Determining the distribution of Dark Matter in the Milky Way

Fabio Iocco

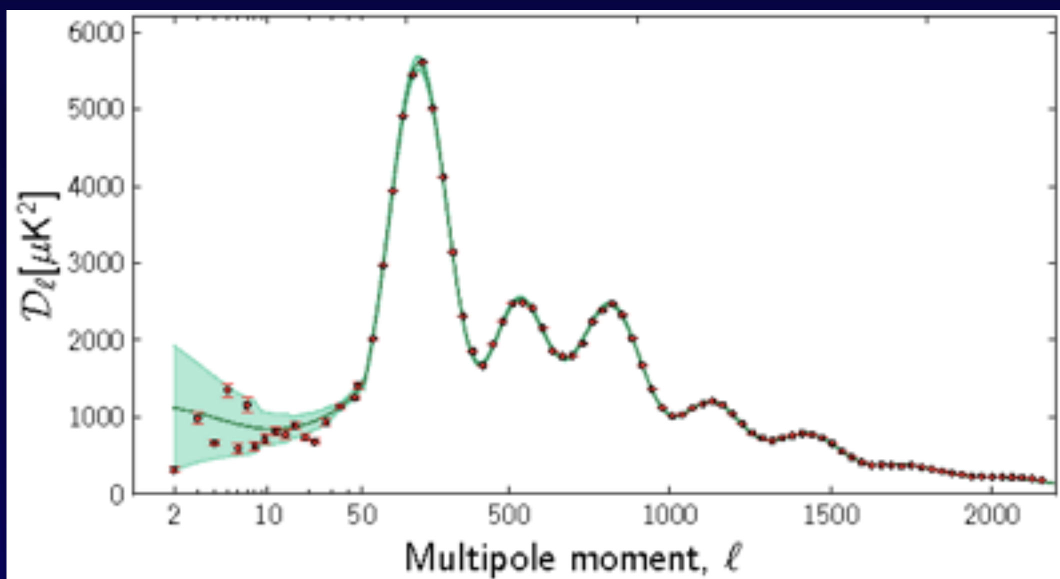
ICTP-SAIFR
IFT-UNESP
São Paulo

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

FAPESP-JSPS meeting
18/2/2019, São Paulo

Dark Matter

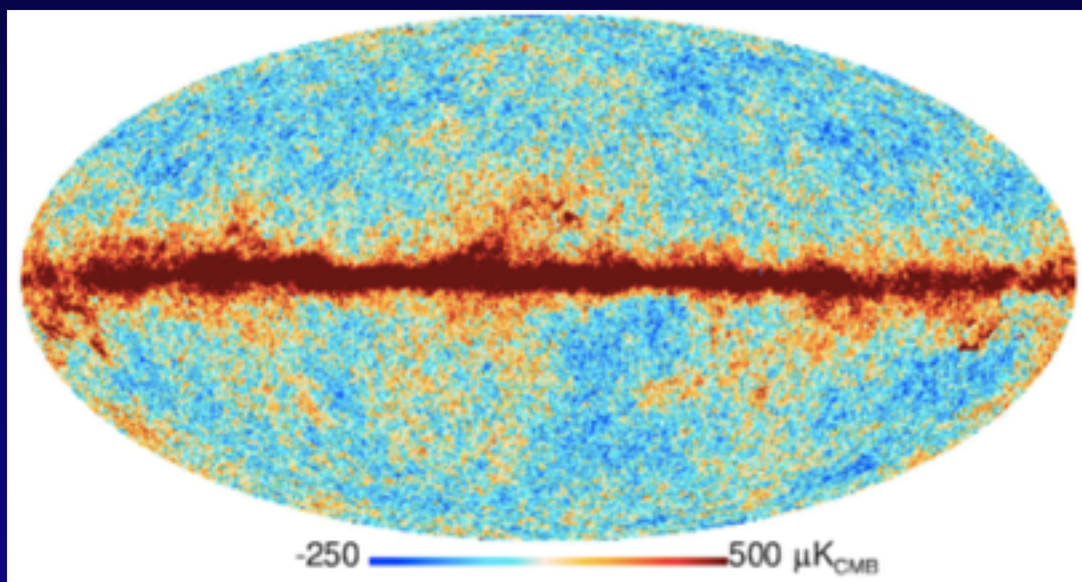
Evidence over large range of scales

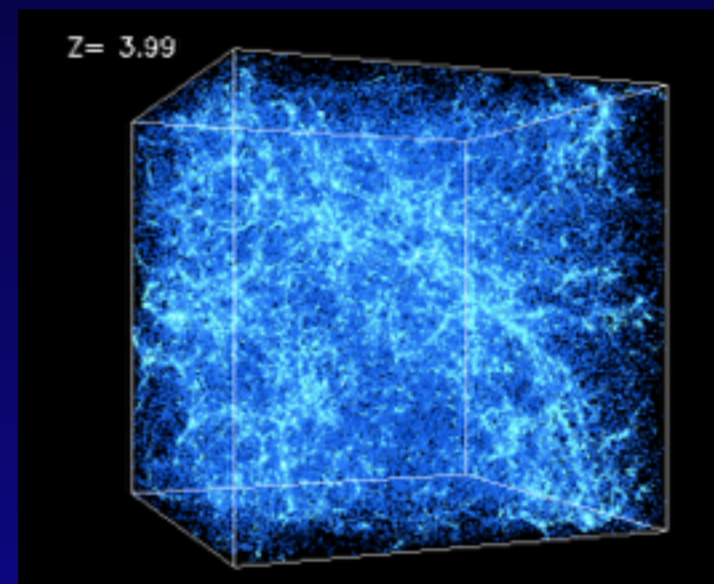


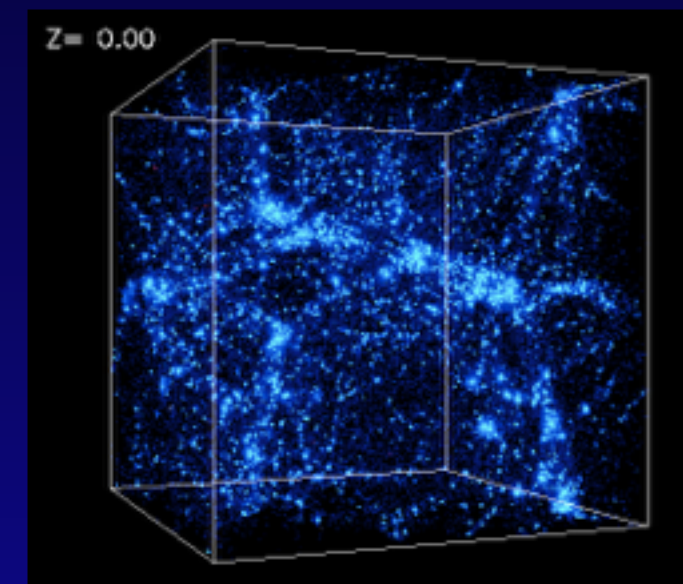
NATURE STILL UNKNOWN

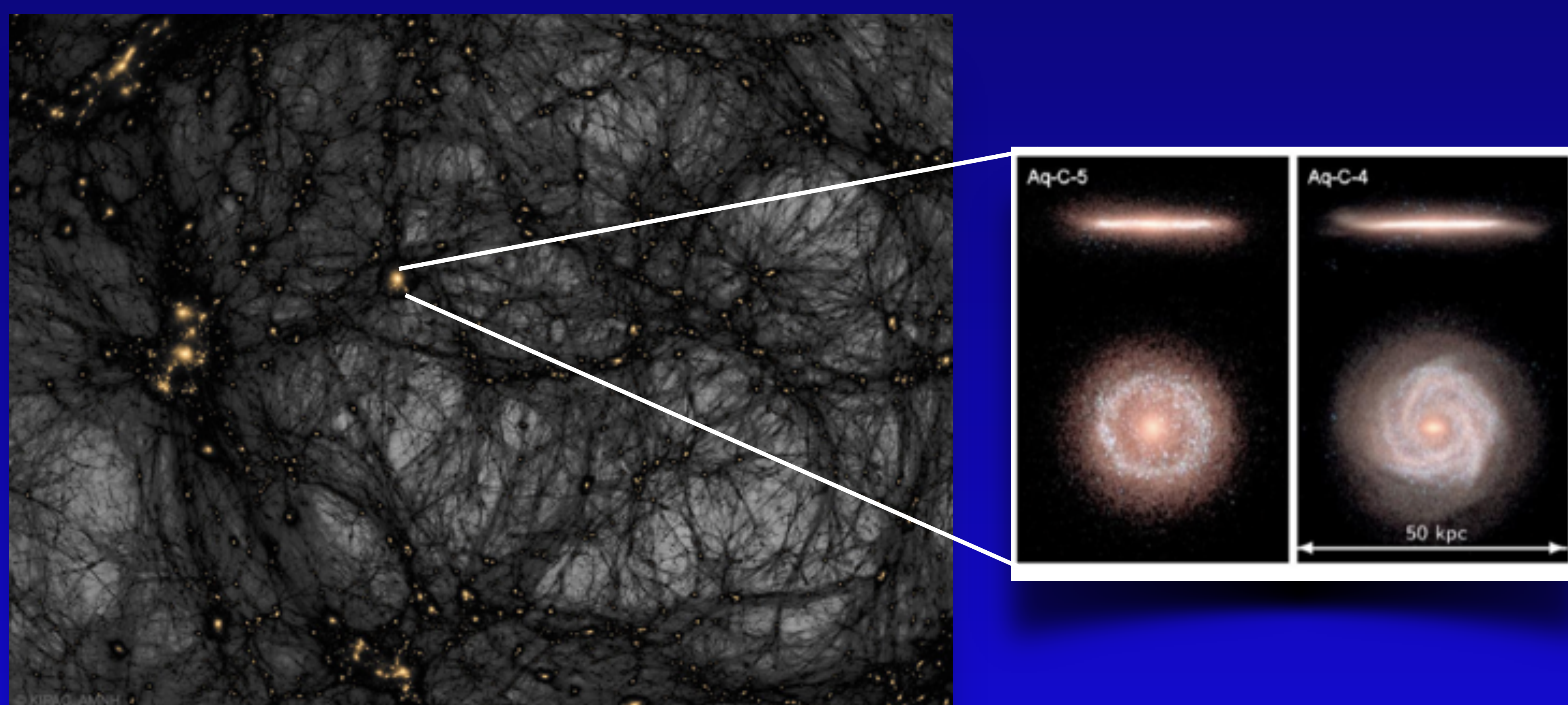
A story of LCDM
I: structure formation

age of Universe





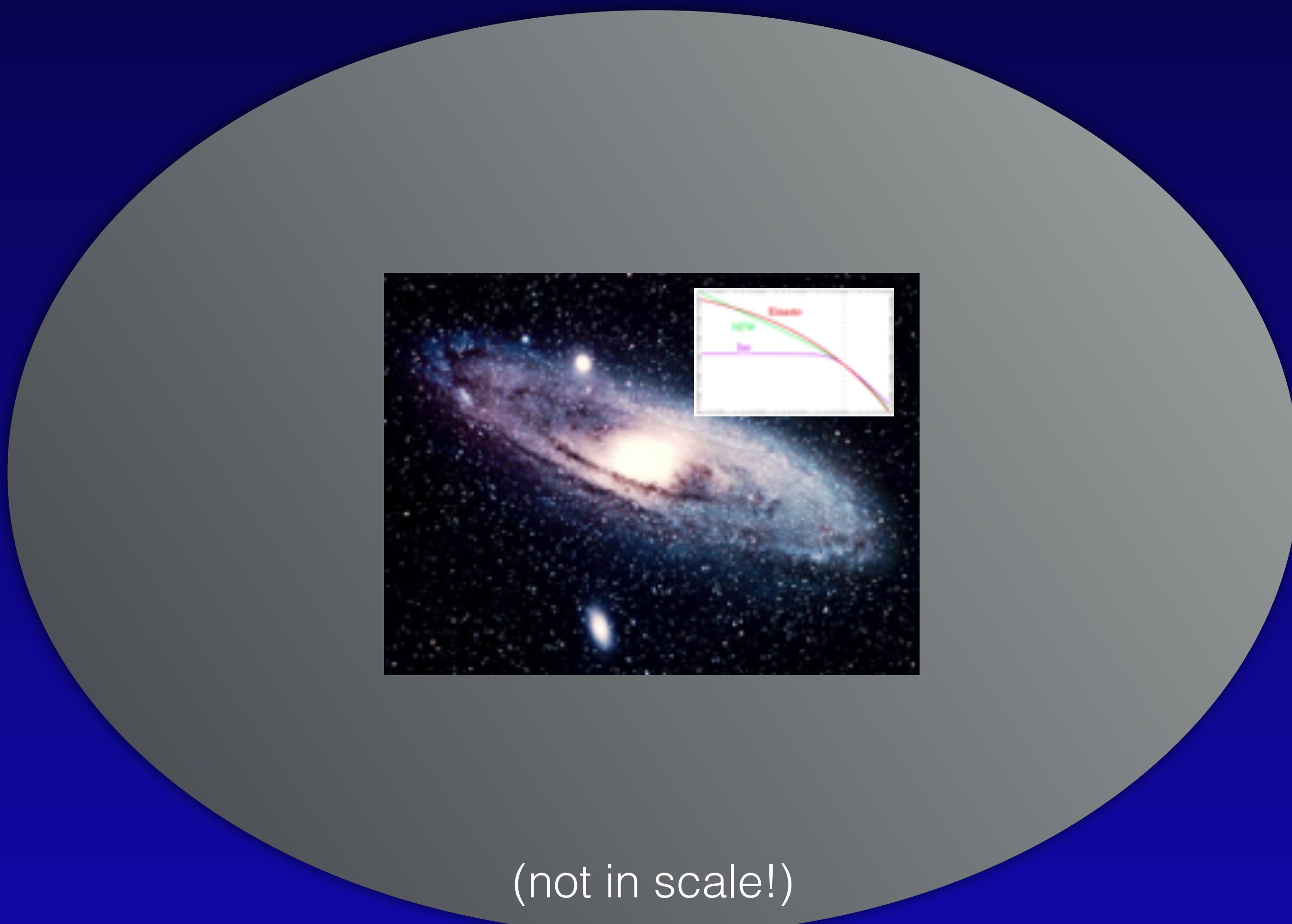


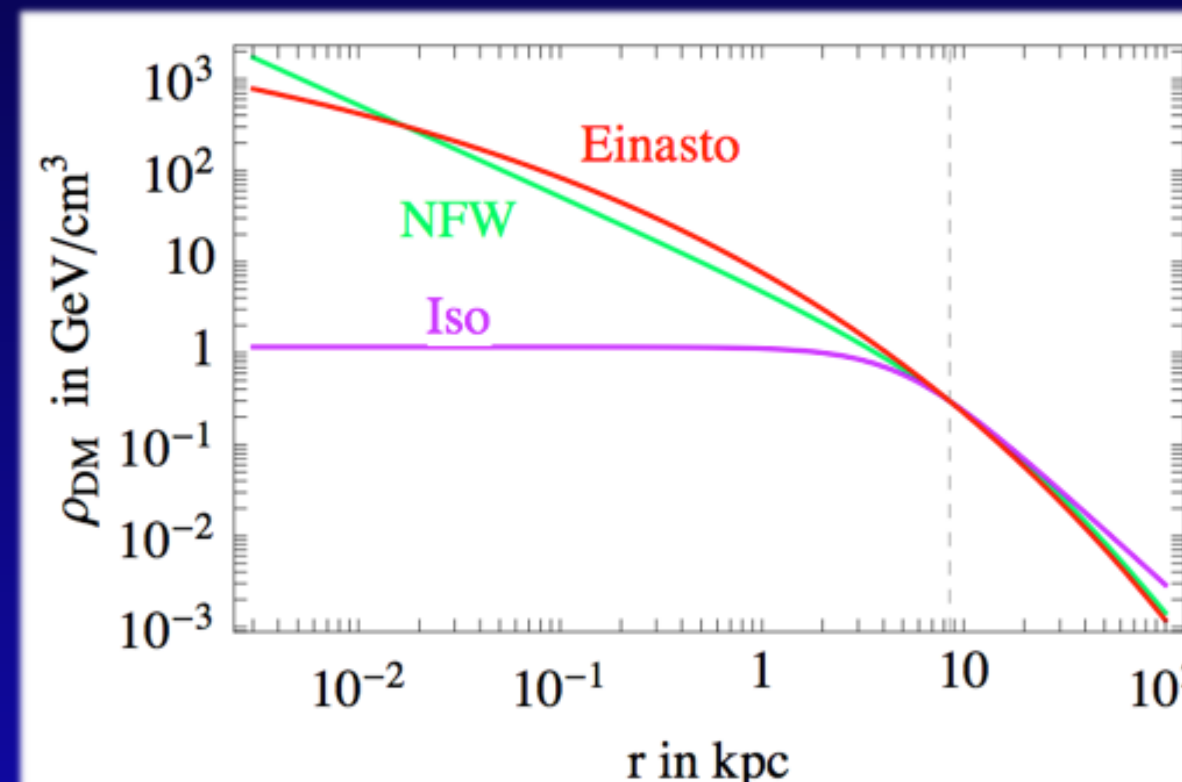


physical size

A story of LCDM
II: the single halo

A "universal" DM profile?

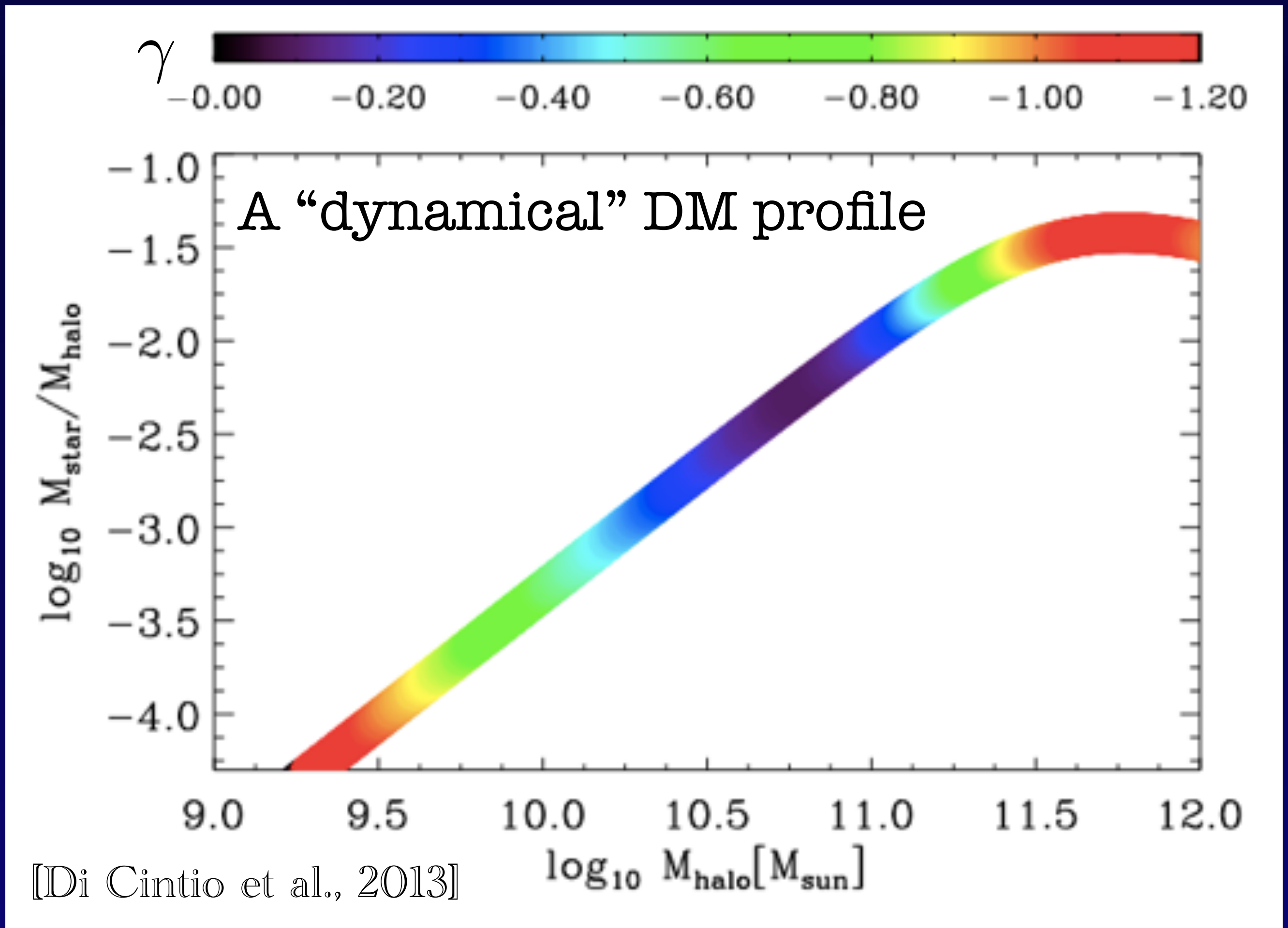


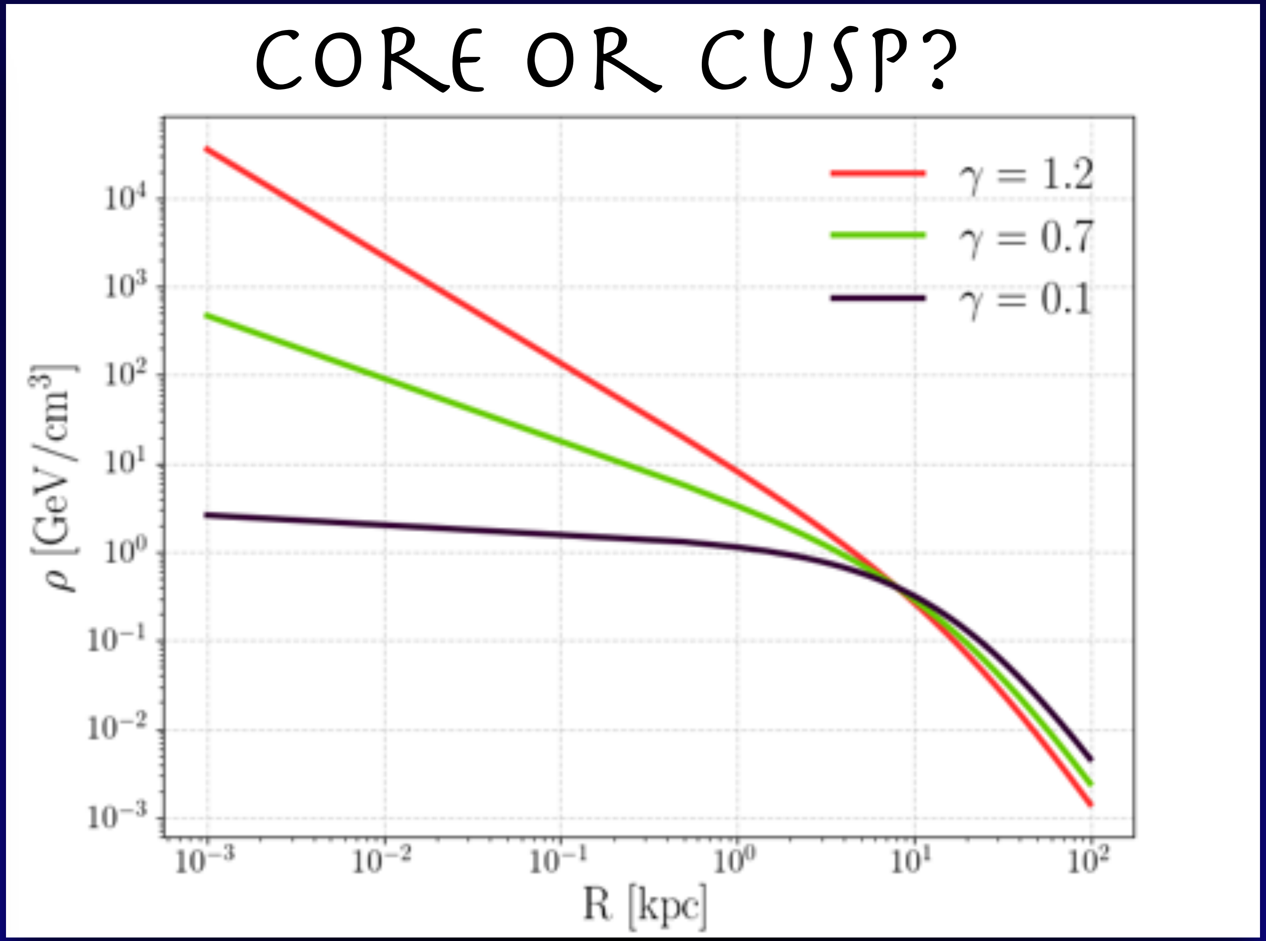


NAVARRO-FRENK-WHITE

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

A story of LCDM
III: the dark matter distribution



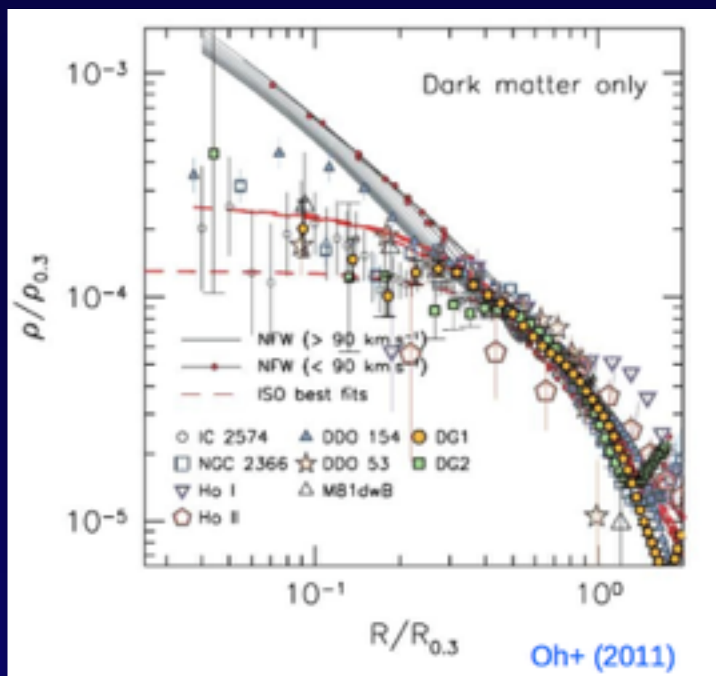


generalized NFW

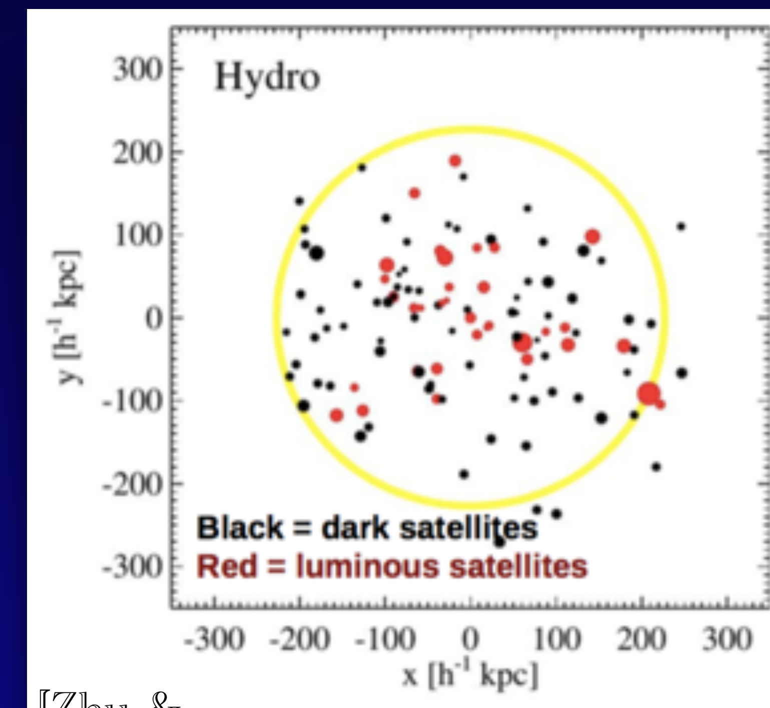
$$\rho_{DM}(R) \propto \rho_0 \left(\frac{R}{R_s}\right)^{-\gamma} \left(1+\frac{R}{R_s}\right)^{-3+\gamma}$$

A story of LCDM
IV: the small scale problems

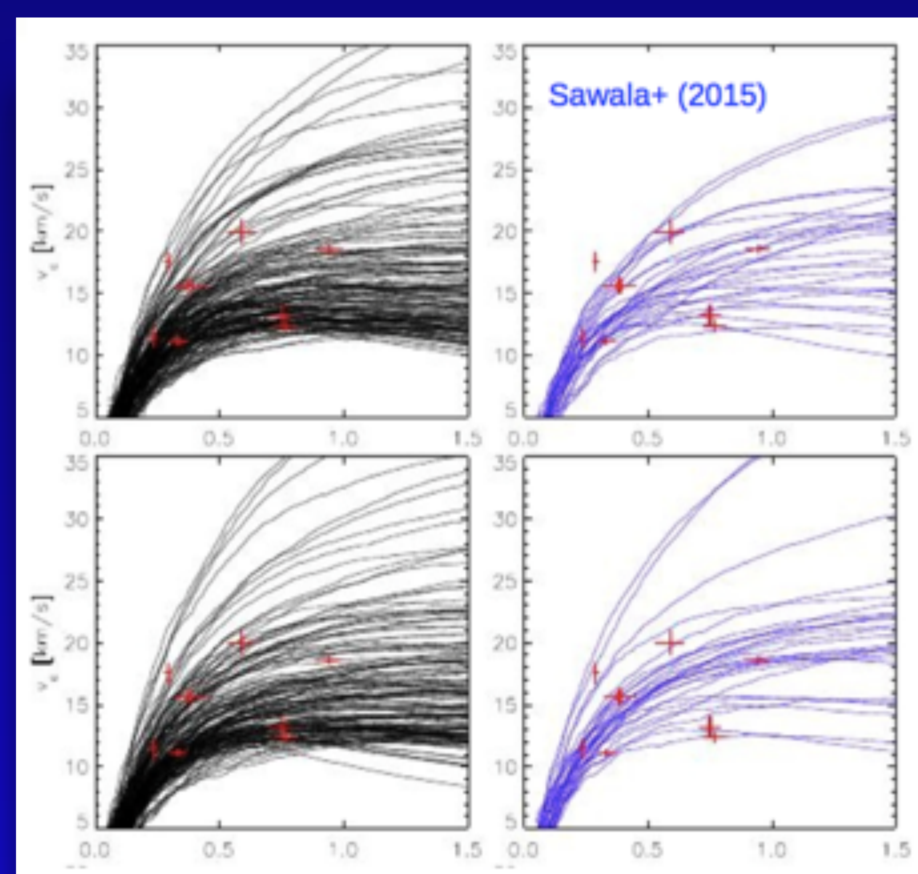
Cusp vs core



Missing satellite

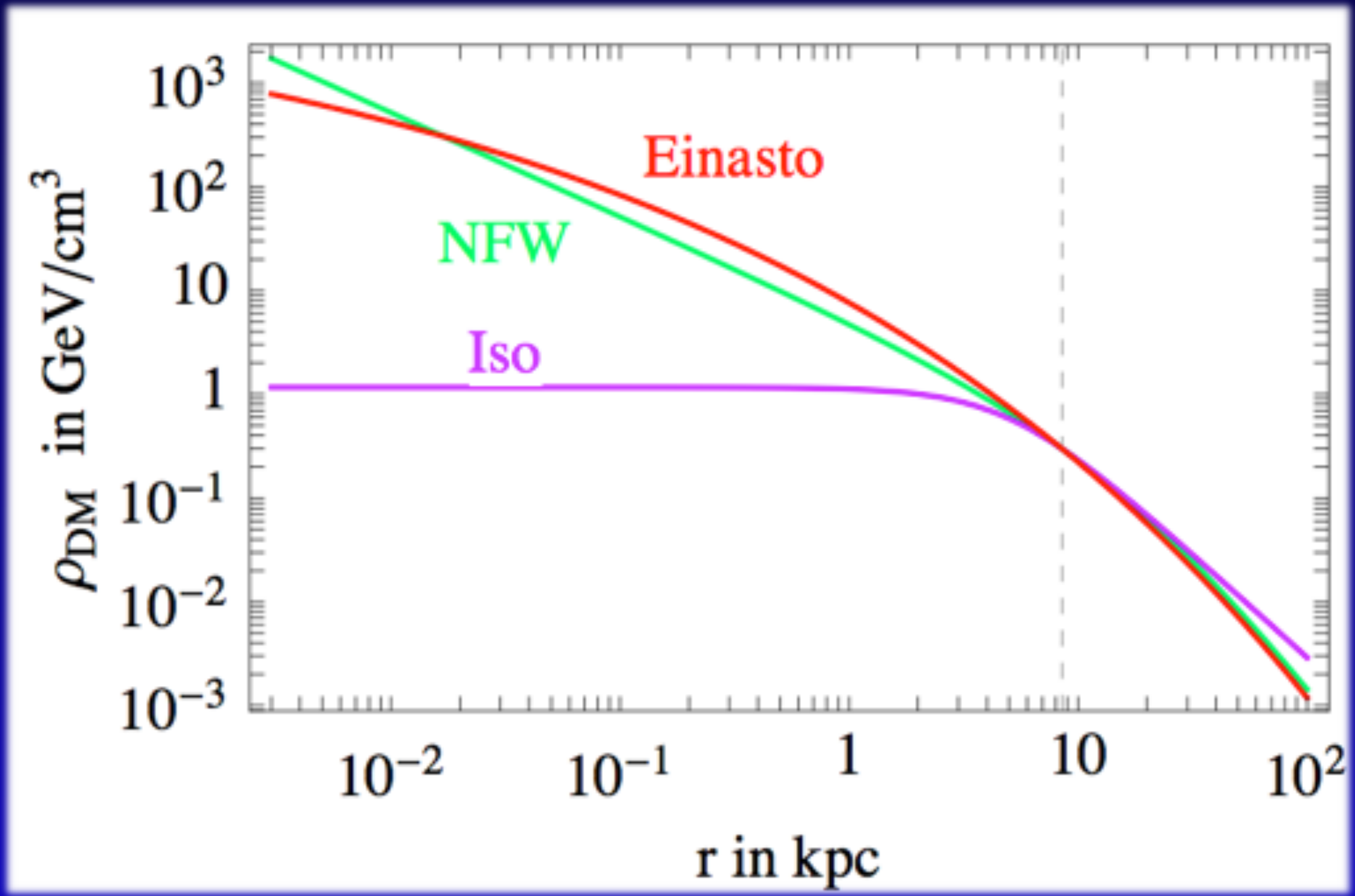


Too big to fail



Ask me later, if interested

The DM distribution in astrophysical sources
a “universal” profile (?)



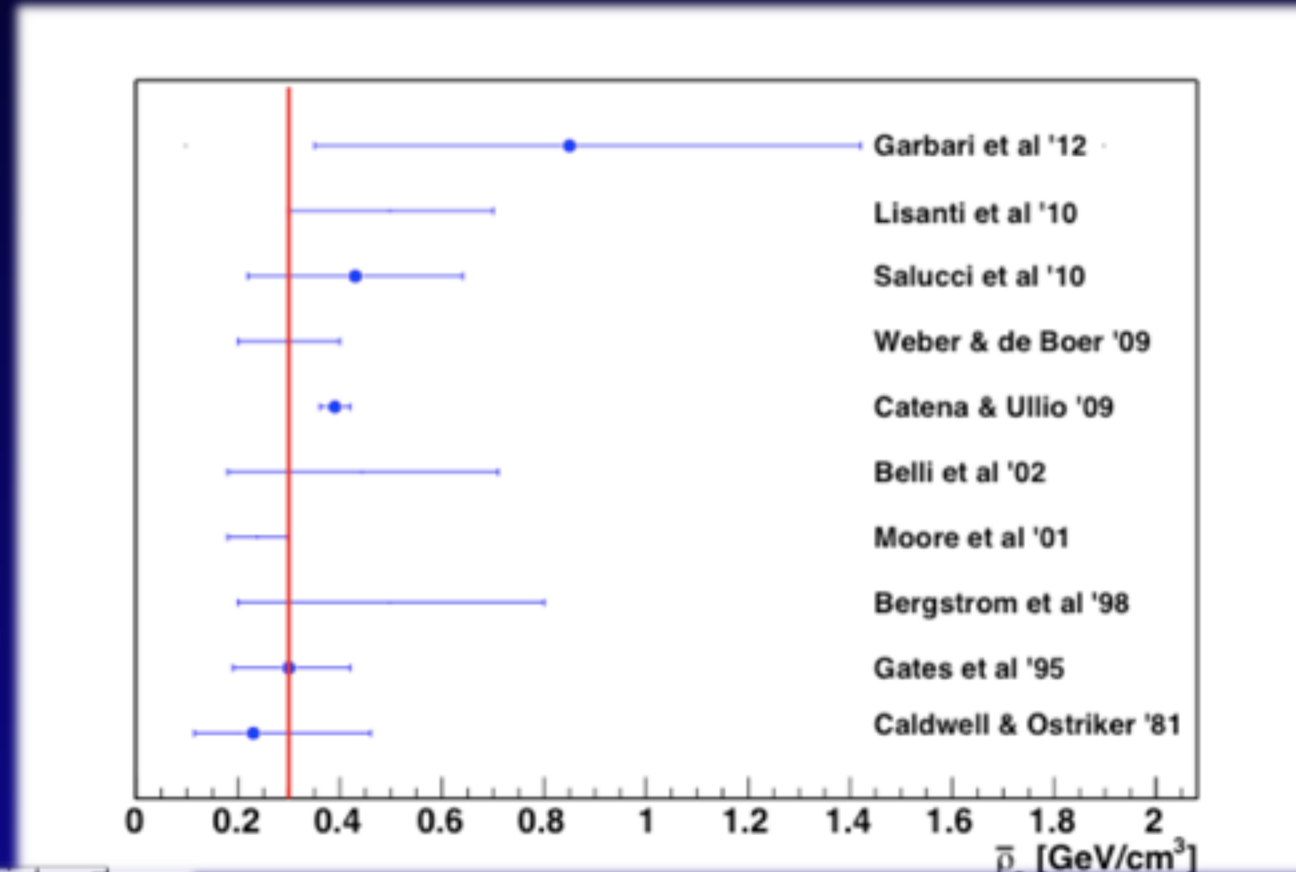
And now for something completely different: the Milky Way

The road to Zeus' home on Olympus
The sacred path of Iberian pilgrims
An average-sized 10^12 Msun spiral,
but the truth is…

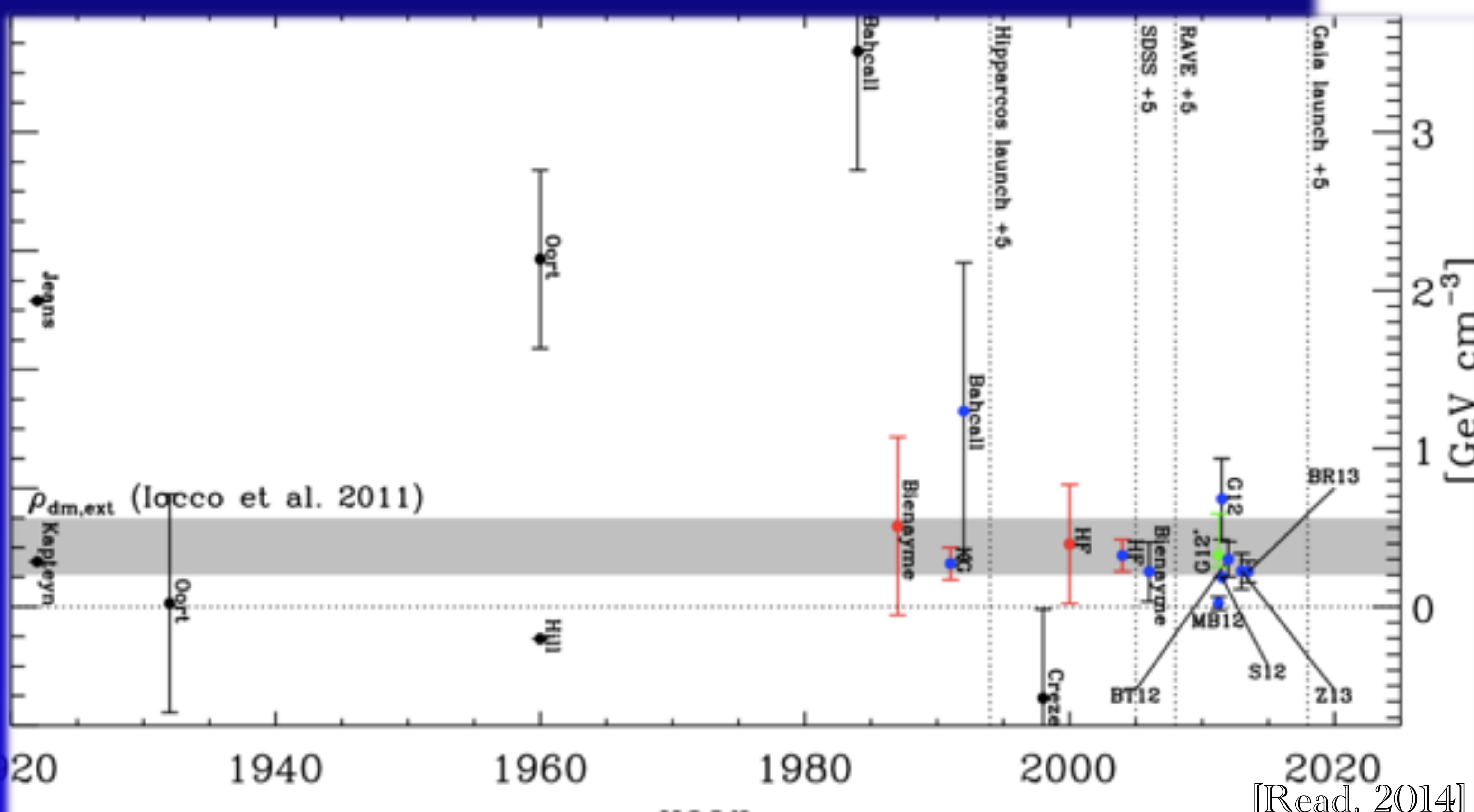
DM density at the Sun = ?

(the path to Stockholm goes through the skies)

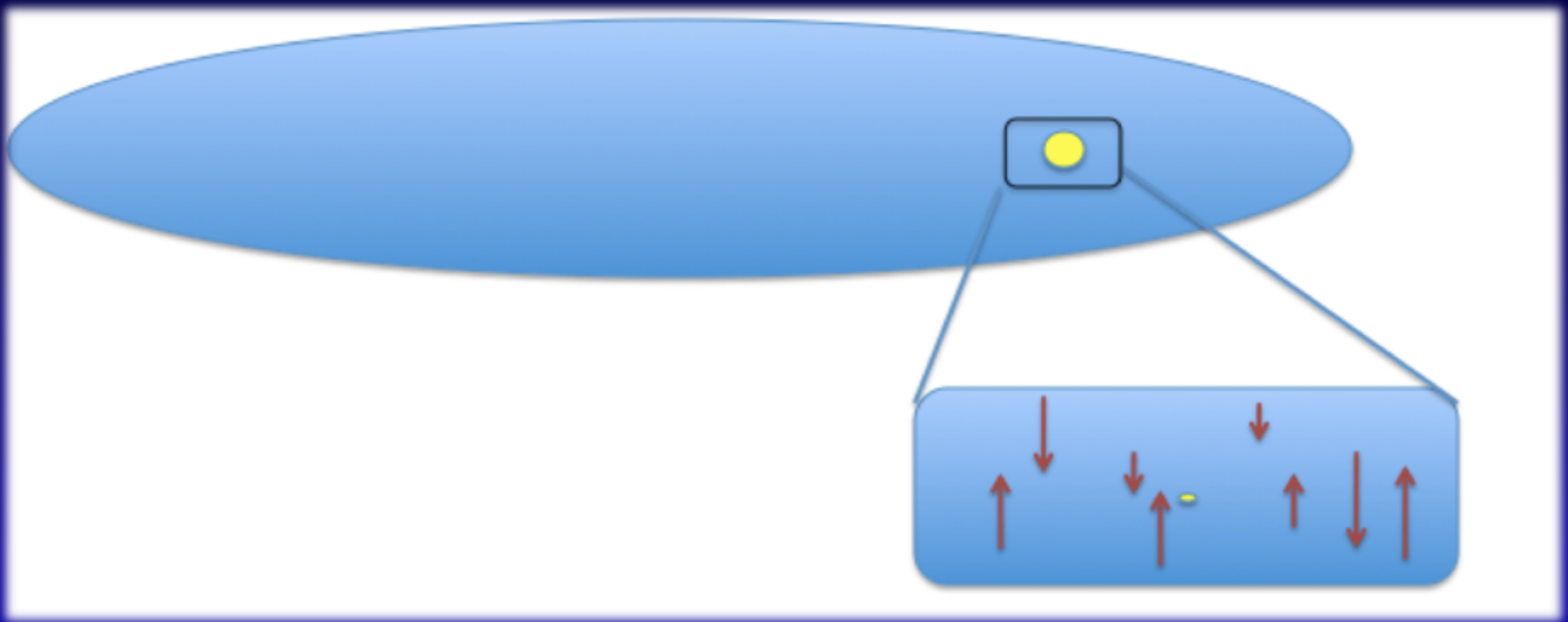
Determining the relevant astrophysical quantities
Local DM density



Determinations of
local DM density
are consistent, but noisy

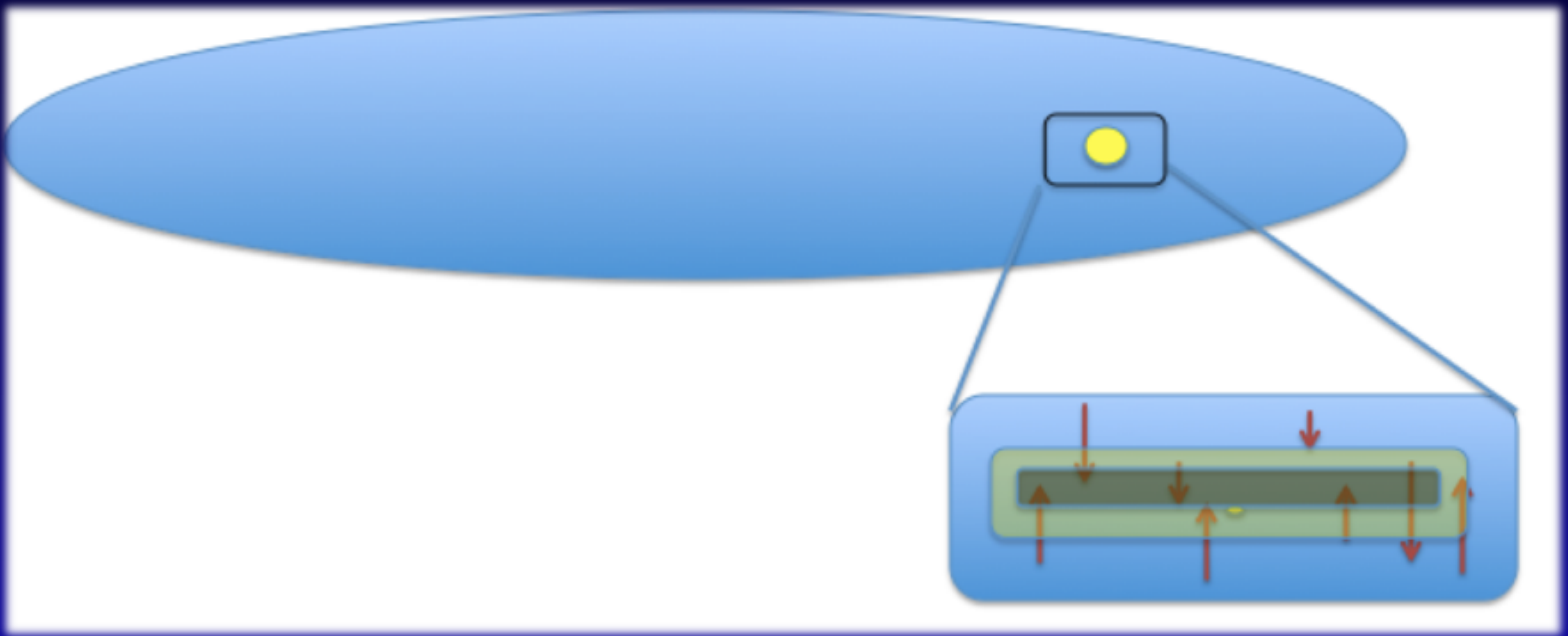


Local determination of ρ_0



Vertical motion of stars, determining the whole local potential

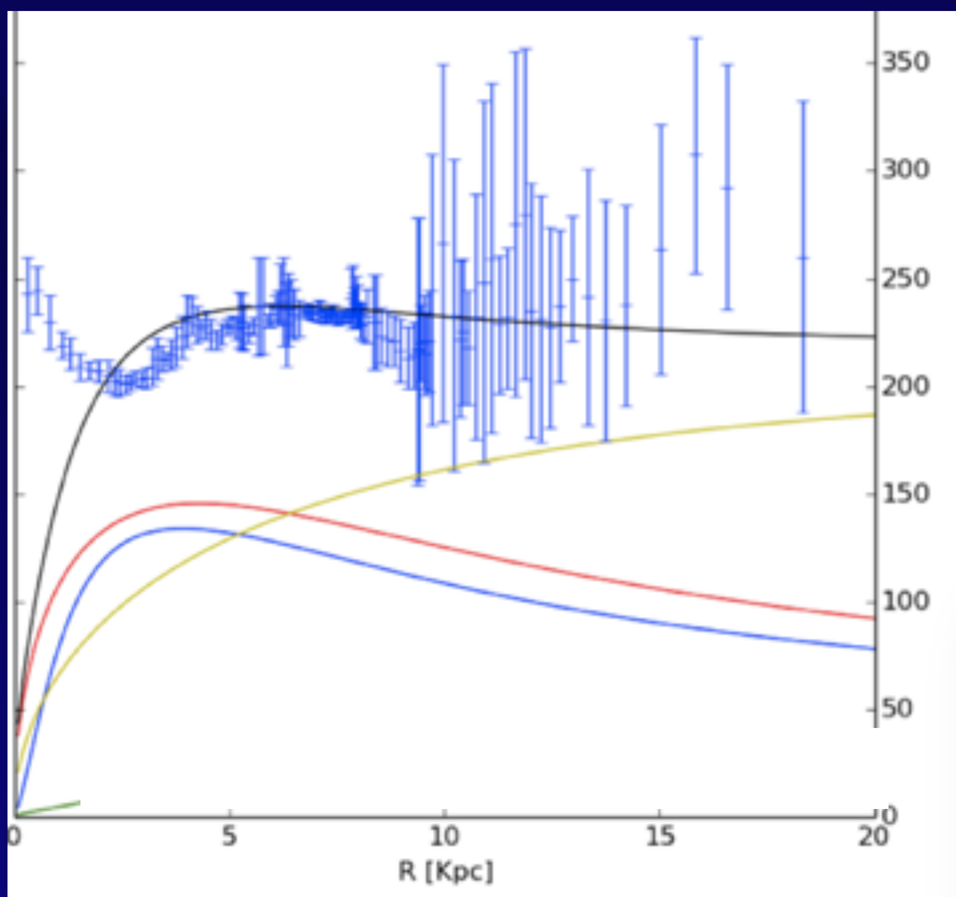
Local determination of ρ_0



Subtracting local baryonic (stellar) contribution to get DM
(no implicit assumption on DM presence)

Inferring the DM density structure

Fitting a pre-assigned shape on top of luminous

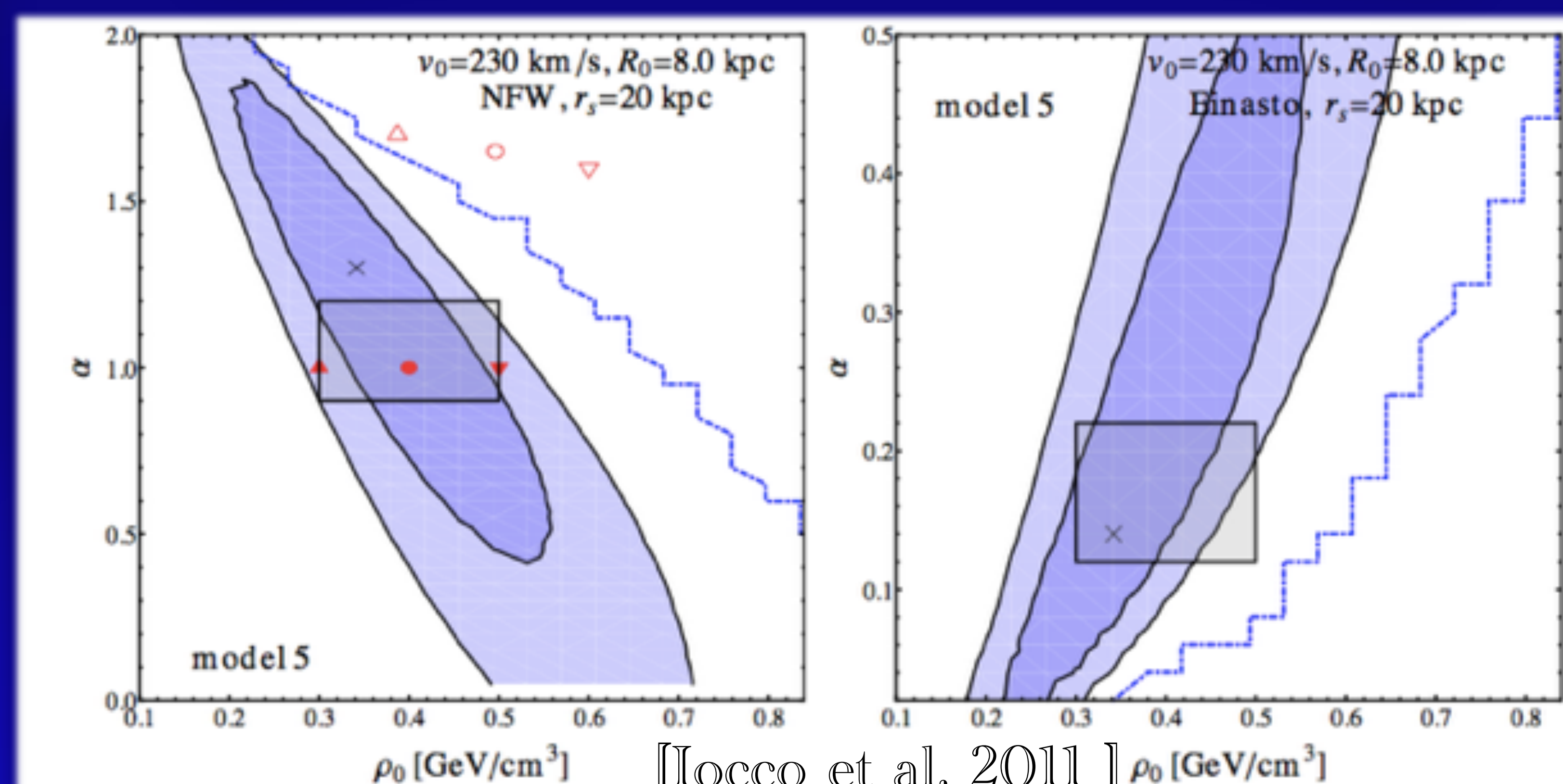


gNFW

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

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

Einasto

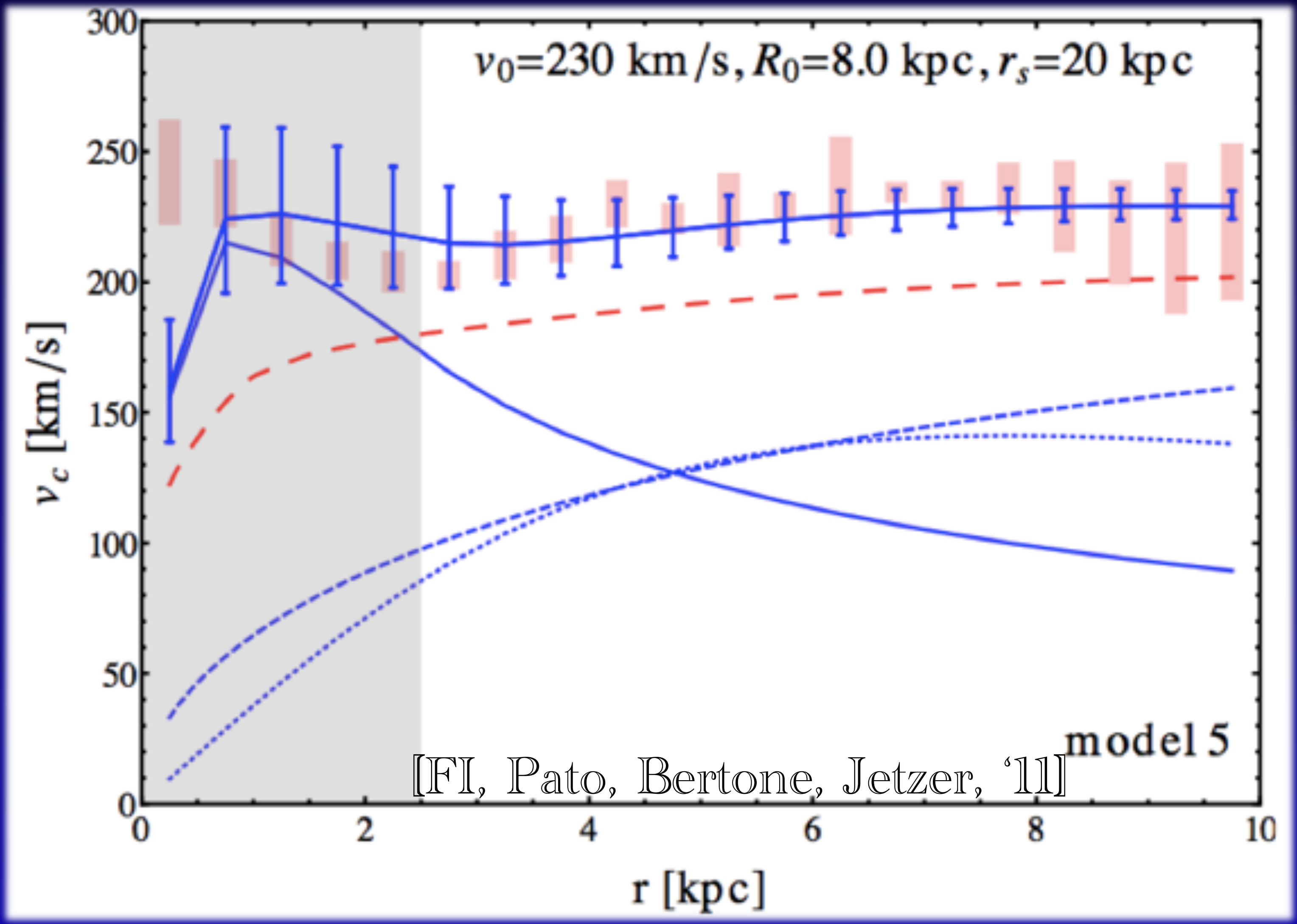


[Iocco et al. 2011]

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

Global determination of ρ(r)

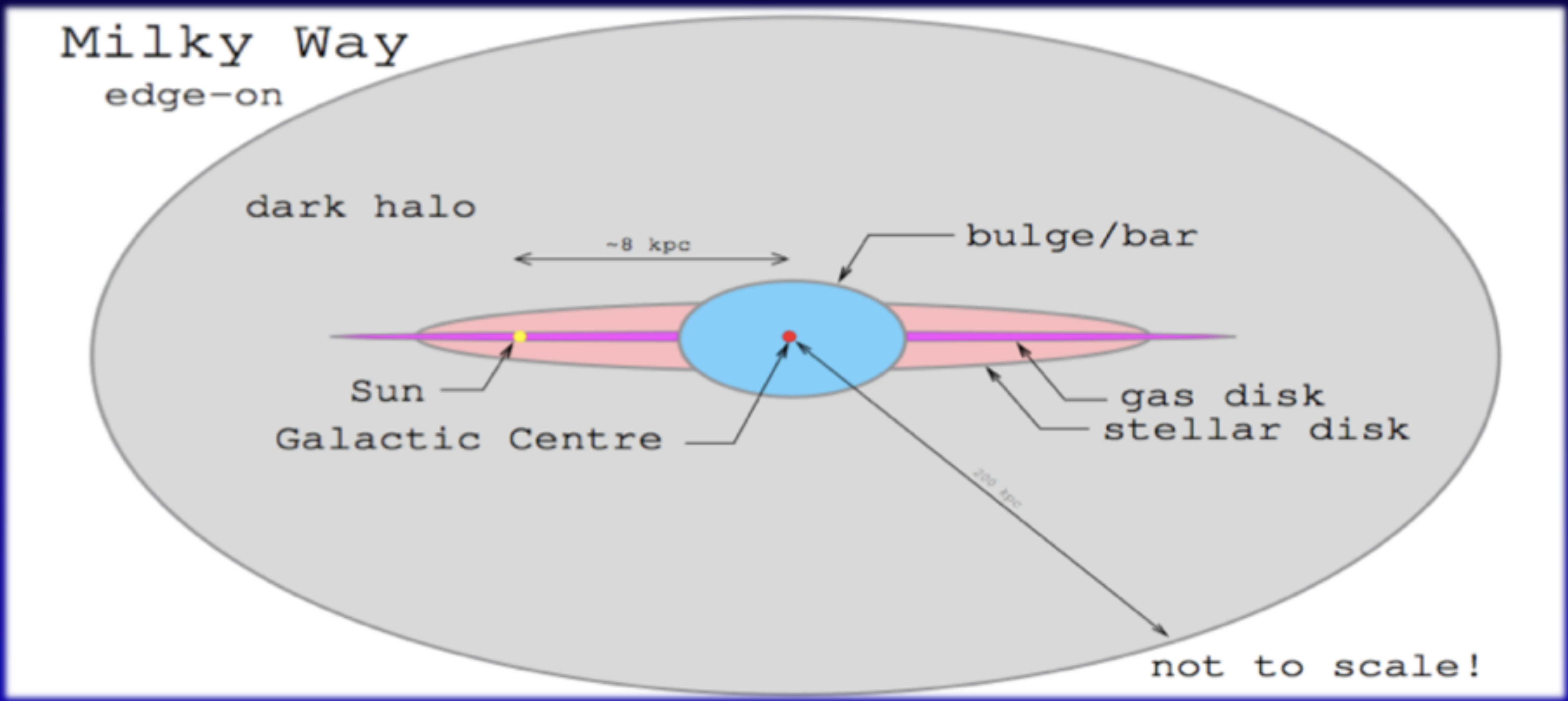
Fitting a DM profile to the Rotation Curve, on top of other components



$$\phi_{\rm tot} = \phi_{\rm bulge} + \phi_{\rm disk} + \phi_{\rm gas} + \phi_{\rm dm}$$

Underlying assumption on DM presence and distribution shape

The case of the Milky Way



Courtesy of Miguel Pato

Dark Matter in the Milky Way: a purely observational approach

Fabio Iocco

Work started with: *Miguel Pato, G. Bertone*
And continued with: *Maria Benito, Ekaterina Karukes*

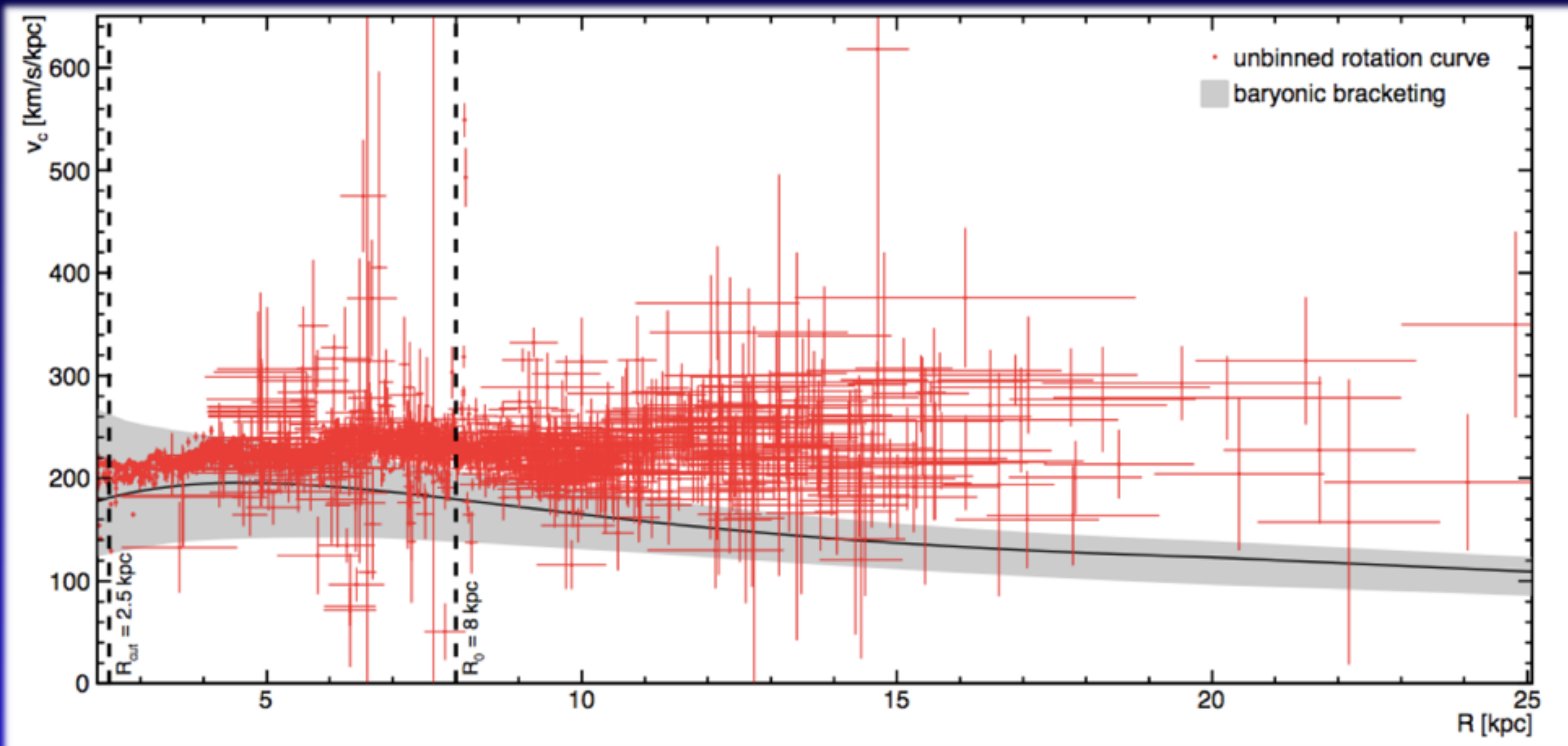
The case of the Milky Way: ingredients

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

- Some “grano salis”

- Working hypothesis (later on)

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



[Iocco, Pato, Bertone, Nature Physics 2015]

The case of the Milky Way: the question

$$\Phi_{\text{tot}} = \Phi_{\text{bulge}} + \Phi_{\text{disk}} + \Phi_{\text{gas}} \quad ??$$

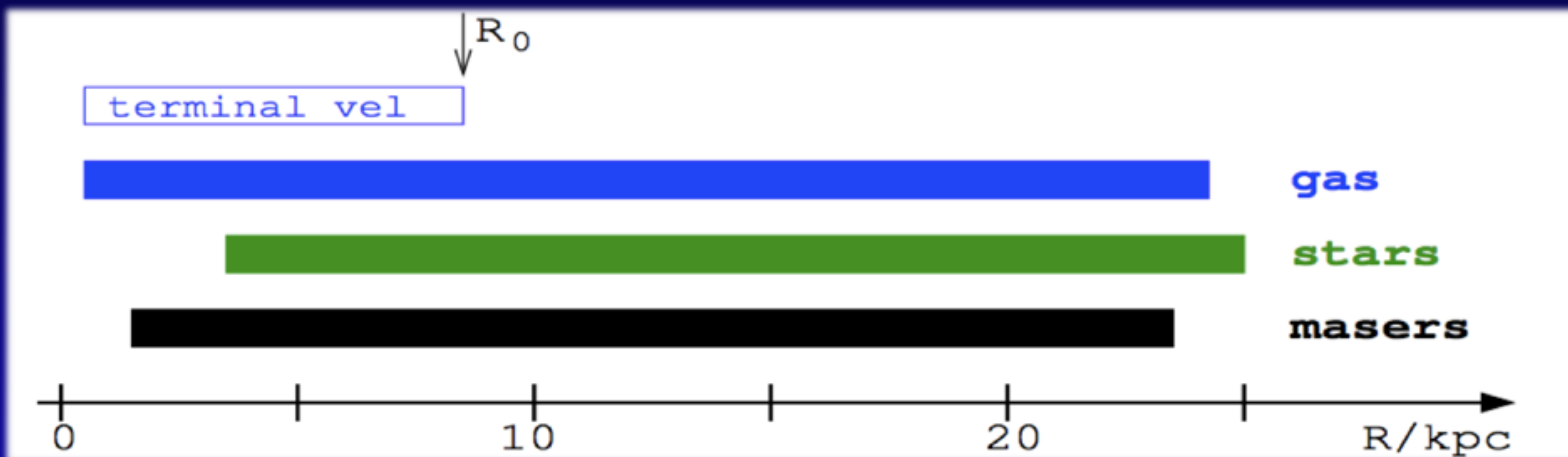
[can the observed, luminous components make up to the whole gravitational potential?]

$$v_c^2 = r \frac{d\phi_{\text{tot}}}{dr}$$

Rotation curve as a tracer of the total potential

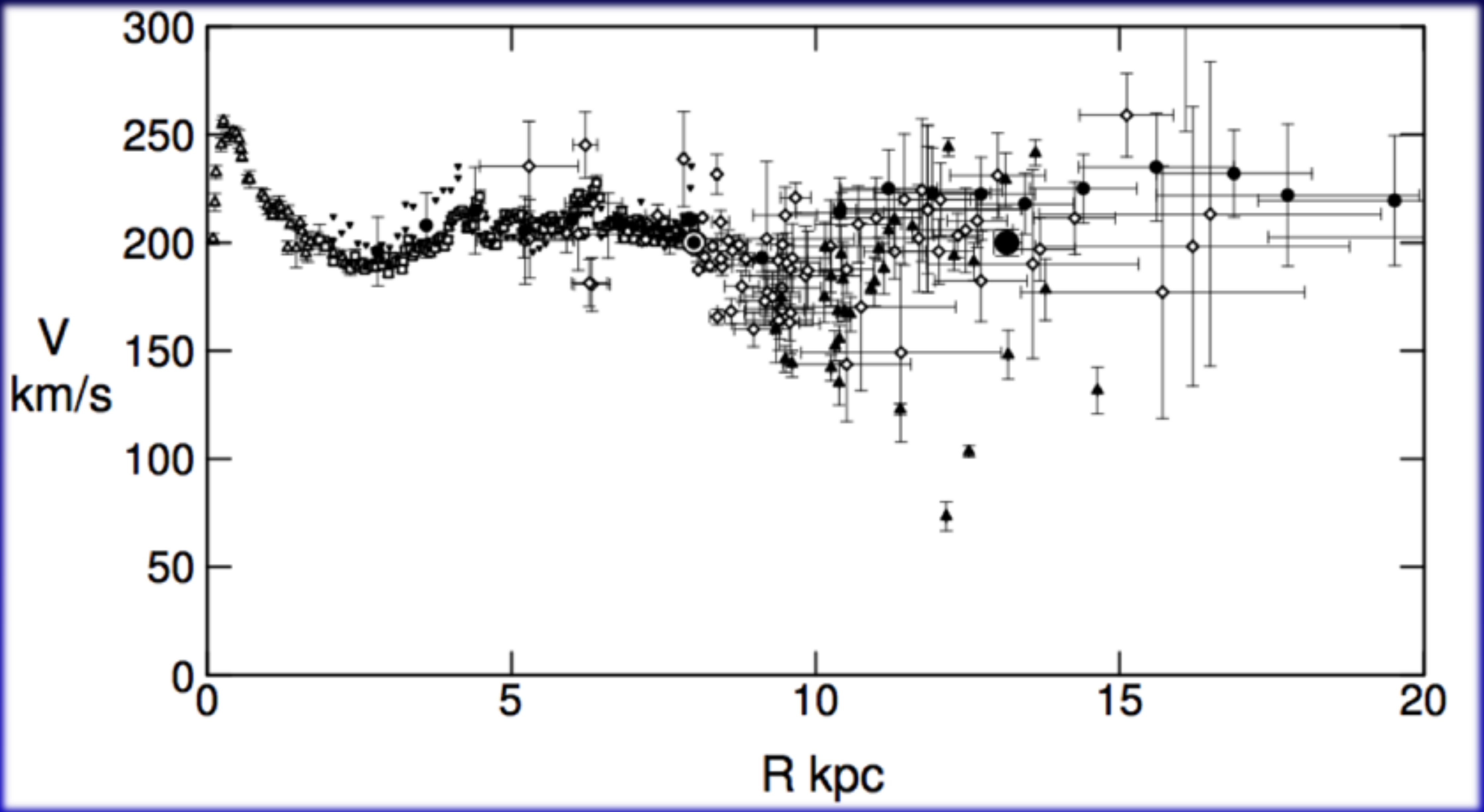
…and if not…

The Milky Way:
observed rotation curve
II. tracers



Doppler shift		distance	
1. gas	(21cm, Hα, CO)	1. terminal velocities	(gas)
2. stars	(H, He, O, ...)	2. photo-spectroscopy	(stars)
3. masers	(H_2O, CH_3OH, ...)	3. parallax	(masers)

The Milky Way:
observed rotation curve
III. curve

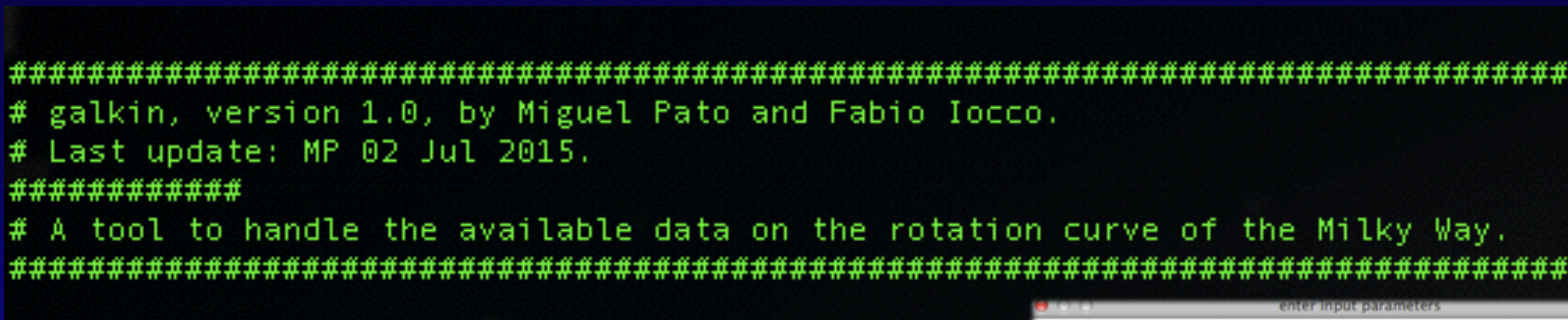


Data compilation by [Sofue et al, '08]

The Milky Way:
observed rotation curve
II’. data again (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

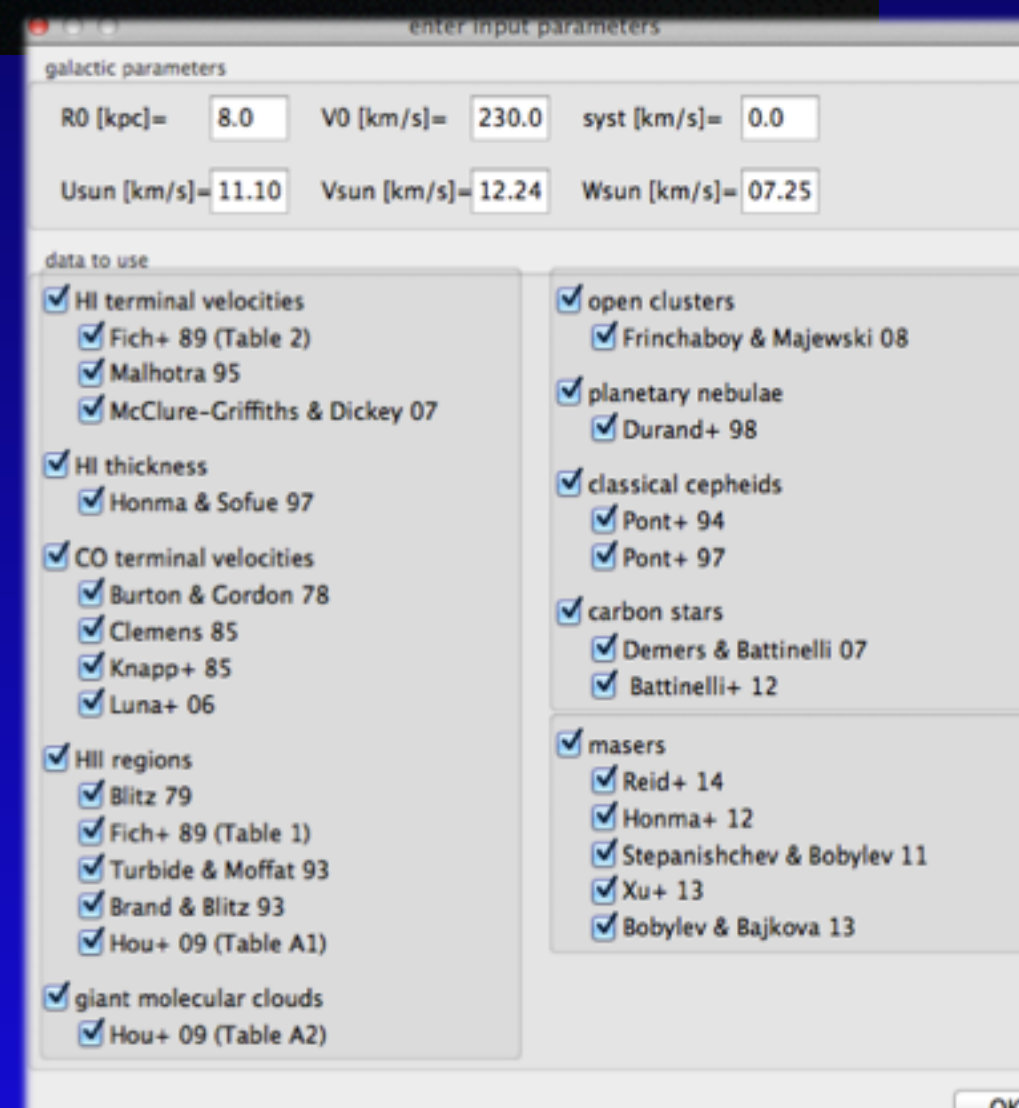
The Milky Way:
observed rotation curve
IV. public tool: galkin



Customizable galactic parameters
(R_0,V_0)
peculiar motions, etc…

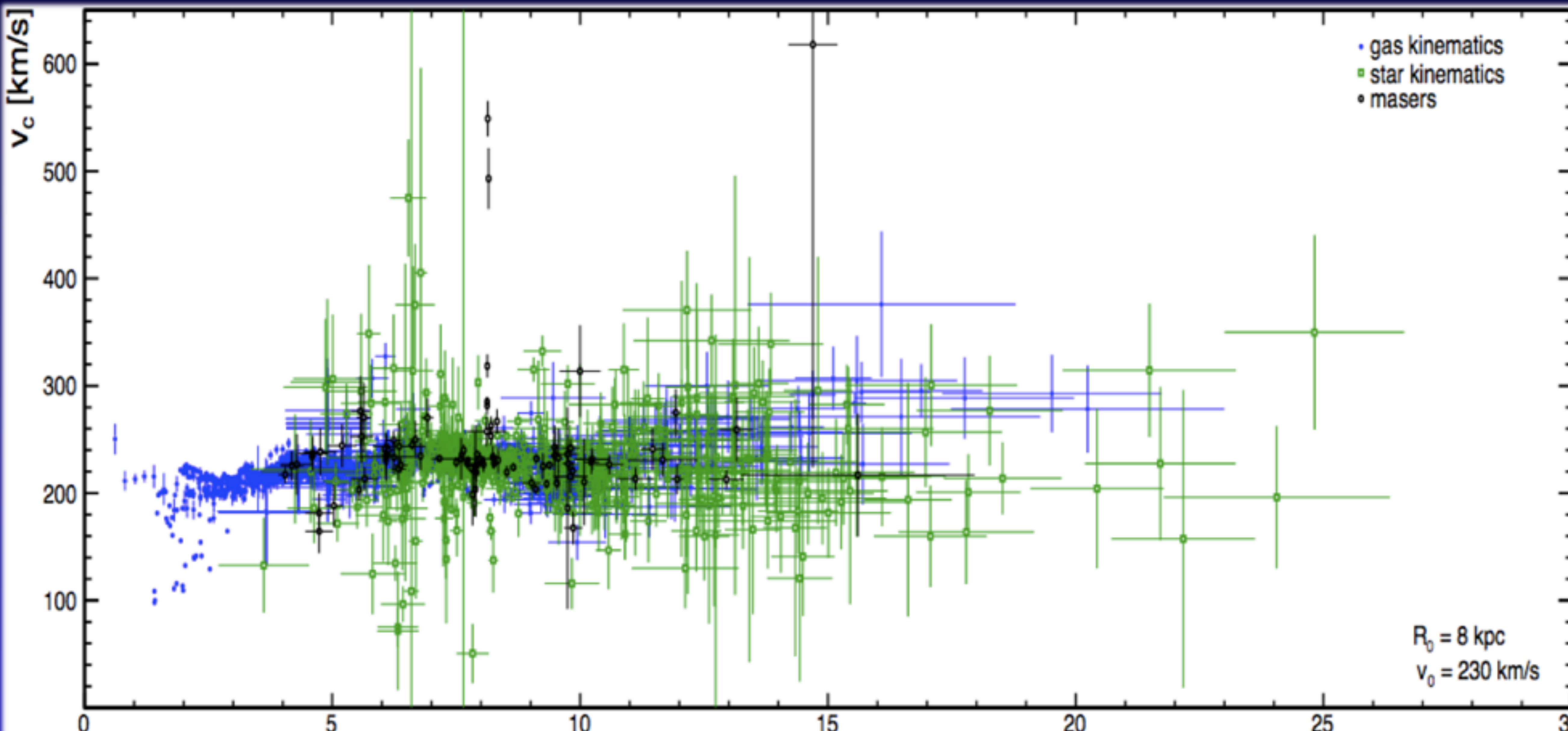
Finally available:
download your copy now

github.com/galkintool/galkin



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

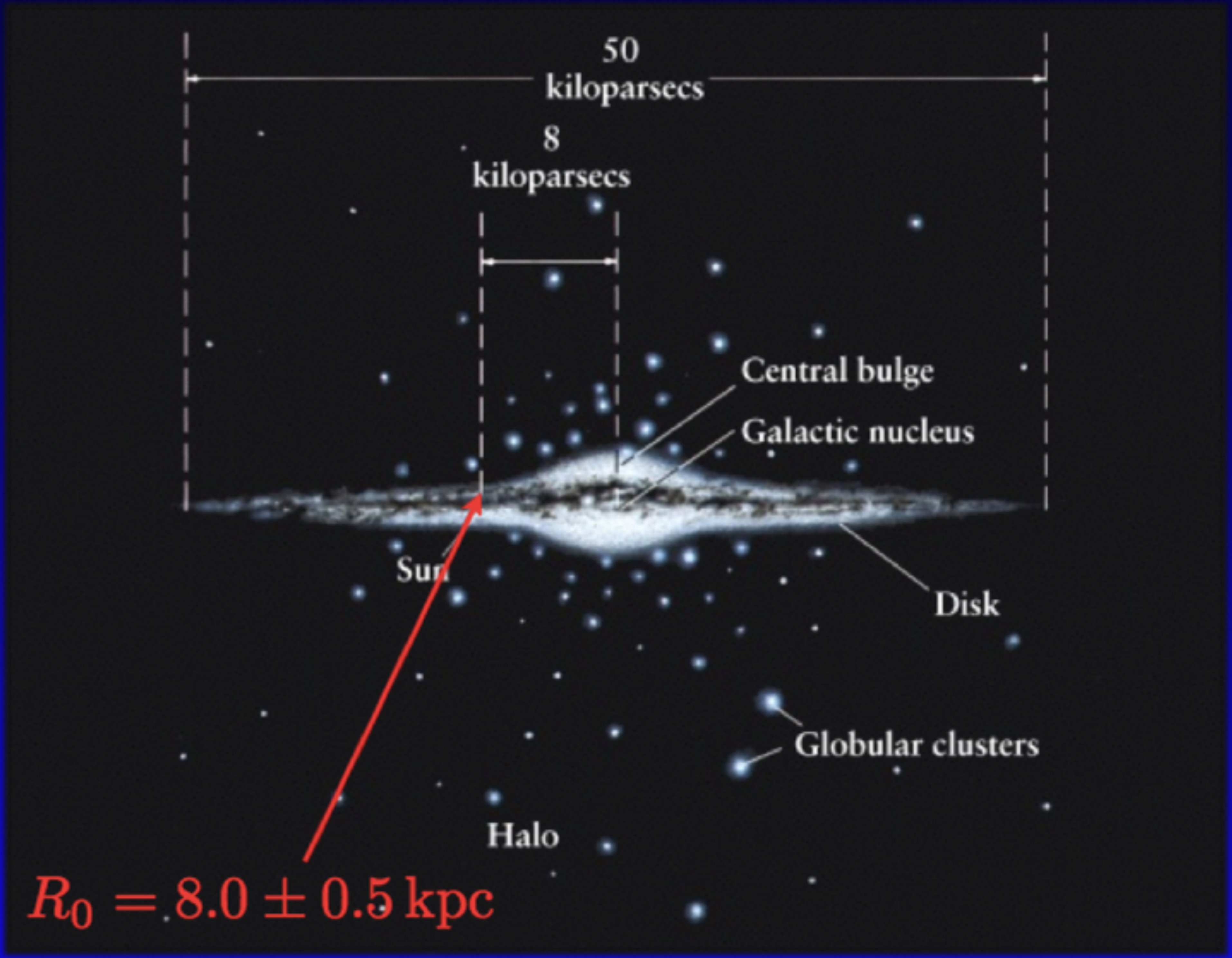
The Milky Way Rotation Curve
as observed



[Iocco, Pato, Bertone, Nature Physics 2015]

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

Modeling the Milky Way: morphological observations



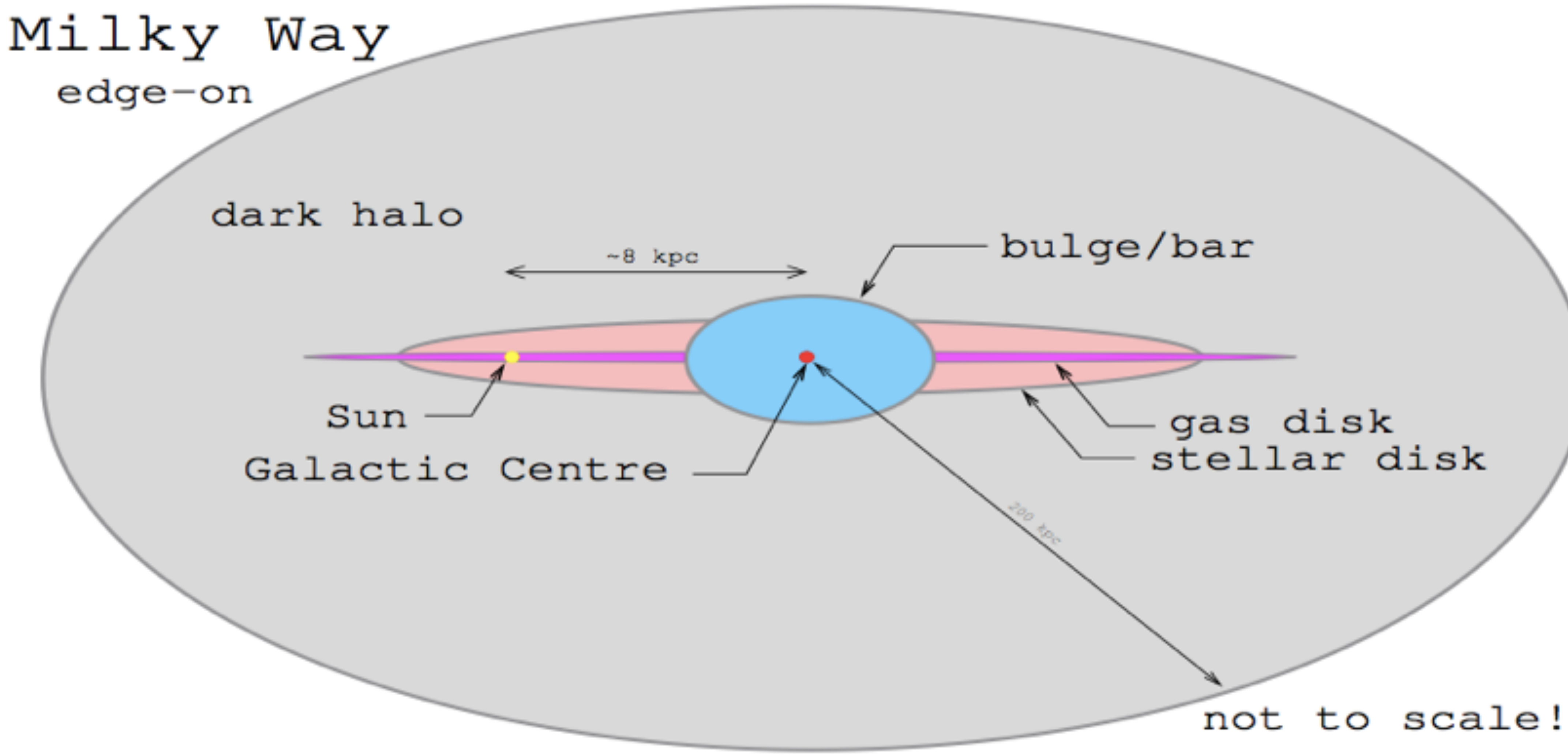
The Milky Way:
expected rotation curve

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

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

Constructing the curve expected from observed mass profiles

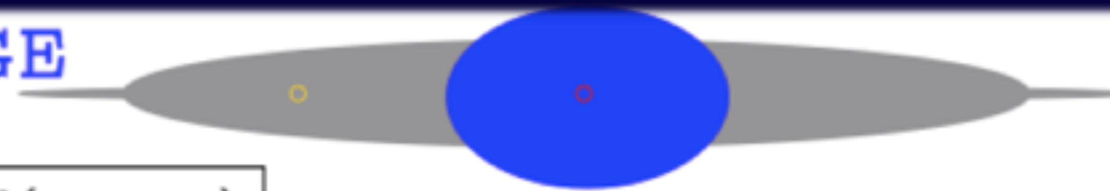
The Milky Way:
expected rotation curve
1. the baryonic components



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

The luminous Milky Way: observations of morphology

2. BARYONS: STELLAR BULGE



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

morphology $f(x, y, z)$

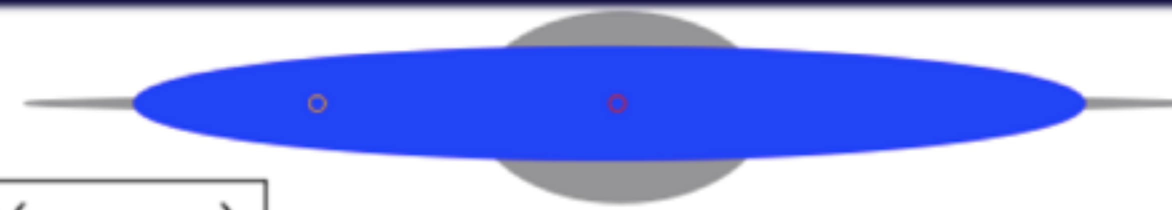
Stanek+ '97 (E2)	e^{-r}	0.9:0.4:0.3	24°	optical
Stanek+ '97 (G2)	$e^{-r_s^2/2}$	1.2:0.6:0.4	25°	optical
Zhao '96	$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	1.5:0.6:0.4	20°	infrared
Bissantz & Gerhard '02	$e^{-r_s^2}/(1+r)^{1.8}$	2.8:0.9:1.1	20°	infrared
Lopez-Corredoira+ '07	Ferrer potential	7.8:1.2:0.2	43°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

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 $f(x,y,z)$

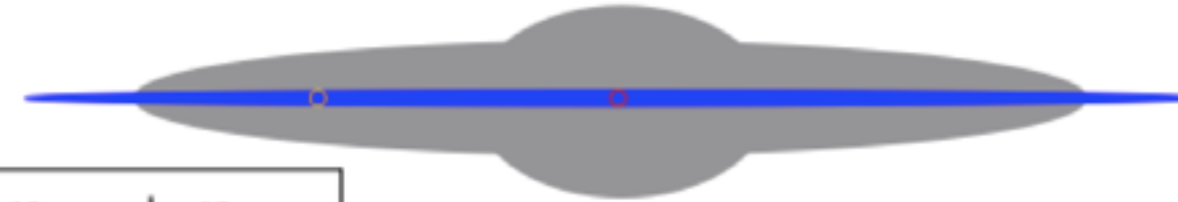
Han & Gould '03	$e^{-R}\mathrm{sech}^2(z)$	2.8:0.27	thin	optical
	$e^{-R-\lvert z\rvert}$	2.8:0.44	thick	
Calchi-Novati & Mancini '11	$e^{-R-\lvert z\rvert}$	2.8:0.25	thin	optical
	$e^{-R-\lvert z\rvert}$	4.1:0.75	thick	
deJong+ '10	$e^{-R-\lvert z\rvert}$	2.8:0.25	thin	optical
	$e^{-R-\lvert z\rvert}$	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

normalisation ρ_0

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

The luminous Milky Way: observations of morphology

2. BARYONS: GAS



$$n_H = 2n_{H_2} + n_{HI} + n_{HII}$$

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.

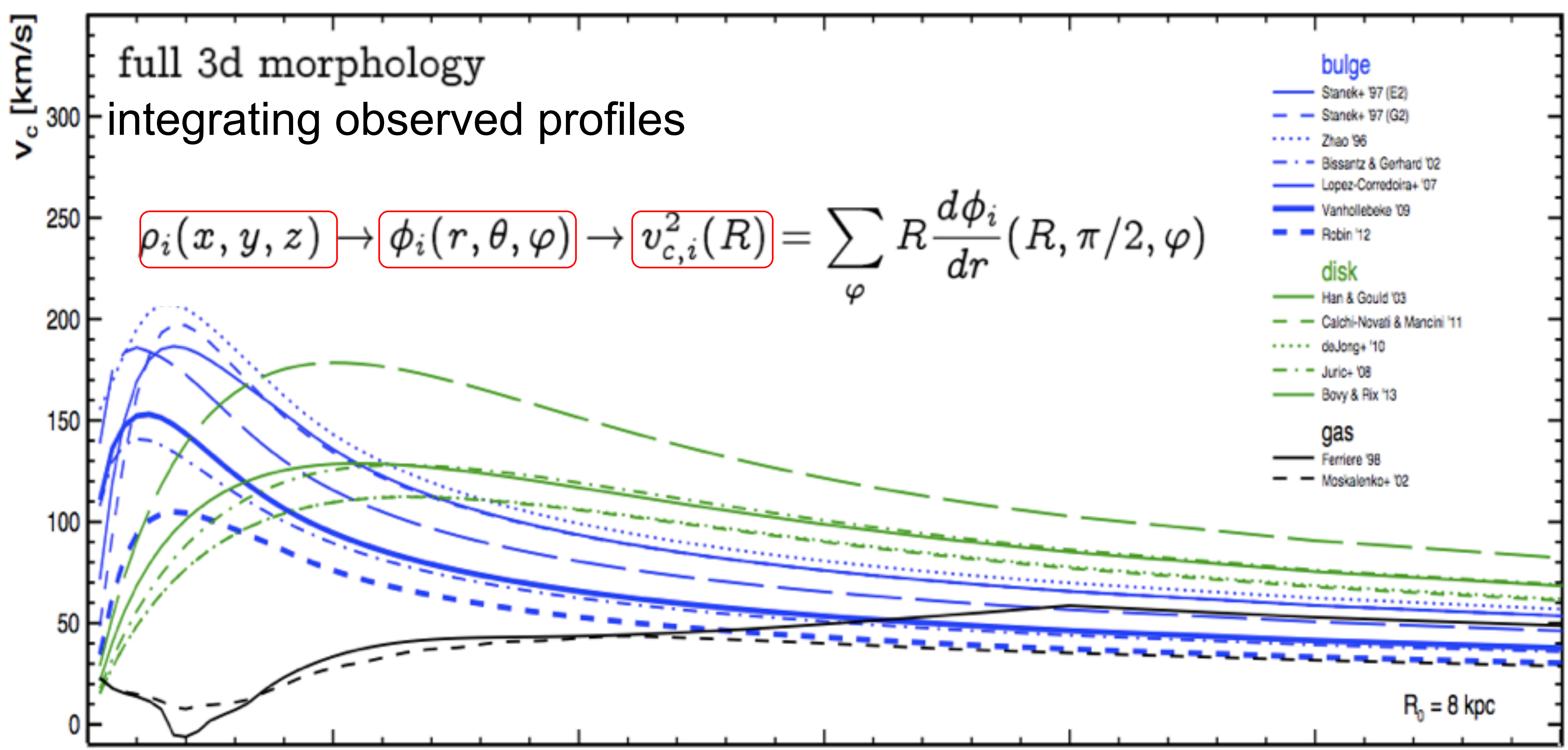
uncertainties

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

[Ferrière+ '07, Ackermann '12]

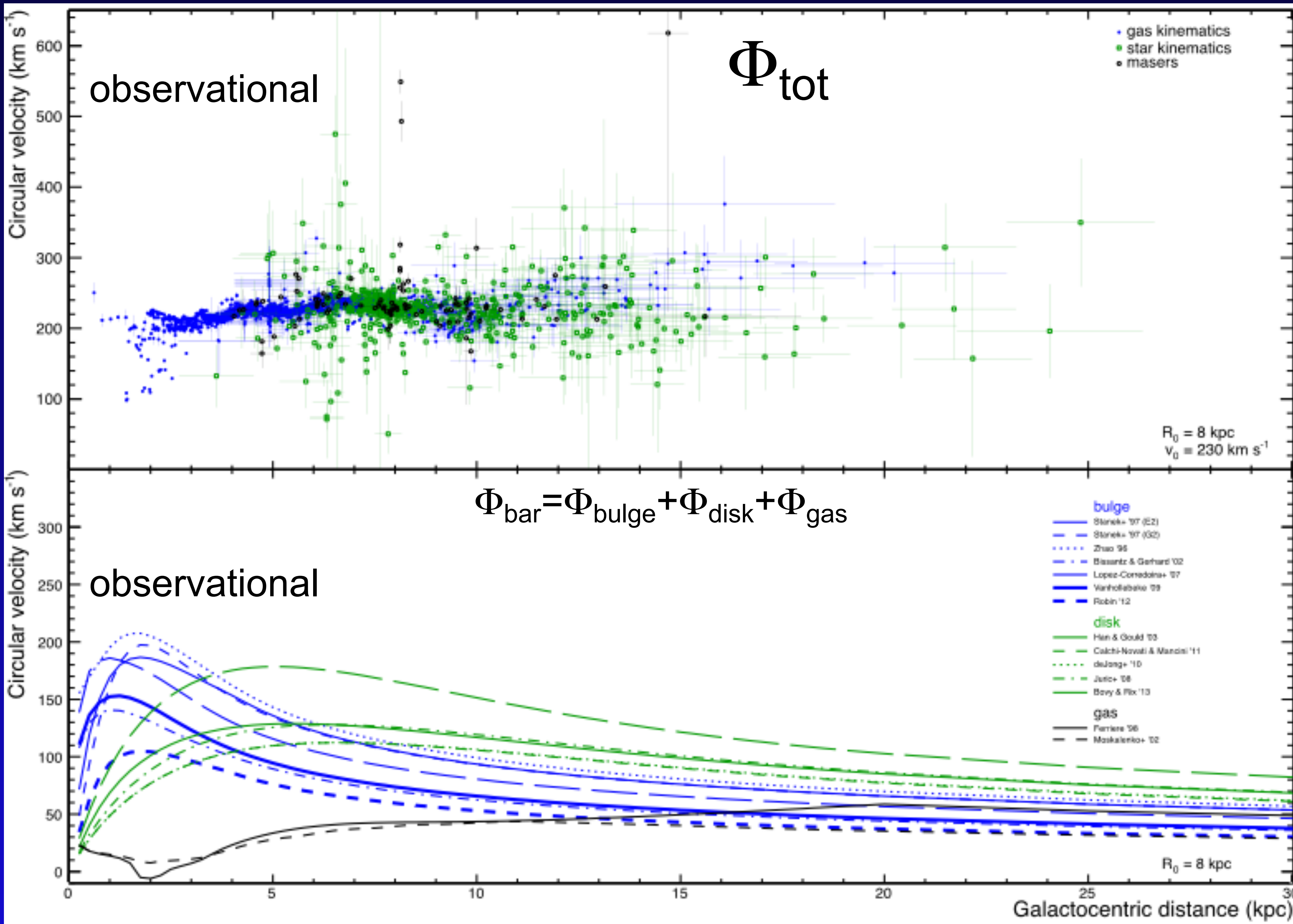
The luminous Milky Way:
expected rotation curve

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

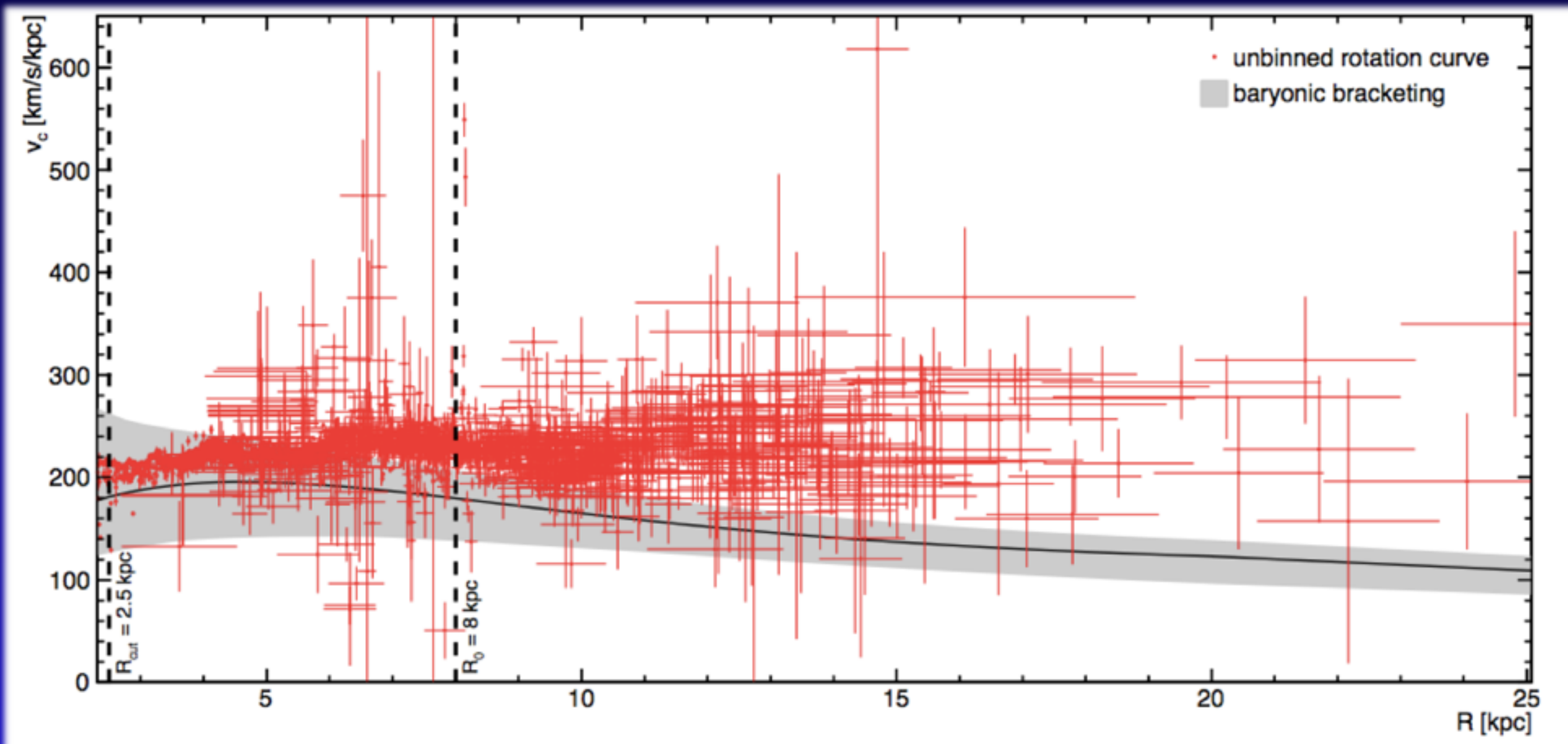


[Iocco, Pato, Bertone, Nature Physics 2015]

The Milky Way: testing expectactions

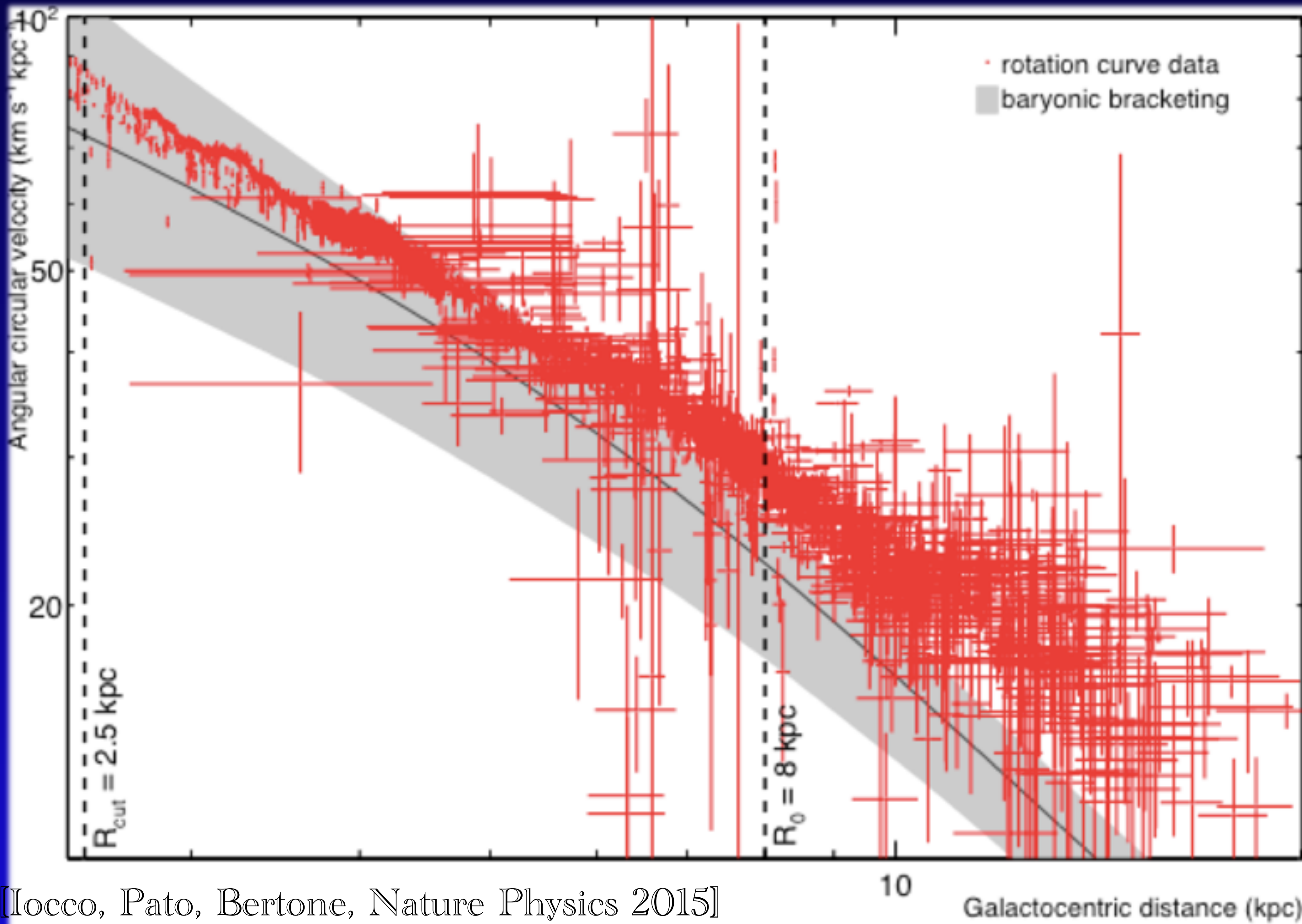


The Milky Way: testing expectactions (with no additional assumptions)



[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

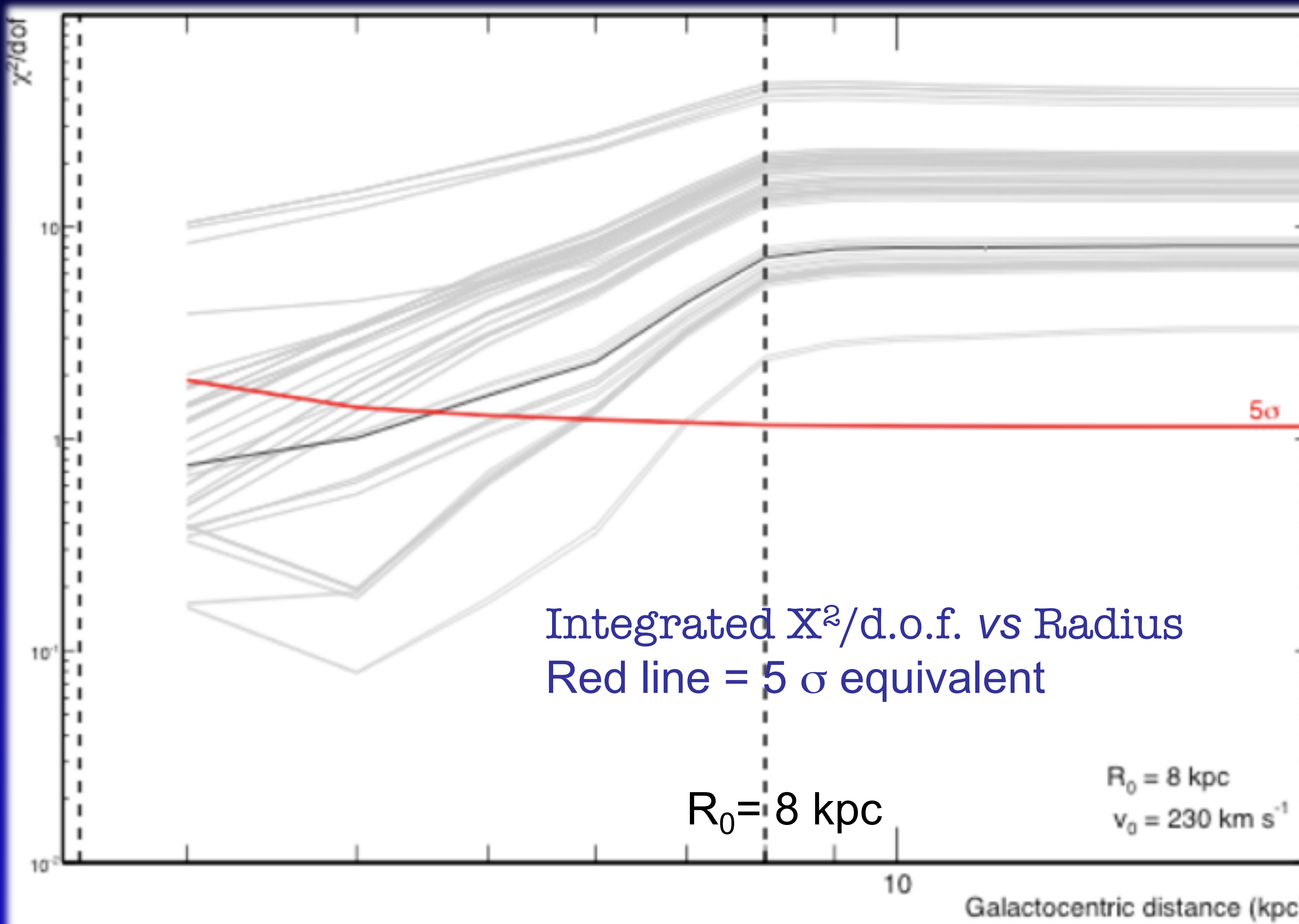
The Milky Way:
testing expectactions
(with no additional assumptions)
((and some technical detail))

- Computing the "badness-of-fit" (discrepancy) of each baryon rot. curve (no DM!!) to observed one

- One COULD bin (and we have done it) but loss of information: using 2D chi-square (uncertainties on R, as well)

$$\chi^2 = \sum_{i=1}^{N} d_i^2 \equiv \sum_{i=1}^{N} \left[\frac{(y_i - y_{b,i})^2}{\sigma_{y,i}^2} + \frac{(x_i - x_{b,i})^2}{\sigma_{x,i}^2} \right]$$

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

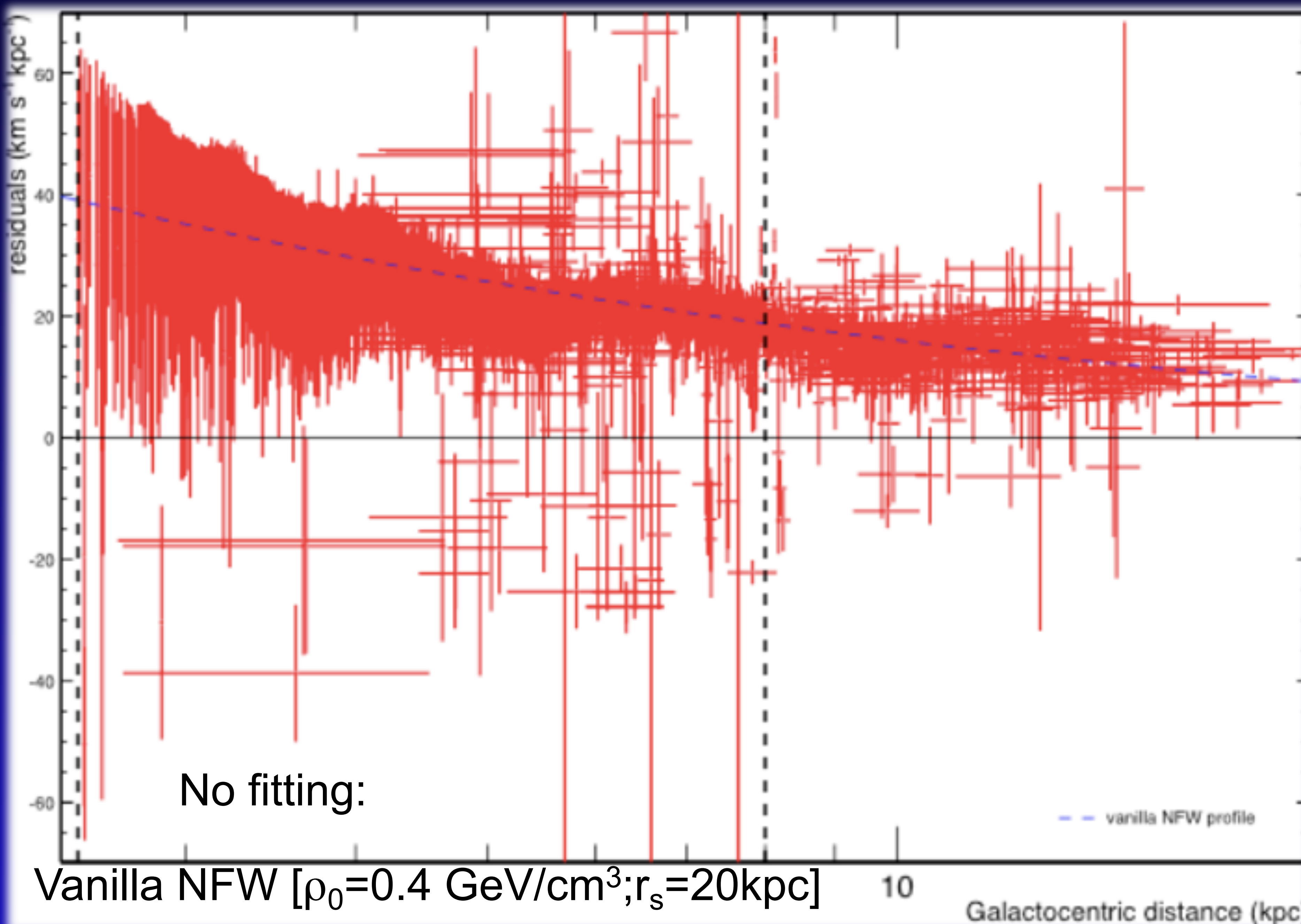


Answer is NO:

Every single model above 5 σ, already at $R<R_0$!!

[Iocco, Pato, Bertone, Nature Physics 2015]

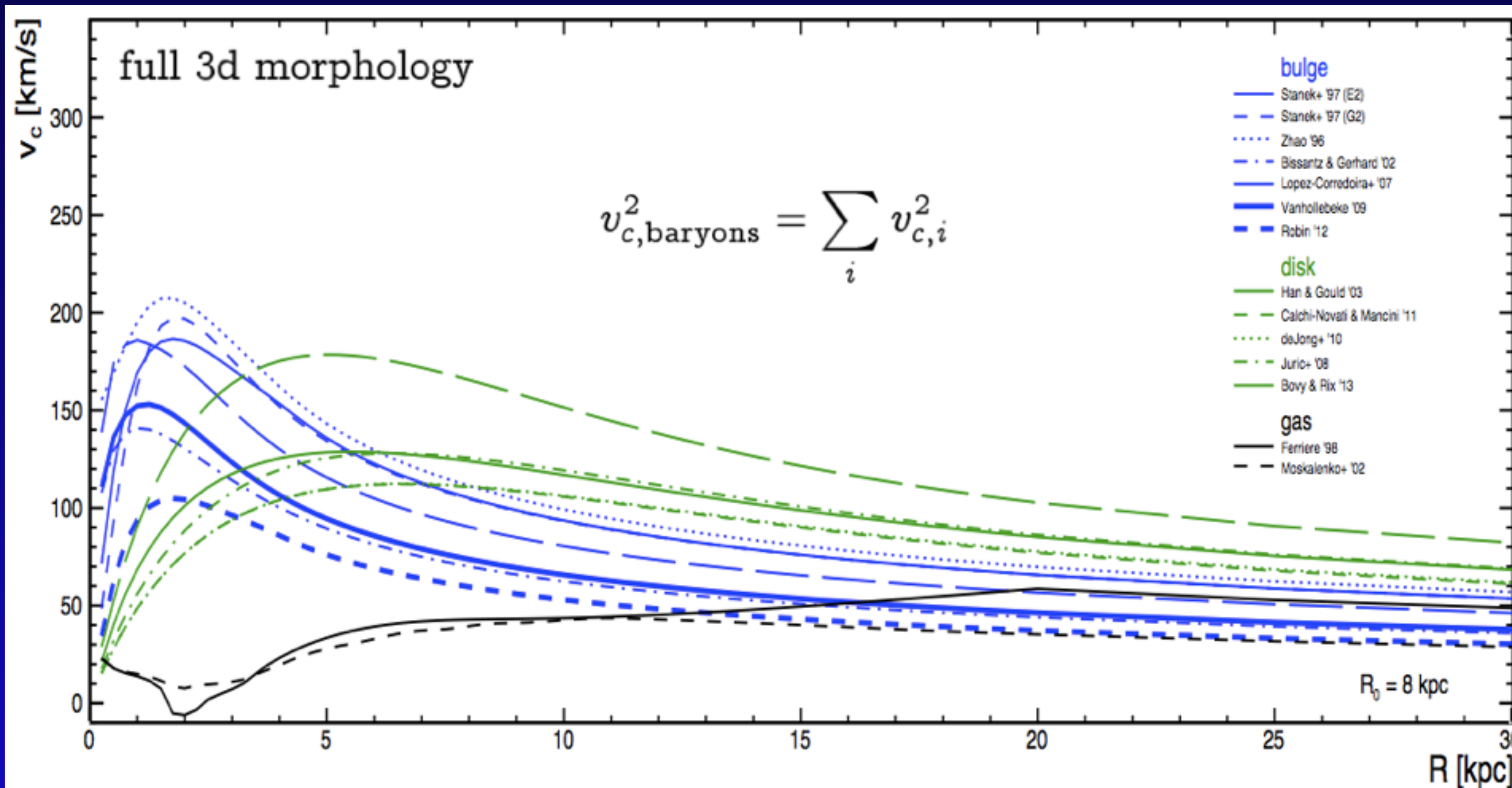
Motivating dark haloes



$$v_{Residual} = (v^2_{tot} - v^2_{bar})^{1/2}$$

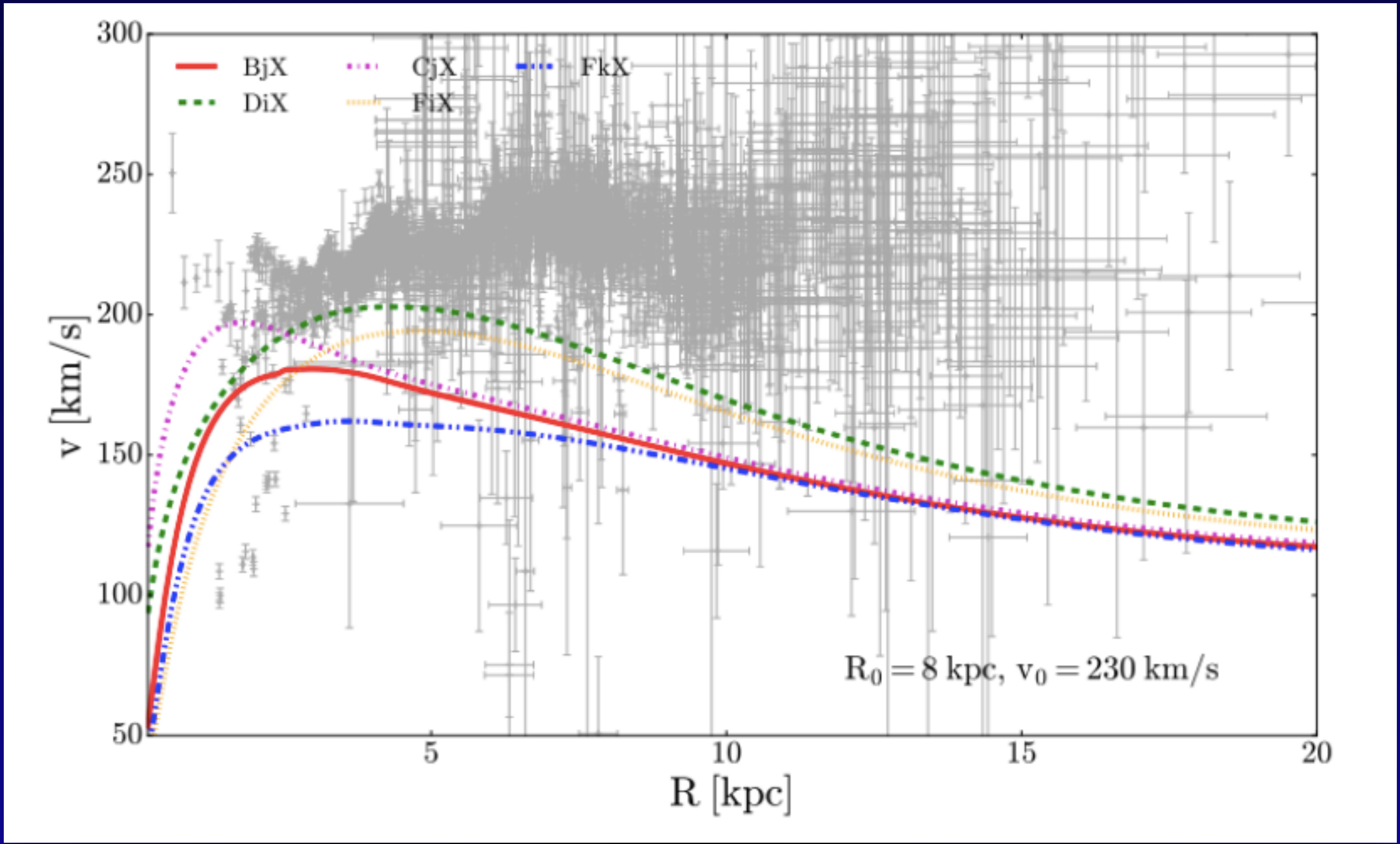
There's more than you are usually told: visible morphology is uncertain

(and don't forget the dependence on Gal Parameters)



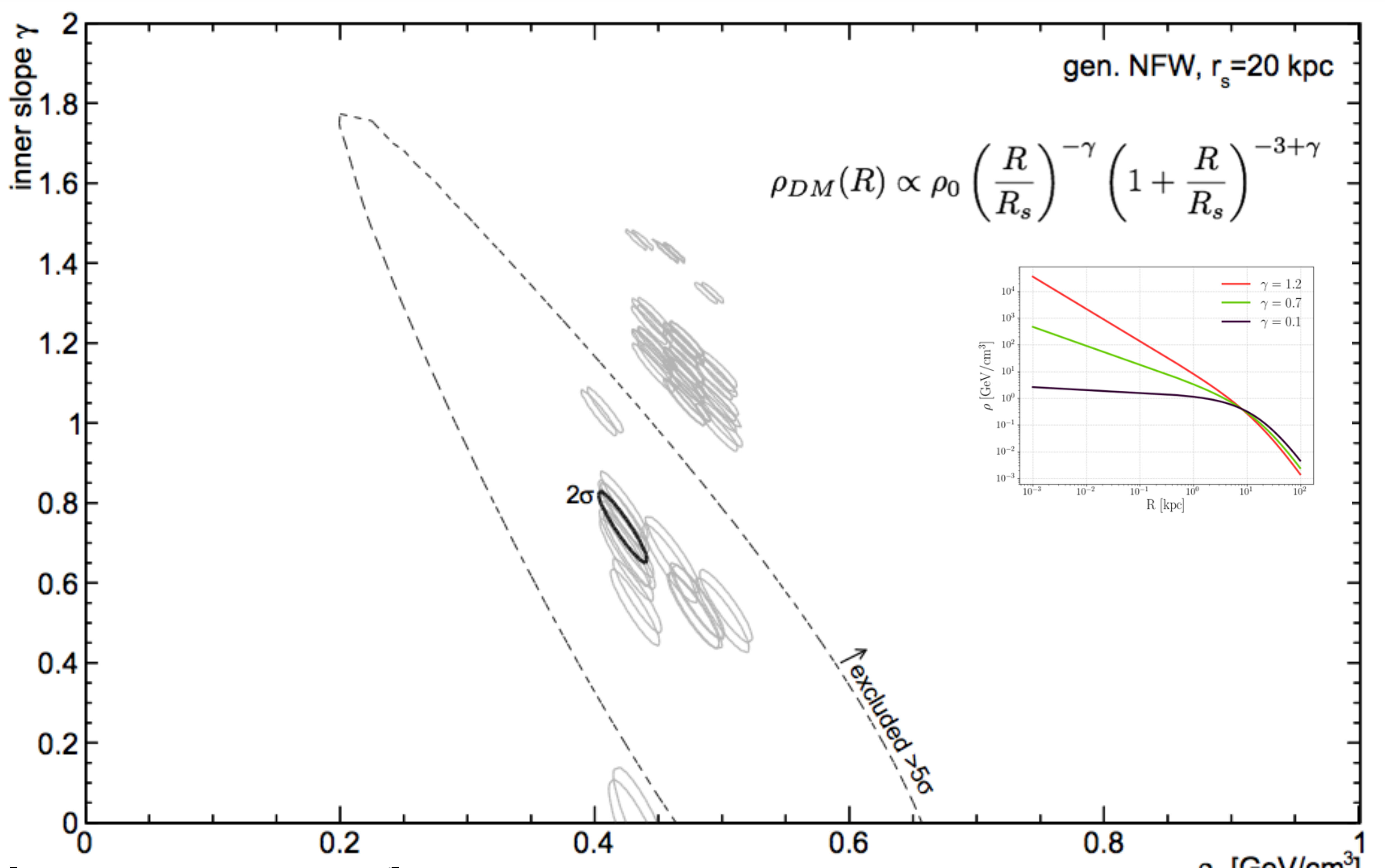
[Iocco, Pato, Bertone, Nature Physics 2015]

Systematic uncertainties
(luminous component)



[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017] [Iocco, Pato, Bertone, Nature Physics 2015]

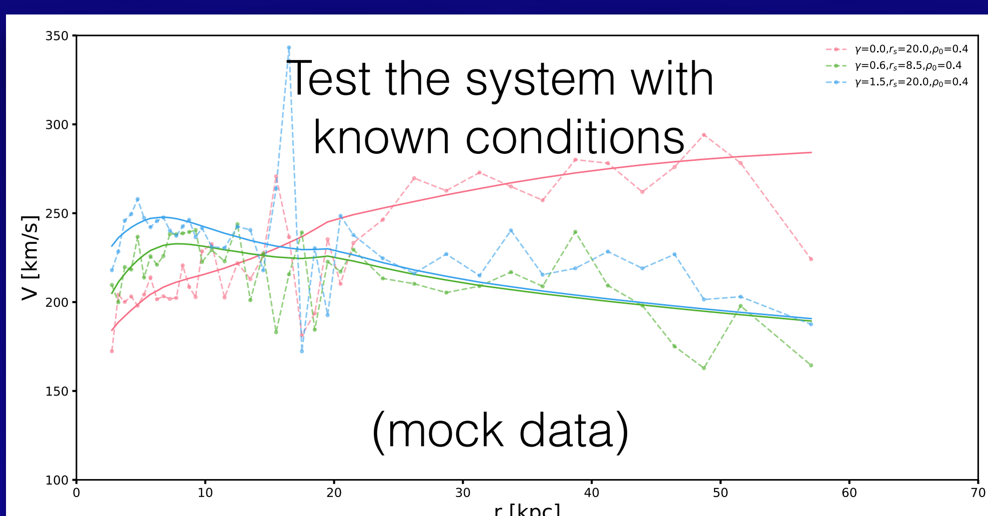
Extracting the DM density structure

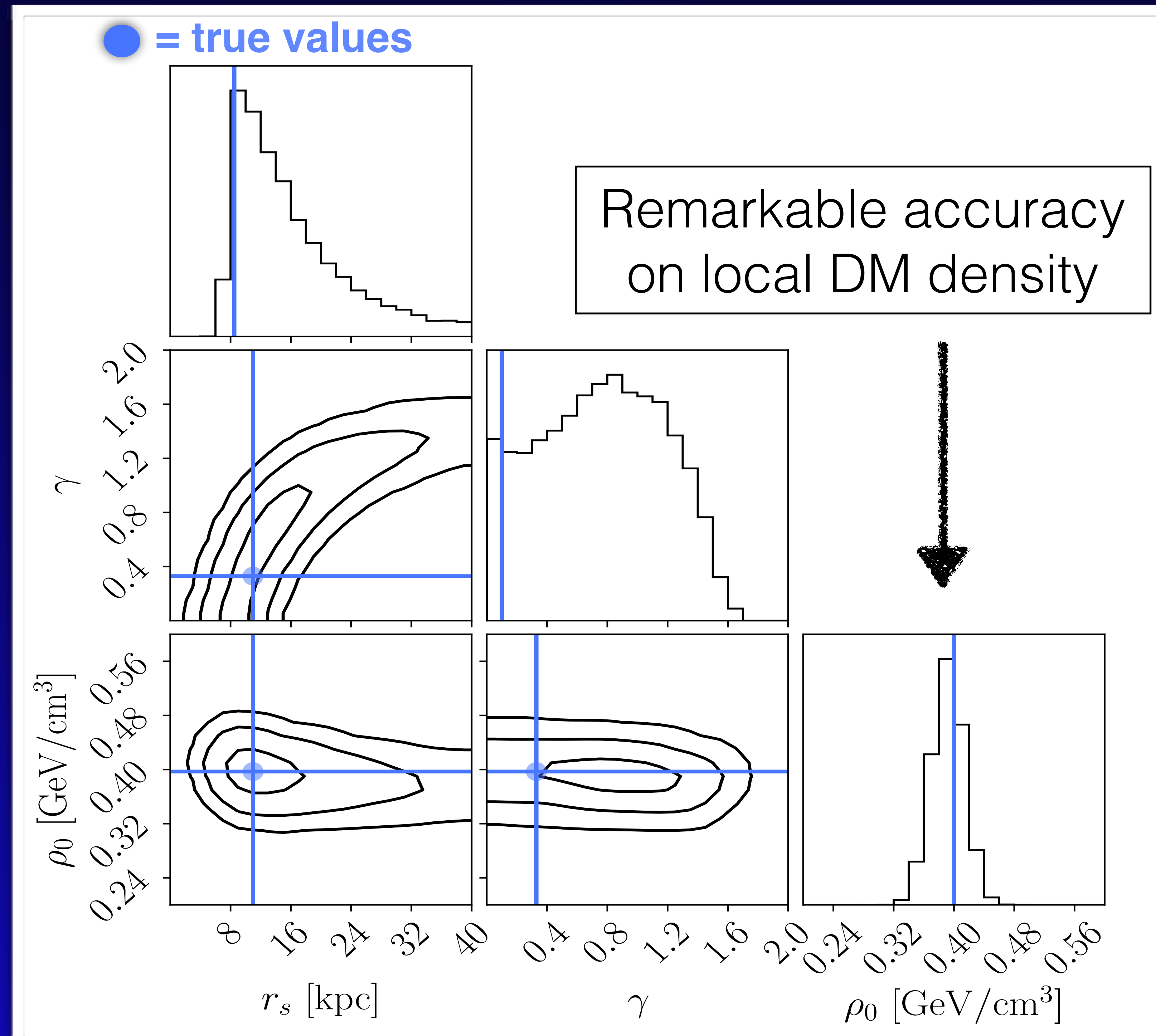


[Pato, Iocco, Bertone, 2015]

Is our measurement correct?

Our instrument is very precise. Is it accurate?





[E. Karukes, M. Benito, F. Iocco, A. Geringer-Sameth, R. Trotta] arXiv:1901.02463

full Bayesian framework

About the Galactic Center:

assumptions for Rotation Curve method fail

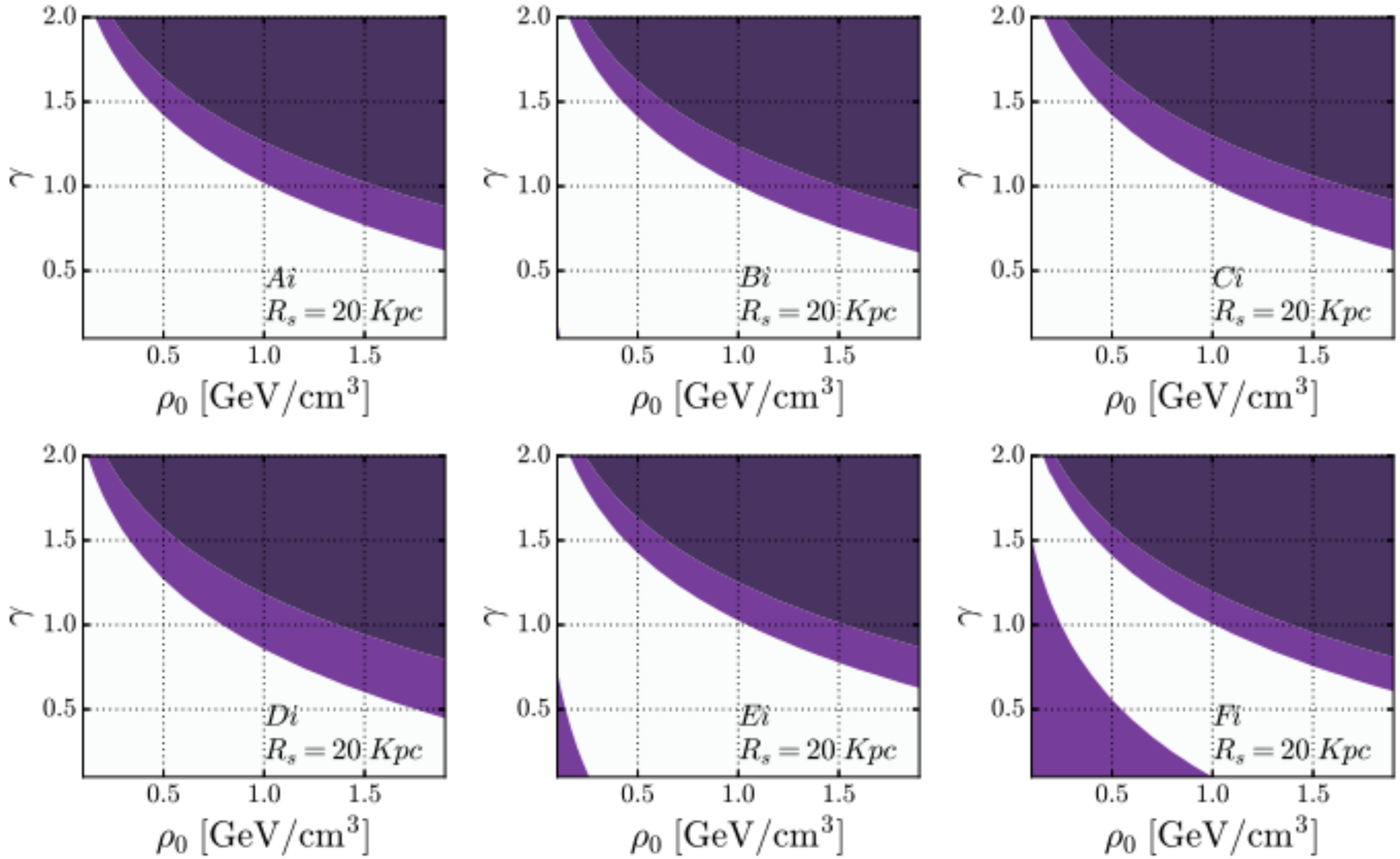
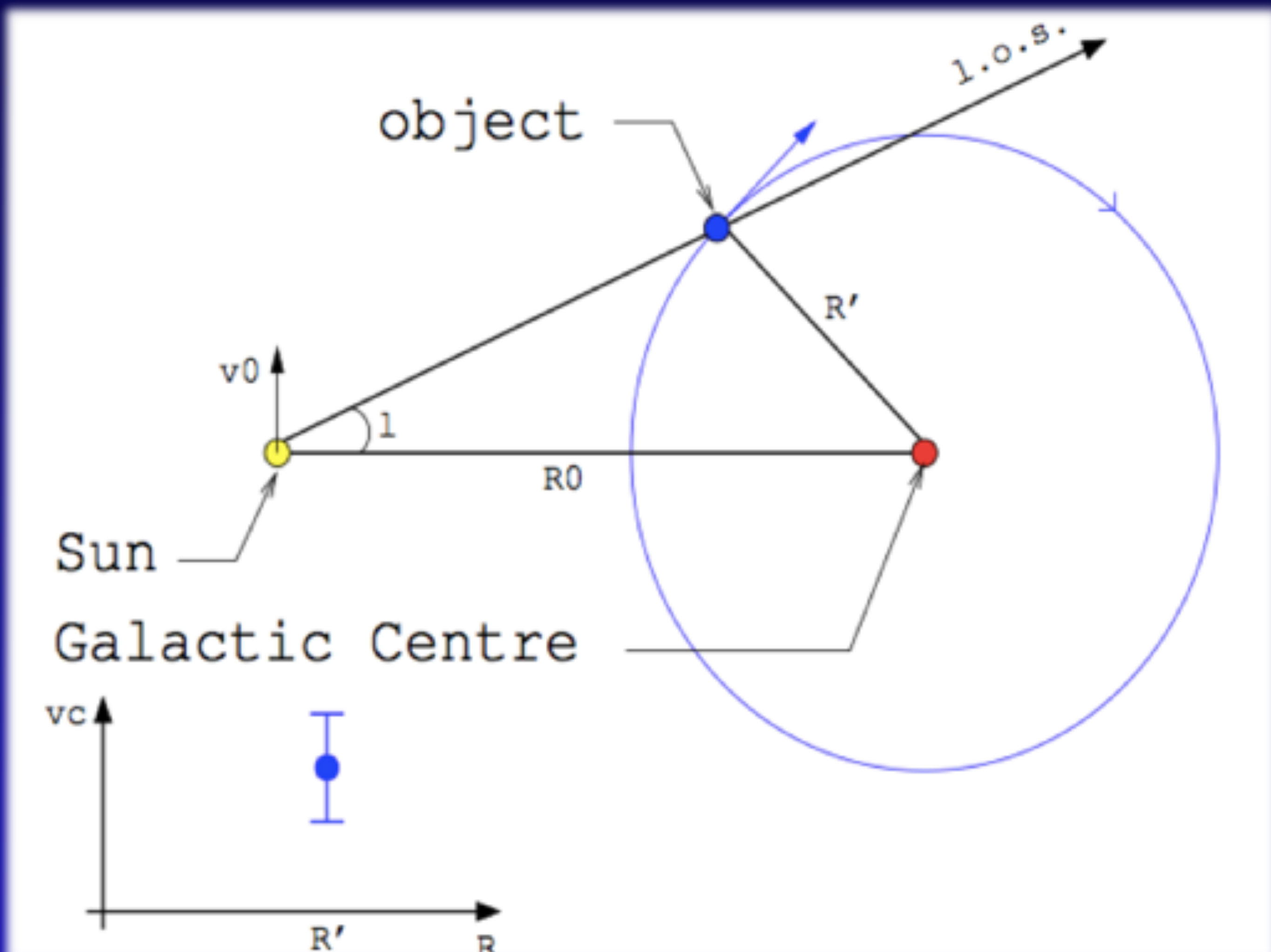


Figure 1: Constraints in the gNFW parameter space, for an assigned value of R_s=20kpc. Different panels show the result of changing bulge morphologies. The disc component is fixed to [26].

[Iocco & Benito, PDU 2017, arXiv:1611.09861]

Adopting different technique, in a baryon dominated region: huge uncertainties on determination of slope “gamma”

The Milky Way:
observed rotation curve
I. principles



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

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

Cuncta stricte

- The existence of a gravitational/non-EM interacting species is solid on vaste range of scales.

- The Milky Way is one excellent probe of the above, among others.

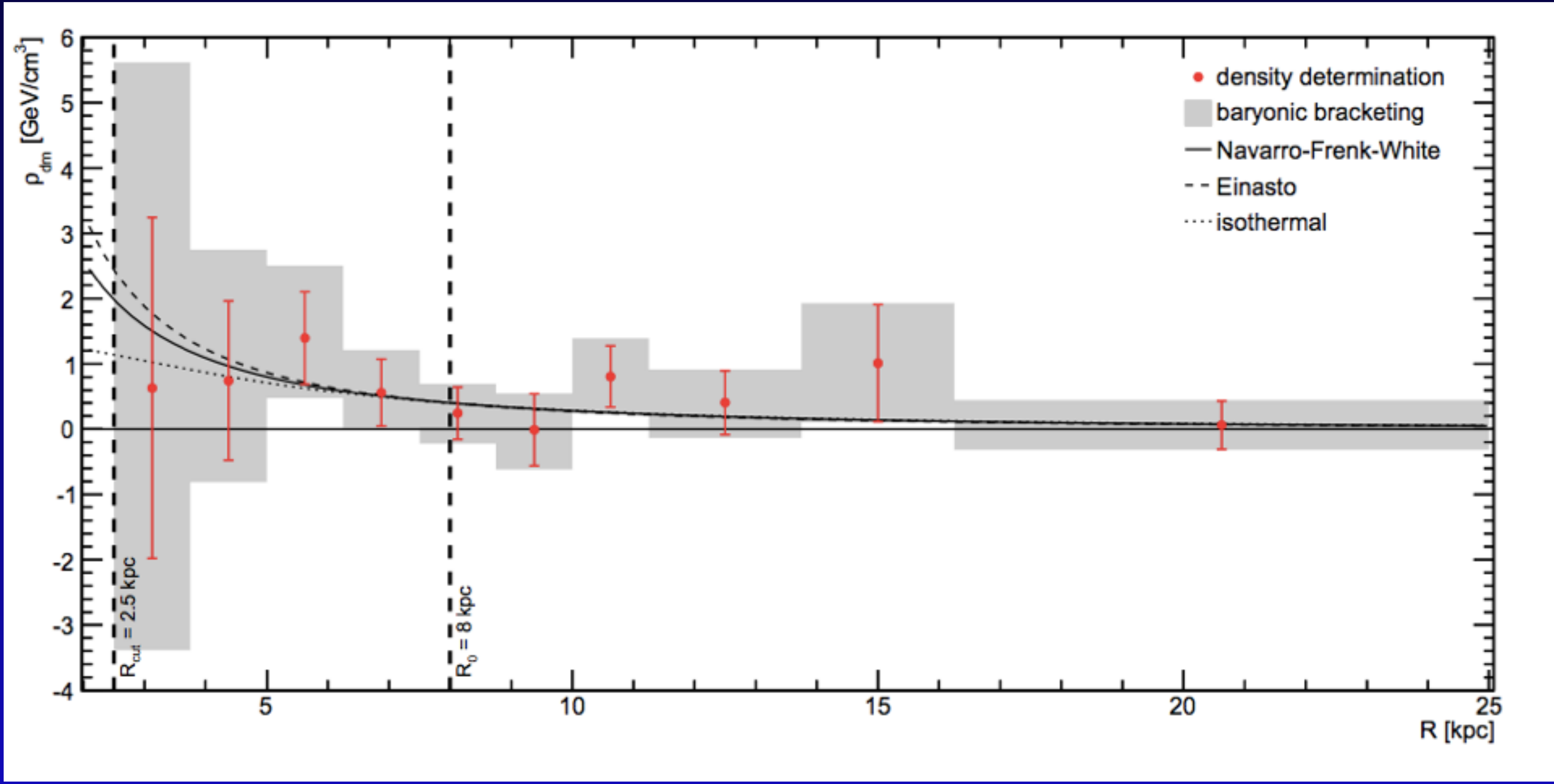
- It is possible to determine the distribution of DM in the Milky Way, with a data-only-driven methodology.

- Systematics over the visible component of the Milky Way are one of the major sources of uncertainty, yet not the only.

- The local DM density is reconstructed with remarkable precision and accuracy.

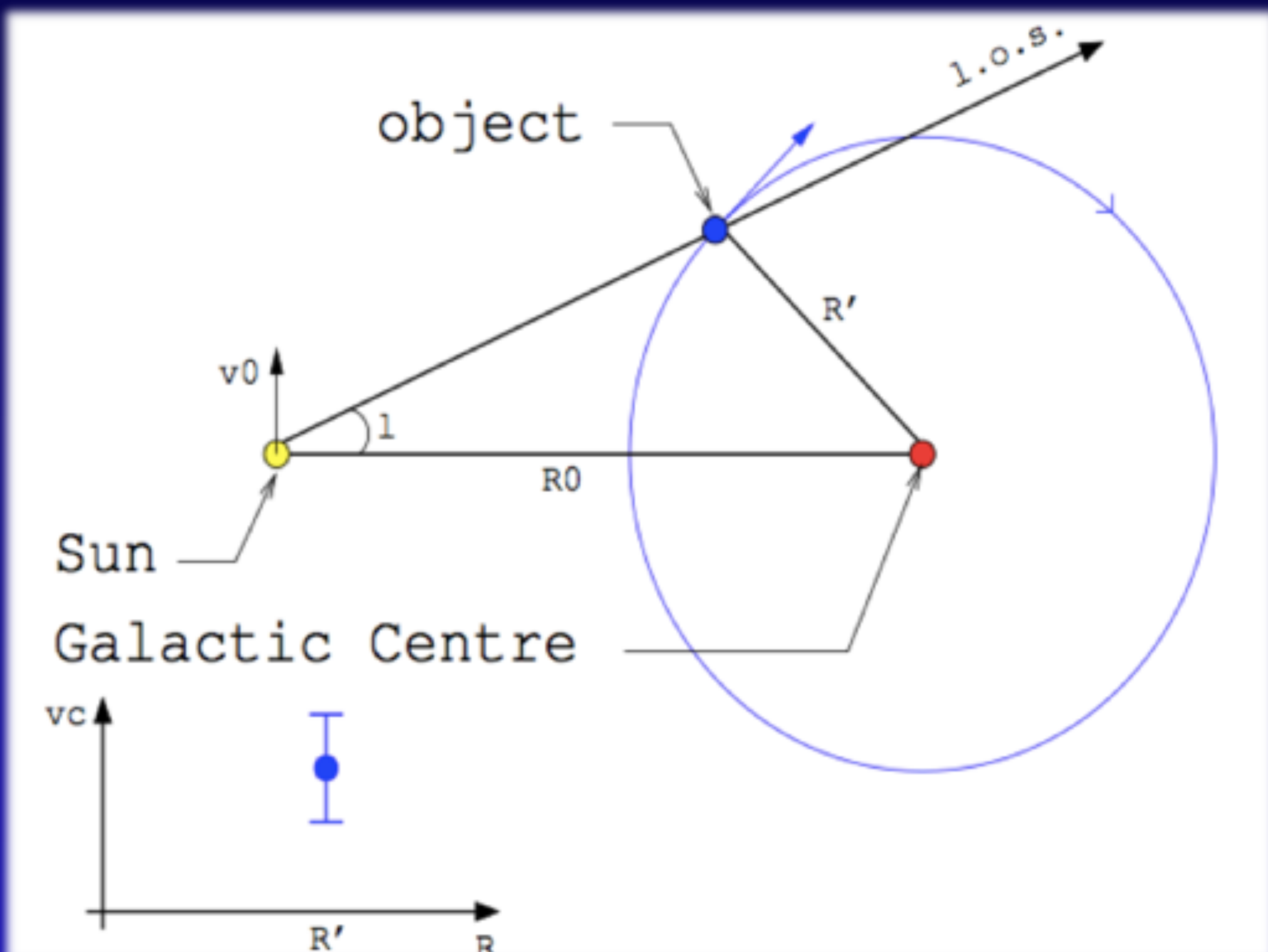
- Effects of all the above on the determination of new physics: Maria Benito's talk on Wednesday

“Mom look, no hands!”
A non-parametric reconstruction of the DM profile



[Pato & FI, 2015]

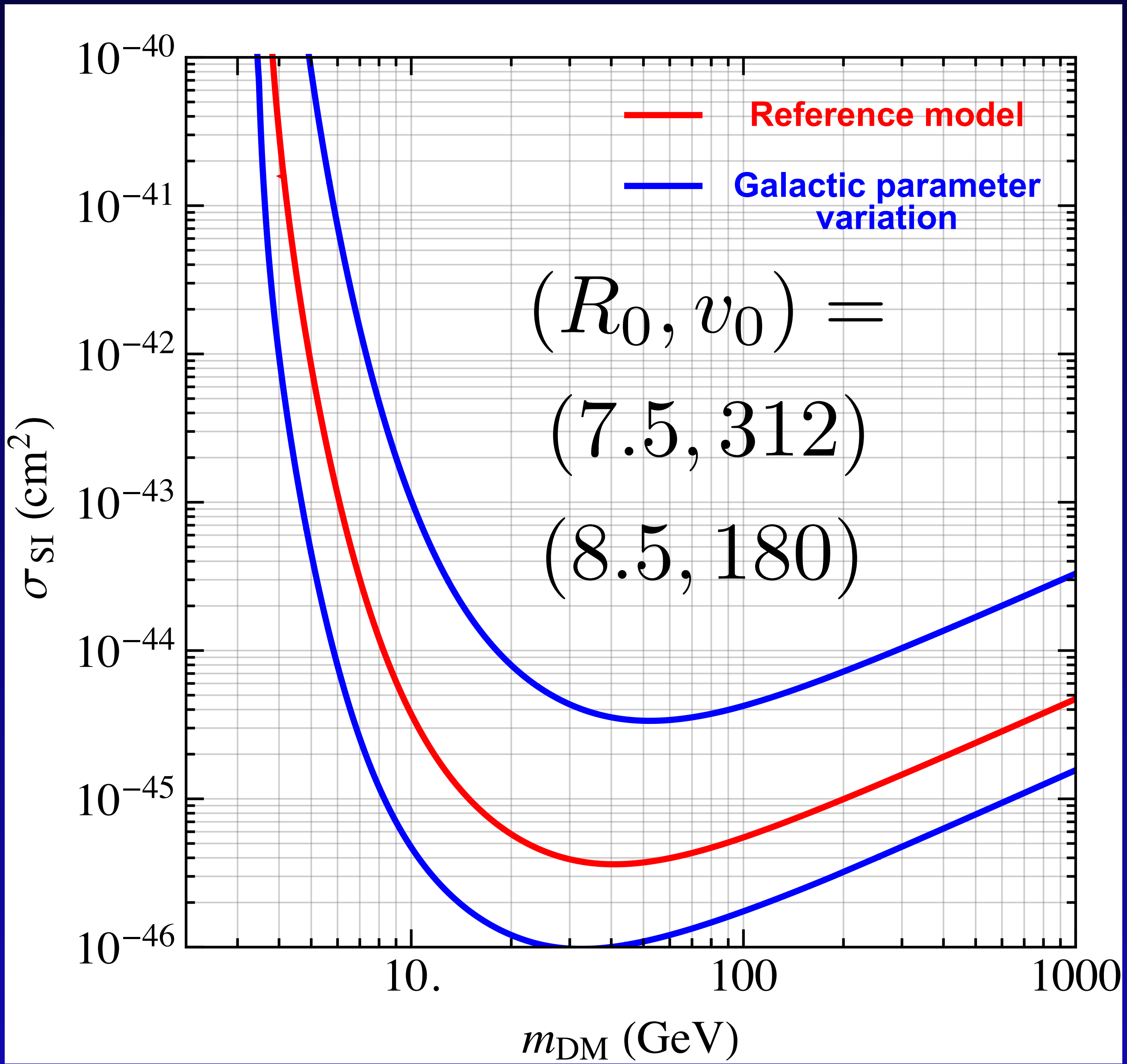
The Milky Way:
observed rotation curve
I. principles



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

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

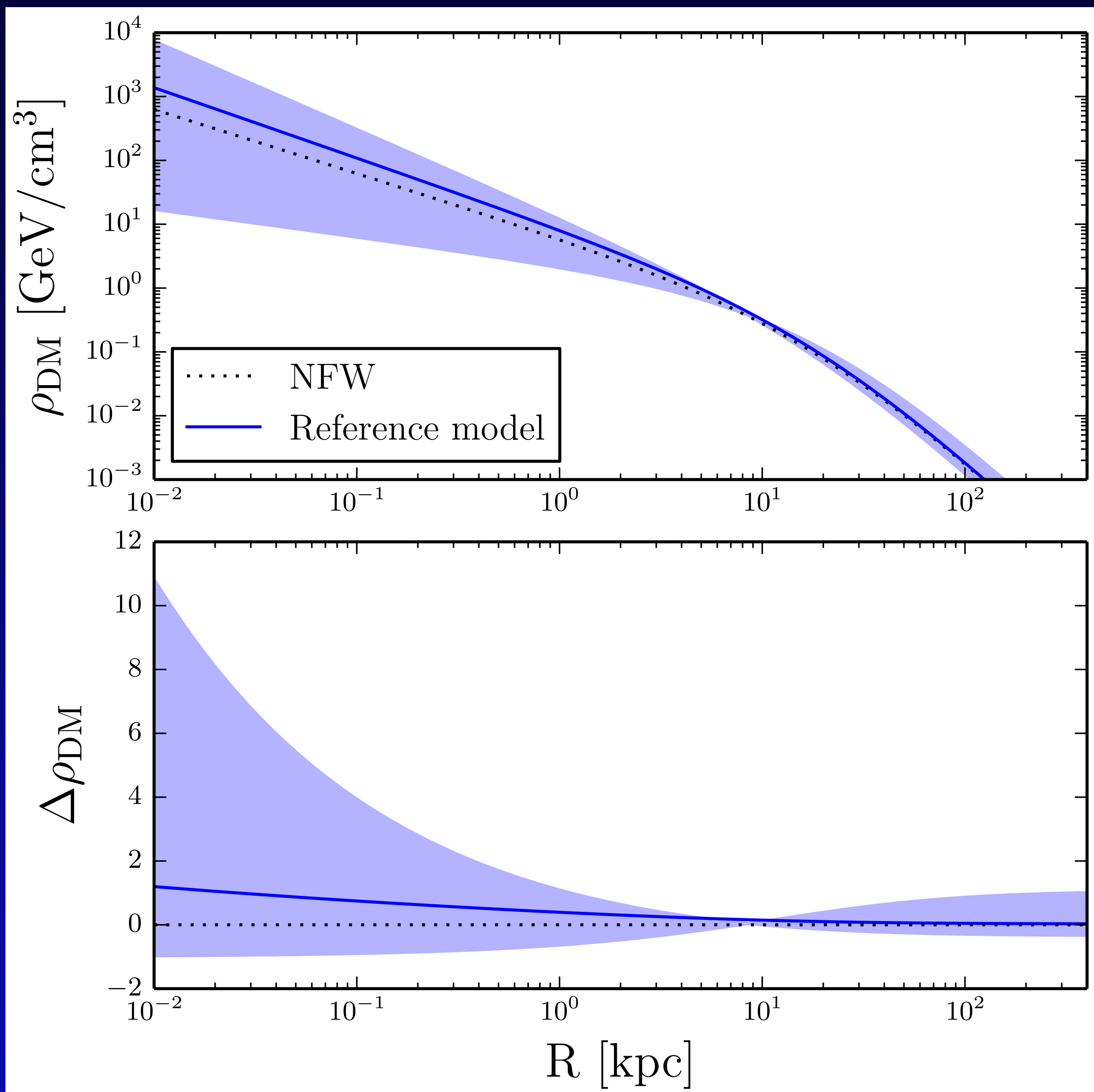
It is well known that uncertainties affect Direct Detection

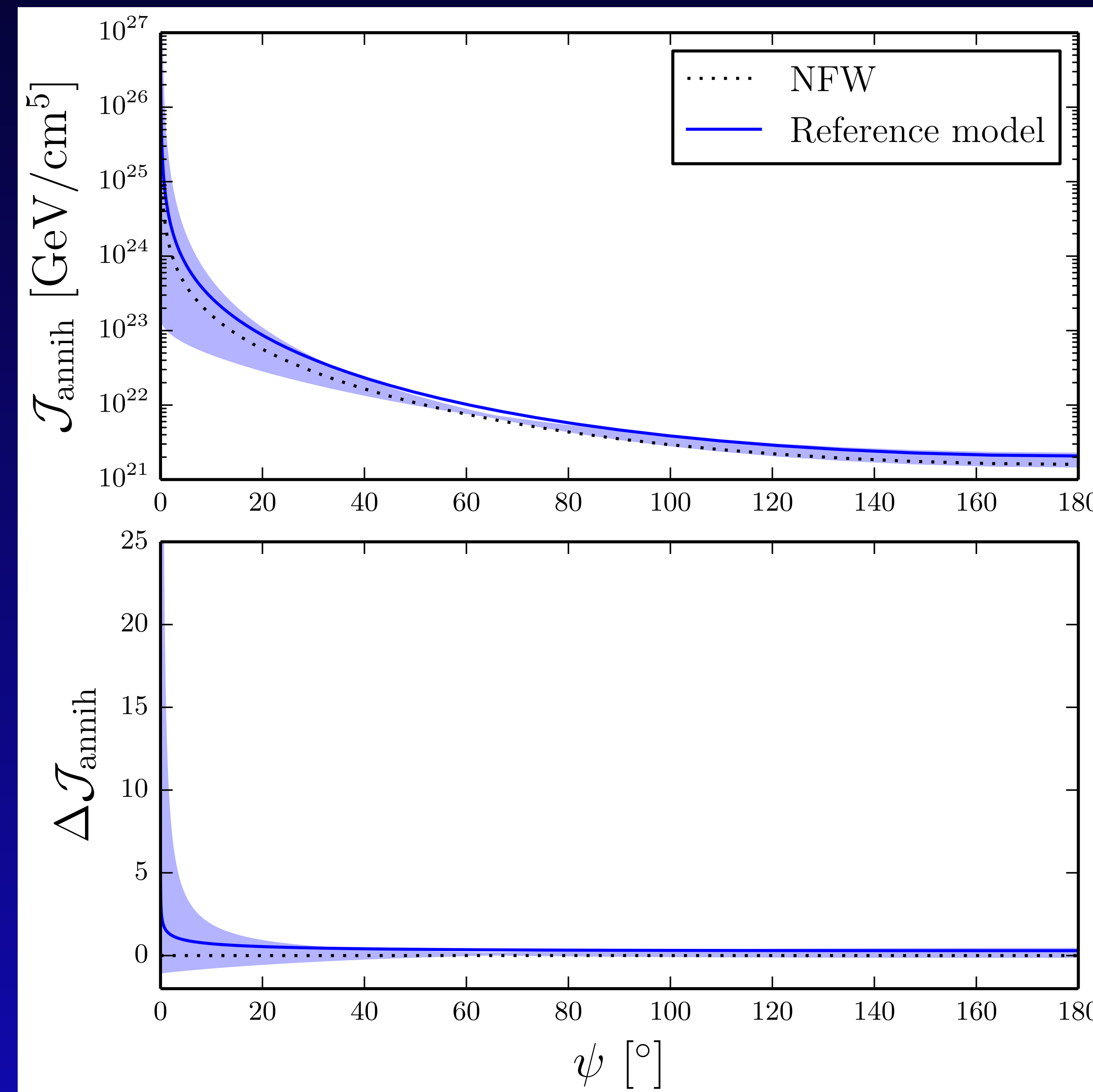


Current LUX limits, varying astrophysical uncertainties

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

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

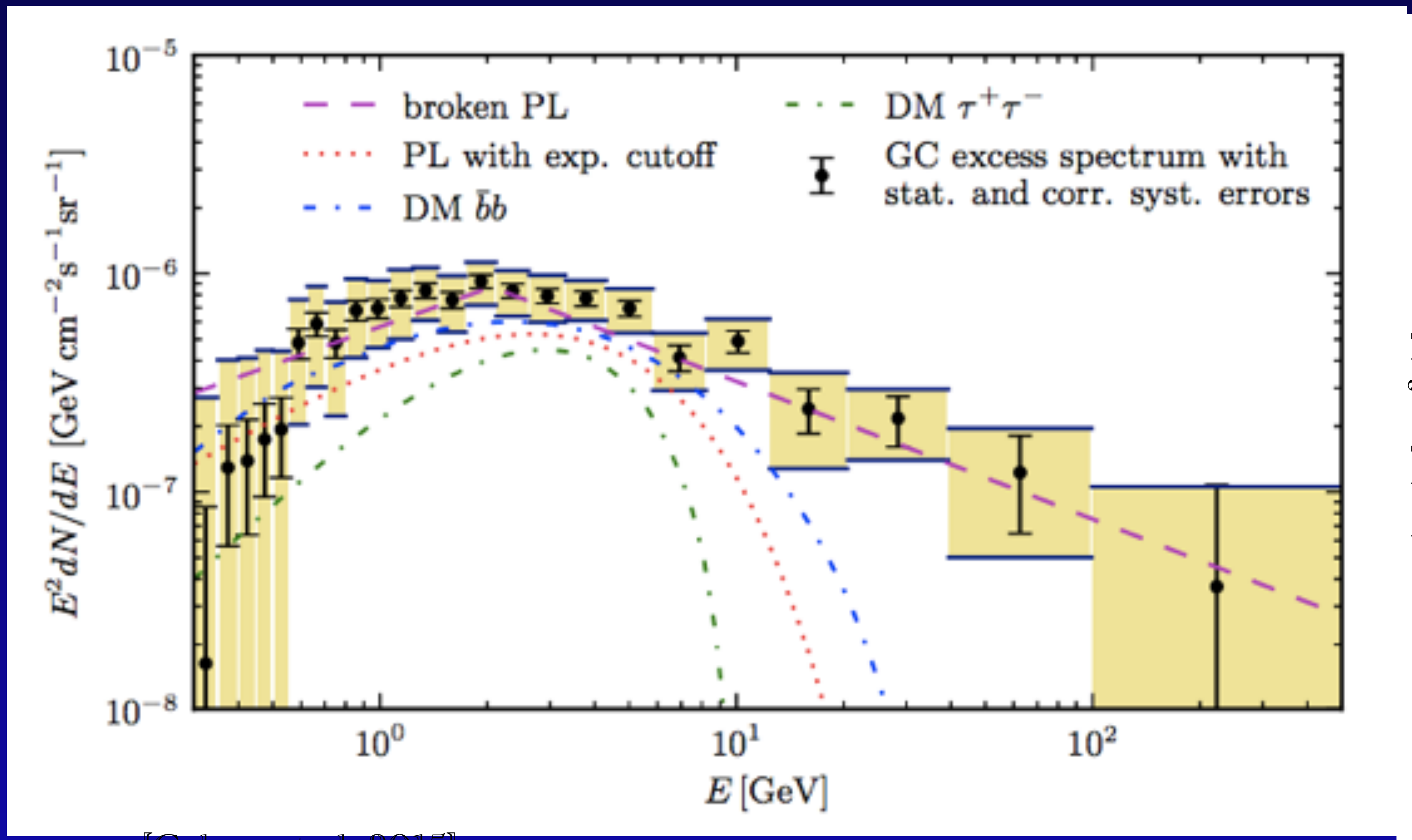




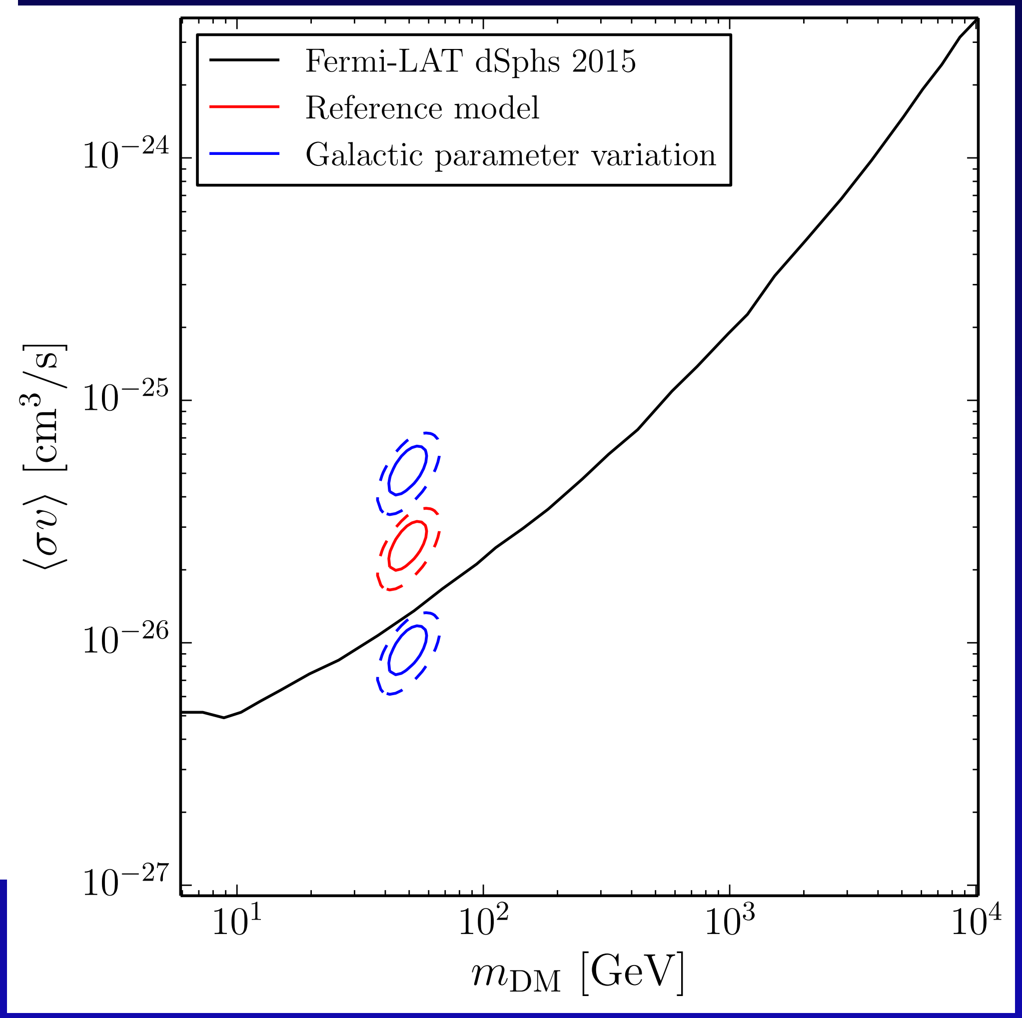
$$J_{annih} \propto \int_{los} \rho^2(r) dV$$

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

It is well known that uncertainties affect inDirect (some more, some less) and its interpretation



[Calore et al, 2015]



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

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

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

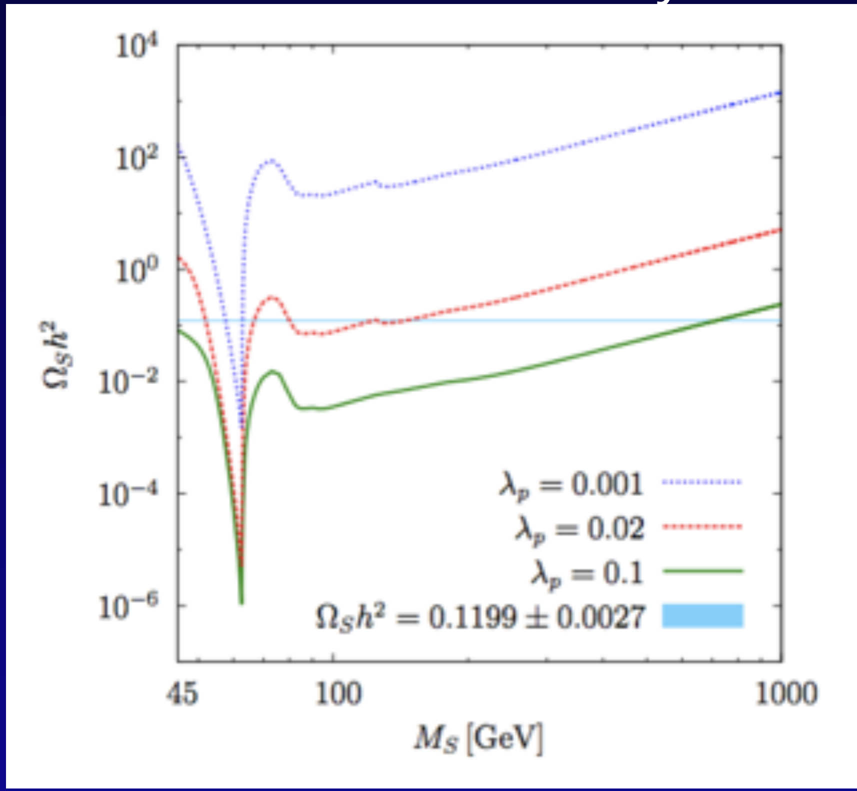
$v_H = 246\ \mathrm{GeV}$ $\langle S \rangle = 0$

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

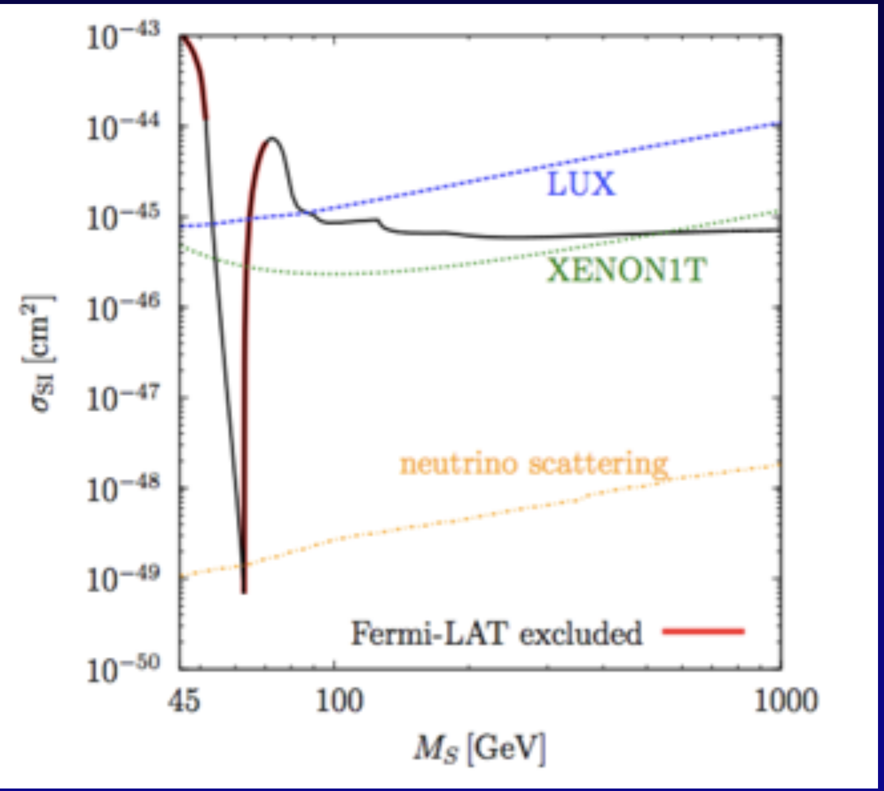
"Wimp phenomenology" entirely dictated by the Higgs coupling and physical DM mass.

Constraints and interplay of experiments

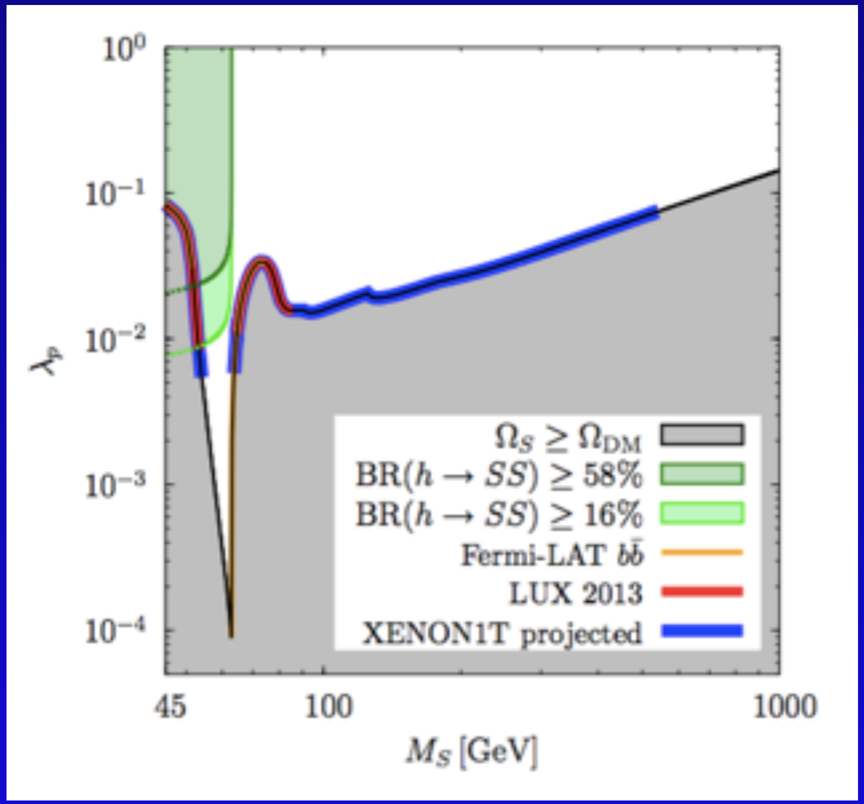
Relic density



Direct detection



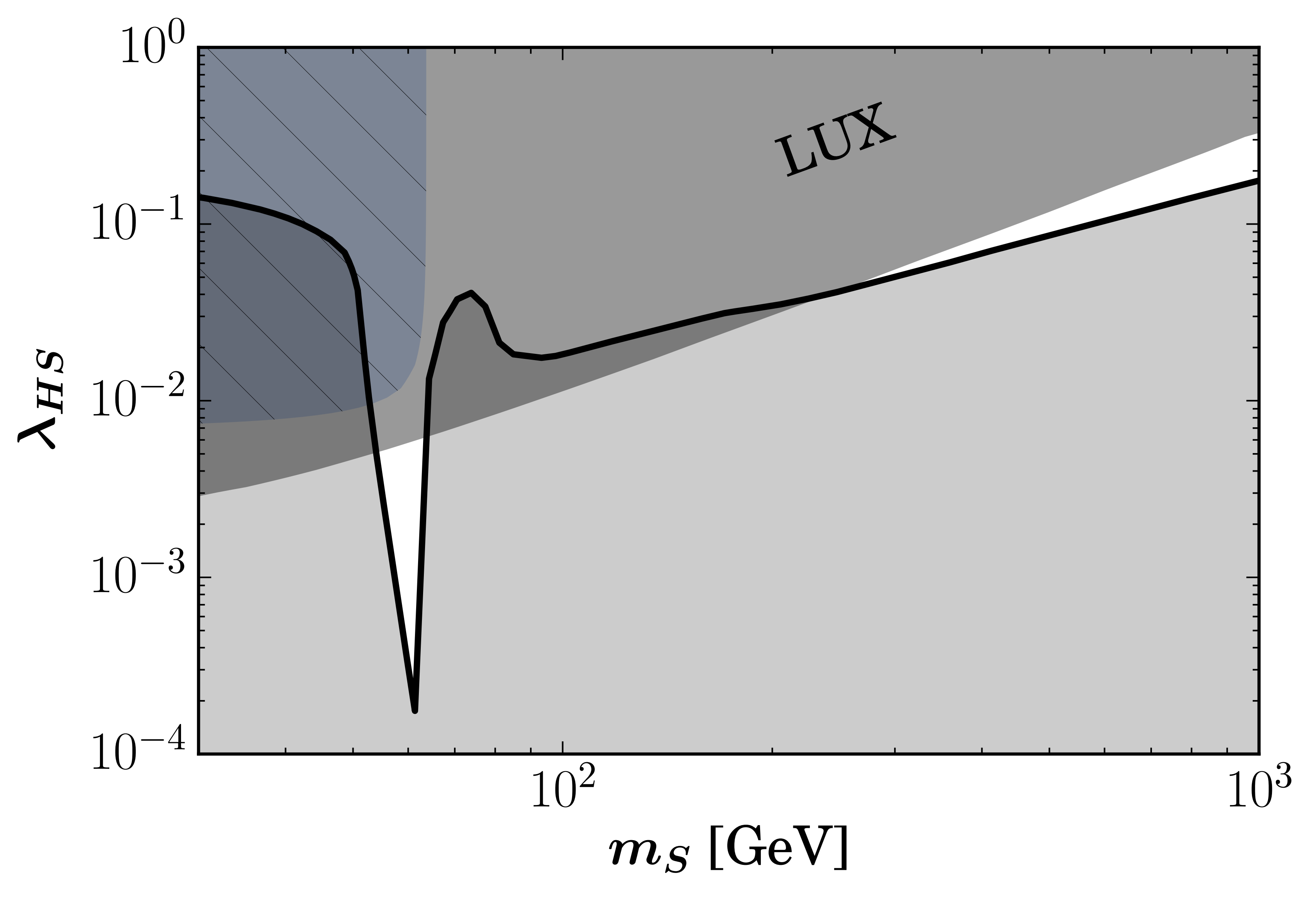
Combined



[Duerr et al, 2015]

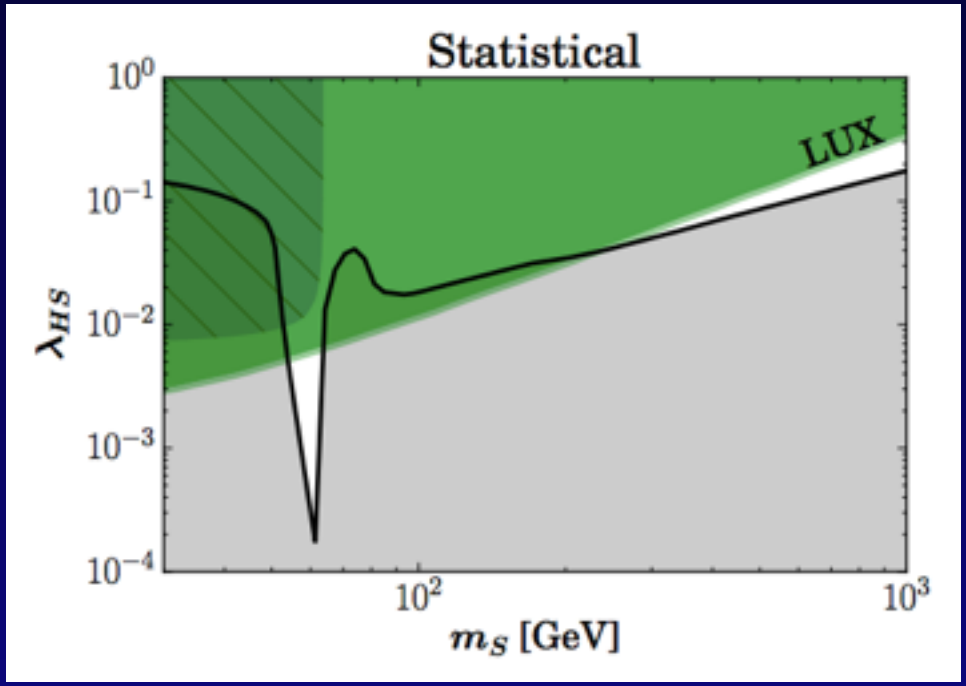
Constraints and interplay of experiments

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



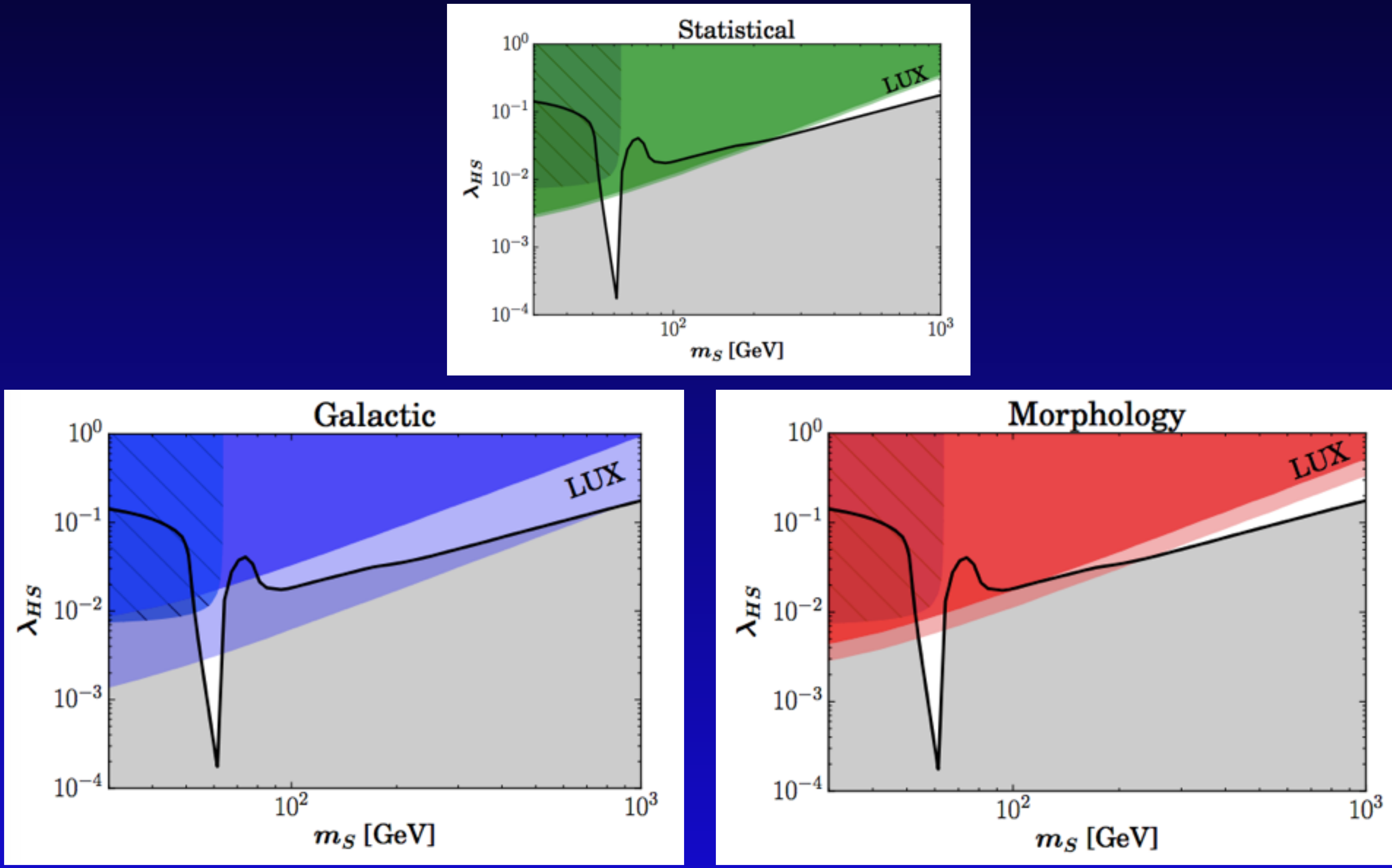
[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

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



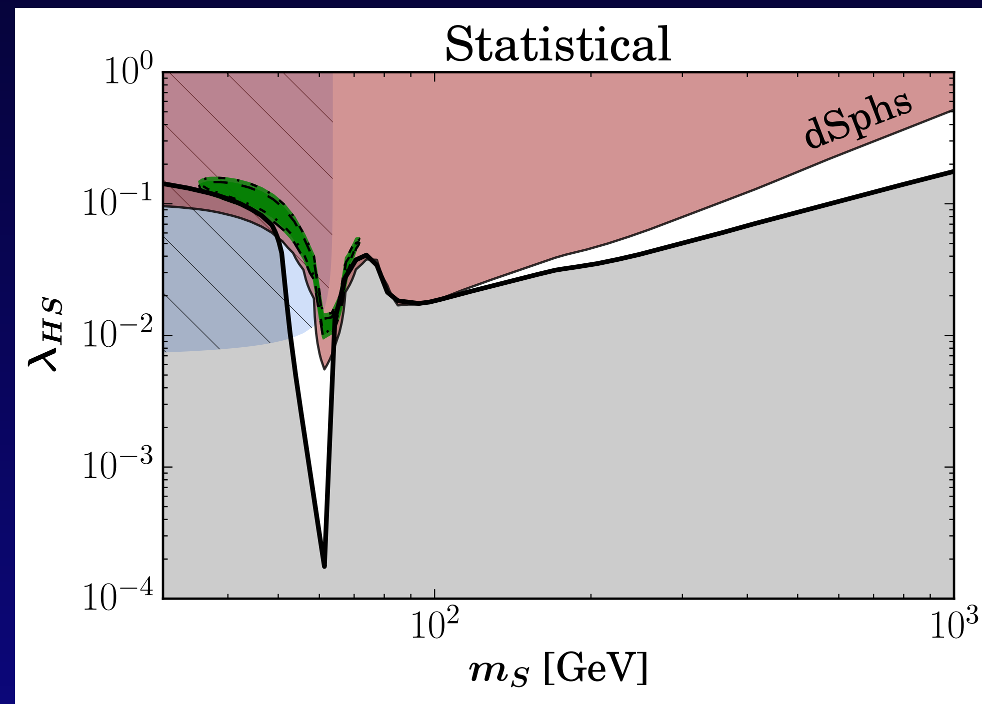
[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

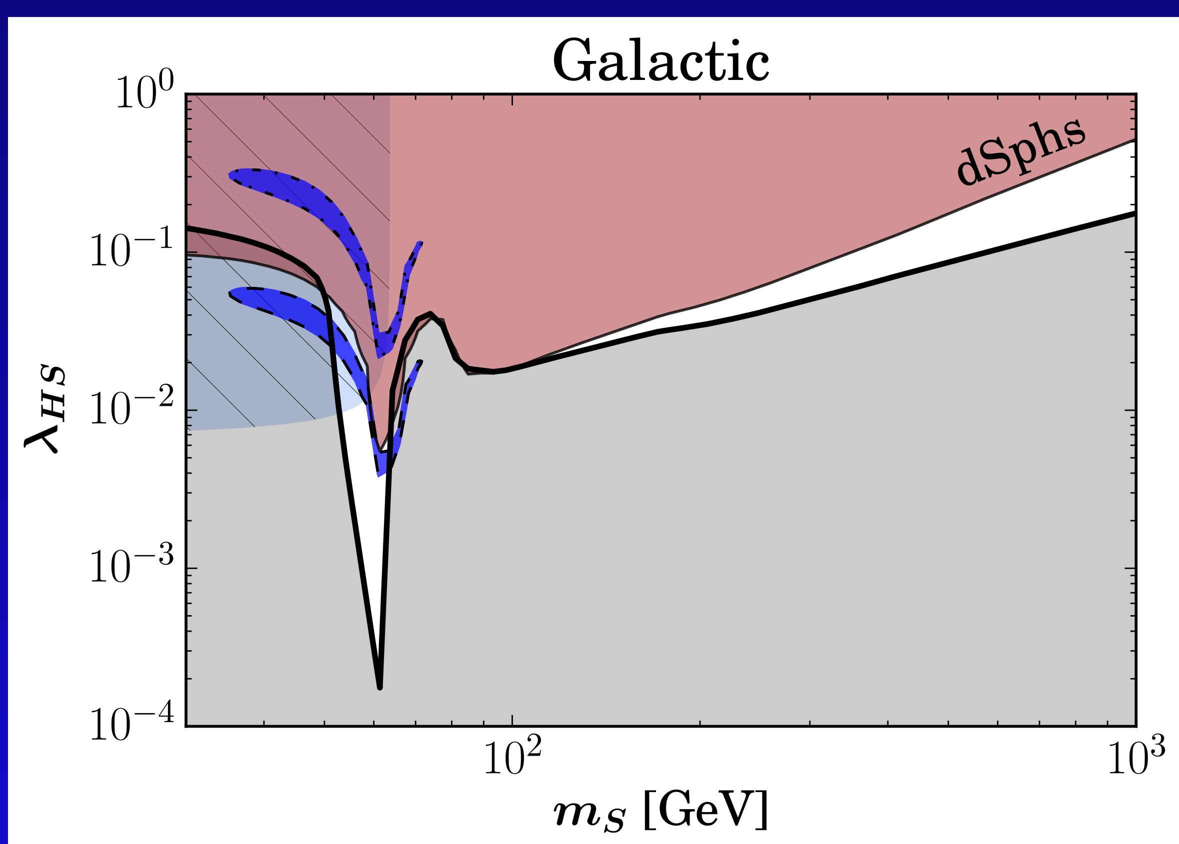
Let's look at the effect of astrophysics uncertainties: Direct Detection

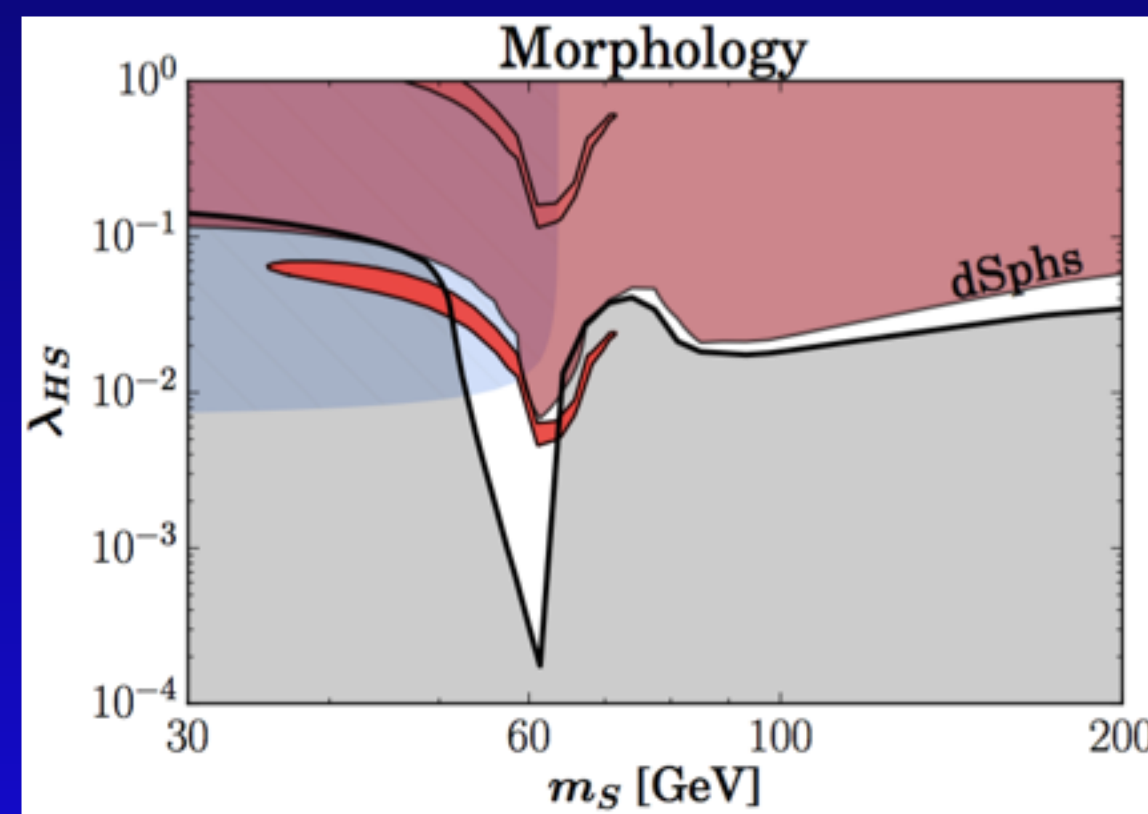


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

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







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

Cuncta stricte

- The existence of a gravitational/non-EM interacting species is solid on vaste range of scales.

- Astrophysics and Cosmology are in very good agreement with the scenario of a warm/cold particle constituting the backbone of cosmic structures.

- We are still ignorant over the very nature of this particle(s), but there's plenty of options.

- We are starting now to achieve sensitivity with a host of probes (not only colliders) on the core region of one of the most popular scenarios.

- Astrophysical uncertainties are actually affecting determination of PP, in virtuous interplay with collider physics, direct and indirect probes.

- Much to learn ahead, from Earth and Skies. Working together.

Advertisement

International Centre for Theoretical Physics
South American Institute for Fundamental Research

São Paulo (not Rio!), Brazil

- School on DM and neutrinos
  July 23-August 3, 2018

http://www.ictp-saifr.org/school-on-dark-matter-and-neutrino-detection/

Alright: Google it

Advertisement

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

São Paulo (not Rio!), Brazil

- Second South American DM workshop
  November 21-23, 2018

http://www.ictp-saifr.org/DMw2018