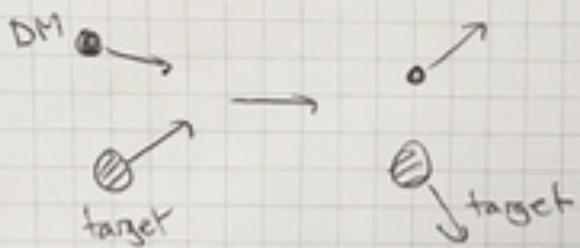
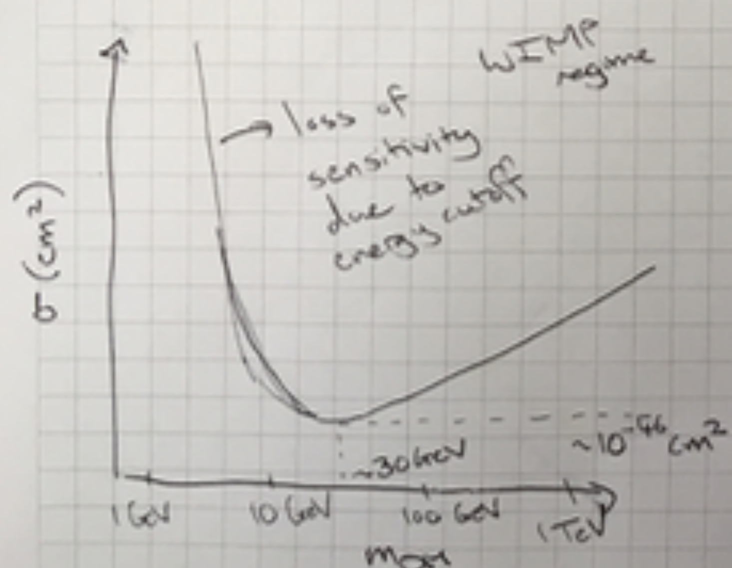
Terrestrial searches for DM

- Searches for particles scattering off targets ("direct detection")
- " " exotic fields oscillating into E/B-fields (ALPs)
- Collider searches
- Also "dark photon" searches – see Cosmic Visions report 1707.04591

Principles of direct detection



- observe recoil of target (nucleus, electron) via e.g. ionization, phonons, scintillation, excitation, etc
- experiments are typically underground + heavily shielded to reduce backgrounds (+ also cooled to low temperatures)
- in principle signal is both directional & time-dependent
  - due to motion of Sun through galaxy, DM has preferred direction ("WIMP wind"), which varies over 1 day period
  - due to motion of Earth around Sun, DM flux is enhanced when Earth + Sun move in same direction relative to DM wind, suppressed when opposite is true – annual modulation



1705.06655 XenonIT

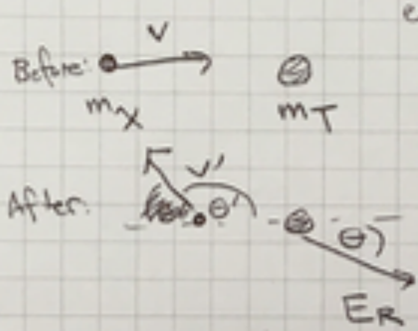
Consider DM of mass m_χ, target of mass m_T (at rest in lab frame)

Want to calculate $\dfrac{dR}{dE_R}$

scattering rate

recoil energy

Kinematics:



$$\frac{1}{2}m_\chi v^2 = \frac{1}{2}m_\chi v'^2 + E_R,$$ assuming elastic scattering

$$m_\chi v = m_\chi v'\cos\theta' + \sqrt{2m_T E_R}\cos\theta$$

$$0 = m_\chi v'\sin\theta' + \sqrt{2m_T E_R}\sin\theta$$

Eliminating v' & θ', some algebra gives:

$$E_R = \frac{2\mu^2 v^2\cos^2\theta}{m_T}, \quad \mu = \frac{m_T m_\chi}{m_\chi + m_T}$$

(Note: $(m_\chi v + \sqrt{2m_T E_R}\cos\theta)^2 + 2m_T E_R\sin^2\theta = m_\chi^2 v'^2 (\cos^2\theta' + \sin^2\theta')$

$= m_\chi^2 v'^2$

$= 2m_\chi \times (\frac{1}{2}m_\chi v^2 - E_R)$

$\Rightarrow \cancel{m_\chi^2 v^2} + 2m_T E_R + 2m_\chi v\sqrt{2m_T E_R}\cos\theta = \cancel{m_\chi^2 v^2} - 2m_\chi E_R$

$E_R(m_\chi + m_T) = m_\chi v\cos\theta\sqrt{2m_T E_R}$

$\Rightarrow \sqrt{E_R} = -\dfrac{m_\chi}{m_\chi + m_T} v\cos\theta\sqrt{2m_T}$

$\Rightarrow E_R = 2\cos^2\theta \dfrac{v^2 m_\chi^2 m_T}{(m_\chi + m_T)^2}$

Spectrum extends from $E_R = 0$ to $E_R = \dfrac{2\mu^2 v^2}{m_T}$

At a given recoil energy E_R, only particles w/ $v > v_{min} = \sqrt{m_T E_R / 2\mu^2}$ can contribute.

Estimate for WIMP range: take target to be nucleus, $m_T \sim 10-100$ GeV, & assume $m_\chi \gtrsim m_T$, so $\mu \approx m_T$. Then typical $E_R \sim \dfrac{\mu^2 v^2}{m_T} \sim v^2 \times (10-100\,\text{GeV}) \sim 10-100$ keV for $\frac{v}{c} \sim 10^{-3}$ (typical halo velocity)

What if $m_\chi \ll m_T$, as in case of light DM? Then $\mu \simeq m_\chi$,

$$E_R \sim \left(\frac{m_\chi}{m_T}\right)^2 \cdot v^2 m_T \sim \left(\frac{m_\chi}{m_T}\right)^2 \times (10\text{-}100\ \text{keV})$$

WIMP-search experiments are typically sensitive to recoils in this 10-100 keV range - lose sensitivity fast for $m_\chi \ll m_T$ (this way)

Detecting light DM requires light targets & low energy thresholds.

What about spectrum? rate?

amplitude for scattering on individual nucleons (fn of v & E_R)

- how does DM couple to quarks/gluons? (particle)
- what is quark/gluon content of nucleons? (nuclear)

- how do nucleon amplitudes interfere? are they spin-dependent?

amplitude for scattering on nucleus

- nuclear form factor (standard to take simple "Helm form factor")

- what is # density of DM? (standard assumption: take $\rho = 0.3\text{-}0.4\ \text{GeV/cm}^3$)
- what is velocity of DM? (distribution) (standard halo model assume Maxwellian distribution)

$$f(v) = \frac{4}{\sqrt{\pi}} \frac{1}{v_0^3} v^2 e^{-v^2/v_0^2}$$

scattering rate

Standard simplifications: assume DM couplings to protons & neutrons described by numbers f_n, f_p; do not depend on velocity/momentum transfer, scattering angle, etc. Often also assume $f_n = f_p$.

Consider 2 cases, spin-independent nucleon amplitudes add coherently, rate $\propto$ (atomic mass)^2 and spin-dependent amplitudes from paired nucleons cancel, rate scales as (total spin)^2.

Often "exotic" or "non-standard" DM models just change 1 or more of these assumptions; can substantially change relative sensitivity of different expts

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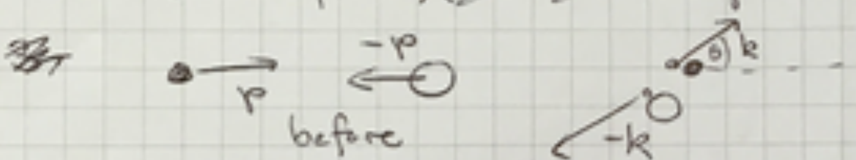
Spectrum calculation (std. case):

Go to COM frame, ~~(will later) scattering xsec is assume independence of scattering angle in this frame for simple models~~



$|\vec{k}| = |\vec{p}| = \mu v_{rel}$ ↳ relative velocity

3-momentum transfer $q^2 = |\vec{p} - \vec{k}|^2 = 2\mu^2 v_{rel}^2 (1 - \cos\theta) = 2 m_T E_R$ ↳ lab-frame recoil energy

$$\Rightarrow E_R = \frac{\mu^2 v_{rel}^2}{m_T}(1 - \cos\theta)$$

↳ COM frame scattering angle

$$\frac{dR}{dE_R} = \frac{m_T}{\mu^2 v_{rel}^2} \frac{dR}{d(\cos\theta)}$$

$$= \frac{2\pi m_T}{\mu^2 v_{rel}^2} \frac{dR}{d\Omega}$$ assuming no dependence on ϕ

↳ COM-frame solid angle

Now $\frac{dR}{d\Omega}$ = differential rate, related to differential xsec by

$$\frac{dR}{d\Omega} = n_\chi N_T v_{rel} \frac{d\sigma}{d\Omega} \Rightarrow \frac{dR}{dE_R} = \frac{2\pi \left(\frac{\rho_\chi}{m_\chi}\right) m_T N_T}{\mu^2 v_{rel}} \frac{d\sigma}{d\Omega}$$

n_χ ↳ DM no. density

N_T ↳ # of target nuclei

Now $\left.\frac{d\sigma}{d\Omega}\right|_{COM} = \underbrace{\frac{\mu^2}{m_\chi^2 m_T^2}}_{= \frac{1}{(m_\chi+m_T)^2} = \frac{1}{s}} \frac{1}{64\pi^2} |\mathcal{M}|^2$

$\hookrightarrow$ matrix element for scattering on nucleus

Assuming spin-independent scattering, contributions from nucleons add coherently,

$\mathcal{M} = \mathcal{F}(q) \left[Z f_p + (A-Z) f_n \right]$

$\hookrightarrow$ form factor

$$\Rightarrow \frac{dR}{dE_R} = \frac{\rho_\chi}{v_{rel}\, m_\chi^3} \times \frac{1}{32\pi} \times \frac{N_T}{m_T} \left|\mathcal{F}\left(q = \sqrt{2 m_T E_R}\right)\right|^2 \left| Z f_p + (A-Z) f_n \right|^2$$

$\downarrow$ write as $\mathcal{F}(E_R)$ later

Let's define an effective "single-nucleon" cross section, which is what's actually plotted:

$$\sigma_{\chi n} = \left.\sigma_{\cancel{\chi T}}\right|_{q=0} \frac{\mu_{\chi n}^2}{\mu^2} \frac{1}{A^2}$$

$$= \frac{1}{16\pi} \frac{\mu_{\chi n}^2}{m_\chi^2 m_T^2} \frac{\left| Z f_p + (A-Z) f_n \right|^2}{A^2}$$

Assume $\frac{d\sigma}{d\Omega}$ independent of θ, ϕ

(i.e f_n, f_p independent of θ, ϕ)

Write observable spectrum as:

$$\frac{dR}{dE_R} = \underbrace{\frac{\sigma_{\chi n}}{m_\chi \mu_{\chi n}^2}}_{\text{particle physics}} \overbrace{A^2 m_T N_T}^{\text{target}} \underbrace{\frac{\rho_\chi}{2 v_{rel}}}_{\text{DM density / velocity}} \overbrace{|\mathcal{F}(E_R)|^2}^{\text{target}}$$

"nuclear physics"

"astrophysics"

This assumes we know v_{rel}, but really DM has distribution of velocities - need to integrate over it. Write $\frac{d\rho_X}{dv_{rel}} = \rho_X\, f(v_{rel})$, where $\int_0^\infty f(v_{rel})\, dv_{rel} = 1$

ρ_X ↳ overall density

Then

$$\frac{dR}{dE_R} = \underbrace{A^2 m_T N_T |F(E_R)|^2}_{\text{target}} \times \underbrace{\frac{\sigma_{Xn}}{2 m_X \mu_{Xn}^2}}_{\substack{\text{DM} \\ \text{particle physics}}} \times \underbrace{\rho_X \int_{v_{min}} dv \, \frac{1}{v} f(v)}_{\text{astrophysics}}$$

suppresses signal at sufficiently high recoil energies

v_{min} depends on E_R as previously - sets spectral shape

$$v_{min} = \sqrt{\frac{m_T E_R}{2\mu^2}}$$

Simple example: take $f(v) = \frac{4}{\sqrt{\pi}} \frac{1}{v_0^3} v^2 e^{-v^2/v_0^2}$

(in reality, will cut off when $v >$ escape velocity of MW)

Then $\int_{v_{min}} dv \, \frac{1}{v} f(v) \longrightarrow \frac{2}{\sqrt{\pi}} \frac{1}{v_0} e^{-E_R m_T / 2\mu^2 v_0^2}$

exponentially falling spectrum

More generally, as E_R increases v_{min} increases, & integrand is ≥ 0, so spectrum is always monotonically decreasing w/ E_R.

Low-energy sensitivity is critical, especially for light WIMPs! (μ small)

Many really interesting ideas for light-WIMP searches aside from nuclear recoils - ask me for references!

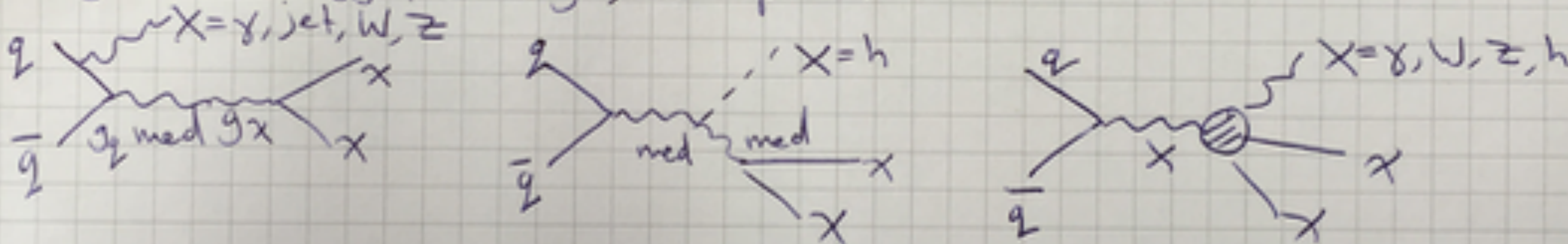
LHC searches

If DM is produced at LHC, it is stable - will escape detector.

Should show up as missing energy/momentum

Most DM searches at LHC are "mono-X" - look for visible partner recoiling off invisible DM (doesn't fundamentally need to be "mono" - could be more than one vis. particle)

e.g mono-Higgs, mono-jet, mono-photon



In particular model classes may be other searches - e.g DM bound states, if they exist, can form resonances that decay to SM particles. For wino, higgsino DM, $\exists$ charged partner particles, can search for those.

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Could occur via radiation from SM side of interaction, or by production of "partners" which decay into WIMP+SM particles

Two broad approaches

(1) Construct UV-complete models w/ full spectrum (e.g SUSY model), search for resulting signatures
 - often Many non-DM particles, can lead to striking effects
 - In SUSY, all SUSY ptcles decay to DM eventually - cascades producing many particles, w/ large MET
 - But not easy to translate constraints between models, searches not model-independent - hard to interpret outside that specific model

(2) Construct simplified model w/ only a few ingredients, develop generic searches
 - Easy to translate to many models, reduce risk of missing signal due to too-narrow search
 - But sometimes extra ingredients are key! No guarantee simplified model can be embedded into reasonable high-energy theory.

Example: DM $\underset{g_\chi}{\text{———}}$ heavy mediator $\underset{g_q}{\text{—}}$ quarks

Can consider different possibilities for mediator - vector, axial vector, scalar, pseudoscalar