MAPPING DARK MATTER IN THE MILKY WAY

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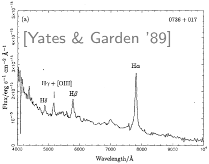
Gamma Rays & Dark Matter Workshop, Obergurgl, 10 Dec 2015

HISTORICAL PARENTHESIS: ANDROMEDA

The kinematics of an object is a prime tool to learn about its mass.



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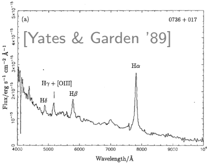

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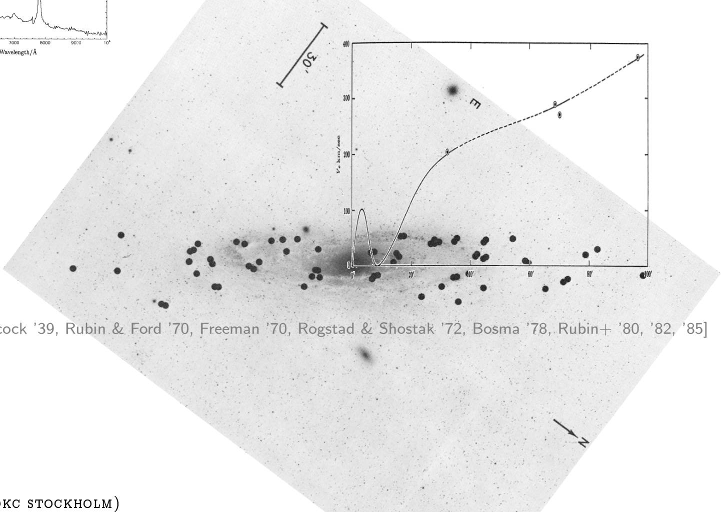

[Babcock '39, Rubin & Ford '70, Freeman '70, Rogstad & Shostak '72, Bosma '78, Rubin+ '80, '82, '85]

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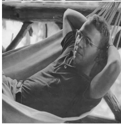

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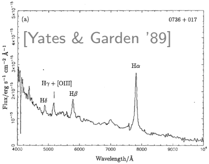

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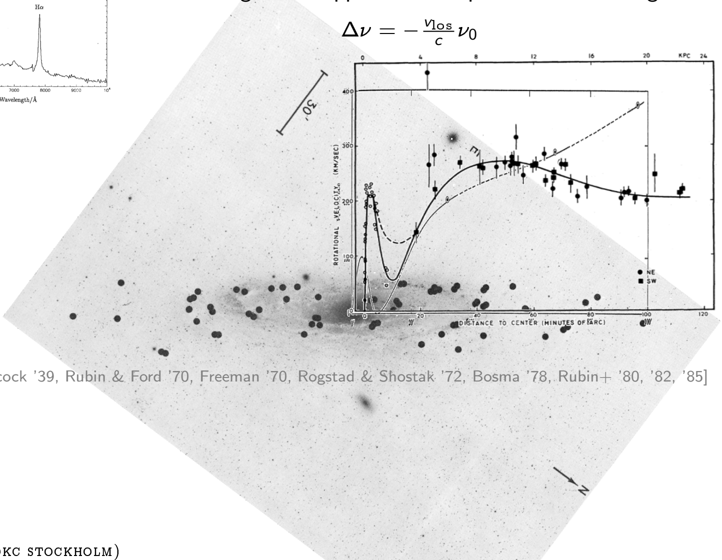

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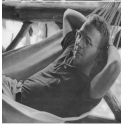

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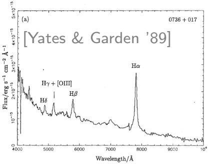

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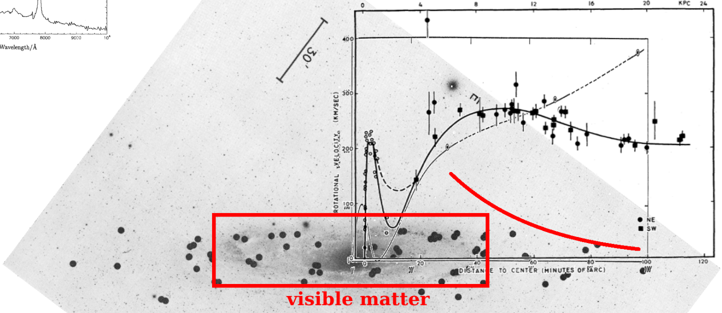

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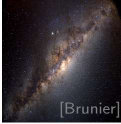
Under Newtonian gravity, a spherical mass induces $\boxed{v_c^2 = \frac{GM(<r)}{r}}$.

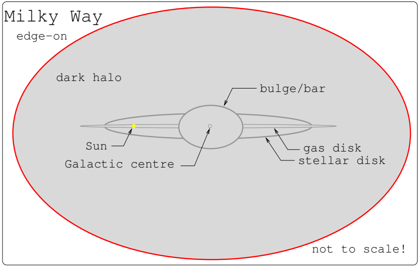
The rotation provided by the visible mass falls off as $v_c \propto 1/\sqrt{r}$ at large r. A flat rotation curve implies* a dark matter halo with $M(<r) \propto r$.

* Modifications of gravity at galactic scales are also feasible. [Milgrom x3 '83]

1. TOUR OF THE GALAXY



The Milky Way is a complex bound system of stars, gas and dark matter.



We can identify the following main components:

- supermassive black hole, with mass $4 \times 10^6\, M_\odot$;
- stellar bulge, with barred shape of scale length $2-3$ kpc and mass $10^{10}\, M_\odot$;
- stellar disc, decomposed into thin and thick components of scale length 10 kpc and total mass $10^{10}\, M_\odot$ with a marked spiral structure;
- gas, in molecular, atomic and ionised phases (mainly H) with a patchy distribution towards the centre and a disc-like structure otherwise; and
- dark matter halo, extending hundreds of kpc.

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

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

The Sun is located slightly above the Galactic plane at $R_0 \simeq 8$ kpc from the Galactic centre, in between two major spiral arms, and travels together with the local standard of rest at about 220 km/s in a roughly circular orbit.

1. TOUR OF THE GALAXY

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

kinematics traces total potential

$R \sim 0.1 - 30$ kpc	rotation curve tracers
$R \sim 8 - 60$ kpc	star population tracers
$R \sim 100 - 300$ kpc	satellite kinematics
$R \sim 300+$ kpc	timing in Local Group

photometry traces individual baryonic components

bulge	star counts, luminosity, microlensing
disc	star counts, luminosity, stellar dynamics
gas	emission lines, dispersion measure

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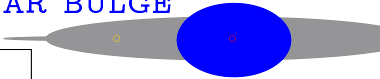
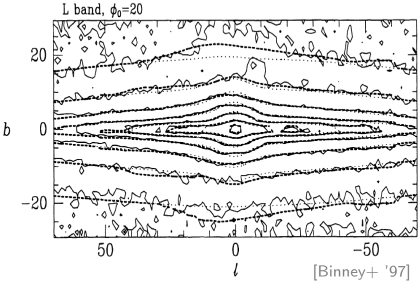
1. TOUR OF THE GALAXY: STELLAR BULGE

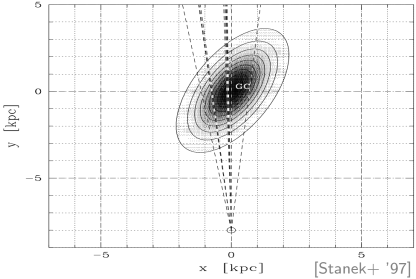


$$\rho_{\rm bulge} = \rho_0 f(x,y,z)$$

morphology $f(x,y,z)$



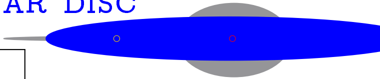
[Binney+ '97]



[Stanek+ '97]

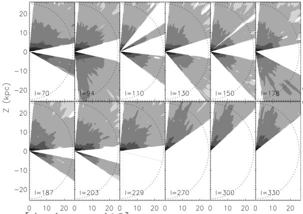
Stanek+ '97 (E2)	e^{-r}	0.9:0.4:0.3	24°	optical
Stanek+ '97 (G2)	$e^{-r_s^2/2}$	1.2:0.6:0.4	25°	optical
Zhao '96	$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	1.5:0.6:0.4	20°	infrared
Bissantz & Gerhard '02	$e^{-r_s^2}/(1+r)^{1.8}$	2.8:0.9:1.1	20°	infrared
Lopez-Corredoira+ '07	Ferrer potential	7.8:1.2:0.2	43°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

1. TOUR OF THE GALAXY: STELLAR DISC

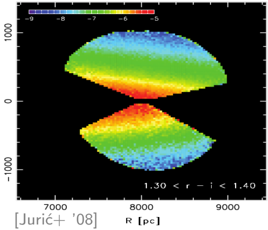


$$\rho_{\rm disc} = \rho_0 f(x,y,z)$$

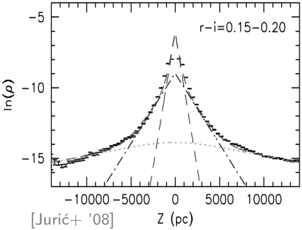
morphology $f(x,y,z)$



[de Jong+ '10]



[Jurić+ '08]



[Jurić+ '08]

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	
de Jong+ '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

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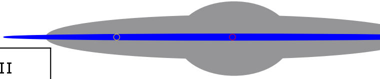
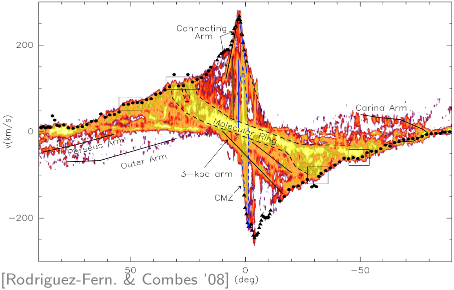
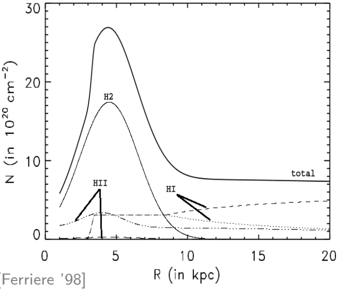


$$n_{\rm H} = 2n_{\rm H_2} + n_{\rm HI} + n_{\rm HII}$$

morphology



[Rodriguez-Fern. & Combes '08]



[Ferriere '98]

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 disc	H_2	CO
		CMZ, holed disc	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.

1. TOUR OF THE GALAXY: PHOTOMETRY

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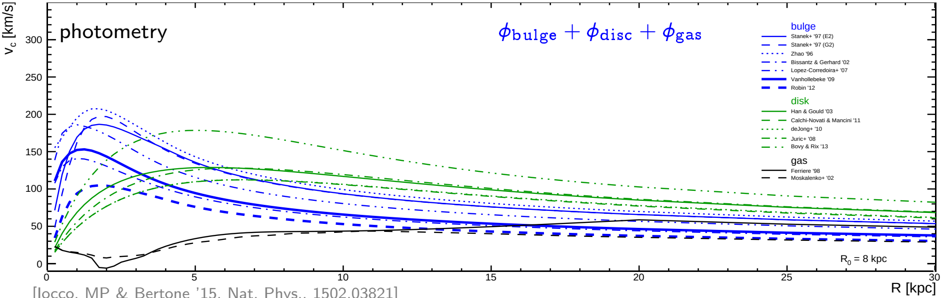

[Iocco, MP & Bertone '15, Nat. Phys., 1502.03821]

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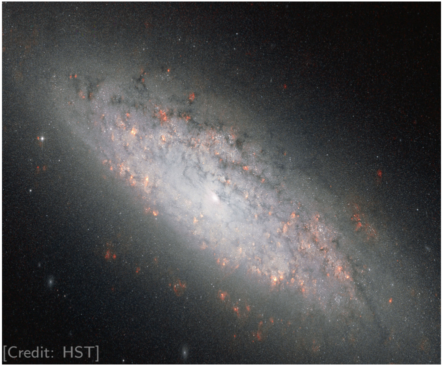
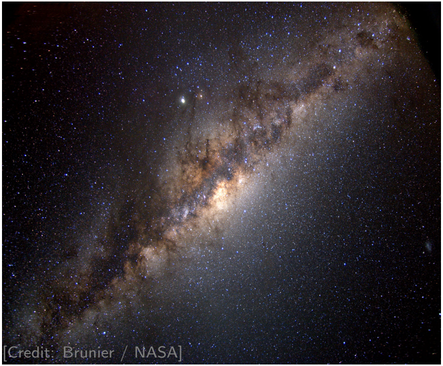
$$v_c^2 = r\frac{\mathrm{d}\phi_{\mathrm{tot}}}{\mathrm{d}r} \overset{\mathrm{sph.}}{=} \frac{G\,M_{\mathrm{tot}}(< r)}{r}$$

Rotation curve tracers are young objects or regions that track galactic rotation. In external galaxies the only available tracer is the gas, while in our Galaxy we can use also some stars and star-forming regions. However, the case of our Galaxy is much more challenging due to our position.



[Credit: HST]



[Credit: Brunier / NASA]

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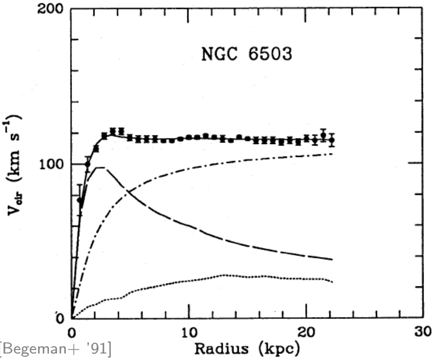
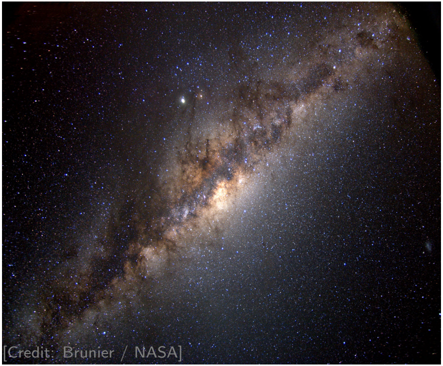


[Begeman+ '91]



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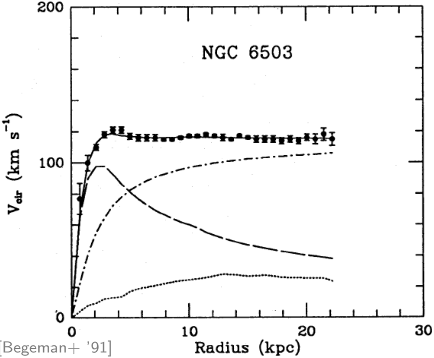

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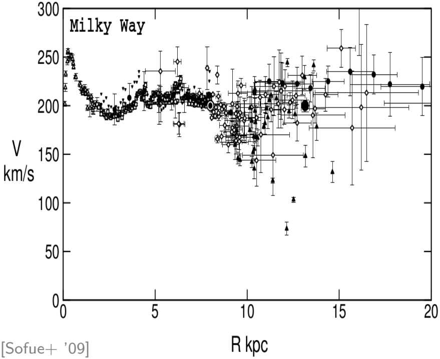

[Sofue+ '09]

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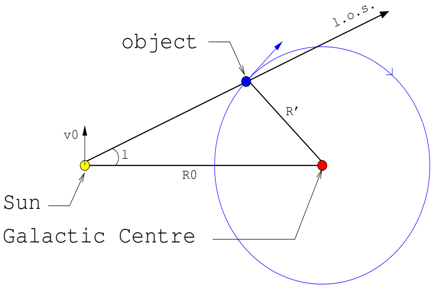

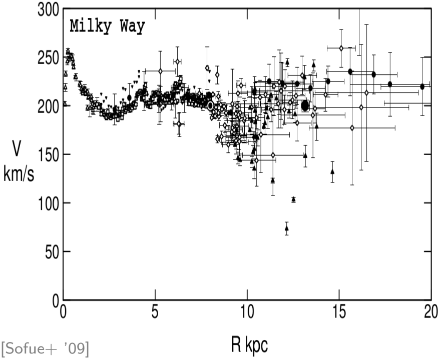

[Sofue+ '09]

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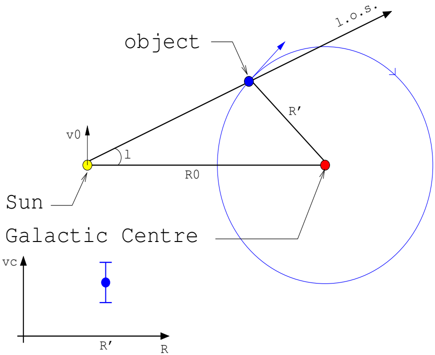

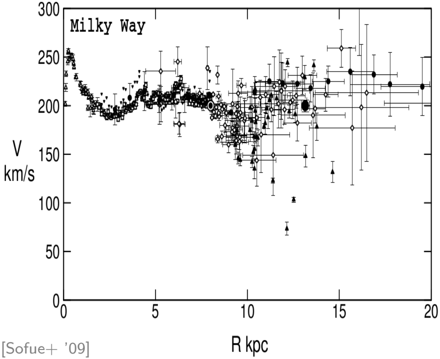

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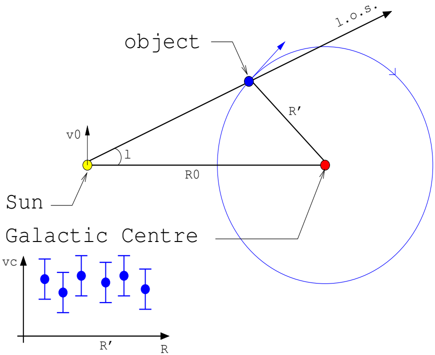

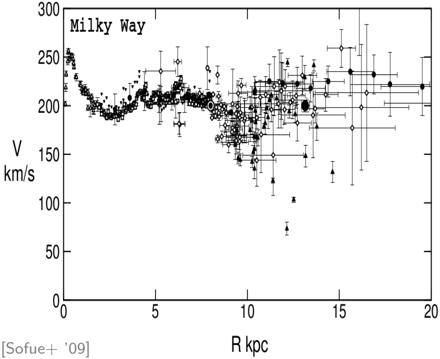

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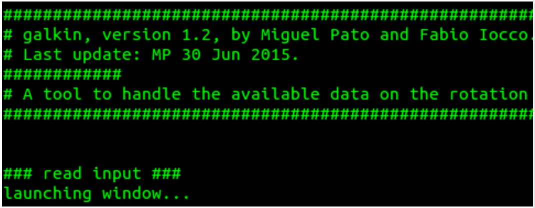
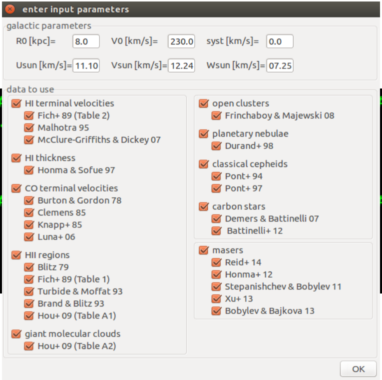
	Object type	R [kpc]	quadrants	# objects
gas	HI terminal velocities			
	Fich+ '89	2.1 – 8.0	1,4	149
	Malhotra '95	2.1 – 7.5	1,4	110
	McClure-Griffiths & Dickey '07	2.8 – 7.6	4	701
	HI thickness method			
	Honma & Sofue '97	6.8 – 20.2	–	13
	CO terminal velocities			
	Burton & Gordon '78	1.4 – 7.9	1	284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

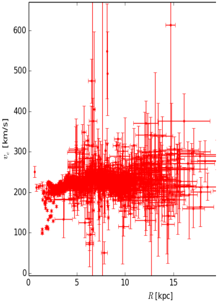
[Iocco, MP & Bertone '15, Nat. Phys., 1502.03821]

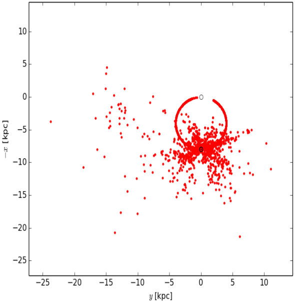
(GALKIN)

coming soon: galkin, public code in python









user-friendly interface

data & parameter selection

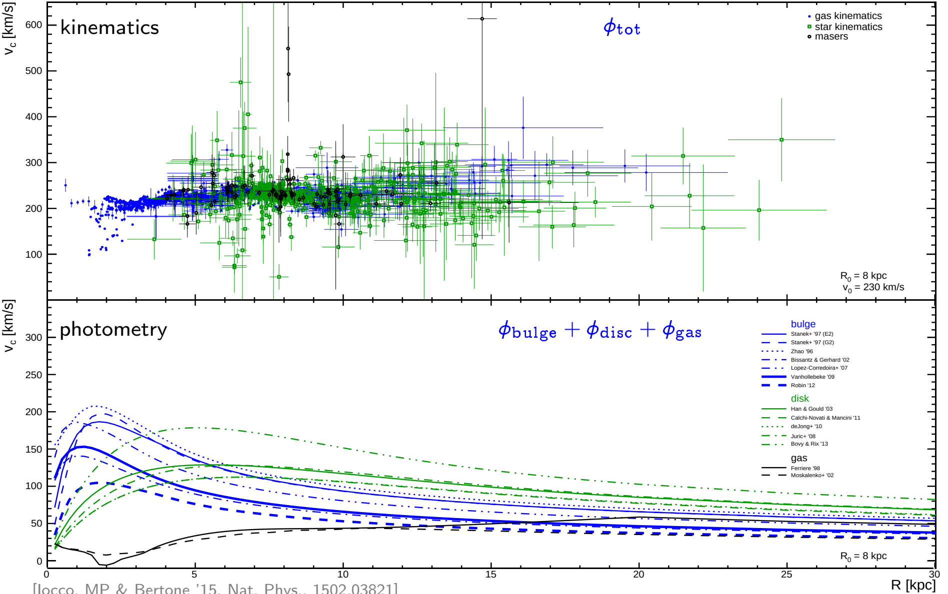
output rotation curve

output positional data

[MP & Iocco, in progress]

1. TOUR OF THE GALAXY: SUMMARY

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



[Iocco, MP & Bertone '15, Nat. Phys., 1502.03821]

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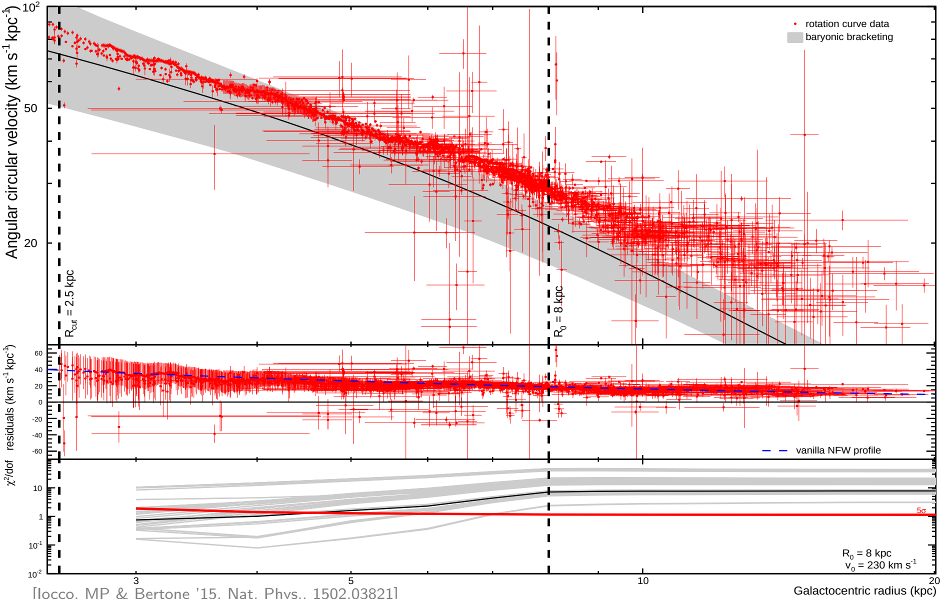

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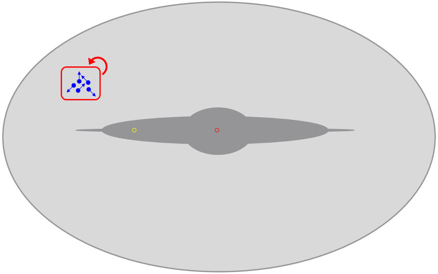
2. DARK MATTER: LOCALISE OR GLOBALISE?

local methods	vs	global methods

aim: use data from a patch of the sky to derive dynamics there.

+ "assumption-free"
− low precision



[Kapteyn '22, Jeans '22, Oort '32, Hill '60, Oort '60, Bahcall '84, Bienaymé+ '87, Kuijken & Gilmore '91, Bahcall+ '92, Creze+ '98, Holmberg & Flynn '00, Holmberg & Flynn '04, Bienaymé+ '06, Garbari+ '11 '12, Moni Bidin+ '12, Bovy & Tremaine '12, Smith+ '12, Zhang+ '13, Bovy & Rix '13, Loebman+ '14, Moni Bidin+ '14]

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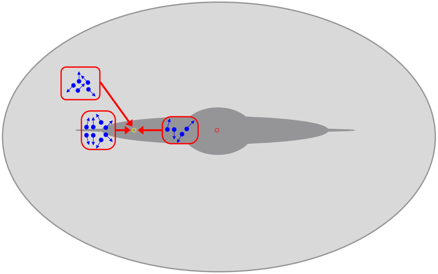

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2. LOCAL METHODS

In a galaxy star encounters are rare and stars feel on average the smooth gravitational potential. We can therefore treat a set of stars as a collisionless gas and apply the collisionless Boltzmann equation, whose first momentum gives the Jeans equations:

$$-\rho_s \frac{\partial \phi_{\rm tot}}{\partial x_j} = \frac{\partial(\rho_s \overline{v_j})}{\partial t} + \sum_i \frac{\partial(\rho_s \overline{v_i v_j})}{\partial x_i} \quad , \quad j = 1,2,3 \; (\texttt{cartesian}) \, .$$

We can couple this to the Poisson equation: $4\pi G \rho_{\rm tot} = \nabla^2 \phi_{\rm tot} \quad .$

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$$-4\pi G \rho_{\mathrm{tot}} = \frac{1}{R}\frac{\partial}{\partial R}(R F_R) + \frac{\partial F_z}{\partial z}$$

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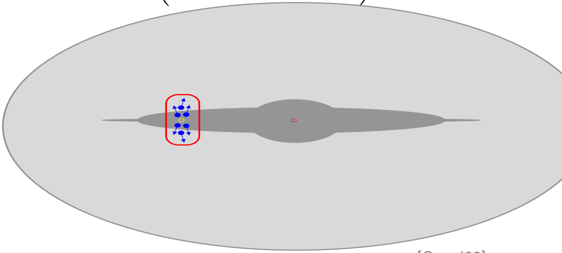

This is the so-called Oort limit.

[Oort '32]

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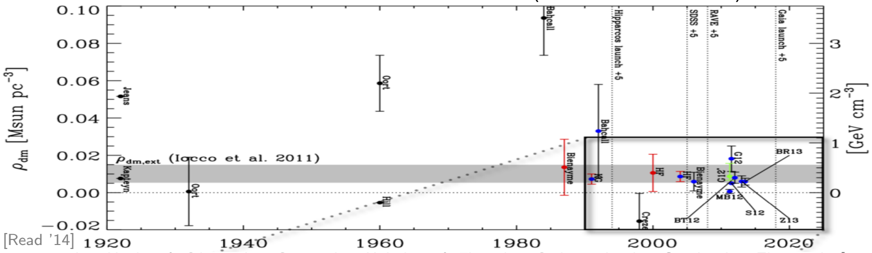

[Read '14]

[Bienayme+ '87, Kuijken & Gilmore '89, Creze+ '98, Holmberg & Flynn '00, Garbari+ '11 '12, Smith+ '12, Zhang+ '13]

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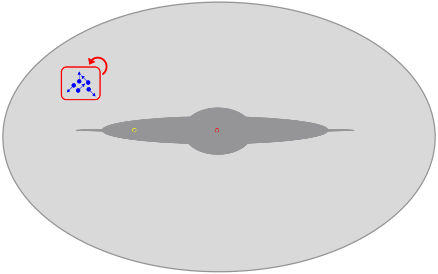

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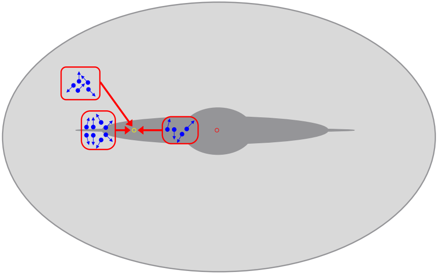

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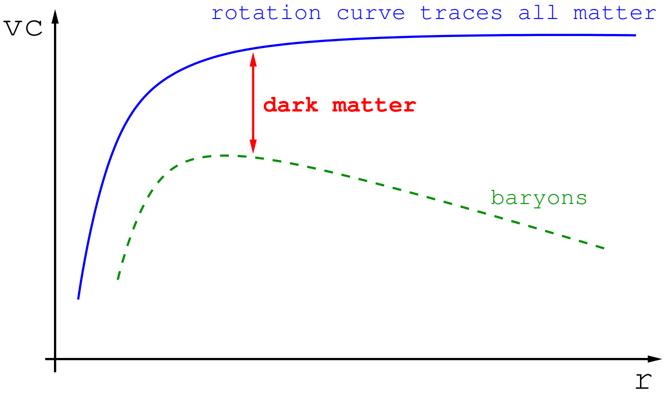

$$v_c^2 = v_{\rm b}^2 + v_{\rm dm}^2$$

$$v_{\rm dm}^2 \stackrel{\rm sph.}{=} G\, M_{\rm dm}(< r)/r \;\rightarrow\; \rho_{\rm dm}$$

[Dehnen & Binney '98, Sofue+ '09, Catena & Ullio '10, Weber & de Boer '10, Salucci+ '10, McMillan '11, Iocco+ '11, Nesti & Salucci '13, Sofue '15]

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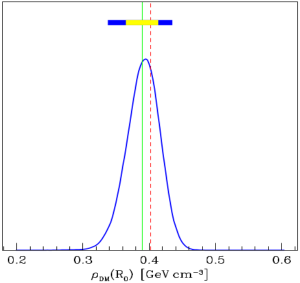
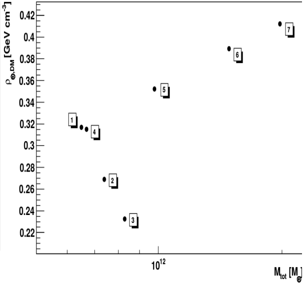


[Catena & Ullio '10]



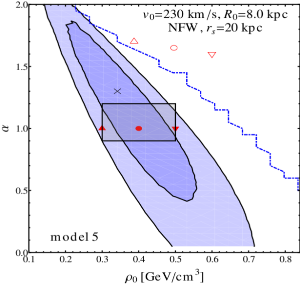
[Weber & de Boer '10]

$$\rho_\odot = \left(0.430 \pm 0.113_{(\alpha_\odot)} \pm 0.096_{(r_{\odot D})}\right) \frac{\text{GeV}}{\text{cm}^3}$$

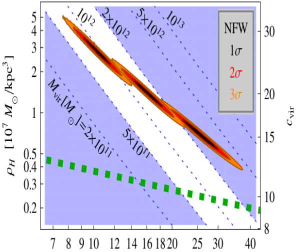
[Salucci '10]

$$0.40 \pm 0.04\,\text{GeV}\,\text{cm}^{-3}$$

[McMillan '11]



[Iocco+ '11]

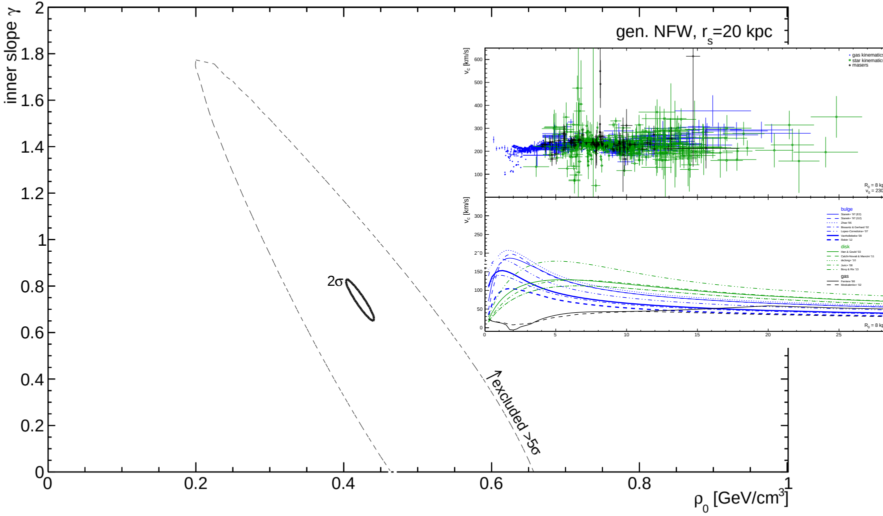


$0.471^{+0.048}_{-0.061}$

[Nesti & Salucci '13]

2. PROFILE FITTING

$\rho_{\rm dm} \propto (r/r_s)^{-\gamma}(1+r/r_s)^{-3+\gamma}$ [MP, Iocco & Bertone '15, 1504.06324]



$$\text{NFW:} \quad \rho_0 = 0.420^{+0.021}_{-0.018}\,(2\sigma) \qquad \text{GeV/cm}^3$$

$$\text{Einasto:} \quad \rho_0 = 0.420^{+0.019}_{-0.021}\,(2\sigma) \qquad \text{GeV/cm}^3$$

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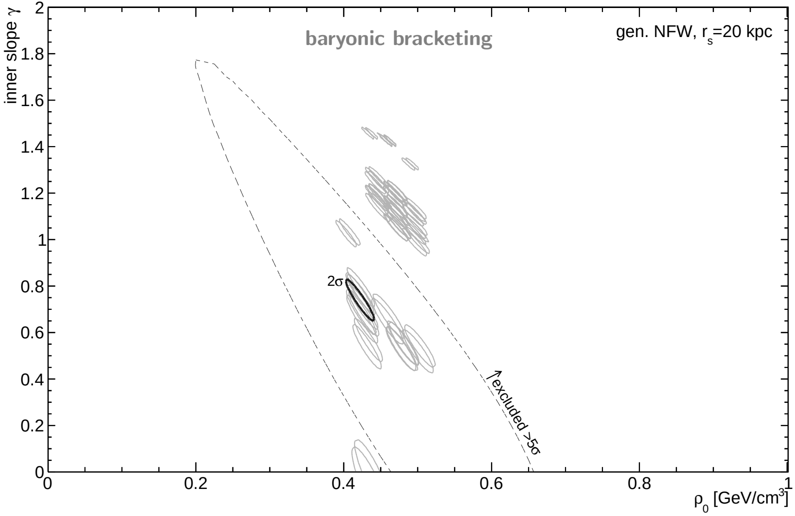

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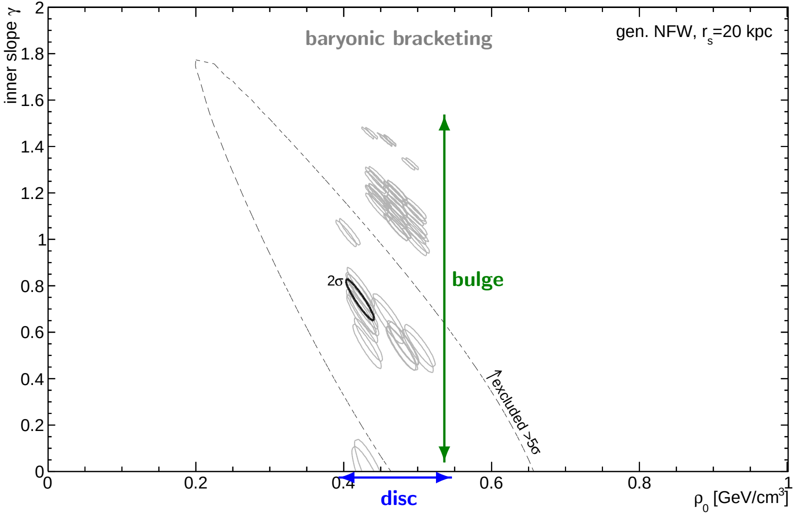

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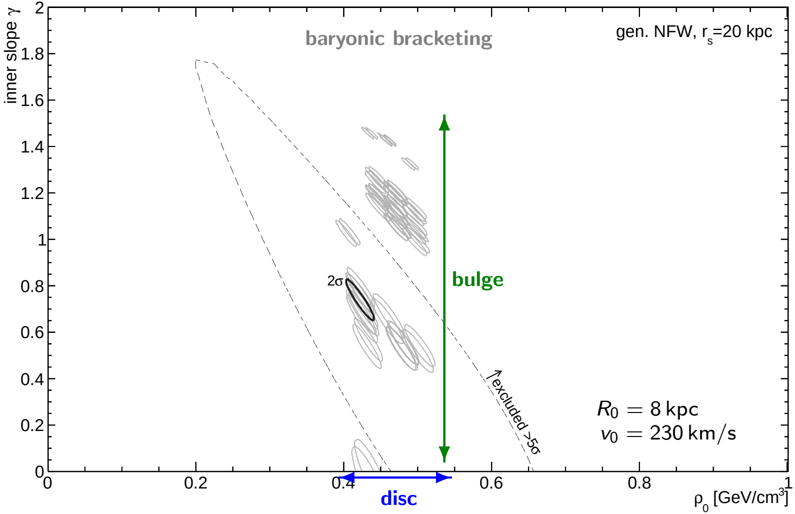

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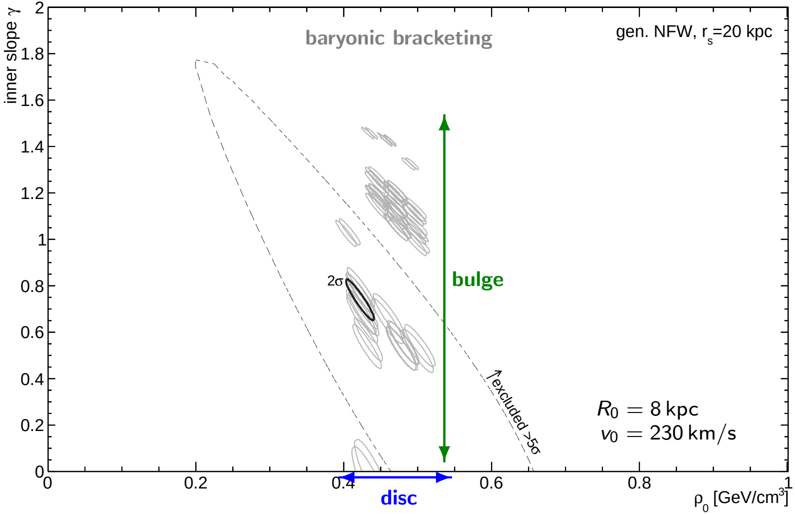

S-stars orbits: $R_0 = 8.33 \pm 0.35\,\mathrm{kpc}$

Sgr A* proper motion: $\Omega_\odot \equiv (v_0 + V_\odot)/R_0 = 30.26 \pm 0.12\,\mathrm{km/s/kpc}$

[Gillessen+ '09, Reid & Brunthaler '04]

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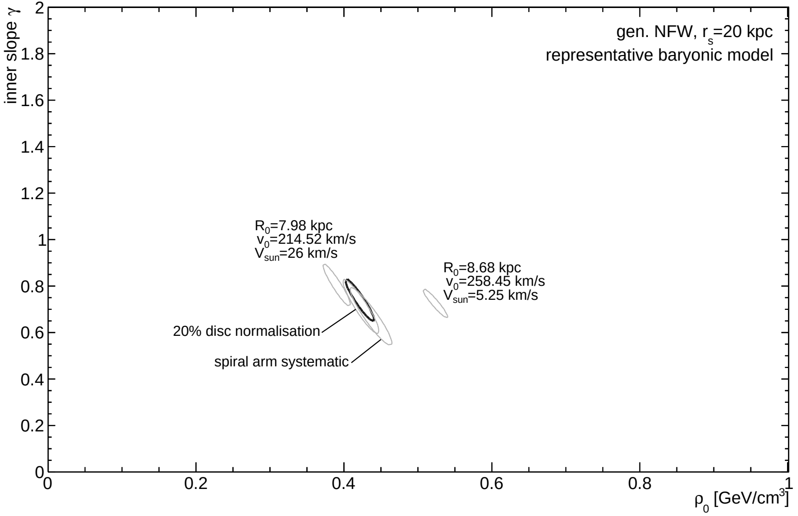

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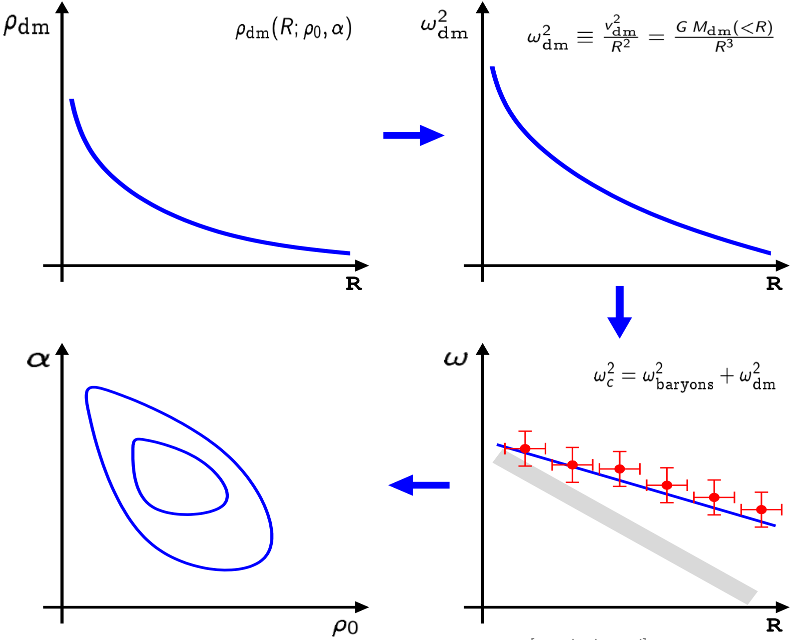
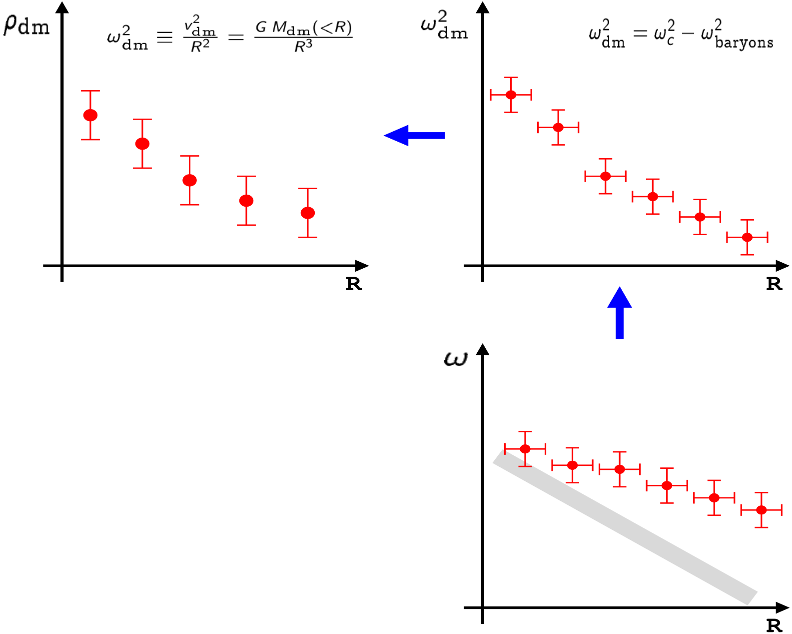


[everybody et al]

2. PROFILE RECONSTRUCTION



[MP & Iocco '15, ApJ Lett., 1504.03317]

2. PROFILE RECONSTRUCTION

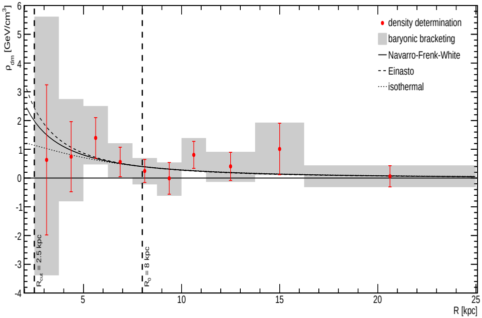
Let us take a spherical dark matter distribution. Then,

$$\omega_{\rm dm}^2 = \omega_c^2 - \omega_{\rm baryons}^2 \quad , \quad \omega_{\rm dm}^2 = \frac{GM_{\rm dm}(< R)}{R^3} = \frac{4\pi G}{R^3}\int_0^R dr\, r^2 \rho_{\rm dm}\, .$$

Solving for $\rho_{\rm dm}$,

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

That is, the deviation from $\omega_{\rm dm}^2 \propto R^{-3}$ (or $v_{dm} \propto R^{-1/2}$) measures the dark matter density at each R. No assumption has been made on the functional form of $\rho_{\rm dm}(R)$.



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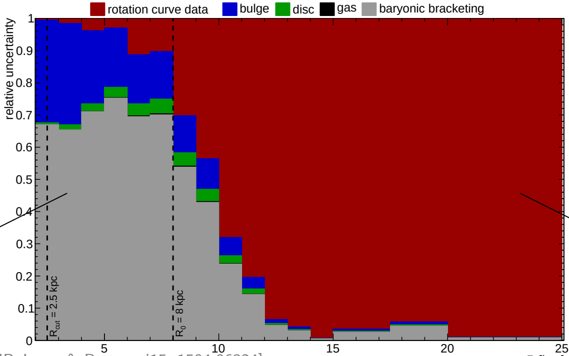
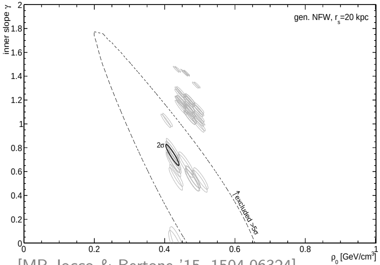
3. FUTURE DIRECTIONS?



baryons

kinematics

[MP, Iocco & Bertone '15, 1504.06324]



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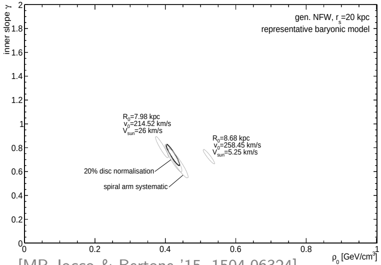

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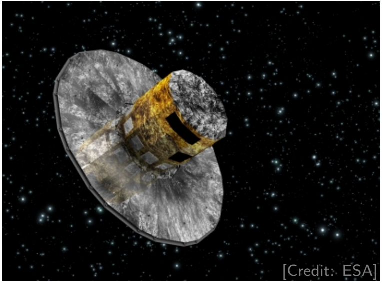
Gaia



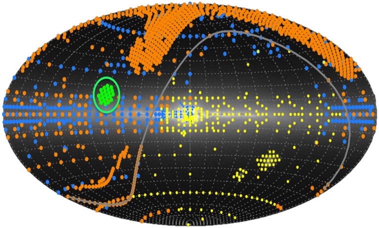
fact sheet

2013-2018
space-based
$\lambda = 320 - 1000\,\mathrm{nm}$
10^9 stars $G < 20$ mag
parallax $\pm 10\,\mu$as
proper motion $\pm 10\,\mu$as/yr
radial velocity ± 1 km/s

wish list

disc modelling
Oort's constants
local density

APOGEE-2 (SDSS-IV)



[Credit: SDSS]

fact sheet

2014-2020
south+north hemispheres
$\lambda = 1510 - 1700\,\mathrm{nm}$
$300,000$ stars
radial velocity ± 0.1 km/s

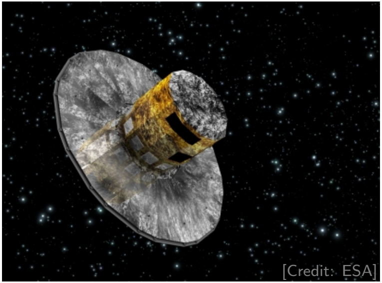
wish list

bulge modelling
disc modelling
kinematics all across

(see also WFIRST, WEAVE and 4MOST)

3. FUTURE DIRECTIONS?

Gaia



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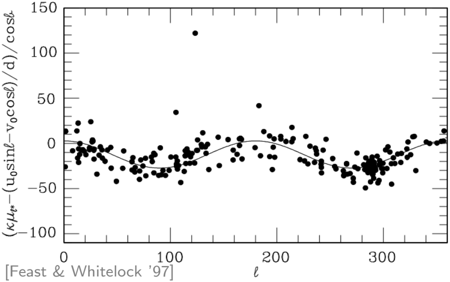


[Feast & Whitelock '97]

Use local kinematics to constrain Oort constants:

$$A = \frac{1}{2}\left(\frac{v_0}{R_0} - v_0'\right) \qquad B = -\frac{1}{2}\left(\frac{v_0}{R_0} + v_0'\right)$$

$$v_{\text{los}} \simeq A d \sin 2\ell \qquad \mu_\ell = \frac{v_t}{d} \simeq B + A\cos 2\ell$$

Hipparcos:
$A = +14.82 \pm 0.84\,\text{km/s/kpc}$
$B = -12.37 \pm 0.64\,\text{km/s/kpc}$

Gaia will largely outperform Hipparcos.
[work in progress with Mattia Fornasa]

4. SUMMARY & CONCLUSION

photometry vs kinematics

- photometry: tracks baryonic matter
- kinematics: tracks total matter
- kinematics – photometry: tracks dark matter

local vs global methods

- local methods: robust but low precision
- global methods: model-dependent but high precision
- both are complementary

current uncertainties

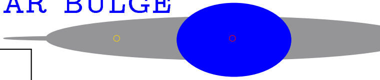
- inner Galaxy: baryons
- outer Galaxy: kinematics

bottomline

The distribution of dark matter in the Milky Way remains largely unconstrained,
but Gaia and other surveys will shrink current uncertainties,
leading to a new precision era in mapping dark matter in the Galaxy.

BACKUP SLIDES

1. TOUR OF THE GALAXY: STELLAR BULGE

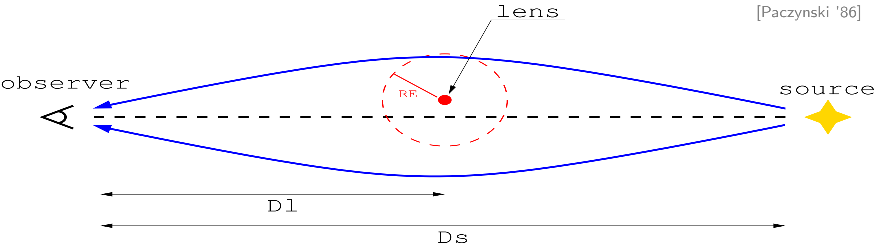


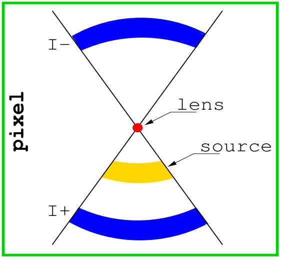
$$\rho_{\text{bulge}} = \rho_0 f(x, y, z)$$

normalisation ρ_0

One possibility to normalise bulge models is to use microlensing.

[Paczynski '86]





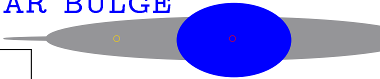
Microlensing is simply a regime of gravitational lensing where the multiple images are not resolved.

Einstein radius $R_E^2 = \frac{4GM_l}{c^2} D_l \left(1 - \frac{D_l}{D_s}\right)$

unresolved images $A(t) = \frac{u^2+2}{u\sqrt{u^2+4}}$

$M_l \sim [10^{-6}, 10^2]\ \mathrm{M}_\odot$: $t_E \sim$ hr − days

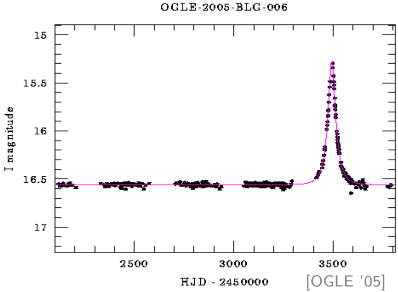
1. TOUR OF THE GALAXY: STELLAR BULGE



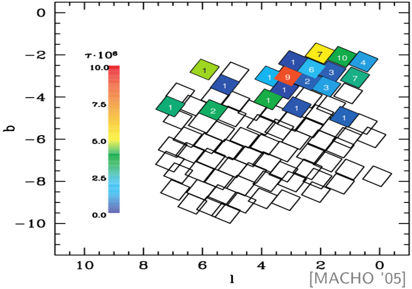
$$\rho_{\text{bulge}} = \rho_0 f(x, y, z)$$

normalisation ρ_0

Microlensing in our Galaxy was predicted in 1986 and observed for the first time in 1993 by MACHO and EROS.



[OGLE '05]



[MACHO '05]

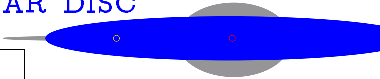
The microlensing optical depth, i.e. the probability for observing a microlensing event,

$$\tau = \int_0^{D_s} dD_l \int dM_l \left(\pi R_E^2\right) \times \left(\frac{d^2 N_l}{dV dM_l}\right) = \frac{4\pi G}{c^2} \int_0^{D_s} dD_l\, \rho_l D_l \left(1 - \frac{D_l}{D_s}\right)$$

is particularly convenient since it depends on ρ_l only, not on M_l.

$\langle \tau \rangle = 2.17^{+0.47}_{-0.38} \times 10^{-6}$, $(\ell, b) = (1.50^\circ, -2.68^\circ)$ [MACHO '05]

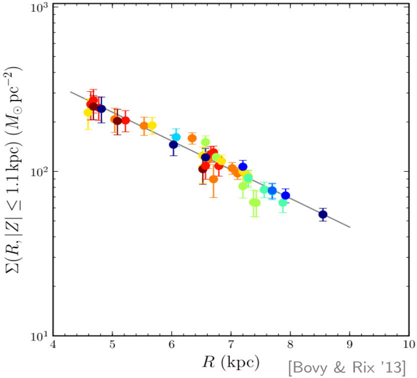
1. TOUR OF THE GALAXY: STELLAR DISC



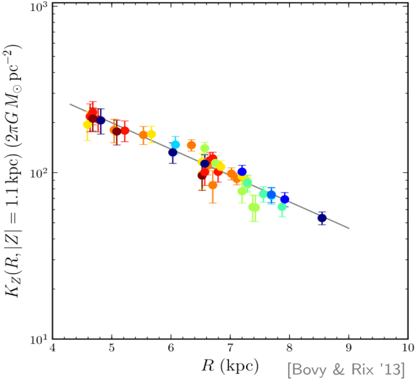
$$\rho_{\rm disc} = \rho_0 f(x, y, z)$$

normalisation ρ_0

The normalisation of the stellar disc can be pinned down with the kinematics of specific stars.



[Bovy & Rix '13]

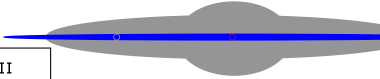


[Bovy & Rix '13]

The latest dynamical measurement uses G dwarfs from SEGUE and fixes the stellar local surface density to

$$\Sigma_* = 38 \pm 4 \mathrm{M}_\odot/\mathrm{pc}^2\,.$$ [Bovy & Rix '13]

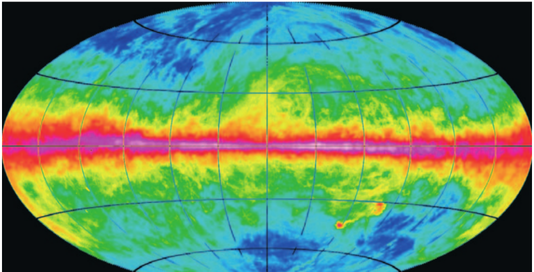
1. TOUR OF THE GALAXY: GAS



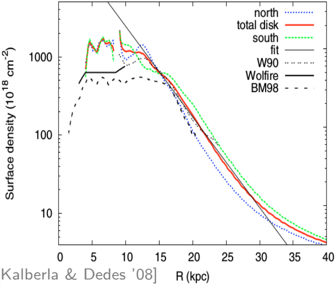
$$n_{\rm H} = 2n_{\rm H_2} + n_{\rm HI} + n_{\rm HII}$$

normalisation

The gas content is dominated by H_2 in the inner Galaxy and H I in the outer Galaxy.



[LAB survey '05]



[Kalberla & Dedes '08]

For H_2, the main normalisation uncertainty arises from the CO-to-H_2 factor,

$$X_{\rm CO} = 0.25 - 1.0 \times 10^{20}\ {\rm cm}^{-2}\,{\rm K}^{-1}\,{\rm km}^{-1}\,{\rm s}\ (r < 2\,{\rm kpc})$$
$$X_{\rm CO} = 0.50 - 3.0 \times 10^{20}\ {\rm cm}^{-2}\,{\rm K}^{-1}\,{\rm km}^{-1}\,{\rm s}\ (r > 2\,{\rm kpc})\ .$$

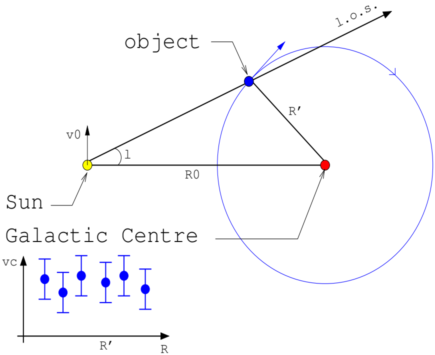
[Ferrière+ '07, Ackermann '12]

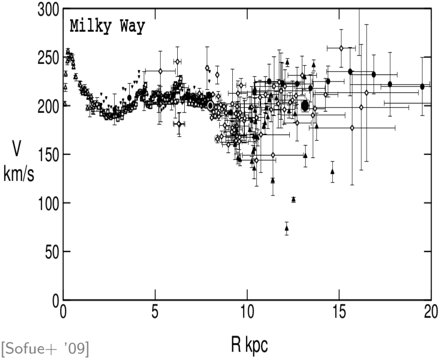
For H I, different surveys disagree by up to a factor ~ 2 in the inner 15 kpc.

1. TOUR OF THE GALAXY: ROTATION CURVE

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

Rotation curve tracers are young objects or regions that track galactic rotation. In external galaxies the only available tracer is the gas, while in our Galaxy we can use also some stars and star-forming regions. However, the case of our Galaxy is much more challenging due to our position.





[Sofue+ '09]

$$v_{\mathrm{lsr}}^{\mathrm{los}} = \left(\frac{v_c(R')}{R'/R_0} - v_0 \right) \cos b \sin \ell$$

Doppler shift

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

1. TOUR OF THE GALAXY: ROTATION CURVE

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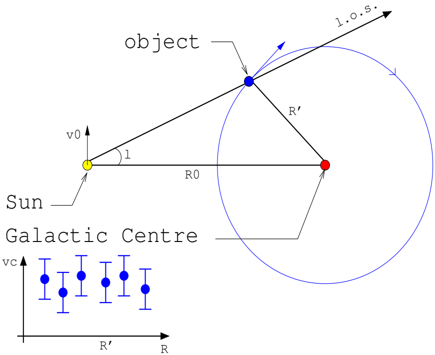

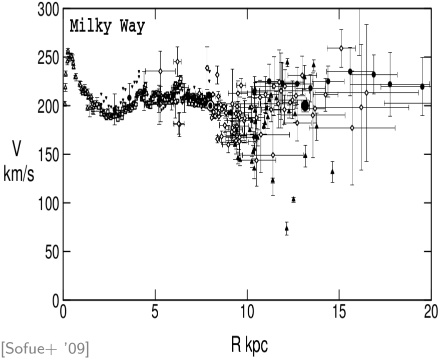

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distance

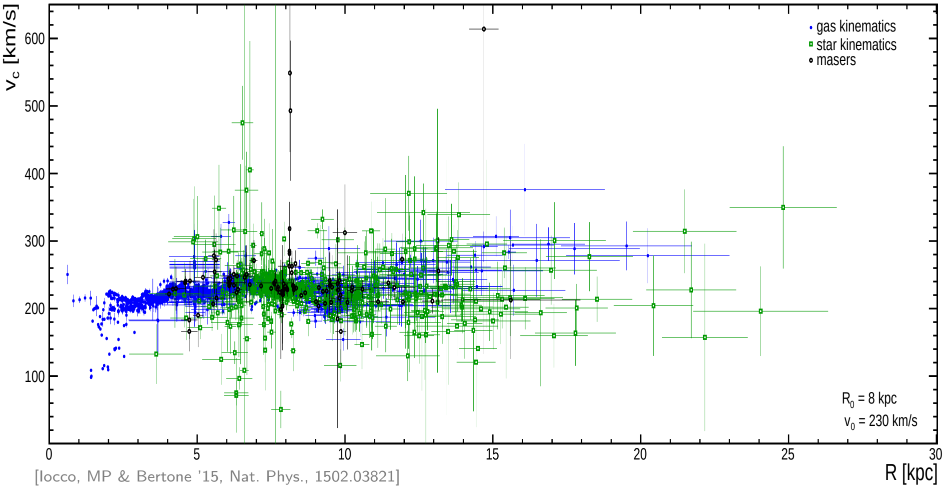
1. terminal velocities (gas)
2. photo-spectroscopy (stars)
3. parallax (masers)

1. TOUR OF THE GALAXY: ROTATION CURVE

optimised to $R = 3 - 20$ kpc

2780 individual measurements

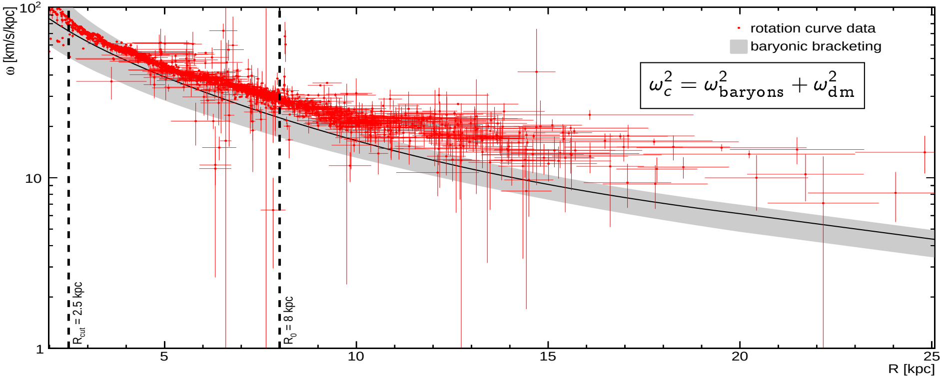
2174/506/100 from gas/stars/masers



[Iocco, MP & Bertone '15, Nat. Phys., 1502.03821]

1. EVIDENCE FOR DARK MATTER

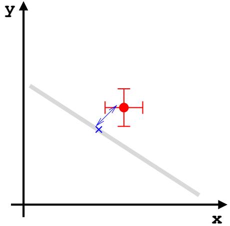
$$\phi_{\mathtt{tot}} = \phi_{\mathtt{bulge}} + \phi_{\mathtt{disc}} + \phi_{\mathtt{gas}} + \phi_{\mathtt{dm}}$$



How bad is a baryon-only fit?

$$x = R/R_0 \qquad y = \omega/\omega_0 - 1$$

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



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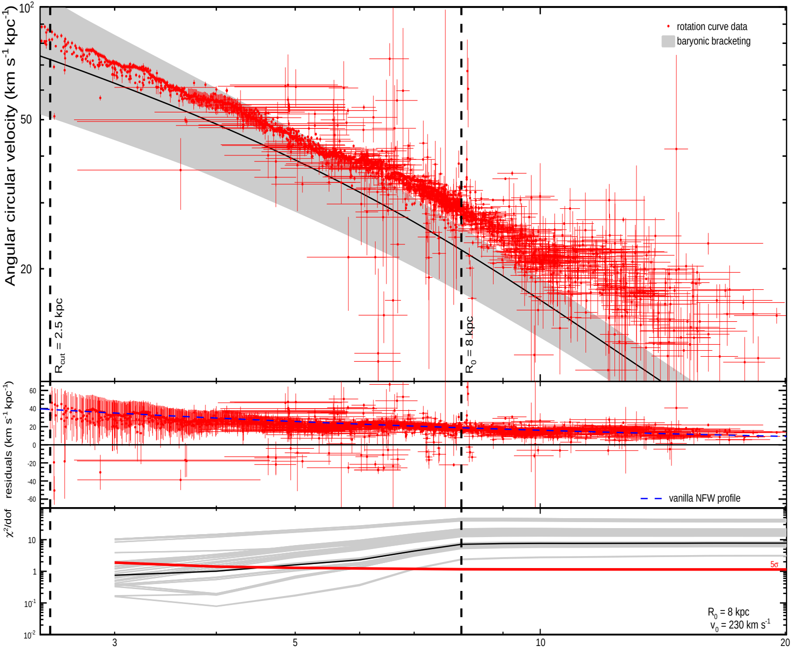

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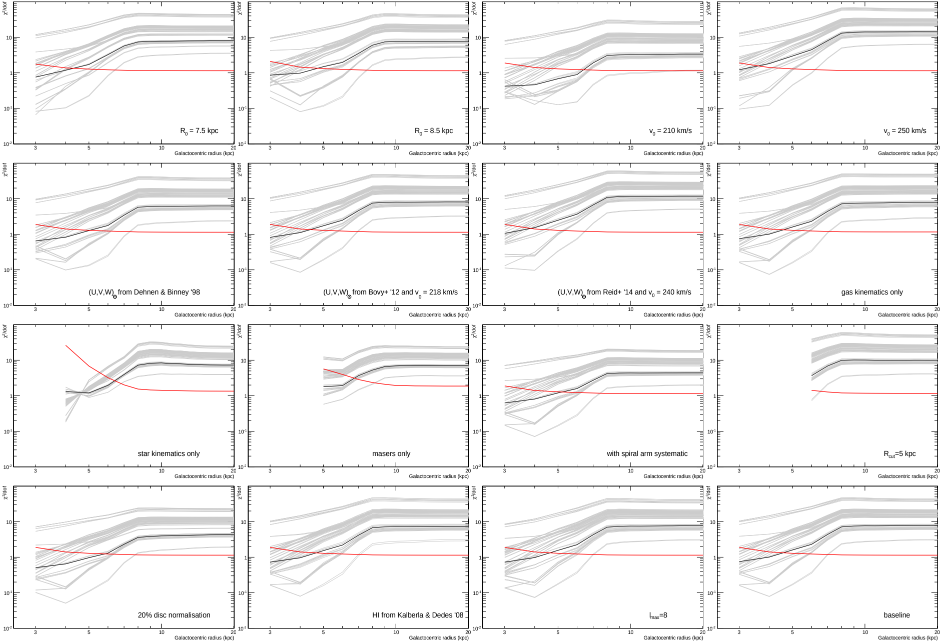

[Iocco, MP & Bertone '15, Nat. Phys., 1502.03821]

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dynamics — traces total potential

$R \sim 0.1 - 30\,\mathrm{kpc}$	rotation curve tracers
$R \sim 8 - 60\,\mathrm{kpc}$	star population tracers
$R \sim 100 - 300\,\mathrm{kpc}$	satellite kinematics
$R \sim 300+\,\mathrm{kpc}$	timing in Local Group

"photometry" — traces individual baryonic components

bulge	star counts, luminosity, microlensing
disc	star counts, luminosity, stellar dynamics
gas	emission lines, dispersion measure

1. TOUR OF THE GALAXY: STAR POPULATION

In a galaxy star encounters are rare and stars feel on average the smooth gravitational potential. We can therefore treat a set of stars as a collisionless gas and apply the collisionless Boltzmann equation, whose first momentum gives the Jeans equations:

$$-\rho_s \frac{\partial \phi_{\rm tot}}{\partial x_j} = \frac{\partial(\rho_s \overline{v_j})}{\partial t} + \sum_i \frac{\partial(\rho_s \overline{v_i v_j})}{\partial x_i} \quad , \quad j = 1, 2, 3 \; (\texttt{cartesian}) \, .$$

ρ_s: star density $\qquad$ v_j: velocity of stars

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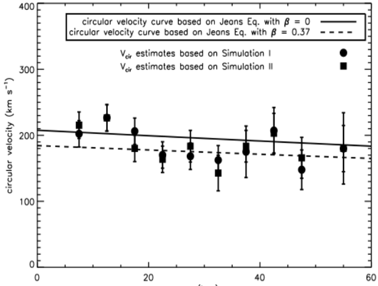
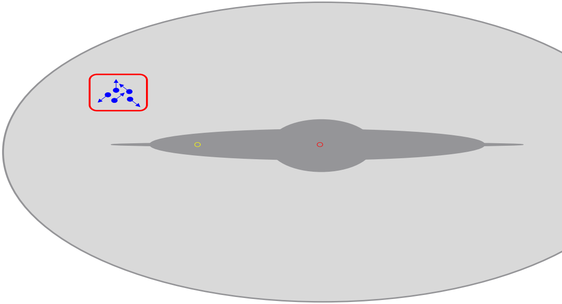


[Xue+ '08]



[Sakamoto+ '03, Dehnen+ '06, Xue+ '08, Bhattacharjee+ '14, Kafle+ '14]

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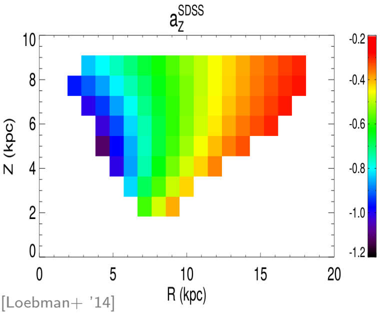
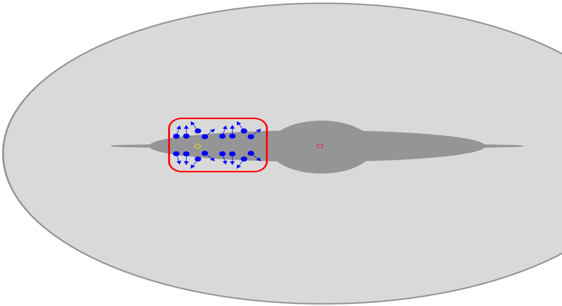


[Loebman+ '14]



[Bovy & Rix '13, Loebman+ '14]

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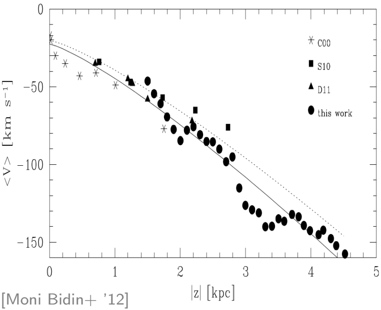
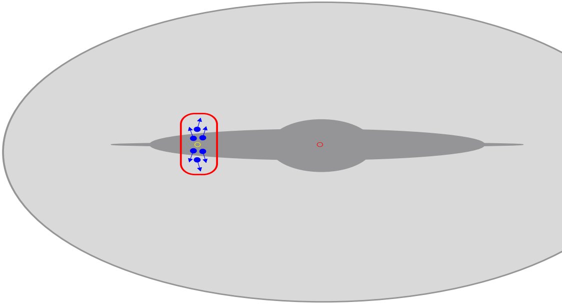


[Moni Bidin+ '12]



[Kuijken & Gilmore '91, Holmberg & Flynn '04, Moni Bidin+ '12, Bovy & Tremaine '12, Moni Bidin+ '14]

2. DARK MATTER CONTENT

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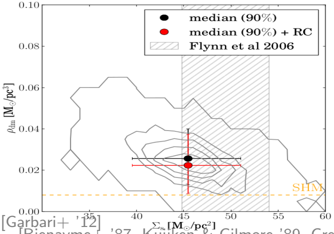
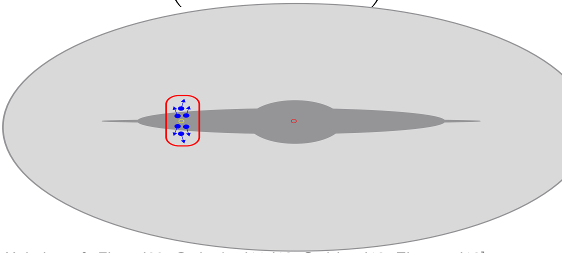
$$-4\pi G \rho_{\rm tot} = \frac{1}{R}\frac{\partial}{\partial R}(R F_R) + \frac{\partial F_z}{\partial z}$$

$$F_R = \frac{1}{\rho_s}\left(\frac{\partial(\rho_s \overline{v_R^2})}{\partial R} + \frac{\partial(\rho_s \overline{v_R v_z})}{\partial z}\right) + \frac{\overline{v_R^2} - \overline{v_\phi^2}}{R}$$

$$F_z = \frac{1}{\rho_s}\left(\frac{\partial(\rho_s \overline{v_R v_z})}{\partial R} + \frac{\partial(\rho_s \overline{v_z^2})}{\partial z}\right) + \frac{\overline{v_R v_z}}{R}$$



[Garbari+ '12]



[Bienayme+ '87, Kuijken & Gilmore '89, Creze+ '98, Holmberg & Flynn '00, Garbari+ '11 '12, Smith+ '12, Zhang+ '13]

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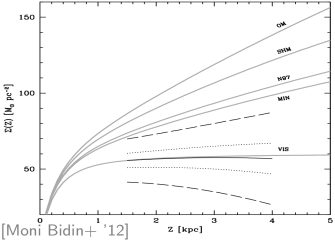
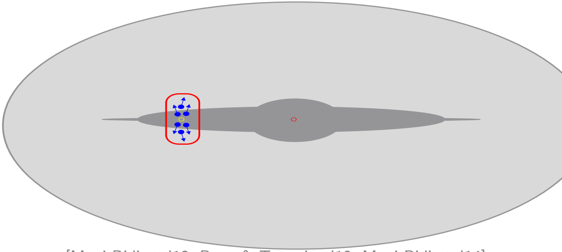
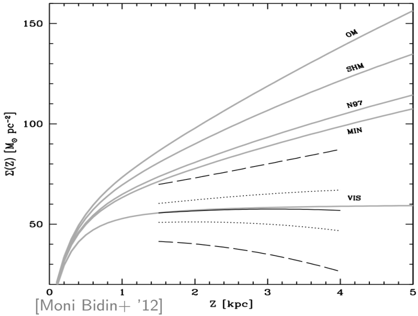


[Moni Bidin+ '12]



[Moni Bidin+ '12, Bovy & Tremaine '12, Moni Bidin+ '14]

2. LOCAL METHODS



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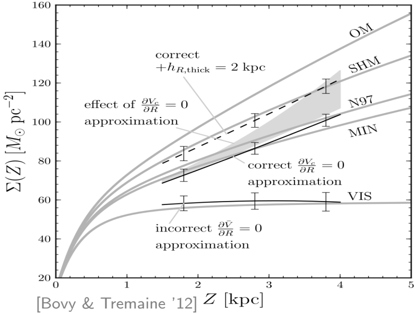
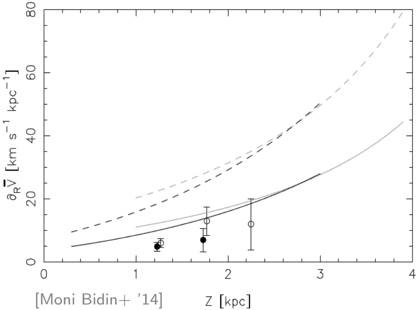


[Bovy & Tremaine '12]



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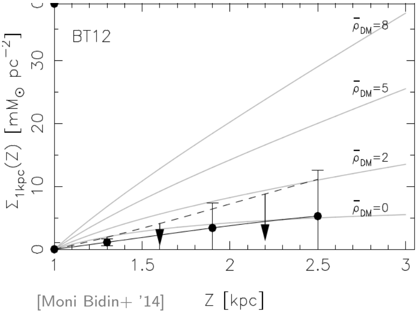

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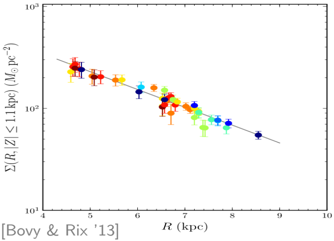
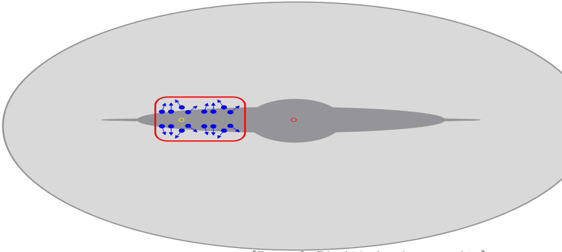


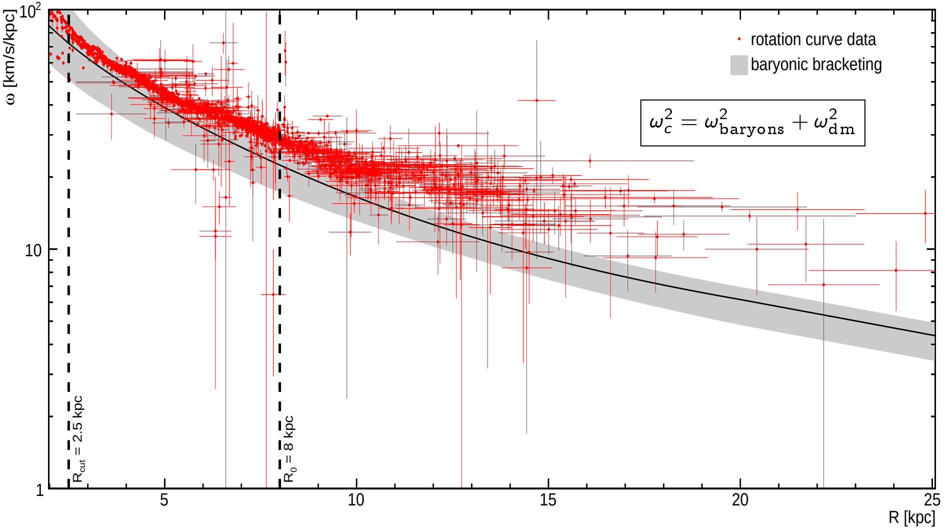
[Bovy & Rix '13]



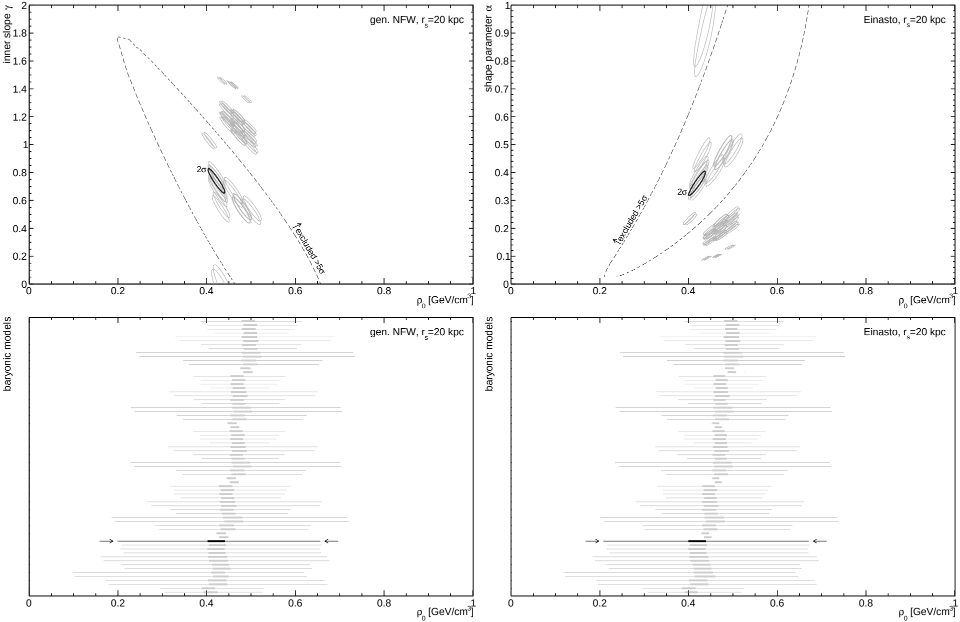
[Bovy & Rix '13, Loebman+ '14]

2. GLOBAL METHODS

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



2. GLOBAL METHODS $\rho_{\rm dm} \propto (r/r_s)^{-\gamma}(1+r/r_s)^{-3+\gamma}, \exp(-2((r/r_s)^\alpha - 1)/\alpha)$

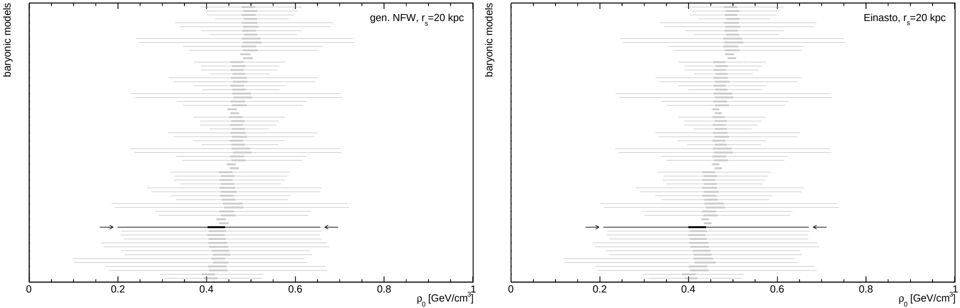


[MP, Iocco & Bertone '15, 1504.06324]

2. GLOBAL METHODS $\rho_{\rm dm} \propto (r/r_s)^{-\gamma}(1+r/r_s)^{-3+\gamma}, \exp(-2((r/r_s)^{\alpha}-1)/\alpha)$

$$\text{NFW:} \quad \rho_0 = 0.420^{+0.021}_{-0.018}\,(2\sigma) \pm 0.025\,\text{GeV/cm}^3$$

$$\text{Einasto:} \quad \rho_0 = 0.420^{+0.019}_{-0.021}\,(2\sigma) \pm 0.026\,\text{GeV/cm}^3$$



[MP, Iocco & Bertone '15, 1504.06324]

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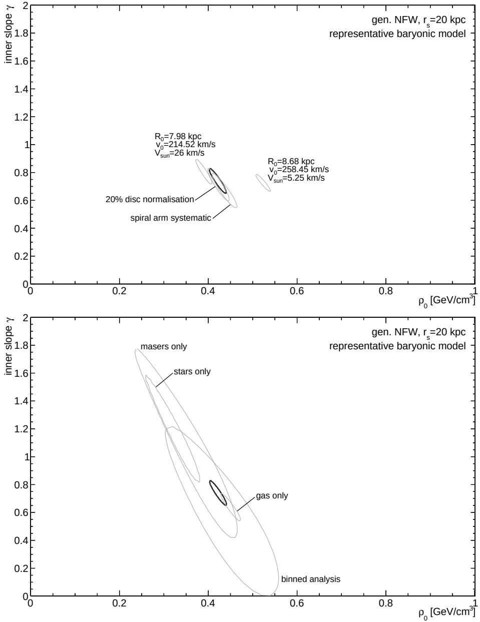


[MP, Iocco & Bertone '15, 1504.06324]

2. MODIFIED NEWTONIAN DYNAMICS

wait, what about MoND?

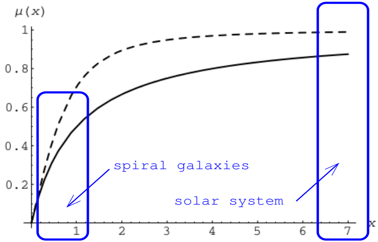
$$\mu\left(\frac{a}{a_0}\right) a = a_N$$

$$a_0 \simeq 10^{-10}\,\mathrm{m/s^2}$$

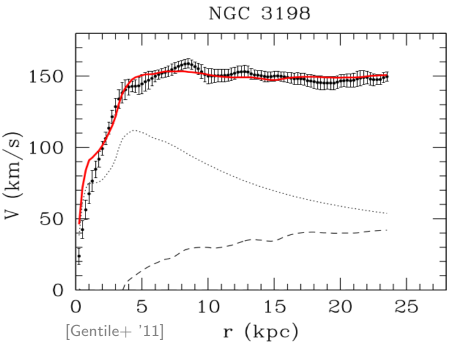
[Milgrom x3 '83]

$$\lim_{x \ll 1} \mu(x) = x \qquad \lim_{x \gg 1} \mu(x) = 1$$

$$\mu_{\rm std}(x) = \frac{x}{\sqrt{1+x^2}} \quad , \quad \mu_{\rm sim}(x) = \frac{x}{1+x}$$



[Bekenstein '07]



[Gentile+ '11]

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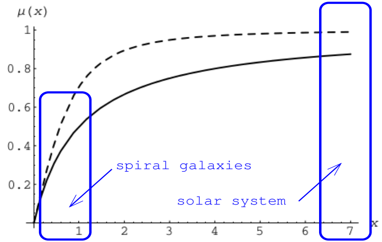

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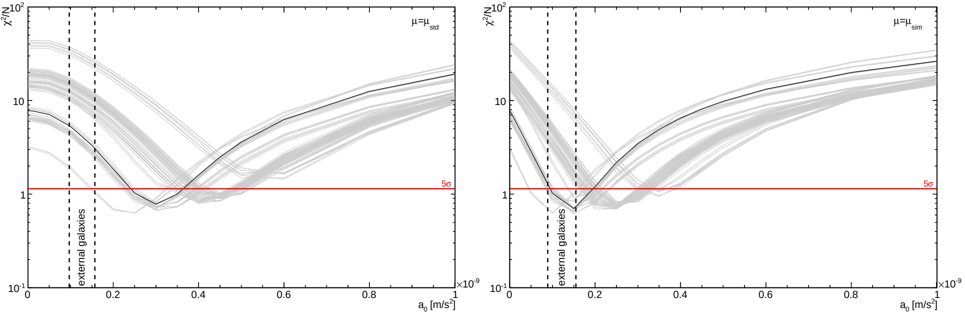

[Iocco, MP & Bertone '15, 1505.05181]

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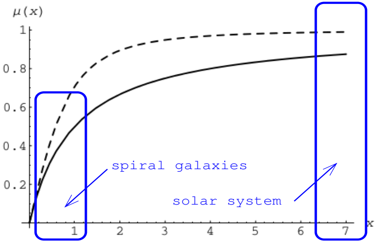

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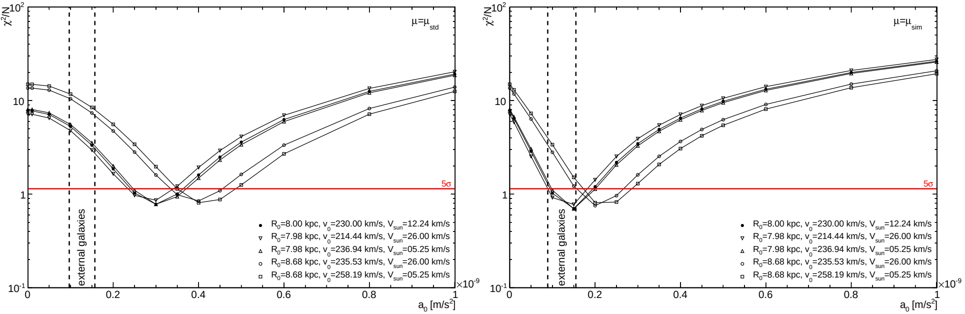

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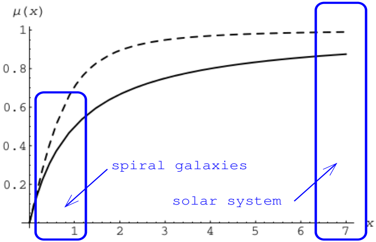

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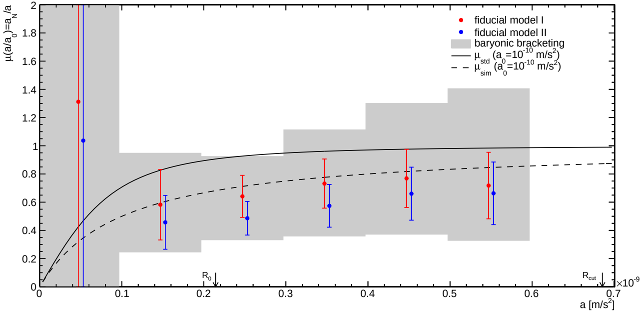
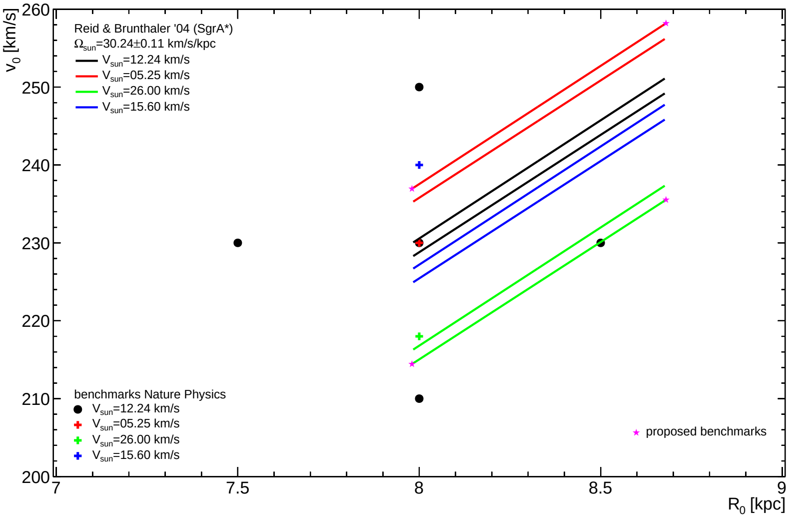


[Iocco, MP & Bertone '15, 1505.05181]

2. GALACTIC PARAMETERS



[Iocco, MP & Bertone '15, 1505.05181]

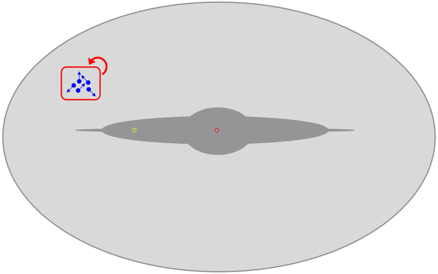
3. FUTURE DIRECTIONS?

local methods vs global methods

local methods

aim: use data from a patch of the sky to derive dynamics there.

+ “assumption-free”
− low precision

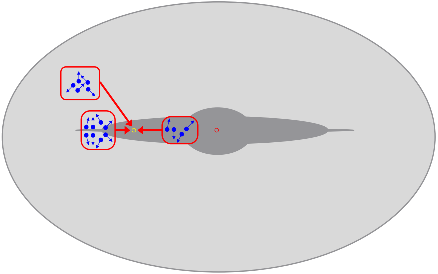


[Kapteyn '22, Jeans '22, Oort '32, Hill '60, Oort '60, Bahcall '84, Bienaymé+ '87, Kuijken & Gilmore '91, Bahcall+ '92, Creze+ '98, Holmberg & Flynn '00, Holmberg & Flynn '04, Bienaymé+ '06, Garbari+ '11 '12, Moni Bidin+ '12, Bovy & Tremaine '12, Smith+ '12, Zhang+ '13, Bovy & Rix '13, Loebman+ '14, Moni Bidin+ '14]

global methods

aim: use data across the Galaxy to derive dynamics somewhere.

− global assumptions
+ high precision



[Caldwell & Ostriker '81, Gates+ '95, Dehnen & Binney '98, Sakamoto+ '03, Dehnen+ '06, Xue+ '08, Sofue+ '09, Strigari & Trotta '09, Catena & Ullio '10, Weber & de Boer '10, Salucci+ '10, Iocco+ '11, McMillan '11, Nesti & Salucci '13, Bhattacharjee+ '14, Kafle+ '14, MP & Iocco '15, MP, Iocco & Bertone '15, Sofue '15]

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local methods vs global methods

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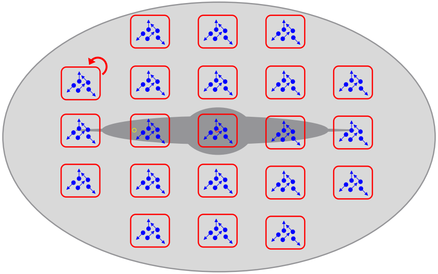

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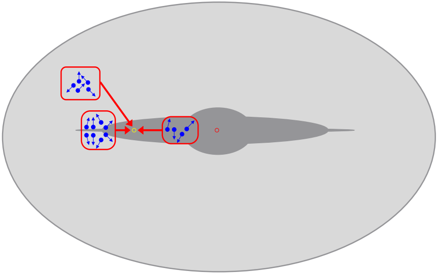

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3. FUTURE DIRECTIONS?

WFIRST

[Credit: NASA]

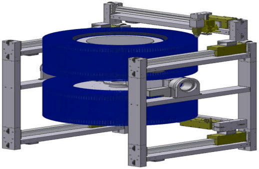
fact sheet

20??-20??+6
space-based
$\lambda = 760 - 2000\,\mathrm{nm}$
radial velocity ?

wish list

(dark energy)
(exoplanets)
bulge modelling?
?

WEAVE



[Credit: WEAVE]

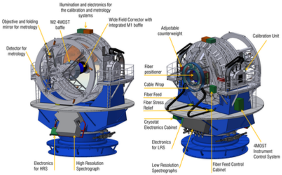
fact sheet

20??-20??
northern hemisphere
$\lambda = 370 - 1000\,\mathrm{nm}$
1000 million stars
radial velocity $\pm 5\,\mathrm{km/s}$

wish list

(cosmology)
kinematics all across
?

4MOST



[Credit: ESO]

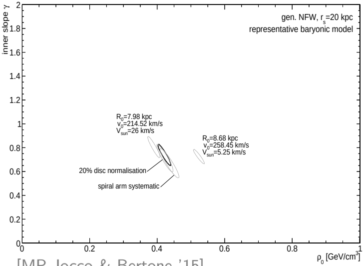
fact sheet

20??-20??+5
southern hemisphere
$\lambda = 390 - 950\,\mathrm{nm}$
30 million stars
radial velocity $\pm 2\,\mathrm{km/s}$

wish list

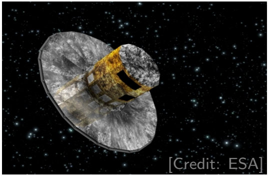
bulge kinematics
disc kinematics
stellar halo kinematics
?

3. FUTURE DIRECTIONS?



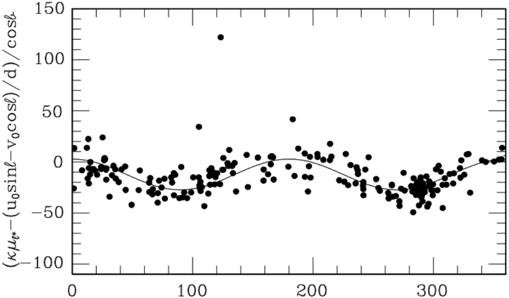
[MP, Iocco & Bertone '15]

Gaia



<u>fact sheet</u>

2013-2018
$\lambda = 320 - 1000\,\mathrm{nm}$
10^9 stars $G < 20\,\mathrm{mag}$
parallax $\pm 10\,\mu\mathrm{as}$
proper motion $\pm 10\,\mu\mathrm{as/yr}$
radial velocity $\pm 1\,\mathrm{km/s}$



[Feast & Whitelock '97]

Oort constants:

$$A = \frac{1}{2}\left(\frac{v_0}{R_0} - v_0'\right) \qquad B = -\frac{1}{2}\left(\frac{v_0}{R_0} + v_0'\right)$$

Hipparcos:

$A = +14.82 \pm 0.84\,\mathrm{km/s/kpc}$
$B = -12.37 \pm 0.64\,\mathrm{km/s/kpc}$

Gaia will improve proper motions, radial velocities and parallaxes by a factor 10-200 wrt Hipparcos.

3. FUTURE DIRECTIONS?

The terminal velocity method is very powerful, but it is only applicable in the inner Galaxy at $R < R_0$. In the solar neighbourhood alternative tracers are needed.

We could for instance measure the line-of-sight velocities of local stars. We have then the same expression as before,

$$v_{\rm los} = \left(v(R)\frac{R_0}{R} - v_0 \right) \sin\ell \, ,$$

but now we are interested in the regime $R \sim R_0$.

Problem #9: Taylor-expand the expression above in powers of the distance to the star.

First, let us expand $\Omega \equiv v/R$: $\Omega(R) \simeq \Omega_0 + (R - R_0)\Omega_0'$, and therefore

$$v_{\rm los} = \left(\Omega_0 R_0 + (R - R_0)\Omega_0' R_0 - v_0 \right) \sin\ell = (R - R_0) R_0 \Omega_0' \sin\ell \equiv -2A(R - R_0)\sin\ell \, ,$$

having defined the Oort's constants $A = -\frac{1}{2} R_0 \Omega_0' = \frac{1}{2}\left(\frac{v_0}{R_0} - v_0' \right)$, $B = -\frac{1}{2}\left(\frac{v_0}{R_0} + v_0' \right)$.

From simple geometry, $\vec{R} = \vec{R}_0 + \vec{d} \Rightarrow R^2 = R_0^2 + d^2 - 2dR_0\cos\ell \simeq R_0^2 - 2dR_0\cos\ell$, so

$$R - R_0 = \frac{R^2 - R_0^2}{R + R_0} \simeq \frac{R^2 - R_0^2}{2R_0} \simeq \frac{-2dR_0\cos\ell}{2R_0} = -d\cos\ell \, .$$

Replacing in the expression of $v_{\rm los}$, we obtain finally $\boxed{v_{\rm los} = Ad\sin 2\ell}$.

Problem #10*: Do the same as in #9 but for the transverse velocity.

Follow Binney & Merrifield, Sec. 10.3.3 to obtain $\boxed{\mu_\ell = B + A\cos 2\ell}$.

The bottomline is that by measuring the motion of local stars we can constrain A, B and thus the local circular velocity: $v_0 = R_0(A - B) \simeq 220\,{\rm km/s}$.