

Direct and Indirect Detection of Dark Matter

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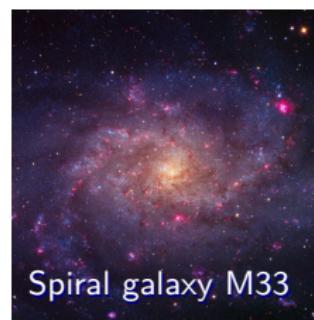


Dark Matter in the Universe

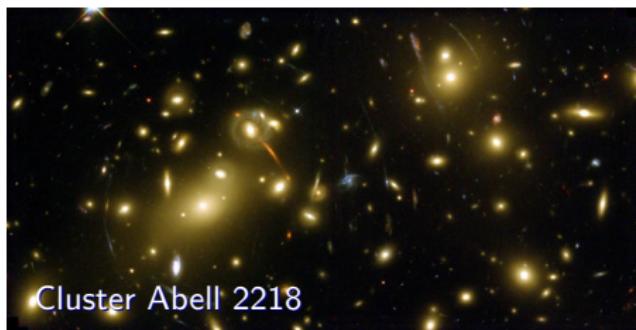
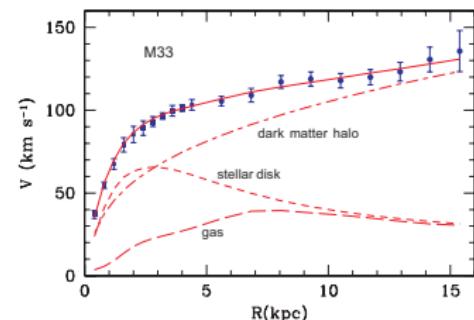
Dark matter (DM) makes up most of the matter component in the Universe, as suggested by astrophysical and cosmological observations



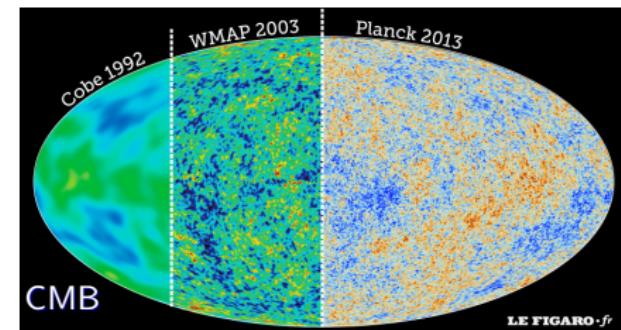
Bullet Cluster



Spiral galaxy M33



Cluster Abell 2218



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

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

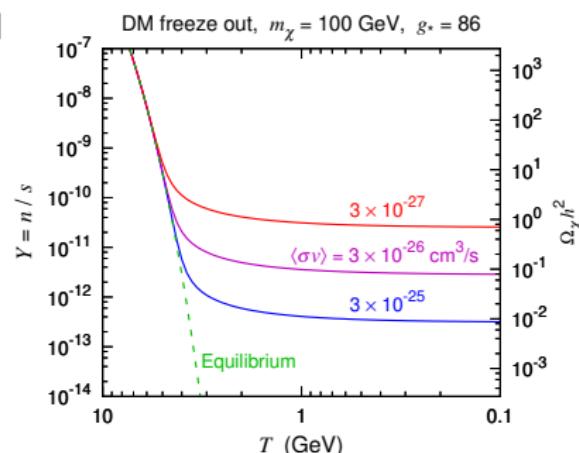
DM Relic Abundance

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

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

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

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



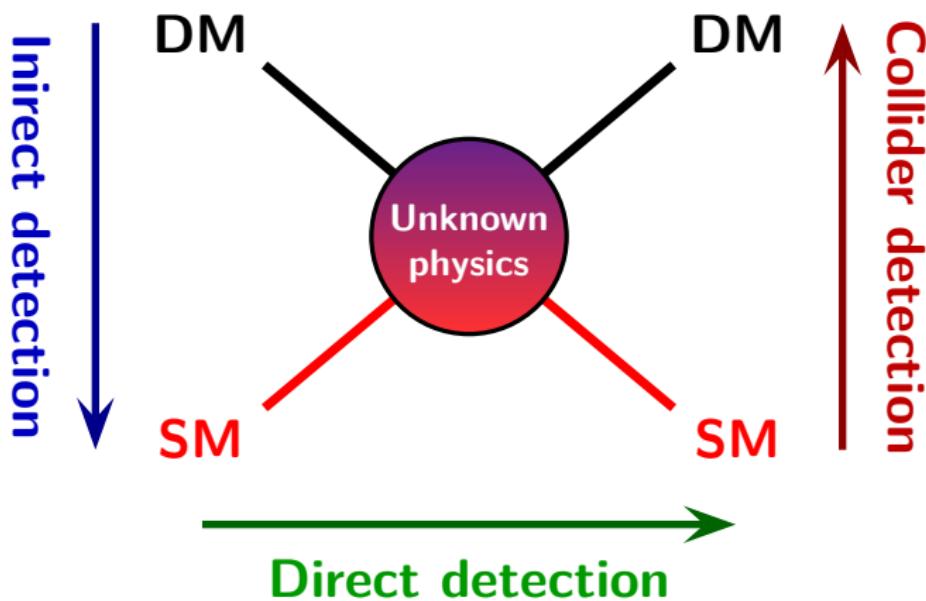
Assuming the annihilation process consists of two weak interaction vertices with the $SU(2)_L$ gauge coupling $g \simeq 0.64$, for $m_\gamma \sim \mathcal{O}(\text{TeV})$ we have

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

⇒ A very attractive class of DM candidates:

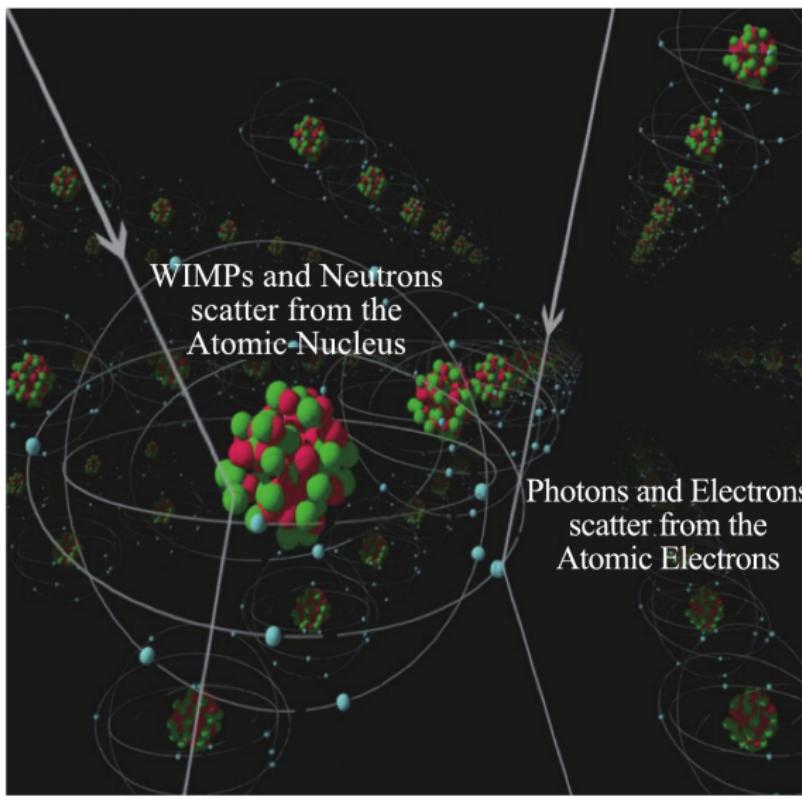
Weakly interacting massive particles (WIMPs)

Experimental Approaches to Dark Matter



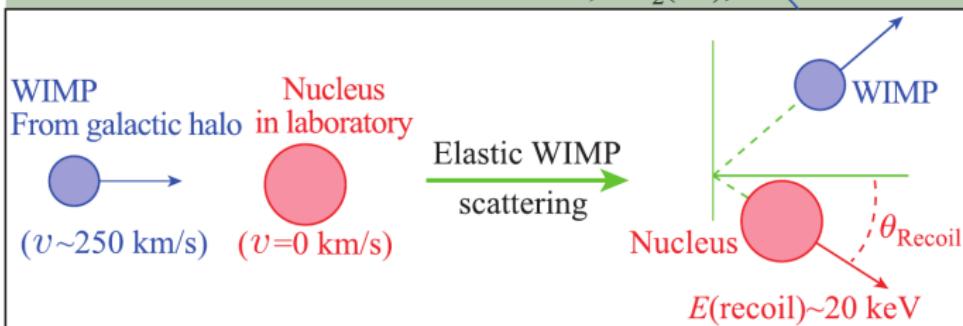
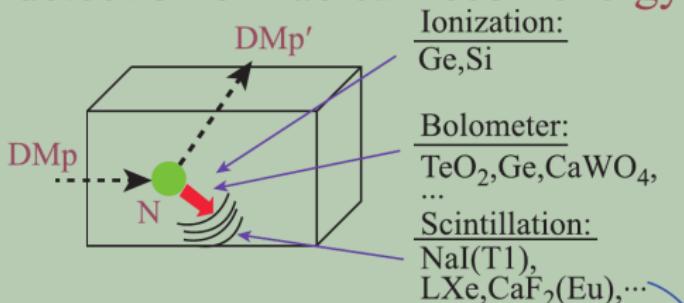


WIMP Scattering off Atomic Nuclei



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**:

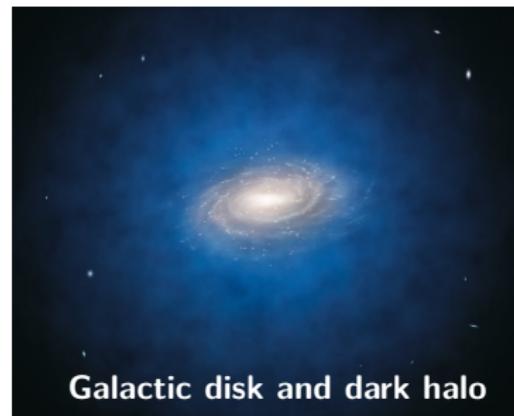
$$\tilde{f}(\tilde{\mathbf{v}})d^3\tilde{v} = \left(\frac{m_\chi}{2\pi k_B T}\right)^{3/2} \exp\left(-\frac{m_\chi \tilde{v}^2}{2k_B T}\right) d^3\tilde{v} = \frac{e^{-\tilde{v}^2/v_0^2}}{\pi^{3/2} v_0^3} d^3\tilde{v}, \quad v_0^2 \equiv \frac{2k_B T}{m_\chi}$$

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

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

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

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



Galactic disk and dark halo

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

[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:

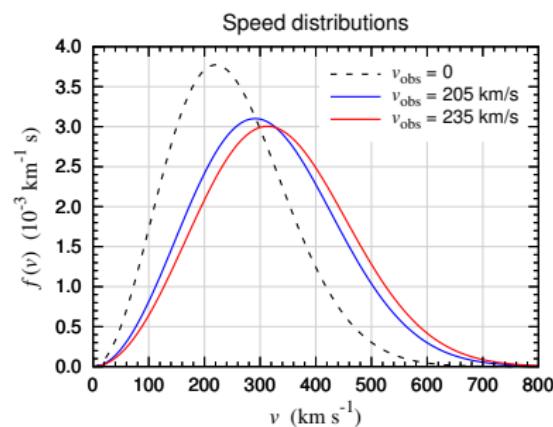
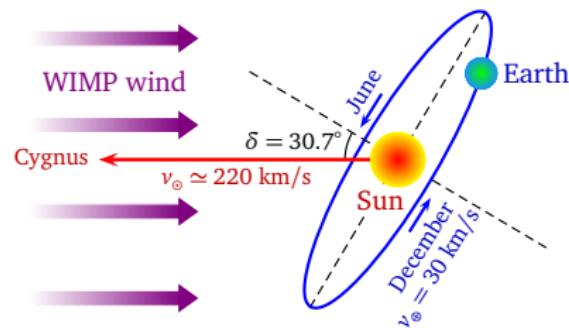
$$f(v)dv = \frac{4v^2}{\sqrt{\pi}v_0^3} \exp\left(-\frac{v^2 + v_{\text{obs}}^2}{v_0^2}\right) \times \frac{\tilde{v}_0^2}{2vv_{\text{obs}}} \sinh\left(\frac{2vv_{\text{obs}}}{v_0^2}\right) dv$$

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

$$v_{\text{obs}}(t) \simeq v_{\odot} + v_{\oplus} \sin \delta \cos[\omega(t - t_0)]$$

$$\simeq 220 \text{ km/s} + 15 \text{ km/s} \cdot \cos[\omega(t - t_0)]$$

⇒ **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:

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

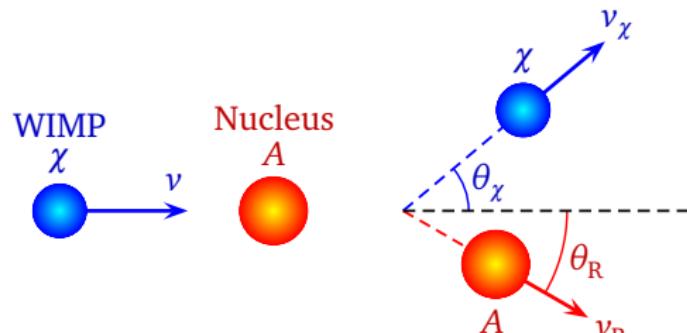
$$m_\gamma v_\gamma \sin \theta_\gamma = m_A v_R \sin \theta_R$$

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

⇒ **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 $q_R^{\max} = 2\mu_{\chi A} v$



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:

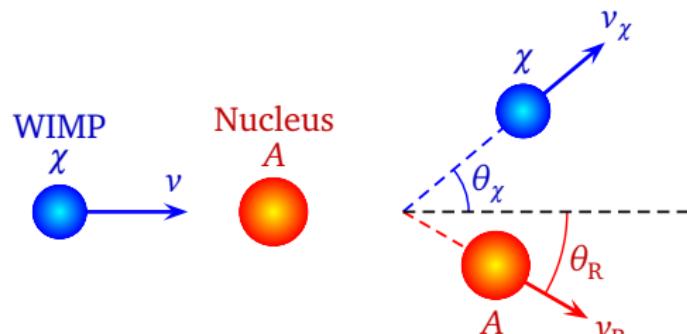
$$m_\gamma v = m_\gamma v_\gamma \cos \theta_\gamma + m_A v_R \cos \theta_R$$

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

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

⇒ **Recoil momentum** (momentum transfer) $q_R = m_A v_R = 2\mu_{\gamma A} v \cos \theta_R$

⇒ **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 $m_\chi = m_A \simeq 100$ 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:

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

Astrophysics factors Particle physics factors Detector factors

N_T : target nucleus number

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

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

$\sigma_{\gamma A}$: 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}

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

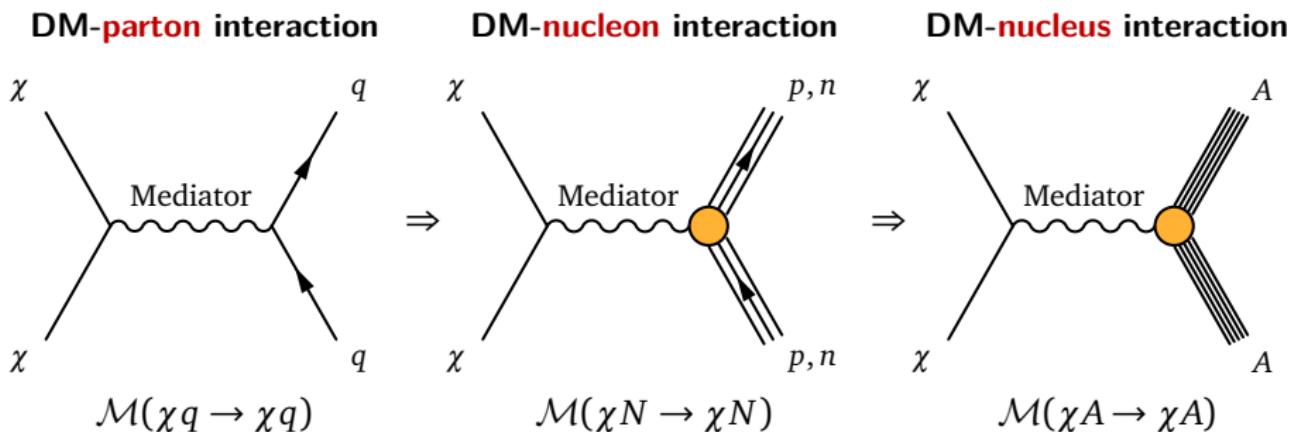
Spin-dependent (SD) cross section: $\sigma_{\chi A}^{\text{SD}} \propto \mu_{\chi A}^2 \frac{J_A + 1}{J_A} (S_p^A G'_p + S_n^A G'_n)^2$

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

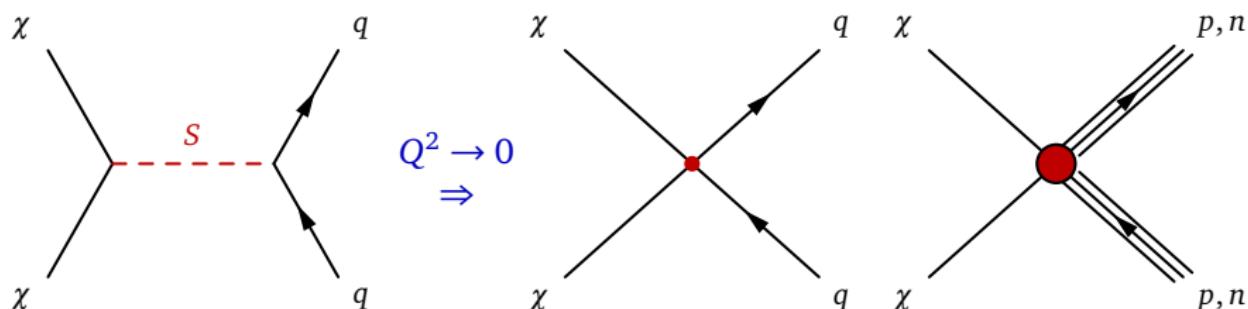
Three Levels of Interaction



- 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**

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: $\frac{i}{Q^2 - m_S^2} \Rightarrow -\frac{i}{m_S^2}$

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

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

$$\bar{\chi} i\gamma_5 \chi \bar{N} i\gamma_5 N, \quad \bar{\chi} \chi \bar{N} i\gamma_5 N, \quad \bar{\chi} i\gamma_5 \chi \bar{N} N, \quad \bar{\chi} \gamma^\mu \chi \bar{N} \gamma_\mu \gamma_5 N, \quad \bar{\chi} \gamma^\mu \gamma_5 \chi \bar{N} \gamma_\mu N$$
- 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 :

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

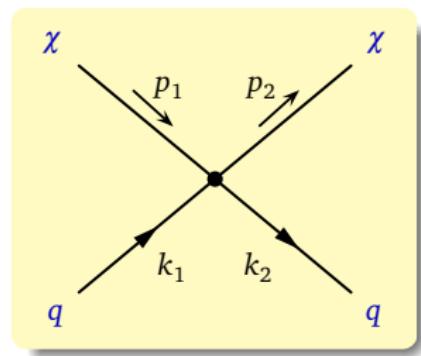
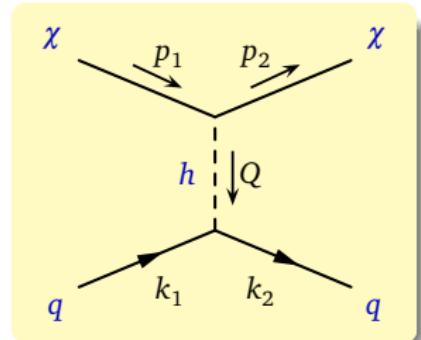
$$\mathcal{L}_{\text{SM}} \supset - \sum_q \frac{m_q}{v} \cancel{h} \bar{q} q, \quad q = d, u, s, c, b, t$$

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

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

Zero momentum transfer $\downarrow Q^2 = (k_2 - k_1)^2 \rightarrow 0$

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



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

Effective Lagrangian: Scalar Type

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

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

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

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 :

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

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

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

Effective Lagrangian in the zero momentum transfer limit:

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

$G_{AV,q} = -\frac{g_\chi g g_V^q}{4c_W m_Z^2}$ leads to $\sigma_{\chi N} \propto |Q^2|$ and can be neglected for direct detection



Effective Lagrangian: Axial Vector Type

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

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

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

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 :

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

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

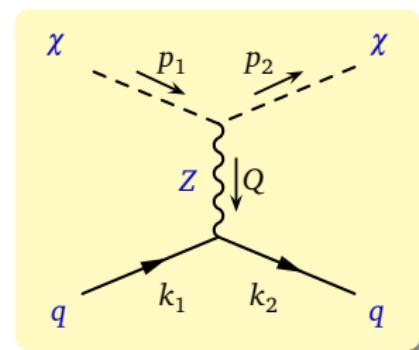
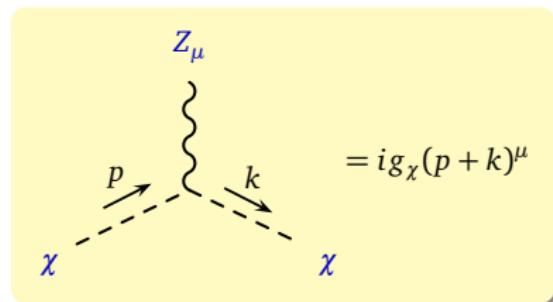
$$i\mathcal{M} = ig_\chi(p_1 + p_2)^\mu \frac{-i(g_{\mu\nu} - Q_\mu Q_\nu/m_Z^2)}{Q^2 - m_Z^2}$$

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

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

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

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



Effective Lagrangian: Vector Type

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

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

The relation between $F_{V,N}$ and $F_{V,g}$ 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

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

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

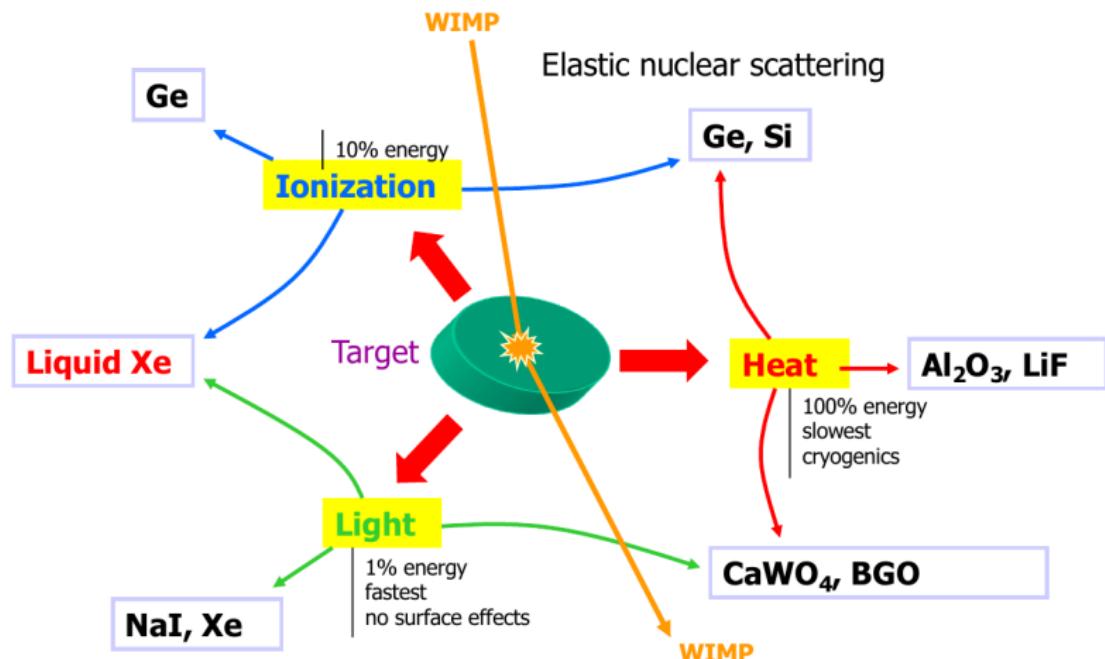
$$\sigma_{\chi N}^{\text{SI}} = \frac{1}{\pi} \mu_{\chi N}^2 G_{V,N}^2, \quad G_{V,p} = 2G_{V,u} + G_{V,d}, \quad G_{V,n} = G_{V,u} + 2G_{V,d}$$

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 Q^2 $	$\bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5 q, \bar{\chi}\chi\bar{q}i\gamma_5 q$	$\chi^*\chi\bar{q}i\gamma_5 q$
	$\bar{\chi}i\gamma_5\chi\bar{q}q, \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma_5 q$	$(\chi^*i\overleftrightarrow{\partial}^\mu\chi)\bar{q}\gamma_\mu\gamma_5 q$
	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu q, \epsilon^{\mu\nu\rho\sigma}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\rho\sigma} q$	
	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 Q^2 $	$\bar{\chi}^\mu i\gamma_5\chi_\mu\bar{q}i\gamma_5 q, \bar{\chi}^\mu\chi_\mu\bar{q}i\gamma_5 q$ $\bar{\chi}^\mu i\gamma_5\chi_\mu\bar{q}q, \bar{\chi}^\nu\gamma^\mu\chi_\nu\bar{q}\gamma_\mu\gamma_5 q$	$\chi_\mu^*\chi^\mu\bar{q}i\gamma_5 q$ $(\chi_\nu^*i\overleftrightarrow{\partial}^\mu\chi^\nu)\bar{q}\gamma_\mu\gamma_5 q$
	$\bar{\chi}^\mu\gamma^\mu\gamma_5\chi_\nu\bar{q}\gamma_\mu q, \epsilon^{\mu\nu\rho\sigma}i(\bar{\chi}_\mu\chi_\nu - \bar{\chi}_\nu\chi_\mu)\bar{q}\sigma_{\rho\sigma} q$	$\epsilon^{\mu\nu\rho\sigma}(\chi_\mu^*\overleftrightarrow{\partial}_\nu\chi_\rho)\bar{q}\gamma_\sigma q$
	$\epsilon^{\mu\nu\rho\sigma}\bar{\chi}^\alpha\sigma_{\mu\nu}\chi_\alpha\bar{q}\sigma_{\rho\sigma} q, (\bar{\chi}^\mu\gamma_5\chi^\nu - \bar{\chi}^\nu\gamma_5\chi^\mu)\bar{q}\sigma_{\mu\nu} q$ $\epsilon^{\mu\nu\rho\sigma}(\bar{\chi}_\mu\gamma_5\chi_\nu - \bar{\chi}_\nu\gamma_5\chi_\mu)\bar{q}\sigma_{\rho\sigma} q$	$\epsilon^{\mu\nu\rho\sigma}i(\chi_\mu^*\chi_\nu - \chi_\nu^*\chi_\mu)\bar{q}\sigma_{\rho\sigma} q$

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

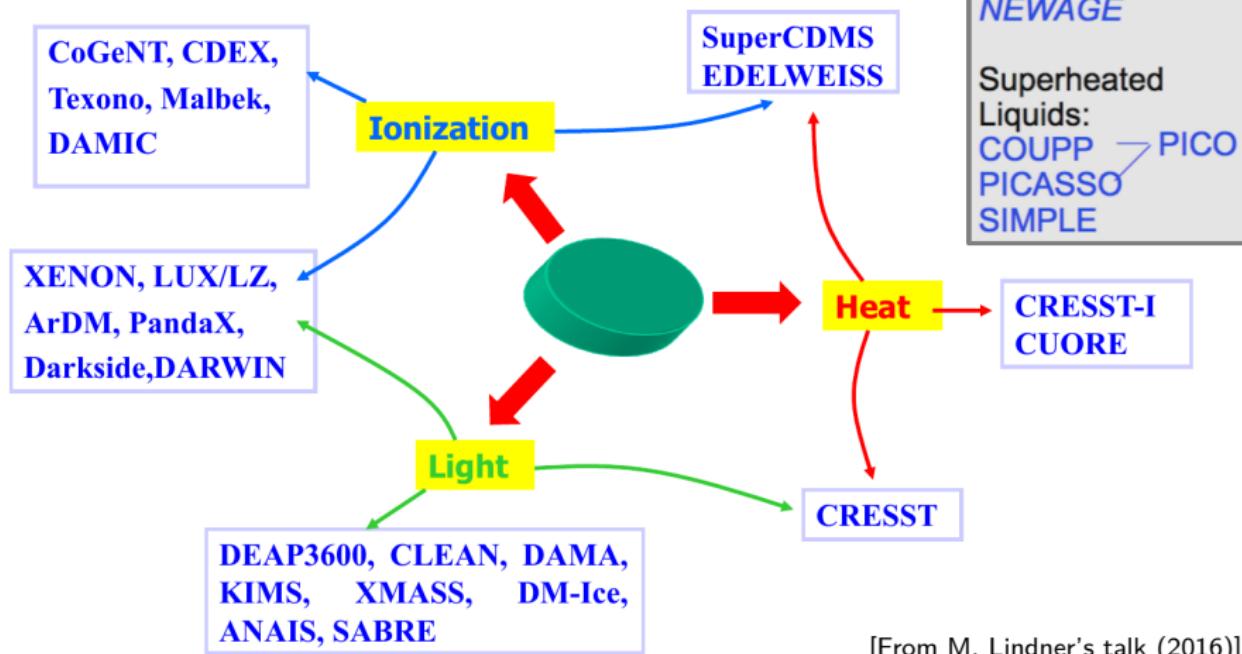
Technologies and Detector Material



[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)]

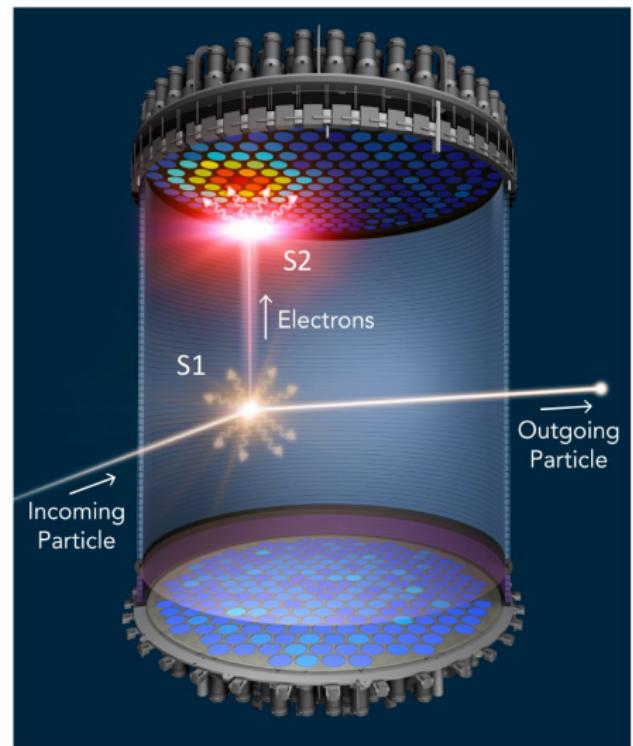
Example: Dual-phase Xenon Time Projection Chamber

Upper: Xenon gas

Lower: Liquid Xenon

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

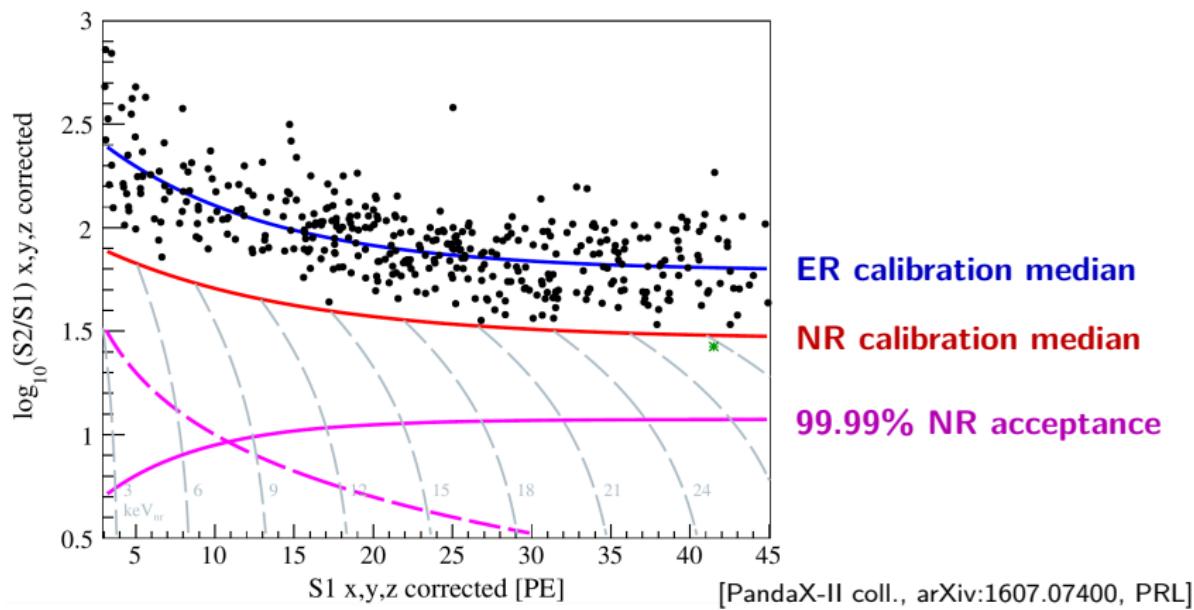
- **Primary scintillation (S1):**
Scintillation light promptly emitted from the interaction vertex
 - **Secondary scintillation (S2):**
Ionization electrons emitted from the interaction are drifted to the surface and into the gas, where they emit proportional scintillation light



[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

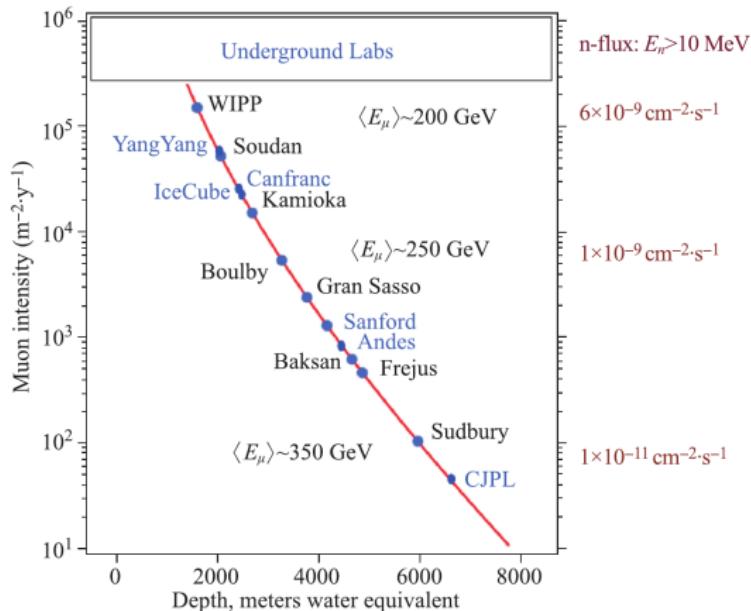
Shielded environments

- **Cosmogenic backgrounds:**

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

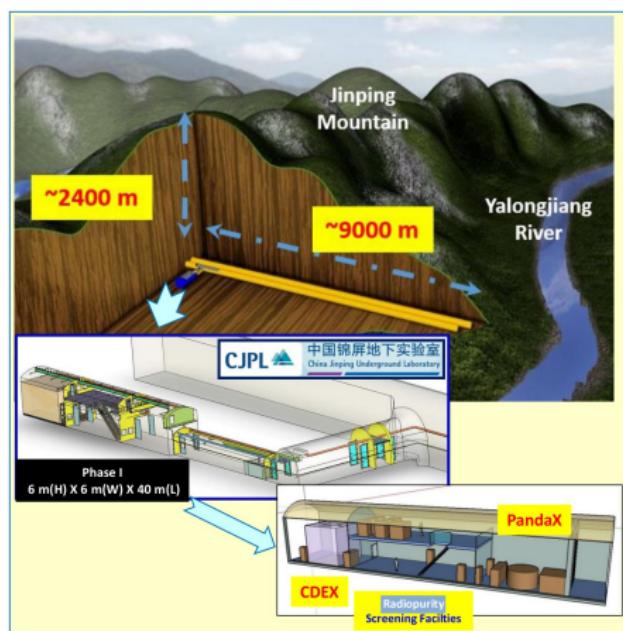
- **Radiogenic backgrounds:**

- 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)

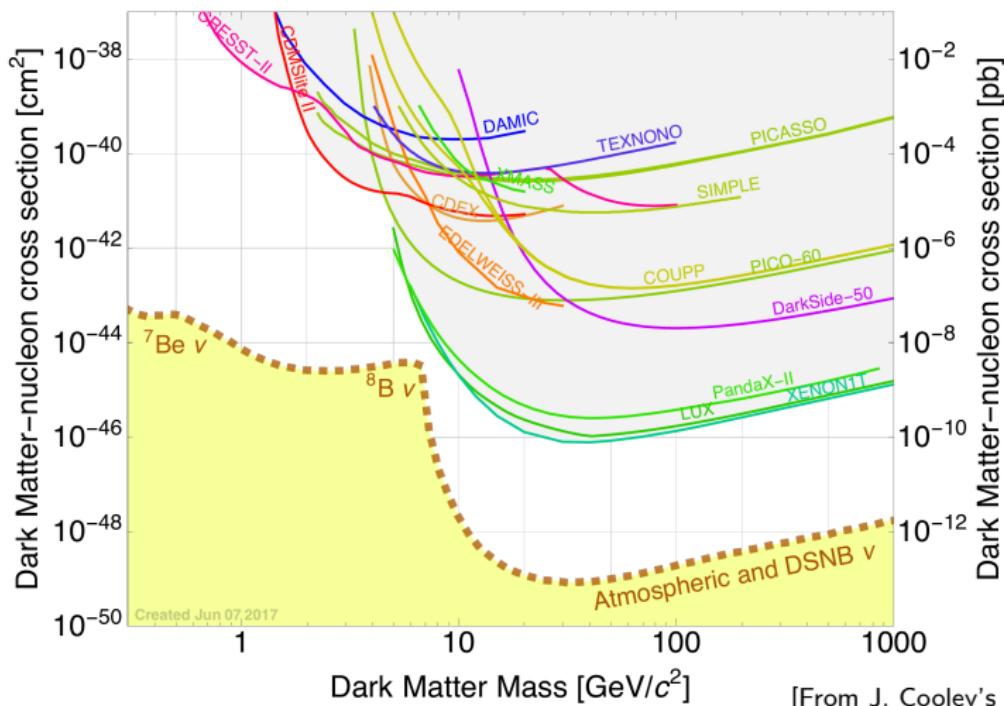


[Yue et al., arXiv:1602.02462]

Experiments: CDEX, PandaX

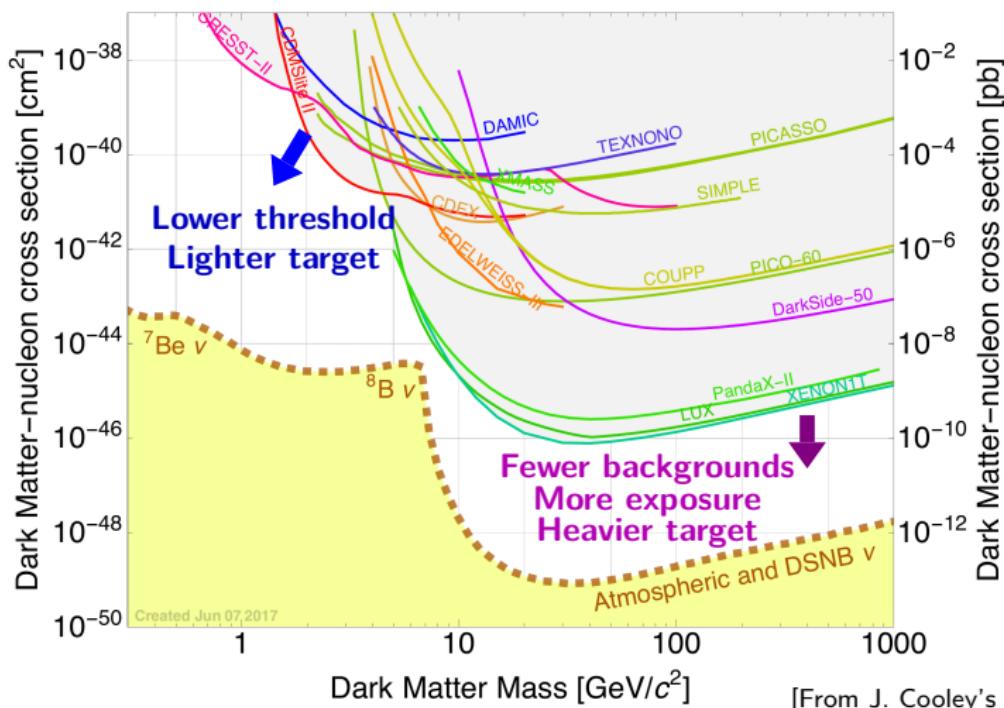
Exclusion Limits for SI Scattering

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



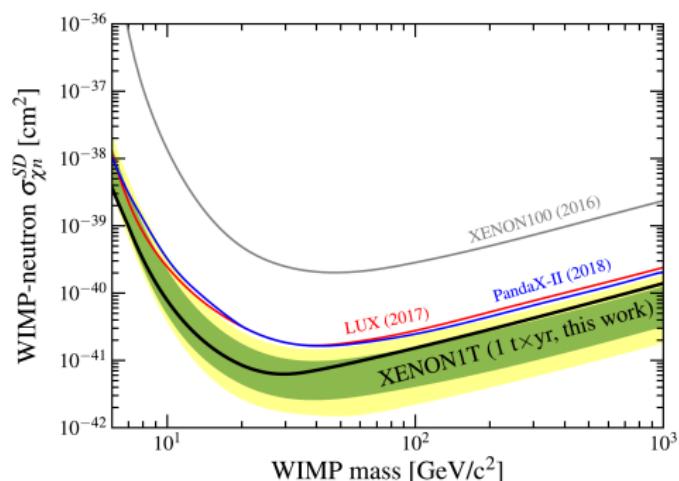
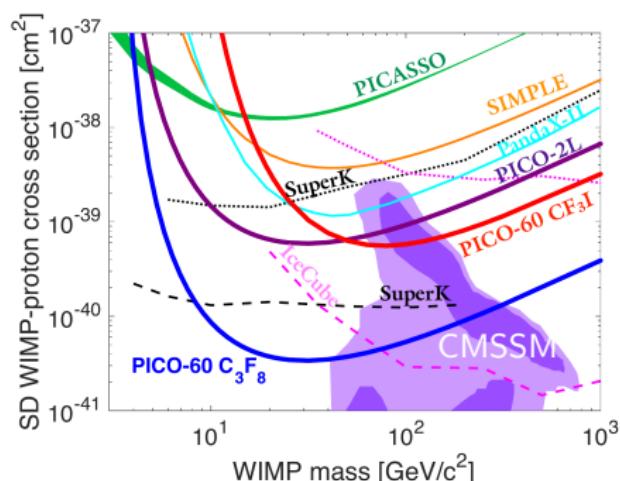
Exclusion Limits for SI Scattering

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





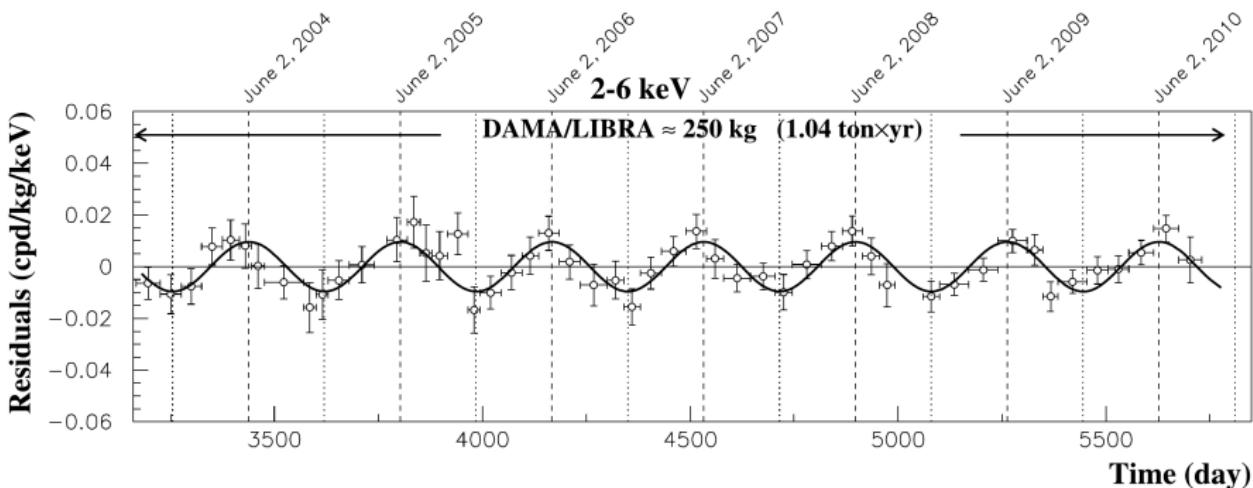
[XENON1T coll., arXiv:1902.03234, PRL]

DAMA/LIBRA Annual Modulation “Signal”

😎 Highly radio-pure scintillating **Nal(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]

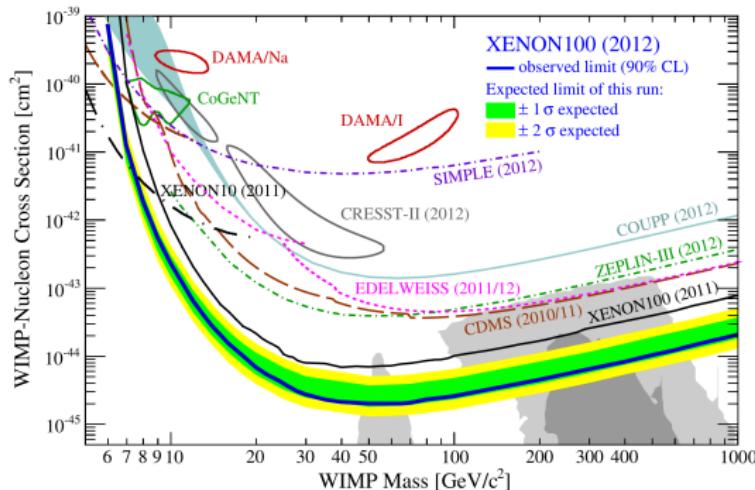


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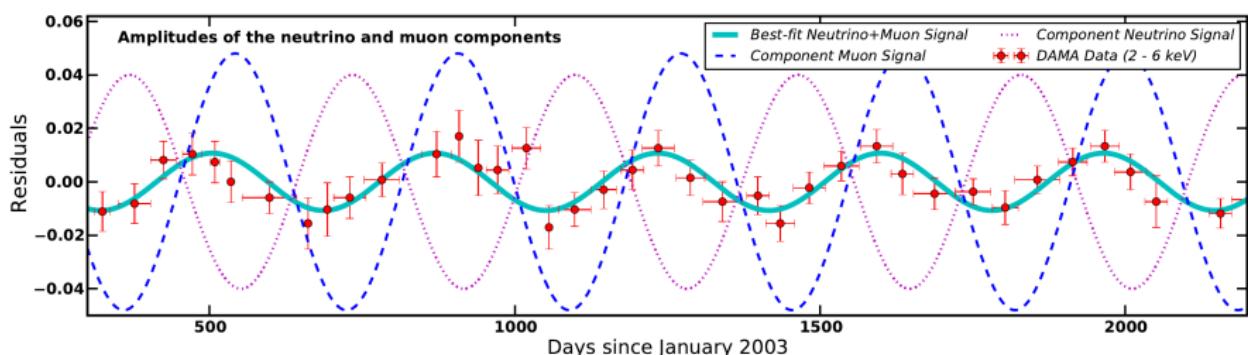
[XENON100 coll., arXiv:1207.5988, PRL]

 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**

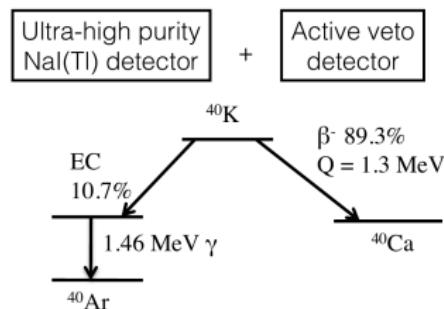


🧐 **Objection:** Klinger & Kudryavtsev, "muon-induced neutrons do not explain the DAMA data," arXiv:1503.07225, PRL

Further Test: SABRE Project

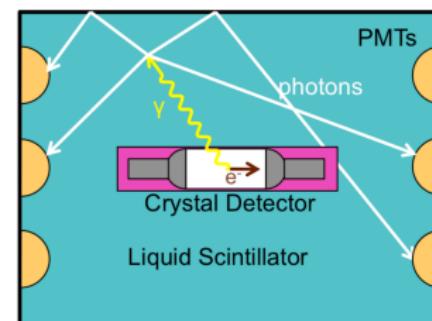
SABRE: Sodium iodide with Active Background REjection

- 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



$^{40}\text{K} \rightarrow ^{40}\text{Ar}$, ~11% branch ratio

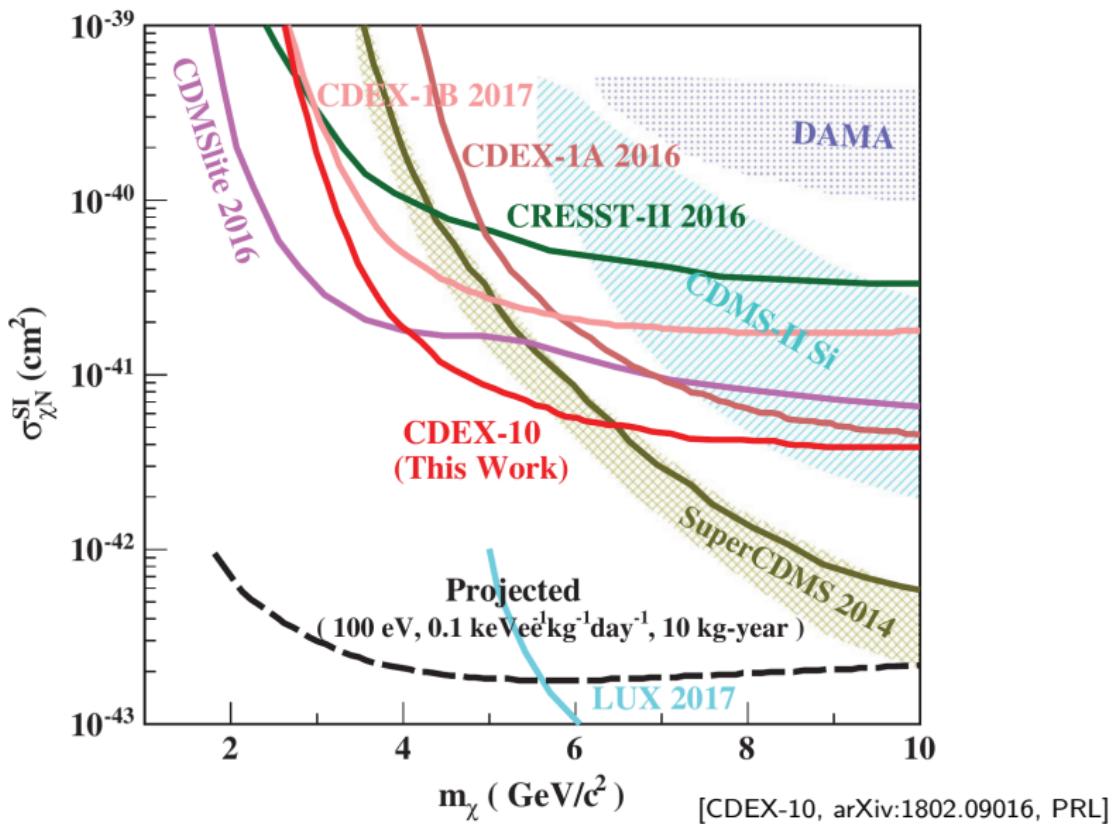
- 3 keV K shell X-ray, Auger e^-
- Background at ~3 keV if γ escapes



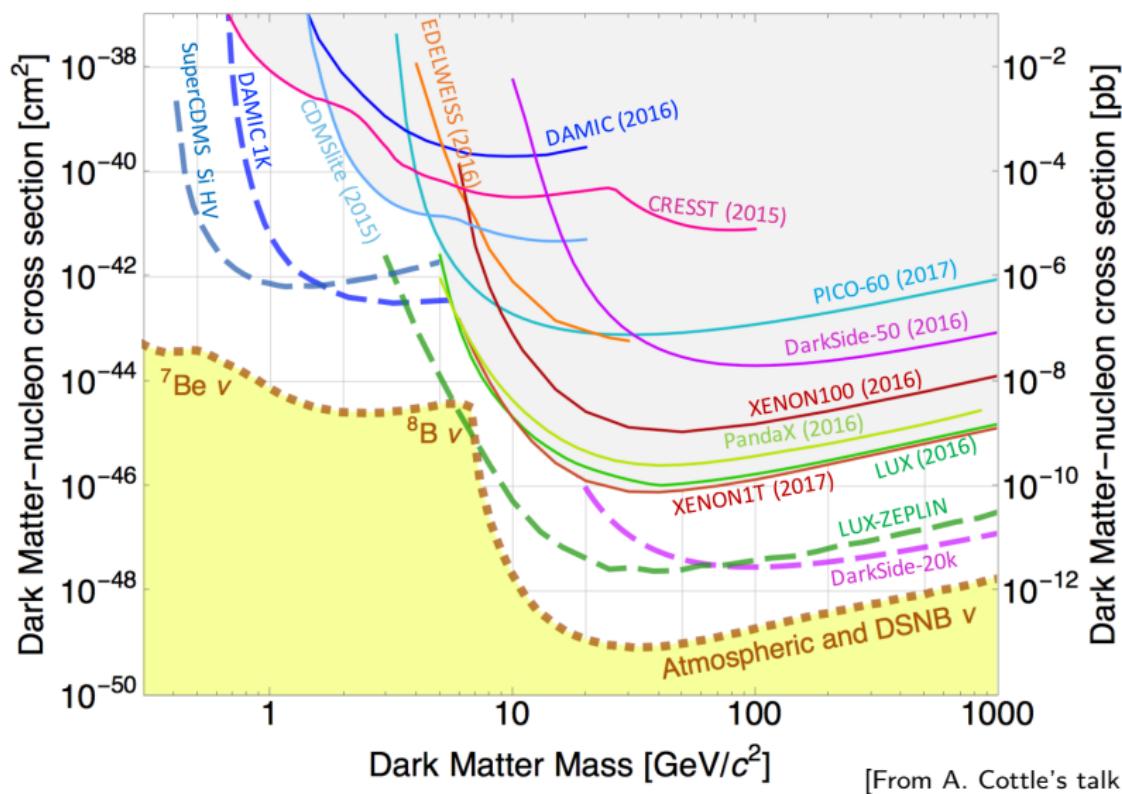
1.46 MeV γ can be detected by a veto.
 ^{40}K background can be rejected.

[From E. Barberio's talk]

Low Mass Region



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

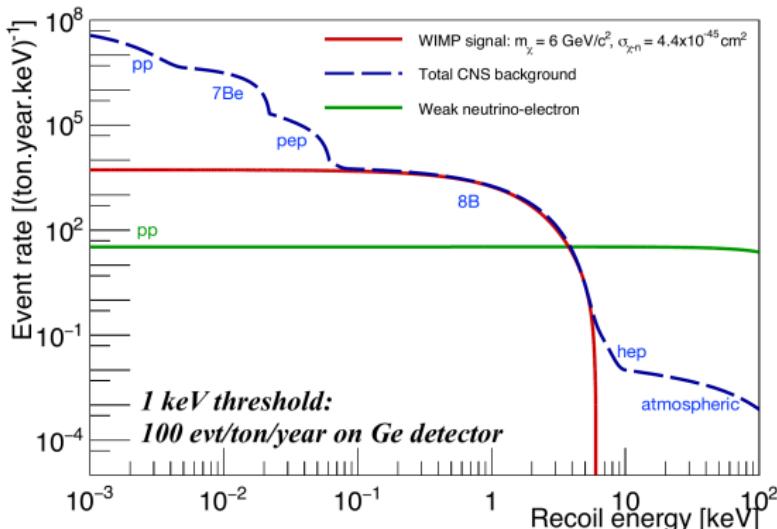
- *pp* neutrinos:
 $p + p \rightarrow D + e^+ + \nu_e$
 - ⁷Be neutrinos:
 $e^- + ^7\text{Be} \rightarrow ^7\text{Li} + \nu_e$
 - *pep* neutrinos:
 $p + e^- + p \rightarrow D + \nu_e$
 - ⁸B neutrinos:
 $^{8\text{B}} \rightarrow {}^{8\text{Be}}^* + e^+ + \nu_e$
 - *Hep* neutrinos:
 ${}^{3\text{He}} + p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

- Atmospheric neutrinos

Cosmic-ray collisions in the atmosphere

- Diffuse supernova neutrino background (DSNB)

All supernova explosions in the past history of the Universe

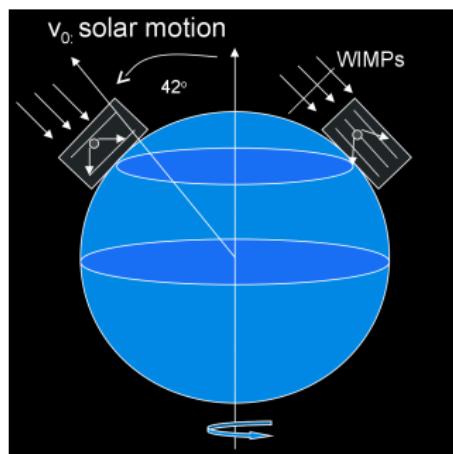


[From J. Billard's talk (2016)]

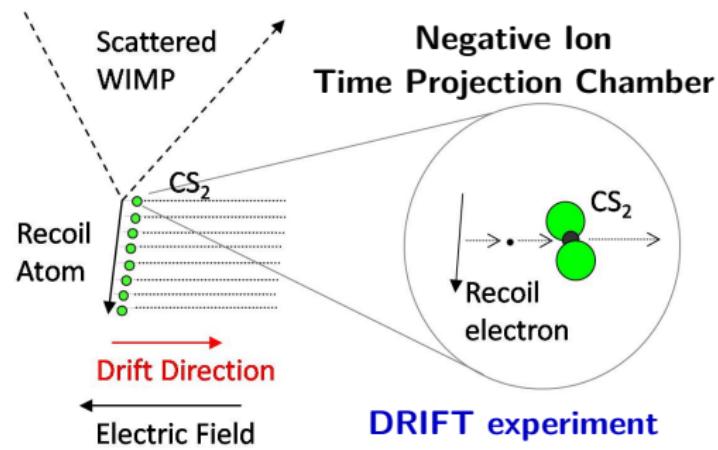
Going beyond the Neutrino Floor

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]



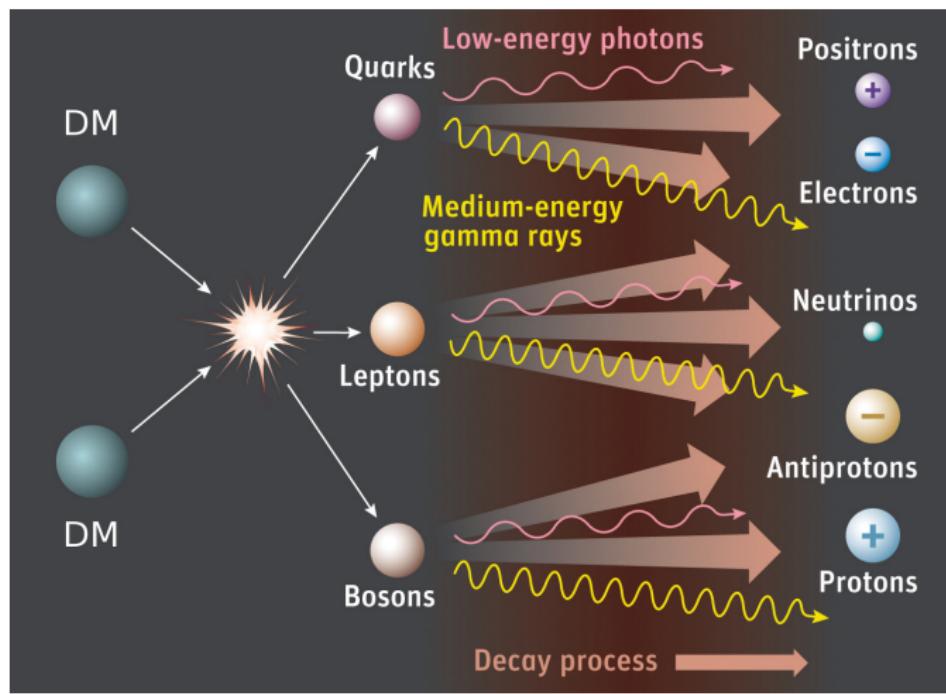
Diurnal modulation



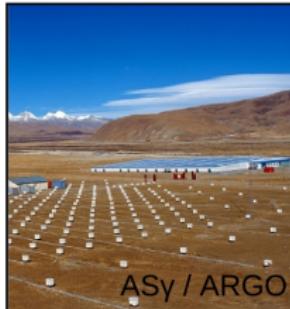
[From J. Spooner's talk (2010)]

Indirect Detection

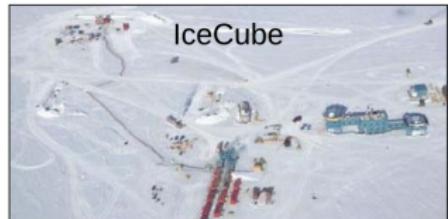
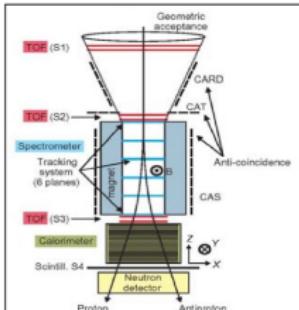
Indirect detection looks for stable products (γ rays, cosmic rays, neutrinos) from dark matter annihilation or decay (if DM is not totally stable) in space



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} , \dots) produced from DM annihilation or decay:

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

Astrophysics factors

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

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

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

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

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

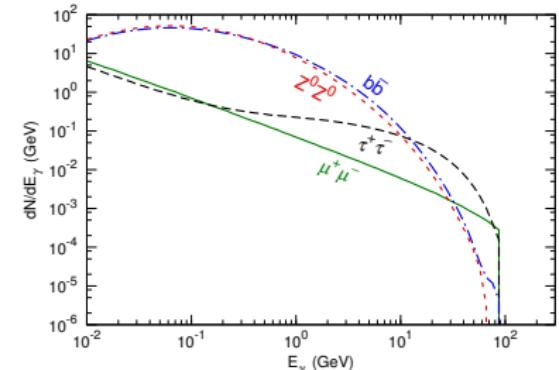
$B_i \equiv \Gamma_i / \Gamma_\chi$: **branching ratio** of the decay channel i

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



**γ -ray emission from final state
radiation or particle decays**

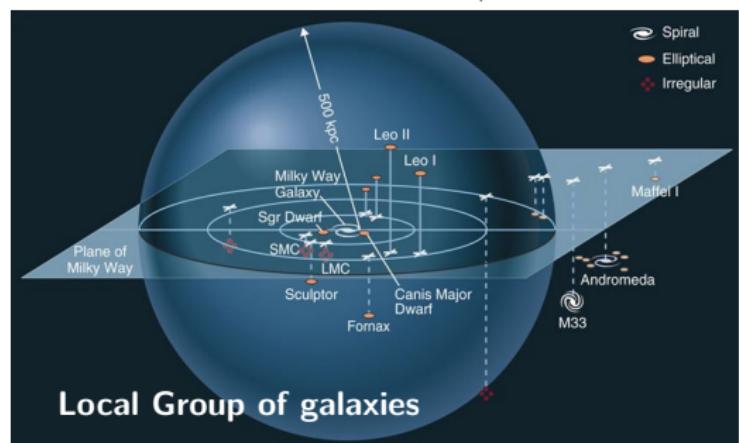


- **Cut-off energy:**

m_χ for DM annihilation
 $m_\chi/2$ for DM decay

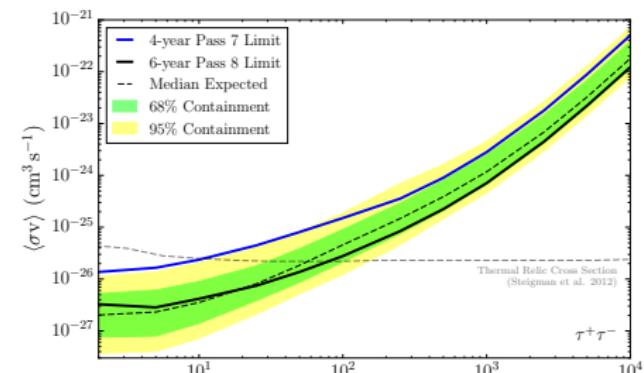
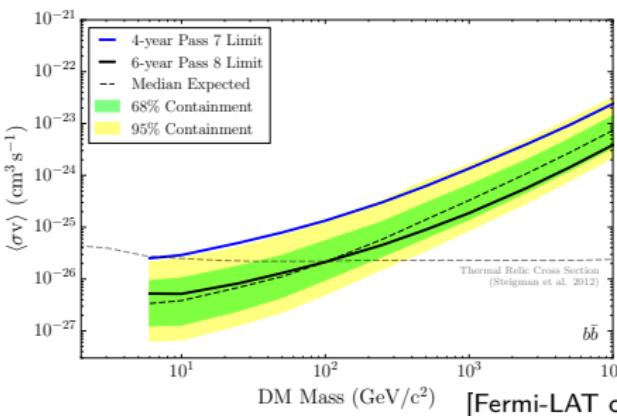
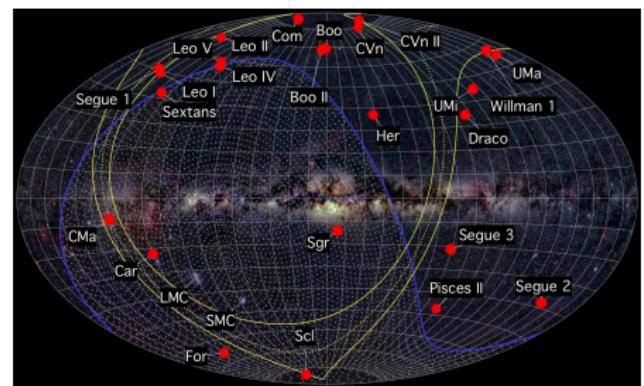
- More promising to look at
DM-dominated regions:

- **Galactic Center**
- **Galactic halo**
- **dwarf galaxies**
- **clusters of galaxies**



γ -ray Observation of Dwarf Galaxies

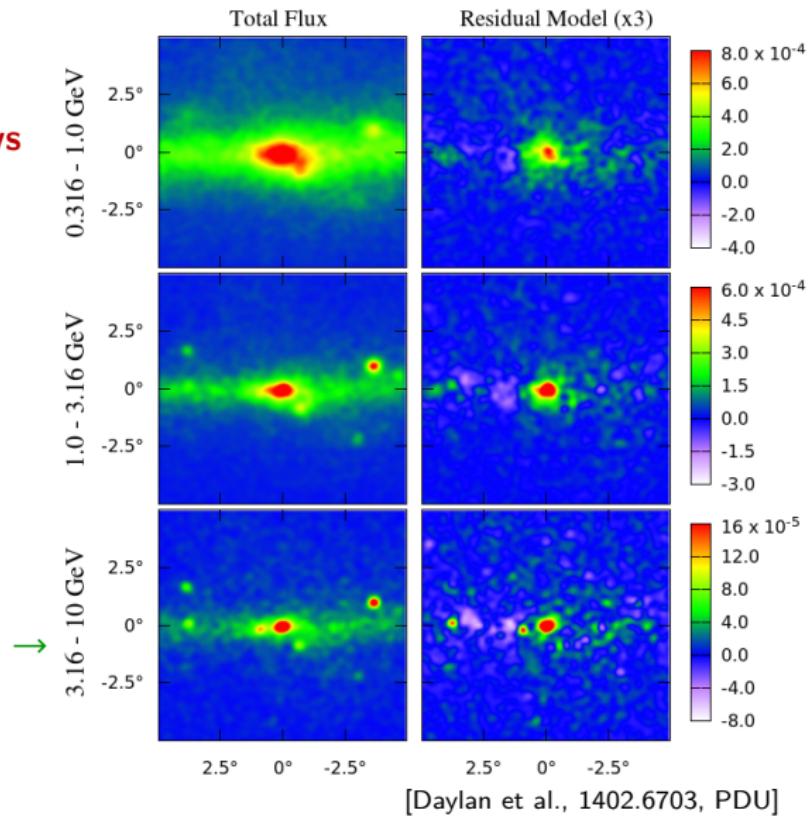
- The space experiment **Fermi-LAT** searched for γ -ray emission from **dwarf spheroidal satellite galaxies** of the Milky Way and found no significant signal
- Based on the 6-year data, upper limits on DM annihilation cross section are given



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

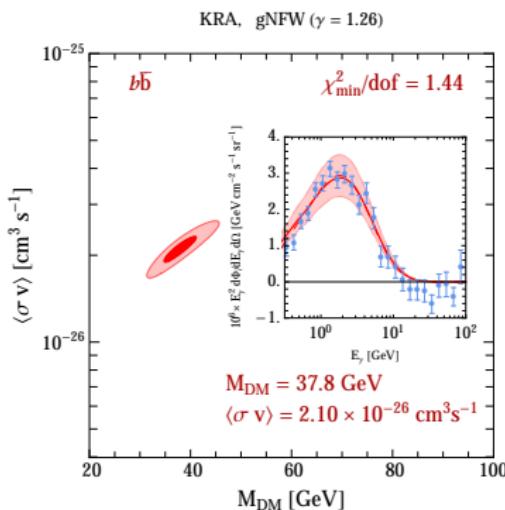
Left: raw γ -ray maps
Right: residual maps after subtracting the Galactic diffuse model, 20 cm template, point sources, and isotropic template



Interpretation with Dark Matter Annihilation

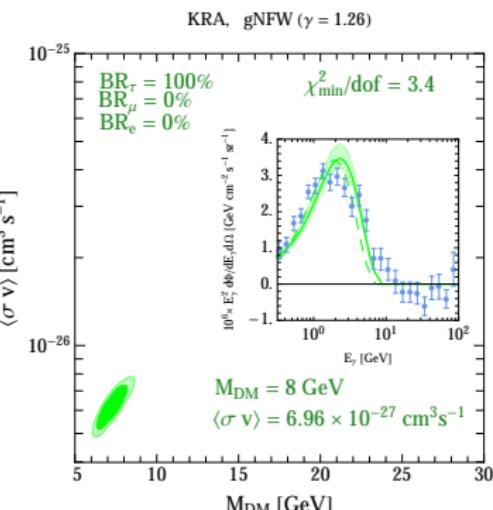
DM annihilation into $b\bar{b}$

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



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

$$\langle\sigma_{\text{ann}} v\rangle \sim 5 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}$$



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

γ rays from DM: Line Spectrum

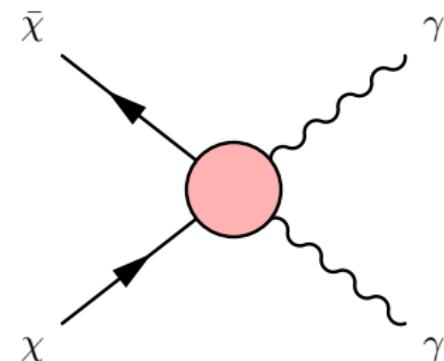
DM particles should **not have electric charge** and thus not directly couple to photons



DM particles may couple to photons via high order loop diagrams



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



γ rays from DM: Line Spectrum

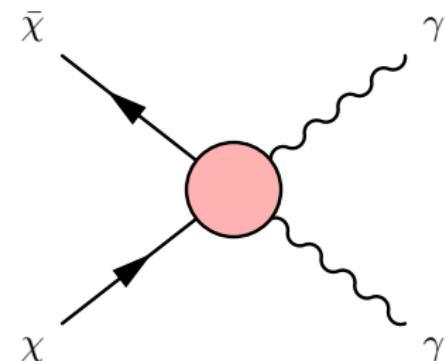
DM particles should **not have electric charge** and thus not directly couple to photons



DM particles may couple to photons via high order loop diagrams



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



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

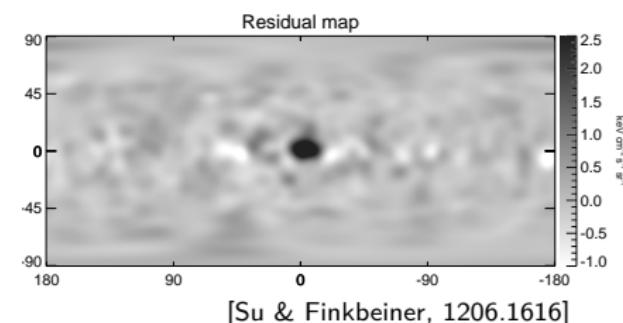
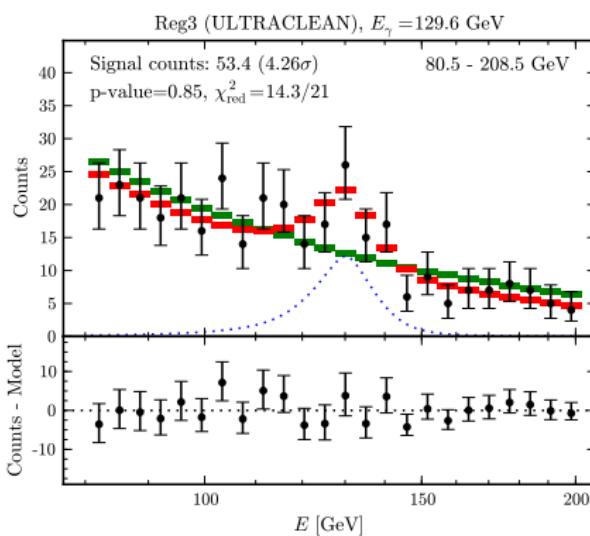


A γ -ray line at energy $\sim m_\chi$
(“smoking gun” for DM particles)



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 $\langle \sigma_{\text{ann}} v \rangle \sim 10^{-27} \text{ cm}^3 \text{s}^{-1}$**

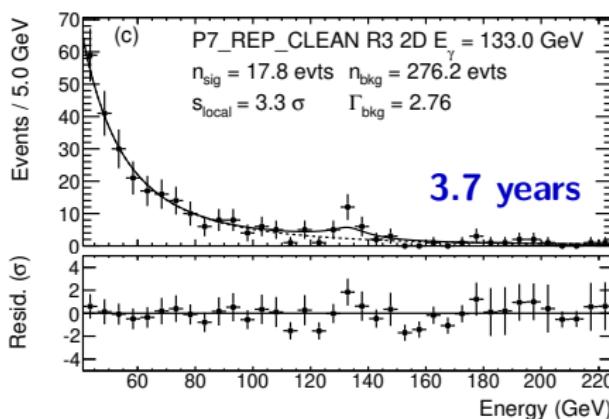


[Weniger, 1204.2797, JCAP]

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]

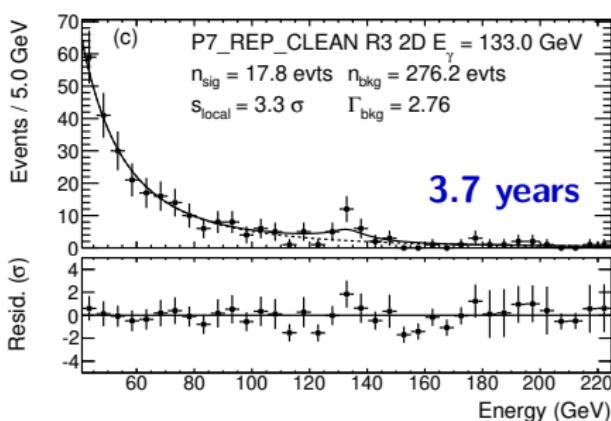
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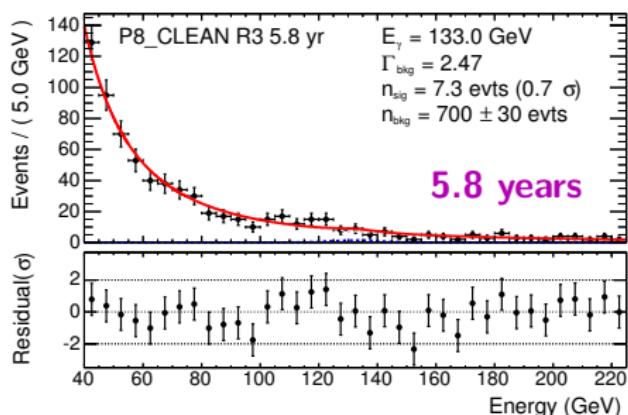
The most significant fit occurred at $E_\gamma = 133$ GeV and had a **local significance** of 3.3σ , translating to a global significance of 1.6σ

- **5.8-year data**

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



[Fermi-LAT Coll., 1305.5597, PRD]



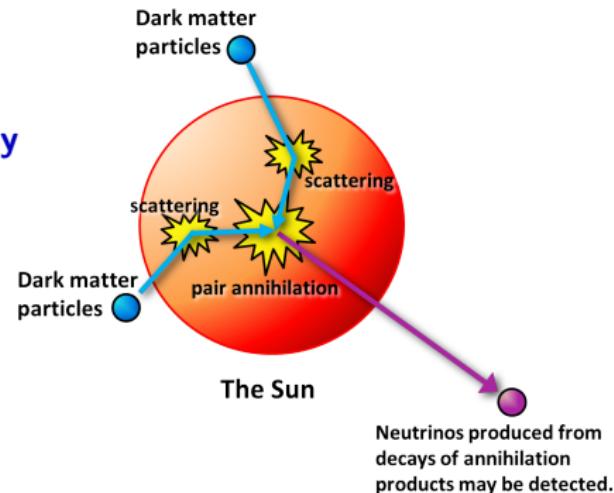
[Fermi-LAT Coll., 1506.00013, PRD]

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:

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

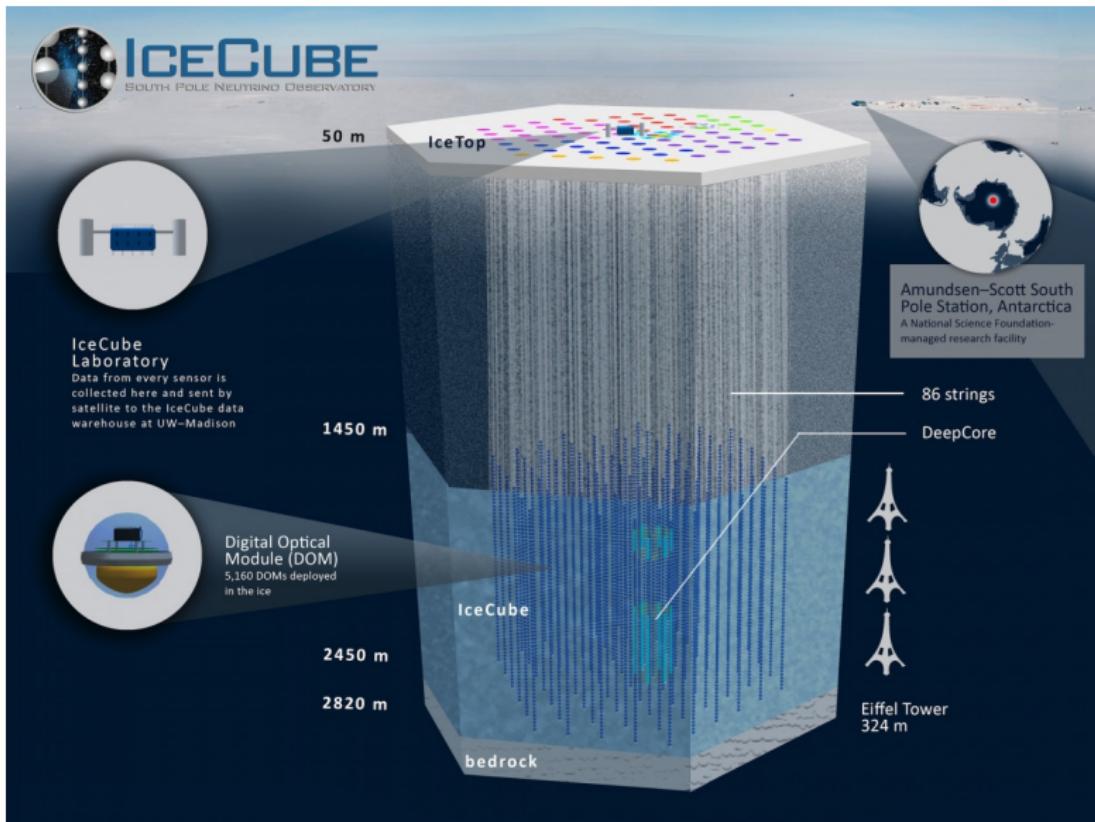


Capture rate C_\odot depends on DM scattering on Hydrogen and Helium

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

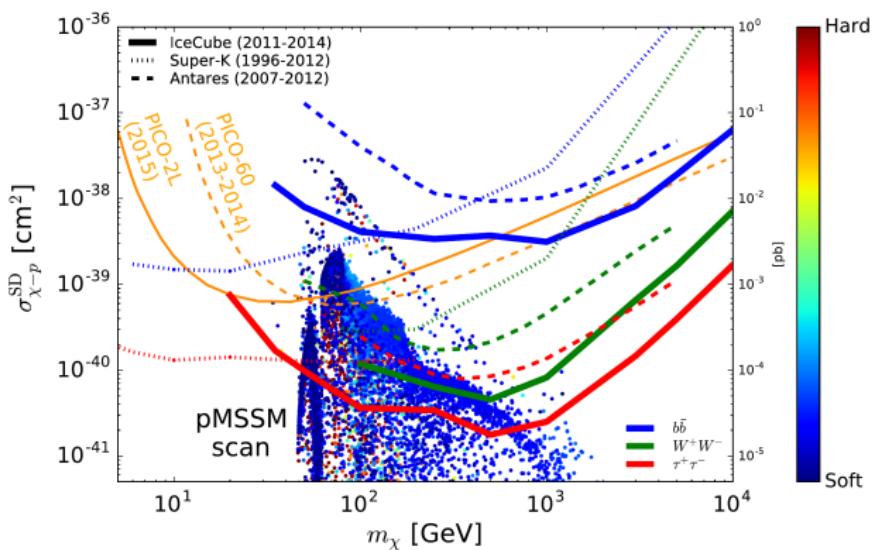
✨ The age of the Sun is long enough (~ 4.6 billion years) to make the capture and annihilation processes reach **equilibrium**: $dN_\chi/dt = 0$

IceCube: South Pole Neutrino Observatory



Searches for Neutrinos from DM Annihilation within the Sun

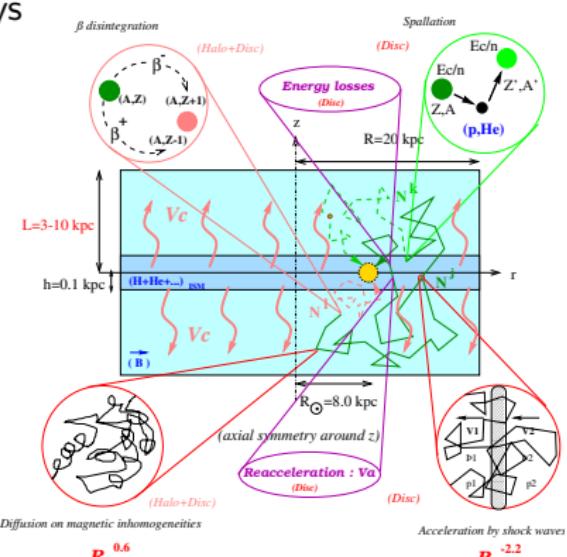
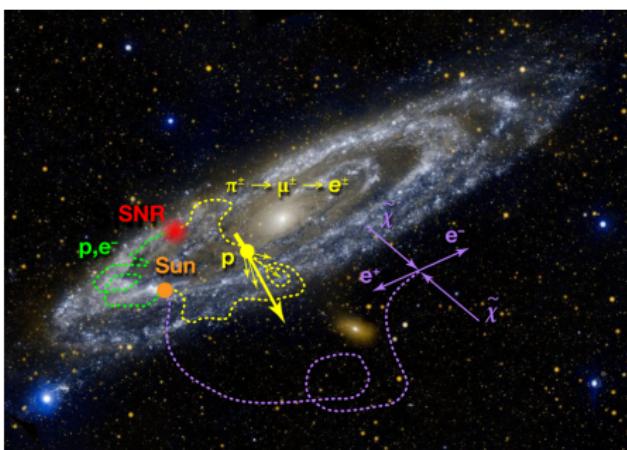
- **No signal detected** in searches for neutrinos with energies of GeV – TeV from DM annihilation at the solar core
- Assuming equilibrium in the capture and annihilation processes, the constraints can be converted to those on the **DM scattering cross section**



[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, ...
- 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

$$\frac{\partial \psi}{\partial t} = Q(\mathbf{x}, p) + \nabla \cdot (D_{xx} \nabla \psi - \mathbf{V}_c \psi) + \frac{\partial}{\partial p} \left[p^2 D_{pp} \frac{\partial}{\partial p} \left(\frac{\psi}{p^2} \right) \right] - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\nabla \cdot \mathbf{V}_c) \psi \right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}$$

$\psi = \psi(\mathbf{x}, p, t)$: 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}_c : convection velocity $\dot{p} \equiv dp/dt$: momentum loss rate

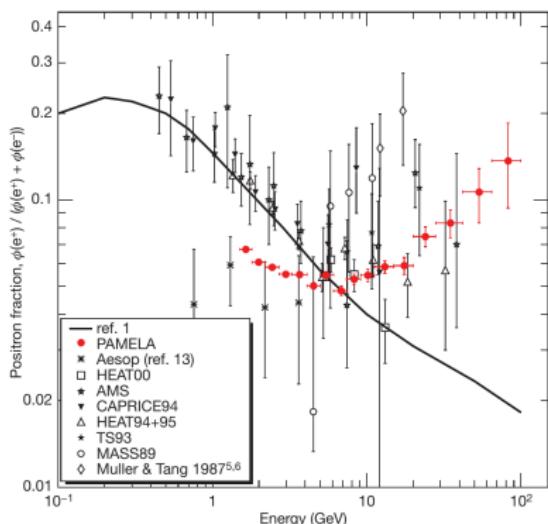
τ_f : fragmentation time scale τ_r : radioactive decay time scale

Numerical tools

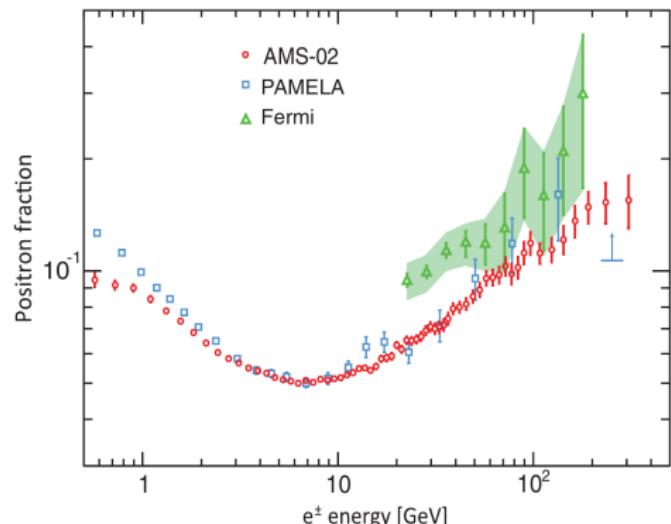
- **GALPROP**: <https://galprop.stanford.edu>
- **DRAGON**: <https://github.com/cosmicrays/DRAGON>

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



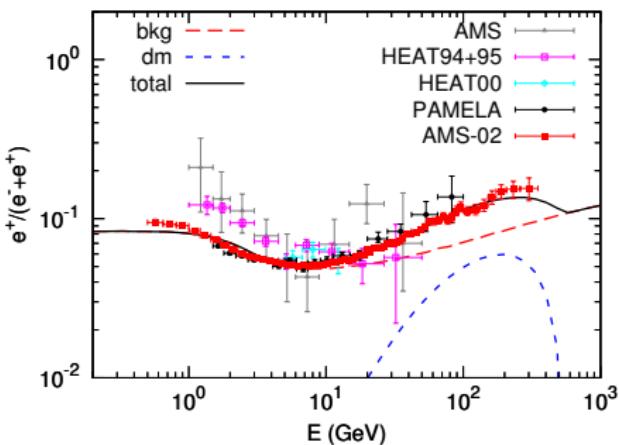
[PAMELA Coll., 0810.4995, Nature]



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

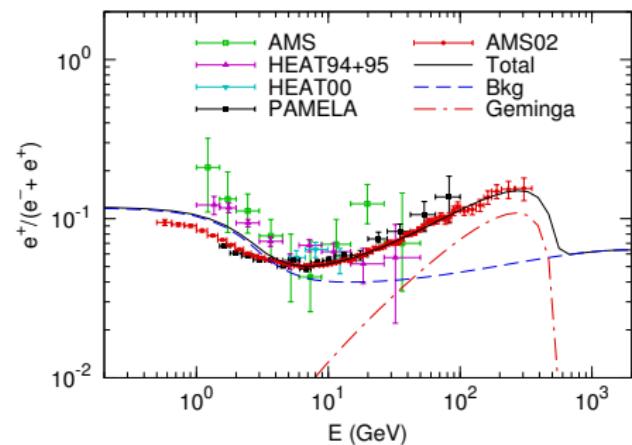
Interpretation: Dark Matter vs Pulsar

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



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

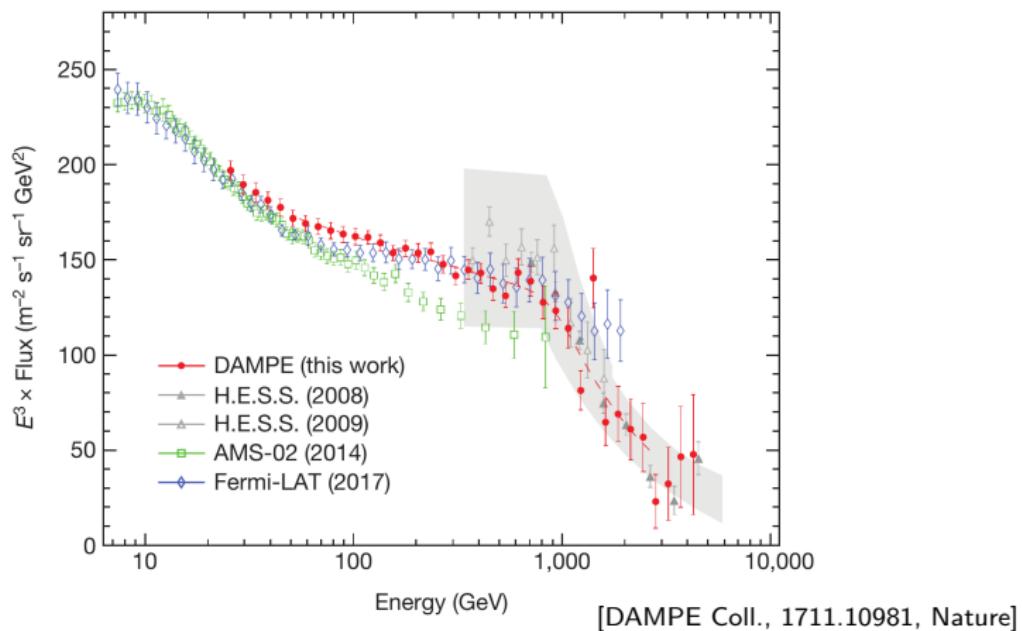
Interpretation with the
nearby pulsar Geminga



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

First Result from DAMPE

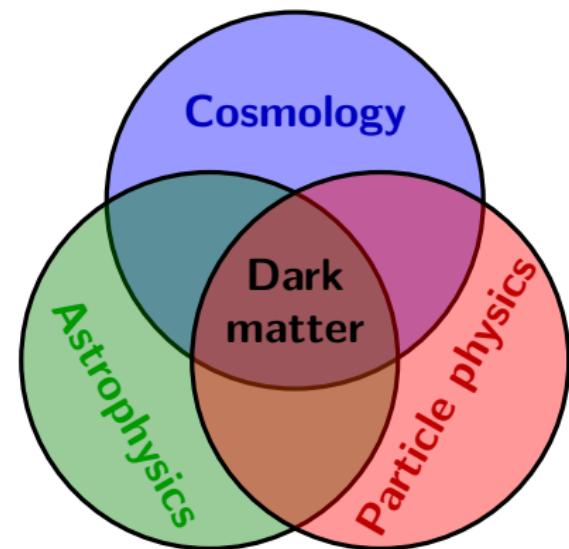
- In November 2017, **DAMPE (悟空)** collaboration released their first measurement of the cosmic-ray spectrum of **electrons and positrons**
- This measurement found a **spectral break** at ~ 0.9 TeV



[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!

