Phenomenological studies in dark matter direct detection: from the impact of the escape speed estimates to tests of halo models

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Mainly based on
J. Lavalle and S. Magni, Phys. Rev. D 91, 023510 (2015) arXiv:1411.1325 [astro-ph.CO]
and ongoing work with J. Lavalle, P. Mollitor and E. Nezri

Torino, Italia TAUP 2015 10/09/2015

Impact of the recent estimates of the Galactic escape speed on dark matter direct detection

- **Direct detection** plagued by **astrophysical uncertainties,** important in the context of **controversial signals and/or discovery perspectives.**
  Studies on the subject: A. Green (2012), R. Catena & P. Ullio (2012), M. Fairbairn & P. Grothaus (2013), N. Bozorgnia, et al. (2013), etc.

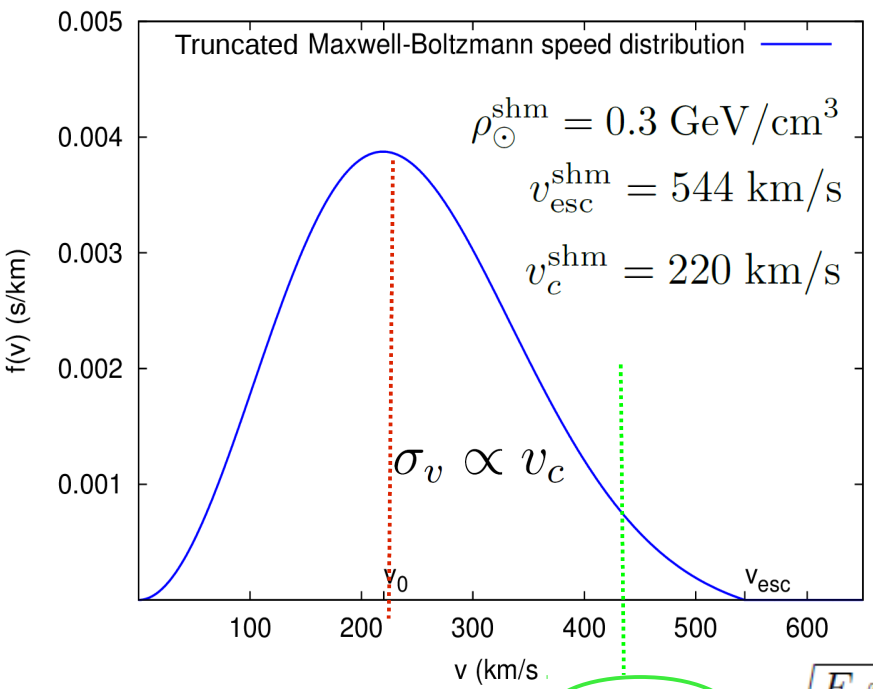
- Focus on recent **estimates of the escape speed** from the RAVE collaboration (Piffl et al. '14), important for **low WIMP masses**

- Investigate the **implications of these results** for direct detection (assuming isotropic velocity distribution for the dark matter)

- Bringing cosmological simulations into the picture

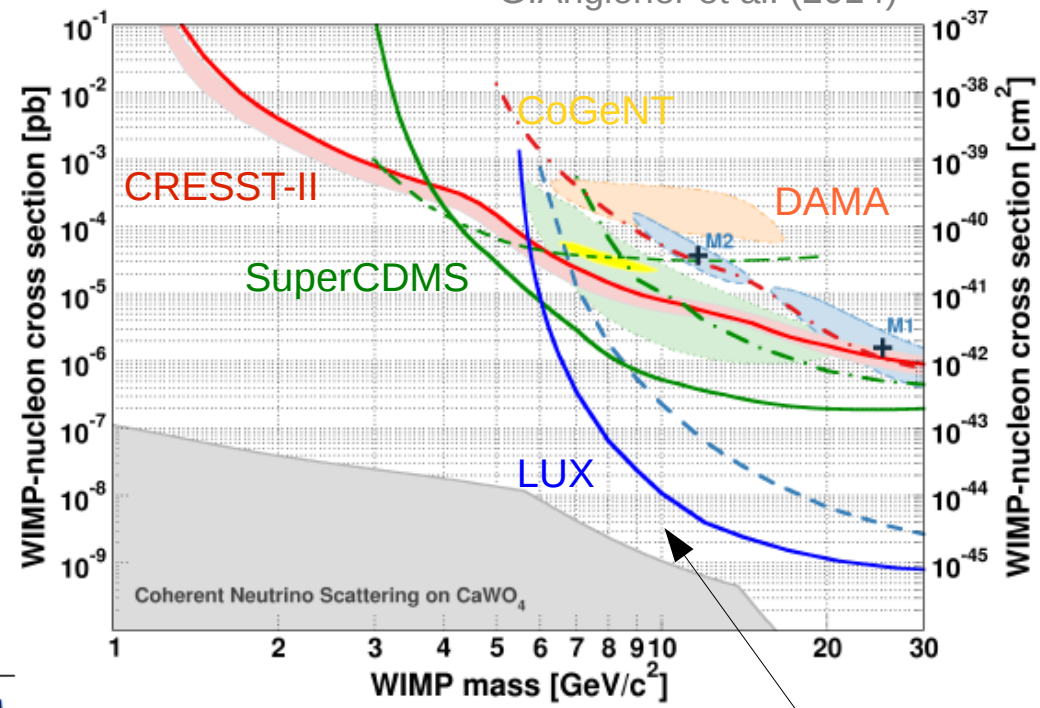
Astrophysics in direct detection: the standard halo model

Standard Halo Model



$$v_{min}(E_r) \doteq \sqrt{\frac{E_r m_A}{2 m_{red}^2}}$$

G.Angloher et al. (2014)



Effects at work:

- Experimental treshold
- $v_{\rm esc} + v_c$
- $\rho_\odot$

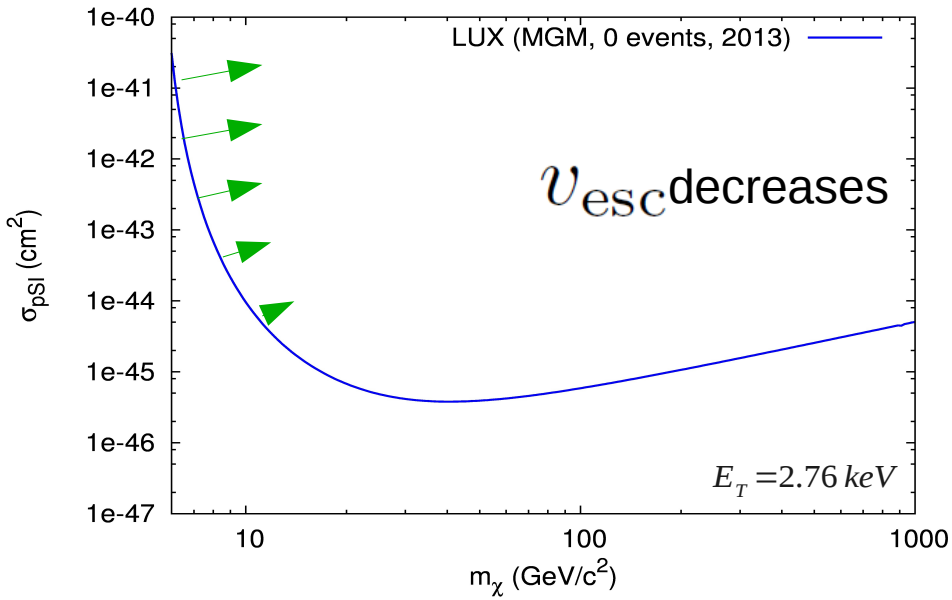
Differential event rate:

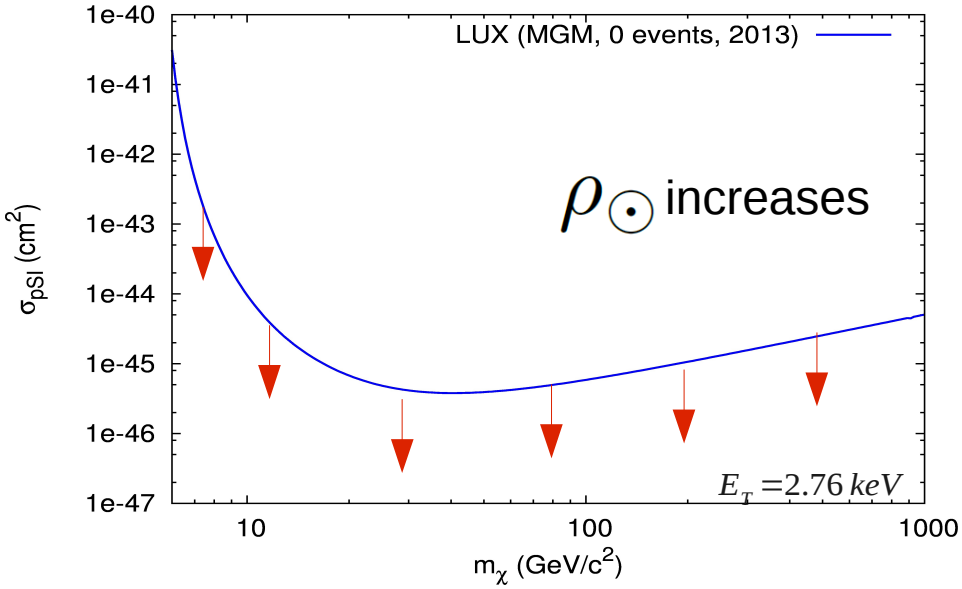
$$\frac{dR}{dE_r}(E_r) = \frac{A^2 \sigma_{p,SI} F^2(E_r)}{2\mu_p^2 m_\chi} \rho_\odot \int_{|\vec{v}|>v_{min}} d^3\vec{v} \frac{f_\oplus(\vec{v})}{v}$$

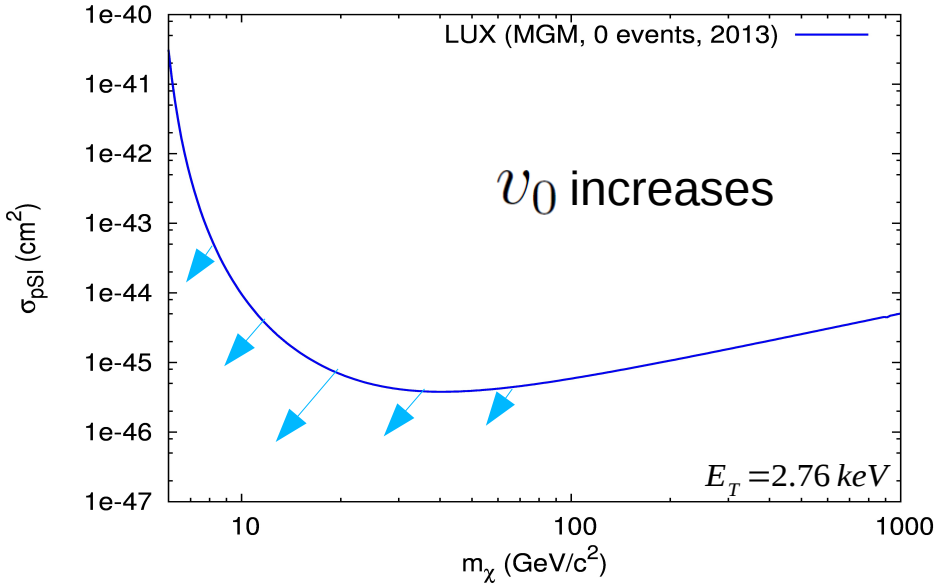
particle + hadronic + nuclear physics

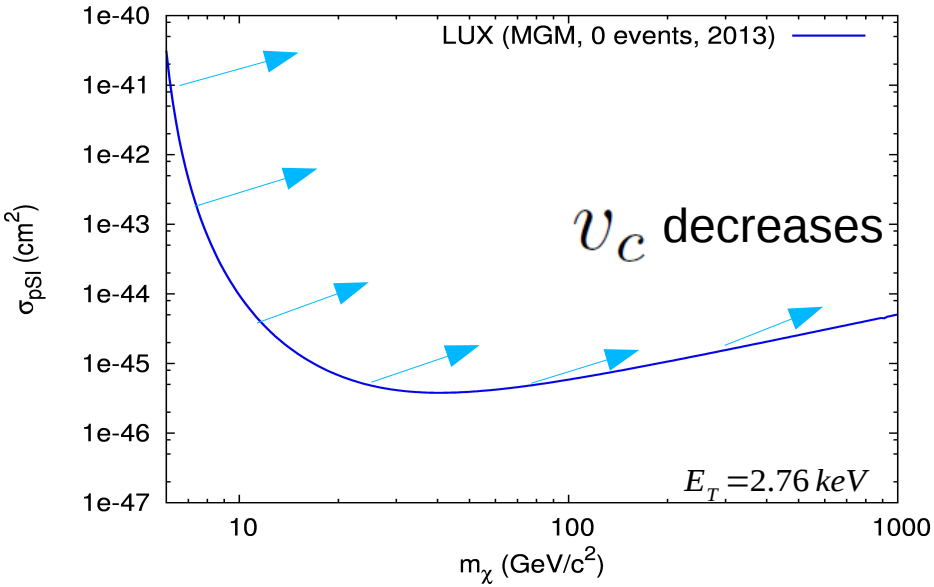
astrophysics

Qualitative impact of astrophysical parameters on exclusion curves









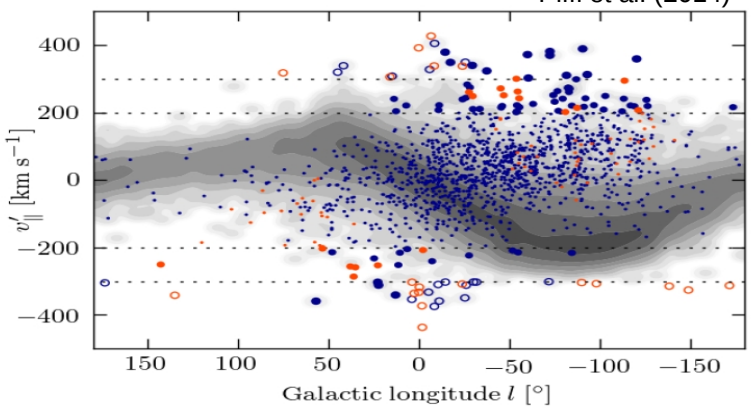
Updated escape speed from the RAVE survey (Piffl et al. '14)

- Previous estimate $v_{\rm esc} = 544^{+64}_{-46}\ {\rm km/s}\ (90\%\ {\rm CL})$ (Smith et al. '07)

- Based on a sample of **~100** high-velocity, **non-corotating stars**, to test the non local gravitational potential

- **Requires assumptions!**

Piffl et al. (2014)



- Power law assumption for the high velocity tail of the stellar distribution:

$$n_\star(v) \propto (v_{\rm esc} - v)^k$$

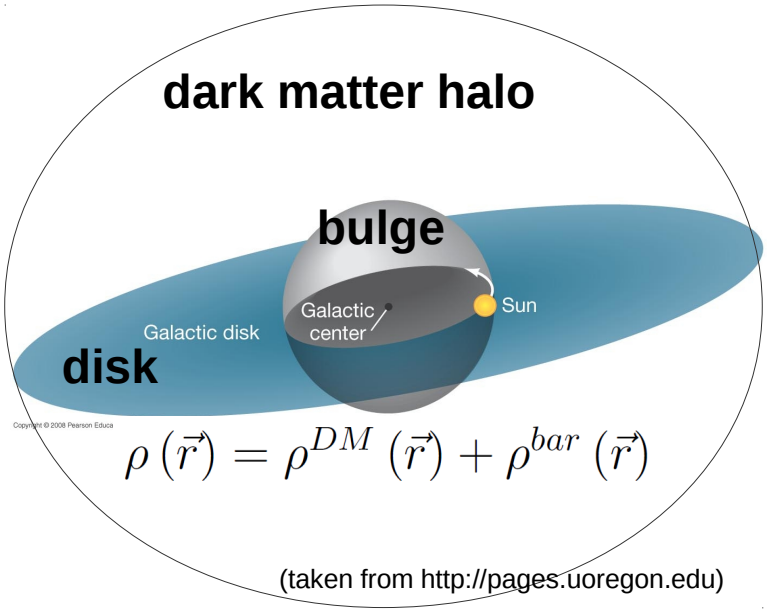
- Correct line-of-sight speeds of observed stars to **"relocate" them at Sun's position** (8.28 kpc)

⇨ <u>Needs gravitational potential at position of each star</u>

⇨ <u>Relies on assuming a **Milky Way mass model**</u>

RAVE's assumption: Milky Way mass model

(taken from: http://universeshots.tumblr.com)



(taken from http://pages.uoregon.edu)

Fixed baryons

- **disk**: Miyamoto-Nagai $\phi_{\rm d}(R,|z|) = -G\frac{M_{\rm d}}{\sqrt{R^2+(R_{\rm d}+\sqrt{z^2+z_{\rm d}^2})^2}}$
- **bulge**: Hernquist $\phi_{\rm b}(r) = -G\frac{M_{\rm b}}{(r+r_{\rm b})}$

+

- **dark matter halo**: NFW $\phi_{\rm dm}(r) = -4\pi G\frac{\rho_s r_s^3}{r}\ln\left(1+\frac{r}{r_s}\right)$

2 free parameters

- **Dark matter density** at Sun's position

$$\rho_\odot = \rho^{DM}(\vec{r}_\odot)$$

- **Galactic escape speed** at Sun's position

$$v_{esc}(\vec{r}_\odot) = \sqrt{2\,|\Phi(\vec{r}_\odot) - \Phi(\vec{r}_{max})|}$$

- **Circular speed** at Sun's position

$$v_c^2(R_\odot,0) = R_\odot\frac{\partial\Phi}{\partial R}(R_\odot,0)$$

RAVE's escape speed reconstruction

- In Piffl et al. '14,
  two different likelihood analyses:

1a) **fixed** $v_c = 240\ \mathrm{km/s}$

$v_{esc} = 511^{+48}_{-35}\ \mathrm{km/s}\ (90\%\ \mathrm{CL})$

1b) **fixed** $v_c = 220\ \mathrm{km/s}$

$v_{esc} = 533^{+54}_{-41}\ \mathrm{km/s}\ (90\%\ \mathrm{CL})$

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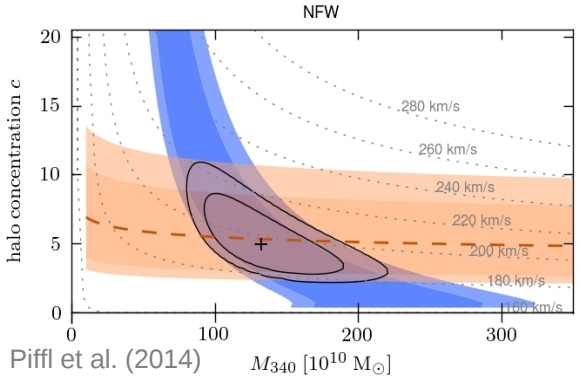
2) **free** v_c

- mostly for MW mass estimates

$v_{\mathrm{esc}} = 537\ \mathrm{km/s}$

(for best fit $v_c = 196\ \mathrm{km/s}$)



Piffl et al. (2014)

Converting RAVE results in the v_c-v_{esc} plane

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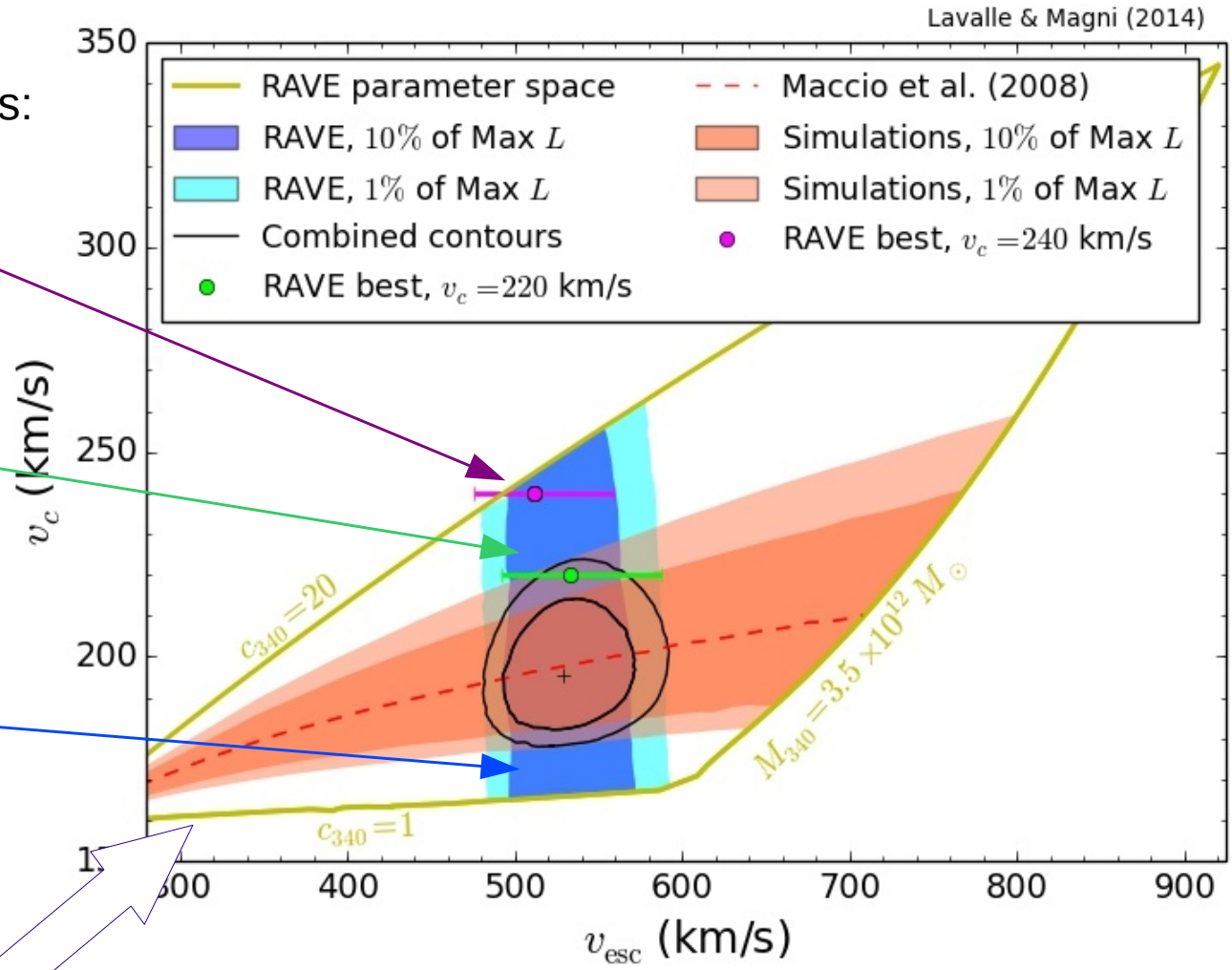

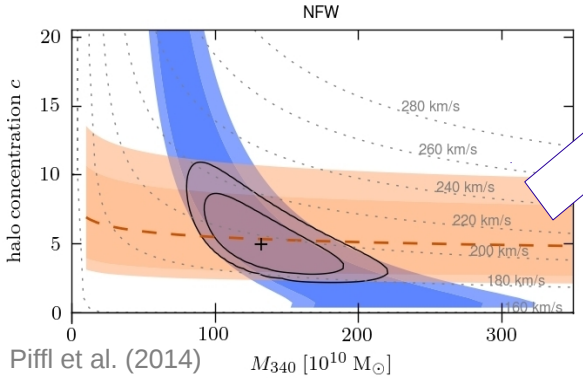

Piffl et al. (2014)

$$v_{\mathrm{esc}}(r_\odot) \equiv \sqrt{2\,\psi_{\mathrm{tot}}(r_\odot)}\,,$$

$$\psi_{\mathrm{tot}}(r_\odot) \equiv -\left(\phi_{\mathrm{tot}}(r_\odot) - \phi_{\mathrm{tot}}(R_{\mathrm{max}})\right)$$

$$v_c^2(r_\odot, z=0) = r_\odot\, G \left\{ \frac{M_{\mathrm{b}}}{(r_\odot + r_{\mathrm{b}})^2} + \frac{r_\odot\, M_{\mathrm{d}}}{(r_\odot^2 + \bar{R}_{\mathrm{d}}^2)^{3/2}} + 4\,\pi\,\frac{\rho_s\, r_s}{x_\odot^2}\left(\ln(1+x_\odot) - \frac{x_\odot}{1+x_\odot}\right)\right\}$$

Beware! MW mass model induces correlations

- In Piffl et al. '14, two different likelihood analyses:

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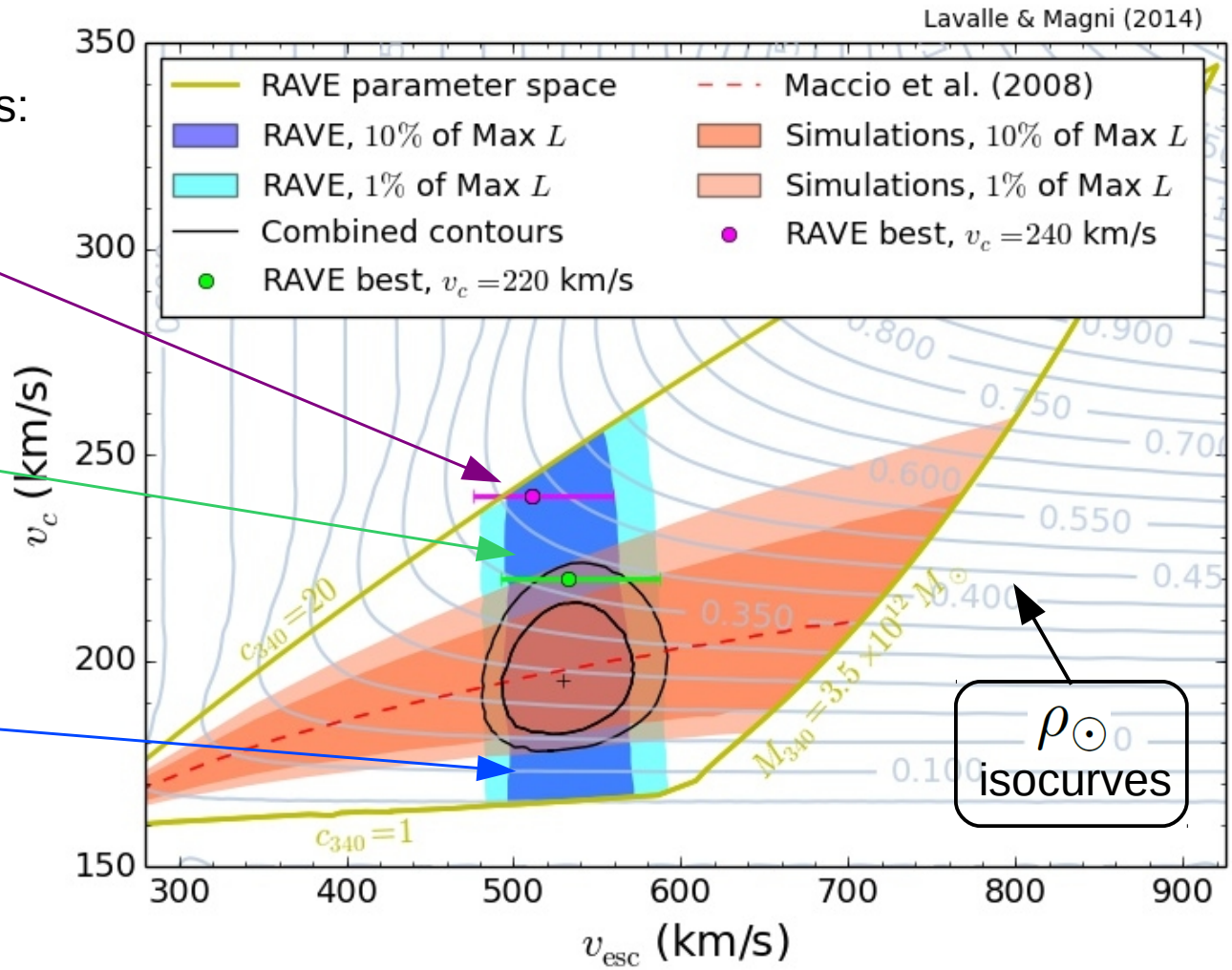


- **Dynamical correlations** between $\rho_\odot$, v_c, and v_{esc} must be taken into account!!!

Model assumptions	v_c (km/s)	v_{esc} (km/s)	ρ_s (GeV/cm^3)	r_s (kpc)	$\rho_\odot$ (GeV/cm^3)
prior $v_c = 220$ km/s	220	$533^{+54+109}_{-41-60}$	$0.42^{+0.26+0.48}_{-0.16-0.24}$	$16.4^{+6.6+13.6}_{-4.5-6.4}$	$0.37^{+0.02+0.04}_{-0.03-0.04}$
prior $v_c = 240$ km/s	240	511^{+48}_{-35}	$1.92^{+1.85}_{-0.82}$	$7.8^{+3.8}_{-2.2}$	$0.43^{+0.05}_{-0.05}$
v_c free	196^{+26}_{-18}	537^{+26}_{-19}	$0.08^{+0.31}_{-0.07}$	$36.7^{+50.7}_{-19.0}$	$0.25^{+0.14}_{-0.12}$

Accounting for dynamical correlations requires self-consistent f(v)

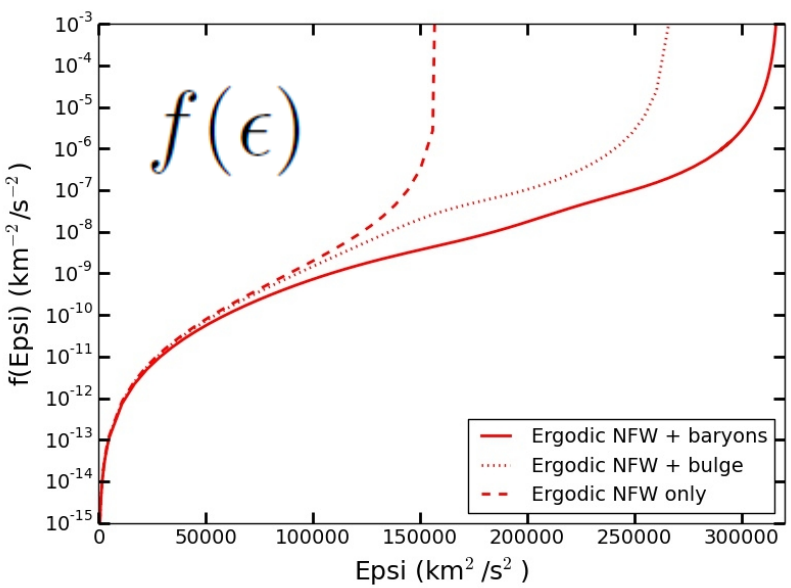
- Shortcomings of Maxwell-Boltzmann:
  - Relies on isothermal assumption
  - Truncated M.-B. not solution of Jeans equation

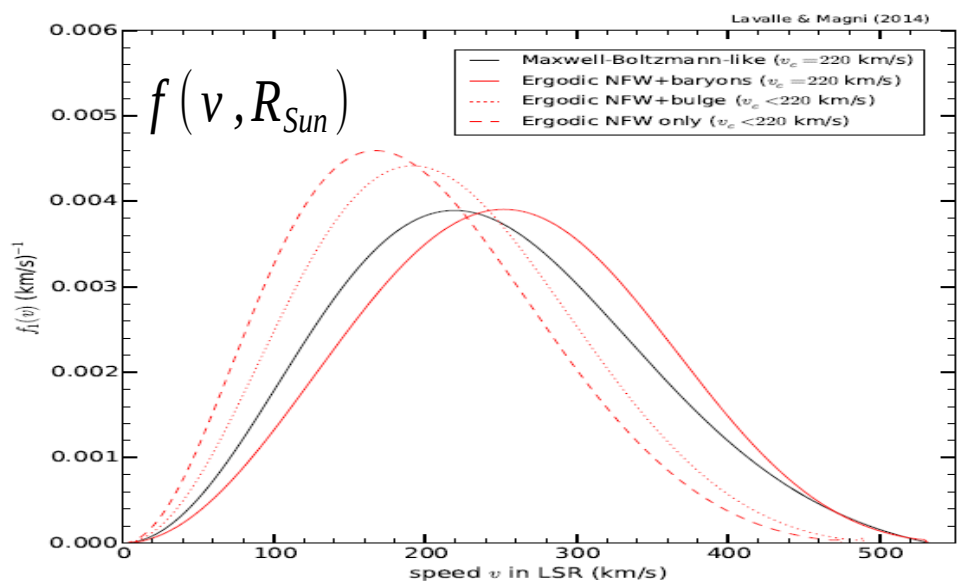
- Use Eddington equation (Ullio & Kamionlowski '01, Vergados & Owens '03)

$$f(\epsilon) = \frac{1}{\sqrt{8}\,\pi^2}\left\{\frac{1}{\sqrt{\epsilon}}\frac{d\rho}{d\psi}\Big|_{\psi=0} + \int_0^{\epsilon}\frac{d\psi}{\sqrt{\epsilon-\psi}}\frac{d^2\rho}{d\psi^2}\right\}$$

$$\Psi = -\Phi_{MW}(r)$$
$$\epsilon = -E_{tot}$$
$$\rho = \rho_{NFW}(r)$$

- From the DM phase-space distribution $f(\epsilon)$ compute the DM speed distribution $f(v, R_{Sun})$





Focus on one case

- In Piffl et al. '14, two different likelihood analyses:

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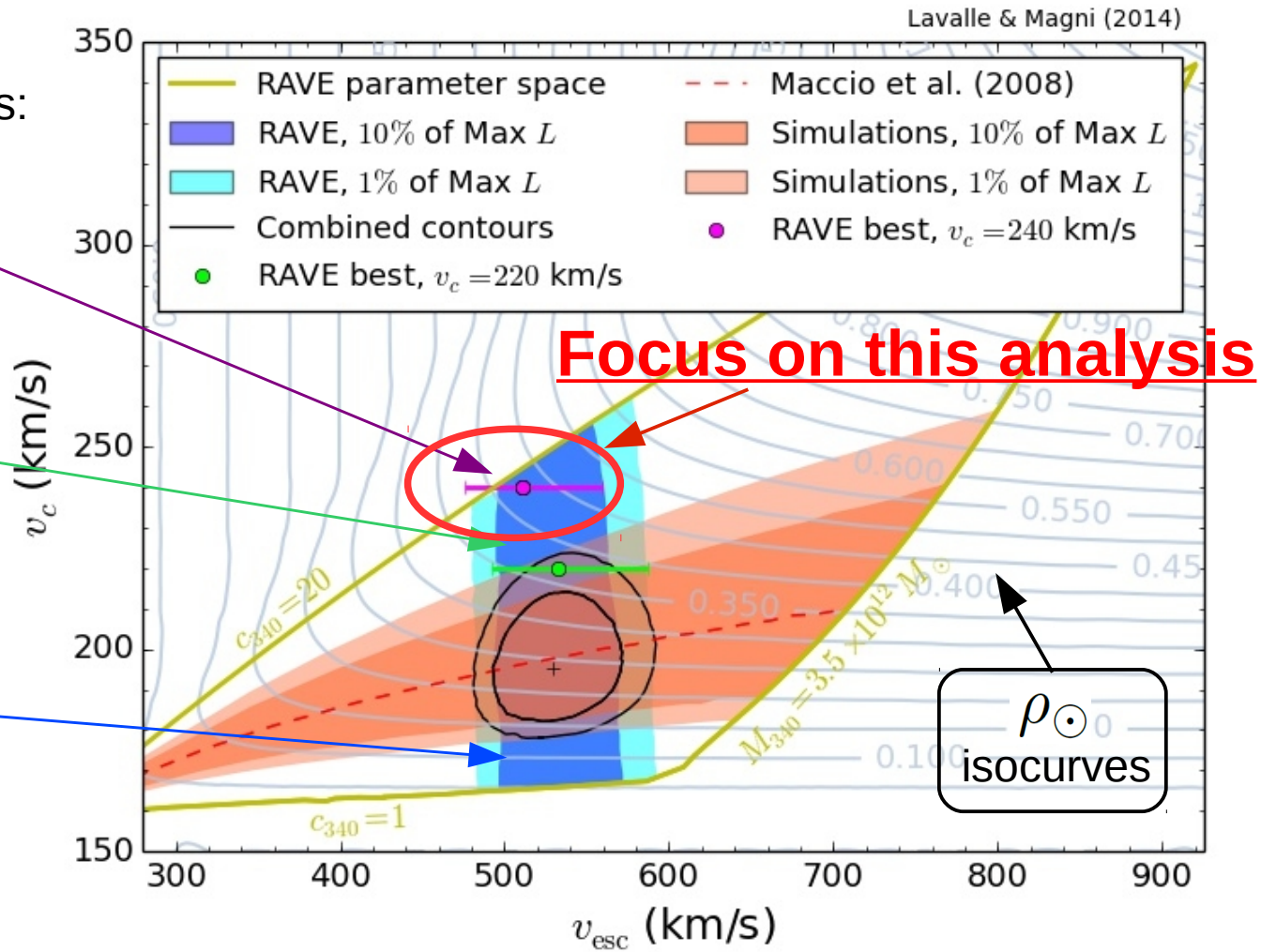
1b) **fixed** $v_c = 220$ km/s

$v_{esc} = 533^{+54}_{-41}$ km/s (90% CL)

2) **free** v_c

- originally estimate of MW Mass
- give independent estimate of v_{esc}

$v_c = 196$ km/s $\quad v_{esc} = 537$ km/s



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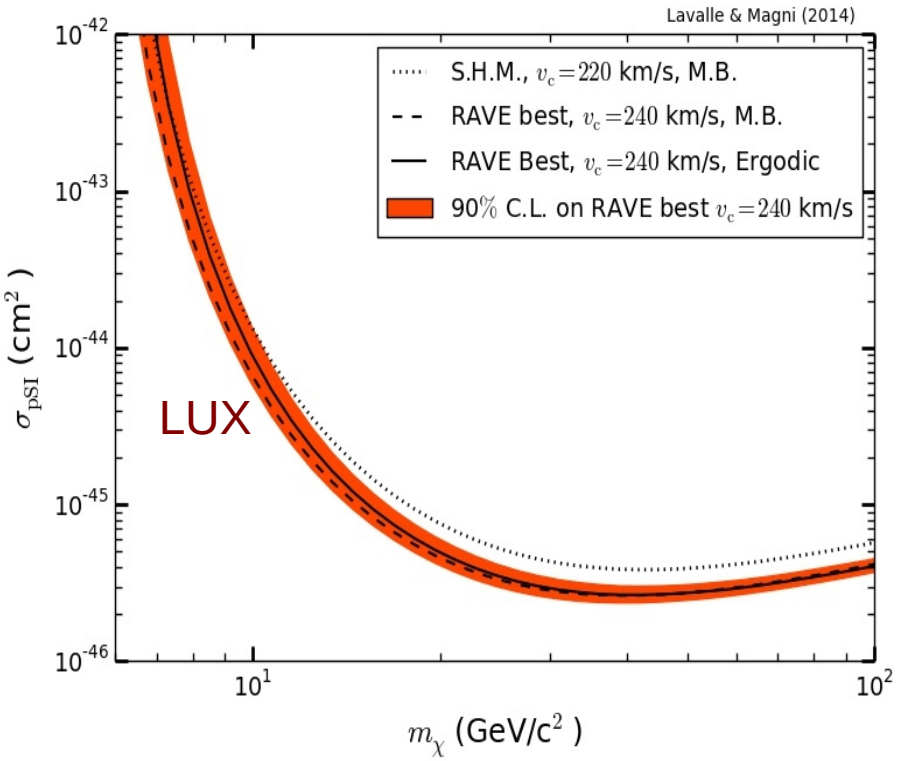
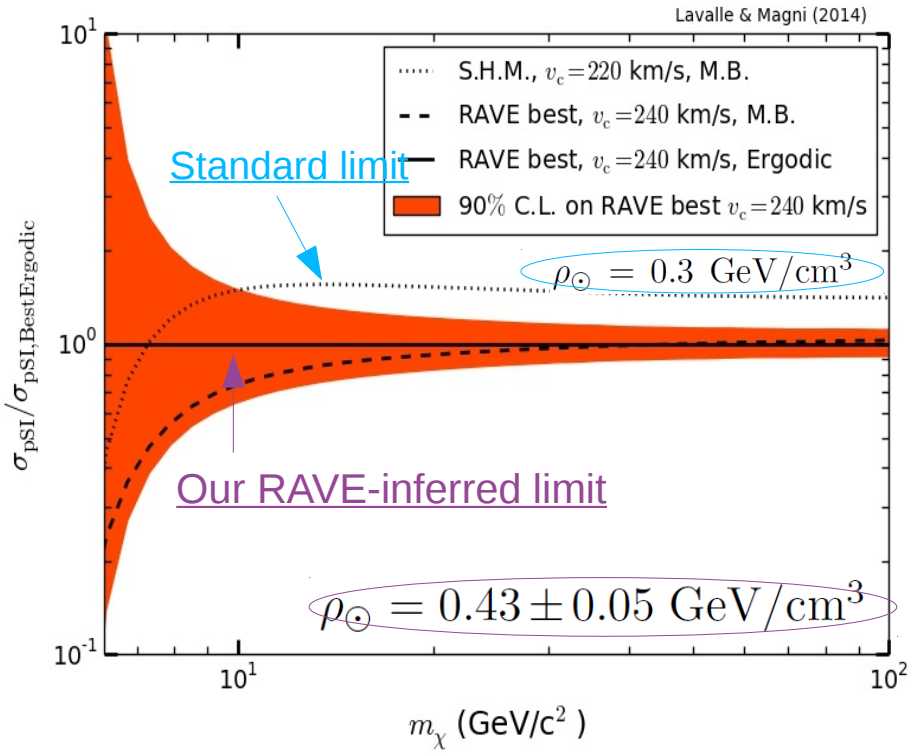
Impact on the direct detection exclusion curves

J. Lavalle and S. Magni, Phys. Rev. D 91, 023510 (2015)





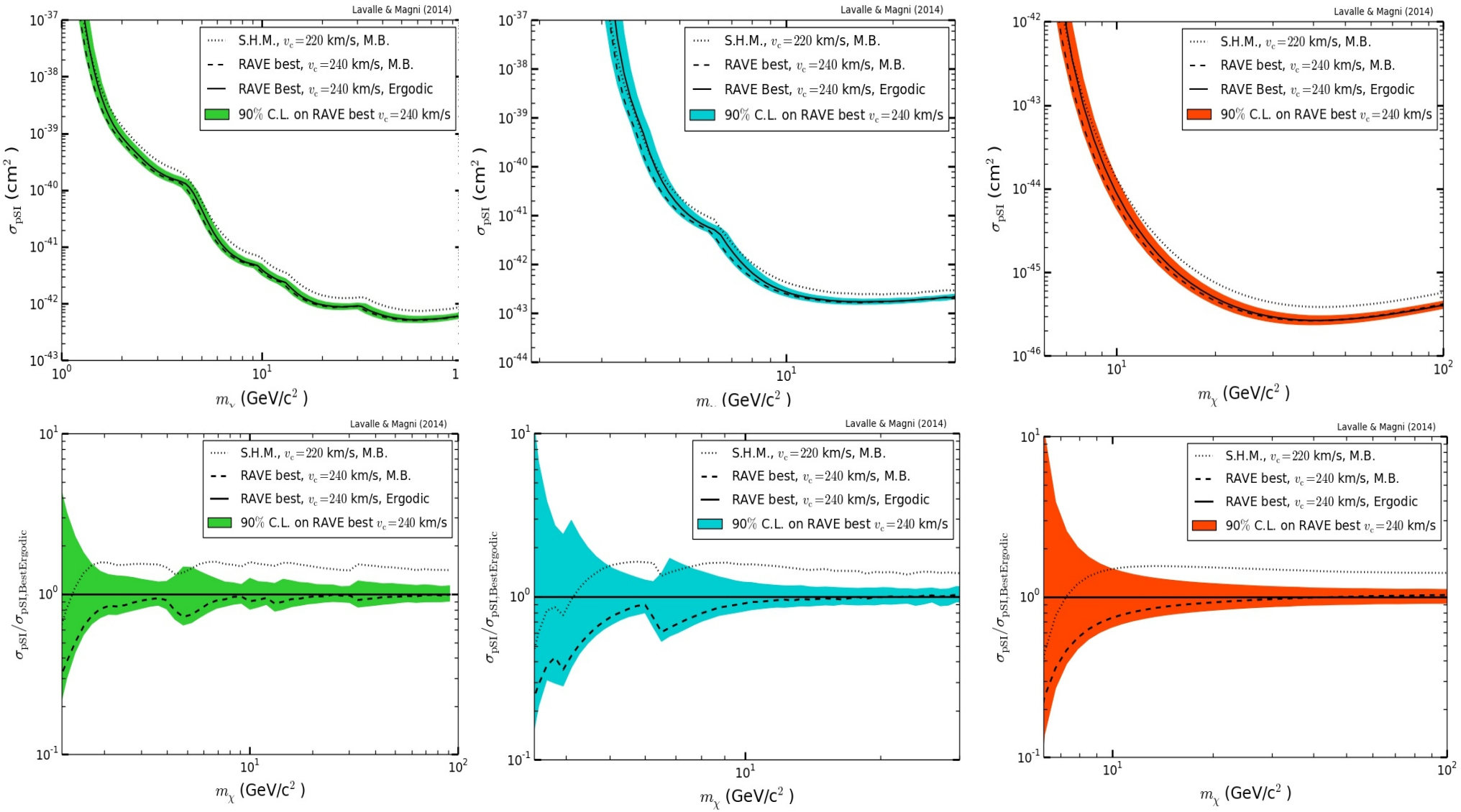
- Above ~10 GeV: **RAVE-inferred limit** **more constraining** than SHM **by 40%** (larger $\rho_\odot$)
- At low masses: **RAVE-inferred limit** **beaten** by SHM because

$$v_c + v_{\rm esc} = 751 \ \ {\rm km/s} \quad \text{VS} \quad v_c + v_{\rm esc} = 764 \ \ {\rm km/s}$$

- The **form of the speed distribution** is relevant only when $m_\chi << m_A$
- Relative RAVE stat. uncertainties saturate at $\pm 10\% \ (90\% \ {\rm CL})$ at large masses

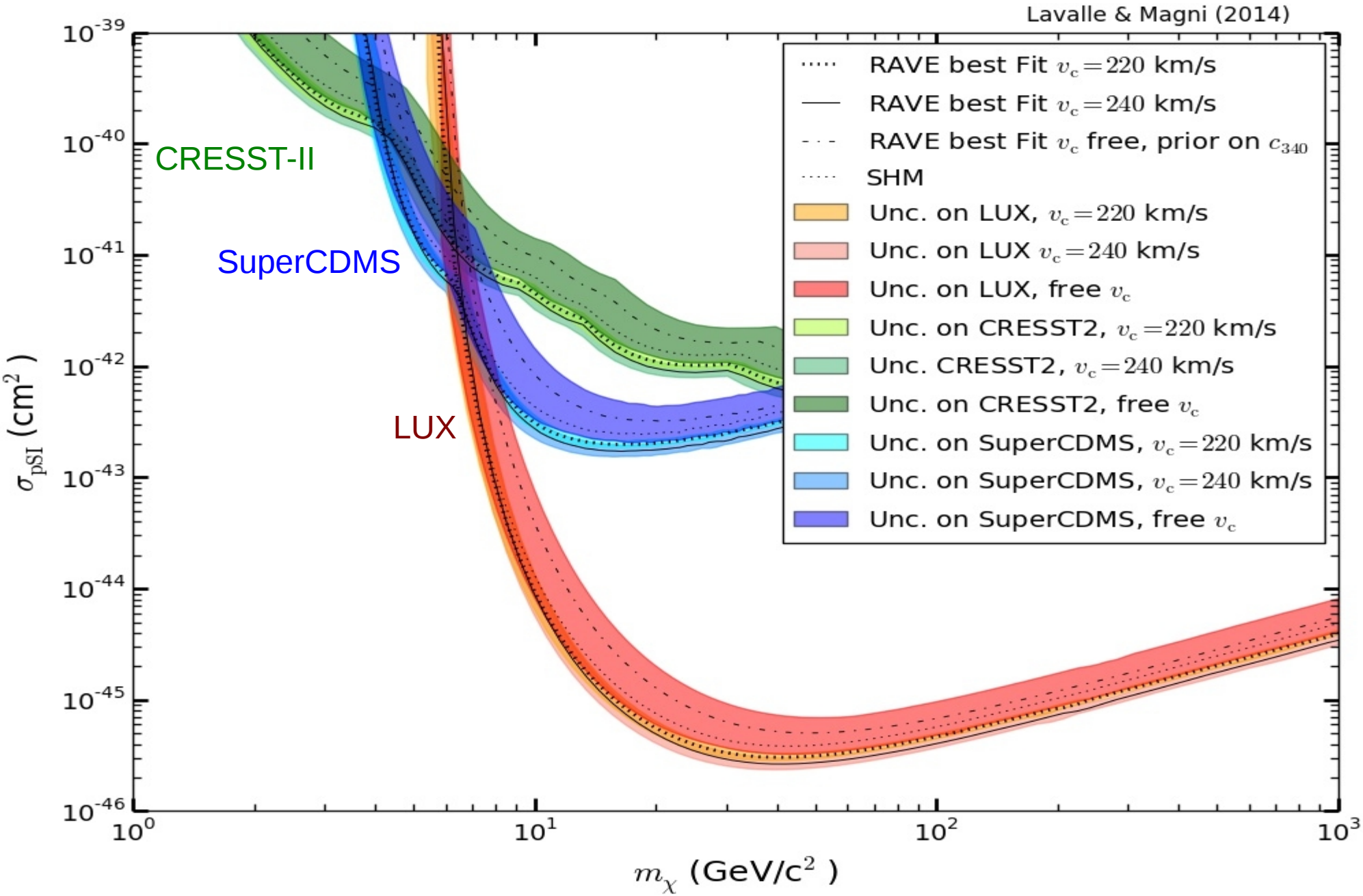
Different direct detection experiments

CRESST-II SuperCDMS LUX



- Reduced uncertainties if more experiments are put together (same for more nuclei)

Different analyses



Perspective I: cross-checks with cosmological simulations

In collaboration with P. Mollitor, E. Nezri, J. Lavalle

- Cosmological hydrodynamical simulation of Milky Way-like Galaxy
  run by our collaborators P. Mollitor, E. Nezri,
  (from P. Mollitor, E. Nezri, R. Teyssier, MNRAS 447 (2015) arXiv:1405.4318 [astro-ph.GA])

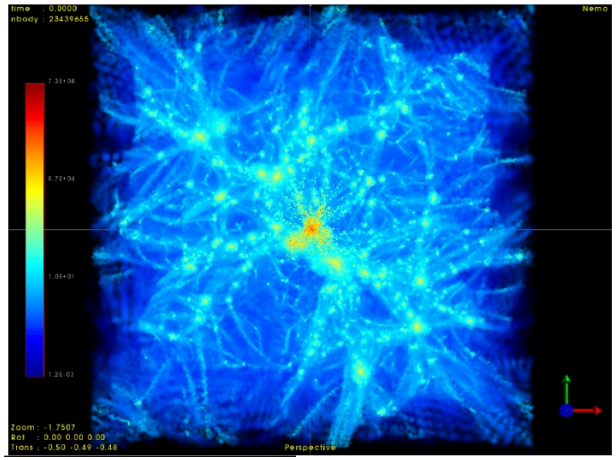
- Using RAMSES code (R. Teyssier 2002)

- Including baryons, important role in central part of galaxy

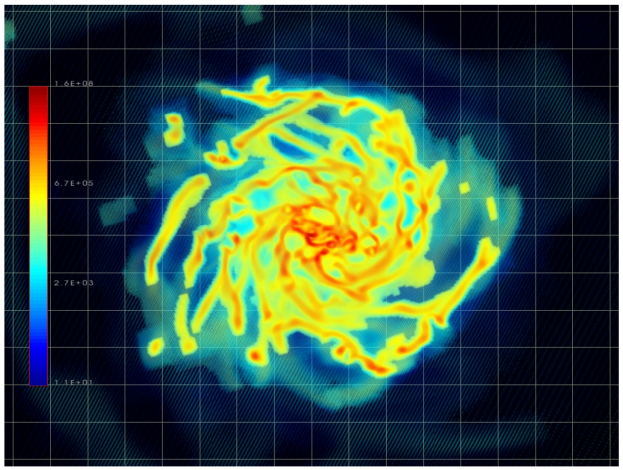
- Balance between star formation and super-Novae feedback

- Presence of a dark disk in this simulation?
  Dark matter component in disk, due to a subhalo, not yet a conclusive answer.

Dark Matter only, density



Gas, density

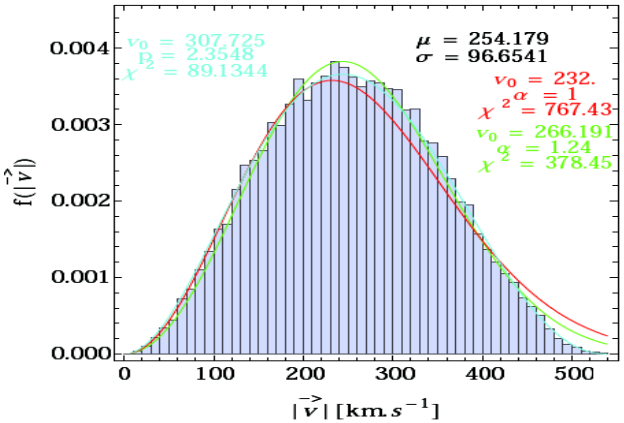


Perspective II:
The escape speed in a simulated galaxy

In collaboration with P. Mollitor, E. Nezri, J. Lavalle

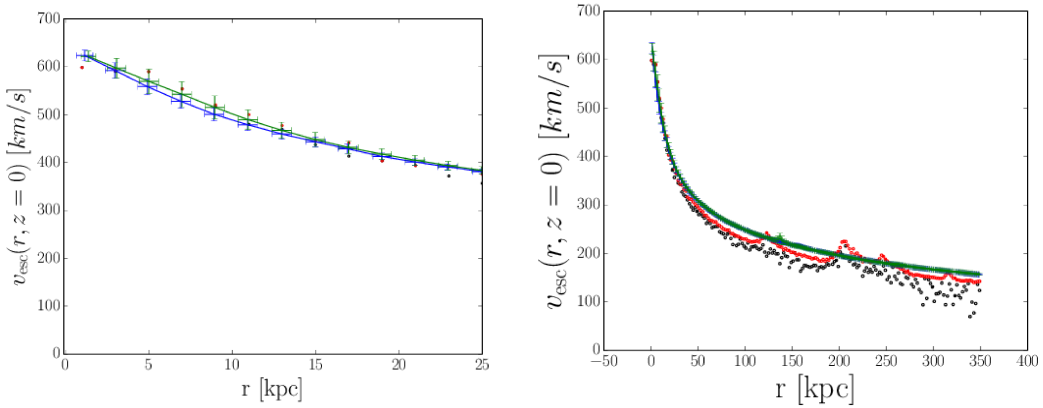
- **Goal:** use simulated galaxy to study how the employed methods behave

- Particularly interesting for this work: the escape speed in the simulation



DM particles in a spherical shell at Sun's position

- Different ways of computing the escape speed:
  - from <u>fitted</u> speed distributions
  - from the last bin
  - from the <u>gravitational potential,</u> which can be computed exactly



Points = max speed of DM particles (red/black for shell/ring)

Crosses = escape speed computed from the gravitational potential (green/blue for shell/ring averaging)

In any case: consider
1) <u>spherical shell</u> or 2) <u>ring</u>

Perspecitve III:
Validity of Eddington equation?

In collaboration with P. Mollitor, E. Nezri, J. Lavalle

- Phase-space distribution from Eddington equation

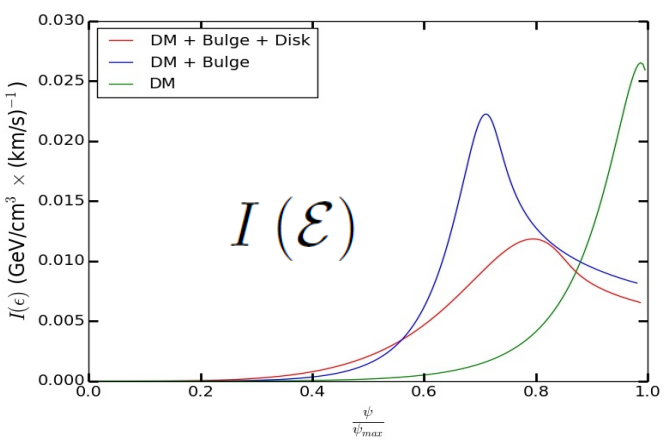
$$f(\epsilon) = \frac{1}{\sqrt{8}\,\pi^2}\left\{\frac{1}{\sqrt{\epsilon}}\frac{d\rho}{d\psi}\Big|_{\psi=0} + \int_0^{\epsilon}\frac{d\psi}{\sqrt{\epsilon-\psi}}\frac{d^2\rho}{d\psi^2}\right\} = \frac{1}{\sqrt{8}\pi^2}\frac{d}{d\mathcal{E}}\overbrace{\int_0^{\mathcal{E}}\frac{d\varrho}{d\Psi}\frac{d\Psi}{\sqrt{\mathcal{E}-\Psi}}}^{I(\mathcal{E})} \overset{?}{\geq} 0$$

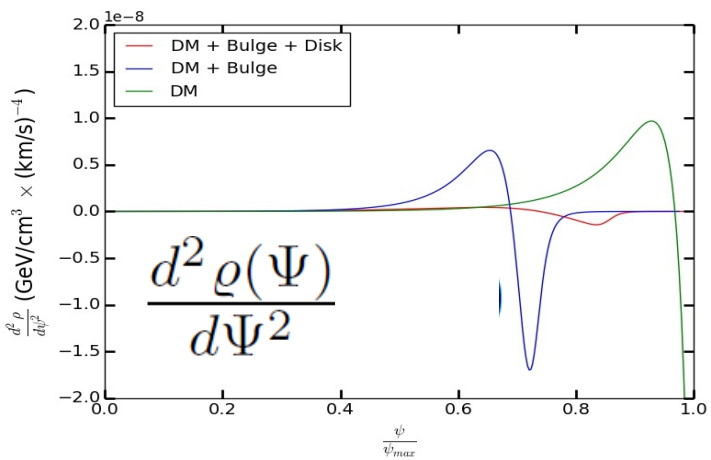
- Issue: **<u>Eddington not applicable to certain couples of</u>** $\varrho(r),\ \psi(r)$.

- Sufficent condition for the applicability of Eddington equation:

$$\frac{d^2\varrho(\Psi)}{d\Psi^2} \geq 0$$

- Eddington not applicable to mass models fit to this simulation:





- Same kind of issue also with generalizations of Eddington procedure to anisotropic velocity distributions

Perspective IV:
Considering anisotropic dark matter velocity distributions

(see e.g. N. Bozorgnia et al. JCAP 1312 (2013) arXiv:1310.0468 [astro-ph.CO])

- Anisotropy parameter: $\beta(r) \doteq 1 - \frac{\overline{v_T^2}(r)}{\overline{2v_r^2}(r)}$

  Tangential velocity dispersion

  Radial velocity dispersion

  Assume: $\begin{cases} \text{spherical symmetry} \\ \overline{v_\vartheta^2} = \overline{v_\varphi^2} \end{cases}$

  $$\overline{v_T^2}(r) \doteq \overline{v_\vartheta^2}(r) + \overline{v_\varphi^2}(r)$$

- Different models to obtain anisotropic velocity distributions from Eddington-like procedures

1) Osipkov-Merrit models

$$f(\mathcal{E}, L) = f(Q) \quad \text{with} \quad Q \doteq \mathcal{E} - \frac{L^2}{2r_a^2} \quad \Longrightarrow \quad \beta(r) = \frac{r^2}{r^2 + r_a^2}$$

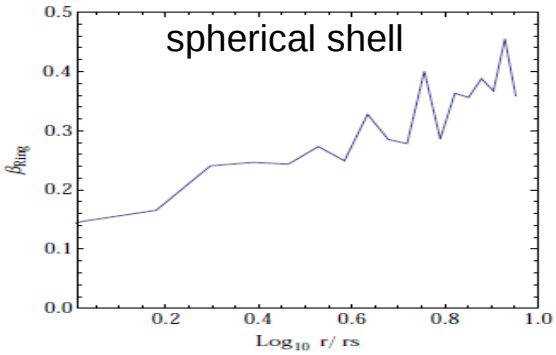
2) Constant anisotropy parameter

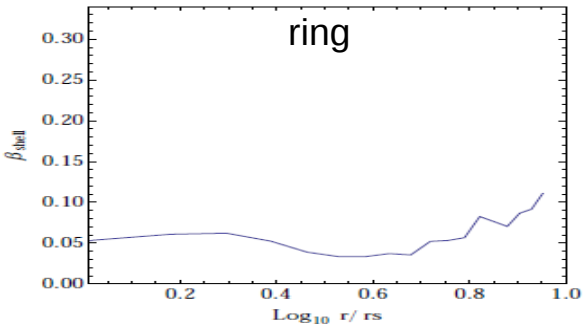
$$f(\mathcal{E}, L) = L^{-2\beta} G(\mathcal{E}) \quad \Longrightarrow \quad \beta(r) = \beta$$

3) Linear combination, useful to reproduce simulations

$$f(\mathcal{E}, L) = w f_{OM}(Q) + (1 - w) f_\beta(\mathcal{E}, L)$$

- In simulations, different behavior of anisotropy parameter between spherical shell and ring





Conclusions

- RAVE's estimates of escape speed cannot be used blindly because **rely on assumptions**
- A **Milky Way mass model** must be assumed, which induces **correlations among the astrophysical parameters**
- These correlations **propagate to limits computed in direct detection**
- Direct detection **limits** on the plane $\sigma_{p,SI} - m_\chi$ self-consistently inferred from RAVE's results **more constraining by up to 40%** w.r.t. SHM (due to larger $\rho_\odot$).
- **Main question:** how reliable is to use current observables to reconstruct dark matter's phase space?

Perspectives

- **Cosmological simulations** to **cross check** the employed procedures (with P. Mollitor, E. Nezri & J. Lavalle)
- **Limits of validity of Eddington equation** (and generalizations)
- **Comparison with uncertainties on WIMP-nucelon interactions** (evaluated by L. Lellouche and C. Torrero using LQCD methods)

Thank you
very much
for your attention!

Backup slides

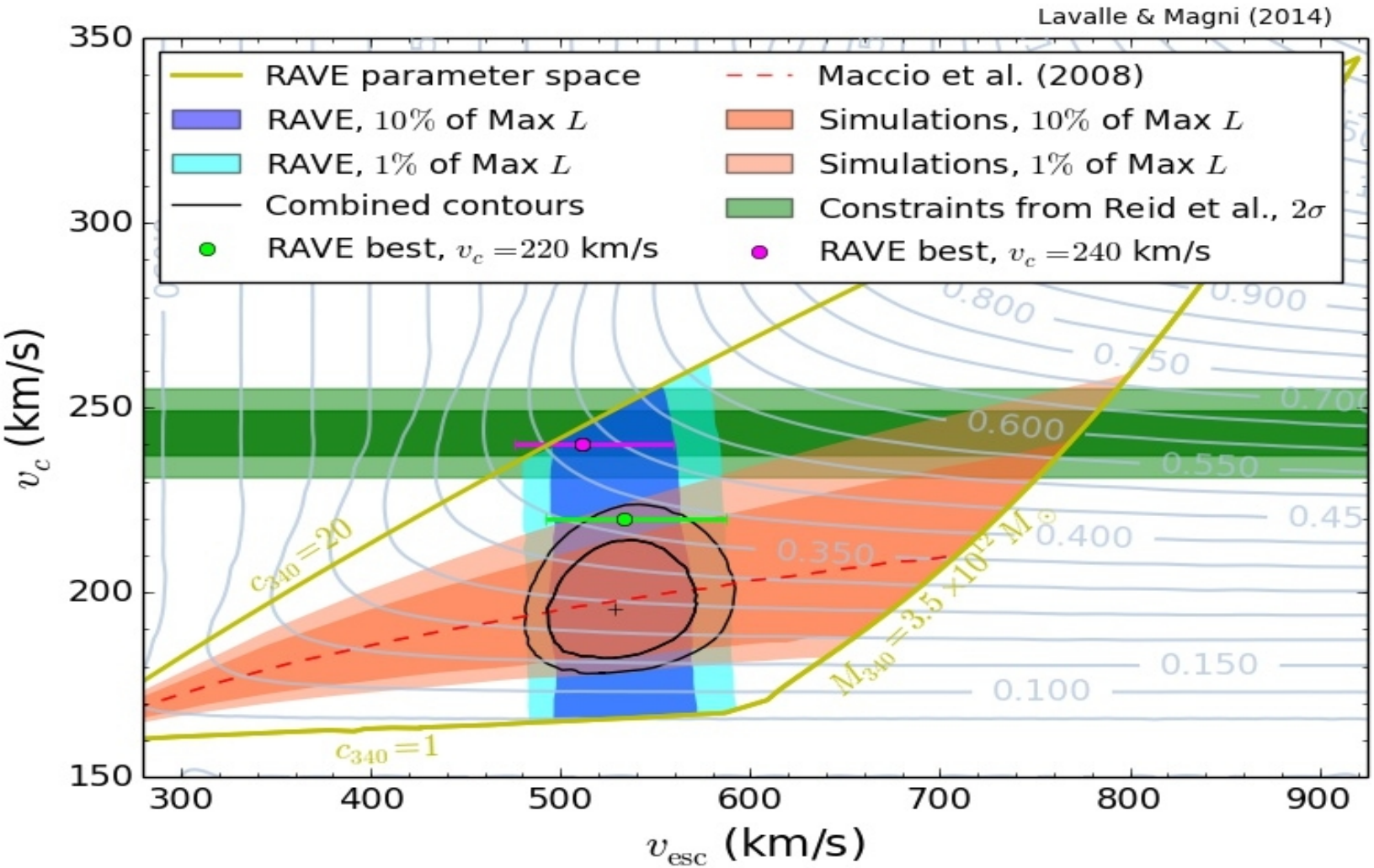
Considering an independent determination of v_c

$$v_c = 243 \pm 6 \text{ km/s} \, (1\,\sigma)$$
$$v_c = 243 \pm 12 \text{ km/s} \, (2\sigma)$$

(Reid et al., '14)

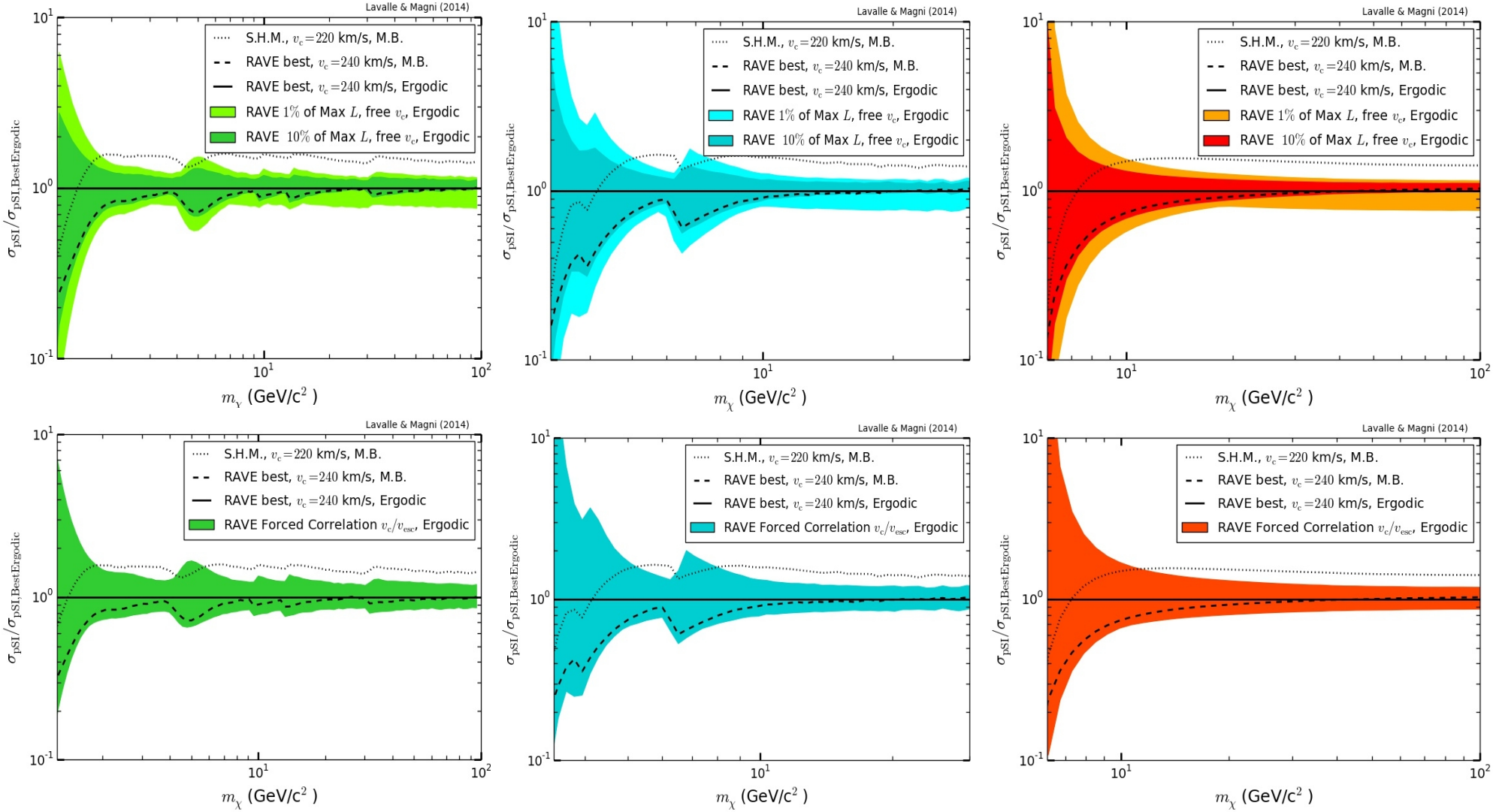
Additional constraints (OK within 3 sigma):

$$dv_c(R)/dR = -0.2 \pm 0.4 \quad \text{km/s/kpc} \qquad r_\odot = 8.33 \pm 0.16 \, \text{kpc}$$



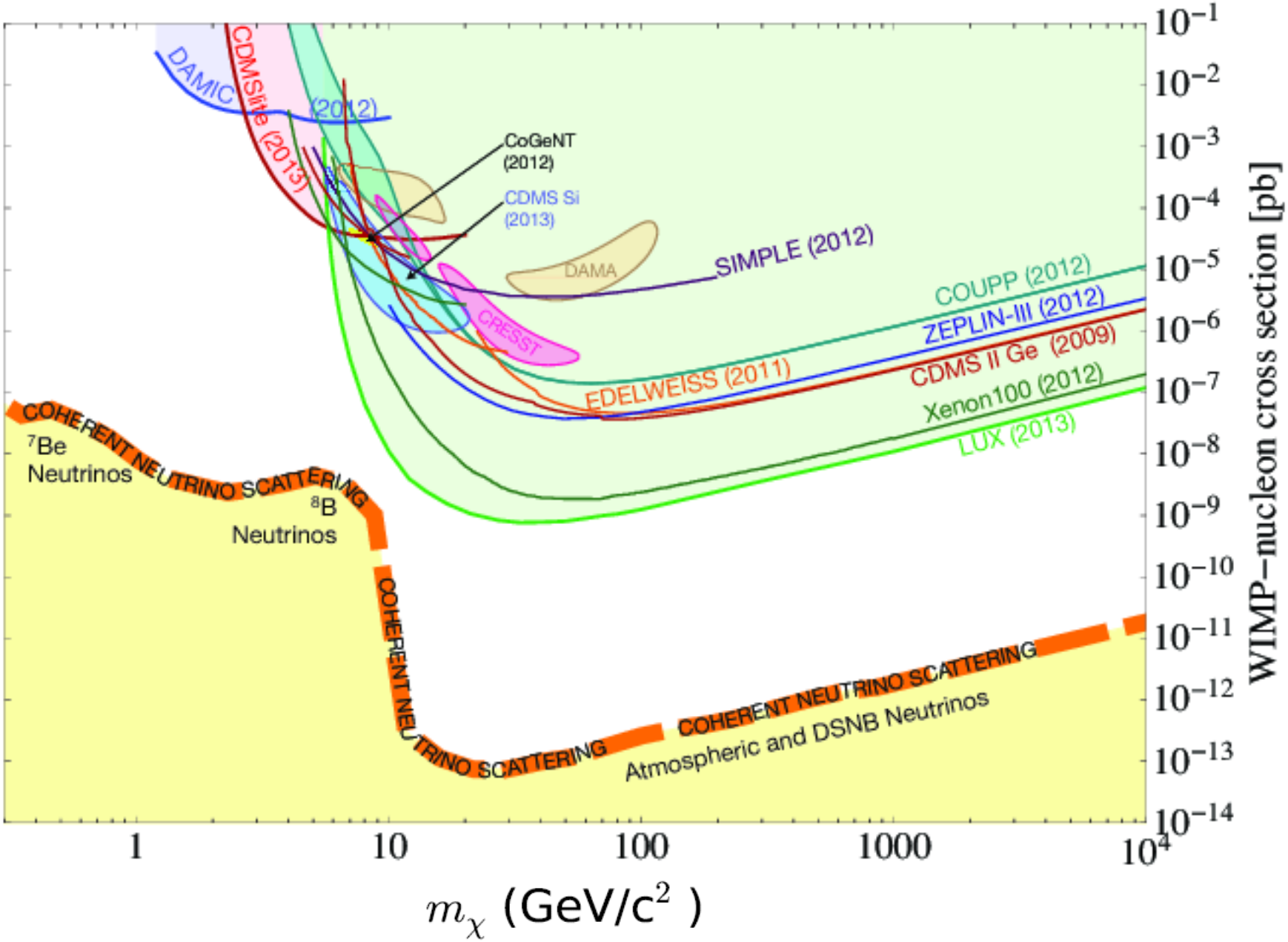
Analysis with free v_c versus forced correlation between v_c and v_{esc}

CRESST-II SuperCDMS LUX



- Taking into account also the v_{esc}, v_c anticorrelation provides the most consistent analysis

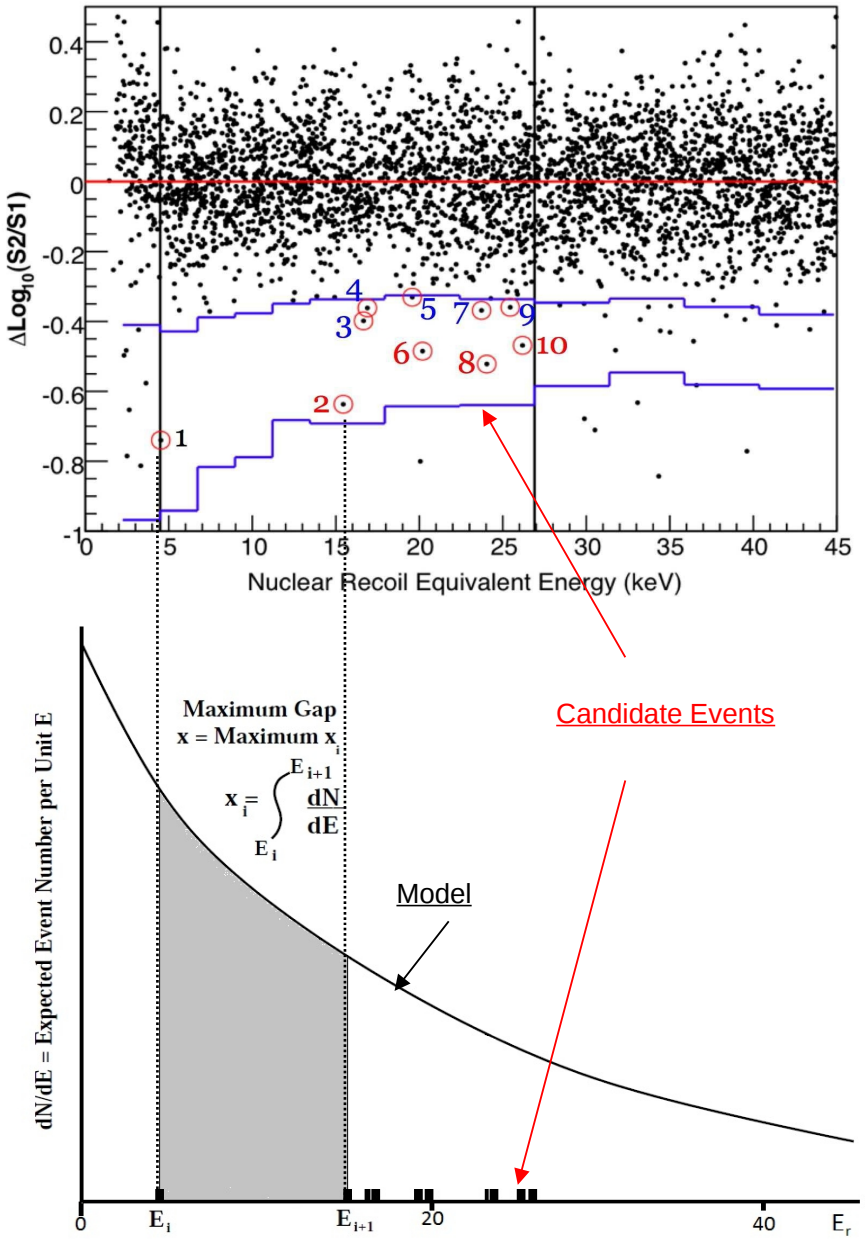
Spin-Independent interpretation of the current experimental results



(Figure from J. Billard Phys.Rev. D89 (2014) 2, 023524)

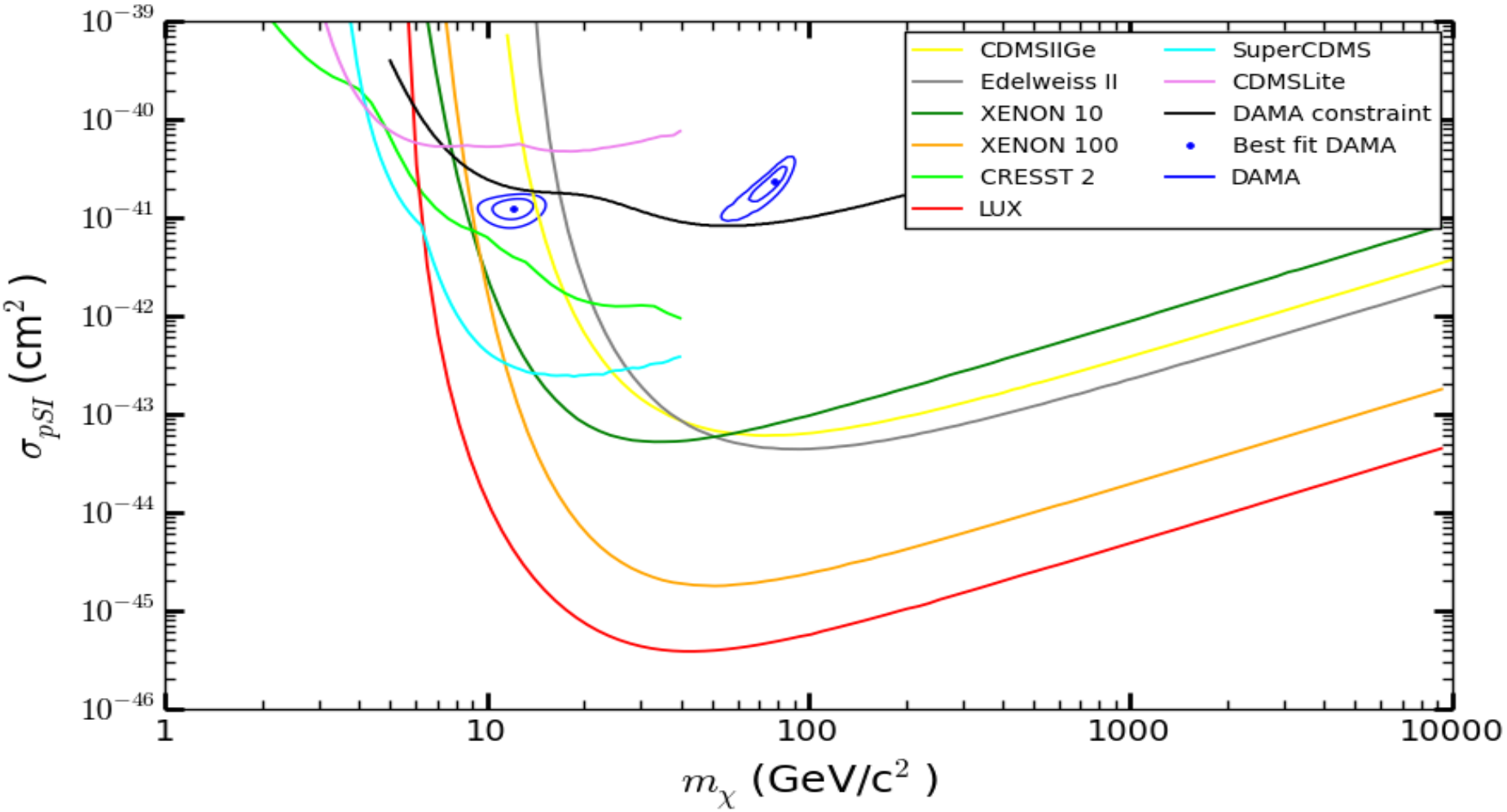
Exclusion curves computed with e.g. the Maximum Gap Method

Example: XENON10 (J. Angle et al, 2007)



(Yellin 2002)

Reproducing the spin independent interpretation of the experimental results



- <u>Total event rate</u>

$$R_i(t) = \int_0^\infty dE_r\, \epsilon(E_r)\, \frac{dR(E_r)}{dE_r} \int_{E_i^{min}}^{E_i^{max}} dE'_r\, G(E_r, E'_r)$$

- Experimental efficency (acceptance)
- Energy resolution
- Time average
- Isotopic composition of targets

The cosmological simulations

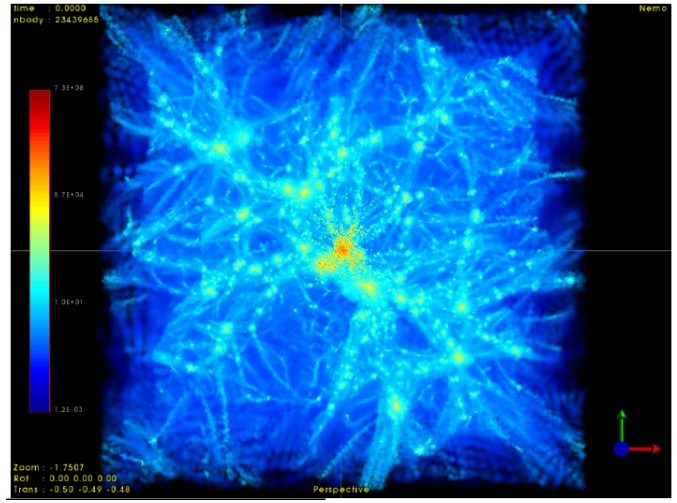
(from P. Mollitor, E. Nezri, R. Teyssier, MNRAS 447 (2015) arXiv:1405.4318 [astro-ph.GA])

- Cosmological hydrodynamical simulation of Milky-Way like Galaxy run by our collaborators P. Mollitor and E. Nezri, (Halo B)
- Using RAMSES code (R. Teyssier 2002)
  - a grid-based hydrodynamical solver with adaptive mesh refinement
  - dark matter only simulations + hydrodinamical simulations of baryons
  - "Zoom-in" simulations (highly resolved structures within a cosmological context)
- Including baryons, the physics of which is very important for galaxies
- Star formation: conversion of gas into star particles (Modeled by a Schmidt law)
- Super-Novae feedback:
  - Explosion 10 Myr after the star (particle) creation
  - 20 % of the star mass is re-injected into the gas
- Balance between star formation rate and super-novae feedback
  - Star formation contracts the dark matter profile
  - Super-Novae feedback originates a core in the dark matter profile

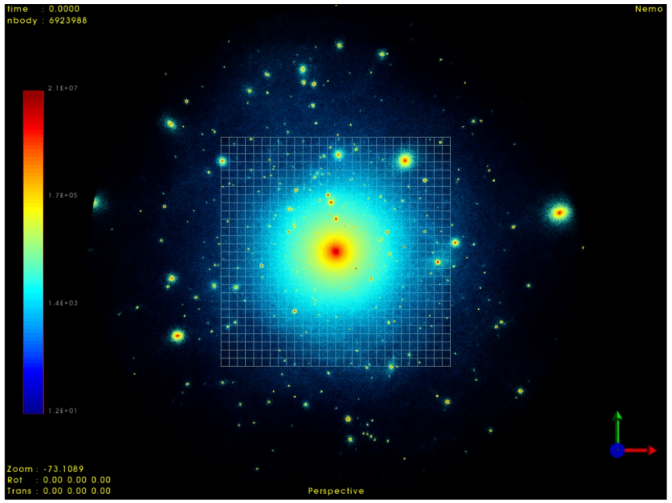
The cosmological simulations

(from P. Mollitor, E. Nezri, R. Teyssier, MNRAS 447 (2015) arXiv:1405.4318 [astro-ph.GA])

Dark Matter only, density

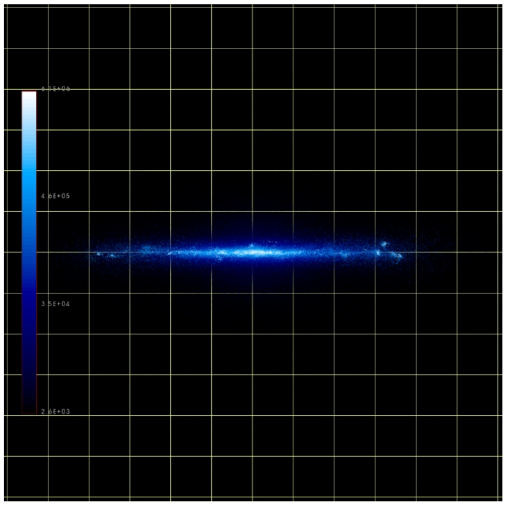


Evolved structure

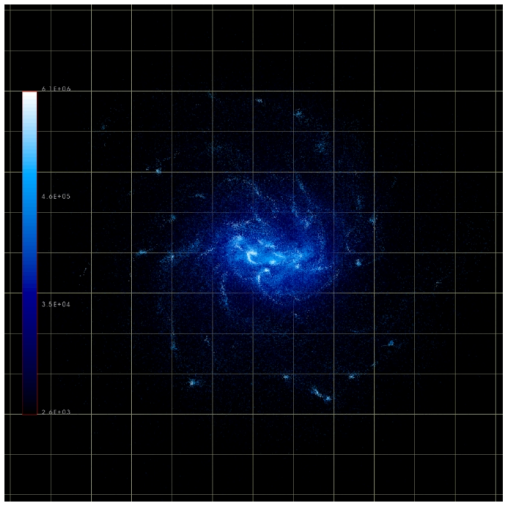


Zoomed dark matter halo

Projected stellar luminosity

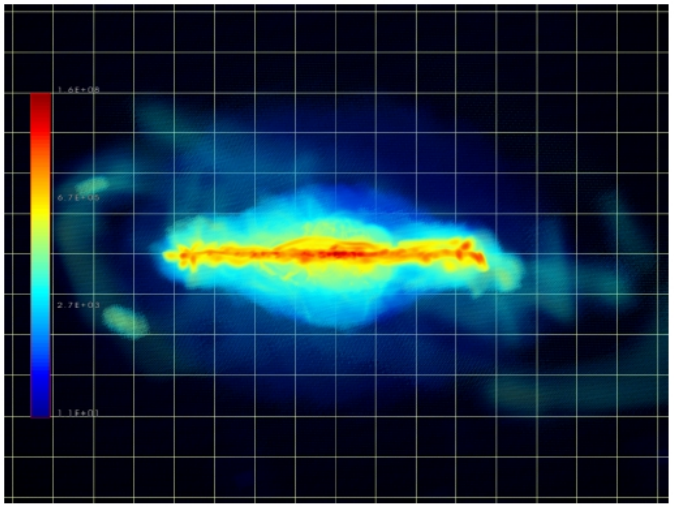


Side-on view

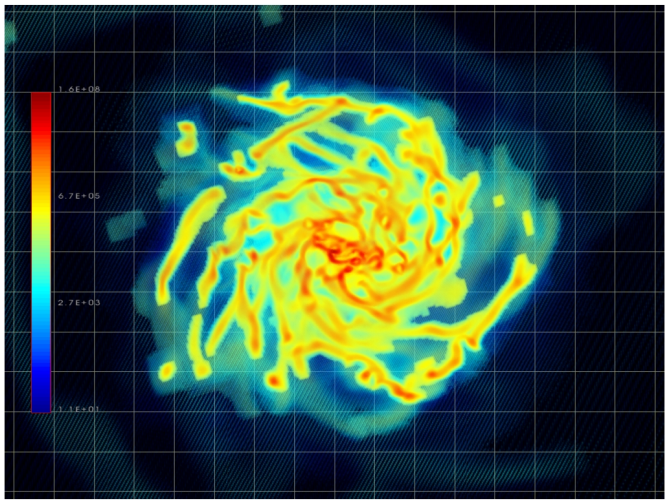


Face-on view

Gas, density



Side-on view



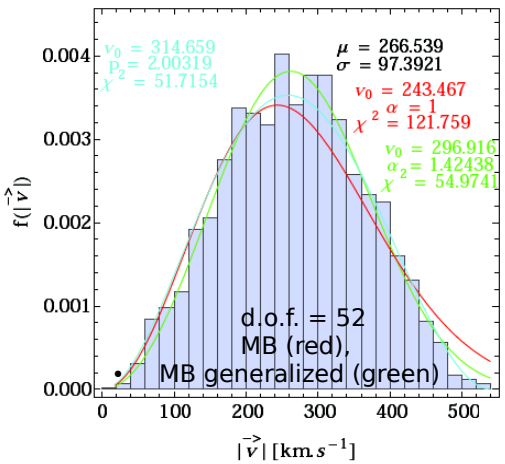
Face-on view

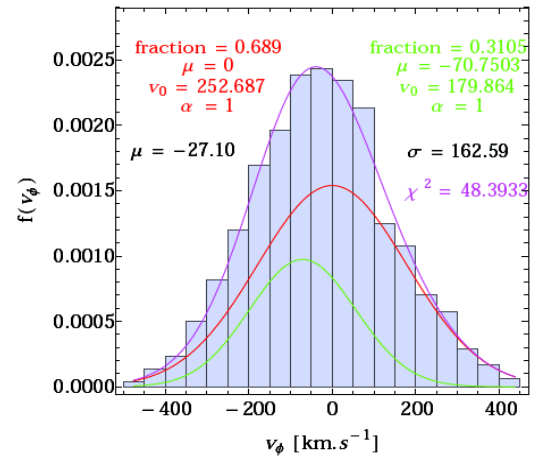
Characterizing astrophysical properties of dark matter in simulation

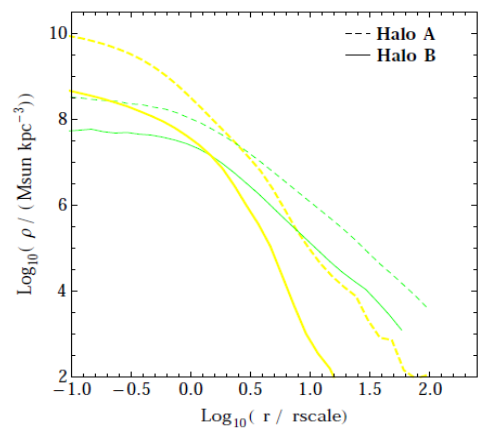
Goals:

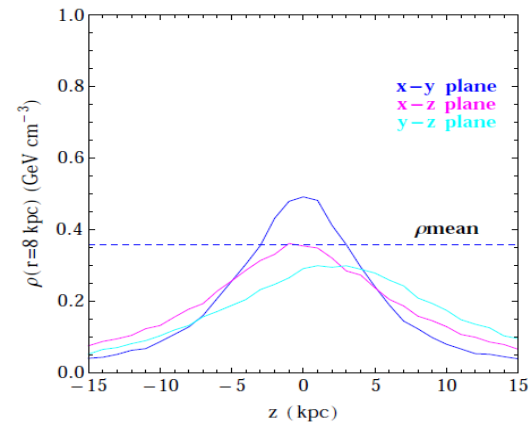
- understanding the physical processes
- project the impact on direct detection
- test analytical methods (Eddington-like)

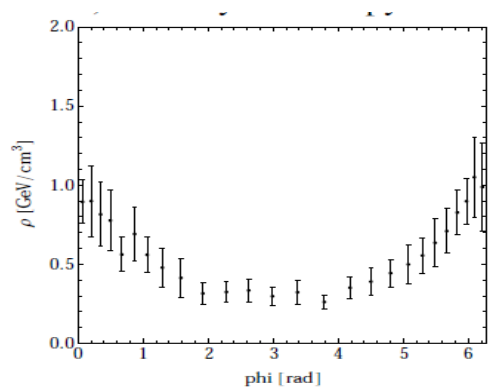
- Dark matter velocity distribution
  - Fundamental for direct detection
  - Fundamental to test on Eddington
- Dark matter spatial distribution
  - Cored dark matter profile
- Dark disk?
  - Suggested by dark matter density
  - Just an effect of the triaxiality of the halo?
- Offset between the centers of dark matter and stellar distributions?
  - Between 0 and 2 kpc...
  - Meaningful definition of “centers”?

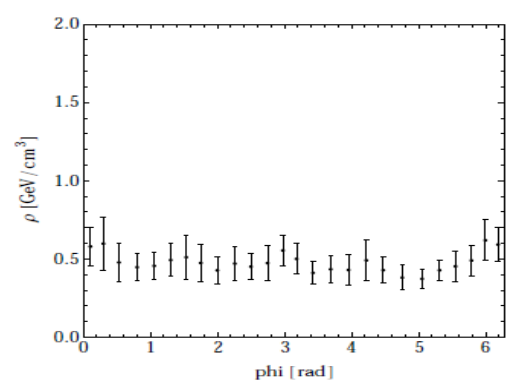












From J. Lavalle, S. Magni, P. Mollitor, E. Nezri, in preparation