Direct and Indirect Detection of Dark Matter

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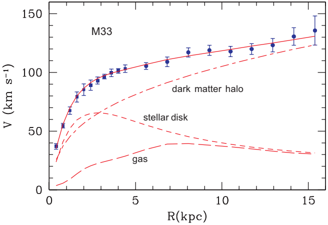
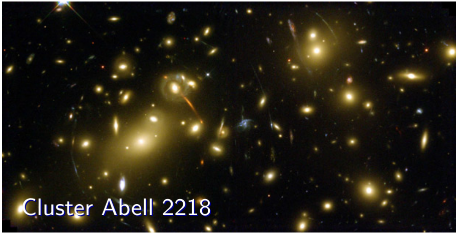
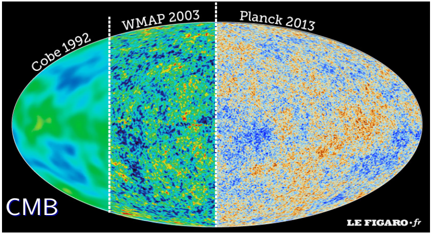
Dark Matter in the Universe

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







Inferred Properties of Dark Matter

- **Dark (electrically neutral):** no light emitted from it
- **Nonbaryonic:** BBN & CMB observations
- **Long lived:** survived from early eras of the Universe to now
- **Colorless:** otherwise, it would bind with nuclei
- **Cold:** structure formation theory
- **Abundance:** more than 80% of all matter in the Universe

$$\rho_{\rm DM} \sim 0.3 - 0.4~\text{GeV/cm}^3 \text{ near the earth}$$

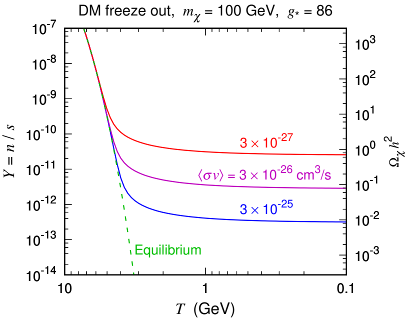
DM Relic Abundance

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

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

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

$$\Rightarrow \quad \langle\sigma_{\mathrm{ann}}v\rangle \simeq 3\times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$$



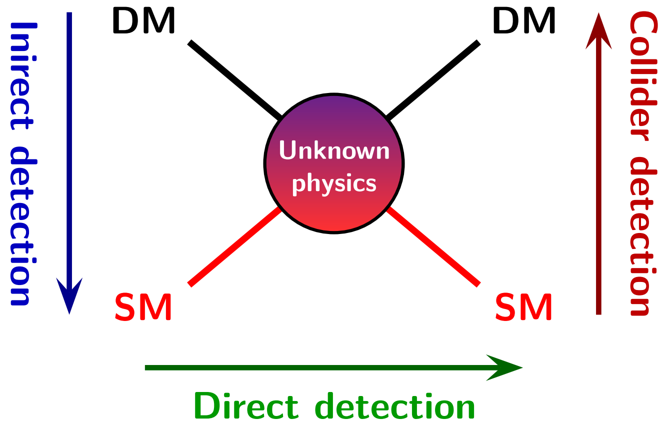
Assuming the annihilation process consists of two weak interaction vertices with the $\mathrm{SU(2)_L}$ gauge coupling $g \simeq 0.64$, for $m_\chi \sim \mathcal{O}(\mathrm{TeV})$ we have

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

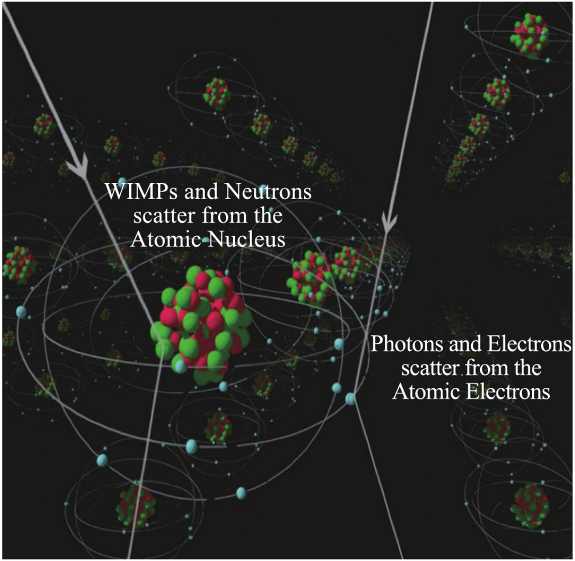
$\Rightarrow$ A very attractive class of DM candidates:

Weakly interacting massive particles (WIMPs)

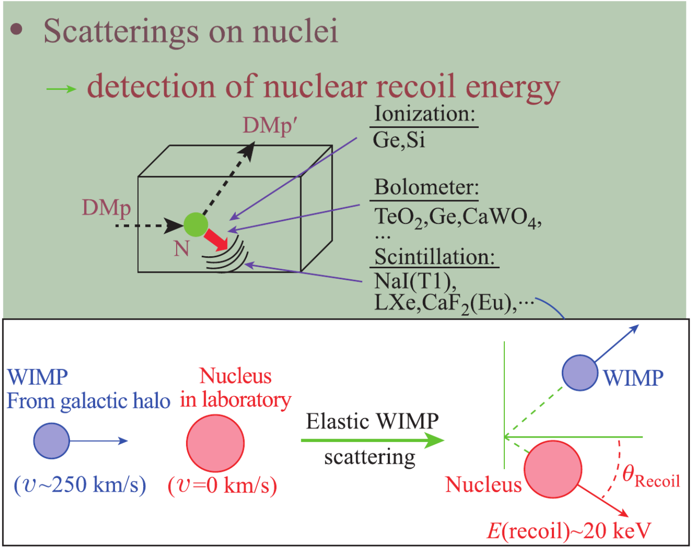
Experimental Approaches to Dark Matter



WIMP Scattering off Atomic Nuclei



Direct Detection



[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**:

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

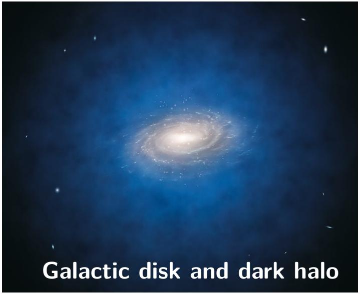
$$\langle \tilde{\mathbf{v}} \rangle = \int \tilde{\mathbf{v}} \tilde{f}(\tilde{\mathbf{v}}) d^3\tilde{v} = \mathbf{0}, \quad \langle \tilde{v}^2 \rangle = \int \tilde{v}^2 \tilde{f}(\tilde{\mathbf{v}}) d^3\tilde{v} = \frac{3}{2} v_0^2$$

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]



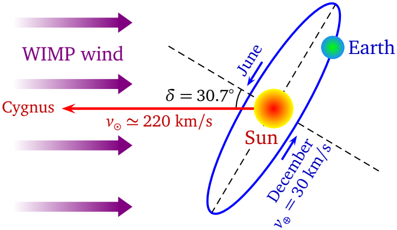
[Credit: ESO/L. Calçada]

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

Earth Rest Frame

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

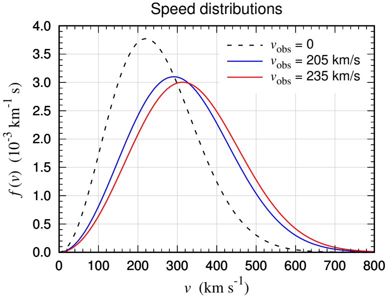
$$\tilde{\mathbf{v}} = \mathbf{v} + \mathbf{v}_{\text{obs}}, \quad \mathbf{v}_{\text{obs}} = \mathbf{v}_{\odot} + \mathbf{v}_{\oplus}$$



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 ($\omega = 2\pi/\text{year}$)

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

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

Nuclear Recoil

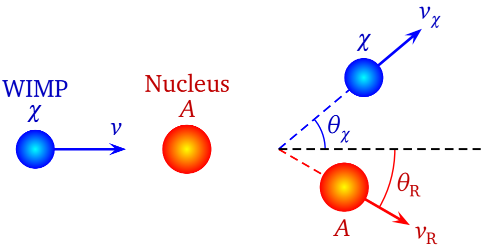
Energy conservation:

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

Momentum conservation:

$$m_\chi v = m_\chi v_\chi \cos\theta_\chi + m_A v_\mathrm{R} \cos\theta_\mathrm{R}$$

$$m_\chi v_\chi \sin\theta_\chi = m_A v_\mathrm{R} \sin\theta_\mathrm{R}$$



$\Rightarrow$ Recoil velocity $v_\mathrm{R} = \dfrac{2m_\chi v \cos\theta_\mathrm{R}}{m_\chi + m_A}$

$\Rightarrow$ **Recoil momentum** (momentum transfer) $q_\mathrm{R} = m_A v_\mathrm{R} = 2\mu_{\chi A} v \cos\theta_\mathrm{R}$

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

Forward scattering ($\theta_\mathrm{R} = 0$) $\Rightarrow$ maximal momentum transfer $q_\mathrm{R}^\mathrm{max} = 2\mu_{\chi A} v$

Nuclear Recoil

Energy conservation:

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

Momentum conservation:

$$m_\chi v = m_\chi v_\chi \cos\theta_\chi + m_A v_\mathrm{R} \cos\theta_\mathrm{R}$$

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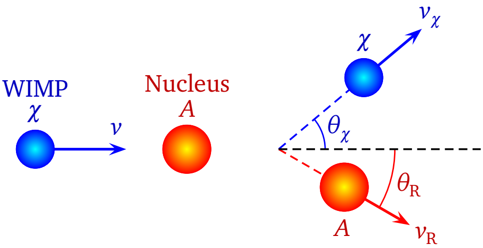


$\Rightarrow$ Recoil velocity $v_\mathrm{R} = \dfrac{2m_\chi v \cos\theta_\mathrm{R}}{m_\chi + m_A}$

$\Rightarrow$ **Recoil momentum** (momentum transfer) $q_\mathrm{R} = m_A v_\mathrm{R} = 2\mu_{\chi A} v \cos\theta_\mathrm{R}$

$\Rightarrow$ **Kinetic energy** of the recoiled nucleus $E_\mathrm{R} = \dfrac{q_\mathrm{R}^2}{2m_A} = \dfrac{2\mu_{\chi A}^2}{m_A} v^2 \cos^2\theta_\mathrm{R}$

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

$$q_\mathrm{R} = m_\chi v \sim 100\ \text{MeV}, \quad E_\mathrm{R} = \frac{1}{2}m_\chi v^2 \sim 50\ \text{keV}$$

Event Rate

Event rate per unit time per unit energy interval:

$$\frac{dR}{dE_\mathrm{R}} = N_\mathrm{T}\frac{\rho_\oplus}{m_\chi}\int_{v_\mathrm{min}}^{v_\mathrm{max}} d^3v\, f(\mathbf{v})v\frac{d\sigma_{\chi A}}{dE_\mathrm{R}}$$

Astrophysics factors
Particle physics factors
Detector factors

N_T: **target nucleus number**

$\rho_\oplus \simeq 0.3 - 0.4\ \mathrm{GeV/cm^3}$: DM **mass density** around the Earth

($\rho_\oplus/m_\chi$ is the DM particle **number density** around the Earth)

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

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

Maximal velocity v_max: determined by the DM **escape velocity** v_esc

($v_\mathrm{esc} \simeq 544$ 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: $\sigma_{\chi A}^{\text{SI}} \propto \mu_{\chi A}^2 [Z G_p + (A - Z) G_n]^2$

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

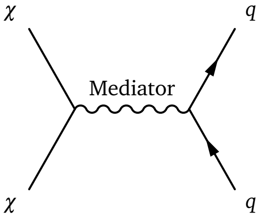
Nucleus properties: **mass number** A, **atomic number** Z, **spin** J_A, expectation value of the **proton (neutron) spin content** in the nucleus S_p^A (S_n^A)

$G_p^{(\prime)}$ 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

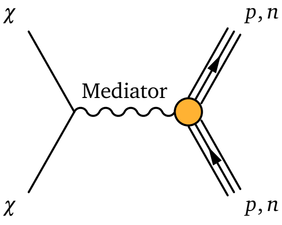
DM-parton interaction



$\mathcal{M}(\chi q \to \chi q)$

$\Rightarrow$

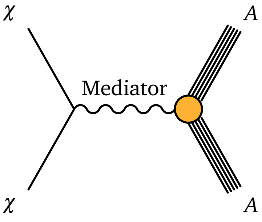
DM-nucleon interaction



$\mathcal{M}(\chi N \to \chi N)$

$\Rightarrow$

DM-nucleus interaction

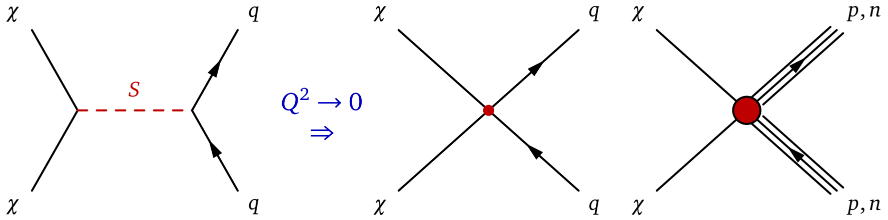


$\mathcal{M}(\chi A \to \chi A)$

- 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**

Zero Momentum Transfer Limit

- As the momentum transfer 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: $\dfrac{i}{Q^2 - m_S^2} \quad \Rightarrow \quad -\dfrac{i}{m_S^2}$

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

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 $\sigma_{\chi N} \propto |Q^2|$:

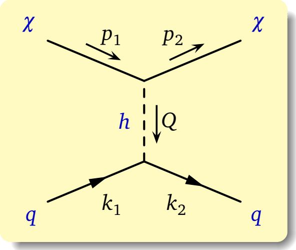
  $\bar{\chi} i\gamma_5 \chi \bar{N} i\gamma_5 N, \quad \bar{\chi}\chi\bar{N} i\gamma_5 N, \quad \bar{\chi} i\gamma_5 \chi \bar{N} N, \quad \bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu\gamma_5 N, \quad \bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}\gamma_\mu N$
- For a **Majorana fermion** χ instead, we have $\bar{\chi}\gamma^\mu\chi = 0$ 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:

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

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



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

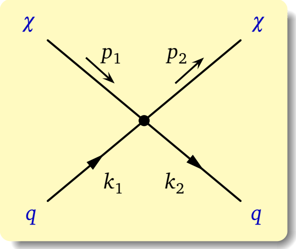
$$i\mathcal{M} = i g_\chi \bar{u}(p_2)u(p_1)\frac{i}{Q^2 - m_h^2}\left(-i\frac{m_q}{v}\right)\bar{u}(k_2)u(k_1)$$

Zero momentum transfer $\Downarrow$ $Q^2 = (k_2 - k_1)^2 \to 0$

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

$$\Downarrow$$

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



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): $f_Q^N = \dfrac{2}{27}\left(1 - \sum_{q=u,d,s} f_q^N\right)$

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

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

Z Portal for Majorana Fermionic DM

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

$$\mathcal{L}_{\mathrm{DM}} \supset \frac{1}{2} g_\chi Z_\mu \bar{\chi} \gamma^\mu \gamma_5 \chi, \quad \mathcal{L}_{\mathrm{SM}} \supset \frac{g}{2c_{\mathrm{W}}} Z_\mu \sum_q \bar{q} \gamma^\mu (g_{\mathrm{V}}^q - g_{\mathrm{A}}^q \gamma_5) q$$

$$g_{\mathrm{V}}^{u_i} = \frac{1}{2} - \frac{4}{3} s_{\mathrm{W}}^2, \quad g_{\mathrm{V}}^{d_i} = -\frac{1}{2} + \frac{2}{3} s_{\mathrm{W}}^2, \quad g_{\mathrm{A}}^{u_i} = \frac{1}{2} = -g_{\mathrm{A}}^{d_i}, \quad c_{\mathrm{W}} \equiv \cos\theta_{\mathrm{W}}, \quad s_{\mathrm{W}} \equiv \sin\theta_{\mathrm{W}}$$

Z **boson propagator** $$\frac{-i}{Q^2 - m_Z^2} \left(g_{\mu\nu} - \frac{Q_\mu Q_\nu}{m_Z^2} \right) \xrightarrow{Q^2 \to 0} \frac{i}{m_Z^2} g_{\mu\nu}$$

Effective Lagrangian in the zero momentum transfer limit:

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

$G_{\mathrm{AV},q} = -\dfrac{g_\chi g g_{\mathrm{V}}^q}{4 c_{\mathrm{W}} m_Z^2}$ leads to $\sigma_{\chi N} \propto |Q^2|$ and can be neglected for direct detection

Effective Lagrangian: Axial Vector Type

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

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

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

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:

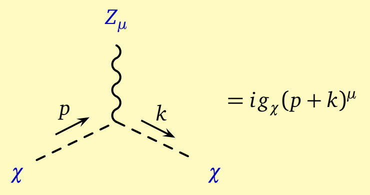
$$\sigma_{\chi N}^{\mathrm{SD}} = \frac{3n_\chi}{\pi}\mu_{\chi N}^2 G_{\mathrm{A},N}^2, \quad n_\chi = \begin{cases} 1, & \text{for Dirac fermion } \chi \\ 4, & \text{for Majorana fermion } \chi \end{cases}$$

Z Portal for Complex Scalar DM

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

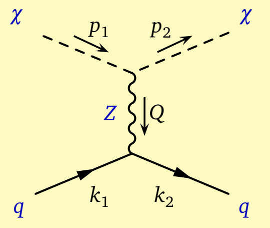
$$\mathcal{L}_{\mathrm{DM}} \supset g_\chi Z_\mu (\chi^* i \overleftrightarrow{\partial^\mu} \chi)$$

$$\mathcal{L}_{\mathrm{SM}} \supset \frac{g}{2c_{\mathrm{W}}} Z_\mu \sum_q \bar{q}\gamma^\mu (g_{\mathrm{V}}^q - g_{\mathrm{A}}^q \gamma_5) q$$



$$i\mathcal{M} = ig_\chi (p_1 + p_2)^\mu \frac{-i(g_{\mu\nu} - Q_\mu Q_\nu / m_Z^2)}{Q^2 - m_Z^2} \times i \frac{g}{2c_{\mathrm{W}}} \bar{u}(k_2)\gamma^\nu (g_{\mathrm{V}}^q - g_{\mathrm{A}}^q \gamma_5) u(k_1)$$

$$\xrightarrow{Q^2 \to 0} -i \frac{g_\chi g}{2c_{\mathrm{W}} m_Z^2} (p_1 + p_2)^\mu \bar{u}(k_2) \gamma_\mu (g_{\mathrm{V}}^q - g_{\mathrm{A}}^q \gamma_5) u(k_1)$$



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

$$F_{\mathrm{V},q} = -\frac{g_\chi g g_{\mathrm{V}}^q}{2c_{\mathrm{W}} m_Z^2}, \quad F_{\mathrm{VA},q} = \frac{g_\chi g g_{\mathrm{A}}^q}{2c_{\mathrm{W}} m_Z^2} (\Rightarrow \sigma_{\chi N} \propto |Q^2|)$$

Effective Lagrangian: Vector Type

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

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

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

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

The vector type induces **SI** DM-nucleon scattering: $\sigma^{\mathrm{SI}}_{\chi N} = \frac{1}{\pi}\mu^2_{\chi N}F^2_{\mathrm{V},N}$

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

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

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

$$\sigma^{\mathrm{SI}}_{\chi N} = \frac{1}{\pi}\mu^2_{\chi N}G^2_{\mathrm{V},N}, \quad G_{\mathrm{V},p} = 2G_{\mathrm{V},u} + G_{\mathrm{V},d}, \quad G_{\mathrm{V},n} = G_{\mathrm{V},u} + 2G_{\mathrm{V},d}$$

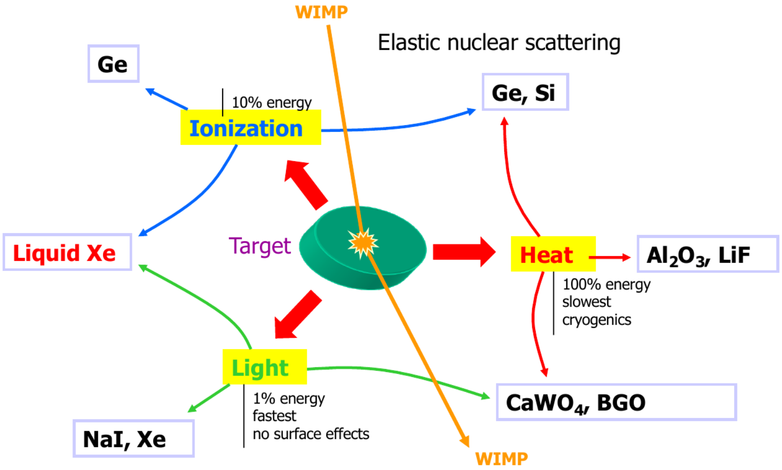
Effective Operators for DM-quark Interactions

	Spin-1/2 DM	Spin-0 DM
SI	$\bar\chi\chi\bar q q, \quad \bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	$\chi^*\chi\bar q q, \quad (\chi^* i\overleftrightarrow{\partial^\mu}\chi)\bar q\gamma_\mu q$
SD	$\bar\chi\gamma^\mu\gamma_5\chi\bar q\gamma_\mu\gamma_5 q, \quad \bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu}q$	
$\sigma_{\chi N}\propto \lvert Q^2\rvert$	$\bar\chi i\gamma_5\chi\bar q i\gamma_5 q, \quad \bar\chi\chi\bar q i\gamma_5 q$ $\bar\chi i\gamma_5\chi\bar q q, \quad \bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma_5 q$ $\bar\chi\gamma^\mu\gamma_5\chi\bar q\gamma_\mu q, \quad \varepsilon^{\mu\nu\rho\sigma}\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\rho\sigma}q$	$\chi^*\chi\bar q i\gamma_5 q$ $(\chi^* i\overleftrightarrow{\partial^\mu}\chi)\bar q\gamma_\mu\gamma_5 q$

	Spin-3/2 DM	Spin-1 DM
SI	$\bar\chi^\mu\chi_\mu\bar q q, \quad \bar\chi^\nu\gamma^\mu\chi_\nu\bar q\gamma_\mu q$	$\chi_\mu^*\chi^\mu\bar q q, \quad (\chi_\nu^* i\overleftrightarrow{\partial^\mu}\chi^\nu)\bar q\gamma_\mu q$
SD	$\bar\chi^\nu\gamma^\mu\gamma_5\chi_\nu\bar q\gamma_\mu\gamma_5 q, \quad \bar\chi^\rho\sigma^{\mu\nu}\chi_\rho\bar q\sigma_{\mu\nu}q$ $i(\bar\chi^\mu\chi^\nu - \bar\chi^\nu\chi^\mu)\bar q\sigma_{\mu\nu}q$	$i(\chi_\mu^*\chi_\nu - \chi_\nu^*\chi_\mu)\bar q\sigma^{\mu\nu}q$ $\varepsilon^{\mu\nu\rho\sigma}(\chi_\mu^*\overleftrightarrow{\partial_\nu}\chi_\rho)\bar q\gamma_\sigma\gamma_5 q$
$\sigma_{\chi N}\propto \lvert Q^2\rvert$	$\bar\chi^\mu i\gamma_5\chi_\mu\bar q i\gamma_5 q, \quad \bar\chi^\mu\chi_\mu\bar q i\gamma_5 q$ $\bar\chi^\mu i\gamma_5\chi_\mu\bar q q, \quad \bar\chi^\nu\gamma^\mu\chi_\nu\bar q\gamma_\mu\gamma_5 q$ $\bar\chi^\mu\gamma^\mu\gamma_5\chi_\nu\bar q\gamma_\mu q, \quad \varepsilon^{\mu\nu\rho\sigma}i(\bar\chi_\mu\chi_\nu - \bar\chi_\nu\chi_\mu)\bar q\sigma_{\rho\sigma}q$ $\varepsilon^{\mu\nu\rho\sigma}\bar\chi^\alpha\sigma_{\mu\nu}\chi_\alpha\bar q\sigma_{\rho\sigma}q, \quad (\bar\chi^\mu\gamma_5\chi^\nu - \bar\chi^\nu\gamma_5\chi^\mu)\bar q\sigma_{\mu\nu}q$ $\varepsilon^{\mu\nu\rho\sigma}(\bar\chi_\mu\gamma_5\chi_\nu - \bar\chi_\nu\gamma_5\chi_\mu)\bar q\sigma_{\rho\sigma}q$	$\chi_\mu^*\chi^\mu\bar q i\gamma_5 q$ $(\chi_\nu^* i\overleftrightarrow{\partial^\mu}\chi^\nu)\bar q\gamma_\mu\gamma_5 q$ $\varepsilon^{\mu\nu\rho\sigma}(\chi_\mu^*\overleftrightarrow{\partial_\nu}\chi_\rho)\bar q\gamma_\sigma q$ $\varepsilon^{\mu\nu\rho\sigma}i(\chi_\mu^*\chi_\nu - \chi_\nu^*\chi_\mu)\bar q\sigma_{\rho\sigma}q$

[Zheng, **ZHY**, Shao, Bi, Li, Zhang, arXiv:1012.2022, NPB;
ZHY, Zheng, Bi, Li, Yao, Zhang, arXiv:1112.6052, NPB]

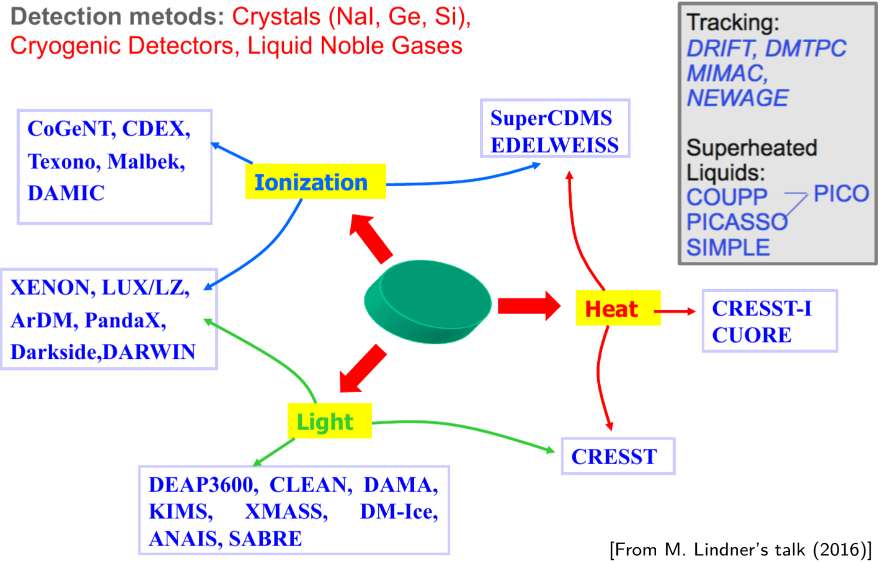
Technologies and Detector Material



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

Technologies and Detector Material

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



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

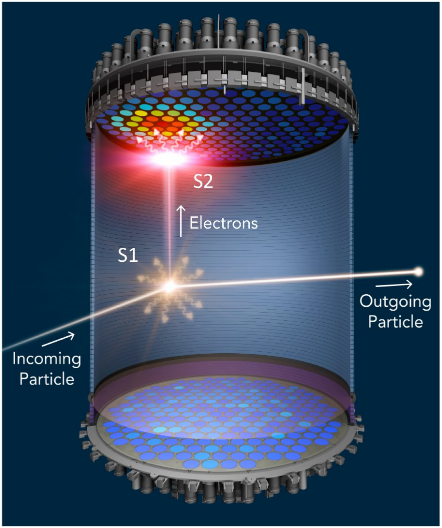
Example: Dual-phase Xenon Time Projection Chamber

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

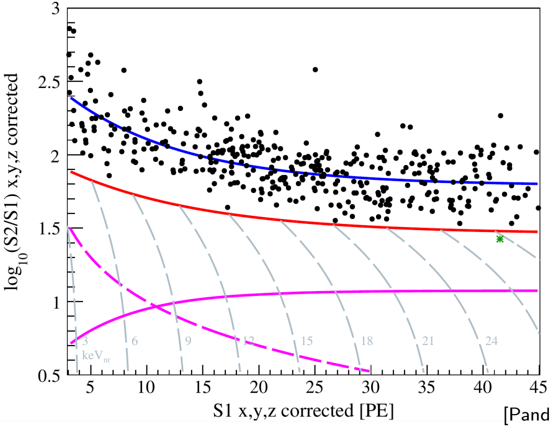
Experiments: XENON, LUX, PandaX



[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



ER calibration median

NR calibration median

99.99% NR acceptance

[PandaX-II coll., arXiv:1607.07400, PRL]

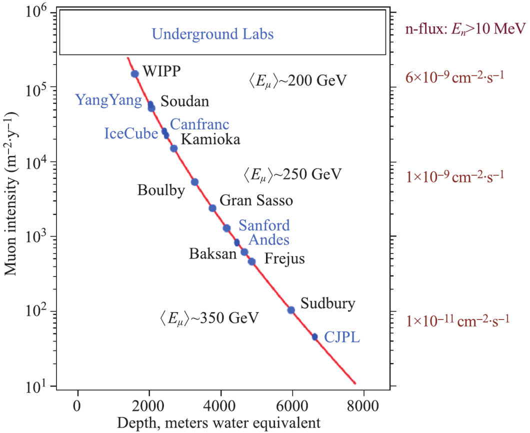
Backgrounds

Background suppression:

Deep underground

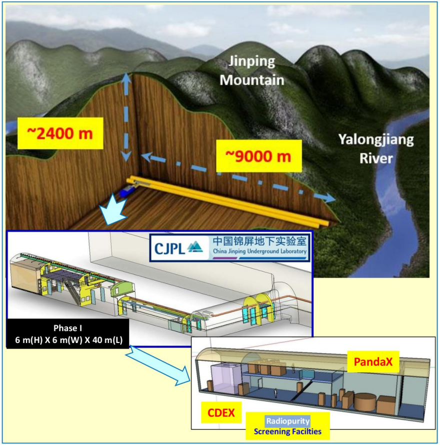
Shielded environments

- **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)

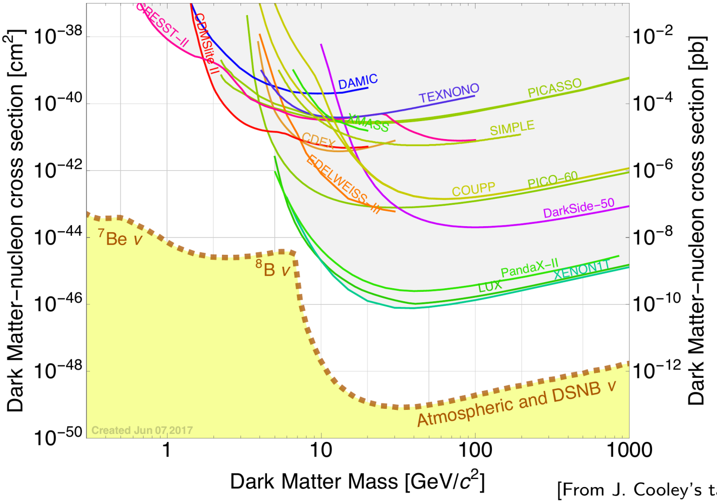


[Yue *et al.*, arXiv:1602.02462]

Experiments: CDEX, PandaX

Exclusion Limits for SI Scattering

💡 Assuming **isospin conservation** ($G_p = G_n$) for **SI scattering**, we can treat protons and neutrons as the same species, **"nucleons"**



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

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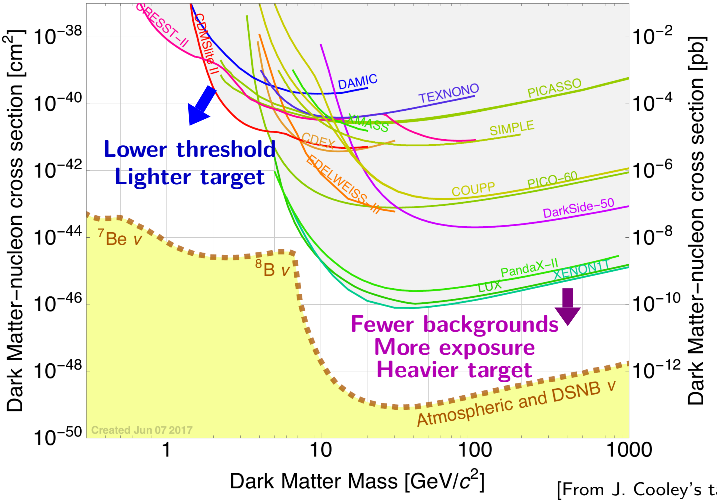
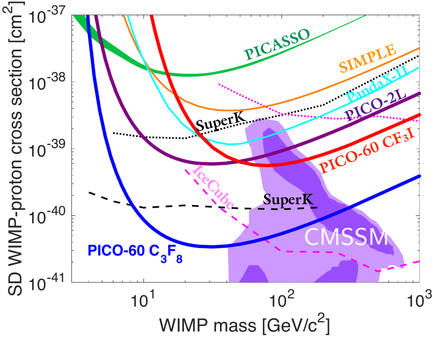


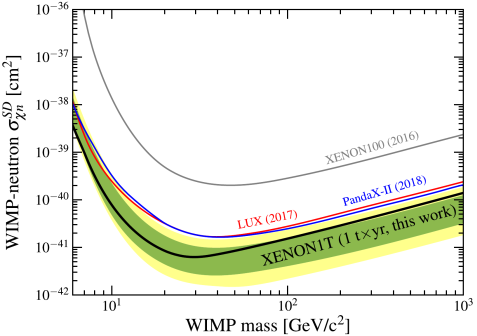
[From J. Cooley's talk (2017)]

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**



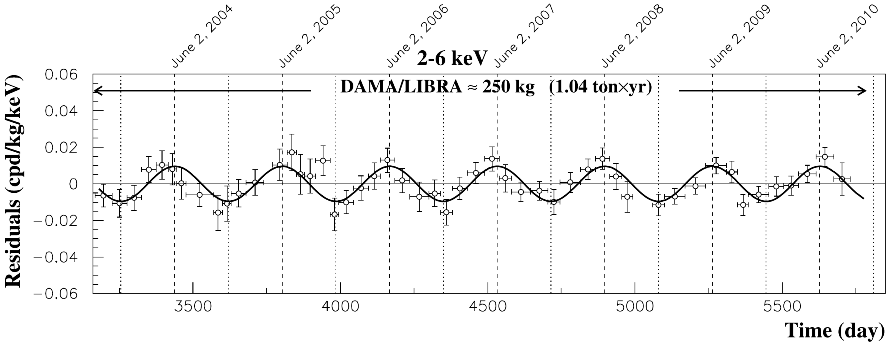
[PICO coll., arXiv:1702.07666, PRL]



[XENON1T coll., arXiv:1902.03234, 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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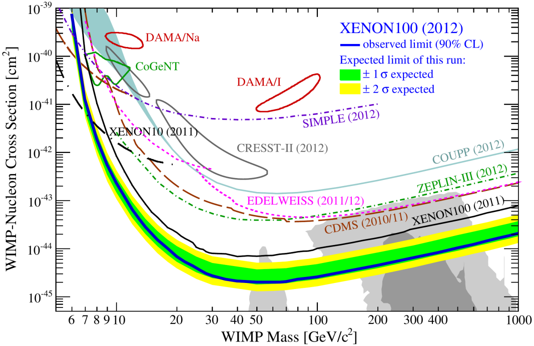


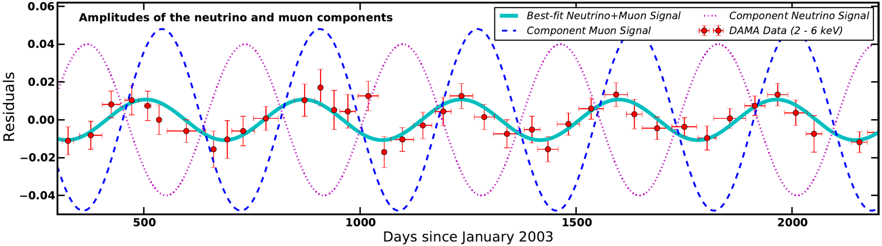
[XENON100 coll., arXiv:1207.5988, PRL]

- 😨 **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**



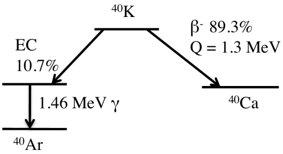
😏 **Objection:** Klinger & Kudryavtsev, "muon-induced neutrons do not explain the DAMA data," arXiv:1503.07225, PRL

Further Test: SABRE Project

SABRE: Sodium iodide with Active Background REjection

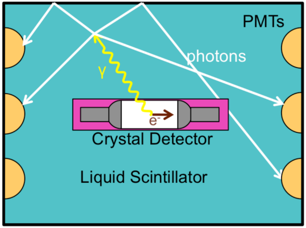
- Complementary tests in **both hemispheres**: one part in Gran Sasso (Italy) and one part in Stawell (Australia)
- Developing **low background** scintillating NaI(Tl) crystals that exceed the radio-purity of DAMA/LIBRA
- A well-shielded **active veto** to reduce internal and external backgrounds

Ultra-high purity NaI(Tl) detector + Active veto detector



^{40}K→^{40}Ar, ~11% branch ratio

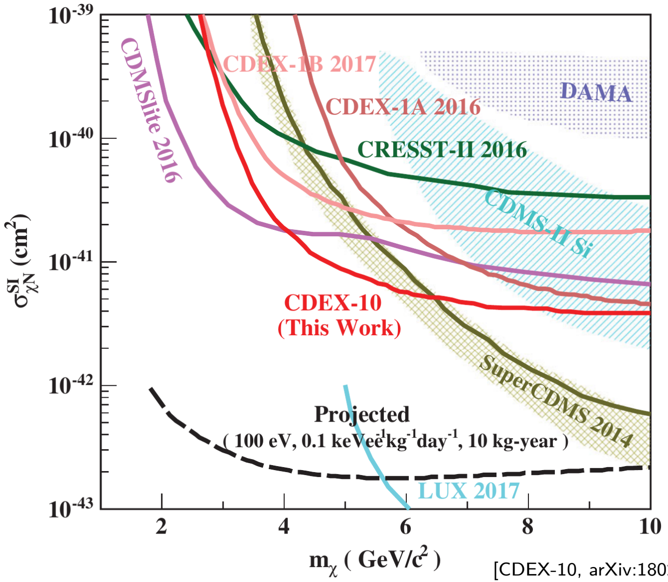
- 3 keV K shell X-ray, Auger e$^-$
- Background at ~3 keV if γ escapes



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

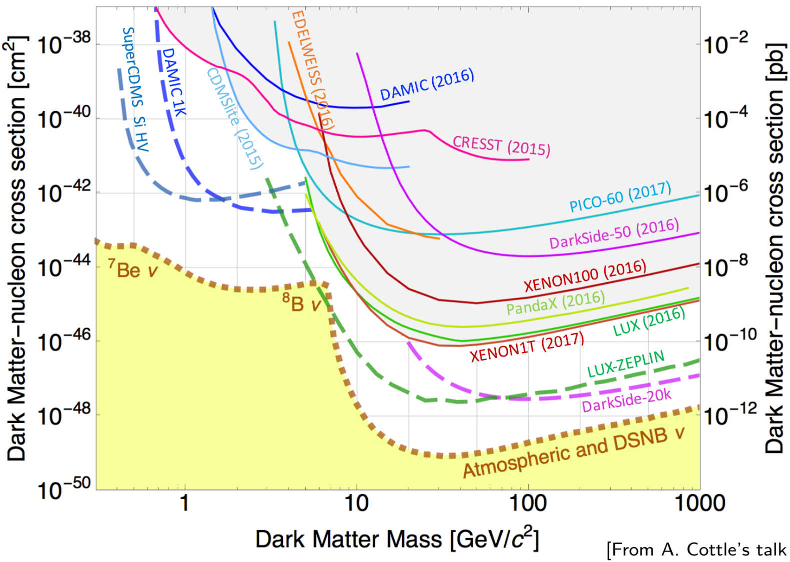
[From E. Barberio's talk]

Low Mass Region



[CDEX-10, arXiv:1802.09016, PRL]

Near Future Prospect

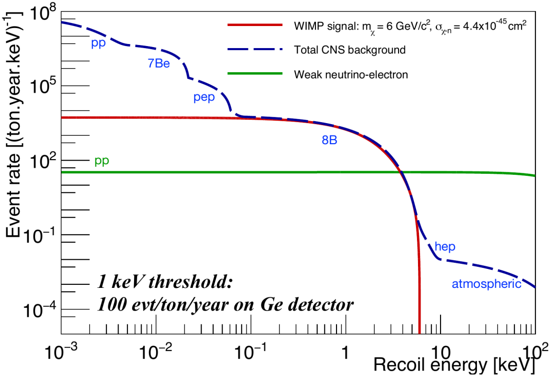


[From A. Cottle's talk (2017)]

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:
    $p + p \to \mathrm{D} + e^+ + \nu_e$
  - ^{7}Be neutrinos:
    $e^- + {}^7\mathrm{Be} \to {}^7\mathrm{Li} + \nu_e$
  - pep neutrinos:
    $p + e^- + p \to \mathrm{D} + \nu_e$
  - ^{8}B neutrinos:
    ${}^8\mathrm{B} \to {}^8\mathrm{Be}^* + e^+ + \nu_e$
  - Hep neutrinos:
    ${}^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$



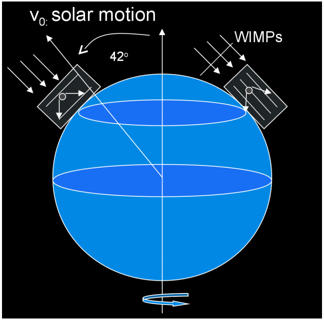
[From J. Billard's talk (2016)]

- **Atmospheric neutrinos**
  Cosmic-ray collisions in the atmosphere
- **Diffuse supernova neutrino background (DSNB)**
  All supernova explosions in the past history of the Universe

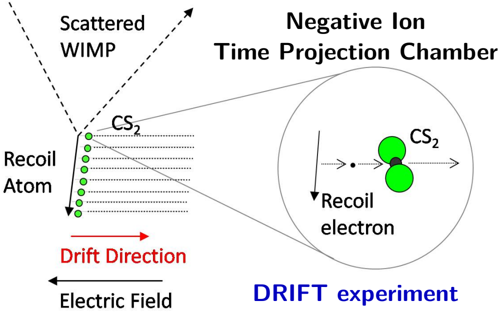
Going beyond the Neutrino Floor

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

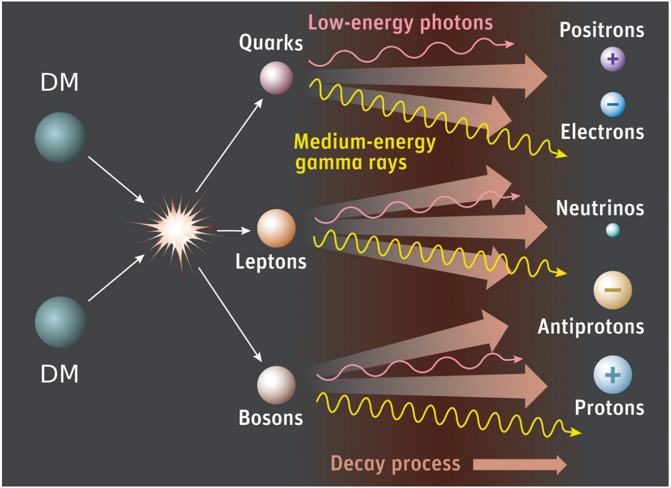


DRIFT experiment

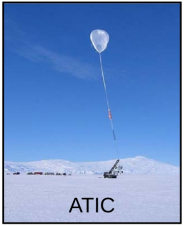
[From J. Spooner's talk (2010)]

Indirect Detection

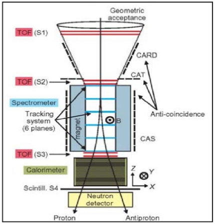
Indirect detection looks for stable products (γ **rays, cosmic rays, neutrinos**) from dark matter **annihilation** or **decay** (if DM is not totally stable) in space

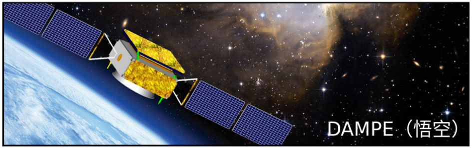


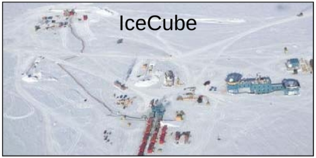
Indirect Detection Experiments



PAMELA







Dark Matter Source Function

Particle number per unit time per unit volume per unit energy interval of a stable species (γ, $e^\pm$, ν, p, $\bar{p}$, $\cdots$) produced from DM annihilation or decay:

(Annihilation) $$Q_{\rm ann}(\mathbf{x}, E) = \frac{\langle \sigma_{\rm ann} v \rangle_{\rm tot}}{2m_\chi^2} \rho^2(\mathbf{x}) \sum_i F_i \left(\frac{dN}{dE} \right)_i$$

(Decay) $$Q_{\rm dec}(\mathbf{x}, E) = \frac{1}{\tau_\chi m_\chi} \rho(\mathbf{x}) \sum_i B_i \left(\frac{dN}{dE} \right)_i$$

Astrophysics factors

Particle physics factors

$\rho(\mathbf{x})$: **DM mass density** at the source position $\mathbf{x}$

$(dN/dE)_i$: number per unit energy interval from a single event in the channel i

$\langle \sigma_{\rm ann} v \rangle_{\rm tot}$: thermal average of the total **annihilation cross section** multiplied by the relative velocity between the two incoming DM particles

$F_i \equiv \langle \sigma_{\rm ann} v \rangle_i / \langle \sigma_{\rm ann} v \rangle_{\rm tot}$: **branching fraction** of the annihilation channel i

$\tau_\chi \equiv 1/\Gamma_\chi$: mean lifetime of the DM particle

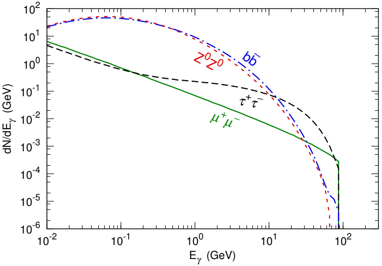
$B_i \equiv \Gamma_i/\Gamma_\chi$: **branching ratio** of the decay channel i

γ rays from DM: Continuous Spectrum

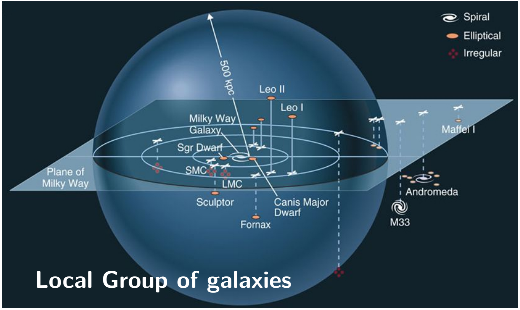
DM pair annihilation or decay into e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, W^+W^-, Z^0Z^0, h^0h^0

$\Downarrow$

γ-ray emission from final state radiation or particle decays

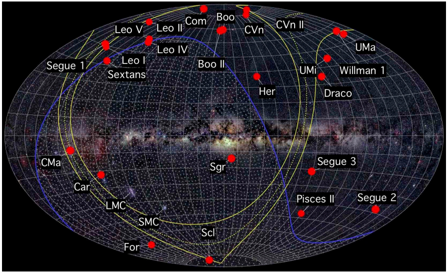


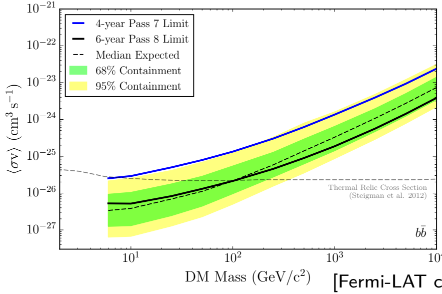
- **Cut-off energy**:
  m_χ for DM annihilation
  $m_\chi/2$ for DM decay
- More promising to look at **DM-dominated regions**:
  💥 Galactic Center
  💥 Galactic halo
  💥 dwarf galaxies
  💥 clusters of galaxies

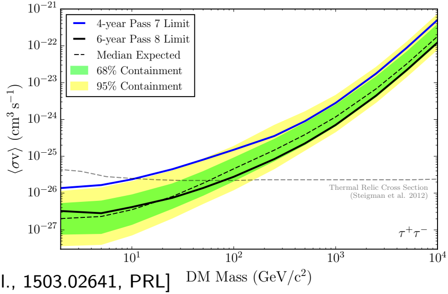


γ-ray Observation of Dwarf Galaxies

- The space experiment **Fermi-LAT** searched for γ-ray emission from **dwarf spheroidal satellite galaxies** of the Milky Way and found no significant signal
- Based on the 6-year data, upper limits on DM annihilation cross section are given







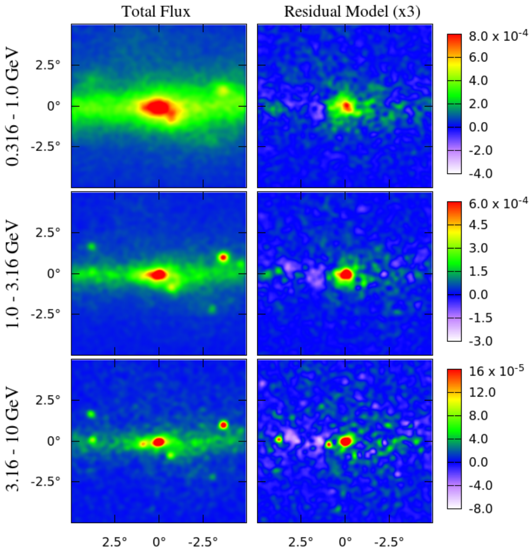
[Fermi-LAT coll., 1503.02641, PRL]

GeV Excess at the Galactic Center?

Since 2009, several groups reported an **excess of continuous spectrum γ-rays** in the **Fermi-LAT data** after subtracting well-known astrophysical backgrounds, locating in the **Galactic Center (GC)** region and peaking at a few GeV

Left: raw γ-ray maps
Right: residual maps after subtracting the Galactic diffuse model, 20 cm template, point sources, and isotropic template

→



[Daylan et al., 1402.6703, PDU]

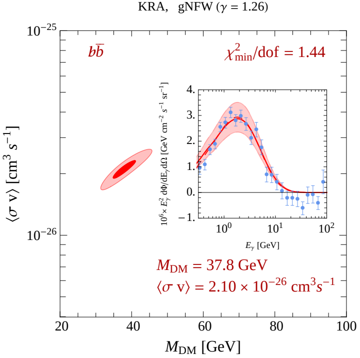
Interpretation with Dark Matter Annihilation

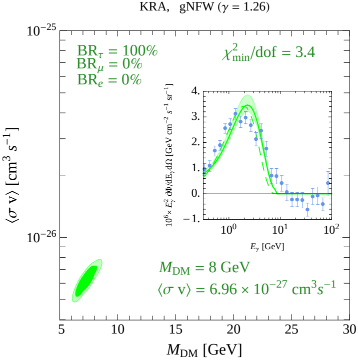
DM annihilation into $b\bar{b}$

$$m_\chi \simeq 30-40\ \text{GeV}$$
$$\langle\sigma_{\text{ann}}v\rangle \sim 10^{-26}\ \text{cm}^3\,\text{s}^{-1}$$

DM annihilation into $\tau^+\tau^-$

$$m_\chi \sim 9\ \text{GeV}$$
$$\langle\sigma_{\text{ann}}v\rangle \sim 5\times10^{-27}\ \text{cm}^3\,\text{s}^{-1}$$





[Cirelli *et al.*, arXiv:1407.2173, JCAP]

γ rays from DM: Line Spectrum

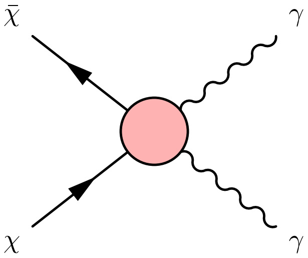
DM particles should **not have electric charge** and thus not directly couple to photons

$\Downarrow$

DM particles may couple to photons via high order loop diagrams

$\Downarrow$

Highly suppressed: branching fraction may be only $\sim 10^{-4} - 10^{-1}$



γ rays from DM: Line Spectrum

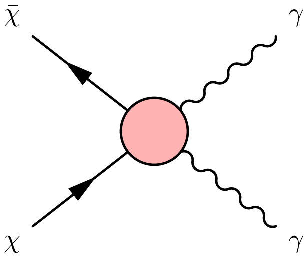
DM particles should **not have electric charge** and thus not directly couple to photons

$\Downarrow$

DM particles may couple to photons via high order loop diagrams

$\Downarrow$

Highly suppressed: branching fraction may be only $\sim 10^{-4} - 10^{-1}$



For **nonrelativistic** DM particles in space, the photons produced in $\chi\chi \to \gamma\gamma$ would be **mono-energetic**

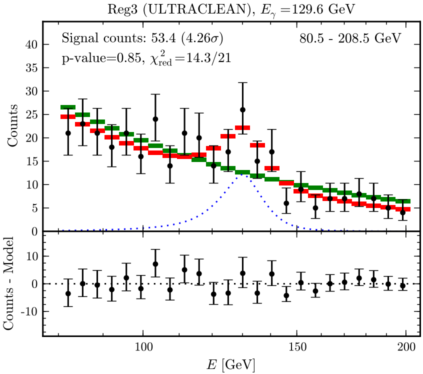
$\Downarrow$

A γ-ray line at energy $\sim m_\chi$

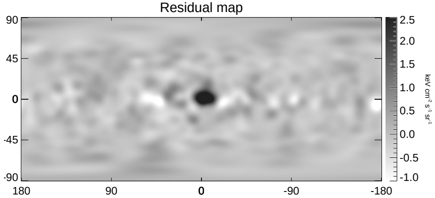
(**"smoking gun"** for DM particles)

A γ-ray Line Signal at the Galactic Center?

- Using the 3.7-year Fermi-LAT γ-ray data, several analyses showed that there might be evidence of **a monochromatic γ-ray line at energy** ~ 130 GeV, originating from the Galactic center region (about $3-4\sigma$)
- It may be explained by **DM annihilation with** $\langle\sigma_{\text{ann}}v\rangle \sim 10^{-27}\,\text{cm}^3\,\text{s}^{-1}$



[Weniger, 1204.2797, JCAP]

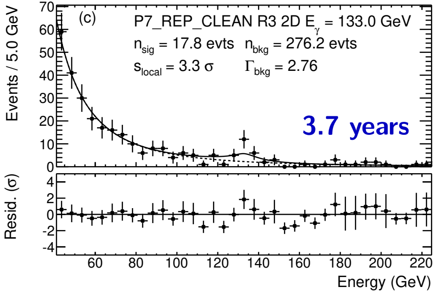


[Su & Finkbeiner, 1206.1616]

Fermi-LAT Official Results: Not Confirmed with More Data

- **3.7-year data**

  The most significant fit occurred at $E_\gamma = 133$ GeV and had a **local significance** of 3.3σ, translating to a global significance of 1.6σ



[Fermi-LAT Coll., 1305.5597, PRD]

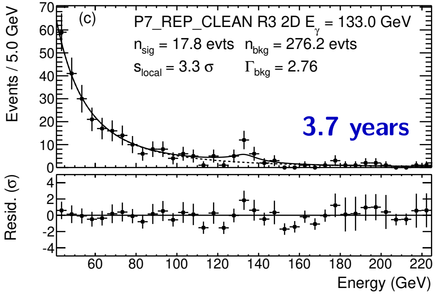
Fermi-LAT Official Results: Not Confirmed with More Data

- **3.7-year data**

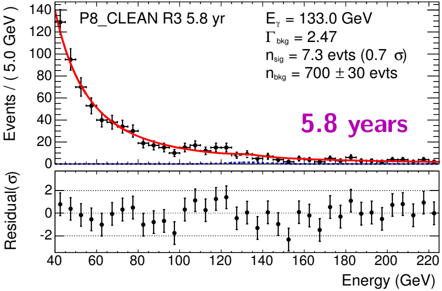
  The most significant fit occurred at $E_\gamma = 133$ GeV and had a **local significance** of 3.3σ, translating to a global significance of 1.6σ

- **5.8-year data**

  The **local significance** has dropped to 0.72σ



[Fermi-LAT Coll., 1305.5597, PRD]



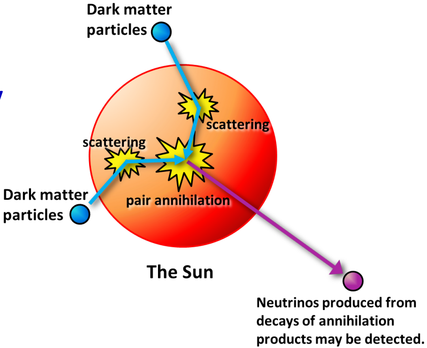
[Fermi-LAT Coll., 1506.00013, PRD]

Neutrinos from DM

💡 Dark matter may be **captured and accumulated** at the core of the Sun ☀️ (or the Earth 🌏), producing **high energy neutrinos** that could freely go out

Change Rate of the number of DM particles in the Sun:

$$\frac{dN_\chi}{dt} = C_\odot(\sigma_{\chi\mathrm{H}}, \sigma_{\chi\mathrm{He}}) + A_\odot(\sigma_{\mathrm{ann}})N_\chi^2$$

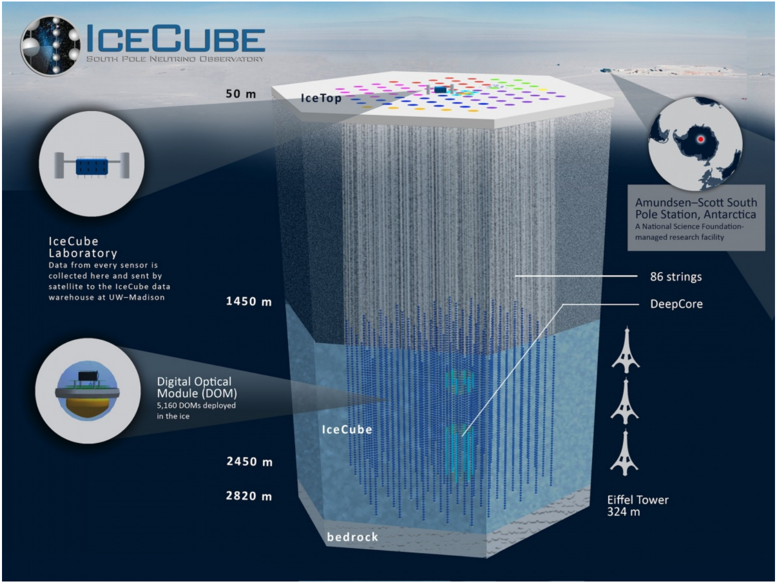


Capture rate $C_\odot$ depends on DM scattering on Hydrogen and Helium

Annihilation rate $A_\odot = \langle\sigma_{\mathrm{ann}}\rangle / V_{\mathrm{eff}}$ depends on DM annihilation as well as the effective volume of the solar core

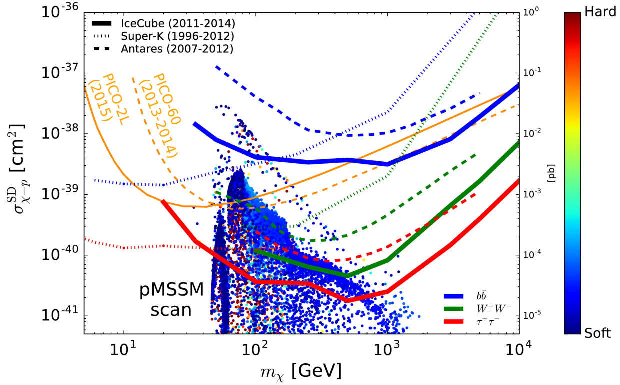
✨ The age of the Sun is long enough (~ 4.6 billion years) to make the capture and annihilation processes reach **equilibrium:** $dN_\chi/dt = 0$

IceCube: South Pole Neutrino Observatory



Searches for Neutrinos from DM Annihilation within the Sun

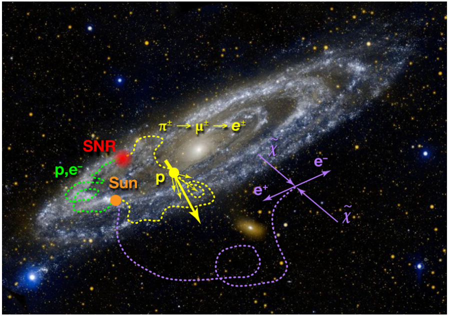
- **No signal detected** in searches for neutrinos with energies of GeV – TeV from DM annihilation at the solar core
- Assuming equilibrium in the capture and annihilation processes, the constraints can be converted to those on the **DM scattering cross section**

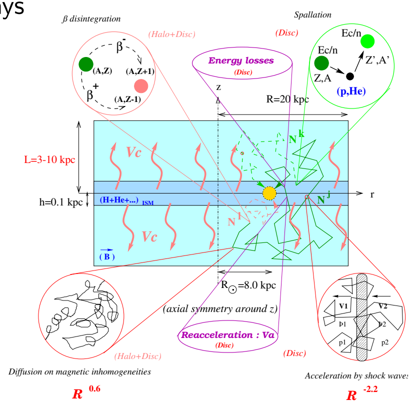


[IceCube Coll, 1612.05949, EPJC]

Cosmic Rays from DM

- After produced in sources, Galactic cosmic rays diffuse in the interstellar space, suffering from several **propagation effects** before they arrive at the Earth: diffusion, energy losses, convection, reacceleration, spallation, $\cdots$
- Unlike γ rays and neutrinos, cosmic rays **typically do not contain direction information of their sources**





[Maurin *et al.*, astro-ph/0212111]

Cosmic Ray Propagation Equation

The **propagation equation** for Galactic cosmic rays is

$$\frac{\partial \psi}{\partial t} = Q(\mathbf{x}, p) + \nabla \cdot (D_{xx} \nabla \psi - \mathbf{V}_{\mathrm{c}} \psi) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{\psi}{p^2}\right)\right]$$
$$- \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla \cdot \mathbf{V}_{\mathrm{c}})\psi\right] - \frac{\psi}{\tau_{\mathrm{f}}} - \frac{\psi}{\tau_{\mathrm{r}}}$$

$\psi = \psi(\mathbf{x}, p, t)$: cosmic ray density per momentum interval

$Q(\mathbf{x}, p)$: cosmic ray source term

D_{xx} : spatial diffusion coefficient

D_{pp} : diffusion coefficient in the momentum space for reacceleration

$\mathbf{V}_{\mathrm{c}}$: convection velocity

$\dot{p} \equiv \mathrm{d}p/\mathrm{d}t$: momentum loss rate

τ_{f} : fragmentation time scale

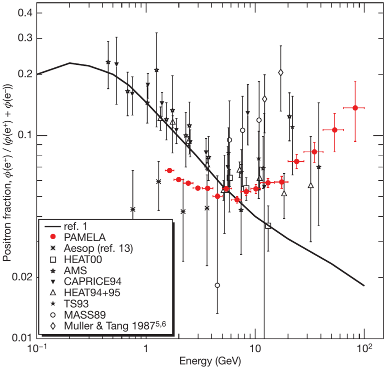
τ_{r} : radioactive decay time scale

Numerical tools

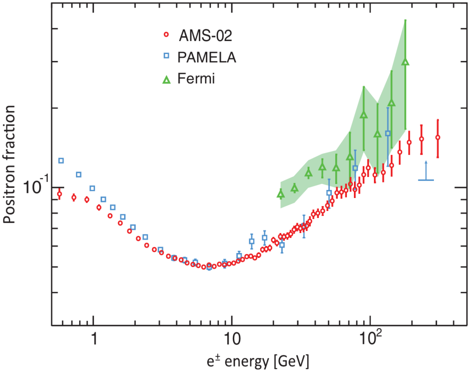
- `GALPROP`: `https://galprop.stanford.edu`
- `DRAGON`: `https://github.com/cosmicrays/DRAGON`

Cosmic-ray Positron Excess

- In 2008, the **PAMELA** experiment found an **unexpected increase** in the cosmic-ray **positron fraction** with $E \gtrsim 10$ GeV
- In 2013, the **AMS-02** experiment **confirmed** such a positron excess



[PAMELA Coll., 0810.4995, Nature]

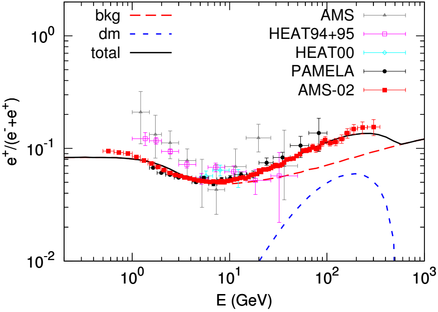


[AMS Coll., PRL 110, 141102 (2013)]

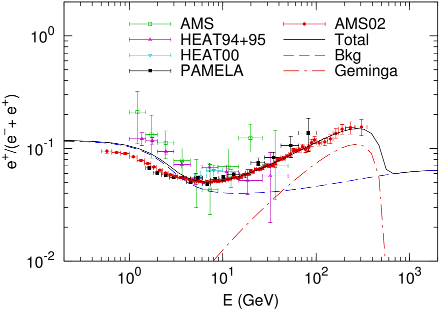
Interpretation: Dark Matter vs Pulsar

Interpretation with Galactic **DM annihilation** into $\tau^+\tau^-$

Interpretation with the **nearby pulsar Geminga**



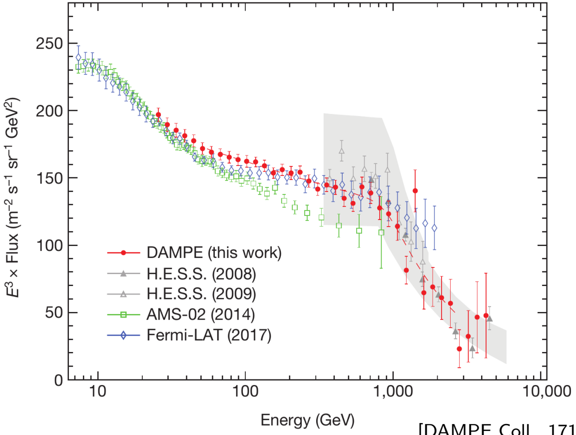
[Yuan, Bi, *et al.*, 1304.1482, APP]



[Yin, **ZHY**, Yuan, Bi, 1304.4128, PRD]

First Result from DAMPE

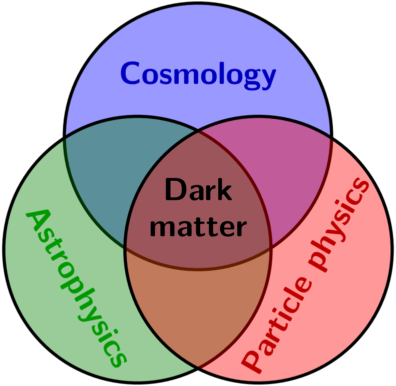
- In November 2017, **DAMPE (悟空)** collaboration released their first measurement of the cosmic-ray spectrum of **electrons and positrons**
- This measurement found a **spectral break** at ~ 0.9 TeV



[DAMPE Coll., 1711.10981, Nature]

Summary

- **Dark matter** connects our knowledge of the Universe from the **largest** to the **smallest** scales
- Although several anomalous observations have been found in direct and indirect searches, there is **no absolutely solid DM detection signal so far**
- **DM detection sensitivities are being improved quickly**; it is very promising to detect robust DM signals in the near future



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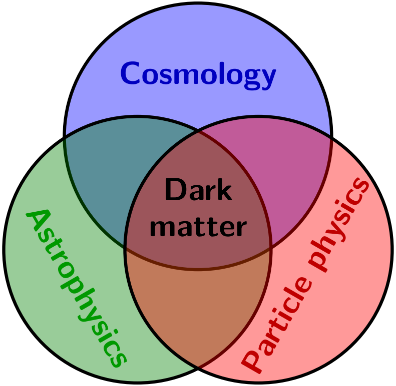

Thank you!