Detection of Dark Matter

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Academic Salon in School of Physics
Sun Yat-Sen University, Guangzhou
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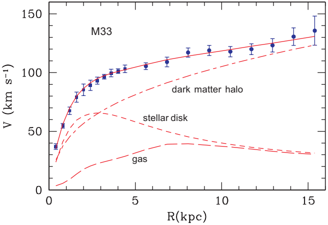
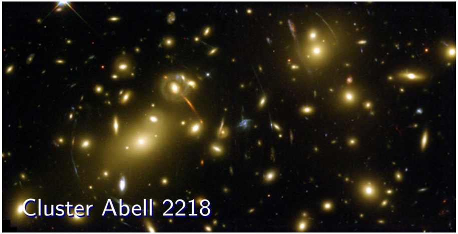
Dark Matter in the Universe

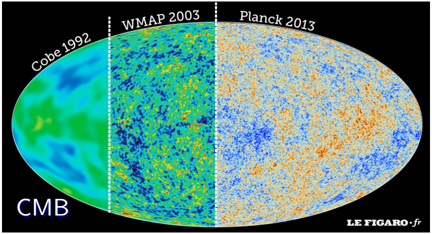
Dark matter (DM) makes up most of the matter component in the Universe, as suggested by astrophysical and cosmological observations


Bullet Cluster


Spiral galaxy M33




Cluster Abell 2218



CMB

Coma Cluster (后发座星系团)

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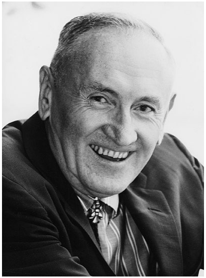


In 1933, Fritz Zwicky found that the **velocity dispersion** of galaxies in the Coma cluster was far too large to be supported by the luminous matter

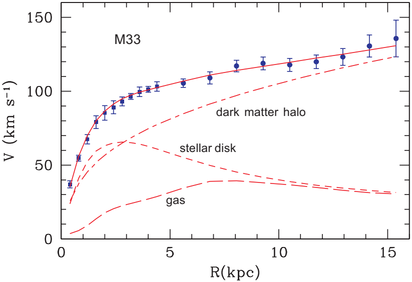
Mass-to-light ratio $\Upsilon_{\text{Coma}} \sim 260\Upsilon_\odot$

[Kent & Gunn, 1982]

Typical spiral galaxy: $\mathcal{O}(10)\Upsilon_\odot$

Spiral Galaxies: Rotation Curves

In the 1970s, Vera Rubin and her collaborators measured the **rotation curves** of spiral galaxies and also found evidence for **non-luminous matter**



[Corbelli & Salucci, astro-ph/9909252]

Spiral Galaxies: Rotation Curves

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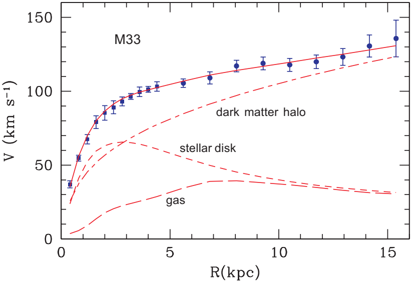
According to Newton's law, the relation between the rotation velocity v and the mass $M(r)$ within radius r should be

$$\frac{v^2}{r} = \frac{G_N M(r)}{r^2}$$

$$M(r) = \text{constant} \quad \Rightarrow \quad v \propto r^{-1/2}$$

$$M(r) \propto r \quad \Rightarrow \quad v = \text{constant}$$



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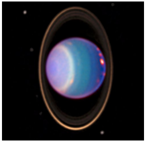
How Can We Explain an Anomalous Phenomenon?



Unexpected movement of **Uranus**

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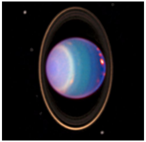

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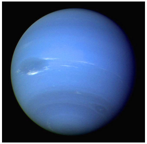
⇓

Perturbed by **Neptune** (discovered in 1846)



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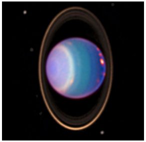

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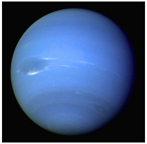

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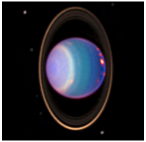

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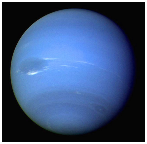

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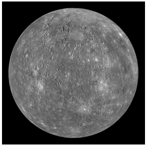

Anomalous perihelion precession of **Mercury**

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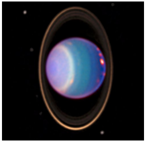

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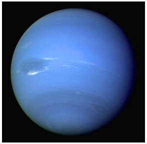

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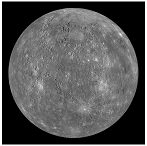

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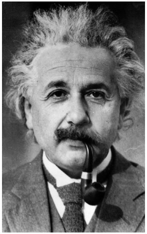
Update Newtonian mechanics to **general relativity**



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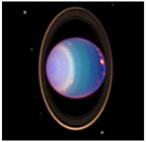

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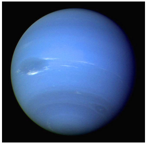

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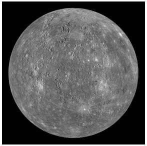

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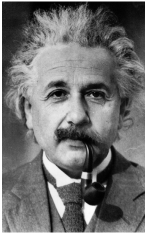

Modify known physical laws!

How about the Anomalous Phenomena Here?

💡 **Modify physical laws** ⇒ **MOdified Newtonian Dynamics** (MOND)

[Milgrom, ApJ, 1983]

Difficult to coherently explain data at all scales with one model

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💡 **Consider new objects** ⇒ **MAssive Compact Halo Objects** (MACHOs)

(**baryonic dark matter**: brown dwarfs, jupiters, stellar black-hole remnants, white dwarfs, neutron stars, ...)

MACHO fraction in the Galactic dark matter halo: $< 8\%$ (95% C.L.)

[EROS-2 coll., astro-ph/0607207]

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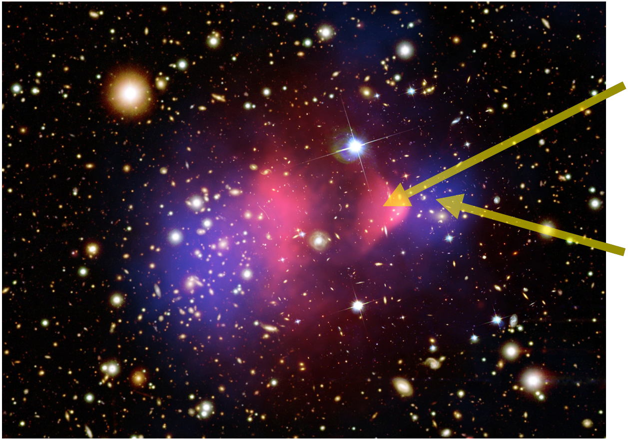
[EROS-2 coll., astro-ph/0607207]

💡 **Consider new substances** ⇒ **Nonbaryonic Dark Matter**

(not constituted by baryons)

Bullet Cluster: Disfavor MOND



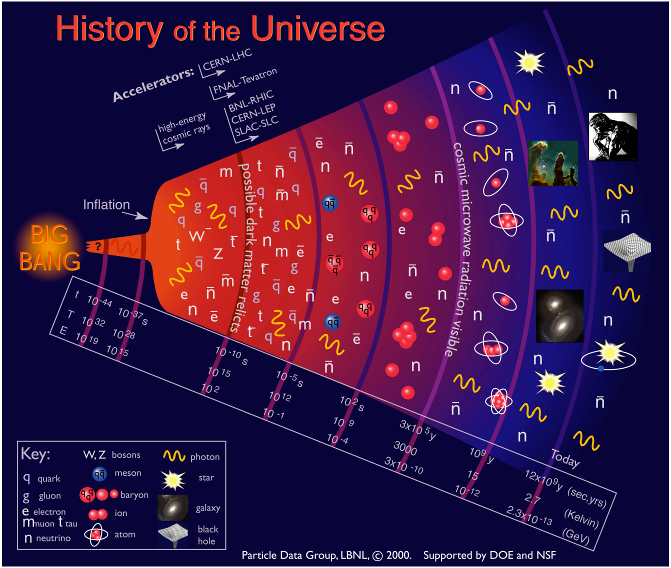
Fluid-like X-ray emitting plasma, *i.e.*, gas (visible matter)

Mass distribution observed by weak gravitational lensing (DM dominated)

An 8σ significance **spatial offset** of the center of the **total mass** from the center of the **baryonic mass peaks** cannot be explained with an alteration of the gravitational force law [Clowe *et al.*, astro-ph/0608407]

Big Bang Cosmology

- ~ 13.8 billion years ago, the Universe was extremely **hot, dense, and homogeneous**
- Everything was in **thermal equilibrium** and interacted with each other
- As the Universe expanded and cooled down; its constituents **decoupled** from the thermal bath **one by one**
- Then nuclei, atoms, stars, and galaxies were formed



Structure Formation: Hot, Cold, and Warm Dark Matter

Small initial fluctuations + Gravitational instability

$\Rightarrow$ Decoupled matter generates cosmological structures

Baryonic matter decoupled too late

Only baryonic matter $\Rightarrow$ Galaxies would not be formed!

$\Rightarrow$ Needs **nonbaryonic dark matter** which decoupled much earlier

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Hot dark matter (such as neutrinos): **relativistic** when it decoupled
⇒ structure forms by fragmentation (top-down)

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Galaxies are older than clusters ⇒ Favors cold dark matter theory

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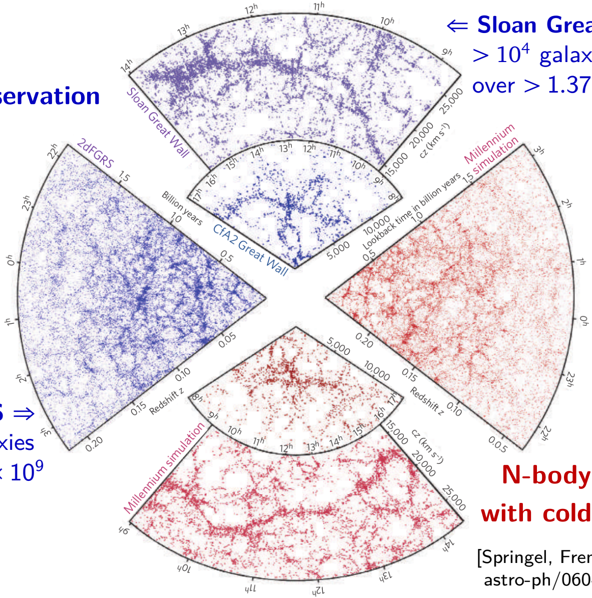
Milky Way dwarf satellites: ~ 60 (observed) vs. ~ 500 (CDM predicted)

"Missing satellites problem" $\Rightarrow$ A component of **warm dark matter**?

Galaxy Distribution: Observation vs Simulation

Observation



⇐ **Sloan Great Wall**
$> 10^4$ galaxies stretching over $> 1.37 \times 10^9$ light years

Half of 2dFGRS ⇒
$> 2.2 \times 10^5$ galaxies in a depth of 2×10^9 light years

N-body simulation with cold dark matter

[Springel, Frenk, White, astro-ph/0604561, Nature]

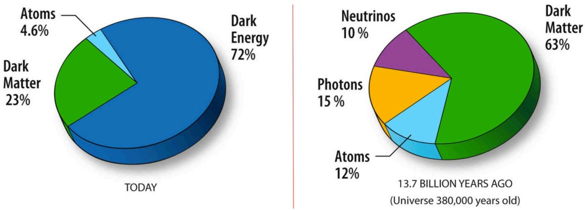
Standard Cosmology: ΛCDM Model

ΛCDM: the standard cosmological model

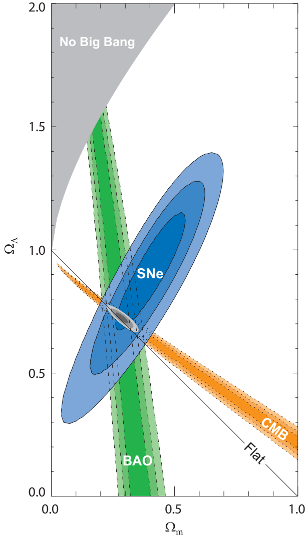
- **Cosmological constant Λ** (dark energy)
- **Cold dark matter** (CDM)

The evolution of the Universe is governed by the **Friedmann equation**

$$\frac{k}{H^2R^2} = \Omega_\Lambda + \Omega_m + \Omega_r - 1$$



[WMAP Science Team]



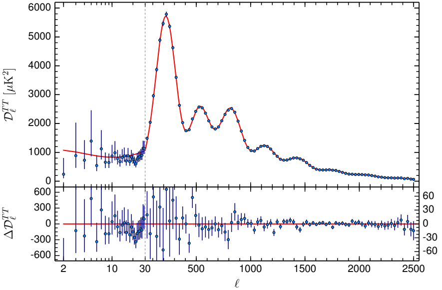
[Kowalski *et al.*, 0804.4142]

Cosmic Microwave Background (CMB)

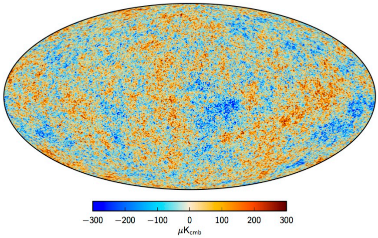
$t \sim 380\ 000$ yr, $T \sim 3000$ K
Electrons + Protons → Hydrogen Atoms
Photons decoupled

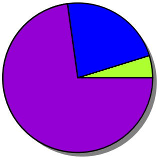
cools ⇓ down

Today, ∼ 2.7 K microwave background



Cosmological parameters, *e.g.*, Ω_Λ, Ω_c, and Ω_b, can be determined by measuring the **CMB anisotropy power spectrum**





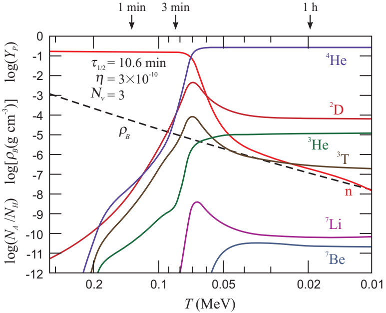
Planck 2015
[1502.01582, 1502.01589]

Cold DM (25.8%)
$\Omega_c h^2 = 0.1186 \pm 0.0020$

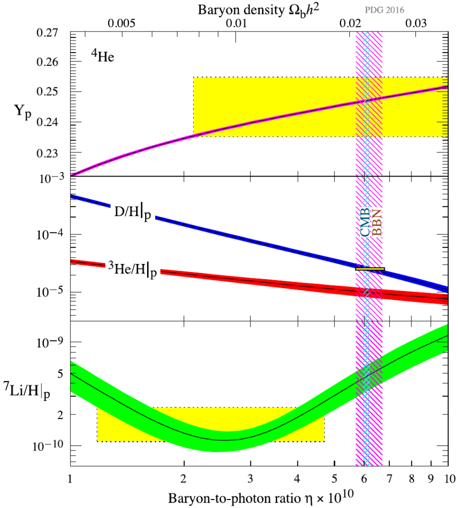
Baryons (4.8%)
$\Omega_b h^2 = 0.02226 \pm 0.00023$

Dark energy (69.3%)
$\Omega_\Lambda = 0.692 \pm 0.012$

Big Bang Nucleosynthesis (BBN): $t \sim 1\ \mathrm{sec} - 1\ \mathrm{hour}$



[Kolb & Turner, *The Early Universe*]



[PDG 2016]

Primordial abundances of light elements

⇓

Infer the **baryon density Ω_b**

(consistent with CMB observations)

⇓

The majority of matter is **nonbaryonic**

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

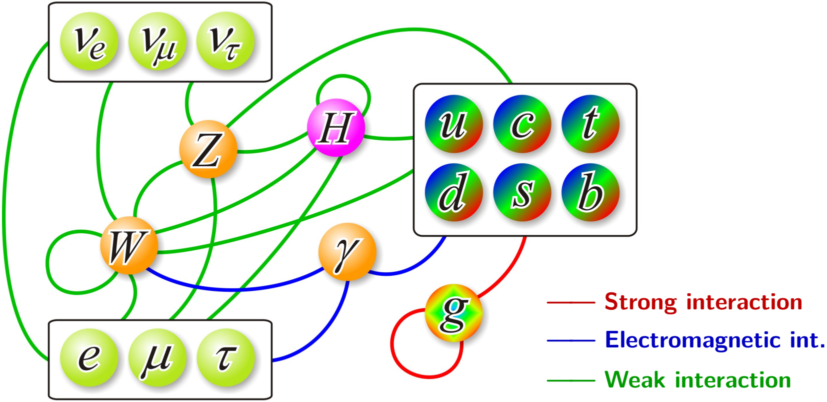
$$\rho_{\mathrm{DM}} \sim 0.3 - 0.4\ \mathrm{GeV/cm^3} \text{ near the earth}$$

Standard Model (SM) of Particle Physics

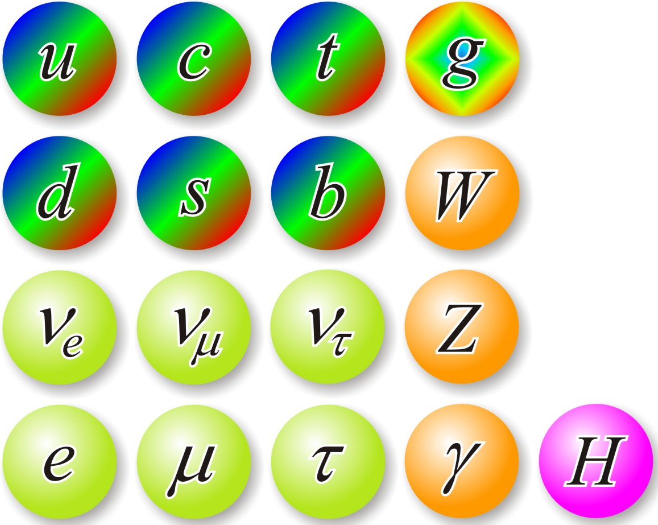
$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ **gauge symmetry** ↗ Fermion masses

$\Downarrow$ **Englert-Brout-Higgs mechanism**

$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{U}(1)_\mathrm{EM}$ **gauge symmetry** ↘ Higgs boson



Are There Dark Matter Candidates in the Standard Model?



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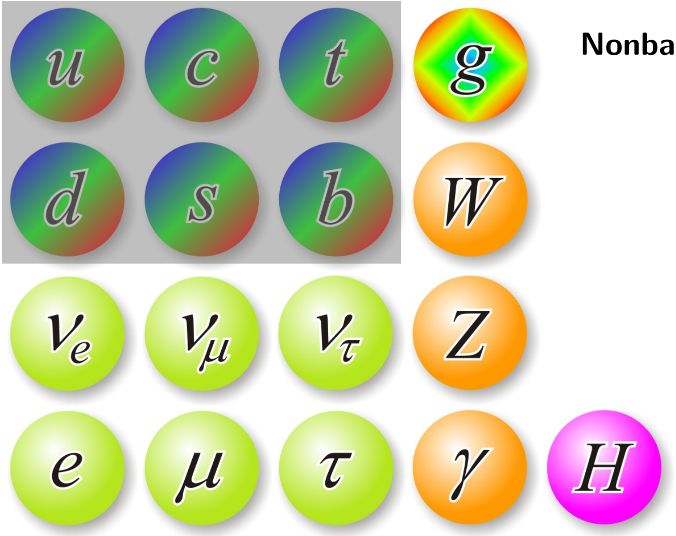

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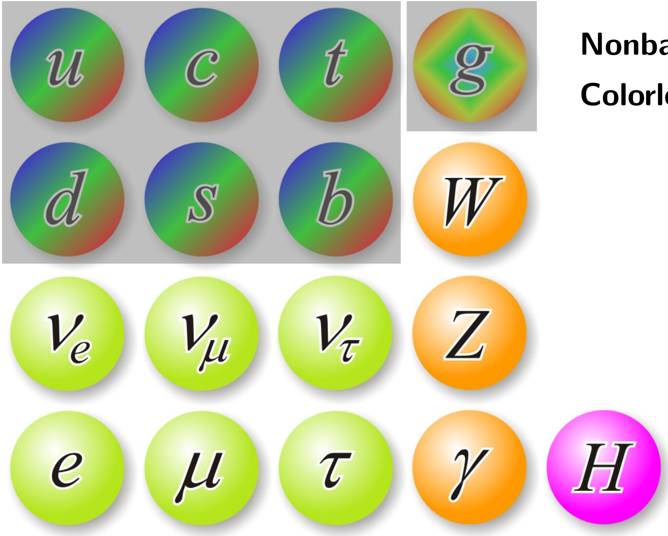

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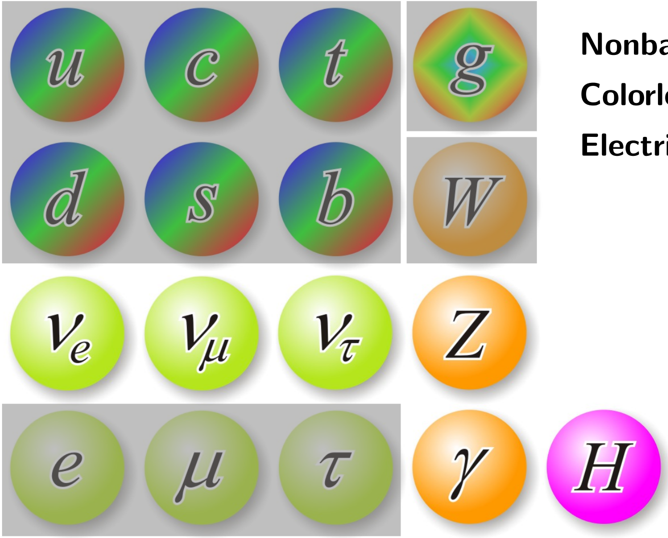

Nonbaryonic

Colorless

Electrically neutral

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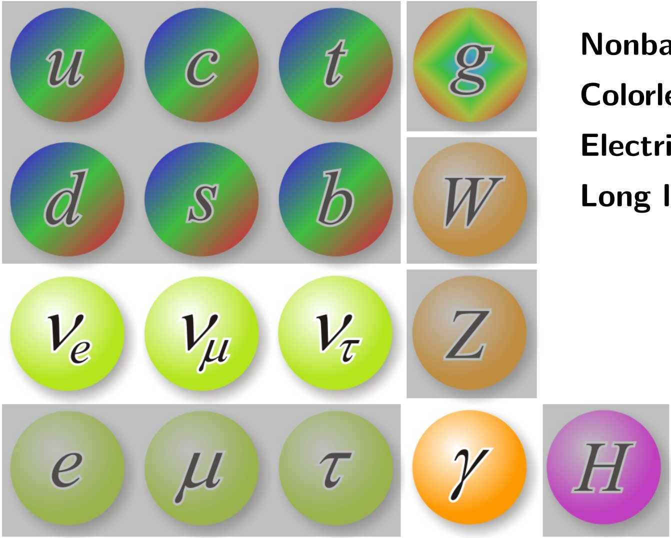

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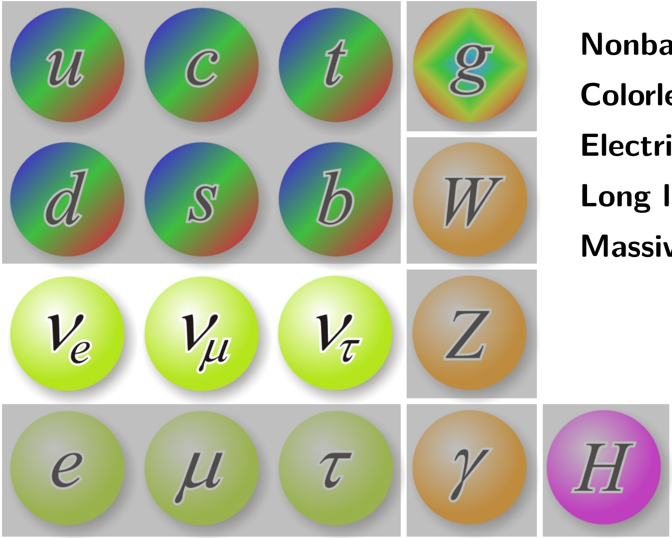

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Massive

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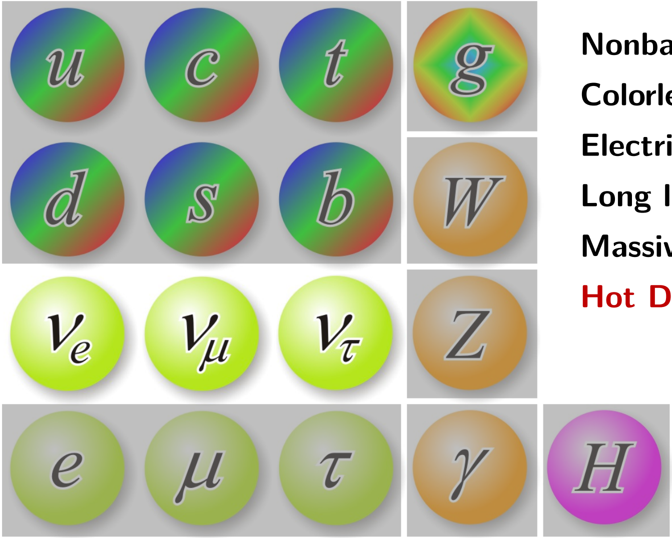

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Hot DM: neutrinos

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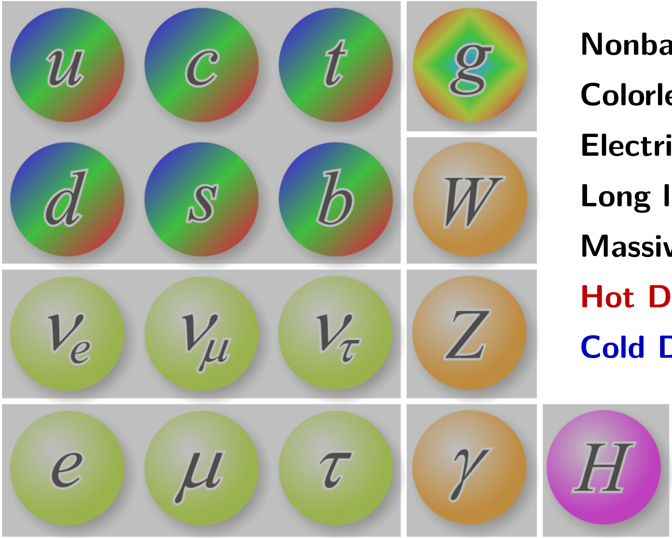

Nonbaryonic

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Electrically neutral

Long lived

Massive

Hot DM: neutrinos

Cold DM: none

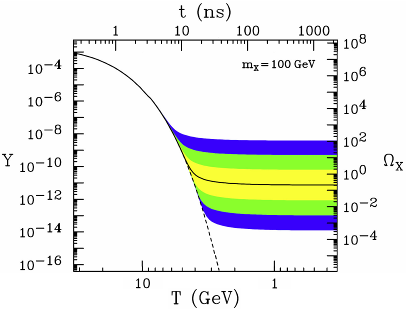
DM Relic Abundance

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

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

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

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



[Feng, arXiv:1003.0904]

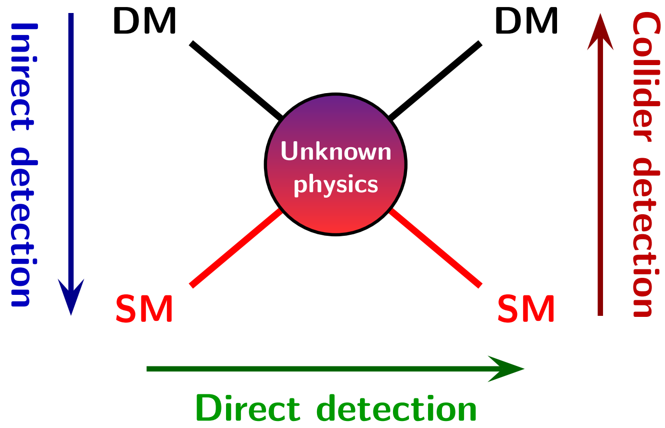
Assuming the annihilation process consists of two weak interaction vertices with the $\text{SU}(2)_{\text{L}}$ gauge coupling $g \simeq 0.64$, for $m_\chi \sim \mathcal{O}(\text{TeV})$ we have

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

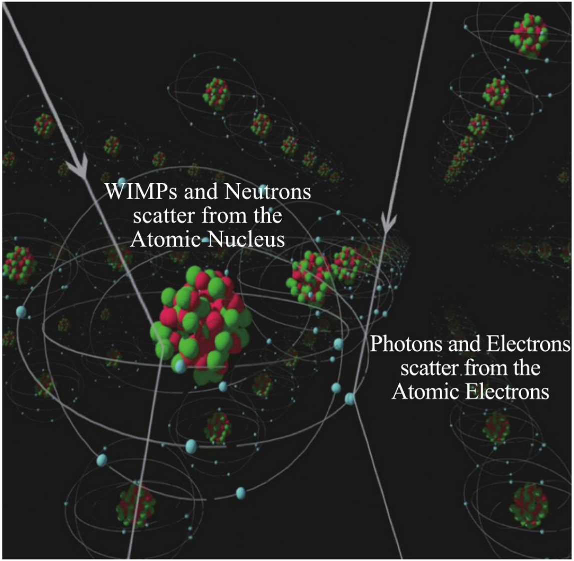
$\Rightarrow$ A very attractive class of DM candidates:

Weakly interacting massive particles (WIMPs)

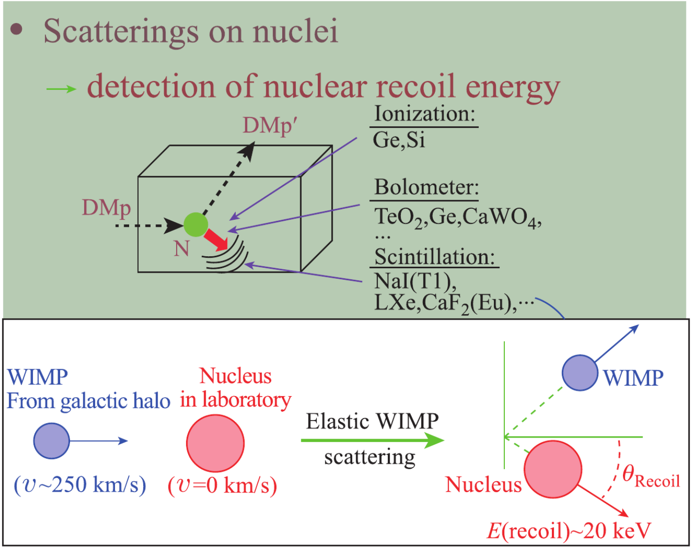
Experimental Approaches to Dark Matter



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**:

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

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

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

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]

Galactic disk and dark halo

[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**

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

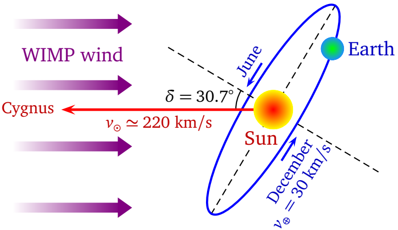
Velocity distribution: $f(\mathbf{v}) = \tilde{f}(\mathbf{v} + \mathbf{v}_{\text{obs}})$

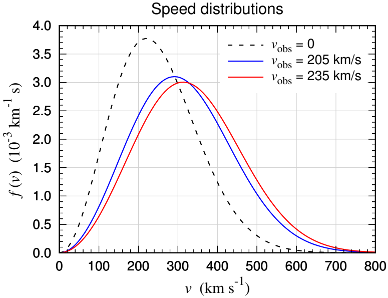
Speed distribution:

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

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)]

Event Rate

Event rate per unit time per unit energy interval:

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

Astrophysics factors
Particle physics factors
Detector factors

N_A: **target nucleus number**

$\rho_\oplus \simeq 0.4$ 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: $\sigma_{\chi A}^{\mathrm{SI}} \propto \mu_{\chi A}^2 [Z G_p + (A - Z) G_n]^2$

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

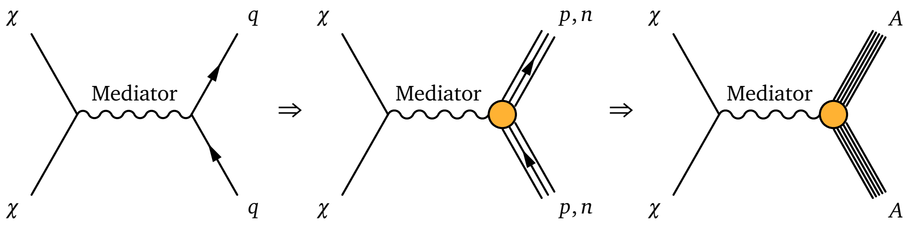
Nucleus properties: **mass number** A, **atomic number** Z, **spin** J_A, expectation value of the **proton (neutron) spin content** in the nucleus S_p^A (S_n^A)

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

- $Z \simeq A/2 \;\Rightarrow\; \sigma_{\chi A}^{\mathrm{SI}} \propto A^2 [(G_p + G_n)/2]^2$
  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 **DM-nucleon interaction** **DM-nucleus interaction**

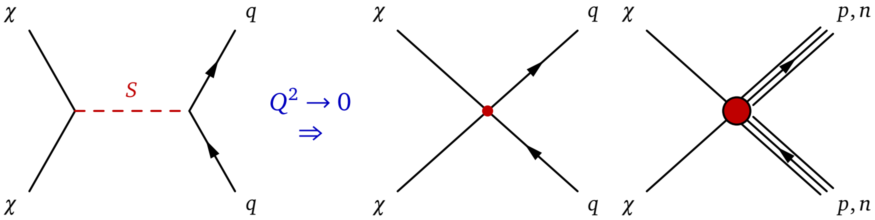


$\mathcal{M}(\chi q \to \chi q)$ $\mathcal{M}(\chi N \to \chi N)$ $\mathcal{M}(\chi A \to \chi A)$

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

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

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

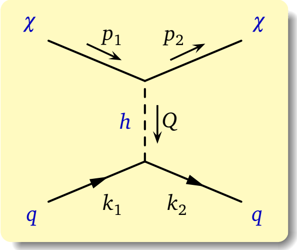
  $\bar{\chi}i\gamma_5\chi\bar{N}i\gamma_5 N, \quad \bar{\chi}\chi\bar{N}i\gamma_5 N, \quad \bar{\chi}i\gamma_5\chi\bar{N}N, \quad \bar{\chi}\gamma^\mu\chi\bar{N}\gamma_\mu\gamma_5 N, \quad \bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}\gamma_\mu N$
- For a **Majorana fermion** χ instead, we have $\bar{\chi}\gamma^\mu\chi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

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

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



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

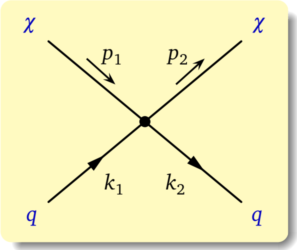
$$i\mathcal{M} = i g_\chi \bar{u}(p_2) u(p_1) \frac{i}{Q^2 - m_h^2} \left(-i\frac{m_q}{v}\right) \bar{u}(k_2) u(k_1)$$

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

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

$$\Downarrow$$

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



Effective Lagrangian: Scalar Type

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

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

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

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

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

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

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

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

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

Z Portal for Majorana Fermionic DM

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

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

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

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:

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

$G_{\text{AV},q} = -\frac{g_\chi g g_{\text{V}}^q}{4c_{\text{W}} m_Z^2}$ 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:

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

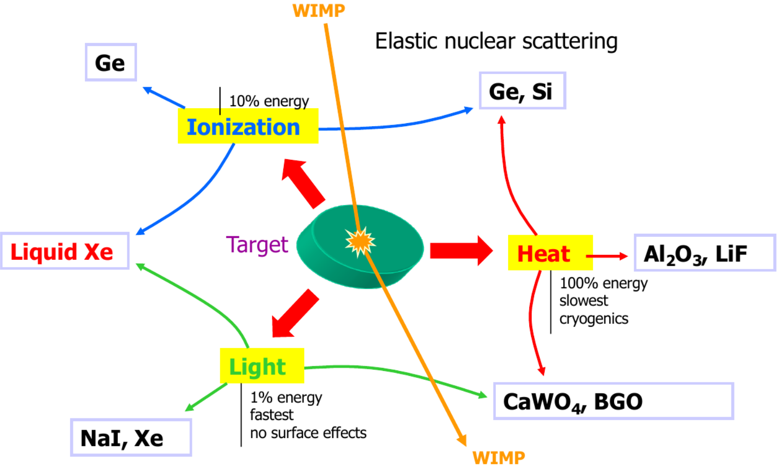
Effective Operators for DM-quark Interactions

	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]

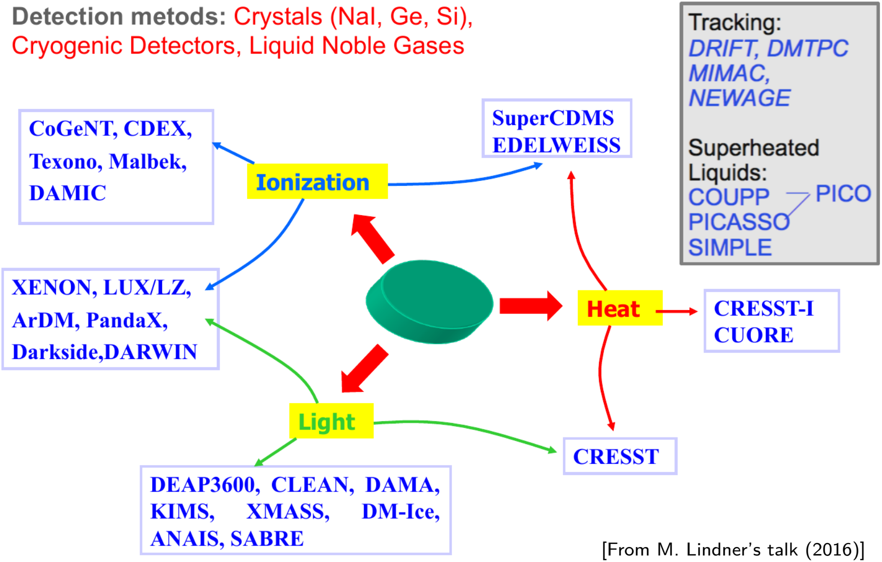
Technologies and Detector Material



[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)]

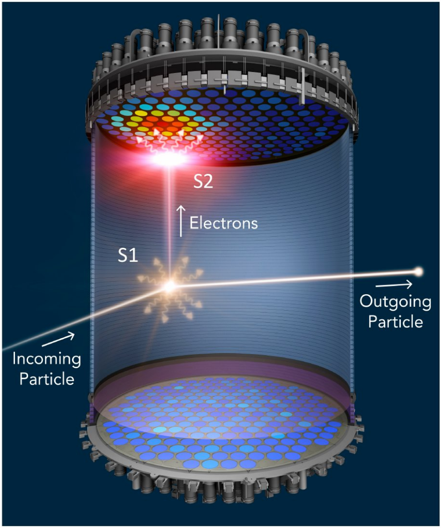
Example: Dual-phase Xenon Time Projection Chamber

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

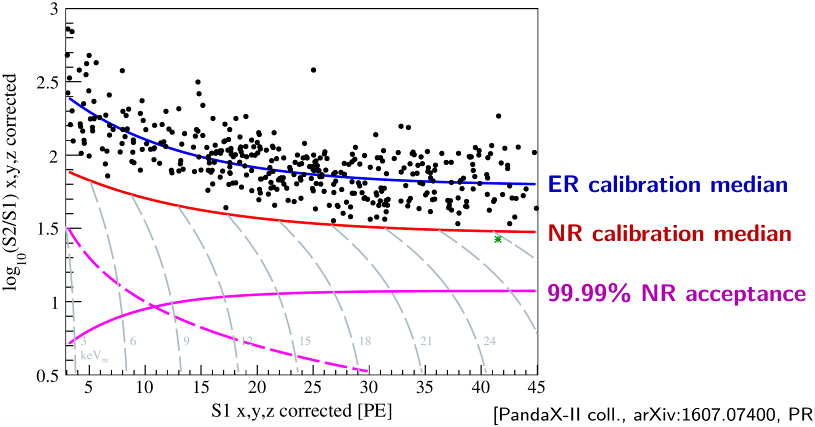
Experiments: XENON, LUX, PandaX



[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



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

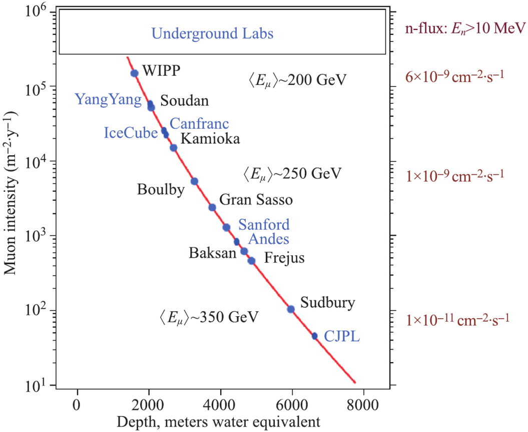
Backgrounds

Background suppression:

Deep underground

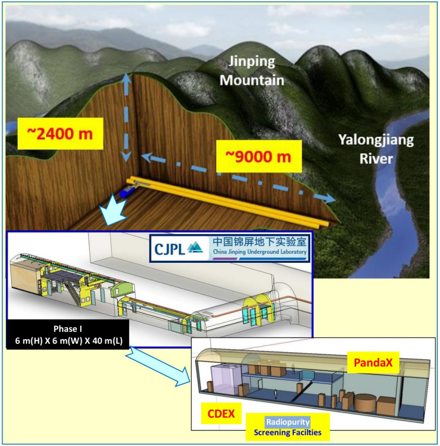
Shielded environments

- **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)

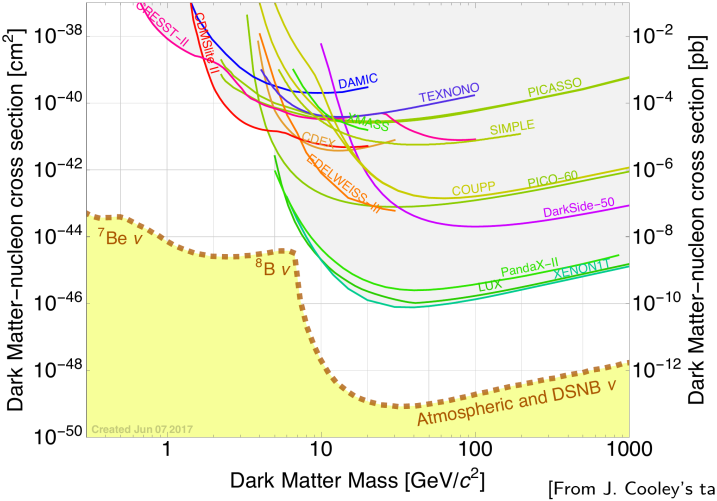


[Yue *et al.*, arXiv:1602.02462]

Experiments: CDEX, PandaX

Exclusion Limits for SI Scattering

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



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

Exclusion Limits for SI Scattering

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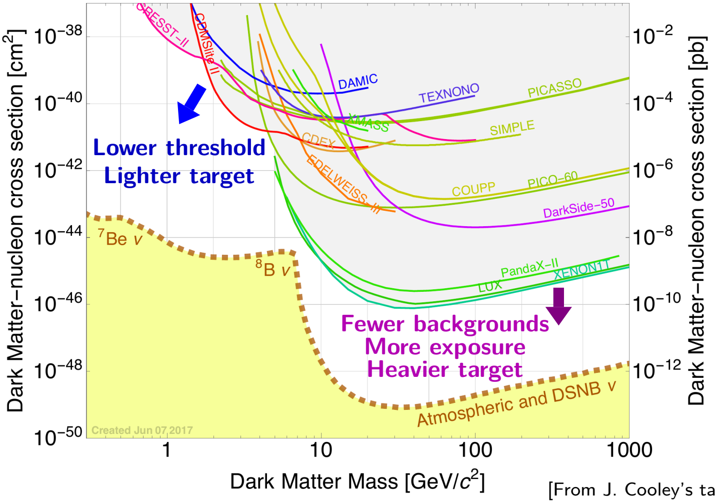
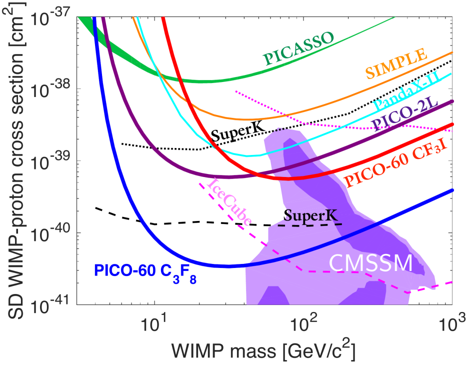


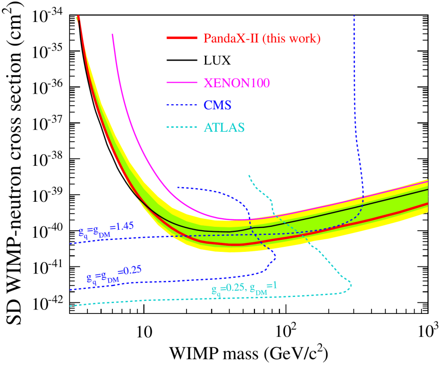
[From J. Cooley's talk (2017)]

Exclusion Limits for SD Scattering

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

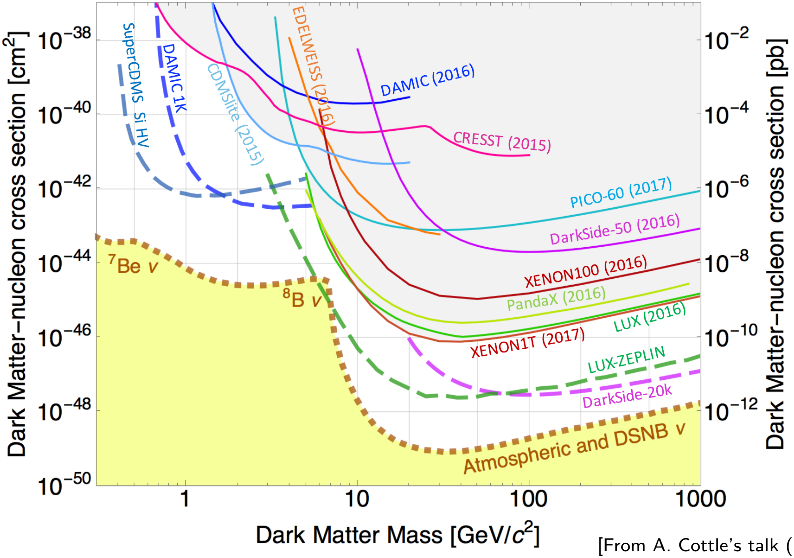


[PICO coll., arXiv:1702.07666, PRL]



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

Near Future Prospect

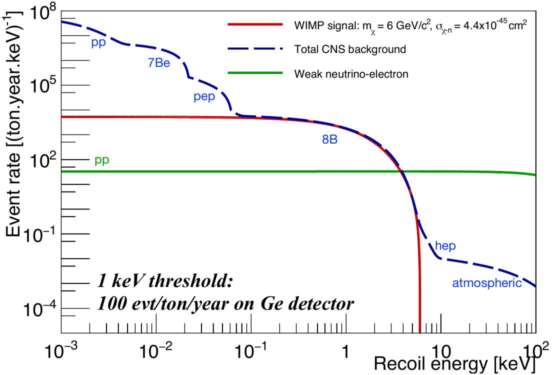


[From A. Cottle's talk (2017)]

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:
    $^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$



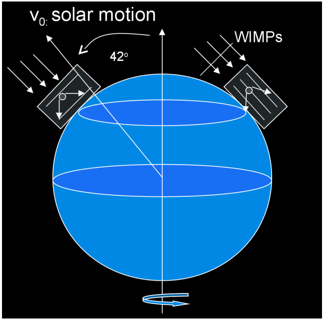
[From J. Billard's talk (2016)]

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

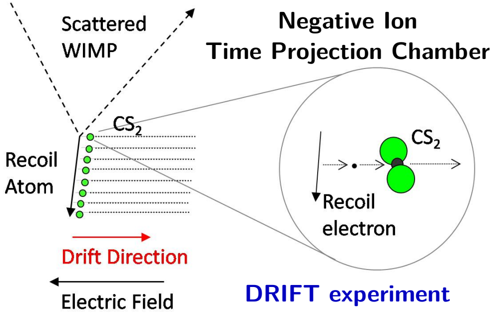
Going beyond the Neutrino Floor

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

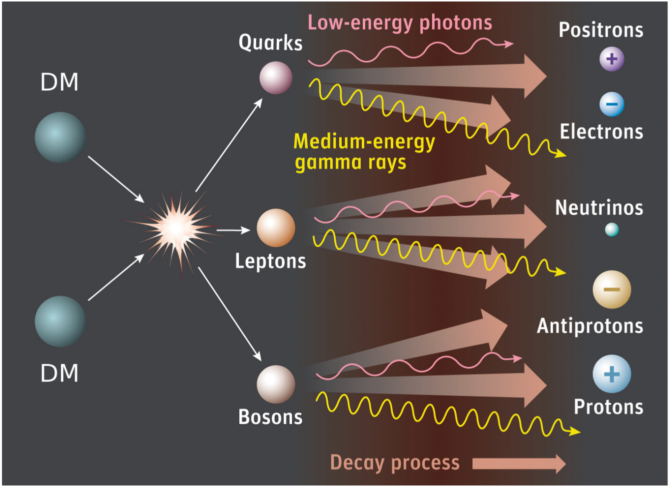


DRIFT experiment

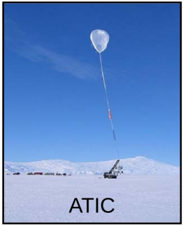
[From J. Spooner's talk (2010)]

Indirect Detection

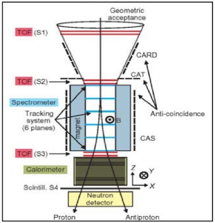
Indirect detection looks for stable products (γ **rays, cosmic rays, neutrinos**) from dark matter **annihilation** or **decay** (if DM is not totally stable) in space

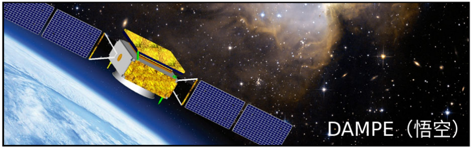


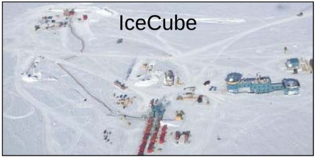
Indirect Detection Experiments



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

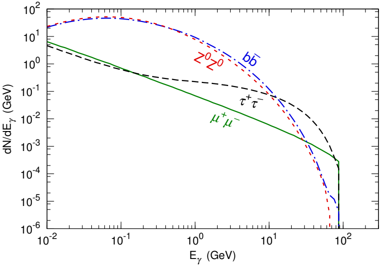
$B_i \equiv \Gamma_i/\Gamma_\chi$: **branching ratio** of the decay channel i

γ rays from DM: Continuous Spectrum

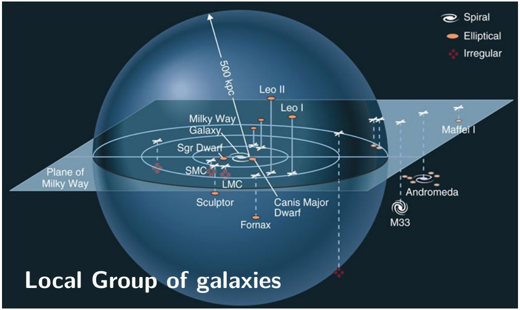
DM pair annihilation or decay into e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, W^+W^-, Z^0Z^0, h^0h^0

$\Downarrow$

γ-ray emission from final state radiation or particle decays

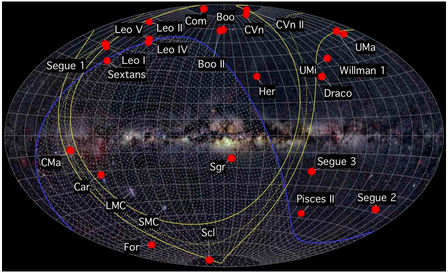


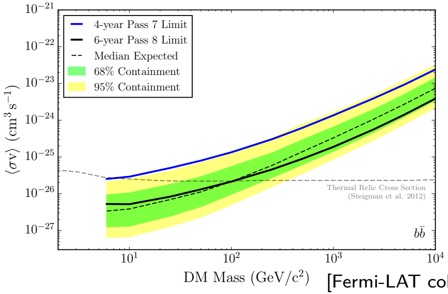
- **Cut-off energy**:
  m_χ for DM annihilation
  $m_\chi/2$ for DM decay
- More promising to look at **DM-dominated regions**:
  💥 **Galactic Center**
  💥 **Galactic halo**
  💥 **dwarf galaxies**
  💥 **clusters of galaxies**

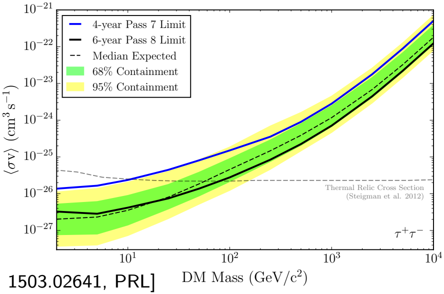


γ-ray Observation of Dwarf Galaxies

- 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







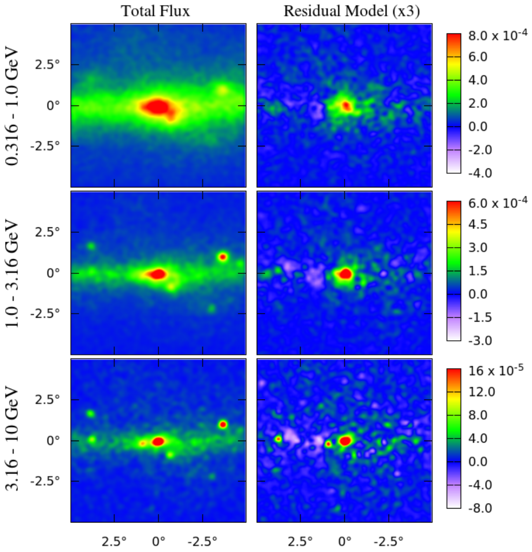
[Fermi-LAT coll., 1503.02641, PRL]

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]

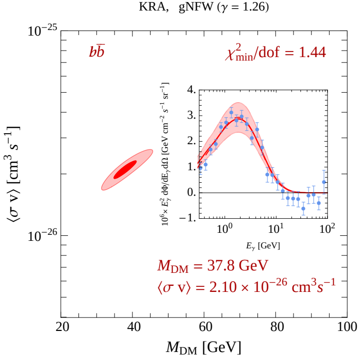
Interpretation with Dark Matter Annihilation

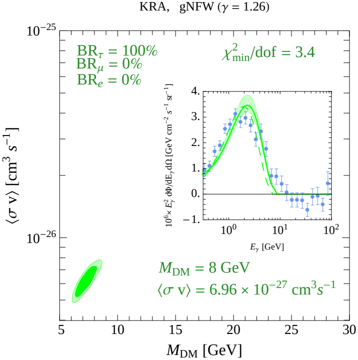
DM annihilation into $b\bar{b}$

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

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

$$m_\chi \sim 9\ \text{GeV}$$
$$\langle \sigma_{\text{ann}} v \rangle \sim 5 \times 10^{-27}\ \text{cm}^3\,\text{s}^{-1}$$





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

γ rays from DM: Line Spectrum

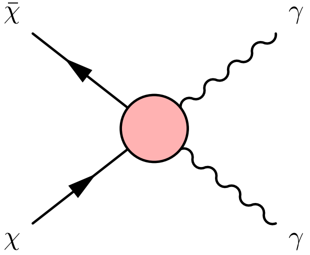
DM particles should **not have electric charge** and thus not directly couple to photons

$\Downarrow$

DM particles may couple to photons via high order loop diagrams

$\Downarrow$

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



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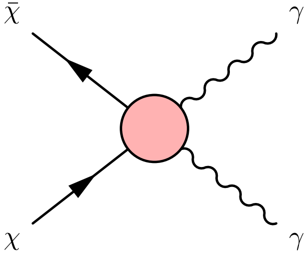


For **nonrelativistic** DM particles in space, the photons produced in $\chi\chi \to \gamma\gamma$ would be **mono-energetic**

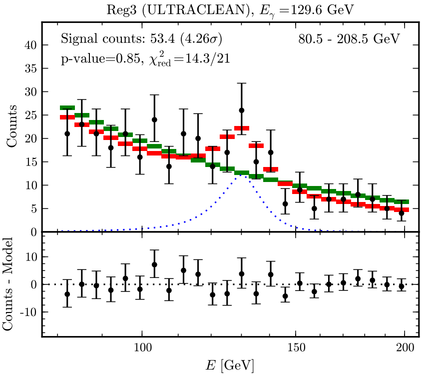
$\Downarrow$

A γ-ray line at energy $\sim m_\chi$

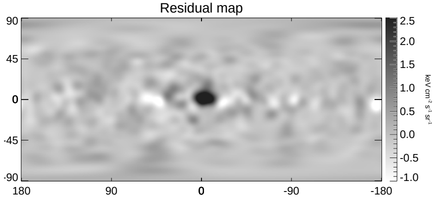
(**"smoking gun"** for DM particles)

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



[Weniger, 1204.2797, JCAP]

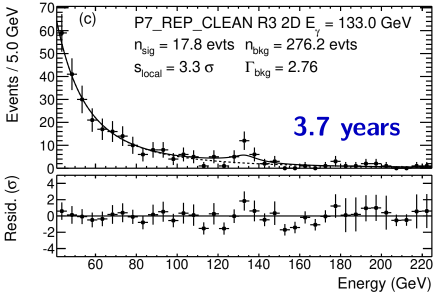


[Su & Finkbeiner, 1206.1616]

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]

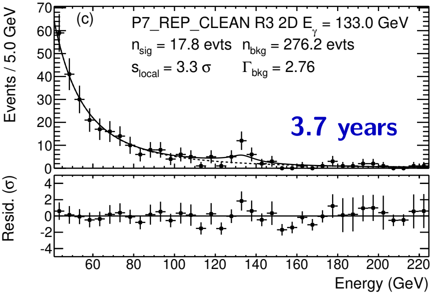
Fermi-LAT Official Results: Not Confirmed with More Data

- **3.7-year data**

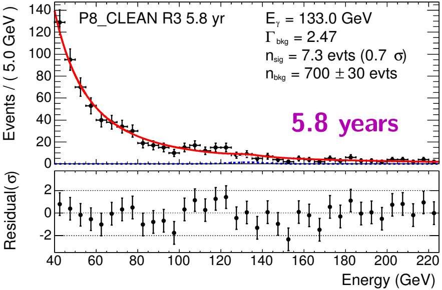
  The most significant fit occurred at $E_\gamma = 133$ GeV and had a **local significance** of 3.3σ, translating to a global significance of 1.6σ

- **5.8-year data**

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



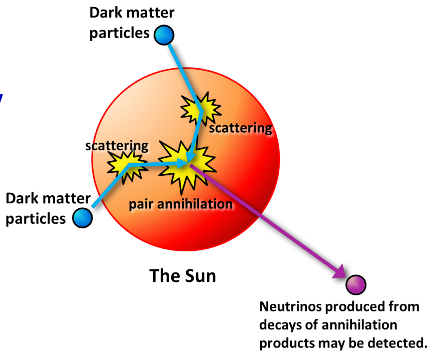
[Fermi-LAT Coll., 1305.5597, PRD]



[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:

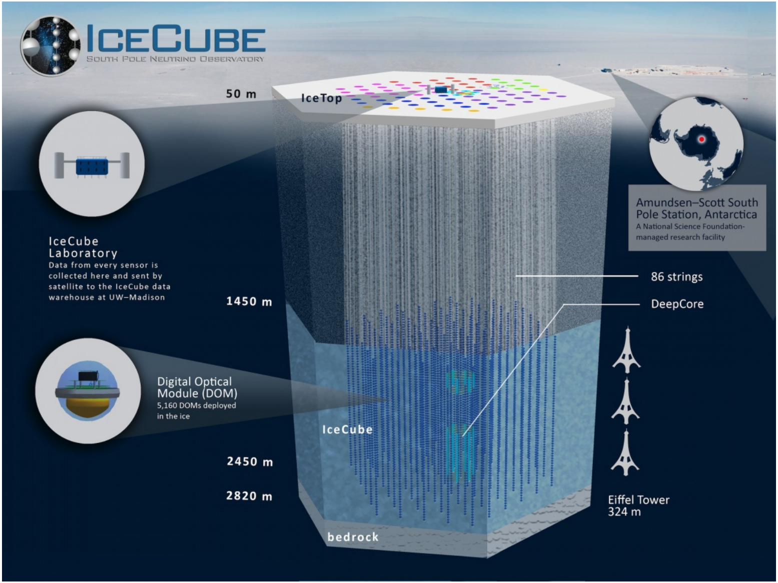
$$\frac{dN_\chi}{dt} = C_\odot(\sigma_{\chi\mathrm{H}}, \sigma_{\chi\mathrm{He}}) + A_\odot(\sigma_{\mathrm{ann}})N_\chi^2$$

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

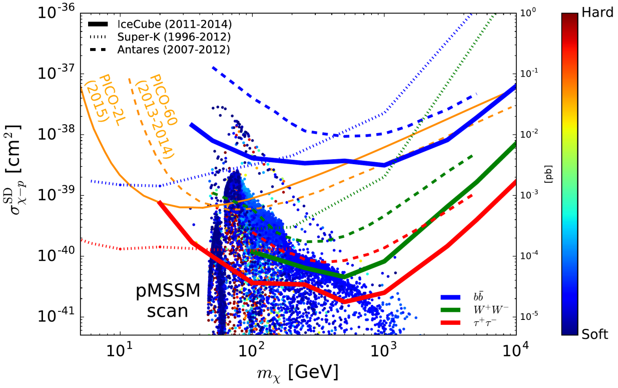
✨ The age of the Sun is long enough ($\sim$ 4.6 billion years) to make the capture and annihilation processes reach **equilibrium:** $dN_\chi/dt = 0$

IceCube: South Pole Neutrino Observatory



Searches for Neutrinos from DM Annihilation within the Sun

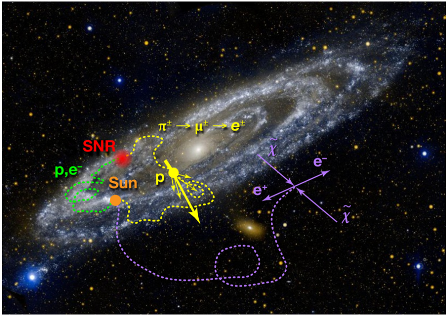
- **No signal detected** in searches for neutrinos with energies of GeV − TeV from DM annihilation at the solar core
- Assuming equilibrium in the capture and annihilation processes, the constraints can be converted to those on the **DM scattering cross section**

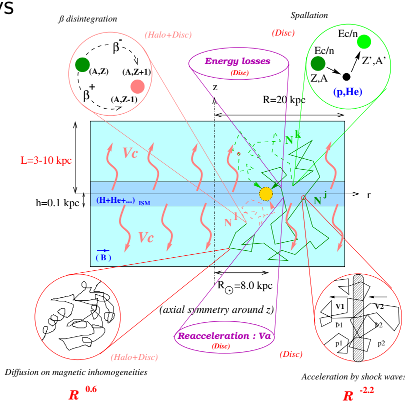


[IceCube Coll, 1612.05949, EPJC]

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**

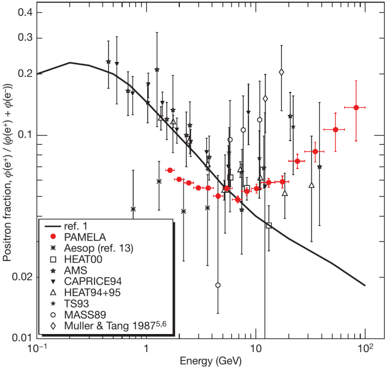




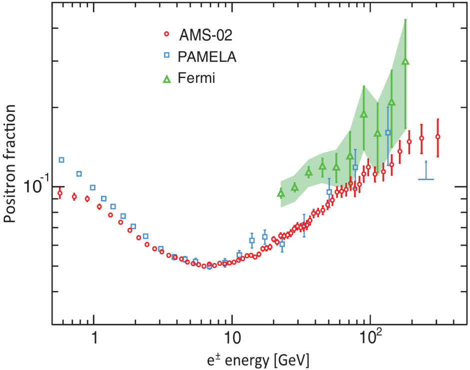
[Maurin *et al.*, astro-ph/0212111]

Cosmic-ray 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]

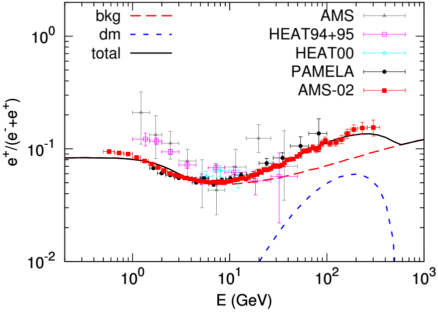


[AMS Coll., PRL 110, 141102 (2013)]

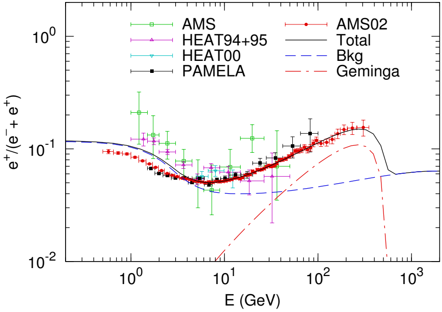
Interpretation: Dark Matter vs Pulsar

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

Interpretation with the **nearby pulsar Geminga**



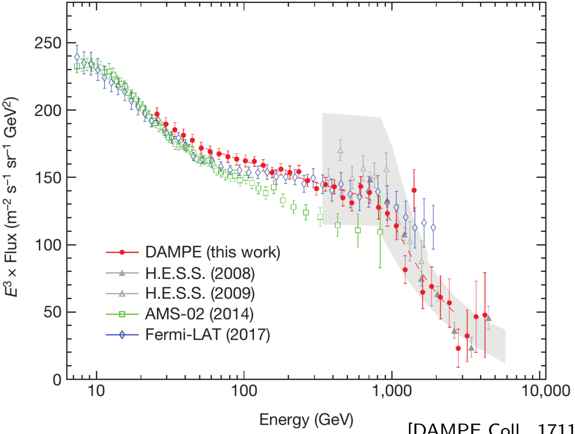
[Yuan, Bi, *et al.*, 1304.1482, APP]



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

First Result from DAMPE

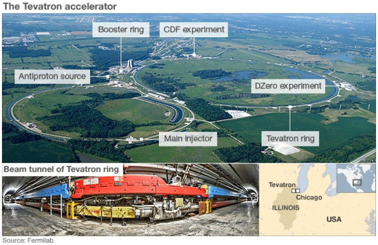
- In November 2017, **DAMPE (悟空)** collaboration released their first measurement of the cosmic-ray spectrum of **electrons and positrons**
- This measurement found a **spectral break** at ~ 0.9 TeV

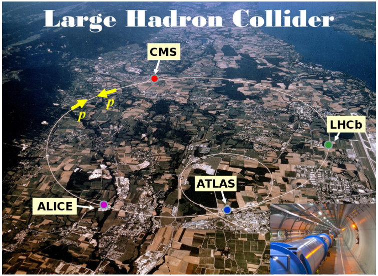


[DAMPE Coll., 1711.10981, Nature]

Past and Current High Energy Colliders

- **TEVATRON**: $p\bar{p}$ collider, 1987-2011
  Circumference: 6.28 km
  Collision energy: $\sqrt{s} = 1.96$ TeV
  Luminosity: $\mathcal{L} \sim 4.3 \times 10^{32}\ \text{cm}^{-2}\,\text{s}^{-1}$
  Detectors: CDF, DØ
- **LEP**: e^+e^- collider, 1989-2000
  Circumference: 26.66 km
  Collision energy: $\sqrt{s} = 91 - 209$ GeV
  Luminosity: $\mathcal{L} \sim (2-10) \times 10^{31}\ \text{cm}^{-2}\,\text{s}^{-1}$
  Detectors: ALEPH, DELPHI, OPAL, L3
- **LHC**: pp (pPb, PbPb) collider, 2009-
  Circumference: 26.66 km
  Collision energy: $\sqrt{s} = 7, 8, 13, 14$ TeV
  Luminosity: $\mathcal{L} \sim (1-5) \times 10^{34}\ \text{cm}^{-2}\,\text{s}^{-1}$
  Detectors: ATLAS, CMS, ALICE, LHCb





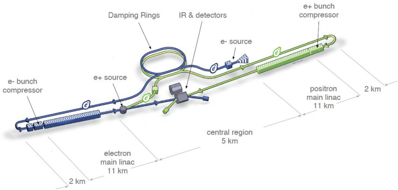
Future Projects

- **ILC**: International Linear Collider

  e^+e^- collider, $\sqrt{s} = 250$ GeV $- 1$ TeV

  $\mathcal{L} \sim 1.5 \times 10^{34}$ cm^{-2} s^{-1}

  Detectors: SiD, ILD



- **CEPC**: Circular Electron-Positron Collider (China)

  e^+e^- collider, $\sqrt{s} \sim 240 - 250$ GeV, $\mathcal{L} \sim 1.8 \times 10^{34}$ cm^{-2} s^{-1}

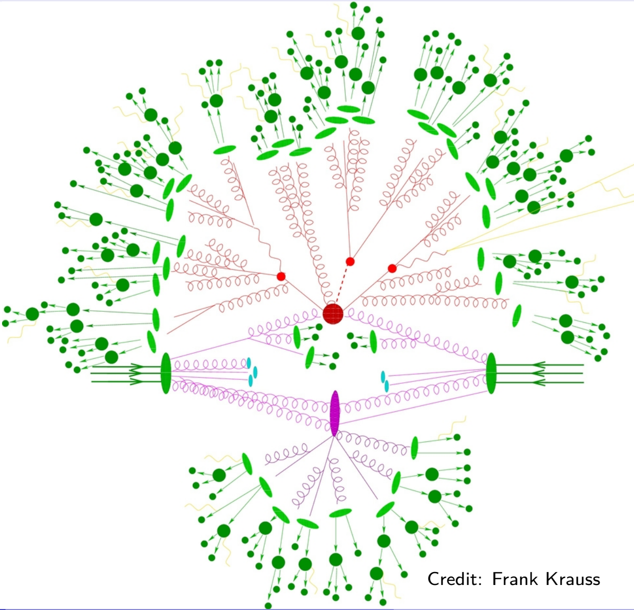
- **SPPC**: Super Proton-Proton Collider (China)

  pp collider, $\sqrt{s} \sim 50 - 70$ TeV, $\mathcal{L} \sim 2.15 \times 10^{35}$ cm^{-2} s^{-1}

- **FCC**: Future Circular Collider (CERN)
  - **FCC-ee**: e^+e^- collider, $\sqrt{s} \sim 90 - 350$ GeV, $\mathcal{L} \sim 5 \times 10^{34}$ cm^{-2} s^{-1}
  - **FCC-hh**: pp collider, $\sqrt{s} \sim 100$ TeV, $\mathcal{L} \sim 5 \times 10^{34}$ cm^{-2} s^{-1}

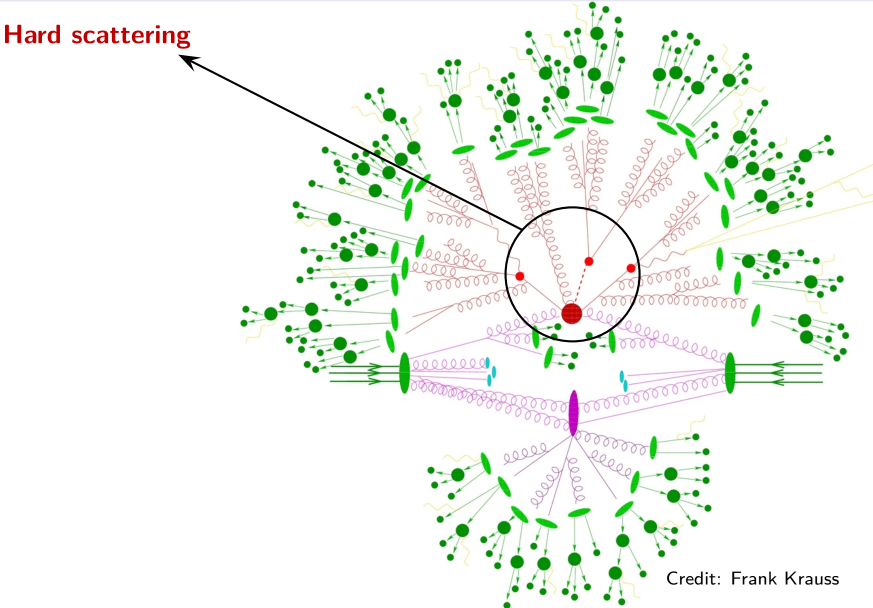
- **CLIC**: Compact Linear Collider, $\sqrt{s} \sim 1 - 3$ TeV, $\mathcal{L} \sim 6 \times 10^{34}$ cm^{-2} s^{-1}

Typical Event in High Energy pp Collisions



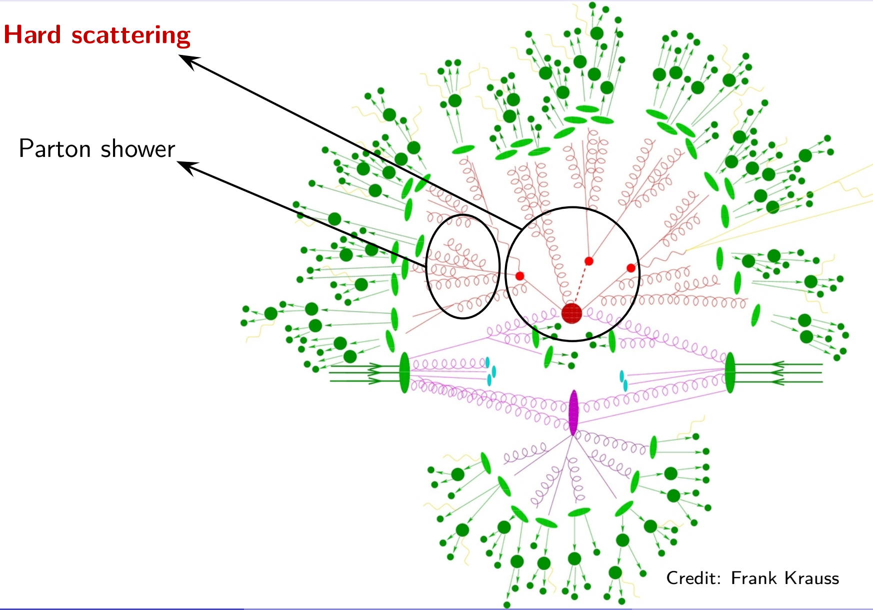
Credit: Frank Krauss

Typical Event in High Energy pp Collisions



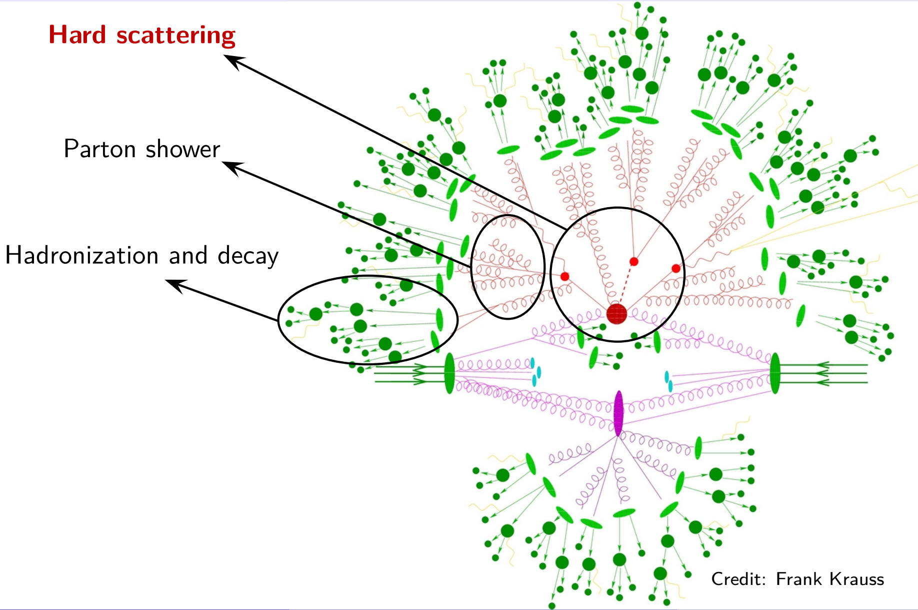
Credit: Frank Krauss

Typical Event in High Energy pp Collisions



Credit: Frank Krauss

Typical Event in High Energy pp Collisions



Typical Event in High Energy pp Collisions

Hard scattering

Parton shower

Hadronization and decay

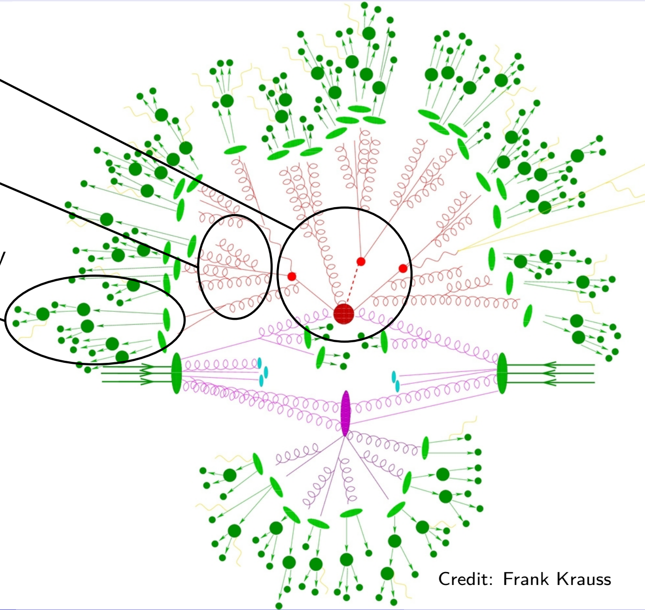
Collimated particles

⇓

Jet

⇓

Mimic to a hard parton



Credit: Frank Krauss

Typical Event in High Energy pp Collisions

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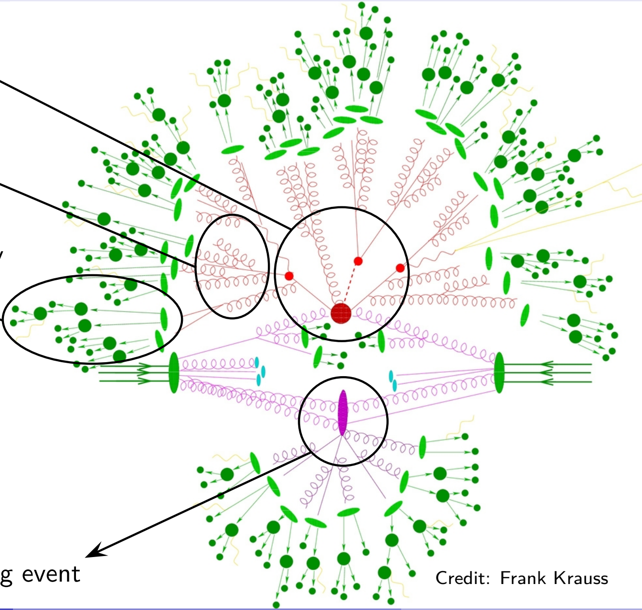
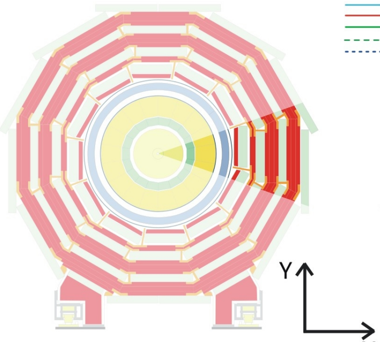


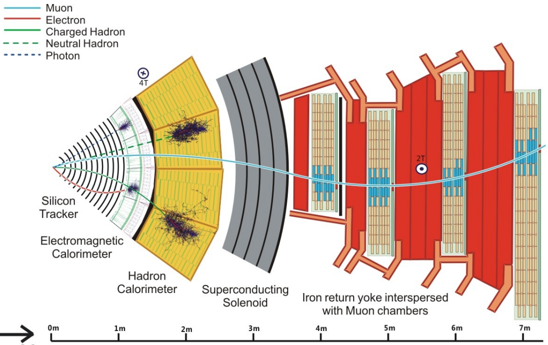
Underlying event

Credit: Frank Krauss

Particle Detectors at Colliders

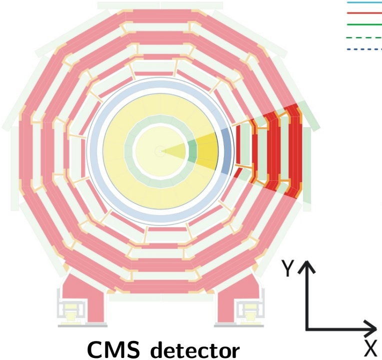


CMS detector

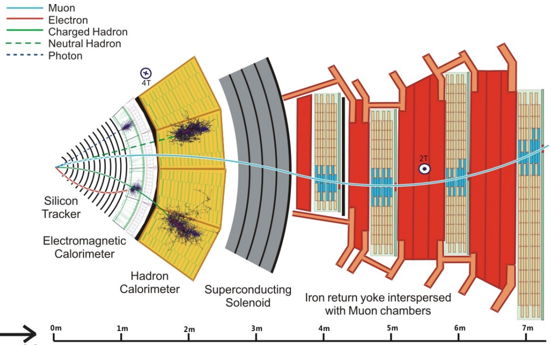


Sub-detectors	γ	$e^\pm$	$\mu^\pm$	Charged hadrons	Neutral hadrons	ν, DM
Tracker, $\lvert\eta\rvert \lesssim 2.5$	$\times$	$\surd$	$\surd$	$\surd$	$\times$	$\times$
ECAL, $\lvert\eta\rvert \lesssim 3$			$\surd$	$\surd$	$\times$	$\times$
HCAL, $\lvert\eta\rvert \lesssim 5$	$\times$	$\times$	$\times$			$\times$
Muon detectors, $\lvert\eta\rvert \lesssim 2.4$	$\times$	$\times$	$\surd$	$\times$	$\times$	$\times$

Particle Detectors at Colliders



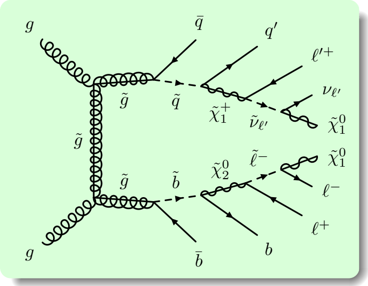
CMS detector

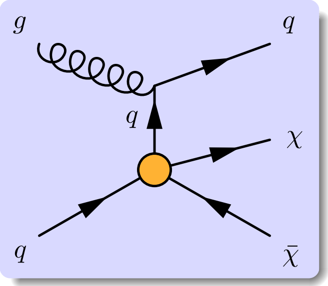


Sub-detectors	γ	$e^\pm$	$\mu^\pm$	Charged hadrons	Neutral hadrons	ν, DM
Tracker, $\lvert\eta\rvert \lesssim 2.5$	×	√	√	√	×	×
ECAL, $\lvert\eta\rvert \lesssim 3$			√	√		×
HCAL, $\lvert\eta\rvert \lesssim 5$	×	×	×			×
Muon detectors, $\lvert\eta\rvert \lesssim 2.4$	×	×	√	×	×	×

Missing energy $\not{E}_\mathrm{T}$

DM Production





Social dark matter

Accompanied by other new particles

Complicated decay chains

Decay products of other particles

Various final states

(jets + leptons + $\not{E}$, ...)

Maverick dark matter

DM particle is the only new particle reachable at the collision energy

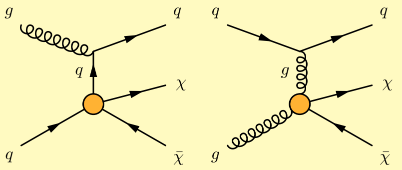
Direct production

Mono-X + $\not{E}$ final states

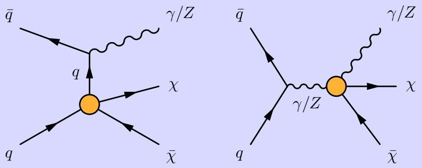
(monojet, mono-γ, mono-W/Z, ...)

[From Rocky Kolb's talk]

DM Direct Production at Hadron Colliders



Monojet $+ \not{E}_{\mathrm{T}}$



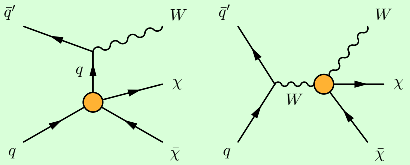
Monophoton/mono-$Z + \not{E}_{\mathrm{T}}$

Sensitive to the DM couplings to

quarks, gluons

photons, Z bosons

$W^{\pm}$ bosons



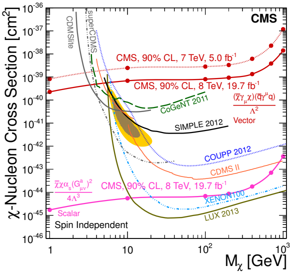
Mono-$W + \not{E}_{\mathrm{T}}$

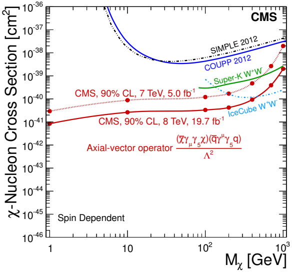
Monojet + $\not{E}_\mathrm{T}$ Channel at the LHC

- In the context of effective field theory, **effective operators** can be used to describe interactions between DM and quarks, which could induce the **monojet + $\not{E}_\mathrm{T}$ signal** at the LHC, as well as **DM-nucleus scattering signals** in DM direct detection experiments
- $\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$ **operators: upper right plot**

  The 8 TeV LHC sensitivity is better than direct detection only when $m_\chi \lesssim 3$ GeV
- $\bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q$ **operators: lower right plot**

  The 8 TeV LHC sensitivity is much better than direct detection

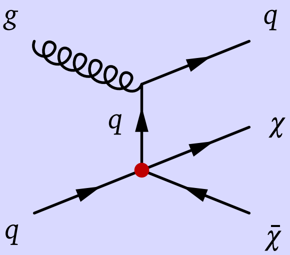




[CMS coll., arXiv:1408.3583, EPJC]

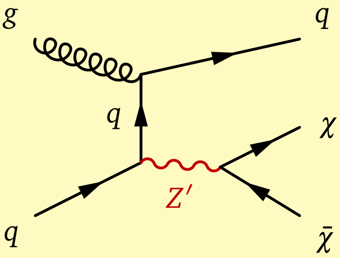
A Little Further than Effective Operators

- The **valid range** of effective field theory is limited: if the **momentum transfer** in scattering is **sufficient large** (comparable to or even larger than the mediator mass), the effective operator approach would **break down**
- In this case, **simplified models** involving **only renormalizable operators** would give a more reasonable description



Effective operators

$\Rightarrow$



Z'-portal simplified models

SPPC Sensitivity to Z'-portal DM Simplified Models

Z'-portal models for **Dirac fermion χ**:

- **FV model**: vector current interaction

$$\mathcal{L}_{\mathrm{FV}} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

- **FA model**: axial vector current int.

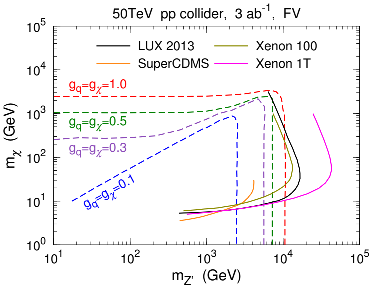
$$\mathcal{L}_{\mathrm{FA}} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu \gamma_5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi$$

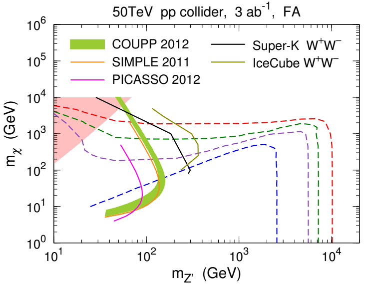
Dashed lines: 90% CL expected exclusion limits at the SPPC with $\sqrt{s} = 50$ TeV

Solid lines: 90% CL exclusion limits from direct detection for $g_q = g_\chi = 0.5$

Light red region: unitarity violation for $g_q = g_\chi = 1$

[Xiang, Bi, Yin, **ZHY**, 1503.02931, PRD]





τ-portal Simplified DM Models

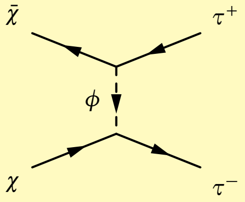
- We studied four **τ-portal simplified models** involving a mediator with additive quantum numbers identical to the right-handed τ^-
- We interpreted the **GC GeV excess signal** as DM annihilation into $\tau^+\tau^-$, and discussed **how to test this interpretation at the LHC**
- **Spin-1/2 fermion χ, spin-0 mediator ϕ:**

$$\mathcal{L}_\phi = \lambda\phi\bar{\tau}_R\chi_L + \text{h.c.}$$

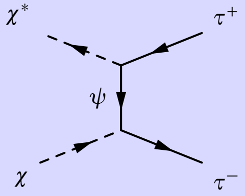
  - **DFDM model:** χ is a Dirac fermion
  - **MFDM model:** χ is a Majorana fermion
- **Spin-0 scalar χ, spin-1/2 mediator ψ:**

$$\mathcal{L}_\psi = \kappa\chi\bar{\tau}_R\psi_L + \text{h.c.}$$

  - **CSDM model:** χ is a complex scalar
  - **RSDM model:** χ is a real scalar



DFDM: annihilation



CSDM: annihilation

DM Annihilation into $\tau^+\tau^-$ in the Low Velocity Limit

DFDM model:

$$\frac{1}{2}\langle\sigma_{\mathrm{ann}}v\rangle = \frac{\lambda^4\, m_\chi^2\, \beta_\tau}{64\pi(m_\phi^2 + m_\chi^2 - m_\tau^2)^2} \simeq 5\times 10^{-27}\ \mathrm{cm^3\,s^{-1}} \left(\frac{m_\chi}{9.4\ \mathrm{GeV}}\right)^2 \left(\frac{\lambda}{m_\phi/179\ \mathrm{GeV}}\right)^4$$

MFDM model:

$$\langle\sigma_{\mathrm{ann}}v\rangle = \frac{\lambda^4\, m_\tau^2\, \beta_\tau}{32\pi(m_\phi^2 + m_\chi^2 - m_\tau^2)^2} \simeq 5\times 10^{-27}\ \mathrm{cm^3\,s^{-1}} \left(\frac{\lambda}{m_\phi/93\ \mathrm{GeV}}\right)^4$$

CSDM model:

$$\frac{1}{2}\langle\sigma_{\mathrm{ann}}v\rangle = \frac{\kappa^4\, m_\tau^2\, \beta_\tau^3}{32\pi(m_\psi^2 + m_\chi^2 - m_\tau^2)^2} \simeq 5\times 10^{-27}\ \mathrm{cm^3\,s^{-1}} \left(\frac{\kappa}{m_\psi/93\ \mathrm{GeV}}\right)^4$$

RSDM model:

$$\langle\sigma_{\mathrm{ann}}v\rangle = \frac{\kappa^4\, m_\tau^2\, \beta_\tau^3}{4\pi(m_\psi^2 + m_\chi^2 - m_\tau^2)^2} \simeq 5\times 10^{-27}\ \mathrm{cm^3\,s^{-1}} \left(\frac{\kappa}{m_\psi/156\ \mathrm{GeV}}\right)^4$$

$(\beta_\tau \equiv \sqrt{1 - m_\tau^2/m_\chi^2};\ \ m_\tau \ll m_\chi \ll m_\phi, m_\psi$ approximation$)$

DM Annihilation into $\tau^+\tau^-$ in the Low Velocity Limit

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MFDM model:

Helicity suppression

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CSDM model:

Helicity suppression

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RSDM model:

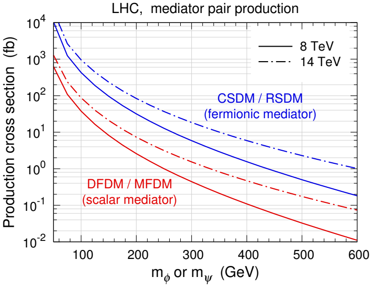
Helicity suppression

$$\langle\sigma_{\rm ann}v\rangle = \frac{\kappa^4\, m_\tau^2\, \beta_\tau^3}{4\pi(m_\psi^2+m_\chi^2-m_\tau^2)^2} \simeq 5\times 10^{-27}\ \mathrm{cm^3\,s^{-1}} \left(\frac{\kappa}{m_\psi/156\ \mathrm{GeV}}\right)^4$$

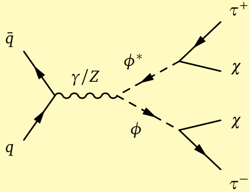
($\beta_\tau \equiv \sqrt{1-m_\tau^2/m_\chi^2}$; $m_\tau \ll m_\chi \ll m_\phi, m_\psi$ approximation)

Mediator Pair Production at the LHC

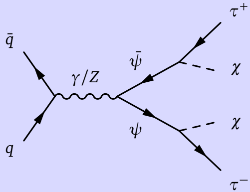
- The mediators ϕ and ψ could be produced at the LHC through **Drell-Yan processes** exchanging s-channel γ or Z, and then decay into $\tau^{\pm}$ and χ
- We found that the **8 TeV LHC data cannot explore the interesting regions** in these models, and went further to investigate the LHC sensitivity at $\sqrt{s} = 14$ TeV with **tight τ_{h}-tagging** techniques



[**ZHY**, Bi, Yan, Yin, 1410.3347, PRD]

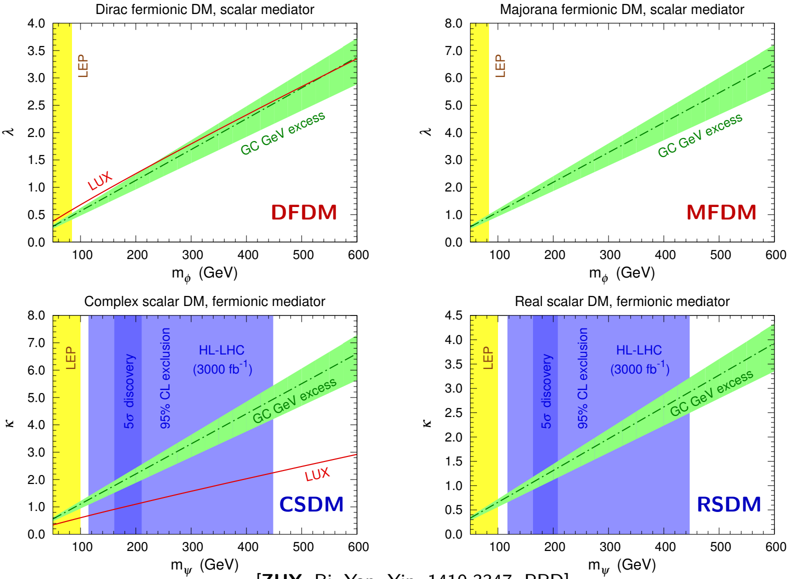


DFDM or MFDM



CSDM or RSDM

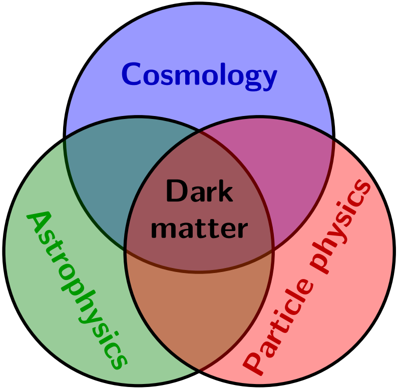
Sensitivity of the 14 TeV High-Luminosity LHC



[**ZHY**, Bi, Yan, Yin, 1410.3347, PRD]

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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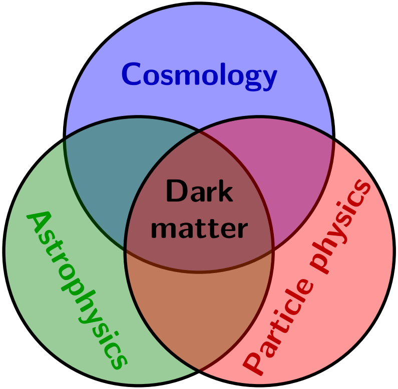

Thank you!