# Making sense of the local escape speed estimates in dark matter direct detection

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Based on collaboration with Julien Lavalle,
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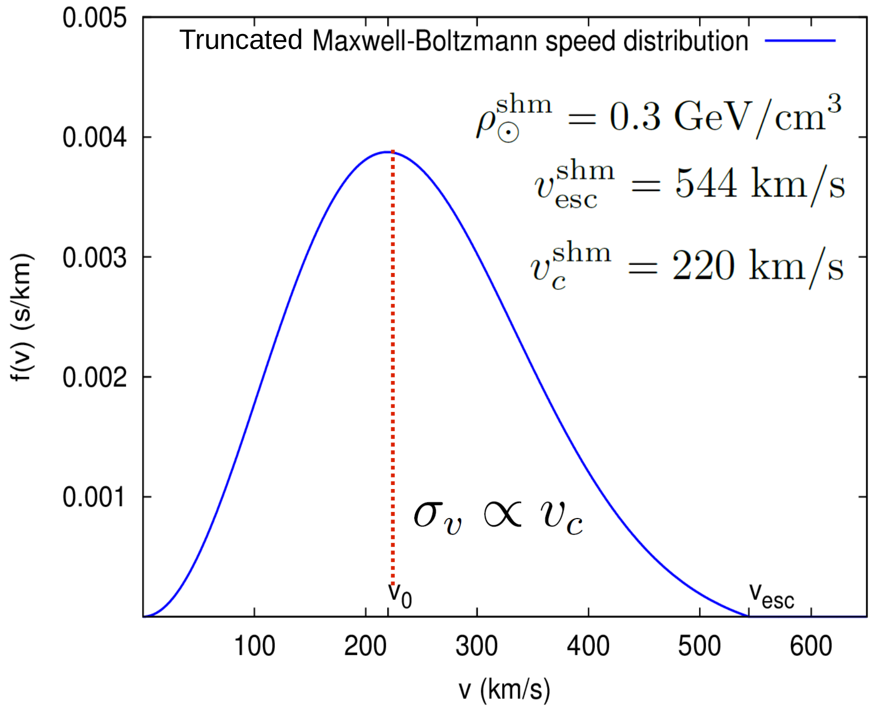
# Introduction

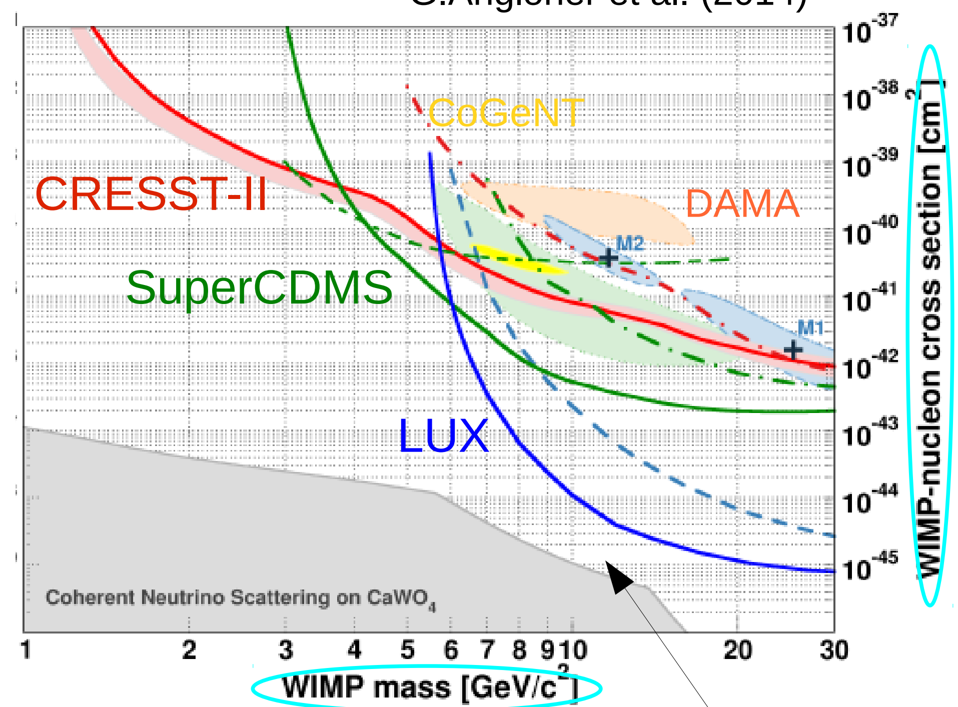
- Dark matter direct detection is plagued with **astrophysical uncertainties**
- Importance of improving control on them in the **context of controversial signals and/or discovery perspectives**
- **Many studies** on astrophysical uncertainties in direct detection:
  A. Green (2012), R. Catena & P. Ullio (2012), M. Fairbairn & P. Grothaus (2013), N. Bozorgnia, et al. (2013), etc.
- Recent **estimate for the escape speed** from the RAVE collaboration (Piffl et al. '14), potentially important for **low WIMP masses**
- Goal: investigate the **implications of these results** in detail (assuming isotropic velocity distribution functions for the dark matter)

# Direct detection rate and exclusion curves

## Standard Halo Model




G.Angloher et al. (2014)




## Differential event rate

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

particle + hadronic + nuclear physics

astrophysics

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

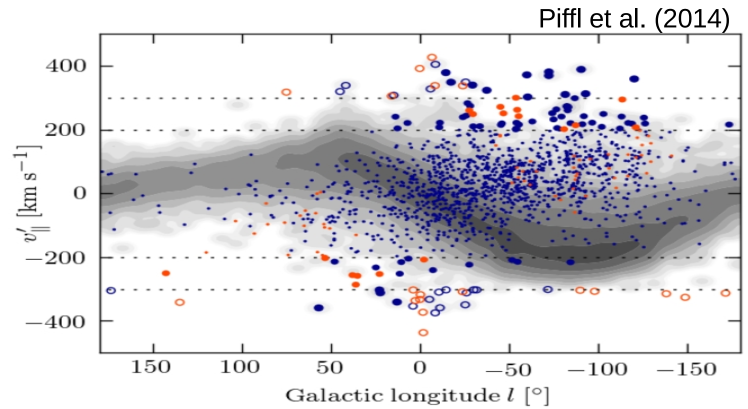
**Effects at work:**

- Threshold Energy
- $v_{esc} + v_c$
- $\rho_\odot$

# 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:

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



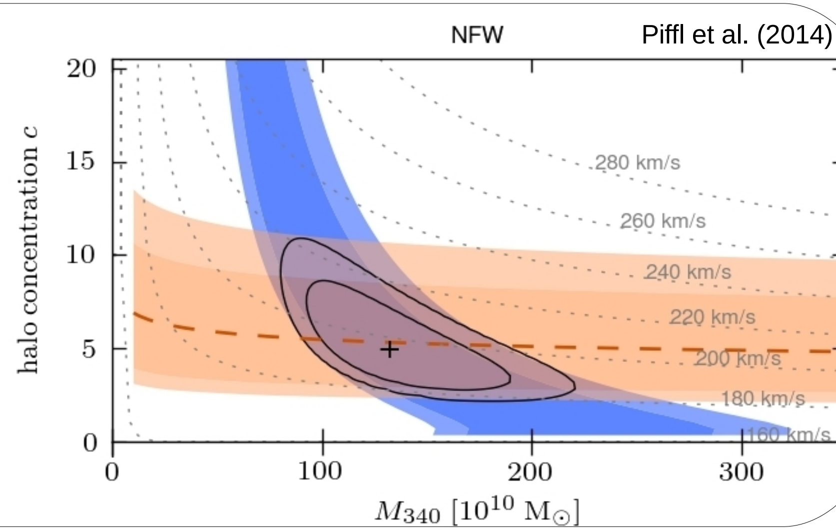

- 2 different likelihood analyses:

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

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

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

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



# Underlying assumption: MW mass model

Important to "relocate" observed stars at 8.28 kpc

Density of matter ⟺ Gravitational Potential

$$\rho(\vec{r}) = \rho^{DM}(\vec{r}) + \rho^{bar}(\vec{r})$$

$$\Phi(\vec{r}) = \Phi^{DM}(\vec{r}) + \Phi^{bar}(\vec{r})$$

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

- **Local dark matter density**

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

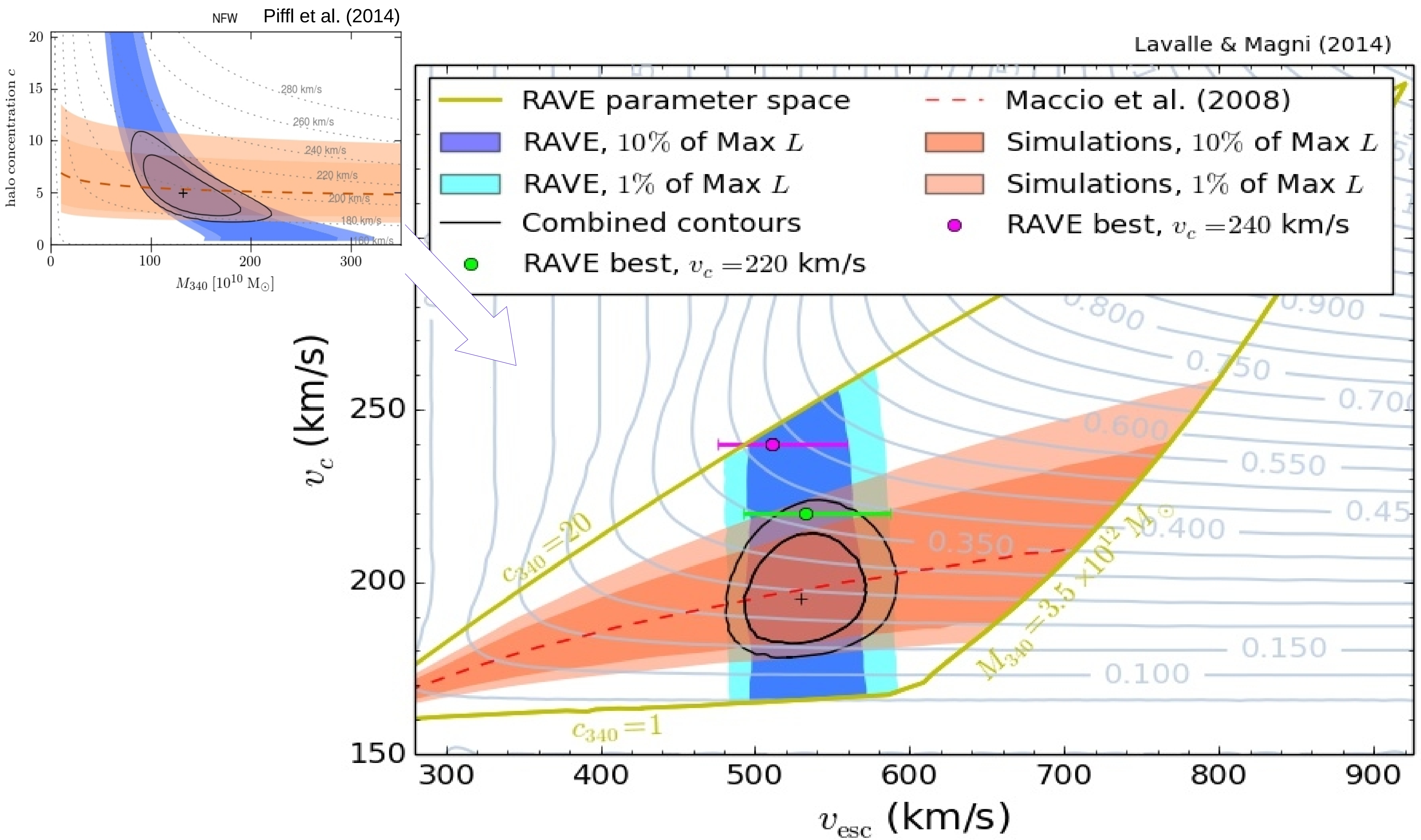
- **Escape speed at Sun position**

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

- **Circular speed at Sun position**

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

# Converting RAVE results in the vc-vesc plane



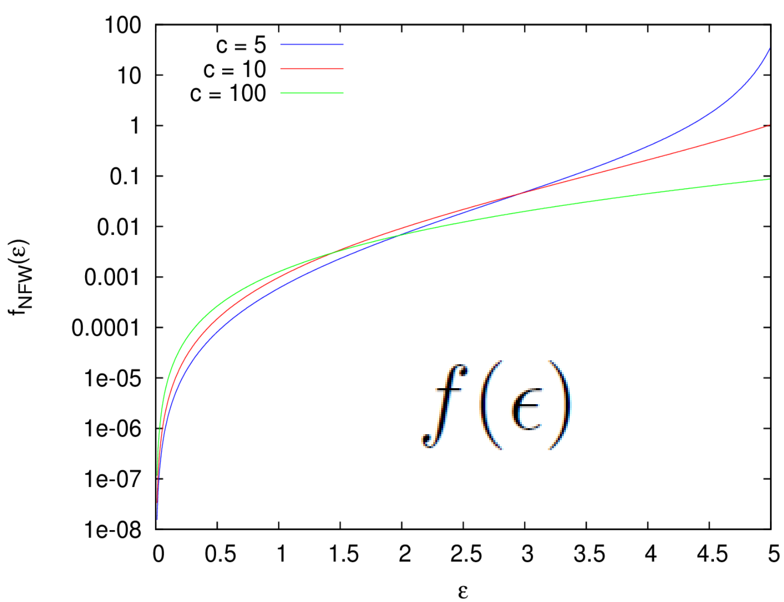

Beware: MW mass model induces correlations among the parameters!

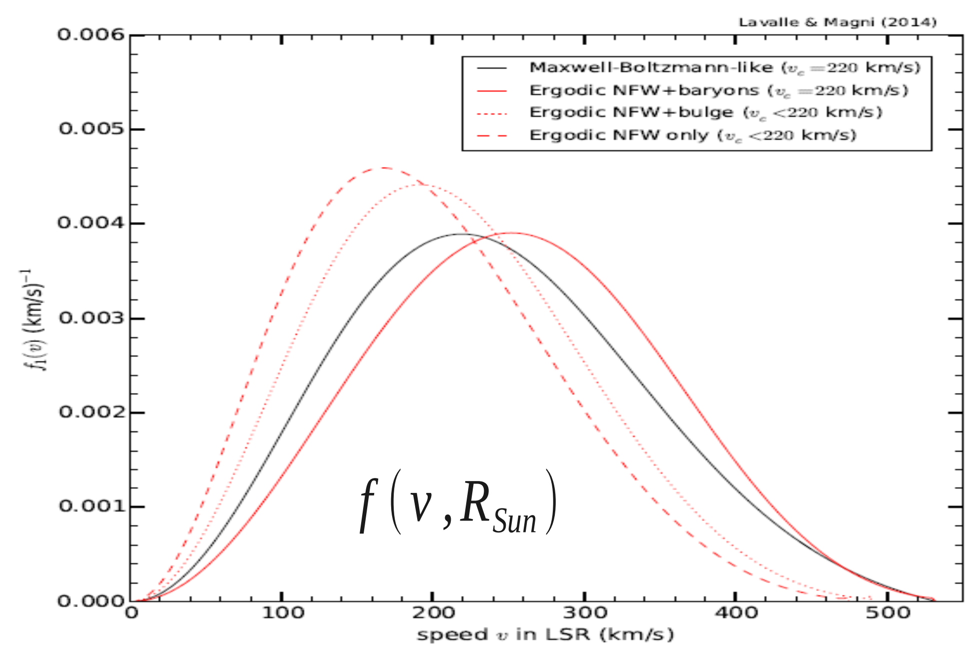
# Dynamical correlations into self-consistent local f(v)

- MB (where $\sigma \propto v_c$) relies on isothermal assumption
- Truncated MB not solution of Jeans equation
- Eddington equation (Ullio & Kamionlowski '01, Vergados & Owens '03)

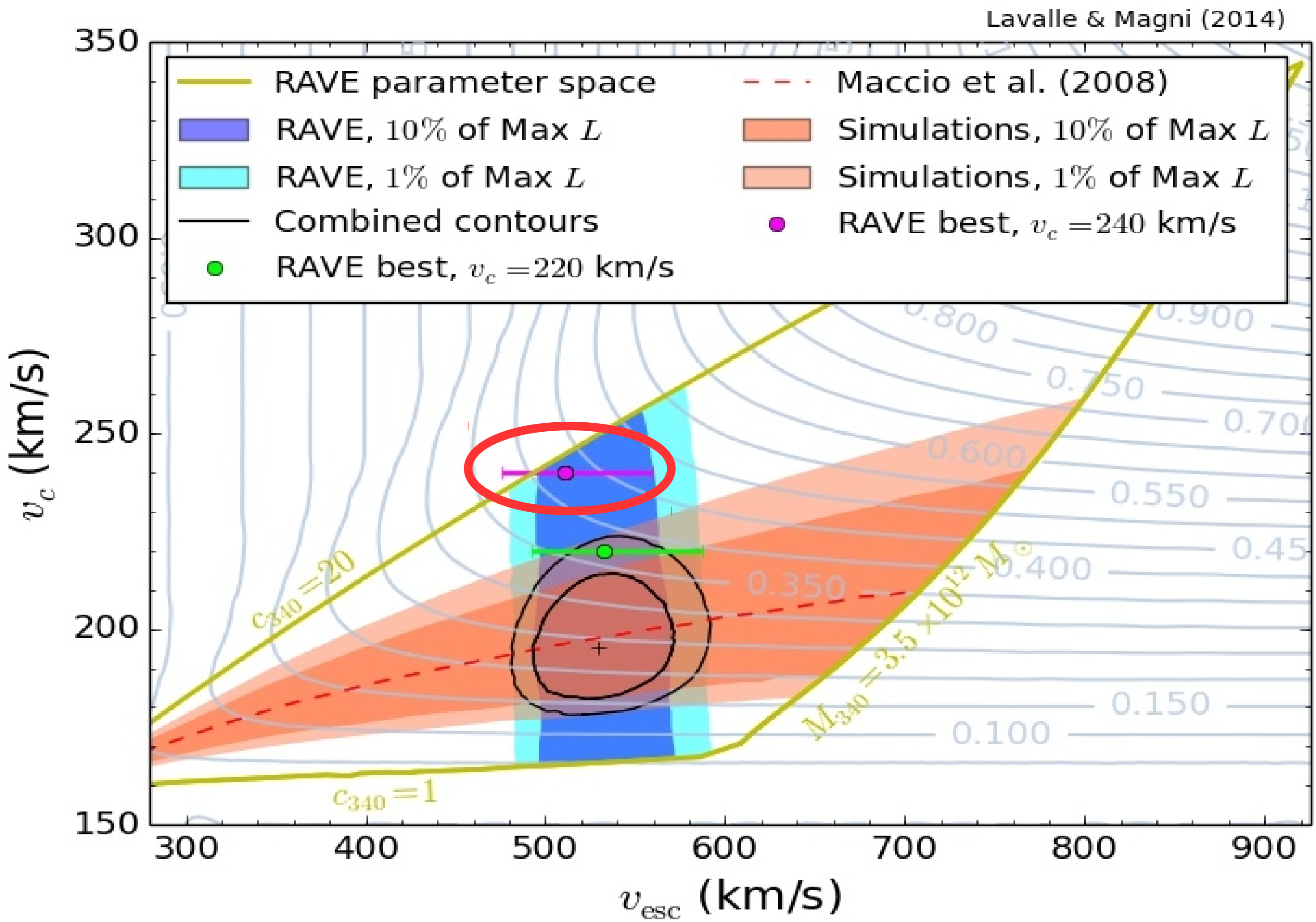
$$f(\epsilon) = \frac{1}{\sqrt{8}\,\pi^2}\left\{\frac{1}{\sqrt{\epsilon}}\frac{d\rho}{d\psi}\Big|_{\psi=0} + \int_0^{\epsilon}\frac{d\psi}{\sqrt{\epsilon-\psi}}\frac{d^2\rho}{d\psi^2}\right\}$$

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



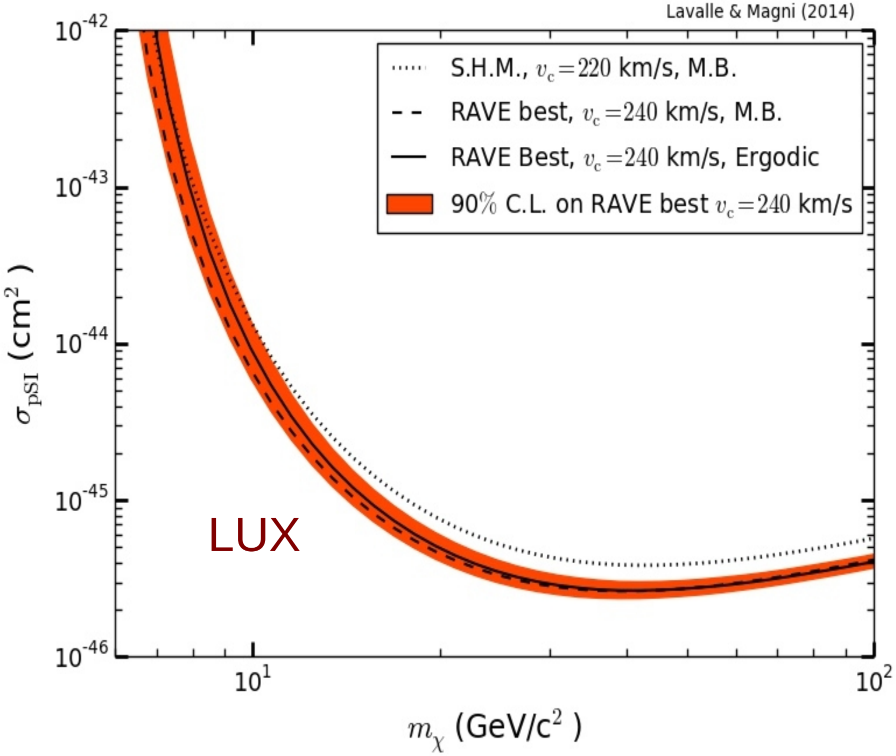



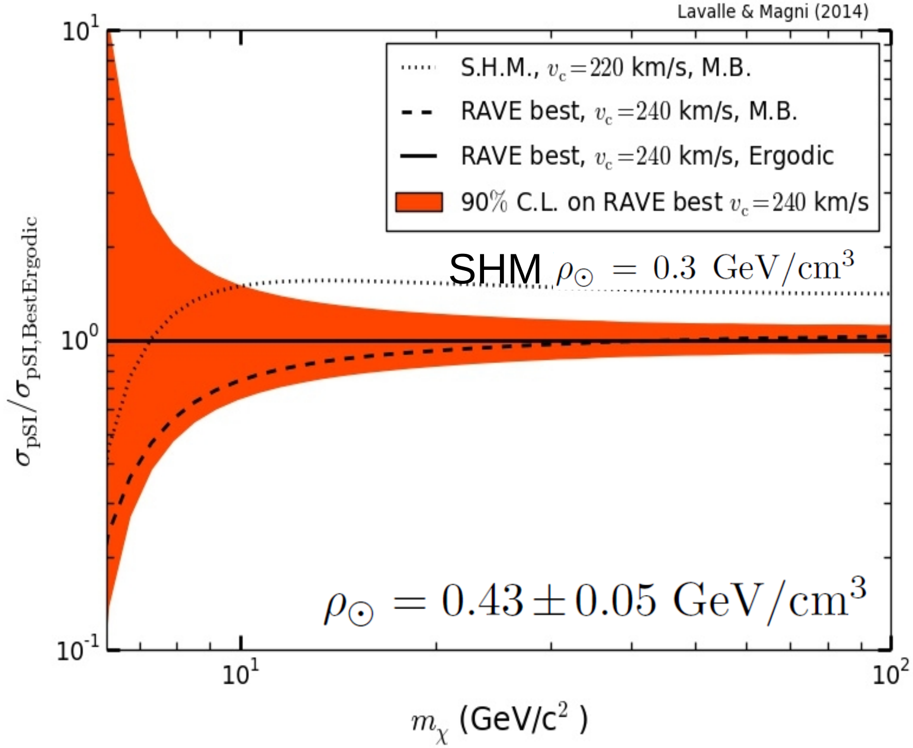
# Let's translate RAVE constraints into DD limits




| Model assumptions | $v_c$ (km/s) | $v_{esc}$ (km/s) | $\rho_s$ (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 | $196^{+26}_{-18}$ | $537^{+26}_{-19}$ | $0.08^{+0.31}_{-0.07}$ | $36.7^{+50.7}_{-19.0}$ | $0.25^{+0.14}_{-0.12}$ |

# Exclusion curve and uncertainties from RAVE best fit point



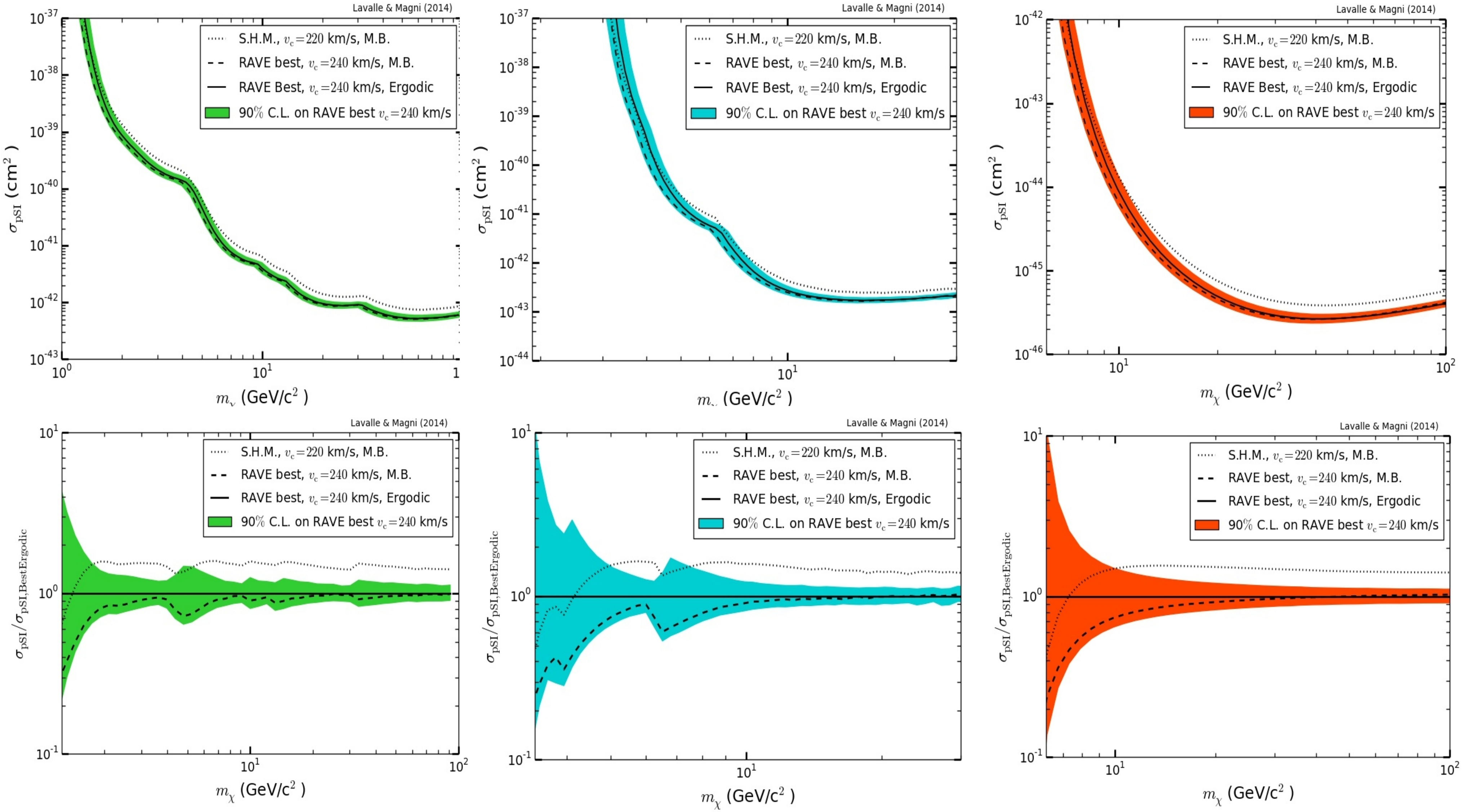

- At high masses: ergodic limit **more constraining** than SHM **by 40%**
- At low masses: ergodic limit **beaten** by SHM because

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

- The **form of the DF** is relevant only at low masses
- **Relative uncertainties saturate** at $\pm 10\%\ (90\%\ \mathrm{CL})$ at large masses

# Uncertainties from RAVE best fit point

CRESST-II SuperCDMS LUX




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

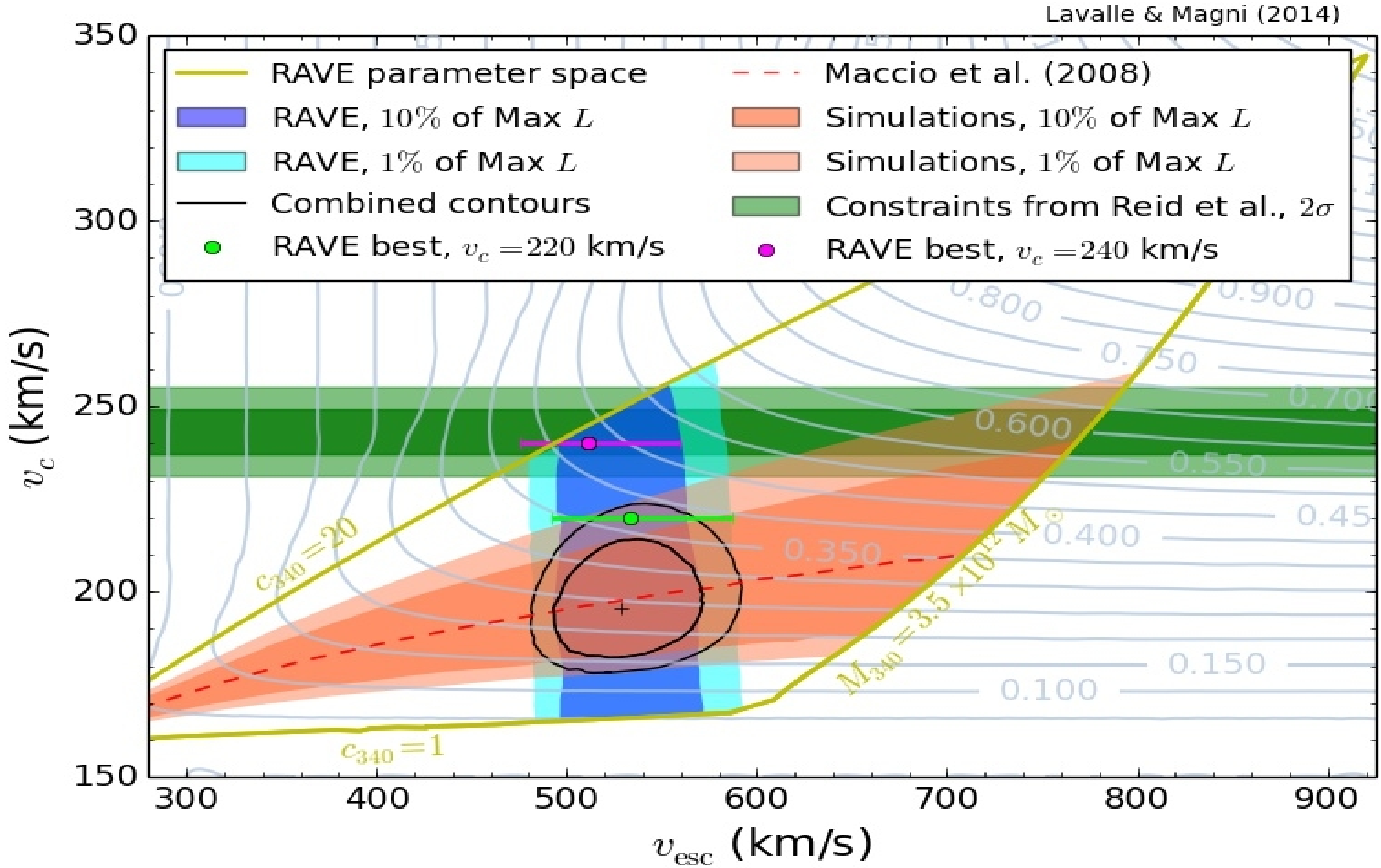
# Additional and independent constraints on the circular speed

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

(Reid et al., '14)

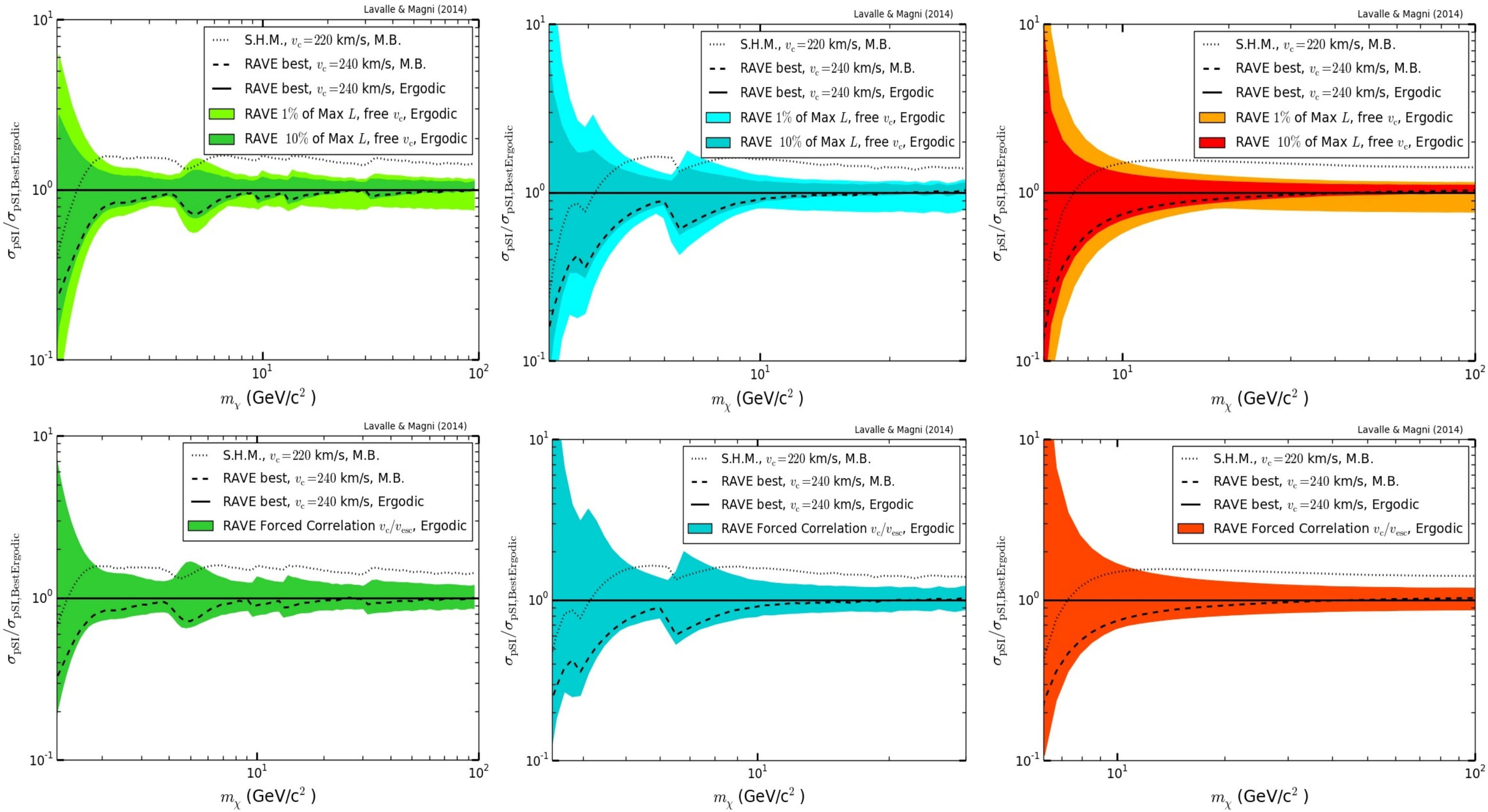
Additional constraints (OK within 3 sigma):

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



# Analysis with free circular speed vs forced correlation between circular end escape speed

CRESST-II SuperCDMS LUX




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

# Conclusions and perspectives

- Escape speed estimates **cannot be used blindly**: they rely on assumptions (as other astrophysical parameters in general)
- **Converting RAVE** results into DD induces **correlations** among astro parameters relevant to DD and leads to **stronger limits** (due to larger $\rho_\odot$), important for low WIMP masses.
- Caveats: based on **RAVE stat. only**
(syst. not included in RAVE paper)
- RAVE results not free of **systematic** effects:

  -> **fixed baryonic content** plus **prior on DM** halo shape

  -> test works on **cosmological simulations**

  (ongoing, with Mollitor & Nezri - see also Lisanti et al. '11)

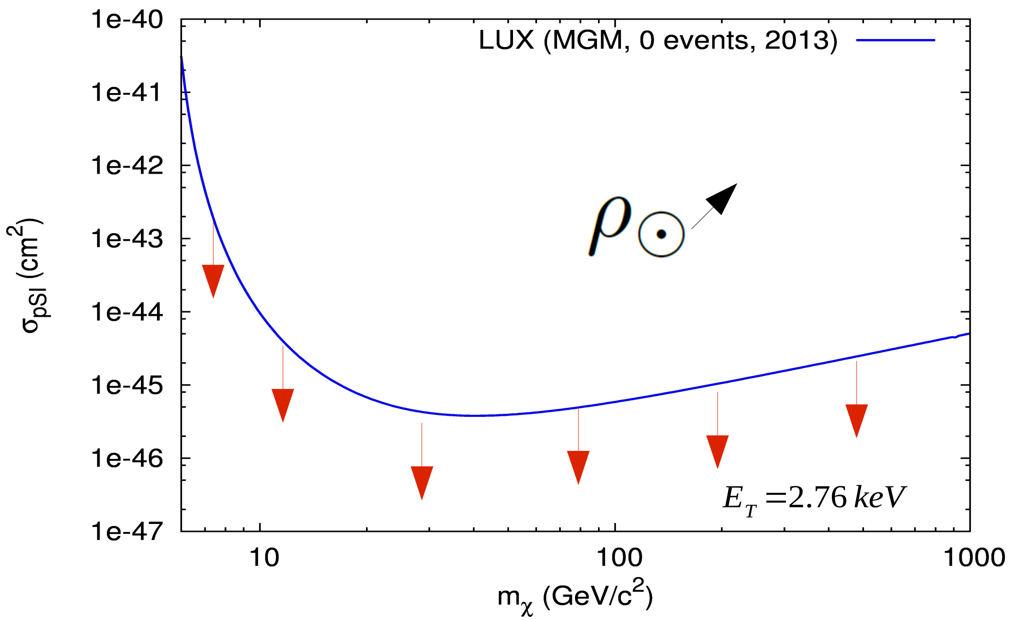
  -> **complementarity** with other dynamical constraints (ongoing)

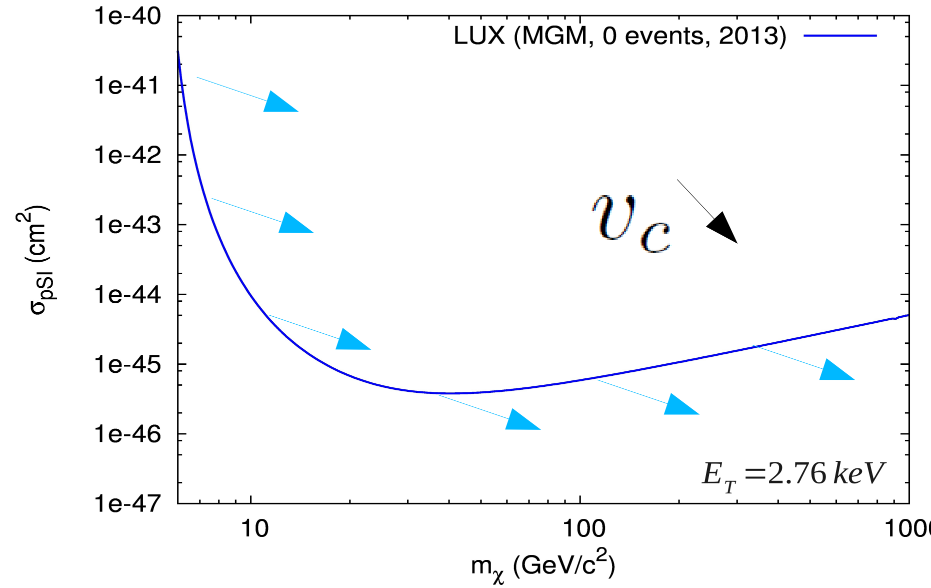
  -> interpretation with **anisotropic f(v)** (ongoing)

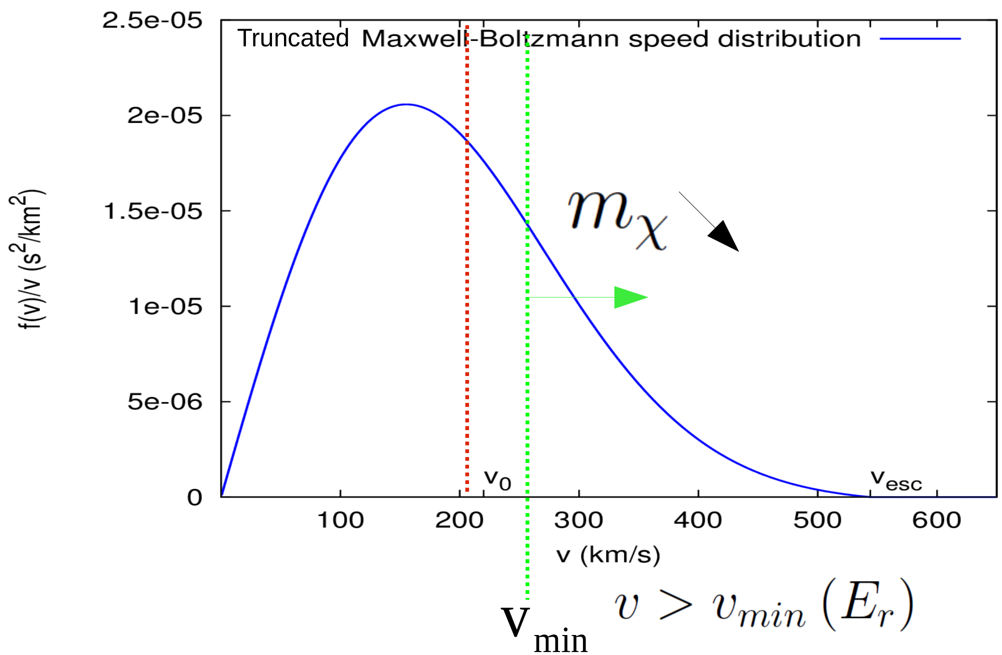
- Comparison between uncertainties from astrophysics and those from WIMP-nucleon interactions (ongoing, with Lellouch & Torrero)

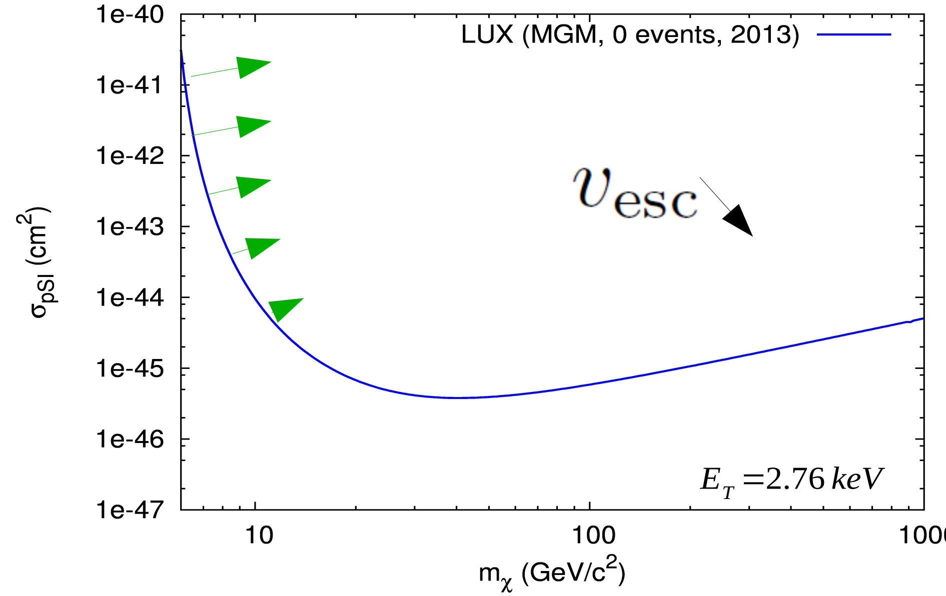
Thank you very much for your attention!

# Qualitative impact of astrophysical parameters on exclusion curves

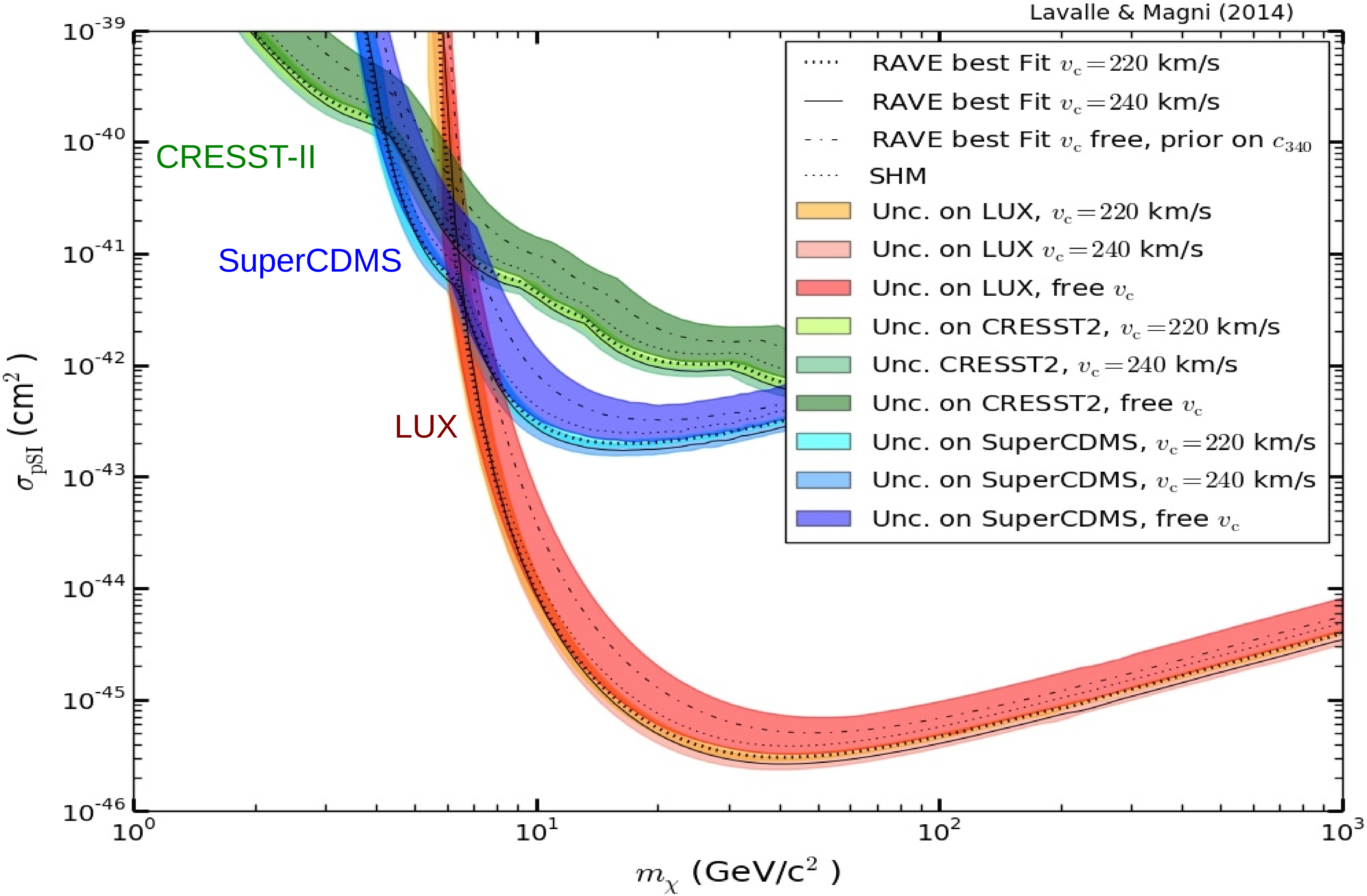


# RAVE's constraints translated into DD exclusions



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Lavalle & Magni (2014)