

Dark Matter in the Milky Way

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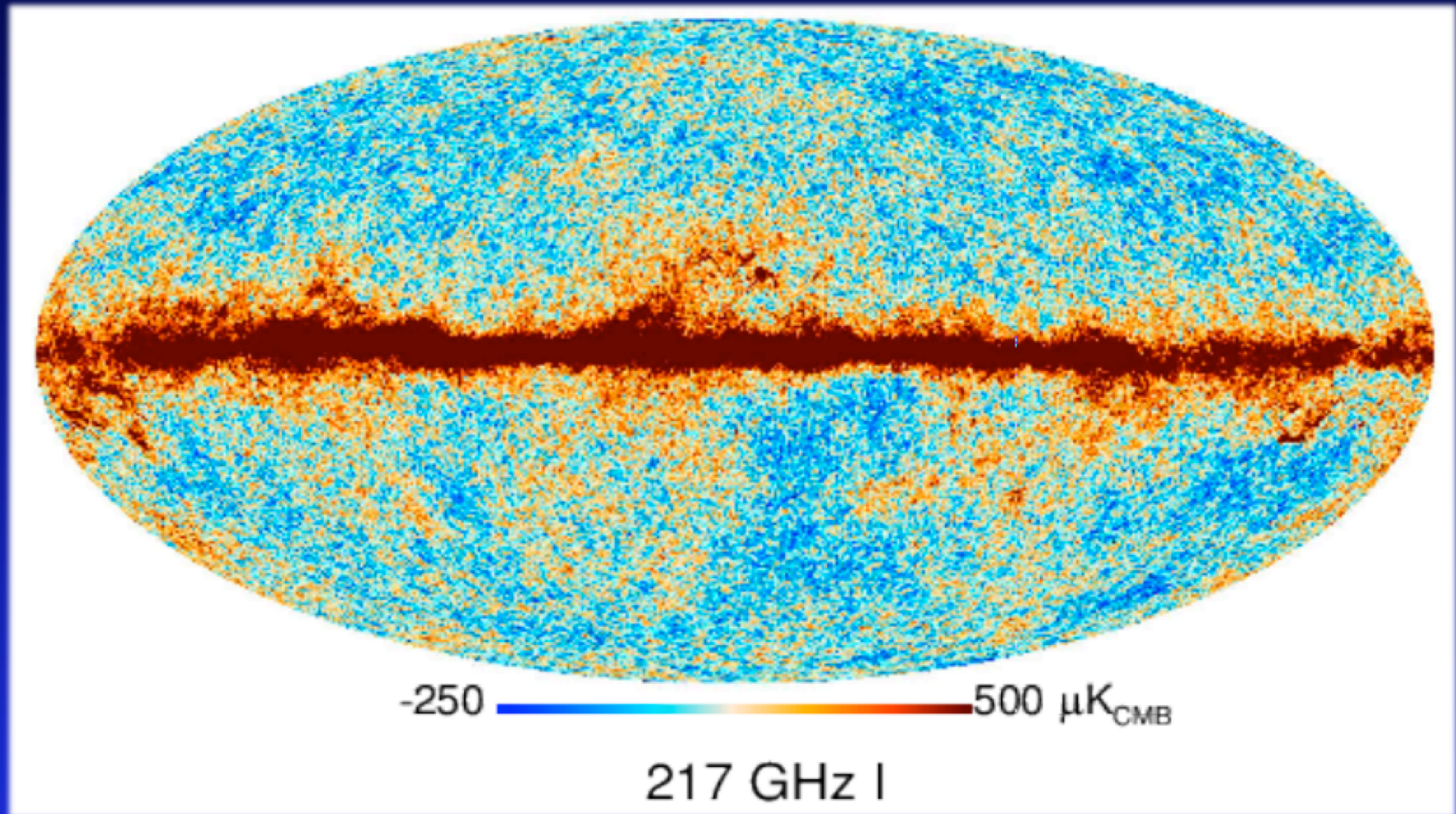
São Paulo



International Centre for Theoretical Physics
South American Institute for Fundamental Research

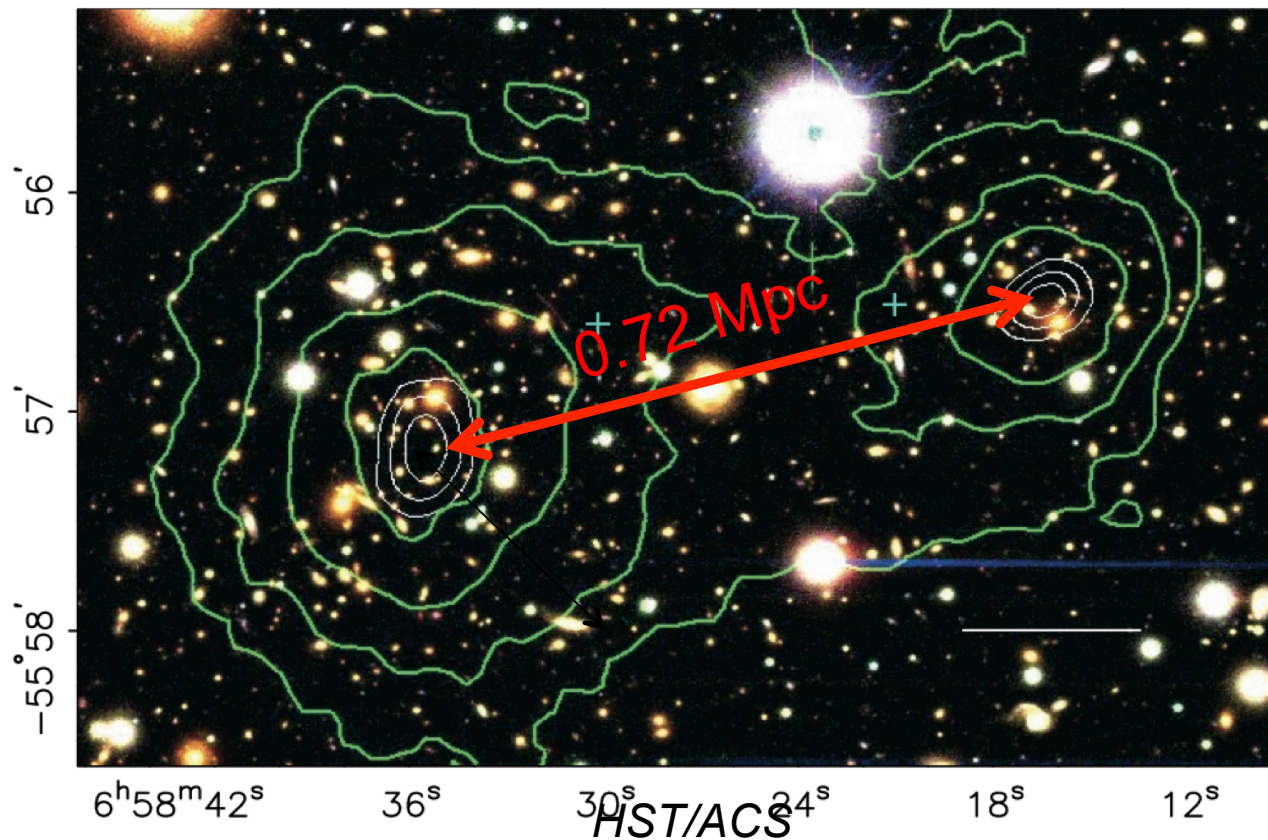
*IV Challenges of
New Physics in Space
Campos do Jordao
26/5/15*

CMB, a dark matter probe



The “Bullet Cluster”

1E 0657-558



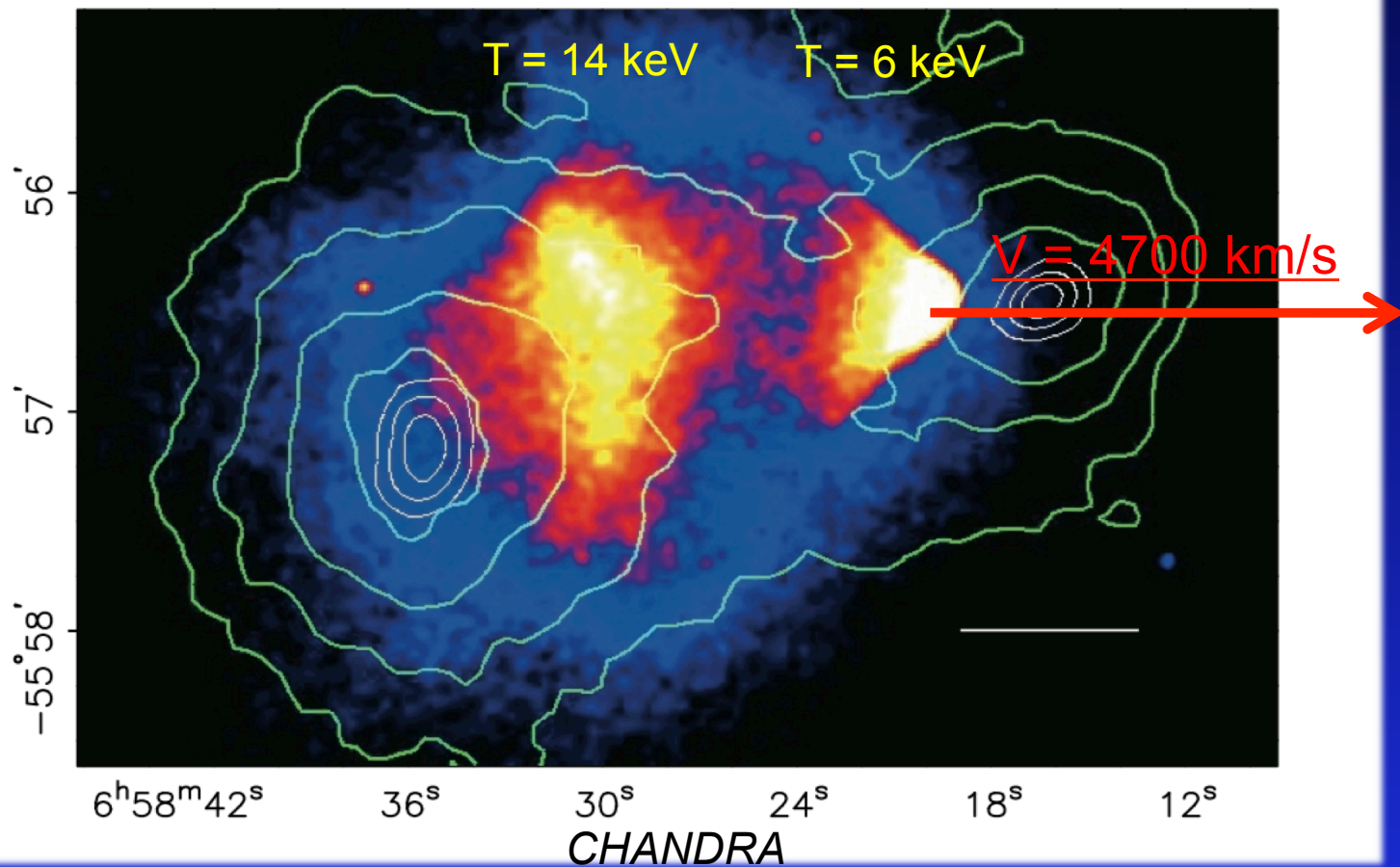
$z = 0.296$

collision in the plane of the sky

[Markevitch et al. '06]

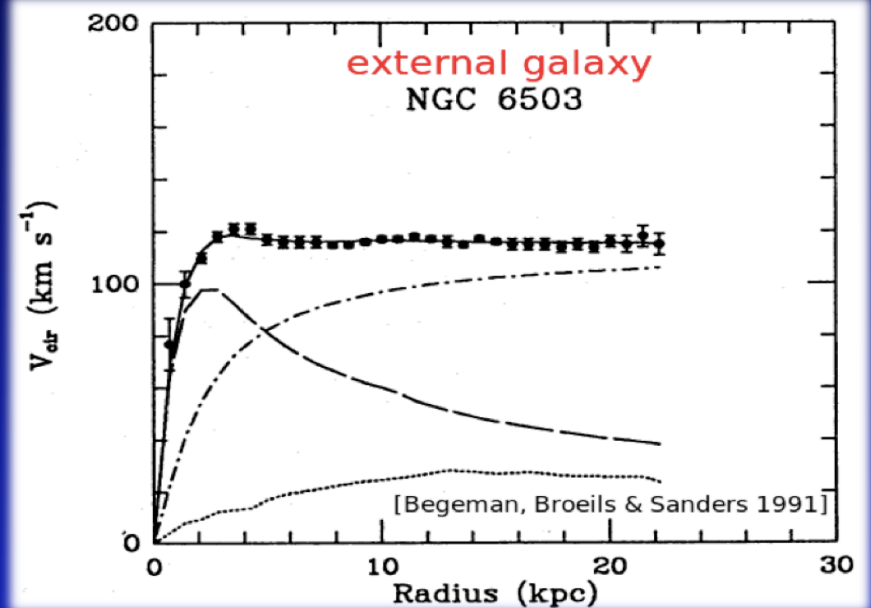
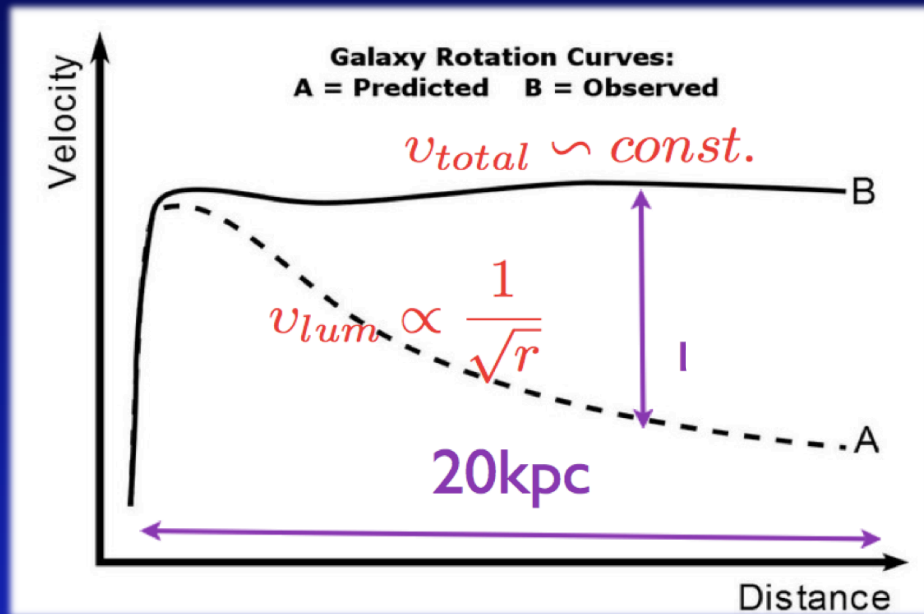
What is the “Bullet Cluster?”

1E 0657-558



Merger 100 Myr ago

Spiral Galaxies rotation curves: an evergreen classic



discrepancy between observed and predicted (on visible matter)

What can we learn from astrophysics (about DM?)

- DM is there, at different scales
(≈ 100 Mpc, ≈ 1 Mpc, ≈ 10 kpc)
- 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*

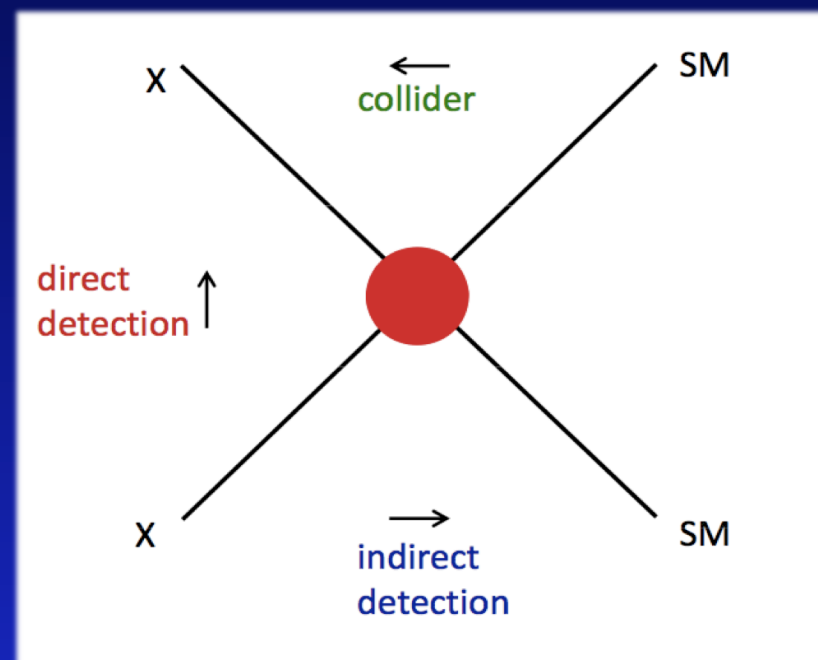
Direct detection:

DM scattering against nuclei, recoil

Indirect detection:

Annihilation in astrophysical enviro.
Observation of SM products of annih.

Production at LHC



Constraining DM nature with local observables (looking for a specific class of particles)

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

$e^+, p, e^- \dots$
subject to magnetic fields

$\nu, \gamma's$:
straight messengers



$\rho_\chi(r) = \text{smooth} + \text{clumps}$

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

Courtesy of P. Salati

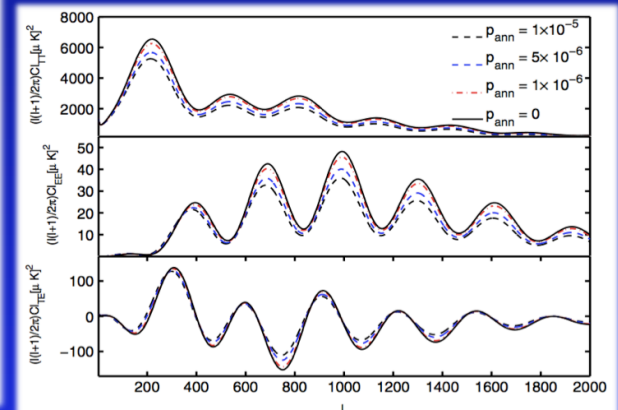
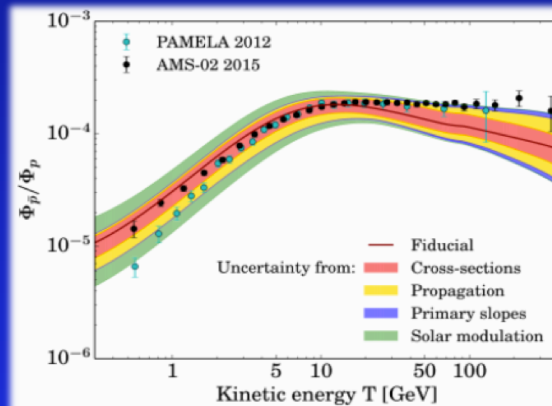
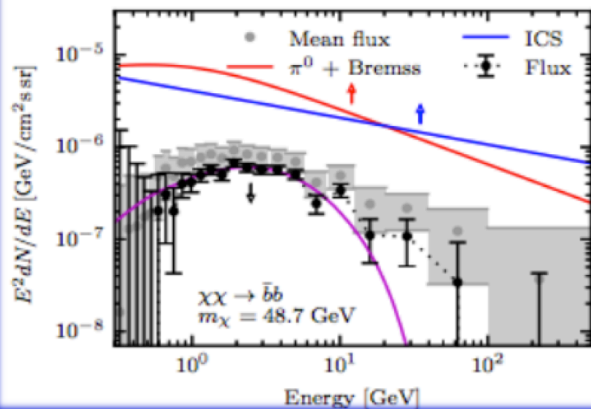
Possible observables for DM annihilation:

Galactic center, Dwarf Galaxies, Galactic Halo...

dependence on density structure

discovery (or constraints) subject to same uncertainty

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

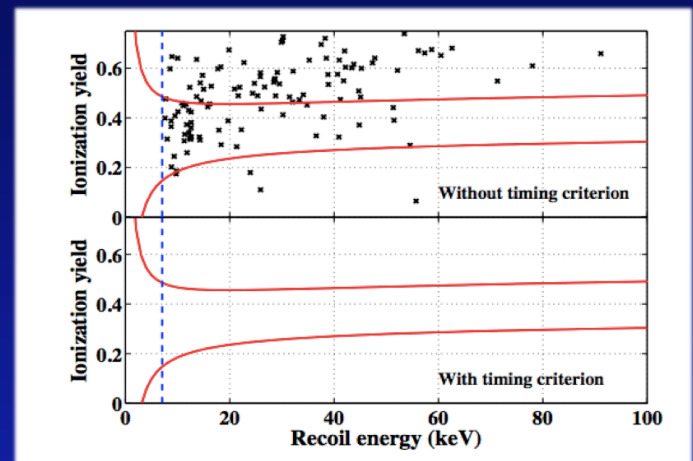


Direct searches of WIMP DM:

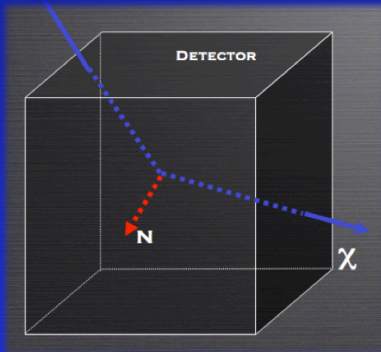
A big mountain (or a mine)



Look at
phonons/ionizations/scintillations

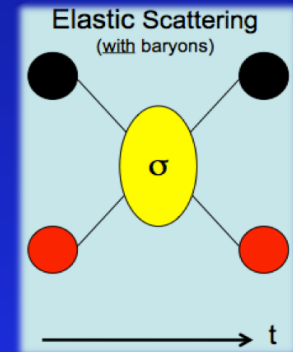


A detector
(underneath)



And, ideally:

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

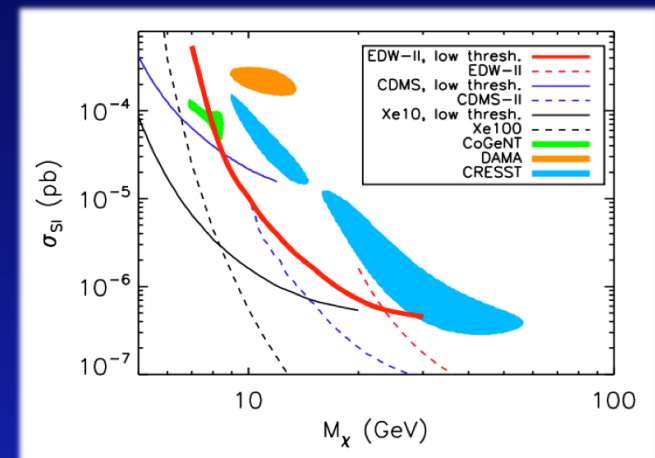
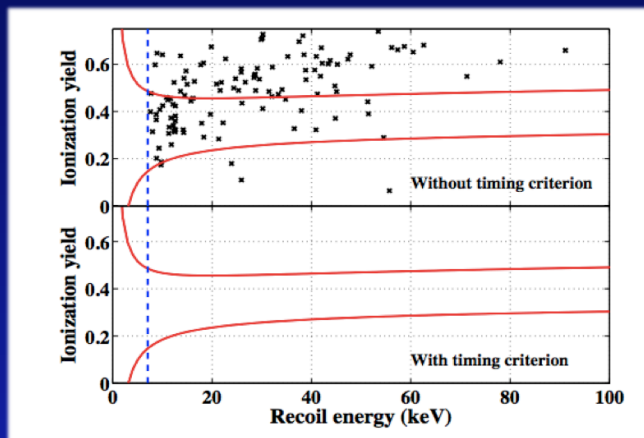


Direct searches of WIMP DM:

from this



to this

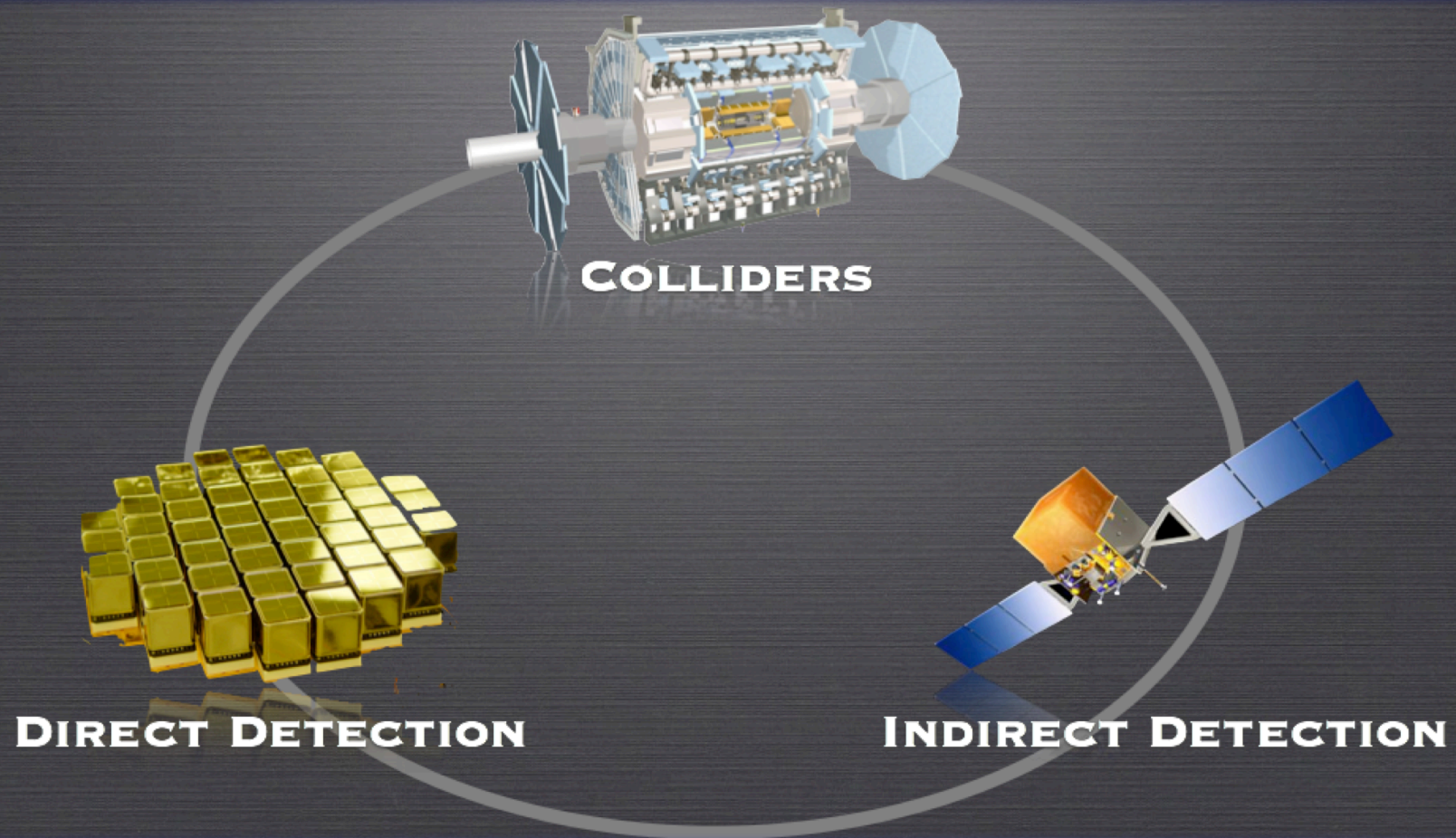


you have to use this

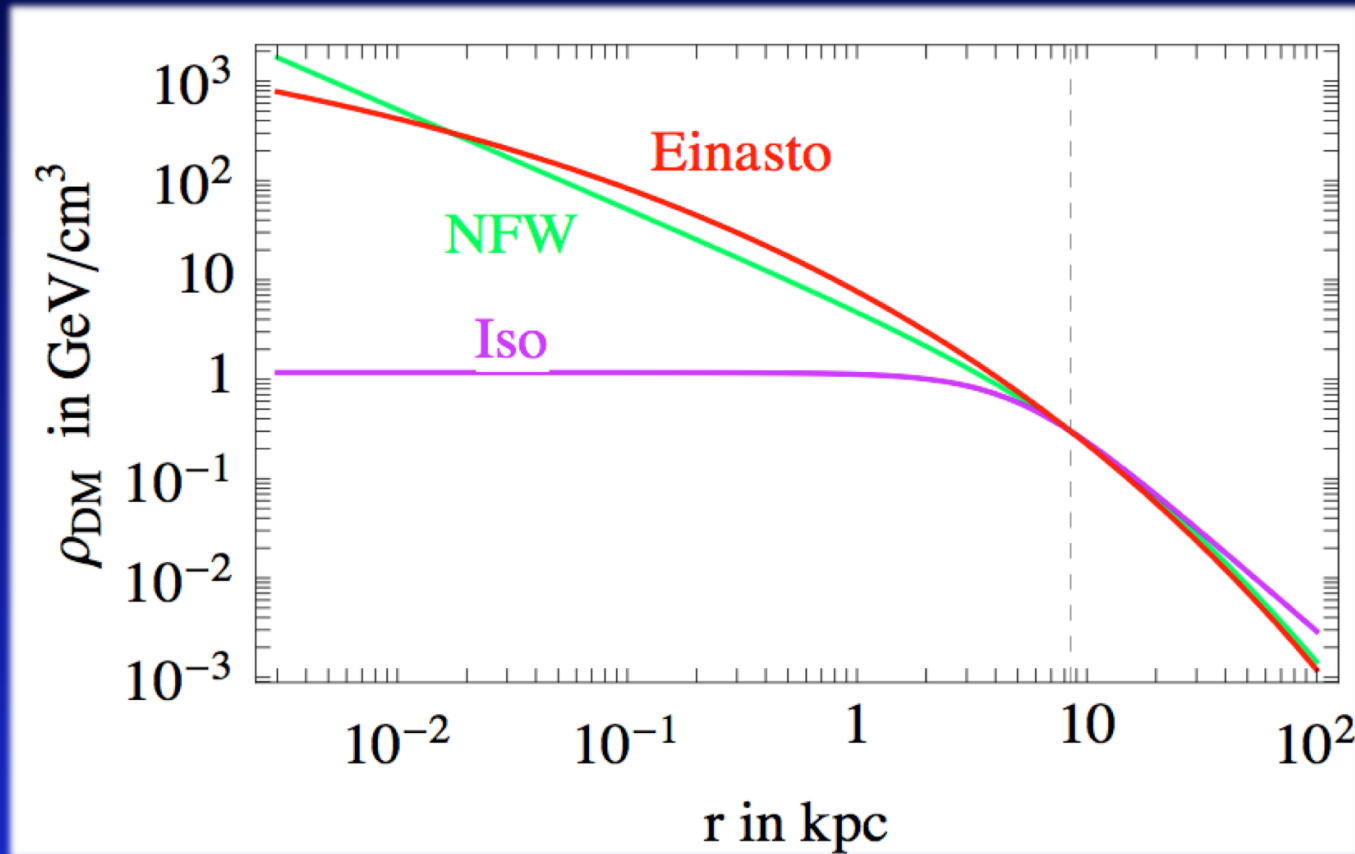
$$\frac{dR_{A,Z}}{dE} = \frac{\sigma_{A,Z}(E)}{2m\mu_{A,Z}^2} \rho \eta(v_{\min}, t)$$

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

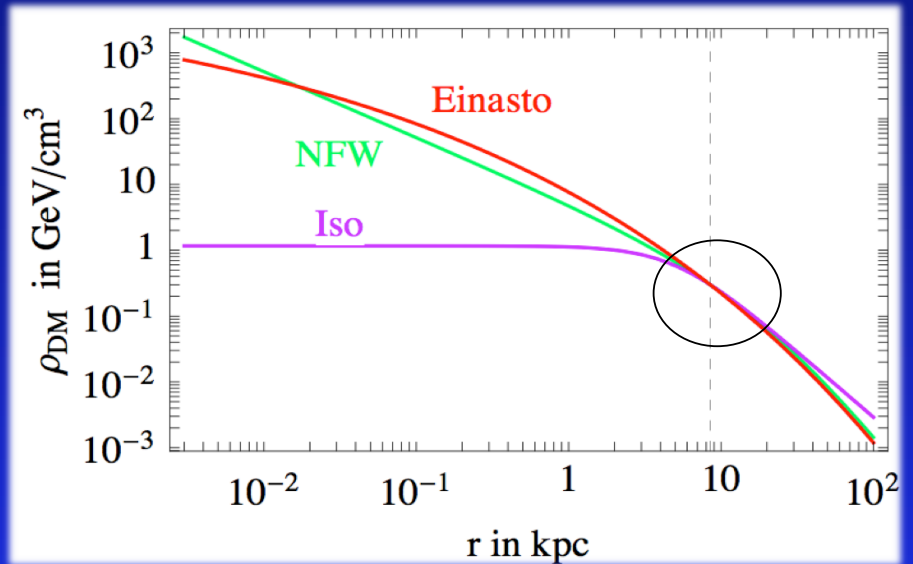


(well motivated)
hints from numerical simulations

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



We know there is
“little” DM here,
But how little?

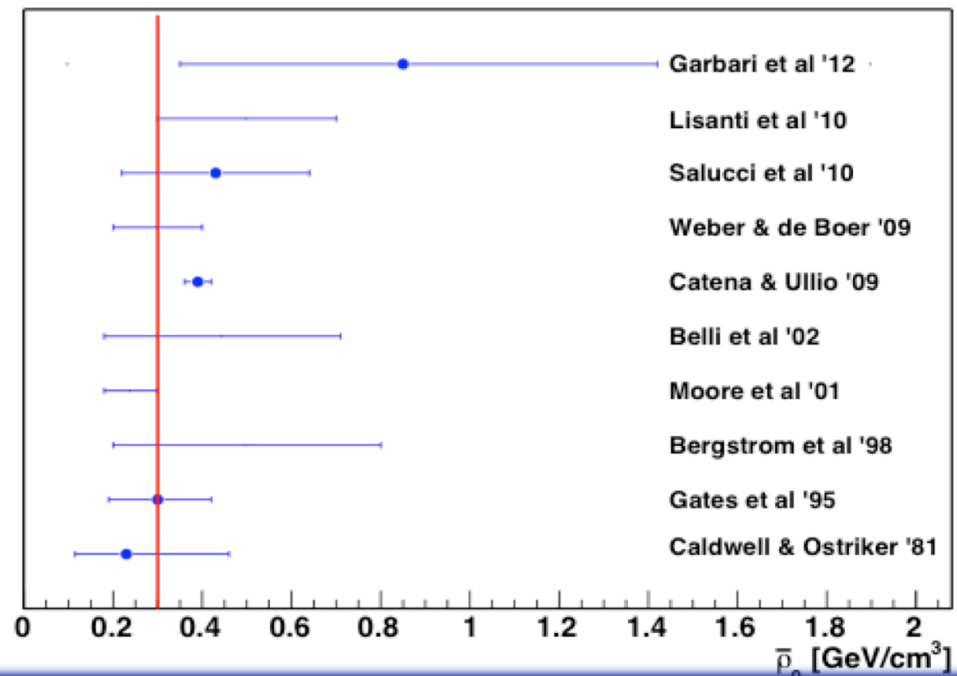


Determination of local DM density ρ_0

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

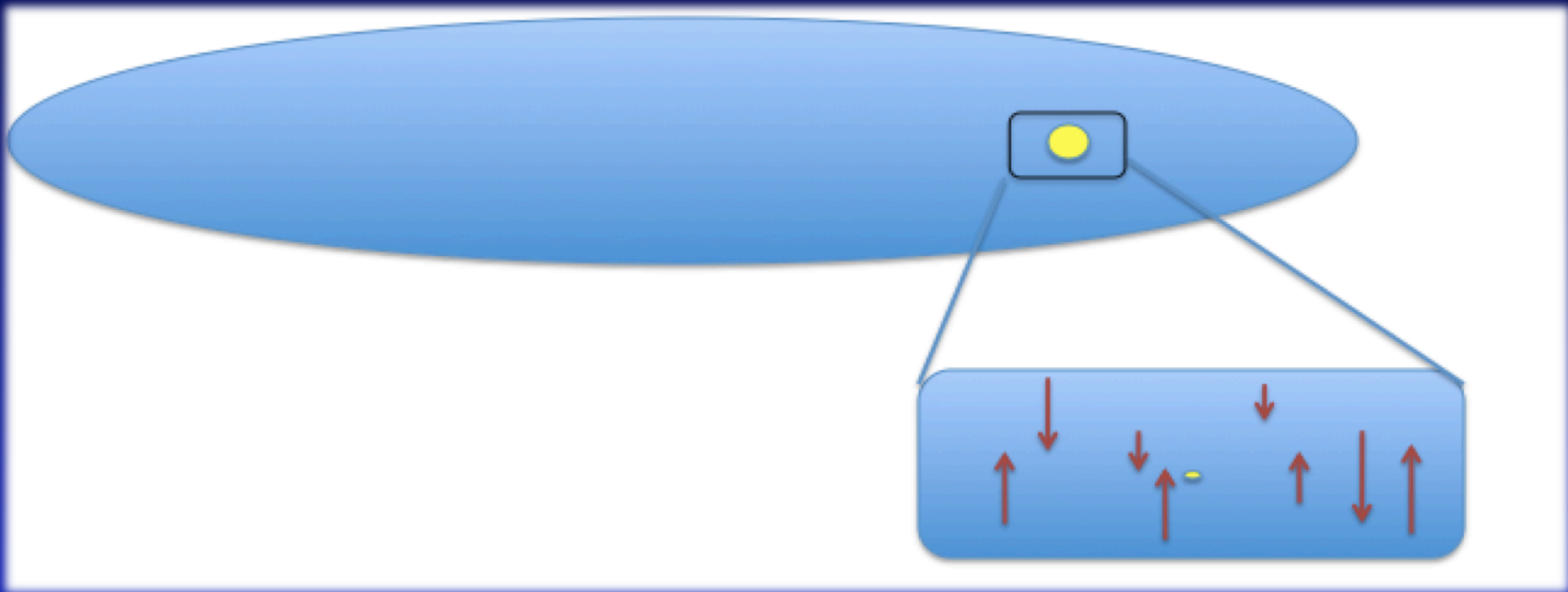
VS

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



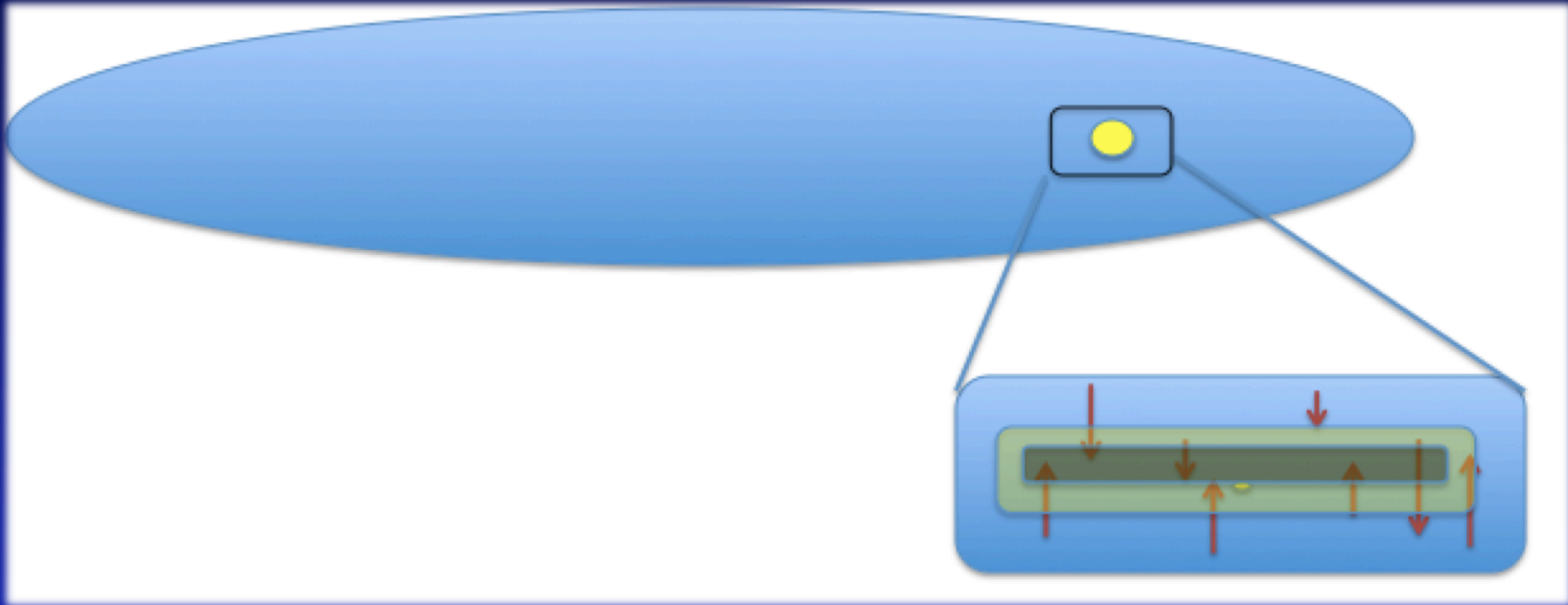
Give consistent results

Local determination of ρ_0



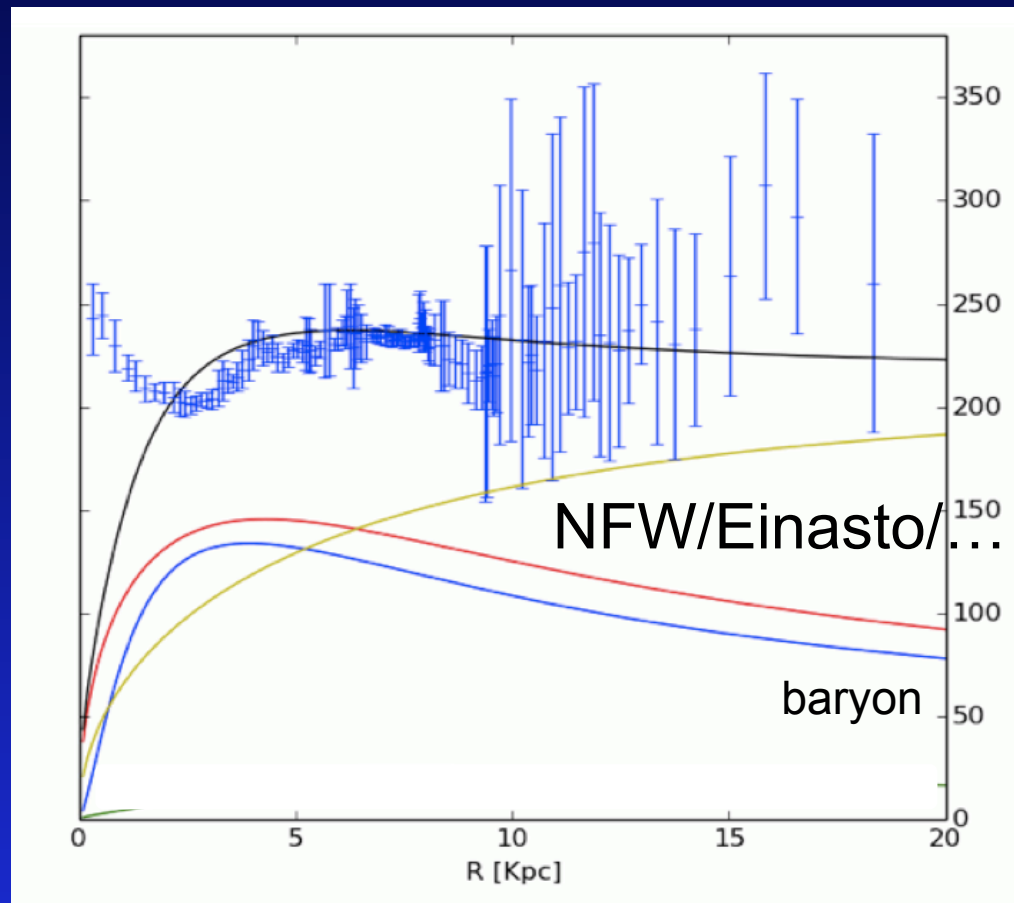
Vertical motion of stars, determining the whole local potential

Local determination of ρ_0



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

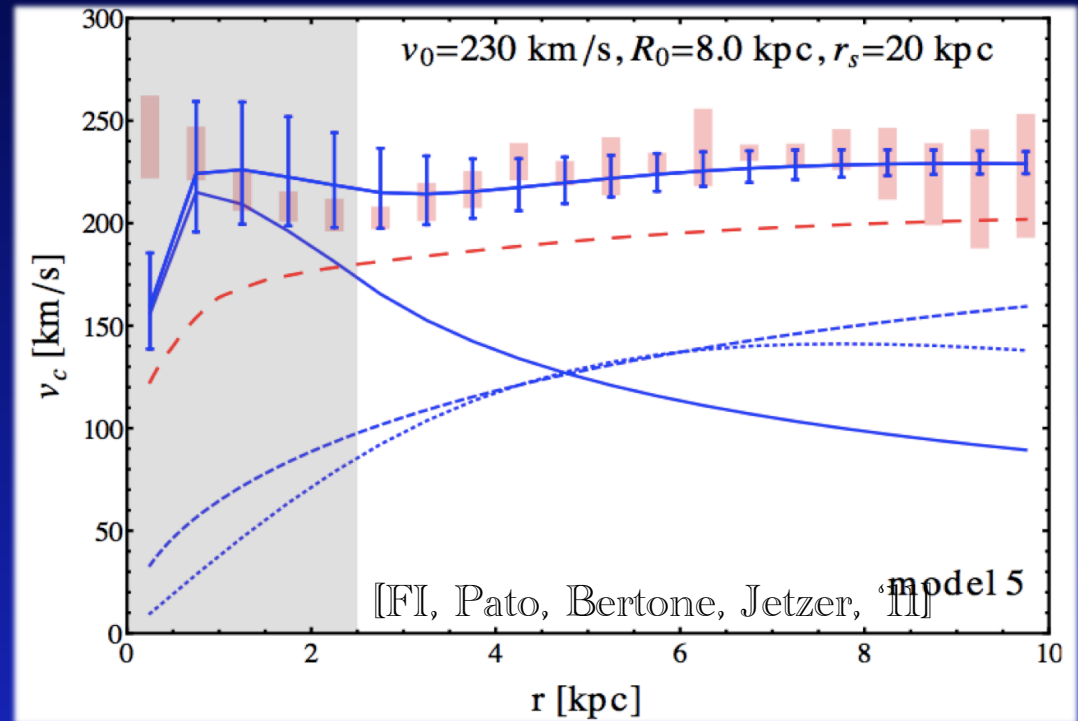
Adding Dark Matter: fitting halo shapes



[M. Benito-Castaño, w.i.p.]

Global determination of $\rho(r)$

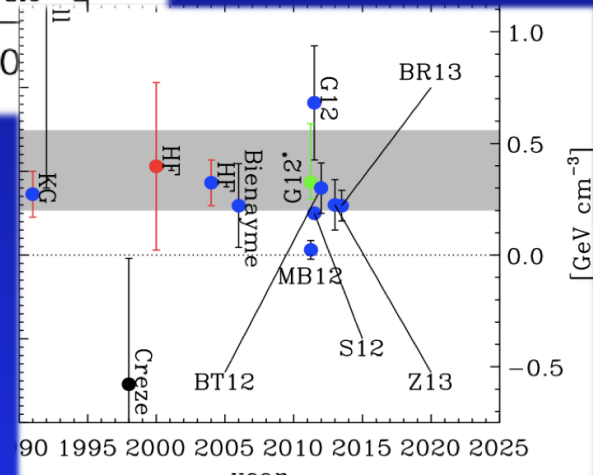
Fitting a DM profile to the
Rotation Curve, on top of
other components



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

Underlying assumption on DM presence and distribution shape

a historical perspective



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

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

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

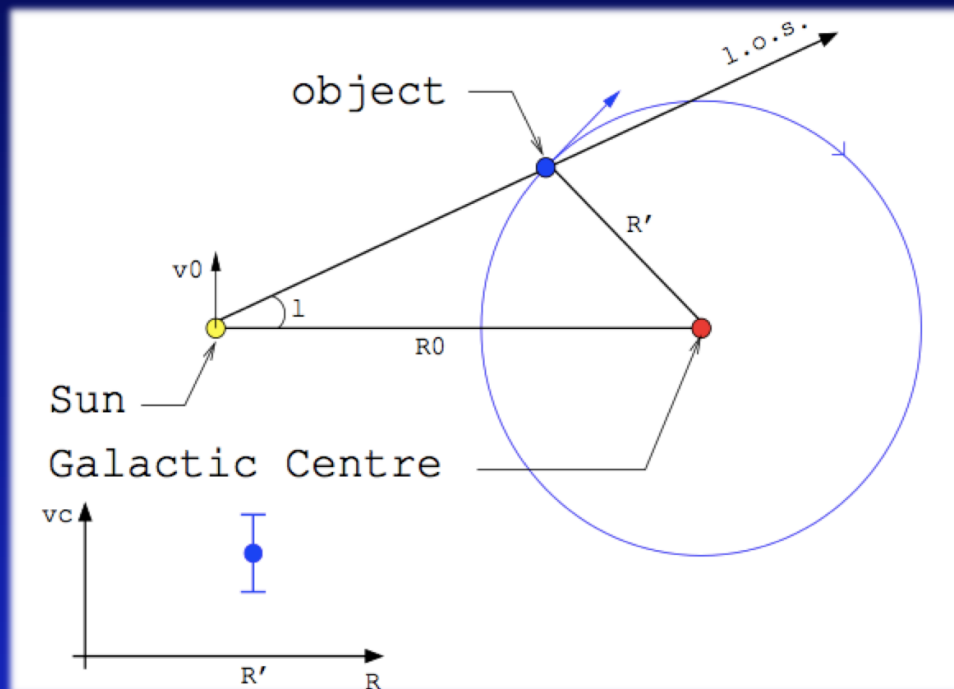
$$v_c^2 = r \frac{d\phi_{\text{tot}}}{dr}$$

Rotation curve as a tracer of the total potential

...and if not...

The Milky Way: observed rotation curve

I. principles

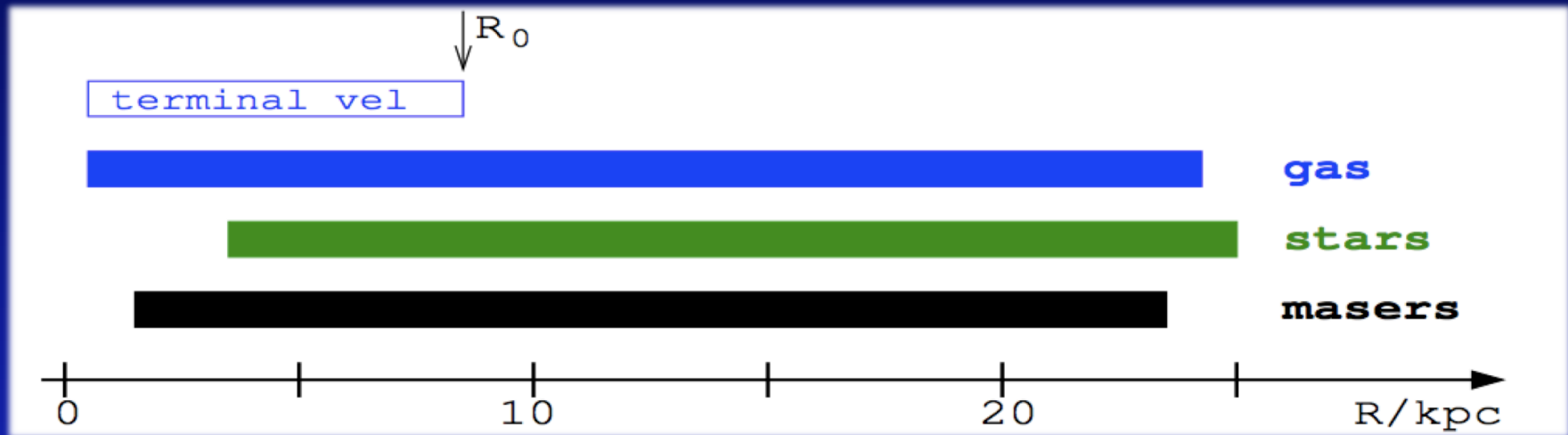


$$v_{\text{LSR}}^{\text{l.o.s.}} = \left(\frac{v_c(R')}{R'/R_0} - v_0 \right) \cos b \sin \ell$$

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

The Milky Way: observed rotation curve

II. tracers



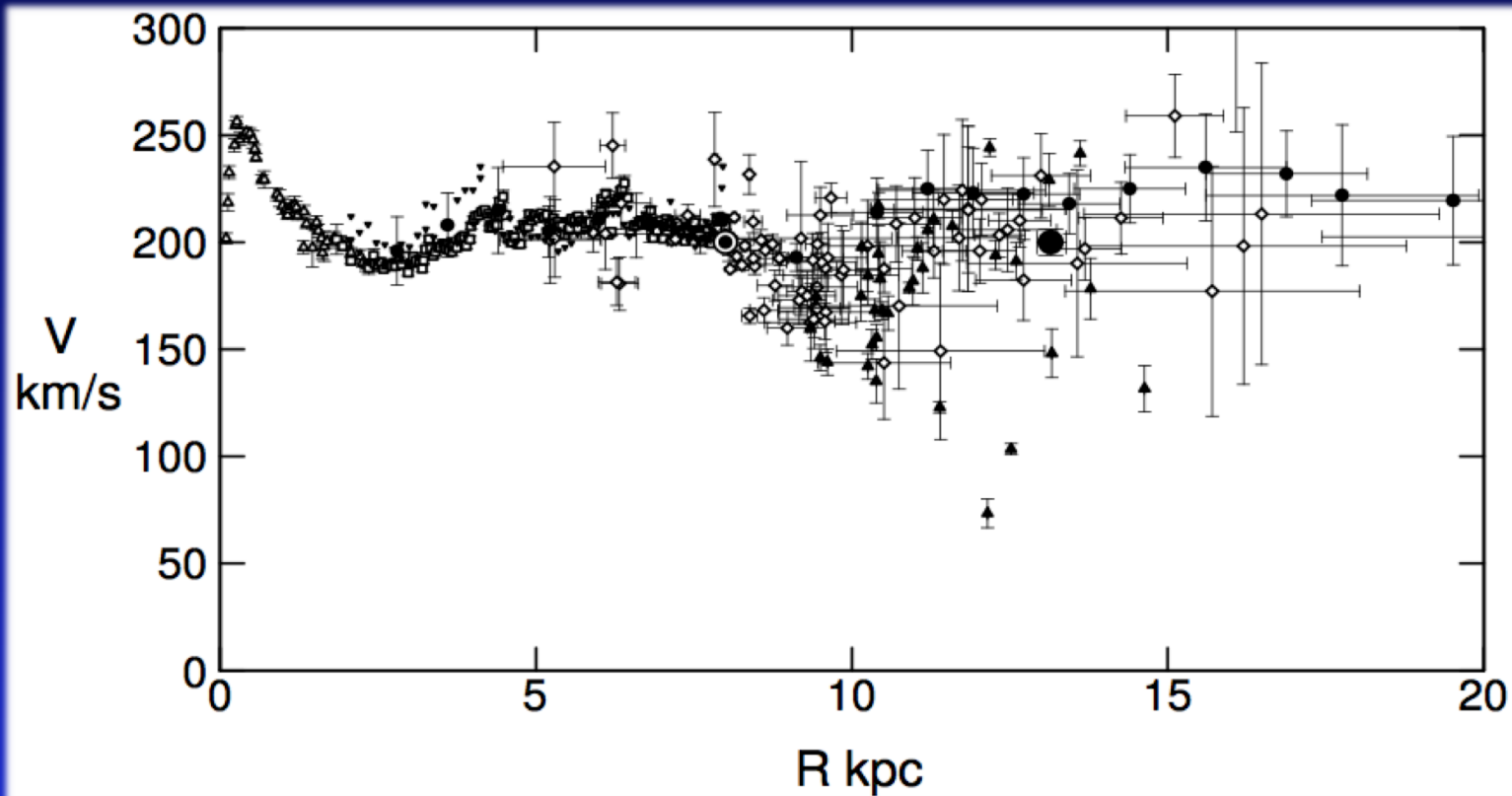
Doppler shift

1. gas (21cm, $\text{H}\alpha$, 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
stars	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
	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
masers	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			
	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]

enter input parameters

galactic parameters

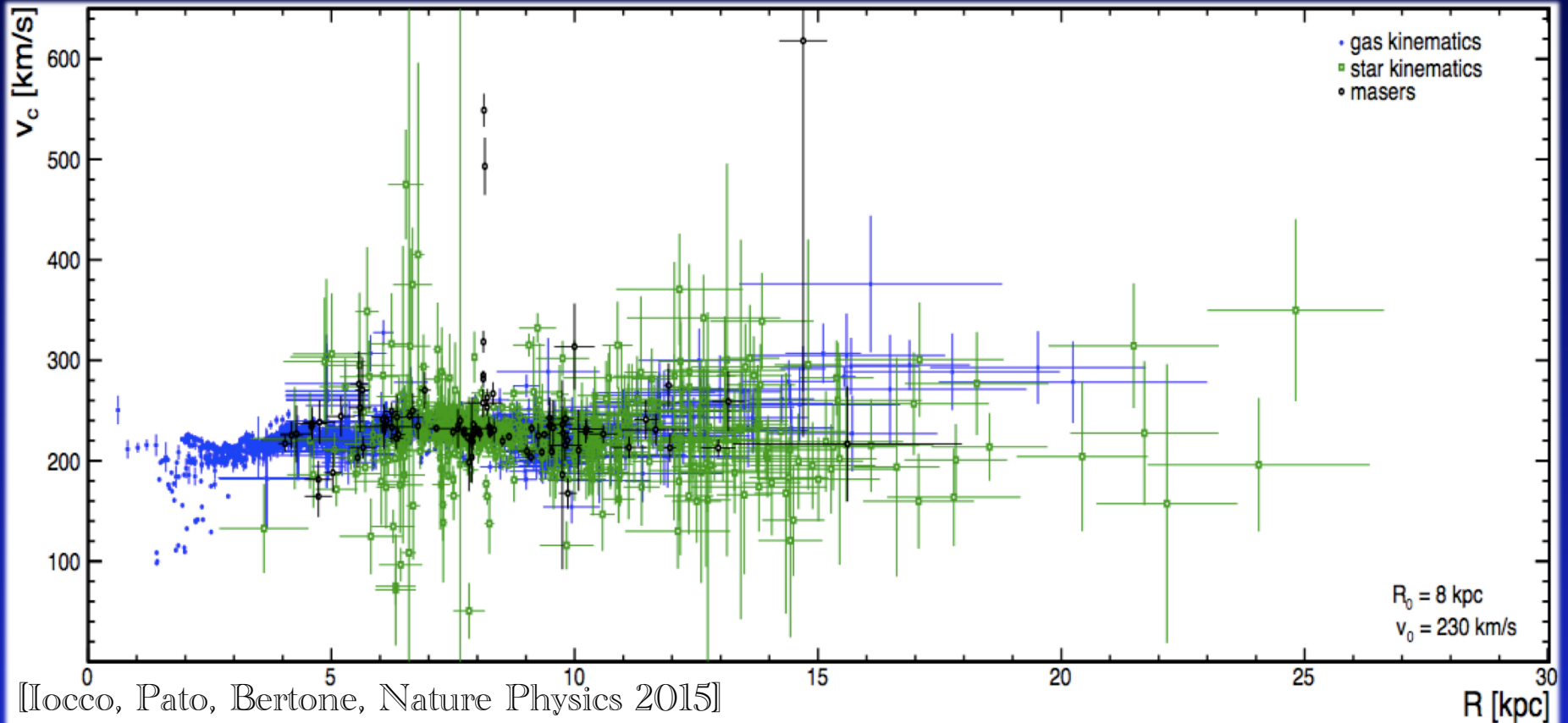
R_0 [kpc]= 8.0 V_0 [km/s]= 230.0 syst [km/s]= 0.0

U_{sun} [km/s]= 11.10 V_{sun} [km/s]= 12.24 W_{sun} [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+ 94
- ☒ carbon stars
 - ☒ Demers & Battinelli 07
 - ☒ Battinelli+ 12
- ☒ masers
 - ☒ Reid+ 14
 - ☒ Honma+ 12
 - ☒ Stepanishchev & Bobylev 11
 - ☒ Xu+ 13
 - ☒ Bobylev & Bajkova 13
- ☐ use proper motions when available
 - ☒ l ☐ b ☐ l and b

The Milky Way Rotation Curve as observed



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

The Milky Way: expected rotation curve

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

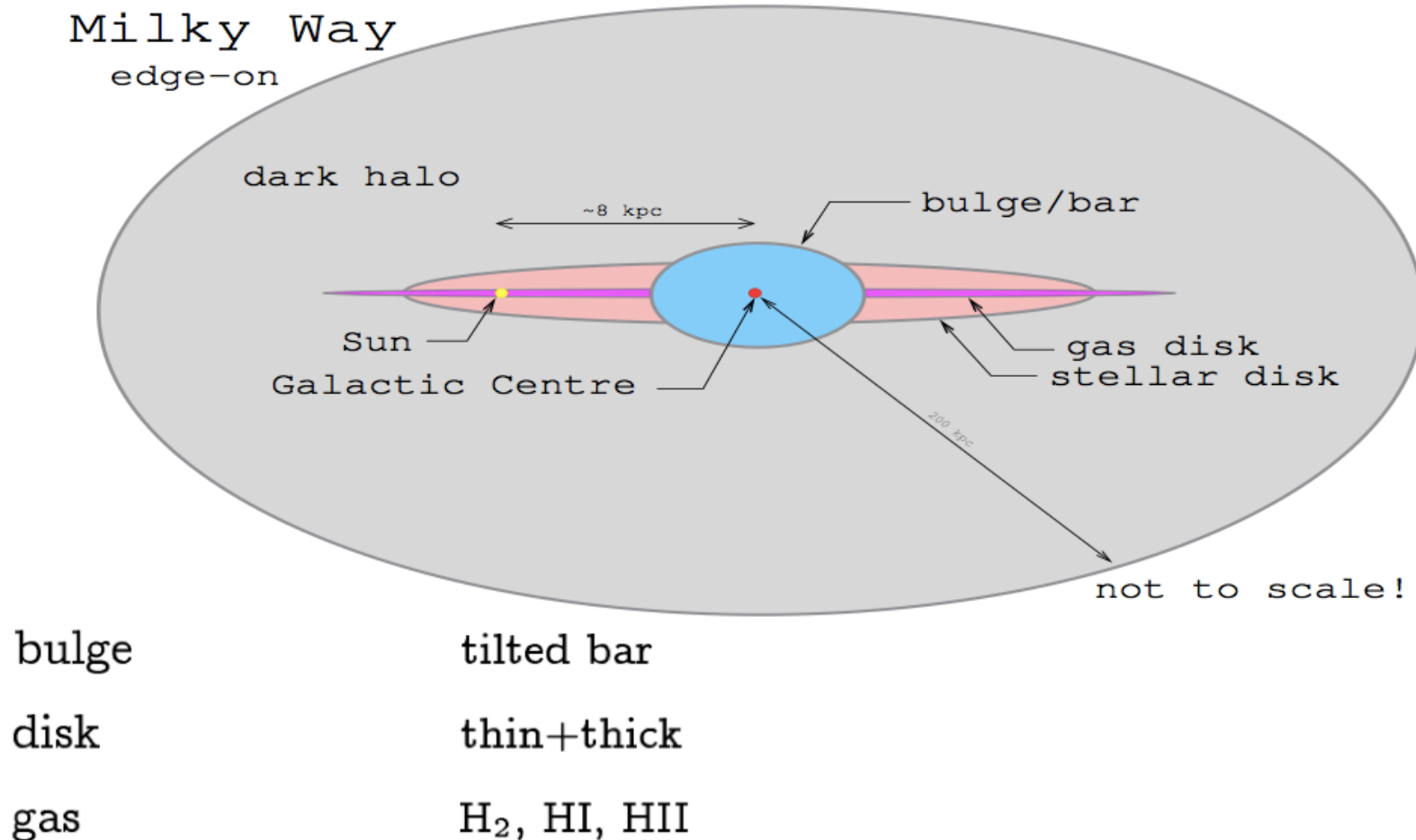
$$\rho_i(x, y, z) \rightarrow \phi_i(r, \theta, \varphi) \rightarrow v_{c,i}^2(R) = \sum_{\varphi} R \frac{d\phi_i}{dr}(R, \pi/2, \varphi)$$

Constructing the curve expected from observed mass profiles

The Milky Way:

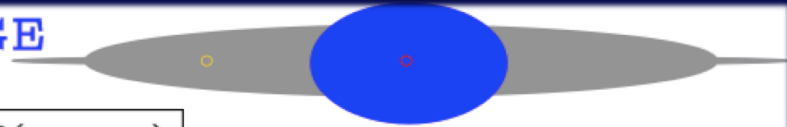
expected rotation curve

1. the baryonic components



The visible Milky Way: observations of morphology

2. BARYONS: STELLAR BULGE



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

morphology $f(x, y, z)$

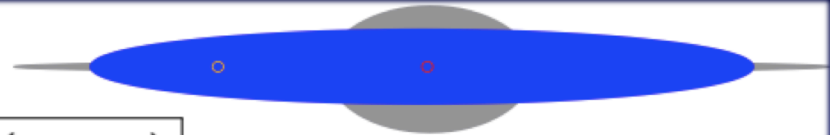
Stanek+ '97 (E2)	e^{-r}	0.9:0.4:0.3	24°	optical
Stanek+ '97 (G2)	$e^{-r_s^2/2}$	1.2:0.6:0.4	25°	optical
Zhao '96	$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	1.5:0.6:0.4	20°	infrared
Bissantz & Gerhard '02	$e^{-r_s^2}/(1+r)^{1.8}$	2.8:0.9:1.1	20°	infrared
Lopez-Corredoira+ '07	Ferrer potential	7.8:1.2:0.2	43°	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: $\langle \tau \rangle = 2.17_{-0.38}^{+0.47} \times 10^{-6}$, $(\ell, b) = (1.50^\circ, -2.68^\circ)$
(MACHO '05)

The visible Milky Way: observations of morphology

2. BARYONS: STELLAR DISK



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

morphology $f(x, y, z)$

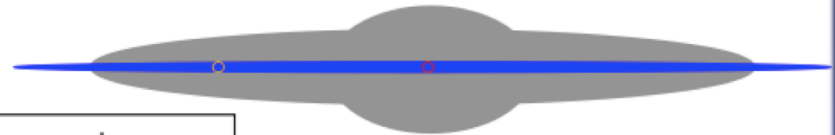
Han & Gould '03	$e^{-R} \text{sech}^2(z)$	2.8:0.27	thin	optical
	$e^{-R- z }$	2.8:0.44	thick	
Calchi-Novati & Mancini '11	$e^{-R- z }$	2.8:0.25	thin	optical
	$e^{-R- z }$	4.1:0.75	thick	
deJong+ '10	$e^{-R- z }$	2.8:0.25	thin	optical
	$e^{-R- z }$	4.1:0.75	thick	
	$(R^2 + z^2)^{-2.75/2}$	1.0:0.88	halo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

The visible Milky Way: observations of morphology

2. BARYONS: GAS



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

morphology

Ferrière '12	$r < 0.01$ kpc	$M_{\text{gas}} \sim 7 \times 10^5 M_{\odot}$	CO, 21cm, H α , ...	
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., H α
Moskalenko+ '02	$r = 3 - 20$ kpc	molecular ring	H ₂	CO
			H I	21cm
			H II	disp. meas.

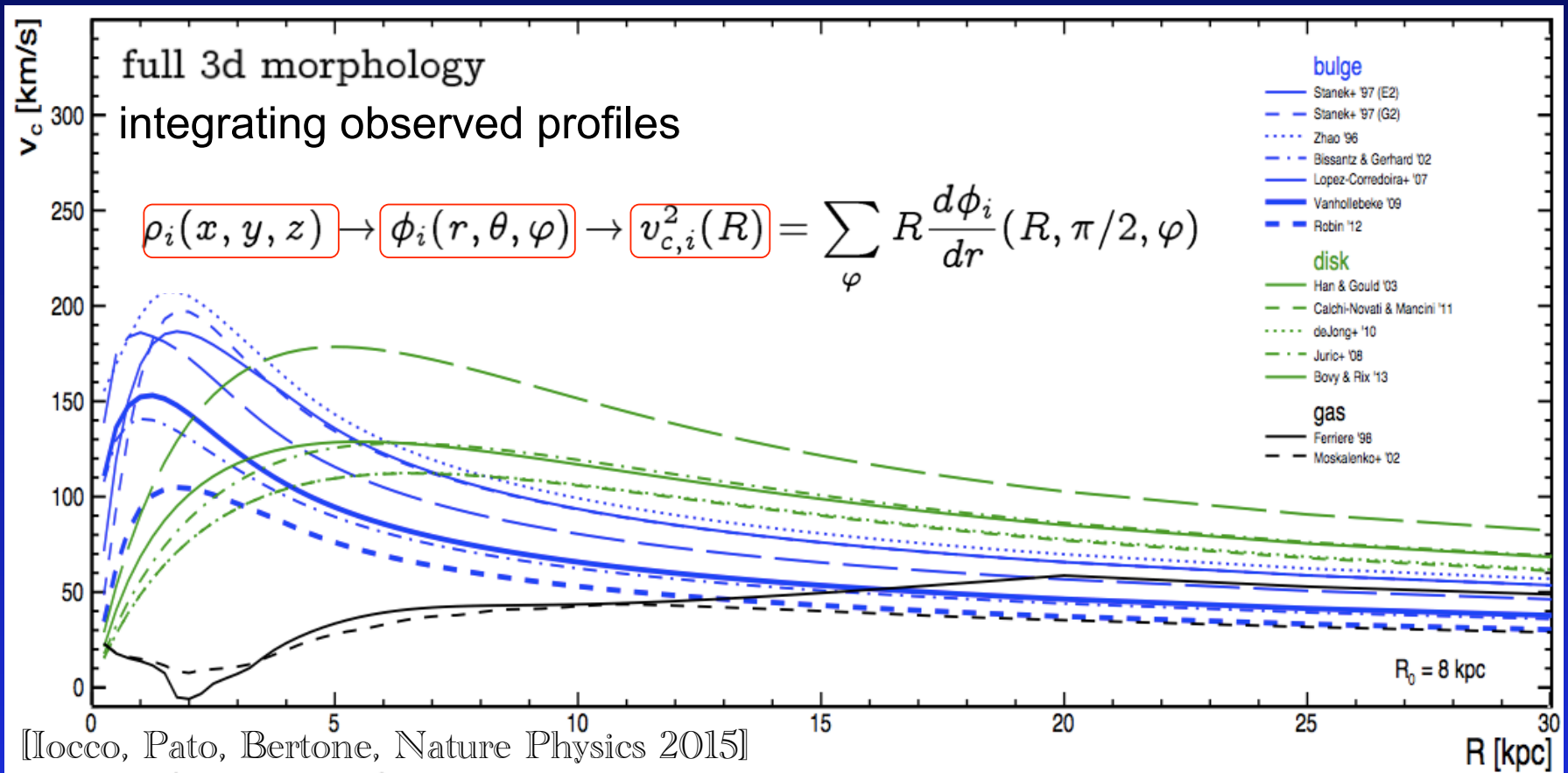
uncertainties

CO-to-H₂ factor: $X_{\text{CO}} = 0.25 - 1.0 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}$ for $r < 2$ kpc
 $X_{\text{CO}} = 0.50 - 3.0 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}$ for $r > 2$ kpc

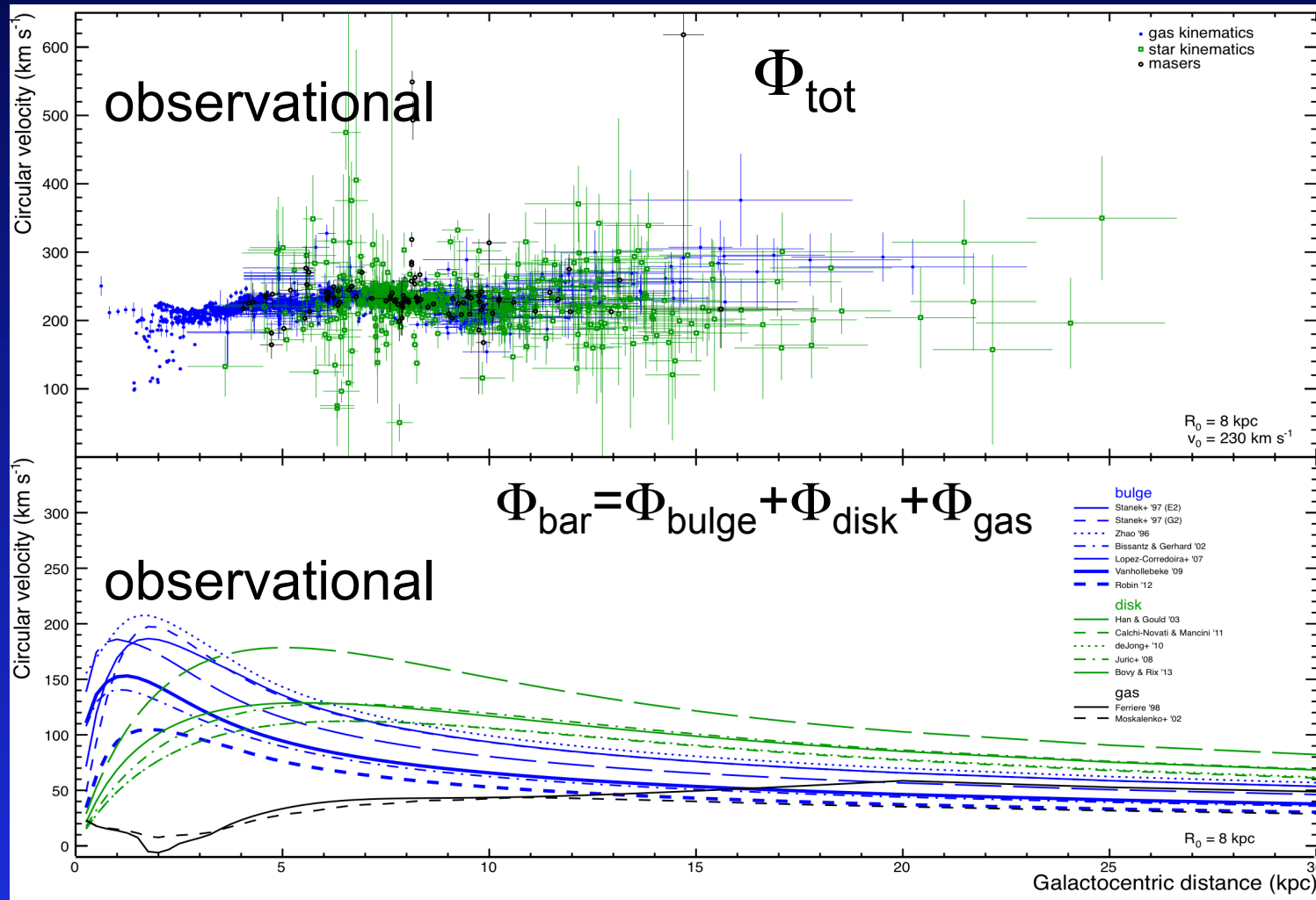
[Ferrière+ '07, Ackermann '12]

The Milky Way: expected rotation curve

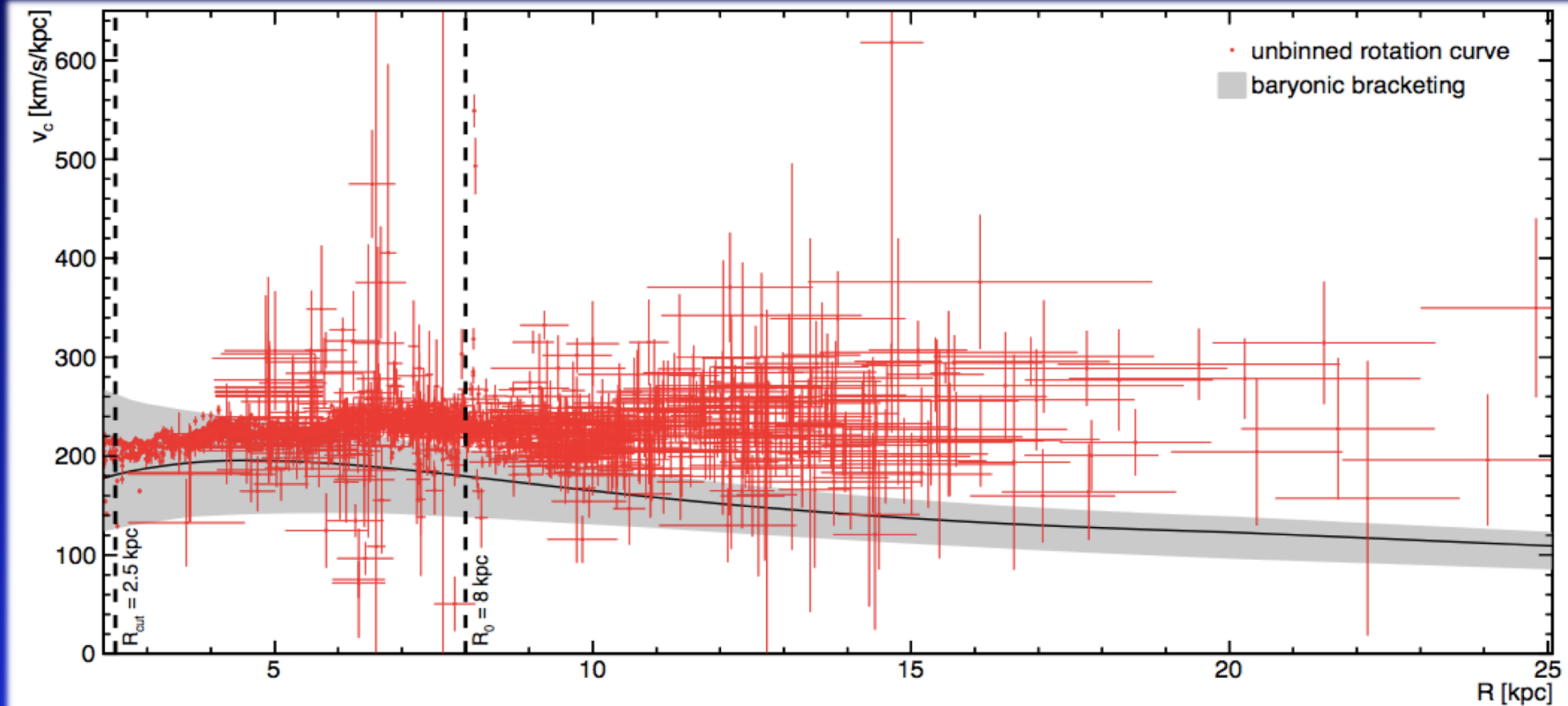
$$\phi_i(r, \theta, \varphi) = -4\pi G \sum_{l,m} \frac{Y_{lm}(\theta, \varphi)}{2l+1} \left[\frac{1}{r^{l+1}} \int_0^r \rho_{i,lm}(a) a^{l+2} da + r^l \int_r^\infty \rho_{i,lm}(a) a^{1-l} da \right]$$



The Milky Way: testing expectations

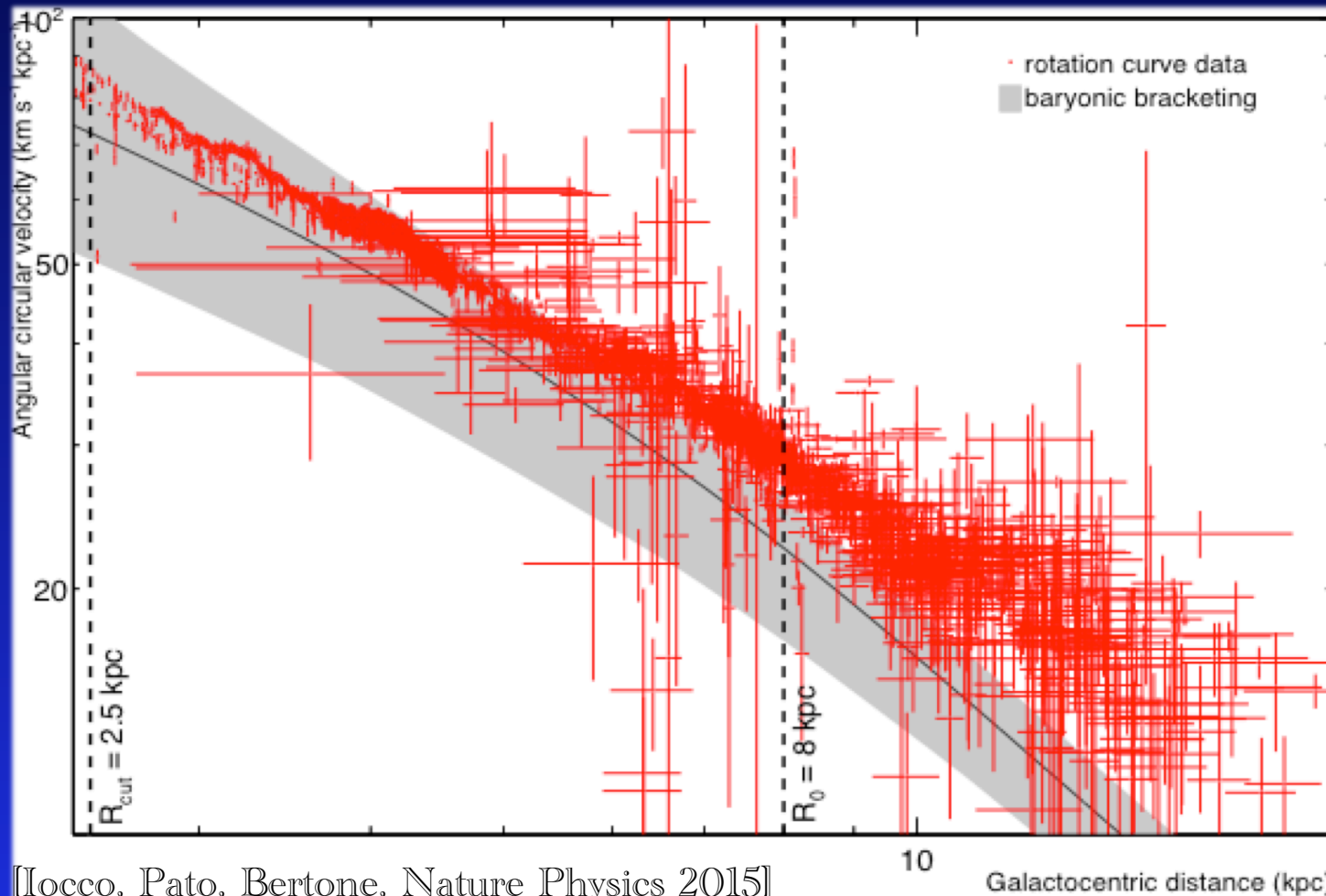


The Milky Way: testing expectations (with no additional assumptions)



[Iocco, Pato, Bertone, 2015]

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



$$\omega = V_c / R_c$$

Uncorrelated
uncertainties

$$R_0 = 8 \text{ kpc}$$
$$V_0 = 230 \text{ km/s}$$

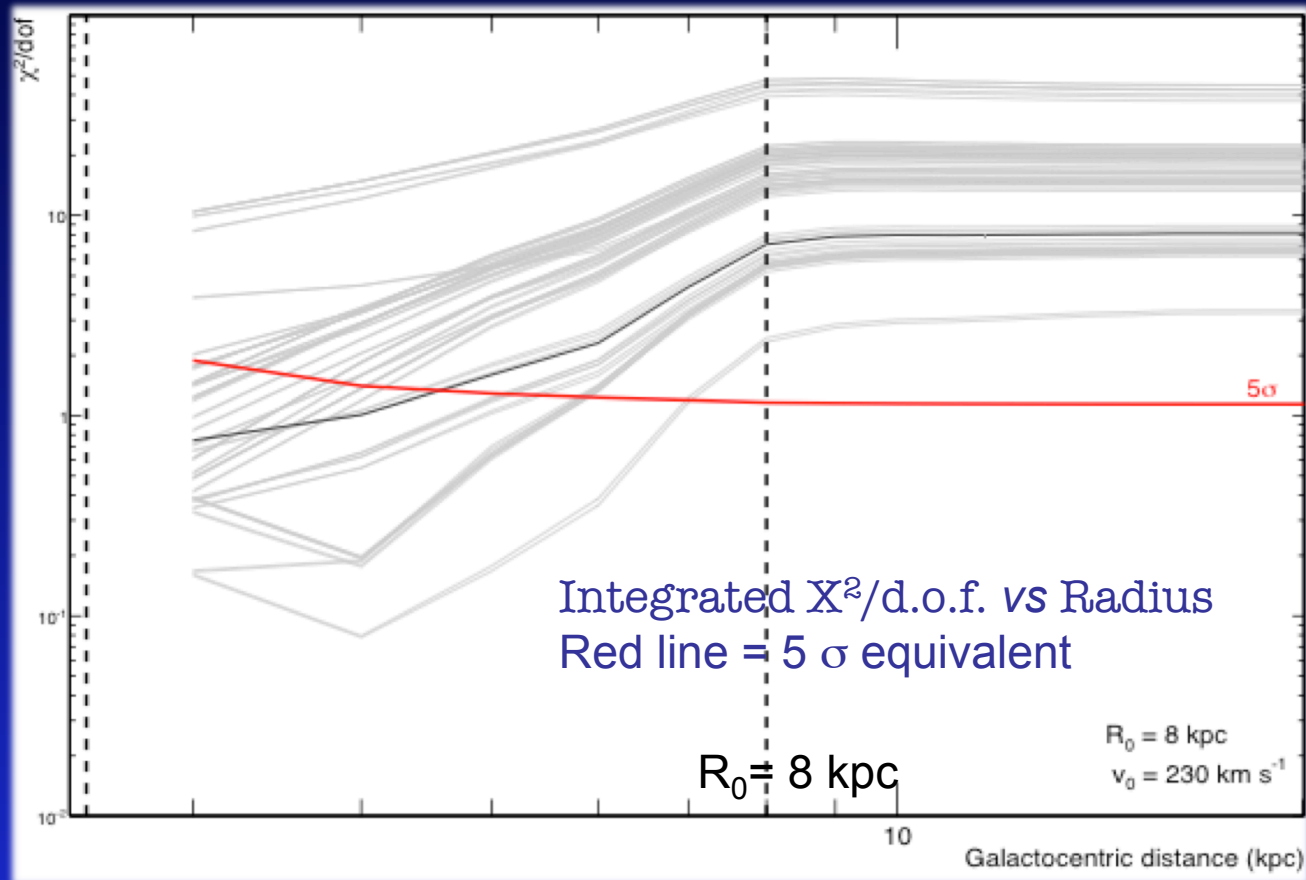
[Iocco, Pato, Bertone, Nature Physics 2015]

The Milky Way:
testing expectations
(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 5σ , 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:

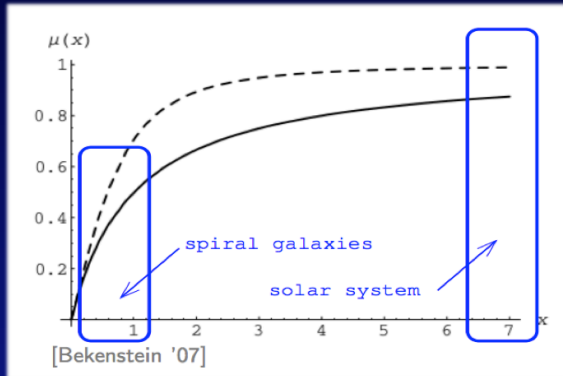
Evidence for Dark Matter ??

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?



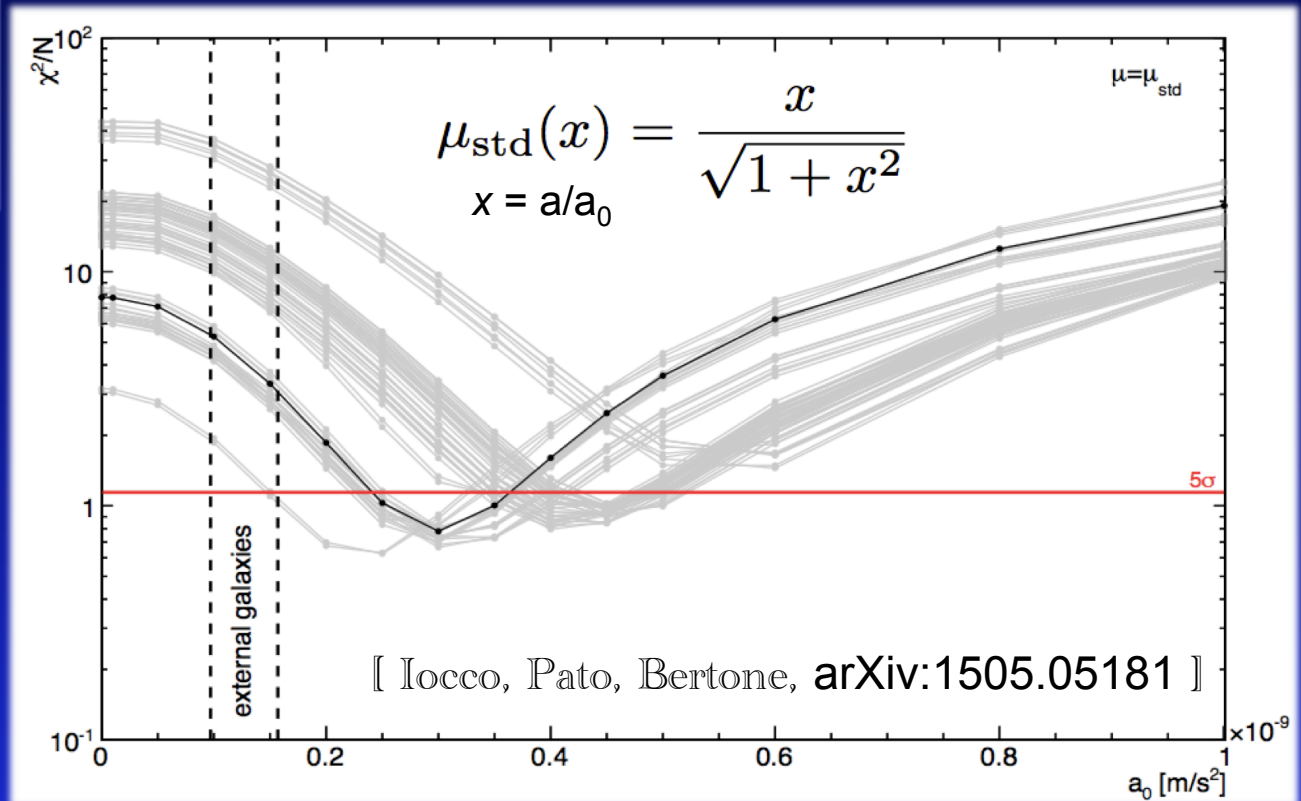
$$\mu\left(\frac{a}{a_0}\right) a = a_N$$

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

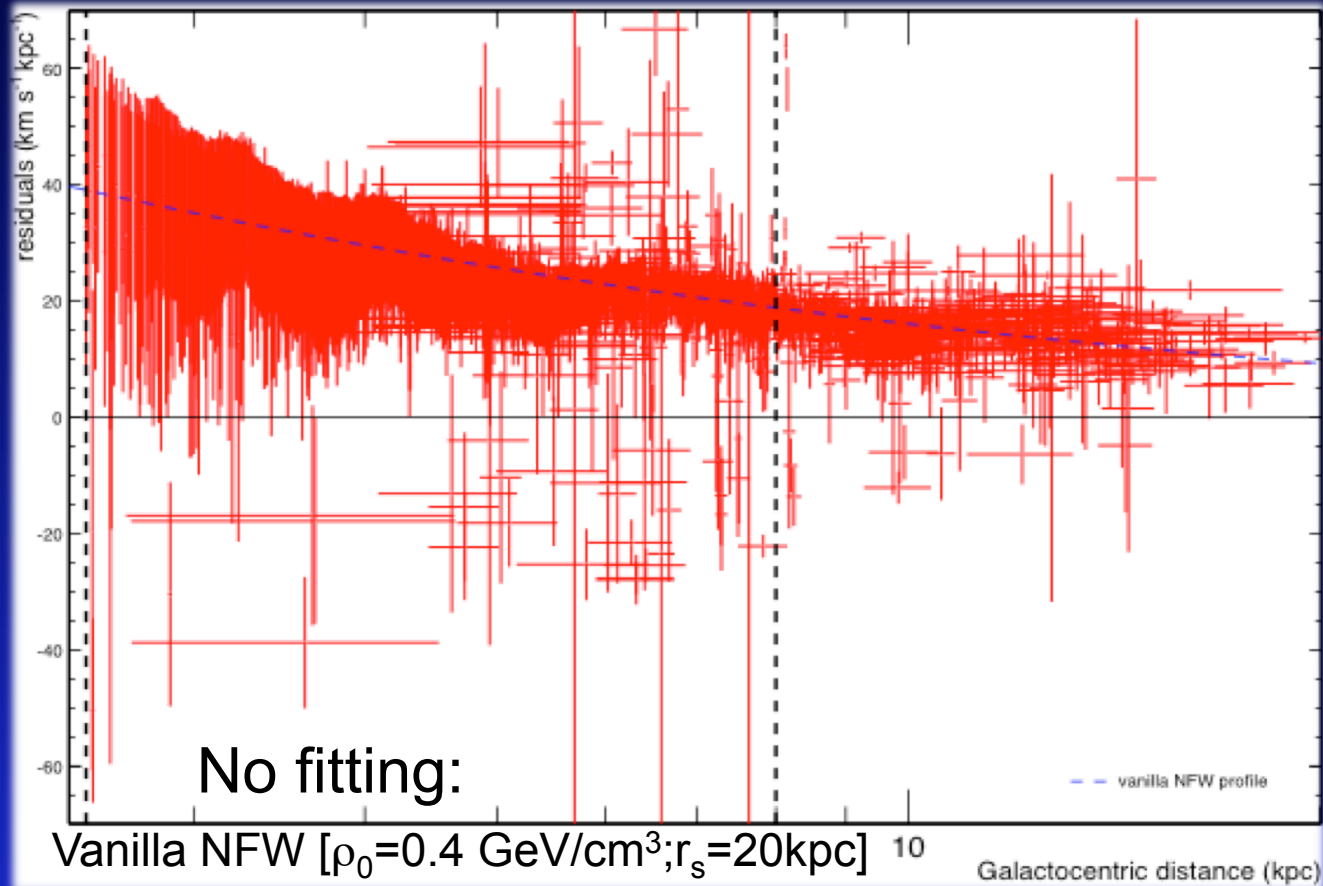
$$\mu(a/a_0) \approx a/a_0, \quad a \ll a_0$$

recovering Newton
in “strong” gravity regime

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

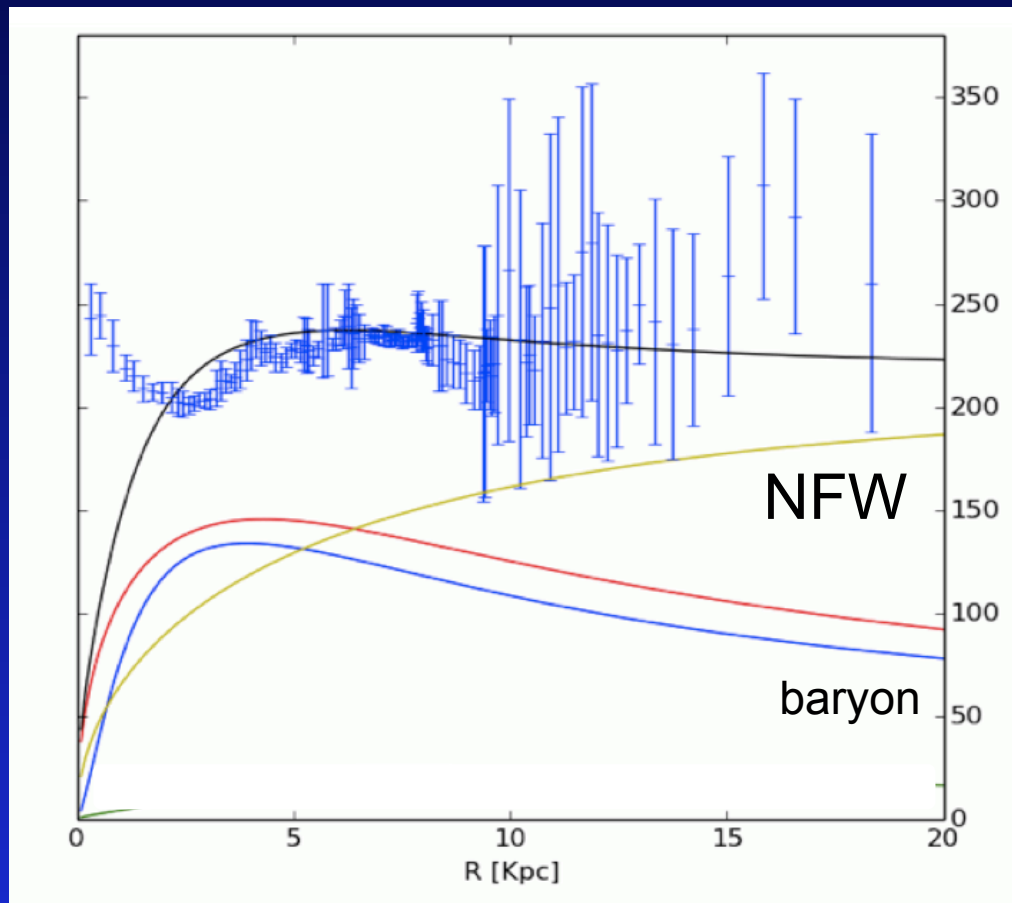


Motivating dark haloes



$$v_{\text{Residual}} = (v_{\text{tot}}^2 - v_{\text{bar}}^2)^{1/2}$$

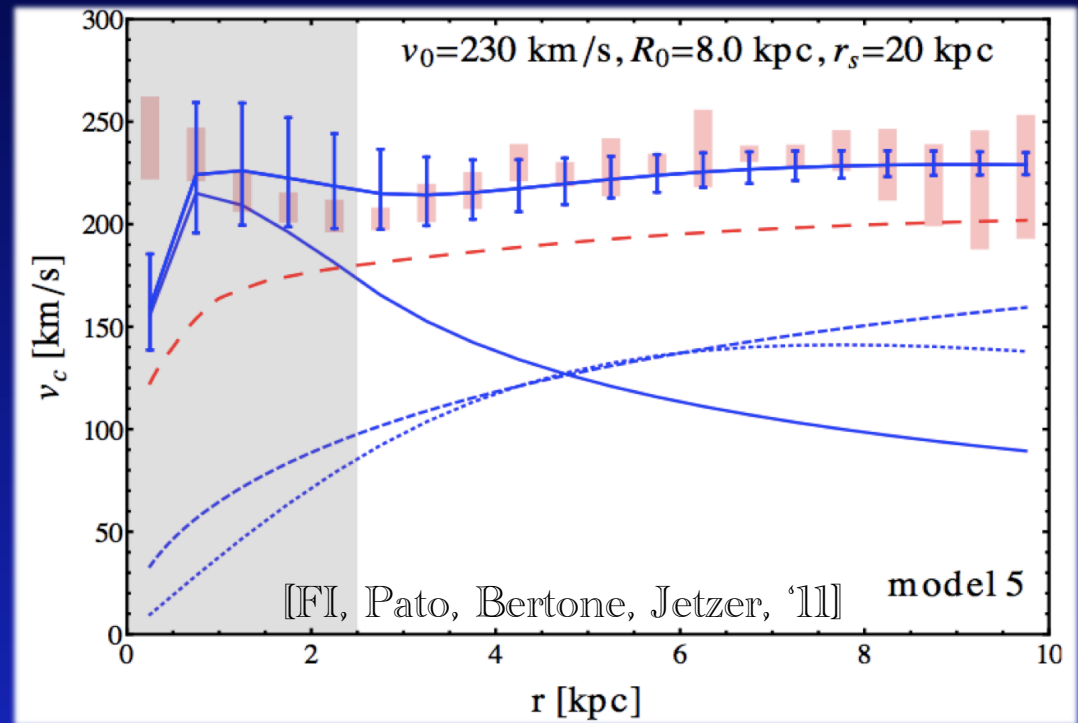
Adding Dark Matter: fitting halo shapes



[M. Benito-Castaño, w.i.p.]

Global determination of halo parameters

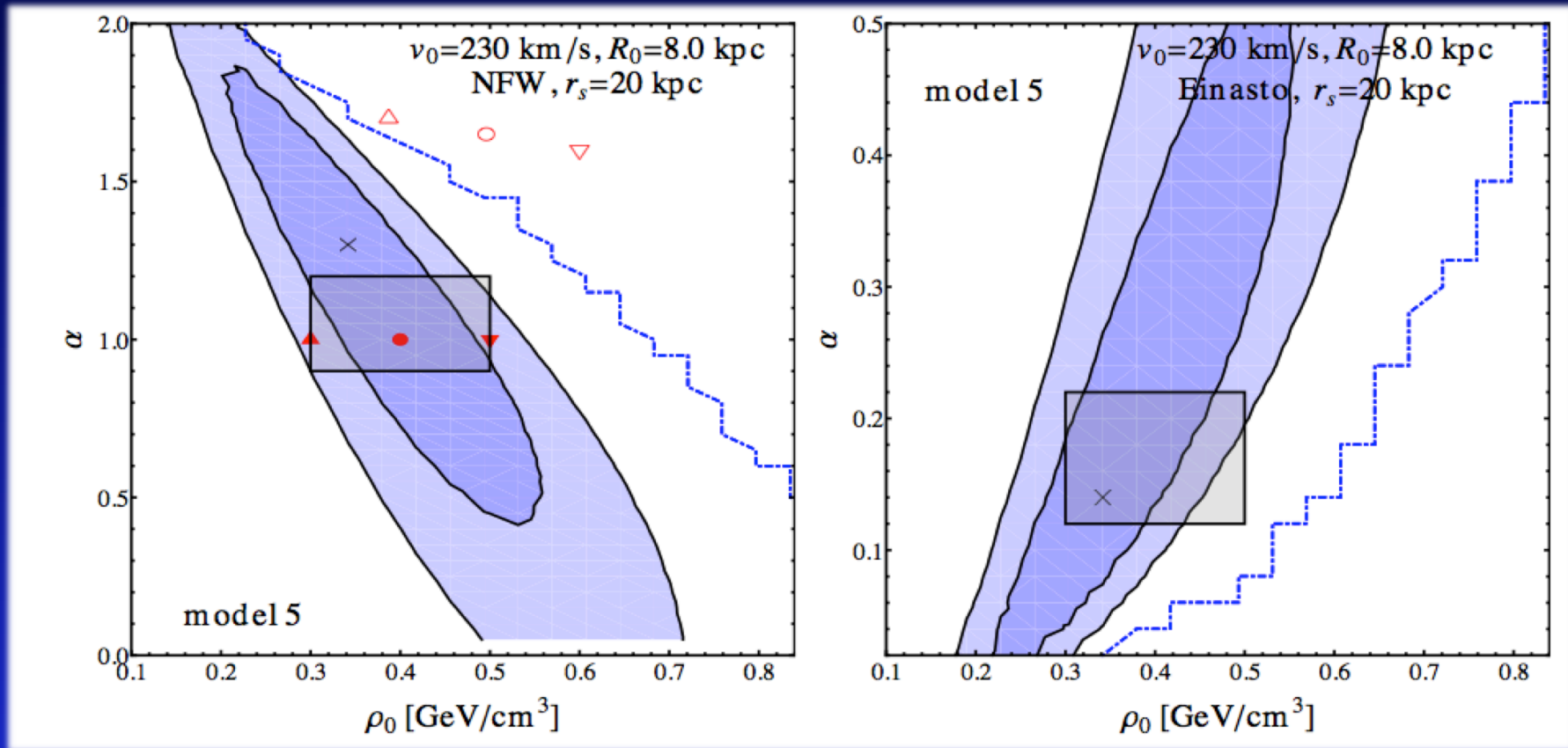
Fitting a DM profile to the
Rotation Curve, on top of
other components



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

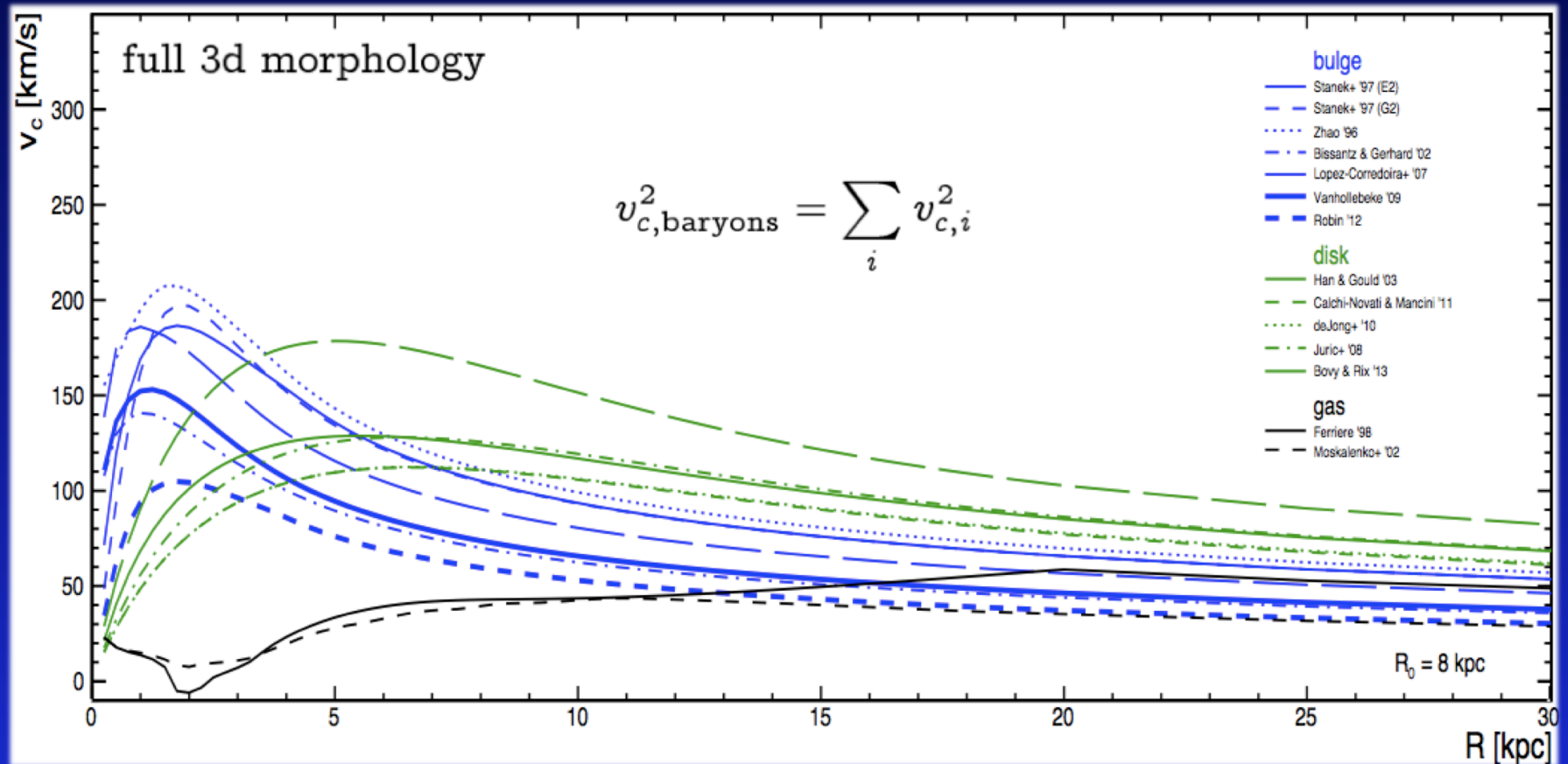
Underlying assumption on DM presence and distribution shape

The Milky Way: fitting Dark Halo parameters



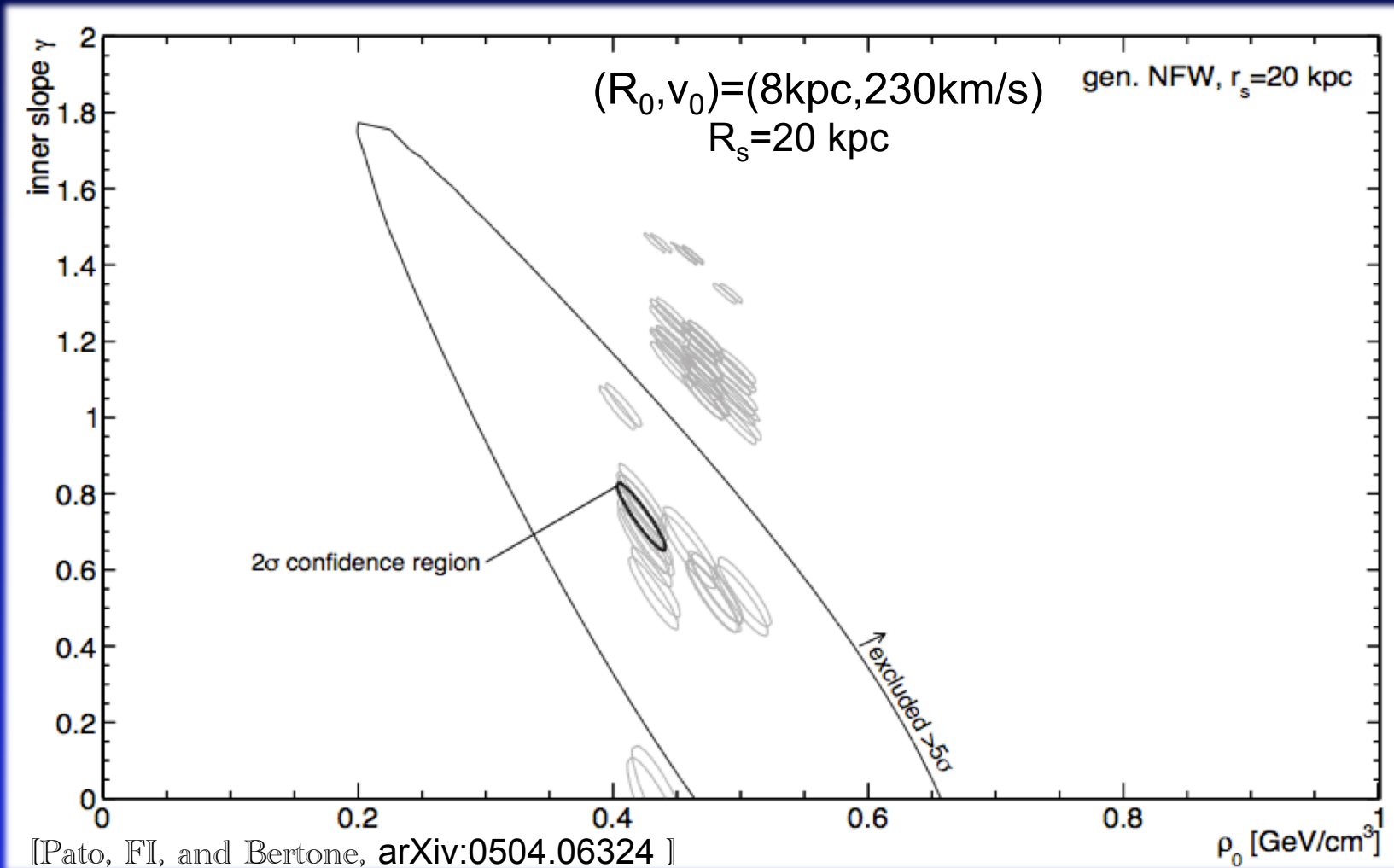
Excellent agreement with simulation parameter space,
and determination of ρ_0 [FI, Pato et al., 2011]

The Milky Way: baryonic morphology

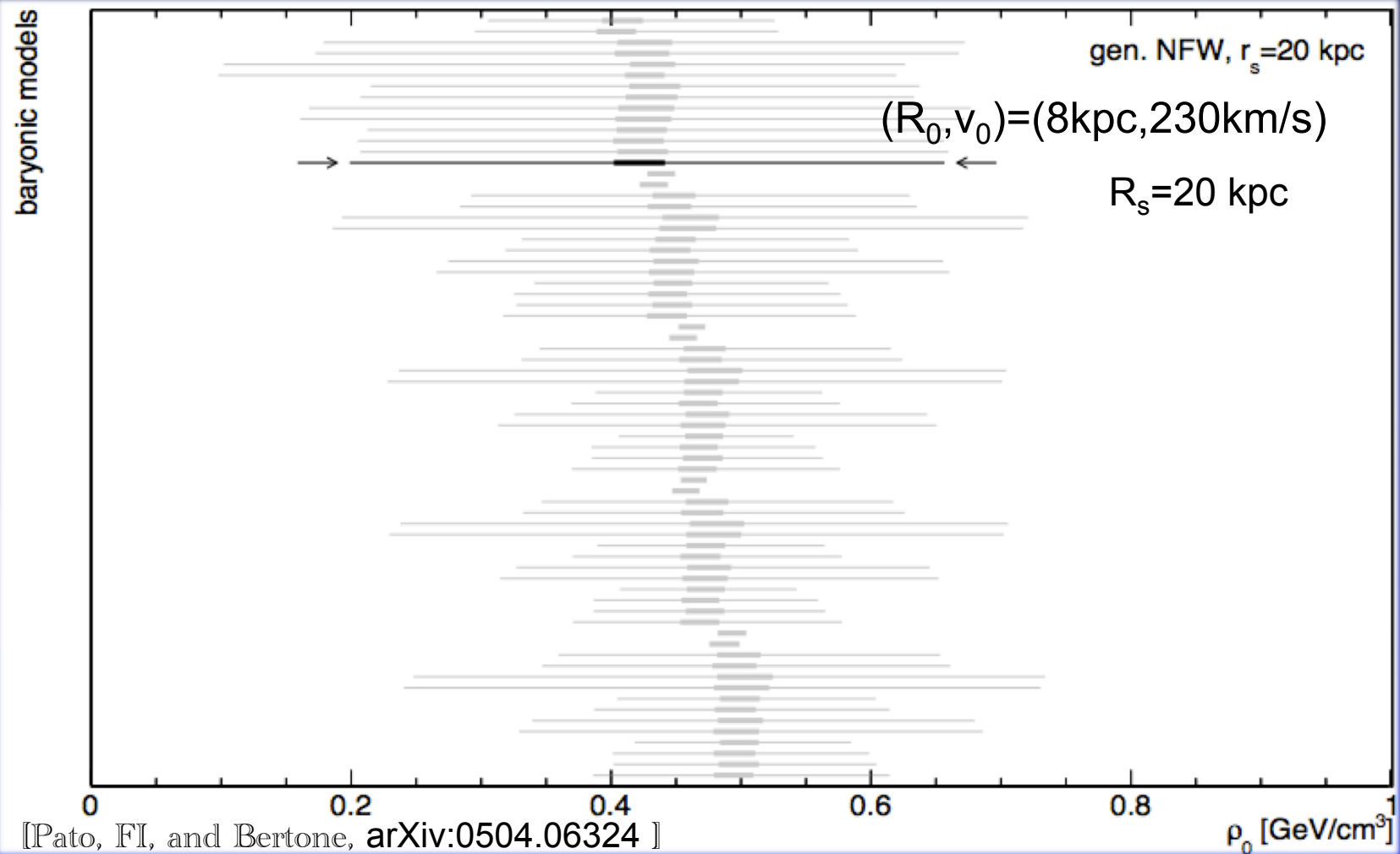


scanning halo parameter space for each baryonic model

The Milky Way: the importance of baryon modelling



The Milky Way: the importance of baryon modelling



The Milky Way's spine: an agnostic approach

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

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

$$\omega_{\text{dm}}^2 = \omega_c^2 - \omega_b^2$$

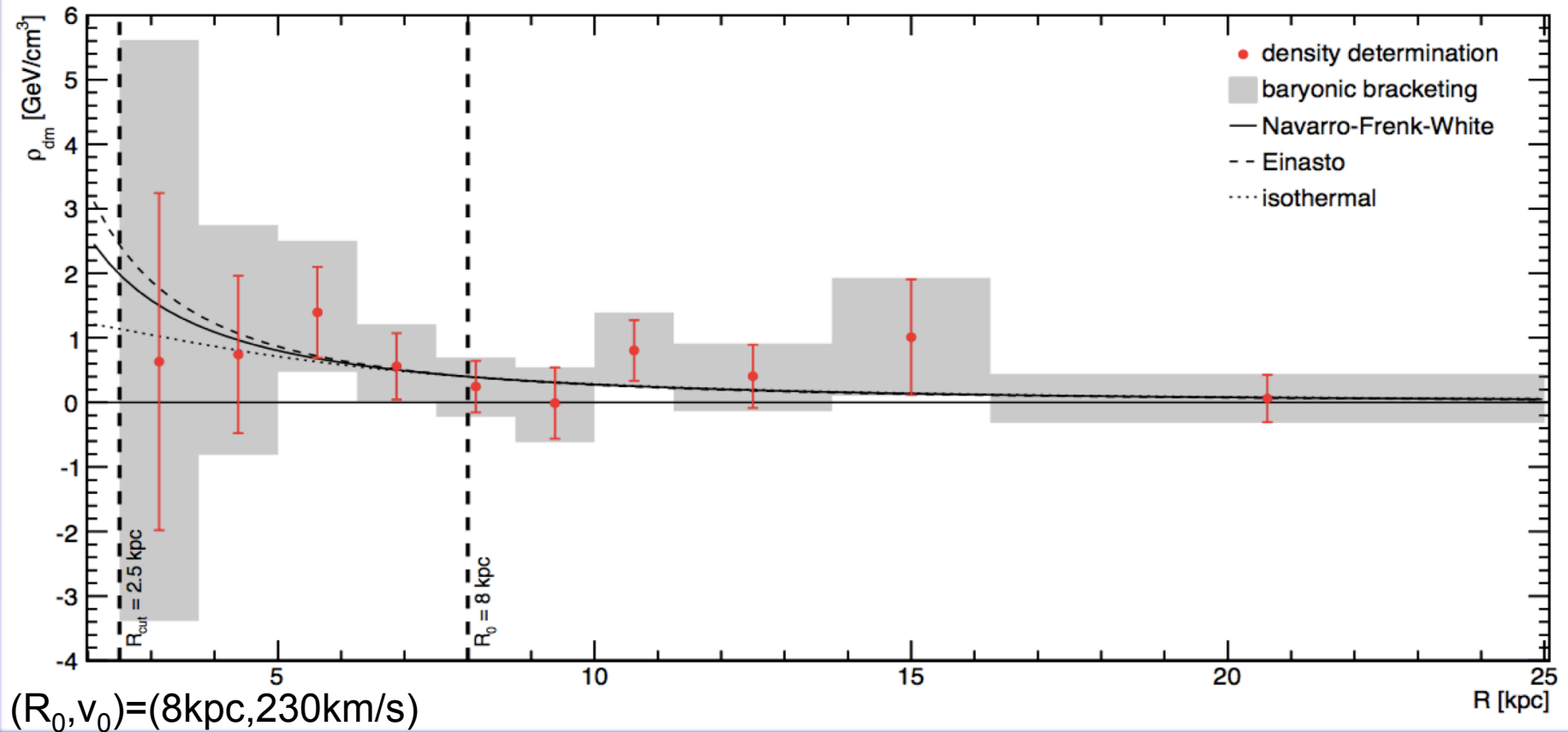
$$d\phi_{\text{tot}}/dR = \omega_c^2 R$$

$$d\phi_b/dR = \omega_b^2 R$$

Assumption of spherical symmetry

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

The Milky Way's spine: an unbiased reconstruction



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
 - 5σ 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 R_s dependence, asphericity of the halo, baryonic contraction effects, etc.)
 - Future looks Dark
(and that's good)