Dark Matter in the Milky Way:

distribution, uncertainties, and their impact on the search for new physics

Fabio Iocco

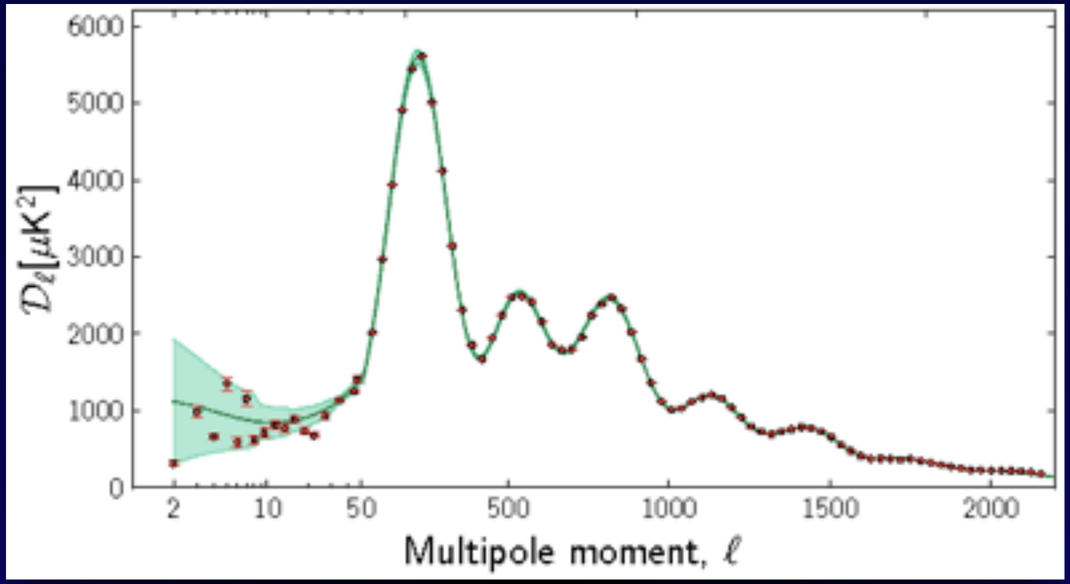
ICTP-SAIFR
IFT-UNESP
São Paulo

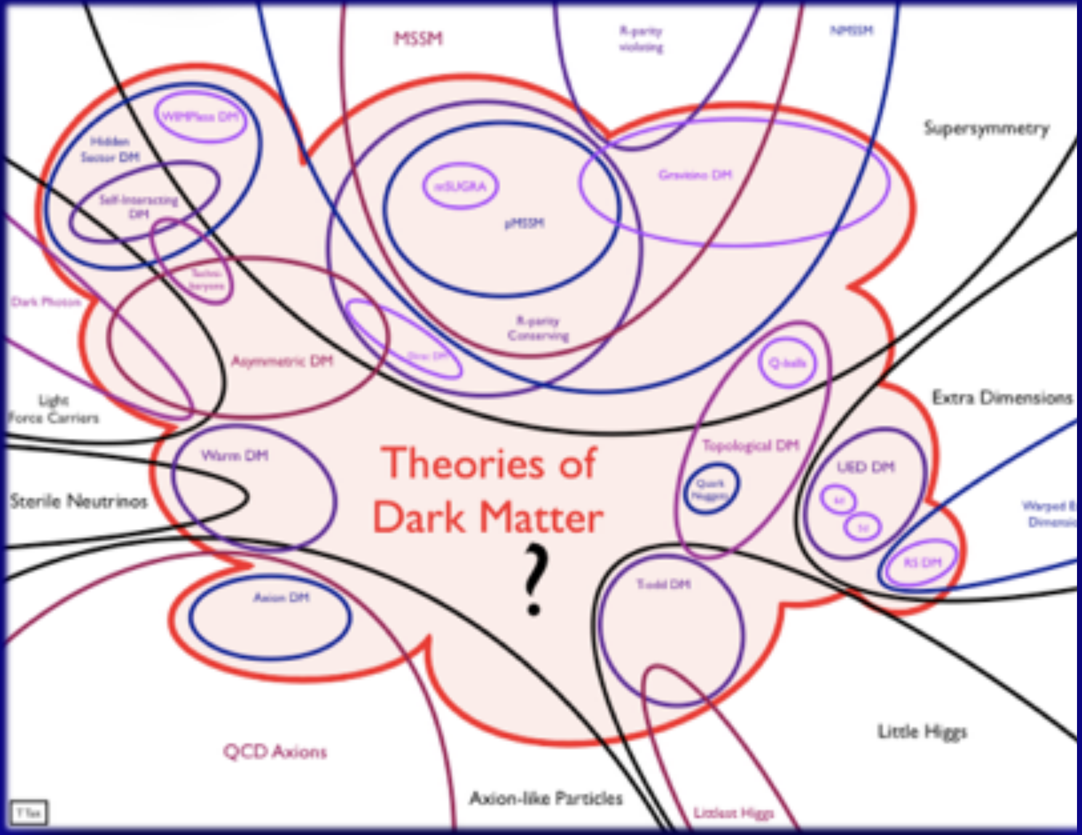
ICTP SAIFR
International Centre for Theoretical Physics
South American Institute for Fundamental Research

TeVPA 2018
August 29, Berlin

Dark Matter

Evidence over large range of scales

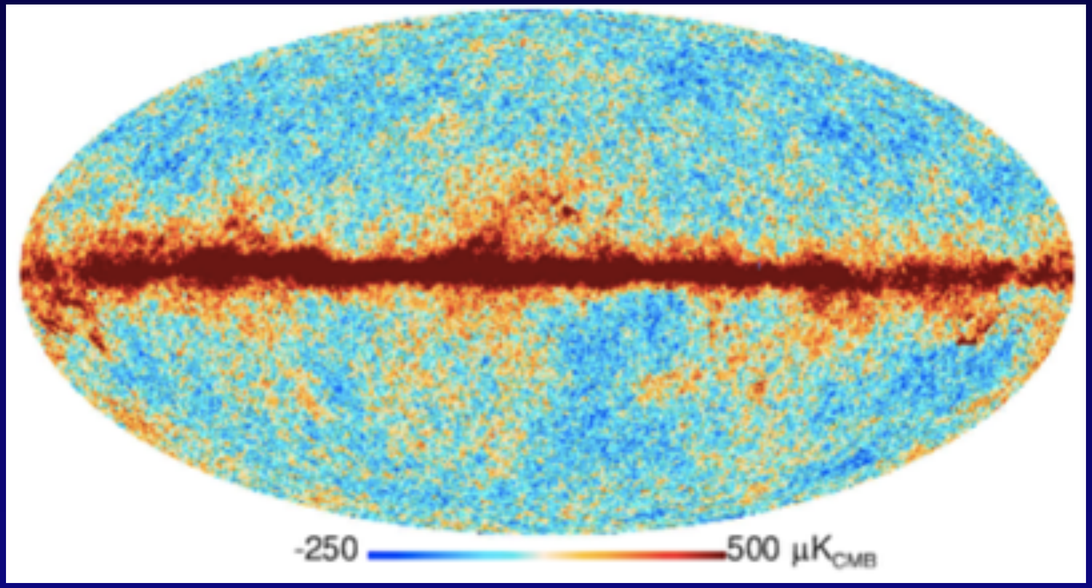


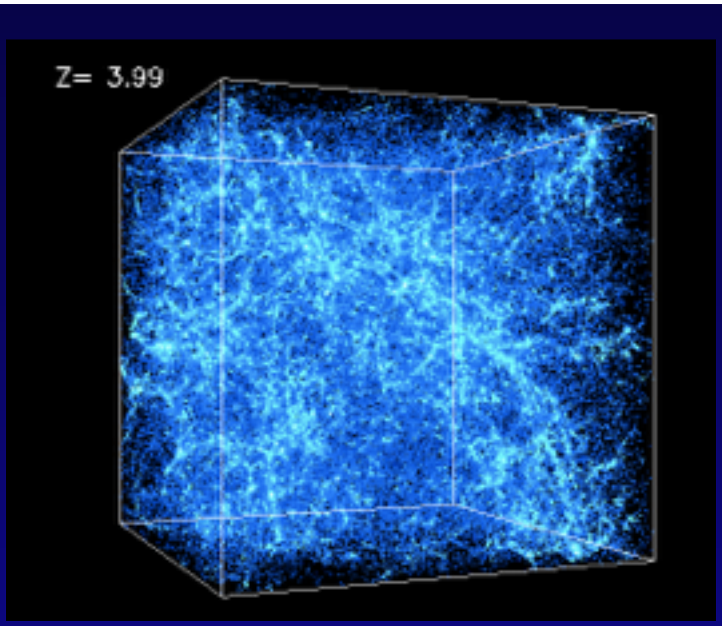


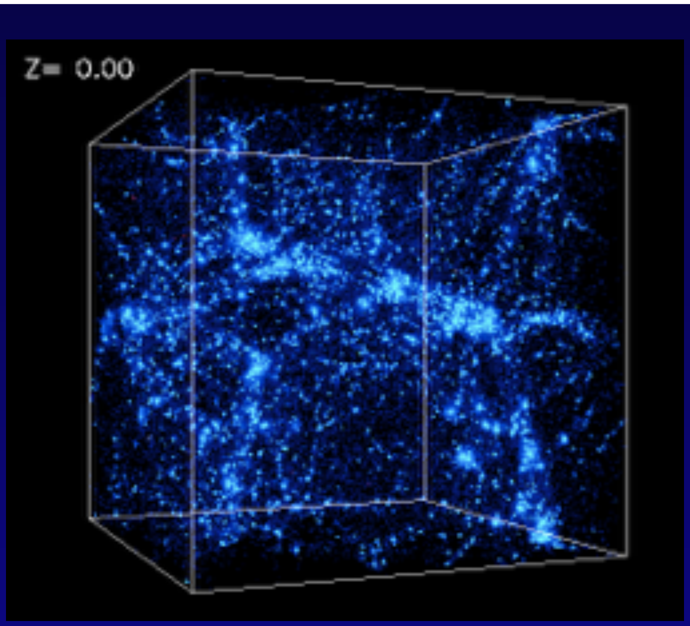
NATURE STILL UNKNOWN

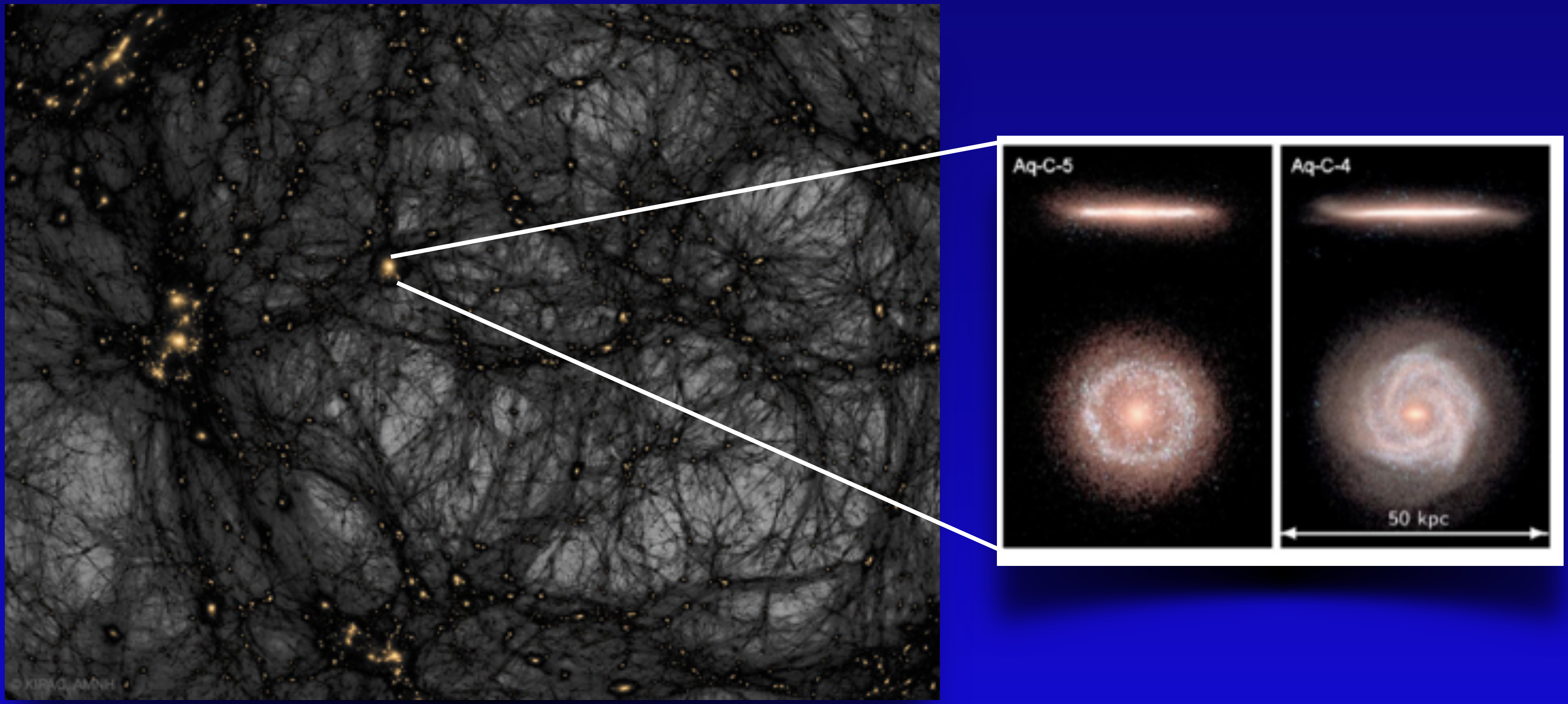
Dark Matter:
a crucial brick in structure formation

age of Universe



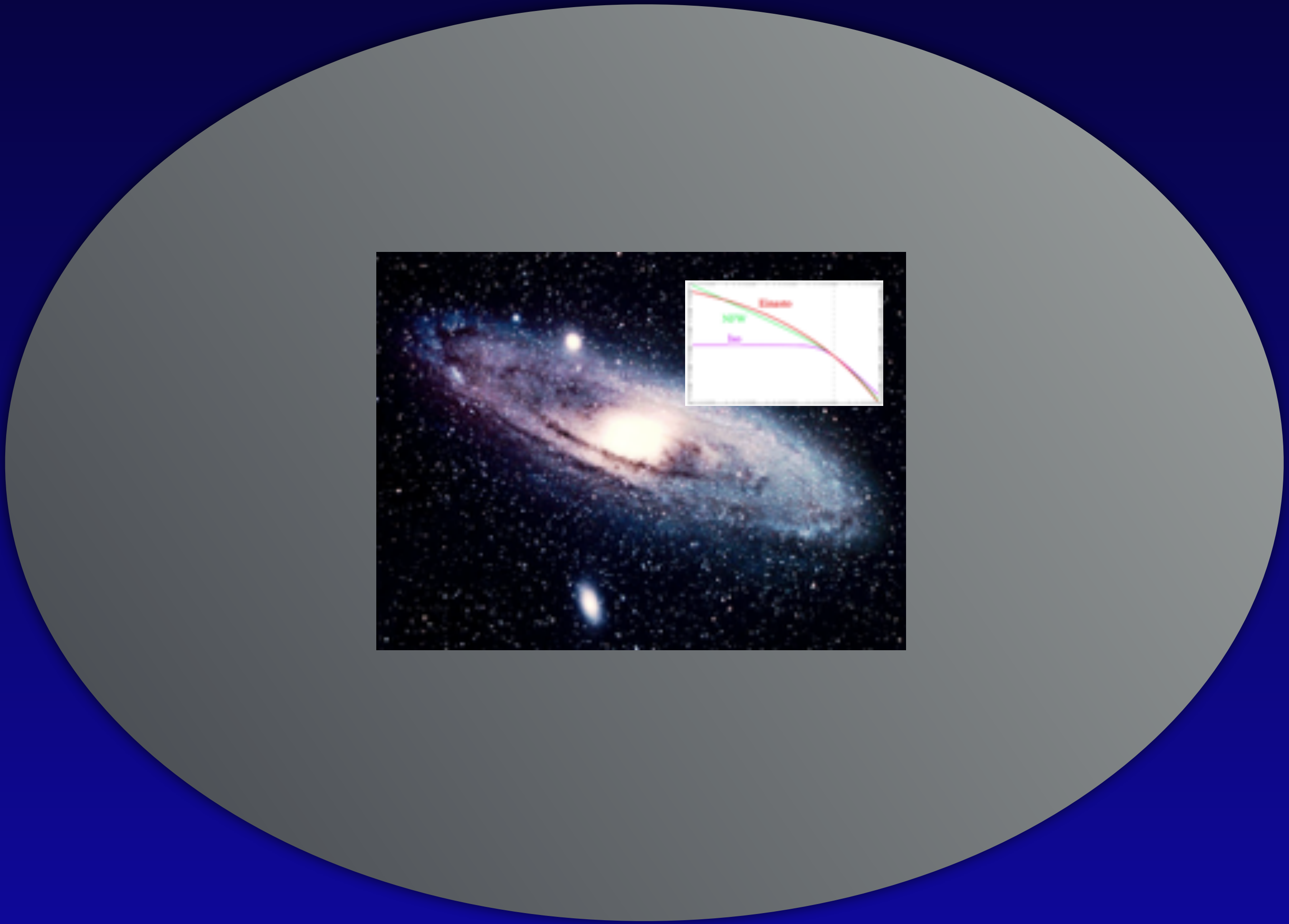


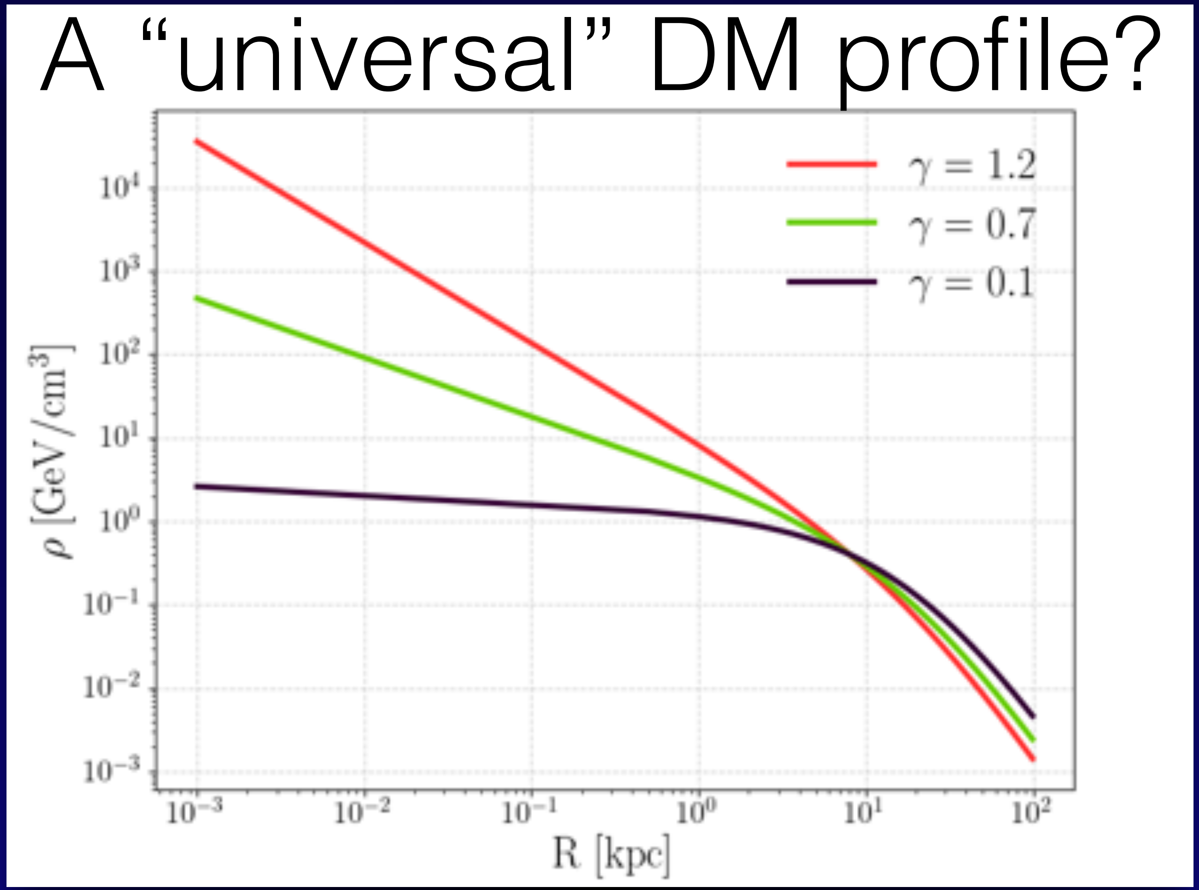




physical size

The halo DM profile





A “universal” DM profile?

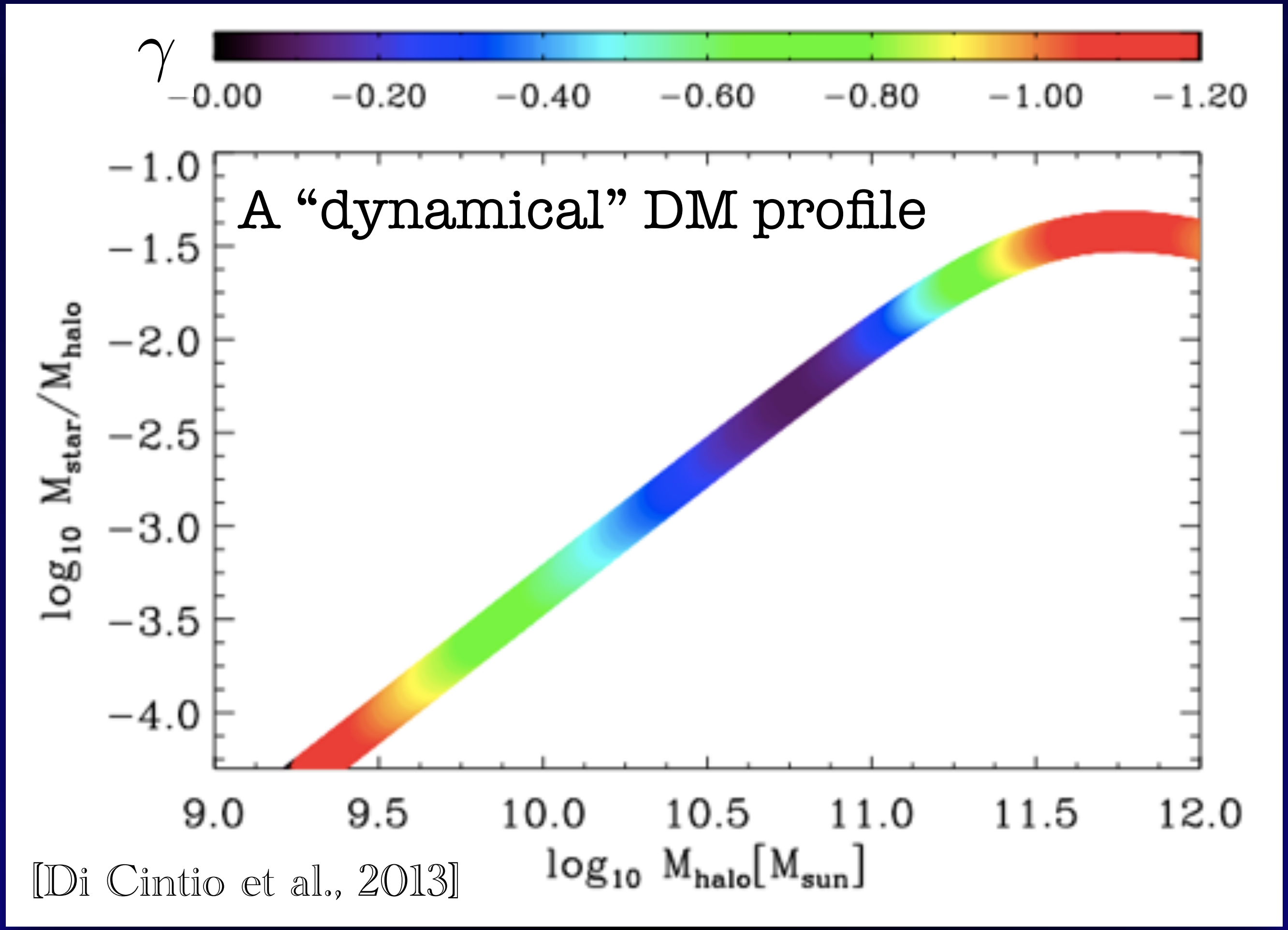
NAVARRO-FRENK-WHITE

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

generalized NFW

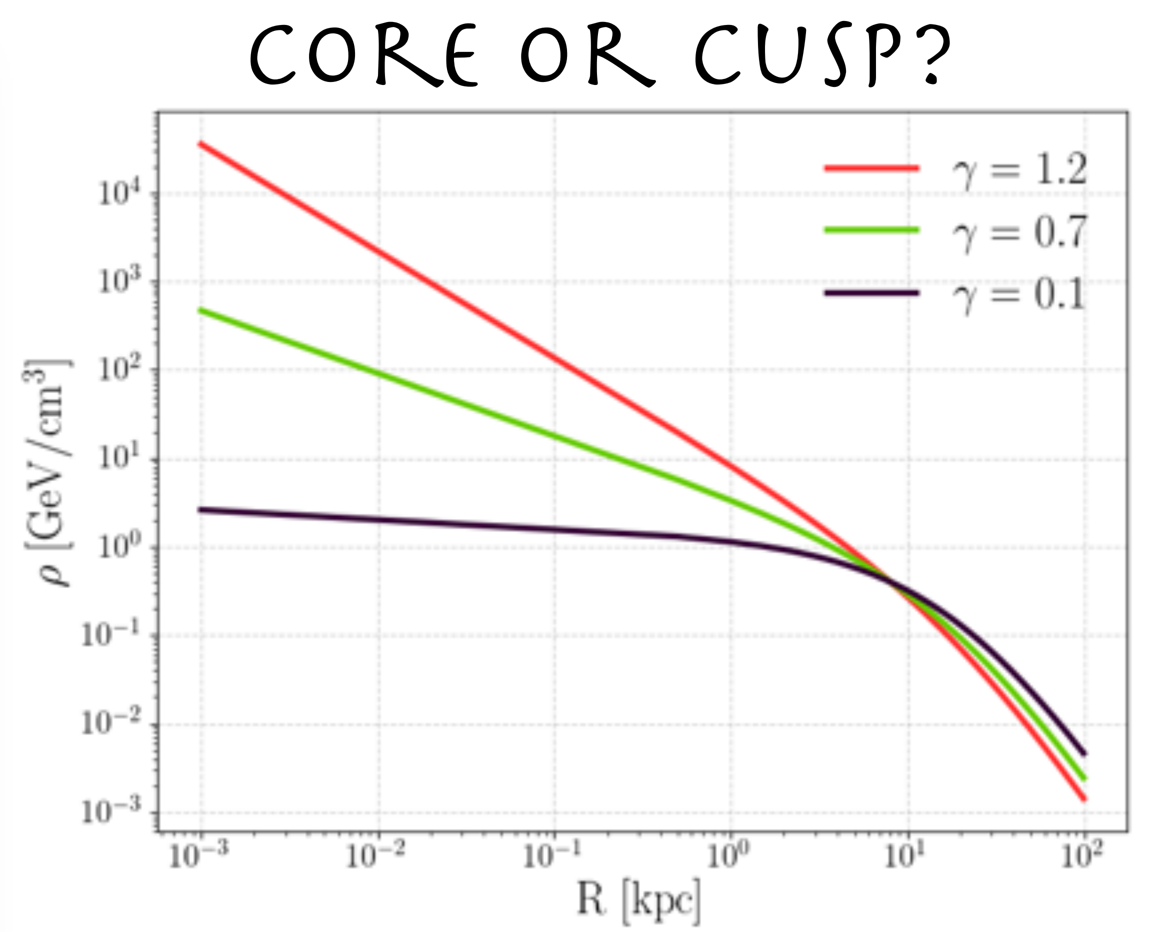
$$\rho_{DM}(R) \propto \rho_0 \left(\frac{R}{R_s}\right)^{-\gamma}\left(1+\frac{R}{R_s}\right)^{-3+\gamma}$$

The dark matter distribution: a dynamical quantity



[Di Cintio et al., 2013]

CORE OR CUSP?

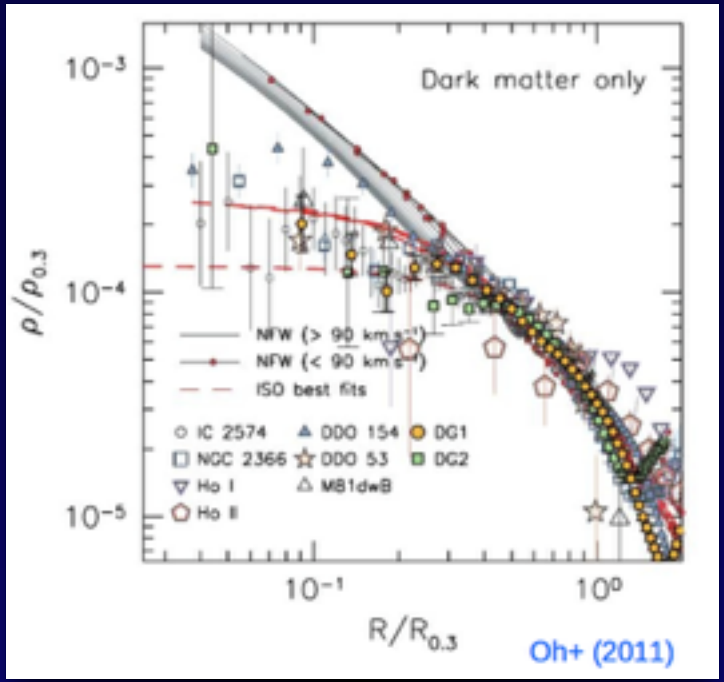


generalized NFW

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

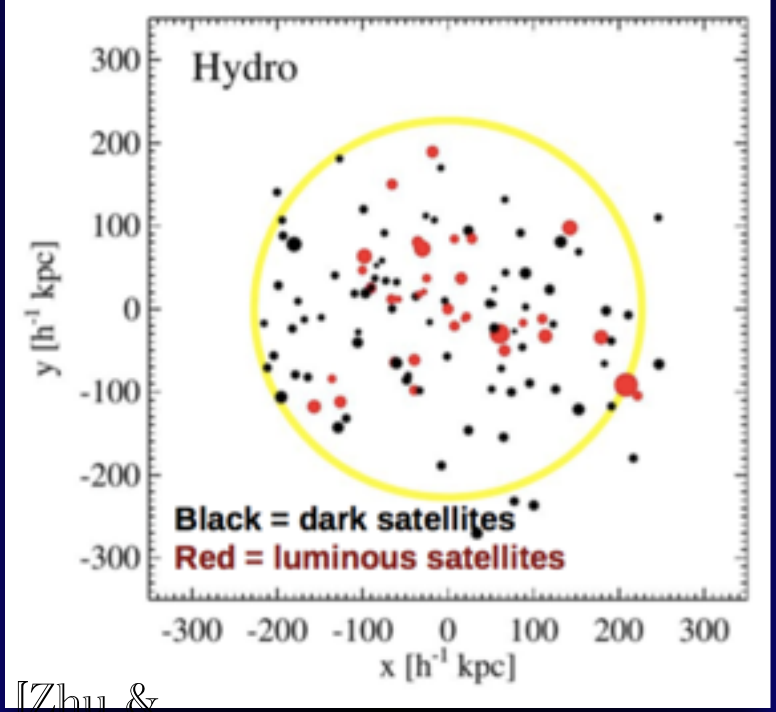
LCDM, small scale problems

Cusp vs core



Oh+ (2011)

Missing satellite

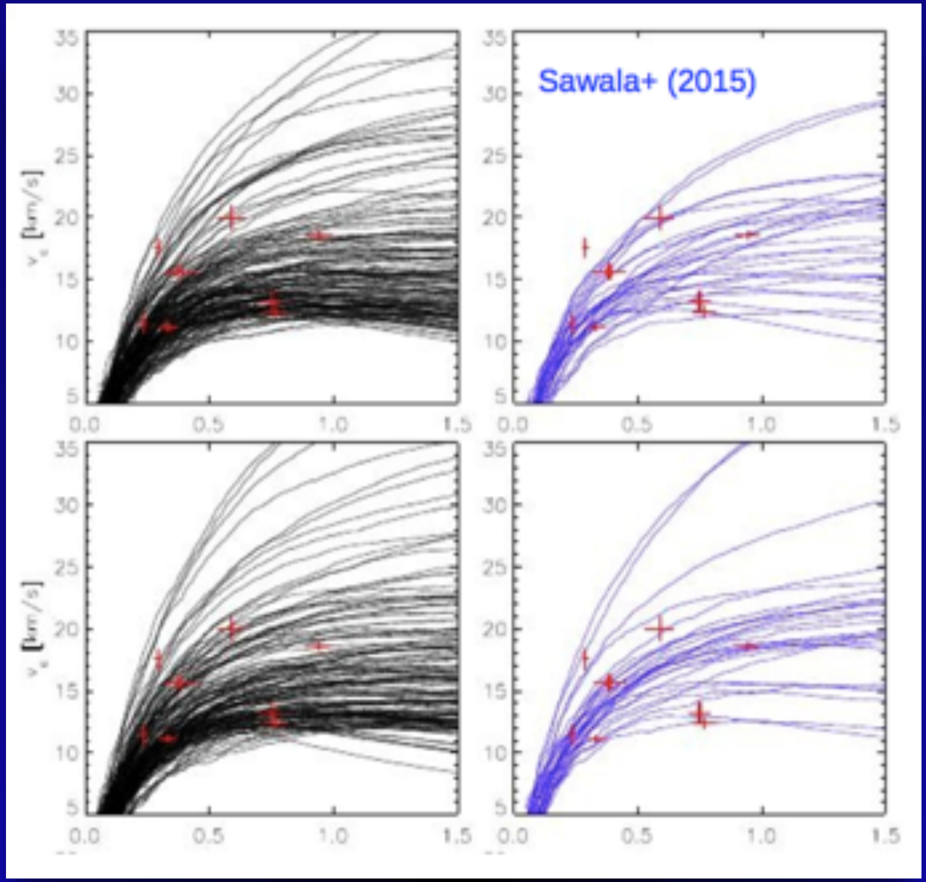


Black = dark satellites

Red = luminous satellites

[Zhu &

Too big to fail



Sawala+ (2015)

For a solution in terms of SIDM, see

Talk by
A. Sokolova

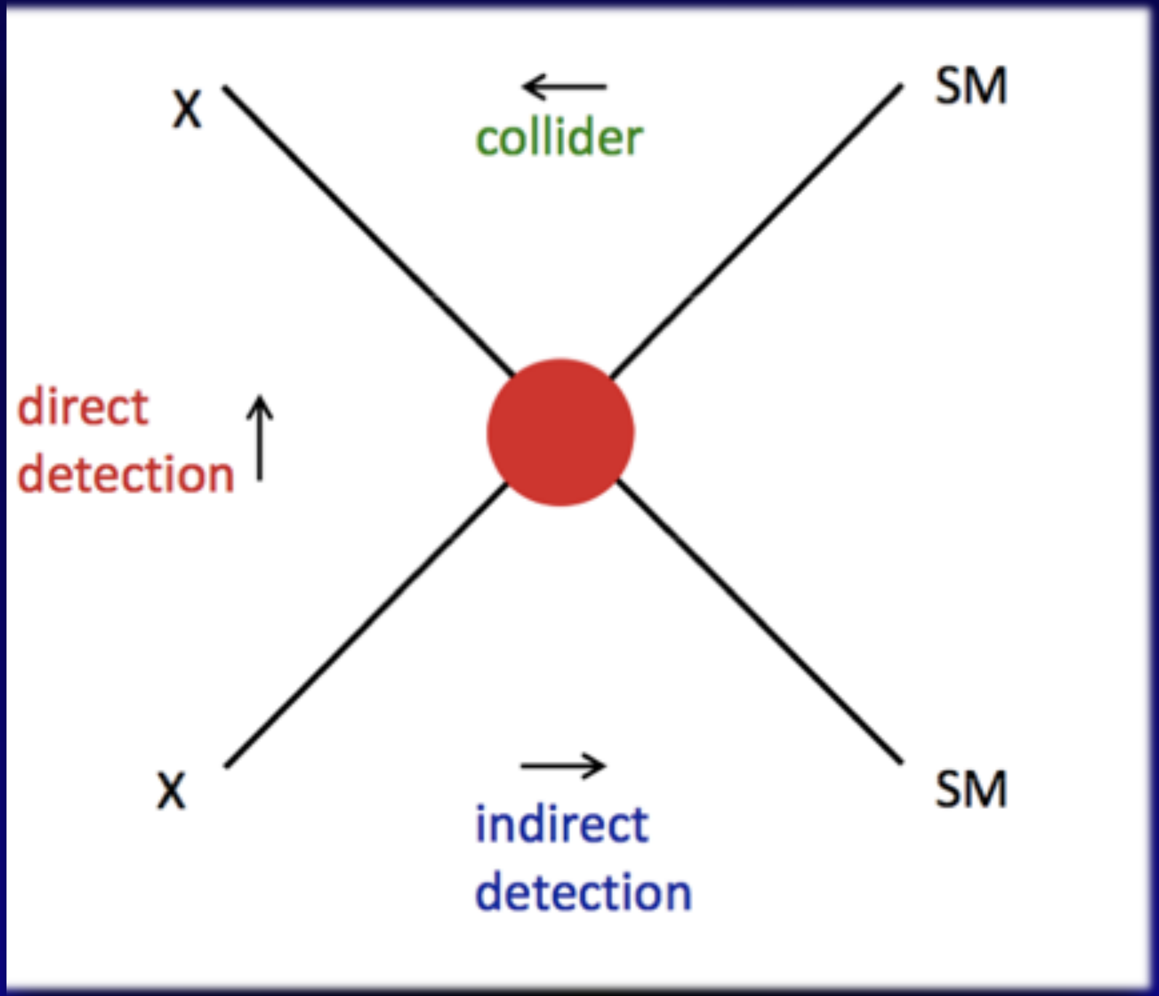
Talk by
M.Vogelsbeger

Direct and indirect searches of WIMP DM

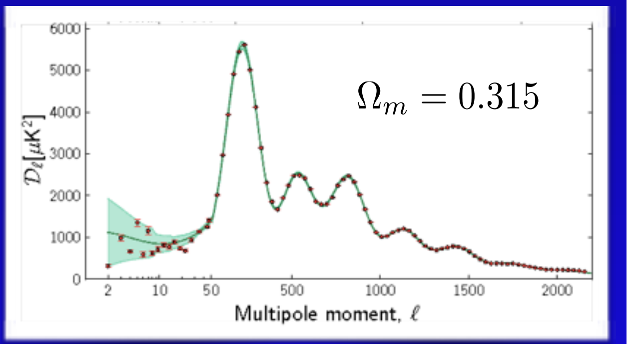
Direct detection:
DM scattering against nuclei, recoil

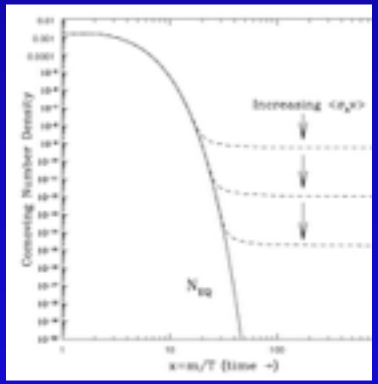
Indirect detection:
Annihilation in astrophysical envir.
Observation of SM products of annih.

Production at LHC



Motivated by cosmological/PP arguments
but not only DM candidate!

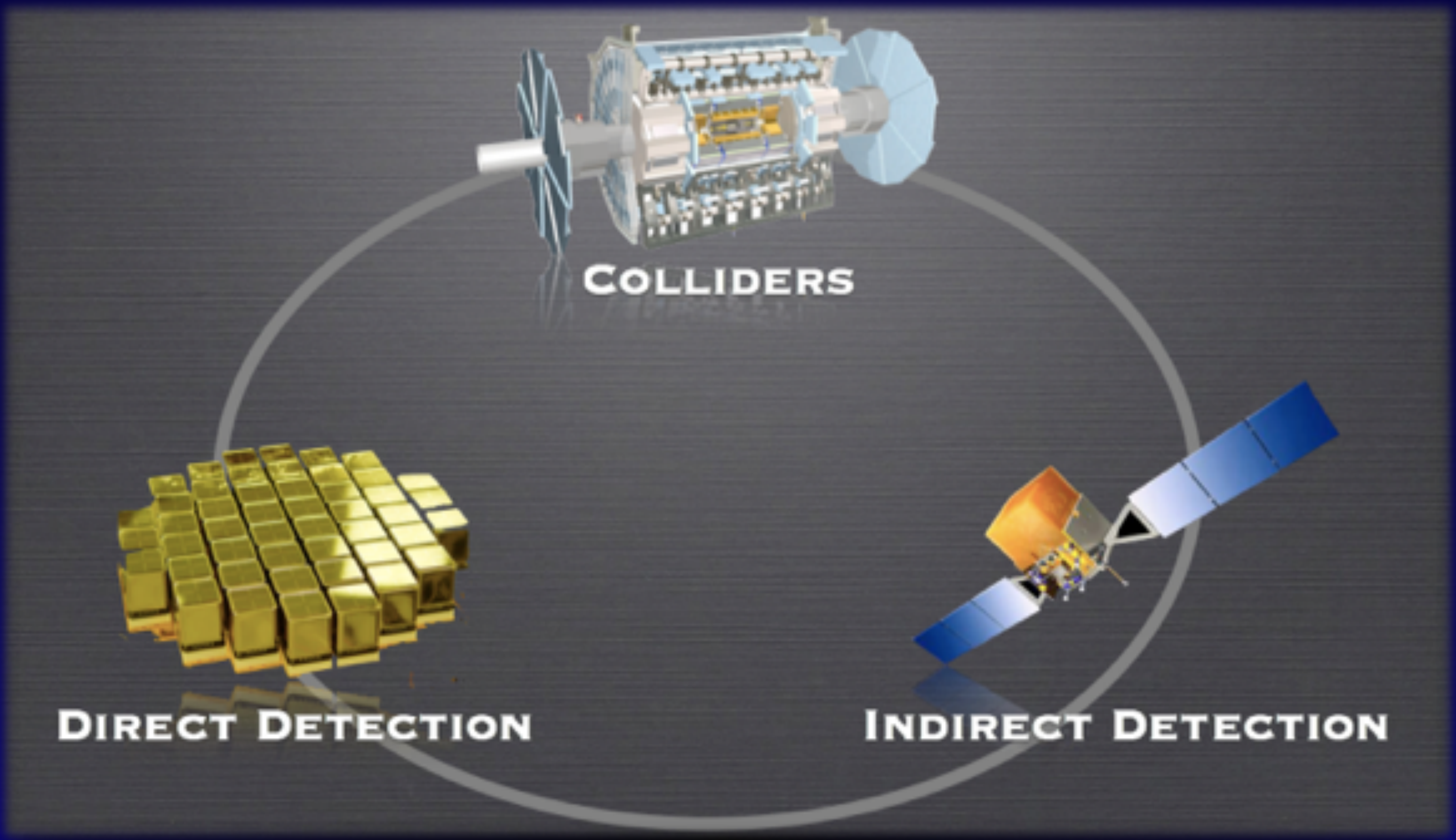


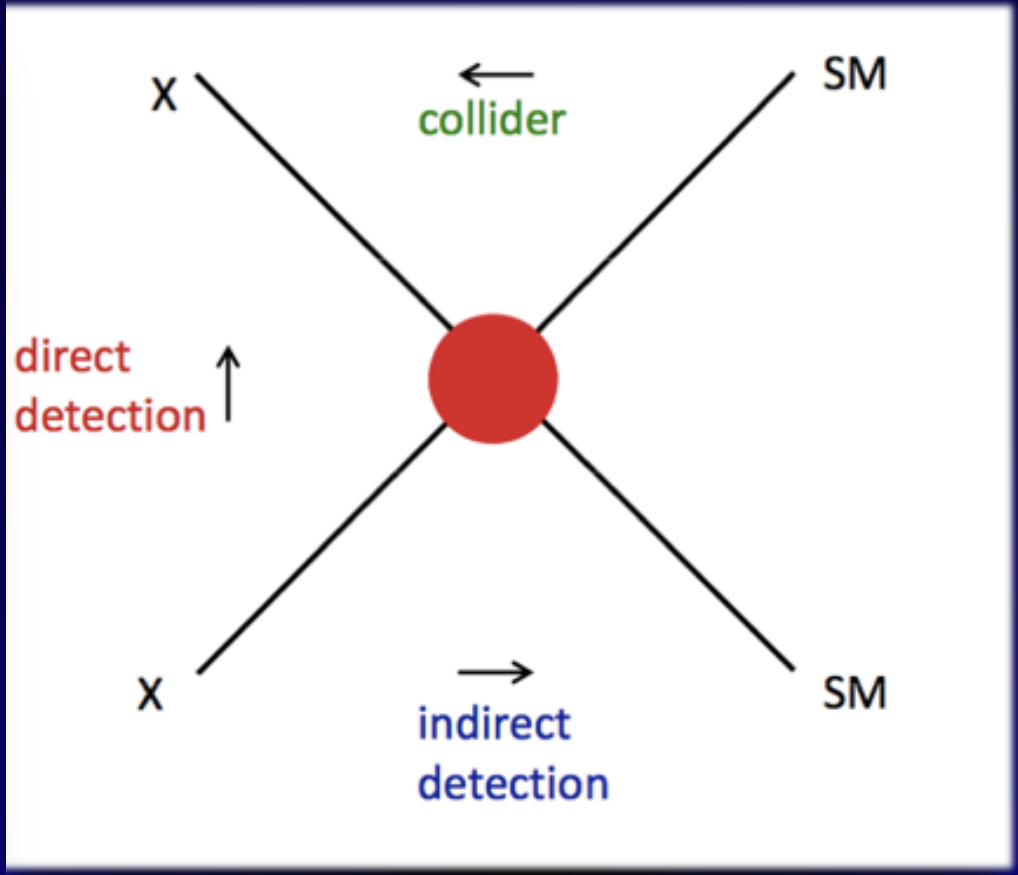


Talks by
R. Laha, R. Poettgen, ...

Complementarity

searching for DM from Earth and in Sky





Direct detection:
DM scattering against nuclei, recoil

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

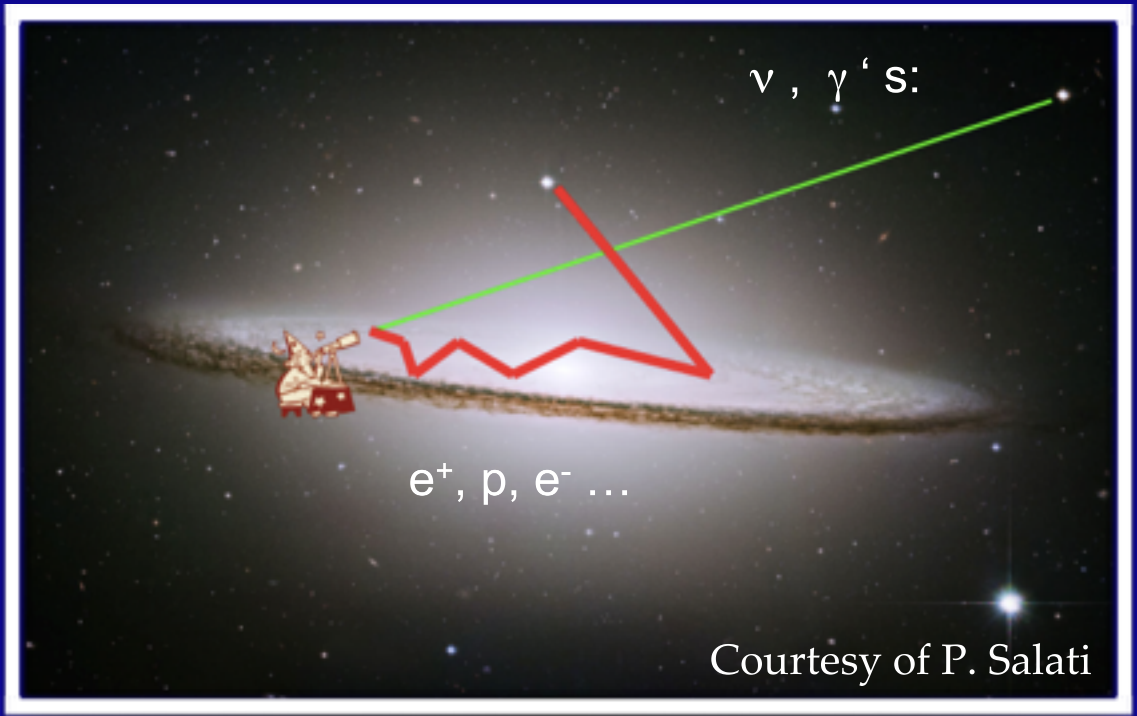
Production at LHC

Indirect Detection: principles and dependencies

Galactic center, Dwarf Galaxies, Galactic Halo…
dependence on density structure
discovery (or constraints) subject to same uncertainty

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

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



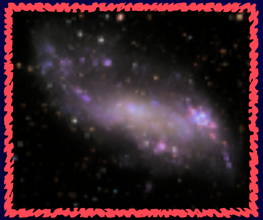
Courtesy of P. Salati

Talk by
F. Calore

Which targets for DM gamma-ray searches?

Clusters

Dwarf Spheroidals
satellites



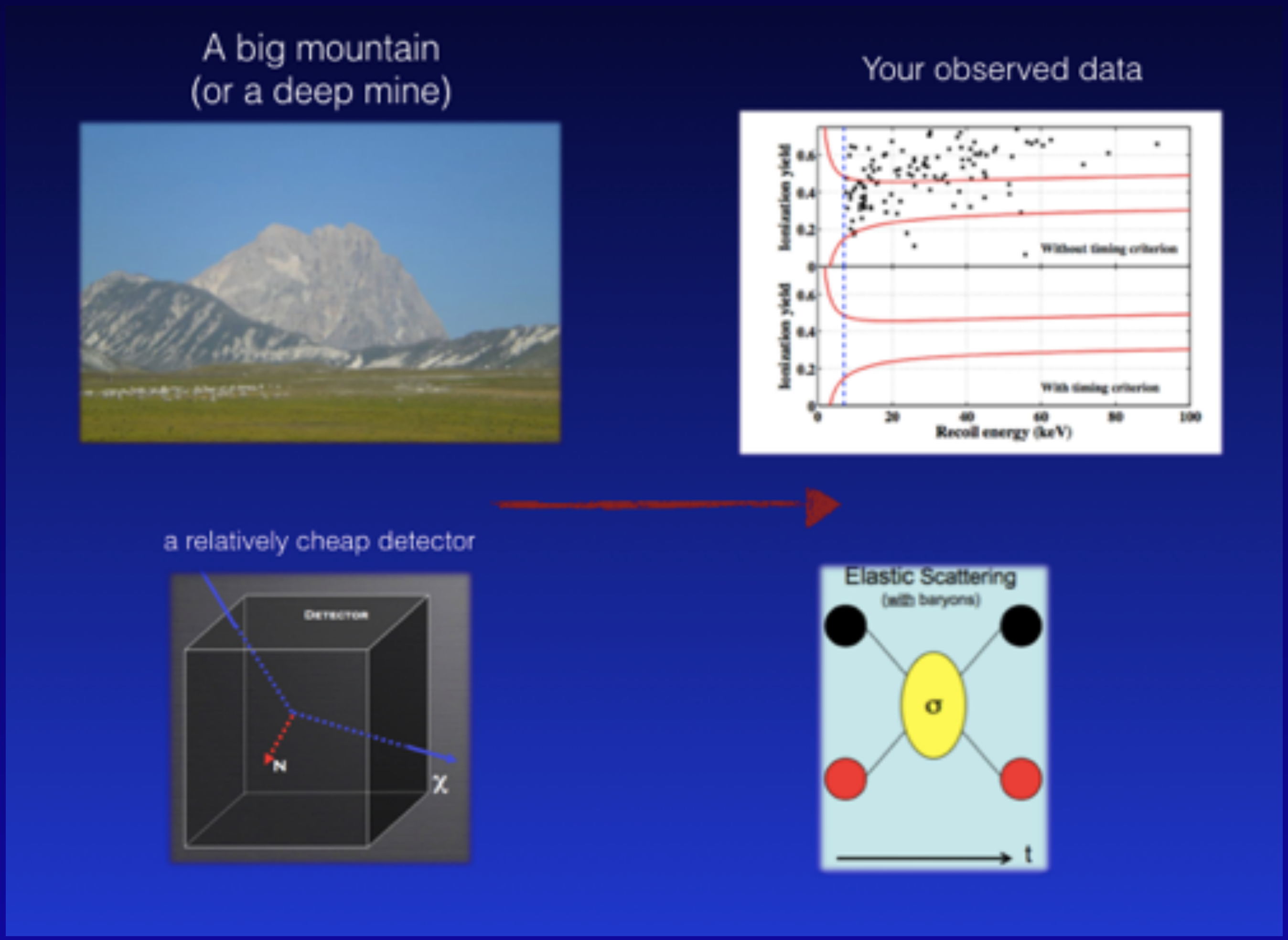
Spiral satellites

Talks by
K. Hayashi, P. Sandick,
S. Ando, M. Stref

Direct Detection: principles and dependencies

from this

to this

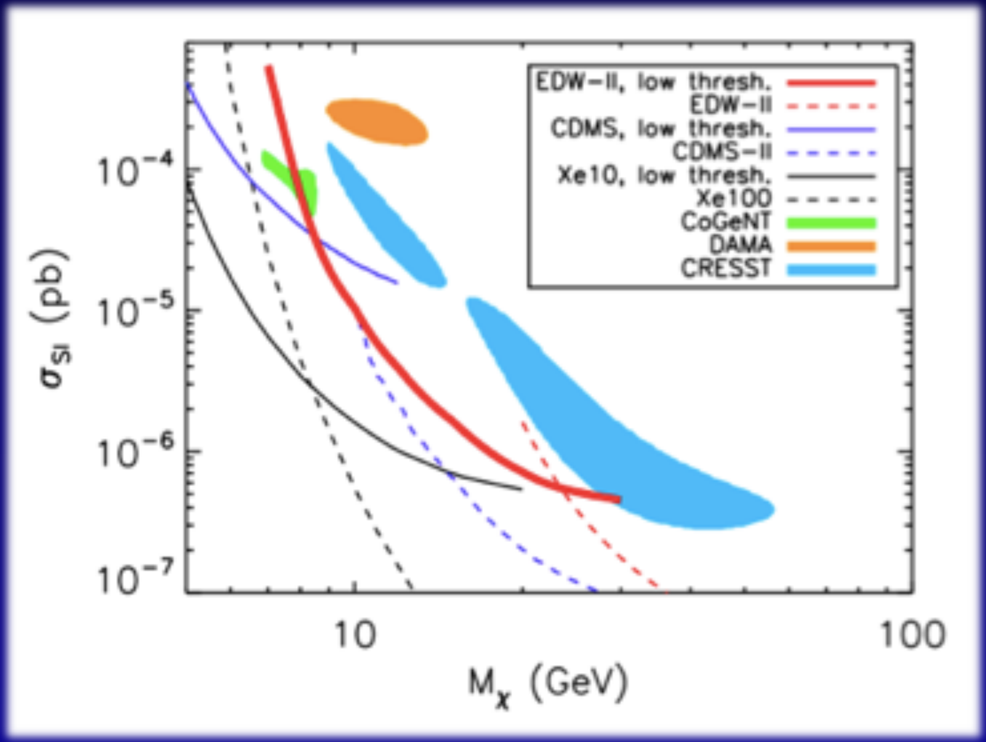


A big mountain
(or a deep mine)

Your observed data

a relatively cheap detector

Elastic Scattering
(with baryons)



you need this

$$\frac{dR}{dE} \propto \frac{\sigma_\chi}{m_\chi} \boxed{\rho_0} \boxed{f(v)}$$

Talk by
T. Marrodan

Talk by
N. Bozorgnia

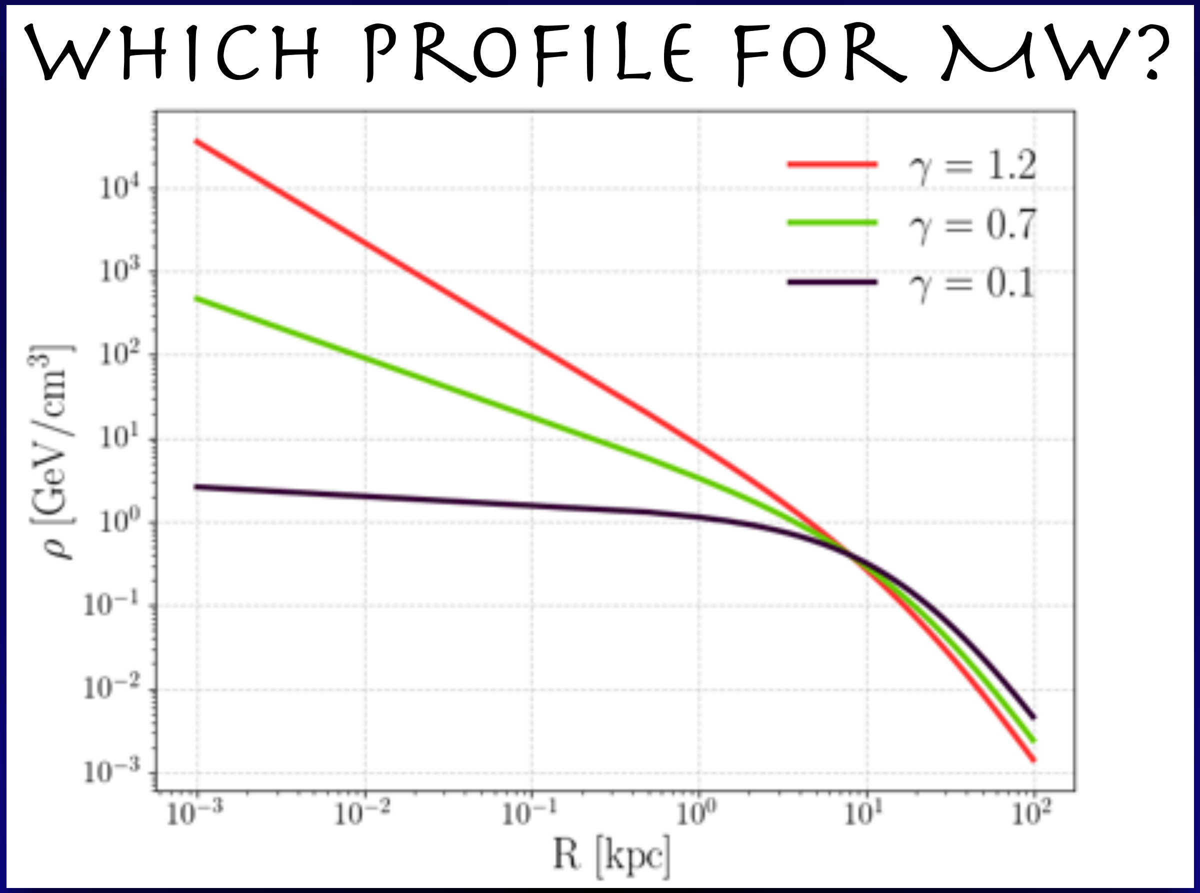
A real case: the Milky Way

S. Tiozzo

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

A real case: the Milky Way

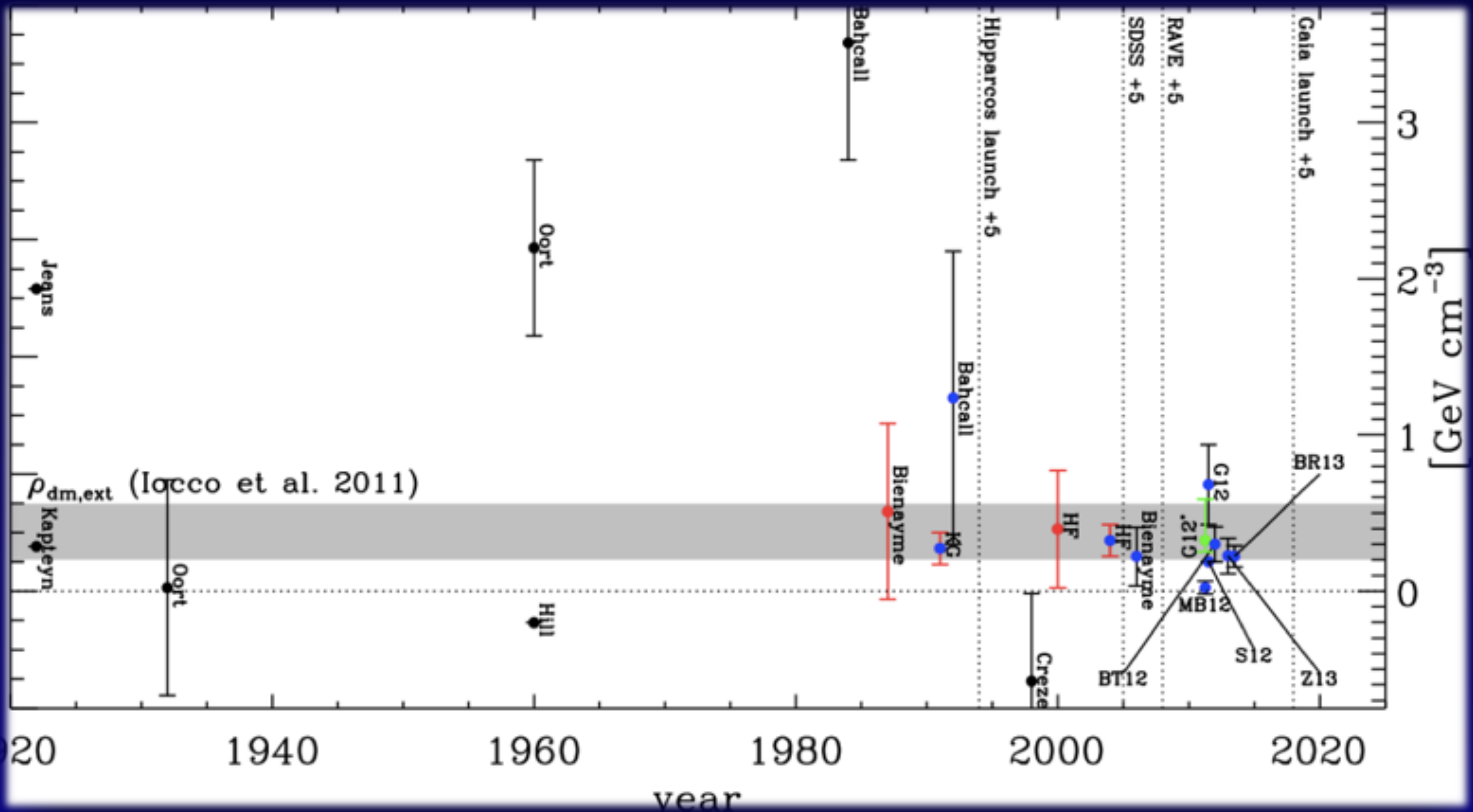
Role of “standard” astrophyiscs



crucial in interpretation of data on “exotic” physics

Inferring DM distribution in the MW

from observations: local DM density

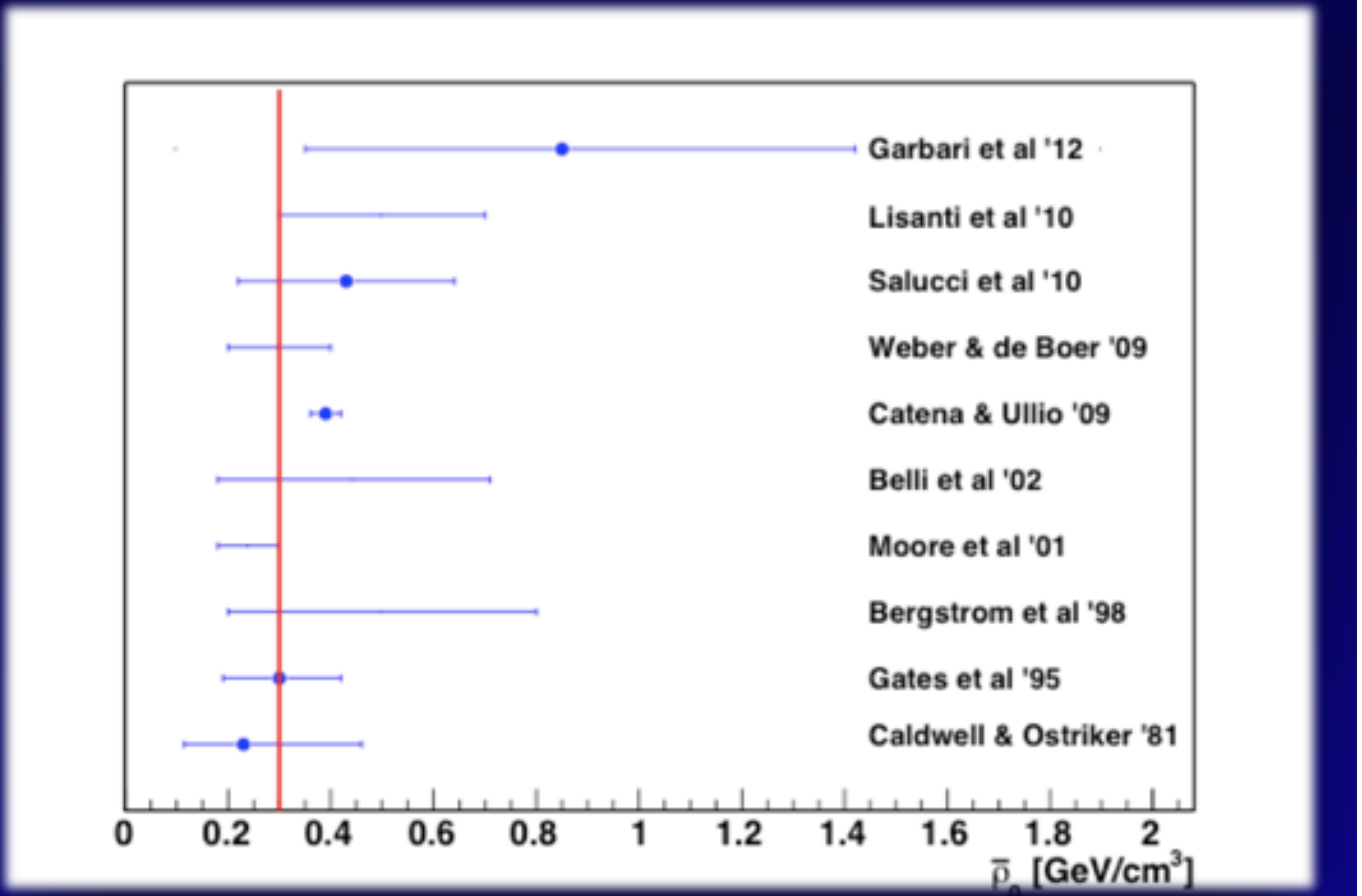


Determinations of local DM density
are consistent, but "noisy"

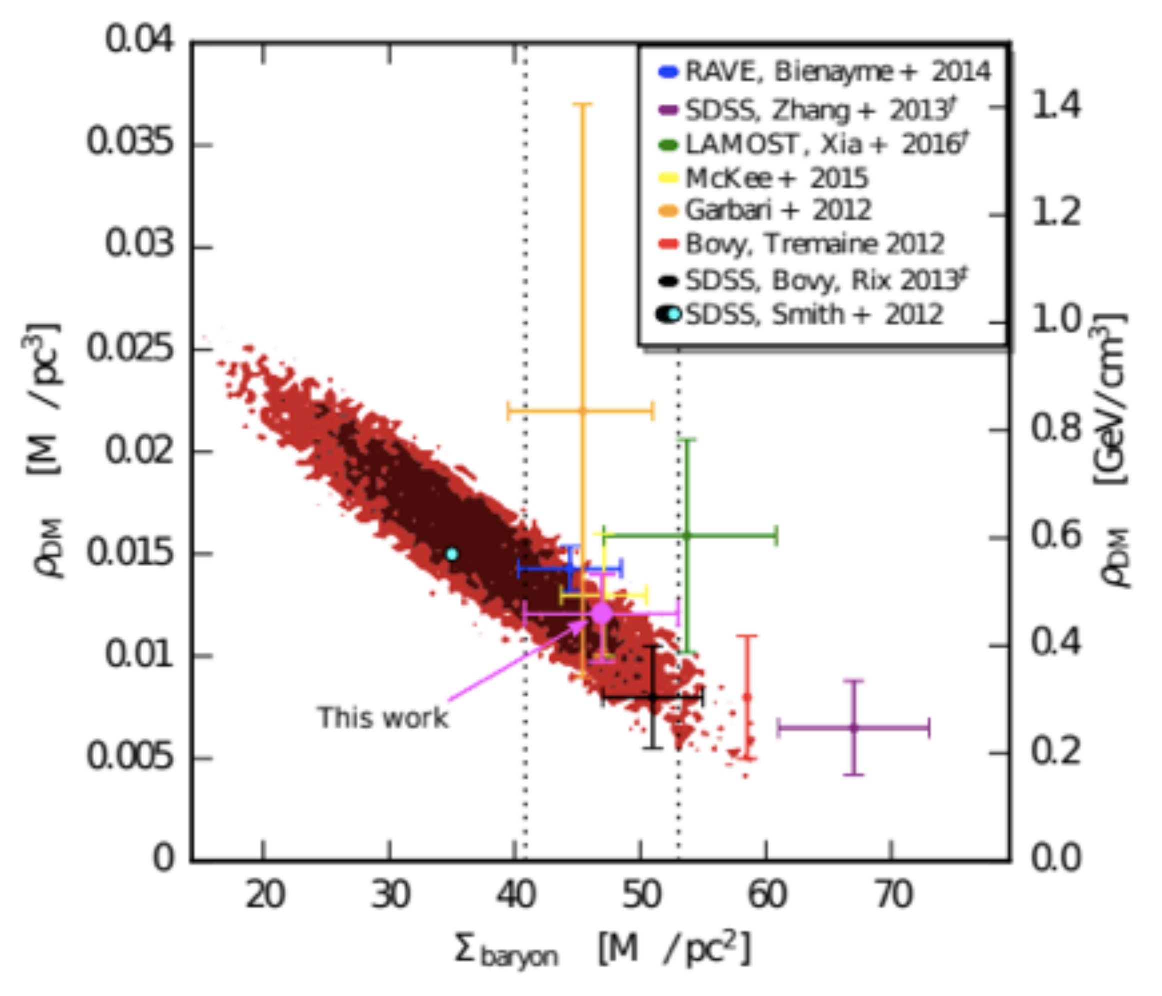
[Read, 2014]

Inferring the DM density structure

from observations: local DM density



[Courtesy of M. Pato]

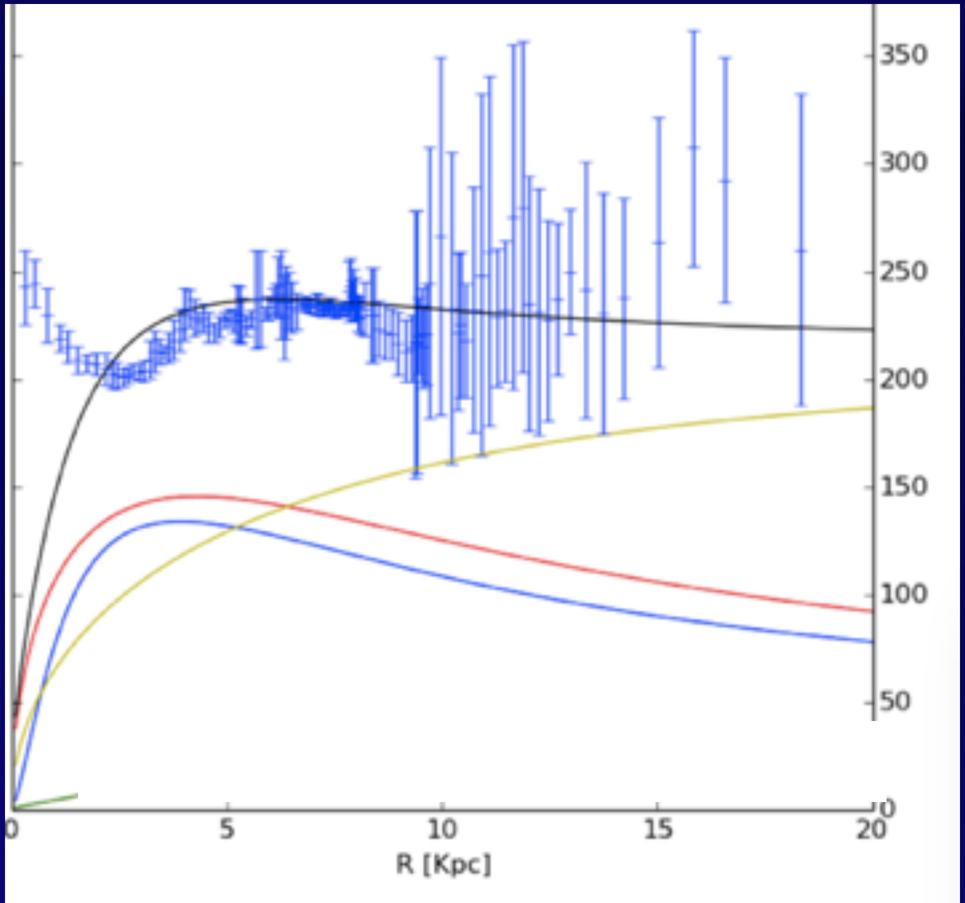


[Sivertsson et al. 2017]

Determinations of local DM density (with different methods) are consistent, but…

Inferring the DM density structure

Fitting a pre-assigned shape
on top of luminous

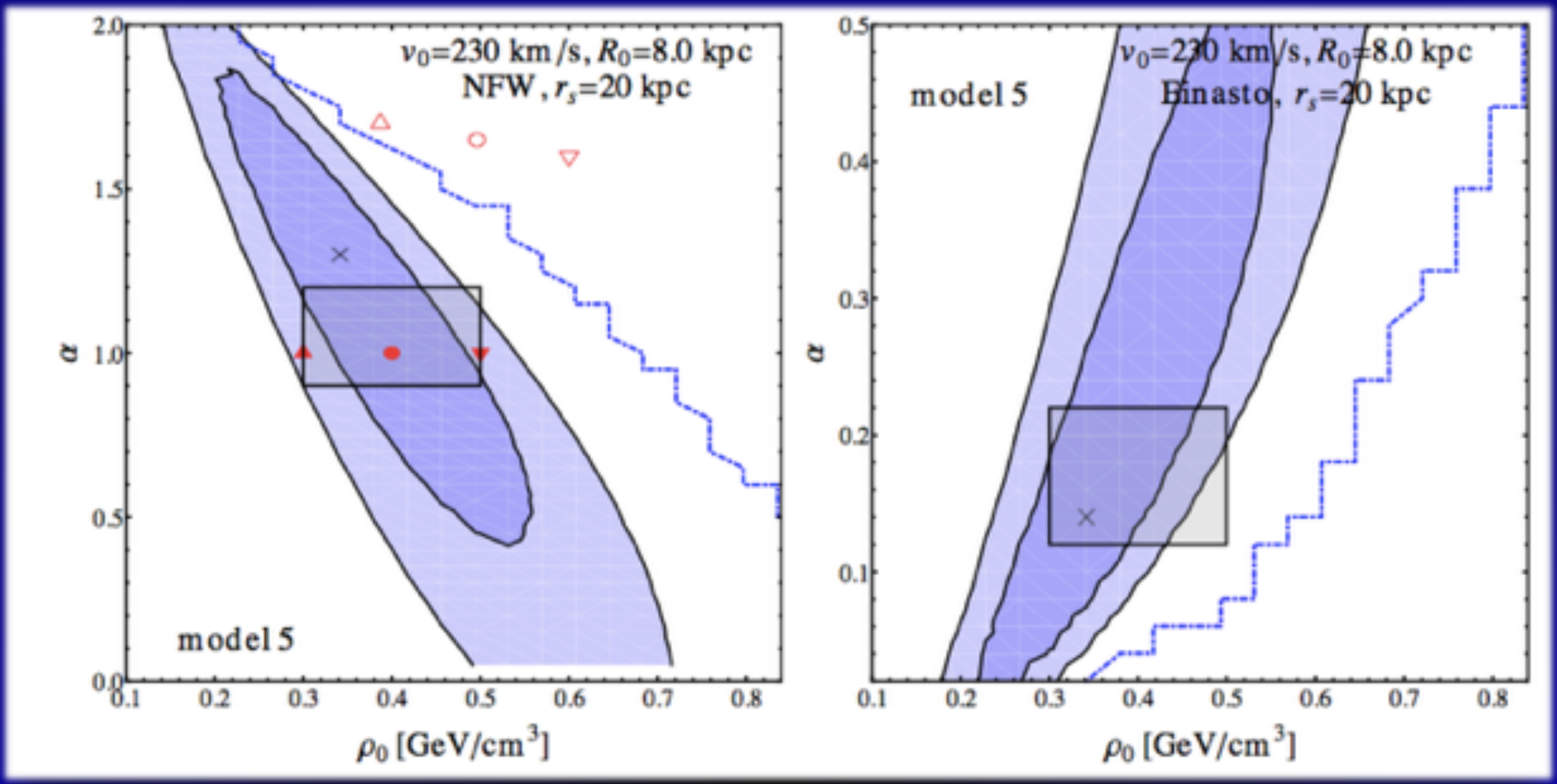


gNFW

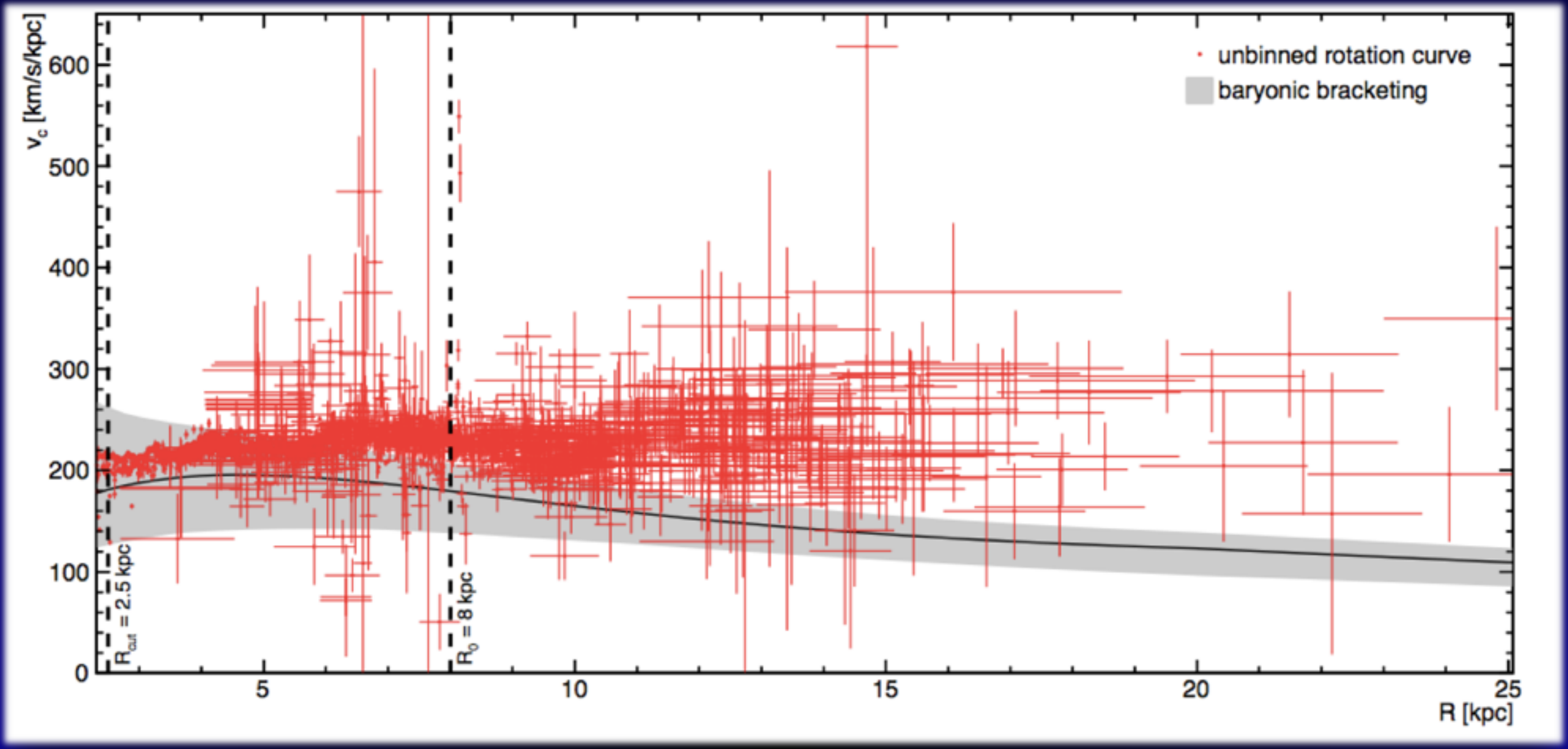
$$\rho_{DM}(R) \propto \rho_0 \left(\frac{R}{R_s}\right)^{-\gamma}\left(1+\frac{R}{R_s}\right)^{-3+\gamma}$$

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

Einasto

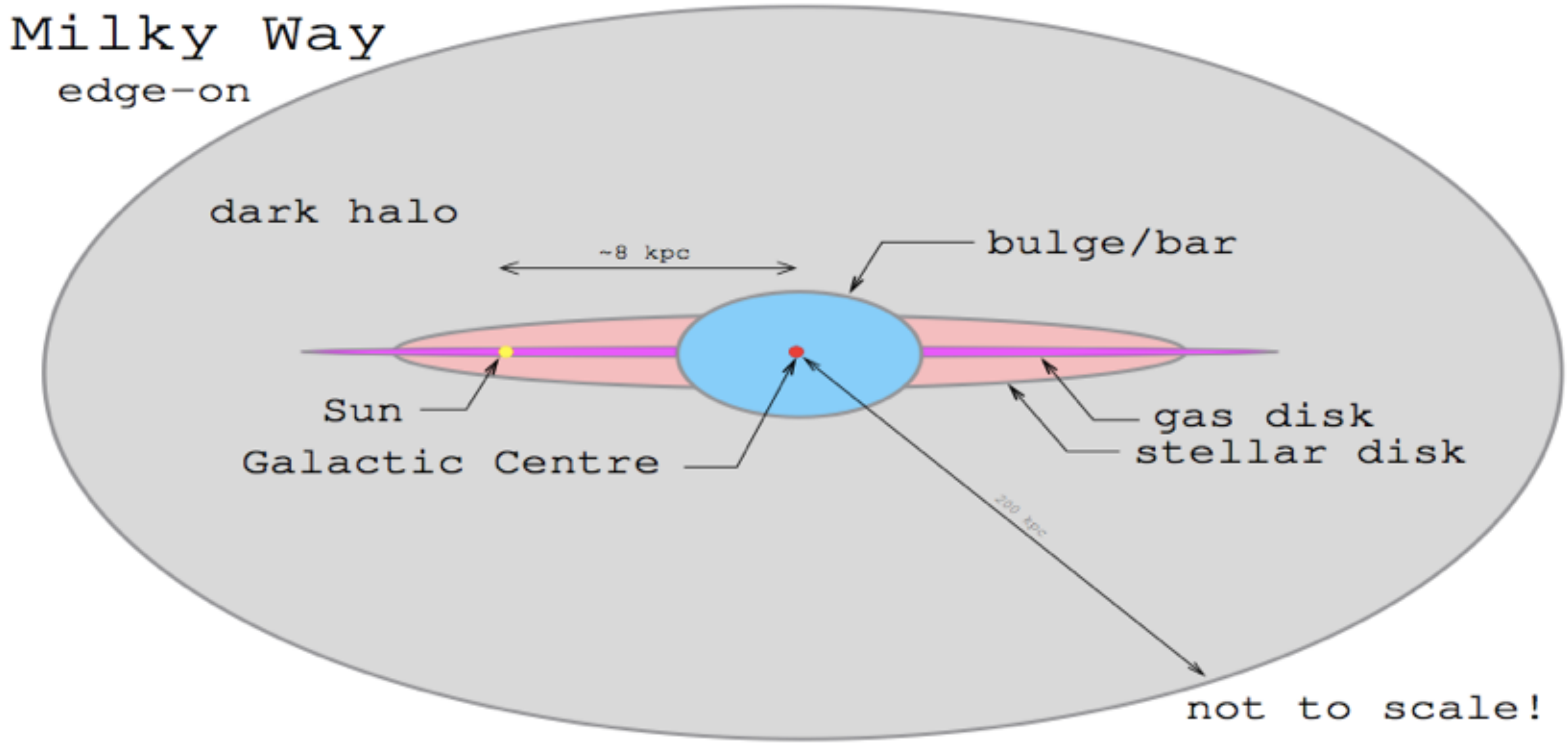


The Milky Way:
one spiral Galaxy



[Iocco, Pato, Bertone, Nature Physics 2015]

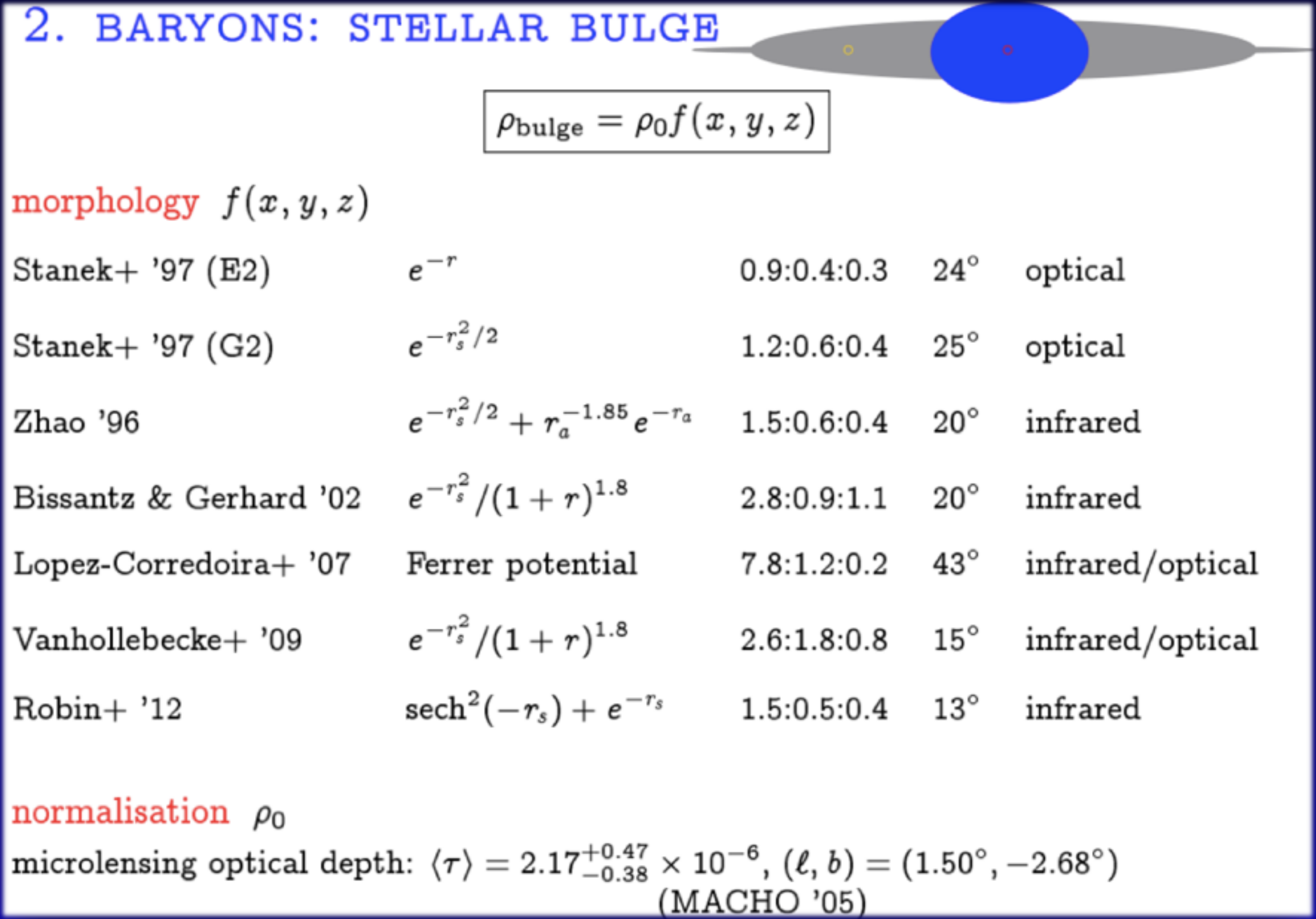
The Milky Way
its luminous component



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

[Courtesy of M. Pato]

The luminous Milky Way: observations of morphology



2. BARYONS: STELLAR BULGE

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

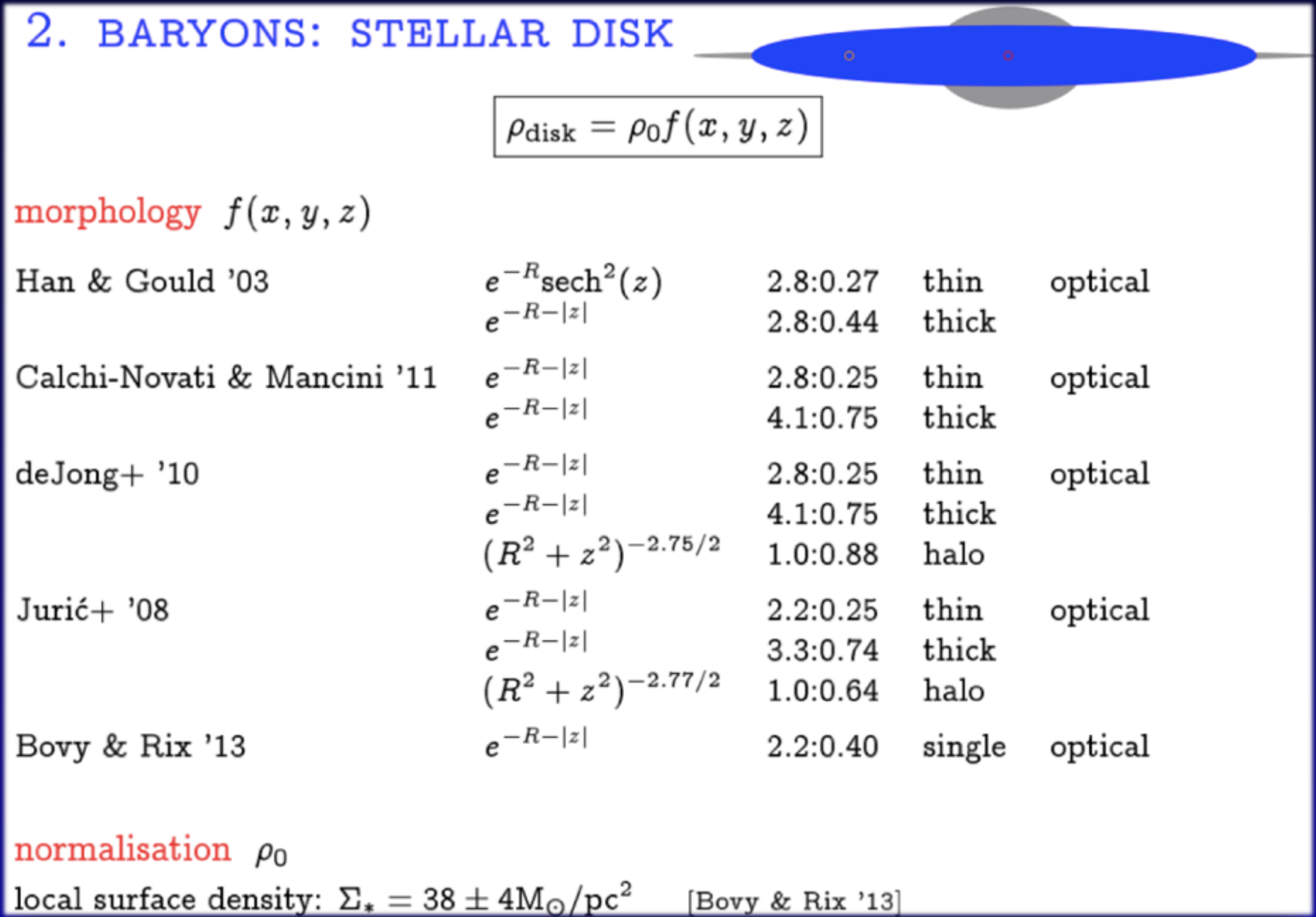
morphology $f(x,y,z)$

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	$\text{sech}^2(-r_s) + e^{-r_s}$	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

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

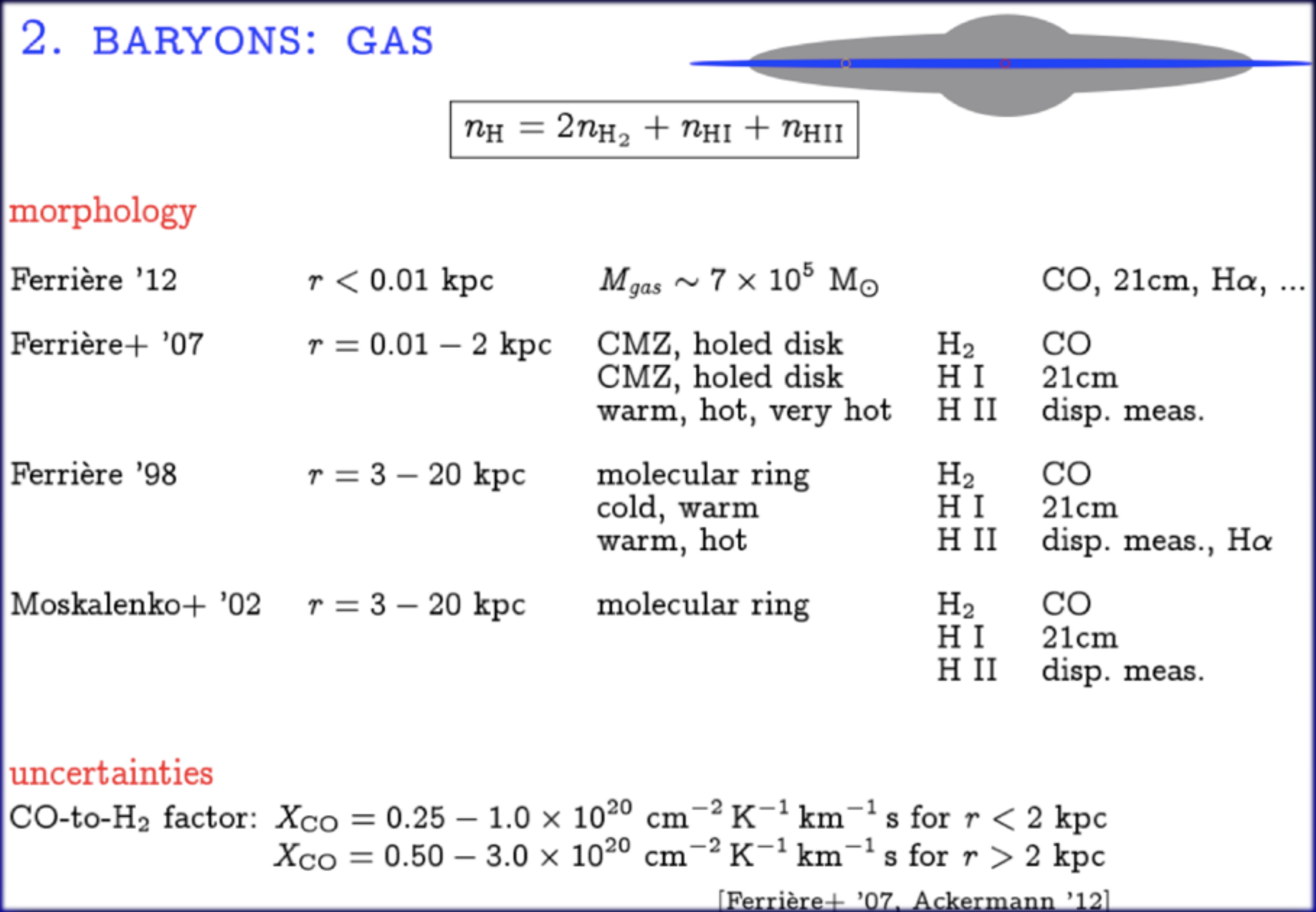
morphology $f(x, y, z)$

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

normalisation ρ_0

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

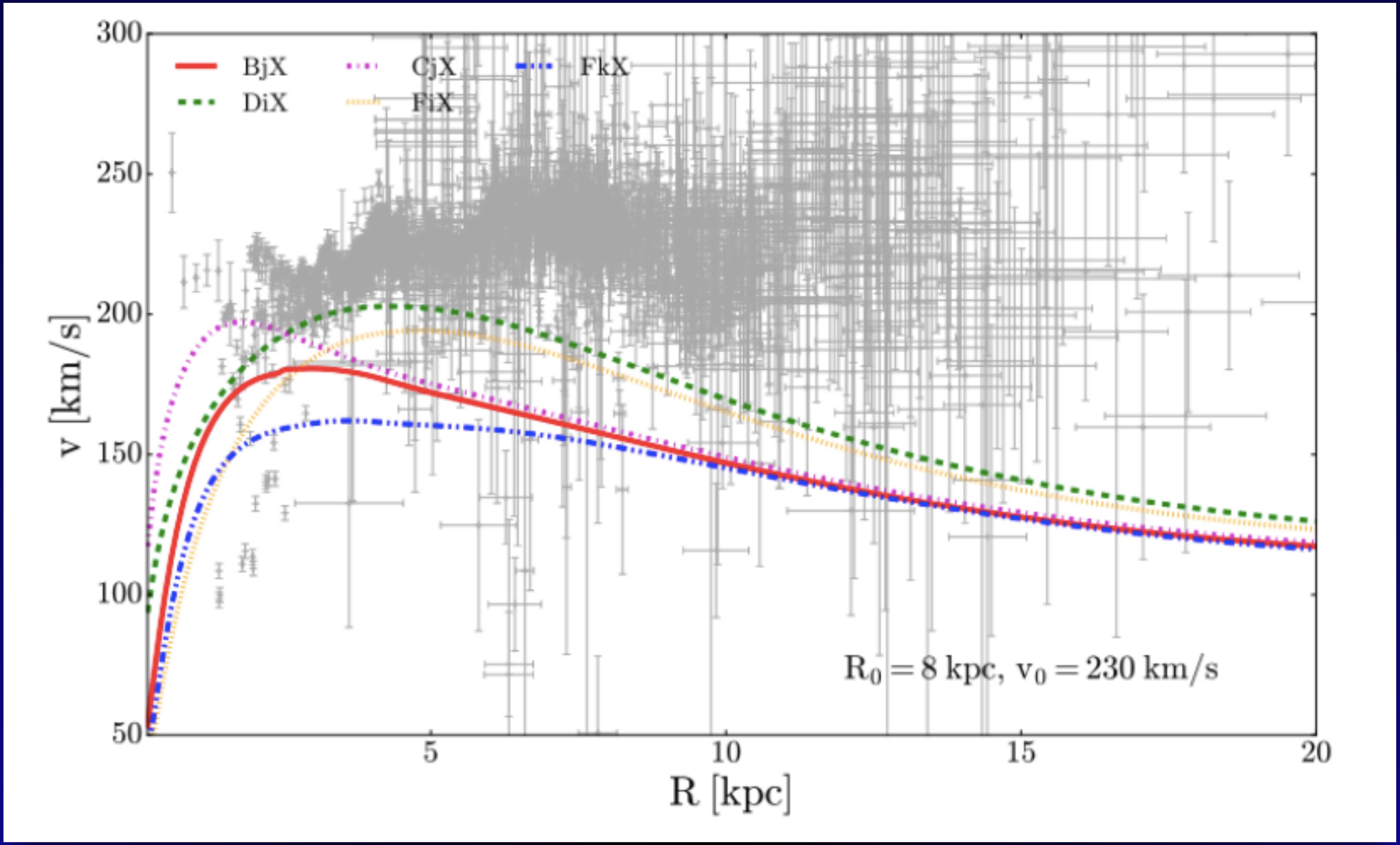
CO-to-H_2 factor: $X_{\mathrm{CO}} = 0.25 - 1.0 \times 10^{20}\ \mathrm{cm}^{-2}\,\mathrm{K}^{-1}\,\mathrm{km}^{-1}\,\mathrm{s}$ for $r < 2$ kpc

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

[Ferrière+ '07, Ackermann '12]

Systematic uncertainties

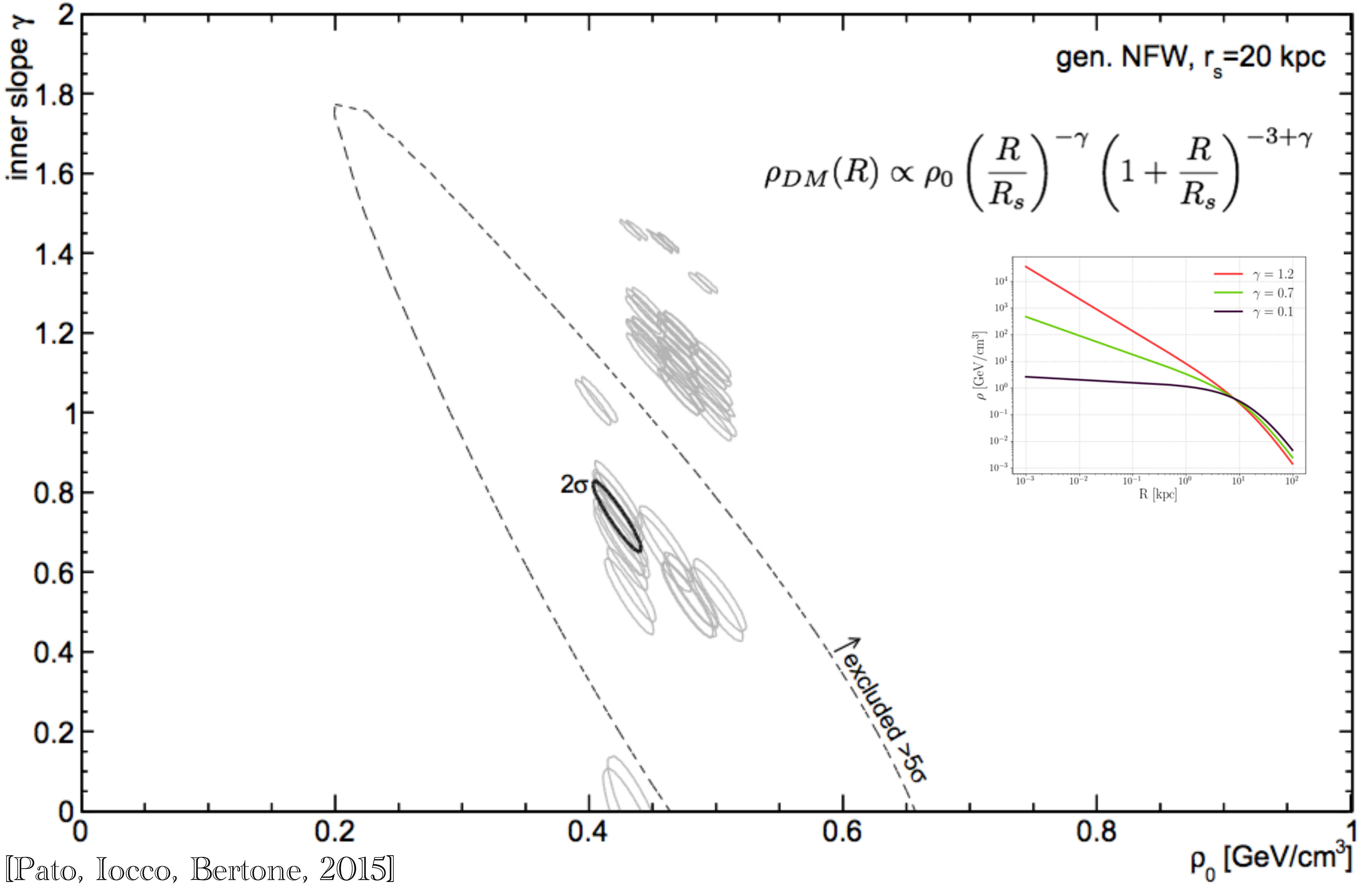
(luminous component)



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

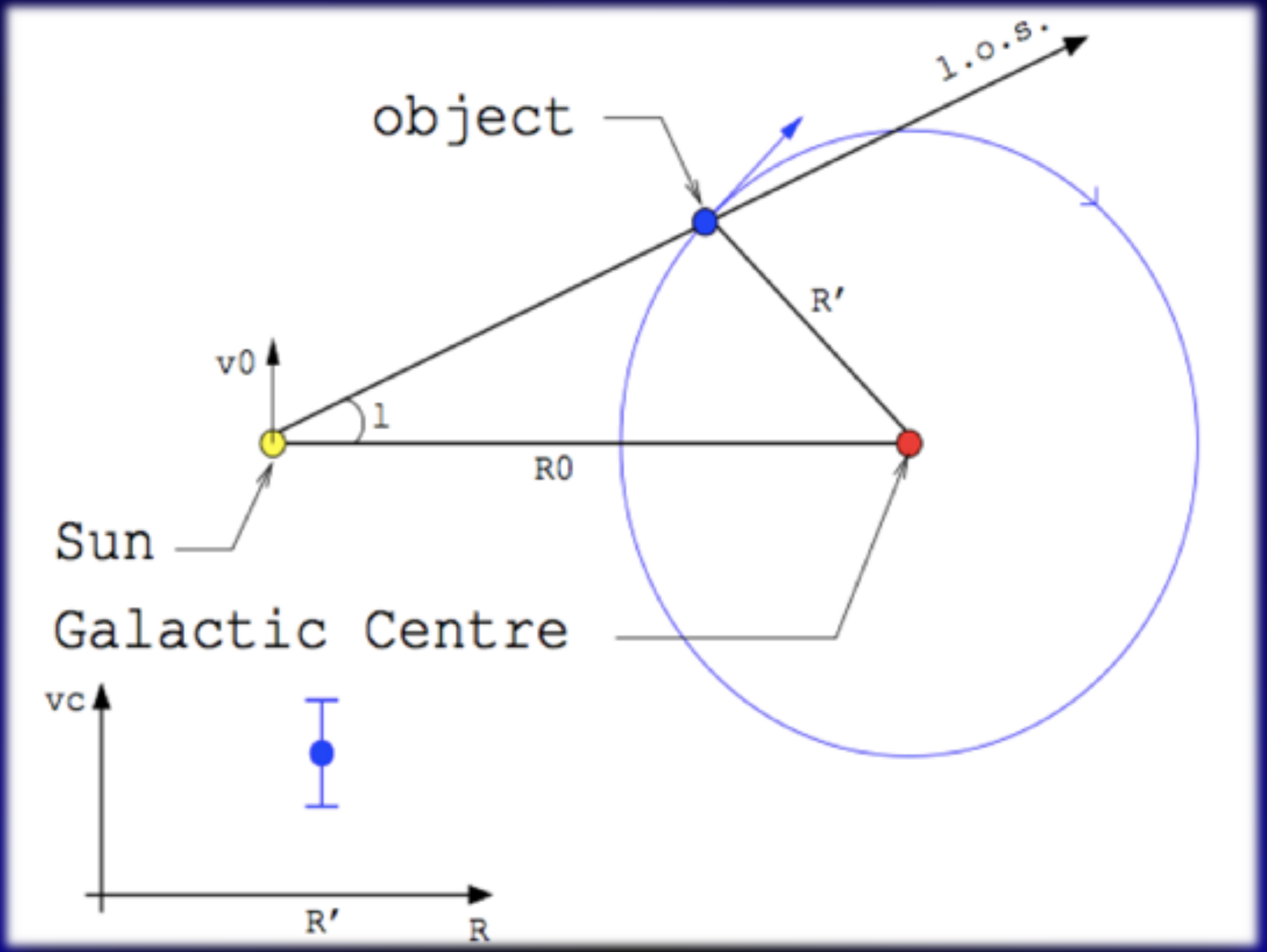
[Iocco, Pato, Bertone, Nature Physics 2015]

Extracting the DM density structure



[Pato, Iocco, Bertone, 2015]

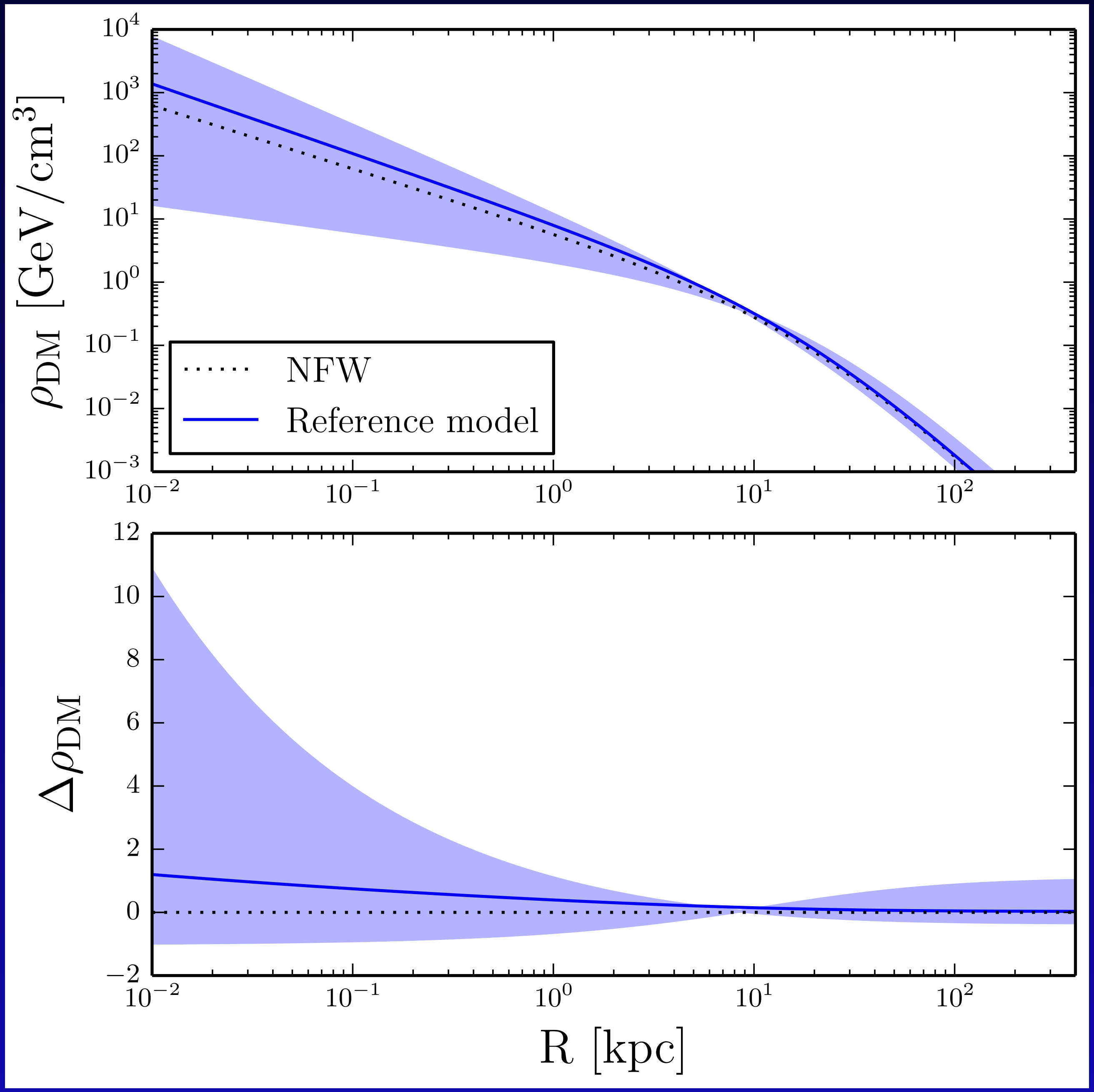
One more source of uncertainty:
"Galactic Parameters"

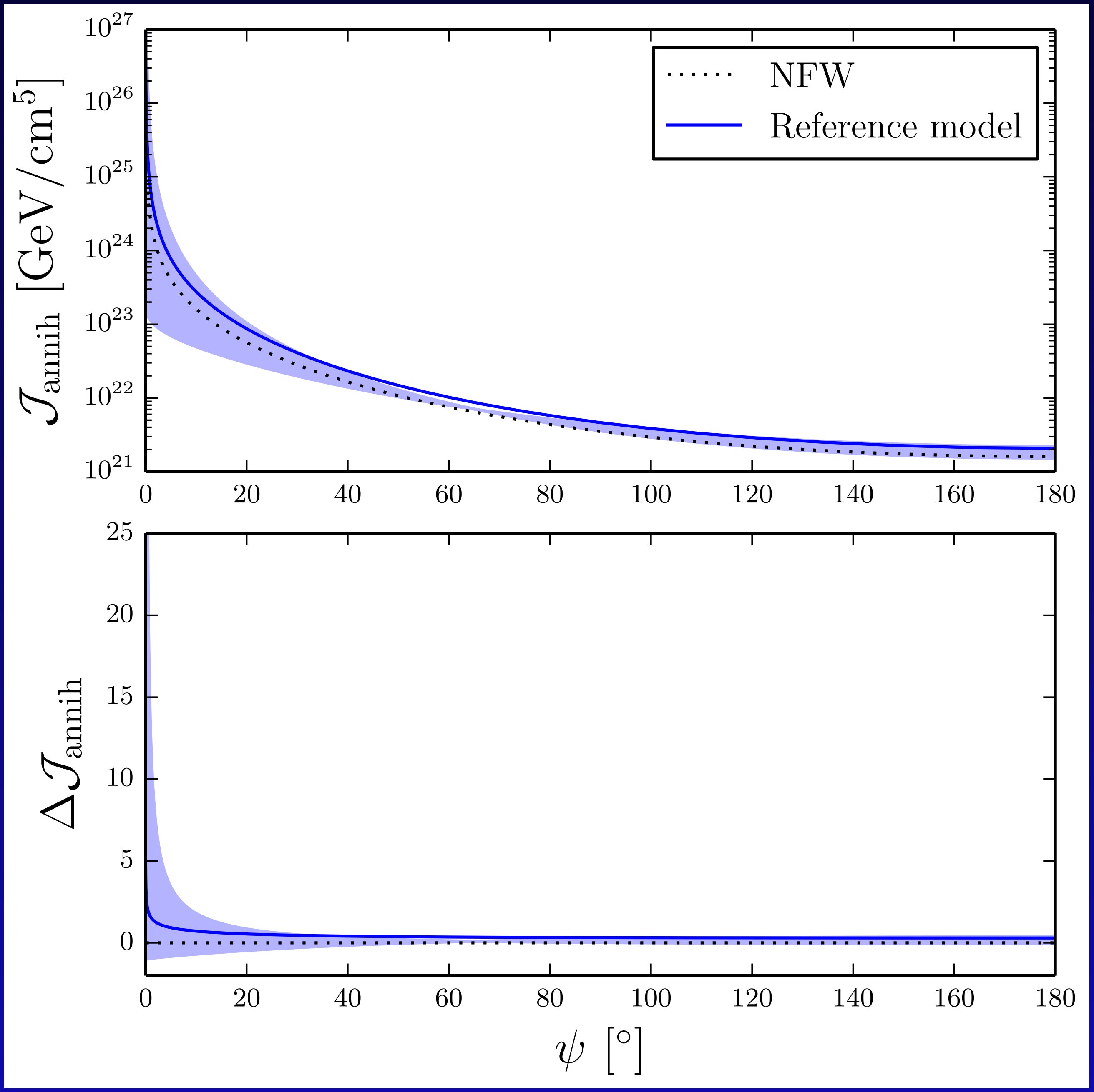


One oft-neglected uncertainty

("No my boy, you are not center of the Galaxy", [my mom, 1984])

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]

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

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

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

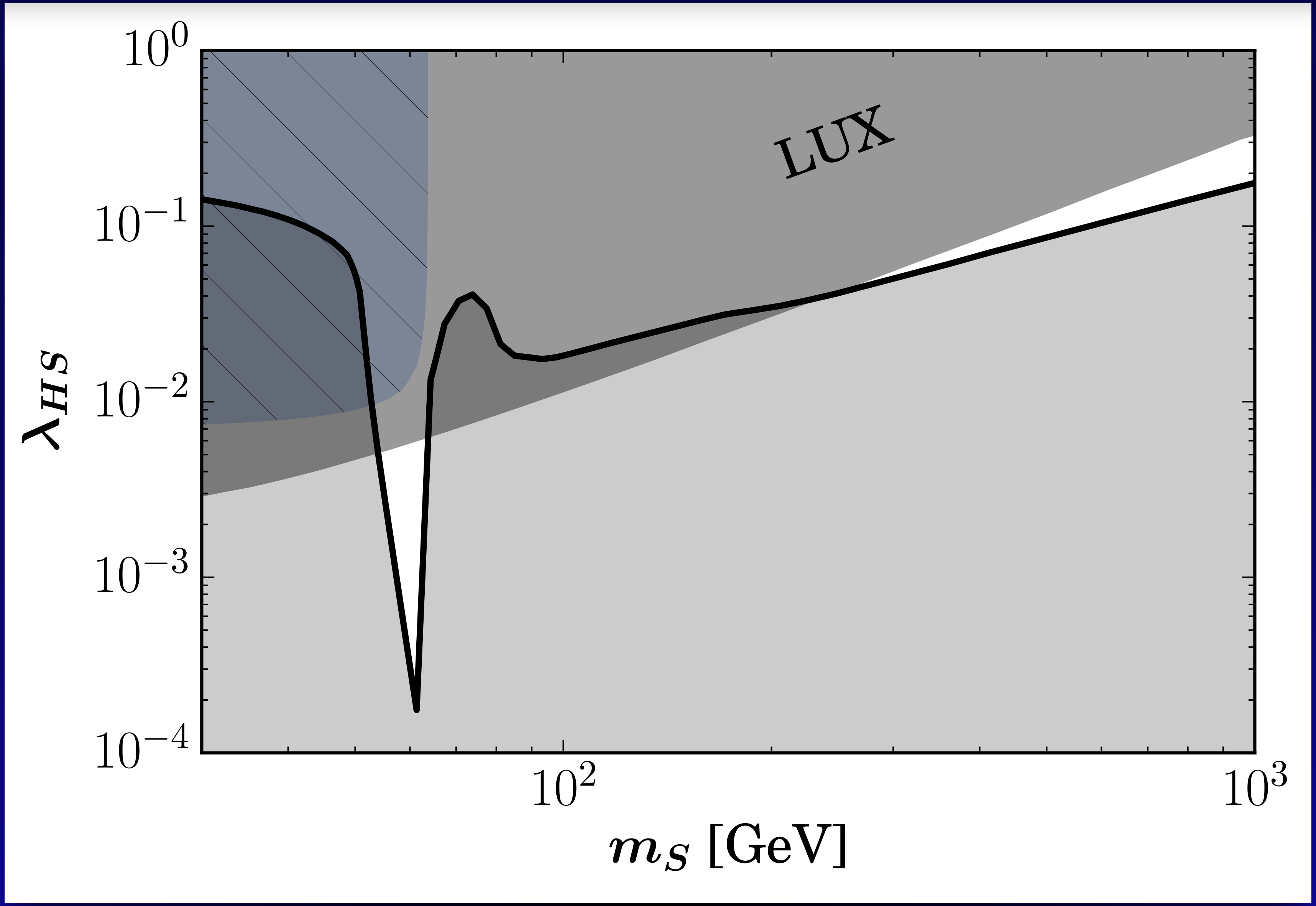
$$m_S^2 = 2\,\mu_S^2 + \lambda_{HS}\,v_H^2$$

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

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

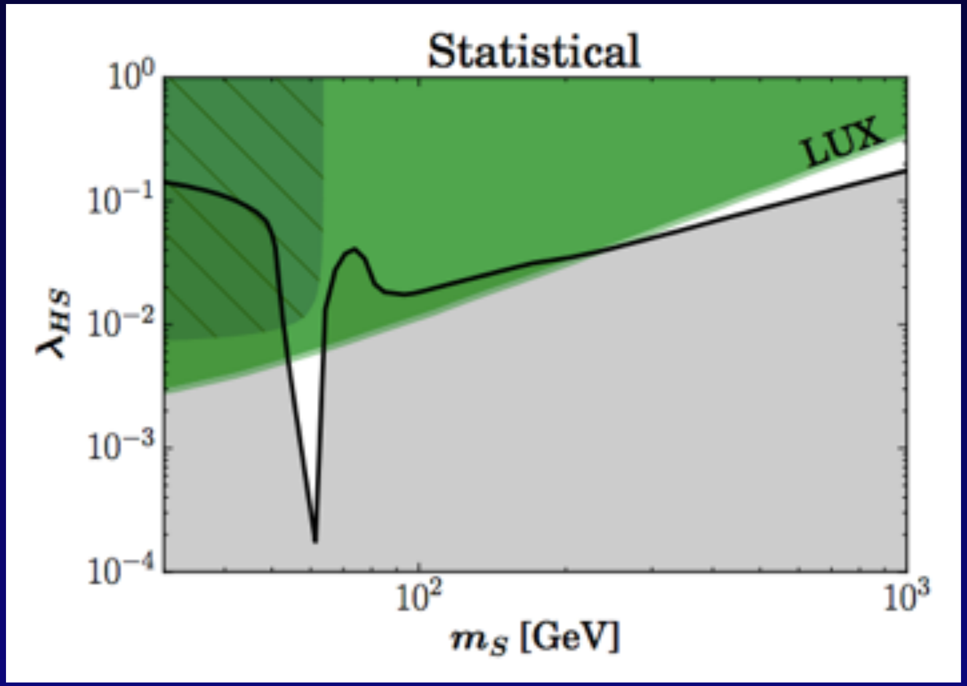
Constraints and interplay of experiments

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



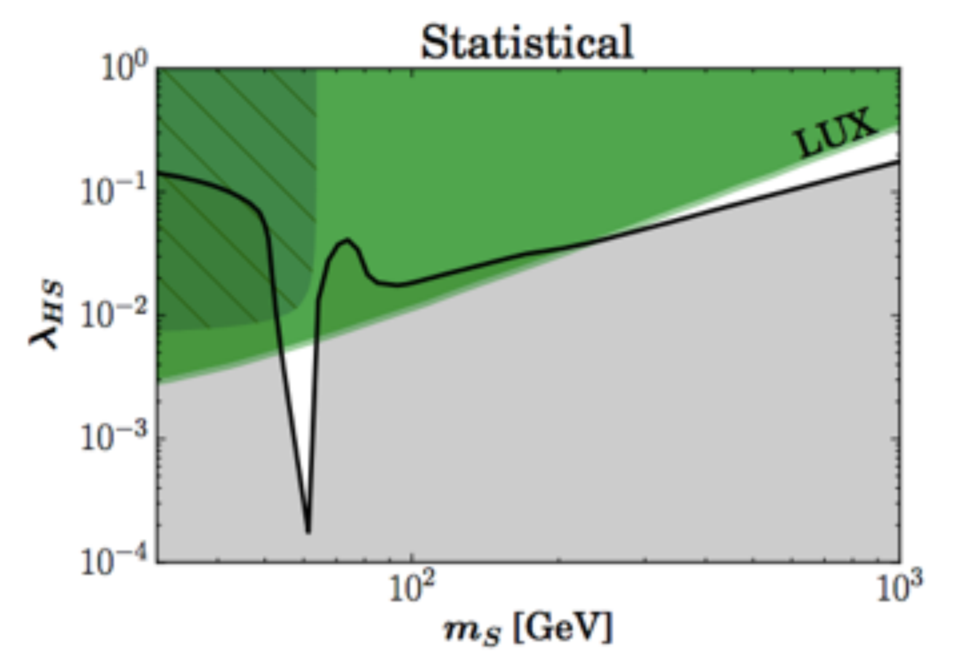
[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

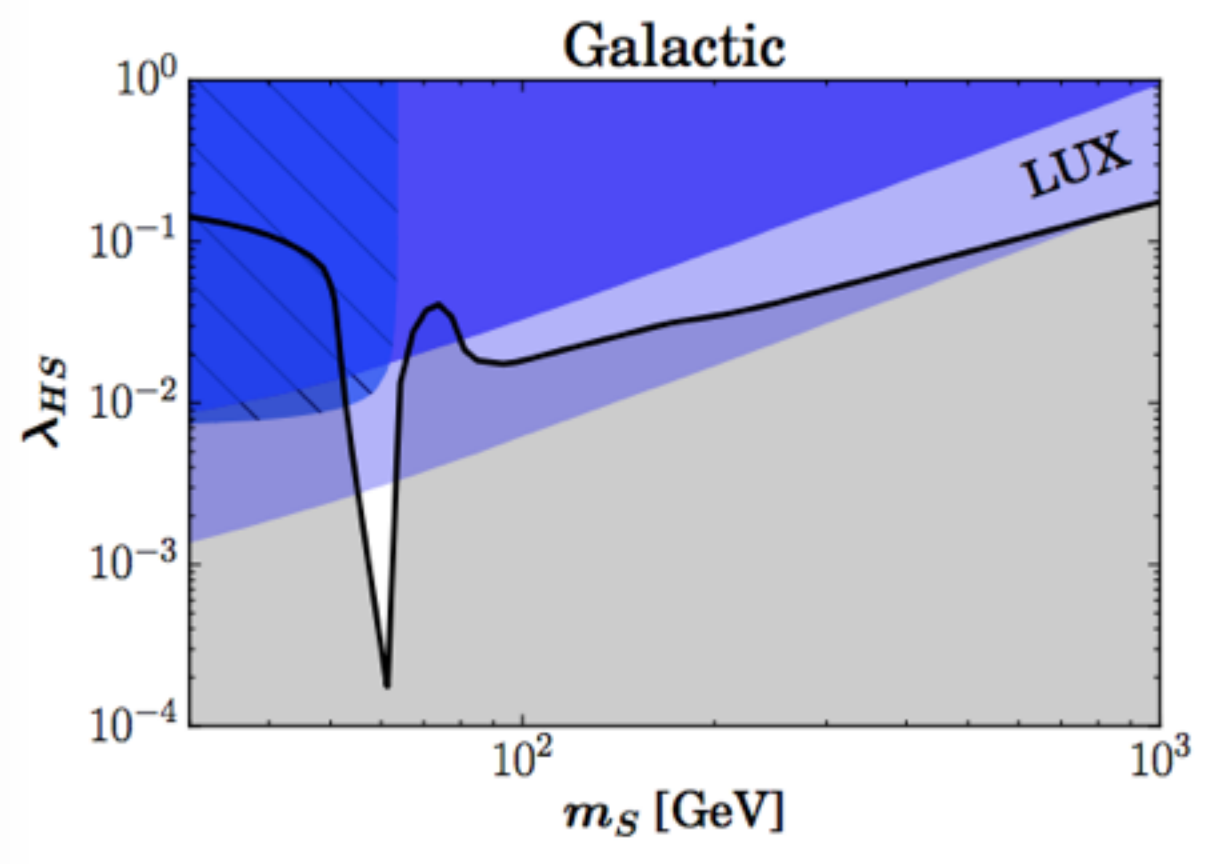
Let's look at the effect of astrophysics uncertainties: Direct Detection

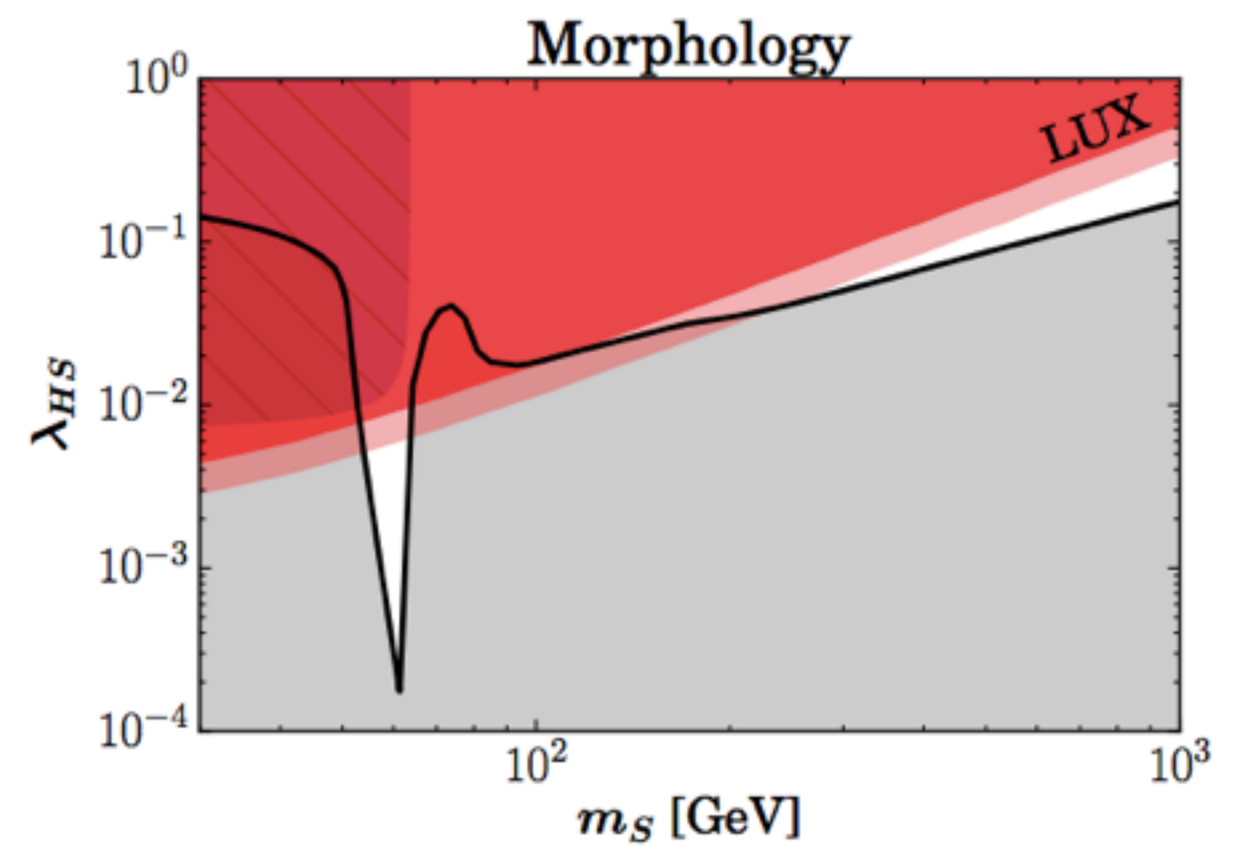


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017]

Effect of astrophysical uncertainty on interpretation of Direct Detection constraints

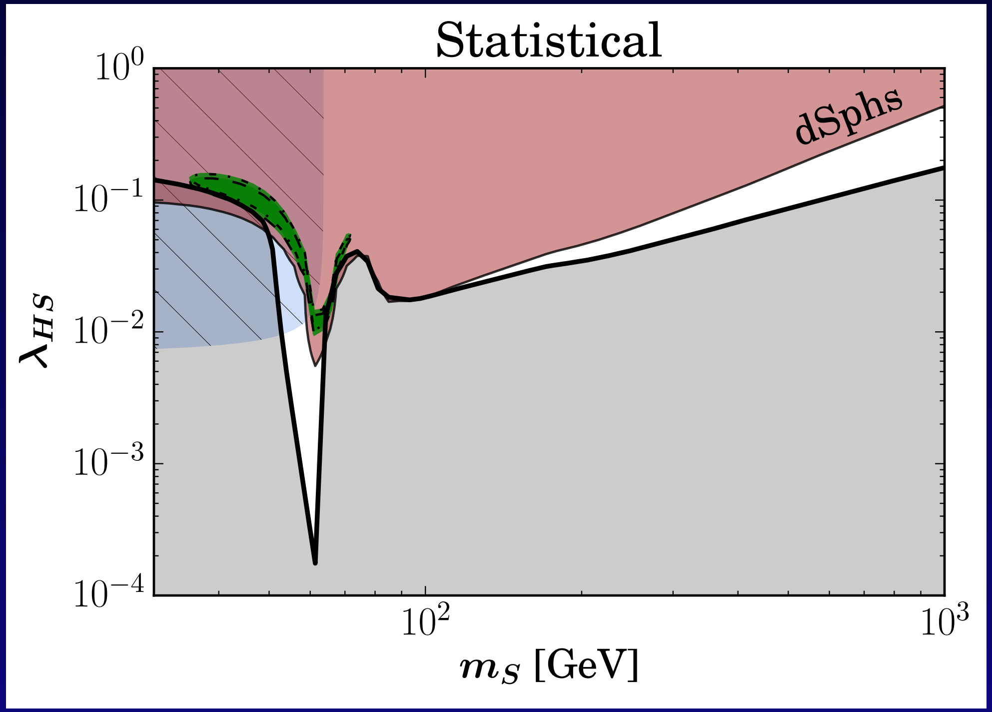


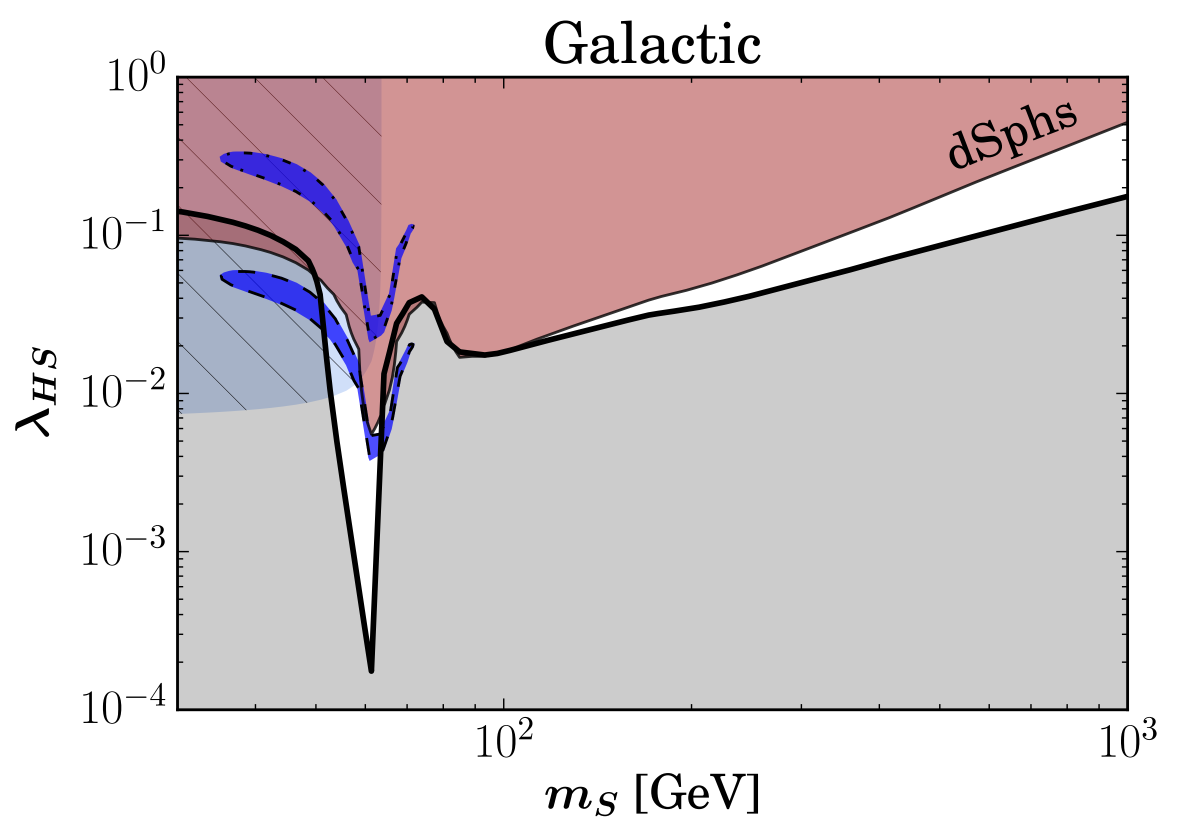


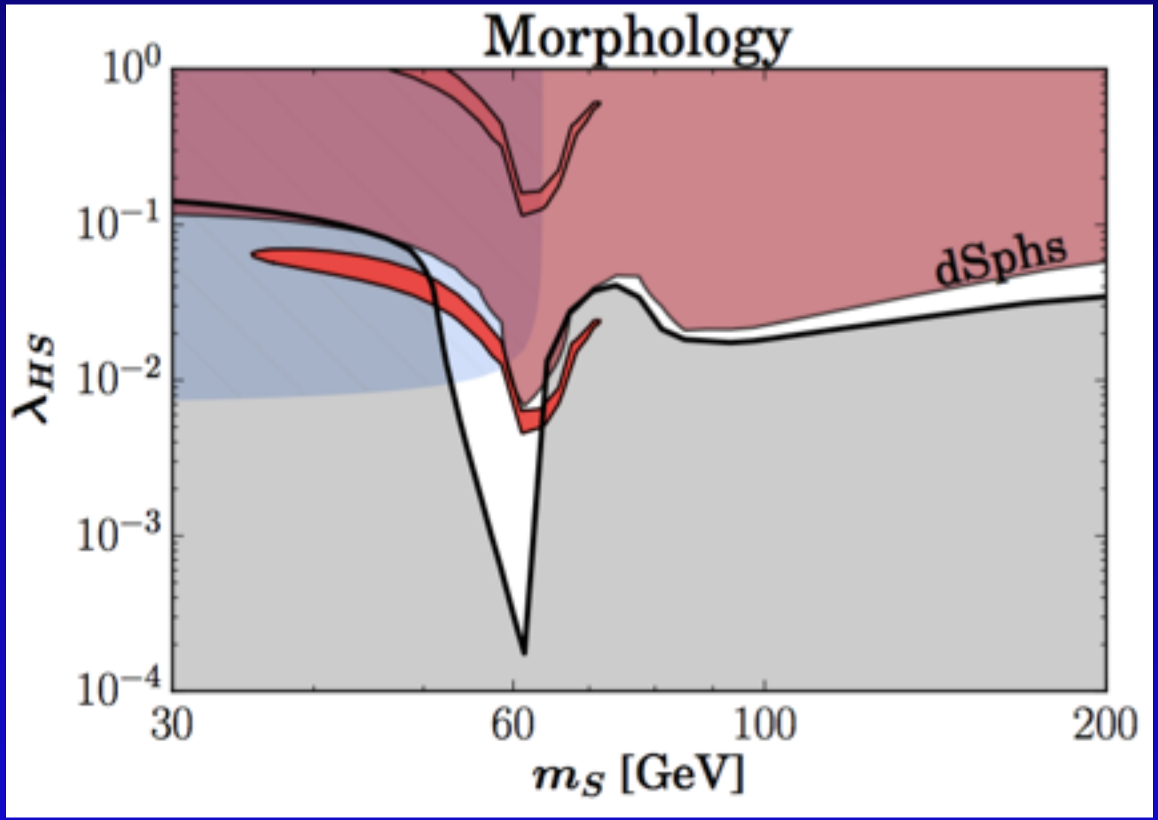


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017]

Effect of astrophysical uncertainty on interpretation of inDirect searches results





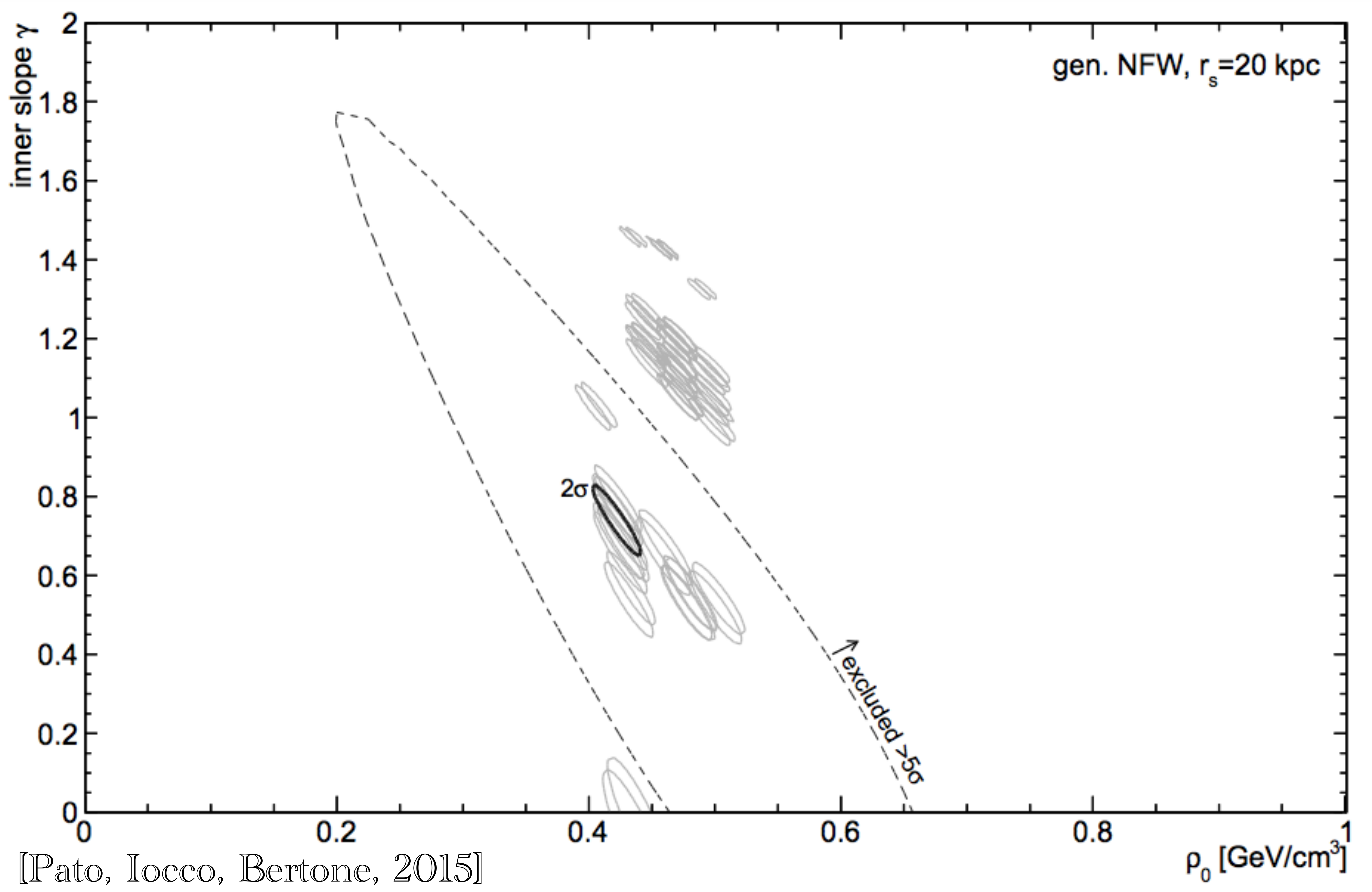


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017]

or even worse, see [Iocco & Benito 2017]

Is our measurement correct?

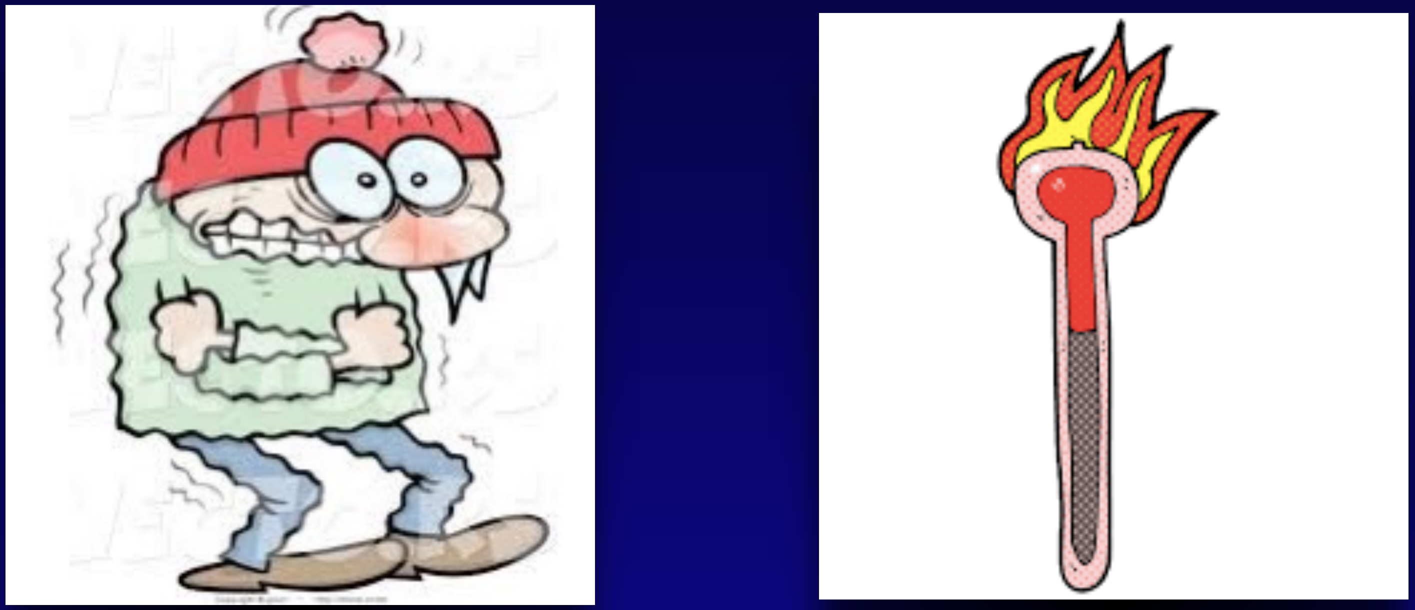
Our instrument is very precise. Is it accurate?



[Pato, Iocco, Bertone, 2015]

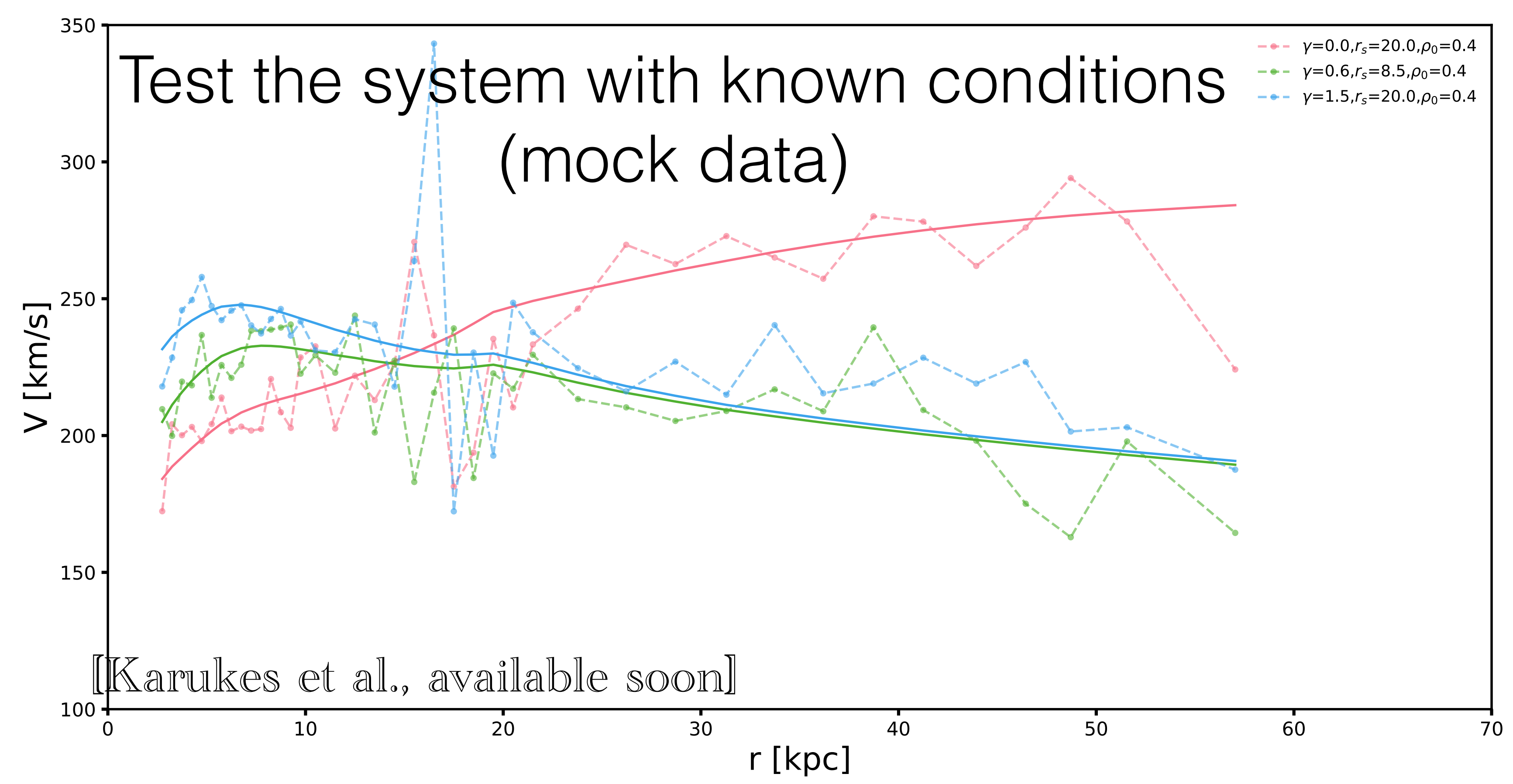
Is our measurement correct?

Our instrument is very precise. Is it accurate?



Is our measurement correct?

Our instrument is very precise. Is it accurate?

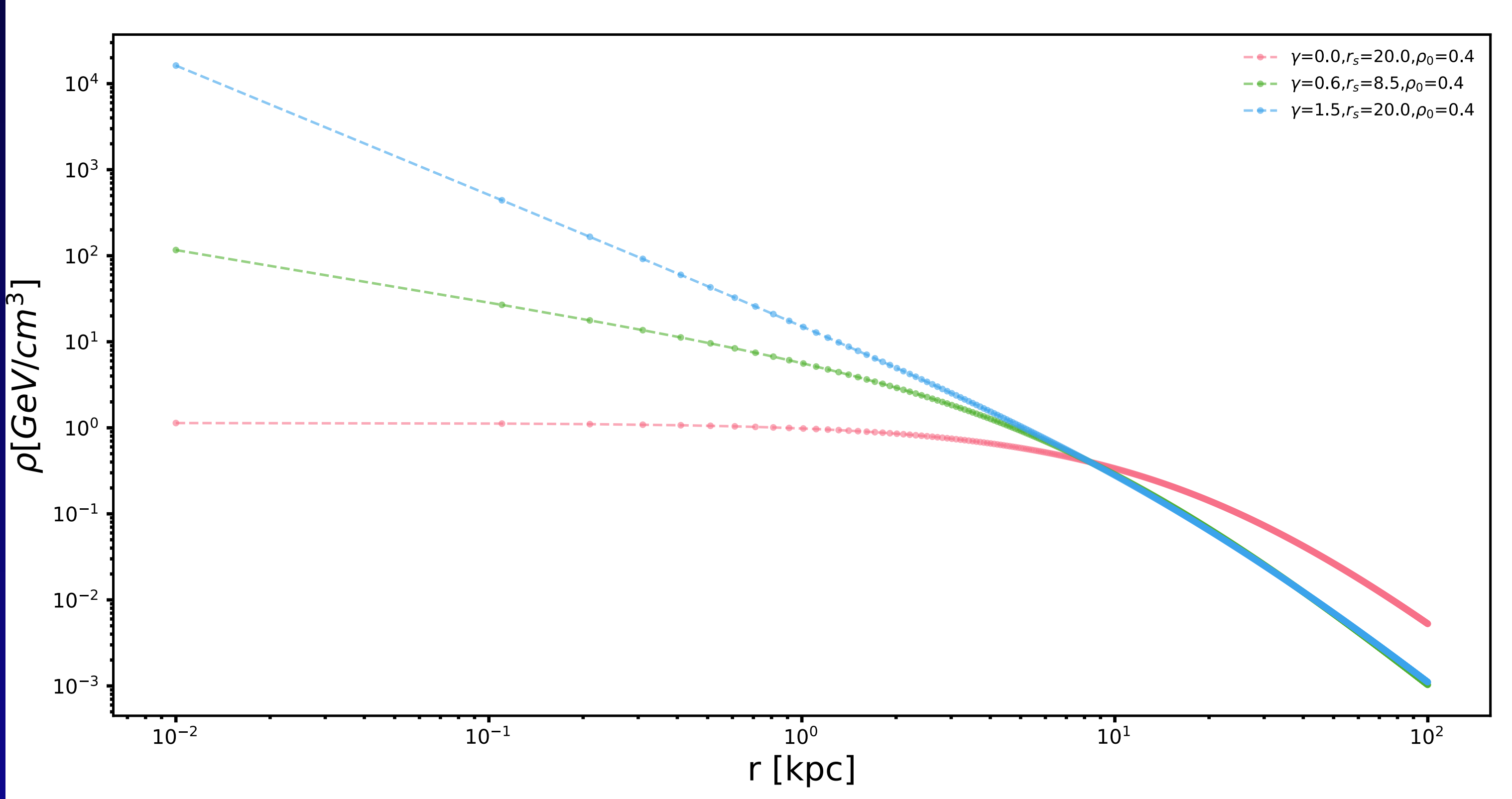


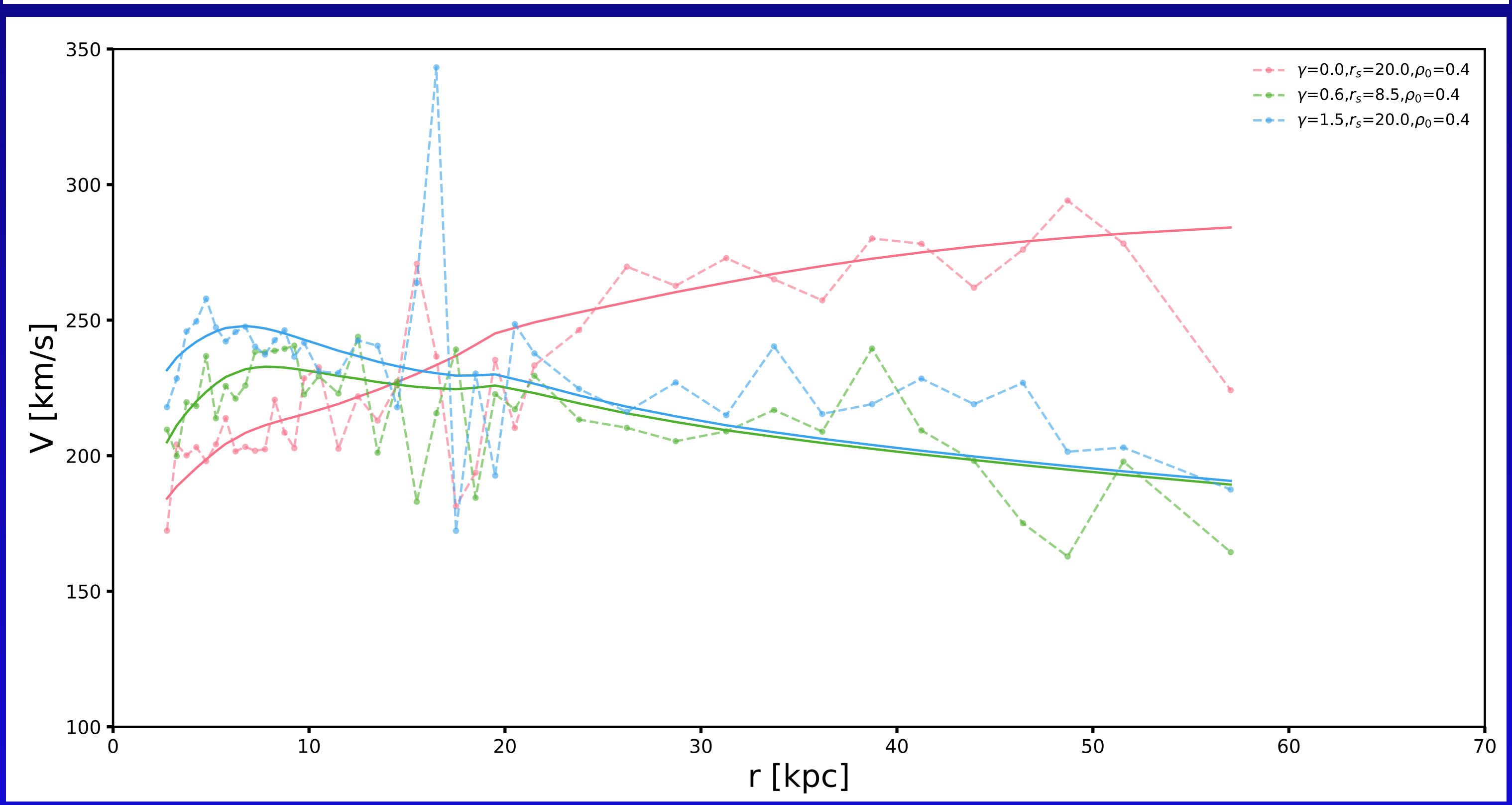
Test the system with known conditions (mock data)

[Karukes et al., available soon]

Is our measurement correct?

Our instrument is very precise. Is it accurate?

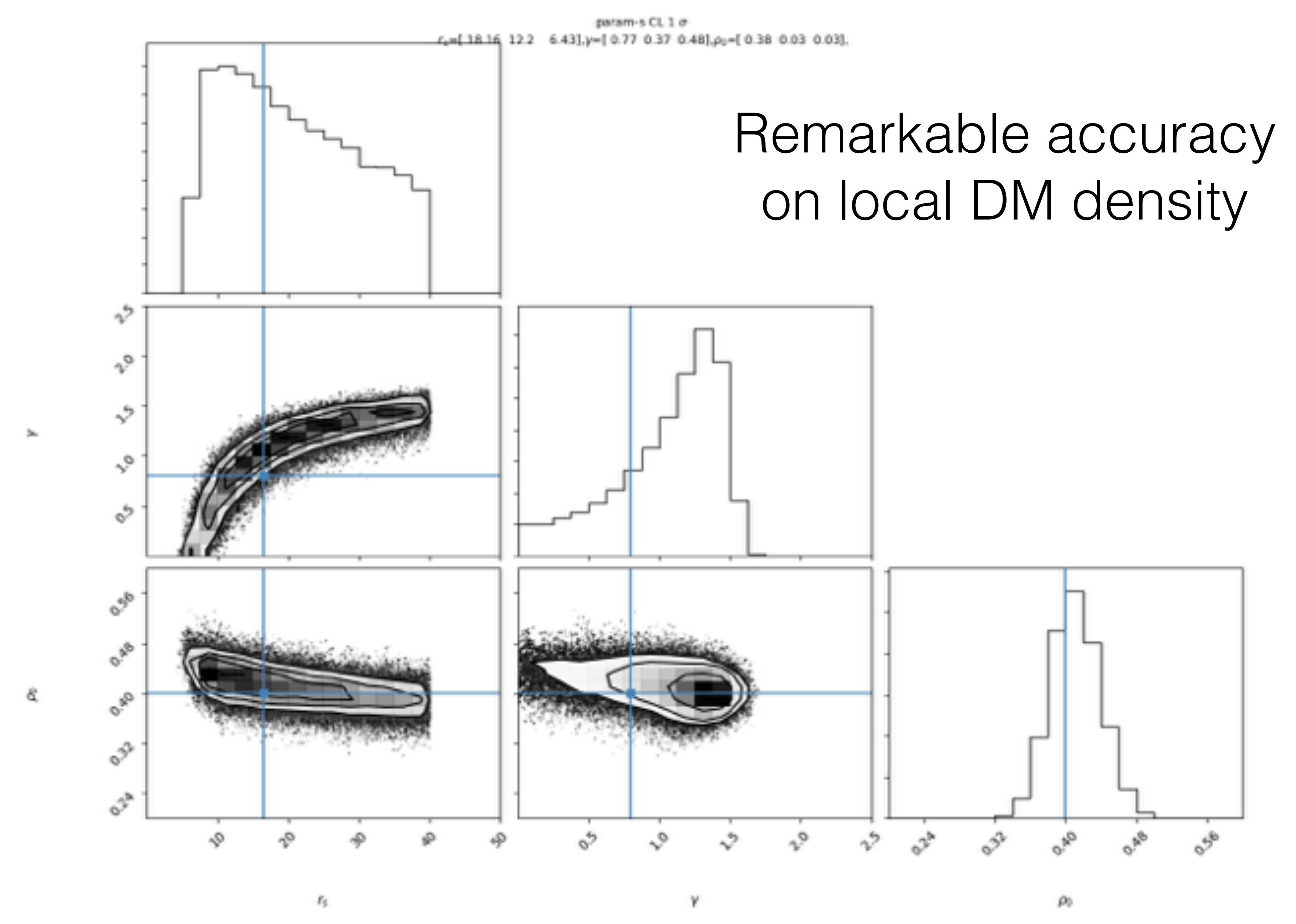




[E. Karukes, M. Benito,
A. Geringer-Sameth,
FI, R. Trotta]
available soon

Is our measurement correct?

Our instrument is very precise. Is it accurate?



Remarkable accuracy on local DM density

[E. Karukes, M. Benito, A. Geringer-Sameth, FI, R. Trotta]

available soon

Advertisement:
South American DM workshop

November 21-23, 2018
São Paulo, Brazil

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

Registration open
(until Sept. 22)

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

II SOUTH AMERICAN DARK MATTER WORKSHOP

November 21-23, 2018
at Instituto de Física Teórica - UNESP, São Paulo, Brazil

SPEAKERS:

Ilias Cholis (Northwestern University, USA)
Francesco D'Eramo (Università di Padova, Italy)
Arman Esmaili (PUC Rio de Janeiro, Brazil)
Azadeh Fattahi (Durham University, UK)
Christopher McCabe (King's College London, UK)
Farinaldo Queiroz (IIP Natal, Brazil)
Cecilia Scannapieco (Universidad de Buenos Aires, Argentina)

The goal of this international workshop is to explore the state of the art of the Dark Matter field, discussing the latest developments in all branches: theoretical, collider, direct and indirect, and astro. By bringing together the South American and international community we aim to foster new collaborations and new long-lasting partnerships, at a most timely moment in the development of the field.

Registration deadline:
September 22, 2018
Online registration form and information:
http://www.ictp-saifr.org/DMw2018

The workshop has no registration fee.

Advertisement:

School on High Energy Astrophysics

August 5-17, 2019

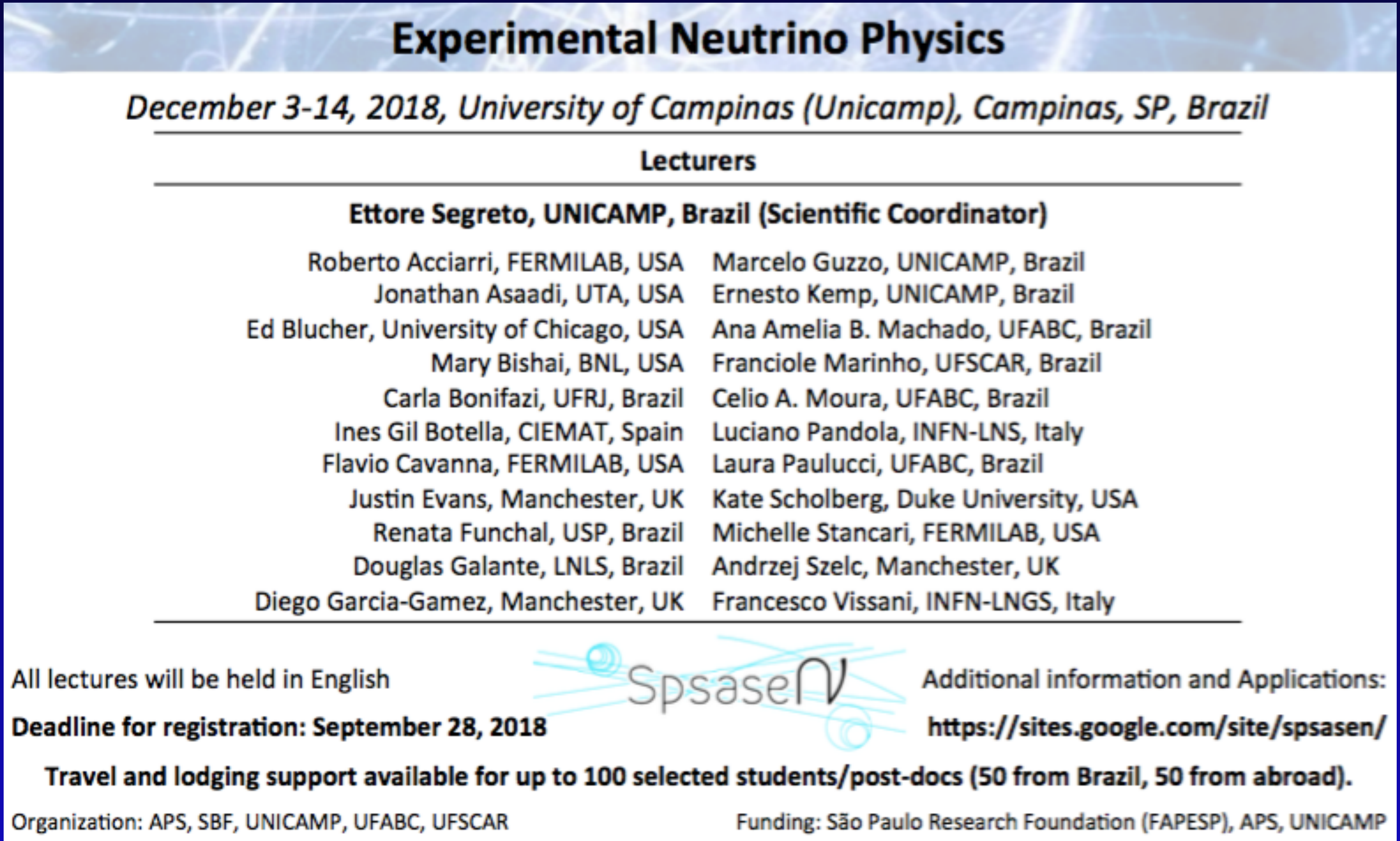
São Paulo, Brazil

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

Organizers:

P. Blasi, V. de Souza, F. Iocco, J. Knapp

Advertisement:
School on



Experimental Neutrino Physics

December 3-14, 2018, University of Campinas (Unicamp), Campinas, SP, Brazil

Lecturers

Ettore Segreto, UNICAMP, Brazil (Scientific Coordinator)

Roberto Acciarri, FERMILAB, USA
Jonathan Asaadi, UTA, USA
Ed Blucher, University of Chicago, USA
Mary Bishai, BNL, USA
Carla Bonifazi, UFRJ, Brazil
Ines Gil Botella, CIEMAT, Spain
Flavio Cavanna, FERMILAB, USA
Justin Evans, Manchester, UK
Renata Funchal, USP, Brazil
Douglas Galante, LNLS, Brazil
Diego Garcia-Gamez, Manchester, UK

Marcelo Guzzo, UNICAMP, Brazil
Ernesto Kemp, UNICAMP, Brazil
Ana Amelia B. Machado, UFABC, Brazil
Franciole Marinho, UFSCAR, Brazil
Celio A. Moura, UFABC, Brazil
Luciano Pandola, INFN-LNS, Italy
Laura Paulucci, UFABC, Brazil
Kate Scholberg, Duke University, USA
Michelle Stancari, FERMILAB, USA
Andrzej Szelc, Manchester, UK
Francesco Vissani, INFN-LNGS, Italy

All lectures will be held in English

Deadline for registration: September 28, 2018

Additional information and Applications:

https://sites.google.com/site/spsasen/

Travel and lodging support available for up to 100 selected students/post-docs (50 from Brazil, 50 from abroad).

Organization: APS, SBF, UNICAMP, UFABC, UFSCAR

Funding: São Paulo Research Foundation (FAPESP), APS, UNICAMP

<u>December 3-14</u>, 2018 Campinas, Brazil

Cuncta stricte

- Precision (/ accuracy) era for determination of Milky Way DM profile. So good that..

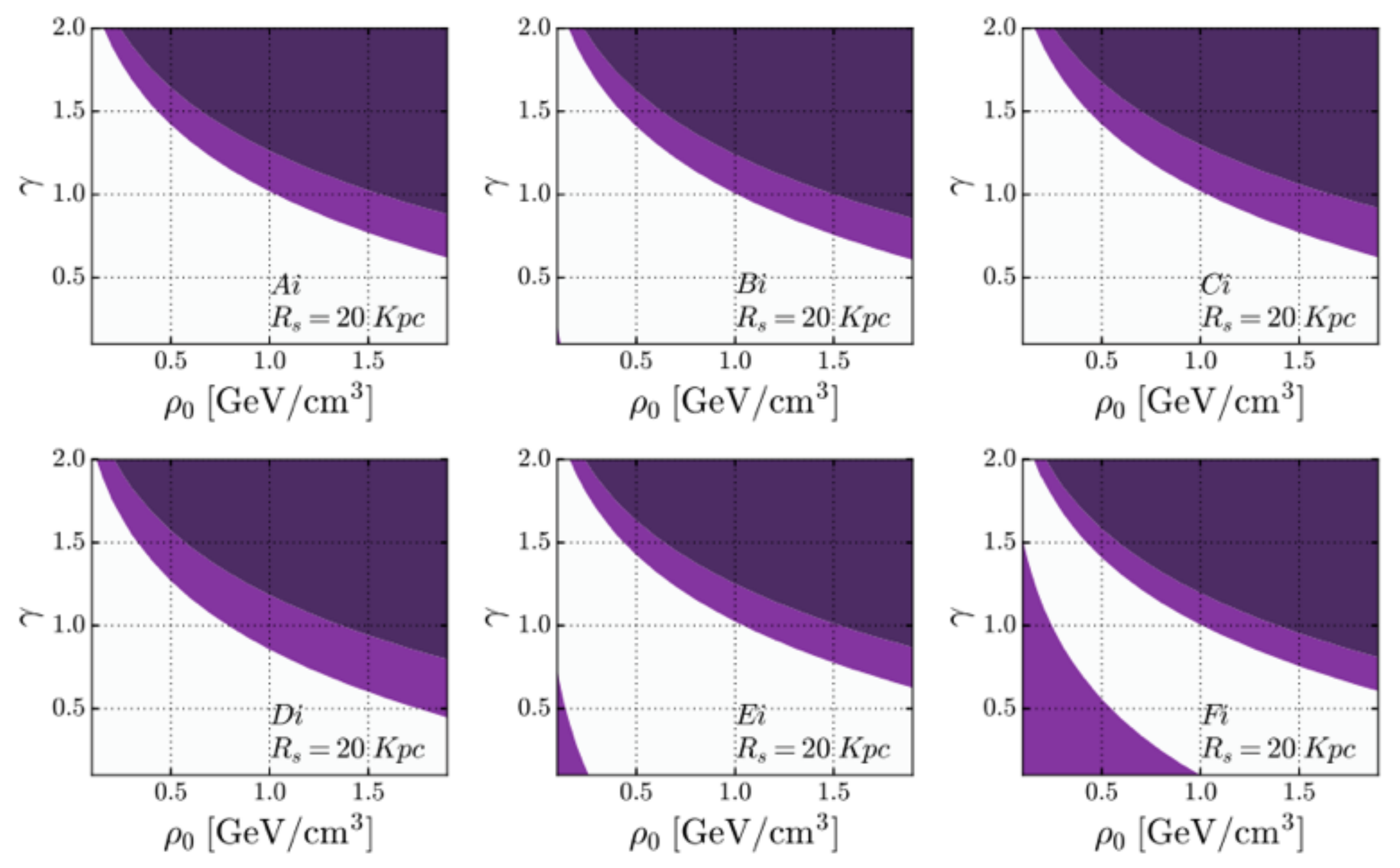
- Astrophysical uncertainties are actually affecting determination of PP determination.

- Interplay with collider physics, direct and indirect probes (if you care about that), calling for much tighter collaboration between different types of experiments, theory, and astrophysics.

- New data, reduction of uncertainties, extension of the method to other sources (inclusion of full astro-likelihood in PP analysis).

About the Galactic Center:

assumptions for Rotation Curve method fail



[Iocco & Benito, 2017]

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

The luminous component

and its gravitational potential

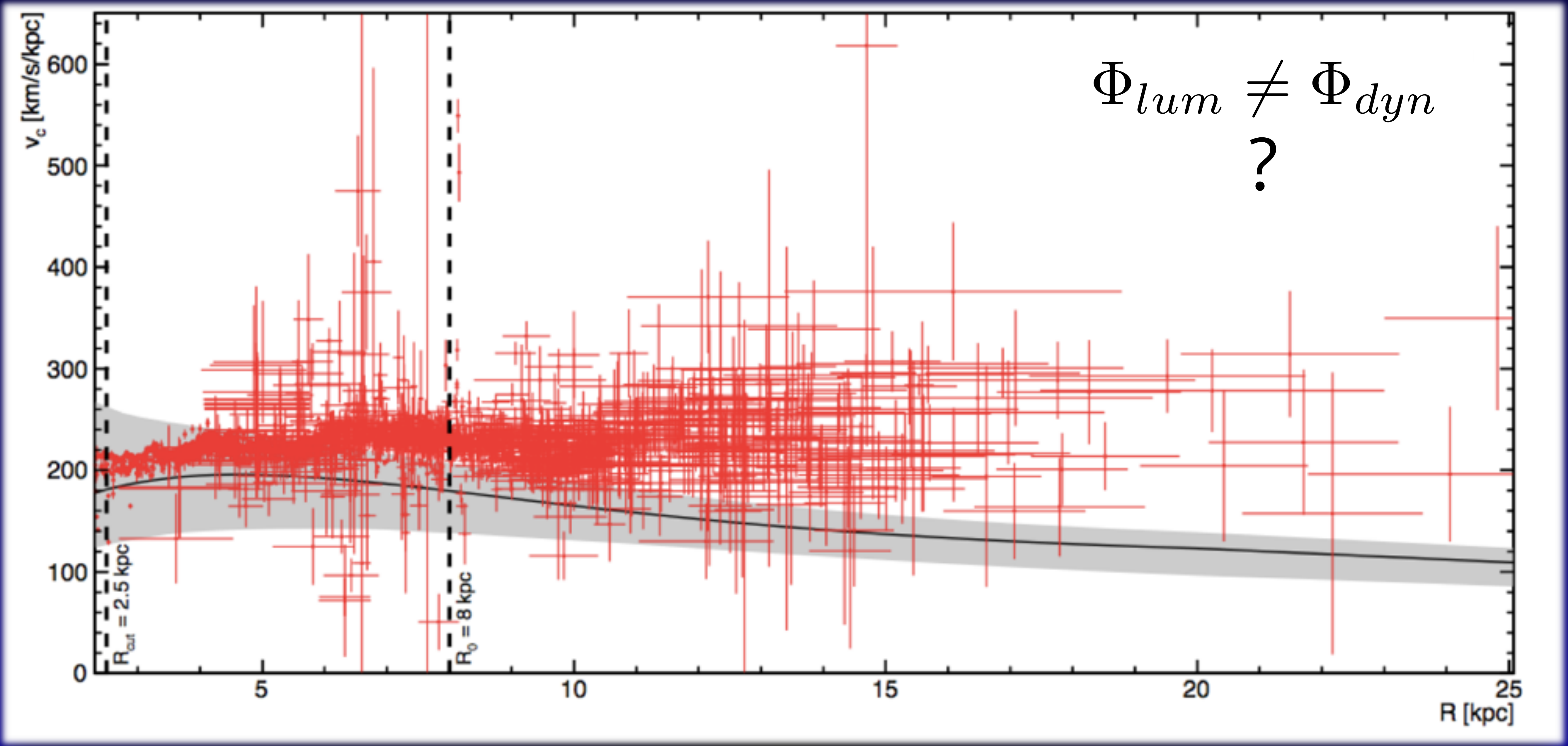
$$\phi_{lum} = \phi_{bulge} + \phi_{disc} + \phi_{gas}$$

$$\rho^i_{lum}(x, y, z) \rightarrow \Phi^i(R, \theta, \phi) \rightarrow v_{lum}(R)$$

Straightforward…

provided one knows the distribution of these components

The dark matter (if any) is in the mismatch



$\Phi_{lum} \neq \Phi_{dyn}$

?

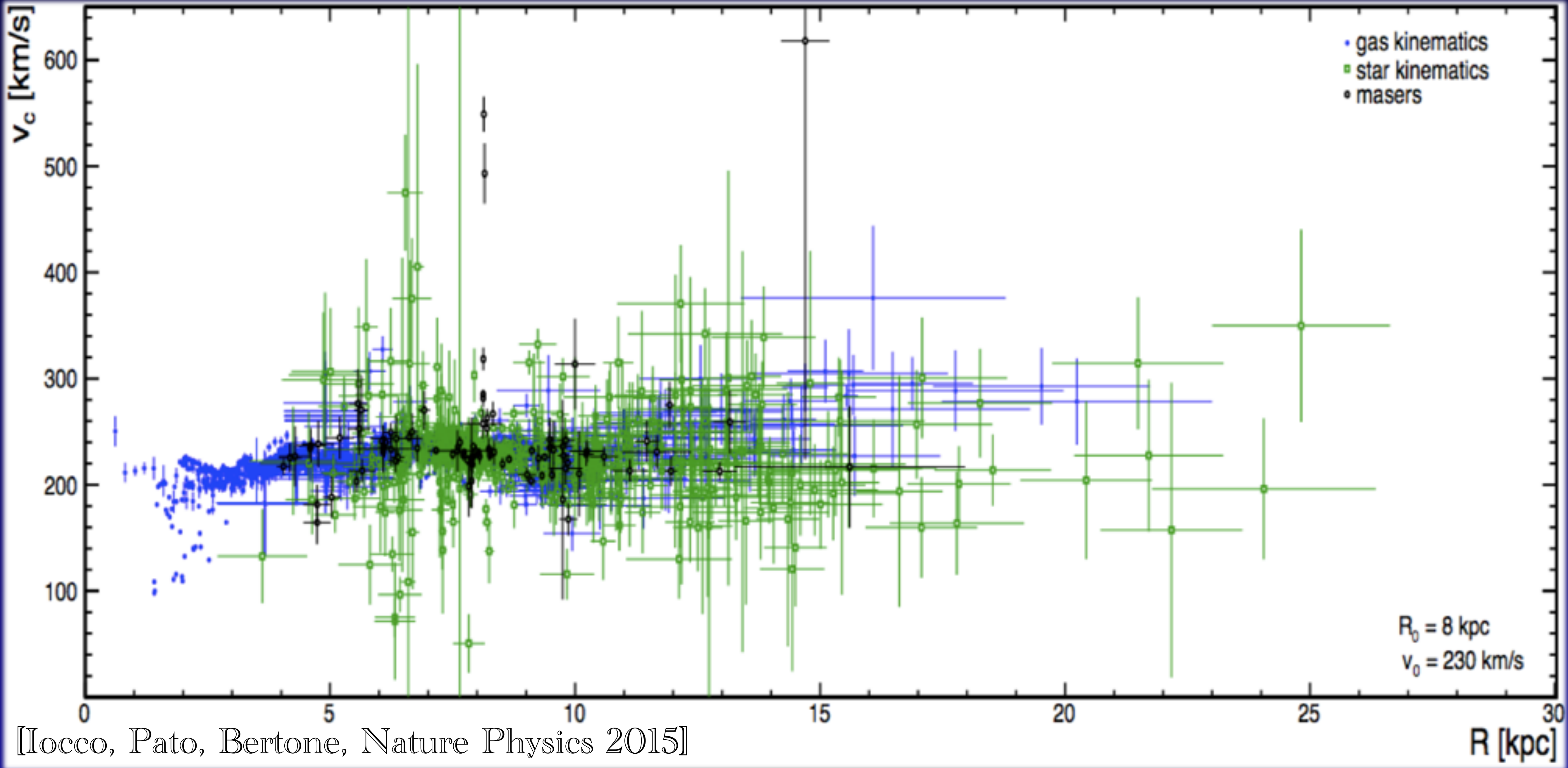
[Iocco, Pato, Bertone, Nature Physics 2015]

Contributing to the subject:

- New compilation of data, Rotation Curve
- Morphologies for visible component
- Estimate of uncertainties in method
- Application to specific theoretical model
- Test of alternative theories of gravity

The Milky Way Rotation Curve

as observed

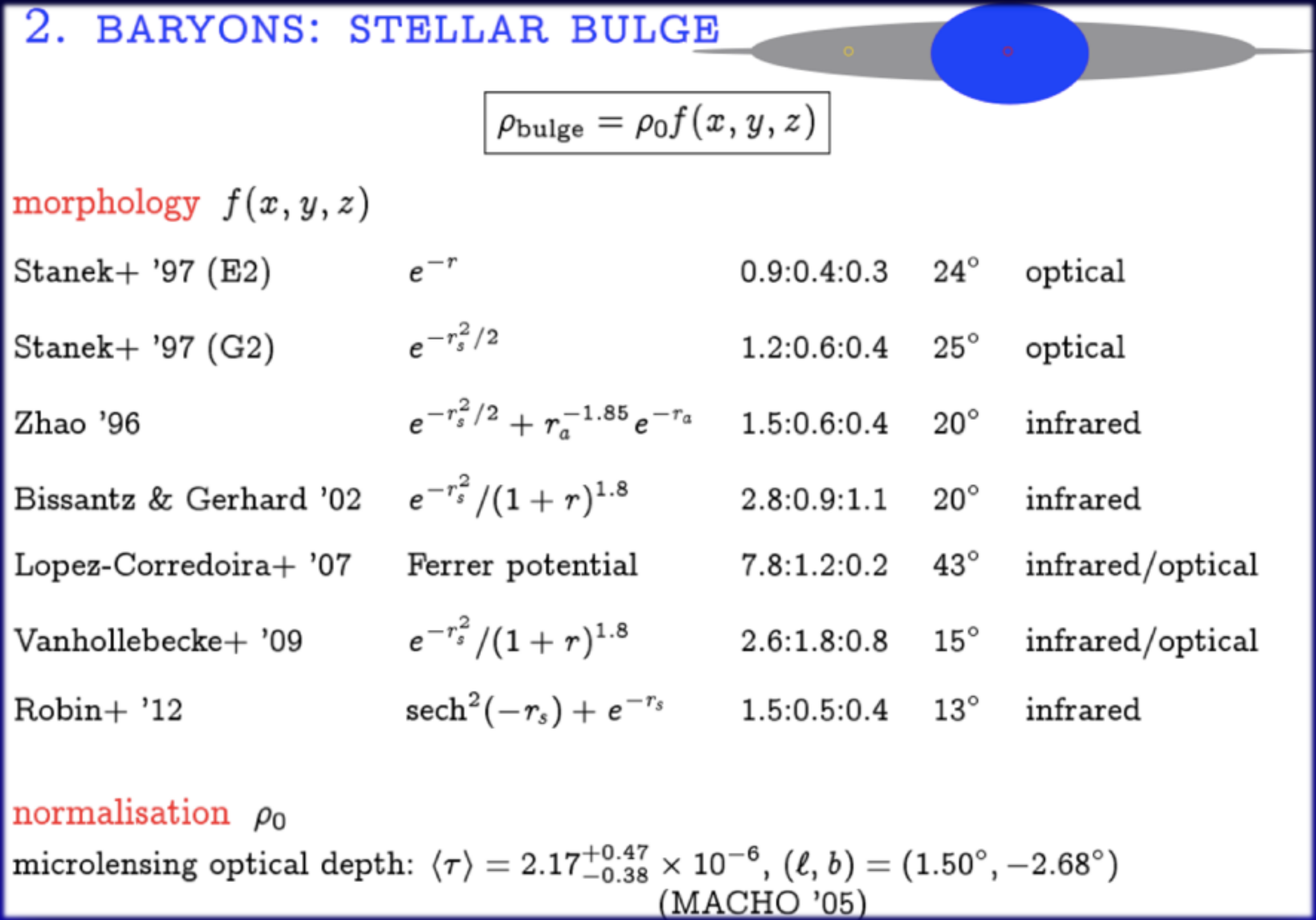


[Iocco, Pato, Bertone, Nature Physics 2015]

A new compilation of old and new data, publicly available

[Pato & Iocco, Software X (2017)]

The luminous Milky Way: observations of morphology



2. BARYONS: STELLAR BULGE

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

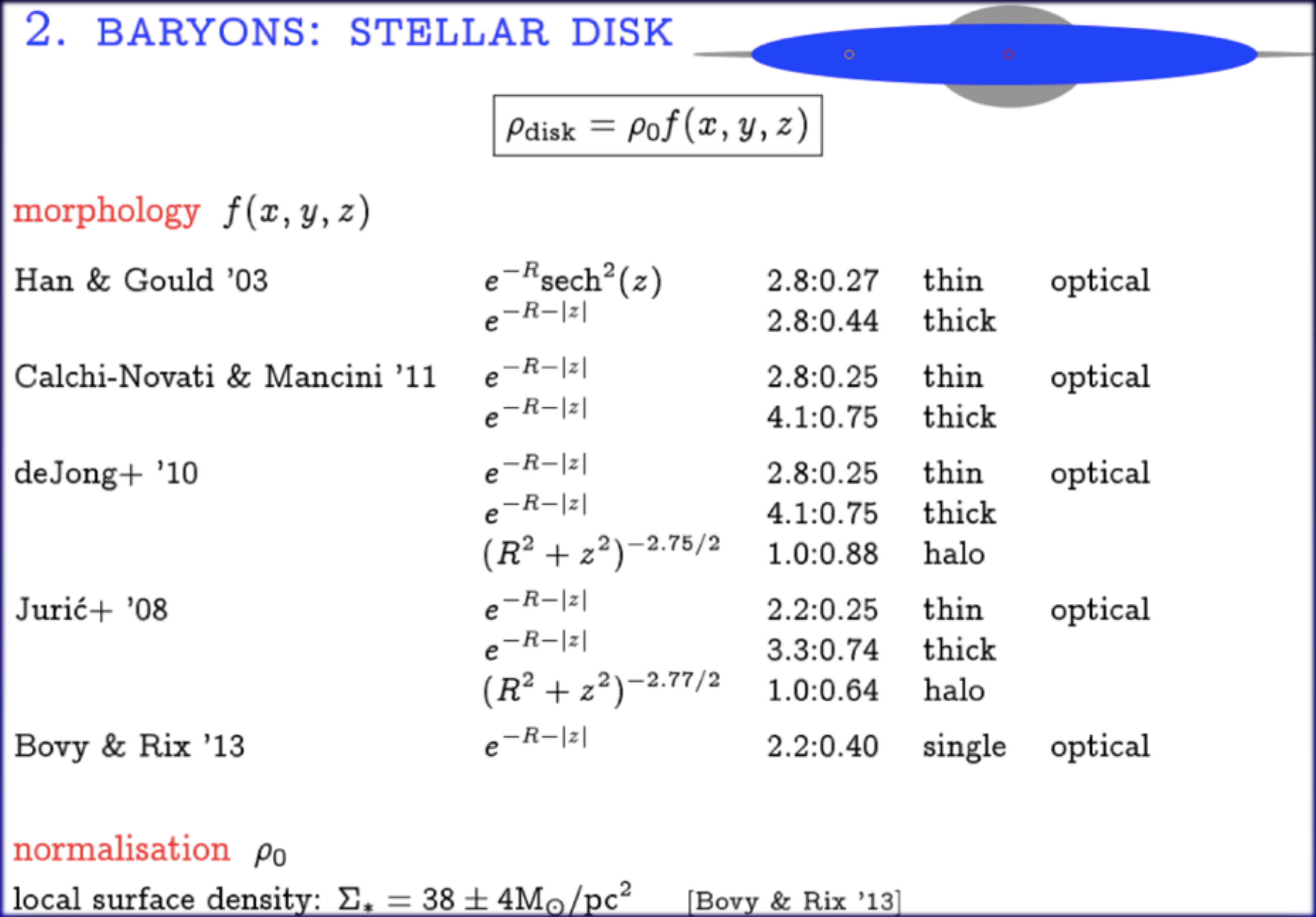
morphology $f(x, y, z)$

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

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

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

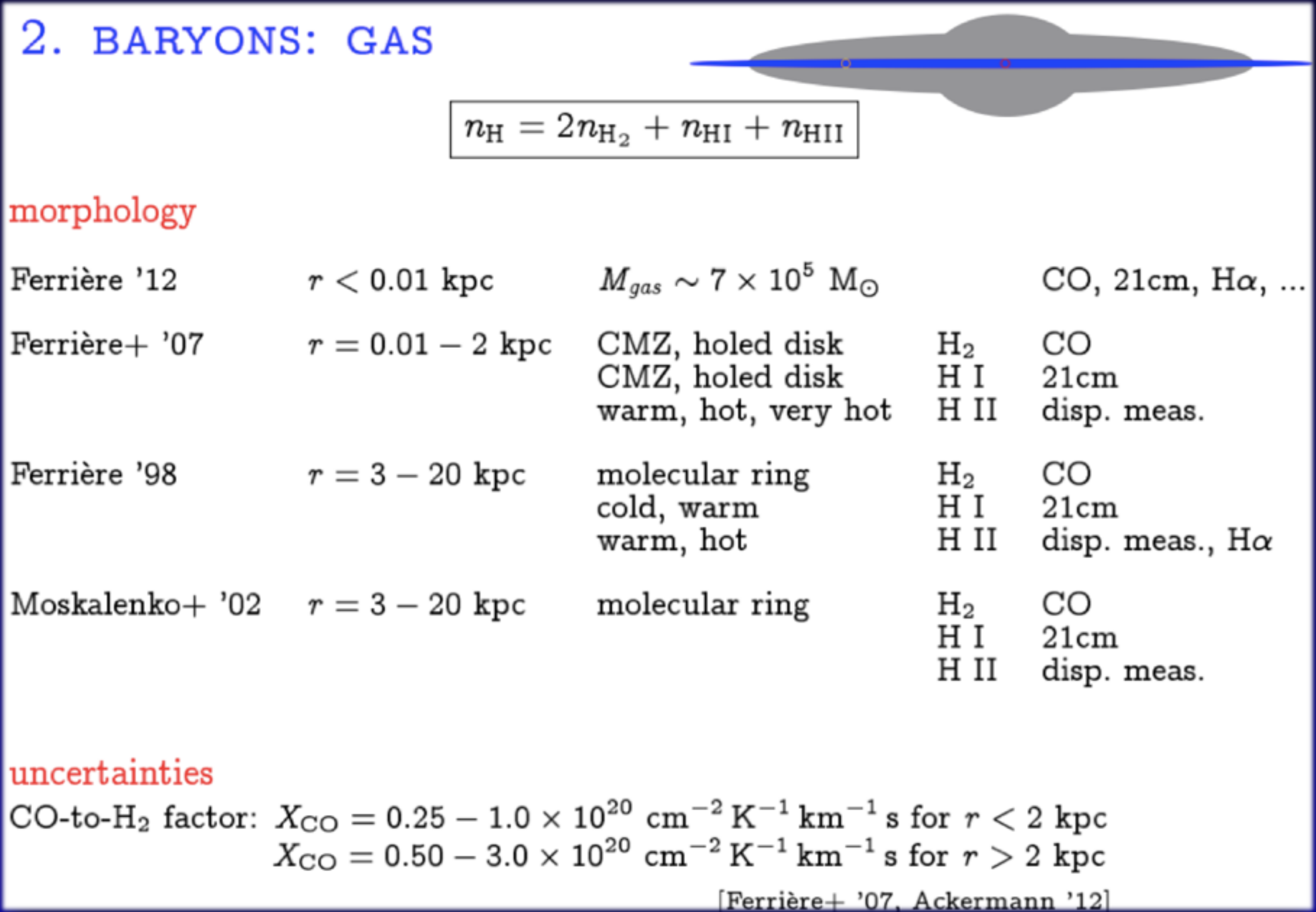
morphology $f(x,y,z)$

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

normalisation ρ_0

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

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

morphology

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

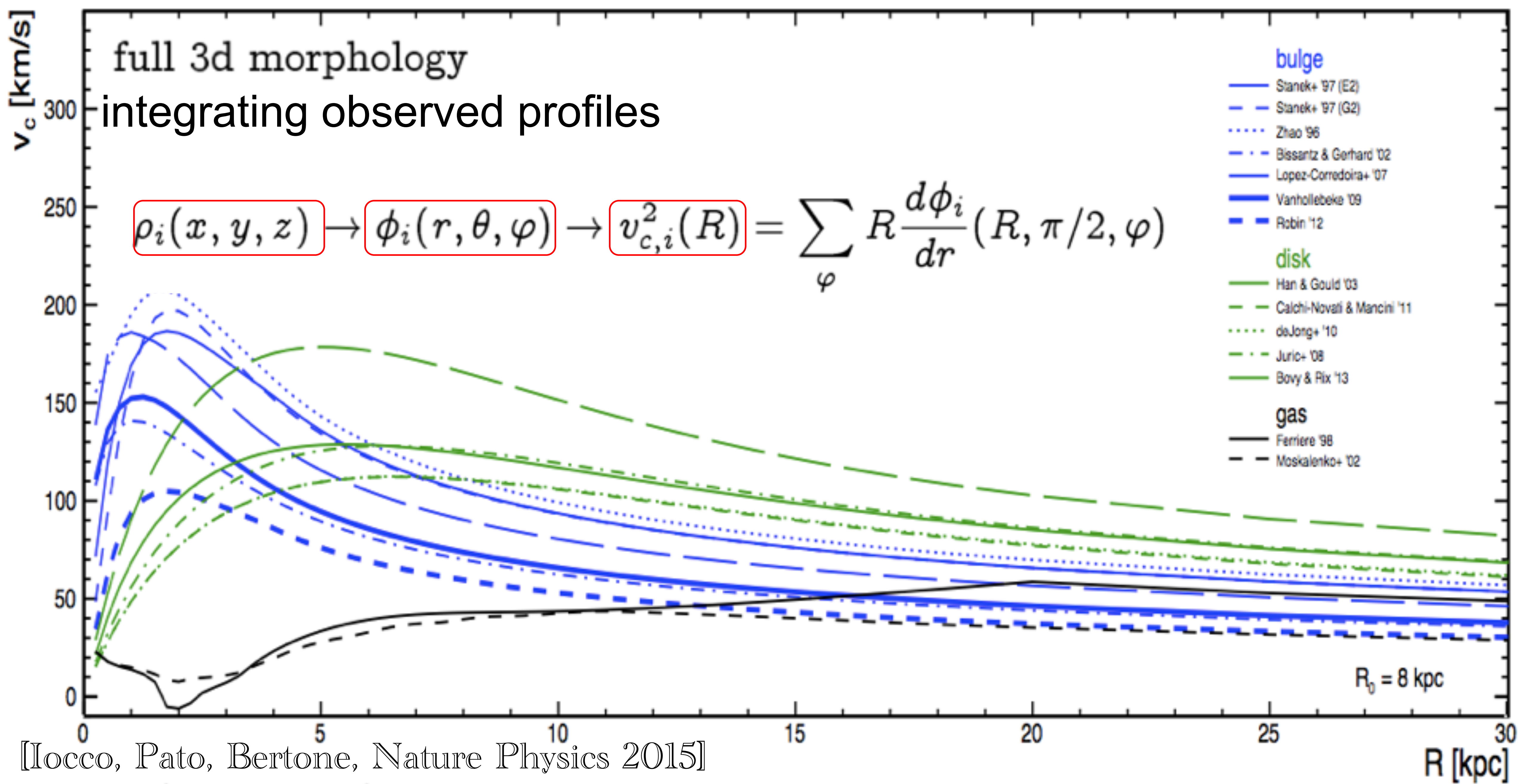
CO-to-H_2 factor: $X_{\rm CO} = 0.25 - 1.0 \times 10^{20}\ {\rm cm^{-2}\,K^{-1}\,km^{-1}\,s}$ for $r < 2$ kpc
$X_{\rm CO} = 0.50 - 3.0 \times 10^{20}\ {\rm cm^{-2}\,K^{-1}\,km^{-1}\,s}$ for $r > 2$ kpc

[Ferrière+ '07, Ackermann '12]

The luminous Milky Way:

expected rotation curve

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



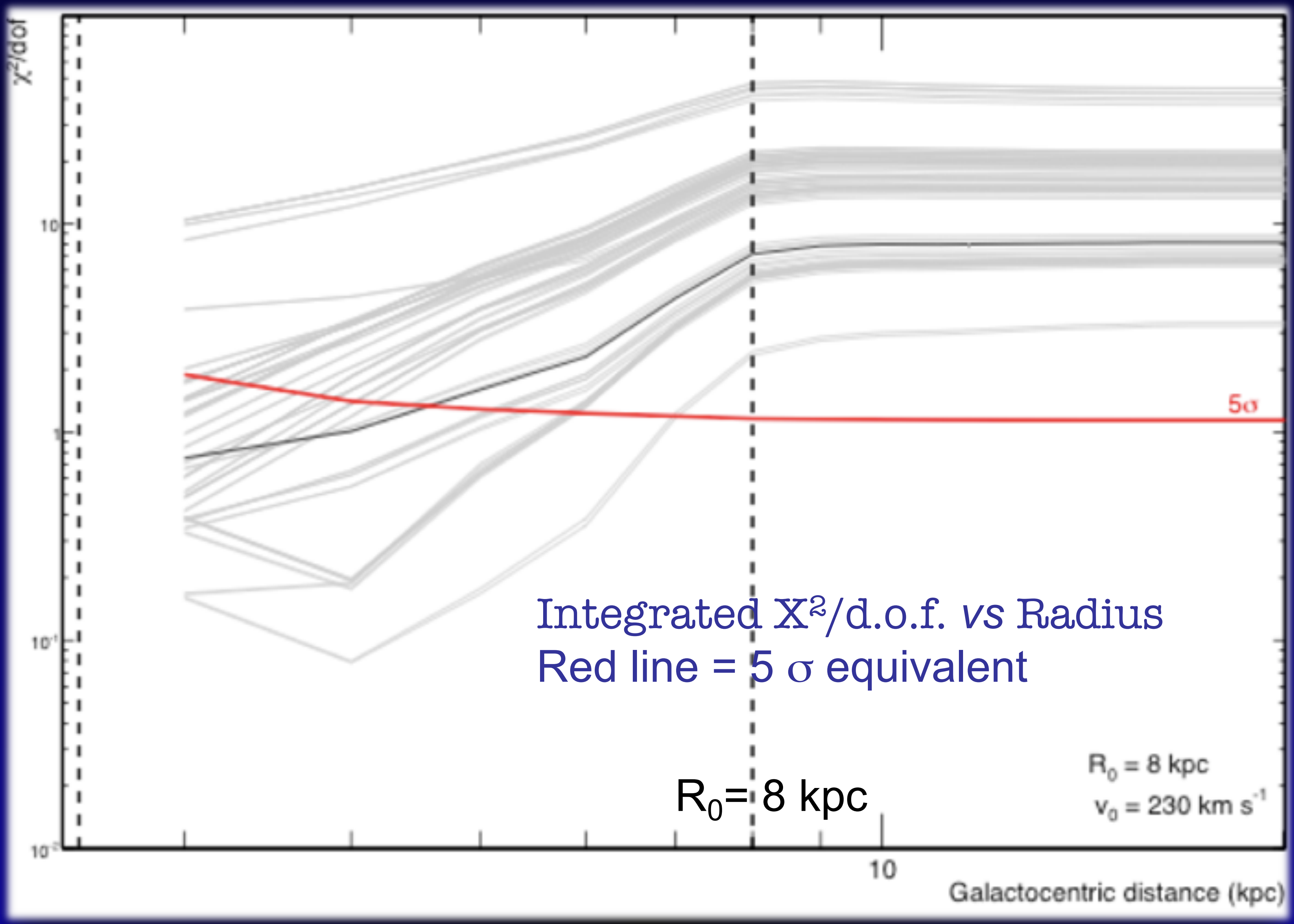
full 3d morphology

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]

Can luminous matter alone fit the observed dynamical curve?



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 $R<R_0$!!

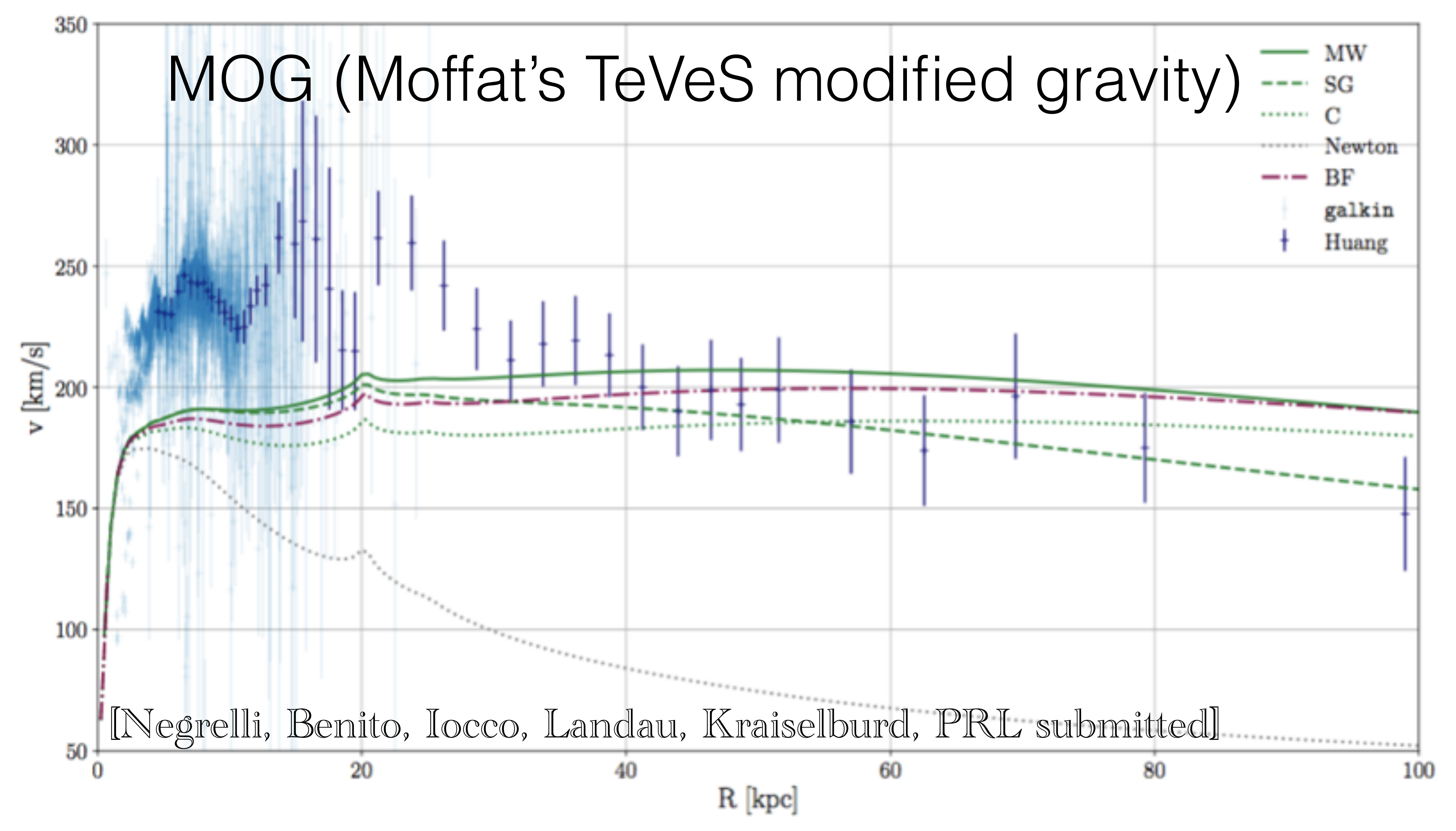
[Iocco, Pato, Bertone, Nature Physics 2015]

Let us test Modified Gravity with the MW

$$\vec{a}(\vec{x}) = -G_N \int \frac{\rho(\vec{x}')(\vec{x}-\vec{x}')}{|\vec{x}-\vec{x}'|^3} \times \left[1+\alpha-\alpha e^{-\mu|\vec{x}-\vec{x}'|}(1+\mu|\vec{x}-\vec{x}'|)\right] d^3\vec{x}'.$$

$$\alpha = \frac{M}{(\sqrt{M}+E)^2}\left(\frac{G_\infty}{G_N}-1\right)$$

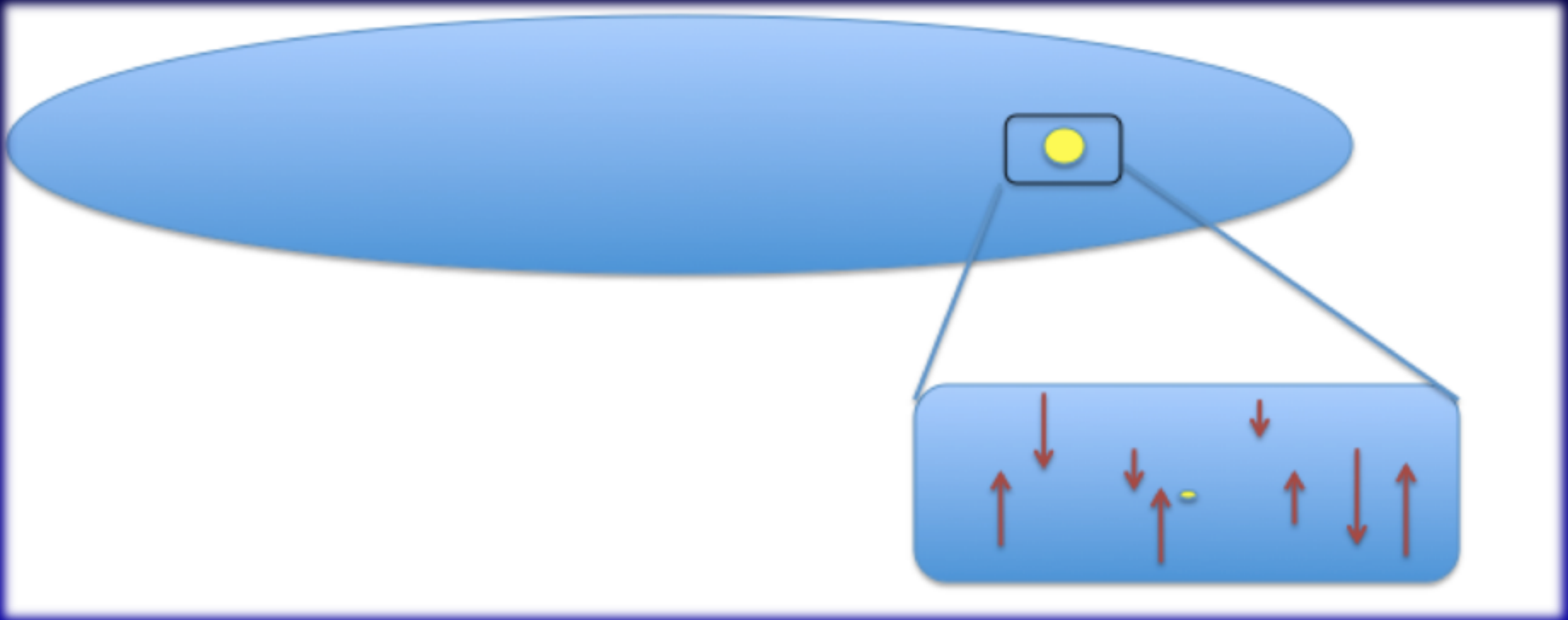
$$\mu = \frac{D}{\sqrt{M}},$$



MOG (Moffat's TeVeS modified gravity)

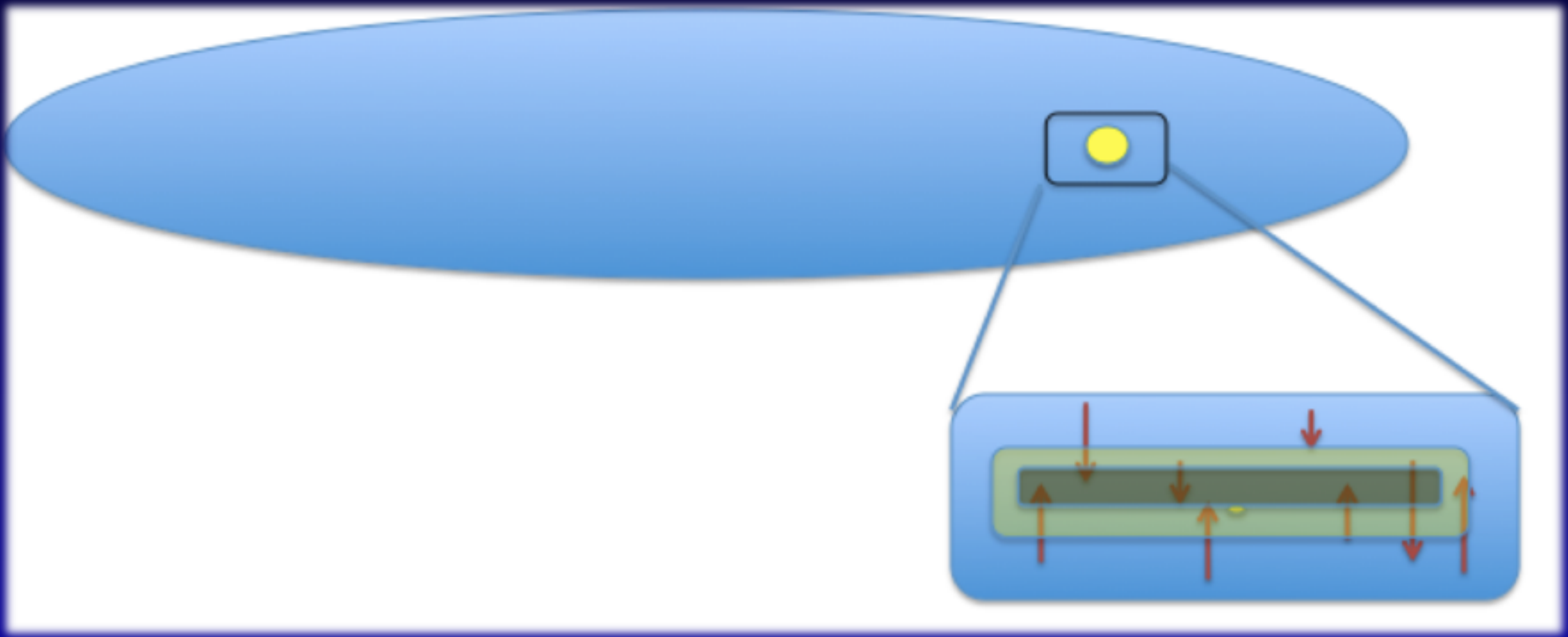
[Negrelli, Benito, Iocco, Landau, Kraiselburd, PRL submitted]

Local determination of ρ_0



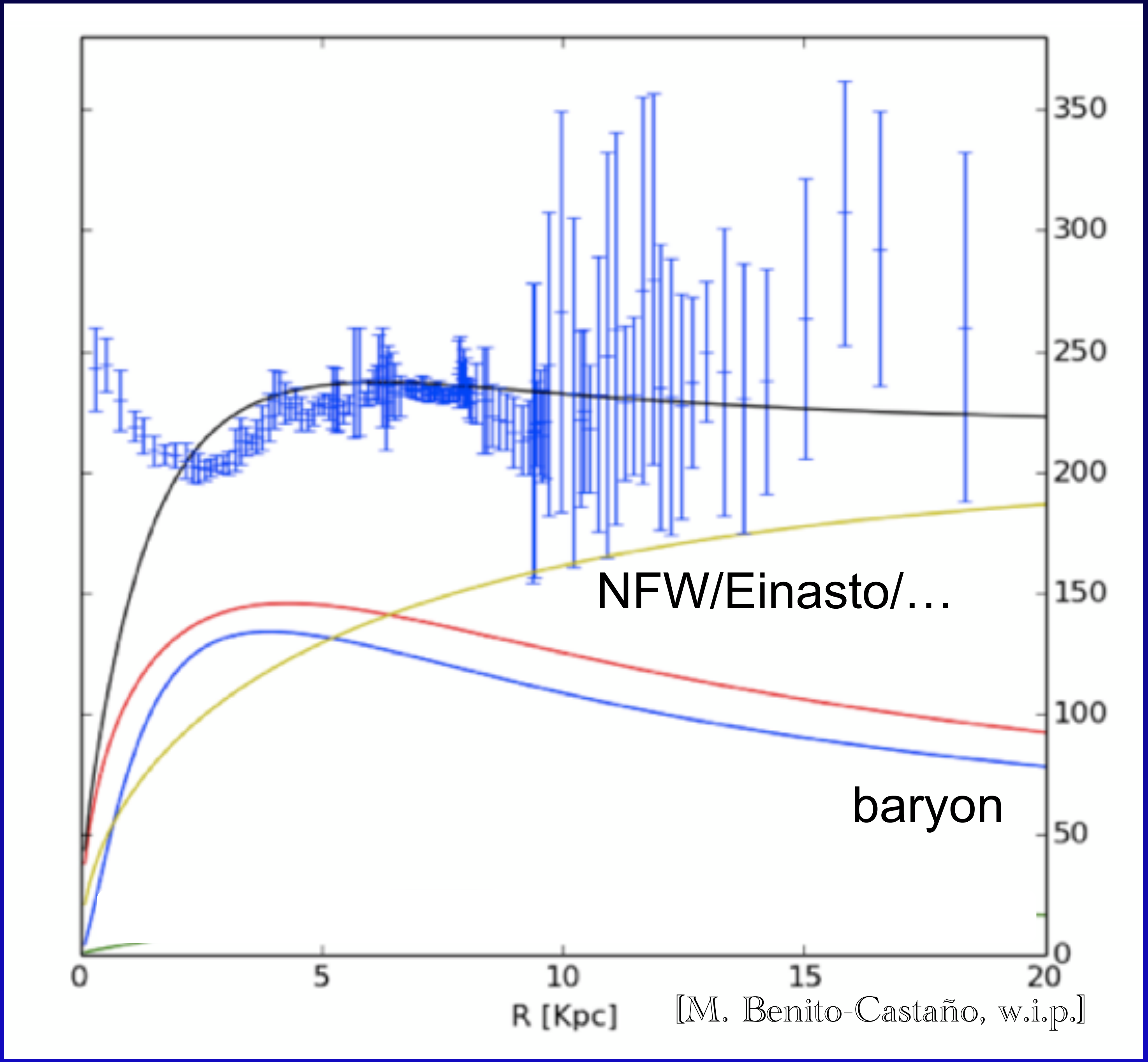
Vertical motion of stars, determining the whole local potential

Local determination of ρ_0



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

Global kinematic methods: fitting halo shapes



NFW/Einasto/…

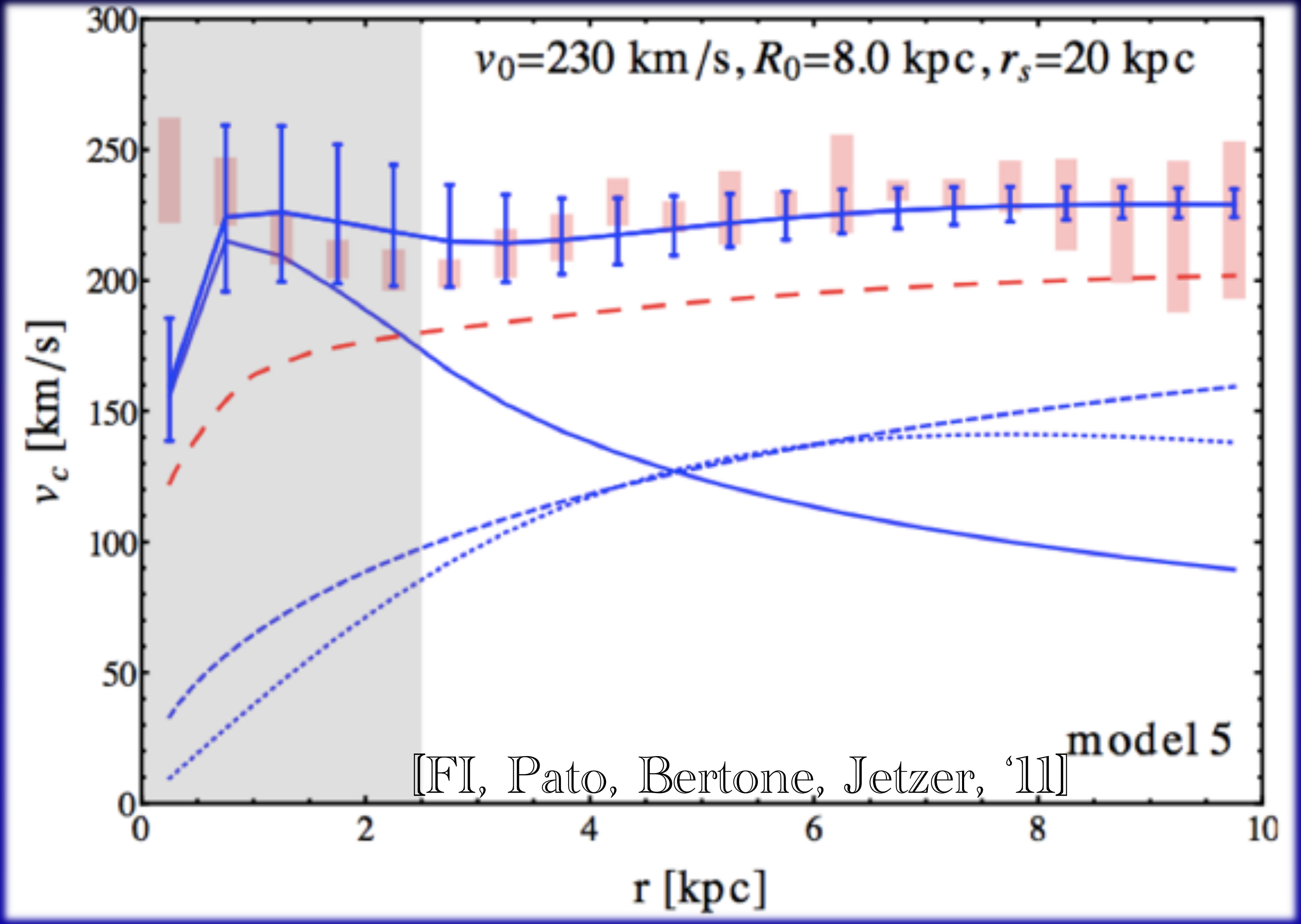
baryon

[M. Benito-Castaño, w.i.p.]

Fitting a DM profile on top of baryons: $\rho_{DM}=\rho_0 R^{\alpha}$

Global determination of ρ(r)

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

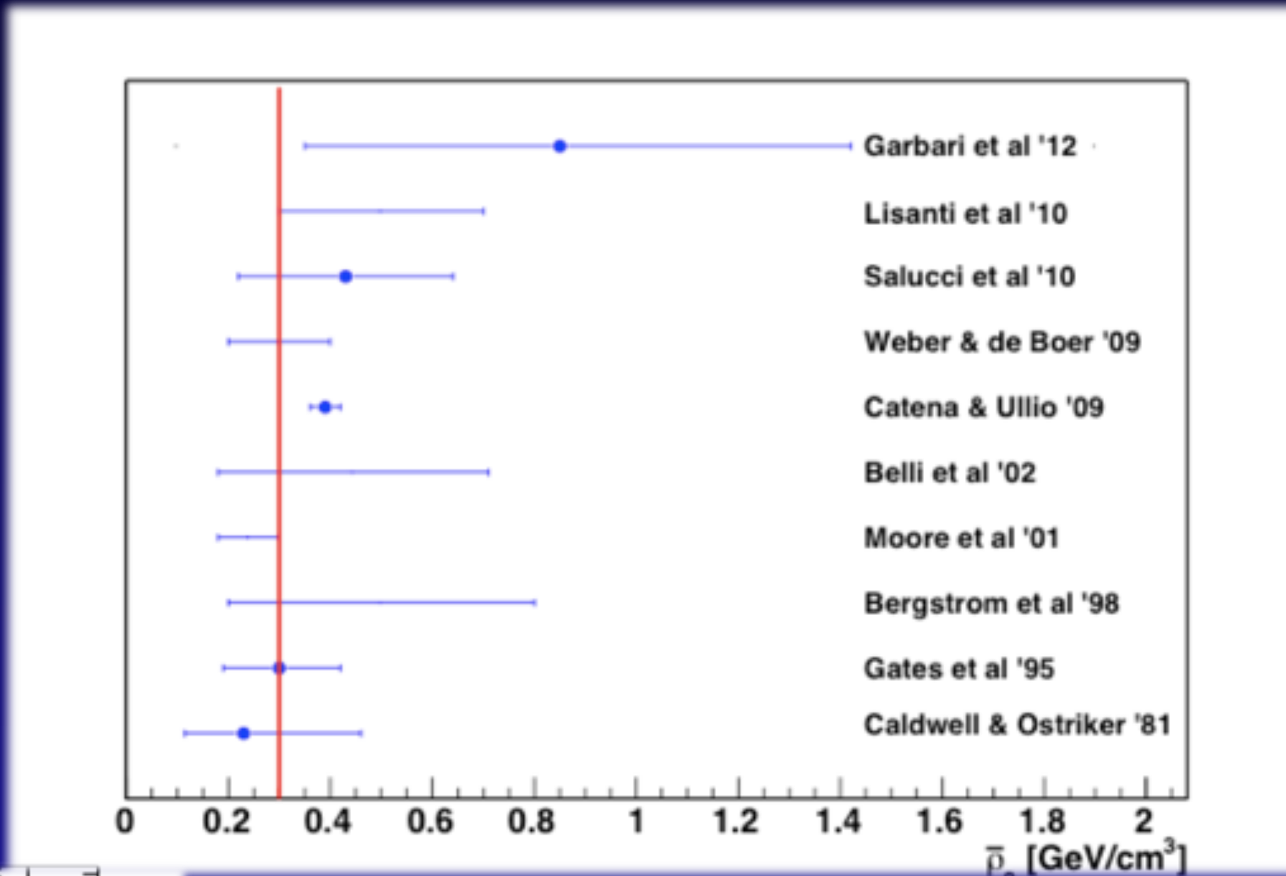


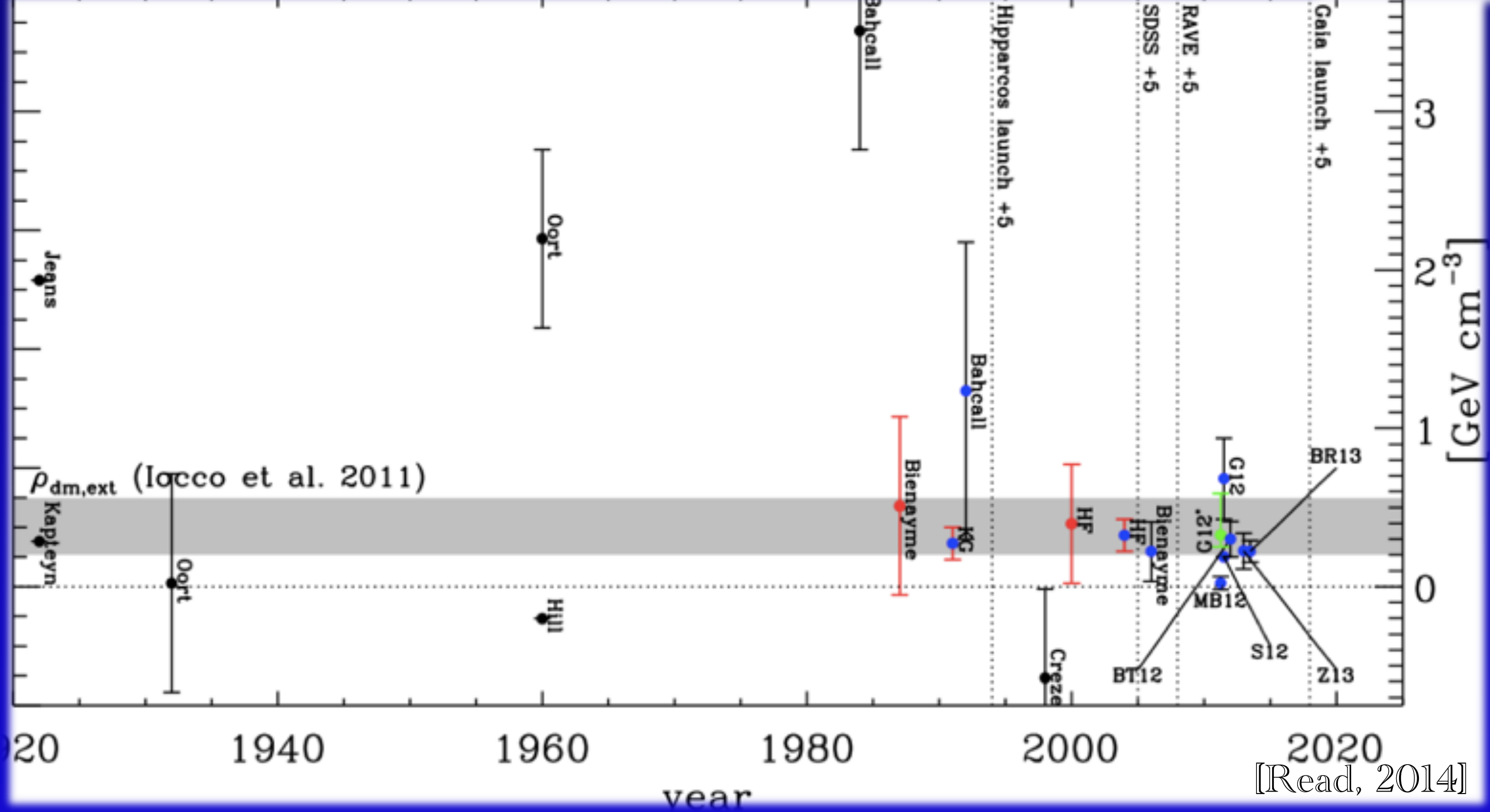
$$\phi_{\rm tot} = \phi_{\rm bulge} + \phi_{\rm disk} + \phi_{\rm gas} + \phi_{\rm dm}$$

Underlying assumption on DM presence and distribution shape

Determining the relevant astrophysical quantities
Local DM density

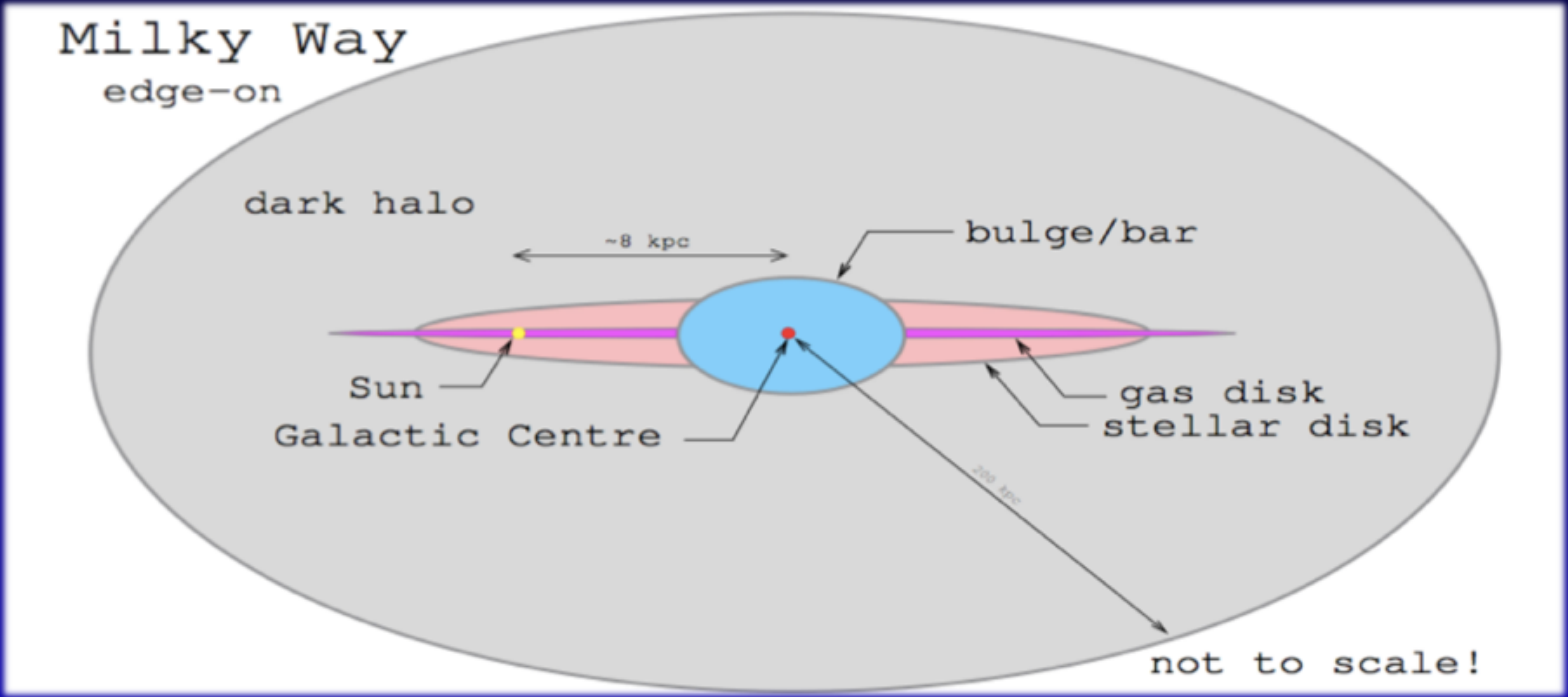
Determinations of
local DM density
are consistent, but noisy





[Read, 2014]

The case of the Milky Way



Courtesy of Miguel Pato

Dark Matter in the Milky Way: a purely observational approach

Fabio Iocco

In collaboration with *Miguel Pato, G. Bertone*

The case of the Milky Way: ingredients

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

- Some “grano salis”

- Working hypothesis (later on)

The case of the Milky Way:
the question

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

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

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

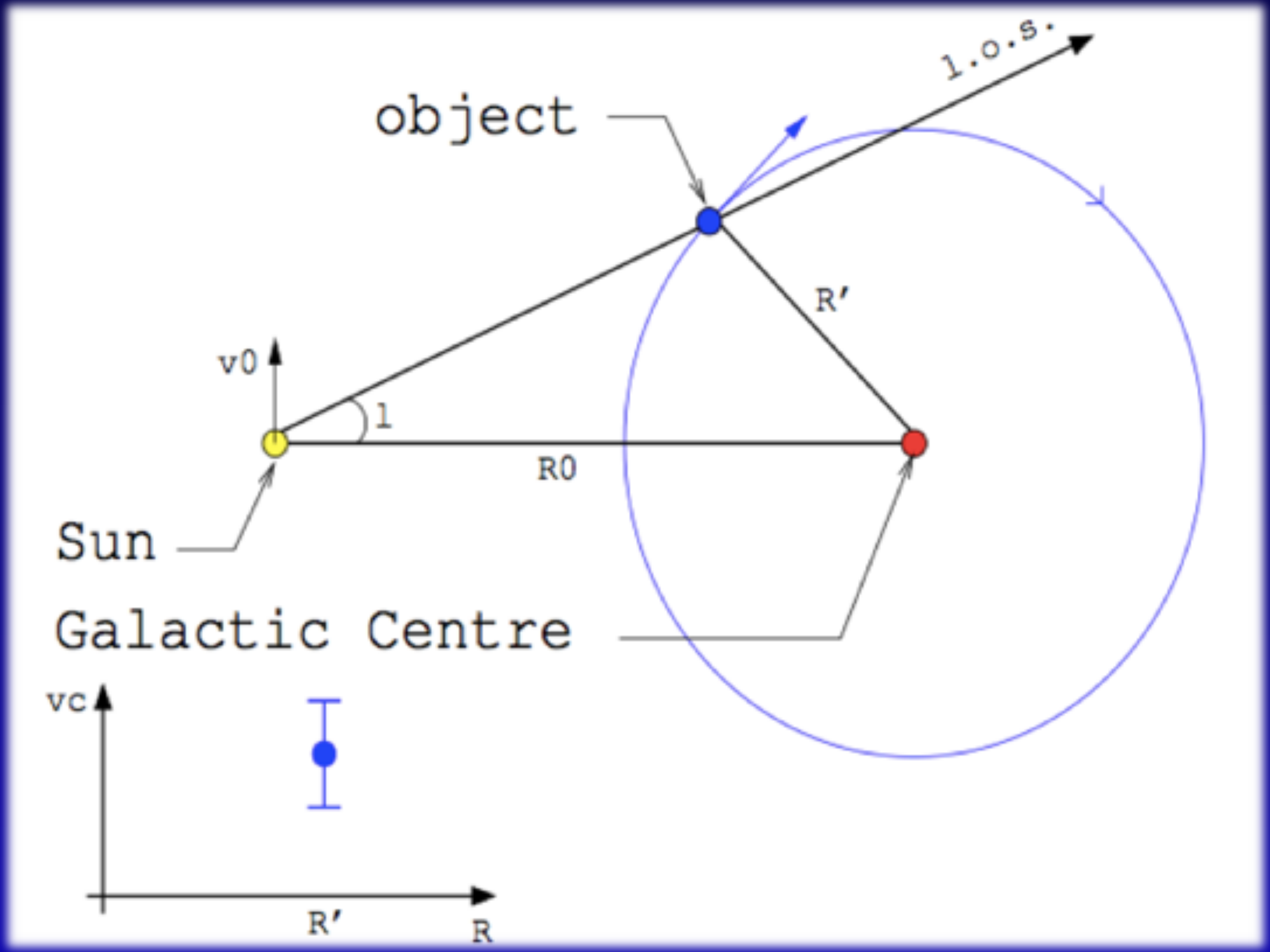
Rotation curve as a tracer of the total potential

…and if not…

The Milky Way:

observed rotation curve

I. principles



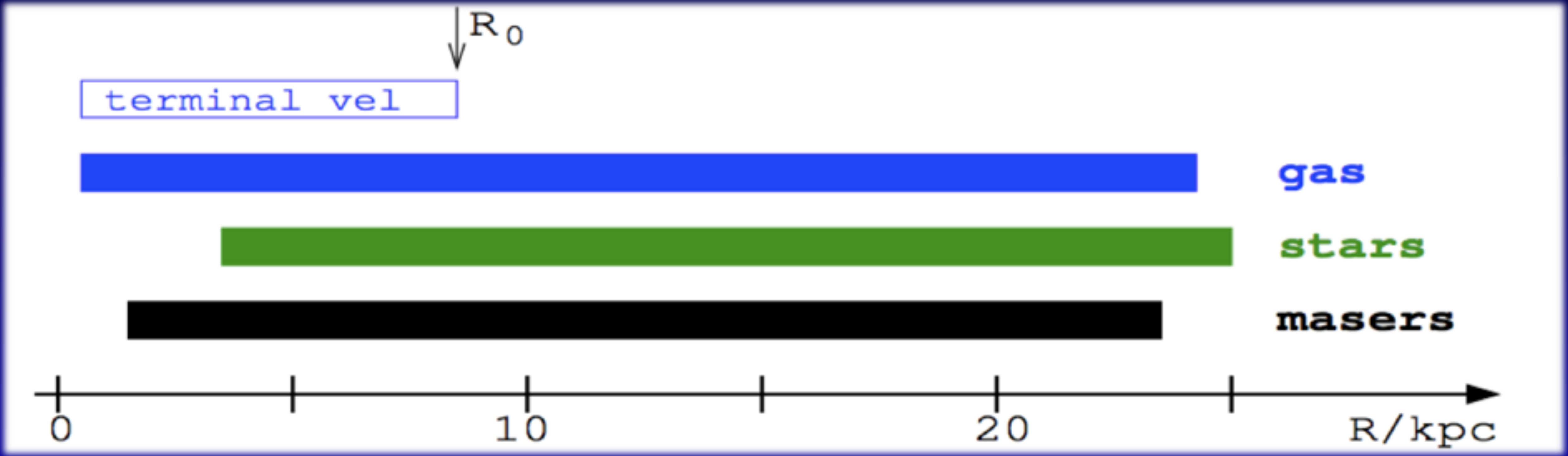
$$v_{\mathrm{LSR}}^{\mathrm{l.o.s.}} = \left(\frac{v_c(R')}{R'/R_0} - v_0 \right) \cos b \sin \ell$$

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

The Milky Way:

observed rotation curve

II. tracers



Doppler shift

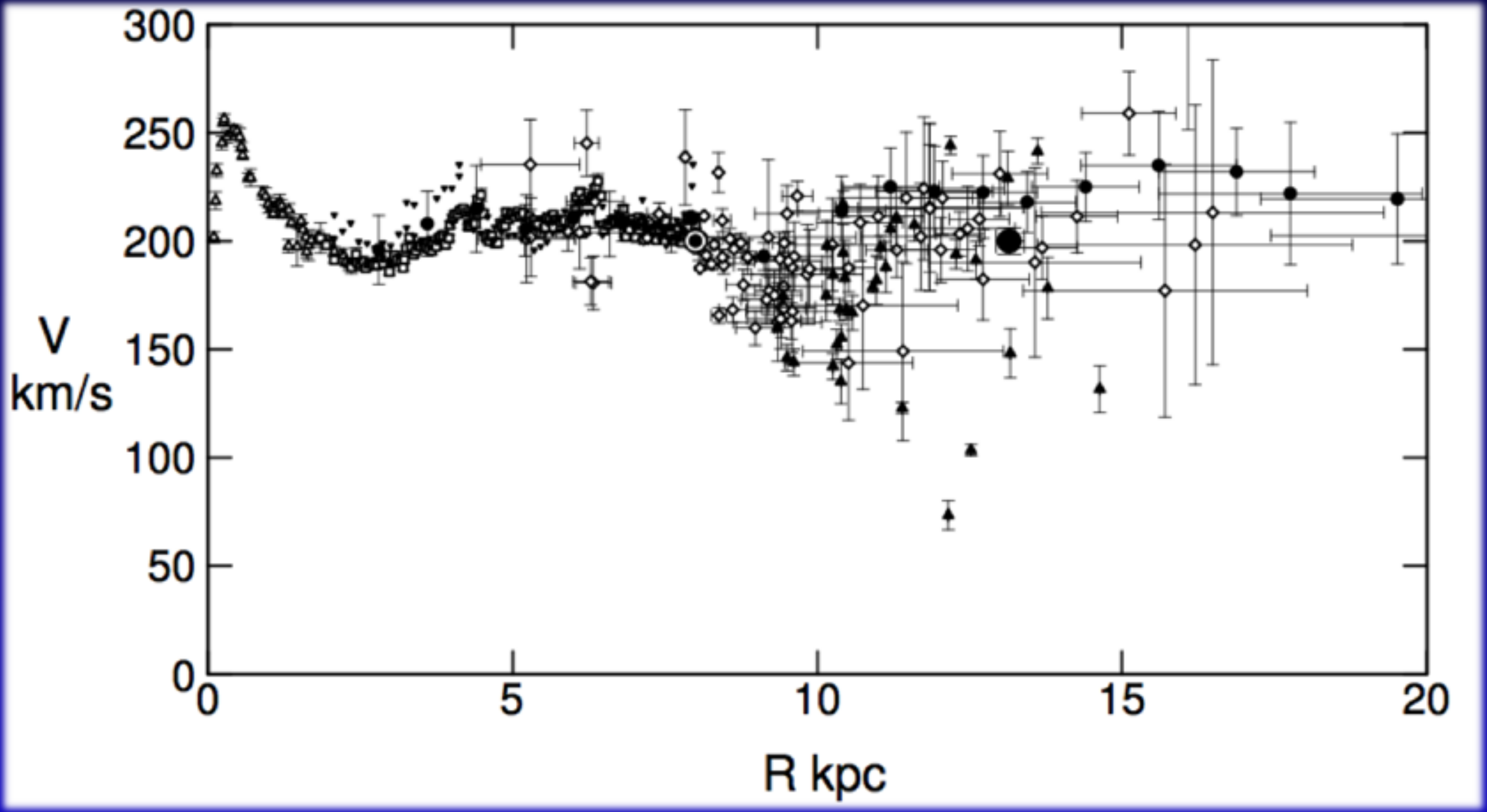
1. gas (21cm, Hα, CO)
2. stars (H, He, O, ...)
3. masers (H_2O, CH_3OH, ...)

distance

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

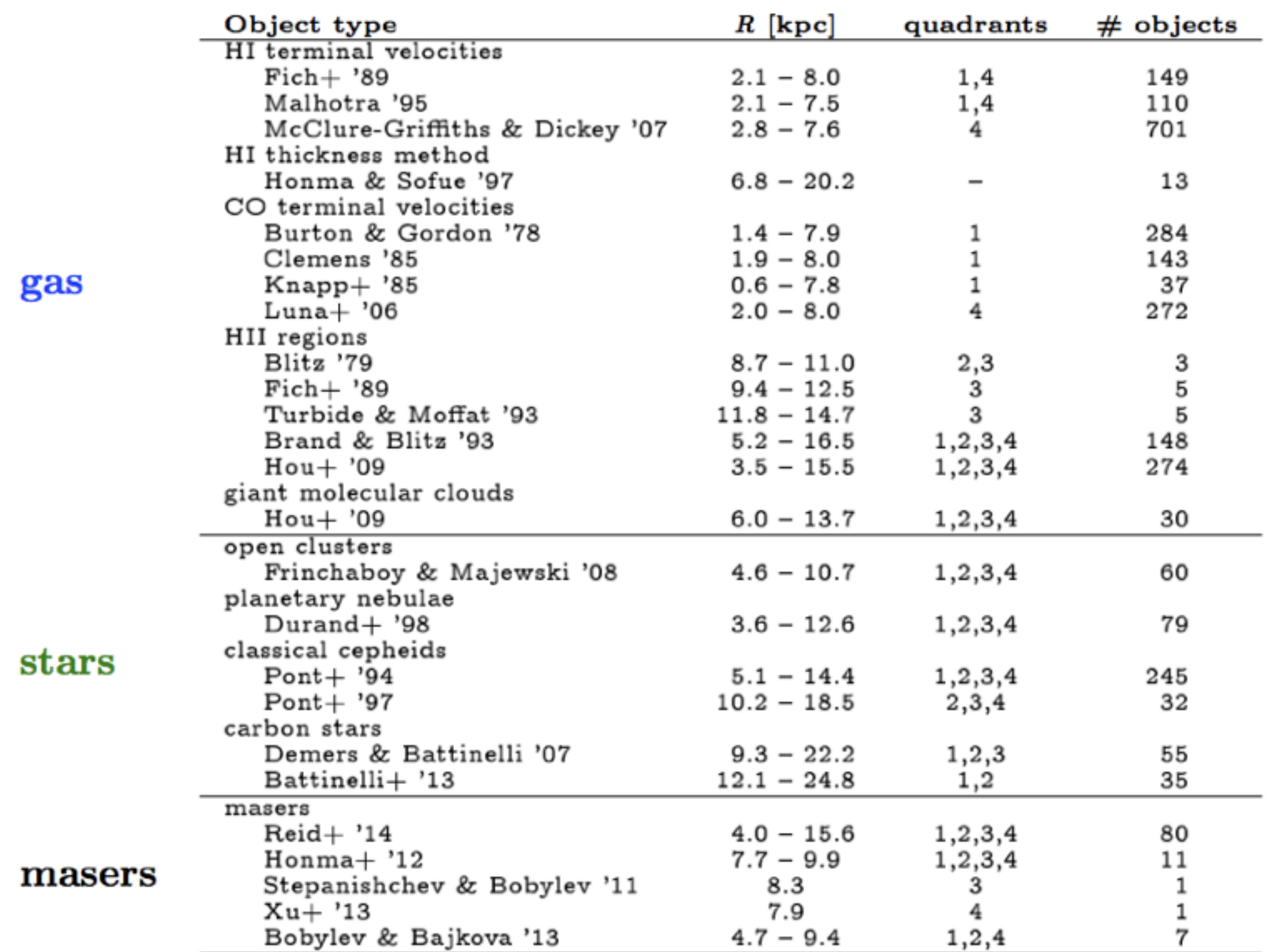
The Milky Way:

observed rotation curve
III. curve



Data compilation by [Sofue et al, '08]

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

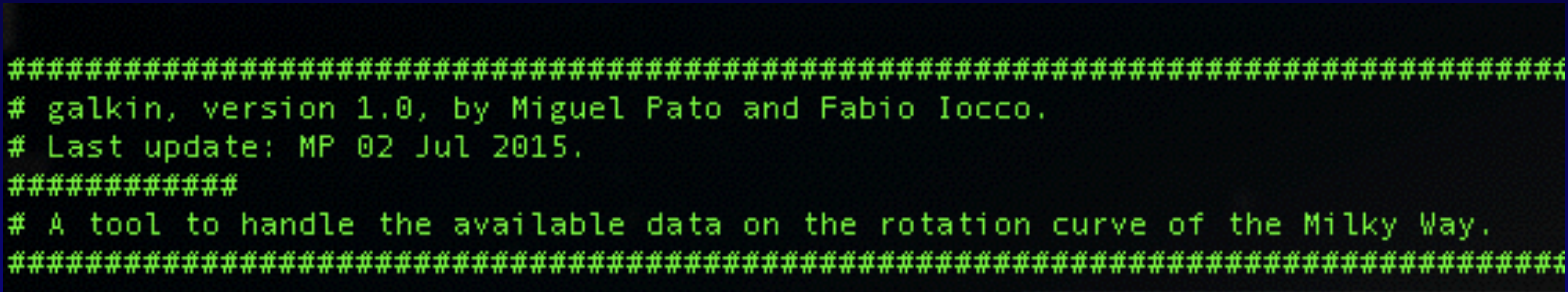


	Object type	R [kpc]	quadrants	# objects
gas	HI terminal velocities			
	Fich+ ’89	2.1 – 8.0	1,4	149
	Malhotra ’95	2.1 – 7.5	1,4	110
	McClure-Griffiths & Dickey ’07	2.8 – 7.6	4	701
	HI thickness method			
	Honma & Sofue ’97	6.8 – 20.2	–	13
	CO terminal velocities			
	Burton & Gordon ’78	1.4 – 7.9	1	284
	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

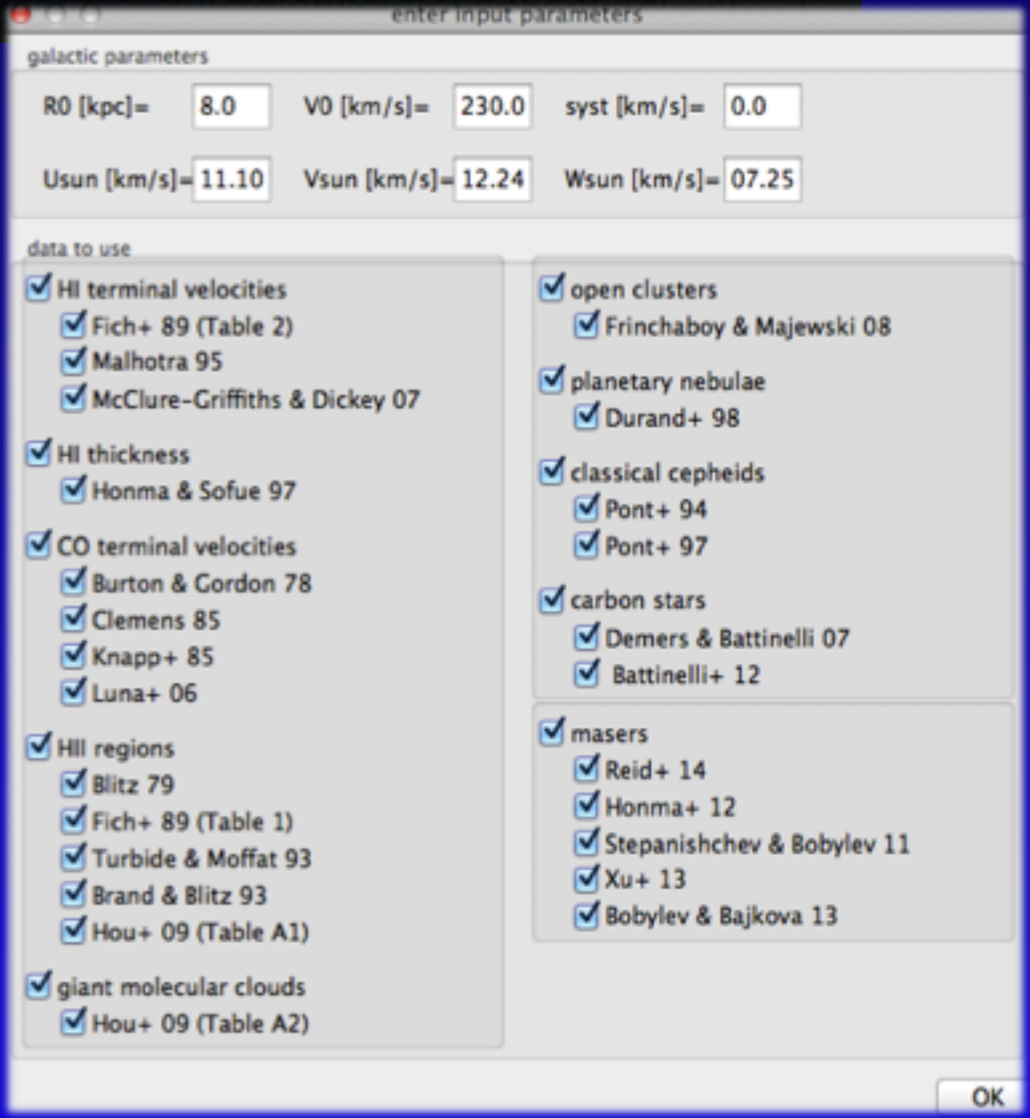


```
#################################################################################
# galkin, version 1.0, by Miguel Pato and Fabio Iocco.
# Last update: MP 02 Jul 2015.
############
# A tool to handle the available data on the rotation curve of the Milky Way.
#################################################################################
```

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

Finally available:
download your copy now

`github.com/galkintool/galkin`



enter input parameters

galactic parameters

R0 [kpc]= 8.0 V0 [km/s]= 230.0 syst [km/s]= 0.0

Usun [km/s]= 11.10 Vsun [km/s]= 12.24 Wsun [km/s]= 07.25

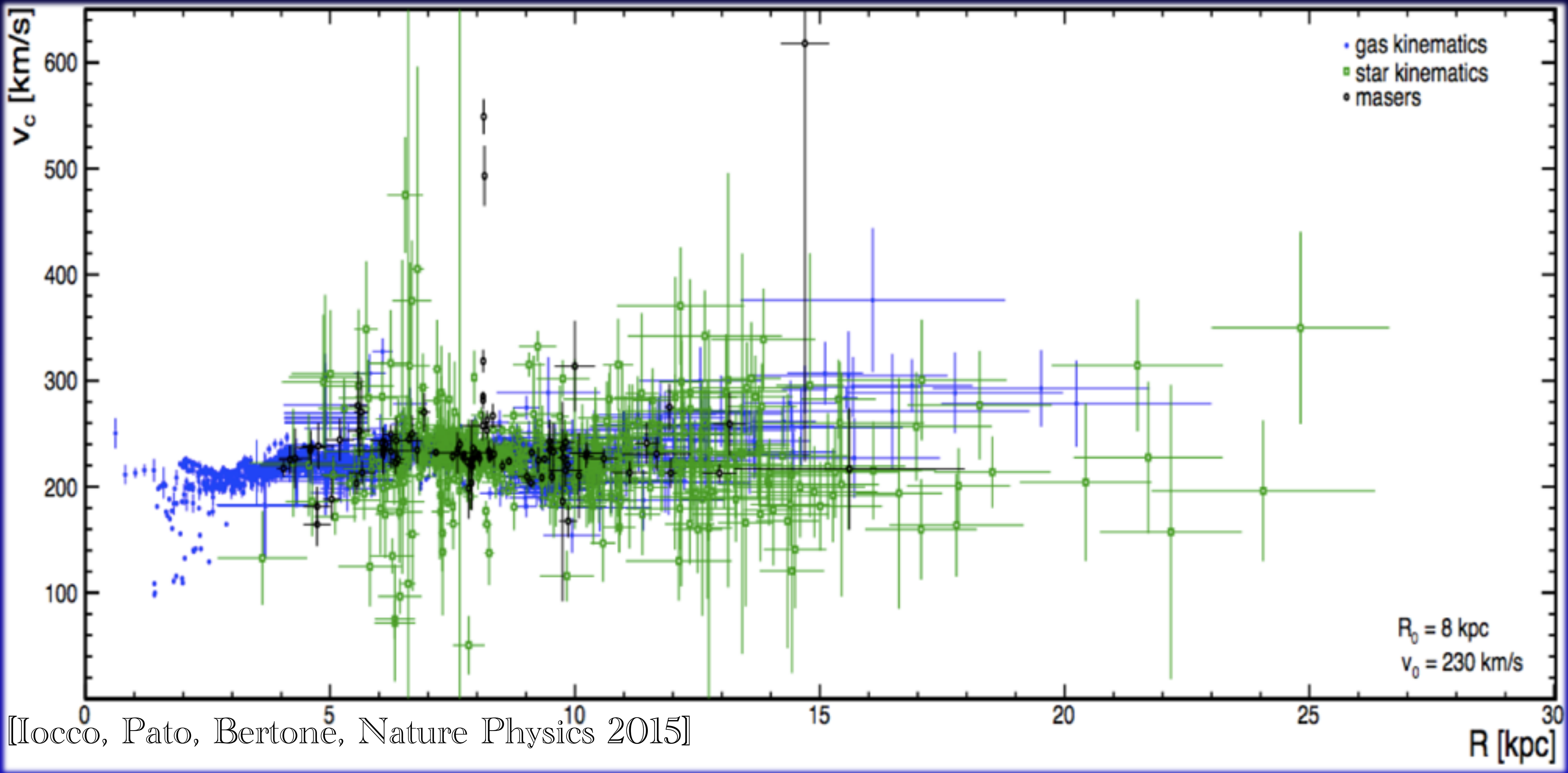
data to use

- ☑ HI terminal velocities
  - ☑ Fich+ 89 (Table 2)
  - ☑ Malhotra 95
  - ☑ McClure-Griffiths & Dickey 07
- ☑ HI thickness
  - ☑ Honma & Sofue 97
- ☑ CO terminal velocities
  - ☑ Burton & Gordon 78
  - ☑ Clemens 85
  - ☑ Knapp+ 85
  - ☑ Luna+ 06
- ☑ HII regions
  - ☑ Blitz 79
  - ☑ Fich+ 89 (Table 1)
  - ☑ Turbide & Moffat 93
  - ☑ Brand & Blitz 93
  - ☑ Hou+ 09 (Table A1)
- ☑ giant molecular clouds
  - ☑ Hou+ 09 (Table A2)
- ☑ open clusters
  - ☑ Frinchaboy & Majewski 08
- ☑ planetary nebulae
  - ☑ Durand+ 98
- ☑ classical cepheids
  - ☑ Pont+ 94
  - ☑ Pont+ 97
- ☑ carbon stars
  - ☑ Demers & Battinelli 07
  - ☑ Battinelli+ 12
- ☑ masers
  - ☑ Reid+ 14
  - ☑ Honma+ 12
  - ☑ Stepanishchev & Bobylev 11
  - ☑ Xu+ 13
  - ☑ Bobylev & Bajkova 13

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

The Milky Way Rotation Curve

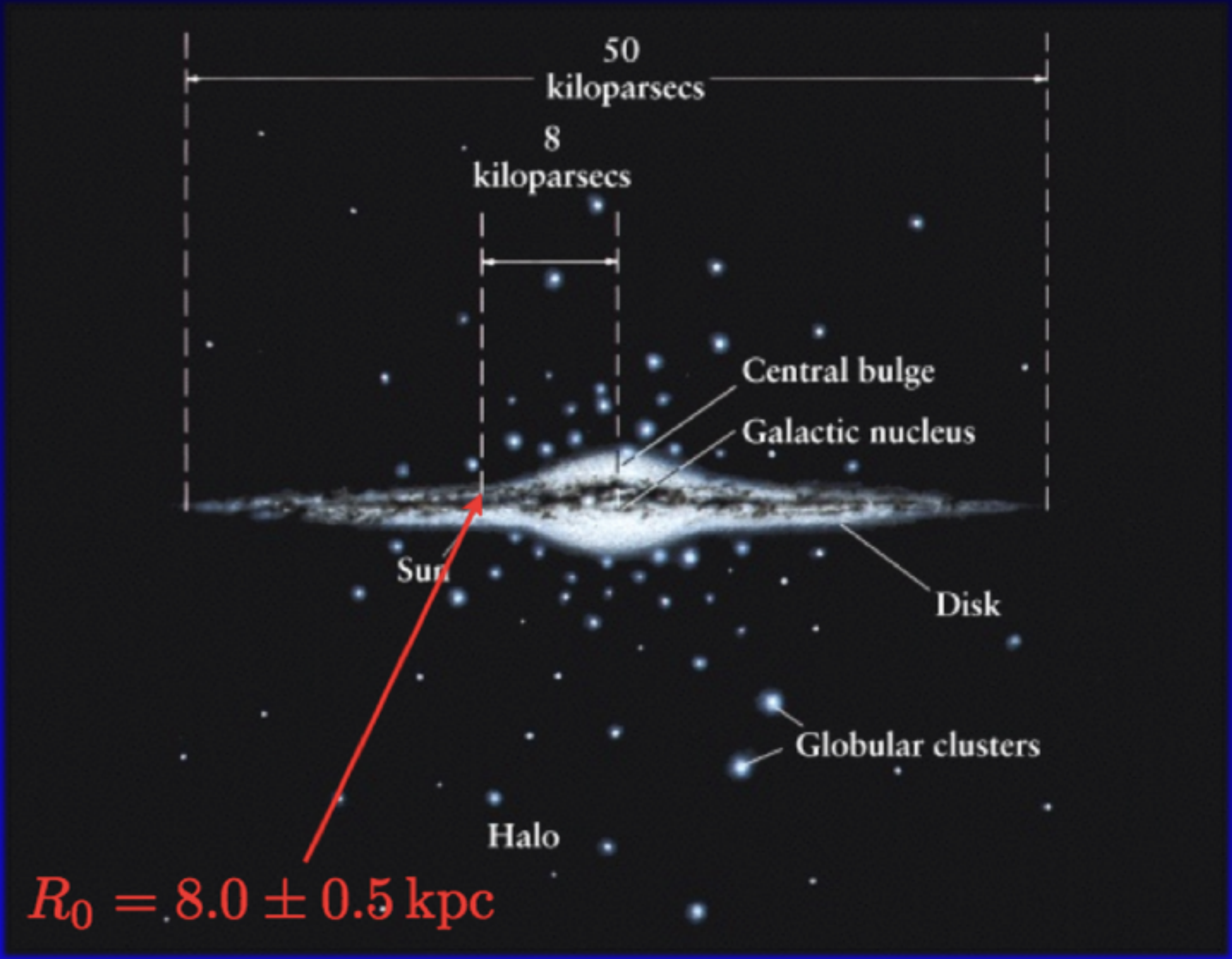
as observed



[Iocco, Pato, Bertone, Nature Physics 2015]

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

Modeling the Milky Way: morphological observations



$R_0 = 8.0 \pm 0.5\,\mathrm{kpc}$

The Milky Way:

expected rotation curve

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

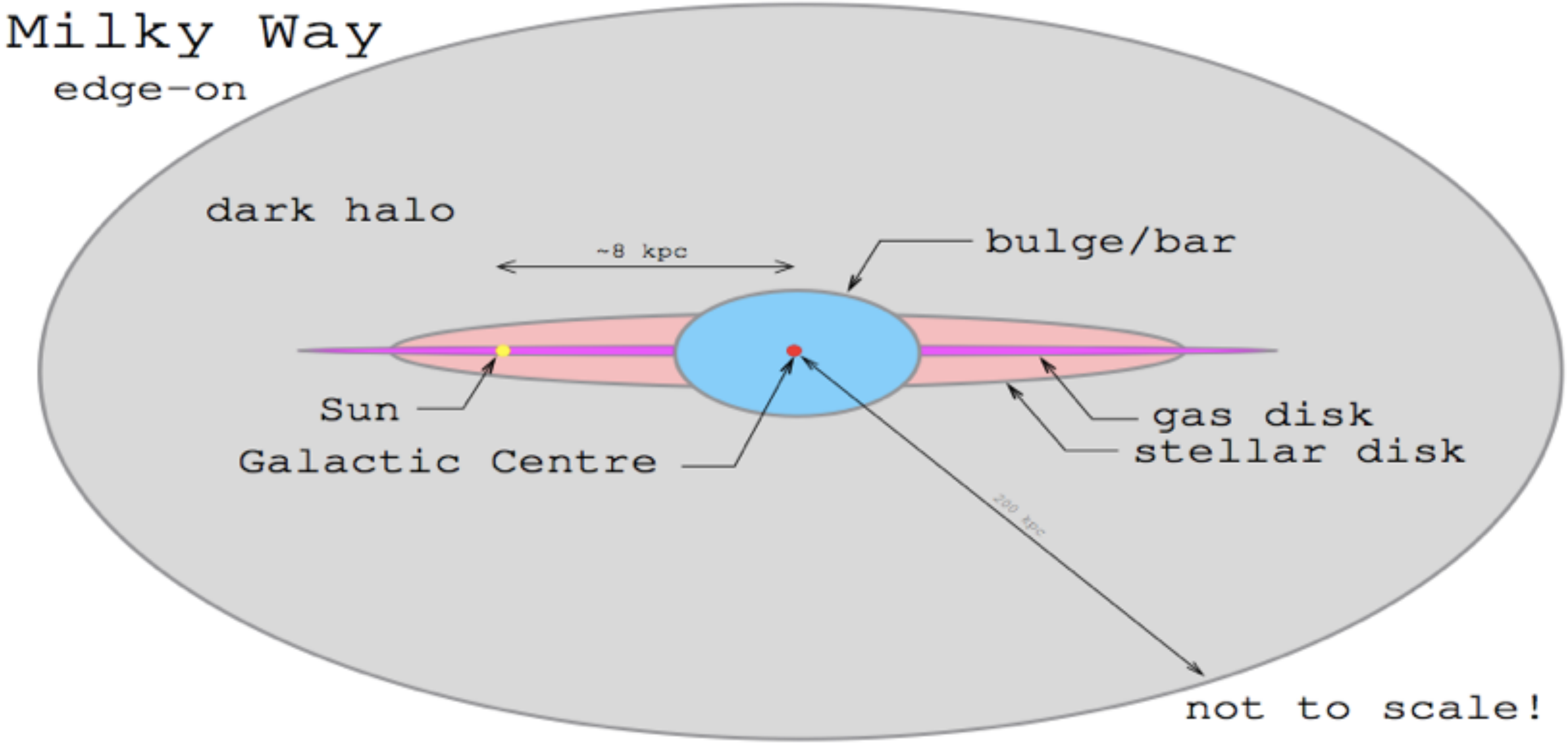
$$\rho_i(x, y, z) \rightarrow \phi_i(r, \theta, \varphi) \rightarrow v^2_{c,i}(R) = \sum_{\varphi} R \frac{d\phi_i}{dr}(R, \pi/2, \varphi)$$

Constructing the curve expected from observed mass profiles

The Milky Way:

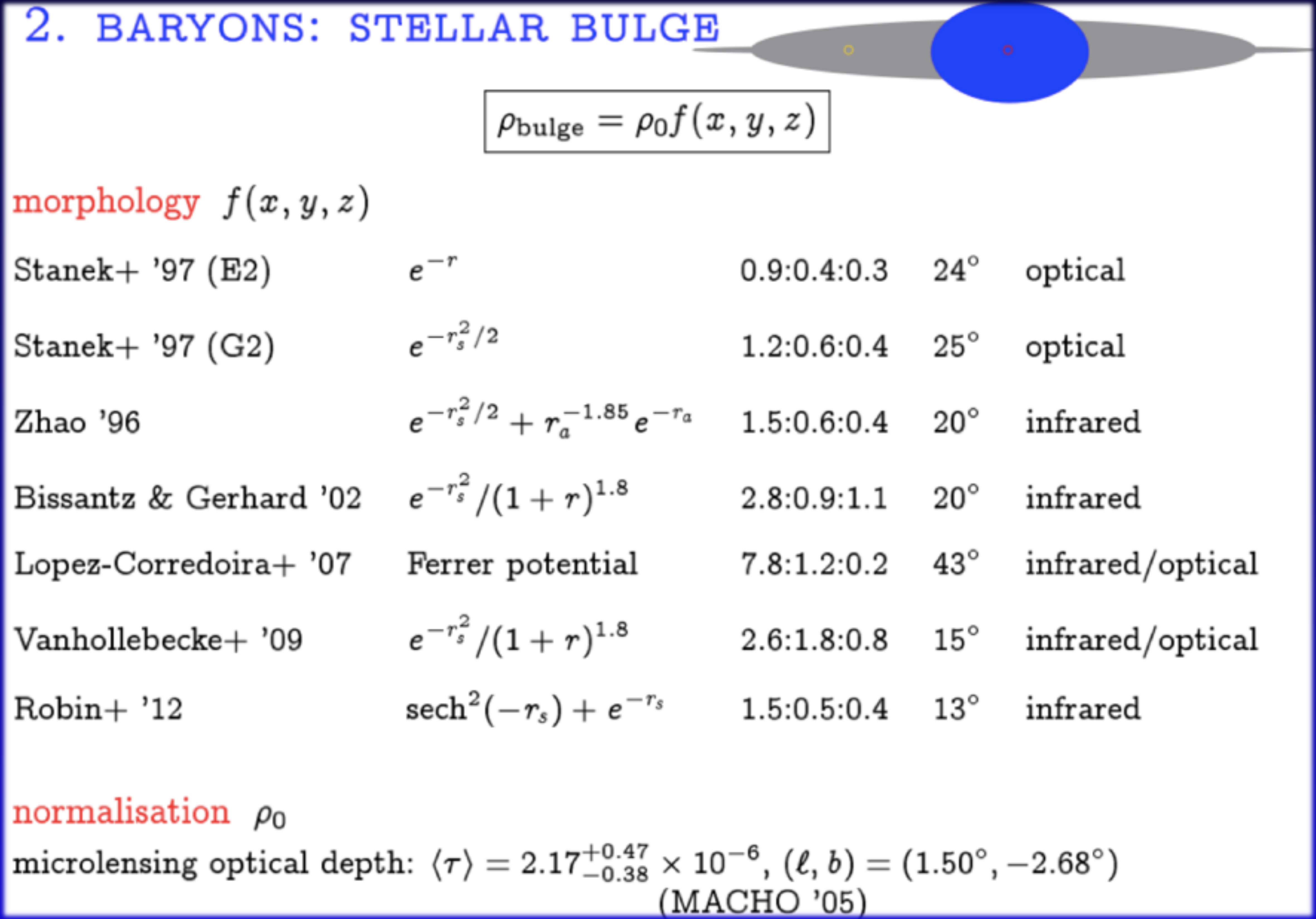
expected rotation curve

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

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

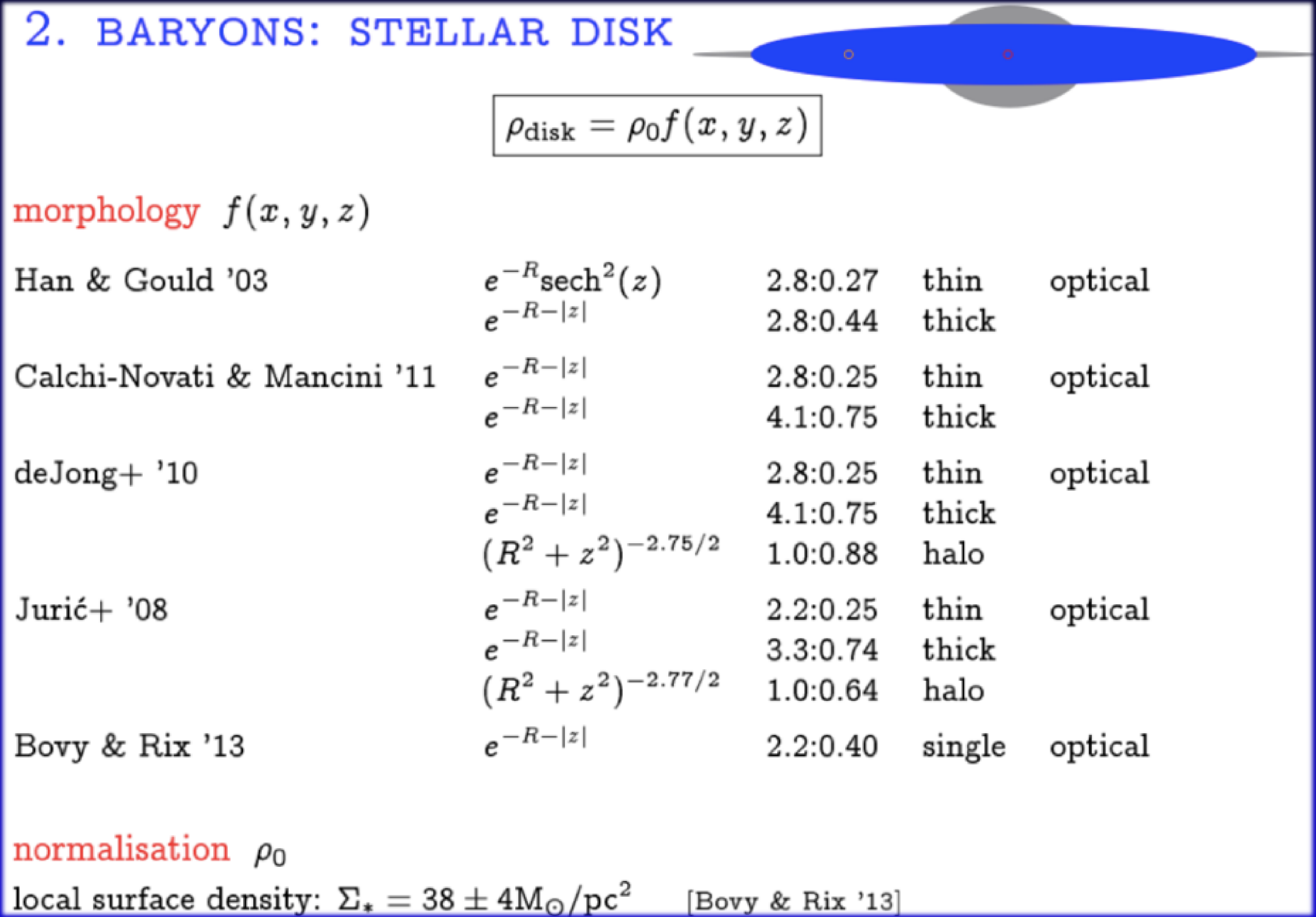
morphology $f(x, y, z)$

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

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

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

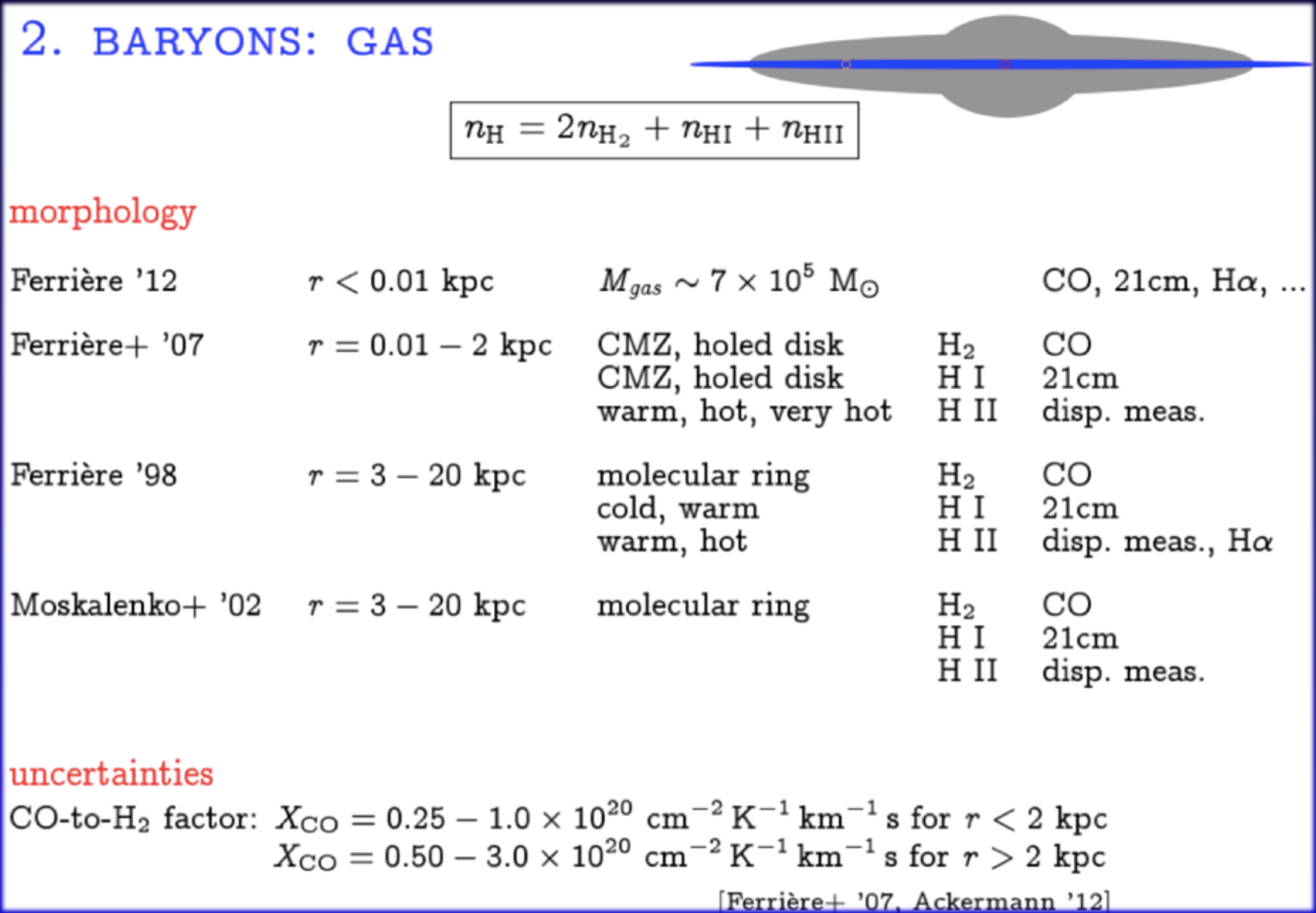
morphology $f(x,y,z)$

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

normalisation ρ_0

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

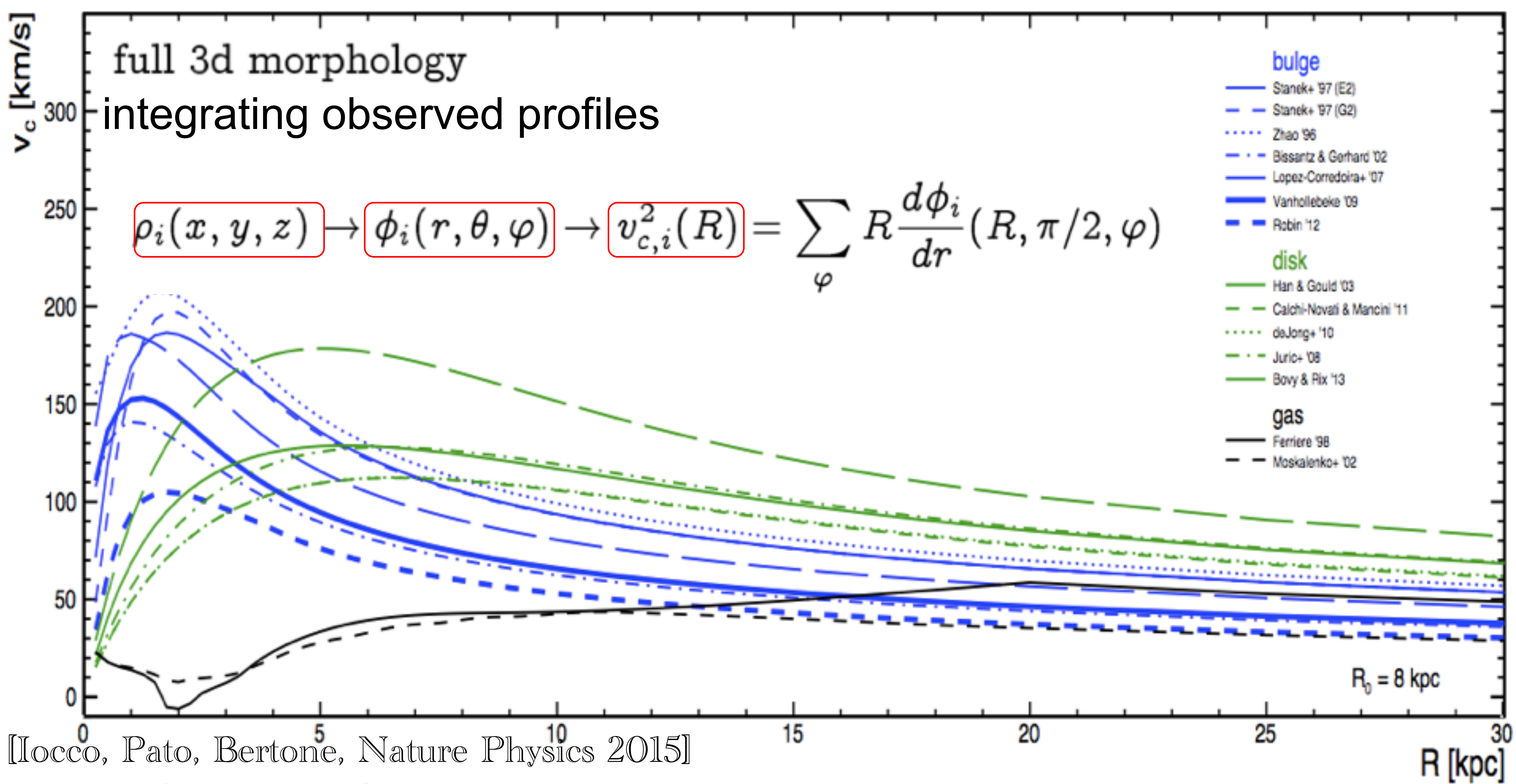
$X_{\mathrm{CO}} = 0.50 - 3.0 \times 10^{20}\ \mathrm{cm}^{-2}\,\mathrm{K}^{-1}\,\mathrm{km}^{-1}\,\mathrm{s}$ for $r > 2$ kpc

[Ferrière+ '07, Ackermann '12]

The luminous Milky Way:

expected rotation curve

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

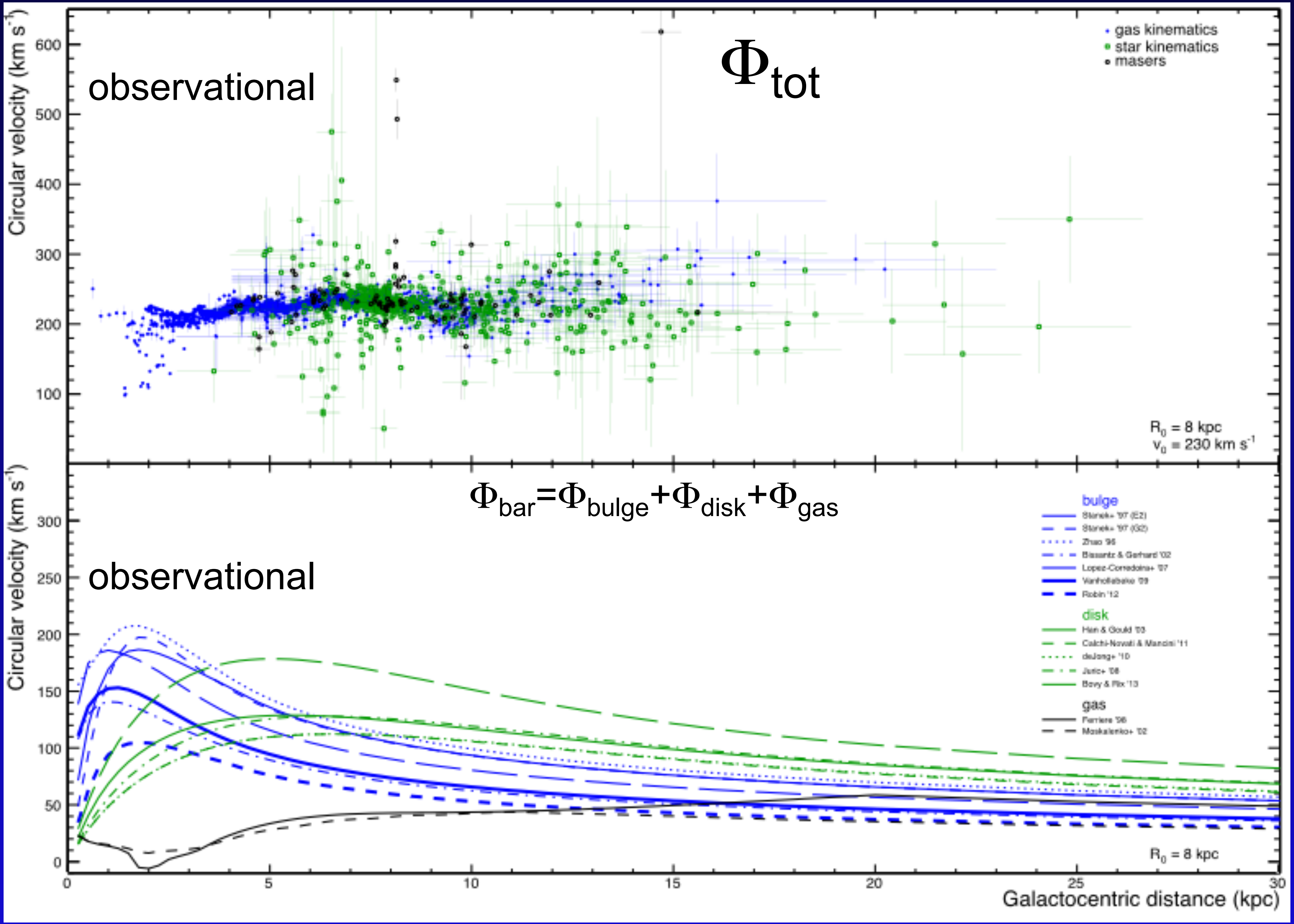


integrating observed profiles

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

[Iocco, Pato, Bertone, Nature Physics 2015]

The Milky Way:
testing expectactions



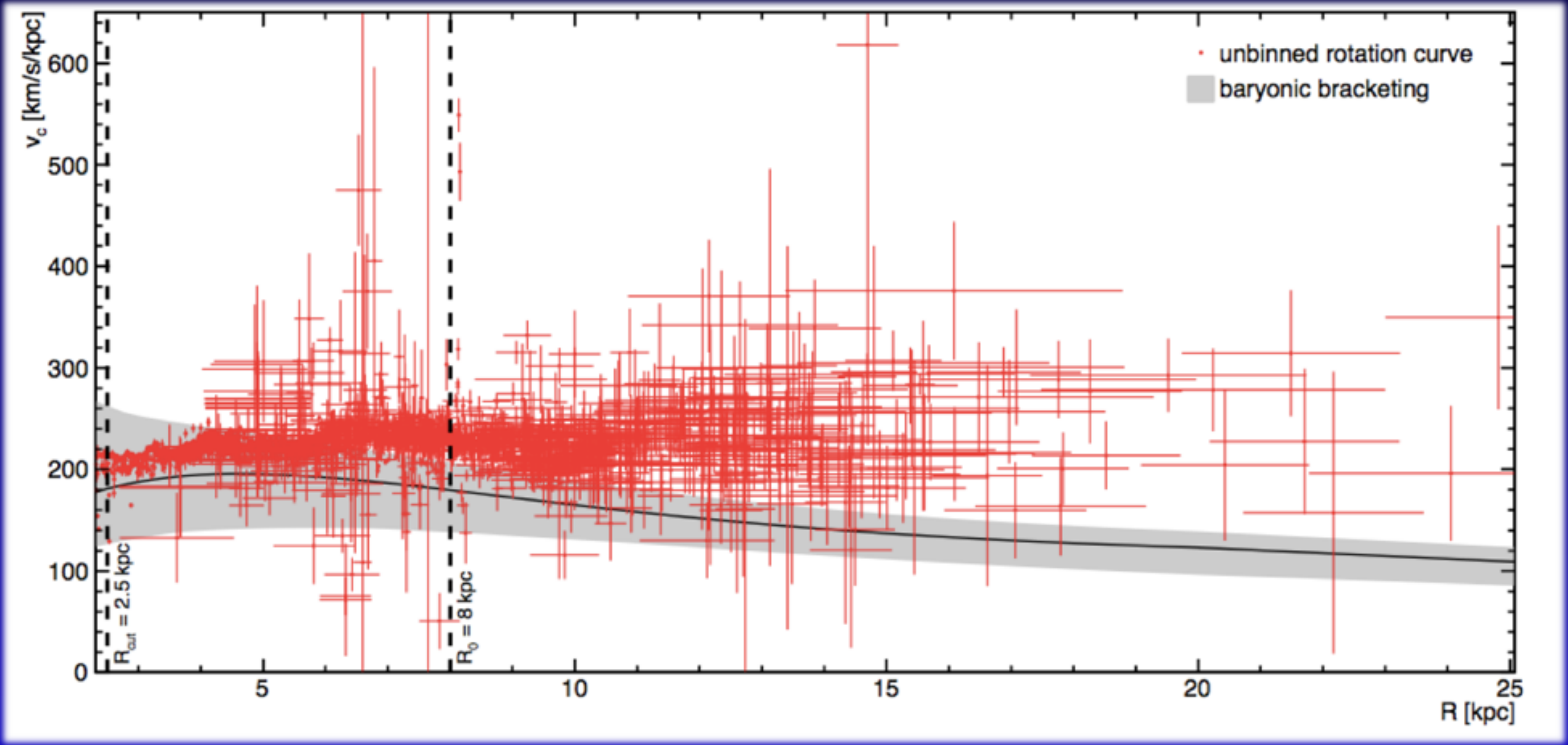
observational

Φ_{tot}

observational

$\Phi_{bar}=\Phi_{bulge}+\Phi_{disk}+\Phi_{gas}$

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

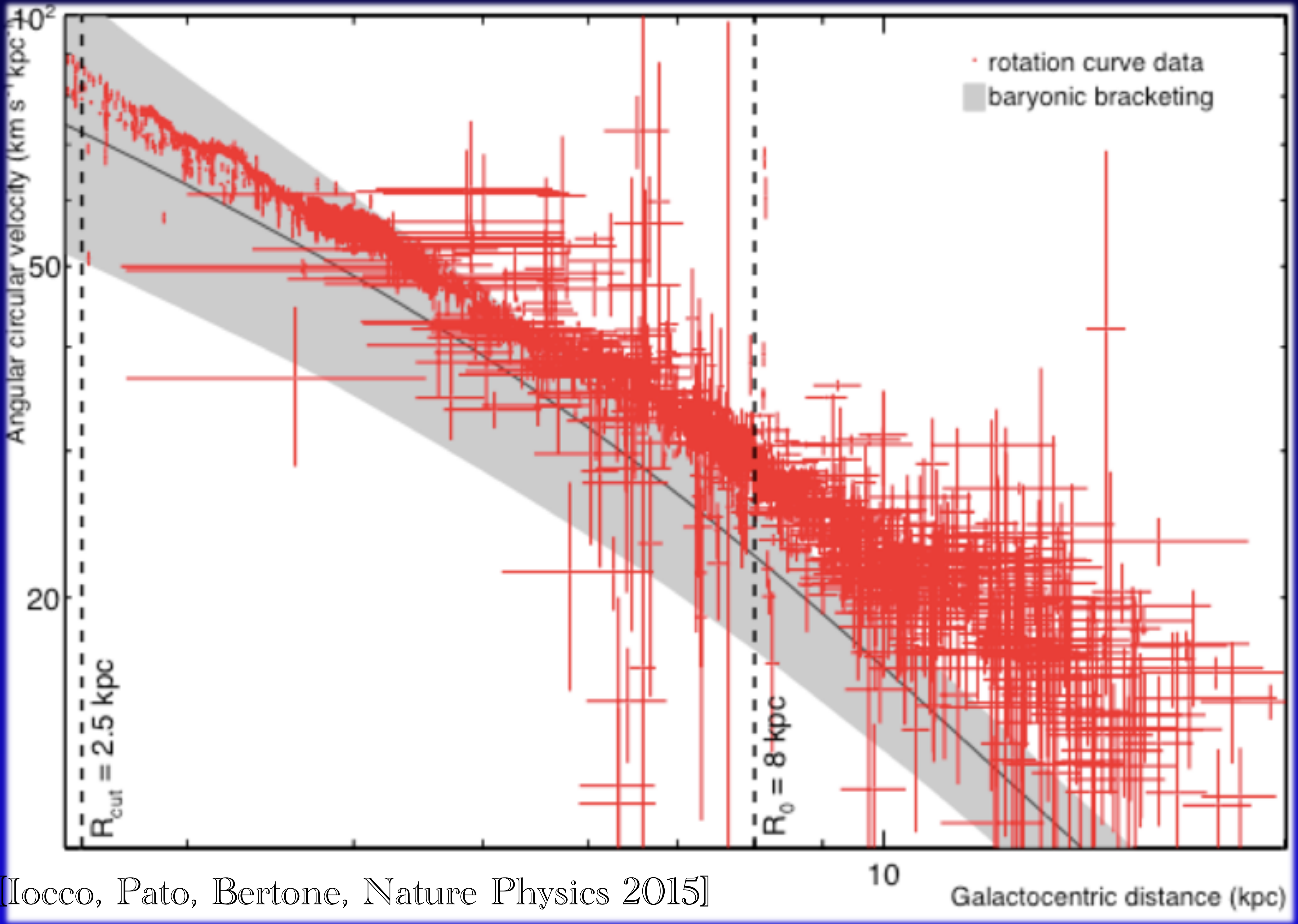


[Iocco, Pato, Bertone, Nature Physics 2015]

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

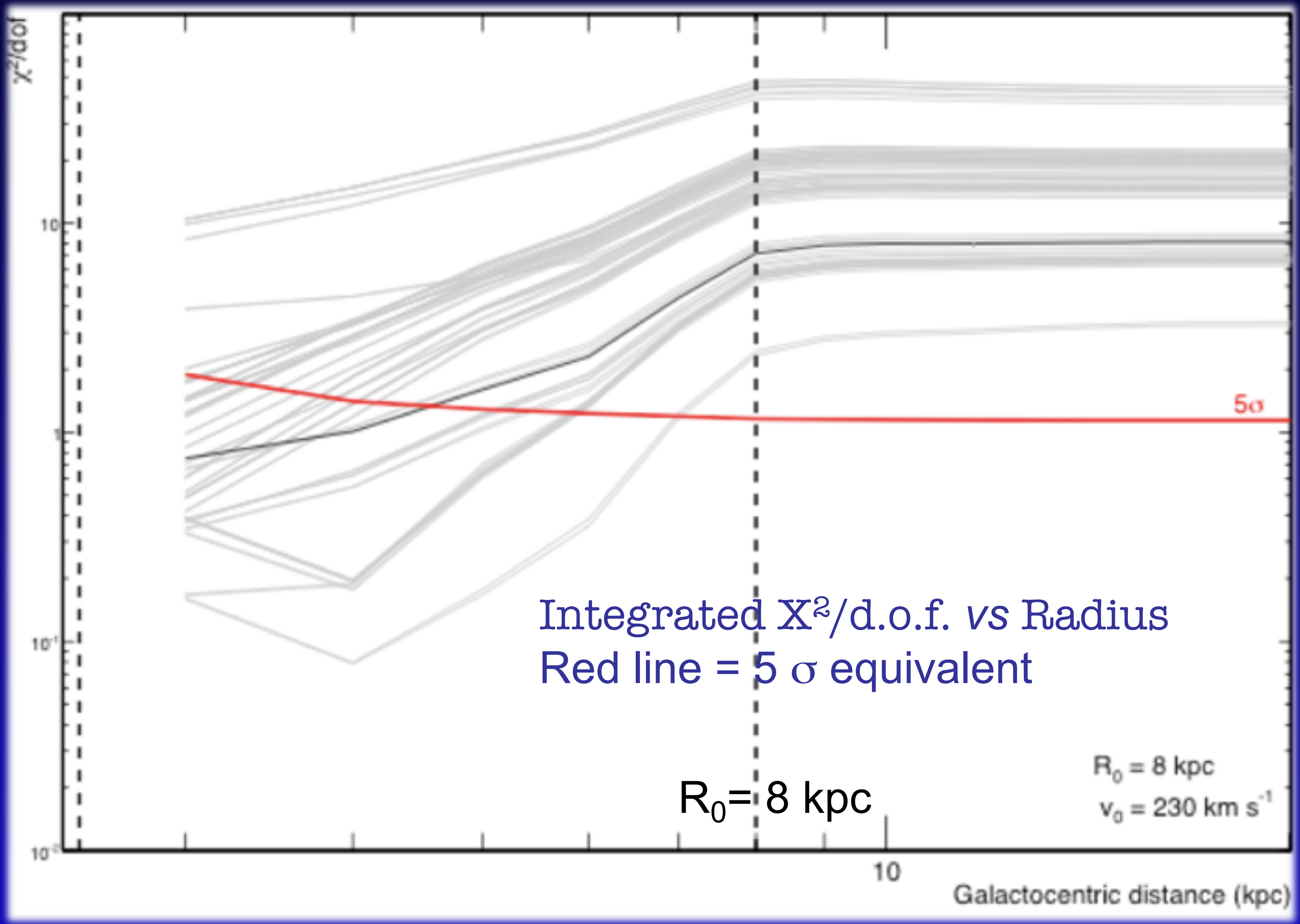
The Milky Way:
testing expectactions
(with no additional assumptions)
((and some technical detail))

- 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?



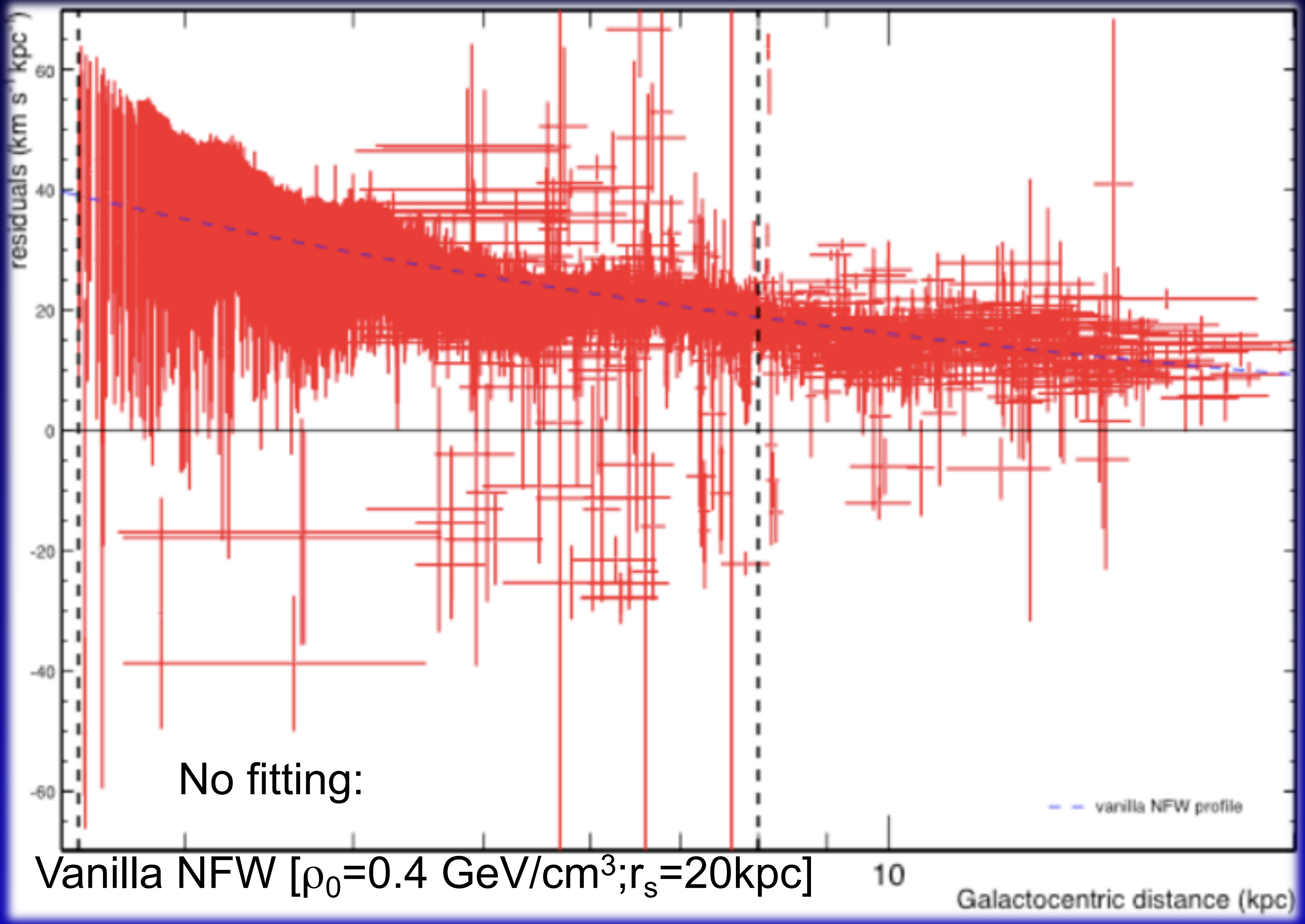
Integrated X^2/d.o.f. *vs* Radius
Red line = 5 σ equivalent

R_0= 8 kpc

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

[Iocco, Pato, Bertone, Nature Physics 2015]

Motivating dark haloes



No fitting:

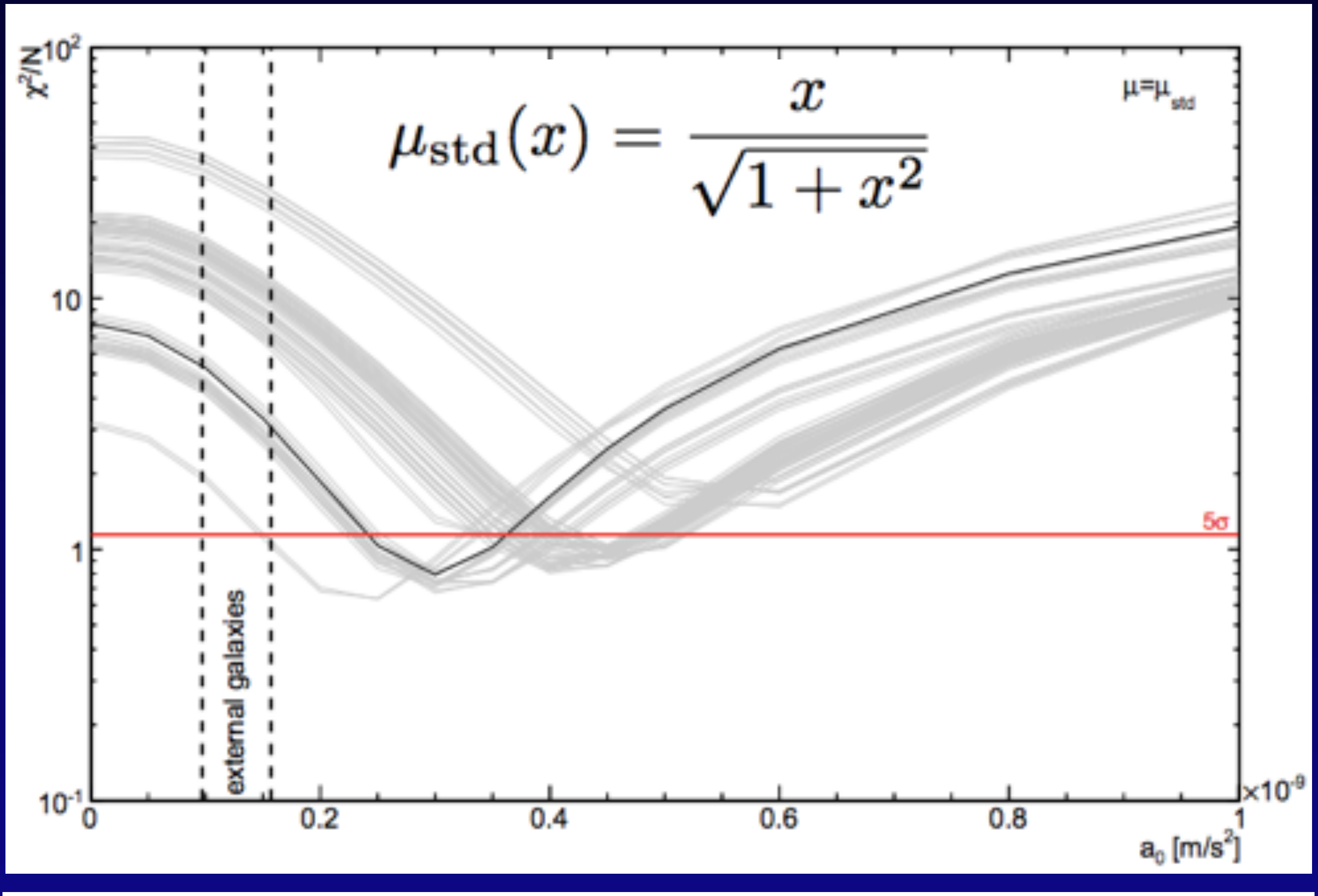
Vanilla NFW [ρ_0=0.4 GeV/cm^3;r_s=20kpc]

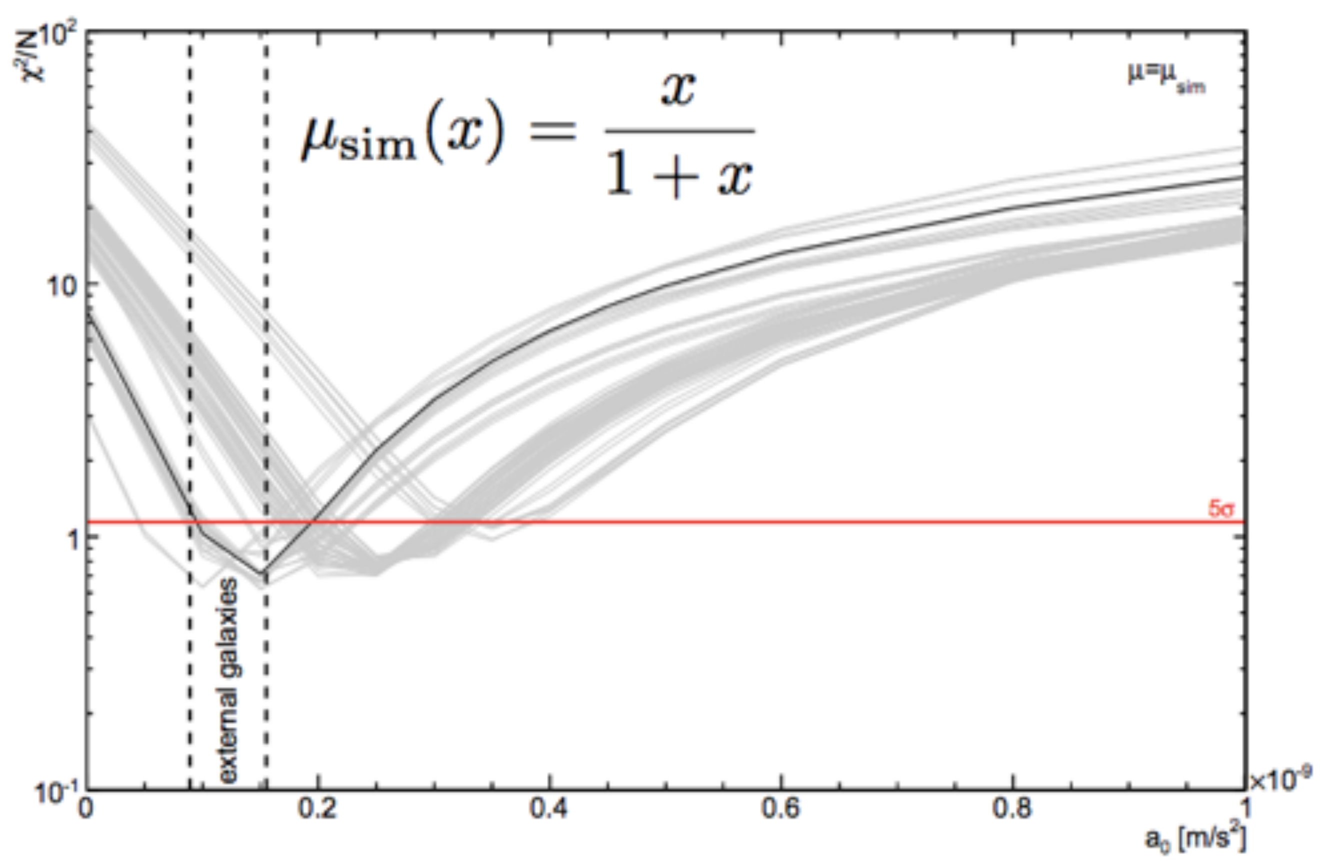
$$v_{Residual} = (v^2_{tot}-v^2_{bar})^{1/2}$$

Let us test Modified Gravity with the MW

Modified Newtonian dynamics
MOND

$$\mu\left(\frac{a}{a_0}\right) a = a_N$$





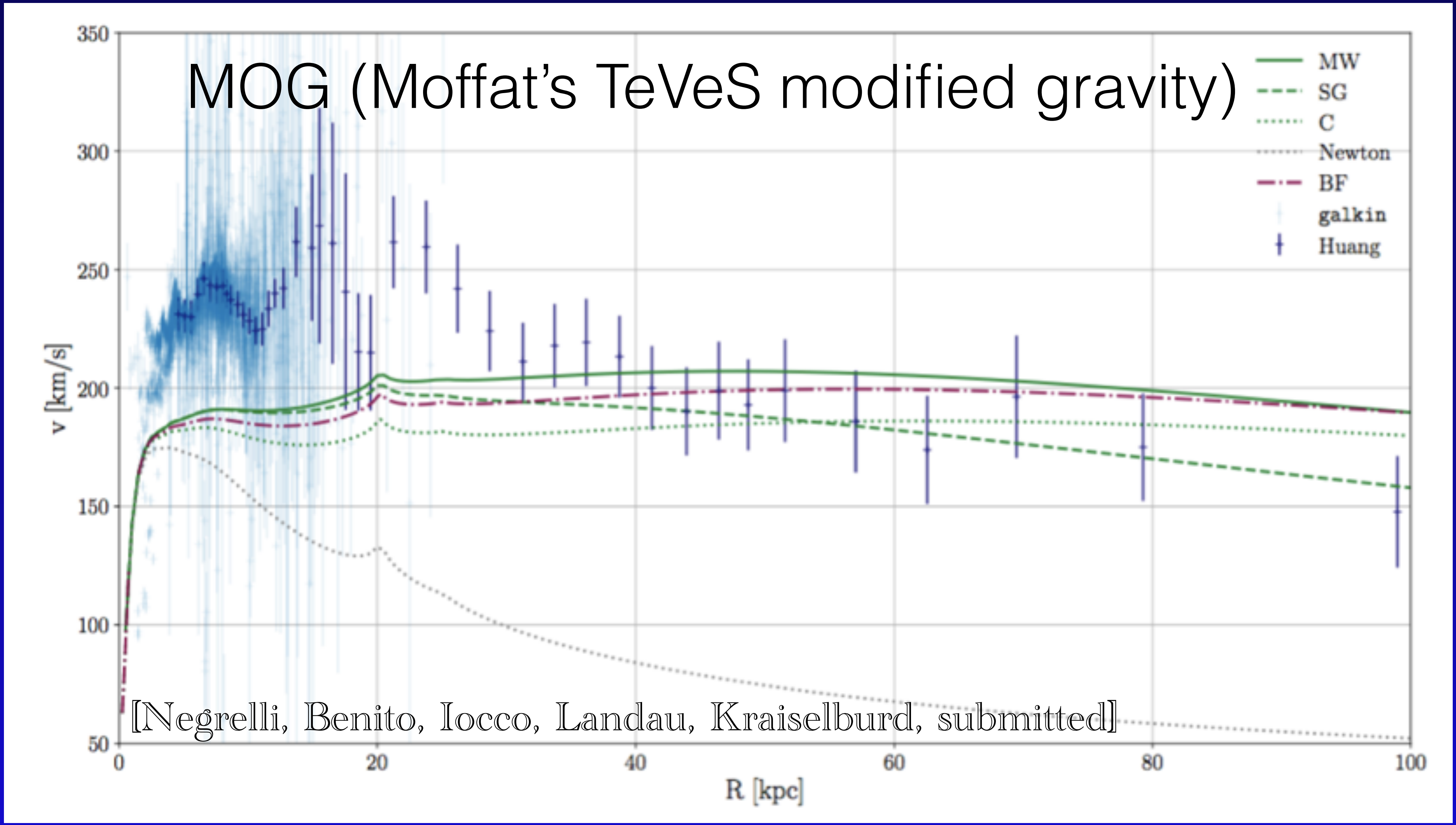
[Iocco, Pato, Bertone, PRD 2015]

Let us test Modified Gravity with the MW

$$\vec{a}(\vec{x}) = -G_N \int \frac{\rho(\vec{x}')(\vec{x}-\vec{x}')}{|\vec{x}-\vec{x}'|^3} \times \left[1+\alpha-\alpha e^{-\mu|\vec{x}-\vec{x}'|}(1+\mu|\vec{x}-\vec{x}'|)\right] d^3\vec{x}'.$$

$$\alpha = \frac{M}{(\sqrt{M}+E)^2}\left(\frac{G_\infty}{G_N}-1\right)$$

$$\mu = \frac{D}{\sqrt{M}},$$



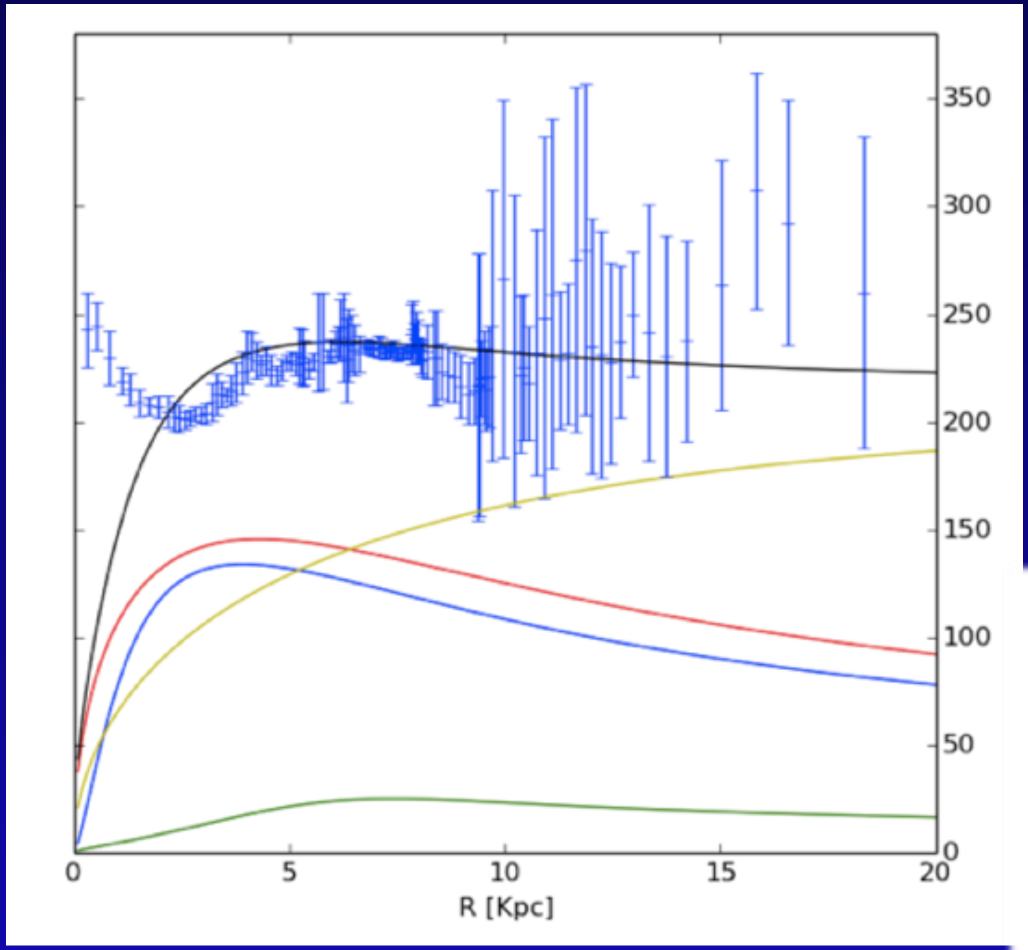
MOG (Moffat's TeVeS modified gravity)

[Negrelli, Benito, Iocco, Landau, Kraiselburd, submitted]

The Milky Way

inferring the relevant astrophysical quantities

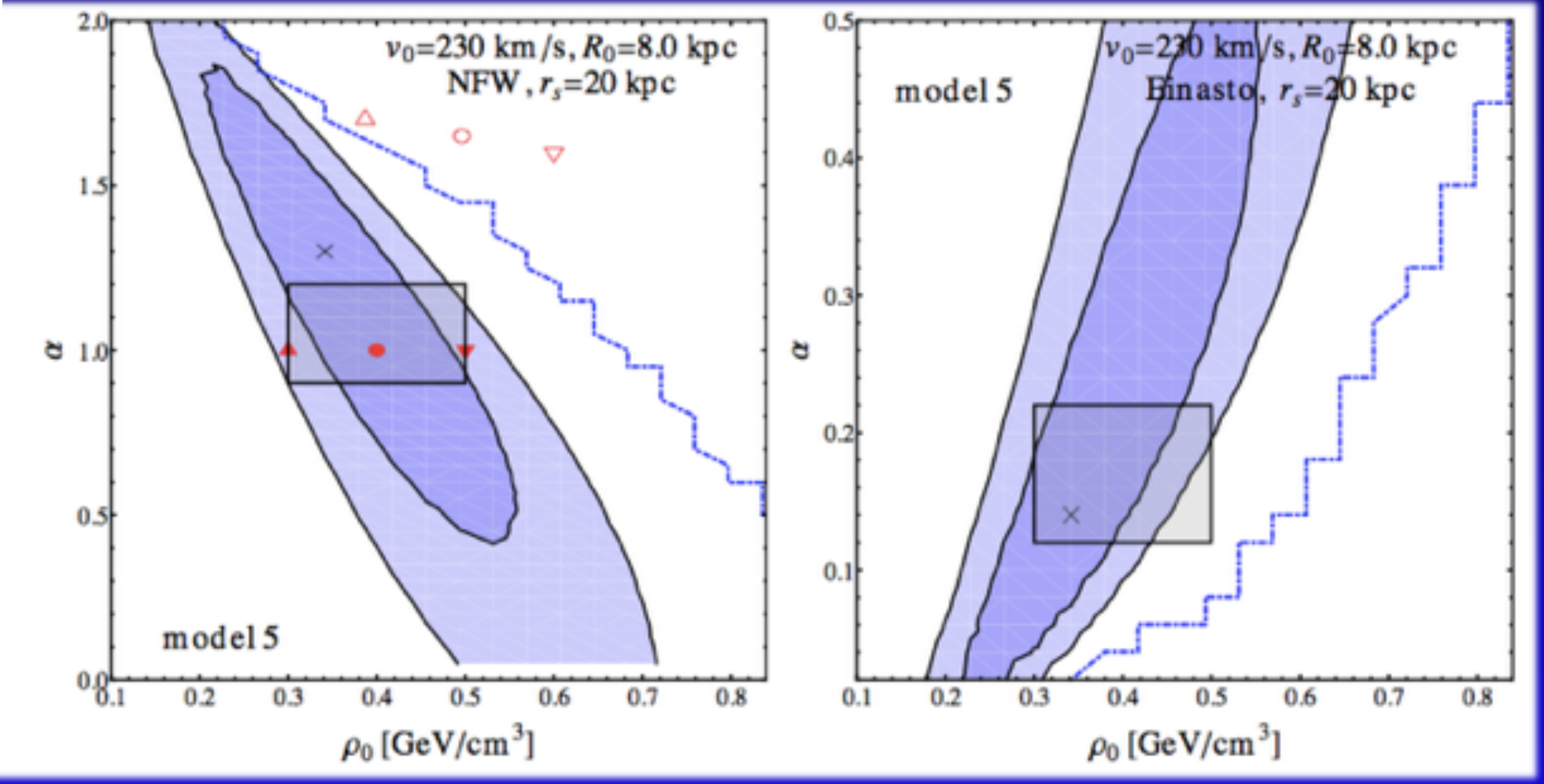
Fitting a pre-assigned shape
on top of baryons



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

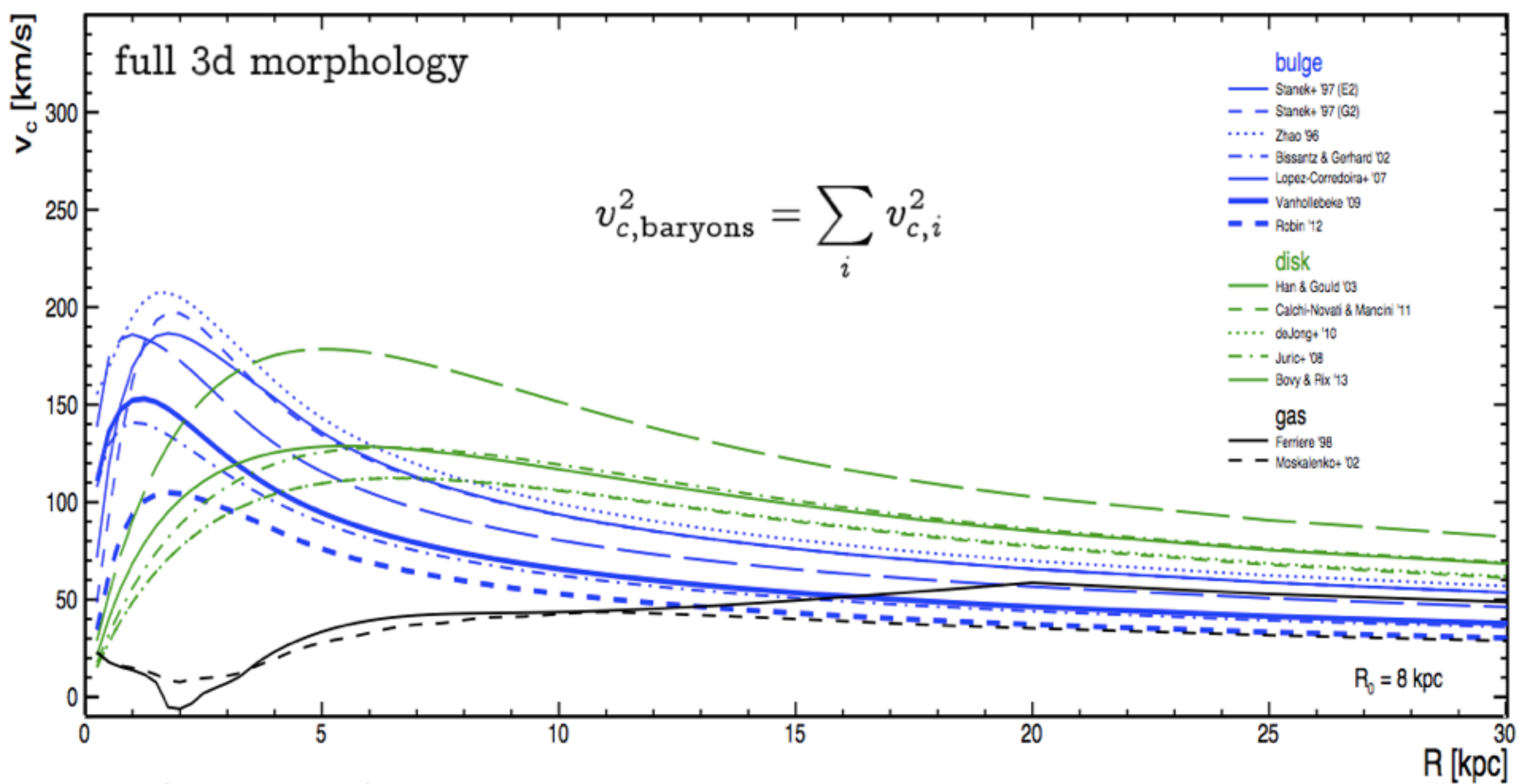
$$\rho_{DM}(R) \propto \rho_0 \exp\left[-\frac{2}{\gamma}\left(\left(\frac{R}{R_s}\right)^{\gamma} - 1\right)\right]$$

Most popular are
gNFW Einasto



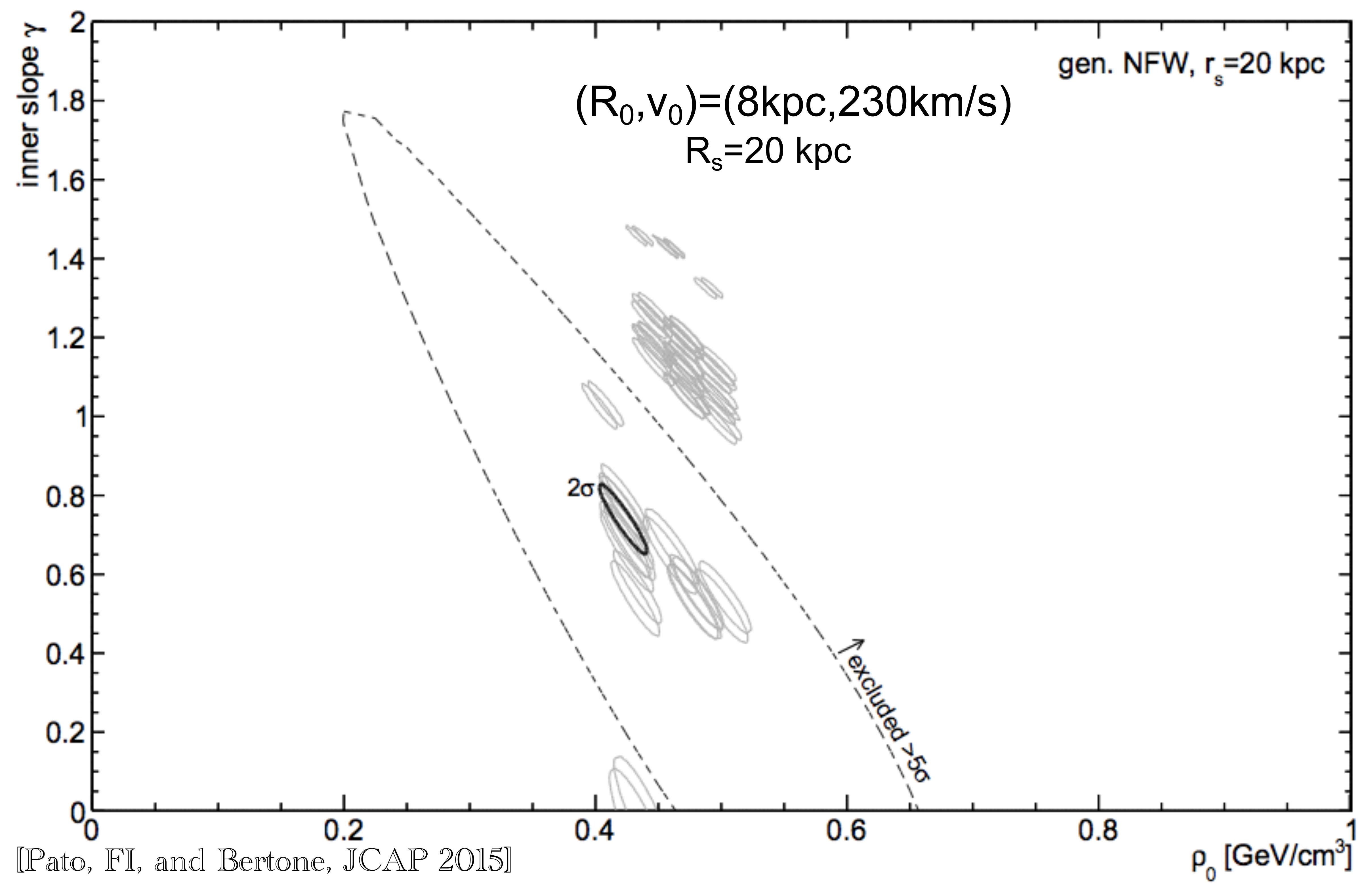
There’s more than you are usually told: visible morphology is uncertain

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



[Iocco, Pato, Bertone, Nature Physics 2015]

Morphology does affect determination of crucial quantities

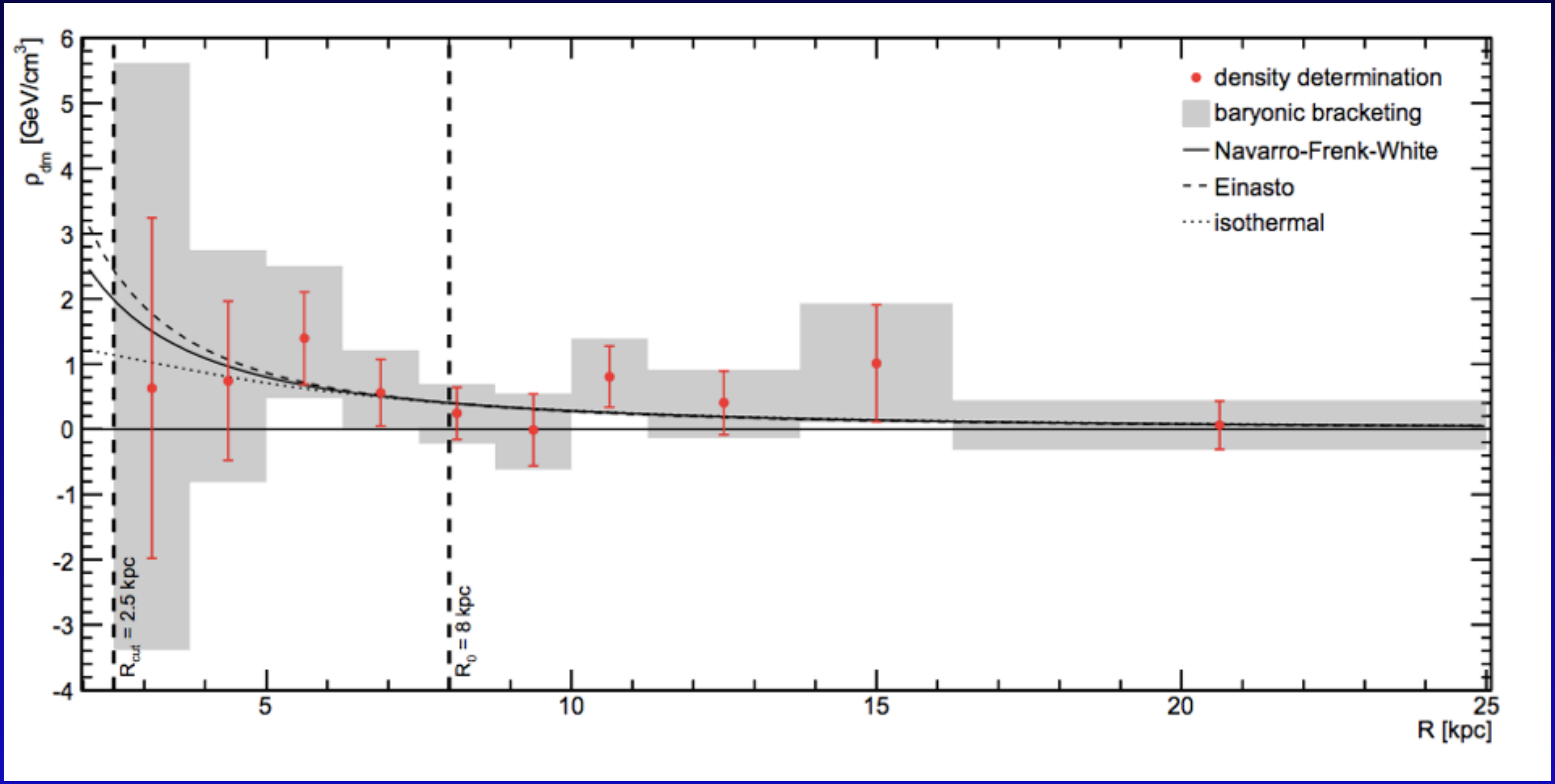


(R_0,v_0)=(8kpc,230km/s)

R_s=20 kpc

[Pato, FI, and Bertone, JCAP 2015]

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

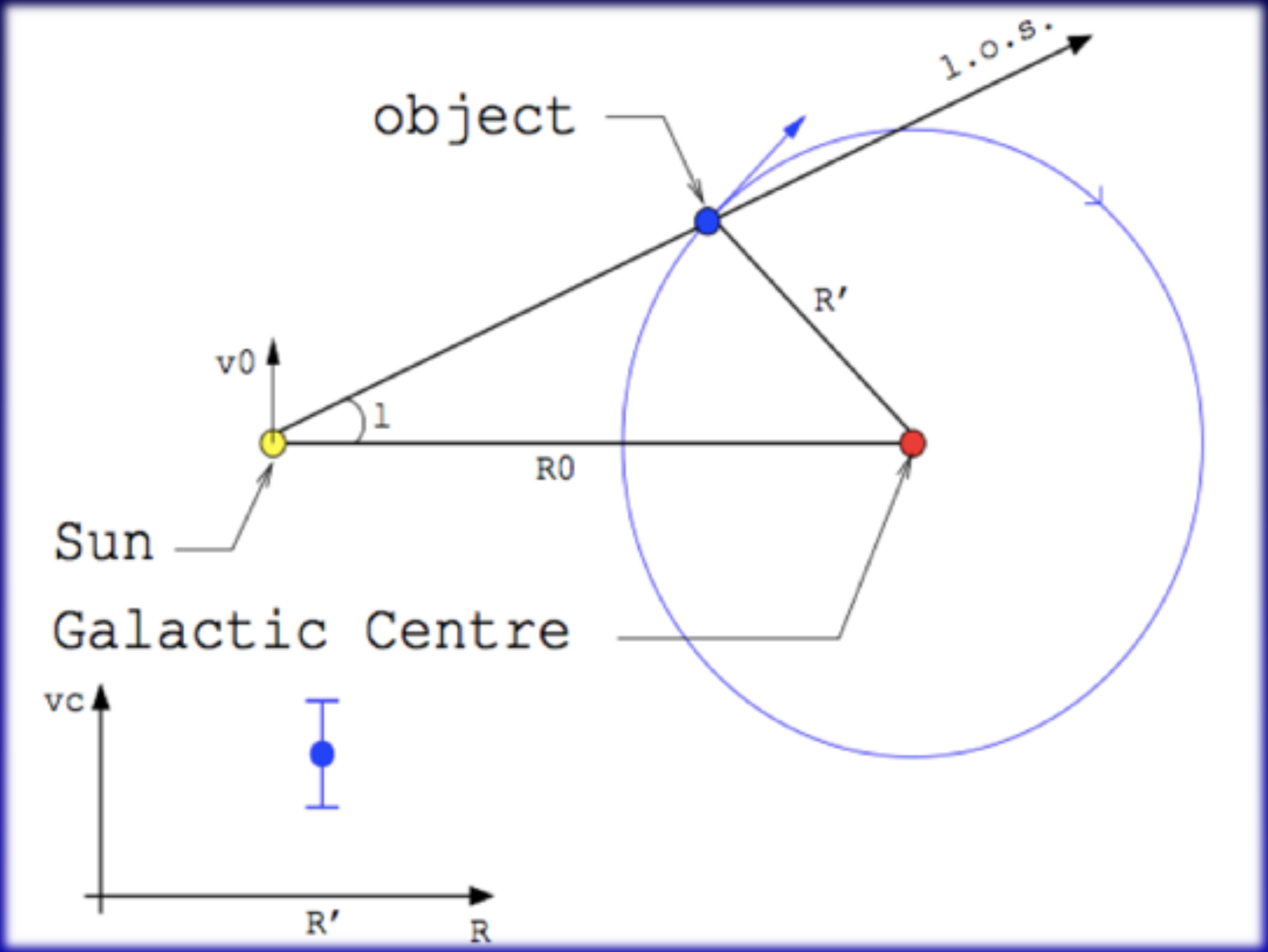


[Pato & FI, 2015]

The Milky Way:

observed rotation curve

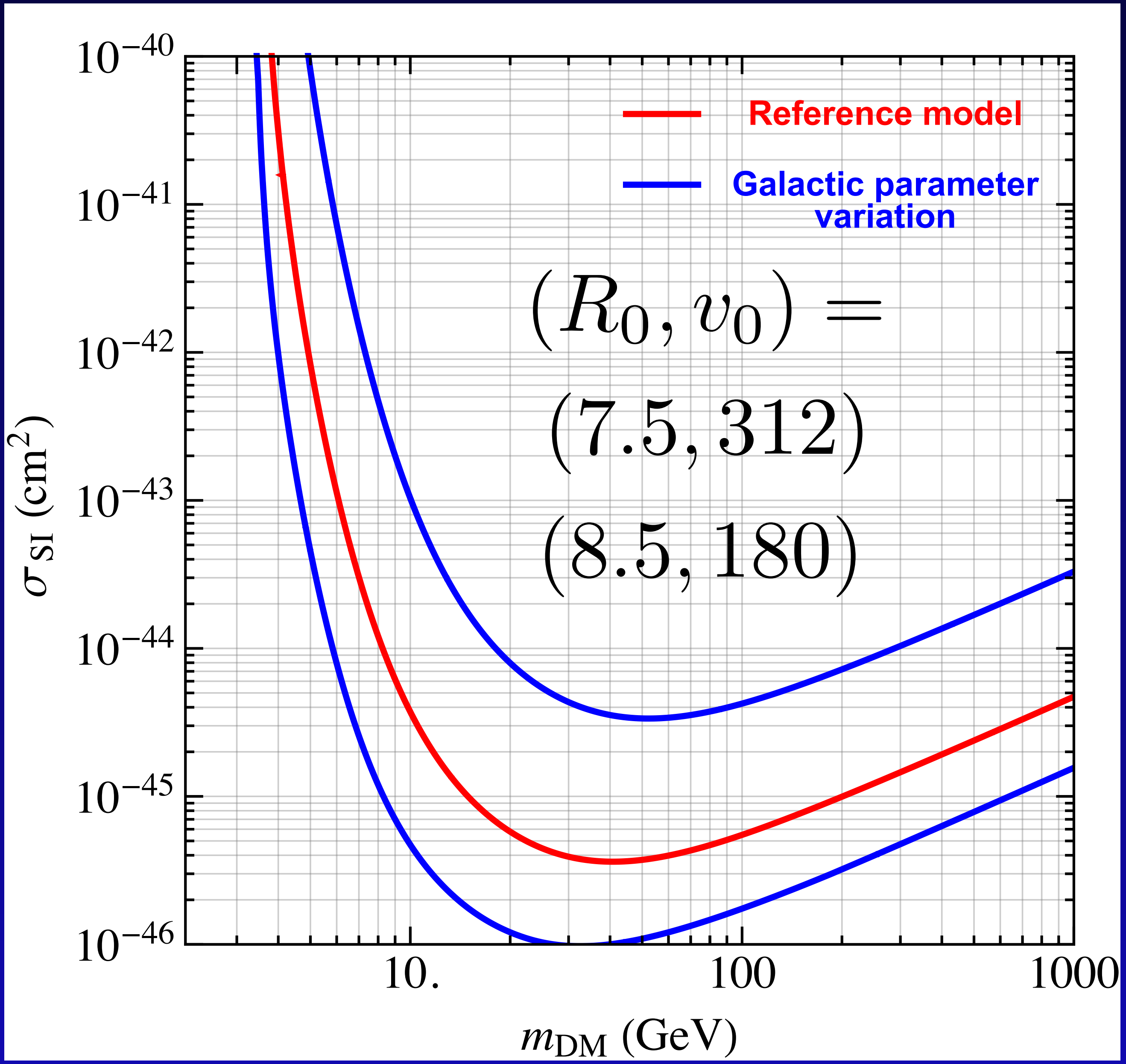
I. principles



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

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

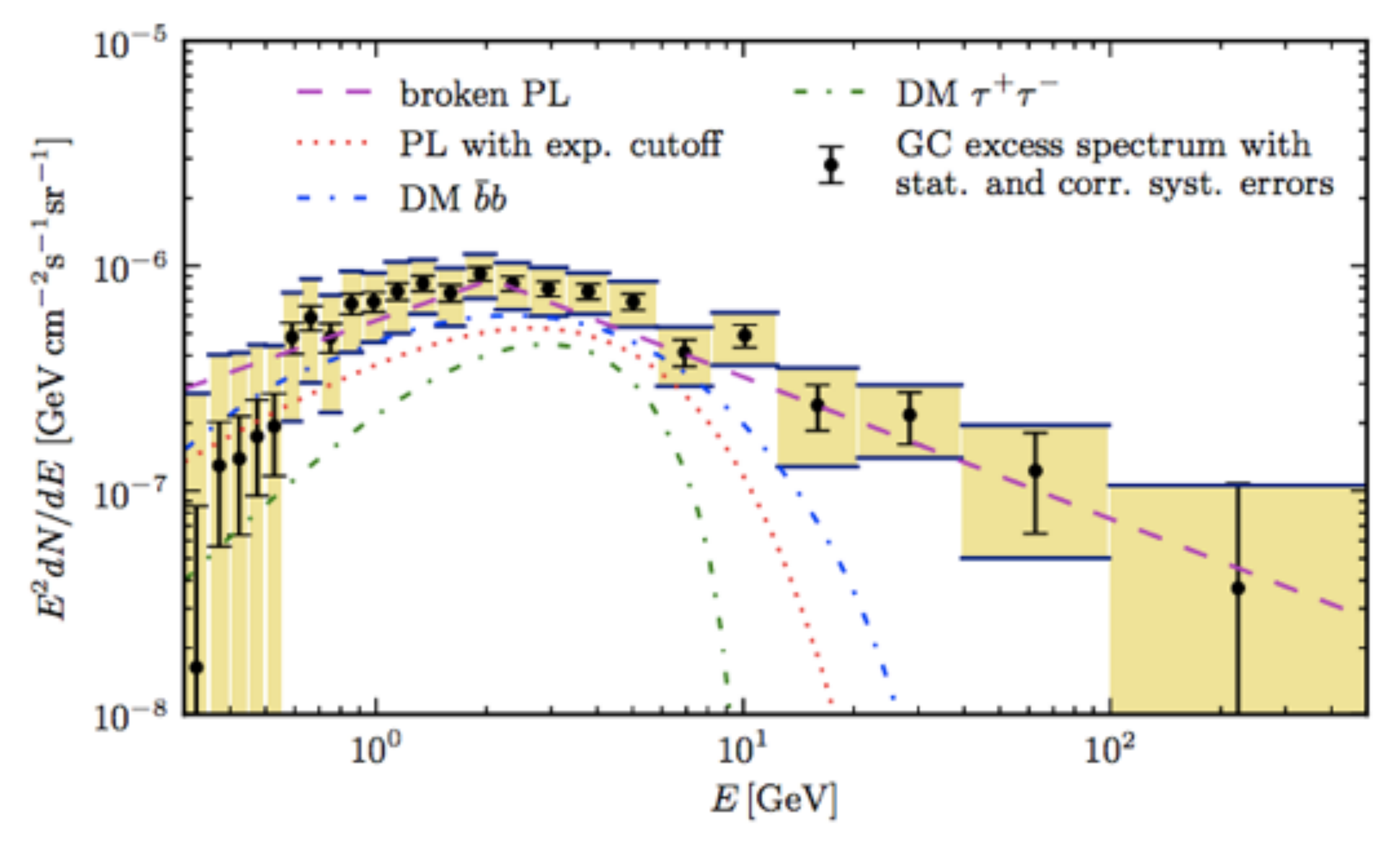
It is well known that uncertainties affect Direct Detection



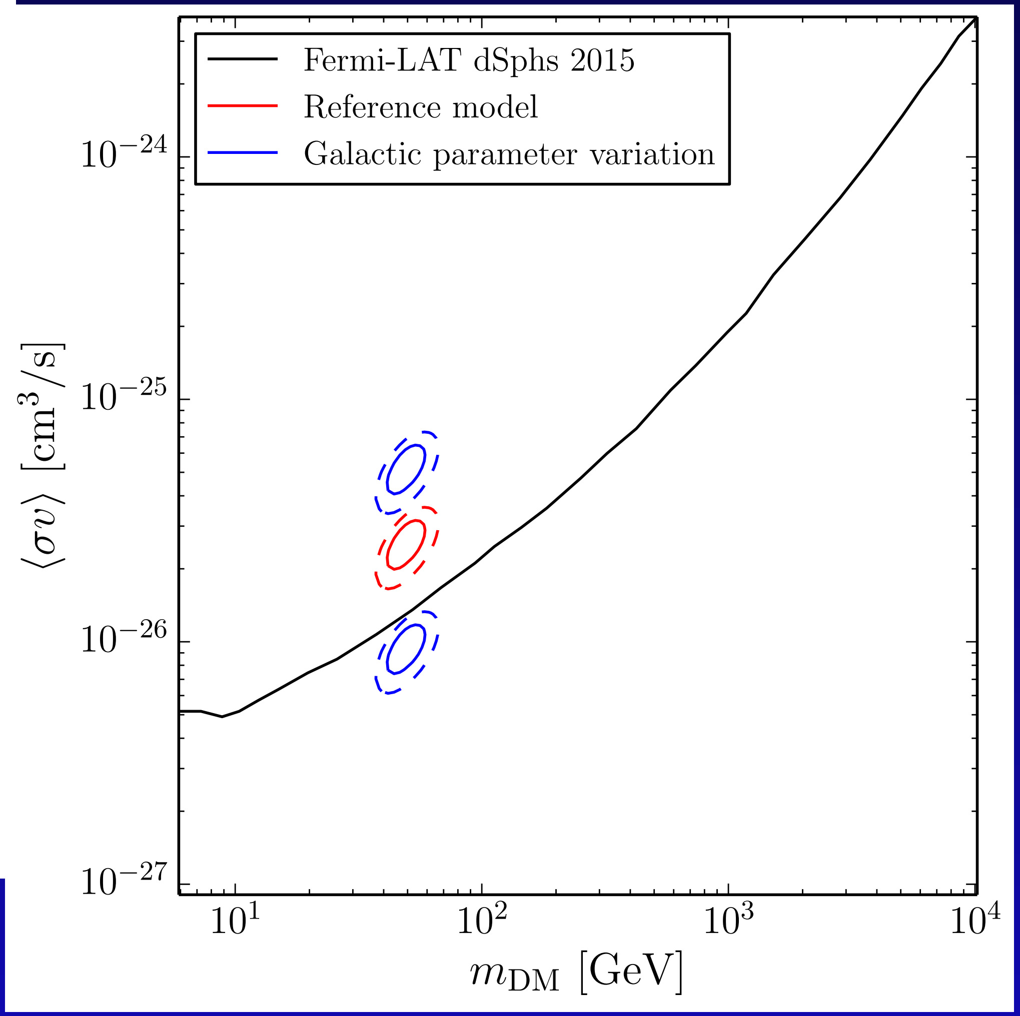
Current LUX limits, varying astrophysical uncertainties

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

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

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

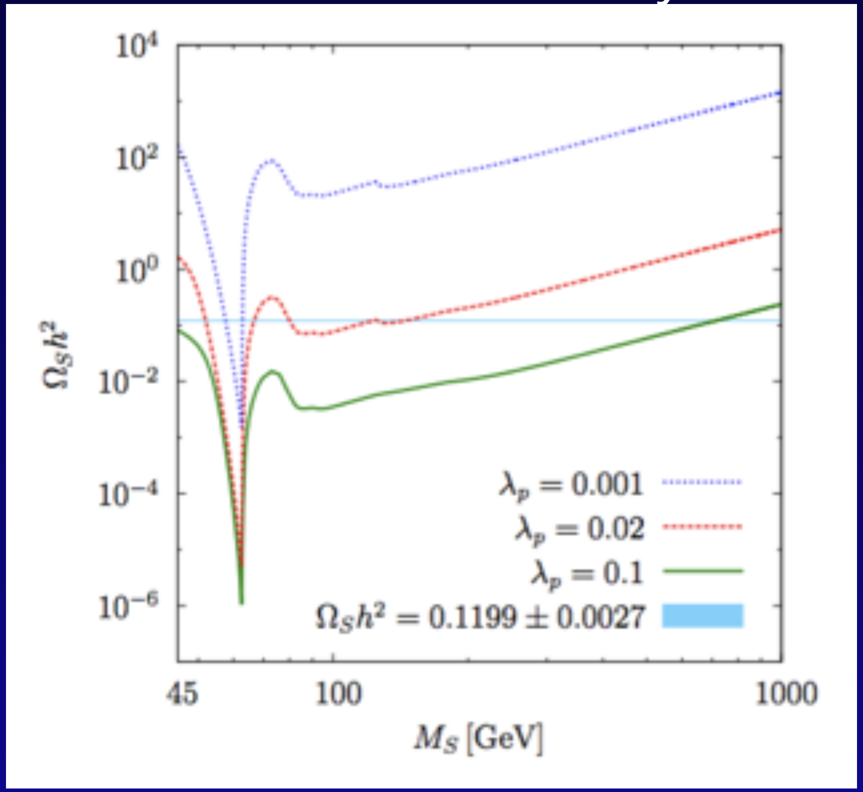
$v_H = 246\ \mathrm{GeV}$ $\langle S \rangle = 0$

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

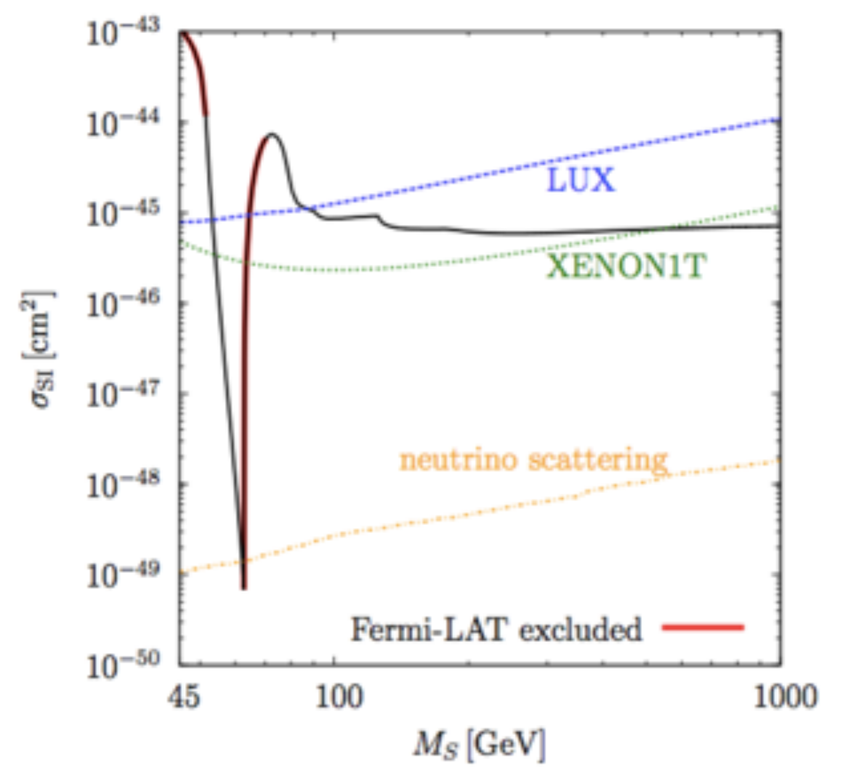
"Wimp phenomenology" entirely dictated by the Higgs coupling and physical DM mass.

Constraints and interplay of experiments

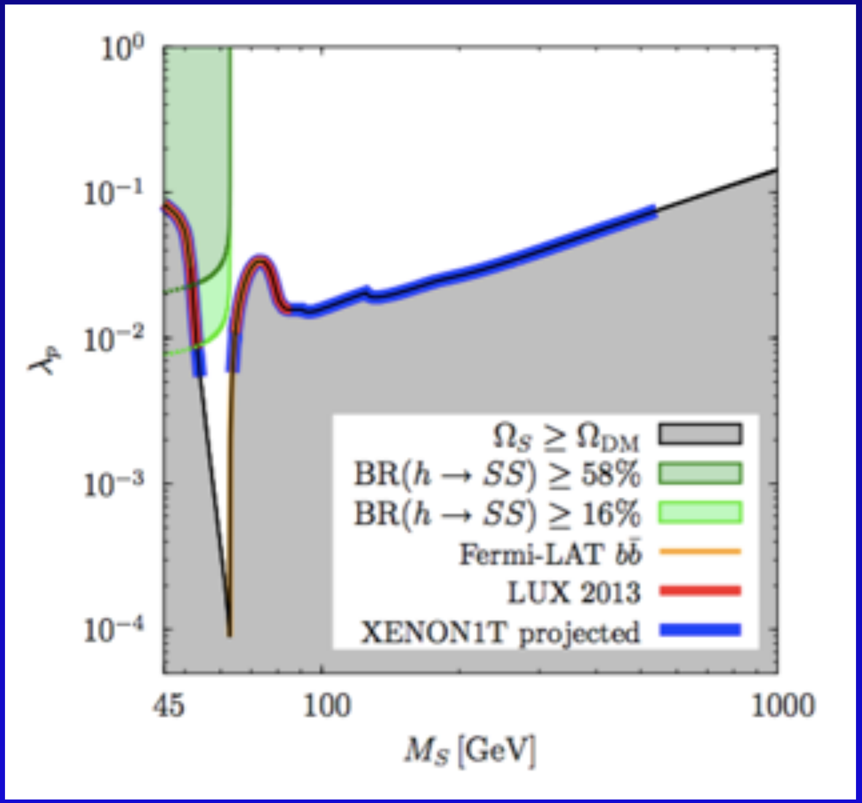
Relic density



Direct detection



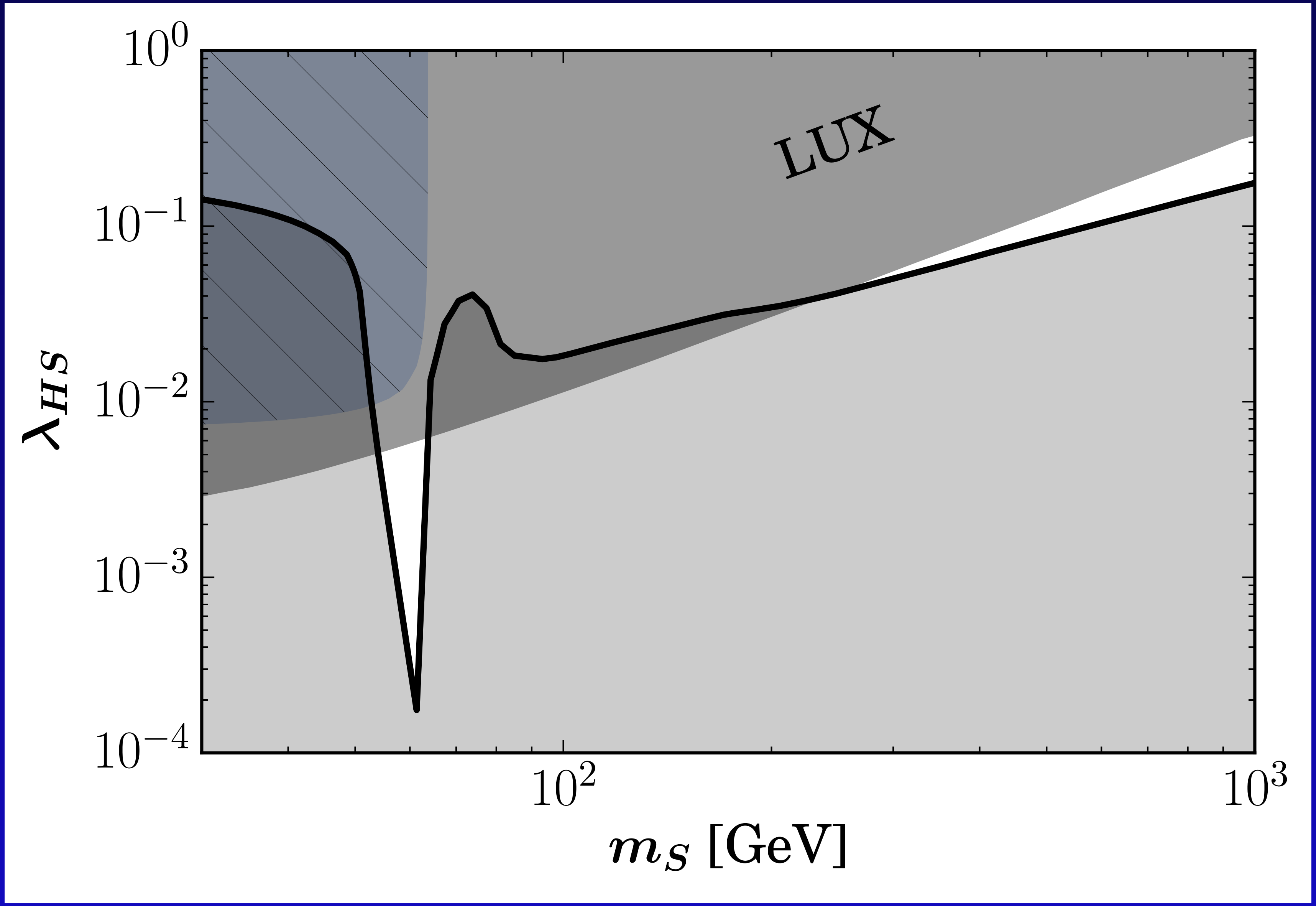
Combined



[Duerr et al, 2015]

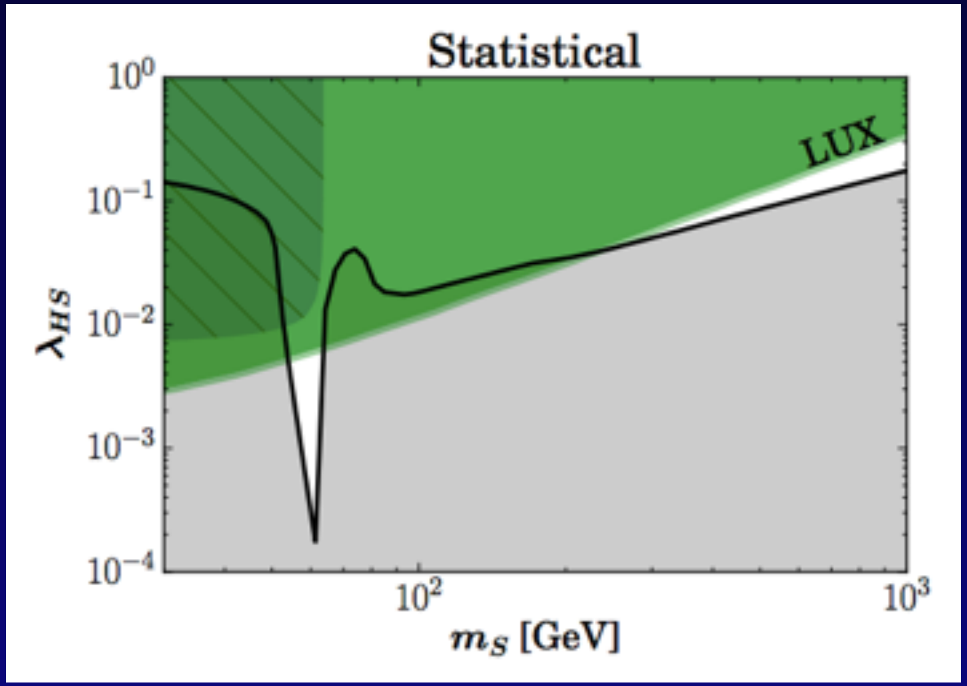
Constraints and interplay of experiments

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



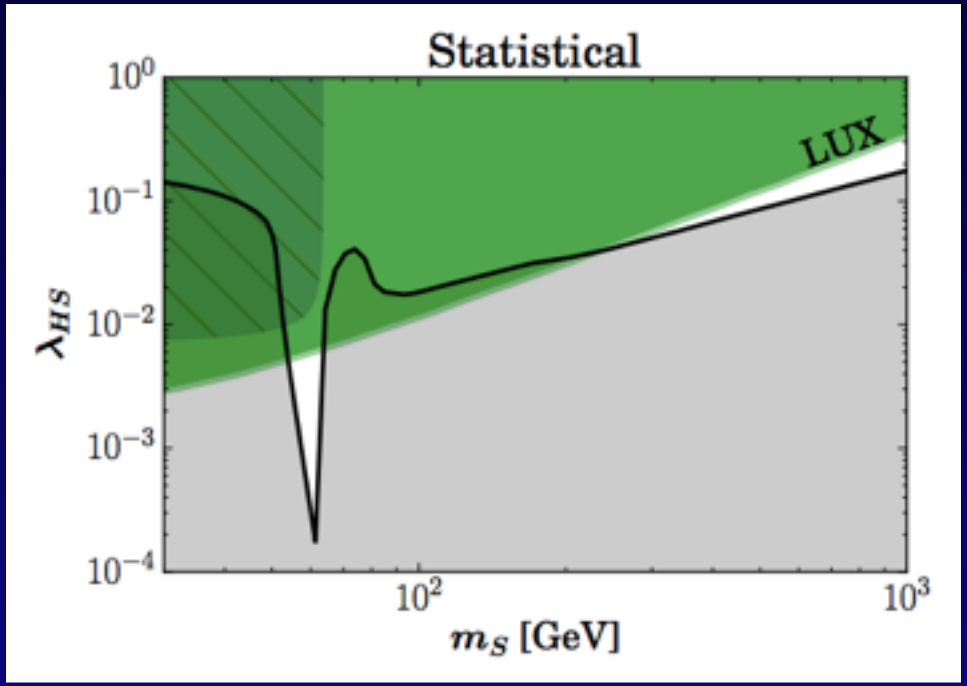
[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

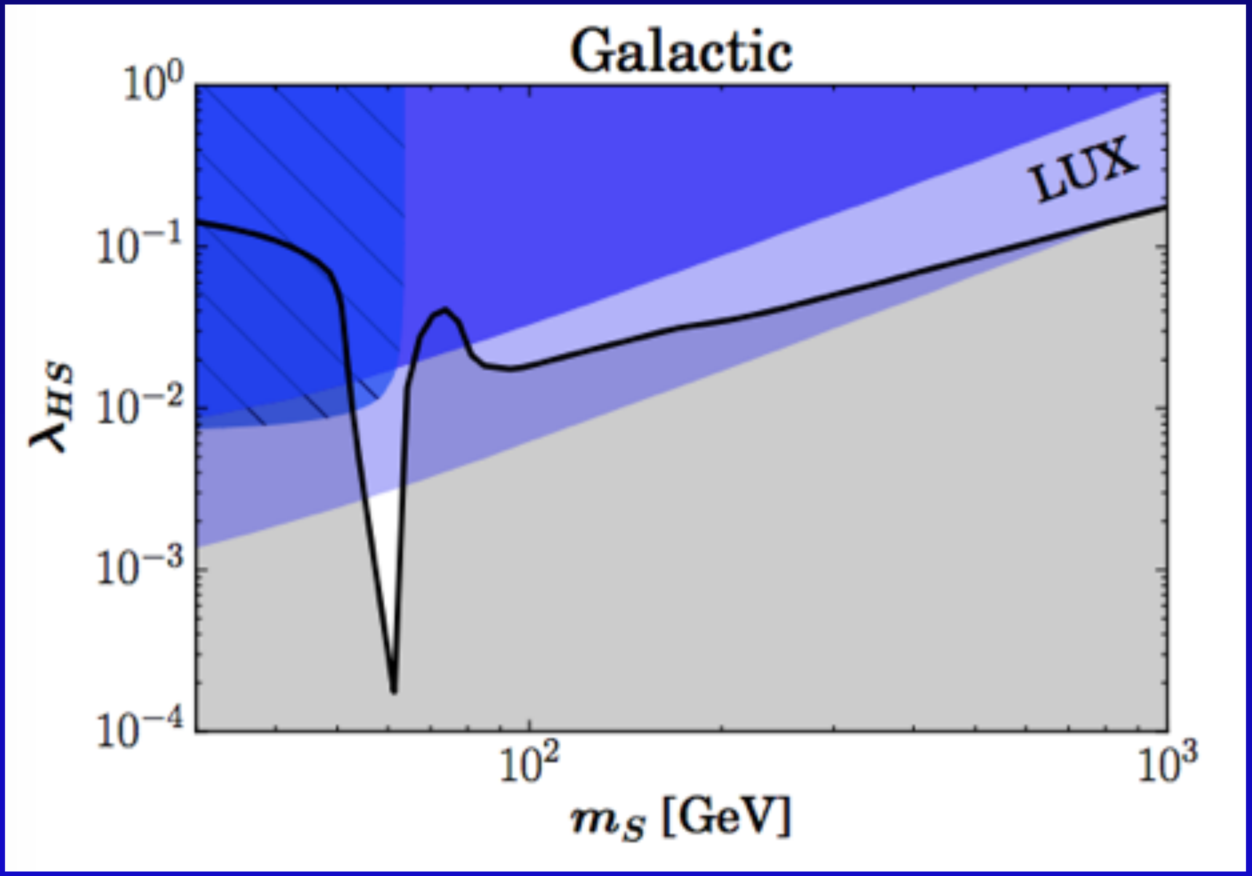
Let's look at the effect of astrophysics uncertainties: Direct Detection

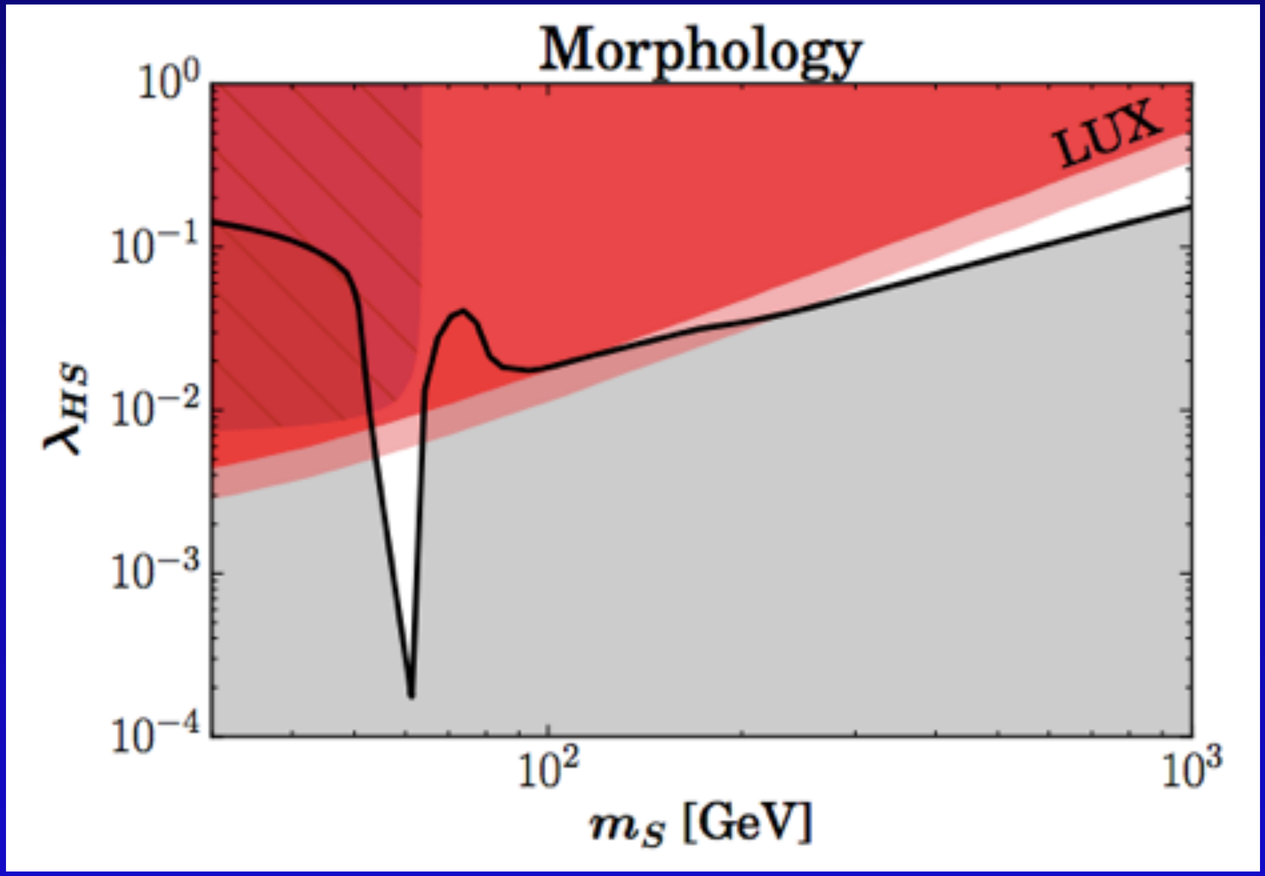


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

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

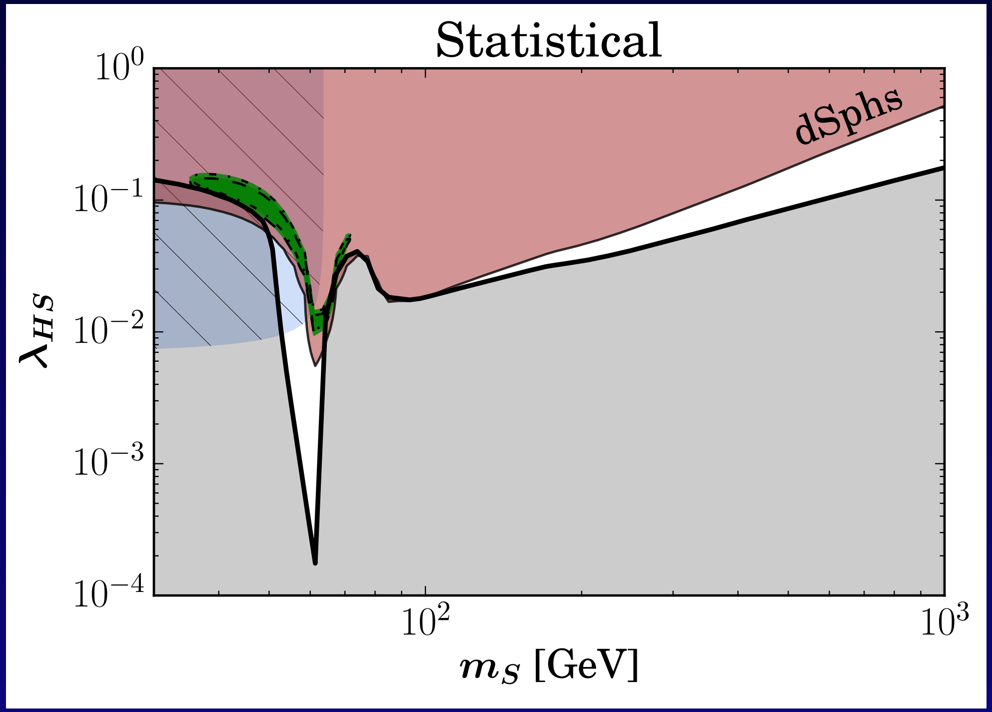


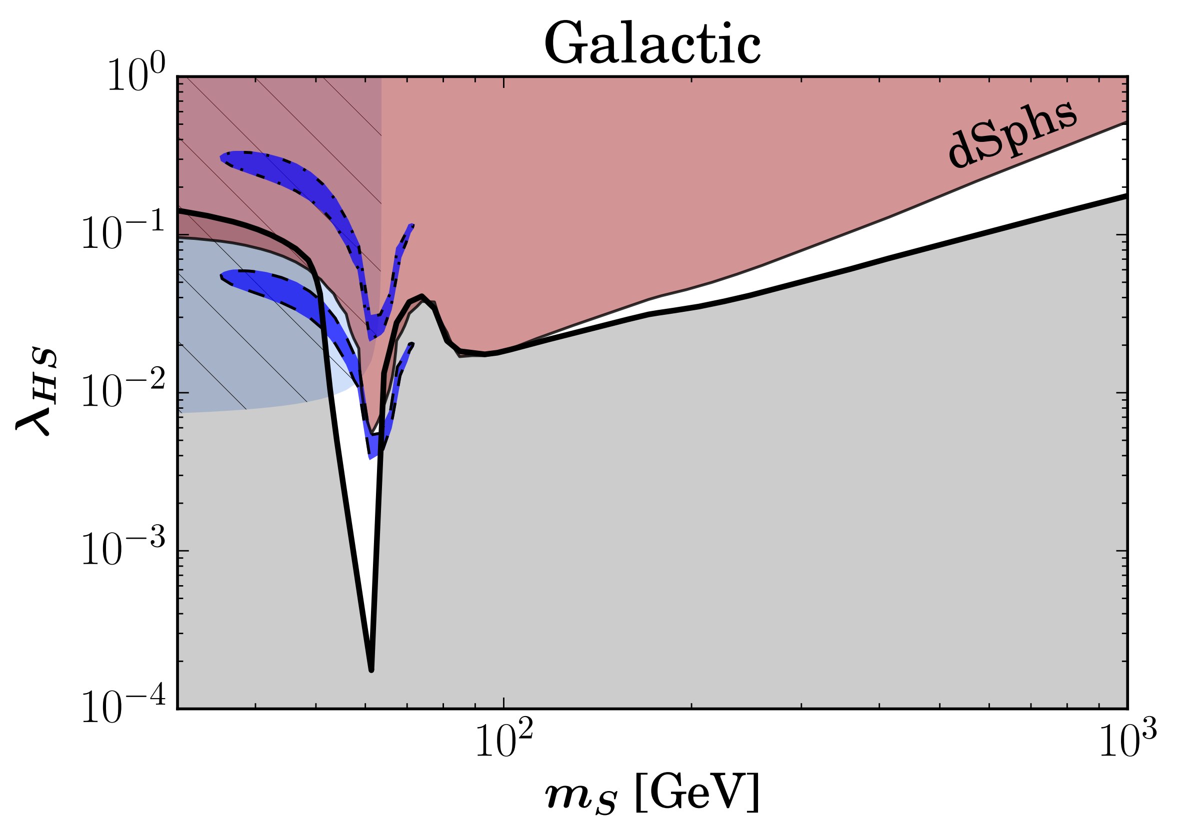


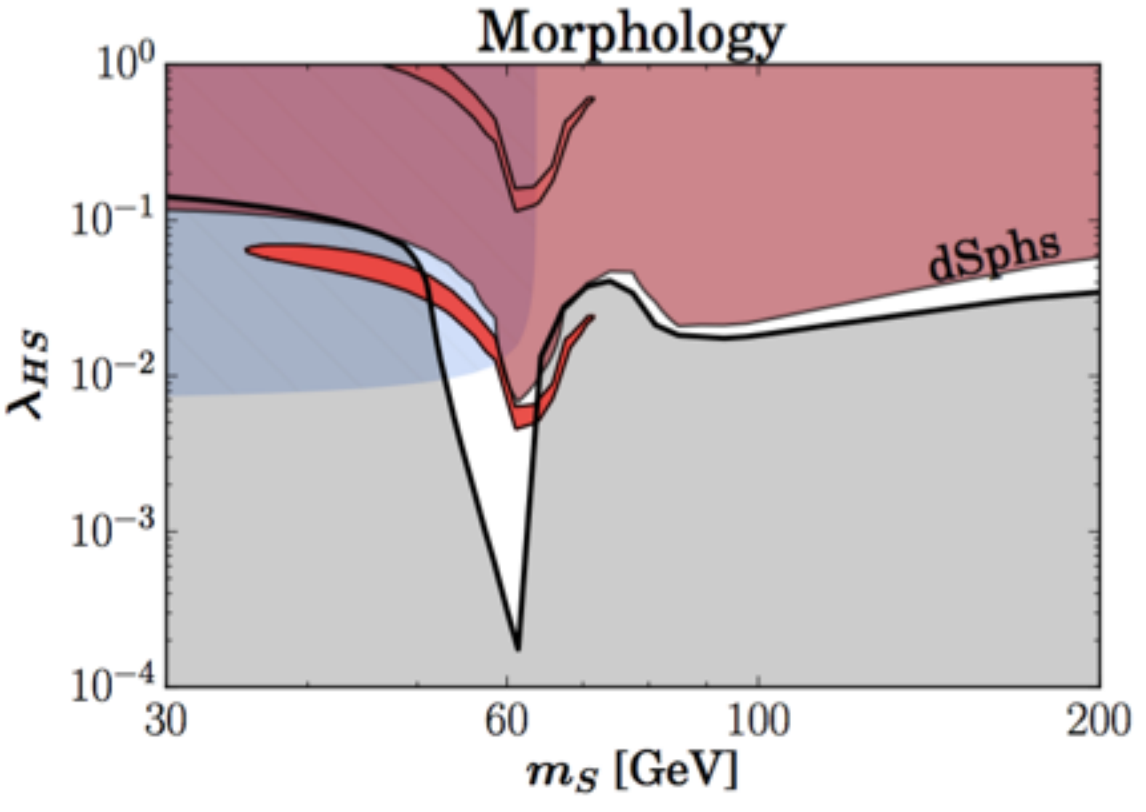


[Benito, Bernàl, Bozorgnia, Calore, Iocco, JCAP 2017; arXiv:1612.02010]

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

ICTP SAIFR 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