systematics uncertainties in the determination of the local dark matter density

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[1] the relevance of the local dark matter density

$$\rho_0 \equiv \rho_{dm}(R_0 \sim 8 \text{ kpc})$$

:: ρ_0 is a main astrophysical unknown for DM searches ::

key ingredient to compute DM signals and draw limits

uncertainties on ρ_0 are crucial in interpreting positive DM detections

scattering off nuclei

$$\frac{dR}{dE} \propto n_{dm} \int_{v_{min}}^{\infty} dv \, \frac{f(v)}{v} \propto \rho_0$$

signal: nuclei recoils

sensitive to $\langle \rho_0 \rangle_{mpc}$

capture in Sun/Earth

$$\frac{dN_{dm}}{dt} = C - 2\Gamma_{ann}$$

$$C \propto n_{dm} \int_0^{v_{max}} dv \, \frac{f(v)}{v} \propto \rho_0$$

signal: ν from Sun/Earth

sensitive to $\langle \rho_0 \rangle$

halo annihilation/decay

$$\frac{d\phi}{dE} \propto \langle \sigma_{ann} v \rangle n_{dm}^k \propto \rho_0^k$$

signals: γ, e^+, $\bar{p}$, ν

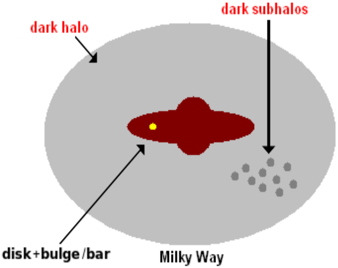
sensitive to $\langle \rho_0 \rangle$

[not the largest unknown]

[1] from dynamical observables to ρ_0

Milky Way mass model

bulge(+bar)	$\lesssim 3$ kpc	$\rho_b(x,y,z)$	x_b, y_b, z_b
disk	$\lesssim 10$ kpc	$\rho_d(r,z)$	Σ_d, r_d, z_d
dark halo	$\lesssim 200$ kpc	$\rho_{dm}(x,y,z) \propto \rho_0$	
+gas...			



a model fixes $M_i(R), \phi_i(R)$

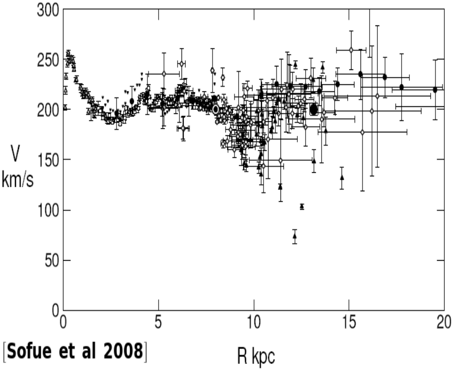
$$\sum_i \frac{d\phi}{dR}(R) \equiv \frac{G}{R^2} \sum_i M_i(< R) = \frac{v^2(R)}{R} \qquad v_0 \equiv v(R_0)$$

spherical average local density

$$\bar{\rho}_0 \simeq \frac{1}{4\pi R_0^2} \left(\frac{1}{G} \frac{\partial \left(v^2 R\right)}{\partial R}\bigg|_{R_0} - \frac{dM_d}{dR}\bigg|_{R_0} \right)$$

[1] from dynamical observables to ρ_0

observables



[Sofue et al 2008]

R_0, $\quad A - B = v_0/R_0$, $\quad A + B = -v_0'$

[fix v_0, v_0']

mass enclosed

$M(< 50 \text{ kpc}) \quad M(< 100 \text{ kpc})$

local surface density

$\Sigma_{|z|<1.1 \text{ kpc}} \quad \Sigma_*$

terminal velocities $\quad R < R_0$

$v(R) = v_T(l) + v_0 sin(l)$

velocity dispersions $\quad R \gtrsim R_0 \quad$ (tracer populations)

Jeans (sph., steady) $\frac{\partial(\nu\sigma_R^2)}{\partial R} + \frac{2\beta\sigma_R^2\nu}{R} = \nu \sum_i \frac{d\phi_i}{dR} = -\frac{\nu G}{R^2} \sum_i M_i(< R)$

$\sigma_{los} \propto \sigma_R$

microlensing

$\tau_{LMC} \sim 10^{-7} \quad \tau_{bulge} \sim 10^{-6} \quad$ [constrain M_b]

[1] from dynamical observables to ρ_0

aim: use observables to constrain mass model parameters

selected references (different models/observables)

Caldwell & Ostriker '81	$\rho_0 = 0.23 \pm \times 2\ \mathrm{GeV/cm^3}$
Gates, Gyuk & Turner '95	$\rho_0 = 0.30^{+0.12}_{-0.11}\ \mathrm{GeV/cm^3}$
Moore et al '01	$\rho_0 \simeq 0.18 - 0.30\ \mathrm{GeV/cm^3}$
Belli et al '02	$\rho_0 \simeq 0.18 - 0.71\ \mathrm{GeV/cm^3}$ (isoth.)
Strigari & Trotta '09	$\Delta\rho_0/\rho_0 = 20\%$ (projected; 2000 halo stars, v_{esc})
Catena & Ullio '09	$\rho_0 \simeq 0.39 \pm 0.03\ \mathrm{GeV/cm^3}$ $\Delta\rho_0/\rho_0 = 7\%$!!
Salucci et al '10	$\rho_0 \simeq 0.43 \pm 0.21\ \mathrm{GeV/cm^3}$

usual assumptions: $\rho_{dm} = \rho_{dm}(r)$, ρ_{dm} from DM-only simulations

[1] the role of baryons on dark matter halos

adiabatic contraction [Blumenthal et al 1986]

spherical mass distribution $M_i(< R_i)$: baryons + dark matter $f_b \sim 0.17$
baryons cool and contract slowly $\rightarrow M_b(< R)$
circular orbits + $L = const$

$$R\,(M_b(< R) + M_{dm}(< R)) = R_i M_i(< R_i) = R_i M_{dm}(< R)/(1 - f_b)$$

$$\rho_{dm} \propto R^{-2}\,\frac{dM_{dm}}{dR}$$

final DM profile is significantly contracted
[+ Gnedin et al 2004, Gustafsson et al 2006]

halo shape

DM-only halos are prolate
+ baryons: more oblate halos (still triaxial)
in any case, $\rho_{dm} \neq \rho_{dm}(r)$

aim

address systematics on ρ_0 in light of recent N-body+hydro simulations
a realistic pdf on ρ_0 is needed if we are to convincingly identify WIMPs

[2] our numerical framework

difficult to obtain a MW-like galaxy at $z = 0$ with simulations

usually large bulges and small disks result (L problem)

recent sucessful attempt: Agertz, Teyssier & Moore 2010

dark matter + gas + stars

<u>cosmological setup</u>

WMAP 5yr cosmology
select DM-only halo
$M_{vir} \sim 10^{12}\ \mathrm{M}_\odot \quad R_{vir} \sim 205$ kpc
no major merger for $z < 1$

<u>baryonic features</u>

star formation (Schmidt law; ϵ_{ff}, n_0)

$$\dot{\rho}_g = -\epsilon_{ff} \frac{\rho_g}{t_{ff}}$$

stellar feedback (SNII, SNIa, wind)

<u>numerical features</u>

$m_{DM} = 2.5 \times 10^6\ \mathrm{M}_\odot$
$\Delta x = 340$ pc

main result

MW-like galaxy with $v_c \sim const, \quad B/D \sim 0.25, \quad r_d \sim 4 - 5$ kpc

[2] our numerical framework

Run	ϵ_{ff}	Feedback	Star formation threshold, n_0
SR6-n01e1	1 %	SNII	$0.1\,\mathrm{cm}^{-3}$
SR6-n01e2	2 %	SNII	$0.1\,\mathrm{cm}^{-3}$
SR6-n01e5	5 %	SNII	$0.1\,\mathrm{cm}^{-3}$
SR6-n01e1ML	1 %	SNII, SNIa, mass loss	$0.1\,\mathrm{cm}^{-3}$
SR6-n01e2ML	2 %	SNII, SNIa, mass loss	$0.1\,\mathrm{cm}^{-3}$
SR6-n01e5ML	5 %	SNII, SNIa, mass loss	$0.1\,\mathrm{cm}^{-3}$
SR6-n1e1	1 %	SNII	$1\,\mathrm{cm}^{-3}$
SR6-n1e2	2 %	SNII	$1\,\mathrm{cm}^{-3}$
SR6-n1e5	5 %	SNII	$1\,\mathrm{cm}^{-3}$

MW like (SR6-n01e1ML)

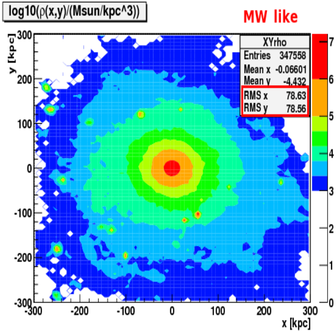
baryon+ (SR6-n01e5ML)

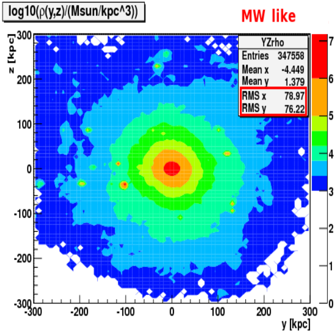
Run	$M_{disk,s}$	$M_{disk,g}$	$M_{bulge,s}$	r_d [kpc] (1)	f_{gas} (2)	B/D	B/T	j_{bar} (3)
SR6-n01e1	8.6	1.6	2.0	3.8	0.13	0.23	0.19	1920
SR6-n01e2	7.4	1.3	4.6	7.6	0.10	0.62	0.38	1655
SR6-n01e5	5.6	0.72	7.0	~ 15.0	0.05	1.25	0.56	1305
SR6-n01e1ML	8.0	2.3	2.2	5.0	0.18	0.27	0.21	1960
SR6-n01e2ML	8.1	1.6	3.8	5.0	0.12	0.47	0.32	1718
SR6-n01e5ML	5.5	0.93	7.2	~ 15.0	0.07	1.30	0.57	1464
SR6-n1e1	6.6	3.3	2.9	2.7	0.26	0.44	0.31	1594
SR6-n1e2	6.4	2.4	4.3	2.5	0.18	0.67	0.40	1804
SR6-n1e5	6.0	2.1	5.2	2.7	0.16	0.87	0.46	1643

[Agertz, Teyssier & Moore 2010]

to bracket uncertainties we consider: DM only, MW like, baryon+

[3] halo shape: a first look

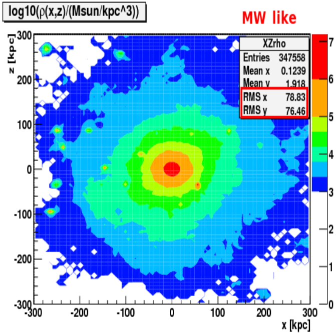




profiles of dark matter density

SR6-n01e1ML :: MW like

$$10^7\ \mathrm{M}_\odot/\mathrm{kpc}^3 \sim 0.38\ \mathrm{GeV}/\mathrm{cm}^3$$



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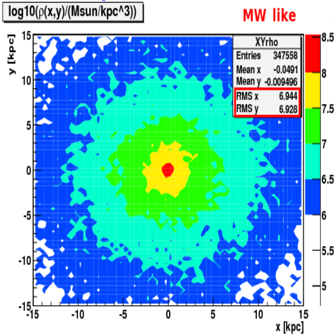
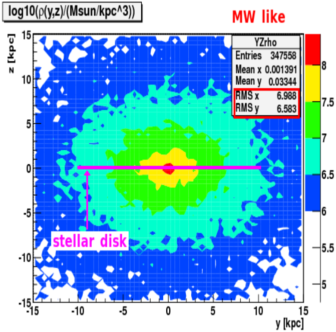


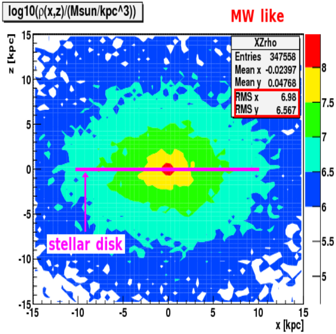


profiles of dark matter density

SR6-n01e1ML :: MW like

approximately axisymmetric halo

$$10^7\ \mathrm{M_\odot/kpc^3} \sim 0.38\ \mathrm{GeV/cm^3}$$



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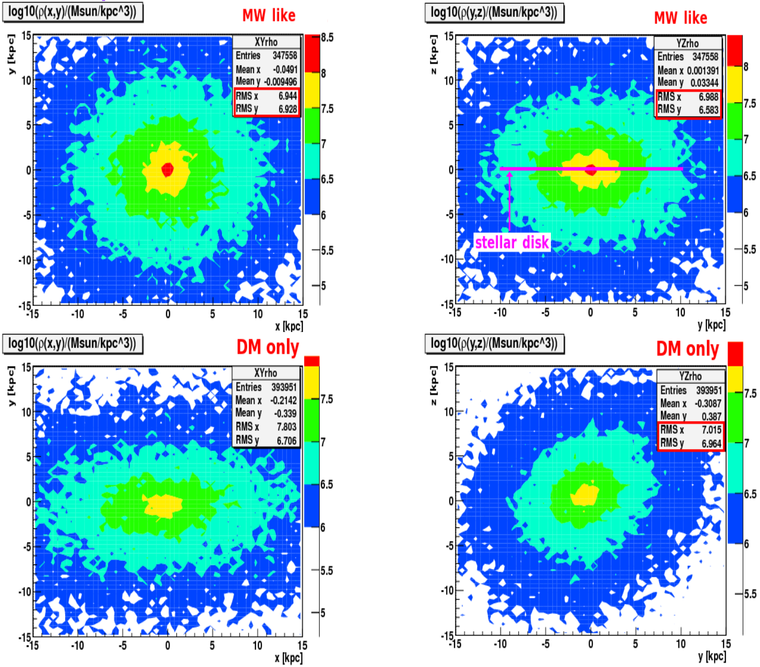

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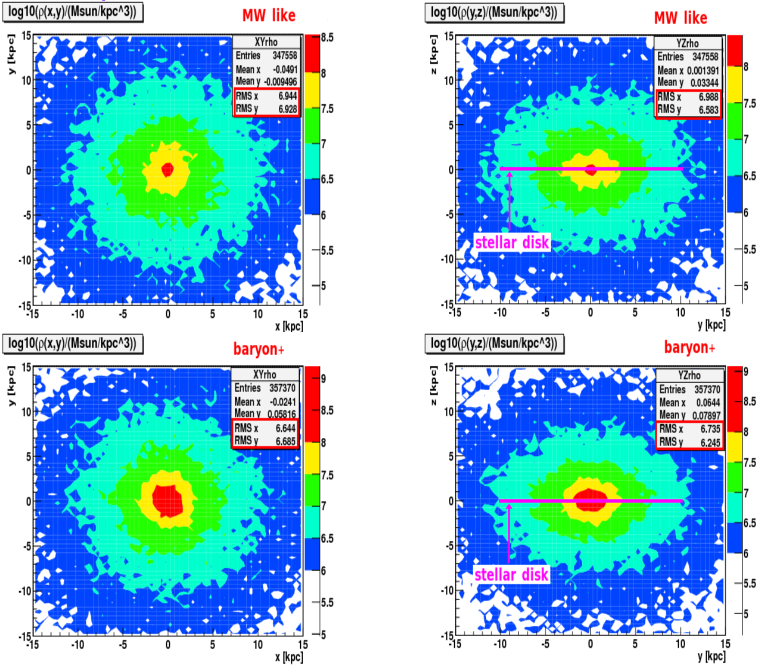

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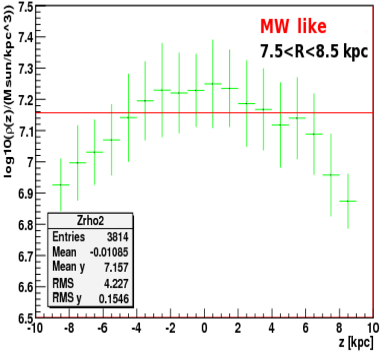


local spherical shell: $7.5 < R < 8.5$ kpc

DM overdensity towards $z \sim 0$
(i.e. stellar disk)

bottomline

baryons make DM halos rounder (but still non-spherical) and flattened along the stellar disk

[3] halo shape: getting more quantitative

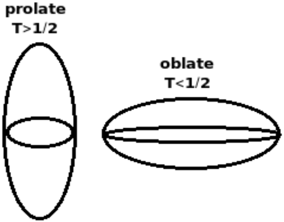
inertia calculations

for a set of N_p particles, $J_{ij} = \frac{\sum_{k=1}^{N_p} m_k x_{i,k} x_{j,k}}{\sum_{k=1}^{N_p} m_k}$

principle axes: eigenvectors $\vec{j}_a$ (major), $\vec{j}_b$ (intermediate), $\vec{j}_c$ (minor)

axis ratios: $b/a = \sqrt{J_b/J_a}$, $c/a = \sqrt{J_c/J_a}$

triaxiality: $T = \frac{1-b^2/a^2}{1-c^2/a^2}$

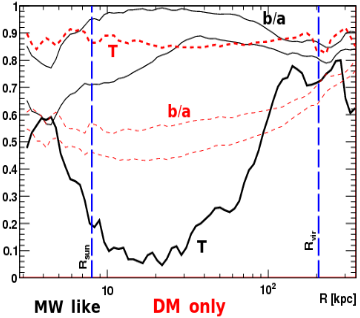


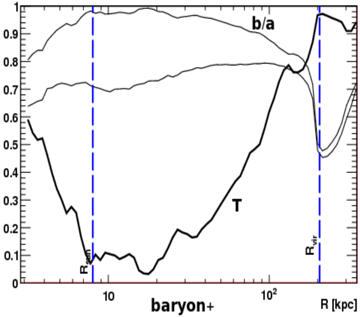
iterative procedure ['a la Katz et al '91]

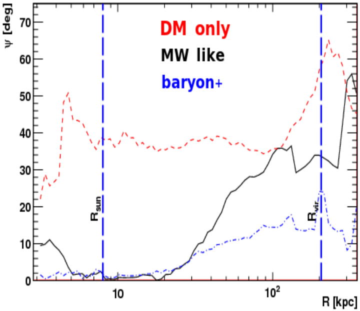
$$r < R \rightarrow b/a,\ c/a,\ \vec{j}_{a,b,c} \rightarrow q = \sqrt{x^2 + \frac{y^2}{(b/a)^2} + \frac{z^2}{(c/a)^2}} < R \rightarrow \ldots$$

convergence criterium: 0.5% change in b/a, c/a

[3] halo shape: getting more quantitative







inclusion of baryons

prolate → oblate halo shape

flattening aligned with stellar disk for $R \lesssim 20$ kpc

[MP, Agertz, Bertone, Moore & Teyssier '10]

[3] halo shape: consequences for ρ_0

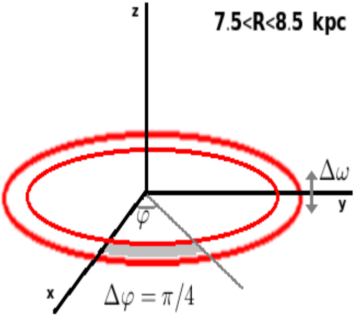
/ many studies assume a spherical halo [e.g. Catena & Ullio, Strigari & Trotta]

/ data then constrains the spherical average local density $\bar{\rho}_0$:

$$\bar{\rho}_0 \simeq \frac{1}{4\pi R_0^2} \left(\frac{1}{G} \left. \frac{\partial\left(v^2 R\right)}{\partial R} \right|_{R_0} - \left. \frac{dM_d}{dR} \right|_{R_0} \right)$$

/ model triaxial halo is tricky (b/a, c/a not known nor constant)

/ to estimate systematic uncertainty compare $\bar{\rho}_0 \leftrightarrow \rho_0$ in simulations



strategy

spherical shell $7.5 < R < 8.5$ kpc

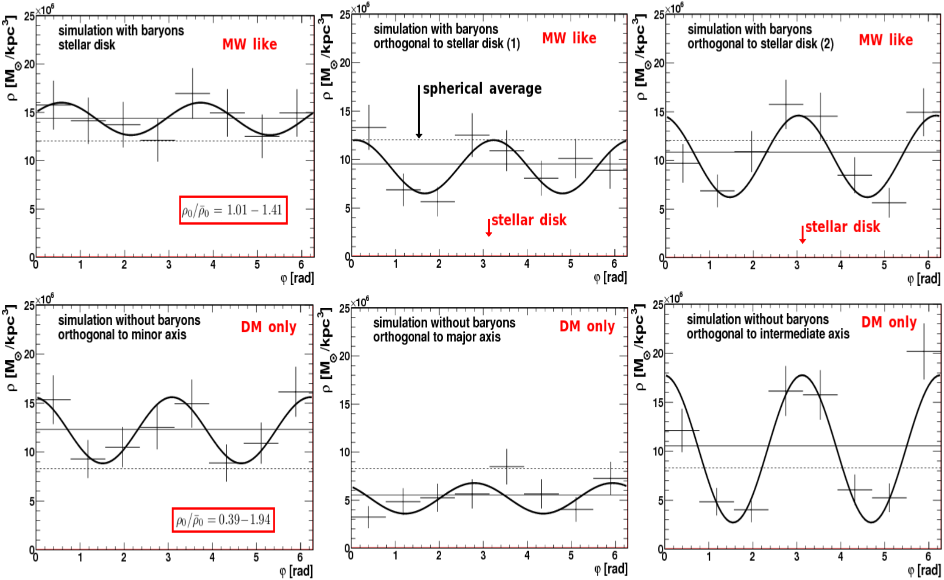
select particles in 3 orthogonal rings

divide rings into 8 portions $\Delta\varphi = \pi/4$

evaluate ρ along the ring, $\rho(\varphi)$

[3] halo shape: consequences for ρ_0

[MP, Agertz, Bertone, Moore & Teyssier '10]



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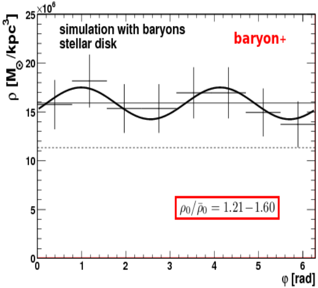
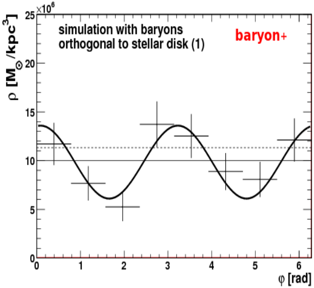
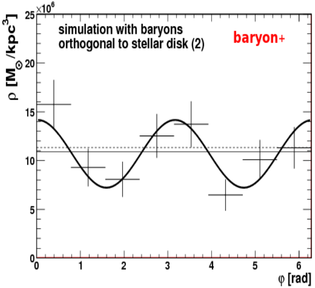


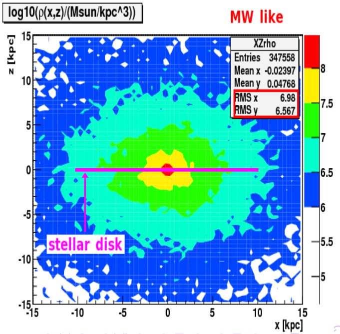




MW like	$\rho_0/\bar{\rho}_0 = 1.01 - 1.41$
baryon+	$\rho_0/\bar{\rho}_0 = 1.21 - 1.60$
DM only	$\rho_0/\bar{\rho}_0 = 0.39 - 1.94$

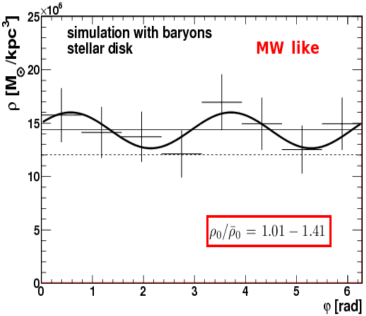
- $\rho(\varphi) > \bar{\rho}_0$ because halo is flattened
- halo-to-halo scatter can change normalisation

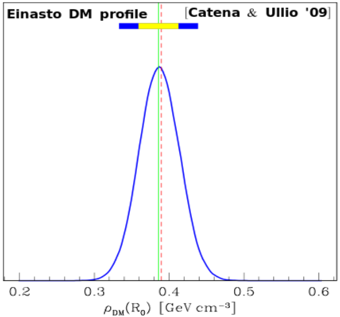
[MP, Agertz, Bertone, Moore & Teyssier '10]



[3] halo shape: consequences for ρ_0

just an exercise...



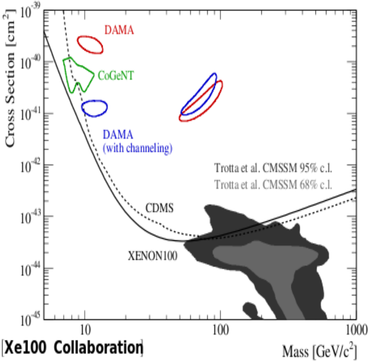


$$\rho_0 = 0.466 \pm 0.033(\mathrm{stat}) \pm 0.077(\mathrm{syst})\ \mathrm{GeV/cm^3}$$

:: syst > stat ::

future: bayesian study with triaxial halo

[4] ρ_0: why do we care?



[Xe100 Collaboration]

direct detection

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}}^{\infty} d^3\vec{v}\, v f(\vec{v} + \vec{v}_E; v_{esp}, v_0) \frac{d\sigma_{\chi N}}{dE_R}$$

standard assumptions

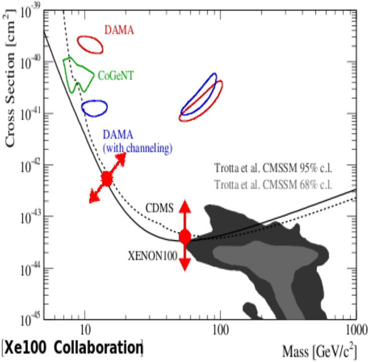
$$\rho_0 = 0.3 \text{ GeV/cm}^3$$

$$f(v) \propto e^{-v^2/v_0^2},\ v_0 \simeq 220 \text{ km/s},\ v_{esc} \simeq 600 \text{ km/s}$$

exclusion limits are not rigid

ρ_0 should really be treated as a nuisance parameter in direct DM searches

[4] ρ_0: why do we care?



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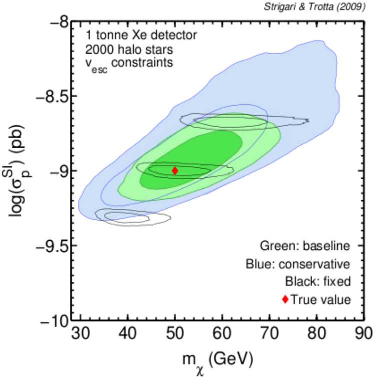
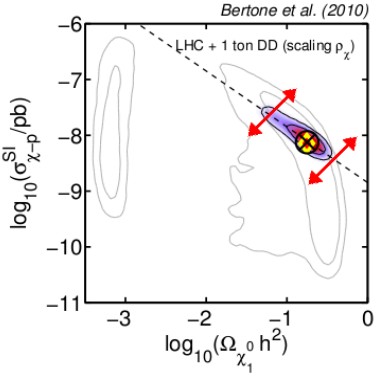
[4] ρ_0: why do we care?

reconstruction capabilities





direct + halo stars

3/4 halo parameters

$\Delta\bar{\rho}_0/\bar{\rho}_0 \sim 20\%$

direct + LHC

$\rho_\chi \propto \rho_0 \Omega_\chi$

no uncertainty on ρ_0

next steps: include astro+nuclear uncertainties
complementarity between different targets in direct detection

[on-going work...]

[..] conclusions

ρ_0 in light of recent N-body+hydro simulations

> baryons turn DM halo from prolate to oblate

> flattening is along the disk

> $\rho_0/\bar{\rho}_0 \simeq 1.21 \pm 0.20$

ρ_0 **uncertainties: not an academic question!**

ultimately limit our ability to combine signals and distinguish particle physics models

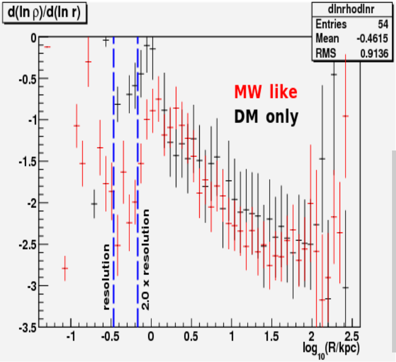
upcoming direct detection experiments and results urge for accurate control over systematics of astrophysical parameters

[+] halo profile

DM-only simulations find NFW|Einasto profiles

$$\frac{\partial ln\rho}{\partial lnR} \rightarrow -1|0 \text{ as } R \rightarrow 0$$

baryons expected to contract DM profile



$$\frac{\partial ln\rho}{\partial lnR} < -1 \text{ for } R < 1 \text{ kpc}$$

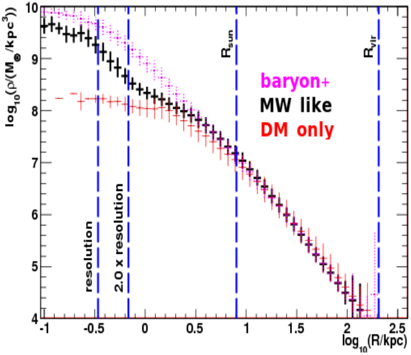
but: no convergence; $R > 2\Delta x$

teaser

if $\rho_{dm} \propto R^{-2}$, extrapolation to pc (why not?) yields extreme annihilation signals

e.g. for Fermi-LAT GC γ,
$\langle\sigma_{ann} v\rangle \lesssim 10^{-28}\ \mathrm{cm}^3/\mathrm{s}$ @ $m_{dm} = 100$ GeV

[+] halo profile



	NFW fit $1 < R/\mathrm{kpc} < 100$		power law fit $0.340 < R/\mathrm{kpc} < 1$	$0.680 < R/\mathrm{kpc} < 10^{0.1}$
	$\log_{10}(\rho_s/(M_\odot/\mathrm{kpc}^3))$	R_s/kpc	γ	γ
SR6-n01e1ML	7.57 (7.61)	9.48 (8.43)	1.97 (1.58)	1.14 (1.16)
DM only	7.08 (6.97)	15.59 (15.42)	0.46 (0.68)	0.24 (0.36)
SR6-n01e5ML	8.13 (7.76)	5.58 (7.38)	1.54 (1.59)	1.85 (2.00)

significant contraction wrt DM-only case

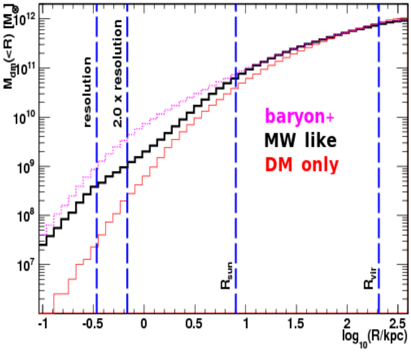
hint for an inner cusp

[+] halo profile: mass enclosed

$M_{dm}(< 3 - 8 \text{ kpc})$: important for dynamical constraints

$\downarrow$

insensitive to inner cusp: $R^{-1.97}$, $\tilde{R} = 3(8)$ kpc $\quad \Delta M_{dm}(< \tilde{R}) = 3(1)\%$



same $M_{dm}(< 8 \text{ kpc})$ for $\frac{\bar{\rho}_0(\text{SR6-n01e1ML})}{\bar{\rho}_0(\text{DM-only})} \simeq 0.9$

but: $A \pm B, \Sigma_*$ constrain $\bar{\rho}_0$ and $M_{dm}(< R_0)$

$\downarrow$

using contracted profiles would lead to smaller c, but same $\bar{\rho}_0$

[+] phase space: a first look

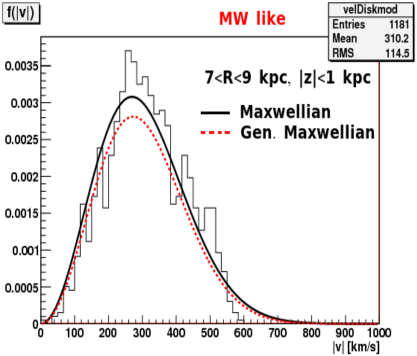
relevance

for direct detection: $\frac{dR}{dE} \propto \int_{v_{min}}^{\infty} dv \, \frac{f(v)}{v}$

for capture in astrophysical objects: $C \propto \int_{0}^{v_{max}} dv \, \frac{f(v)}{v}$

standard approach: use Maxwellian $f(v) = \sqrt{\frac{2}{\pi}} \frac{v^2}{\sigma^3} exp\left(-\frac{v^2}{2\sigma^2}\right)$, $\sigma = 270$ km/s

uncertainties related to mismodelling of $f(v)$



MW like (SR6-n01e1ML)

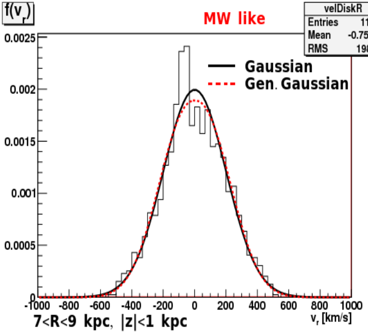
local stellar disk $7 < R < 9$ kpc and $|z| < 1$ kpc

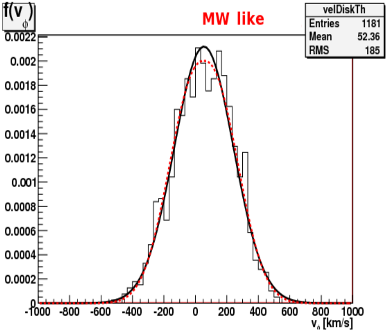
v wrt $\langle v \rangle_{R<50 \text{ kpc}}$

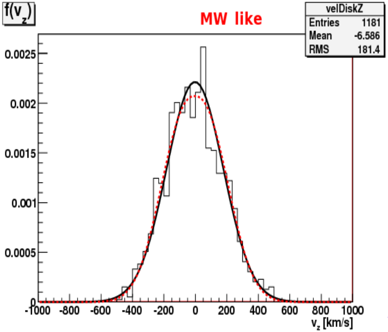
Maxwellian and generalised Maxwellian give poor fits $\chi^2/N_{dof} \simeq 3-4$

[ongoing work...]

[+] phase space: a first look







Gaussian ok (generalised forms not needed)

$\langle v_\phi \rangle \sim 50$ km/s

no dark disk apparent, but need more particles

[ongoing work...]