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

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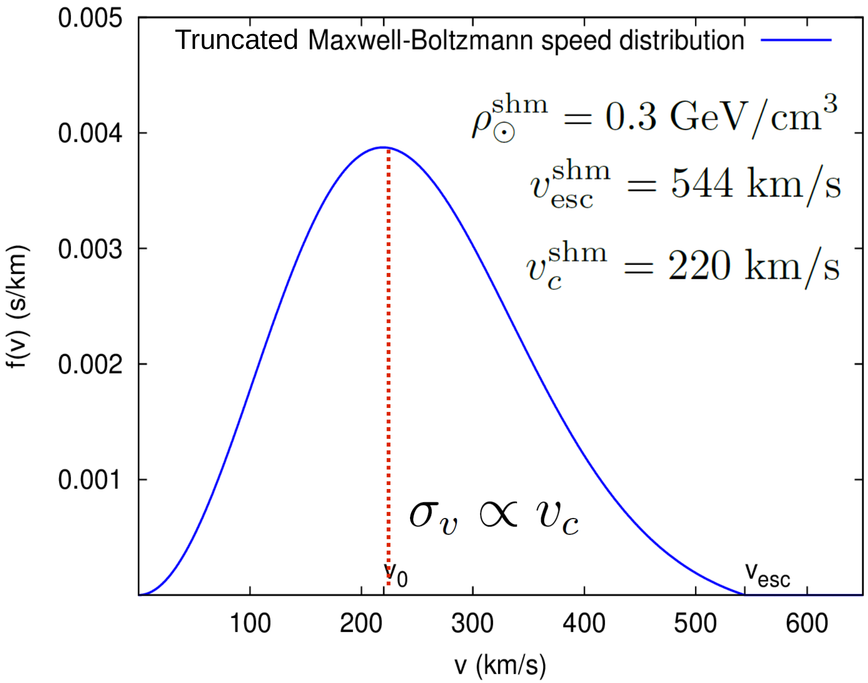
Introduction

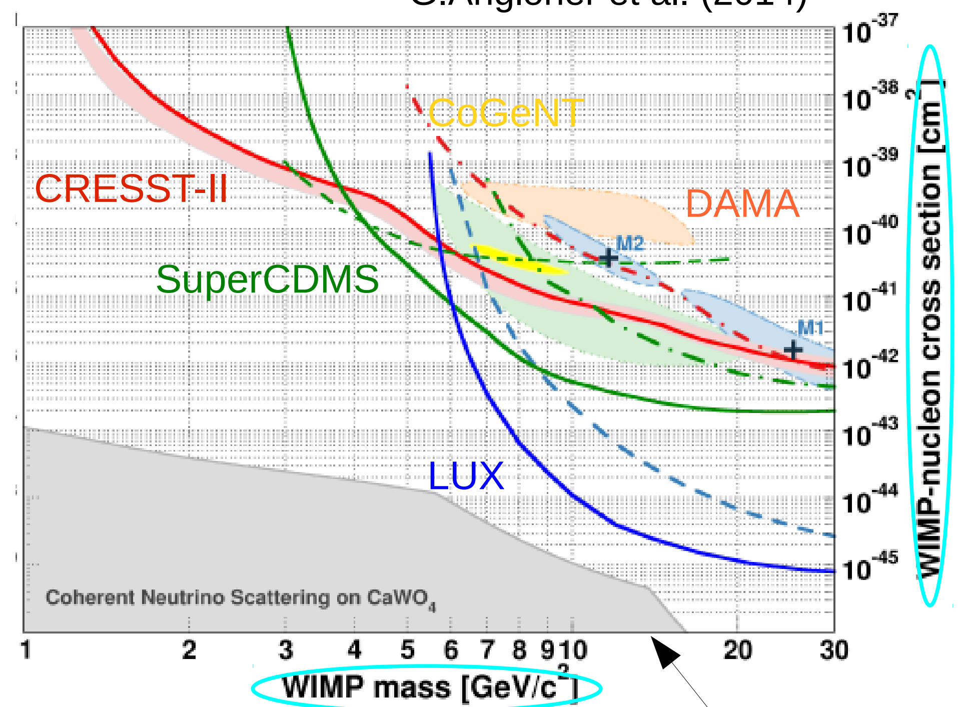
- Dark matter direct detection is plagued with **astrophysical uncertainties**
- Importance of improving control on them in the **context of controversial signals and/or discovery perspectives**
- **Many studies** on astrophysical uncertainties in direct detection:
  A. Green (2012), R. Catena & P. Ullio (2012), M. Fairbairn & P. Grothaus (2013), N. Bozorgnia, et al. (2013), etc.
- Most are based on **rotation curves** plus sometimes (flat or Gaussian) priors on Vesc
- 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)



Effects at work:

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

Differential event rate

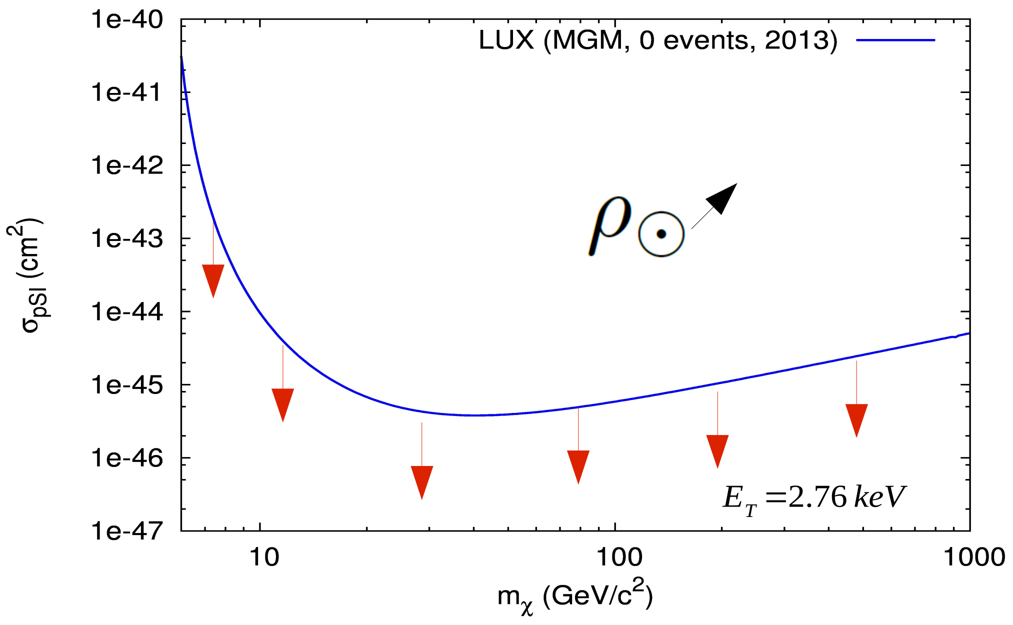
$$\frac{dN}{dE_r}(E_r) = \frac{A^2 \sigma_{p,SI} F^2(E_r)}{2\mu_p^2 m_\chi} \rho_\odot \int_{|\vec{v}|>v_{min}} d^3\vec{v} \frac{f_\oplus(\vec{v})}{v}$$

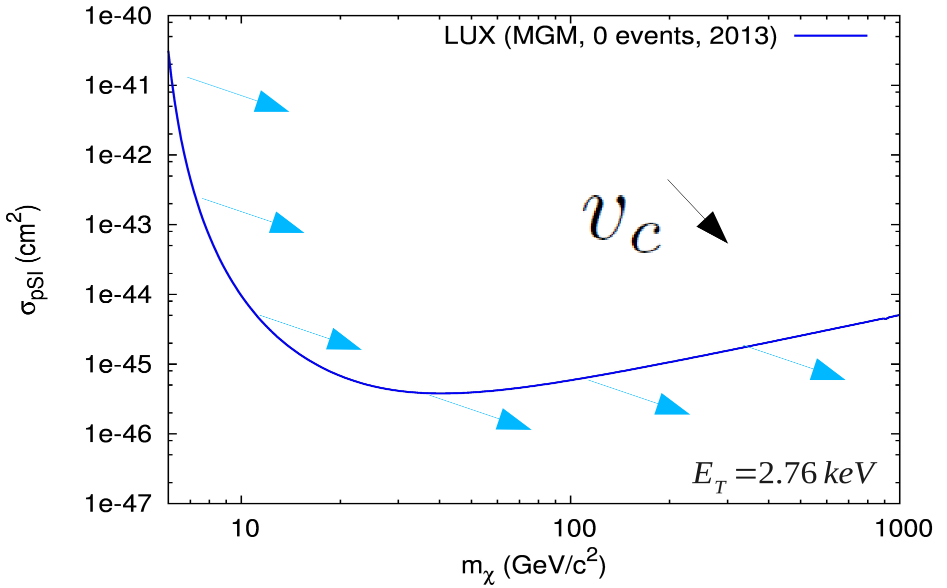
particle + hadronic + nuclear physics

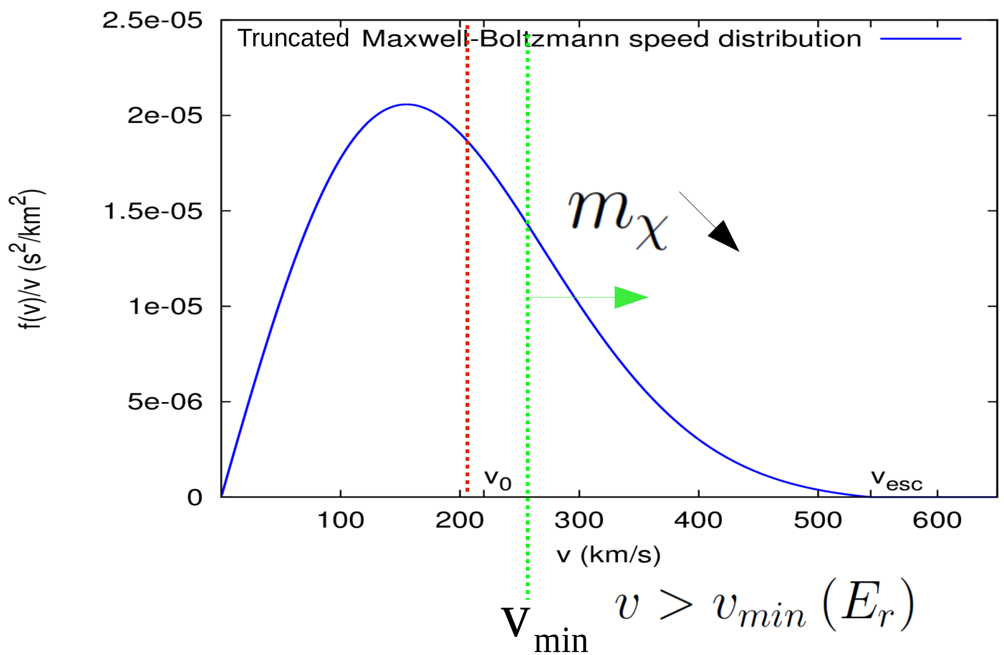
astrophysics

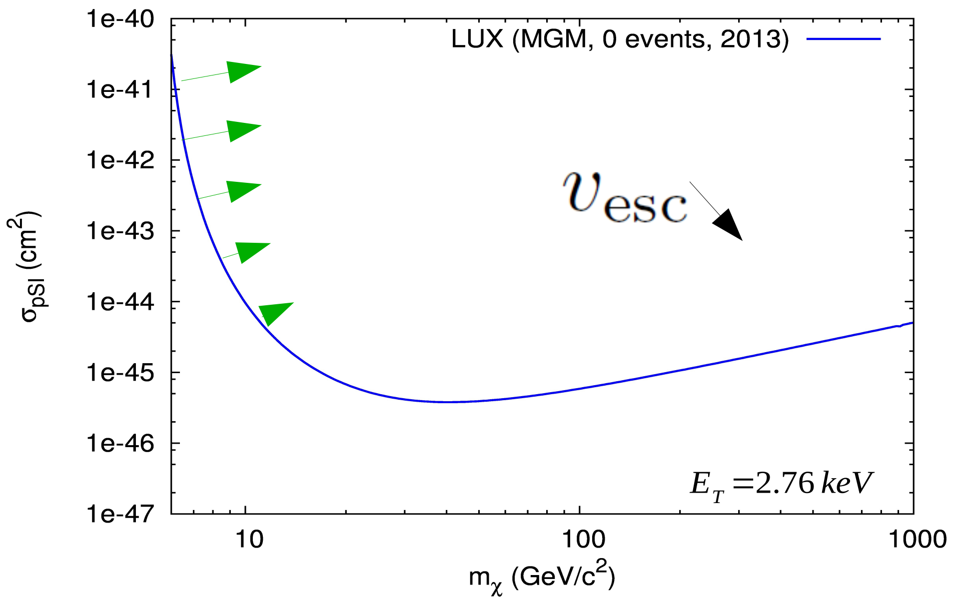
$$v_{min}(E_r) \doteq \sqrt{\frac{E_r m_A}{2 m_{red}^2}}$$

Qualitative impact of astrophysical parameters on exclusion curves





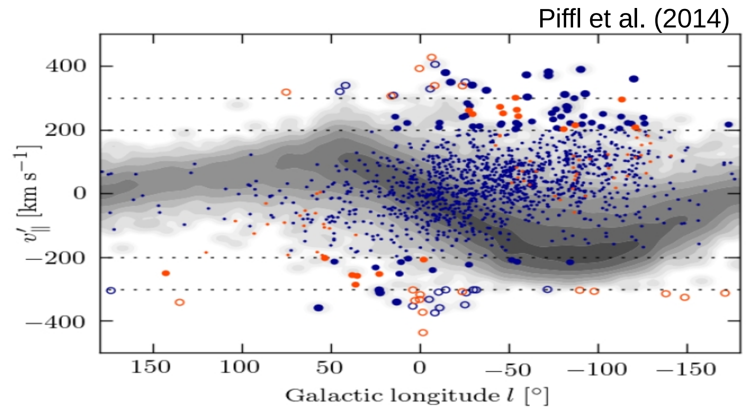




Escape speed estimate from the RAVE survey (Piffl et al. '14)

- 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:

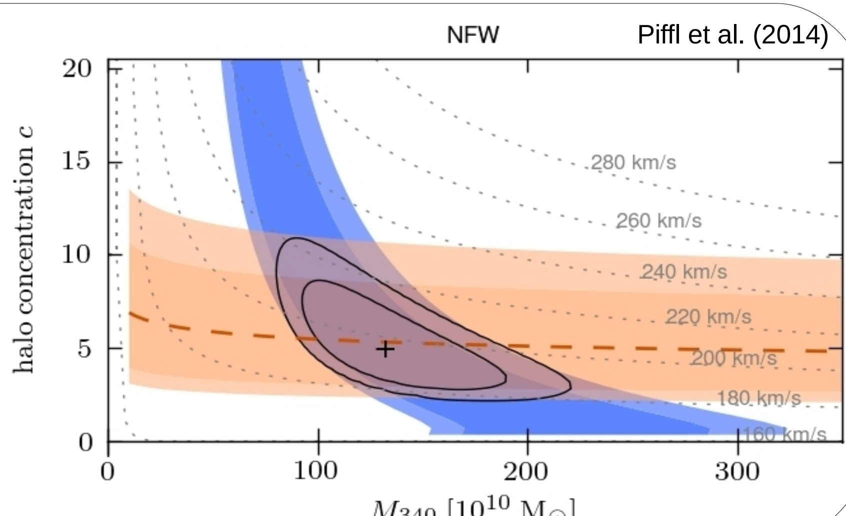
1) **fixed** v_c: a) $v_c = 220\,{\rm km/s}$ b) $v_c = 240\,{\rm km/s}$

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

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:

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



Underlying assumption: MW mass model

important to "relocate" observed stars at 8.28 kpc

<u>Density of matter</u> ⟺ <u>Gravitational Potential</u>

$$\rho\left(\vec{r}\right) = \rho^{DM}\left(\vec{r}\right) + \rho^{bar}\left(\vec{r}\right) \qquad \Phi\left(\vec{r}\right) = \Phi^{DM}\left(\vec{r}\right) + \Phi^{bar}\left(\vec{r}\right)$$

- Mass model assumed: **NFW + fixed baryons**
  - **<u>baryonic bulge</u>**<u>: Hernquist</u> $\phi_{\rm b}(r) = -G\frac{M_{\rm b}}{(r+r_{\rm b})}$
  - **<u>baryonic disk</u>**<u>: Miyamoto-Nagai</u> $\phi_{\rm d}(R,|z|) = -G\frac{M_{\rm d}}{\sqrt{R^2+(R_{\rm d}+\sqrt{z^2+z_{\rm d}^2})^2}}$
  - **<u>Dark matter halo</u>**<u>: NFW</u> $\phi_{\rm dm}(r) = -4\pi G\frac{\rho_s r_s^3}{r}\ln\left(1+\frac{r}{r_s}\right)$

2 free parameters

- **Local dark matter density**

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

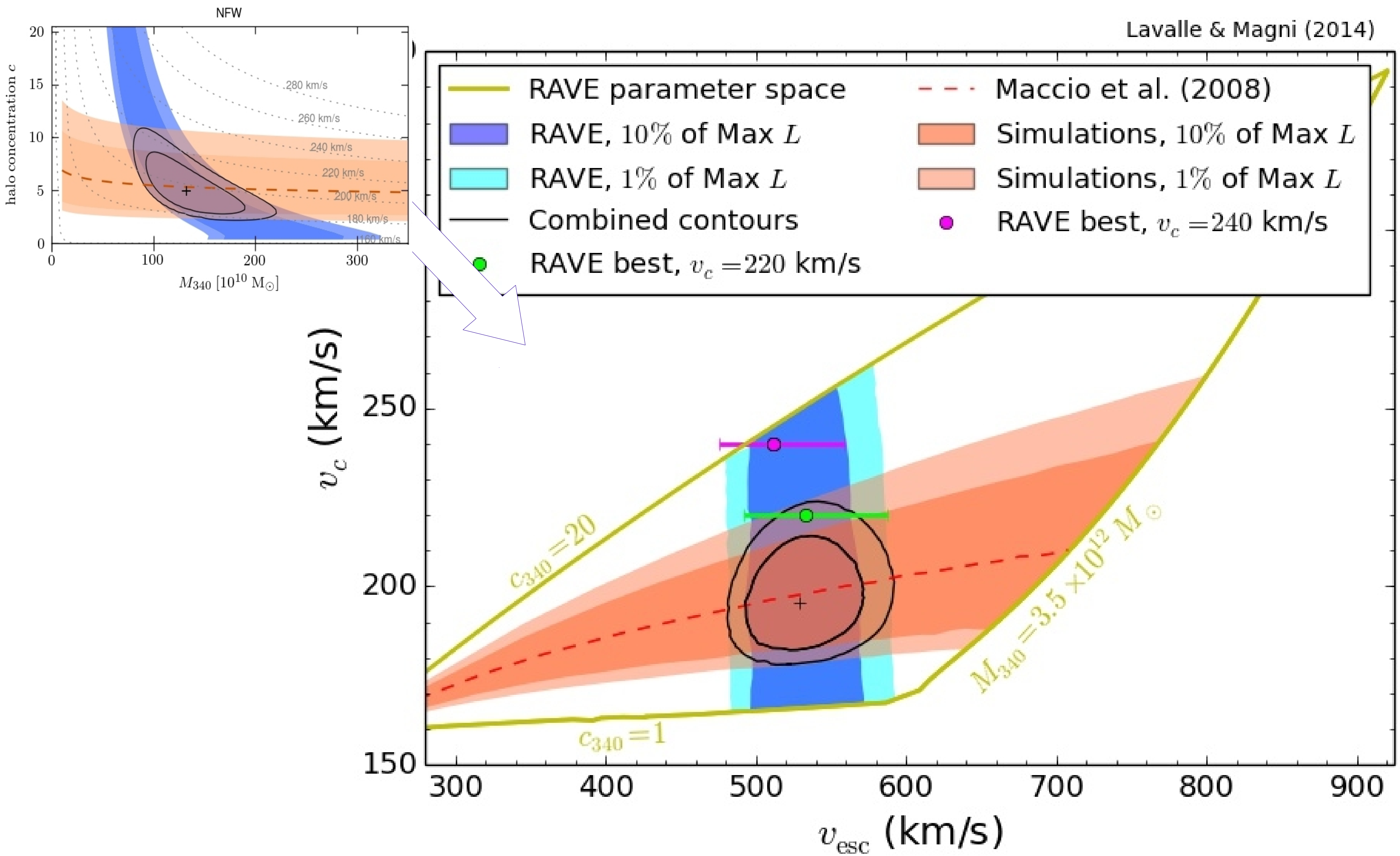
- **Escape speed at Sun position**

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

- **Circular speed at Sun position**

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

Converting RAVE results in the vc-vesc plane

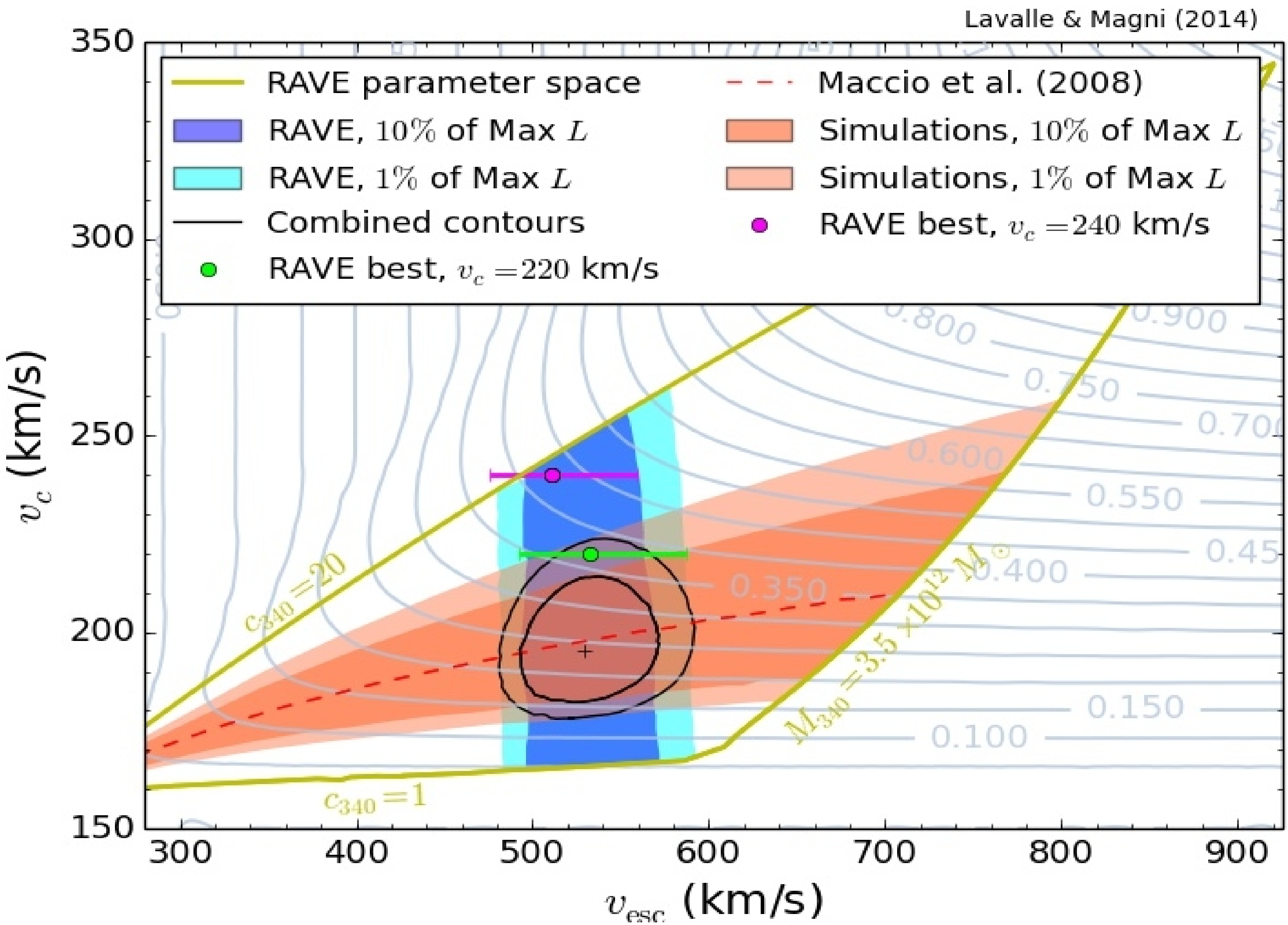


$$v_c^2(r_\odot, z=0) = r_\odot\, G \left\{ \frac{M_b}{(r_\odot + r_b)^2} + \frac{r_\odot\, M_d}{(r_\odot^2 + \bar{R}_d^2)^{3/2}} + 4\pi \frac{\rho_s\, r_s}{x_\odot^2} \left(\ln(1 + x_\odot) - \frac{x_\odot}{1 + x_\odot} \right) \right\}$$

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

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

Beware! MW mass model induces correlations



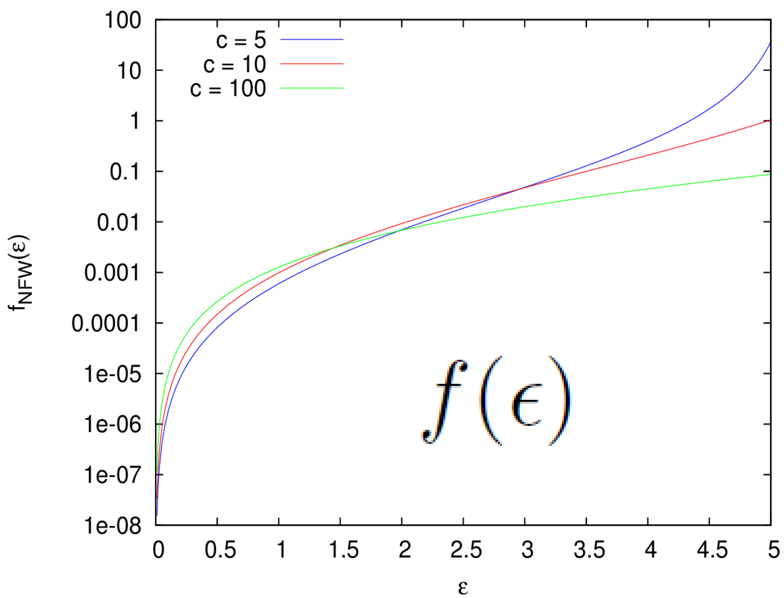
Model assumptions	v_c (km/s)	v_{esc} (km/s)	ρ_s (GeV/cm^3)	r_s (kpc)	$\rho_\odot$ (GeV/cm^3)
prior $v_c = 220$ km/s	220	$533^{+54+109}_{-41-60}$	$0.42^{+0.26+0.48}_{-0.16-0.24}$	$16.4^{+6.6+13.6}_{-4.5-6.4}$	$0.37^{+0.02+0.04}_{-0.03-0.04}$
prior $v_c = 240$ km/s	240	511^{+48}_{-35}	$1.92^{+1.85}_{-0.82}$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

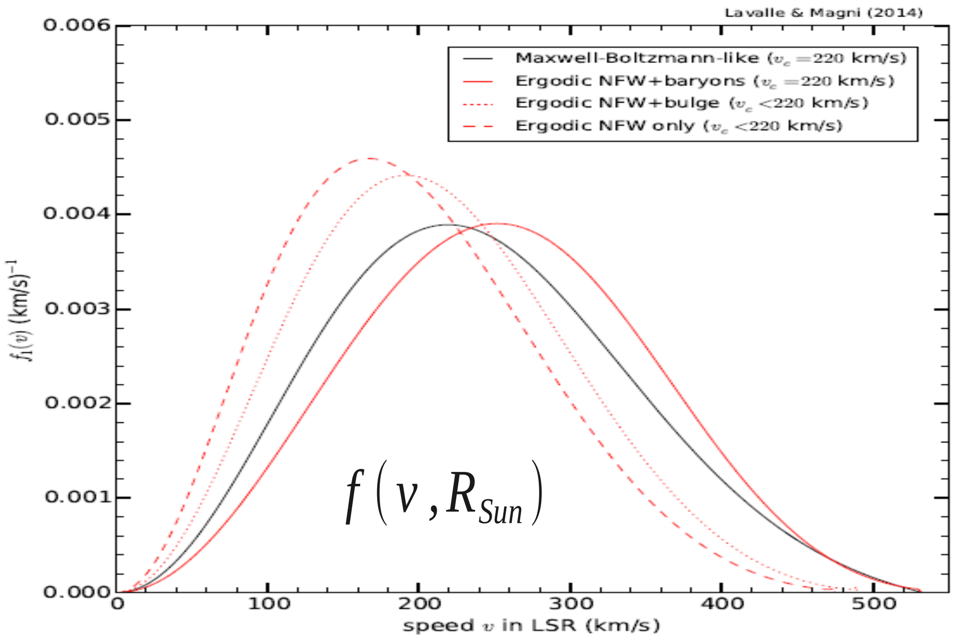
Dynamical correlations into self-consistent local f(v)

- 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)

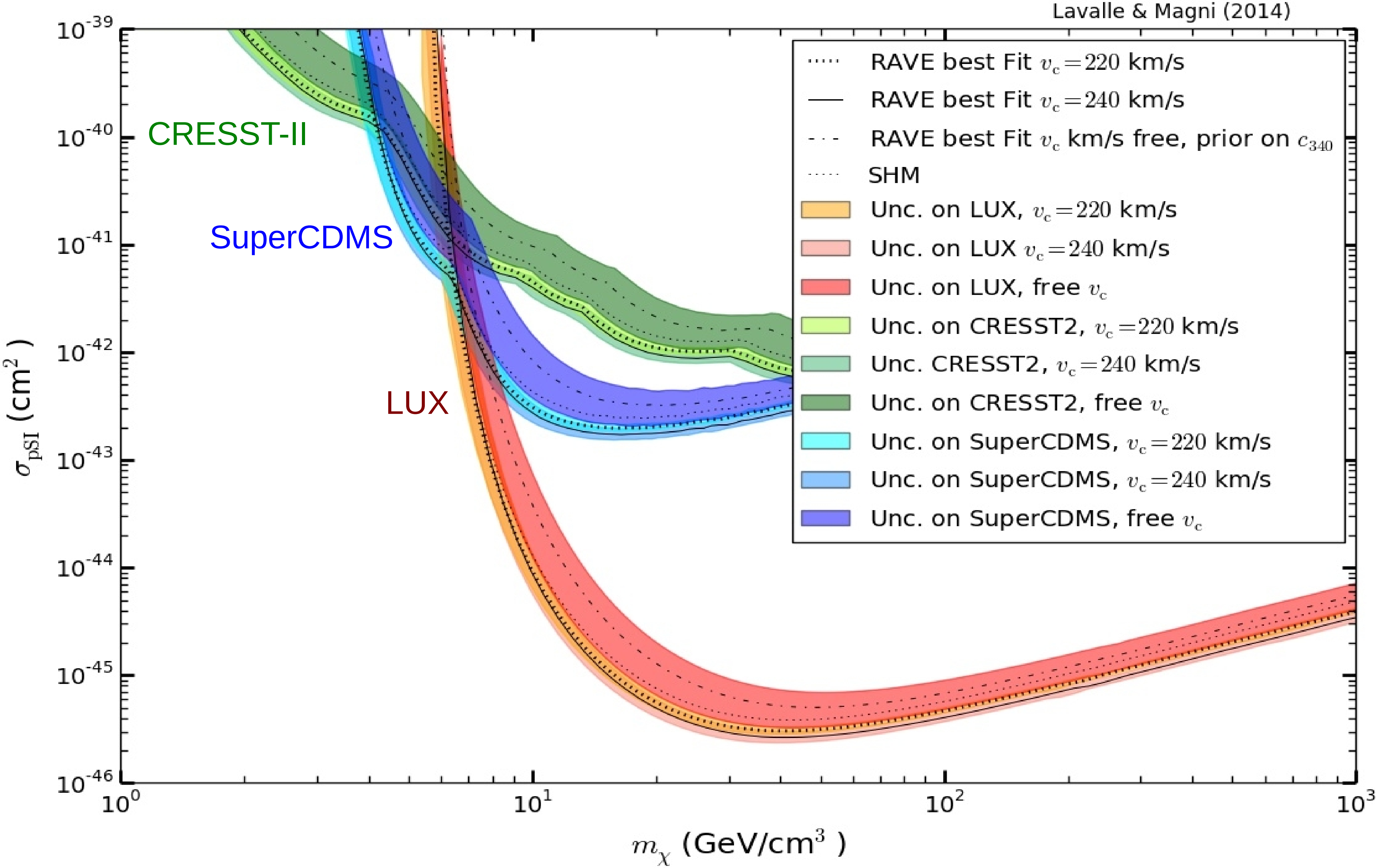
$$f(\epsilon) = \frac{1}{\sqrt{8}\,\pi^2}\left\{\frac{1}{\sqrt{\epsilon}}\frac{d\rho}{d\psi}\Big|_{\psi=0} + \int_0^{\epsilon}\frac{d\psi}{\sqrt{\epsilon-\psi}}\frac{d^2\rho}{d\psi^2}\right\}$$

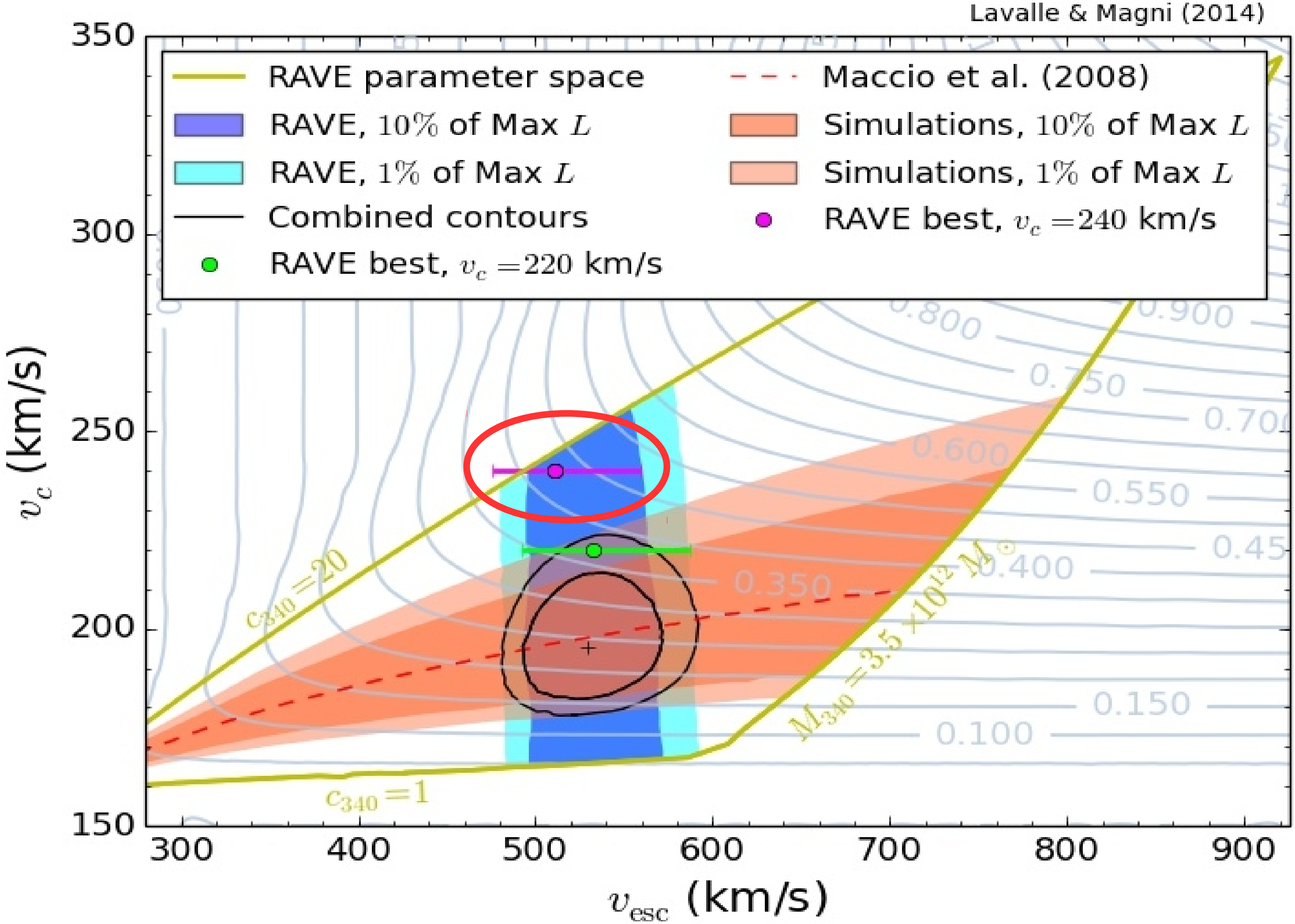
$$\Psi = -\Phi_{MW}(r)$$
$$\epsilon = -E_{tot}$$
$$\rho = \rho_{NFW}(r)$$





RAVE's constraints translated into DD exclusions





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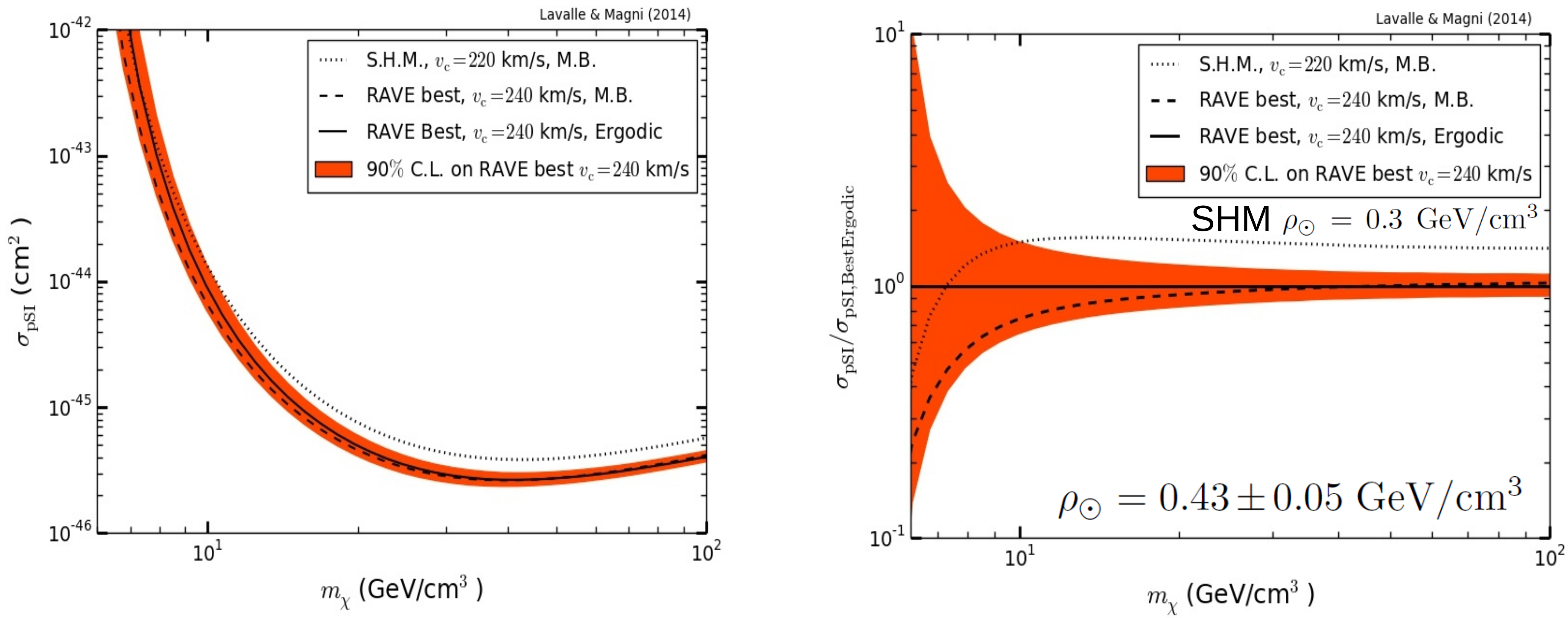
Uncertainties from RAVE best fit point

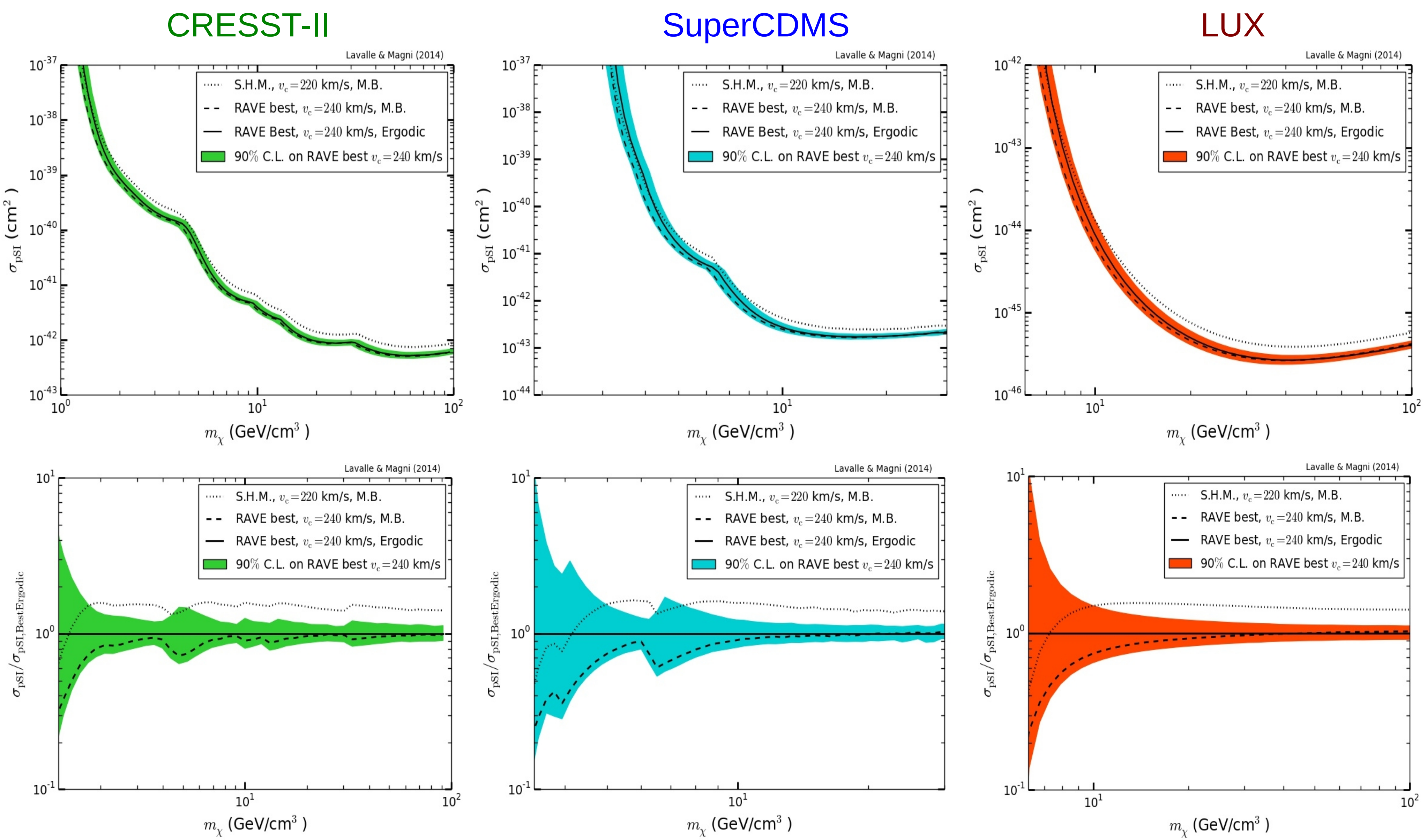


- At high masses: ergodic limit **more constraining** than SHM **by 40%**
- At low masses: ergodic limit **beaten** by SHM because

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

- The **form of the DF** is relevant only at low masses
- **Relative uncertainties saturate** at $\pm 10\% \ (90\% \ {\rm CL})$ at large masses,
- Uncertainties at high masses from v_c and $\rho_\odot$, at low masses from v_c and $v_{\rm esc}$

Uncertainties from RAVE best fit point



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

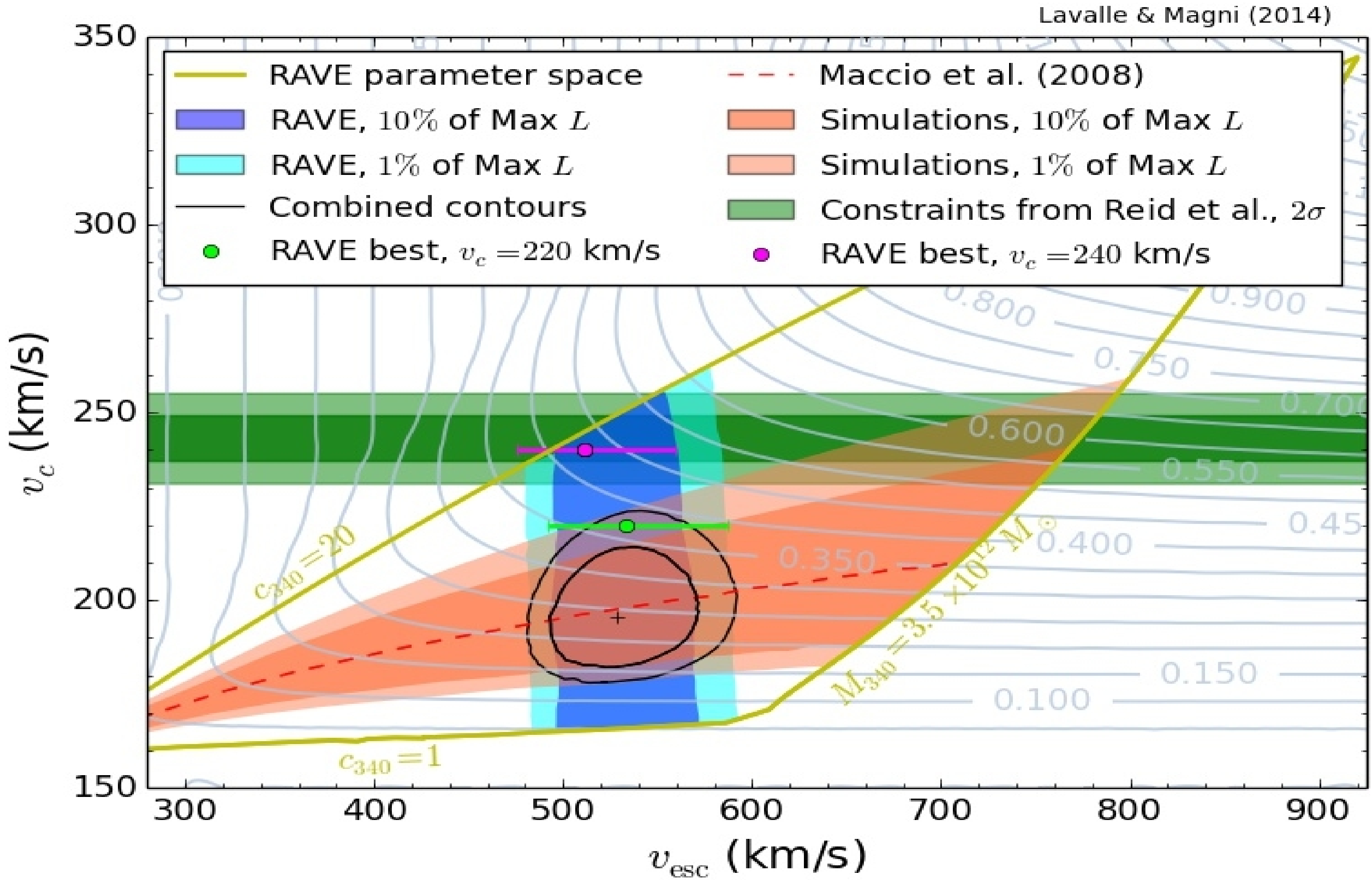
Additional and independent constraints on the circular speed

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

(Reid et al., '14)

Additional constraints (OK within 3 sigma):

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



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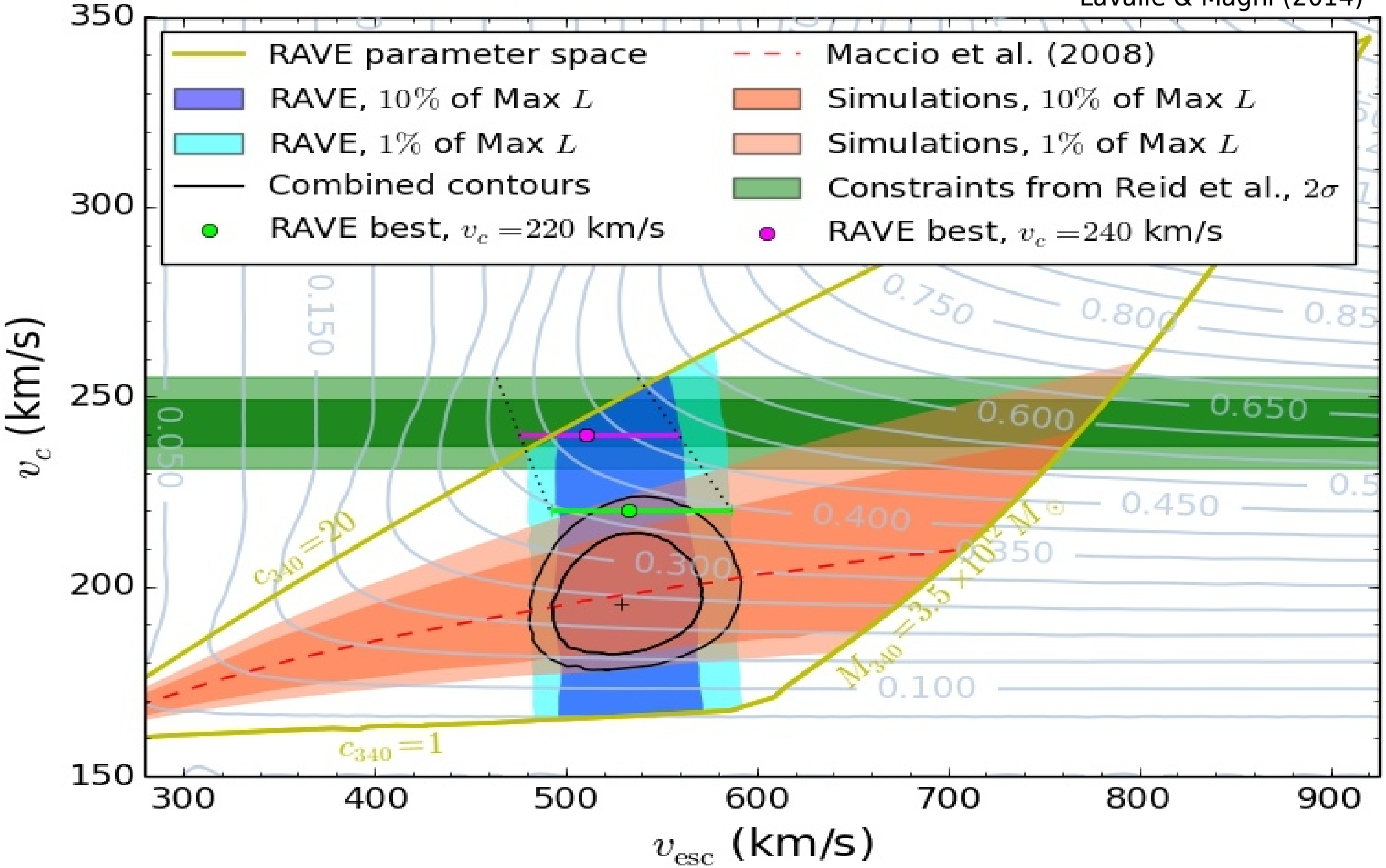
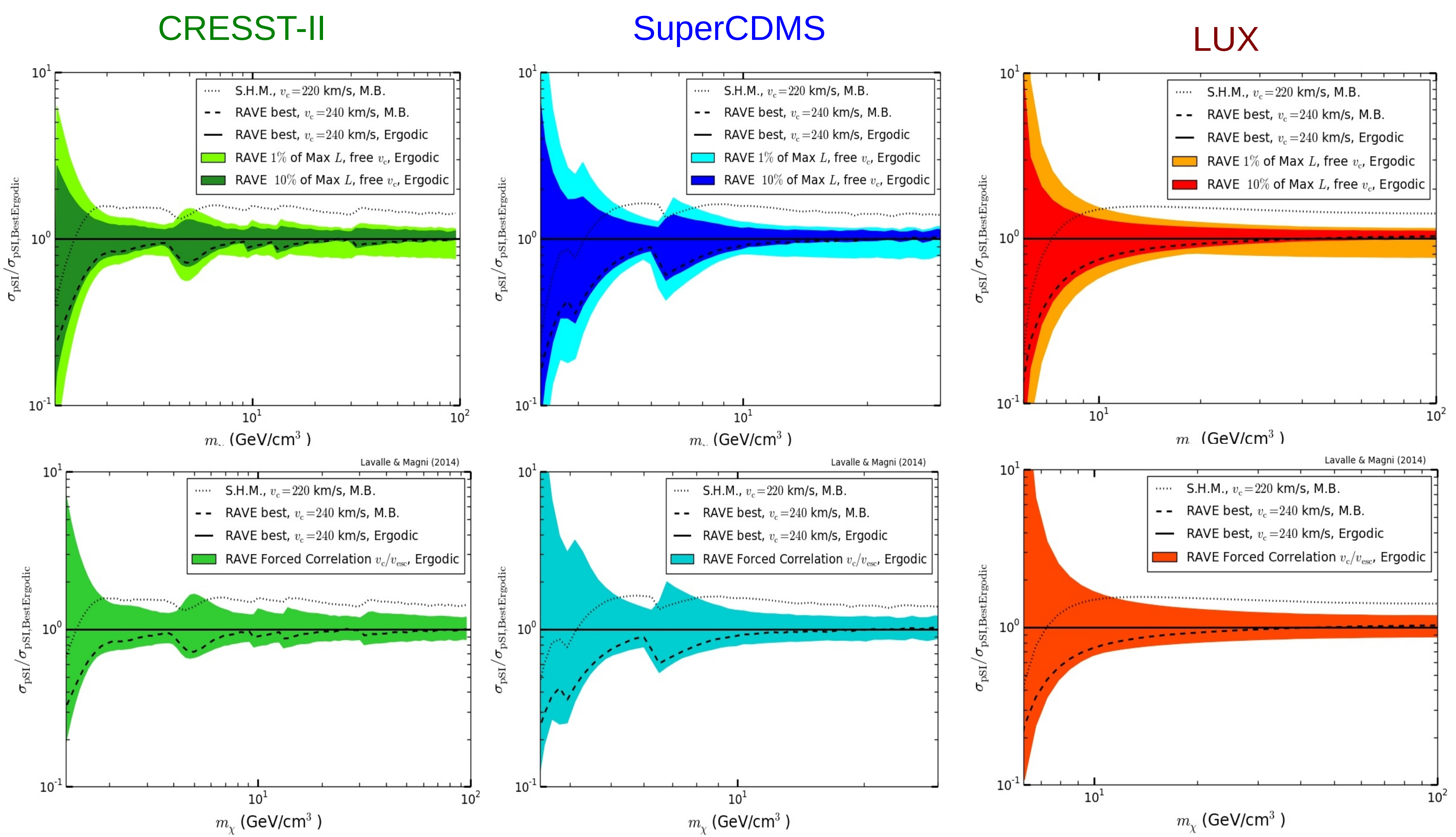
Lavalle & Magni (2014)



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



- No big differences, but second way more consistent

Conclusions and perspectives

- Escape speed estimates **cannot be used blindly**: 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)

Thank you very much for your attention!