Technische Universität München

Oskar Klein centre

DYNAMICAL CONSTRAINTS ON THE DARK MATTER DISTRIBUTION IN THE MILKY WAY

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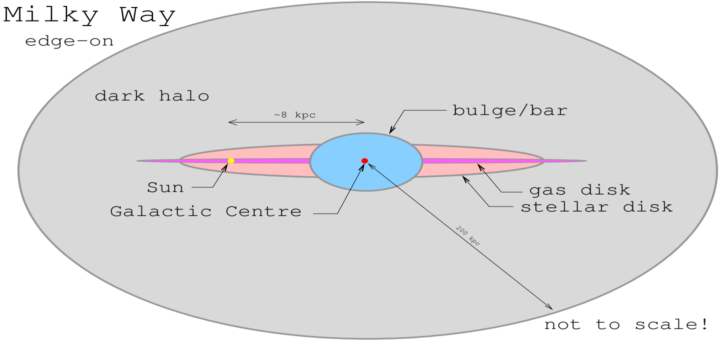
Fabio Iocco

in collaboration with Gianfranco Bertone

APS 4th meeting, Amsterdam, 29 Sep 2014

GALACTIC MODELLING



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

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

how can we constrain the parameters of a galactic mass model?

GALACTIC MODELLING

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dynamics traces <u>total</u> potential

rotation curve	$R \sim 0.1 - 30$ kpc	
local stars	$R \sim R_0 \sim 8$ kpc	(Oort's limit)
tracers	$R \sim 20 - 60$ kpc	(radial Jeans)
satellites	$R \sim 100 - 300$ kpc	(virial)

"photometry" traces <u>individual baryonic</u> components

star counts	bulge, disk
luminosity	bulge, disk
gravitational microlensing	bulge
emission lines	gas

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2.

[Iocco, MP, Bertone & Jetzer, JCAP11(2011)029]
[Iocco, MP, Bertone, submitted]

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$$v_c^2 = r \frac{d\phi_{\rm tot}}{dr} \overset{\rm sph.}{=} \frac{G\,M(<r)}{r}$$

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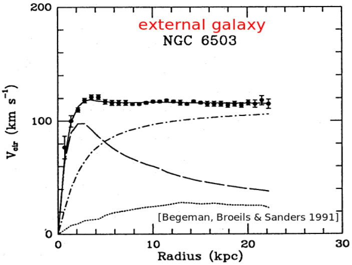

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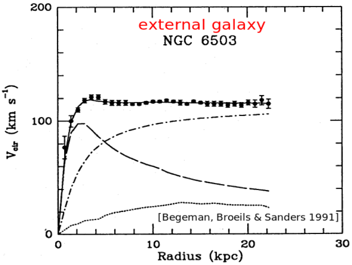

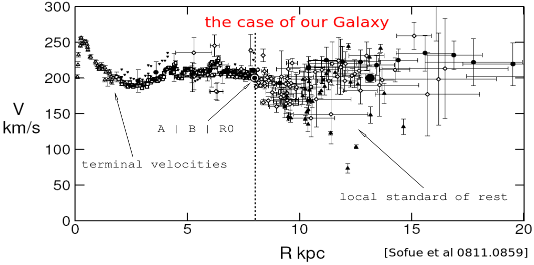

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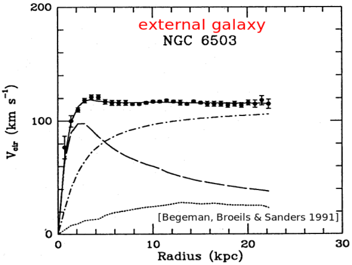

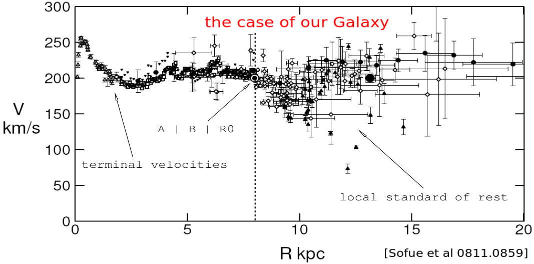

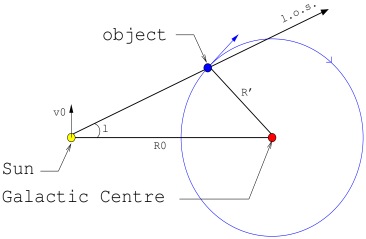

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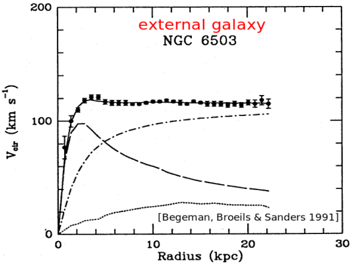

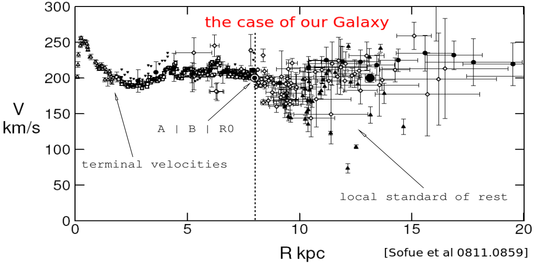

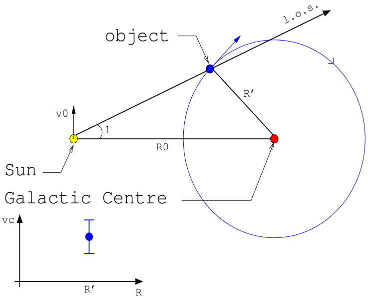

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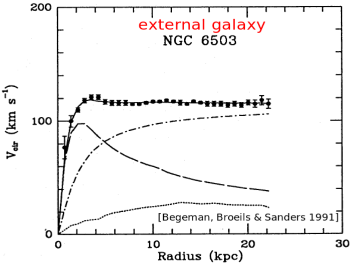

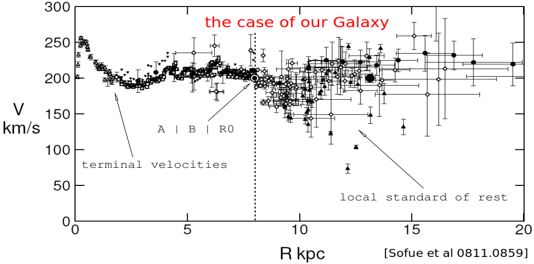

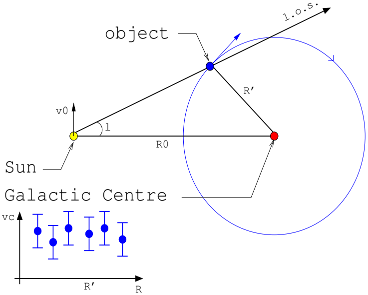

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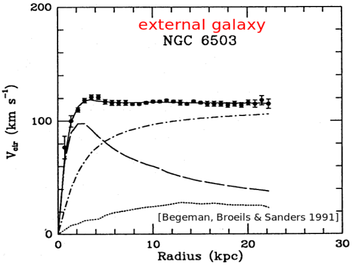

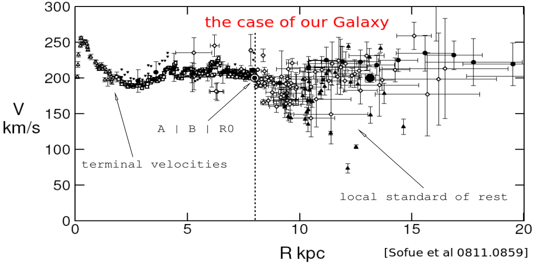

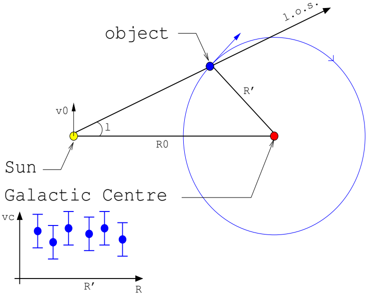

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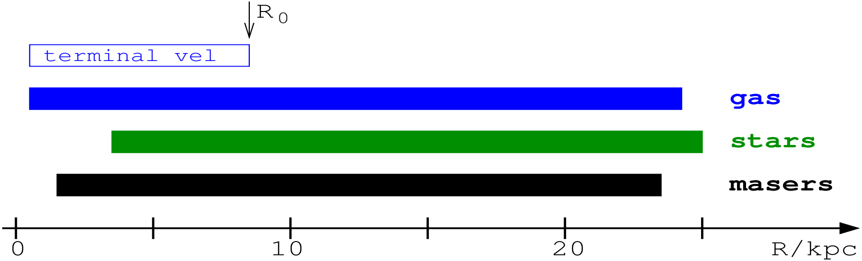

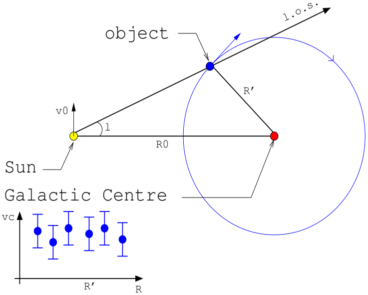

$$v_{LSR}^{l.o.s.} = \left(\frac{v_c(R')}{R'/R_0} - v_0\right)\cos b \sin \ell$$

Doppler shift

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

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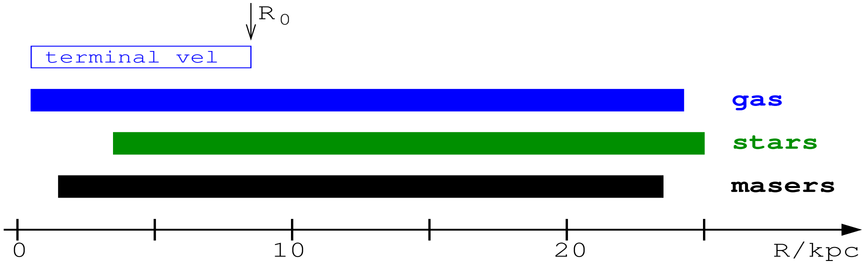

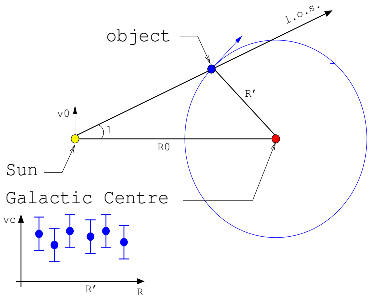

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distance

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

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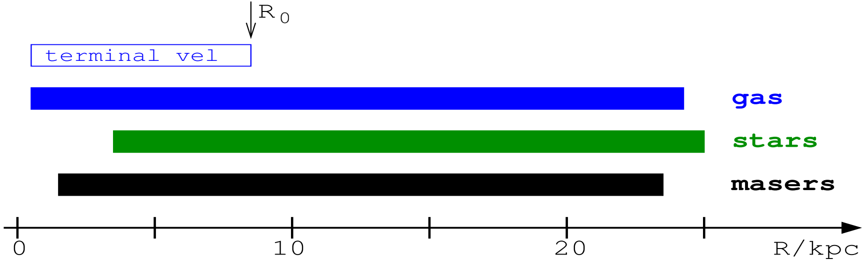
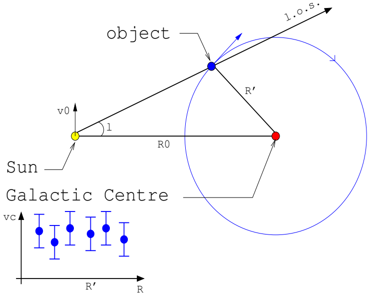
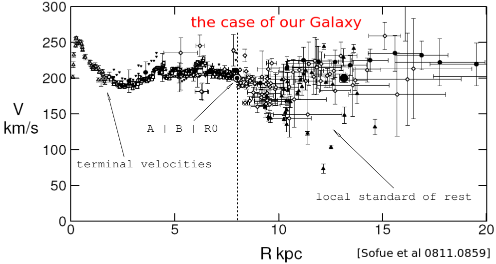




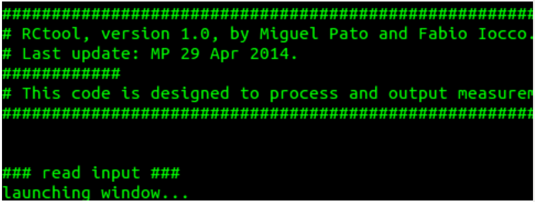


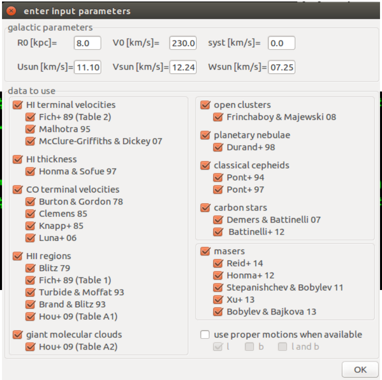
1. ROTATION CURVE: A NEW COMPILATION

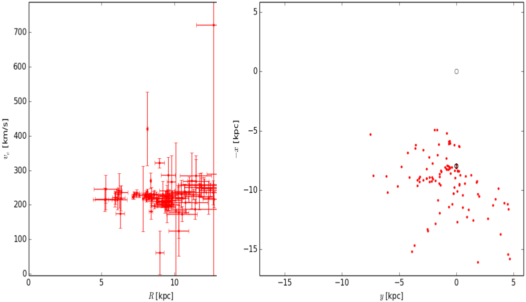
	Object type	R [kpc]	quadrants	# objects
gas	HI terminal velocities			
	Fich+ '89	2.1 – 8.0	1,4	149
	Malhotra '95	2.1 – 7.5	1,4	110
	McClure-Griffiths & Dickey '07	2.8 – 7.6	4	701
	HI thickness method			
	Honma & Sofue '97	6.8 – 20.2	–	13
	CO terminal velocities			
	Burton & Gordon '78	1.4 – 7.9	1	284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

1. ROTATION CURVE: A NEW COMPILATION

coming soon: public code in python







user-friendly interface

data & parameter selection

output rotation curve

output positional data

[MP & Iocco, in progress]

1. ROTATION CURVE: A NEW COMPILATION

optmised to $R = 3 - 20$ kpc

2780 individual measurements

2174/506/100 from gas/stars/masers

[Iocco, MP & Bertone, submitted]

GALACTIC MODELLING

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

dynamics	traces <u>total</u> potential	
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[Iocco, MP, Bertone & Jetzer, JCAP11(2011)029]
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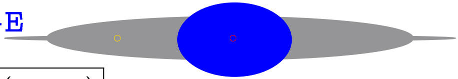
2. BARYONS: STELLAR BULGE



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

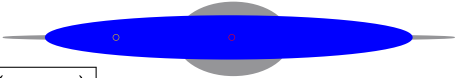
morphology $f(x,y,z)$

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)

2. BARYONS: STELLAR DISK



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

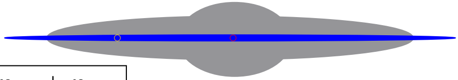
morphology $f(x,y,z)$

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]

2. BARYONS: GAS



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

morphology

Ferrière '12	$r < 0.01$ kpc	$M_{gas} \sim 7 \times 10^5$ 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: $X_{\rm CO} = 0.25 - 1.0 \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s for $r < 2$ kpc
$X_{\rm CO} = 0.50 - 3.0 \times 10^{20}$ cm^{-2} K^{-1} km^{-1} s for $r > 2$ kpc

[Ferrière+ '07, Ackermann '12]

2. BARYONS: ROTATION CURVE

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

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

2. BARYONS: ROTATION CURVE

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

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full 3d morphology

$$v_{c,\mathrm{baryons}}^2 = \sum_i v_{c,i}^2$$

please be patient!

SUMMARY

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

purely observational $\phi_{\rm tot}$

please be patient!

purely observational $\phi_{\rm bulge} + \phi_{\rm disk} + \phi_{\rm gas}$

what can we infer about dark matter?

[Iocco, MP & Bertone, submitted]

REMARK #1: ANGULAR VELOCITY

please be patient!

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

.. error of R and v_c strongly correlated

.. use instead the angular velocity $w_c \equiv v_c / R$

REMARK #1: ANGULAR VELOCITY

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.. error of R and v_c strongly correlated

.. use instead the angular velocity $w_c \equiv v_c / R$

.. this will be the starting point for Fabio

REMARK #2: HOW TO USE THE RESIDUALS?

$$\phi_{\rm tot} = \phi_{\rm b} + \phi_{\rm dm}$$

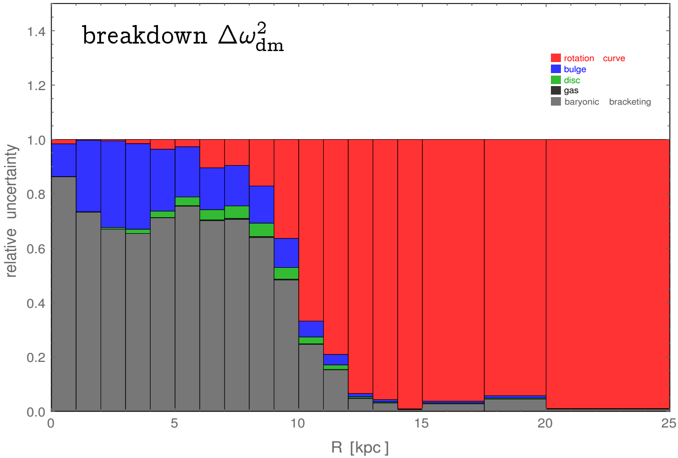
$$\downarrow$$

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

$$\boxed{\omega_{\rm dm}^2 R = \frac{{\rm d}\phi_{\rm dm}(\rho_{\rm dm})}{{\rm d}R}}$$

1. assume functional $\rho_{\rm dm}$ to "fit" and derive constraints
   [Iocco, MP & Bertone, in progress]
2. extract $\rho_{\rm dm}$ directly
   [MP & Iocco, in progress]

REMARK #3: HOW TO IMPROVE?



.. $R < R_0$: baryonic modelling

.. $R > R_0$: rotation curve

please be patient!