MAPPING DARK MATTER IN THE MILKY WAY

Miguel Pato
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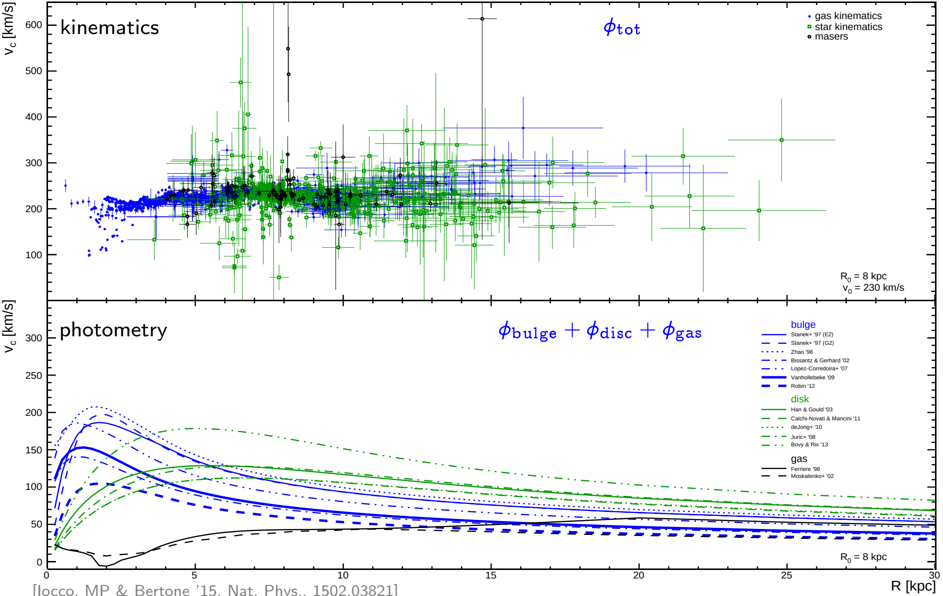
in collaboration with Fabio Iocco and Gianfranco Bertone

TAUP 2015, Torino, 8 Sep 2015

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]

1. TOUR OF THE GALAXY: SUMMARY

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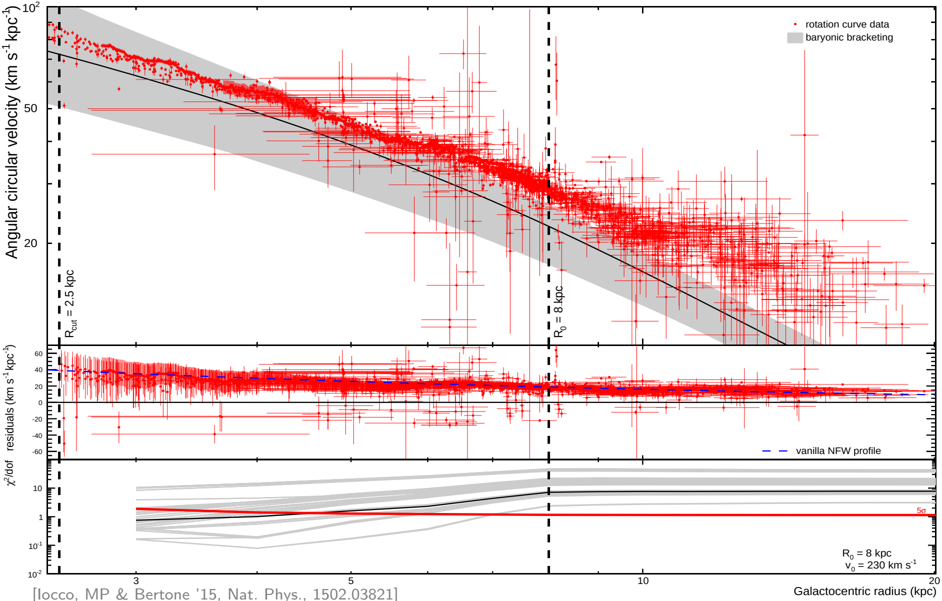


[Iocco, MP & Bertone '15, Nat. Phys., 1502.03821]

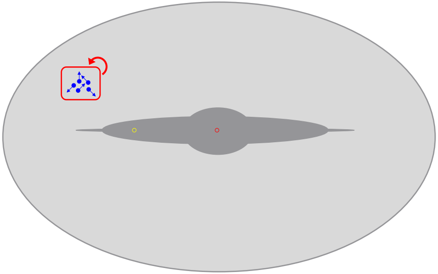
2. DARK MATTER: LOCALISE OR GLOBALISE?

local methods vs global methods

local methods

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

+ "assumption-free"
− low precision



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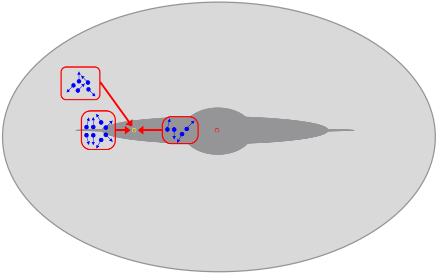
global methods

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

− global assumptions
+ high precision



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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: $\quad 4\pi G \rho_{\rm tot} = \nabla^2 \phi_{\rm tot} \quad .$

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

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

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

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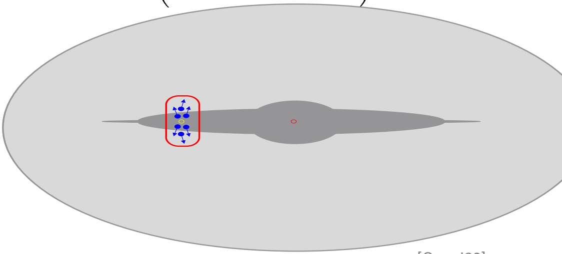
$$\boxed{-4\pi G \rho_{\rm tot} = \frac{\partial}{\partial z}\left(\frac{1}{\rho_s} \frac{\partial(\rho_s \overline{v_z^2})}{\partial z} \right)}$$

This is the so-called Oort limit.



[Oort '32]

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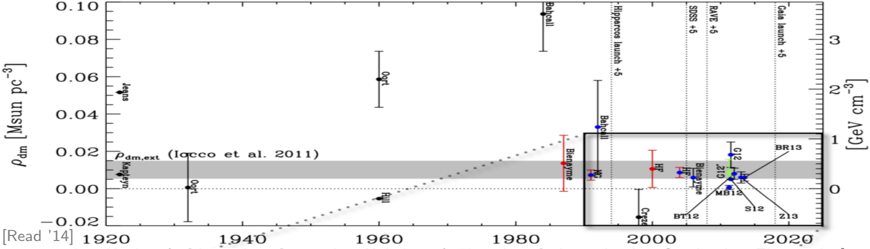

[Read '14] [Bienayme+ '87, Kuijken & Gilmore '89, Creze+ '98, Holmberg & Flynn '00, Garbari+ '11 '12, Smith+ '12, Zhang+ '13]

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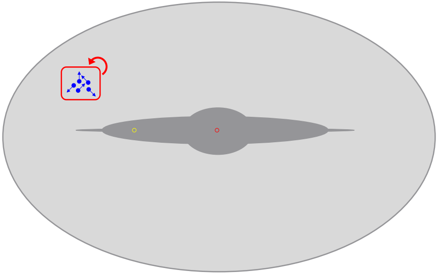

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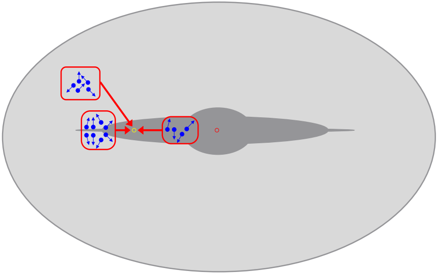

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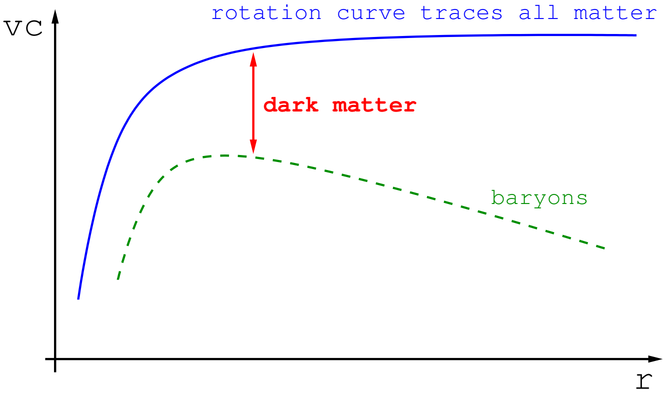
$$\phi_{\rm tot} = \phi_{\rm bulge} + \phi_{\rm disc} + \phi_{\rm gas} + \phi_{\rm dm}$$



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

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

[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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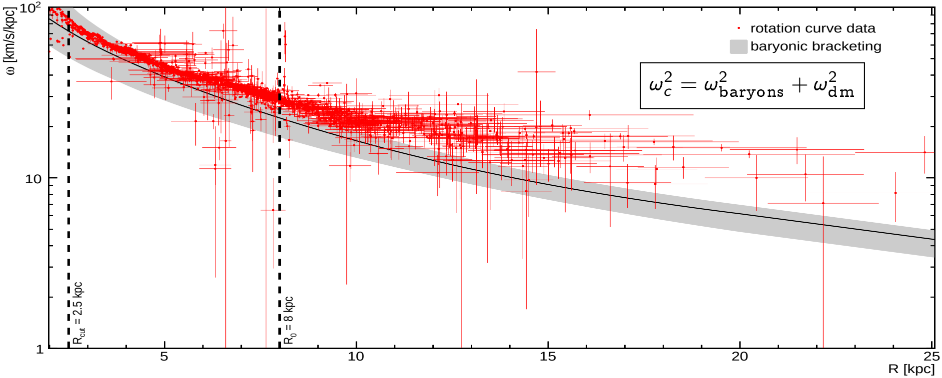

evidence for dark matter

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profile fitting

[MP, Iocco & Bertone '15, 1504.06324]

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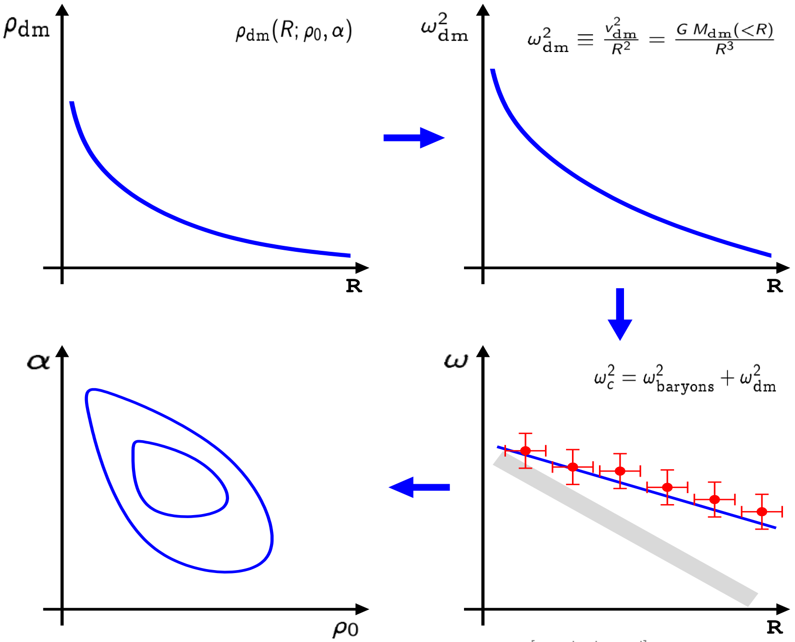

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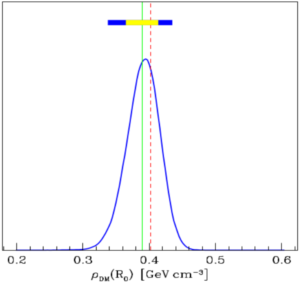
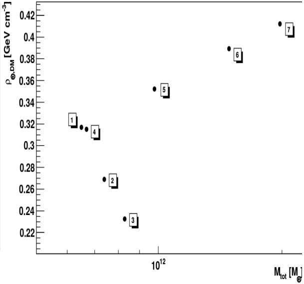


[Catena & Ullio '10]



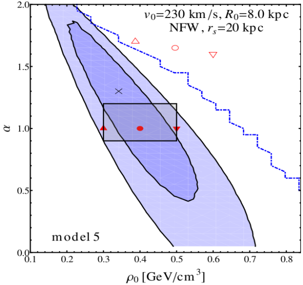
[Weber & de Boer '10]

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

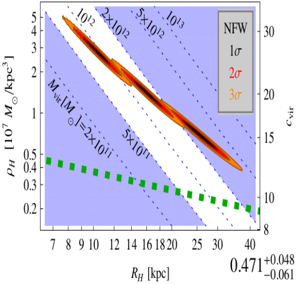
[Salucci '10]

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

[McMillan '11]



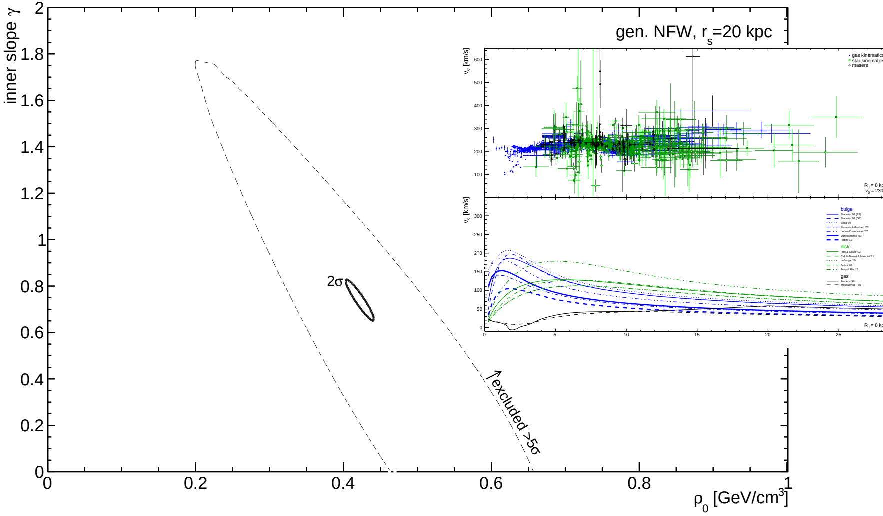
[Iocco+ '11]



[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]



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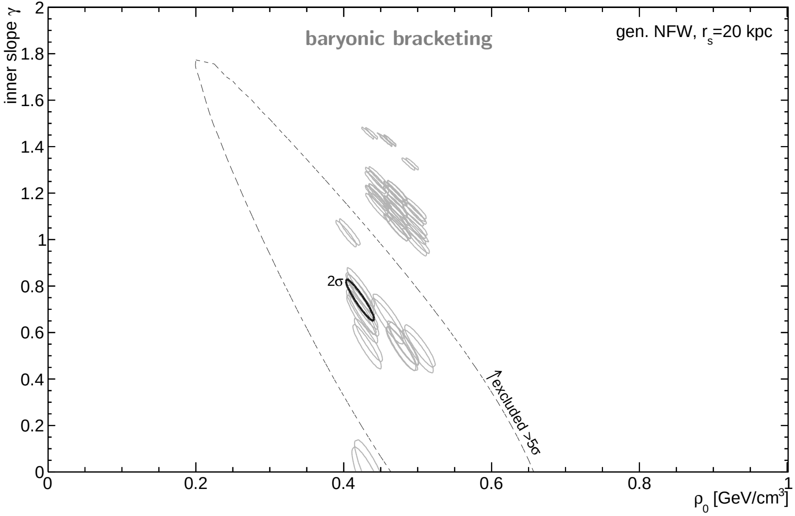

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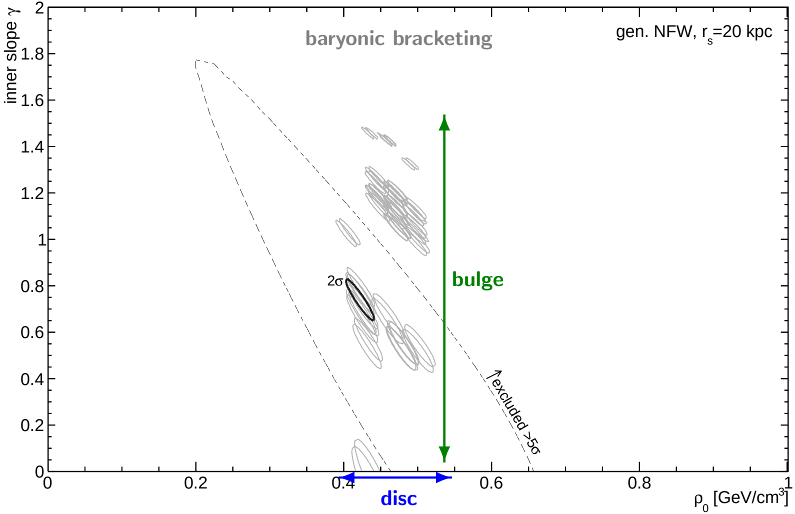

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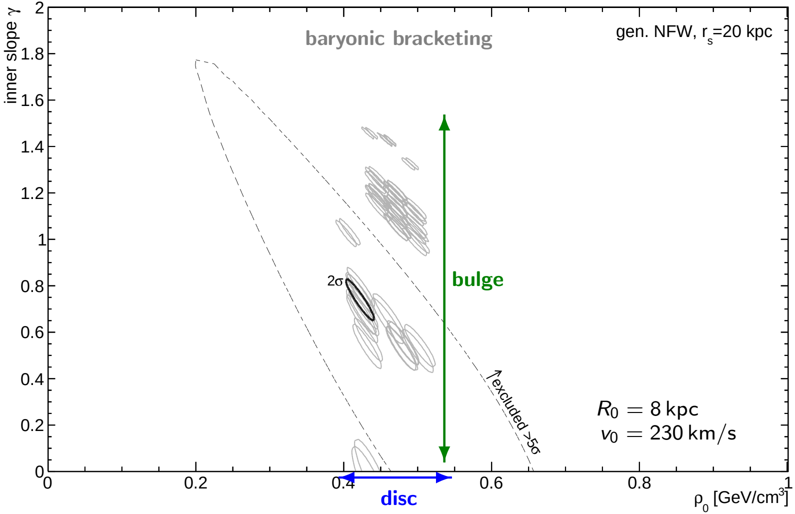

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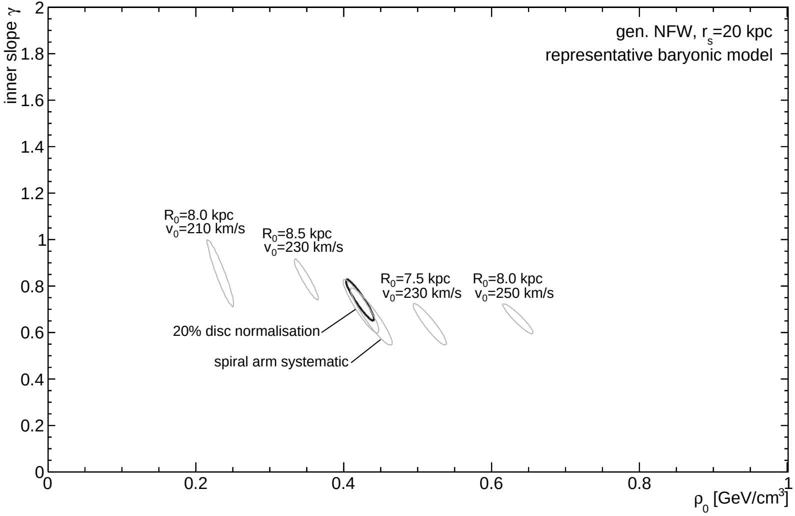


2. MODIFIED NEWTONIAN DYNAMICS

wait, what about MoND?

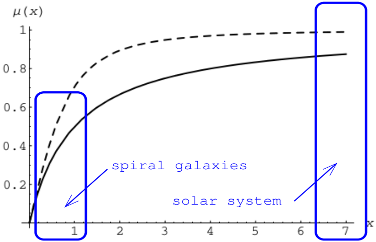
$$\mu\left(\frac{a}{a_0}\right) a = a_N$$

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

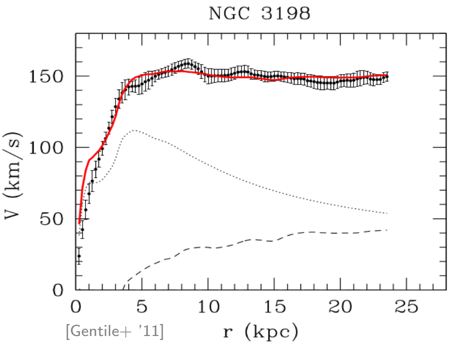
[Milgrom x3 '83]

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

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



[Bekenstein '07]



[Gentile+ '11]

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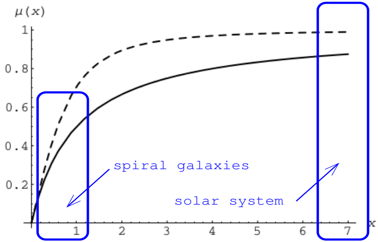

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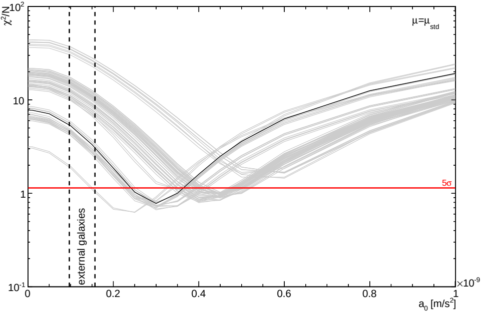

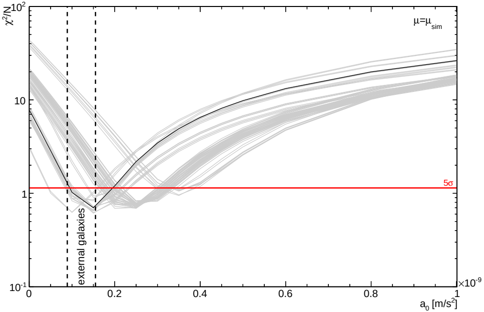

[Iocco, MP & Bertone '15, 1505.05181]

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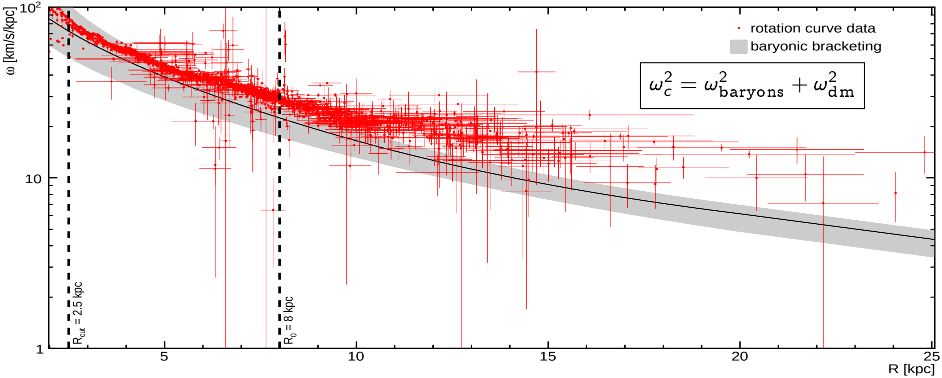

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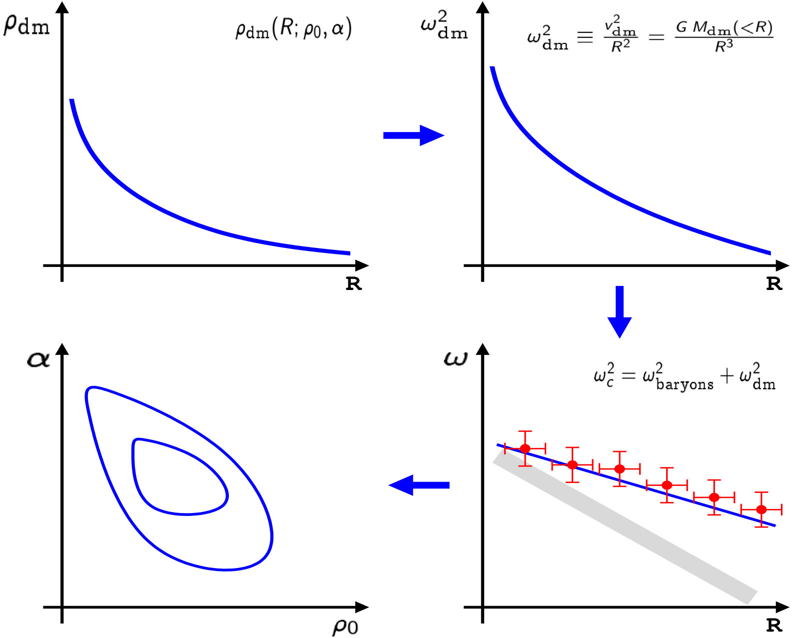

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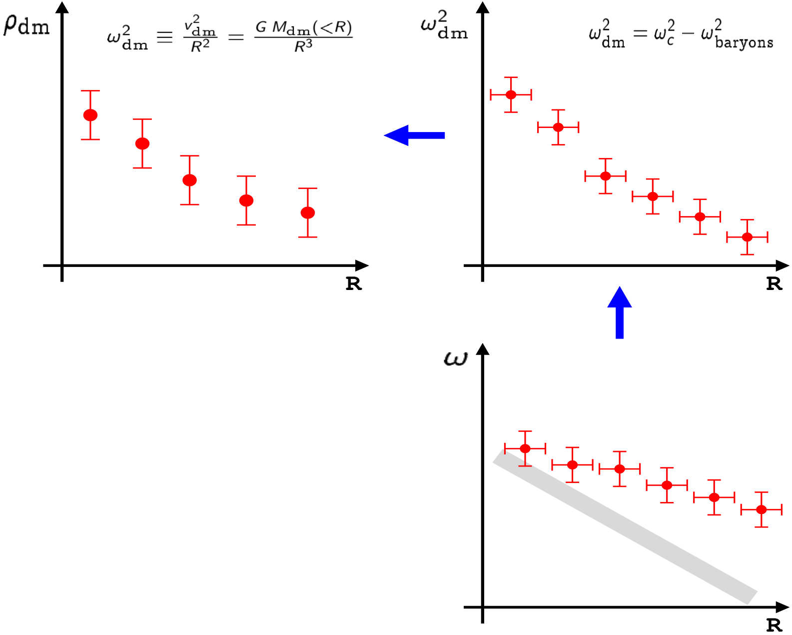

[MP & Iocco '15, ApJ Lett., 1504.03317]

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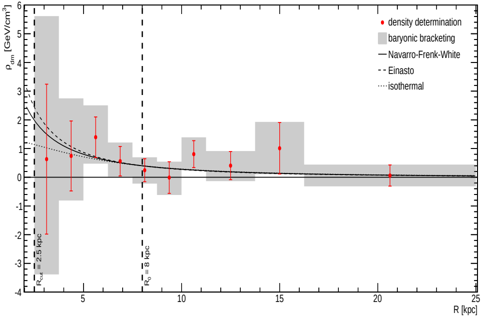
Let us take a spherical dark matter distribution. Then,

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

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

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

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?

local methods vs global methods

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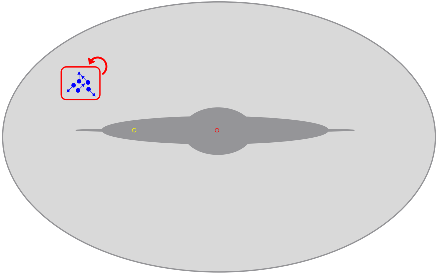

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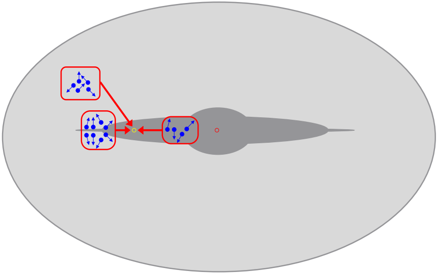


[Caldwell & Ostriker '81, Gates+ '95, Dehnen & Binney '98, Sakamoto+ '03, Dehnen+ '06, Xue+ '08, Sofue+ '09, Strigari & Trotta '09, Catena & Ullio '10, Weber & de Boer '10, Salucci+ '10, Iocco+ '11, McMillan '11, Nesti & Salucci '13, Bhattacharjee+ '14, Kafle+ '14, MP & Iocco '15, MP, Iocco & Bertone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

3. FUTURE DIRECTIONS?

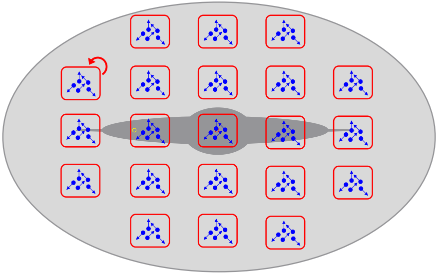
local methods vs global methods

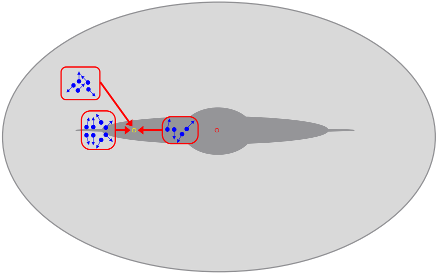
aim: use data from a patch of the sky to derive dynamics there.

+ "assumption-free"
− low precision

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

− global assumptions
+ high precision

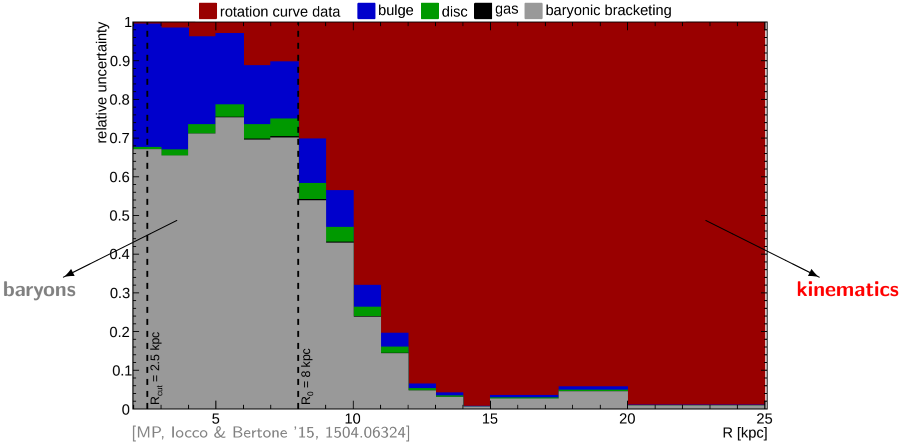




[Kapteyn '22, Jeans '22, Oort '32, Hill '60, Oort '60, Bahcall '84, Bienaymé+ '87, Kuijken & Gilmore '91, Bahcall+ '92, Creze+ '98, Holmberg & Flynn '00, Holmberg & Flynn '04, Bienaymé+ '06, Garbari+ '11 '12, Moni Bidin+ '12, Bovy & Tremaine '12, Smith+ '12, Zhang+ '13, Bovy & Rix '13, Loebman+ '14,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

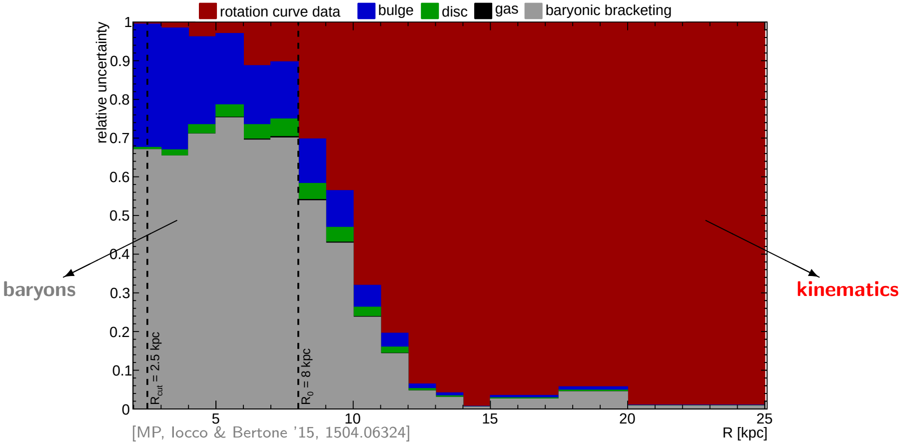
[Caldwell & Ostriker '81, Gates+ '95, Dehnen & Binney '98, Sakamoto+ '03, Dehnen+ '06, Xue+ '08, Sofue+ '09, Strigari & Trotta '09, Catena & Ullio '10, Weber & de Boer '10, Salucci+ '10, Iocco+ '11, McMillan '11, Nesti & Salucci '13, Bhattacharjee+ '14, Kafle+ '14, MP & Iocco '15, MP, Iocco & Bertone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

3. FUTURE DIRECTIONS?



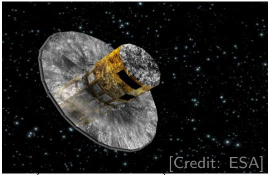
[MP, Iocco & Bertone '15, 1504.06324]

3. FUTURE DIRECTIONS?



[MP, Iocco & Bertone '15, 1504.06324]

Gaia



fact sheet

2013-2018
$\lambda = 320 - 1000\,\mathrm{nm}$
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

3. CONCLUSION (FABIO'S AND MINE)

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
  - profile fitting
  - MoND constraints
  - profile reconstruction

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: SUMMARY

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

kinematics — traces total potential

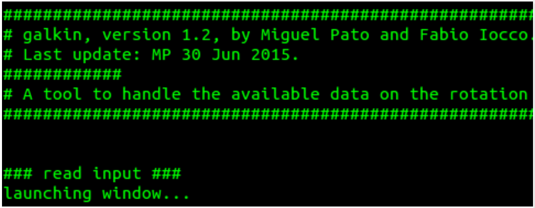
$R \sim 0.1 - 30\,\text{kpc}$	rotation curve tracers
$R \sim 8 - 60\,\text{kpc}$	star population tracers
$R \sim 100 - 300\,\text{kpc}$	satellite kinematics
$R \sim 300+\,\text{kpc}$	timing in Local Group

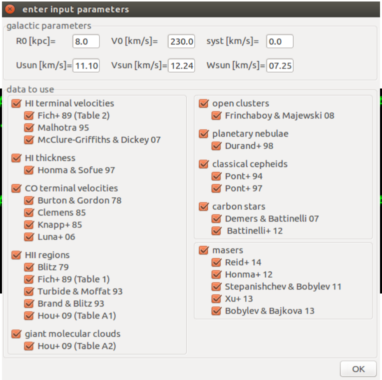
photometry — traces individual baryonic components

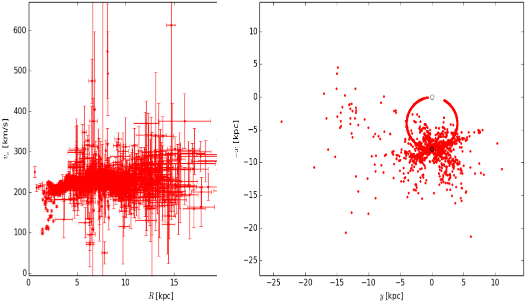
bulge	star counts, luminosity, microlensing
disc	star counts, luminosity, stellar dynamics
gas	emission lines, dispersion measure

1. GALKIN

coming soon: galkin, public code in python







user-friendly interface

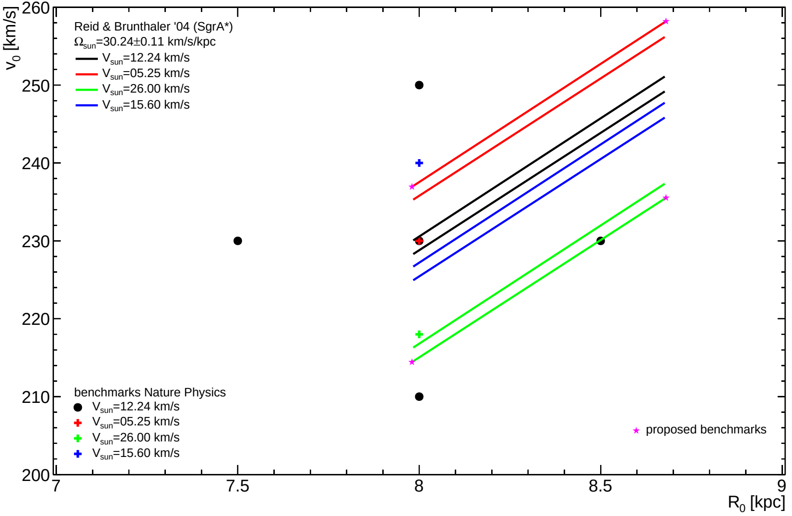
data & parameter selection

output rotation curve

output positional data

[MP & Iocco, in progress]

2. GALACTIC PARAMETERS



[Iocco, MP & Bertone '15, 1505.05181]

2. MODIFIED NEWTONIAN DYNAMICS

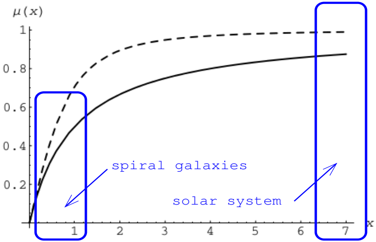
$$\mu\left(\frac{a}{a_0}\right) a = a_N$$

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

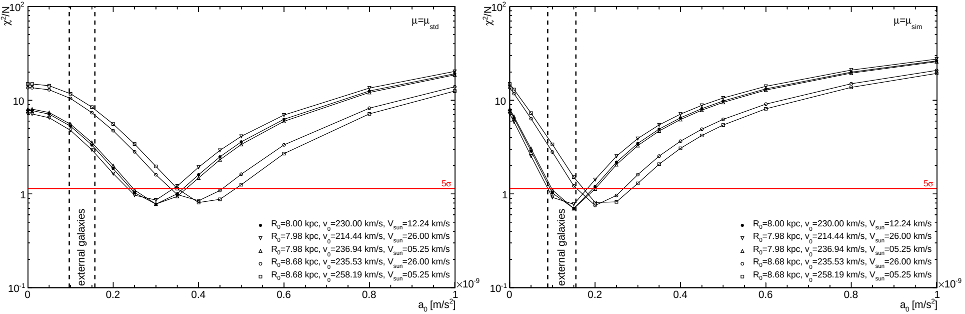
[Milgrom x3 '83]

$$a \to R\omega_c^2 \qquad a_N = R\omega_b^2$$

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



[Bekenstein '07]



[Iocco, MP & Bertone '15, 1505.05181]

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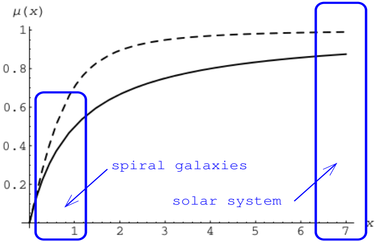

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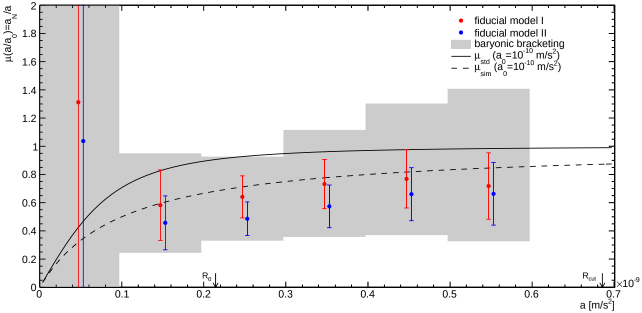

[Iocco, MP & Bertone '15, 1505.05181]