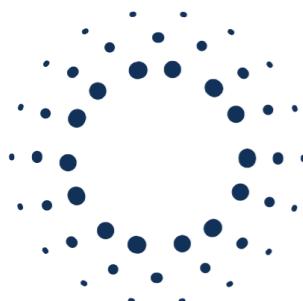


The Dark Matter distribution of the Milky Way:

its uncertainties and their effect on the
determination of new physics

María Benito

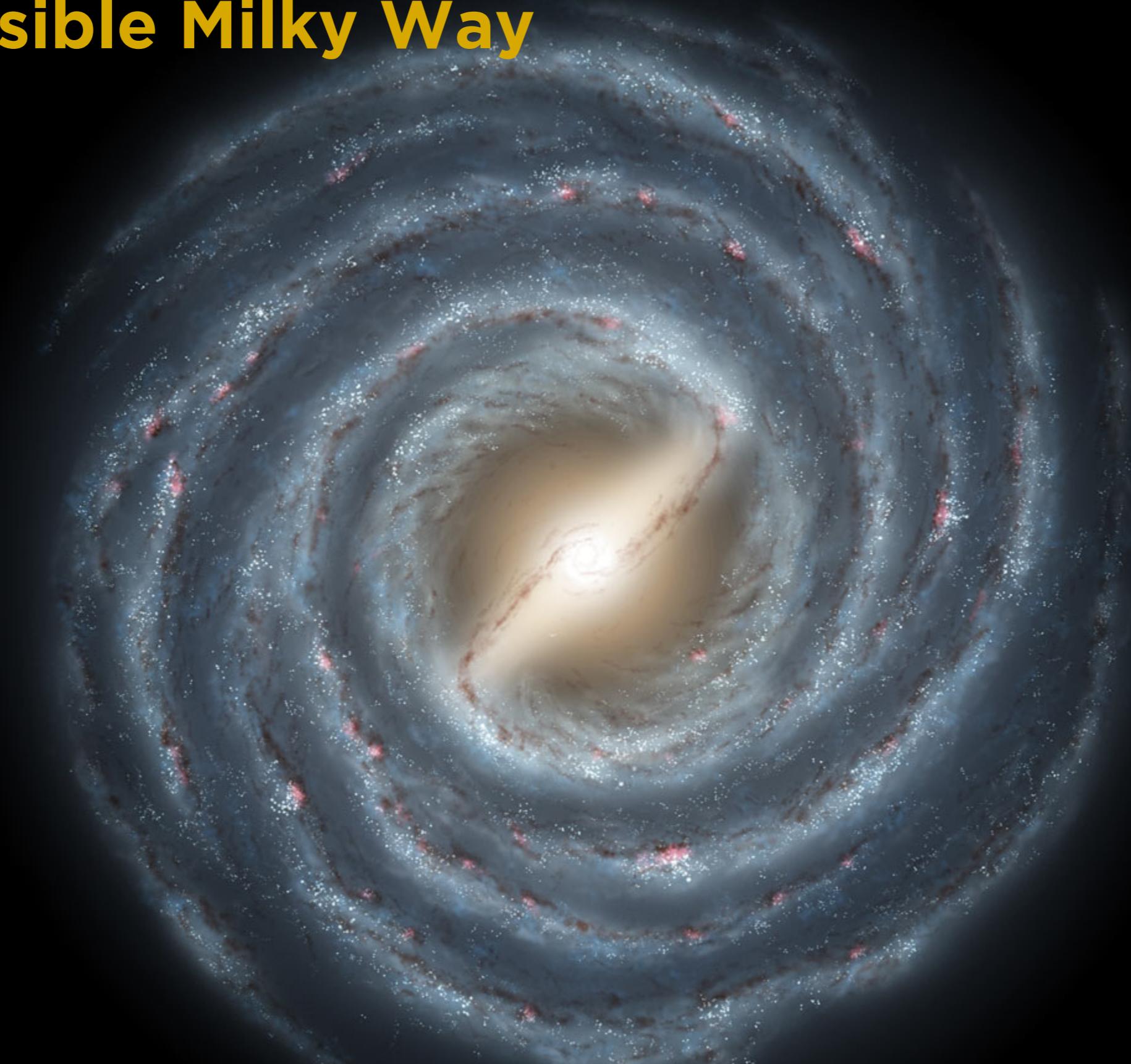


IFT - UNESP
INSTITUTO DE FÍSICA
TEÓRICA - UNESP

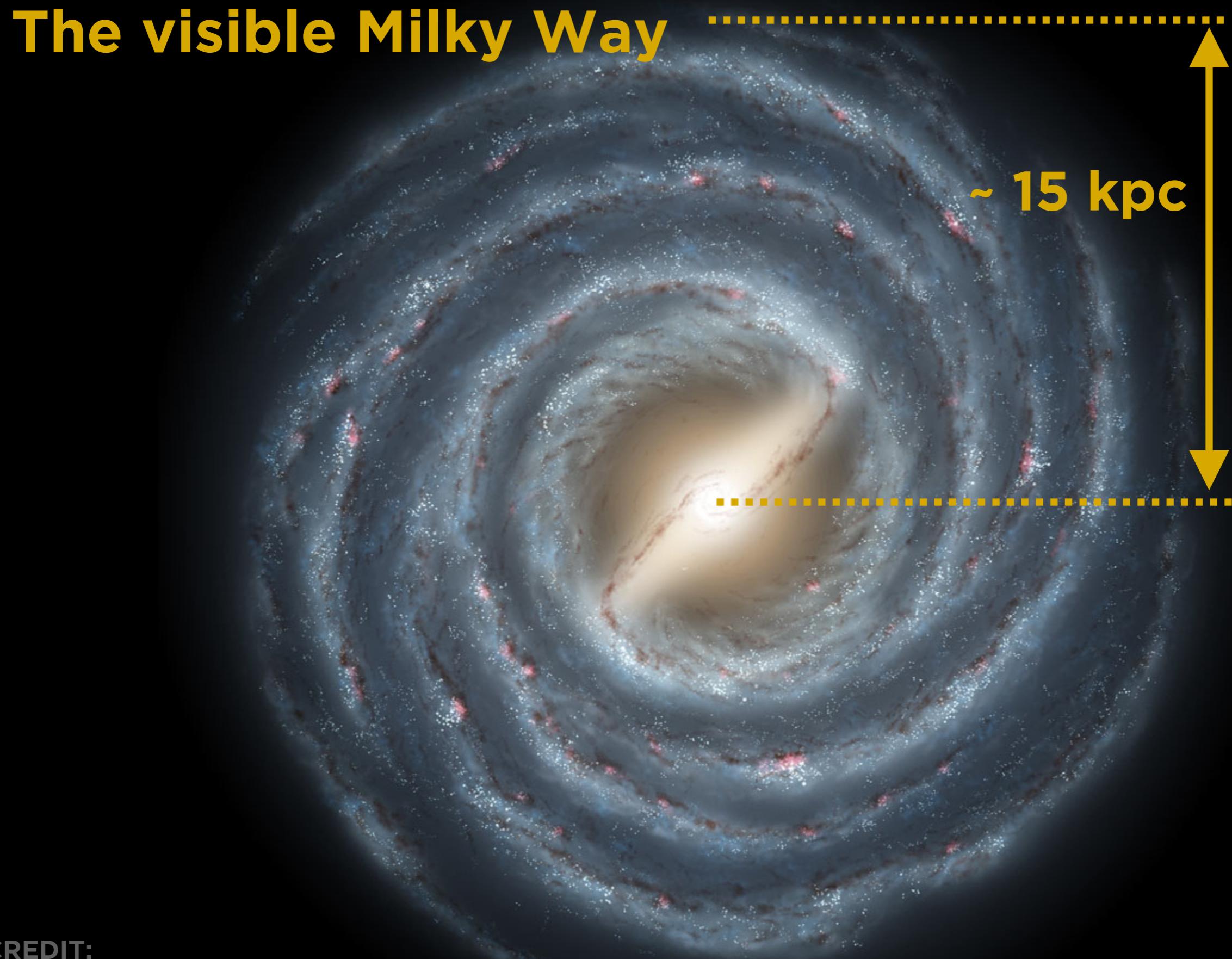


Next Frontiers in the
Search for Dark Matter
23/09/2019

The visible Milky Way



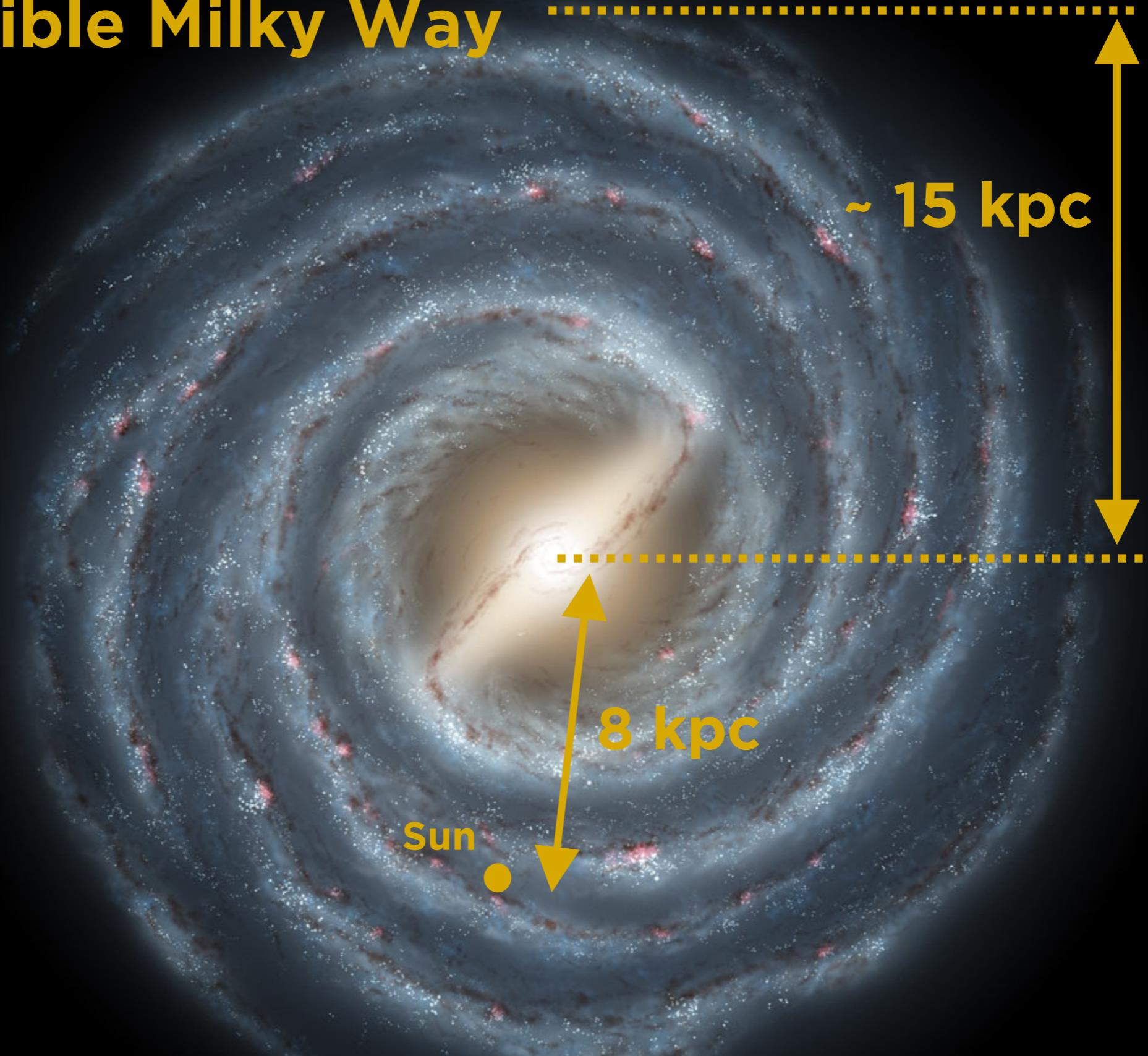
CREDIT:
NASA/JPL-Caltech/ESO/R. Hurt



~ 15 kpc

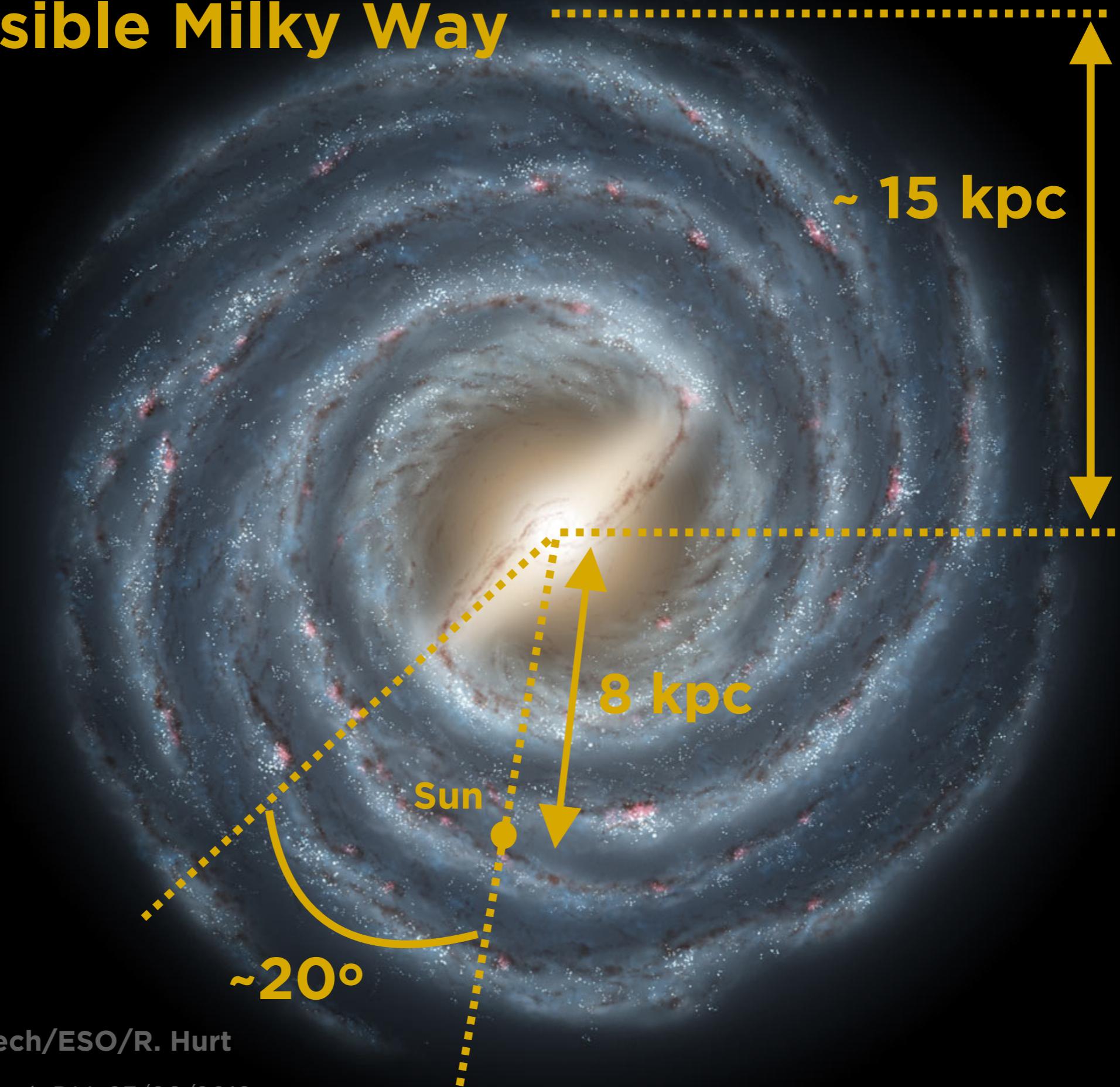
CREDIT:
NASA/JPL-Caltech/ESO/R. Hurt

The visible Milky Way



CREDIT:
NASA/JPL-Caltech/ESO/R. Hurt

The visible Milky Way

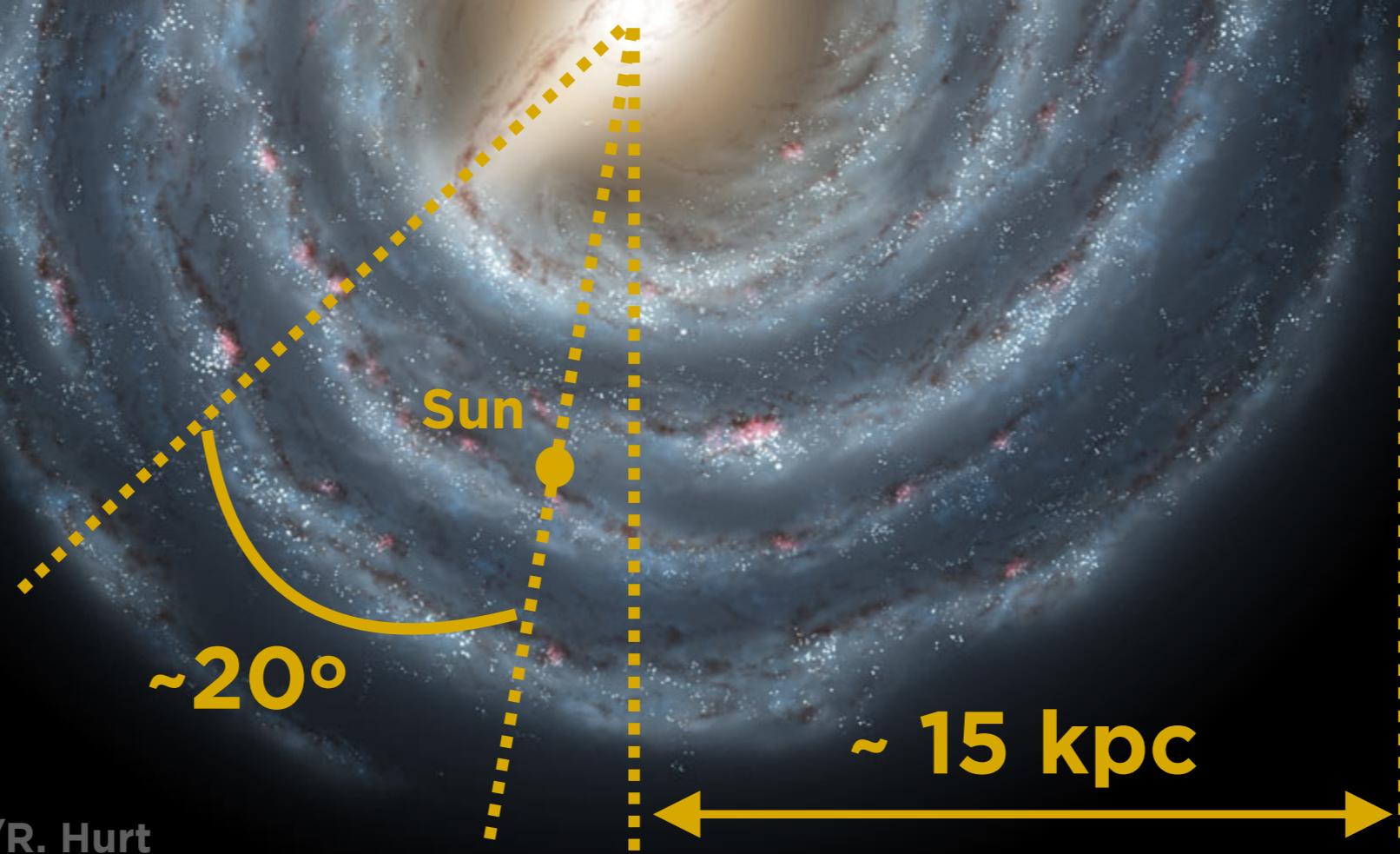


CREDIT:
NASA/JPL-Caltech/ESO/R. Hurt

The Milky Way

$M_{200} \sim 10^{12} M_\odot$

$M_{\text{baryons}} \sim 7 \times 10^{10} M_\odot$



CREDIT:
NASA/JPL-Caltech/ESO/R. Hurt

The Milky Way

$$M_{200} \sim 10^{12} M_\odot$$

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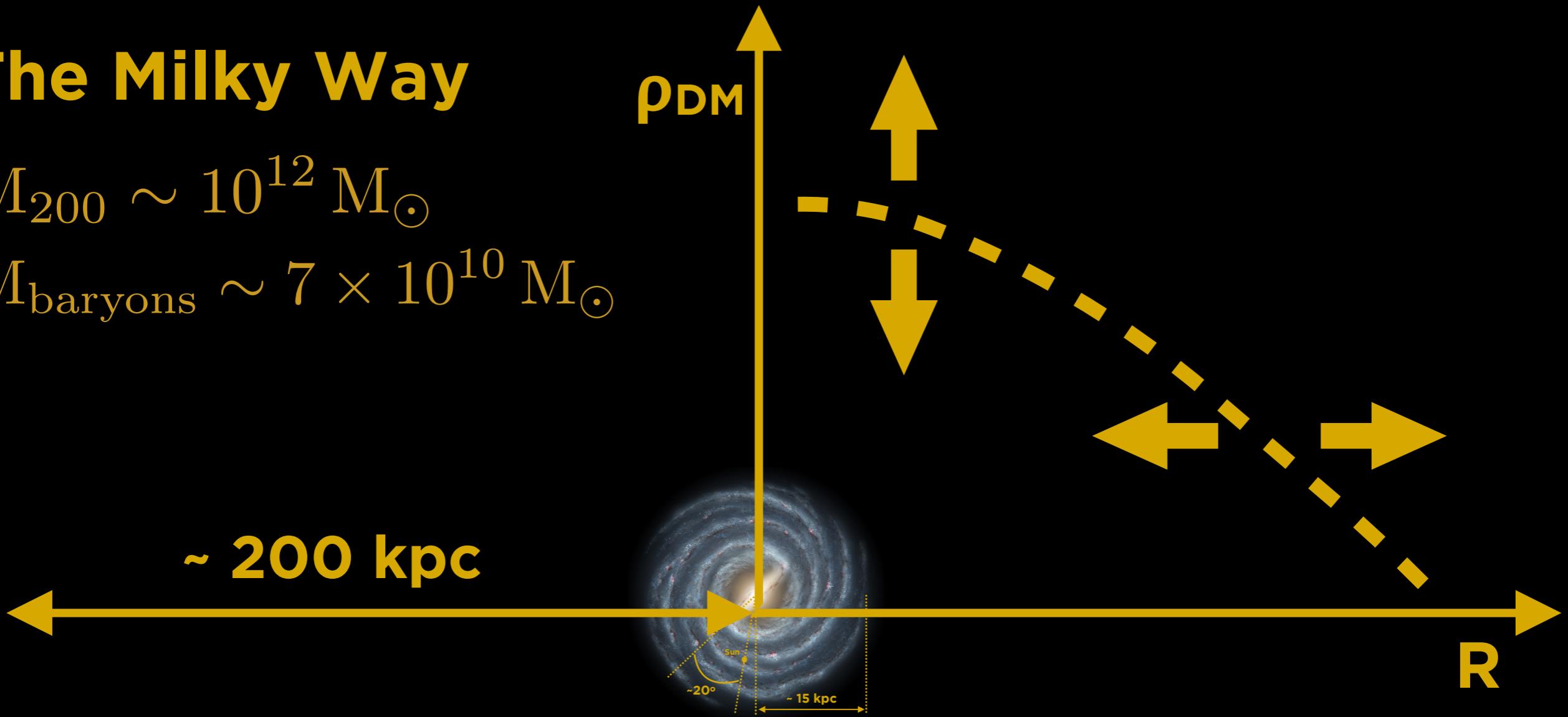


CREDIT:
NASA/JPL-Caltech/ESO/R. Hurt

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$M_{200} \sim 10^{12} M_\odot$

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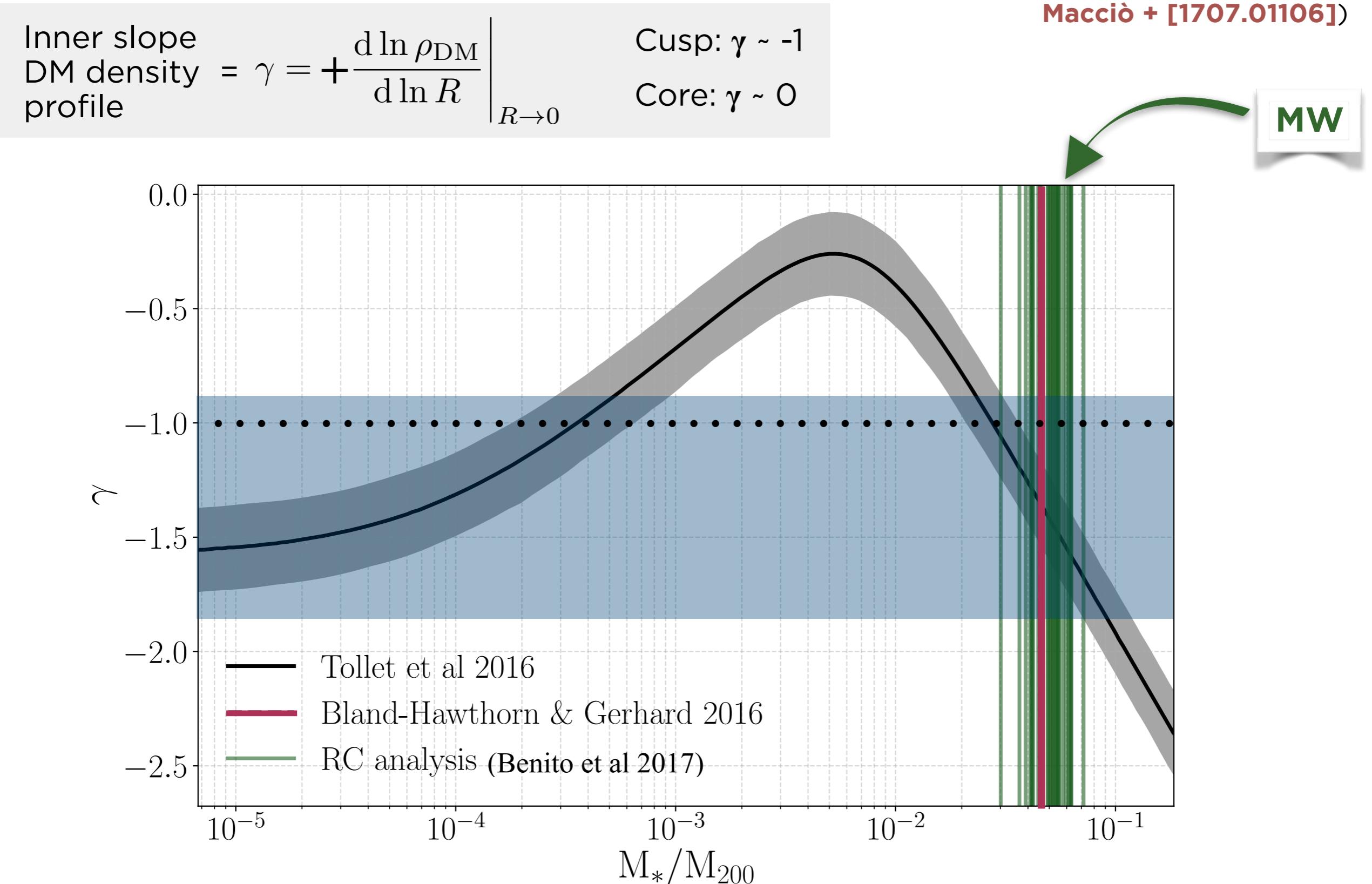


What is the actual distribution of DM in the MW?

CREDIT:
NASA/JPL-Caltech/ESO/R. Hurt

Why it is important?

Correlation between inner slope and star formation efficiency (e.g. DiCintio + [1306.0898]
Tollet + [1507.03590] Macciò + [1707.01106])

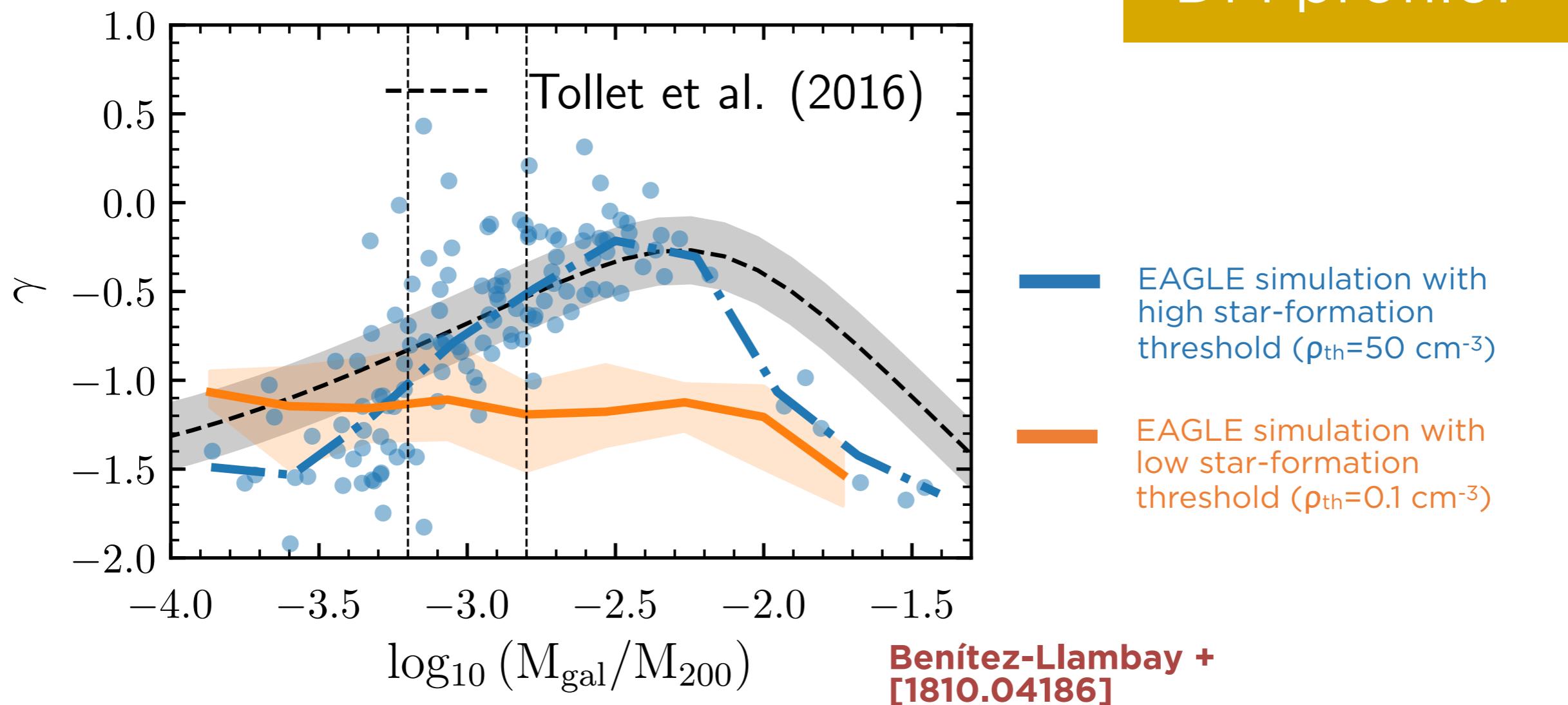


Why it is important?

The precise effect of baryonic feedback processes on the distribution of DM is unknown

Inner slope
DM density profile = $\gamma = +\frac{d \ln \rho_{\text{DM}}}{d \ln R} \Big|_{R \rightarrow 0}$

Cusp: $\gamma \sim -1$
Core: $\gamma \sim 0$

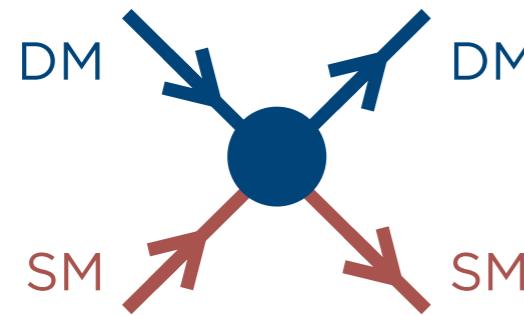


Why it is important?

Direct/Indirect WIMP searches

Simplified version

Direct



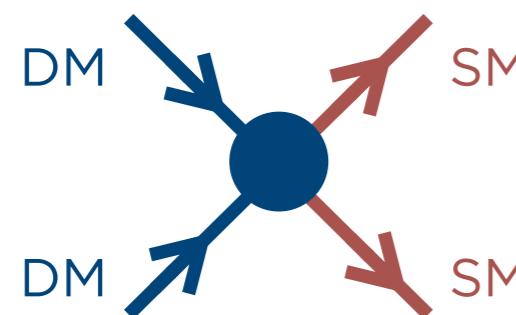
Recoil spectrum for DM-nucleus interaction:

$$\frac{dR}{dE} \sim C_{\text{PP}} \rho_0 \int_{v > v_{\min}} d^3v \frac{f(\mathbf{v}, t)}{v}$$

Dependence on astrophysics

Impact of velocity distribution function:
Bozorgnia & Bertone
[1705.05853]
Evans + [1810.11468]

Indirect

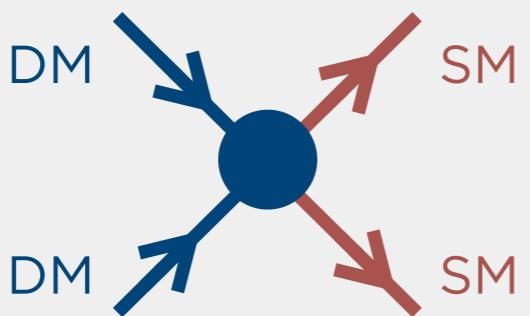


Flux due to DM self-annihilation:

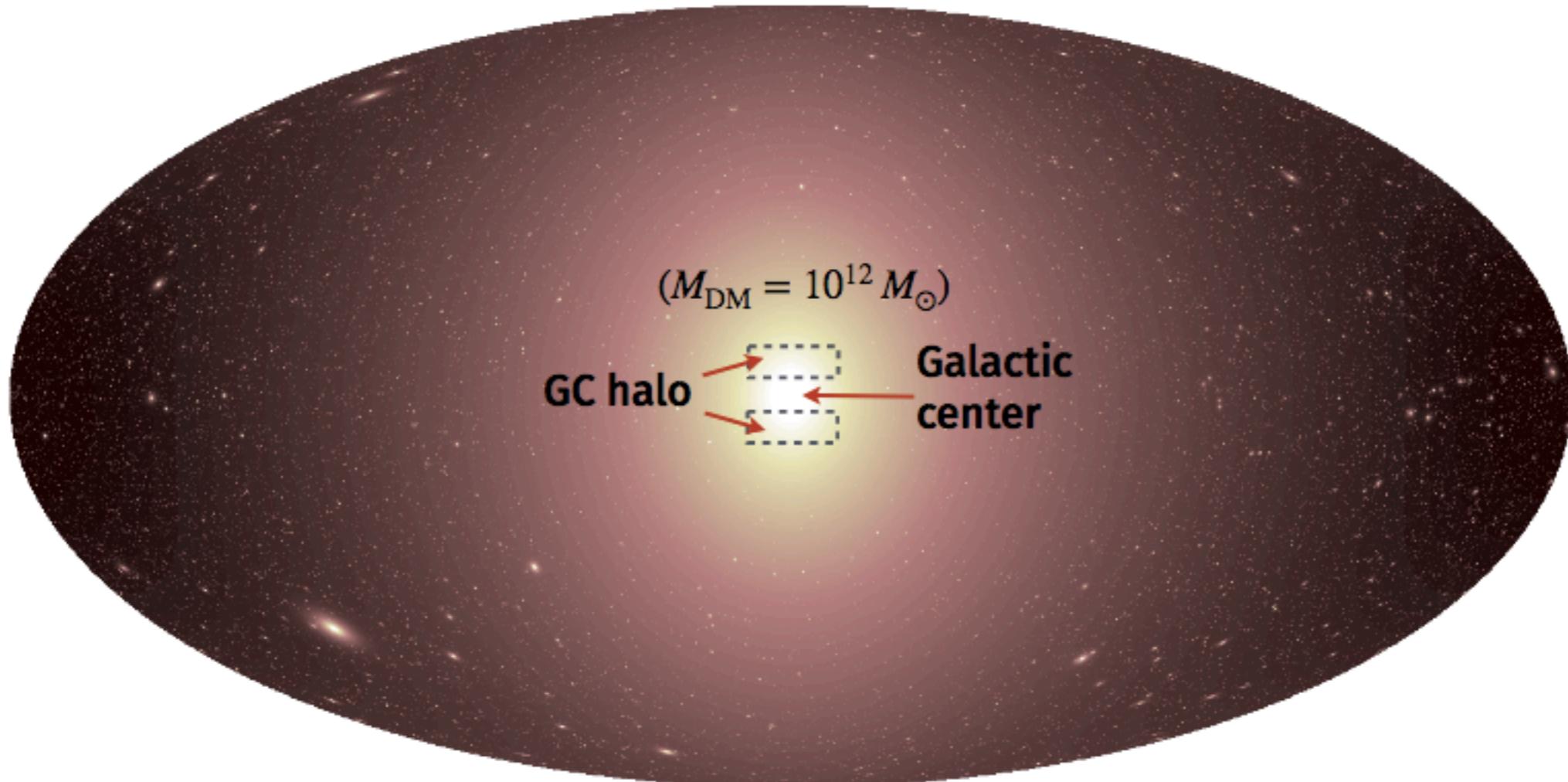
$$\Phi_{\text{DM}} \sim \Phi_{\text{PP}} \int_{\text{l.o.s}} dl \rho_{\text{DM}}^2$$

Dependence on astrophysics

Targets for indirect WIMP searches: our Galaxy



$$\Phi_{\text{DM}} \sim \Phi_{\text{PP}} \int_{\text{l.o.s}} dl \rho_{DM}^2$$



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

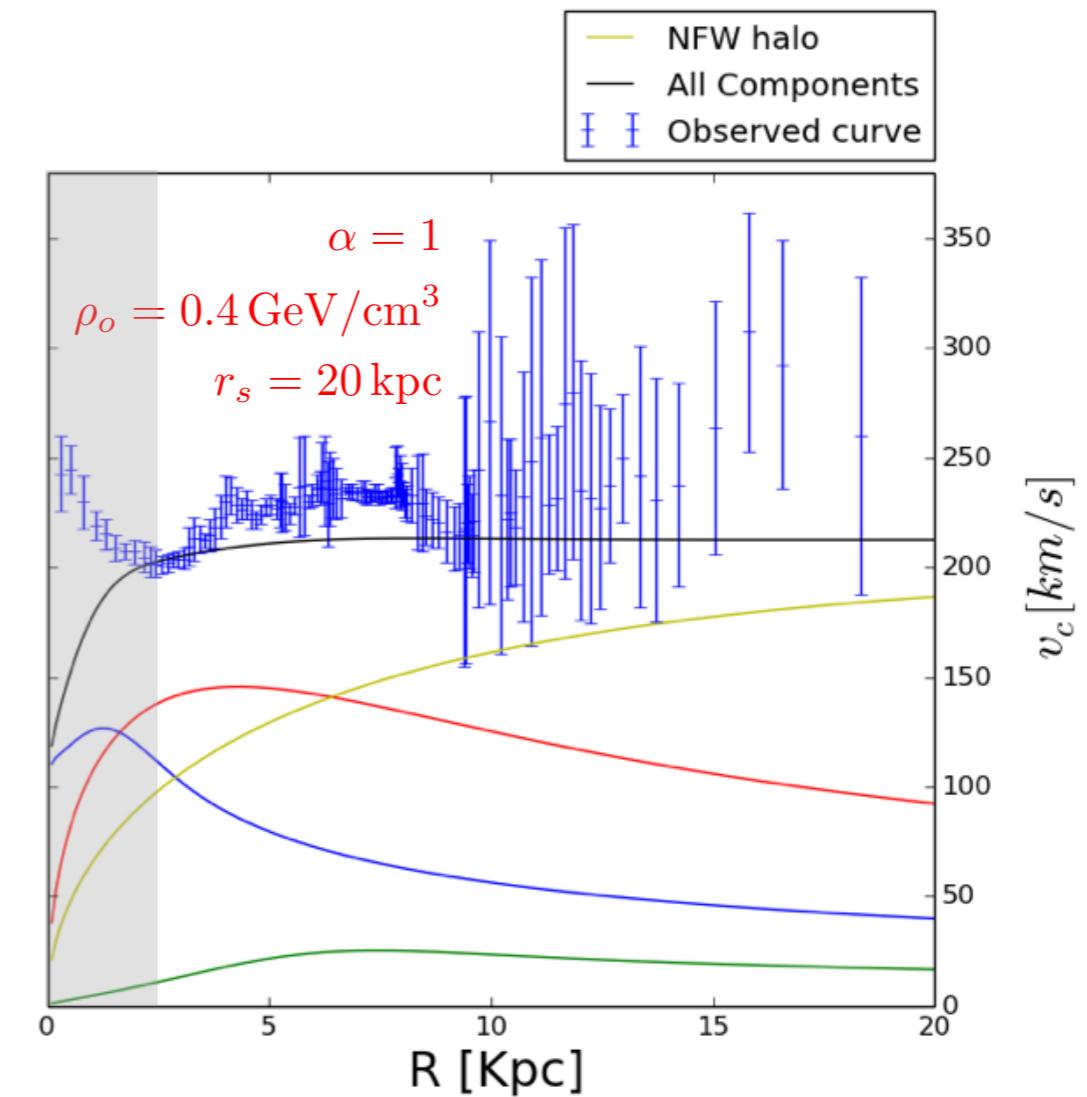
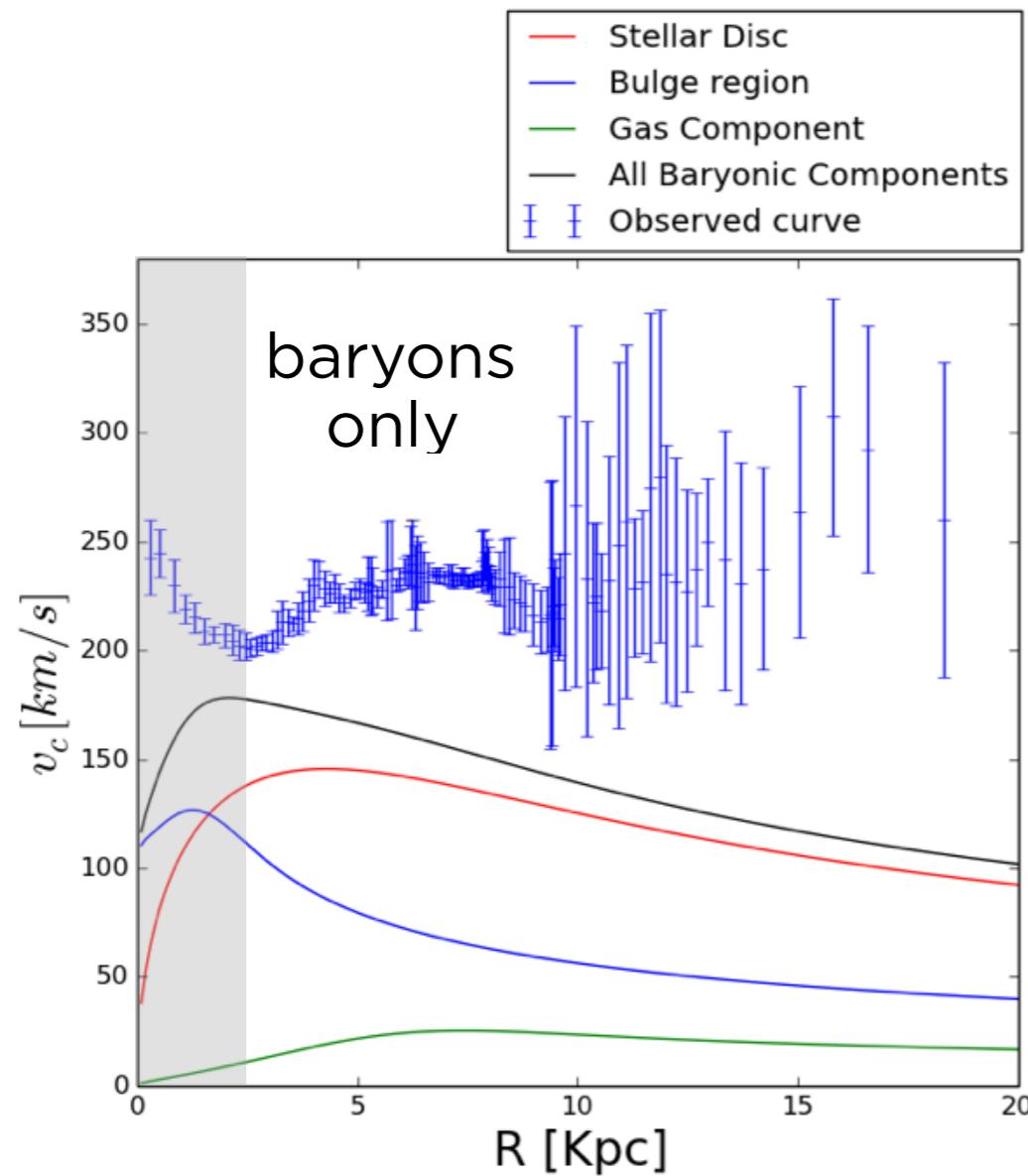
Credit: M. Hütten

Goal:

Quantify uncertainties on the reconstructed DM density profile of the MW

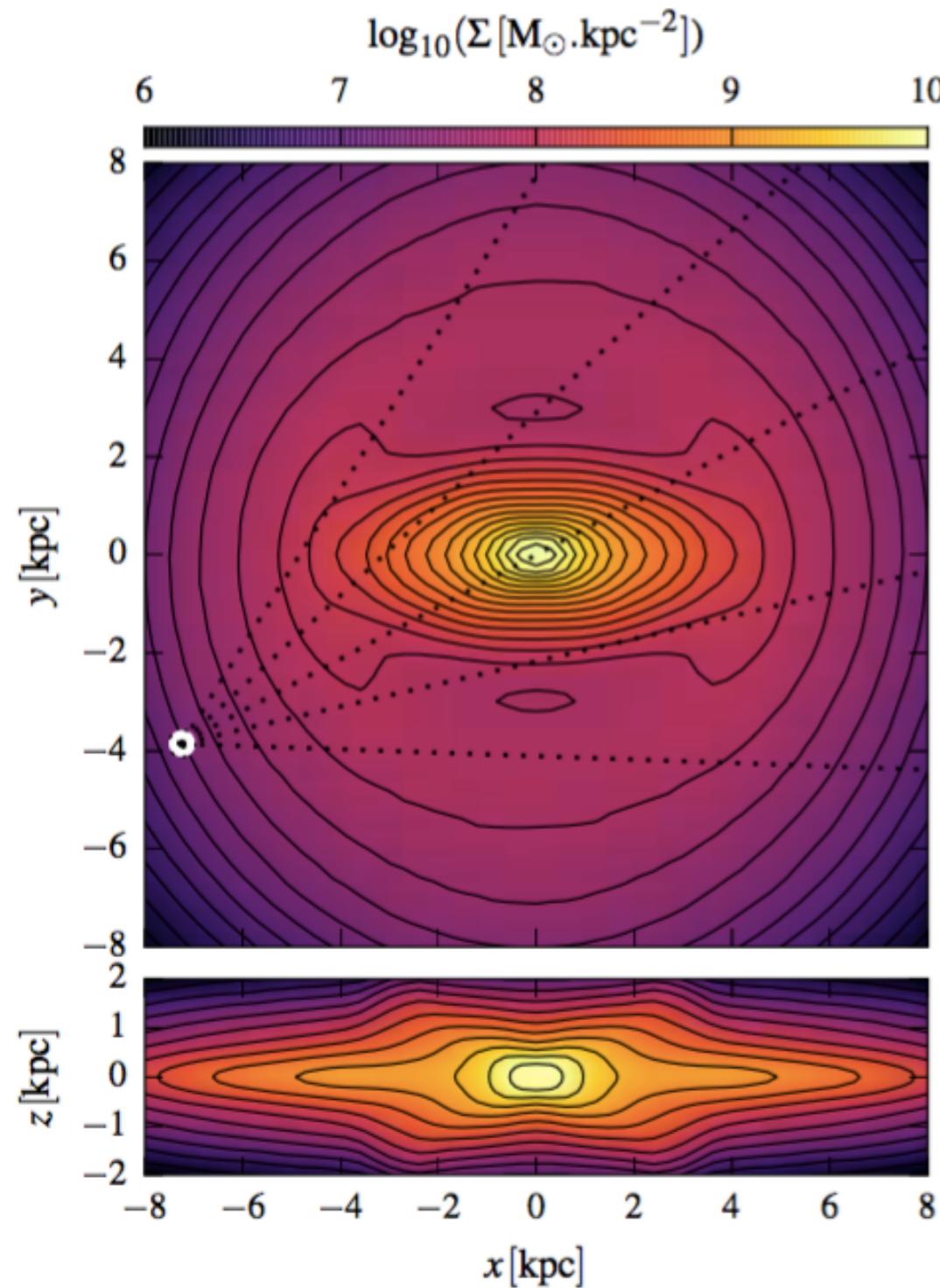
How?

Rotation Curve method



How to determine DM density profile?

Rotation Curve method



Assumptions:

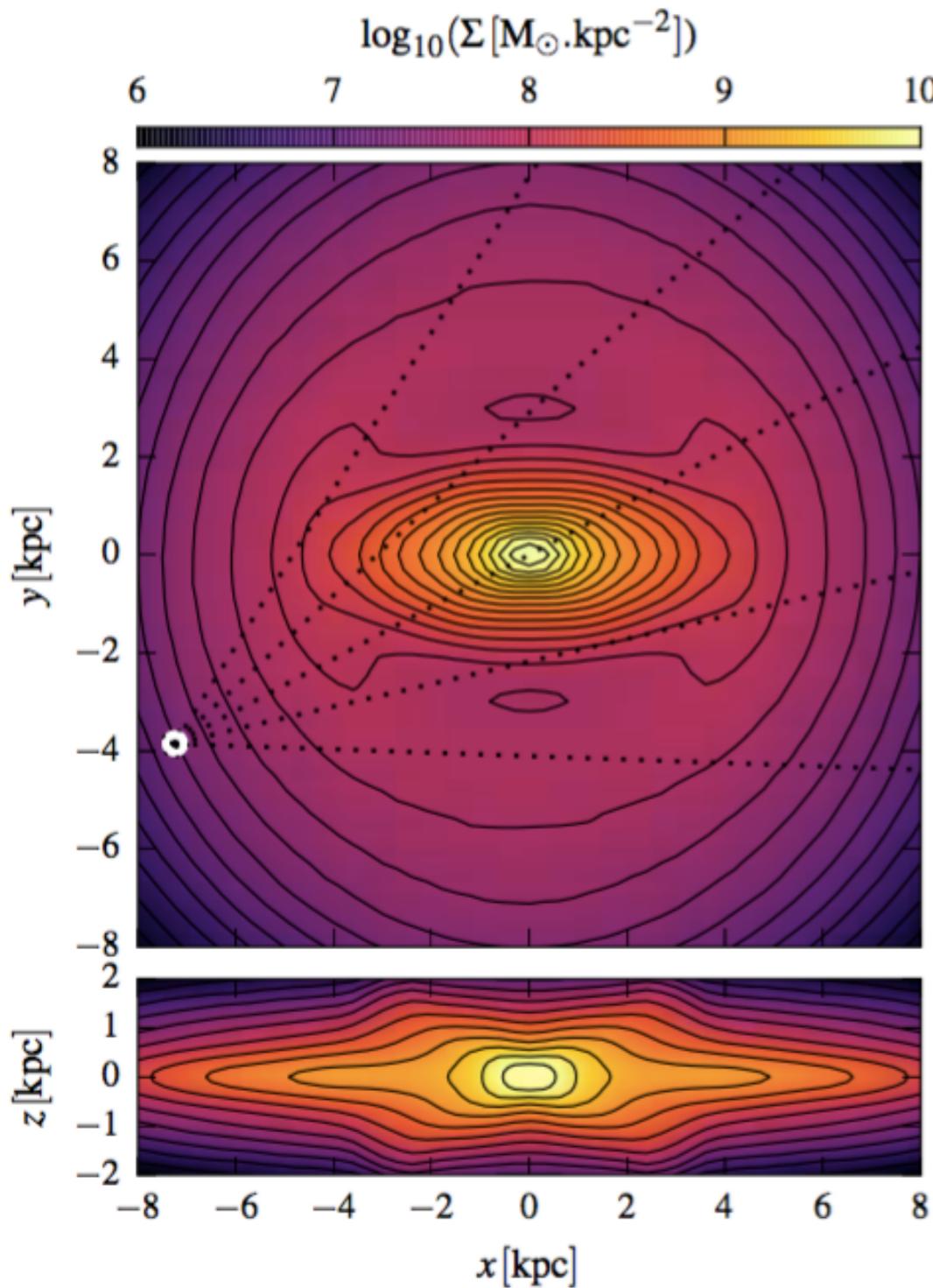
- ▶ Rotationally supported
- ▶ Objects move in circular orbits around the GC
- ▶ The gravitational potential is axisymmetric

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

Portal +
[1608.07954]

How to determine DM density profile?

Rotation Curve method



Assumptions:

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

Only applies for $R > 2.5 \text{ kpc}$

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

Portal +
[1608.07954]

How to determine DM density profile?

Rotation Curve method

► Observed RC:

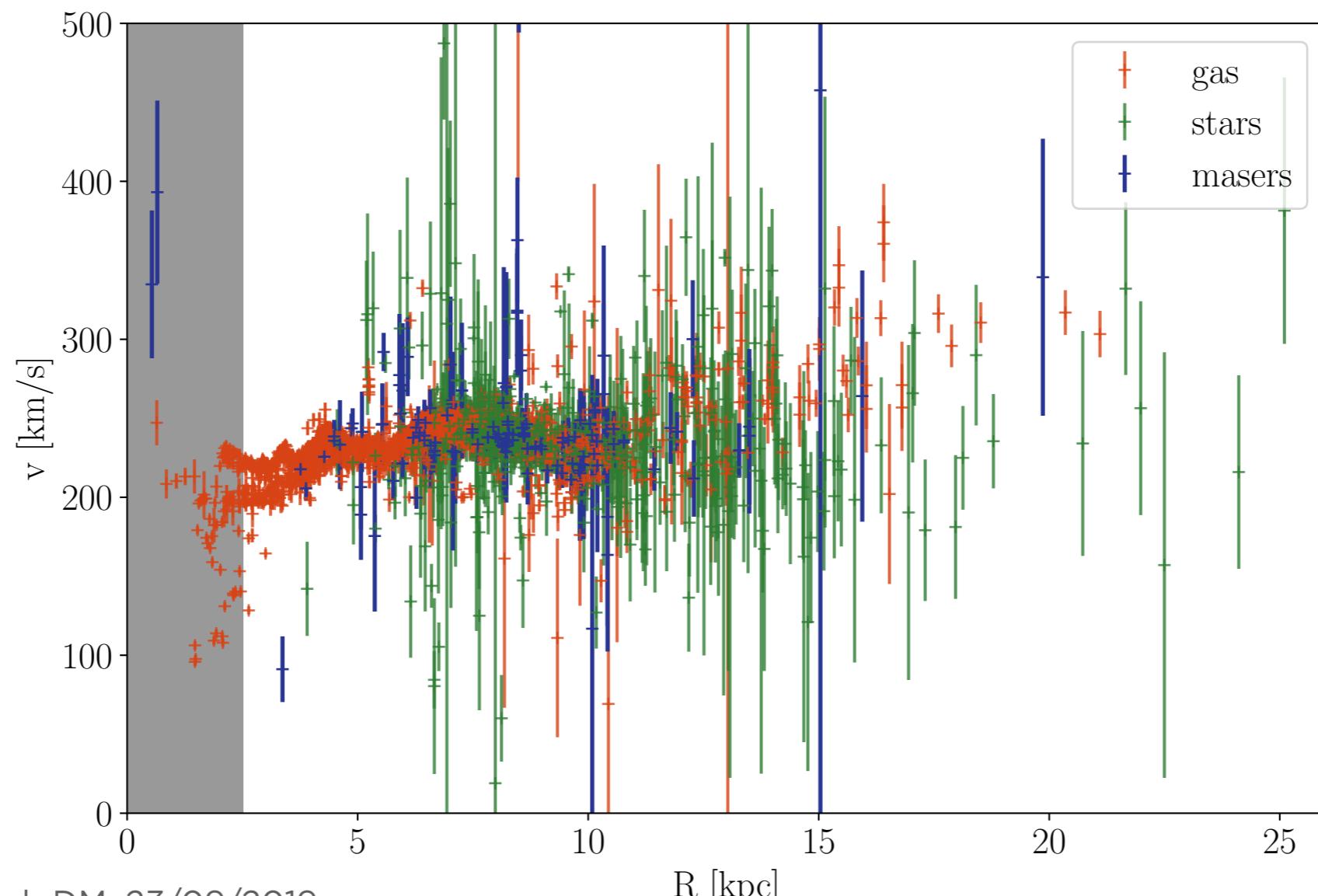
galkin **Pato & Iocco [1703.00020]**

$2.5 < R < 22$ kpc

One source of
uncertainties!

Galactic parameters:

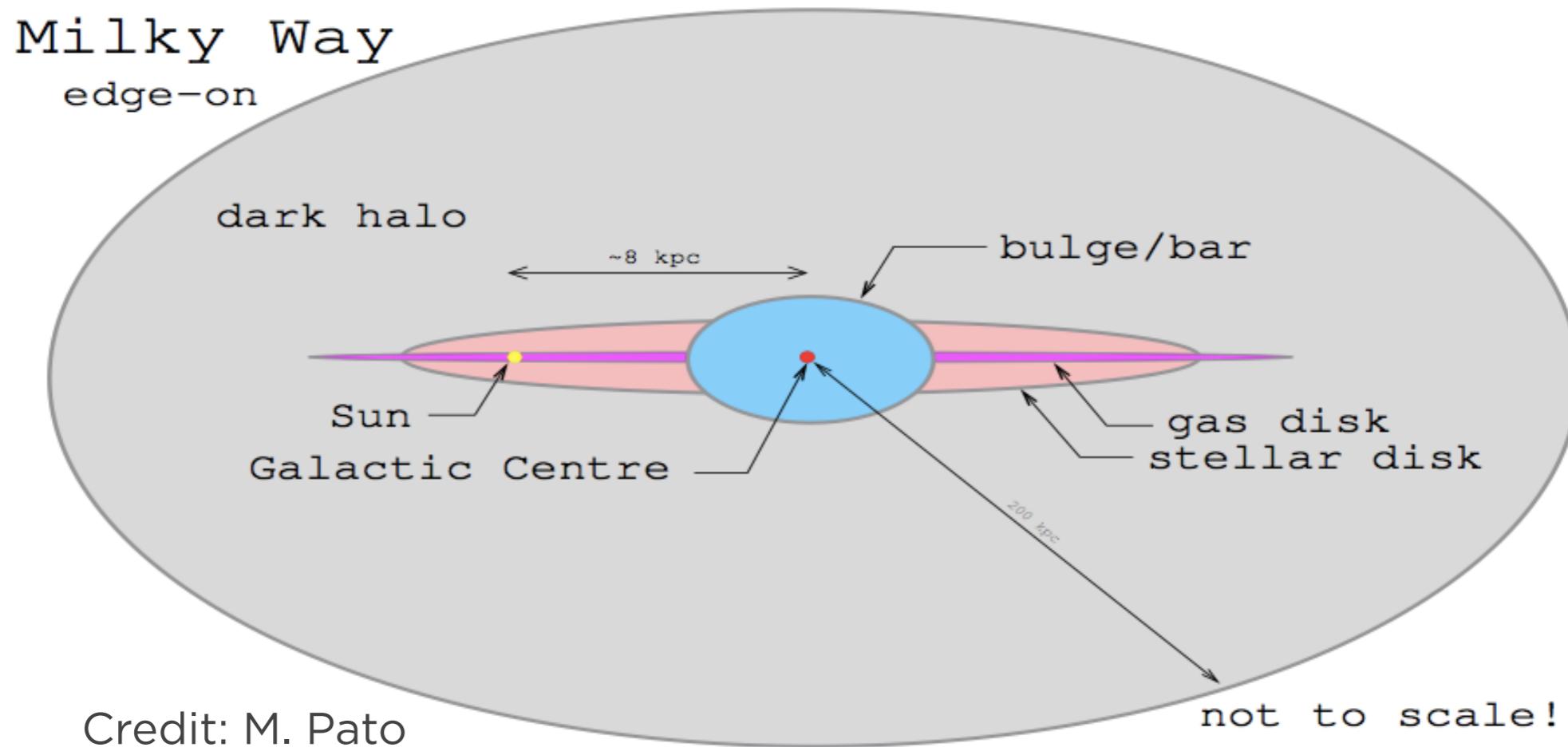
$$R_0 = 8.34 \text{ kpc} \quad V_0 = 239.89 \text{ km/s} \quad (U_\odot, V_\odot, W_\odot) = (7.01, 10.13, 4.95) \text{ km/s}$$



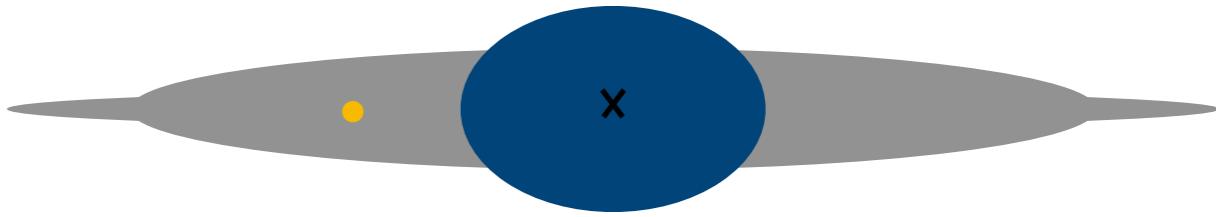
Luminous component of the Milky Way

$$\begin{array}{ccc} \rho_{\text{bulge}}(x, y, z) & & \Phi_{\text{bulge}}(x, y, z) \\ \rho_{\text{disc}}(r, z) & \xrightarrow{\hspace{2cm}} & \Phi_{\text{disc}}(r, z) \\ \rho_{\text{gas}}(x, y, z) & & \Phi_{\text{gas}}(x, y, z) \end{array} \quad \begin{aligned} v^2(r) &= \sum_i v_i^2(r) \\ v_i^2(r) &= r \frac{d\Phi_i}{dr} \end{aligned}$$

see e.g. locco + [1502.03821]



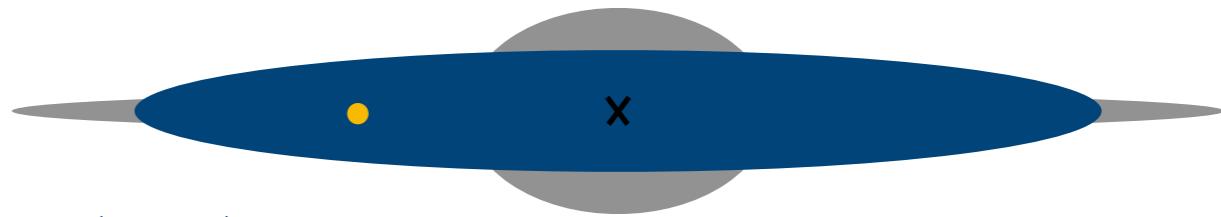
Bulge distribution:



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

$f(x, y, z)$	Bar angle [°]	x ₀ :y ₀ :z ₀	Reference
e^{-r}	25	2.8 : 1.4 : 1	Stanek +, ApJ'97 [G2]
$e^{-r_s^2/2}$	24	3.6 : 1.5 : 1	Stanek +, ApJ'97 [E2]
$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	20	3.7 : 1.5 : 1	Zhao, MNRAS'96
$e^{-r_s^2}/(1 + r_s)^{1.8}$	20	2.6 : 0.8 : 1	Bissantz & Gerhard, MNRAS'02
$\text{sech}^2(-r_s) + e^{-r_s}$	13	3.7 : 1.3 : 1	Robin +, AAp'12
$e^{-r_s^2}/(1 + r_s)^{1.8}$	15	3.2 : 2.2 : 1	Vanhollebeke +, [0903.0946]

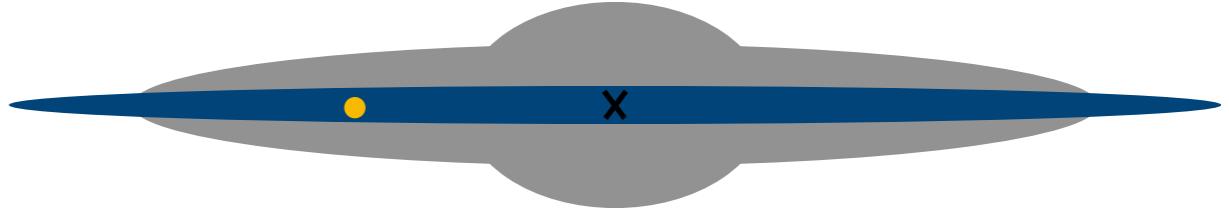
Stellar disc distribution:



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

$f(r, z)$		Scale-length [kpc]	Scale-height [kpc]	Reference
$e^{-r} \operatorname{sech}^2(z)$	thin	2.75	0.27 $\eta(r)$	Han & Gould, ApJ'03
$e^{-r} e^{-(z+z_0)}$	thick	2.75	0.44 $\eta(r)$	
$e^{-r} e^{- z }$	thin	2.6	0.30	Juric +, ApJ'08
$e^{-r} e^{- z }$	thick	3.6	0.90	
$(r^2 + z^2)^{-2.77/2}$	halo			
$e^{-r} e^{- z }$	thin	2.75	0.25	De Jong +, ApJ'10
$e^{-r} e^{- z }$	thick	4.1	0.75	
$(r^2 + z^2)^{-2.75/2}$	halo			
$e^{-r} e^{- z }$	thin	2.75	0.25	Calchi Novati & Mancini, MNRAS'11
$e^{-r} e^{- z }$	thick	4.1	0.75	
$e^{-r} e^{- z }$	single	2.15	0.4	Bovy & Rix, ApJ'13

Gas distribution:



$$\rho_g(x, y, z) = \rho_{\text{H}_2}(x, y, z) + \rho_{\text{H}_\text{I}}(x, y, z) + \rho_{\text{H}_{\text{II}}}(x, y, z)$$

Components		Range	Reference
molecular ring	H_2	$r = 3 - 20 \text{ kpc}$	Ferrière, ApJ'98
cold, warm	HI		
warm, hot	HII		
CMZ, disc	H_2	$r = 0.01 - 3 \text{ kpc}$	Ferrière + [astro-ph/0702532]
CMZ, disc	HI		
warm, hot, very hot	HII		

Uncertainties

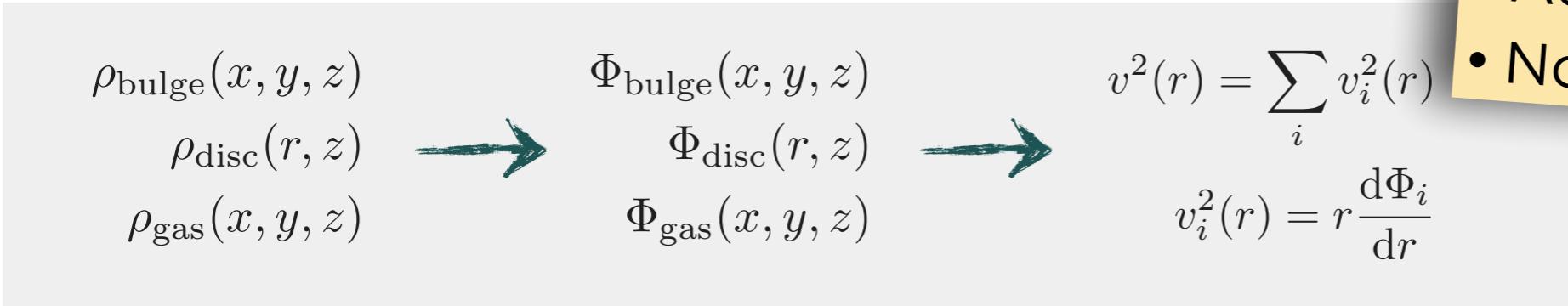
CO-to- H_2 factor: $X_{\text{CO}}(r > 3 \text{ kpc}) = (5.0 \pm 2.5) \times 10^{19} \text{ cm}^{-2} \text{K}^{-1} \text{km}^{-1} \text{s}$

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

Ferriere + [astro-ph/0702532]

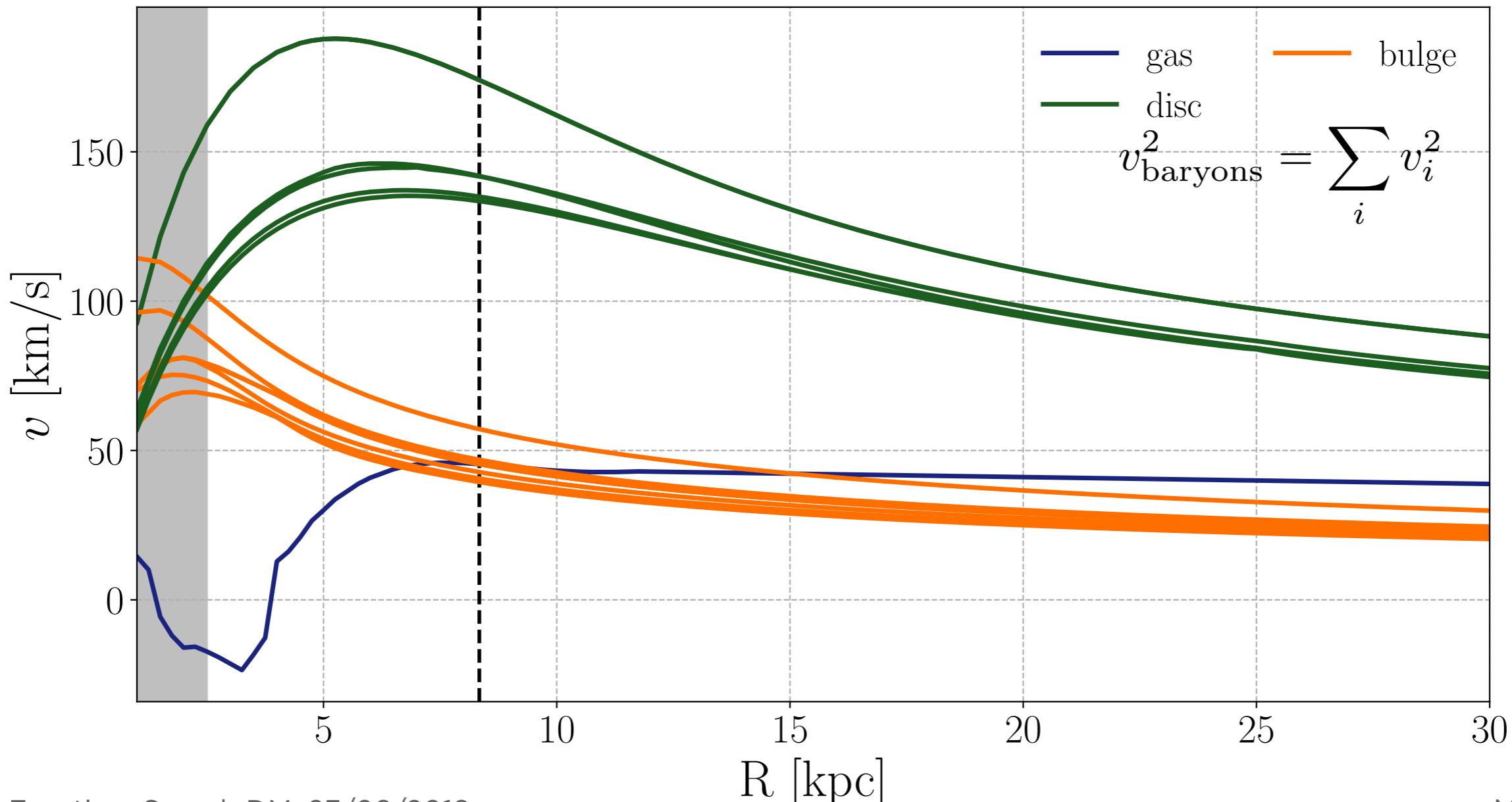
Systematic uncertainties

Luminous component



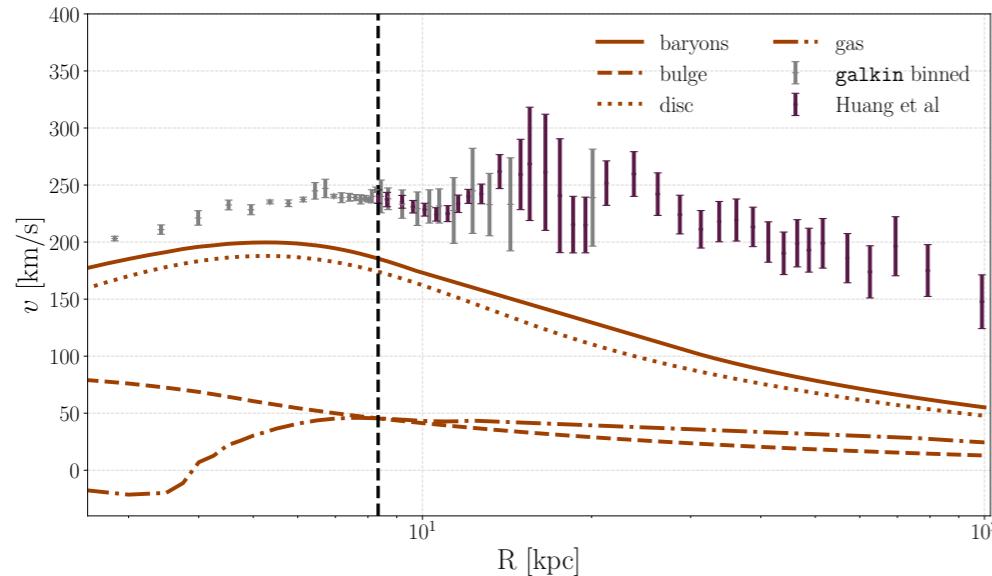
Sources of uncertainties:

- Actual shape of baryons
- Normalisation of baryons



How to determine DM density profile?

Rotation Curve method

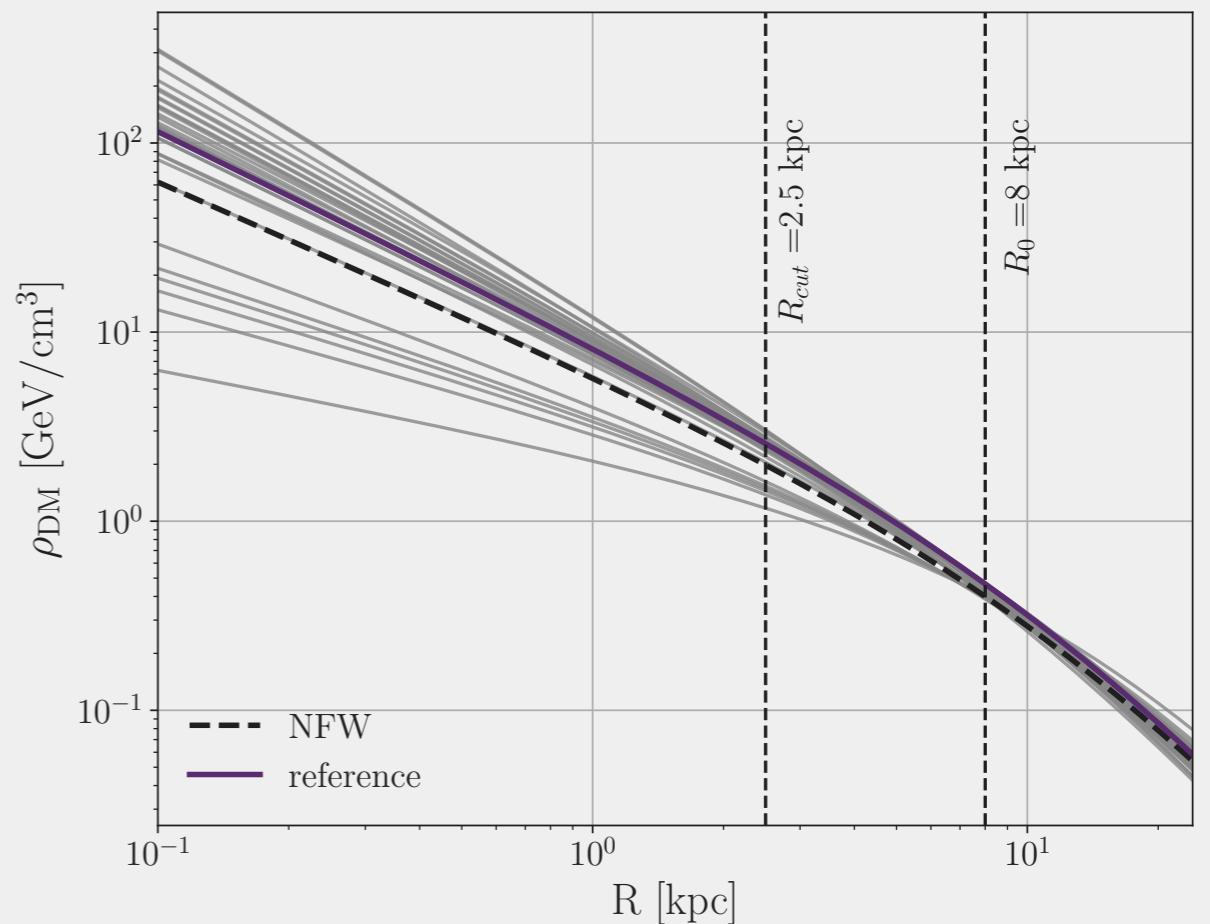


- 1) Observed RC
- 2) RC for the luminous component

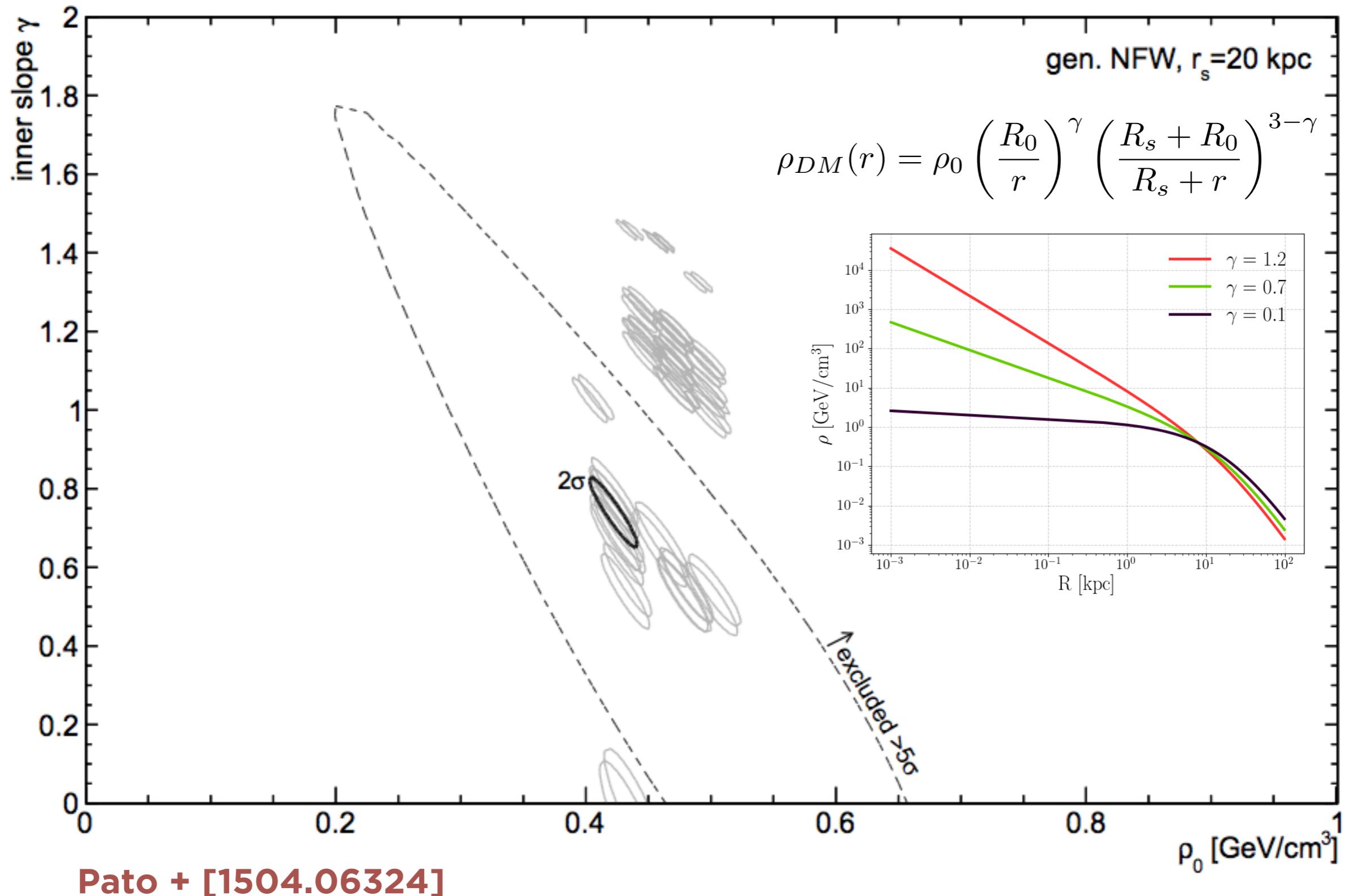
gNFW density profile

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

Three free parameters: γ , R_s , ρ_0



Extracting the DM density structure



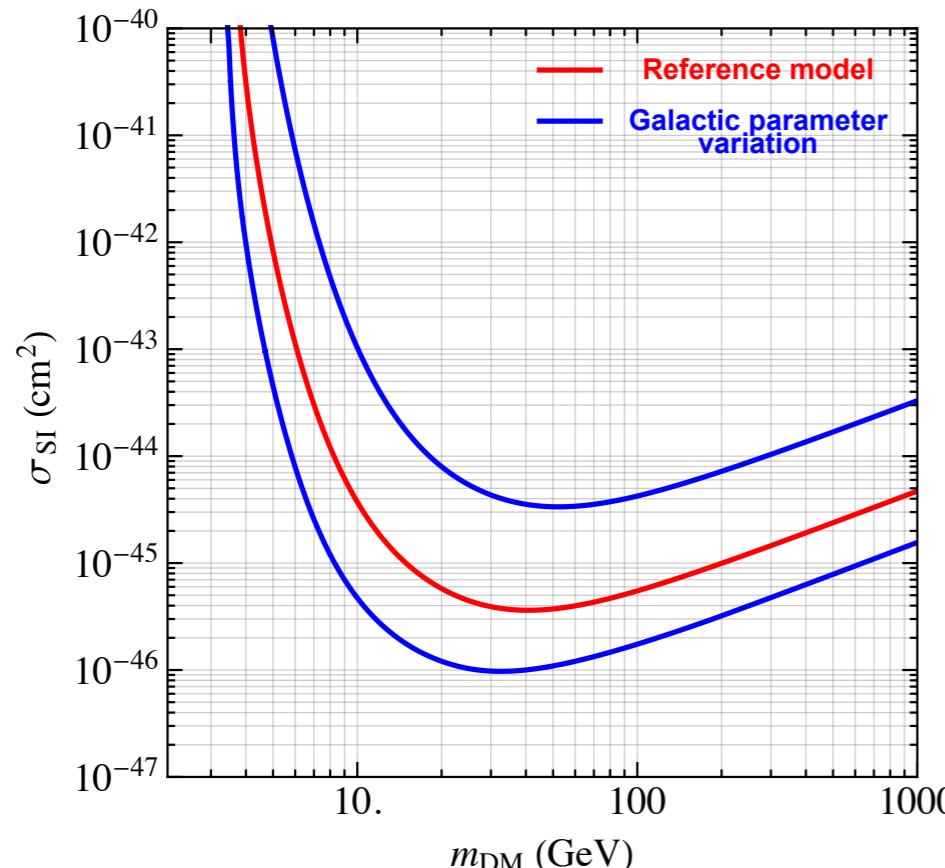
Problem:

Particle
physics

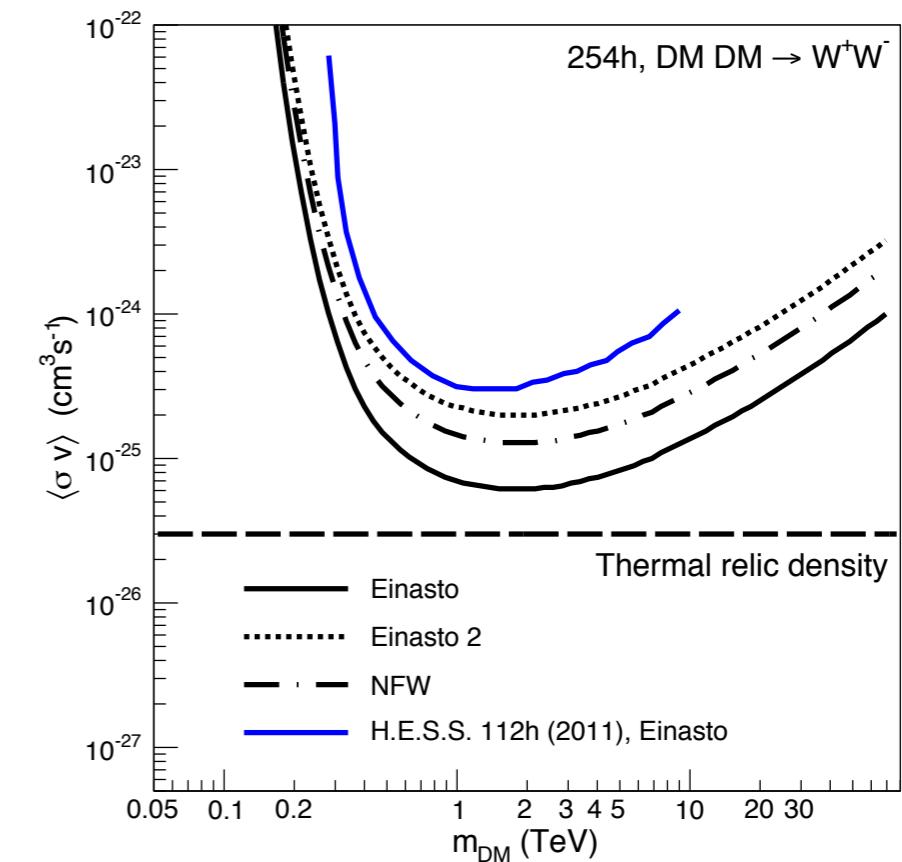
Direct/Indirect
searches

DM density

Astrophysical
observable



MB +
[1612.02010]



H.E.S.S. collaboration
[1607.08142]

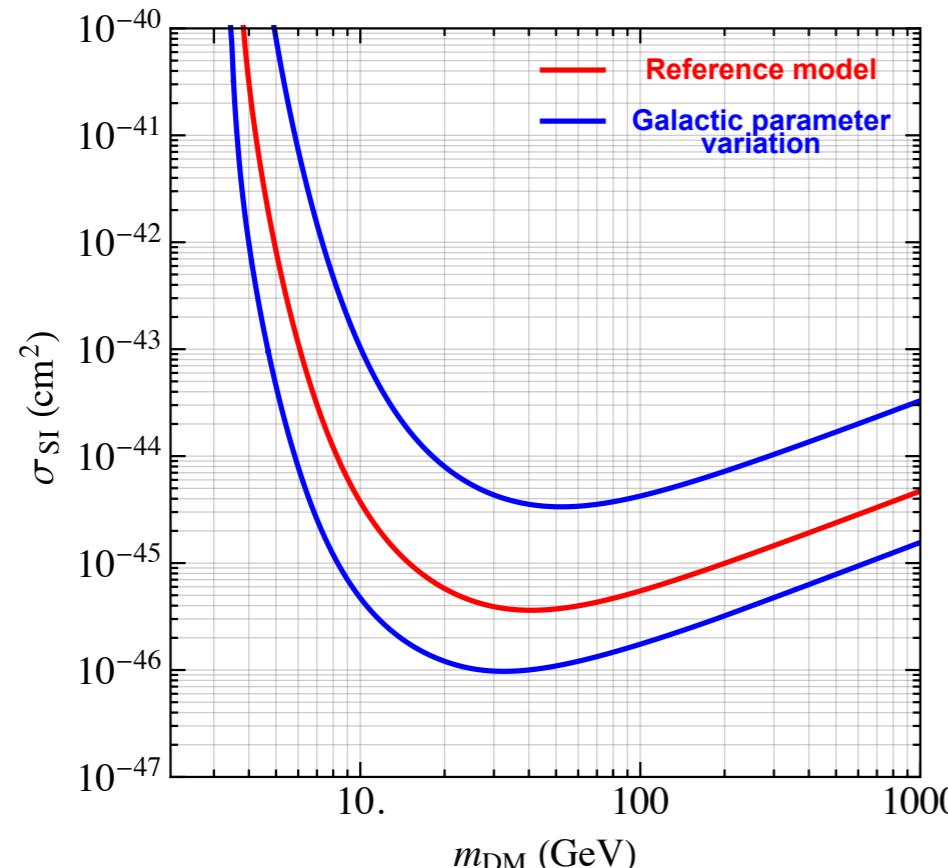
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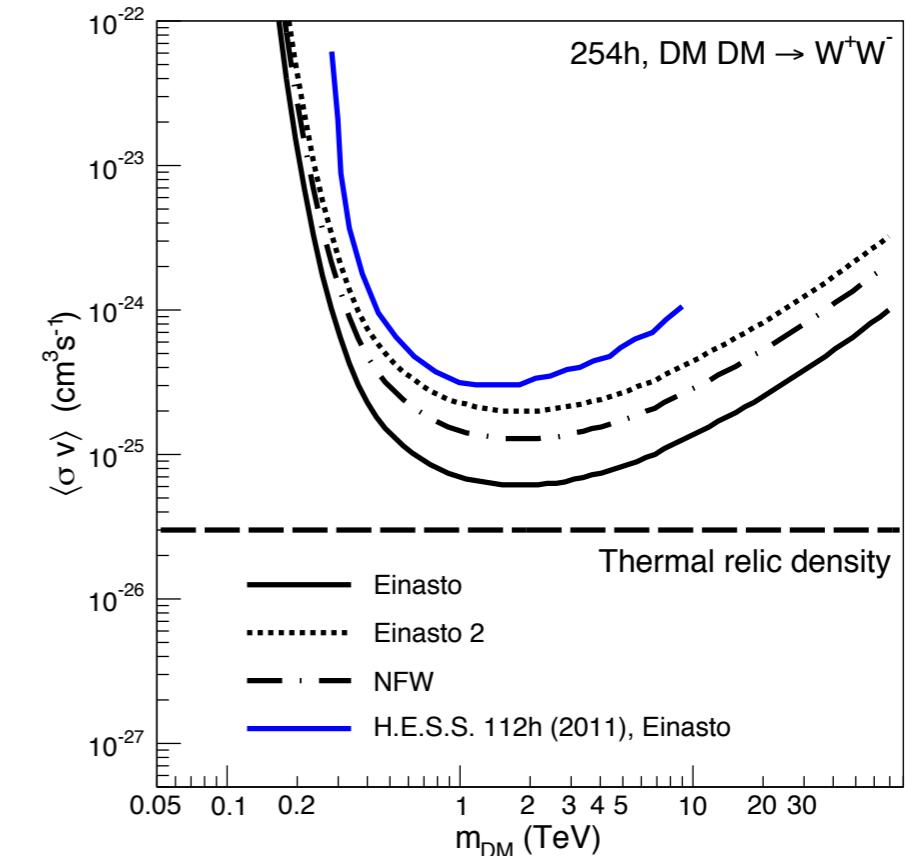
Direct/Indirect
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MB +
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H.E.S.S. collaboration
[1607.08142]

But do Galactic uncertainties affect PP, for real?

But do Galactic uncertainties affect PP, for real?

A simple case: Singlet Scalar DM

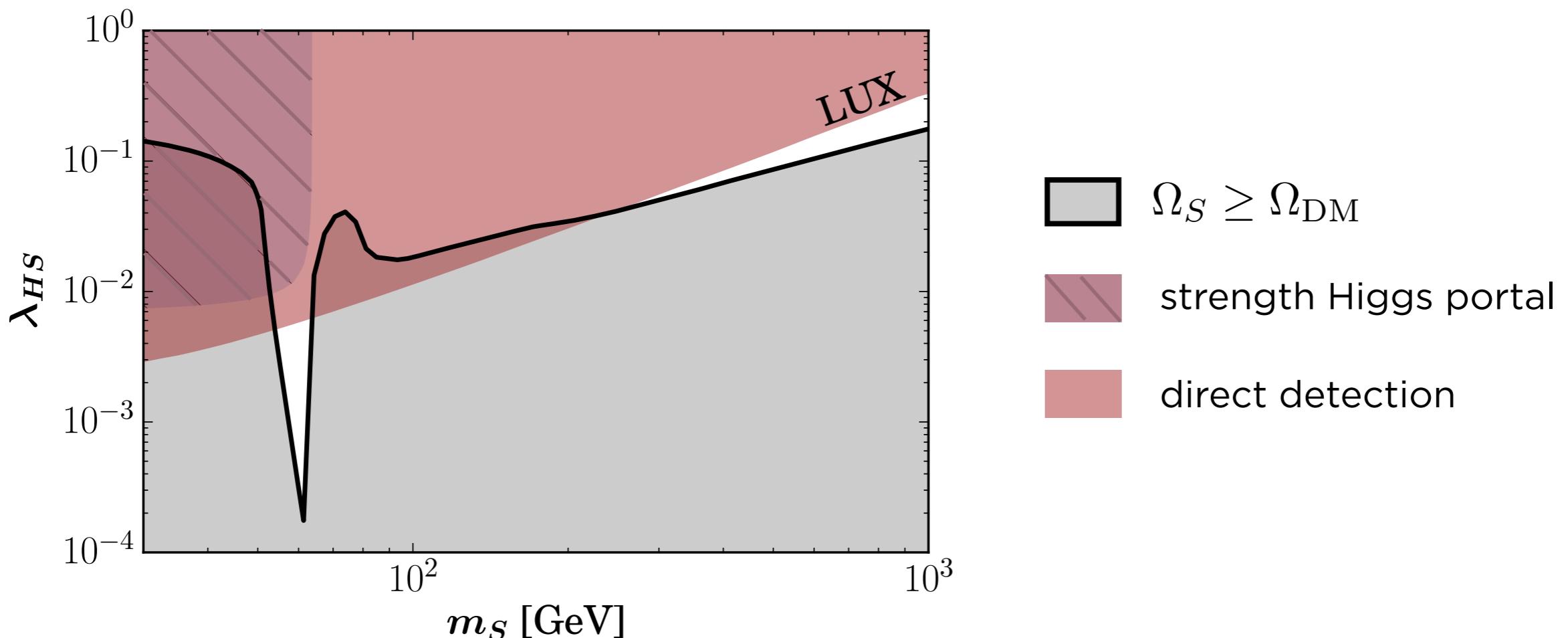
$$V = \mu_H^2 |H|^2 + \lambda_H |H|^4 + \mu_S^2 S^2 + \lambda_S S^4 + \lambda_{HS} |H|^2 S^2$$

Mc Donald [arXiv:hep-ph/0702143]

Burgess, Pospelov & Velthuis [hep-ph/0011335]

$$m_S^2 = 2\mu_S^2 + \lambda_{HS} v_H^2$$

Constraints and interplay of experiments

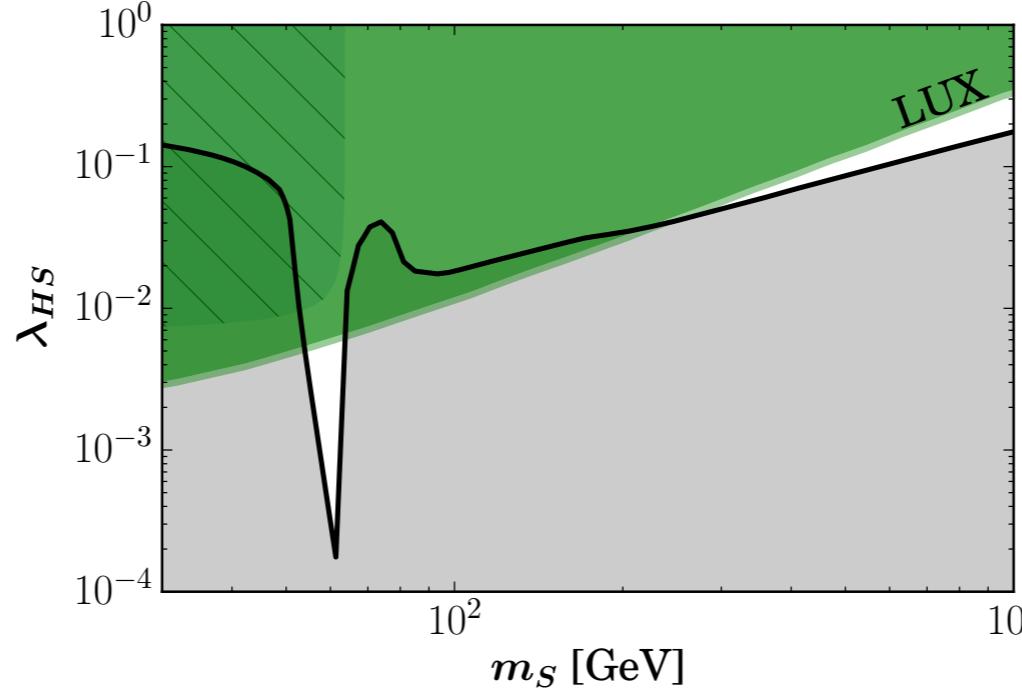


Effect of Galactic astrophysical uncertainties

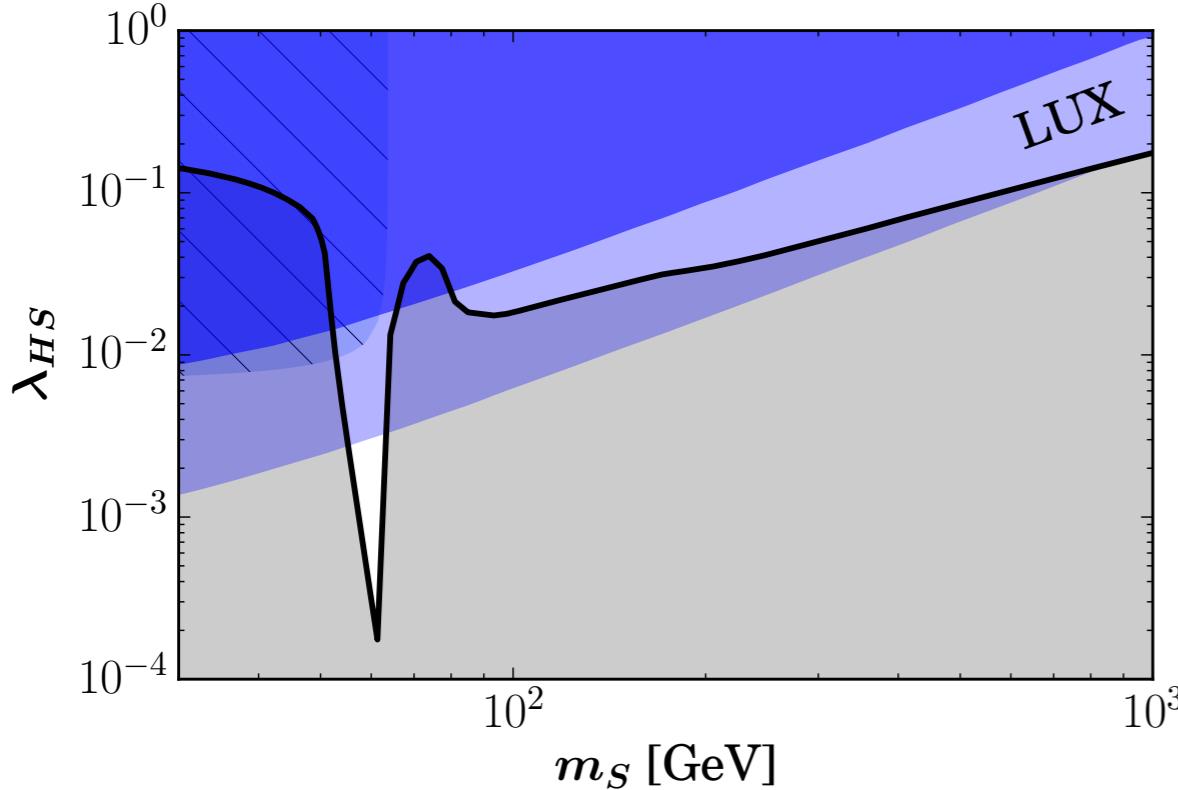
Direct detection constraints

Statistics

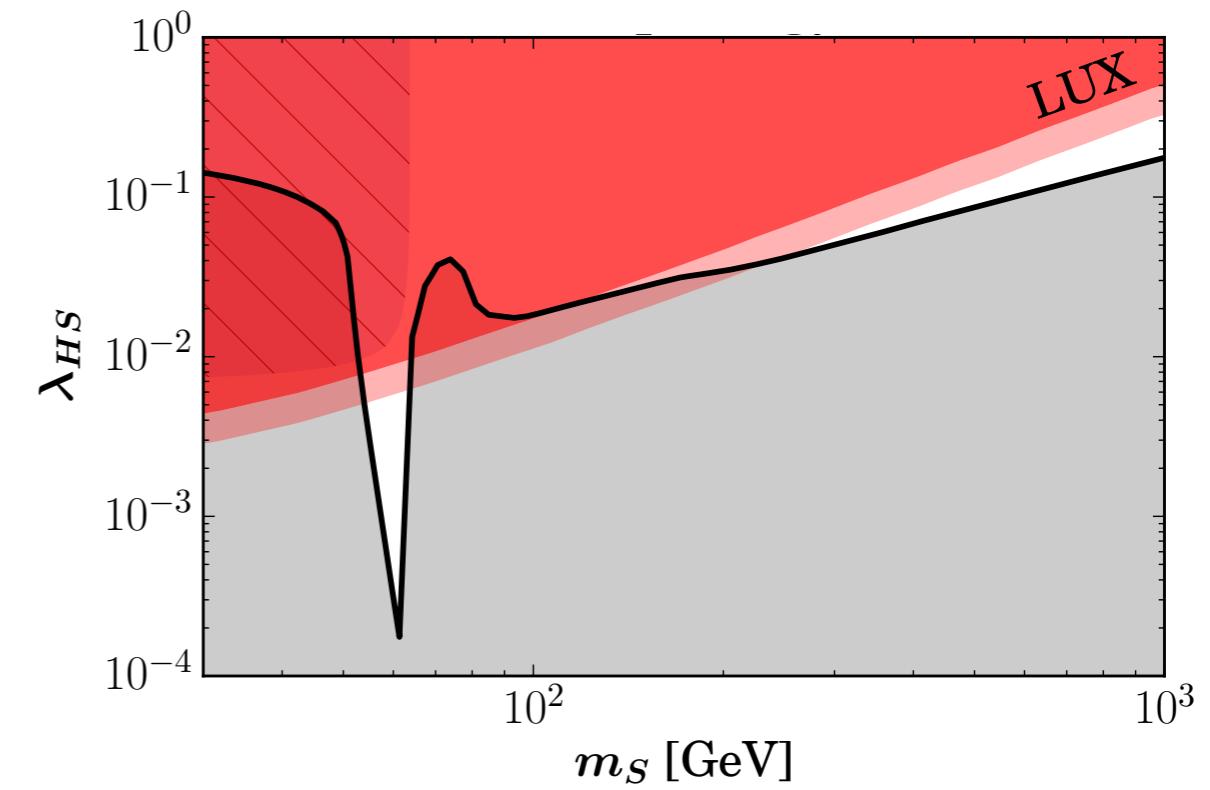
MB + [1612.02010]



Galactic parameters



Baryonic morphology

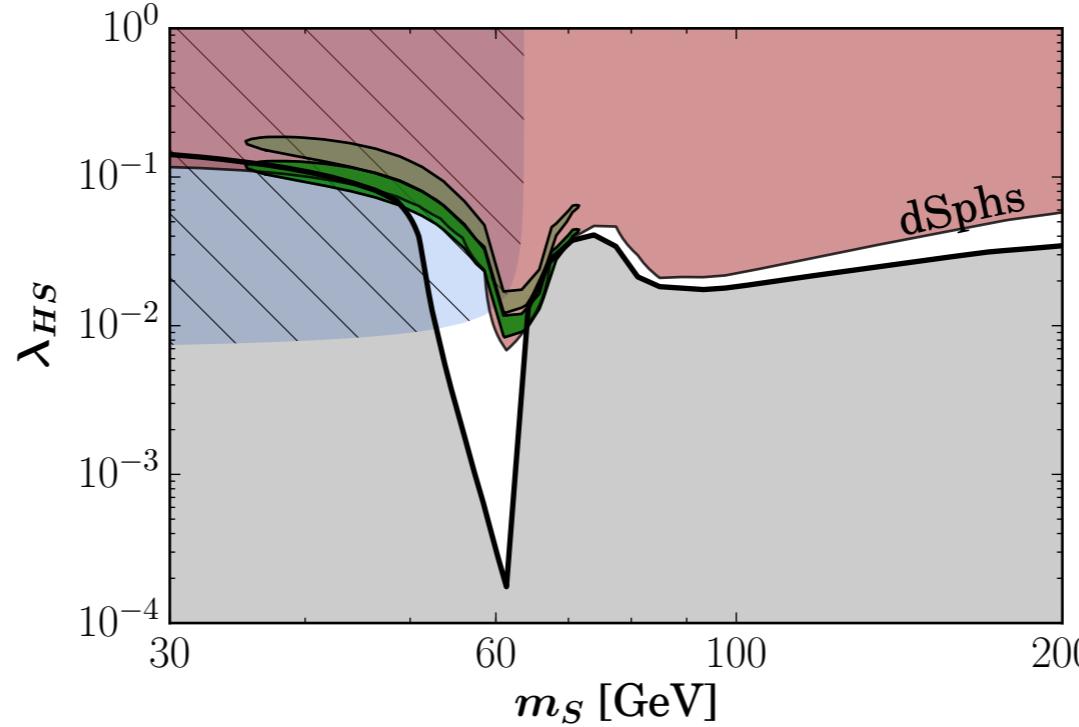


Effect of Galactic astrophysical uncertainties

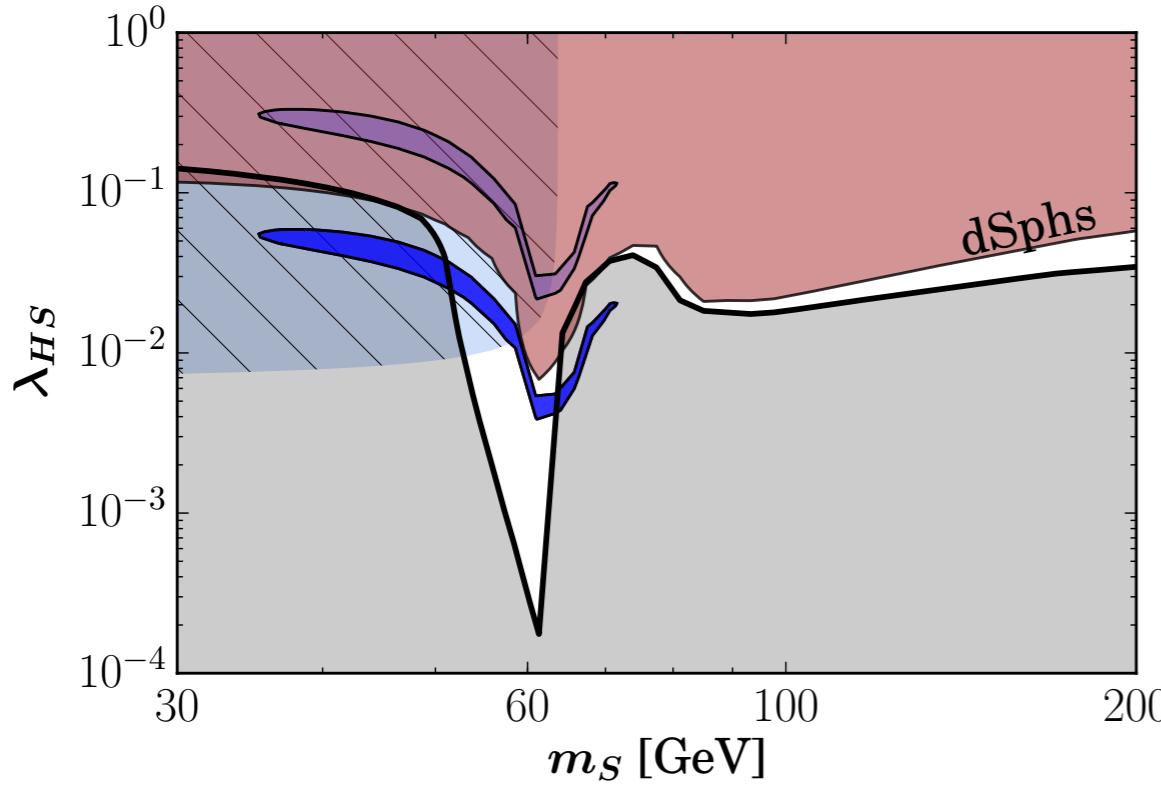
Indirect detection constraints

Statistics

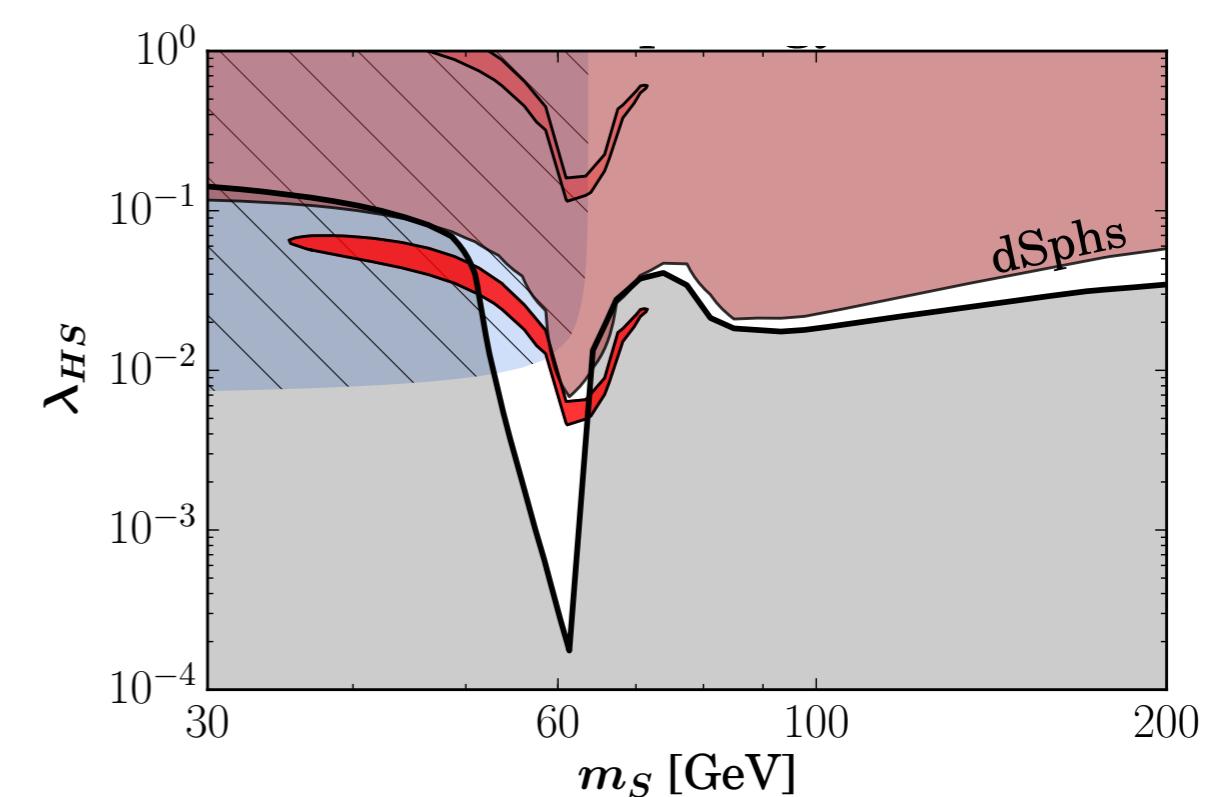
MB + [1612.02010]



Galactic parameters



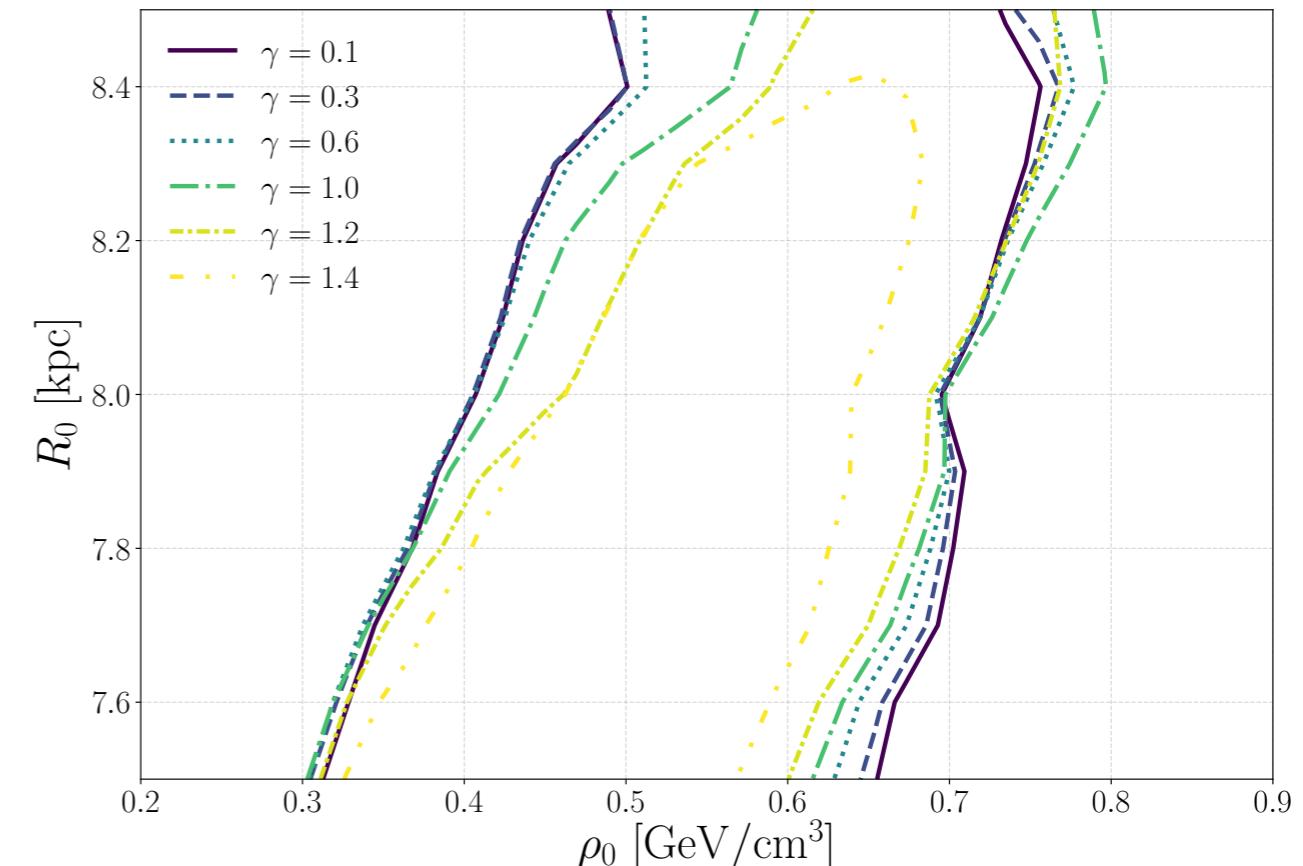
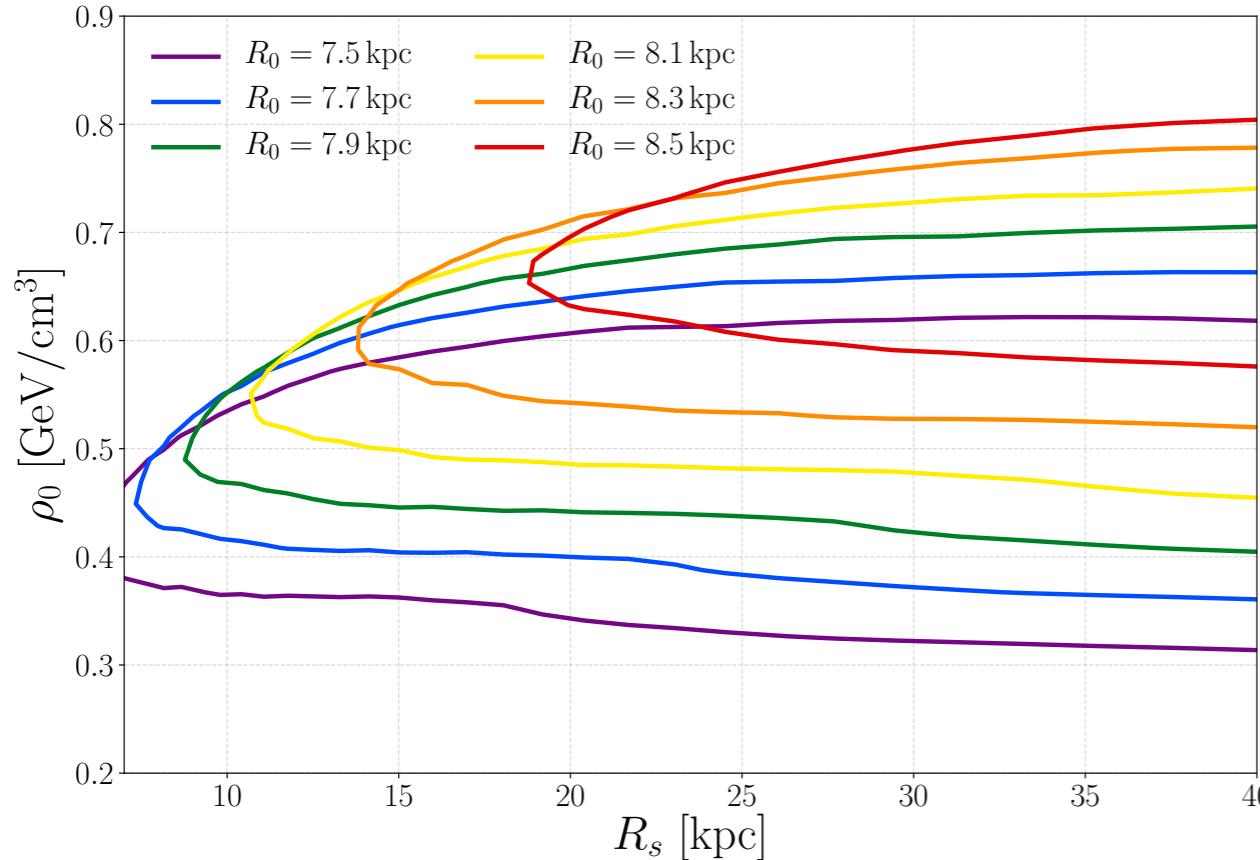
Baryonic morphology



Include astrophysical uncertainties in your own analysis

Ready-to-use likelihood publicly available @

<https://github.com/mariabenitocst/UncertaintiesDMinTheMW>

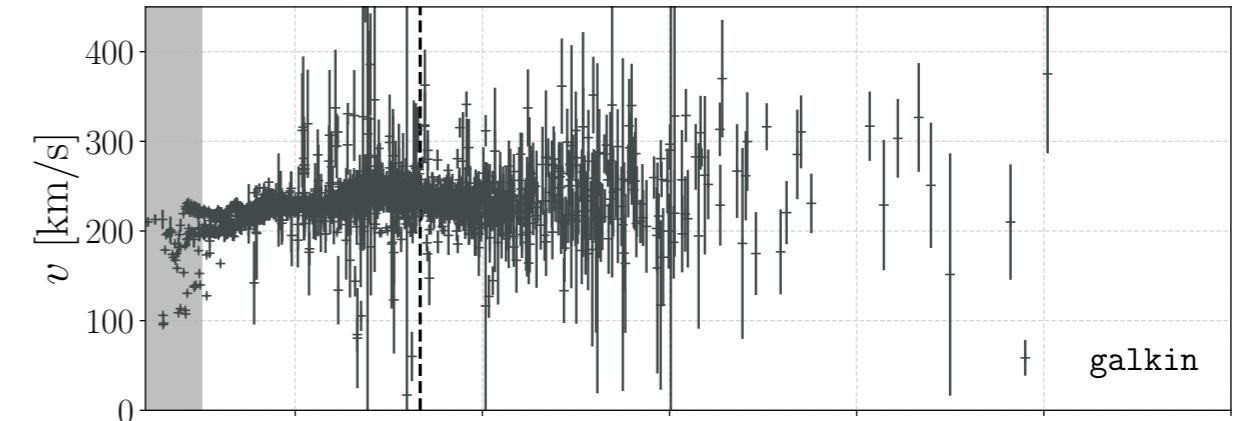


MB + [1901.02460]

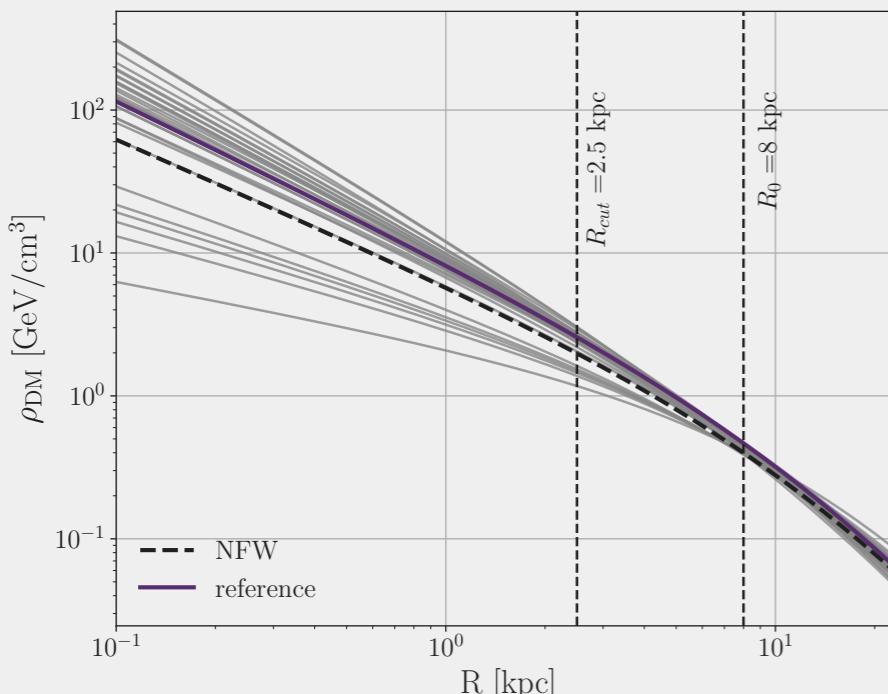
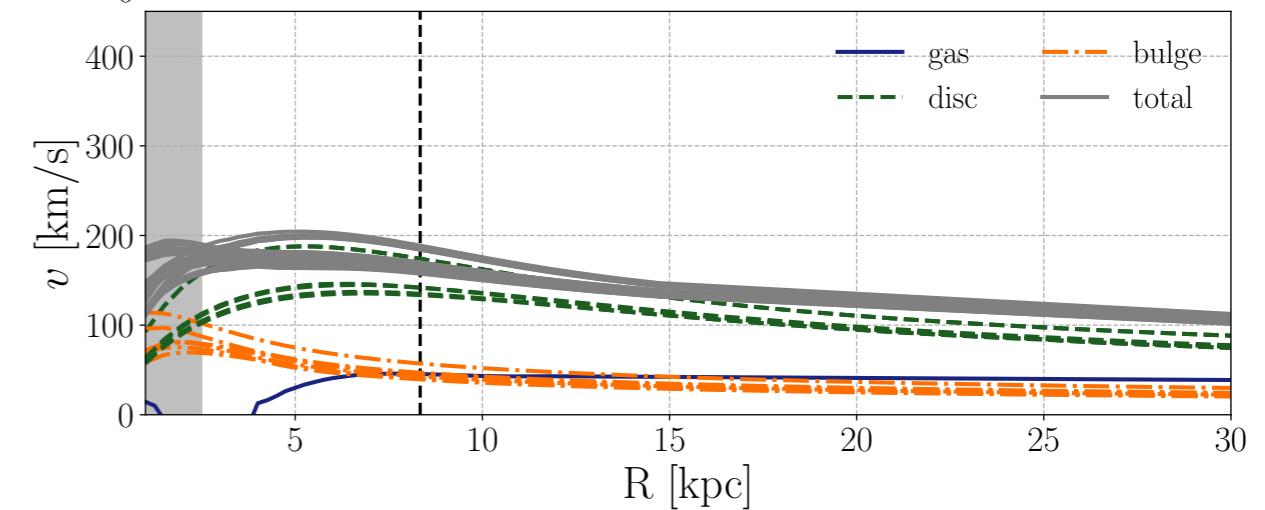
How to determine DM density profile?

Rotation Curve method

1) Observed RC



2) RC for the luminous component



3) gNFW density profile

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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	

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Rotation Curve method

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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:

$$\mathcal{M}_i, \gamma, R_s, \rho_0, R_0, \Sigma_*, \langle\tau\rangle$$

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

Normalisation bulge

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

Popowski + 2005
[astrop-ph/0410319]

Normalisation disc

$$\Sigma_*^{obs} = 38 \pm 4 \text{ M}_\odot \text{pc}^{-2}$$

Bovy & Rix 2013
[1309.0809]

Scan the 7D parameter space to obtain the Likelihood profile

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[1309.0809]

Scan the 7D parameter space to obtain the Likelihood profile

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

7D parameter space:

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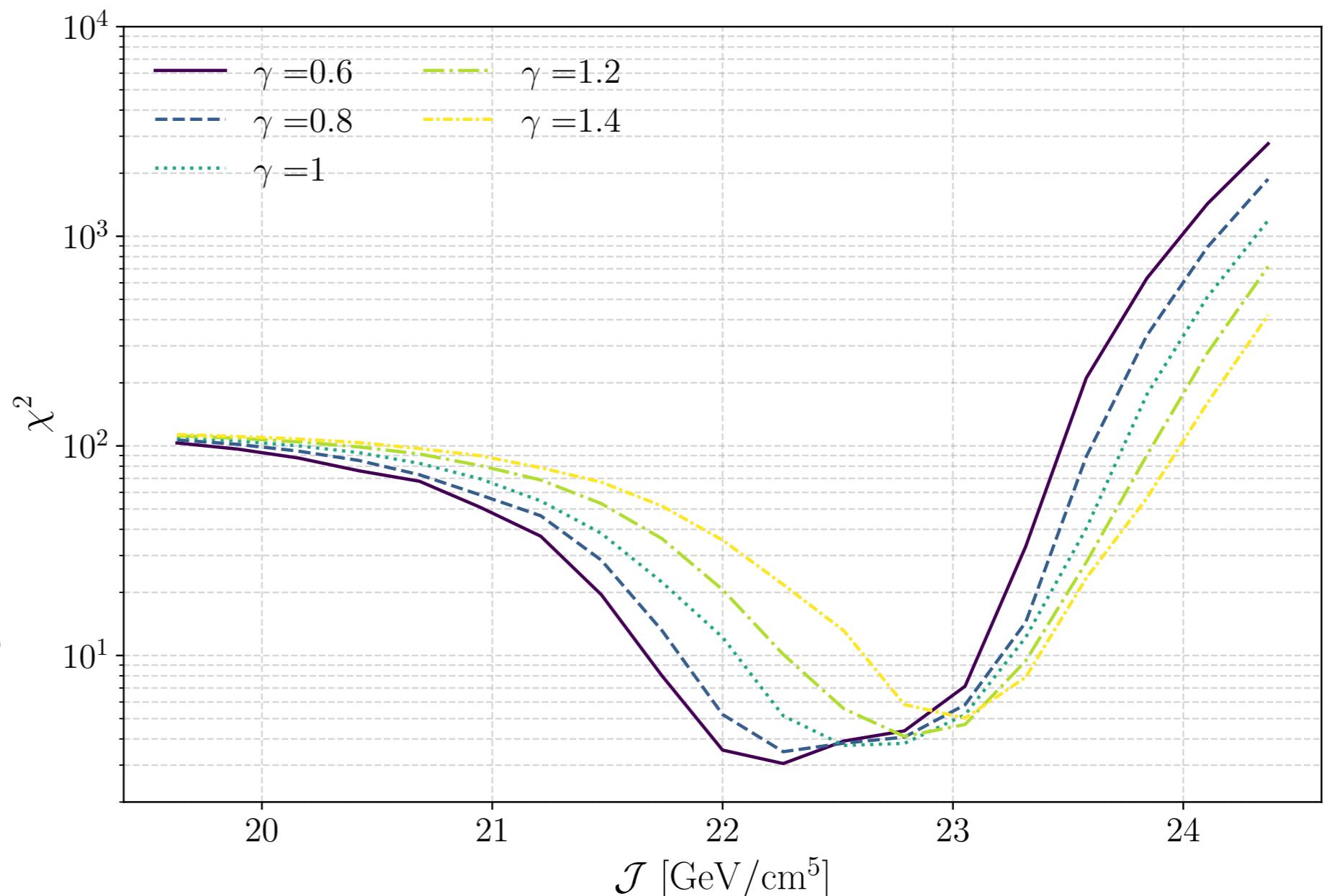
$$\chi^2_{\text{RC}}(R_s, \rho_0, \gamma, R_0)$$

Publicly
available!

Example: Galactic center GeV excess

χ^2 profiled over:

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



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

ROI:

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

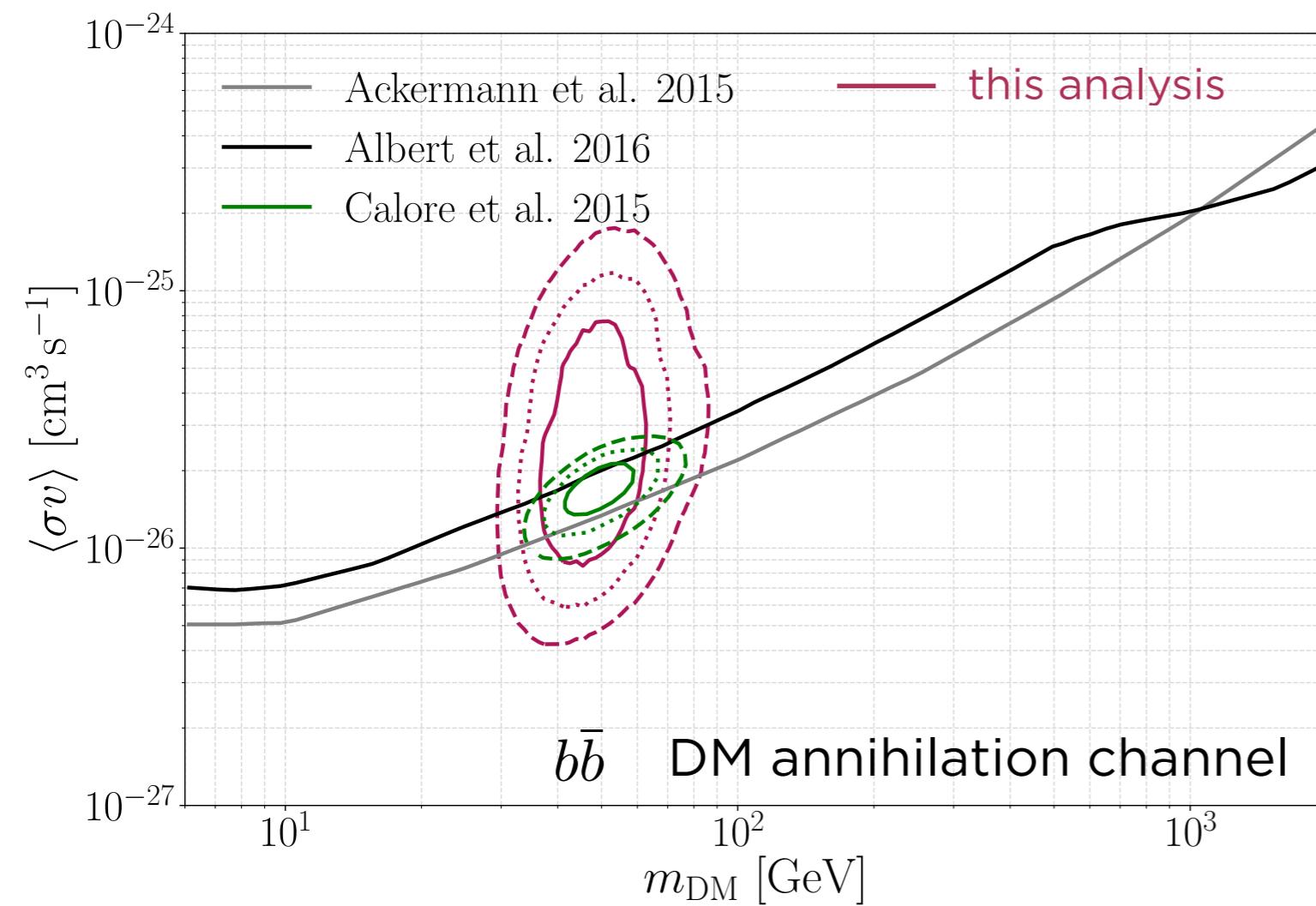
Example: Galactic Center excess

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

GCE analysis

RC analysis

Priors



Calore analysis:
observed GC signal
(only stat. on gamma flux)

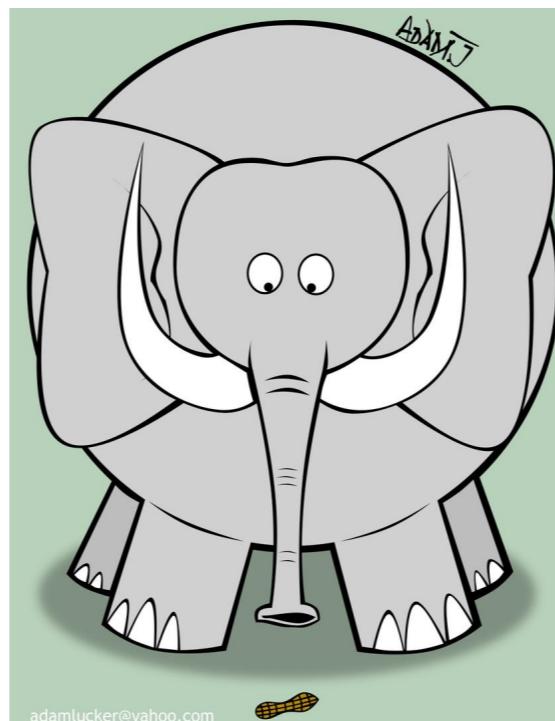
This analysis:
observed GC signal
+
DM density profile
(Gal. Param. + Morphologies + stat.)

Take away point

Astrophysical uncertainties in the distribution of DM are

- relevant on determining new physics and
- important to be taken into account when claiming tension between experimental results.

Caveats



Sphericity of
inner DM halo:

Bowden + [1502.00484]

Bovy + [1609.01298]