



Stockholm
University

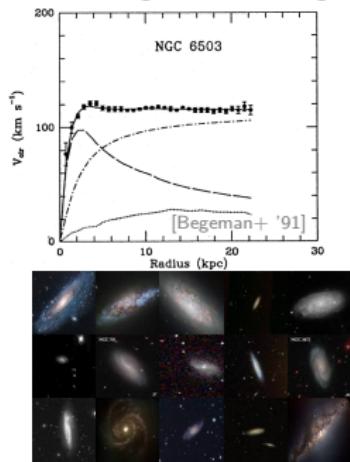
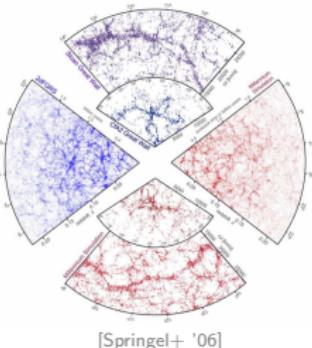
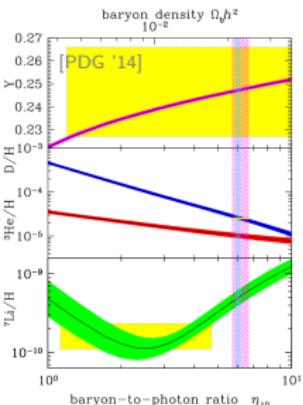
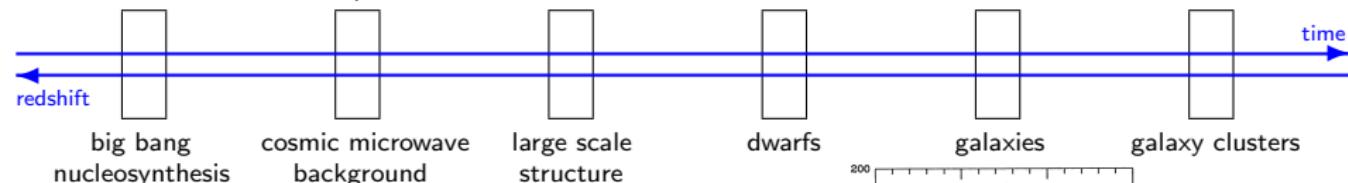
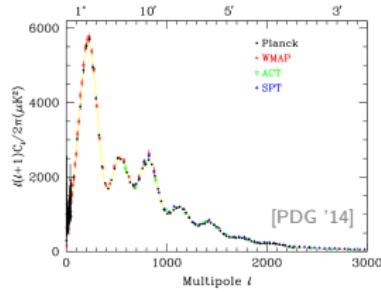
MAPPING DARK MATTER IN THE MILKY WAY

Miguel Pato

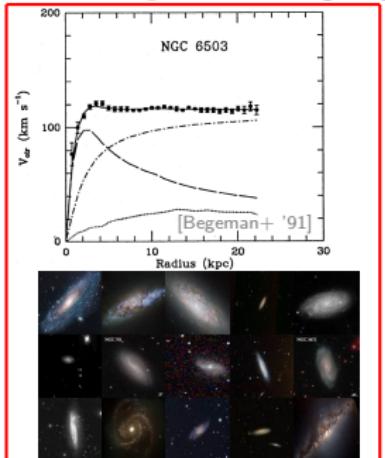
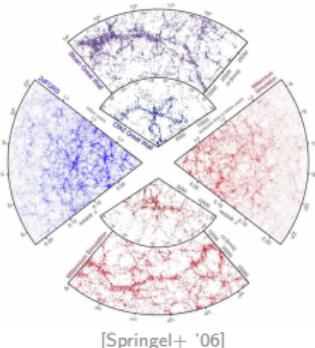
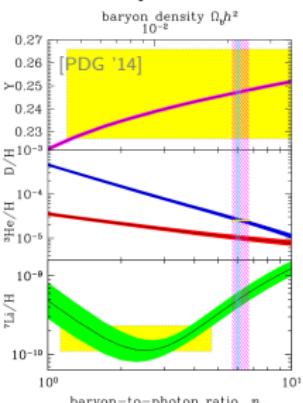
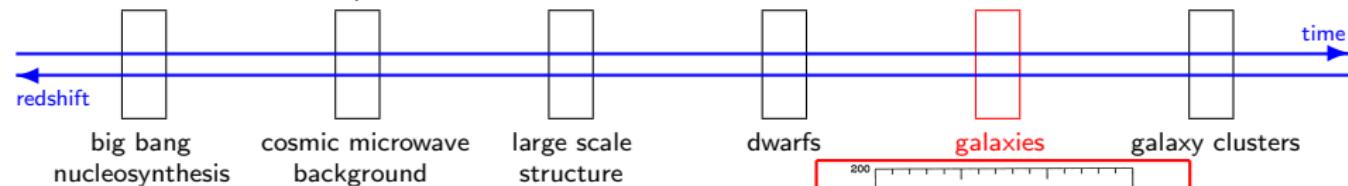
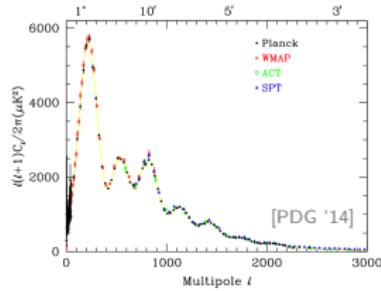
Wenner-Gren Fellow

The Oskar Klein Centre for Cosmoparticle Physics, Stockholm University

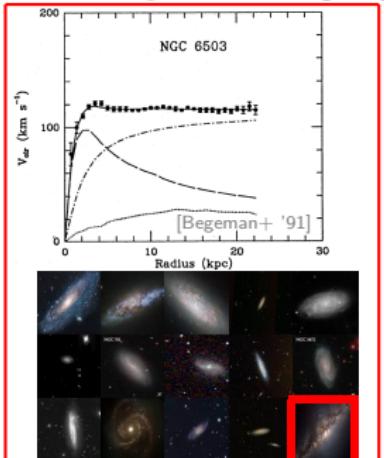
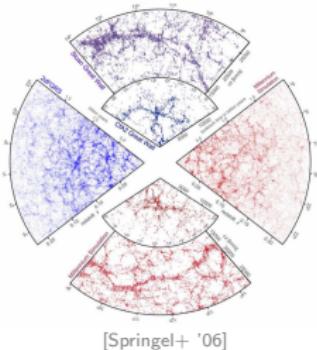
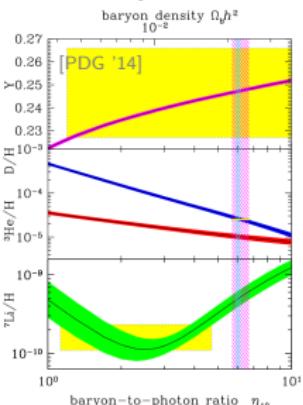
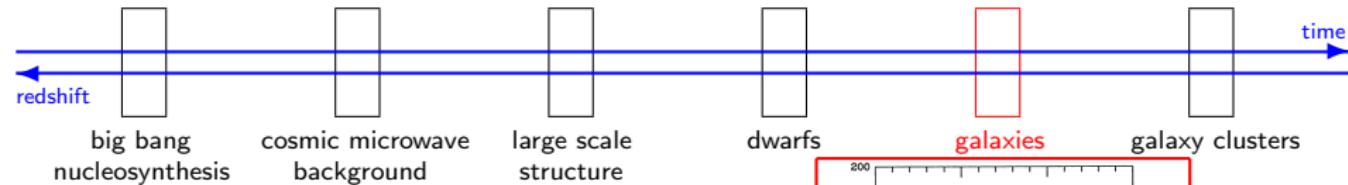
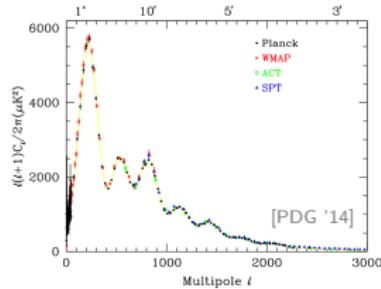
DARK MATTER IN THE UNIVERSE



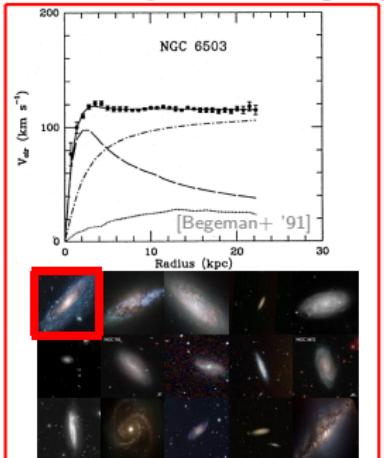
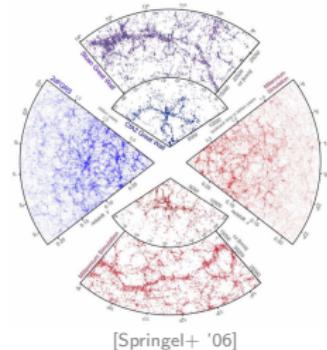
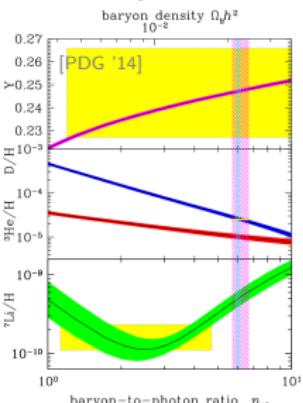
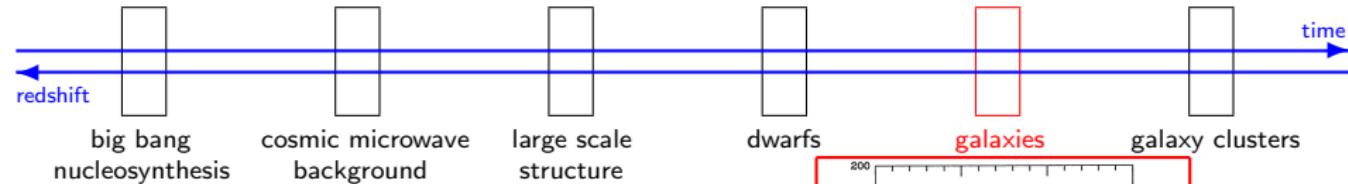
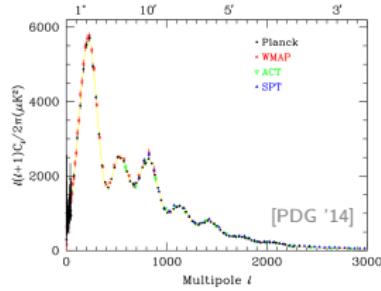
DARK MATTER IN GALAXIES



DARK MATTER IN THE MILKY WAY

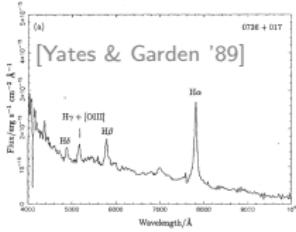


DARK MATTER IN ANDROMEDA



HISTORICAL PARENTHESIS: ANDROMEDA

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



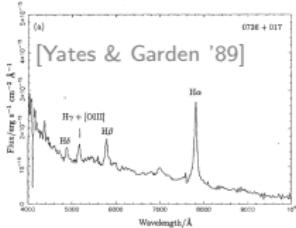
The kinematics of Andromeda has been studied since the 1930s through the Doppler shift of spectral lines in the gas.

$$\Delta\nu = -\frac{v_{\text{los}}}{c} \nu_0$$

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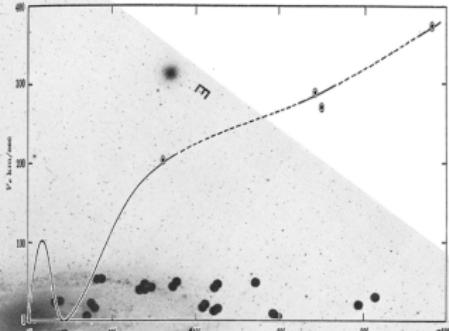


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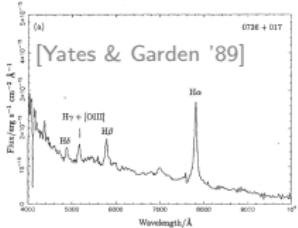
$$\Delta\nu = -\frac{v_{\text{los}}}{c} \nu_0$$



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

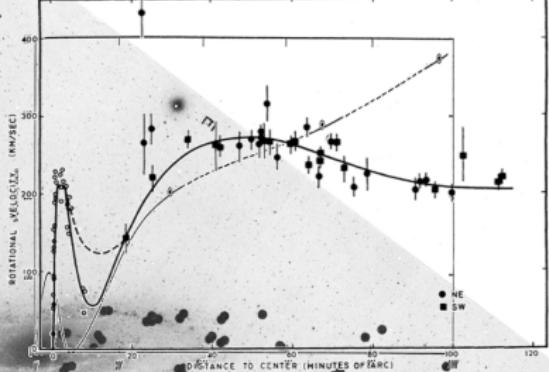
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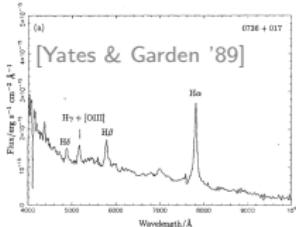


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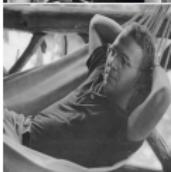
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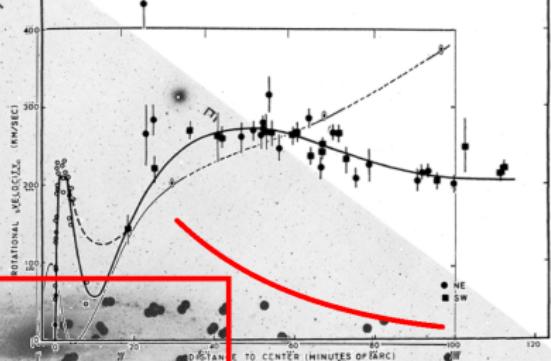
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$$\Delta\nu = -\frac{v_{\text{los}}}{c} \nu_0$$



visible matter

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

Under Newtonian gravity, a spherical mass induces

$$v_c^2 = \frac{GM(< r)}{r}$$

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 $M(< r) \propto r$.

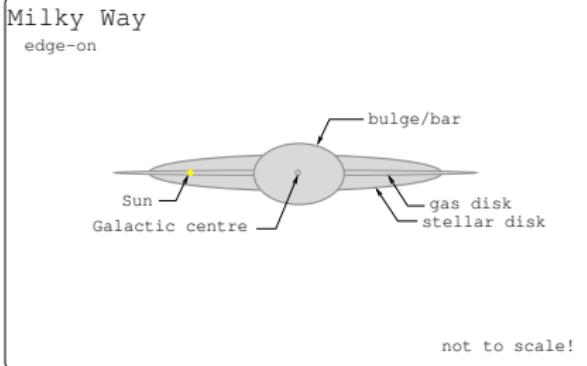
* Modifications of gravity at galactic scales are also feasible. [Milgrom x3 '83]

1. TOUR OF THE GALAXY

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

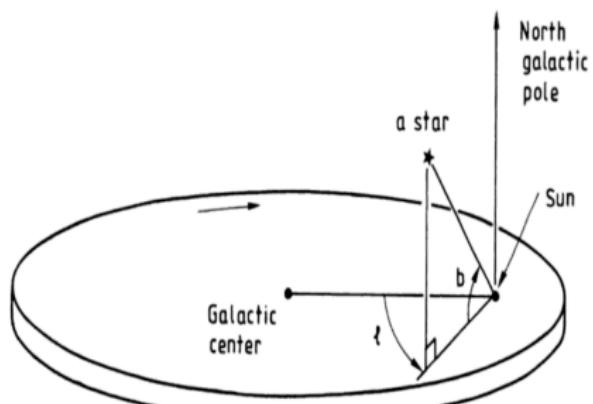


[Brunier]



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 $2 - 3 \text{ kpc}$ 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

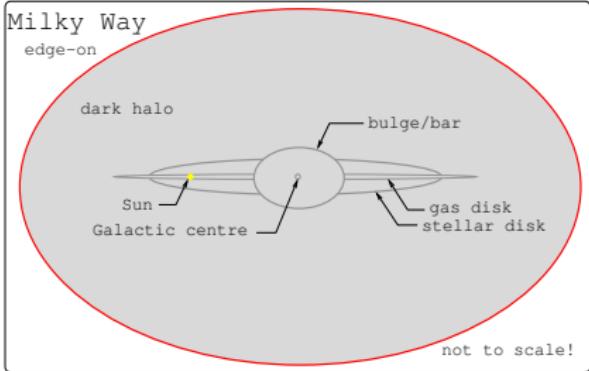


The Sun is located slightly above the Galactic plane at $R_0 \simeq 8 \text{ kpc}$ from the Galactic centre, in between two major spiral arms, and travels together with the local standard of rest at about 220 km/s in a roughly circular orbit.

[Binney & Tremaine '87]

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- 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.

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

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

The Sun is located slightly above the Galactic plane at $R_0 \simeq 8 \text{ kpc}$ 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

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

kinematics traces total potential

- | | |
|--------------------------------|-------------------------|
| $R \sim 0.1 - 30 \text{ kpc}$ | rotation curve tracers |
| $R \sim 8 - 60 \text{ kpc}$ | star population tracers |
| $R \sim 100 - 300 \text{ kpc}$ | satellite kinematics |
| $R \sim 300+ \text{ kpc}$ | 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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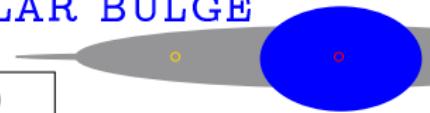
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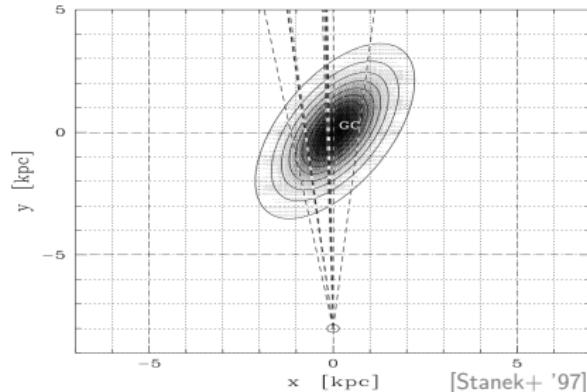
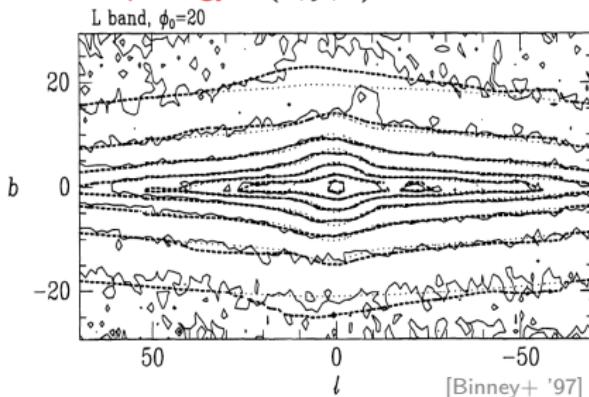
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1. TOUR OF THE GALAXY: STELLAR BULGE



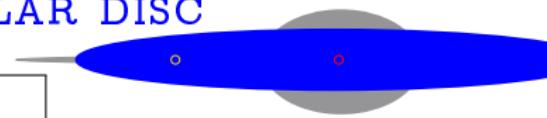
$$\rho_{\text{bulge}} = \rho_0 f(x, y, z)$$

morphology $f(x, y, z)$



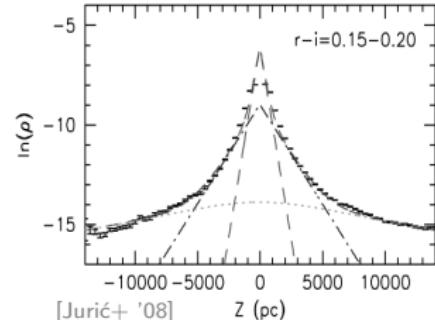
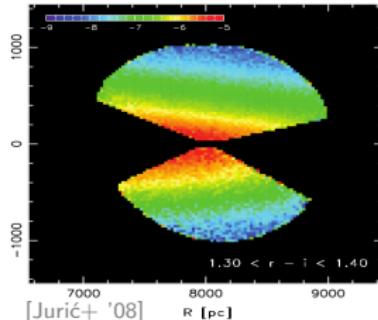
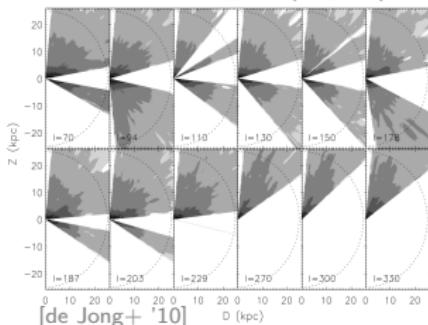
Stanek+ '97 (E2)	e^{-r}	0.9:0.4:0.3	24°	optical
Stanek+ '97 (G2)	$e^{-r_s^2/2}$	1.2:0.6:0.4	25°	optical
Zhao '96	$e^{-r_s^2/2} + r_a^{-1.85} e^{-r_a}$	1.5:0.6:0.4	20°	infrared
Bissantz & Gerhard '02	$e^{-r_s^2/(1+r)^{1.8}}$	2.8:0.9:1.1	20°	infrared
Lopez-Corredoira+ '07	Ferrer potential	7.8:1.2:0.2	43°	infrared/optical
Vanhollebeke+ '09	$e^{-r_s^2/(1+r)^{1.8}}$	2.6:1.8:0.8	15°	infrared/optical
Robin+ '12	$\operatorname{sech}^2(-r_s) + e^{-r_s}$	1.5:0.5:0.4	13°	infrared

1. TOUR OF THE GALAXY: STELLAR DISC



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

morphology $f(x, y, z)$



Han & Gould '03

$$e^{-R} \operatorname{sech}^2(z)$$

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

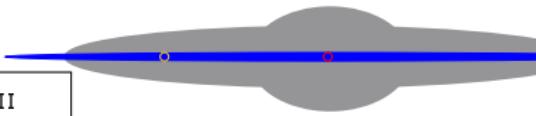
$$e^{-R-|z|}$$

2.2:0.40

single

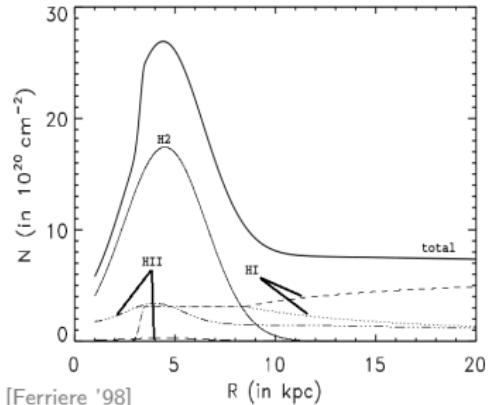
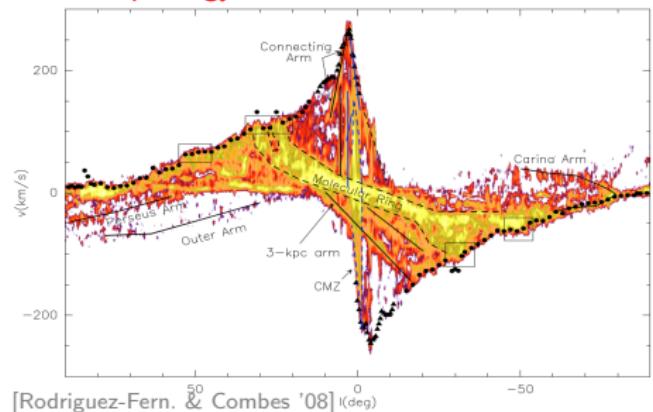
optical

1. TOUR OF THE GALAXY: GAS



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

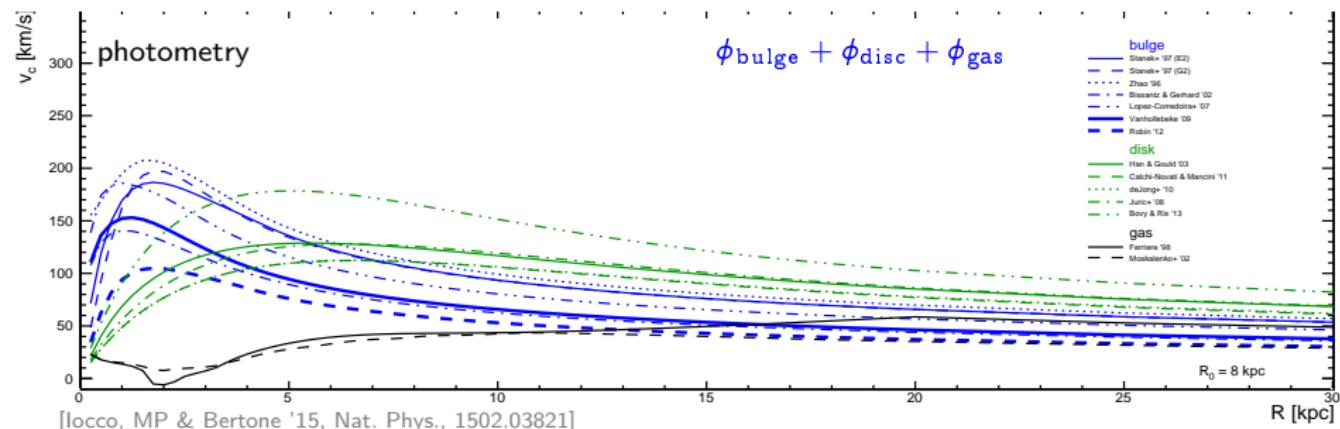
morphology



Ferrière '12	$r < 0.01 \text{ kpc}$	$M_{\text{gas}} \sim 7 \times 10^5 M_{\odot}$	CO, 21cm, H α , ...
Ferrière+ '07	$r = 0.01 - 2 \text{ kpc}$	CMZ, holed disc	H ₂ CO
		CMZ, holed disc	H I 21cm
		warm, hot, very hot	H II disp. meas.
Ferrière '98	$r = 3 - 20 \text{ kpc}$	molecular ring	H ₂ CO
		cold, warm	H I 21cm
		warm, hot	H II disp. meas., H α
Moskalenko+ '02	$r = 3 - 20 \text{ kpc}$	molecular ring	H ₂ CO
			H I 21cm
			H II disp. meas.

1. TOUR OF THE GALAXY: PHOTOMETRY

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



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disc star counts, luminosity, stellar dynamics

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1. TOUR OF THE GALAXY: ROTATION CURVE

$$v_c^2 = r \frac{d\phi_{\text{tot}}}{dr} \stackrel{\text{sph.}}{\equiv} \frac{G M_{\text{tot}}(< r)}{r}$$

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]

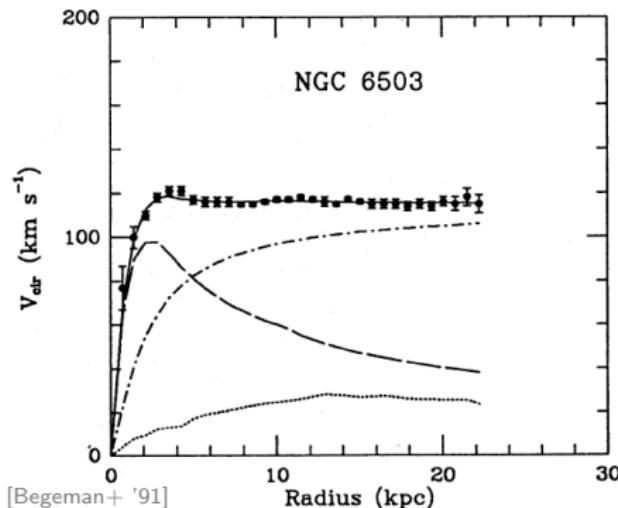


[Credit: Brunier / NASA]

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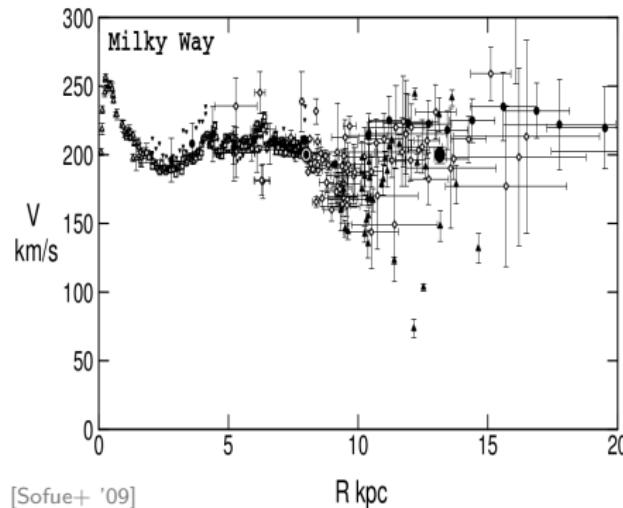
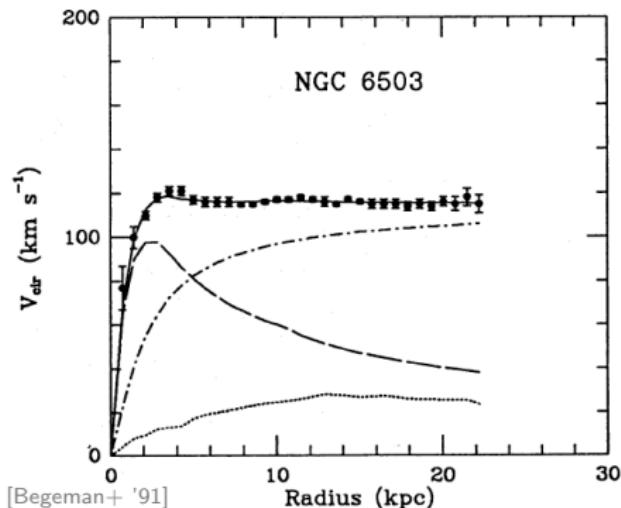
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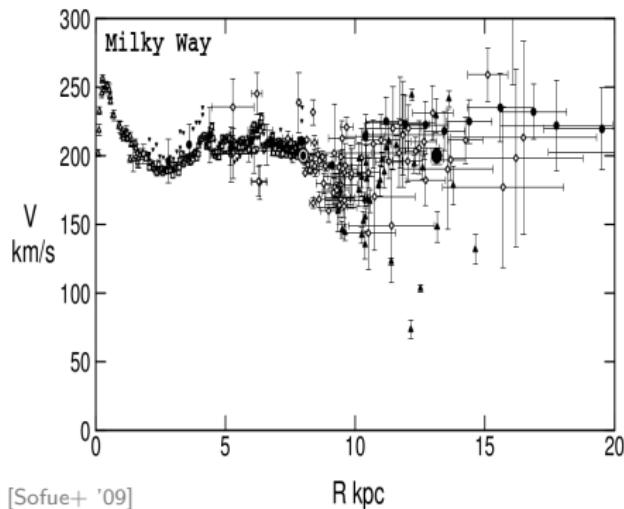
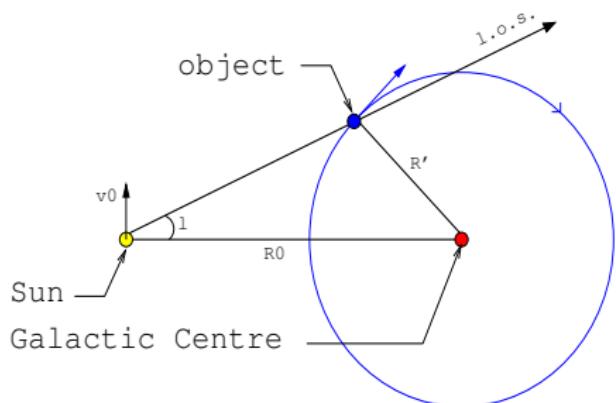
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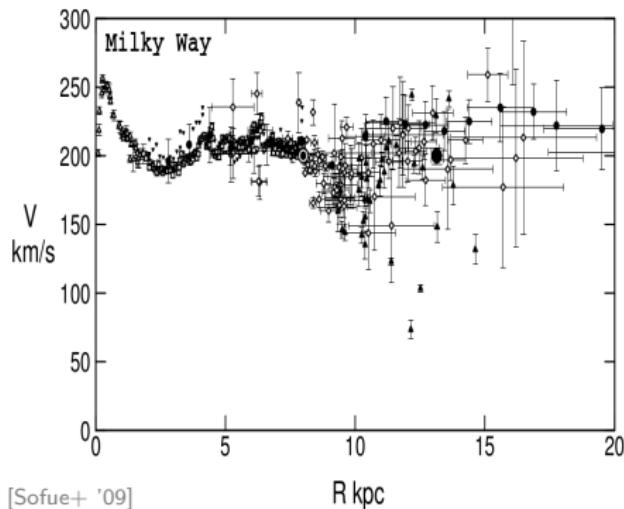
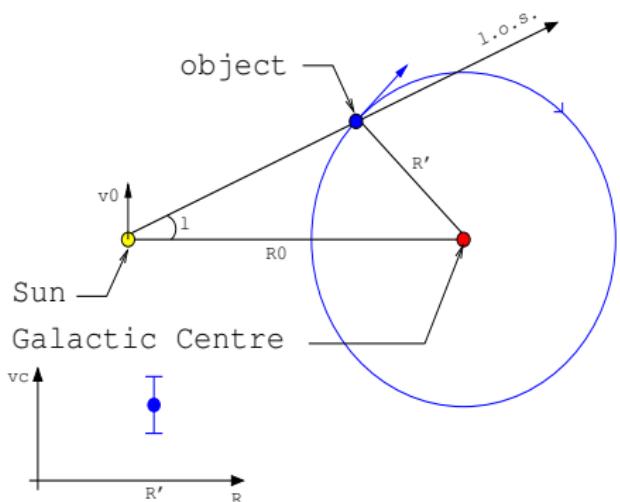


$$v_{\text{los}}^{\text{obs}} = \left(\frac{v_c(R')}{R'/R_0} - v_0 \right) \cos b \sin \ell$$

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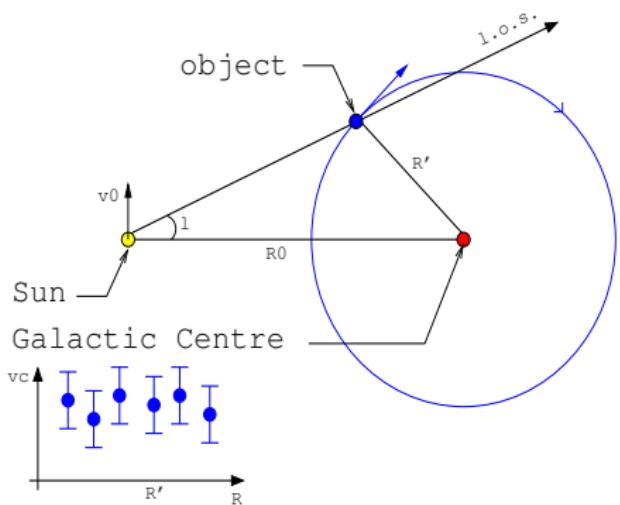


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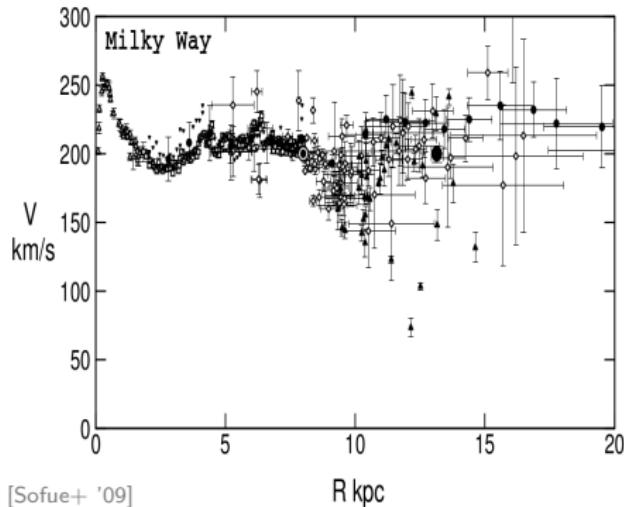
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Rotation curve tracers are young objects or regions that track galactic rotation. In external galaxies the only available tracer is the gas, while in our Galaxy we can use also some stars and star-forming regions. However, the case of our Galaxy is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

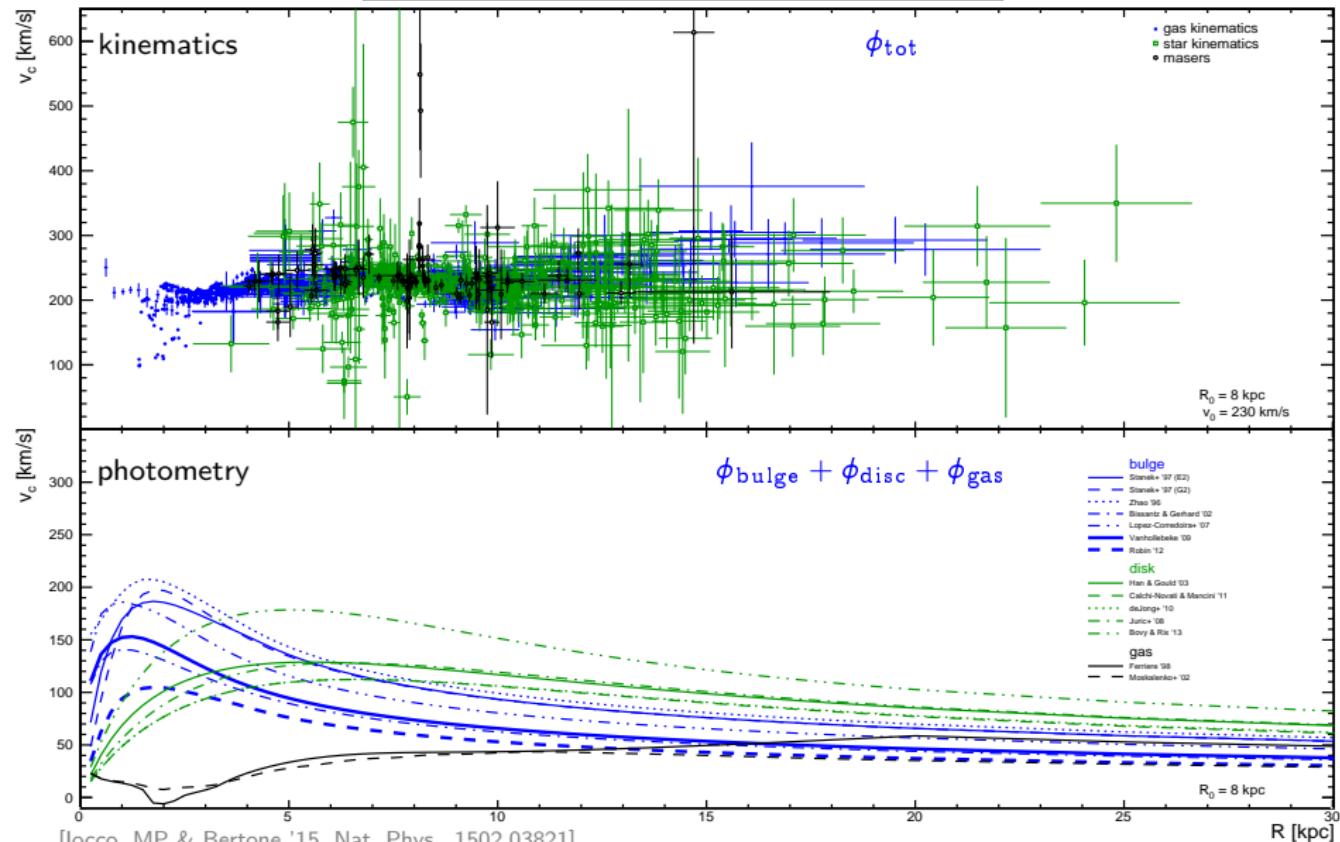


$$v_{\text{los}}^{\text{ISR}} = \left(\frac{v_c(R')}{R'/R_0} - v_0 \right) \cos b \sin \ell$$



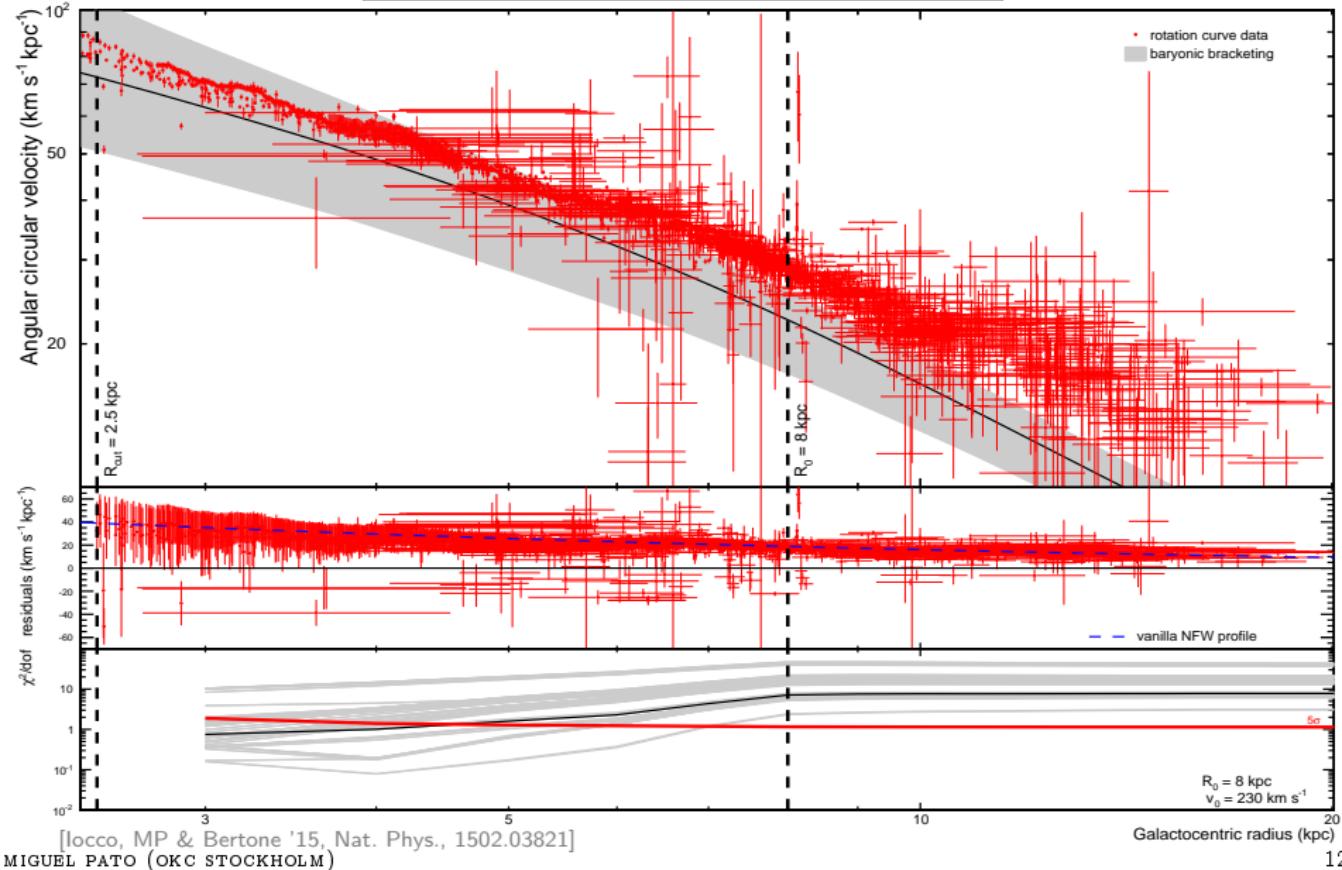
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2. DARK MATTER: LOCALISE OR GLOBALISE?

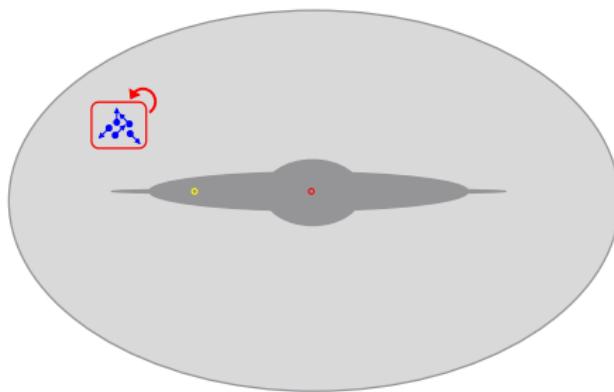
local methods

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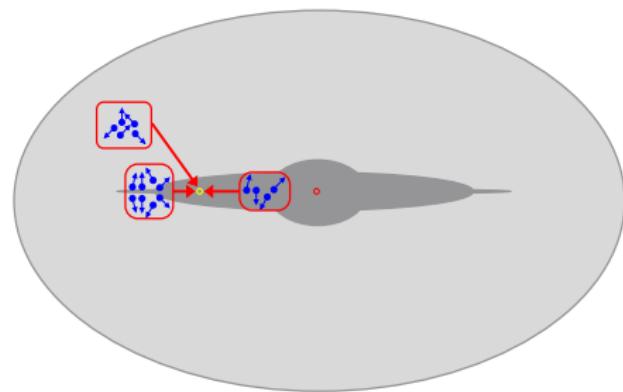
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- + “assumption-free”
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2. LOCAL METHODS

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**:

$$-\rho_s \frac{\partial \phi_{\text{tot}}}{\partial x_j} = \frac{\partial(\rho_s \bar{v}_j)}{\partial t} + \sum_i \frac{\partial(\rho_s \bar{v}_i \bar{v}_j)}{\partial x_i} , \quad j = 1, 2, 3 \text{ (cartesian)} .$$

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$$\phi_{\text{tot}}(R, z) \quad \partial/\partial t \rightarrow 0 \quad -F_R = \partial \phi_{\text{tot}} / \partial R \quad -F_z = \partial \phi_{\text{tot}} / \partial z$$

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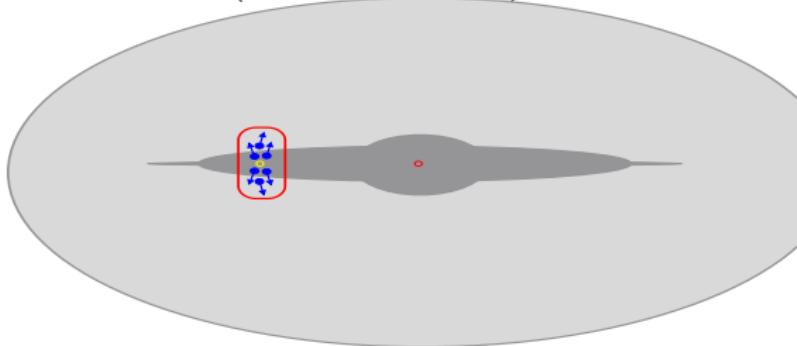
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This is the so-called Oort limit.

[Oort '32]

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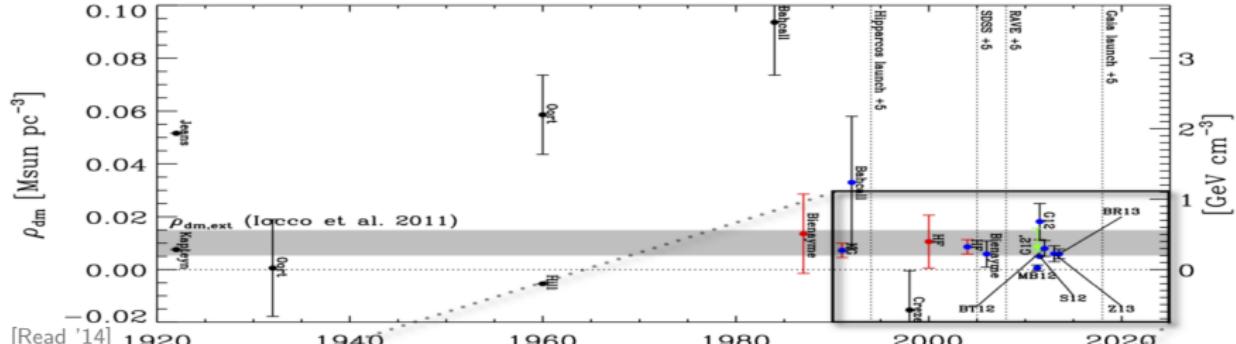
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[Read '14], [Bienaymé+ '87, Kuijken & Gilmore '89, Creze+ '98, Holmberg & Flynn '00, Garbari+ '11 '12, Smith+ '12, Zhang+ '13]

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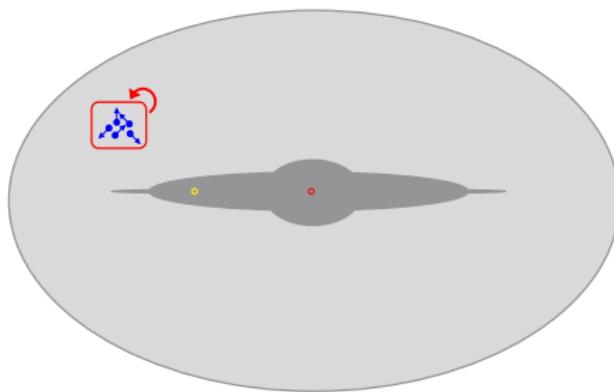
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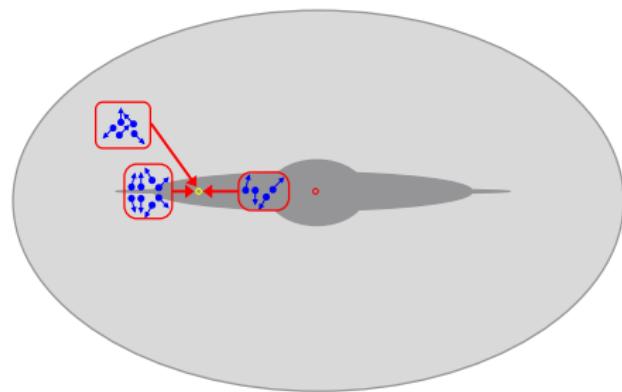
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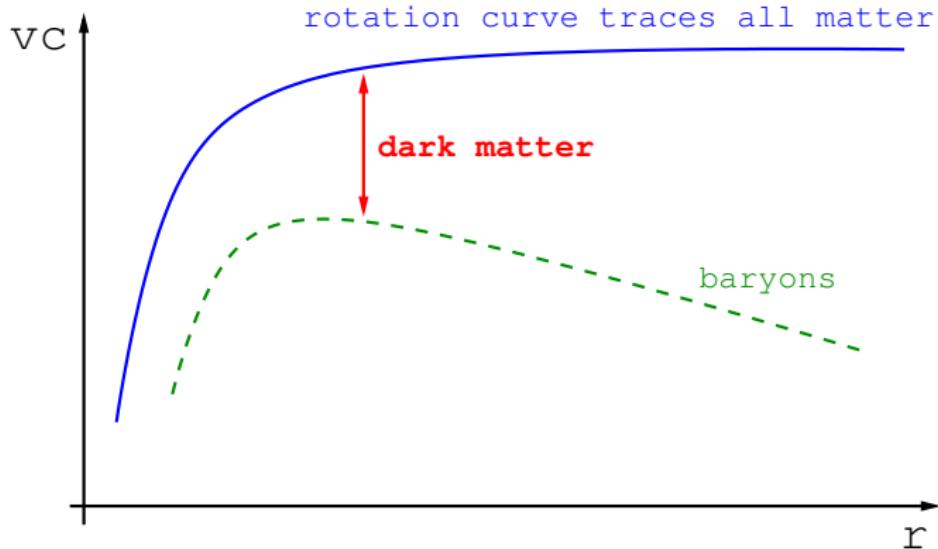


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2. GLOBAL METHODS

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

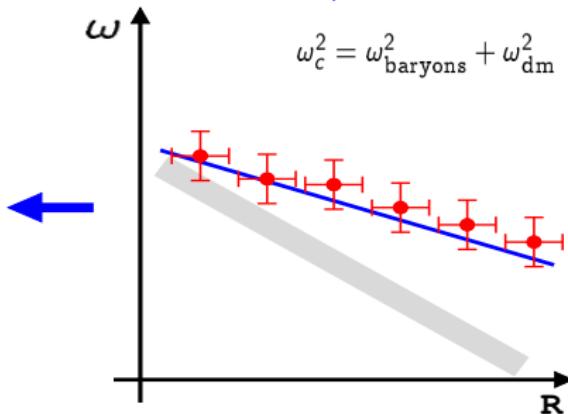
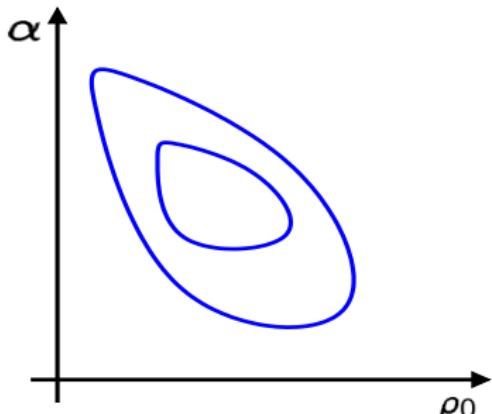
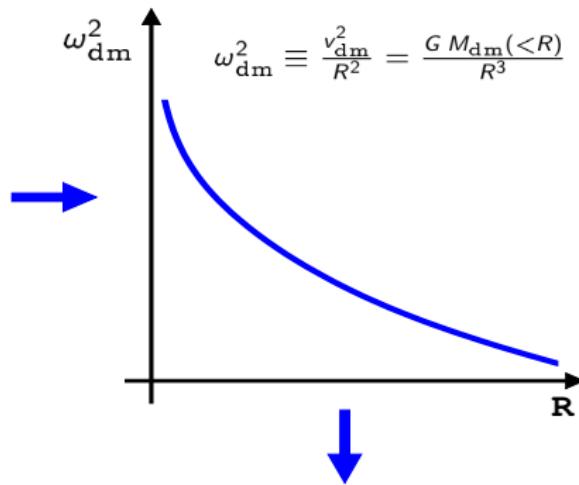
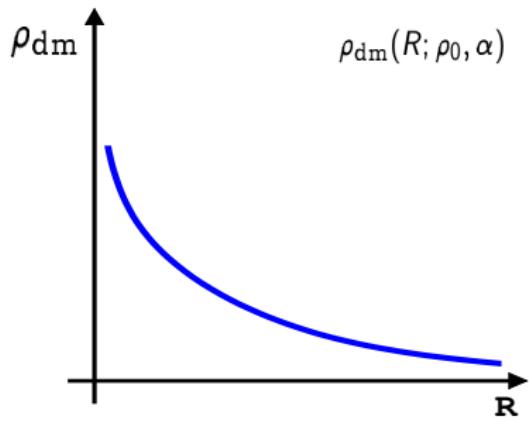


$$v_c^2 = v_b^2 + v_{\text{dm}}^2$$

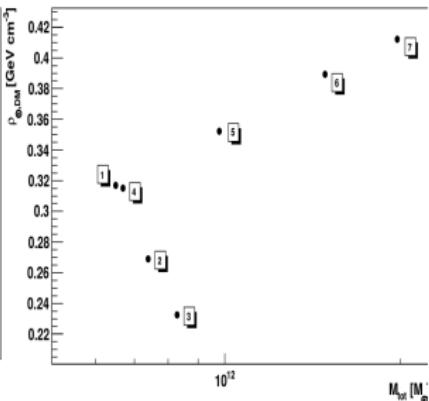
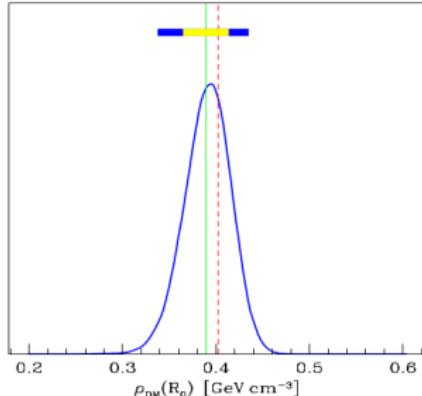
$$v_{\text{dm}}^2 \stackrel{\text{sph.}}{=} G M_{\text{dm}}() / r \rightarrow \rho_{\text{dm}}$$

[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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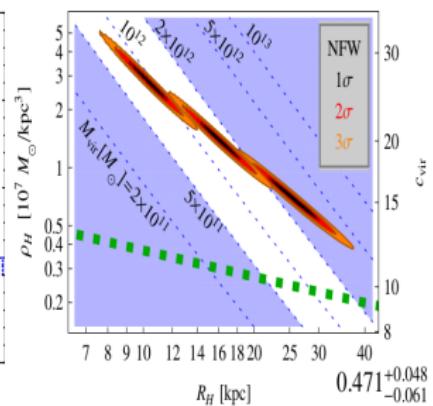
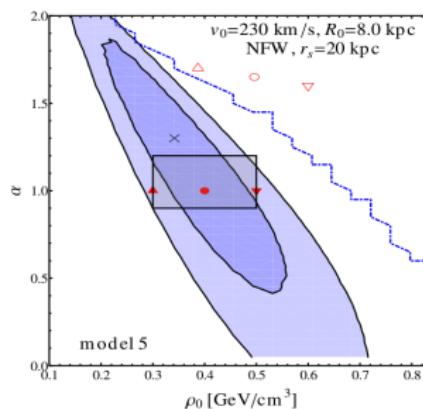
2. GLOBAL METHODS



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

[Salucci '10]

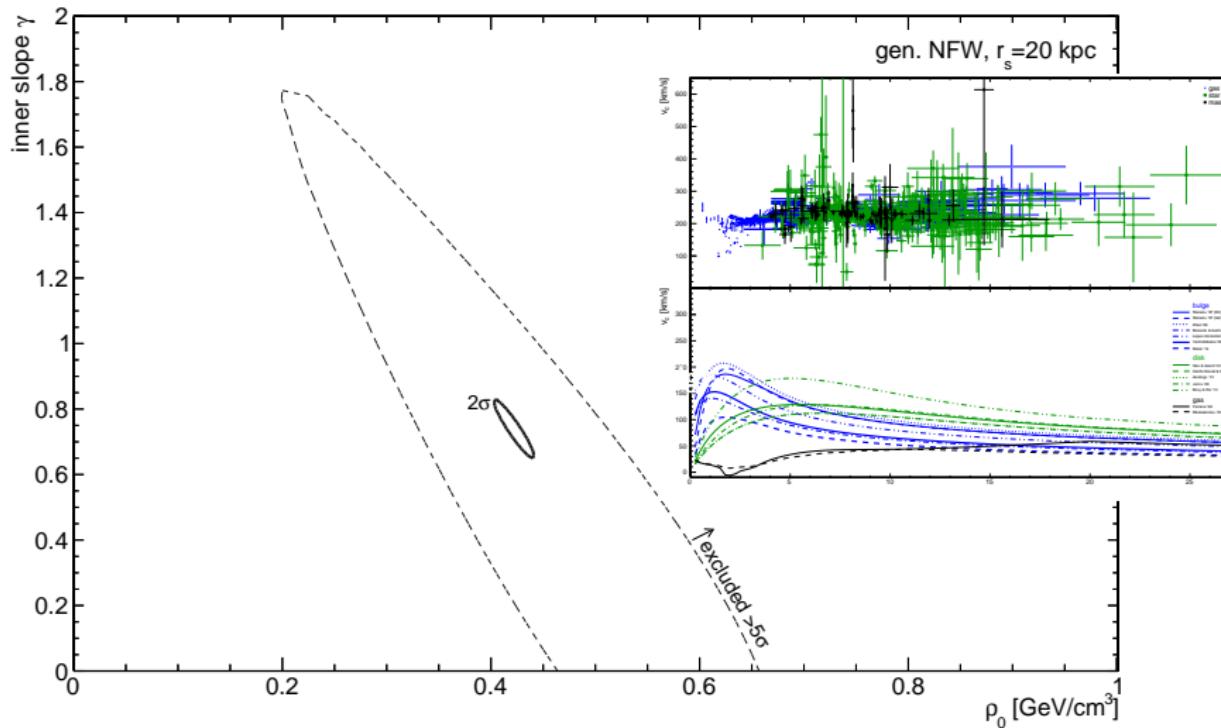
$$0.40 \pm 0.04 \text{ GeV cm}^{-3}$$



[McMillan '11]

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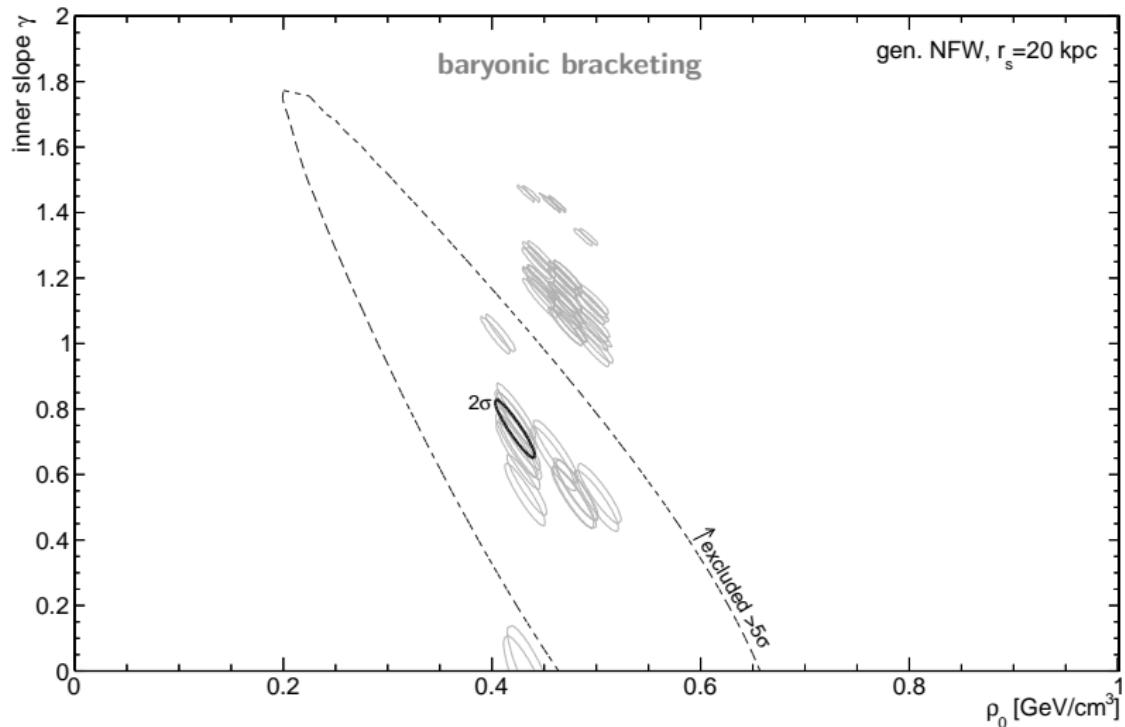
$\rho_{\text{dm}} \propto (r/r_s)^{-\gamma} (1+r/r_s)^{-3+\gamma}$ [MP, Iocco & Bertone '15, 1504.06324]



$$\text{NFW: } \rho_0 = 0.420^{+0.021}_{-0.018} \text{ (2}\sigma\text{)}$$

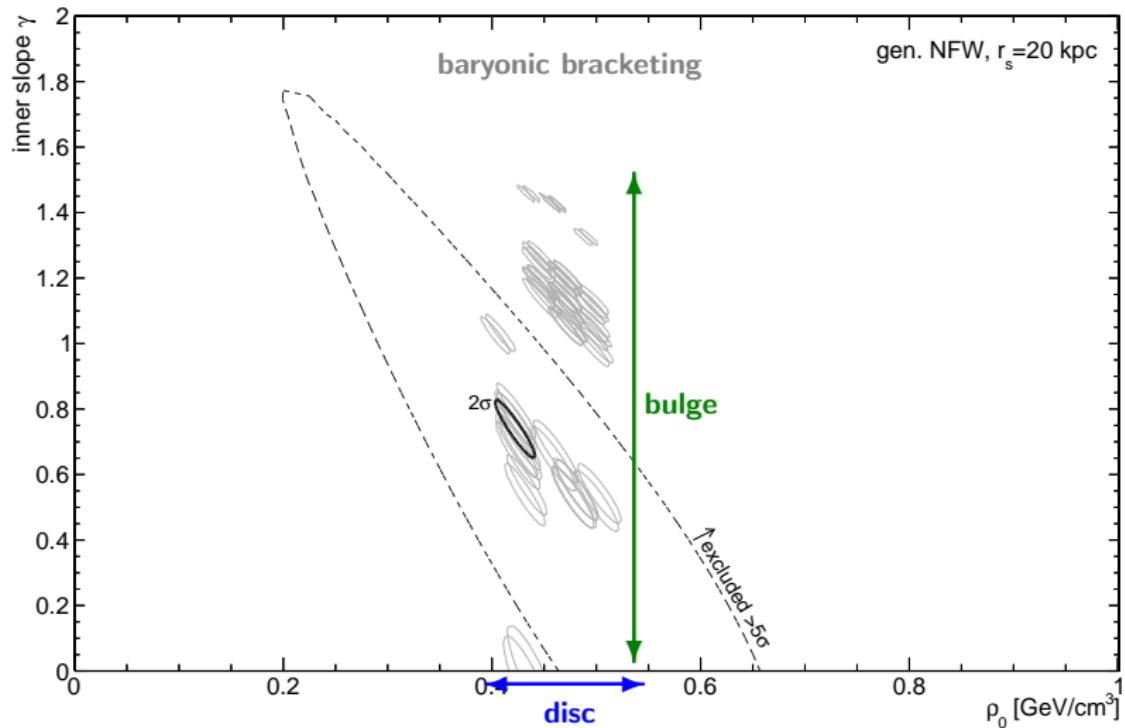
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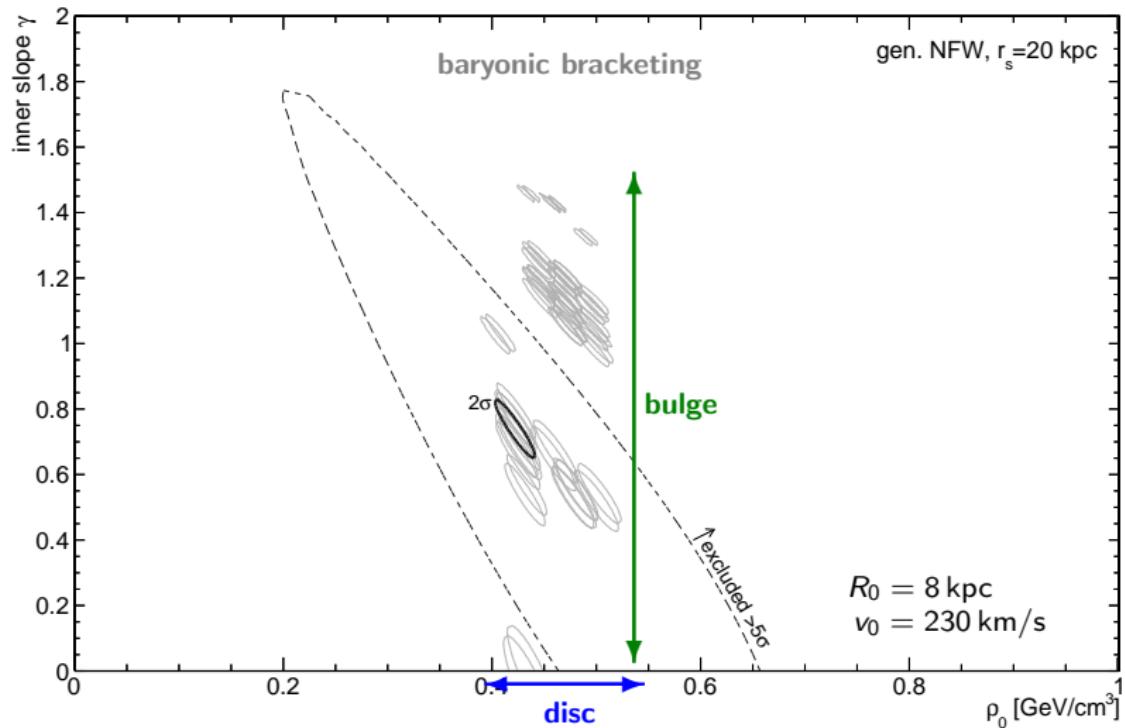
$$\text{NFW: } \rho_0 = 0.420^{+0.021}_{-0.018} (2\sigma) \pm 0.025 \text{ GeV/cm}^3$$

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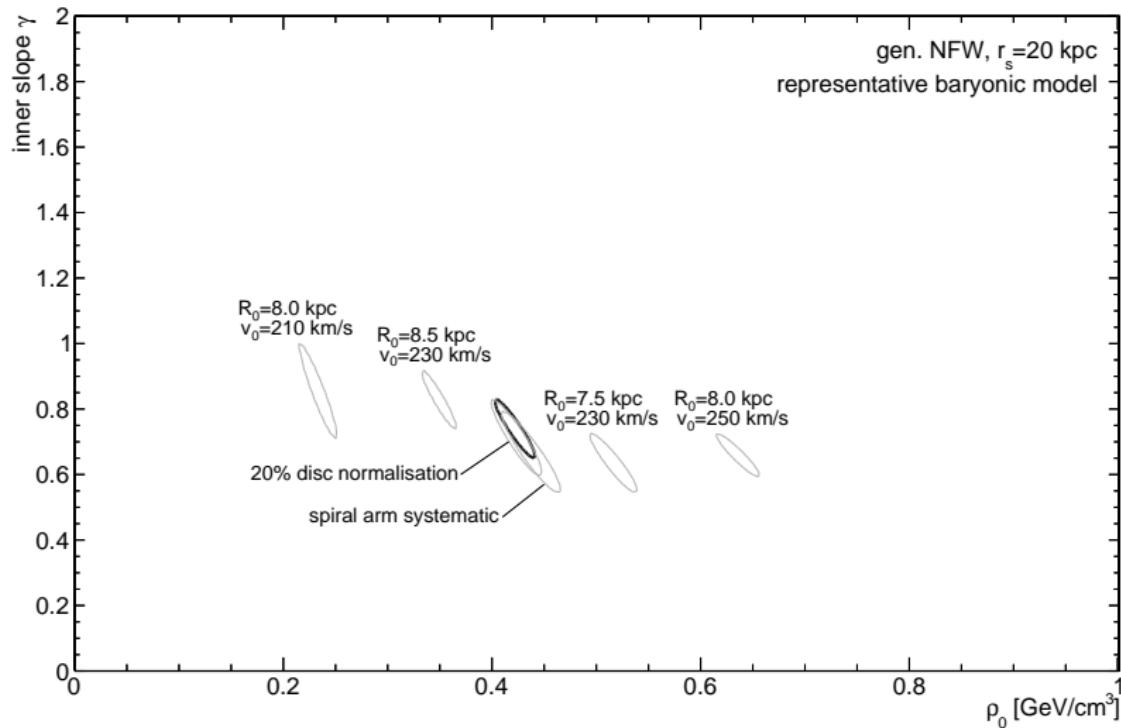
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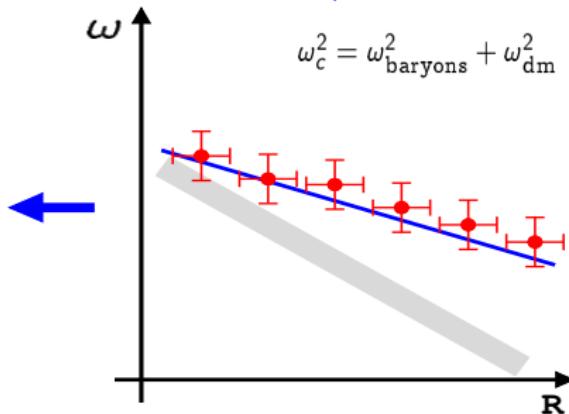
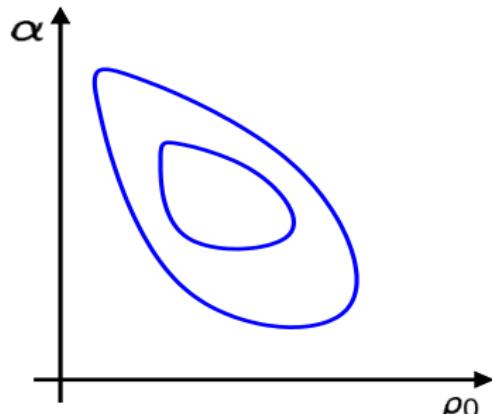
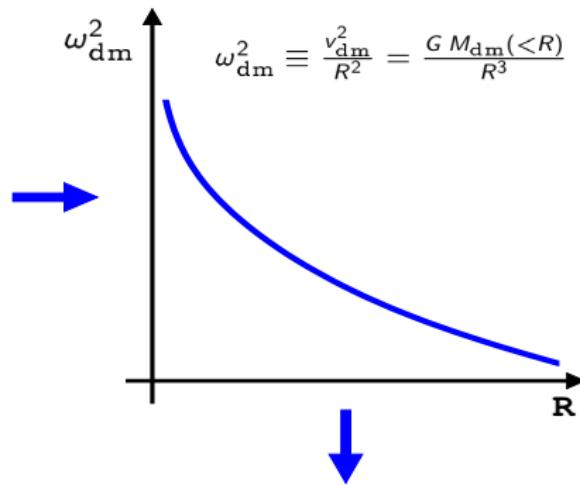
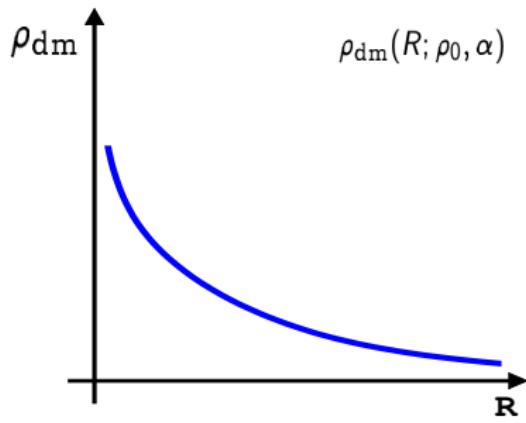
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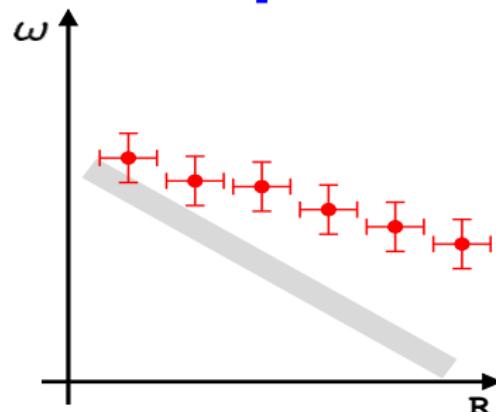
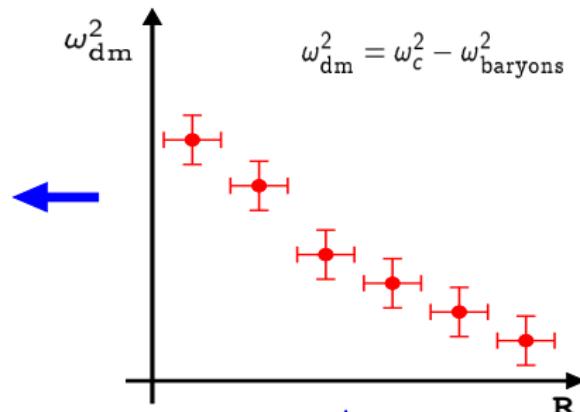
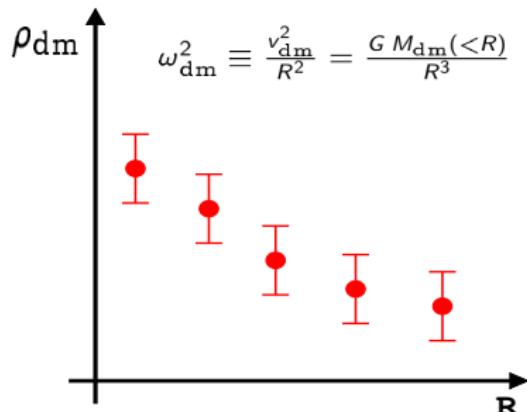
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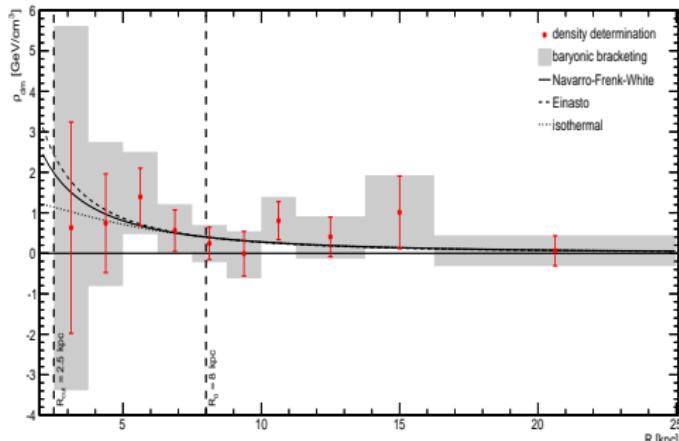
Let us take a spherical dark matter distribution. Then,

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

Solving for ρ_{dm} ,

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

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



3. FUTURE DIRECTIONS?

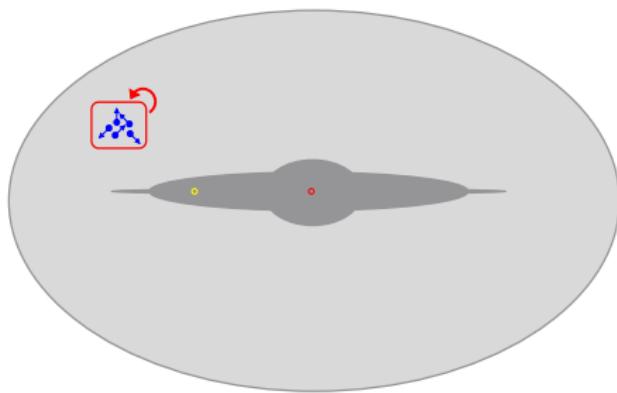
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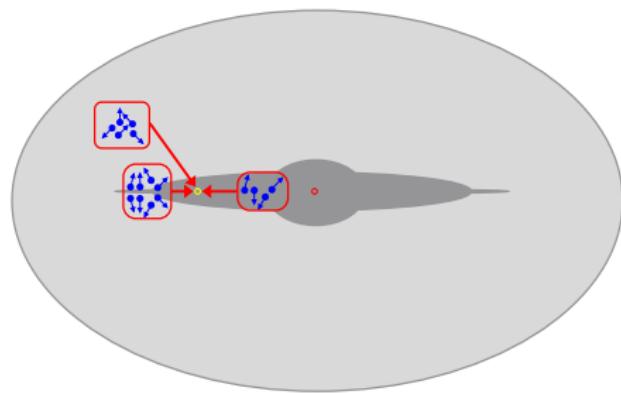
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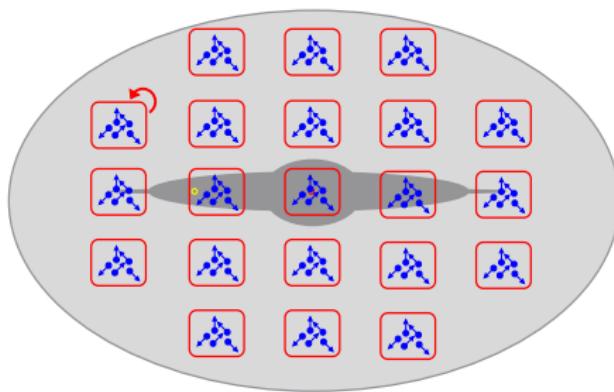
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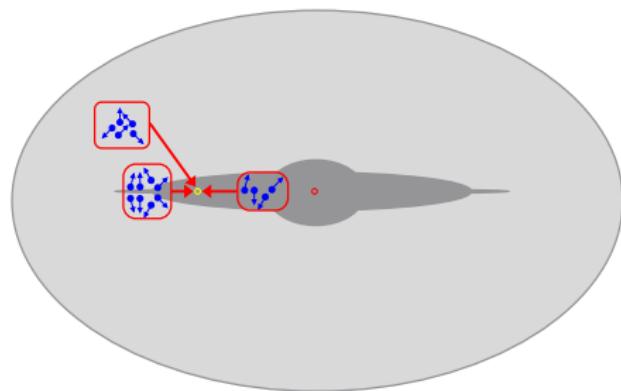
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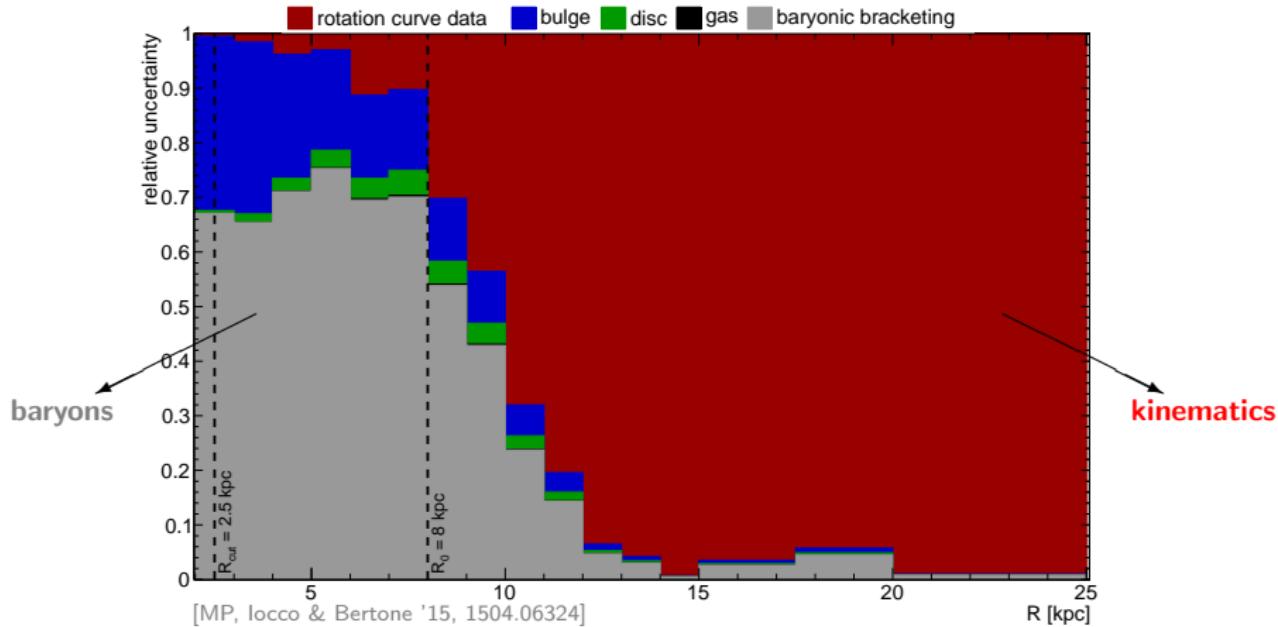
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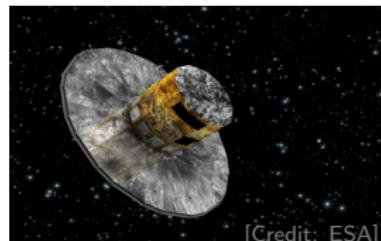
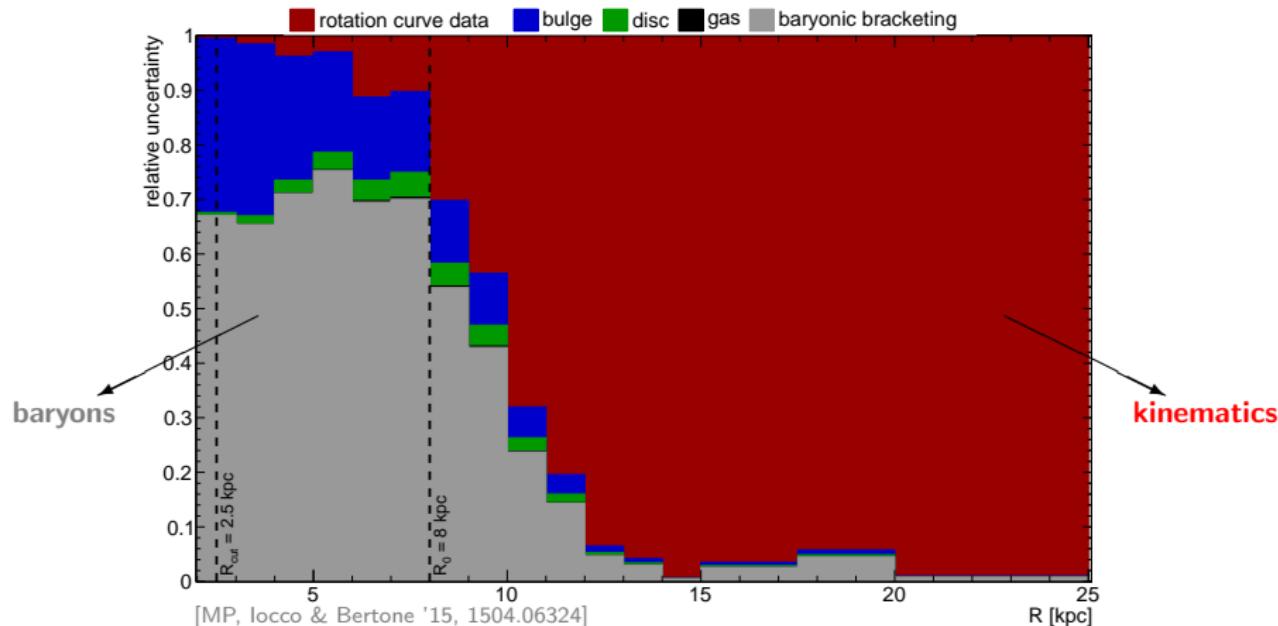
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[Credit: ESA]

Gaia

fact sheet

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

wish list

disc modelling
Oort's constants
local density

4. EXECUTIVE 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.