Searching for new physics (and DM):

Implications of uncertainties in the determination of DM distribution in the MW

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JSPS-FAPESP Workshop
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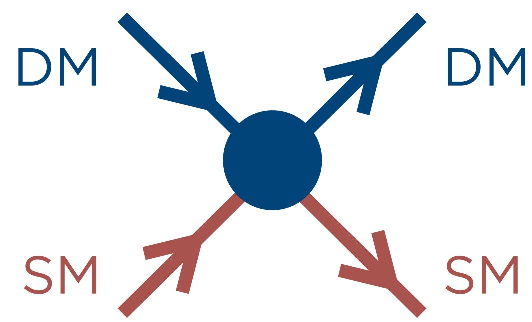
Why it is important?

Direct/Indirect WIMP searches

Simplified version

Direct



Recoil spectrum for DM-nucleus interaction:

$$\frac{\mathrm{d}R}{\mathrm{d}E} \sim C_{\mathrm{PP}}\, \rho_0 \int_{v>v_{\min}} \mathrm{d}^3 v\, \frac{f(\mathbf{v},t)}{v}$$

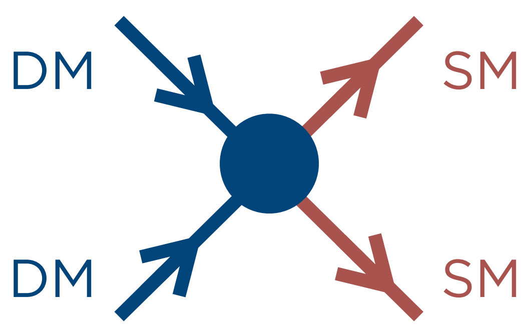
Impact of velocity distribution function:

Bozorgnia & Bertone Int.J.Mod.Phys. A32 (2017)

Bozorgnia + JCAP 1605 (2016)

Dependence on astrophysics

Indirect

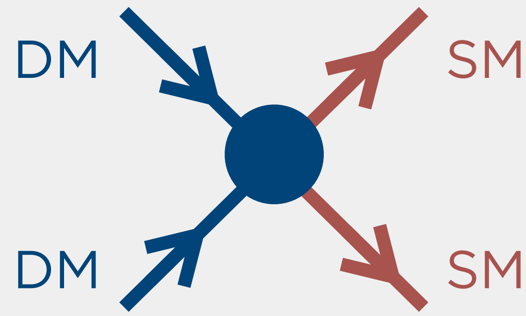


Flux due to DM self-annihilation:

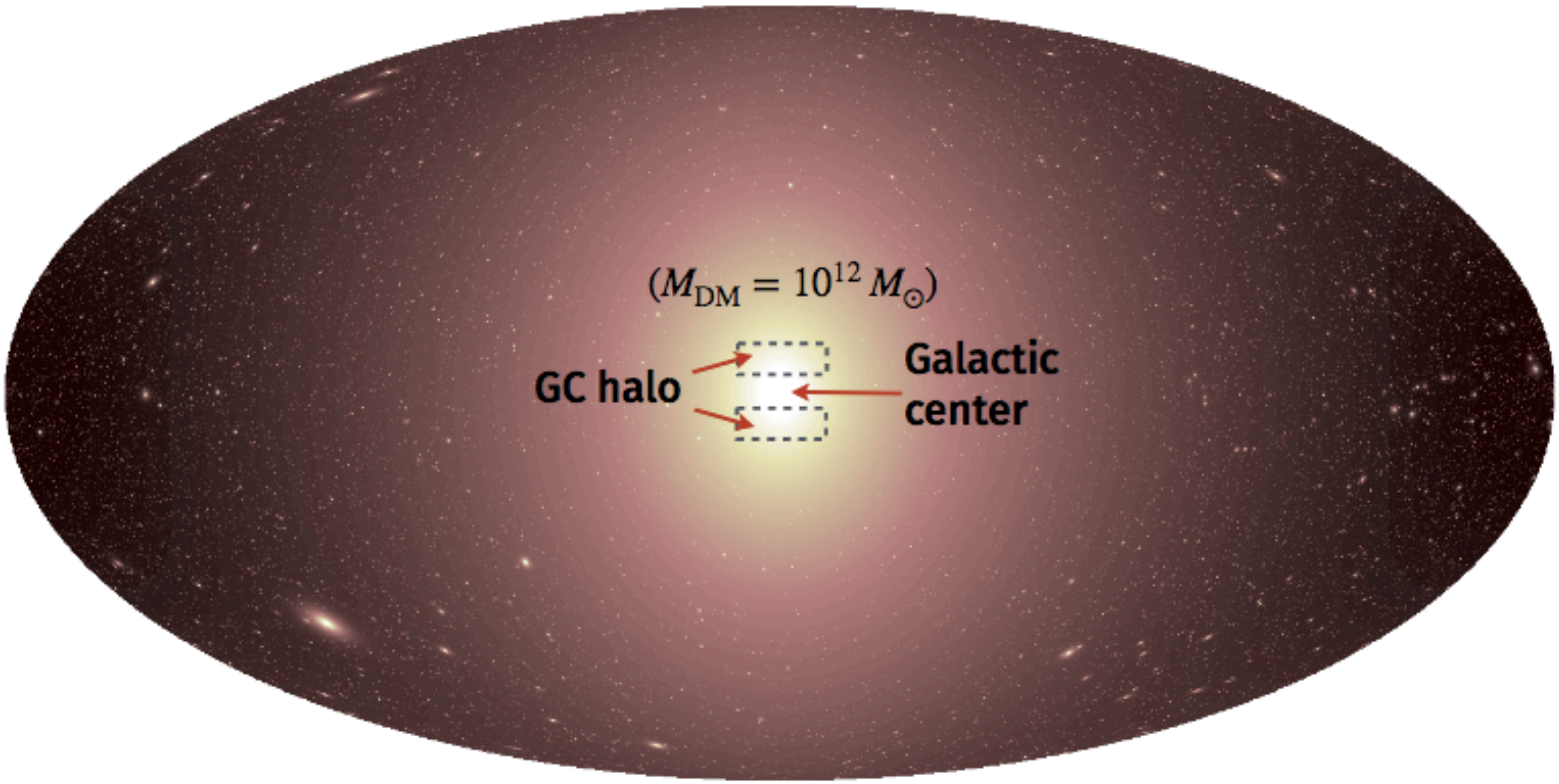
$$\Phi_{\mathrm{DM}} \sim \Phi_{\mathrm{PP}} \int_{\mathrm{l.o.s}} \mathrm{d}l\; \rho^2_{DM}$$

Dependence on astrophysics

Targets for indirect WIMP searches: our Galaxy



$$\Phi_{\rm DM} \sim \Phi_{\rm PP} \int_{\rm l.o.s} {\rm d}l\ \rho^2_{DM}$$



Synthetic γ-ray intensity map from DM annihilation (created with CLUMPY)

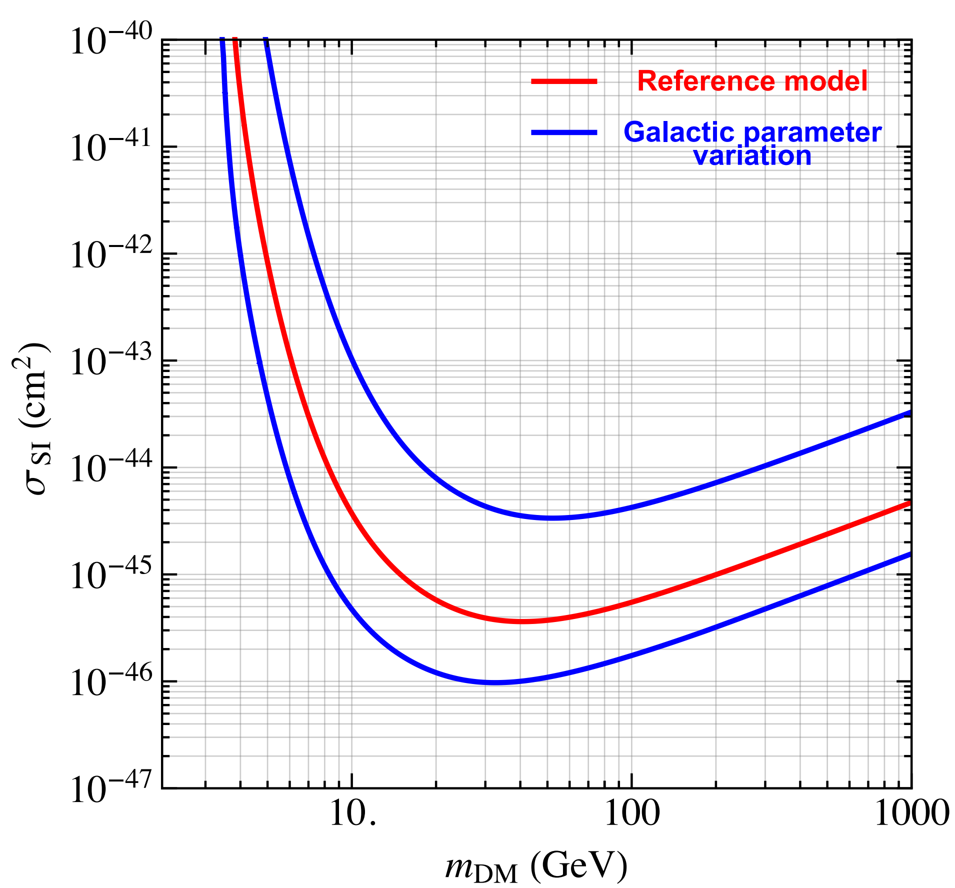
Credit: M. Hütten

Problem:

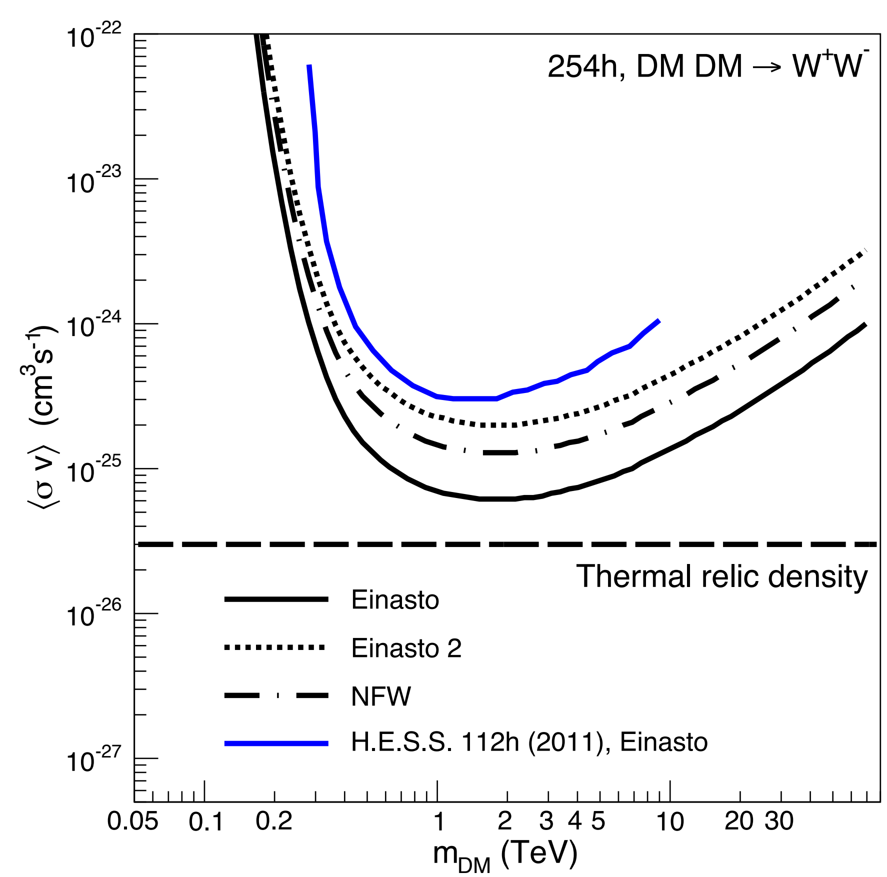
MW reconstructed DM profile proceeds from astrophysical observations - uncertainties need to be properly accounted for!

Interpretation of direct/indirect searches depend upon DM density [local/in target (MW)]

Particle physics ← Direct/Indirect searches ← DM density ← Astrophysical observable



MB +
JCAP 1702 (2017)



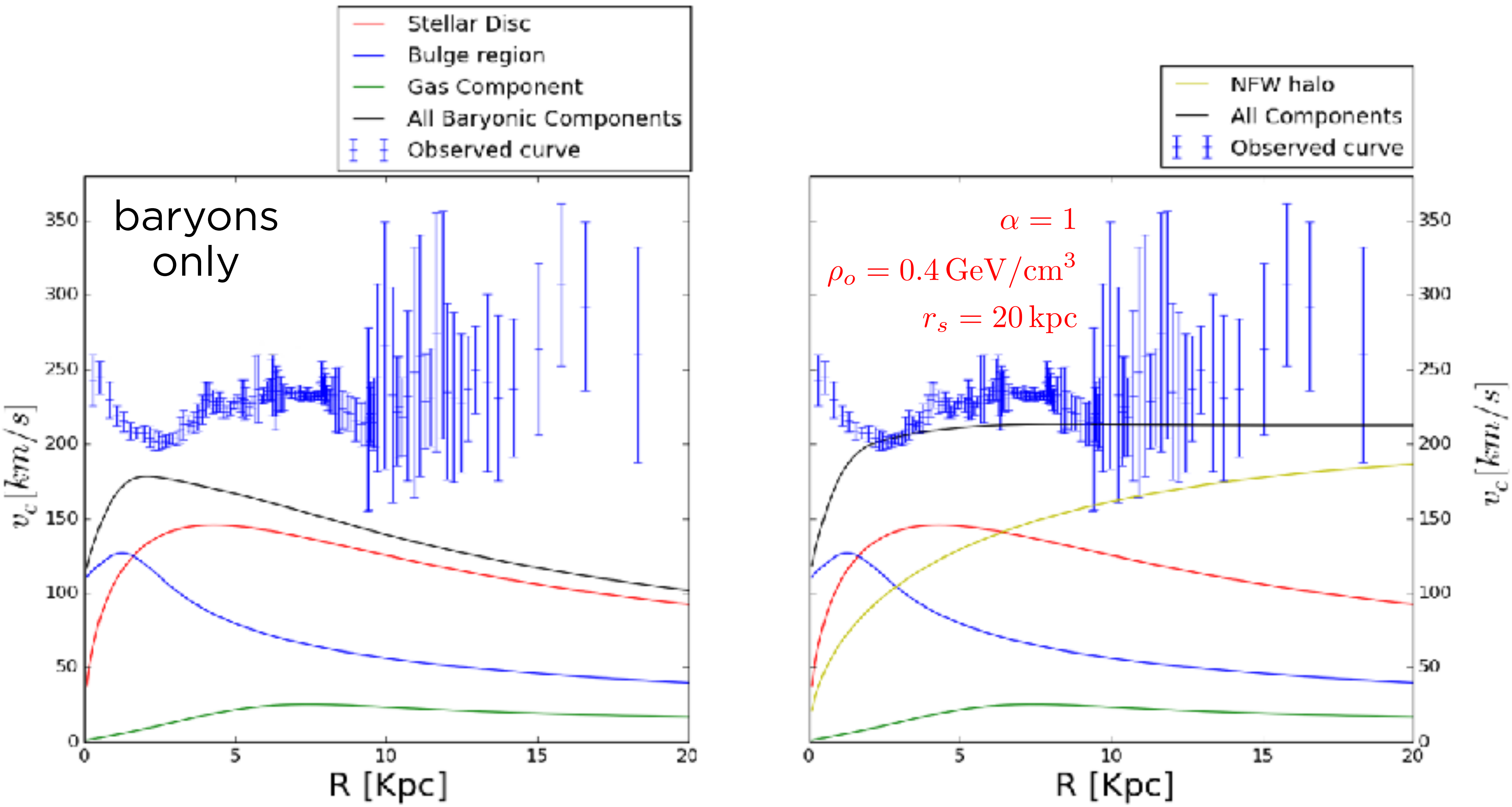
H.E.S.S. collaboration
PRL 117 (2016)

Goal:

Quantify uncertainties on the reconstructed DM density profile of the MW

How?

Rotation Curve method



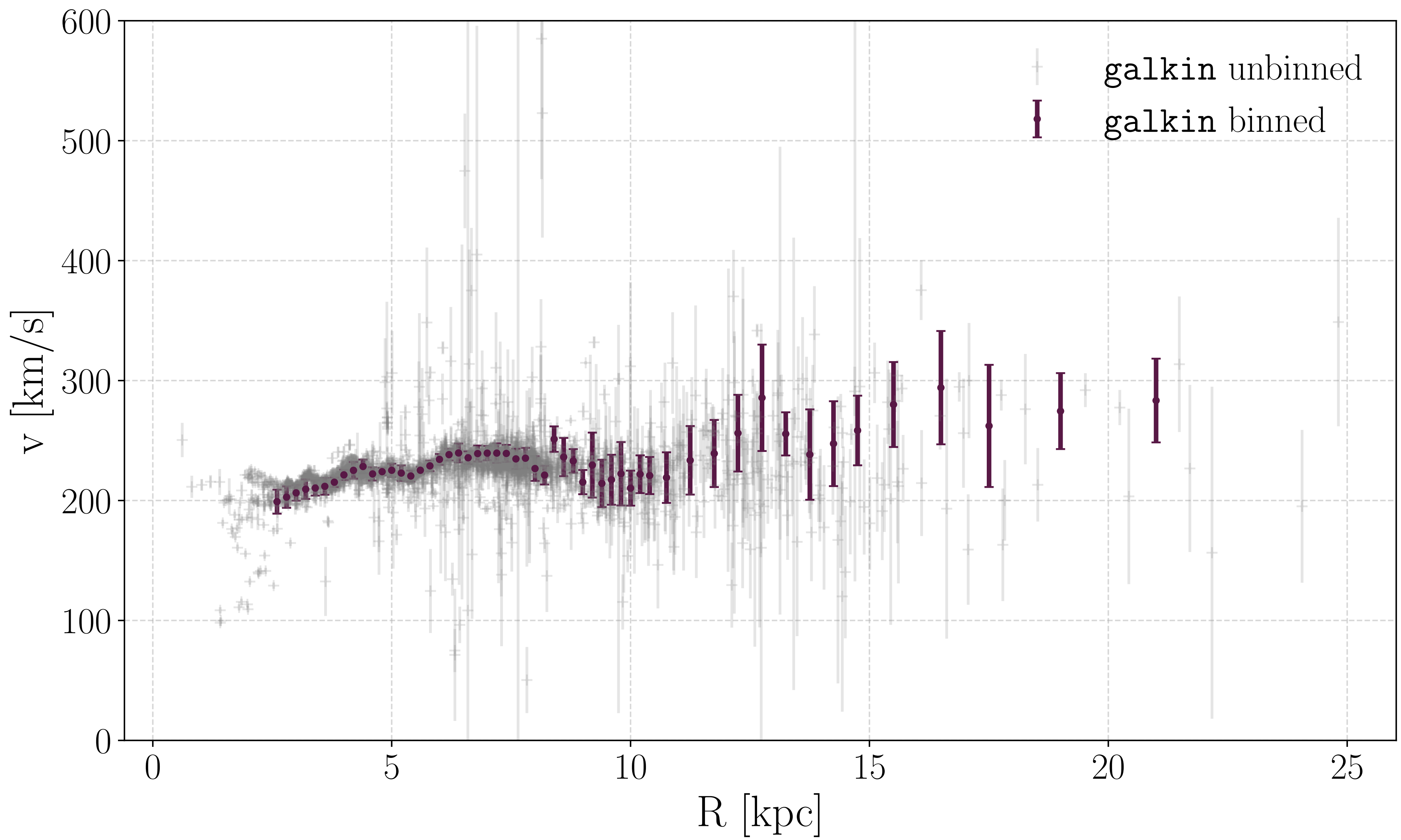
How to determine DM density profile?

Rotation Curve method

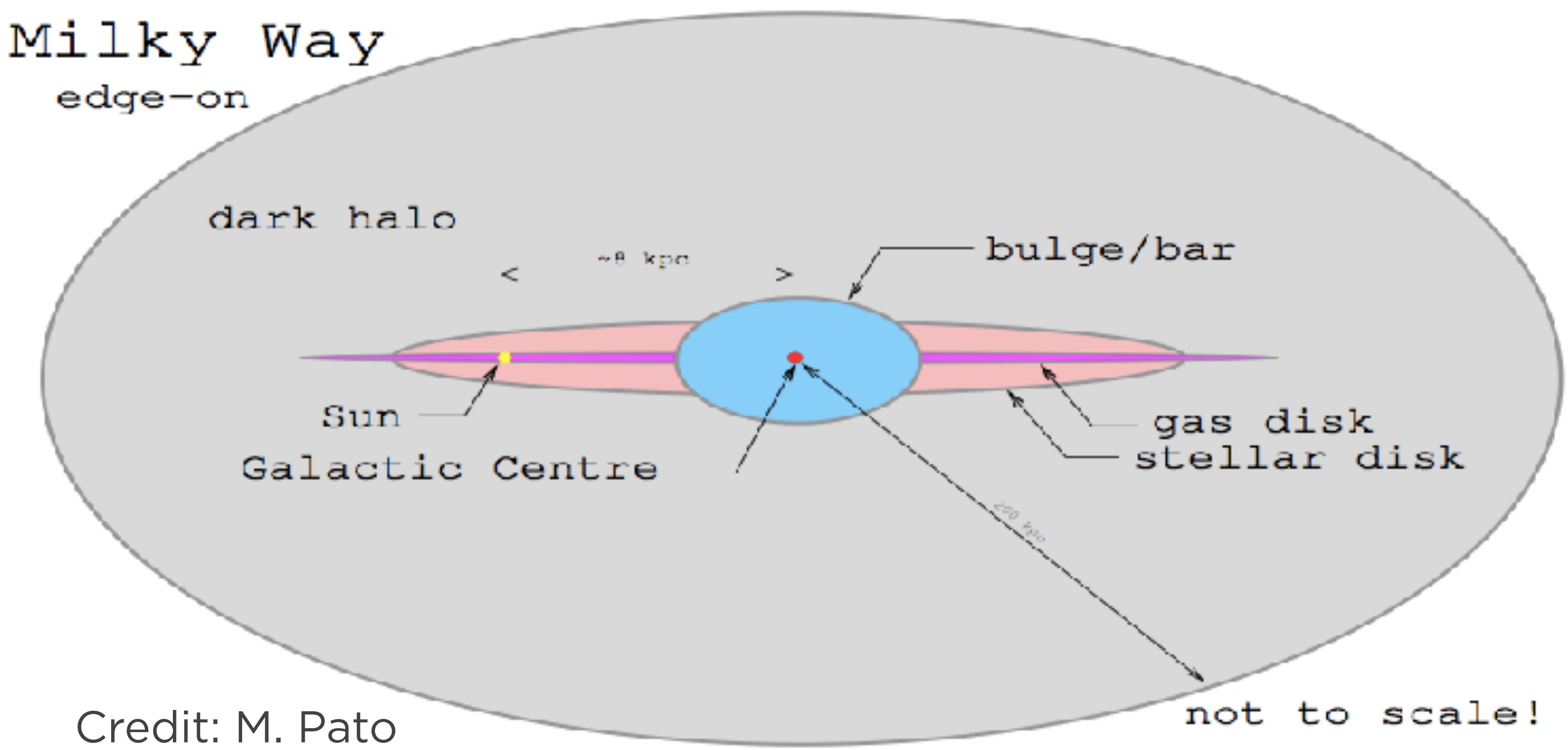
- Observed RC:

  `galkin` Pato & Iocco, SoftwareX 6 (2017)

  $2.5 < \mathrm{R} < 22\ \mathrm{kpc}$



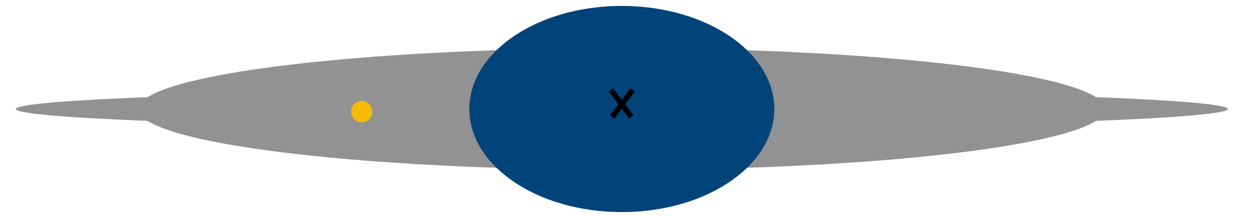
Luminous component of the Milky Way



Credit: M. Pato

$$\rho_{\rm bulge}(x,y,z) \quad \rho_{\rm disc}(r,z) \quad \rho_{\rm gas}(x,y,z) \;\longrightarrow\; \Phi_{\rm bulge}(x,y,z) \quad \Phi_{\rm disc}(r,z) \quad \Phi_{\rm gas}(x,y,z) \;\longrightarrow\; v^2(r) = \sum_i v_i^2(r), \quad v_i^2(r) = r\frac{{\rm d}\Phi_i}{{\rm d}r}$$

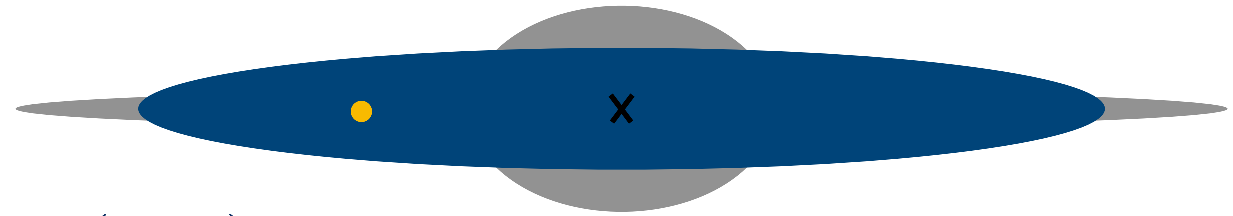
Bulge distribution:



$$\rho_b(x,y,z) = \bar{\rho}_b f(x,y,z)$$

$f(x,y,z)$	Bar angle [°]	x0:y0:z0	Reference
e^{-r}	25	2.8 : 1.4 : 1	K.Z. Stanek + (1996) [G2]
$e^{-r_s^2/2}$	24	3.6 : 1.5 : 1	K.Z. Stanek + (1996) [E2]
$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	20	3.7 : 1.5 : 1	H. Zhao (1996)
$e^{-r_s^2}/(1+r_s)^{1.8}$	20	2.6 : 0.8 : 1	N. Bissantz & O. Gerhard (2002)
$\mathrm{sech}^2(-r_s) + e^{-r_s}$	13	3.7 : 1.3 : 1	A.C. Robin + (2012)
$e^{-r_s^2}/(1+r_s)^{1.8}$	15	3.2 : 2.2 : 1	E. Vanhollebeke + (2013)

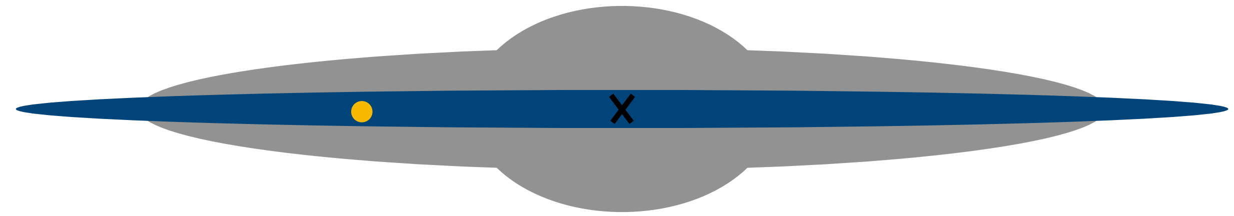
Stellar disc distribution:



$$\rho_d(r,z) = \bar{\rho}_d f(r,z)$$

$f(r,z)$		Scale-length [kpc]	Scale-height [kpc]	Reference
$e^{-r}\,\mathrm{sech}^2(z)$	thin	2.75	0.27 η(r)	C. Han & A. Gould (2003)
$e^{-r}\,e^{-(z+z_0)}$	thick	2.75	0.44 η(r)	
$e^{-r}\,e^{-\|z\|}$	thin	2.6	0.30	M. Juric + (2008)
$e^{-r}\,e^{-\|z\|}$	thick	3.6	0.90	
$(r^2+z^2)^{-2.77/2}$	halo			
$e^{-r}\,e^{-\|z\|}$	thin	2.75	0.25	J. T. A. De Jong + (2010)
$e^{-r}\,e^{-\|z\|}$	thick	4.1	0.75	
$(r^2+z^2)^{-2.75/2}$	halo			
$e^{-r}\,e^{-\|z\|}$	thin	2.75	0.25	S. Calchi Novati & L. Mancini (2011)
$e^{-r}\,e^{-\|z\|}$	thick	4.1	0.75	
$e^{-r}\,e^{-\|z\|}$	single	2.15	0.4	J. Bovy & H.W. Rix (2013)

Gas distribution:



$$\rho_g(x,y,z) = \rho_{H_2}(x,y,z) + \rho_{H_I}(x,y,z) + \rho_{H_{II}}(x,y,z)$$

Components		Range	Reference
molecular ring	H_2	$r = 3 - 20$ kpc	K. Ferrière (1998)
cold, warm	HI		
warm, hot	HII		
CMZ, disc	H_2	$r = 0.01 - 3$ kpc	K. Ferrière + (2007)
CMZ, disc	HI		
warm, hot, very hot	HII		

Uncertainties

CO-to-H_2 factor: $X_{CO}(r > 3\,\text{kpc}) = (5.0 \pm 2.5) \times 10^{19}\,\text{cm}^{-2}\text{K}^{-1}\text{km}^{-1}\text{s}$

$X_{CO}(r < 3\,\text{kpc}) = (1.9 \pm 1.4) \times 10^{20}\,\text{cm}^{-2}\text{K}^{-1}\text{km}^{-1}\text{s}$

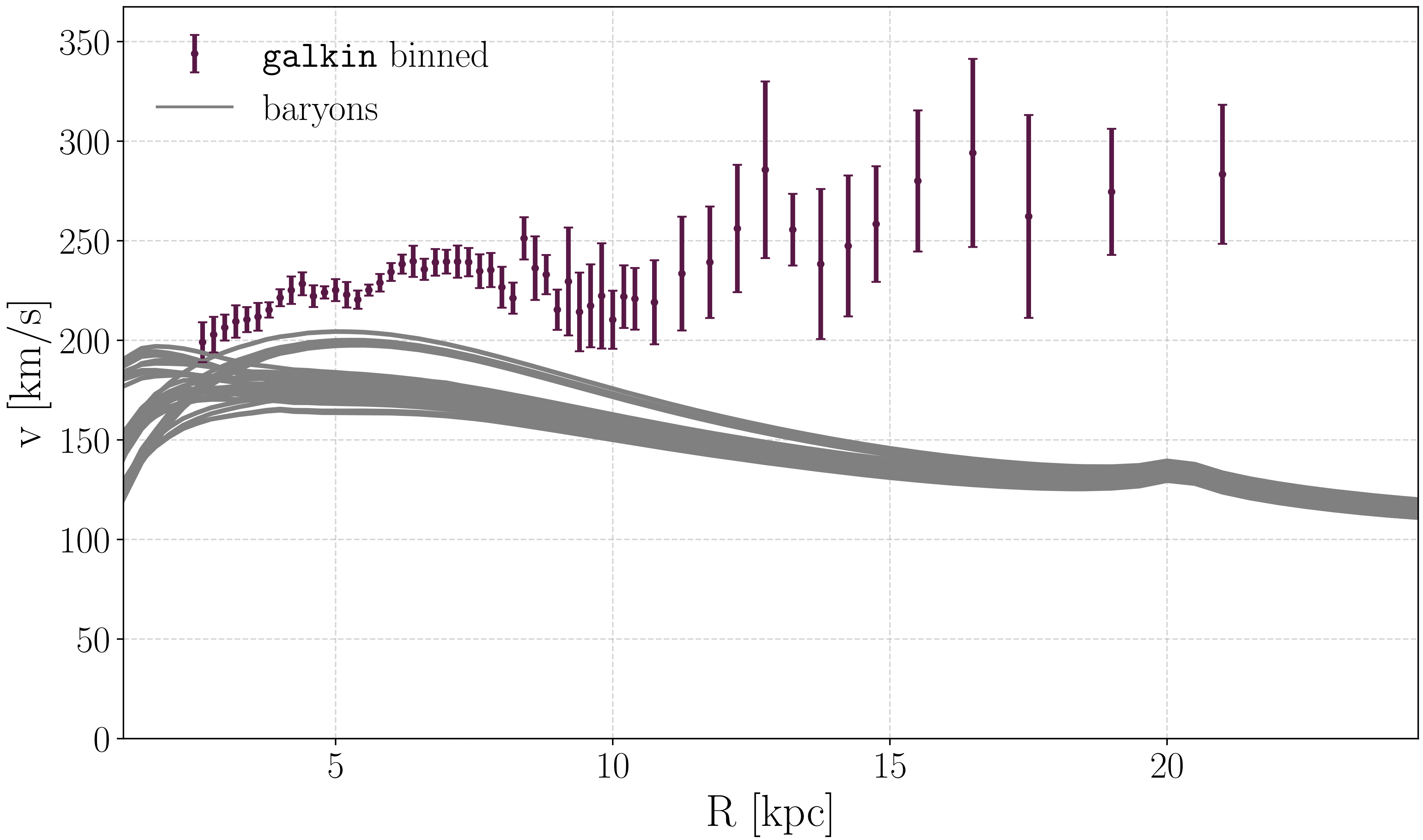
K. Ferriere +
ApJ 467 (2007)

How to reconstruct DM density profile?

Rotation Curve method

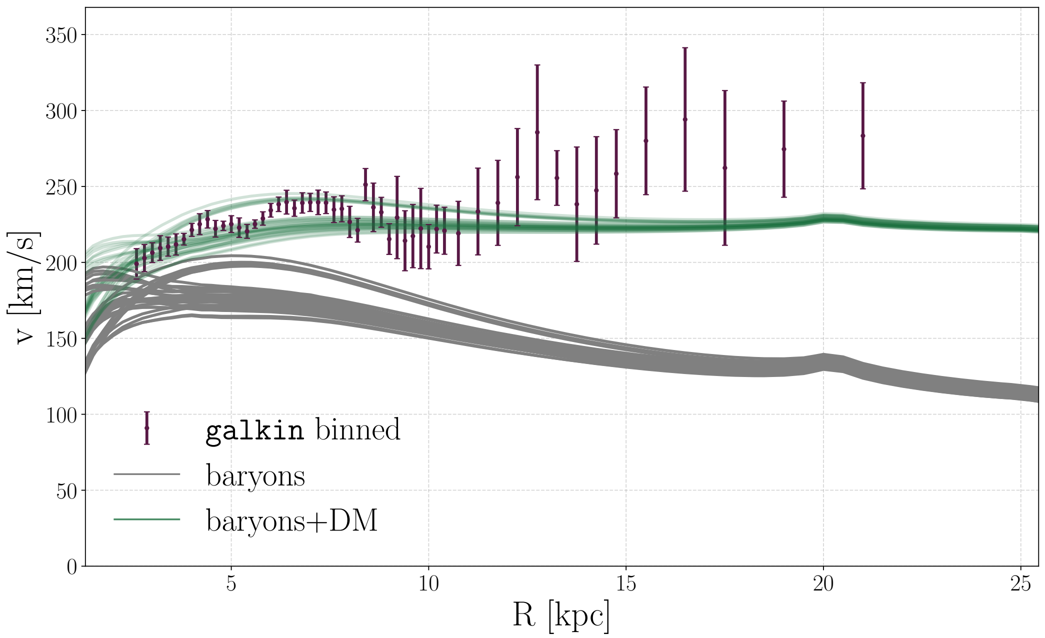
$$\rho_{\rm bulge}(x,y,z) \quad \rho_{\rm disc}(r,z) \quad \rho_{\rm gas}(x,y,z) \rightarrow \Phi_{\rm bulge}(x,y,z) \quad \Phi_{\rm disc}(r,z) \quad \Phi_{\rm gas}(x,y,z) \rightarrow v^2(r) = \sum_i v_i^2(r)$$

$$v_i^2(r) = r\frac{{\rm d}\Phi_i}{{\rm d}r}$$



How to reconstruct DM density profile?

Rotation Curve method



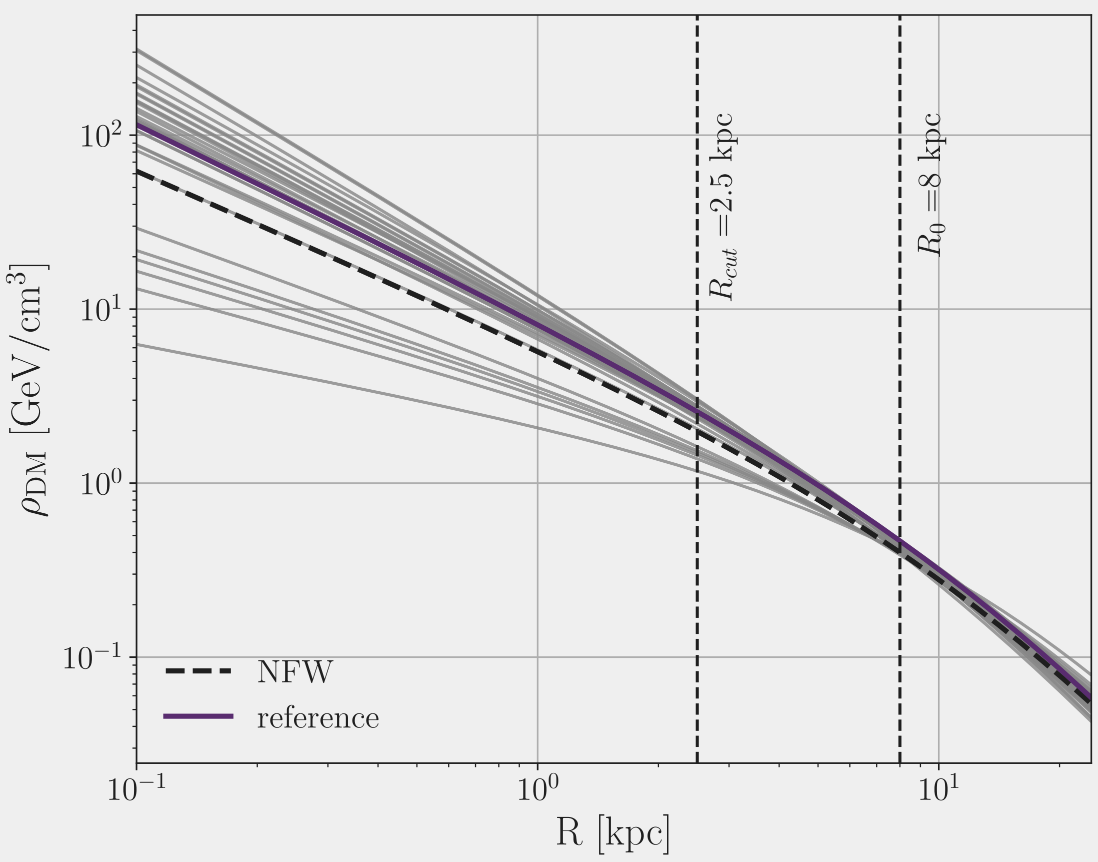
1) Observed RC

2) RC for the luminous component

gNFW density profile

$$\rho_{DM}(r) = \rho_0 \left(\frac{R_0}{r}\right)^{\gamma} \left(\frac{R_s + R_0}{R_s + r}\right)^{3-\gamma}$$

Three free parameters: γ, R_s, ρ_0



How to reconstruct DM density profile?

Rotation Curve method

No.	Parameters of our analysis	
1	$\mathcal{M}_i$	30 baryonic morphologies
2	ρ_0	DM parameters
3	R_s	
4	γ	
5	R_0	Sun's galactocentric distance
6	Σ_*	baryonic normalisation
7	$\langle \tau \rangle$	

7D parameter space: $\mathcal{M}_i,\ \gamma,\ R_s,\ \rho_0,\ R_0,\ \Sigma_*,\ \langle\tau\rangle$

$$\chi^2 = \sum_j \frac{\left(v_j - v_j^{obs}\right)^2}{\sigma^2_{v_j^{obs}}} + \frac{\left(\langle\tau\rangle - \langle\tau\rangle^{obs}\right)^2}{\sigma^2_{\langle\tau\rangle^{obs}}} + \frac{\left(\Sigma_* - \Sigma_*^{obs}\right)^2}{\sigma^2_{\Sigma_*^{obs}}}$$

Normalisation bulge

$\langle\tau\rangle^{obs} = 2.17^{+0.47}_{-0.38} \times 10^{-6} \quad (\ell, b) = (1.50^o, -2.68^o)$

Popowski +
ApJ 631 (2005)

Normalisation disc

$\Sigma_*^{obs} = 38 \pm 4\,\mathrm{M_\odot pc^{-2}}$

Bovy & Rix
ApJ 779 (2013)

Scan the 7D parameter space to obtain the Likelihood profile

Further profile over $\mathcal{M}_i,\ \langle\tau\rangle, \Sigma_*$

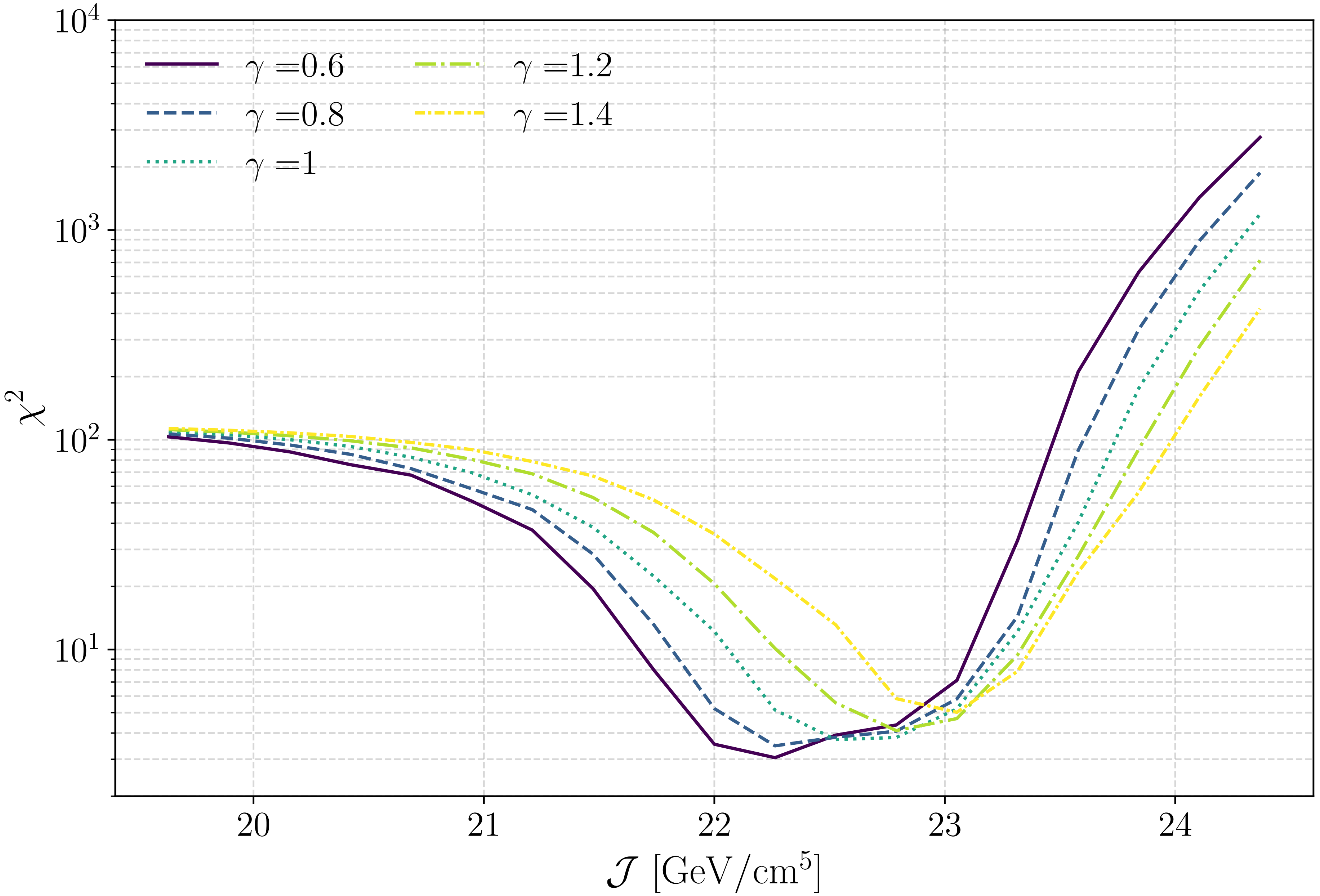
$$\chi^2_{\mathrm{RC}}(R_s, \rho_0, \gamma, R_0)$$

Publicly available!

Example: Galactic Center γ-ray excess

χ^2 profiled over:

- baryonic morphology and normalisation,
- Sun's distance to GC,
- DM parameters (scale radius and local DM density)



$$\mathcal{J} = \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} ds\, \rho^2_{\rm DM}(r(s,\psi))$$

ROI:

40°x40° around GC with a strip of ±2° along the Galactic plane excluded

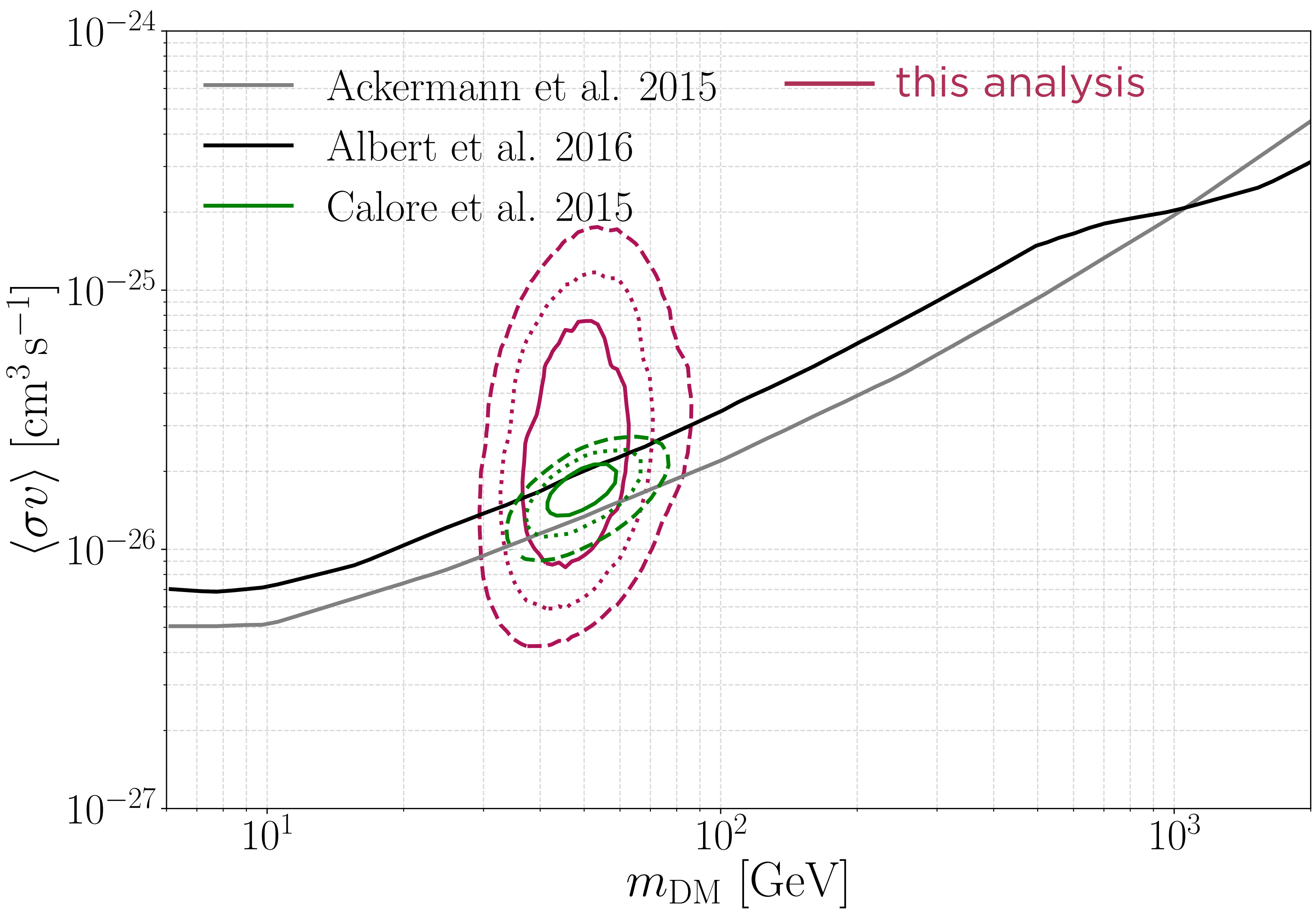
Example: Galactic Center excess

$$\chi^2_{\rm total} = \chi^2_{\rm GCE}(\langle\sigma v\rangle, m_{\rm DM}, \mathcal{J}) + \chi^2_{\rm RC}(R_s, \rho_0, \gamma, R_0) + \chi^2_{R_s,\rho_0,\gamma,R_0}$$

GCE analysis

RC analysis

Priors



$b\bar{b}$ DM annihilation channel

Take away I

Likelihood profile (based on real data) for the reconstructed DM density profile in the MW.

It represents state-of-the-art from observations only (no simulations).

It takes into account astrophysical uncertainties on:

- 3D distribution of baryons (stars+gas) in the Galaxy;
- weight of baryons with respect to total mass budget;
- Sun's galactocentric distance and
- observed RC.

Available at:

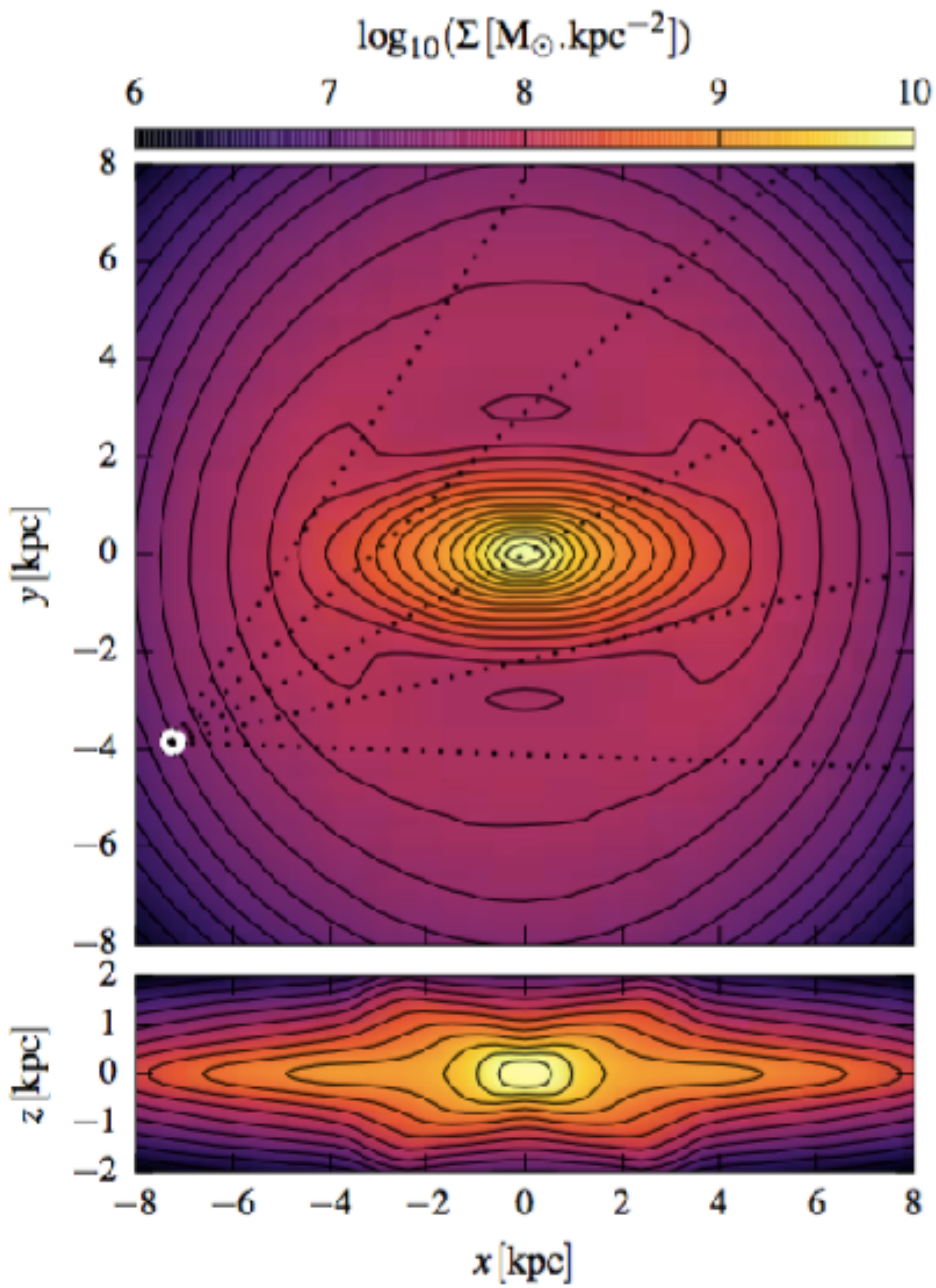
https://github.com/mariabenitocst/UncertaintiesDMinTheMW

It can be used in direct/indirect searches (e.g. GC/Galactic halo DM searches in gamma-rays, DM neutrinos searches, direct DM searches and local DM searches with antimatter).

How to determine DM density profile?

Rotation Curve method

CAVEAT



Assumptions:

- Rotationally supported
- Objects move in circular orbits around the GC
- The gravitational potential is axisymmetric

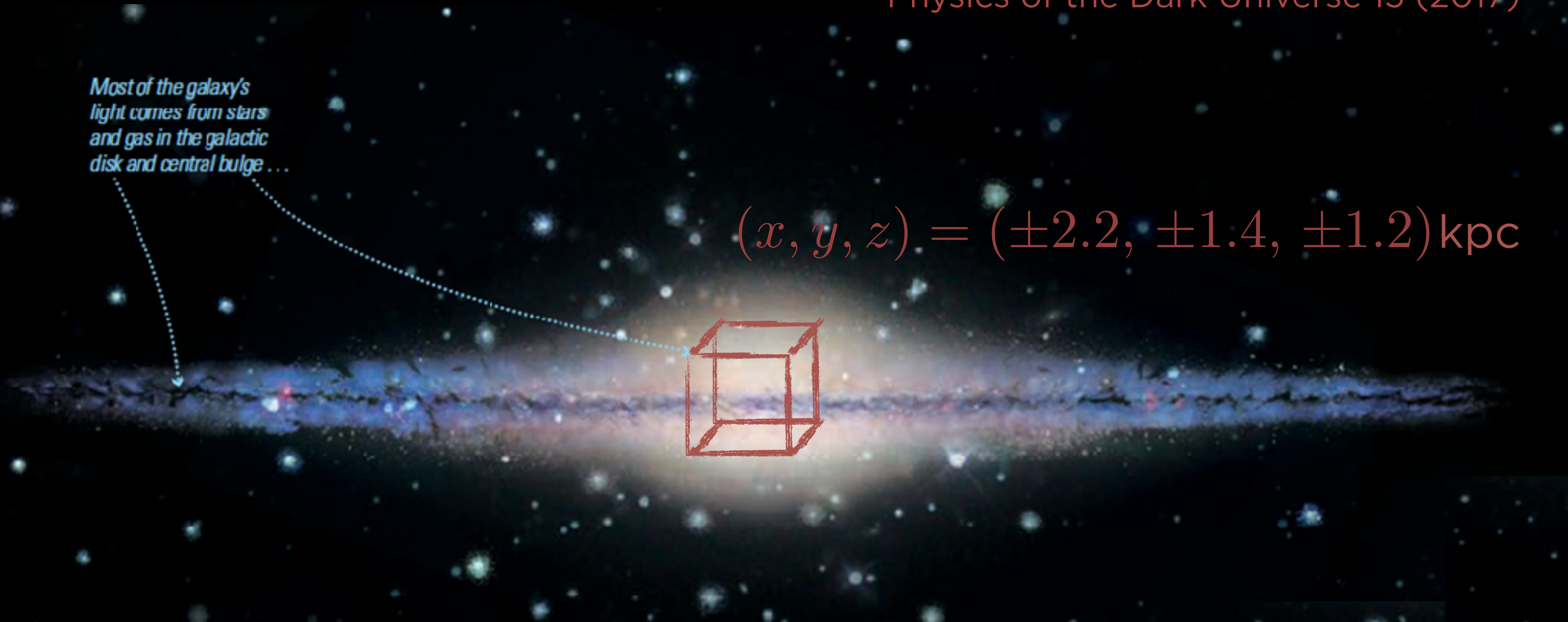
Only applies for R > 2.5 kpc

Face-on (upper) and side-on (lower) projection of the 3D density of the MW bulge

Portail +
MNRAS 465 (2017)

How to reconstruct DM density profile in Galactic Bulge region?

Iocco & MB
Physics of the Dark Universe 15 (2017)



$(x, y, z) = (\pm 2.2,\ \pm 1.4,\ \pm 1.2)$ kpc

Total mass

$$M_{total} = (1.85 \pm 0.05) \times 10^{10}\,\mathrm{M}_{\odot}$$

Portail +
MNRAS 465 (2017)

Stellar mass

$$M_*^i = \int_{box} \rho_*^i(x, y, z)\,\mathrm{d}V$$

Methodology

Allowed DM mass

$$M_{total} - M_*^i = M_{DM}^i$$

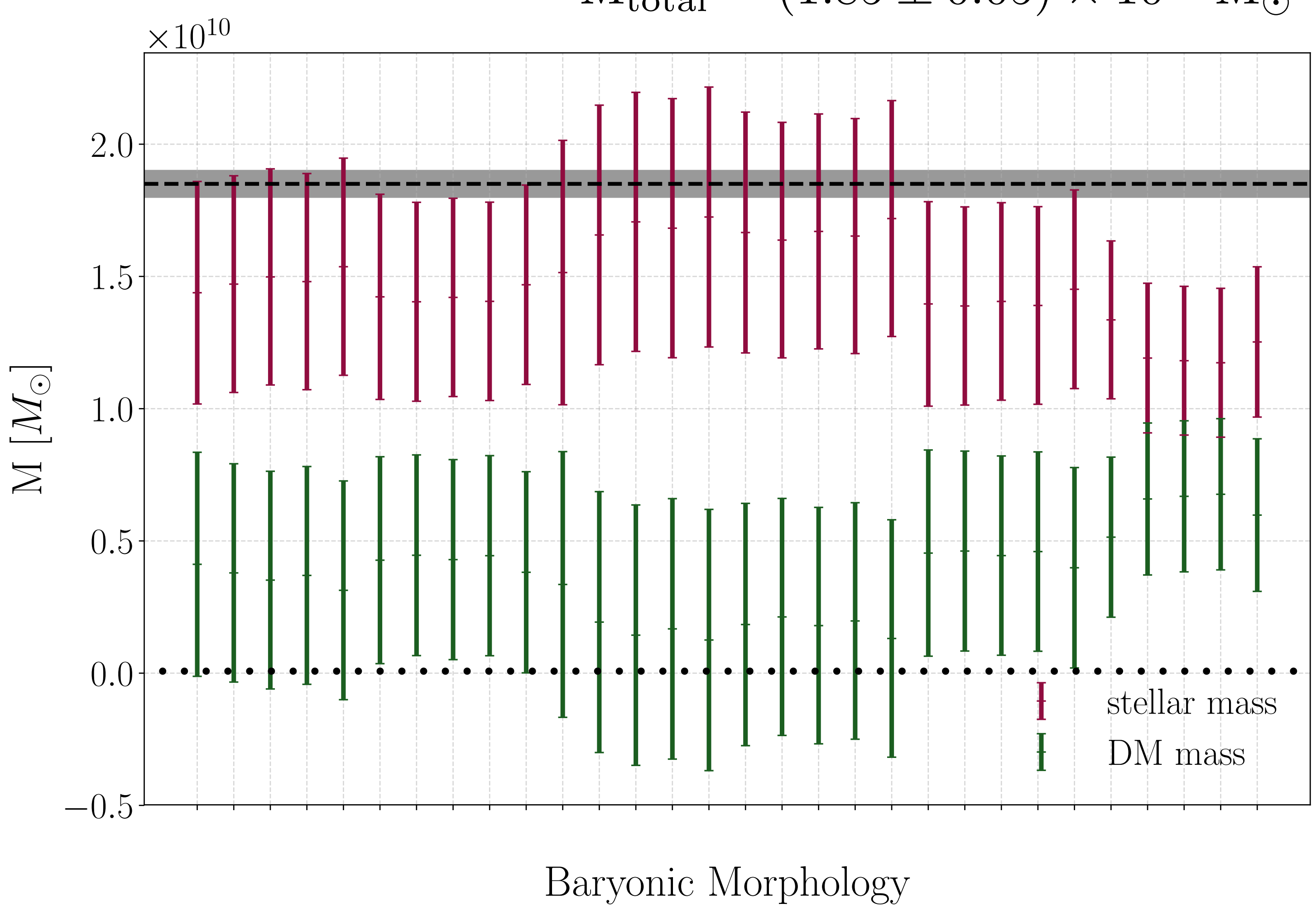
$$\sigma_{M_{DM}^i} = \sqrt{\sigma^2_{M_{total}} + \sigma^2_{M_*^i}}$$

$$\mathrm{M}_* = (1.1 - 1.7) \times 10^{10}\mathrm{M}_\odot$$

$$\mathrm{M}_{\mathrm{DM}} = (0.1 - 0.7) \times 10^{10}\mathrm{M}_\odot$$

DM mass corresponds to 7-37%

$$\mathrm{M}_{\mathrm{total}} = (1.85 \pm 0.05) \times 10^{10}\,\mathrm{M}_\odot$$

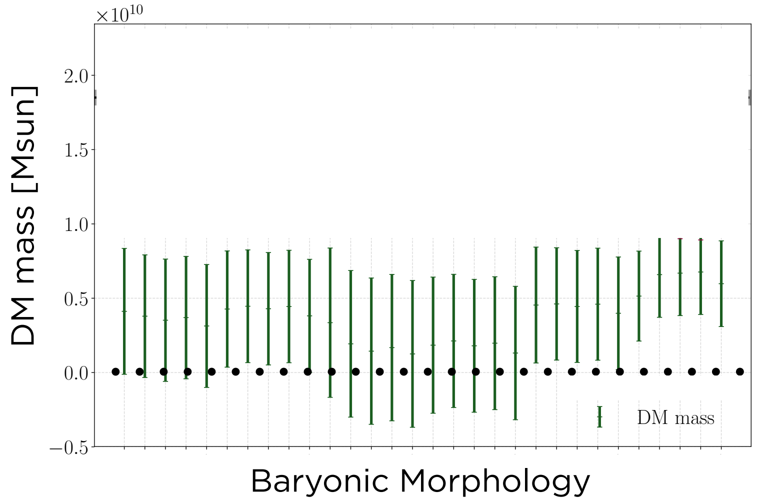


gNFW density profile

$$\rho_{DM}(r) = \rho_0 \left(\frac{R_0}{r}\right)^{\gamma} \left(\frac{R_s + R_0}{R_s + r}\right)^{3-\gamma}$$

Study parameter space that gives a mass in excess or defect with respect to the allowed DM mass

Galactic Bulge Region - Results: varying bulge morphology



$$R_s = 20\,\mathrm{kpc}$$

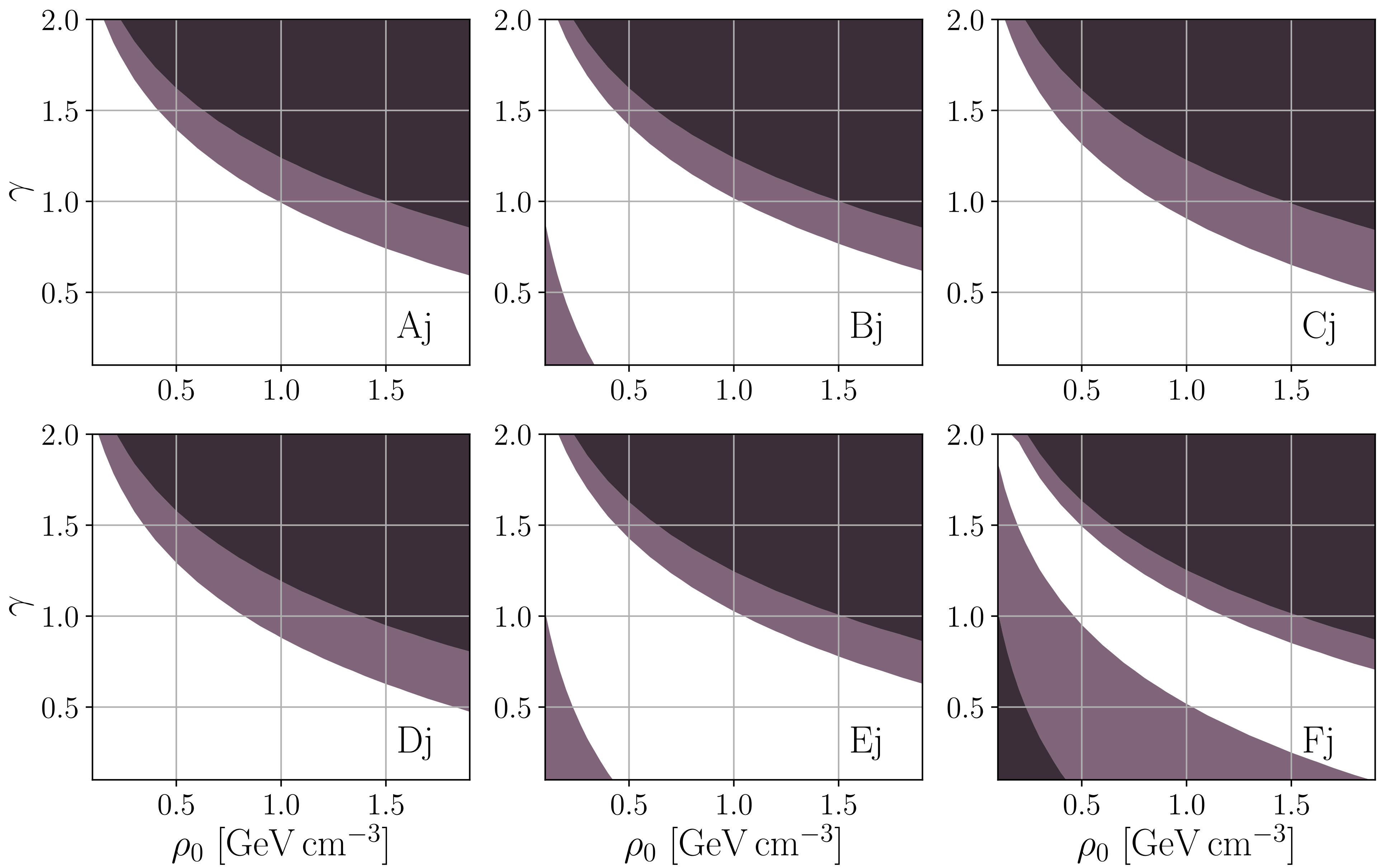
$$R_0 = 8\,\mathrm{kpc}$$

Same disc, varying bulge

Allowed at 1σ

Allowed at 2σ

Excluded at 2σ

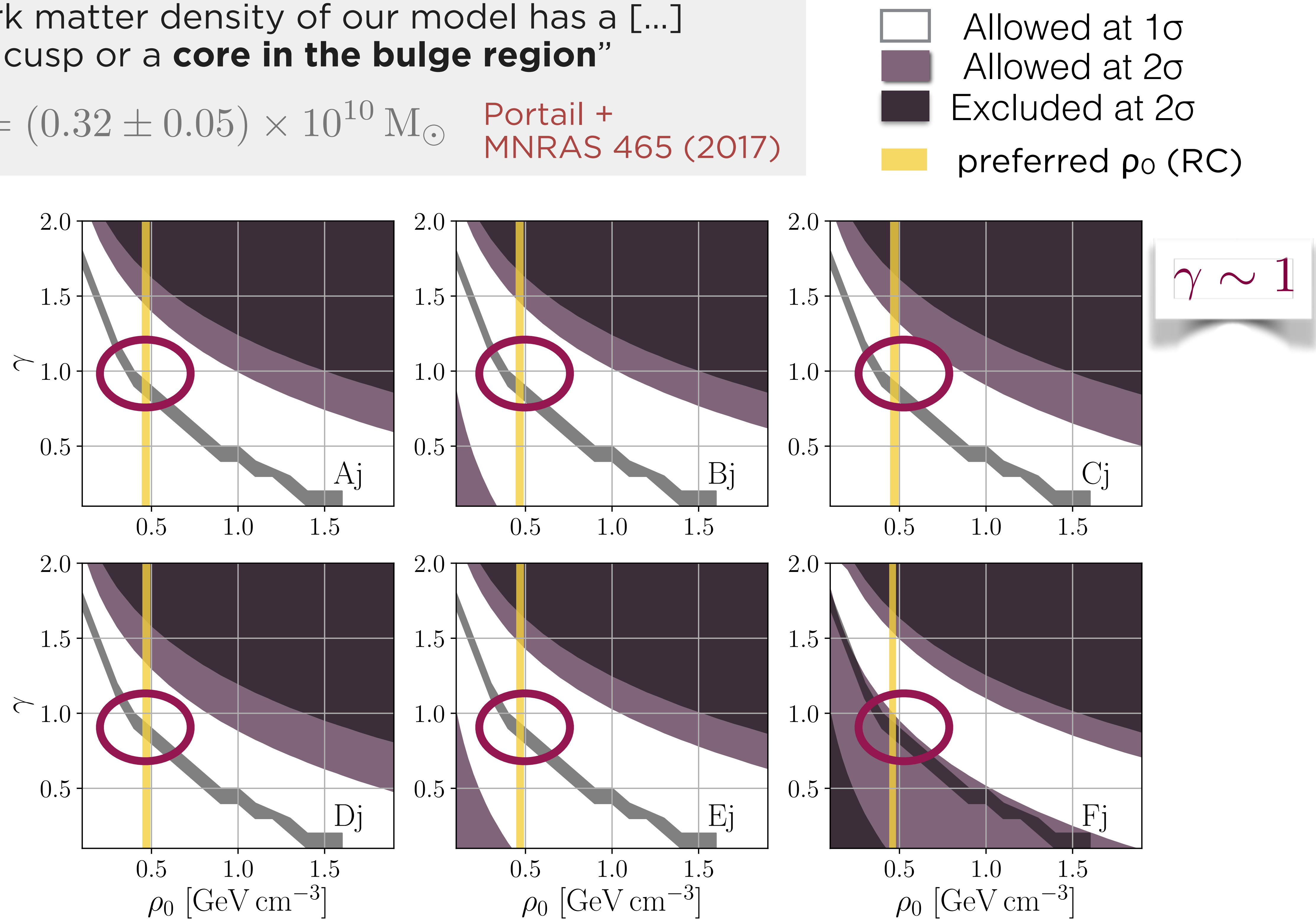


Galactic Bulge Region - Results: varying bulge morphology

"the dark matter density of our model has a [...] shallow cusp or a **core in the bulge region**"

$$M_{DM} = (0.32 \pm 0.05) \times 10^{10}\, M_{\odot}$$

Portail +
MNRAS 465 (2017)

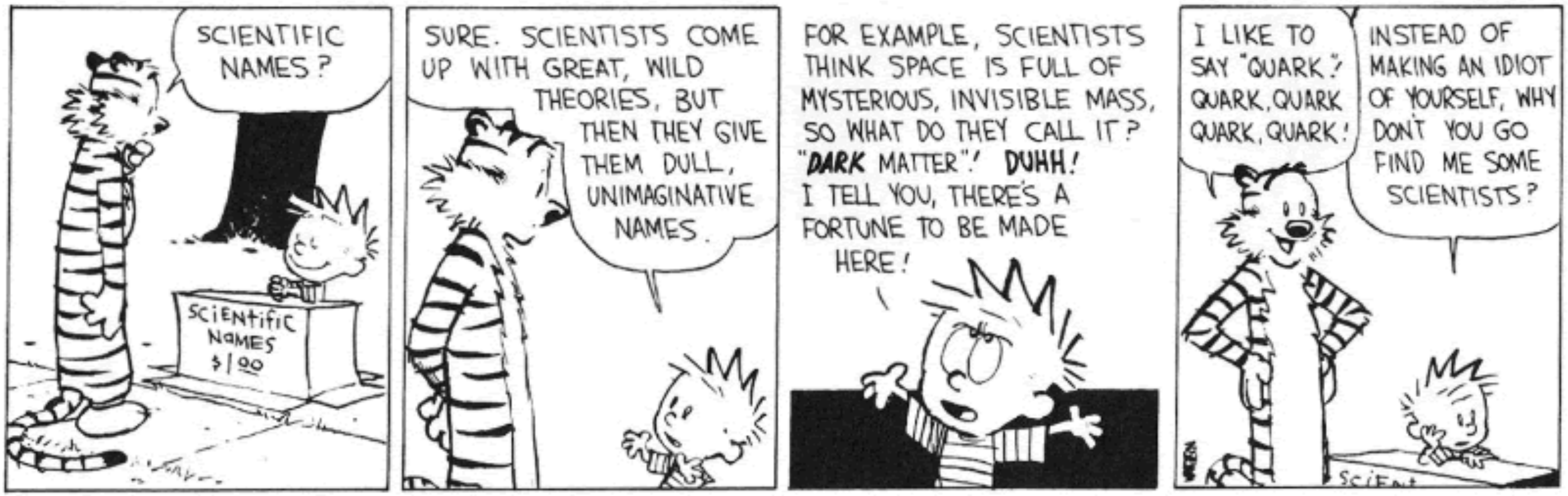


Core is not a necessary condition!

Take away II

- Our ignorance about the morphology of the bulge and the normalisation of the visible component **prevents strong conclusions on the DM distribution in the inner 2.5 kpc**.

- Larger uncertainties for the slope of the profile (γ), **DM distribution remain yet inconclusive.**



ありがとう

Obrigada

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