The Dark Matter distribution of the Milky Way

(its uncertainties and their effects on the determination of new physics)

Fabio Iocco

Università Federico II, NAPOLI

PASCOS 2025
Durham, July 22nd

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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

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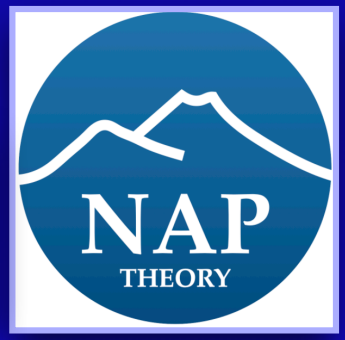
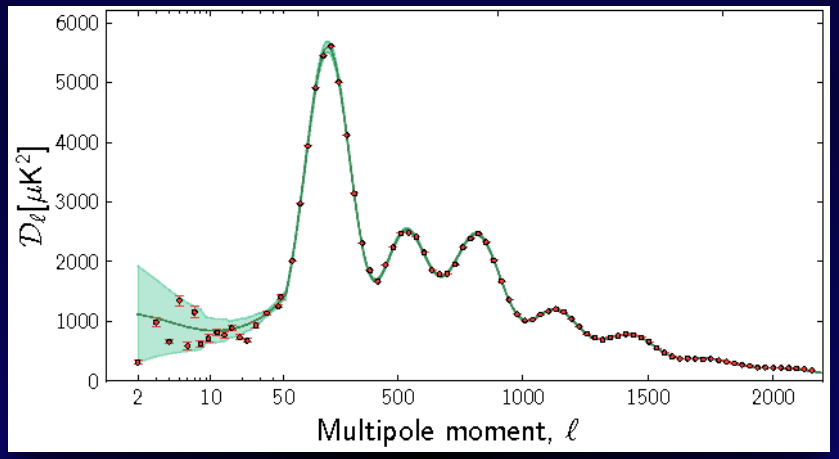
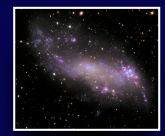
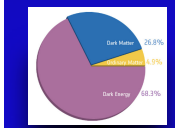


A story of LCDM
chapter I: evidence on diverse scales







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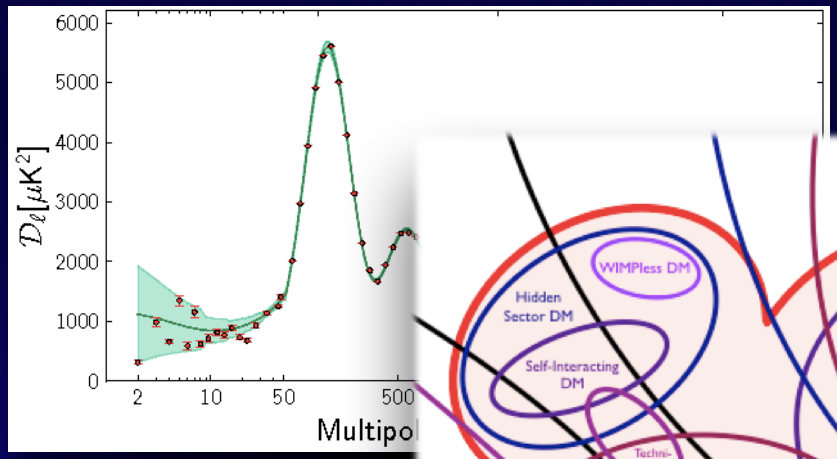
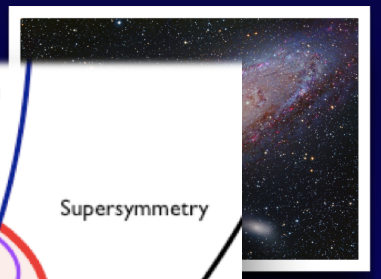
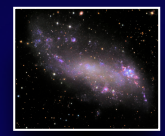
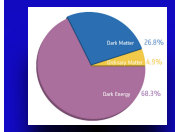


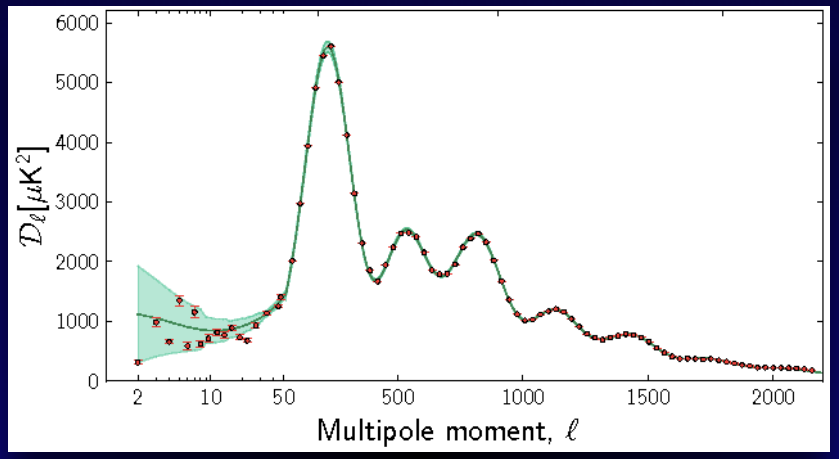


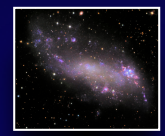


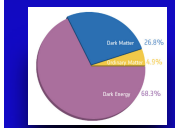


NATURE STILL UNKNOWN

A story of LCDM
chapter I: evidence on diverse scales

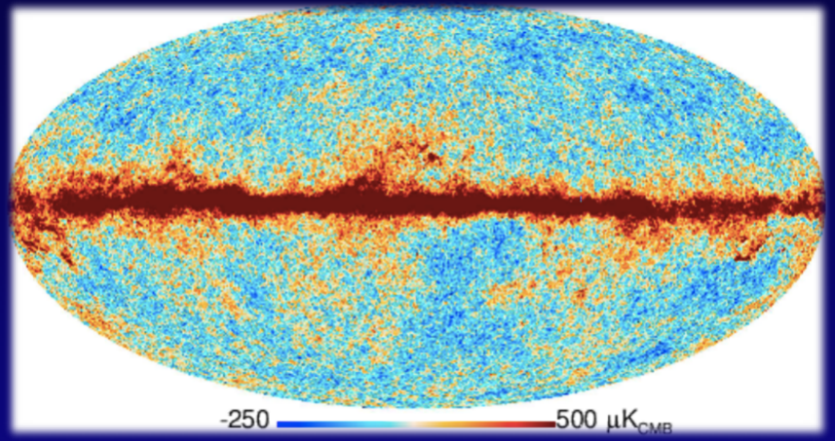


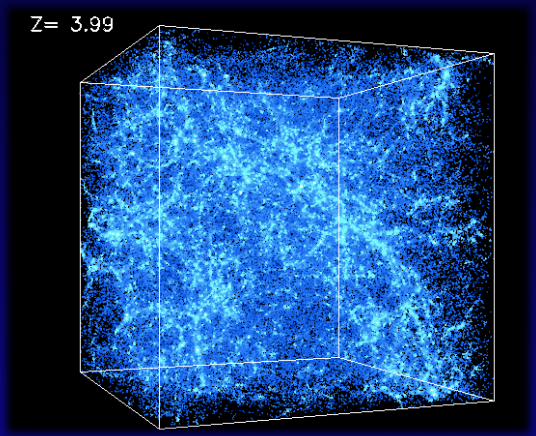


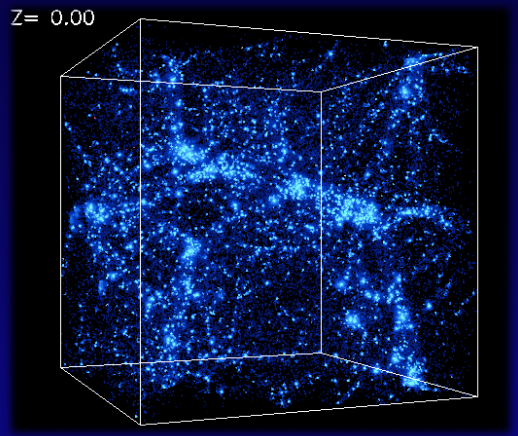


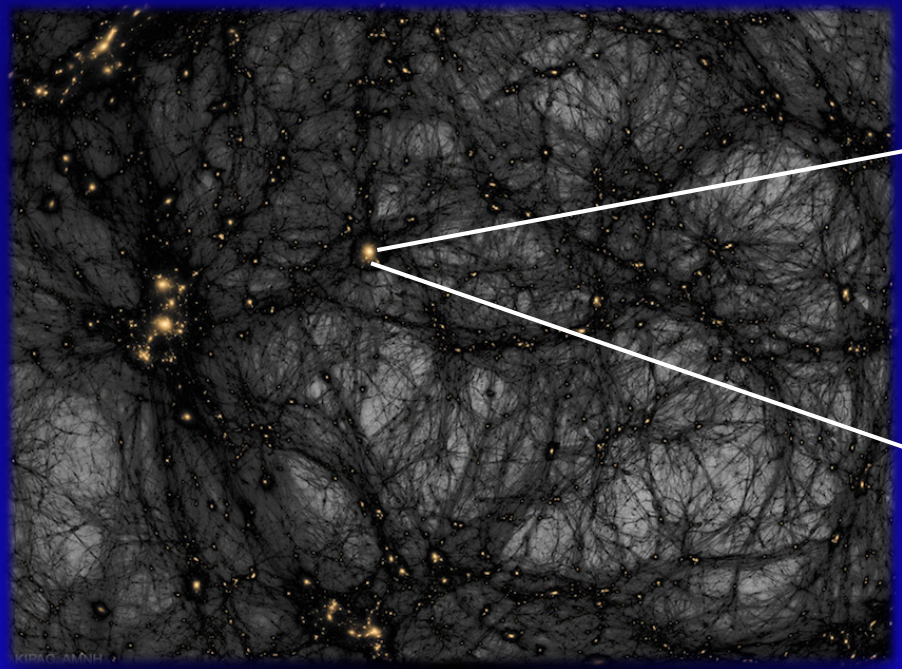
A story of LCDM
chapter II: structure formation

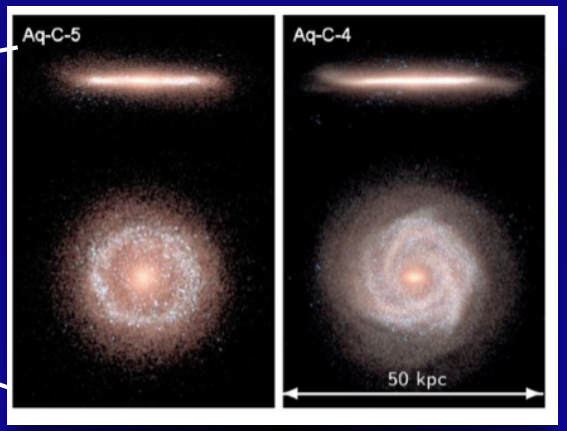
age of Universe











physical size

Milky Way or 银河系

this is how it looks like:

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]

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

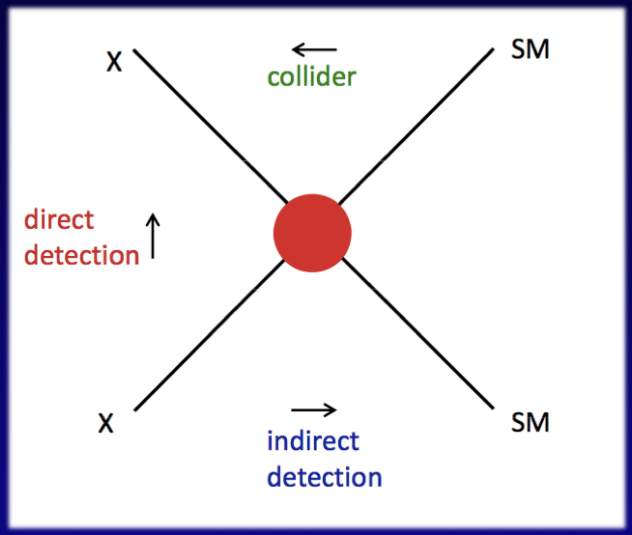
And if you care about the proximity of the Sun?

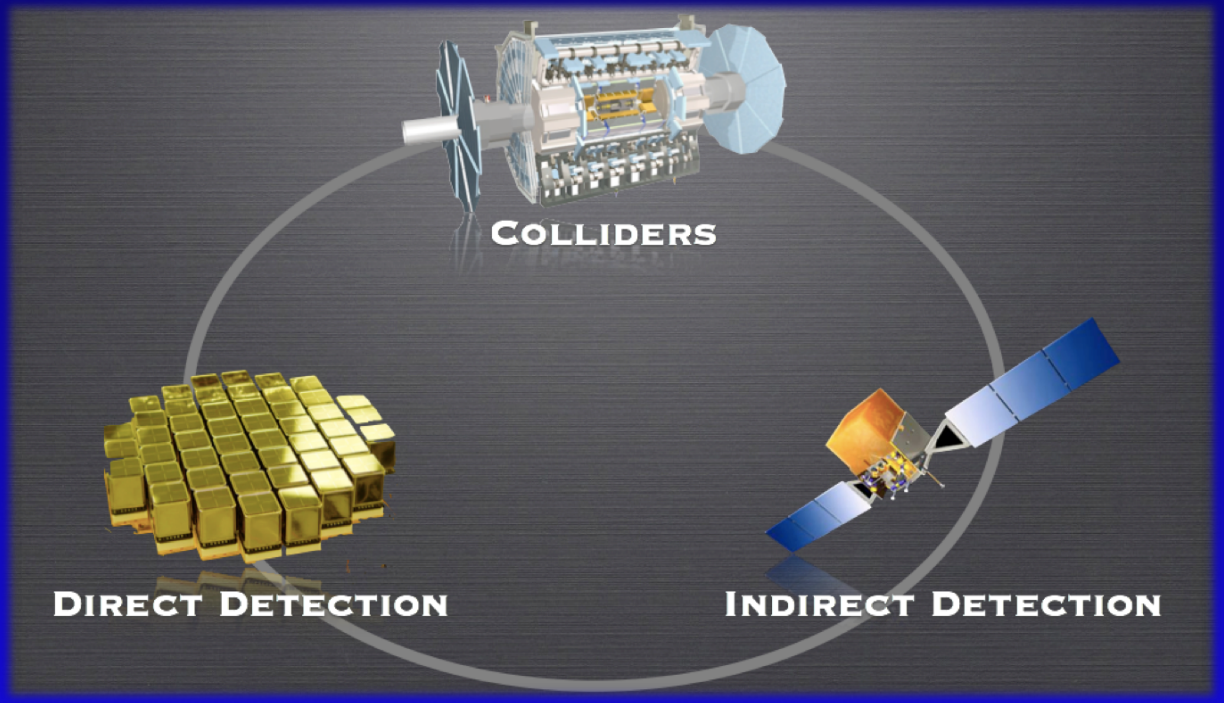
Synergic searches of WIMP DM
(Colliders, "direct", "indirect")

Direct detection:
DM scattering against nuclei, recoil

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

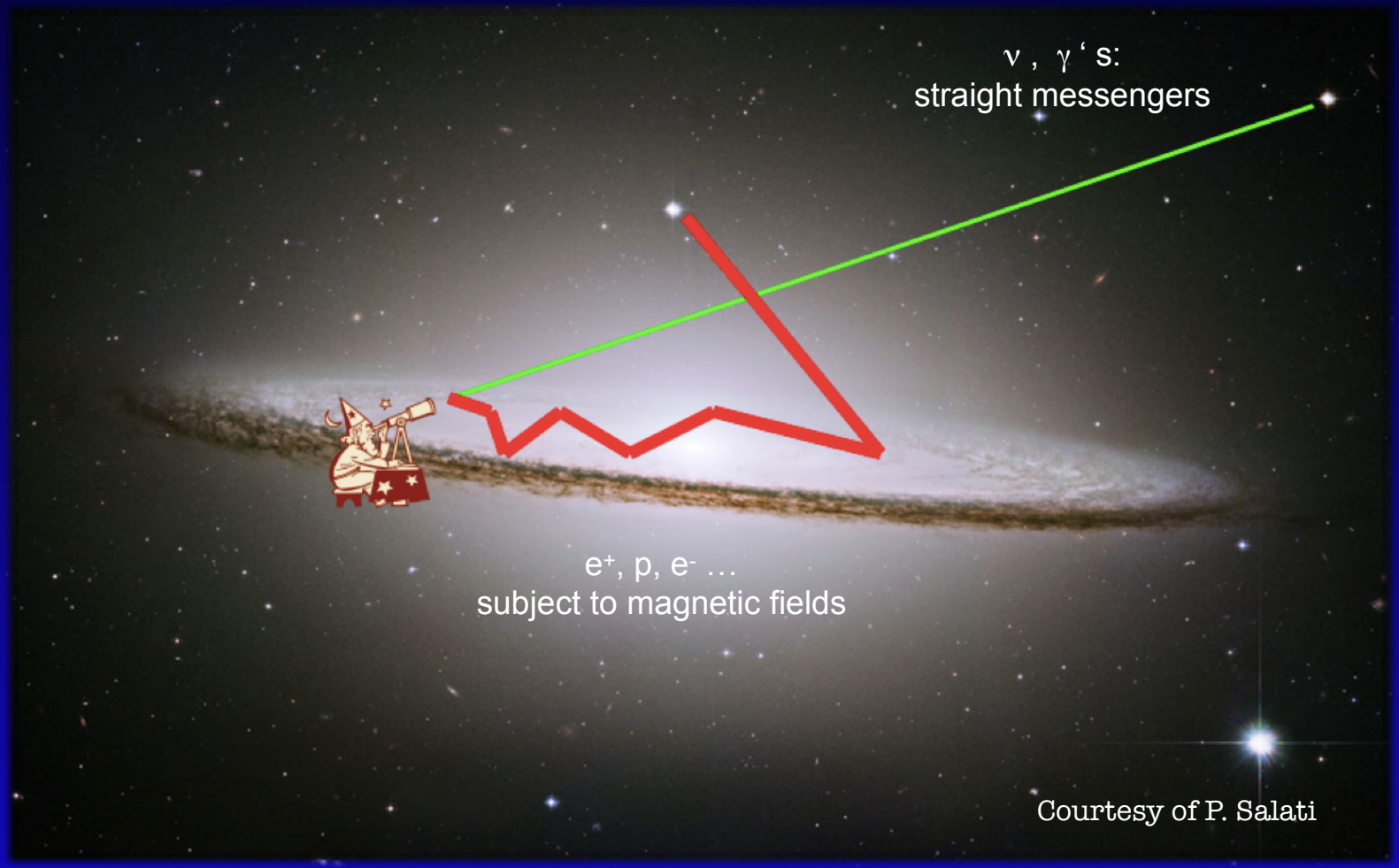
Production at LHC





Indirect Detection: principles and dependencies

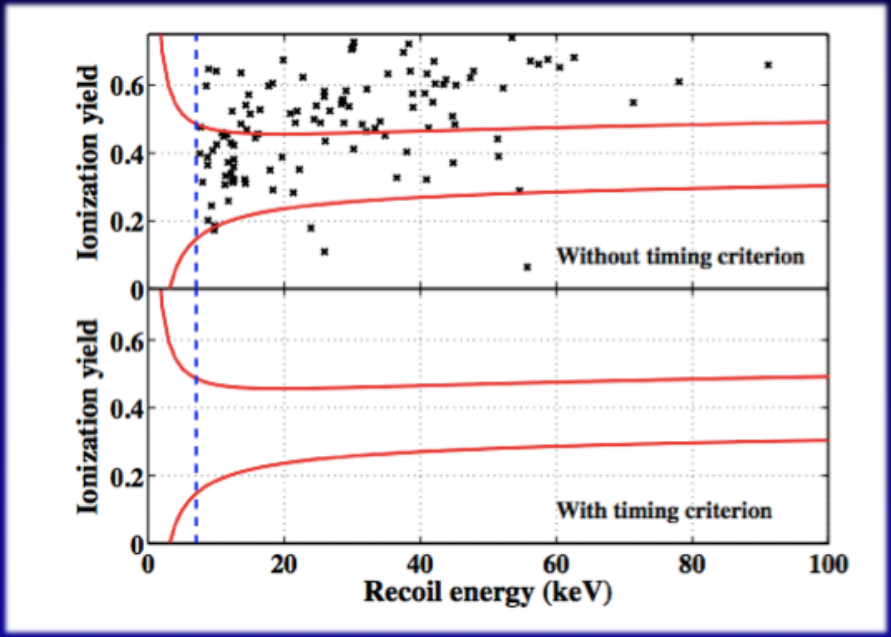
$$\chi + \chi \to q\bar{q}, W^+W^-, \ldots \to \gamma, \bar{p}, \ \bar{D}, \ e^+ \ \& \ \nu's$$



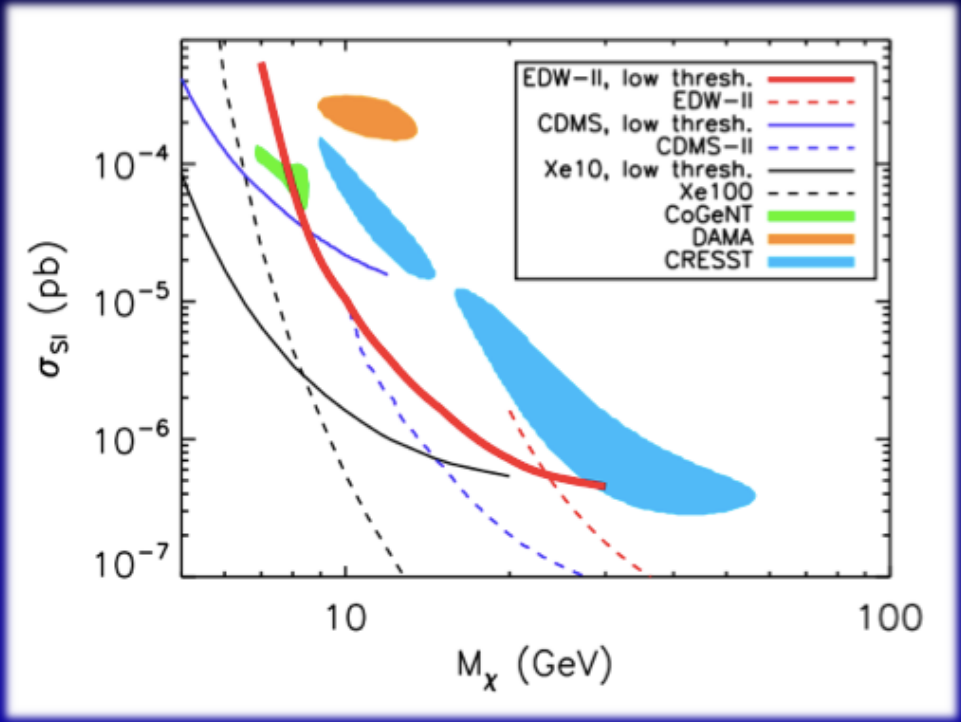
$$F_i \propto \frac{1}{4\pi d^2} B_i \frac{\langle \sigma v \rangle}{m_\chi} \int \rho^2(r) dV$$

Direct Detection: principles and dependencies (to go…)

from this



to this

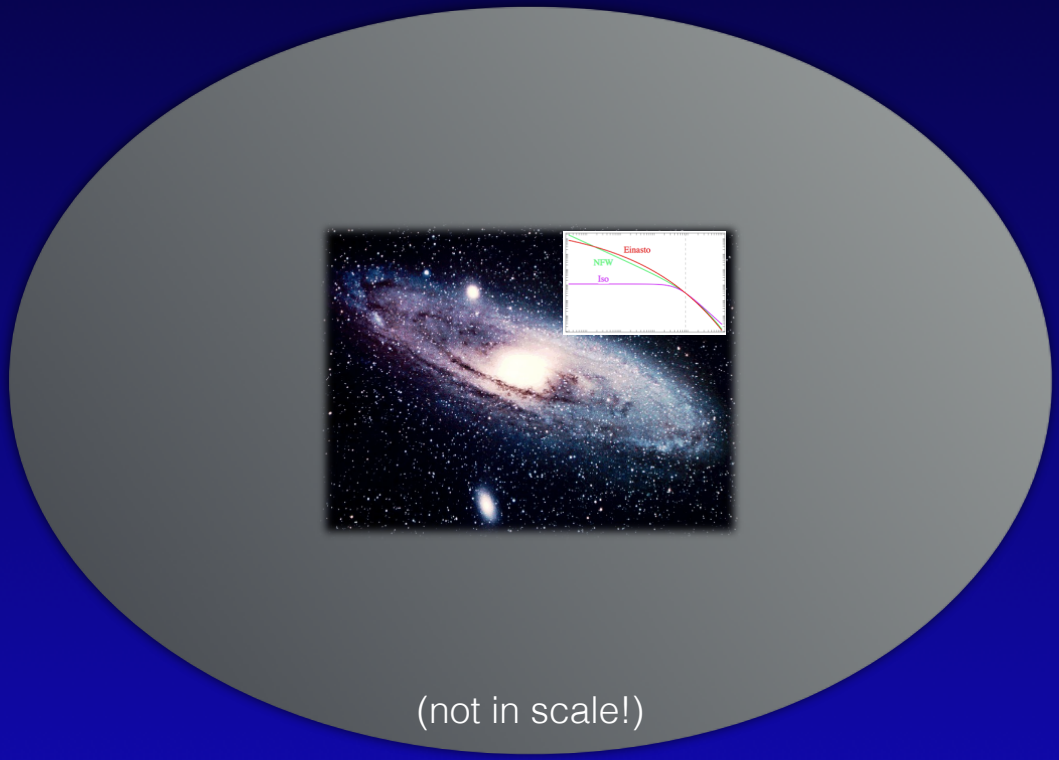


you need this

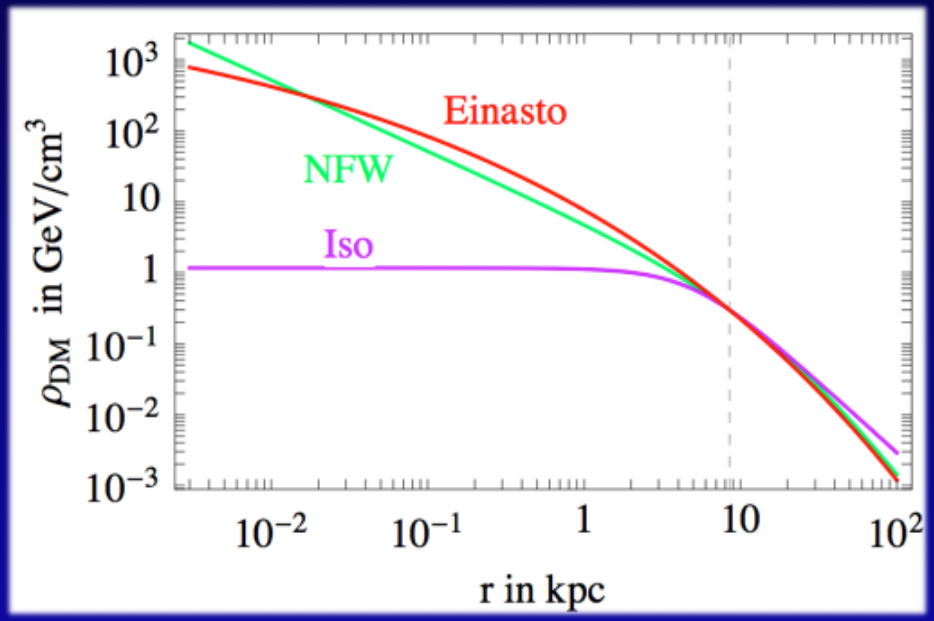
$$\frac{dR}{dE} \propto \frac{1}{\mu^2} \frac{\sigma_\chi}{m_\chi} \rho_0 \eta(v,t)$$

A story of LCDM chapter III: the single halo

A "universal" DM profile?



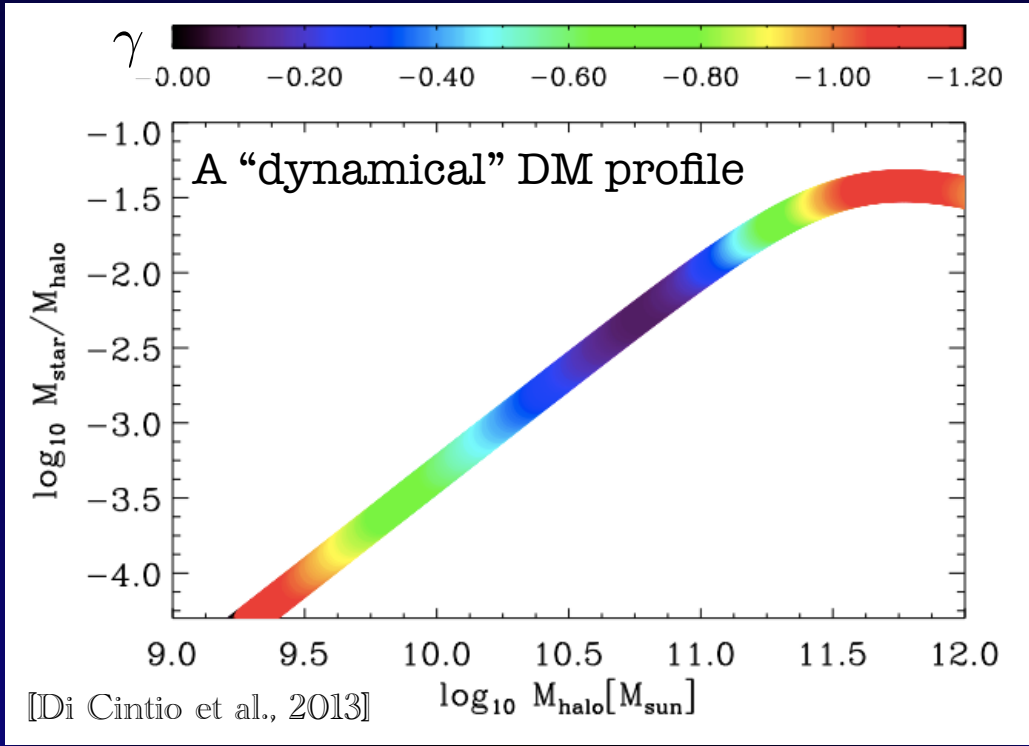
(not in scale!)

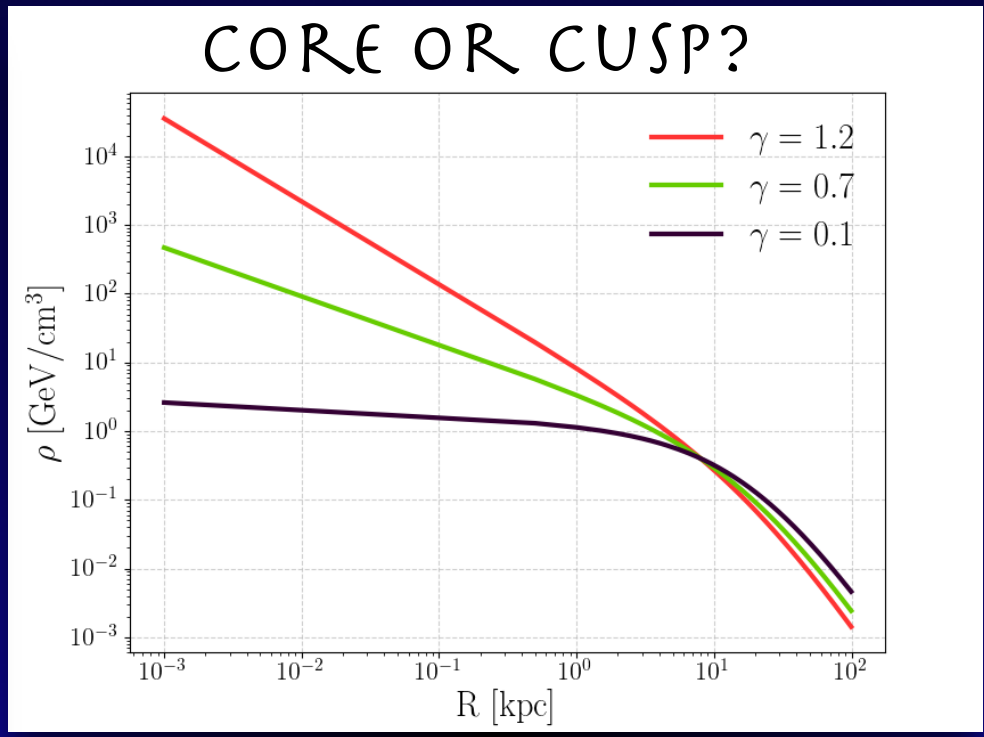


NAVARRO-FRENK-WHITE

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

A story of LCDM
chapter IV: the dark matter distribution





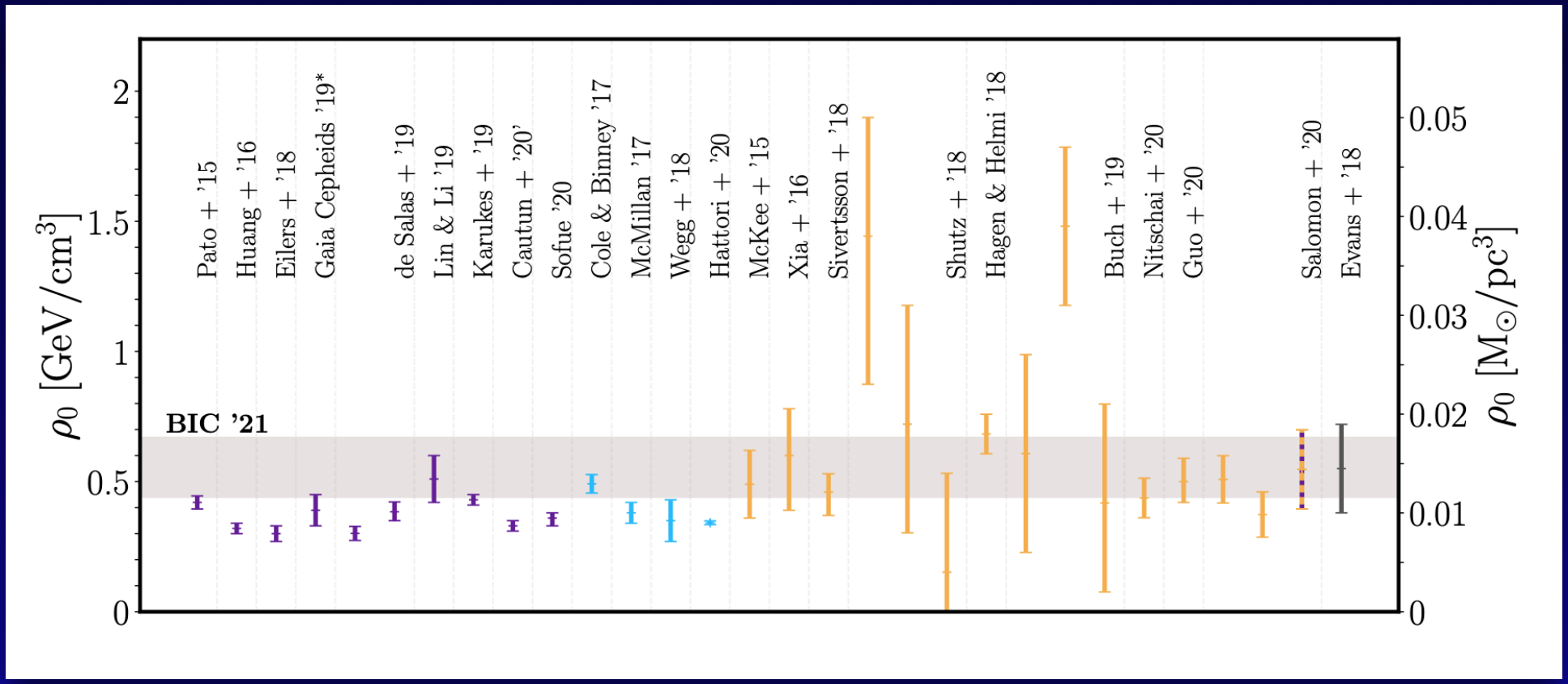
generalized NFW

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

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

And if you care about the proximity of the Sun?

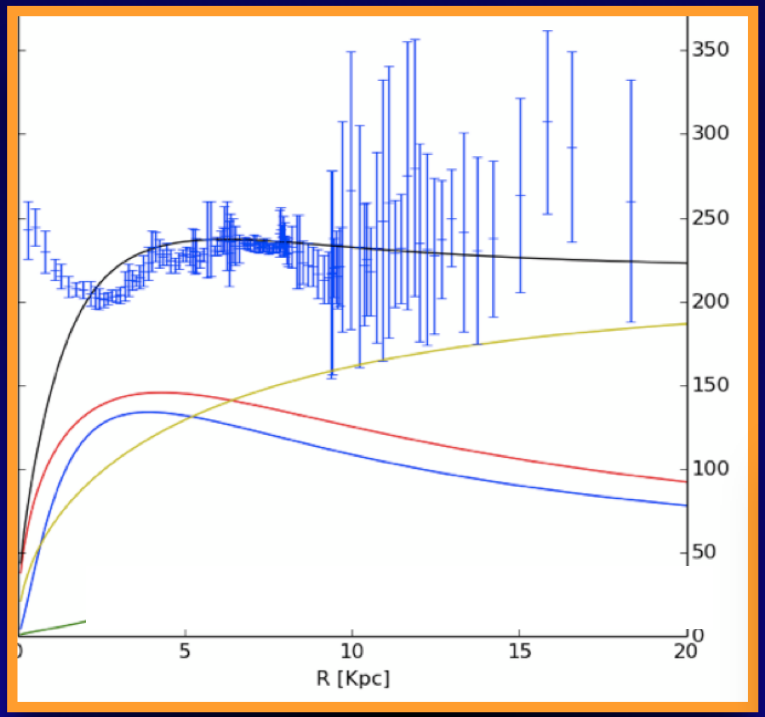
Empirical determination of local DM density: recent determinations



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

The DM distribution in disk galaxies: the Rotation Curve method

Fitting a pre-assigned shape on top of luminous

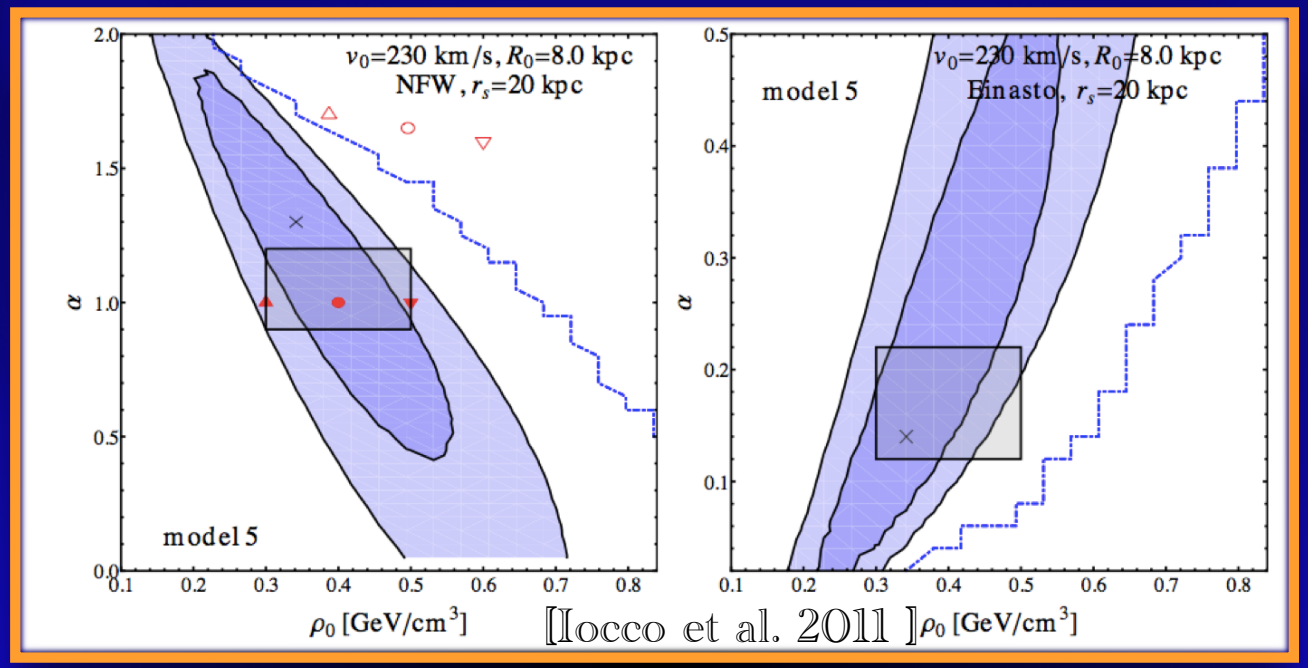


gNFW

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

Einasto

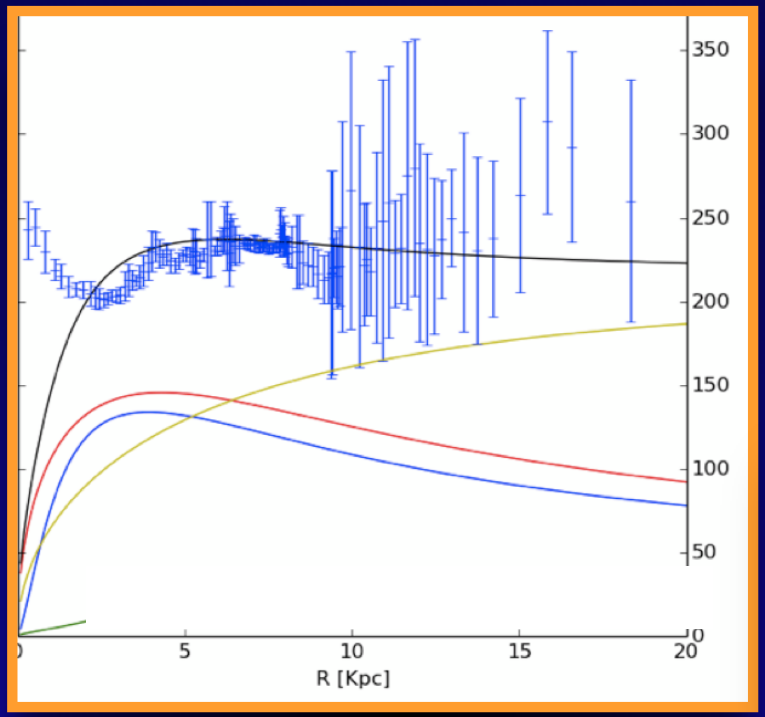
$$\rho_{DM}(R) \propto \rho_0 \exp\left[-\frac{2}{\gamma}\left(\left(\frac{R}{R_s}\right)^{\gamma}-1\right)\right]$$



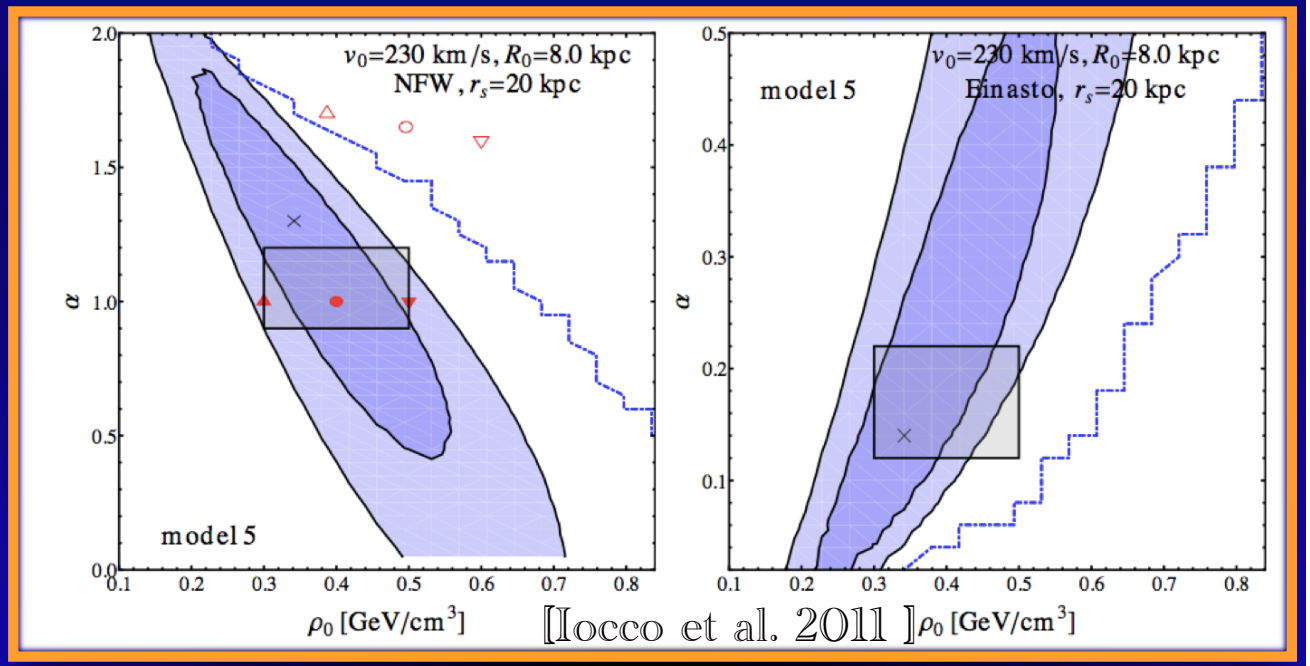
[Iocco et al. 2011]

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

The Rotation Curve method requires a lot of (fortunate) conditions



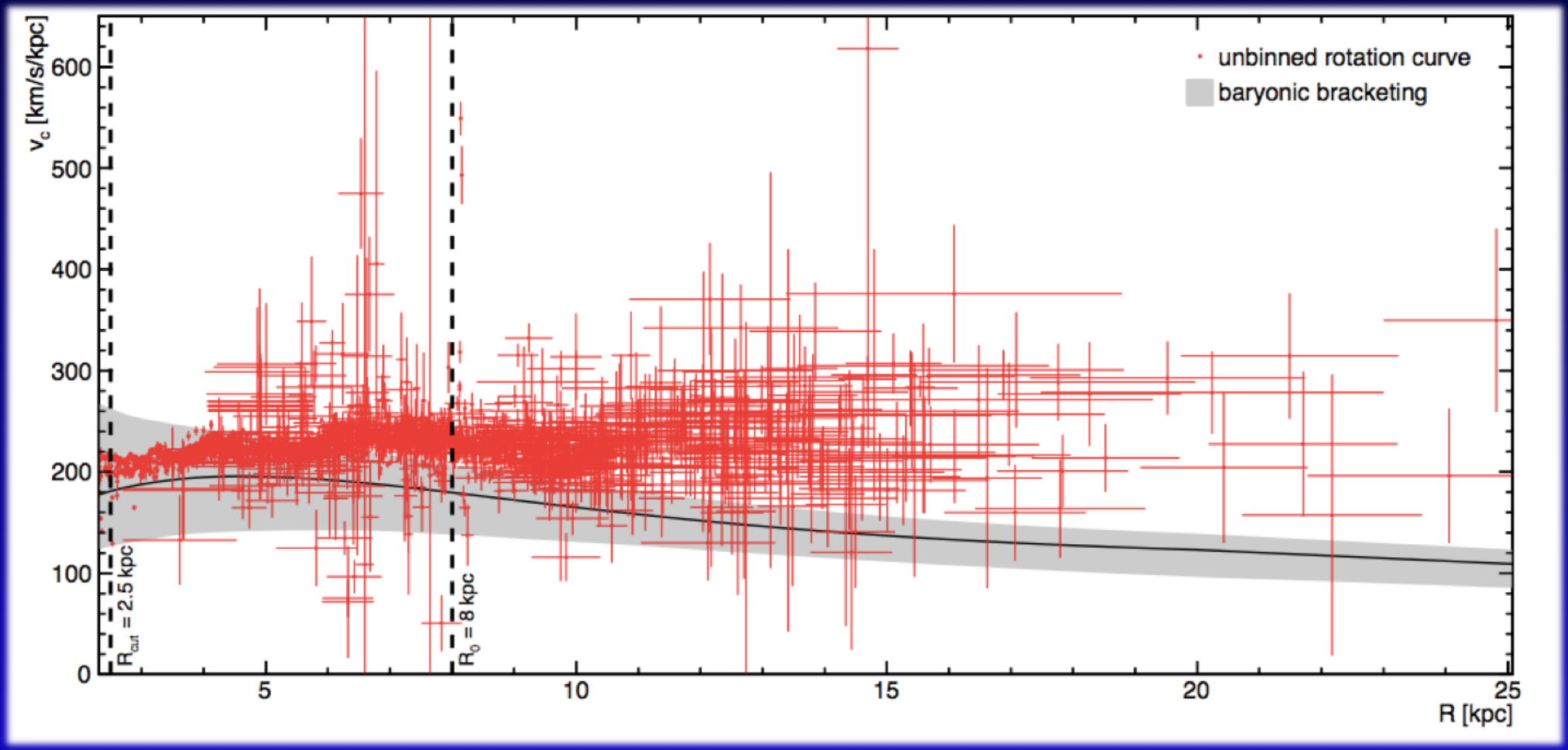
The Anna Karenina principle:
"all happy families are alike"



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

[Iocco et al. 2011]

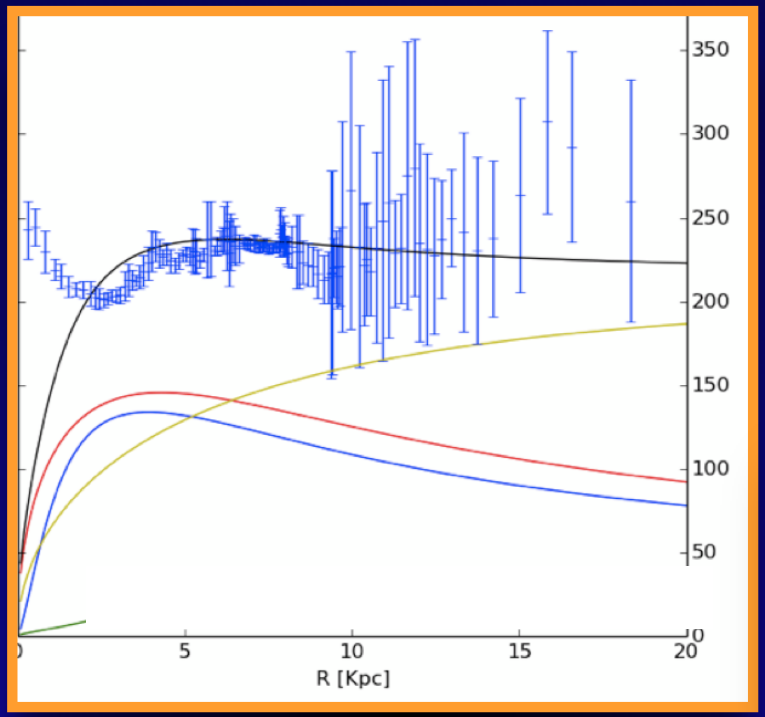
The Milky Way rotation curve



[Iocco, Pato, Bertone, Nature Physics 2015]

The DM distribution in disk galaxies: the Rotation Curve method

Fitting a pre-assigned shape on top of luminous



gNFW

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

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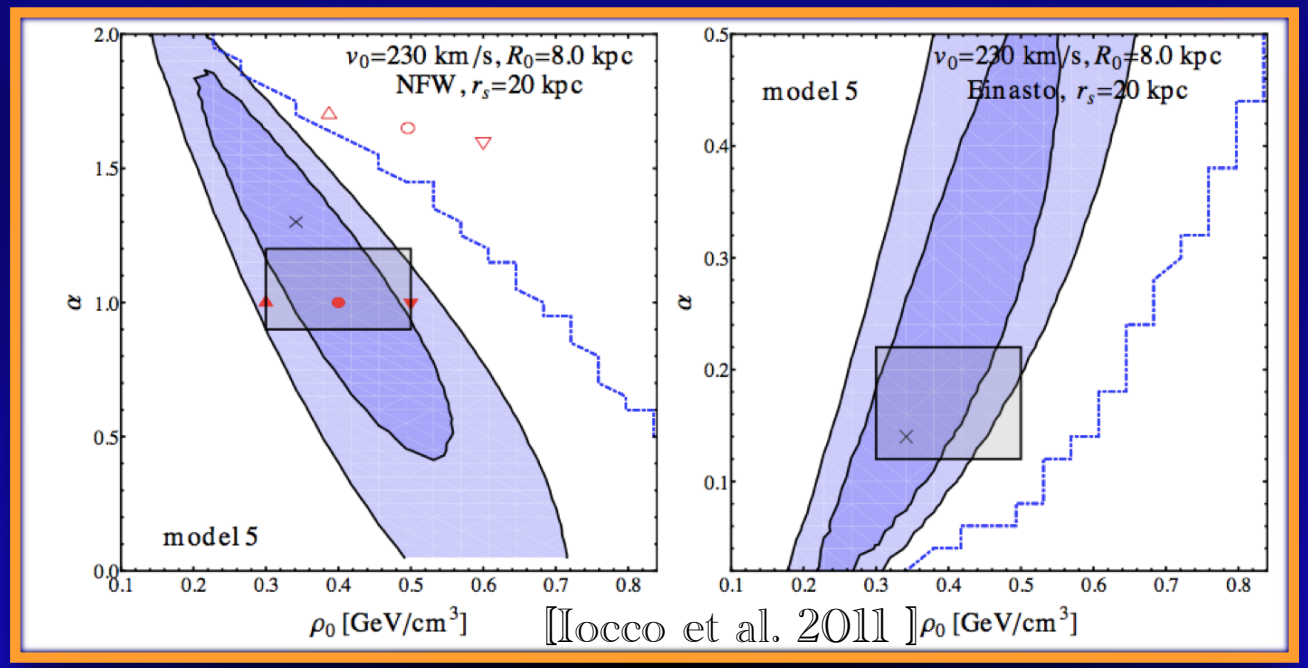
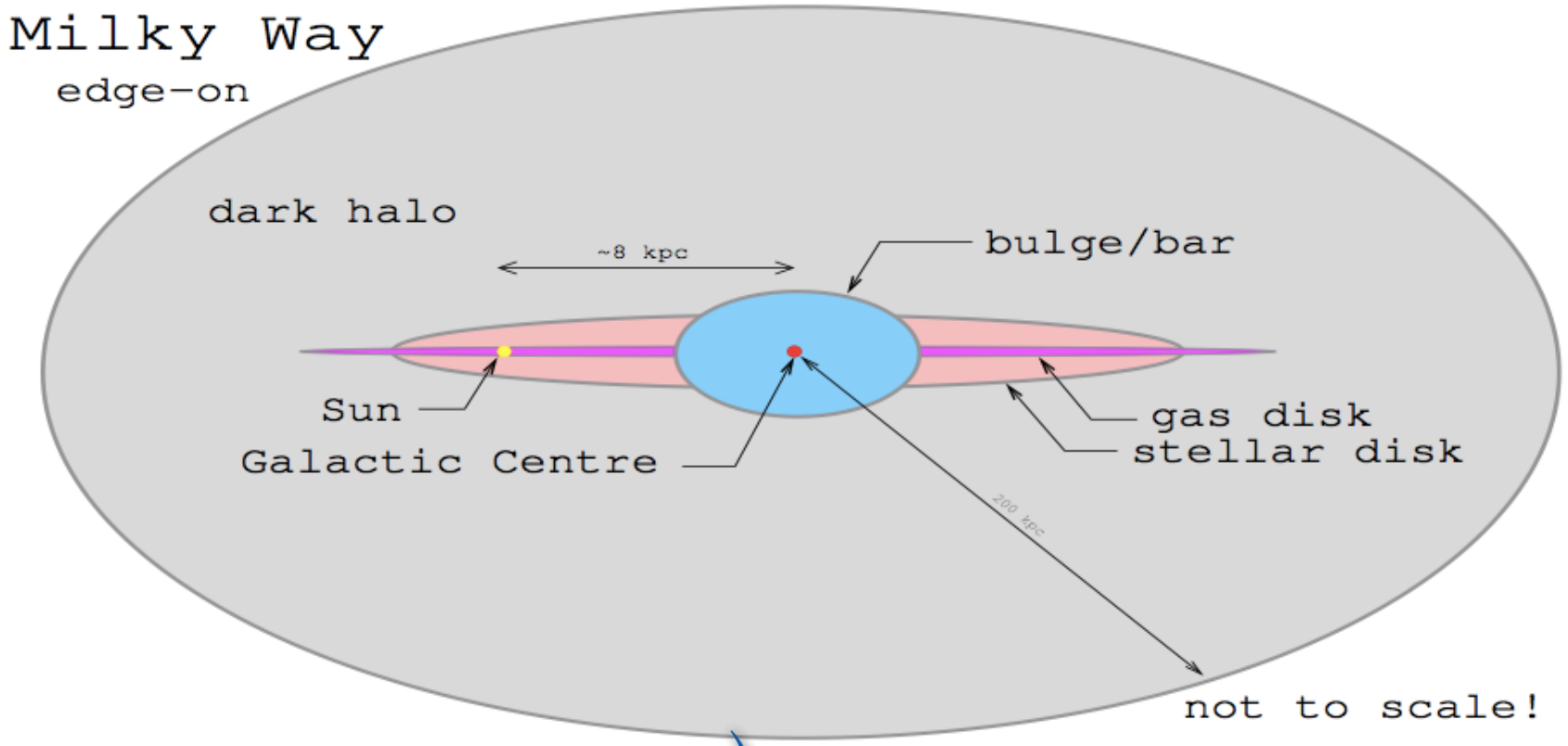
$$\rho_{DM}(R) \propto \rho_0 \exp\left[-\frac{2}{\gamma}\left(\left(\frac{R}{R_s}\right)^{\gamma}-1\right)\right]$$



[Iocco et al. 2011]

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

The Rotation Curve method, an example: the Milky Way



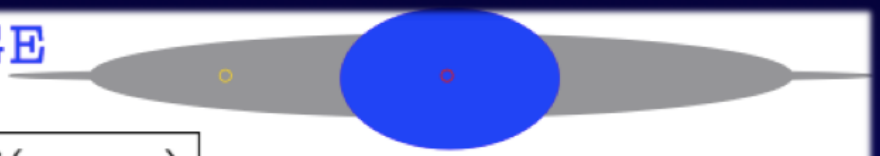
bulge	tilted bar
disk	thin+thick
gas	H_2, HI, HII

observations (<u>with uncertainties</u>)

Courtesy of Miguel Pato

The luminous Milky Way: observations of morphology

2. BARYONS: STELLAR BULGE



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

morphology $f(x,y,z)$

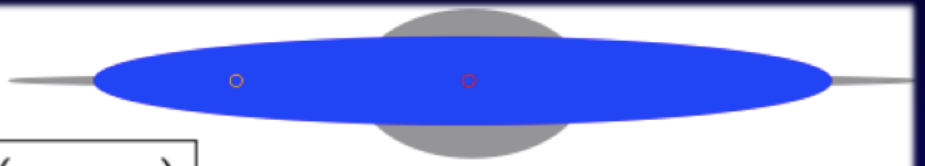
Stanek+ '97 (E2)	e^{-r}	0.9:0.4:0.3	24°	optical
Stanek+ '97 (G2)	$e^{-r_s^2/2}$	1.2:0.6:0.4	25°	optical
Zhao '96	$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	1.5:0.6:0.4	20°	infrared
Bissantz & Gerhard '02	$e^{-r_s^2}/(1+r)^{1.8}$	2.8:0.9:1.1	20°	infrared
Lopez-Corredoira+ '07	Ferrer potential	7.8:1.2:0.2	43°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



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

morphology $f(x,y,z)$

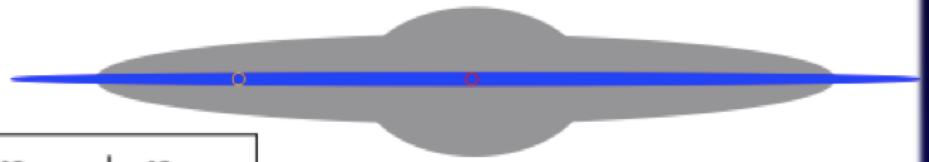
Han & Gould '03	$e^{-R}\mathrm{sech}^2(z)$	2.8:0.27	thin	optical
	$e^{-R-\lvert z\rvert}$	2.8:0.44	thick	
Calchi-Novati & Mancini '11	$e^{-R-\lvert z\rvert}$	2.8:0.25	thin	optical
	$e^{-R-\lvert z\rvert}$	4.1:0.75	thick	
deJong+ '10	$e^{-R-\lvert z\rvert}$	2.8:0.25	thin	optical
	$e^{-R-\lvert z\rvert}$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

normalization and its statistical uncertainties

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



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

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

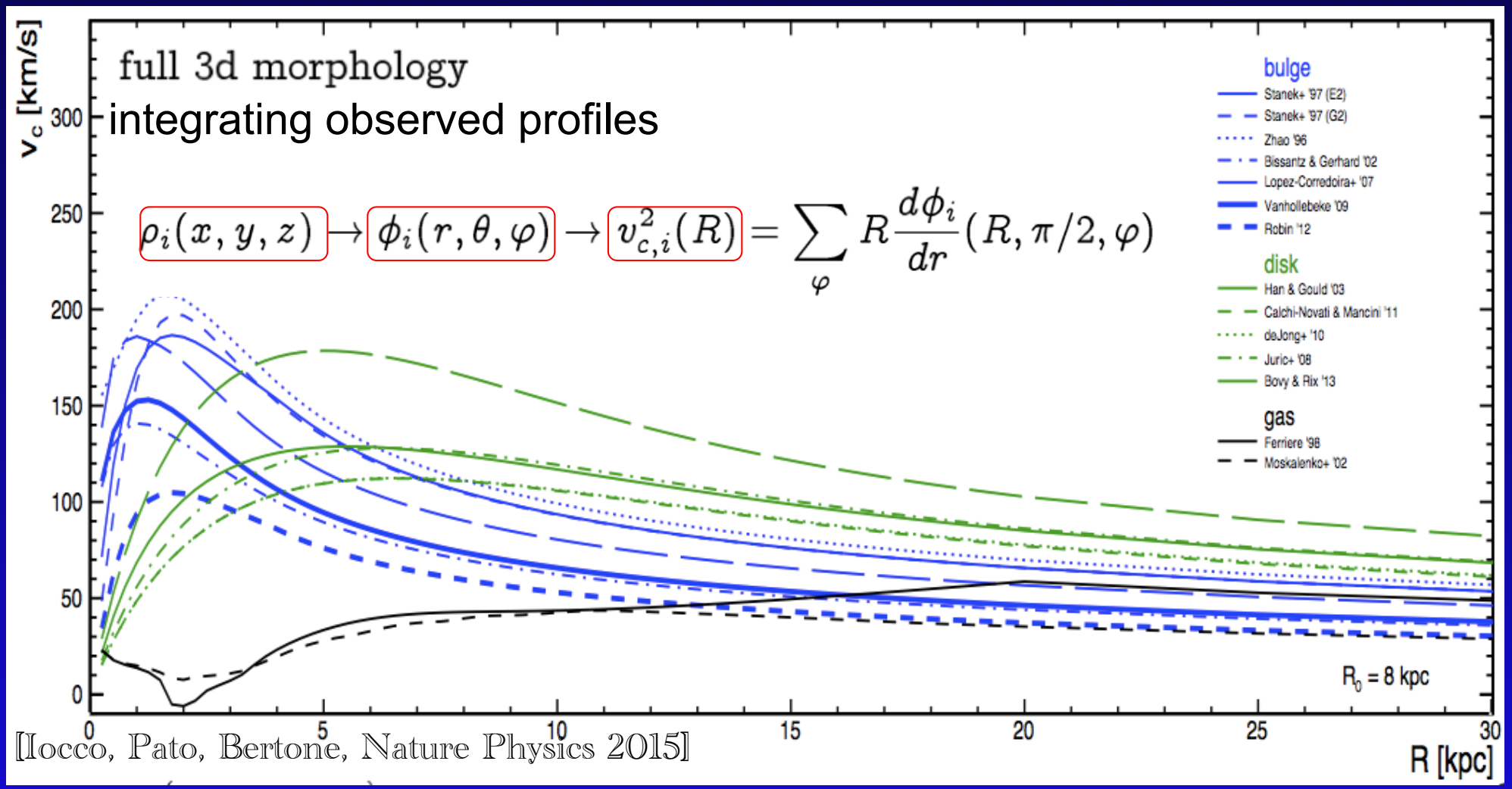
CO-to-H_2 factor: $X_{\rm CO} = 0.25 - 1.0 \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s for $r < 2$ kpc

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

[Ferrière+ '07, Ackermann '12]

The luminous Milky Way:
expected rotation curve

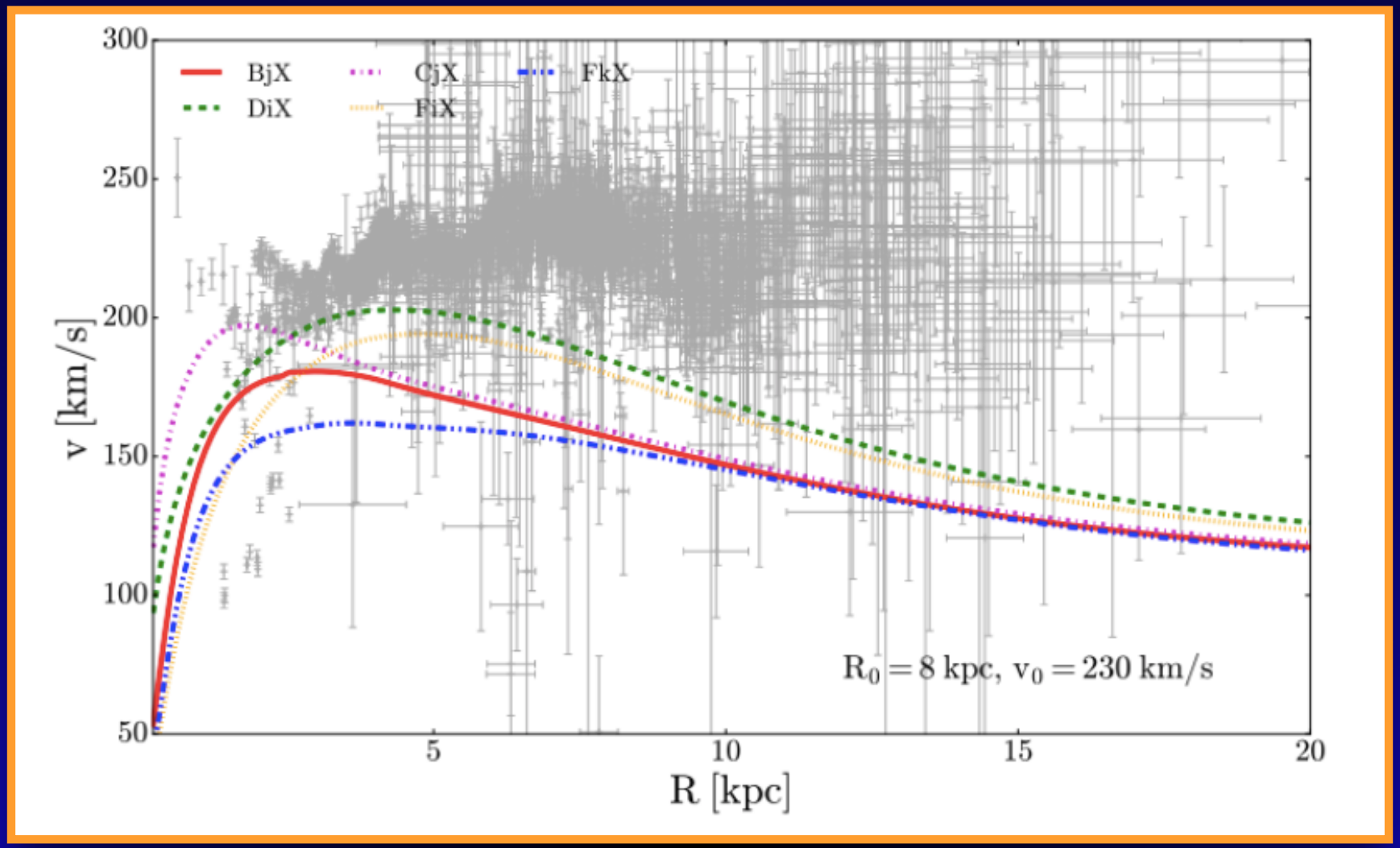
$$\phi_i(r,\theta,\varphi) = -4\pi G \sum_{l,m} \frac{Y_{lm}(\theta,\varphi)}{2l+1} \left[\frac{1}{r^{l+1}} \int_0^r \rho_{i,lm}(a)\, a^{l+2}\, da + r^l \int_r^\infty \rho_{i,lm}(a)\, a^{1-l}\, da \right]$$



[Iocco, Pato, Bertone, Nature Physics 2015]

Systematic uncertainties

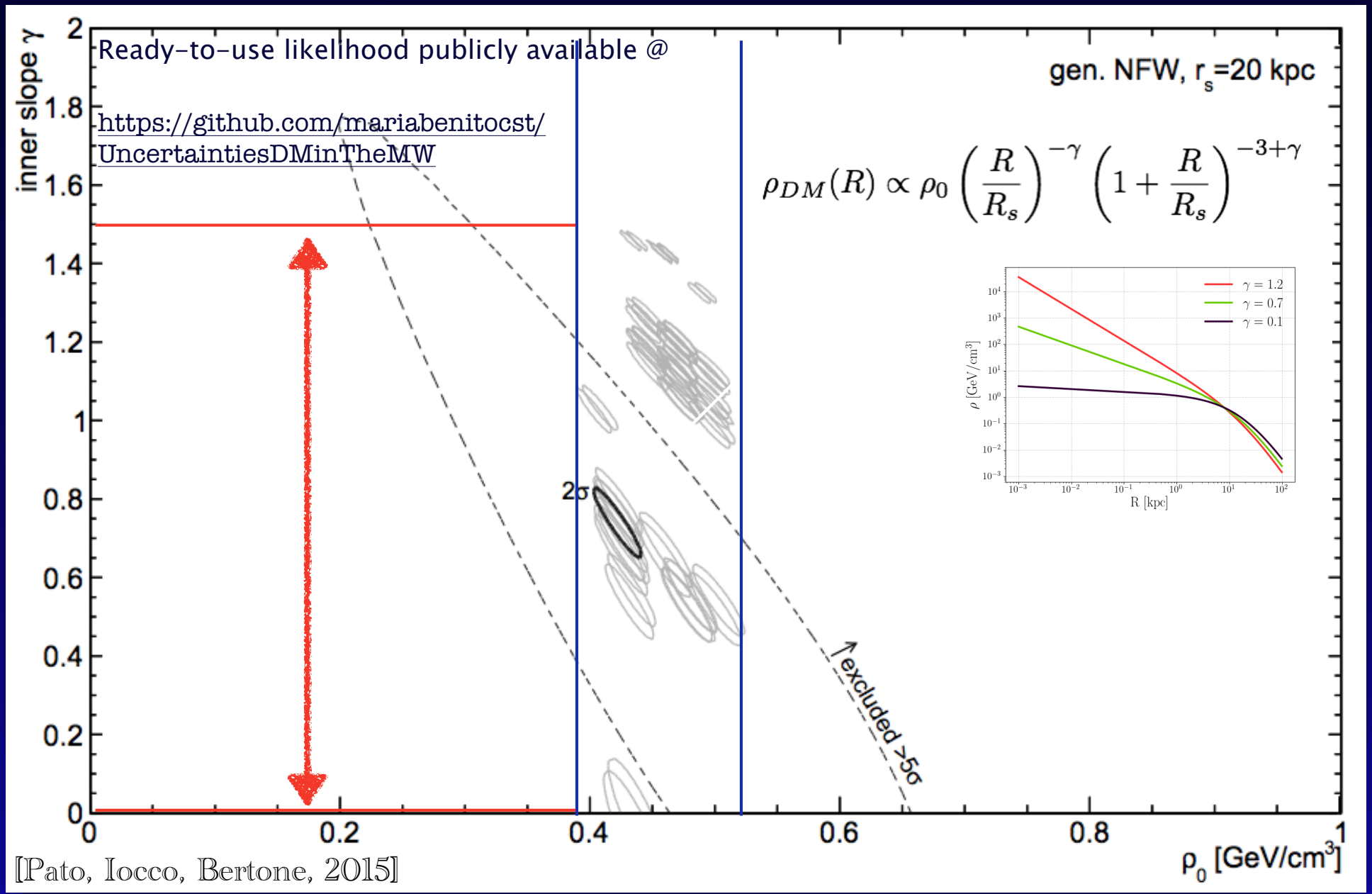
(luminous component)



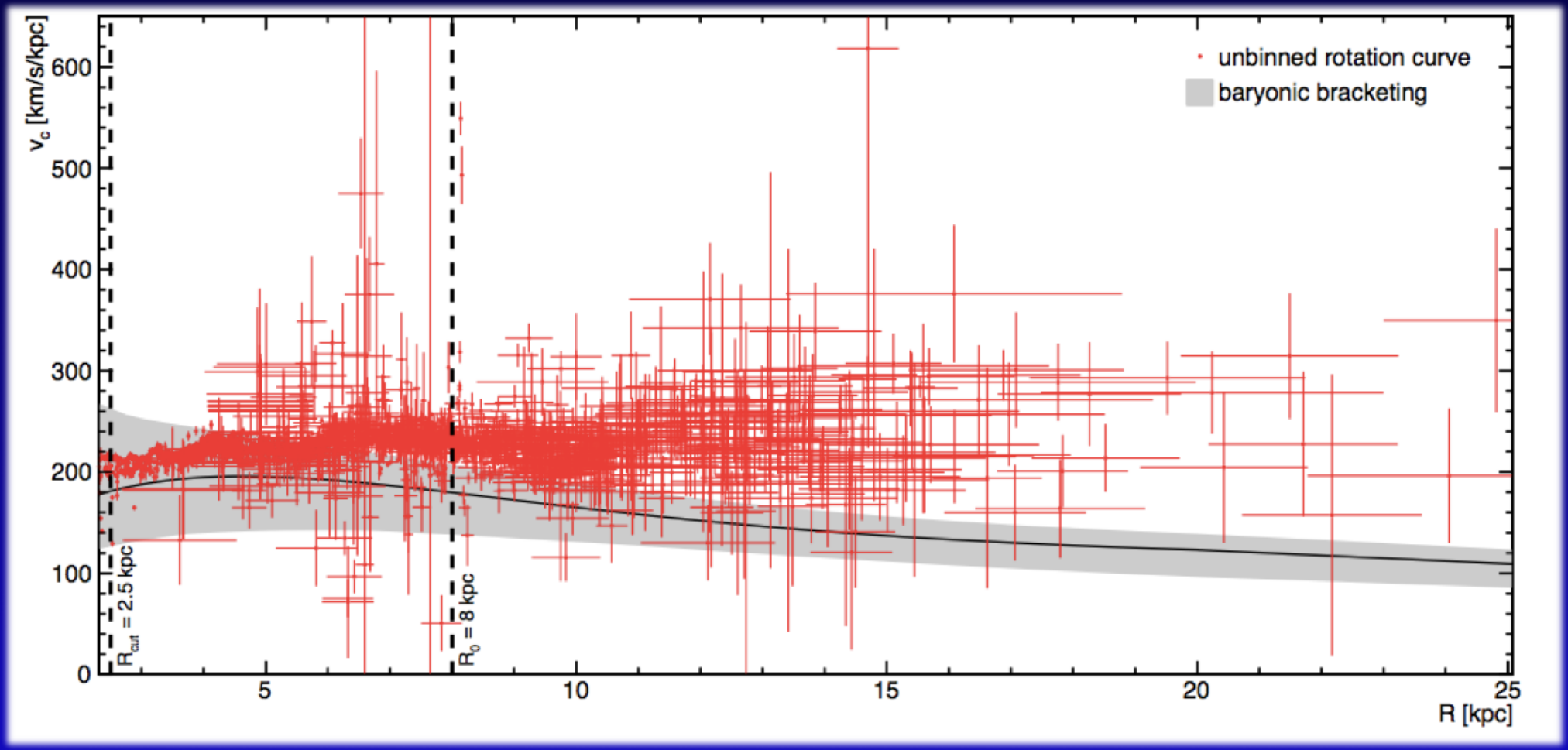
[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017]

[Iocco, Pato, Bertone, Nature Physics 2015]

Extracting the DM density structure



The Rotation Curve method, an example: the Milky Way



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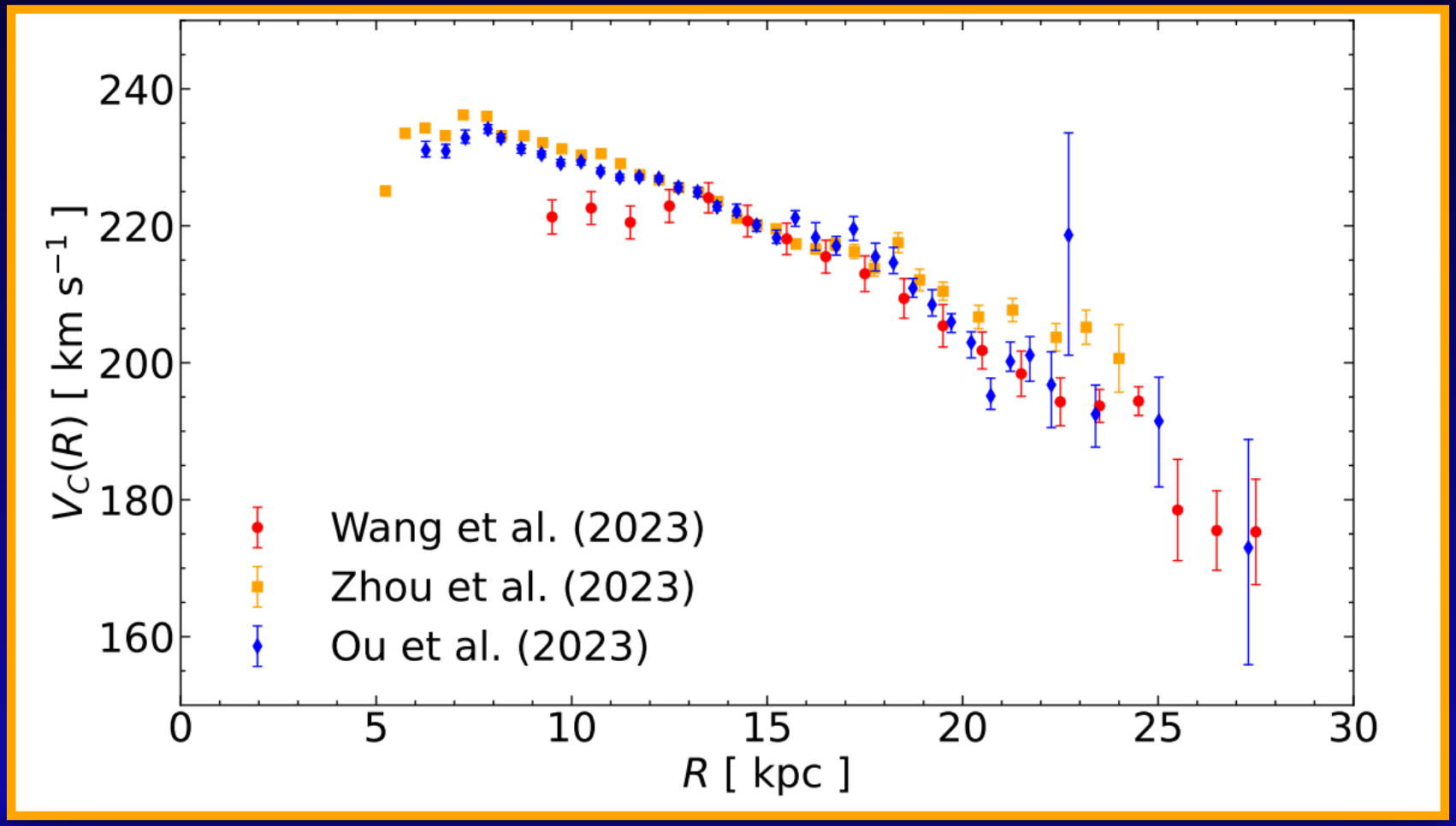
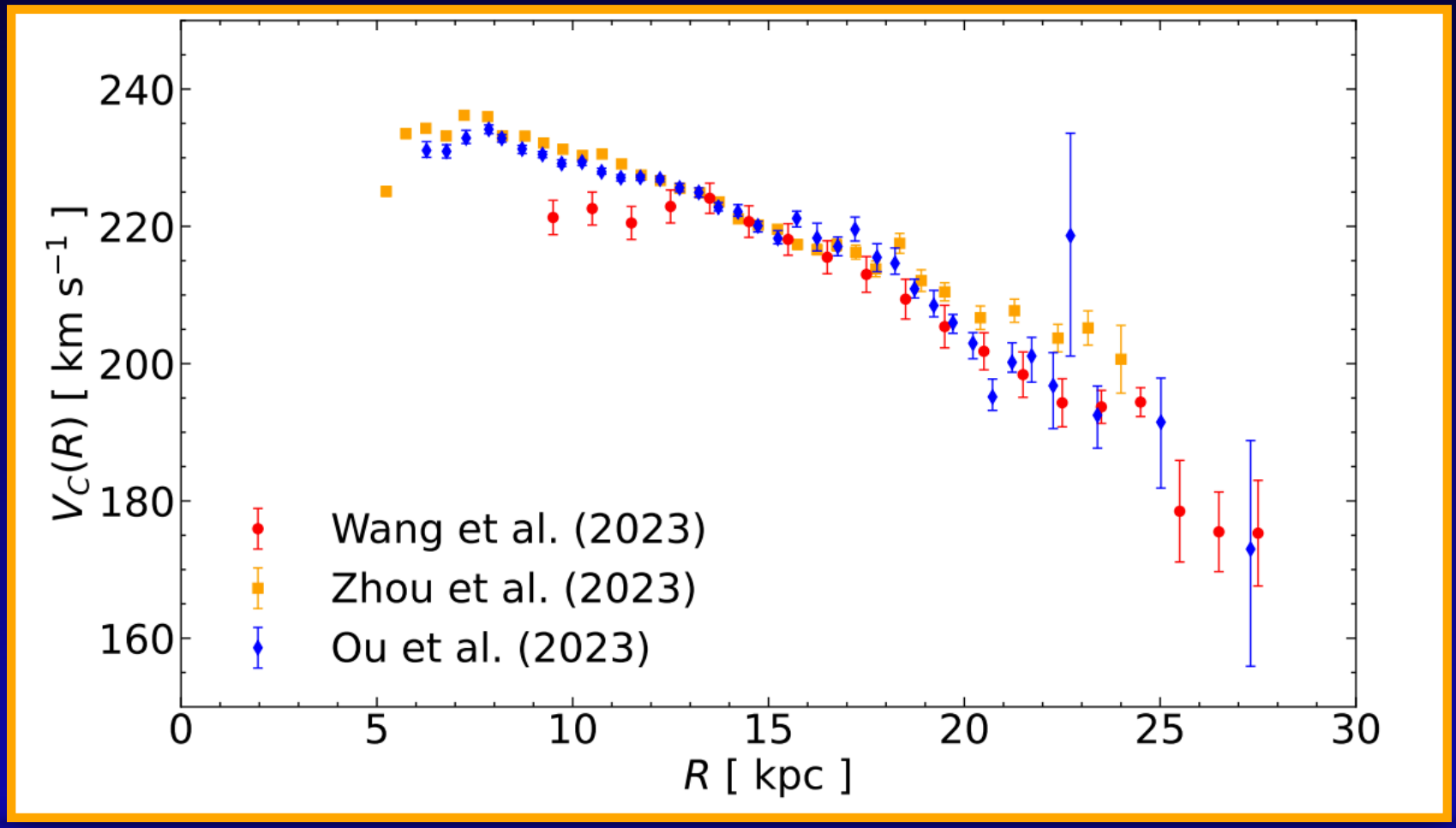
Recently, enters Gaia (data):



Recently, enters Gaia (data):



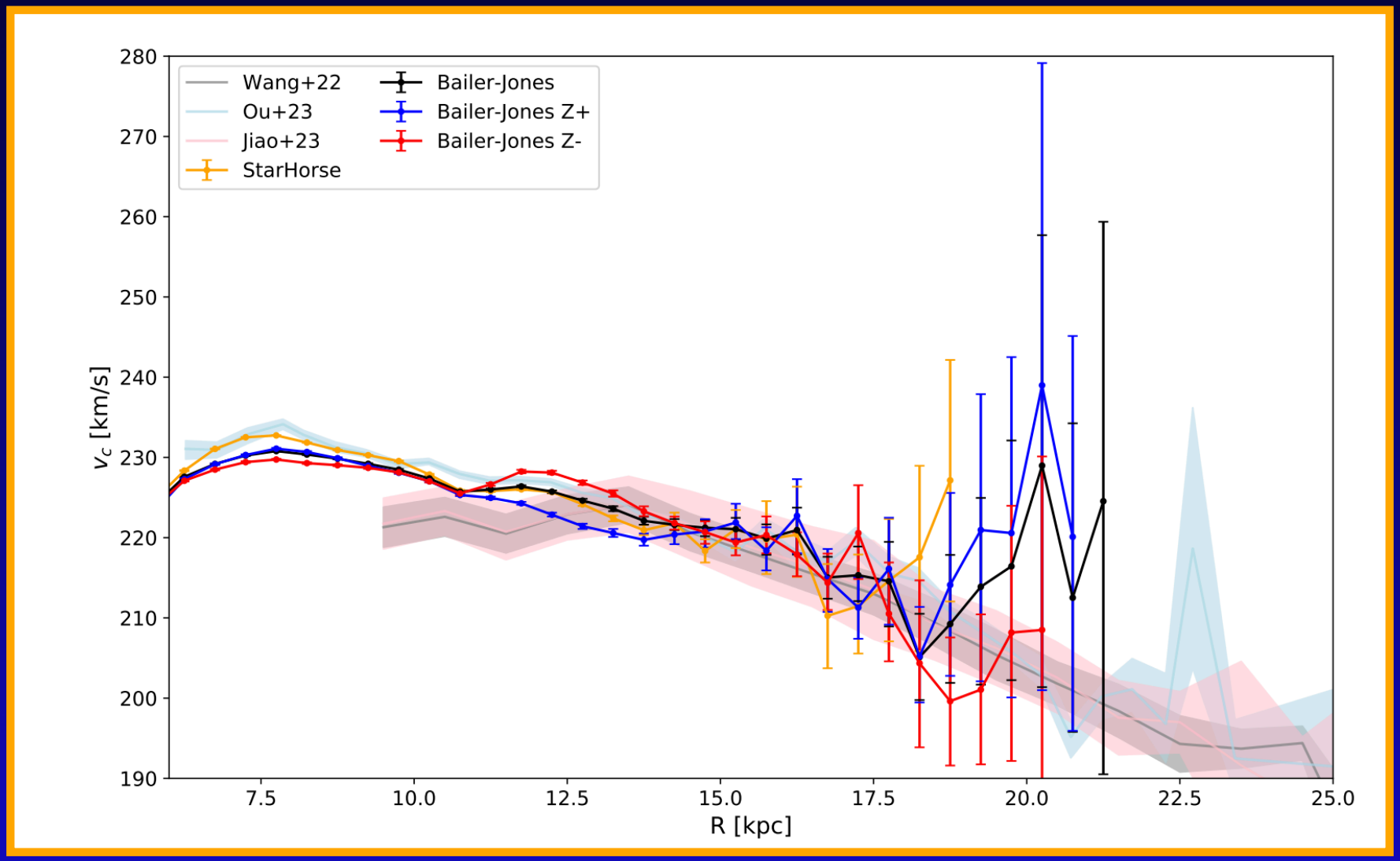
The devil is in the details
(read the small print)

$$\frac{\partial(\nu\,\langle v_R^2\rangle)}{\partial R} + \frac{\partial(\nu\,\langle v_R v_z\rangle)}{\partial z} + \nu\left(\frac{\langle v_R^2\rangle - \langle v_\phi^2\rangle}{R} + \frac{\partial\Phi}{\partial R}\right)$$

$$\langle v_R^2\rangle(R) \propto \exp\left(\frac{-R}{R_{\mathrm{exp},\langle v_R^2\rangle}}\right)$$

[Koop et al, 2024]

Recently, enters Gaia (data):



[Koop et al, 2024]

Worrisome enough: history apparently repeats itself

(to DM ot not to DM?)

Kinematical and chemical vertical structure of the Galactic thick disk[1,2]
II. A lack of dark matter in the solar neighborhood

C. Moni Bidin

On the local dark matter density

Jo Bovy[1] and Scott Tremaine

Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA

[2012]

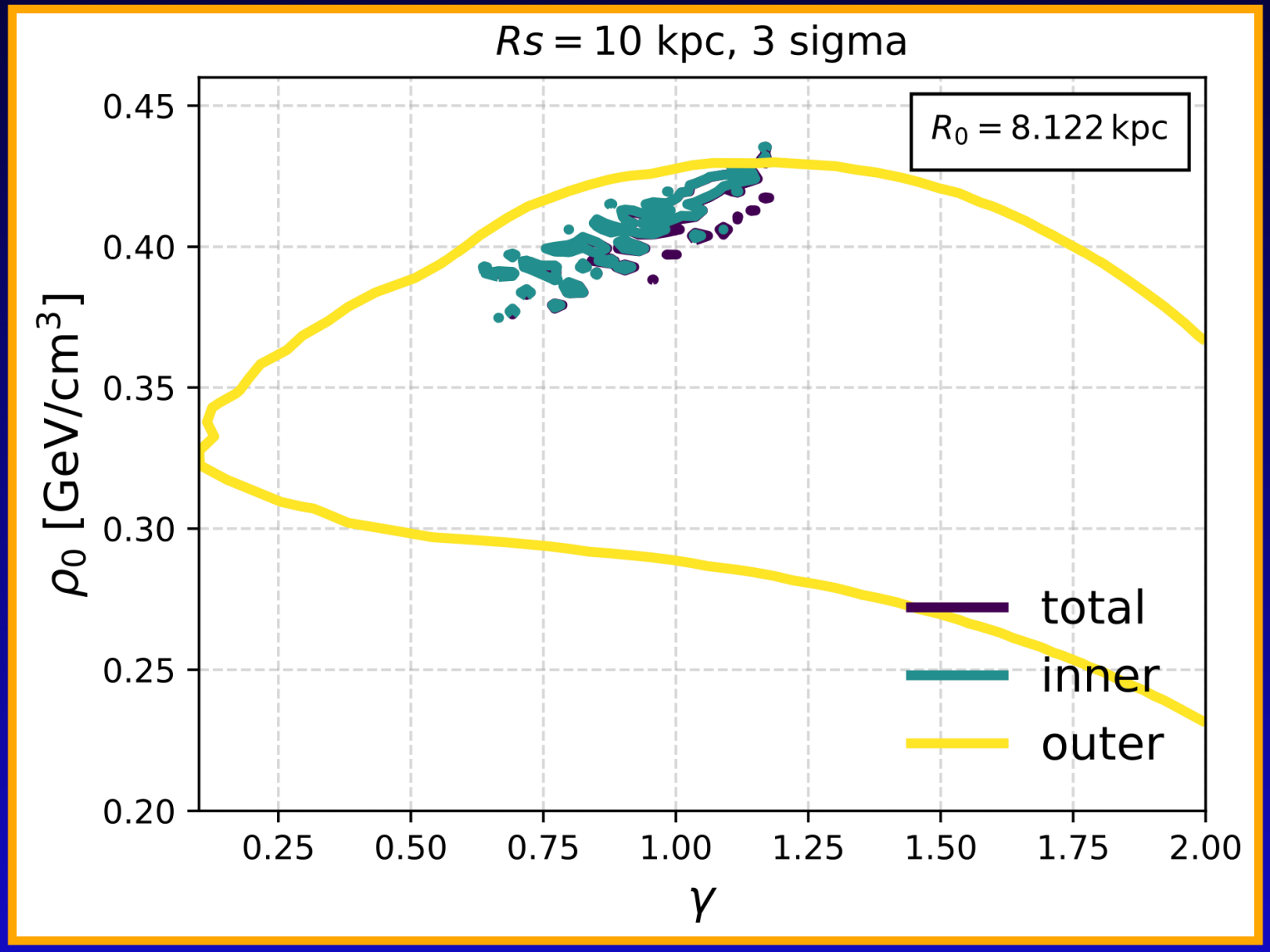
$$F_R(R,Z) = -\frac{\partial\Phi(R,Z)}{\partial R} = \frac{1}{\nu}\frac{\partial\left(\nu\sigma_U^2\right)}{\partial R} + \frac{1}{\nu}\frac{\partial\left(\nu\sigma_{UW}^2\right)}{\partial Z} + \frac{\sigma_U^2 - \sigma_V^2 - \bar{V}^2}{R}$$

Evidence for dark matter in the inner Milky Way

Fabio Iocco[1,2], Miguel Pato[3,4] & Gianfranco Bertone[5]

[2015]

Comforting enough: no dramatic effect on DM distribution

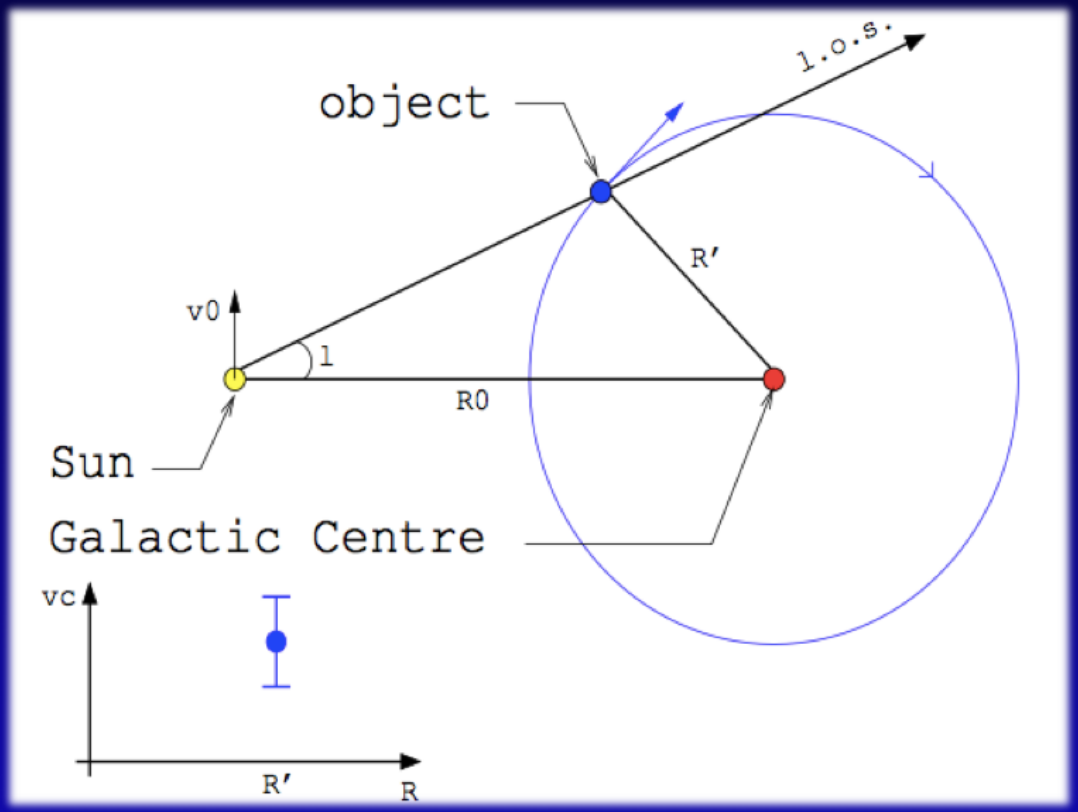


[Maria and myself, w.i.p.]

The Milky Way:

observed rotation curve

Neglecting some quite remarkable uncertainties (for now)



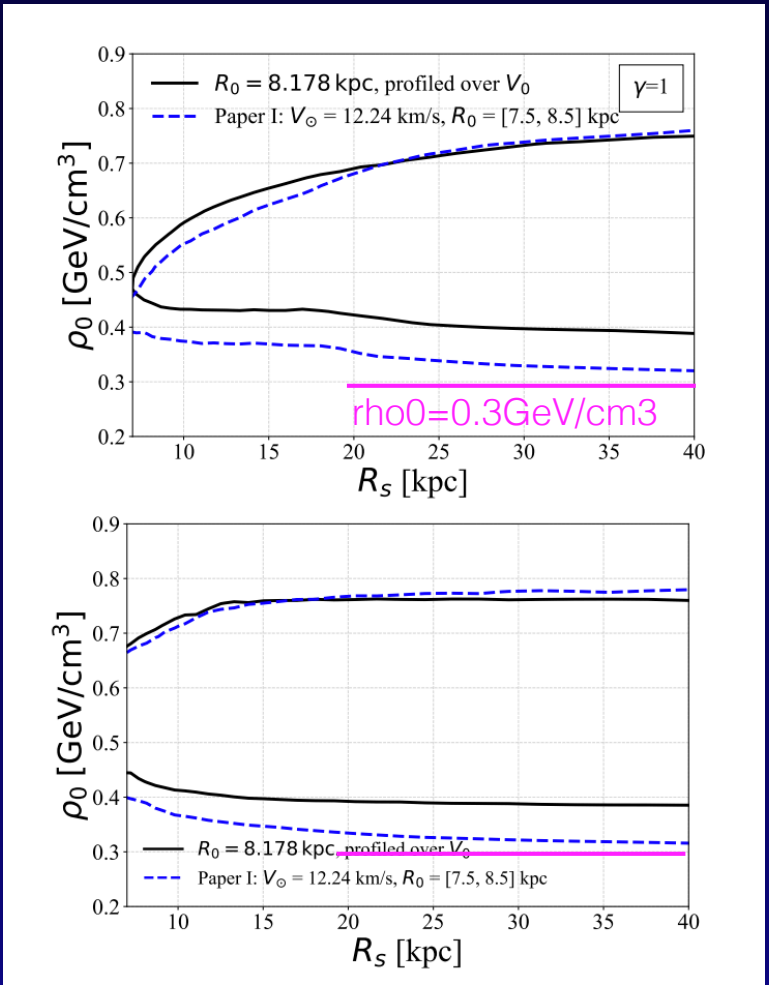
$$v_{\mathrm{LSR}}^{\mathrm{l.o.s.}} = \left(\frac{v_c(R')}{R'/R_0} - v_0 \right) \cos b \sin \ell$$

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

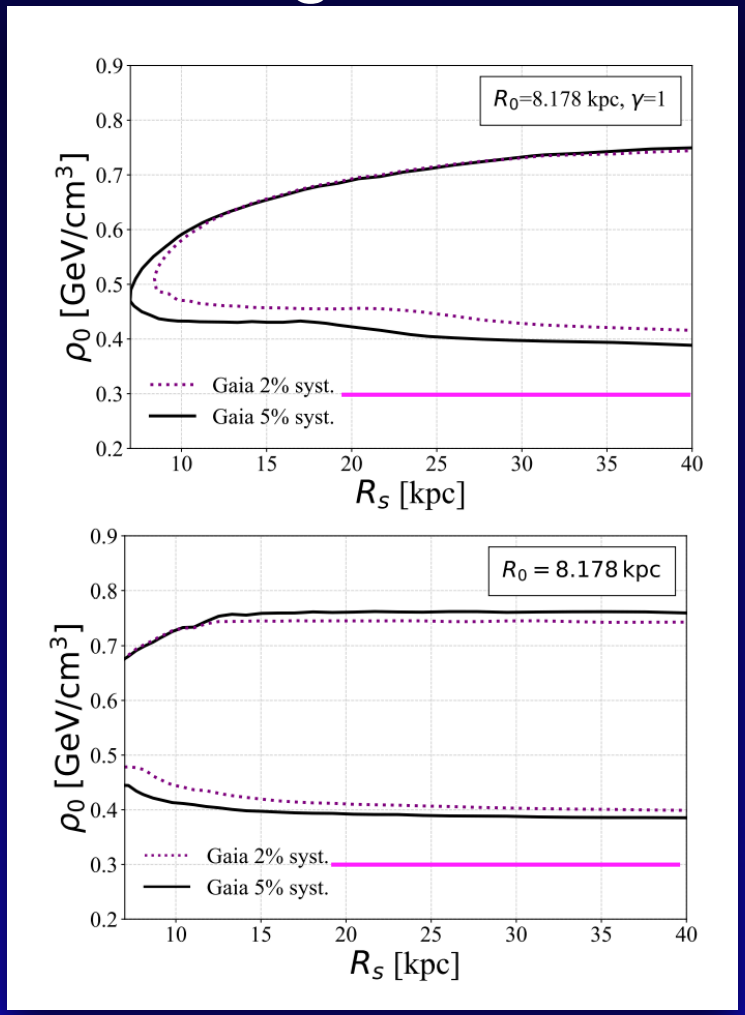
Uncertainties on (R0,v0) ultimately affects our determination of (rho0, gamma)

Profiling over Galactic uncertainties

Testing approaches



Testing datasets



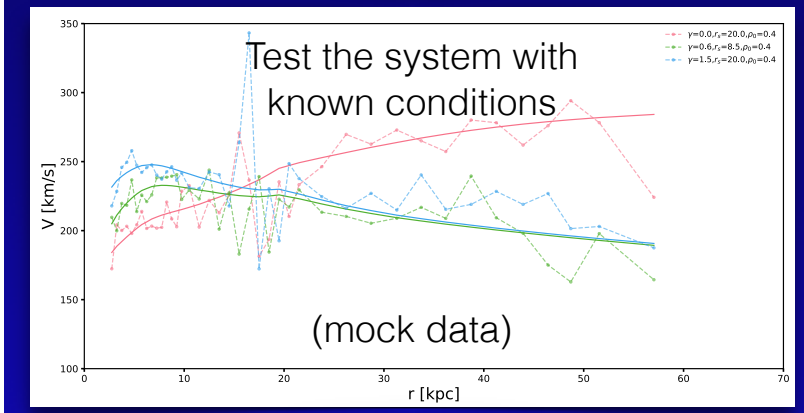
Please use the full likelihood: publicly available!!

https://github.com/mariabenitocst/UncertaintiesDMinTheMW

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

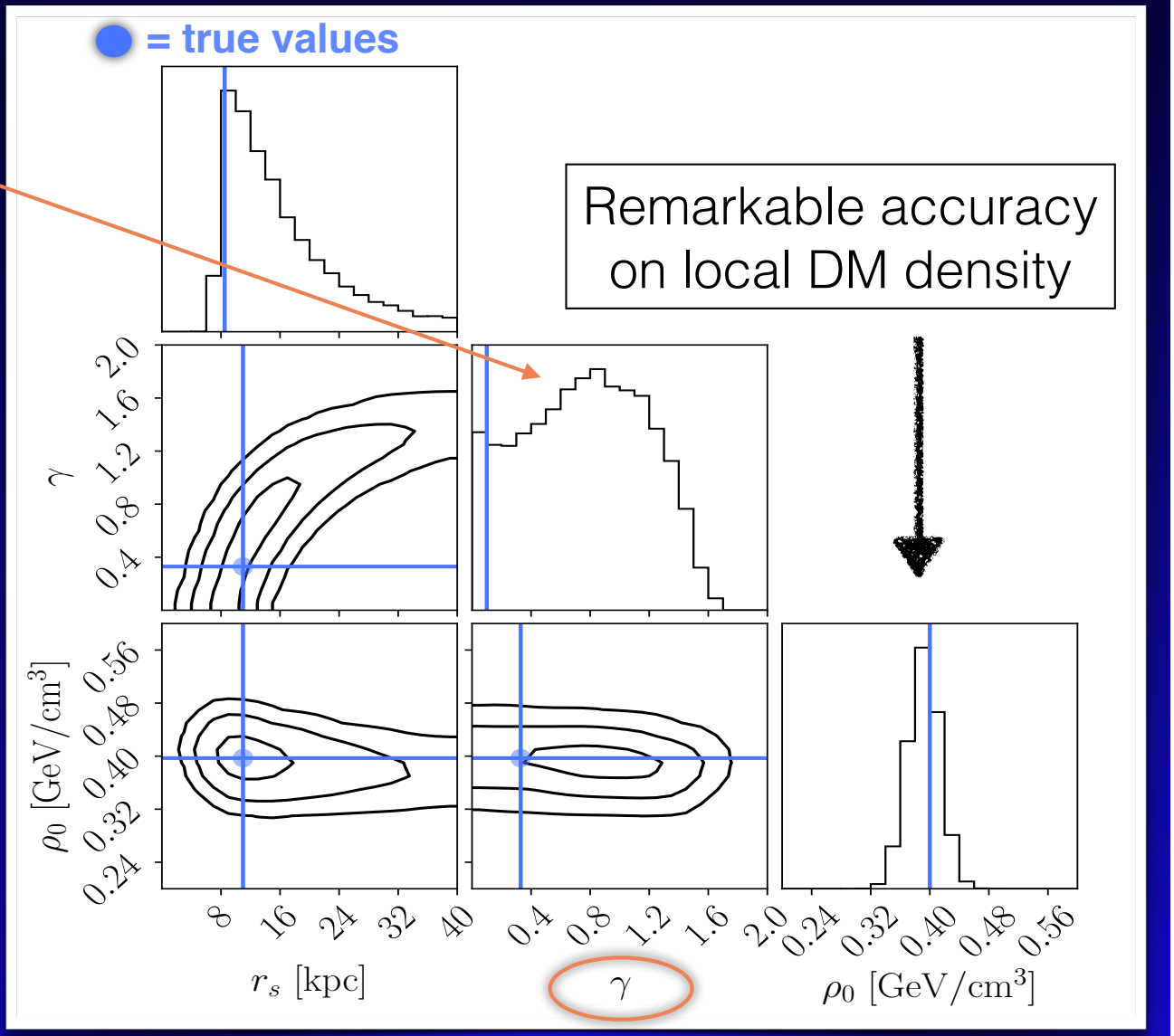
What to do of our measurement?

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



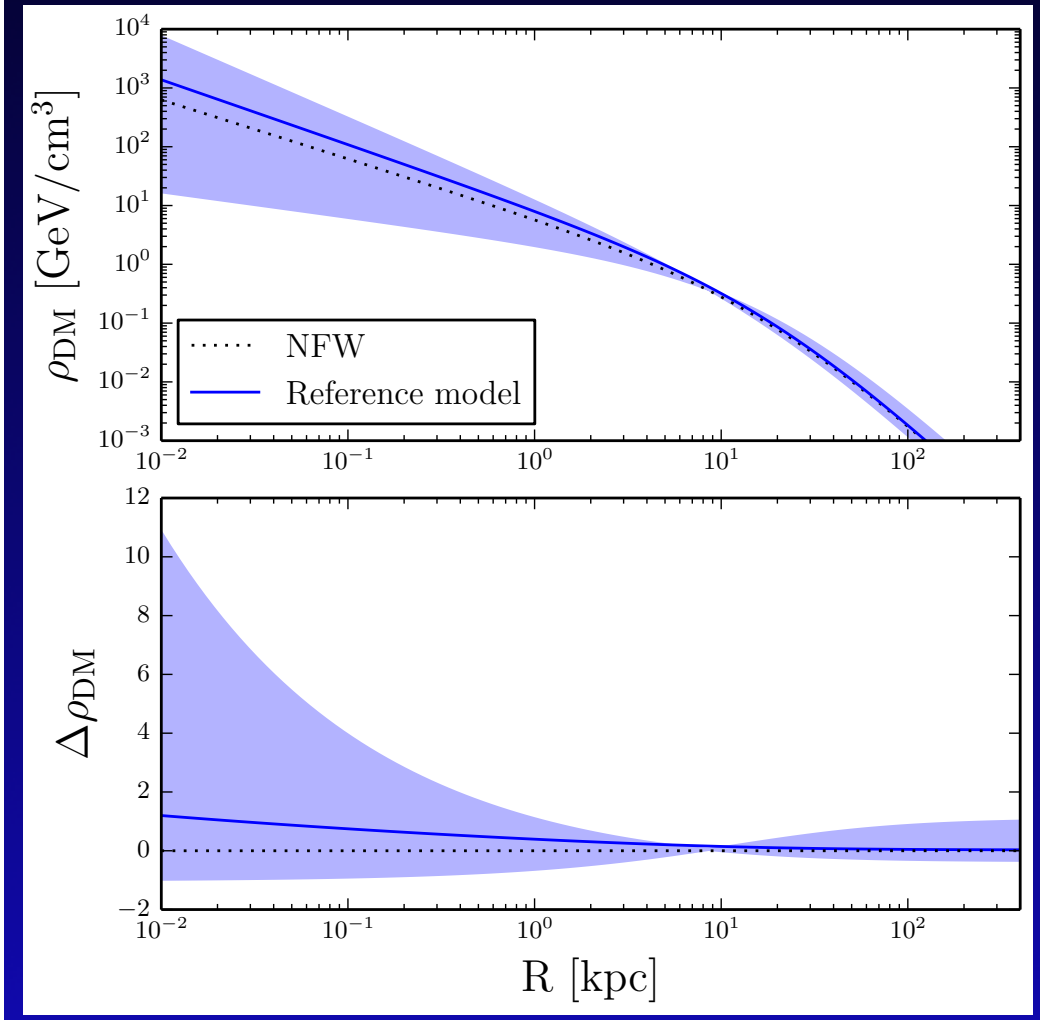
● = true values

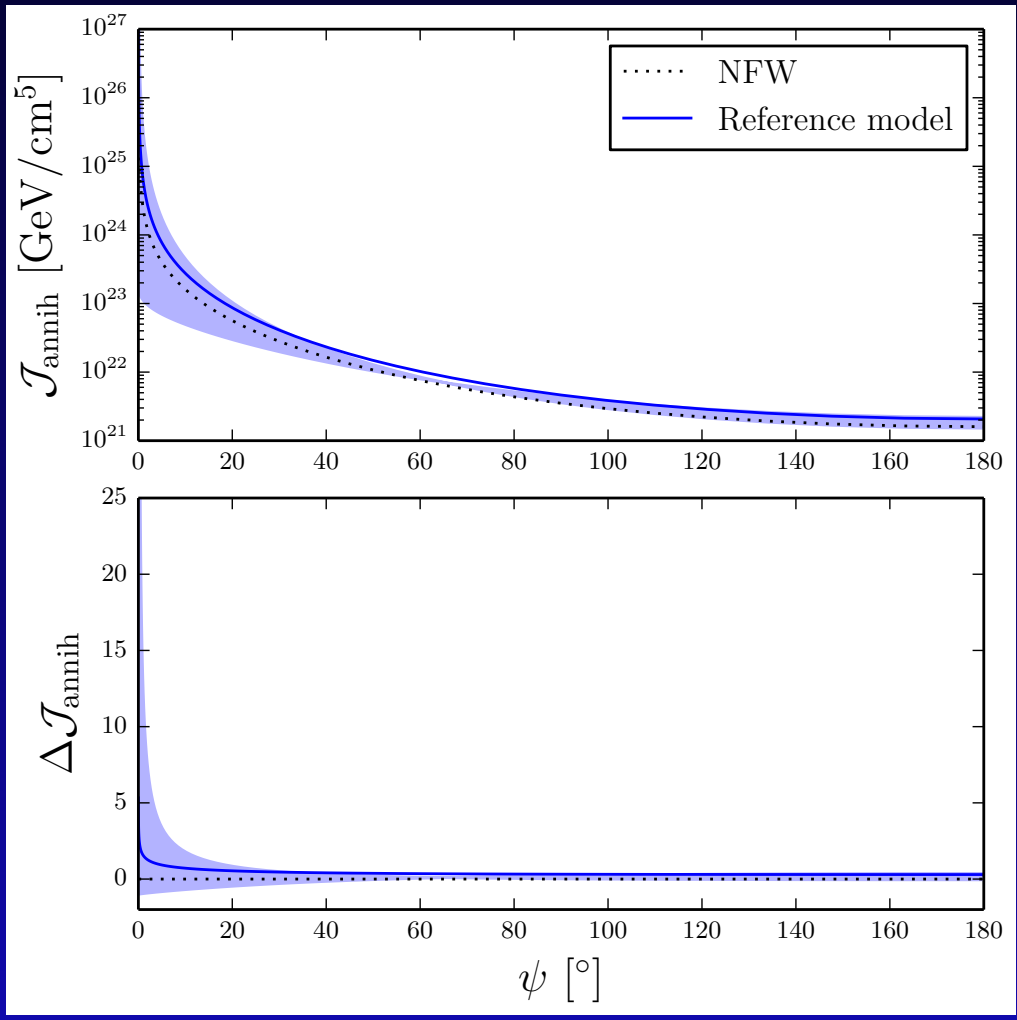
Remarkable accuracy
on local DM density



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

But do Galactic uncertainties affect PP, for real?

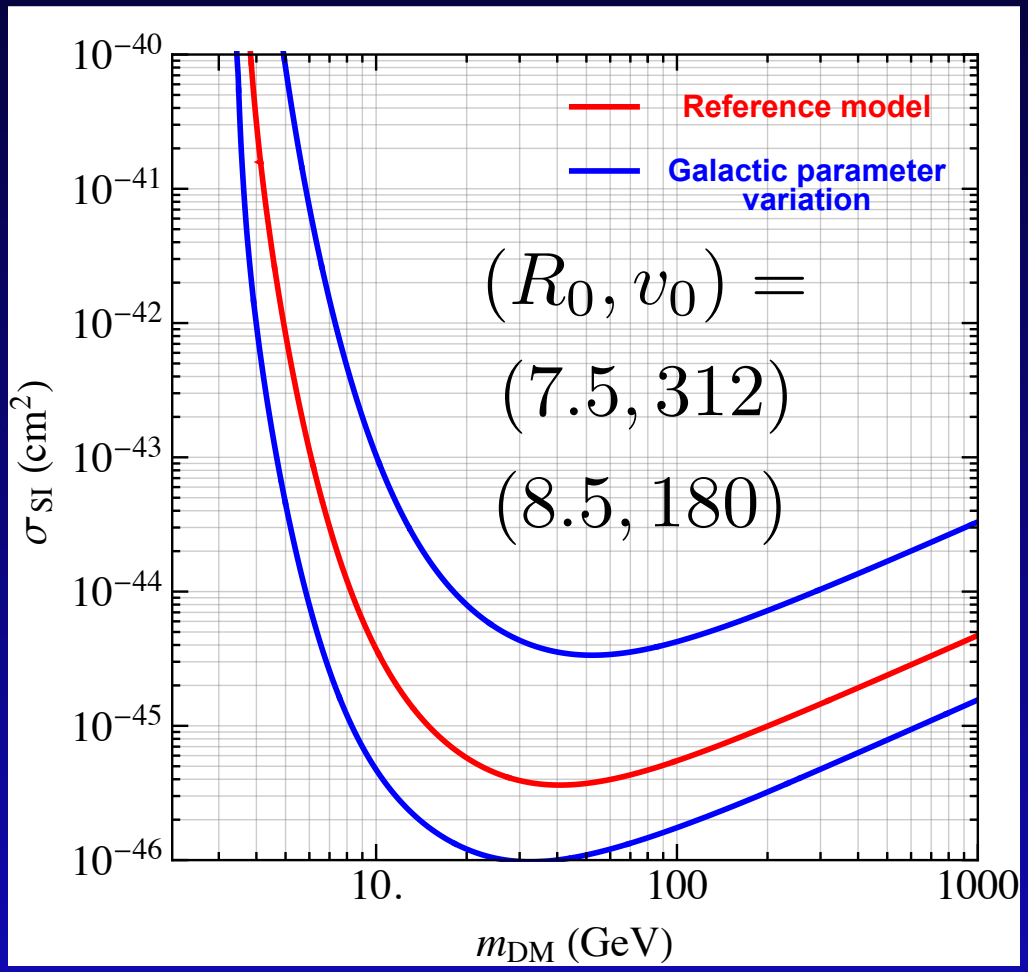




$$J_{annih} \propto \int_{los} \rho^2(r) dV$$

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

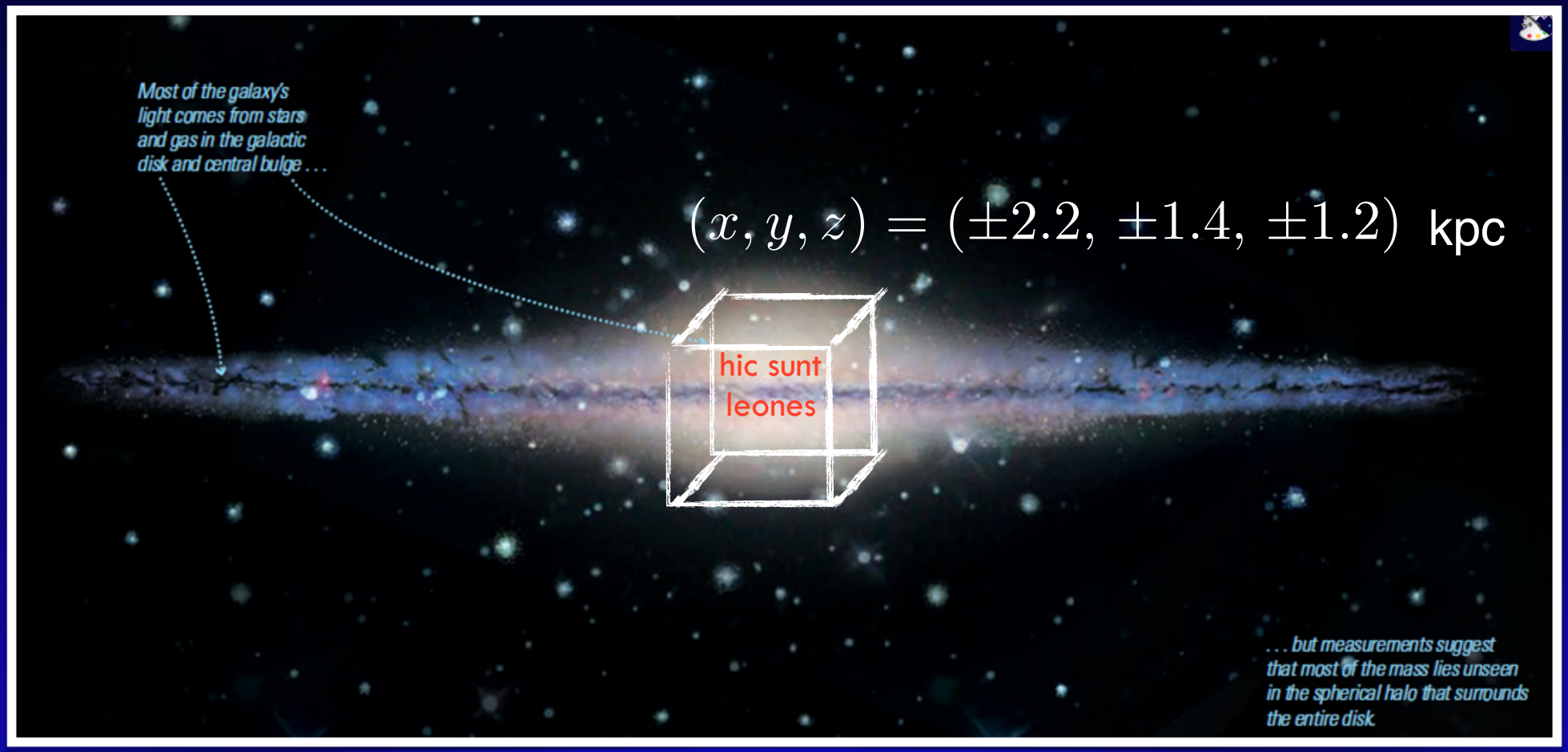
It is well known that uncertainties affect Direct Detection



2015 LUX limits, varying astrophysical uncertainties

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

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

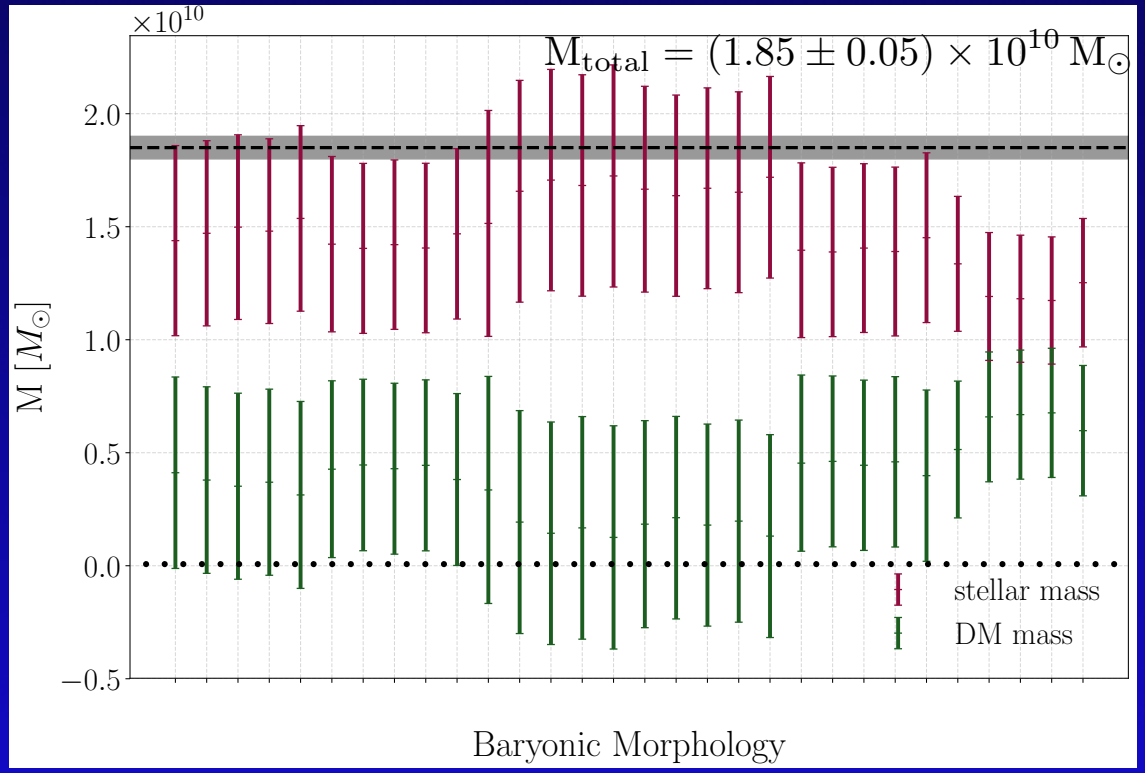
$$\mathrm{M_{total}} - \mathrm{M^i_*} = \mathrm{M^i_{DM}}$$

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

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

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

DM mass corresponds to 7-37%



[Iocco & Benito, PDU 2017] arXiv:1611.09861

(+ M. Benito's thesis)

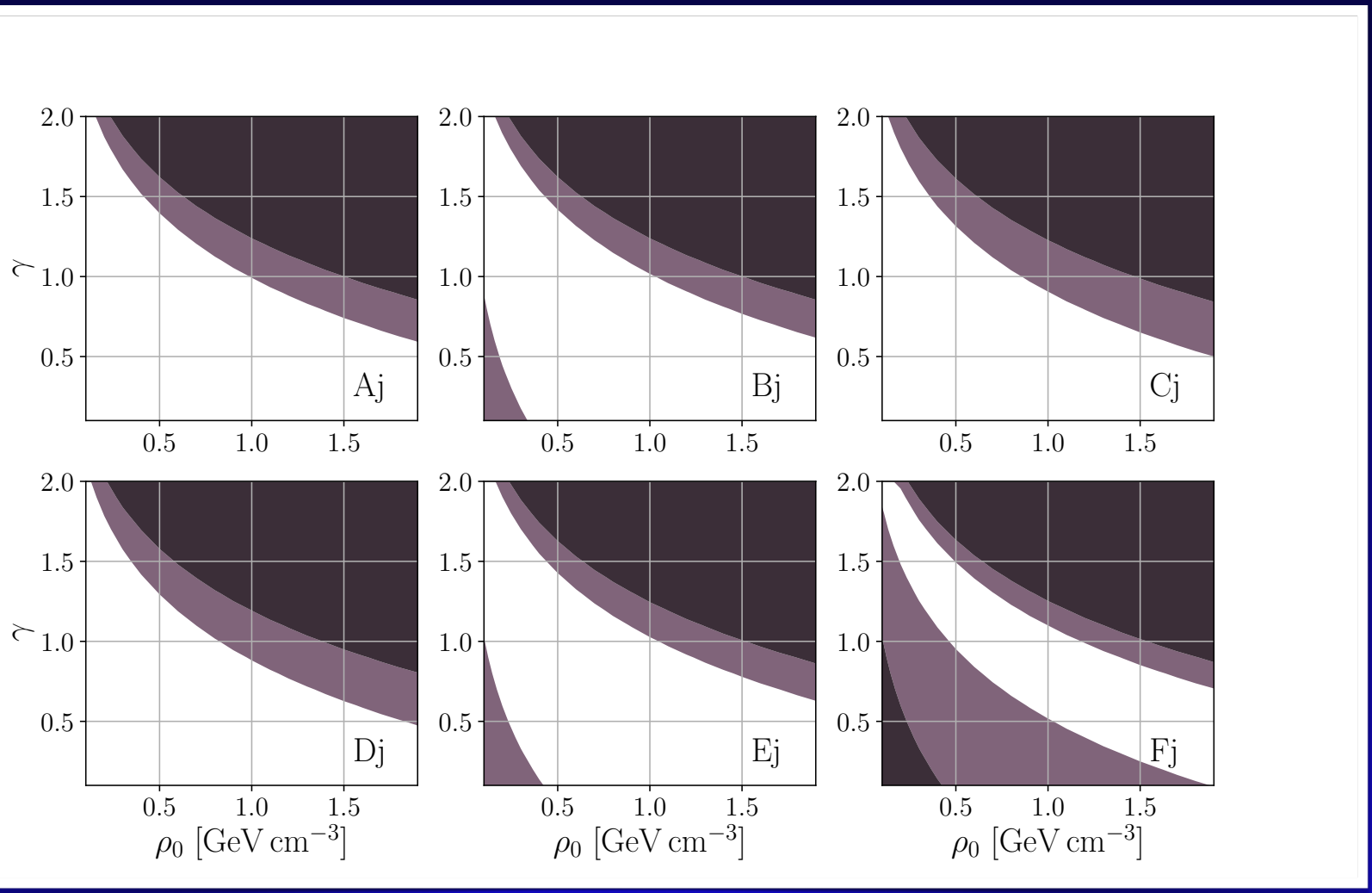
gNFW density profile

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

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

Galactic Bulge Region

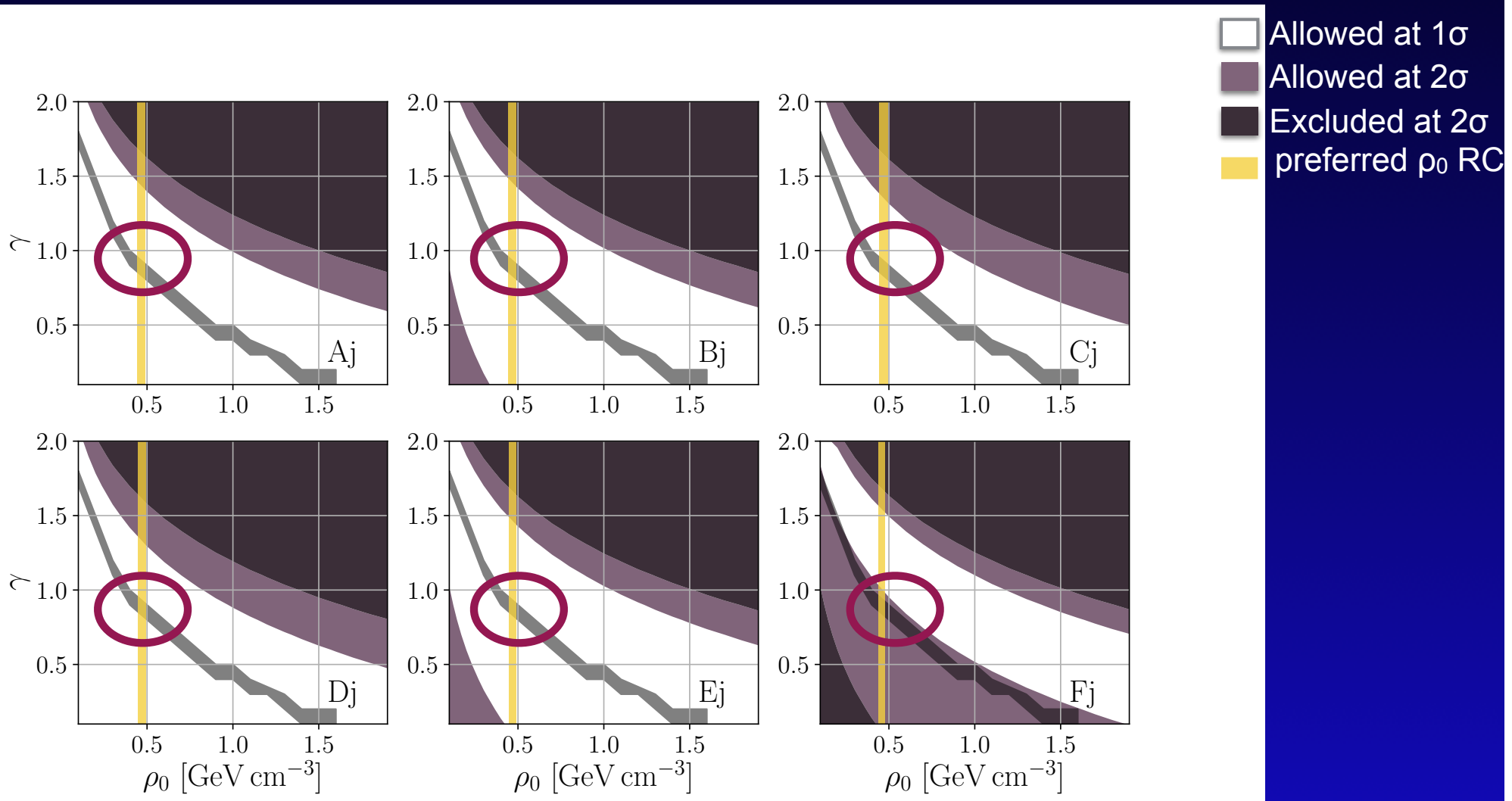
Results: varying bulge morphology



[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)

The effect of astrophysical uncertainties

on the determination of new physics

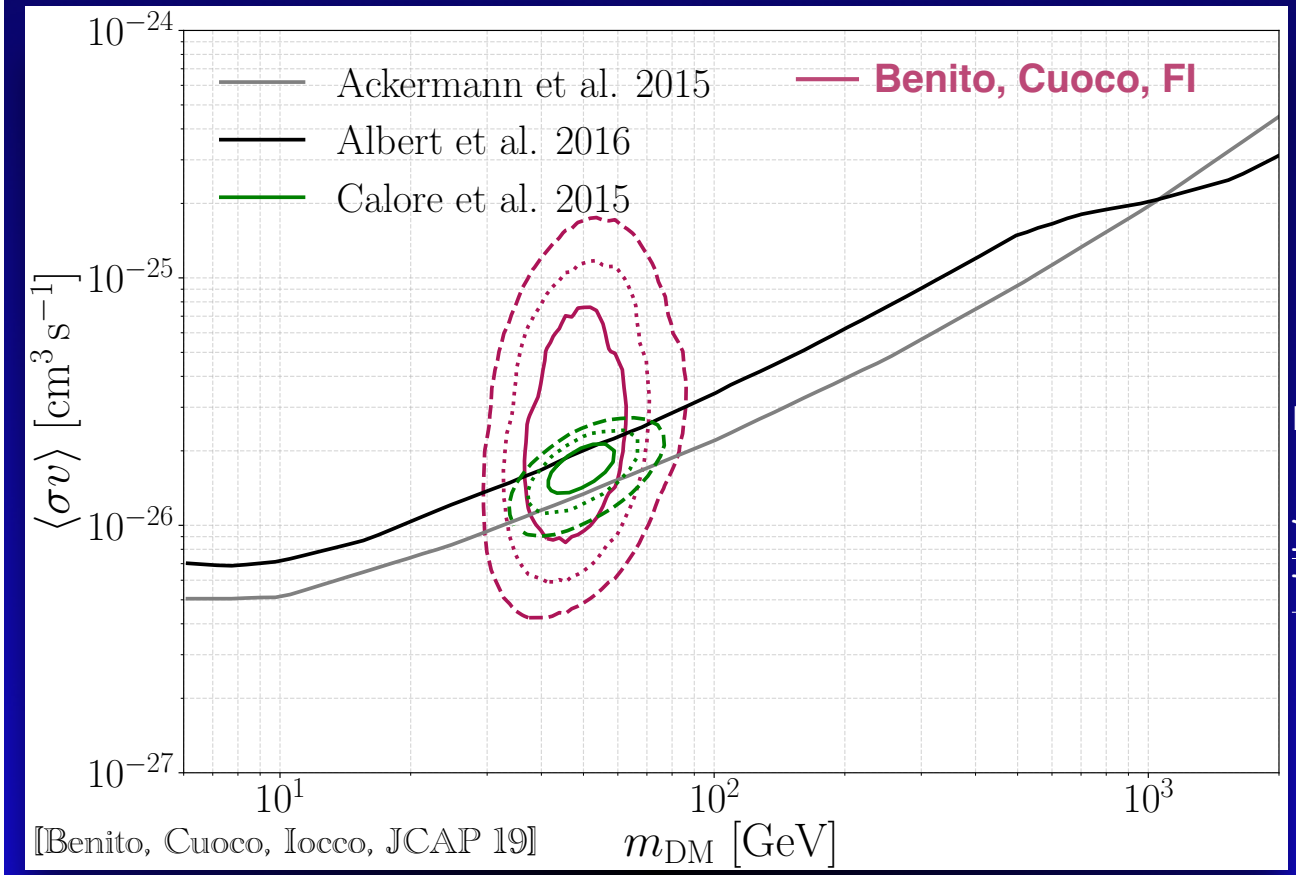
Uncertainties accounted for:

Calore analysis:

observed GC signal
(only stat. on gamma flux)

This analysis:

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



[Benito, Cuoco, Iocco, JCAP 19]

Ready-to-use likelihood publicly available @

https://github.com/mariabenitocst/UncertaintiesDMinTheMW

with Gaia-era
(R0,v0) determination,
updated in 2020

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

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

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

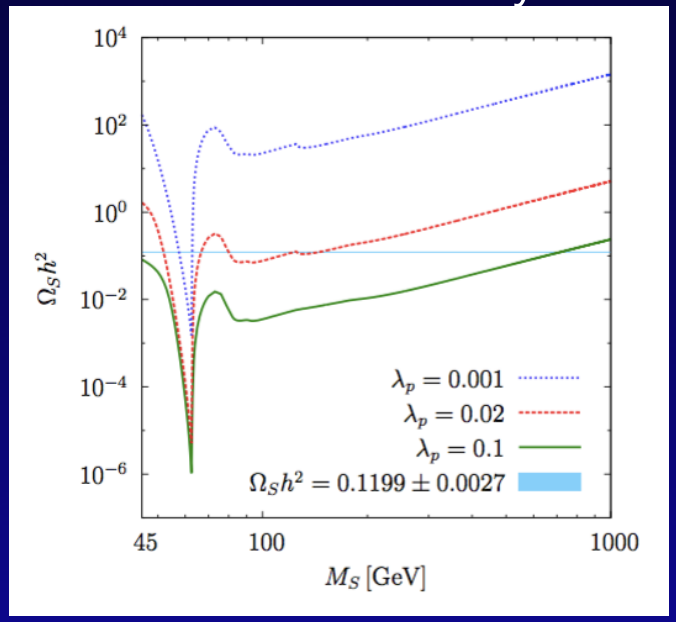
$$m_S^2 = 2\,\mu_S^2 + \lambda_{HS}\, v_H^2$$

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

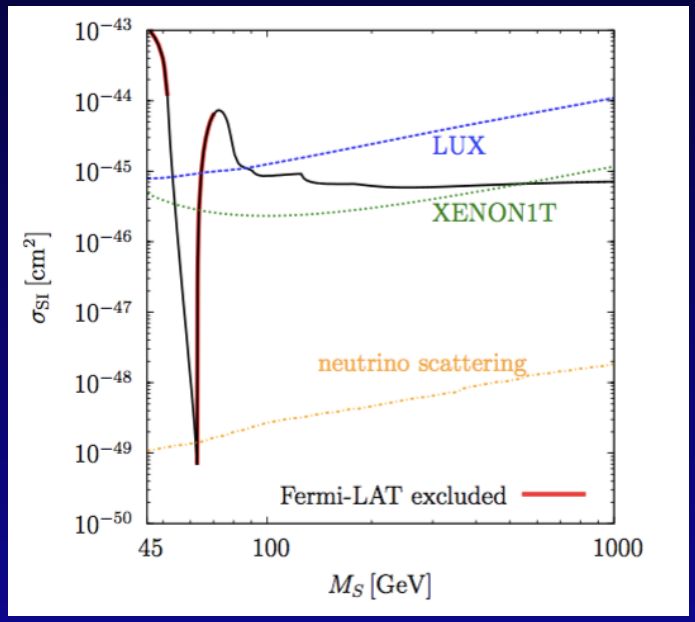
[Mc Donald, 1994] [Burgess, Pospelov, Velthuis, 2001]

Singlet Scalar DM
Constraints and interplay of experiments

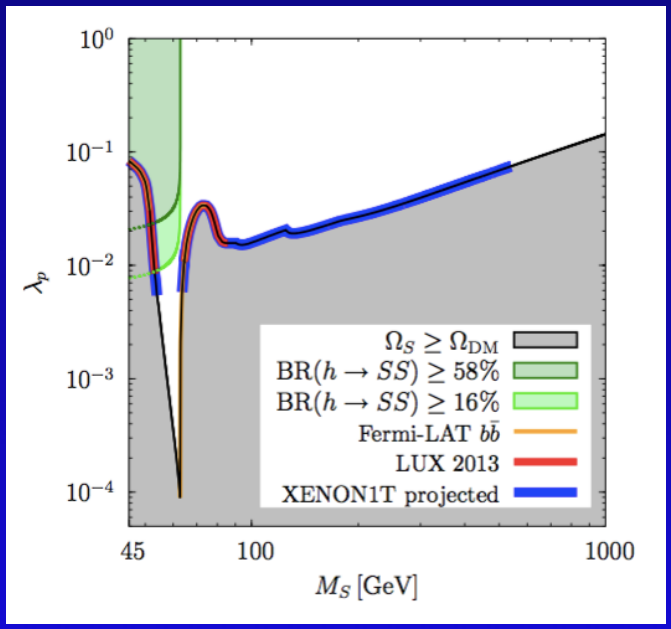
Relic density



Direct detection



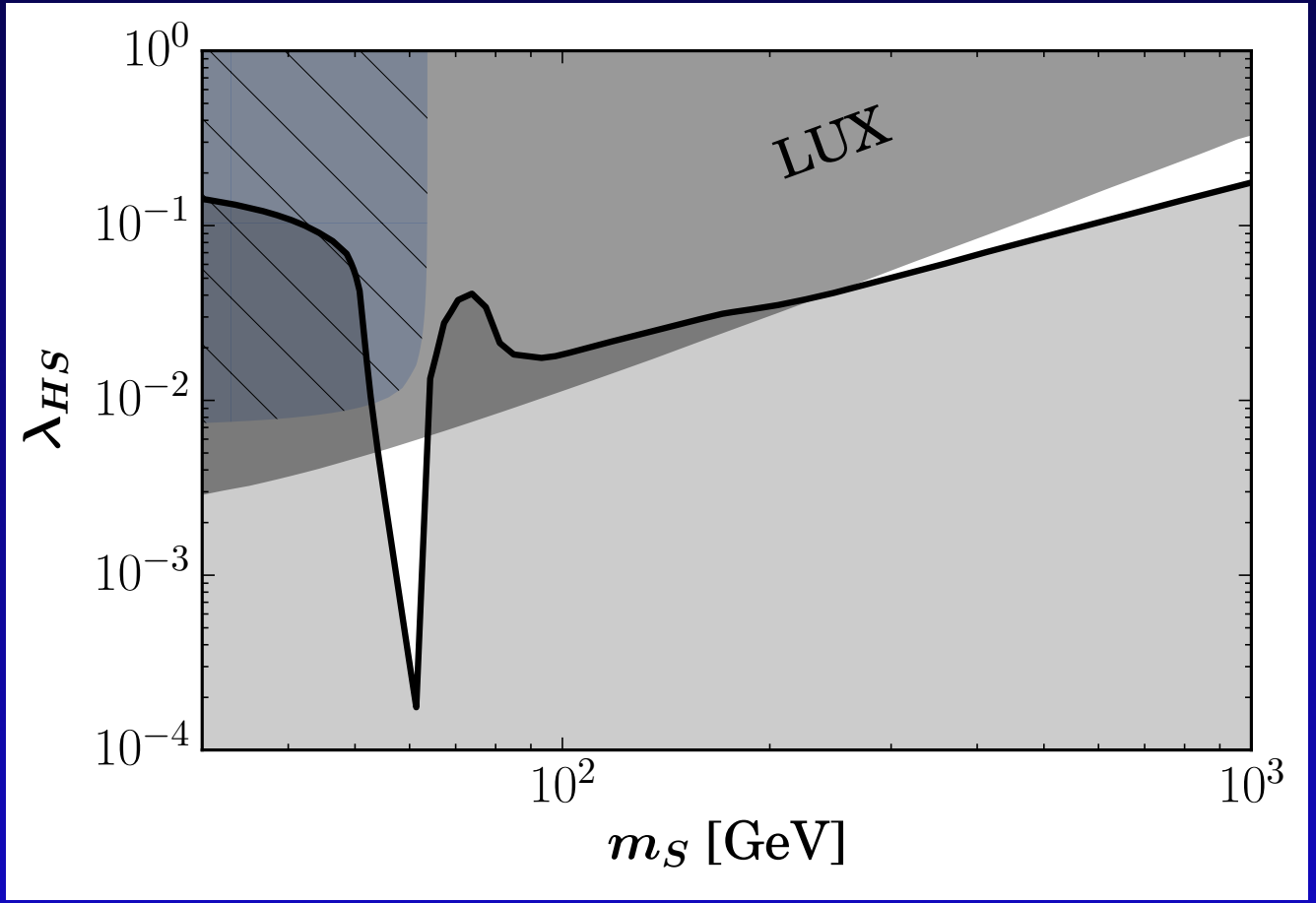
Combined



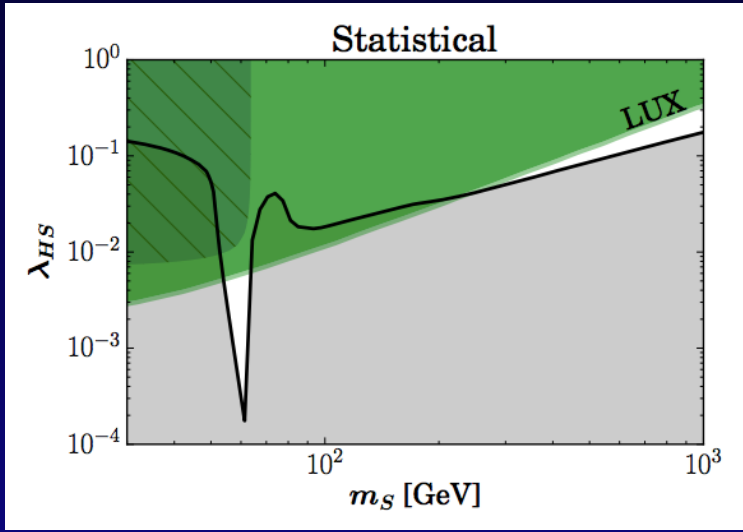
[Duerr et al, 2015]

Singlet Scalar DM
Constraints and interplay of experiments

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

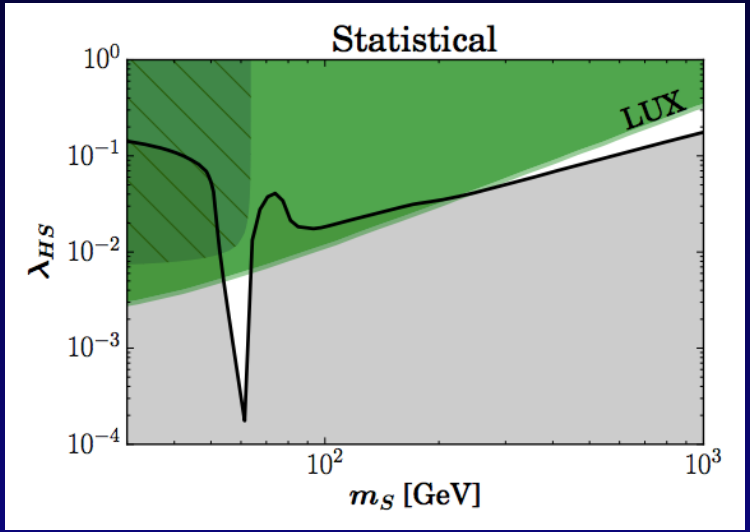


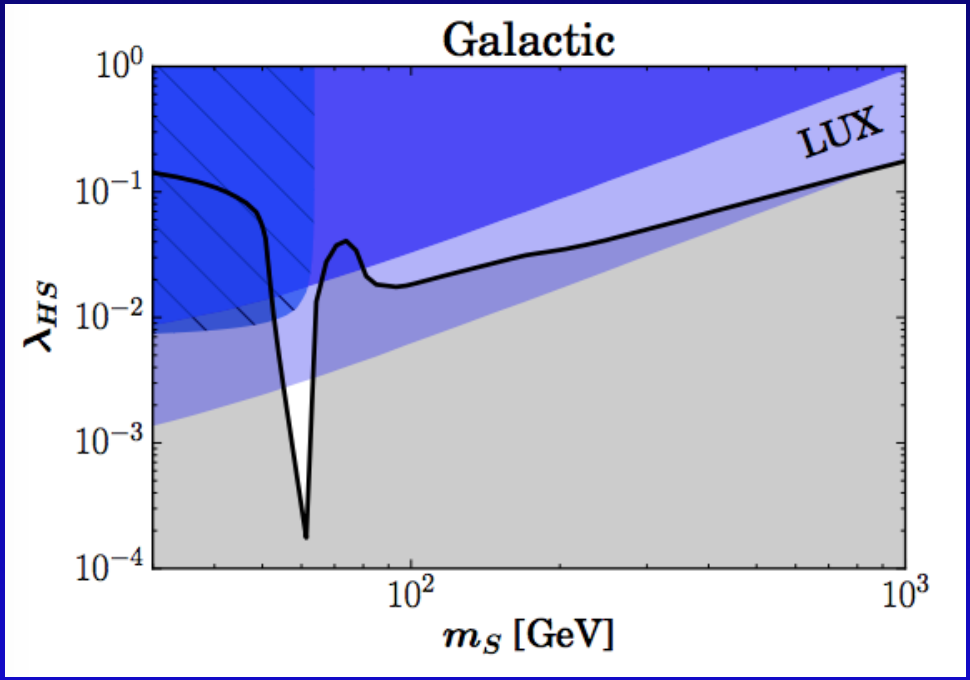
Let's look at the effect of astrophysics uncertainties: Direct Detection

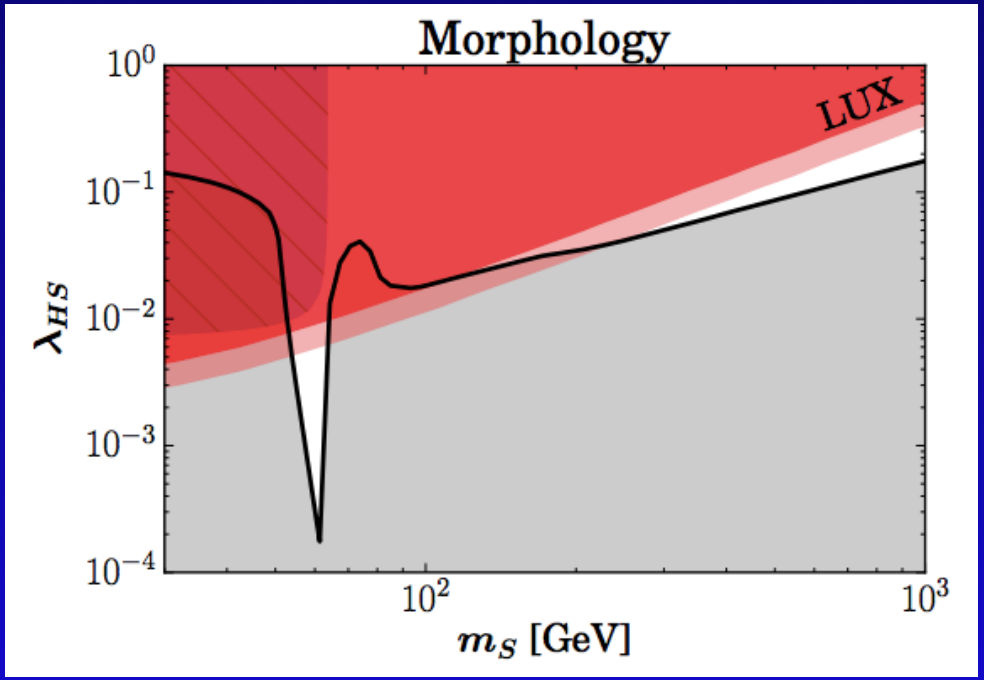


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

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

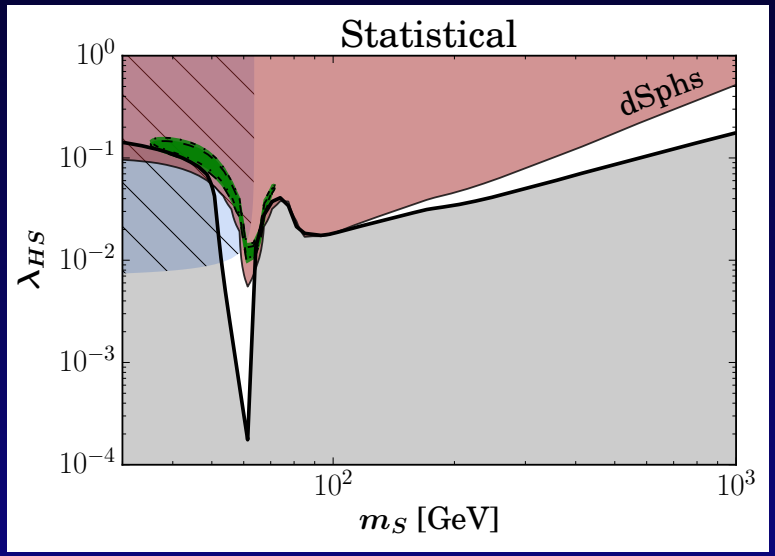


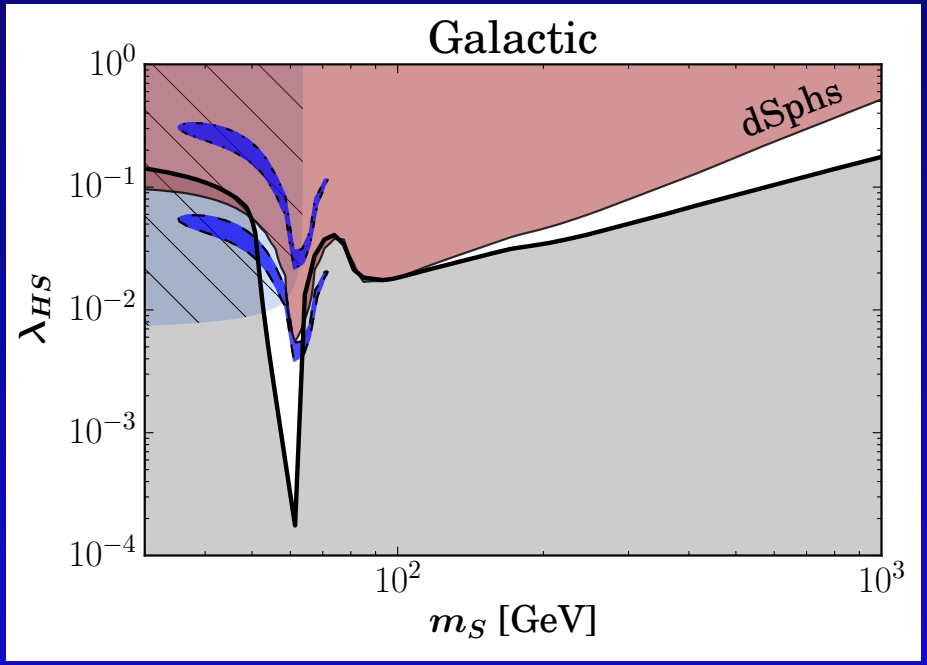


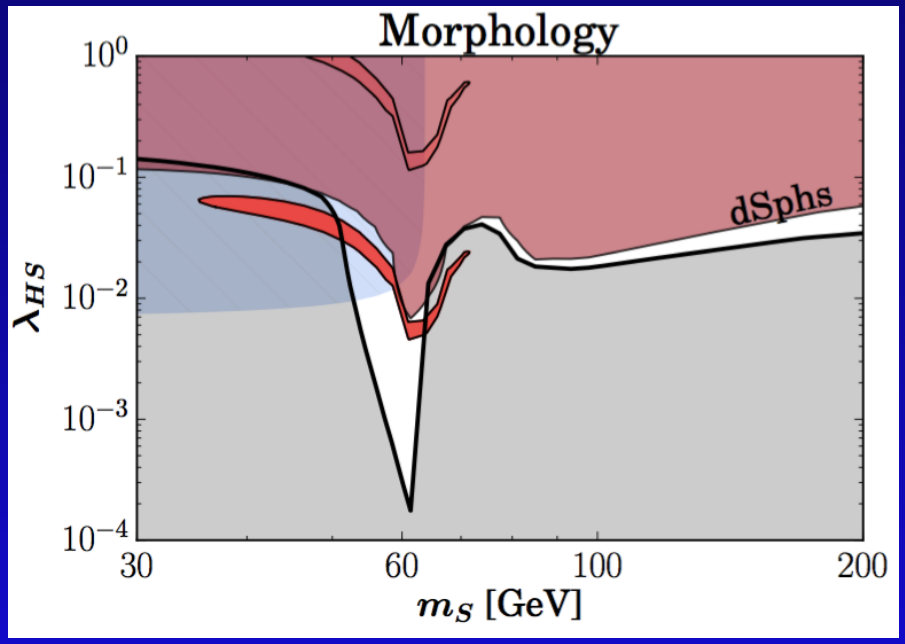


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

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





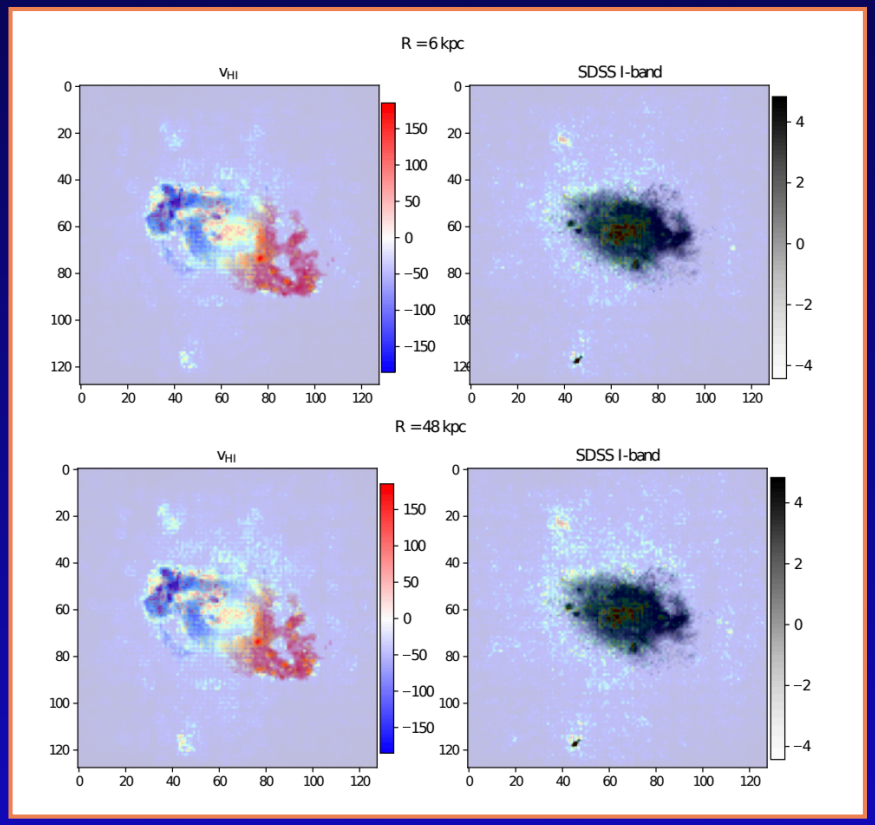


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

Cuncta stricte

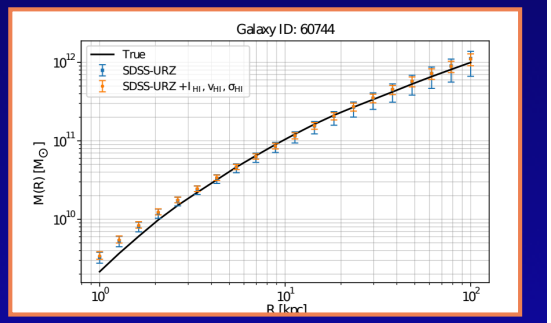
- It is possible to reconstruct the DM distribution of our own Galaxy (with some inherent uncertainties).
- Gaia data should not have you worried about the local DM. (Gaia should have you excited for many other reasons, though).
- Total mass determination is solid, local DM density is solid, slope/profile mhh-mhh (not reliable).
- Forget about the galactic centre.
- Going beyond RC methods for MW-like: a method which is environment tested (tool accuracy).
- Deep learning algorithms do actually reconstruct the DM amount and distribution, within a synthetic environment (simulations).

DM in disk galaxies: is there a better method than Rotation Curves?

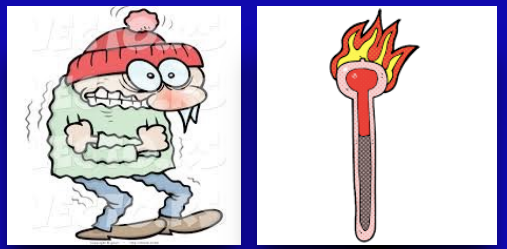


photometry + spectroscopy

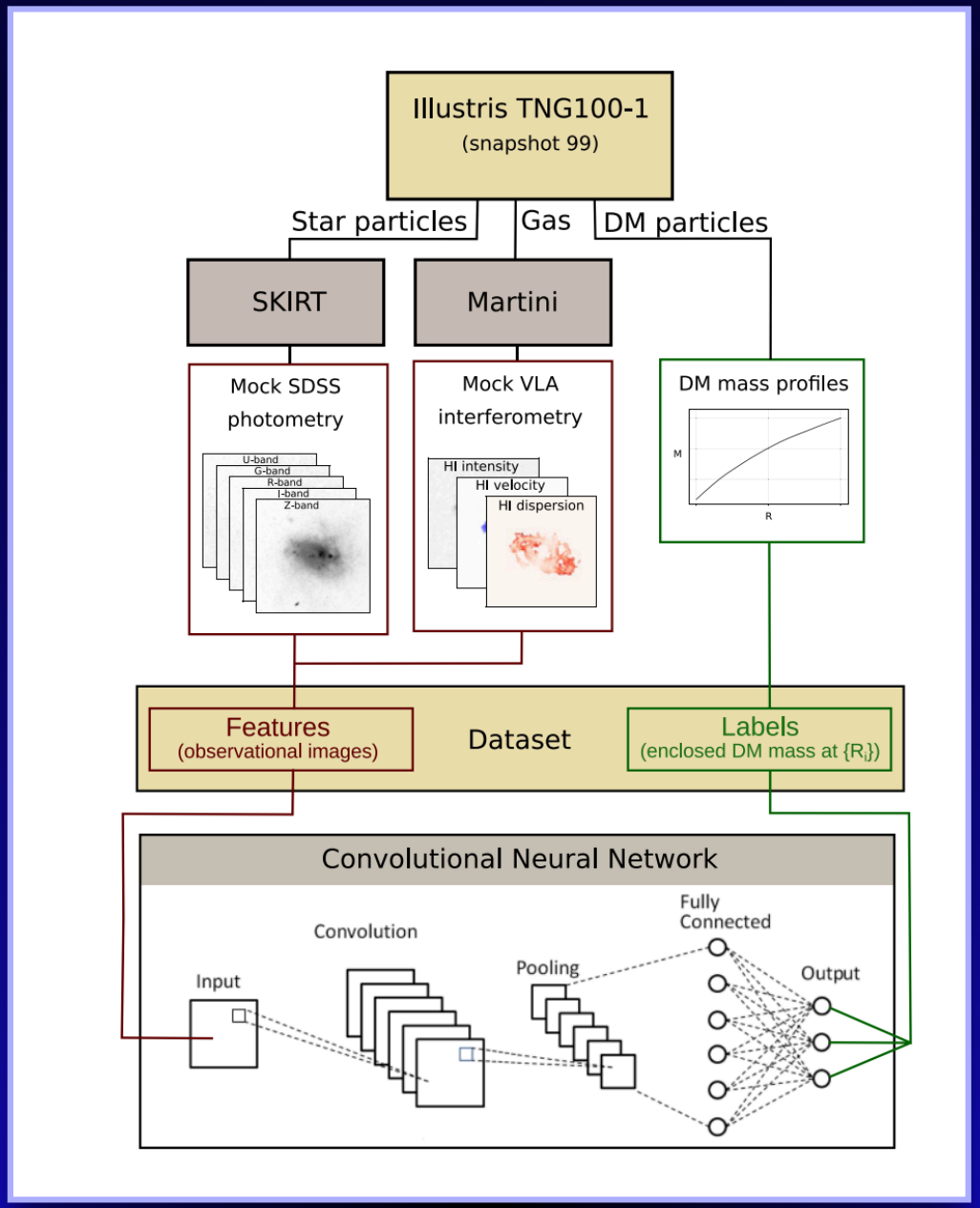
assumptions



DM distr.



The rationale of our machine algorithms



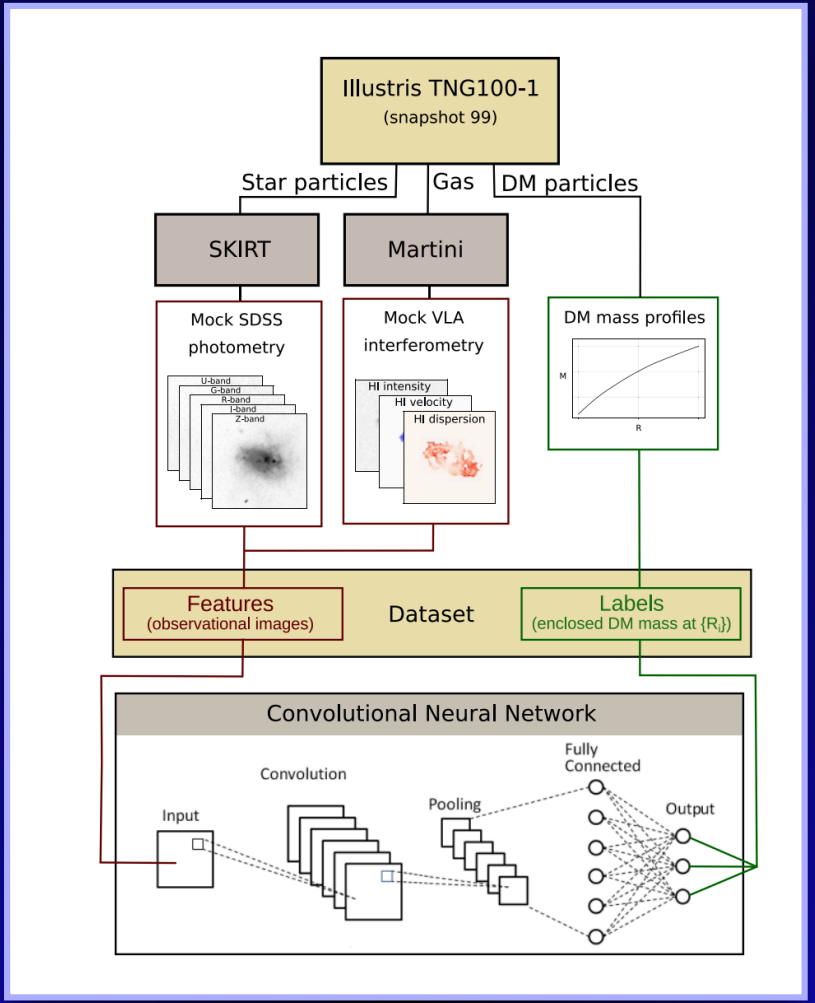
[deLosRios, Petac, Zaldivar, Calore, Bonaventura, FI arXiV:2111.08725]

Choice of galaxies in our database

TNG100 Simulation

- Planck cosmology
- 106.5 Mpc by side
- 1820^3 DM particles
- 1820^3 hydrodynamic cells
- DM resolution 7.5 *10^6 M⊙
- Baryon resolution 1.4*10^6 M⊙
- 136 snapshots from z=127 to z=0

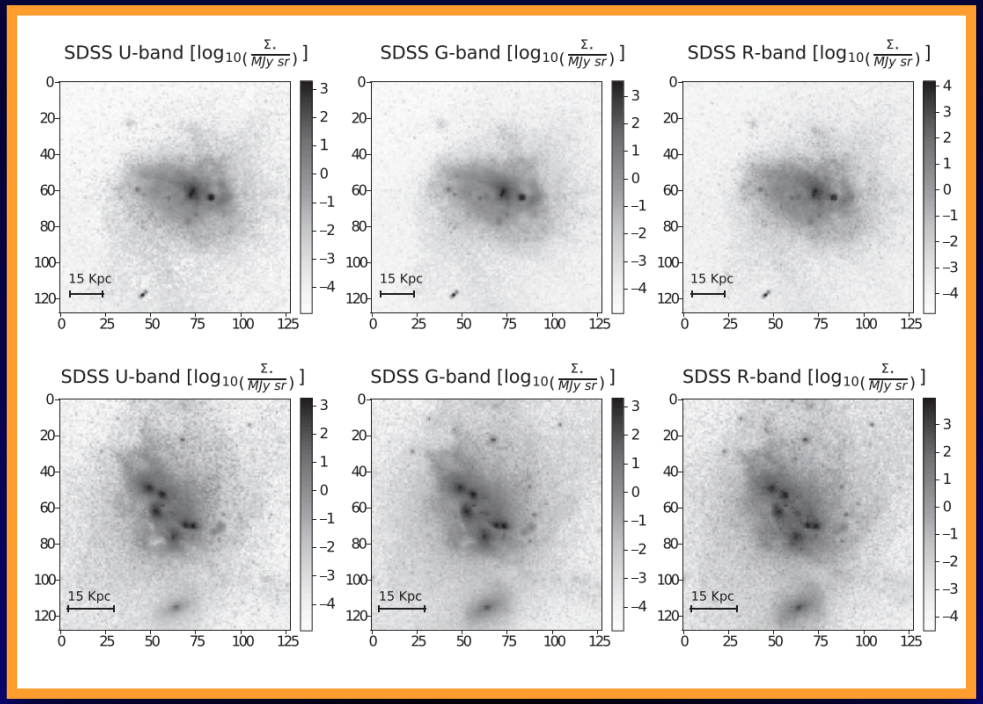
Property	Criterium
Simulation snapshot	$99\ (z = 0)$
Stellar mass	$10^{10}\ M_\odot \leq M_\star \leq 10^{12}\ M_\odot$
Star formation rate	$\mathrm{SFR} \geq 0.1\ M_\odot/\mathrm{yr}$
Central galaxy	$\mathrm{SubhaloParent} = 0$
Cosmological origin	$\mathrm{SubhaloFlag} = 1$



[deLosRios, Petac, Zaldivar, Calore, Bonaventura, FI arXiV:2111.08725]

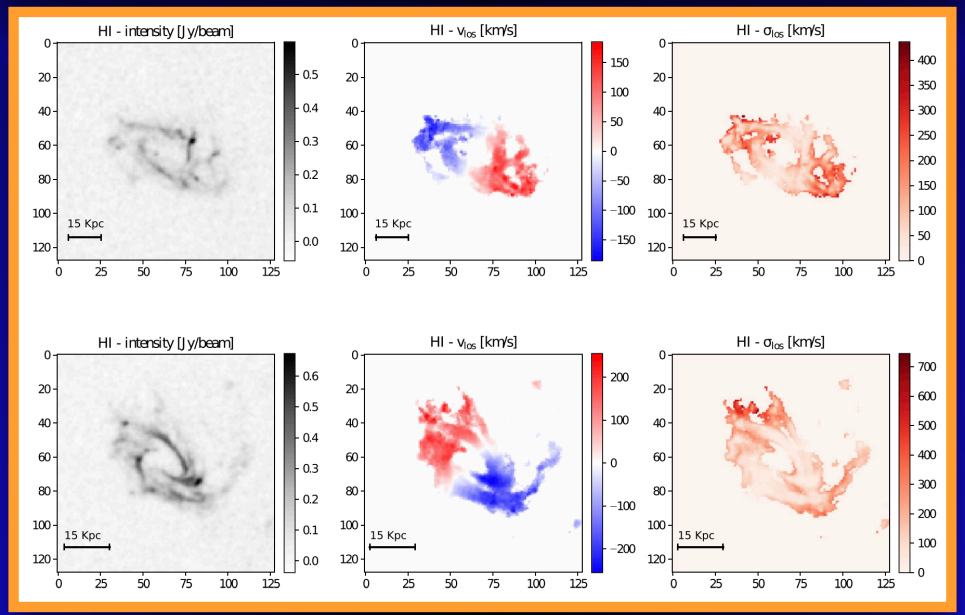
A flavor of what machines “see”

Photometry



Baryons

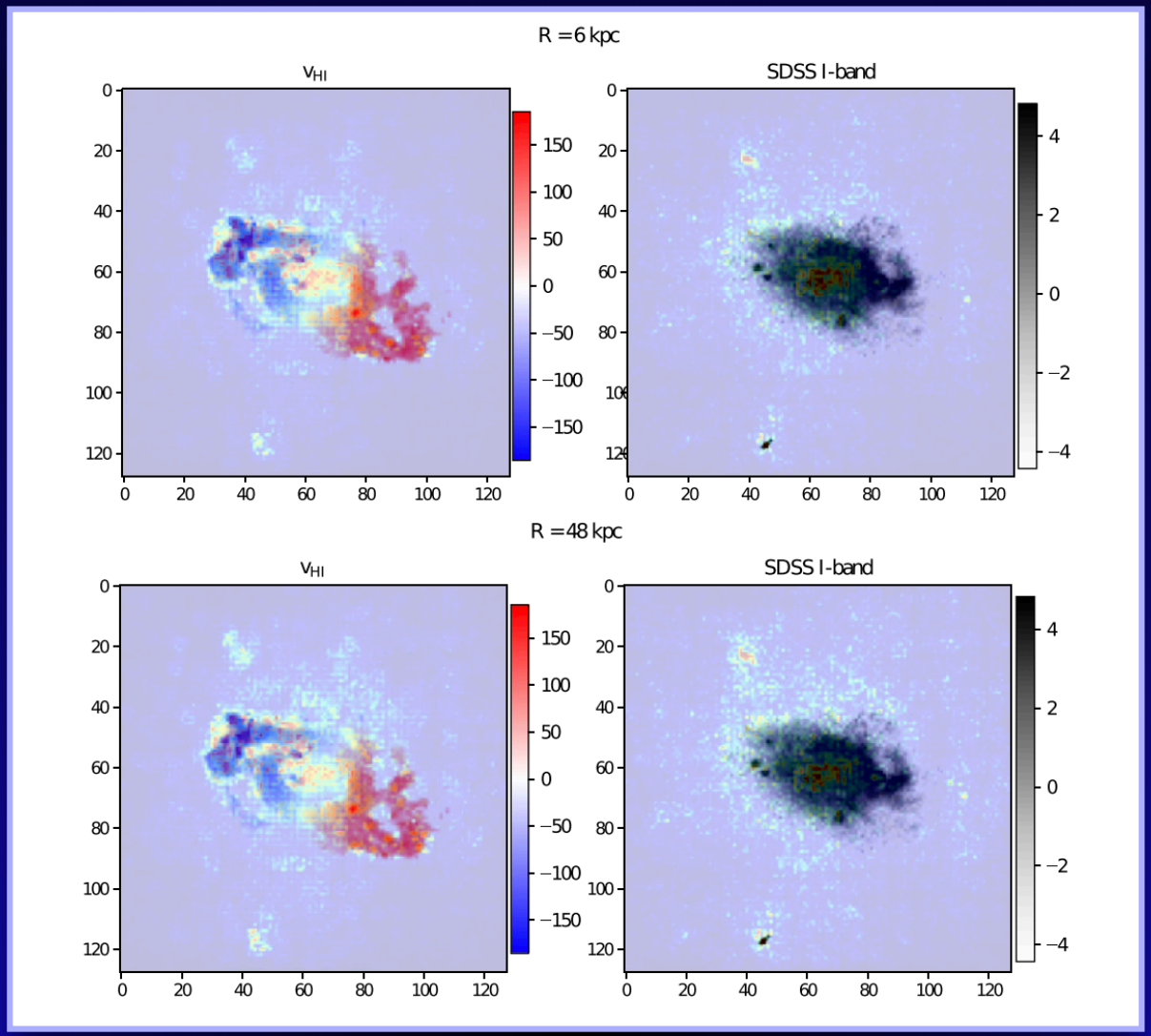
Spectroscopy



Velocity (total potential)

[deLosRios, Petac, Zaldivar, Calore, Bonaventura, FI arXiV:2111.08725]

A flavor of what machines “see”

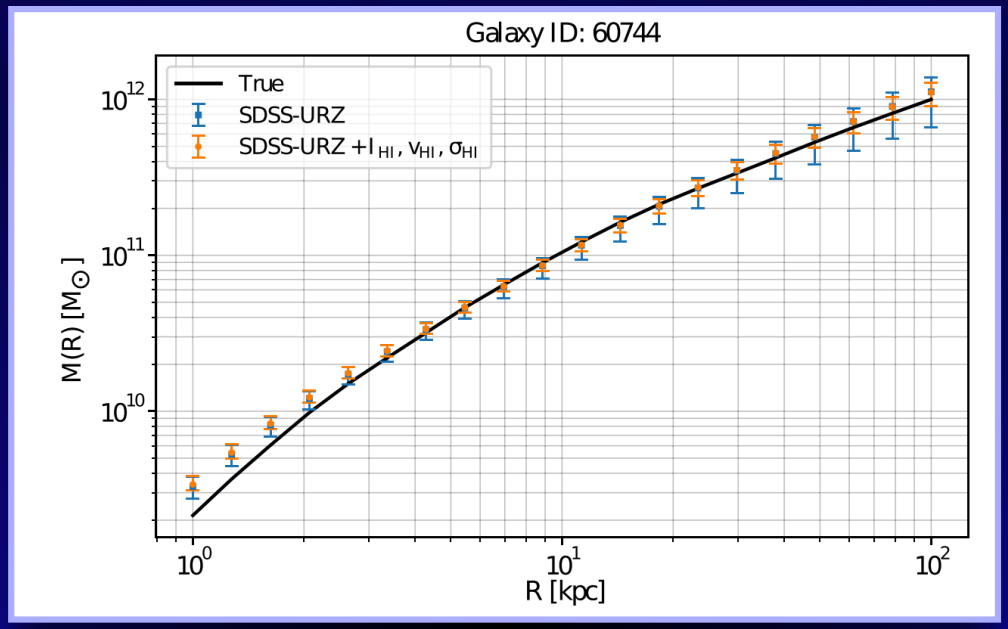


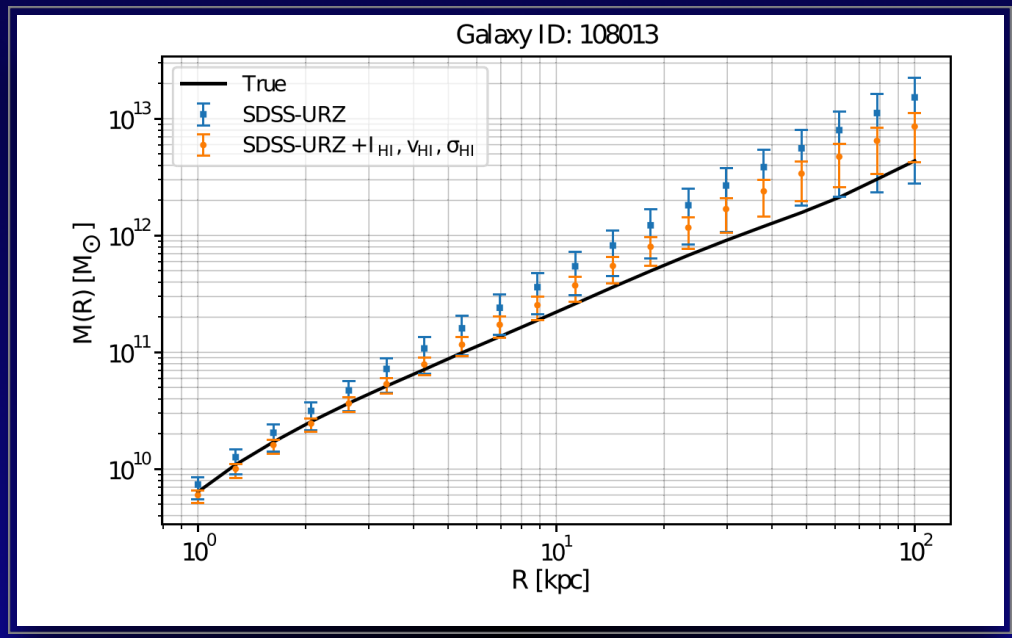
Spectroscopy

Photometry

[deLosRios, Petac, Zaldivar, Calore, Bonaventura, FI arXiV:2111.08725]

Let's open the box

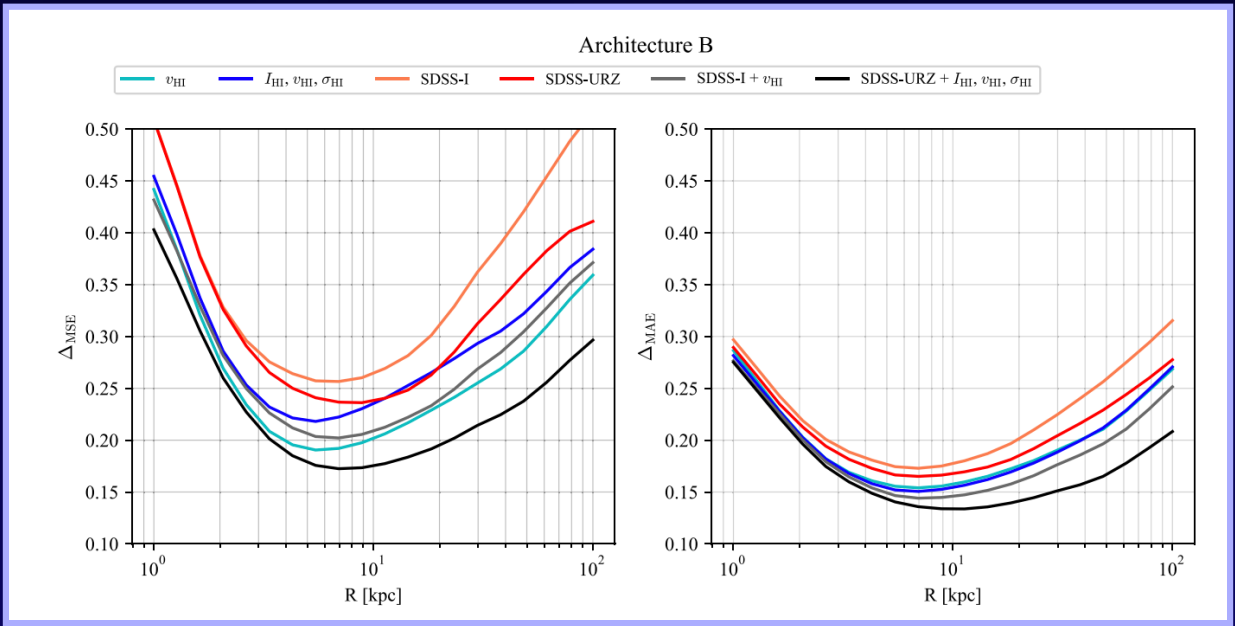




No "fitting" to pre-existing shape: free reconstruction

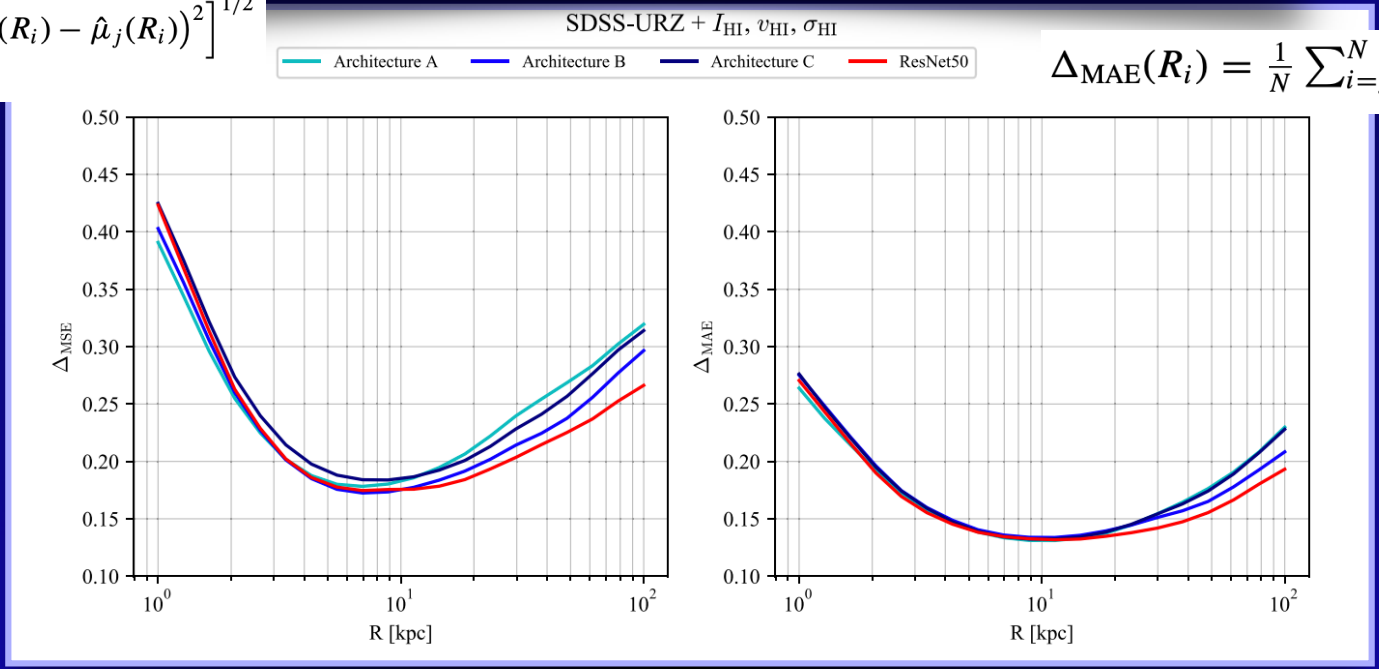
[deLosRios, Petac, Zaldivar, Calore, Bonaventura, FI arXiV:2111.08725]

It's always about the performance



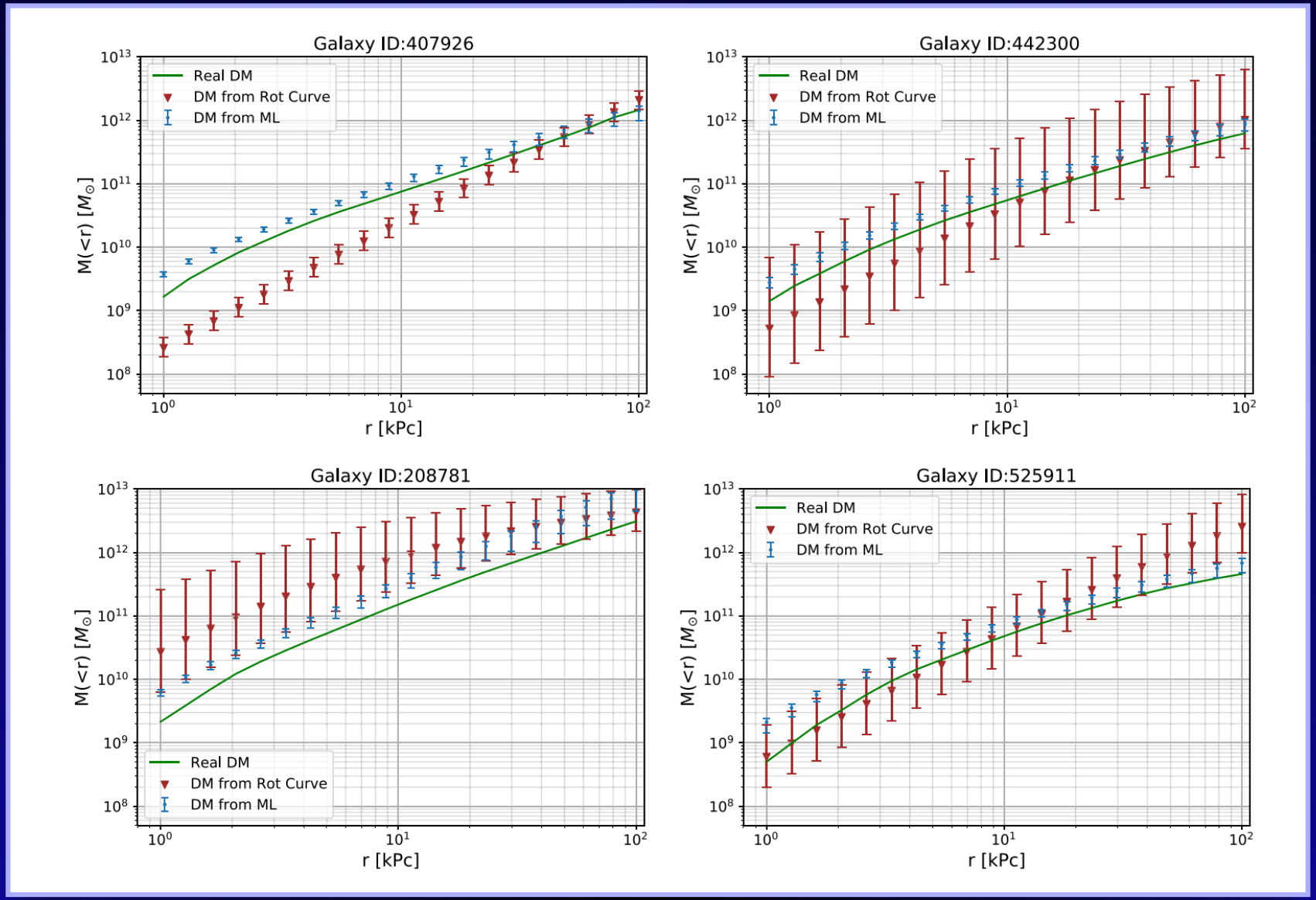
$$\Delta_{MSE}(R_i) = \left[\frac{1}{N}\sum_{j=1}^{N}\left(\mu_j(R_i) - \hat{\mu}_j(R_i)\right)^2\right]^{1/2}$$

$$\Delta_{MAE}(R_i) = \frac{1}{N}\sum_{i=j}^{N}|\mu_j(R_i) - \hat{\mu}_j(R_i)|$$



[deLosRios, Petac
Zaldivar, Calore,
Bonaventura, FI
arXiV:2111.08725]

Rotation Curves vs Machines



[deLosRios, Petac, Zaldivar, Calore, Bonaventura, FI, arXiV:2111.08725]