

# Astrophysical aspects of dark matter direct detection

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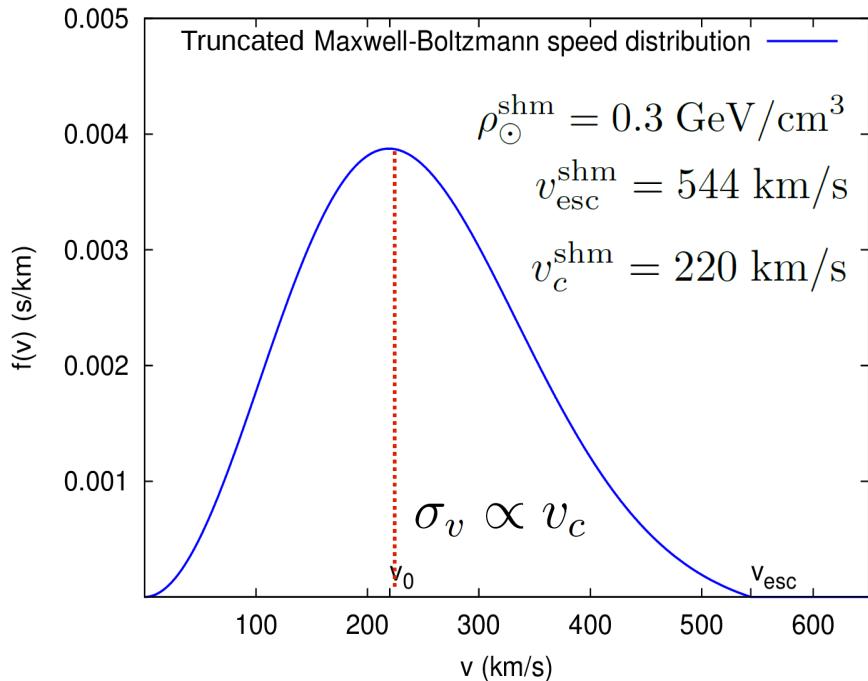
Based on collaboration with Julien Lavalle,  
arXiv: 1411.1325 astro-ph.CO

# Introduction

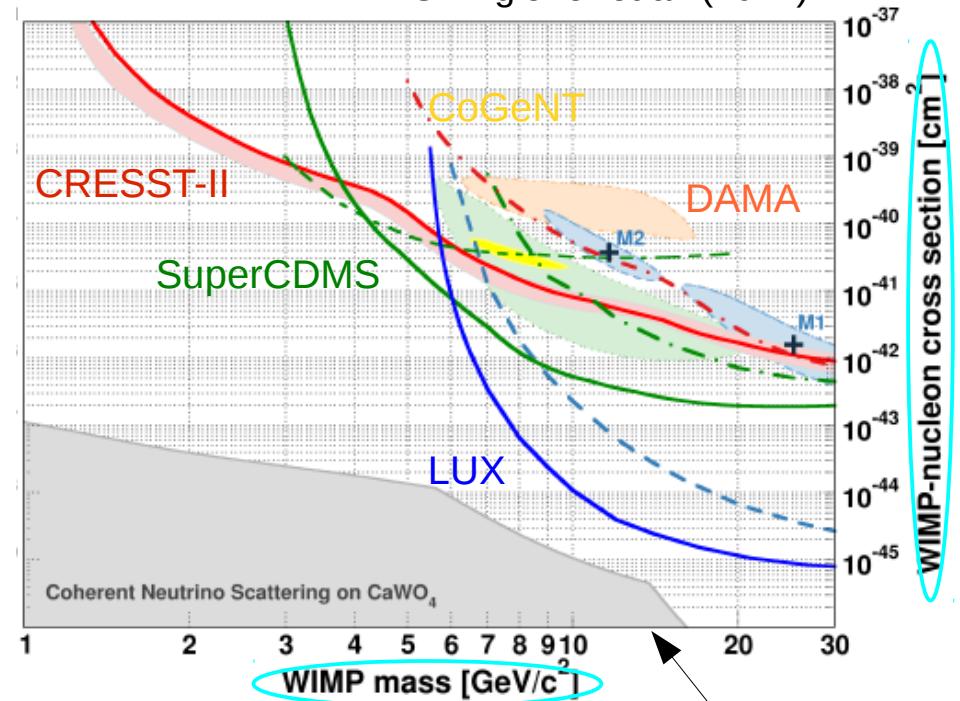
- Dark matter direct detection is plagued with **astrophysical uncertainties**
- Importance of improving control on them in the **context of controversial signals and/or discovery perspectives**
- **Many studies** on astrophysical uncertainties in direct detection:  
A. Green (2012), R. Catena & P. Ullio (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  $V_{\text{esc}}$
- 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

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

particle + hadronic + nuclear physics

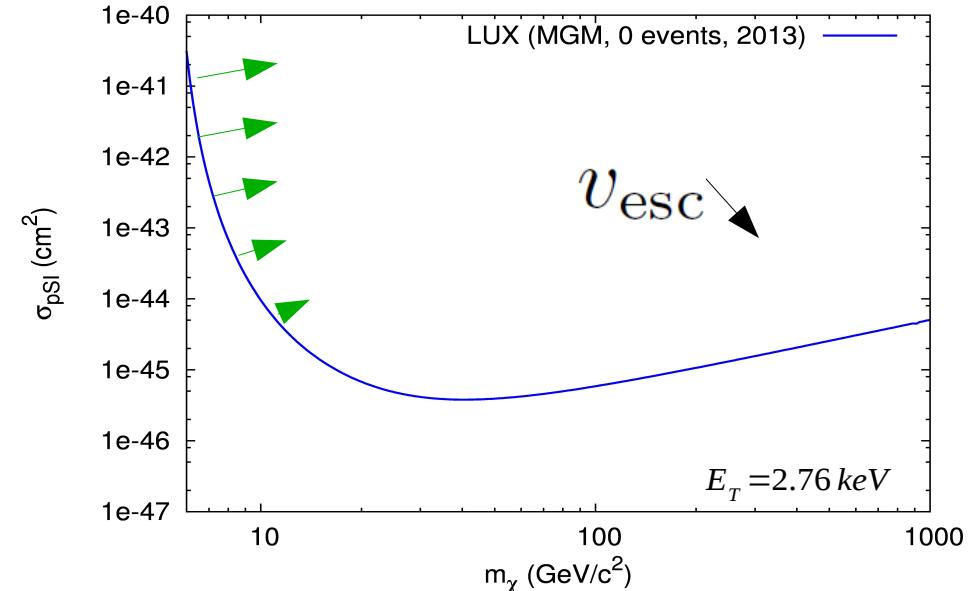
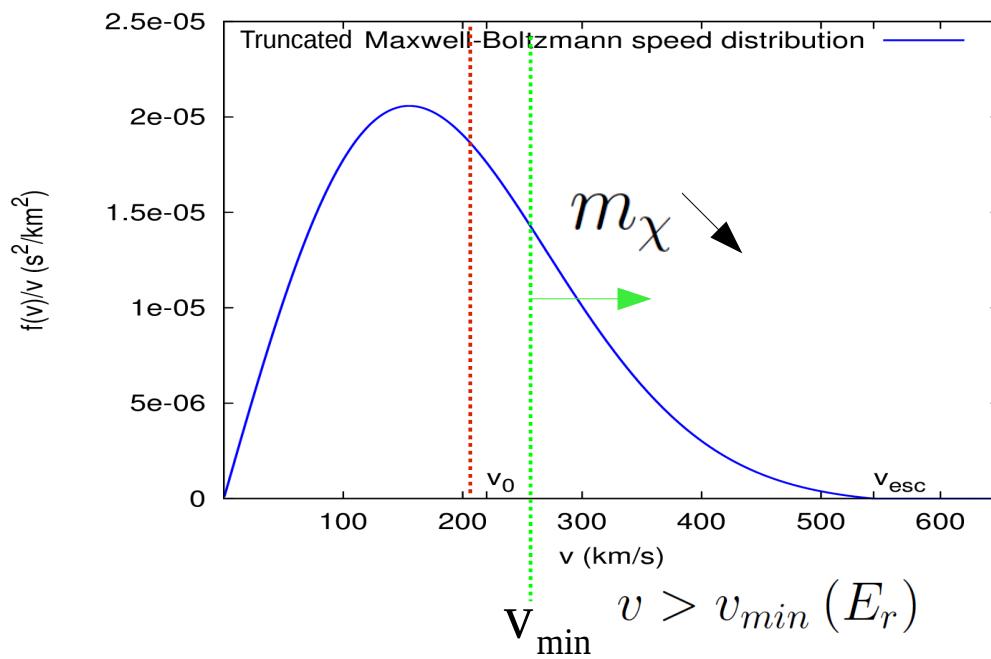
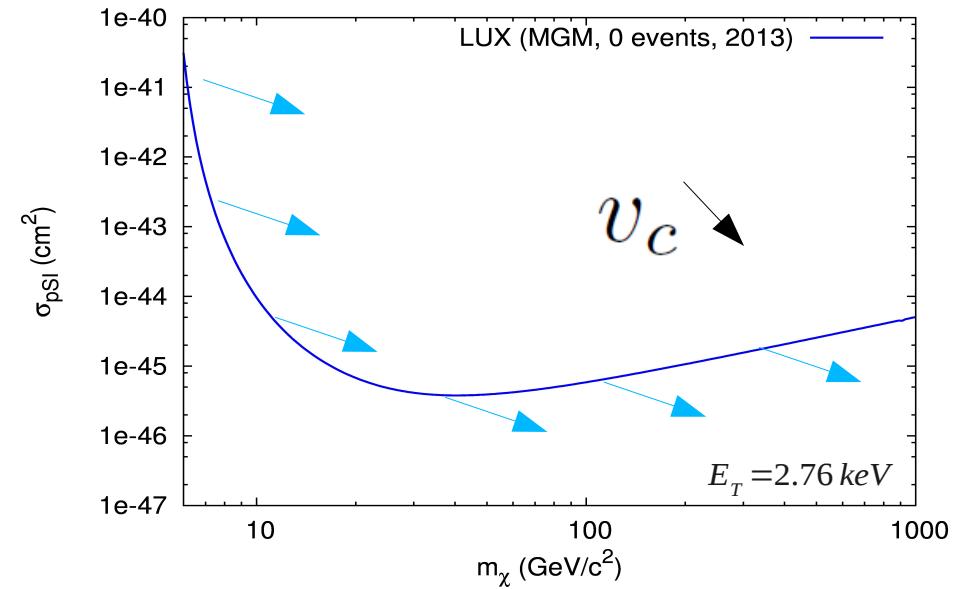
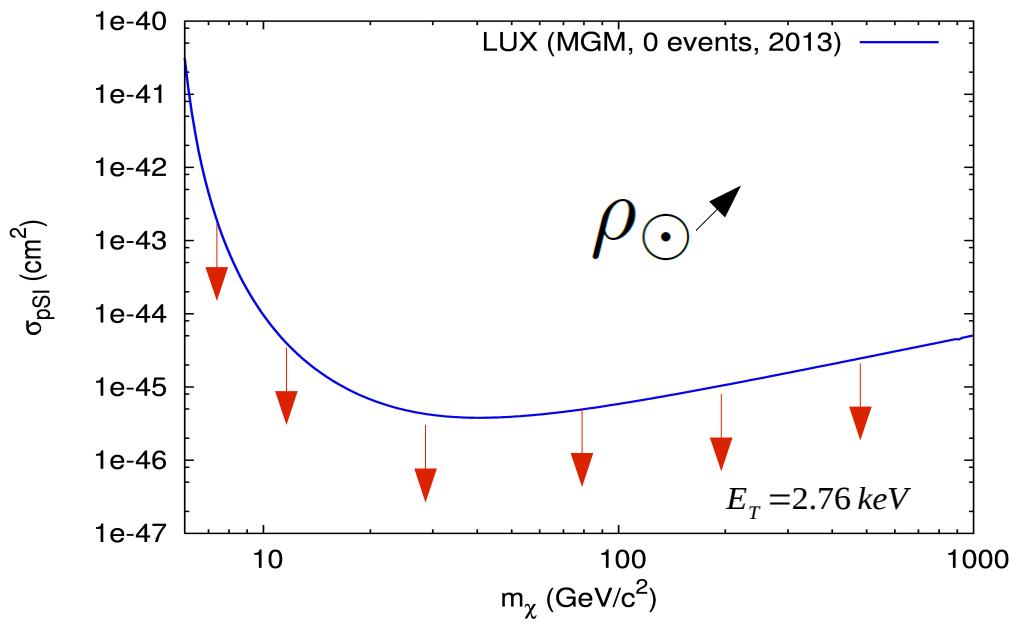
astrophysics

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

## Effects at work:

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

# Qualitative impact of astrophysical parameters on exclusion curves



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

- Updates the previous estimate of  $v_{\text{esc}} = 544^{+64}_{-46} \text{ km/s}$  (90% 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:

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

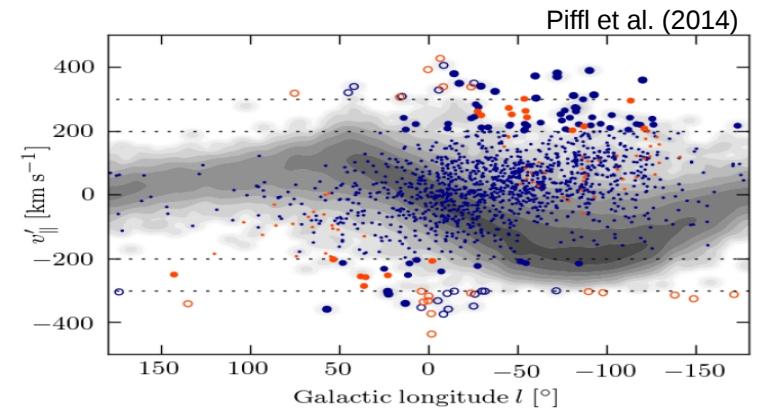
- 2 different likelihood analyses:

1) **fixed**  $v_c$ : a)  $v_c = 220 \text{ km/s}$

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

b)  $v_c = 240 \text{ km/s}$

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



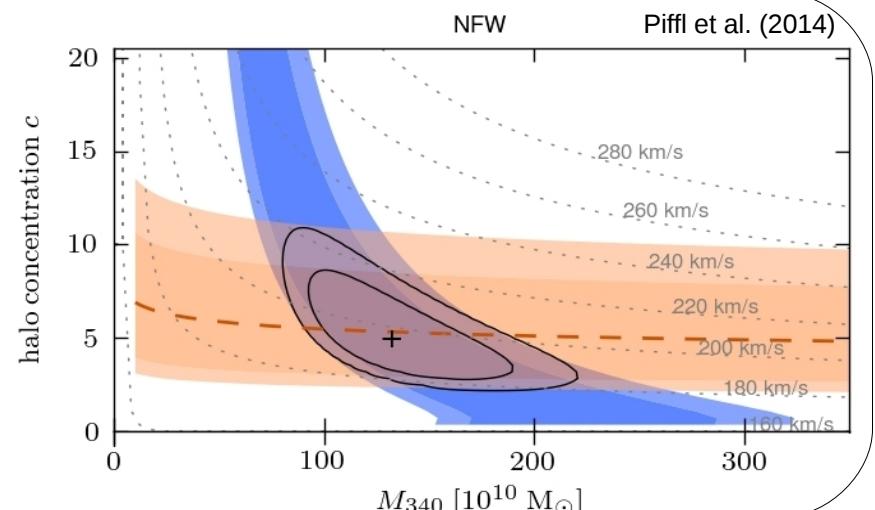
2) **free**  $v_c$ :

+ additional prior on concentration

- originally an estimate of the MW Mass

- gives an independent estimate of  $v_{\text{esc}}$ , best fits are:

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



# Underlying assumption: MW mass model

Important to "relocate" observed stars at 8.28 kpc

## Density of matter

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



## Gravitational Potential

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

- Mass model assumed: **NFW + fixed baryons**

- › baryonic bulge: Hernquist

$$\phi_b(r) = -G \frac{M_b}{(r+r_b)}$$

- › baryonic disk: Miyamoto-Nagai

$$\phi_d(R, |z|) = -G \frac{M_d}{\sqrt{R^2 + (R_d + \sqrt{z^2 + z_d^2})^2}}$$

- › 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

- Local dark matter density

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

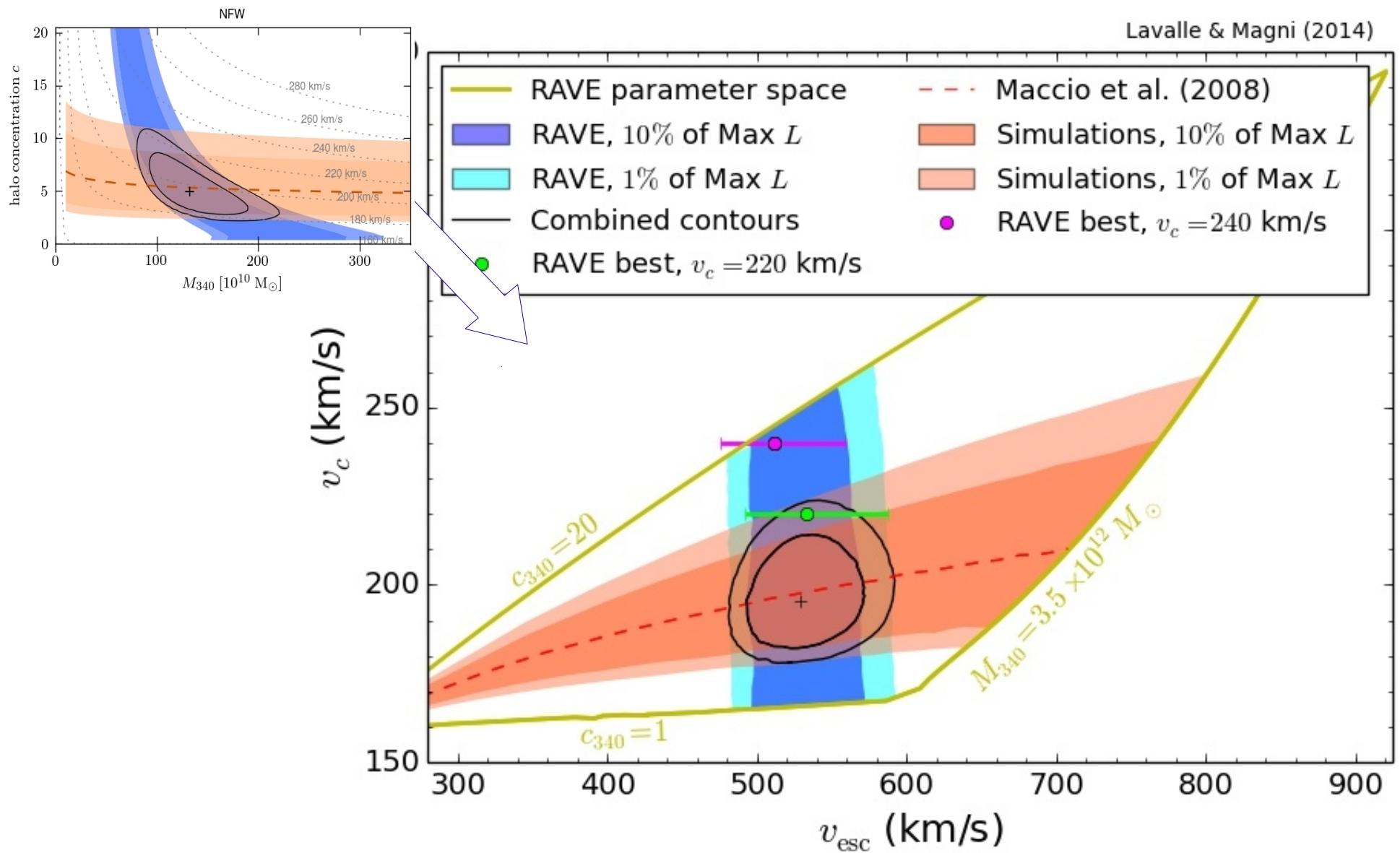
- Escape speed at Sun position

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

- Circular speed at Sun position

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

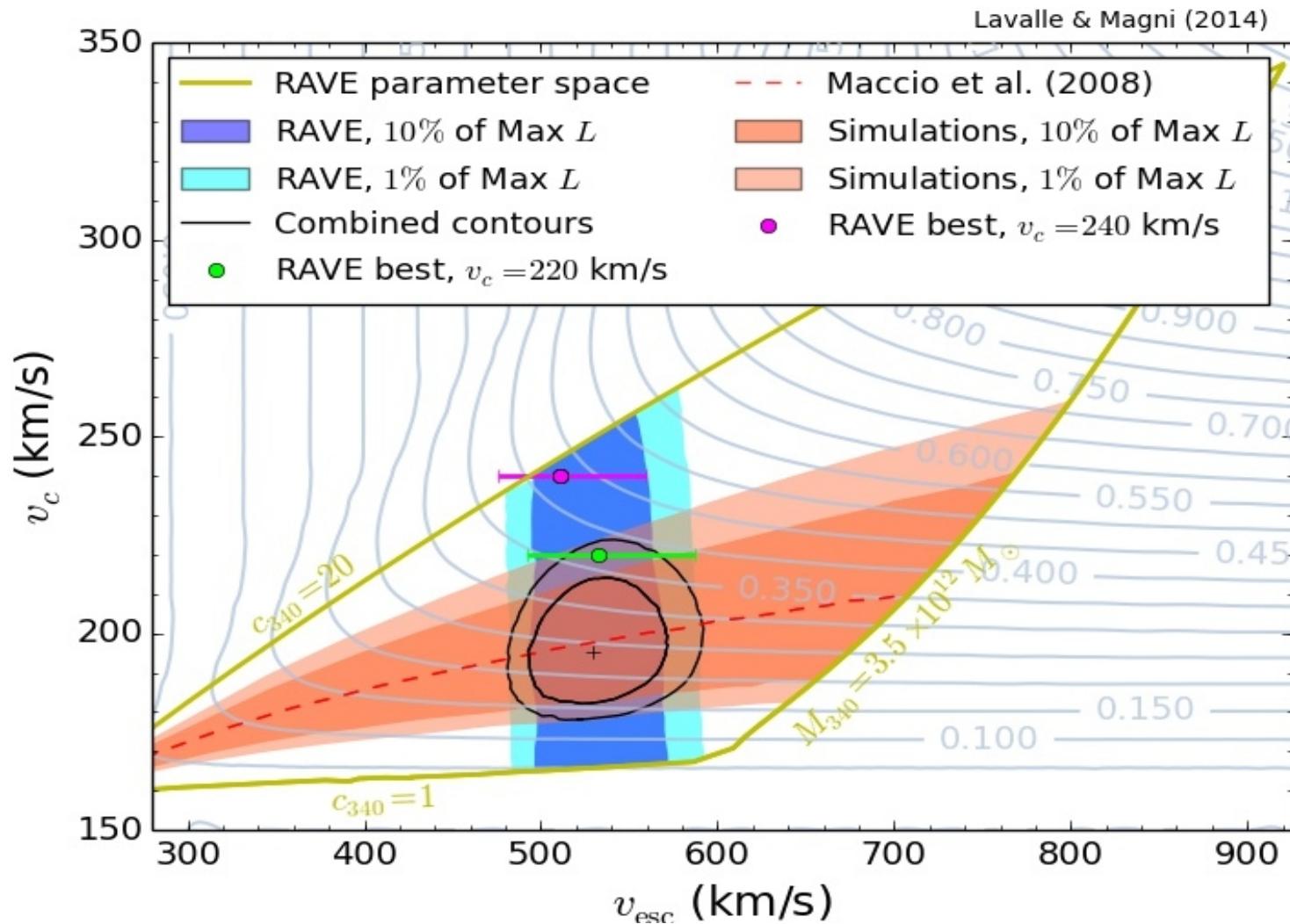
# Converting RAVE results in the vc-vesc plane



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

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

# Beware! MW mass model induces correlations



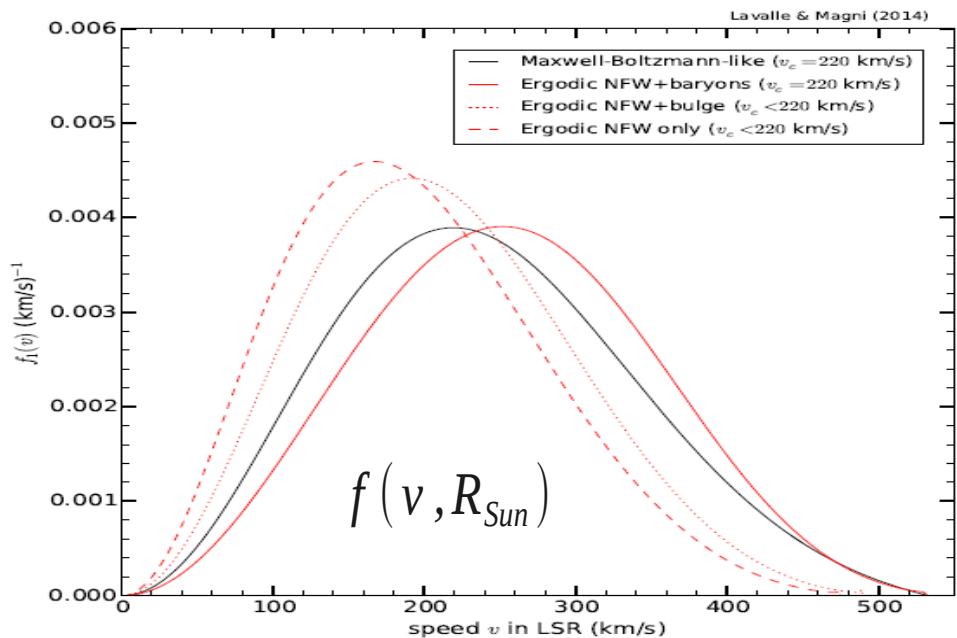
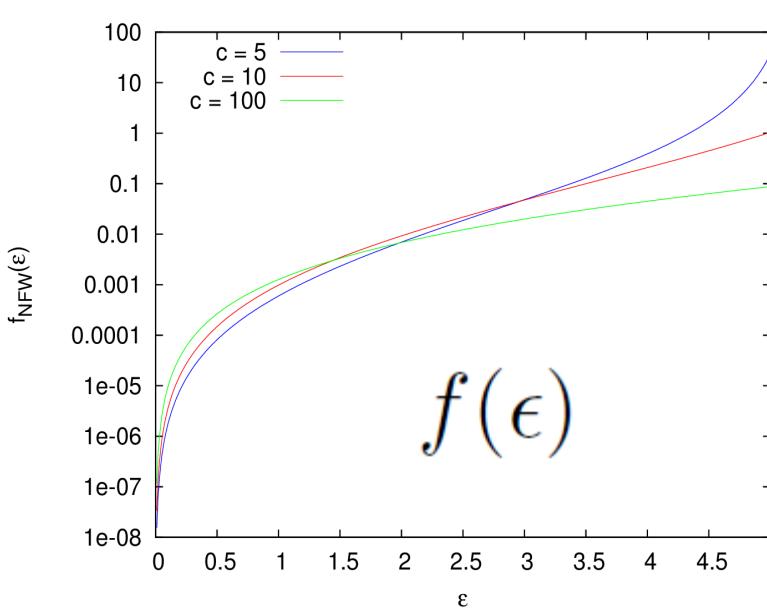
Model assumptions	$v_c$ (km/s)	$v_{\text{esc}}$ (km/s)	$\rho_s$ (GeV/cm <sup>3</sup> )	$r_s$ (kpc)	$\rho_\odot$ (GeV/cm <sup>3</sup> )
prior $v_c = 220$ km/s	220	$533^{+54+109}_{-41-60}$	$0.42^{+0.26+0.48}_{-0.16-0.24}$	$16.4^{+6.6+13.6}_{-4.5-6.4}$	$0.37^{+0.02+0.04}_{-0.03-0.04}$
prior $v_c = 240$ 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 $f(v)$

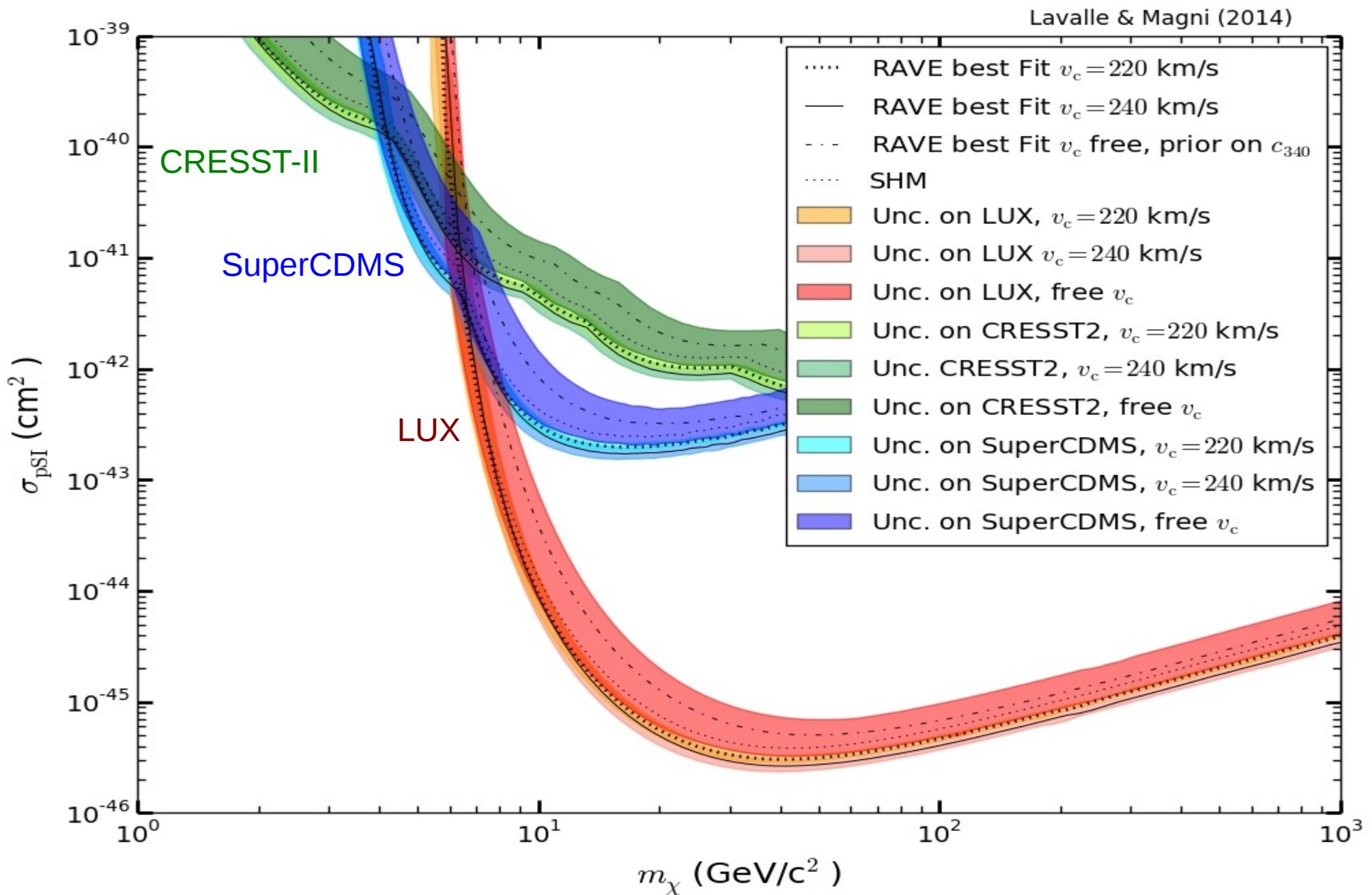
- MB (where  $\sigma \propto v_c$ ) relies on isothermal assumption
- Truncated MB not solution of Jeans equation
- Eddington equation (Ullio & Kamionkowski '01, Vergados & Owens '03)

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

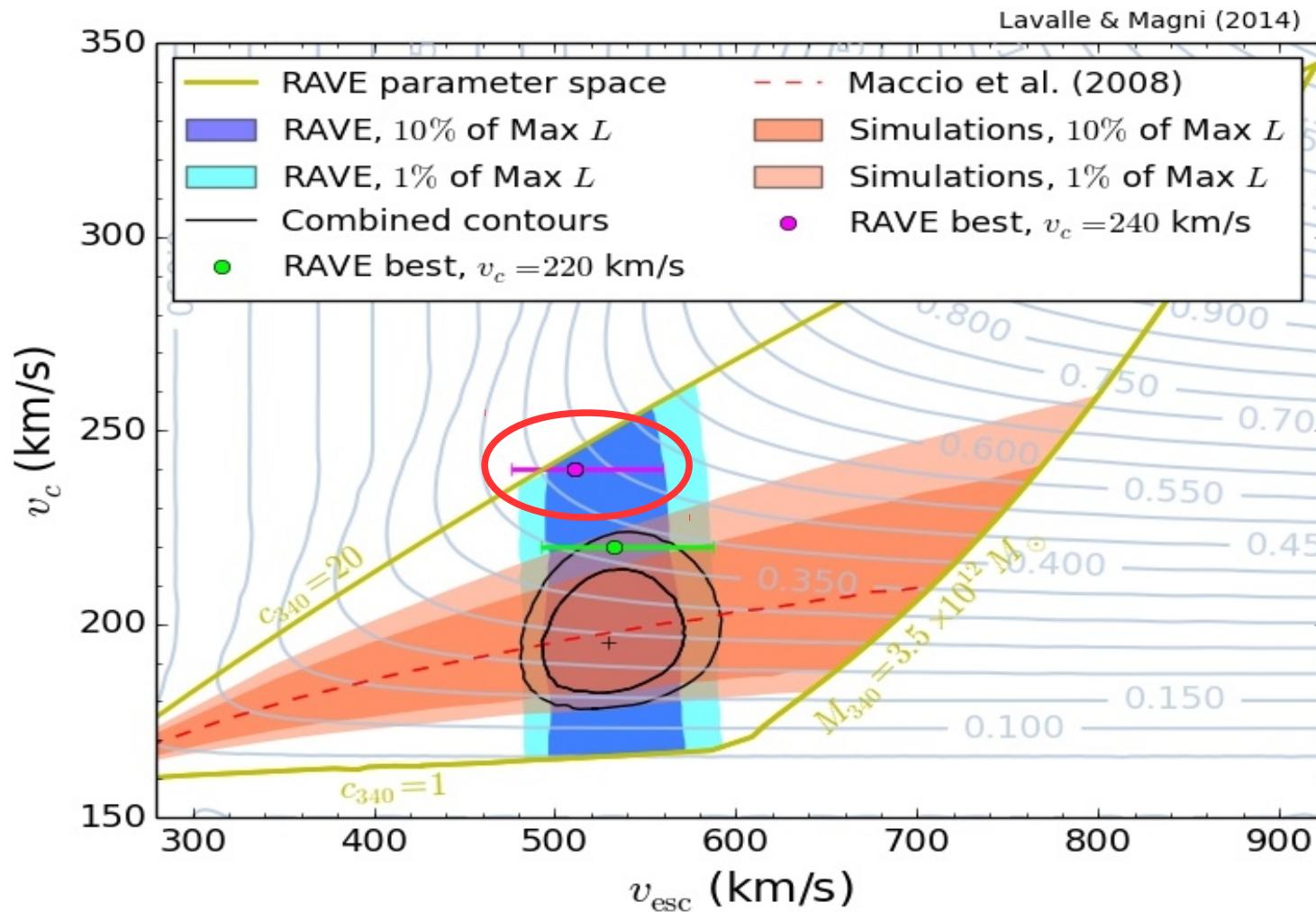
$\Psi = -\Phi_{MW}(r)$   
 $\epsilon = -E_{tot}$   
 $\rho = \rho_{NFW}(r)$



# RAVE's constraints translated into DD exclusions



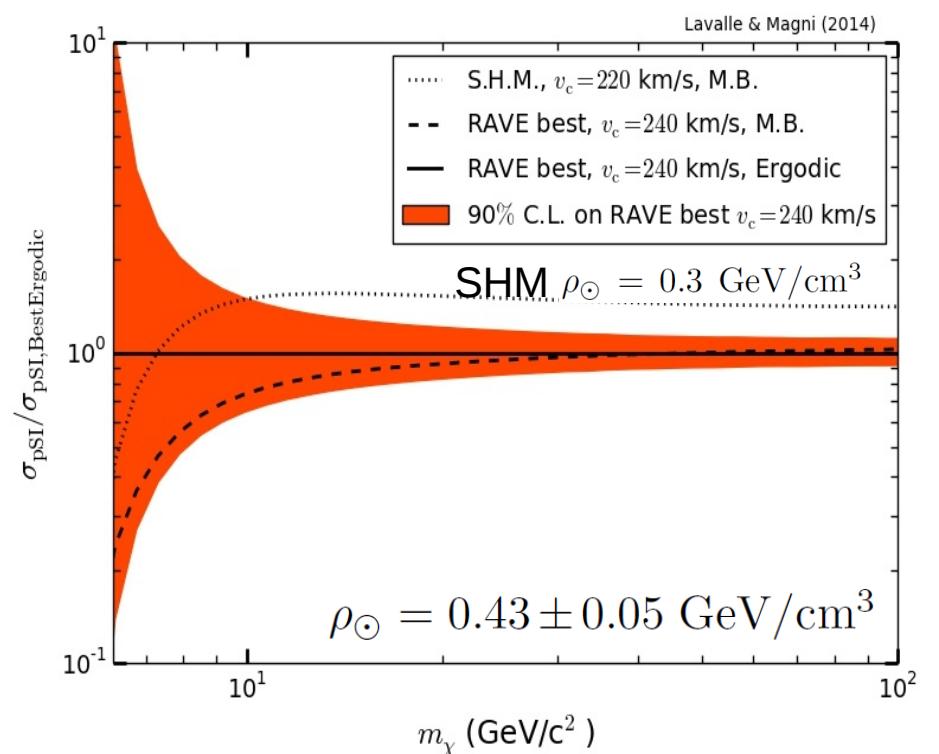
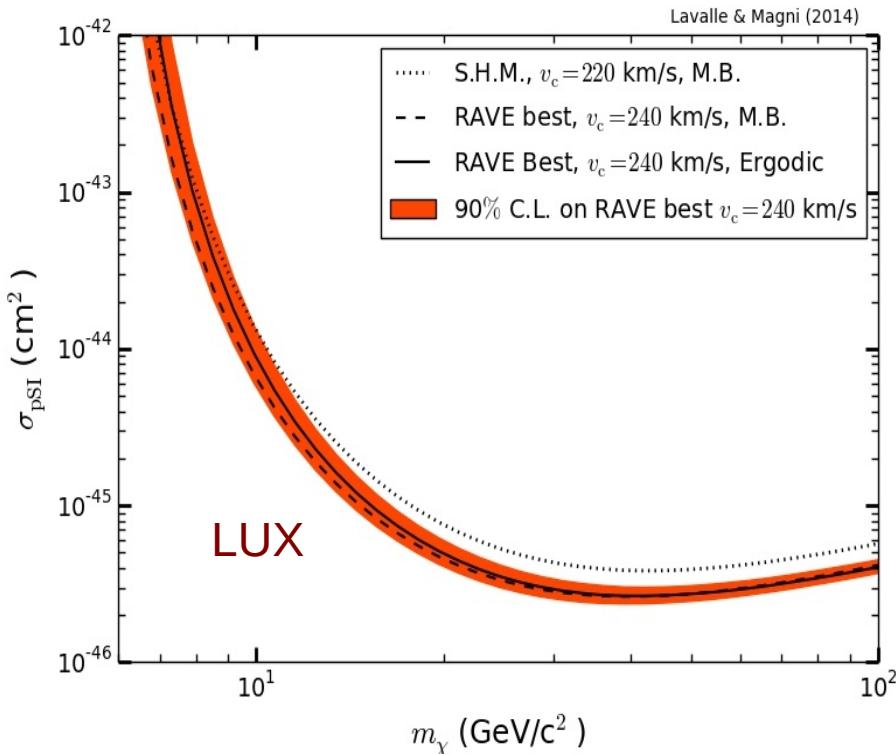
# Focus first on the analysis with circular speed fixed at 240 km/s



Model assumptions

	$v_c$ (km/s)	$v_{\text{esc}}$ (km/s)	$\rho_s$ (GeV/cm <sup>3</sup> )	$r_s$ (kpc)	$\rho_\odot$ (GeV/cm <sup>3</sup> )
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# Exclusion curve and uncertainties from RAVE best fit point

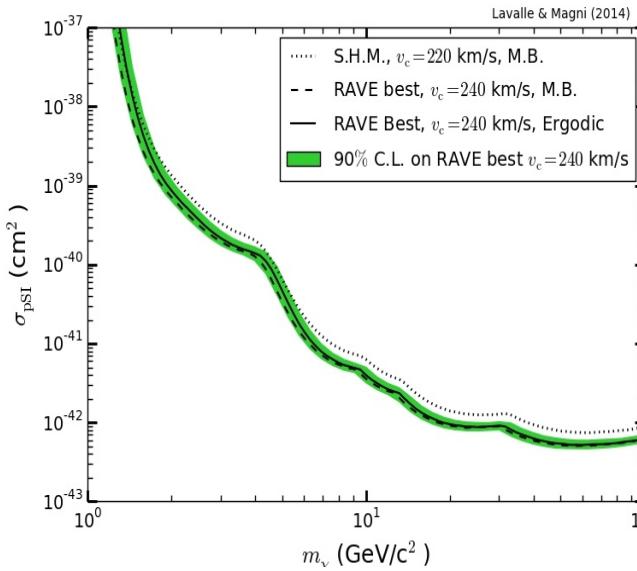


- At high masses: ergodic limit **more constraining** than SHM by 40%
- At low masses: ergodic limit **beaten** by SHM because
 

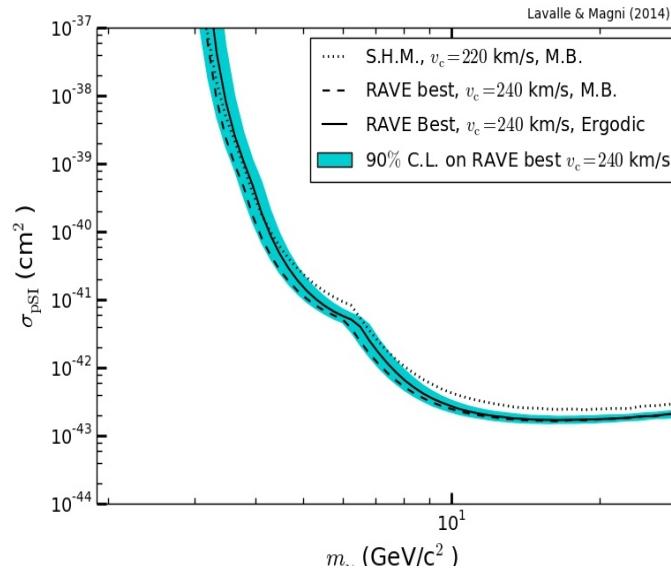
$v_c + v_{\text{esc}} = 751 \text{ km/s}$ 
VS
 $v_c + v_{\text{esc}} = 764 \text{ km/s}$
- The **form of the DF** is relevant only at low masses
- **Relative uncertainties saturate** at  $\pm 10\%$  (90% CL) at large masses

# Uncertainties from RAVE best fit point

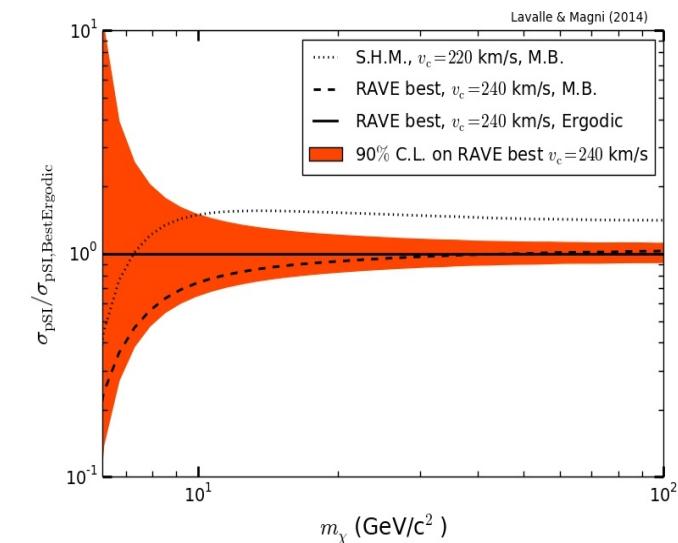
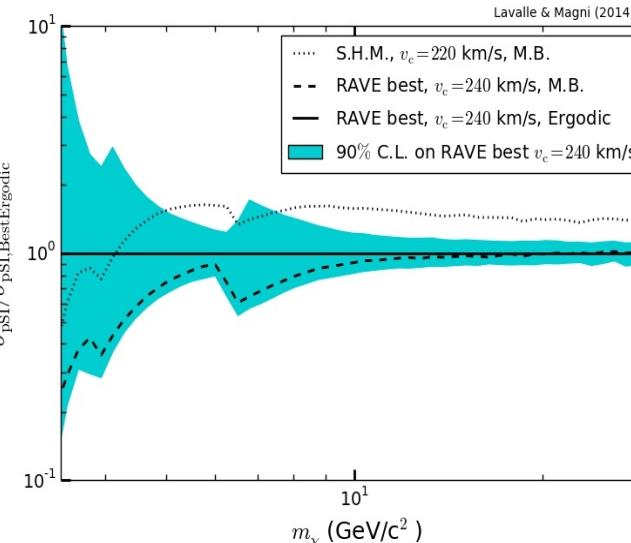
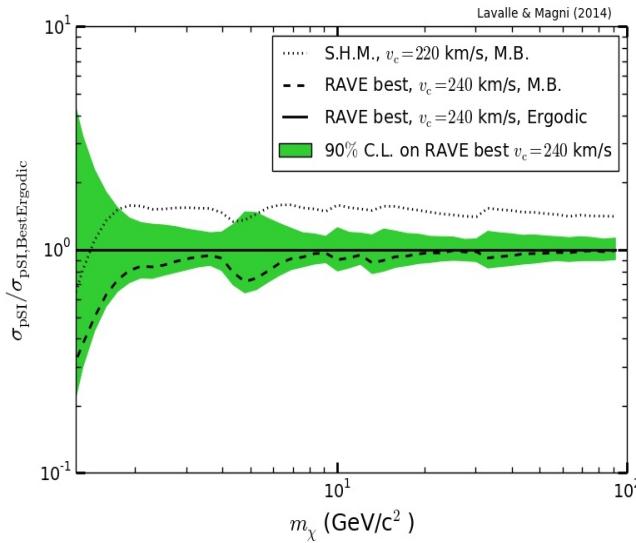
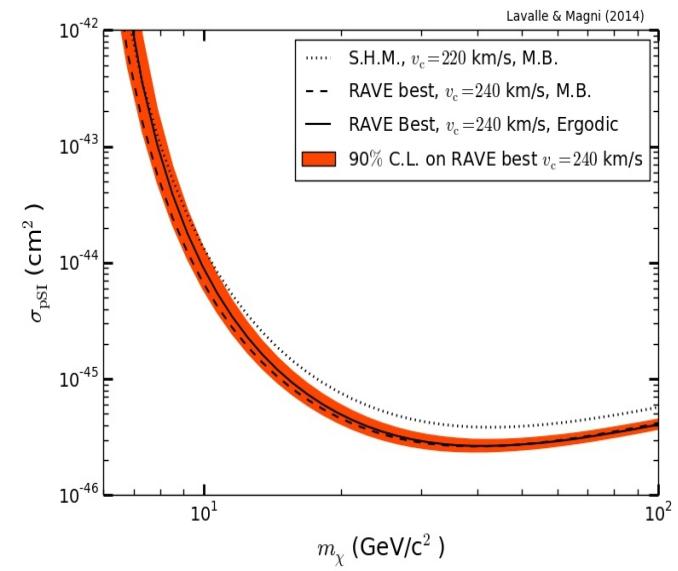
CRESST-II



SuperCDMS



LUX



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

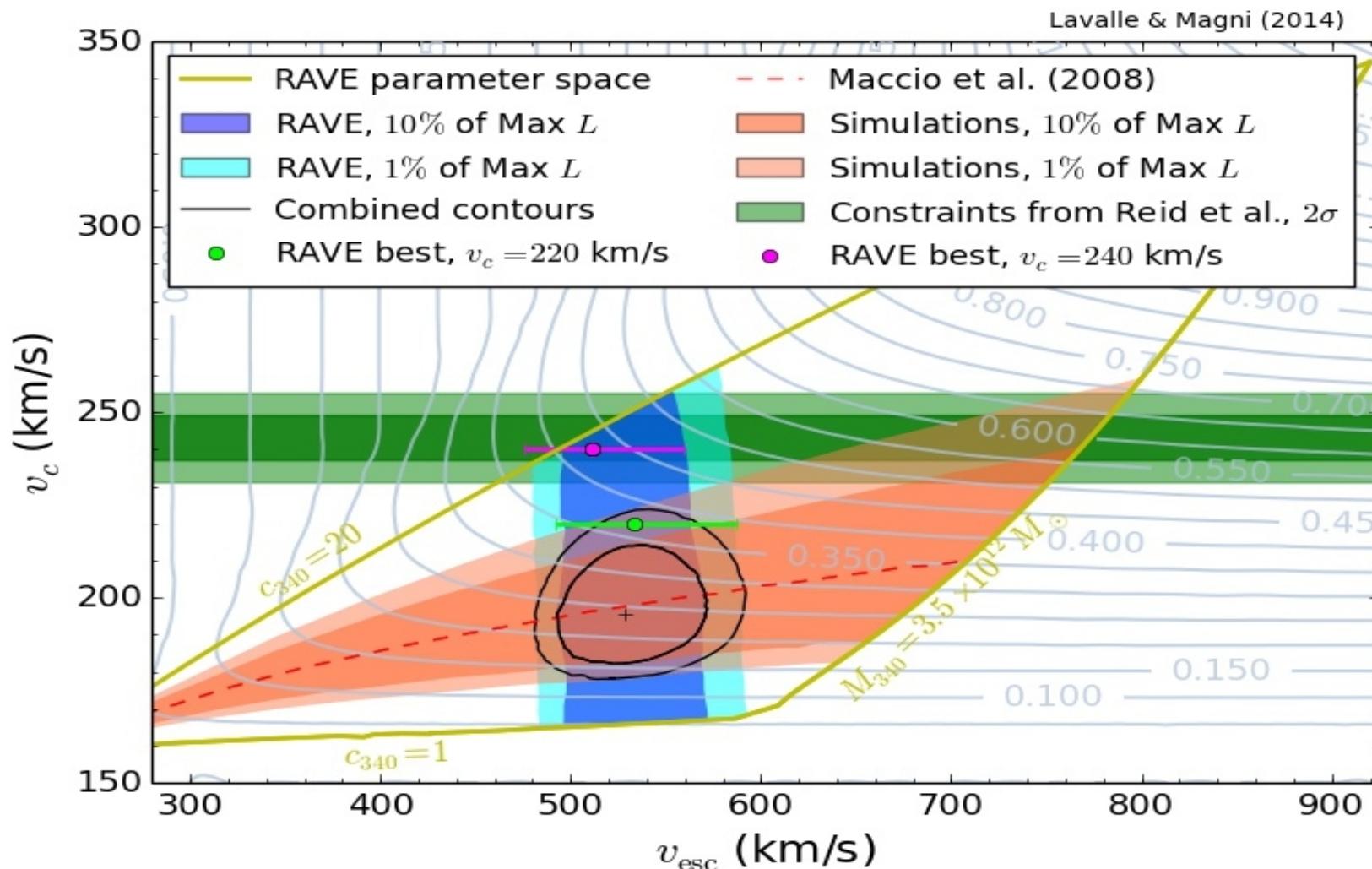
# Additional and independent constraints on the circular speed

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

(Reid et al., '14)

Additional constraints (OK within 3 sigma):

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

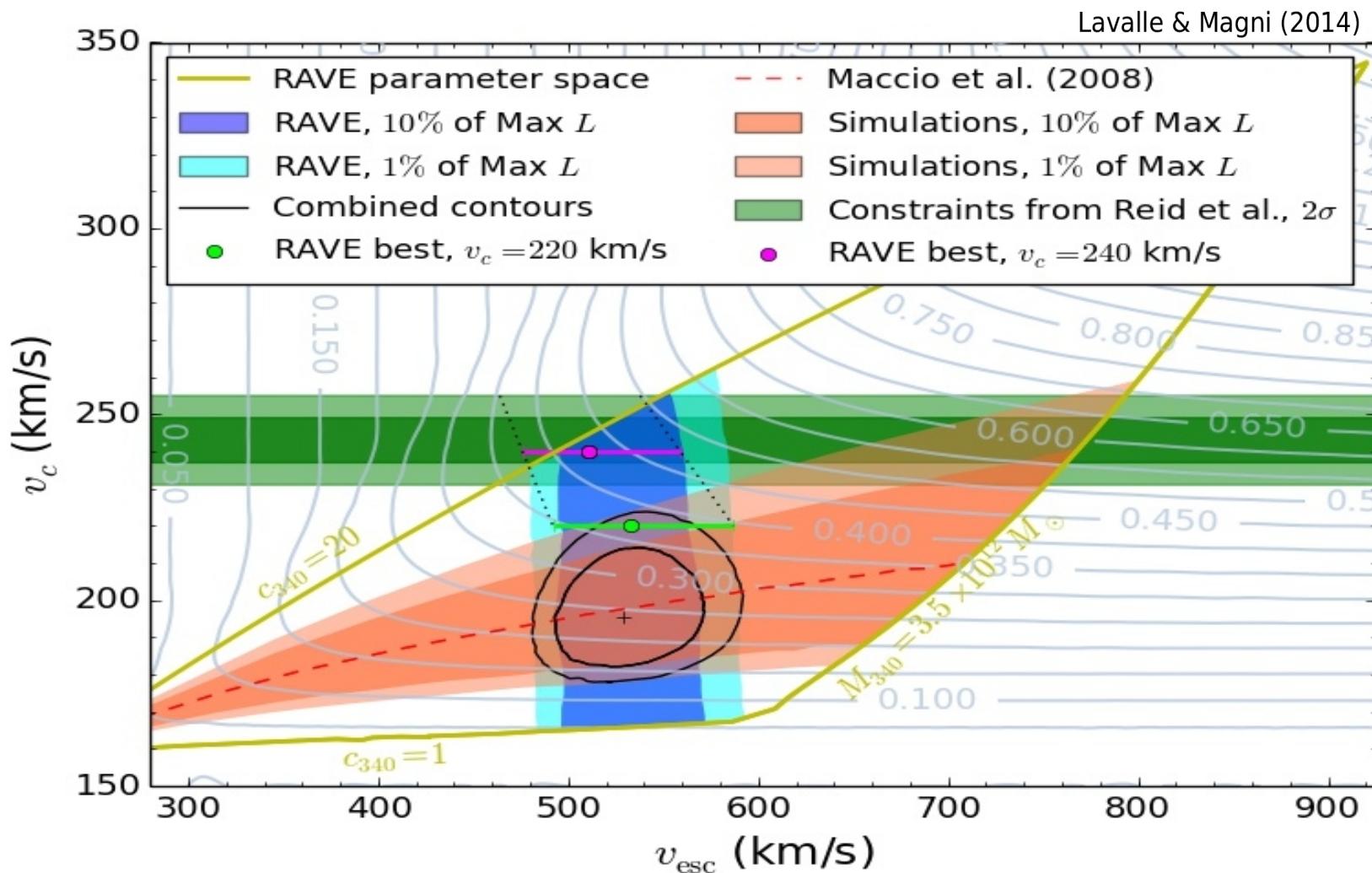


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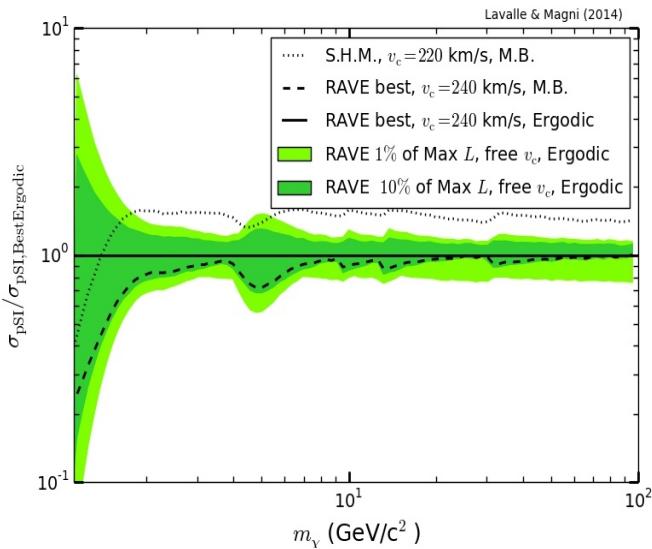
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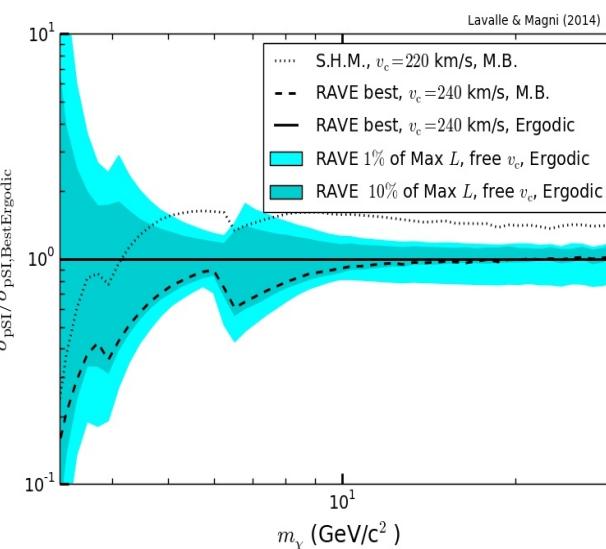


# Analysis with free circular speed vs forced correlation between circular end escape speed

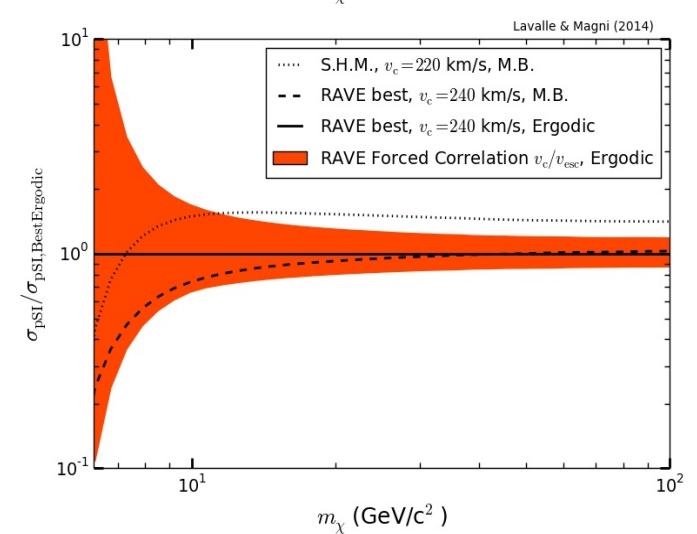
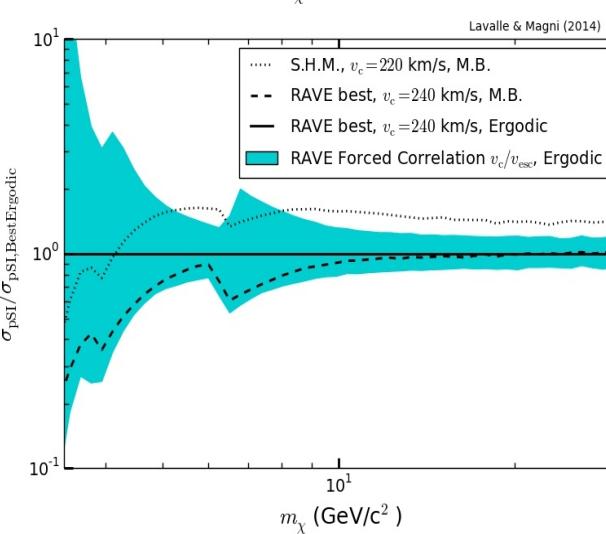
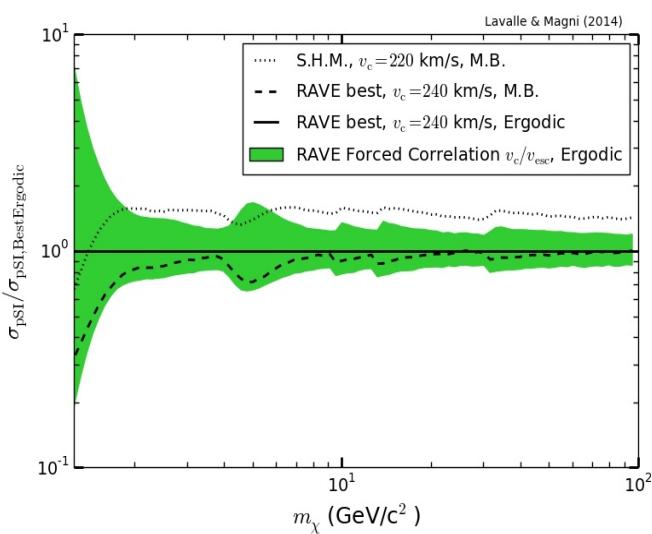
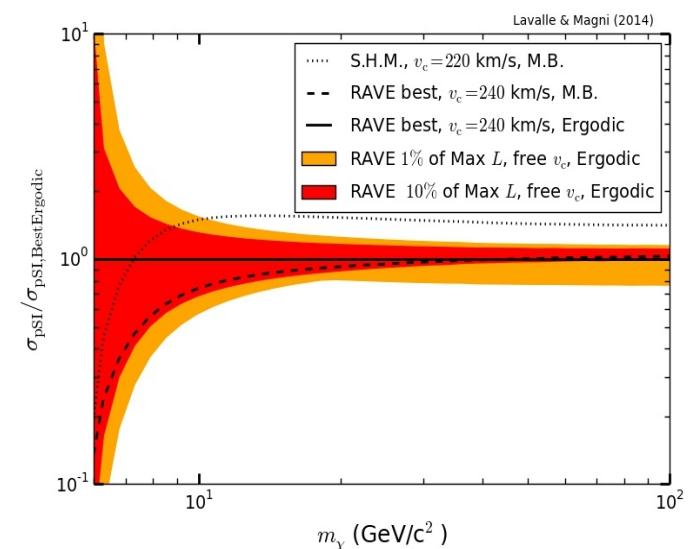
CRESST-II



SuperCDMS



LUX



- Taking into account also the  $v_{\text{esc}}, v_c$  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, Mollitor & Nezri)

Thank you very  
much for your  
attention!