Dark Matter in the Milky Way:

The Impact of Galactic Astrophysical Uncertainties on the Reconstruction of Dark Matter Properties

María Benito

IFT - UNESP
INSTITUTO DE FÍSICA TEÓRICA - UNESP

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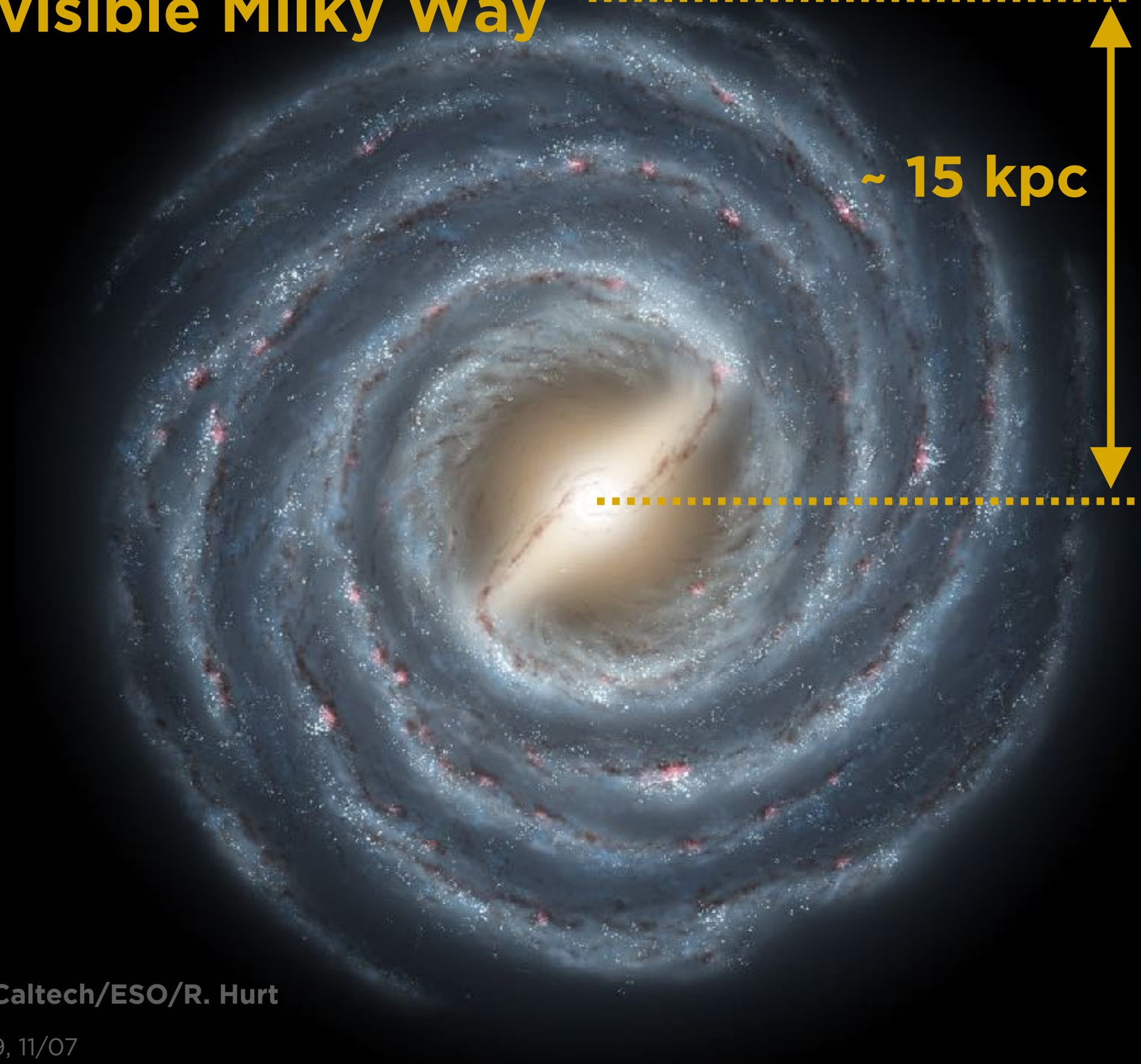
CYGNUS 2019
11/07

The visible Milky Way

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

The visible Milky Way



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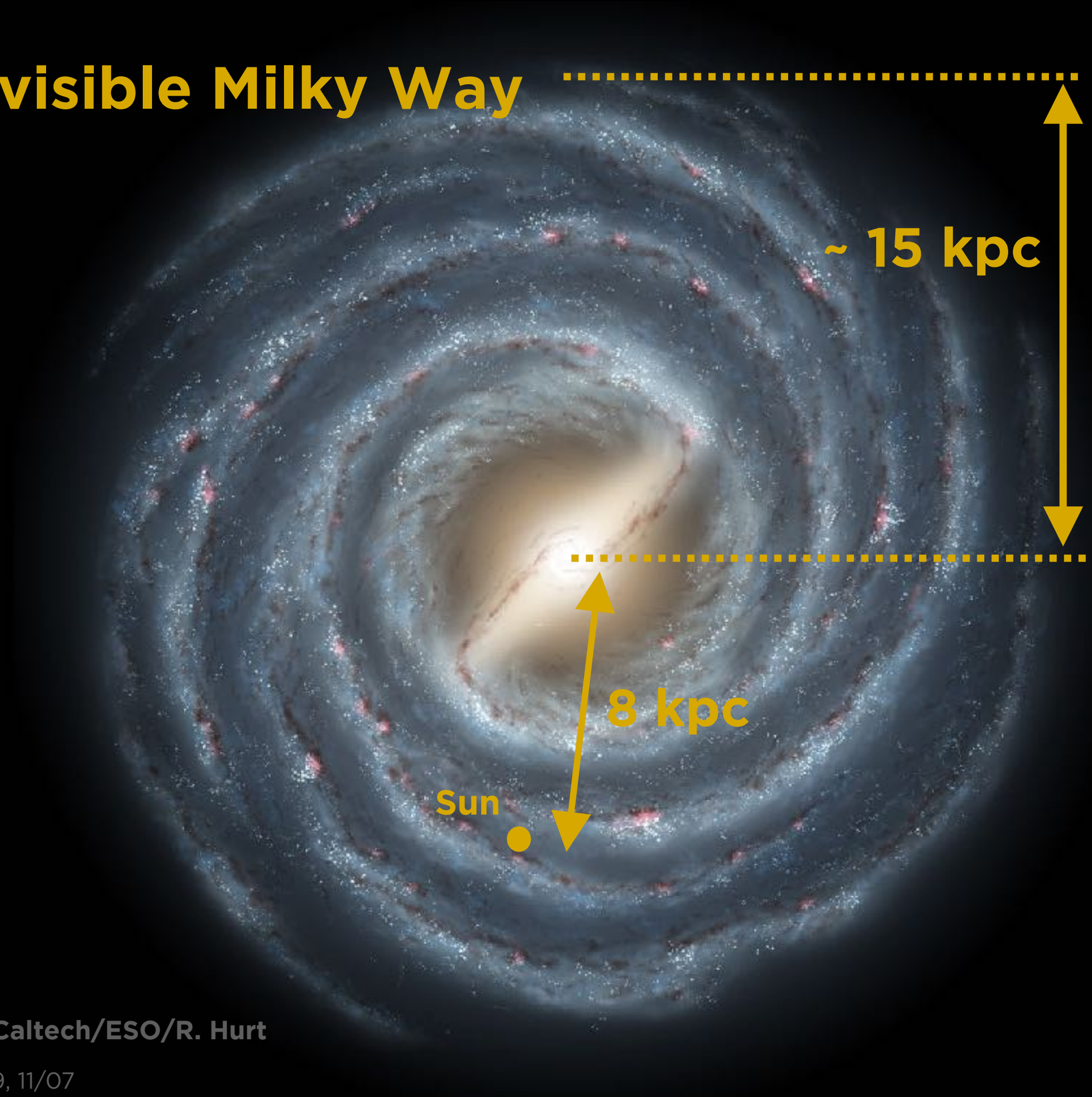
The visible Milky Way



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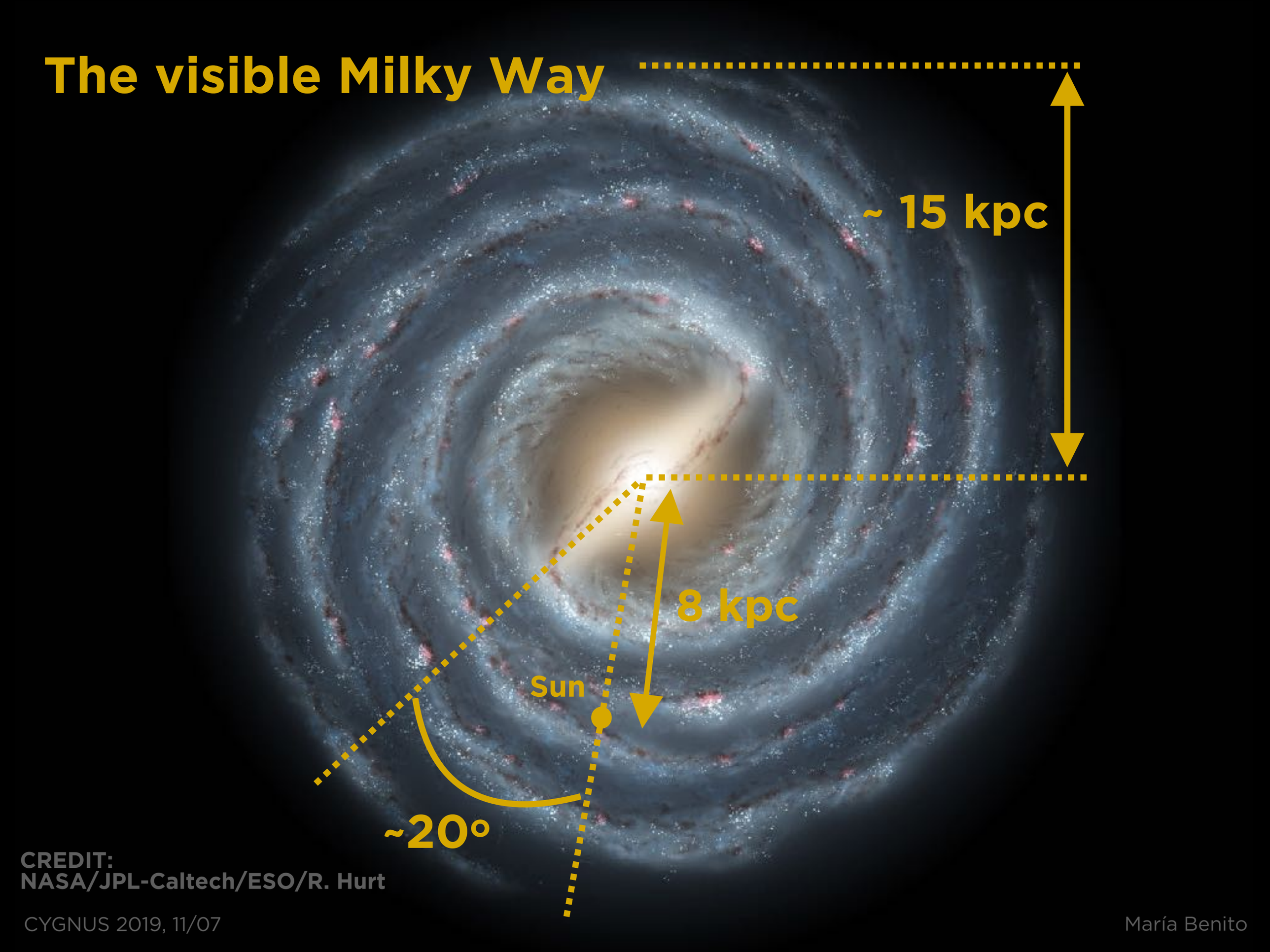

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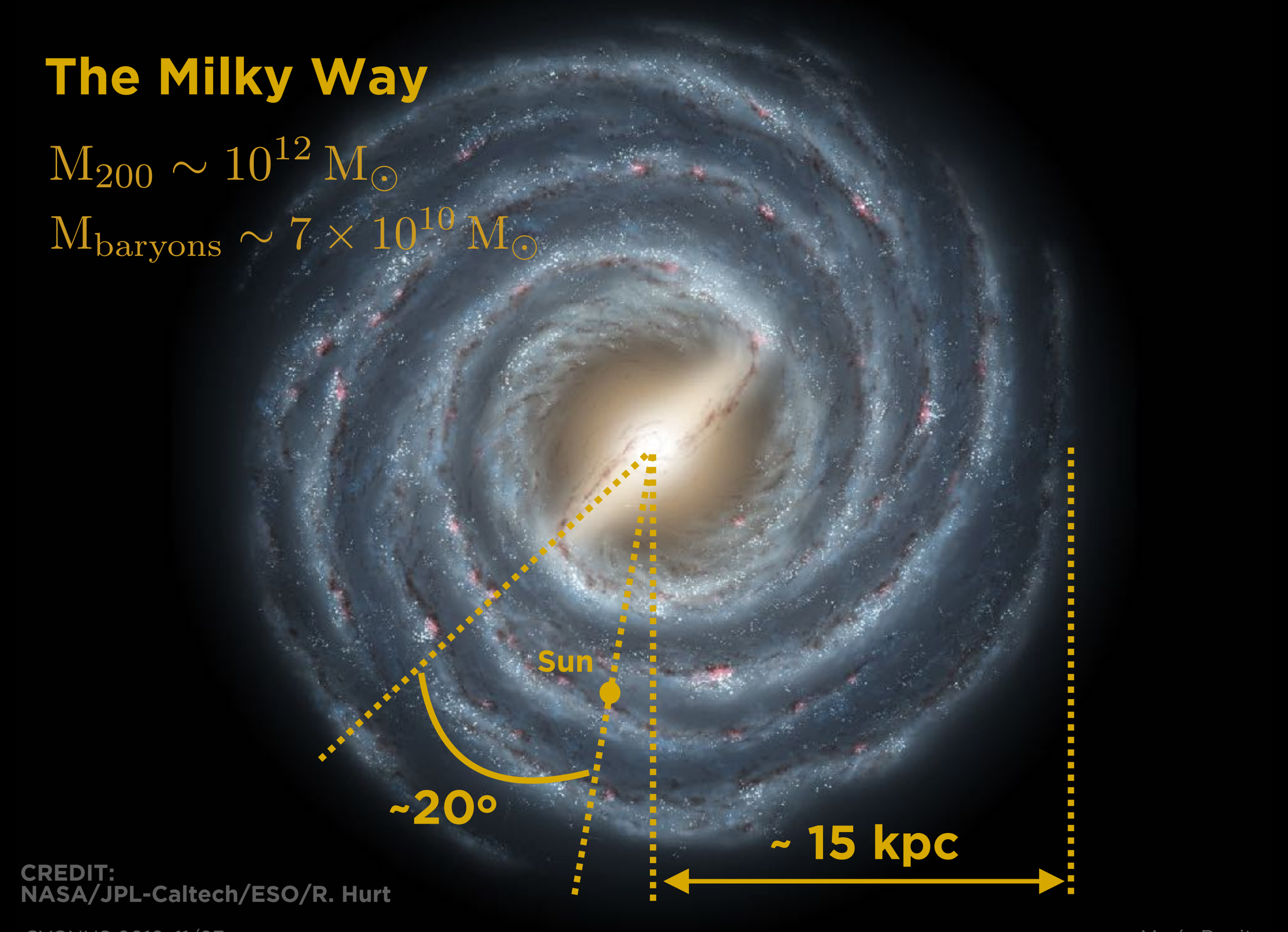
The Milky Way

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

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



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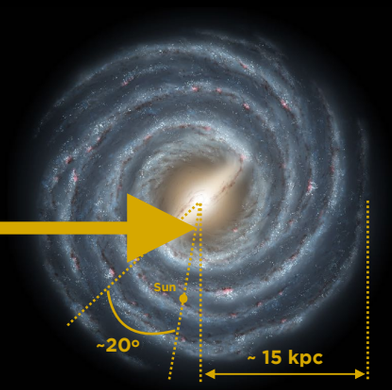
The Milky Way

$\mathrm{M}_{200} \sim 10^{12}\,\mathrm{M}_{\odot}$

$\mathrm{M}_{\mathrm{baryons}} \sim 7 \times 10^{10}\,\mathrm{M}_{\odot}$

~ 200 kpc



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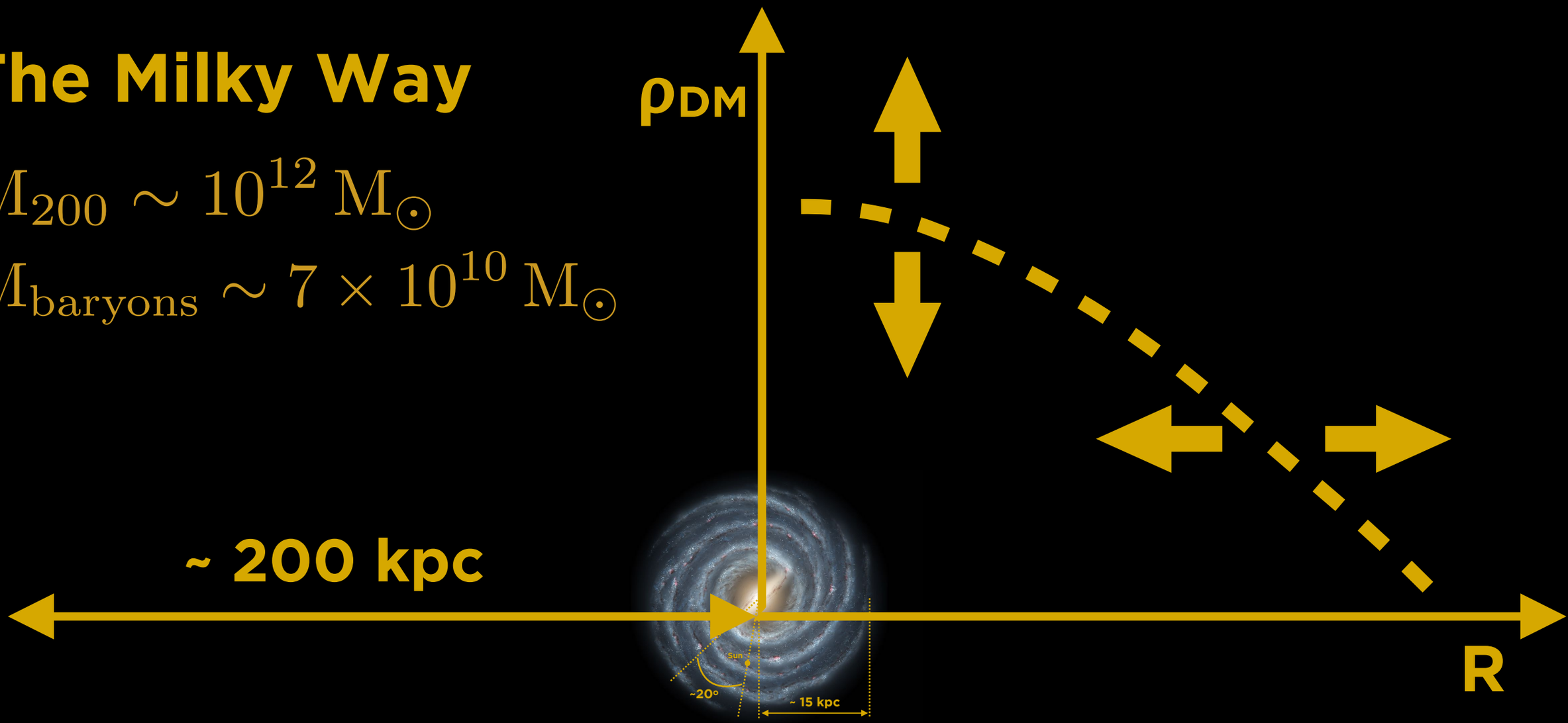

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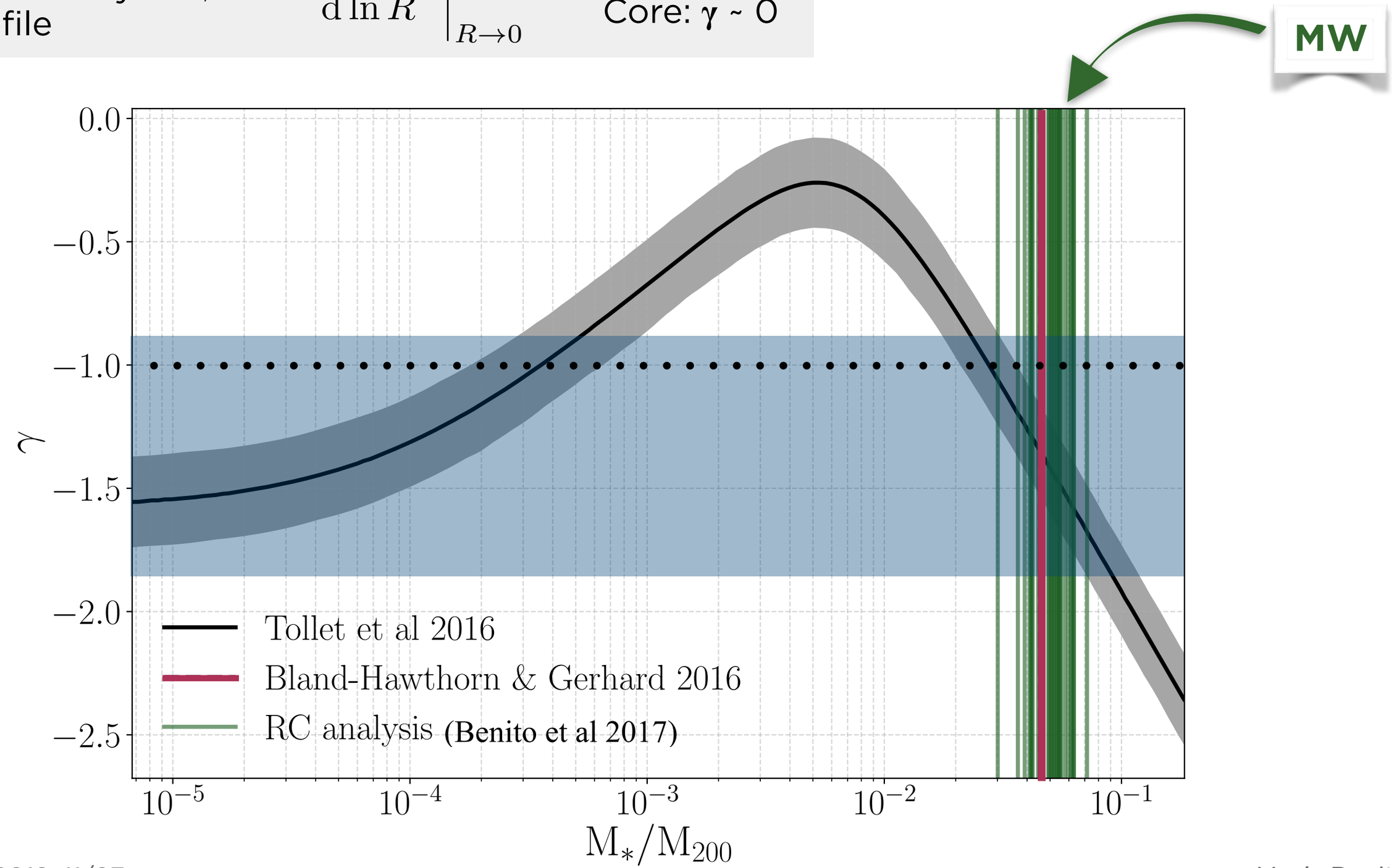
Why it is important?

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

Inner slope DM density profile = $\gamma = + \left. \frac{\mathrm{d} \ln \rho_{\mathrm{DM}}}{\mathrm{d} \ln R} \right|_{R \to 0}$

Cusp: γ ~ -1

Core: γ ~ 0



Why it is important?

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

Inner slope DM density profile = $\gamma = + \left. \frac{\mathrm{d} \ln \rho_{\mathrm{DM}}}{\mathrm{d} \ln R} \right|_{R \to 0}$

Cusp: γ ~ -1

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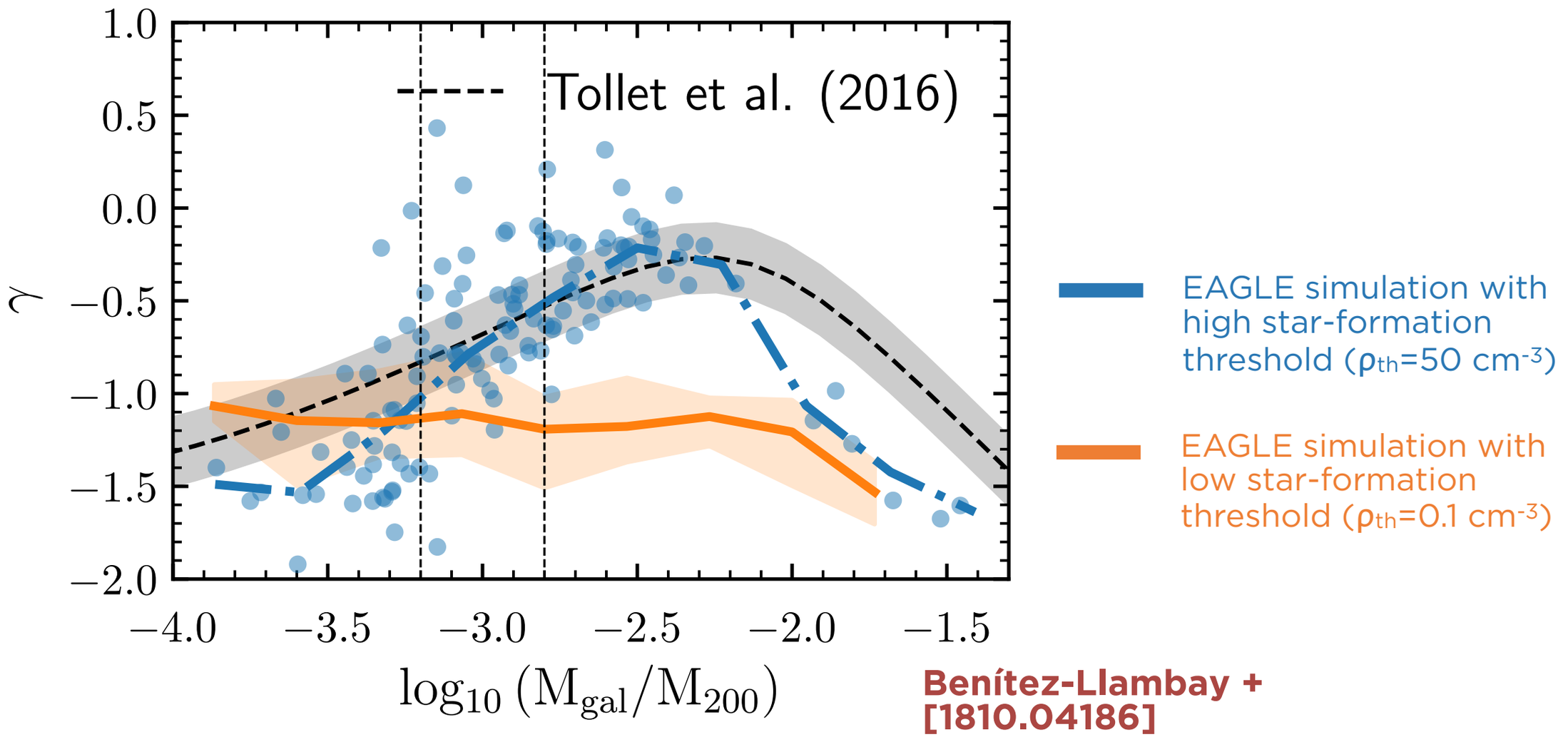


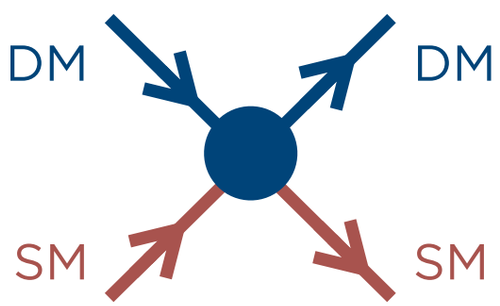
Benítez-Llambay + [1810.04186]

Why it is important?

Direct/Indirect DM searches

Simplified version

Direct



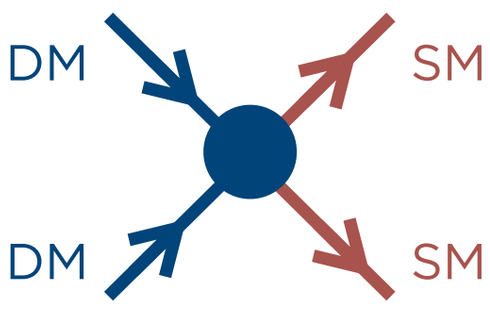
Recoil spectrum for DM-nucleus interaction:

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

Dependence on astrophysics

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

Indirect

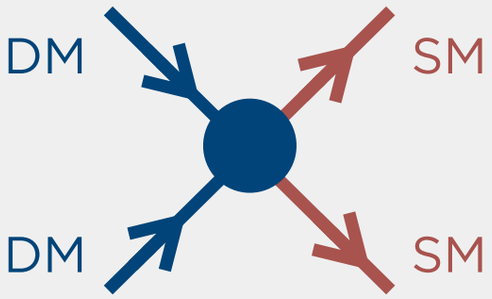


Flux due to DM self-annihilation:

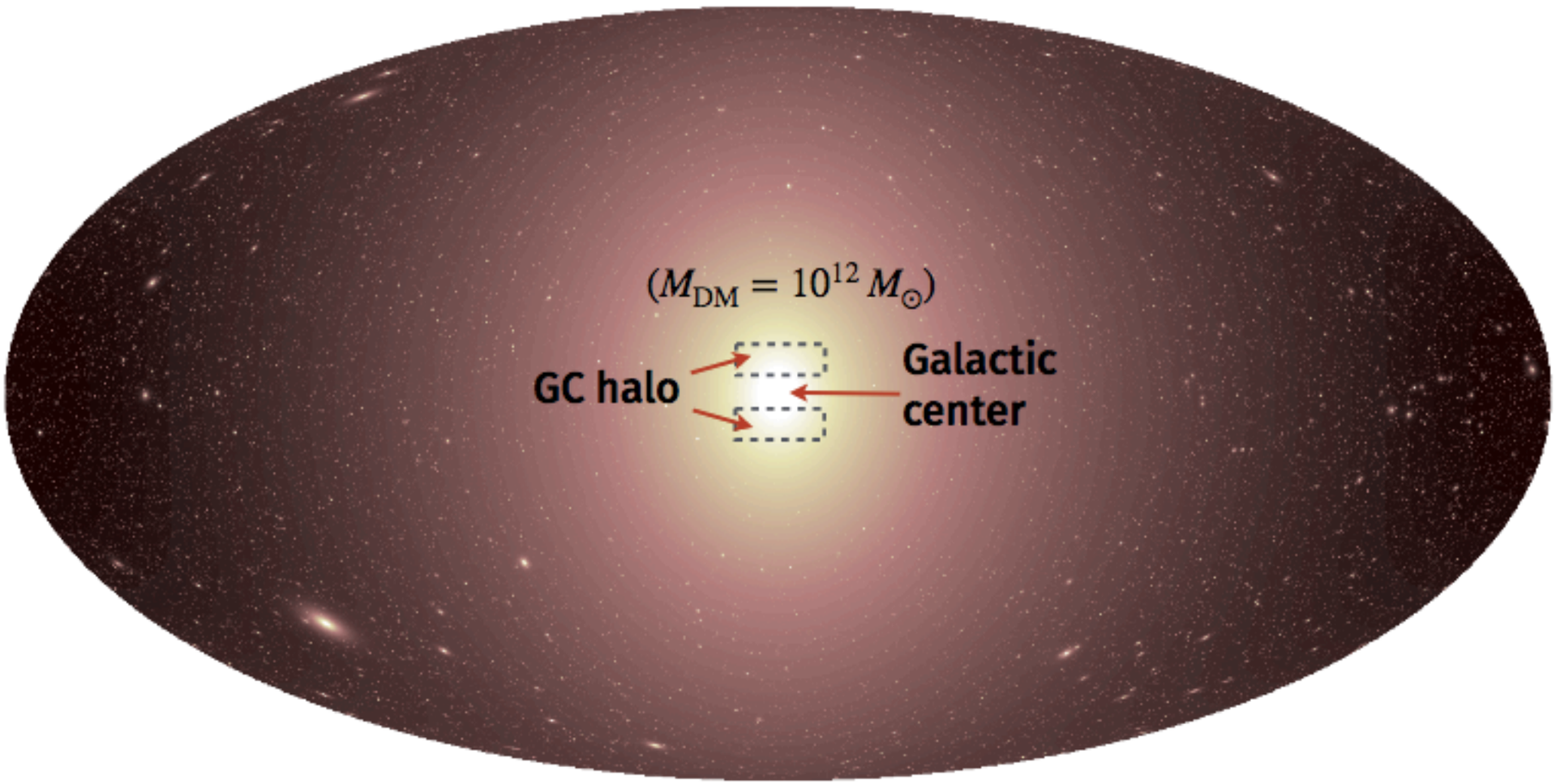
$$\Phi_{\mathrm{DM}} \sim \Phi_{\mathrm{PP}} \int_{\mathrm{l.o.s}} \mathrm{d}l\; \rho^2_{DM}$$

Dependence on astrophysics

Targets for indirect WIMP searches: our Galaxy



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

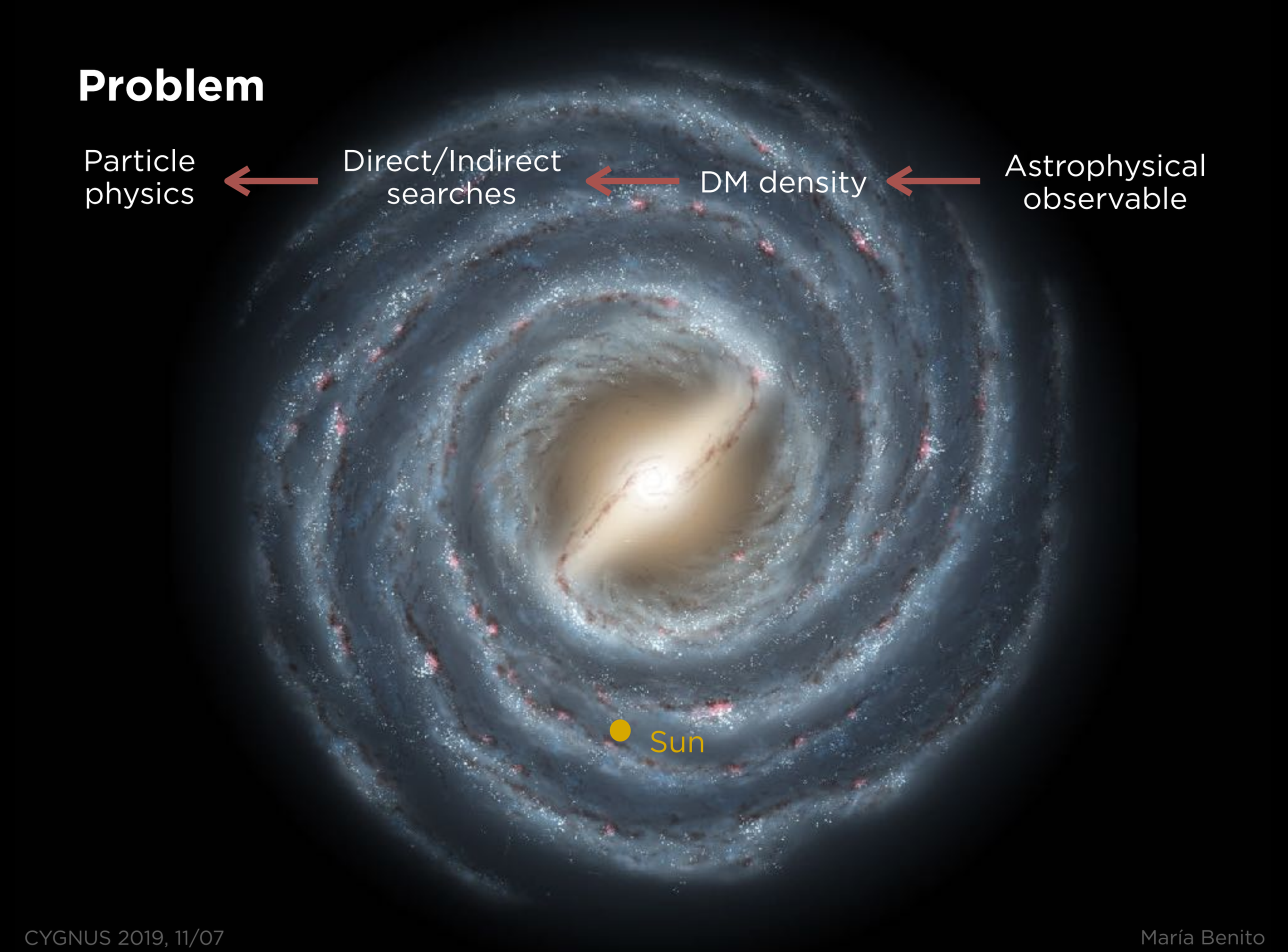


Synthetic γ-ray intensity map from DM annihilation (created with CLUMPY)

Credit: M. Hütten

Problem

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



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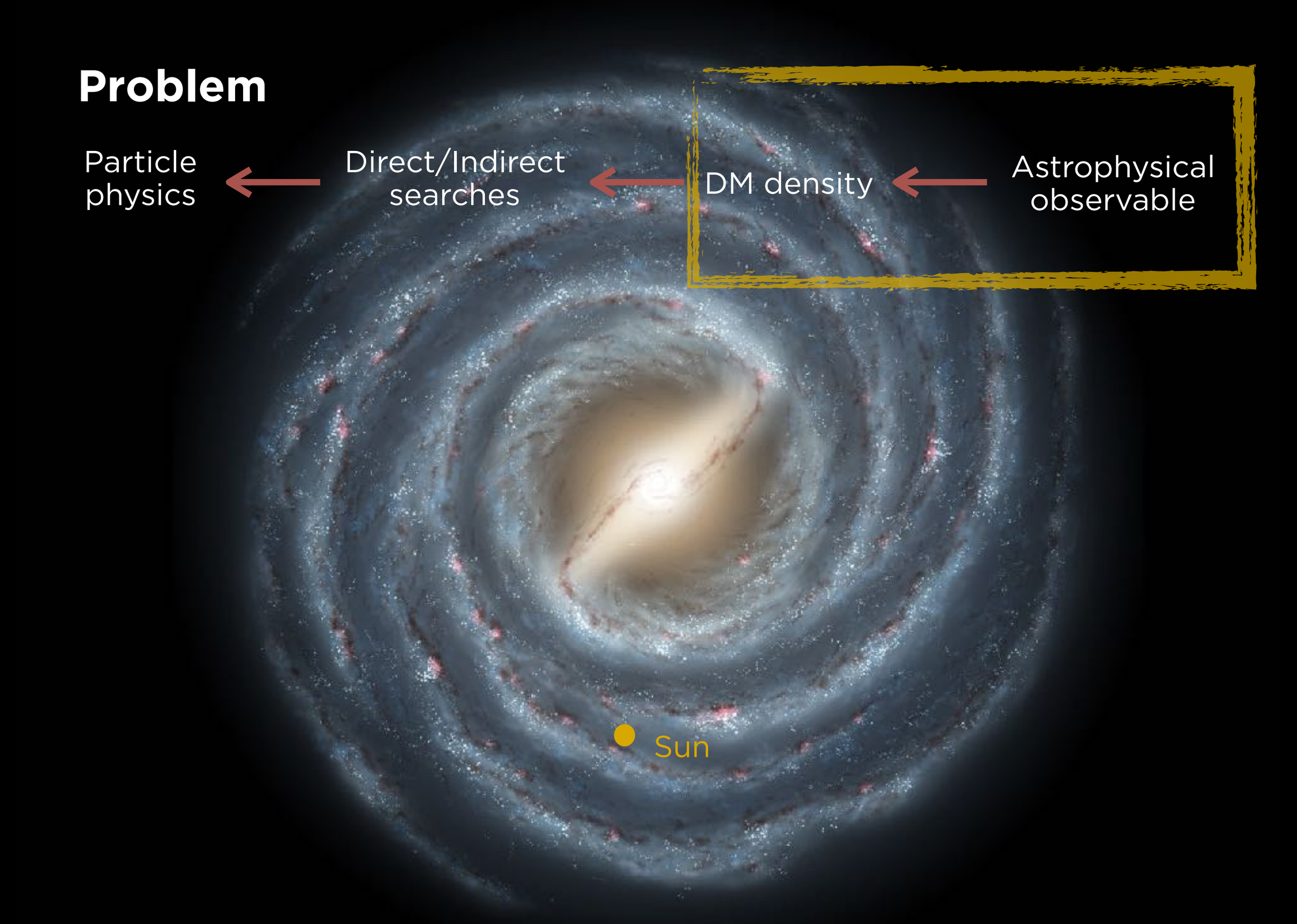
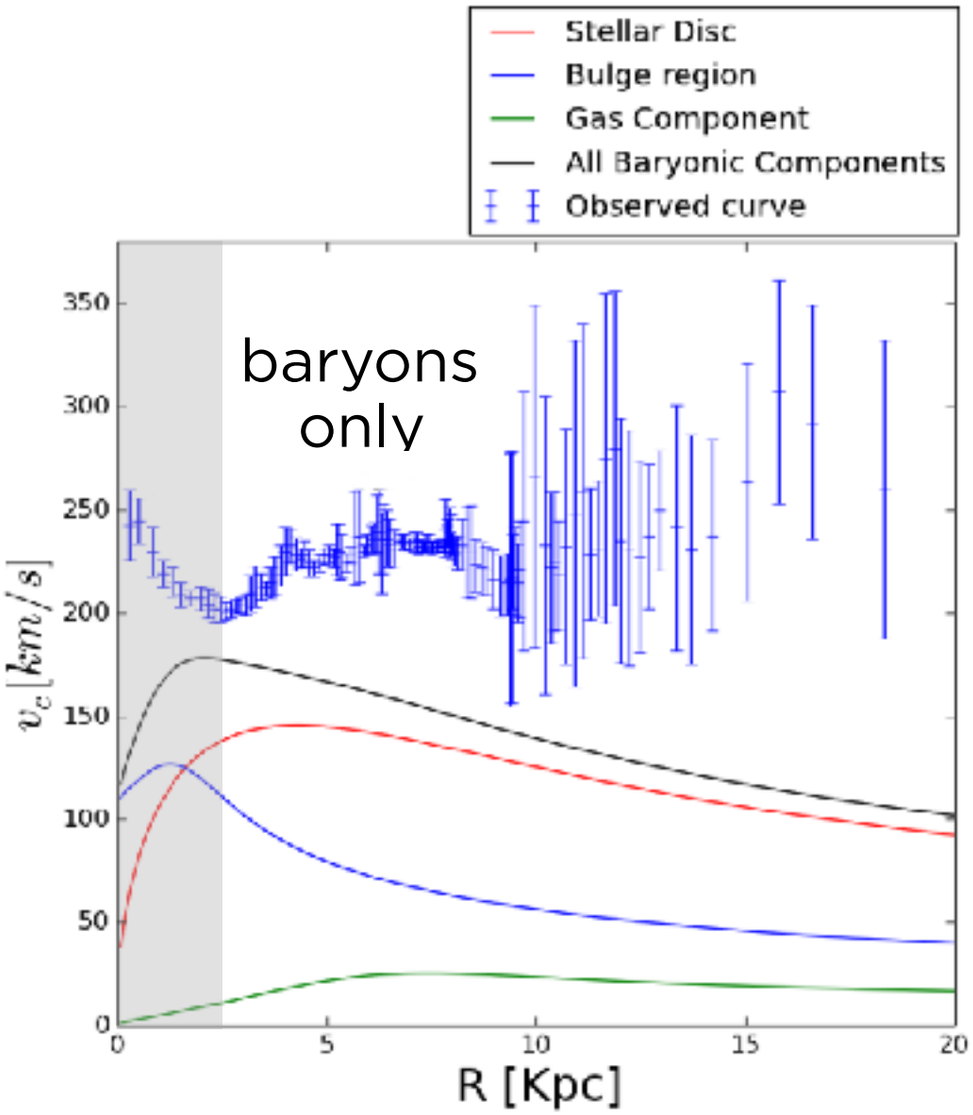
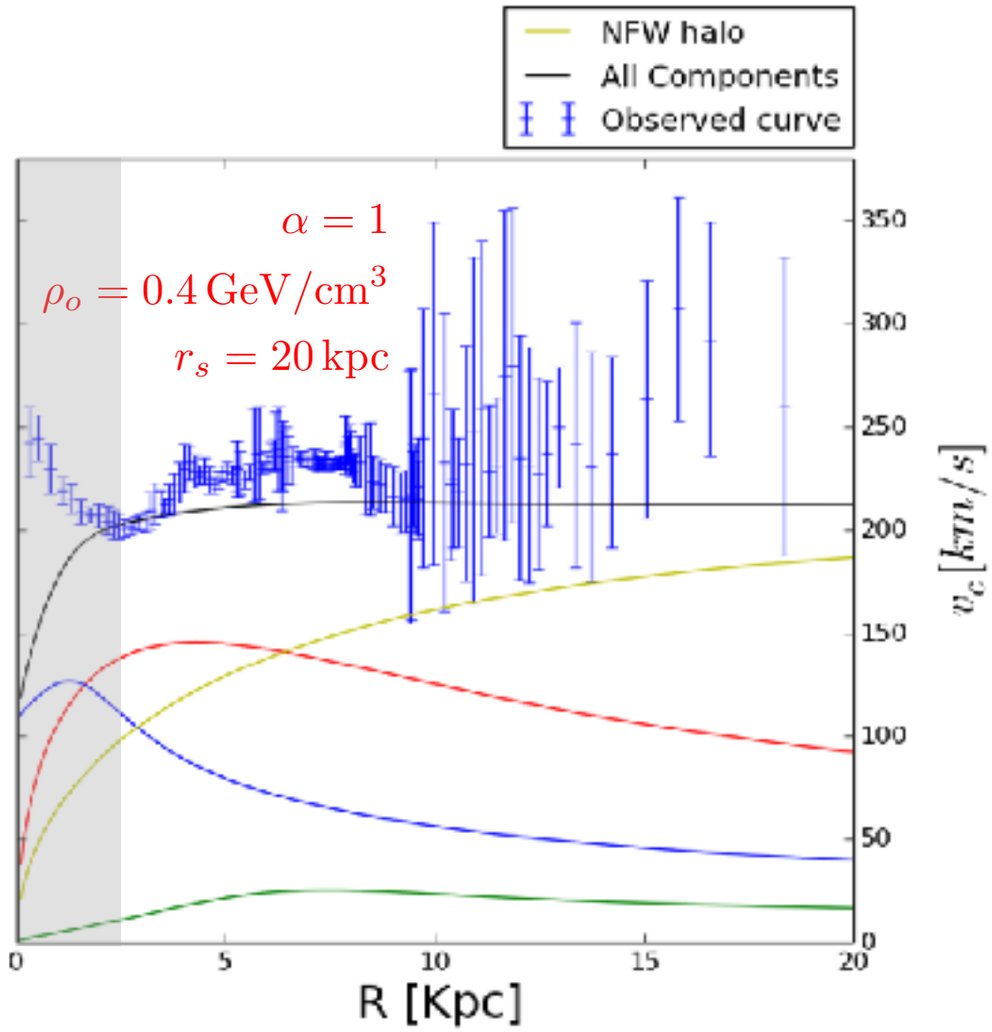


How to determine DM density profile?

Rotation Curve method





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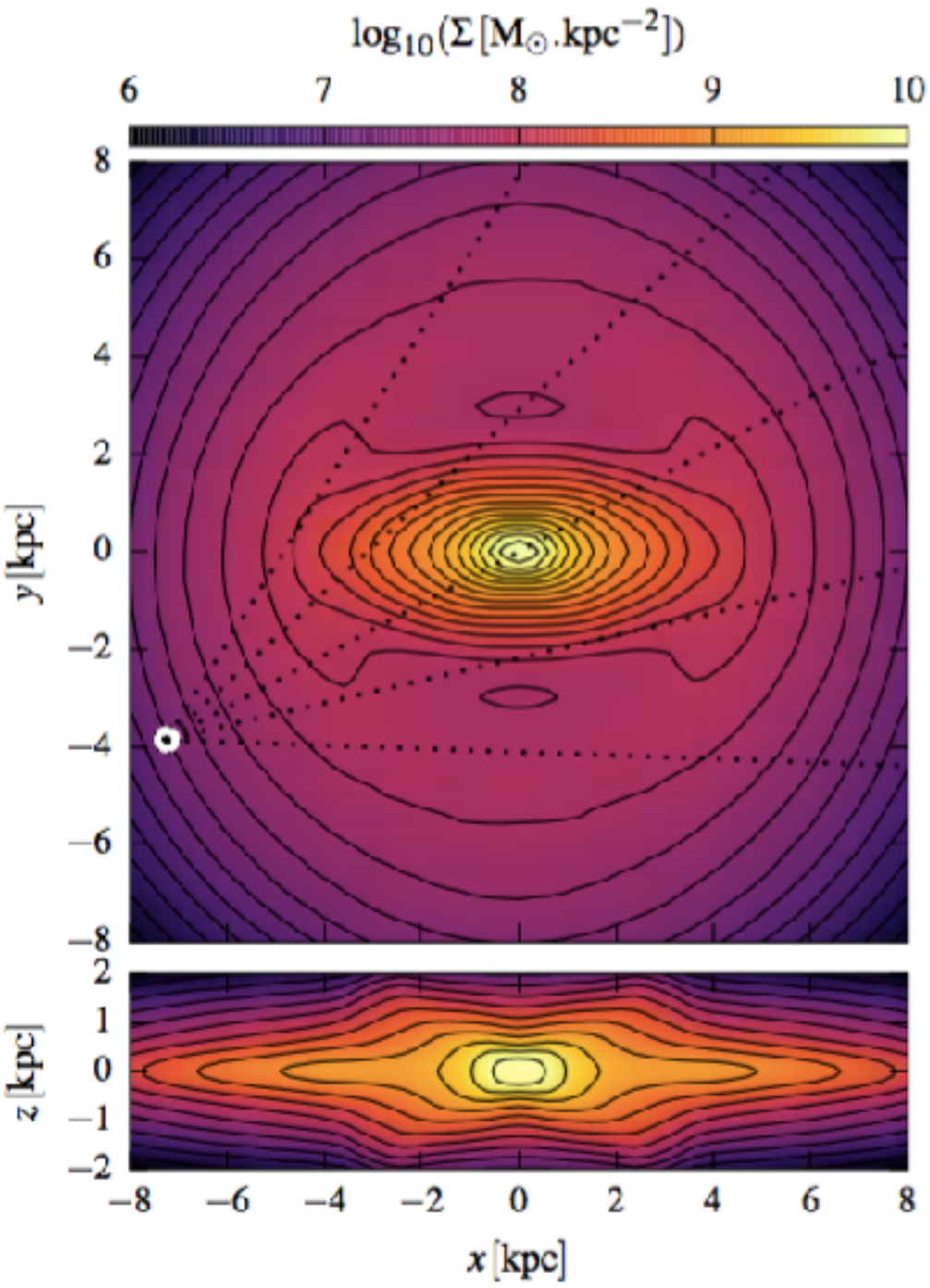


Assumptions:

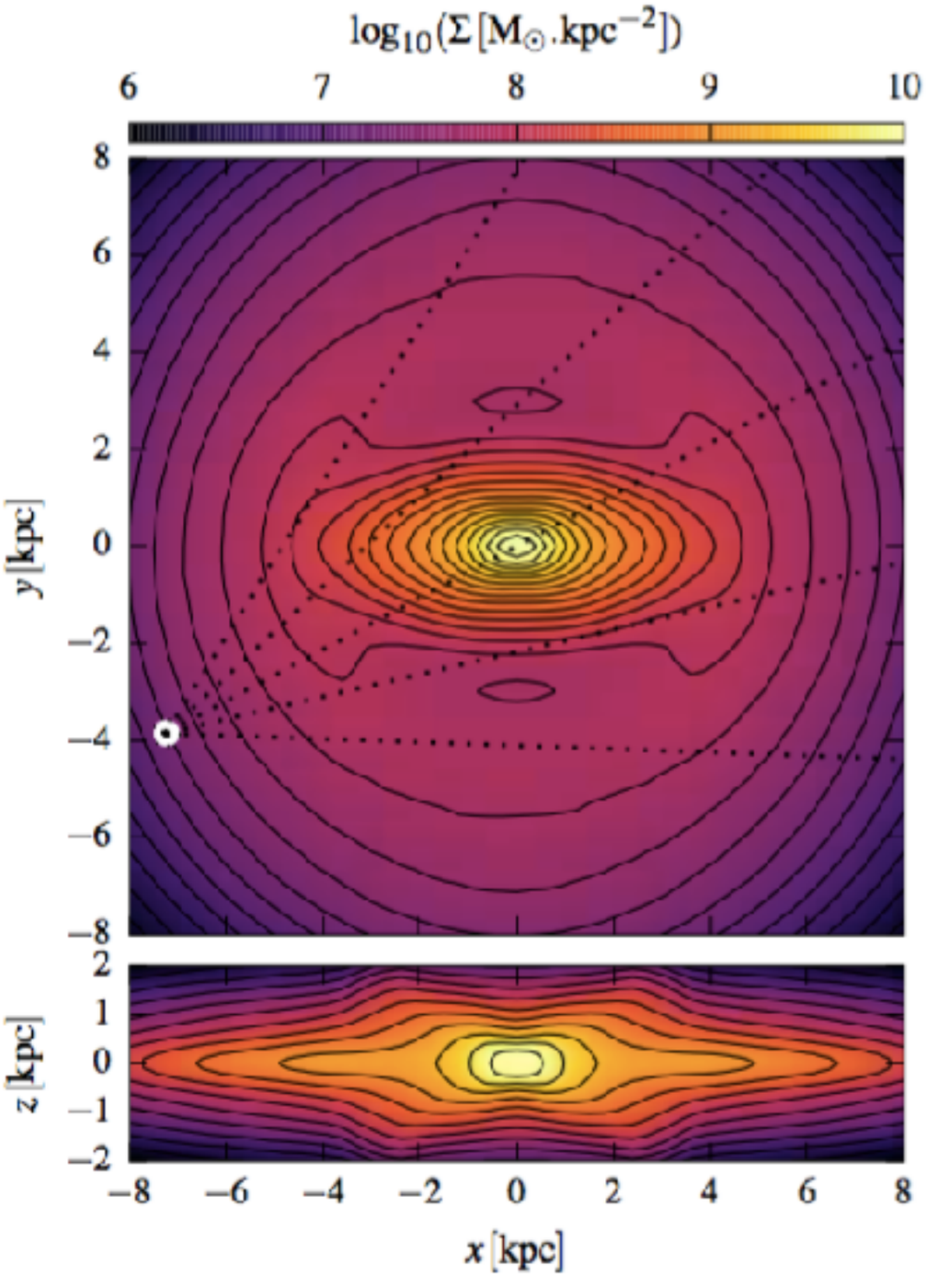
- Rotationally supported
- Objects move in circular orbits around the GC
- The gravitational potential is axisymmetric

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

Portail + [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 kpc

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

Portail + [1608.07954]

How to determine DM density profile?

Rotation Curve method

- Observed RC:

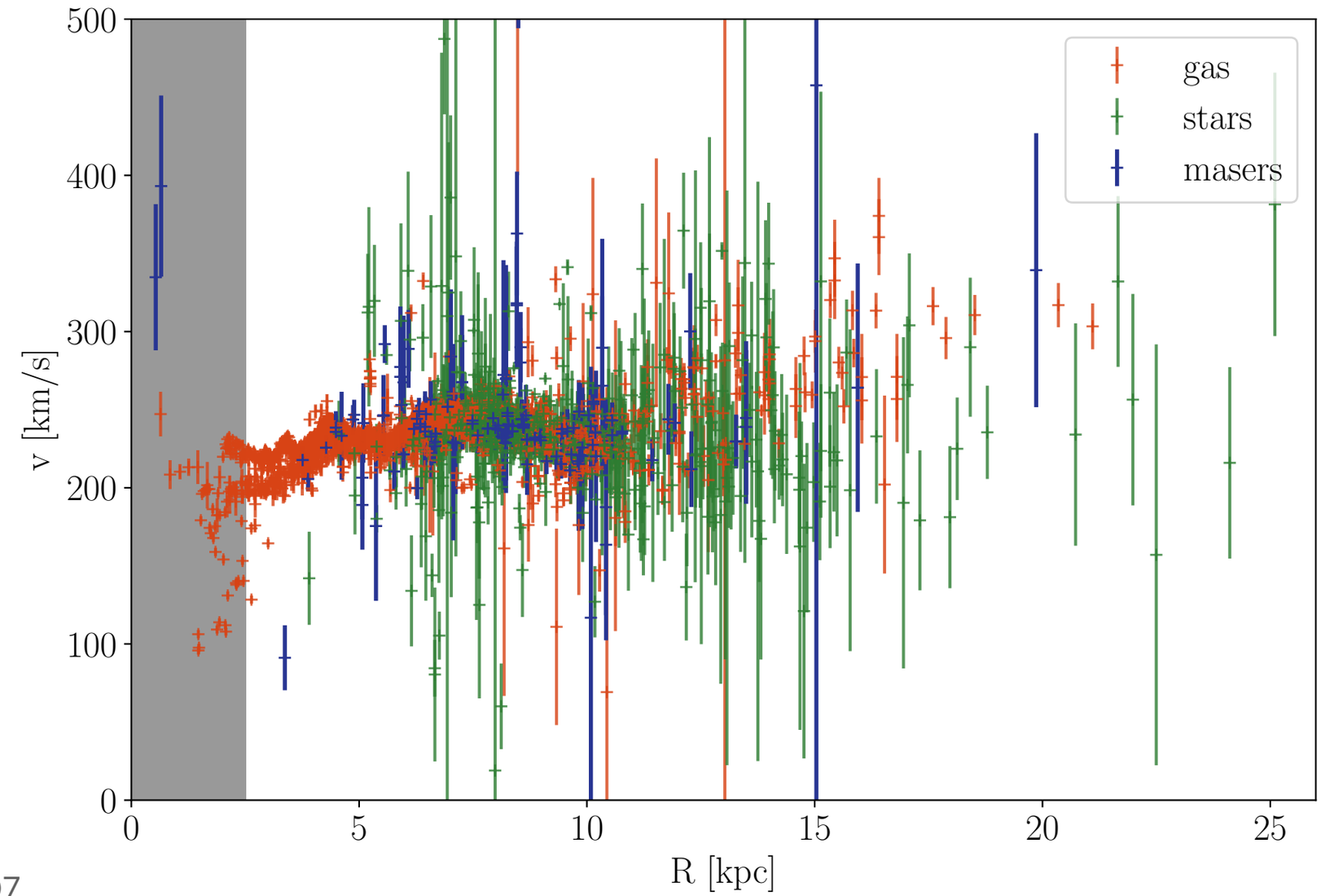
  `galkin` **Pato & Iocco [1703.00020]**

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

One source of uncertainties!

Galactic parameters:

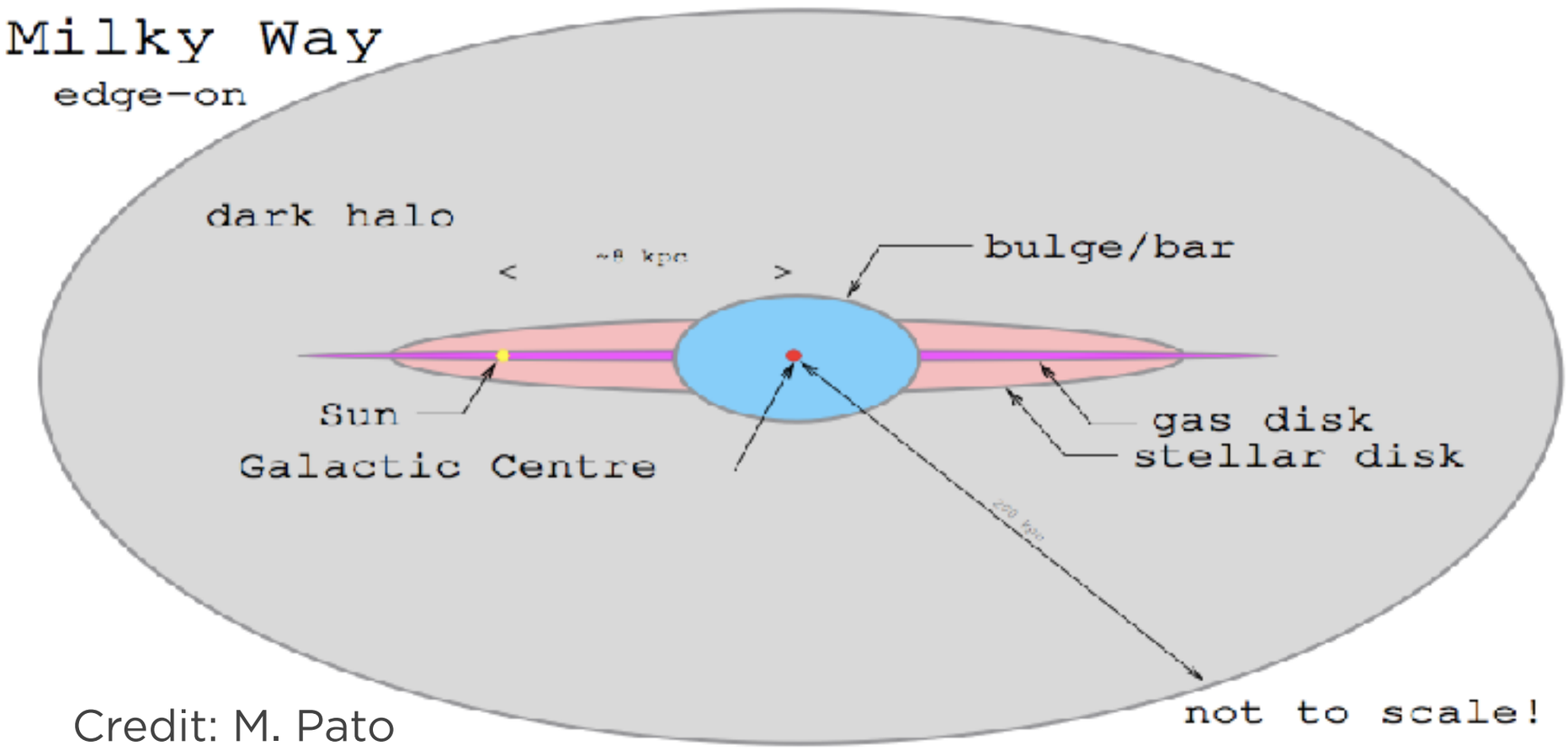
$R_0 = 8.34\,\mathrm{kpc}$ $V_0 = 239.89\,\mathrm{km/s}$ $(U_\odot, V_\odot, W_\odot) = (7.01, 10.13, 4.95)\,\mathrm{km/s}$



Luminous component of the Milky Way

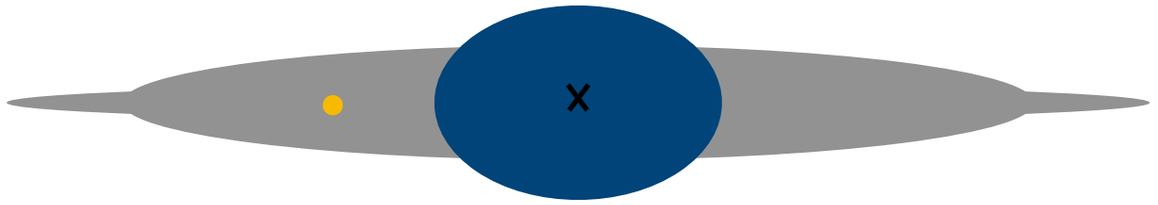
$$\begin{array}{rcl} \rho_{\rm bulge}(x,y,z) & & \Phi_{\rm bulge}(x,y,z) \\ \rho_{\rm disc}(r,z) & \rightarrow & \Phi_{\rm disc}(r,z) \\ \rho_{\rm gas}(x,y,z) & & \Phi_{\rm gas}(x,y,z) \end{array} \rightarrow \begin{array}{r} v^2(r) = \sum_i v_i^2(r) \\ v_i^2(r) = r\dfrac{{\rm d}\Phi_i}{{\rm d}r} \end{array}$$

see e.g. **Iocco + Nature'15**



Credit: M. Pato

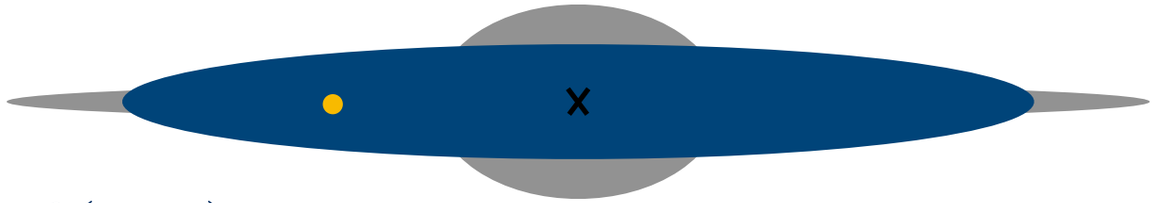
Bulge distribution:



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

$f(x,y,z)$	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
$\mathrm{sech}^2(-r_s) + e^{-r_s}$	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]

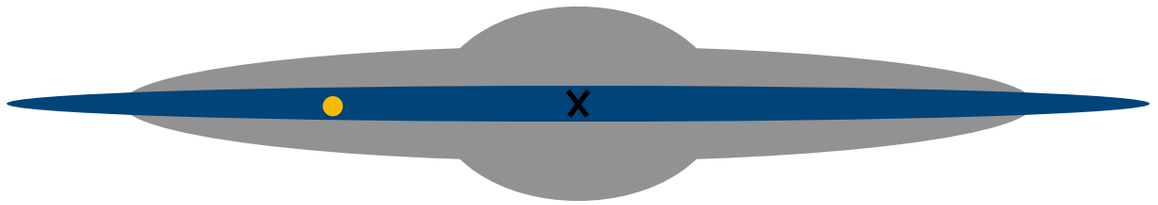
Stellar disc distribution:



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

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

Gas distribution:



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

Components		Range	Reference
molecular ring	H_2	$r = 3 - 20\,\mathrm{kpc}$	Ferrière, ApJ'98
cold, warm	HI		
warm, hot	HII		
CMZ, disc	H_2	$r = 0.01 - 3\,\mathrm{kpc}$	Ferrière +, AAp'07
CMZ, disc	HI		
warm, hot, very hot	HII		

Uncertainties

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

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

Ferriere +, ApJ'07

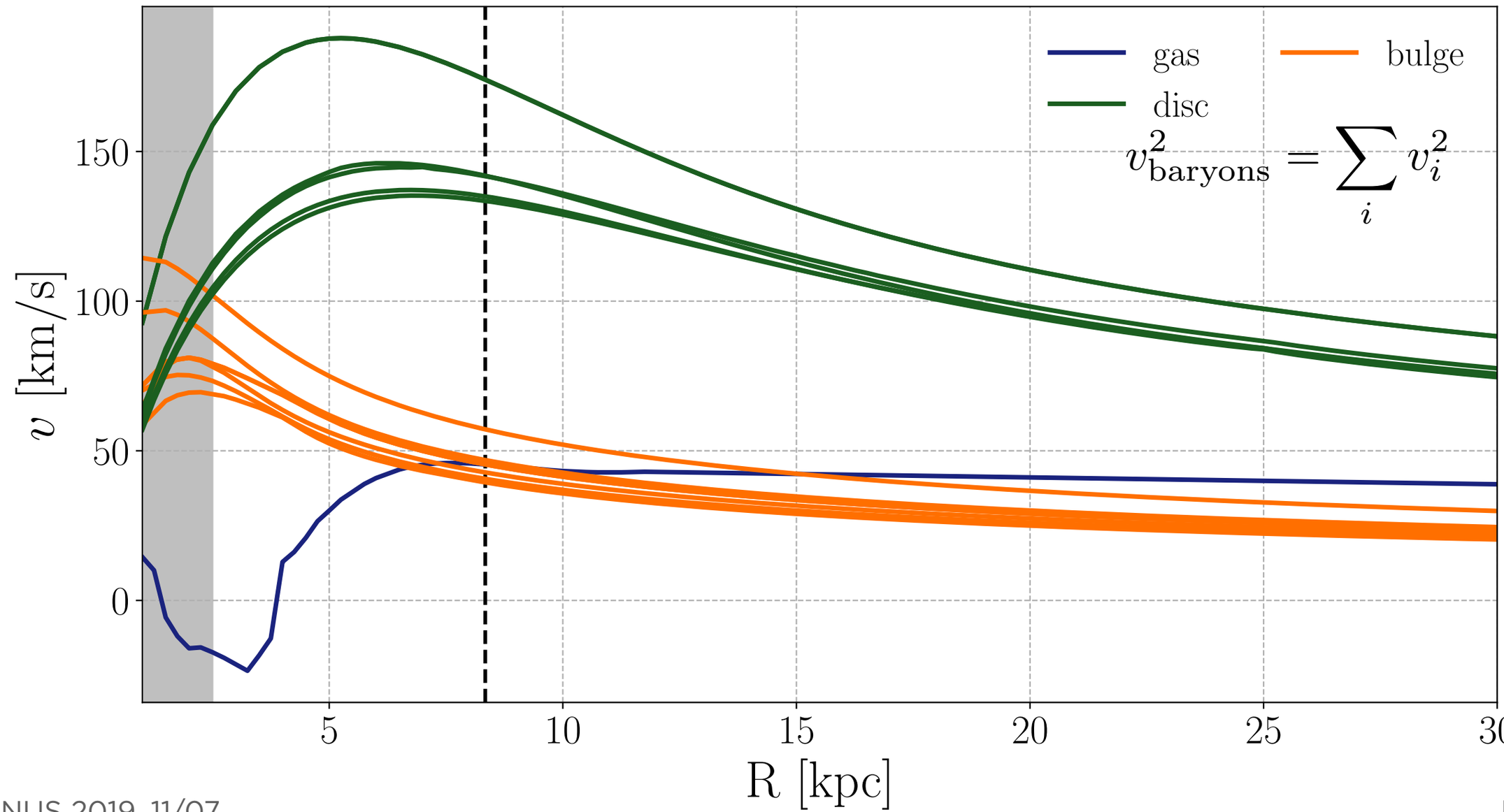
Systematic uncertainties

Luminous component

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

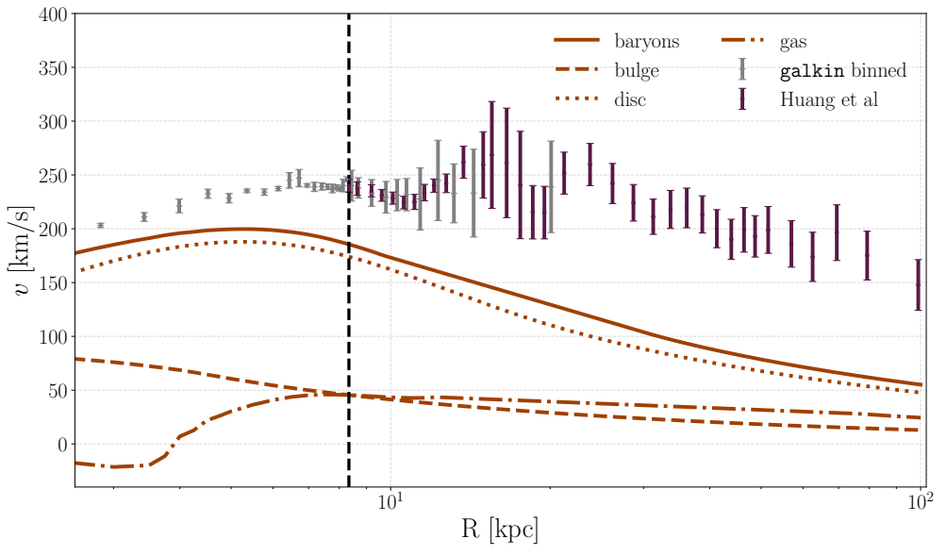
Sources of uncertainties:

- Actual shape of baryons
- Normalisation of baryons



How to determine DM density profile?

Rotation Curve method



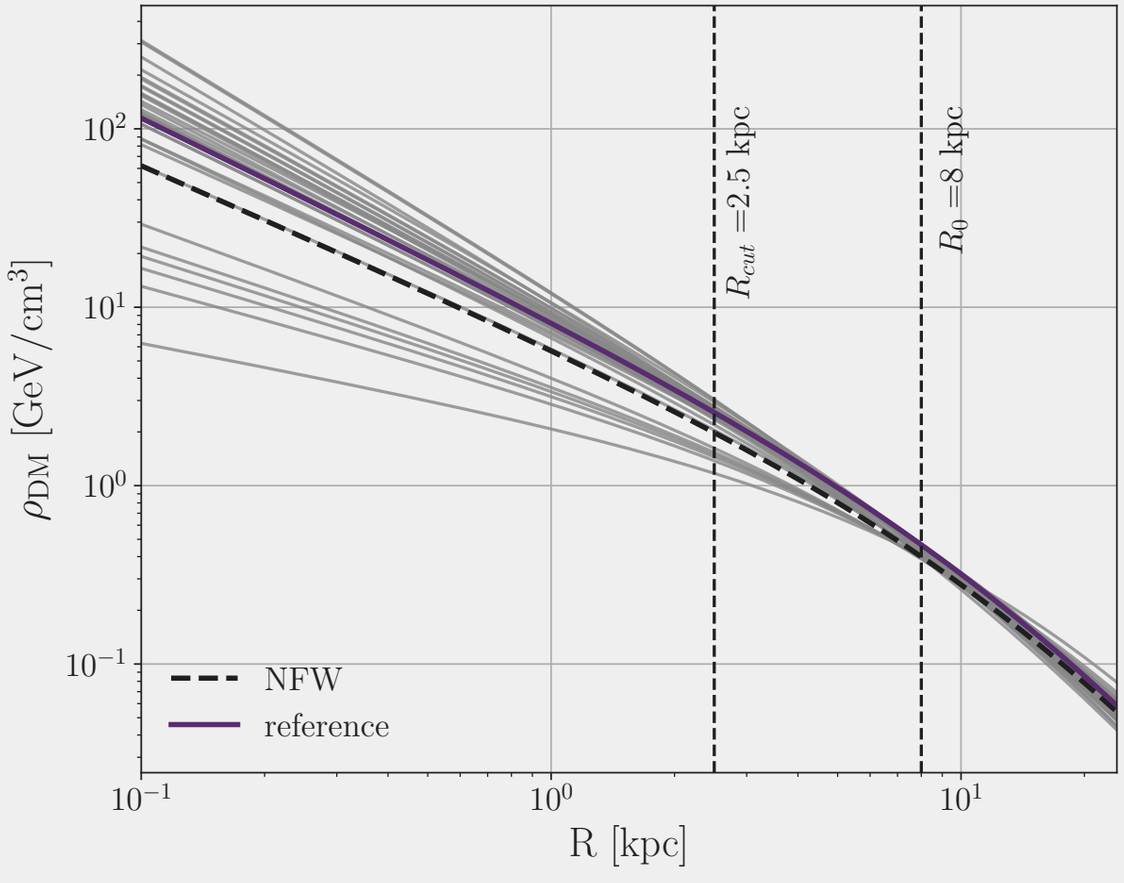
1) Observed RC

2) RC for the luminous component

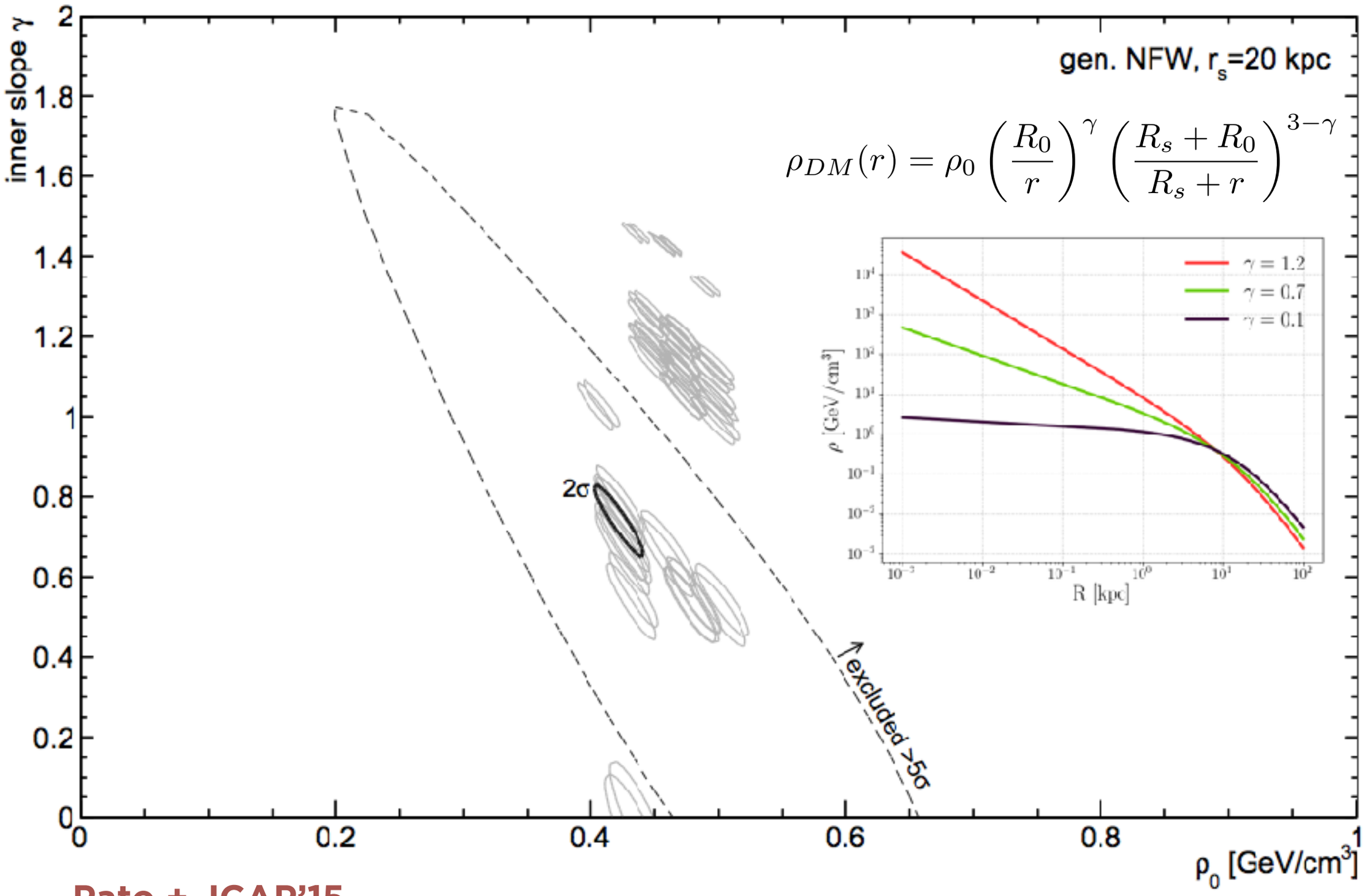
gNFW density profile

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

Three free parameters: γ, R_s, ρ_0



Extracting the DM density structure

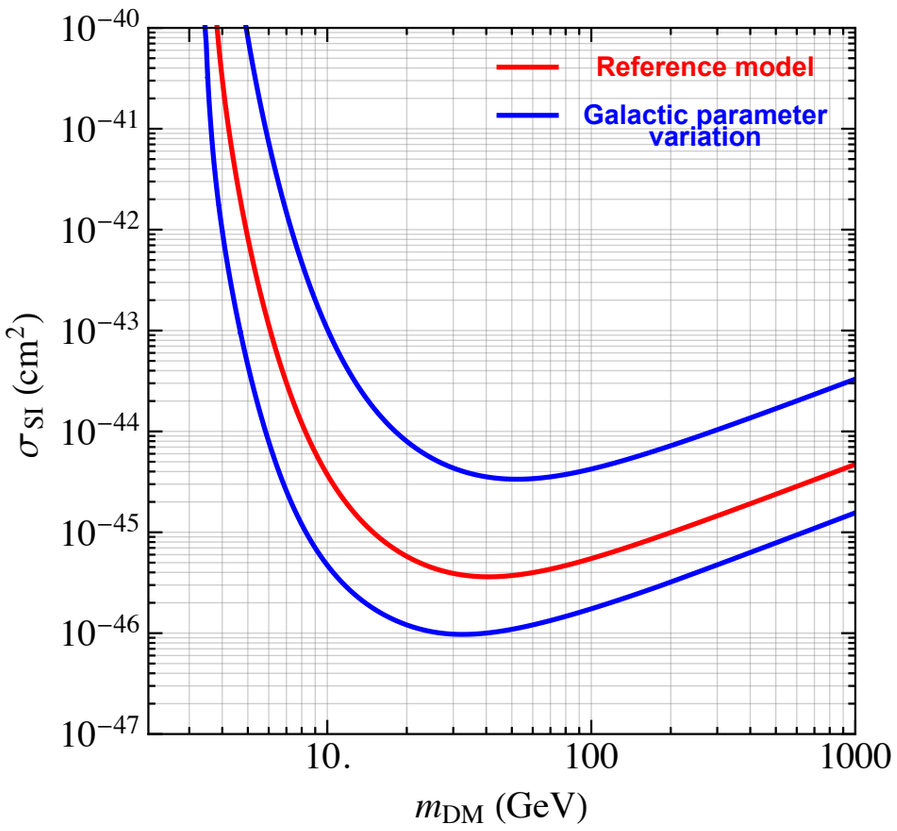


Pato + JCAP'15

Problem:

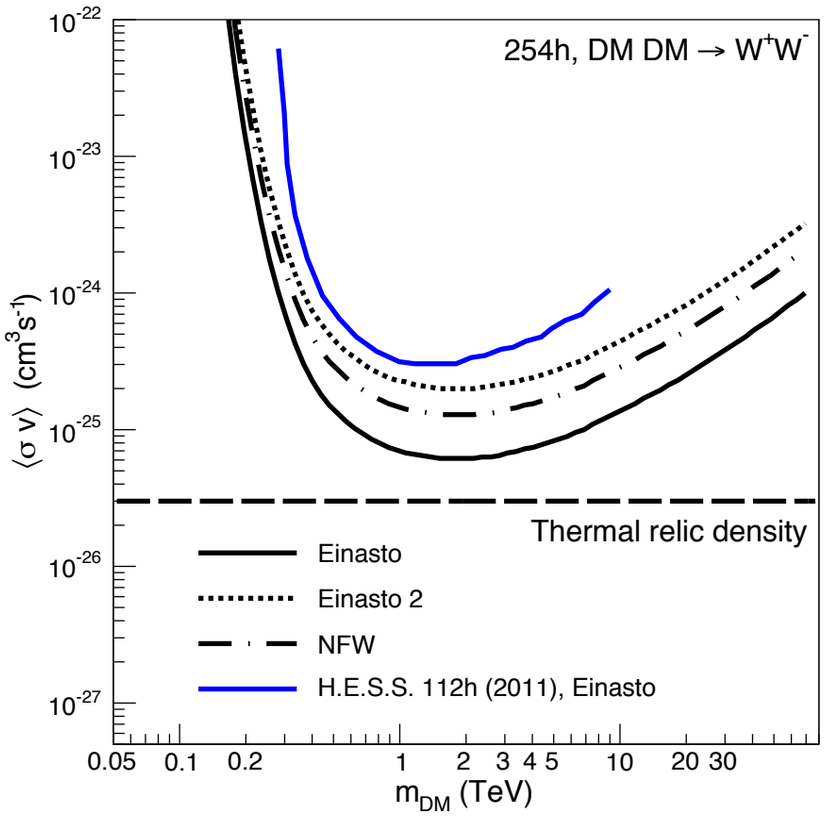
Particle physics ← Direct/Indirect searches ← DM density ← Astrophysical observable

Direct



MB + [1612.02010]

Indirect



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

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

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

$$v_H = 246\,\mathrm{GeV} \quad \langle S \rangle = 0$$

Phenomenology dictated by the Higgs coupling to the dark sector and the DM mass

Mc Donald, PRD'94

Burgess, Pospelov & Velthuis, Nucl.Phys.B'01

But do Galactic uncertainties affect PP, for real?

A simple case: Singlet Scalar DM

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

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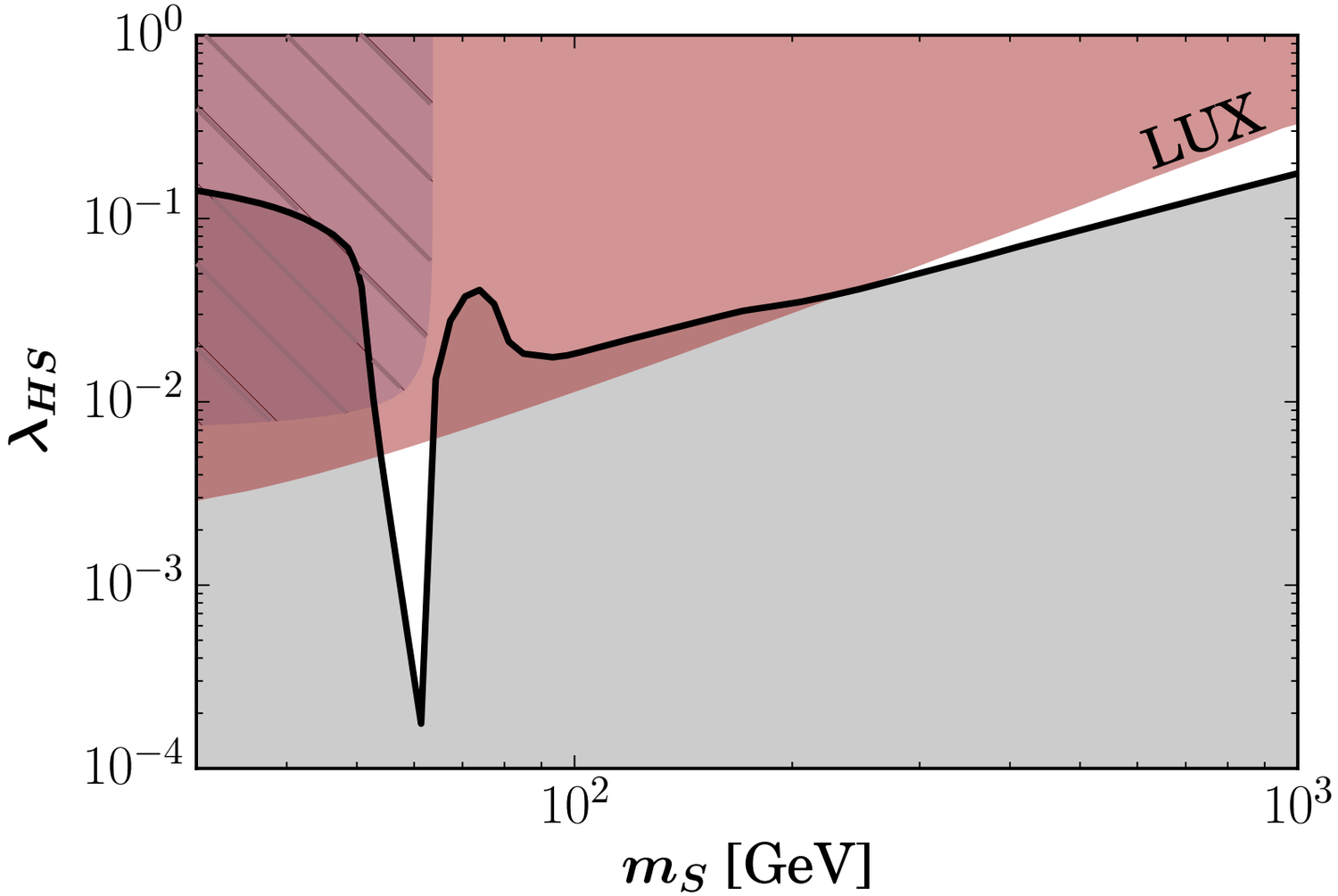
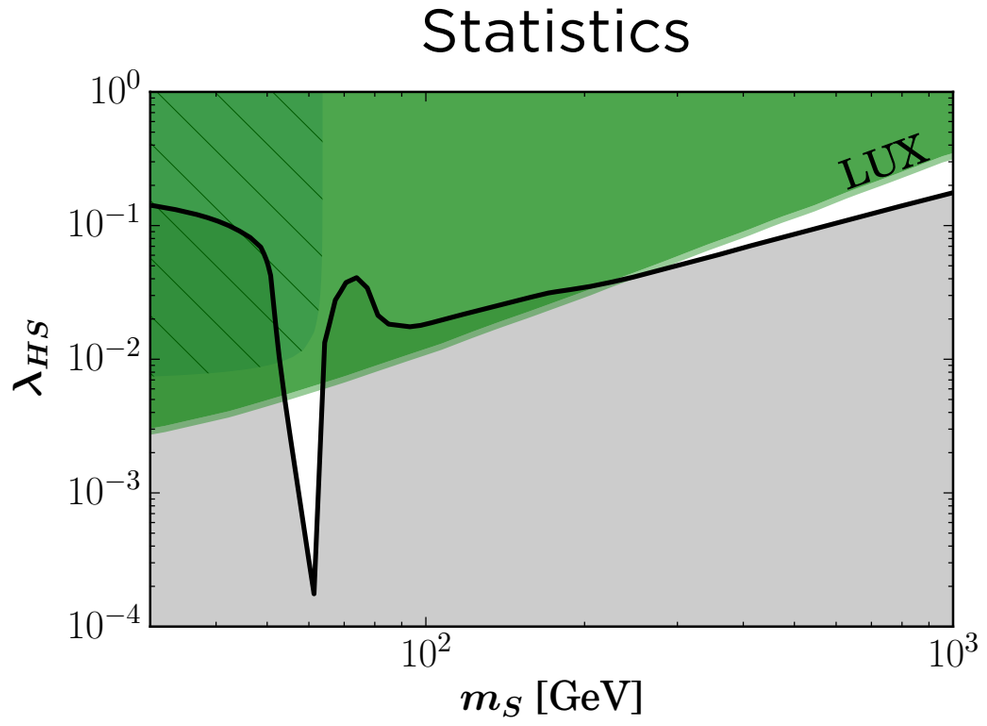
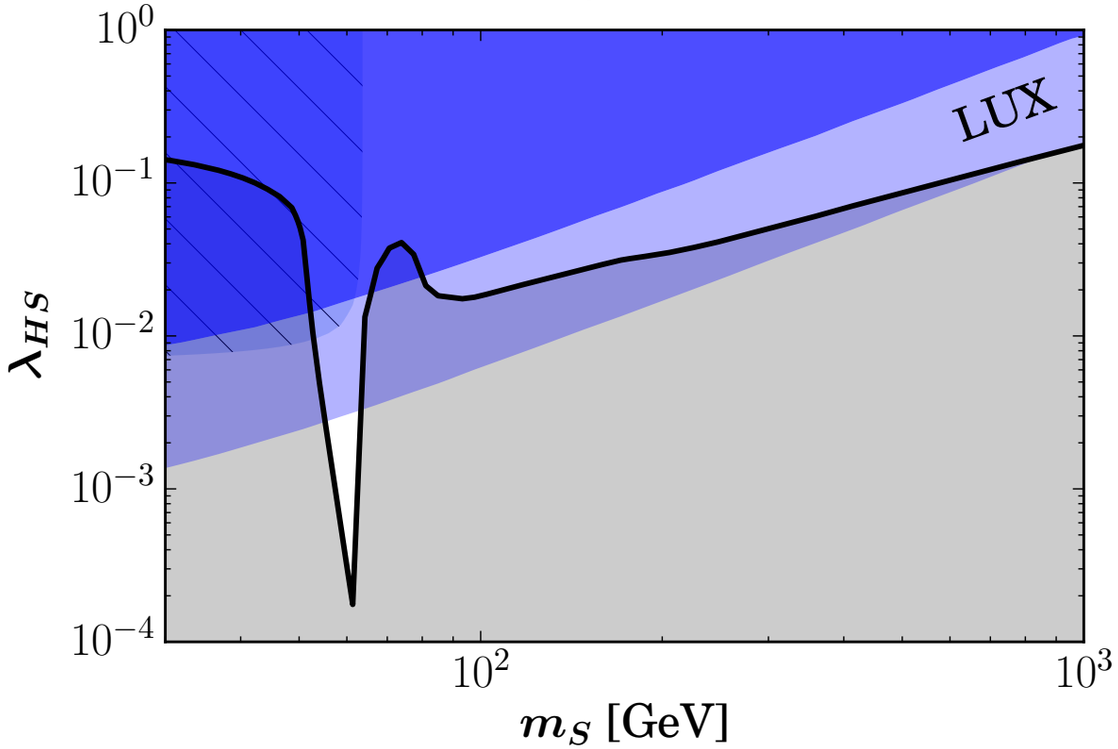


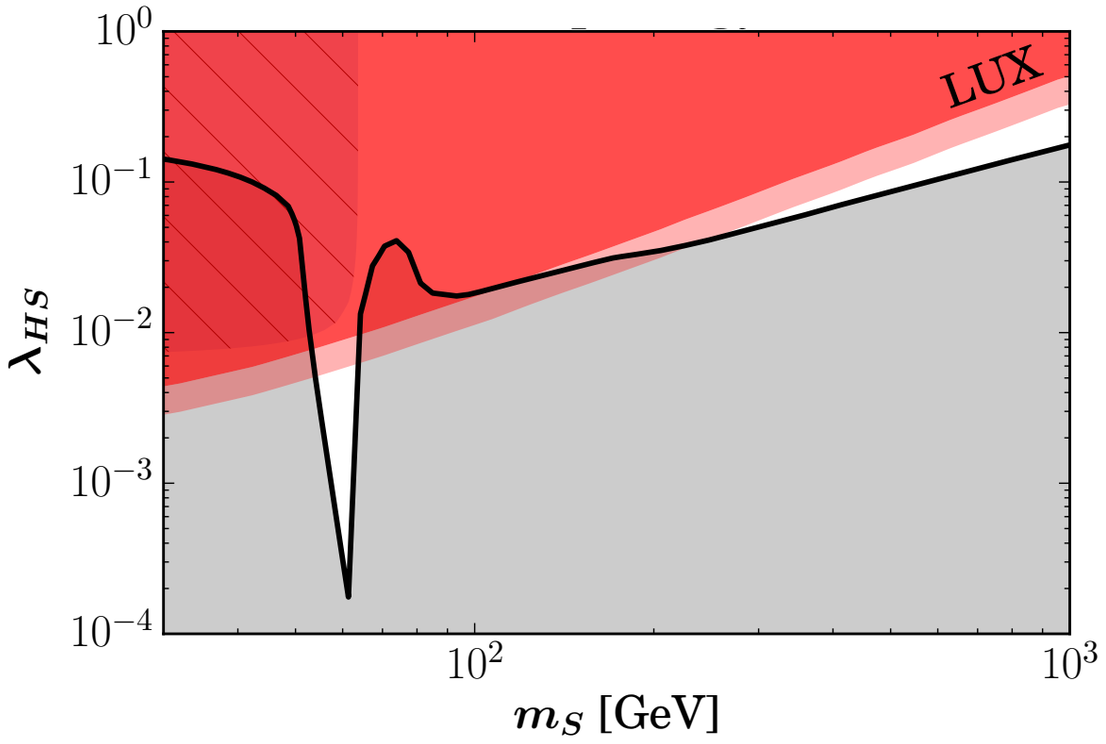
Effect of Galactic astrophysical uncertainties

Direct detection constraints

MB + [1612.02010]





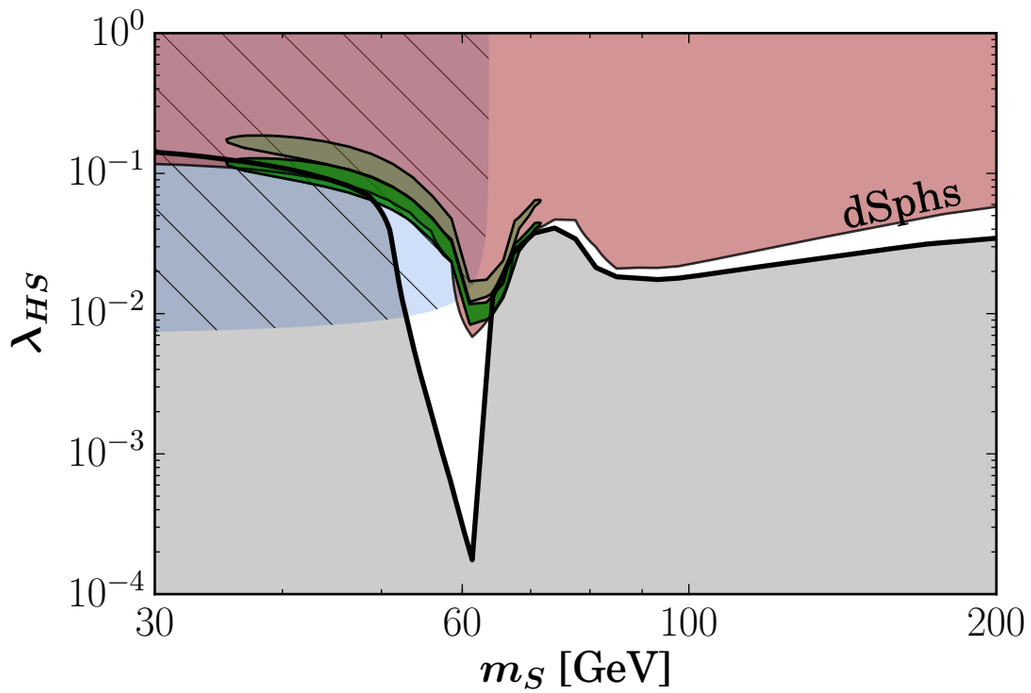


Effect of Galactic astrophysical uncertainties

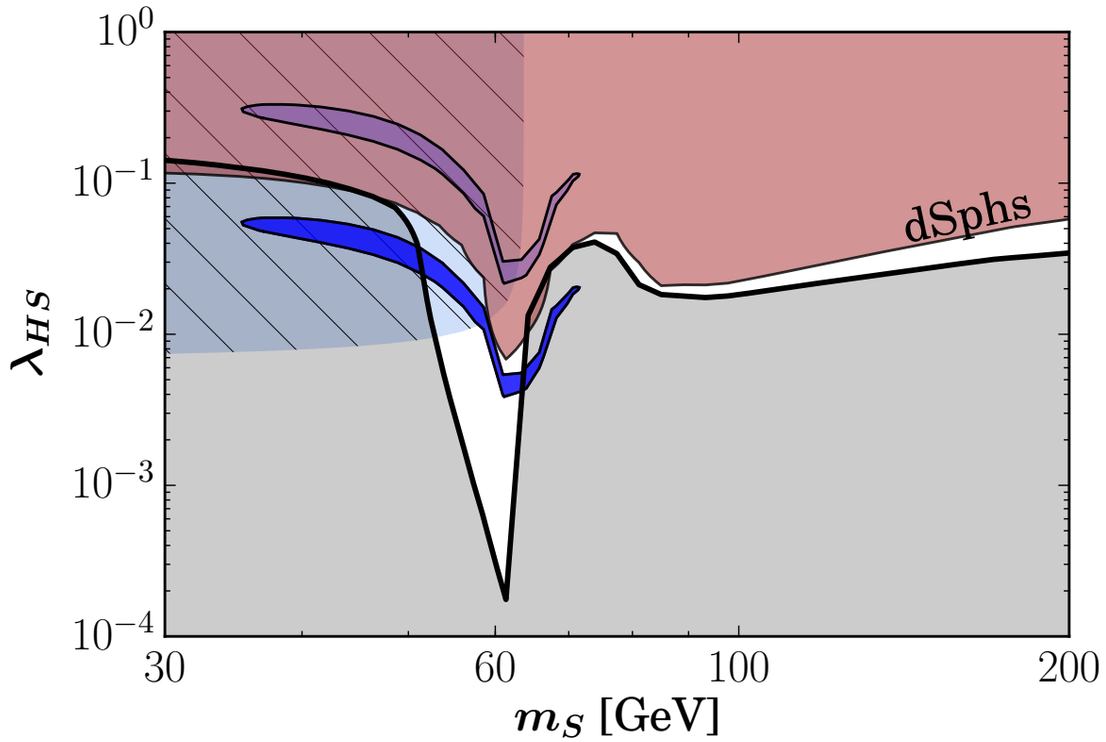
Indirect detection constraints

MB + [1612.02010]

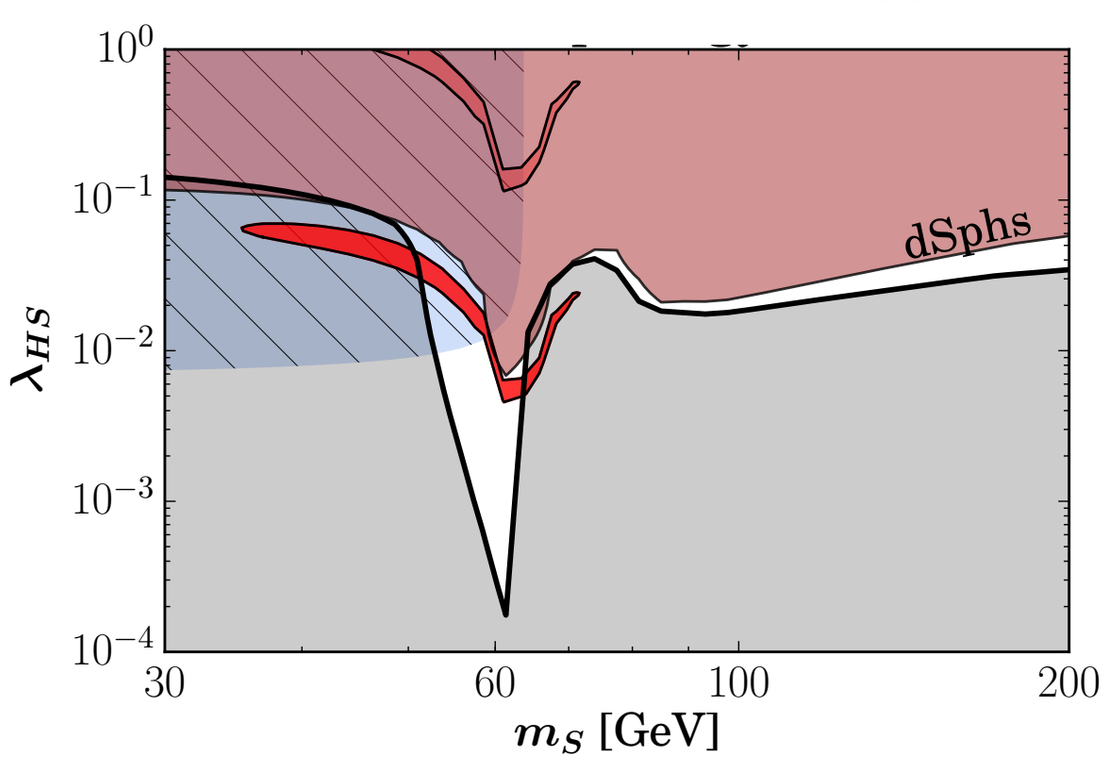
Statistics



Galactic parameters



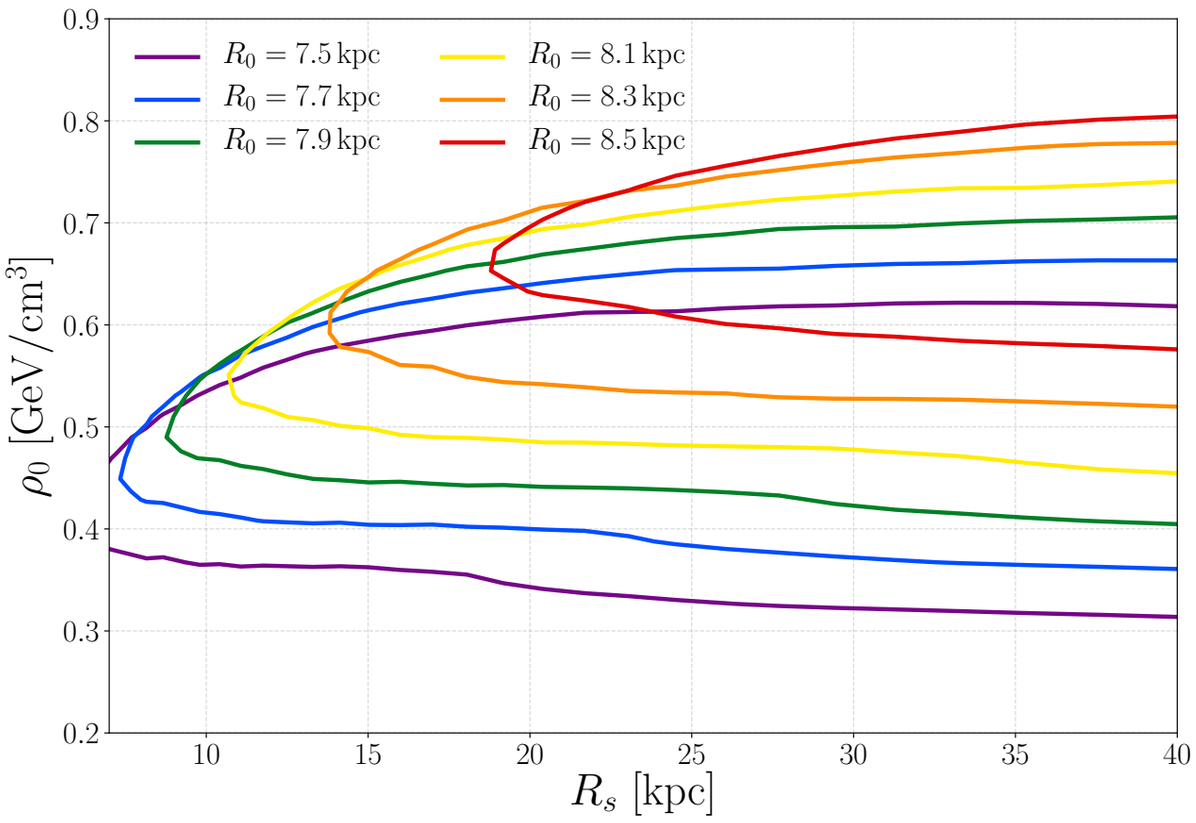
Baryonic morphology

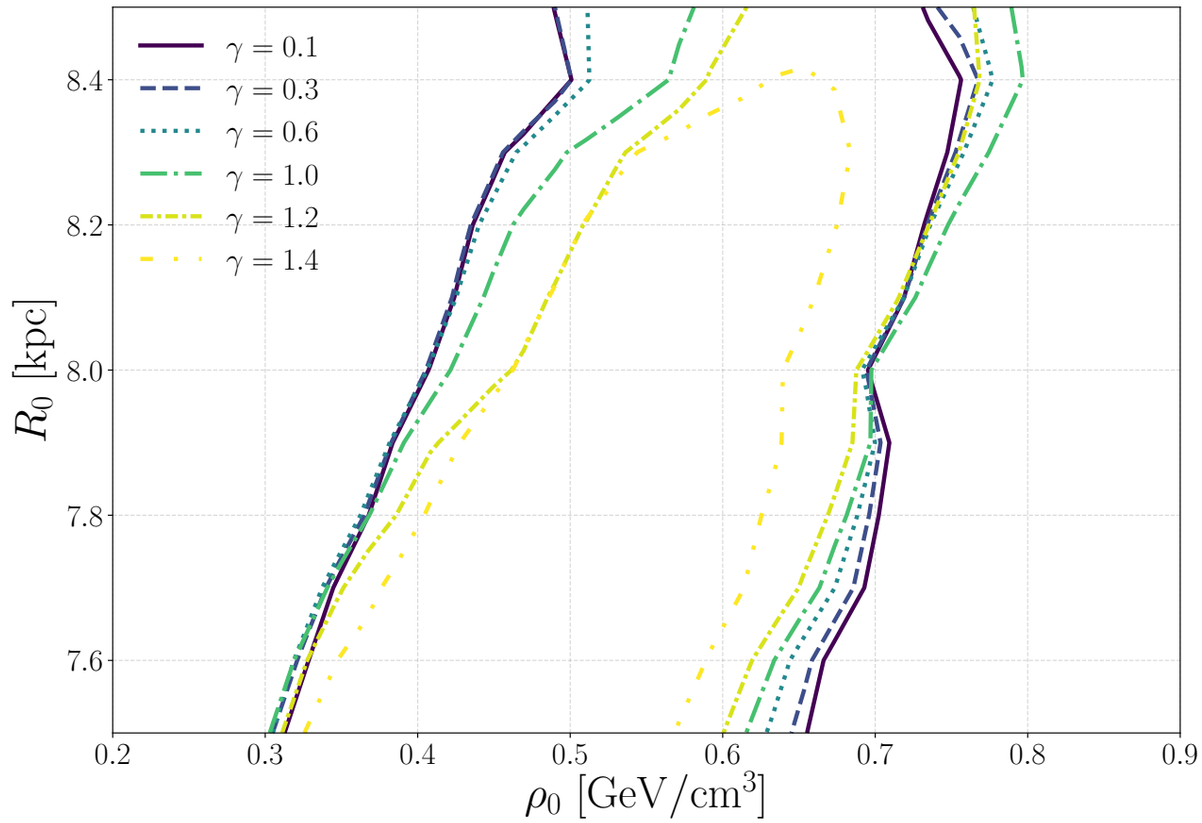


Include astrophysical uncertainties in your own analysis

Full likelihood available at:

https://github.com/mariabenitocst/UncertaintiesDMinTheMW





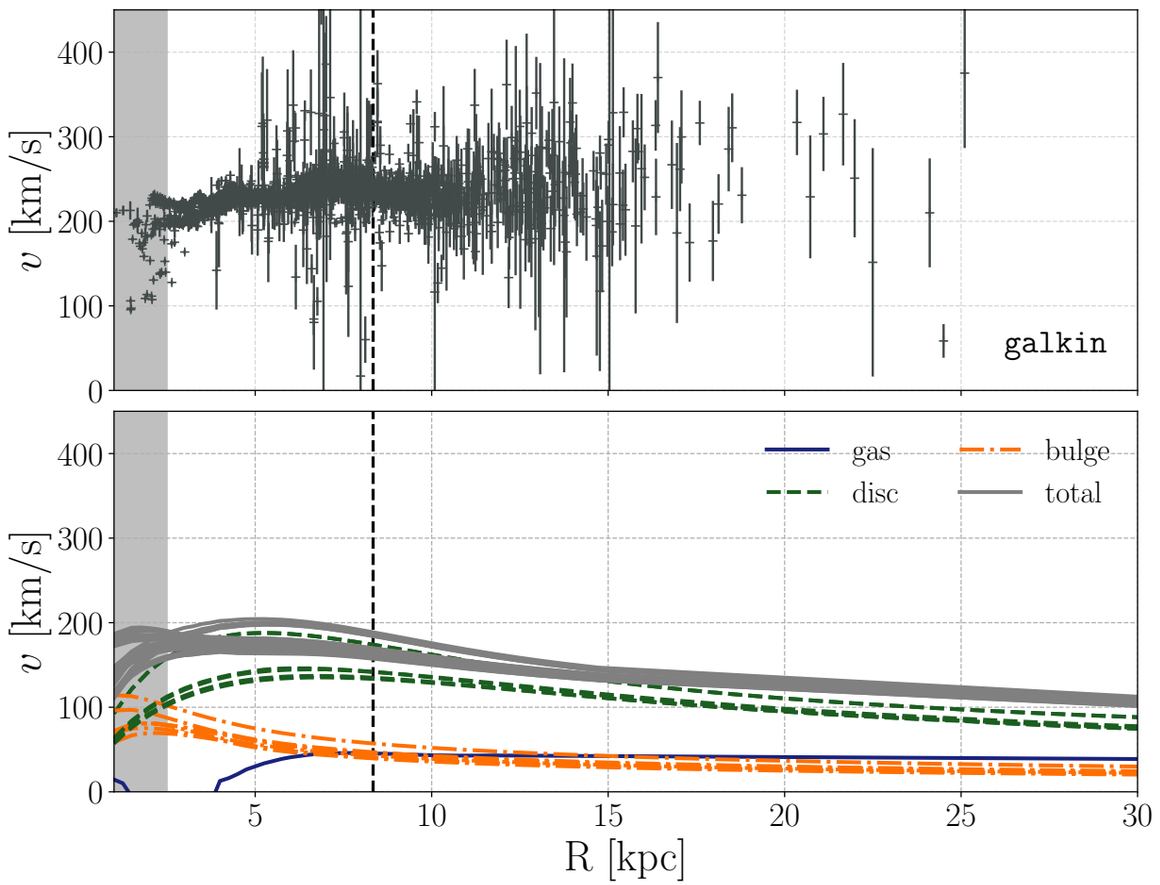
MB + [1901.02460]

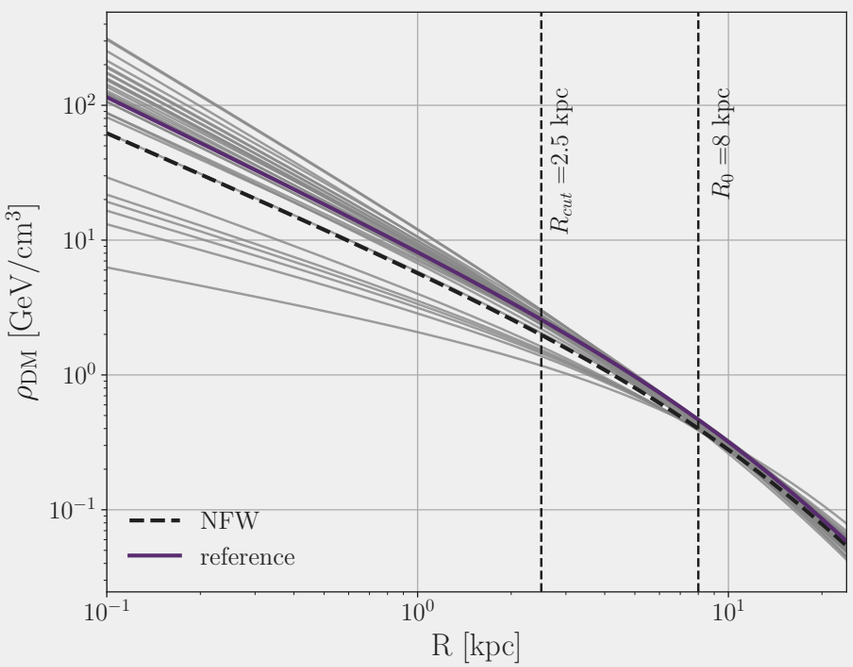
How to determine DM density profile?

Rotation Curve method

1) Observed RC

2) RC for the luminous component





3) gNFW density profile

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

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	

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5	R_0	Sun's galactocentric distance

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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

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

Popowski + 2005 [astrop-ph/0410319]

Normalisation disc

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

Bovy & Rix 2013 [1309.0809]

Scan the 7D parameter space to obtain the Likelihood profile

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

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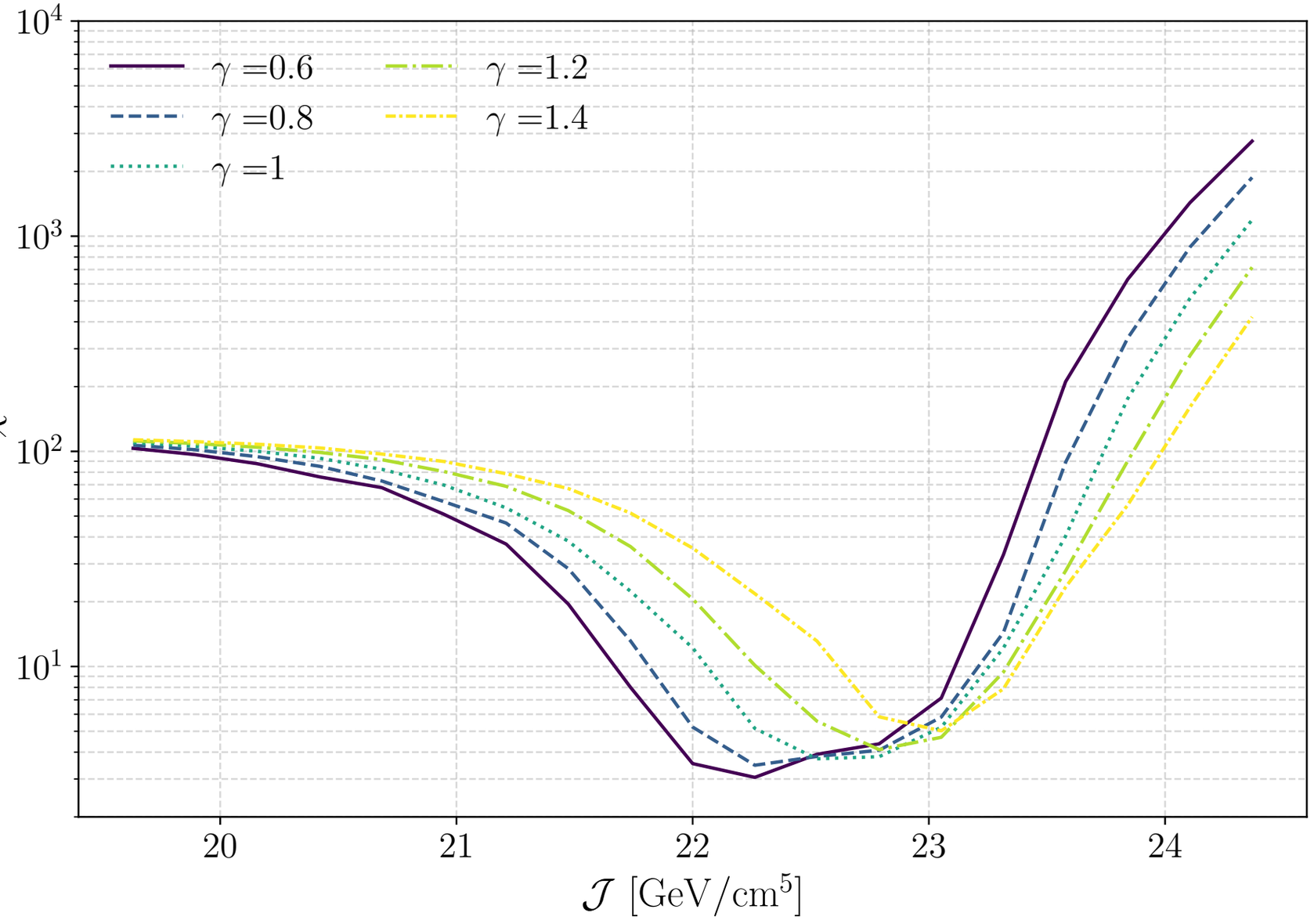
$$\chi^2_{\rm RC}(R_s, \rho_0, \gamma, R_0)$$

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)



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

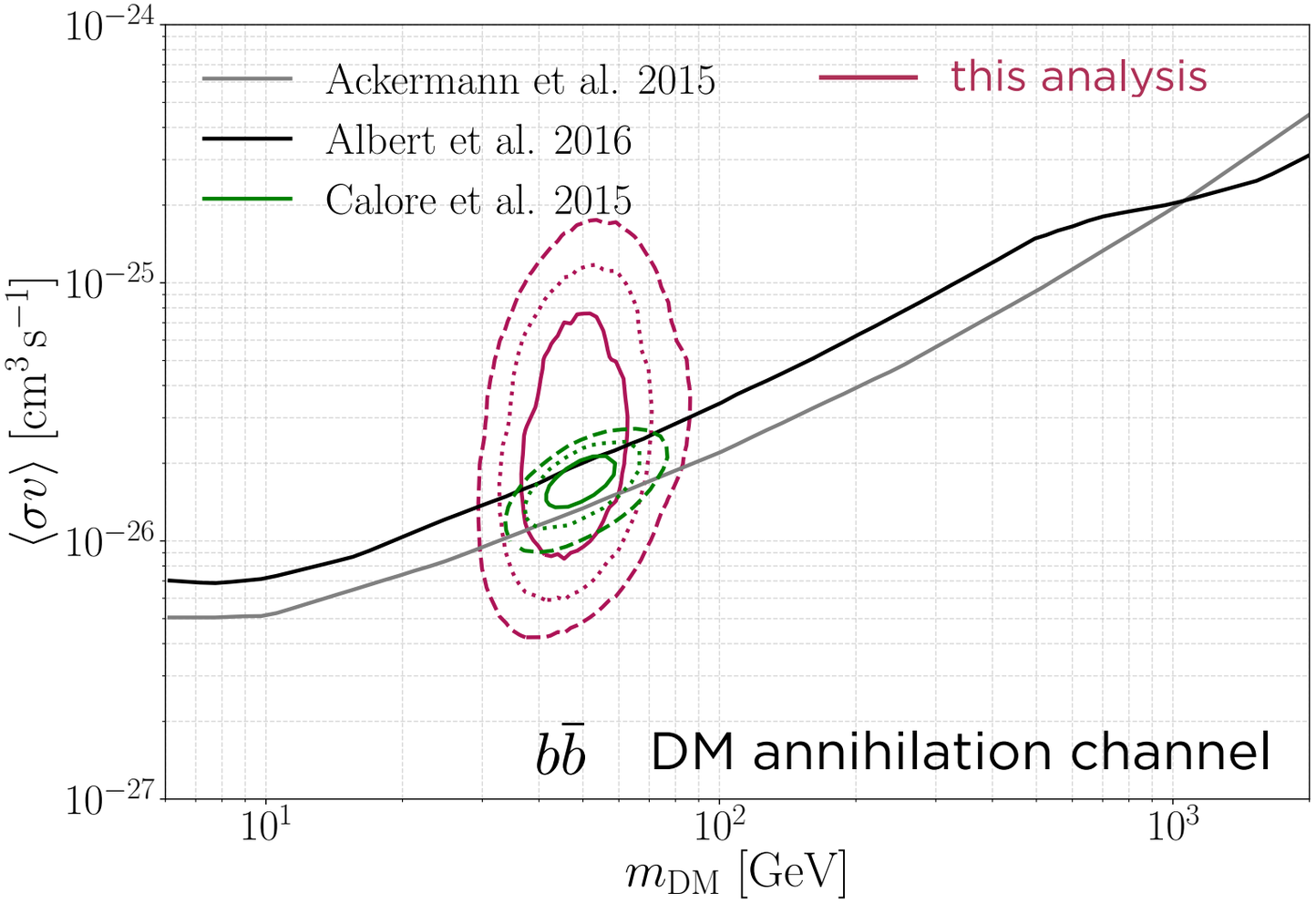
ROI:

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



Calore analysis:

observed GC signal

(only stat. on gamma flux)

This analysis:

observed GC signal

+

DM density profile

(Gal. Param. + Morphologies + stat.)

Take away points

Uncertainties in the distribution of DM are relevant on determining new physics

Likelihood profile (based on real data) quantifies the following astrophysical uncertainties that affect DM distribution in MW:

- 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

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).