Dark Matter in the Milky Way

Fabio Iocco

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

And most notably in the proximity of the Sun?

And in the Galactic Center, too? Please bear with me until the end.

Dark Matter in the Milky Way

FROM THE SKIES TO THE UNDERGROUND, HOW ASTROPHYSICAL UNCERTAINTIES AFFECT SYNERGIC SEARCHES FOR DM.

CHAPTER ONE: A GALAXY CLOSE, CLOSE BY

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INFN

NAP THEORY

The Milky Way: literature credits

The origin of the Milky Way

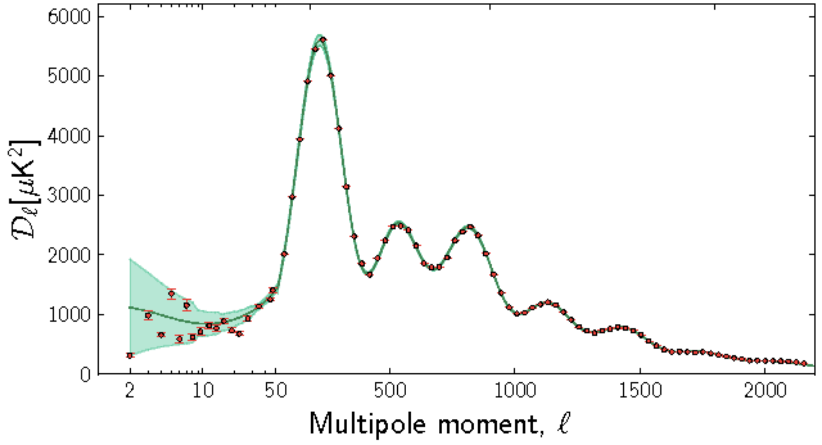
[Jacopo Tintoretto, ca 1575. The National Gallery, London]

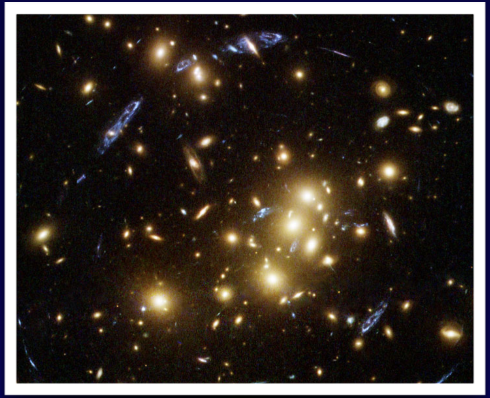
The origin of the Milky Way

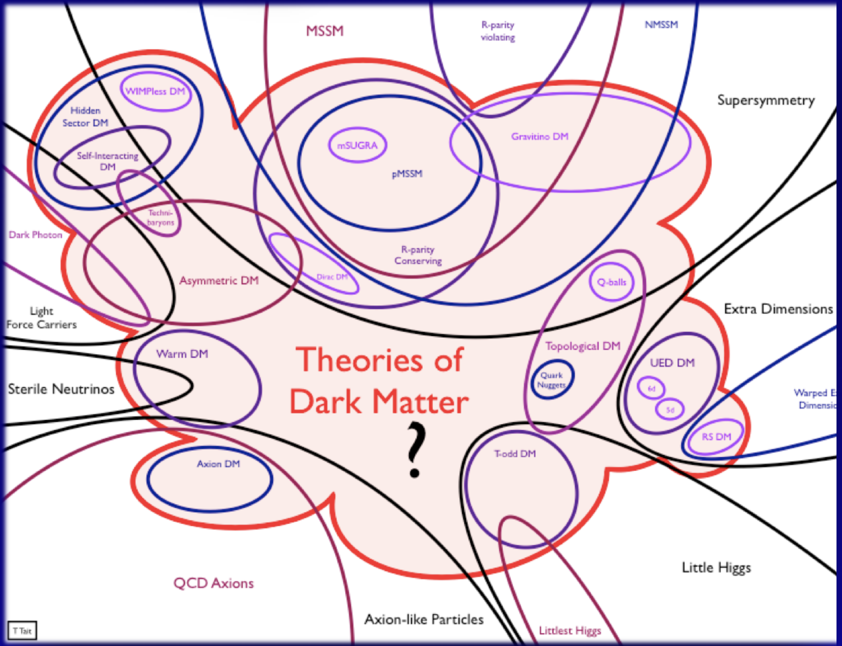
[Peter Paul Rubens, ca 1636. Museo del Prado, Madrid]

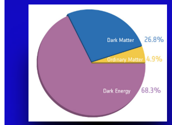
Dark Matter

Evidence over large range of scales





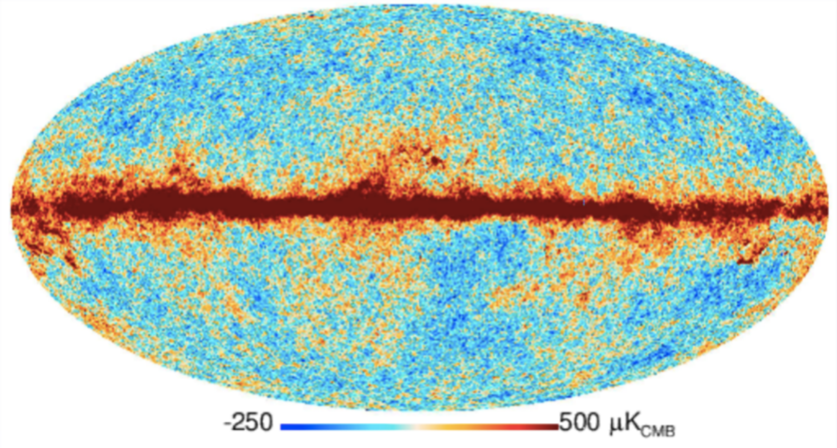


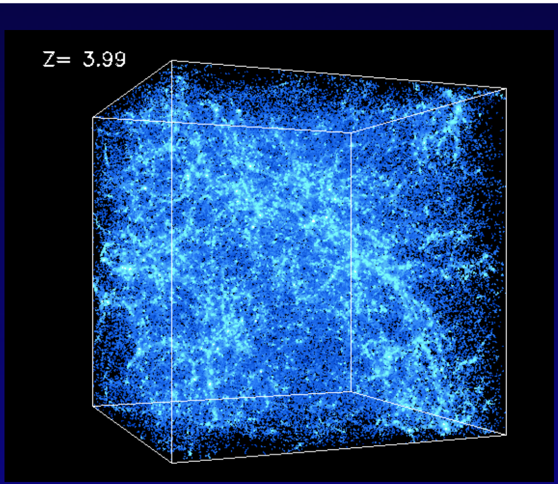


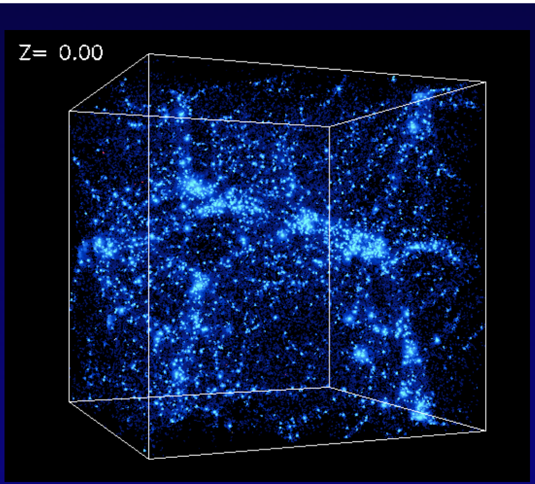
NATURE STILL UNKNOWN

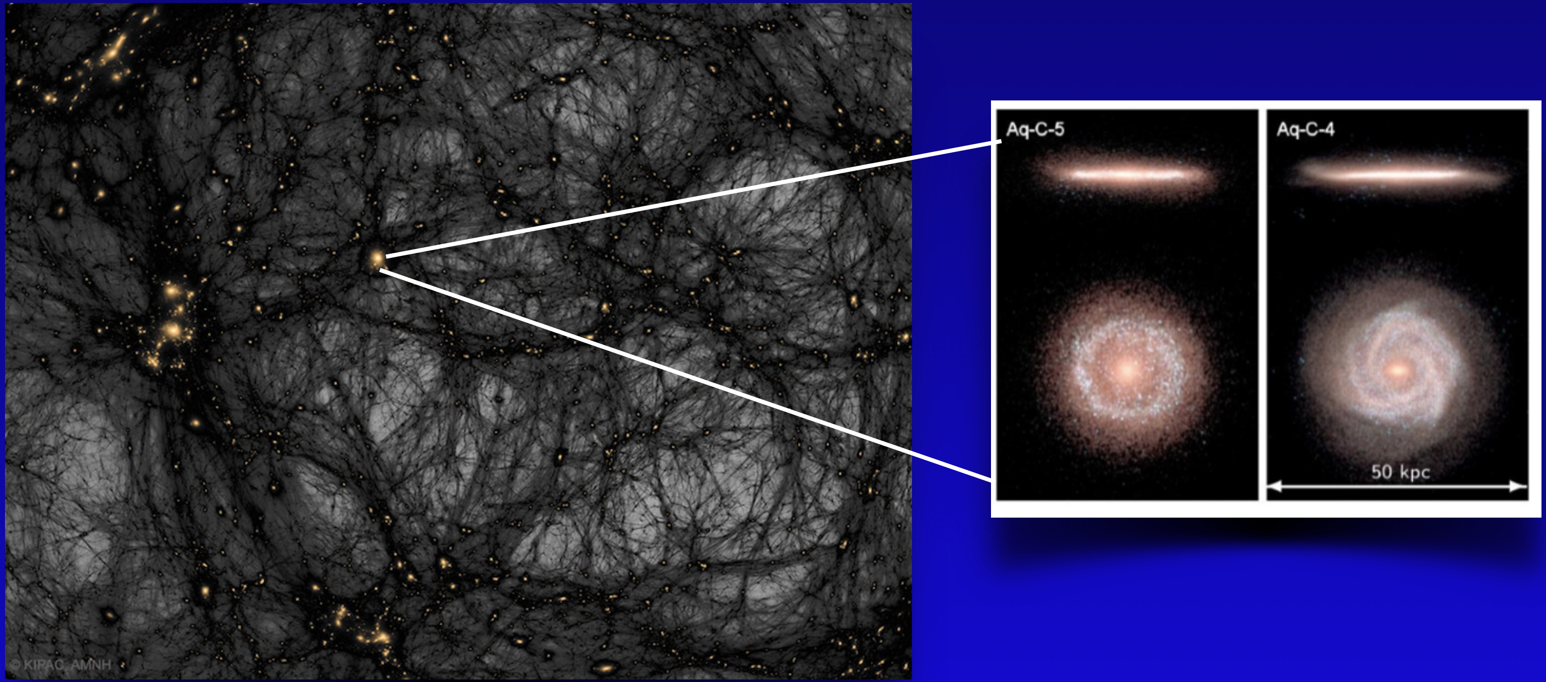
A story of LCDM
I: structure formation

age of Universe





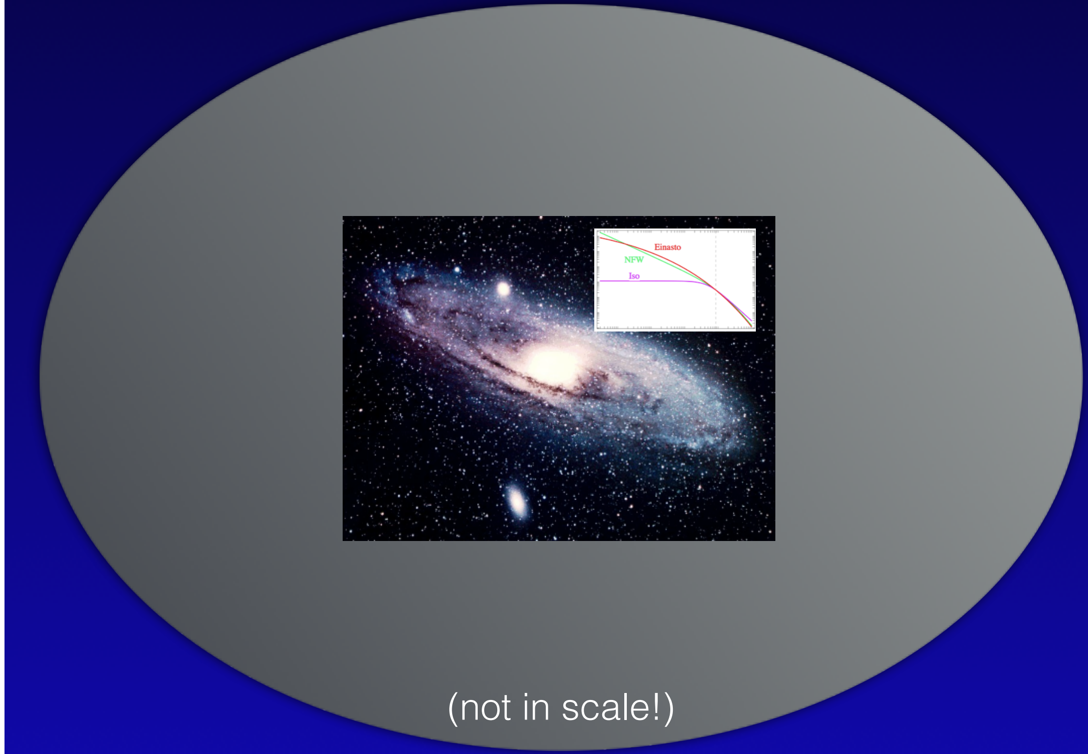




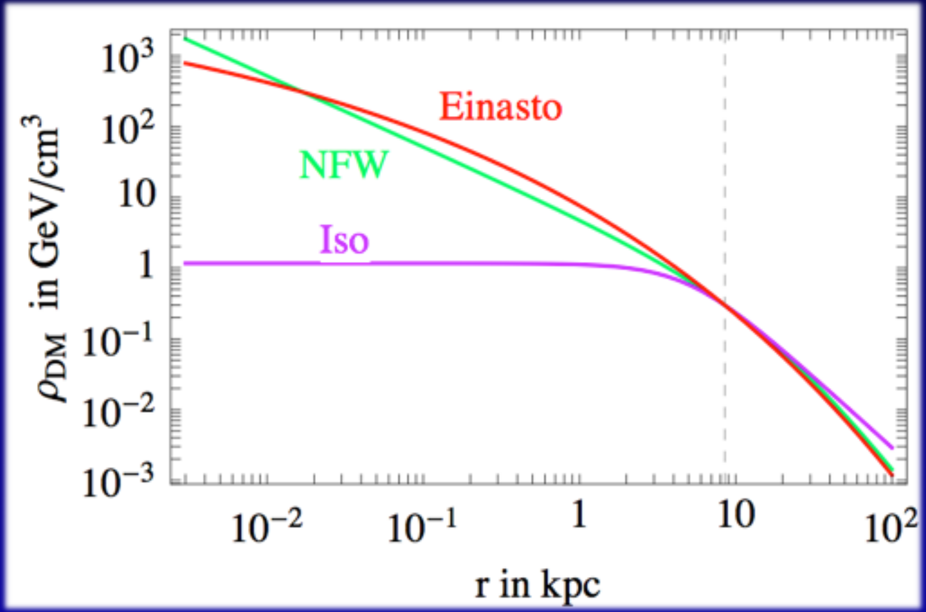
physical size

A story of LCDM
II. the single halo

A “universal” DM profile?



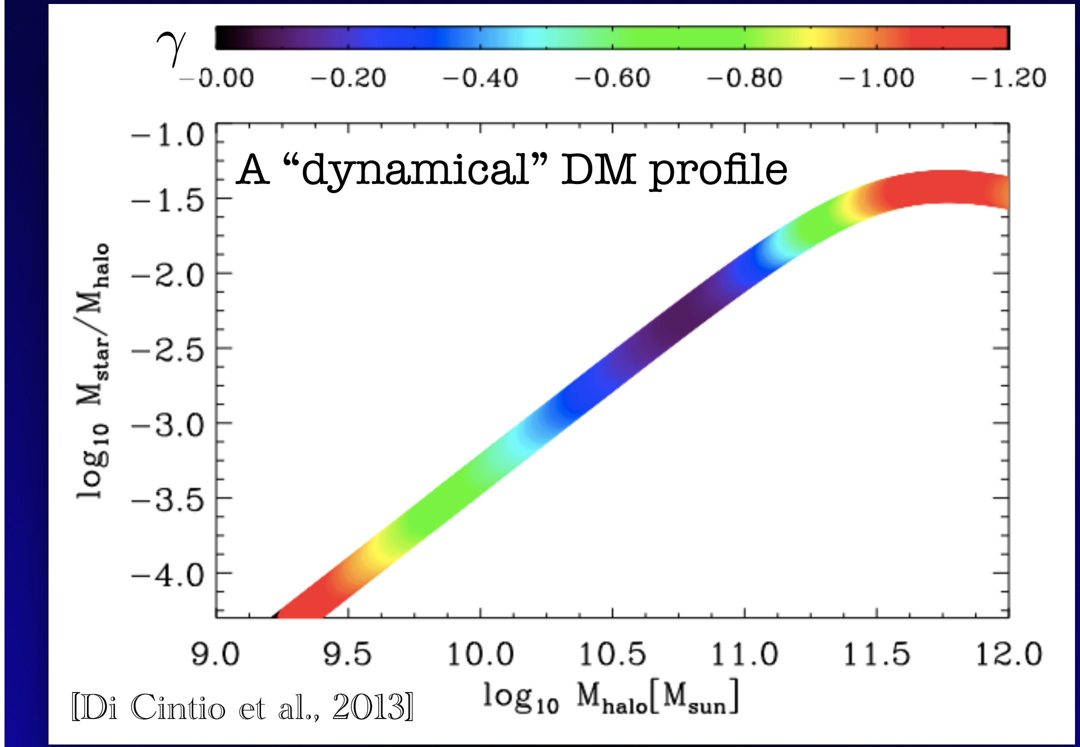
(not in scale!)



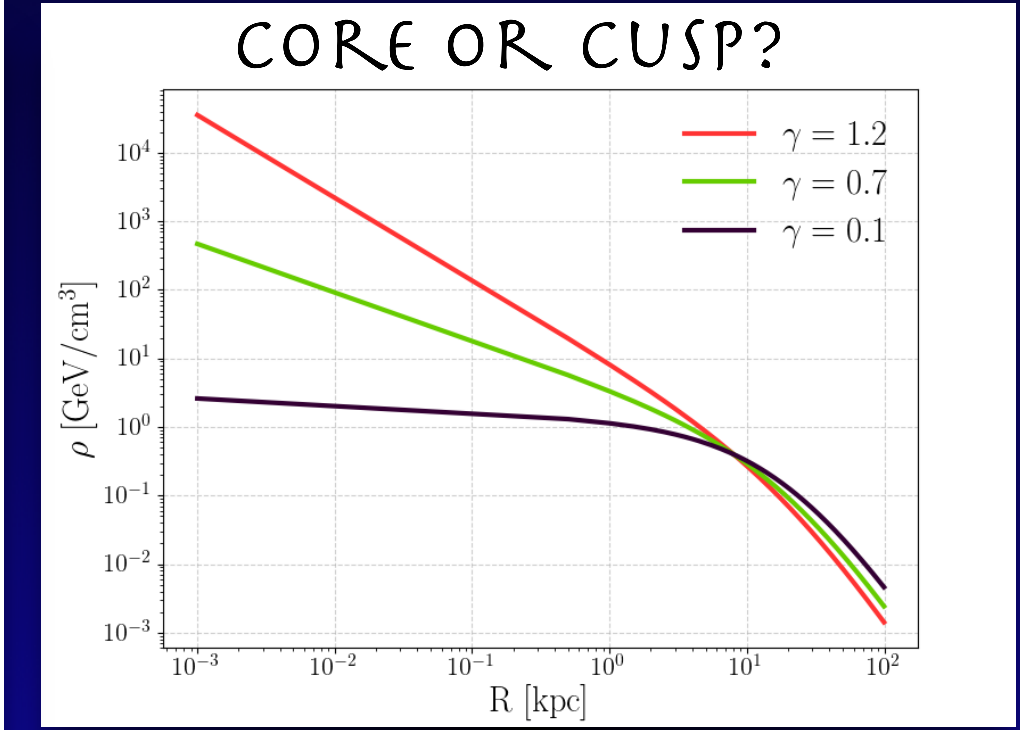
NAVARRO-FRENK-WHITE

$$\rho(R) \propto \frac{R_s}{R}\left(1+\frac{R}{R_s}\right)^{-2}$$

A story of LCDM
III. the dark matter distribution



[Di Cintio et al., 2013]



CORE OR CUSP?

generalized NFW

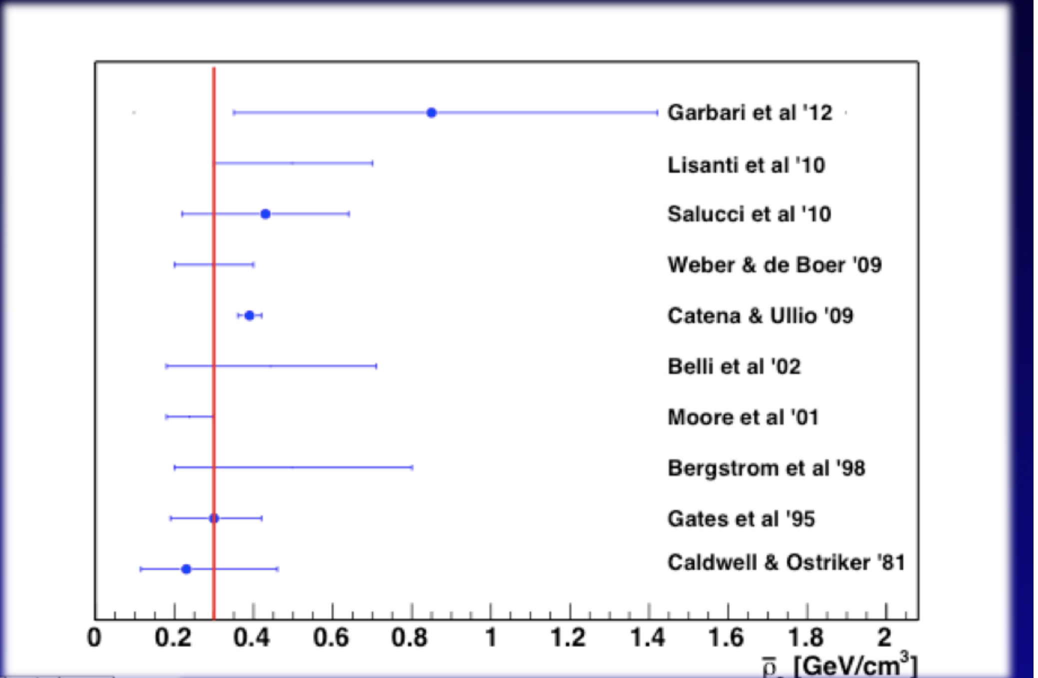
$$\rho_{DM}(R) \propto \rho_0 \left(\frac{R}{R_s}\right)^{-\gamma} \left(1 + \frac{R}{R_s}\right)^{-3+\gamma}$$

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

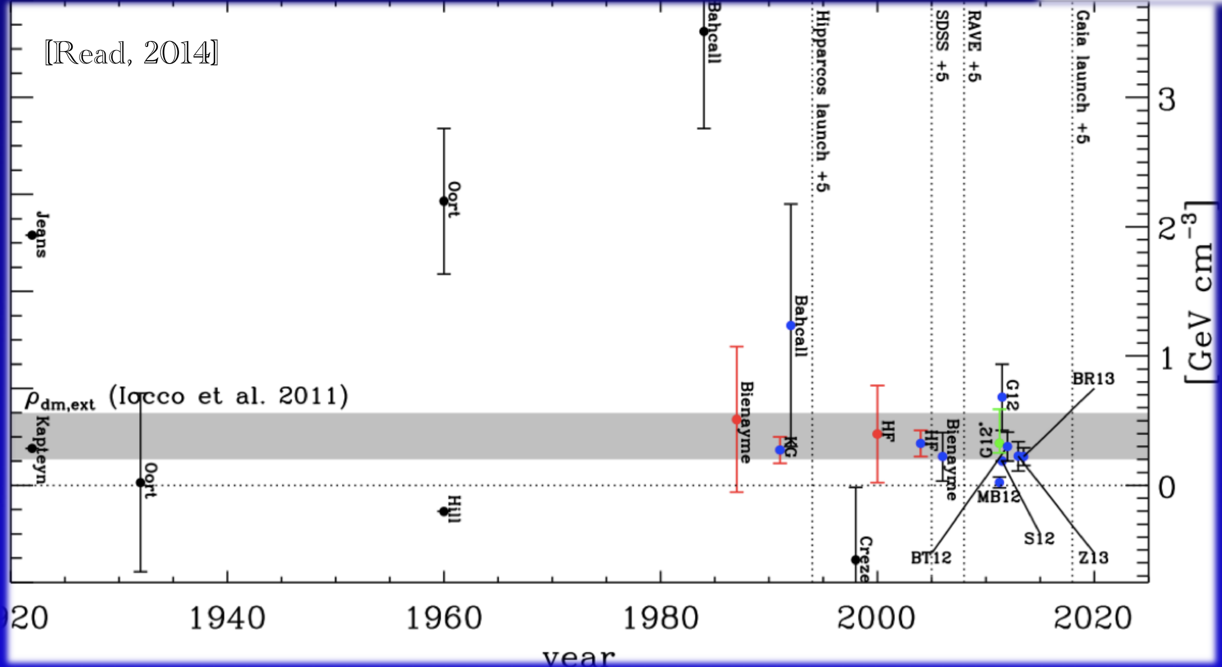
And most notably in the proximity of the Sun?

And the Galactic Center, as requested. Please bear with me until the end.

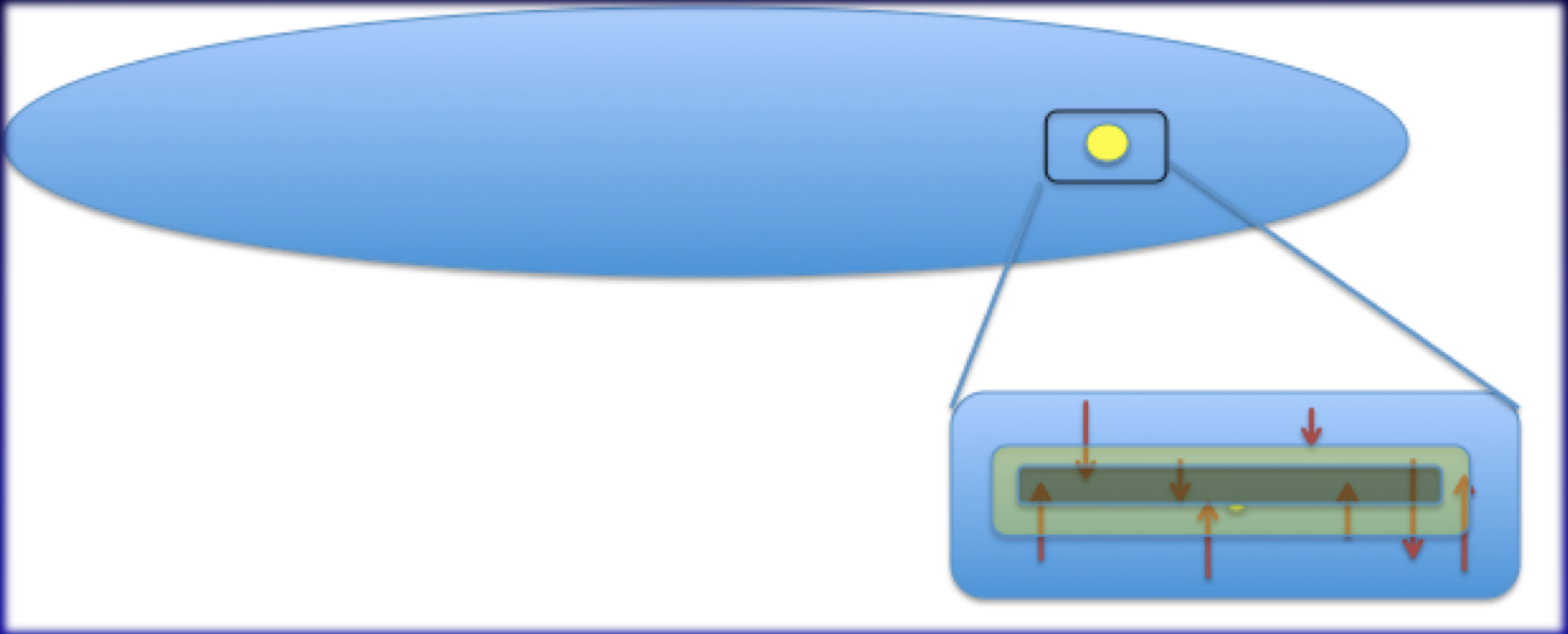
Empirical determination of local DM density



Determinations of
local DM density
are consistent, but noisy


[Read, 2014]

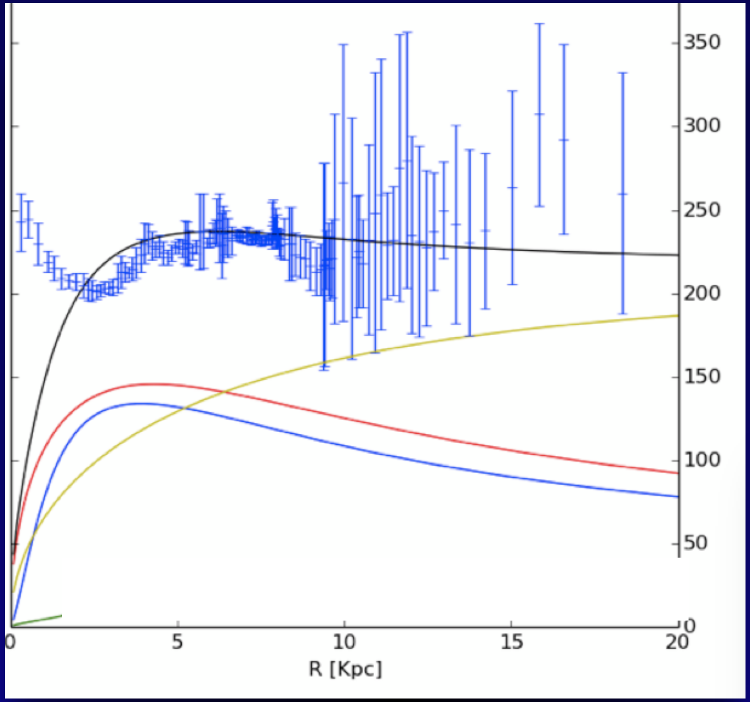
Local determination of ρ_0



Vertical motion of stars in local region O(100pc) provides total Grav Pot
Subtracting visible (stellar) contribution
Obtain (or not) DM without assuming its presence

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

Fitting a pre-assigned shape
on top of luminous

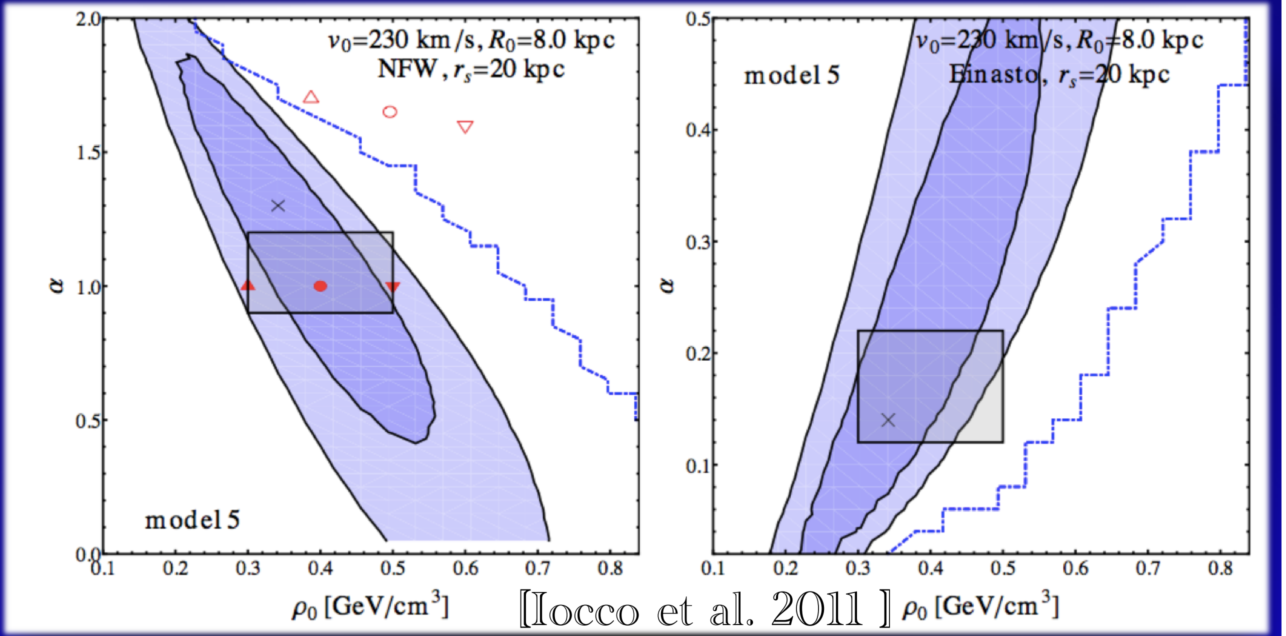


gNFW

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

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

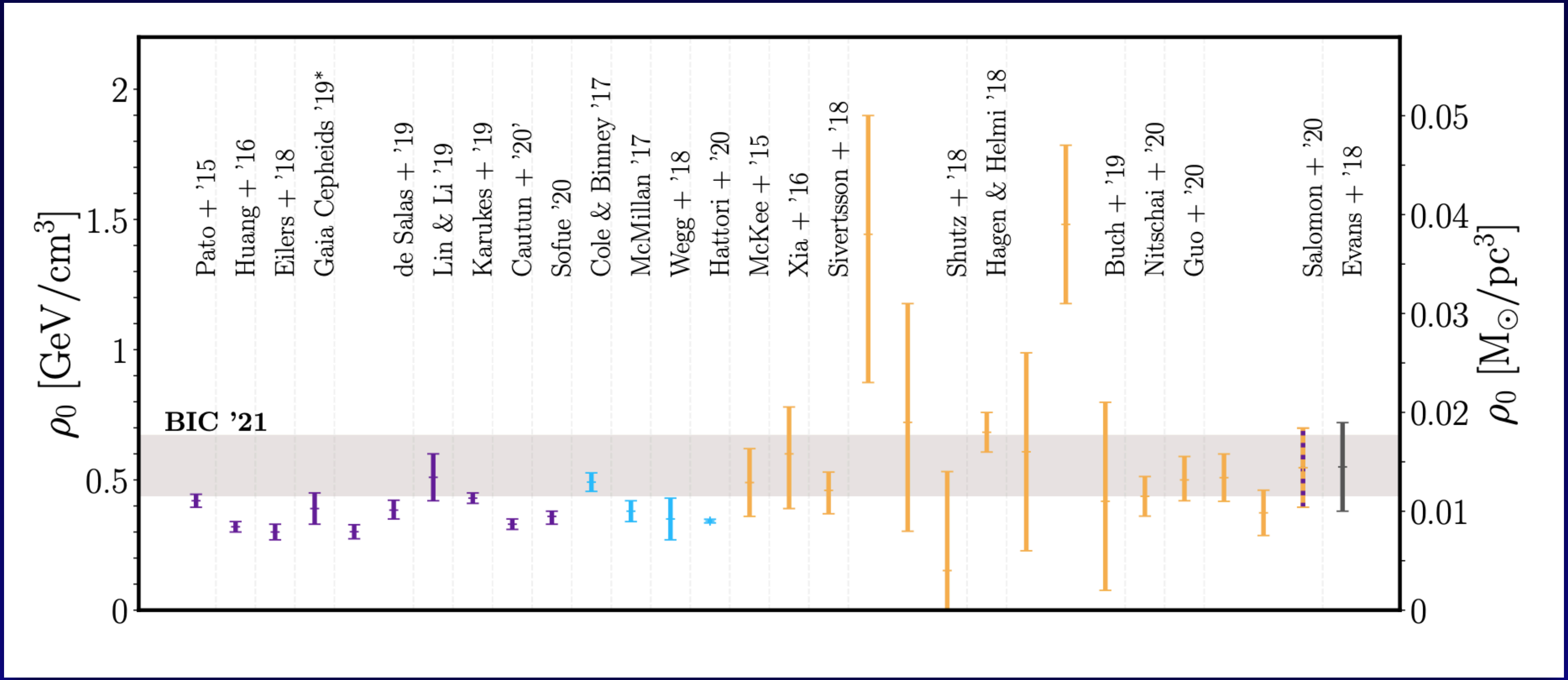
Einasto



[Iocco et al. 2011]

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

Empirical determination of local DM density: recent determinations



[Benito, Iocco, Cuoco, PDU 2021, arxiV:2009.13523]

The case of the Milky Way
Recipe for unifying data & formalism.

Ingredients:

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

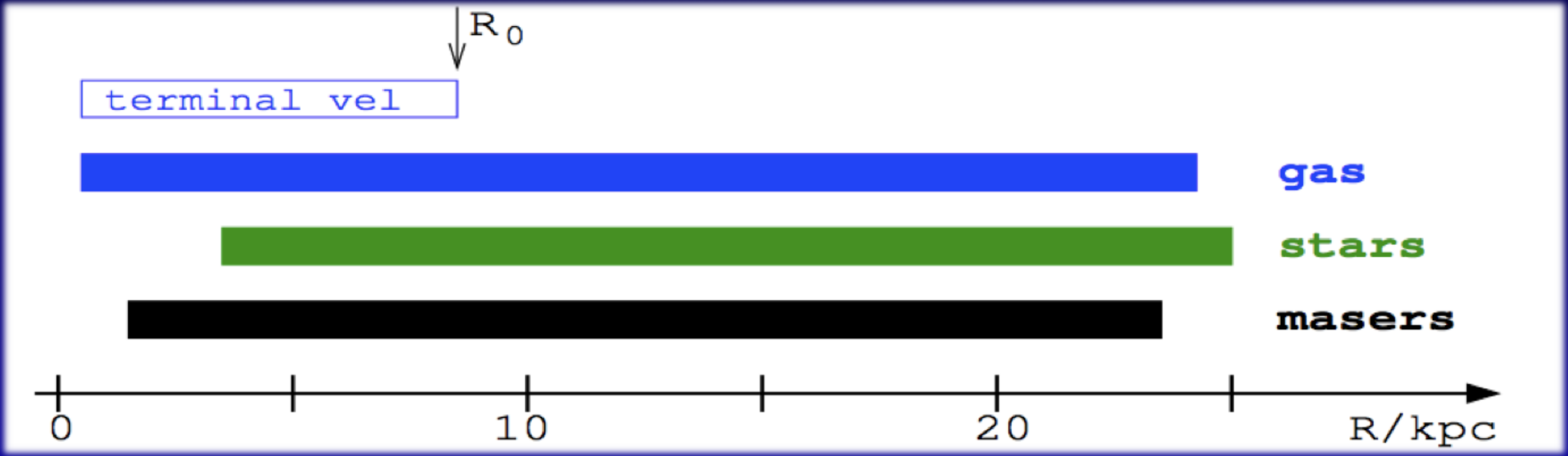
- Some “grano salis”

- Working hypothesis (later on)

The Milky Way:

observed rotation curve

the tracers of the gravitational potential



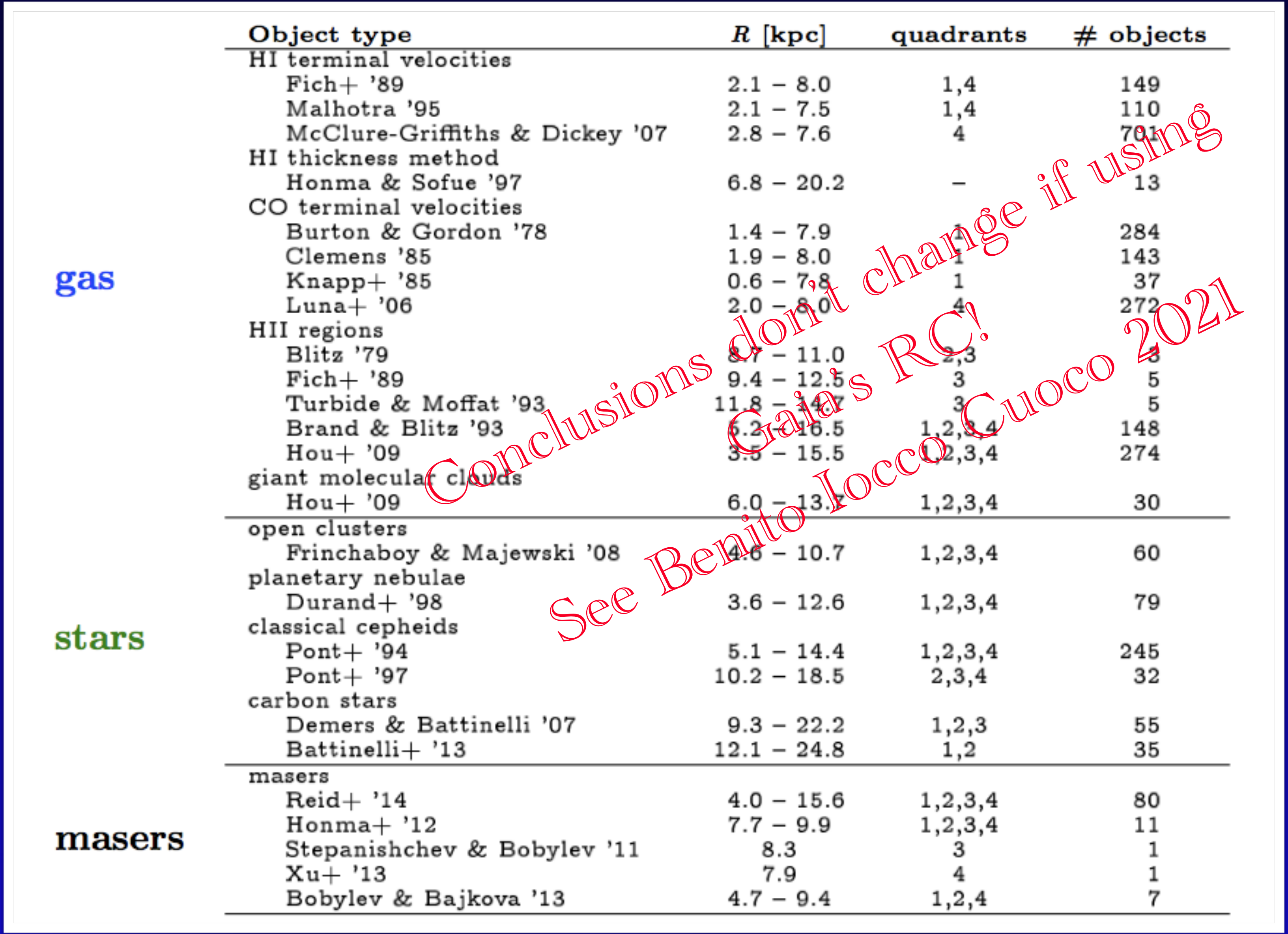
Doppler shift

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:
observed rotation curve
the data: a new compilation



	Object type	*R* [kpc]	quadrants	# objects
gas	HI terminal velocities			
	Fich+ '89	2.1 – 8.0	1,4	149
	Malhotra '95	2.1 – 7.5	1,4	110
	McClure-Griffiths & Dickey '07	2.8 – 7.6	4	701
	HI thickness method			
	Honma & Sofue '97	6.8 – 20.2	–	13
	CO terminal velocities			
	Burton & Gordon '78	1.4 – 7.9	1	284
	Clemens '85	1.9 – 8.0	1	143
	Knapp+ '85	0.6 – 7.8	1	37
	Luna+ '06	2.0 – 8.0	4	272
	HII regions			
	Blitz '79	8.7 – 11.0	2,3	3
	Fich+ '89	9.4 – 12.5	3	5
	Turbide & Moffat '93	11.8 – 14.7	3	5
	Brand & Blitz '93	5.2 – 16.5	1,2,3,4	148
	Hou+ '09	3.5 – 15.5	1,2,3,4	274
	giant molecular clouds			
	Hou+ '09	6.0 – 13.7	1,2,3,4	30
stars	open clusters			
	Frinchaboy & Majewski '08	4.6 – 10.7	1,2,3,4	60
	planetary nebulae			
	Durand+ '98	3.6 – 12.6	1,2,3,4	79
	classical cepheids			
	Pont+ '94	5.1 – 14.4	1,2,3,4	245
	Pont+ '97	10.2 – 18.5	2,3,4	32
	carbon stars			
	Demers & Battinelli '07	9.3 – 22.2	1,2,3	55
	Battinelli+ '13	12.1 – 24.8	1,2	35
masers	masers			
	Reid+ '14	4.0 – 15.6	1,2,3,4	80
	Honma+ '12	7.7 – 9.9	1,2,3,4	11
	Stepanishchev & Bobylev '11	8.3	3	1
	Xu+ '13	7.9	4	1
	Bobylev & Bajkova '13	4.7 – 9.4	1,2,4	7

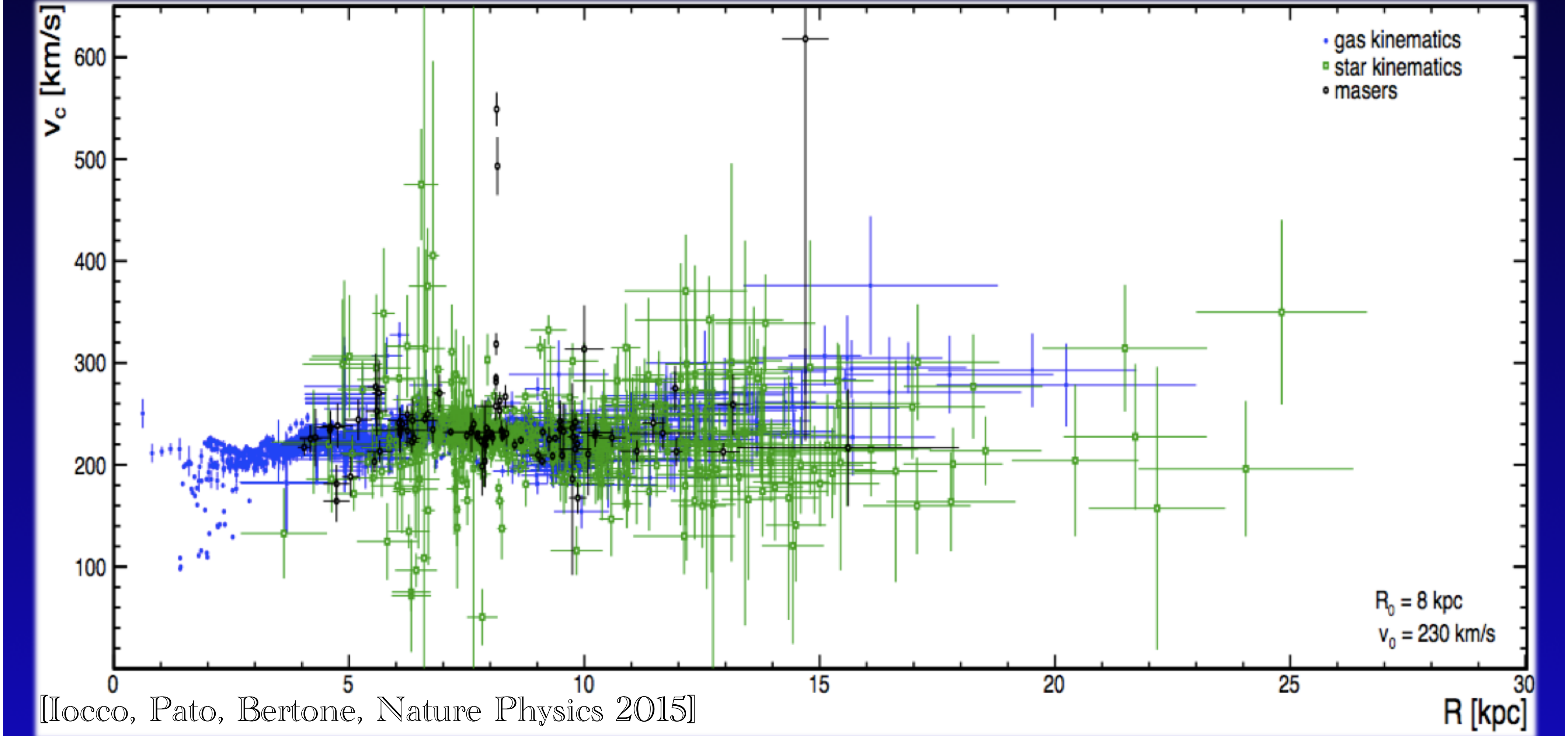
Conclusions don't change if using Gaia's RC!

See Benito Iocco Cuoco 2021

[Iocco, Pato, Bertone, Nature Physics 2015] [Pato & FI, arXivV:1703.00020 , Software X (2017)]

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

from visible (baryon) component

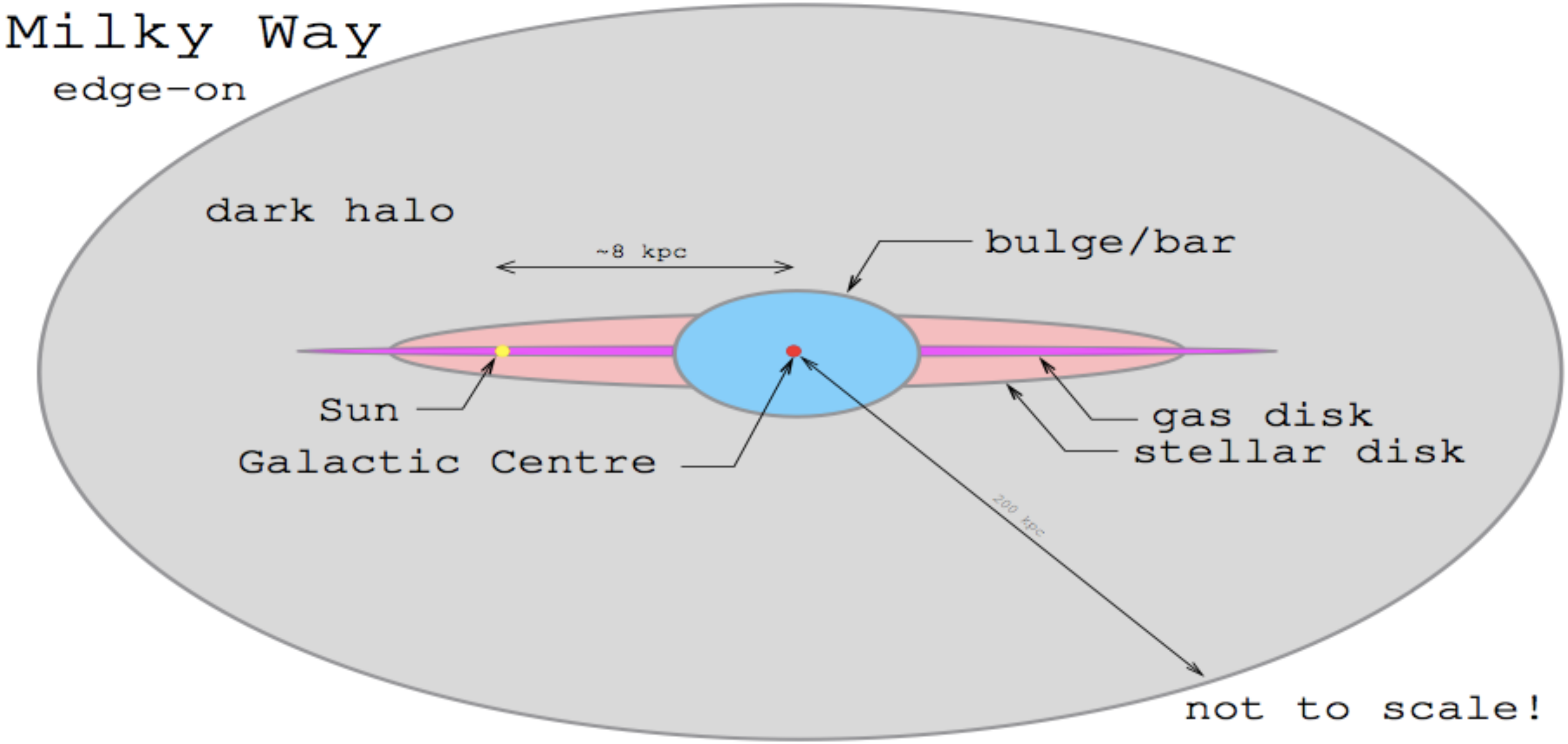
$$\Phi_{\mathrm{baryon}} = \Phi_{\mathrm{bulge}} + \Phi_{\mathrm{disk}} + \Phi_{\mathrm{gas}}$$

$$\rho_i(x,y,z) \rightarrow \phi_i(r,\theta,\varphi) \rightarrow v_{c,i}^2(R) = \sum_{\varphi} R \frac{d\phi_i}{dr}(R,\pi/2,\varphi)$$

Constructing the curve expected from observed mass profiles

The Milky Way:

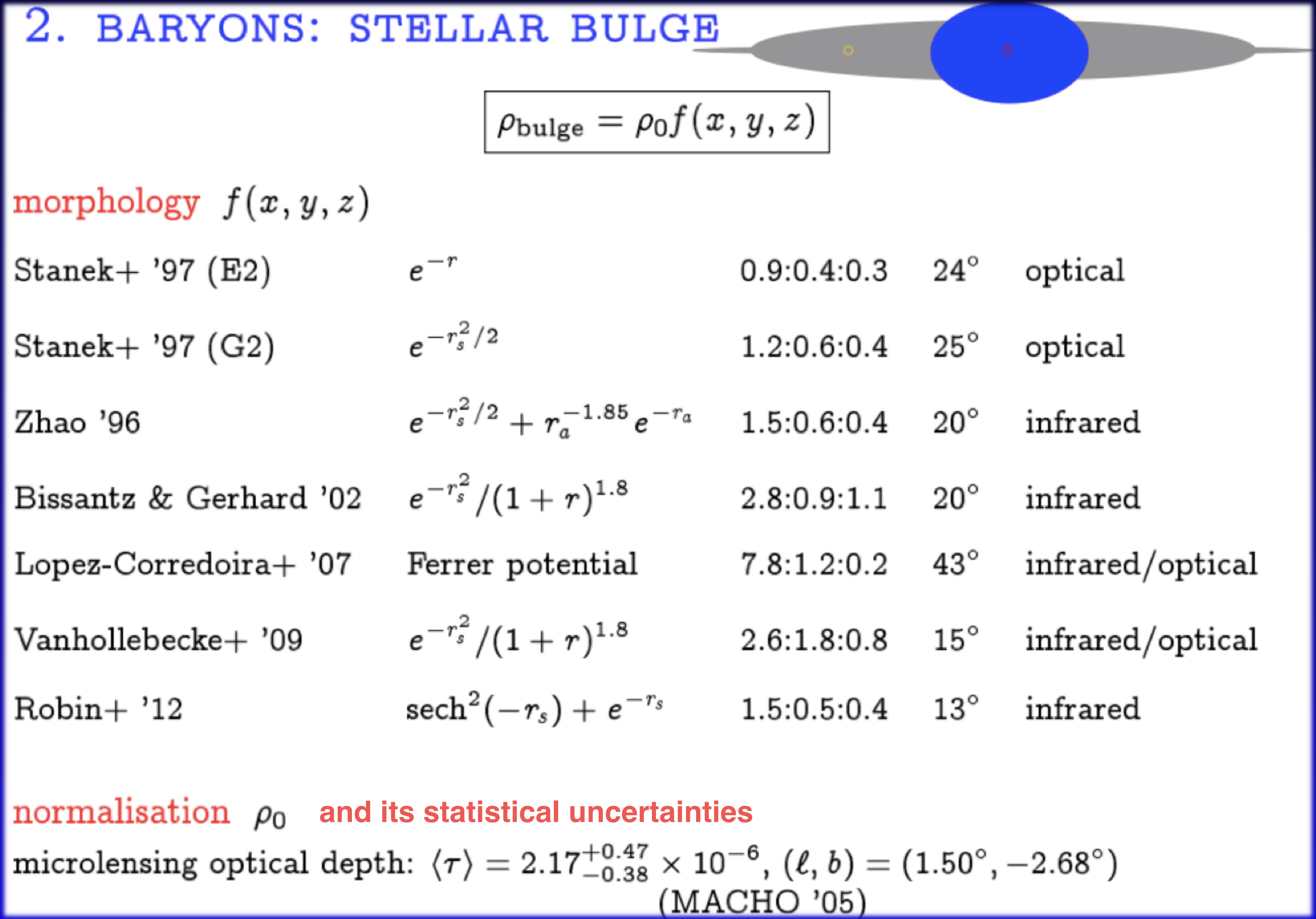
expected rotation curve
the baryonic components



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

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

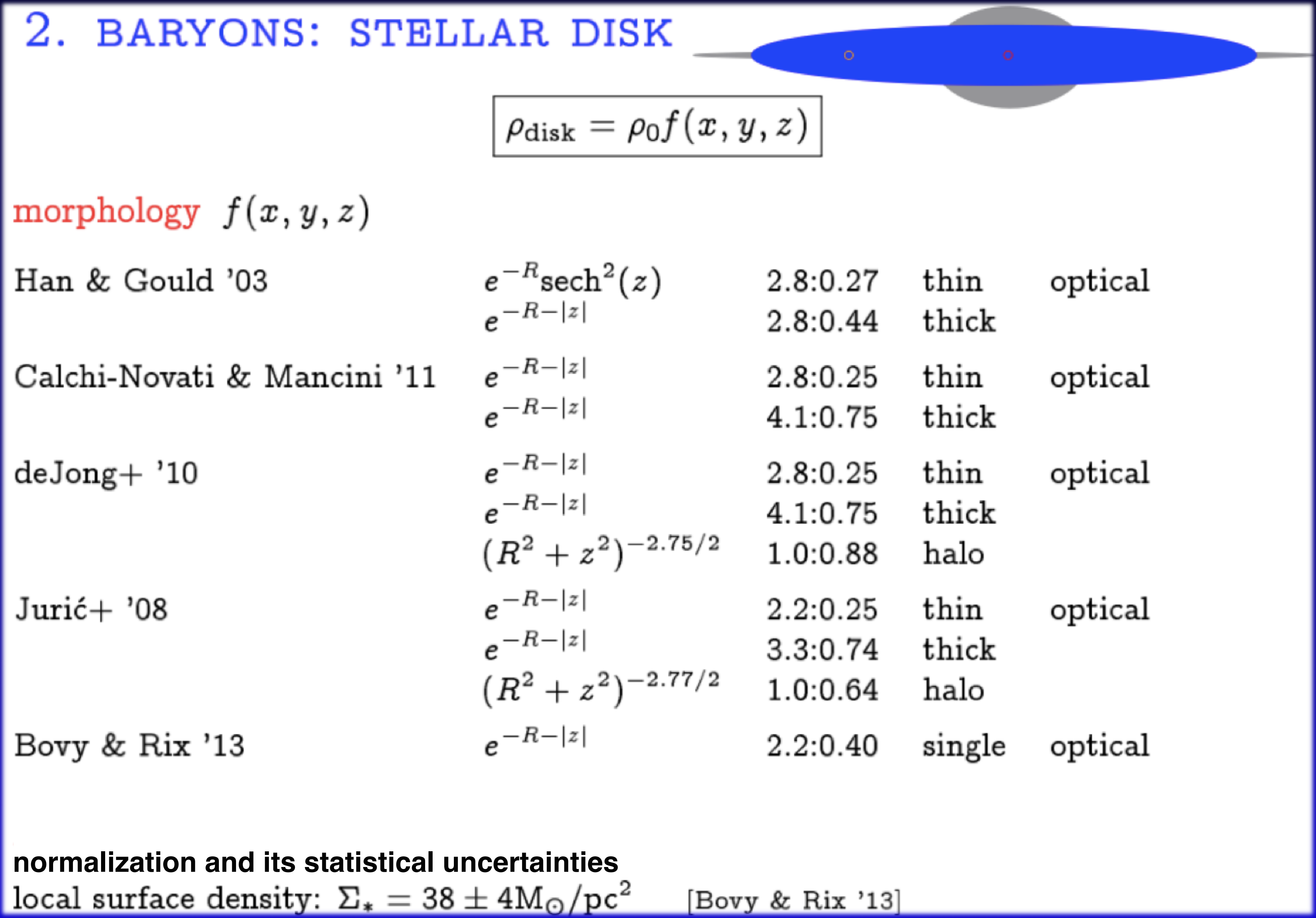
morphology $f(x,y,z)$

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

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

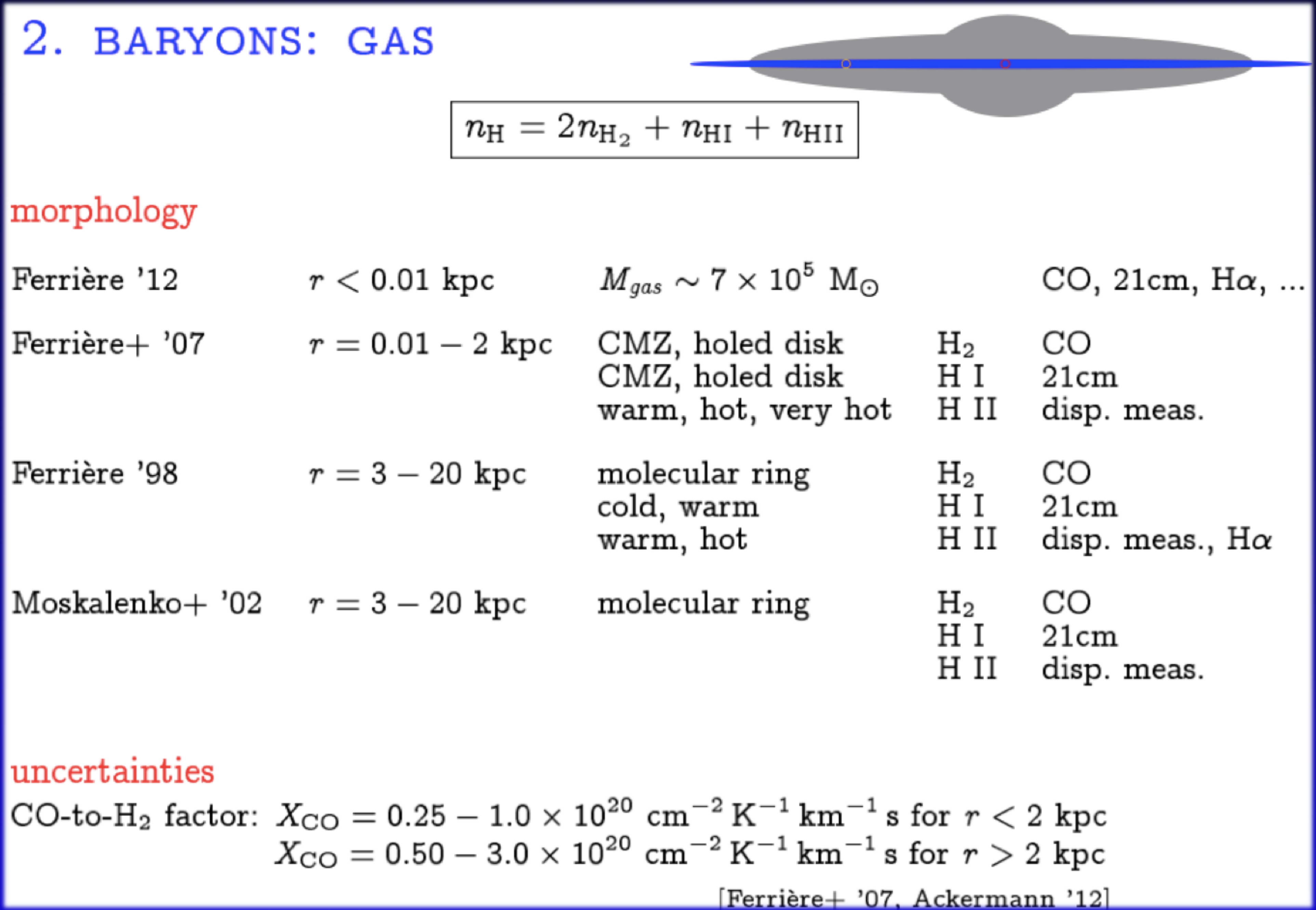
morphology $f(x,y,z)$

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

normalization and its statistical uncertainties

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

The luminous Milky Way: observations of morphology



2. BARYONS: GAS

$$\boxed{n_{\mathrm{H}} = 2n_{\mathrm{H}_2} + n_{\mathrm{HI}} + n_{\mathrm{HII}}}$$

morphology

Ferrière '12	$r < 0.01$ kpc	$M_{gas} \sim 7 \times 10^5\ \mathrm{M}_\odot$		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: $X_{\mathrm{CO}} = 0.25 - 1.0 \times 10^{20}\ \mathrm{cm^{-2}\,K^{-1}\,km^{-1}\,s}$ for $r < 2$ kpc

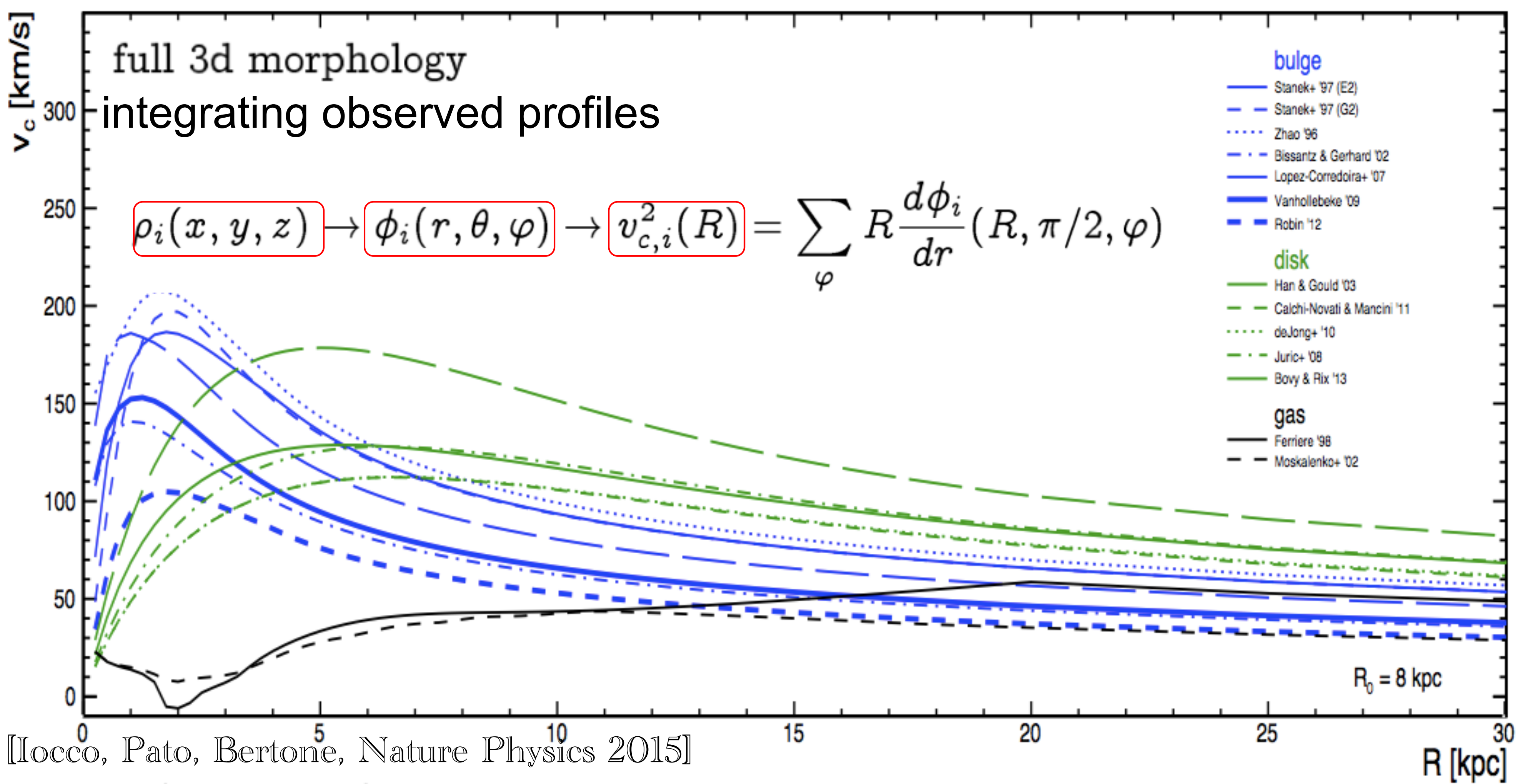
$X_{\mathrm{CO}} = 0.50 - 3.0 \times 10^{20}\ \mathrm{cm^{-2}\,K^{-1}\,km^{-1}\,s}$ for $r > 2$ kpc

[Ferrière+ '07, Ackermann '12]

The luminous Milky Way:

expected rotation curve

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

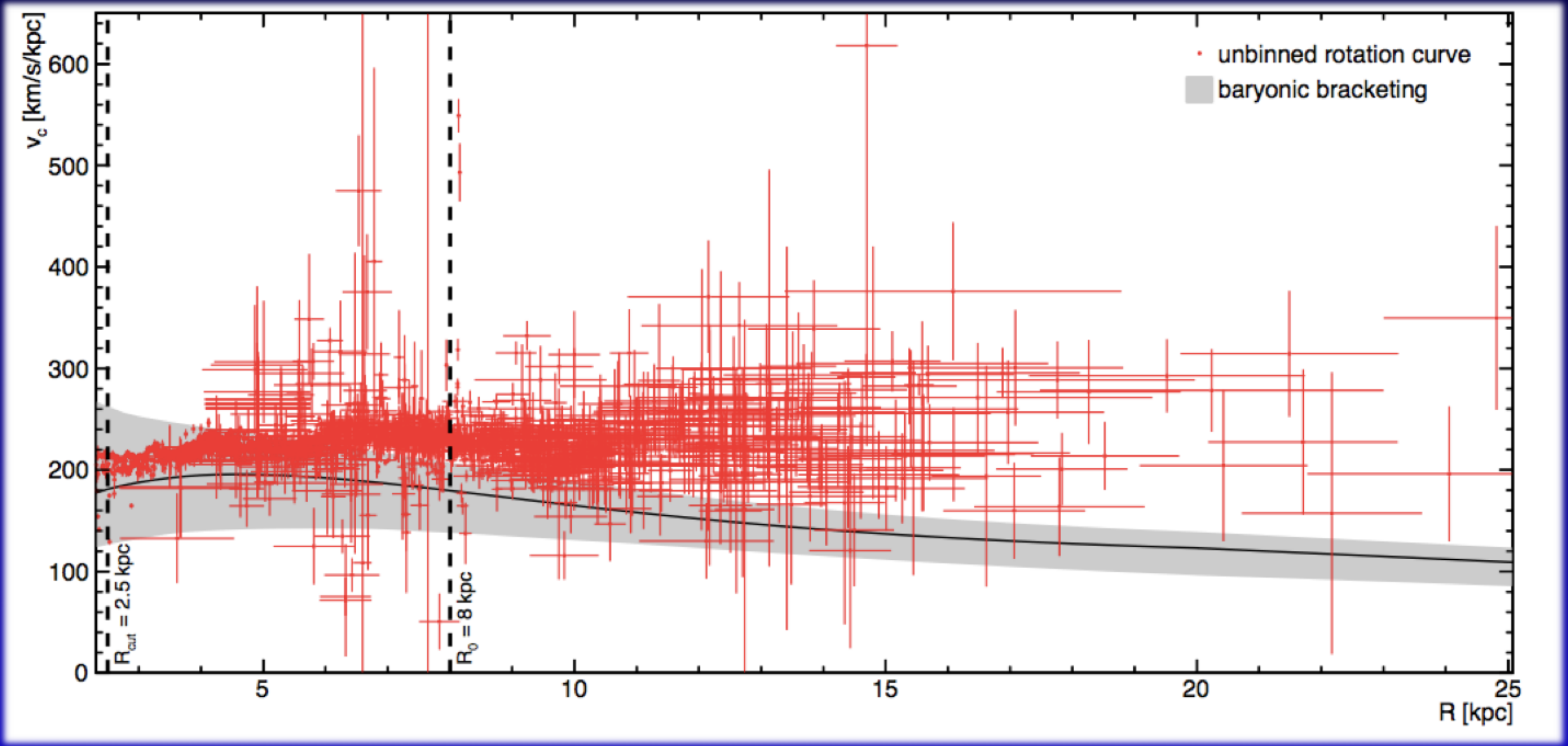


integrating observed profiles

$$\boxed{\rho_i(x,y,z)} \rightarrow \boxed{\phi_i(r,\theta,\varphi)} \rightarrow \boxed{v^2_{c,i}(R)} = \sum_{\varphi} R\,\frac{d\phi_i}{dr}(R,\pi/2,\varphi)$$

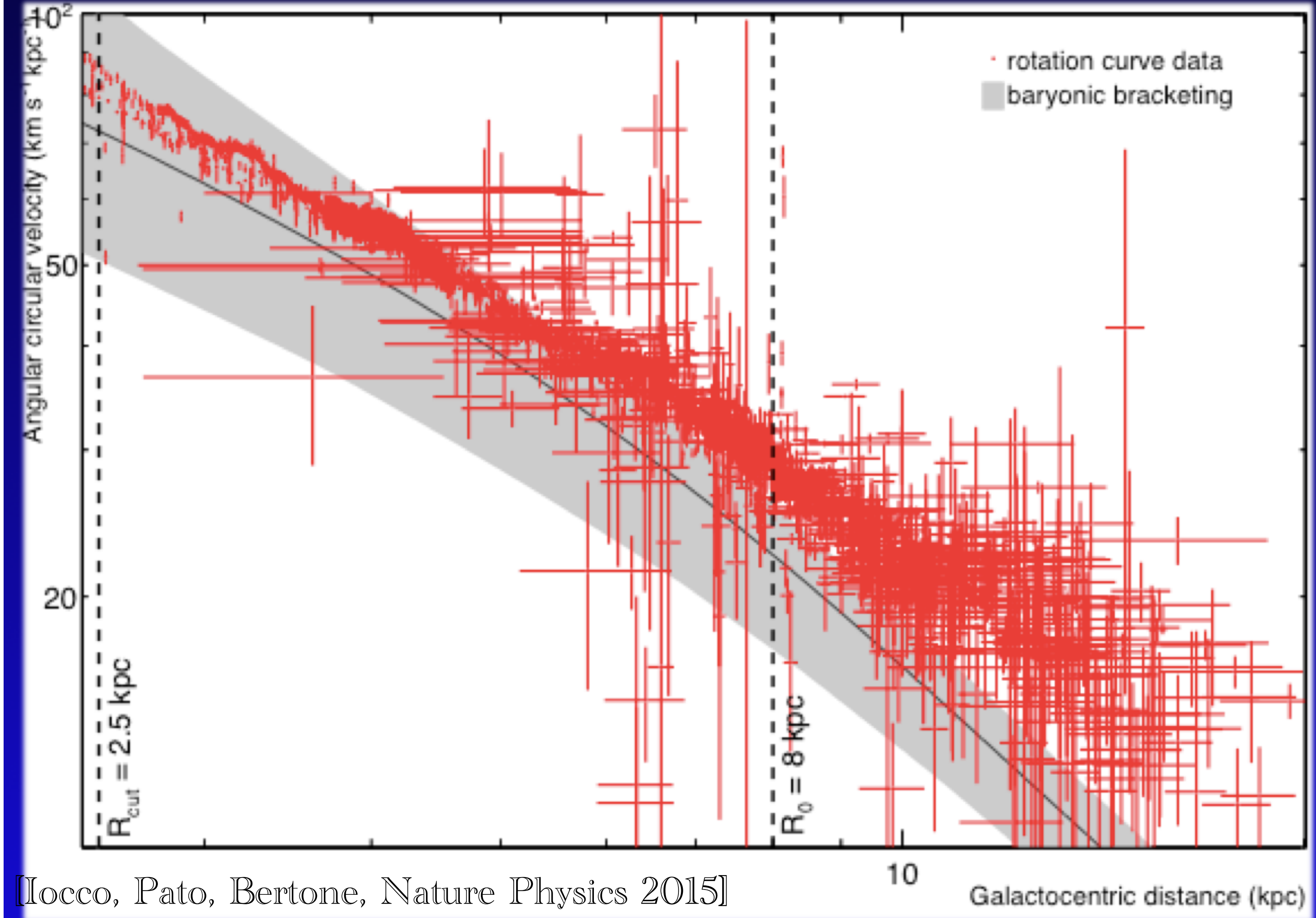
[Iocco, Pato, Bertone, Nature Physics 2015]

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



[Iocco, Pato, Bertone, Nature Physics 2015]

The Milky Way:
testing expectactions
(with no additional assumption)
((and some technical detail))



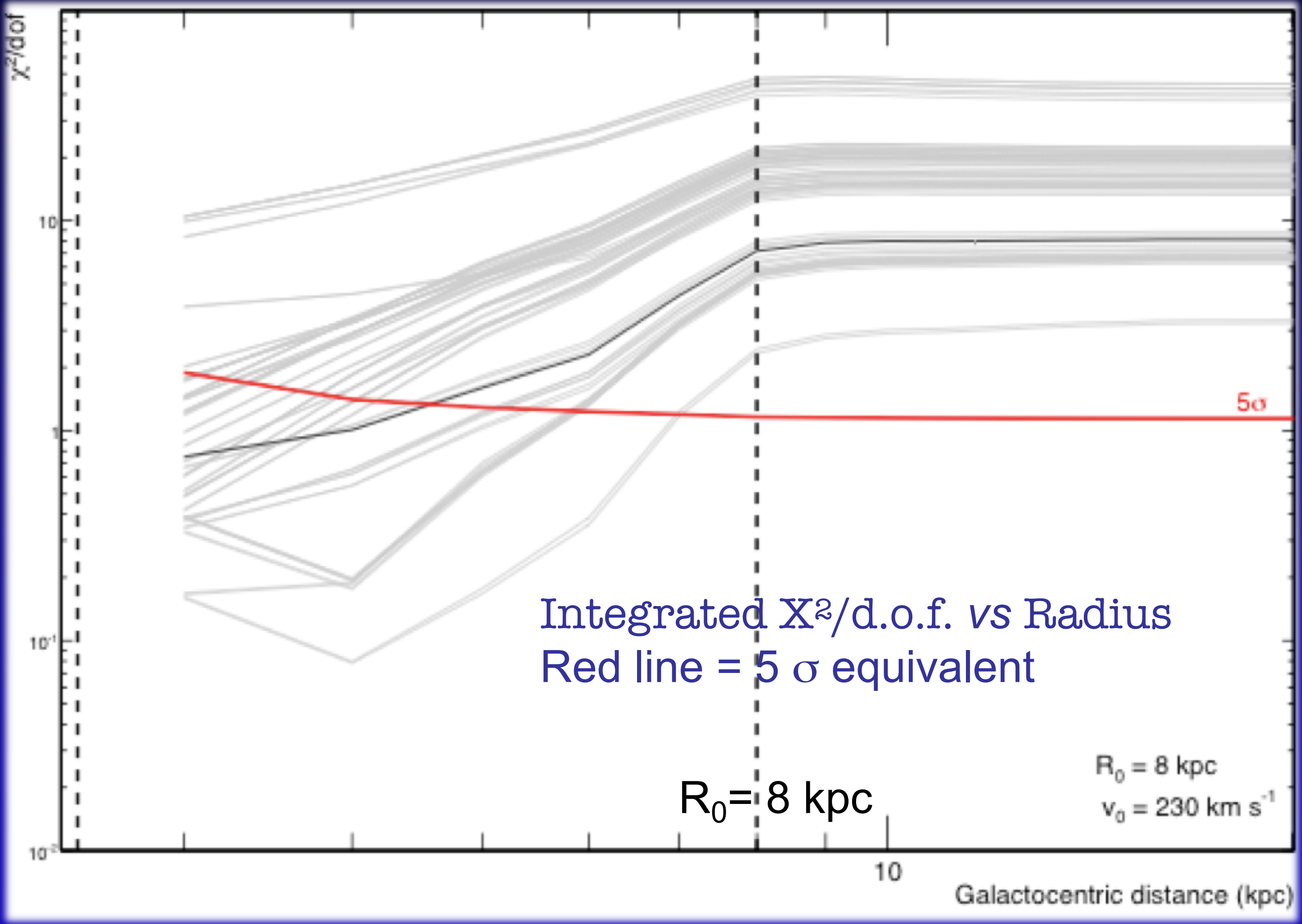
[Iocco, Pato, Bertone, Nature Physics 2015]

$\omega = V_c / R_c$

Uncorrelated uncertainties

R_0=8 kpc
V_0=230 km/s

Do the baryon-only curves fit with the observed RC?



Integrated X^2/d.o.f. *vs* Radius
Red line = 5 σ equivalent

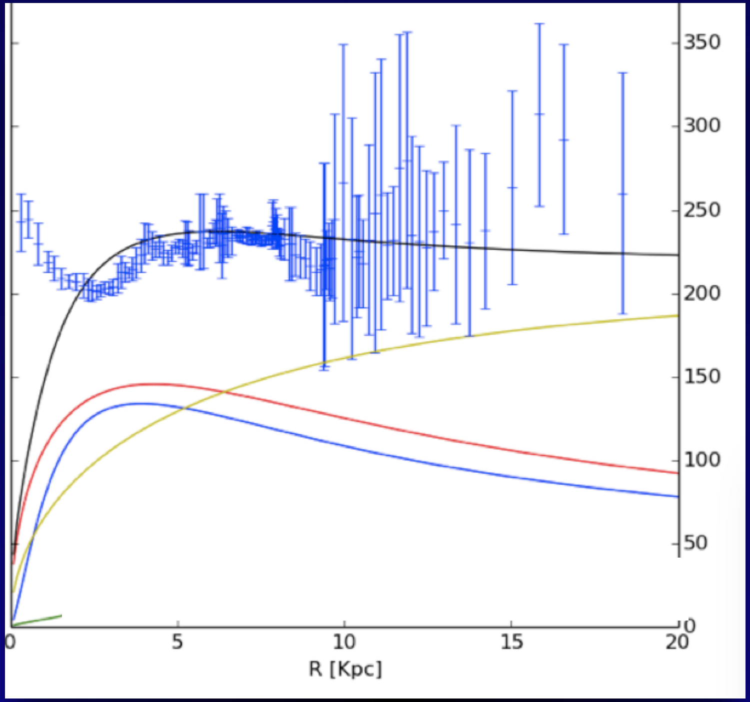
R_0= 8 kpc

Answer is NO:
Every single model above 5 σ, already at $R<R_0$!!

[Iocco, Pato, Bertone, Nature Physics 2015]

Inferring the DM density structure

Fitting a pre-assigned shape
on top of luminous

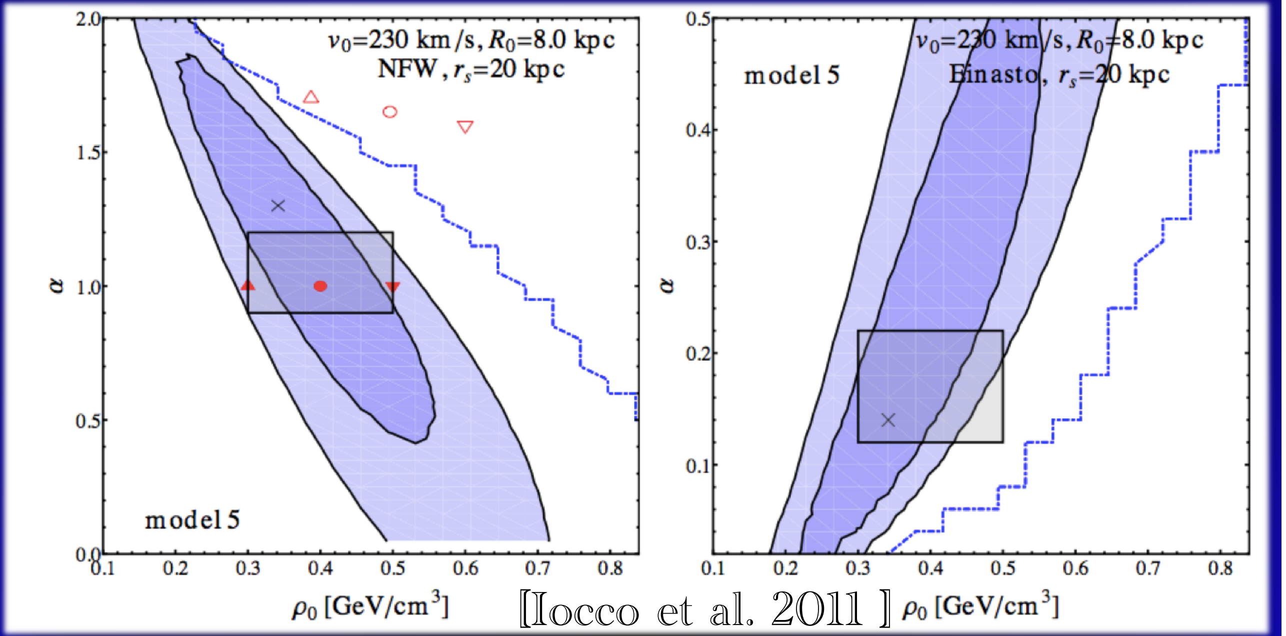


gNFW

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

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

Einasto

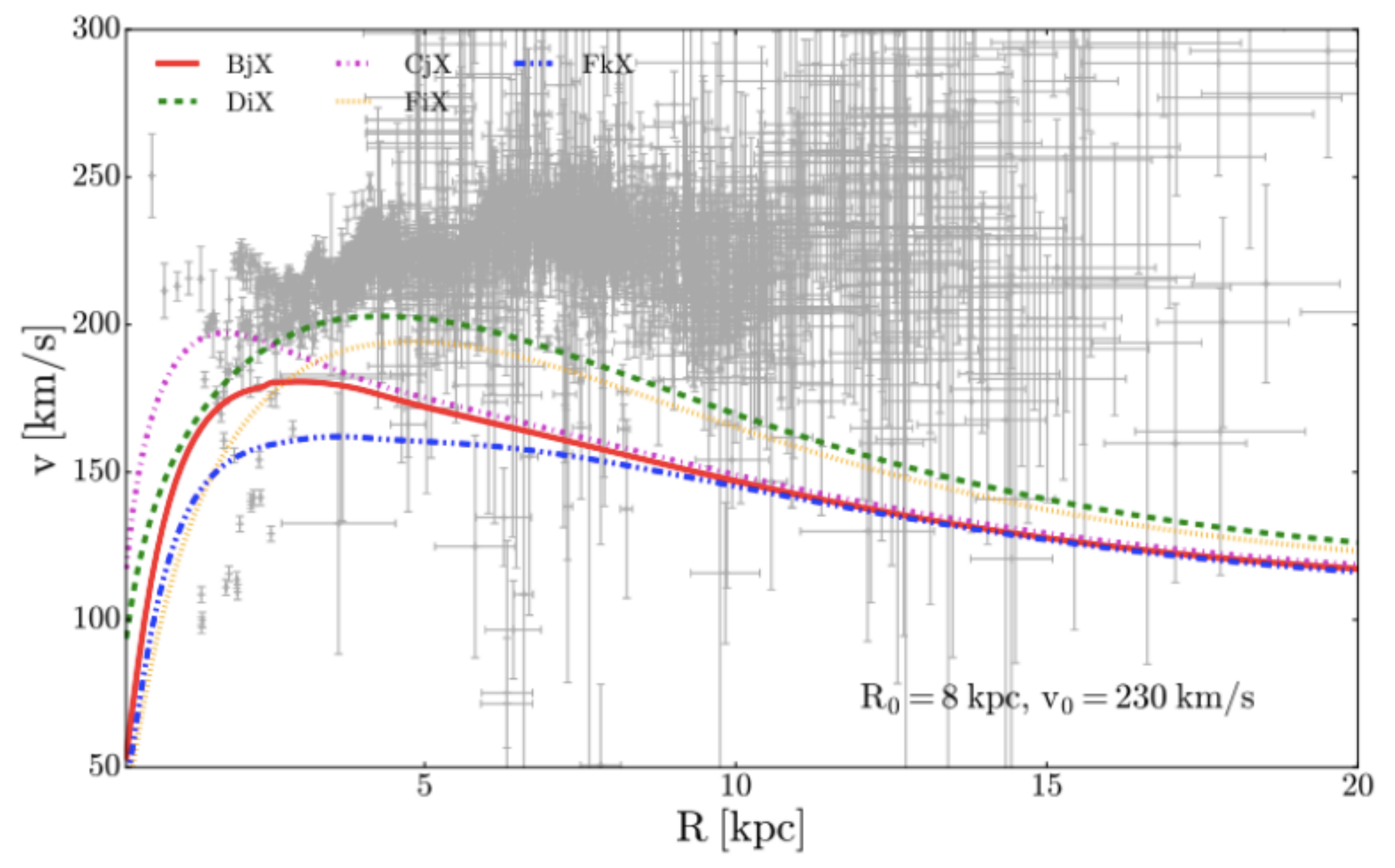


[Iocco et al. 2011]

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

Systematic uncertainties

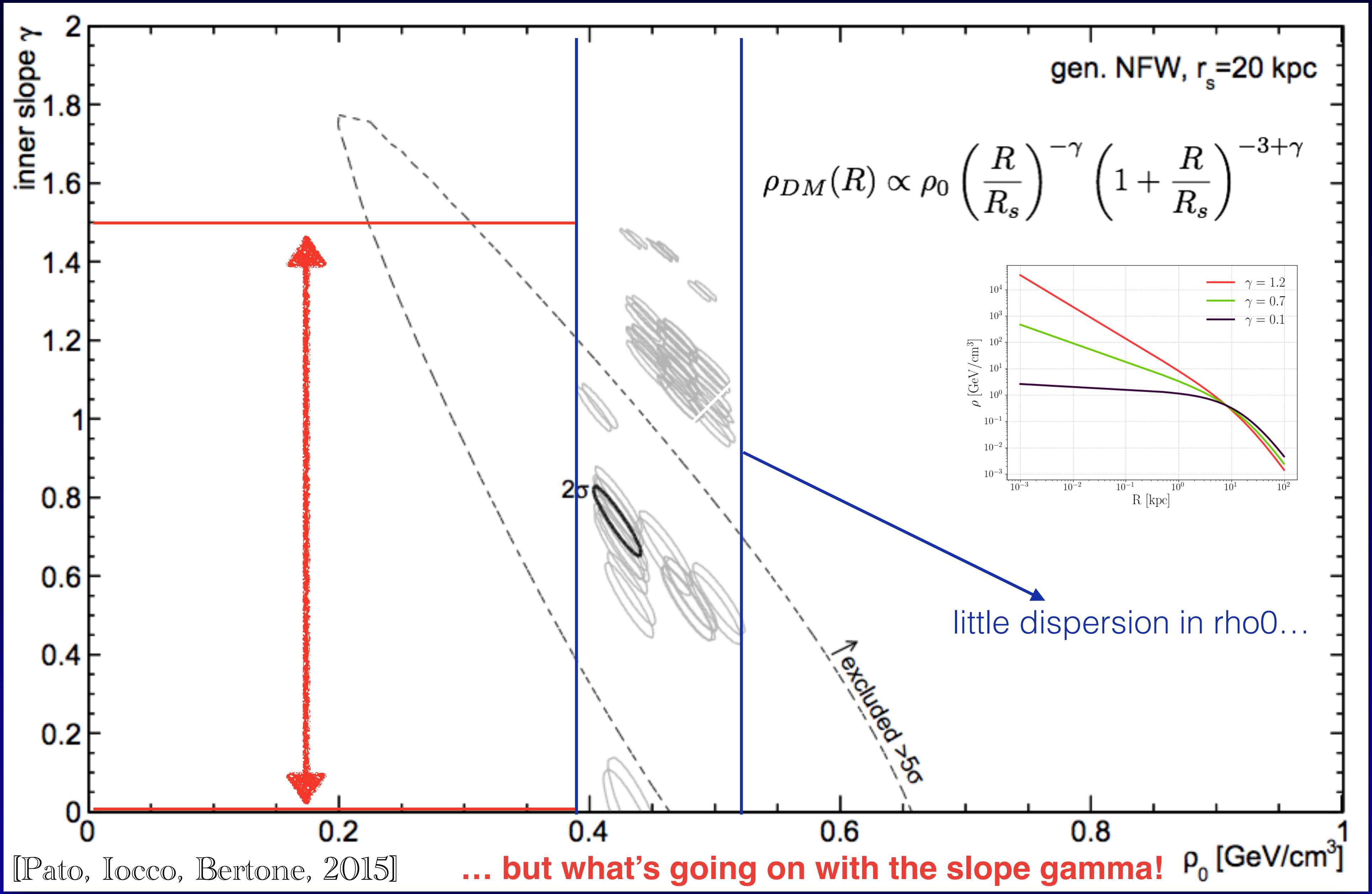
(luminous component)



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

[Iocco, Pato, Bertone, Nature Physics 2015]

Extracting the DM density structure



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

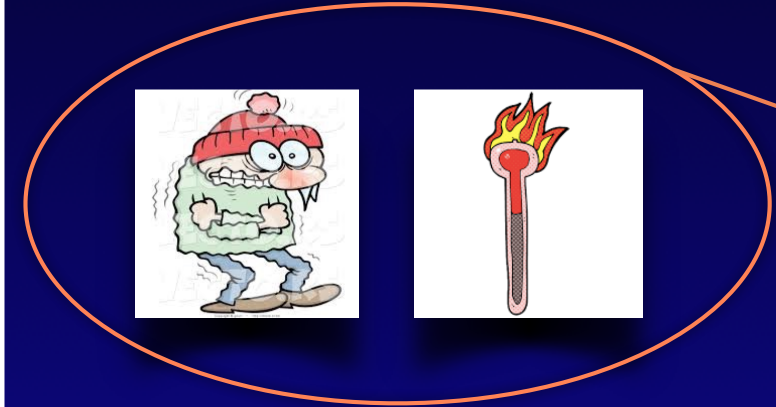
little dispersion in rho0…

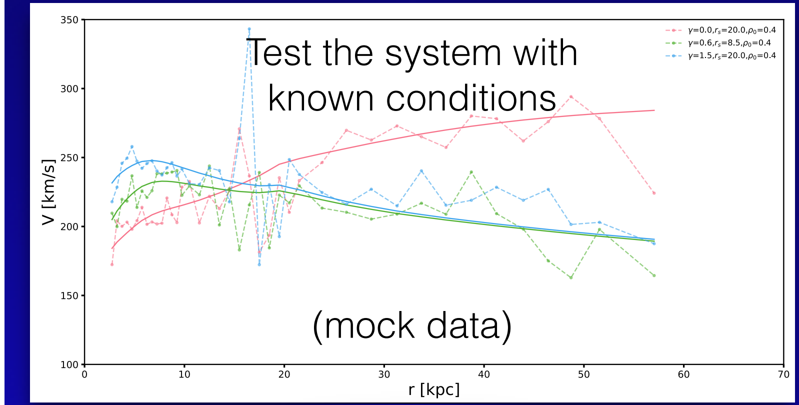
[Pato, Iocco, Bertone, 2015]

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

What to do of our measurement?

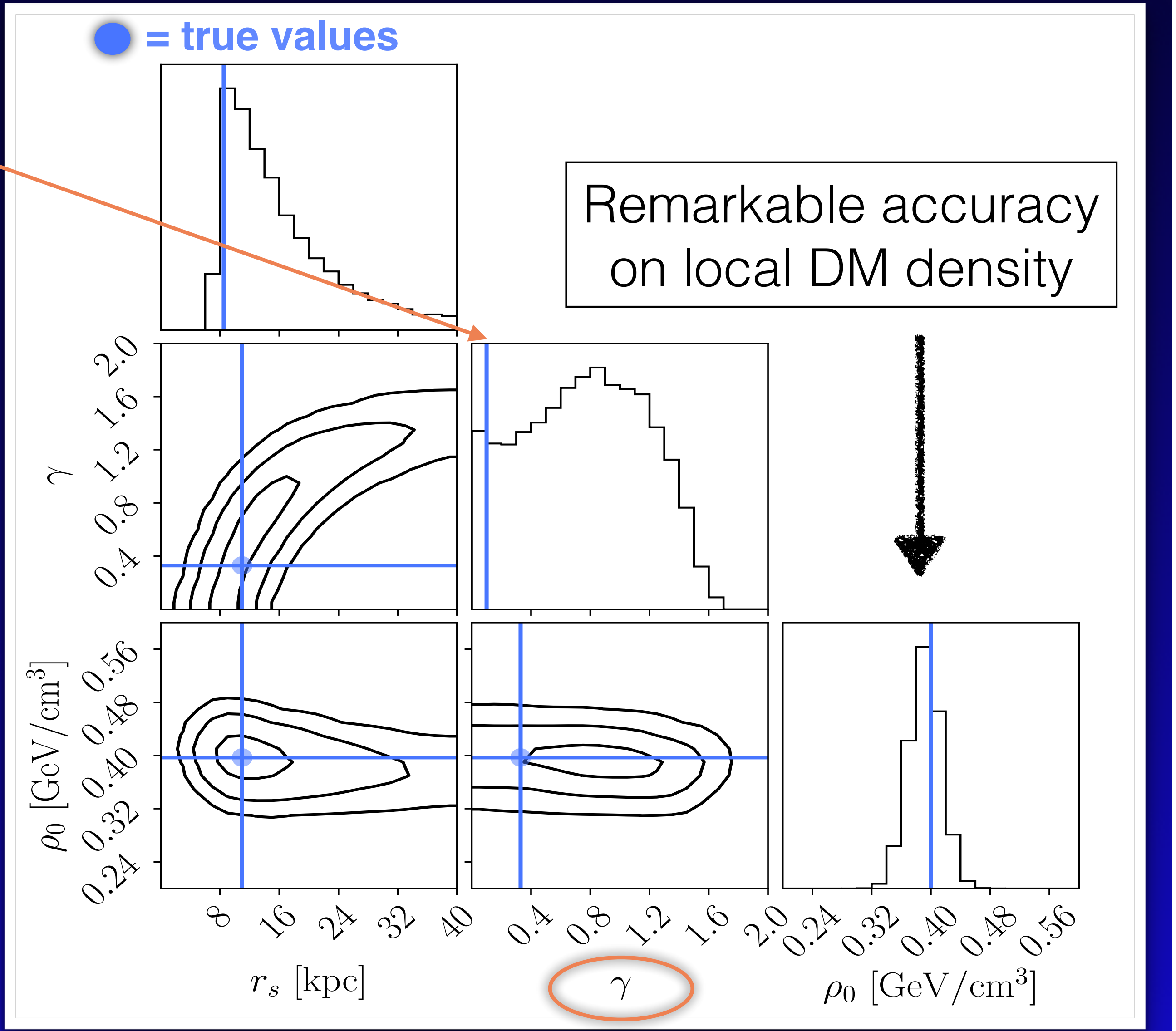
(Our instrument is very precise. Is it accurate?)





Test the system with known conditions

(mock data)



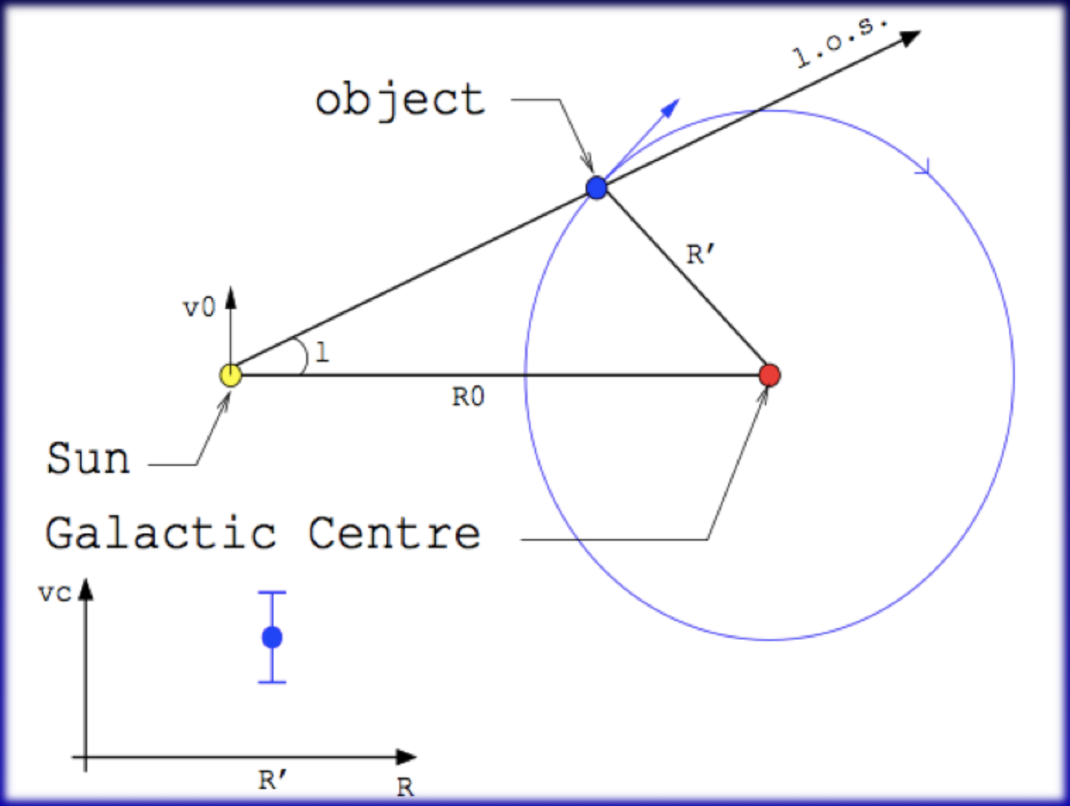
Remarkable accuracy on local DM density

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

The Milky Way:

observed rotation curve

Neglecting some quite remarkable uncertainties (for now)



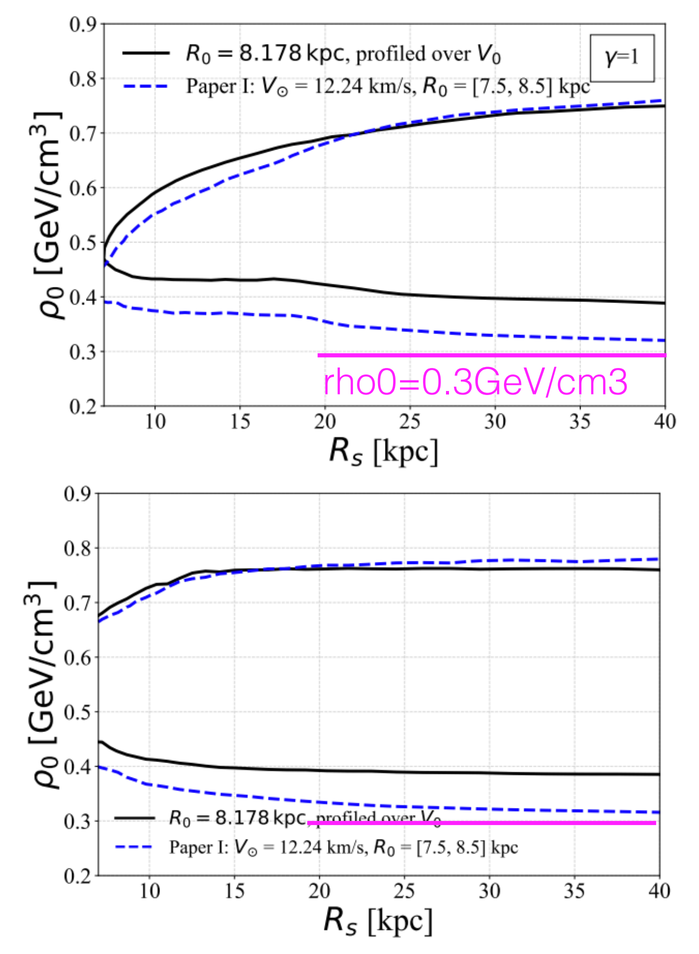
$$v_{\mathrm{LSR}}^{\mathrm{l.o.s.}} = \left(\frac{v_c(R')}{R'/R_0} - v_0 \right) \cos b \sin \ell$$

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

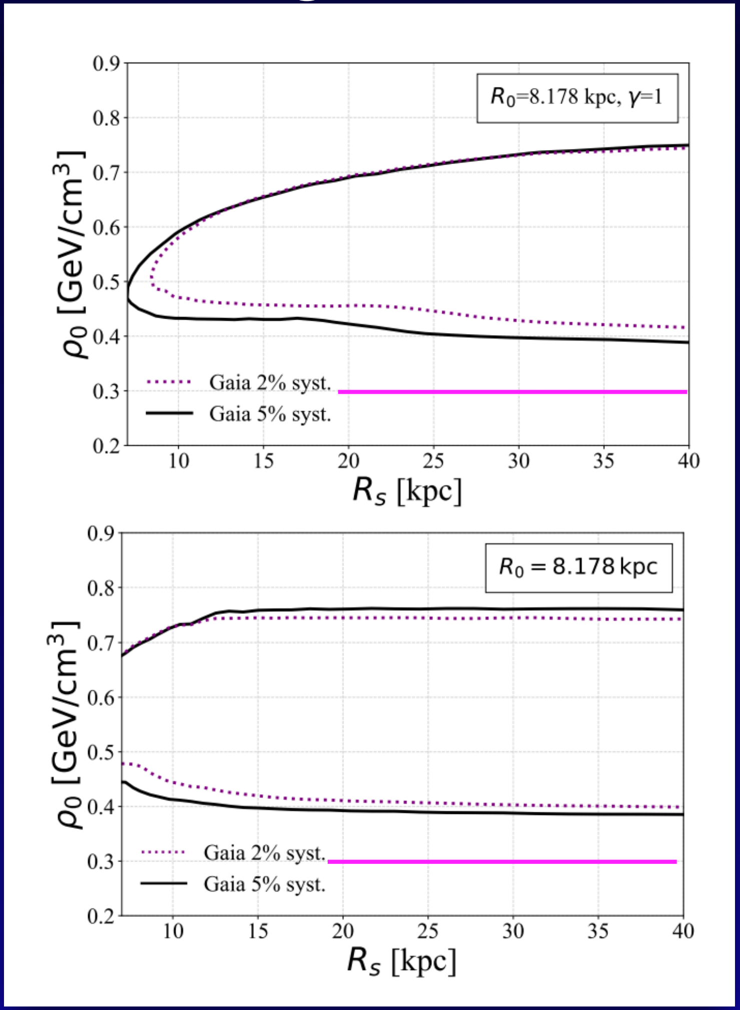
Uncertainties on (R0,v0) ultimately affects our determination of (rho0, gamma)

Profiling over Galactic uncertainties

Testing approaches



Testing datasets



Please use the full likelihood:
publicly available!!

https://github.com/mariabenitocst/UncertaintiesDMinTheMW

[Benito, Iocco, Cuoco, PDU 2021, arXiV:2009.13523]

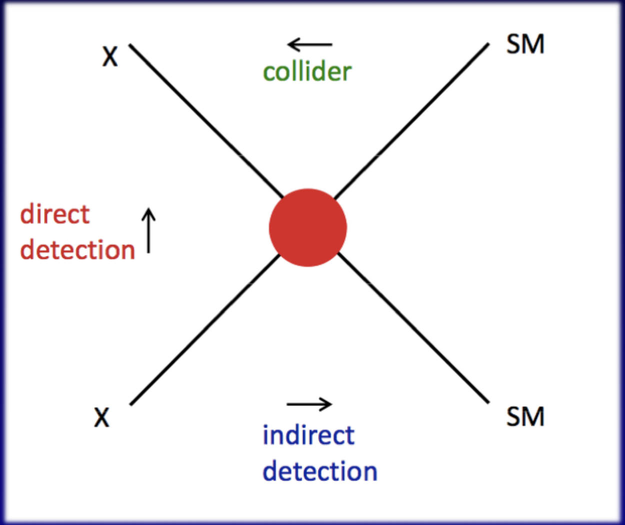
Direct and indirect searches of WIMP DM

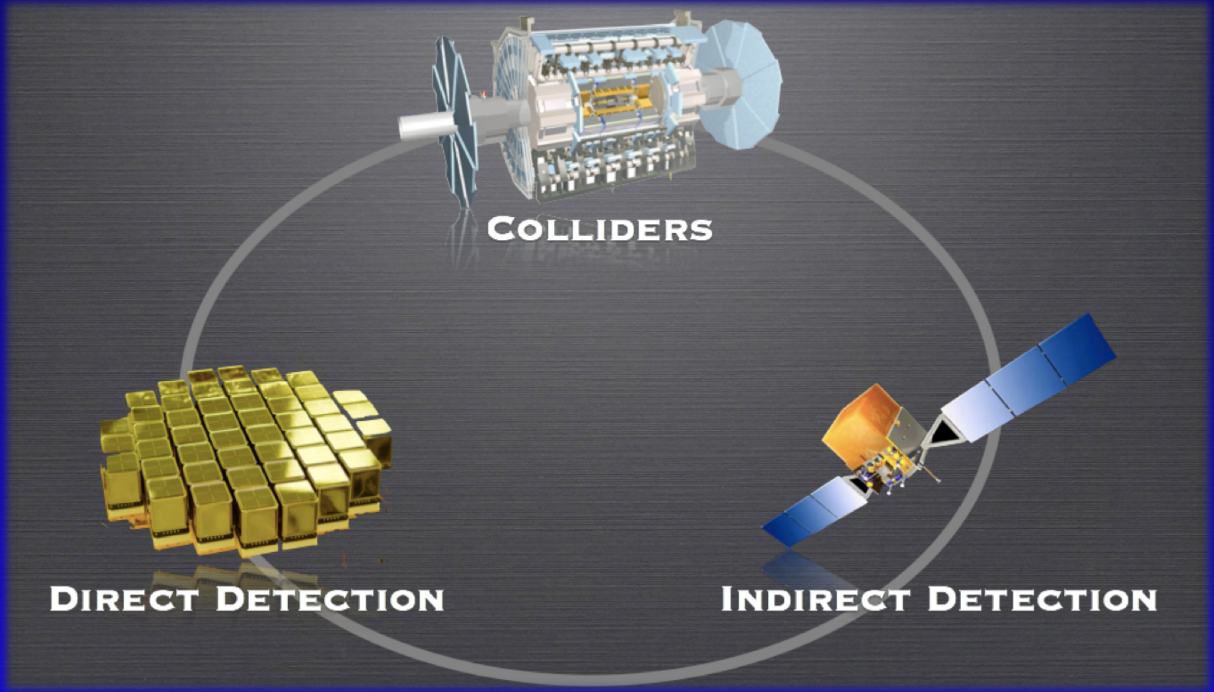
complementary to colliders

Direct detection:
DM scattering against nuclei, recoil

Indirect detection:
Annihilation in astrophysical envir.
Observation of SM products of annih.

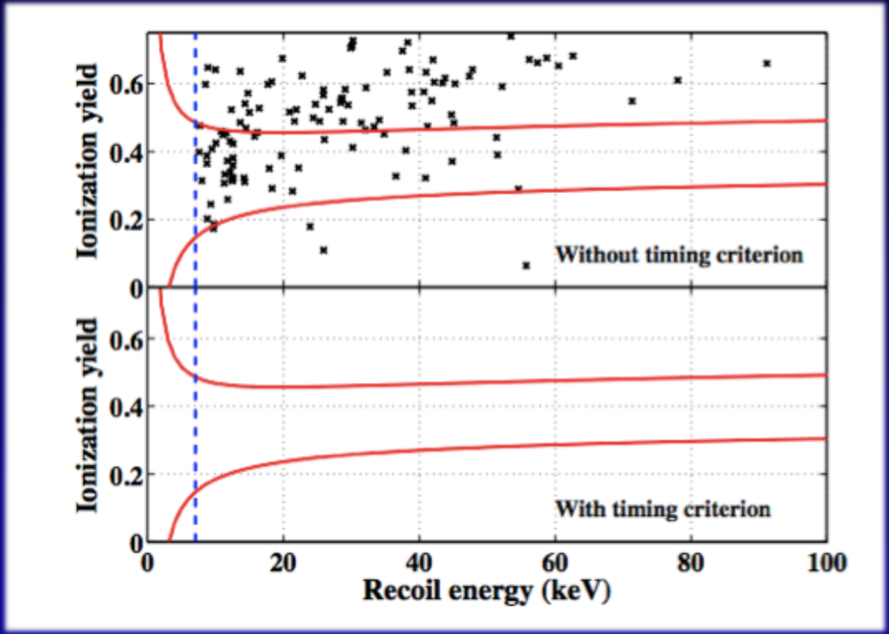
Production at LHC

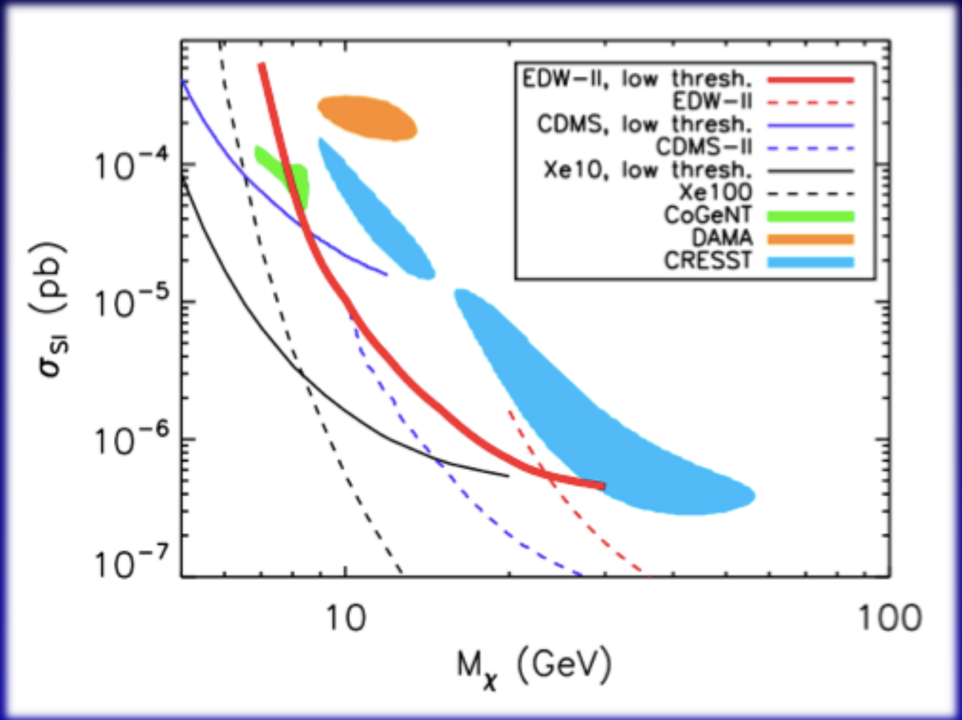




Direct Detection: principles and dependencies (to go…)

from this → to this

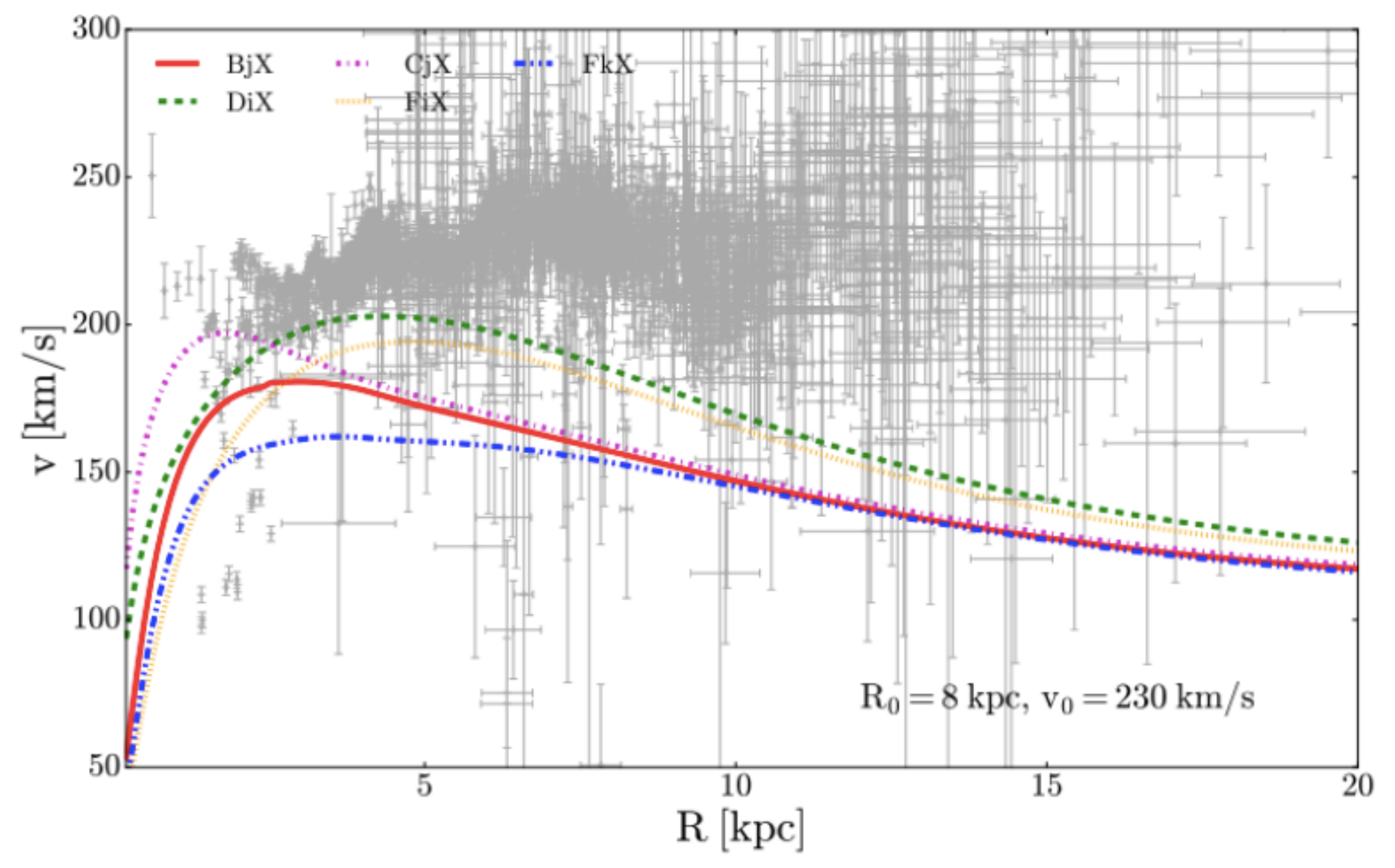




you need this

$$\frac{dR}{dE} \propto \frac{1}{\mu^2}\frac{\sigma_\chi}{m_\chi}\rho_0\eta(v,t)$$

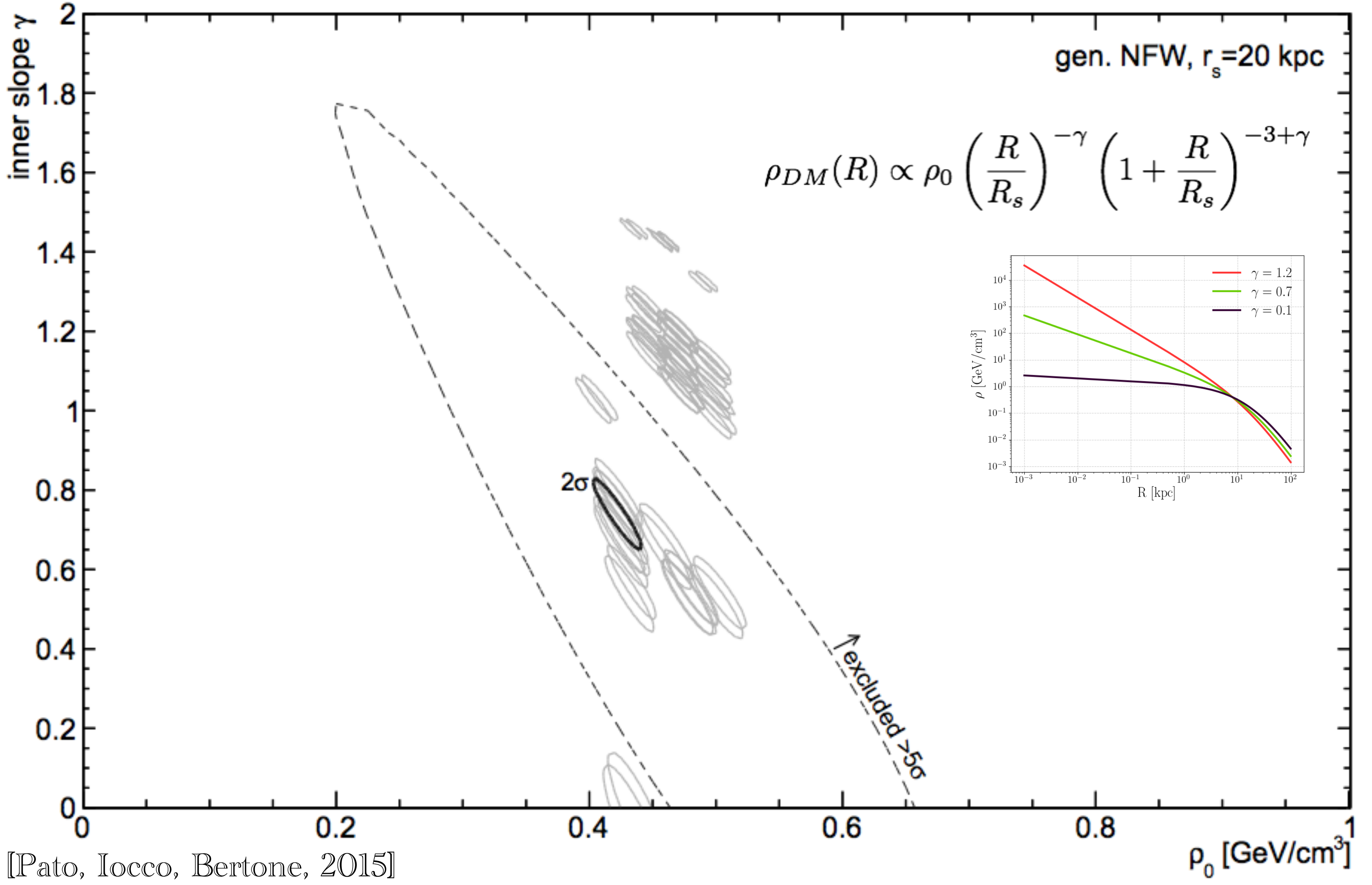
Systematic uncertainties
(luminous component)



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

[Iocco, Pato, Bertone, Nature Physics 2015]

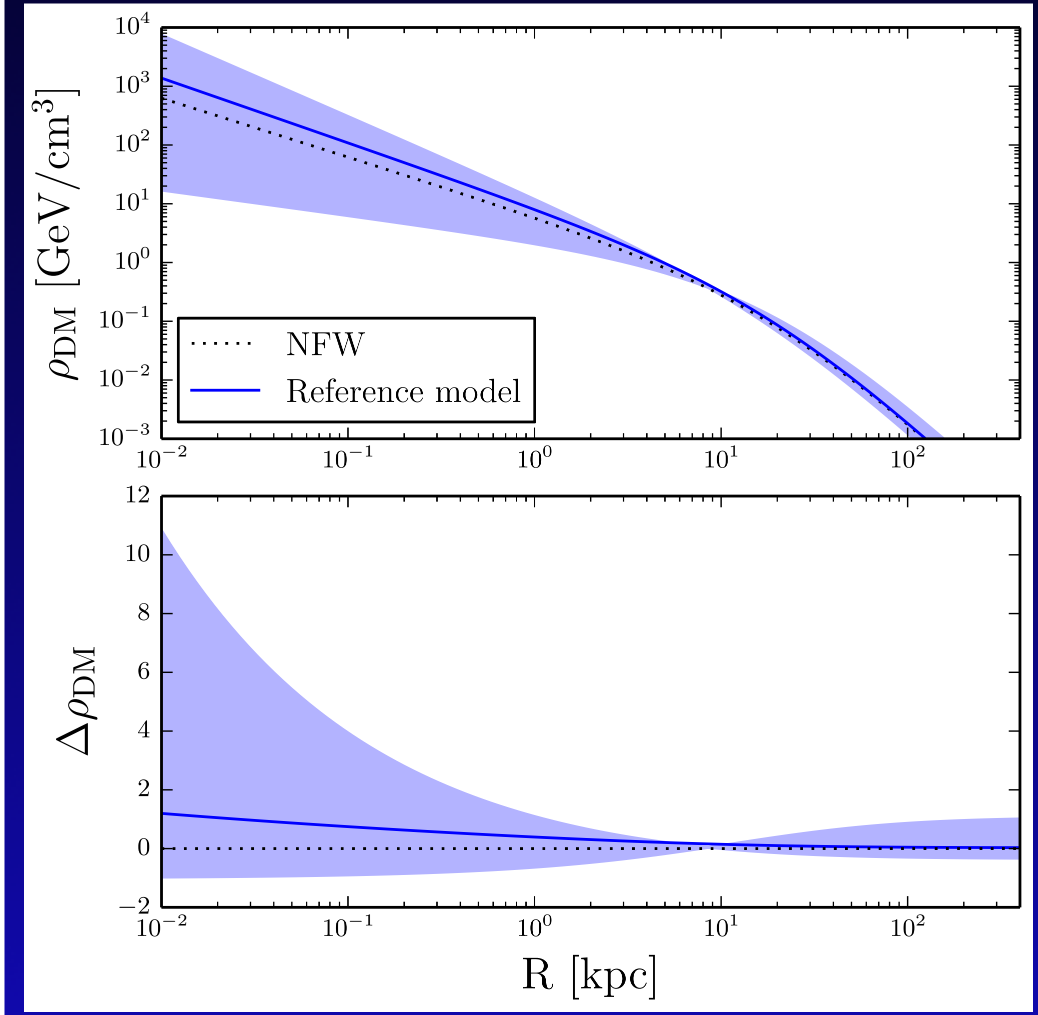
Extracting the DM density structure

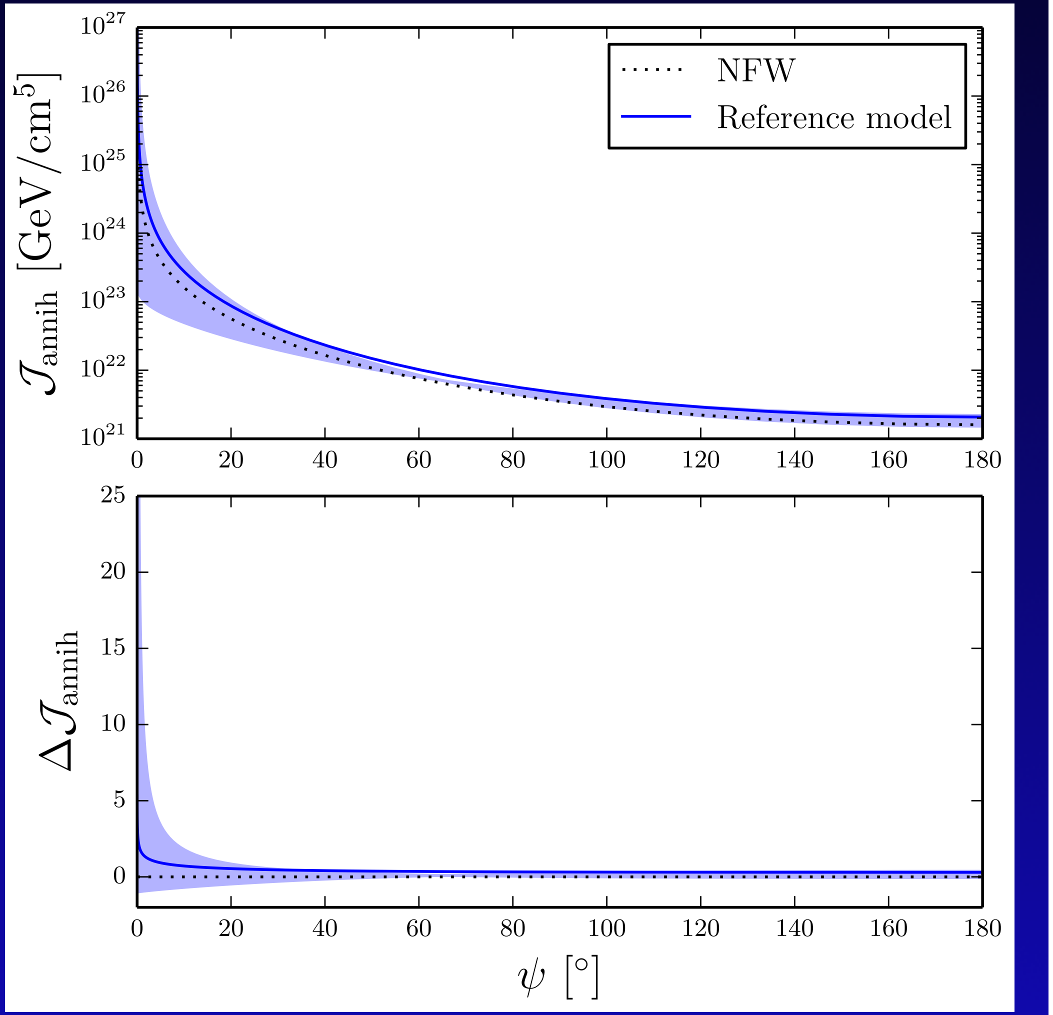


$$\rho_{DM}(R) \propto \rho_0 \left(\frac{R}{R_s}\right)^{-\gamma} \left(1+\frac{R}{R_s}\right)^{-3+\gamma}$$

[Pato, Iocco, Bertone, 2015]

But do Galactic uncertainties affect PP, for real?

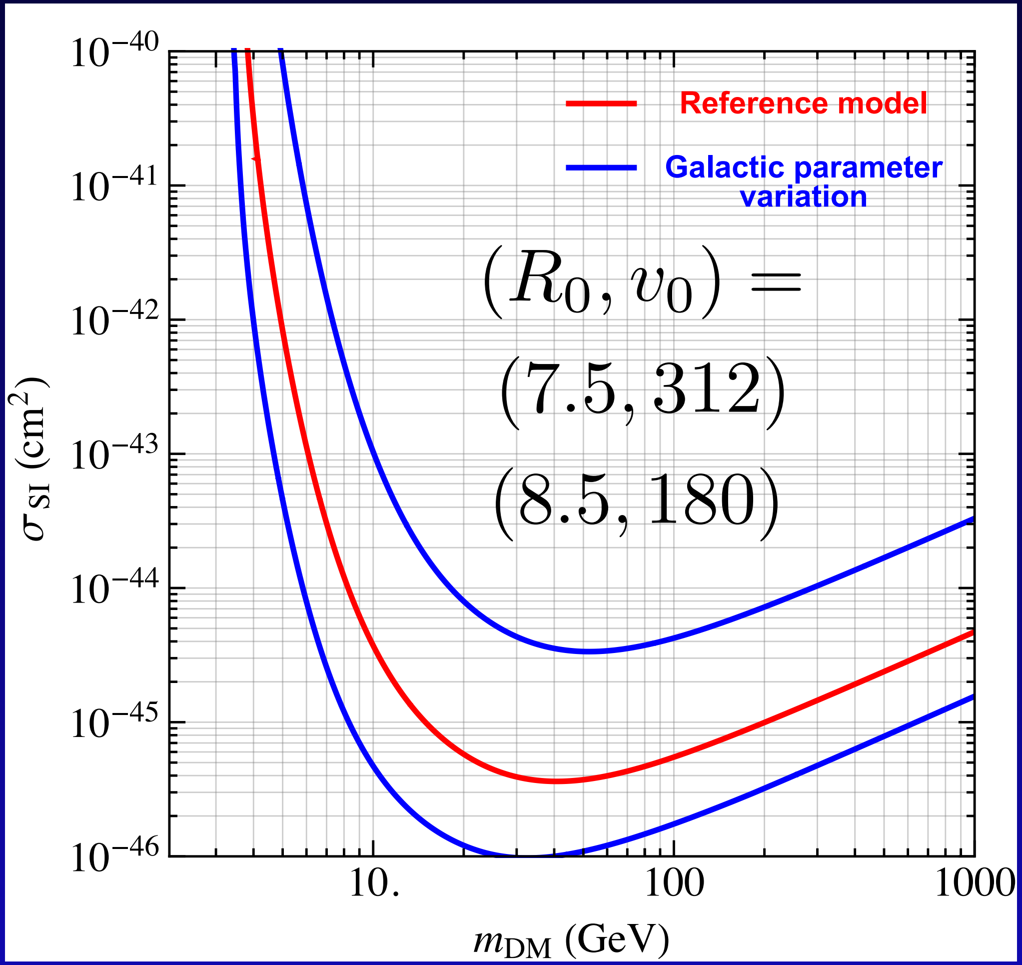




$$J_{annih} \propto \int_{los} \rho^2(r)\, dV$$

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

It is well known that uncertainties affect Direct Detection



2015 LUX limits, varying astrophysical uncertainties

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

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

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

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

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

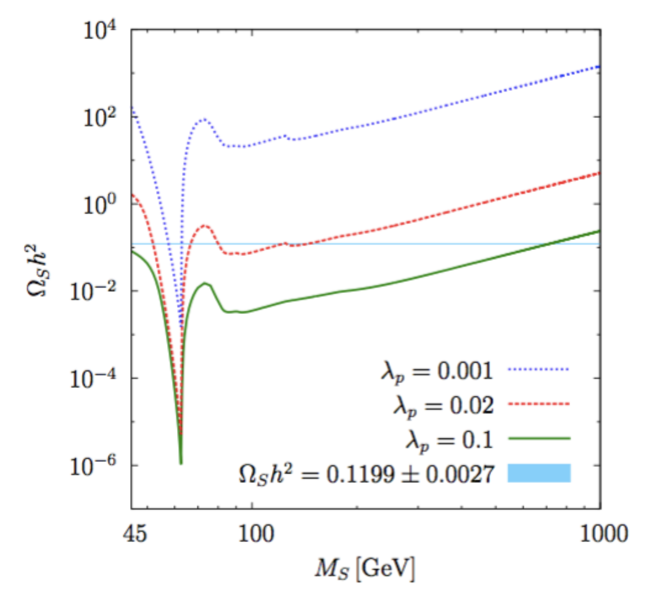
"WIMP phenomenology" entirely dictated by the Higgs coupling and physical DM mass.

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

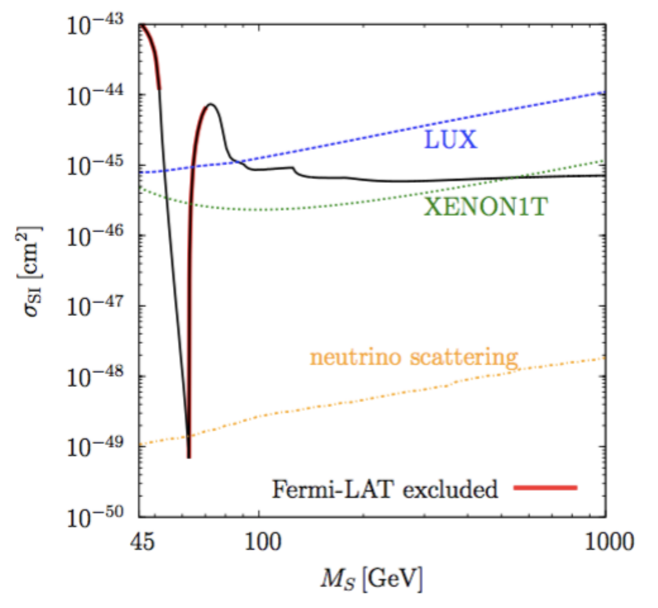
Singlet Scalar DM

Constraints and interplay of experiments

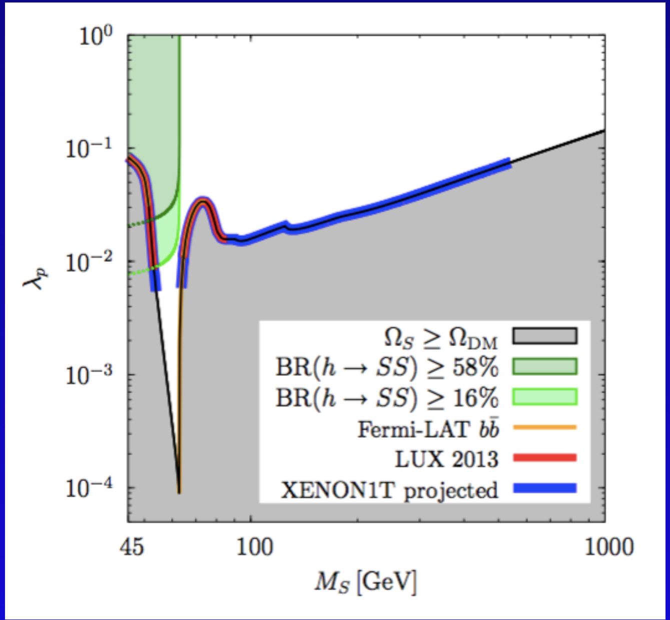
Relic density



Direct detection



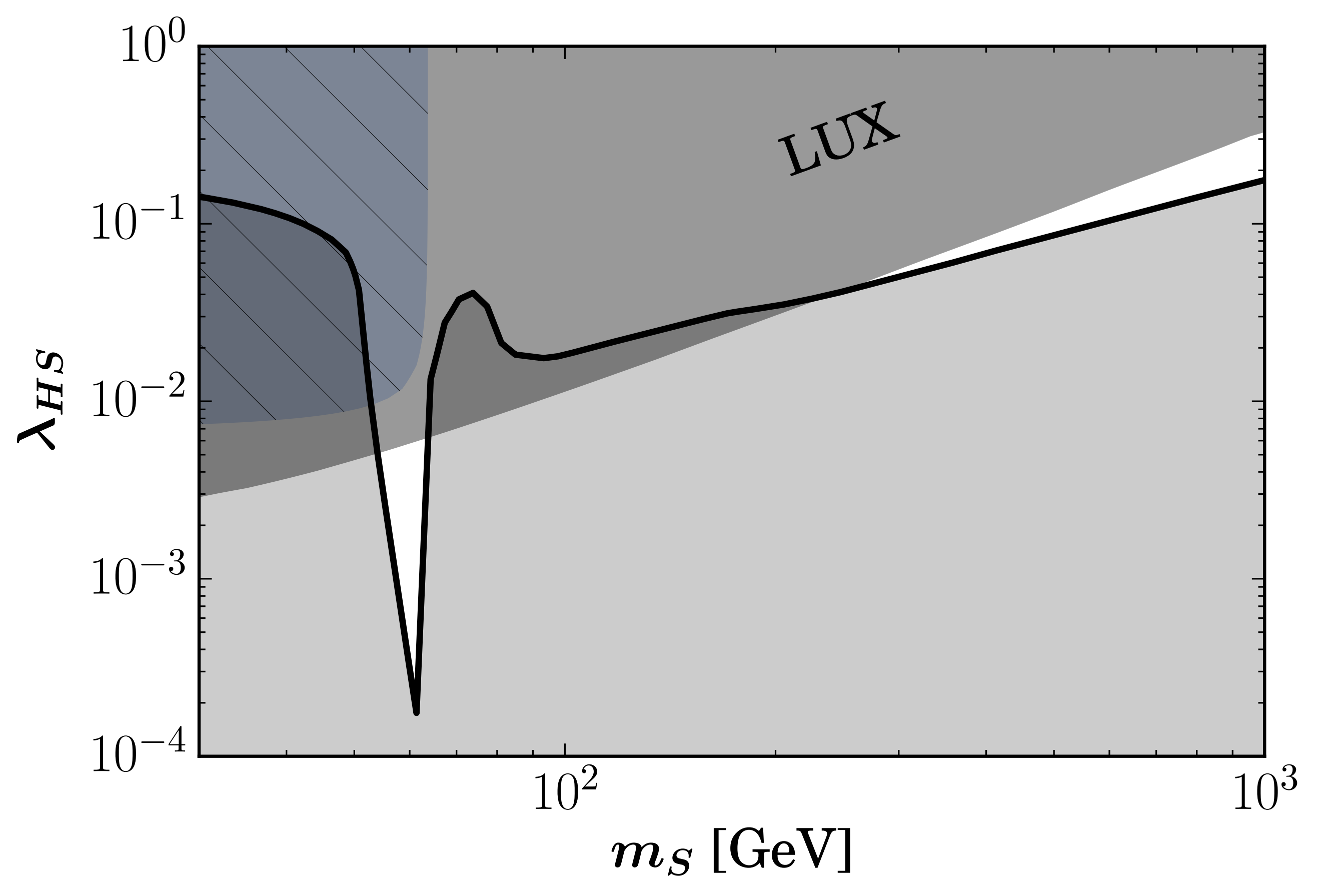
Combined



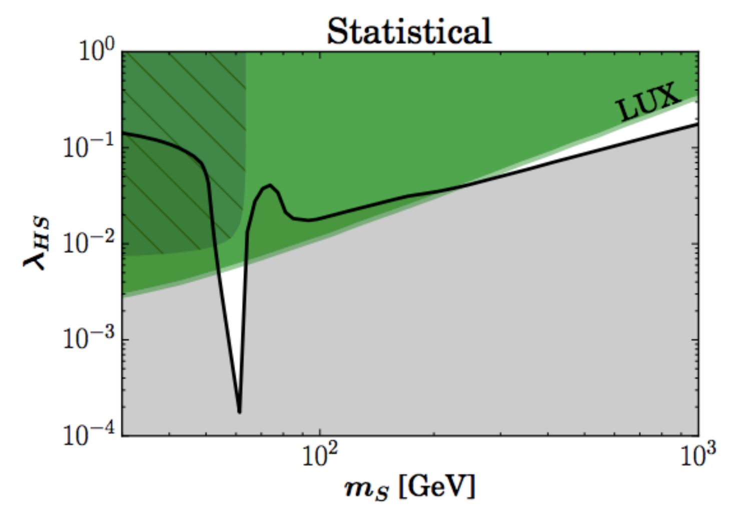
[Duerr et al, 2015]

Singlet Scalar DM
Constraints and interplay of experiments

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

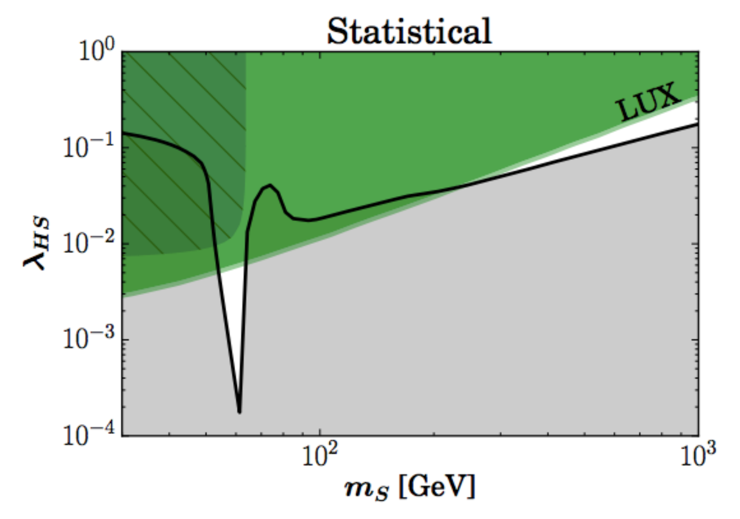


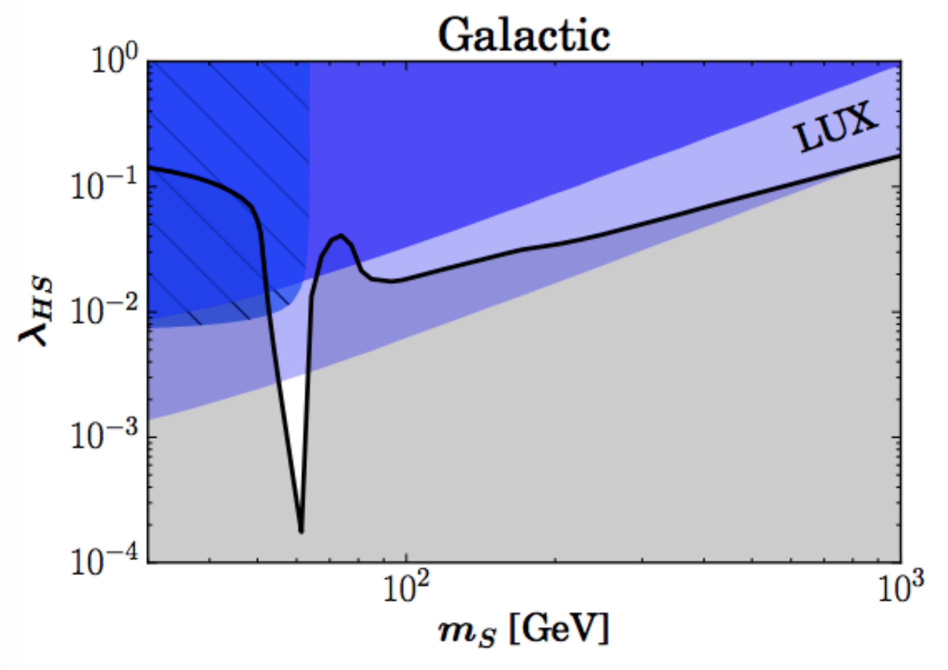
Let's look at the effect of astrophysics uncertainties: Direct Detection

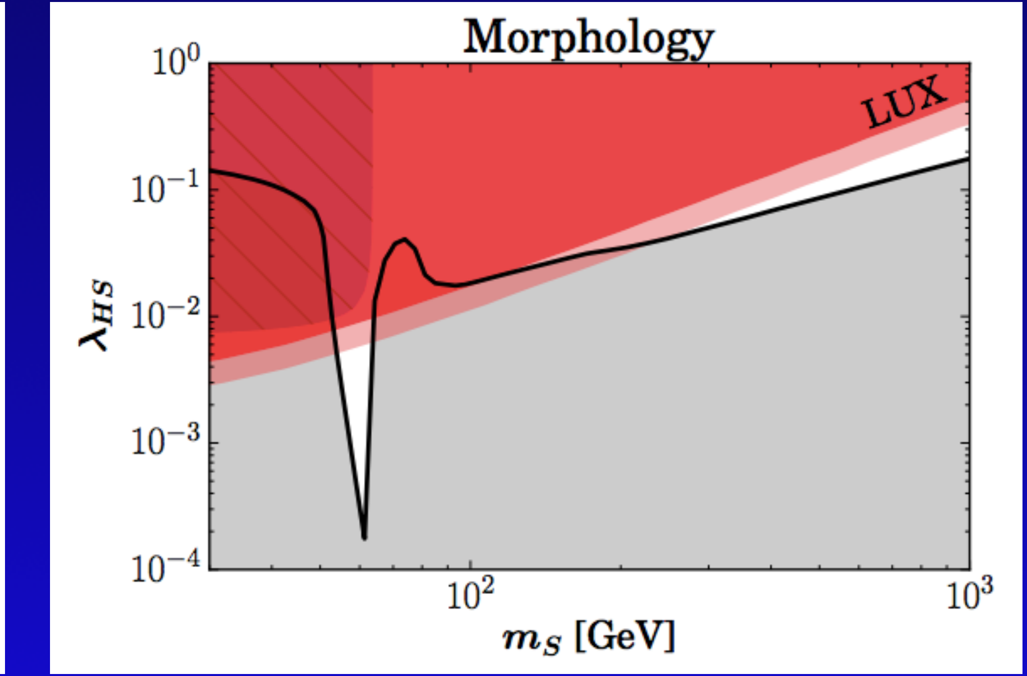


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

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

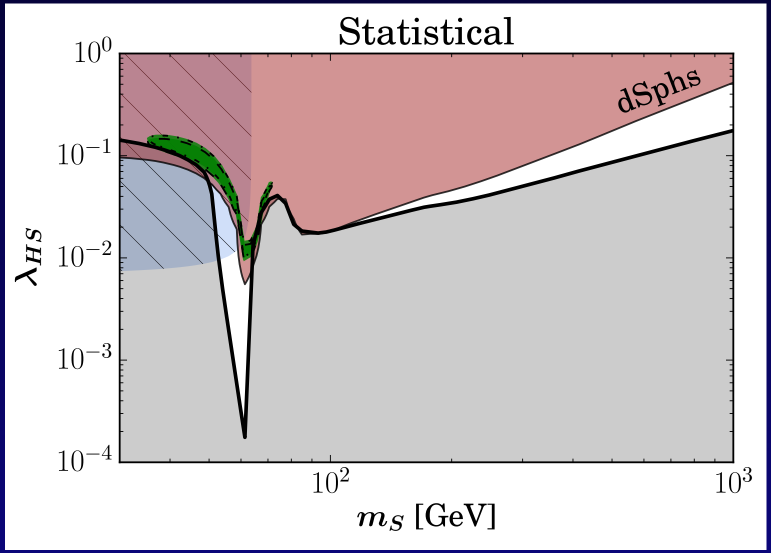


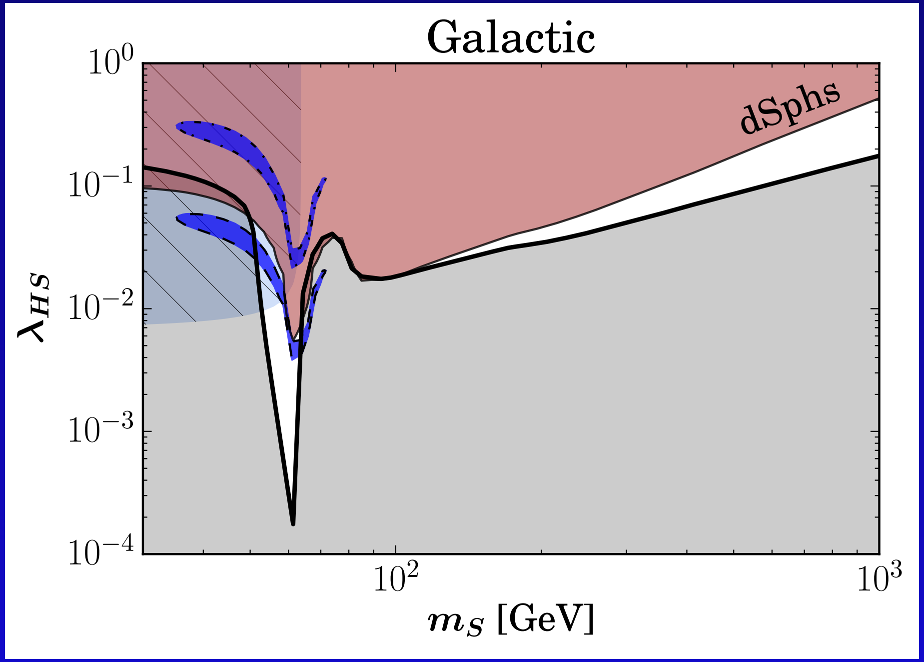


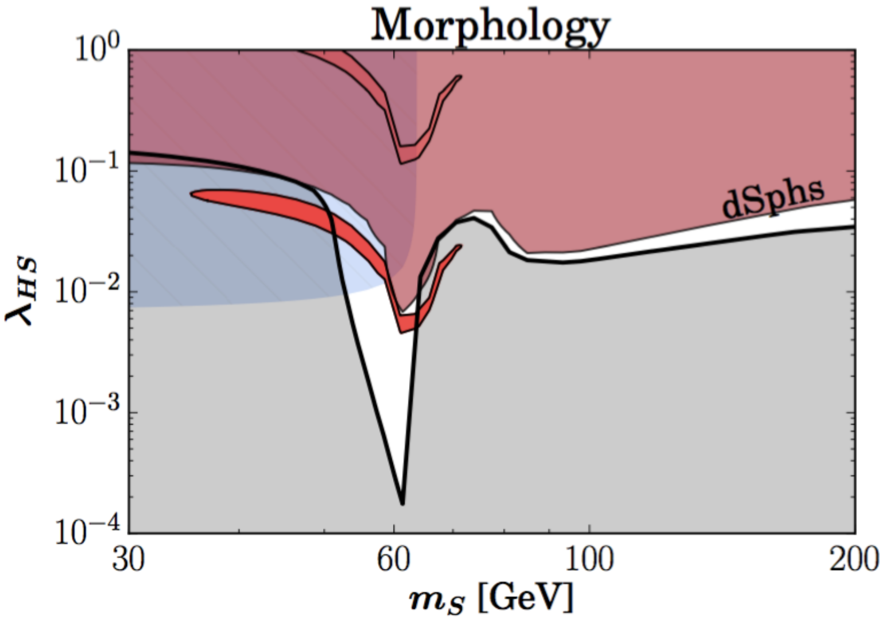


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

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

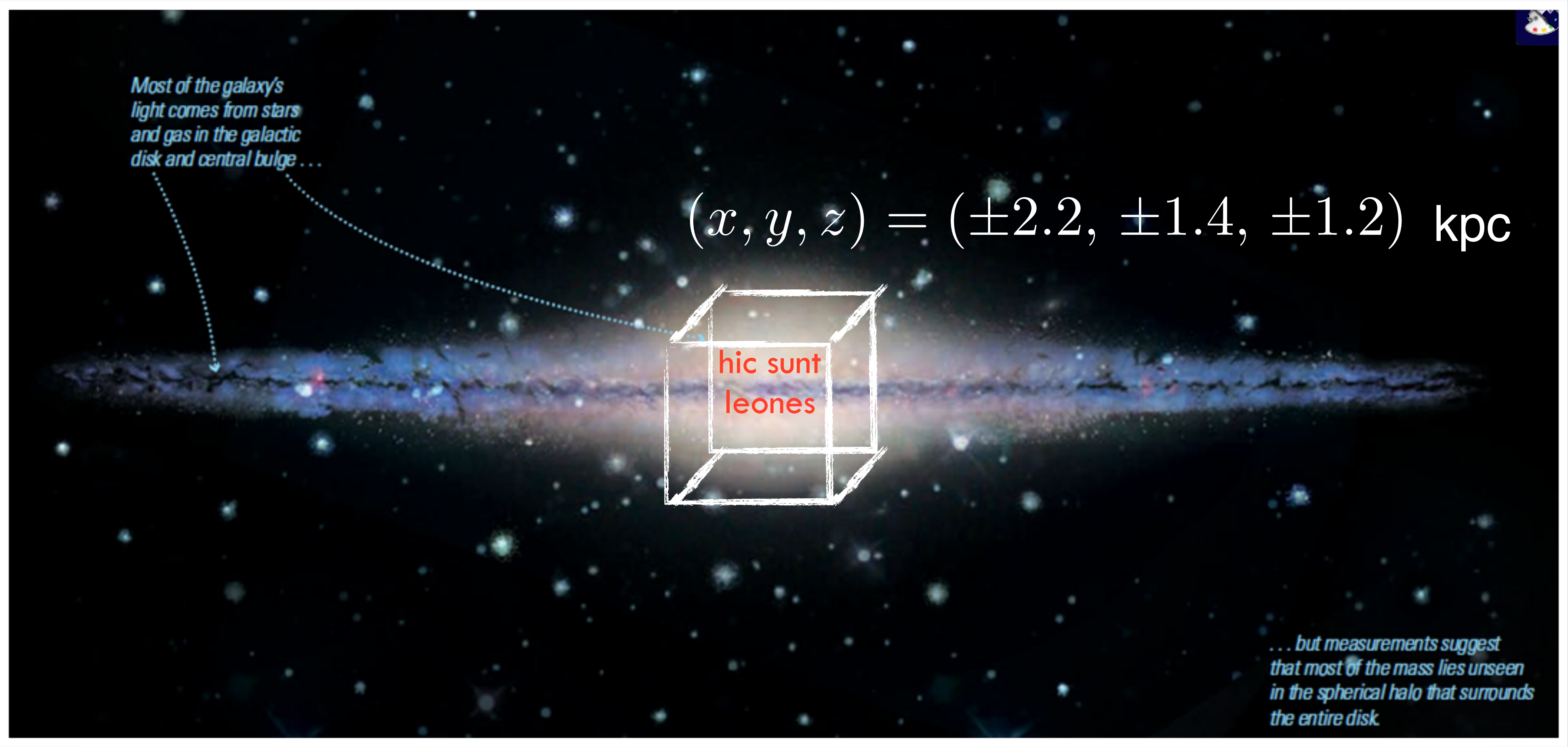






[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

Galactic Center: a beast of its own



Most of the galaxy's light comes from stars and gas in the galactic disk and central bulge . . .

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

. . . but measurements suggest that most of the mass lies unseen in the spherical halo that surrounds the entire disk.

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

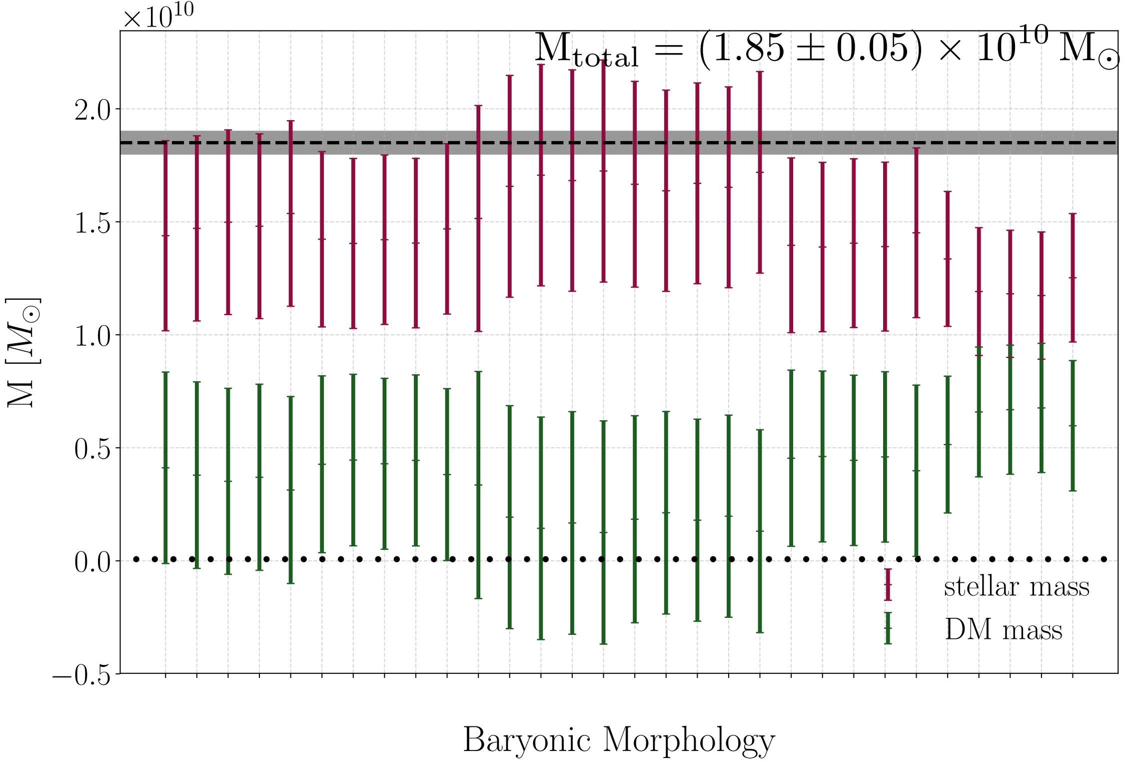
$$\mathrm{M_{total}} - \mathrm{M}_*^{\mathrm{i}} = \mathrm{M}_{\mathrm{DM}}^{\mathrm{i}}$$

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

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

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

DM mass corresponds to 7-37%



[Iocco & Benito, PDU 2017] arXiv:1611.09861

(+ M. Benito's thesis)

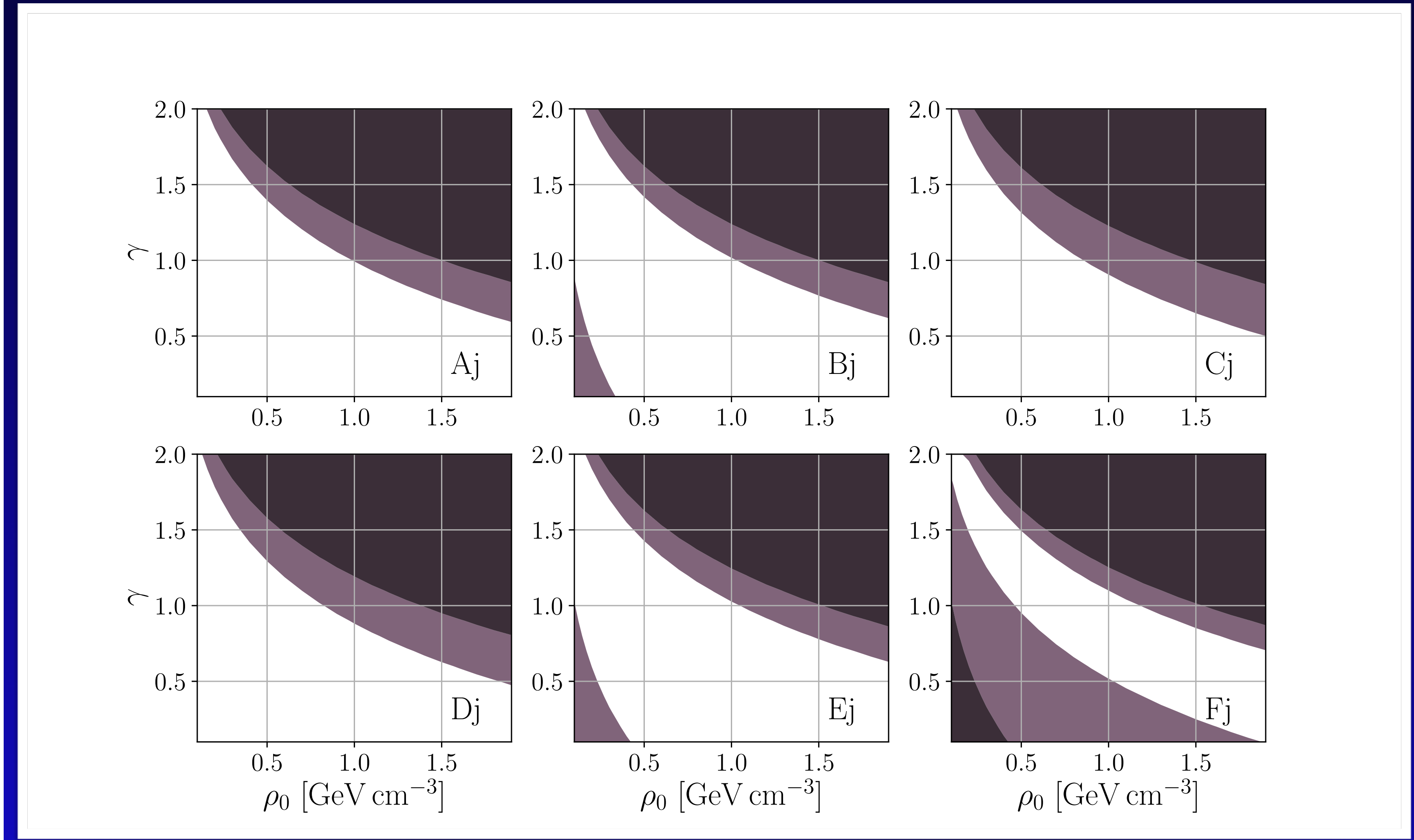
gNFW density profile

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

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



☐ Allowed at 1σ

▨ Allowed at 2σ

■ Excluded at 2σ

[Iocco & Benito, 2017] arXiv:1611.09861

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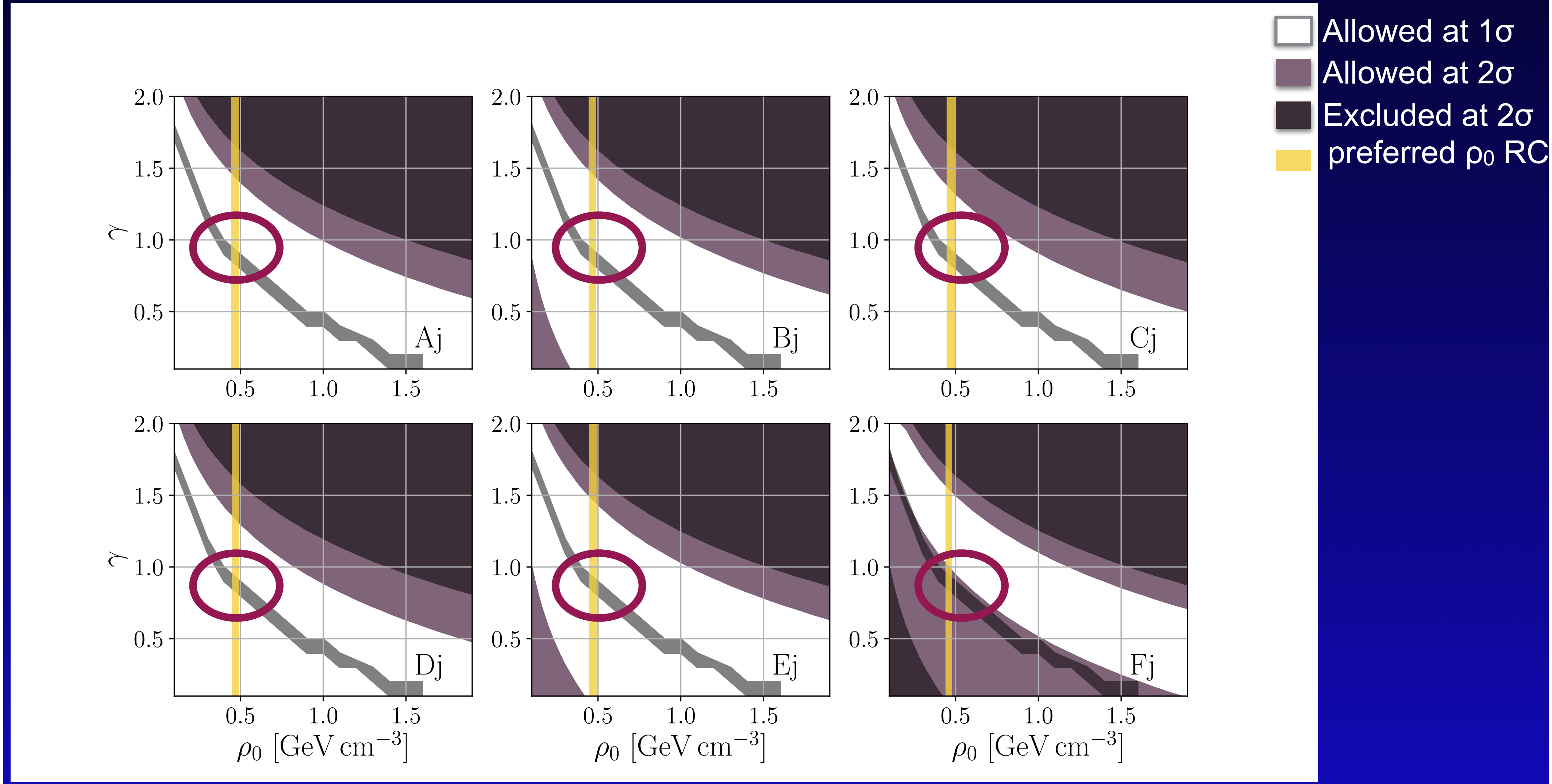
Galactic Bulge Region and RC curve compatibility



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

"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)

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