Dark Matter in the Milky Way

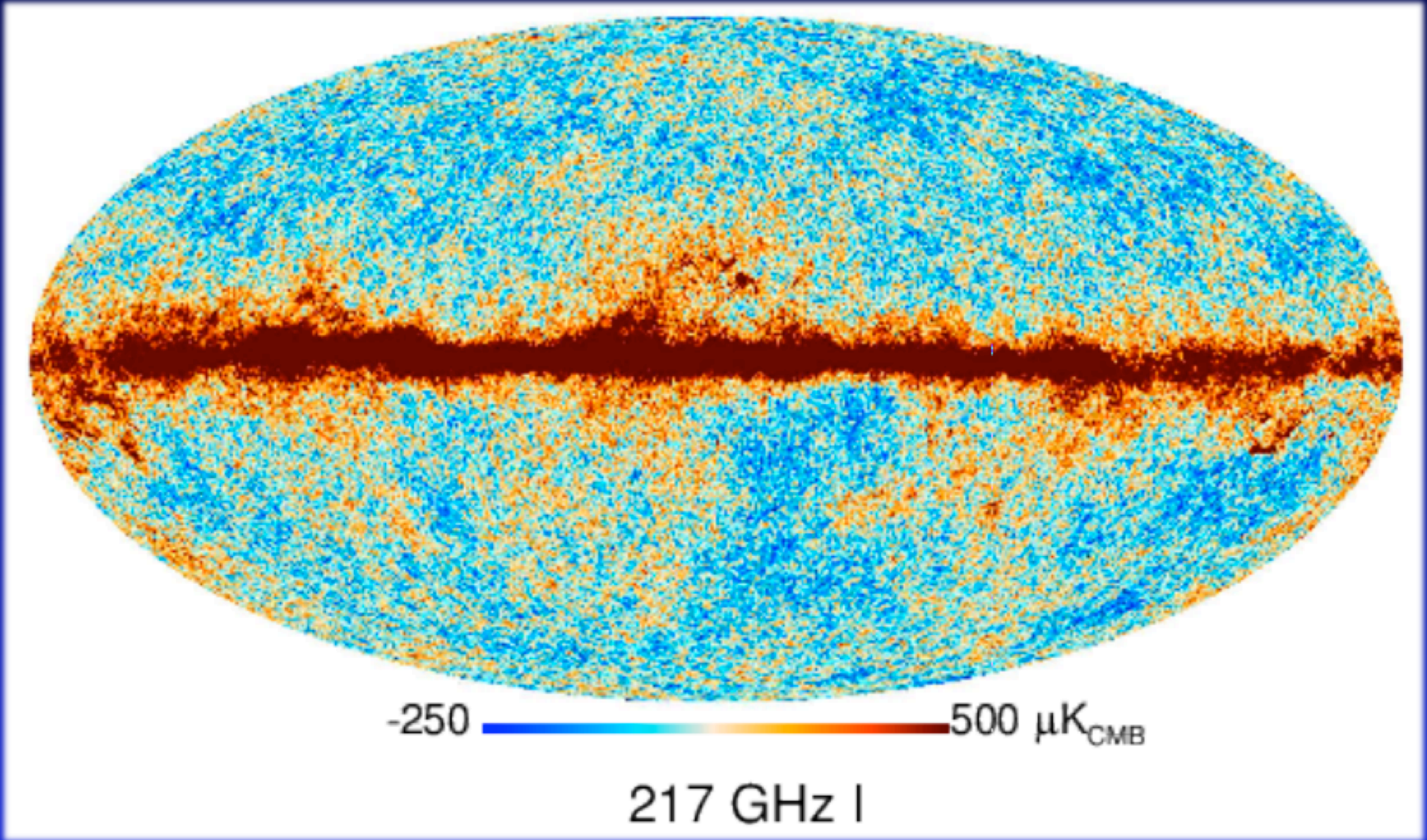
Fabio Iocco

ICTP-SAIFR
IFT-UNESP
São Paulo

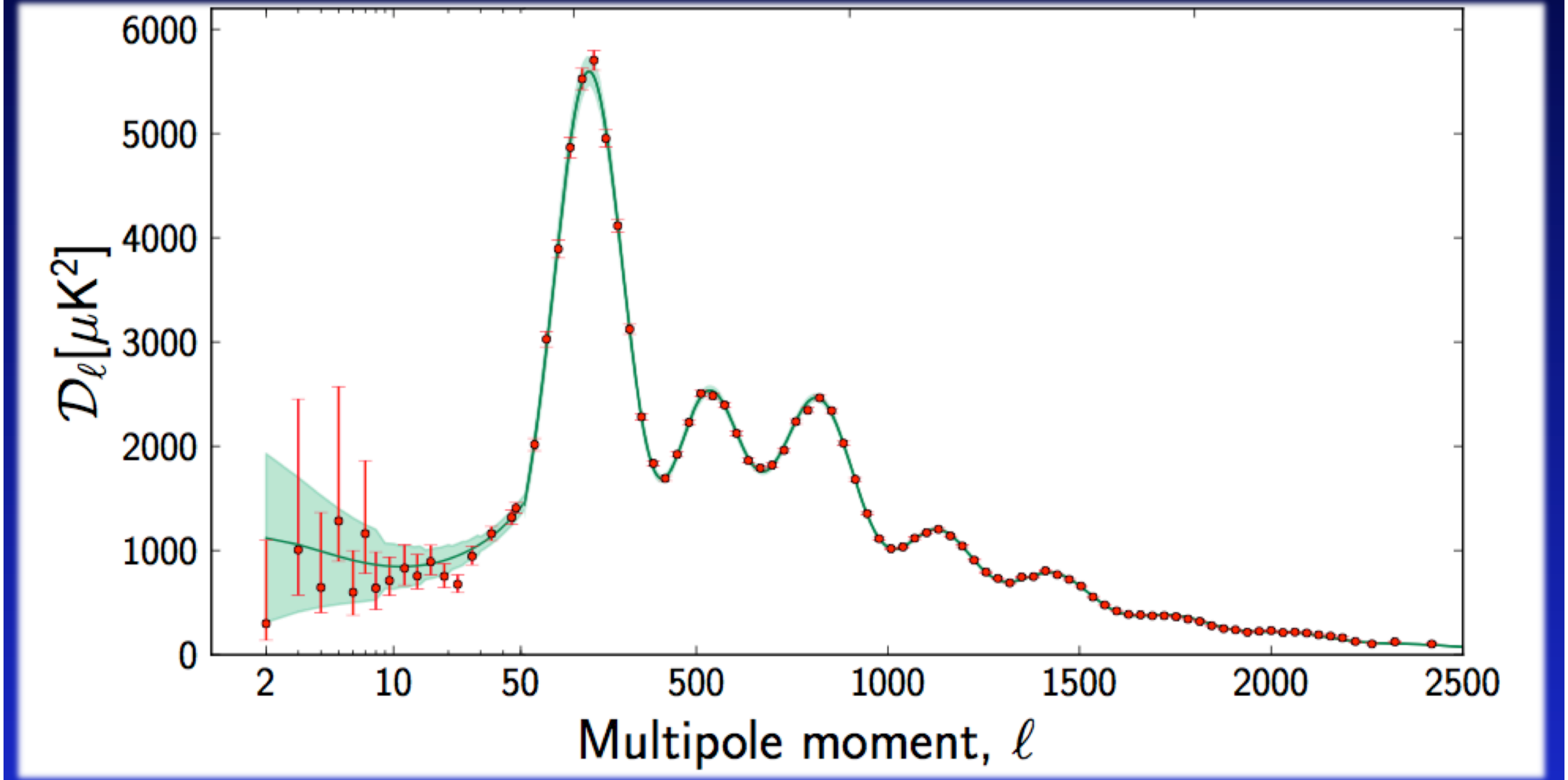
ICTP SAIFR
International Centre for Theoretical Physics
South American Institute for Fundamental Research

MPP, Munich
24/05/16

CMB, a dark matter probe



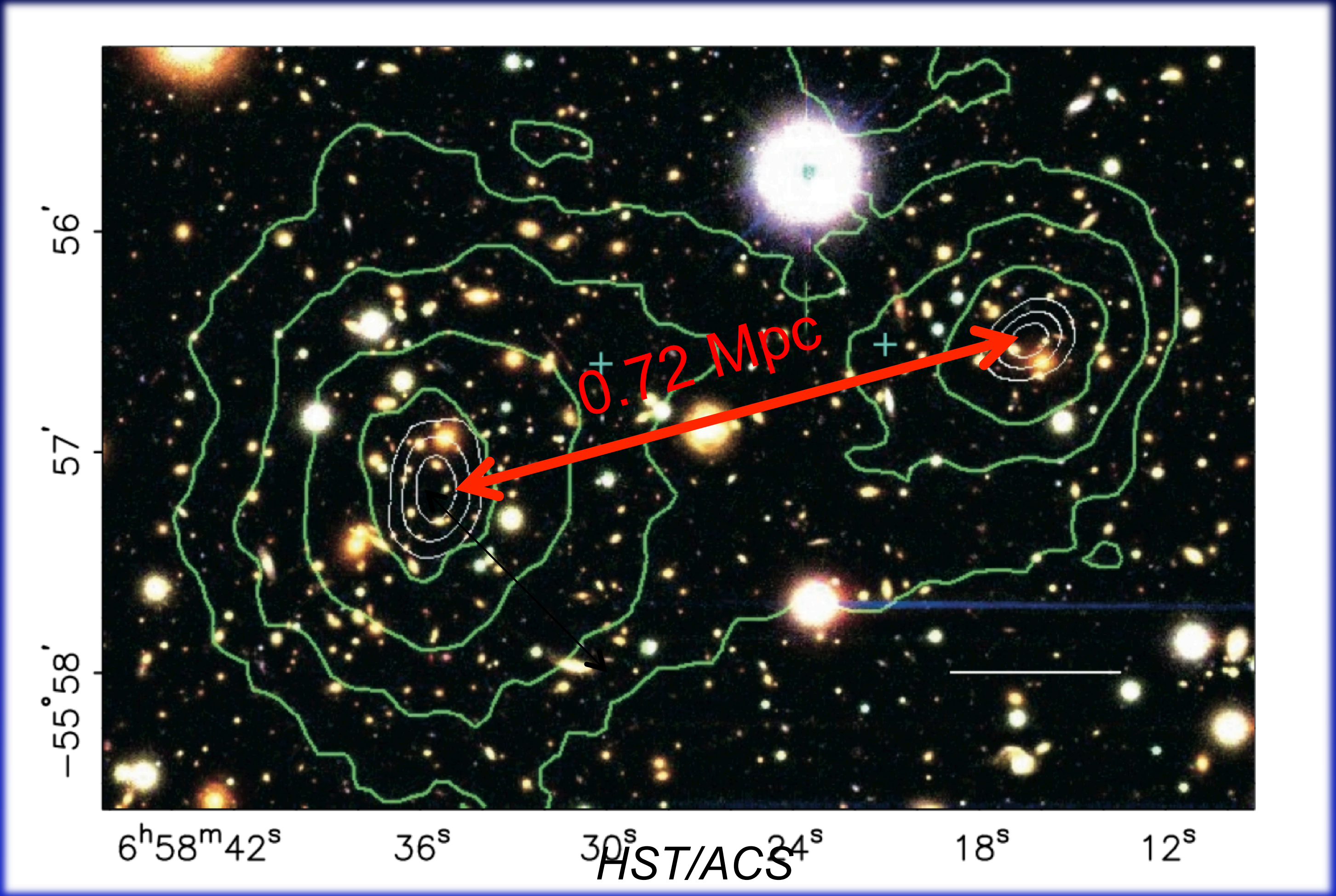
CMB2: power spectrum



ω_m and ω_{bar} from CMB only

The “Bullet Cluster”

1E 0657-558



HST/ACS

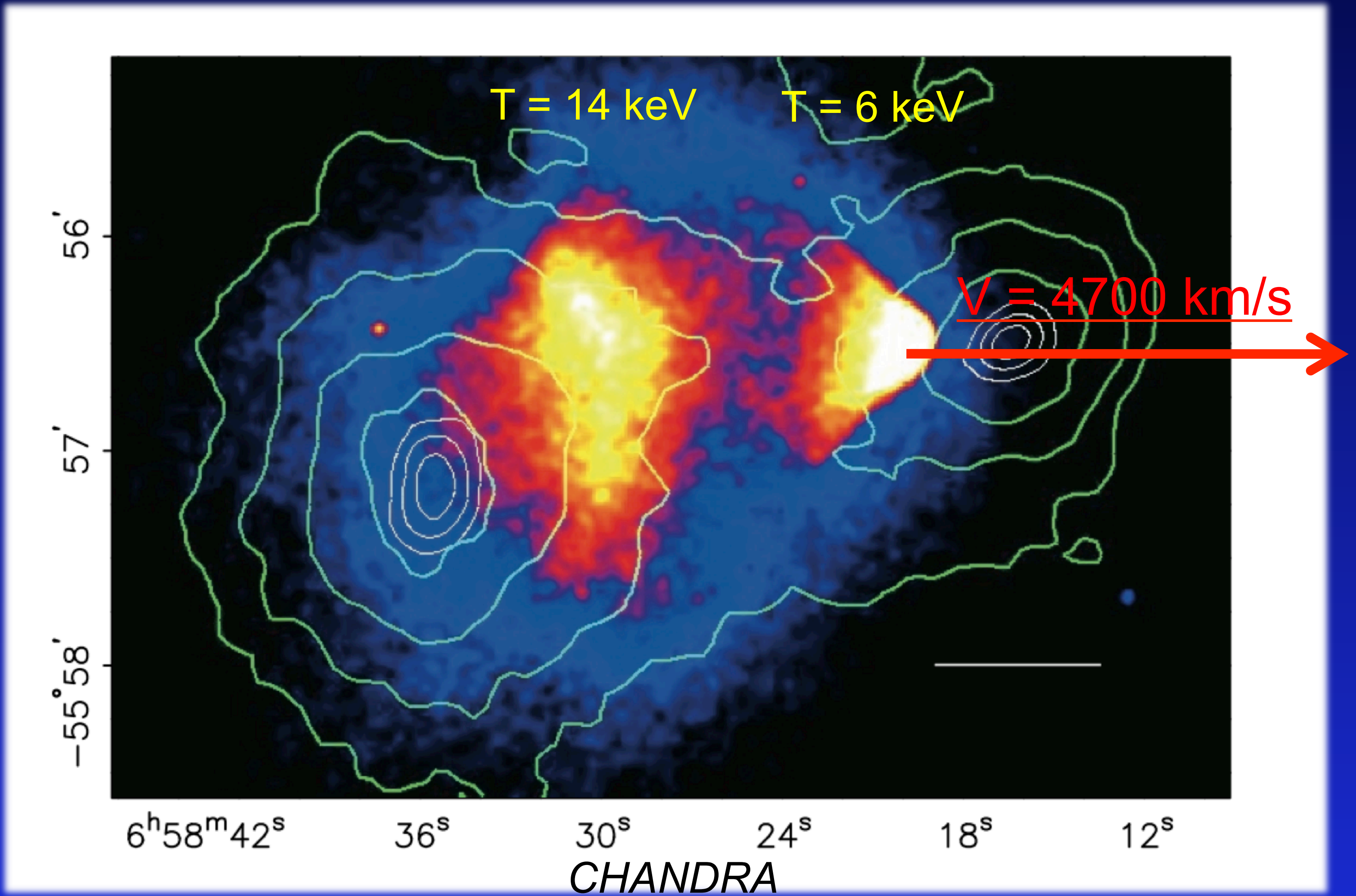
Z = 0.296

collision in the plane of the sky

[Markevitch et al. `06]

The “Bullet Cluster”

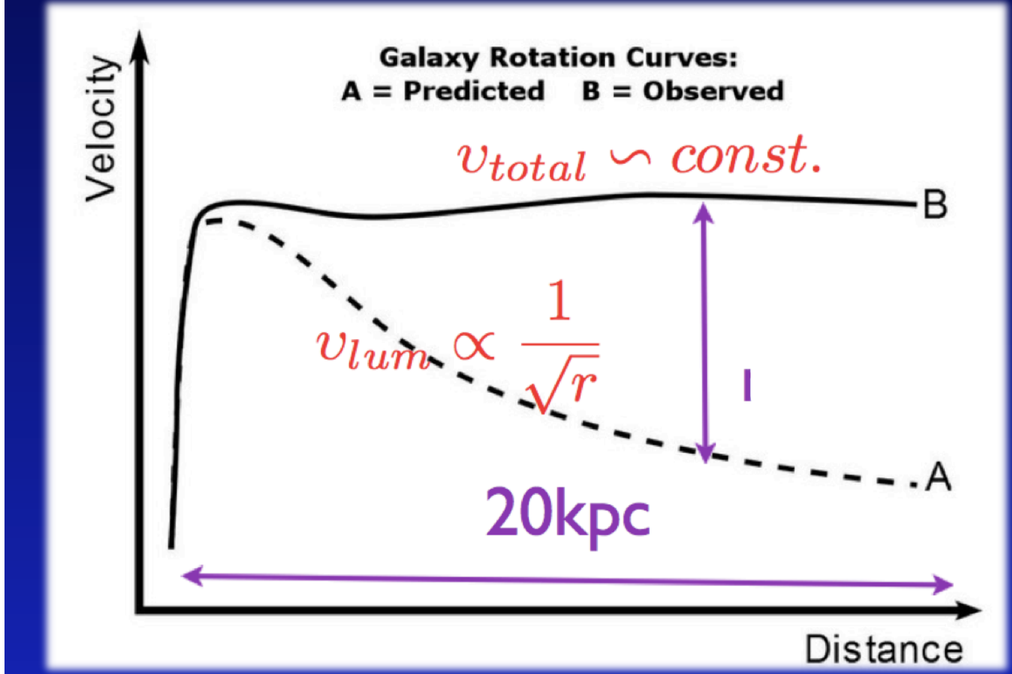
1E 0657-558

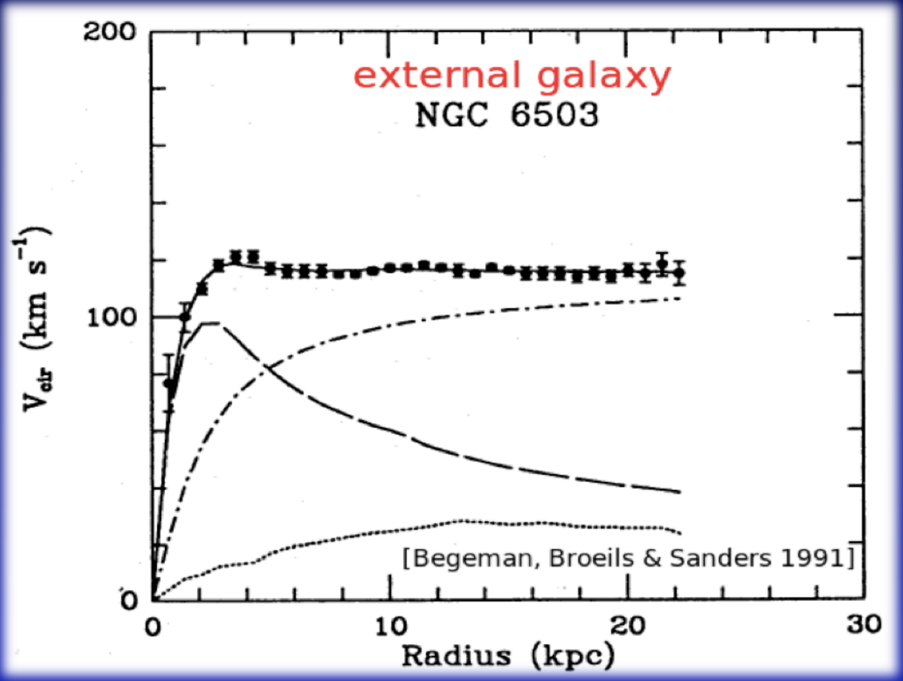


CHANDRA

Merger 100 Myr ago

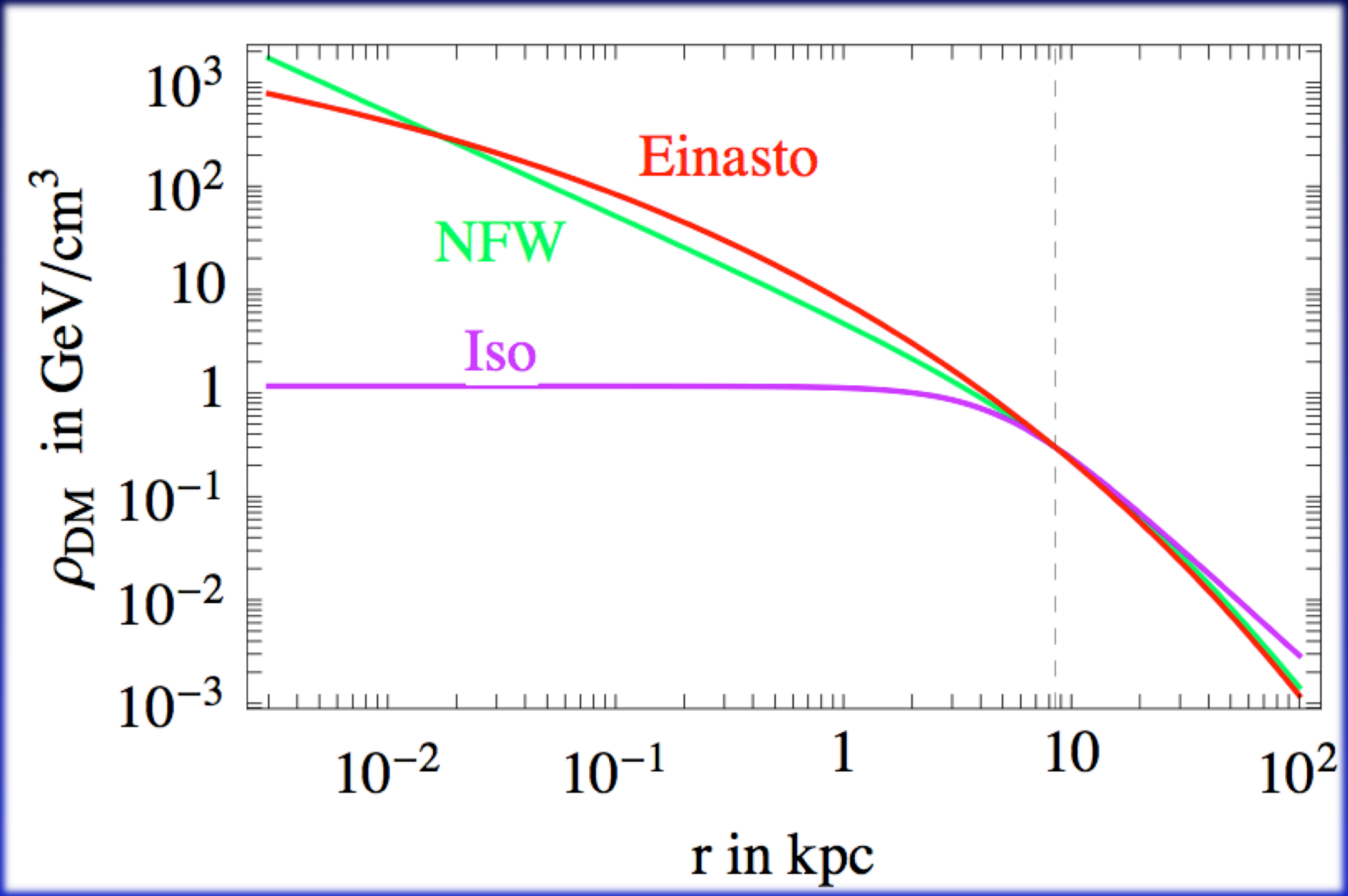
Spiral Galaxies rotation curves: the evergreen classic





discrepancy between observed and predicted (from visible matter only)

DM distribution is a crucial ingredient of LCDM



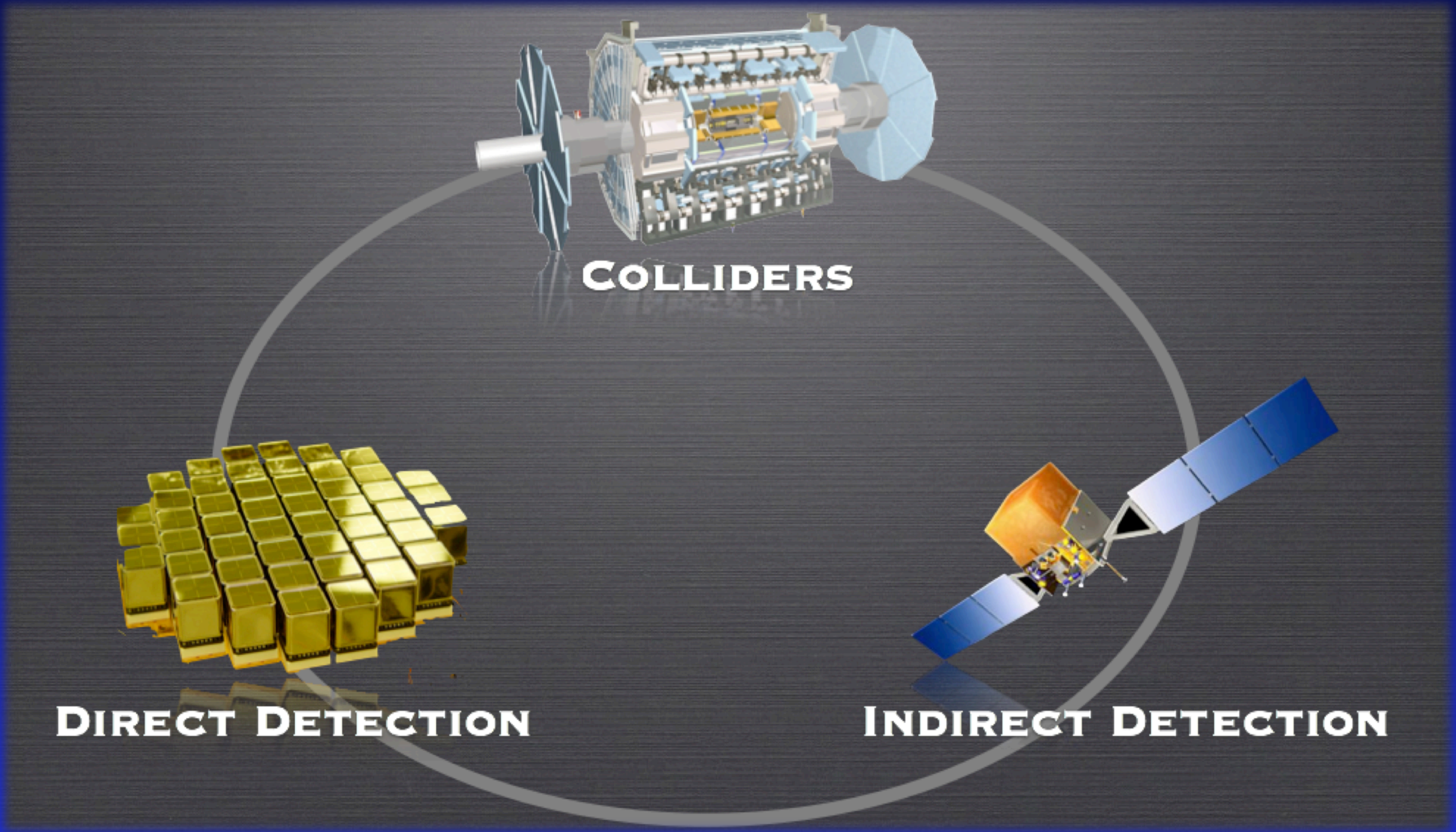
(well motivated)
hints from numerical simulations

What can we learn from astrophysics (about DM?)

- DM is there, at different scales (≈100 Mpc, ≈1Mpc, ≈10kpc)
- Upper limits on DM coupling to the baryons
- Upper limits on the DM coupling to itself
- Upper limits on the “warmth” of DM

Direct and indirect searches of WIMP DM

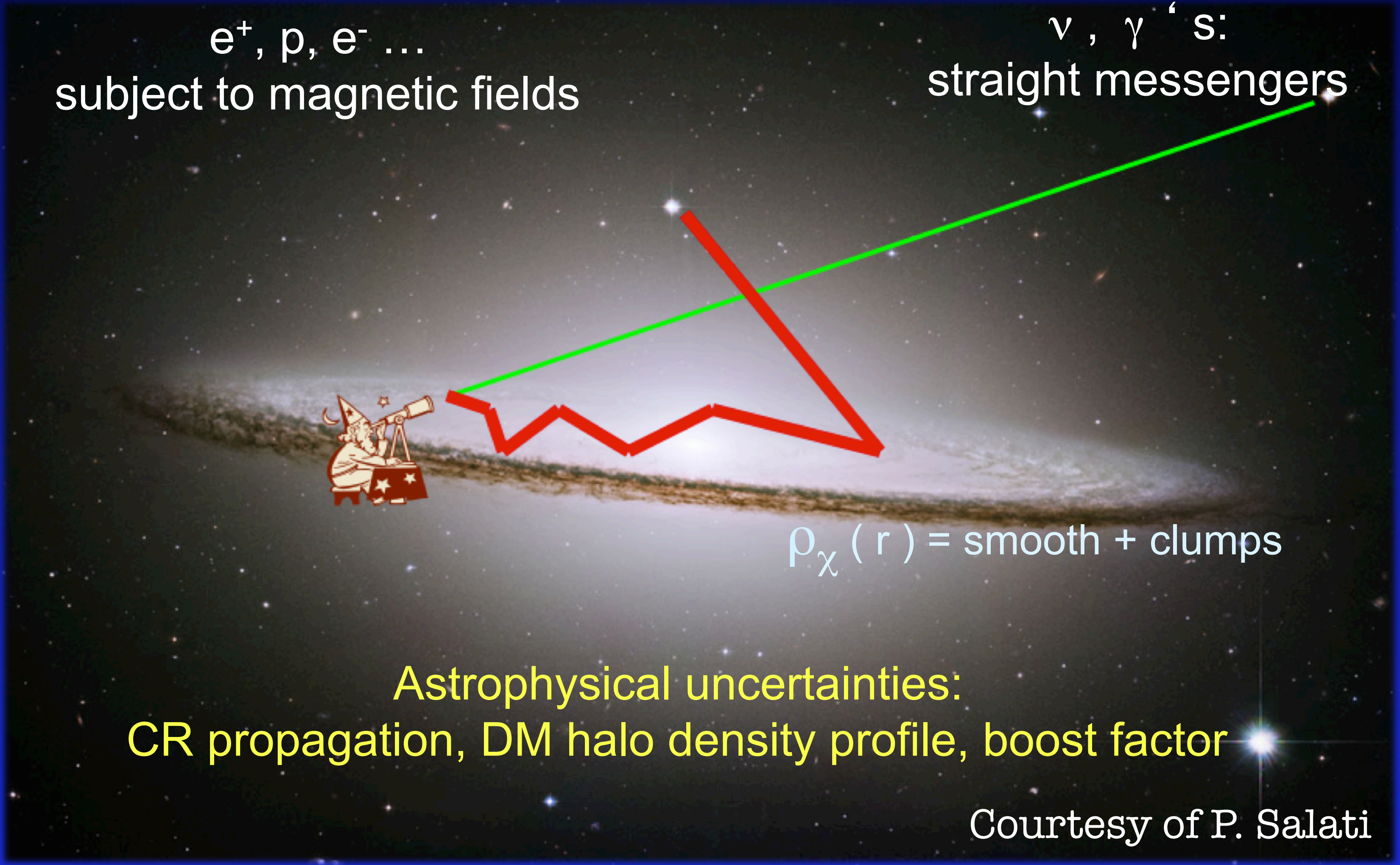
complementary to colliders



Constraining DM nature with local observables

(InDirect searches of WIMP DM)

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



e^+, p, e^- …
subject to magnetic fields

ν , γ ' s:
straight messengers

ρ_χ (r) = smooth + clumps

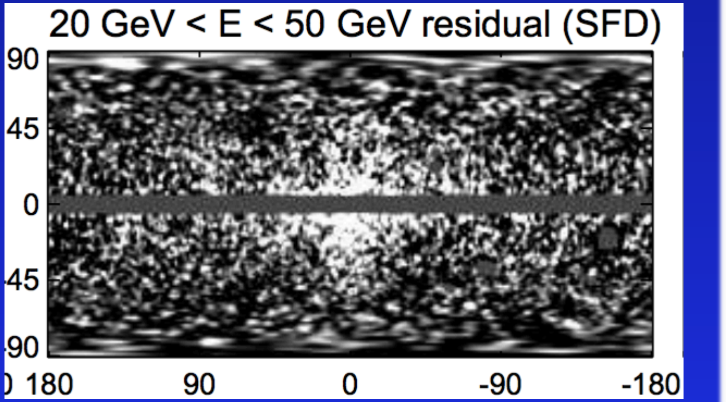
Astrophysical uncertainties:
CR propagation, DM halo density profile, boost factor

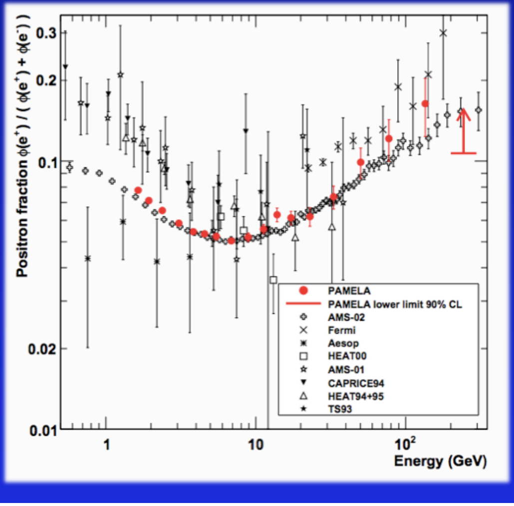
Courtesy of P. Salati

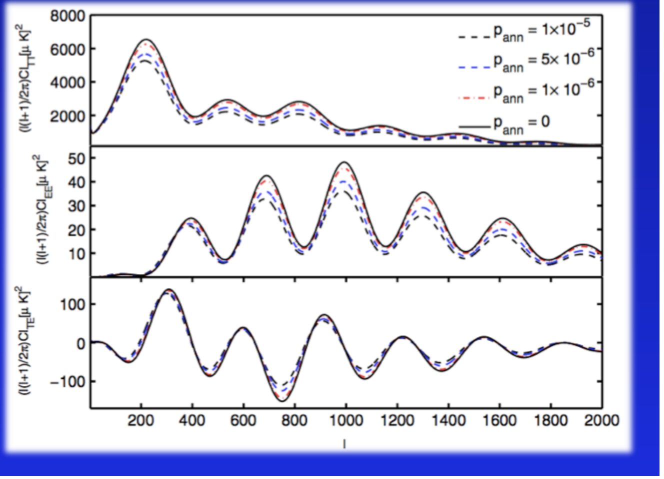
InDirect searches of WIMP DM:

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

$$F = \frac{1}{2}\frac{1}{4\pi d^2}\frac{N_\gamma \boxed{\langle\sigma v\rangle}}{m_\chi^2}\int_0^R \boxed{\rho^2(r)}\,d^3r$$



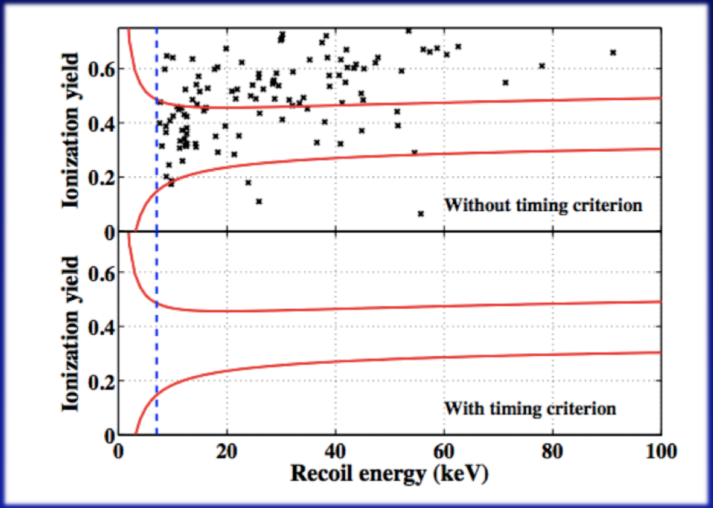




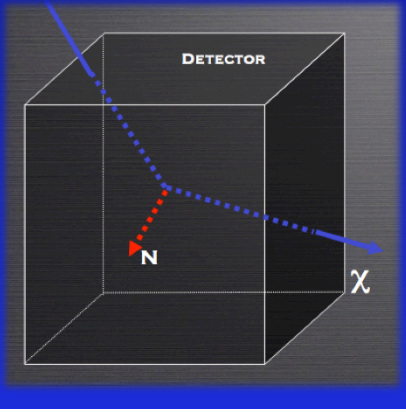
Direct searches of WIMP DM:

A big mountain (or a mine)

Look at phonons/ionizations/scintillations

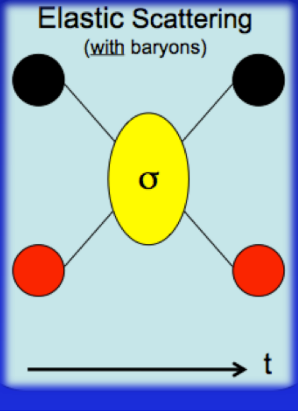


A detector (underneath)



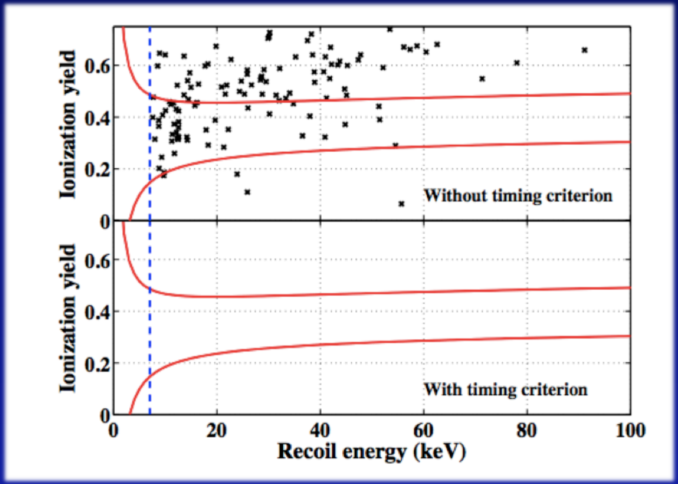
And, ideally:

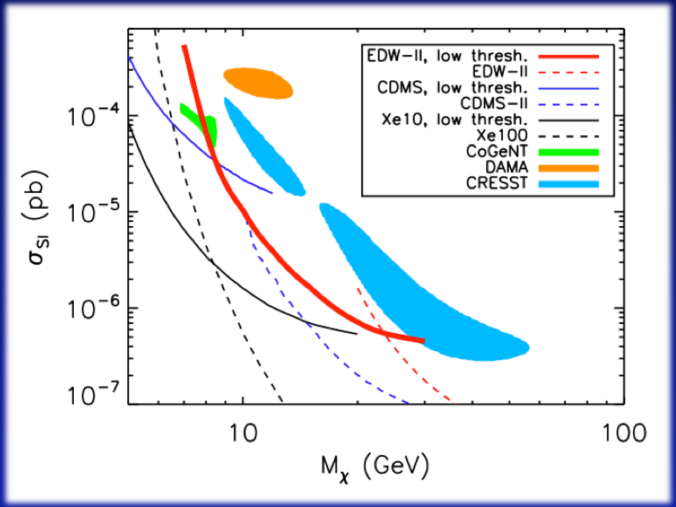
$$\frac{dR_{A,Z}}{dE} = \frac{\boxed{\sigma_{A,Z}(E)}}{2m\mu^2_{A,Z}} \boxed{\rho\,\eta(v_{\min},t)}$$



Direct searches of WIMP DM:

from this → to this





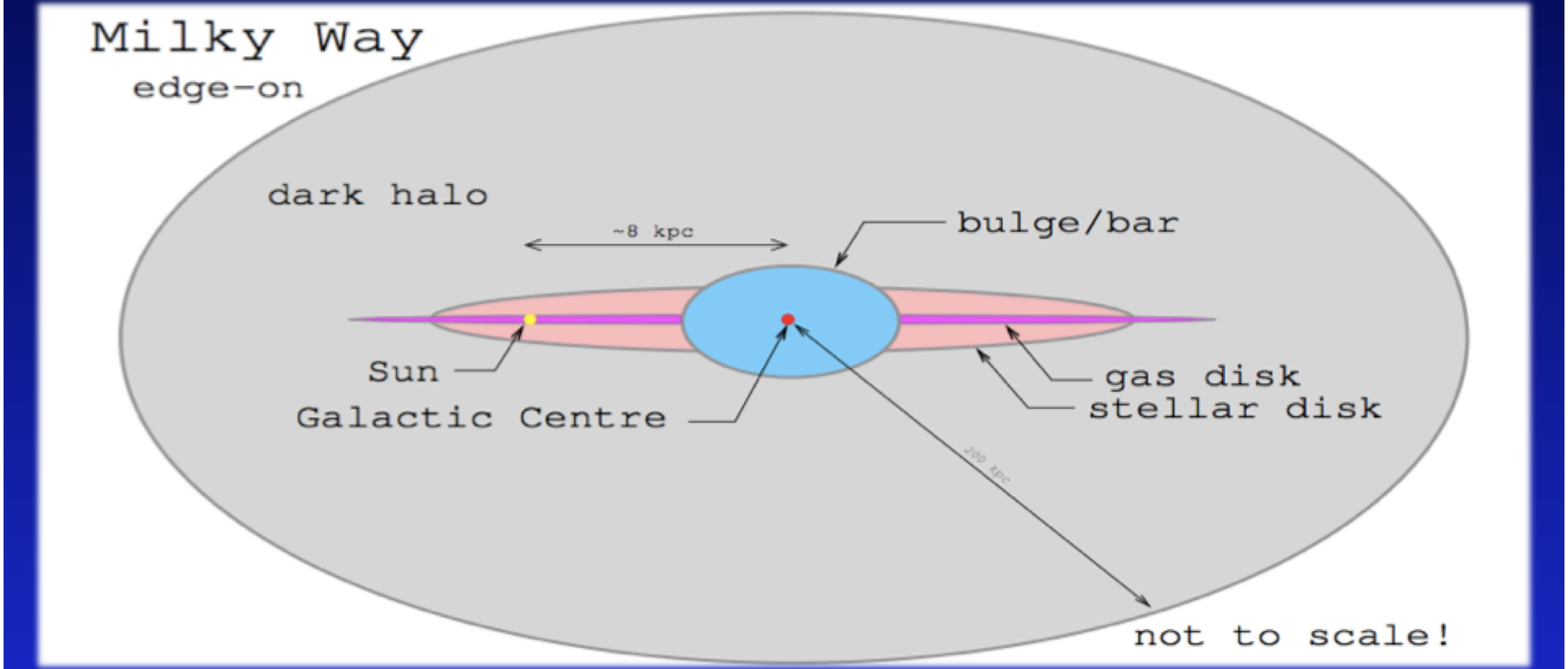
you have to use this

$$\frac{dR_{A,Z}}{dE} = \frac{\boxed{\sigma_{A,Z}(E)}}{2m\mu^2_{A,Z}}\boxed{\rho}\,\boxed{\eta(v_{\min},t)}$$

Velocity distribution properties of DM

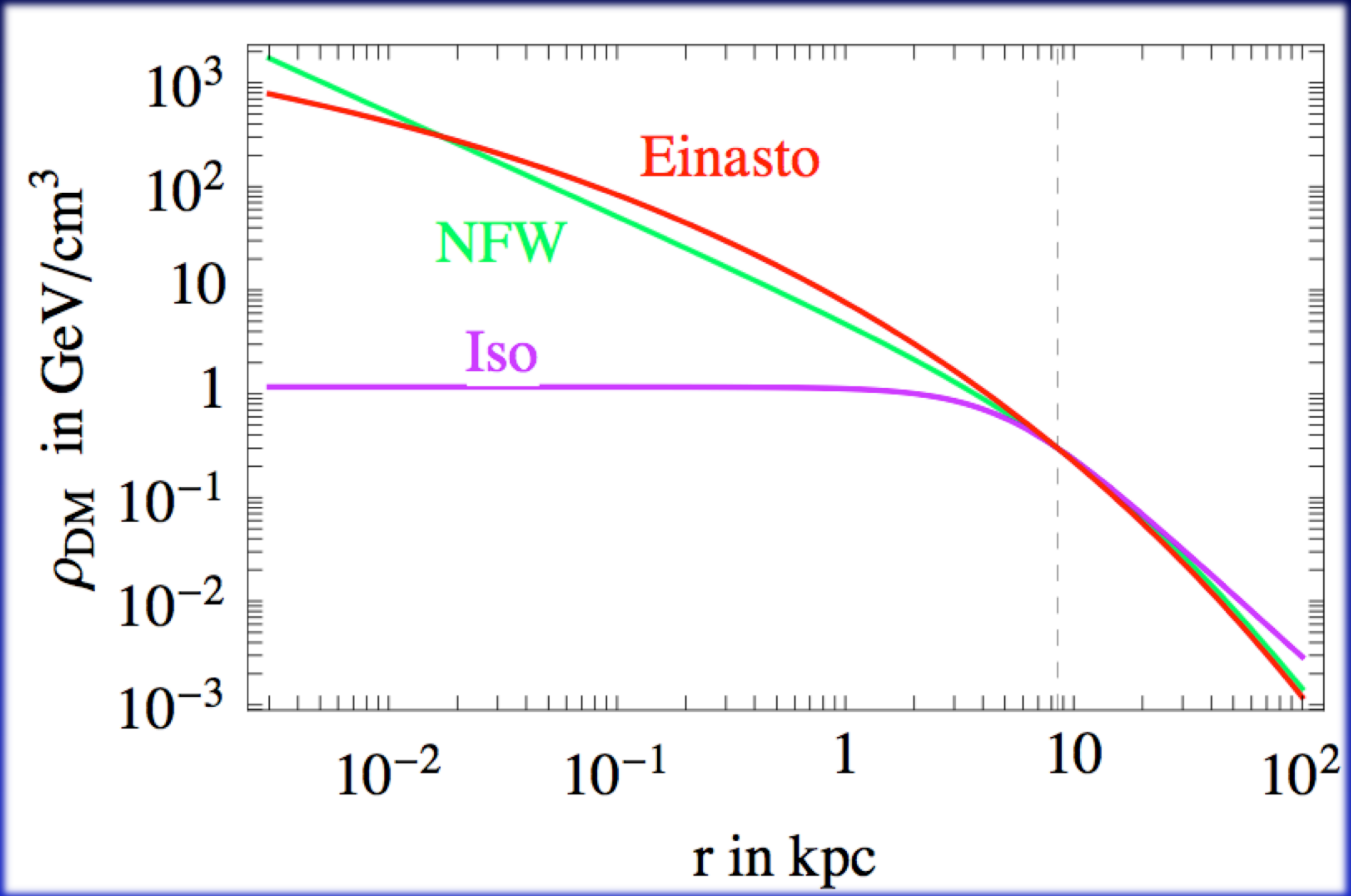
DM density at the Sun’s location, ρ_0

A schematic view of the Galaxy



[shamelessly stolen from M. Pato, without asking]

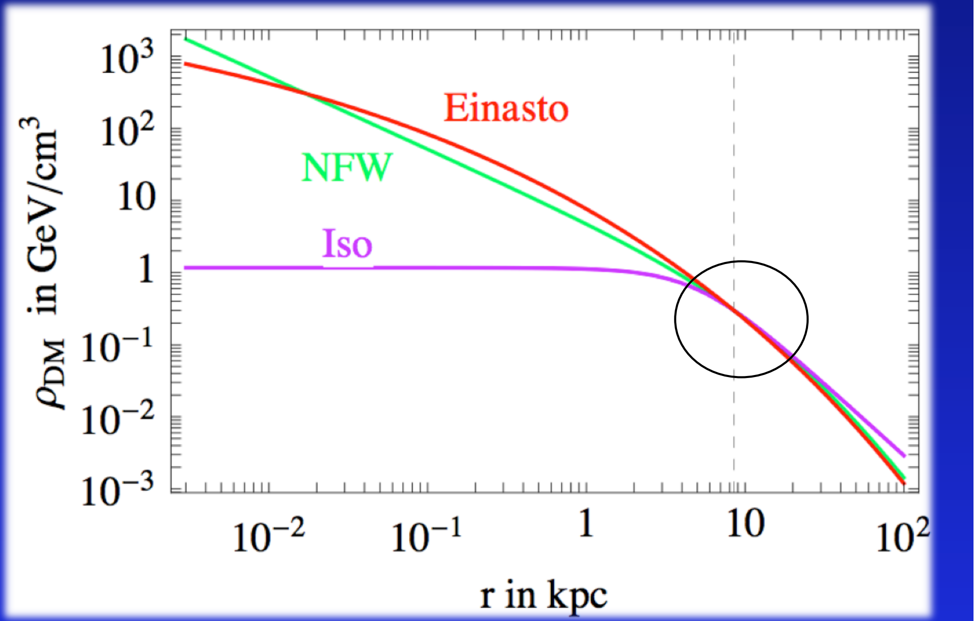
DM distribution is a crucial ingredient of LCDM



(well motivated)
hints from numerical simulations

DM density at the Sun: $\rho_0 = ?$

We know there is "little" DM here, But how little?

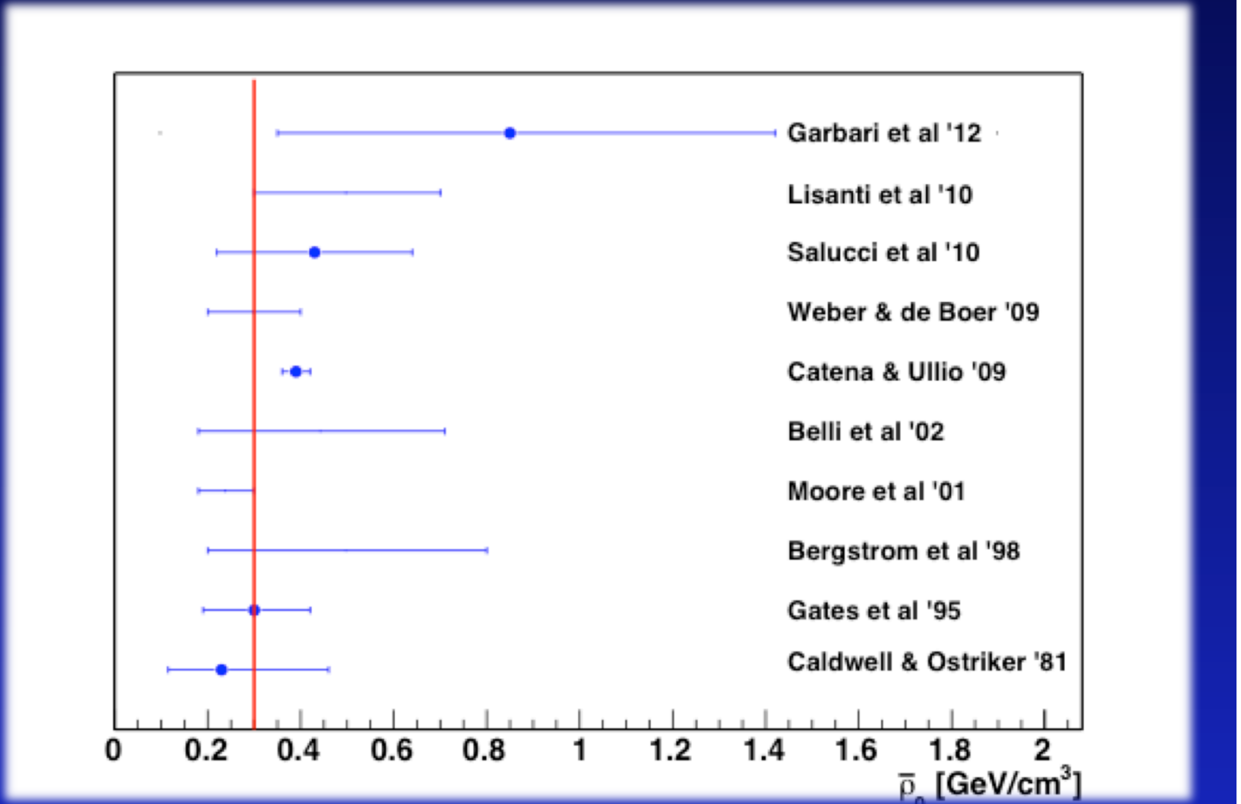


Determination of local DM density ρ_0

Local observables
(e.g. Garbari et al.)

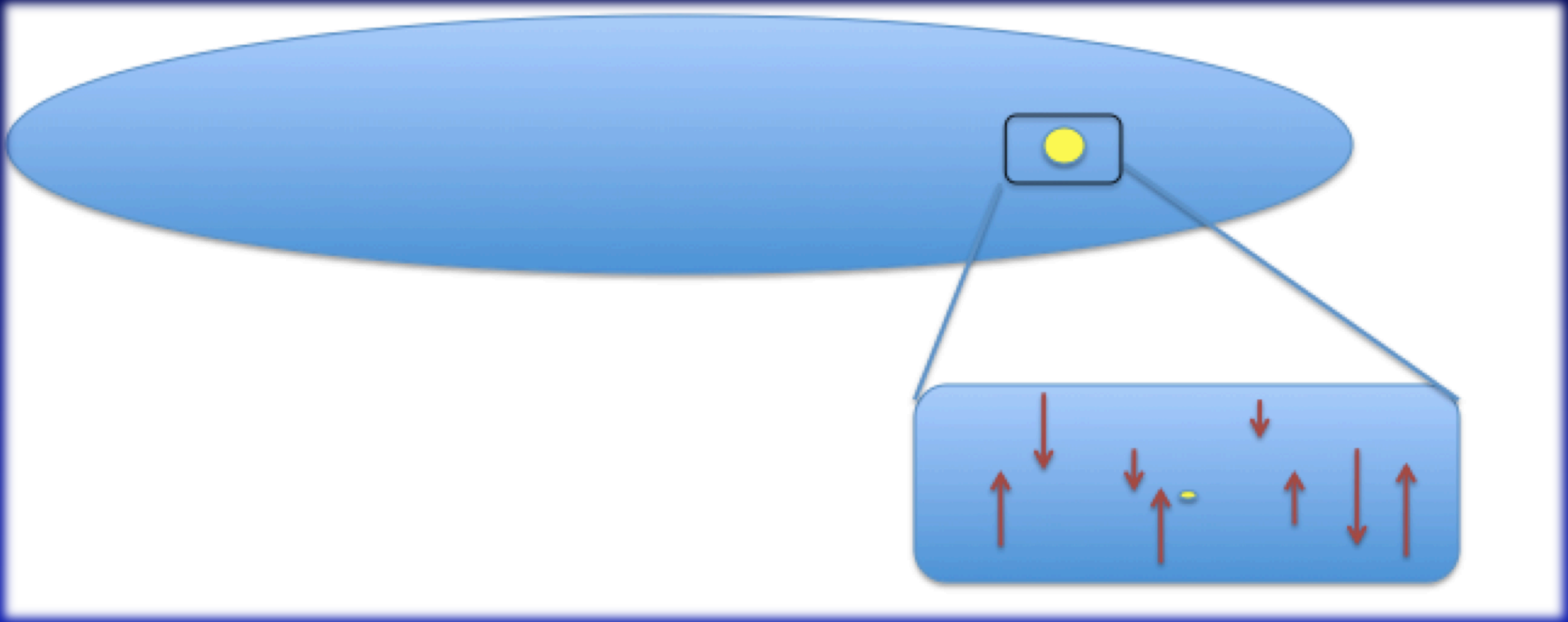
vs

global modelling of MW
(e.g. Catena & Ullio)



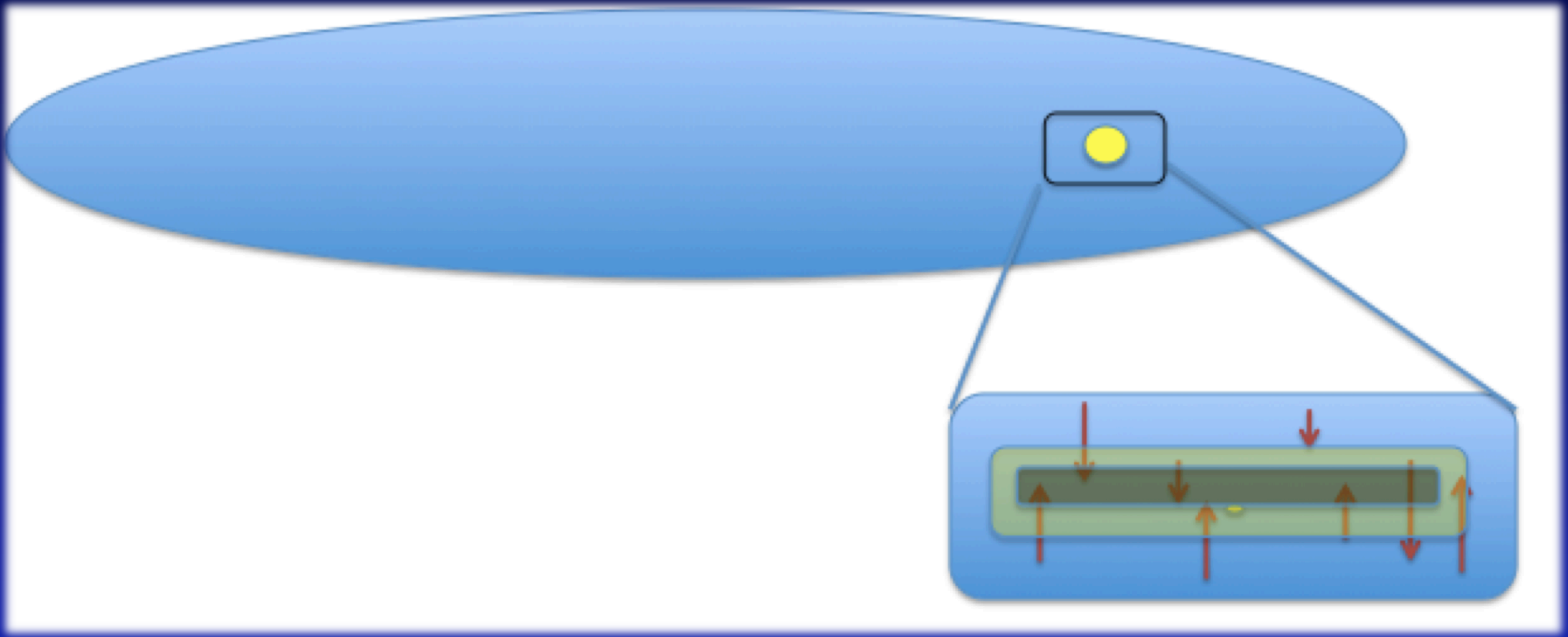
Give consistent results

Local determination of ρ_0



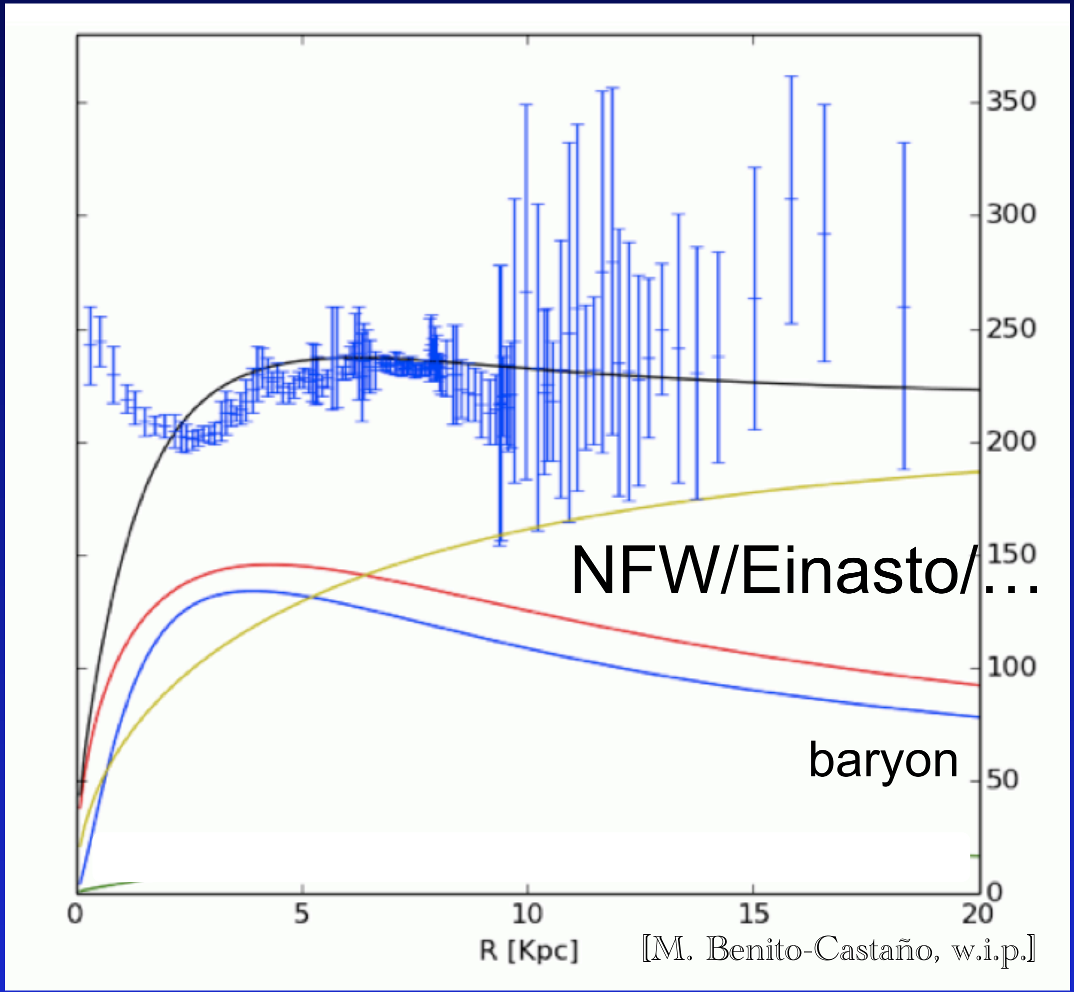
Vertical motion of stars, determining the whole local potential

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/…

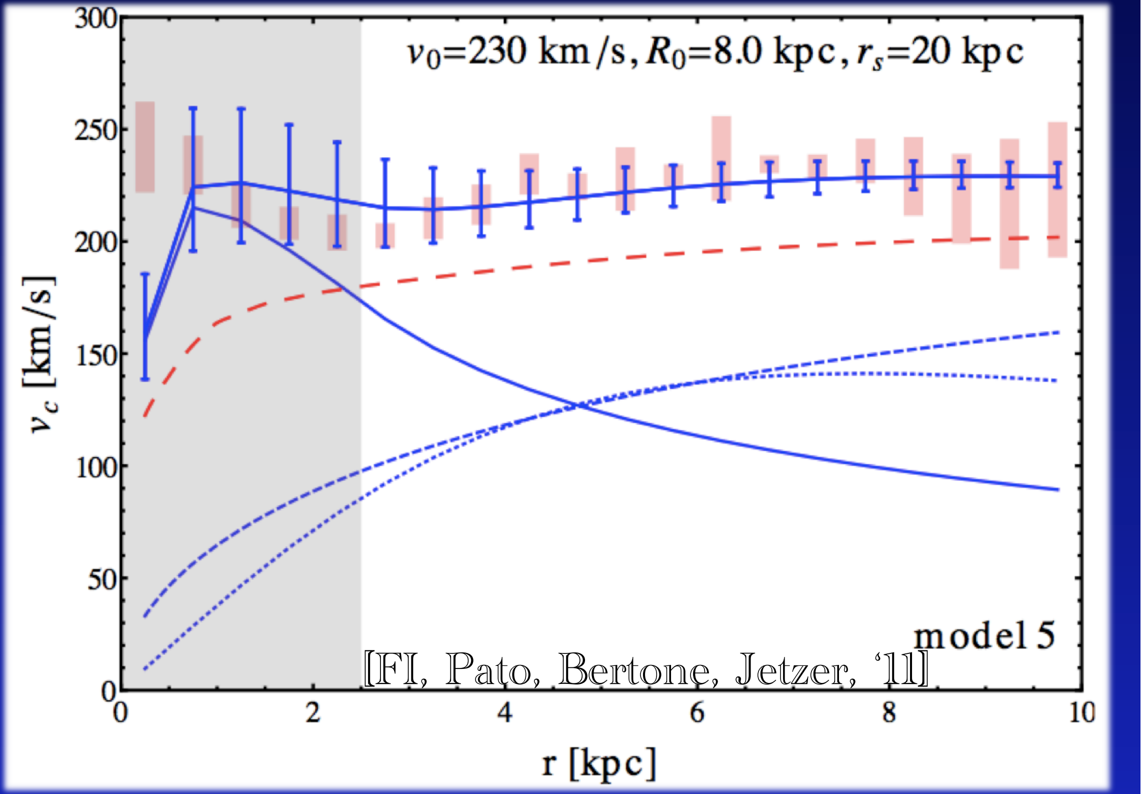
baryon

[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



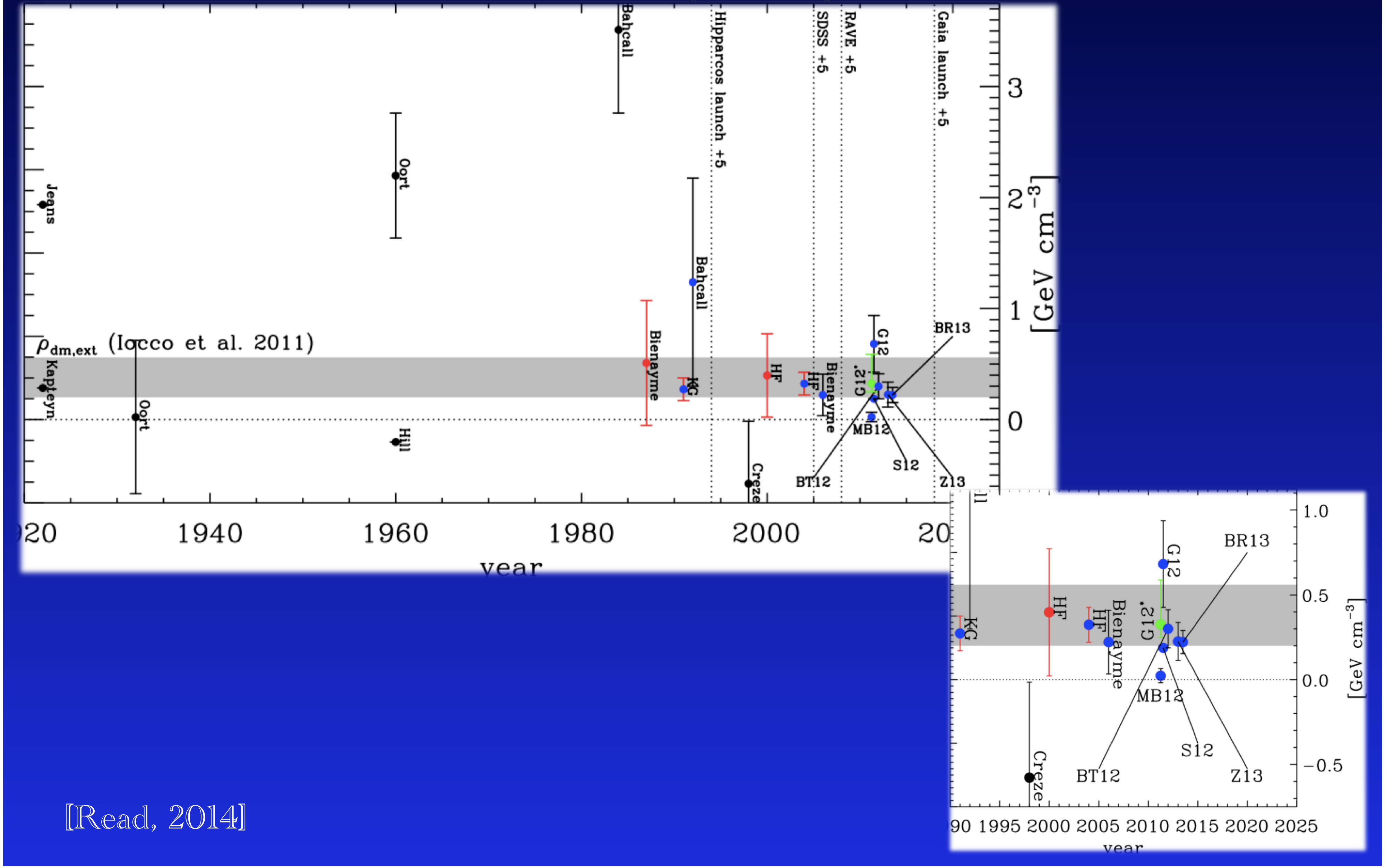
[FI, Pato, Bertone, Jetzer, '11]

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

Underlying assumption on DM presence and distribution shape

Determination of local DM density ρ_0

a historical perspective



[Read, 2014]

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?]

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

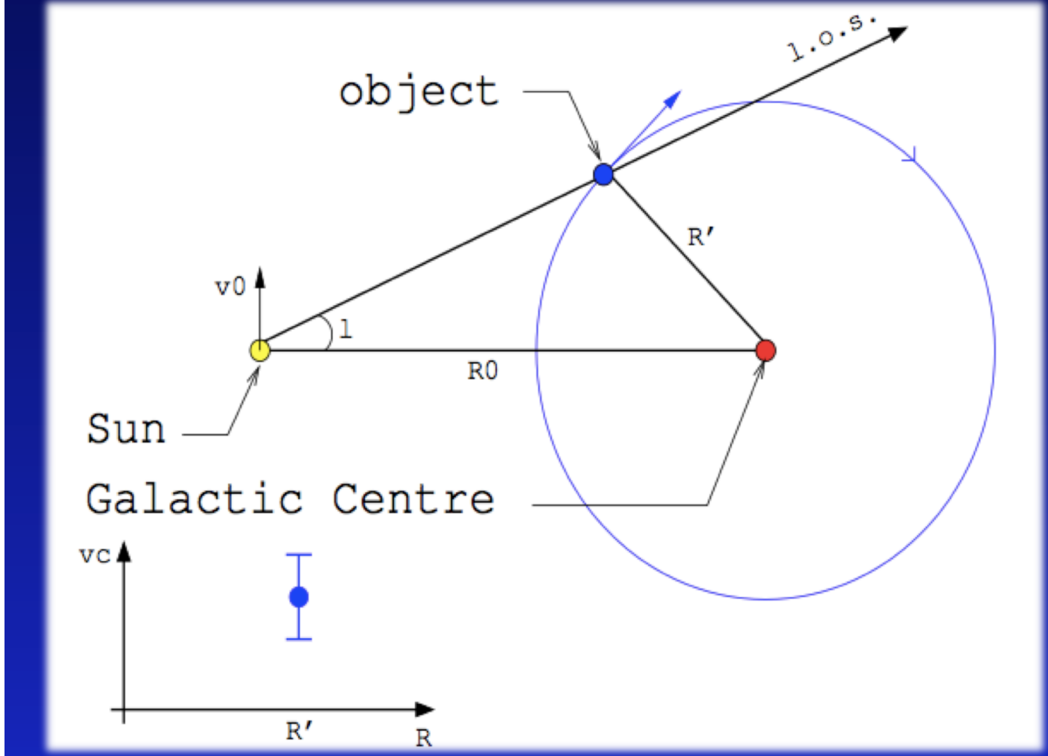
Rotation curve as a tracer of the total potential

…and if not…

The Milky Way:

observed rotation curve

I. principles



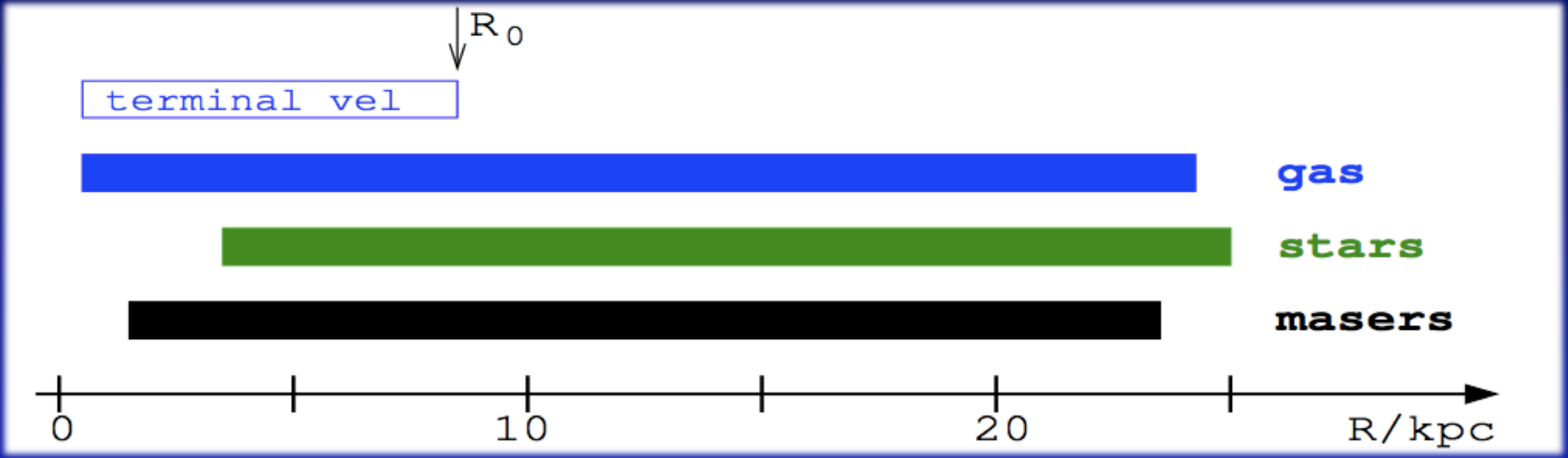
$$v_{\mathrm{LSR}}^{\mathrm{l.o.s.}} = \left(\frac{v_c(R')}{R'/R_0} - v_0 \right) \cos b \sin \ell$$

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

The Milky Way:

observed rotation curve

II. tracers



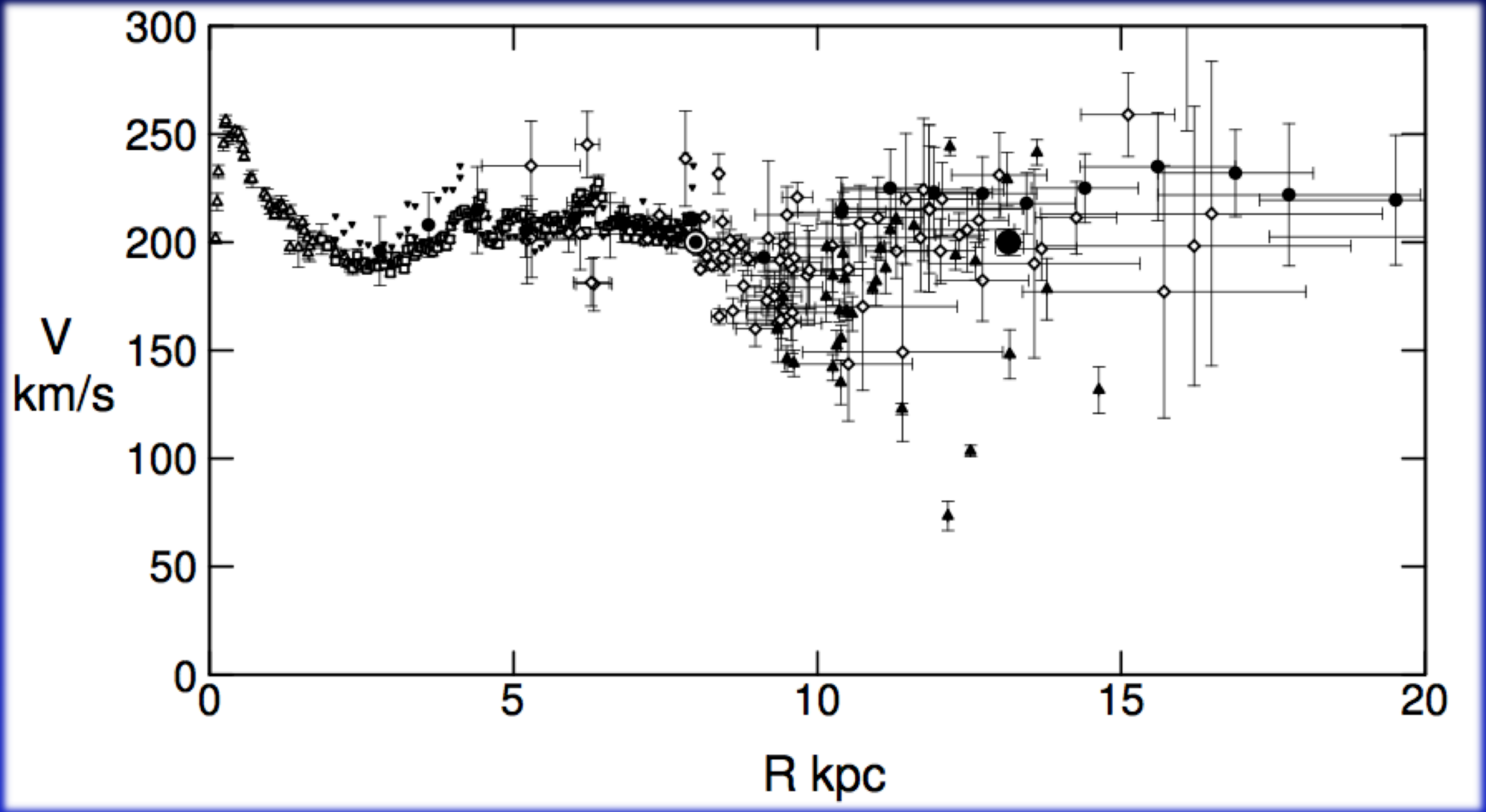
Doppler shift	
1. gas	(21cm, Hα, CO)
2. stars	(H, He, O, ...)
3. masers	(H_2O, CH_3OH, ...)

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

The Milky Way:

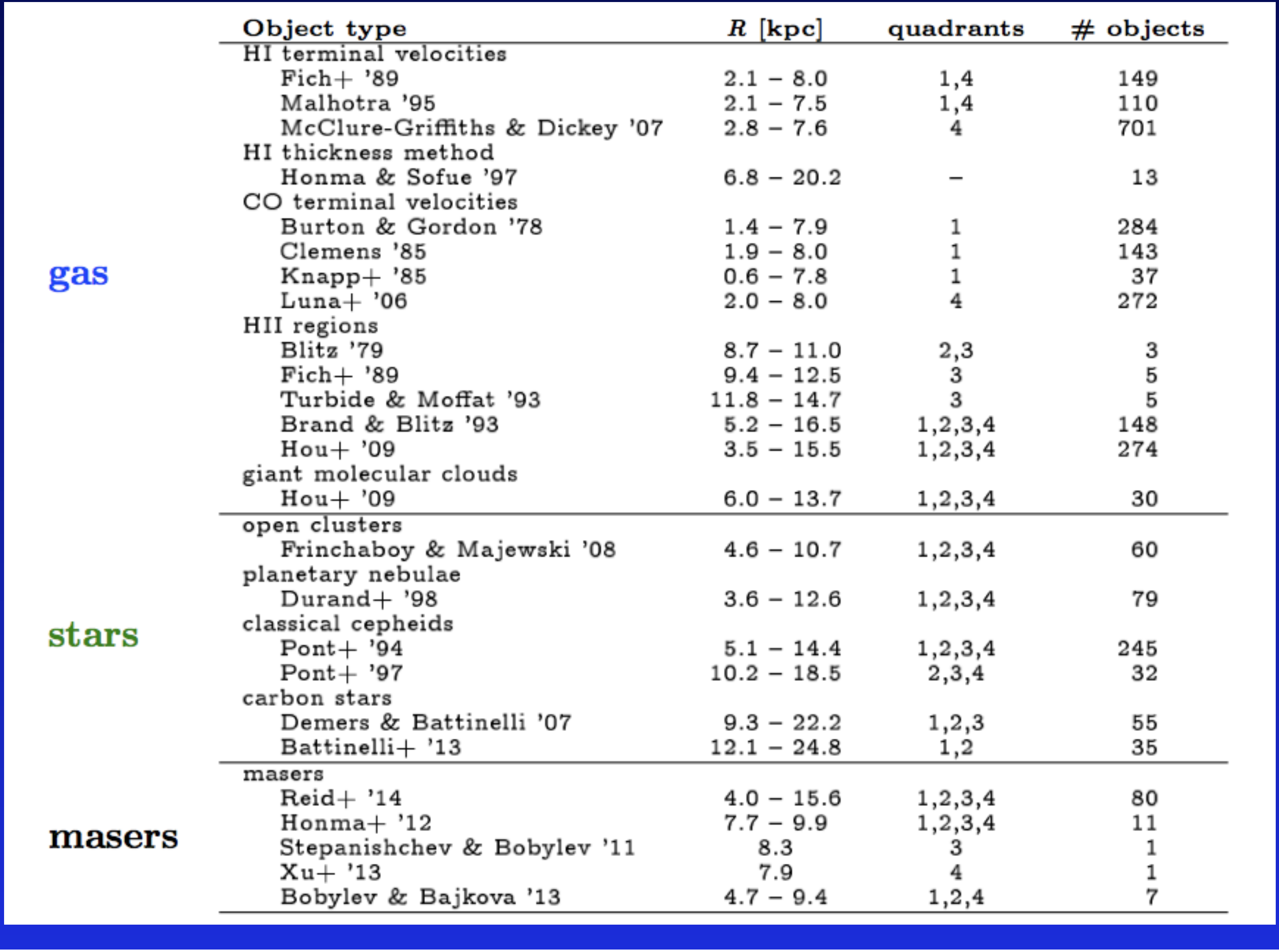
observed rotation curve

III. curve



Data compilation by [Sofue et al, '08]

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

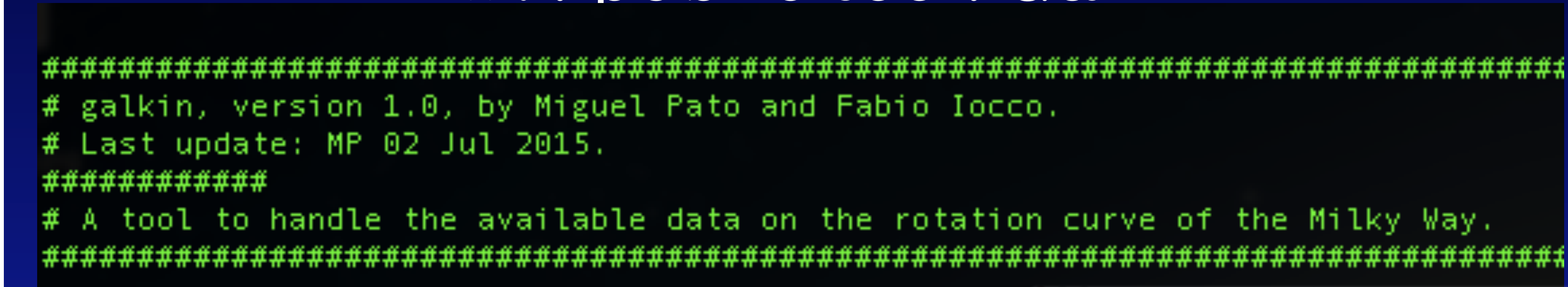


	Object type	R [kpc]	quadrants	# objects
gas	HI terminal velocities			
	Fich+ '89	2.1 – 8.0	1,4	149
	Malhotra '95	2.1 – 7.5	1,4	110
	McClure-Griffiths & Dickey '07	2.8 – 7.6	4	701
	HI thickness method			
	Honma & Sofue '97	6.8 – 20.2	–	13
	CO terminal velocities			
	Burton & Gordon '78	1.4 – 7.9	1	284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

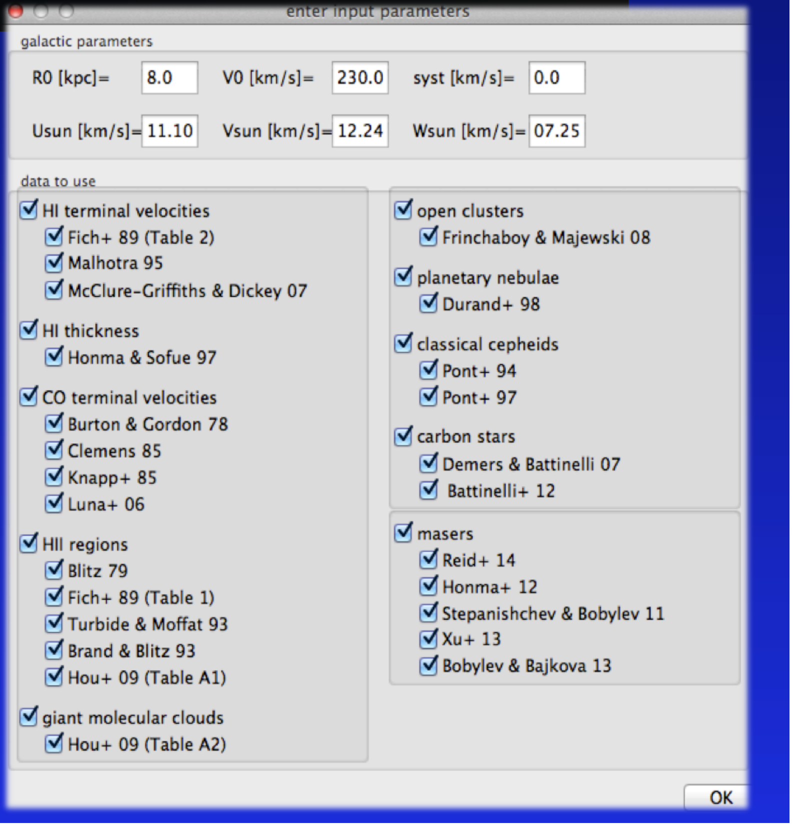


```
##################################################################################
# galkin, version 1.0, by Miguel Pato and Fabio Iocco.
# Last update: MP 02 Jul 2015.
############
# A tool to handle the available data on the rotation curve of the Milky Way.
##################################################################################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

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

Available soon:
reserve your copy now!

[Pato & FI, soon]



galactic parameters

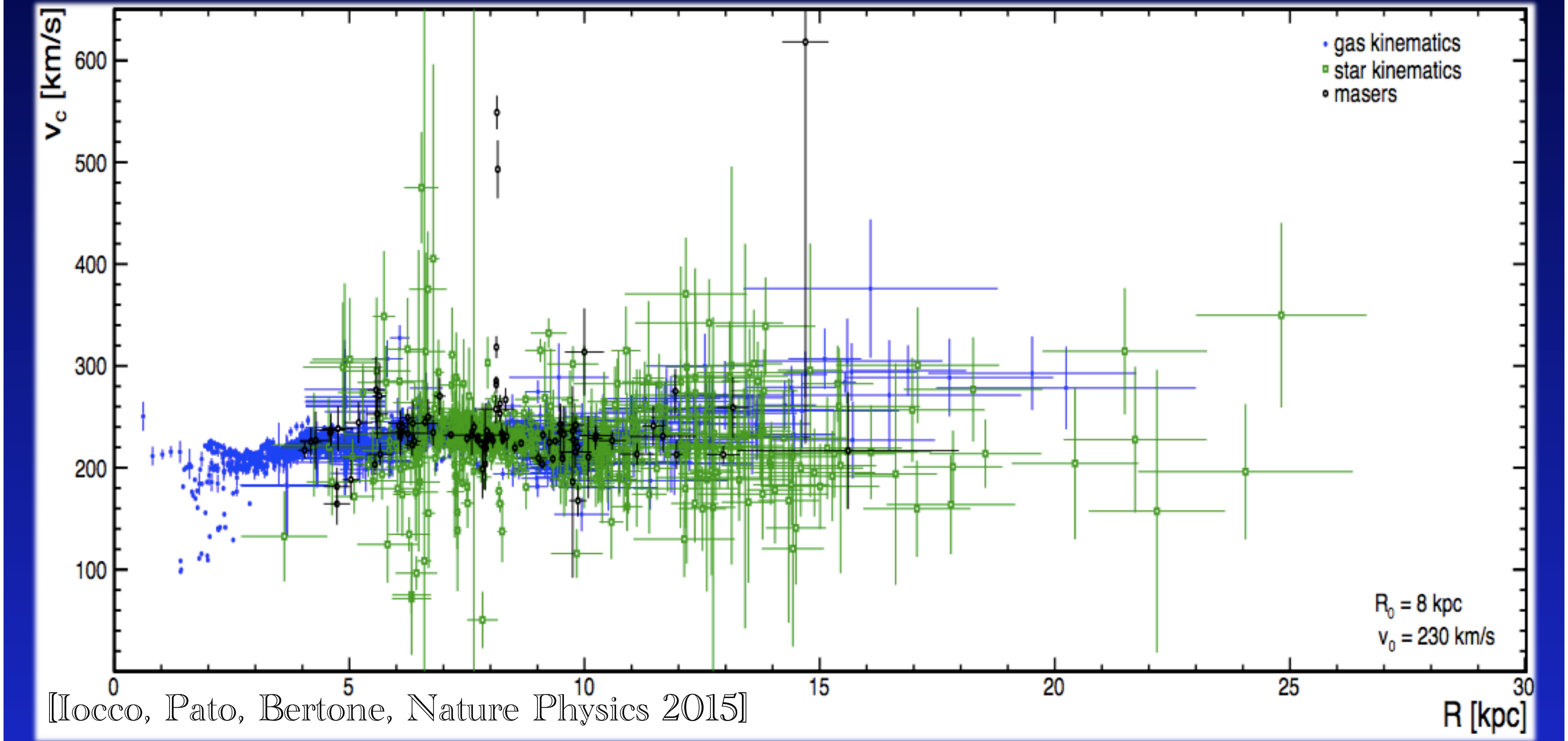
R0 [kpc]= 8.0
V0 [km/s]= 230.0
syst [km/s]= 0.0
Usun [km/s]= 11.10
Vsun [km/s]= 12.24
Wsun [km/s]= 07.25

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

The Milky Way Rotation Curve

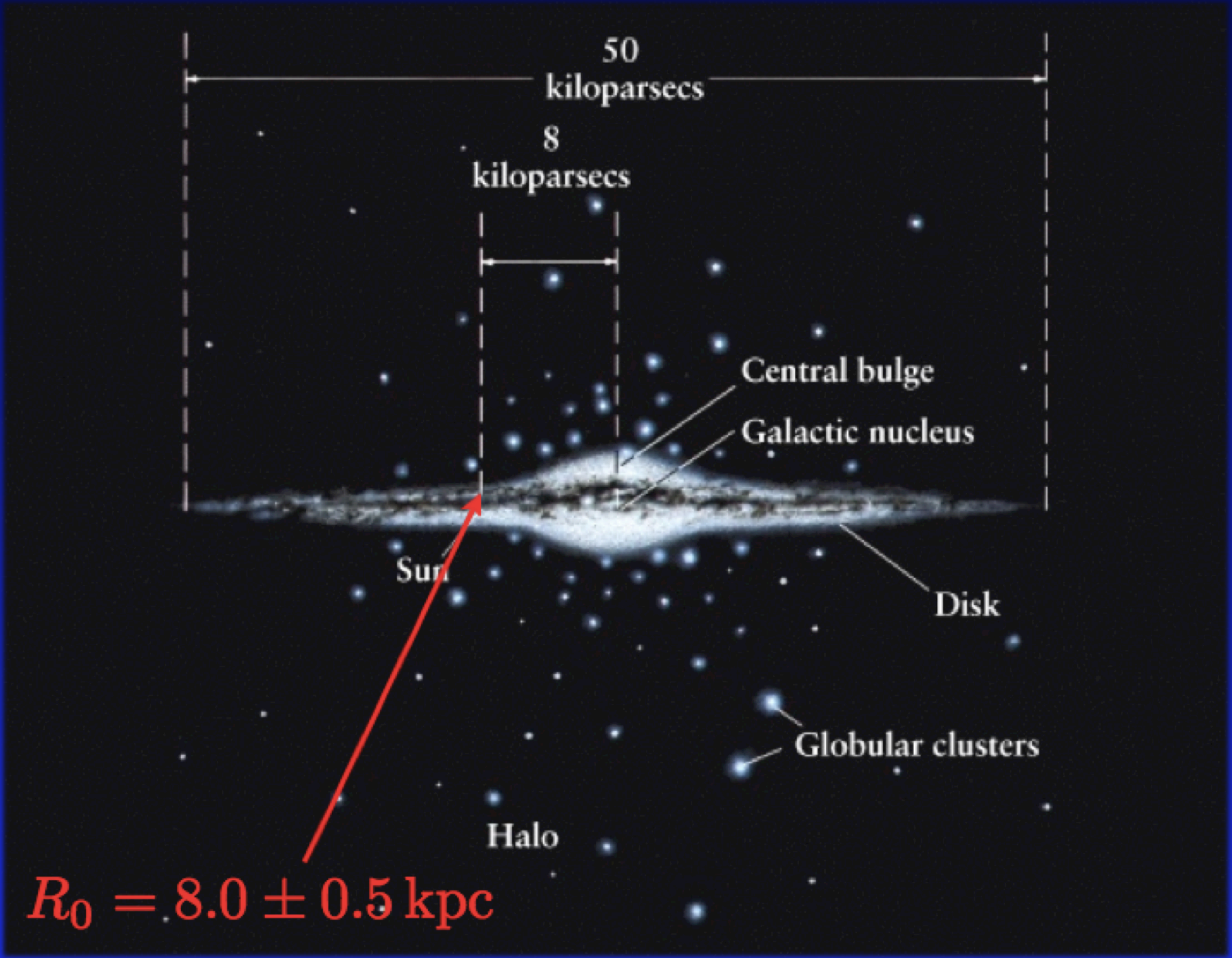
as observed



[Iocco, Pato, Bertone, Nature Physics 2015]

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

Modeling the Milky Way: morphological observations

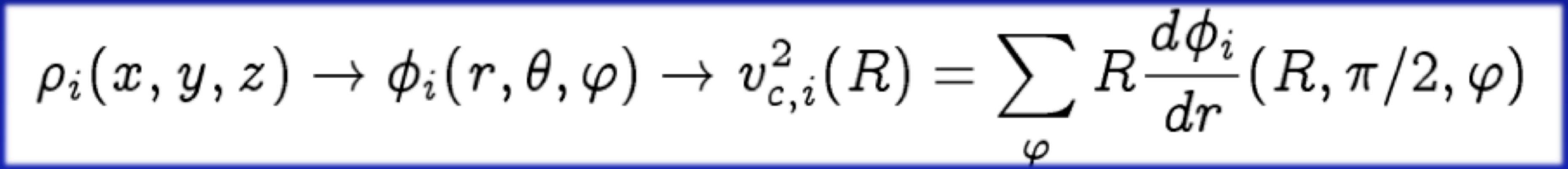


$R_0 = 8.0 \pm 0.5\,\mathrm{kpc}$

The Milky Way:

expected rotation curve

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



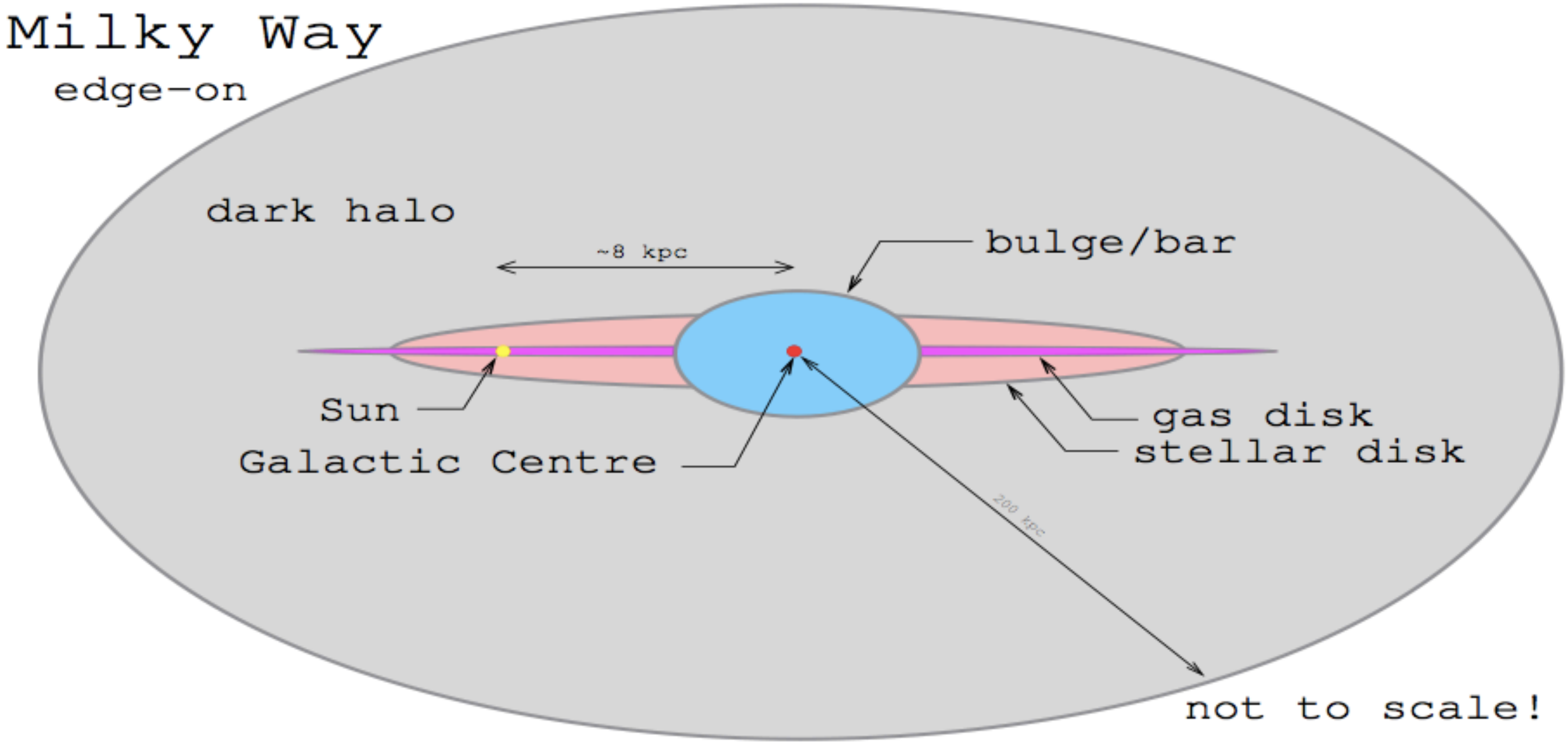
$$\rho_i(x, y, z) \rightarrow \phi_i(r, \theta, \varphi) \rightarrow v_{c,i}^2(R) = \sum_{\varphi} R \frac{d\phi_i}{dr}(R, \pi/2, \varphi)$$

Constructing the curve expected from observed mass profiles

The Milky Way:

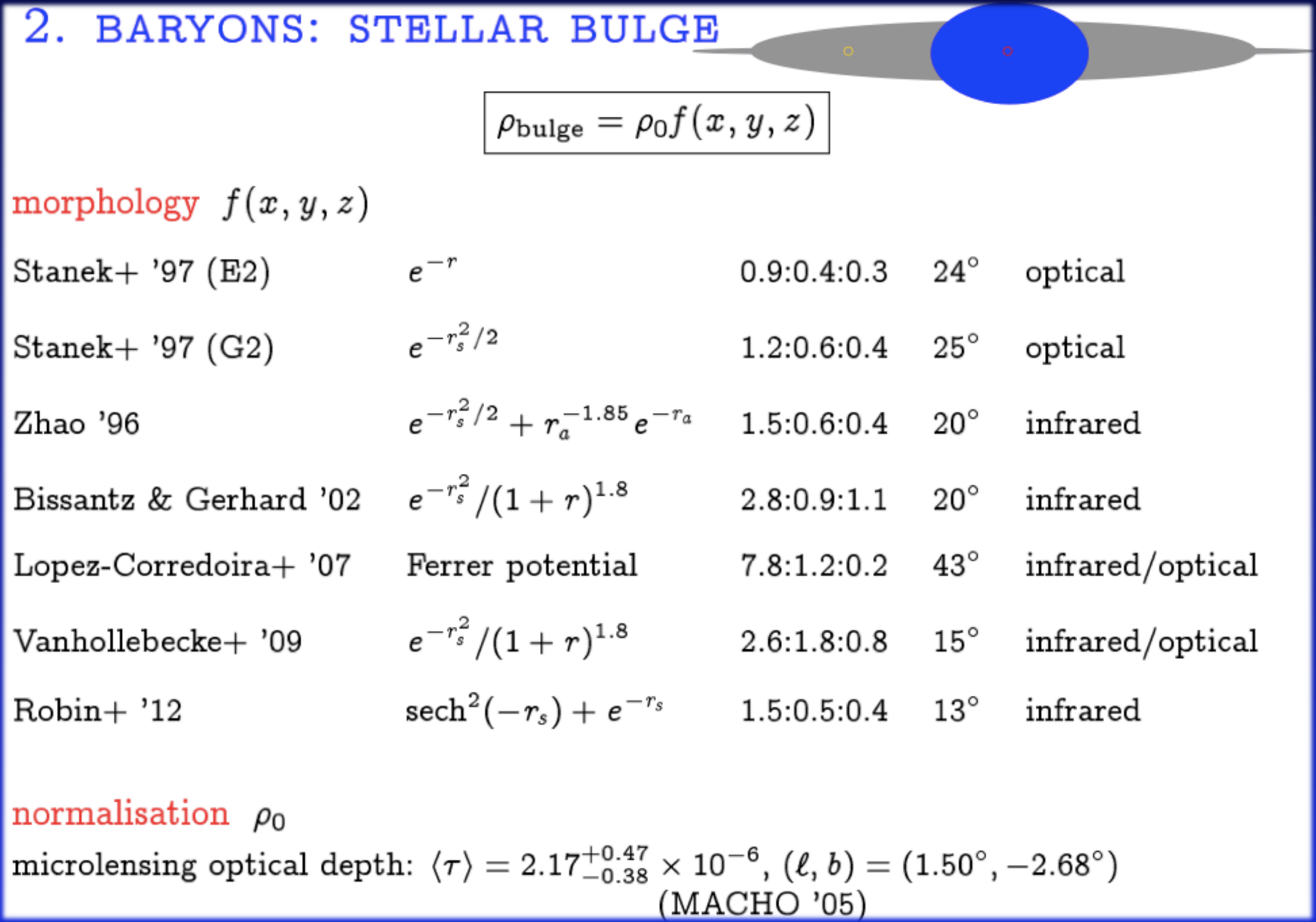
expected rotation curve

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 $f(x, y, z)$

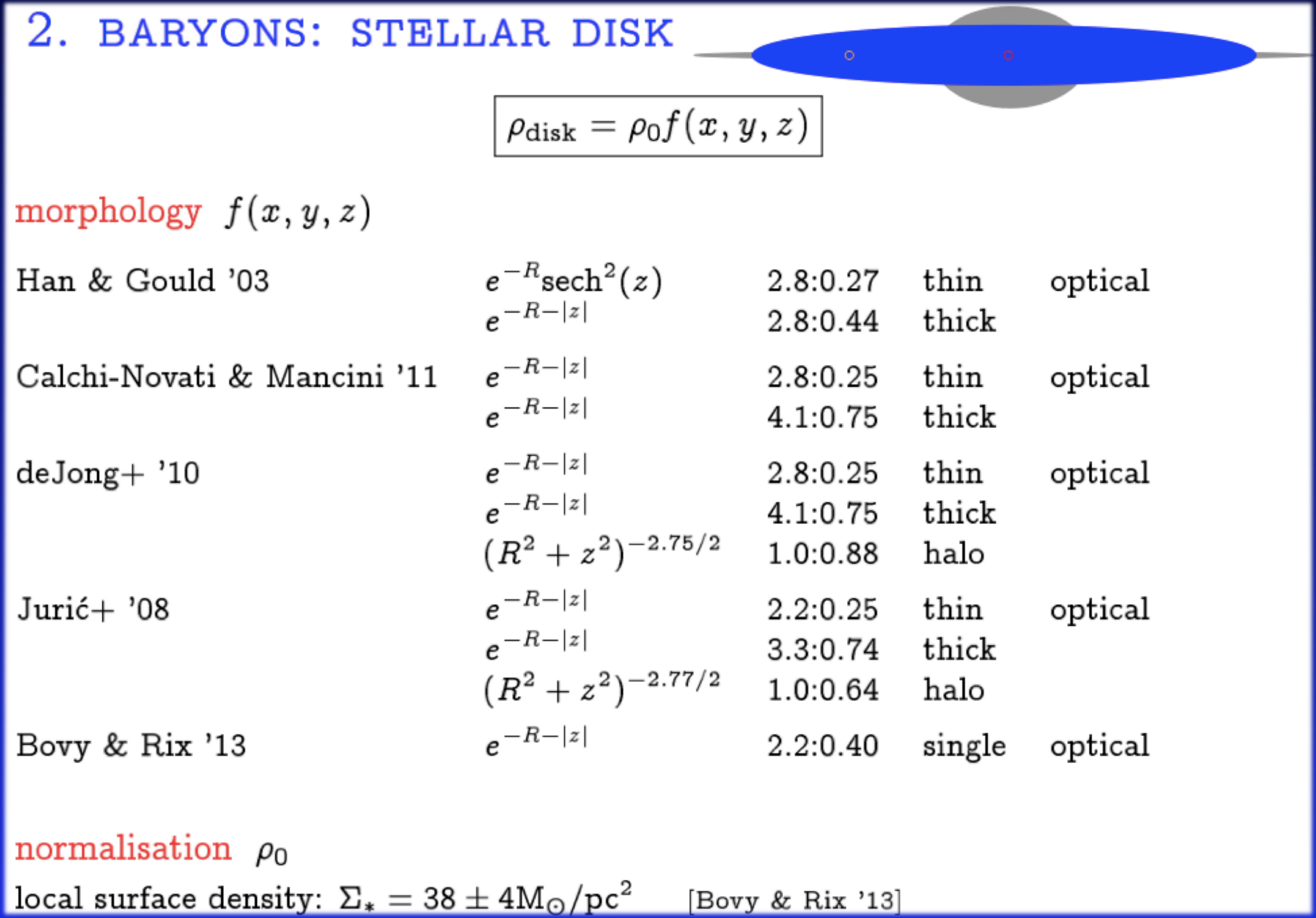
Stanek+ '97 (E2)	e^{-r}	0.9:0.4:0.3	24°	optical
Stanek+ '97 (G2)	$e^{-r_s^2/2}$	1.2:0.6:0.4	25°	optical
Zhao '96	$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	1.5:0.6:0.4	20°	infrared
Bissantz & Gerhard '02	$e^{-r_s^2}/(1+r)^{1.8}$	2.8:0.9:1.1	20°	infrared
Lopez-Corredoira+ '07	Ferrer potential	7.8:1.2:0.2	43°	infrared/optical
Vanhollebecke+ '09	$e^{-r_s^2}/(1+r)^{1.8}$	2.6:1.8:0.8	15°	infrared/optical
Robin+ '12	$\text{sech}^2(-r_s) + e^{-r_s}$	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

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

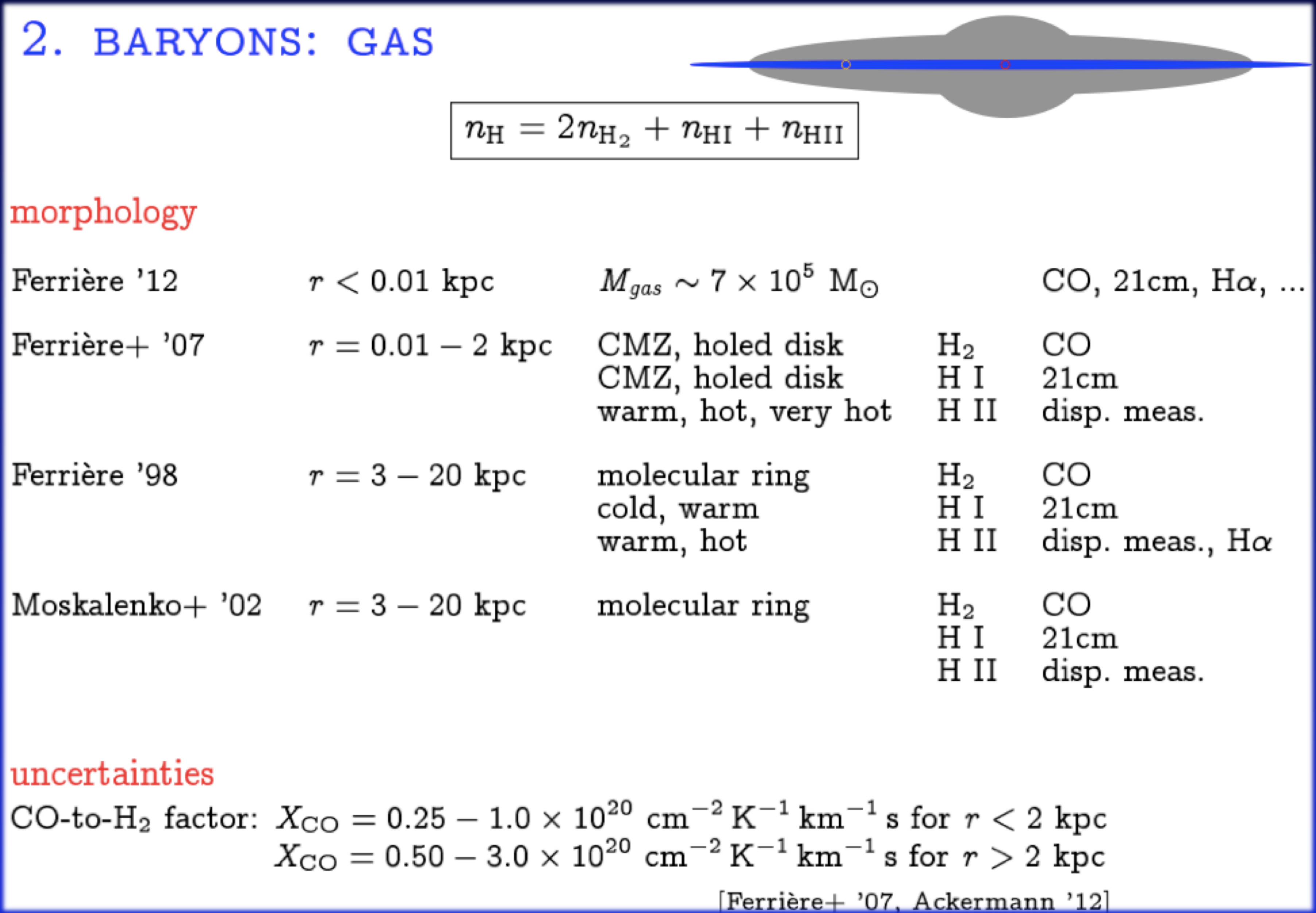
morphology $f(x,y,z)$

Han & Gould '03	$e^{-R}\text{sech}^2(z)$	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: $\Sigma_* = 38 \pm 4 M_\odot/\text{pc}^2$ [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

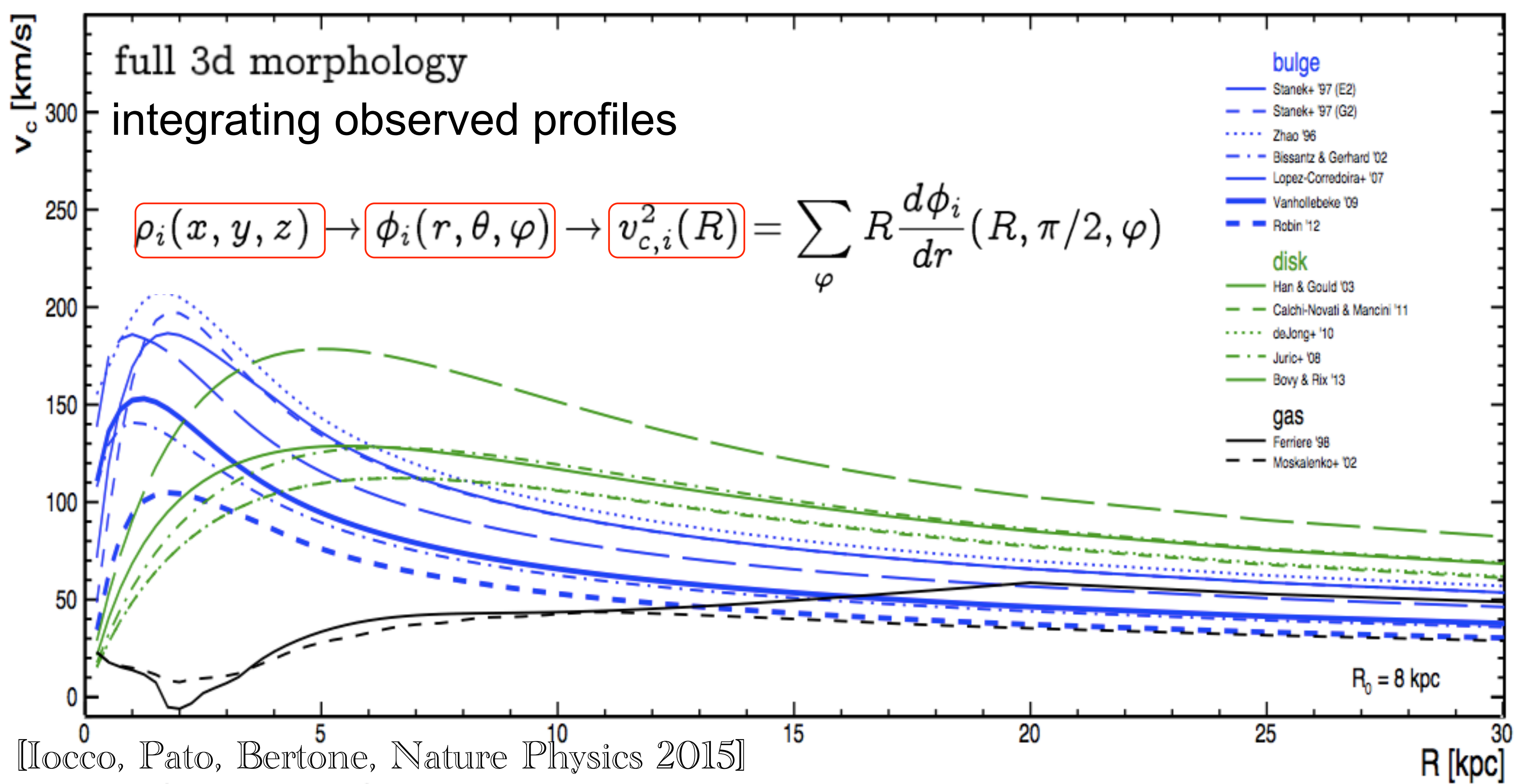
CO-to-H_2 factor: $X_{\rm CO} = 0.25 - 1.0 \times 10^{20}\ \rm cm^{-2}\,K^{-1}\,km^{-1}\,s$ for $r < 2$ kpc
$X_{\rm CO} = 0.50 - 3.0 \times 10^{20}\ \rm cm^{-2}\,K^{-1}\,km^{-1}\,s$ for $r > 2$ kpc

[Ferrière+ '07, Ackermann '12]

The luminous Milky Way:

expected rotation curve

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



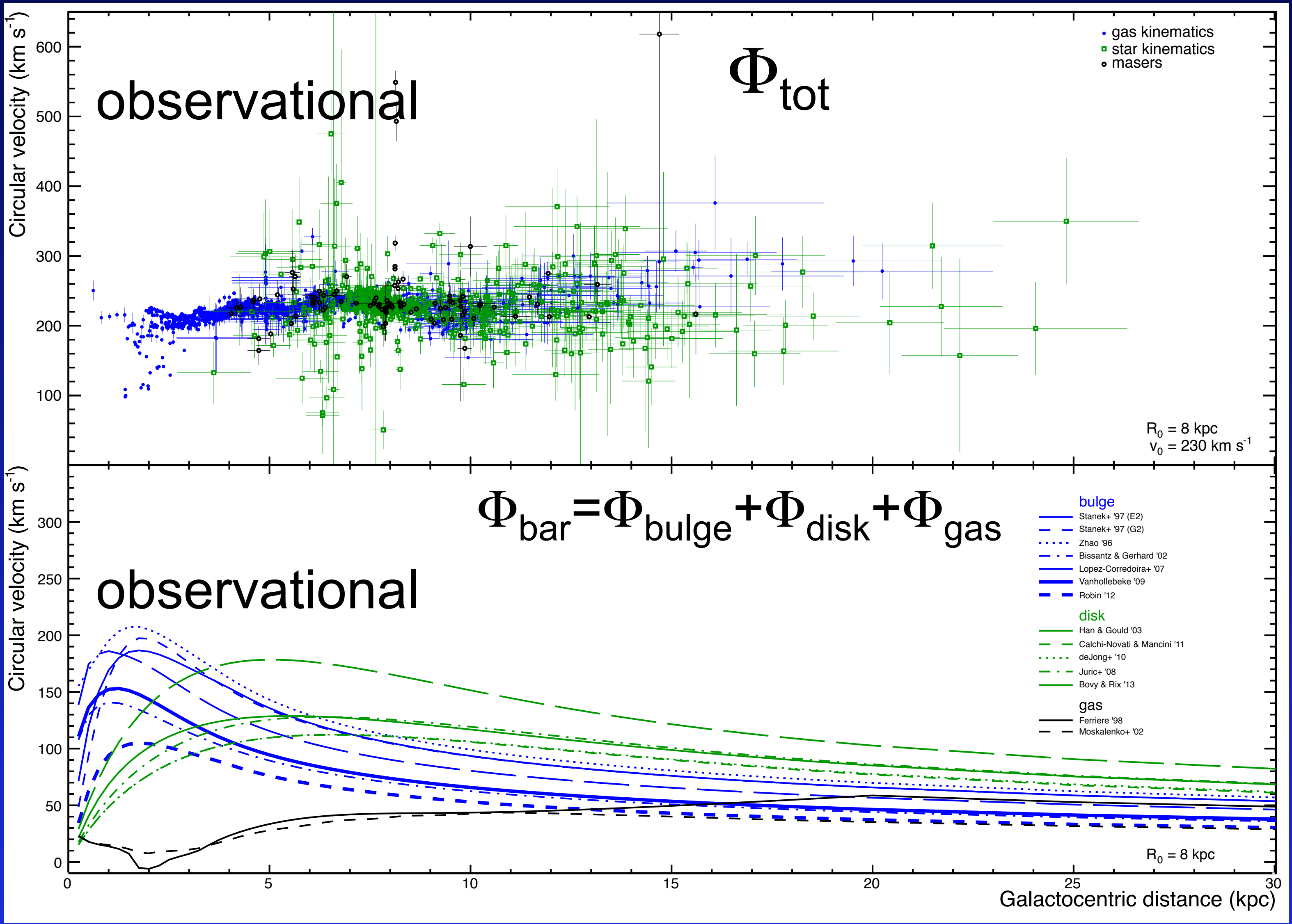
full 3d morphology

integrating observed profiles

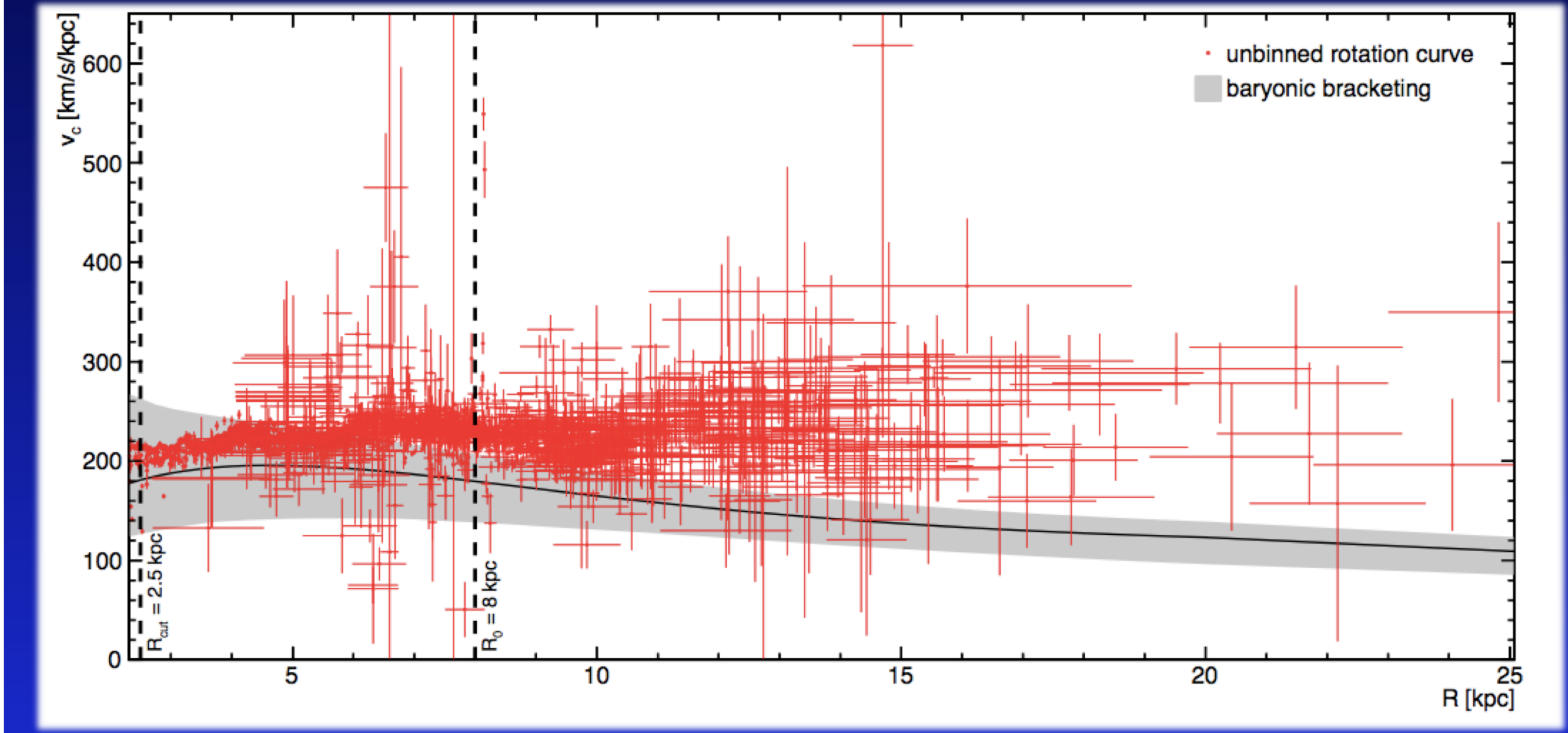
$$\boxed{\rho_i(x,y,z)} \rightarrow \boxed{\phi_i(r,\theta,\varphi)} \rightarrow \boxed{v^2_{c,i}(R)} = \sum_{\varphi} R \frac{d\phi_i}{dr}(R,\pi/2,\varphi)$$

[Iocco, Pato, Bertone, Nature Physics 2015]

The Milky Way: testing expectactions



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

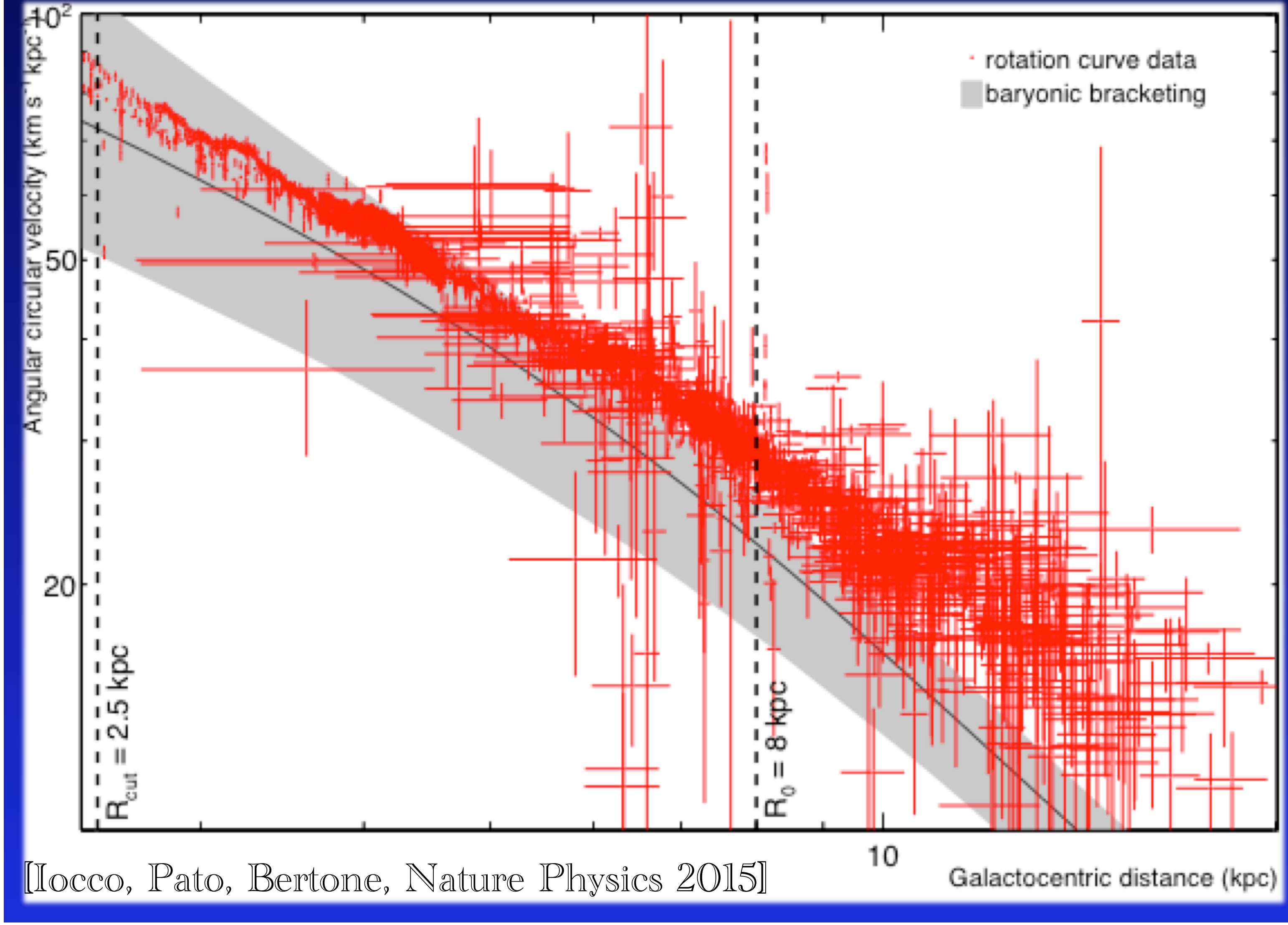


[Iocco, Pato, Bertone, Nature Physics 2015]

The Milky Way: testing expectactions

(with no additional assumption)

((and some technical detail))



[Iocco, Pato, Bertone, Nature Physics 2015]

$\omega = V_c / R_c$

Uncorrelated uncertainties

R_0=8 kpc

V_0=230 km/s

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

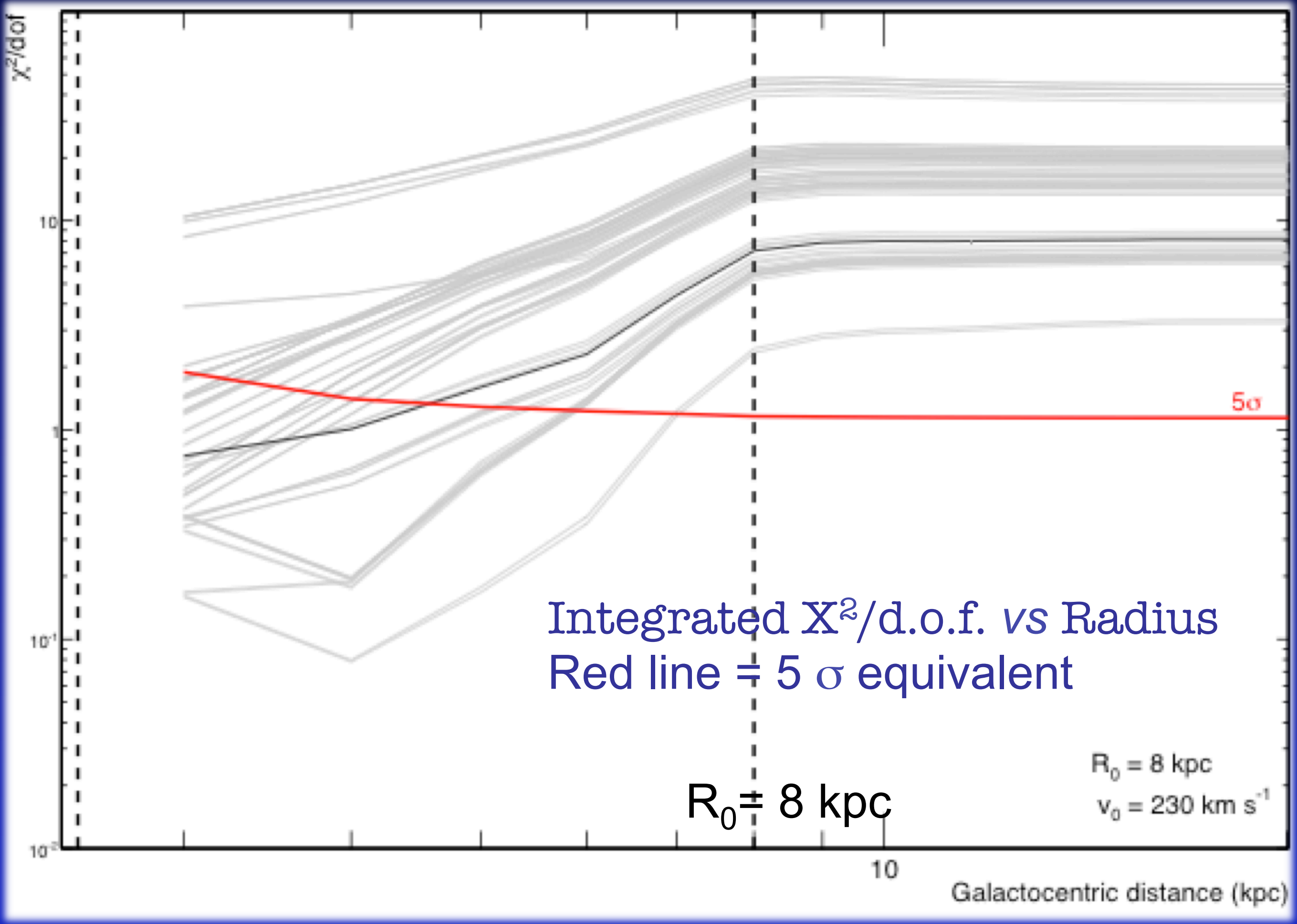
- Computing the “badness-of-fit” (discrepancy) of each baryon rot. curve (no DM!!) to observed one

- One COULD bin (and we have done it) but loss of information: using 2D chi-square

(uncertainties on R, as well)

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

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



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

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

[Iocco, Pato, Bertone, Nature Physics 2015]

Some performed checks

(please do ask for details)

- Variation of Galactic parameters
- (De)selection of tracer class / datasets
- Spiral Arm systematics
- Binning (/averaging/statistics)
- Lower Radius cut (asymm. effects from bulge/bar)
- Of course, different (heavier) normal. of baryonic comp.
- Whatnot…

I forgot something? You got a problem?
email me at
iocco@ift.unesp.br
before posting on arXiv
(and perhaps read the paper first)

The Milky Way:

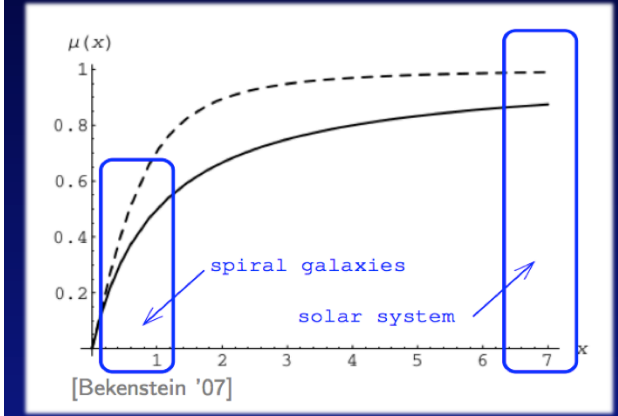
Evidence for Dark Matter ??

Discrepancy between:
observed rotation curve and observation-based expectations

assuming Newton’s law of gravity

Ansatz for the following is that same physics is valid at all scales (remember Clusters and CMB)

Modified Newtonian Dynamics?



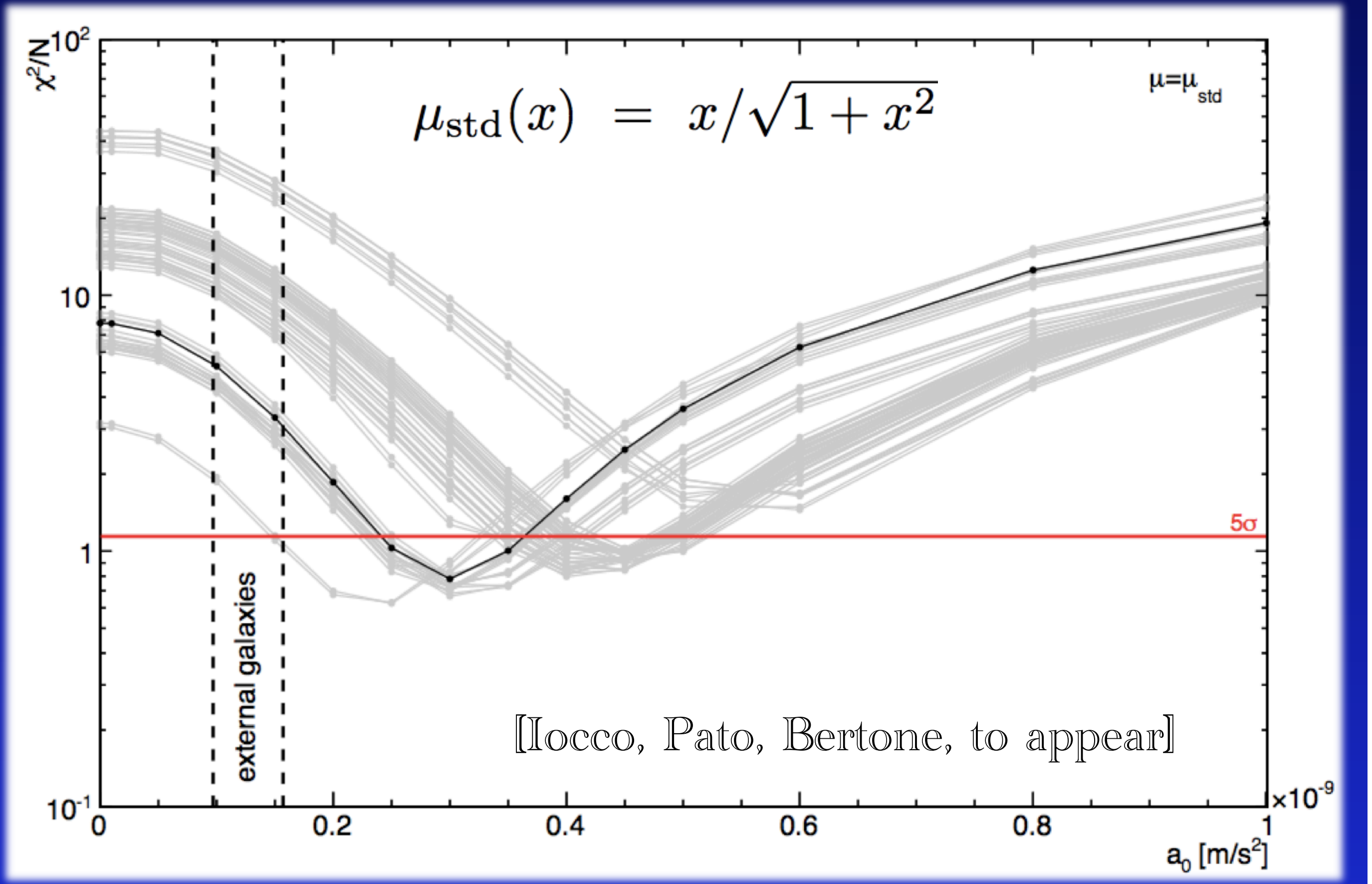
[Bekenstein '07]

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

$\mu(a/a_0) \approx 1$, $a \gg a_0$

$\mu(a/a_0) \approx a/a_0$, $a \ll a_0$

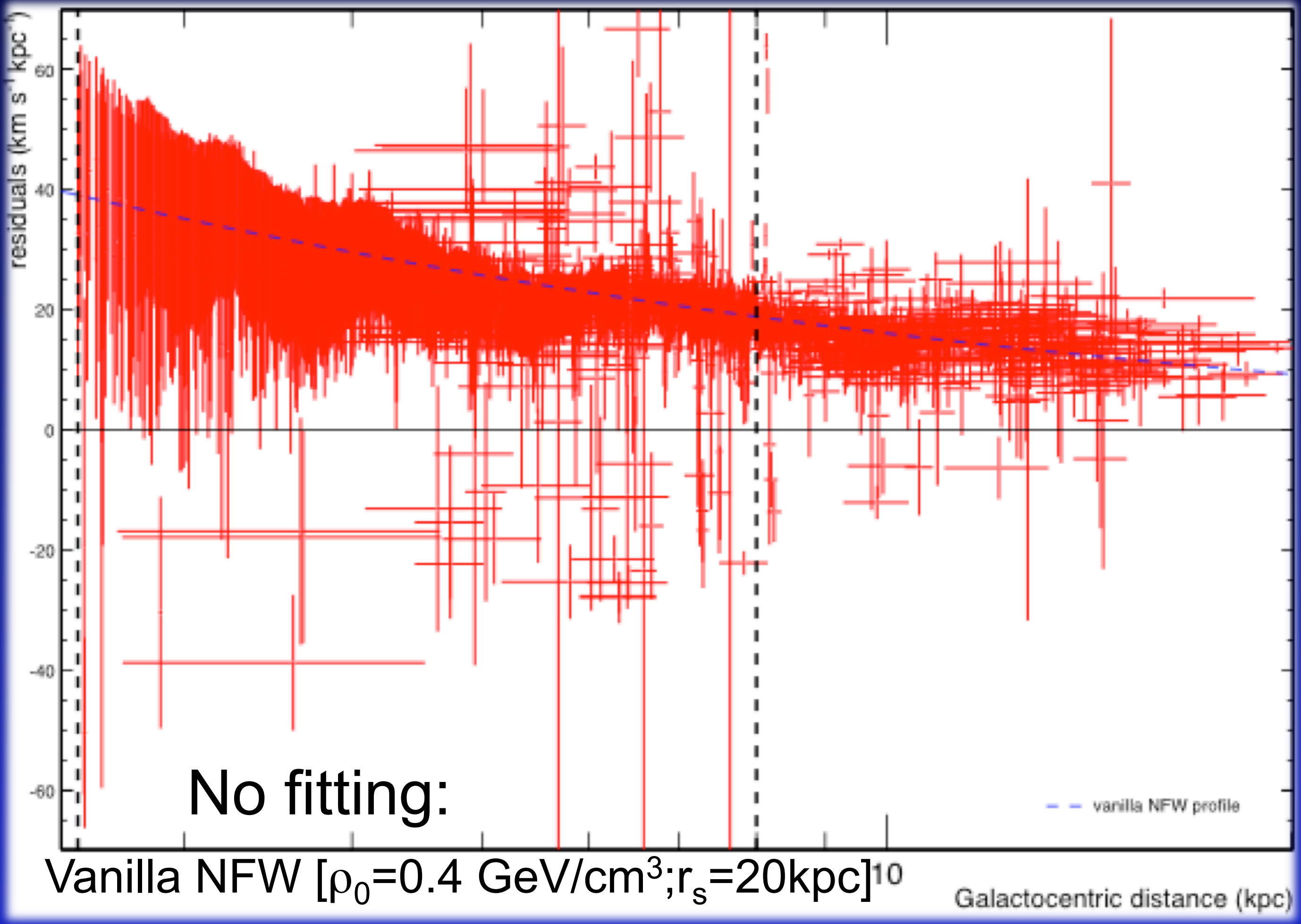
recovering Newton
in "strong" gravity regime



[Iocco, Pato, Bertone, to appear]

$\mu(a/a_0)$ analytical fit to data,
not from first principles

Motivating dark haloes

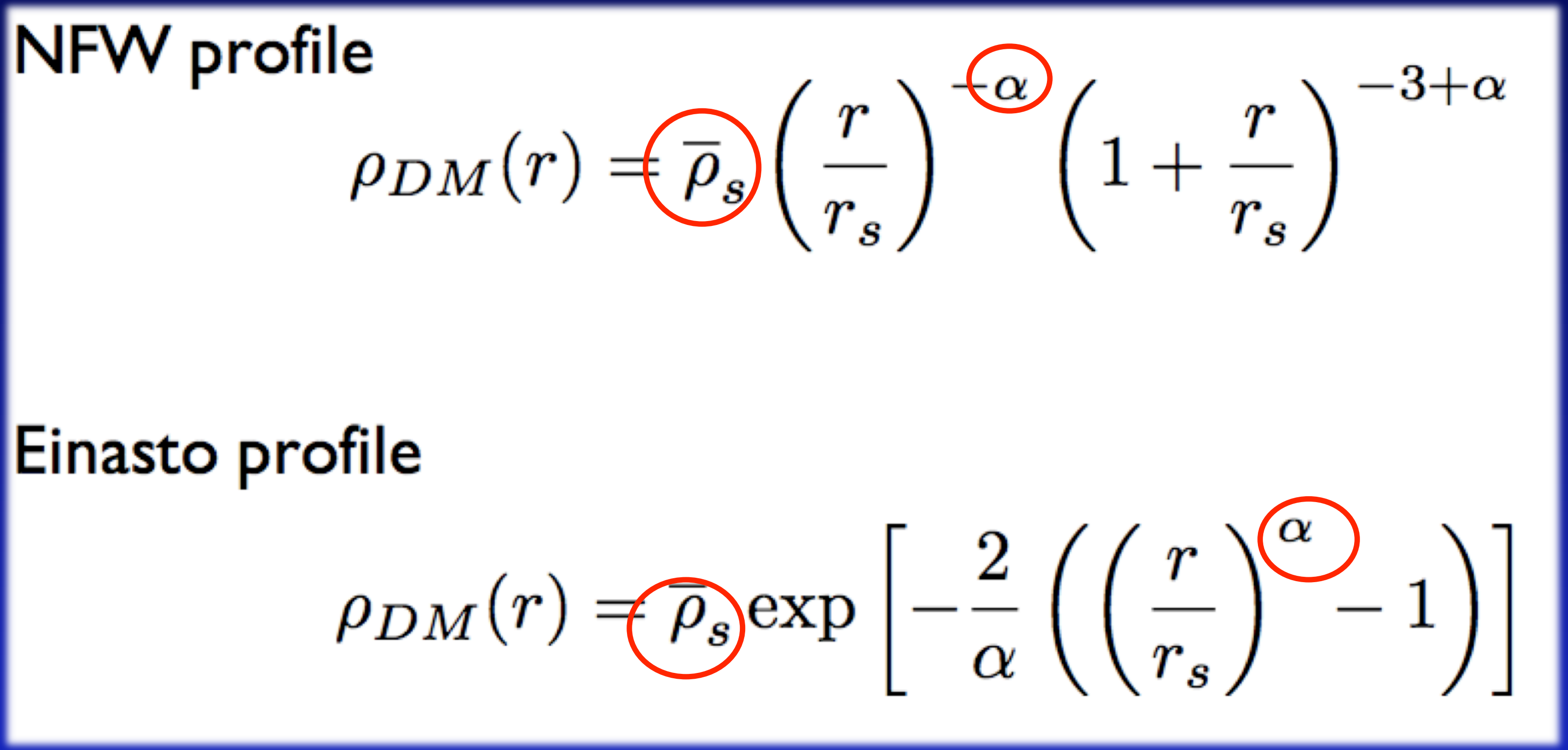


No fitting:

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

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

The Milky Way:
Dark Halos



NFW profile

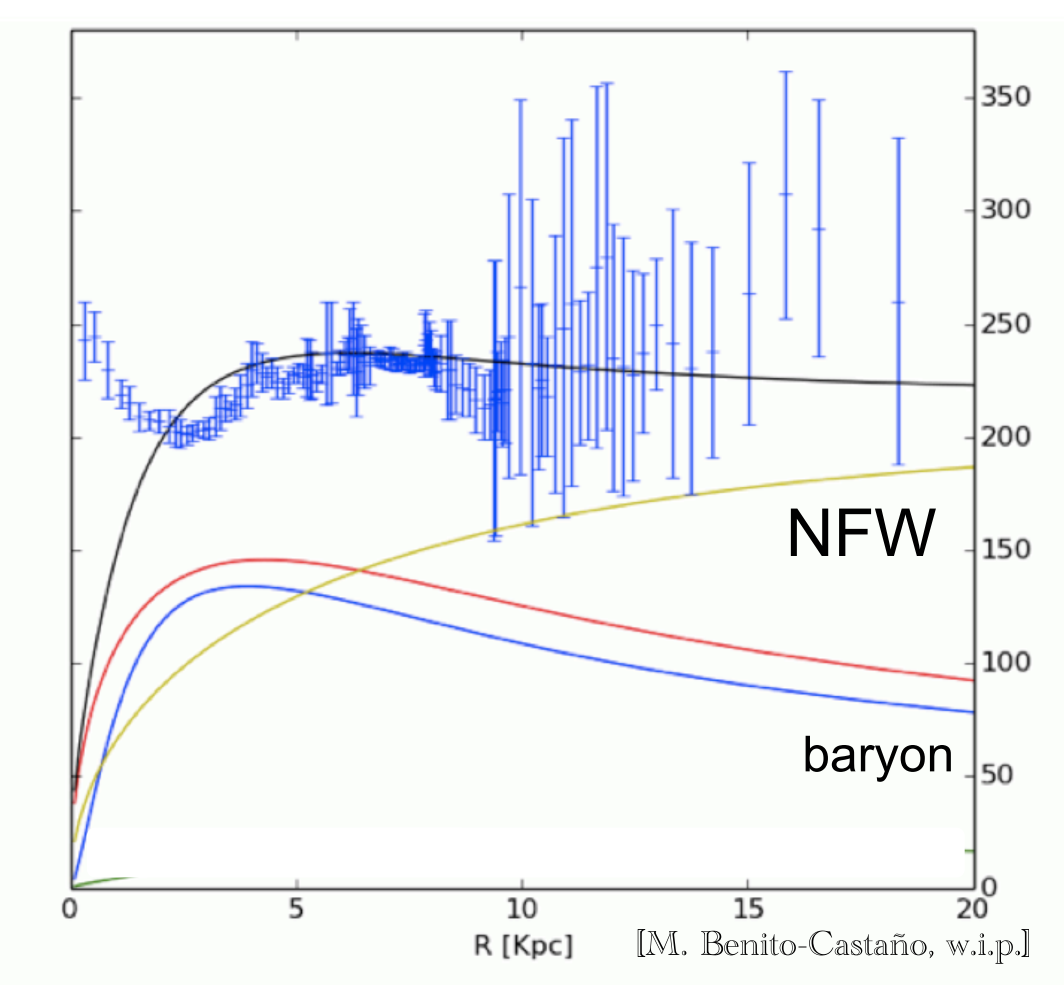
$$\rho_{DM}(r) = \bar{\rho}_s \left(\frac{r}{r_s}\right)^{-\alpha} \left(1 + \frac{r}{r_s}\right)^{-3+\alpha}$$

Einasto profile

$$\rho_{DM}(r) = \bar{\rho}_s \exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right]$$

Spherical profiles suggested by simulations

Adding Dark Matter: fitting halo shapes

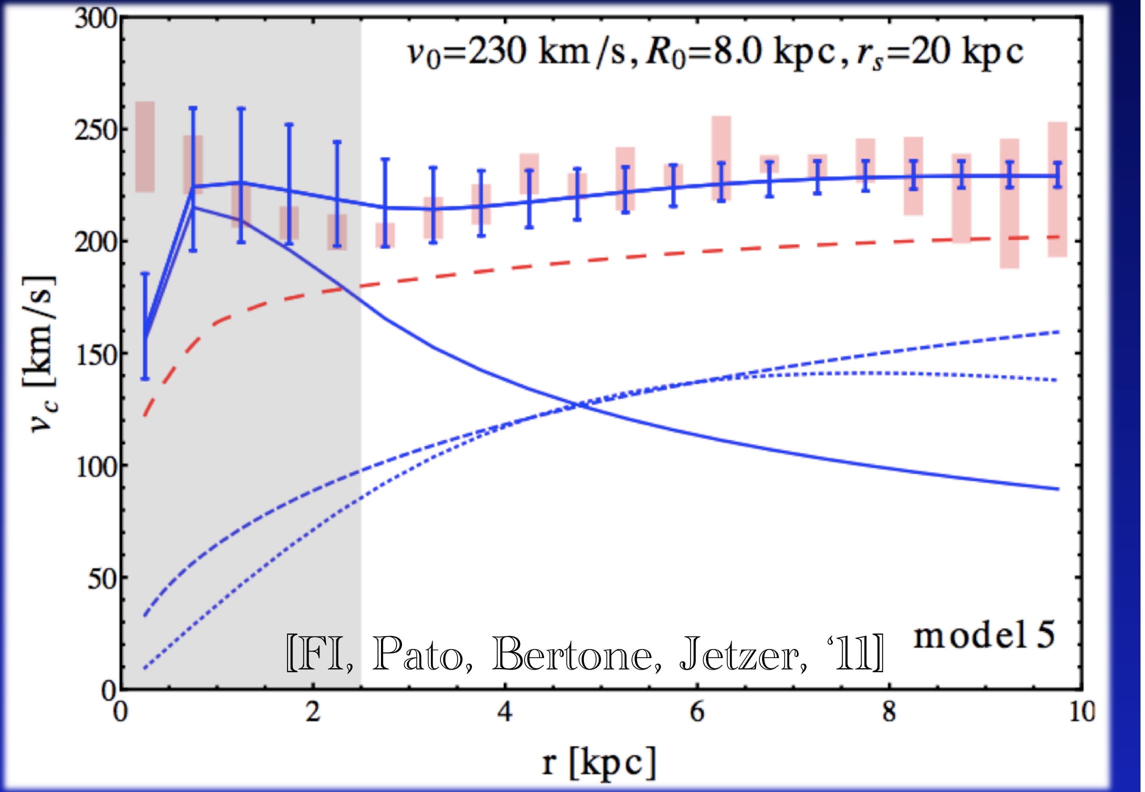


[M. Benito-Castaño, w.i.p.]

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

Global determination of halo parameters

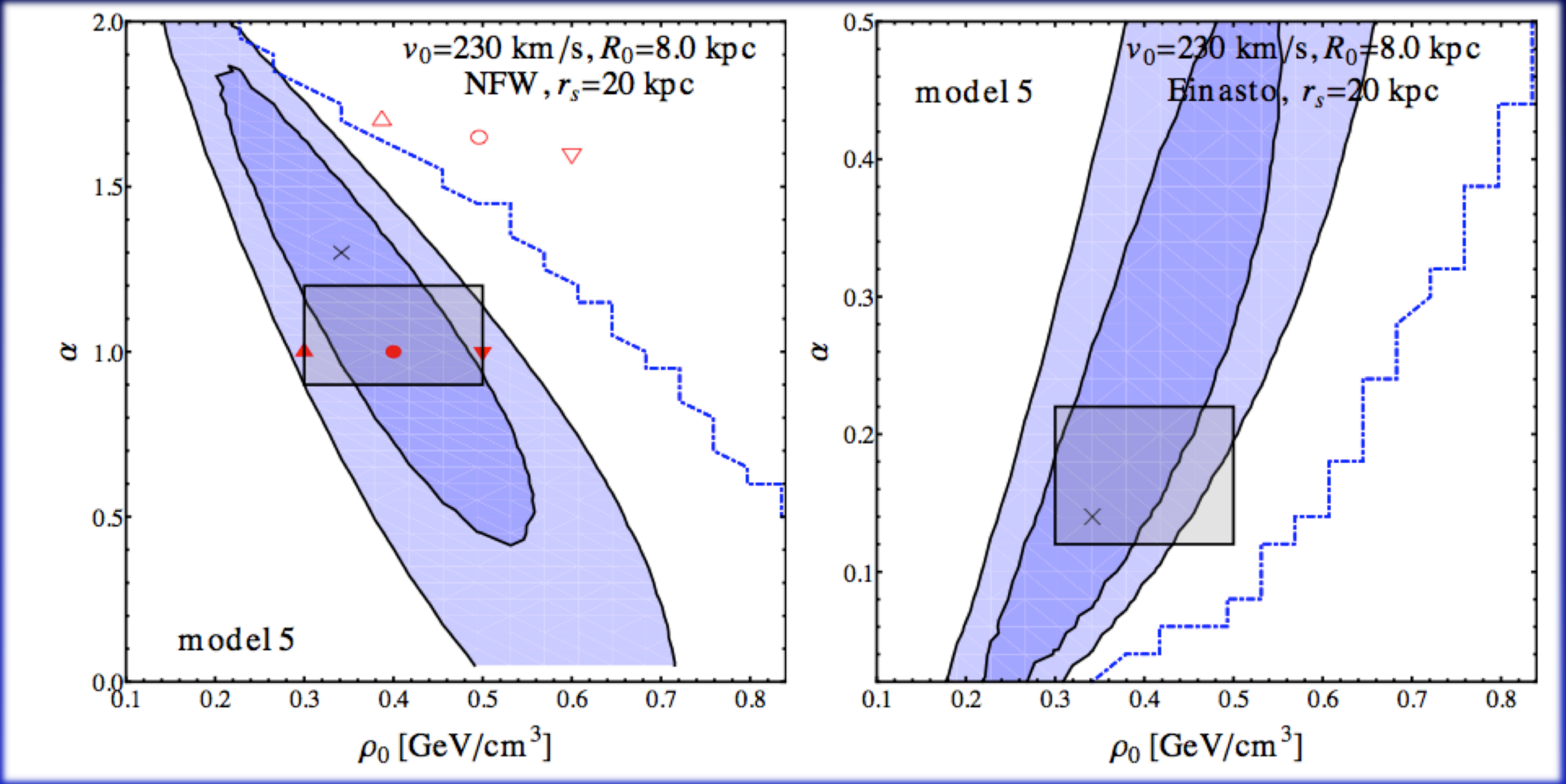
Fitting a DM profile to the Rotation Curve, on top of other components



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

Underlying assumption on DM presence and distribution shape

The Milky Way: fitting Dark Halo parameters

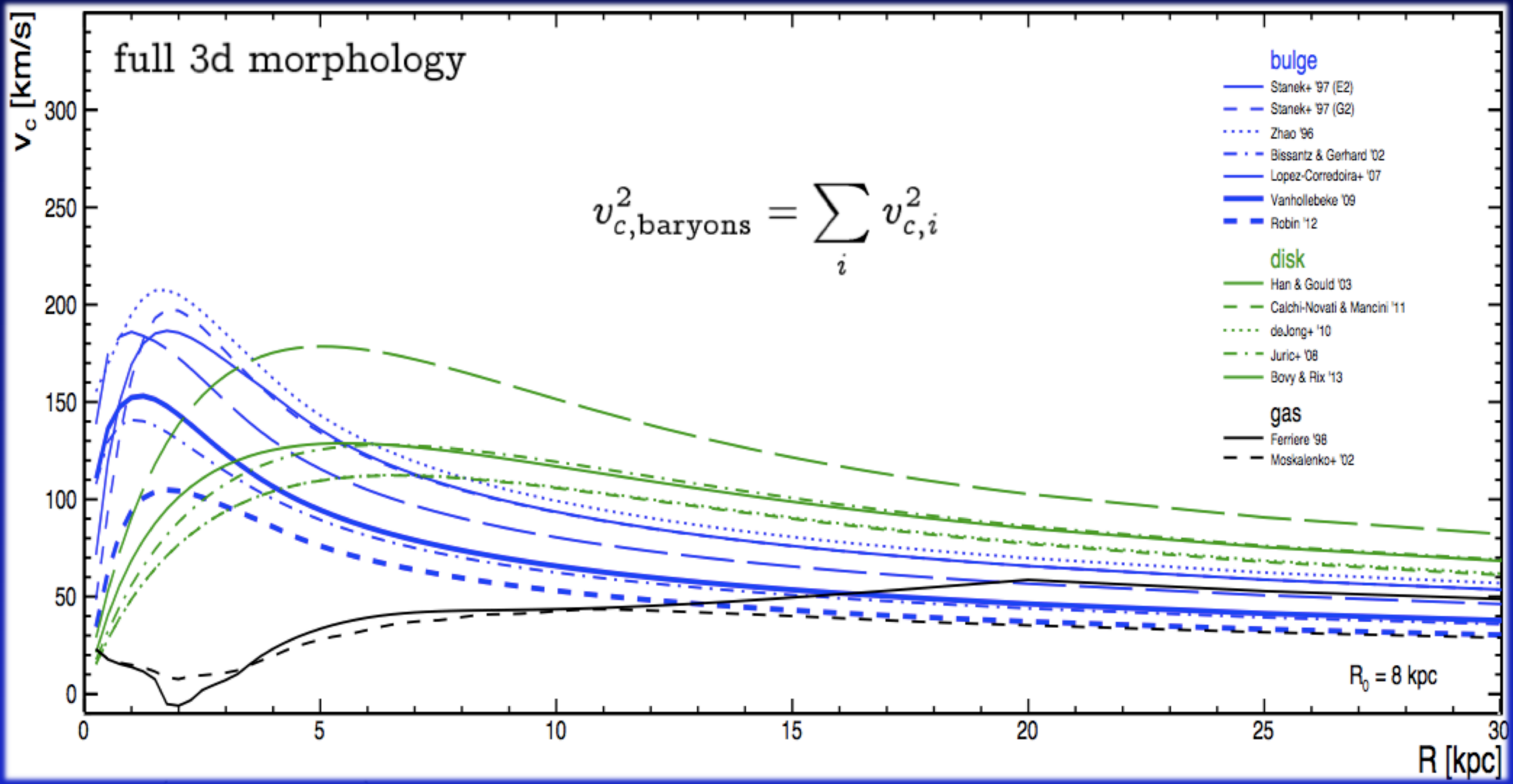


Excellent agreement with simulation parameter space,
And determination of ρ_0

[FI, Pato et al., 2011]

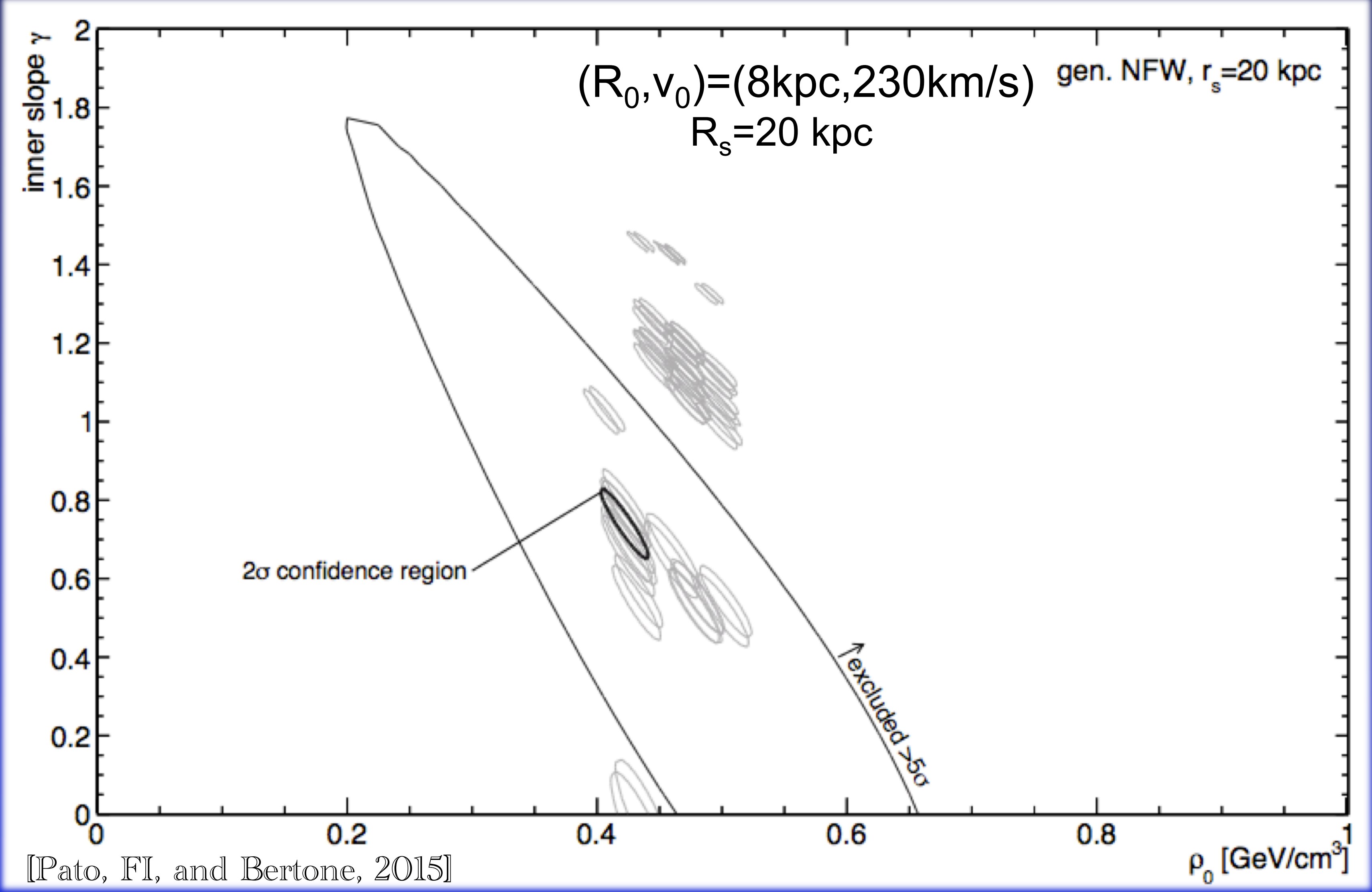
The Milky Way:

spherical halos on top of baryonic models



scanning halo parameter space for each baryonic model

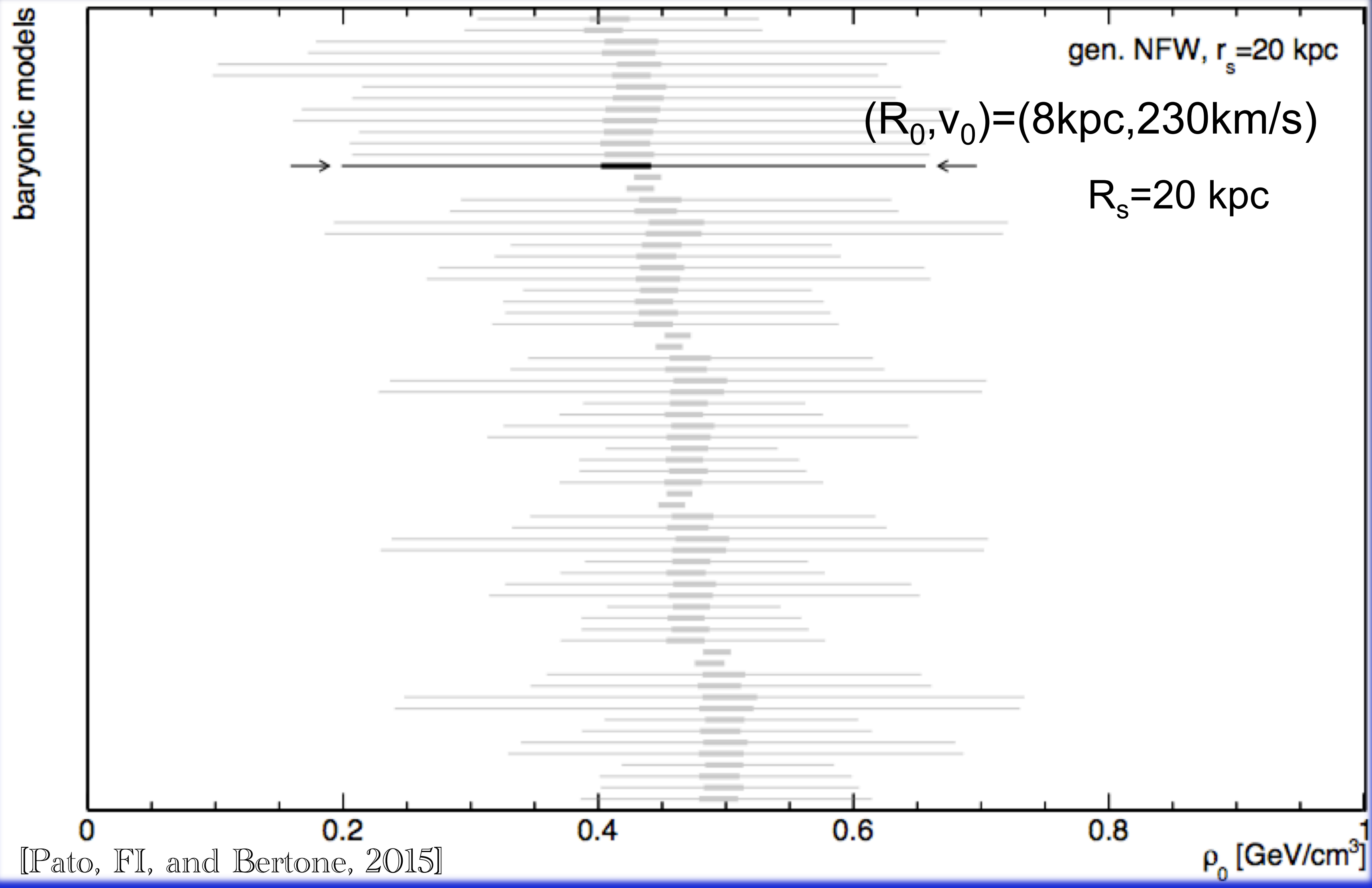
The Milky Way:
the importance of baryon modelling



(R_0,v_0)=(8kpc,230km/s)
R_s=20 kpc

[Pato, FI, and Bertone, 2015]

The Milky Way:
the importance of baryon modelling

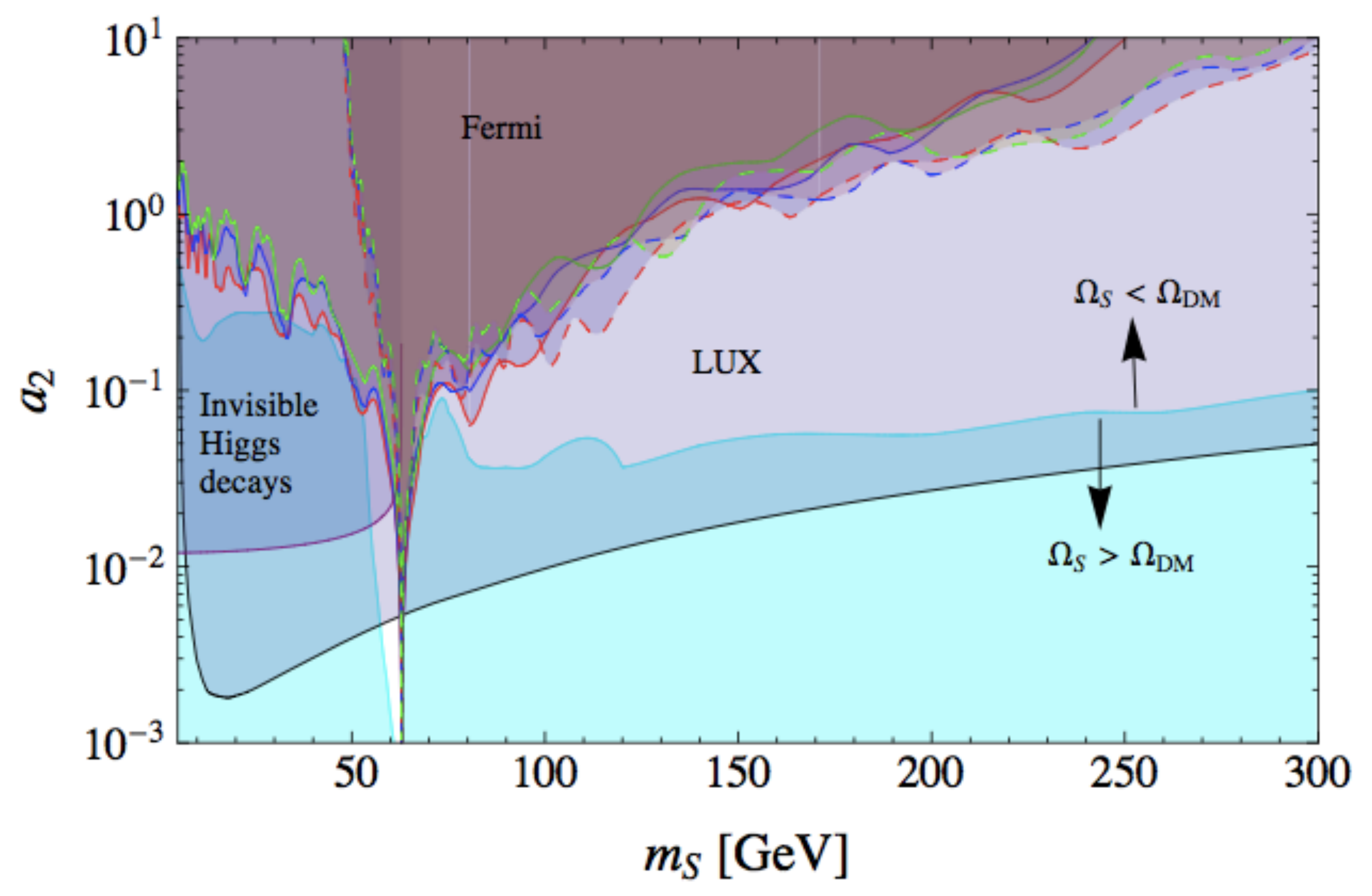


(R_0,v_0)=(8kpc,230km/s)

R_s=20 kpc

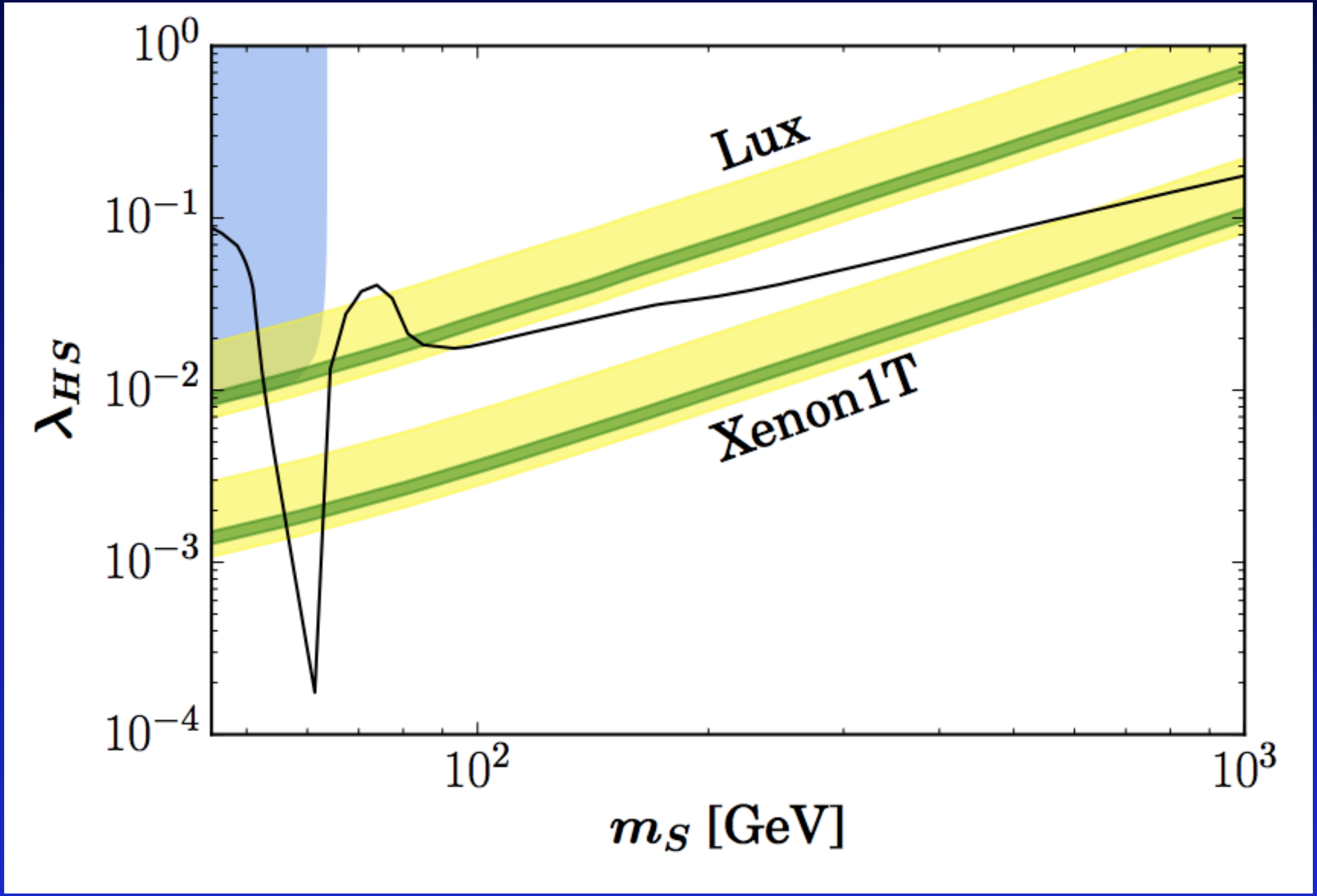
[Pato, FI, and Bertone, 2015]

Why should a theorist care?



[Feng, Profumo, Ubaldi, 2014]

Why should a theorist care?



[Bernàl, Bozorgnia, Calore, FI, work in progress]

The Milky Way's backbone: an agnostic approach

reconstructing the profile from observations alone

no assumptions on the shape of the profile

$$v_{\mathrm{dm}}^2 = GM_{\mathrm{dm}}(<R)/R$$

$$\mathrm{d}\phi_{\mathrm{tot}}/\mathrm{d}R = \omega_c^2 R$$

$$\omega_{\mathrm{dm}}^2 = \omega_c^2 - \omega_{\mathrm{b}}^2$$

$$\mathrm{d}\phi_{\mathrm{b}}/\mathrm{d}R = \omega_{\mathrm{b}}^2 R$$

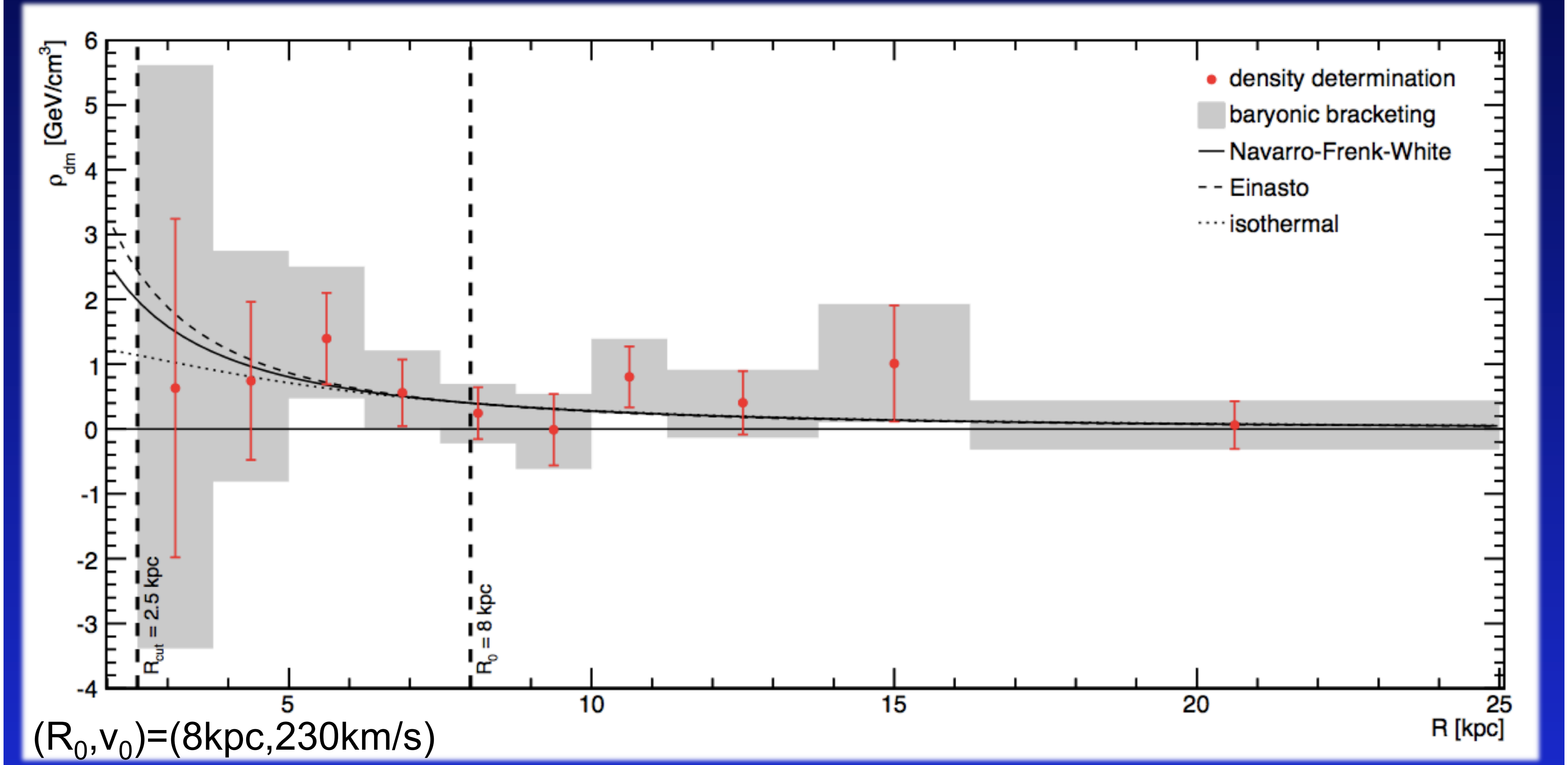
Assumption of spherical symmetry

$$\rho_{\mathrm{dm}} = \frac{1}{4\pi G}\left(3\,\omega_{\mathrm{dm}}^2 + R\,\frac{\mathrm{d}\omega_{\mathrm{dm}}^2}{\mathrm{d}R}\right)$$

"The DM profile of the MW, a non-parametric reconstruction"

Pato and FI, ApJL 2015

The Milky Way's backbone: an unbiased reconstruction



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

"The DM profile of the MW, a non-parametric reconstruction"
Pato and FI, ApJL 2015

CUNCTA STRICTE

- Model-independent, assumption-free analysis
  - Based on observational data only
    - DM “not included”

- Evidence for discrepancy between Observed and theoretical (obs. infer.) RC
  - 5 σ at $R < R_0$ (inner Galaxy)
- Analysis is solid against galactic parameter variation and systematics

IN PROGRESS

- Determination of (ρ_0,α) with different galactic configurations
- Direct determination of DM profile
- Impact on particle physics determination

FUTURUS

- Generalization to non-spherical profiles
- Test adiabatic contraction (spike)