Revisiting the escape speed impact on dark matter direct detection

Stefano Magni
Ph.D. Student - LUPM (Montpellier)

Based on collaborations with Julien Lavalle, paper in preparation
Outline

- Introduction
- Astrophysical parameters and uncertainties
- Insights from the escape speed after the RAVE survey
- Consistent astrophysical modeling and impact on exclusion curves
- Conclusions
Direct detection rate and exclusion curves

\[ \frac{dN}{dE_r}(E_r) = \Delta M \Delta t \frac{A^2 \sigma_{p,SI} F^2(E_r)}{2m_{\text{red}}^2} \rho_0 \int d^3 \vec{v}' \frac{1}{v'} f_{v}(|\vec{v}'| > v'_{\text{min}}(E_r)) \]

\[ v_{\text{min}}(E_r) = \sqrt{\frac{E_r m_A}{2m_{\text{red}}^2}} \]

\[ \rho_0 \eta(E_r) \]

Detector

AstroPhysics

Particle + hadronic + nuclear physics
Reference speed function: the Standard Halo Model (SHM)

Maxwell-Boltzmann speed distribution

Relies on isothermal assumption

\[
f_v(v) = 4\pi v^2 f_\nu(\vec{v}) = \frac{4v^2}{\pi^{1/2} v_0^3} e^{-\left(\frac{v^2}{v_0^2}\right)}
\]

(plus exponential cutoff at \( V_{esc} \))

Important parameters and their standard values

\[
V_{esc} = 544 \text{ km/s} \quad v_0 = 220 \text{ km/s} \quad \rho_0 = 0.3 \text{ GeV/cm}^3
\]
Impact of astrophysical parameters on exclusion curves
Astrophysical uncertainties

- Astrophysical parameters should be correlated: gravitational dynamics
- Several studies based on kinematic data + mass models: Fairbairn et al. ('12), Catena & Ullio ('12), Bozorgna et al. ('13), Fornasa & Green ('13), etc.
- We focus on the latest estimate of the escape speed (RAVE survey) which cannot be used blindly (relies on assumptions)
- We work out a consistent modeling, complementarity to kinematical studies
- Escape speed important at low WIMP masses
Why focus on the escape speed?

Several effects at work:

- Experimental threshold
- Energy resolution
- Escape speed!

Where $v > v_{\text{min}}(E_r)$

$\nu > \nu_{\text{esc}}$ (Del Nobile et al, 2014)
Escape speed from RAVE  (Piffl et al '13)

- Based on a selection of some stars from a catalog of 420000.

- Assumptions:
  - $n(v) \propto (v_{esc} - v)^k$  
    (Leonard & Tremaine '90)
  - $R_0 = 8.28 \text{ kpc}$
  - Mass model (NFW + fixed baryons)
    $$\Phi_{MW}(R, z) = \Phi_{NFW}^DM(r) + \Phi_{BAR}(R, z)$$
    - 2 free parameters

- Different analyses:
  1) likelihood analysis at fixed $v_0 = 220 \text{ km/s}$
    $$v_{esc} = 533^{+54}_{-41} \text{ km/s}$$
    (90% C.L.)

  2) analysis with same likelihood but free $v_0$

\[
p_{NFW}(r) = \frac{\delta(c) \rho_c}{r} \left(1 + \frac{r}{r_s}\right)^2
\]

\[
\rho_{NFW}(r) = \frac{\delta(c) \rho_c}{r} \left(1 + \frac{r}{r_s}\right)^2
\]

Old RAVE:  $v_{esc} = 544^{+64}_{-46} \text{ km/s}$  
(Smith et al. '07)
Reminder on mass models

Density of matter
\[ \rho(\vec{r}) = \rho_{DM}(\vec{r}) + \rho_{baryons}(\vec{r}) \]

Gravitational Potential
\[ \Phi(\vec{r}) = \Phi_{DM}(\vec{r}) + \Phi_{baryons}(\vec{r}) \]

- Local dark matter density
- Escape speed
- Circular speed

\[ \rho_0 = \rho_{DM}(\vec{r}_0) \quad v_{esc}(\vec{r}) = \sqrt{2|\Phi(\vec{r}) - \Phi(\vec{r}_{max})|} \quad v_c^2(R,0) = R \frac{\partial \Phi(R,0)}{\partial R} \]

So the correlation between \( v_0, \rho_0, R_\odot \) and \( v_{esc} \) is clear.
From RAVE's mass constraints to circular and escape speed
From RAVE's mass constraints to circular and escape speed
Impact on direct detection from uncorrelated astrophysical parameters

- $0.2 \text{ GeV/cm}^3 \leq \rho_0 \leq 0.5 \text{ GeV/cm}^3$
  \[ \text{(Bovy et al., 2012)} \]

- $29.9 \pm 1.7 \leq v_c / R_0 \leq 31.6 \pm 1.7 \text{ km s}^{-1} \text{kpc}^{-1}$
  \[ \text{(Mc Millan & Binney, 2009)} \]

$\nu_{esc}$ consistent with RAVE's second analysis
Correlating the astrophysical parameters consistently with the RAVE's results

\[ v_c(R_0) \propto f_1(\Phi(R_0)) \quad \text{and} \quad v_{esc}(R_0) \propto f_2(\Phi(R_0)) \]

functions of the mass model

Exclusion more severe

Now only \(0.374 \text{ GeV/cm}^3 \leq \rho_0 \leq 0.5 \text{ GeV/cm}^3\)

Uncertainties reduced:

(6.2 \pm 3.4) \times 10^{-45} \text{ cm}^2 \quad @ m_\chi = 10 \text{ GeV}

(4.3 \pm 0.7) \times 10^{-46} \text{ cm}^2 \quad @ m_\chi = 100 \text{ GeV}

Consistent way to use RAVE estimate of \(v_{esc}\)
Beyond Maxwell-Boltzmann: ergodic speed distribution

References: Vergados '14, Bozorgna et al. '13, etc.

- MB (where $\sigma \propto v_0$) relies on isothermal assumption
- Eddington equation

$$f(\varepsilon) = \frac{1}{\sqrt{8\pi^2}} \left[ \int_0^\varepsilon d\psi \frac{d^2\rho}{d\psi^2} \frac{1}{\sqrt{\varepsilon - \psi}} + \frac{1}{\varepsilon^{1/2}} \left( \frac{d\rho}{d\psi} \right)_{\psi=0} \right]$$

$$\psi = -\Phi_{MW}(r)$$
$$\varepsilon = -E$$
$$\rho = \rho_{NFW}(r)$$

References:
- Vergados '14
- Bozorgna et al. '13, etc.

\[\varepsilon = \frac{1}{\sqrt{8\pi^2}} \left[ \int_0^\varepsilon d\psi \frac{d^2\rho}{d\psi^2} \frac{1}{\sqrt{\varepsilon - \psi}} + \frac{1}{\varepsilon^{1/2}} \left( \frac{d\rho}{d\psi} \right)_{\psi=0} \right] \]

\[\psi = -\Phi_{MW}(r)\]

\[\varepsilon = -E\]

\[\rho = \rho_{NFW}(r)\]
Beyond Maxwell-Boltzmann - Results

- Reference values and uncertainties:
  - $\sigma_{PSI}(cm^2) = (6.9 \pm 3.7) \times 10^{-45} cm^2$ @ $m_\chi = 10 GeV$
  - $\sigma_{PSI}(cm^2) = (4.3 \pm 0.6) \times 10^{-46} cm^2$ @ $m_\chi = 100 GeV$

- Less constraining at low masses w.r.t. MB, with more uncertainties
Comparison with Germanium (used in SUPER CDMS)

\[ v_{\min}(E_r) = \sqrt{\frac{E_r m_A}{2m_{\text{red}}^2}} \]

- The exclusion curves are translated toward lower masses
- So for any given (low) \( m_\chi \) uncertainties are reduced

\[ m_{\text{Xe}} = 131.29 \text{ a.m.u.} \]
(most common isotope: \( A = 132 \))

\[ m_{\text{Ge}} = 72.63 \text{ a.m.u.} \]
(most common isotope: \( A = 74 \))
Conclusions and perspectives

- We have revisited RAVE's estimate of the escape speed
- It cannot be used blindly as it relies on assumptions
- We have converted the full information consistently into direct detection limits
  - Astro parameters correlated + Maxwell-Boltzmann + ergodic distribution
  - Stronger bounds
  - Uncertainties: $(6.9 \pm 3.7) \times 10^{-45} \text{cm}^2$ @ $m_\chi = 10 \text{GeV}$
    $(4.3 \pm 0.6) \times 10^{-46} \text{cm}^2$ @ $m_\chi = 100 \text{GeV}$
  - Complementary to kinematic methods
- RAVE's method is not free of systematic uncertainties (as the escape speed definition)
- Test the method with cosmological simulations (P. Mollitor, E. Nezri)
- Go beyond isotropic case with generalized ergodic functions