Making sense of the estimates of the local Galactic escape speed in direct dark matter searches

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SCIENCES ET TECHNIQUES

with J. Lavalle (Ph.D. supervisor)

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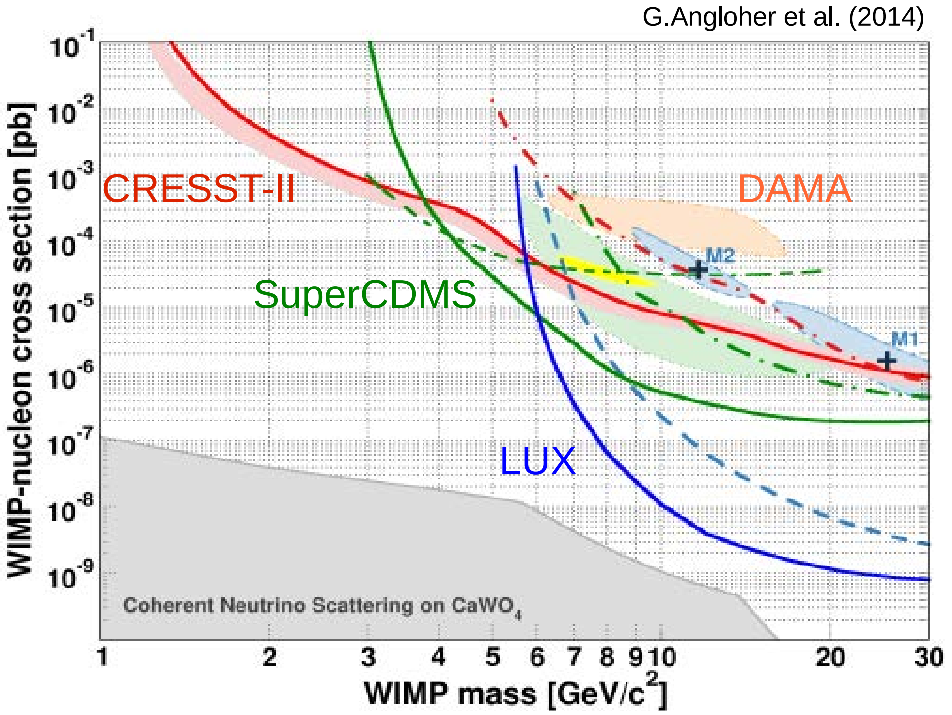
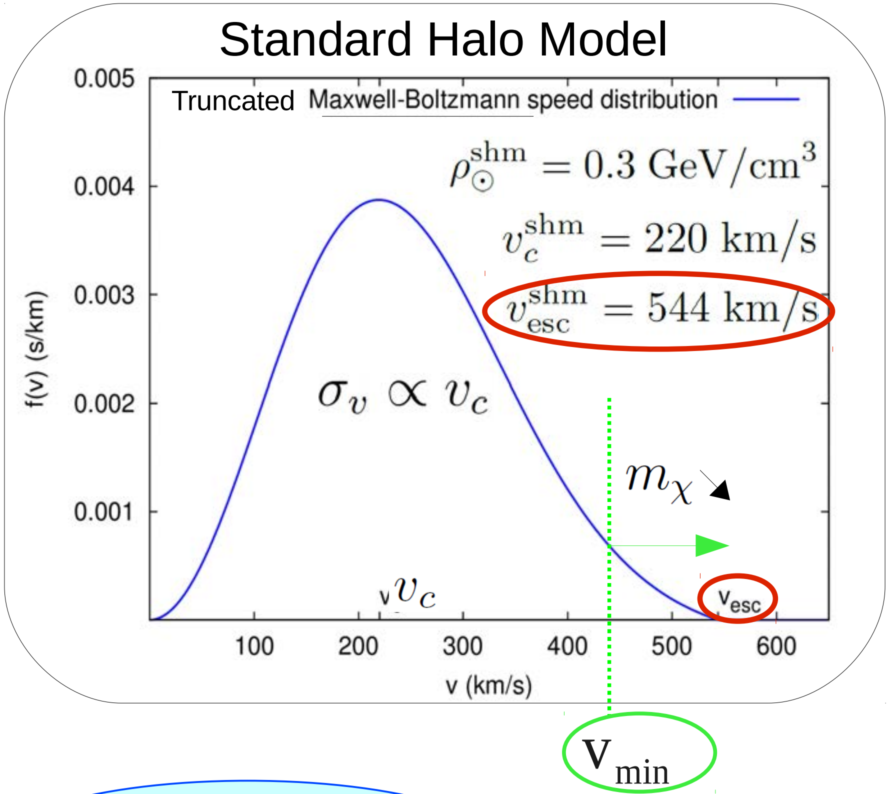
50th Rencontres de Moriond – Electroweak session
La Thuile, March 16th 2015

Standard astrophysics in direct detection

- **Dark matter direct detection: astrophysical uncertainties do matter.**
  ⇨ important in **low WIMP mass controversy** + **exclusion/discovery** perspectives
  (A. Green (2012), R. Catena & P. Ullio (2012), M. Fairbairn & P. Grothaus (2013), N. Bozorgnia, et al. (2013), etc.)





- **Differential event rate**

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

Astrophysics

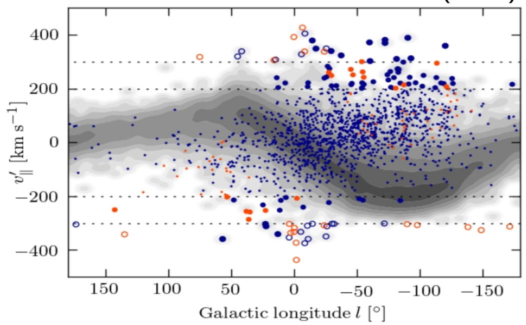
Goal: check how **Galactic escape speed** is obtained from **RAVE survey** **(Piffl et al. '14)**
+ potential **implications** on direct detection

Underlying assumption: Milky Way mass model

- RAVE estimate of escape speed based on high-velocity, non-corotating stars
  ⇨ **requires assumptions!**

- Correct line-of-sight speeds of observed stars to **"relocate" them at Sun's position**
  ⇨ Needs gravitational potential
  ⇨ Relies on **Milky Way mass model**

Piffl et al. (2014)



Fixed baryons

- **disk**: Miyamoto-Nagai $\phi_d(R,|z|) = -G\frac{M_d}{\sqrt{R^2 + (R_d + \sqrt{z^2+z_d^2})^2}}$
- **bulge**: Hernquist $\phi_b(r) = -G\frac{M_b}{(r+r_b)}$

\+

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

2 free parameters

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

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

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

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

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

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

Using the escape speed estimates from the RAVE survey

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

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

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

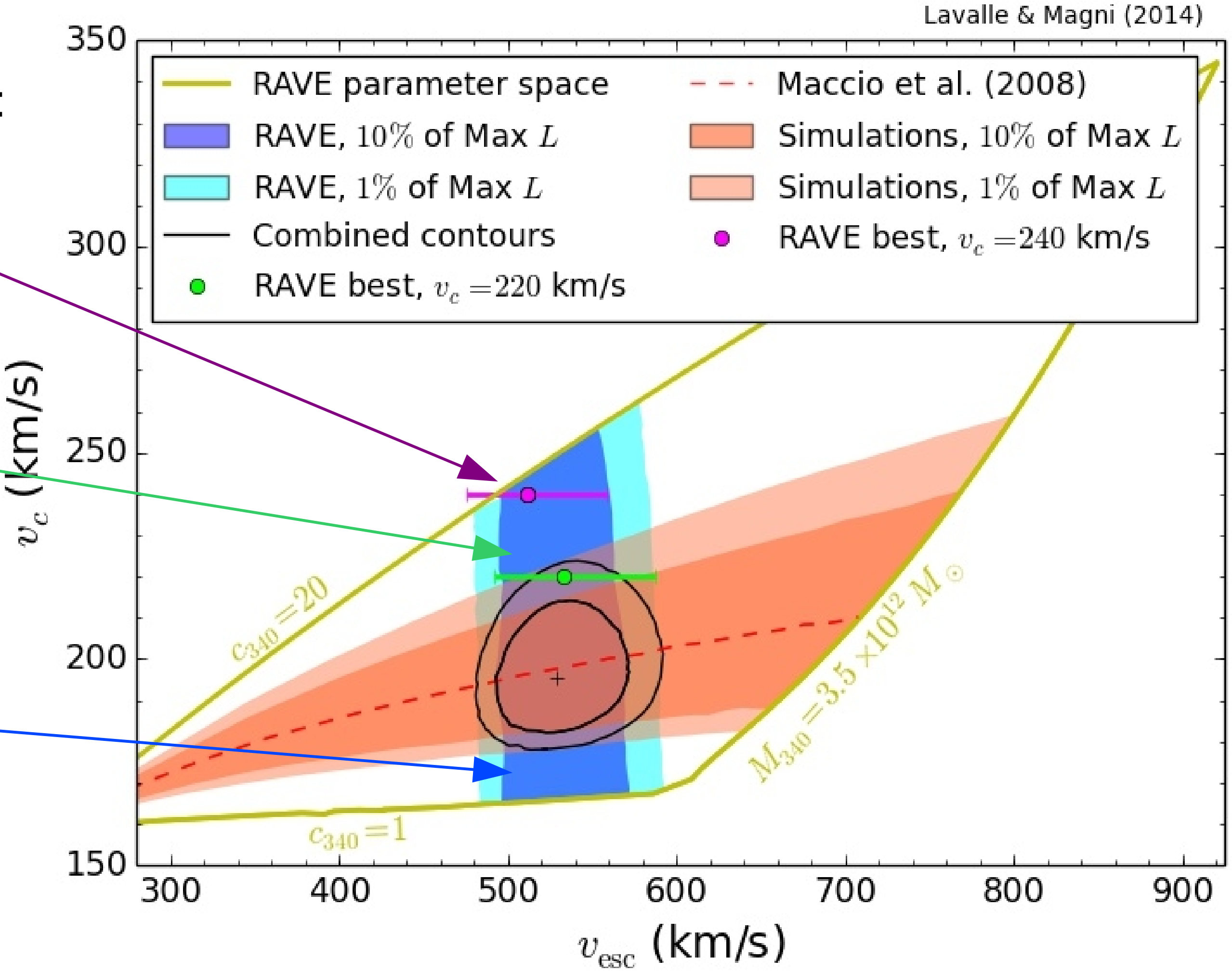
1b) **fixed** $v_c = 220\ \mathrm{km/s}$

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

2) **free** v_c

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

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



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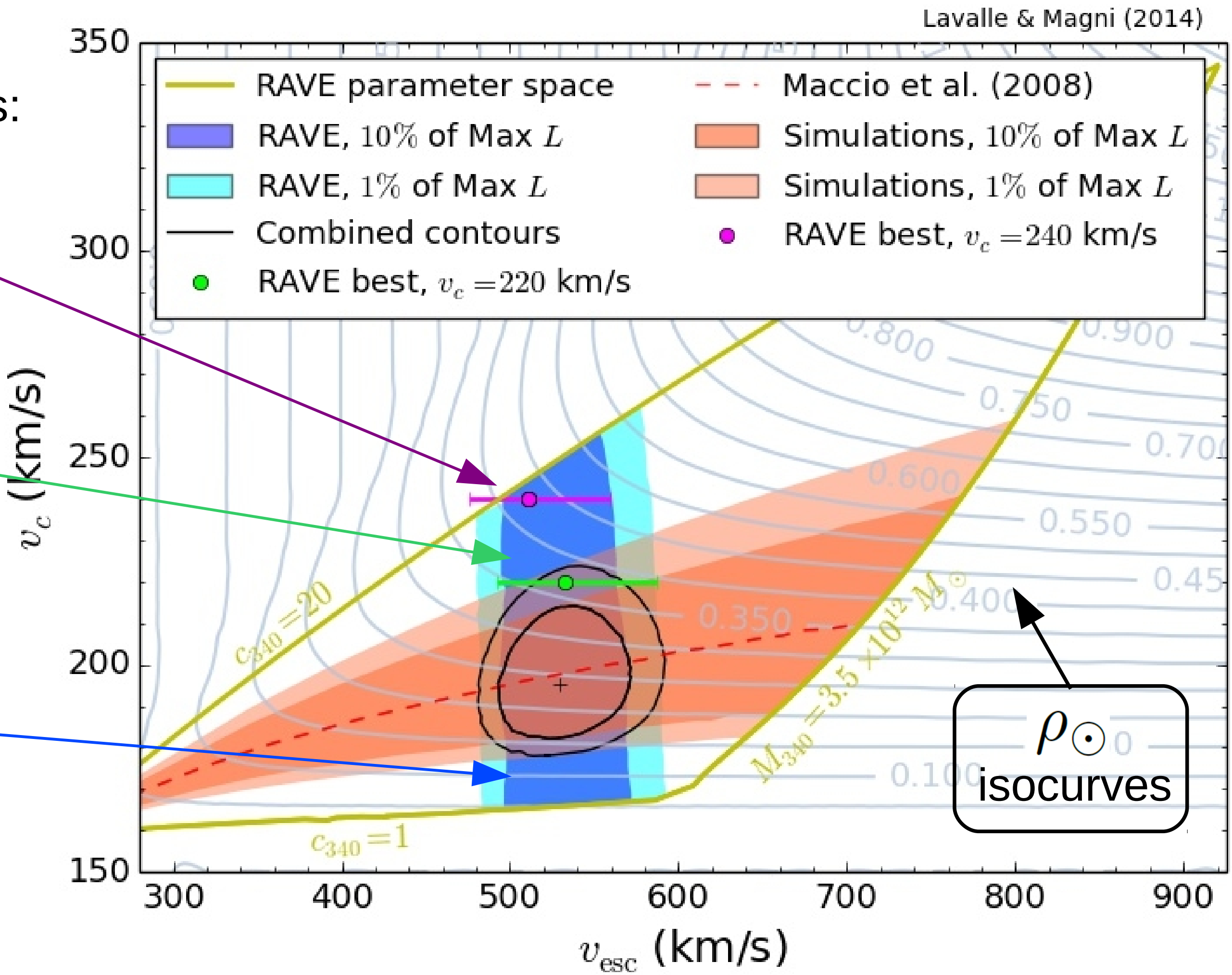

- **Dynamical correlations** between $\rho_\odot$, v_c, and $v_{\rm esc}$ must be taken into account!!!

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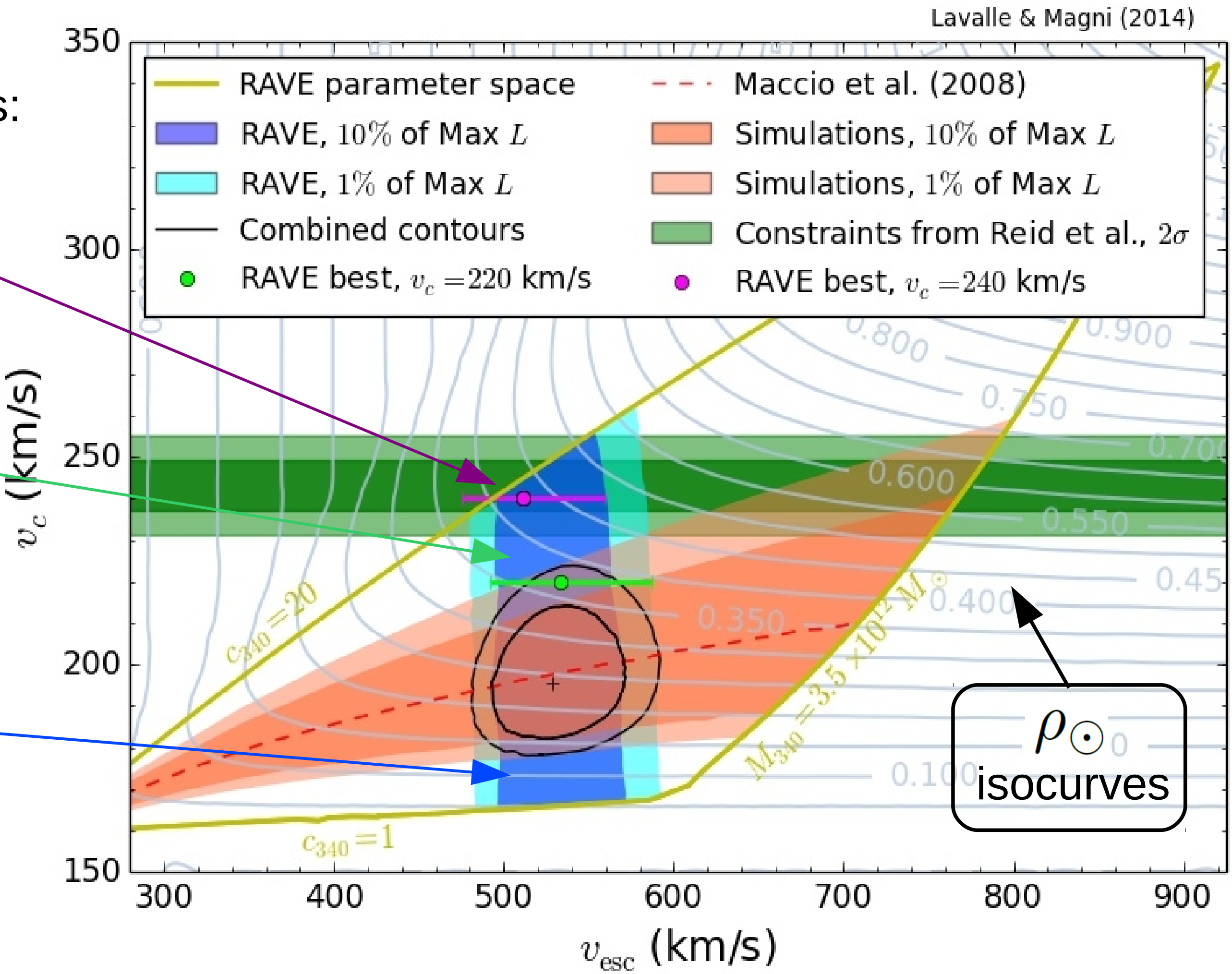

- **<u>Dynamical correlations</u>** <u>between $\rho_\odot$, v_c, and $v_{\rm esc}$ must be taken into account!!!</u>
  - Also free v_c analysis + independent constraint on v_c (Reid et al., '14)

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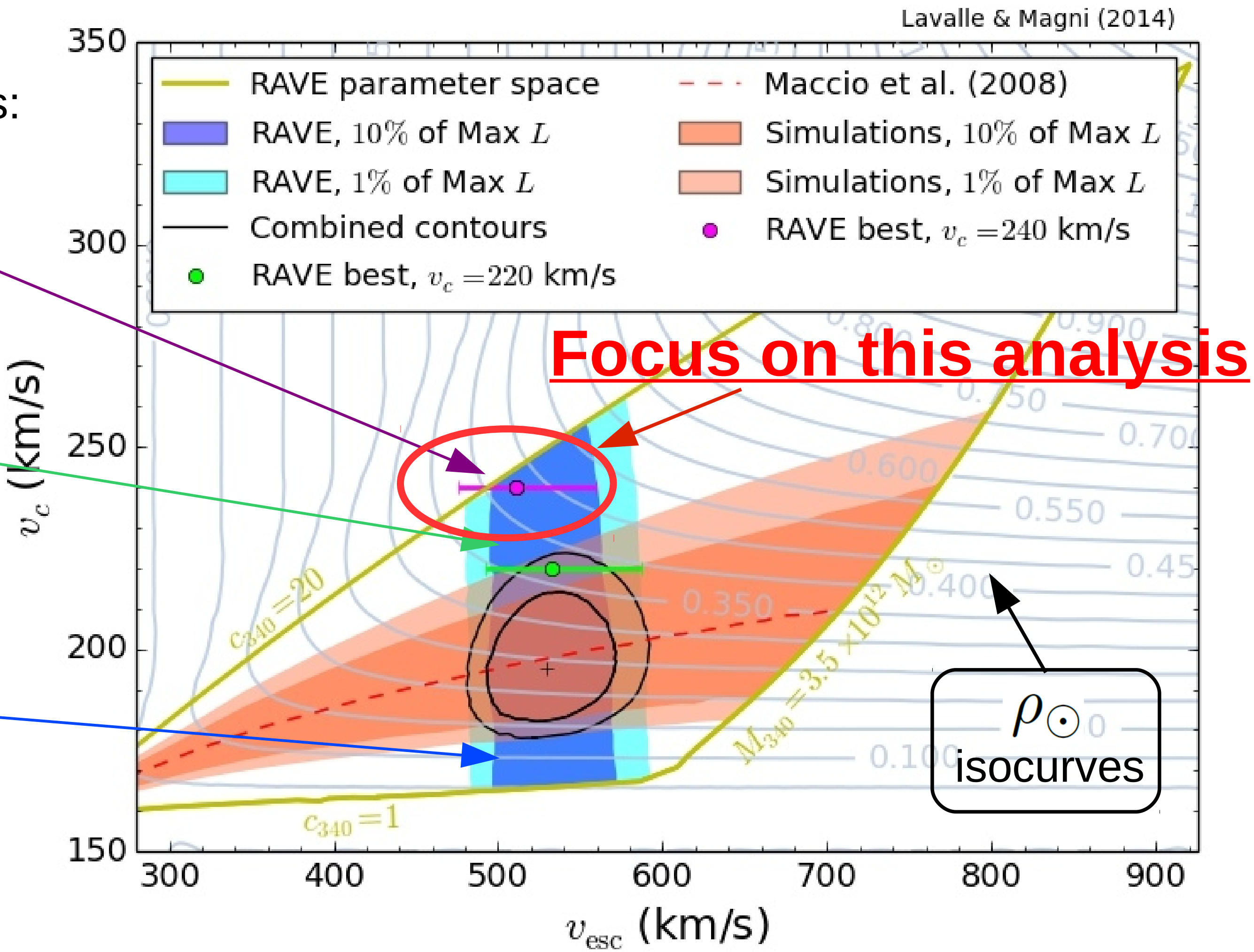

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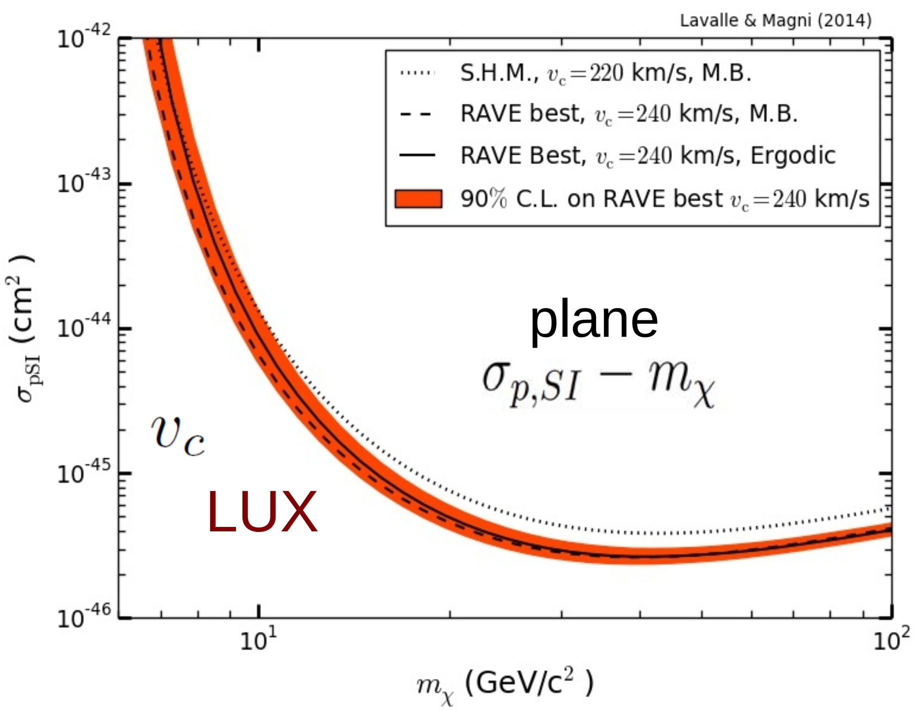
Impact on the direct detection exclusion curves

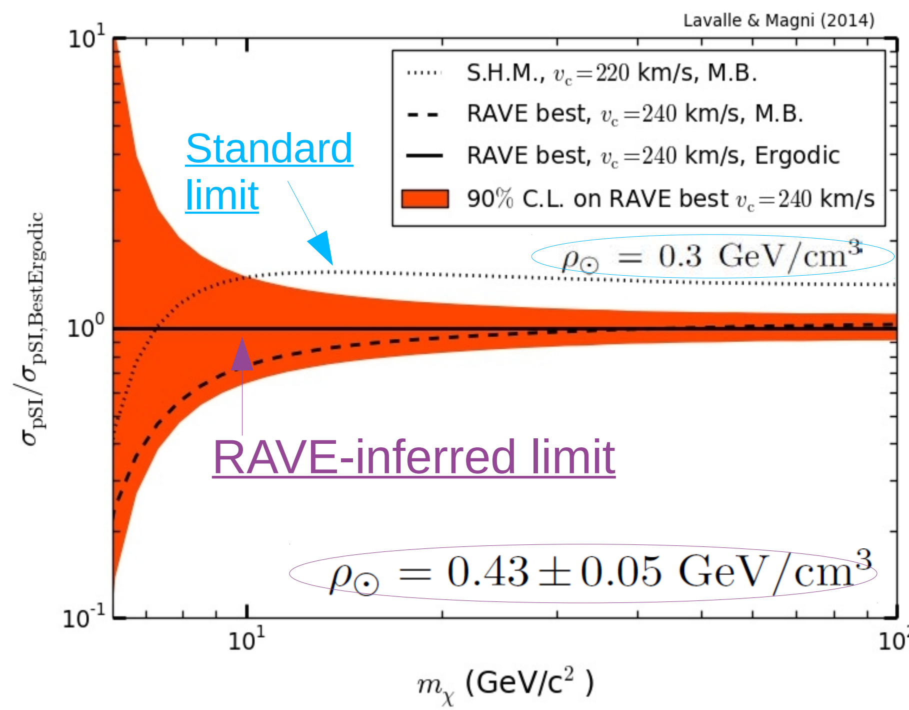
- From NFW profile + gravitational potential $\Longrightarrow$ derive the **dark matter speed distribution** through

<u>**Eddington Equation**</u>

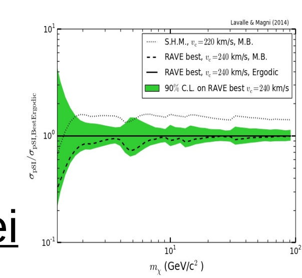
$$f(\epsilon) = \frac{1}{\sqrt{8}\,\pi^2}\left\{\frac{1}{\sqrt{\epsilon}}\frac{d\rho}{d\psi}\Big|_{\psi=0} + \int_0^{\epsilon}\frac{d\psi}{\sqrt{\epsilon-\psi}}\frac{d^2\rho}{d\psi^2}\right\}$$

<u>(induces self-consistent correlation between astro parameters)</u>





- <u>Above ~10 GeV: **RAVE-inferred limit** **more constraining** than SHM **by 40% (larger $\rho_\odot$)**</u>
- The **form of the speed distribution** is relevant only at low masses
- <u>Relative RAVE stat. uncertainties saturate</u> at $\pm 10\%$ (90% CL) <u>at large masses</u>
- Similar for SuperCDMS and CRESST2, <u>reduced uncertainties if more target nuclei</u>



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Take home messages:

- RAVE **estimates of the escape speed** rely on **assumptions**: should be used consistently.
- **Dynamical correlations** should be included for consistent direct detection exclusions.
- Future surveys will help refine Milky Way mass models.

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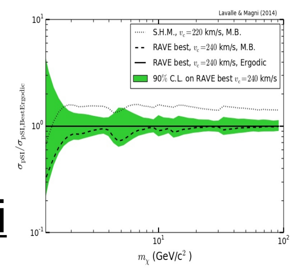
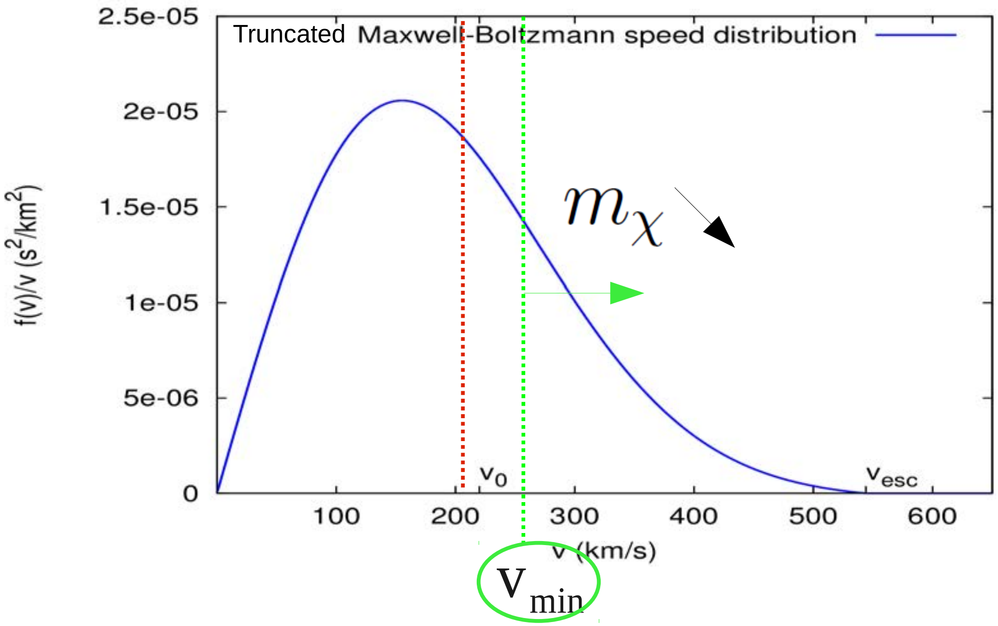
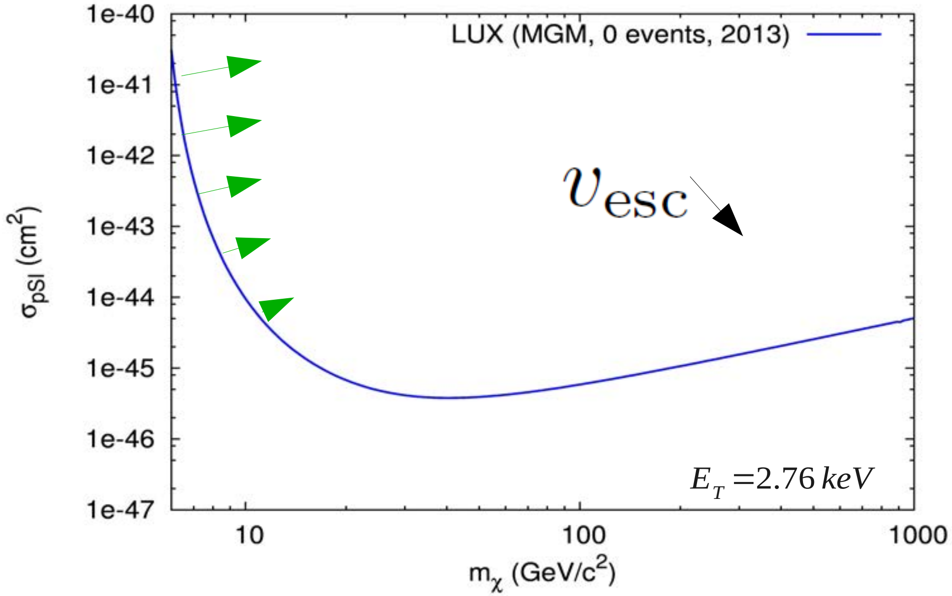
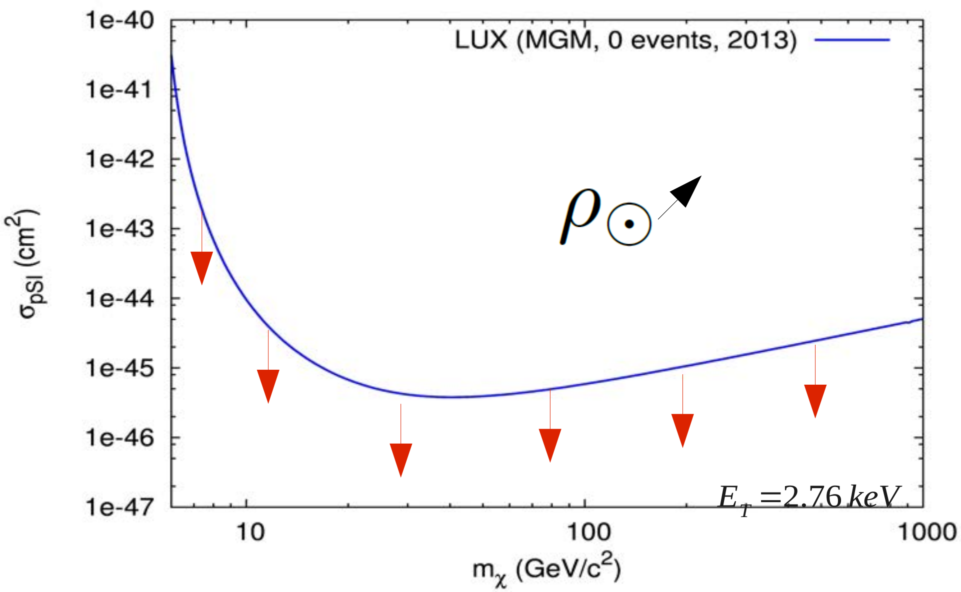


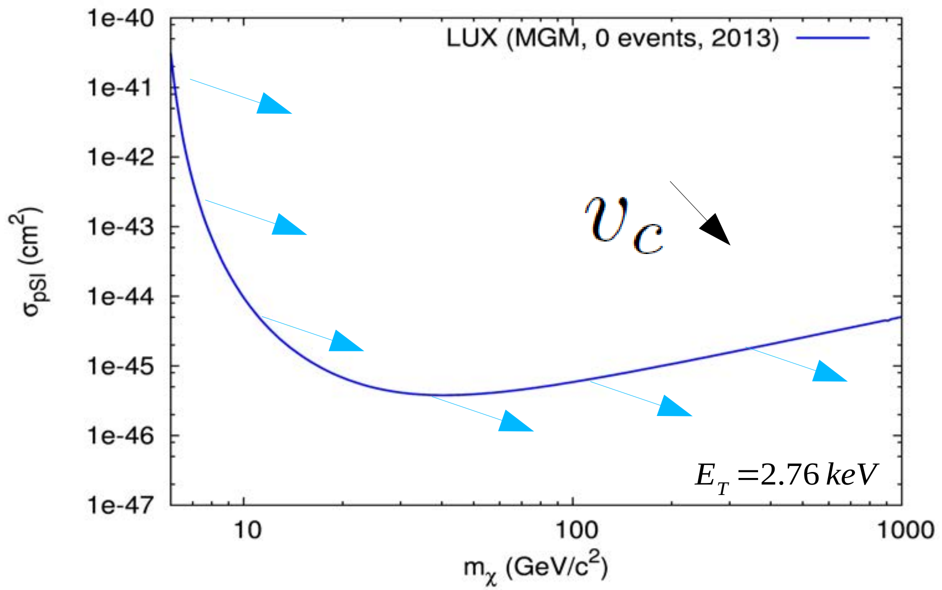
Backup Slides

Qualitative impact of astrophysical parameters on exclusion curves





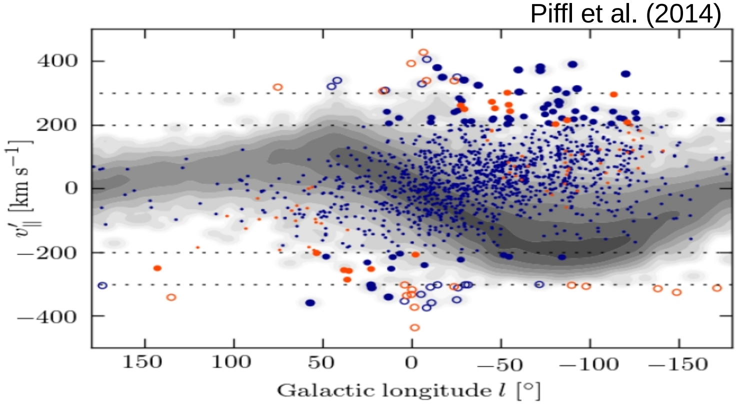




Escape speed estimate from the RAVE survey (Piffl et al. '14)

- Updates the previous estimate of $v_{\rm esc} = 544^{+64}_{-46}\,{\rm km/s}\,(90\%\ {\rm CL})$ (Smith et al. '07)
- Selects a sample of **~100 non corotating stars**, to test the non local gravitational potential
- Power law assumption for the high velocity tail of the stellar distribution:

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



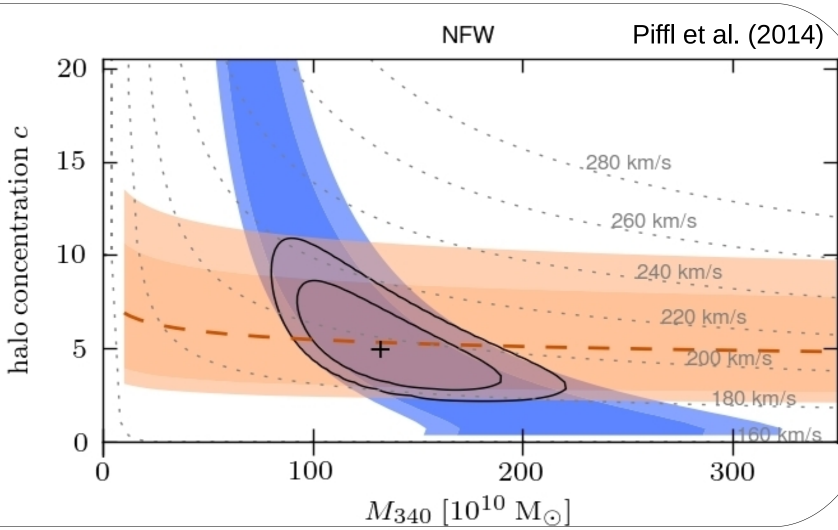
- 2 different likelihood analyses:

1) **fixed** v_c: a) $v_c = 220\,{\rm km/s}$ b) $v_c = 240\,{\rm km/s}$

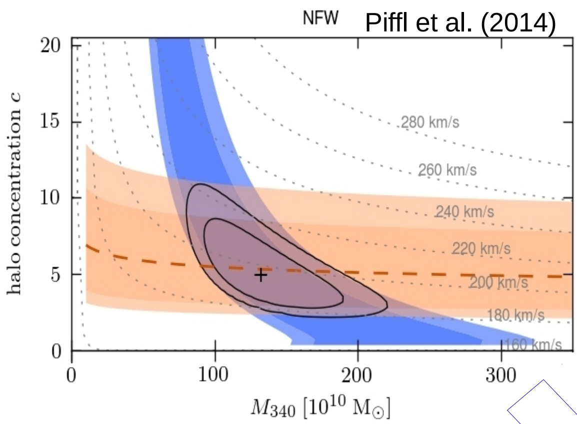
$v_{esc} = 533^{+54}_{-41}\,km/s$ (90% CL) $v_{esc} = 511^{+48}_{-35}\,km/s$ (90% CL)

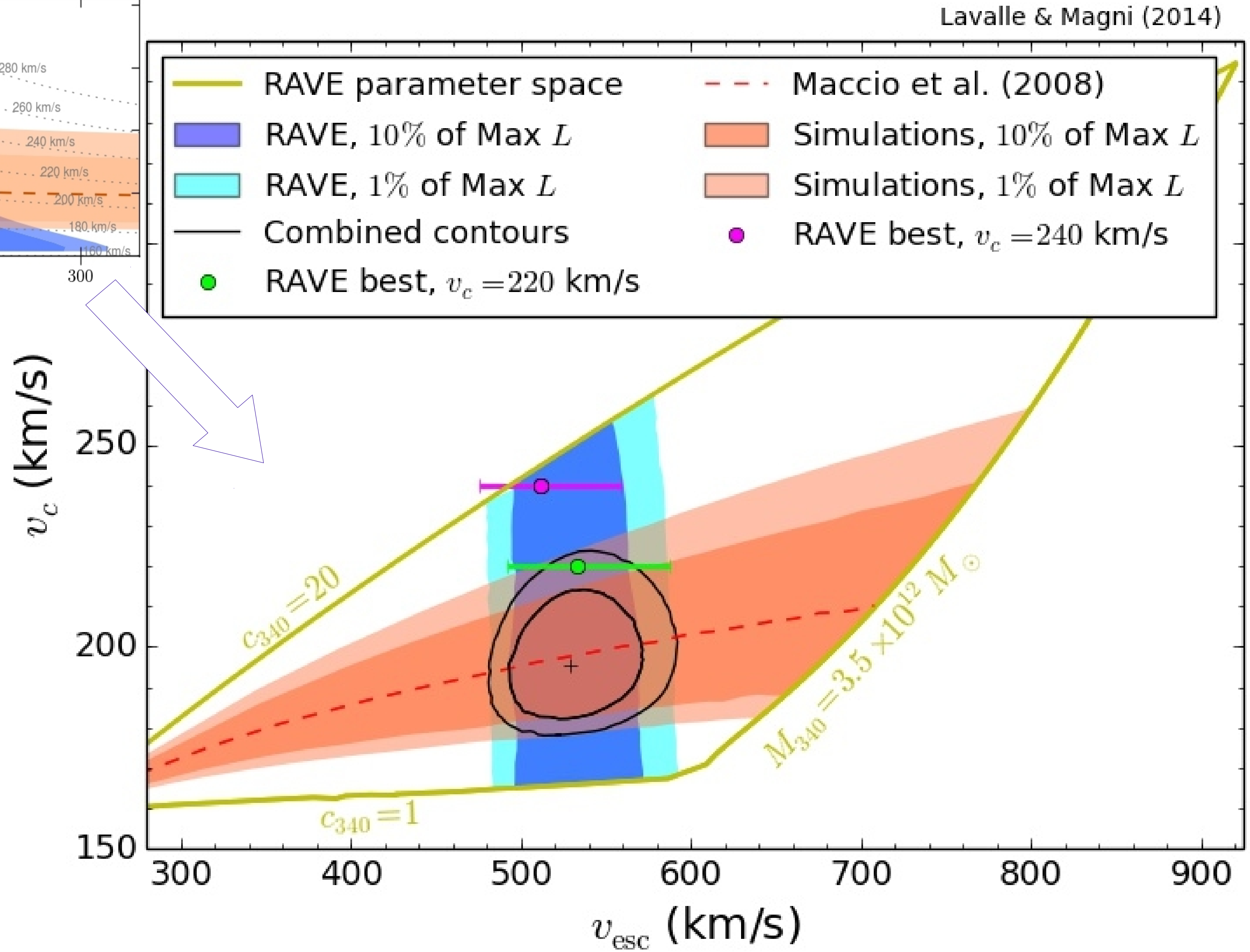
2) **free** v_c:
+ additional prior on halo concentration
- originally an estimate of the MW Mass
- gives an independent estimate of $v_{\rm esc}$, best fits are:

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



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





$$v_c^2(r_\odot, z=0) = r_\odot\, G \left\{ \frac{M_b}{(r_\odot + r_b)^2} + \frac{r_\odot\, M_d}{(r_\odot^2 + \bar{R}_d^2)^{3/2}} + 4\pi \frac{\rho_s\, r_s}{x_\odot^2} \left(\ln(1 + x_\odot) - \frac{x_\odot}{1 + x_\odot} \right) \right\}$$

$$v_{esc}(r_\odot) \equiv \sqrt{2\, \psi_{tot}(r_\odot)}\,,$$
$$\psi_{tot}(r_\odot) \equiv -\left(\phi_{tot}(r_\odot) - \phi_{tot}(R_{max})\right)$$

Dynamical correlations into self-consistent local f(v)

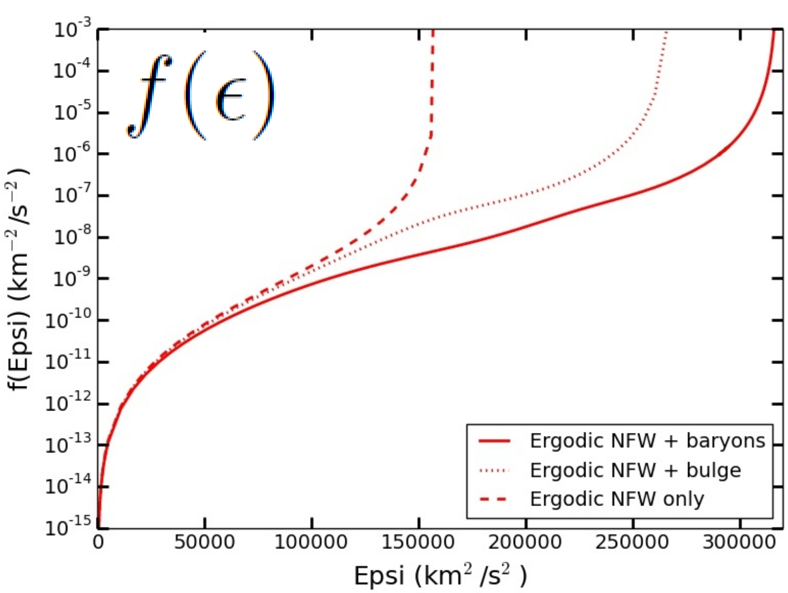
- Shortcomings of Maxwell-Boltzmann:
  - Relies on isothermal assumption
  - Truncated M-B not solution of Jeans equation

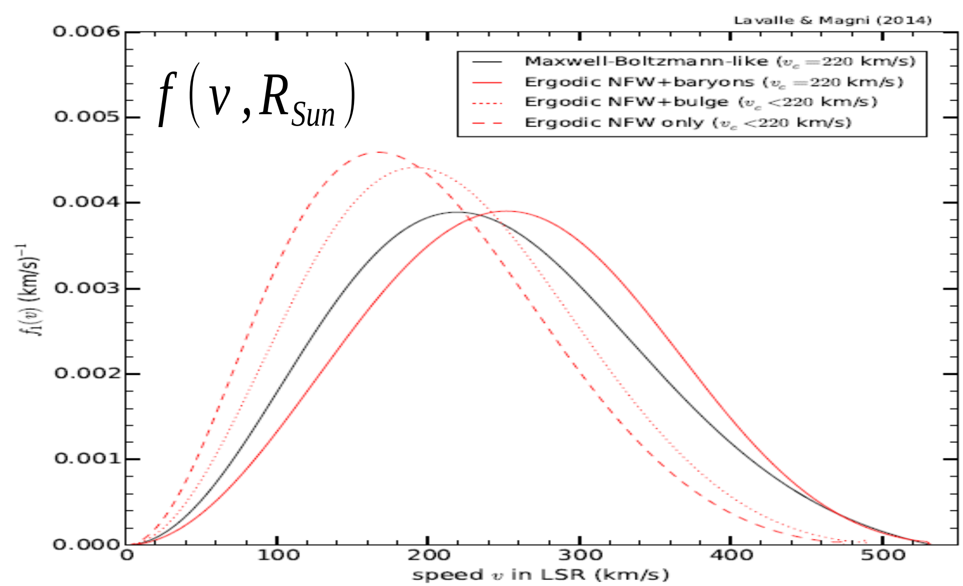
- From the DM density $\rho(r)$ compute the corresponding phase-space distribution $f(\epsilon)$ given the Milky Way mass model, using Eddington equation (Ullio & Kamionlowski '01, Vergados & Owens '03)

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

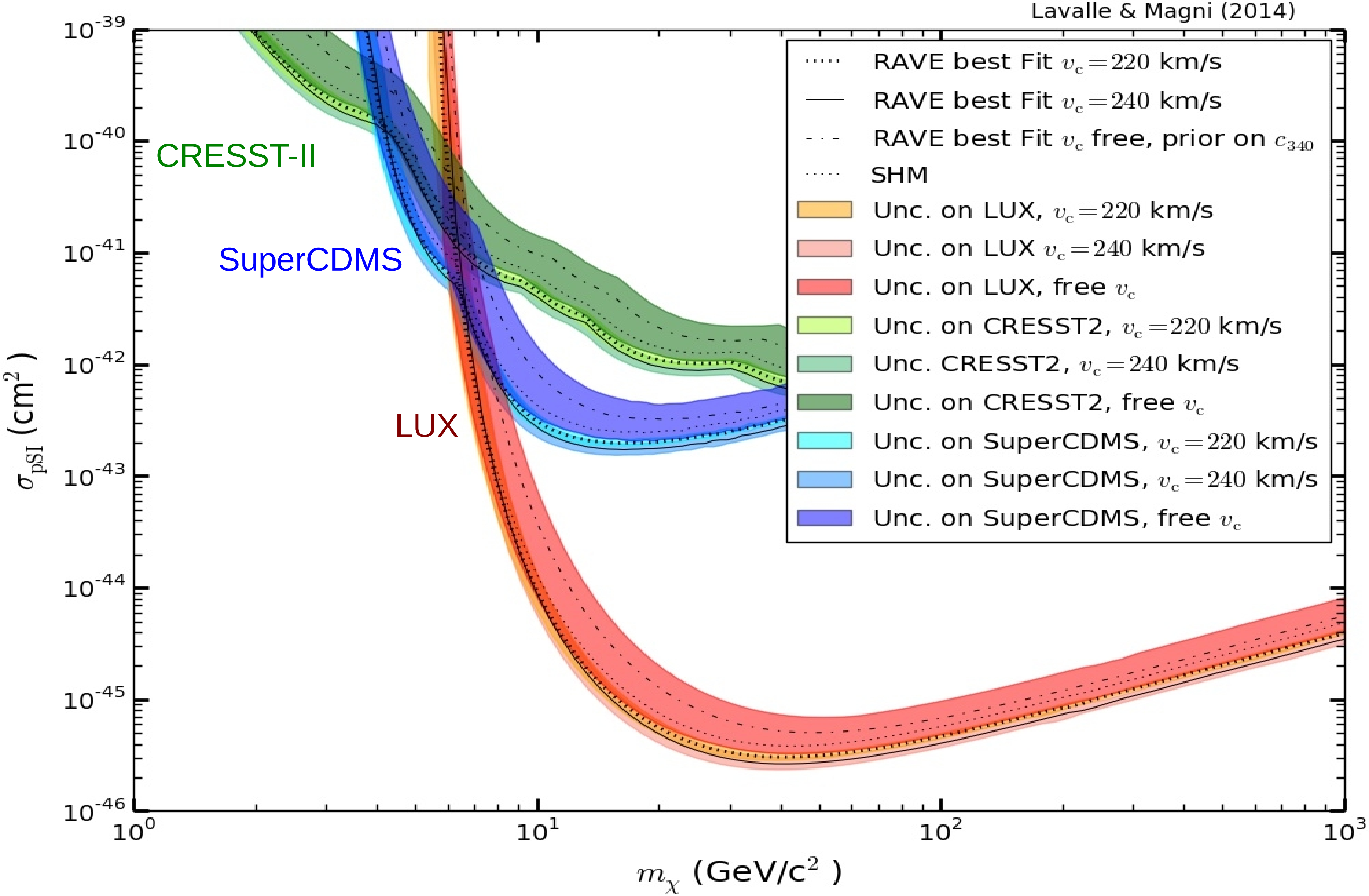
$$\Psi = -\Phi_{MW}(r)$$
$$\epsilon = -E_{tot}$$
$$\rho = \rho_{NFW}(r)$$

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



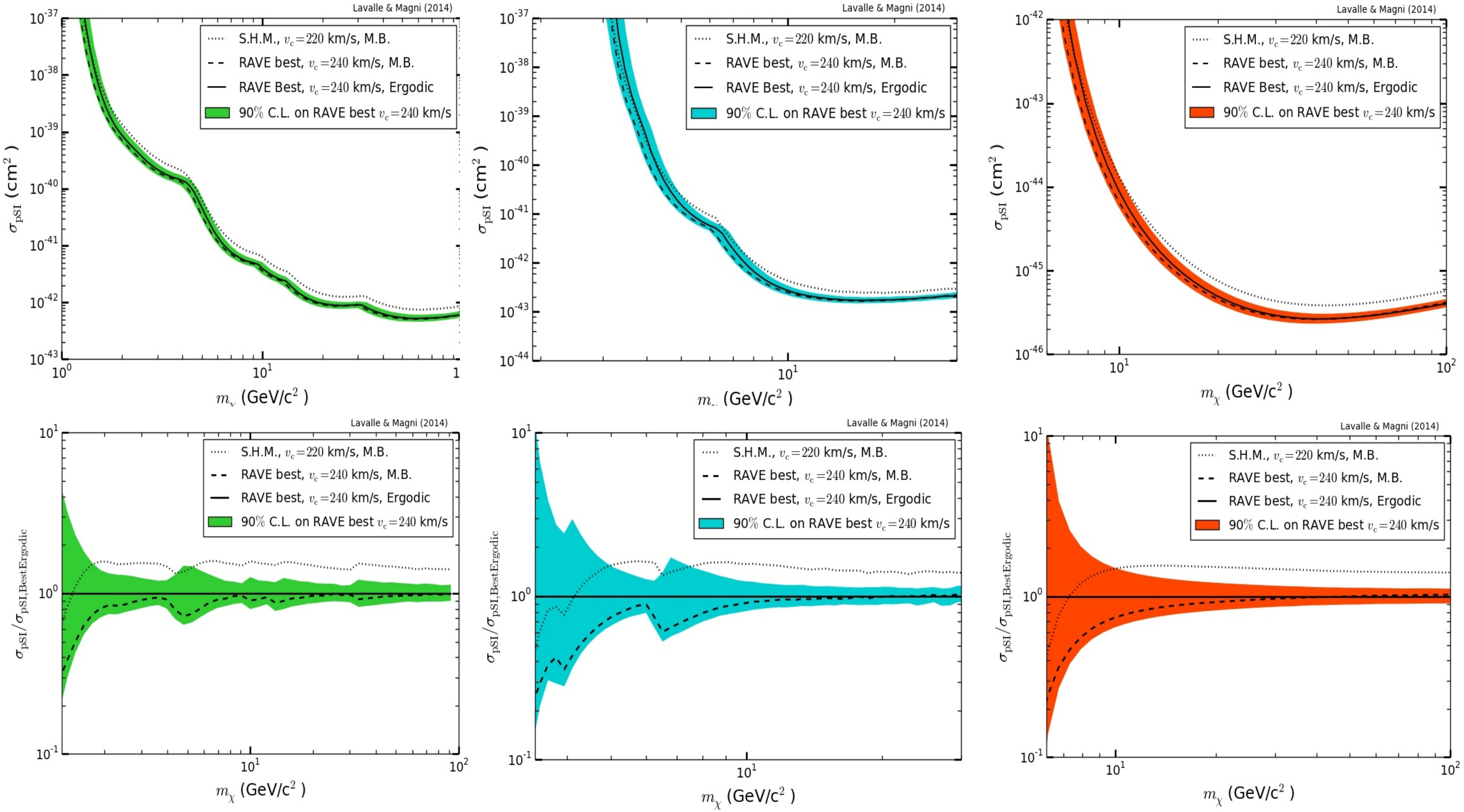


RAVE's constraints translated into DD exclusions



Different direct detection experiments

CRESST-II SuperCDMS LUX



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

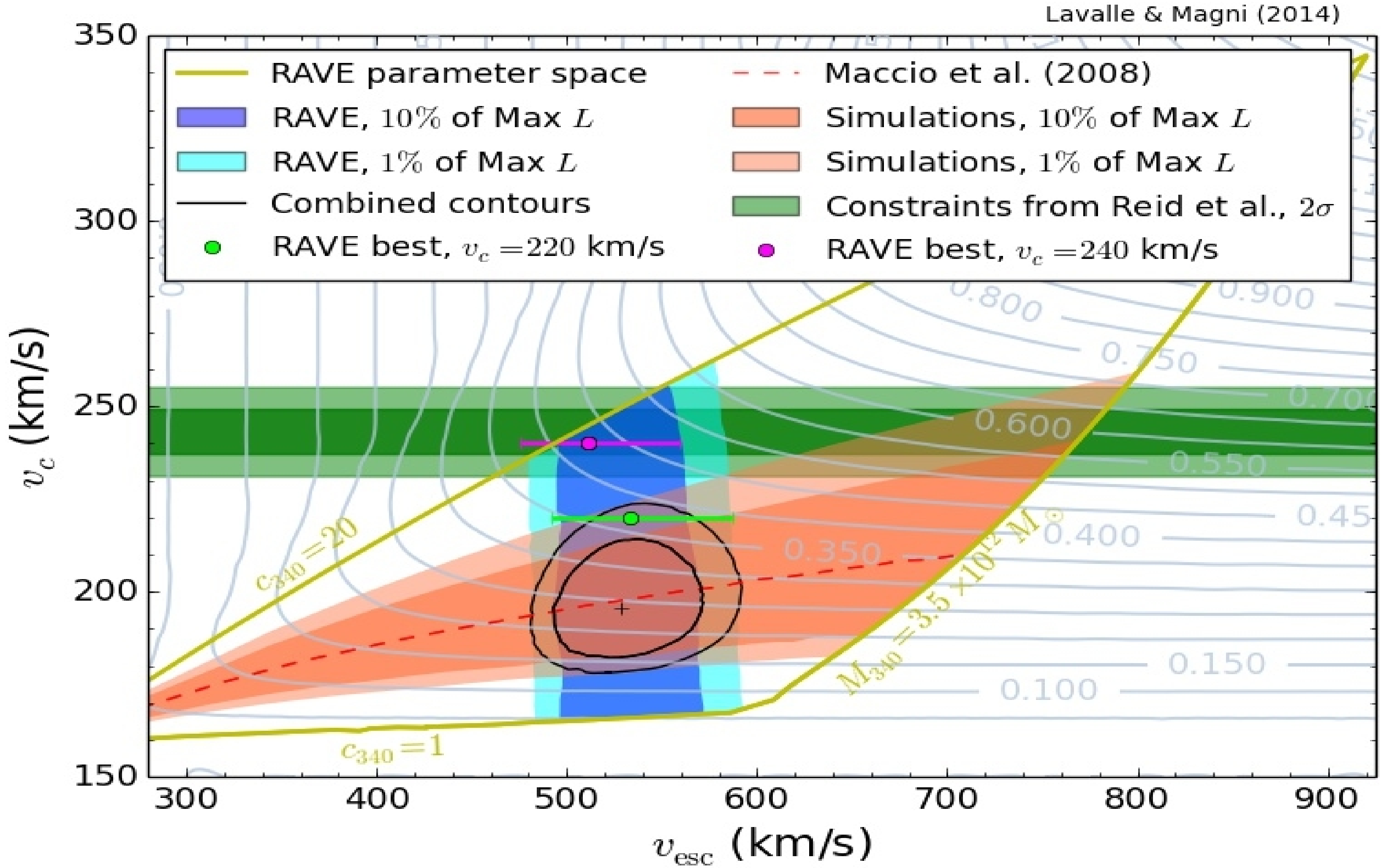
Considering an independent determination of v_c

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

(Reid et al., '14)

Additional constraints (OK within 3 sigma):

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

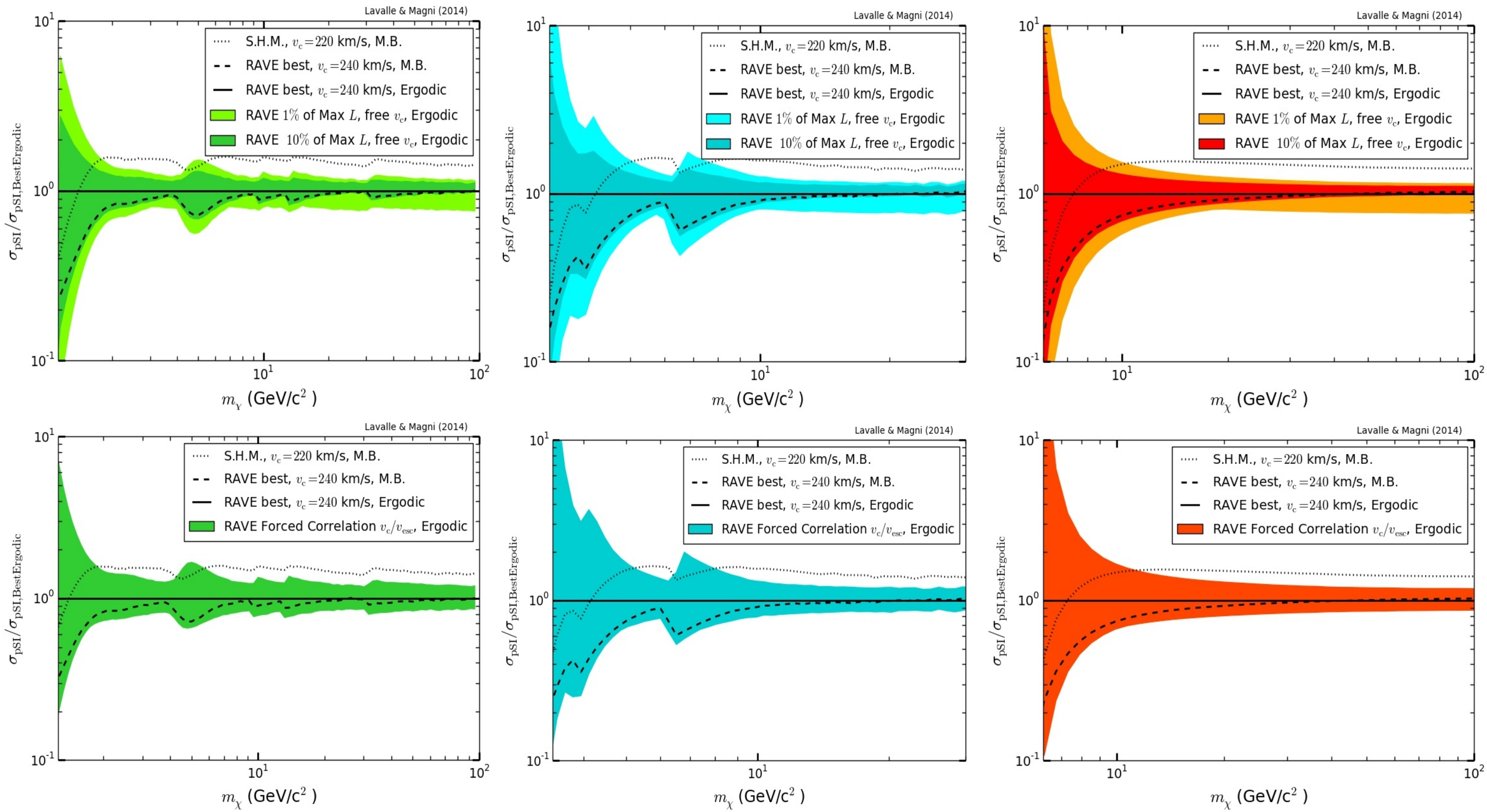


Analysis with free v_c versus forced correlation between v_c and v_{esc}

CRESST-II

SuperCDMS

LUX



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

Perspectives

- RAVE results not free of **systematic** effects: **fixed baryonic content** plus **prior on DM** halo shape, etc.
  → testing RAVE assumptions on **cosmological simulations** (ongoing, with P. Mollitor & E. Nezri)

- Generalisation to **anisotropic f(v)** (ongoing)

- **Complementarity** with other dynamical constraints (ongoing)

- Comparison among uncertainties from astrophysics and those from WIMP-nucleon interactions (ongoing, with L. Lellouch, C. Torrero, P. Mollitor & E. Nezri)