Extracting information about WIMP properties from direct detection experiments- astrophysical uncertainties

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- why?
- (theoretical) introduction to direct detection
- astrophysical input
- implications

Why?

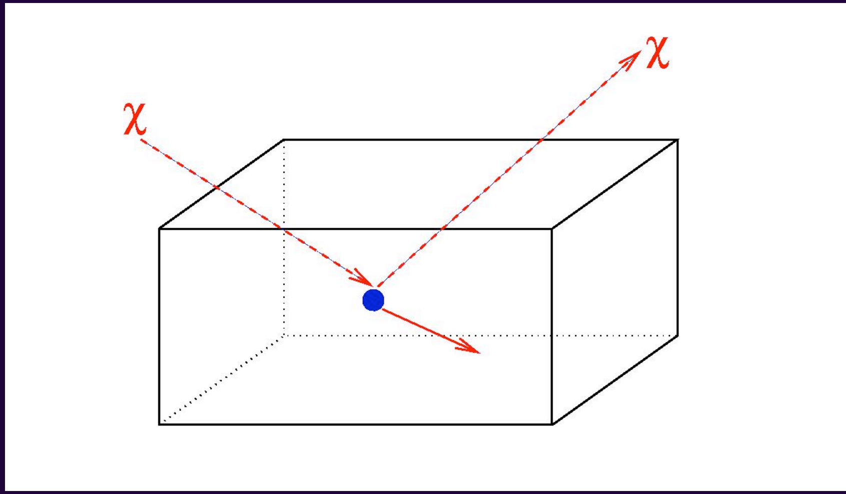
✳ (assuming WIMPs are detected....) Measuring the WIMP mass and cross-section will shed light on the particle nature of the WIMP and constrain SUSY/UED/... models

✳ Convincing WIMP discovery *may* require consistent detections (i.e. same inferred mass etc.) by multiple experiments in multiple channels (direct/indirect/collider).

Theoretical introduction to direct detection

Via elastic scattering on detector nuclei in the lab:

$$\chi + N \to \chi + N$$



Differential event rate: (per kg/day/keV)

assuming spin-independent (scalar) coupling

$$\frac{\mathrm{d}R}{\mathrm{d}E} \propto \sigma_{\mathrm{p}} \rho_\chi A^2 F^2(E) \int_{v_{\min}}^{\infty} \frac{f(v)}{v}\, \mathrm{d}v$$

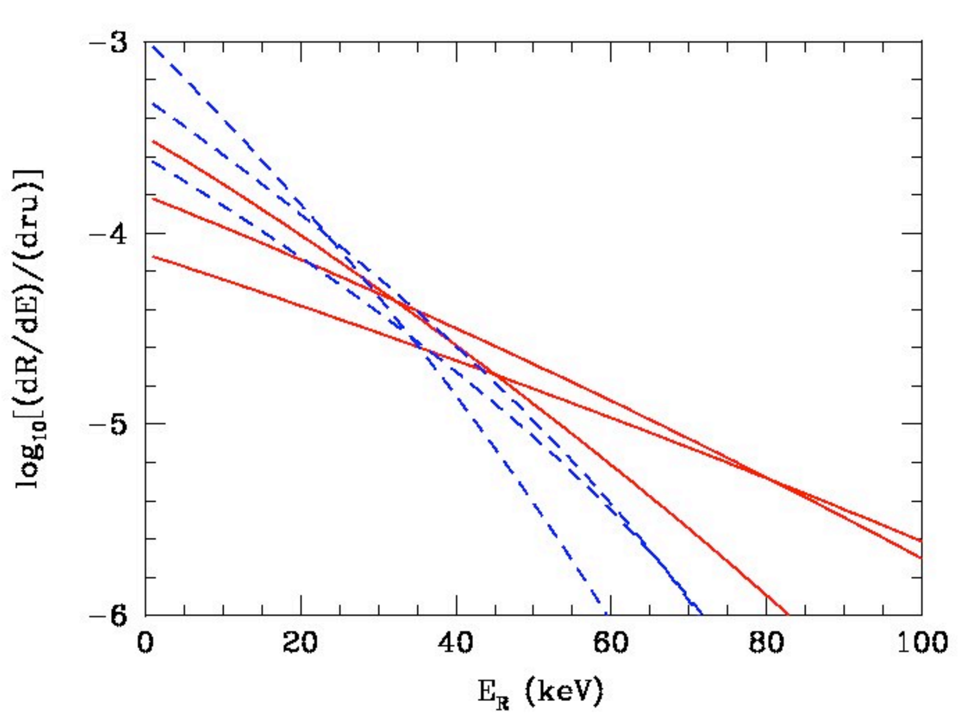
$$v_{\min} = \left(\frac{E(m_A + m_\chi)^2}{m_A m_\chi^2} \right)^{1/2}$$

Signals:

Assuming (for now) the standard halo model with an isotropic gaussian speed distribution:

$$f(v) \propto \exp\left(-\frac{v^2}{v_c^2}\right)$$

i) energy dependence of event rate Lewin & Smith



Ge and Xe m_χ = 50, 100, 200 GeV

Energy spectrum has characteristic energy:

$$E_R = \frac{2\mu_{A\chi}^2 v_c^2}{m_A}$$

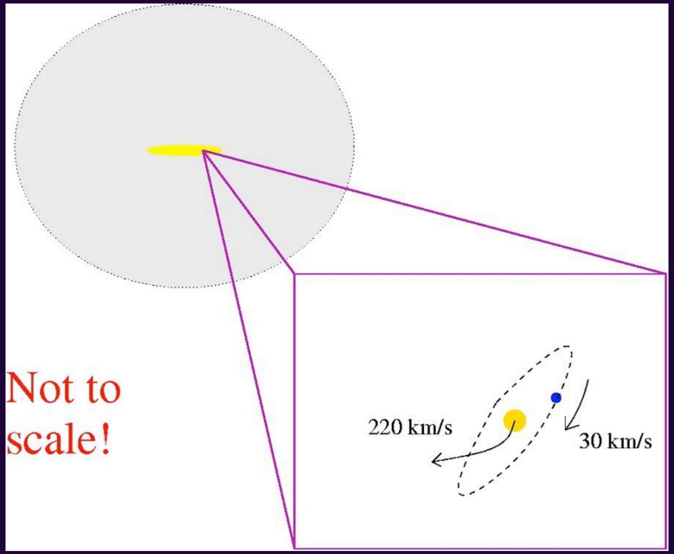
$$\propto m_\chi^2 \qquad m_\chi \ll m_A$$

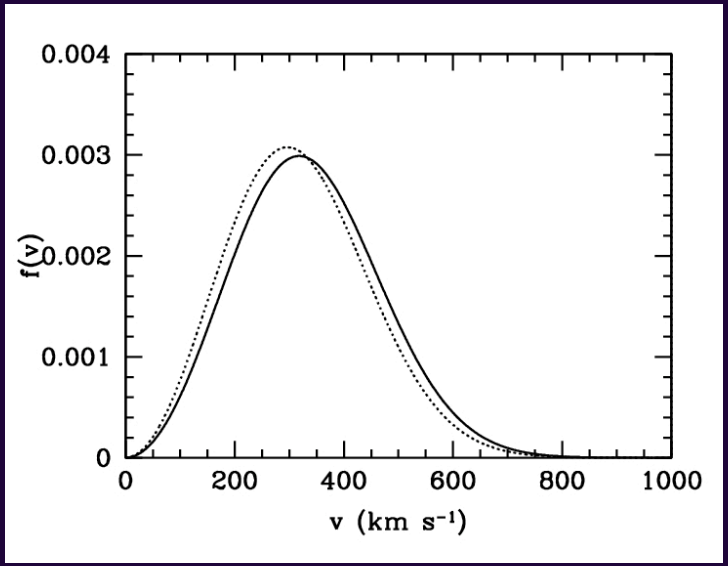
$$\sim \text{const} \qquad m_\chi \gg m_A$$

Therefore can extract measurement of WIMP mass from energy spectrum (provided WIMP mass not too large or too small)

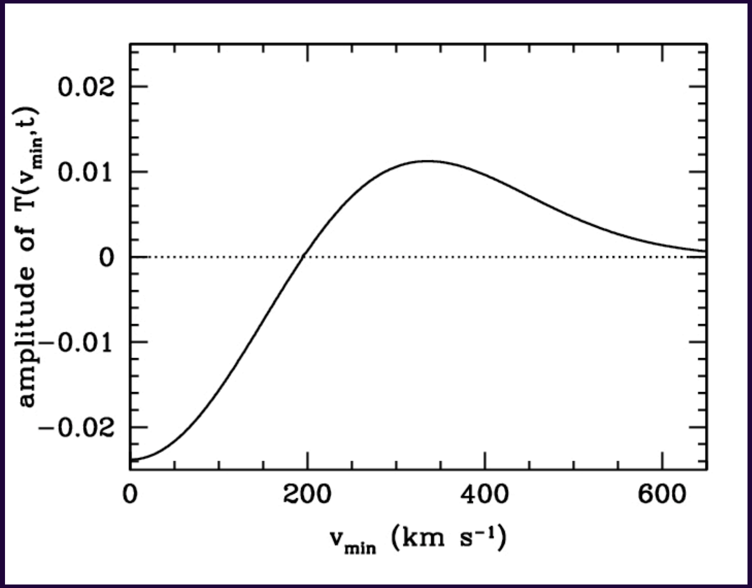
ii) annual modulation of event rate

Drukier, Freese & Spergel





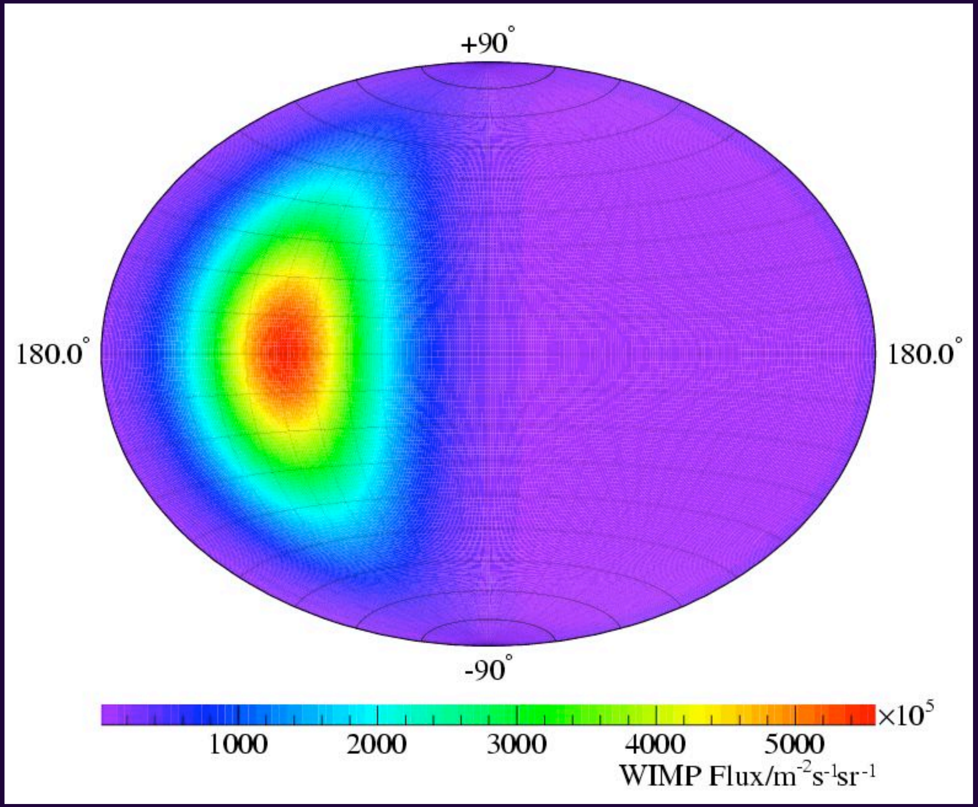
WIMP ‘standard’ (Maxwellian) speed dist. in detector rest frame (summer and winter)



modulation amplitude

Signal O(few per-cent), therefore need large exposure.

iii) direction dependence of event rate Spergel



WIMP flux

Large signal (potentially only O(10) events required [Morgan, Green & Spooner]) but need detector which can measure recoil directions, e.g. DMTPC, DRIFT, MIMAC, NEWAGE.

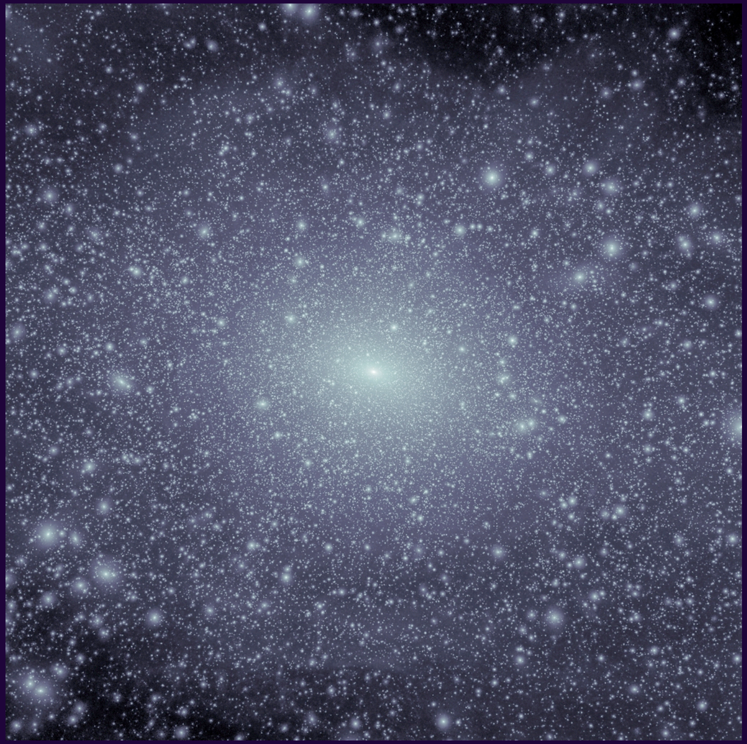
See talk by Billard this afternoon

Astrophysical input

Direct detection experiments probe the ultra-local dark matter velocity and density distribution.

Standard halo model: isothermal sphere with isotropic Maxwellian velocity distribution with local density $\rho_0 = 0.3\,\mathrm{GeV\,cm^{-3}}$

BUT "observed" and simulated halos are triaxial, anisotropic and contain substructure.



Via Lactea II, Diemand et al.

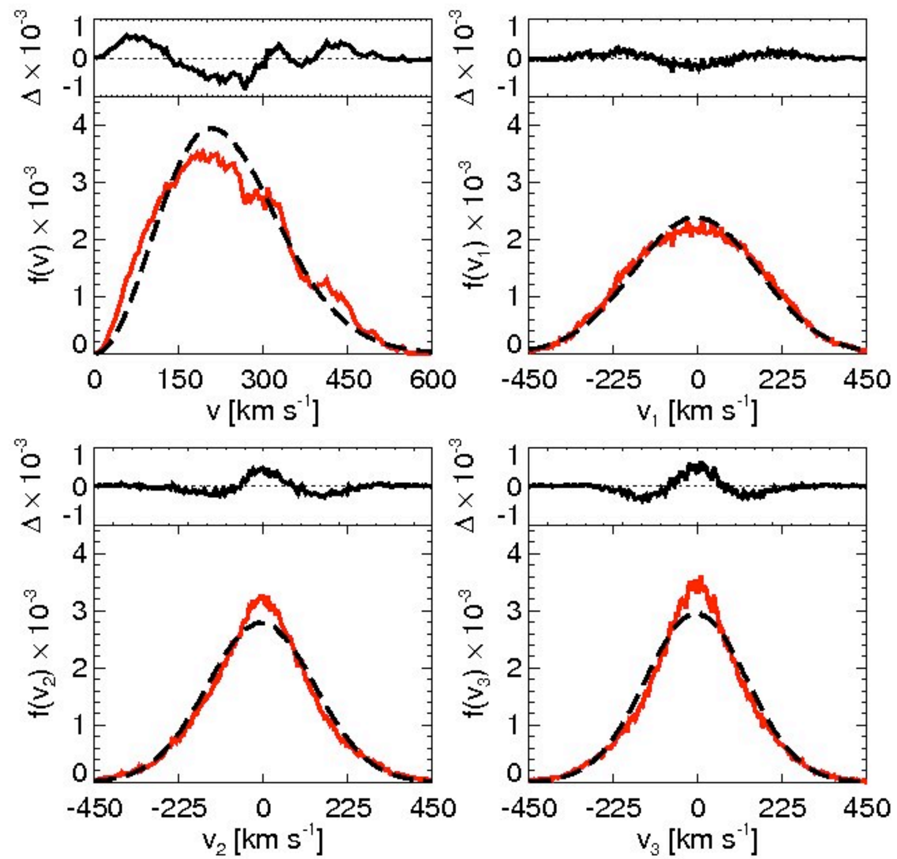
Numerical simulations:

Vogelsberger et al.:

systematic deviations from multi-variate gaussian.

including high v features.

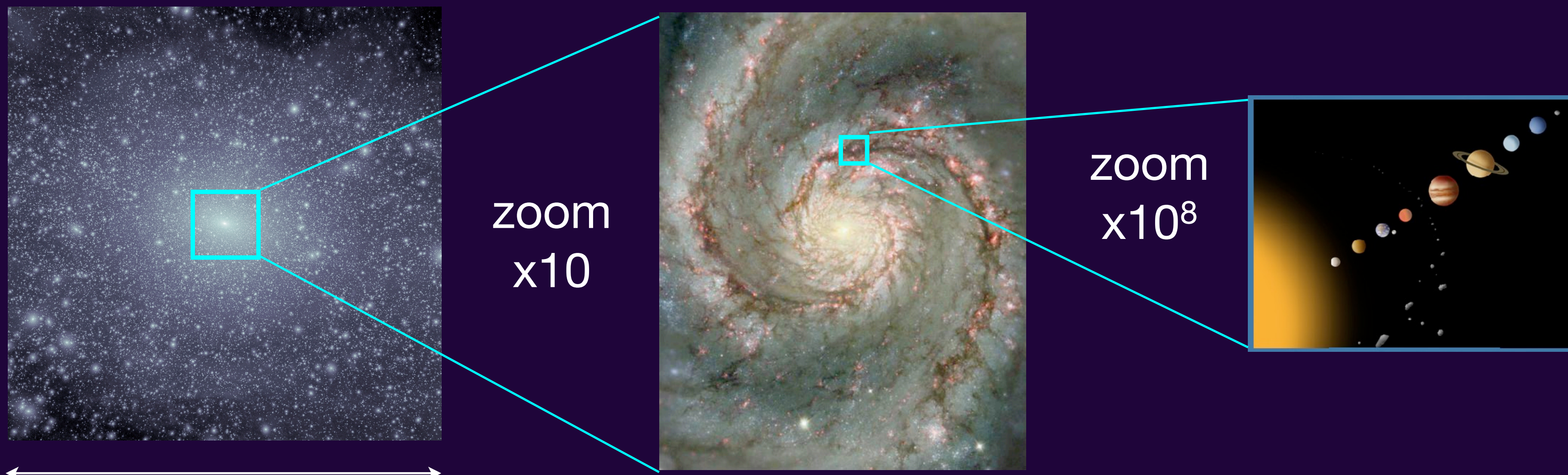
Hansen et al., Fairbairn & Schwetz and Kuhlen et al. have found similar results.



Speed distribution (top left)
+ distribution of principle components
[red lines: simulation data,
black lines: best fit multi-variate Gaussian]

Caveats:

i) scales resolved by simulations are many orders of magnitude larger than those probed by direct detection experiments



~300 kpc ~30 kpc ~0.3 mpc

Vogelsberger and White: no fine structure in ultra-local DM distribution

ii) effect of baryons on DM speed distribution?

Sub-halos merging at $z<1$ preferentially dragged towards disc, where they're destroyed leading to the formation of a rotating dark disc.

Read et al, Bruch et al., Ling et al.

Observations:

n.b. Direct detection is the only way of directly observing the ultra-local DM distribution......

Local density:

Traditionally: $\rho_0 = (0.2 - 0.8)\,\mathrm{GeV\,cm^{-3}}$

Widrow et al. using spherical halo models with a cusp ($\rho(r) \propto r^{-\alpha} \quad \mathrm{as}\ r \rightarrow 0$):

$$\rho_0 = (0.3 \pm 0.05)\,\mathrm{GeV\,cm^{-3}}$$

Catena & Ullio using NFW & Einasto profiles (motivated by simulations)

$$\rho_0 = (0.39 \pm 0.03)\,\mathrm{GeV\,cm^{-3}}$$

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Local circular speed:

closely related to local velocity dispersion

Traditionally: $v_c(R_0) = (220 \pm 20)\,\mathrm{km\,s^{-1}}$

In past year:

$(254 \pm 16)\,\mathrm{km\,s^{-1}}$	$(200 - 280)\,\mathrm{km\,s^{-1}}$	$(236 \pm 11)\,\mathrm{km\,s^{-1}}$
Reid et al.	McMillan & Binney	Bovy et al.

Implications

constraints on/measurements of σ

$$\frac{\mathrm{d}R}{\mathrm{d}E} \propto \sigma_{\mathrm{p}} \rho_{\chi} A^2 F^2(E) \int_{v_{\mathrm{min}}}^{\infty} \frac{f(v)}{v} \, \mathrm{d}v$$

Event rate proportional to product of σ and ρ, therefore uncertainties in ρ translate directly into uncertainties in σ.

time (and direction) averaged differential event rate

$$\frac{\mathrm{d}R}{\mathrm{d}E} \propto \sigma_{\mathrm{p}} \rho_{\chi} A^2 F^2(E) \int_{v_{\mathrm{min}}}^{\infty} \frac{f(v)}{v} \, \mathrm{d}v \qquad v_{\mathrm{min}} = \left(\frac{E(m_A + m_{\chi})^2}{m_A m_{\chi}^2} \right)^{1/2}$$

Uncertainty in velocity dispersion (local circular velocity) is most important.

Characteristic energy depends on this and the WIMP mass:

$$\frac{\Delta m_{\chi}}{m_{\chi}} = [1 + (m_{\chi}/m_A)] \frac{\Delta v_{\mathrm{c}}}{v_{\mathrm{c}}}$$

Effect of changing *shape* of speed distribution:

Relatively small since energy spectrum proportional to integral over speed distribution. [Unless experiment is only sensitive to high speed tail of speed distribution (i.e. if WIMP is light or threshold energy is high).]

<5% systematic uncertainty in WIMP mass determination [Green].

With multiple detectors/target nuclei could in principle measure WIMP mass without any assumptions about the speed distribution [Drees & Shan].

annual modulation

Arises from small shift in lab speed distribution between Summer and Winter, therefore far more sensitive to detailed WIMP velocity distribution (amplitude, phase & even shape can change).

e.g. region of WIMP mass-cross-section parameter space corresponding to DAMA annual modulation signal changes significantly if ‘non-standard’ halo models are considered.

[various authors]

direction dependence

Rear-front asymmetry robust.

Peak/median recoil direction of high energy recoils may deviate somewhat from direction of solar motion. [Kuhlen et al.]

With sufficient data could reconstruct WIMP velocity distribution.

[Gondolo]

Future directions:

Strigari & Trotta

use data (kinematics of MW halo stars and measurements of local escape speed) and model for MW mass distribution in MCMC likelihood analysis of direct detection data.

Peter

combine data sets from different direct detection experiments and jointly constrain WIMP parameters (mass & cross-section) and parameterisation of WIMP speed distribution.

Summary

✳ Energy, time and direction dependence of event rate depend on ultra-local dark matter distribution.

✳ Deviations from ‘standard halo model’ expected:

uncertainty in local DM density → uncertainty in event rate and hence cross-section

uncertainty in local circular density (WIMP velocity dispersion) → uncertainty in characteristic scale of energy spectrum and hence WIMP mass

uncertainty in shape of WIMP velocity dispersion → uncertainty in amplitude and phase of annual modulation signal and hence WIMP parameters

✳ (potential) solution: jointly constrain astrophysical and WIMP parameters (need reliable/robust model for Milky Way).

✳ In long term could **measure** ultra-local DM distribution using direct detection experiments.