ELEMENTARY PARTICLE PHYSICS
Current Topics in Particle Physics
Laurea Magistrale in Fisica,
curriculum Fisica Nucleare e Subnucleare
Lecture 11

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Preliminaries

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Bibliography

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- *The Particle Detector Brief Book*,(BB)
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Specific bibliography is given in each lecture

Lecture Contents - 1 part

1. Introduction. Lep Legacy
2. Proton Structure
3. Hard interactions of quarks and gluons: Introduction to LHC Physics
4. Collider phenomenolgy
5. The machine LHC
6. Inelastic cros section pp
7. W and Z Physics at LHC
8. Top Physics: Inclusive and Differential cross section $t\bar{t}$ W, $t\bar{t}$ Z
9. Top Physics: quark top mass, single top production
10. Dark matter
    - Indirect searches
    - Direct searches

Specific Bibliography

♠ Bibliography of this Lecture

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  The Review of Particle Physics (2017) C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update. (PDG-Rev-Cosmo) rpp2016-rev-cosmological
- M. Drees and G. Gerbier *Dark Matter*
  The Review of Particle Physics (2017) C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update. (PDG-Rev-dark) rpp2016-rev-dark-matter
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Contents

Our dark halo

Direct detection of WIMPs

Billions of WIMPs may be passing through the Earth each second, but they very rarely interact.

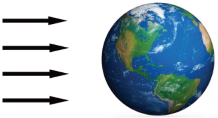


Figure : Schematic

Direct detection experiments operate underground and search for WIMPs via their scattering with atomic nuclei in the detector.

- WIMP **velocity $\sim 10^{-3}$c** $\Longrightarrow$ **non-realtivistic**
- Expected **recoil energies $\sim$ 10 keV**
- Expected **$<$ 1 event/kg/year**

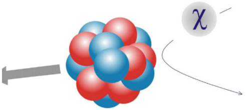
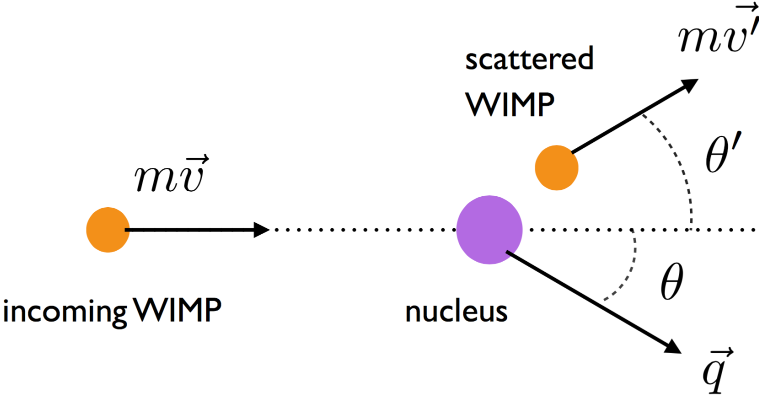


Figure : Schematic

- WIMP-nucleus **elastic collision**

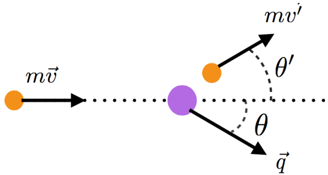


m : mass of WIMP

M : mass of nucleus

WIMP-nucleus interaction

- Energy-momentum conservation



$$
\begin{aligned}
\frac{1}{2}mv^2 &= \frac{1}{2}mv'^2 + \frac{q^2}{2M} \\
mv'\cos\theta' &= mv - q\cos\theta \\
mv'\sin\theta' &= q\sin\theta
\end{aligned}
$$

- Eliminate θ' and v'

$$q = 2\mu v\cos\theta \qquad \boldsymbol{\mu = \frac{mM}{m+M}}$$ **Reduced mass**

WIMP-nuceus interaction

$$q = 2\mu v \cos\theta$$

- Magnitude of recoil momentum varies in the range:

$$0 \leq q \leq q_{\rm max} \equiv 2\mu v \qquad E_{\rm max} \equiv \frac{2\mu^2 v^2}{M}$$

- Minimum WIMP speed required to produce a recoil energy E:

$$\boxed{v_m = \frac{q}{2\mu} = \sqrt{\frac{ME}{2\mu^2}}}$$

The expected event rate

- The **strongly simplified expected event rate** :

$$R \propto N\Phi_\chi\sigma$$

  - N = number of target nuclei in the detector,
  - Φ_χ = flux of WIMPs,
  - σ = WIMP-nucleus cross section

- $$\Phi_\chi = n < v >$$

  - n : WIMP number density $n = \frac{\rho}{m}$, ρ local DM mass density
  - $< v >$:average WIMP velocity with respect to the detector

The expected event rate

- Let's estimate the expected flux of WIMPs on Earth assuming:

$$\rho \;=\; 0.3\; GeV/cm^3,\; <v> =\; 220\; km/s,\; m \;=\; 100\;\; \text{GeV}$$

$$\Phi_\chi \;=\; \frac{\rho}{m} \times <v> =\; 6.6 \cdot 10^4 cm^{-2} s^{-1}$$

- The **flux is large enough** that even though WIMPs are weakly interacting, we would have a small but blue **potentially measurable rate** in direct detection experiments.

The expected event rate

- Strongly semplified **event rate per unit detector mass**, assuming[1] :

$$\sigma = 10^{-38} cm^2, M = 100 GeV$$
$$R = \frac{N}{NM} \Phi_\chi \sigma \sim 0.12 \text{ events/kg/yr}$$

  - M = number of nuclei in the detector
  - NM = detector mass

- More realistic and proper calculation of the event rate are necessary.

[1] $1kg = 15.6 \cdot 10^{26}$ GeV, Xenon atom weight $2.1810 \cdot 10^{-22} g$.

The differential event rate

- To find the differential event rate, we need the following ingredients:
  - WIMP-nucleus scattering cross section which describes the interaction of a WIMP with the nucleus. **(particle physics input)**
  - Local DM density and velocity distribution in the detector reference frame **(astrophysics input)**.

The differential event rate

- The differential event rate per unit detector mass is determined from differential cross section[2]

$$\boxed{\frac{d\sigma}{dE}}$$

- Multiply the number N of the nuclei in the detector. Divide by the detector mass MN.
- Multiply the flux of WIMPs with velcity $\vec{v}$ in the velocity space elment d^3v:

$$nvf(\vec{v})d^3v, \qquad n = \frac{\rho}{m}$$

- $f(\vec{v})$ WIMP velocity distribution in the *detector reference frame.*

[2] $R = \frac{N}{NM}\Phi_\chi\sigma$ and $\Phi_\chi = \frac{\rho}{m}\times < v >$

The differential event rate

The differential event rate per unit detector mass [3]:

$$\frac{dR}{dE} = \frac{\rho}{m}\frac{1}{M}\int_{v>v_m} d^3v \frac{d\sigma}{dE} v f(\vec{v})$$

Recap: Many **unknowns** enter in event rate:

- R, expected event rate
- E, recoil energy of detector nucleus
- $\frac{\rho}{m}$ DM number (ρ=DM density, m = DM mass)
- v ,DM speed
- v_m, minimum DM speed required to produce a recoil energy E
- $f(\vec{v})$, DM velocity distribution in the *detector reference frame.*
- σ, DM-nucleus scattering cross section

[3] The divided by M

Particle physics input: cross section

The differential cross section

The WIMP-nucleus differential cross section encodes how DM interacts with ordinary matter:

- **WIMP-quark interaction:**strongly depends on the DM model, and is calculated in terms of an effective Lagrangian which describes the interaction of the WIMP candidate with quarks and gluons.
- **WIMP-nucleon cross section:**calculated using hadronic matrix elements which describe the nucleon content in quarks and gluons$\Longrightarrow$ *subject to large uncertainties.*
- **Total WIMP-nucleus cross section:**calculated by adding the spin and scalar components of nucleons.

The differential cross section

- The standard theoretical framework assumed for **direct detection experiments** is inspired by models of **supersymmetric DM**.
- It assumes interactions mediated by heavy particles (i.e. *contact interactions*), and includes only the **leading-order interactions in the non-relativistic limit**.

The differential cross section

- Differential **WIMP-nucleus scattering cross section** for standard contact interactions:

$$\frac{d\sigma}{dE} = \frac{\sigma_0}{E_{\max}} F^2(E) = \frac{M}{2\mu^2 v^2} \sigma_0 F^2(E)$$

- σ_0: total scattering section with point-like nucleus.
- $F^2(E)$: nuclear form factor (normalized to 1); takes into account the finite size of the nucleus and encode the dependence e on momentum transfer ($q = \sqrt{2ME}$).

The differential cross section

- When momentum transfer is small, the DM doesn't probe the size of the nucleus and coherently scatters off the entire nucleus:

$$F^2(E) \to 1$$

- As momentum transfer increases, the DM becomes sensitive to the spatial structure of the nucleus:

$$F^2(E) < 1$$

- The effect is strong for heavy target nuclei. $\Longrightarrow$ **Event rate suppression**.

The differential cross section

Two relevant contributions to the cross section:

- **Spin-independent (SI)**: coherent interaction of the WIMP with all nucleons; no dependence on nuclear spin.
- **Spin-dependent (SD)**: the WIMP interacts with the spin of the nucleus.

Considering both spin-independent and spin-dependent WIMP-nucleus interactions in the non-relativistic limit:

$$\frac{d\sigma}{dE} = \frac{M}{2\mu^2 v^2}\left[\sigma_0^{SI} F_{SI}^2 + \sigma_0^{SD} F_{SD}^2\right]$$

Spin-independent interaction

- The SI contribution to the cross section can arise from scalar couplings of DM to quarks, which occurs through the operator $(\bar{\chi}\chi)(\bar{q}q)$
- For a WIMP with scalar interactions, the SI **WIMP-nucleus** cross section is:

$$\sigma_0^{SI} = \frac{4\mu^2}{\pi}\left[Z \boldsymbol{f_p} + (A - Z)\boldsymbol{f_n}\right]^2$$

- where $\boldsymbol{f_p}, \boldsymbol{f_n}$ are **couplings of the WIMP with point- like protons and neutrons**, respectively.Z and A-Z are the number of protons and neutrons in the nucleus.

Spin-independent interaction

- To compare data from different direct detection experiments which have different target nuclei, it is convenient to consider the **WIMP-proton cross section**:

$$\sigma_{SI} = \frac{4\mu_p^2}{\pi}(f_p)^2$$

μ_p: WIMP proton reduced mass, $\frac{mM}{m+M}$ Reduced mass;M: mass of nucleus.

- Then we have:

$$\sigma_0^{SI} = \sigma_{SI}\left[Z + (A - Z)\left(\frac{f_n}{f_p}\right)\right]^2\left(\frac{\mu}{\mu_p}\right)^2$$

Spin-independent interaction

- For most WIMP candidates one can assume $f_n \simeq f_p$ and the **SI scattering cross section of WIMPs with protons and neutrons** are roughly **comparable**. For identical couplings, $\boldsymbol{f_n = f_p}$, and

$$\sigma_0^{SI} = \sigma_{SI} A^2 \left(\frac{\mu}{\mu_p}\right)^2$$

- The SI **cross section increases** rapidly with nuclear mass $\boldsymbol{A^2}$. $\Longrightarrow$ **heavy target are favored** .
- The A^2 dependence comes from the fact that the contributions to the total SI cross section of a nucleus is a coherent sum over the individual protons and neutrons.

Spin-independent interaction

- The SI form factor is essentially a Fourier transform of the mass distribution of nucleus: the mass distribution of the nucleus:

$$F(\boldsymbol{q}) = \int d^3x \rho(\boldsymbol{x}) e^{i\boldsymbol{q}\cdot\boldsymbol{x}}$$

- An accurate approximation[4]

$$F(q) = 3e^{-q^2s^2/2} \frac{\sin(qr) - qr\cos(qr)}{(qr)^3}$$

s= 1 fm skin ticness, a solid sphere, approximating spin-independent interaction with the whole nucleus (single outer shell nucleon for spin dependent) effective nuclear radius $r \approx A^{1/3}$

[4] J.D.Lewin, P.F. Smith *For a complete review: Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoil* Astroparticle Physics 6 (1996), 87 Form factor, protected

Spin-independent interaction

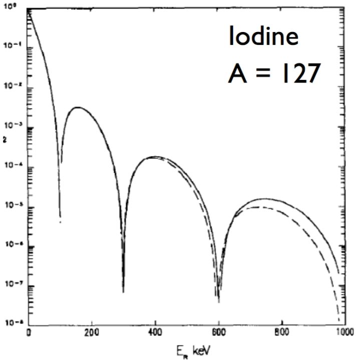


Figure : Nuclear form factor

- **Uncertainties in the determination of the nuclear form factor will affect the theoretical prediction for event rate.**

Spin-dependent interaction

- SD scattering is due to the interaction of a WIMP with the spin of the nucleus.It can arise from axial vector couplings of DM to quarks[5] It happens only in detector nuclei with an **odd number of protons and/or neutrons**.
- Unlike the SI case, the two SD couplings may be quite different, and we cannot simplify the cross section as we did for the SI case.
- **No A^2 enhancement** of SD cross section as SI case.
- The **SD** is **not as significant as SI scattering** in direct detection experiments.
- The SD form factor depends on the spin structure of a nucleus

$$\Downarrow$$

I will consider **only SI interactions** in my lecture.

[5] which occurs through the operator $(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$.

The differential event rate

$$\frac{dR}{dE} = \frac{\rho}{m}\frac{1}{M}\int_{v>v_m} d^3v \frac{d\sigma}{dE} v f(\vec{v})$$

$$\frac{d\sigma}{dE} = \frac{M}{2\mu^2 v^2}\sigma_0 F^2(E)$$

$$\frac{dR}{dE} = \rho \underbrace{\frac{\sigma_0 F^2(E)}{2m\mu^2}}_{\text{particle physics}} \underbrace{\int_{v>v_m} d^3v \frac{\vec{v}}{v}}_{\text{astrophysics}}$$

- astrophysics
- particle physics

Halo integral

- Let's define **halo integral** as:

$$\boxed{\eta(v_m) \equiv \int_{v>v_m} d^3v \frac{\vec{v}}{v}}$$

- The event rate can be written as [6]

$$\frac{dR}{dE} = \frac{\rho\sigma_0 F^2(E)}{2m\mu^2} \underbrace{\eta(v_m)}_{\text{astrophysics}}$$

$$\text{For SI case}: \frac{dR}{dE} = \frac{\rho A^2 \sigma_{SI} F^2(E)}{2m\mu_p^2} \underbrace{\eta(v_m)}_{\text{astrophysics}}$$

[6] $\sigma_0^{SI} = \sigma_{SI} A^2 \left(\frac{\mu}{\mu_p}\right)^2$

Astrophysics input input: DM distribution

Standard Halo Model

- The dark matter halo in the local neighborhood is most likely dominated by a smooth component with an **average density**:

$$\rho_\chi \approx 0.3 \text{ GeV cm}^{-3}$$

- The simplest model for this smooth component is often taken to be the SHM, Standard Halo Model an isothermal sphere with an **isotropic, Maxwellian velocity distribution** and rms velocity dispersion σ_v. [7]

[7] Freese, Lisanti and Savage, *Colloquium: Annual modulation of dark matter* Rev. Mod. Phys. 85 (2013) 1561 ??

Standard Halo Model

$$f_{\text{gal}}(\vec{\boldsymbol{v}}) = \begin{cases} \frac{1}{N_{\text{esc}}}\left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2}, \left[e^{-3\vec{\boldsymbol{v}}^{\mathbf{2}}/2\sigma_v^2} - e^{-3\vec{\boldsymbol{v}}^{\mathbf{2}}/2\sigma_v^2}\right] & \text{for } |\vec{\boldsymbol{v}}| < v_{\text{esc}} \\ 0, & \text{otherwise} \end{cases}$$

$$N_{\text{esc}} = \text{erf}(z) - \frac{2}{\sqrt{\pi}} z e^{-z^2}$$

$$z \equiv v_{\text{esc}}/v_0 \text{ is a normalization factor}$$

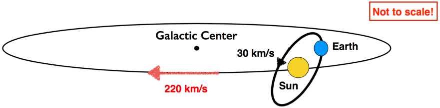
$$v_0 = \sqrt{2/3}\sigma_v$$

- **$v_0 \approx 235$ km/s is the most probable speed**.
- The Maxwellian distribution is **truncated at the escape velocity**$v_{\text{esc}}$to account for the fact that **WIMPs with sufficiently high velocities escape** the Galaxy's potential well and, thus, the high-velocity tail of the distribution is depleted.

The Dark Matter velocity distribution depends on the halo model.

DM velocity distribution

To compute the event rate, we need the WIMP velocity, $\vec{v}$, distribution in the **detector reference frame**. Need to transform from the galactic frame to the detector frame.

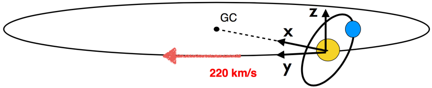


$$f_{\rm det}(\vec{v}, t) = f_{\rm det}\left(\vec{v} + \vec{v}_e(t)\right) = f_{\rm gal}\left(\vec{v} + \vec{v}_s(t) + \vec{v}_e(t)\right)$$

- $\vec{v}_e(t)$, Earth's velocity wrt the Sun
- $\vec{v}_s(t)$, Sun's velocity wrt the Galaxy

Sun's orbit around the Galaxy

Galactic coordinate system:



Origin at the position of the Sun.

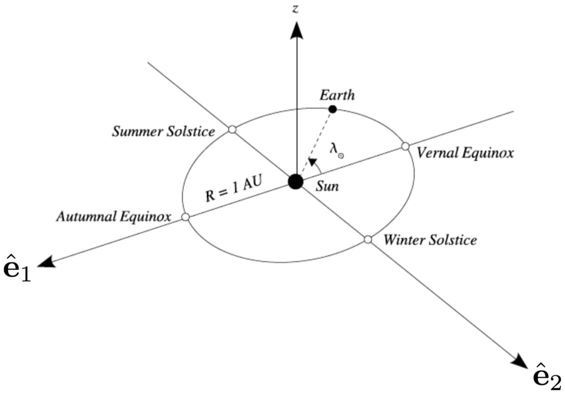
x-axis points towards the Galactic Center.

y-axis points towards the direction of the Galactic rotation.

z-axis points to the North Galactic pole

$$\vec{v}_s(t) = (0, 220, 0) + (10, 13, 7)\text{km/s}$$

Earth's orbit around the Sun



Sun's ecliptic longitude $\lambda(t)$ changes from 0 to 360 degrees as the Earth orbits the Sun.

Earth?s orbit around the Sun

- In the approximation of circular orbit, we have

$$\lambda(t) = \frac{2\pi}{1yr}(t - 0.218)$$

- t is the time during the year running from 0 to 1 year, with t=0 on January first
- 0.218is the fraction of year before the spring equinox (March 21).
- The position vector of the Earth is:

$$\vec{r}_e(t) = -\left[\cos\lambda(t)\hat{e}_1 + \sin\lambda(t)\hat{e}_2\right]\mathrm{AU}$$

- 1 AU is the average distance between the Earth and the Sun.

Earth's orbit around the Sun

- **Earth's velocity**around the Sun is **time dependent**:

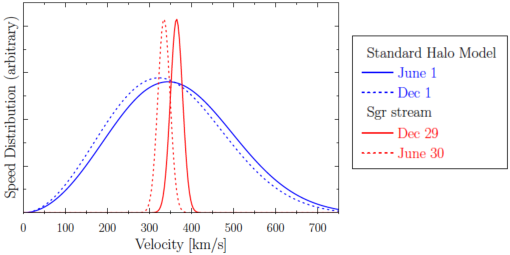
$$\vec{v}_e(t) \;=\; v_e\big[\sin\lambda(t)\hat{\boldsymbol{e}}_{\mathbf{1}} \;-\; \cos\lambda(t)\hat{\boldsymbol{e}}_{\mathbf{2}}\big]$$

- $v_e = 29.8$ km/s
- Orthogonal vectors spanning the plane of the plane of the Earth's orbit:

$$\begin{aligned}\hat{\boldsymbol{e}}_{\mathbf{1}} &= (-0.0670, 0.4927, -0.8676)\\ \hat{\boldsymbol{e}}_{\mathbf{2}} &= (-0.9931, 0.1170, -0.01032)\end{aligned}$$

DM velocity distribution

- Comparison of **two different model in the lab frame(on the earth)** after accounting the motion of Solar System relative to Galactic center:
  - SHM, *Standard Halo Model* an isothermal sphere with an isotropic, Maxwellian velocity distribution and rms velocity dispersion σ_v.
  - *Tidal stream*, the material in the stream has not had the time to spatially mix, the stream has a small velocity dispersion in comparison: $f_{\rm str}(\vec{v}) = \delta^3(\vec{v})$



Freese et al. 1209.3339

The differential event rate

The **recoil spectrum falls off exponentially in the galactic rest frame**for the SHM (neglecting form factors), due to the exponential drop-off with velocity [8] Even when form factors and the motion of the Earth through the halo are accounted for, the **spectrum**is still approximately **exponential in the laboratory frame**:

$$\frac{\mathrm{dR}}{\mathrm{dE}} \sim e^{-E/E_0} \qquad E_0 \sim \mathcal{O}(10keV) \text{ For typical WIMP and target mass}$$

•Large contribution to the rate is at low energies.

8

$$f_{\text{gal}}(\vec{\boldsymbol{v}}) = \begin{cases} \frac{1}{N_{\text{esc}}}\left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2}, [e^{-3\vec{\boldsymbol{v}}^{\mathbf{2}}/2\sigma_v^2} - e^{-3\vec{\boldsymbol{v}}^{\mathbf{2}}/2\sigma_v^2}] & \text{for } |\vec{\boldsymbol{v}}| < v_{\text{esc}} \\ 0, & \text{otherwise} \end{cases}$$

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$$z \equiv v_{\text{esc}}/v_0 \text{ is a normalization factor}$$

$$v_0 = \sqrt{2/3}\sigma_v$$

The differential event rate

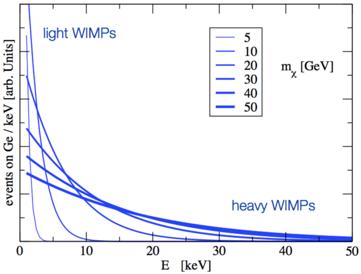
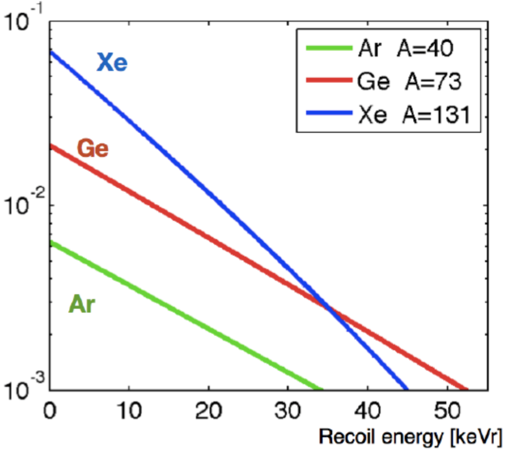


Figure : Event rate

- **Spectrum**is featureless: **exponentially falling off**.
- Spectrum is shifted to **low energies for low WIMP masses**.To detect light WIMPs, need low energy threshold (and light target nuclei).
- Expect **different rates for different targets**.
- Rate **depends on** $A^2 \Longrightarrow$ heavier targets are favored in direct detection experiments.

The differential event rate

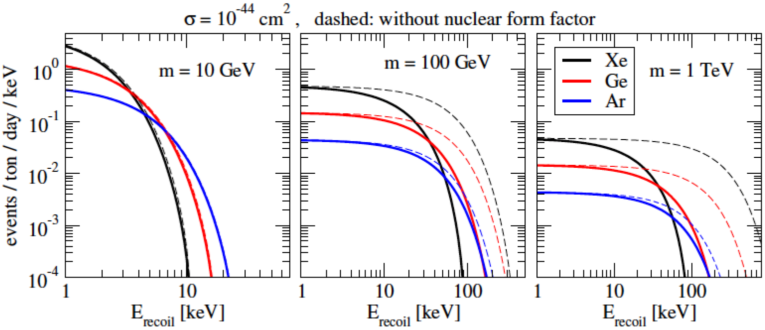


$$m = 100 \text{ GeV}$$

$$\sigma_{SI} = 10^{-44} \text{ cm}^2$$

$$\rho = 0.3 \text{ GeV/cm}^3$$

The differential event rate



Nuclear form factor is less important for light WIMPs

Summary

- We discussed the different ingredients which enter in the expected event rate in direct detection experiments.
  - **particle physics input**:cross section. SI cross section scales as A^2
  - **astrophysics input**: local DM density and velocity distribution. Maxwell distribution in the Standard Halo Model.
- **Recoil spectrumexponentially falling off** and featureless.
- **Direct detection experiment need to achieve low energy threshold.**