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

Mitchell Workshop
Texas A & M
5/21/15

Direct and indirect searches of WIMP DM

complementary to colliders

Direct detection:

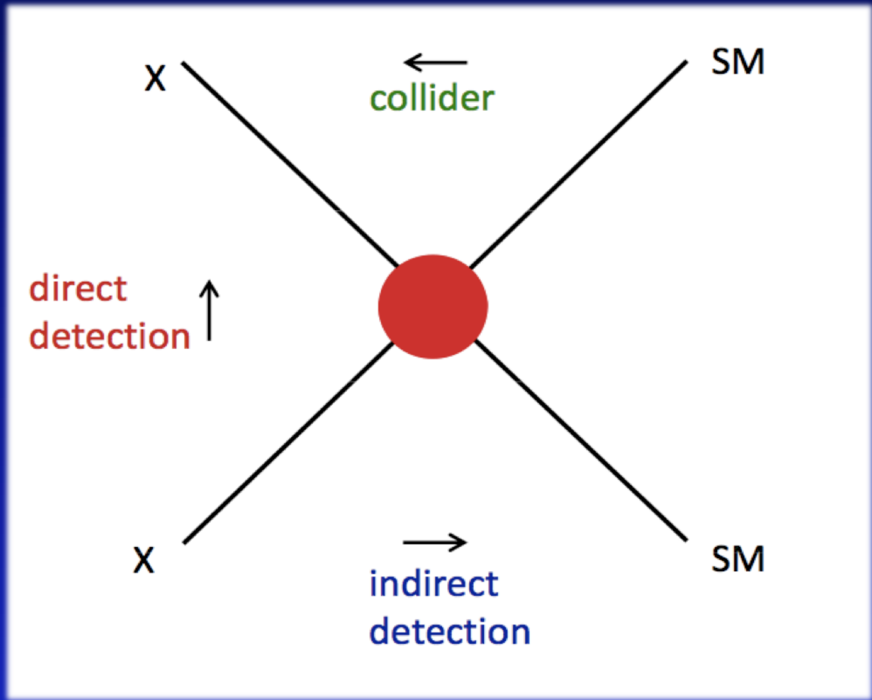
DM scattering against nuclei, recoil

Indirect detection:

Annihilation in astrophysical envir.

Observation of SM products of annih.

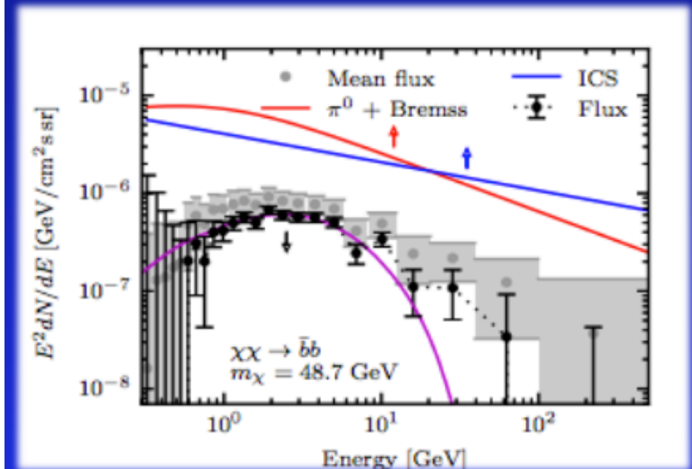
Production at LHC

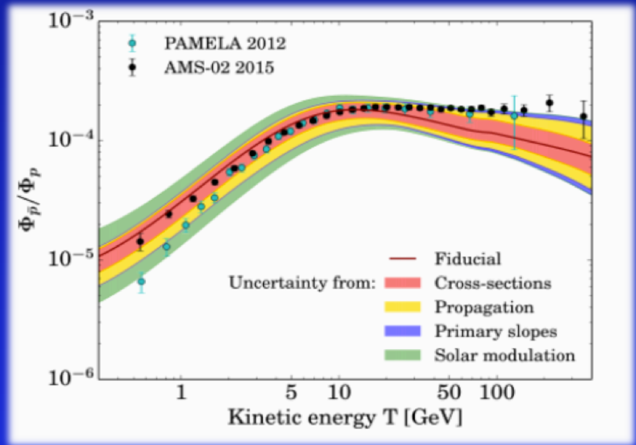


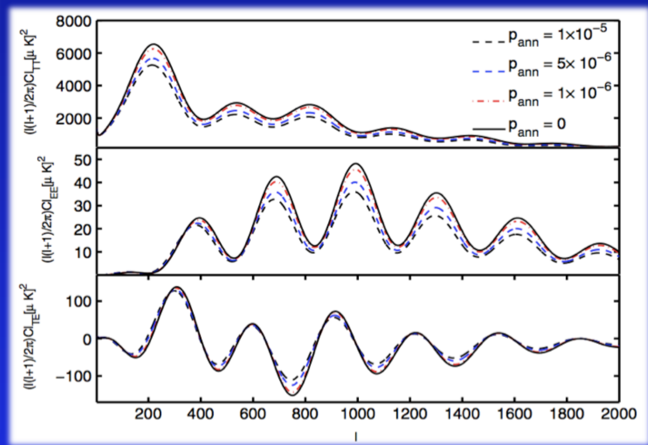
Possible observables for DM annihilation:

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

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

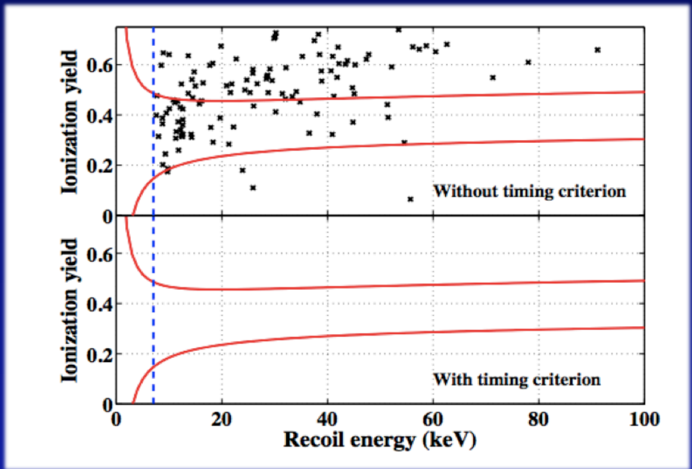


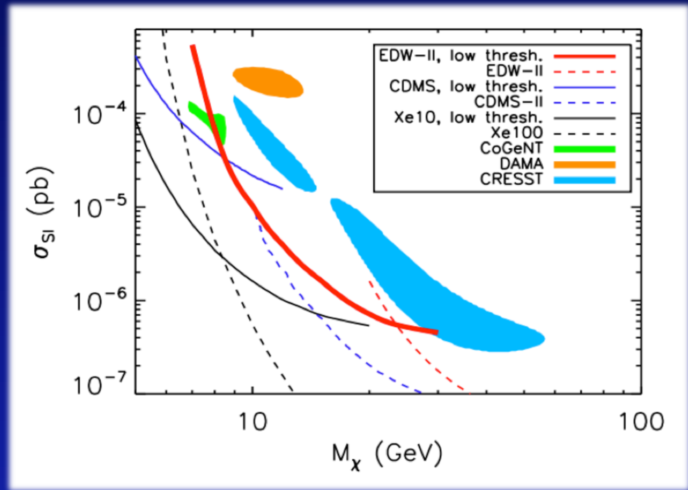




Direct searches of WIMP DM:

from this → to this





you have to use this

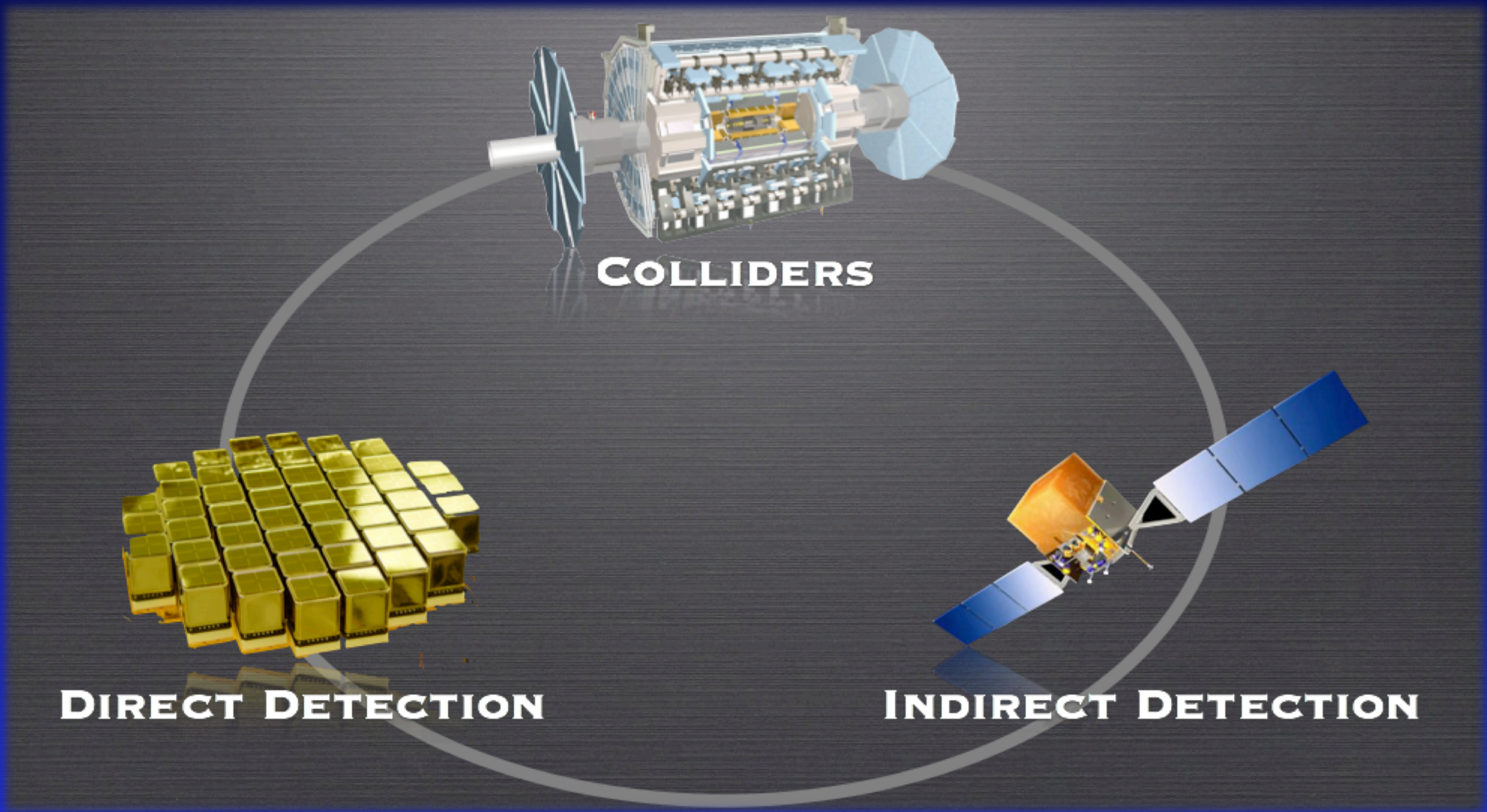
$$\frac{dR_{A,Z}}{dE} = \frac{\sigma_{A,Z}(E)}{2m\mu^2_{A,Z}} \rho\, \eta(v_{\min}, t)$$

Velocity distribution properties of DM

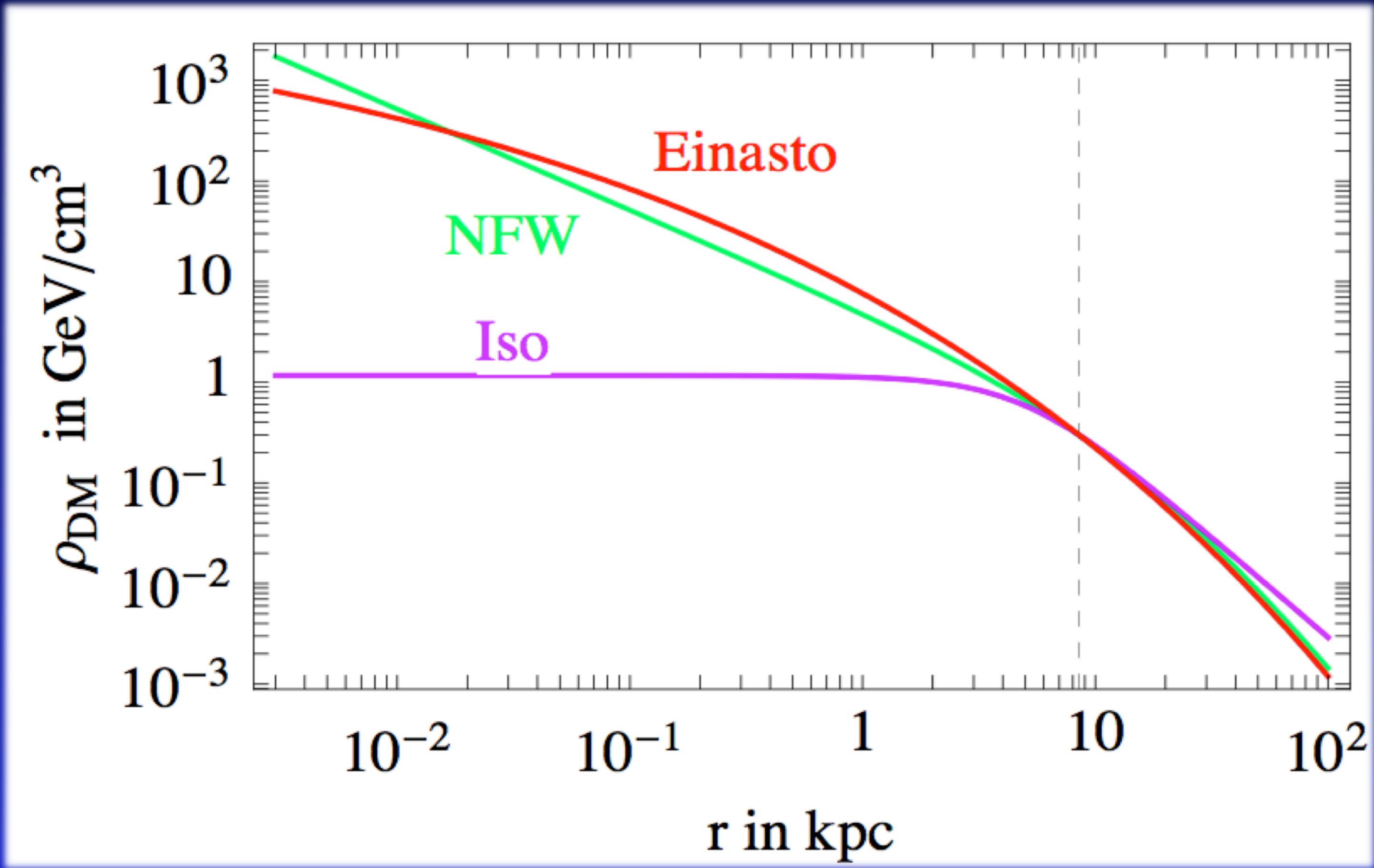
DM density at the Sun’s location, ρ_0

Direct and indirect searches

complementary to colliders



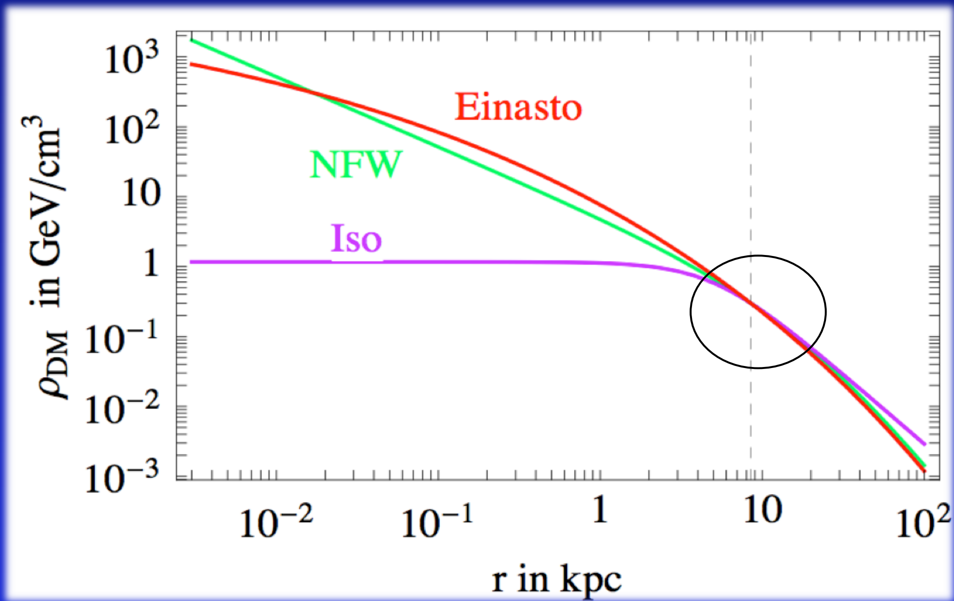
Direct and inDirect
crucially depend on DM distribution



(well motivated)
hints from numerical simulations

DM density at the Sun: ρ_0 = ?

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

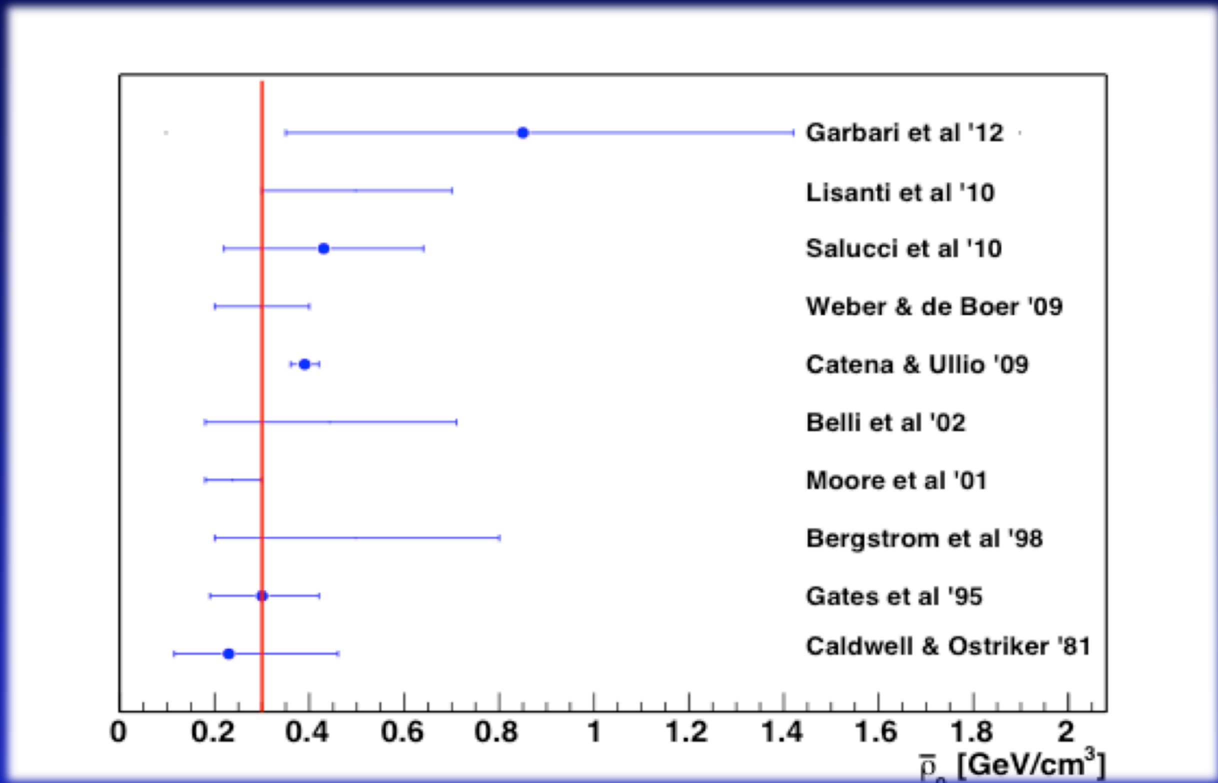


Determination of local DM density ρ_0

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

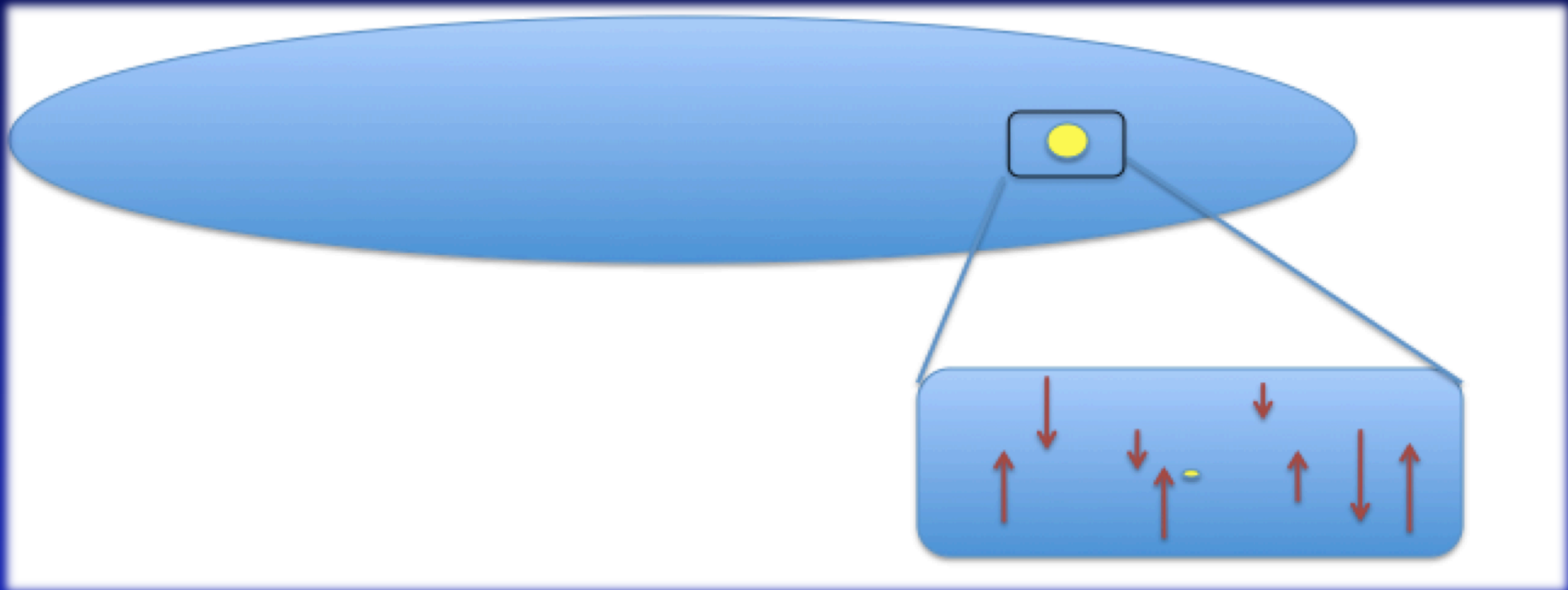
vs

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



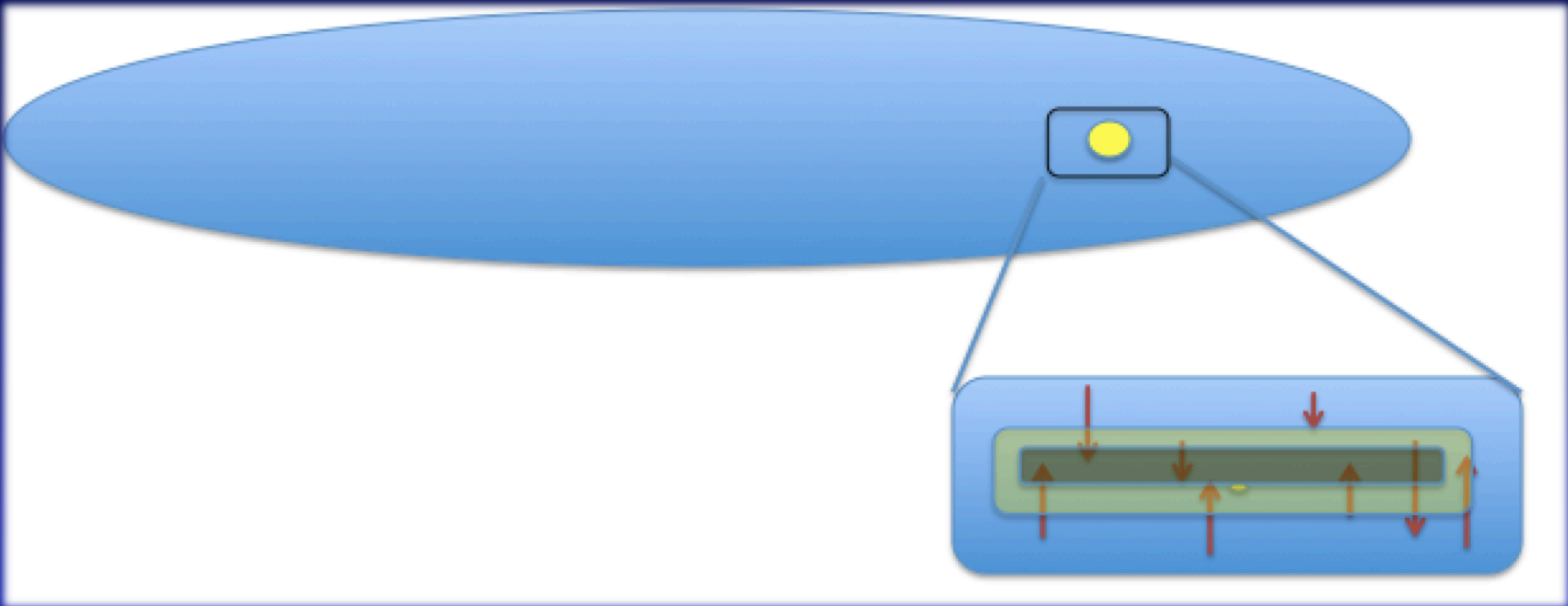
Give consistent results

Local determination of ρ_0



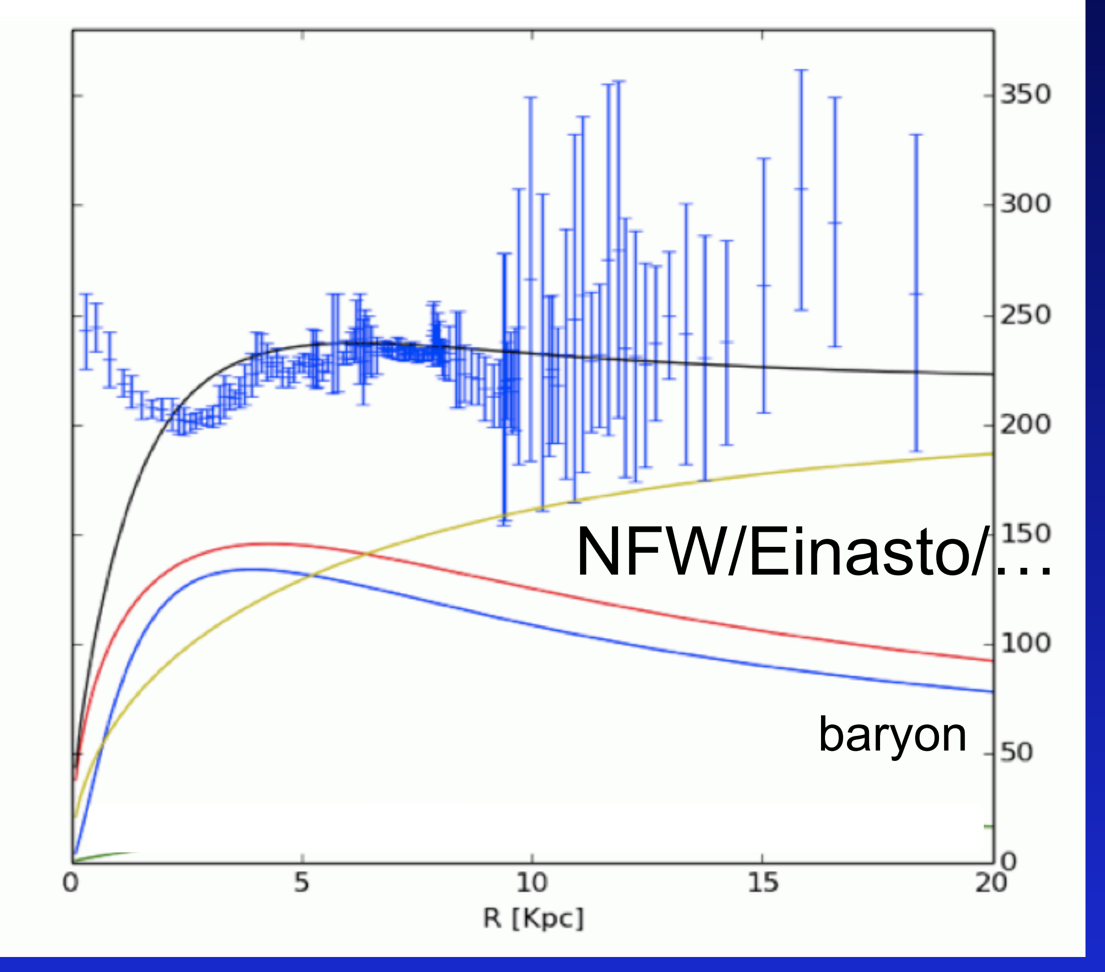
Vertical motion of stars, determining the whole local potential

Local determination of ρ_0



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

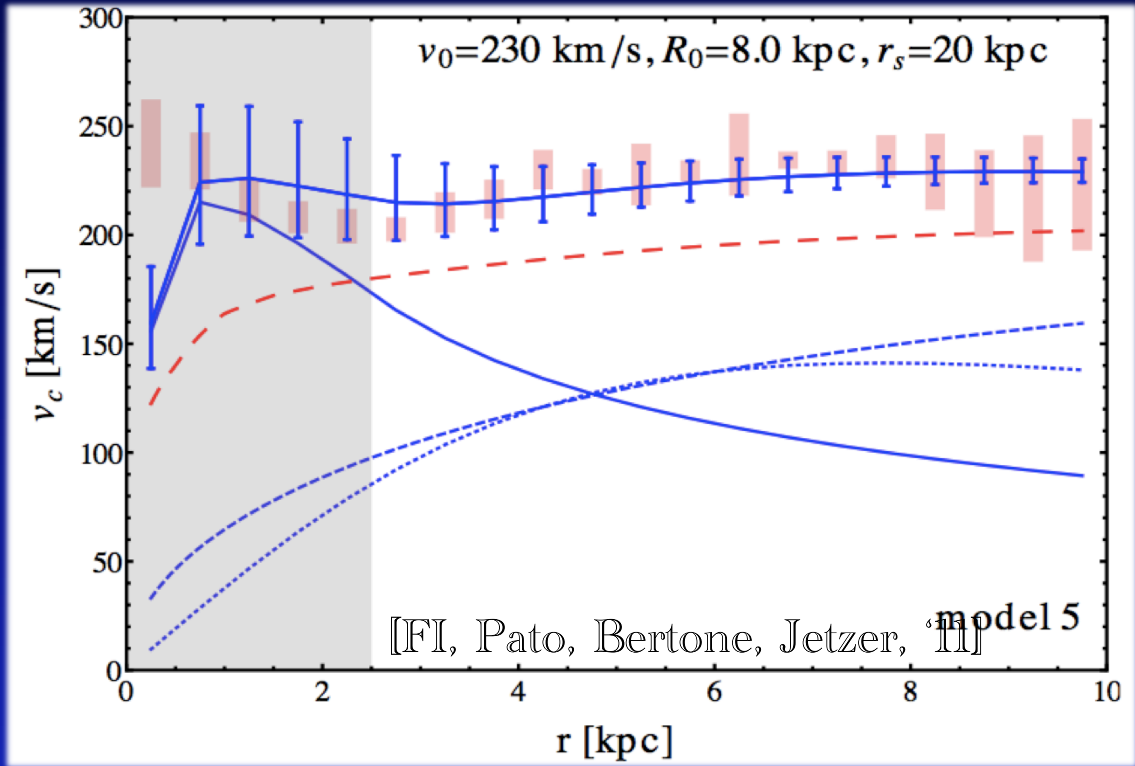
Adding Dark Matter: fitting halo shapes



[M. Benito-Castaño, w.i.p.]

Global determination of ρ(r)

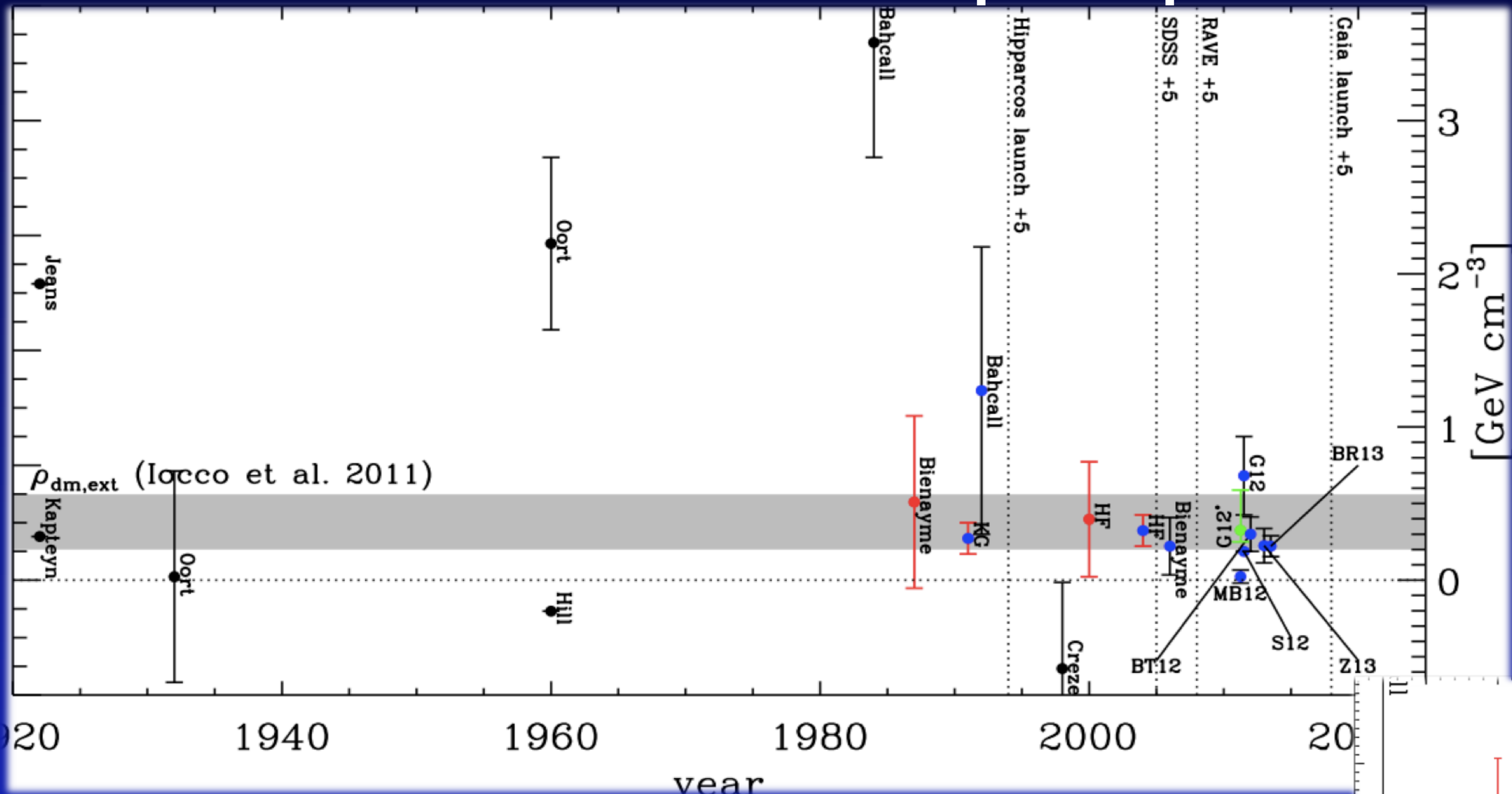
Fitting a DM profile to the Rotation Curve, on top of other components

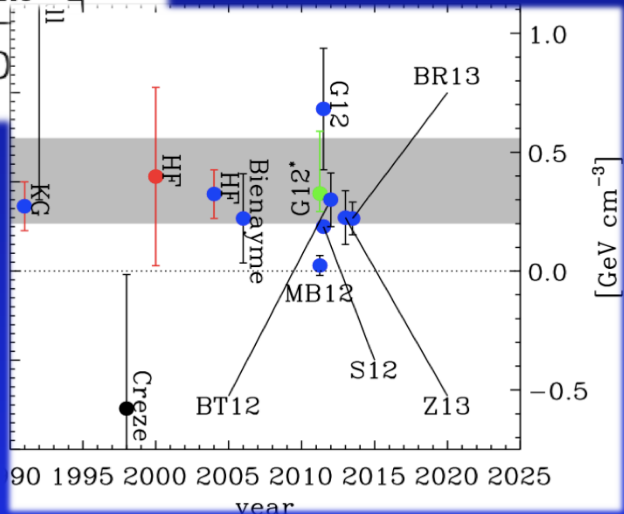


$$\phi_{\rm tot} = \phi_{\rm bulge} + \phi_{\rm disk} + \phi_{\rm gas} + \phi_{\rm dm}$$

Underlying assumption on DM presence and distribution shape

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

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

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

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

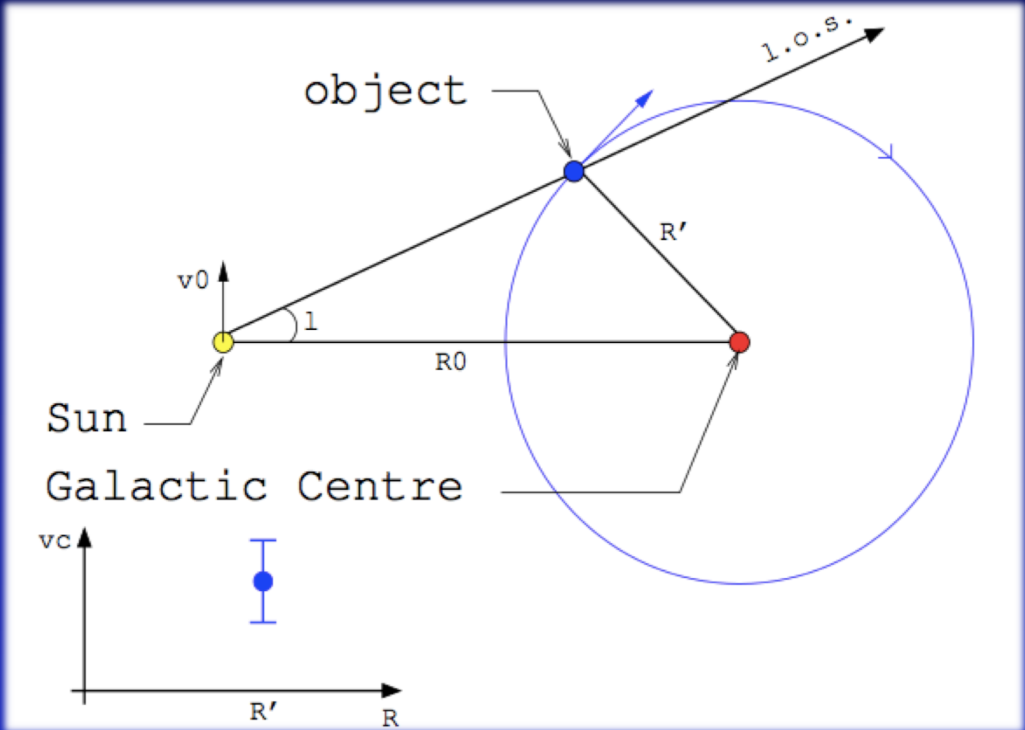
Rotation curve as a tracer of the total potential

…and if not…

The Milky Way:

observed rotation curve

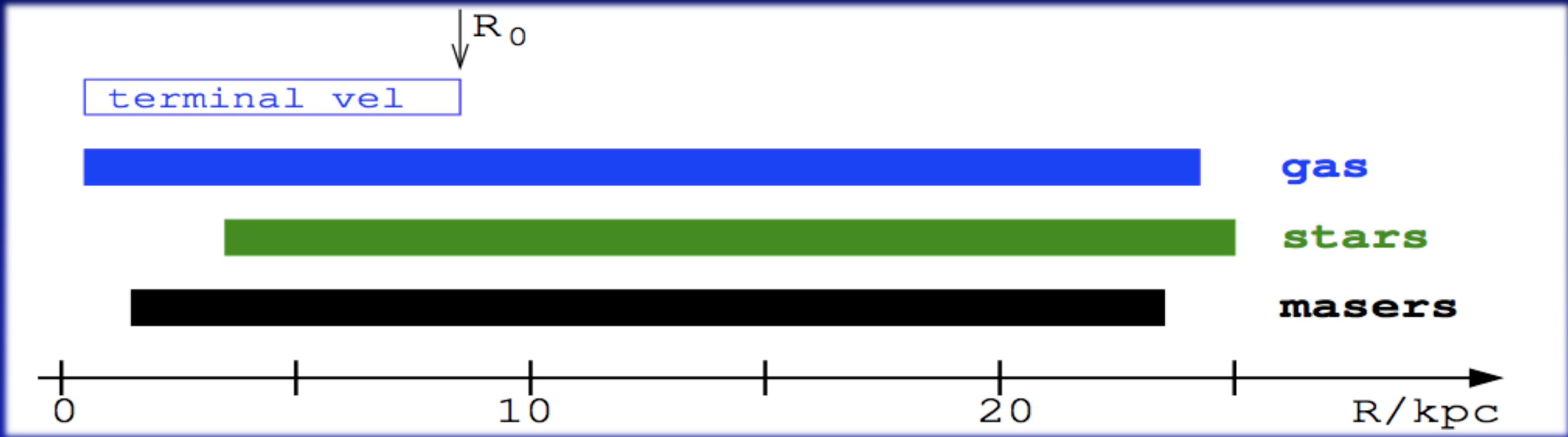
I. principles



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

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

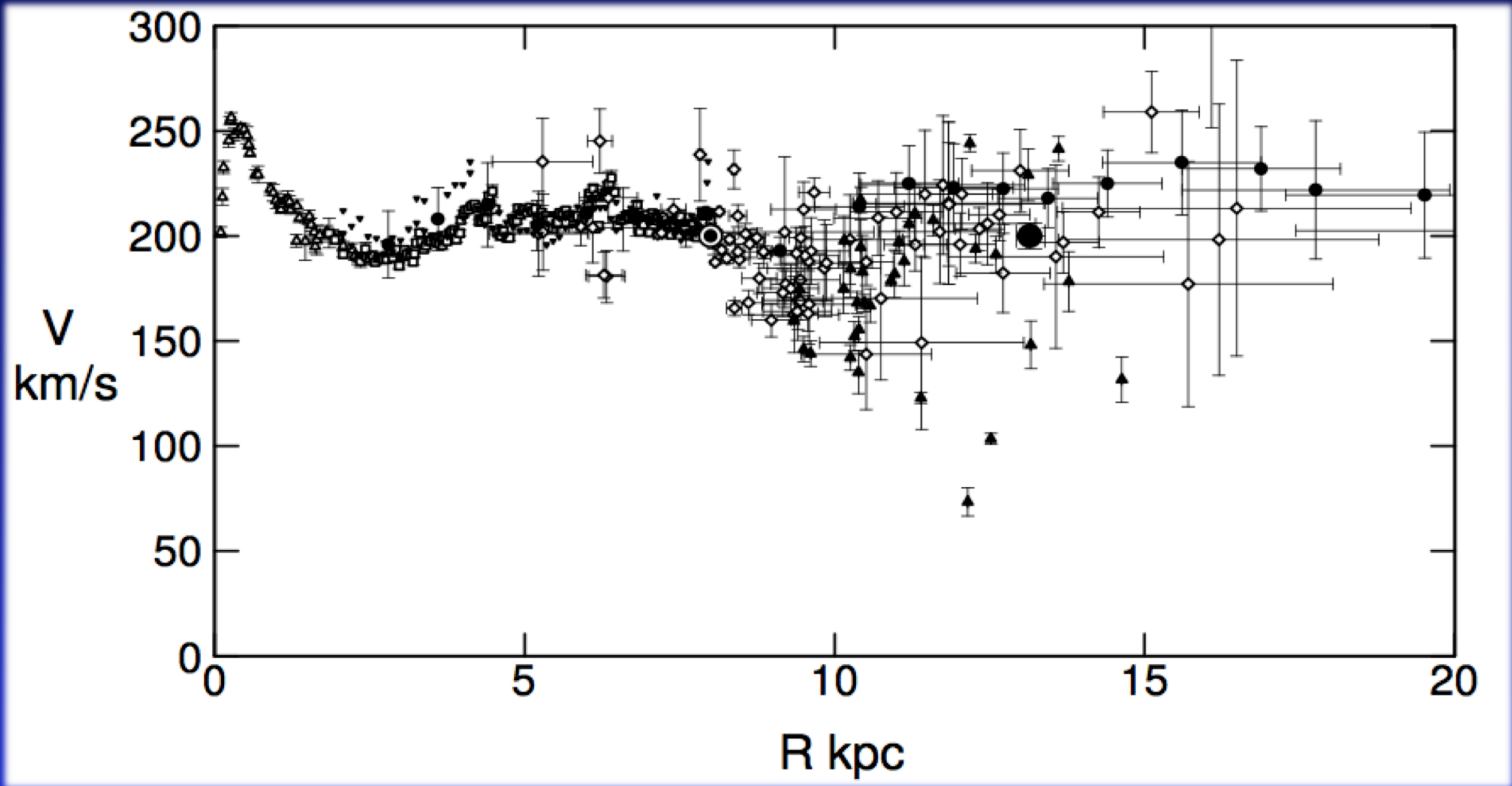
The Milky Way:
observed rotation curve
II. tracers



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

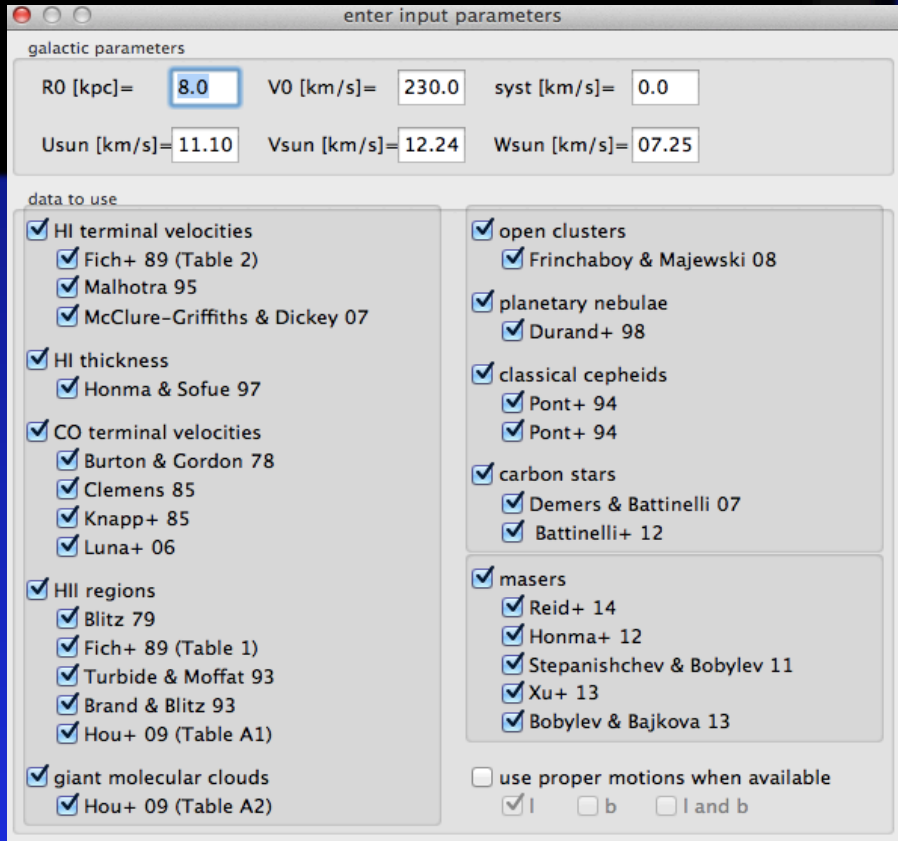
The Milky Way:

observed rotation curve

IV. public tool

```
#################################################################################
# RCtool, version 1.0, by Miguel Pato and Fabio Iocco.
# Last update: MP 29 Apr 2014.
############
# This code is designed to process and output measurements on the rotation curve of our Galaxy.
#################################################################################

### read input ###
launching window...
```



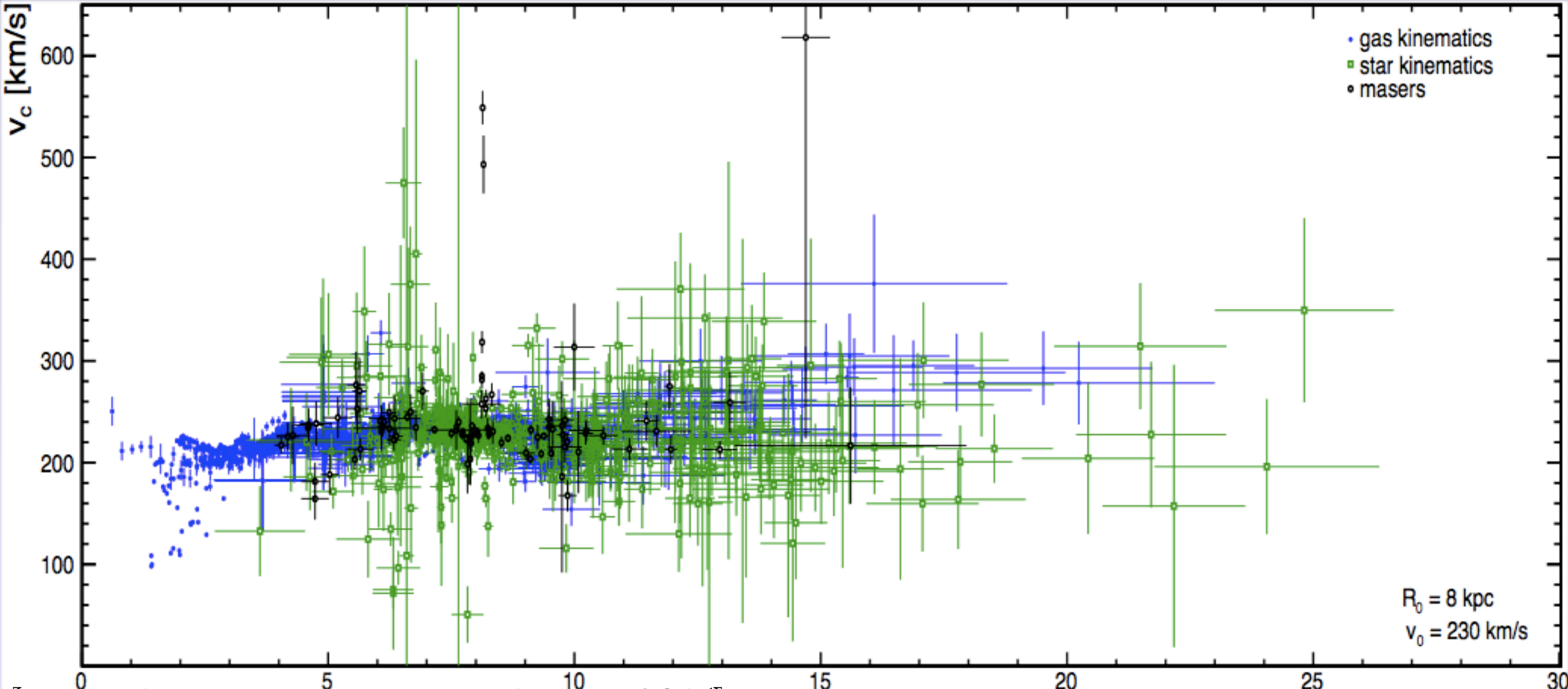
Customizable galactic parameters
(R_0,V_0)
peculiar motions, etc…

Available soon:
reserve your copy now!

[Pato & FI, soon]

The Milky Way Rotation Curve

as observed



[Iocco, Pato, Bertone, Nature Physics 2015]

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

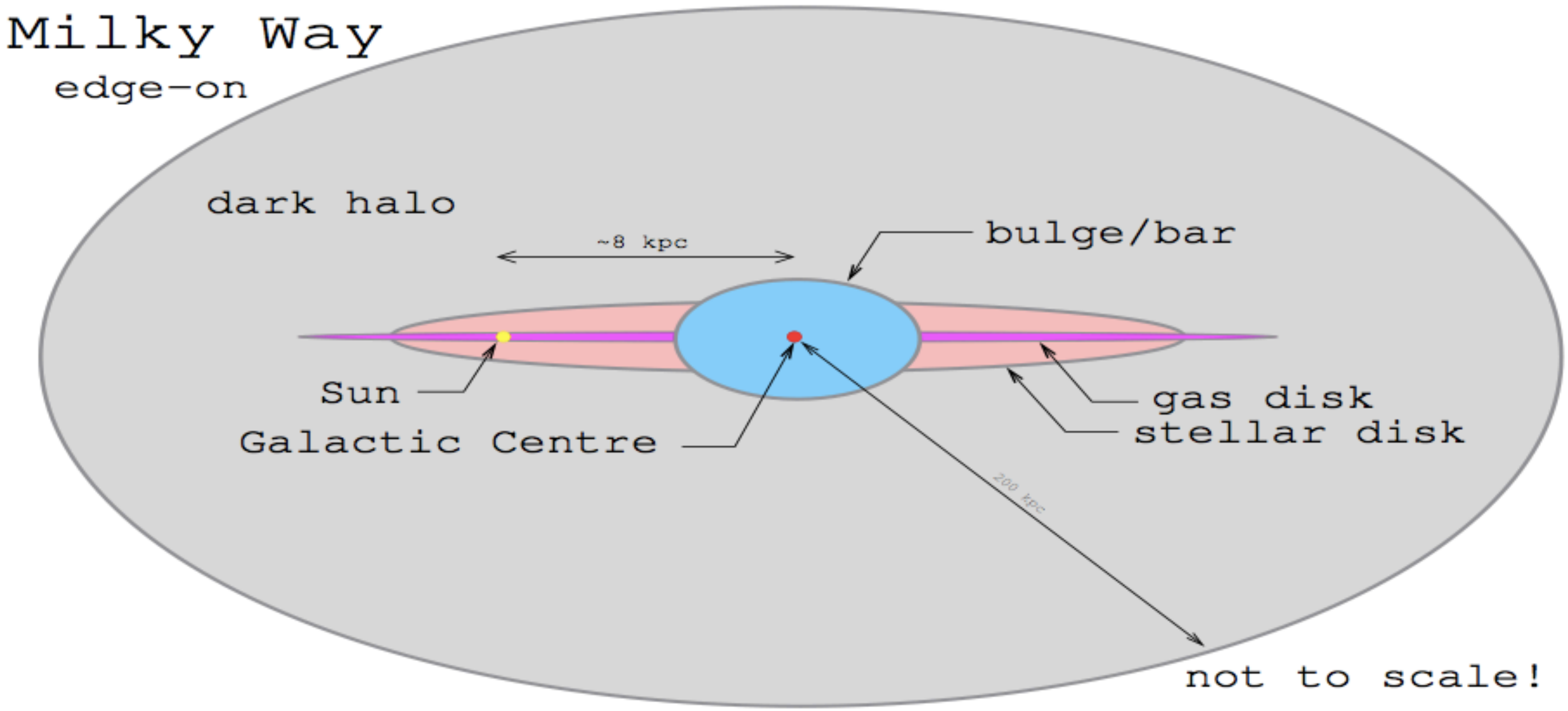
The Milky Way:
expected rotation curve

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

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

Constructing the curve expected from observed mass profiles

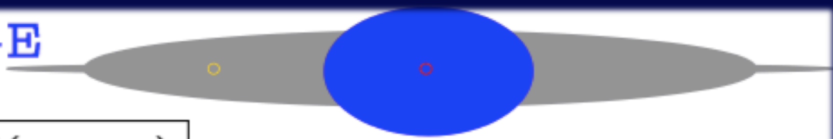
The Milky Way:
expected rotation curve
1. the baryonic components



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

The visible Milky Way: observations of morphology

2. BARYONS: STELLAR BULGE



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

morphology $f(x,y,z)$

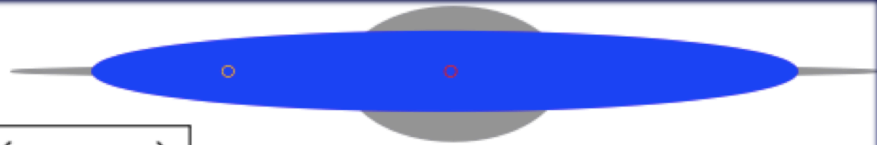
Stanek+ '97 (E2)	e^{-r}	0.9:0.4:0.3	24°	optical
Stanek+ '97 (G2)	$e^{-r_s^2/2}$	1.2:0.6:0.4	25°	optical
Zhao '96	$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	1.5:0.6:0.4	20°	infrared
Bissantz & Gerhard '02	$e^{-r_s^2}/(1+r)^{1.8}$	2.8:0.9:1.1	20°	infrared
Lopez-Corredoira+ '07	Ferrer potential	7.8:1.2:0.2	43°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

microlensing optical depth: $\langle\tau\rangle = 2.17^{+0.47}_{-0.38} \times 10^{-6}$, $(\ell, b) = (1.50°, -2.68°)$
(MACHO '05)

The visible Milky Way: observations of morphology

2. BARYONS: STELLAR DISK



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

morphology $f(x,y,z)$

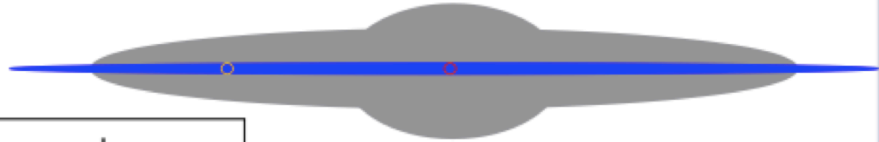
Han & Gould '03	$e^{-R}\mathrm{sech}^2(z)$	2.8:0.27	thin	optical
	$e^{-R-\|z\|}$	2.8:0.44	thick	
Calchi-Novati & Mancini '11	$e^{-R-\|z\|}$	2.8:0.25	thin	optical
	$e^{-R-\|z\|}$	4.1:0.75	thick	
deJong+ '10	$e^{-R-\|z\|}$	2.8:0.25	thin	optical
	$e^{-R-\|z\|}$	4.1:0.75	thick	
	$(R^2+z^2)^{-2.75/2}$	1.0:0.88	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: $\Sigma_* = 38 \pm 4 M_\odot/\mathrm{pc}^2$ [Bovy & Rix '13]

The visible Milky Way: observations of morphology

2. BARYONS: GAS



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

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

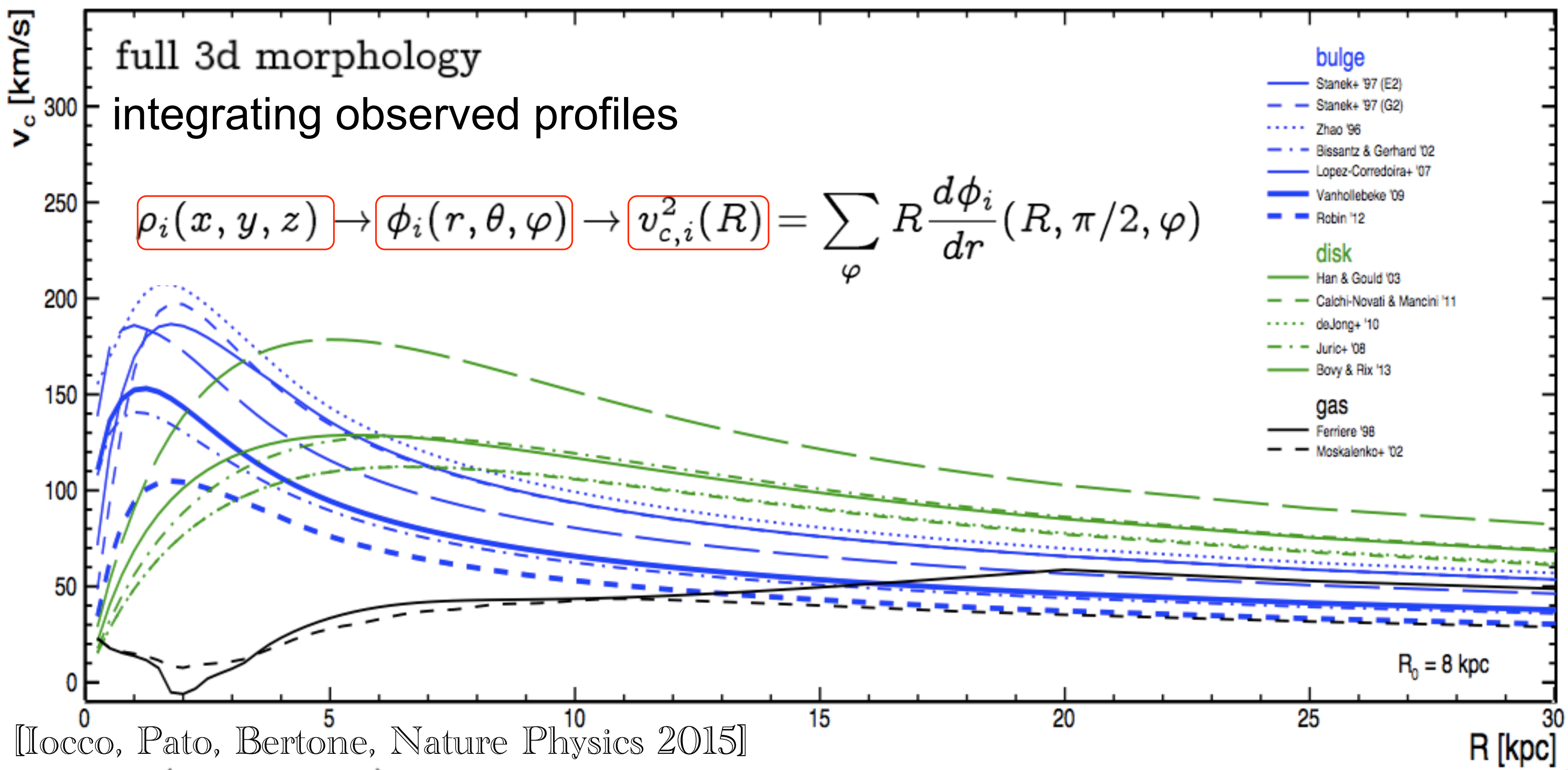
CO-to-H_2 factor: $X_{\mathrm{CO}} = 0.25 - 1.0 \times 10^{20}\ \mathrm{cm}^{-2}\,\mathrm{K}^{-1}\,\mathrm{km}^{-1}\,\mathrm{s}$ for $r < 2$ kpc

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

[Ferrière+ '07, Ackermann '12]

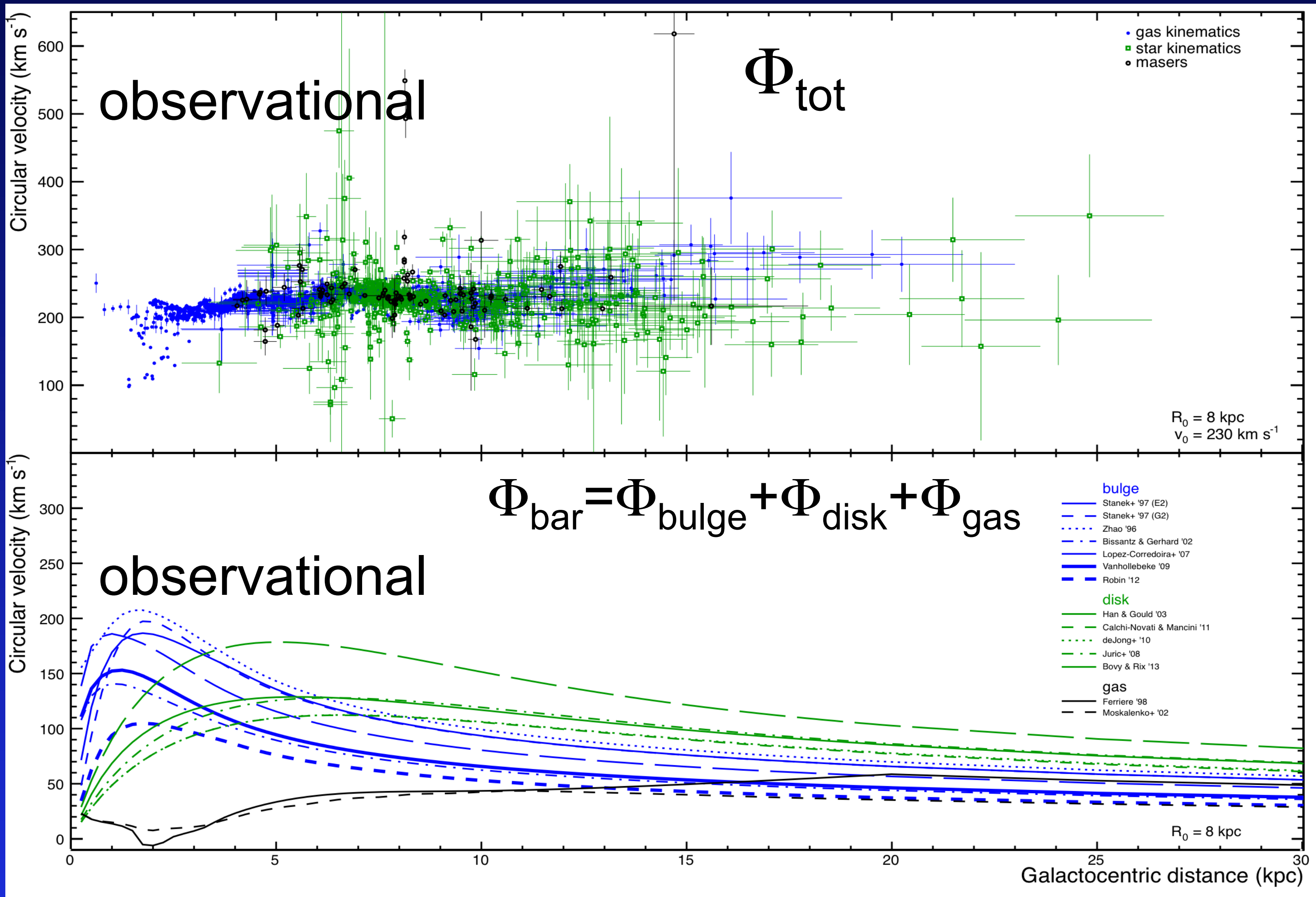
The Milky Way:
expected rotation curve

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

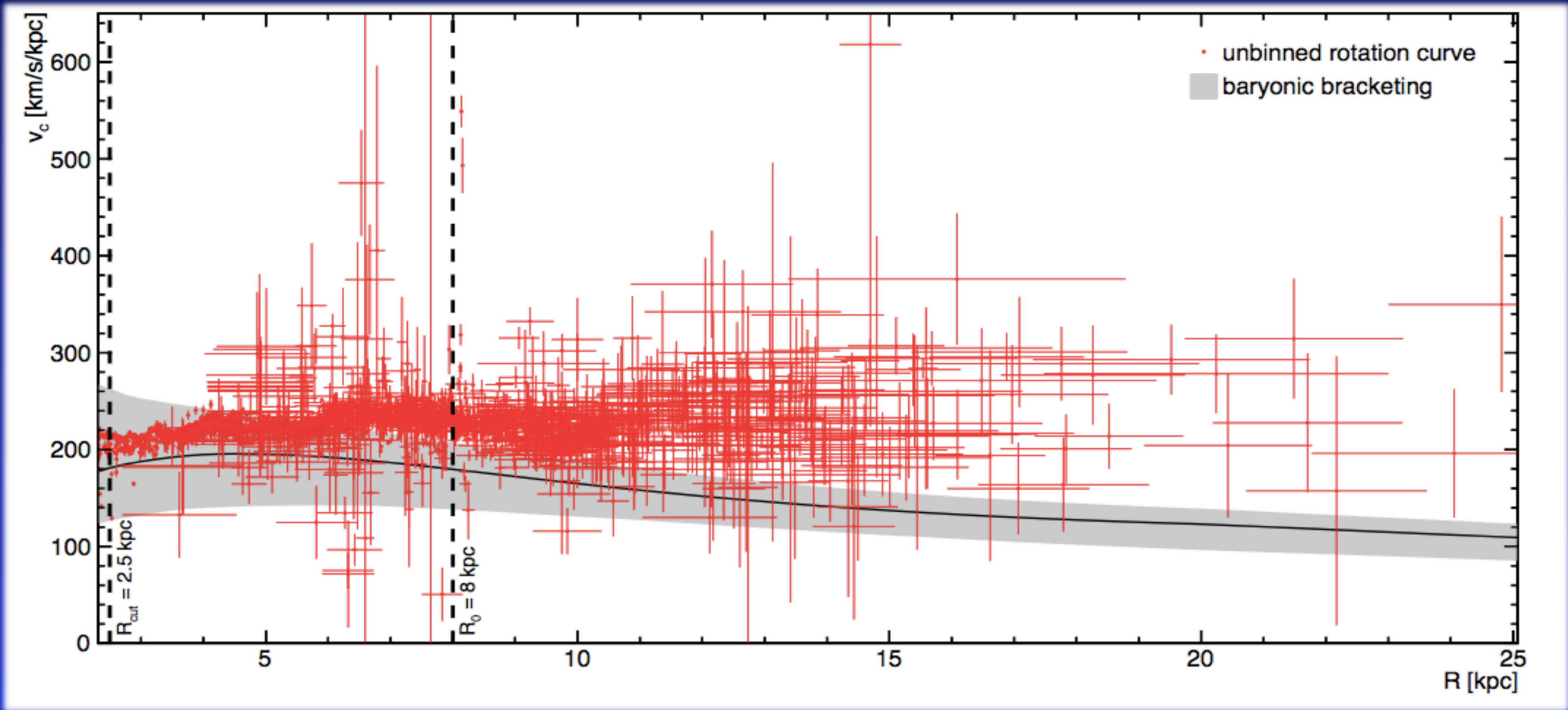


[Iocco, Pato, Bertone, Nature Physics 2015]

The Milky Way: testing expectactions

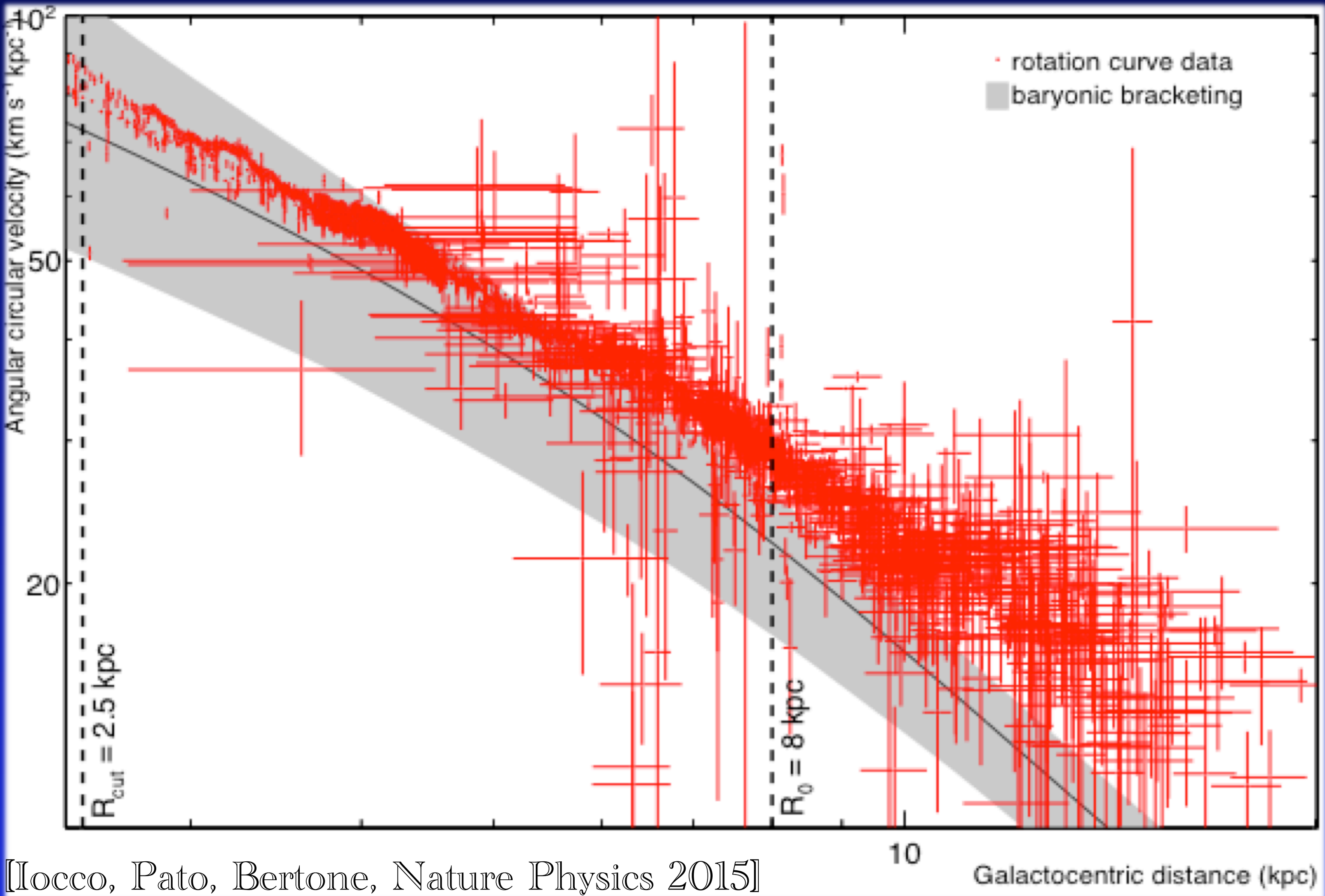


The Milky Way: testing expectactions (with no additional assumptions)



[Iocco, Pato, Bertone, 2015]

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



[Iocco, Pato, Bertone, Nature Physics 2015]

$\omega = V_c / R_c$

Uncorrelated uncertainties

R_0=8 kpc
V_0=230 km/s

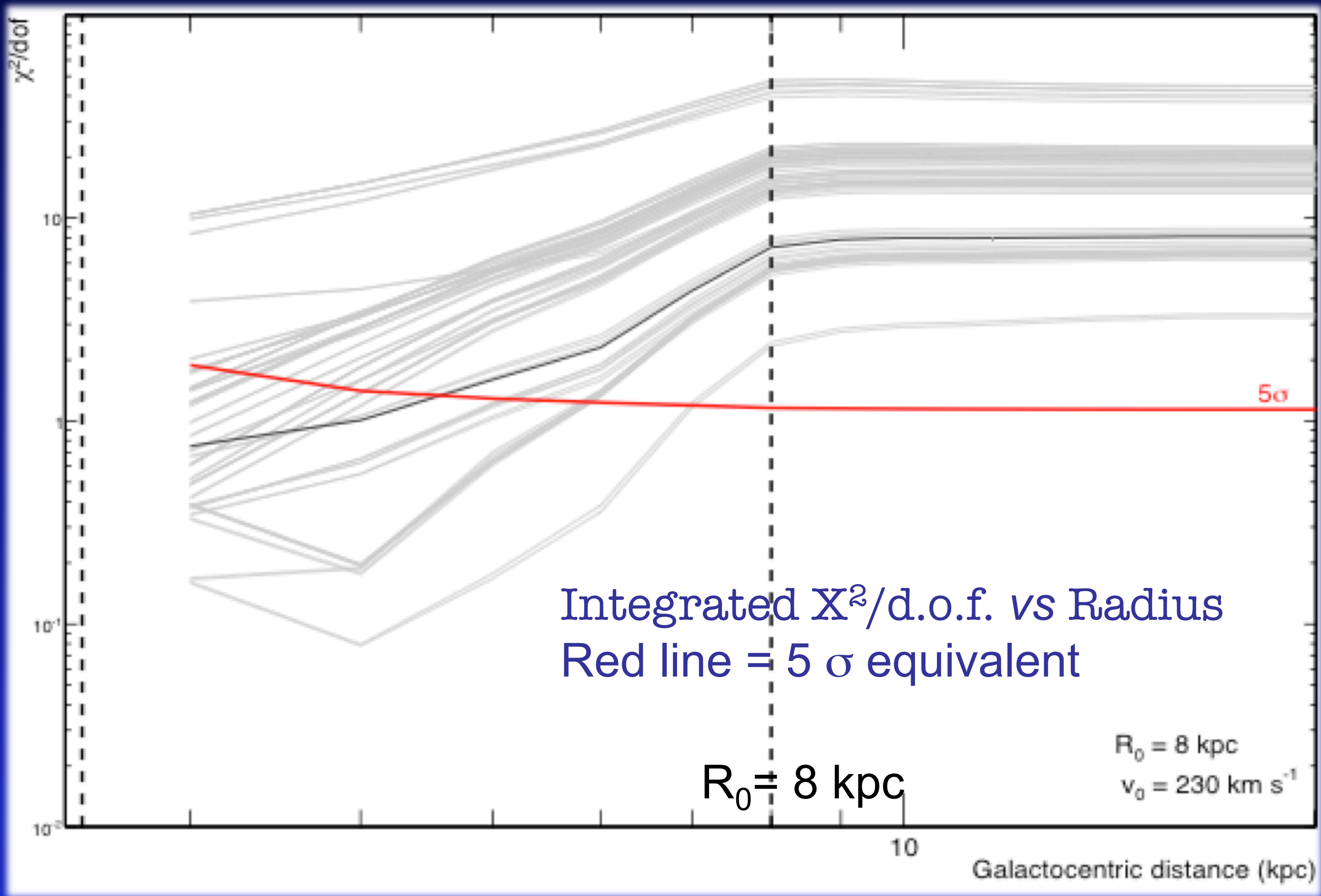
The Milky Way: testing expectactions (with no additional assumptions) ((and some technical detail))

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

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

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

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



Answer is NO:

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

[Iocco, Pato, Bertone, Nature Physics 2015]

Some performed checks
(ask me for details)

- Variation of Galactic parameters
- (De)selection of tracer class / datasets
- Spiral Arm systematics
- Binning (/averaging/statistics)
- Lower Radius cut (axsimmetry breaking)
- 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

The Milky Way:

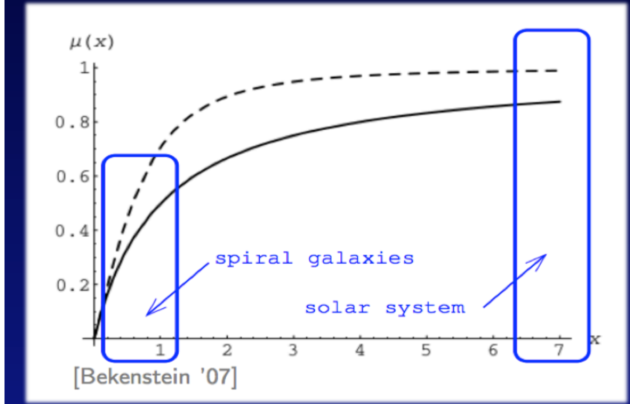
Evidence for Dark Matter ??

Discrepancy between:
observed rotation curve and observation-based expectations

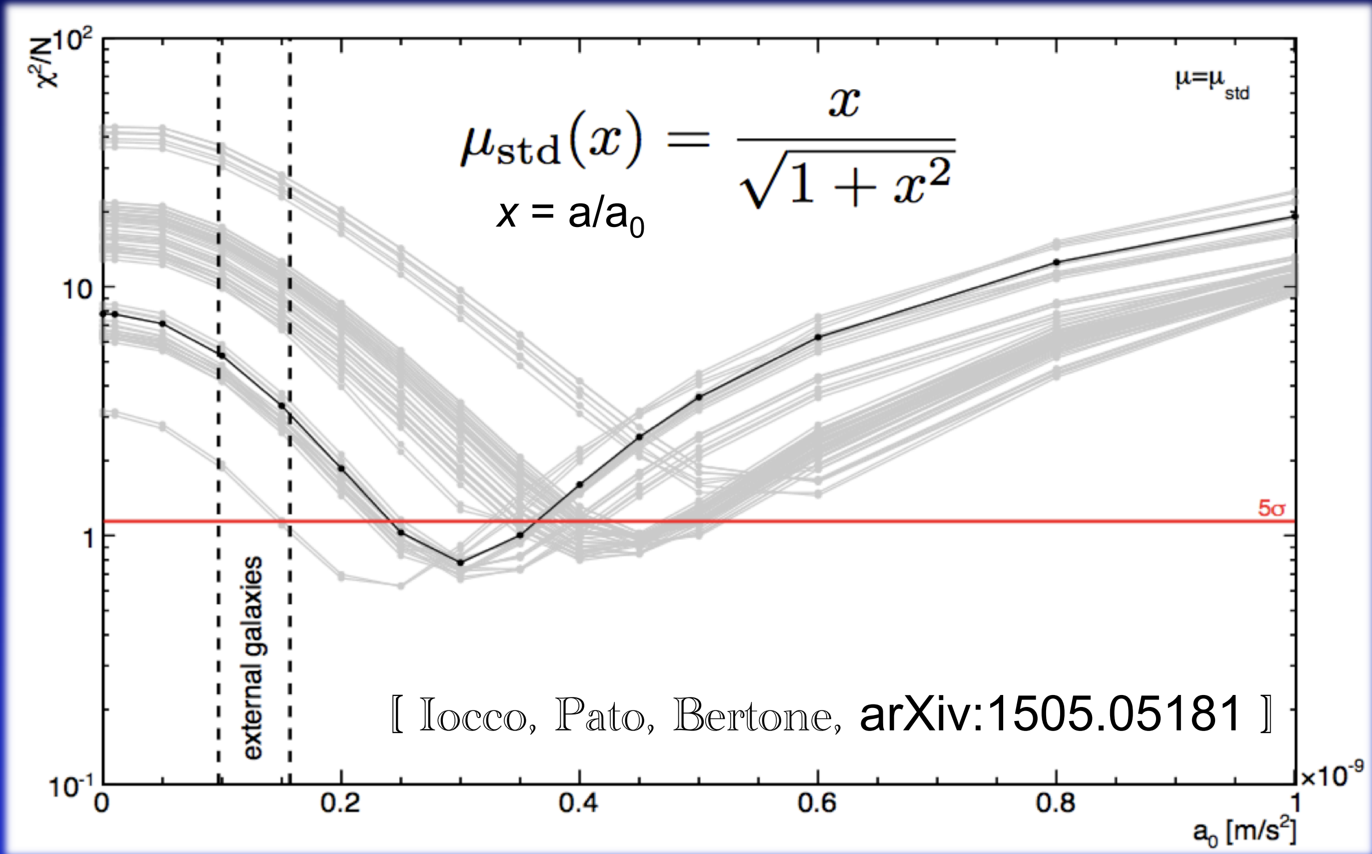
assuming Newton's law of gravity

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

Modified Newtonian Dynamics?



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



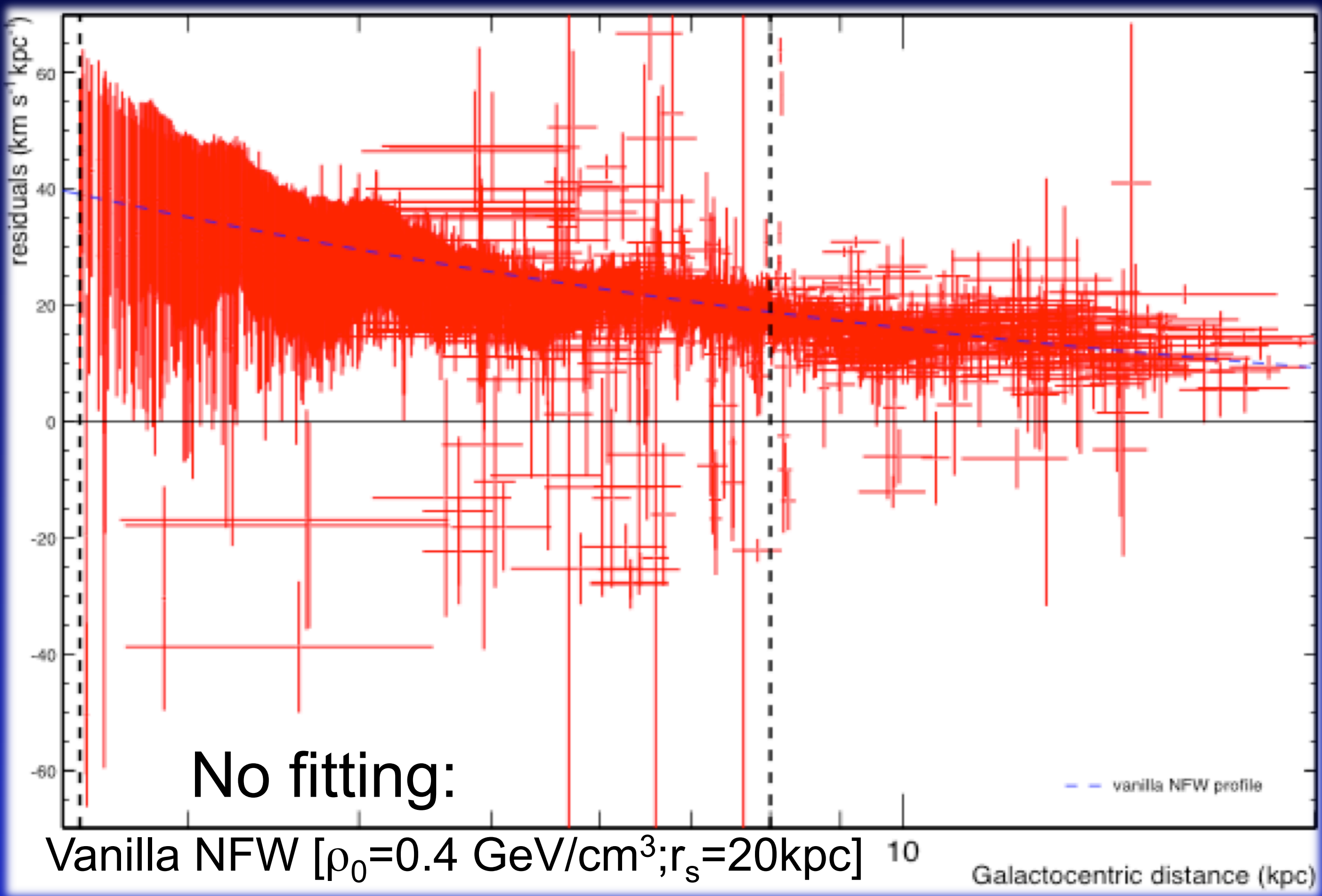
$\mu(a/a_0) \approx 1$, $a >> a_0$

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

recovering Newton
in "strong" gravity regime

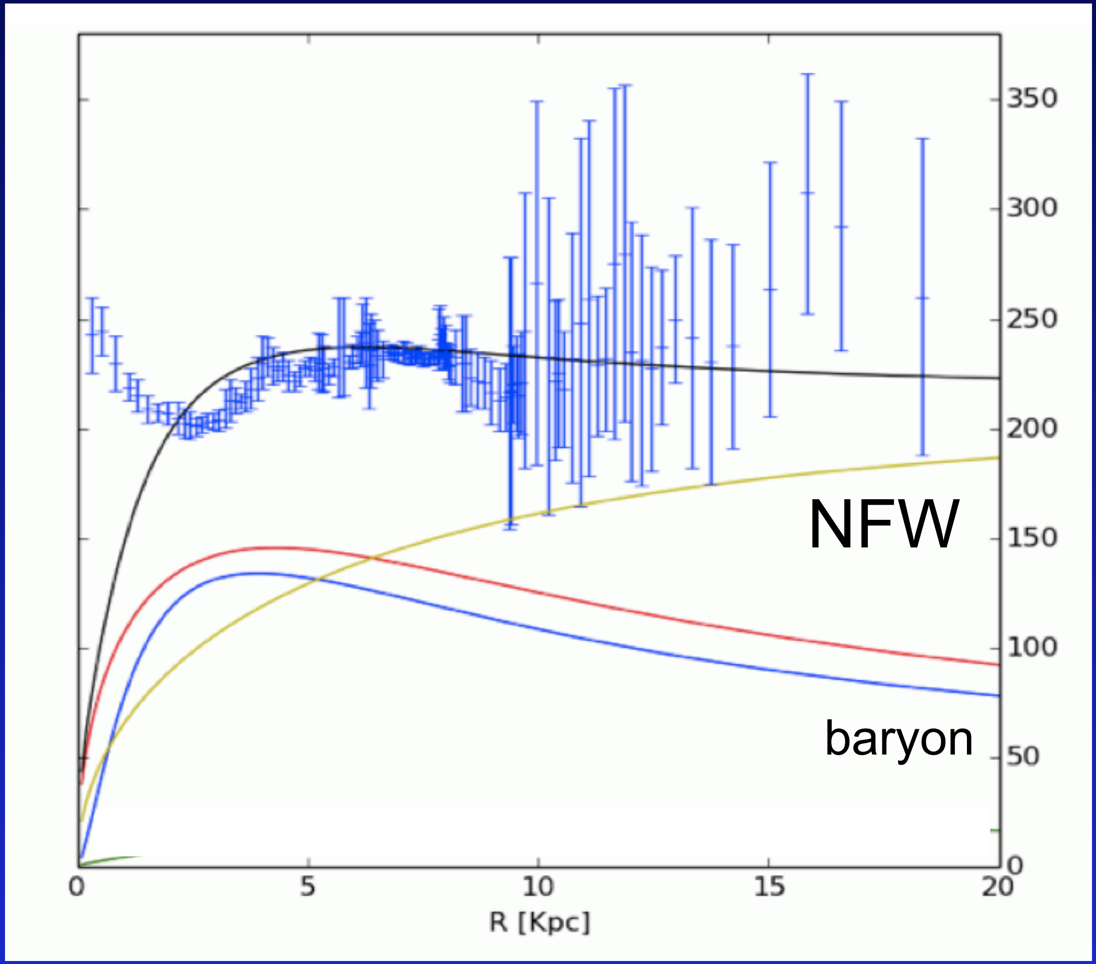
$\mu(a/a_0)$ analytical fit to data,
not from first principles

Motivating dark haloes



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

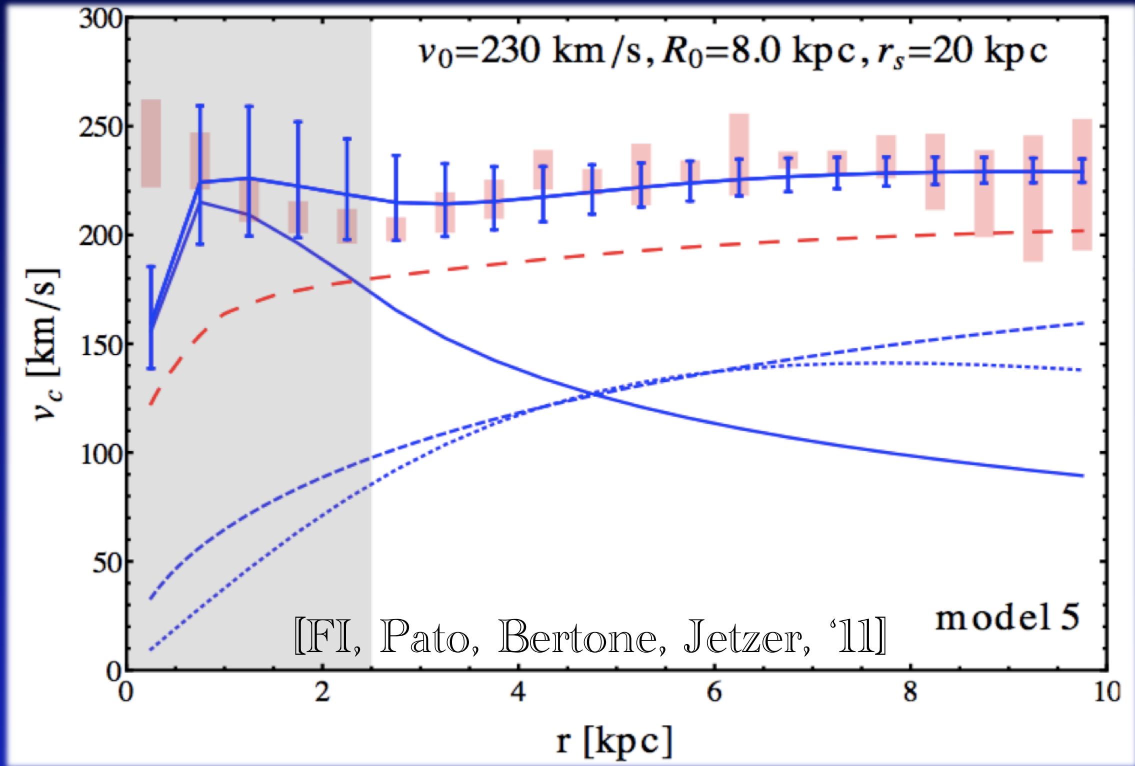
Adding Dark Matter: fitting halo shapes



[M. Benito-Castaño, w.i.p.]

Global determination of halo parameters

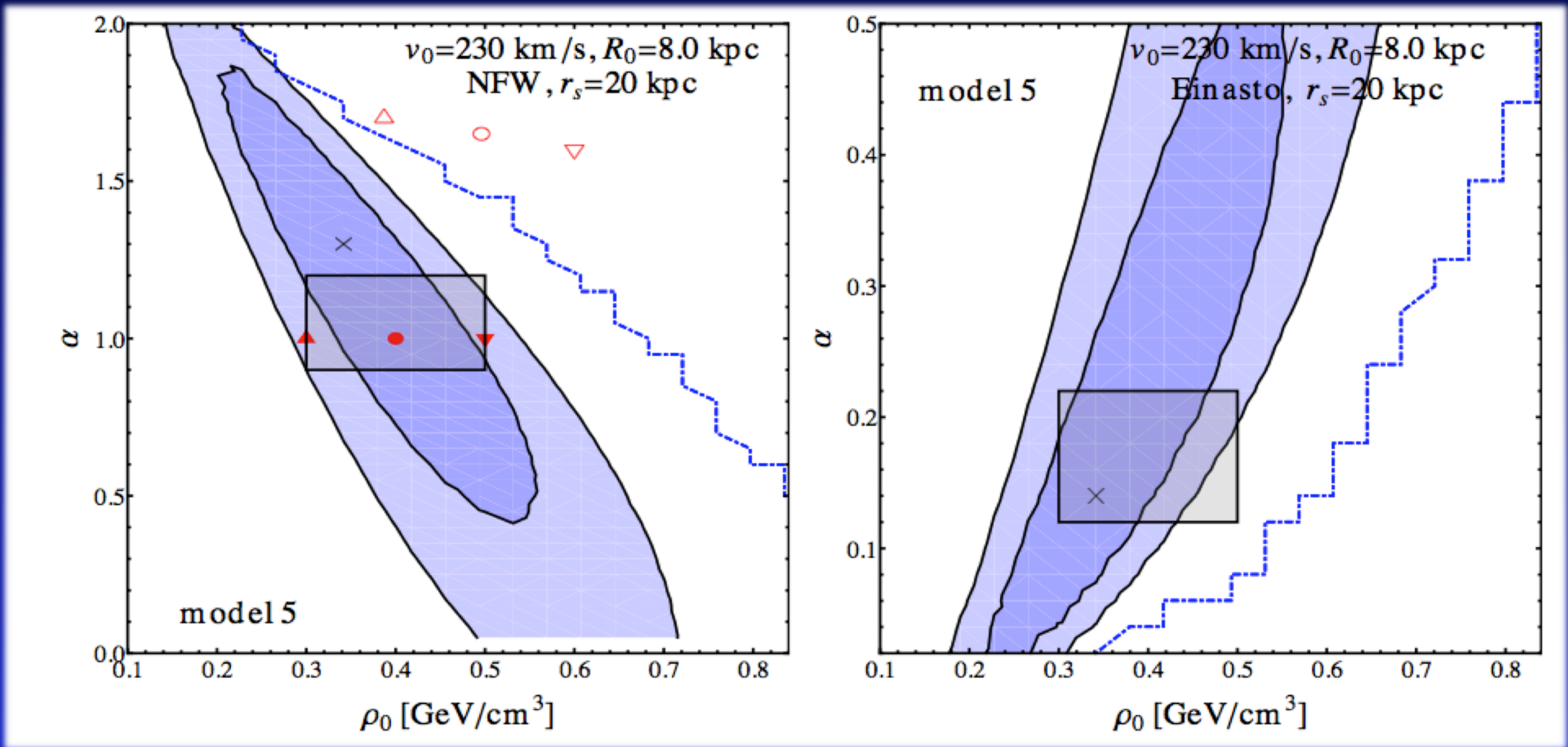
Fitting a DM profile to the Rotation Curve, on top of other components



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

Underlying assumption on DM presence and distribution shape

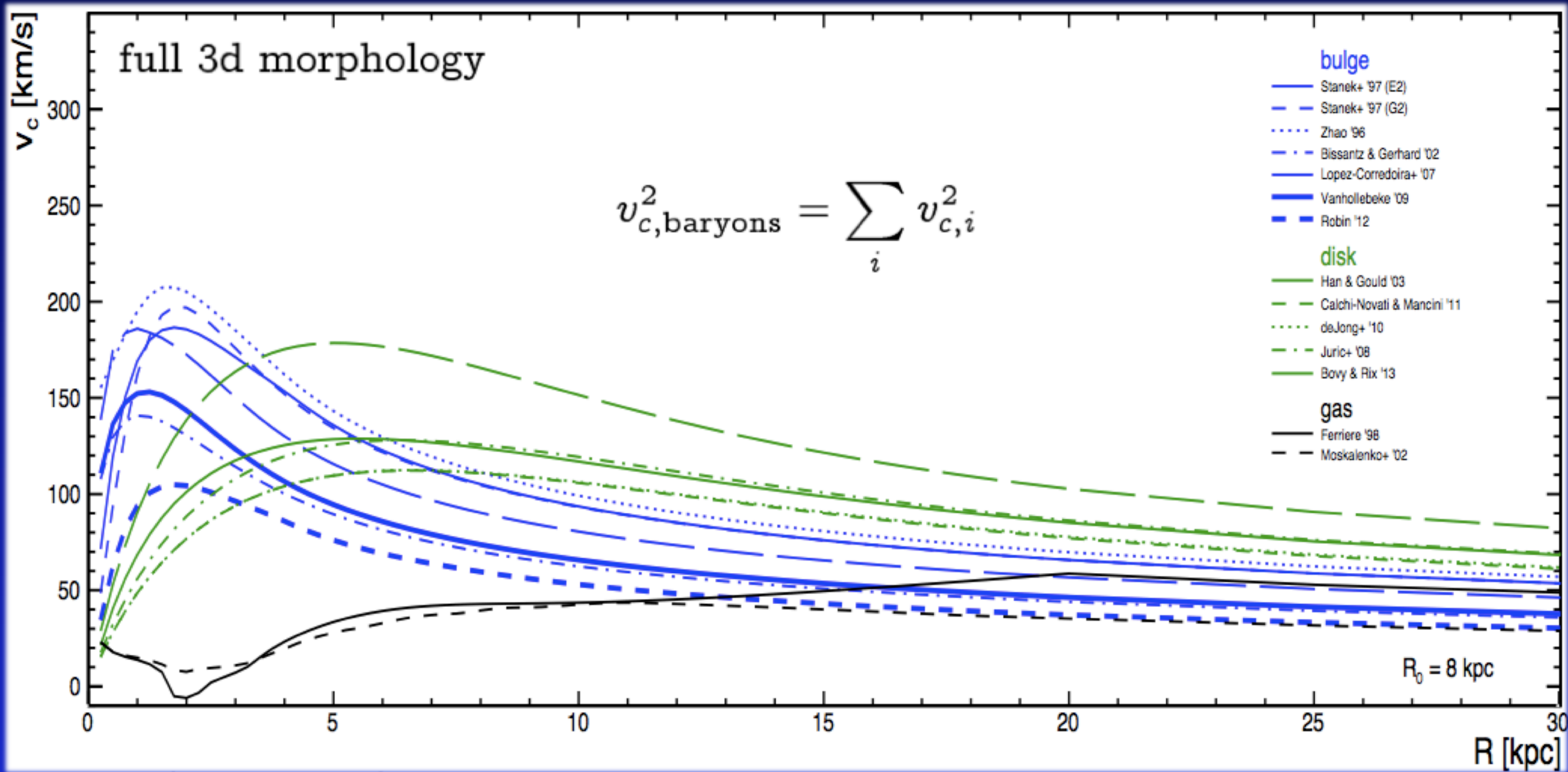
The Milky Way: fitting Dark Halo parameters



Excellent agreement with simulation parameter space, and determination of ρ_0

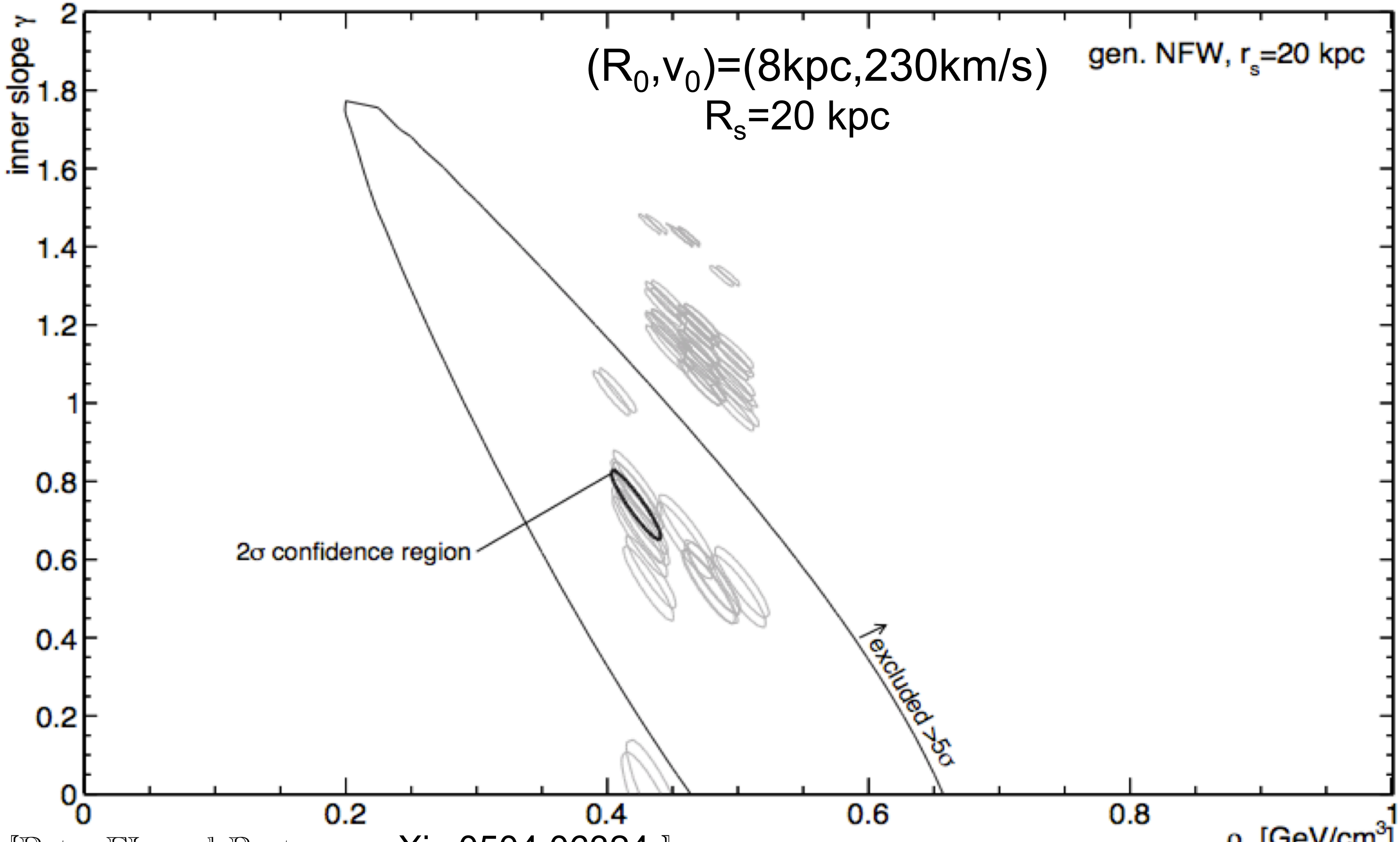
[FI, Pato et al., 2011]

The Milky Way:
spherical halos on top of baryonic models



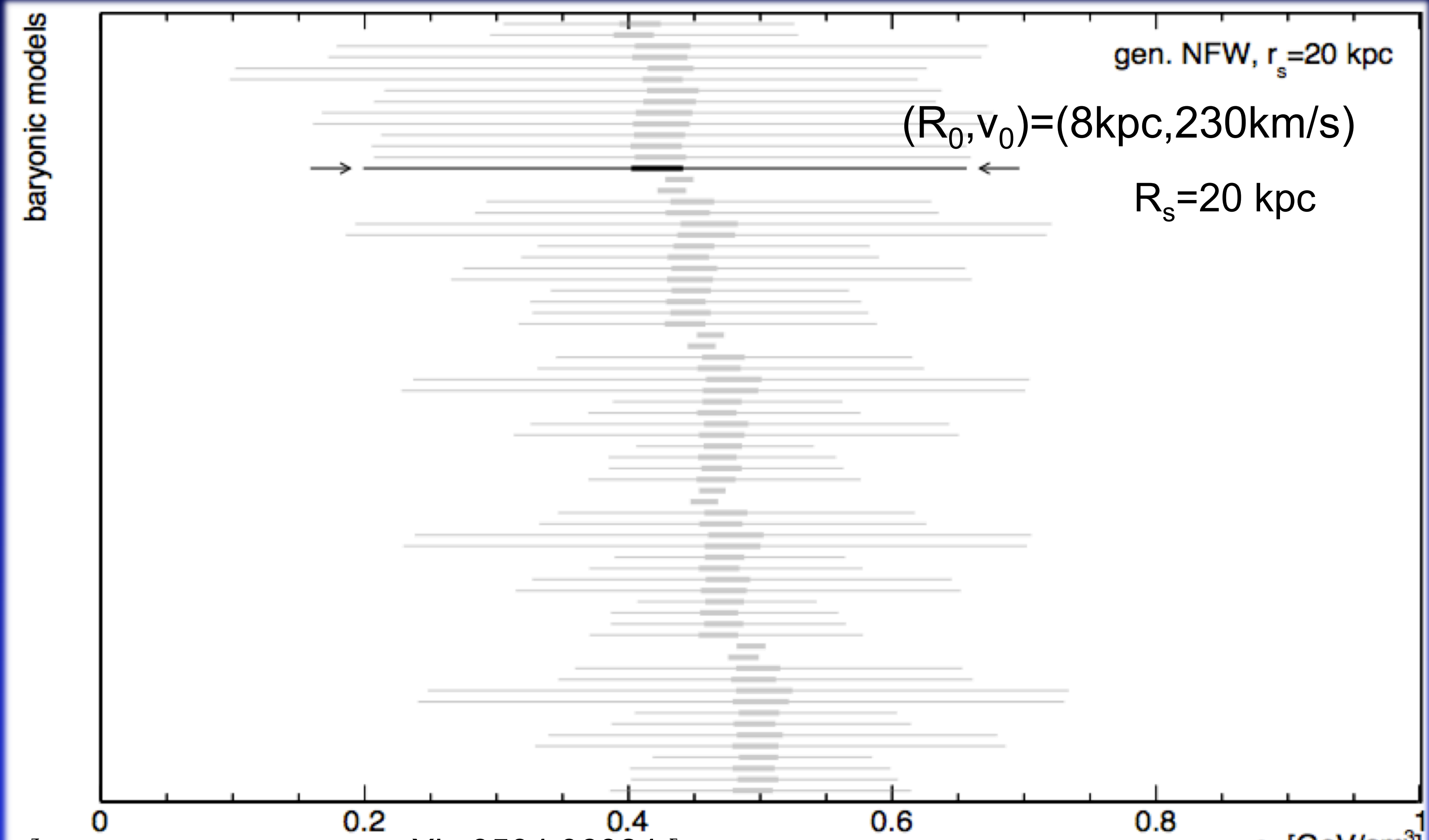
scanning halo parameter space for each baryonic model

The Milky Way: the importance of baryon modelling



[Pato, FI, and Bertone, arXiv:0504.06324]

The Milky Way: the importance of baryon modelling



[Pato, FI, and Bertone, arXiv:0504.06324]

The Milky Way's spine: an agnostic approach

reconstructing the profile from observations alone
no assumptions on the shape of the profile

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

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

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

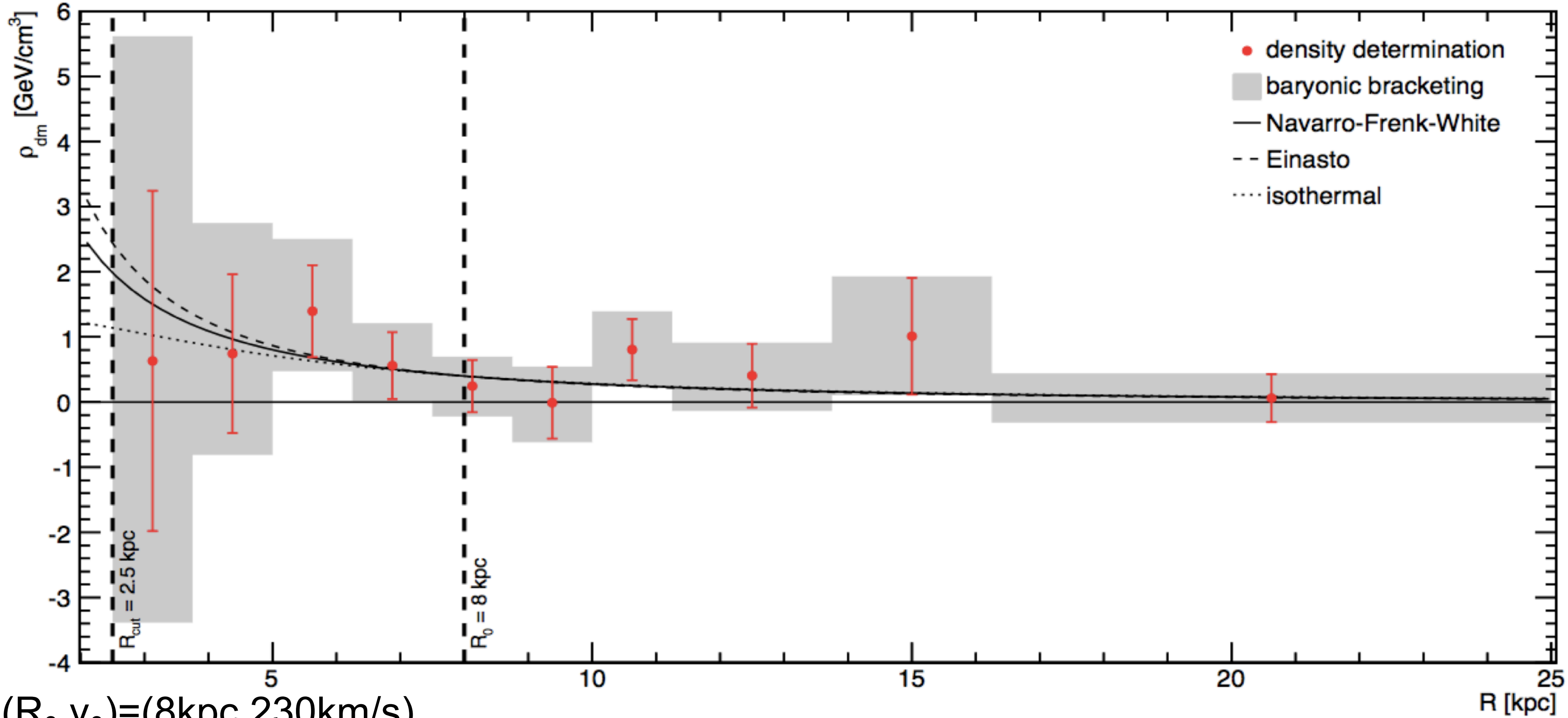
$$\mathrm{d}\phi_{\rm b}/\mathrm{d}R = \omega_{\rm b}^2 R$$

Assumption of spherical symmetry

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

Pato and FI, ApJL 2015

The Milky Way's spine: an unbiased reconstruction



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

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

Cuncta stricte

- Dramatic increase in precision determining DM distr.
- Highlights we have little accuracy

(dependence of DM parameters from prior on atrophys)

- More work to be done

(marginalization on Galactic parameters, full Rs dependence)

- Future looks Dark

(and that’s good)

In progress

- Determination of (ρ_0,α) with different galactic configurations

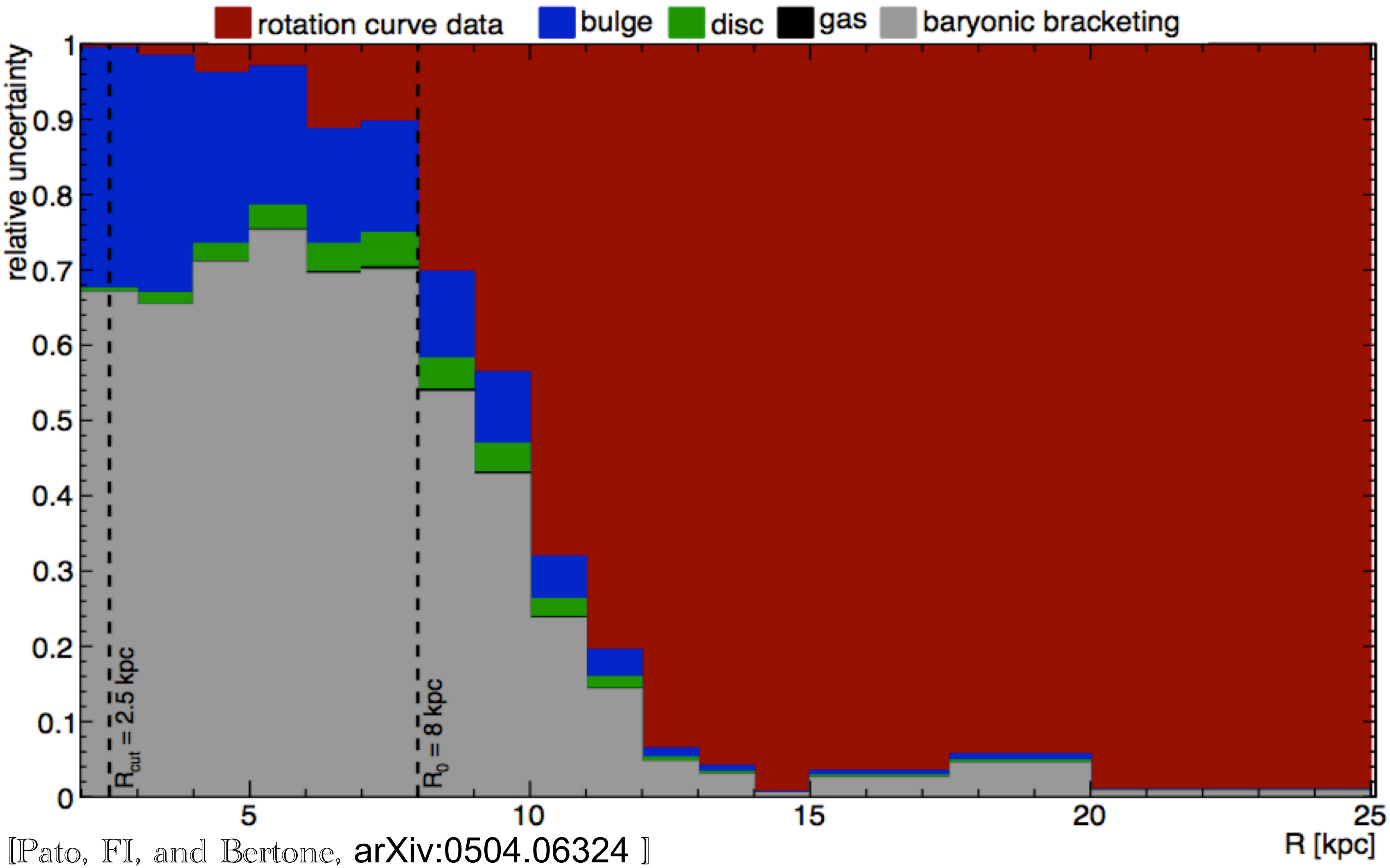
- Direct determination of DM profile

- Testing alternatives

FUTURUS

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

A closer look at uncertainties



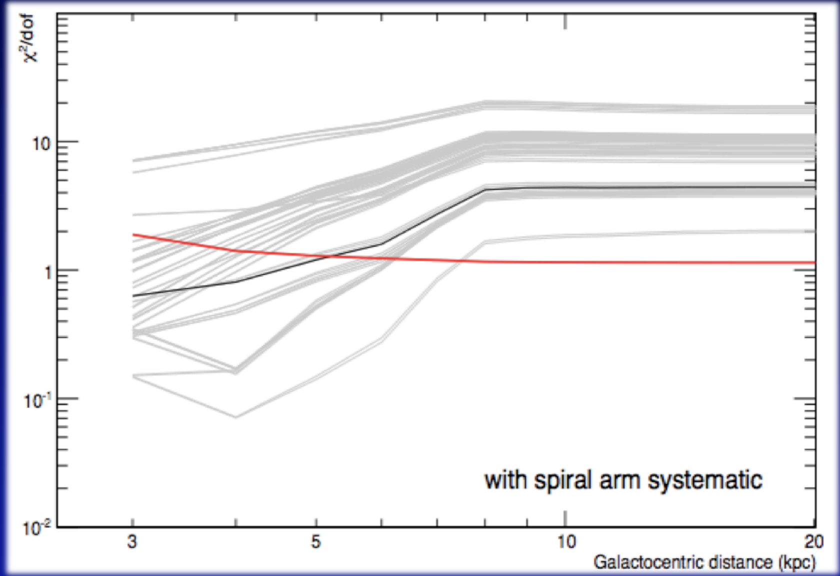
[Pato, FI, and Bertone, arXiv:0504.06324]

Testing different setups
(systematics and parameters)

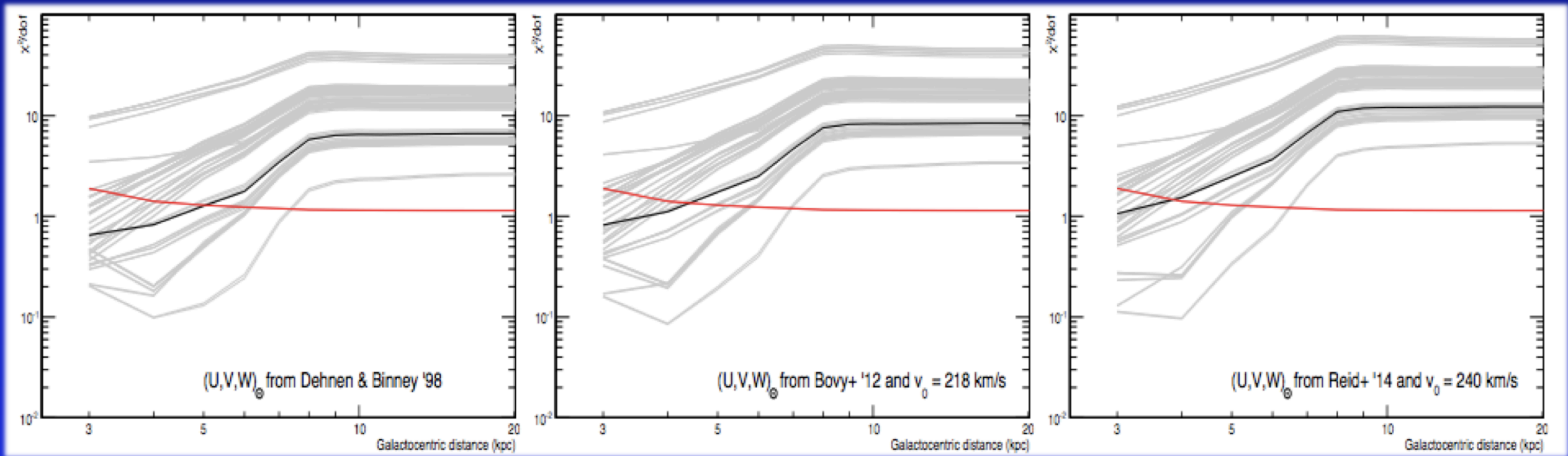
Same conclusions if scanning:

Spiral Arms syst.

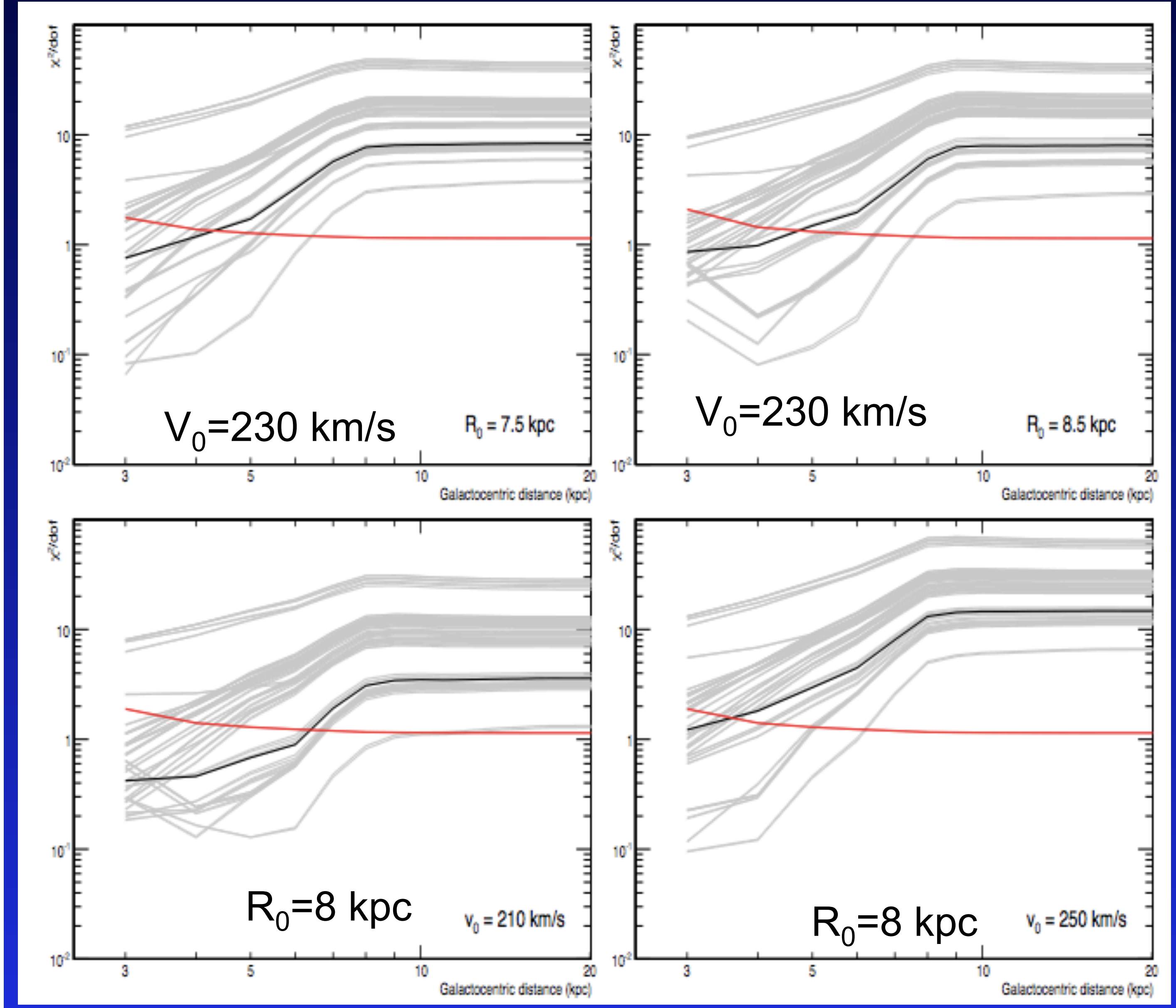
LSR values



R_0=8 kpc
V_0=230 km/s



Testing galactic parameter variation

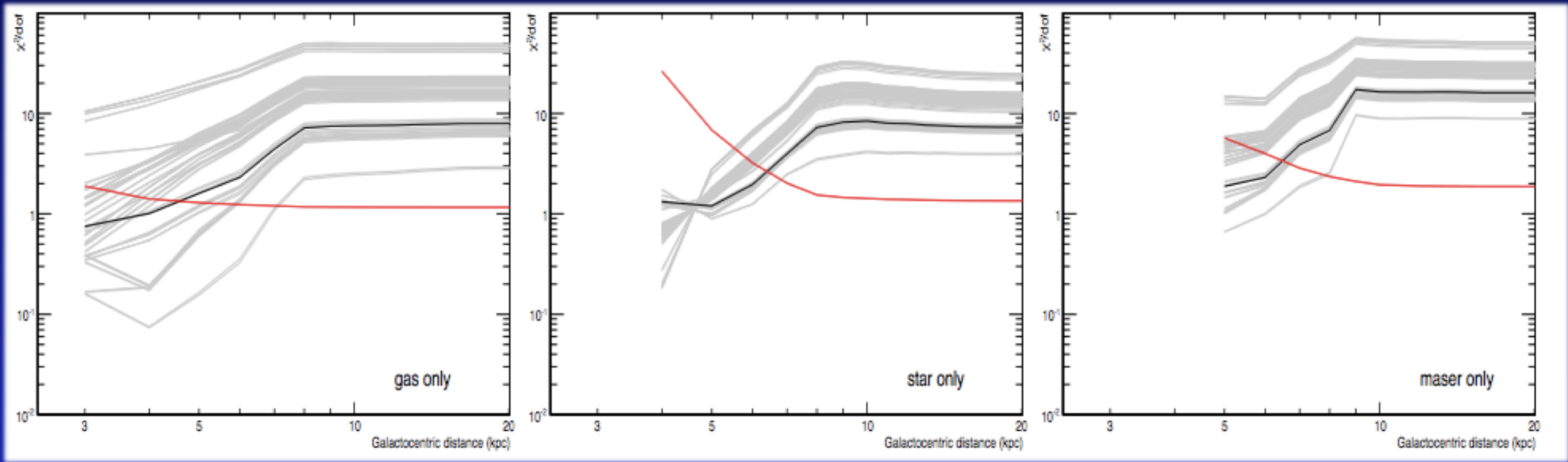


Same conclusions if scanning:

Local circular velocity

Solar distance

Dissecting Rotation Curve
(testing separate tracers)

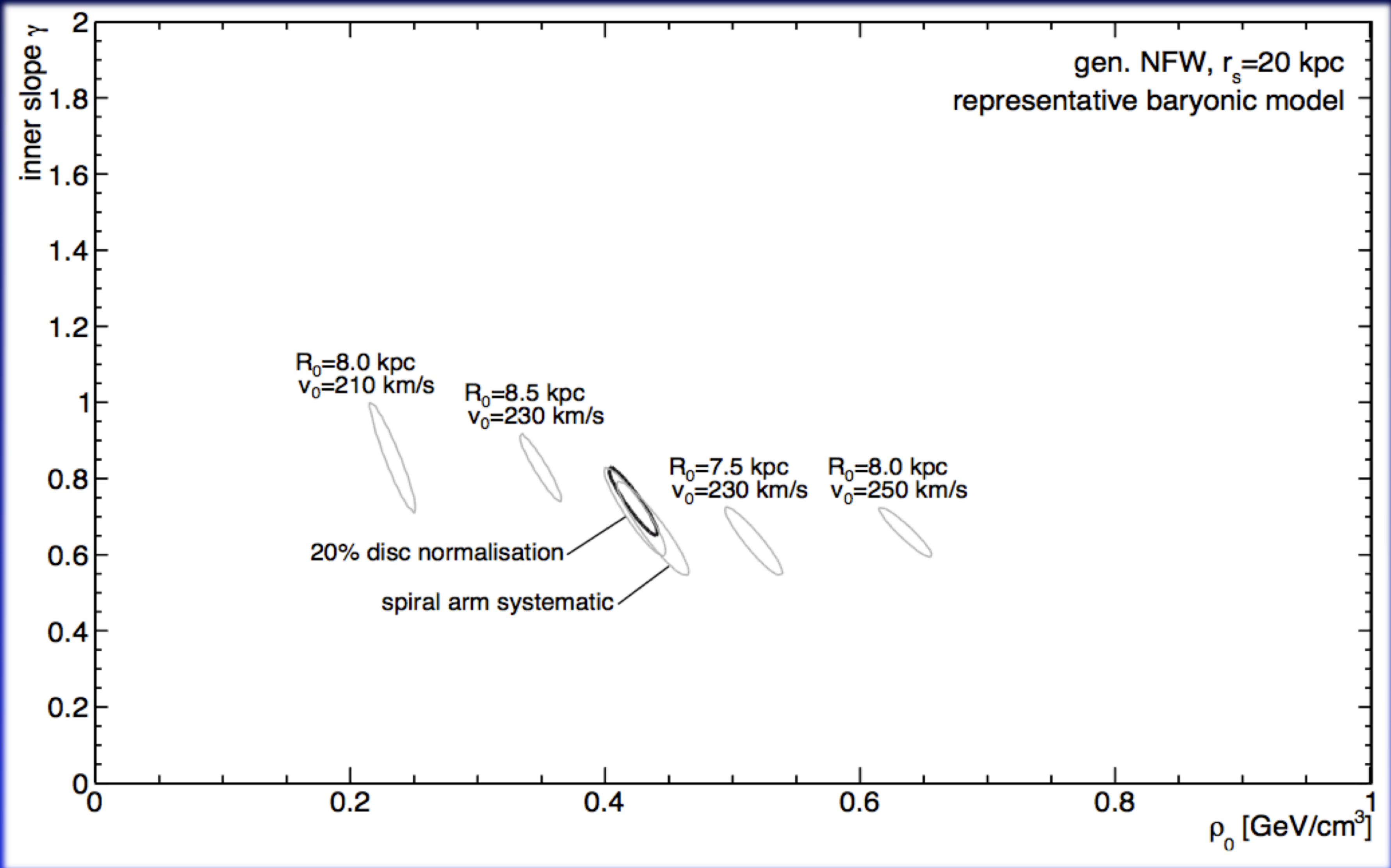


Same conclusions if using:

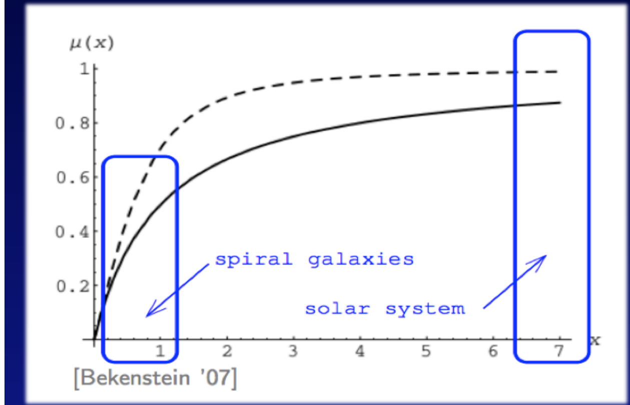
R_0=8 kpc
V_0=230 km/s

Stellar objects only
Masers only
Gas kinematics only

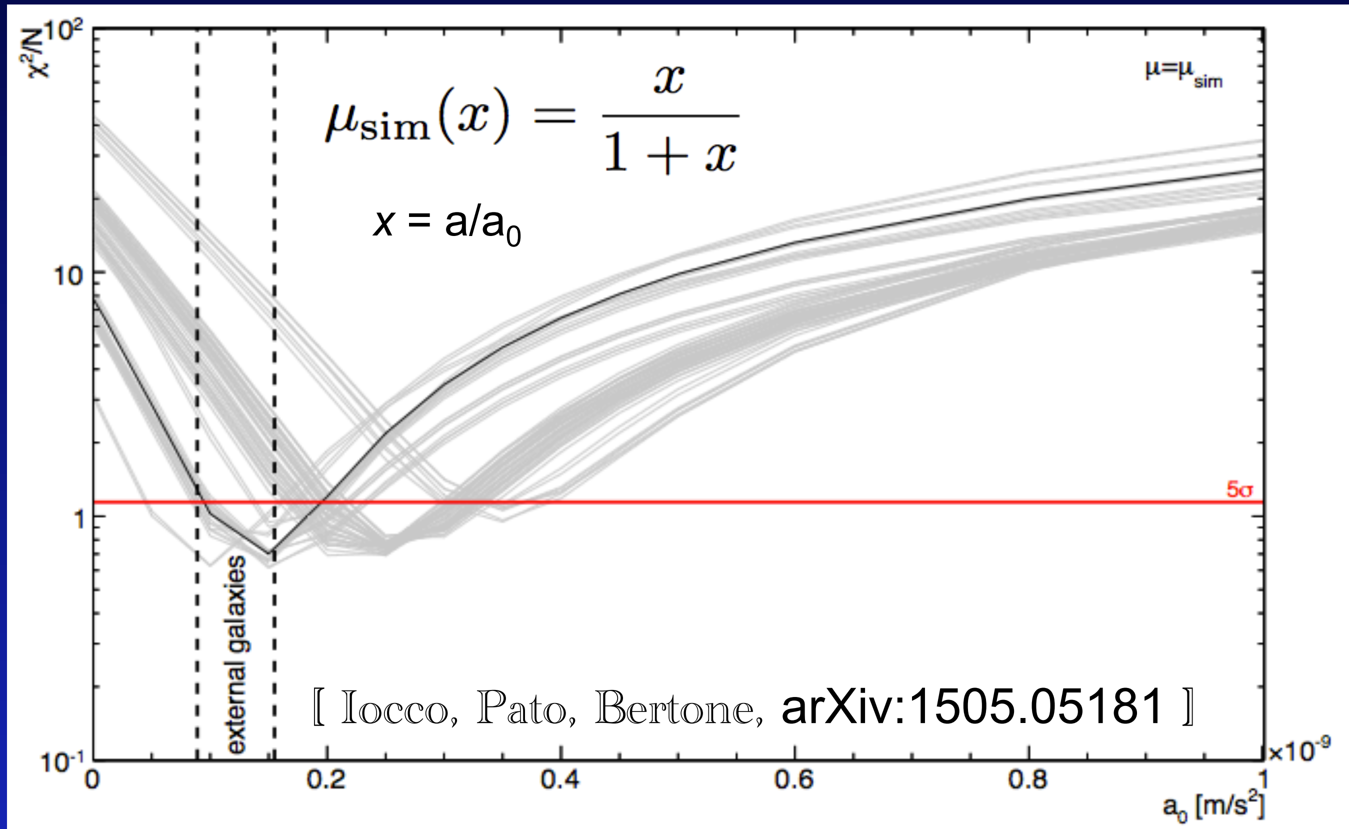
Some more checks



Modified Newtonian Dynamics?



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



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

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

recovering Newton
in "strong" gravity regime

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