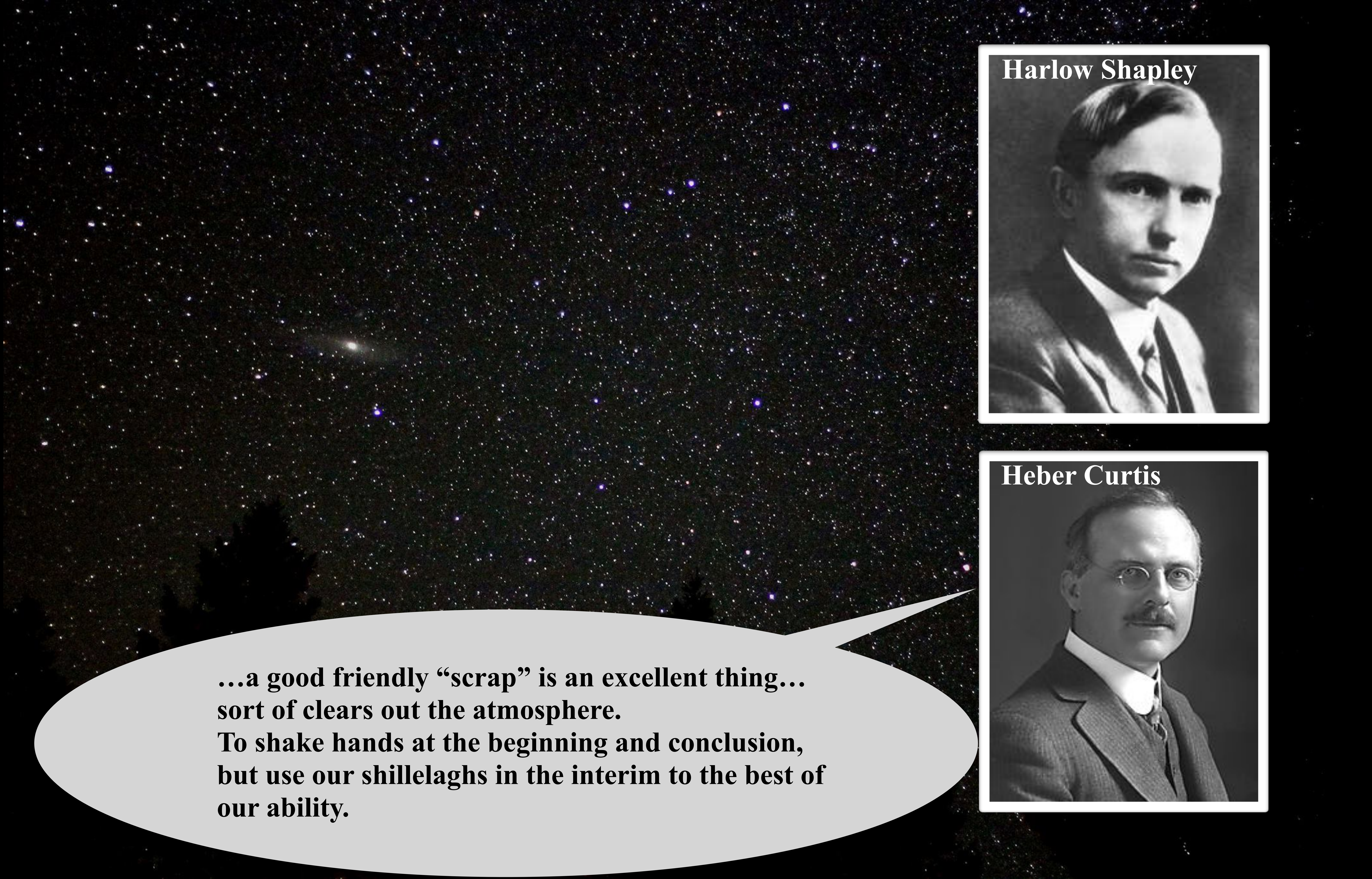


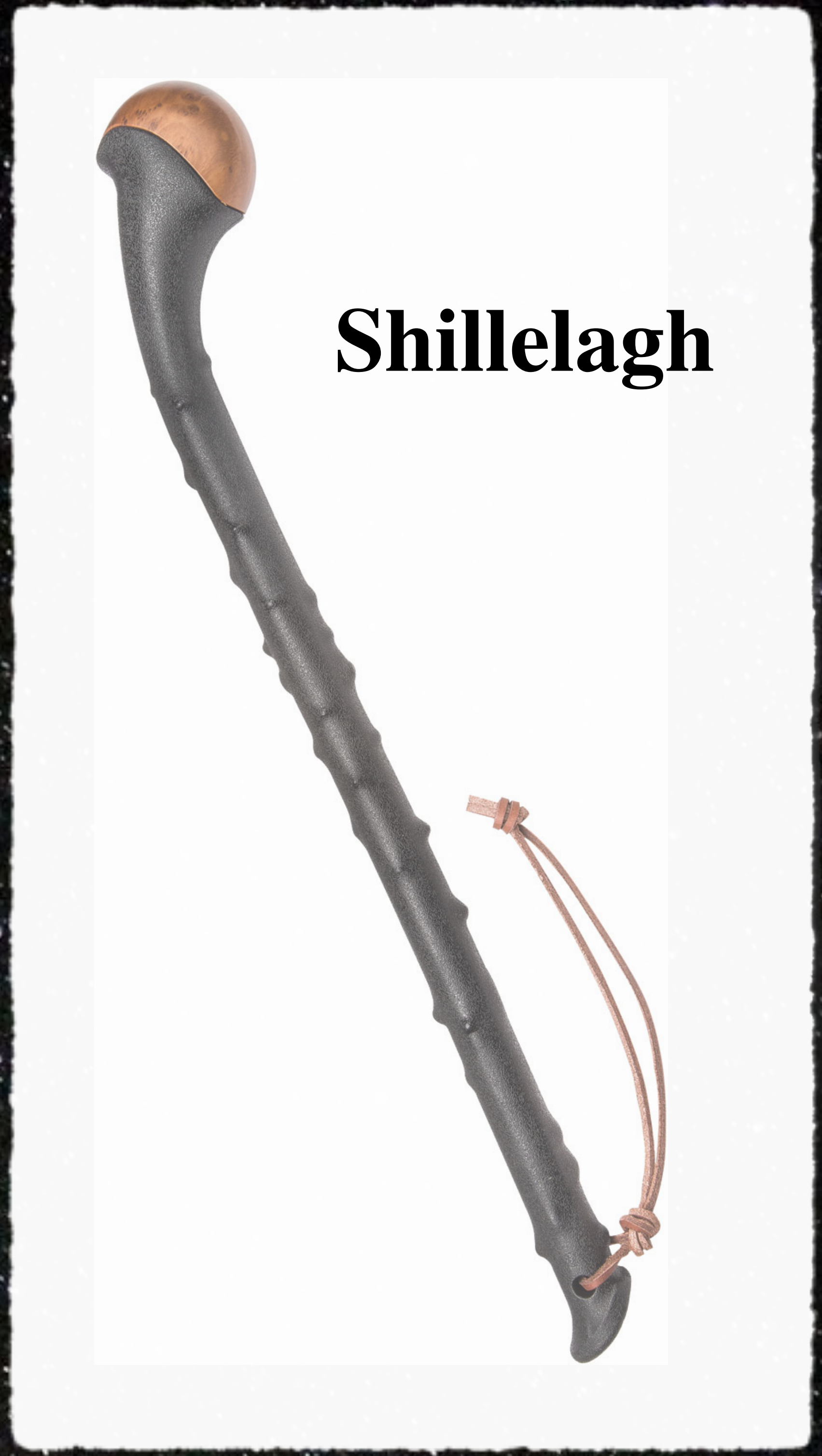


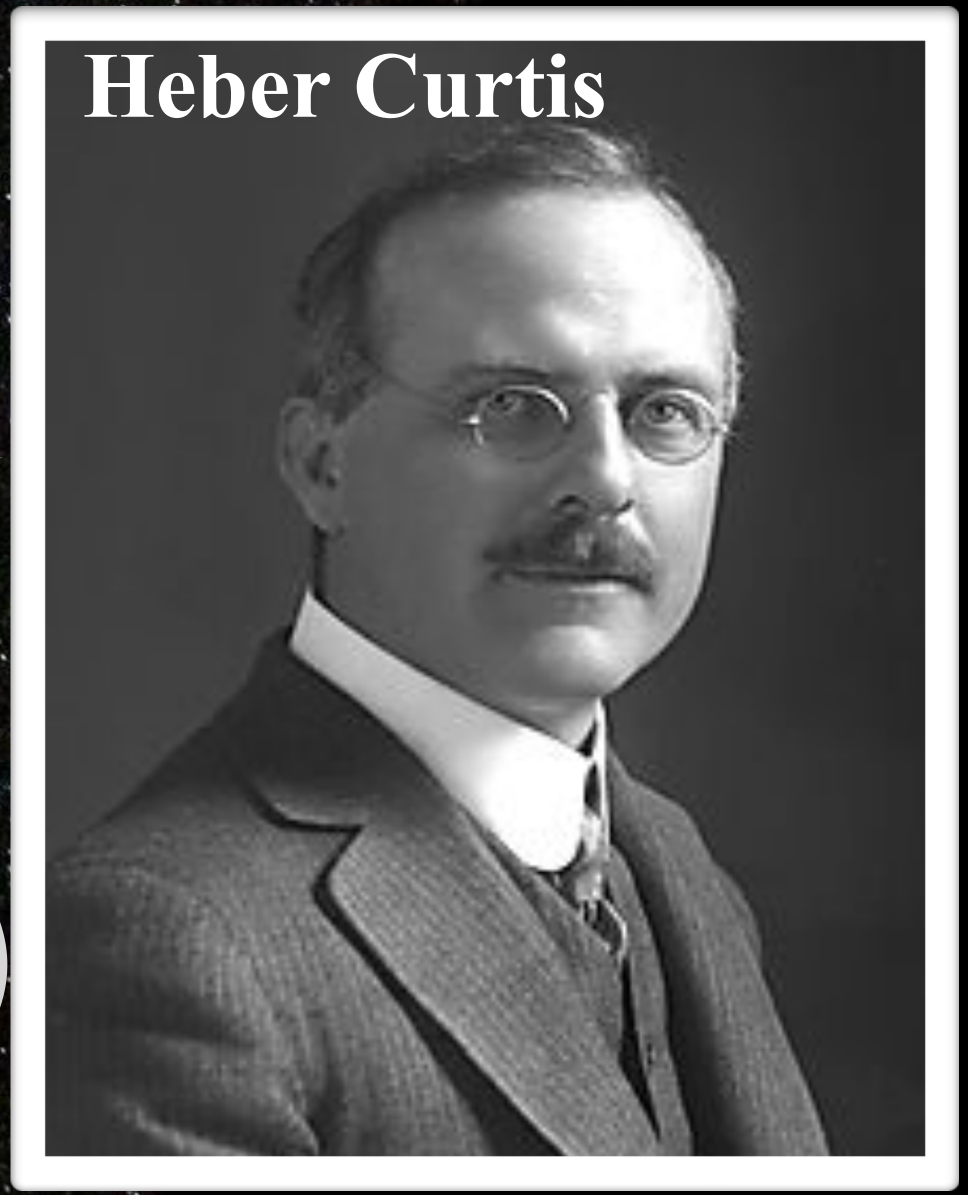

عبدالرحمن صوفی
Al-Sufi,
around 1000 AD



The Great Debate 1920


Harlow Shapley
Heber Curtis
…a good friendly "scrap" is an excellent thing… sort of clears out the atmosphere. To shake hands at the beginning and conclusion, but use our shillelaghs in the interim to the best of our ability.





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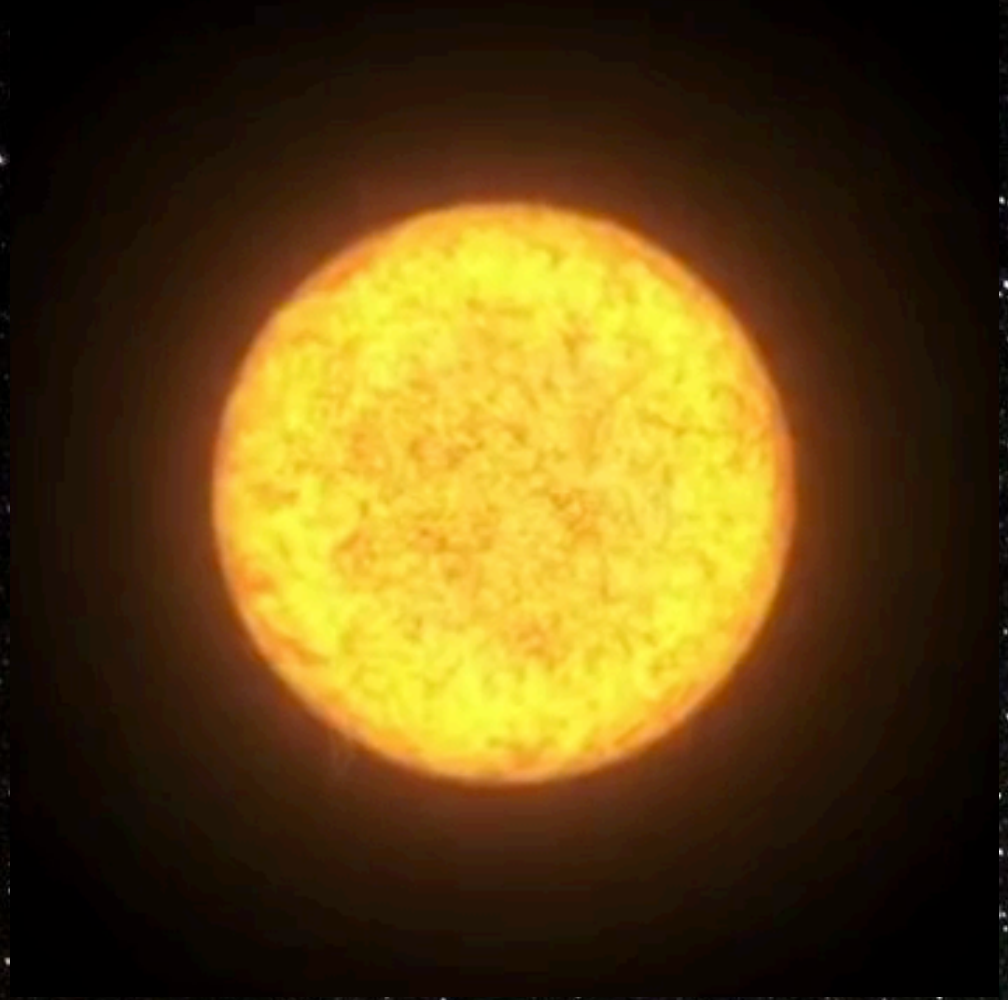
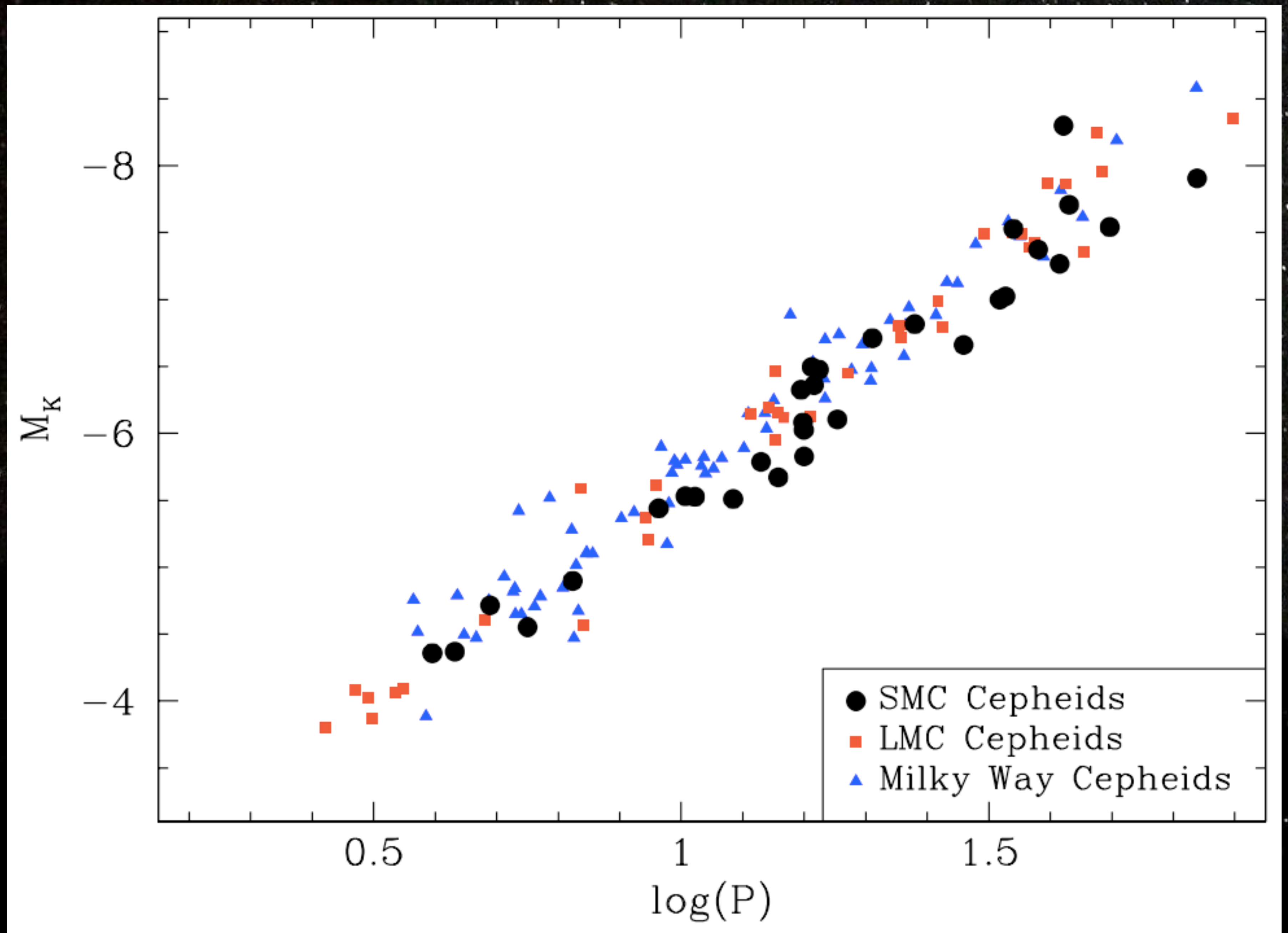
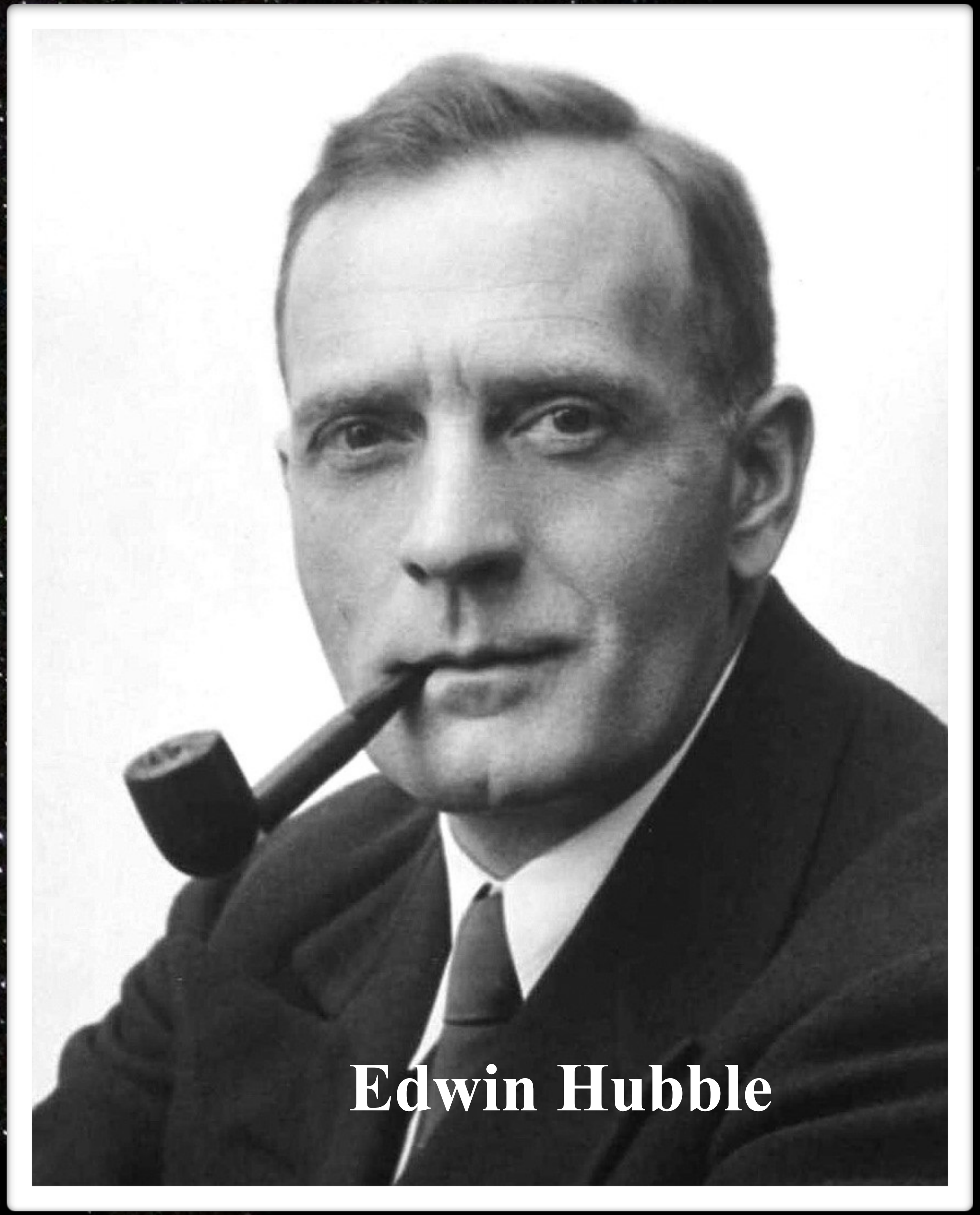
1923





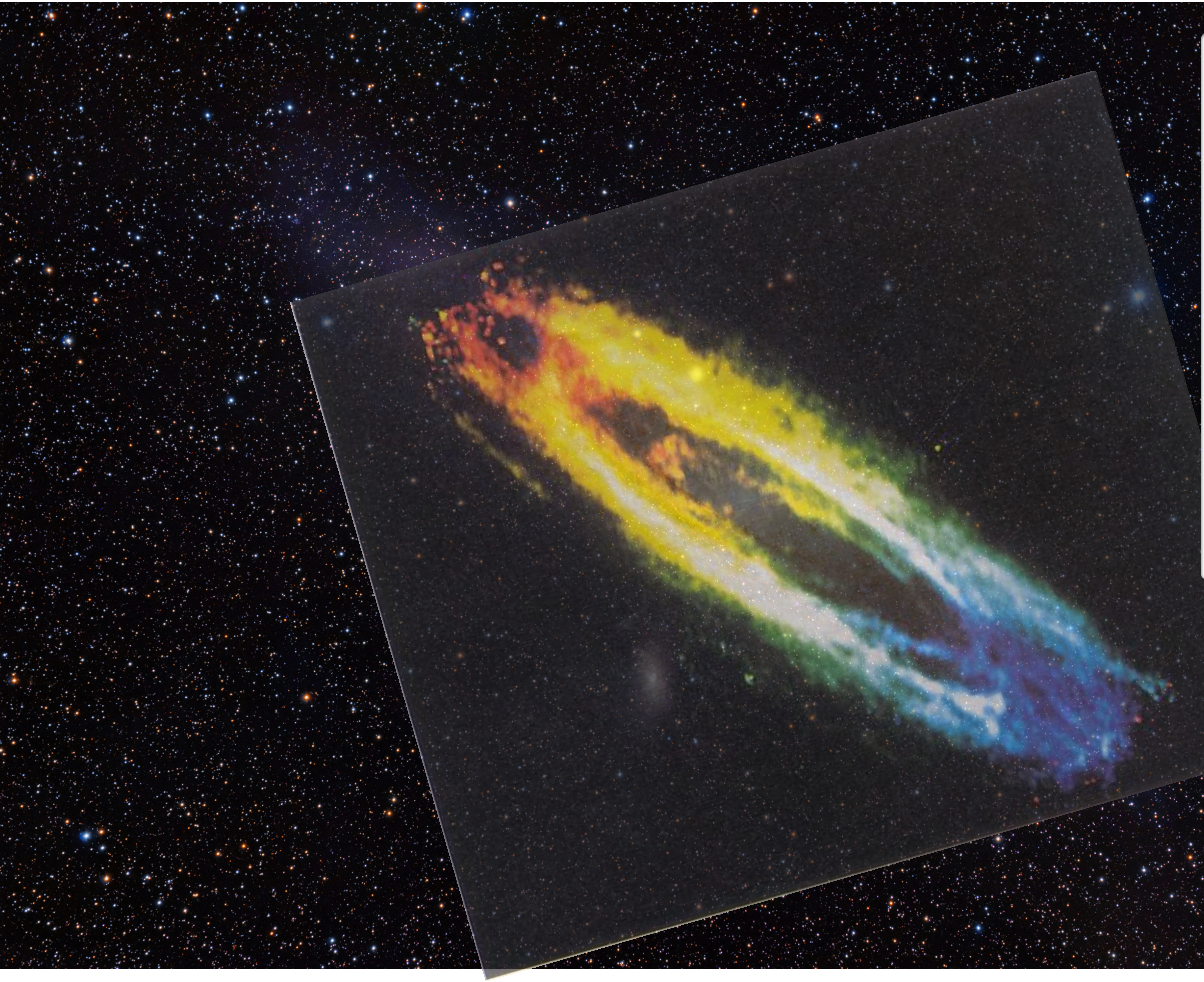
−8
−6
−4
M_K
0.5
1
1.5
log(P)
SMC Cepheids
LMC Cepheids
Milky Way Cepheids

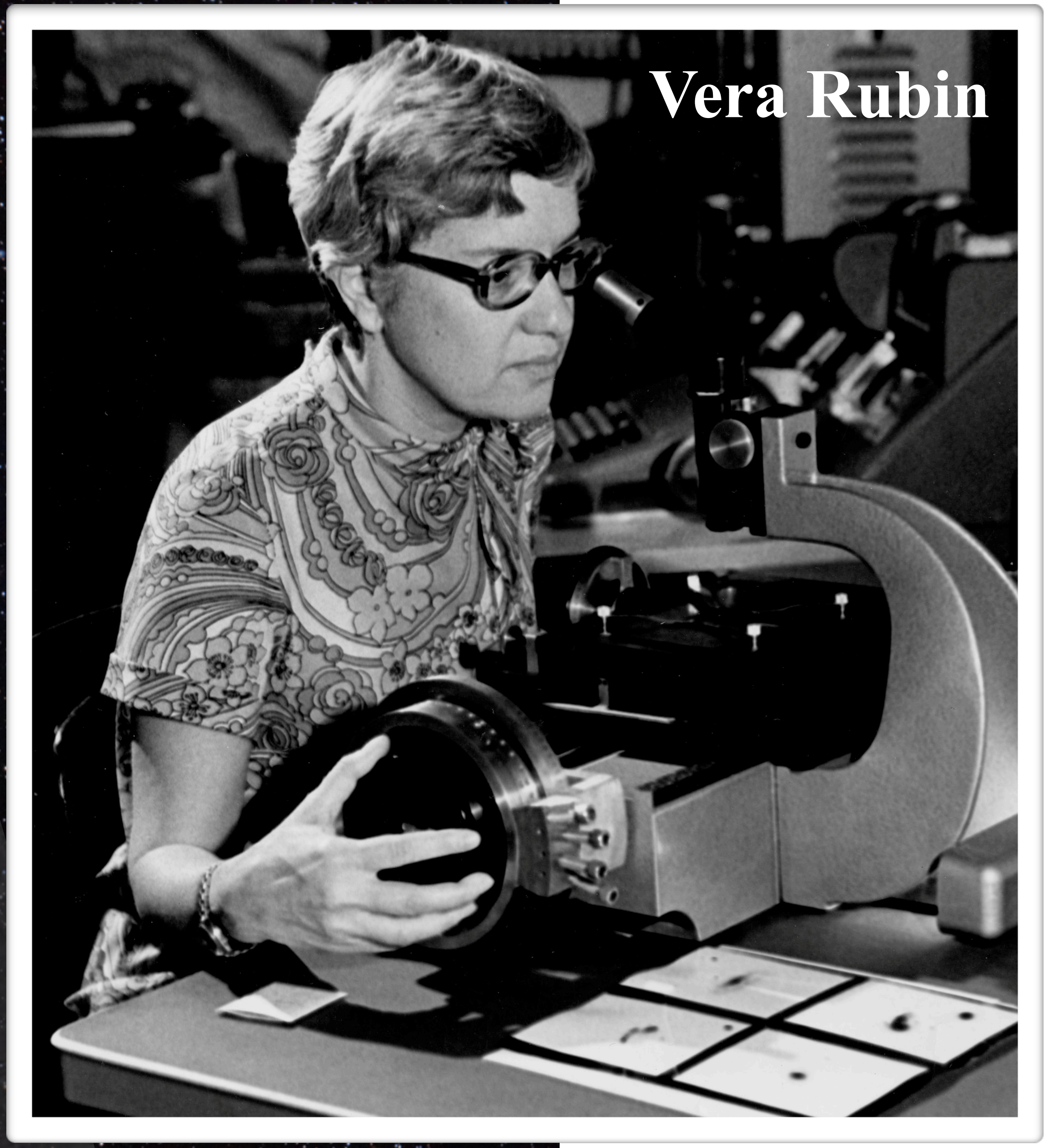


Edwin Hubble

1923

Dark matter





Dark matter

THE ASTROPHYSICAL JOURNAL, Vol. 159, February 1970

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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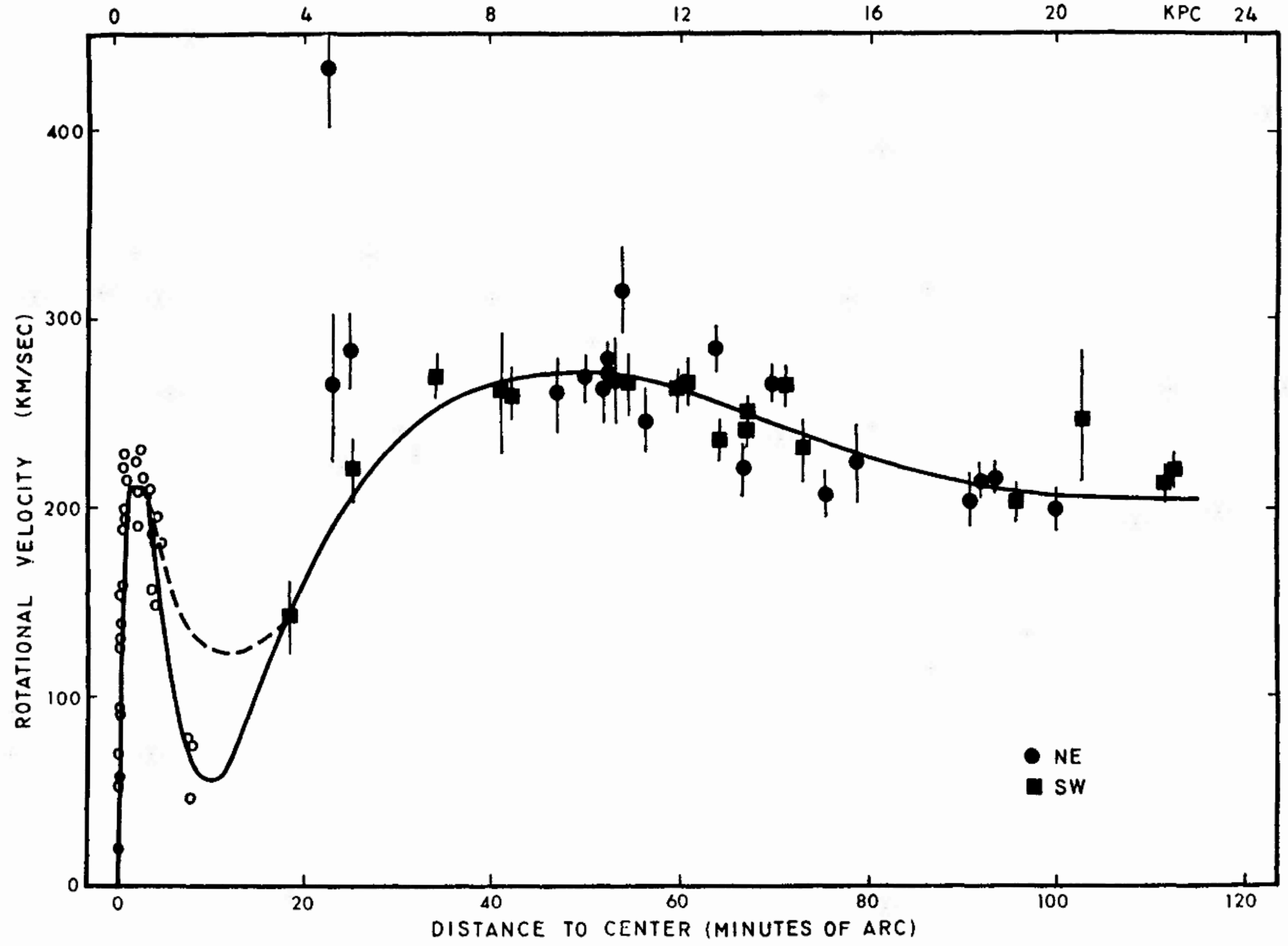

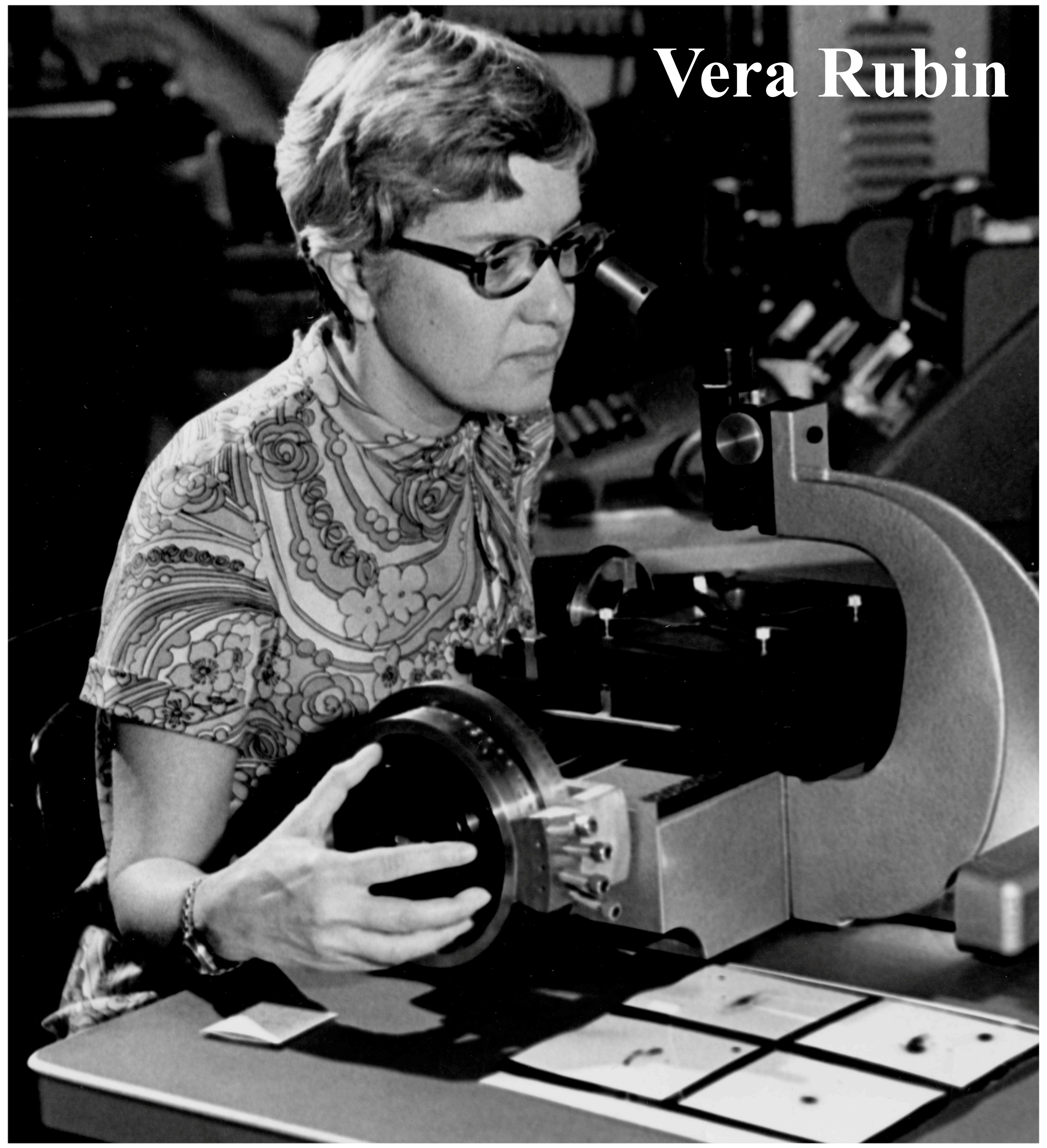

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Dark halos of M 31 and the Milky Way

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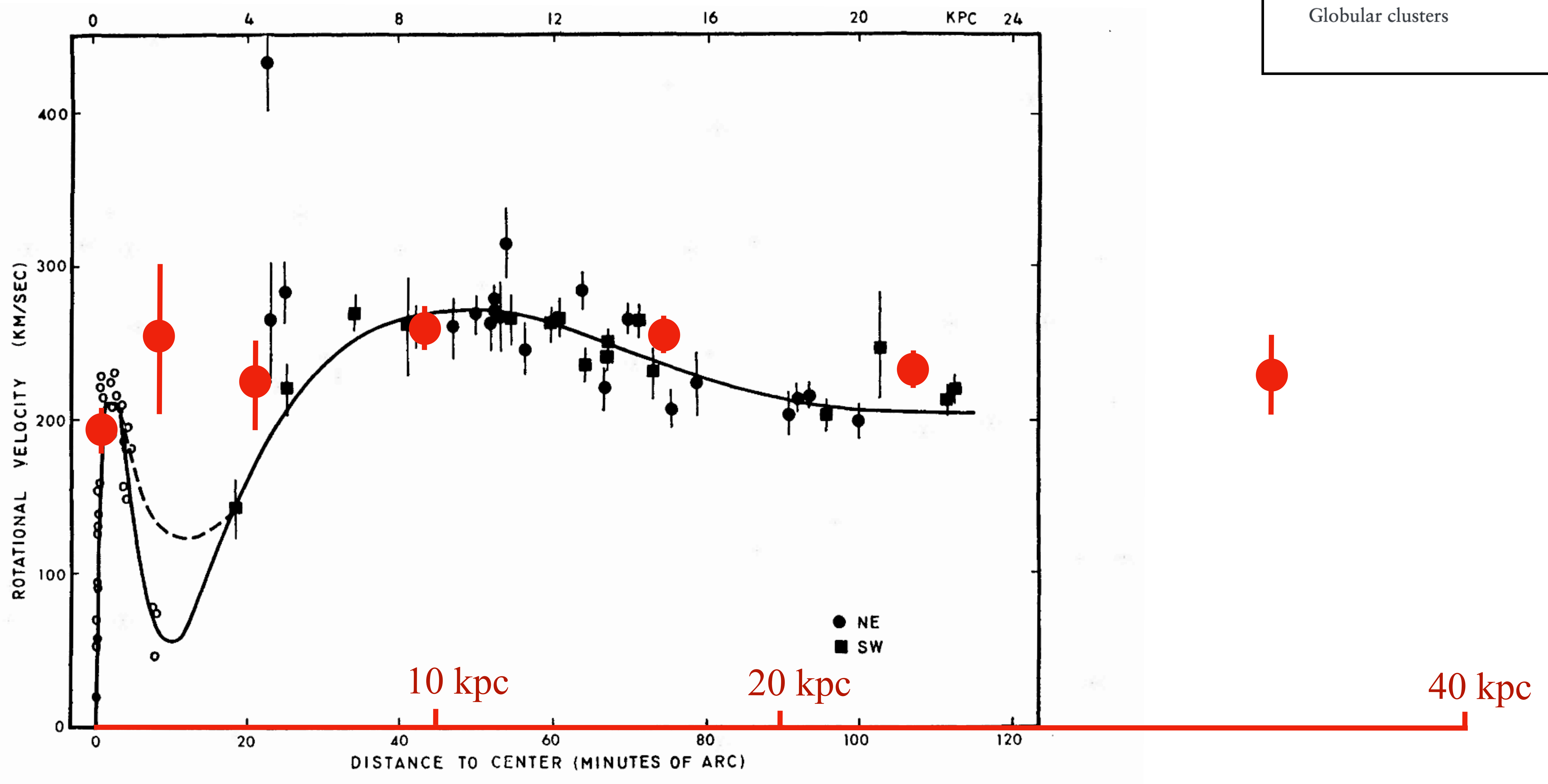

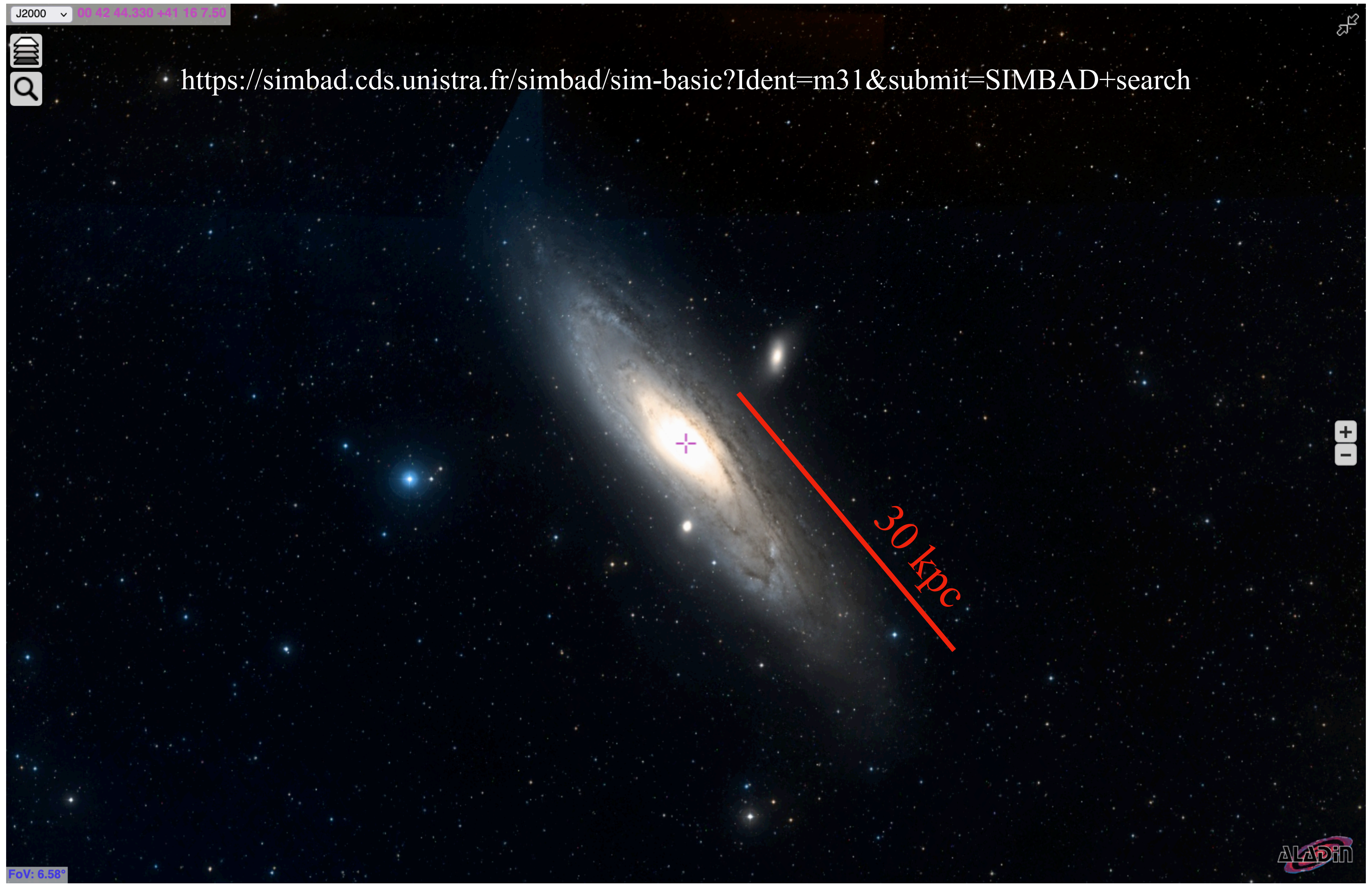

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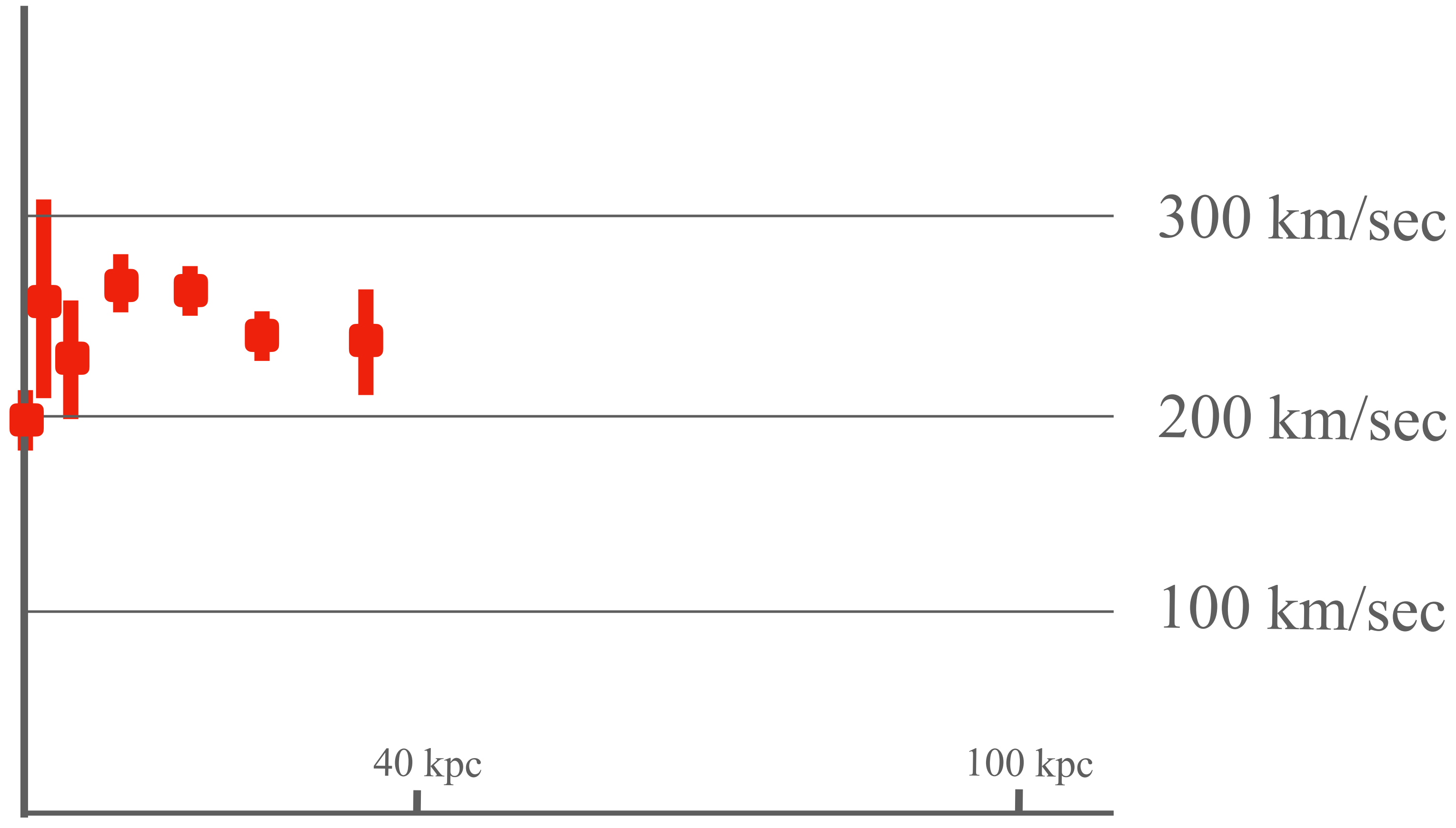

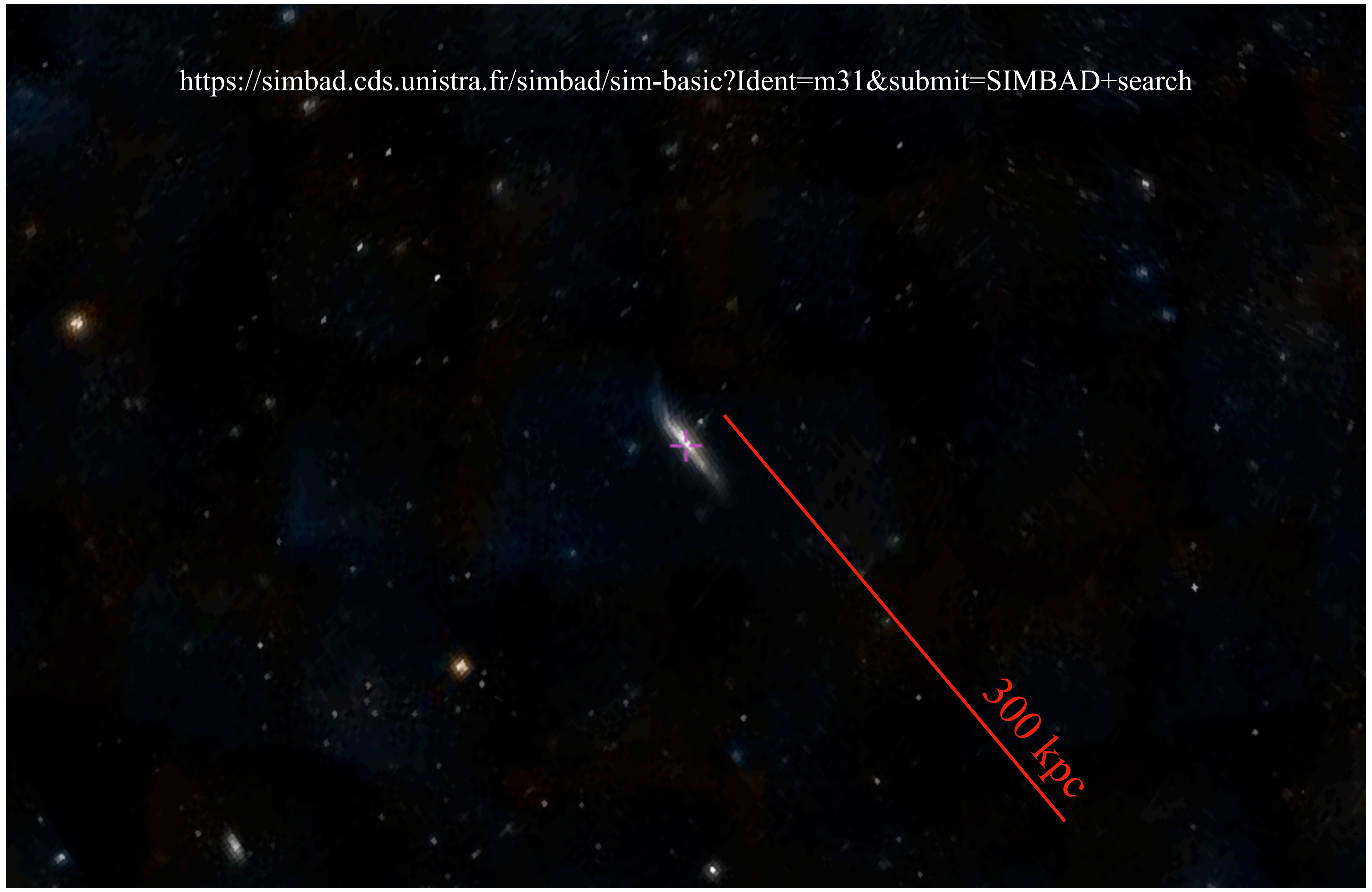

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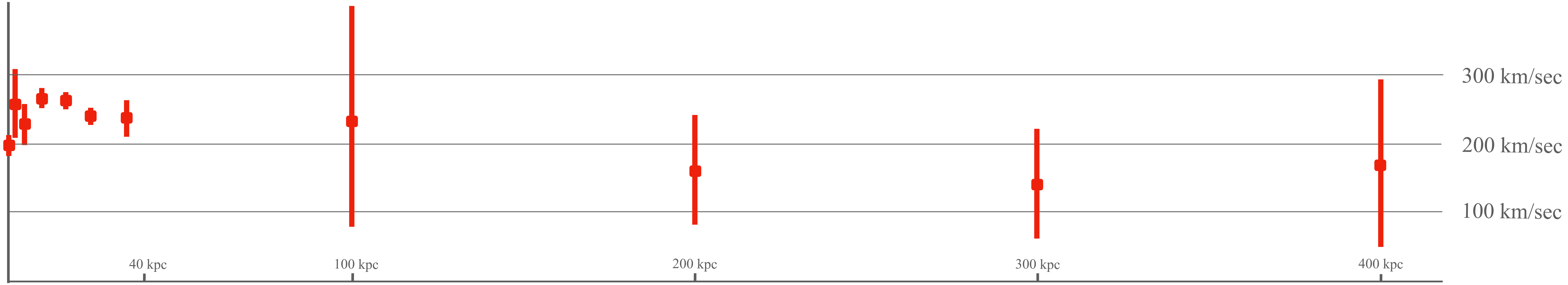

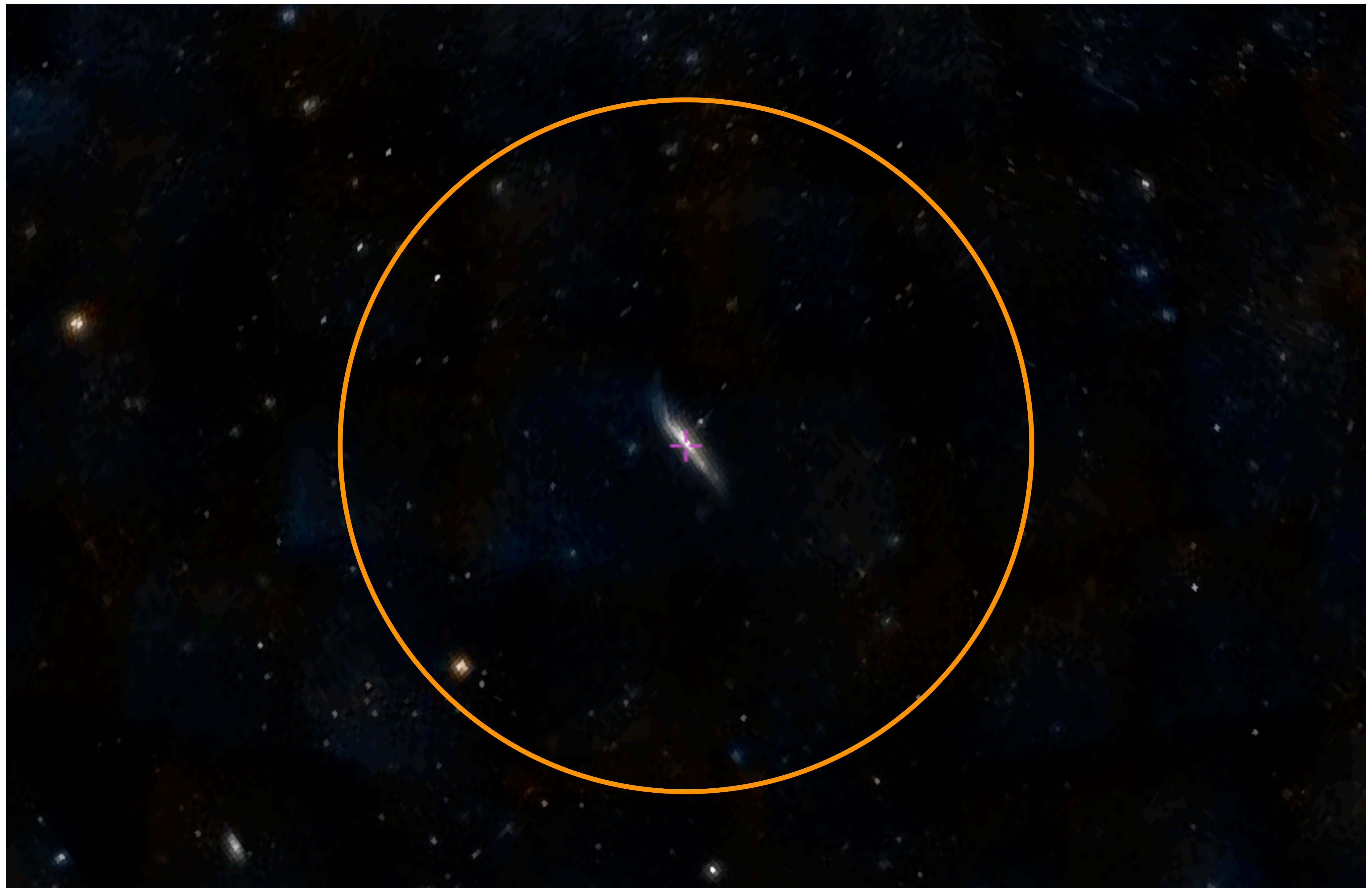

A&A 546, A4 (2012)
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Astronomy & Astrophysics

Stellar mass map and dark matter distribution in M 31

A. Tamm[1], E. Tempel[1,2], P. Tenjes[1,3], O. Tihhonova[1,3], and T. Tuvikene[1]

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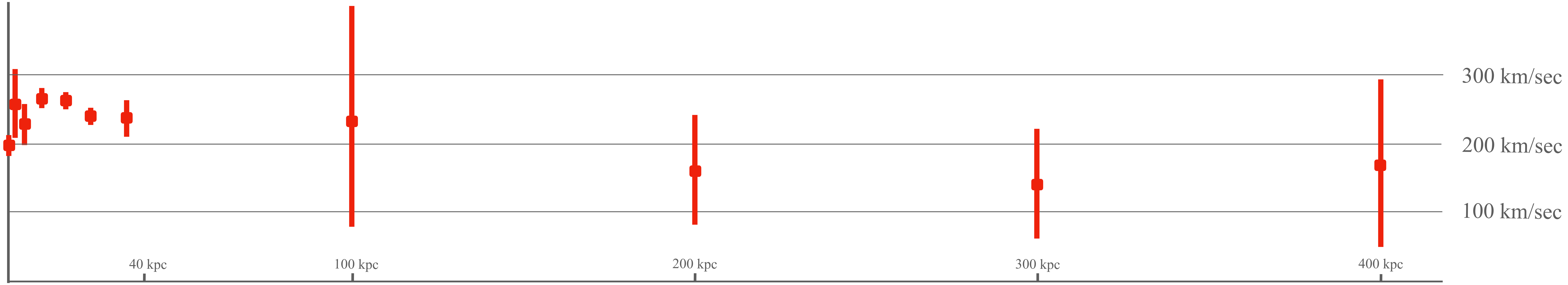

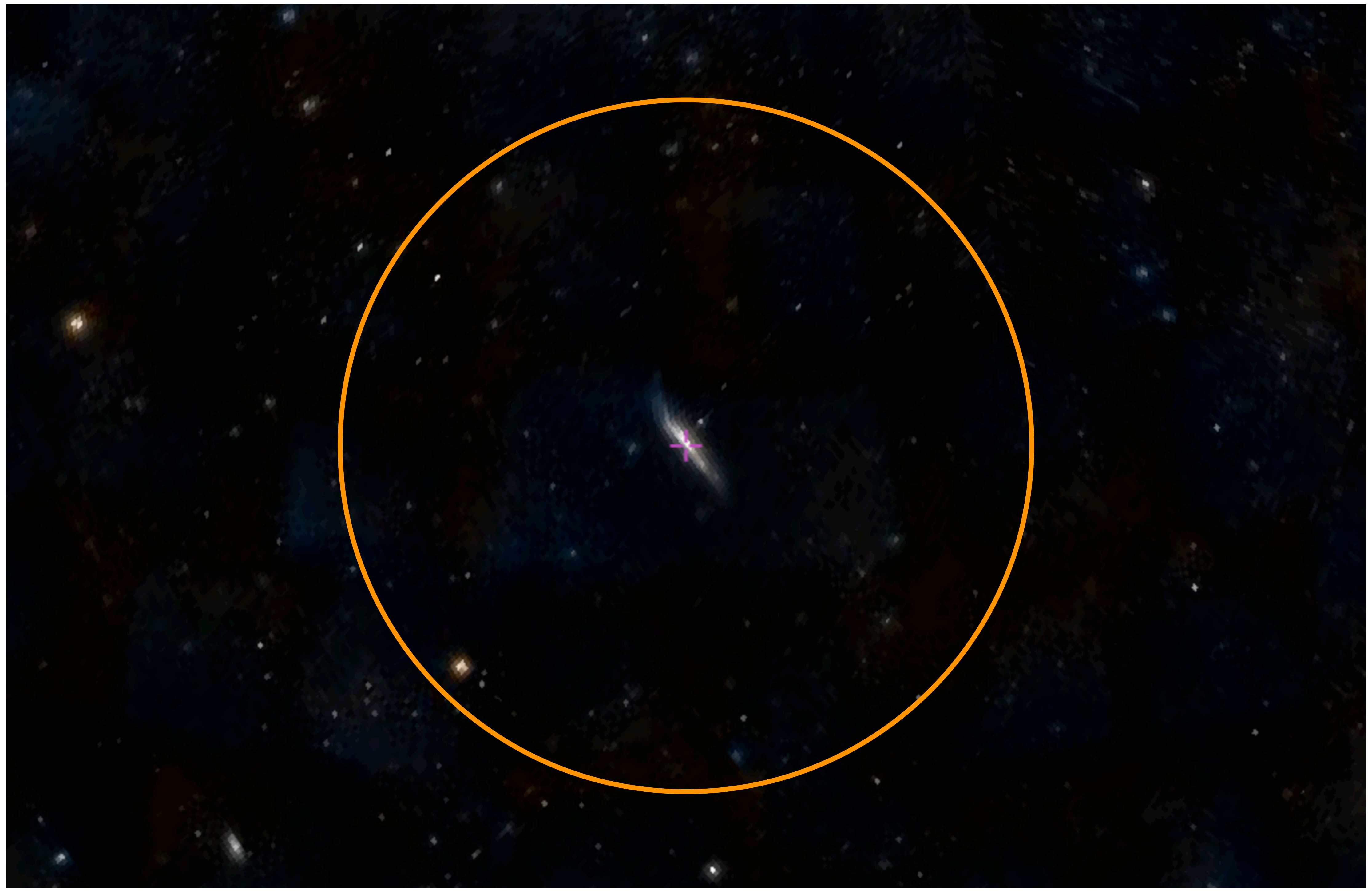

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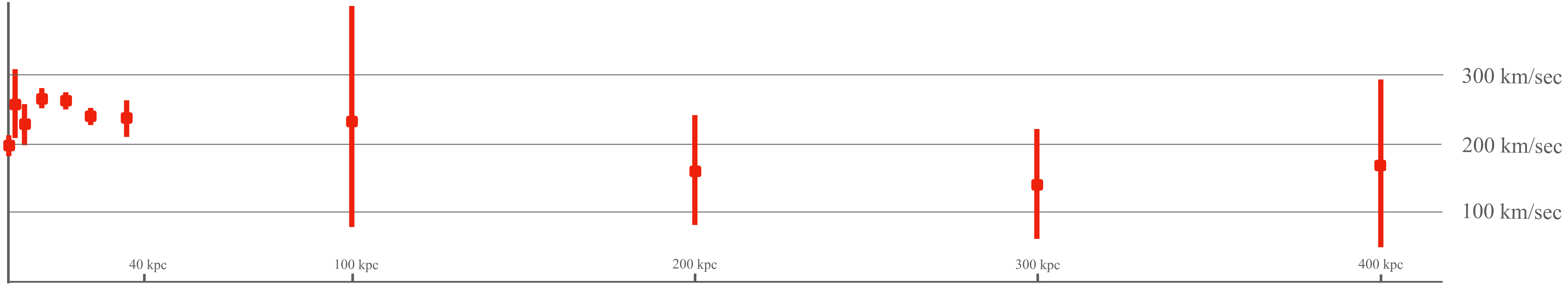

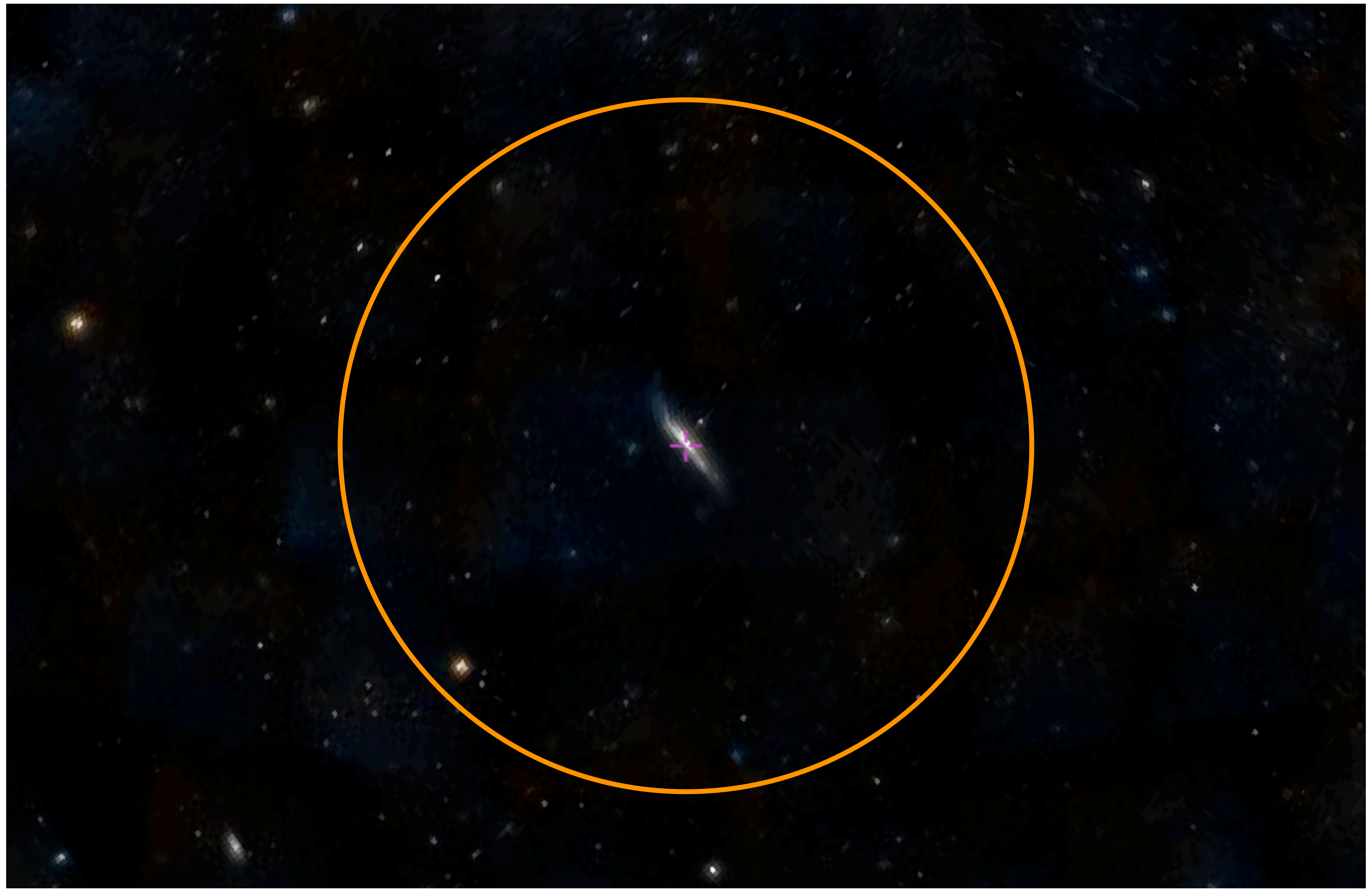

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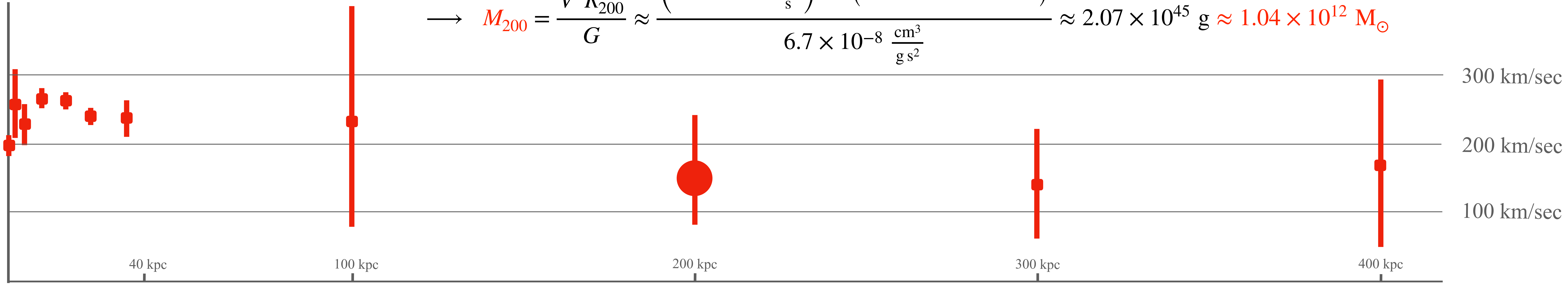
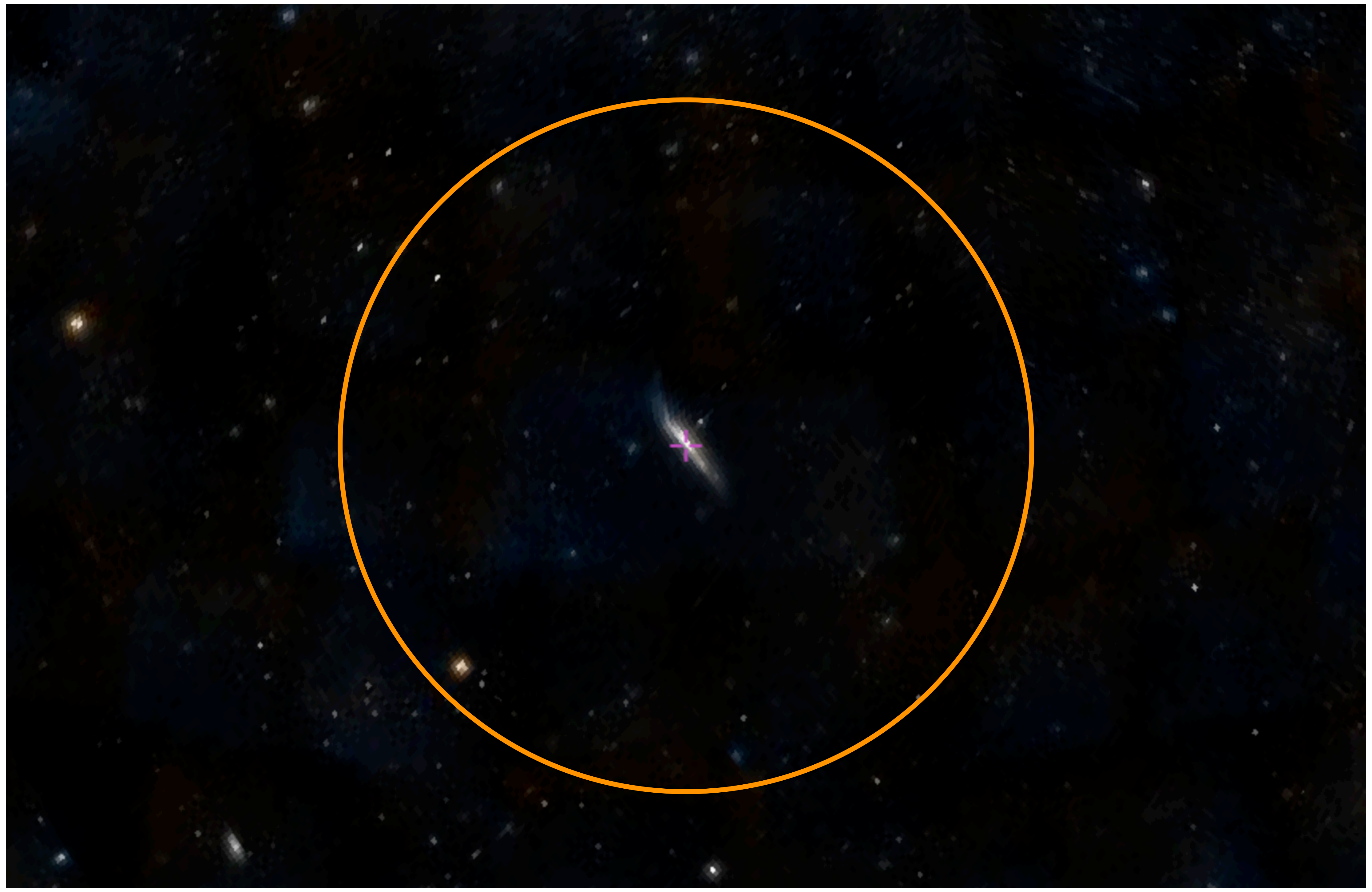
$$V^2 = \frac{GM}{R}$$

$$\longrightarrow M_{200} = \frac{V^2 R_{200}}{G} \approx \frac{\left(150 \times 10^5\ \frac{\mathrm{cm}}{\mathrm{s}}\right)^2 \times \left(200 \times 3 \times 10^{21}\ \mathrm{cm}\right)}{6.7 \times 10^{-8}\ \frac{\mathrm{cm}^3}{\mathrm{g\,s}^2}} \approx 2.07 \times 10^{45}\ \mathrm{g} \approx 1.04 \times 10^{12}\ \mathrm{M}_\odot$$





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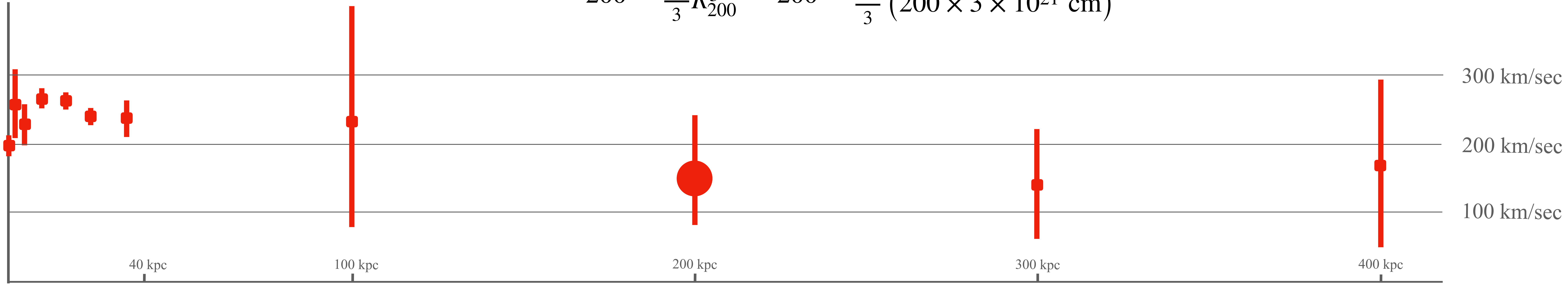
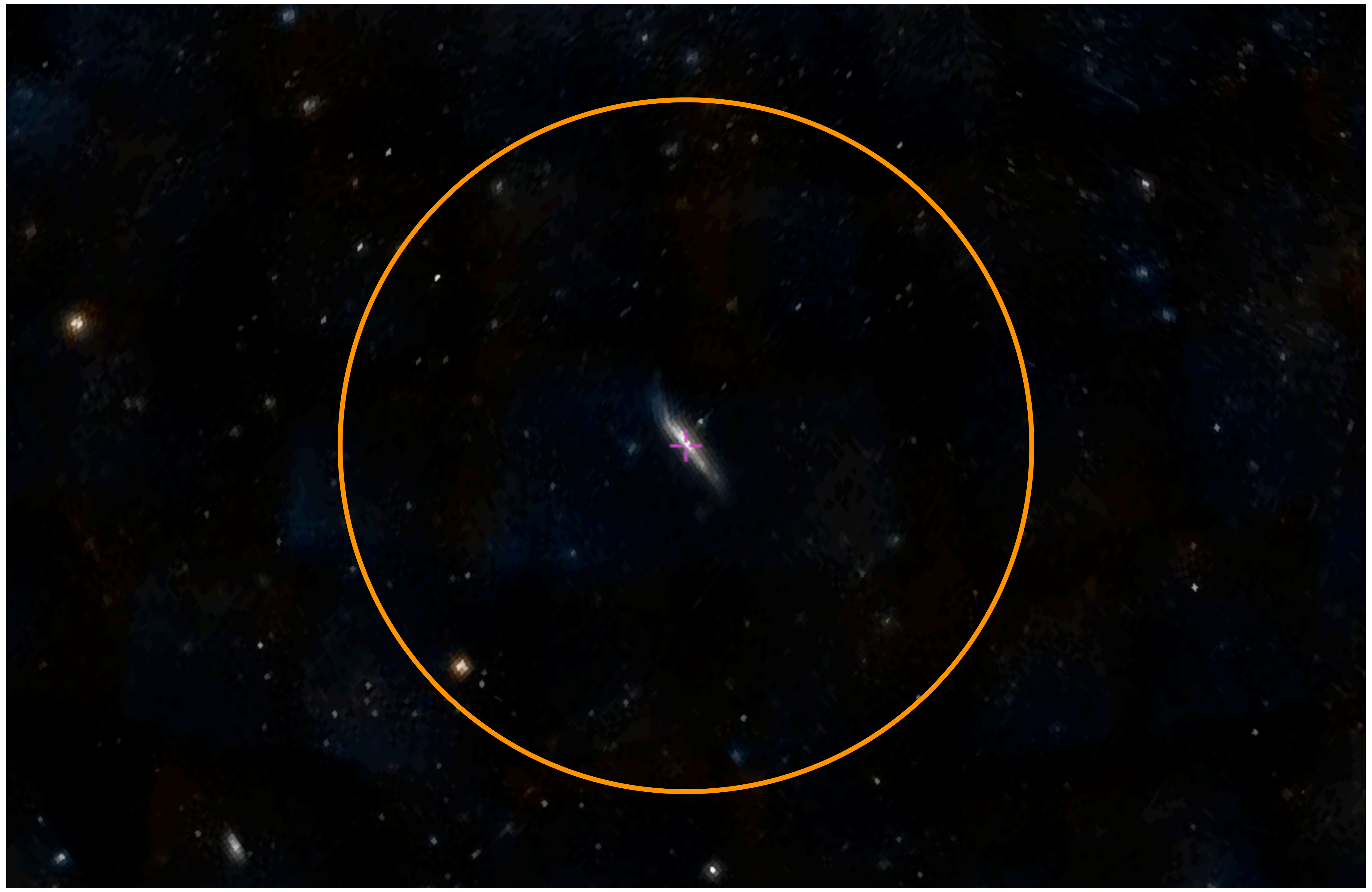
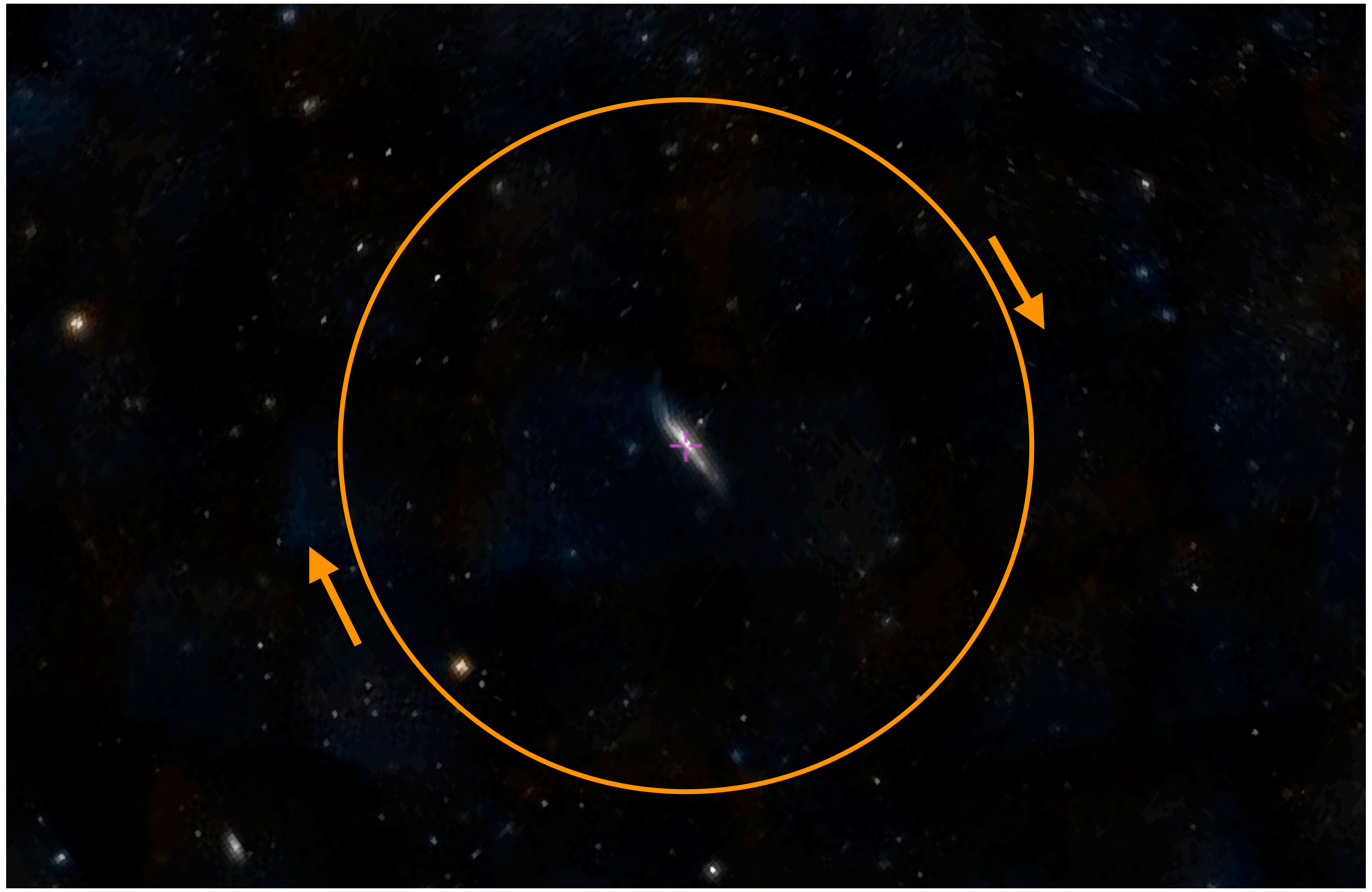
$$\frac{1}{200} \times \frac{M_{200}}{\frac{4\pi}{3} R_{200}^3} \approx \frac{1}{200} \times \frac{10^{12} \times 2 \times 10^{33}\ \text{g}}{\frac{4\pi}{3}\left(200 \times 3 \times 10^{21}\ \text{cm}\right)^3} \approx 1.1 \times 10^{-29}\ \text{g/cm}^3 \sim \rho_c$$





Where does it end?



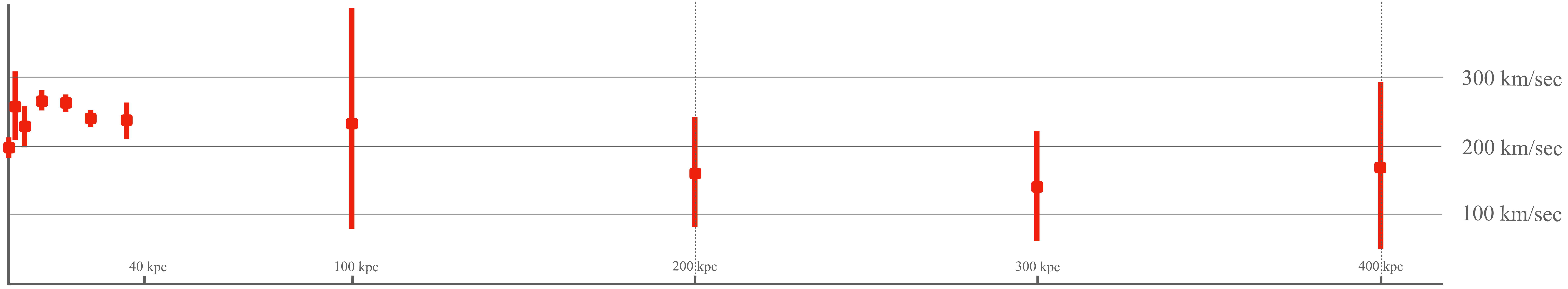
Where does it end?

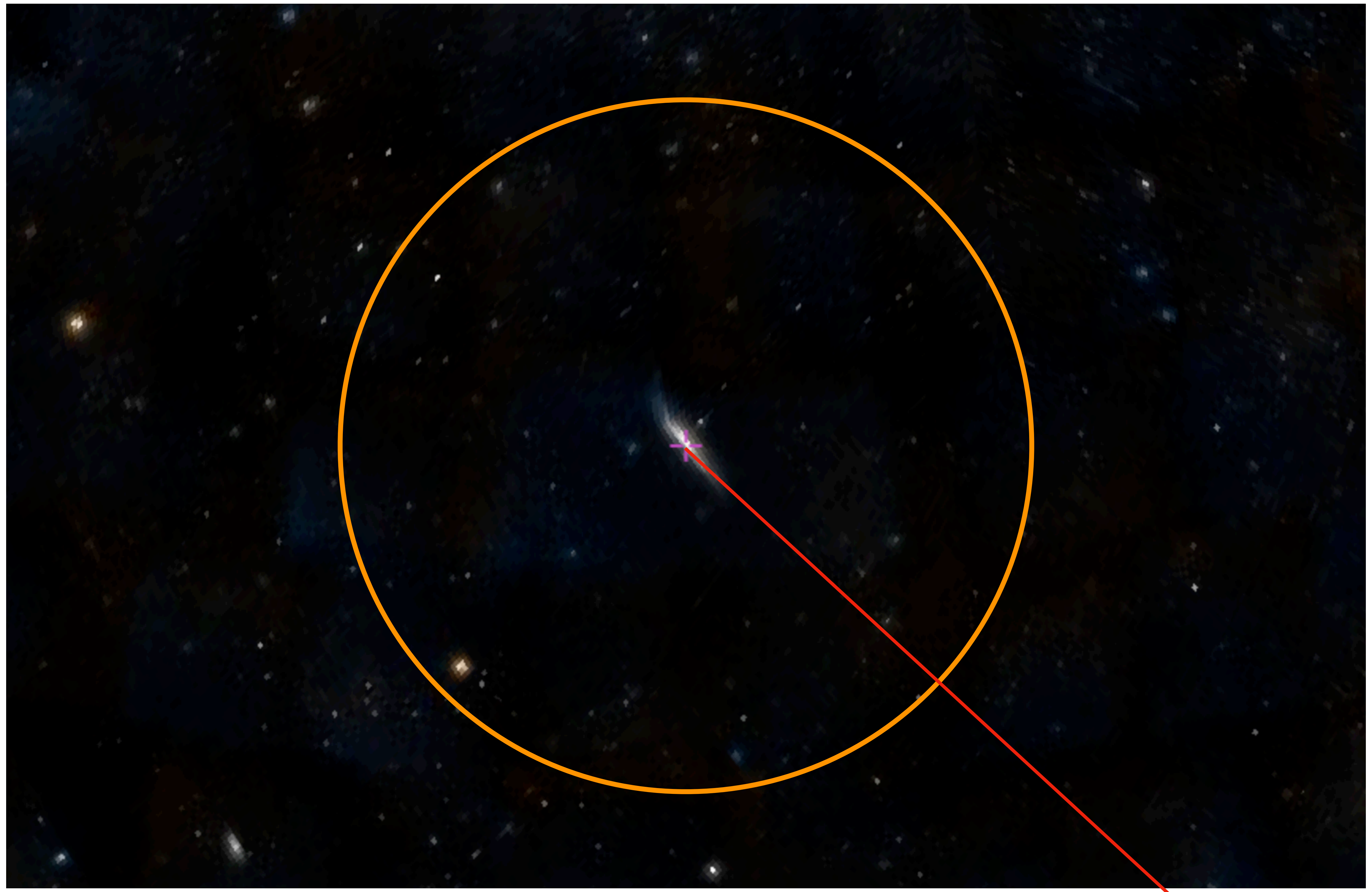
Time to make 1 revolution:

$$T = \frac{2\pi R}{V}$$

$$T = \frac{2\pi R}{V} \approx \frac{2\pi \times (200\text{ kpc})}{(150\text{ km/s})} \approx 8.2\text{ Gyr}$$

$$\frac{2\pi \times (400\text{ kpc})}{(150\text{ km/s})} \approx 16.4\text{ Gyr}$$



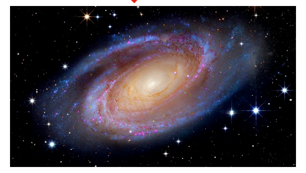


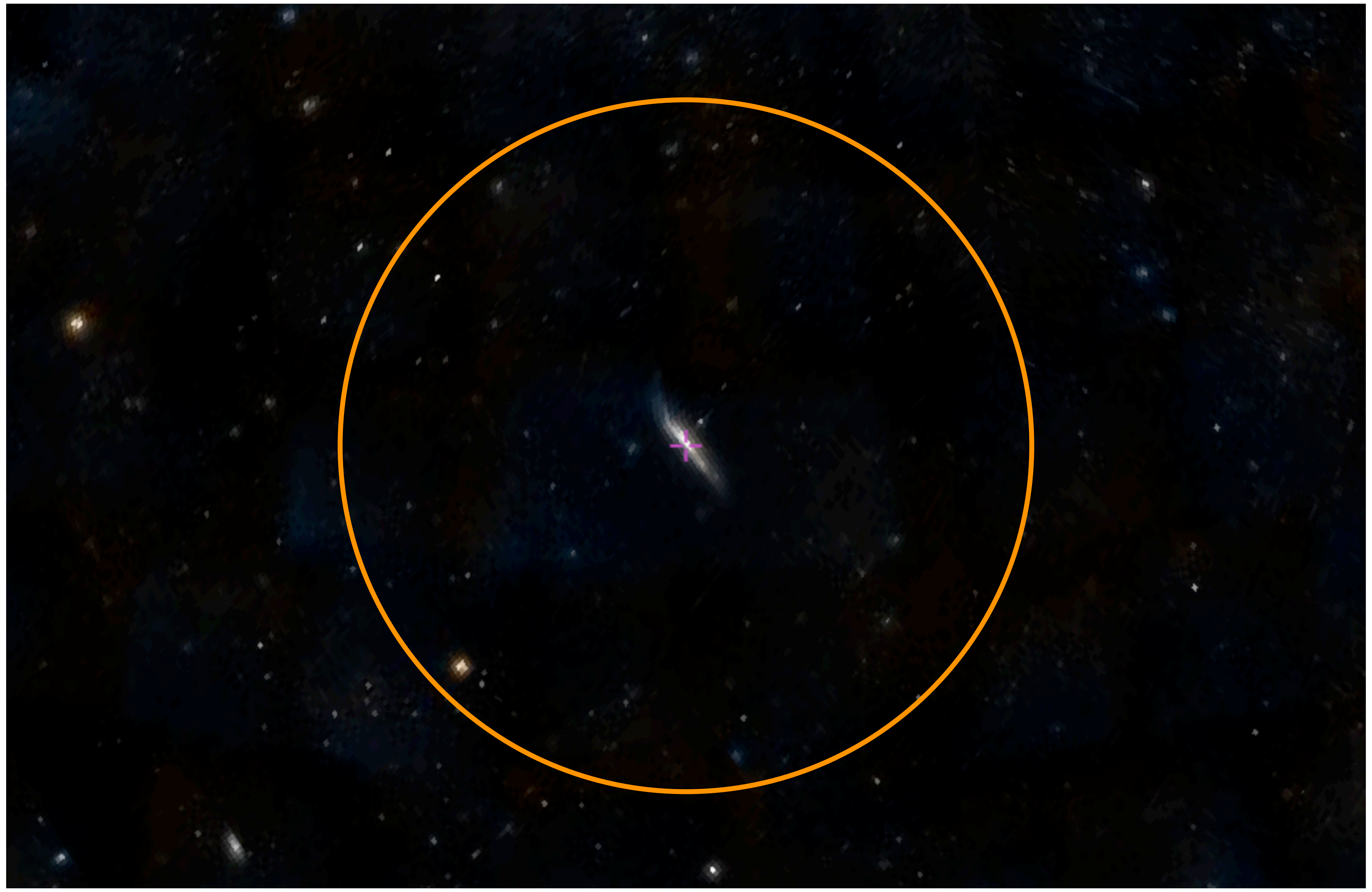
Where does it end?

Cosmic neighbors:

MW-M31 distance ~ 770 kpc

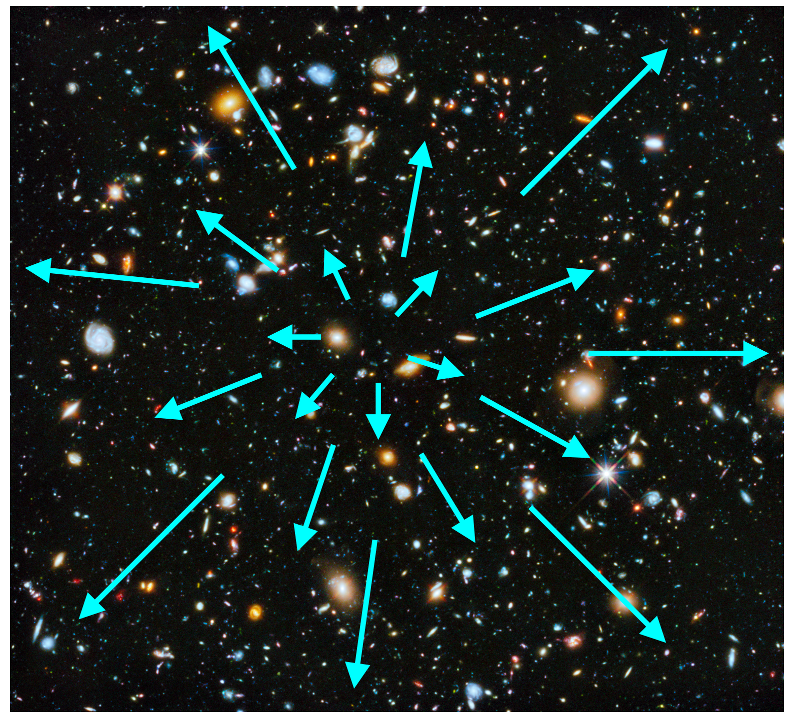
$$\rho_m \approx 0.3\,\rho_c \approx \frac{10^{12}\ \mathrm{M}_\odot}{(3\ \mathrm{Mpc})^3}$$



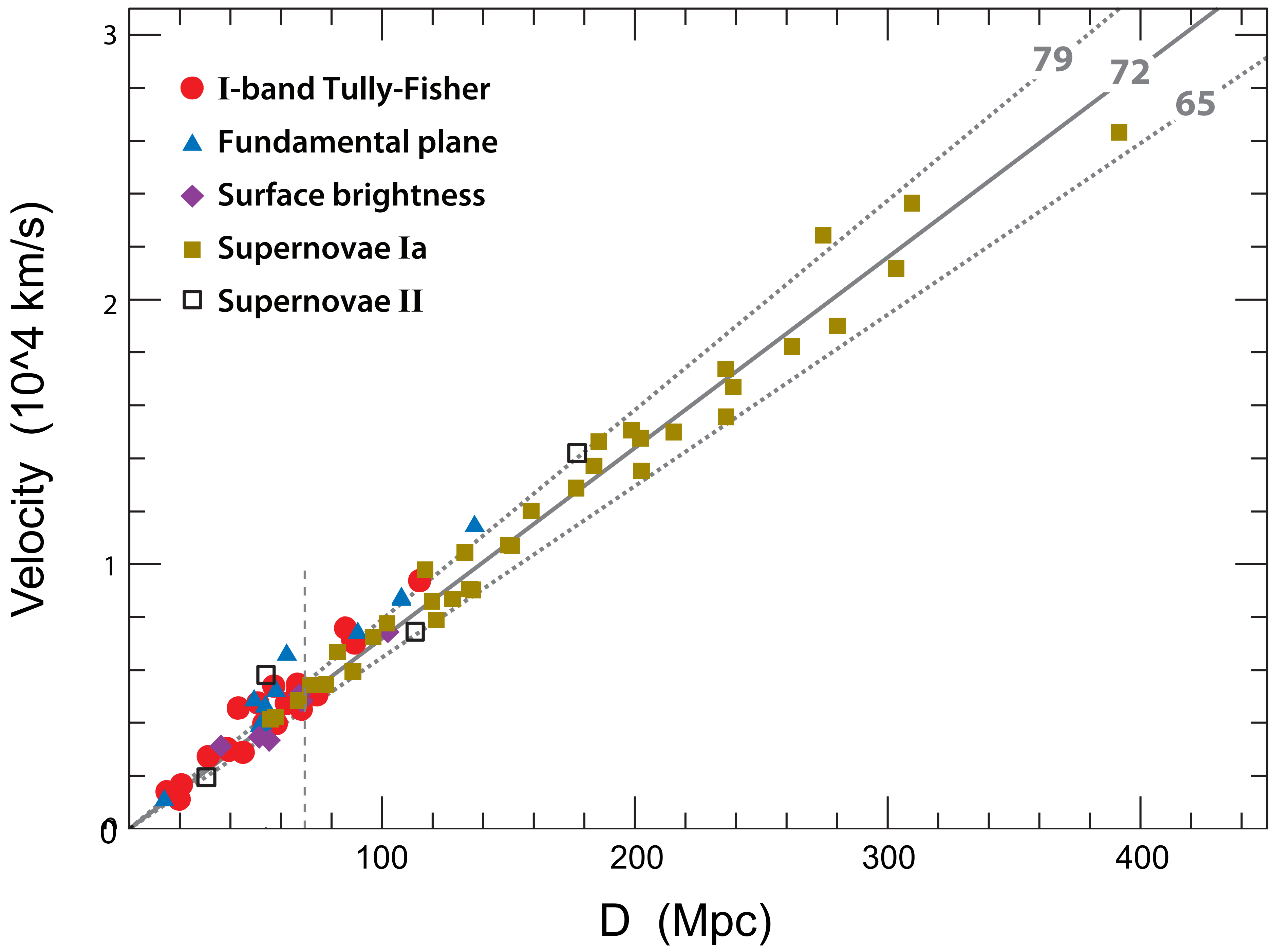


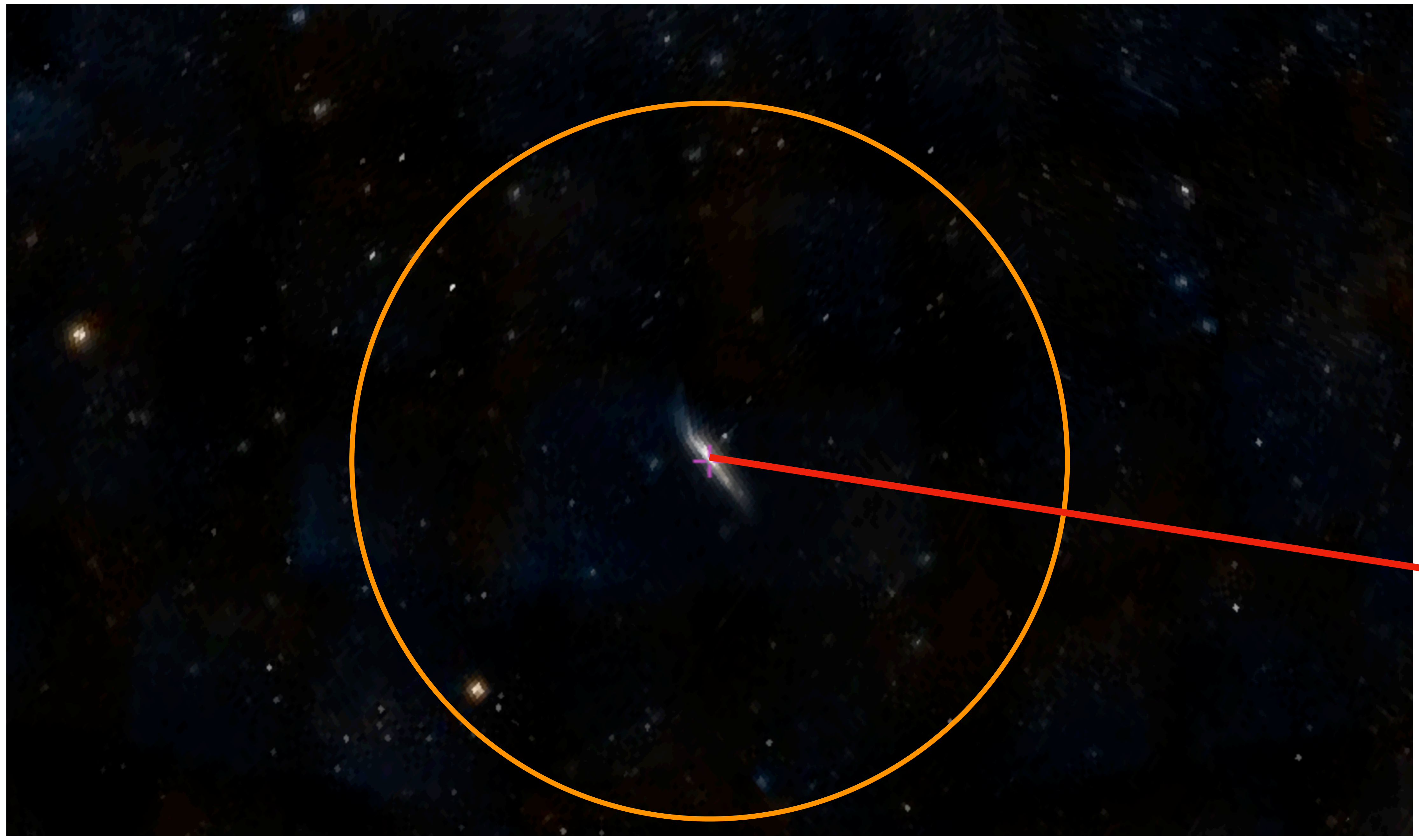
Where does it end?

Cosmic expansion:



Freedman & Madore, Ann. Rev. A&A, vol. 48, p.673-710





Where does it end?

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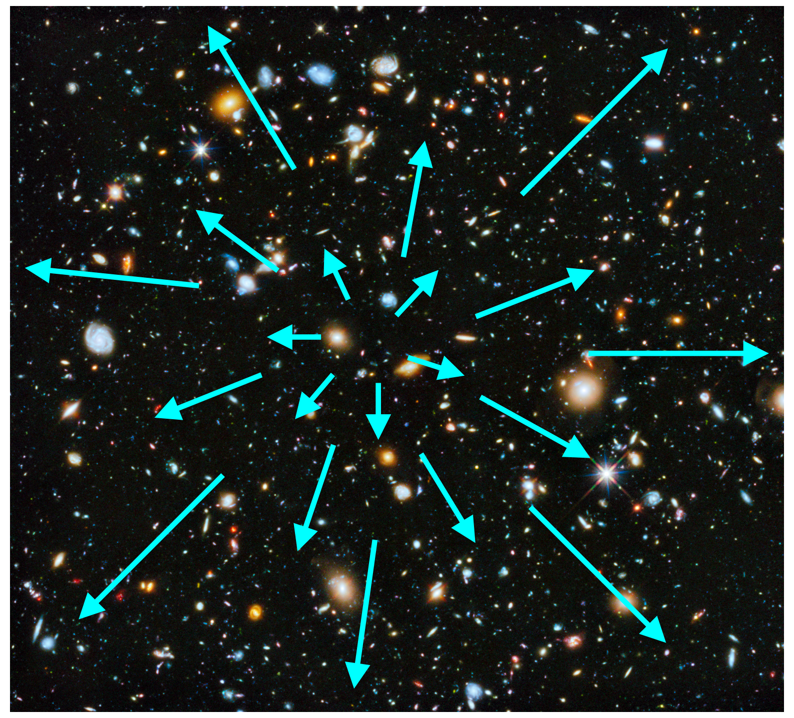

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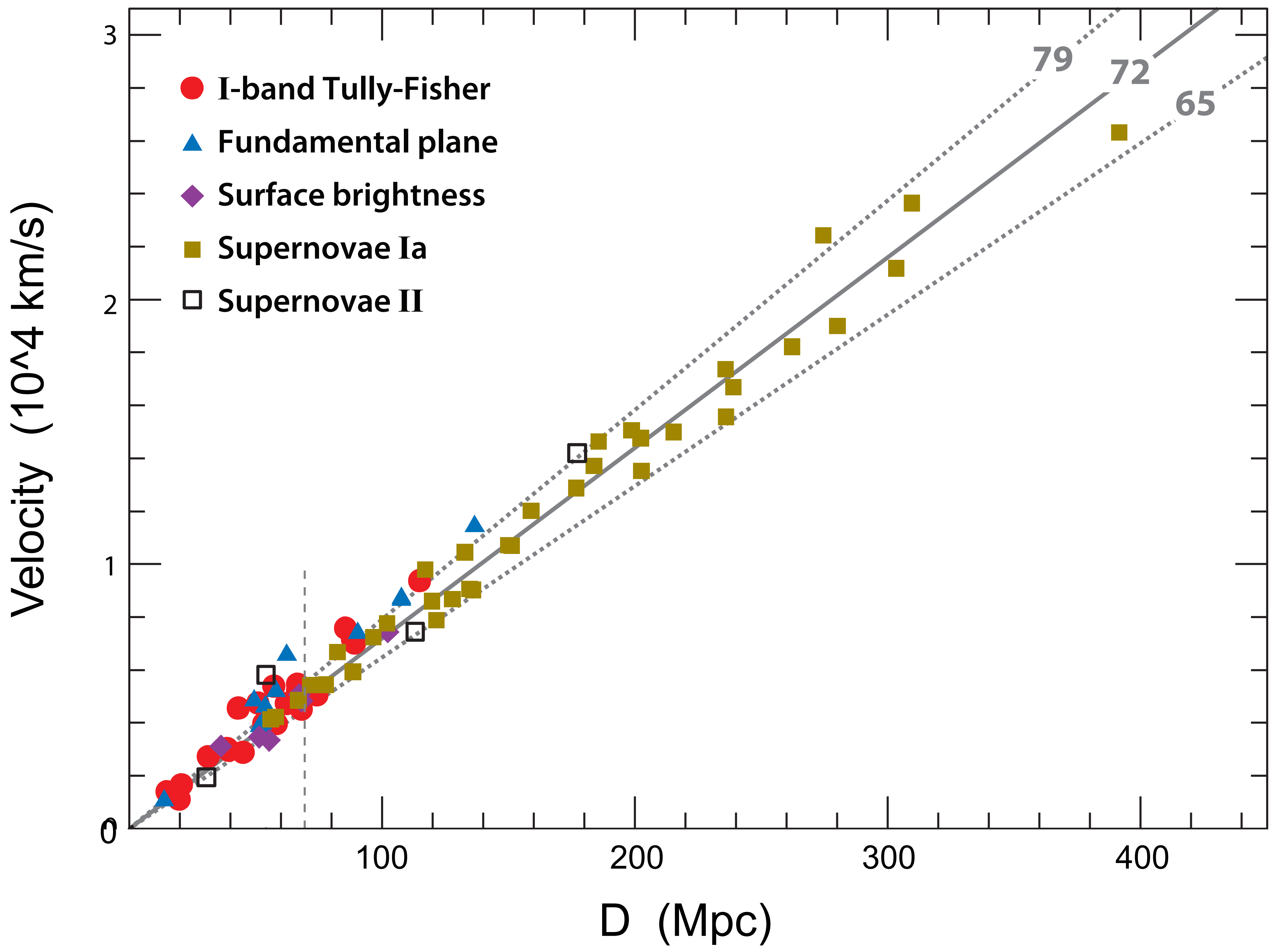
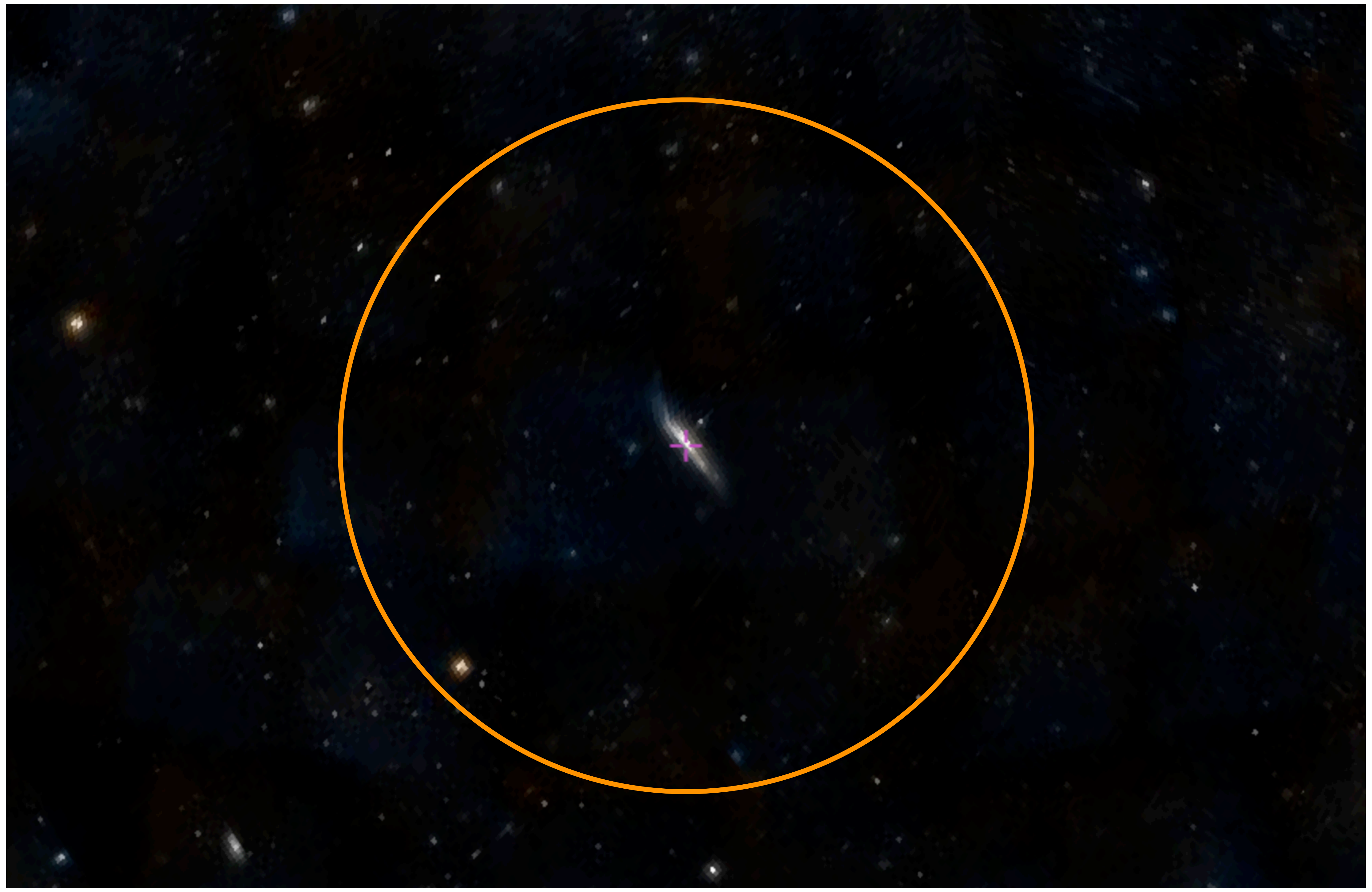


Expansion modifies law of rotation around a point mass M:

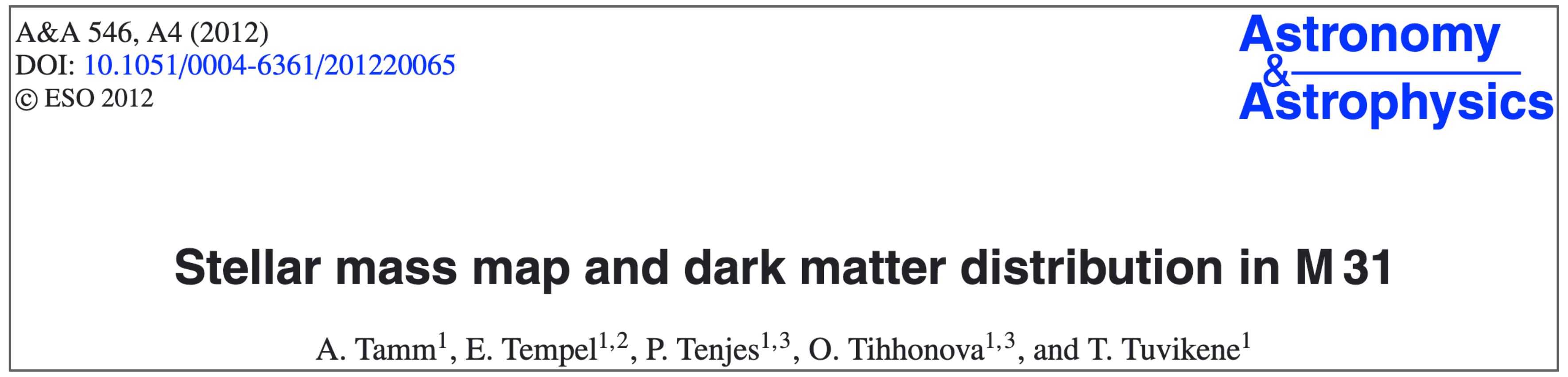
$$\Omega^2 = \frac{GM}{R^3}\left(1 - \frac{H_0^2 R^3}{GM}\right)$$

$$V = \Omega R \quad \longrightarrow \quad V^2 = \frac{GM}{R}\left(1 - \frac{R^3}{R_c^3}\right)$$

$$R_c = \left(\frac{GM}{H_0^2}\right)^{\frac{1}{3}} \approx 0.9 \left(\frac{M}{10^{12}\ \mathrm{M}_\odot}\right)^{\frac{1}{3}} \left(\frac{10^{-29}\ \mathrm{g/cm^3}}{\rho_c}\right)^{\frac{1}{3}}\ \mathrm{Mpc}$$



Dark matter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Astronomy & Astrophysics

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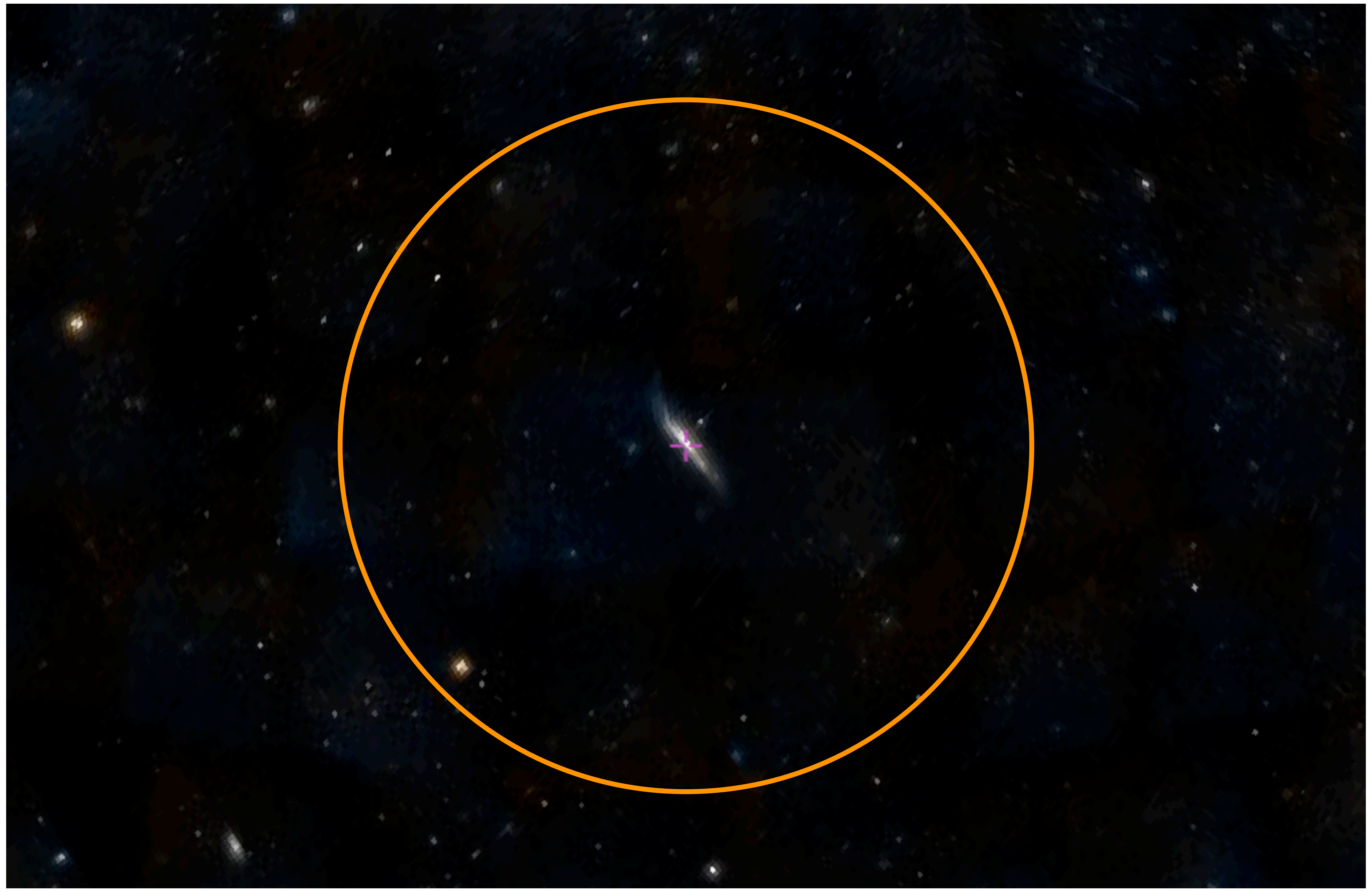

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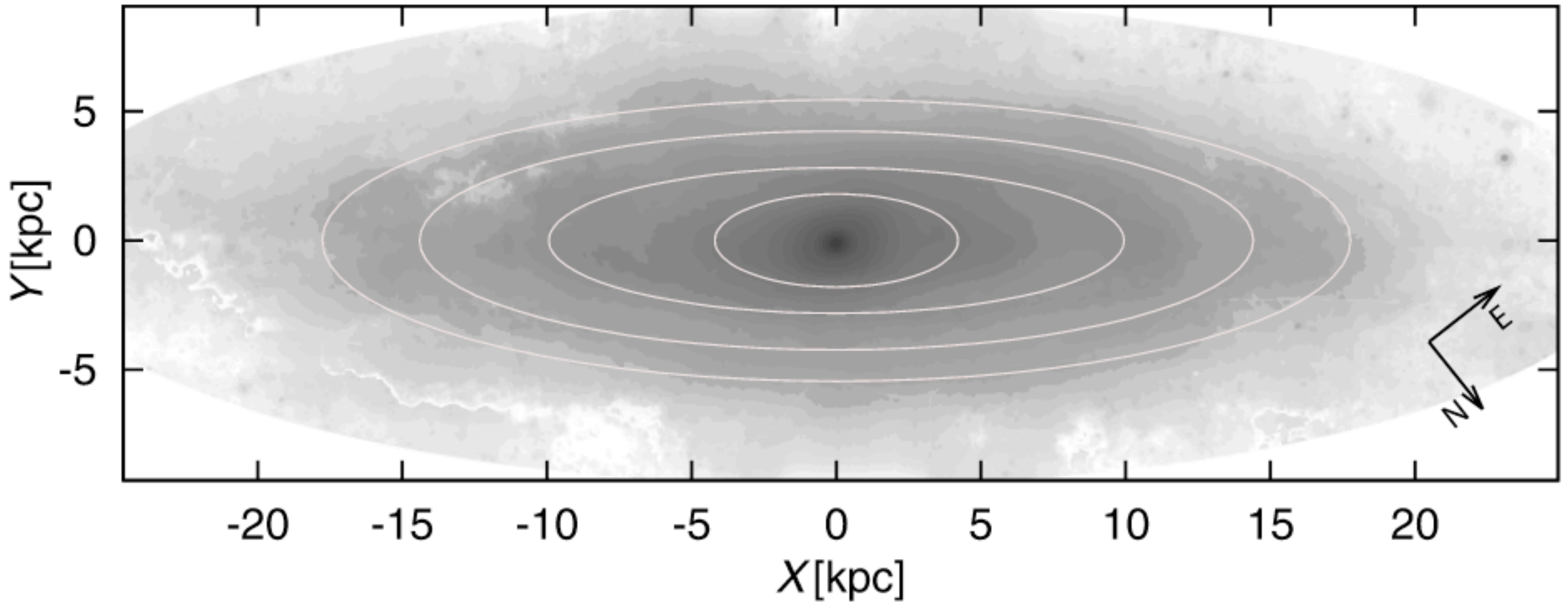

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B07-3	0.4–1	0.05	0.47	0.50	0.56	0.003
B07-4	7–12	0.03	5.05	3.87	3.12	0.983
M05-1	1	0.00	1.11	1.00	0.85	0.008
M05-2	2	0.00	2.18	1.70	1.43	0.002
M05-3	4	0.00	3.99	3.03	2.56	0.214
M05-4	12	0.00	11.6	8.08	6.47	0.767
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GALEV-1	1, 10	0.04	2.88	3.14	2.92	0.004
GALEV-2	2, 11	0.07	4.35	4.13	3.65	0.011
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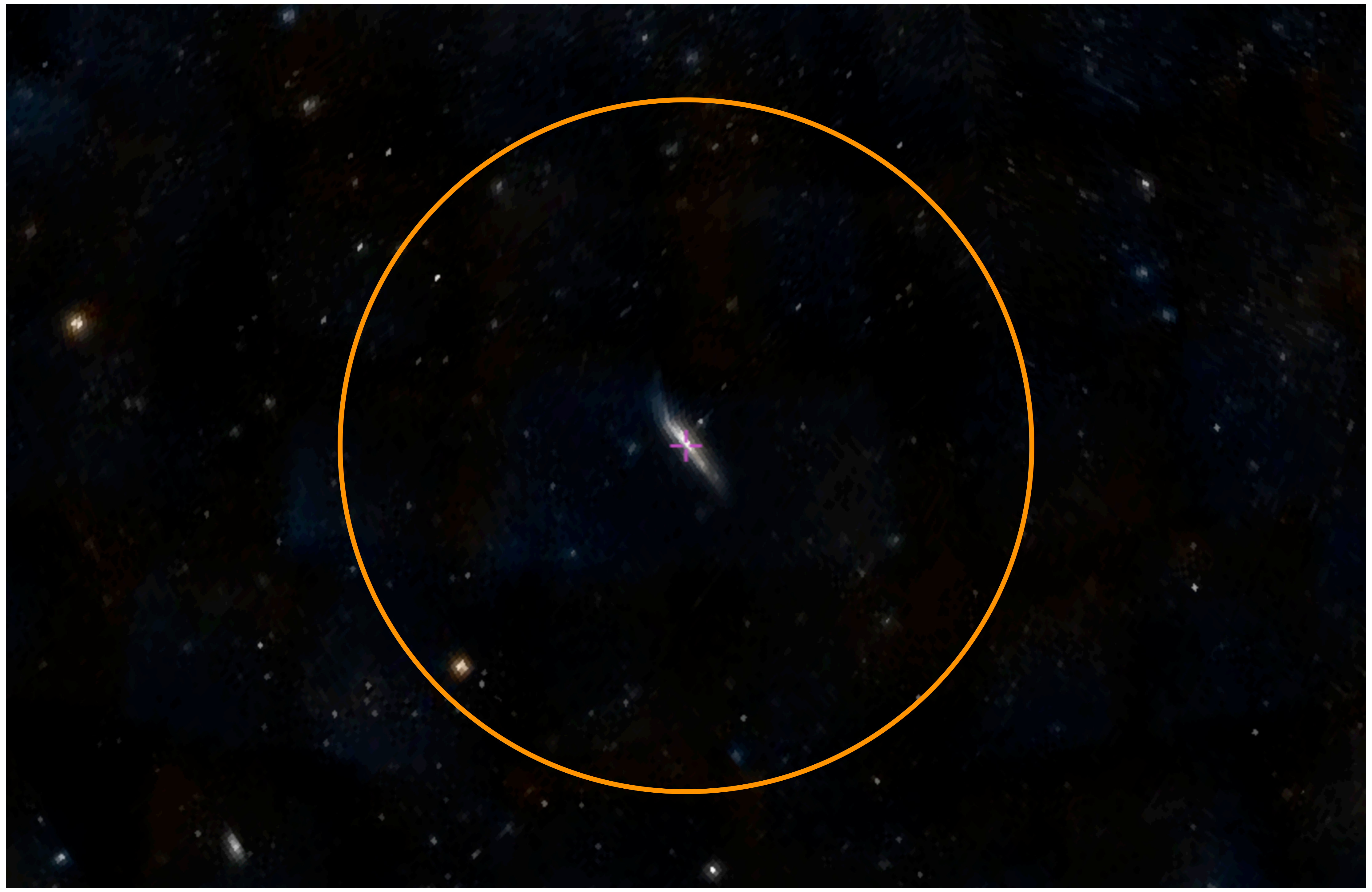

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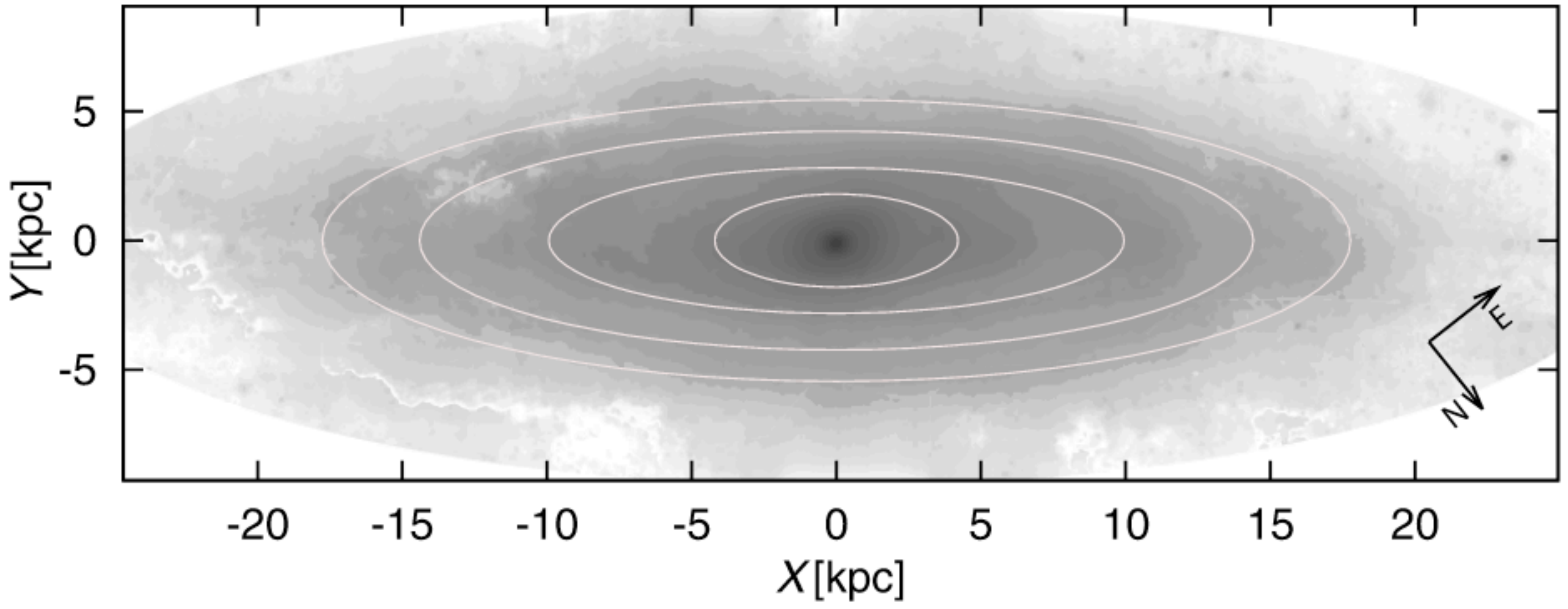

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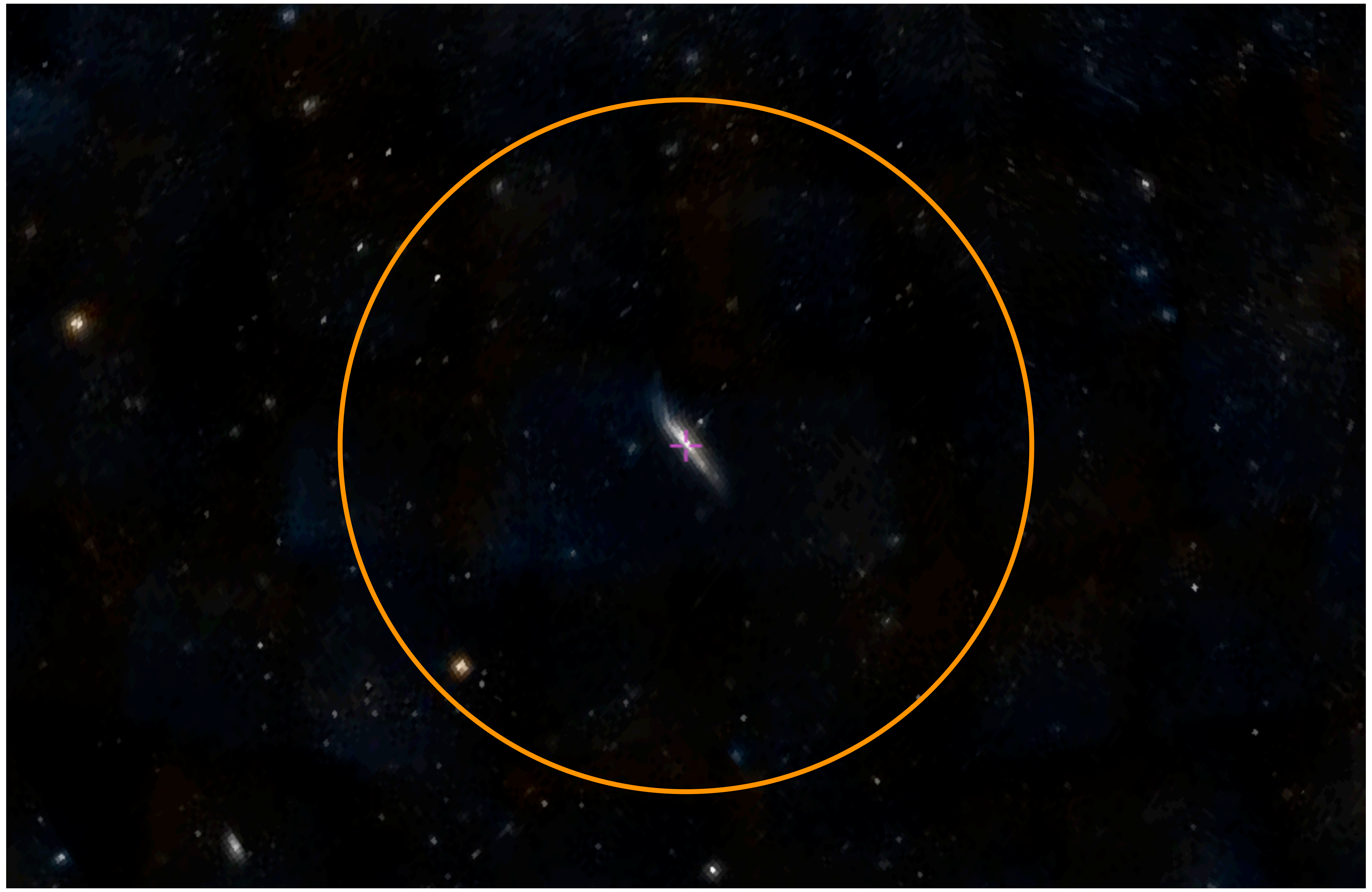

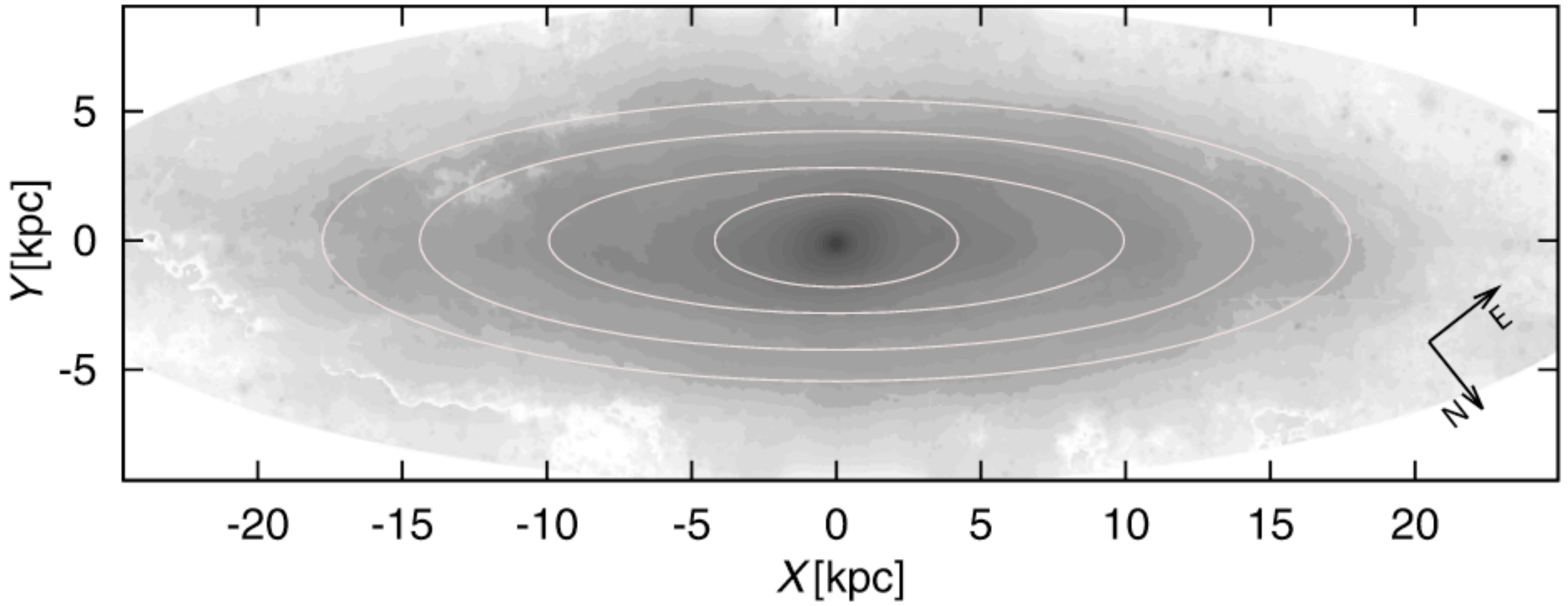

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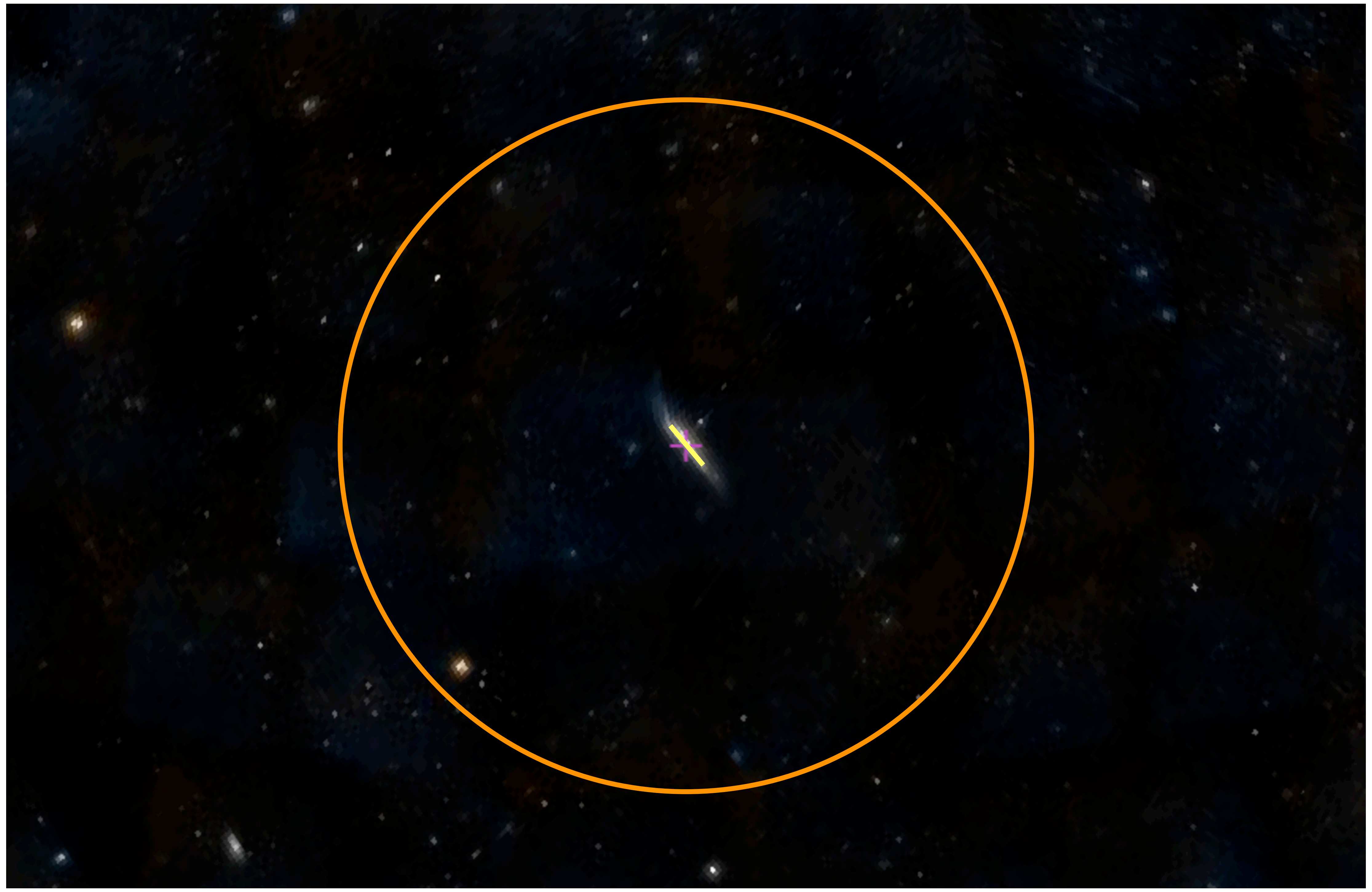

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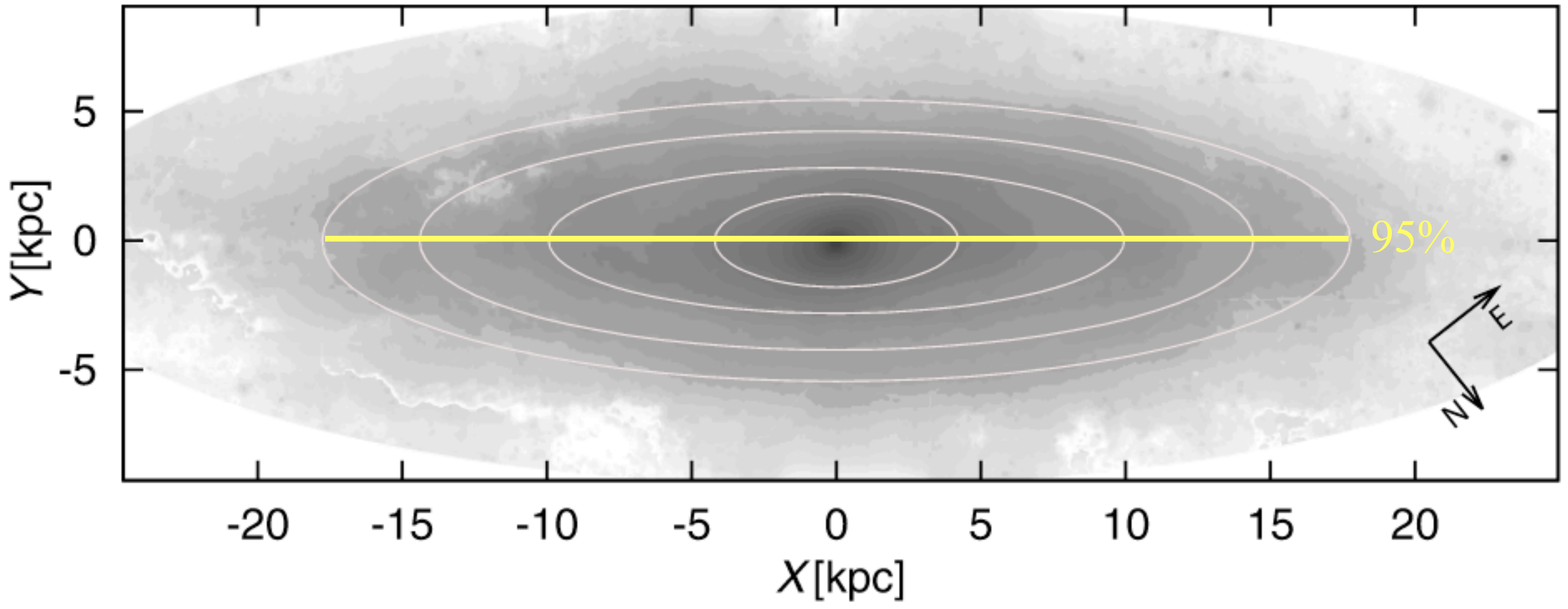

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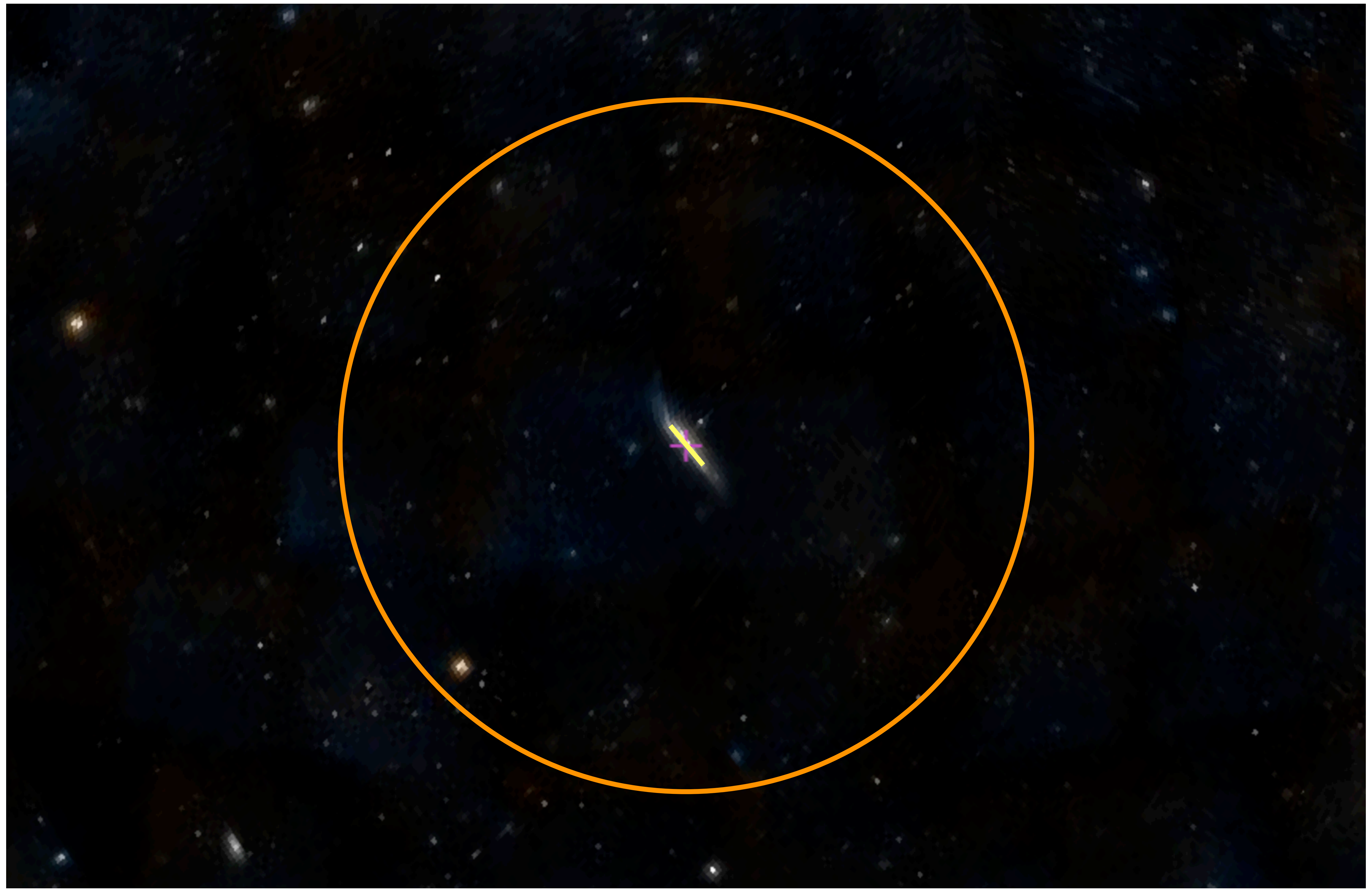

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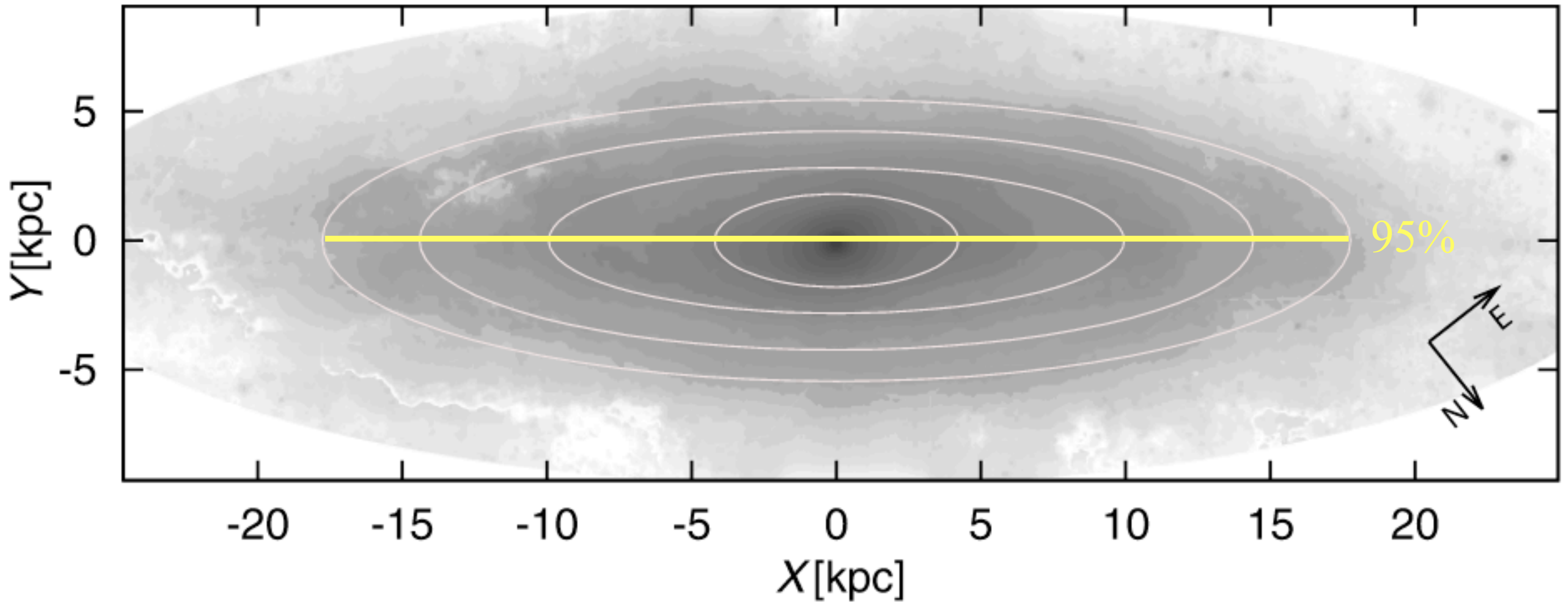

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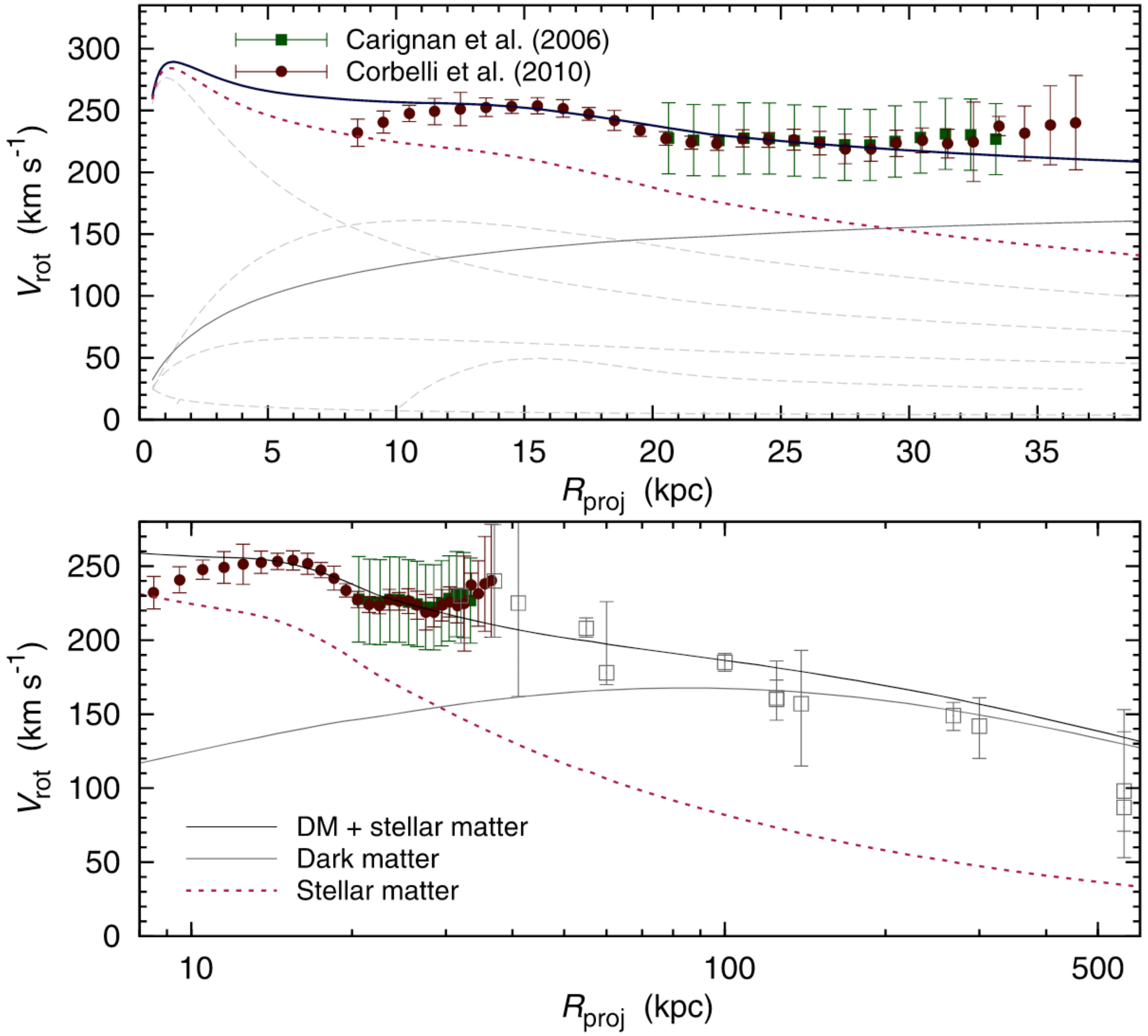
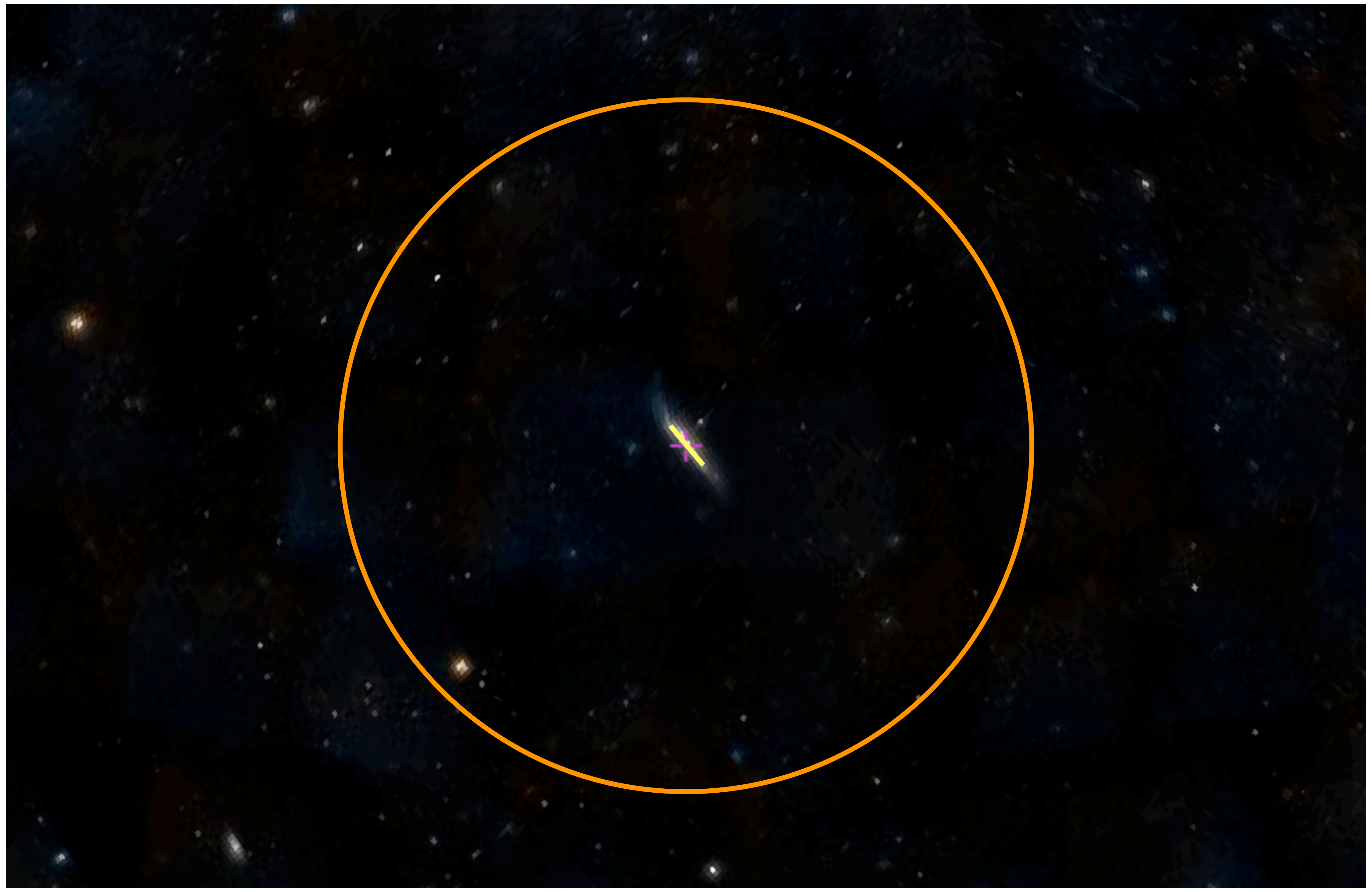


Fig. 7. Observed rotation curve together with the maximum-stellar model, in which the stellar masses are 1.5 times higher than in the B07 model.



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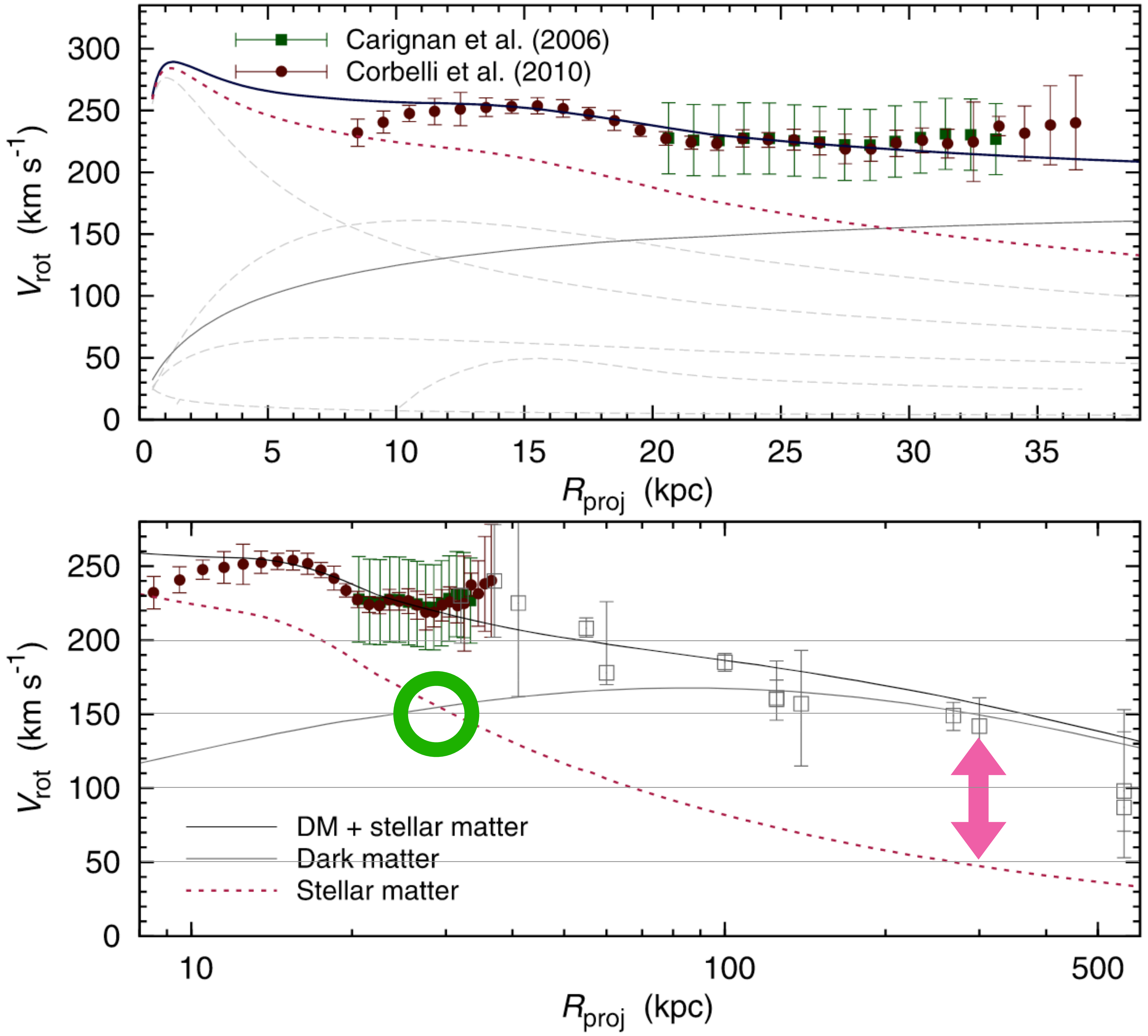


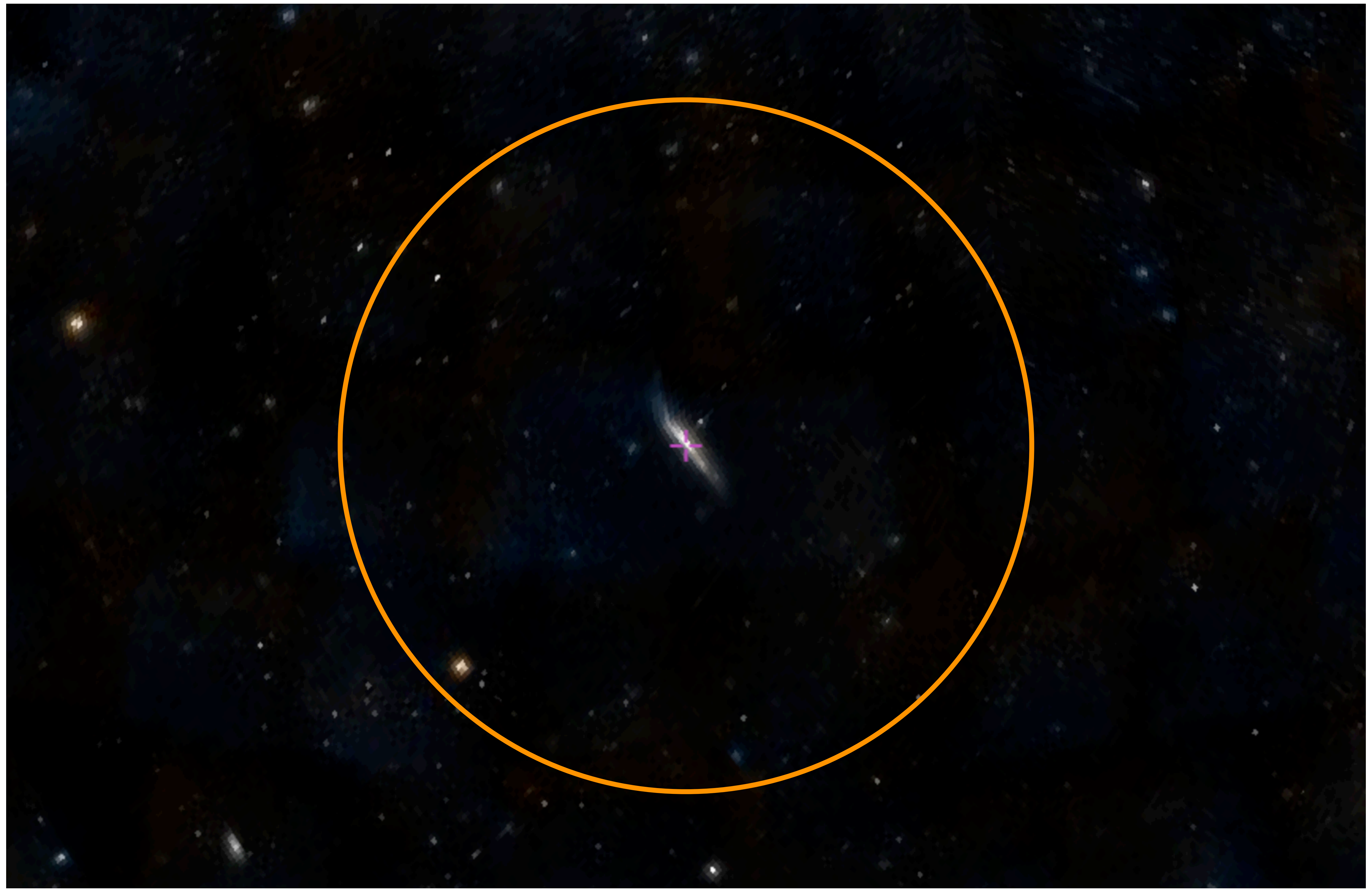
Fig. 7. Observed rotation curve together with the maximum-stellar model, in which the stellar masses are 1.5 times higher than in the B07 model.

At ~30 kpc:

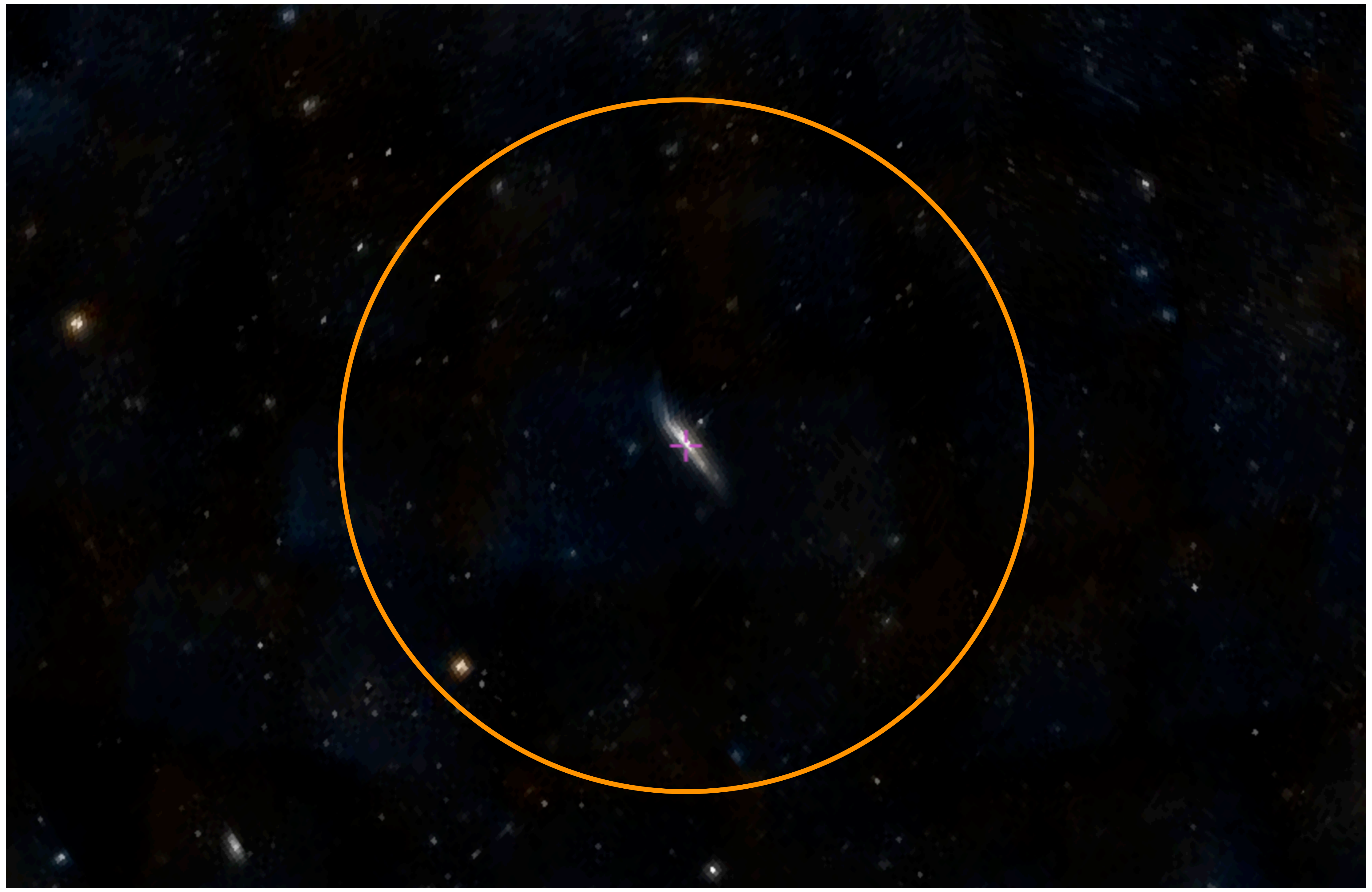
M(DM)/M(stars) ~ 1

At ~300 kpc:

M(DM)/M(stars) ~ 10



How does this fit into the big picture?



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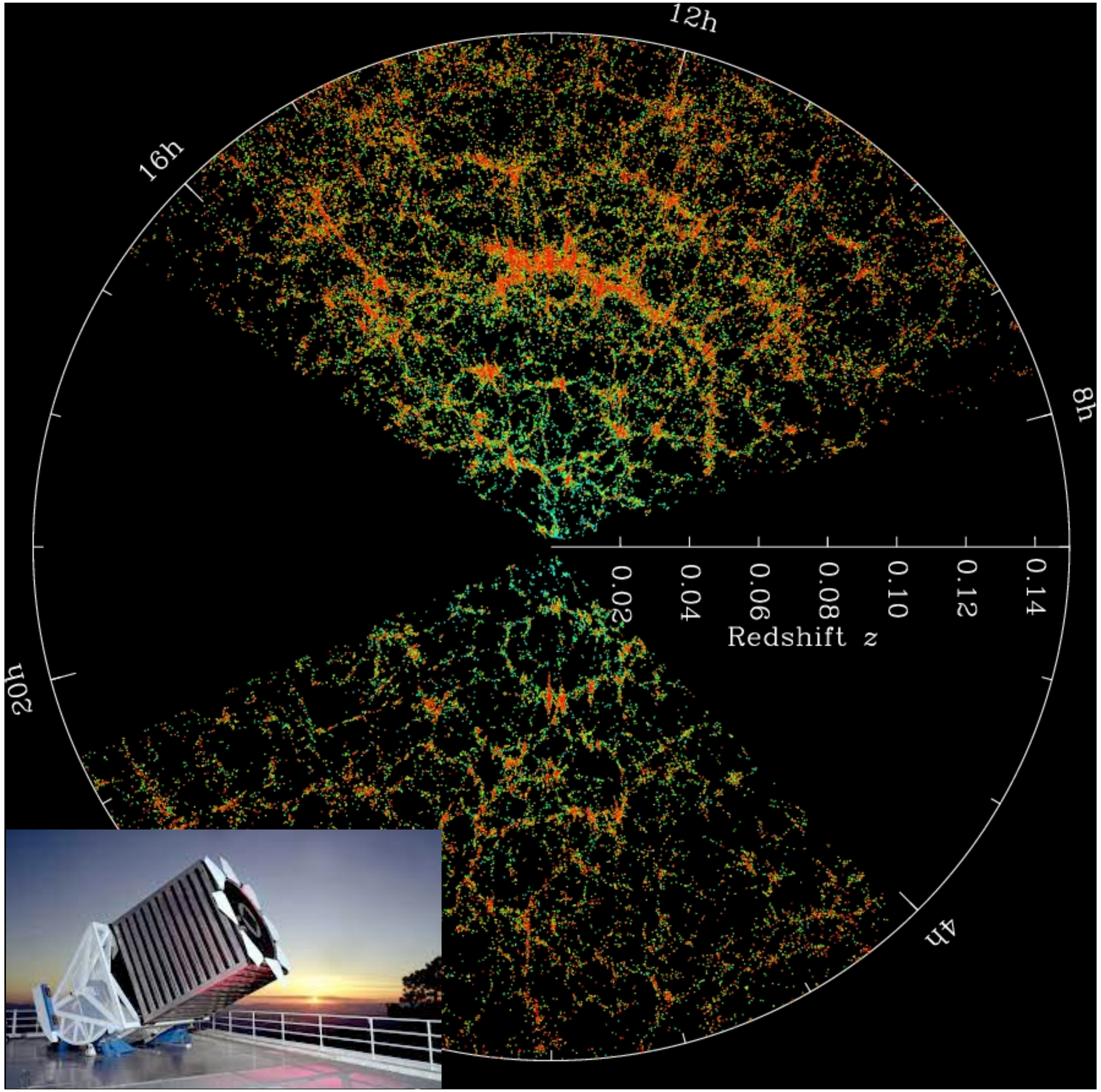

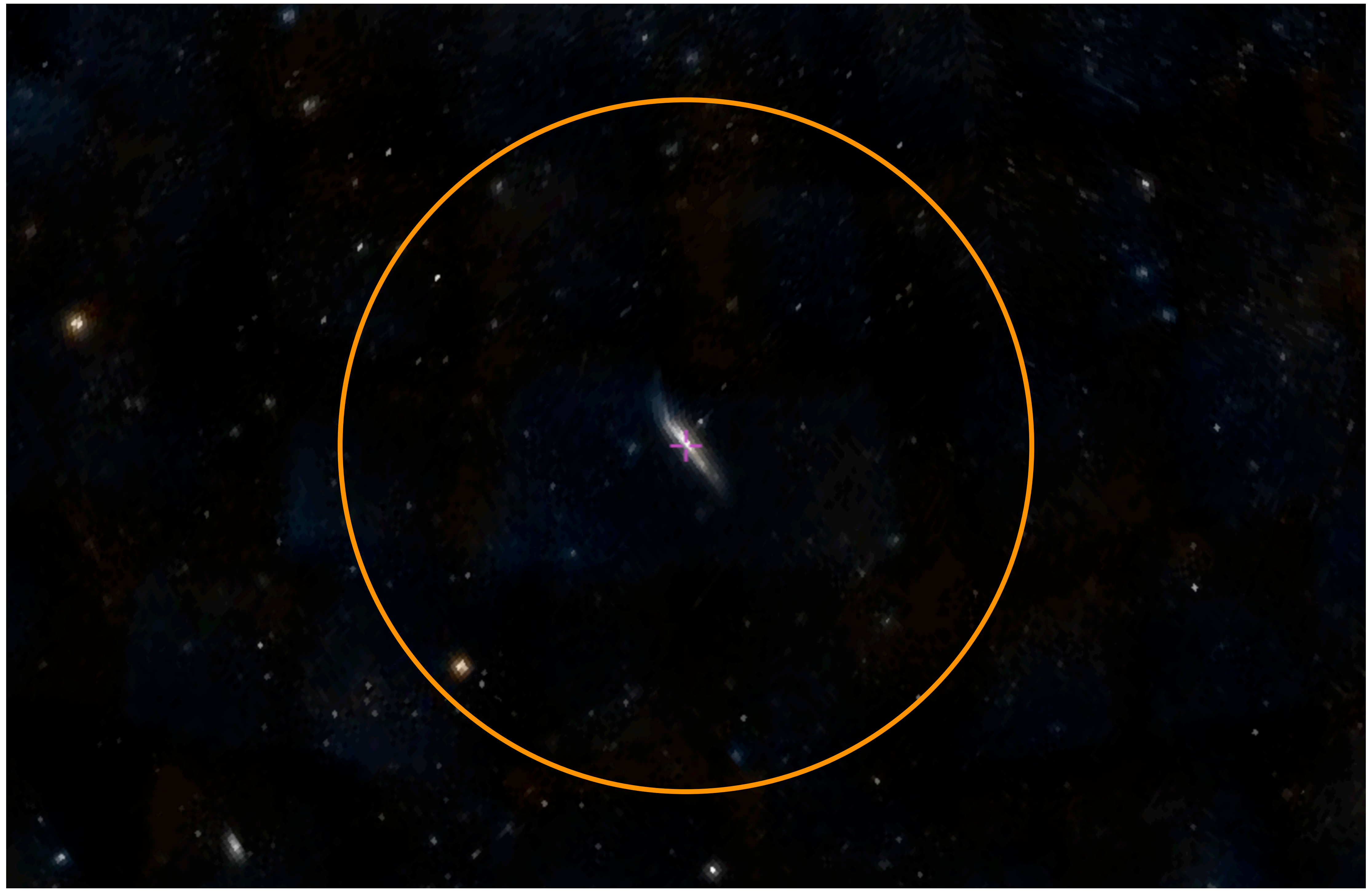

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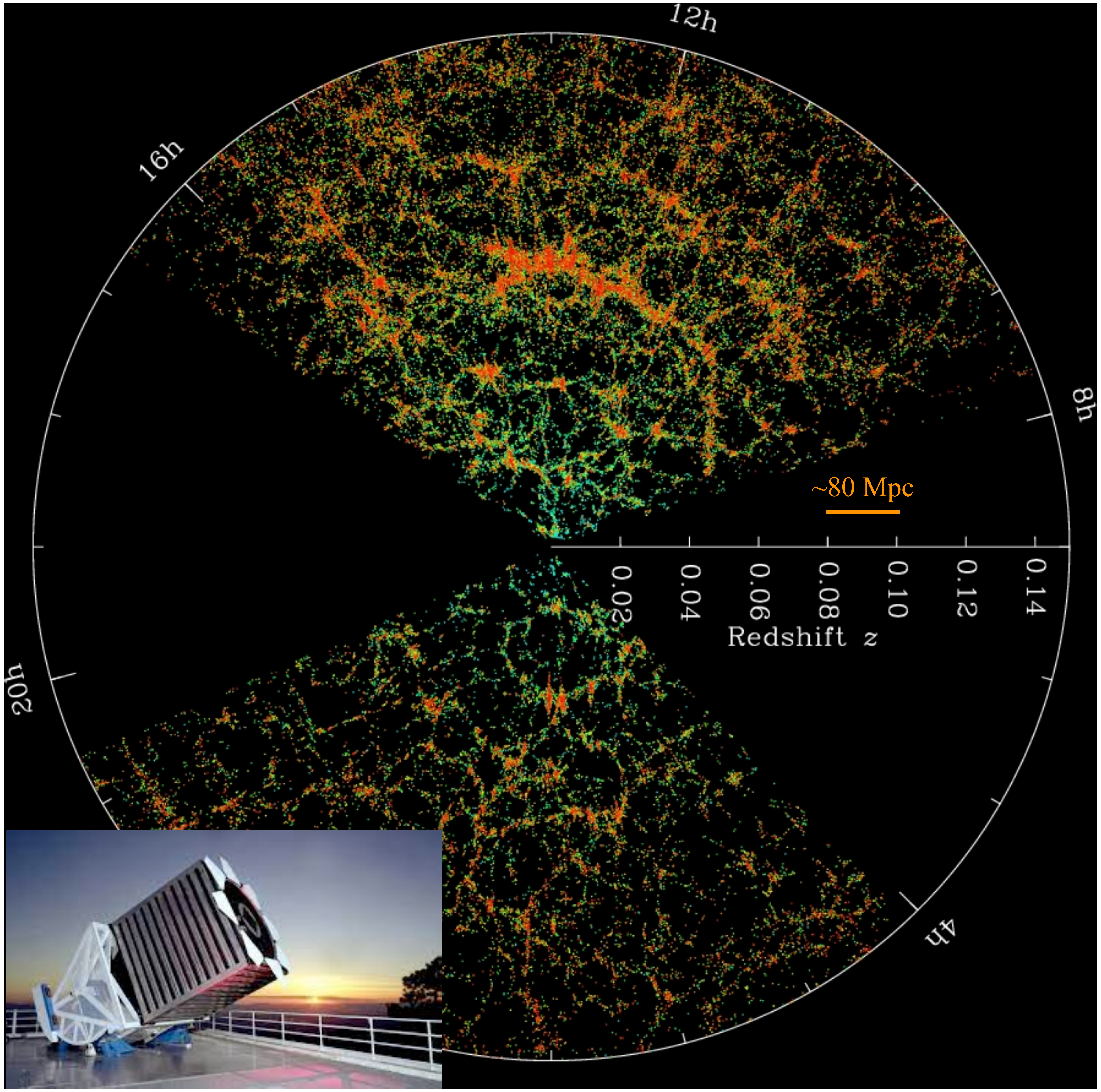
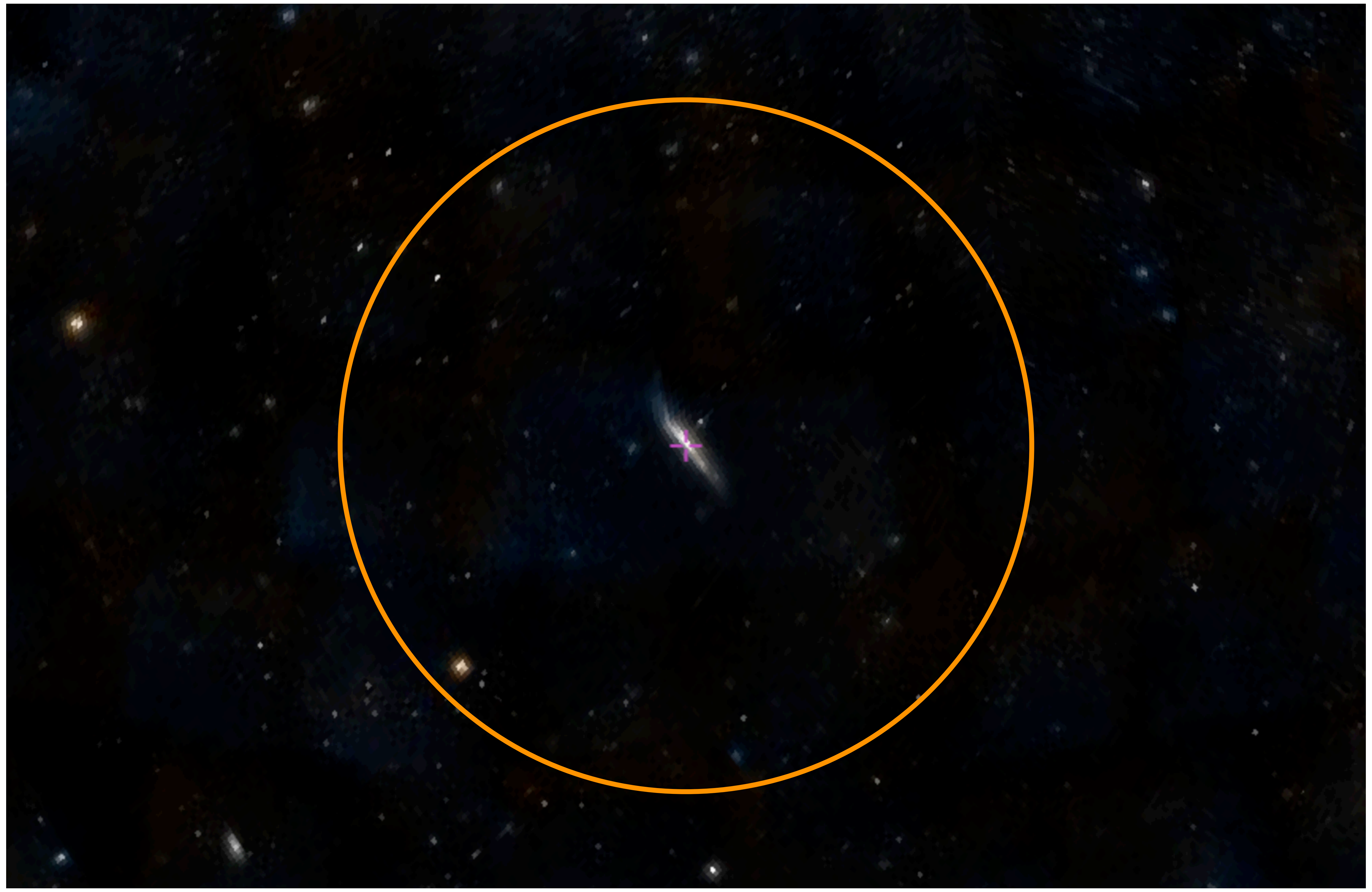


Map d = 400 kpc (today) into Δz near $z \sim 0$:

$$\Delta\eta = c\int_{t_1}^{t_2}\frac{dt'}{a(t')} = c\int_{z}^{z+\Delta z}\frac{dz'}{H(z')} \approx \frac{c}{H_0}\int_{z}^{z+\Delta z}\frac{dz'}{\sqrt{\Omega_\Lambda + (1+z')^3\Omega_m}}$$

$$\approx \frac{c\Delta z}{H_0\sqrt{\Omega_\Lambda + (1+z)^3\Omega_m}}$$

$$\approx 400\ \text{kpc}\ \frac{\Delta z}{10^{-4}}$$

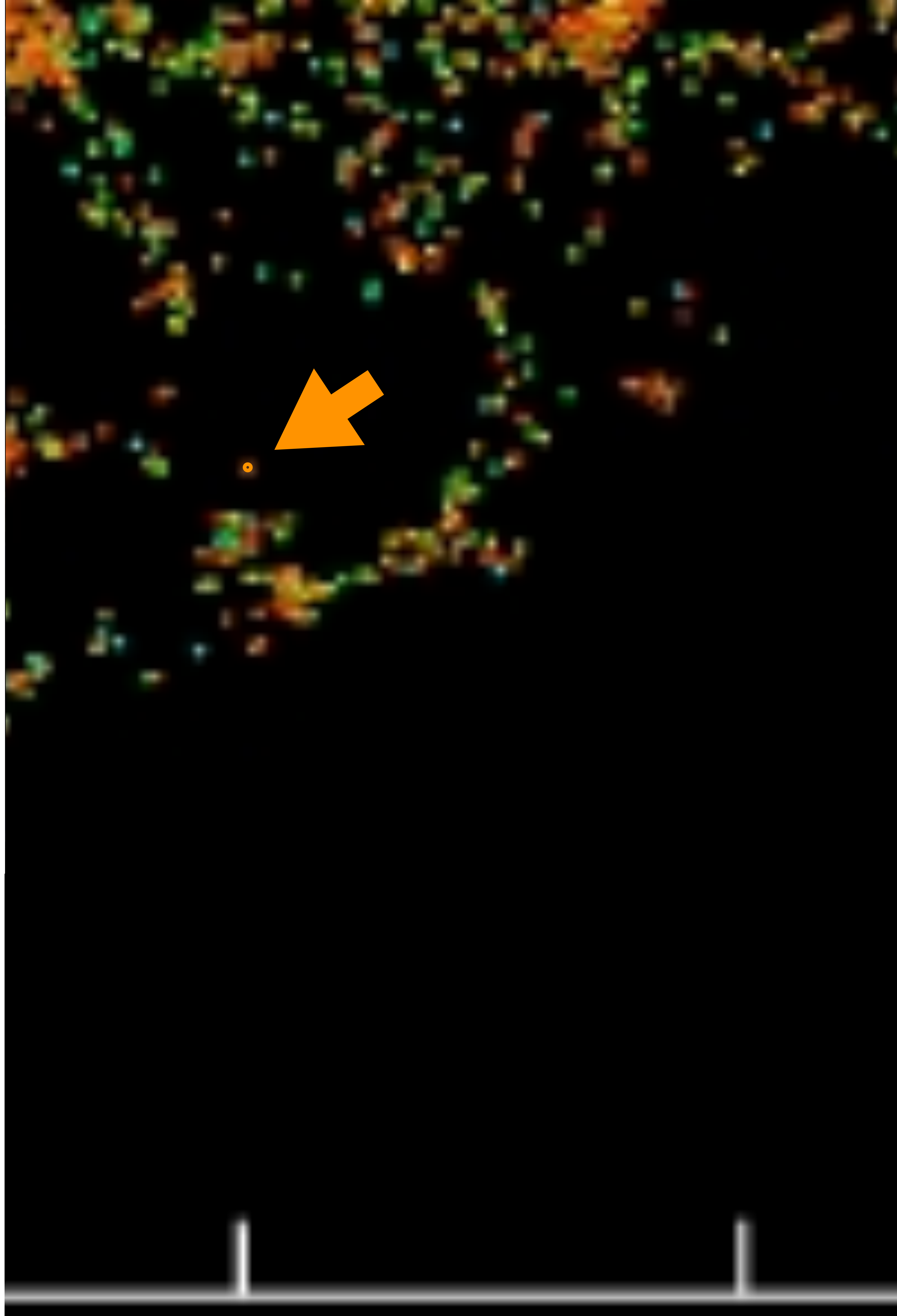


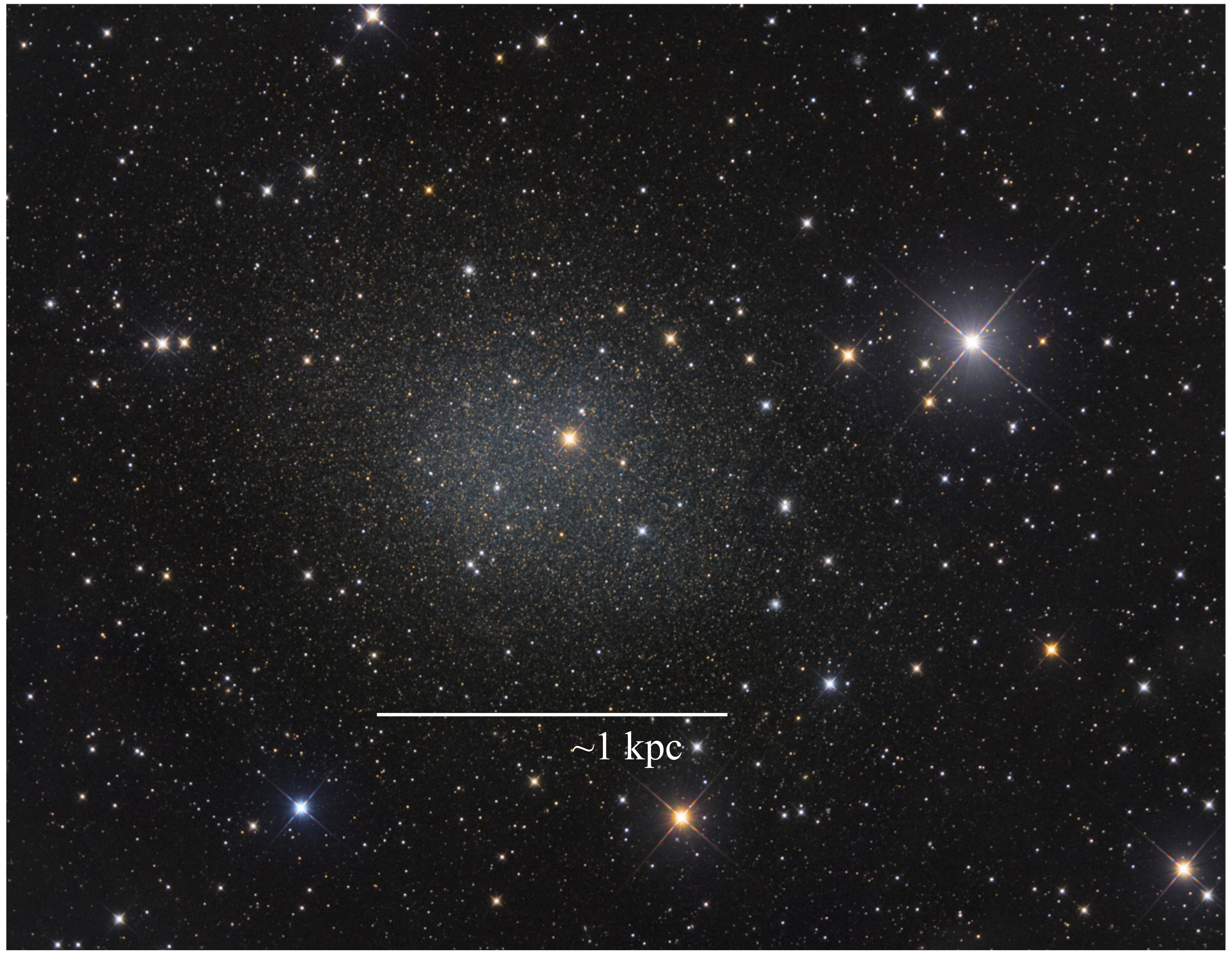
Map d = 1 Mpc (today) into Δz near $z \sim 0$:

$$\Delta\eta = c\int_{t_1}^{t_2}\frac{dt'}{a(t')} = c\int_{z}^{z+\Delta z}\frac{dz'}{H(z')} \approx \frac{c}{H_0}\int_{z}^{z+\Delta z}\frac{dz'}{\sqrt{\Omega_\Lambda + (1+z')^3\Omega_m}}$$

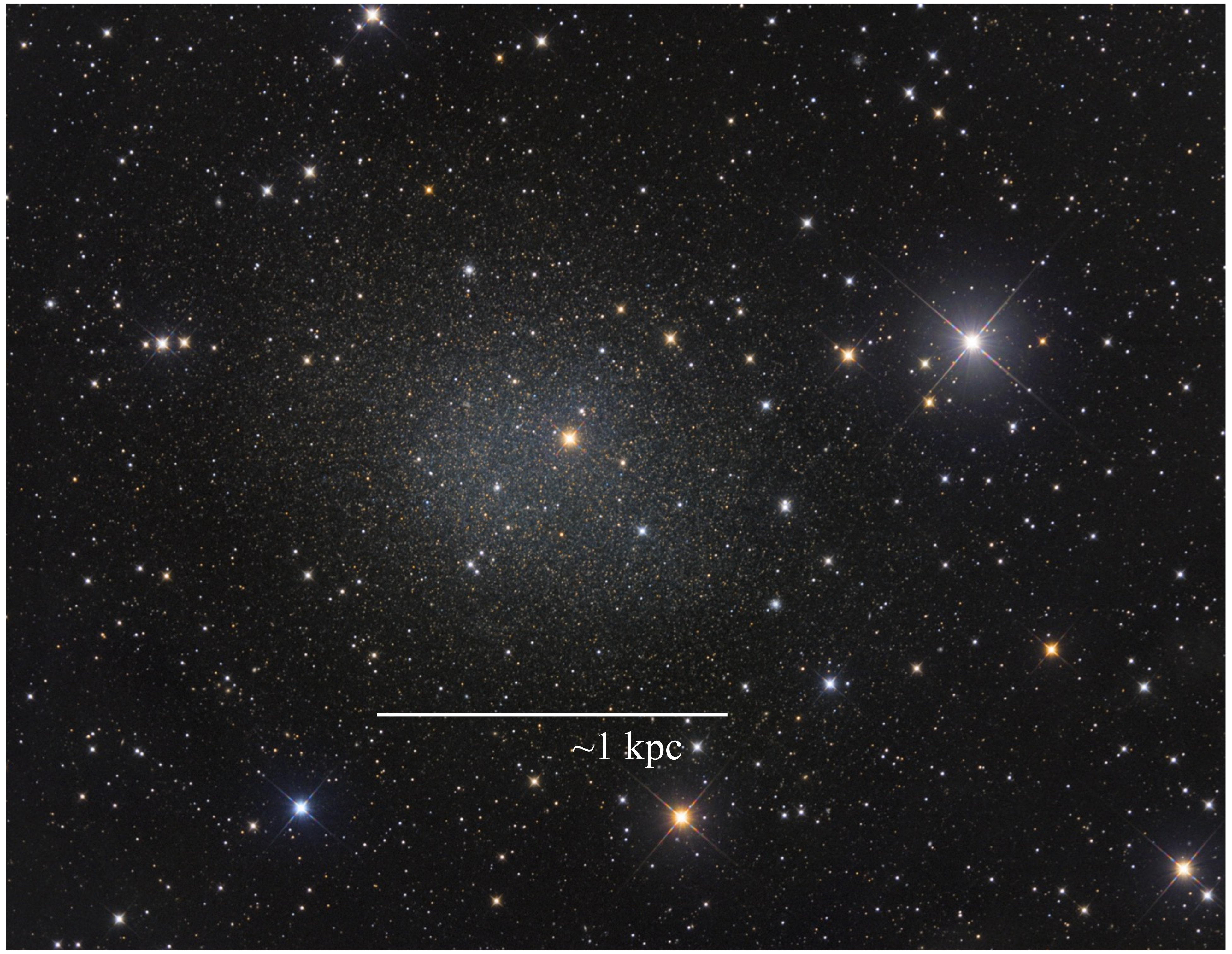
$$\approx \frac{c\Delta z}{H_0\sqrt{\Omega_\Lambda + (1+z)^3\Omega_m}}$$

$$\approx 1\ \text{Mpc}\ \frac{\Delta z}{2.5\times 10^{-4}}$$

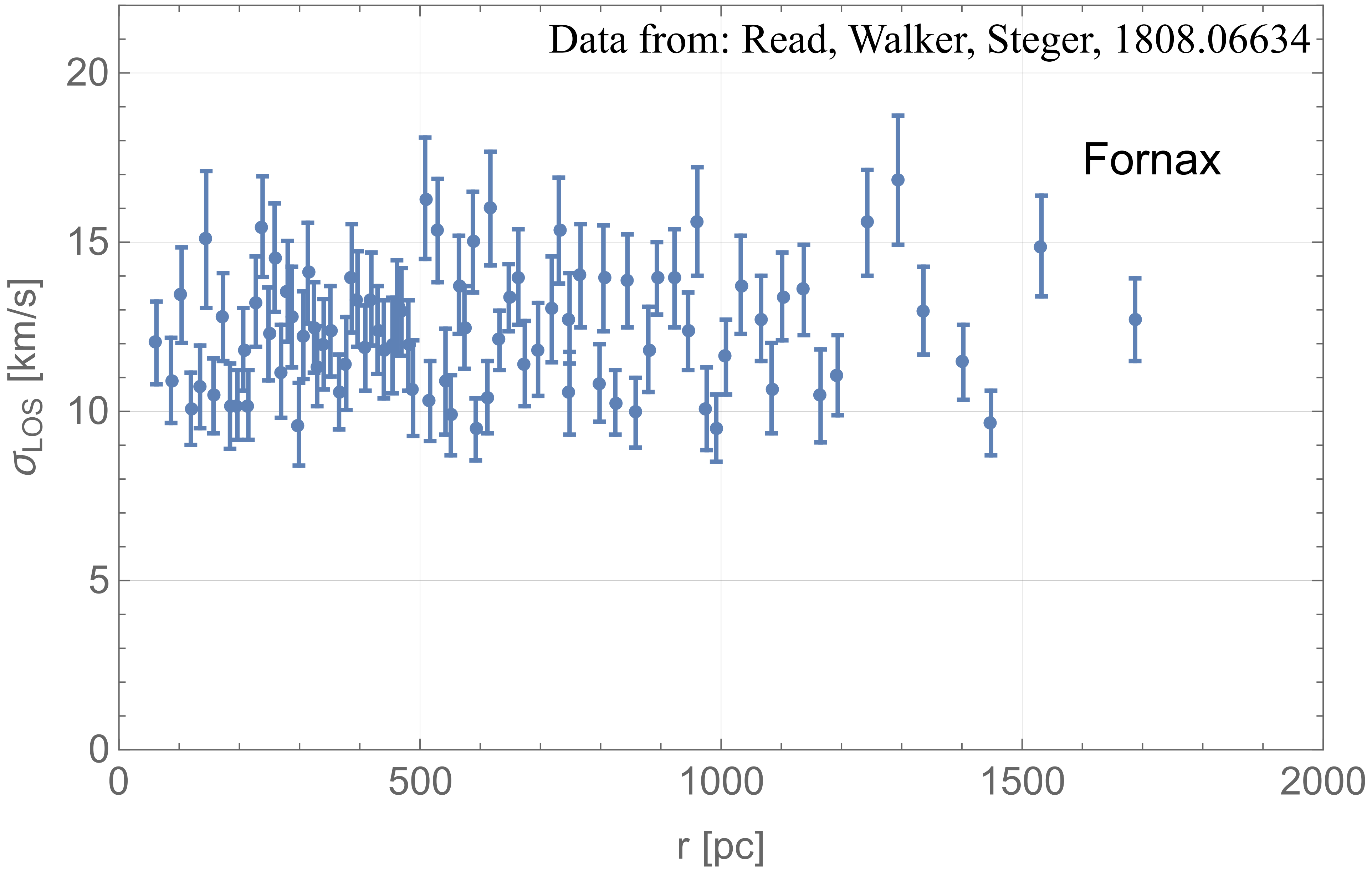


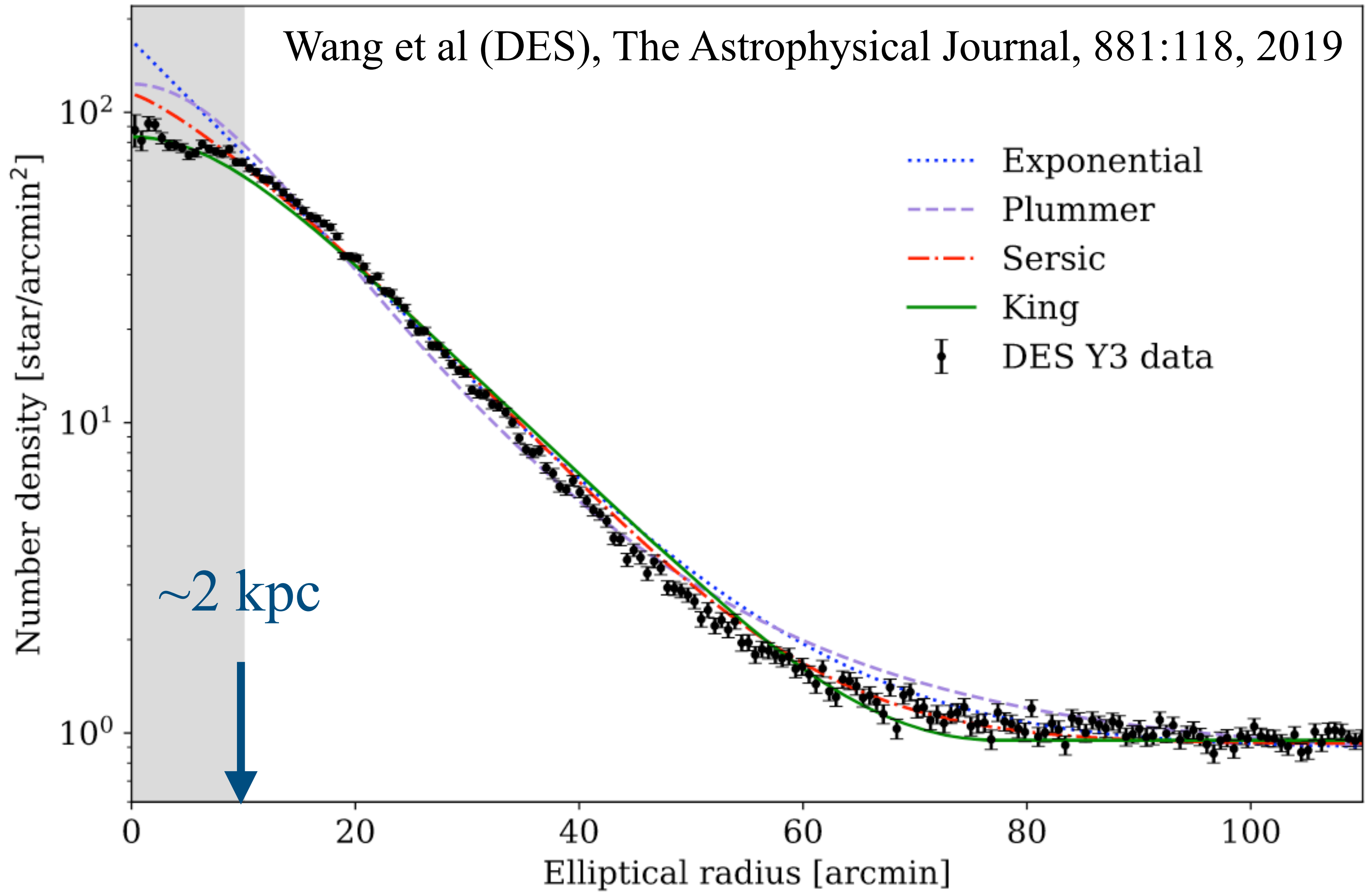


Fornax dwarf spheroidal, satellite galaxy of the Milky Way

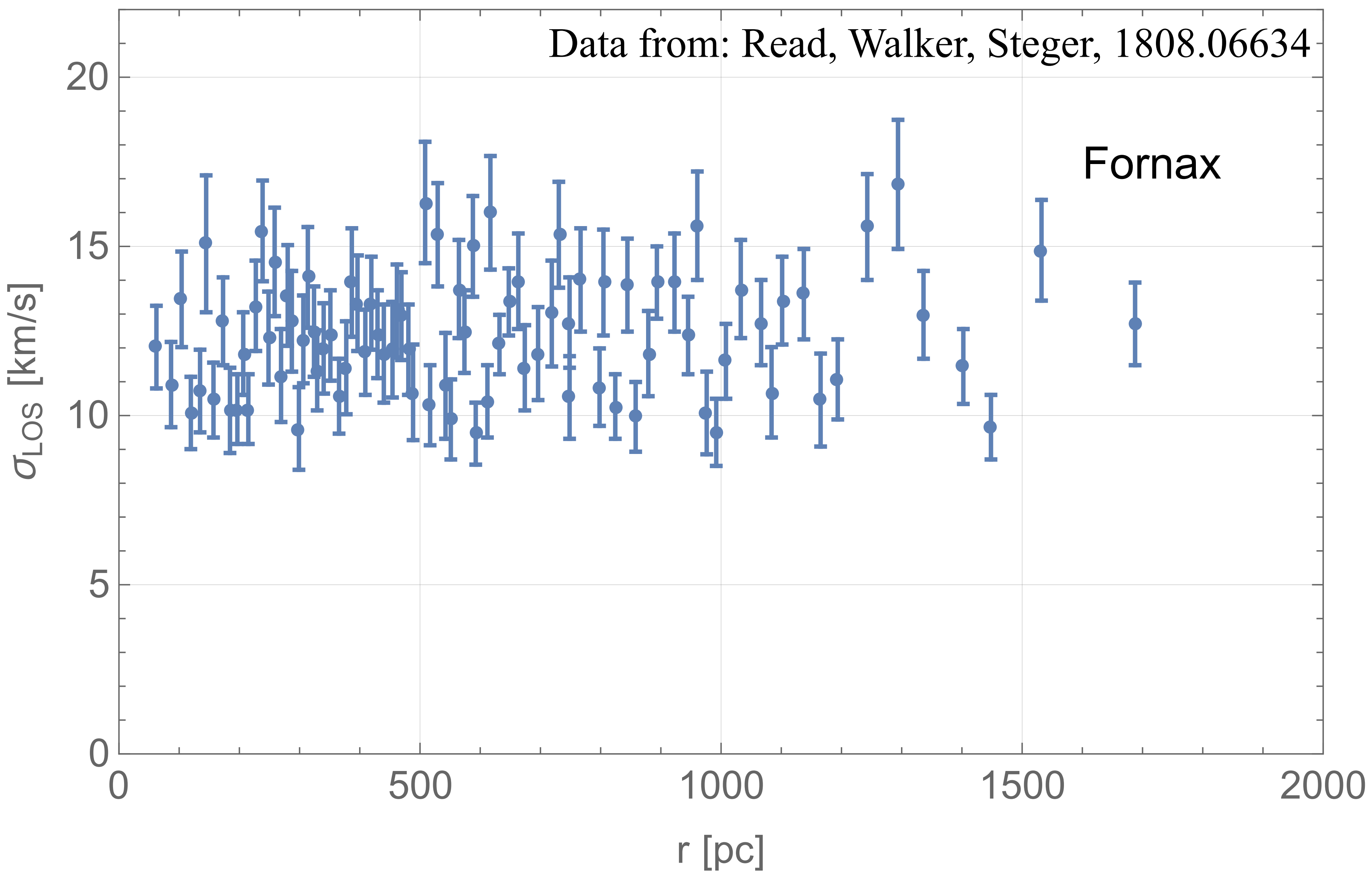


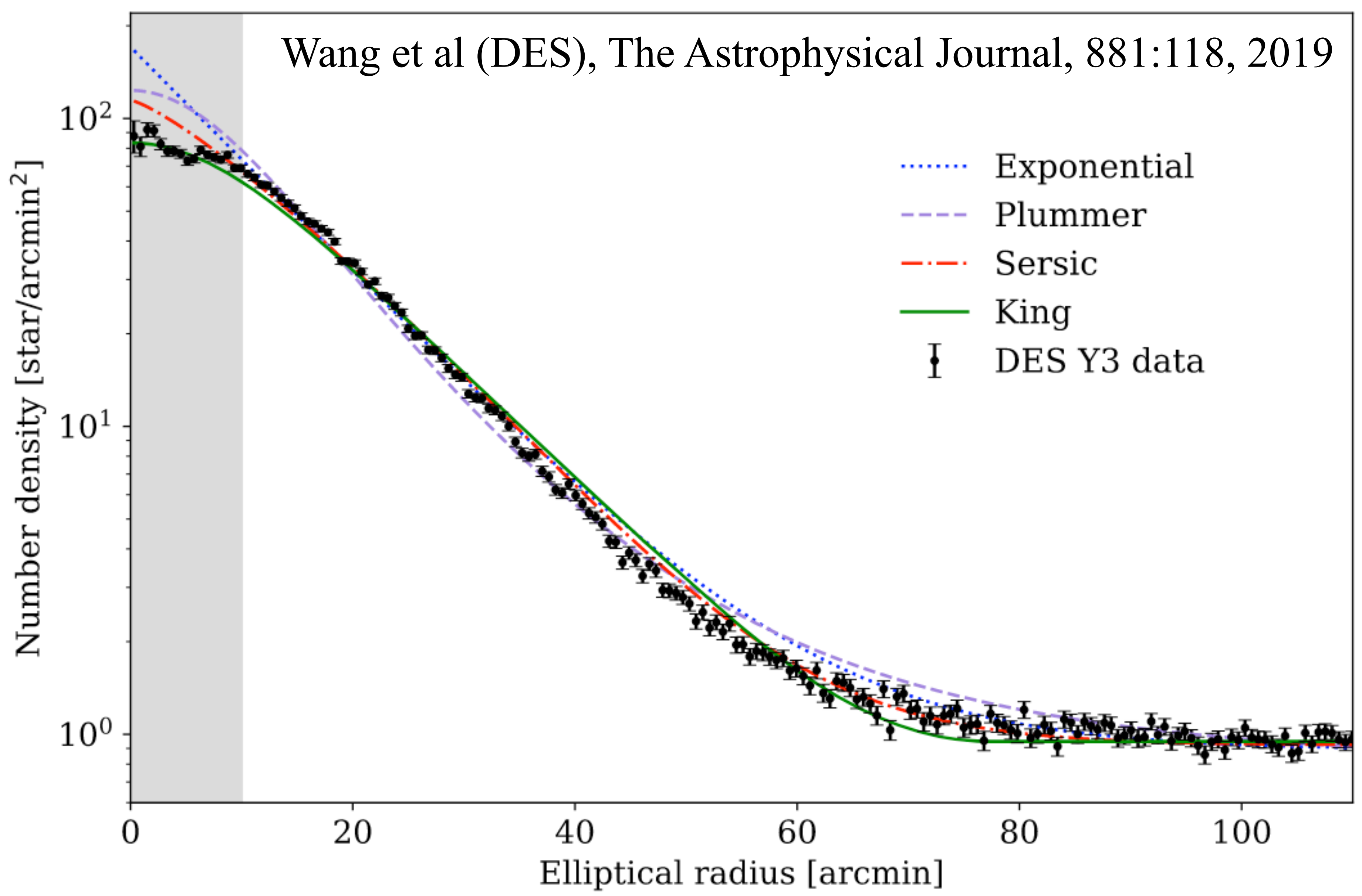
What is observed:
1. Line-of-sight velocities
2. Column density of stars



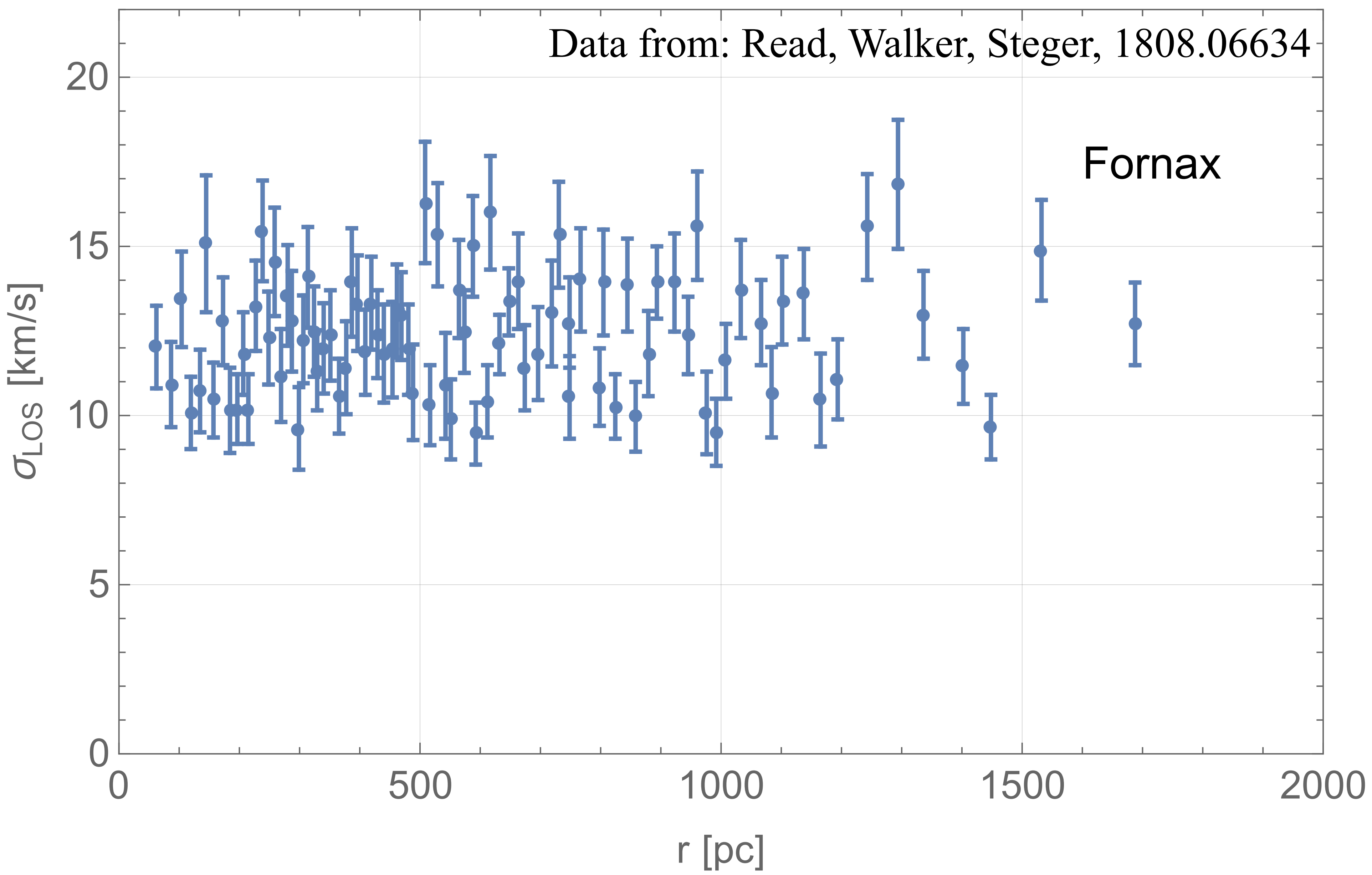


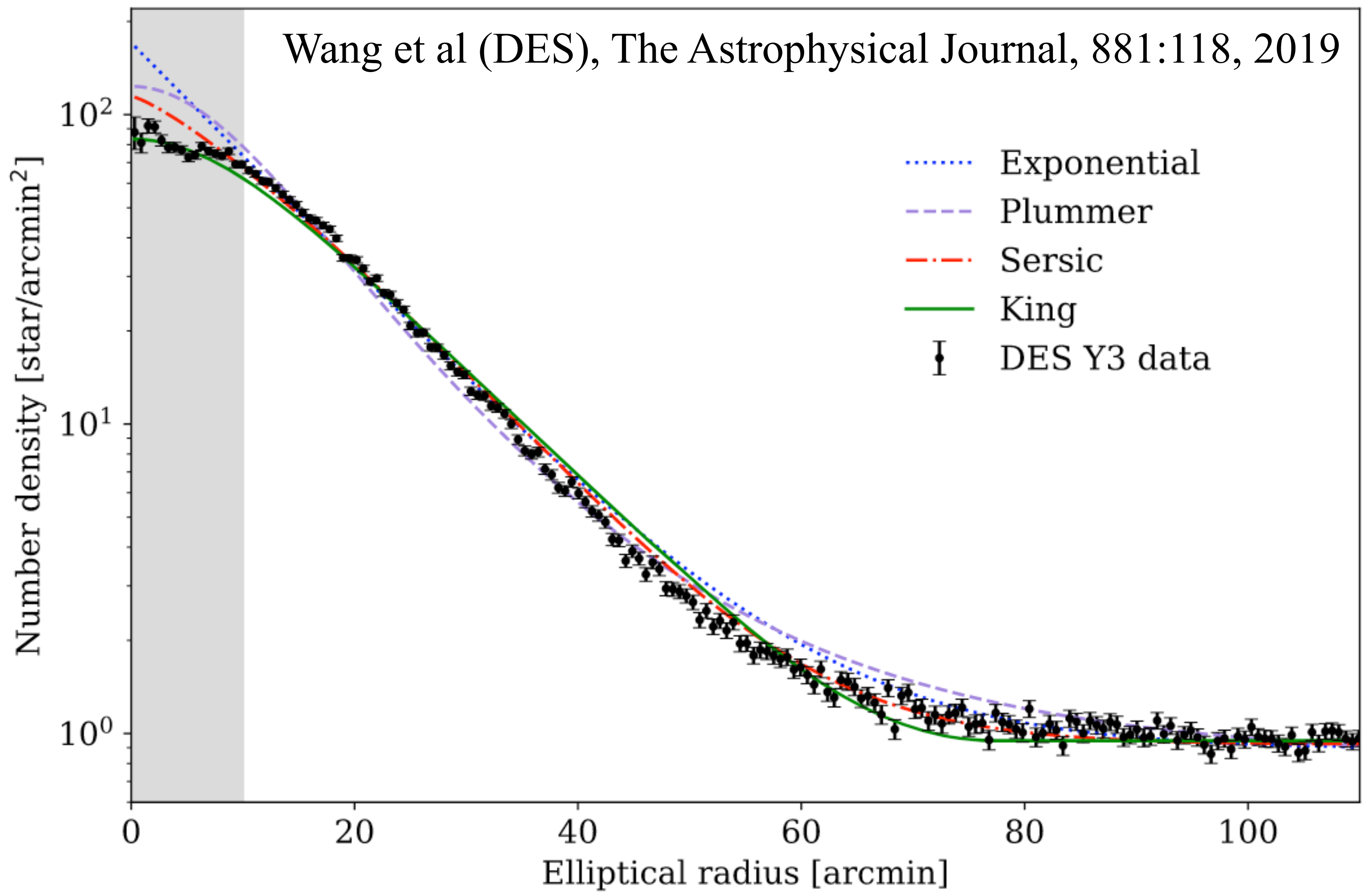
$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \dot{x}_i \frac{\partial f}{\partial x_i} + \dot{p}_i \frac{\partial f}{\partial p_i} = 0$$





$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \dot{x}_i \frac{\partial f}{\partial x_i} + \dot{p}_i \frac{\partial f}{\partial p_i} = \frac{\partial f}{\partial t} + v_i \frac{\partial f}{\partial x_i} - \frac{\partial \Phi}{\partial x_i} \frac{\partial f}{\partial v_i} = 0$$





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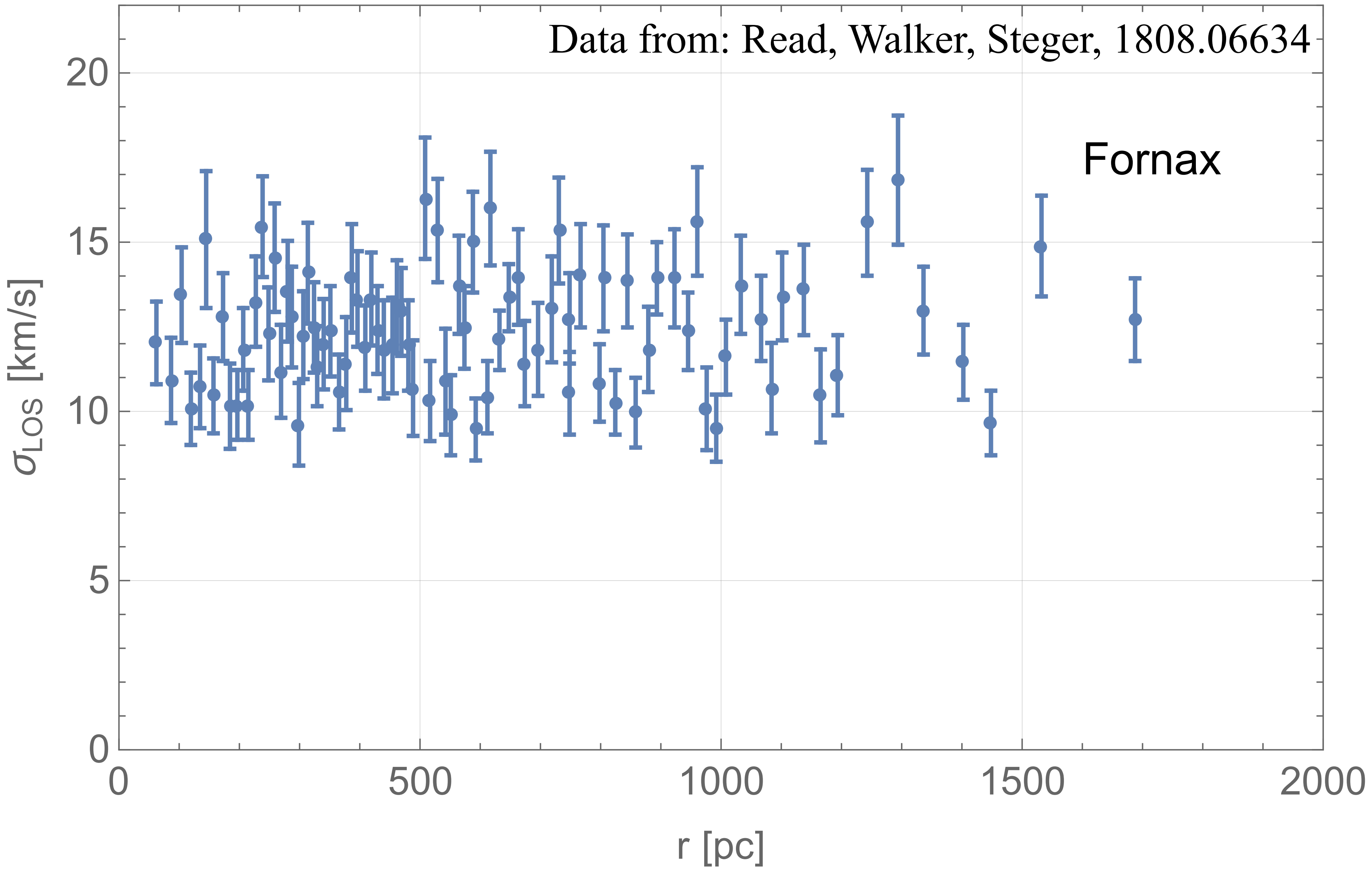
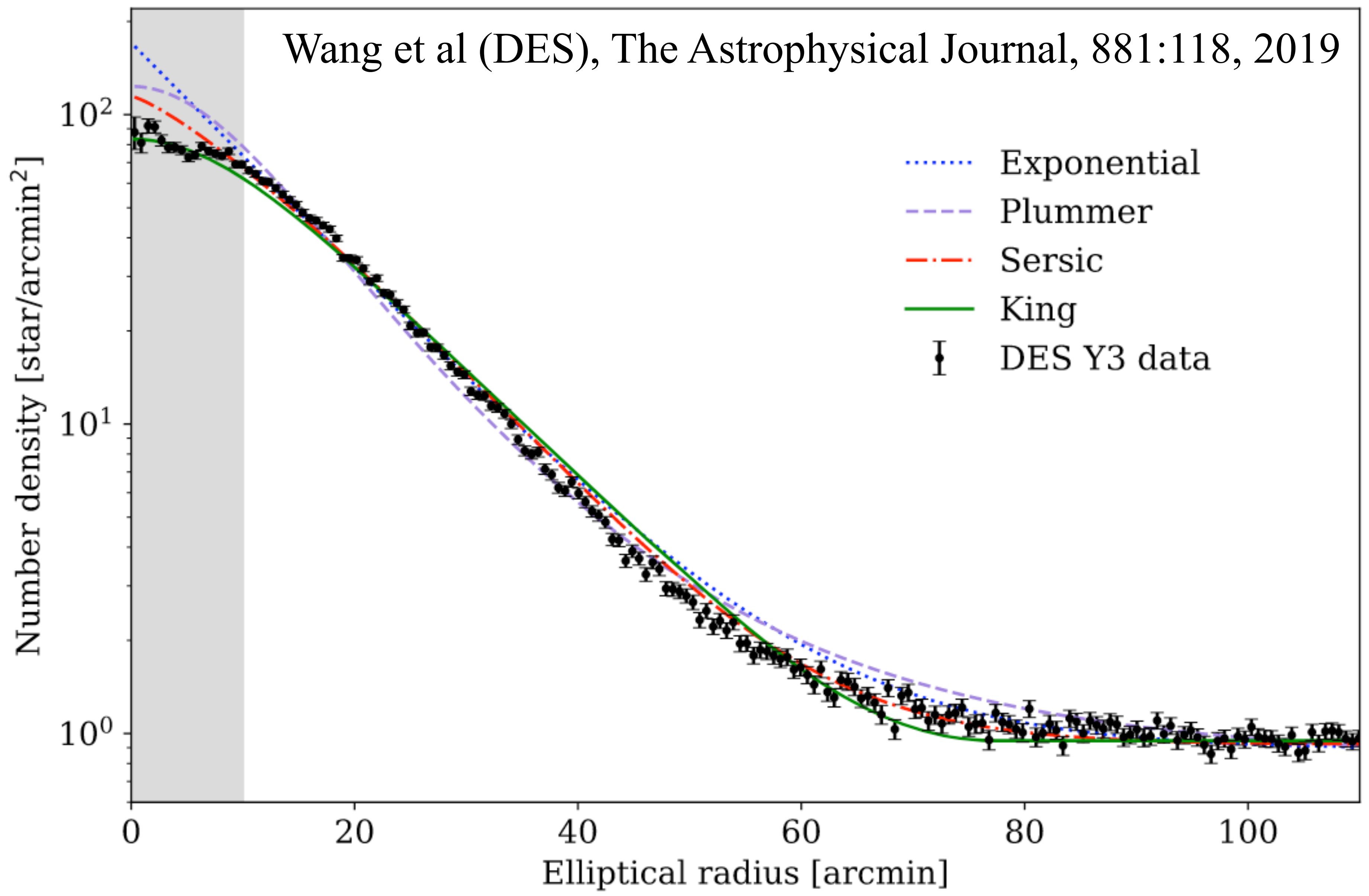
$$\int d^3p\, v_j \left(\frac{\partial f}{\partial t} + v_i \frac{\partial f}{\partial x_i} - \frac{\partial \Phi}{\partial x_i}\frac{\partial f}{\partial v_i} \right) = \boxed{\frac{\partial}{\partial t}\left(n\bar{v}_j\right) + \frac{\partial}{\partial x_i}\left(n\overline{v_i v_j}\right) + n\frac{\partial \Phi}{\partial x_j} = 0}$$

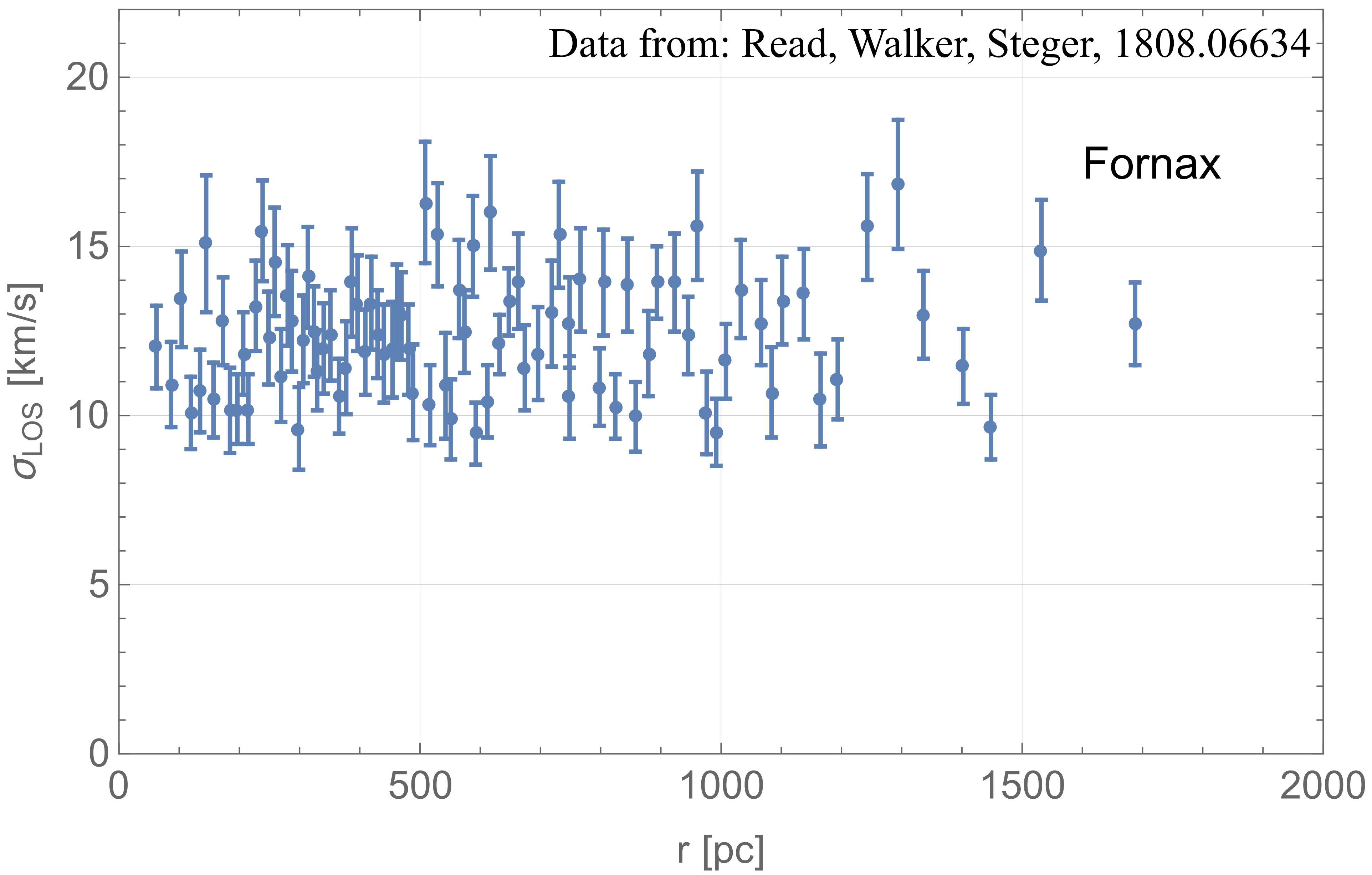
$$n\overline{v_i v_j}(\mathbf{x}) = \int d^3p\, v_i\, v_j\, f(\mathbf{x}, \mathbf{v})$$

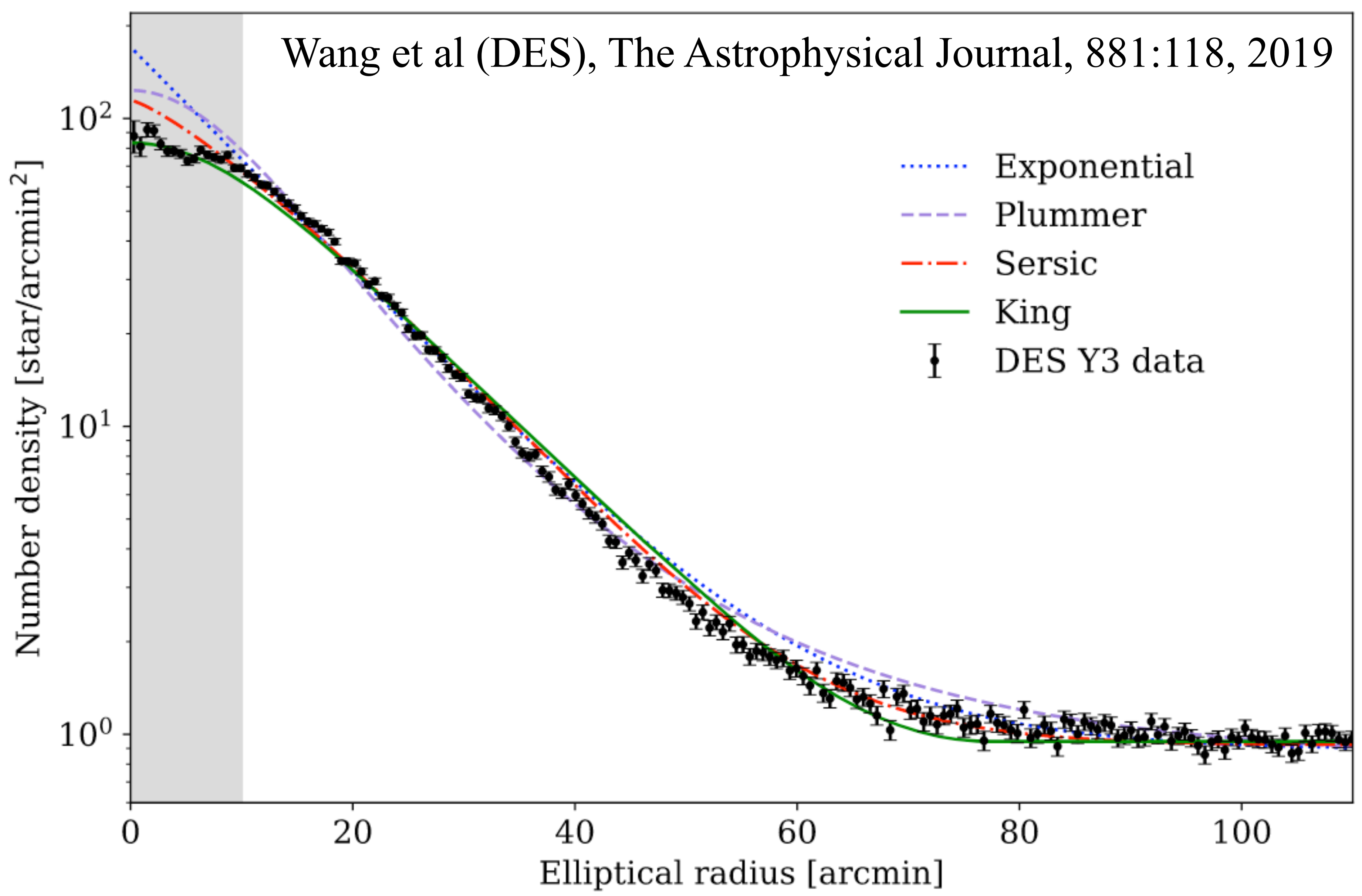




Assume steady state

$$\frac{\partial}{\partial t}\left(n\bar{v}_j\right) + \frac{\partial}{\partial x_i}\left(n\overline{v_i v_j}\right) + n\frac{\partial \Phi}{\partial x_j} = 0$$





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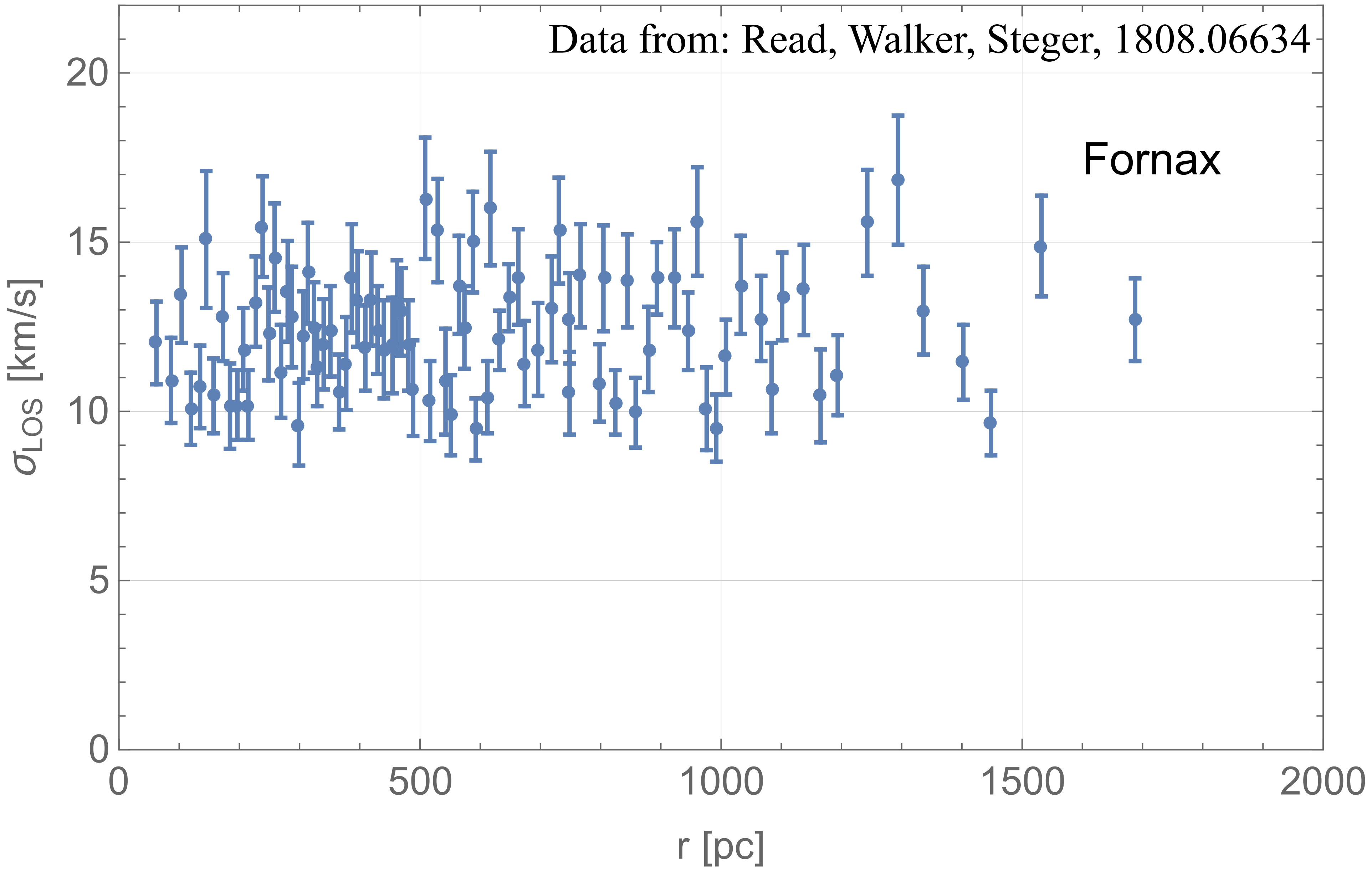
$$\frac{\partial}{\partial t}\left(n\bar{v}_j\right) + \frac{\partial}{\partial x_i}\left(n\overline{v_i v_j}\right) + n\frac{\partial \Phi}{\partial x_j} = 0$$

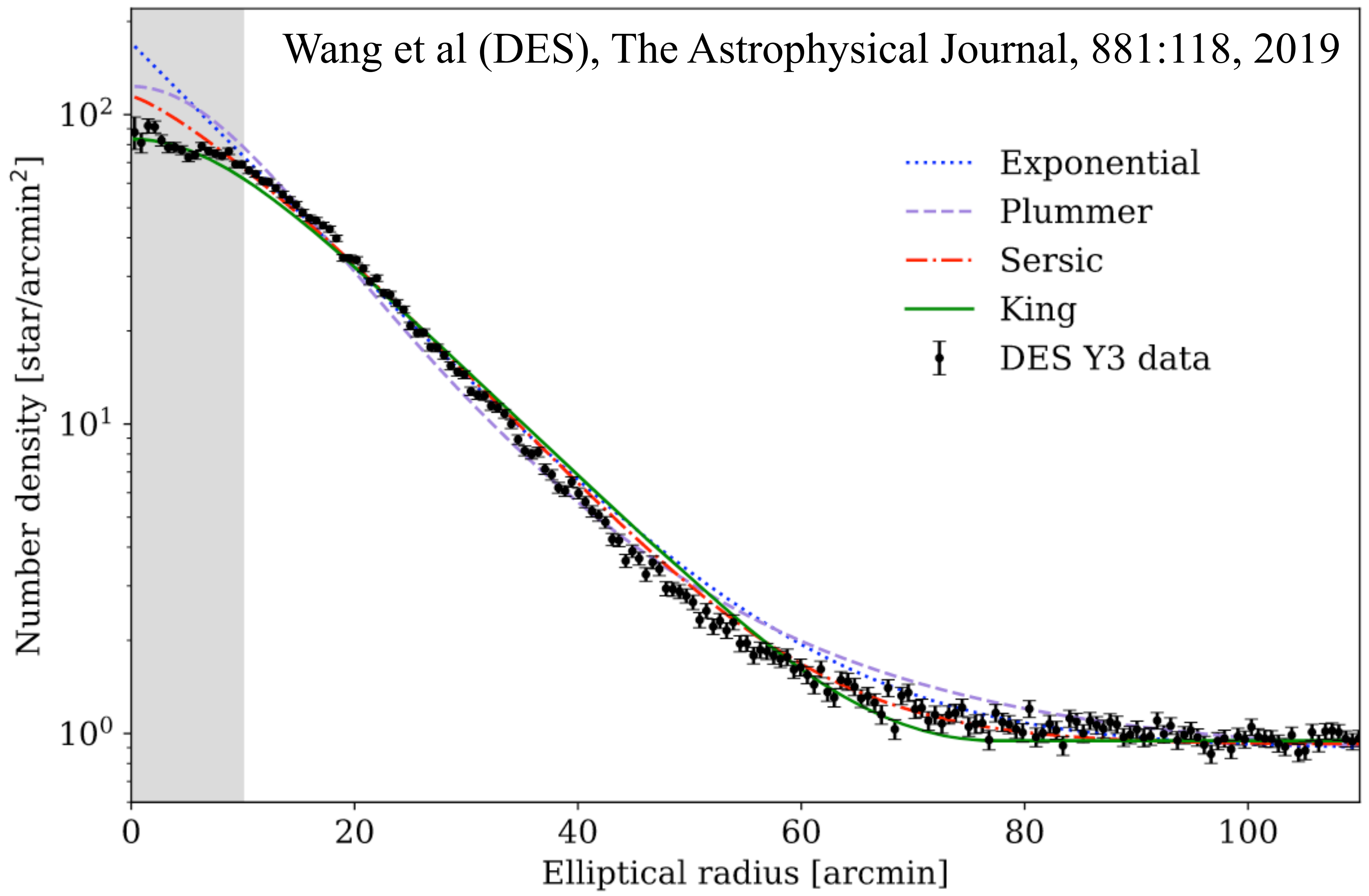
Spherical symmetry

$$\frac{\partial}{\partial x_i}\left(n\overline{v_i v_j}\right) \to \frac{\partial}{\partial r}\left(n\overline{v_r^2}\right) + n\frac{2\overline{v_r^2} - \overline{v_t^2}}{r} = \frac{\partial}{\partial r}\left(n\overline{v_r^2}\right) + \frac{2n\beta\overline{v_r^2}}{r}$$

$$\frac{\partial \Phi}{\partial x_j} \to \frac{GM(r)}{r^2}$$

$$\beta = 1 - \frac{\overline{v_t^2}}{2\overline{v_r^2}}$$





Assume steady state

$$\cancel{\frac{\partial}{\partial t}\left(n\bar{v}_j\right)} + \frac{\partial}{\partial x_i}\left(n\overline{v_i v_j}\right) + n\frac{\partial \Phi}{\partial x_j} = 0$$

Spherical symmetry

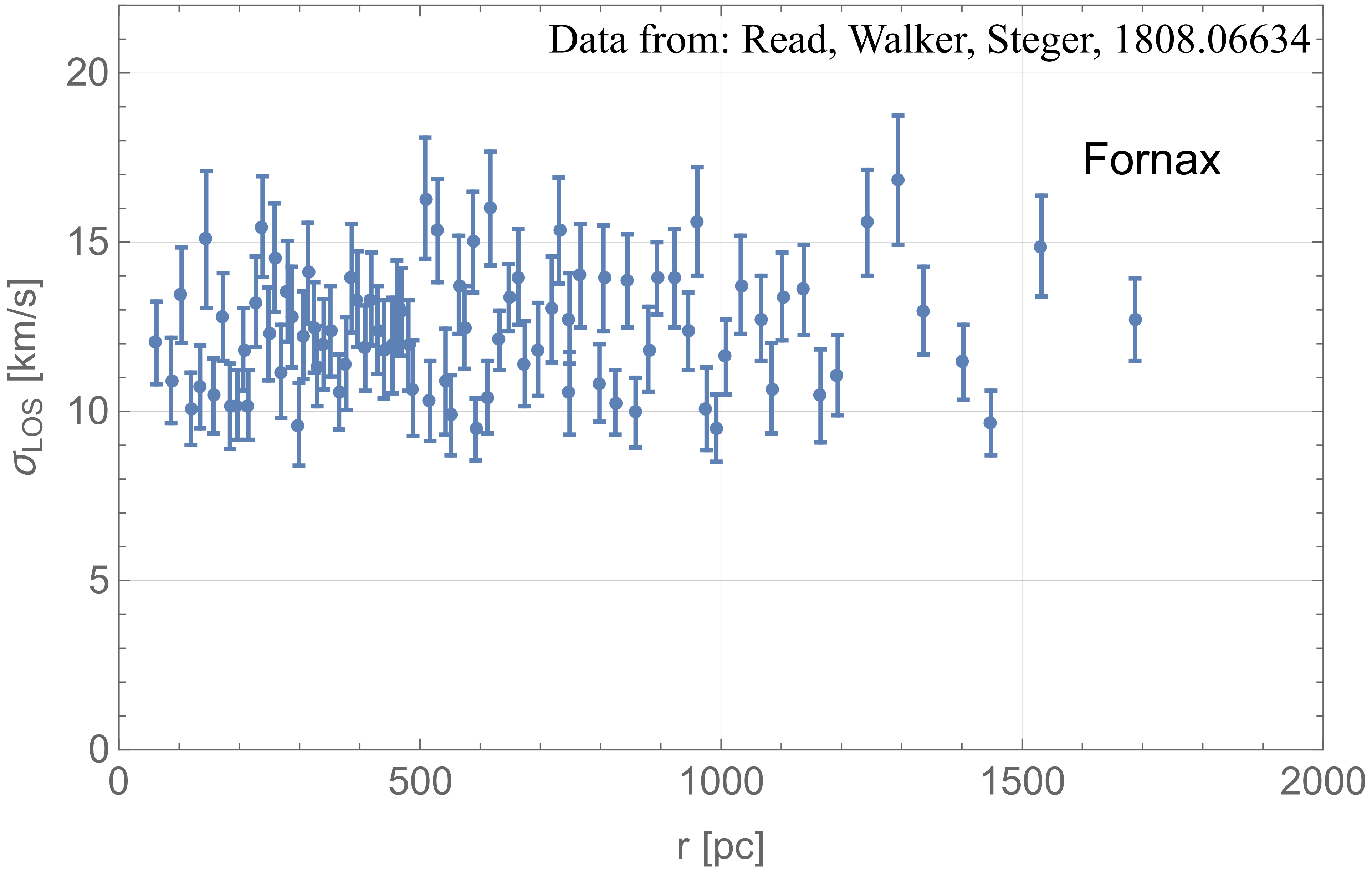
$$\frac{\partial}{\partial x_i}\left(n\overline{v_i v_j}\right) \to \frac{\partial}{\partial r}\left(n\overline{v_r^2}\right) + n\frac{2\overline{v_r^2} - \overline{v_t^2}}{r} = \frac{\partial}{\partial r}\left(n\overline{v_r^2}\right) + \frac{2n\beta\overline{v_r^2}}{r}$$

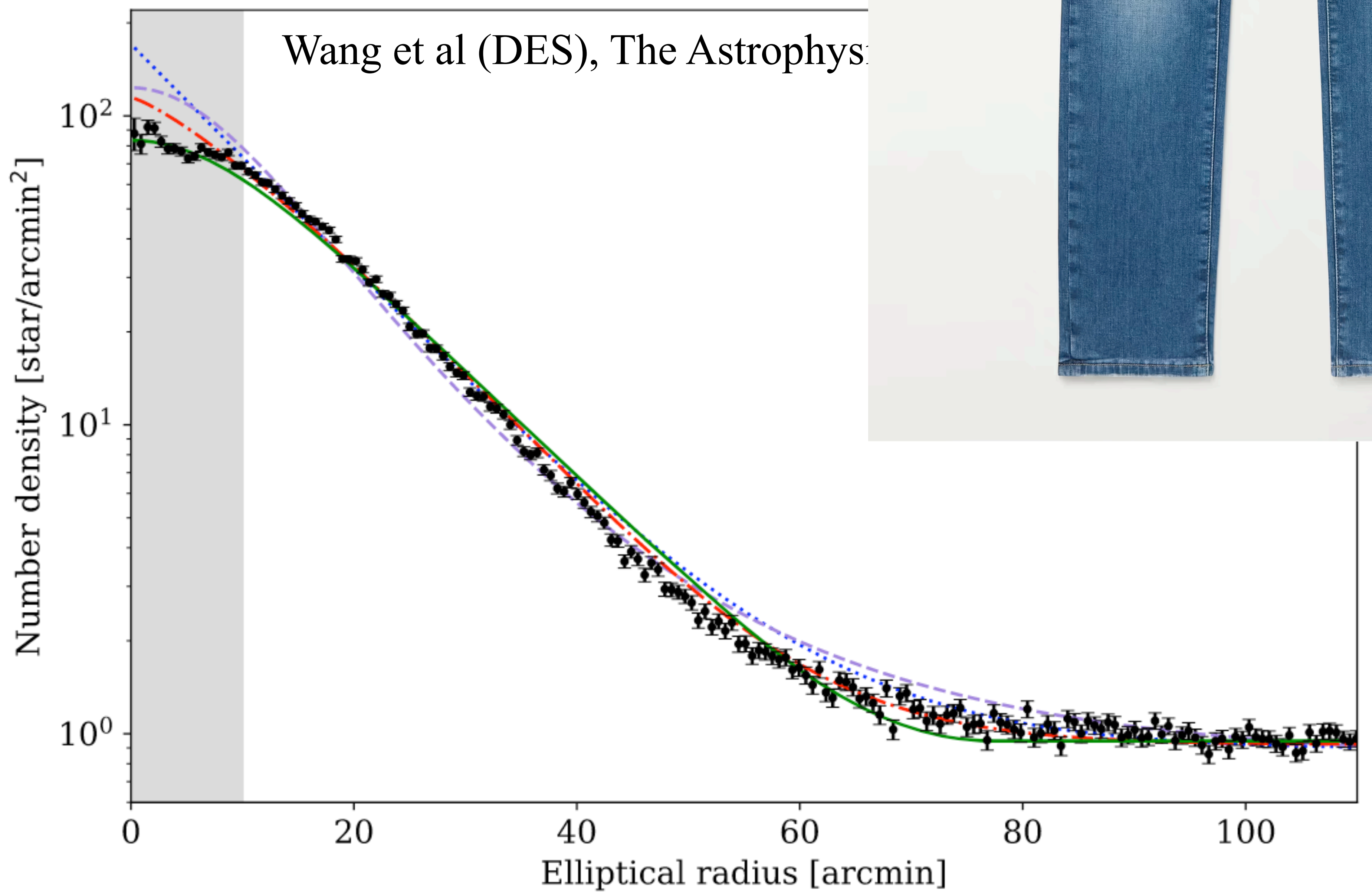
$$\frac{\partial \Phi}{\partial x_j} \to \frac{GM(r)}{r^2}$$

$$\beta = 1 - \frac{\overline{v_t^2}}{2\overline{v_r^2}}$$

Jeans equation

$$\frac{1}{n}\frac{d}{dr}\left(n\overline{v_r^2}\right) + \frac{2\beta}{r}\overline{v_r^2} = -\frac{GM(r)}{r^2}$$

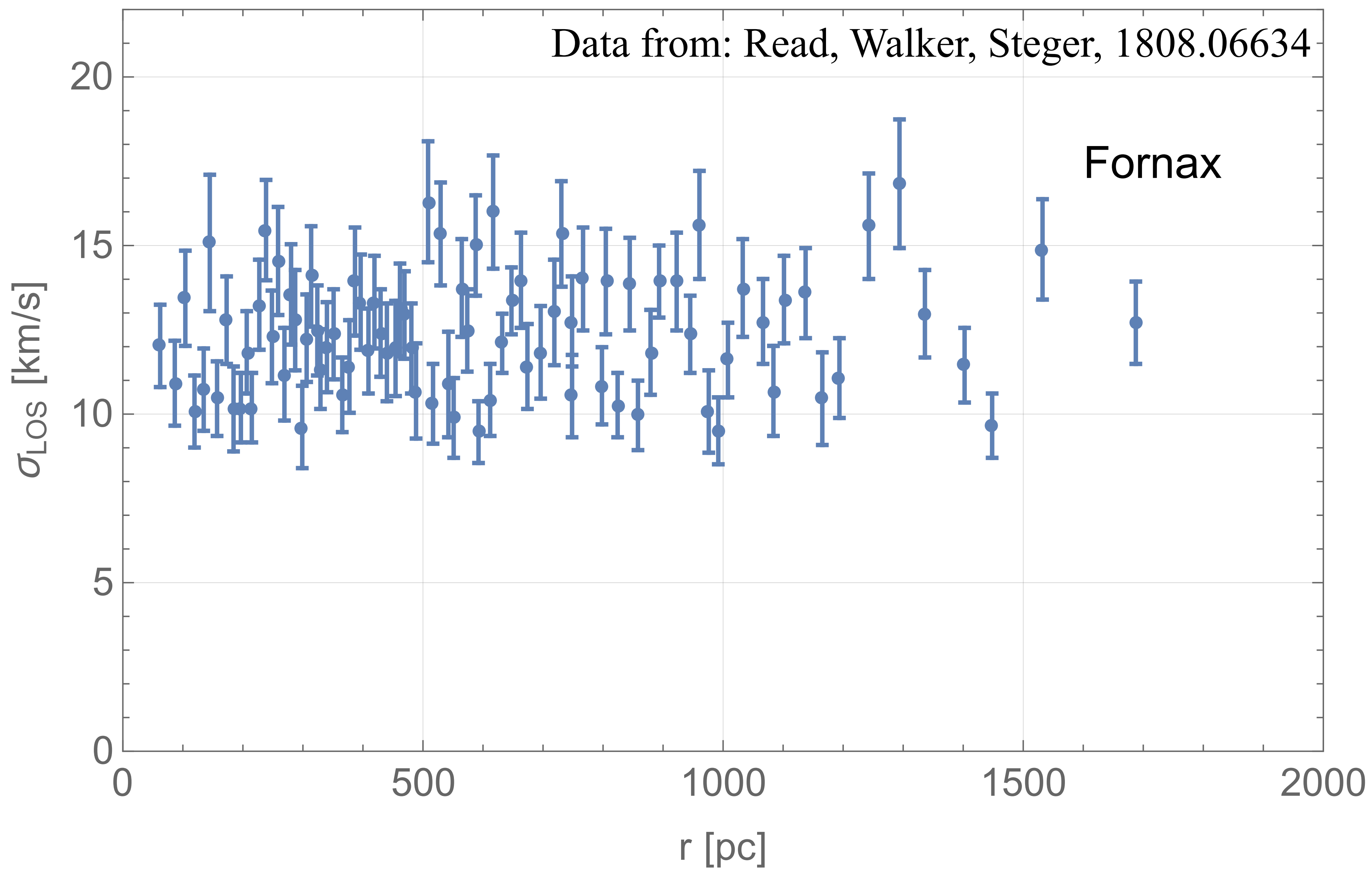


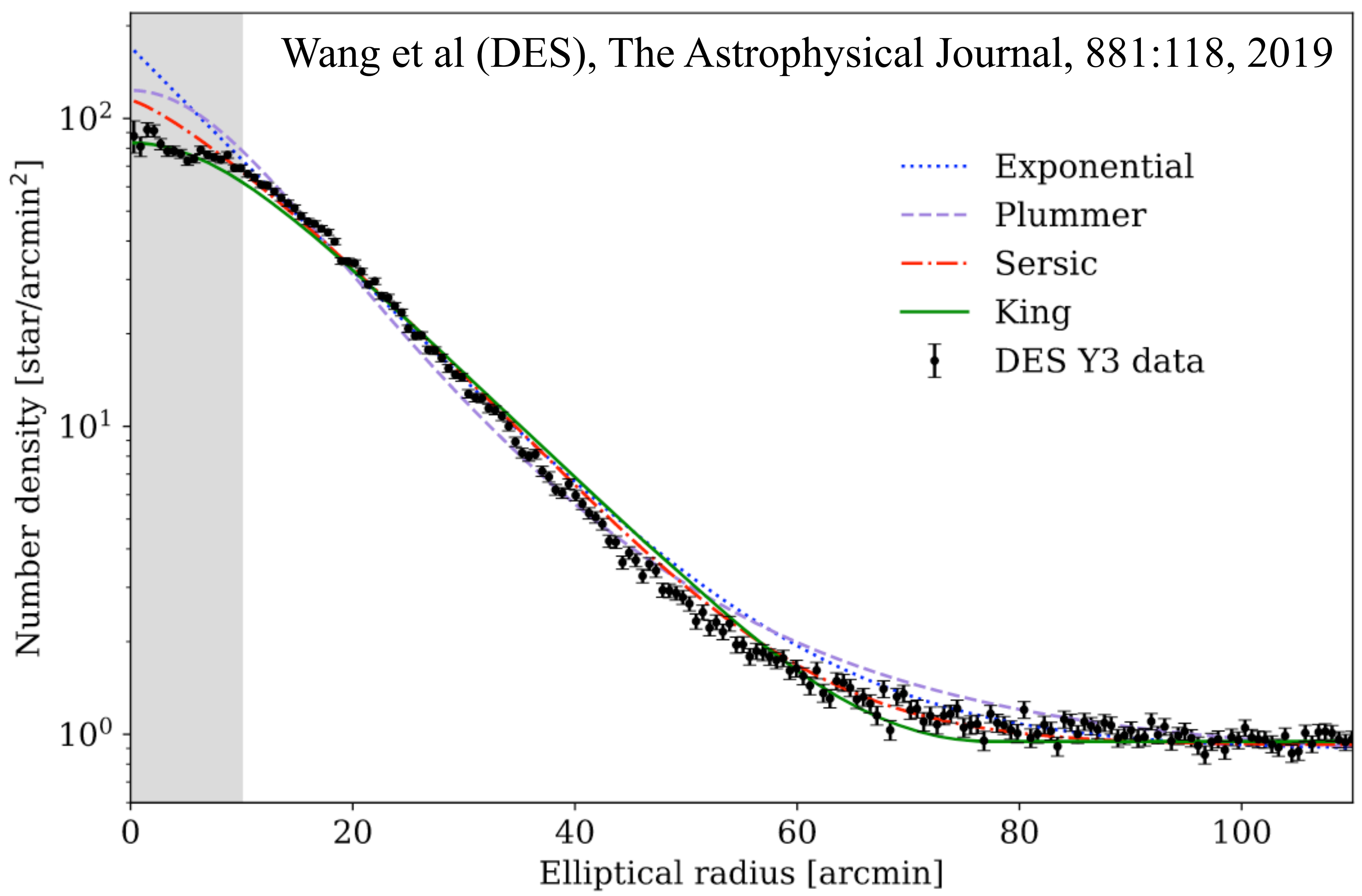


$$\frac{1}{n}\frac{d}{dr}\left(n\overline{v_r^2}\right) + \frac{2\beta}{r}\overline{v_r^2} = -\frac{GM(r)}{r^2}$$

If β is constant in r:

$$n\overline{v_r^2} = \frac{G}{r^{2\beta}}\int_r^\infty dy y^{2\beta-2} n(y) M(y)$$





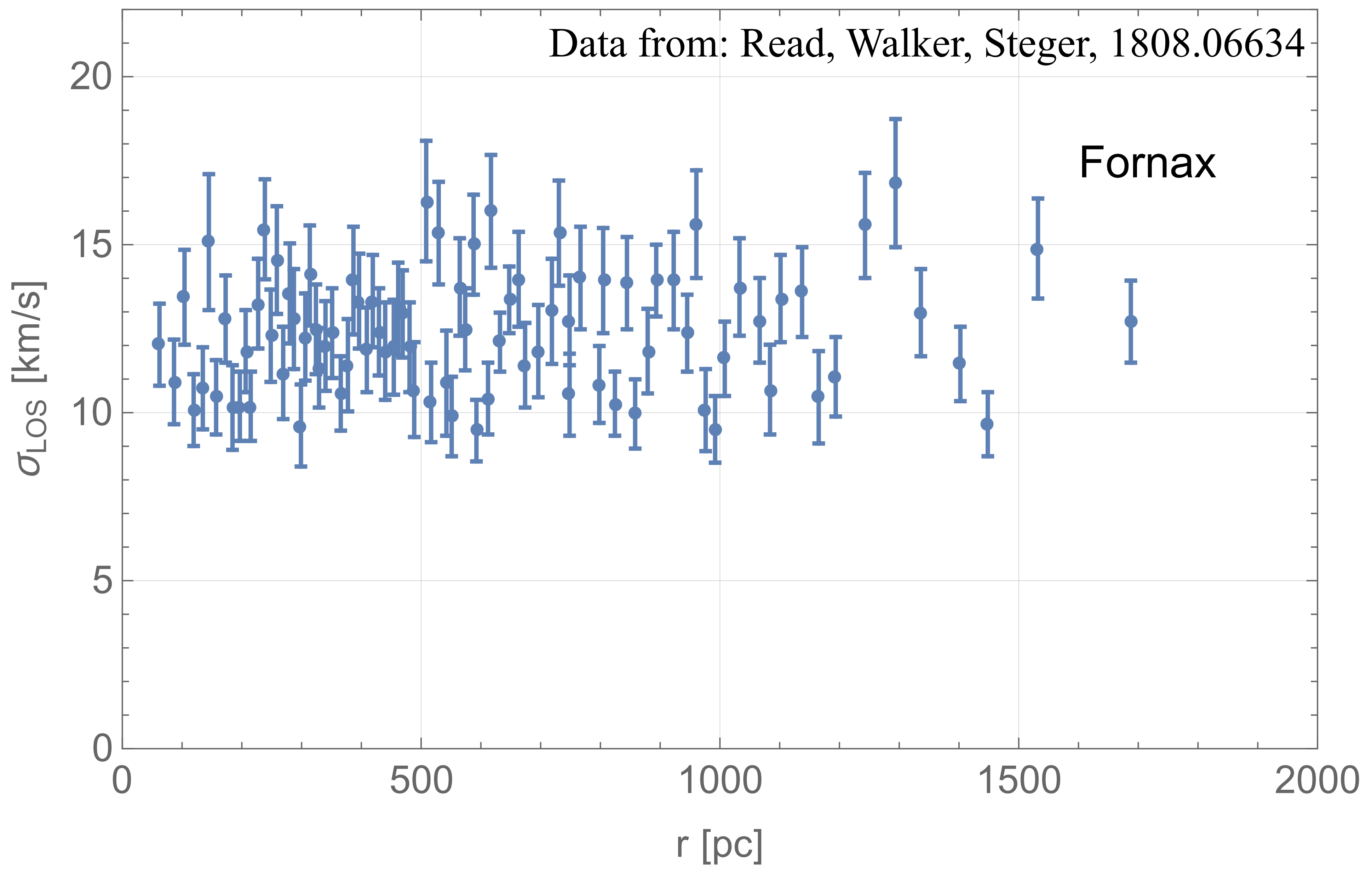
$$\frac{1}{n}\frac{d}{dr}\left(n\overline{v_r^2}\right) + \frac{2\beta}{r}\overline{v_r^2} = -\frac{GM(r)}{r^2}$$

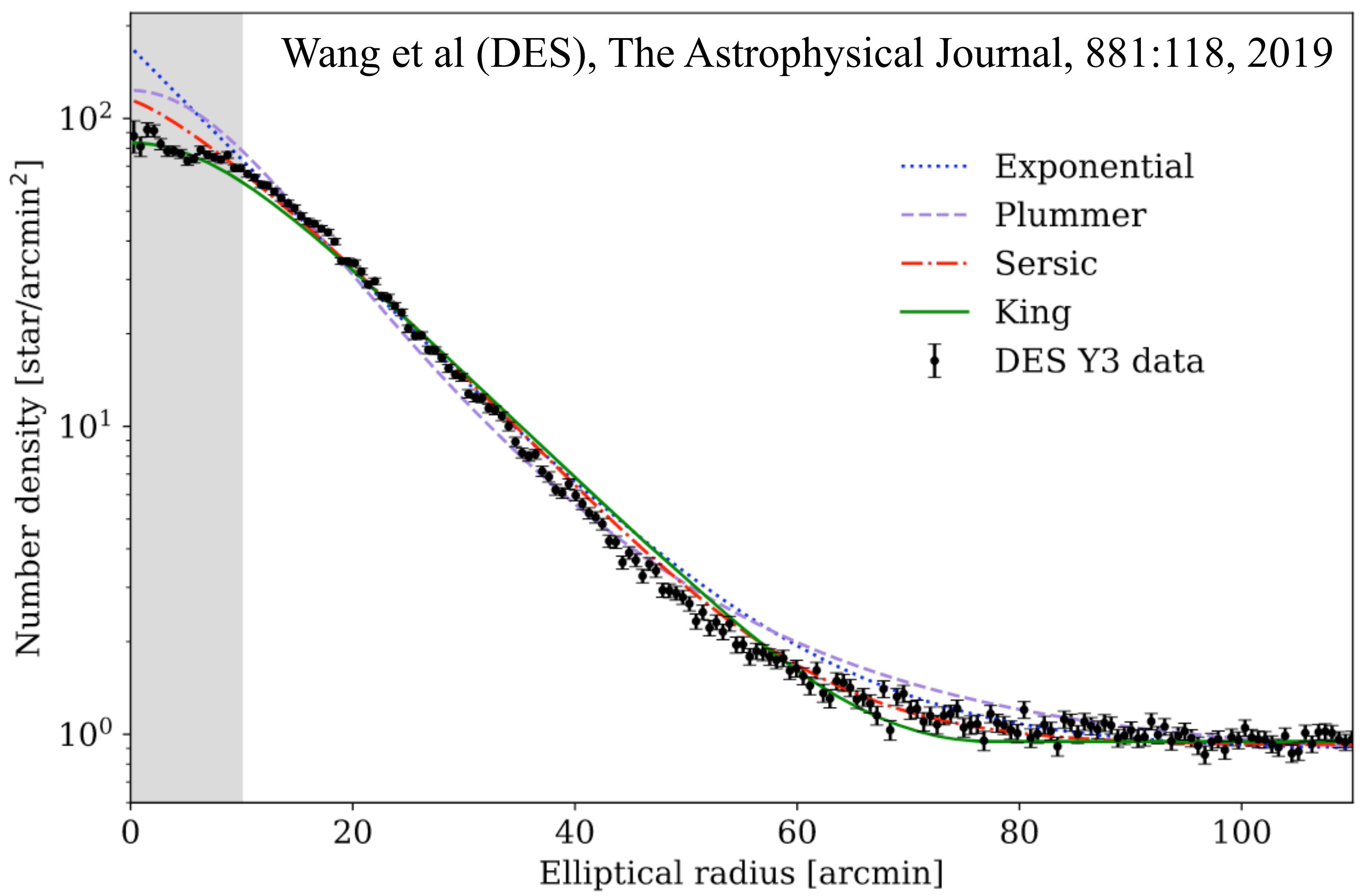
If β is constant in r:

$$n\overline{v_r^2} = \frac{G}{r^{2\beta}}\int_r^\infty dy y^{2\beta-2} n(y) M(y)$$

What is actually observed — line-of-sight velocity:

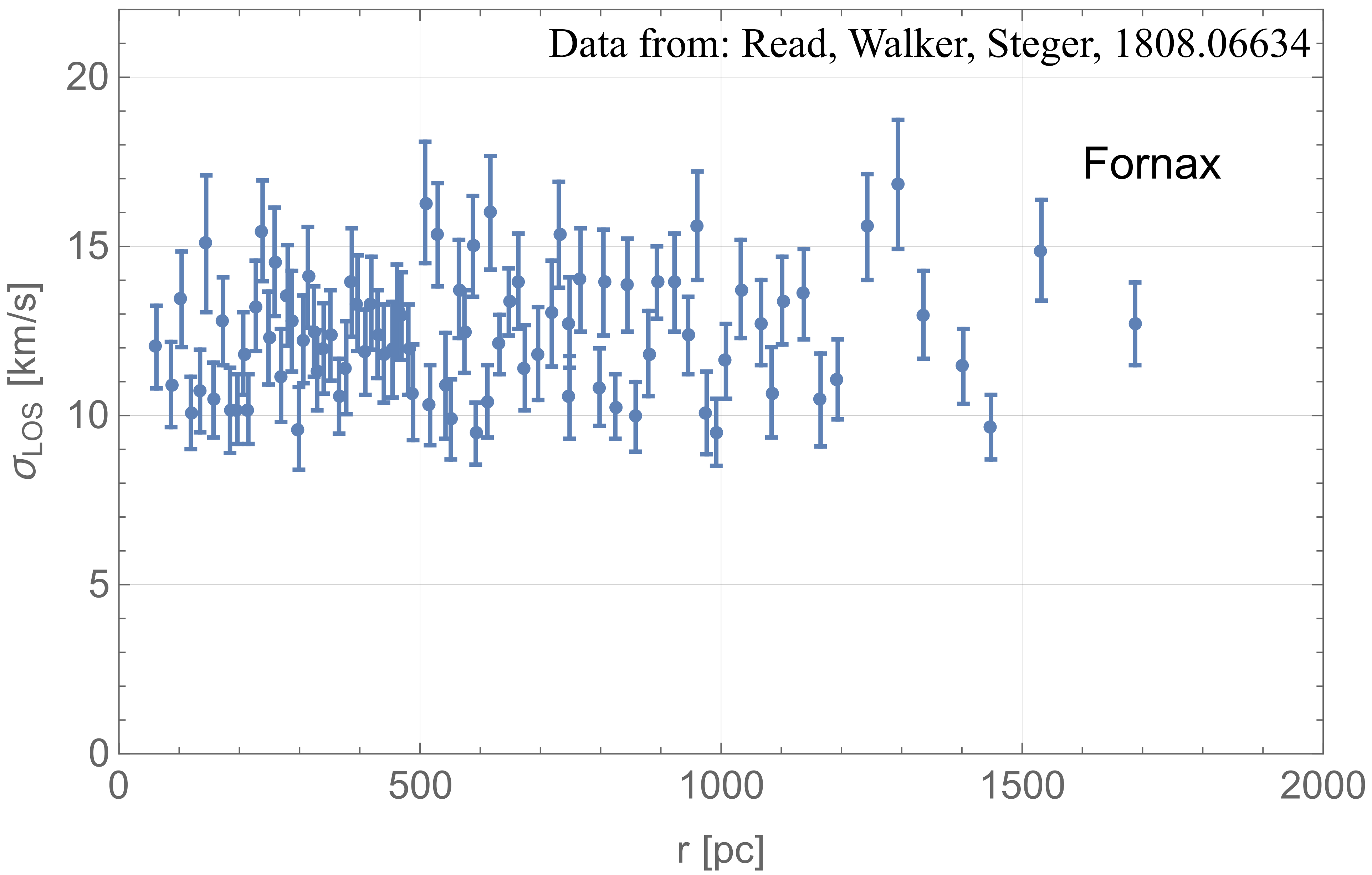
$$\sigma_{\rm LOS}^2(r) = \frac{2l}{I(r)}\int_r^\infty dy \left(1 - \frac{\beta r^2}{y^2}\right)\frac{y\, n\overline{v_r^2}(y)}{\sqrt{y^2 - r^2}}$$

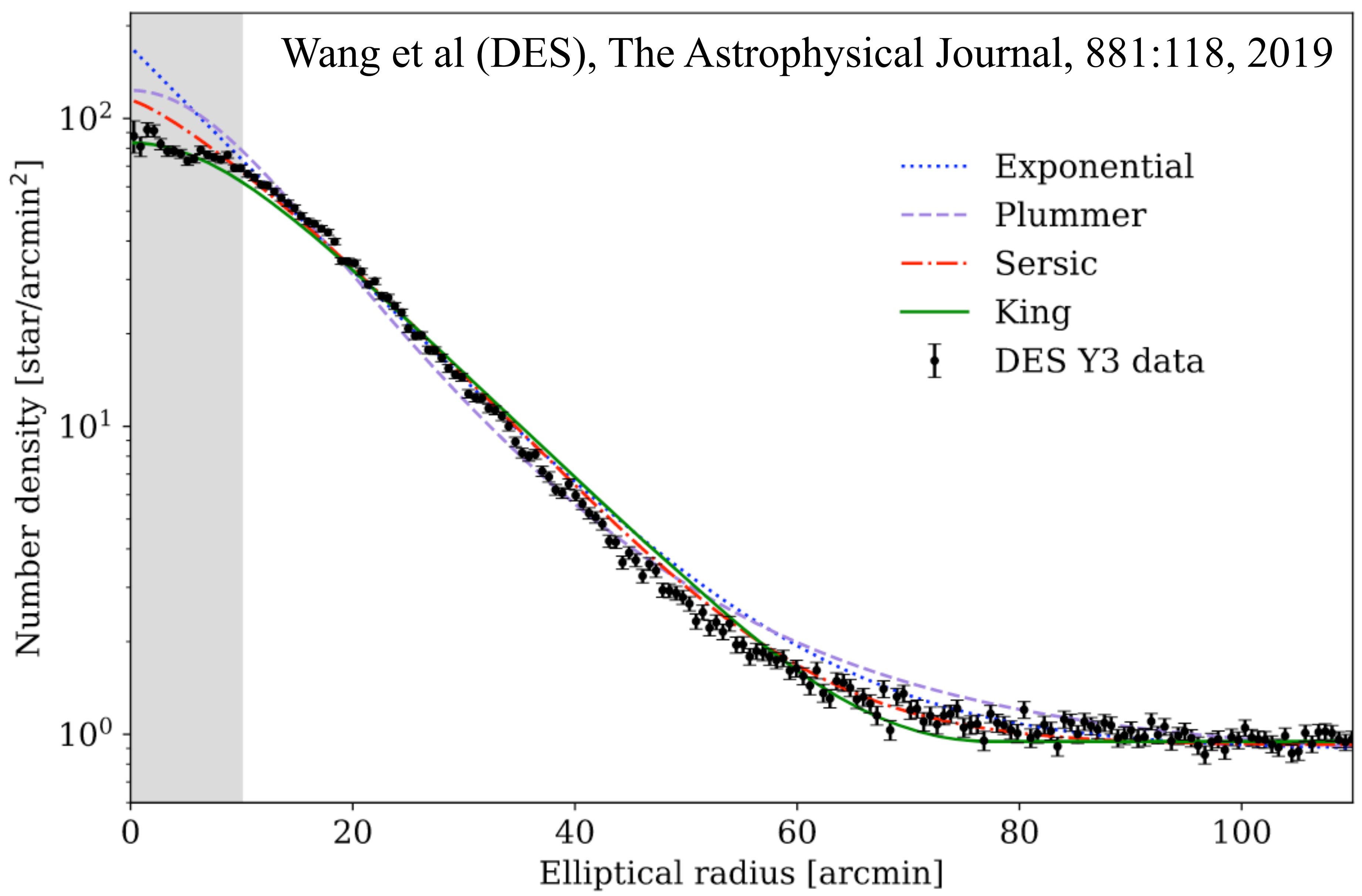




$$\overline{nv_r^2} = \frac{G}{r^{2\beta}} \int_r^\infty dy y^{2\beta-2} n(y) M(y)$$

$$\sigma_{\rm LOS}^2(r) = \frac{2l}{I(r)} \int_r^\infty dy \left(1 - \frac{\beta r^2}{y^2}\right) \frac{y\, \overline{nv_r^2}(y)}{\sqrt{y^2 - r^2}}$$



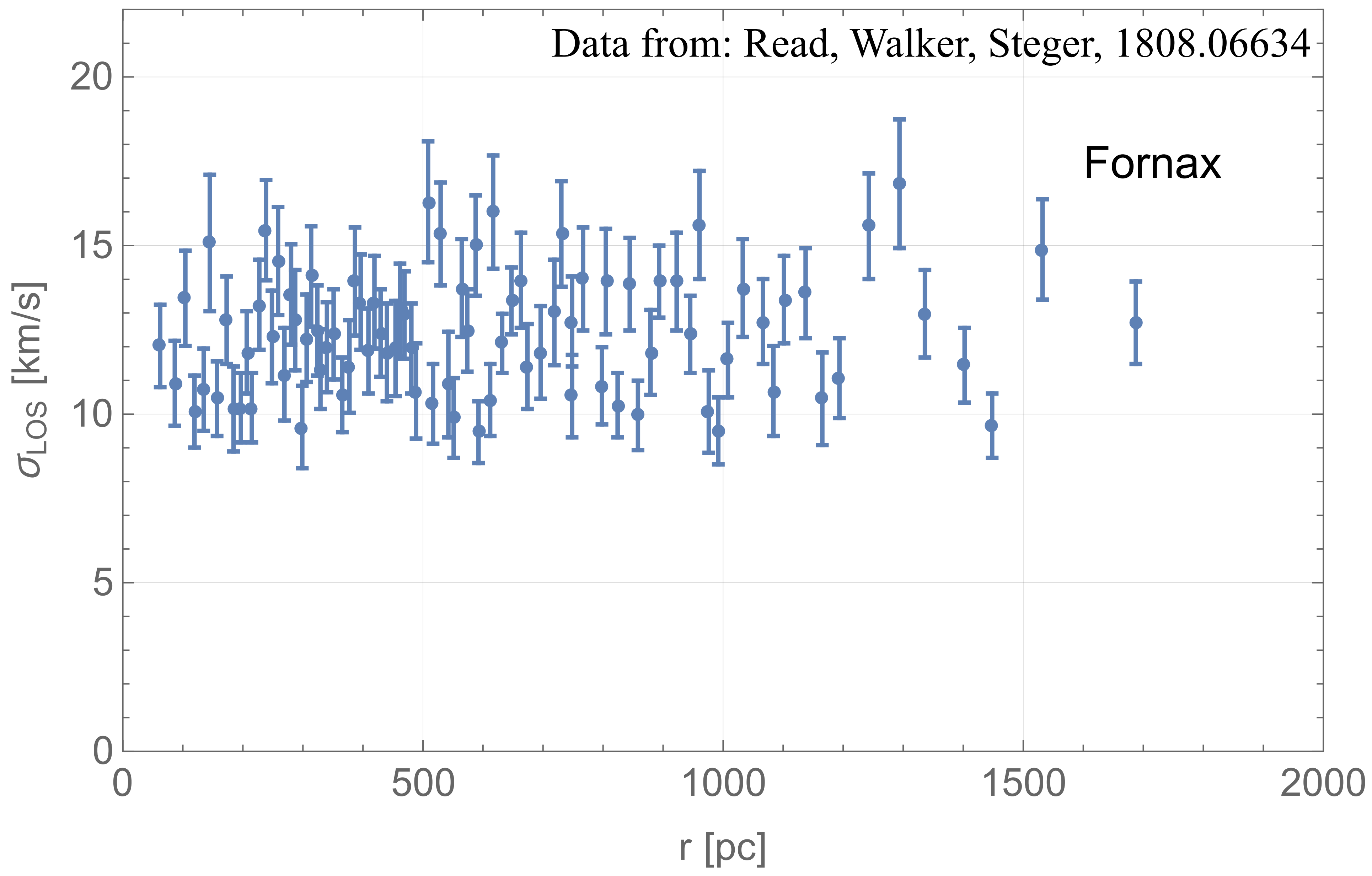


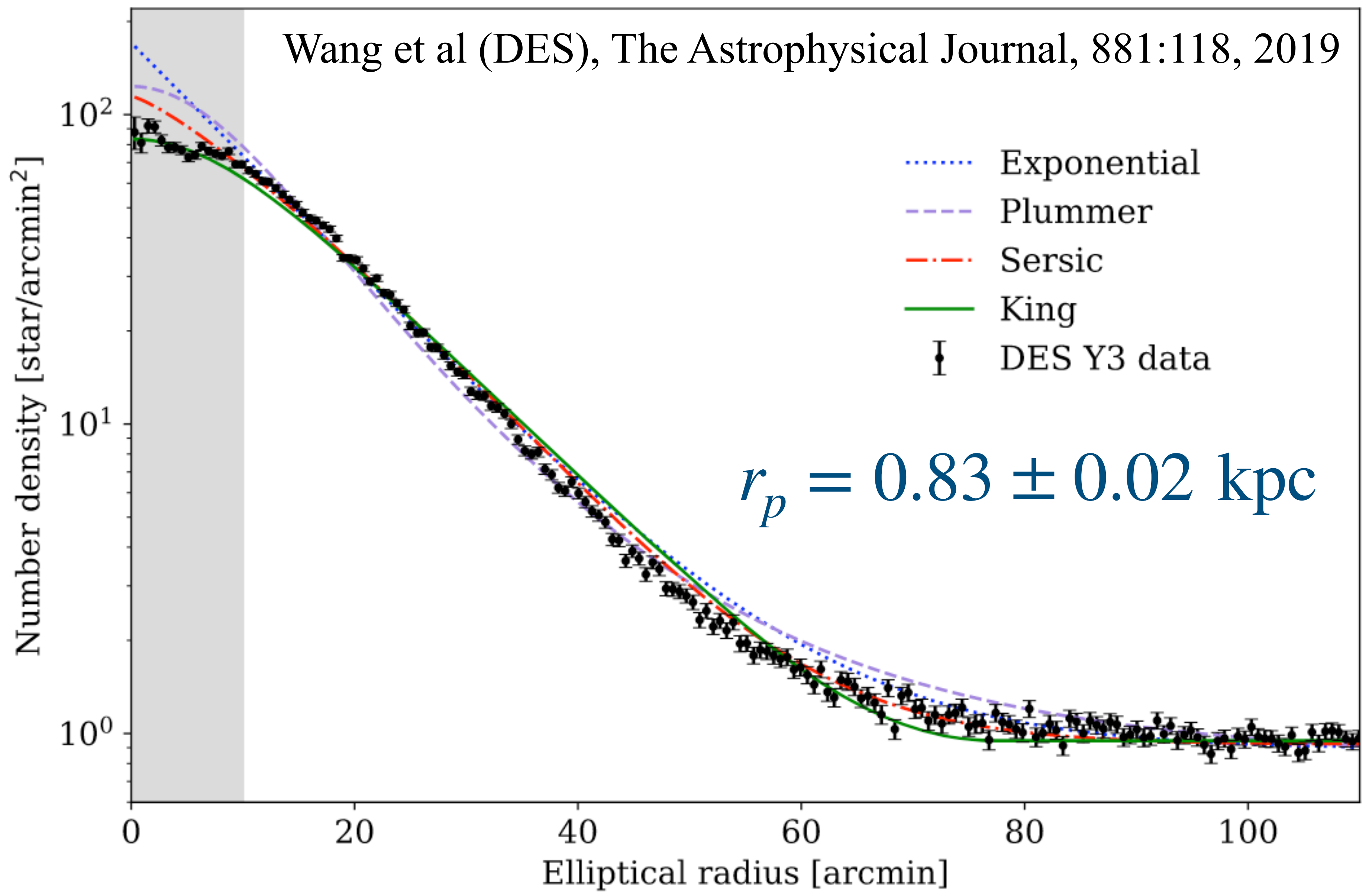
$$\overline{nv_r^2} = \frac{G}{r^{2\beta}} \int_r^\infty dy y^{2\beta-2} n(y) M(y)$$

$$\sigma_{\rm LOS}^2(r) = \frac{2l}{I(r)} \int_r^\infty dy \left(1 - \frac{\beta r^2}{y^2}\right) \frac{y\, \overline{nv_r^2}(y)}{\sqrt{y^2 - r^2}}$$

E.g., Plummer profile:

$$I(r) = \frac{L}{\pi r_p^2 \left(1 + \frac{r^2}{r_p^2}\right)^2} \qquad n(r) = \frac{3(L/l)}{4\pi r_p^3 \left(1 + \frac{r^2}{r_p^2}\right)^{\frac{5}{2}}}$$





$$\overline{nv_r^2} = \frac{G}{r^{2\beta}} \int_r^\infty dy y^{2\beta-2} n(y) M(y)$$

$$\sigma_{\rm LOS}^2(r) = \frac{2l}{I(r)} \int_r^\infty dy \left(1 - \frac{\beta r^2}{y^2}\right) \frac{y\, \overline{nv_r^2}(y)}{\sqrt{y^2 - r^2}}$$

E.g., Navarro-Frenk-White (NFW):

$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

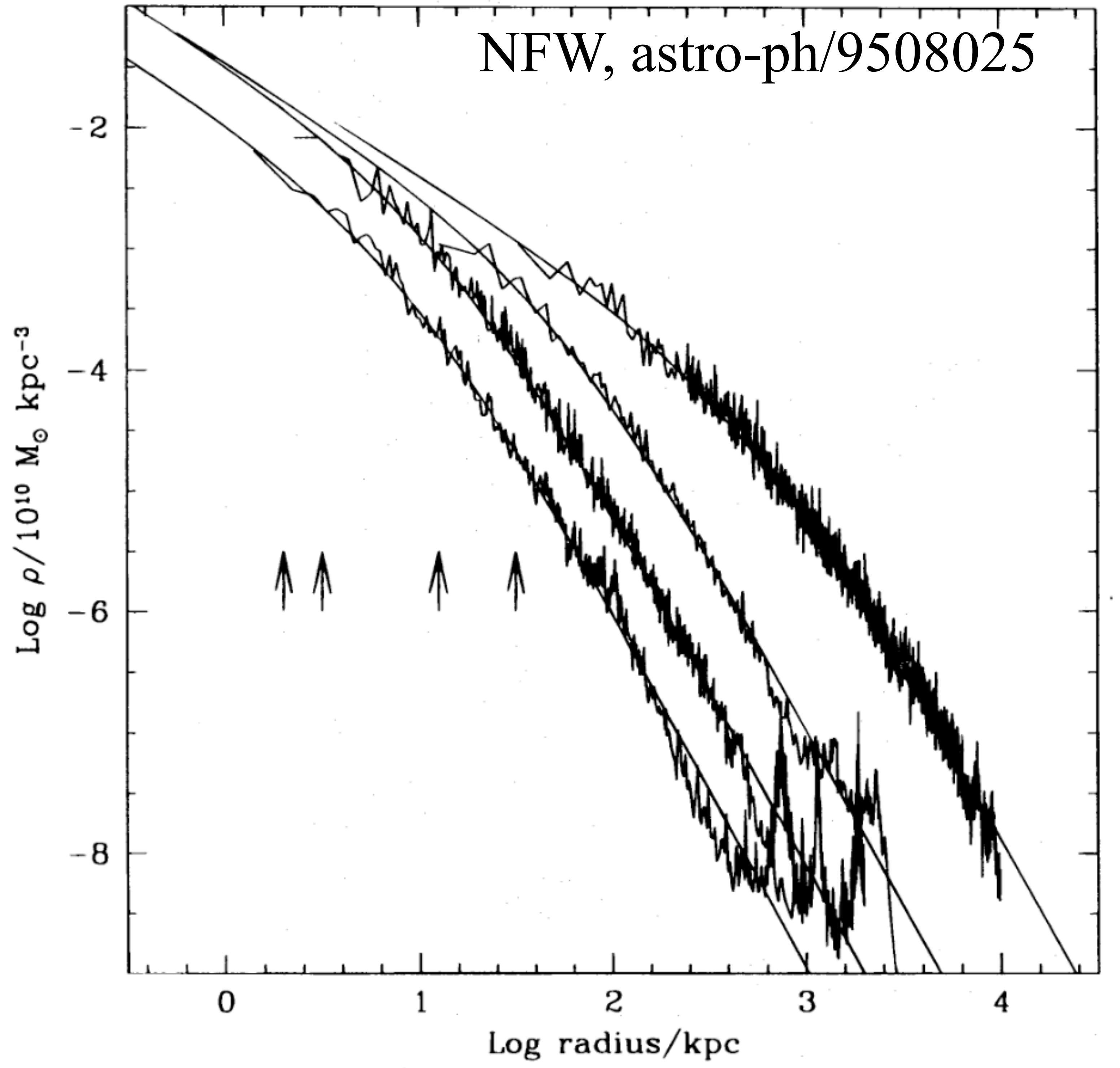
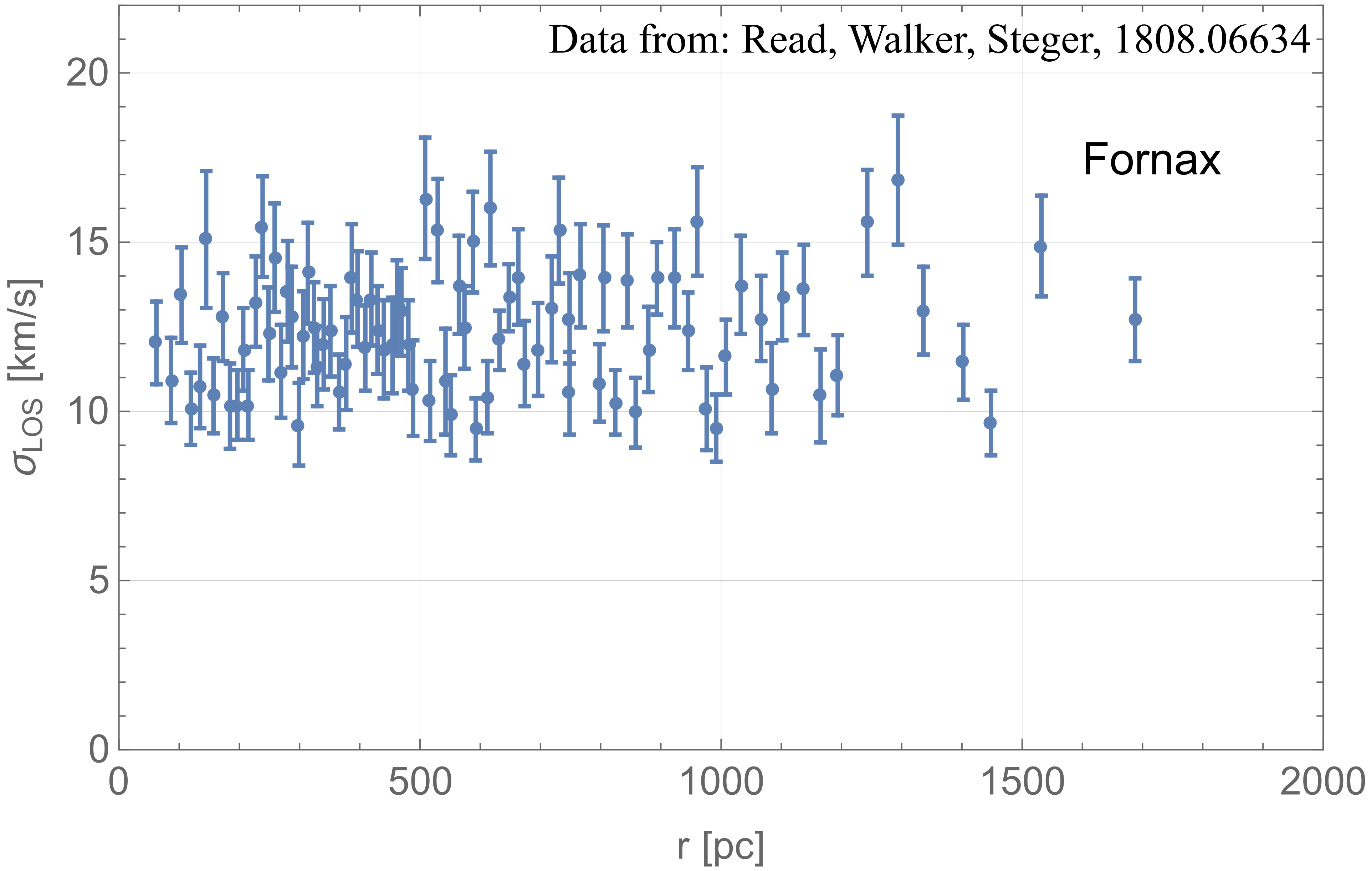


FIG. 3.—Density profiles of four halos spanning 4 orders of magnitude in mass. The arrows indicate the gravitational softening, h_g, of each simulation. Also shown are fits from eq. (3). The fits are good over two decades in radius, approximately from h_g out to the virial radius of each system.



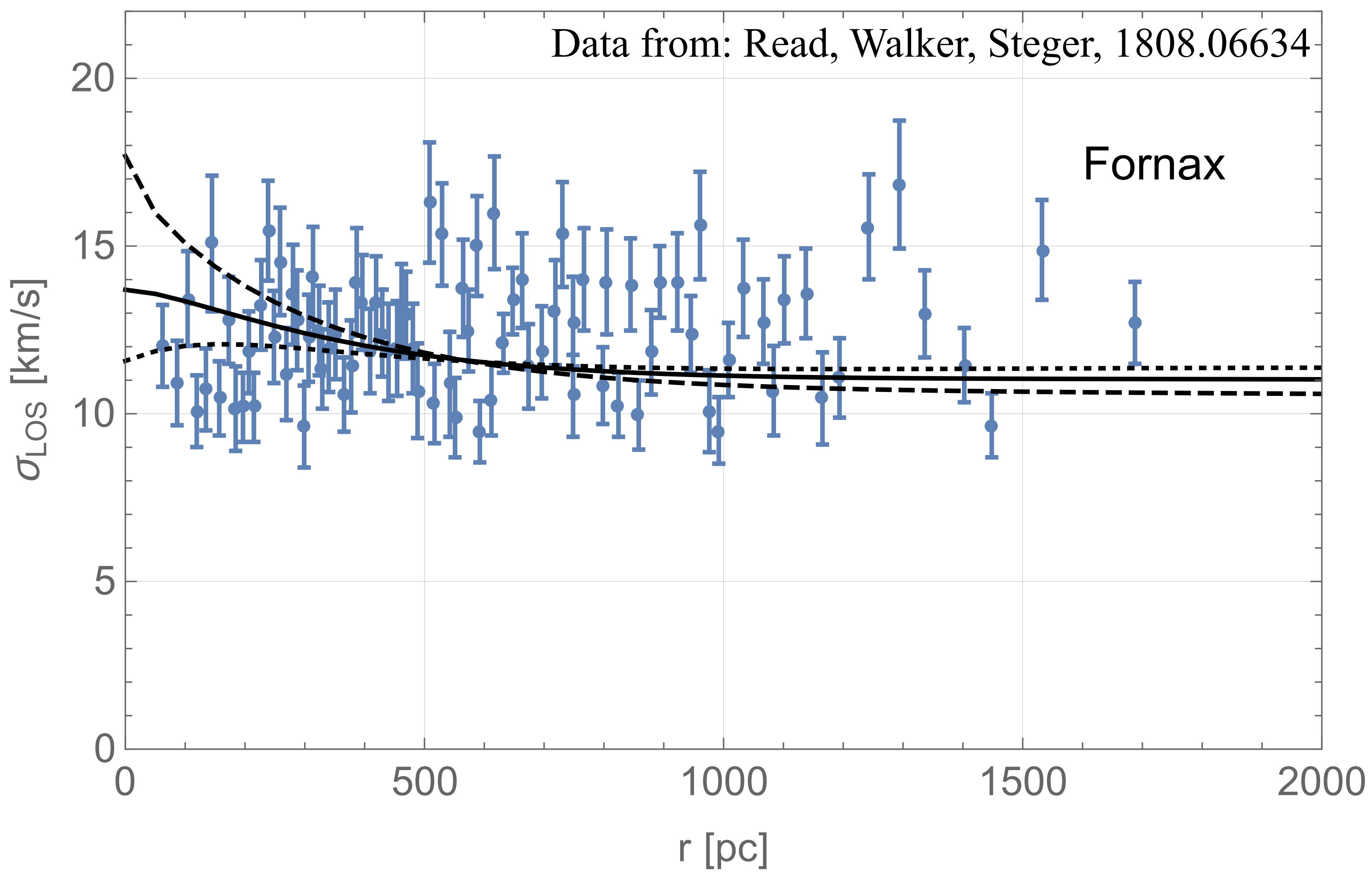
$$\overline{nv_r^2} = \frac{G}{r^{2\beta}} \int_r^\infty dy\, y^{2\beta-2} n(y) M(y)$$

$$\sigma_{\rm LOS}^2(r) = \frac{2l}{I(r)} \int_r^\infty dy \left(1 - \frac{\beta r^2}{y^2}\right) \frac{y\, \overline{nv_r^2}(y)}{\sqrt{y^2 - r^2}}$$

E.g., Navarro-Frenk-White (NFW):

$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2} \qquad r_s = 2\ \text{kpc},\ \ \rho_s = 1.2 \times 10^7\ \frac{\text{M}_\odot}{\text{kpc}^3}$$

$$M(r) = 4\pi \rho_s r_s^3 \left(\ln\left(1 + \frac{r}{r_s}\right) - \frac{r}{r + r_s}\right)$$



$$\overline{nv_r^2} = \frac{G}{r^{2\beta}} \int_r^\infty dy\, y^{2\beta-2} n(y) M(y)$$

$$\sigma_{\rm LOS}^2(r) = \frac{2l}{I(r)} \int_r^\infty dy \left(1 - \frac{\beta r^2}{y^2}\right) \frac{y\, \overline{nv_r^2}(y)}{\sqrt{y^2 - r^2}}$$

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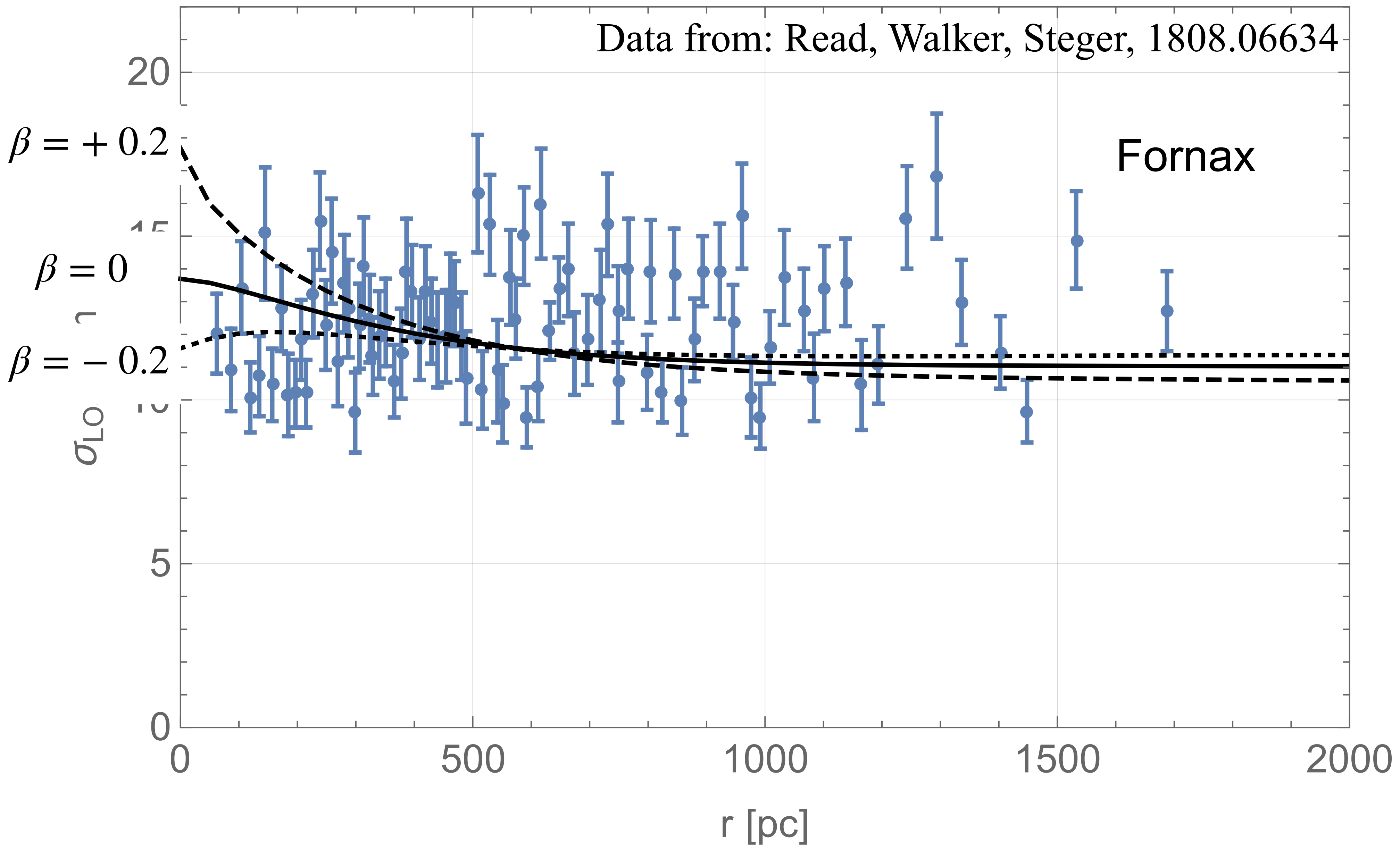
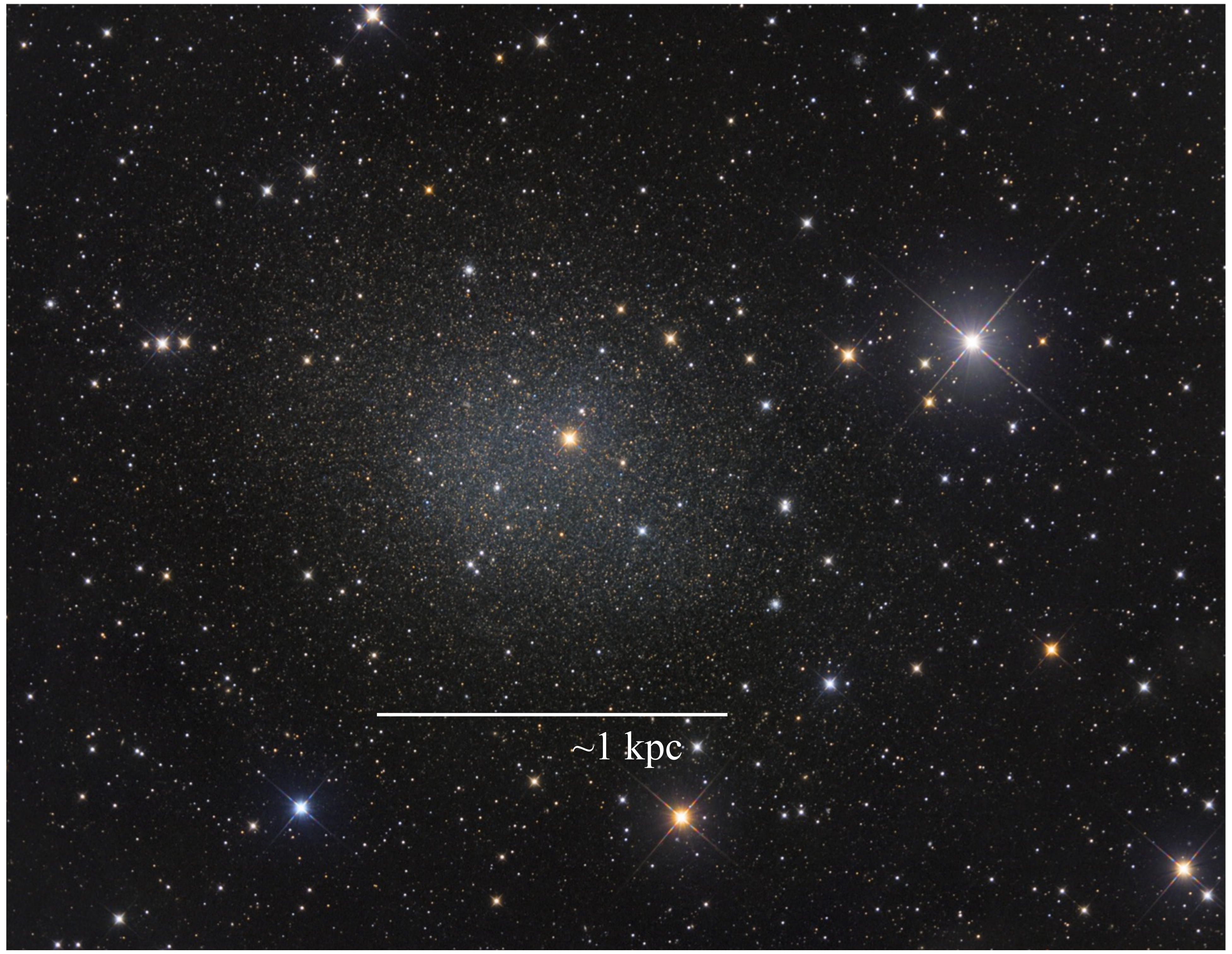
$$M(r) = 4\pi \rho_s r_s^3 \left(\ln\left(1 + \frac{r}{r_s}\right) - \frac{r}{r + r_s} \right)$$





$$\overline{nv_r^2} = \frac{G}{r^{2\beta}} \int_r^\infty dy y^{2\beta-2} n(y) M(y)$$

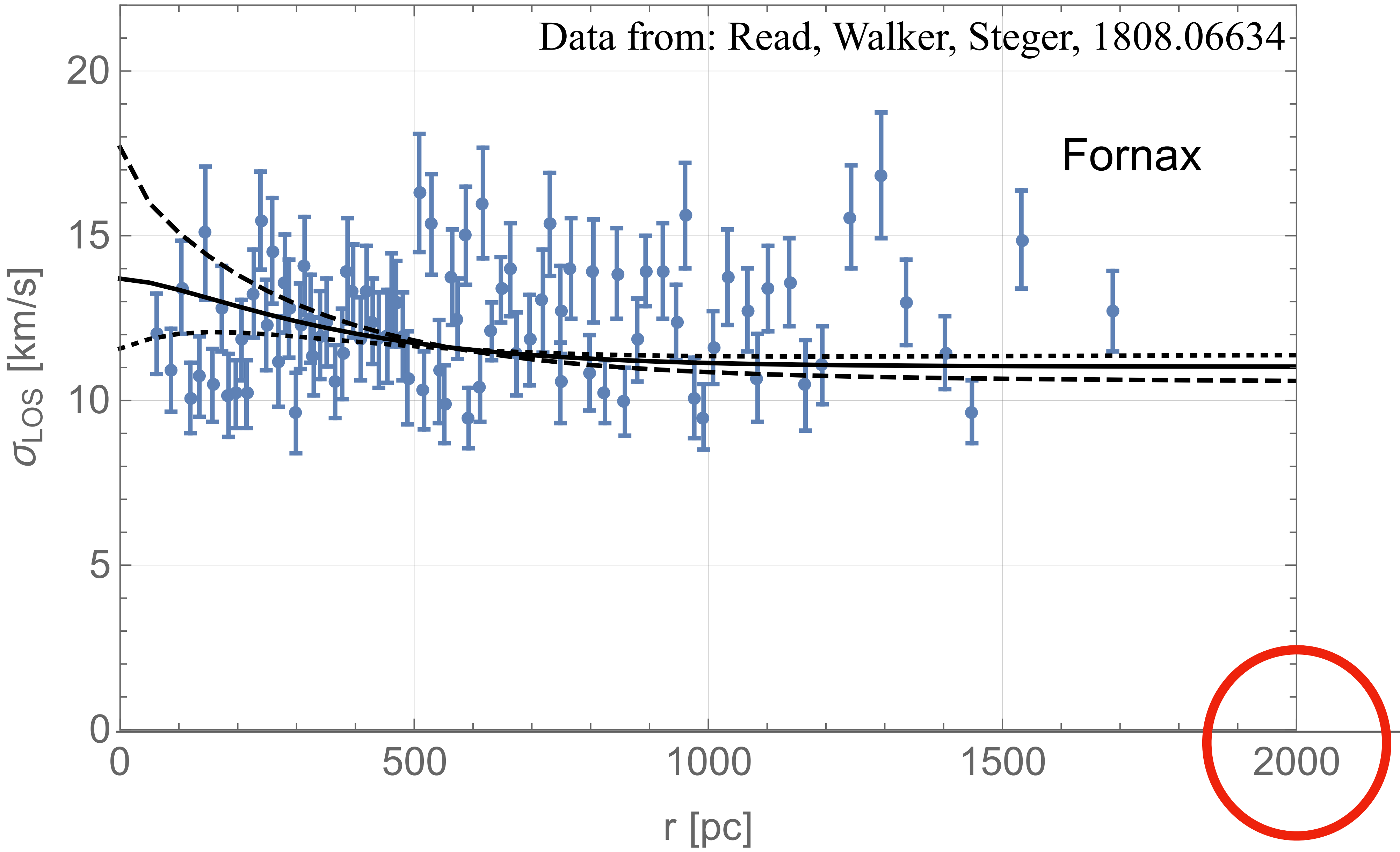
$$\sigma_{LOS}^2(r) = \frac{2l}{I(r)} \int_r^\infty dy \left(1 - \frac{\beta r^2}{y^2}\right) \frac{y\, \overline{nv_r^2}(y)}{\sqrt{y^2 - r^2}}$$

E.g., Navarro-Frenk-White (NFW):

$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2} \qquad r_s = 2\ \text{kpc},\ \ \rho_s = 1.2 \times 10^7\ \frac{\text{M}_\odot}{\text{kpc}^3}$$

$$M(r) = 4\pi\rho_s r_s^3 \left(\ln\left(1 + \frac{r}{r_s}\right) - \frac{r}{r + r_s}\right)$$

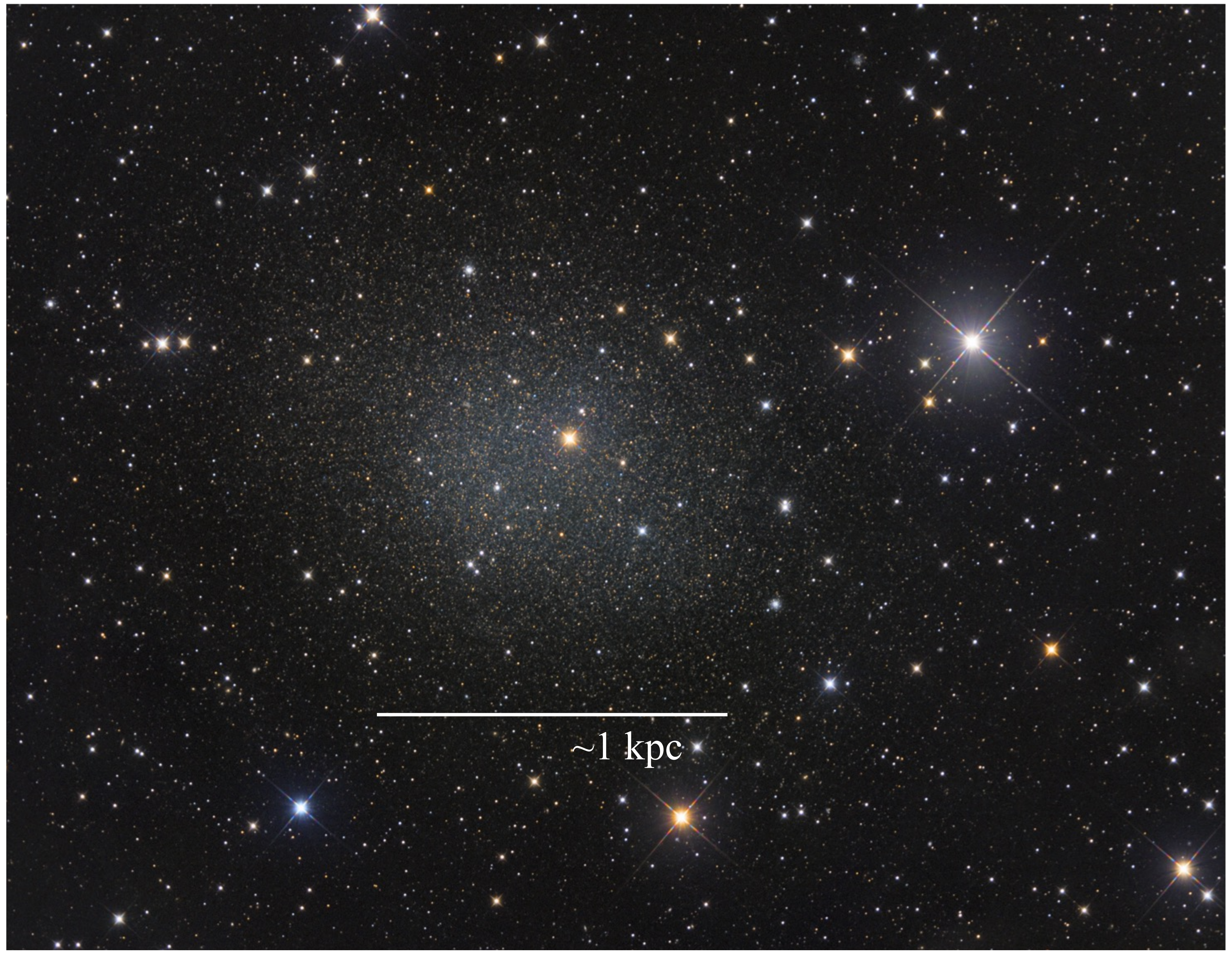
$$R_{200} \approx r_s \left(\frac{\rho_s}{200\rho_c}\right)^{\frac{1}{3}} \approx 16\ \text{kpc},\ M_{200} \approx 1.6 \times 10^9\ \text{M}_\odot$$

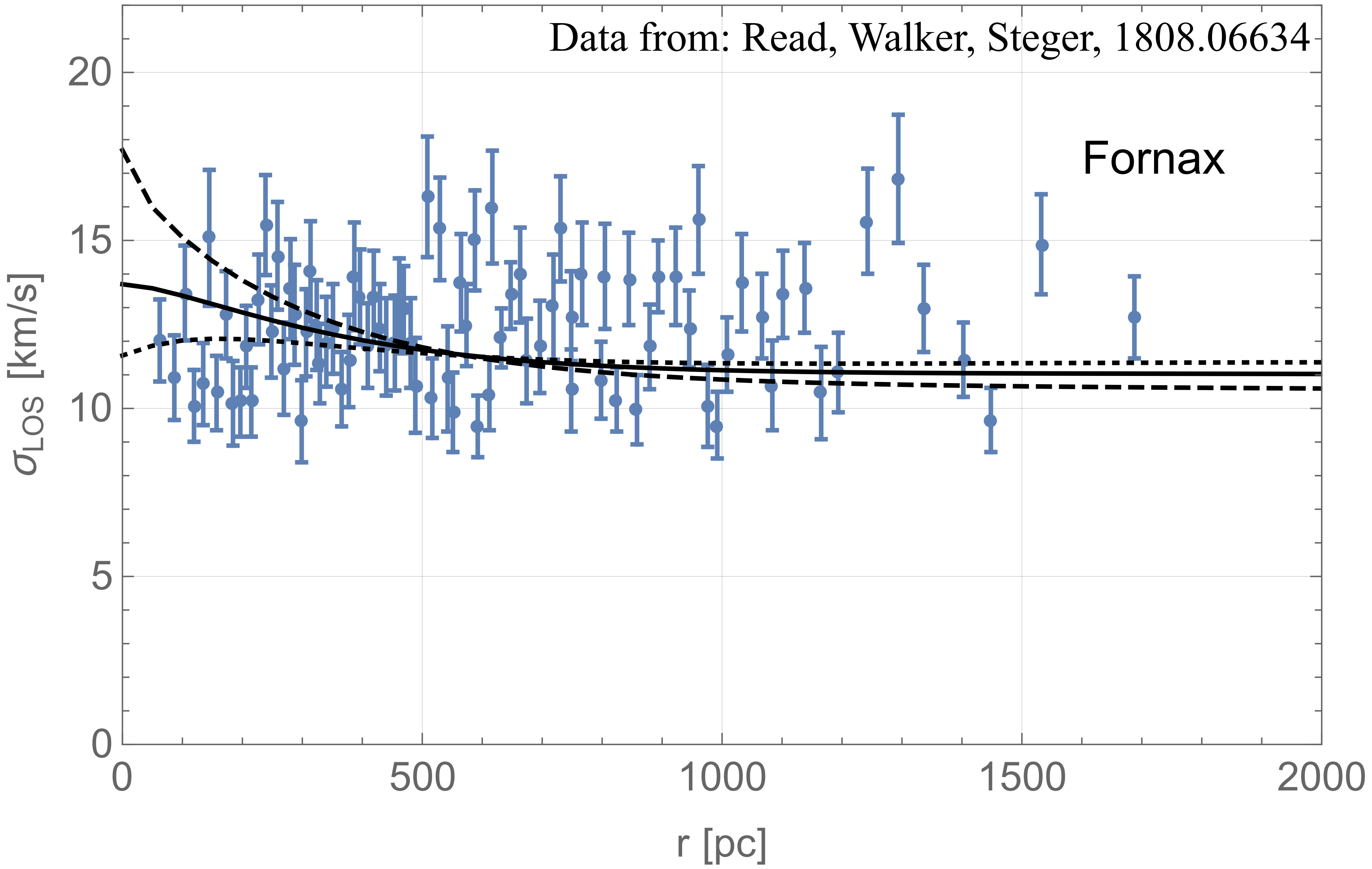


$$M(2\ \text{kpc}) \approx 2.3 \times 10^8\ \text{M}_\odot$$

//

16000





de Boer et al (A&A 544, A73 (2012)) — stellar population synthesis:

Total stellar mass $M_* \approx 4.3 \times 10^7 \ \mathrm{M}_\odot$

This means:

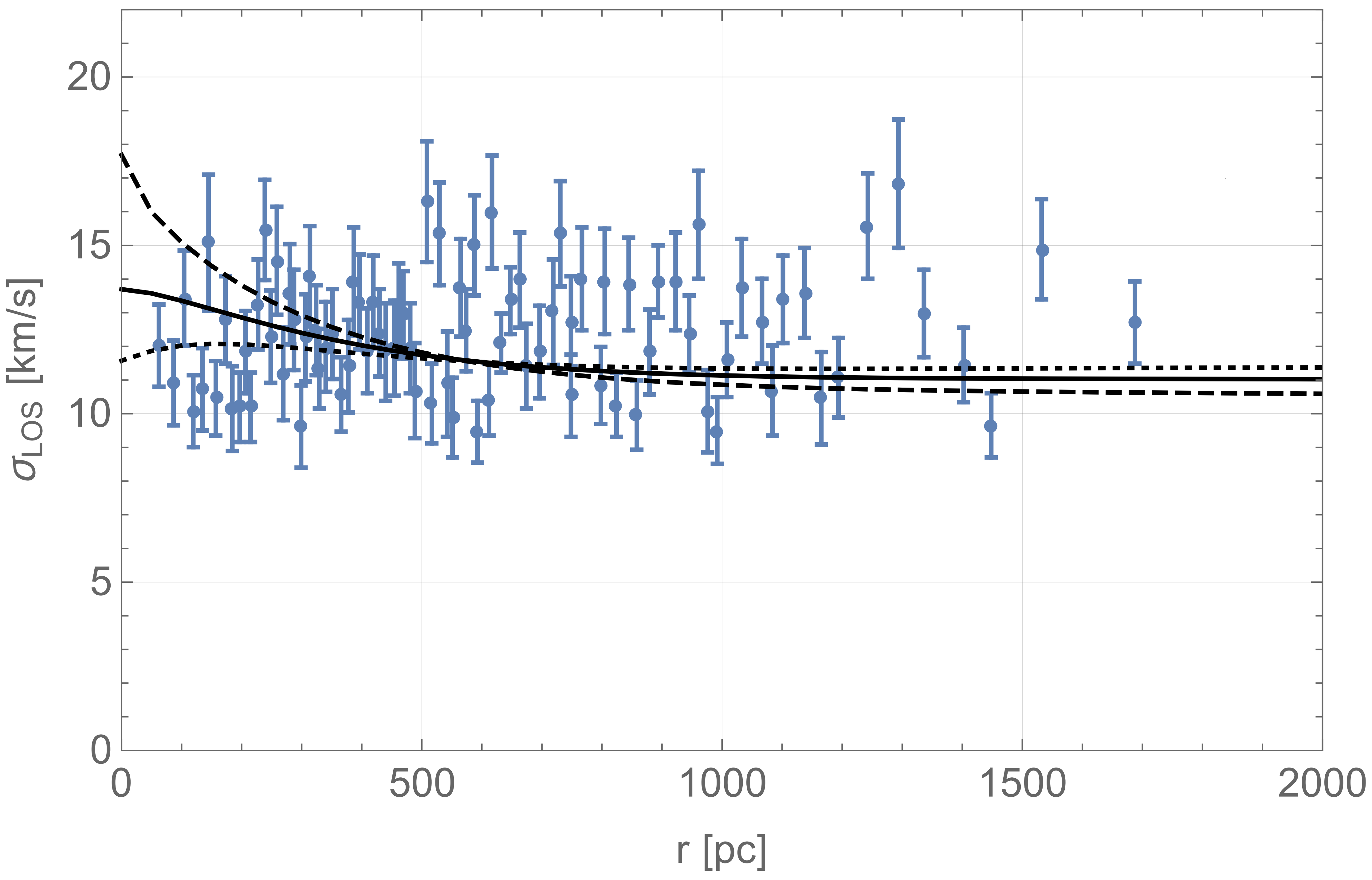
$$\frac{M(r_s \approx 2 \text{ kpc})}{M_*} \approx 5.3$$

$$\frac{M(R_{200} \approx 16 \text{ kpc})}{M_*} \approx 37$$

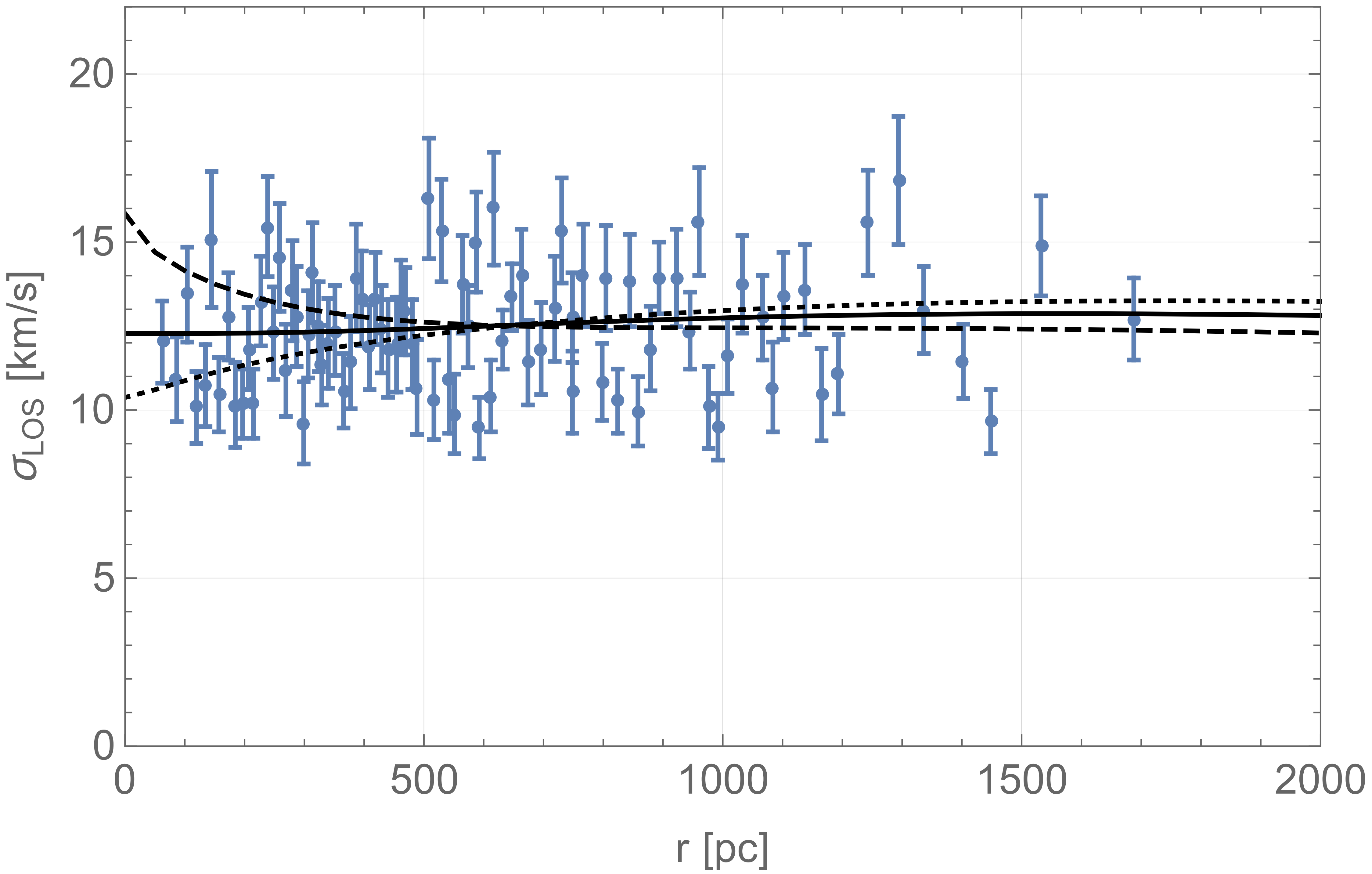
core / cusp

McGaugh et al 2001,
Gored et al 2006,
de Blok 2010,
Teyssier et al 2013,
Del Popolo & Face 2015,
Bullock & Boylan-Kolchin, 2017,
Meadows et al, 2019,
Santos-Santos et al 2020,…

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

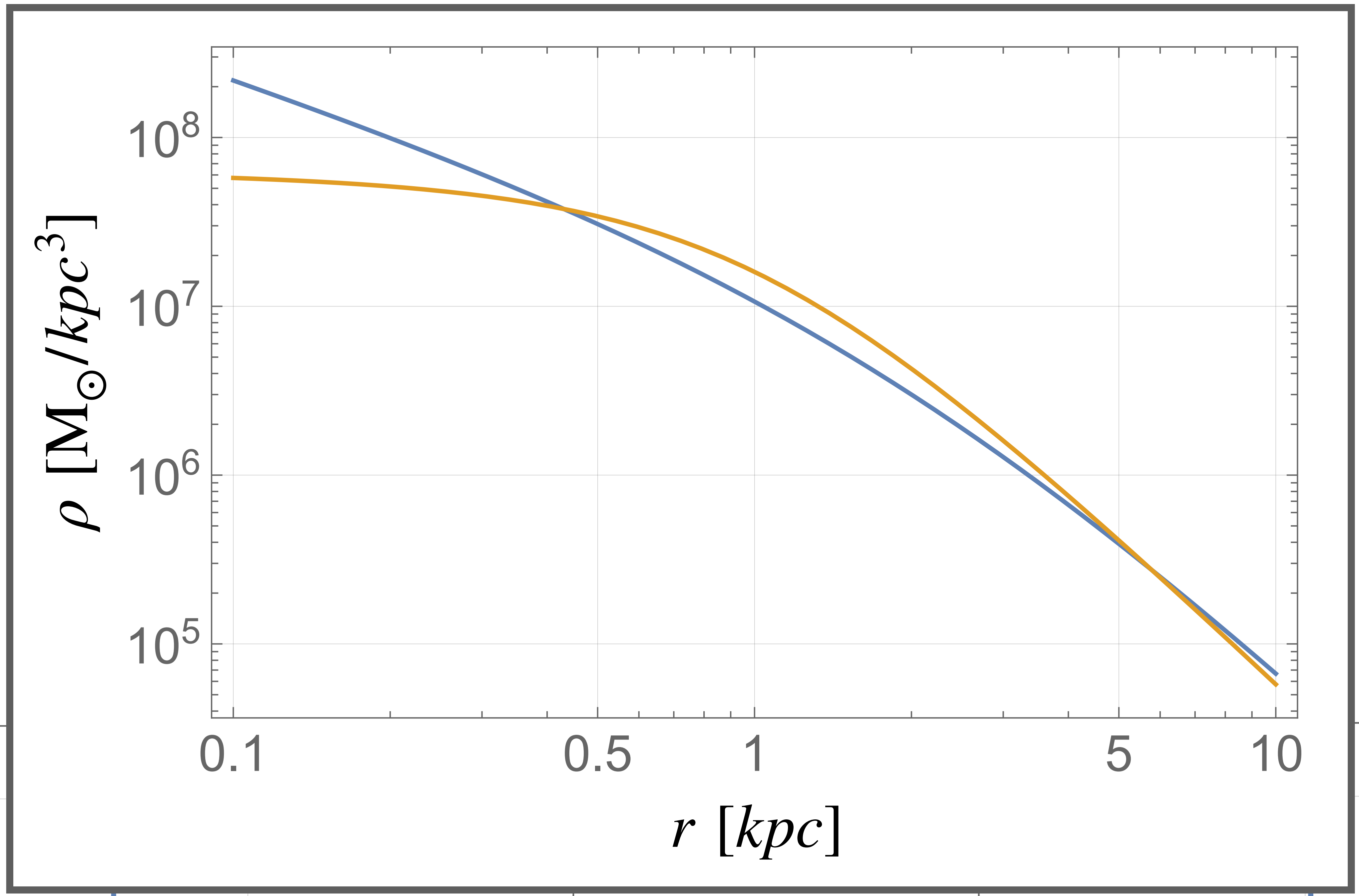


$$\rho_{\rm Burkert} = \frac{\rho_0}{\left(1+\frac{r}{r_0}\right)\left(1+\frac{r^2}{r_0^2}\right)}$$

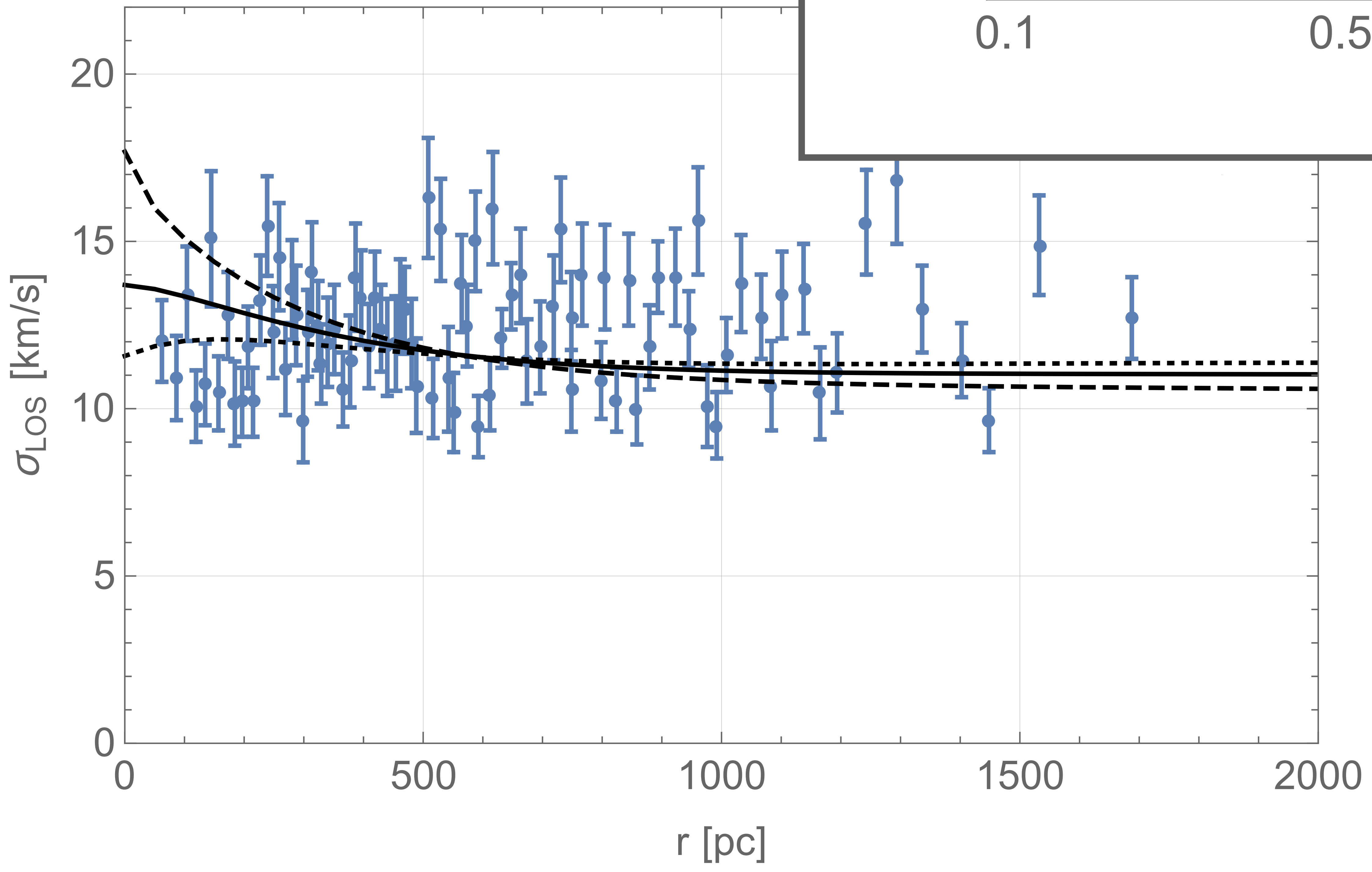


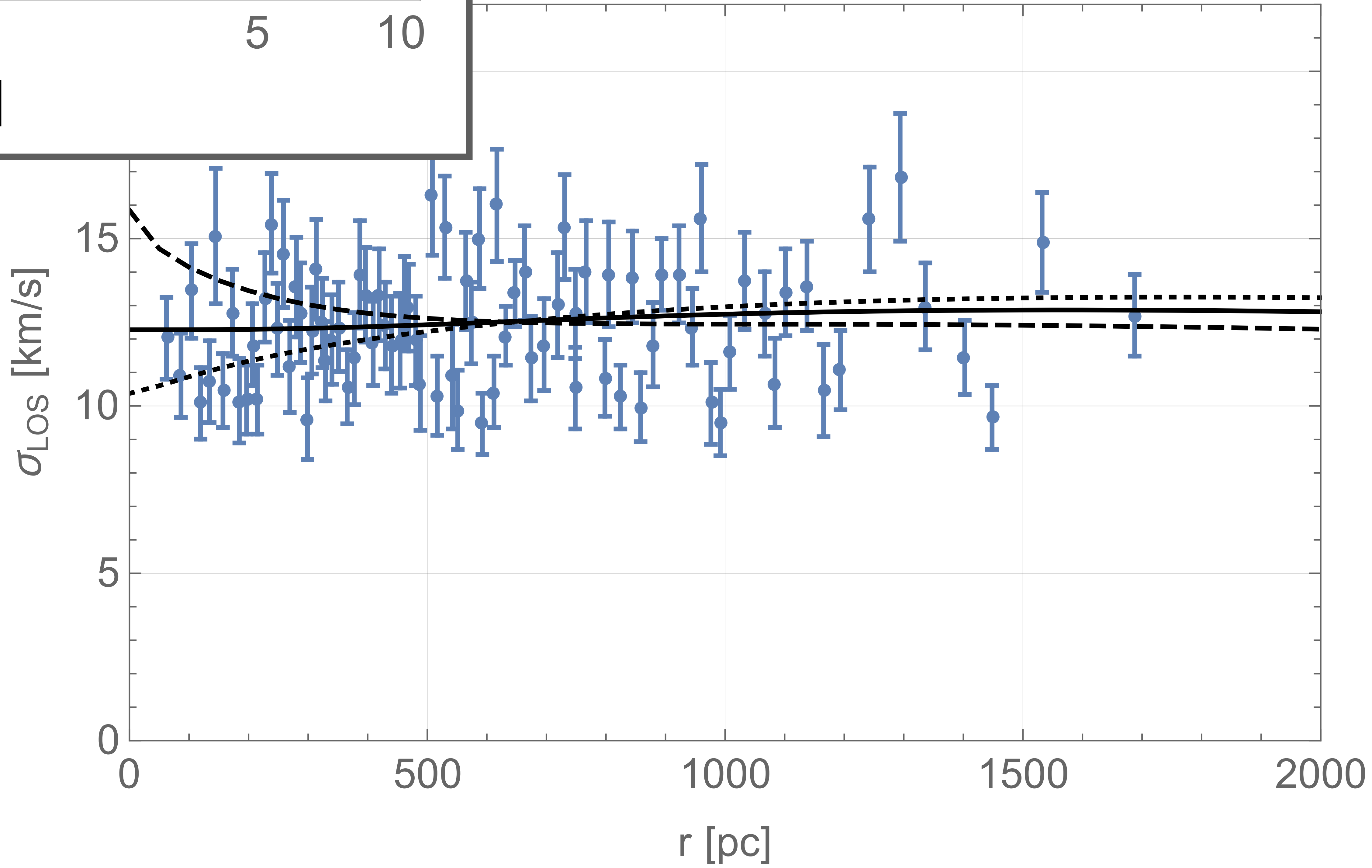
core / cusp

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

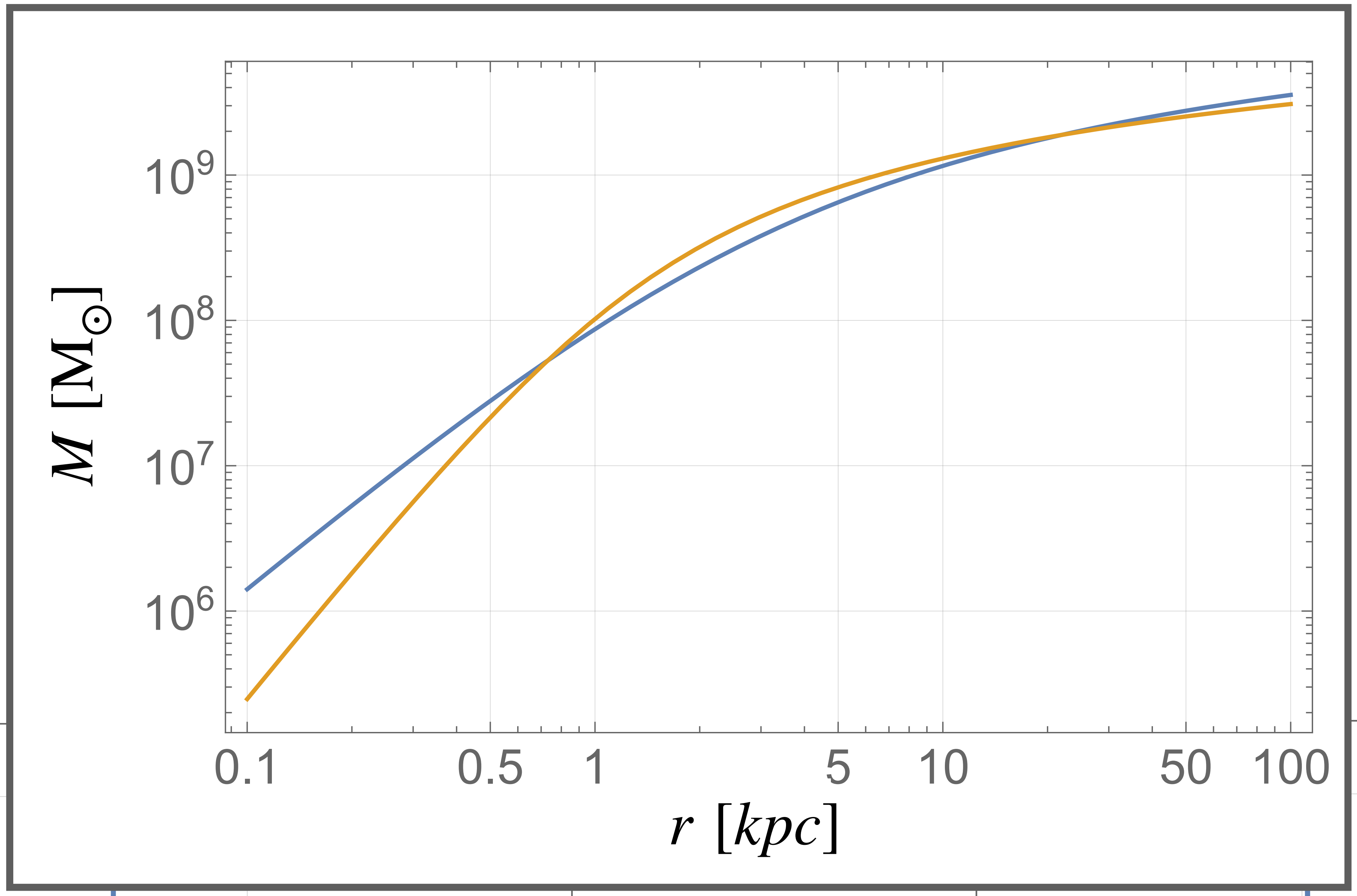


$$\rho_{\mathrm{Burkert}} = \frac{\rho_0}{\left(1+\frac{r}{r_0}\right)\left(1+\frac{r^2}{r_0^2}\right)}$$

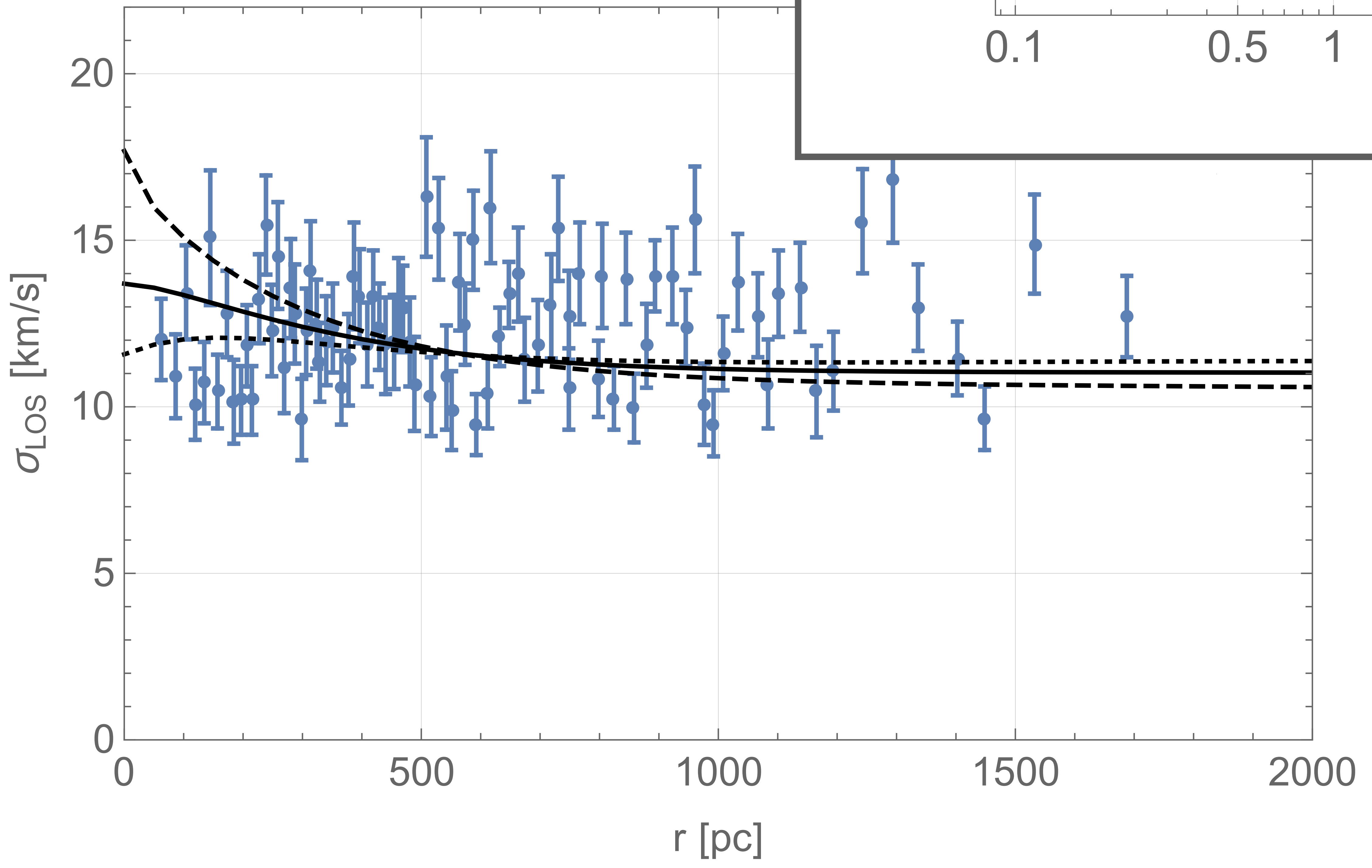




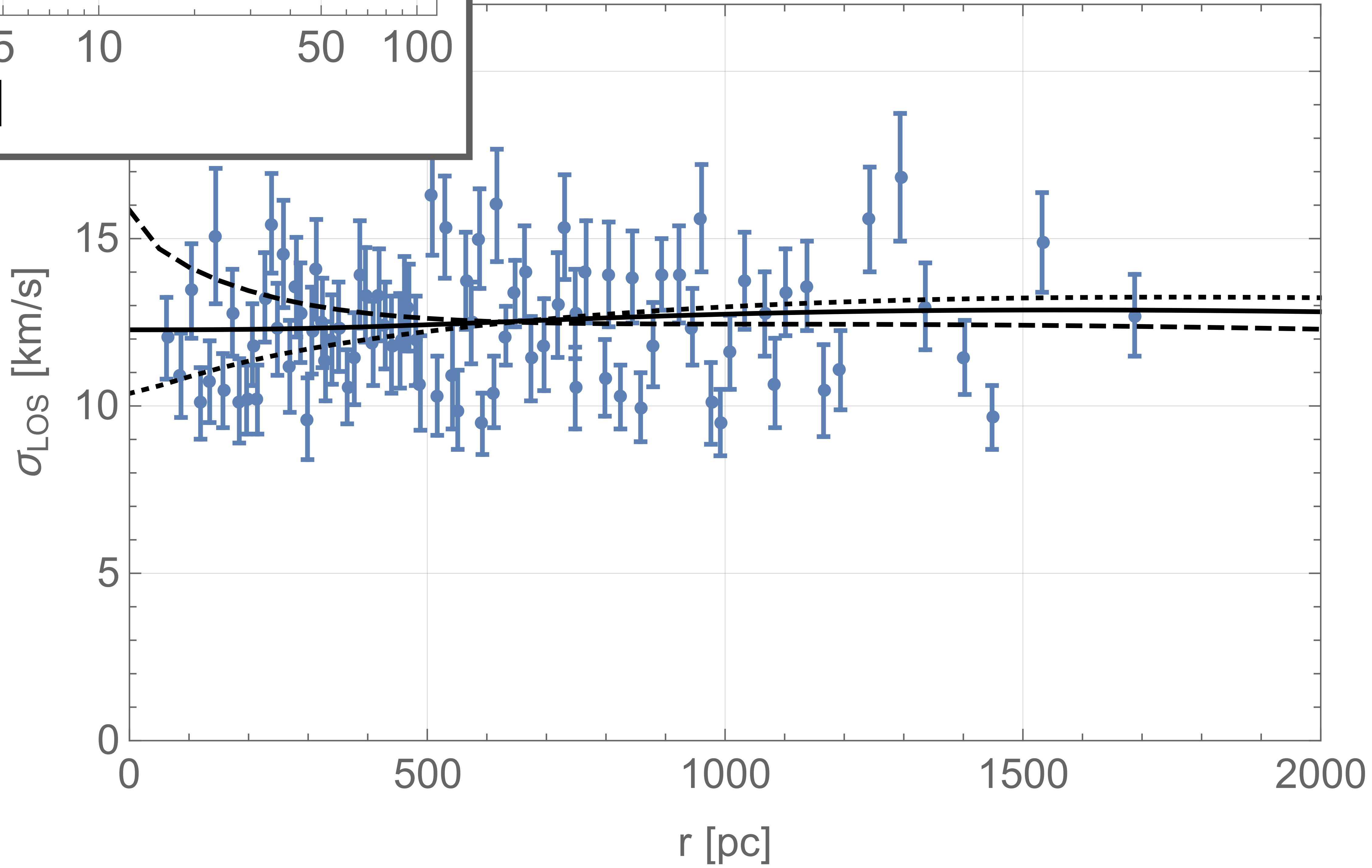
core / cusp

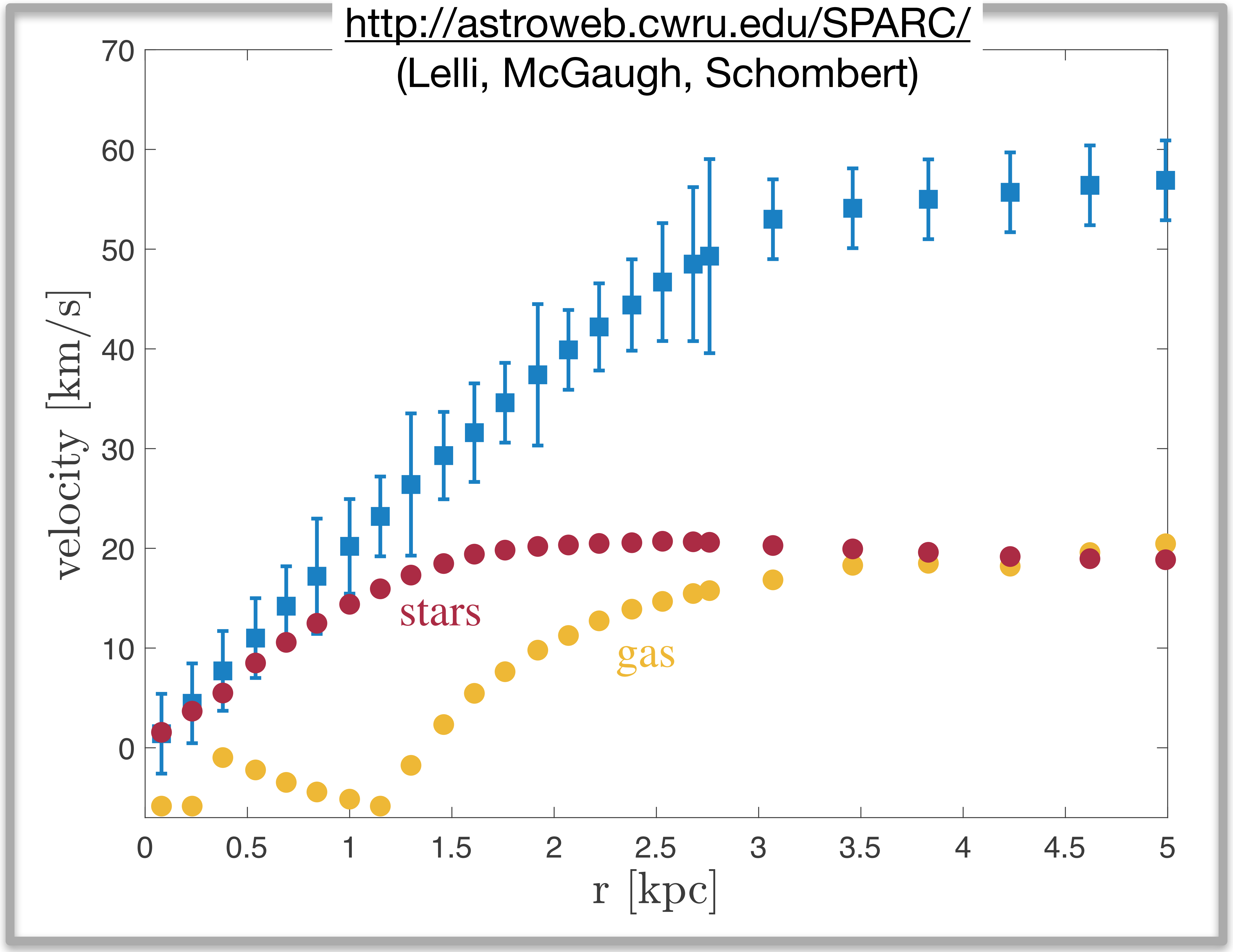


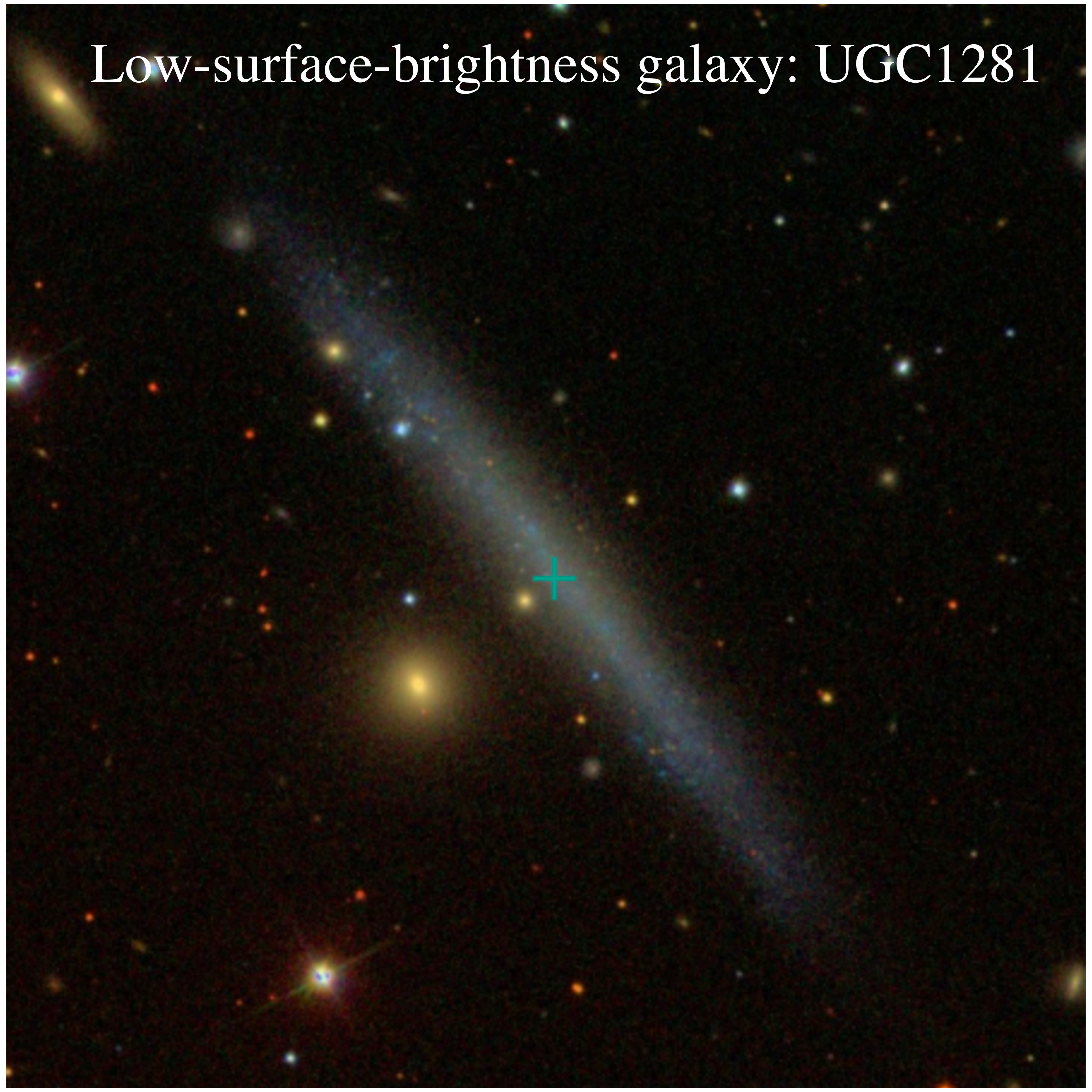
$$\rho_{\mathrm{NFW}} = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

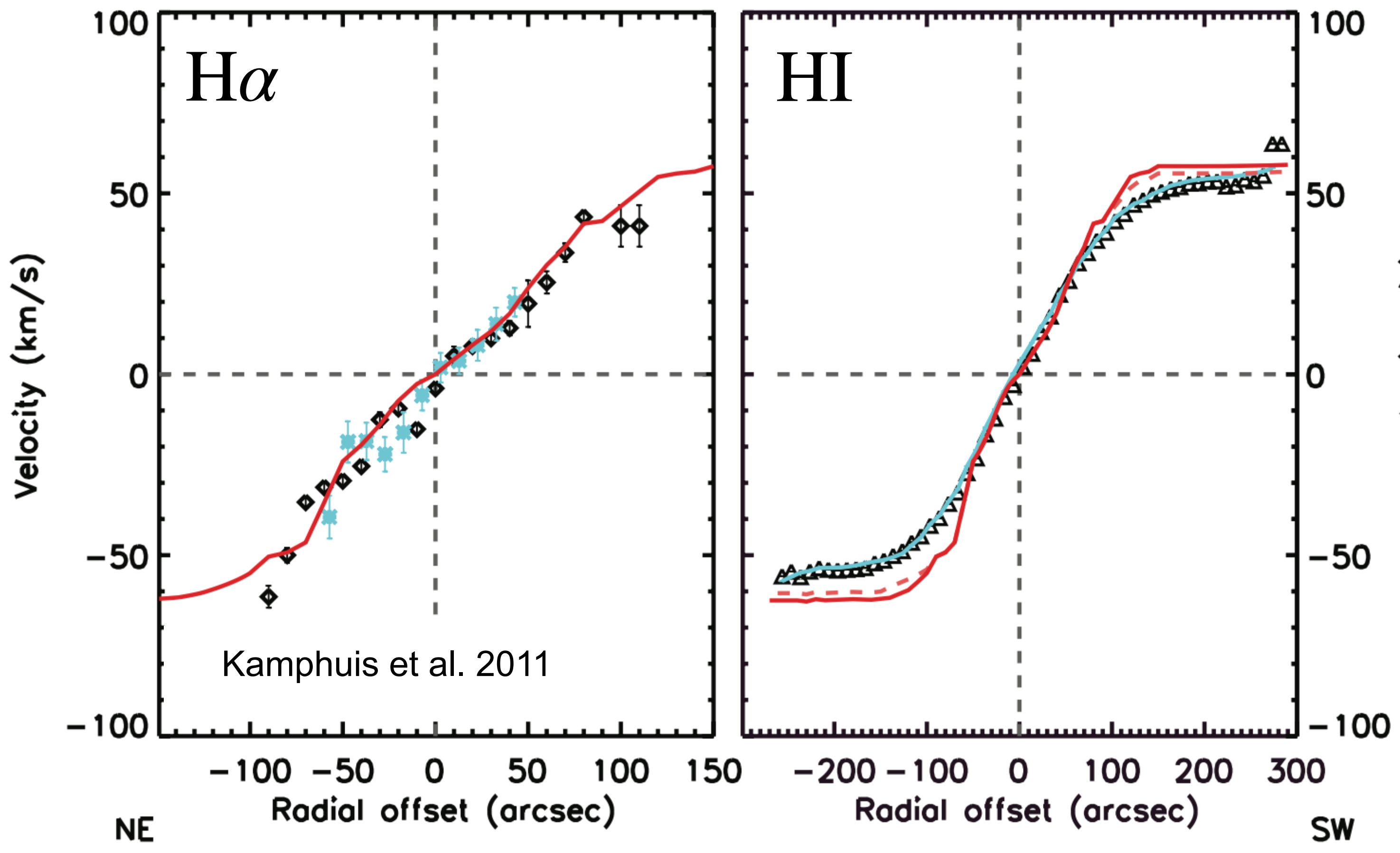


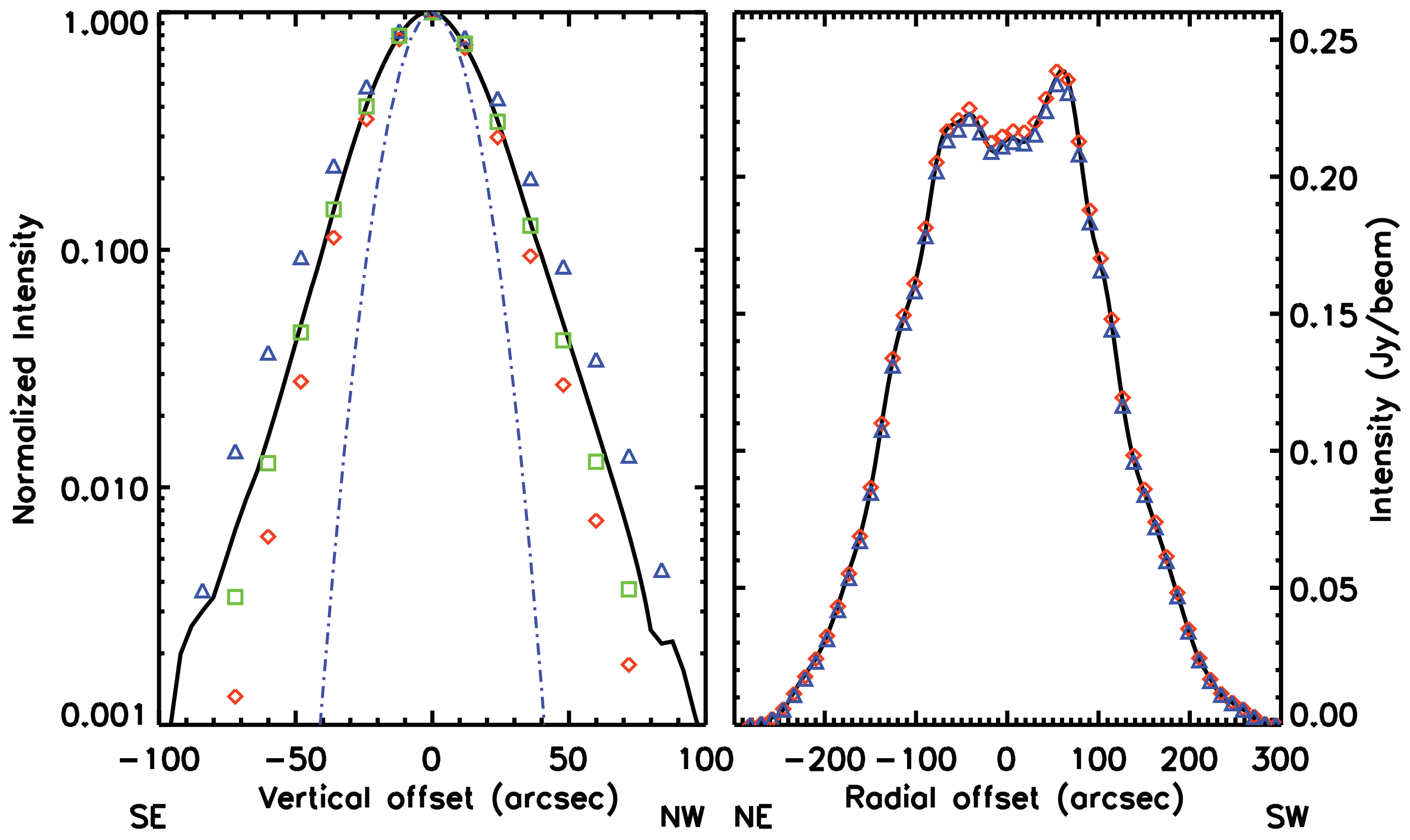
$$\rho_{\mathrm{Burkert}} = \frac{\rho_0}{\left(1 + \frac{r}{r_0}\right)\left(1 + \frac{r^2}{r_0^2}\right)}$$

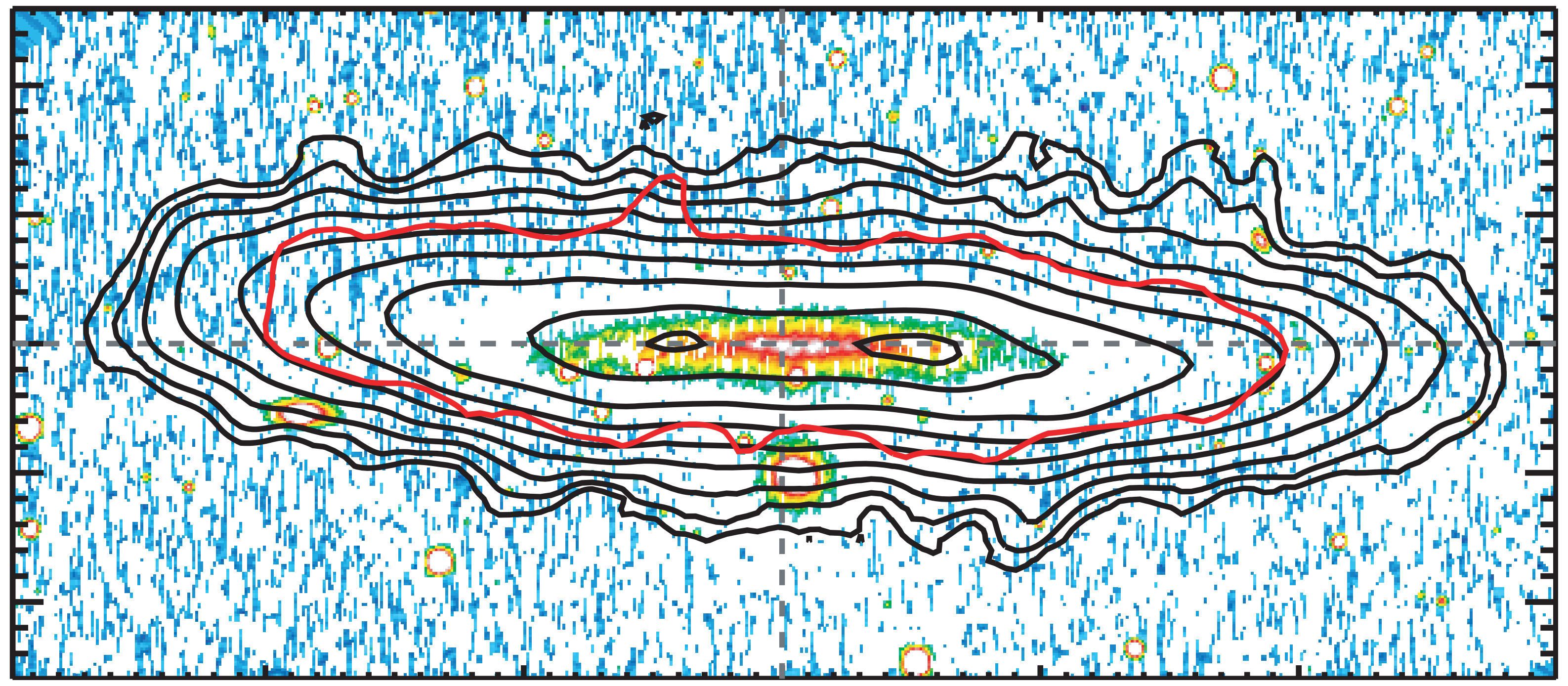


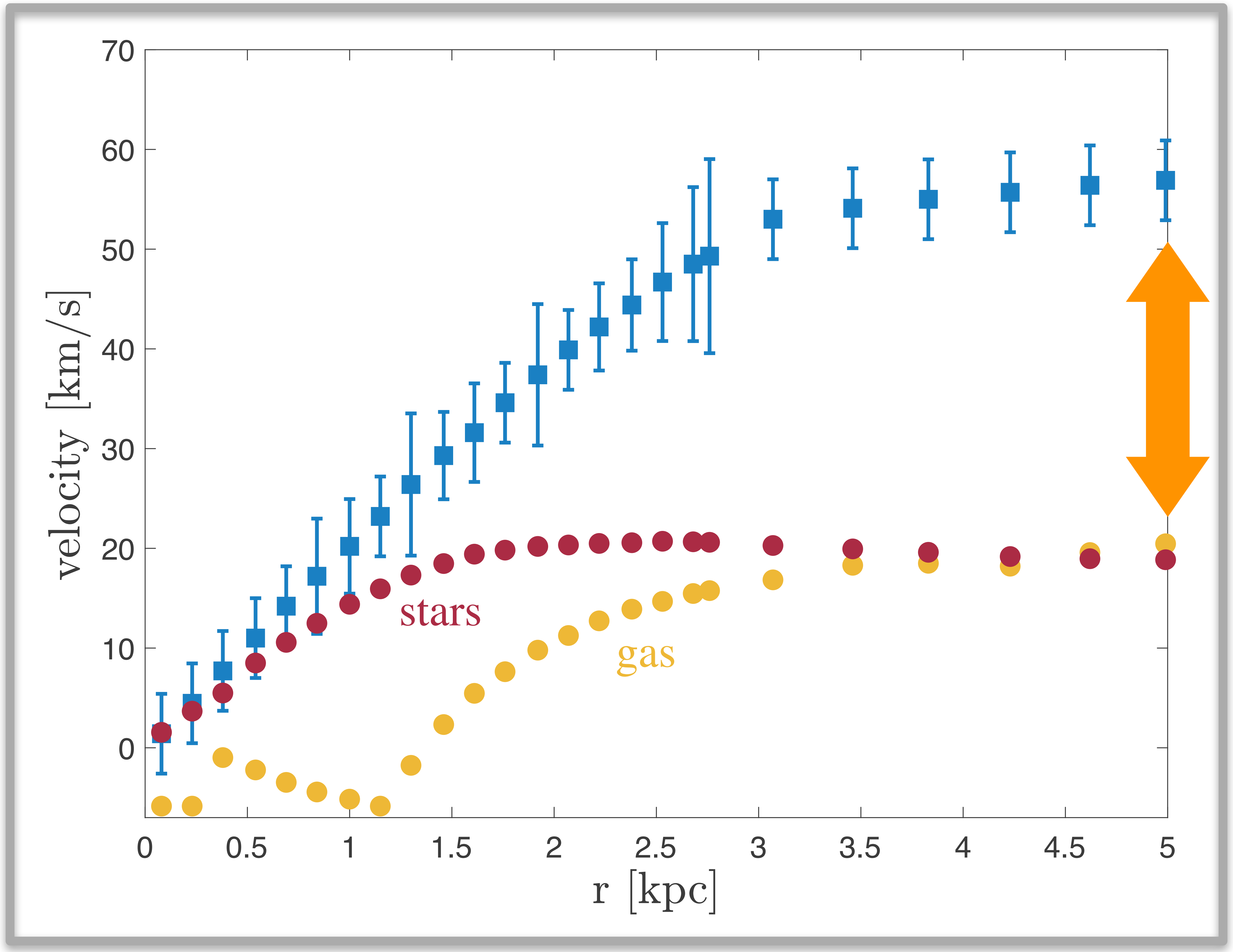

http://astroweb.cwru.edu/SPARC/
(Lelli, McGaugh, Schombert)
velocity [km/s]
r [kpc]
stars
gas
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

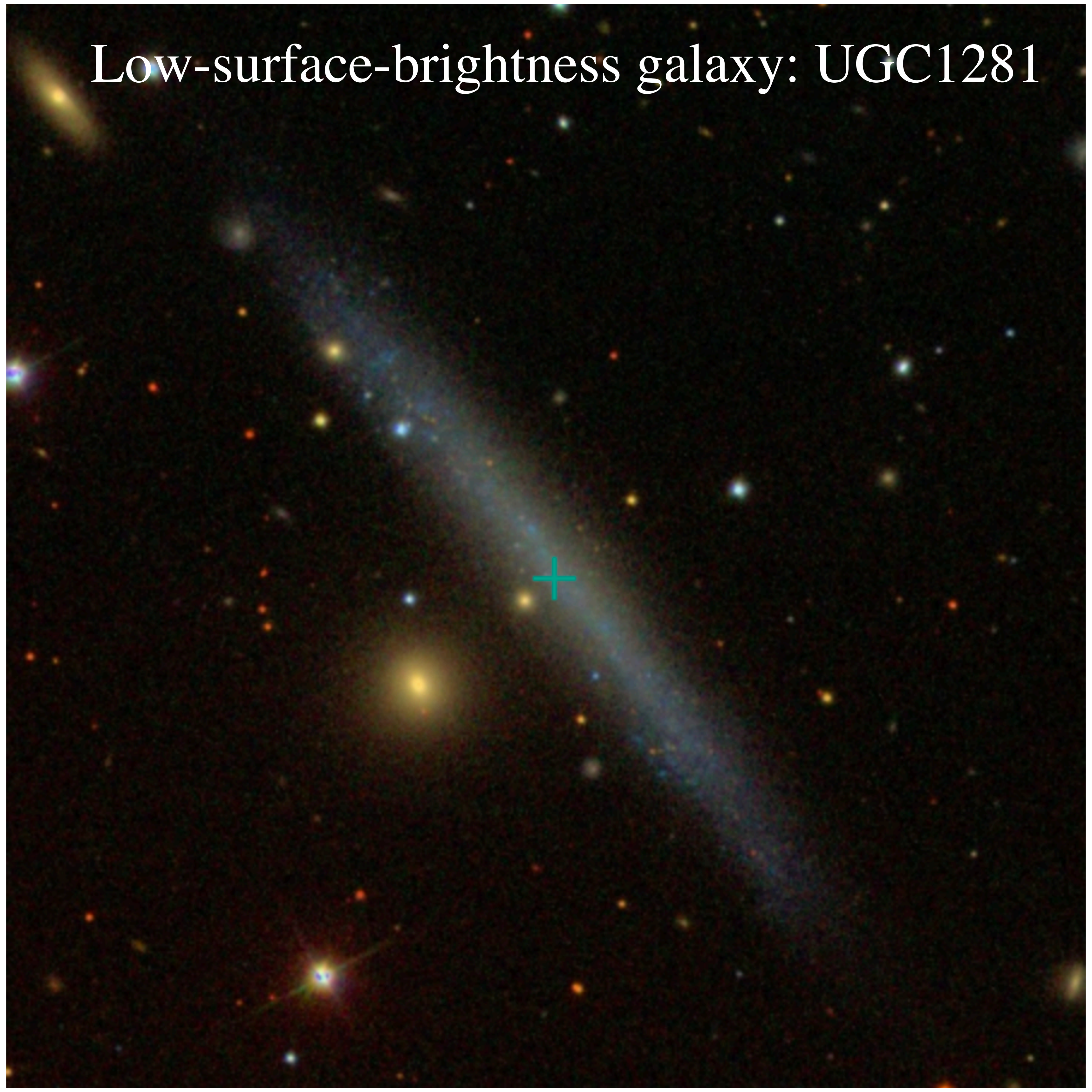

Low-surface-brightness galaxy: UGC1281

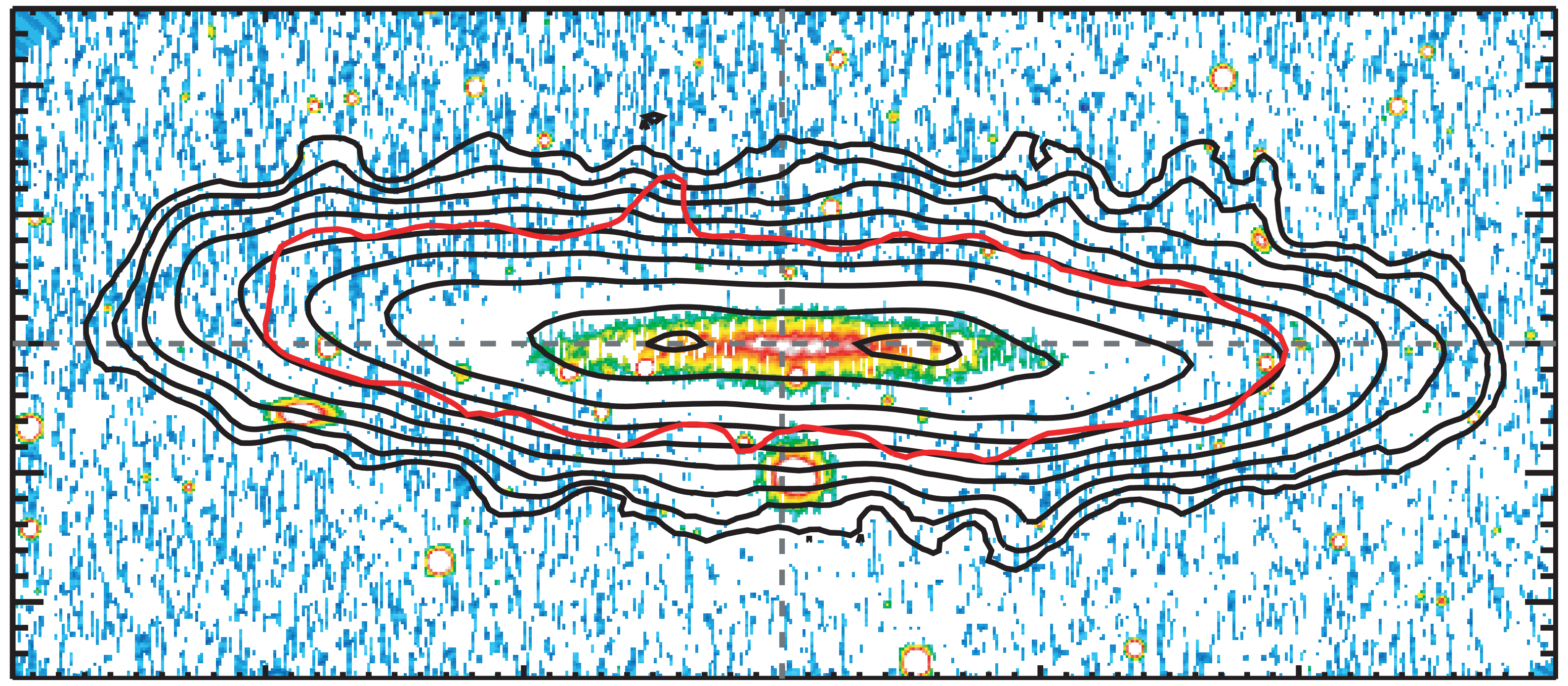

Hα
HI
Velocity (km/s)
Velocity (km/s)
Kamphuis et al. 2011
Radial offset (arcsec)
Radial offset (arcsec)
NE
SW
100
50
0
−50
−100
−100 −50 0 50 100 150
−200 −100 0 100 200 300


Normalized Intensity
Intensity (Jy/beam)
Vertical offset (arcsec)
Radial offset (arcsec)
SE
NW
NE
SW
1.000
0.100
0.010
0.001
0.25
0.20
0.15
0.10
0.05
0.00
−100 −50 0 50 100
−200 −100 0 100 200 300





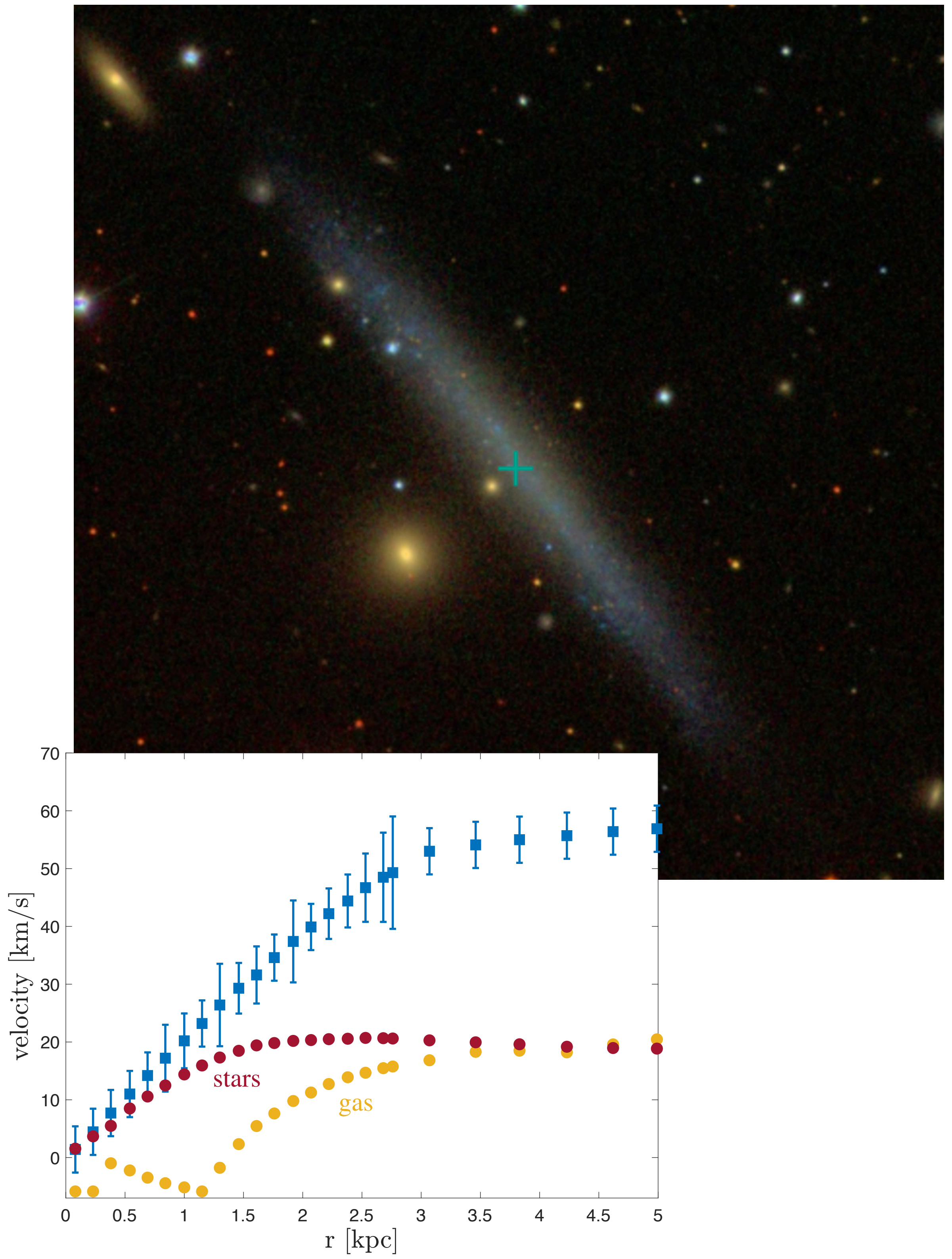


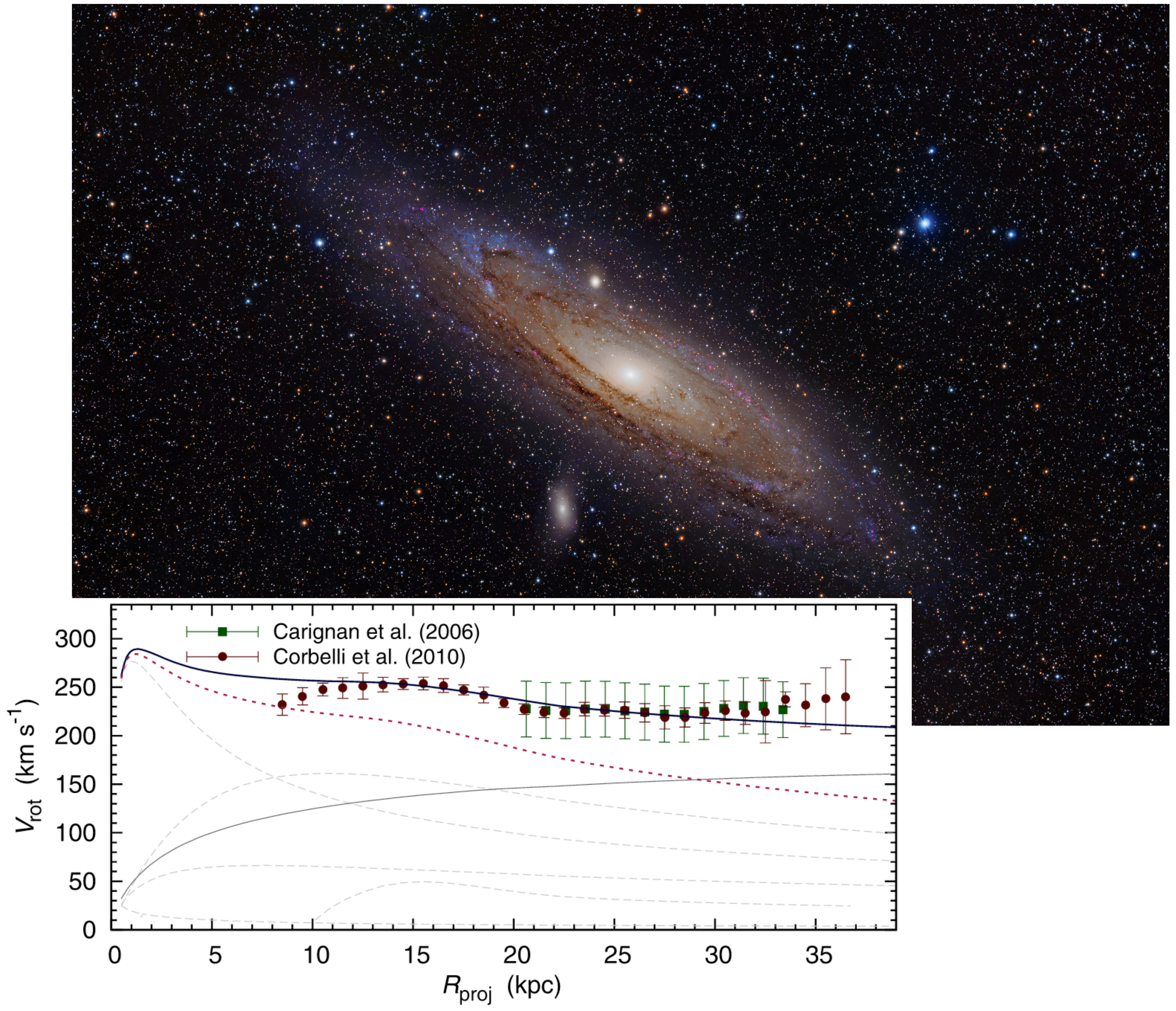


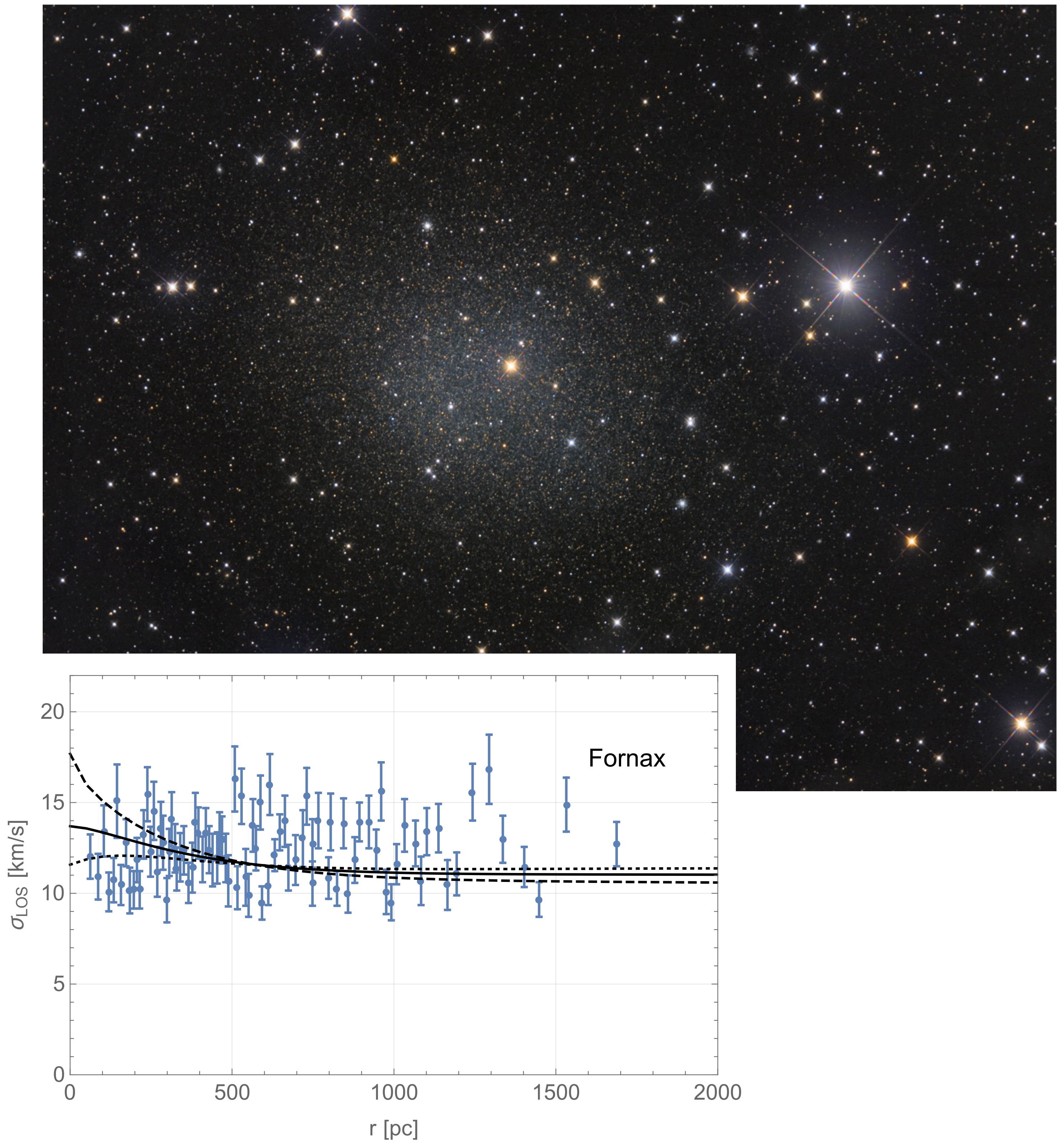
<u>At ~5 kpc:</u>

$$\textbf{M(DM)/M(stars+gas)} \sim \frac{55^2 - 2 \times 20^2}{2 \times 20^2} \sim 3$$

Dark matter


velocity [km/s]
r [kpc]
stars
gas
0
10
20
30
40
50
60
70
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


Carignan et al. (2006)
Corbelli et al. (2010)
V_{rot} (km s^{-1})
R_{proj} (kpc)
0
50
100
150
200
250
300
5
10
15
20
25
30
35

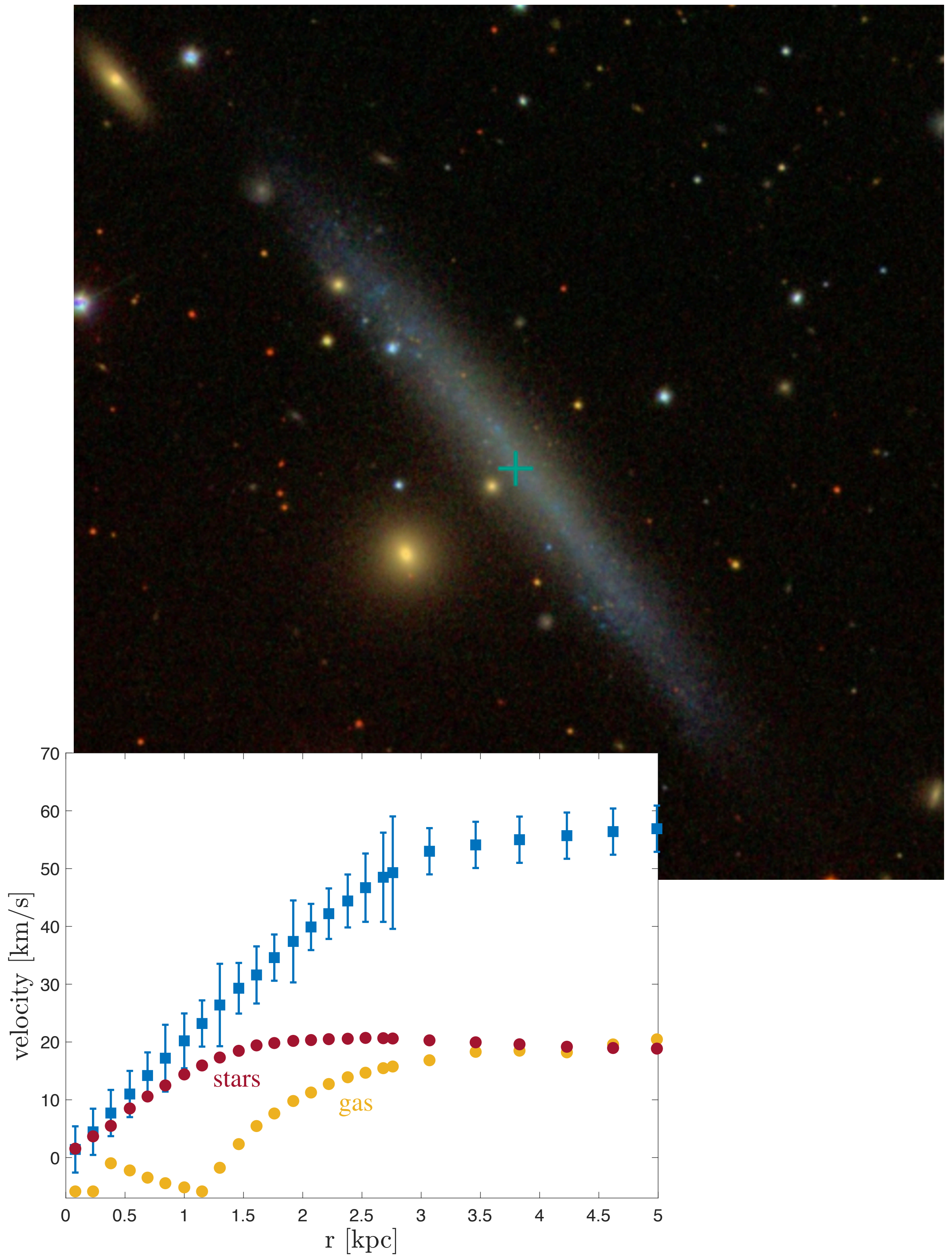

Fornax
σ_{LOS} [km/s]
r [pc]
0
5
10
15
20
500
1000
1500
2000

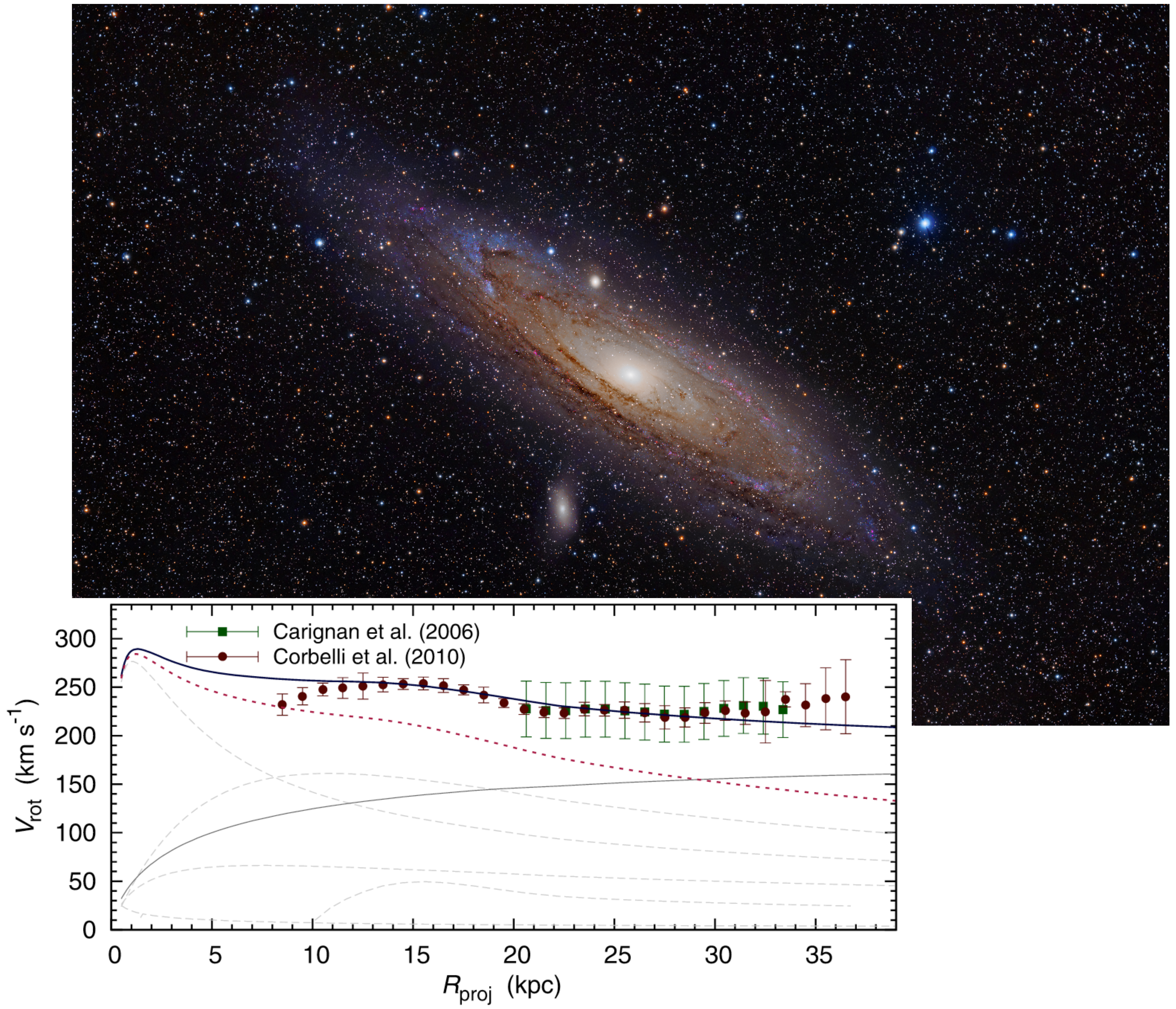
Dark matter

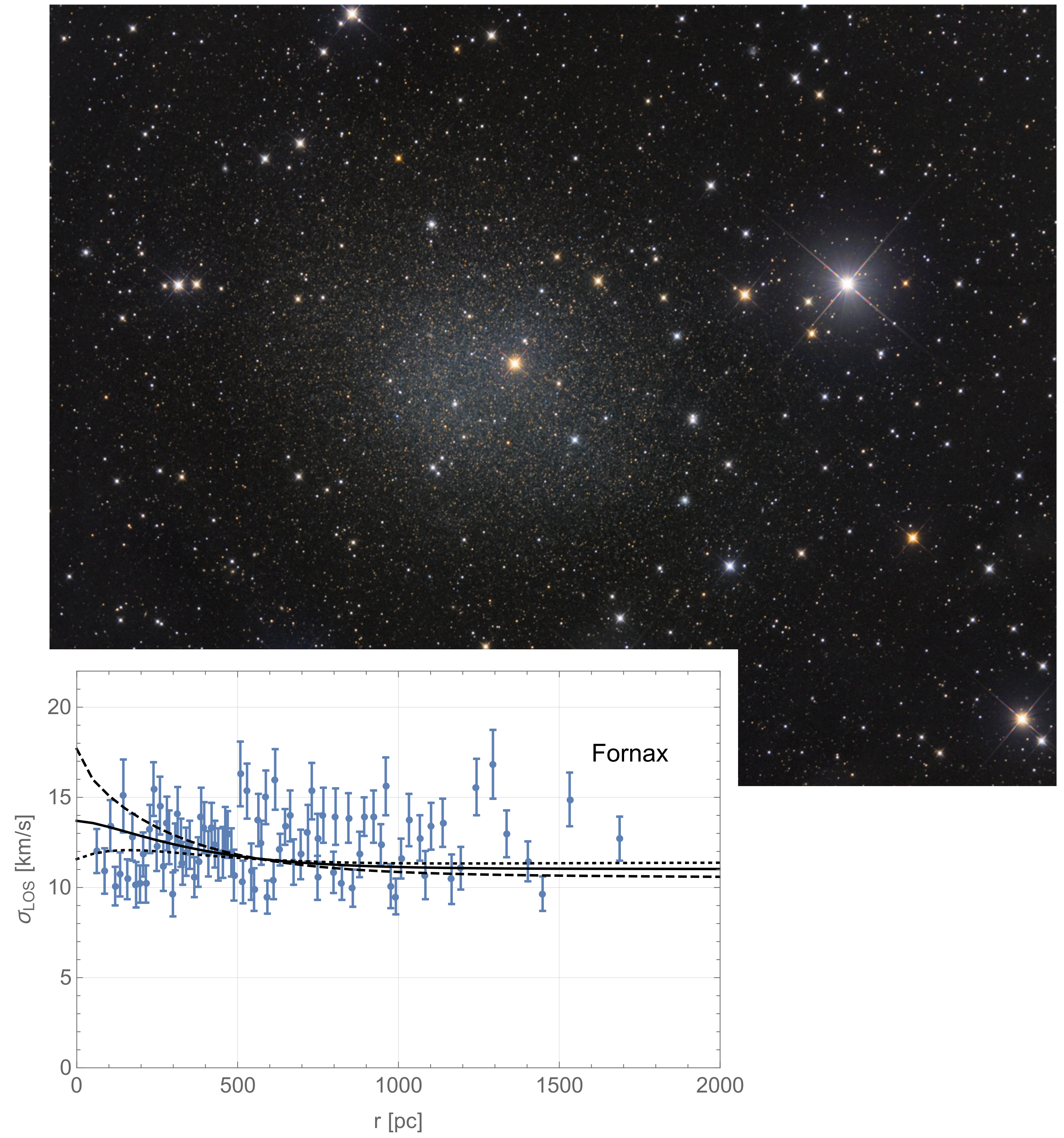
m_X

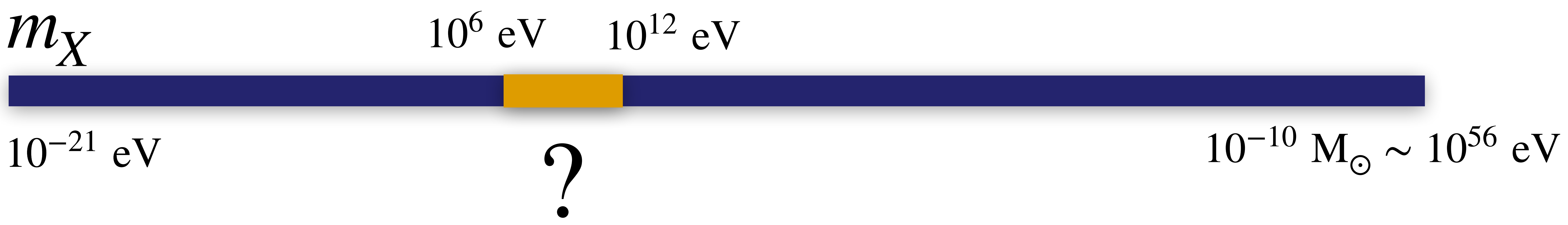
10^{-21} eV

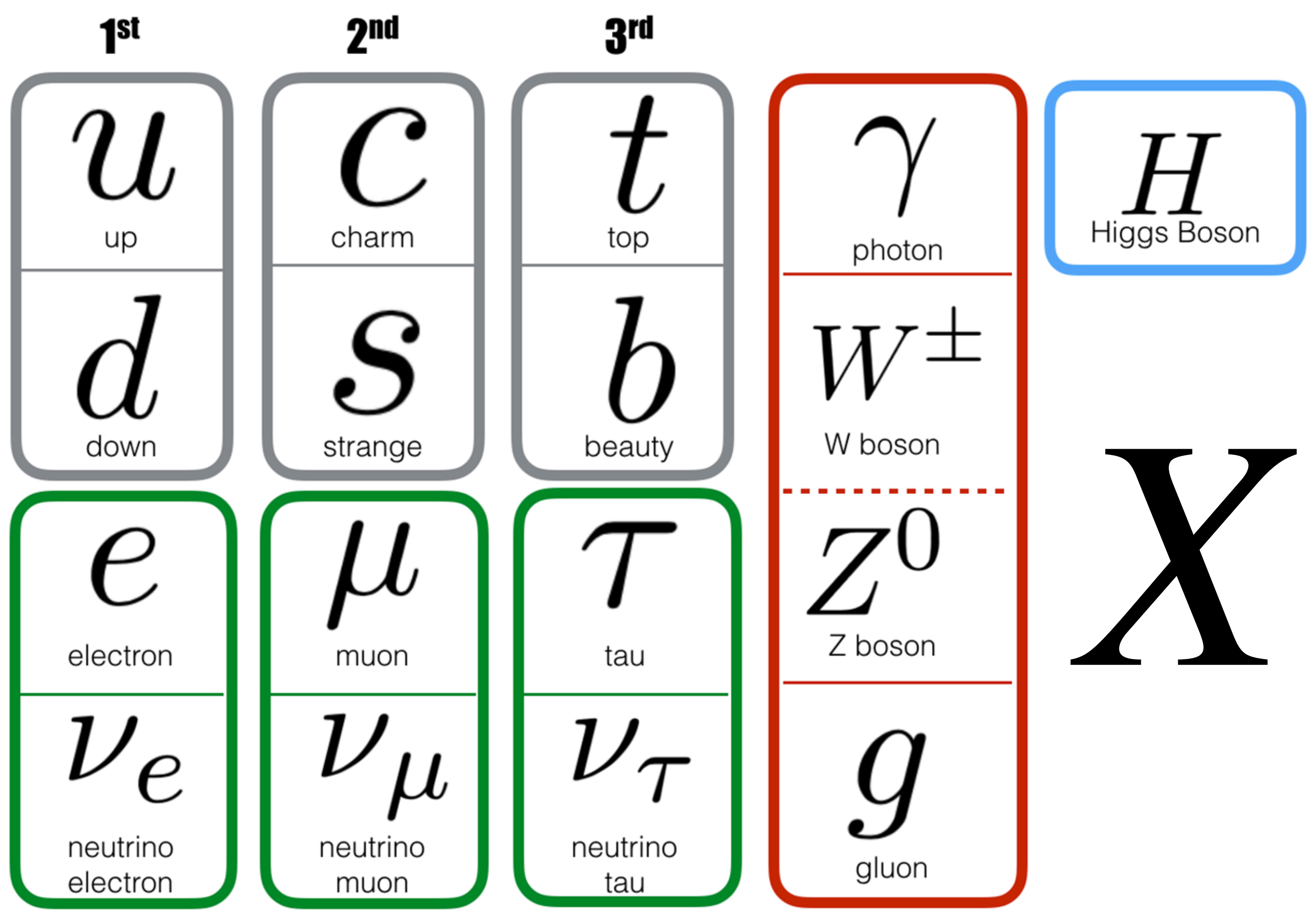
$10^{-10}\ M_\odot \sim 10^{56}$ eV

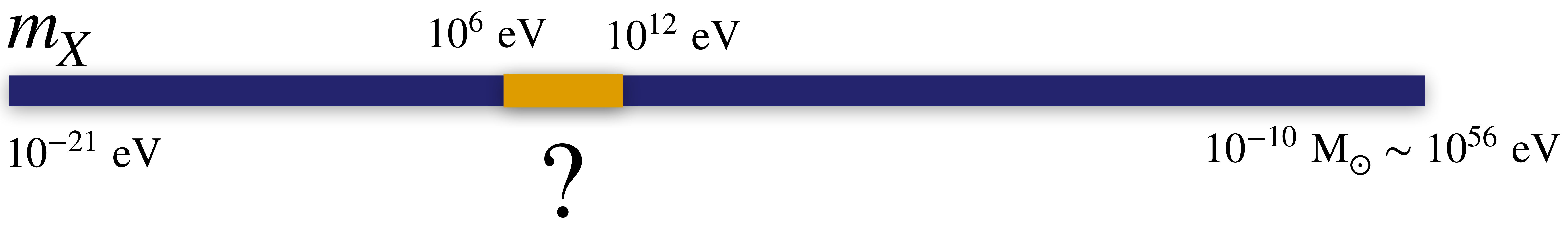







m_X
10^{6} eV
10^{12} eV
10^{-21} eV
?
$10^{-10}\ M_{\odot} \sim 10^{56}$ eV

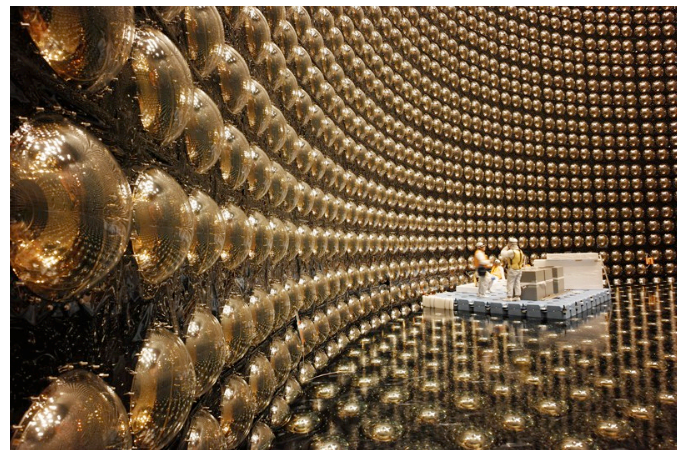

1st
2nd
3rd
u up
c charm
t top
d down
s strange
b beauty
e electron
μ muon
τ tau
ν_e neutrino electron
ν_μ neutrino muon
ν_τ neutrino tau
γ photon
$W^{\pm}$ W boson
Z^0 Z boson
g gluon
H Higgs Boson
X



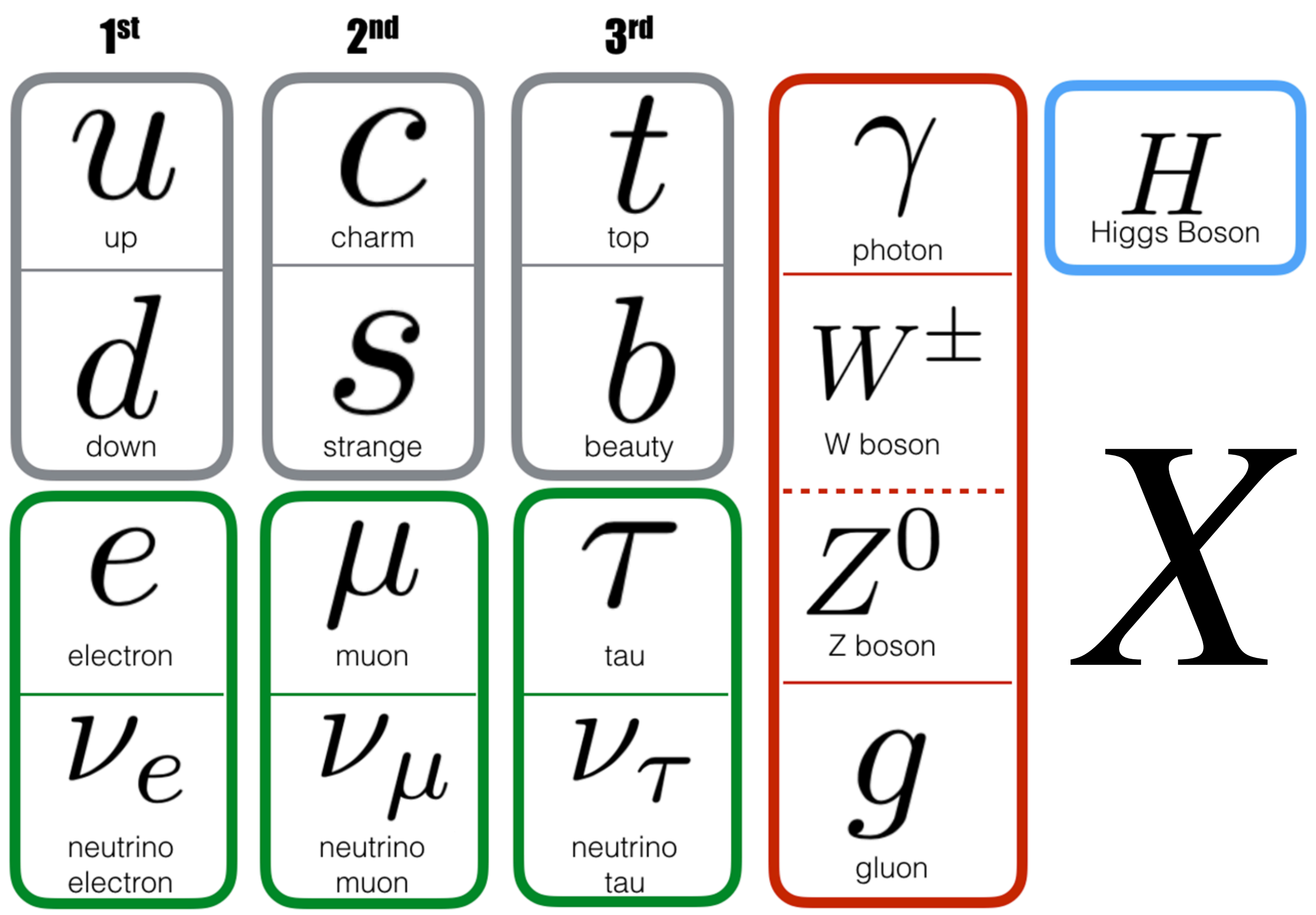
"Indirect"


AMS


Fermi

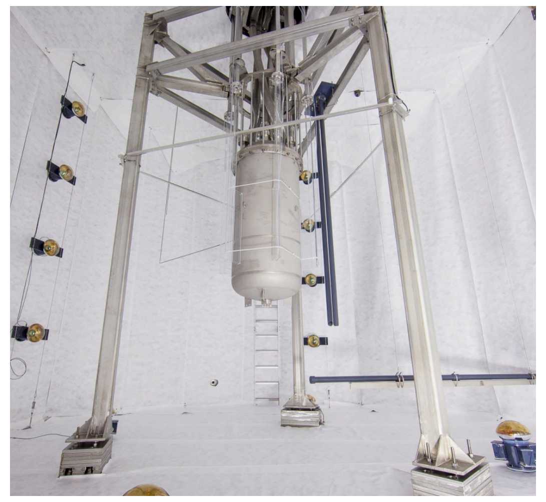

Super K

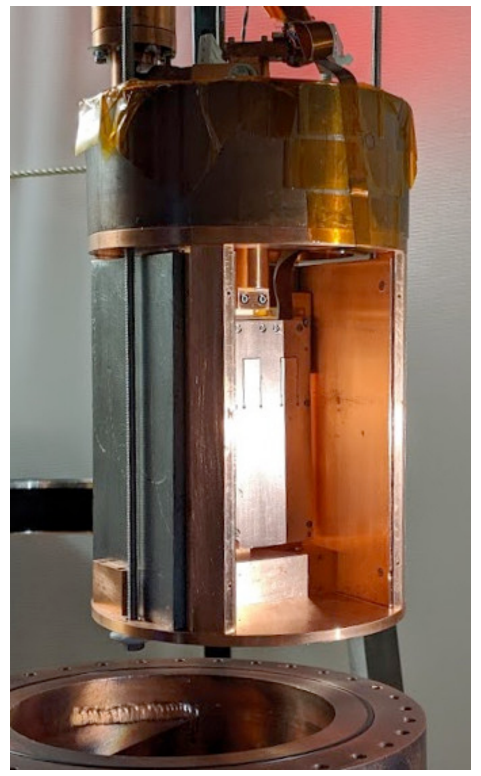

HESS

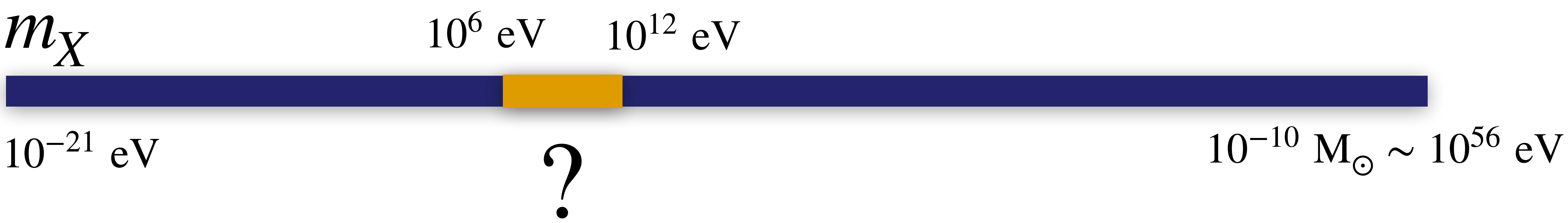


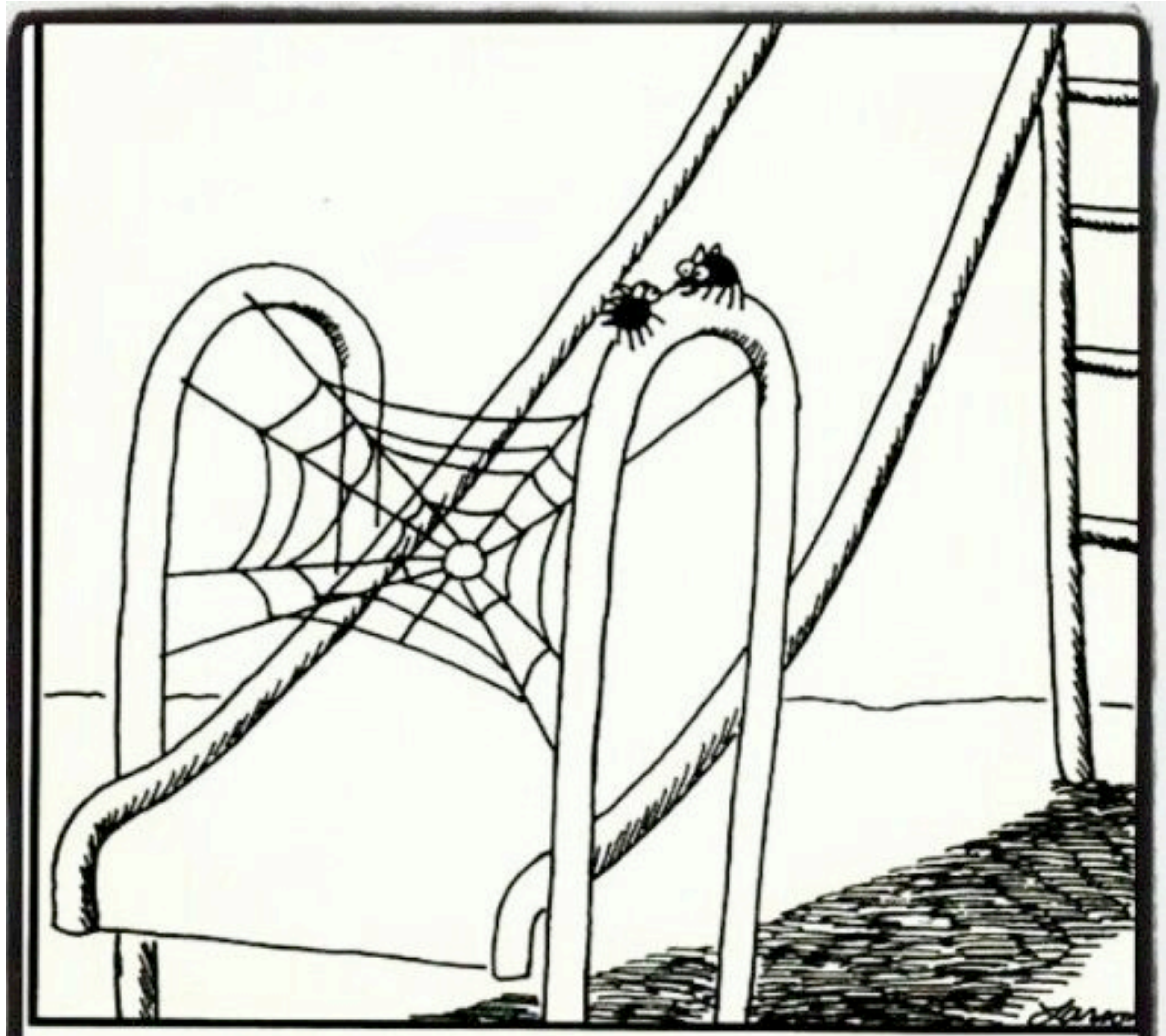
"Direct"


Xenon1T


LUX


SENSEI





"If we pull this off, we'll eat like kings."

m_X

10^{-21} eV — $10^{-10}\ M_\odot \sim 10^{56}$ eV


Gravity alone
m_X
10^{-21} eV
$10^{-10}\ M_\odot \sim 10^{56}$ eV

Gravity alone

1. Ultralight dark matter

2. Beyond mean-field: dynamical friction / heating

3. Gravitational lensing

Gravity alone

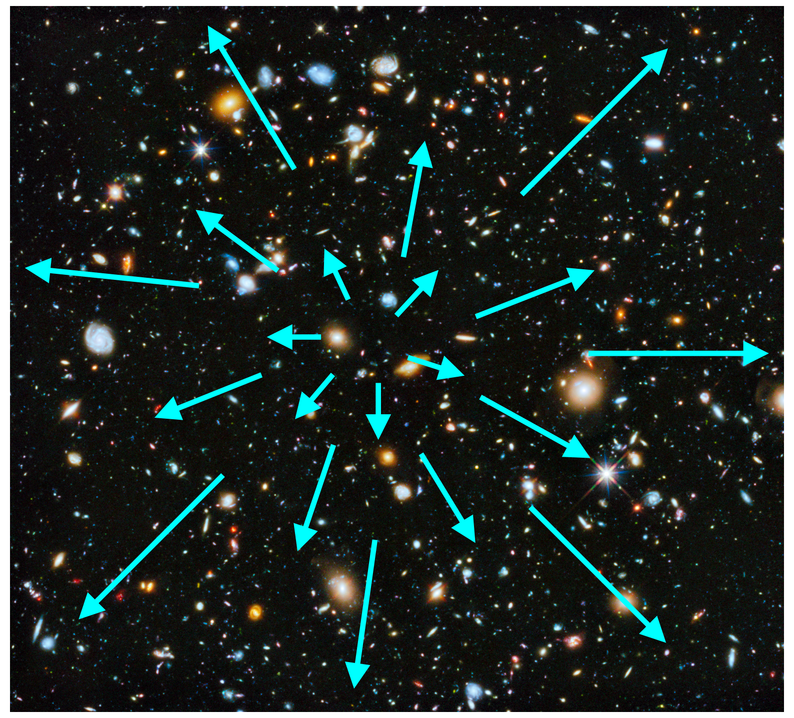
m_X

10^{-21} eV — $10^{-10}\ M_\odot \sim 10^{56}$ eV

Thank you!

Where does it end?

Cosmic expansion:



$$\chi\nu = \begin{pmatrix} t \\ r \\ \theta \\ \varphi \end{pmatrix}; \qquad g\mu\nu = \begin{pmatrix} f[r] & 0 & 0 & 0 \\ 0 & -\frac{1}{f[r]} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2\,\mathrm{Sin}[\theta]^2 \end{pmatrix};$$

```
gIμν = Inverse[gμν];
dgdxtab = Table[{D[gμν, χν[[i, 1]]]}, {i, 1, 4}];
Γ = Table[{Table[1/2 Sum[gIμν[[i, μ]] (dgdxtab[[k, 1]][[μ, j]] + dgdxtab[[j, 1]][[μ, k]] - dgdxtab[[μ, 1]][[j, k]]), {μ, 1, 4}], {j, 1, 4}, {k, 1, 4}]}, {i, 1, 4}];
Rμν = (Table[Sum[D[Γ[[α, 1]][[μ, ν]], χν[[α, 1]]], {α, 1, 4}], {μ, 1, 4}, {ν, 1, 4}] - Table[Sum[D[Γ[[α, 1]][[μ, α]], χν[[ν, 1]]], {α, 1, 4}], {μ, 1, 4}, {ν, 1, 4}]
    + Table[Sum[(Γ[[α, 1]][[λ, α]]) (Γ[[λ, 1]][[μ, ν]]), {α, 1, 4}, {λ, 1, 4}], {μ, 1, 4}, {ν, 1, 4}] - Table[Sum[(Γ[[λ, 1]][[μ, α]]) (Γ[[α, 1]][[λ, ν]]),
      {α, 1, 4}, {λ, 1, 4}], {μ, 1, 4}, {ν, 1, 4}]);
R = Sum[gIμν[[μ, ν]] × Rμν[[μ, ν]], {μ, 1, 4}, {ν, 1, 4}];
```

$$x\nu = \begin{pmatrix} t \\ r \\ \theta \\ \varphi \end{pmatrix}; \qquad g\mu\nu = \begin{pmatrix} f[r] & 0 & 0 & 0 \\ 0 & -\frac{1}{f[r]} & 0 & 0 \\ 0 & 0 & -r^2 & 0 \\ 0 & 0 & 0 & -r^2\,\mathrm{Sin}[\theta]^2 \end{pmatrix};$$

In[∘]:= $f[r\_] := 1 - \frac{2}{r} - H^2\, r^2;$

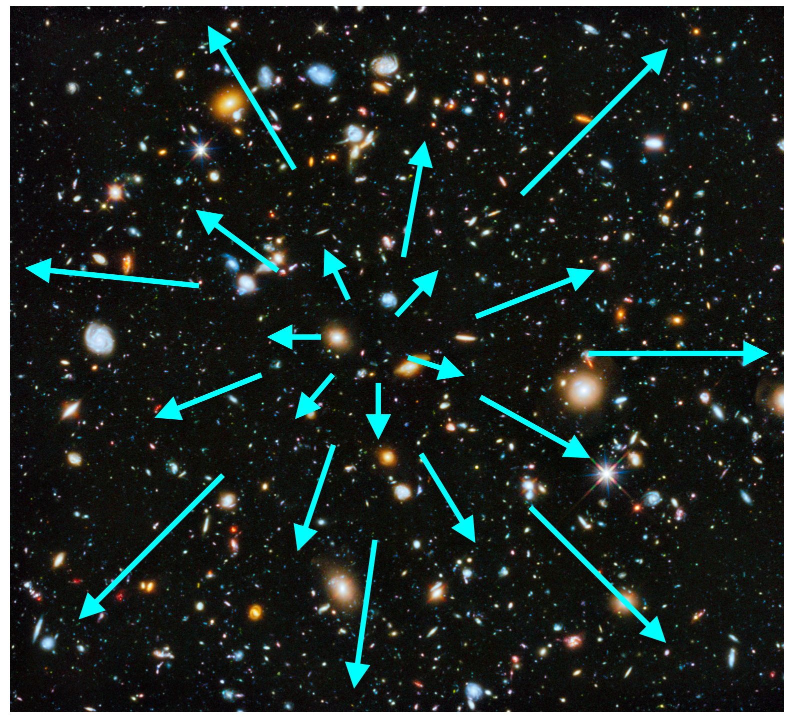
$\mathrm{FullSimplify}\left[\left(R\mu\nu - \frac{1}{2} R\, g\mu\nu - 3\, H^2\, g\mu\nu\right) \,//\, \mathrm{MatrixForm}\right]$

Out[∘]//MatrixForm=

$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Where does it end?

Cosmic expansion:



$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

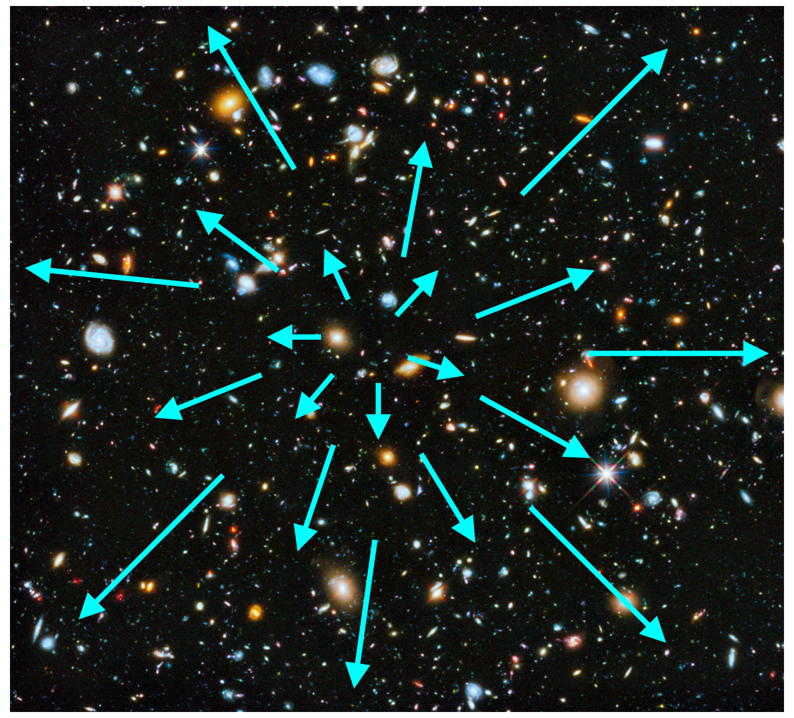
$$T_{\mu\nu} \approx g_{\mu\nu}\rho_\Lambda, \qquad H_0^2 \approx \frac{8\pi}{3} G\rho_\Lambda$$

$$\longrightarrow \quad R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 3H_0^2\, g_{\mu\nu}$$

Solved by: $f(r) = 1 - \dfrac{2}{r} - H_0^2\, r^2$

Where does it end?

Cosmic expansion:



$$\frac{d^2x^\mu}{dp^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{dp}\frac{dx^\beta}{dp} = 0$$

```
In[•]:= χvp = (t'[p]
               r'[p]
               θ'[p]
               φ'[p]);

Simplify[r''[p] + Sum[Simplify[Flatten[Γ[[2]], 1][[μ]][[ν]]] × χvp[[μ]] × χvp[[ν]], {μ, 1, 4}, {ν, 1, 4}]] == 0
Simplify[θ''[p] + Sum[Simplify[Flatten[Γ[[3]], 1][[μ]][[ν]]] × χvp[[μ]] × χvp[[ν]], {μ, 1, 4}, {ν, 1, 4}]] == 0
Simplify[φ''[p] + Sum[Simplify[Flatten[Γ[[4]], 1][[μ]][[ν]]] × χvp[[μ]] × χvp[[ν]], {μ, 1, 4}, {ν, 1, 4}]] == 0
Simplify[t''[p] + Sum[Simplify[Flatten[Γ[[1]], 1][[μ]][[ν]]] × χvp[[μ]] × χvp[[ν]], {μ, 1, 4}, {ν, 1, 4}]] == 0
```

Out[•]= $\left\{\frac{(1-H^2 r^3)\, r'[p]^2}{r\,(2-r+H^2 r^3)} + \frac{(-1+H^2 r^3)\,(2-r+H^2 r^3)\, t'[p]^2}{r^3} + (2-r+H^2 r^3)\,\theta'[p]^2 + (2-r+H^2 r^3)\,\mathrm{Sin}[\theta]^2\,\varphi'[p]^2 + r''[p]\right\} == 0$

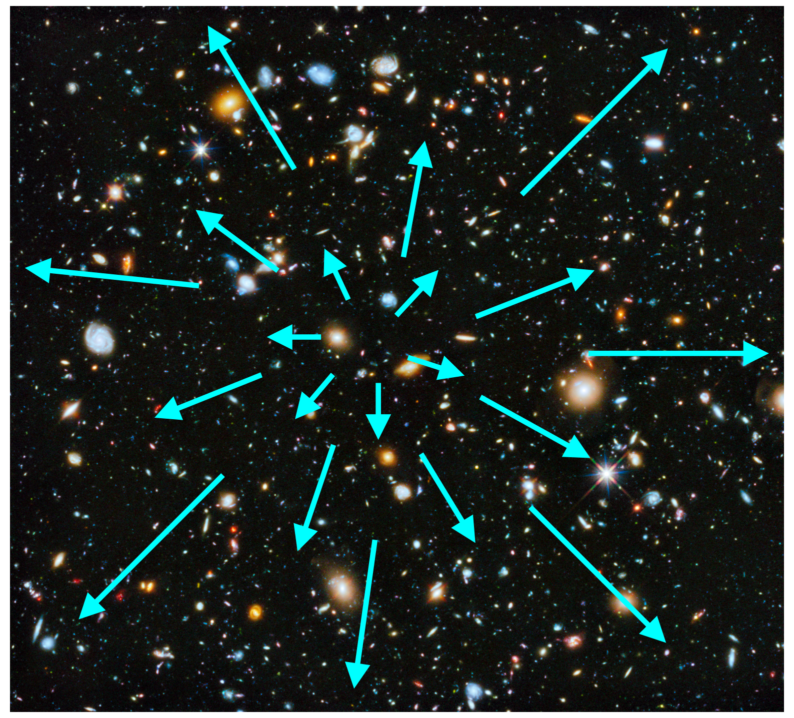
Out[•]= $\left\{\frac{2\, r'[p]\,\theta'[p]}{r} - \mathrm{Cos}[\theta]\,\mathrm{Sin}[\theta]\,\varphi'[p]^2 + \theta''[p]\right\} == 0$

Out[•]= $\left\{\frac{2\, r'[p]\,\varphi'[p]}{r} + 2\,\mathrm{Cot}[\theta]\,\theta'[p]\,\varphi'[p] + \varphi''[p]\right\} == 0$

Out[•]= $\left\{\frac{2\,(-1+H^2 r^3)\, r'[p]\, t'[p]}{r\,(2-r+H^2 r^3)} + t''[p]\right\} == 0$

Where does it end?

Cosmic expansion:



$$\frac{d^2x^\mu}{dp^2} + \Gamma^\mu_{\alpha\beta}\frac{dx^\alpha}{dp}\frac{dx^\beta}{dp} = 0$$

Looking for a circular orbit solution:

$$\theta = \frac{\pi}{2} = \text{Const}, \qquad r = R = \text{Const}$$

Leads to:

$$\frac{d\varphi}{dp} = C\,\Omega = \text{Const}$$

$$\frac{dt}{dp} = C = \text{Const}$$

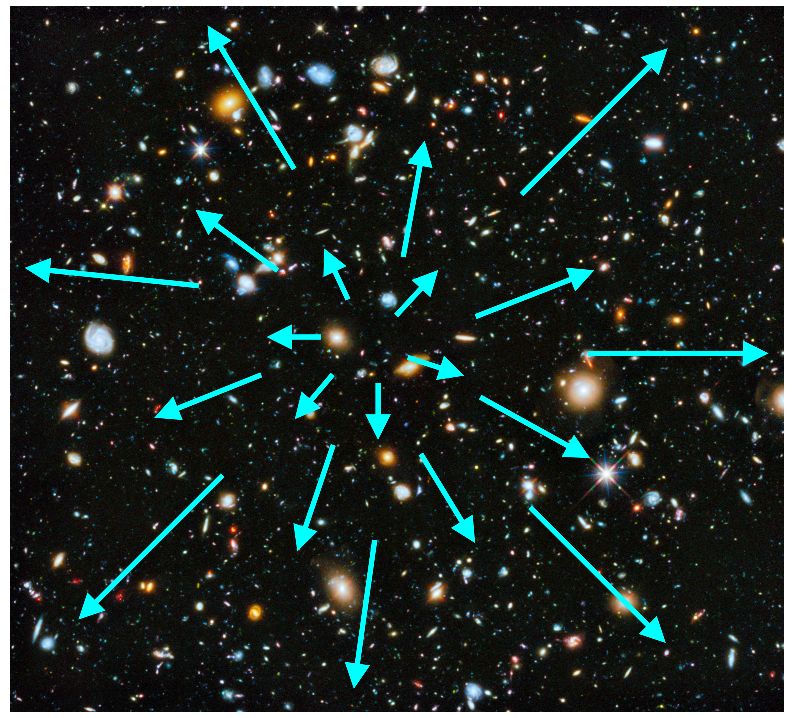
The r equation becomes:

$$\left(2 - R + H_0^2 R^3\right)\Omega^2 - \frac{\left(1 - H_0^2 R^3\right)\left(2 - R + H_0^2 R^3\right)}{R^3} = 0$$

Restoring units: $\Omega^2 = \frac{GM}{R^3}\left(1 - \frac{H_0^2 R^3}{GM}\right)$

Where does it end?

Cosmic expansion:



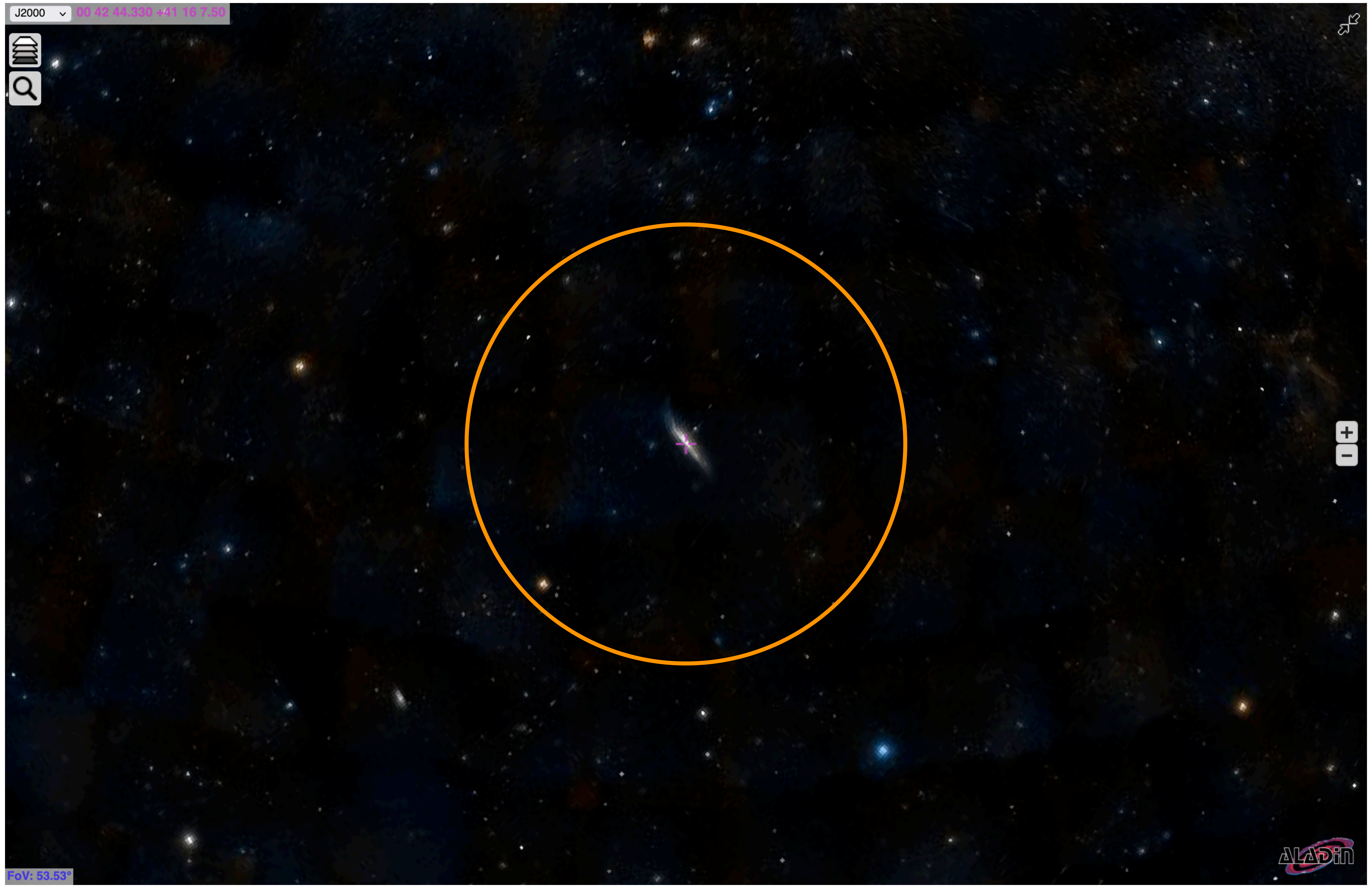
Expansion modifies law of rotation around a point mass M:

$$\Omega^2 = \frac{GM}{R^3}\left(1 - \frac{H_0^2 R^3}{GM}\right)$$

The Astrophysical Journal, 900:9 (44pp), 2020 September 1 https://doi.org/10.3847/1538-4357/aba49c

Project AMIGA: The Circumgalactic Medium of Andromeda*

Nicolas Lehner[1], Samantha C. Berek[1,2,20], J. Christopher Howk[1], Bart P. Wakker[3], Jason Tumlinson[4,5], Edward B. Jenkins[6], J. Xavier Prochaska[7], Ramona Augustin[4], Suoqing Ji[8], Claude-André Faucher-Giguère[9], Zachary Hafen[9], Molly S. Peeples[4,5], Kat A. Barger[10], Michelle A. Berg[1], Rongmon Bordoloi[11], Thomas M. Brown[4], Andrew J. Fox[12], Karoline M. Gilbert[4,5], Puragra Guhathakurta[7], Jason S. Kalirai[13], Felix J. Lockman[14], John M. O'Meara[15], D. J. Pisano[16,17,21], Joseph Ribaudo[18], and Jessica K. Werk[19]



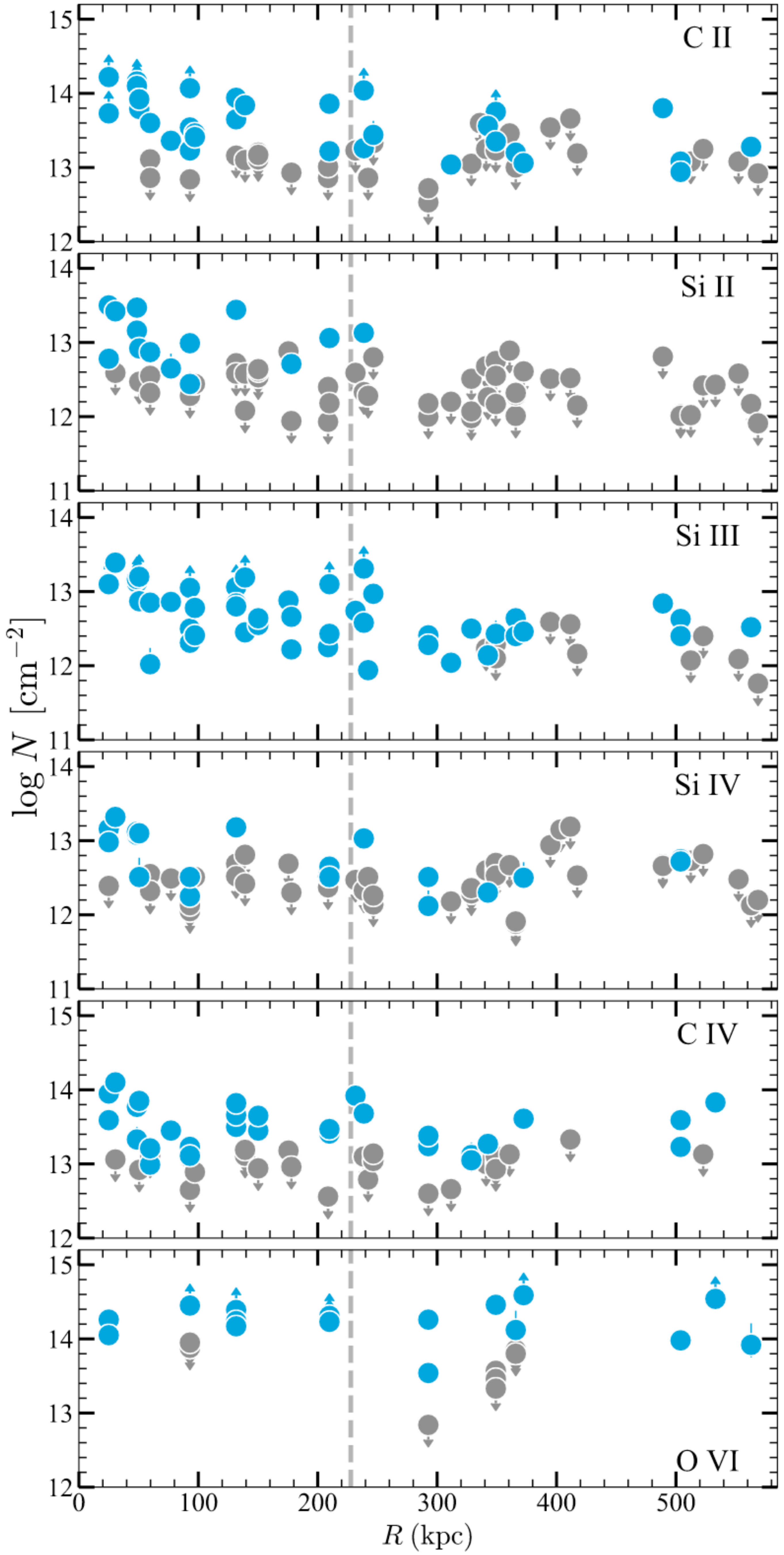
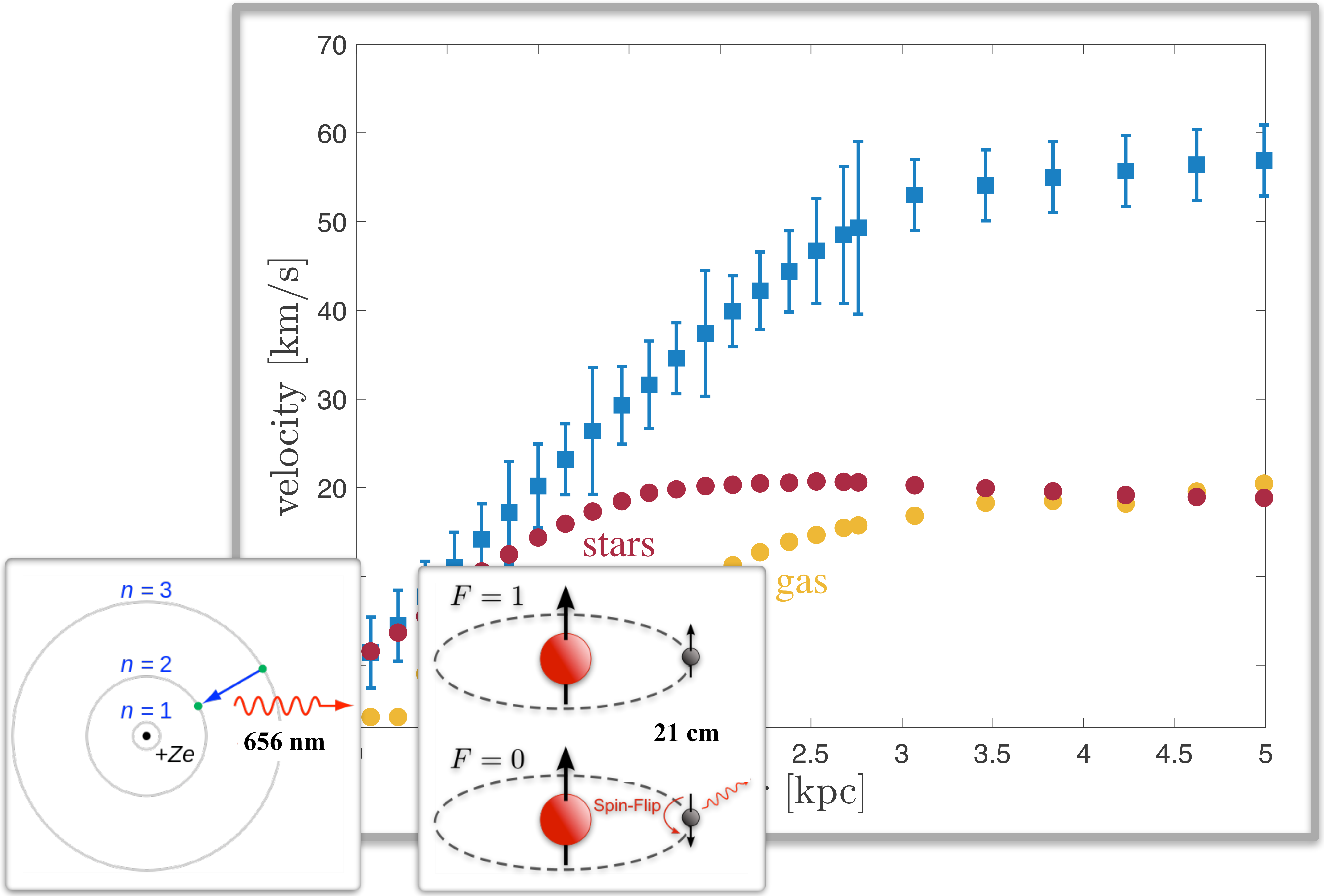
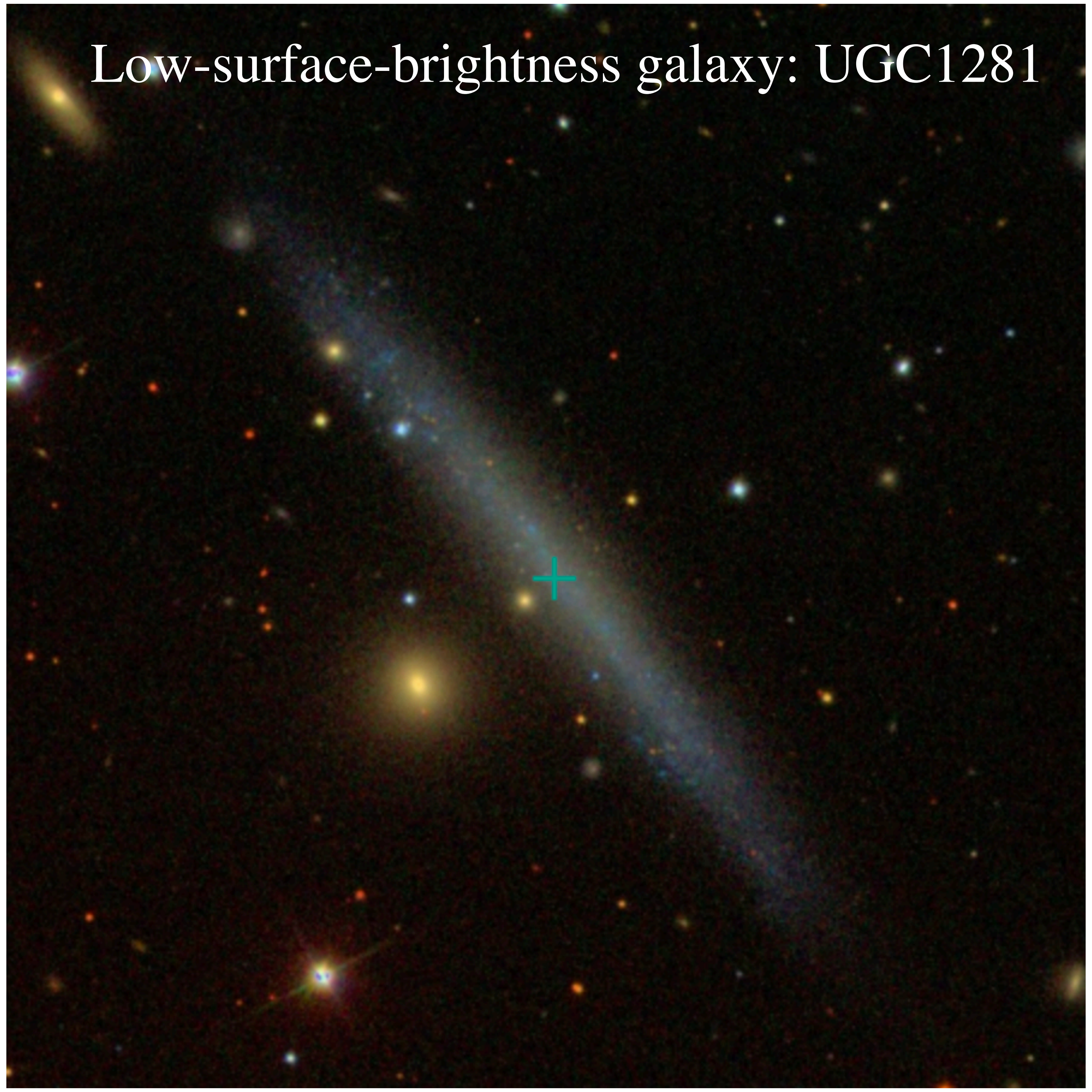
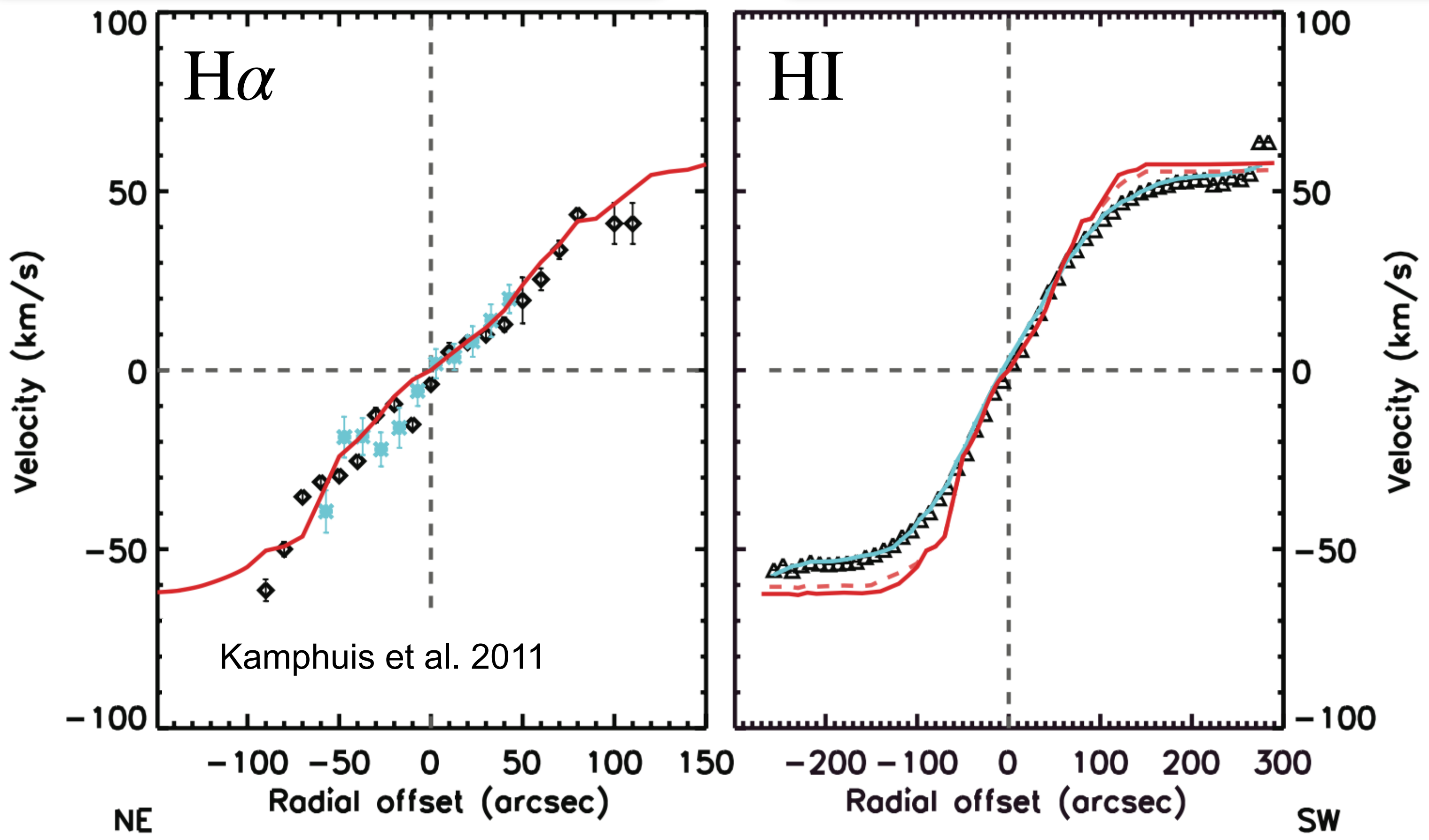
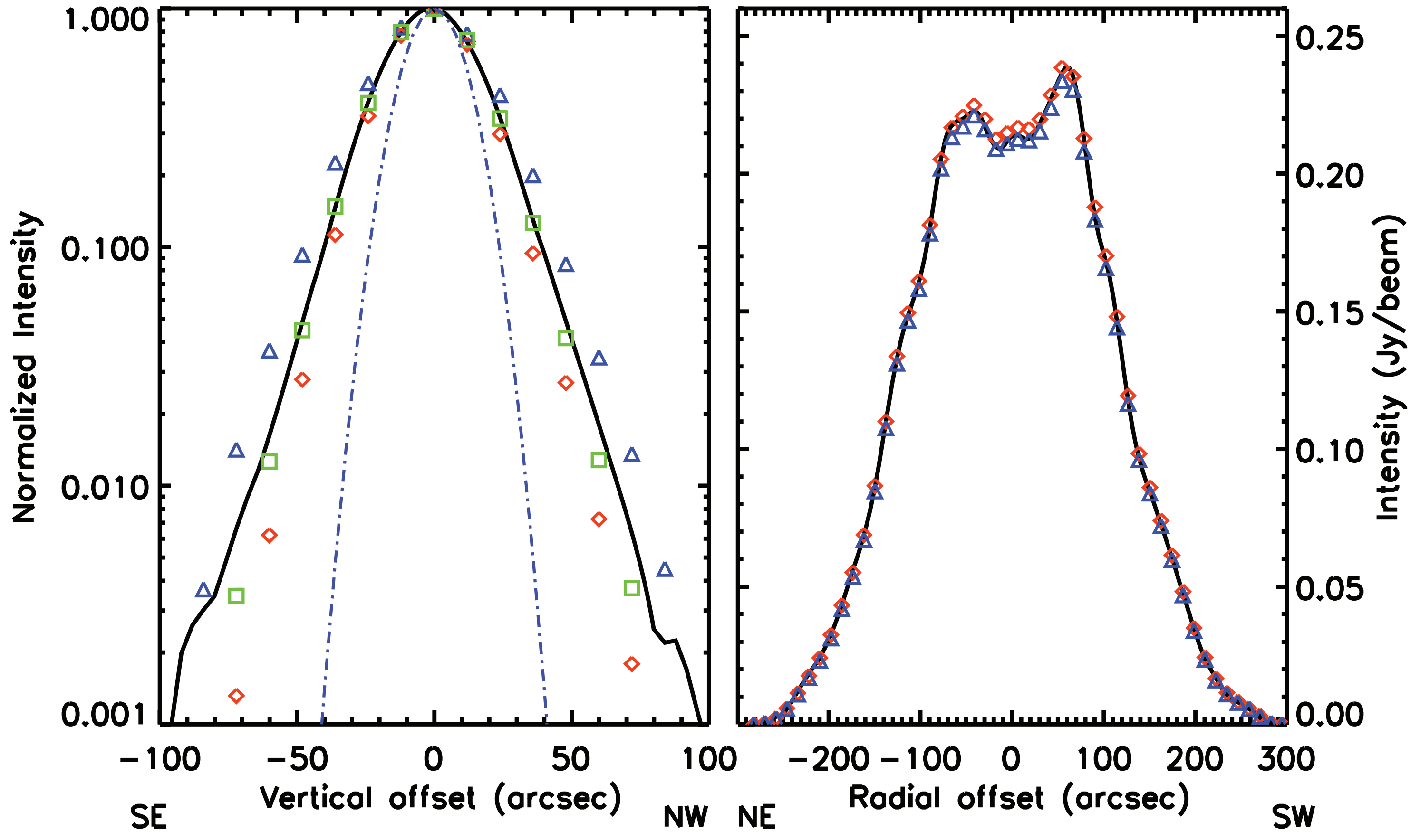


Figure 9. Logarithm of the column densities for the individual components of various ions (low to high ions from top to bottom) as a function of the projected distances from M31 of the background QSOs. Blue circles are detections, while


70
60
50
40
30
20
velocity [km/s]
stars
gas
2.5
3
3.5
4
4.5
5
[kpc]
n = 3
n = 2
n = 1
+Ze
656 nm
F = 1
21 cm
F = 0
Spin-Flip


Low-surface-brightness galaxy: UGC1281


Hα
HI
Velocity (km/s)
Velocity (km/s)
100
50
0
−50
−100
Kamphuis et al. 2011
−100 −50 0 50 100 150
−200 −100 0 100 200 300
Radial offset (arcsec)
Radial offset (arcsec)
NE
SW


Normalized Intensity
1.000
0.100
0.010
0.001
−100 −50 0 50 100
Vertical offset (arcsec)
SE
NW
NE
−200 −100 0 100 200 300
Radial offset (arcsec)
SW
Intensity (Jy/beam)
0.25
0.20
0.15
0.10
0.05
0.00