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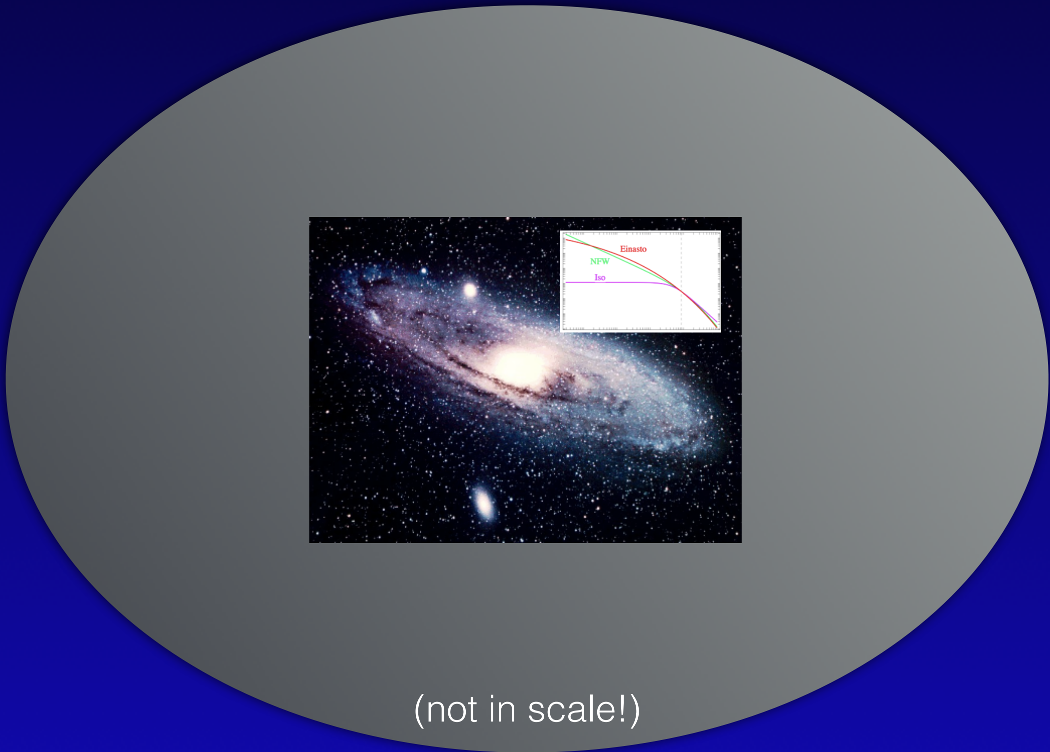
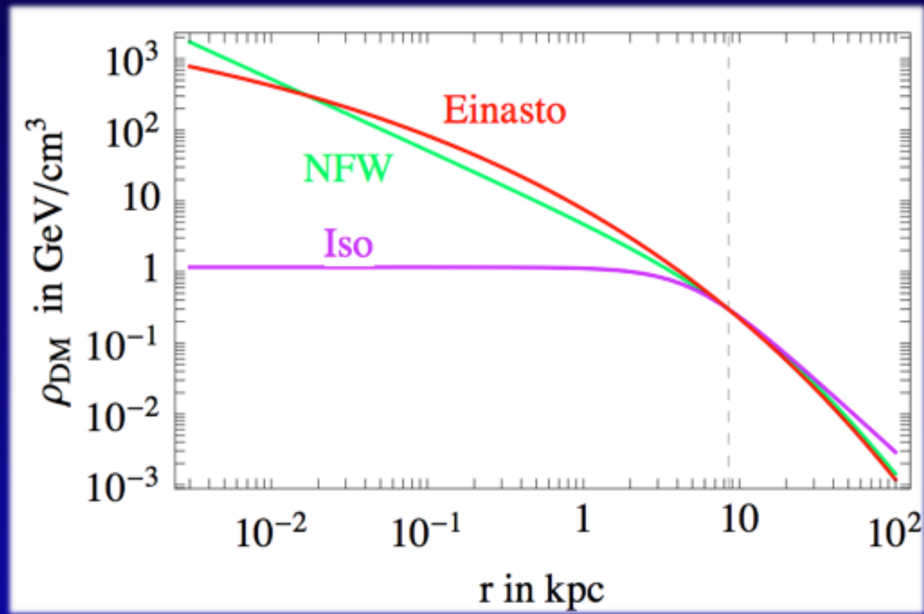
ICTP SAIFR International Centre for Theoretical Physics South American Institute for Fundamental Research

DSU 2019, July 17
Buenos Aires

A story of LCDM
the single halo

A "universal" DM profile?

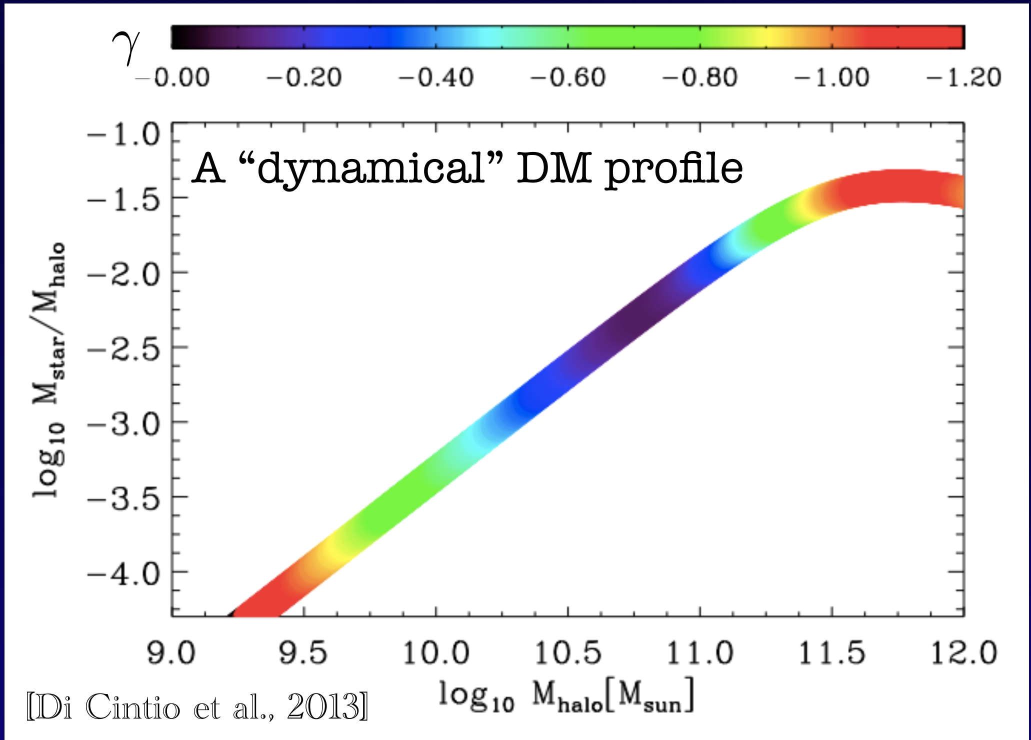




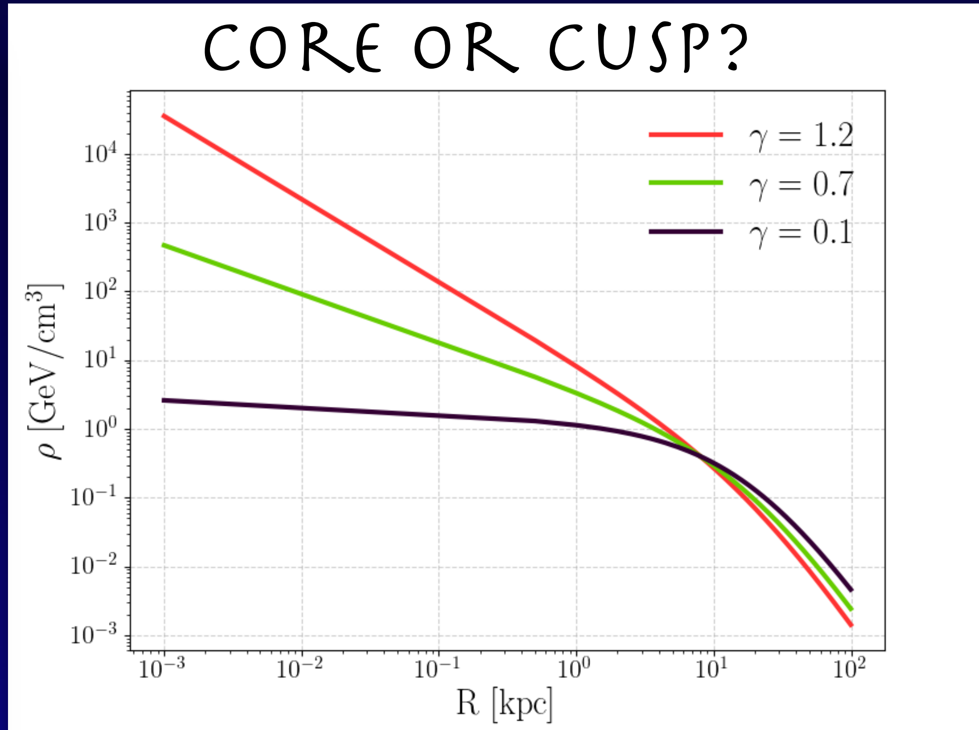
NAVARRO-FRENK-WHITE

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

A story of LCDM
the dark matter distribution



[Di Cintio et al., 2013]



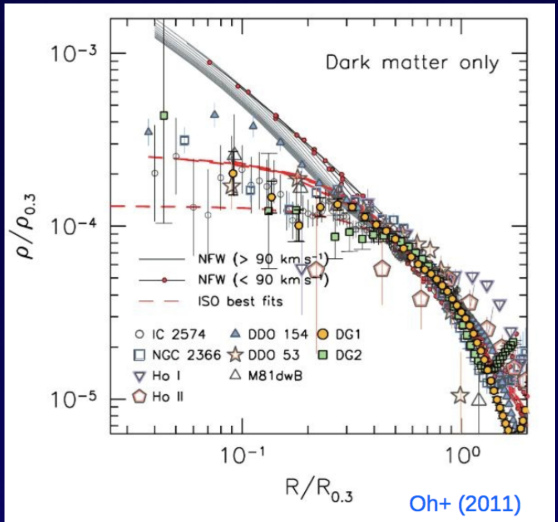
generalized NFW

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

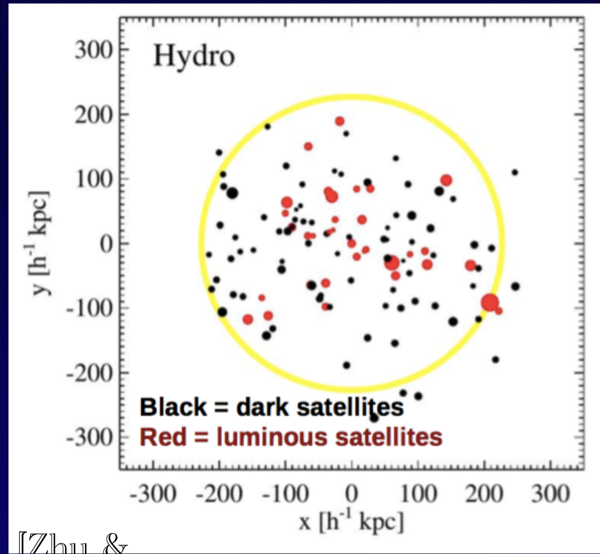
See talks by
J. Navarro
S. White

A story of LCDM
the small scale problems

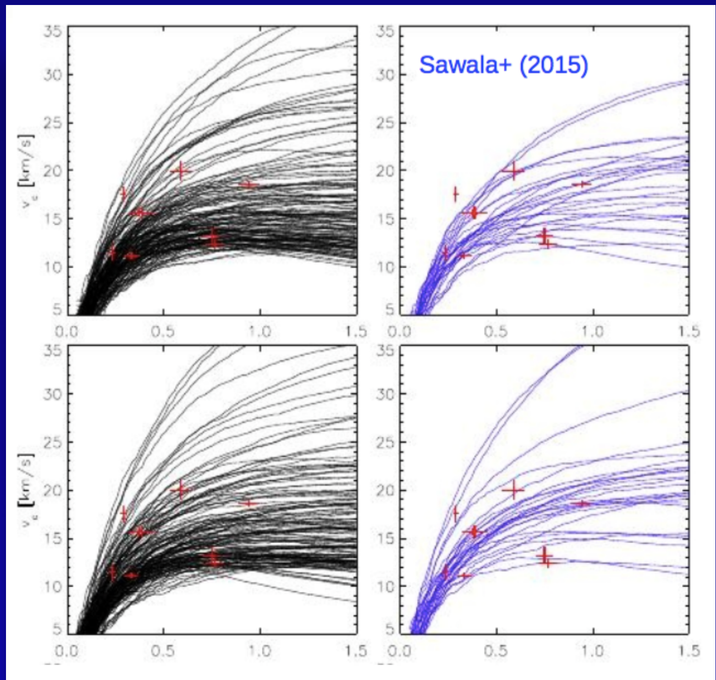
Cusp vs core



Missing satellite



Too big to fail



…and more:

See talk by
J. Navarro

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…

The Milky Way:
una mirada desde el Sur

...Ya nunca alumbraré con las estrellas
nuestra marcha sin querellas
por las noches de Pompeya...

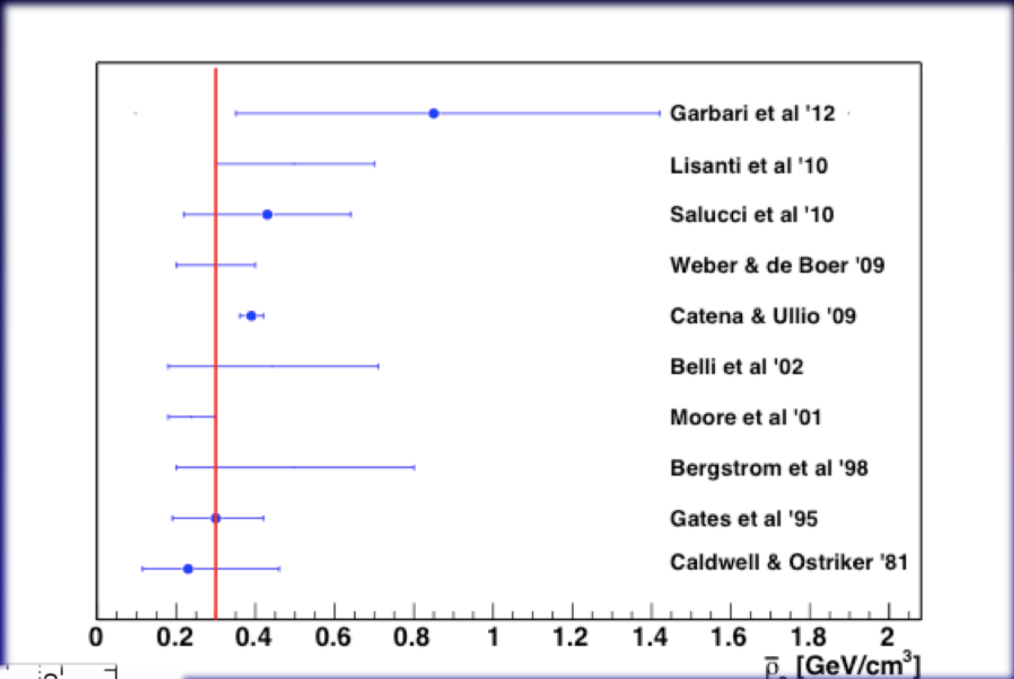
e.g [H. Manzi], and many others...

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

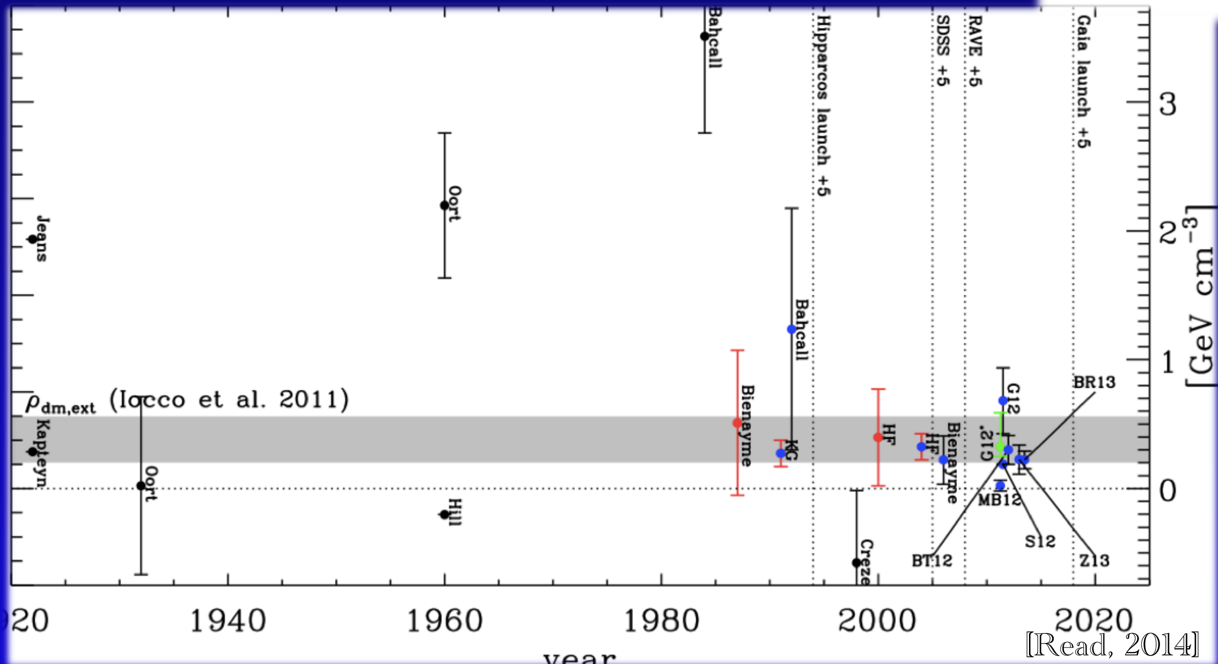
And most notably in the proximity of the Sun?

Some additional hints on why you would care, later on.
Bear with me (but you should know, really)…

Empirical determination of local DM density

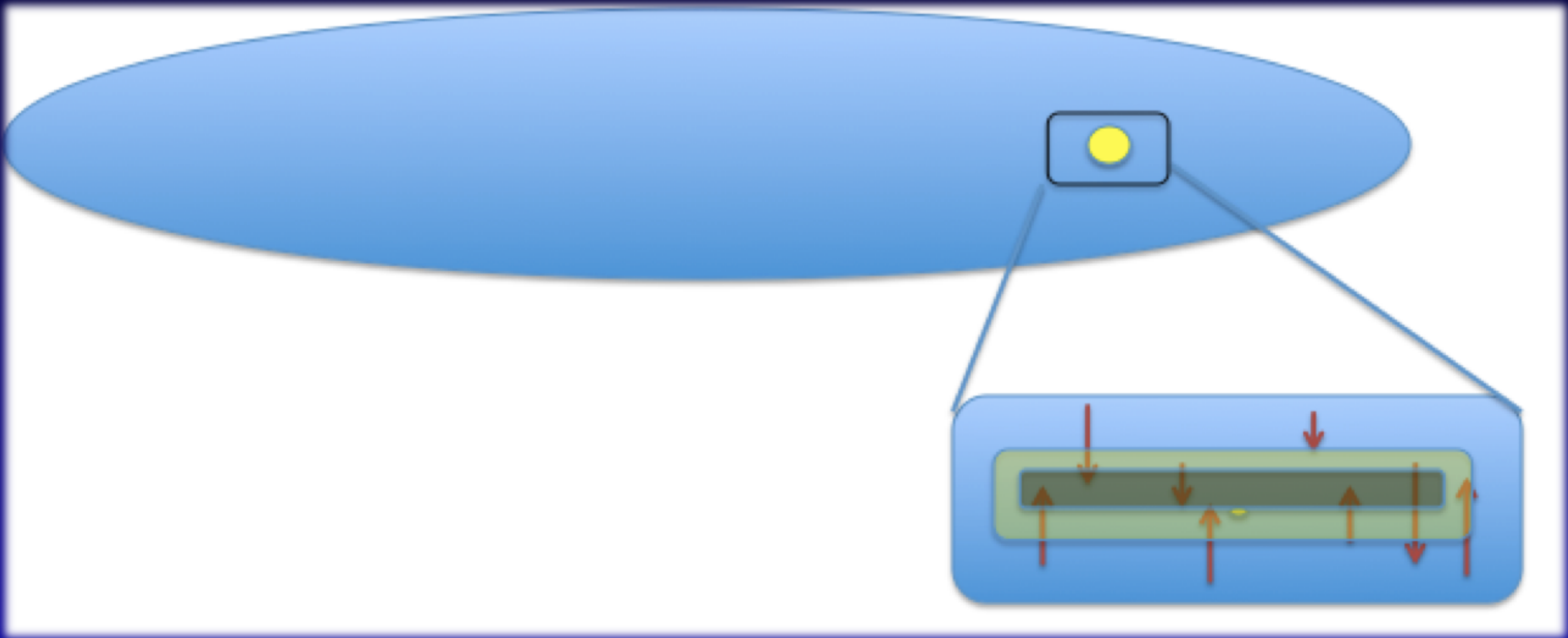


Determinations of
local DM density
are consistent, but noisy



[Read, 2014]

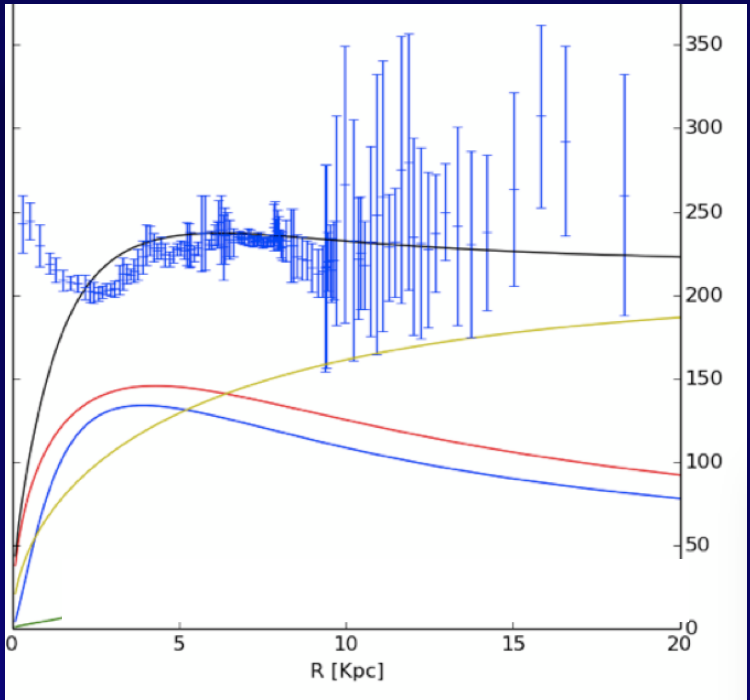
Local determination of ρ_0



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

Inferring the DM density structure

Fitting a pre-assigned shape
on top of luminous

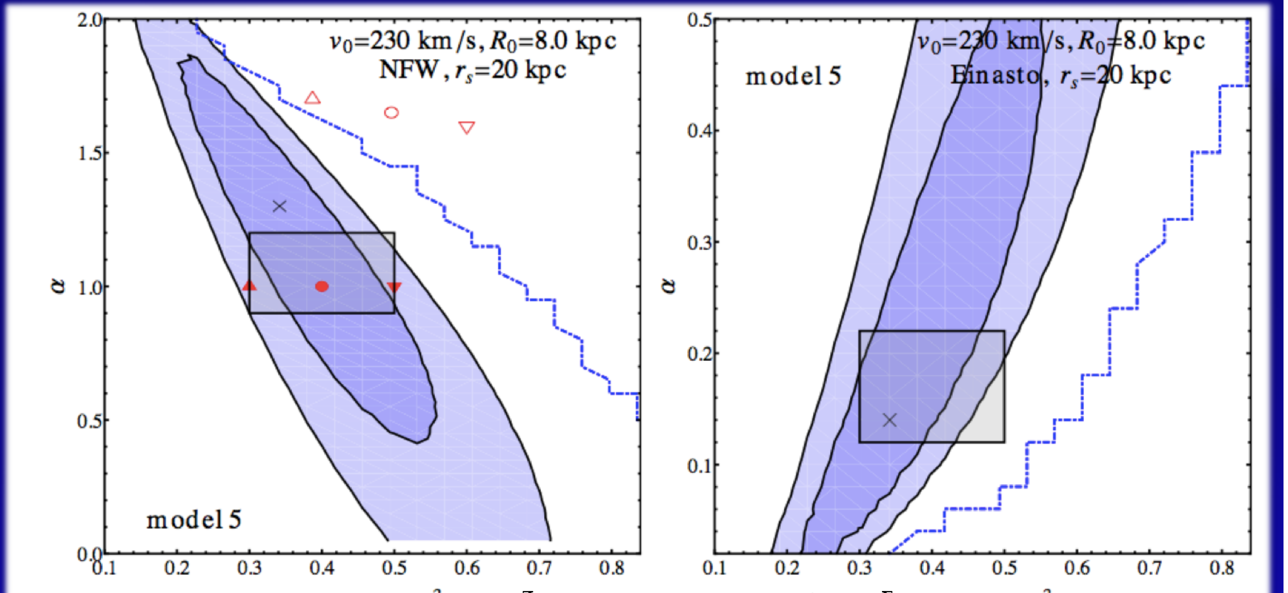


gNFW

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

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

Einasto



[Iocco et al. 2011]

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

Dark Matter in the Milky Way: a purely observational approach

Fabio Iocco

Work started with: *Miguel Pato, Gianfranco Bertone (2011-2015)*
and continued with: *Maria Benito, Ekaterina Karukes (2016-2019)*

The case of the Milky Way: ingredients

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

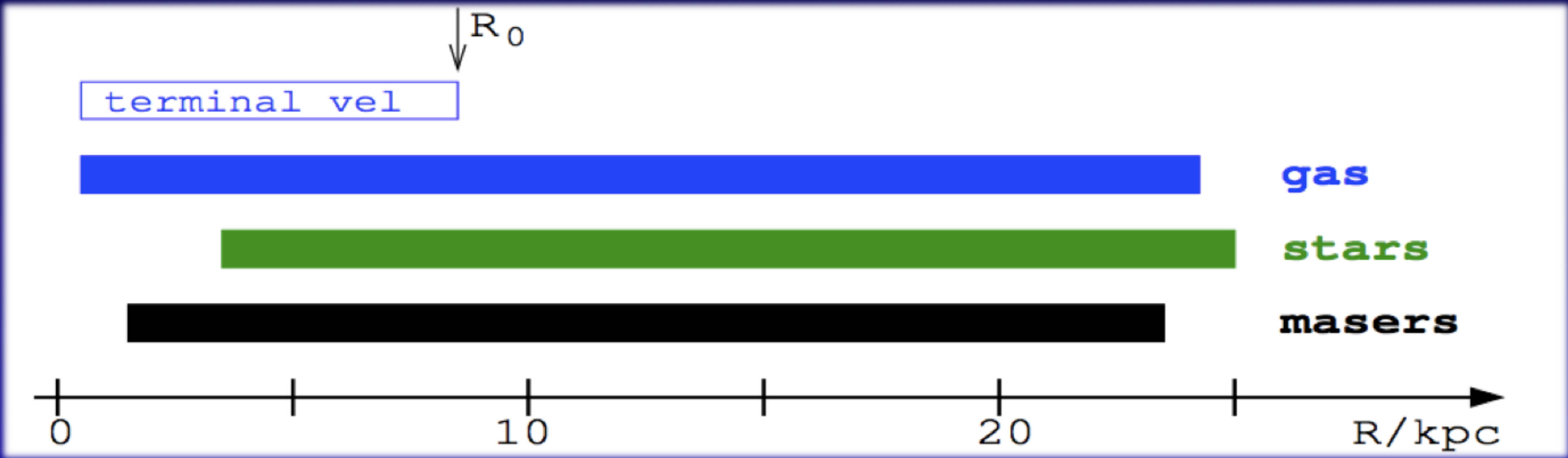
- Some “grano salis”

- Working hypothesis (later on)

The Milky Way:

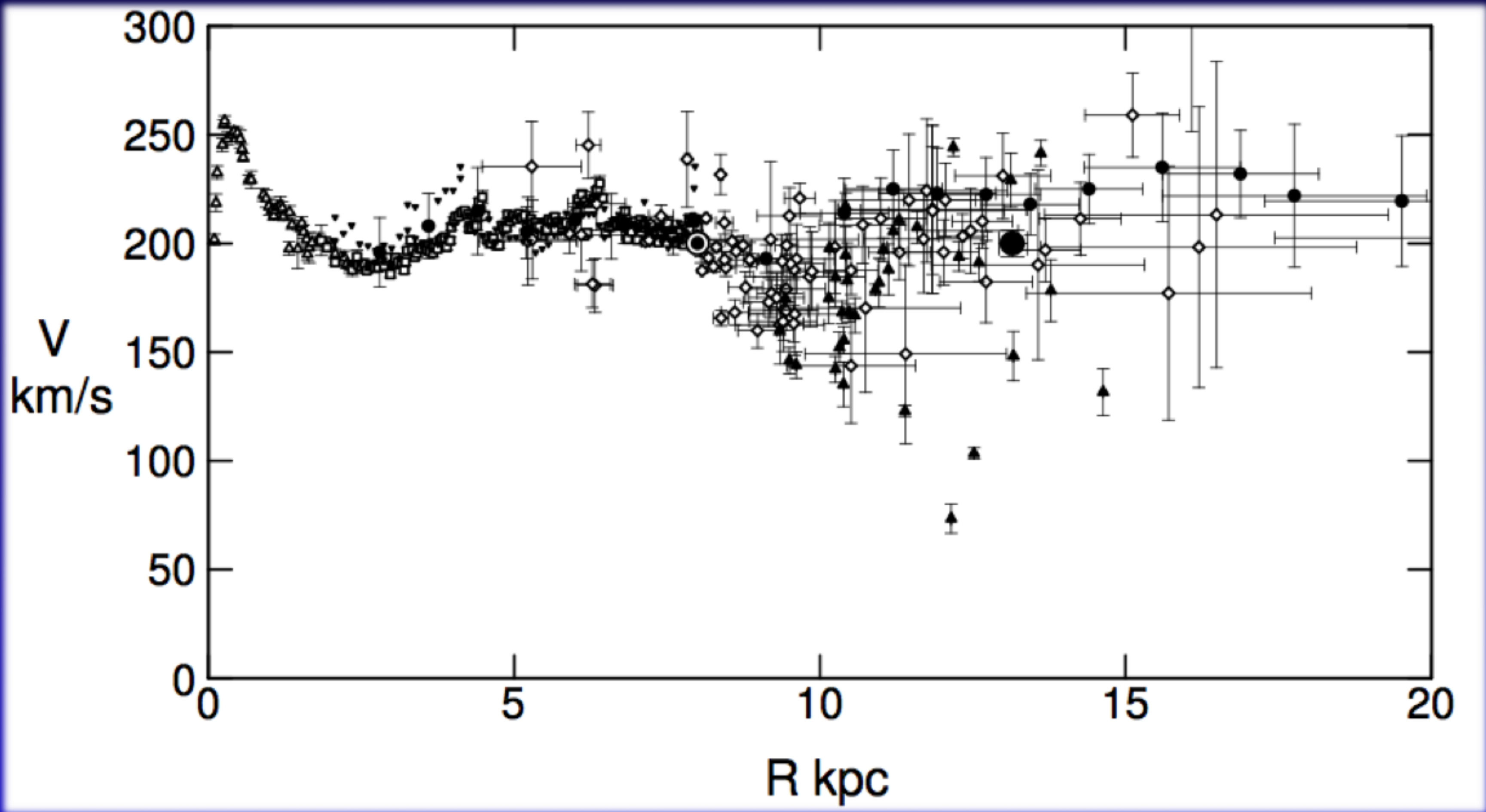
observed rotation curve

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]

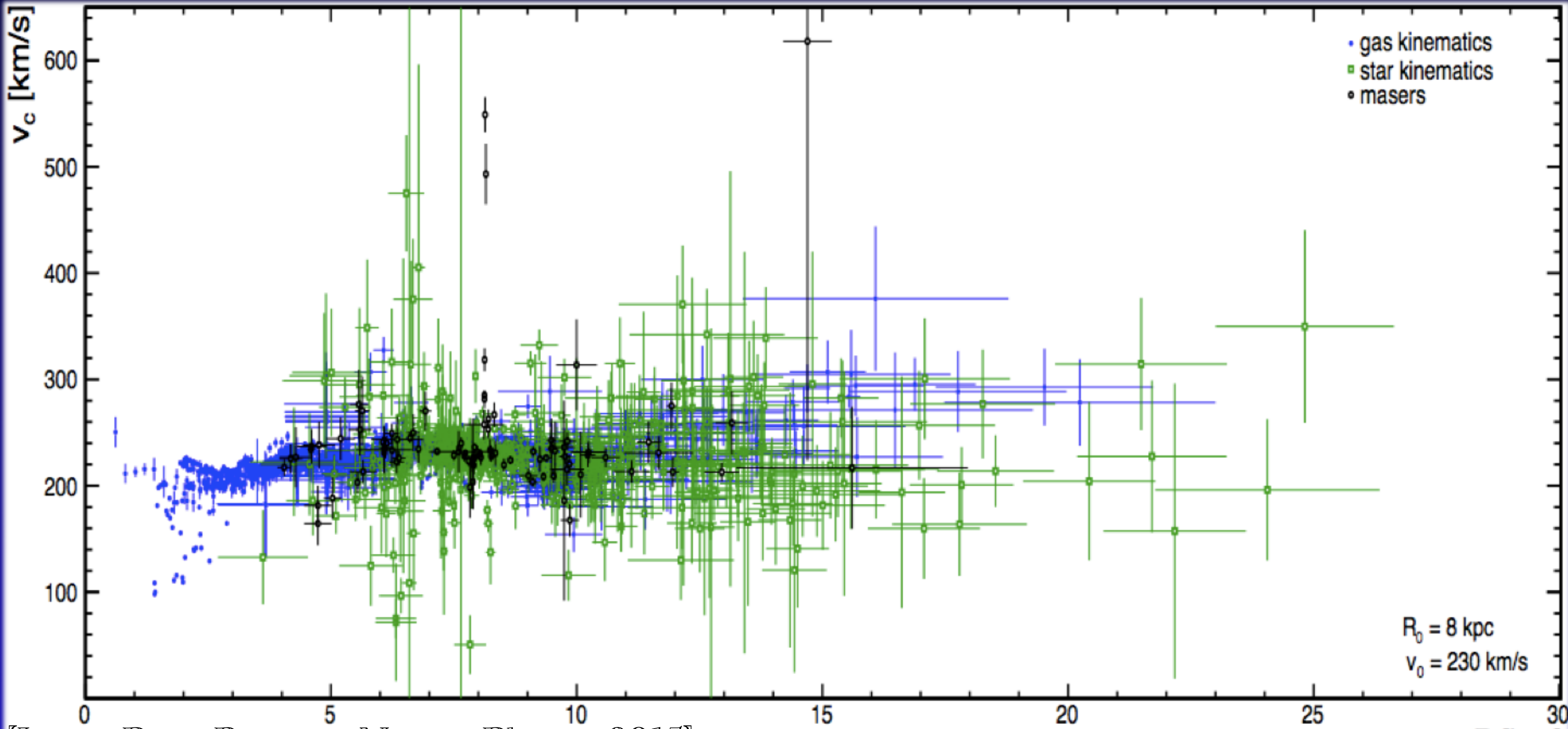
The Milky Way:
observed rotation curve
II'. data again (a new compilation)

	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

[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

The Milky Way:

“expected” rotation curve

from visible (baryon) component

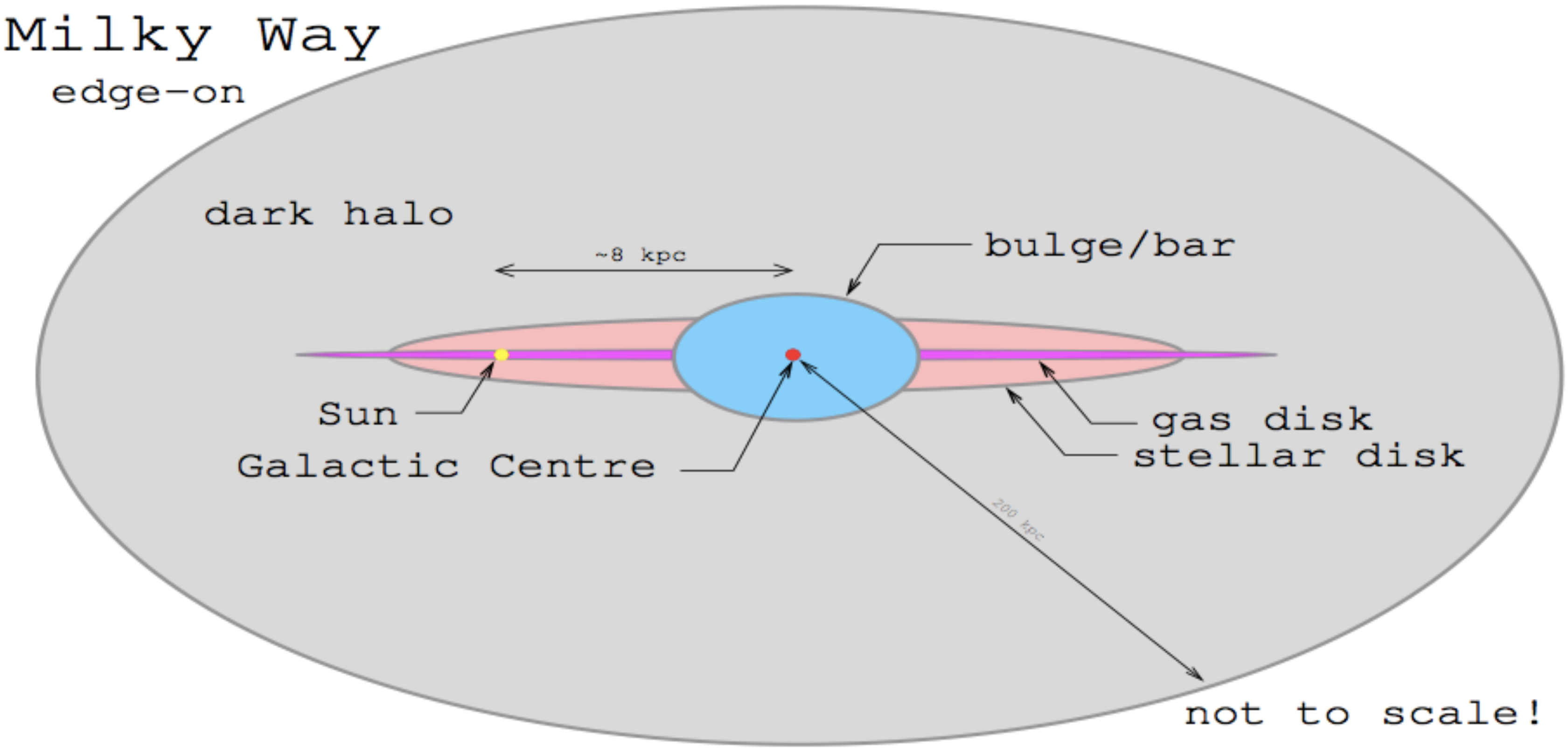
$$\Phi_{\text{baryon}} = \Phi_{\text{bulge}} + \Phi_{\text{disk}} + \Phi_{\text{gas}}$$

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

Constructing the curve expected from observed mass profiles

The Milky Way:

expected rotation curve
1. the baryonic components

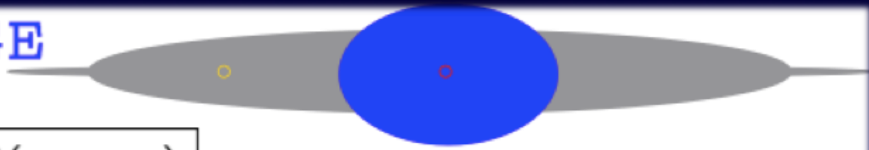


bulge	tilted bar
disk	thin+thick
gas	H_2, HI, HII

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 $f(x, y, z)$

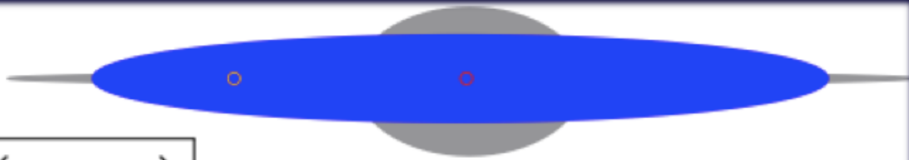
Stanek+ '97 (E2)	e^{-r}	0.9:0.4:0.3	24°	optical
Stanek+ '97 (G2)	$e^{-r_s^2/2}$	1.2:0.6:0.4	25°	optical
Zhao '96	$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	1.5:0.6:0.4	20°	infrared
Bissantz & Gerhard '02	$e^{-r_s^2}/(1+r)^{1.8}$	2.8:0.9:1.1	20°	infrared
Lopez-Corredoira+ '07	Ferrer potential	7.8:1.2:0.2	43°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

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 $f(x,y,z)$

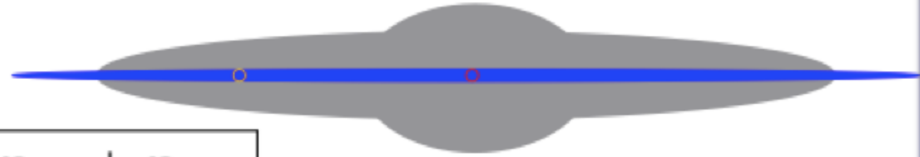
Han & Gould '03	$e^{-R}\mathrm{sech}^2(z)$	2.8:0.27	thin	optical
	$e^{-R-\lvert z\rvert}$	2.8:0.44	thick	
Calchi-Novati & Mancini '11	$e^{-R-\lvert z\rvert}$	2.8:0.25	thin	optical
	$e^{-R-\lvert z\rvert}$	4.1:0.75	thick	
deJong+ '10	$e^{-R-\lvert z\rvert}$	2.8:0.25	thin	optical
	$e^{-R-\lvert z\rvert}$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



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

morphology

Ferrière '12	$r < 0.01$ kpc	$M_{gas} \sim 7 \times 10^5$ 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

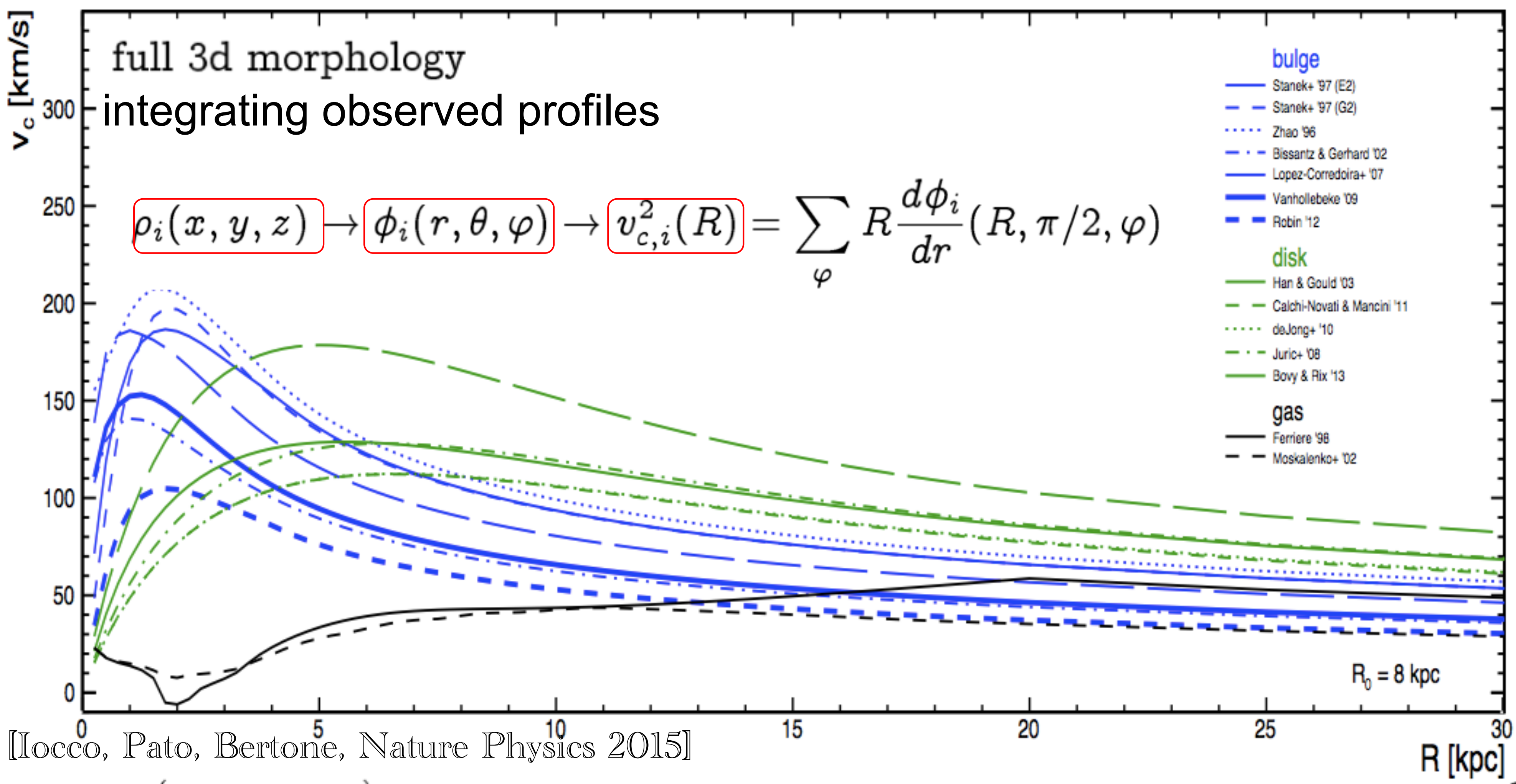
CO-to-H_2 factor: $X_{\mathrm{CO}} = 0.25 - 1.0 \times 10^{20}\ \mathrm{cm^{-2}\,K^{-1}\,km^{-1}\,s}$ for $r < 2$ kpc

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

[Ferrière+ '07, Ackermann '12]

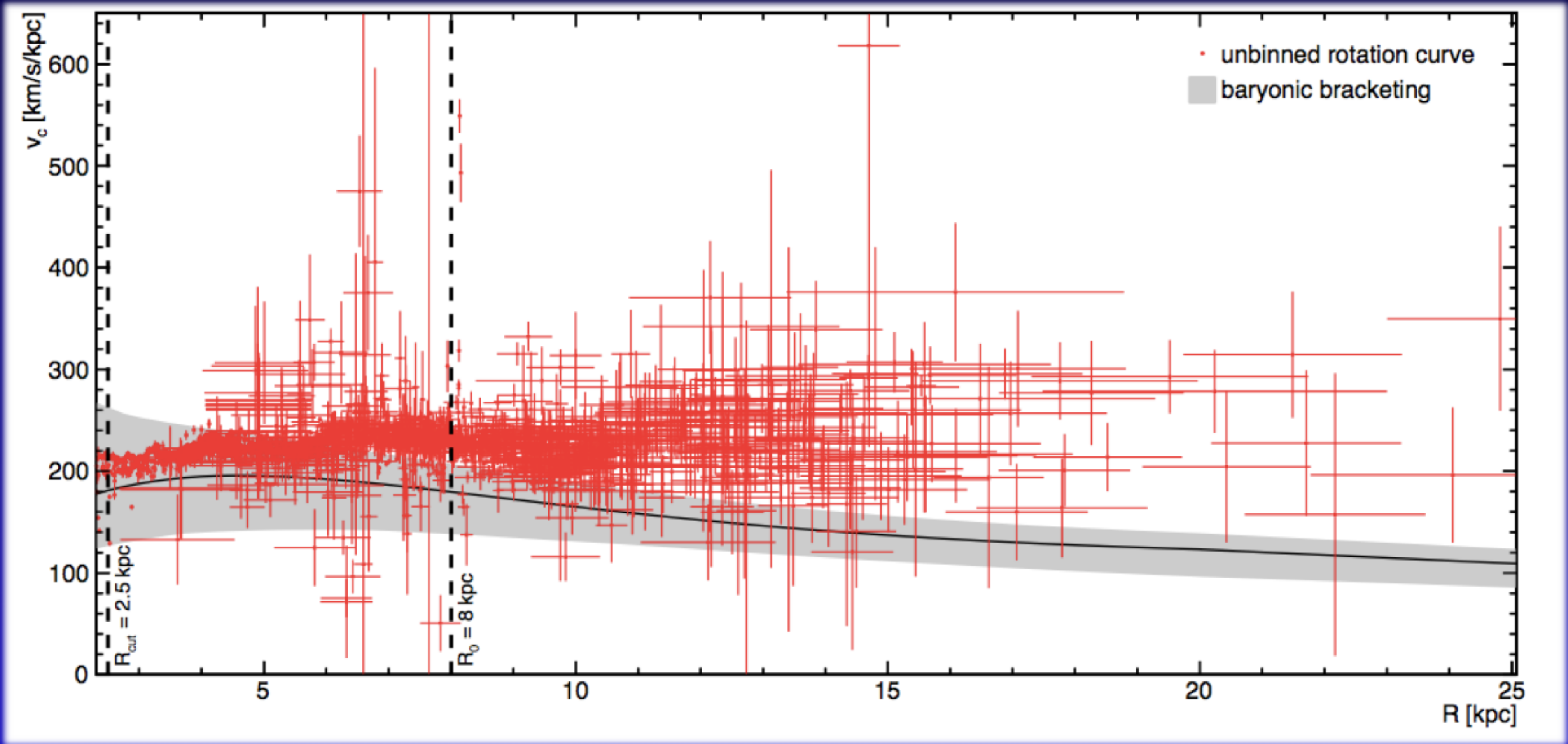
The luminous Milky Way:
expected rotation curve

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



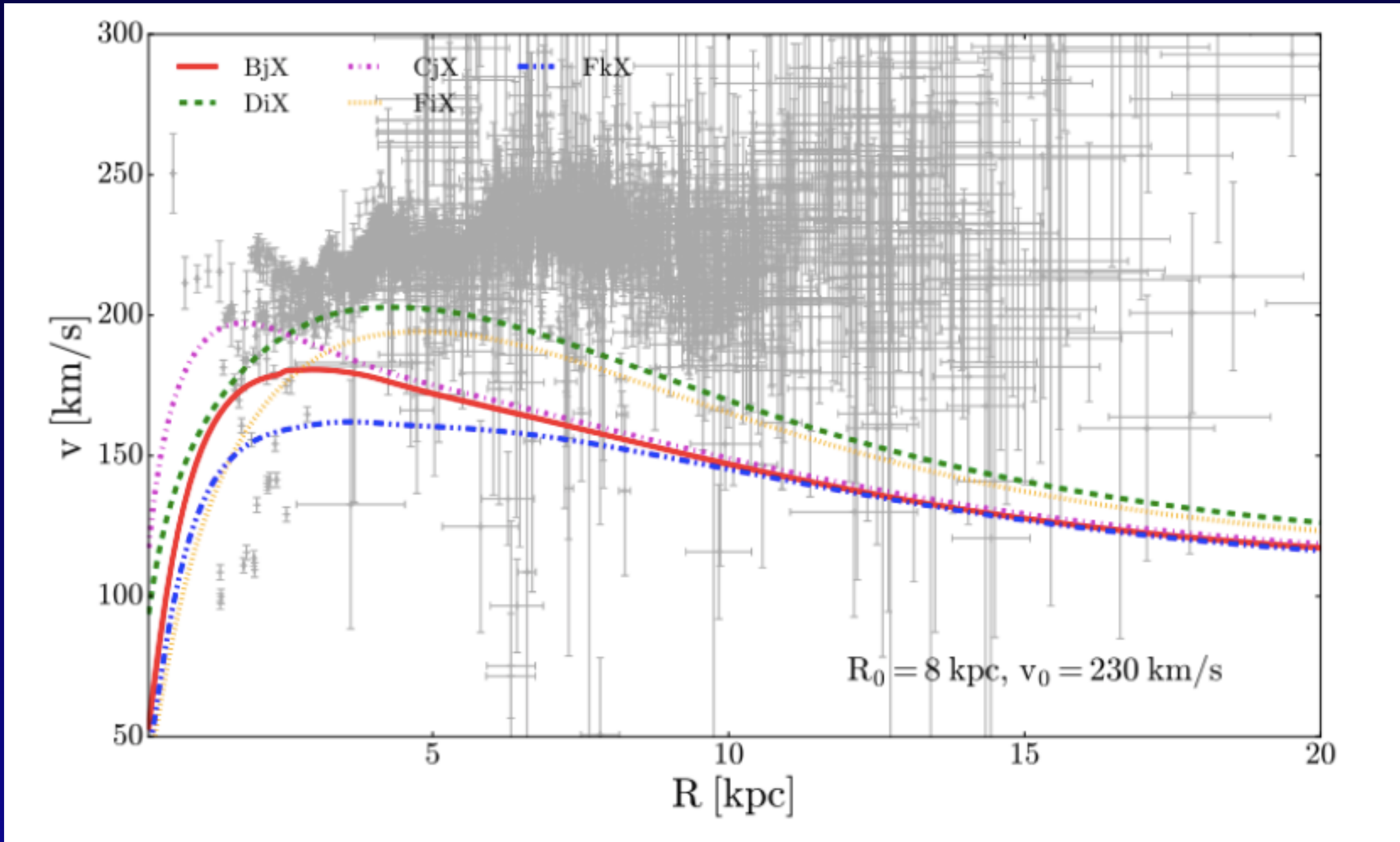
[Iocco, Pato, Bertone, Nature Physics 2015]

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



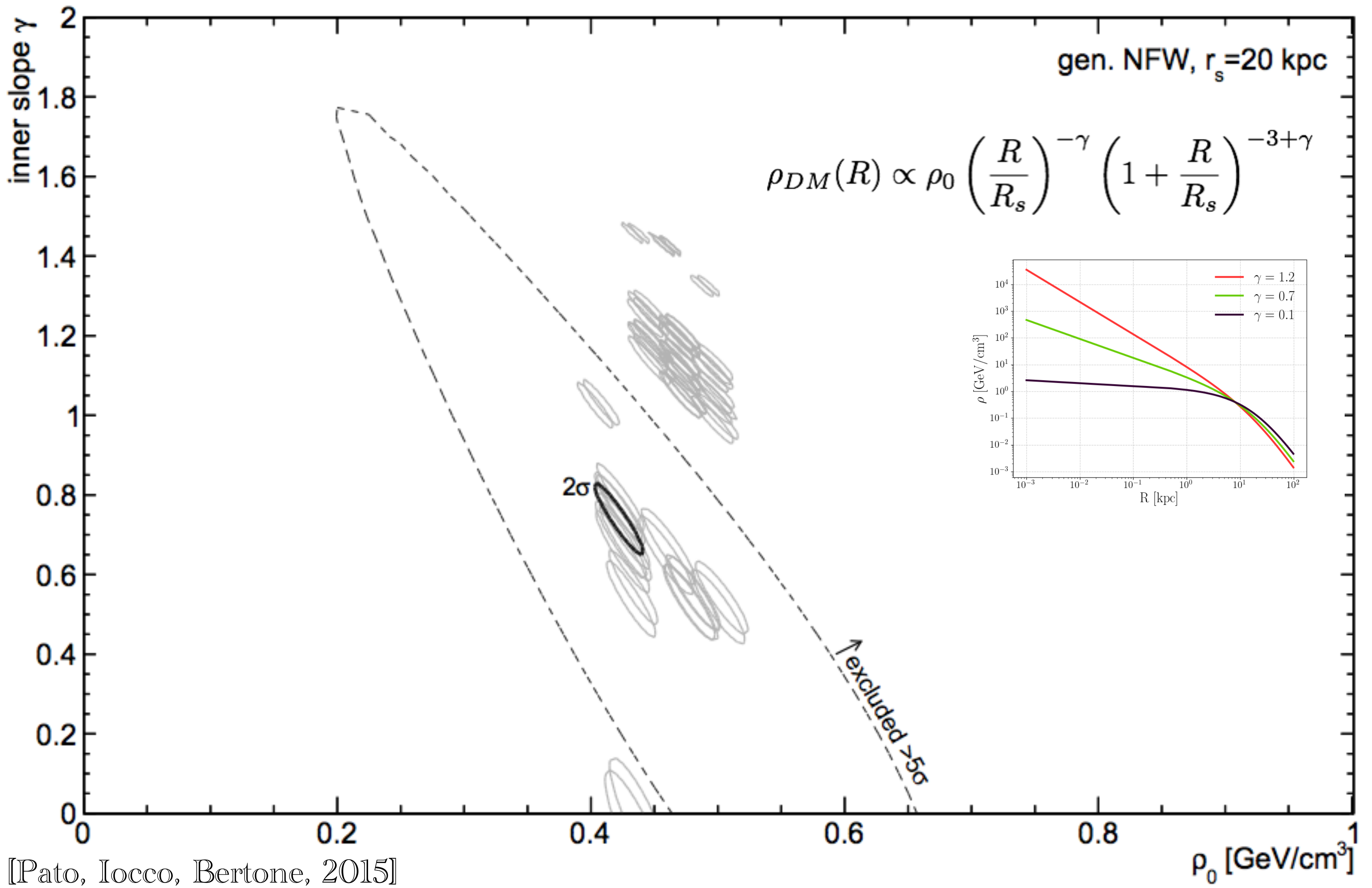
[Iocco, Pato, Bertone, Nature Physics 2015]

Systematic uncertainties
(luminous component)



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

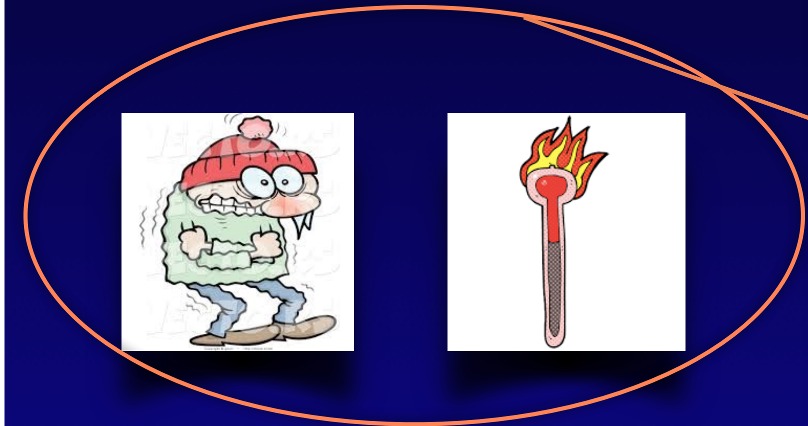
Extracting the DM density structure

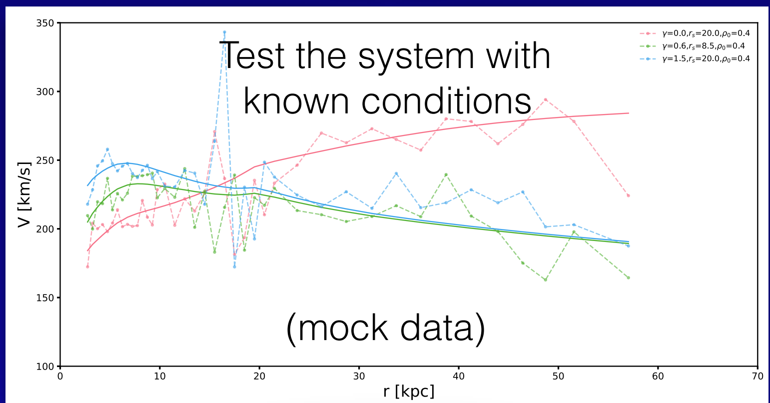


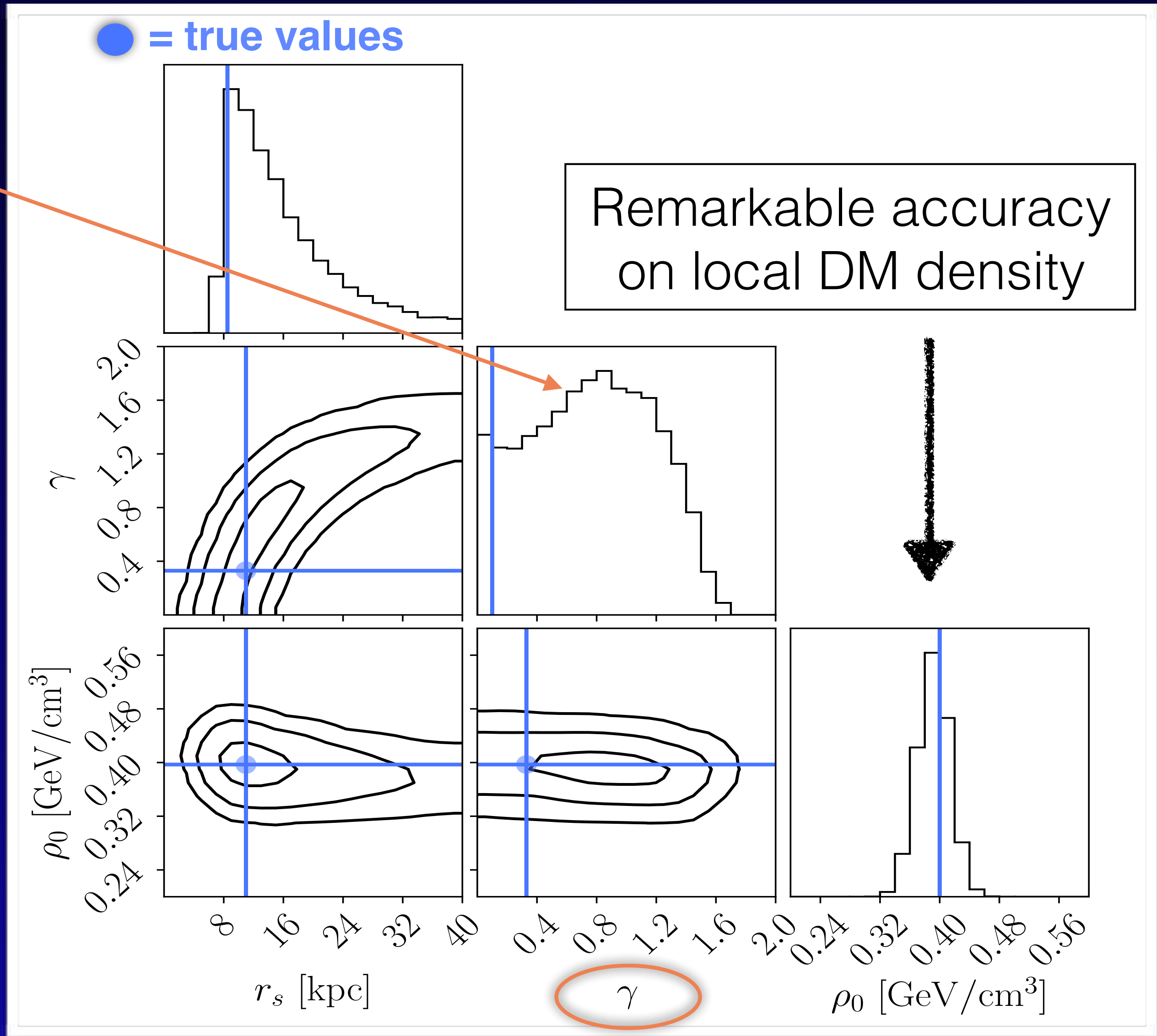
[Pato, Iocco, Bertone, 2015]

What to do of our measurement?

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







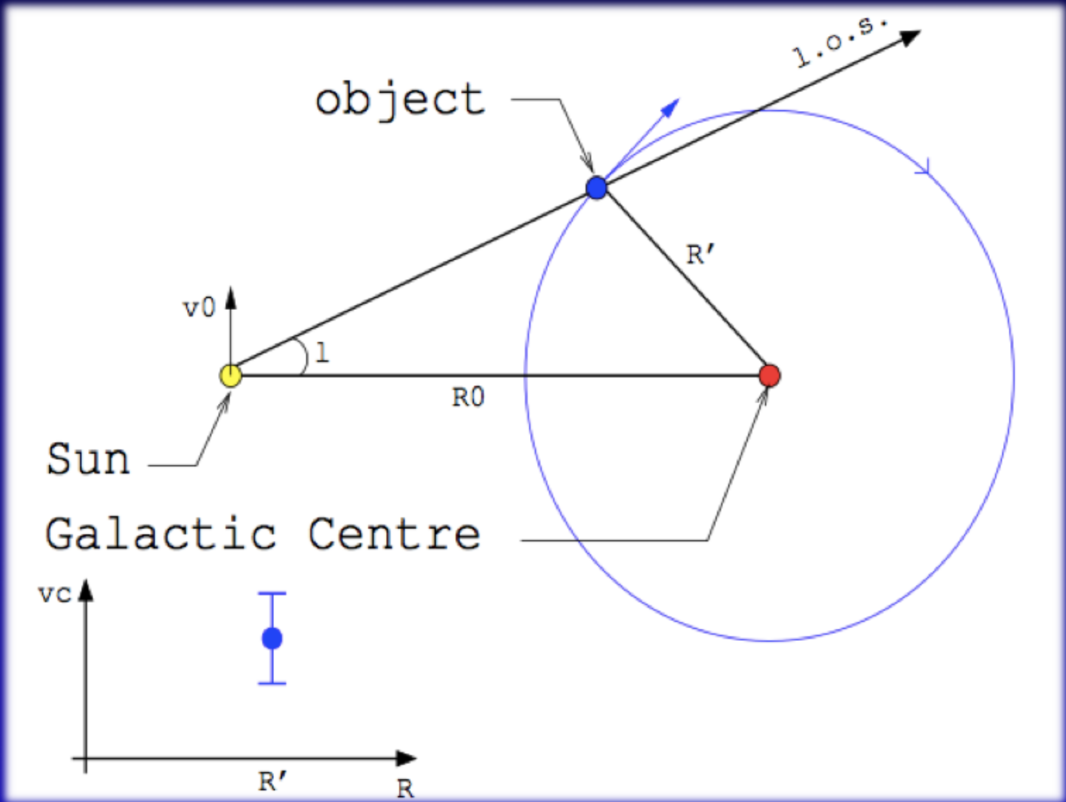
[E. Karukes, M. Benito, F. Iocco, A. Geringer-Sameth, R. Trotta] arXiv:1901.02463

full Bayesian framework, test of data consistency, more to in the paper when what telling you here

The Milky Way:

observed rotation curve

Neglecting some quite remarkable uncertainties (for now)

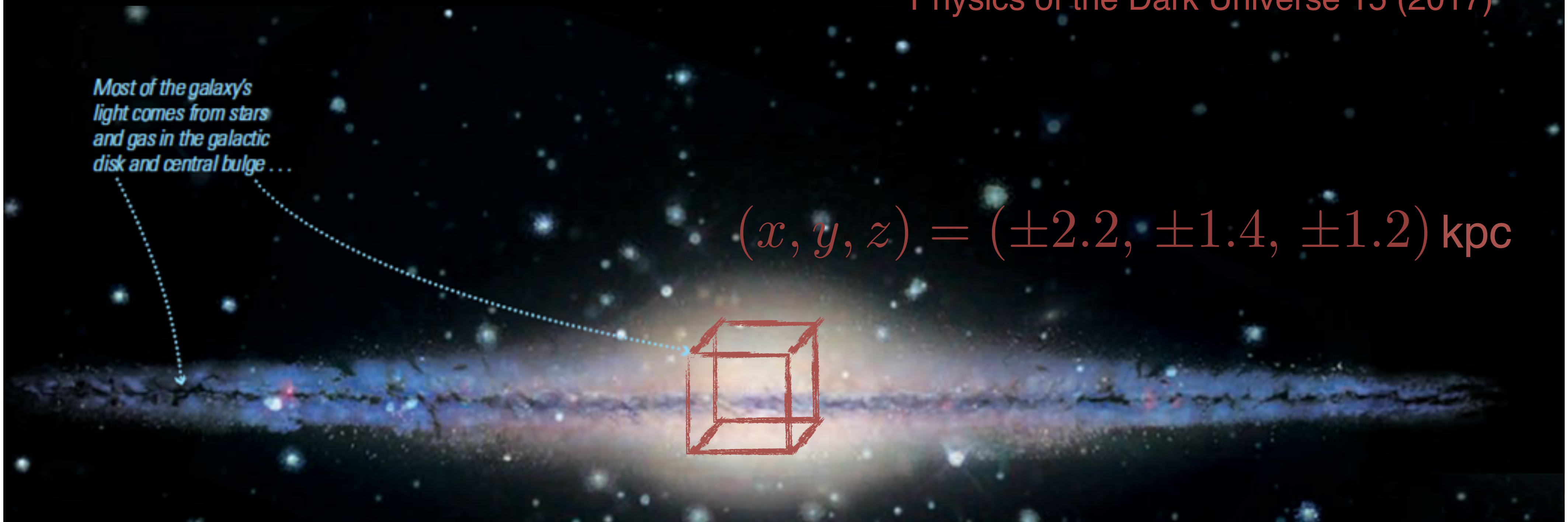


$$v_{\mathrm{LSR}}^{\mathrm{l.o.s.}} = \left(\frac{v_c(R')}{R'/R_0} - v_0 \right) \cos b \sin \ell$$

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

How to reconstruct DM density profile in Galactic Bulge region?

Iocco & MB
Physics of the Dark Universe 15 (2017)



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

Total mass

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

Portail +
MNRAS 465 (2017)

Stellar mass

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

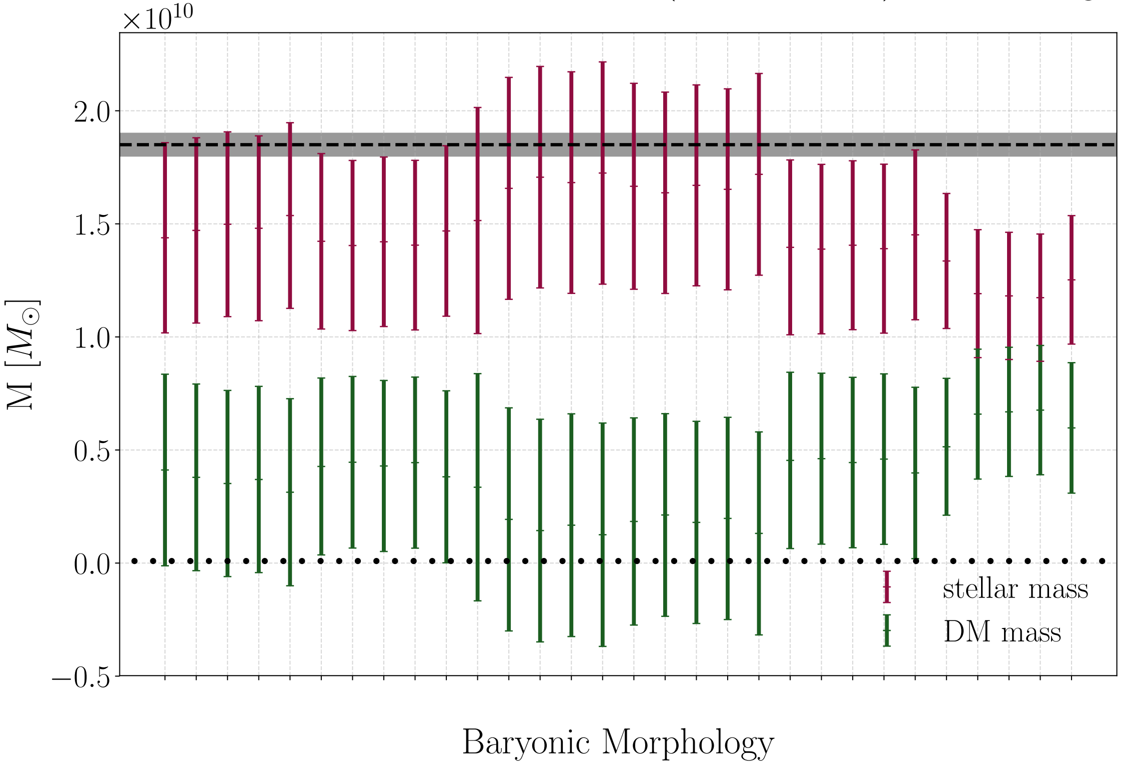
Methodology

Allowed DM mass

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

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

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



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

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

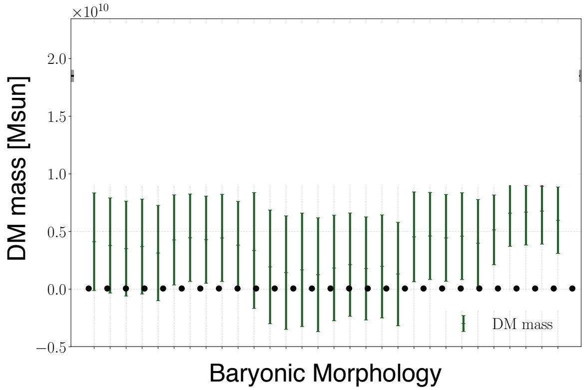
DM mass corresponds to 7-37%

gNFW density profile

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

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

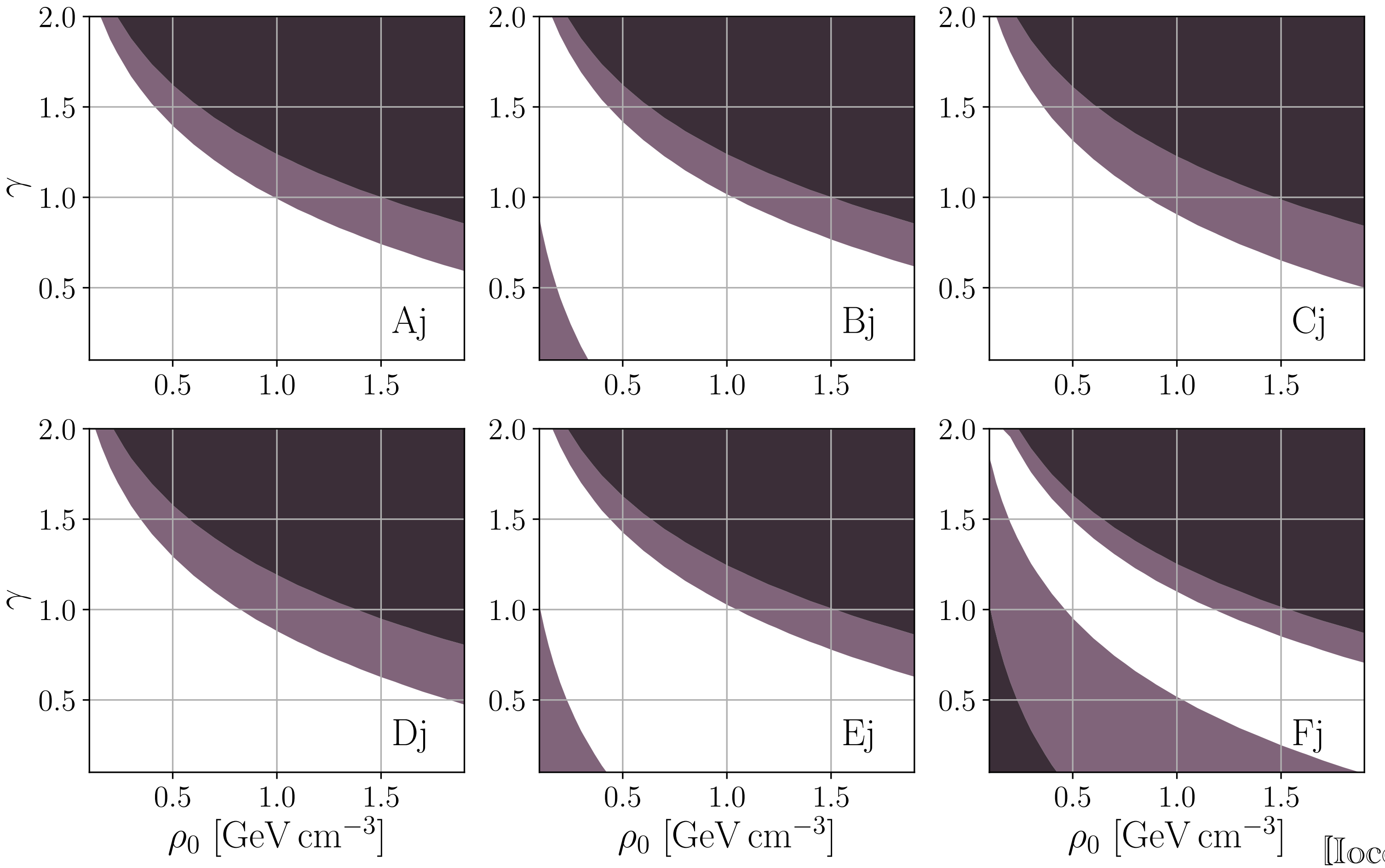


$$R_s = 20\,\mathrm{kpc}$$

$$R_0 = 8\,\mathrm{kpc}$$

Same disc, varying bulge

Allowed at 1σ
Allowed at 2σ
Excluded at 2σ



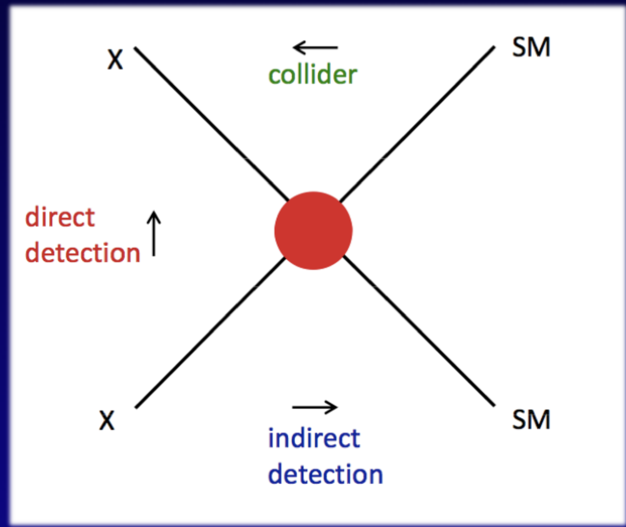
[Iocco & Benito, 2017]
arXiv:1611.09861

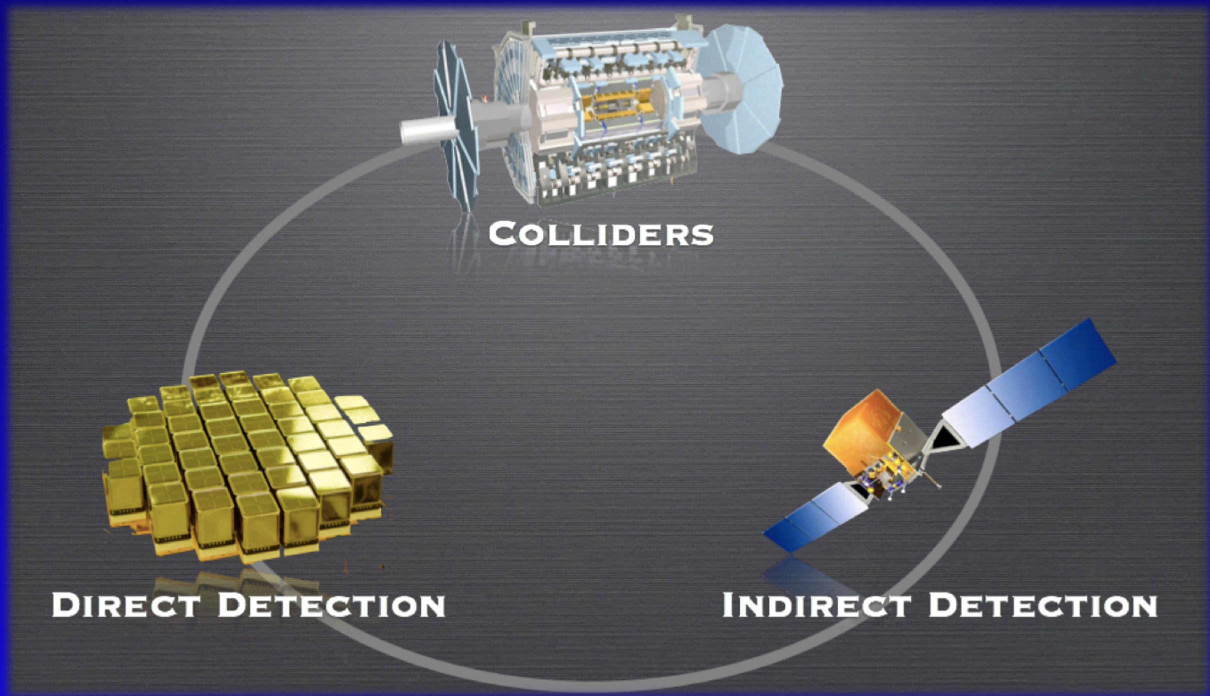
Direct and indirect searches of WIMP DM
complementary to colliders

Direct detection:
DM scattering against nuclei, recoil

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

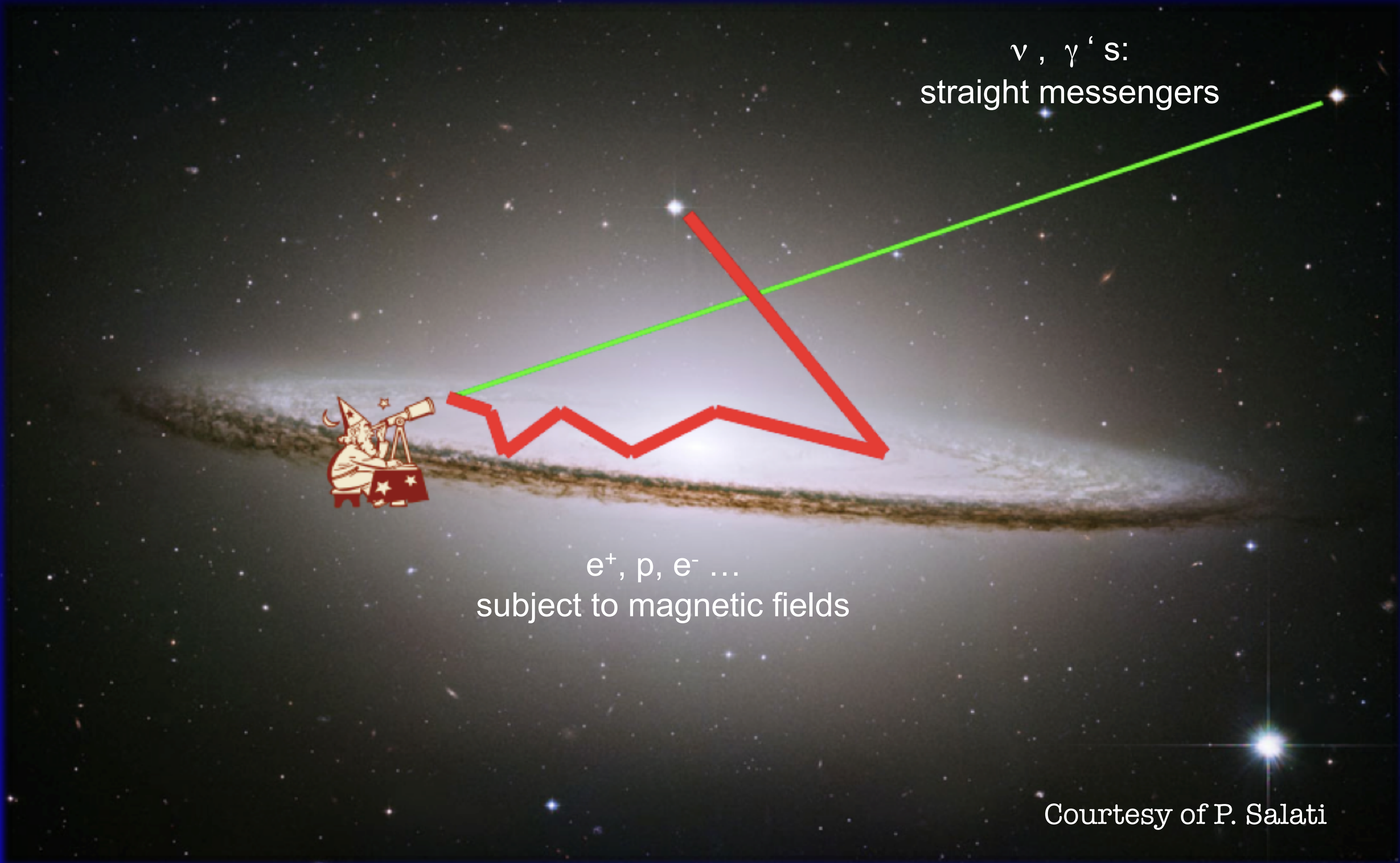
Production at LHC





Indirect Detection: principles and dependencies

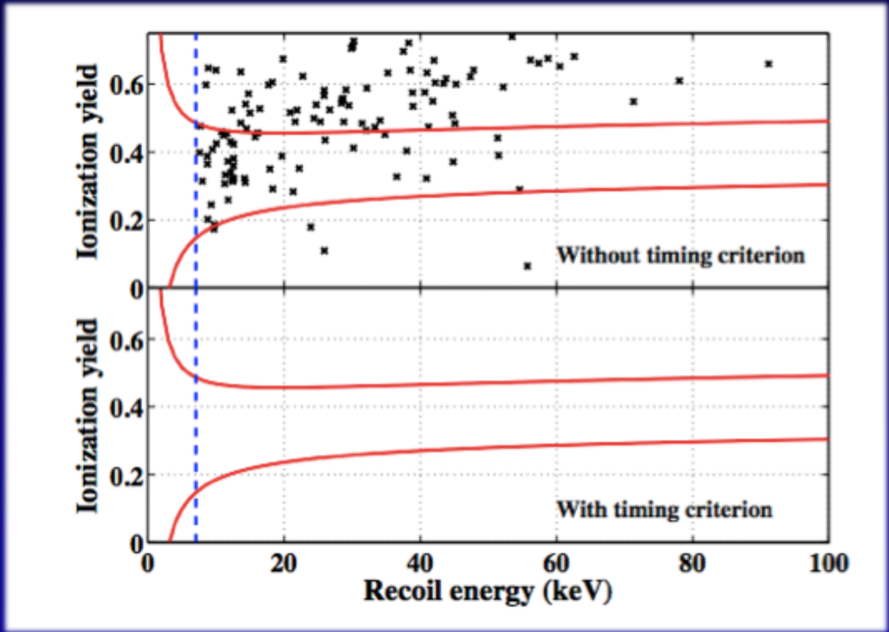
$$\chi + \chi \to q\bar{q}, W^+W^-, \ldots \to \gamma, \bar{p}, \ \bar{D}, \ e^+ \ \& \ \nu's$$

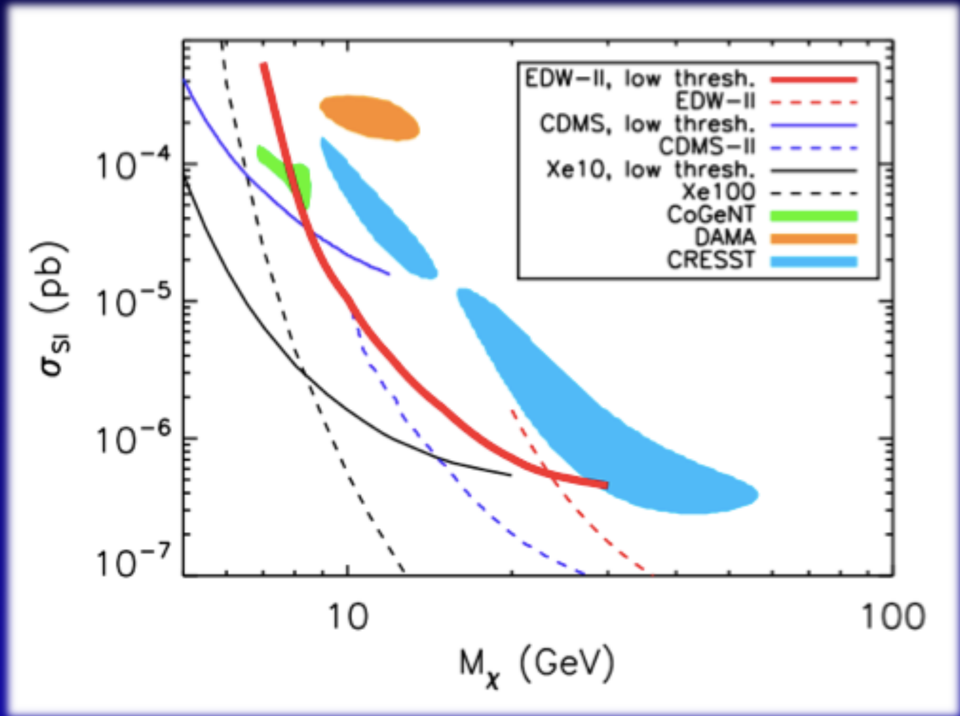


$$F_i \propto \frac{1}{4\pi d^2} B_i \frac{\langle \sigma v \rangle}{m_\chi} \int \rho^2(r) dV$$

Direct Detection: principles and dependencies (to go…)

from this → to this



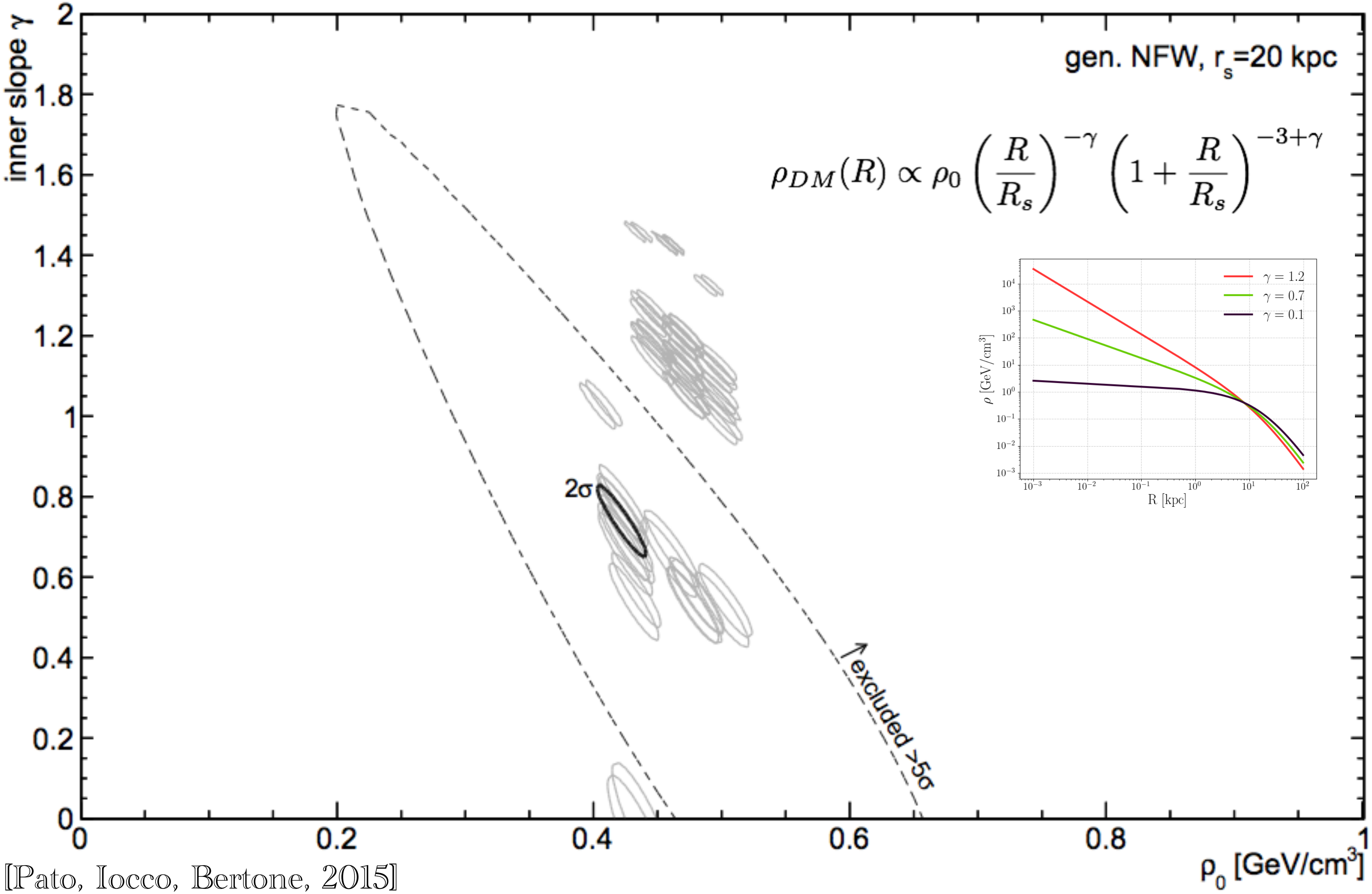


you need this

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

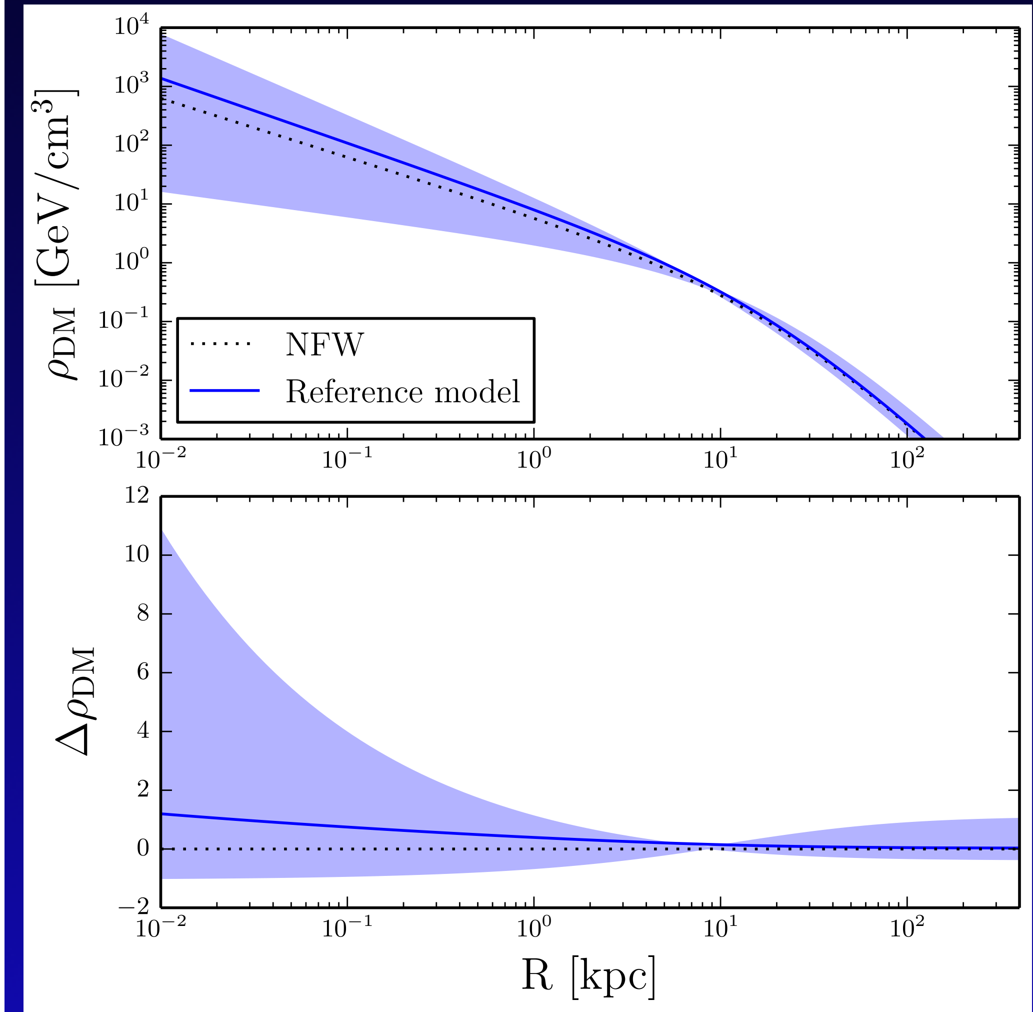
See talk by A. Ibarra

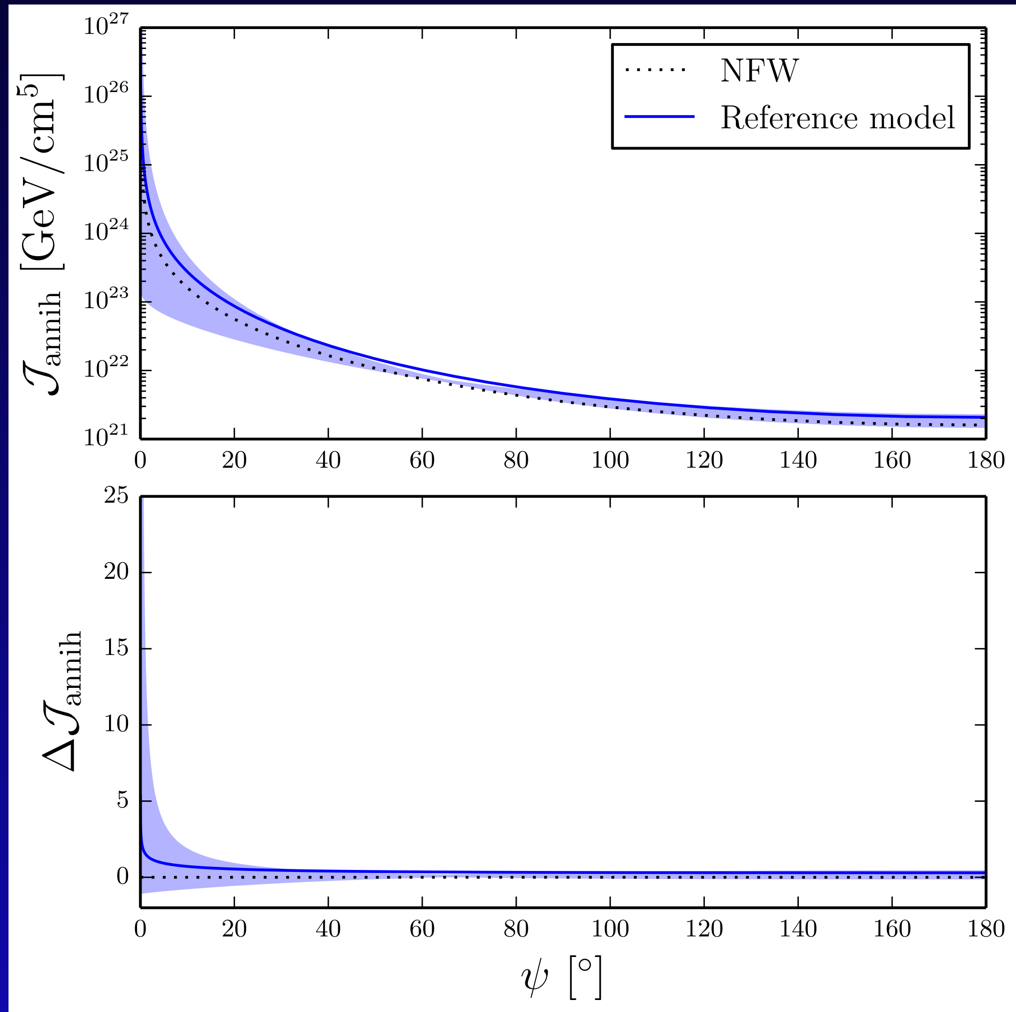
Extracting the DM density structure



[Pato, Iocco, Bertone, 2015]

But do Galactic uncertainties affect PP, for real?

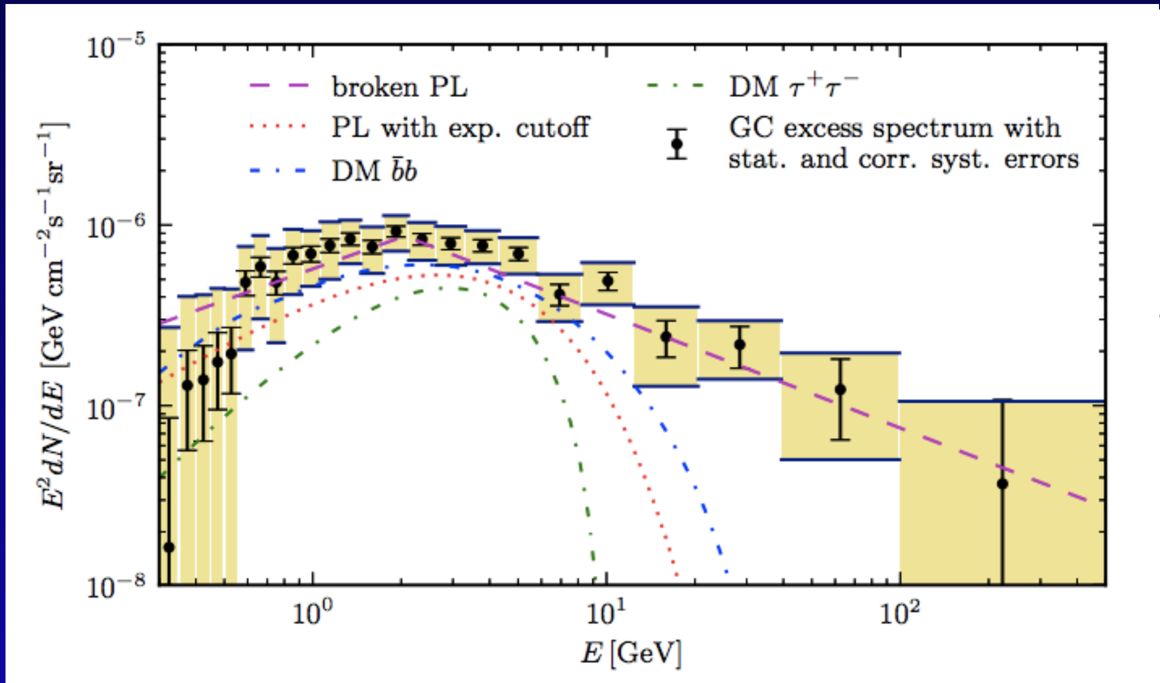




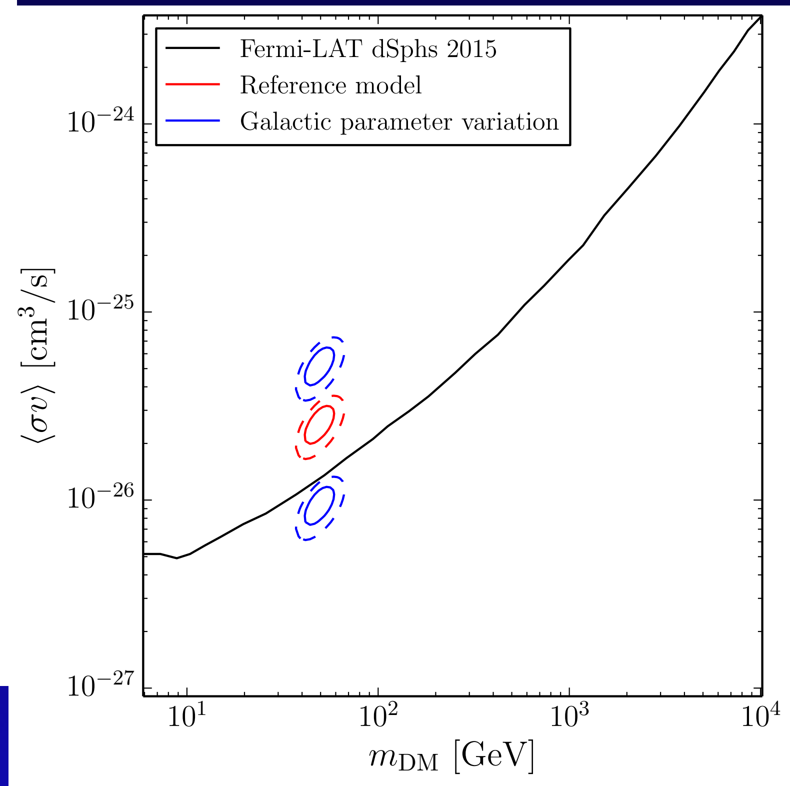
$$J_{annih} \propto \int_{los} \rho^2(r)dV$$

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

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

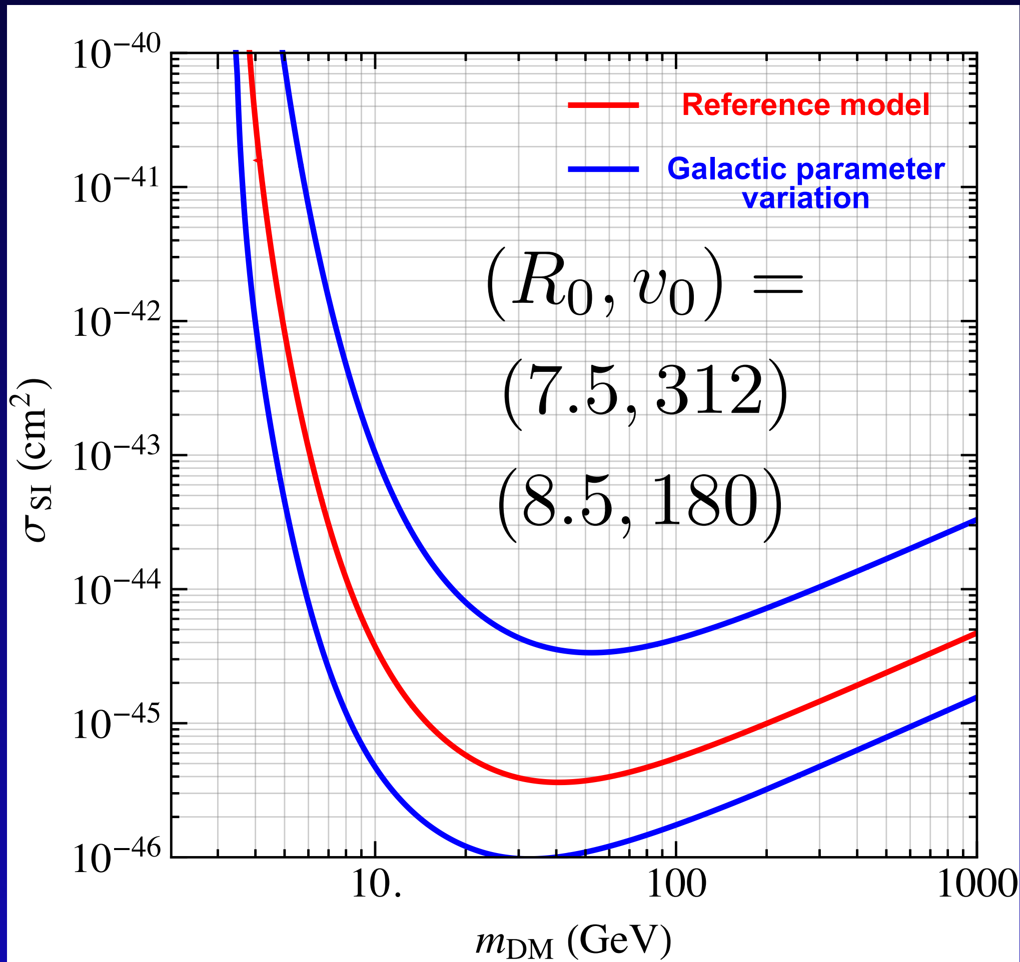


[Calore et al, 2015]



[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

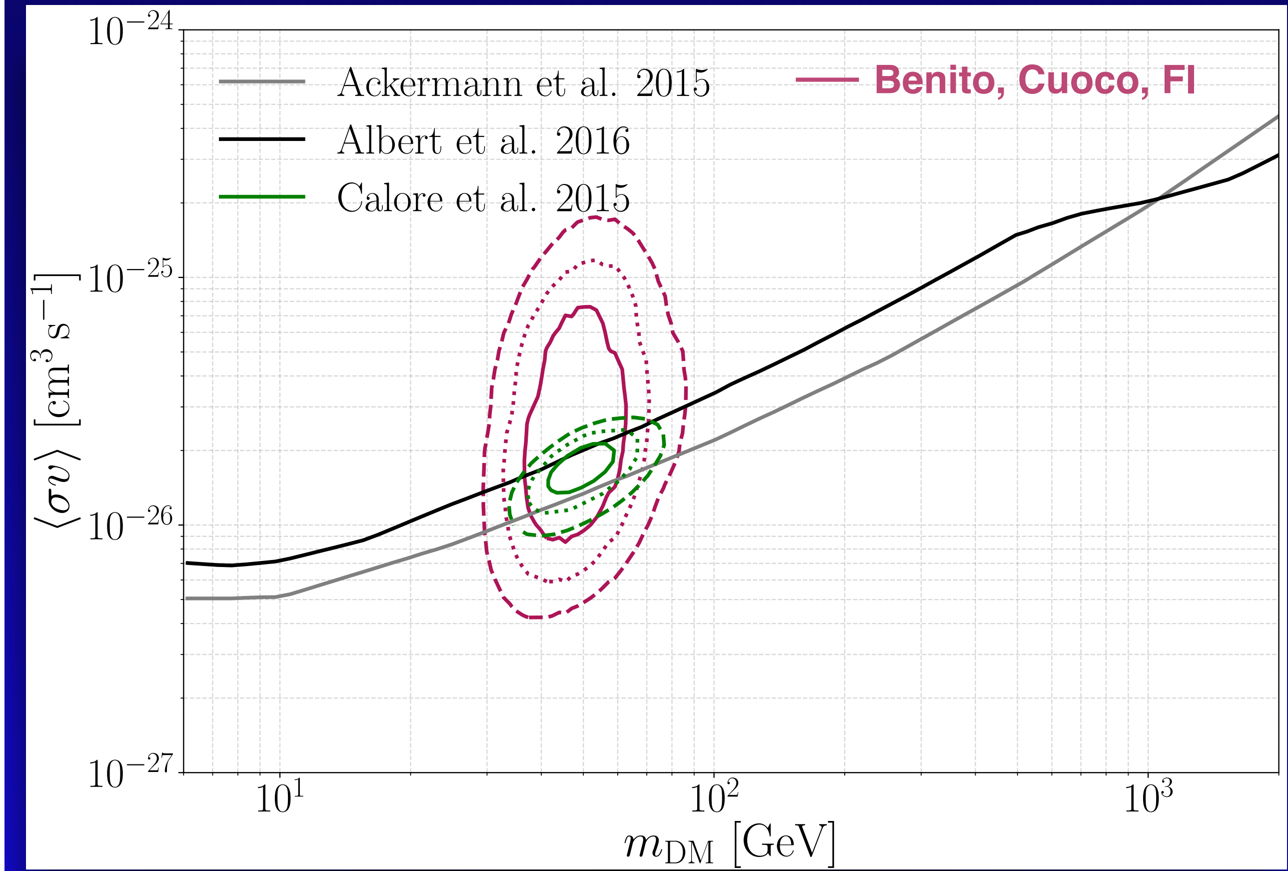
Uncertainties accounted for:

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

[Benito, Cuoco, Iocco, JCAP arXiv:1901.02460]

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

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

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

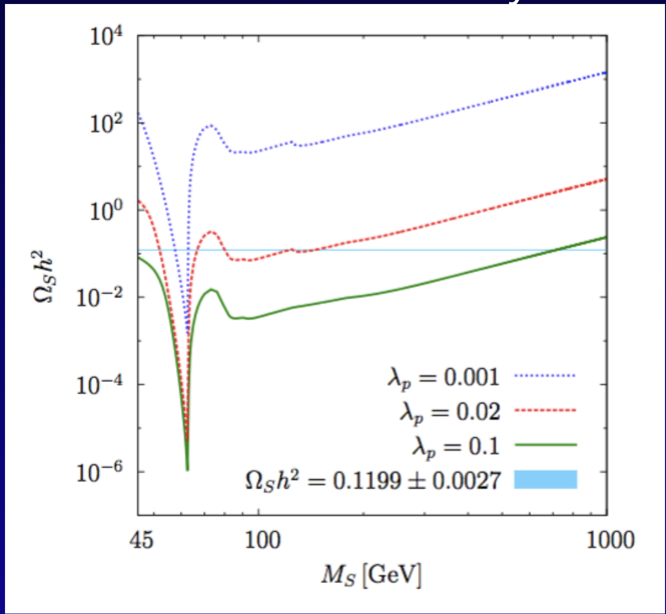
$$m_S^2 = 2 \, \mu_S^2 + \lambda_{HS} \, v_H^2$$

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

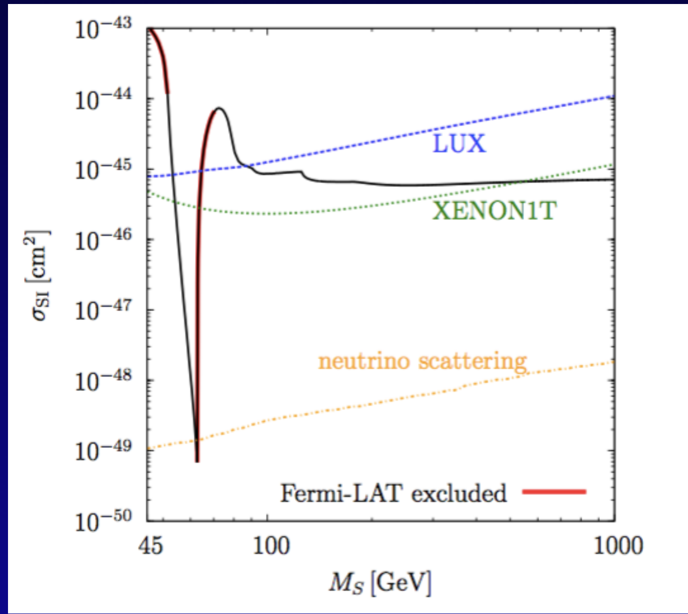
[Mc Donald, 1994] [Burgess, Pospelov, Velthuis, 2001]

Singlet Scalar DM
Constraints and interplay of experiments

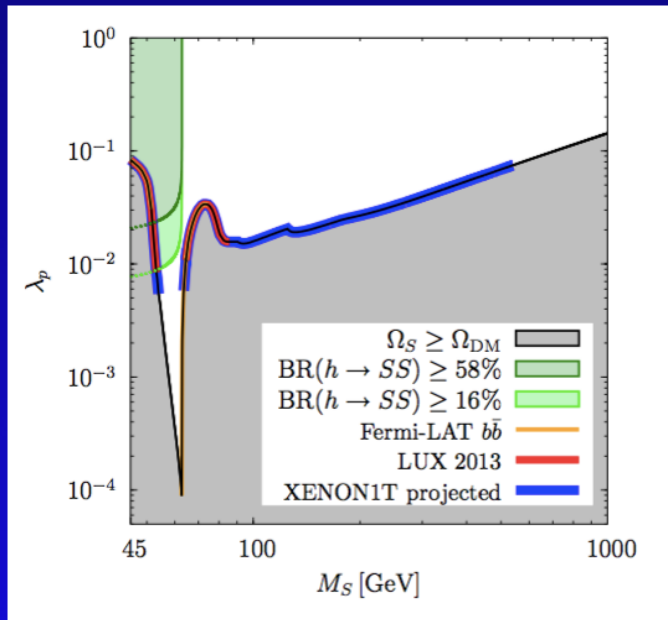
Relic density



Direct detection



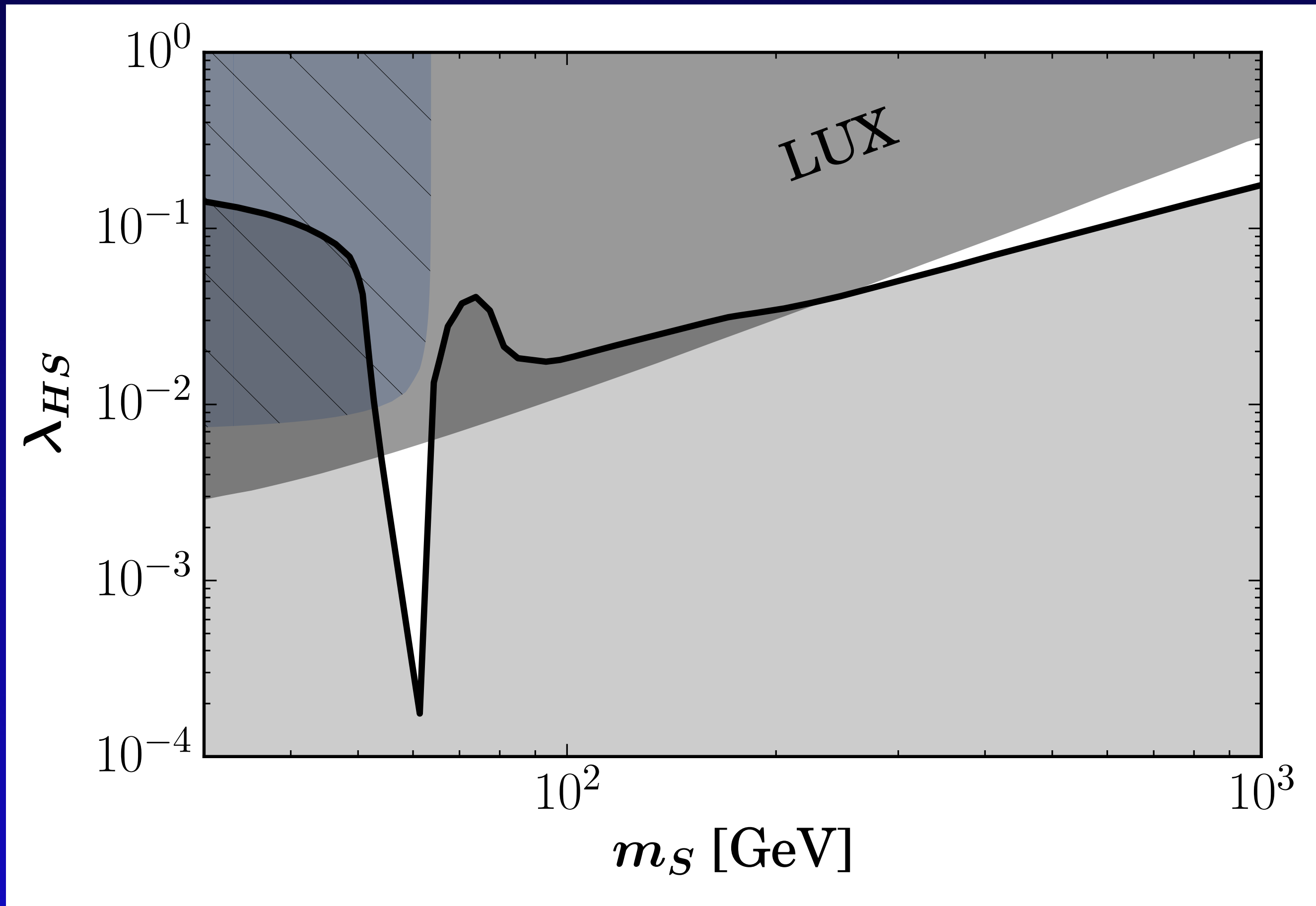
Combined



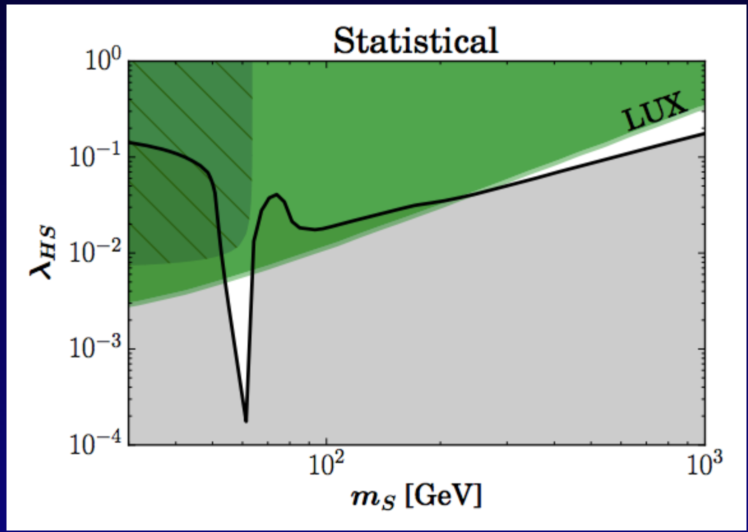
[Duerr et al, 2015]

Singlet Scalar DM
Constraints and interplay of experiments

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

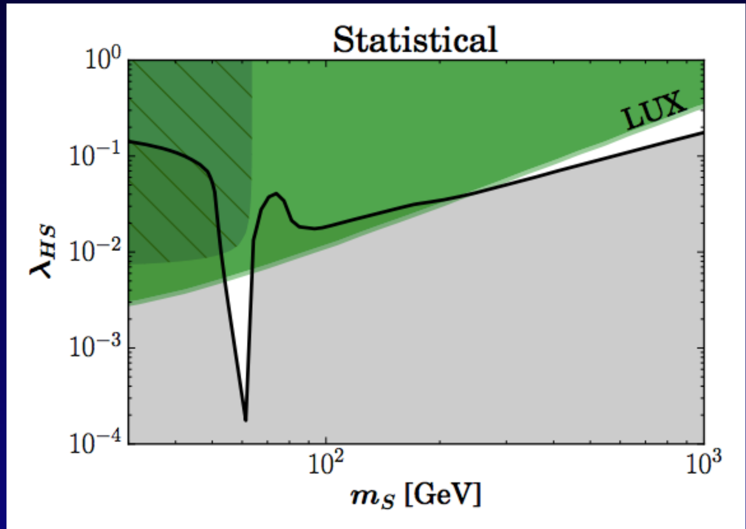


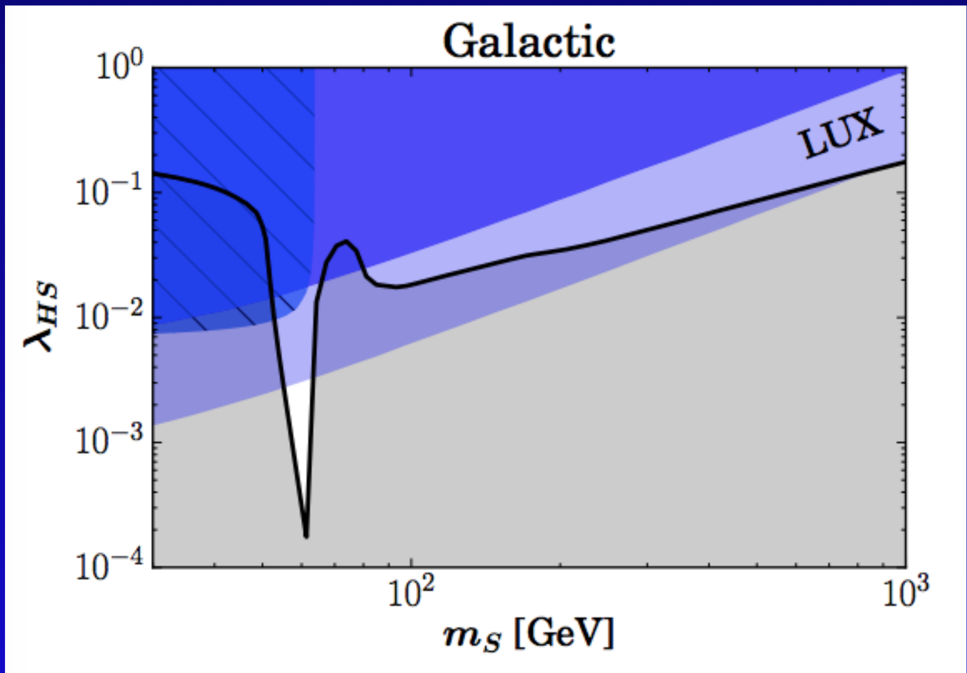
Let's look at the effect of astrophysics uncertainties: Direct Detection

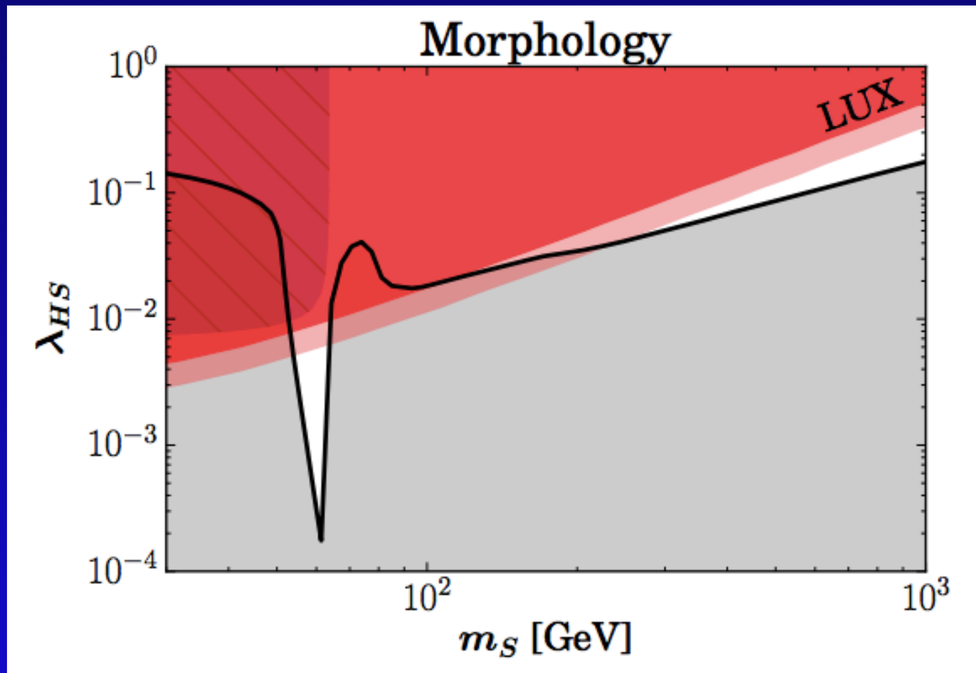


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

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

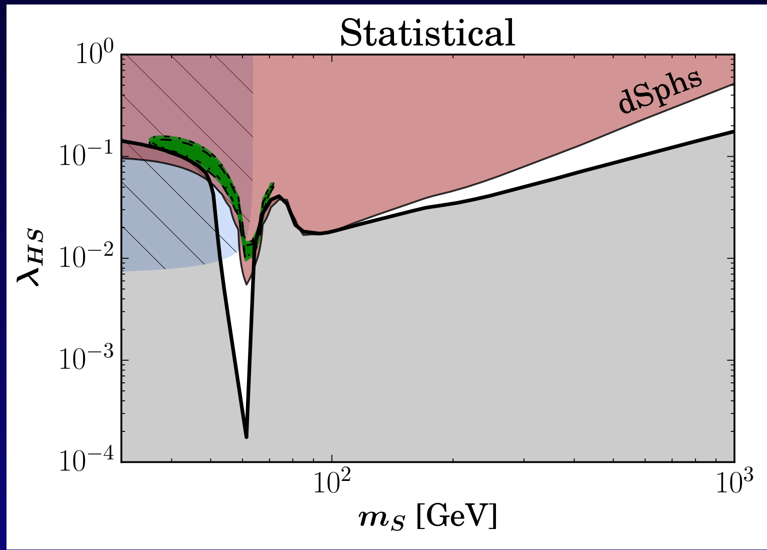


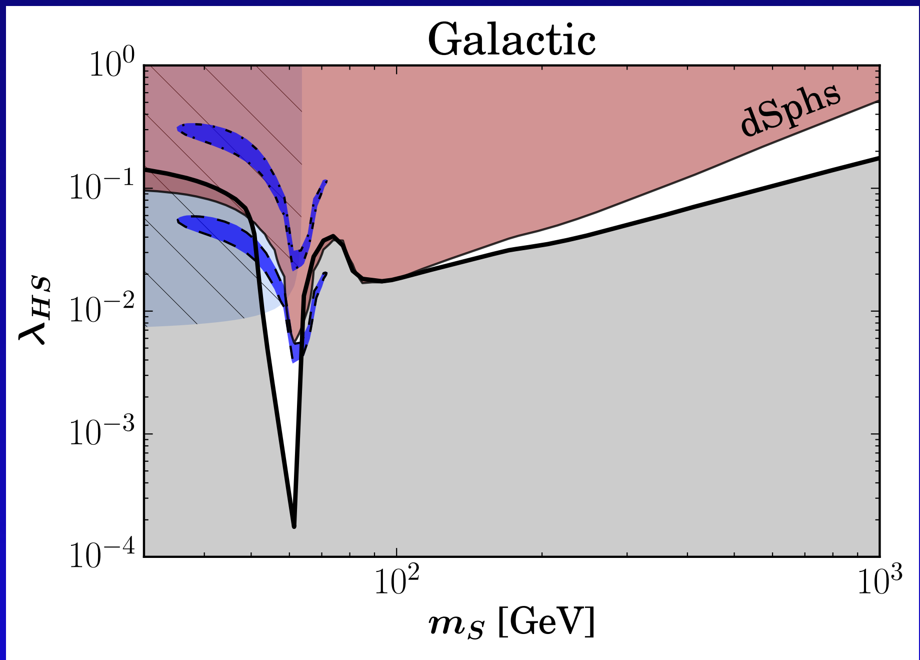


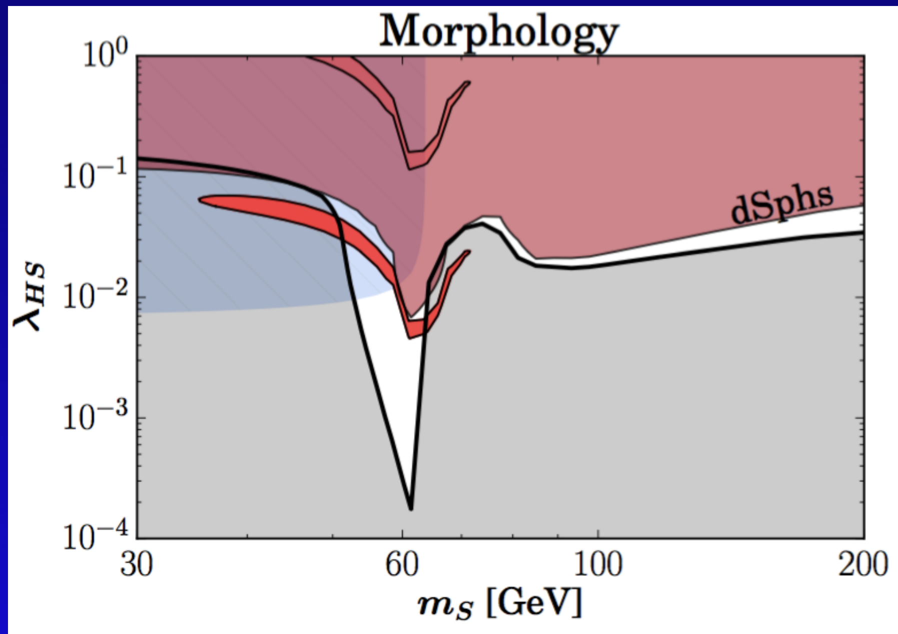


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

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







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

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.

- 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

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

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

Invited speakers have included (e.g.):

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!)