The Dark Matter distribution of the Milky Way

(its uncertainties and consequences on the determination of new physics)

An empirical approach

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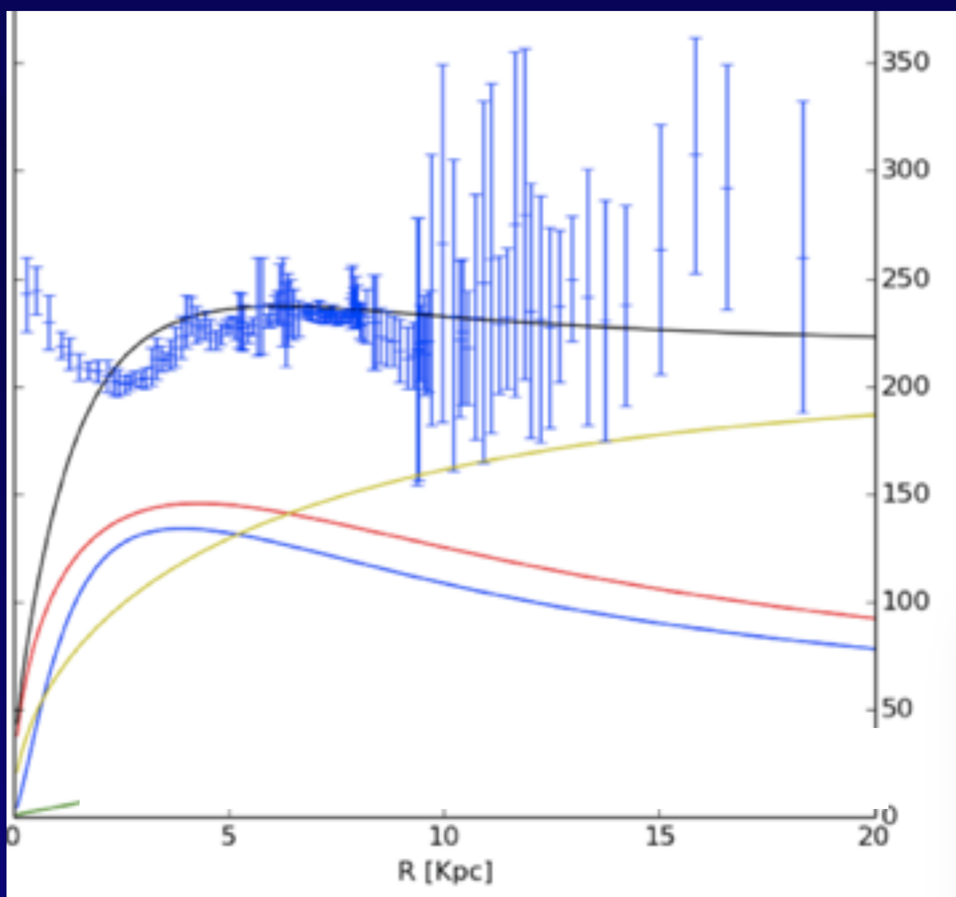
Durham, Dec. 3, 2019

What is the actual distribution of DM in the Milky Way?

And most notably in the proximity of the Sun?

Inferring the whole DM distribution (MW's 'backbone')

Fitting a pre-assigned shape on top of luminous

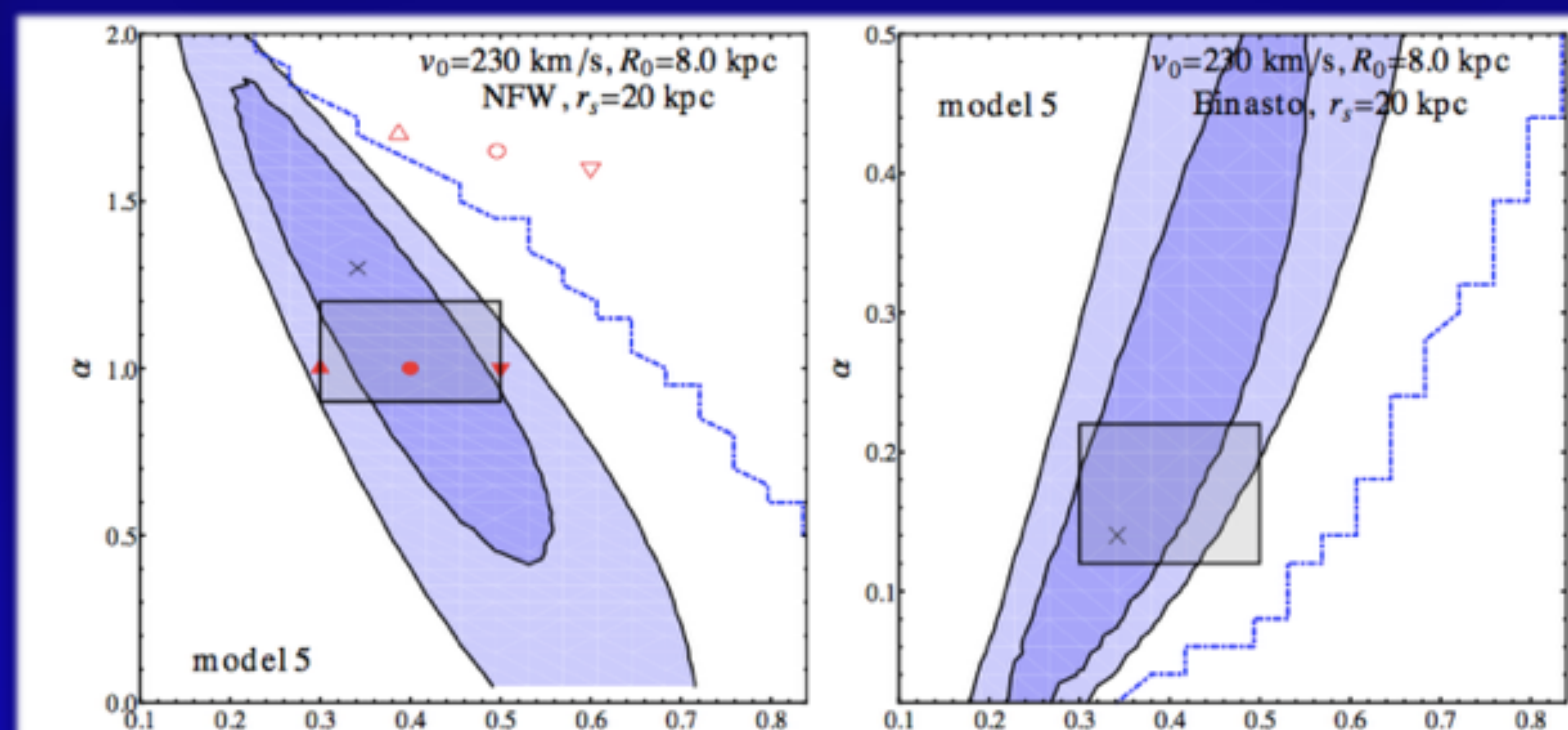


gNFW

$$\rho_{DM}(R) \propto \rho_0 \left(\frac{R}{R_s}\right)^{-\gamma} \left(1 + \frac{R}{R_s}\right)^{-3+\gamma}$$

$$\rho_{DM}(R) \propto \rho_0 \exp\left[-\frac{2}{\gamma}\left(\left(\frac{R}{R_s}\right)^{\gamma} - 1\right)\right]$$

Einasto



[Iocco et al. 2011]

[many autors, e.g. Iocco et al. 2011]

The case of the Milky Way

Ingredients:

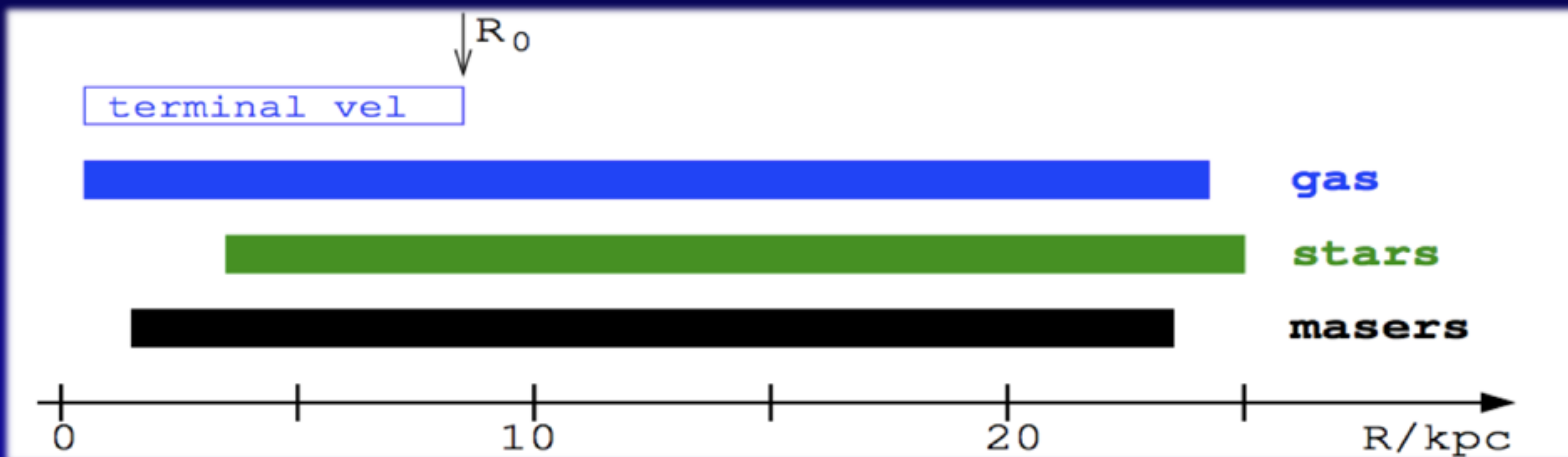
- The observed rotation curve
- The “expected” rotation curve

- Some “grano salis”

- Working hypothesis (later on)

The Milky Way:

observed rotation curve
the tracers of the gravitational potential

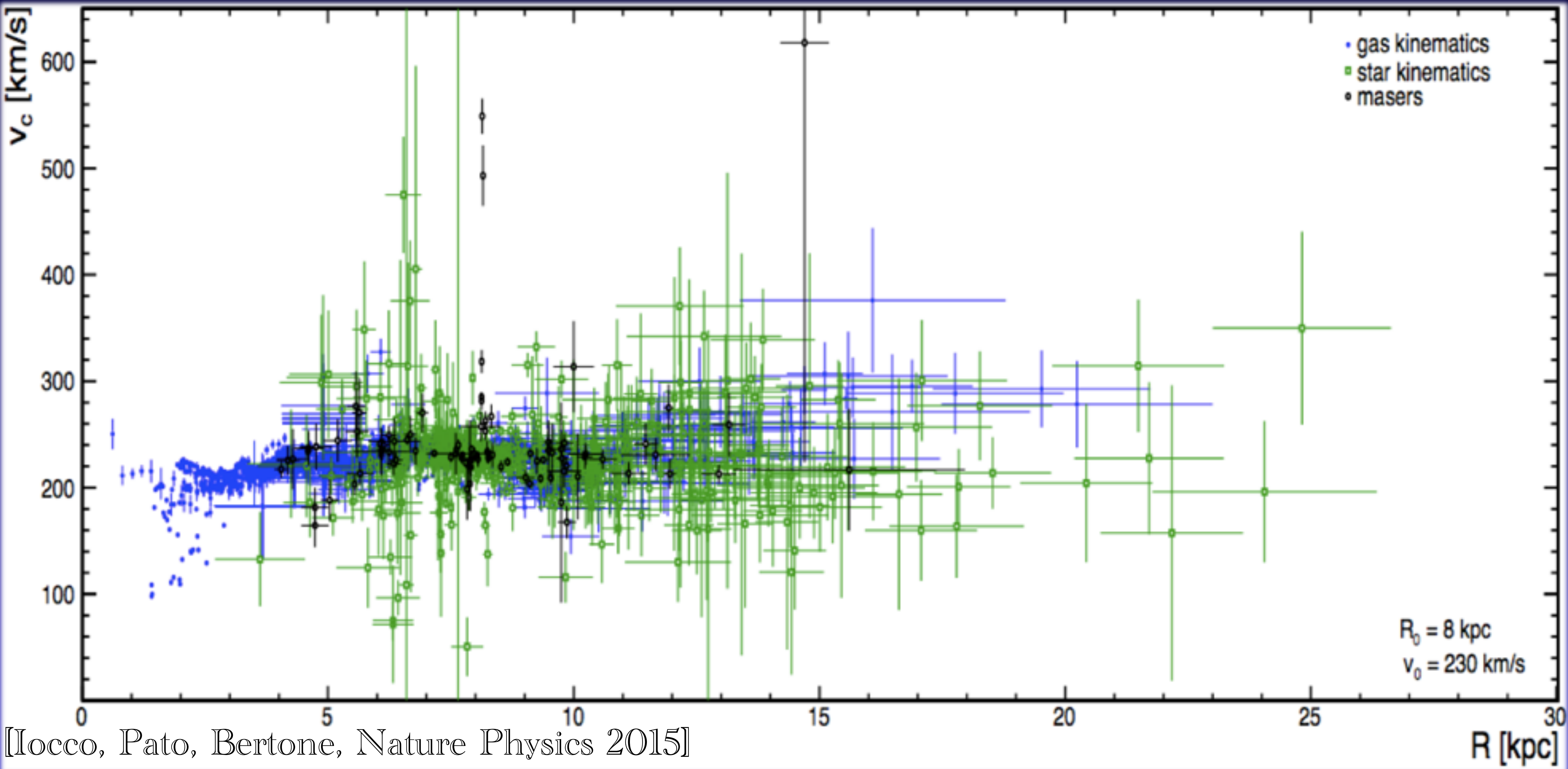


Doppler shift
1. gas (21cm, Hα, CO)
2. stars (H, He, O, ...)
3. masers (H_2O, CH_3OH, ...)

distance
1. terminal velocities (gas)
2. photo-spectroscopy (stars)
3. parallax (masers)

The Milky Way Rotation Curve

as observed



[Iocco, Pato, Bertone, Nature Physics 2015]

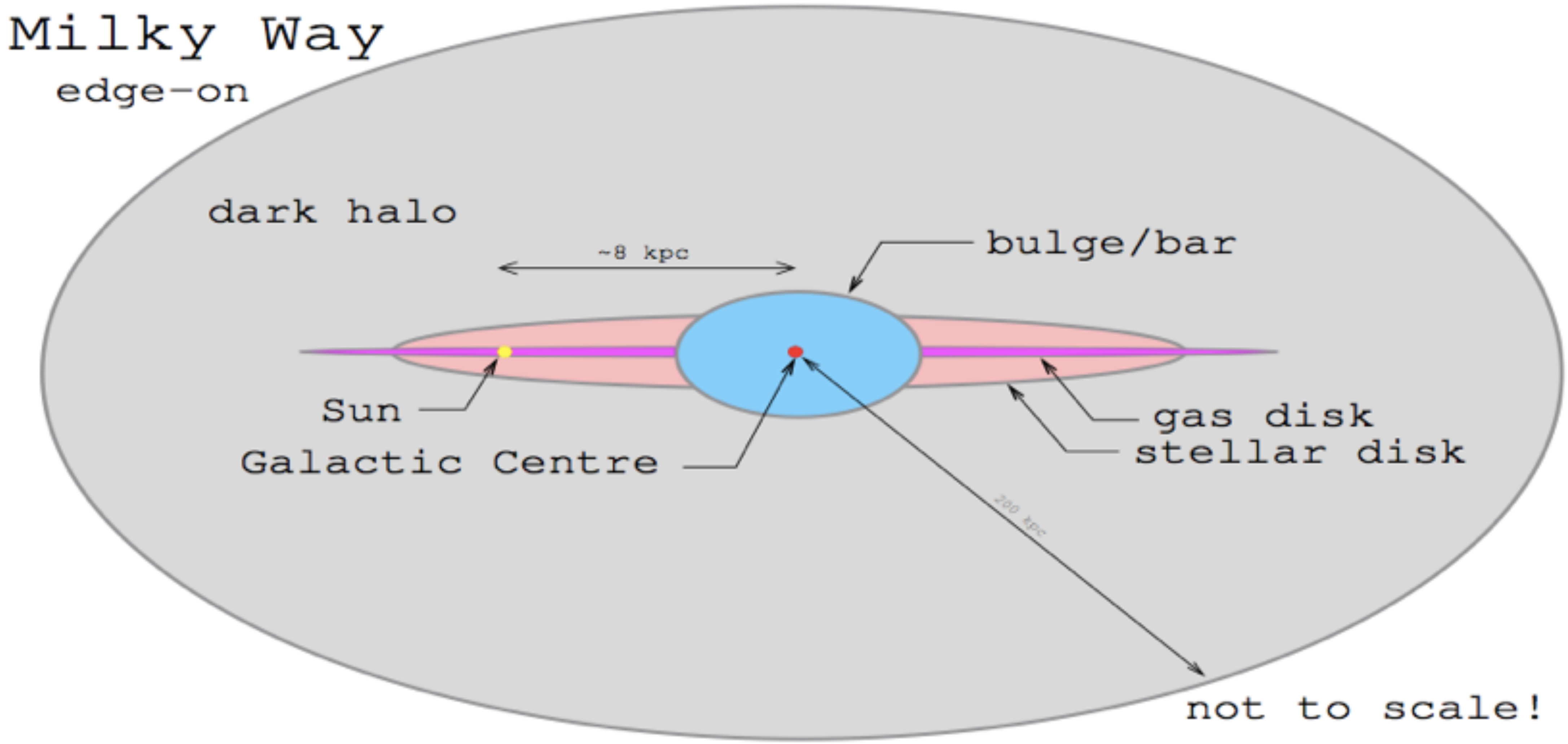
All tracers, optimized for precision between R=3-20 kpc

For more details on data treatment (as well as inclusion of different datasets) …

galkin compilation [Pato & FI, arXivV:1703.00020 , Software X (2017)]

The Milky Way:

expected rotation curve
the baryonic components

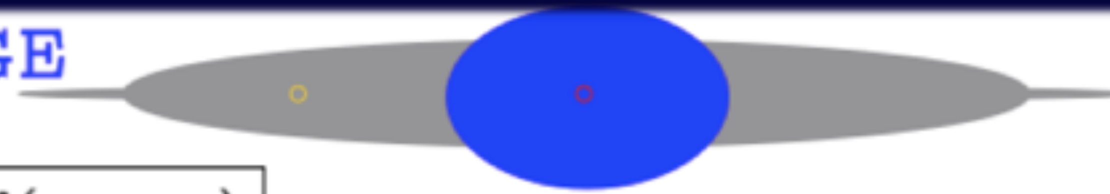


bulge	tilted bar
disk	thin+thick
gas	H_2, HI, HII

Courtesy of Miguel Pato

The luminous Milky Way: observations of morphology

2. BARYONS: STELLAR BULGE



$$\boxed{\rho_{\rm bulge} = \rho_0 f(x,y,z)}$$

morphology $f(x,y,z)$

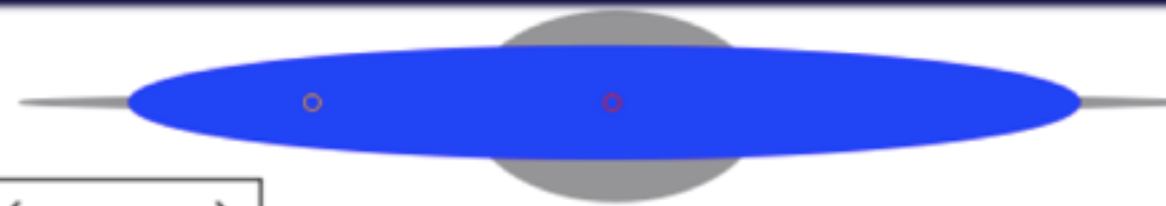
Stanek+ '97 (E2)	e^{-r}	0.9:0.4:0.3	24°	optical
Stanek+ '97 (G2)	$e^{-r_s^2/2}$	1.2:0.6:0.4	25°	optical
Zhao '96	$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	1.5:0.6:0.4	20°	infrared
Bissantz & Gerhard '02	$e^{-r_s^2}/(1+r)^{1.8}$	2.8:0.9:1.1	20°	infrared
Lopez-Corredoira+ '07	Ferrer potential	7.8:1.2:0.2	43°	infrared/optical
Vanhollebecke+ '09	$e^{-r_s^2}/(1+r)^{1.8}$	2.6:1.8:0.8	15°	infrared/optical
Robin+ '12	$\mathrm{sech}^2(-r_s) + e^{-r_s}$	1.5:0.5:0.4	13°	infrared

normalisation ρ_0 and its statistical uncertainties

microlensing optical depth: $\langle\tau\rangle = 2.17^{+0.47}_{-0.38} \times 10^{-6}$, $(\ell, b) = (1.50°, -2.68°)$
(MACHO '05)

The luminous Milky Way: observations of morphology

2. BARYONS: STELLAR DISK



$$\rho_{\text{disk}} = \rho_0 f(x, y, z)$$

morphology $f(x, y, z)$

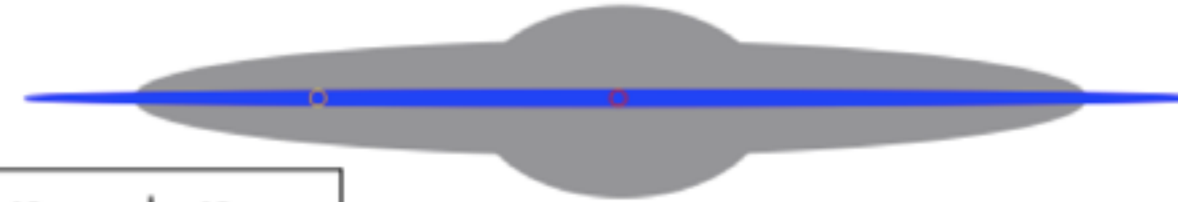
Han & Gould '03	$e^{-R}\text{sech}^2(z)$	2.8:0.27	thin	optical
	$e^{-R-\lvert z\rvert}$	2.8:0.44	thick	
Calchi-Novati & Mancini '11	$e^{-R-\lvert z\rvert}$	2.8:0.25	thin	optical
	$e^{-R-\lvert z\rvert}$	4.1:0.75	thick	
deJong+ '10	$e^{-R-\lvert z\rvert}$	2.8:0.25	thin	optical
	$e^{-R-\lvert z\rvert}$	4.1:0.75	thick	
	$(R^2+z^2)^{-2.75/2}$	1.0:0.88	halo	
Jurić+ '08	$e^{-R-\lvert z\rvert}$	2.2:0.25	thin	optical
	$e^{-R-\lvert z\rvert}$	3.3:0.74	thick	
	$(R^2+z^2)^{-2.77/2}$	1.0:0.64	halo	
Bovy & Rix '13	$e^{-R-\lvert z\rvert}$	2.2:0.40	single	optical

normalization and its statistical uncertainties

local surface density: $\Sigma_* = 38 \pm 4 M_\odot/\text{pc}^2$ [Bovy & Rix '13]

The luminous Milky Way: observations of morphology

2. BARYONS: GAS



$$n_{\rm H} = 2n_{\rm H_2} + n_{\rm HI} + n_{\rm HII}$$

morphology

Ferrière '12	$r < 0.01$ kpc	$M_{gas} \sim 7 \times 10^5\ M_\odot$		CO, 21cm, Hα, ...
Ferrière+ '07	$r = 0.01 - 2$ kpc	CMZ, holed disk	H_2	CO
		CMZ, holed disk	H I	21cm
		warm, hot, very hot	H II	disp. meas.
Ferrière '98	$r = 3 - 20$ kpc	molecular ring	H_2	CO
		cold, warm	H I	21cm
		warm, hot	H II	disp. meas., Hα
Moskalenko+ '02	$r = 3 - 20$ kpc	molecular ring	H_2	CO
			H I	21cm
			H II	disp. meas.

uncertainties

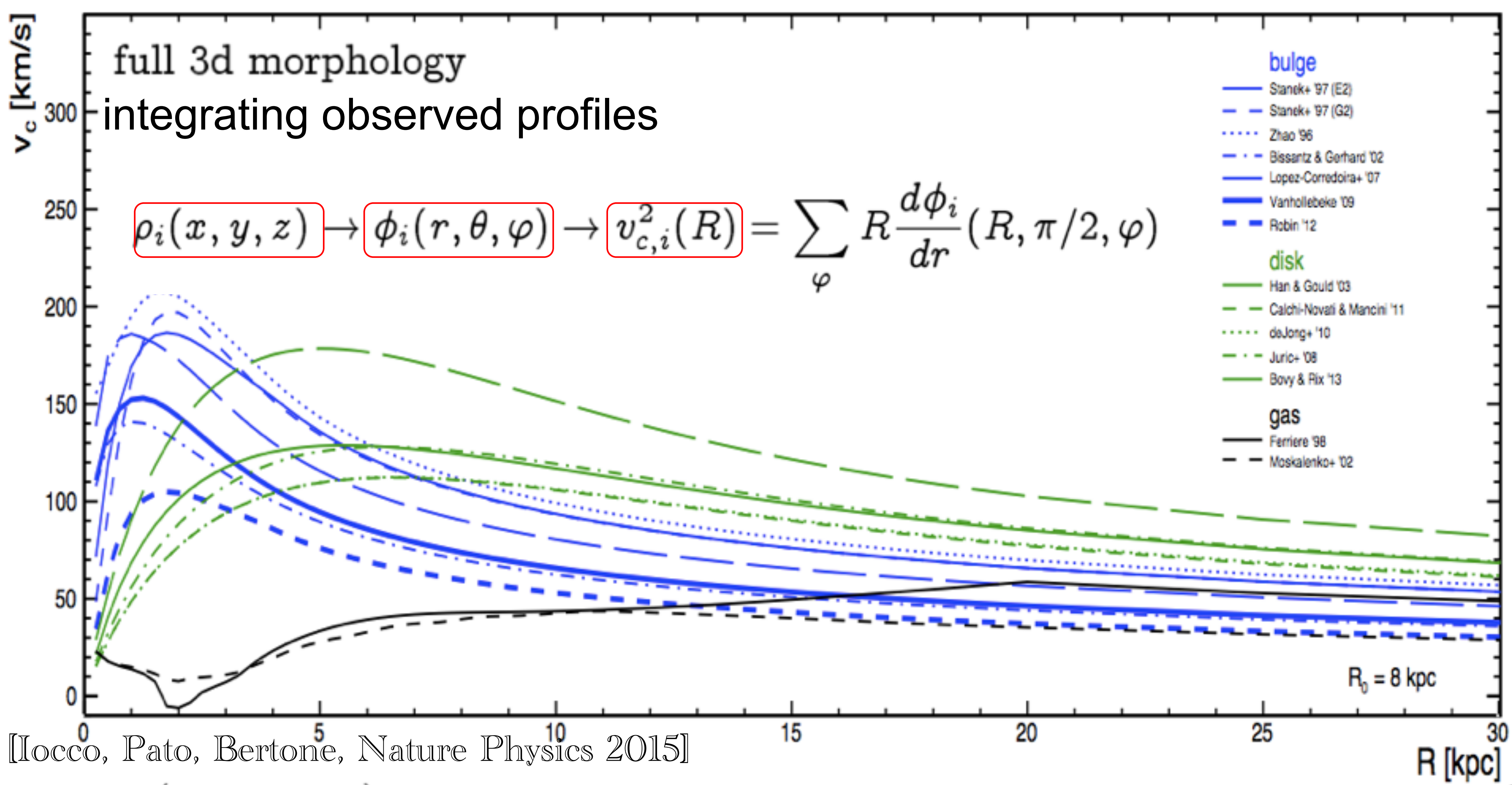
CO-to-H_2 factor: $X_{\rm CO} = 0.25 - 1.0 \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s for $r < 2$ kpc
$X_{\rm CO} = 0.50 - 3.0 \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s for $r > 2$ kpc

[Ferrière+ '07, Ackermann '12]

The luminous Milky Way:

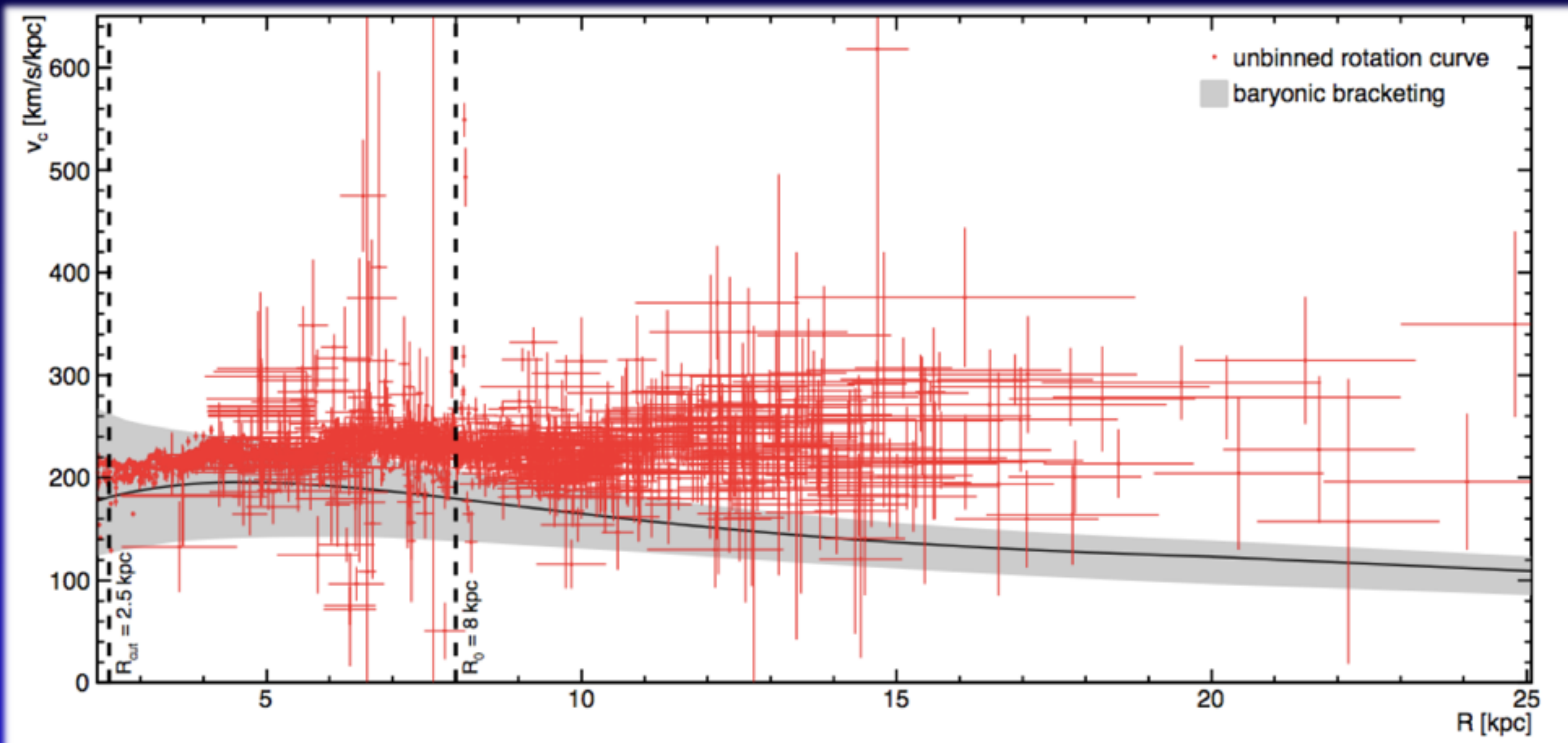
expected rotation curve

$$\phi_i(r,\theta,\varphi) = -4\pi G \sum_{l,m} \frac{Y_{lm}(\theta,\varphi)}{2l+1} \left[\frac{1}{r^{l+1}} \int_0^r \rho_{i,lm}(a)\, a^{l+2}\, da + r^l \int_r^\infty \rho_{i,lm}(a)\, a^{1-l}\, da \right]$$



[Iocco, Pato, Bertone, Nature Physics 2015]

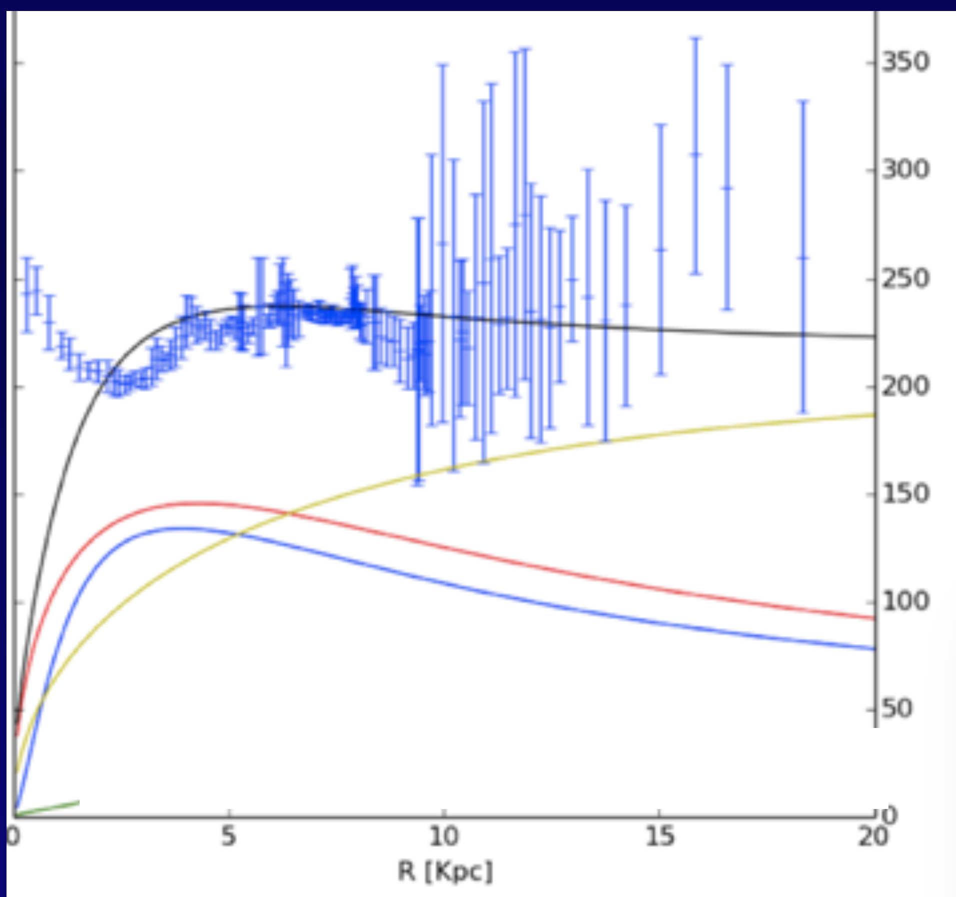
The Milky Way: testing expectactions (with no additional assumptions)



[Iocco, Pato, Bertone, Nature Physics 2015]

Inferring the DM density structure

Fitting a pre-assigned shape on top of luminous



gNFW

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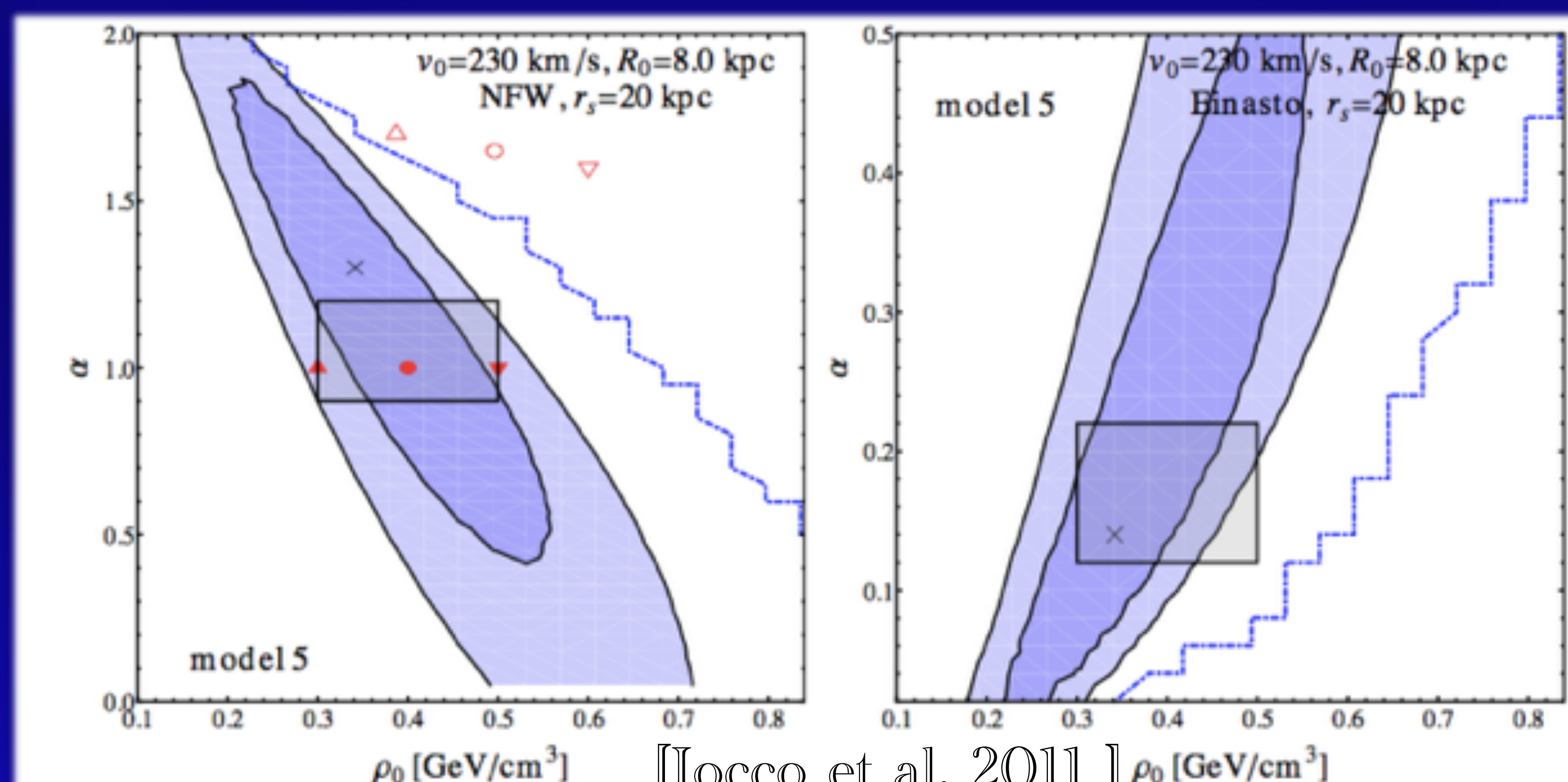
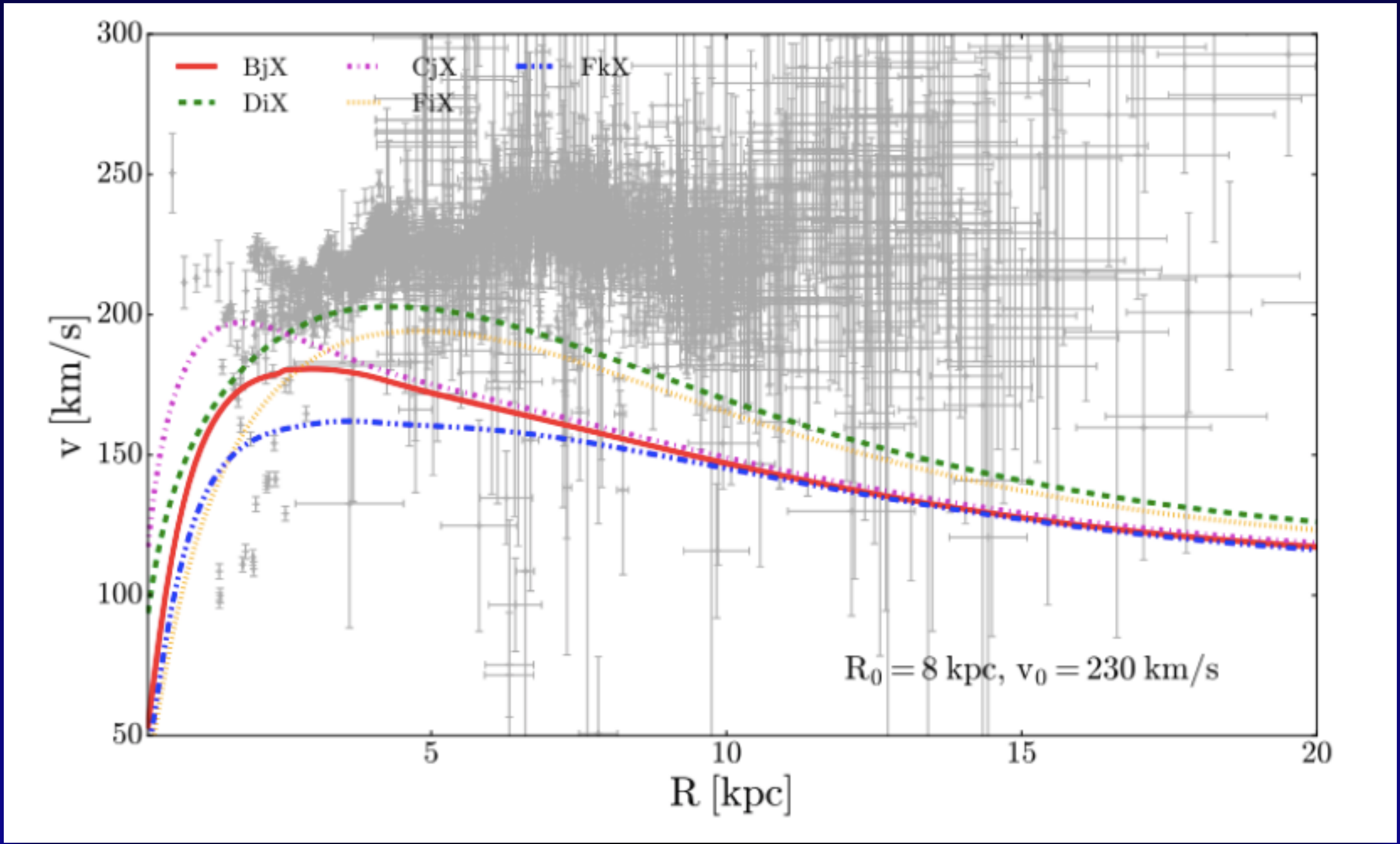
Einasto



[Iocco et al. 2011]

[many autors, e.g. Iocco et al. 2011]

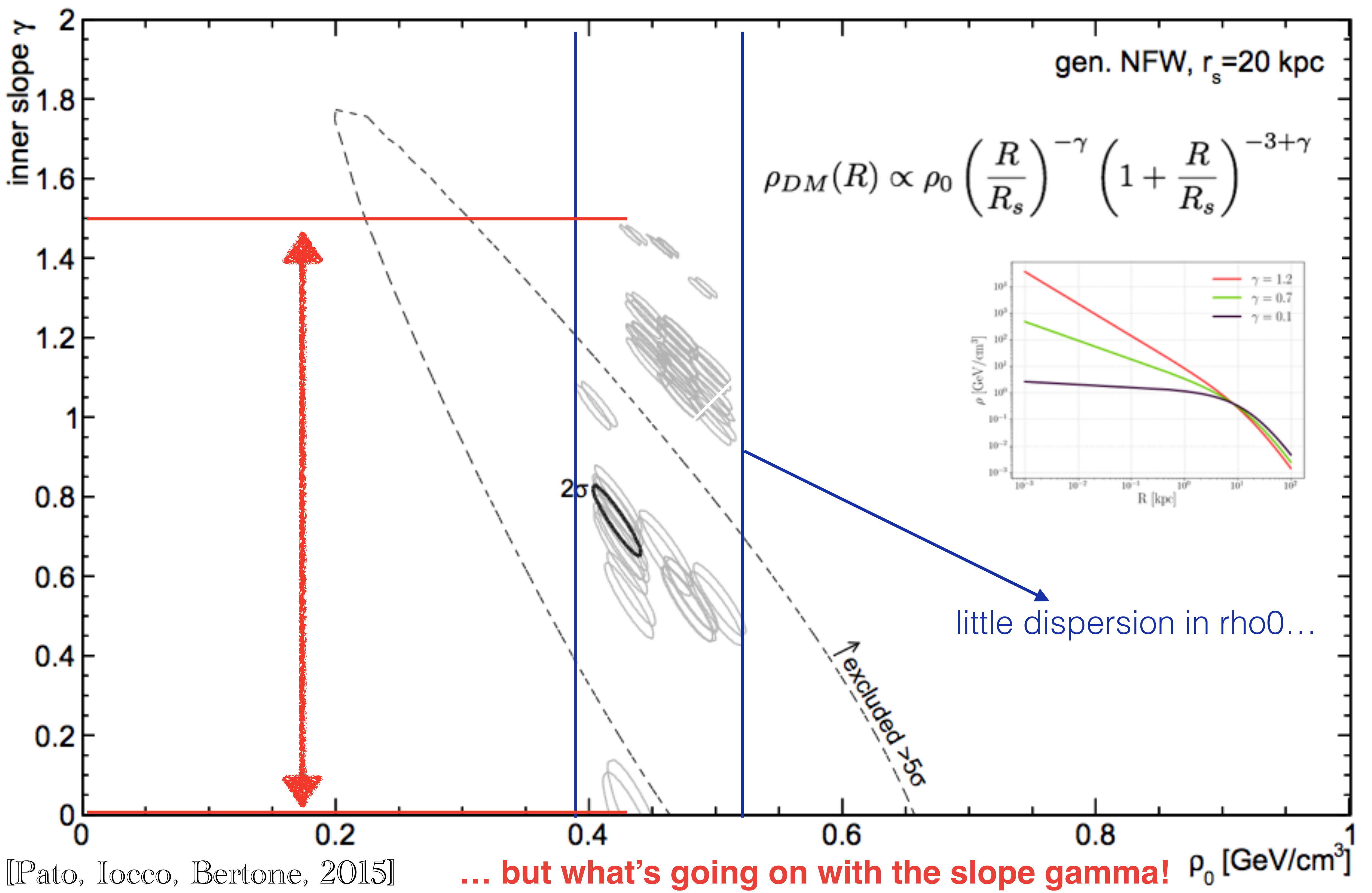
Systematic uncertainties
(luminous component)



[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017]

[Iocco, Pato, Bertone, Nature Physics 2015]

Extracting the DM density structure

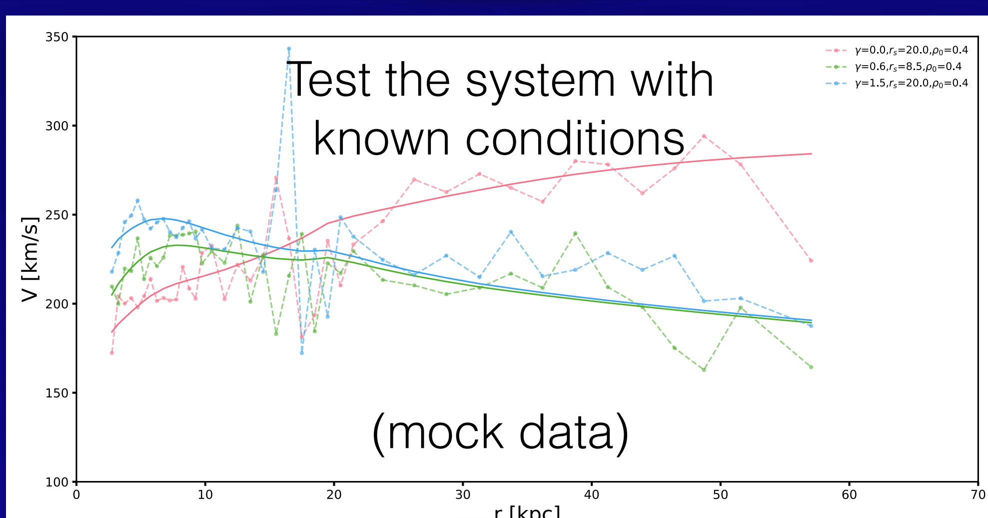


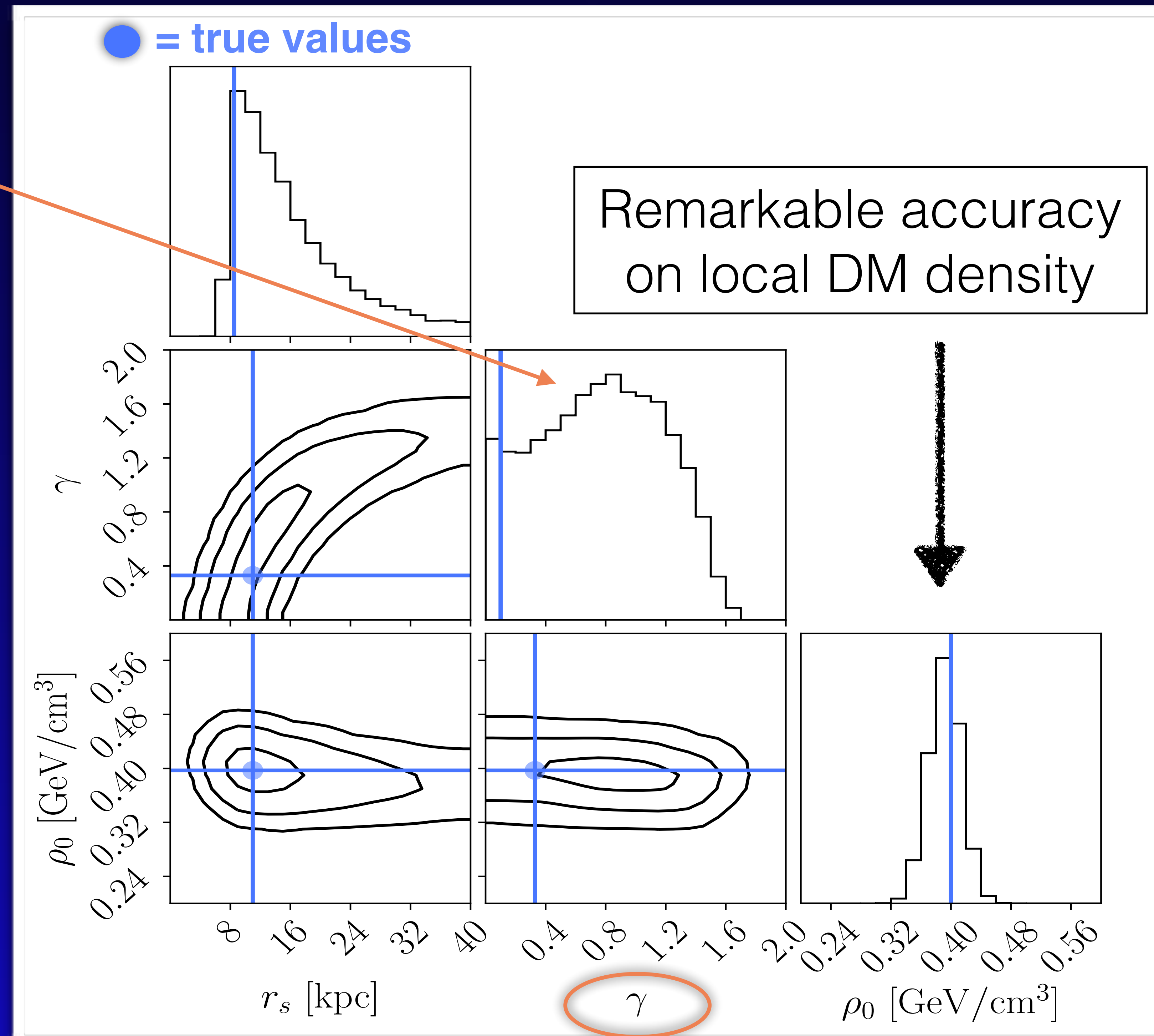
[Pato, Iocco, Bertone, 2015]

… but what's going on with the slope gamma!

What to do of our measurement?

(Our instrument is very precise. Is it accurate?)



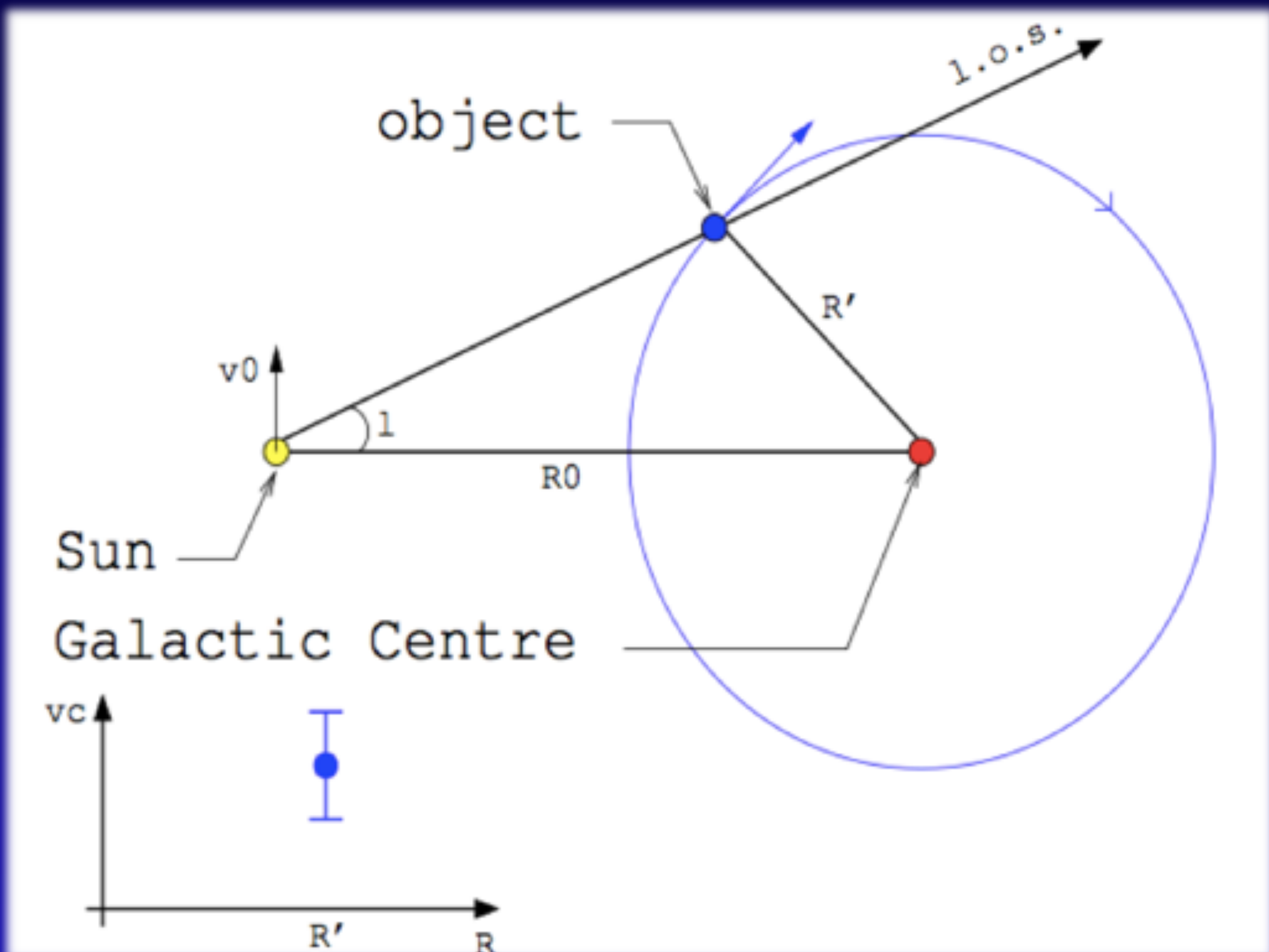


[Karukes, Benito, F.I., Geringer-Sameth, Trotta] arXiv:1901.02463, JCAP 2019

The Milky Way:

observed rotation curve

Neglecting some quite remarkable uncertainties (for now)

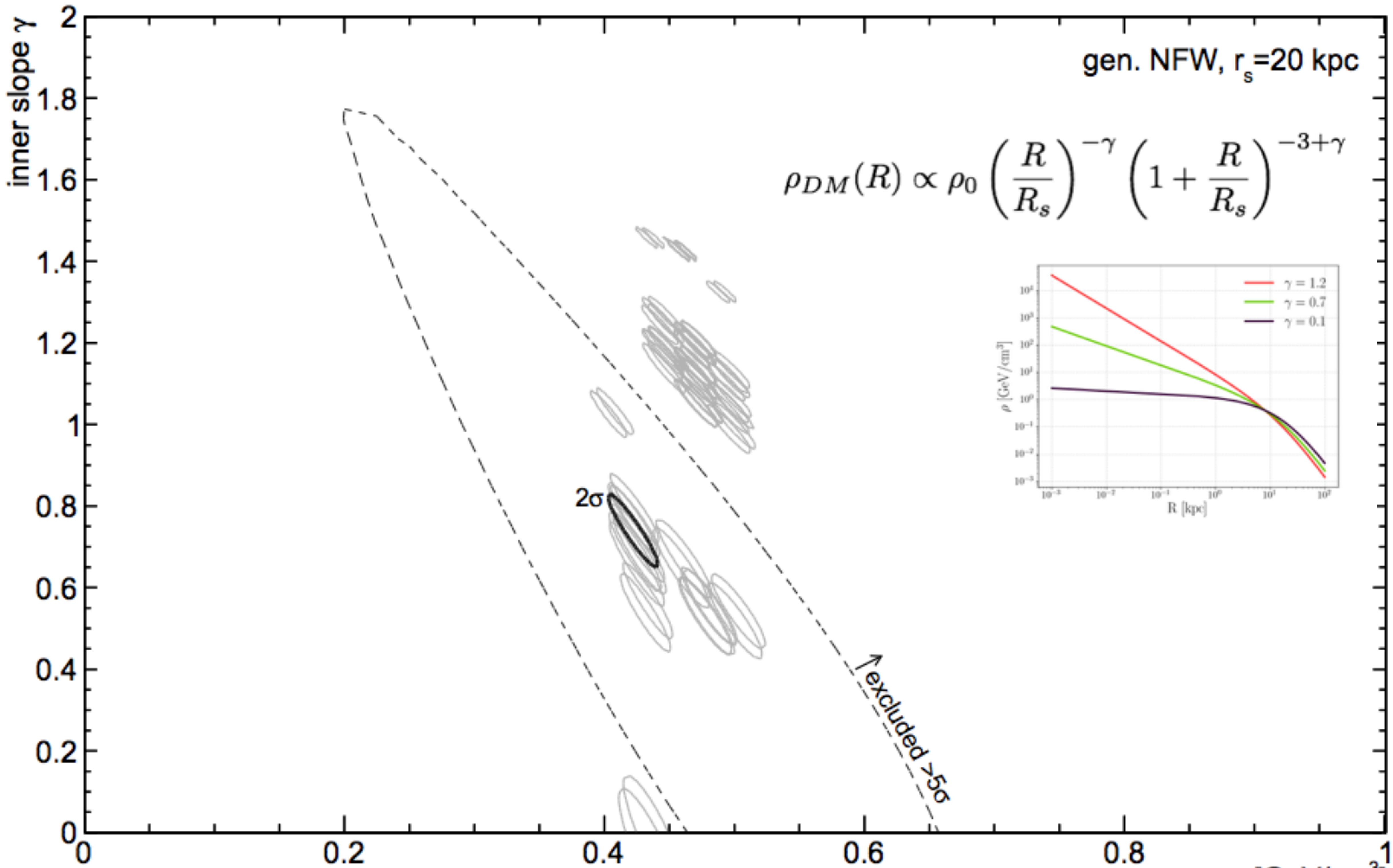


$$v_{\mathrm{LSR}}^{\mathrm{l.o.s.}} = \left(\frac{v_c(R')}{R'/R_0} - v_0 \right) \cos b \sin \ell$$

observing tracers from our own position, transforming into GC-centric reference frame

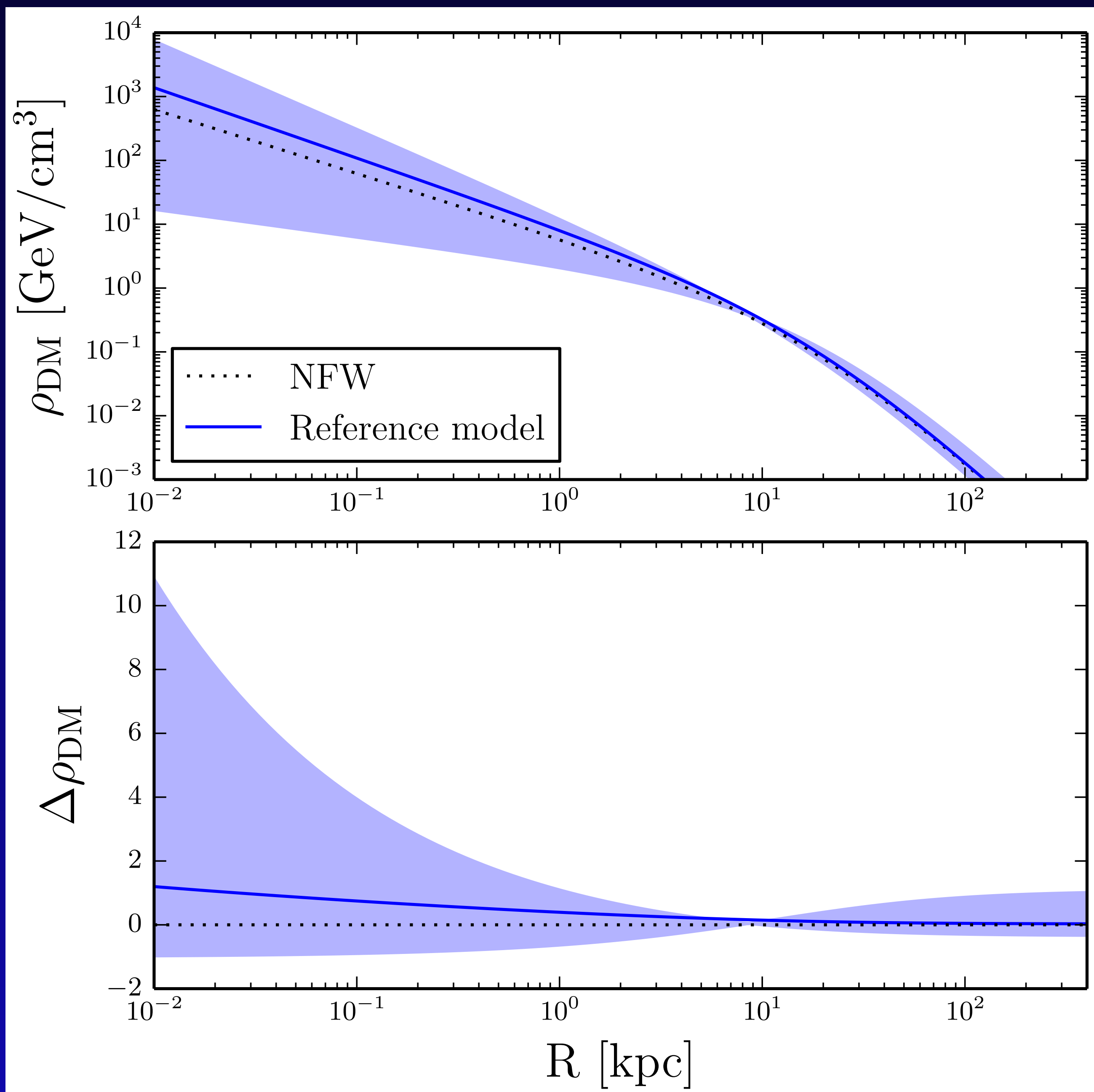
Uncertainties on (R0,v0) ultimately affects our determination of (rho0, gamma)

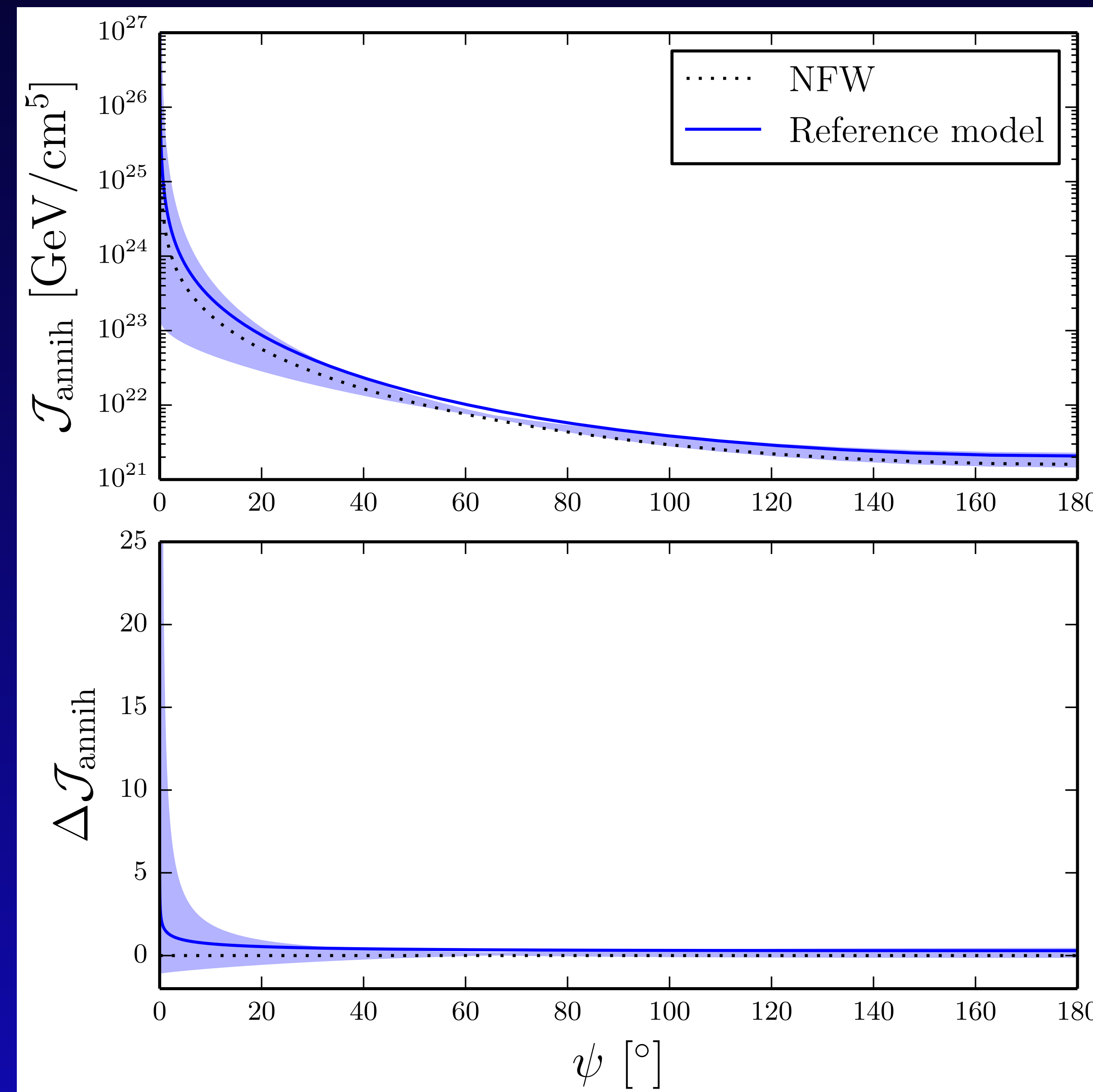
Extracting the DM density structure



[Pato, Iocco, Bertone, 2015]

But do Galactic uncertainties affect PP, <u>for real</u>?

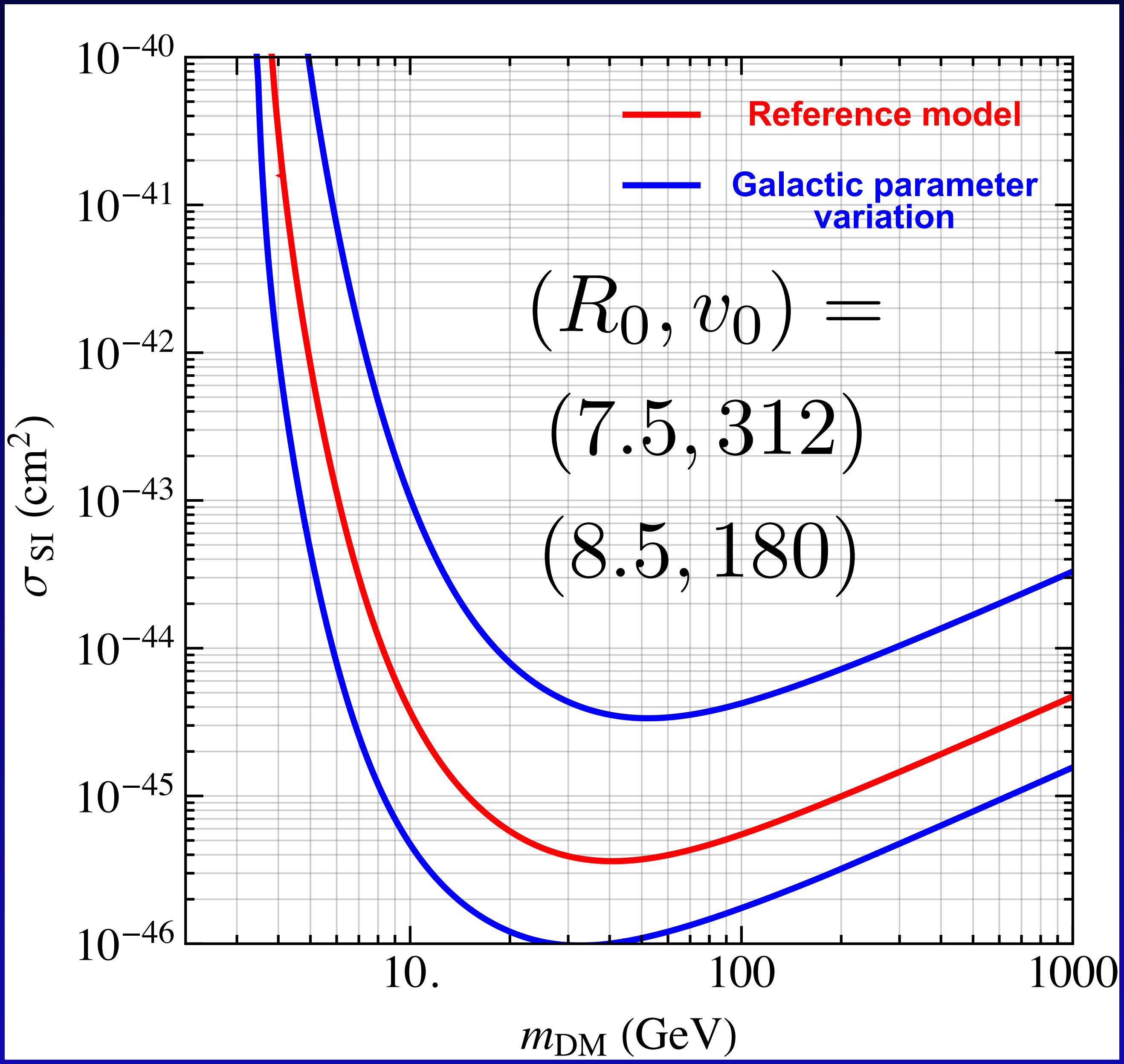




$$J_{annih} \propto \int_{los} \rho^2(r)dV$$

[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017, arXiv:1612.02010]

It is well known that uncertainties affect Direct Detection



Current LUX limits, but varying astrophysical uncertainties

[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017, arXiv:1612.02010]

The effect of astrophysical uncertainties
on the determination of new physics

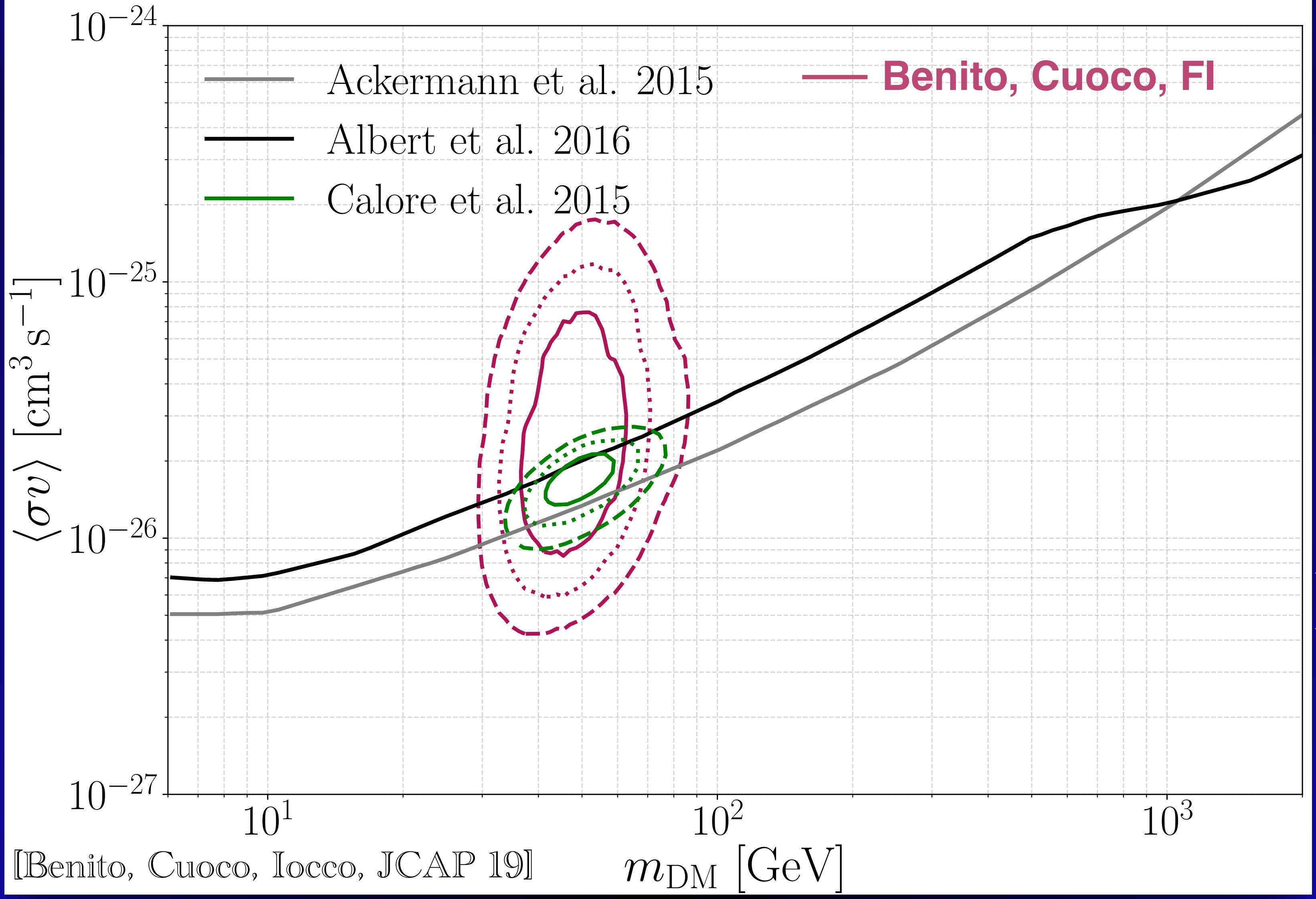
Uncertainties accounted for:

Calore analysis:

observed GC signal
(only stat. on gamma flux)

This analysis:

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



Ready-to-use likelihood publicly available @

https://github.com/mariabenitocst/UncertaintiesDMinTheMW

with Gaia-era
(R0,v0) determination,
update in progress

Let's quantify this effect in a specific case: Singlet Scalar DM

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

$v_H = 246 \text{ GeV}$ $\langle S \rangle = 0$

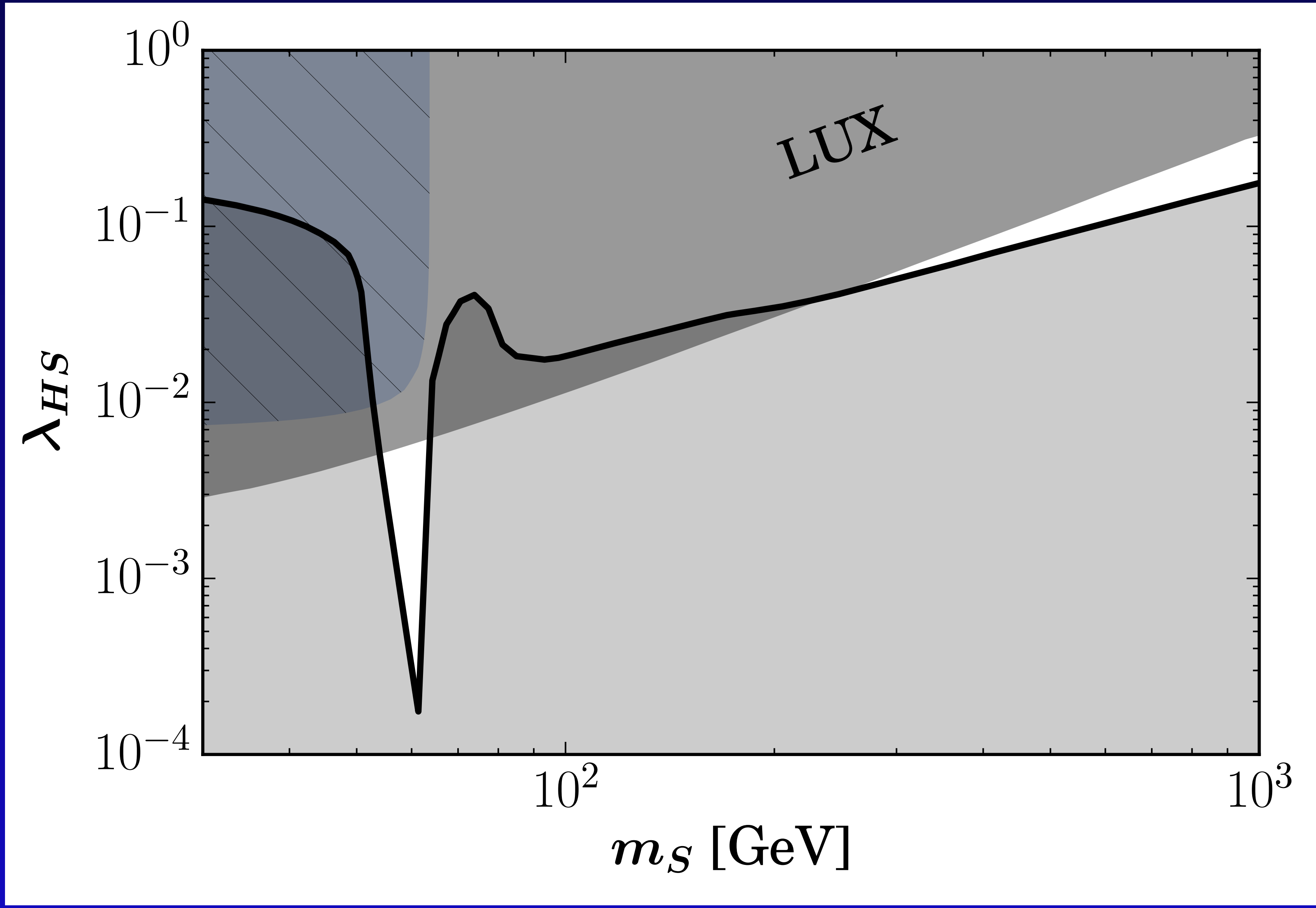
$$m_S^2 = 2 \, \mu_S^2 + \lambda_{HS} \, v_H^2$$

"WIMP phenomenology" entirely dictated by the Higgs coupling and physical DM mass.

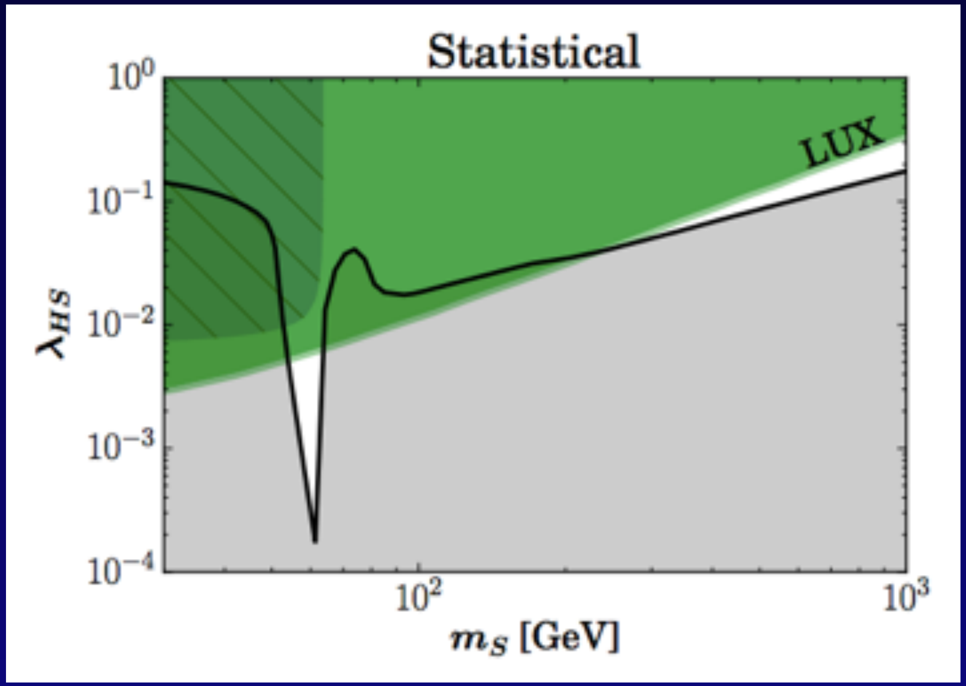
[Mc Donald, 1994] [Burgess, Pospelov, Velthuis, 2001]

Singlet Scalar DM
Constraints and interplay of experiments

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



Let's look at the effect of astrophysics uncertainties: Direct Detection



[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

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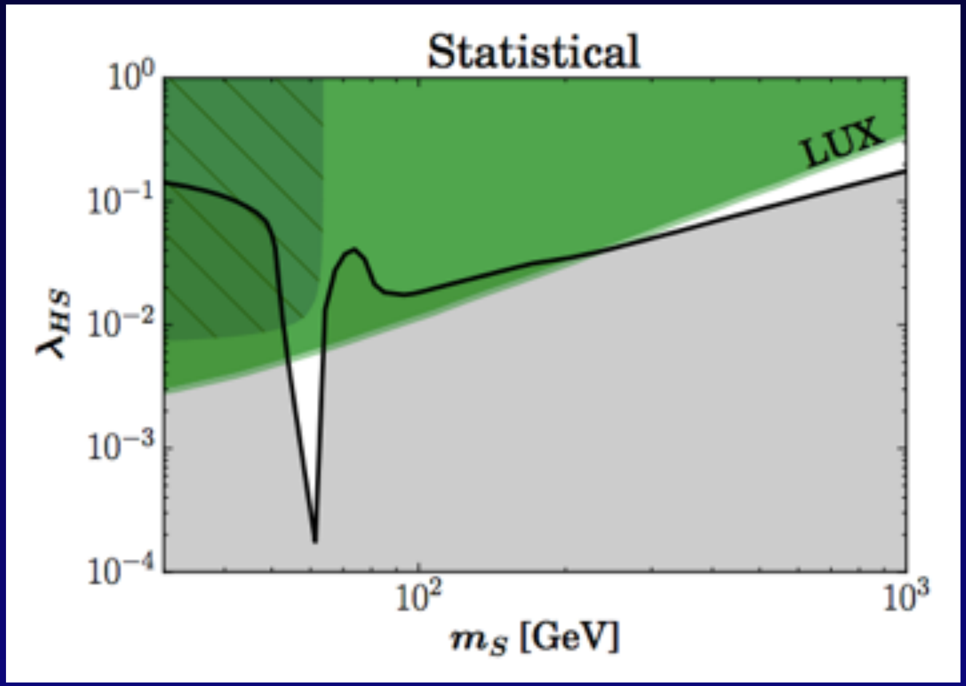
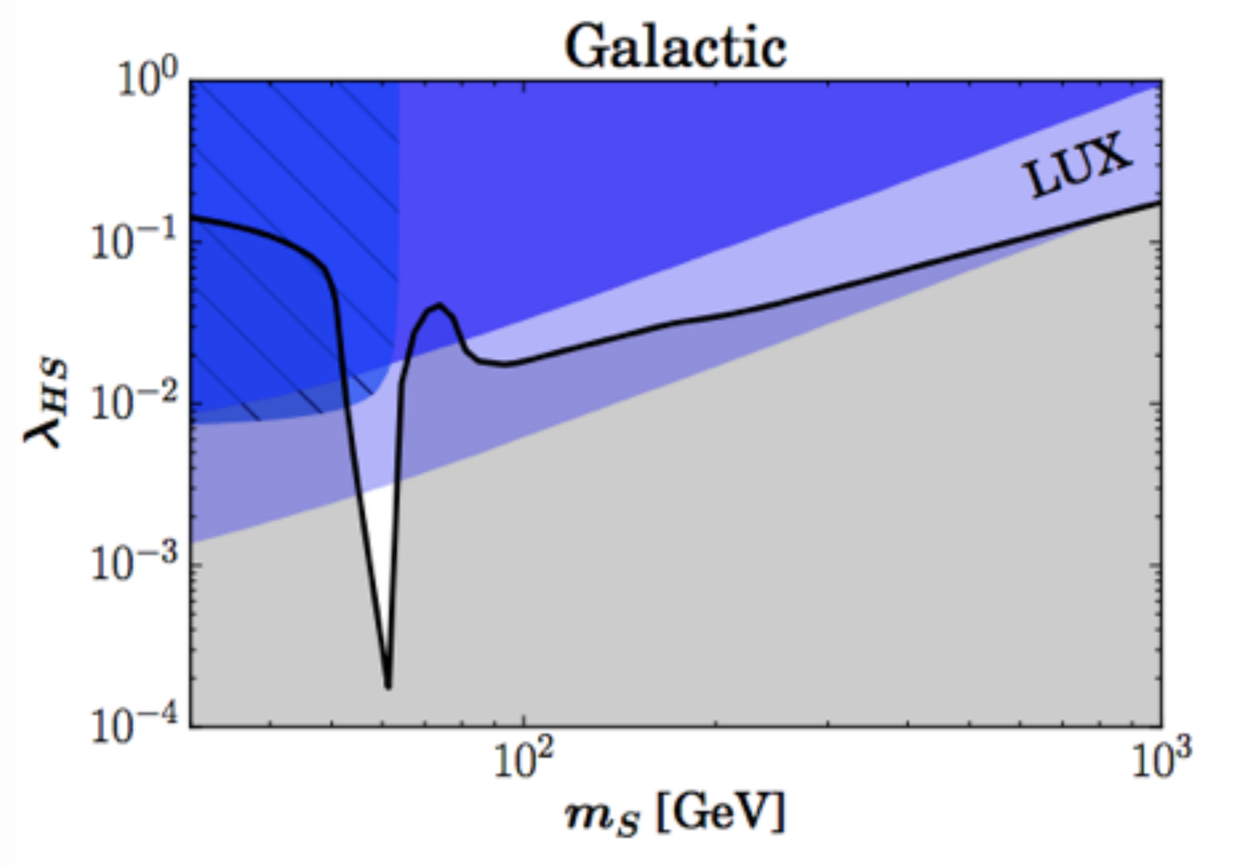
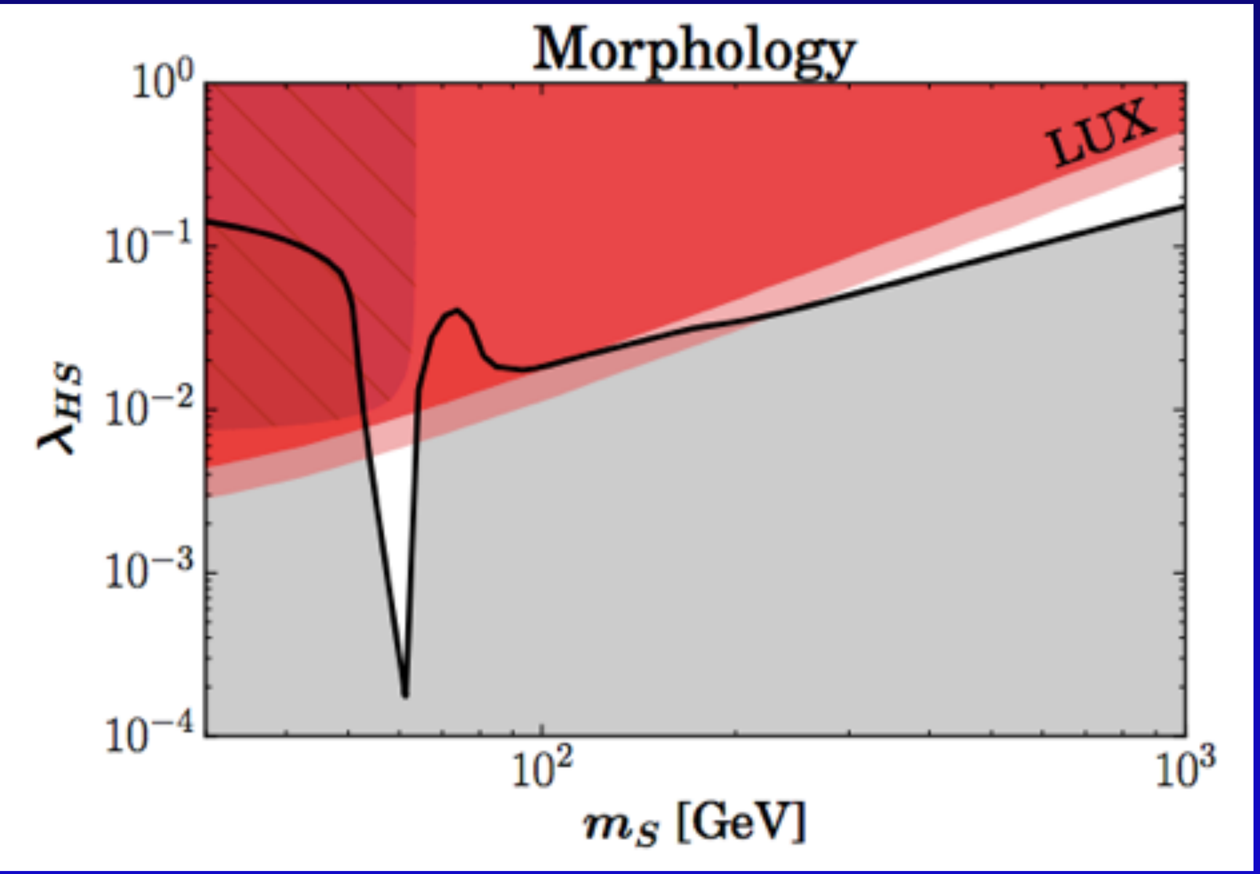
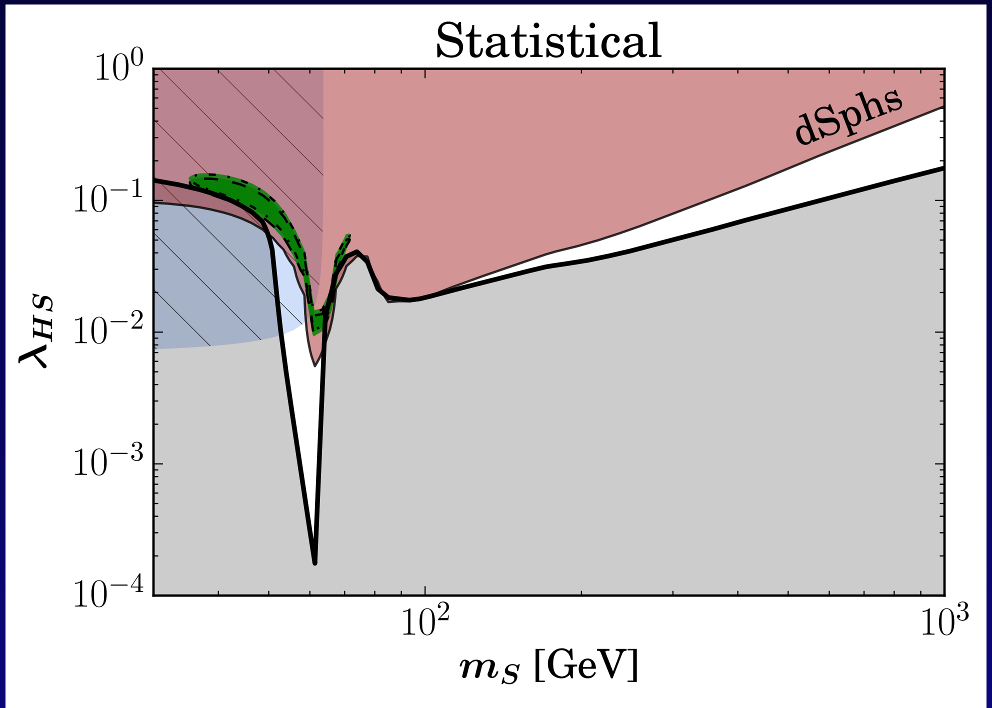


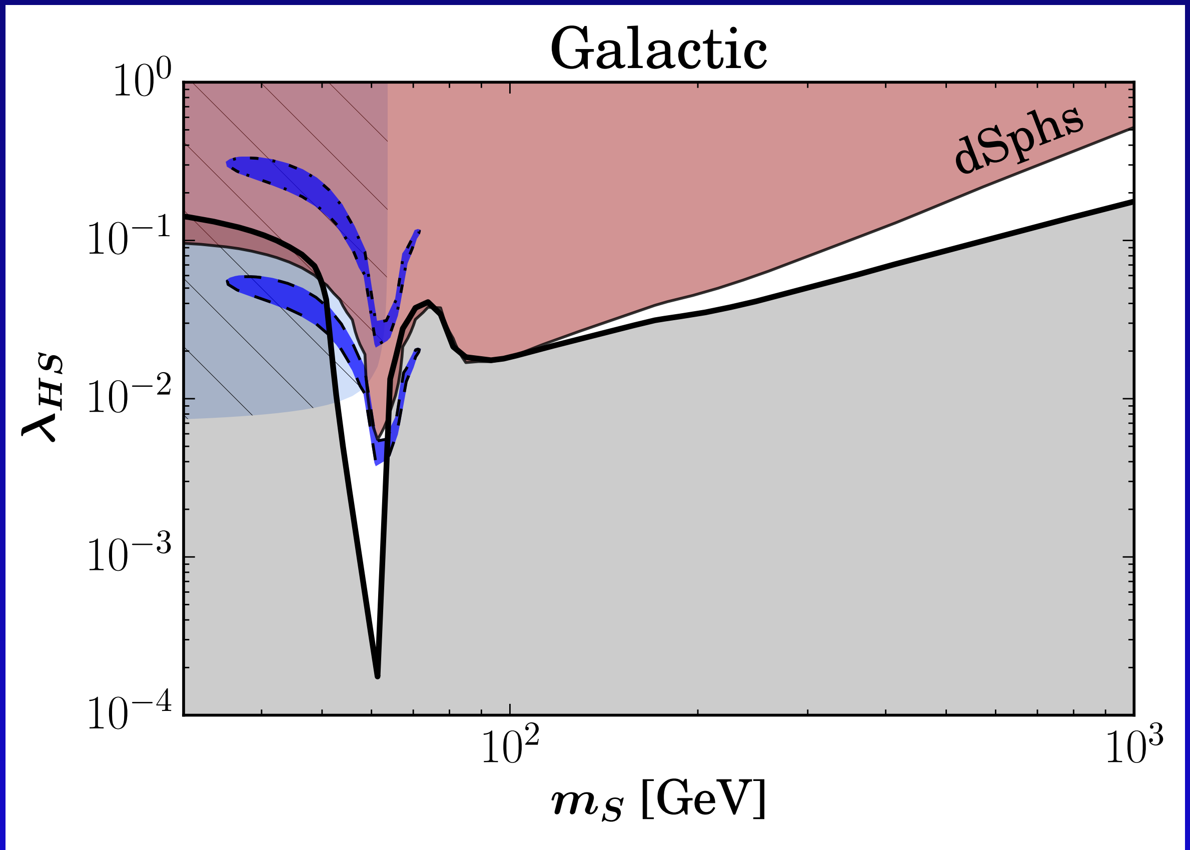


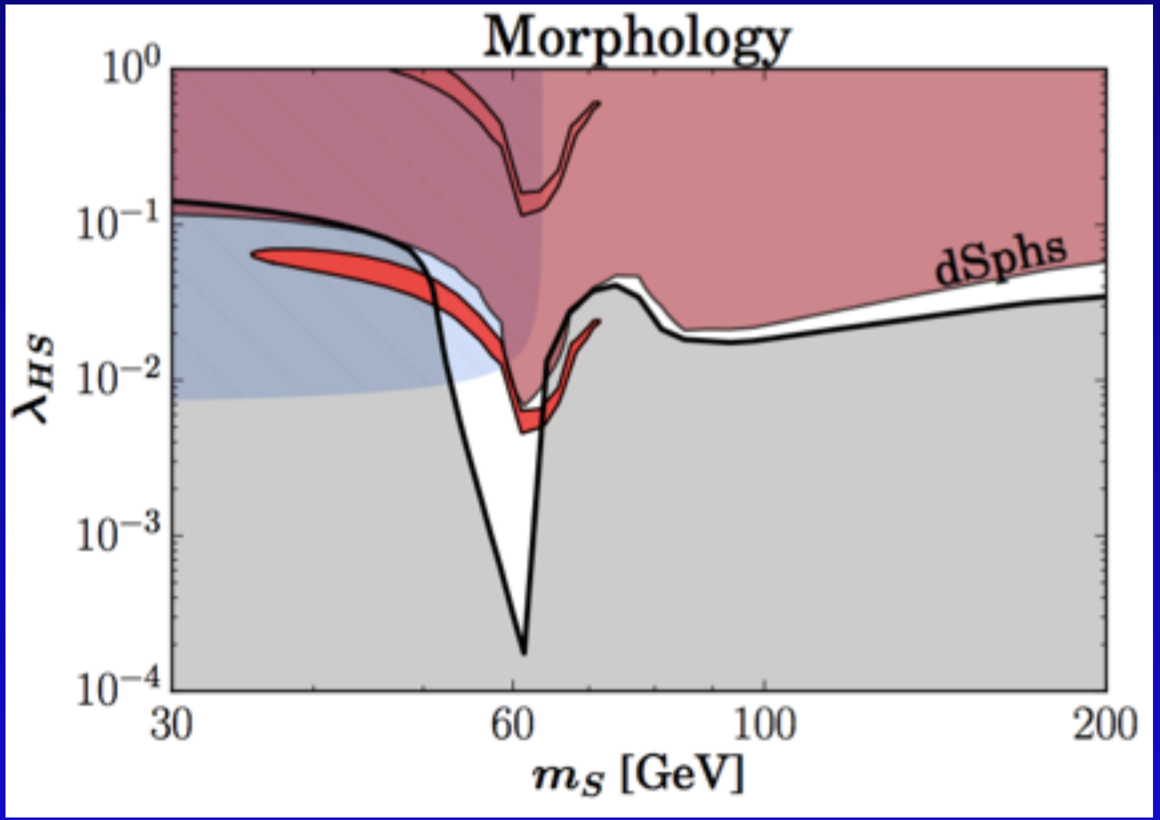


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

Let's look at the effect of astrophysics uncertainties: Indirect Detection







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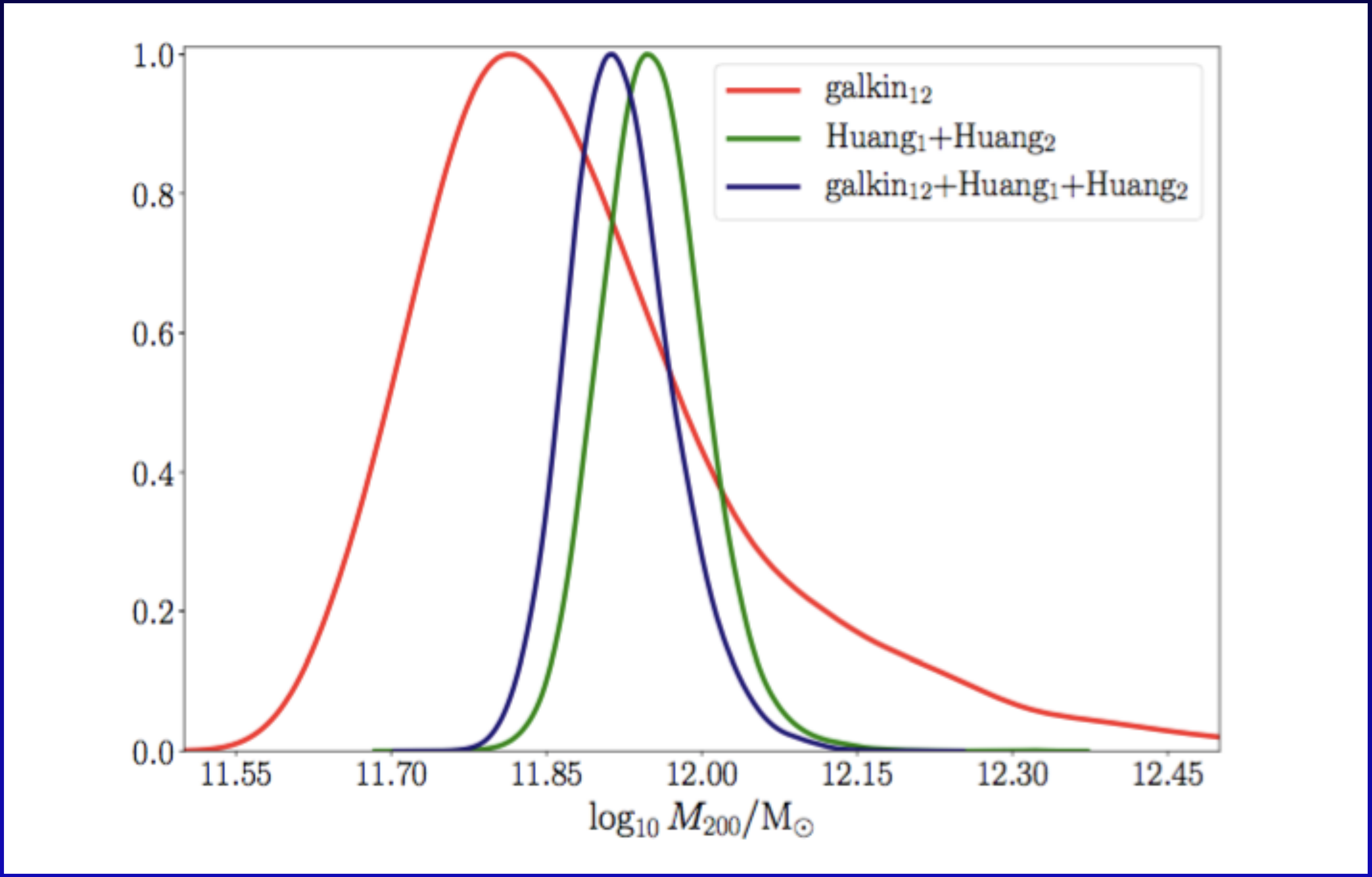
Determining the MW mass (and its uncertainties)



Different datasets (often: regions) compatibility

[Karukes, Benito, F.I., Geringer-Sameth, Trotta] arXiV:1912.04296

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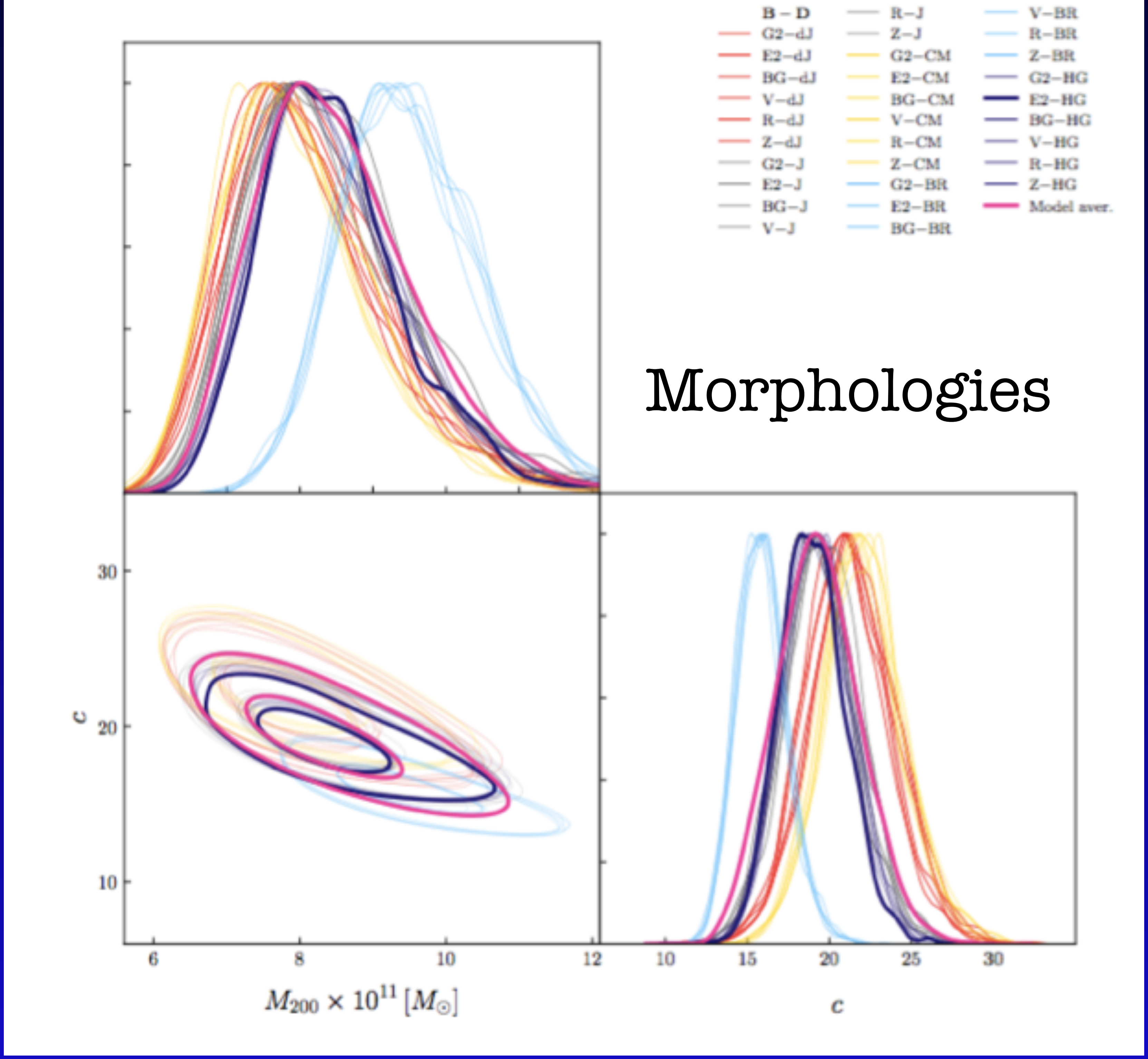

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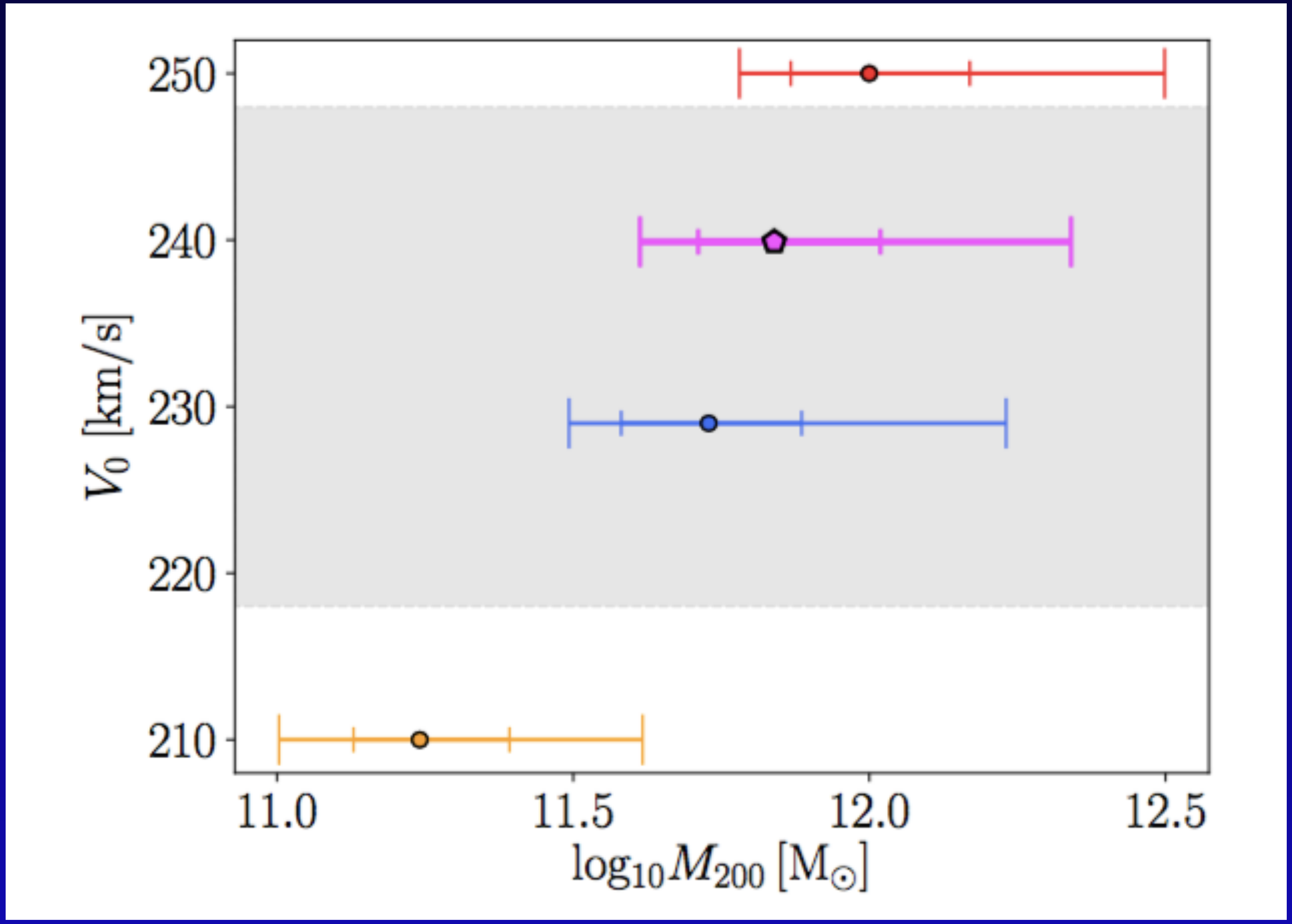

Galactic parameters (R0,VO)

[Karukes, Benito, F.I., Geringer-Sameth, Trotta] arXiV:1912.04296

Determining the MW mass
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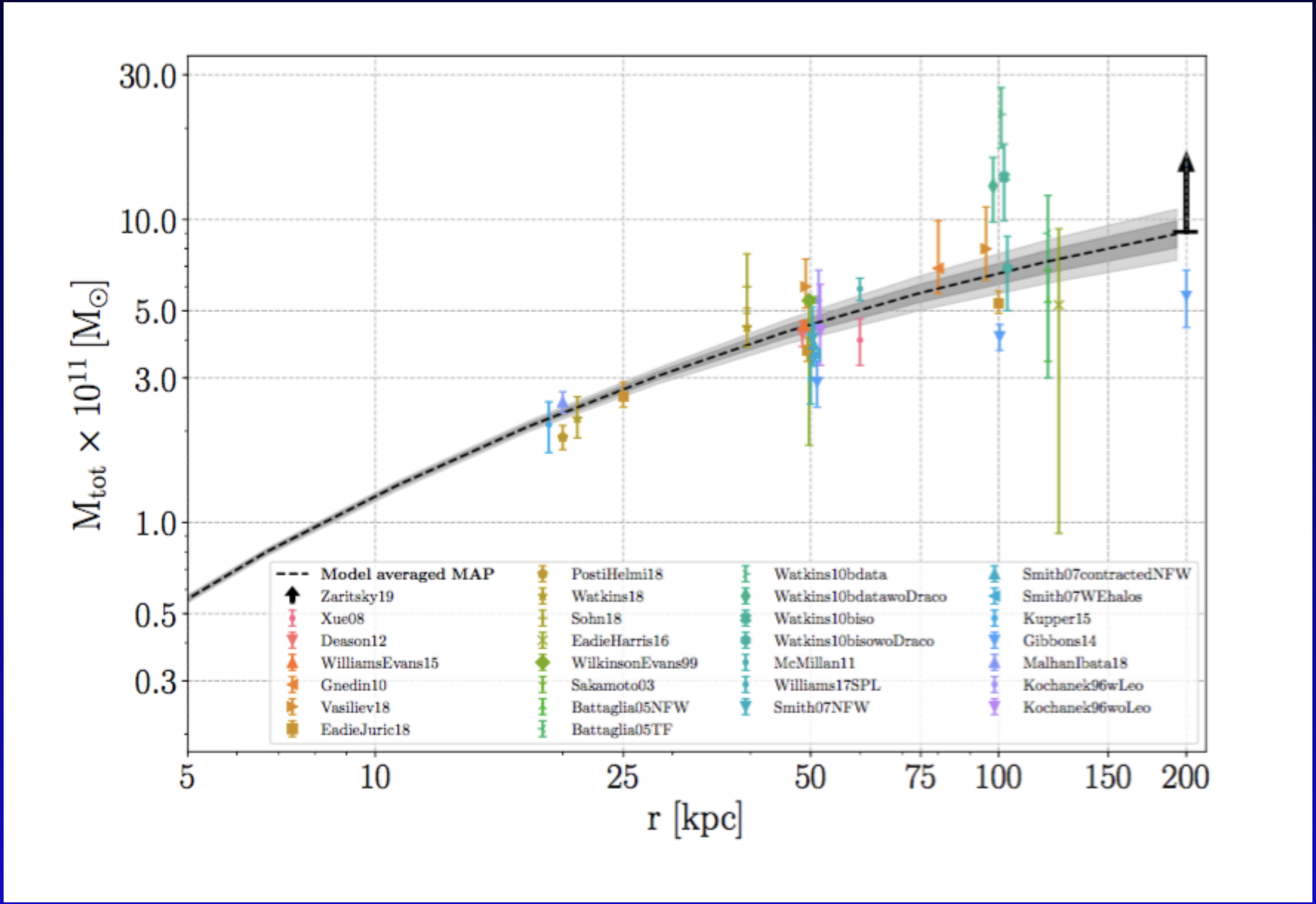

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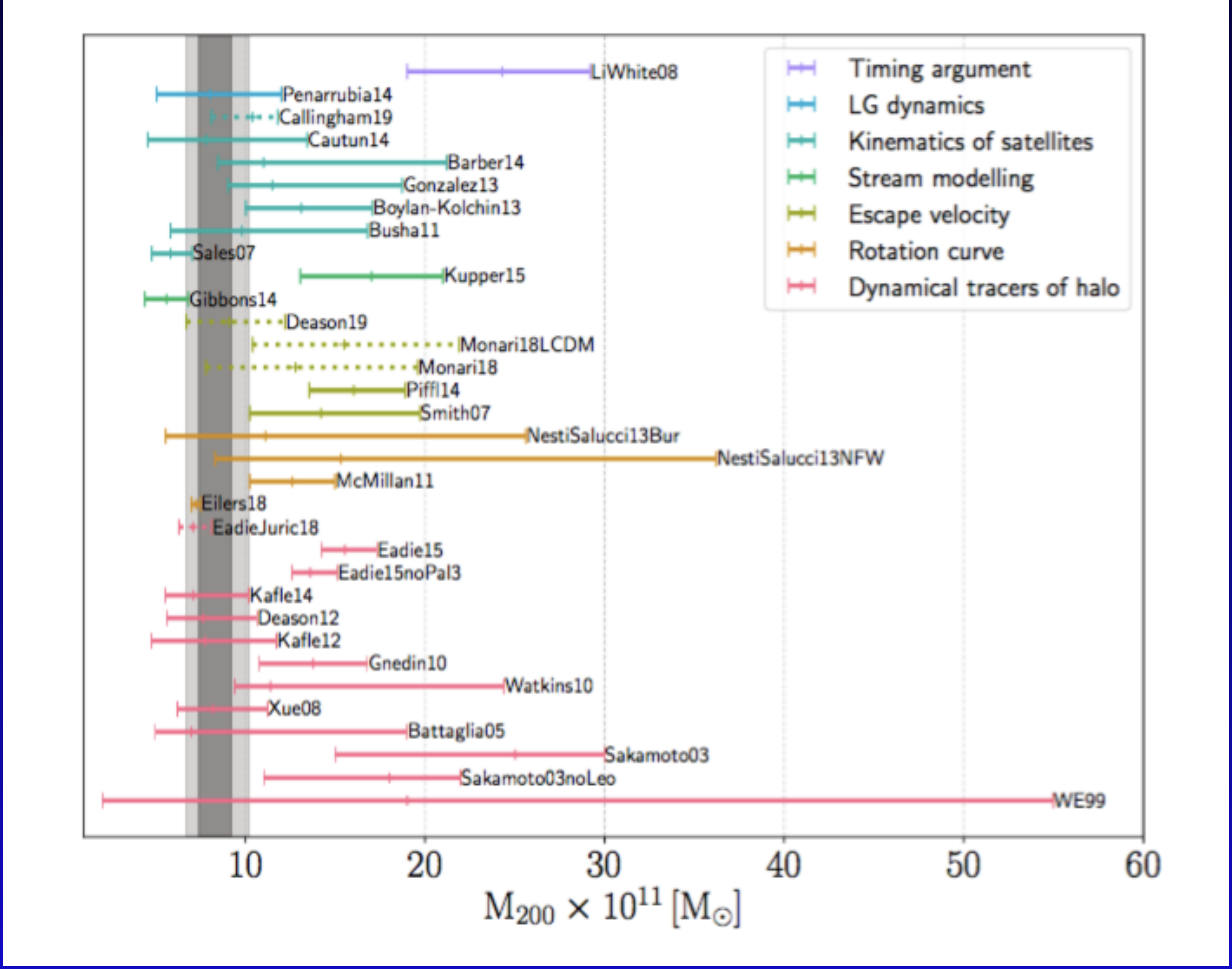

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- South American Dark Matter workshop
December 2-4, 2020

Third of a new series (2017, 2018)
www.ictp-saifr.org/DMw2018

Previous speakers included:

… Azadeh Fattahi
Graciela Gelmini
Christopher McCabe
Cecilia Scannapieco
Tomer Volansky …

ICTP SAIFR | International Centre for Theoretical Physics
South American Institute for Fundamental Research

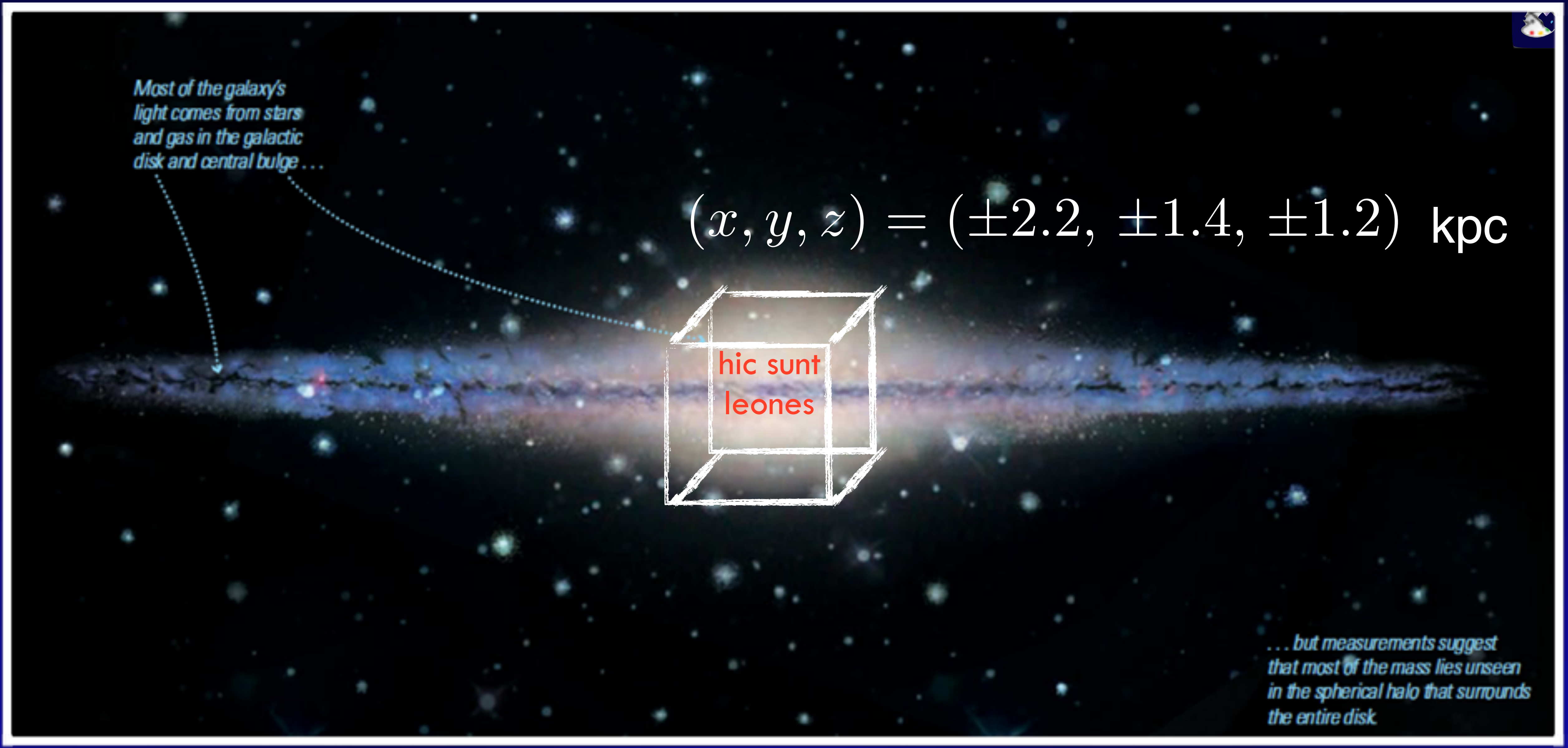
São Paulo,
Brazil
(not Rio de Janeiro!)

Organizers: I. Albuquerque, E. Bertuzzo, F. Iocco

Cuncta stricte

- Determining the local DM density from actual data is possible
- RC method is accurate and precise, in spite of large range of observational systematic and statistical uncertainties.
- Slope (i.e. full profile of MW) is not very accurate, and quite depending from several systematics. (Galactic Center region further complicated.)
- Astrophysical uncertainties are actually affecting determination of PP, in virtuous interplay with collider physics, direct and indirect probes.
- Providing a ready-to-use likelihood for PP use, including astrophysical uncertainties on DM distribution

Galactic Center: a beast of its own



Total mass

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

Portail +
MNRAS 465 (2017)

Stellar mass

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

[Iocco & Benito] PDU 15 (2017)

Methodology:

Allowed DM mass

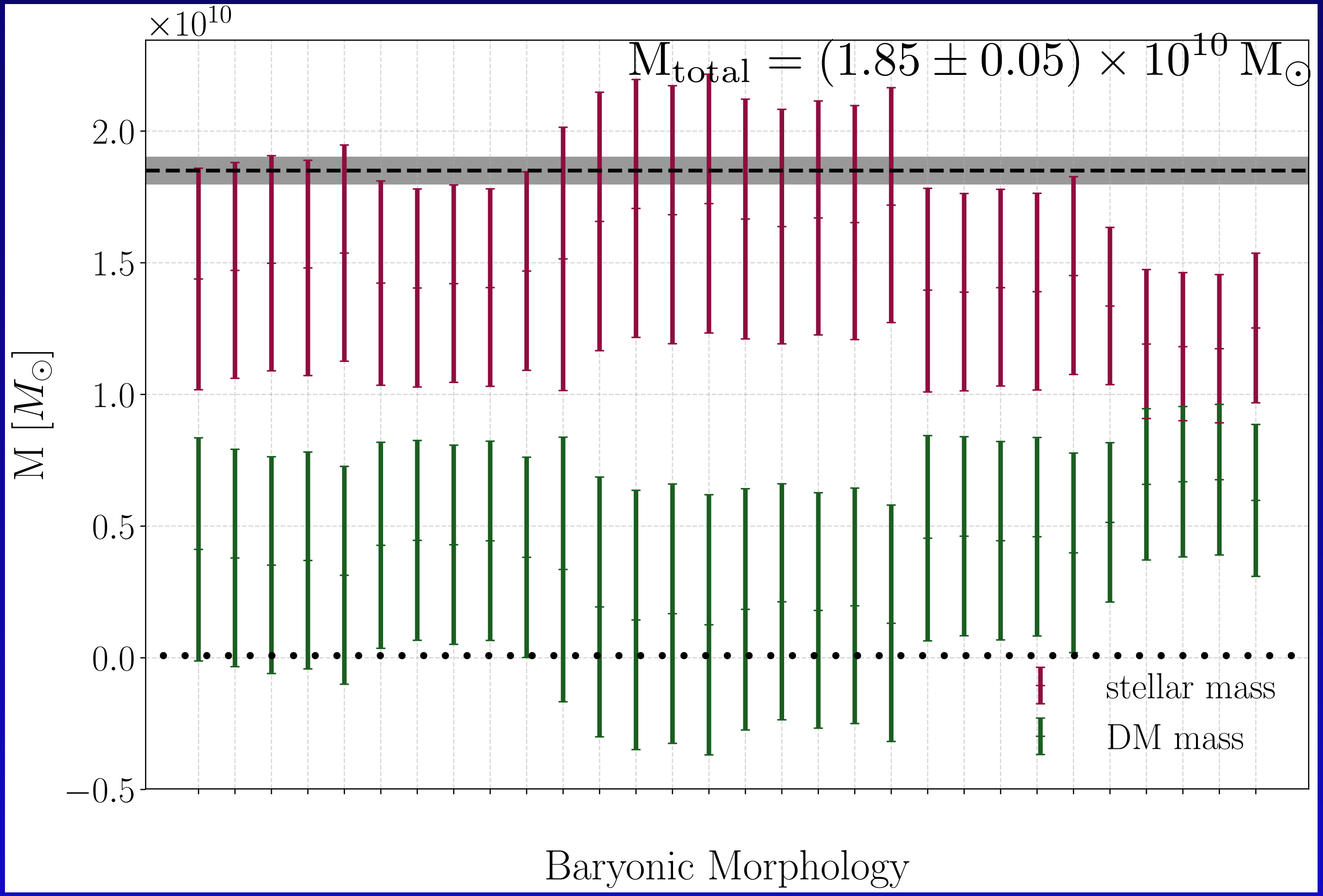
$$\mathrm{M_{total}} - \mathrm{M_*^i} = \mathrm{M_{DM}^i}$$

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

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

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

DM mass corresponds to 7-37%



[Iocco & Benito, PDU 2017] arXiv:1611.09861

(+ M. Benito's thesis)

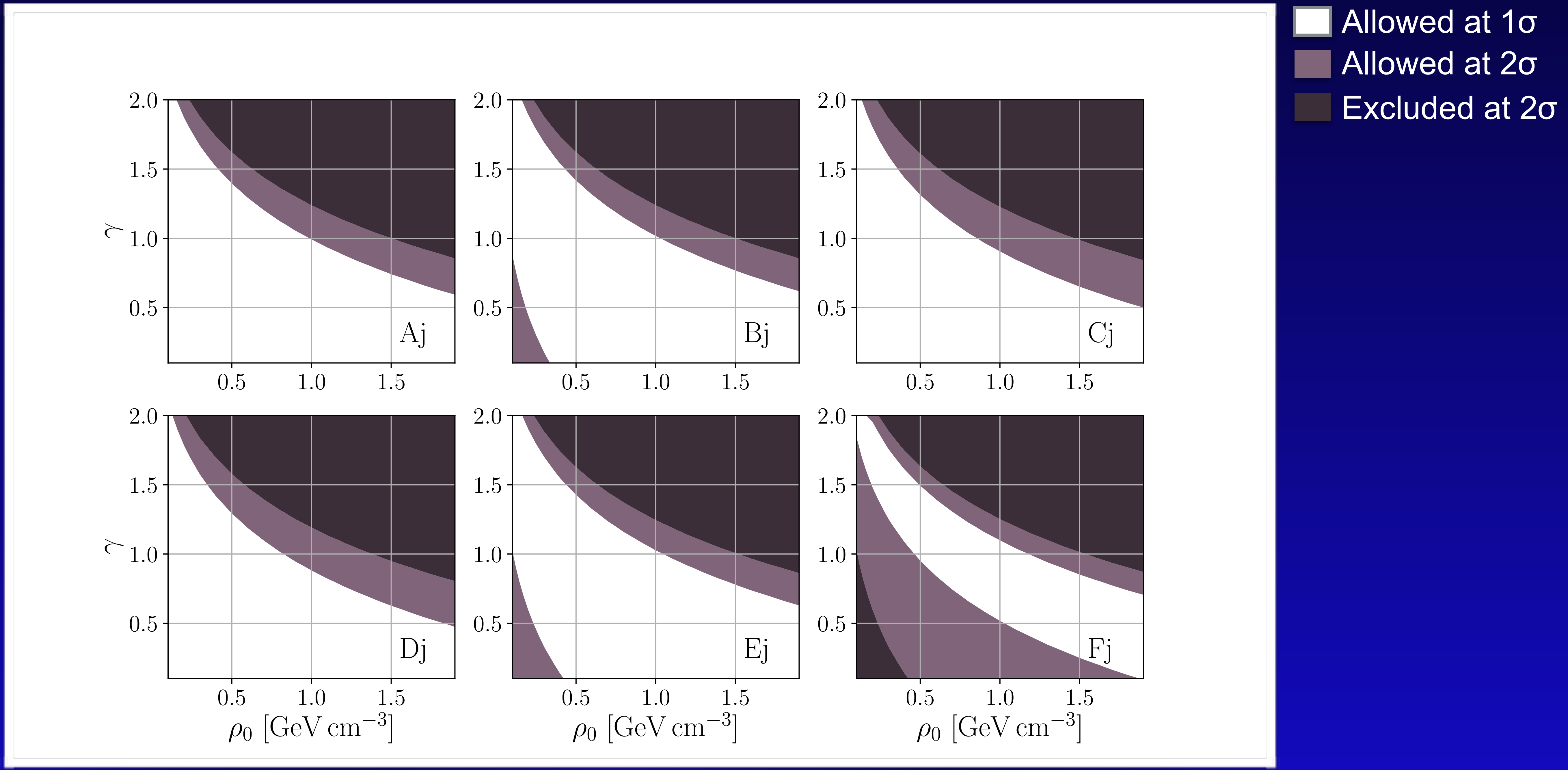
gNFW density profile

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

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

Galactic Bulge Region

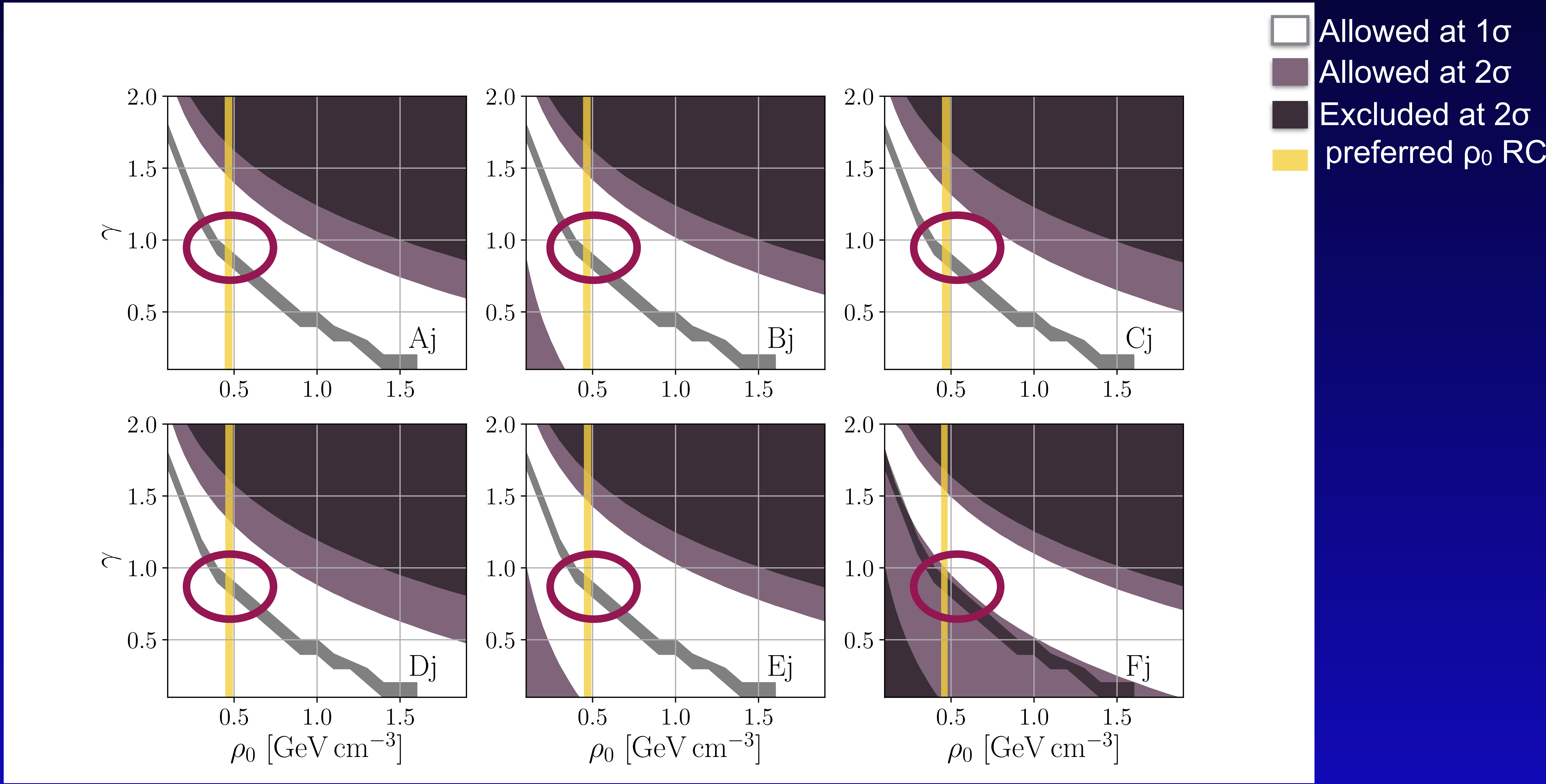
Results: varying bulge morphology



[Iocco & Benito, 2017] arXiv:1611.09861

(+ M. Benito's thesis)

Galactic Bulge Region and RC curve compatibility



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

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

Portail + MNRAS 465 (2017)

[Iocco & Benito, 2017] arXiv:1611.09861 (+ M. Benito's thesis)