Evidence for Dark Matter in the inner Milky Way

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An outline of this and following talk:
Dark Matter in the Milky Way

- Fabio:
  - the observed rotation curve
  - the expected (baryonic) rotation curve
  - null hypothesis approach analysis
- Miguel:
  - the recovery of DM profile: fitting
  - testing the MOND hypothesis
  - the recovery of DM profile: non-parametric

- Based on (different order of authors, in collaboration with G. Bertone)

Nat. Phys 2015, ApJL 2015, arXiv:1504.06324, arXiv:1505.05181, arXiv:15soon.really

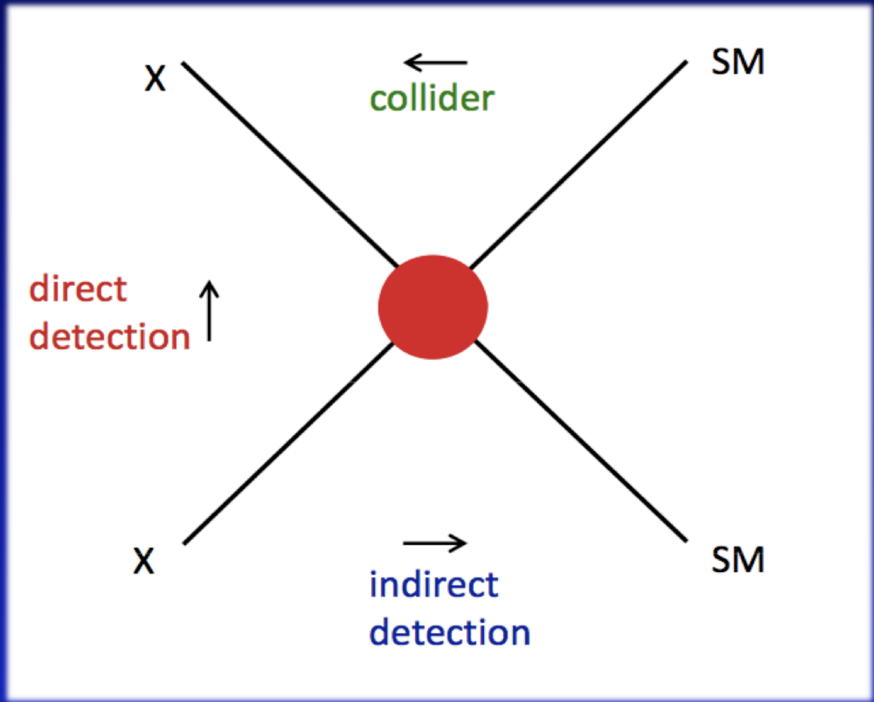
Direct and indirect searches of WIMP DM

complementary to colliders

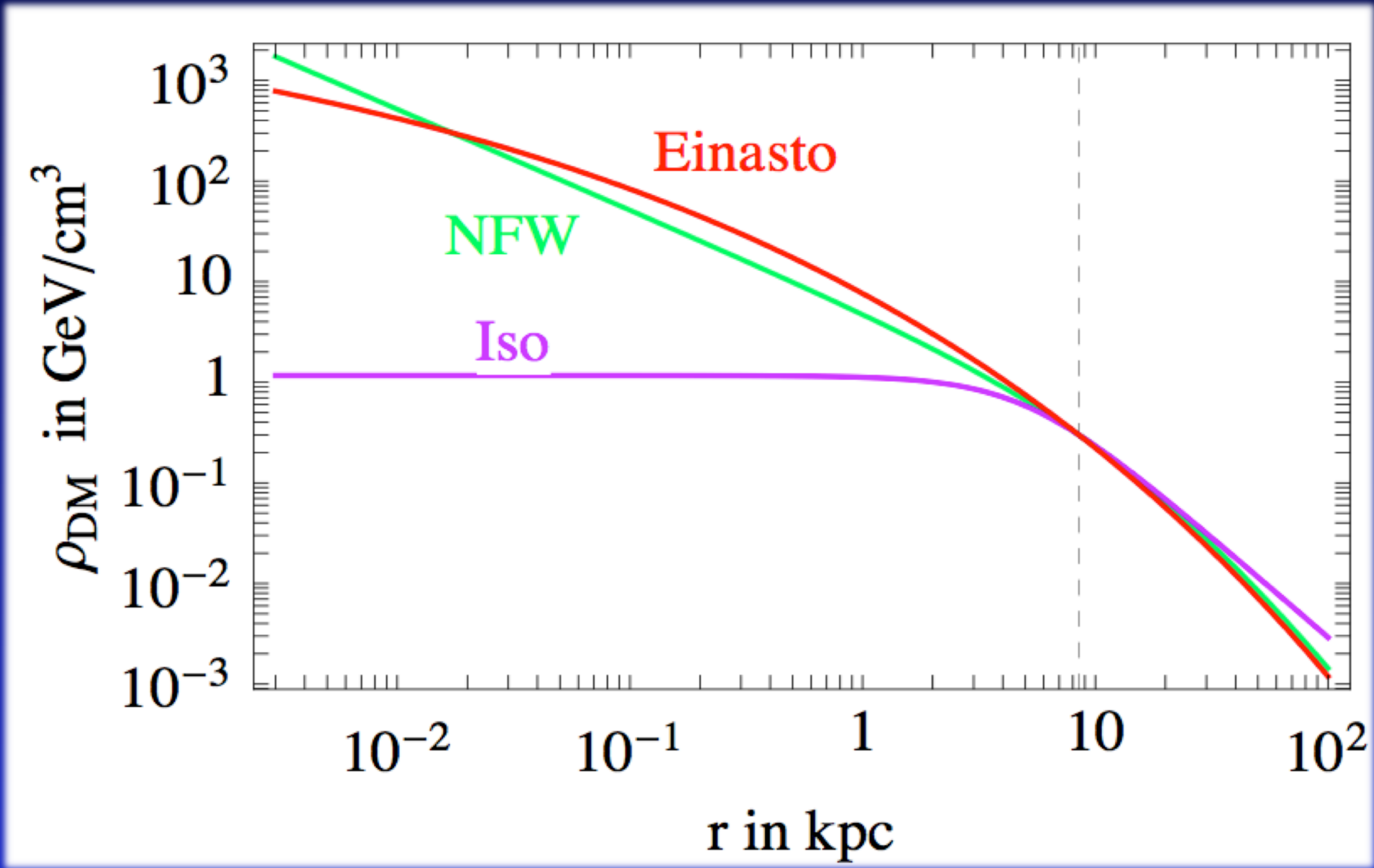
Direct detection:
DM scattering against nuclei, recoil

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

Production at LHC



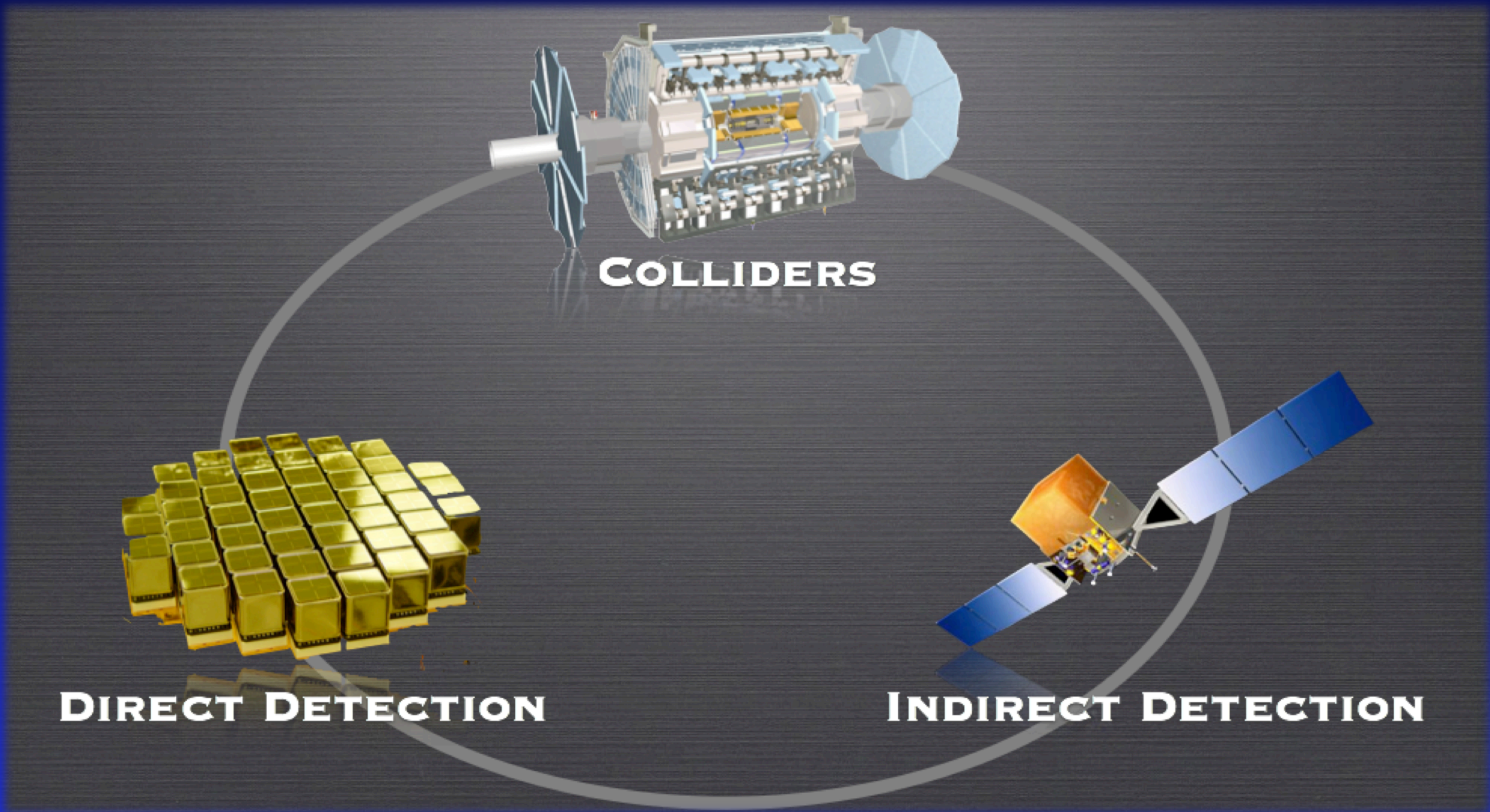
Direct and inDirect crucially depend on DM distribution



(well motivated)
hints from numerical simulations

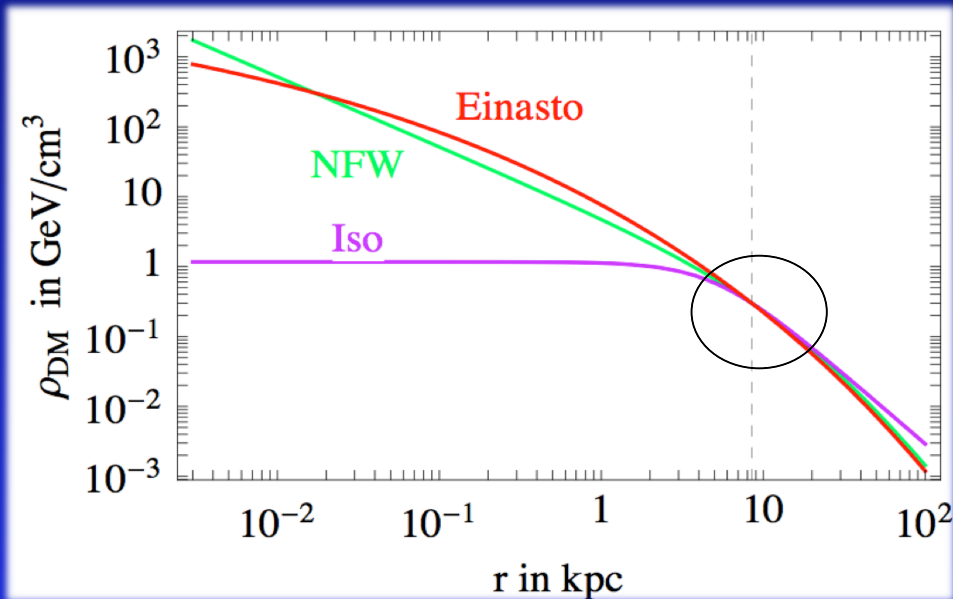
Direct and indirect searches

complementary to colliders



DM density at the Sun: ρ_0 = ?

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

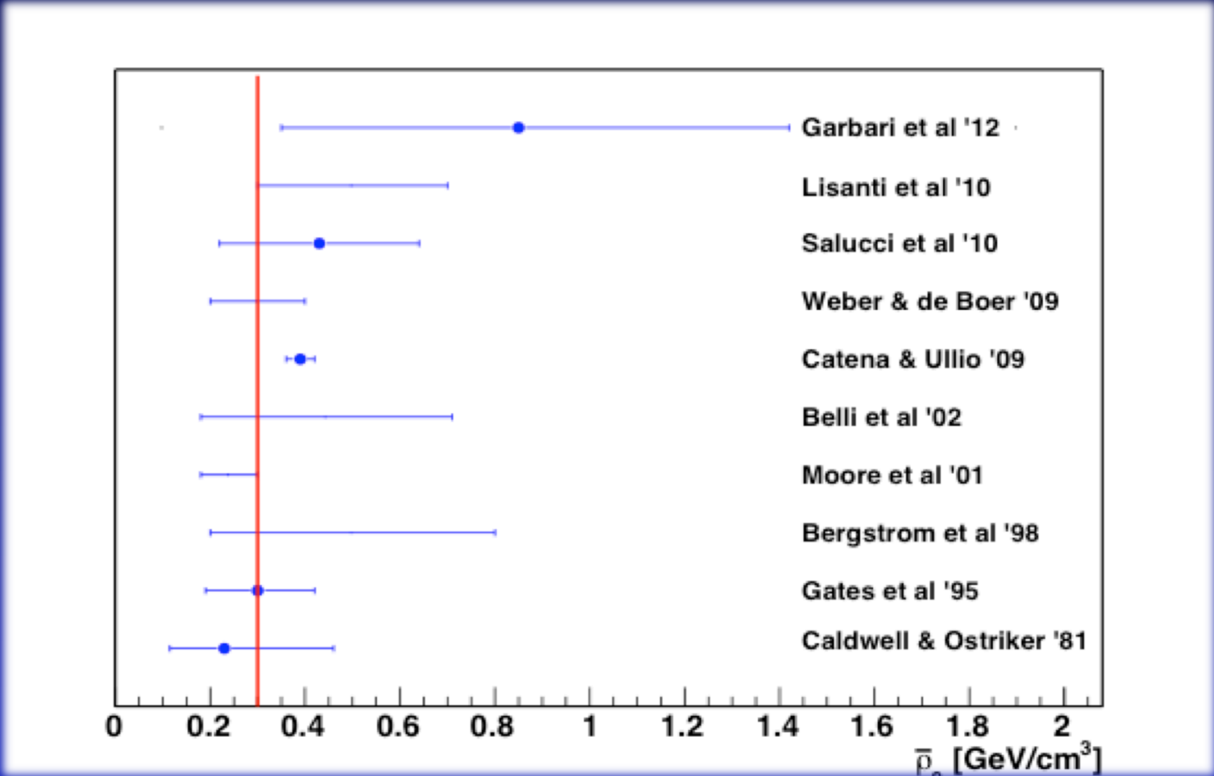


Determination of local DM density ρ_0

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

vs

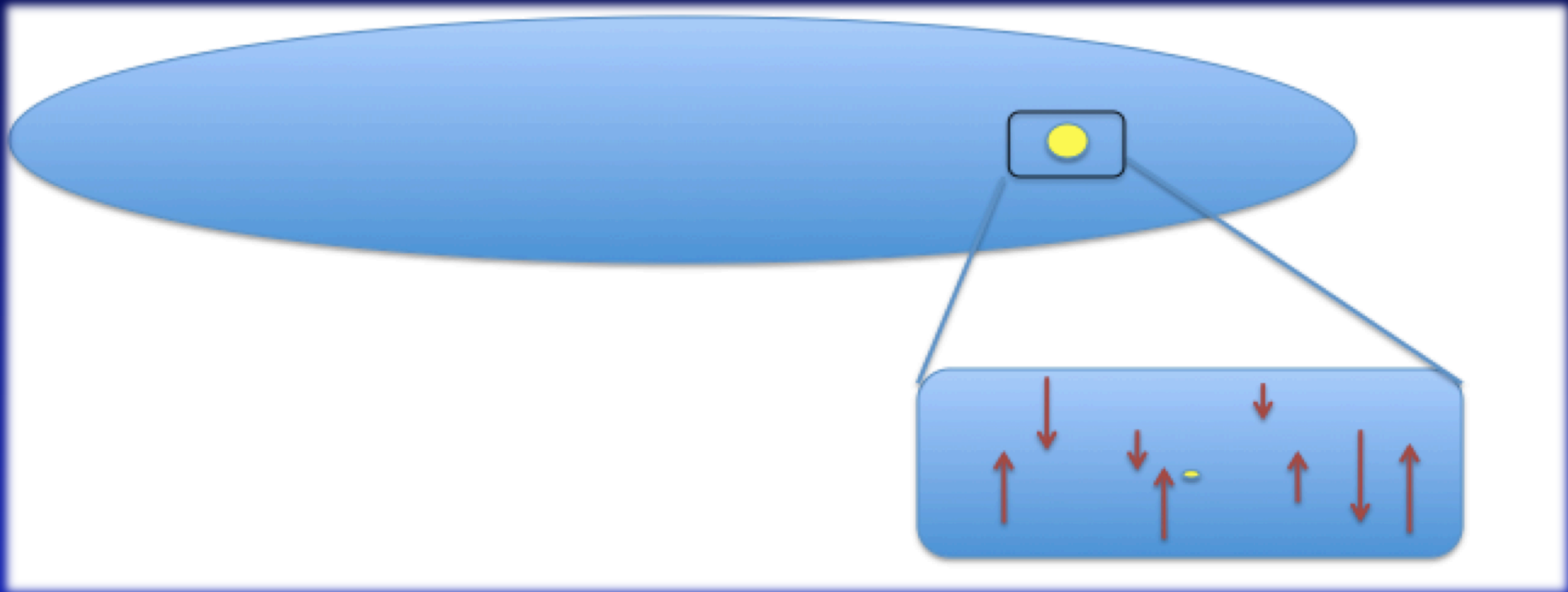
global modelling of MW
(e.g. Catena & Ullio)



Give consistent results, but…

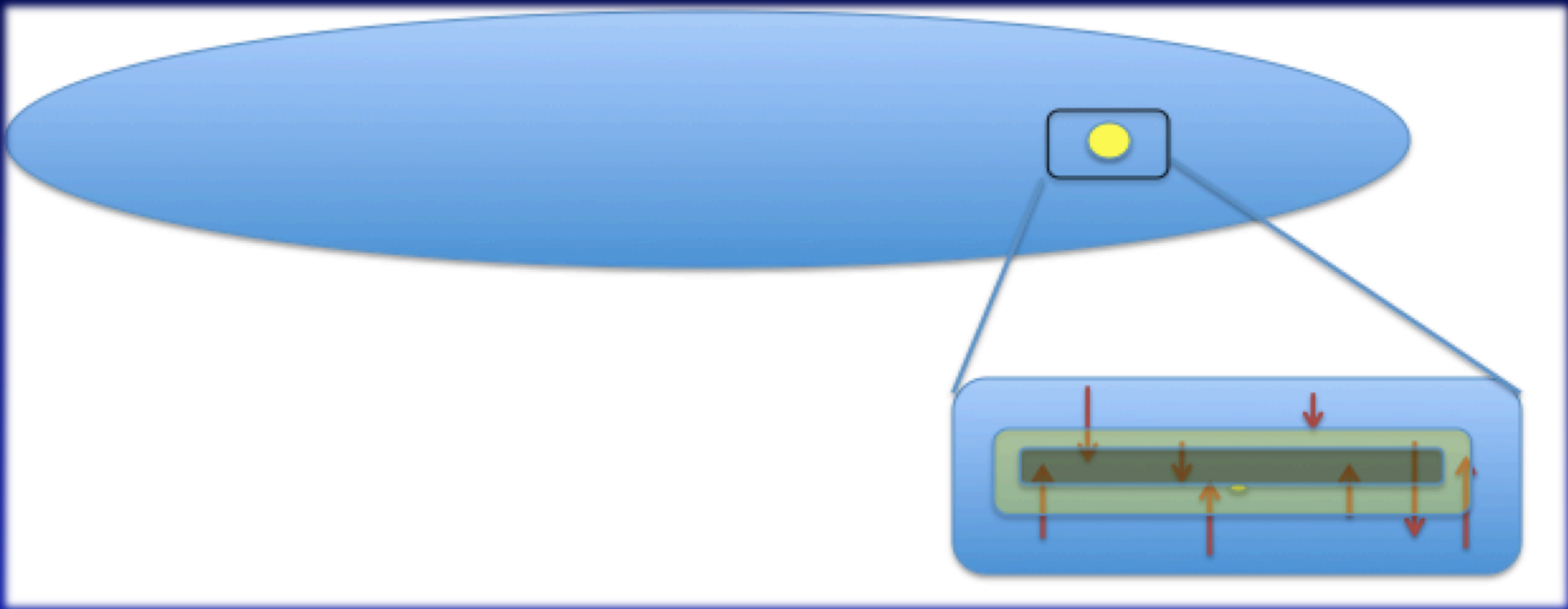
For more details on such methods
see Miguel Pato's talk

Local determination of ρ_0



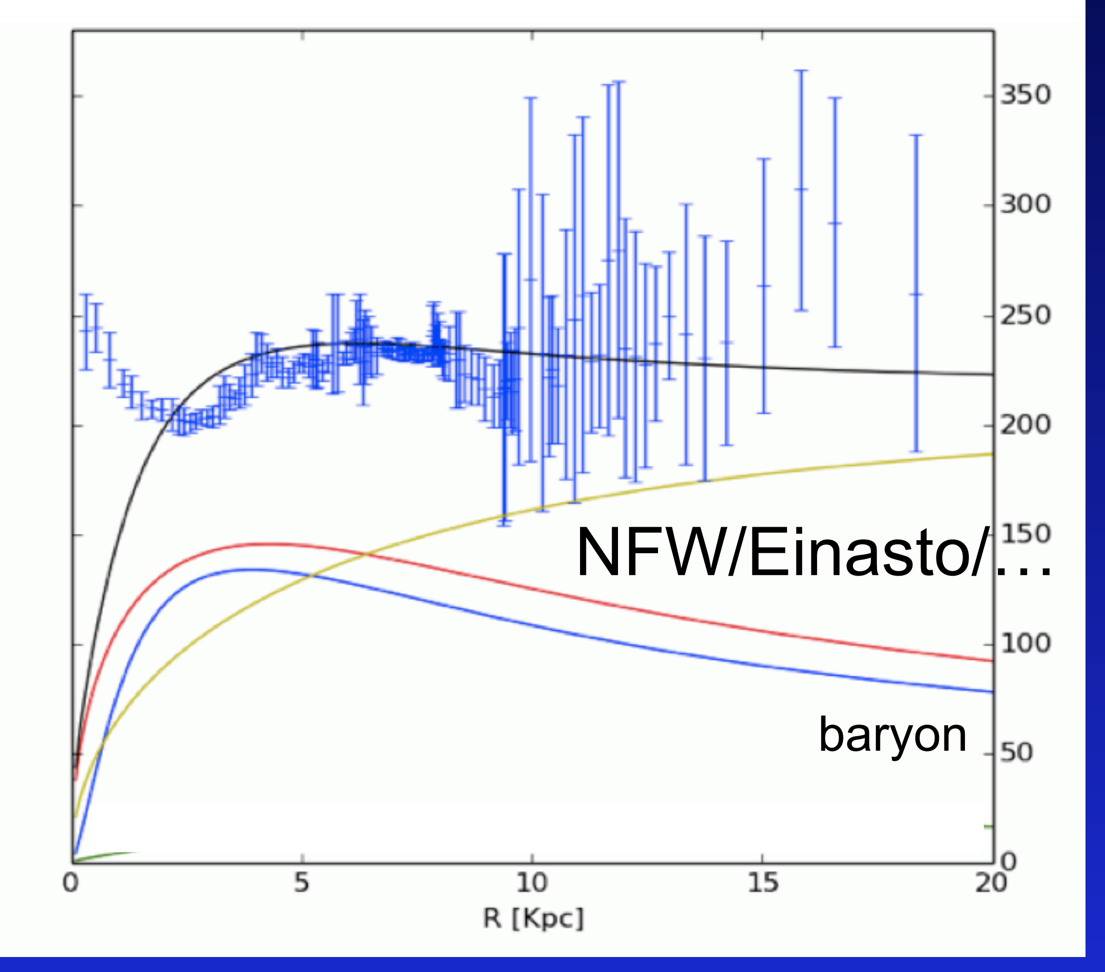
Vertical motion of stars, determining the whole local potential

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



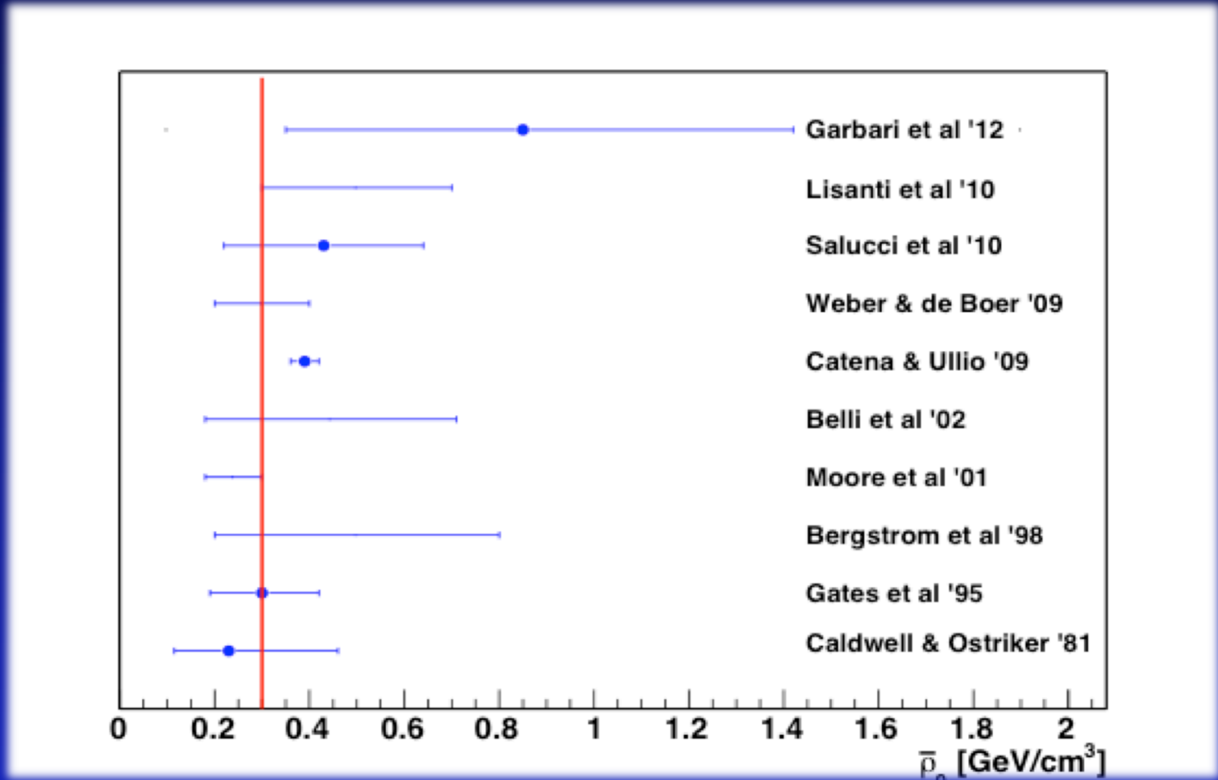
Fitting a DM profile on top of baryons: $\rho_{DM}=\rho_0 R^\alpha$

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, but…

For more details on such methods
see Miguel Pato's talk

The case of the Milky Way: the question

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

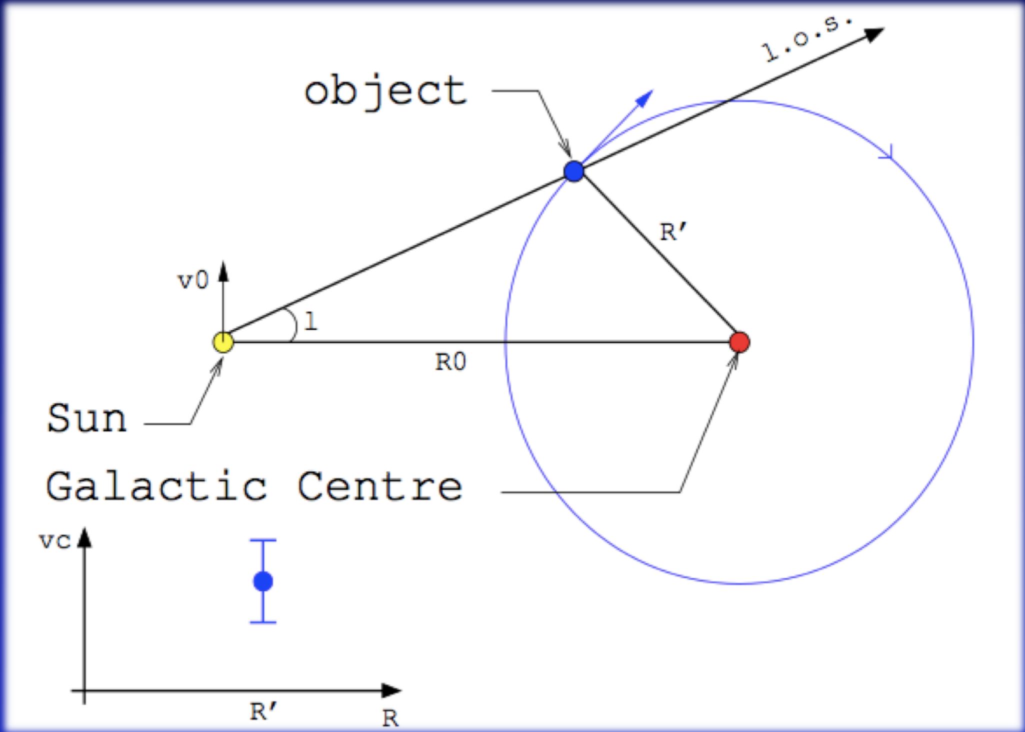
[can the observed, luminous components make up the whole gravitational potential?]

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

Rotation curve as a tracer of the total potential

…and if not…

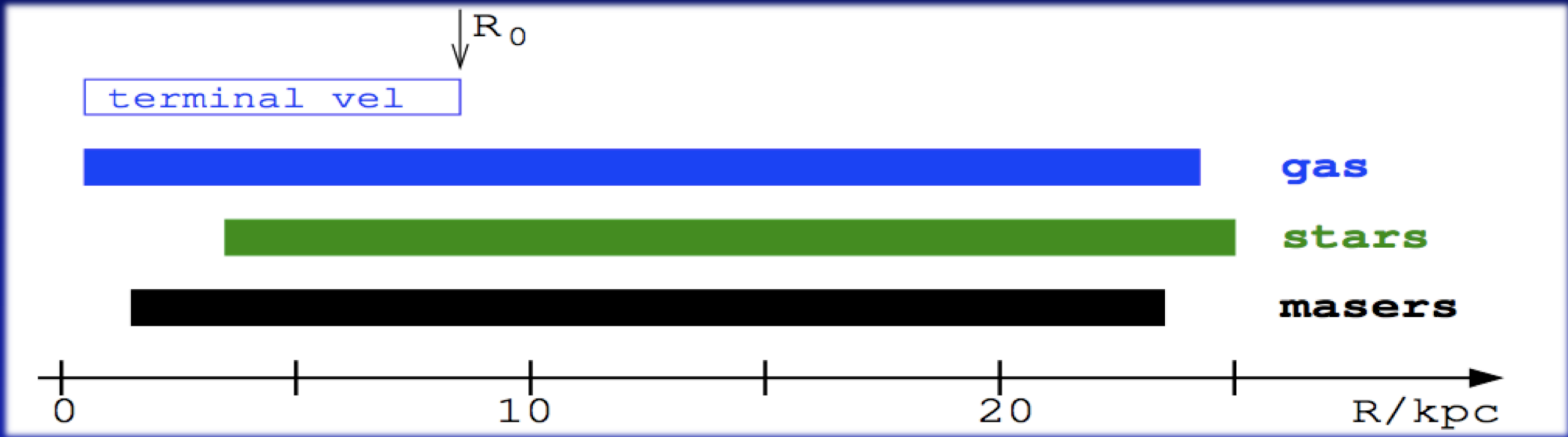
The Milky Way:
observed rotation curve
I. principles



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

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

The Milky Way:
observed rotation curve
II. tracers



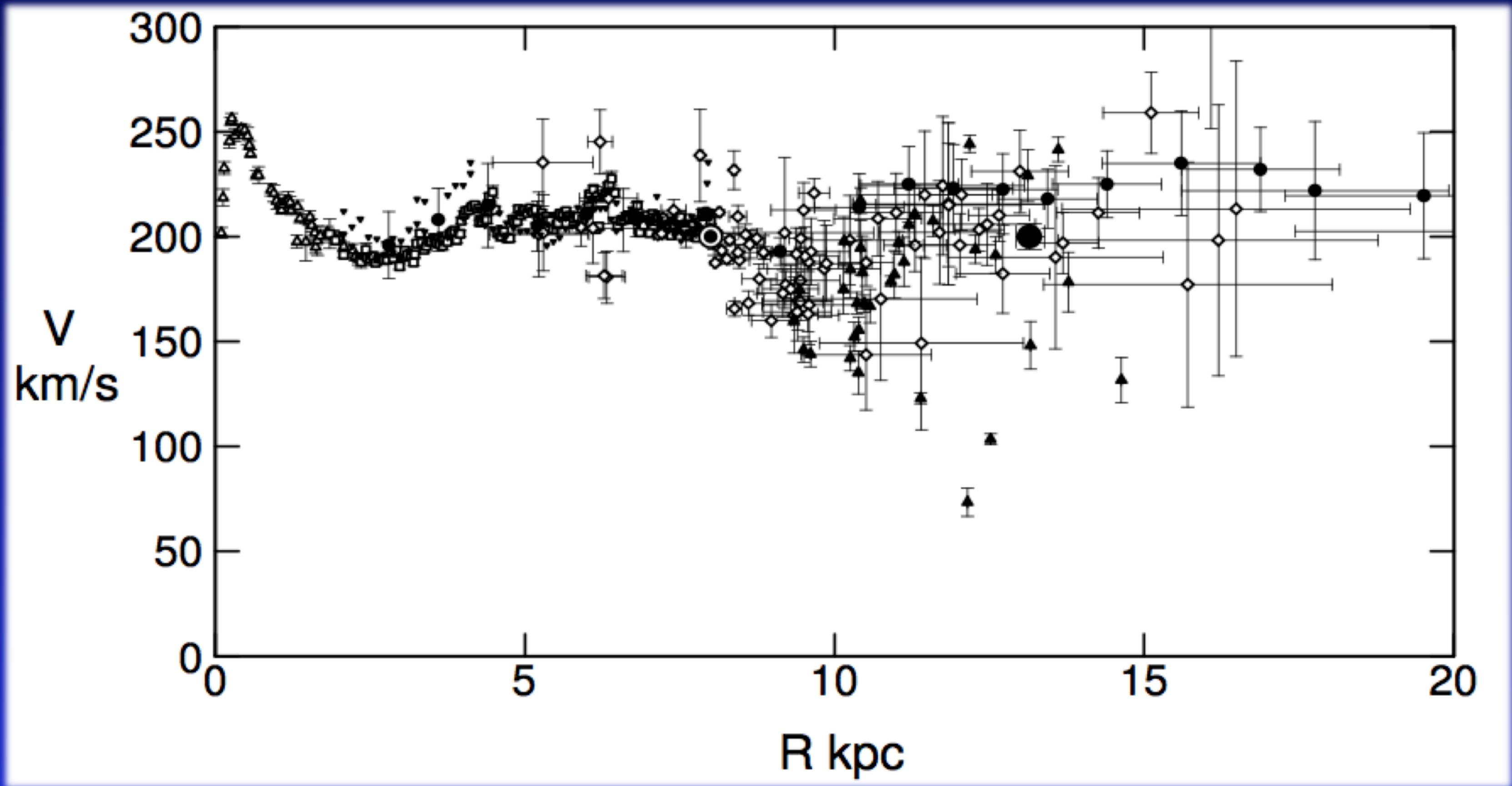
Doppler shift

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

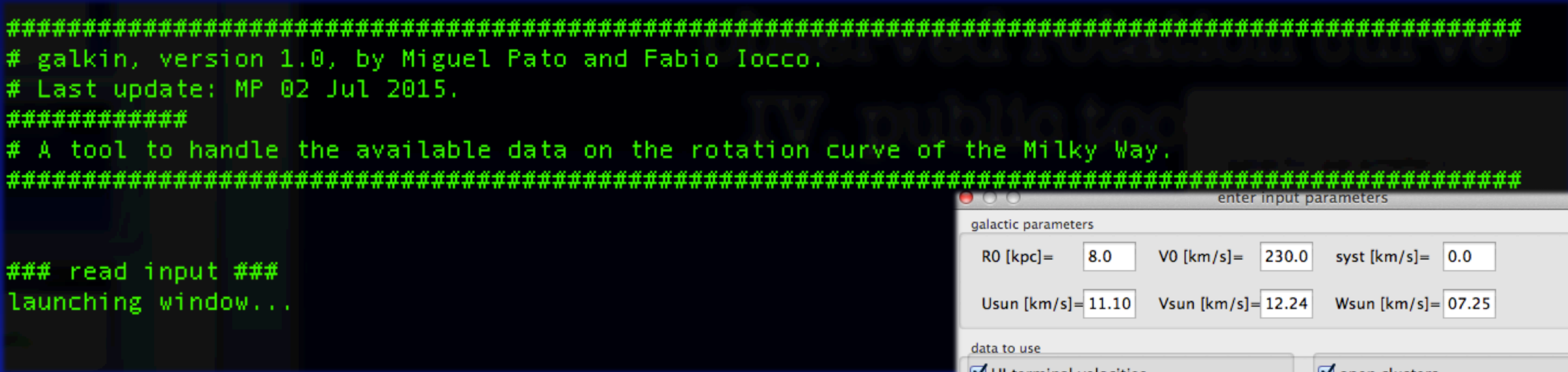


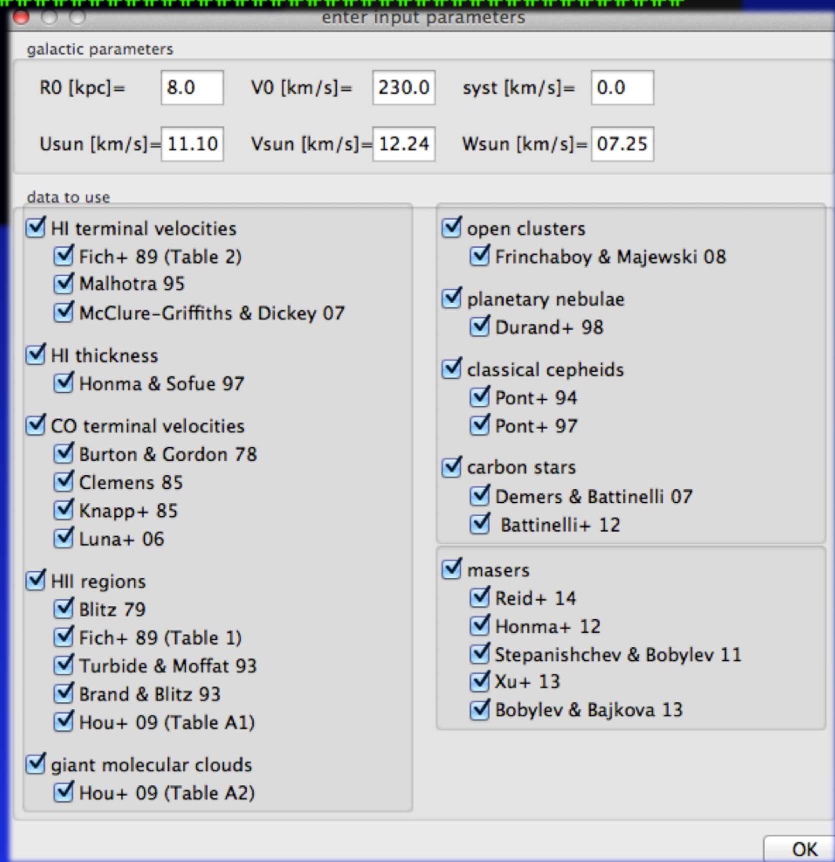
Data compilation by [Sofue et al, '08]

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





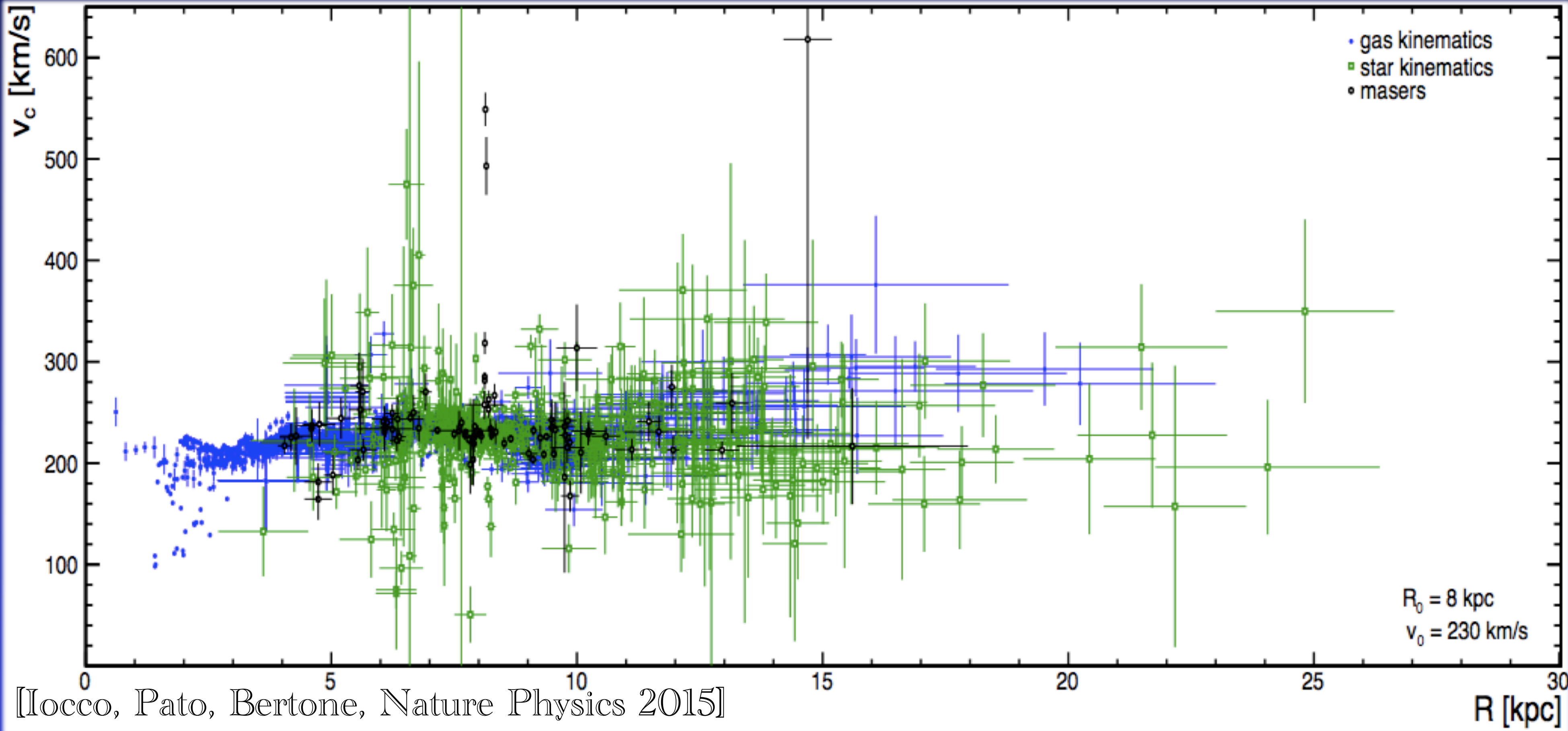
Customizable galactic parameters
(R_0,V_0)
peculiar motions, etc…

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

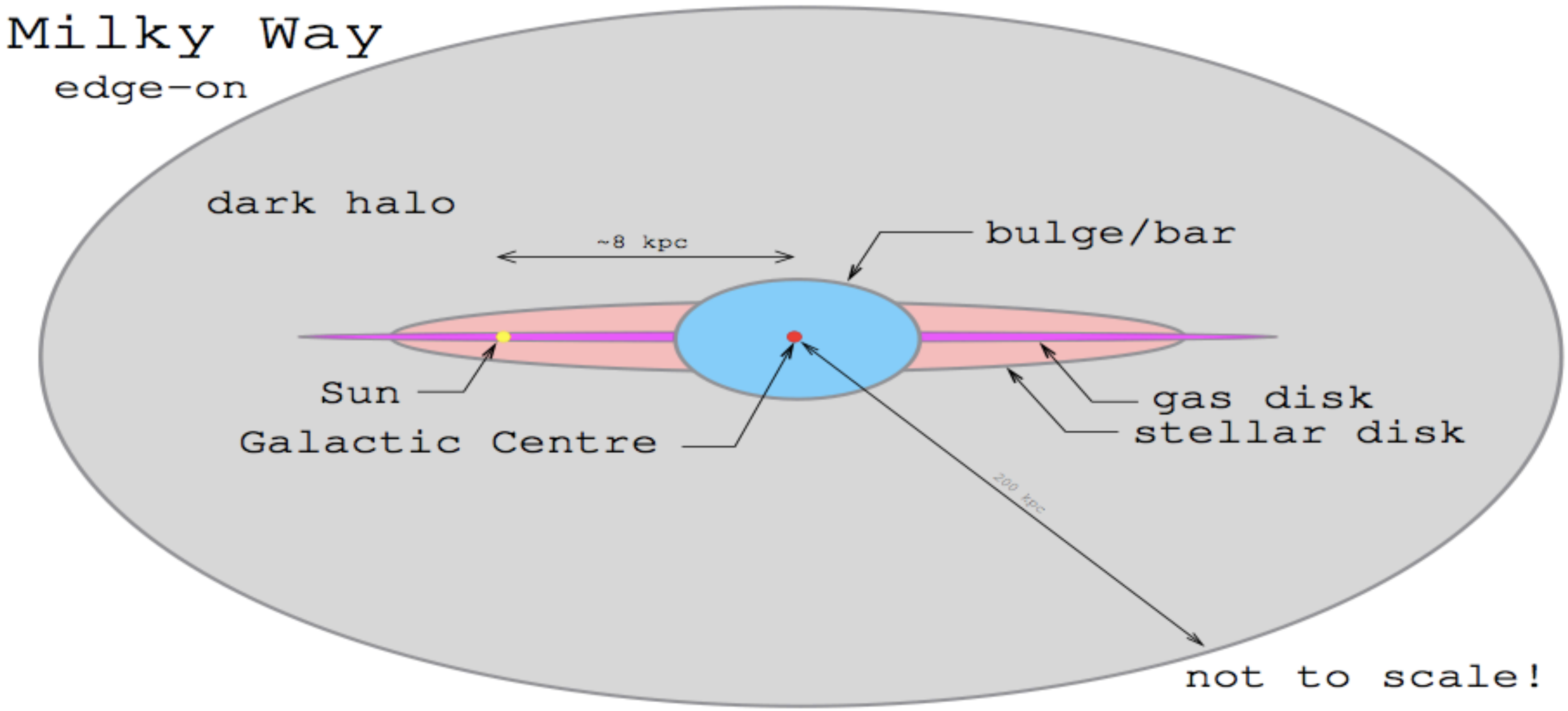
The Milky Way:
expected rotation curve

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

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

Constructing the curve expected from observed mass profiles

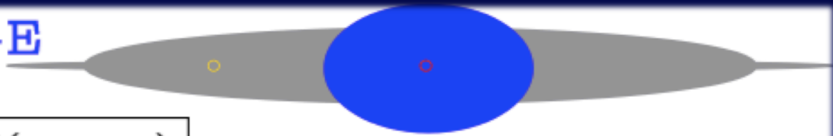
The Milky Way:
expected rotation curve
1. the baryonic components



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

The visible Milky Way: observations of morphology

2. BARYONS: STELLAR BULGE



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

morphology $f(x,y,z)$

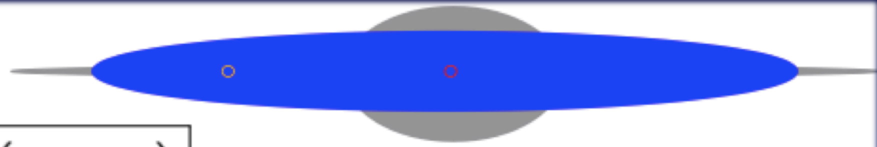
Stanek+ '97 (E2)	e^{-r}	0.9:0.4:0.3	24°	optical
Stanek+ '97 (G2)	$e^{-r_s^2/2}$	1.2:0.6:0.4	25°	optical
Zhao '96	$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	1.5:0.6:0.4	20°	infrared
Bissantz & Gerhard '02	$e^{-r_s^2}/(1+r)^{1.8}$	2.8:0.9:1.1	20°	infrared
Lopez-Corredoira+ '07	Ferrer potential	7.8:1.2:0.2	43°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

2. BARYONS: STELLAR DISK



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

morphology $f(x,y,z)$

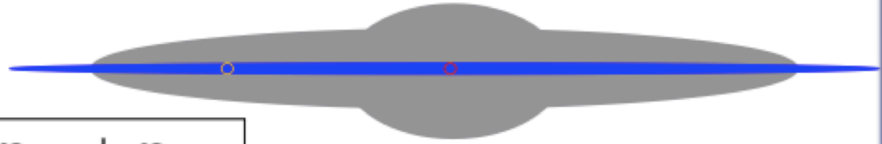
Han & Gould '03	$e^{-R}\mathrm{sech}^2(z)$	2.8:0.27	thin	optical
	$e^{-R-\|z\|}$	2.8:0.44	thick	
Calchi-Novati & Mancini '11	$e^{-R-\|z\|}$	2.8:0.25	thin	optical
	$e^{-R-\|z\|}$	4.1:0.75	thick	
deJong+ '10	$e^{-R-\|z\|}$	2.8:0.25	thin	optical
	$e^{-R-\|z\|}$	4.1:0.75	thick	
	$(R^2+z^2)^{-2.75/2}$	1.0:0.88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

The visible 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

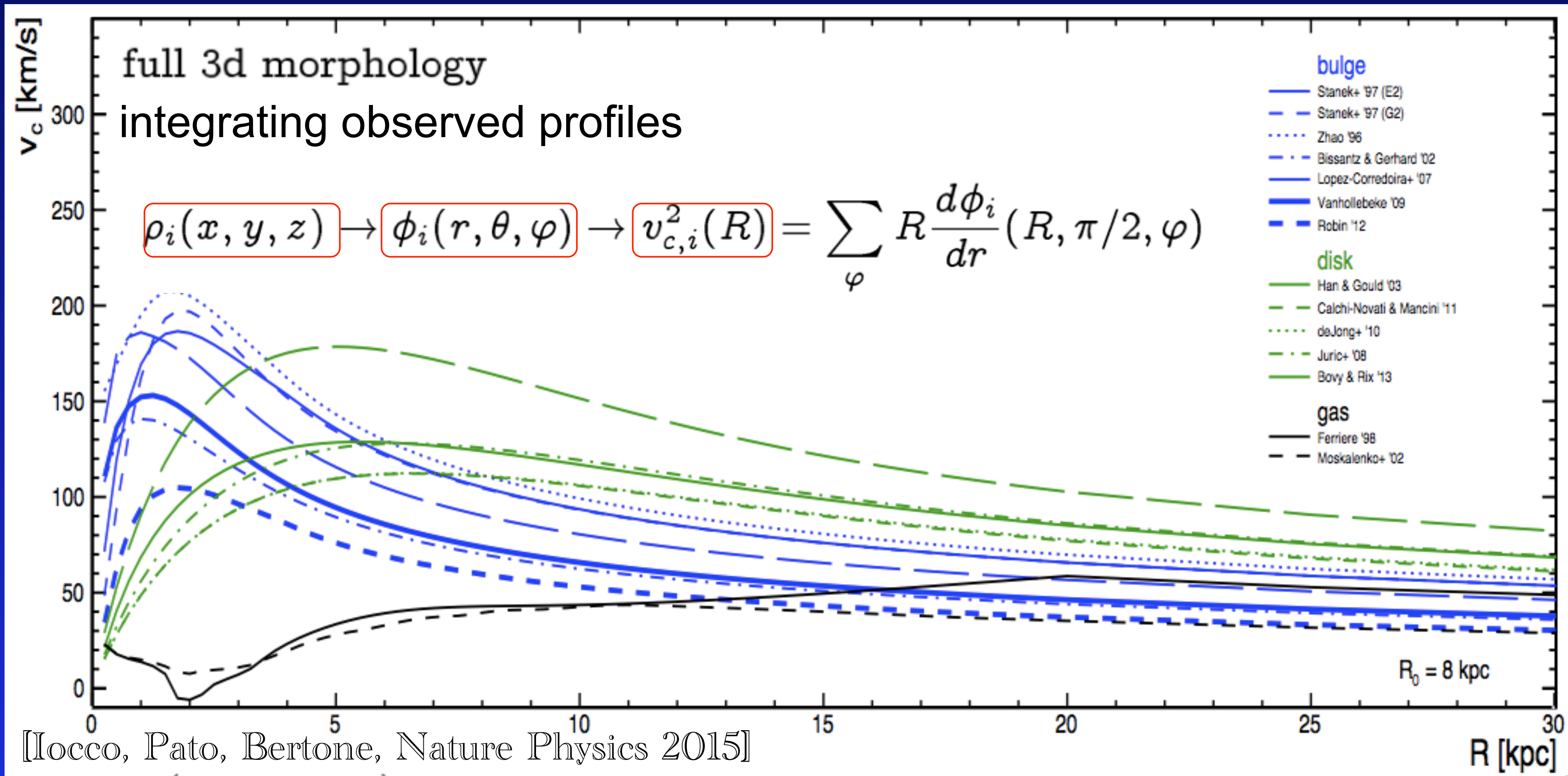
CO-to-H_2 factor: $X_{\mathrm{CO}} = 0.25 - 1.0 \times 10^{20}\ \mathrm{cm}^{-2}\,\mathrm{K}^{-1}\,\mathrm{km}^{-1}\,\mathrm{s}$ for $r < 2$ kpc

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

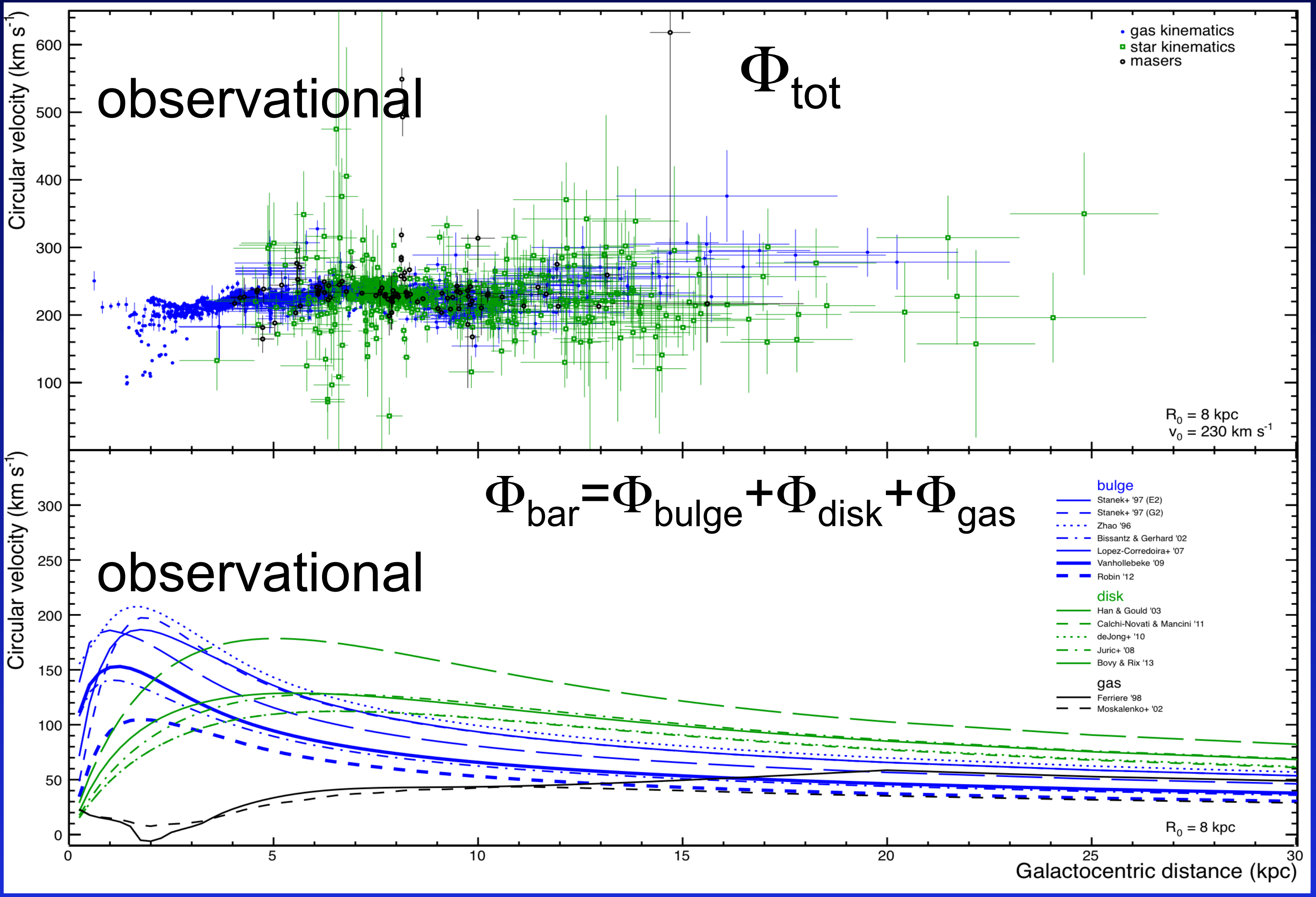
[Ferrière+ '07, Ackermann '12]

The Milky Way:
expected rotation curve

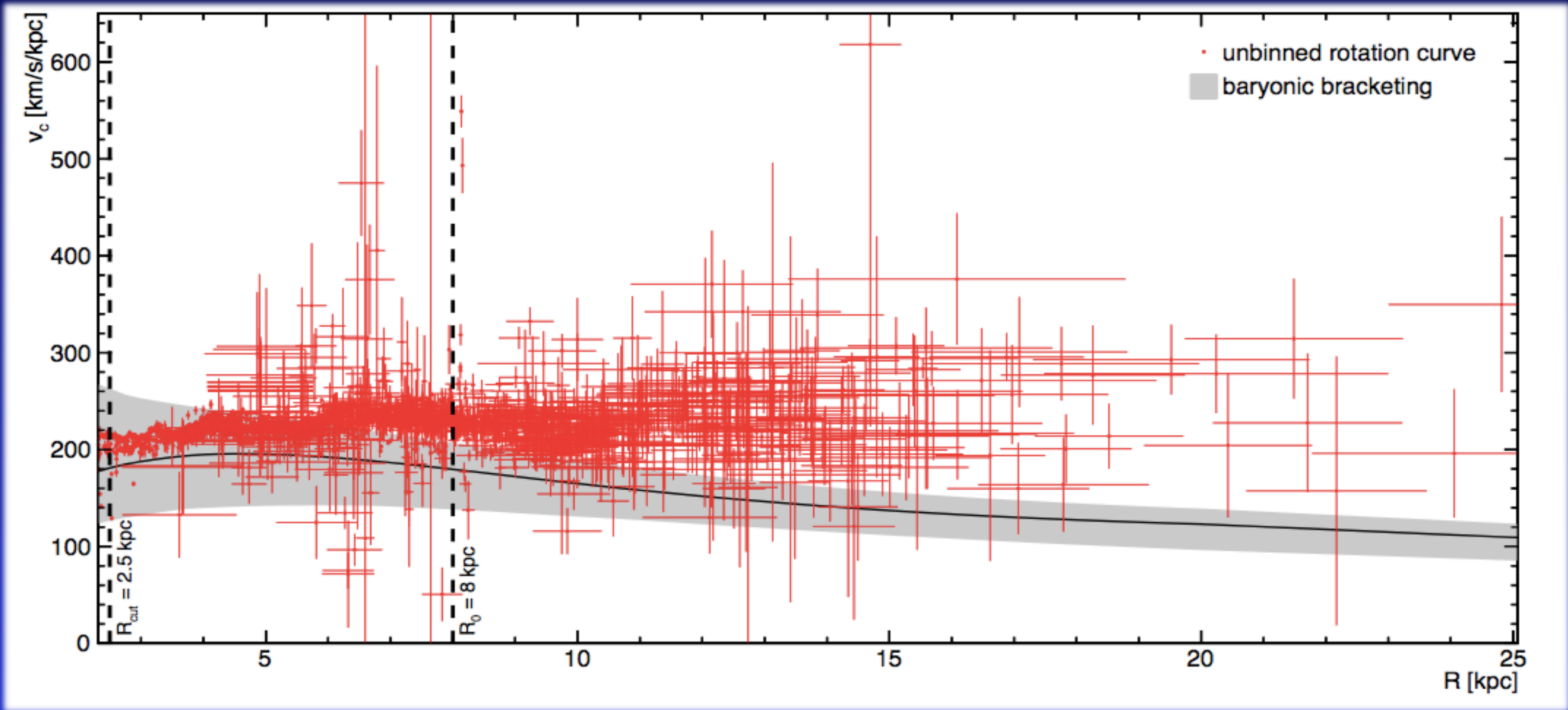
$$\boxed{\phi_i(r,\theta,\varphi)} = -4\pi G \sum_{l,m} \frac{Y_{lm}(\theta,\varphi)}{2l+1}\left[\frac{1}{r^{l+1}}\int_0^r \boxed{\rho_{i,lm}}(a)\,a^{l+2}\,da + r^l \int_r^\infty \boxed{\rho_{i,lm}}(a)\,a^{1-l}\,da\right]$$



The Milky Way: testing expectactions

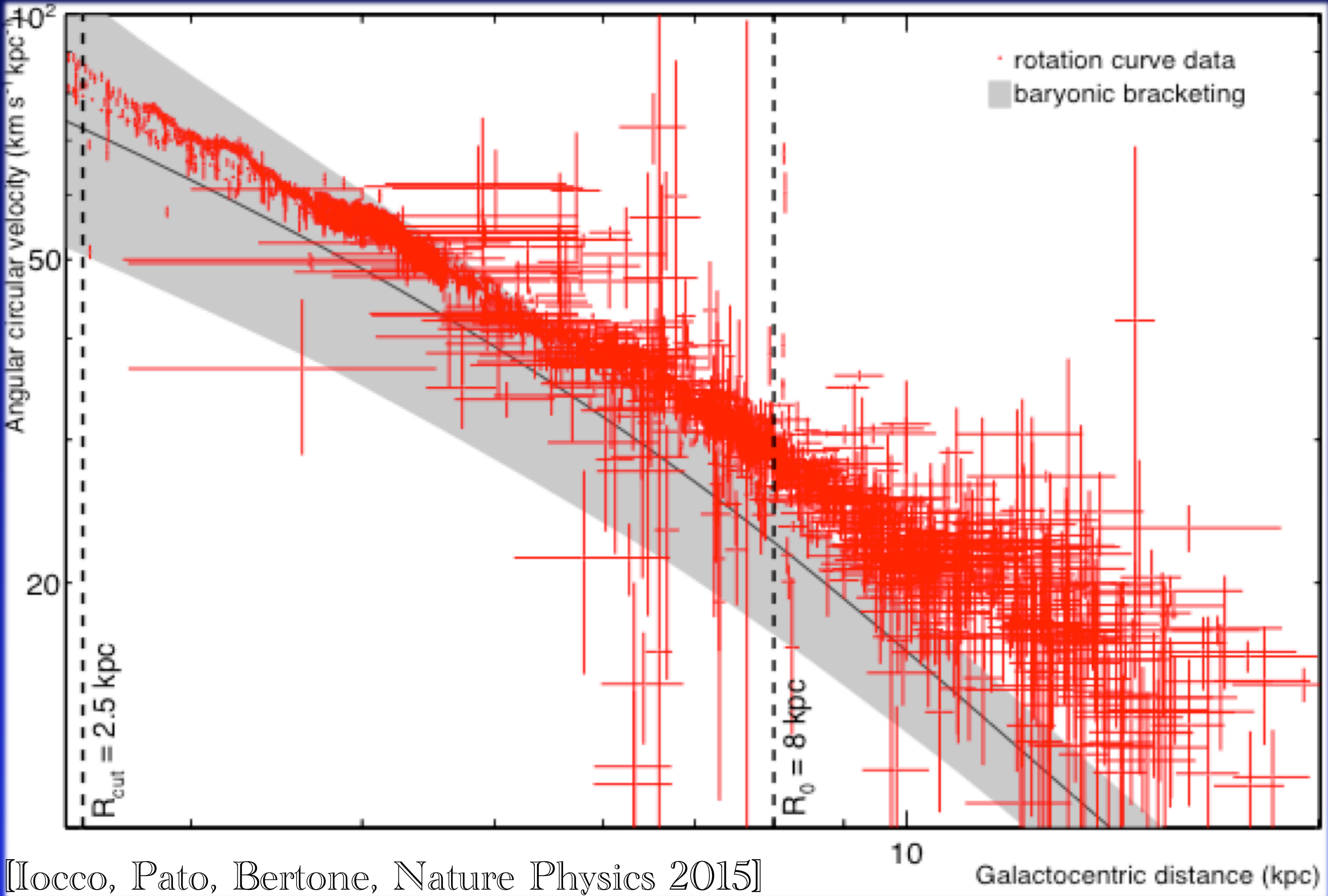


The Milky Way:
testing expectactions
(with no additional assumptions)



[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

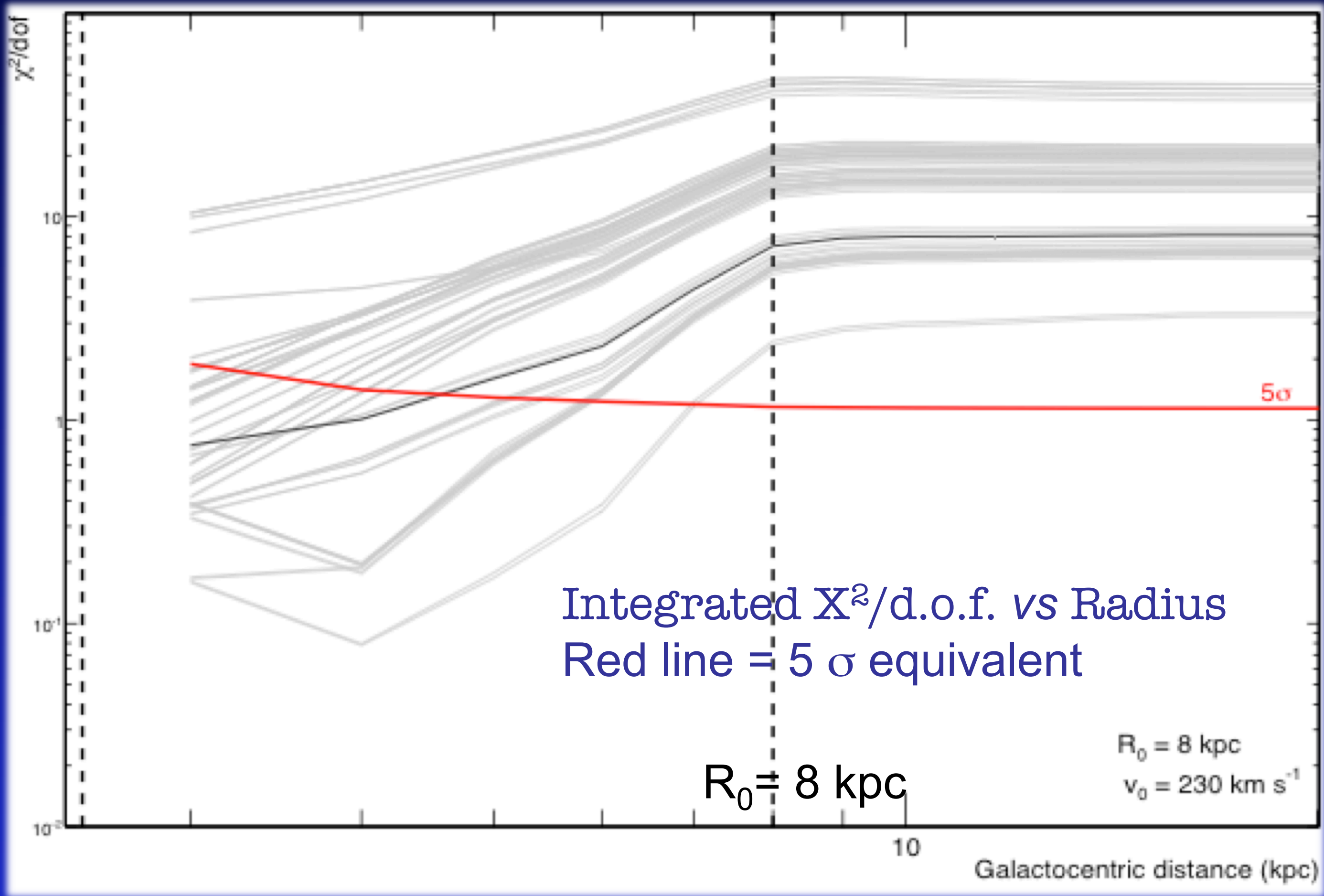
The Milky Way: testing expectactions (with no additional assumptions) ((and some technical detail))

- 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 $R<R_0$!!

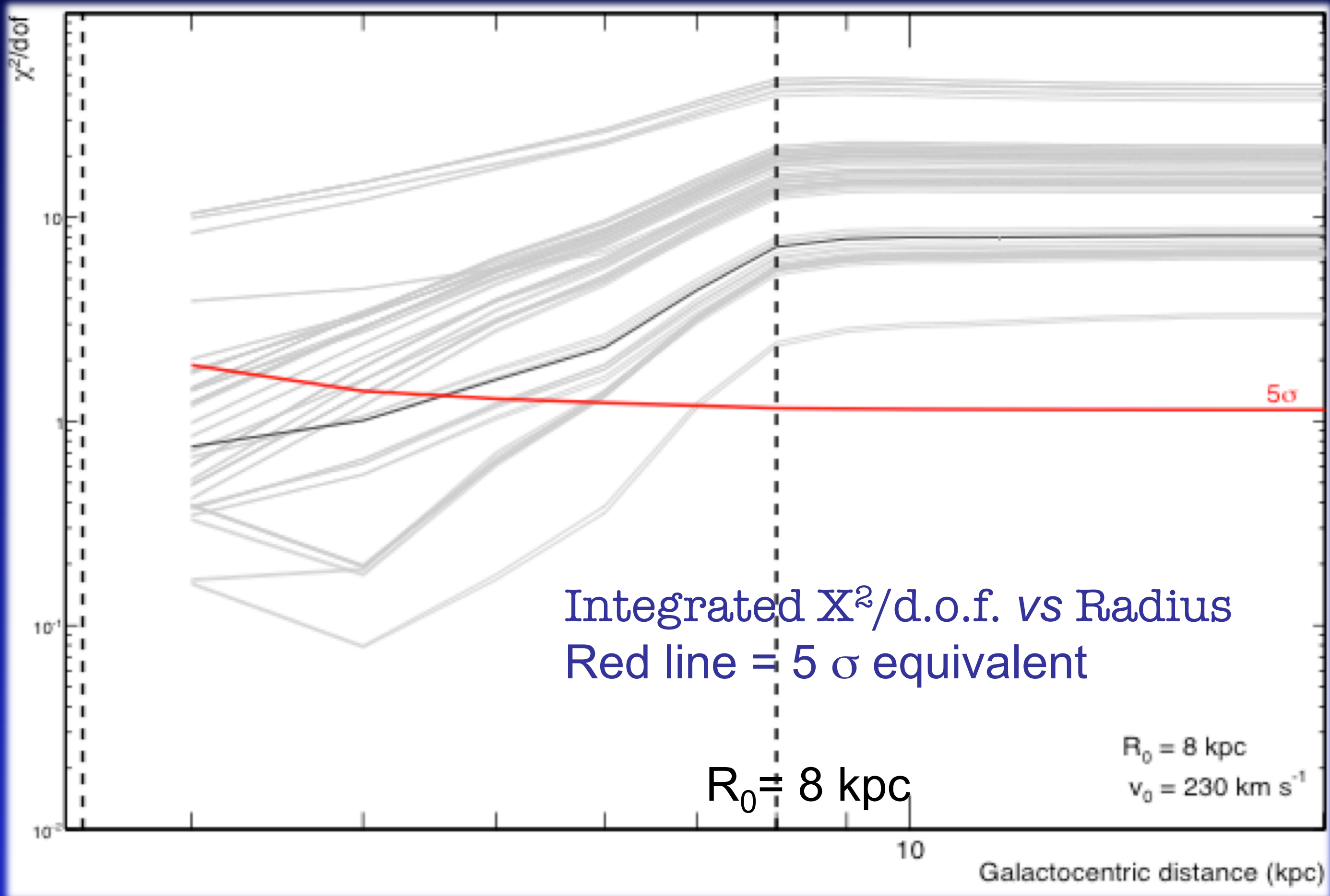
[Iocco, Pato, Bertone, Nature Physics 2015]

Some performed checks
(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

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]

Cuncta stricte

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

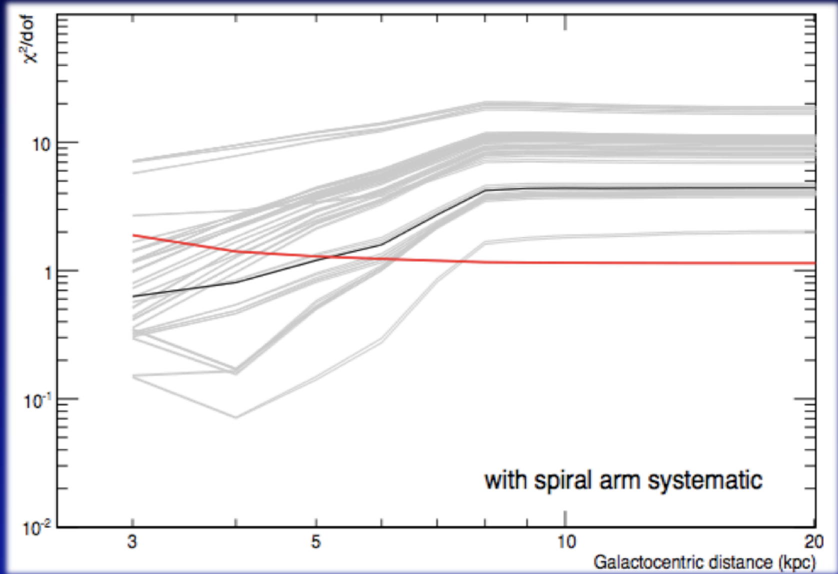
- Evidence for discrepancy between Observed and theoretical (obs. infer.) RC
  - 5 σ at $R < R_0$ (inner Galaxy)
- Analysis is solid against galactic parameter variation and systematics

Testing different setups
(systematics and parameters)

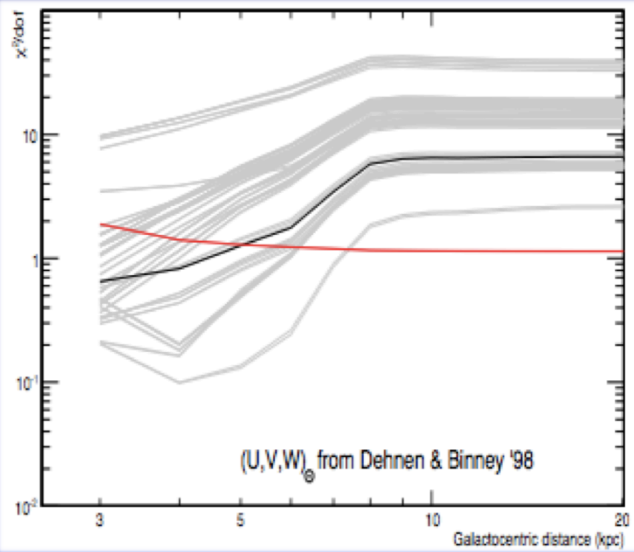
Same conclusions if scanning:

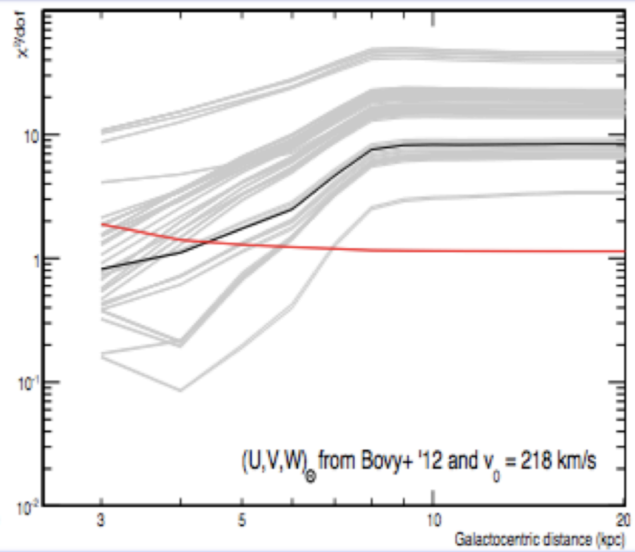
Spiral Arms syst.

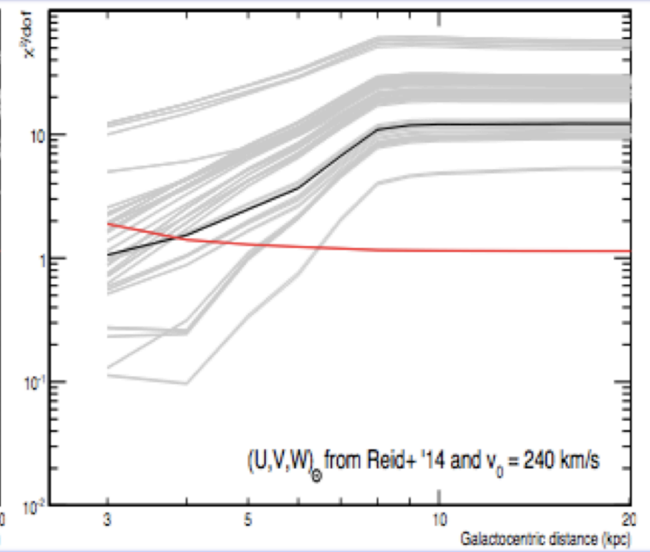
LSR values



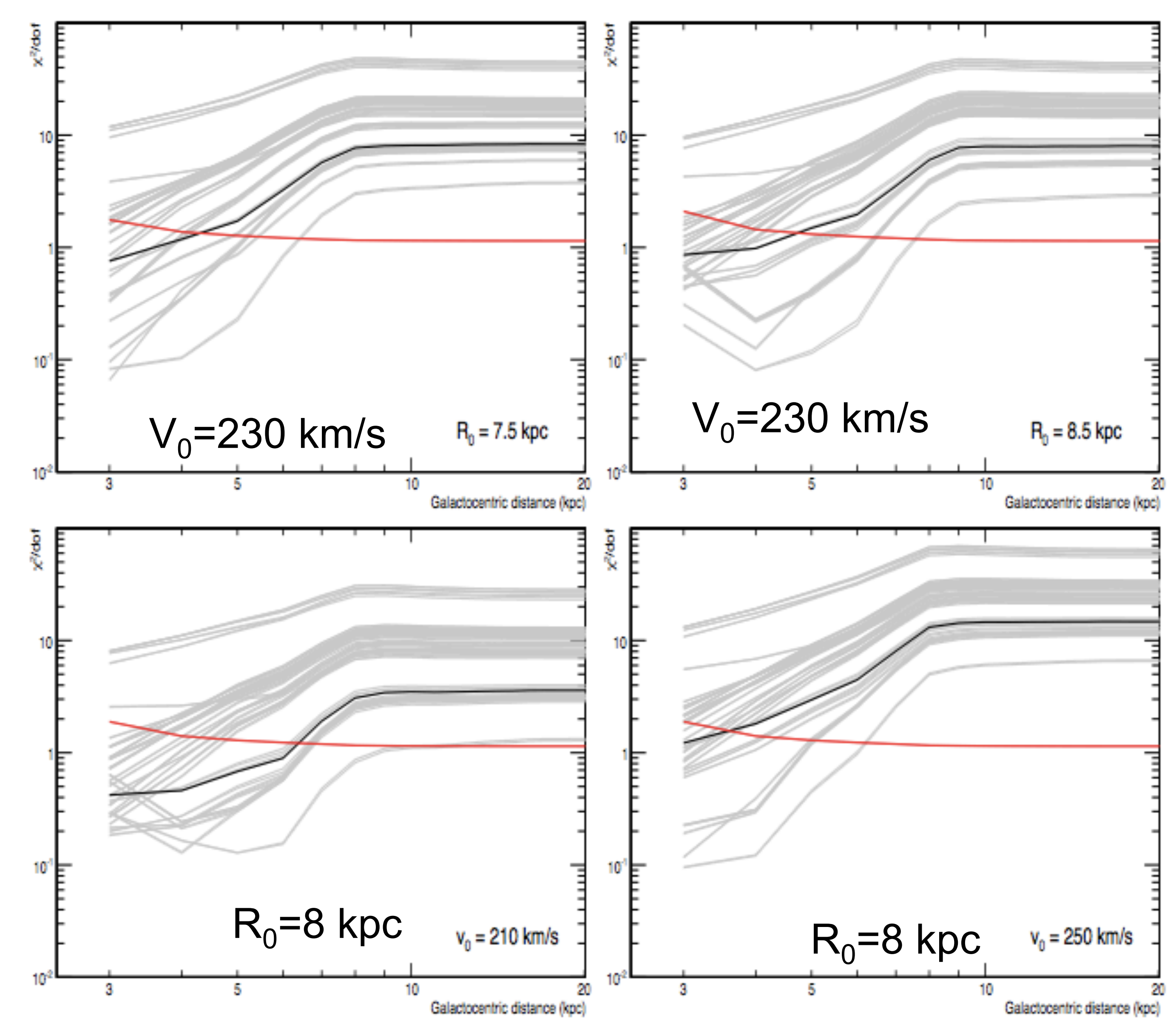
R_0=8 kpc
V_0=230 km/s







Testing galactic parameter variation

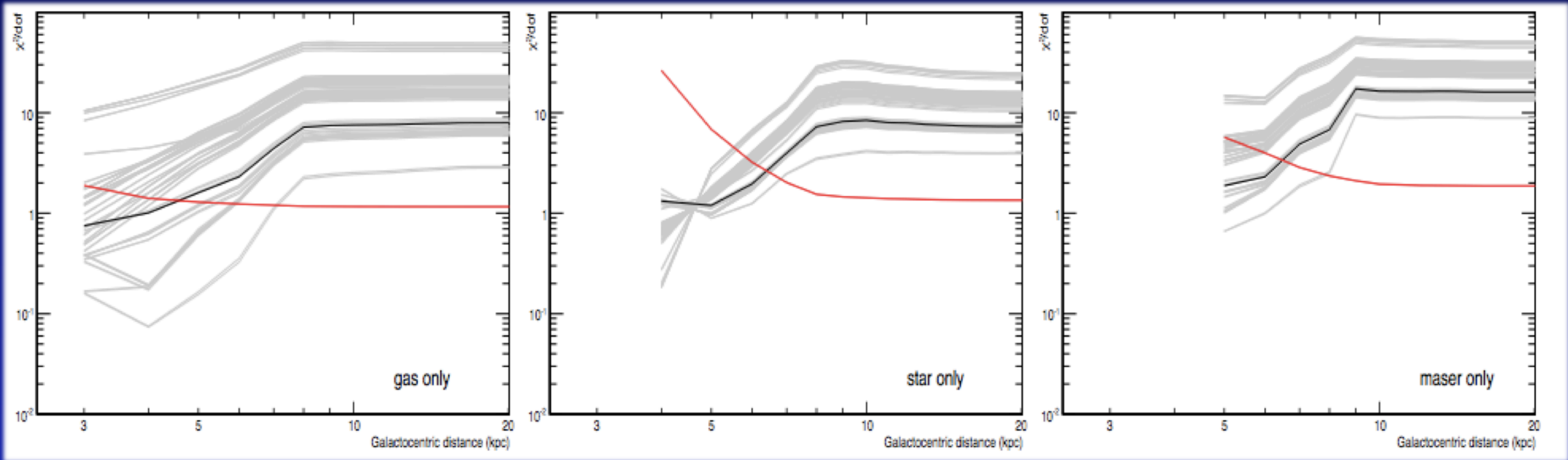


Same conclusions if scanning:

Local circular velocity

Solar distance

Dissecting Rotation Curve
(testing separate tracers)



Same conclusions if using:

Stellar objects only
Masers only
Gas kinematics only

R_0=8 kpc
V_0=230 km/s

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)

Microlensing observations of GC

MACHO CGR = average of 9 fields

$$(\ell, b) = (1.50^\circ, -2.68^\circ)$$

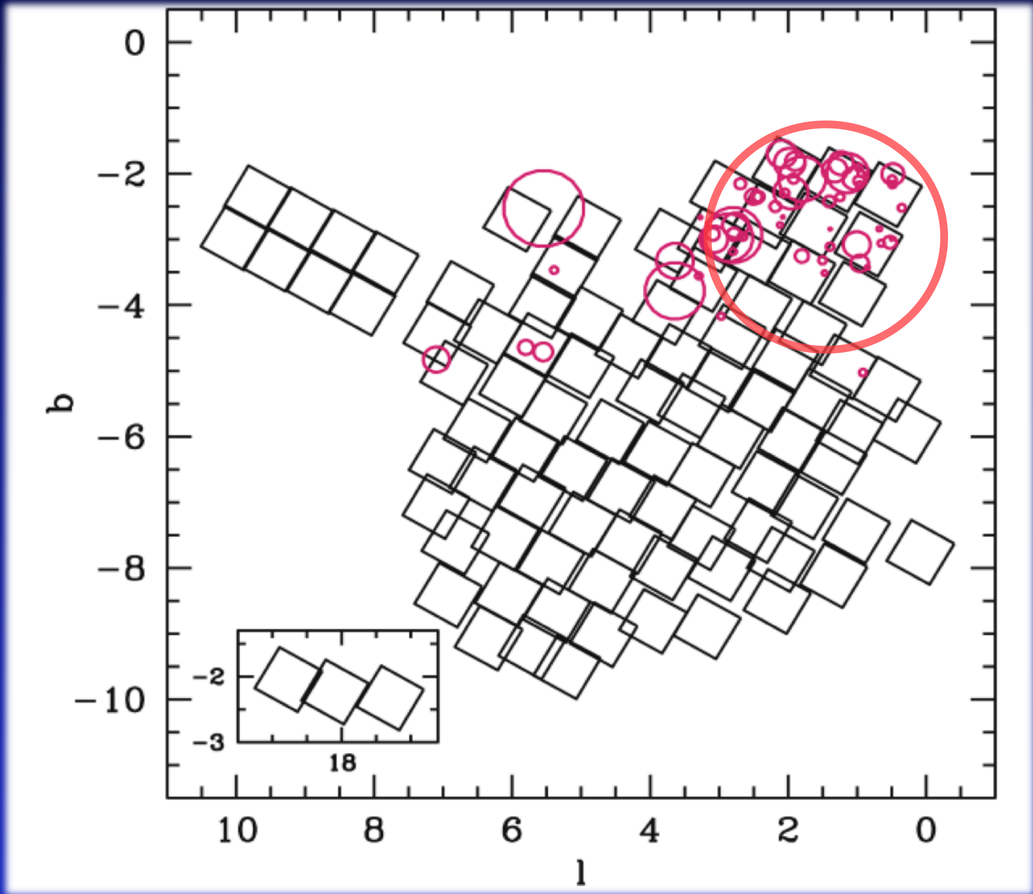
$$\langle \tau \rangle = 2.17^{+0.47}_{-0.38} \times 10^{-6}$$

few < t_E/days < 700

10^{-3} < M_l/Msun < 80

Sources: red clump giant in the bulge

Insensitive to recently discovered Jupiter mass objects, However, below uncertainty: 0.1% mass content

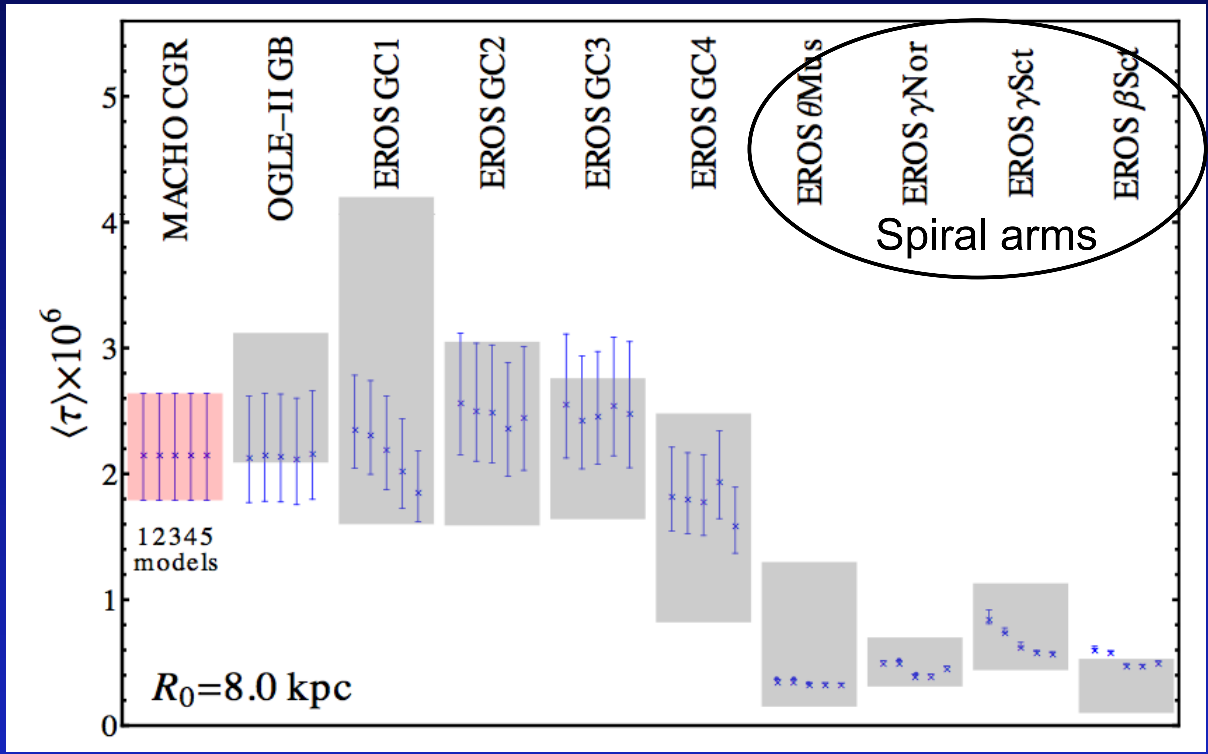


MACHO [Popowski et al. 2005]

Galactic baryonic models

They fit quite well other microlensing observations:

GC and beyond!!



Mass ditribution used to obtain gravitational potential (circular velocities) using non-spherical Poisson equation; Not adding DM yet (see the following…)