

Lecture 1: Introduction to Dark Matter Direct Detection

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COEPP

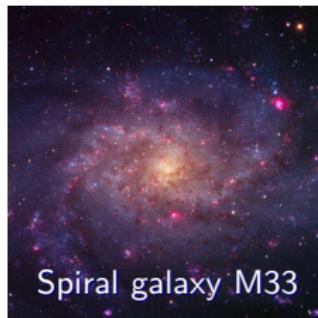
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Dark Matter in the Universe

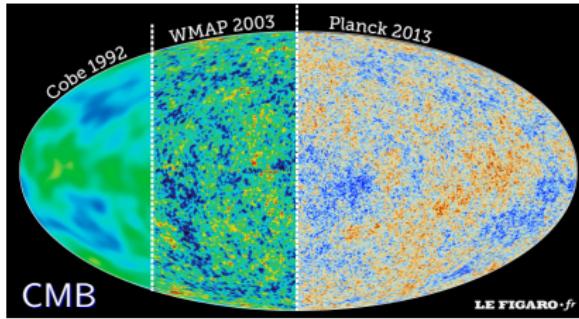
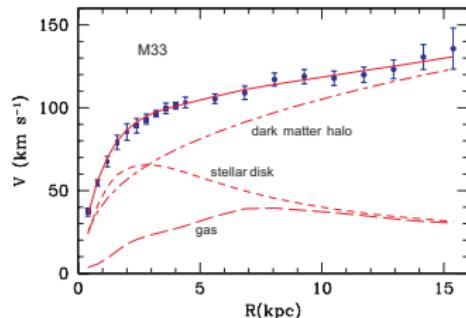
Dark matter (DM) makes up most of the matter component in the Universe, as suggested by astrophysical and cosmological observations



Bullet Cluster



Spiral galaxy M33



A pie chart divided into three segments: a large purple segment, a smaller blue segment, and a very small green segment.

Cold DM (25.8%)

$$\Omega_c h^2 = 0.1186 \pm 0.0020$$

Baryons (4.8%)

$$\Omega_b h^2 = 0.02226 \pm 0.00023$$

Dark energy (69.3%)

$$\Omega_\Lambda = 0.692 \pm 0.012$$

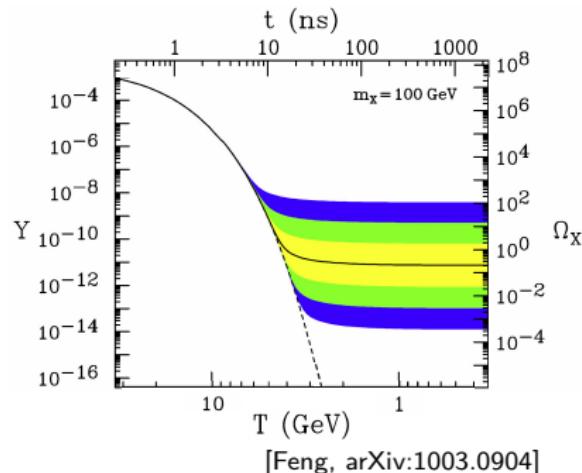
DM Relic Abundance

If DM particles (χ) were thermally produced in the early Universe, their **relic abundance** would be determined by the annihilation cross section $\langle\sigma_{\text{ann}} v\rangle$:

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle}$$

Observation value $\Omega_\chi h^2 \simeq 0.1$

$$\Rightarrow \langle \sigma_{\text{ann}} v \rangle \cong 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$



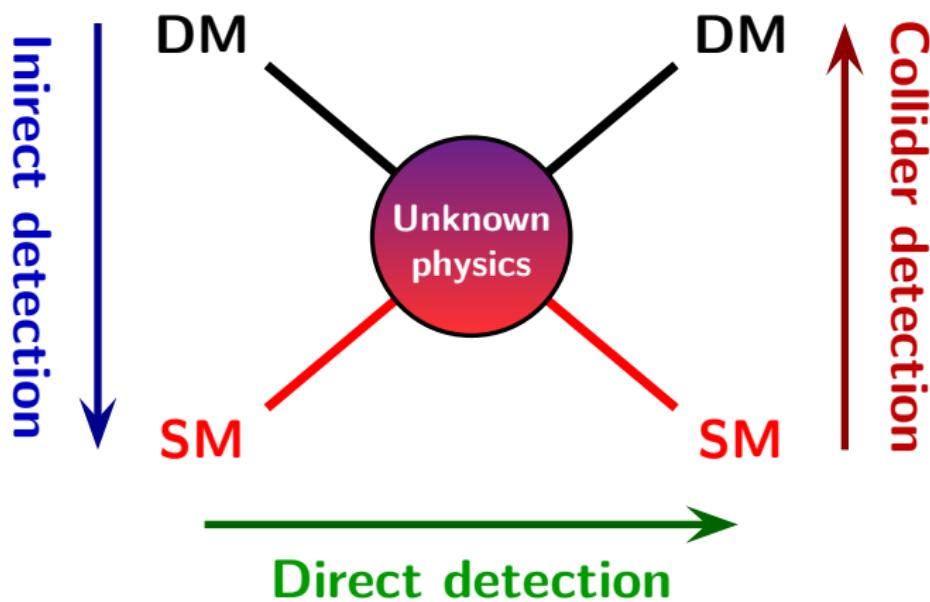
Assuming the annihilation process consists of two weak interaction vertices with the $SU(2)_L$ gauge coupling $g \simeq 0.64$, for $m_\gamma \sim \mathcal{O}(\text{TeV})$ we have

$$\langle \sigma_{\text{ann}} v \rangle \sim \frac{g^4}{16\pi^2 m_\chi^2} \sim \mathcal{O}(10^{-26}) \text{ cm}^3 \text{ s}^{-1}$$

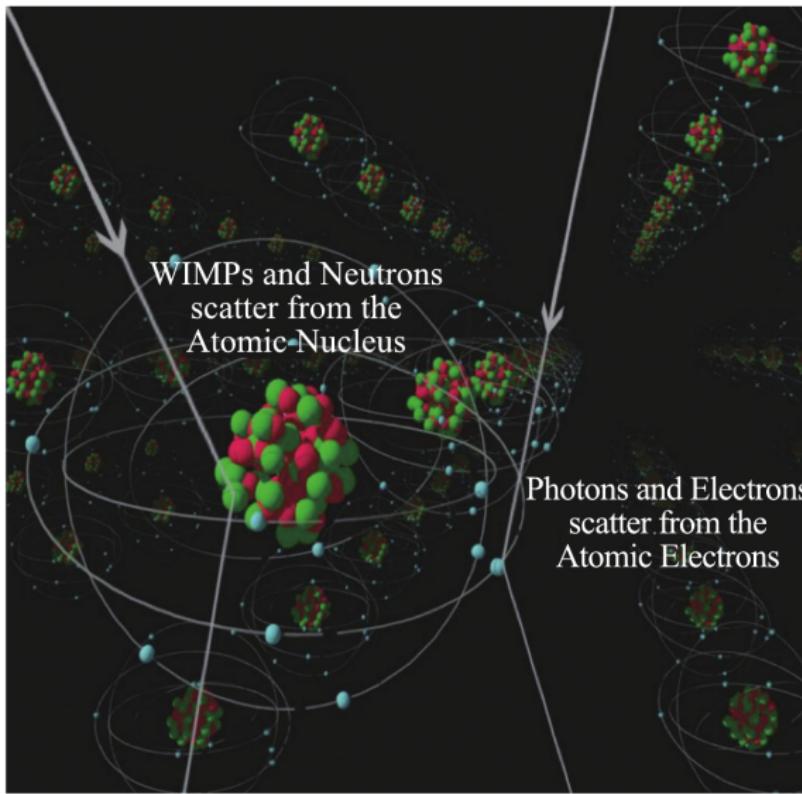
⇒ A very attractive class of DM candidates:

Weakly interacting massive particles (WIMPs)

Experimental Approaches to WIMP Dark Matter

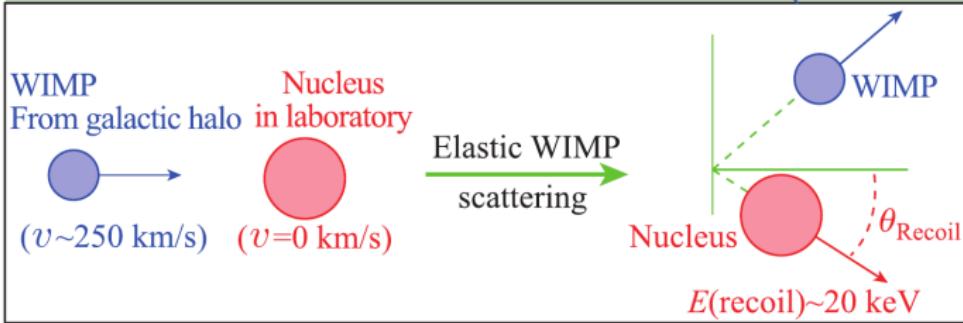
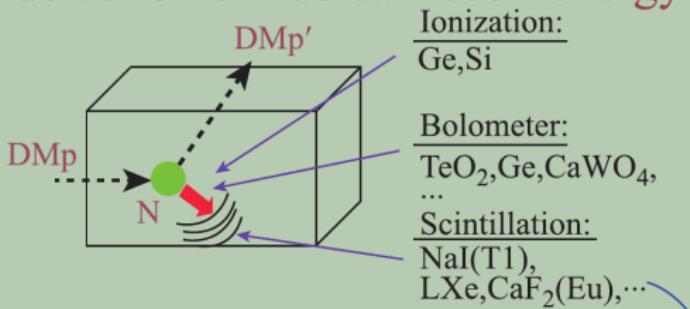


WIMP Scattering off Atomic Nuclei



Direct Detection

- Scatterings on nuclei
→ detection of nuclear recoil energy



[Bing-Lin Young, Front. Phys. 12, 121201 (2017)]

WIMP Velocity Distribution

During the collapse process which formed the Galaxy, WIMP velocities were “thermalized” by fluctuations in the gravitational potential, and WIMPs have a **Maxwell-Boltzmann velocity distribution** in the **Galactic rest frame**:

$$\tilde{f}(\tilde{\mathbf{v}})d^3\tilde{\mathbf{v}} = \left(\frac{m_\chi}{2\pi k_B T} \right)^{3/2} \exp\left(-\frac{m_\chi \tilde{v}^2}{2k_B T}\right) d^3\tilde{\mathbf{v}} = \frac{e^{-\tilde{v}^2/v_0^2}}{\pi^{3/2} v_0^3} d^3\tilde{\mathbf{v}}, \quad v_0^2 \equiv \frac{2k_B T}{m_\chi}$$

$$\langle \tilde{\mathbf{v}} \rangle = \int \tilde{\mathbf{v}} \tilde{f}(\tilde{\mathbf{v}}) d^3\tilde{\mathbf{v}} = \mathbf{0}, \quad \langle \tilde{v}^2 \rangle = \int \tilde{v}^2 \tilde{f}(\tilde{\mathbf{v}}) d^3\tilde{\mathbf{v}} = \frac{3}{2} v_0^2$$

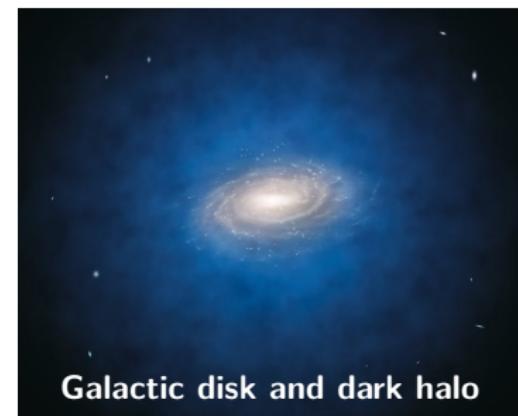
Speed distribution: $\tilde{f}(\tilde{v})d\tilde{v} = \frac{4\tilde{v}^2}{\sqrt{\pi}v_0^3} e^{-\tilde{v}^2/v_0^2} d\tilde{v}$

For an **isothermal** halo, the local value of v_0 equals to the **rotational speed of the Sun**:

$$v_0 = v_\odot \simeq 220 \text{ km/s}$$

[Binney & Tremaine, *Galactic Dynamics*, Chapter 4]

Velocity dispersion: $\sqrt{\langle \tilde{v}^2 \rangle} = \sqrt{3/2} v_0 \simeq 270 \text{ km/s}$



Galactic disk and dark halo

[Credit: ESO/L. Calçada]

Earth Rest Frame

The WIMP velocity distribution $f(\mathbf{v})$ seen by an observer on the Earth can be derived via **Galilean transformation**

$$\tilde{\mathbf{v}} = \mathbf{v} + \mathbf{v}_{\text{obs}}, \quad \mathbf{v}_{\text{obs}} = \mathbf{v}_{\odot} + \mathbf{v}_{\oplus}$$

Velocity distribution: $f(\mathbf{v}) = \tilde{f}(\mathbf{v} + \mathbf{v}_{\text{obs}})$

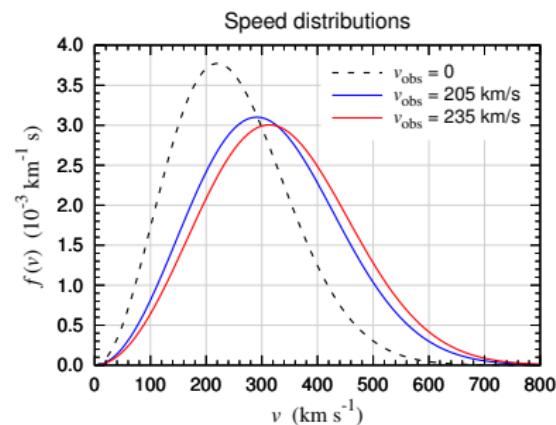
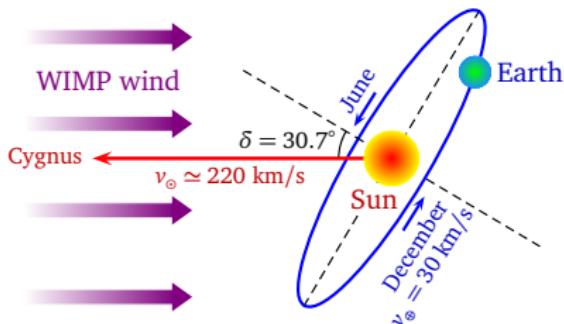
Speed distribution:

$$f(v)dv = \frac{4v^2}{\sqrt{\pi}v_0^3} \exp\left(-\frac{v^2 + v_{\text{obs}}^2}{v_0^2}\right) \times \frac{\tilde{v}_0^2}{2vv_{\text{obs}}} \sinh\left(\frac{2vv_{\text{obs}}}{v_0^2}\right) dv$$

Since $v_{\oplus} \ll v_{\odot}$, we have ($\omega = 2\pi/\text{year}$)

$$\begin{aligned} v_{\text{obs}}(t) &\simeq v_{\odot} + v_{\oplus} \sin \delta \cos[\omega(t - t_0)] \\ &\simeq 220 \text{ km/s} + 15 \text{ km/s} \cdot \cos[\omega(t - t_0)] \end{aligned}$$

⇒ **Annual modulation signal peaked on June 2** [Freese *et al.*, PRD 37, 3388 (1988)]



Nuclear Recoil

Energy conservation:

$$\frac{1}{2}m_\chi v^2 = \frac{1}{2}m_\chi v_\chi^2 + \frac{1}{2}m_A v_R^2$$

Momentum conservation:

$$m_\chi v = m_\chi v_\chi \cos \theta_\chi + m_A v_R \cos \theta_R$$

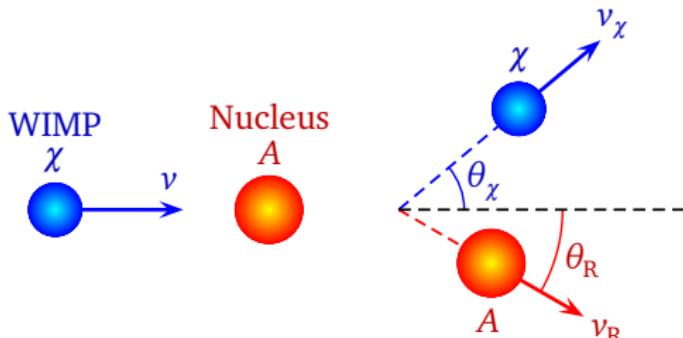
$$m_\chi v_\chi \sin \theta_\chi = m_A v_R \sin \theta_R$$

$$\Rightarrow \text{Recoil velocity } v_R = \frac{2m_\chi v \cos \theta_R}{m_\chi + m_A}$$

$$\Rightarrow \text{Recoil momentum (momentum transfer) } q_R = m_A v_R = 2\mu_{\chi A} v \cos \theta_R$$

Reduced mass of the χA system $\mu_{\chi A} \equiv \frac{m_\chi m_A}{m_\chi + m_A} = \begin{cases} m_A, & \text{for } m_\chi \gg m_A \\ \frac{1}{2}m_\chi, & \text{for } m_\chi = m_A \\ m_\chi, & \text{for } m_\chi \ll m_A \end{cases}$

Forward scattering ($\theta_R = 0$) \Rightarrow maximal momentum transfer $q_R^{\max} = 2\mu_{\chi A} v$



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Momentum conservation:

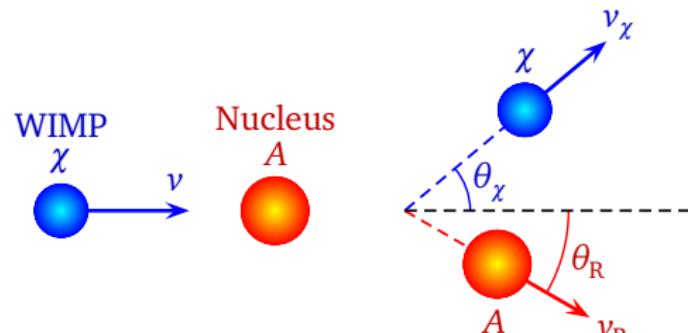
$$m_\chi v = m_\chi v_\chi \cos \theta_\chi + m_A v_R \cos \theta_R$$

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$$\Rightarrow \text{Recoil momentum (momentum transfer) } q_R = m_A v_R = 2\mu_{\chi A} v \cos \theta_R$$

$$\Rightarrow \text{Kinetic energy of the recoiled nucleus } E_R = \frac{q_R^2}{2m_A} = \frac{2\mu_{\chi A}^2}{m_A} v^2 \cos^2 \theta_R$$



As $v \sim 10^{-3}c$, for $m_\chi = m_A \simeq 100 \text{ GeV}$ and $\theta_R = 0$,

$$q_R = m_\chi v \sim 100 \text{ MeV}, \quad E_R = \frac{1}{2}m_\chi v^2 \sim 50 \text{ keV}$$

Event Rate

Event rate per unit time per unit energy interval:

$$\frac{dR}{dE_R} = N_A \frac{\rho_{\oplus}}{m_{\chi}} \int_{v_{\min}}^{v_{\max}} d^3v f(v) v \frac{d\sigma_{\chi A}}{dE_R}$$

Astrophysics factors
Particle physics factors
Detector factors

N_A : target nucleus number

$\rho_{\oplus} \simeq 0.4 \text{ GeV/cm}^3$: DM mass density around the Earth

(ρ_{\oplus}/m_{χ} is the DM particle number density around the Earth)

$\sigma_{\chi A}$: DM-nucleus scattering cross section

Minimal velocity $v_{\min} = \left(\frac{m_A E_R^{\text{th}}}{2\mu_{\chi A}^2} \right)^{1/2}$: determined by the detector threshold of nuclear recoil energy, E_R^{th}

Maximal velocity v_{\max} : determined by the DM escape velocity v_{esc}

($v_{\text{esc}} \simeq 544 \text{ km/s}$ [Smith et al., MNRAS 379, 755])

Cross Section Dependence on Nucleus Spin

There are two kinds of DM-nucleus scattering

Spin-independent (SI) cross section: $\sigma_{\chi A}^{\text{SI}} \propto \mu_{\chi A}^2 [ZG_p + (A-Z)G_n]^2$

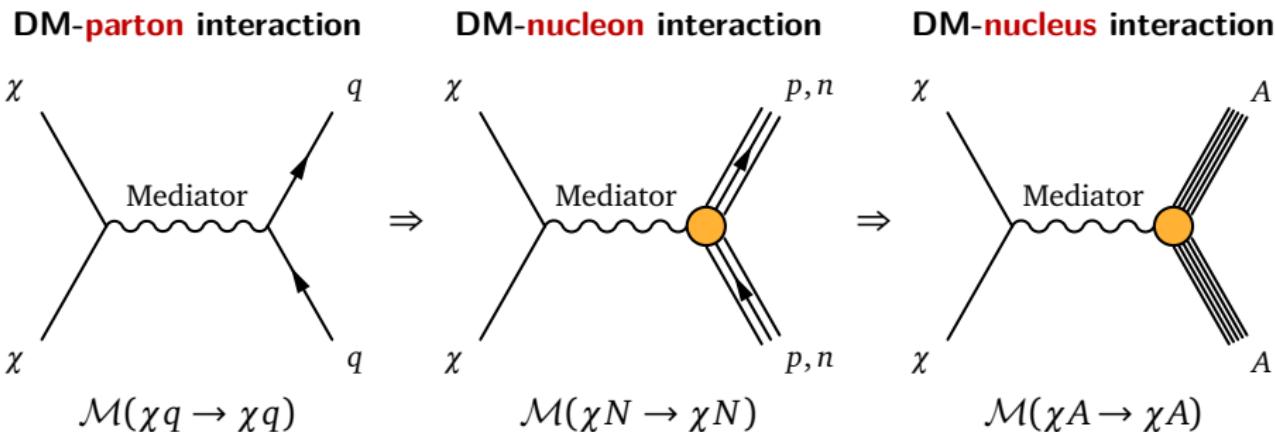
Spin-dependent (SD) cross section: $\sigma_{\chi A}^{\text{SD}} \propto \mu_{\chi A}^2 \frac{J_A + 1}{J_A} (S_p^A G'_p + S_n^A G'_n)^2$

Nucleus properties: mass number A , atomic number Z , spin J_A ,
expectation value of the proton (neutron) spin content in the nucleus S_p^A (S_n^A)

$G_p^{(\prime)}$ and $G_n^{(\prime)}$: **DM effective couplings** to the proton and the neutron

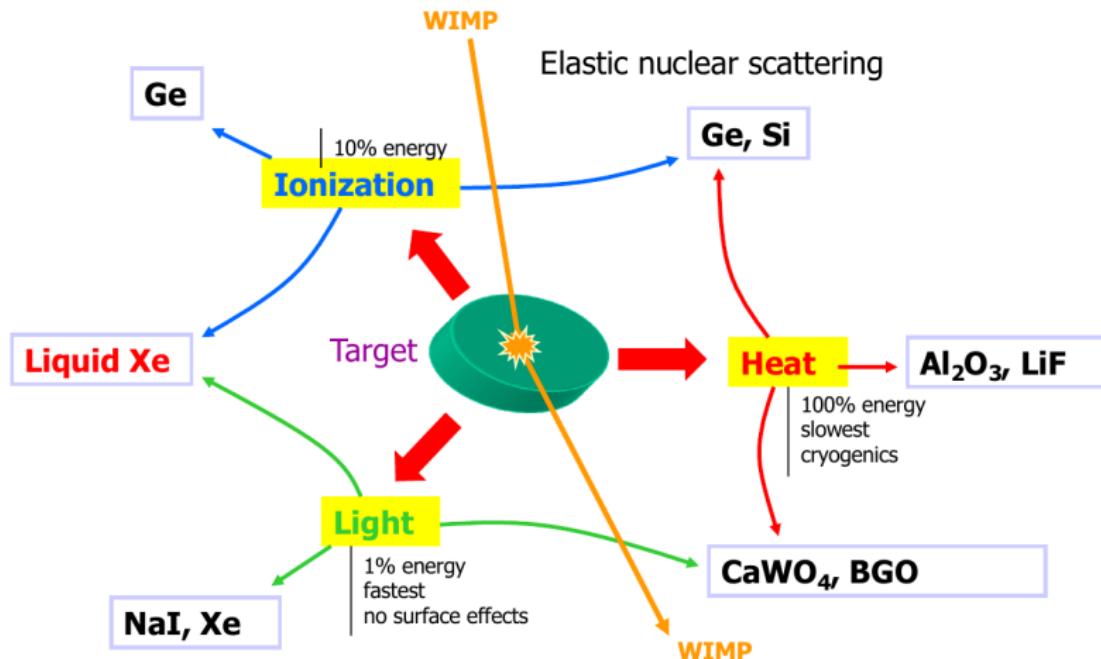
- $Z \simeq A/2 \Rightarrow \sigma_{\chi A}^{\text{SI}} \propto A^2 [(G_p + G_n)/2]^2$
Strong **coherent enhancement** for **heavy** nuclei
- Spins of nucleons tend to **cancel out** among themselves:
 - $S_N^A \simeq 1/2$ ($N = p$ or n) for a nucleus with an **odd** number of N
 - $S_N^A \simeq 0$ for a nucleus with an **even** number of N

Three Levels of Interaction



- As a variety of target nuclei are used in direct detection experiments, results are usually compared with each other at the **DM-nucleon level**
- The DM-nucleon level is related to the DM-parton level via **form factors**, which describe the probabilities of finding partons inside nucleons
- Relevant partons involve not only valence quarks, but also **sea quarks and gluons**

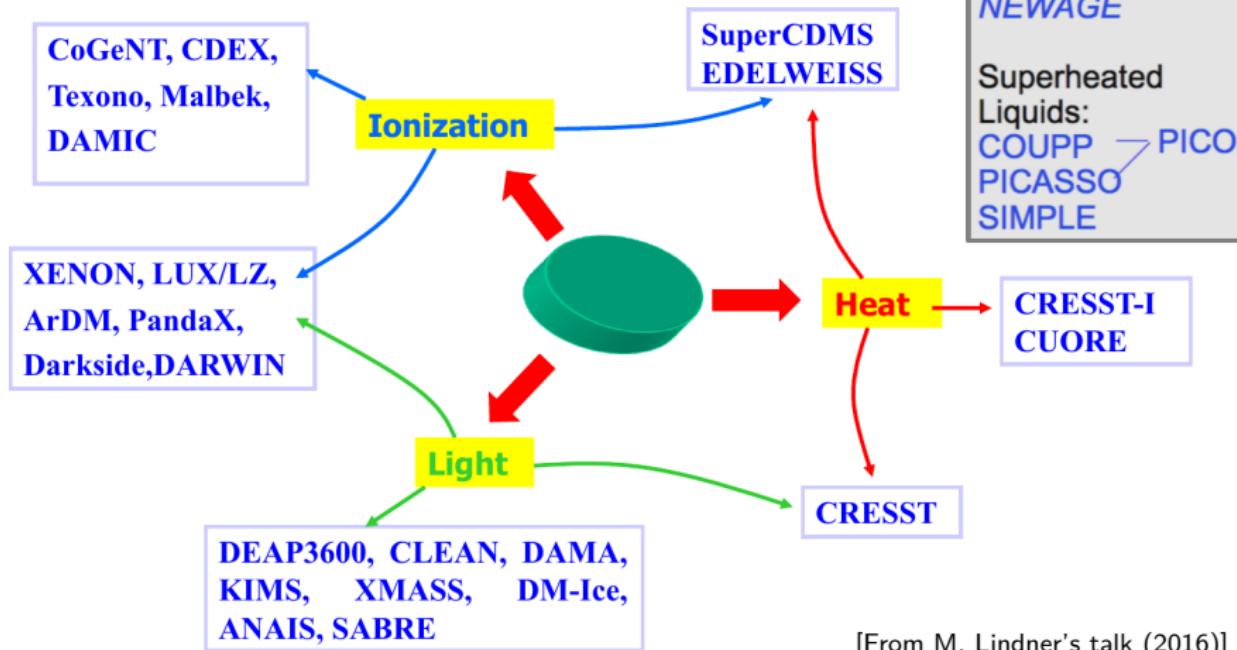
Technologies and Detector Material



[From M. Lindner's talk (2016)]

Technologies and Detector Material

Detection methods: Crystals (NaI, Ge, Si),
Cryogenic Detectors, Liquid Noble Gases



[From M. Lindner's talk (2016)]

Example: Dual-phase Xenon Time Projection Chamber

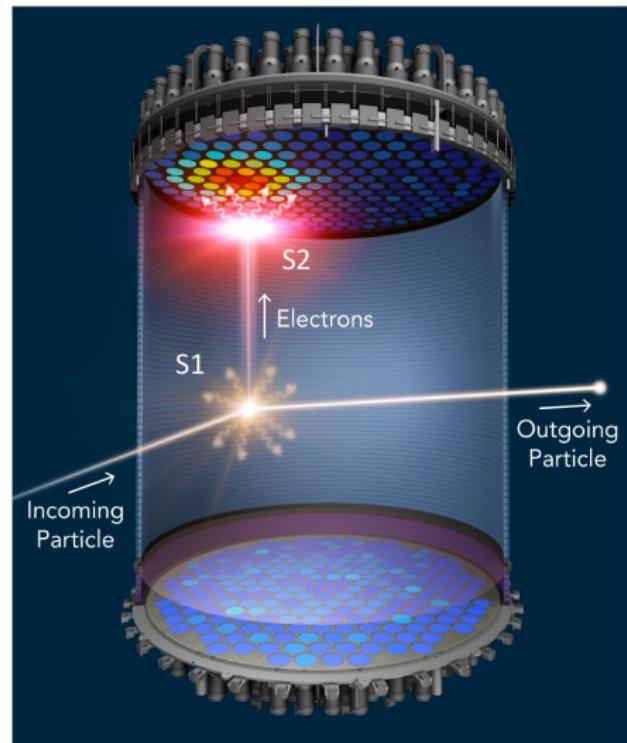
Upper: **Xenon gas**

Lower: **Liquid Xenon**

UV scintillation photons recorded by photomultiplier tube (PMT) arrays on top and bottom

- **Primary scintillation (S1):**
Scintillation light promptly emitted from the interaction vertex
- **Secondary scintillation (S2):**
Ionization electrons emitted from the interaction are drifted to the surface and into the gas, where they emit proportional scintillation light

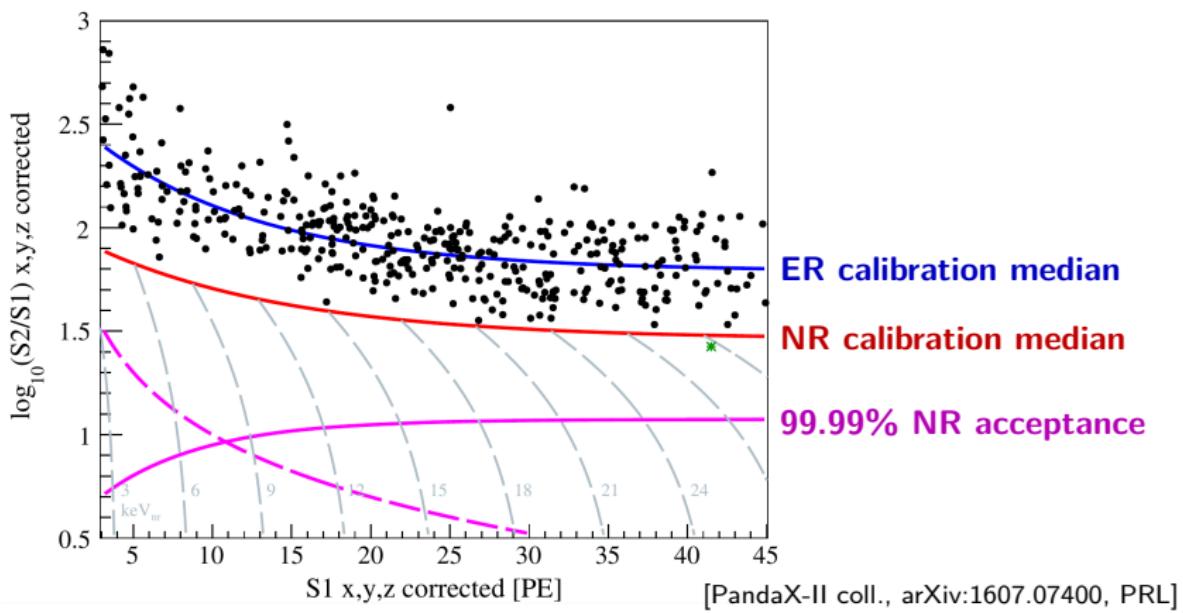
Experiments: XENON, LUX, PandaX



[From A. Cottle's talk (2017)]

PandaX-II Real Data: S1 versus S2

- S1 and S2: characterized by numbers of **photoelectrons (PEs)** in PMTs
 - The γ **background**, which produces **electron recoil (ER)** events, can be distinguished from **nuclear recoil (NR)** events using the S2-to-S1 ratio



Backgrounds

Background suppression:

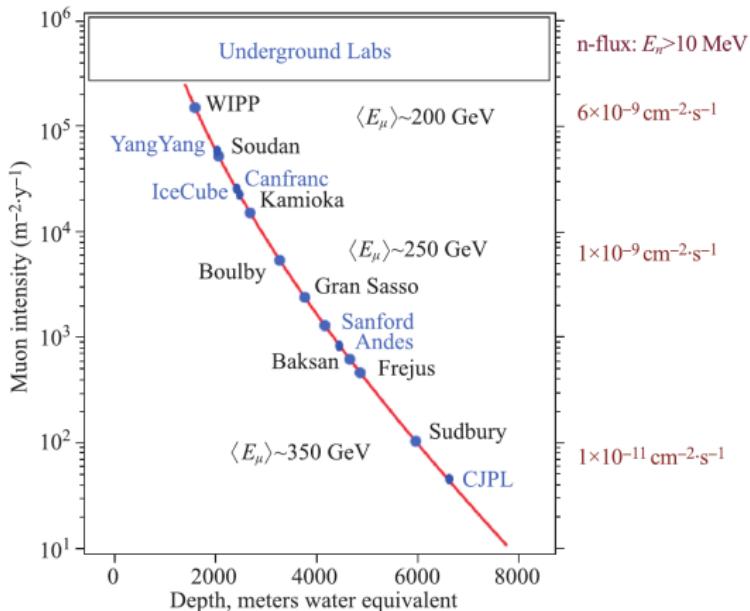
- Deep** underground
- Shielded** environments

• Cosmogenic backgrounds:

- Cosmic rays and secondary reactions
- Activation products in shields and detectors

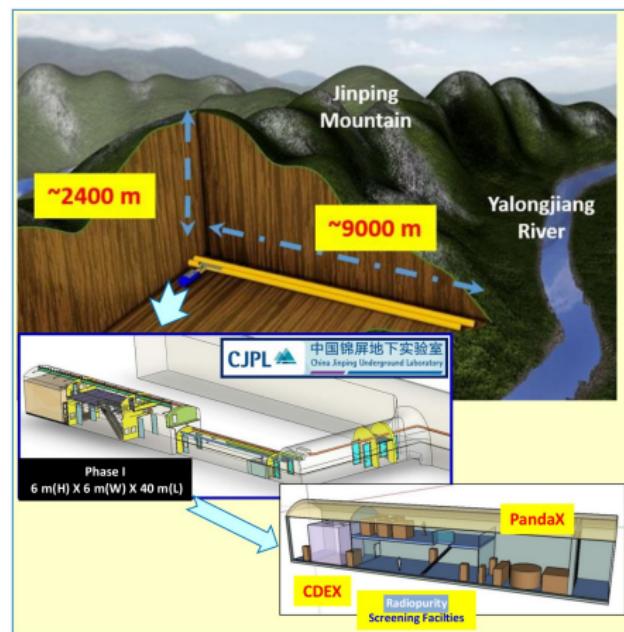
• Radiogenic backgrounds:

- External natural radioactivity: walls, structures of site, radon
- Internal radioactivity:
shield and construction materials, detector contamination in manufacture, naturally occurring radio-isotopes in target material



[From P. Cushman's talk (2014)]

China JinPing Underground Laboratory (CJPL)

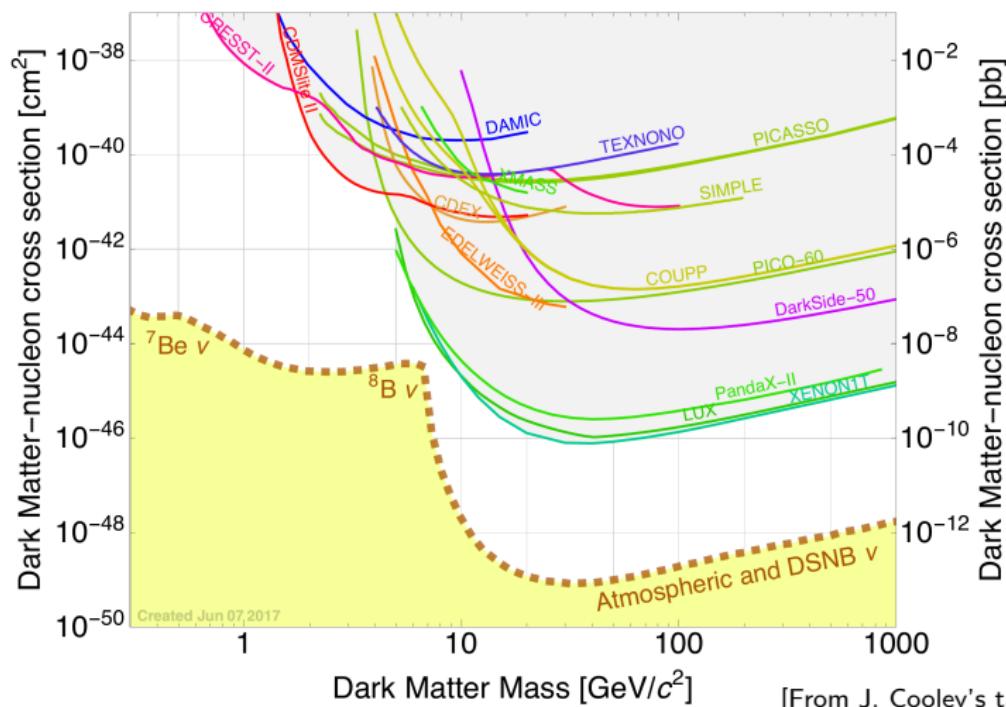


[Yue et al., arXiv:1602.02462]

Experiments: CDEX, PandaX

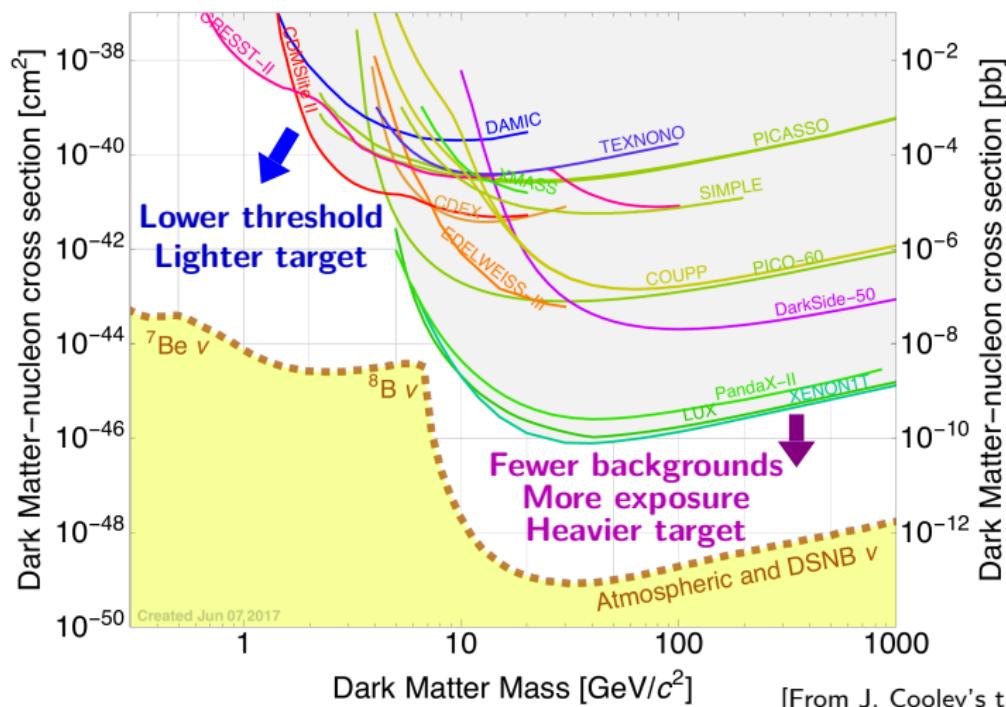
Exclusion Limits for SI Scattering

For **SI scattering**, the **coherent enhancement** allows us to treat protons and neutrons as the same species, “**nucleons**”



Exclusion Limits for SI Scattering

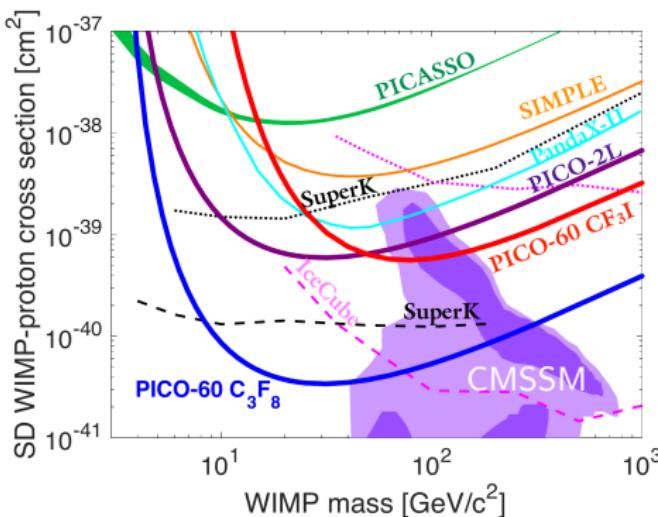
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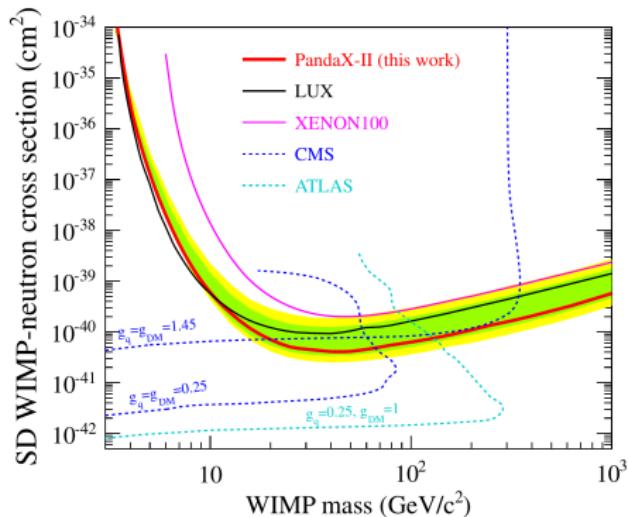
[From J. Cooley's talk (2017)]

Exclusion Limits for SD Scattering

- For **SD scattering**, specific detection material usually has **very different** sensitivities to WIMP-**proton** and WIMP-**neutron** cross sections
- As there is no coherent enhancement for SD scattering, the sensitivity is **lower** than the SI case by **several orders of magnitude**



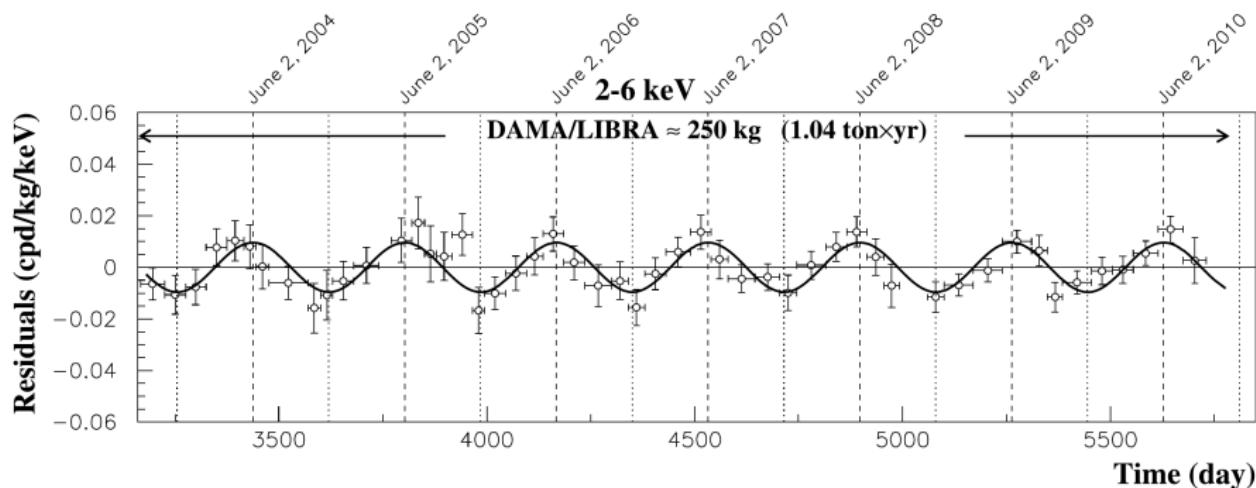
[PICO coll., arXiv:1702.07666, PRL]



[PandaX-II coll., arXiv:1611.06553, PRL]

DAMA/LIBRA Annual Modulation “Signal”

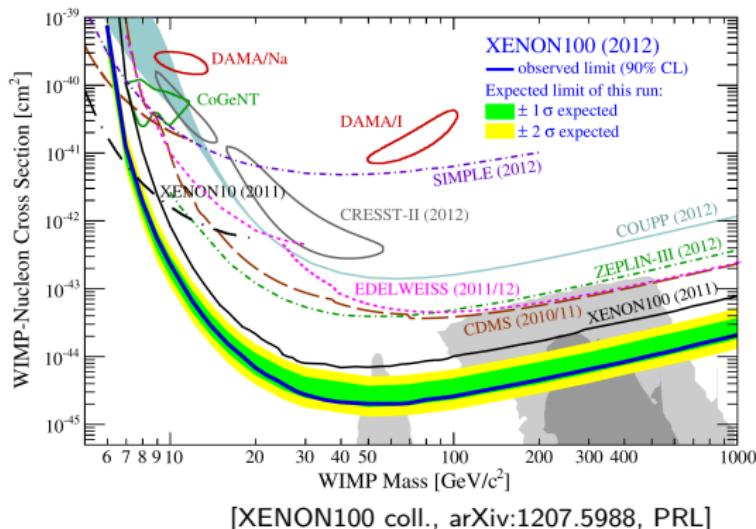
- 😊 Highly radio-pure scintillating **NaI(Tl) crystals** at Gran Sasso, Italy
- 😊 **Annual modulation signal** observed over 14 cycles at **9.3σ significance**
- 😢 **No background/signal discrimination**



[Bernabei *et al.*, arXiv:1308.5109, EPJC]

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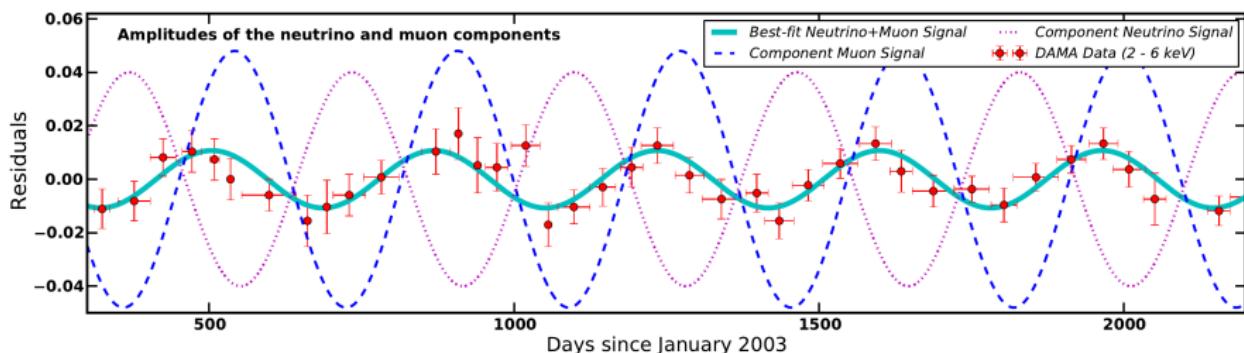


- 😢 **Favored regions excluded by other direct detection experiments**

Other Sources for DAMA/LIBRA Signal

The DAMA/LIBRA signal might be composed of **neutrons** liberated in the material surrounding the detector by **two sources** [Davis, arXiv:1407.1052, PRL]

- **Atmospheric muons:** flux depends on the **temperature of the atmosphere**, peaked on **June 21st**
- **Solar neutrinos:** flux depends on the **distance between the Earth and the Sun**, peaked on **January 4th**

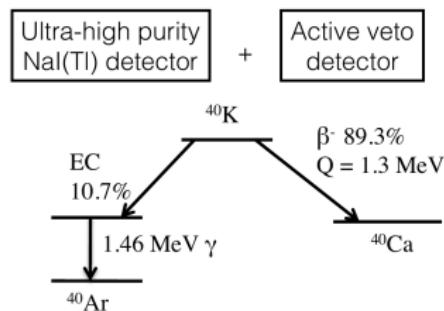


Objection: Klinger & Kudryavtsev, "muon-induced neutrons do not explain the DAMA data," arXiv:1503.07225, PRL

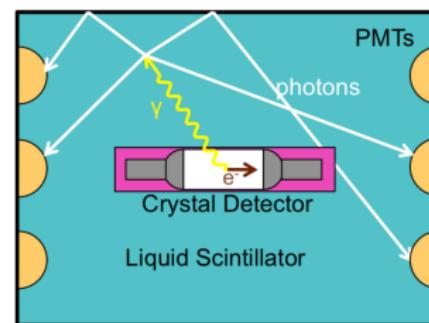
Further Test: SABRE Project

SABRE: Sodium iodide with Active Background REjection

- Complementary tests in **both hemispheres**: one part in Gran Sasso (Italy) and one part in Stawell (Australia)
- Developing **low background** scintillating NaI(Tl) crystals that exceed the radio-purity of DAMA/LIBRA
- A well-shielded **active veto** to reduce internal and external backgrounds



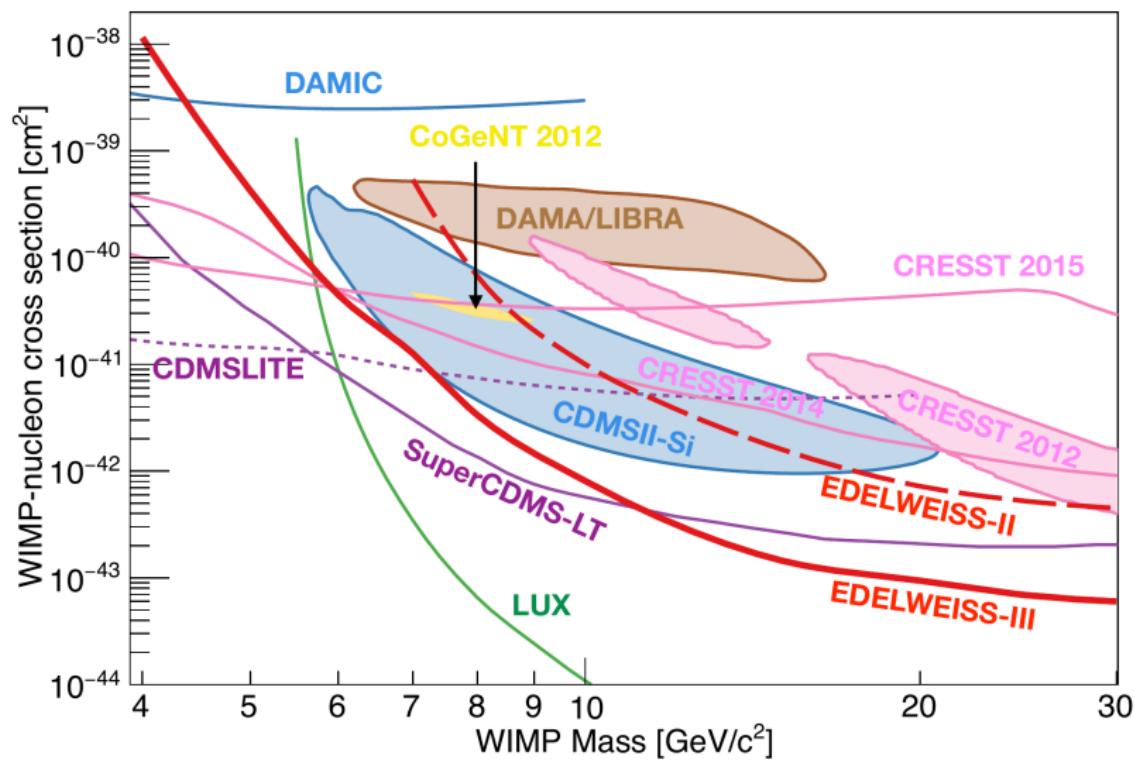
- $^{40}\text{K} \rightarrow ^{40}\text{Ar}$, ~11% branch ratio
- 3 keV K shell X-ray, Auger e^-
 - Background at ~3 keV if γ escapes



1.46MeV γ can be detected by a veto.
 ^{40}K background can be rejected.

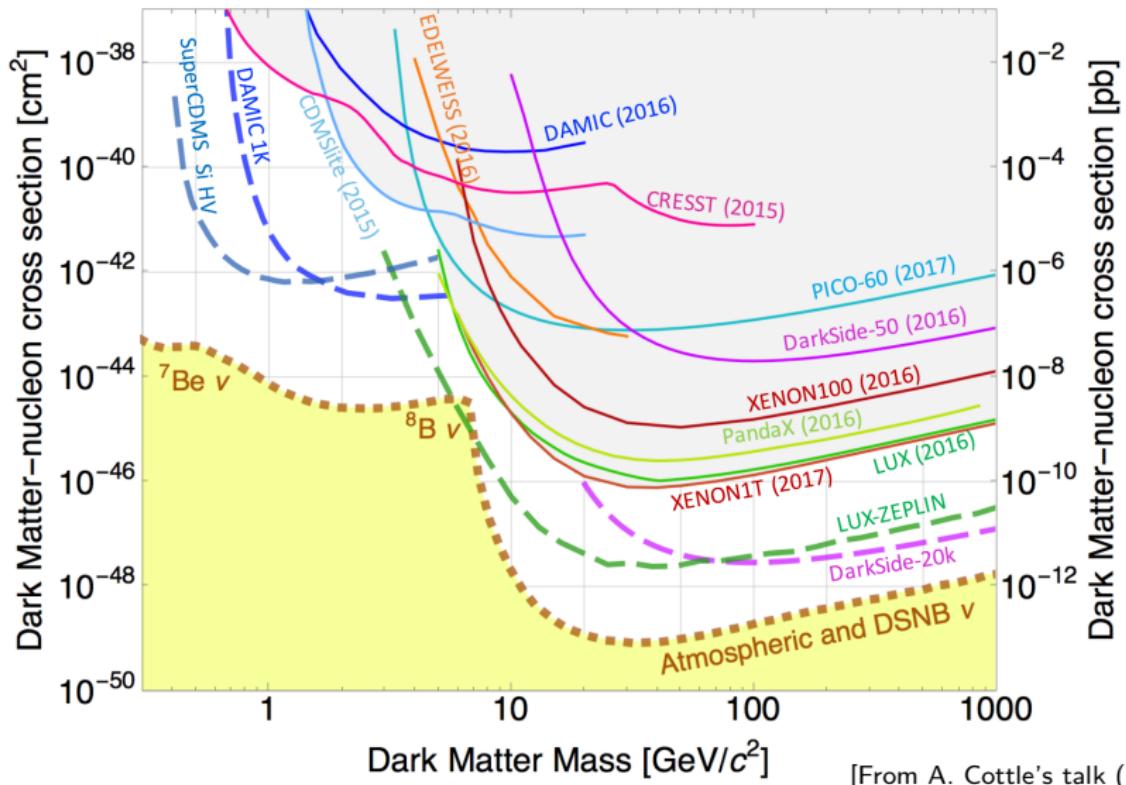
[From E. Barberio's talk]

Low Mass Situation



[From J. Billard's talk (2016)]

Near Future Prospect



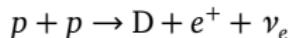
[From A. Cottle's talk (2017)]

Neutrino Backgrounds

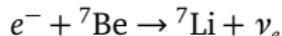
Direct detection experiments will be sensitive to **coherent neutrino-nucleus scattering (CNS)** due to astrophysical neutrinos [Billard et al., arXiv:1307.5458, PRD]

- **Solar neutrinos**

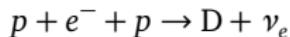
- *pp* neutrinos:



- ${}^7\text{Be}$ neutrinos:



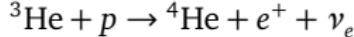
- *pep* neutrinos:



- ${}^8\text{B}$ neutrinos:



- *Hep* neutrinos:

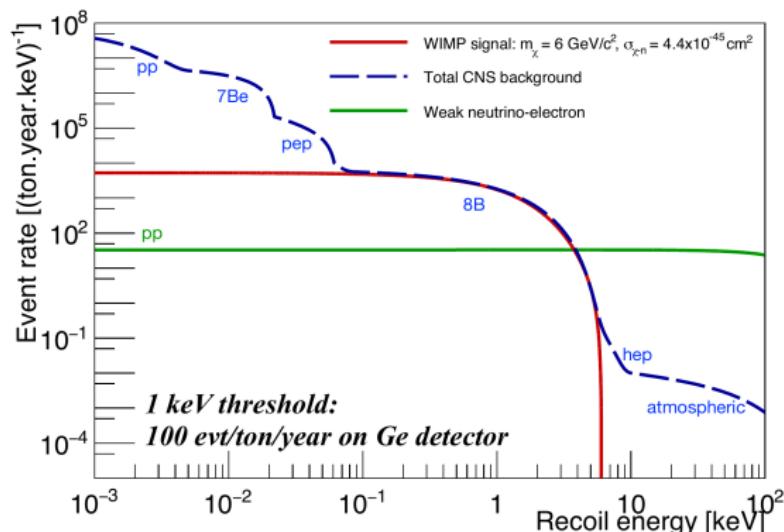


- **Atmospheric neutrinos**

Cosmic-ray collisions in the atmosphere

- **Diffuse supernova neutrino background (DSNB)**

All supernova explosions in the past history of the Universe

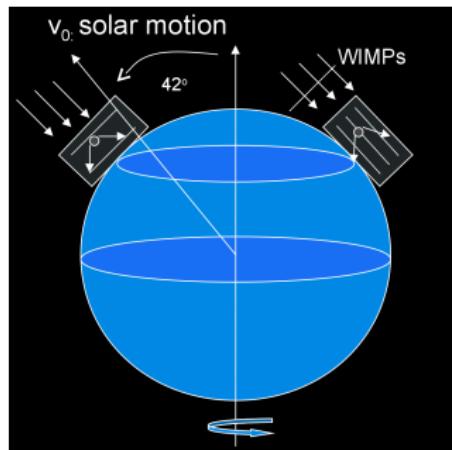


[From J. Billard's talk (2016)]

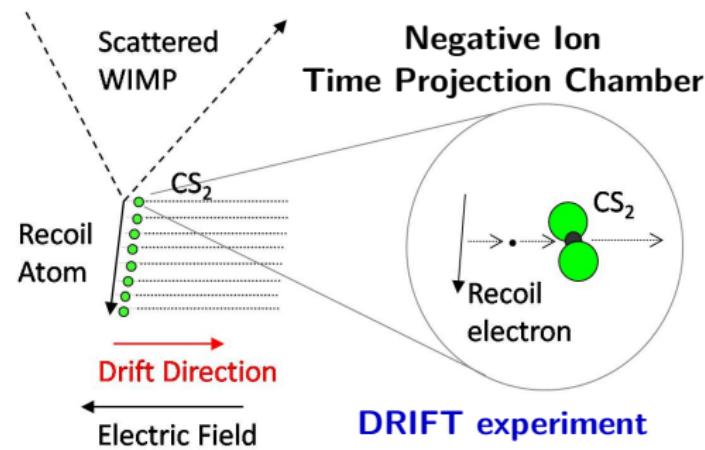
Going beyond the Neutrino Floor

Possible ways to reduce the impact of neutrino backgrounds:

- Reduction of **systematic uncertainties** on neutrino fluxes
- Utilization of **different target nuclei** [Ruppin et al., arXiv:1408.3581, PRD]
- Measurement of **annual modulation** [Davis, arXiv:1412.1475, JCAP]
- Measurement of **nuclear recoil direction** [O'Hare, et al., arXiv:1505.08061, PRD]



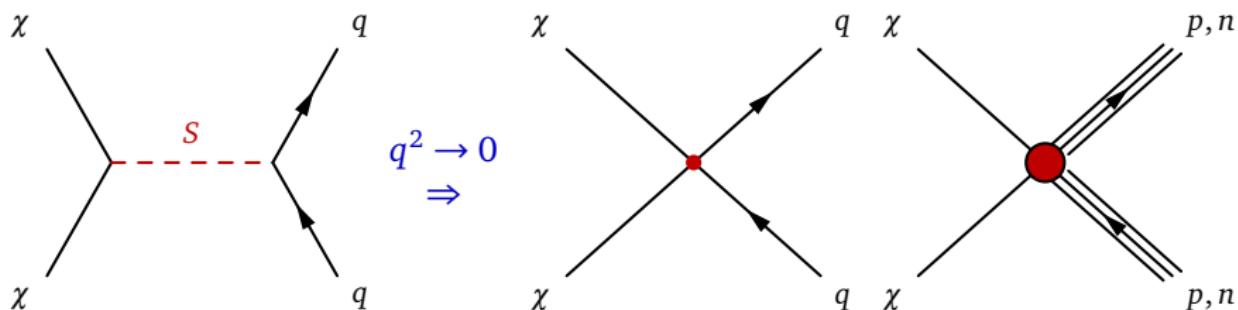
Diurnal modulation



[From J. Spooner's talk (2010)]

Zero Momentum Transfer Limit

- As the momentum transfer (q_R in the nucleus rest frame) is typically much smaller than the underlying energy scale (e.g., mediator mass), the **zero momentum transfer limit** is a good approximation for calculation
- In this limit, the mediator field can be integrated out, and the interaction can be described by **effective operators** in **effective field theory**



Scalar mediator propagator: $\frac{i}{q^2 - m_S^2} \Rightarrow -\frac{i}{m_S^2}$

Lagrangian: $\mathcal{L}_{\text{int}} = g_\chi S \bar{\chi} \chi + g_q S \bar{q} q \Rightarrow \mathcal{L}_{\text{eff}} = G_{\text{eff}} \bar{\chi} \chi \bar{q} q, \quad G_{\text{eff}} = \frac{g_\chi g_q}{m_S^2}$

Effective Operators for DM-nucleon interactions

Assuming the DM particle is a **Dirac fermion χ** and using **Dirac fields p** and **n** to describe the proton and the neutron, the effective Lagrangian reads

$$\mathcal{L}_{\text{eff},N} = \sum_{N=p,n} \sum_{ij} G_{N,ij} \bar{\chi} \Gamma^i \chi \bar{N} \Gamma_j N, \quad \Gamma^i, \Gamma^j \in \{1, i\gamma_5, \gamma^\mu, \gamma^\mu \gamma_5, \sigma^{\mu\nu}\}$$

[Bélanger *et al.*, arXiv:0803.2360, Comput.Phys.Commun.]

- **Lorentz indices** in Γ^i and Γ_j should be contracted in pair
- Effective couplings $G_{N,ij}$ have a mass dimension of -2 : $[G_{N,ij}] = [\text{Mass}]^{-2}$
- $\bar{\chi} \chi \bar{N} N$ and $\bar{\chi} \gamma^\mu \chi \bar{N} \gamma_\mu N$ lead to **SI** DM-nucleon scattering
- $\bar{\chi} \gamma^\mu \gamma_5 \chi \bar{N} \gamma_\mu \gamma_5 N$ and $\bar{\chi} \sigma^{\mu\nu} \chi \bar{N} \sigma_{\mu\nu} N$ lead to **SD** DM-nucleon scattering
- The following operators lead to scattering cross sections $\sigma_{\chi N} \propto v^2$:
 $\bar{\chi} i\gamma_5 \chi \bar{N} i\gamma_5 N, \quad \bar{\chi} \chi \bar{N} i\gamma_5 N, \quad \bar{\chi} i\gamma_5 \chi \bar{N} N, \quad \bar{\chi} \gamma^\mu \chi \bar{N} \gamma_\mu \gamma_5 N, \quad \bar{\chi} \gamma^\mu \gamma_5 \chi \bar{N} \gamma_\mu N$
- For a **Majorana fermion χ** instead, we have $\bar{\chi} \gamma^\mu \chi = 0$ and $\bar{\chi} \sigma^{\mu\nu} \chi = 0$, and hence the related operators vanish

Higgs Portal for Majorana Fermionic DM

Interactions for a **Majorana fermion** χ , the **SM Higgs boson** h , and quarks q :

$$\mathcal{L}_{\text{DM}} \supset \frac{1}{2} g_\chi h \bar{\chi} \chi$$

$$\mathcal{L}_{\text{SM}} \supset - \sum_q \frac{m_q}{v} h \bar{q} q, \quad q = d, u, s, c, b, t$$

The amplitude for $\chi(p_1) + q(k_1) \rightarrow \chi(p_2) + q(k_2)$:

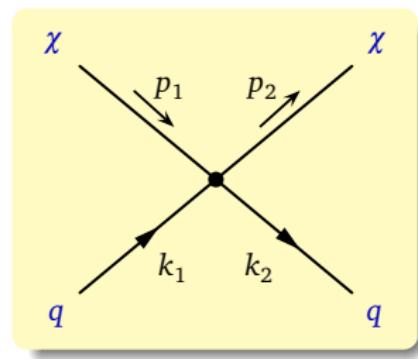
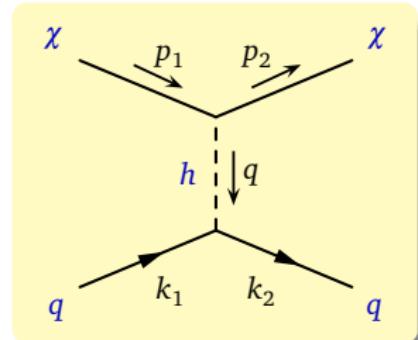
$$i\mathcal{M} = i g_\chi \bar{u}(p_2) u(p_1) \frac{i}{q^2 - m_h^2} \left(-i \frac{m_q}{v} \right) \bar{u}(k_2) u(k_1)$$

Zero momentum transfer $\Downarrow q^2 = (k_2 - k_1)^2 \rightarrow 0$

$$i\mathcal{M} = -i \frac{g_\chi m_q}{v m_h^2} \bar{u}(p_2) u(p_1) \bar{u}(k_2) u(k_1)$$

\Downarrow

$$\mathcal{L}_{\text{eff},q} = \sum_q G_{S,q} \bar{\chi} \chi \bar{q} q, \quad G_{S,q} = -\frac{g_\chi m_q}{2 v m_h^2}$$



Effective Lagrangian: Scalar Type

Scalar-type effective Lagrangian for a **spin-1/2 fermion** χ :

$$\mathcal{L}_{S,q} = \sum_q G_{S,q} \bar{\chi} \chi \bar{q} q \quad \Rightarrow \quad \mathcal{L}_{S,N} = \sum_{N=p,n} G_{S,N} \bar{\chi} \chi \bar{N} N$$

$$G_{S,N} = m_N \left(\sum_{q=u,d,s} \frac{G_{S,q}}{m_q} f_q^N + \sum_{q=c,b,t} \frac{G_{S,q}}{m_q} f_Q^N \right)$$

The second term accounts for DM interactions with gluons through loops of heavy quarks (c , b , and t): $f_Q^N = \frac{2}{27} \left(1 - \sum_{q=u,d,s} f_q^N \right)$

Form factor f_q^N is the contribution of q to m_N : $\langle N | m_q \bar{q} q | N \rangle = f_q^N m_N$

$$f_u^p \simeq 0.020, \quad f_d^p \simeq 0.026, \quad f_u^n \simeq 0.014, \quad f_d^n \simeq 0.036, \quad f_s^p = f_s^n \simeq 0.118$$

[Ellis et al., arXiv:hep-ph/0001005, PLB]

The scalar type induces **SI** DM-nucleon scattering with a cross section of

$$\sigma_{\chi N}^{\text{SI}} = \frac{n_\chi}{\pi} \mu_{\chi N}^2 G_{S,N}^2, \quad \mu_{\chi N} \equiv \frac{m_\chi m_N}{m_\chi + m_N}, \quad n_\chi = \begin{cases} 1, & \text{for Dirac fermion } \chi \\ 4, & \text{for Majorana fermion } \chi \end{cases}$$

Z Portal for Majorana Fermionic DM

Interactions for a **Majorana fermion** χ , the **Z boson**, and quarks q :

$$\mathcal{L}_{\text{DM}} \supset \frac{1}{2} g_\chi Z_{\mu} \bar{\chi} \gamma^\mu \gamma_5 \chi, \quad \mathcal{L}_{\text{SM}} \supset \frac{g}{2c_W} Z_{\mu} \sum_q \bar{q} \gamma^\mu (g_V^q - g_A^q \gamma_5) q$$

$$g_V^{u_i} = \frac{1}{2} - \frac{4}{3} s_W^2, \quad g_V^{d_i} = -\frac{1}{2} + \frac{2}{3} s_W^2, \quad g_A^{u_i} = \frac{1}{2} = -g_A^{d_i}, \quad c_W \equiv \cos \theta_W, \quad s_W \equiv \sin \theta_W$$

Z boson propagator

$$\frac{-i}{q^2 - m_Z^2} \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{m_Z^2} \right) \xrightarrow{q^2 \rightarrow 0} \frac{i}{m_Z^2} g_{\mu\nu}$$

Effective Lagrangian in the zero momentum transfer limit:

$$\mathcal{L}_{\text{eff},q} = \sum_q \bar{\chi} \gamma^\mu \gamma_5 \chi (G_{A,q} \bar{q} \gamma_\mu \gamma_5 q + G_{AV,q} \bar{q} \gamma_\mu q), \quad G_{A,q} = \frac{g_\chi g g_A^q}{4c_W m_Z^2}$$

$$G_{AV,q} = -\frac{g_\chi g g_V^q}{4c_W m_Z^2}$$

leads to $\sigma_{\chi N} \propto v^2$ and can be neglected for direct detection

Effective Lagrangian: Axial Vector Type

Axial-vector-type effective Lagrangian for a **spin-1/2 fermion χ** :

$$\mathcal{L}_{A,q} = \sum_q G_{A,q} \bar{\chi} \gamma^\mu \gamma_5 \chi \bar{q} \gamma_\mu \gamma_5 q \quad \Rightarrow \quad \mathcal{L}_{A,N} = \sum_{N=p,n} G_{A,N} \bar{\chi} \gamma^\mu \gamma_5 \chi \bar{N} \gamma_\mu \gamma_5 N$$

$$G_{A,N} = \sum_{q=u,d,s} G_{A,q} \Delta_q^N, \quad 2\Delta_q^N s_\mu \equiv \langle N | \bar{q} \gamma_\mu \gamma_5 q | N \rangle$$

Form factors Δ_q^N account the contributions of quarks and anti-quarks to the nucleon spin vector s_μ , and can be extracted from lepton-proton scattering data:

$$\Delta_u^p = \Delta_d^n \simeq 0.842, \quad \Delta_d^p = \Delta_u^n \simeq -0.427, \quad \Delta_s^p = \Delta_s^n \simeq -0.085$$

[HERMES coll., arXiv:hep-ex/0609039, PRD]

Neutron form factors are related to proton form factors by **isospin symmetry**

The axial vector type induces **SD** DM-nucleon scattering:

$$\sigma_{\chi N}^{\text{SD}} = \frac{3n_\chi}{\pi} \mu_{\chi N}^2 G_{A,N}^2, \quad n_\chi = \begin{cases} 1, & \text{for Dirac fermion } \chi \\ 4, & \text{for Majorana fermion } \chi \end{cases}$$

Z Portal for Complex Scalar DM

Interactions for a **complex scalar χ** , the **Z boson**, and quarks q :

$$\mathcal{L}_{\text{DM}} \supset g_\chi Z_\mu (\chi^* i \overleftrightarrow{\partial}^\mu \chi)$$

$$\mathcal{L}_{\text{SM}} \supset \frac{g}{2c_W} Z_\mu \sum_q \bar{q} \gamma^\mu (g_V^q - g_A^q \gamma_5) q$$

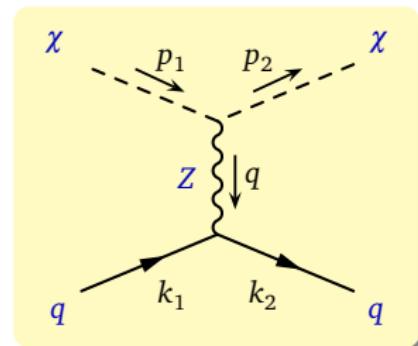
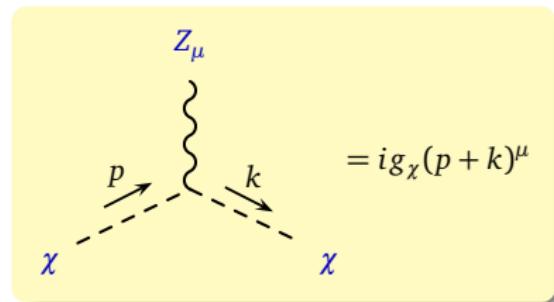
$$i\mathcal{M} = ig_\chi (p_1 + p_2)^\mu \frac{-i(g_{\mu\nu} - q_\mu q_\nu / m_Z^2)}{q^2 - m_Z^2}$$

$$\times i \frac{g}{2c_W} \bar{u}(k_2) \gamma^\nu (g_V^q - g_A^q \gamma_5) u(k_1)$$

$$\xrightarrow{q^2 \rightarrow 0} -i \frac{g_\chi g}{2c_W m_Z^2} (p_1 + p_2)^\mu \bar{u}(k_2) \gamma_\mu (g_V^q - g_A^q \gamma_5) u(k_1)$$

$$\mathcal{L}_{\text{eff},q} = \sum_q (\chi^* i \overleftrightarrow{\partial}^\mu \chi) (F_{V,q} \bar{q} \gamma_\mu q + F_{VA,q} \bar{q} \gamma_\mu \gamma_5 q)$$

$$F_{V,q} = -\frac{g_\chi g g_V^q}{2c_W m_Z^2}, \quad F_{VA,q} = \frac{g_\chi g g_A^q}{2c_W m_Z^2} (\Rightarrow \sigma_{\chi N} \propto v^2)$$



Effective Lagrangian: Vector Type

 Vector-type effective Lagrangian for a **complex scalar** χ :

$$\mathcal{L}_{V,q} = \sum_q F_{V,q} (\chi^* i \overleftrightarrow{\partial}^\mu \chi) \bar{q} \gamma_\mu q \quad \Rightarrow \quad \mathcal{L}_{A,N} = \sum_{N=p,n} F_{V,N} (\chi^* i \overleftrightarrow{\partial}^\mu \chi) \bar{N} \gamma_\mu N$$

The relation between $F_{V,N}$ and $F_{V,q}$ reflects the valence quark numbers in N :

$$F_{V,p} = 2F_{V,u} + F_{V,d}, \quad F_{V,n} = F_{V,u} + 2F_{V,d}$$

The vector type induces **SI** DM-nucleon scattering: $\sigma_{\chi N}^{\text{SI}} = \frac{1}{\pi} \mu_{\chi N}^2 F_{V,N}^2$

 Vector-type effective Lagrangian for a **Dirac fermion** χ :

$$\mathcal{L}_{V,q} = \sum_q G_{V,q} \bar{\chi} \gamma^\mu \chi \bar{q} \gamma_\mu q \quad \Rightarrow \quad \mathcal{L}_{A,N} = \sum_{N=p,n} G_{V,N} \bar{\chi} \gamma^\mu \chi \bar{N} \gamma_\mu N$$

It also induces **SI** DM-nucleon scattering:

$$\sigma_{\chi N}^{\text{SI}} = \frac{1}{\pi} \mu_{\chi N}^2 G_{V,N}^2, \quad G_{V,p} = 2G_{V,u} + G_{V,d}, \quad G_{V,n} = G_{V,u} + 2G_{V,d}$$

Effective Operators for DM-quark Interactions

| | Spin-1/2 DM | Spin-0 DM |
|-------------------------------|--|---|
| SI | $\bar{\chi}\chi\bar{q}q, \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ | $\chi^*\chi\bar{q}q, (\chi^*i\overleftrightarrow{\partial}^\mu\chi)\bar{q}\gamma_\mu q$ |
| SD | $\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q, \bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$ | |
| $\sigma_{\chi N} \propto v^2$ | $\bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5 q, \bar{\chi}\chi\bar{q}i\gamma_5 q$ $\bar{\chi}i\gamma_5\chi\bar{q}q, \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma_5 q$ $\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu q, \epsilon^{\mu\nu\rho\sigma}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\rho\sigma} q$ | $\chi^*\chi\bar{q}i\gamma_5 q$ $(\chi^*i\overleftrightarrow{\partial}^\mu\chi)\bar{q}\gamma_\mu\gamma_5 q$ |
| | Spin-3/2 DM | Spin-1 DM |
| SI | $\bar{\chi}^\mu\chi_\mu\bar{q}q, \bar{\chi}^\nu\gamma^\mu\chi_\nu\bar{q}\gamma_\mu q$ | $\chi_\mu^*\chi^\mu\bar{q}q, (\chi_\nu^*i\overleftrightarrow{\partial}^\mu\chi^\nu)\bar{q}\gamma_\mu q$ |
| SD | $\bar{\chi}^\nu\gamma^\mu\gamma_5\chi_\nu\bar{q}\gamma_\mu\gamma_5 q, \bar{\chi}^\rho\sigma^{\mu\nu}\chi_\rho\bar{q}\sigma_{\mu\nu} q$ $i(\bar{\chi}^\mu\chi^\nu - \bar{\chi}^\nu\chi^\mu)\bar{q}\sigma_{\mu\nu} q$ | $i(\chi_\mu^*\chi_\nu - \chi_\nu^*\chi_\mu)\bar{q}\sigma^{\mu\nu} q$ $\epsilon^{\mu\nu\rho\sigma}(\chi_\mu^*\overleftrightarrow{\partial}_\nu\chi_\rho)\bar{q}\gamma_\sigma\gamma_5 q$ |
| $\sigma_{\chi N} \propto v^2$ | $\bar{\chi}^\mu i\gamma_5\chi_\mu\bar{q}i\gamma_5 q, \bar{\chi}^\mu\chi_\mu\bar{q}i\gamma_5 q$ $\bar{\chi}^\mu i\gamma_5\chi_\mu\bar{q}q, \bar{\chi}^\nu\gamma^\mu\chi_\nu\bar{q}\gamma_\mu\gamma_5 q$ $\bar{\chi}^\mu\gamma^\mu\gamma_5\chi_\nu\bar{q}\gamma_\mu q, \epsilon^{\mu\nu\rho\sigma}i(\bar{\chi}_\mu\chi_\nu - \bar{\chi}_\nu\chi_\mu)\bar{q}\sigma_{\rho\sigma} q$ $\epsilon^{\mu\nu\rho\sigma}\bar{\chi}^\alpha\sigma_{\mu\nu}\chi_\alpha\bar{q}\sigma_{\rho\sigma} q, (\bar{\chi}^\mu\gamma_5\chi^\nu - \bar{\chi}^\nu\gamma_5\chi^\mu)\bar{q}\sigma_{\mu\nu} q$ $\epsilon^{\mu\nu\rho\sigma}(\bar{\chi}_\mu\gamma_5\chi_\nu - \bar{\chi}_\nu\gamma_5\chi_\mu)\bar{q}\sigma_{\rho\sigma} q$ | $\chi_\mu^*\chi^\mu\bar{q}i\gamma_5 q$ $(\chi_\nu^*i\overleftrightarrow{\partial}^\mu\chi^\nu)\bar{q}\gamma_\mu\gamma_5 q$ $\epsilon^{\mu\nu\rho\sigma}(\chi_\mu^*\overleftrightarrow{\partial}_\nu\chi_\rho)\bar{q}\gamma_\sigma q$ $\epsilon^{\mu\nu\rho\sigma}i(\chi_\mu^*\chi_\nu - \chi_\nu^*\chi_\mu)\bar{q}\sigma_{\rho\sigma} q$ |

[Zheng, ZHY, Shao, Bi, Li, Zhang, arXiv:1012.2022, NPB; ZHY, Zheng, Bi, Li, Yao, Zhang, arXiv:1112.6052, NPB; Ding & Liao, arXiv:1201.0506, JHEP]

Homework

- ① Derive the speed distribution $f(v)$ in Page 8 from $f(\mathbf{v}) = \tilde{f}(\mathbf{v} + \mathbf{v}_{\text{obs}})$
- ② Calculate the normalization factor for the velocity distribution $\tilde{f}(\tilde{\mathbf{v}})$ in Page 7 if the escape velocity v_{esc} is taken into account
- ③ Derive the recoil velocity v_R in Page 9 from the laws of energy and momentum conservation
- ④ Examine the conservation of electric charge, lepton number, and baryon number for the reactions producing solar neutrinos in Page 26
- ⑤ Evaluate the values of DM-nucleon effective couplings $G_{S,p}$ ($G_{A,p}$) and $G_{S,n}$ ($G_{A,n}$) for the Higgs-portal (Z-portal) model in Page 30 (32) using the values of form factors listed in Page 31 (33)
- ⑥ Proof the expressions for $\sigma_{\chi N}^{\text{SI}}$ and $\sigma_{\chi N}^{\text{SD}}$ shown in Pages 31, 33, and 35
- ⑦ Examine the hermiticity of the operators tabulated in Page 36