Introduction to Dark Matter

Zhao-Huan Yu（余钊焕）

School of Physics, Sun Yat-Sen University

https://yzhxxzxy.github.io

Guangzhou University, Guangzhou

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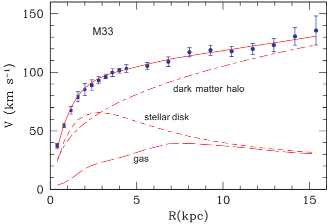
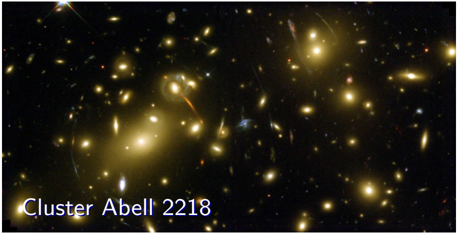
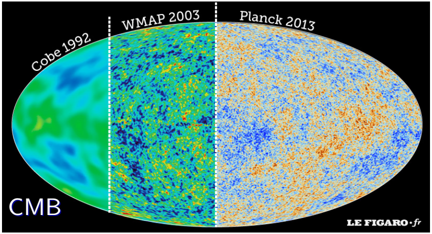
Dark Matter in the Universe

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







Coma Cluster (后发座星系团)

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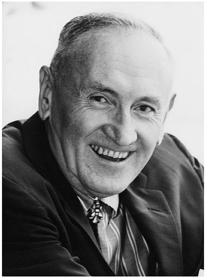


✨ In 1933, **Fritz Zwicky** found that the **velocity dispersion** of **galaxies** in the **Coma cluster** was **far too large** to be supported by the **luminous matter**

🌧 **Mass-to-light ratio** $\Upsilon_{\text{Coma}} \sim 240\Upsilon_{\odot}$

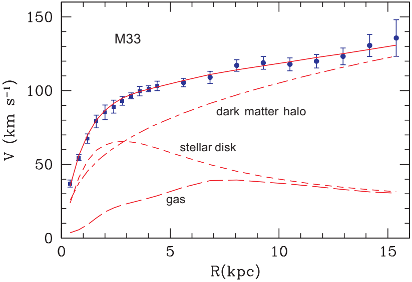
[Kent & Gunn, Astron.J., **87**, 945 (1982)]

💧 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**

Triangulum galaxy M33



[Corbelli & Salucci, astro-ph/9909252, MNRAS]

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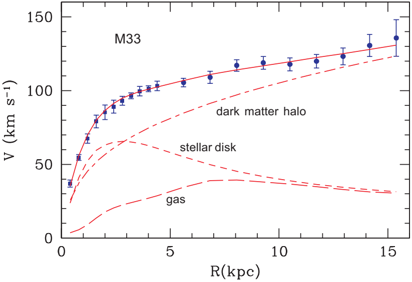
According to **Newton's law** of **universal gravitation**, the relation between the **rotation velocity** v and the **mass** $M(r)$ within the **radius** r should be

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

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

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



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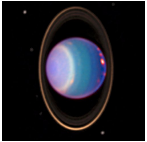
How Can We Explain an Anomalous Phenomenon?



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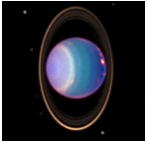

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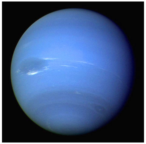

✏️ Calculations independently given by **John Adams** and **Urbain Le Verrier**

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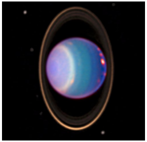

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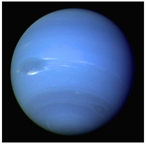

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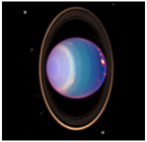

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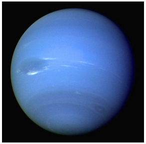

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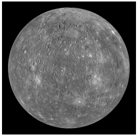

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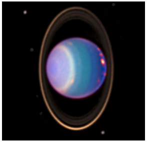

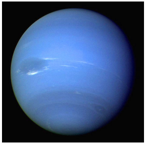

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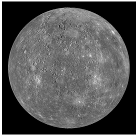

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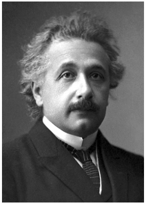
🚀 Update Newton's laws to **general relativity** (1915)



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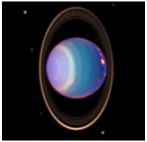

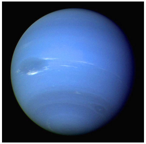

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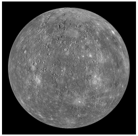

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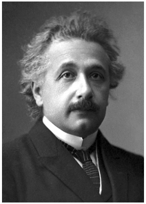
💣 **Modify known physical laws!**



How about the Anomalous Phenomena Here?

💣 **Modify physical laws** 👉 **MOdified Newtonian Dynamics** (MOND)

[Milgrom, ApJ, **270**, 365 (1983)]

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

☄️ They belong to **baryonic dark matter**, including **jupiters**, **brown dwarfs**, **white dwarfs**, **neutron stars**, **black holes**, *etc.*

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

[EROS-2 Coll., astro-ph/0607207, A&A]

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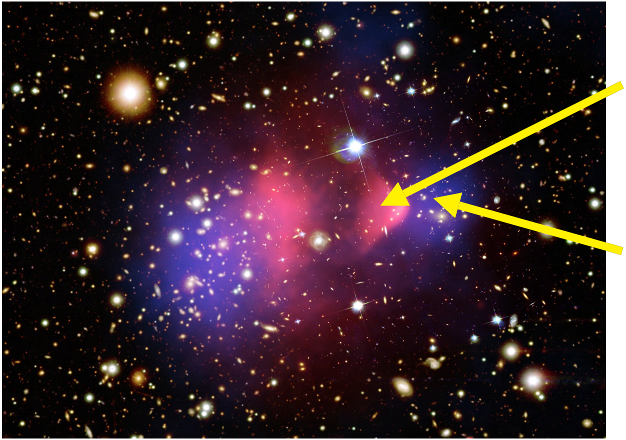
🕯️ **Consider new substances** 👉 **Nonbaryonic Dark Matter**

(not constituted by baryons)

Bullet Cluster: Disfavor MOND



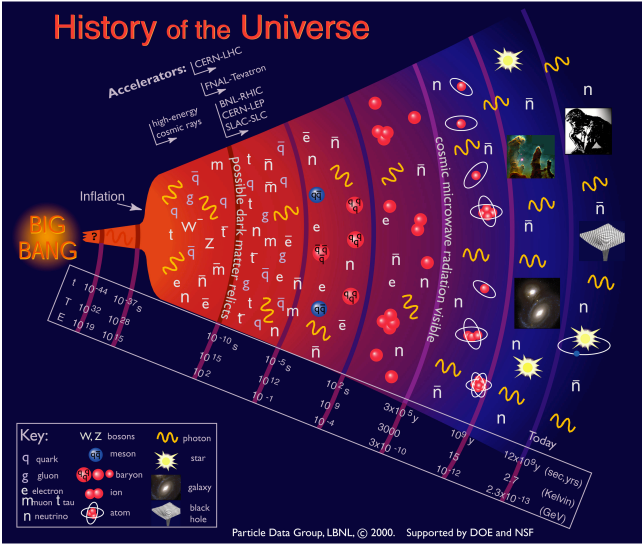
Fluid-like X-ray emitting plasma, *i.e.*, **gas** **(luminous matter)**

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 a **modification** of the **gravitational force law** [Clowe *et al.*, astro-ph/0608407, ApJL]

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**

👉 **Decoupled matter** generates **cosmological structures**

⌛ **Baryonic matter decoupled too late**

🌐 Only baryonic matter 👉 **Galaxies would not** be formed!

👉 Needs **nonbaryonic dark matter** which **decoupled much earlier**

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👉 Structures are formed by **fragmentation** (**top-down**)

🍨 **Cold dark matter (CDM)**: **nonrelativistic** when it decoupled

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🥗 The observation that **galaxies** are **older** than **clusters** favors **cold dark matter**

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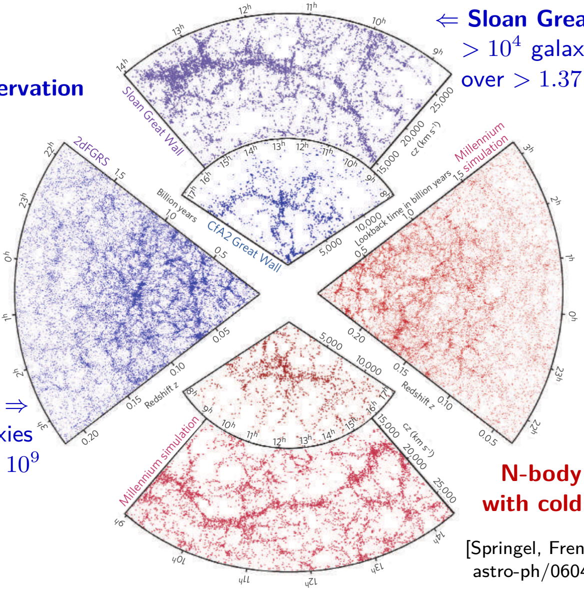
🛰 **Milky Way dwarf satellites**: ~ 60 **(observed)** vs. ~ 500 **(CDM predicted)**

☕ **"Missing satellites problem"** 👉 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

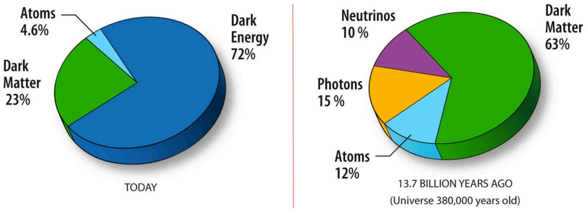
N-body simulation with cold dark matter

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

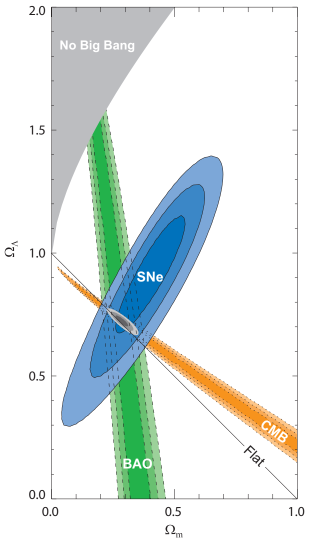
Standard Cosmology: ΛCDM Model

- 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**

$$\frac{k}{H^2R^2} = \Omega_\Lambda + \Omega_{\rm m} + \Omega_{\rm r} - 1$$



[WMAP Science Team]



[Kowalski *et al.*, 0804.4142, ApJ]

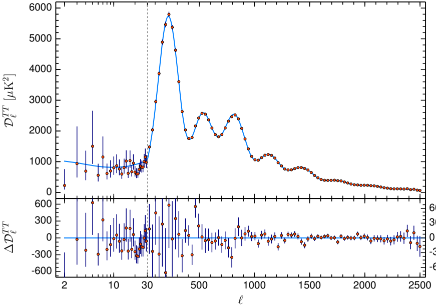
Cosmic Microwave Background (CMB)

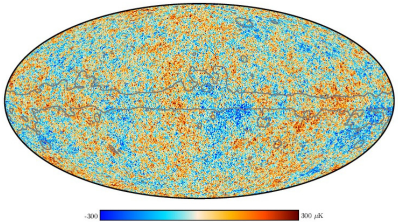
$t \sim 380\ 000$ yr, $T \sim 3000$ K
Electrons + Protons → Hydrogen Atoms
Photons decoupled

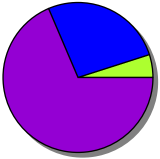
Cools ⇓ down

Today, ~ 2.7 K microwave background

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







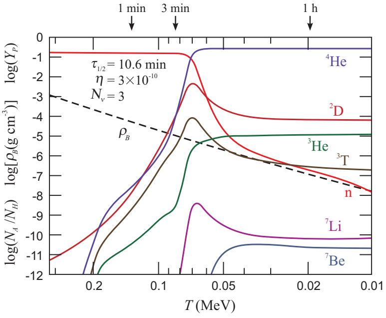
Planck 2018
[1807.06205, 1807.06209]

Cold DM (26.5%)
$\Omega_\mathrm{c} h^2 = 0.1200 \pm 0.0012$

Baryons (4.9%)
$\Omega_\mathrm{b} h^2 = 0.02237 \pm 0.00015$

Dark energy (68.6%)
$\Omega_\Lambda = 0.6847 \pm 0.0073$

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



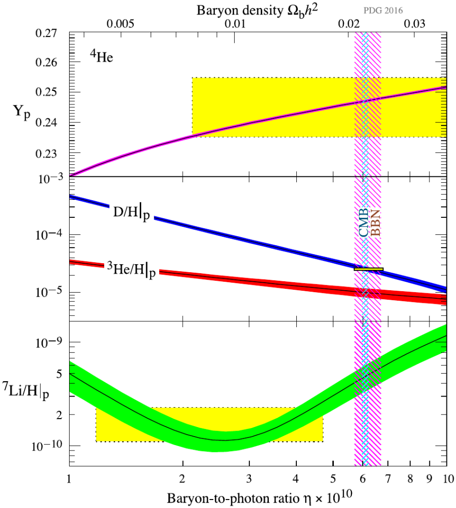
[Kolb & Turner, *The Early Universe*]

Light element primordial abundances

Infer the **baryon density** Ω_b

(consistent with **CMB observations**)

The majority of matter is **nonbaryonic**



[PDG 2016]

Inferred Properties of Dark Matter

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

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

Standard Model (SM) of Particle Physics

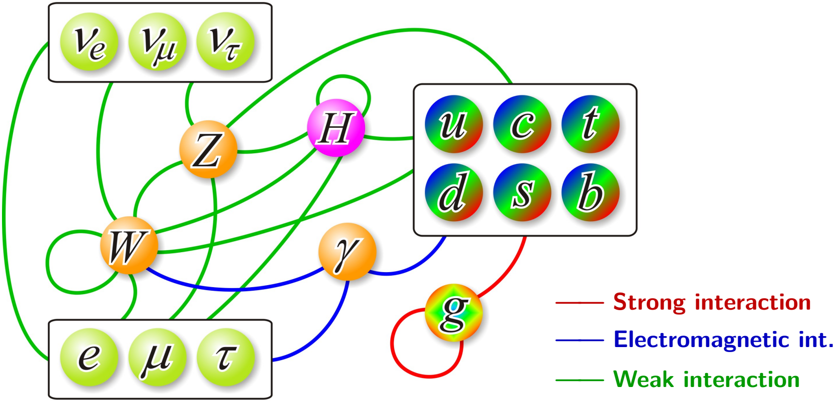
$\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ gauge symmetry

Englert-Brout-Higgs mechanism

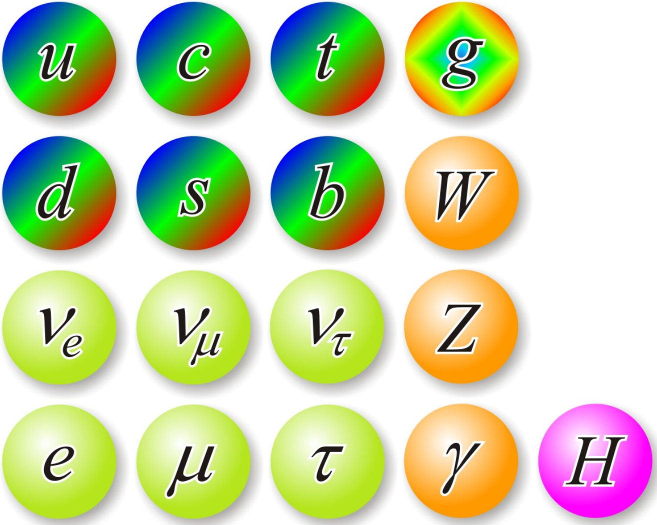
$\mathrm{SU(3)_C \times U(1)_{EM}}$ gauge symmetry

↗ Fermion masses

↘ Higgs boson



Are There Dark Matter Candidates in the Standard Model?



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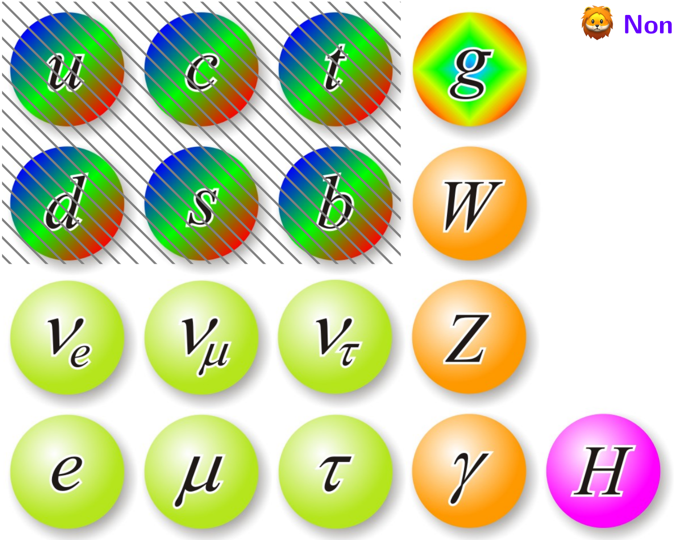

Nonbaryonic

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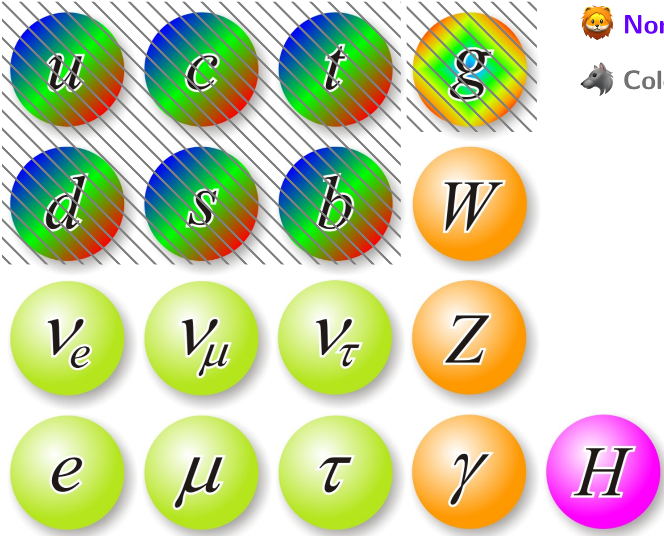

🦁 Nonbaryonic

🐺 Colorless

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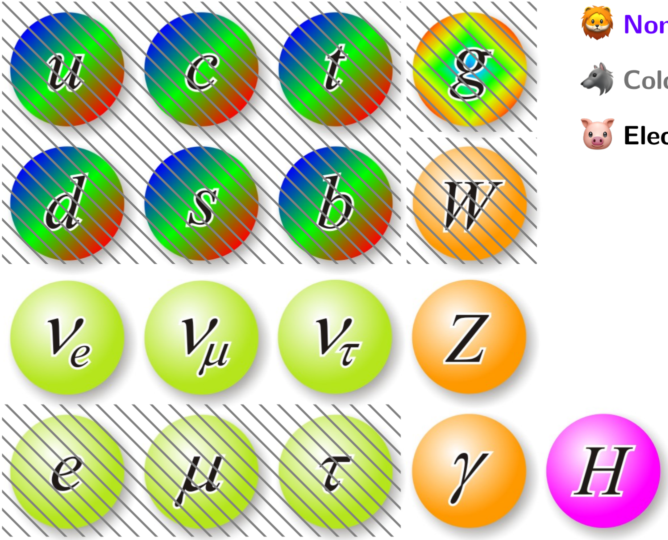

- 🦁 Nonbaryonic
- 🐺 Colorless
- 🐷 Electrically neutral

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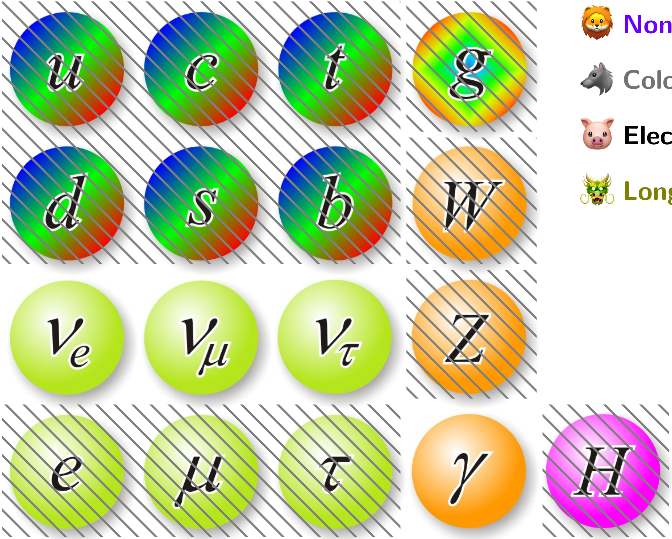

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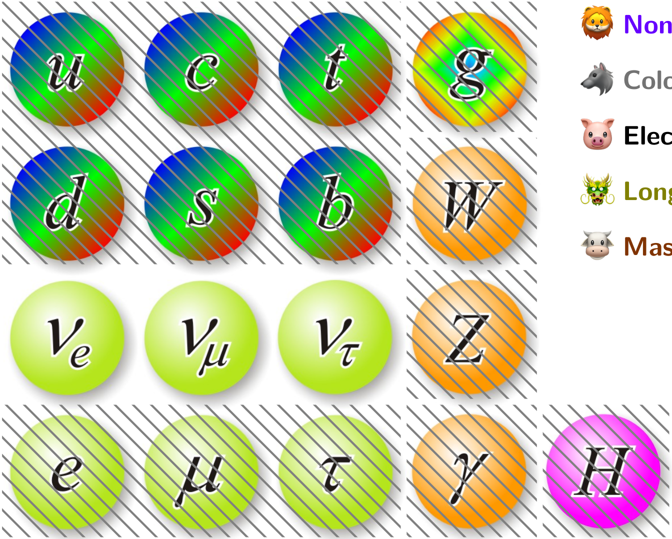

- Nonbaryonic
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- Electrically neutral
- Long lived
- Massive

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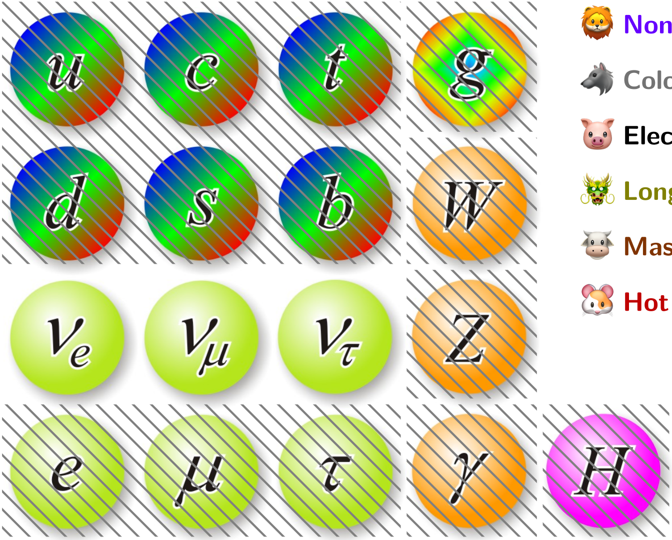

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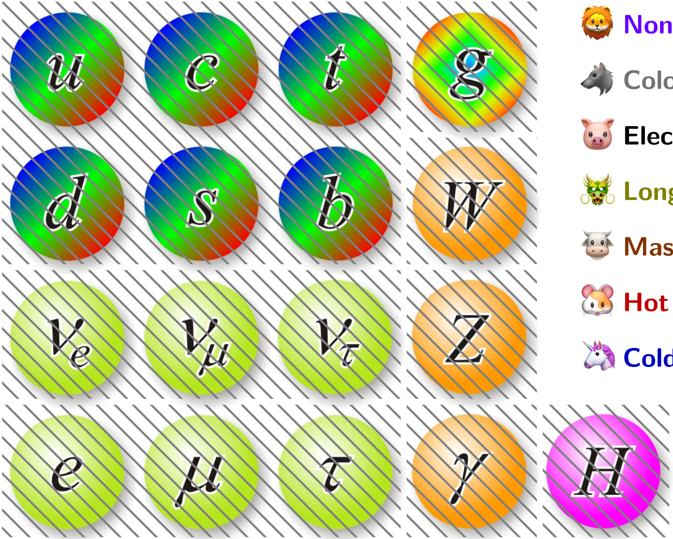


- Nonbaryonic
- Colorless
- Electrically neutral
- Long lived
- Massive
- Hot DM: neutrinos
- Cold DM: none

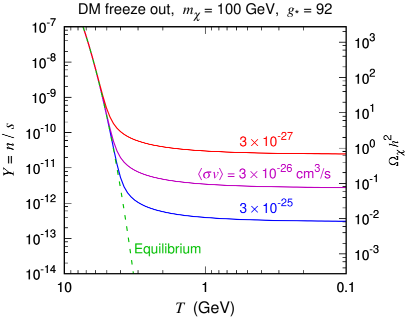
DM Relic Abundance from Thermal Production

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

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

Observed value $\Omega_\chi h^2 \simeq 0.12$

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



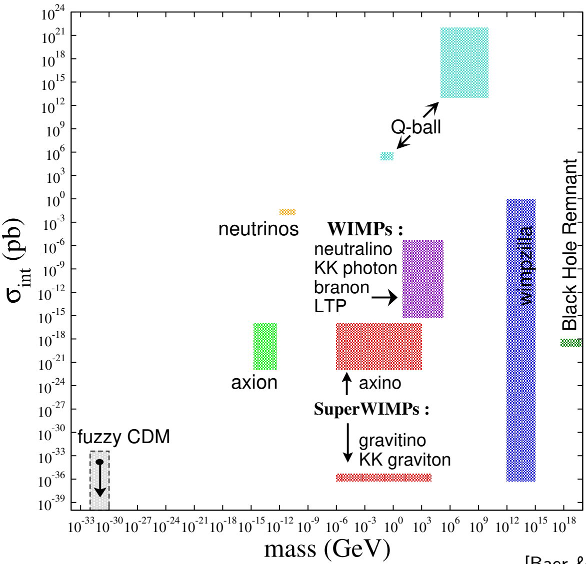
Assuming the **annihilation** process consists of two **weak interaction vertices** with the $\mathrm{SU}(2)_\mathrm{L}$ **gauge coupling** $g \simeq 0.64$, for $m_\chi \sim \mathcal{O}(\mathrm{TeV})$ we have

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

A very attractive class of DM candidates:

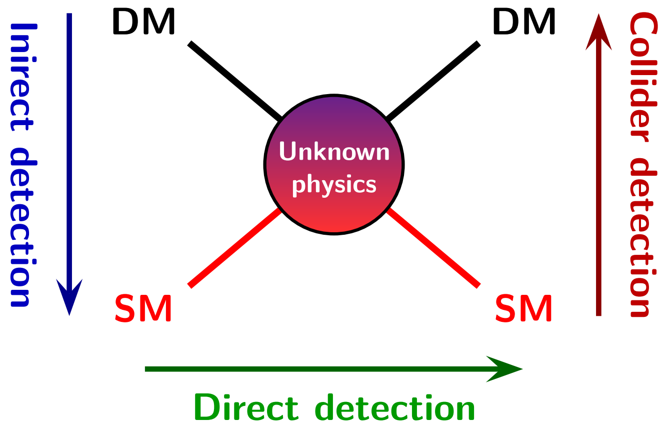
Weakly interacting massive particles (WIMPs)

DM Particle Candidates

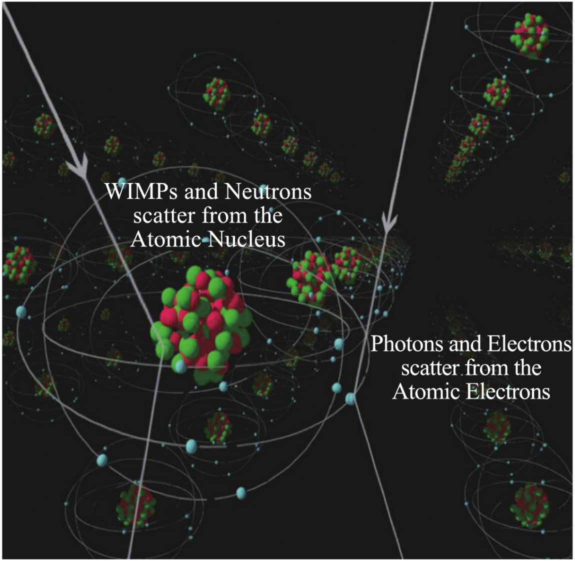


[Baer & Tata, 0805.1905]

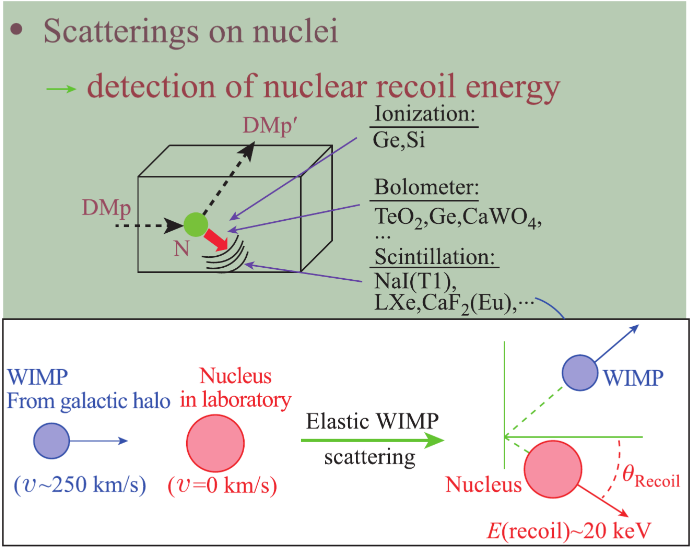
Experimental Approaches to Dark Matter



WIMP Scattering off Atomic Nuclei



Direct Detection



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

DM Velocity Distribution

During the collapse process which formed the Galaxy, the velocities of DM particles were **"thermalized"** by **fluctuations** in the gravitational potential, and DM particles have a **Maxwell-Boltzmann velocity distribution** in the **Galactic rest frame**:

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

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

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

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

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

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

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

[Credit: ESO/L. Calçada]

Earth Rest Frame

🦒 The DM 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:** $f(\mathbf{v}) = \tilde{f}(\mathbf{v} + \mathbf{v}_{\text{obs}})$

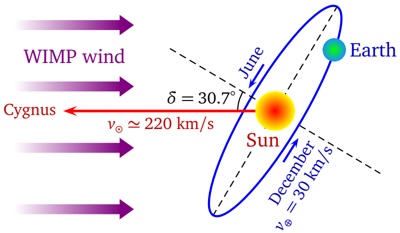
🦌 **Speed distribution:**

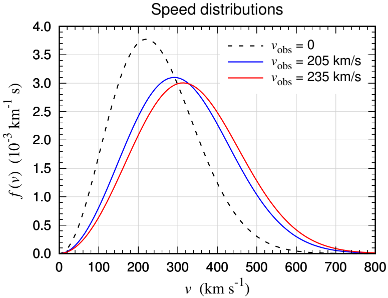
$$f(v)\,dv = \frac{4v^2}{\sqrt{\pi}v_0^3}\exp\left(-\frac{v^2+v_{\text{obs}}^2}{v_0^2}\right) \times \frac{\tilde{v}_0^2}{2vv_{\text{obs}}}\sinh\left(\frac{2vv_{\text{obs}}}{v_0^2}\right)dv$$

🐎 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

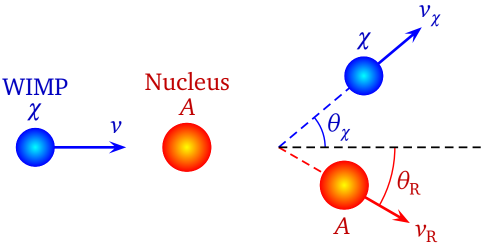
Energy conservation:

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

Momentum conservation:

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

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



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

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

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

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

Nuclear Recoil

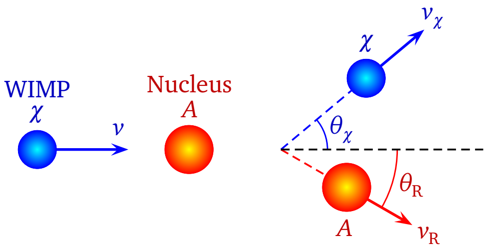
Energy conservation:

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

Momentum conservation:

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

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



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

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

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

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

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

Event Rate

Event rate per unit time per unit energy interval in direct detection experiments:

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

- **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 $v_\mathrm{min} = \left(\dfrac{m_A E_\mathrm{R}^\mathrm{th}}{2\mu_{\chi A}^2}\right)^{1/2}$: 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 $\sigma_{\chi A}^{\mathrm{SD}} \propto \mu_{\chi A}^2 \dfrac{J_A + 1}{J_A} (S_p^A G'_p + S_n^A G'_n)^2$

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**

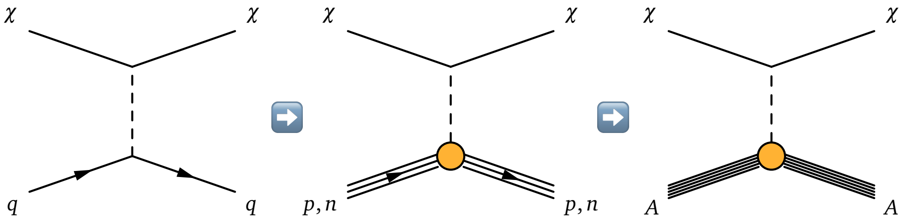
- $Z \simeq A/2$ 👉 $\sigma_{\chi A}^{\mathrm{SI}} \propto A^2 [(G_p + G_n)/2]^2$

  ❗ 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**



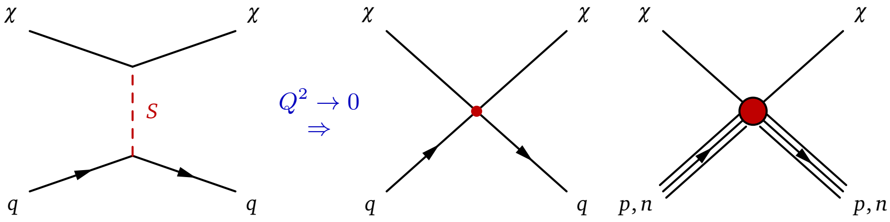
$\mathcal{M}(\chi q \to \chi q)$ | $\mathcal{M}(\chi N \to \chi N)$ | $\mathcal{M}(\chi A \to \chi A)$

- 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**
- The **relevant partons** involve not only **valence quarks**, but also **sea quarks** and **gluons**

Zero-Momentum Transfer Limit

As the **momentum transfer** is typically **much smaller** than the **underlying energy scale** (*e.g.*, **mediator mass**), the **zero-momentum transfer limit** is a good approximation for calculation

In this limit, the mediator field can be integrated out, and the interaction can be described by **effective operators** in **effective field theory**



Scalar mediator propagator: $\dfrac{\mathrm{i}}{Q^2 - m_S^2} \quad \Rightarrow \quad -\dfrac{\mathrm{i}}{m_S^2}$

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

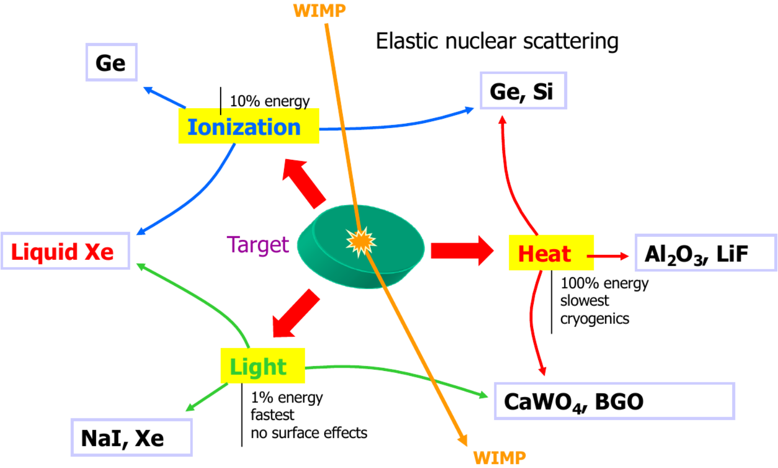
Effective Operators for DM-quark Interactions

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

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

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

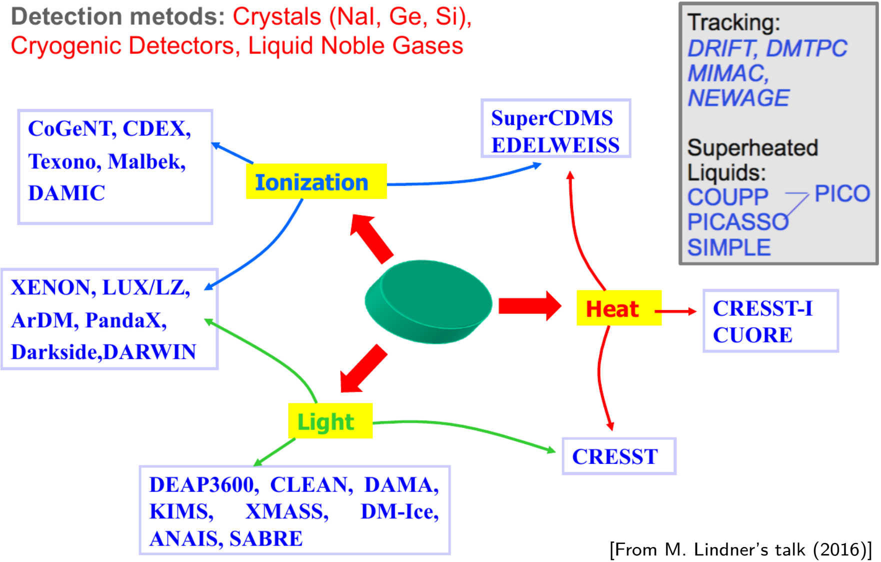
Technologies and Detector Material



[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)]

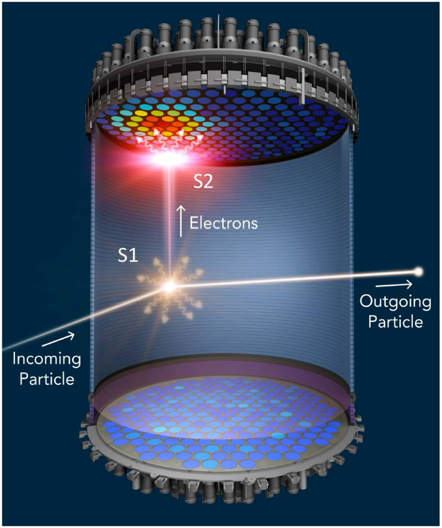
Example: Dual-phase Xenon Time Projection Chamber

- **Upper: Xenon gas**
- **Lower: Liquid Xenon**

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

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

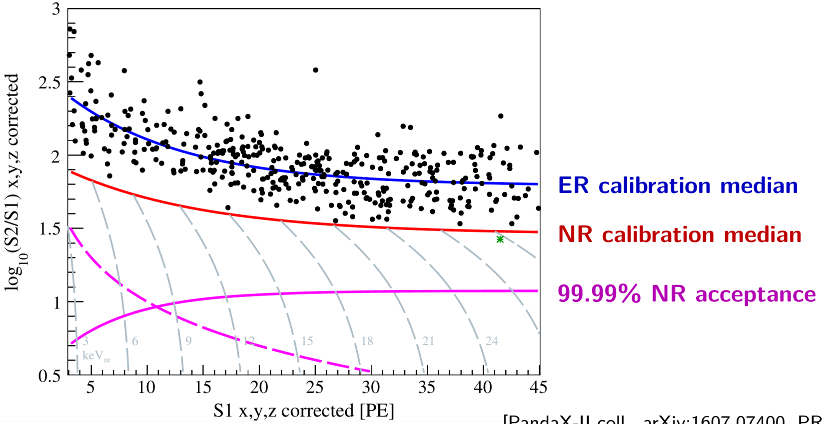
Experiments: **PandaX**, **XENON**, **LZ**



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

PandaX-II Real Data: S1 versus S2

- **S1** and **S2** are 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

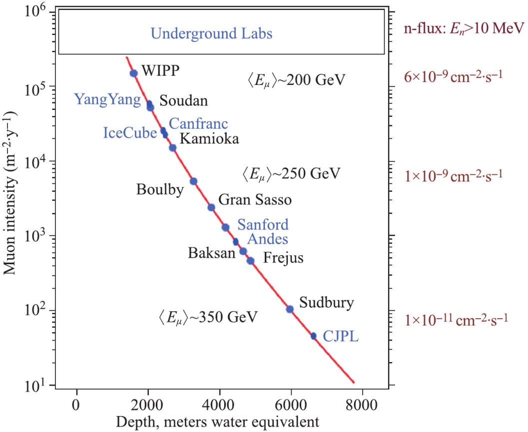
Shielded environments

Cosmogenic backgrounds

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

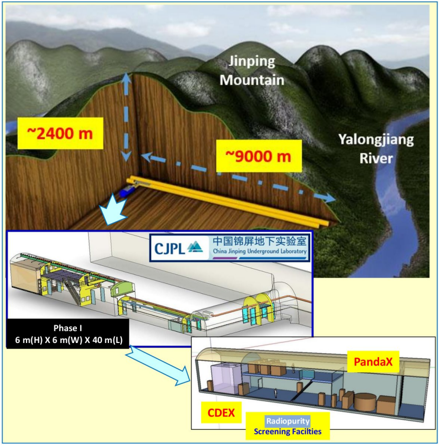
Radiogenic backgrounds

- **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)

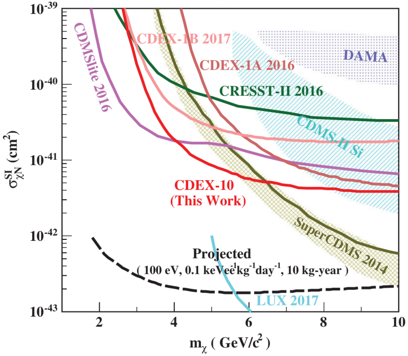


[Yue *et al.*, arXiv:1602.02462]

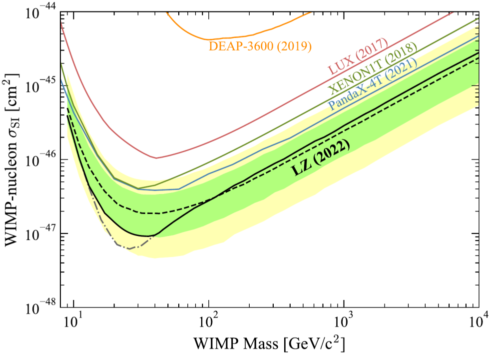
Experiments: **CDEX**, **PandaX**

Exclusion Limits for SI Scattering

- For **isospin-conserving SI scattering**, **protons** and **neutrons** can be treated as the **same** species, *i.e.*, **"nucleons"**
- **Lower thresholds** and **lighter targets** are needed to probe the **low mass regime**
- It requires **more exposure**, **heavier targets**, and **fewer backgrounds** to explore the **high mass regime**



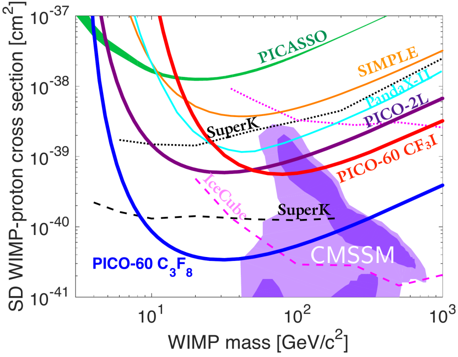
[CDEX Coll., arXiv:1802.09016, PRL]



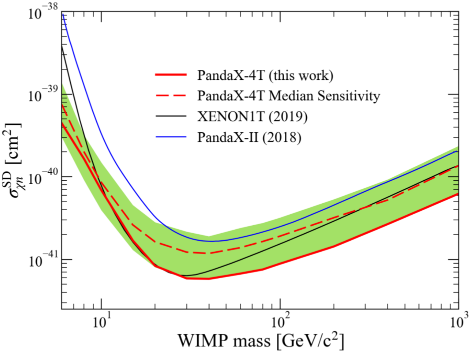
[LZ Coll., arXiv:2207.03764, PRL]

Exclusion Limits for SD Scattering

- For **SD scattering**, specific detection material usually has **very different** sensitivities to **DM-proton** and **DM-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**



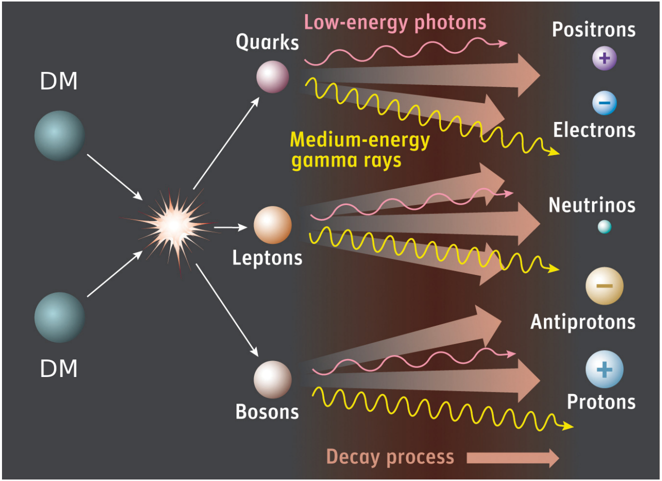
[PICO coll., arXiv:1702.07666, PRL]



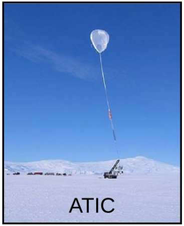
[PandaX-4T coll., arXiv:2208.03626, PLB]

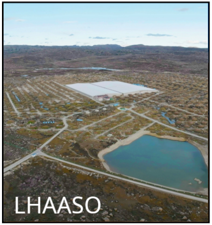
Indirect Detection

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

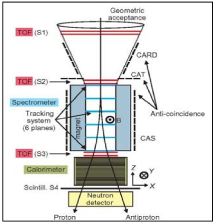


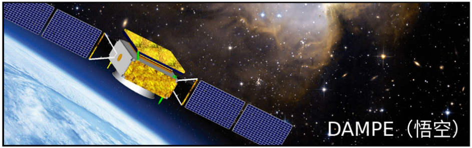
Indirect Detection Experiments

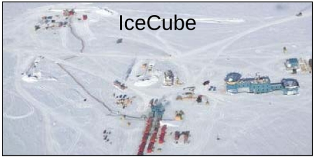




PAMELA







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**:

$$Q_{\mathrm{ann}}(\mathbf{x}, E) = \frac{\langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{tot}}}{2 m_\chi^2} \rho^2(\mathbf{x}) \sum_i F_i \left(\frac{\mathrm{d}N}{\mathrm{d}E} \right)_i \quad \textbf{(annihilation)}$$

$$Q_{\mathrm{dec}}(\mathbf{x}, E) = \frac{1}{\tau_\chi m_\chi} \rho(\mathbf{x}) \sum_i B_i \left(\frac{\mathrm{d}N}{\mathrm{d}E} \right)_i \quad \textbf{(decay)}$$

Astrophysics factors

Particle physics factors

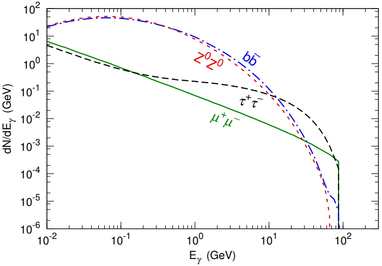
- $\rho(\mathbf{x})$: **DM mass density** at the source position $\mathbf{x}$
- $(\mathrm{d}N/\mathrm{d}E)_i$: **number per unit energy interval** from a single event in the **channel** i
- $\langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{tot}}$: thermal average of the total **annihilation cross section** multiplied by the relative velocity between the two incoming DM particles
- $F_i \equiv \langle \sigma_{\mathrm{ann}} v \rangle_i / \langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{tot}}$: **branching fraction** of the annihilation channel i
- $\tau_\chi \equiv 1/\Gamma_\chi$: **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 **annihilation** or **decay** into e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, W^+W^-, Z^0Z^0, h^0h^0

👇

🌟 **γ-ray emissions** from **final state radiation** or **particle decays**



📉 **Cutoff energy**:

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

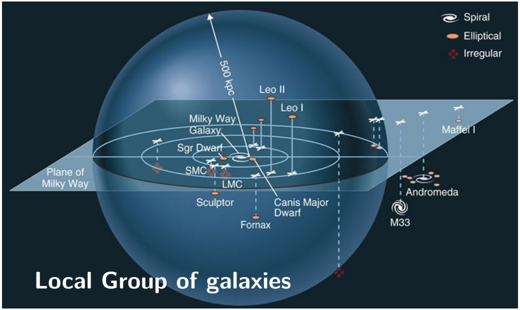
🔍 More promising to look at **DM-dominated regions**:

👑 **Galactic Center**

🎩 **Galactic halo**

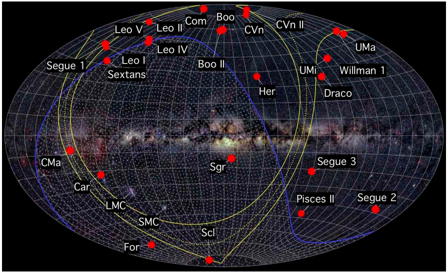
👒 **dwarf galaxies**

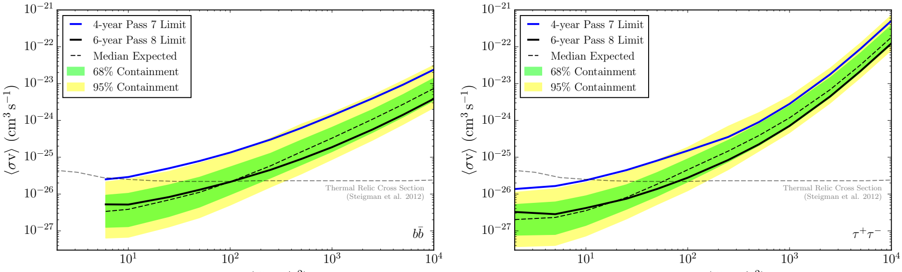
🧢 **clusters of galaxies**



γ-ray Observation of Dwarf Galaxies

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





[Fermi-LAT coll., 1503.02641, PRL]

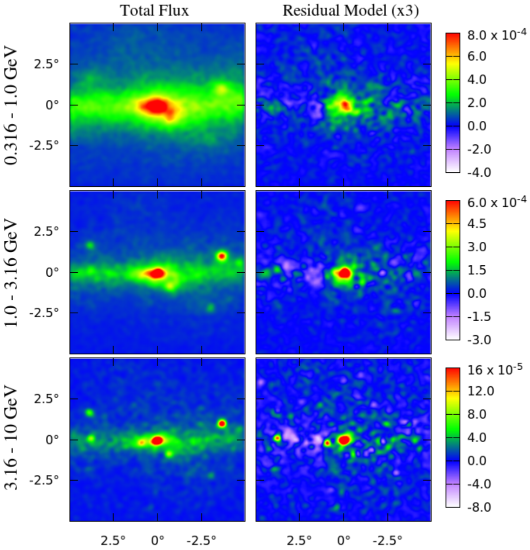
GeV Excess at the Galactic Center?

🏮 Since 2009, several research groups reported an **excess** of **continuous spectrum γ-rays** in the **Fermi-LAT data** after **subtracting** well-known **astrophysical backgrounds**,

🪔 It locates in the **Galactic Center (GC)** region and peaks at a few GeV

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

➡️



[Daylan et al., 1402.6703, PDU]

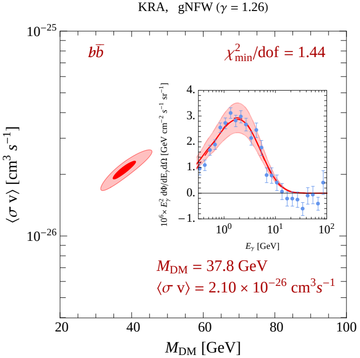
Interpretation with Dark Matter Annihilation

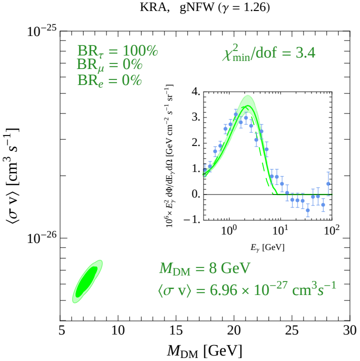
DM annihilation into $b\bar{b}$

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

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

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





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

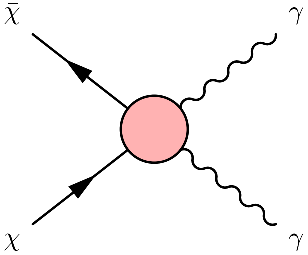
γ rays from DM: Line Spectrum

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

👓 Nonetheless, DM particles **may couple to photons** via **high-order loop diagrams**

👇

🦺 **Highly suppressed:** the $\chi\bar{\chi} \to \gamma\gamma$ **branching fraction** may be only $\sim 10^{-4} - 10^{-1}$



γ rays from DM: Line Spectrum

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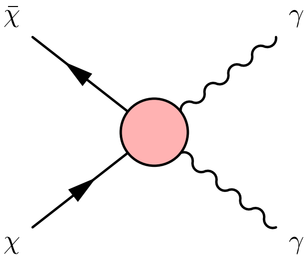


Highly suppressed: the $\chi\bar{\chi} \to \gamma\gamma$ **branching fraction** may be only $\sim 10^{-4} - 10^{-1}$

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

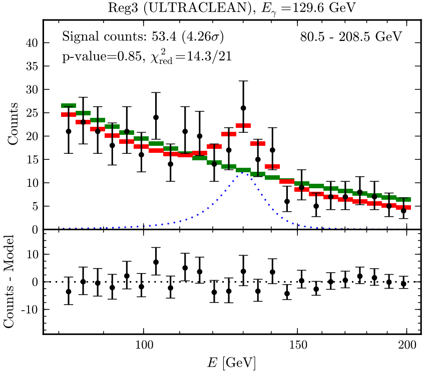
A γ-ray line at energy $\sim m_\chi$

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

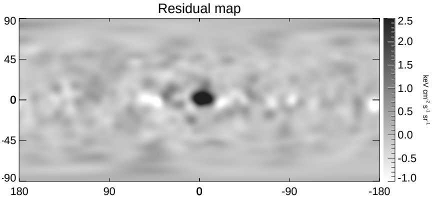
A γ-ray Line Signal at the Galactic Center?

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 3–4σ)

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]

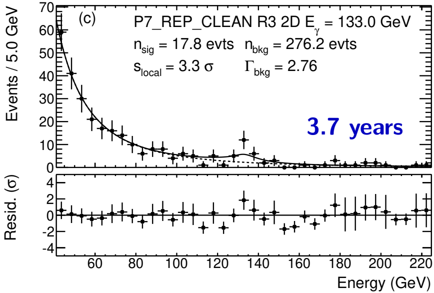


[Su & Finkbeiner, 1206.1616]

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]

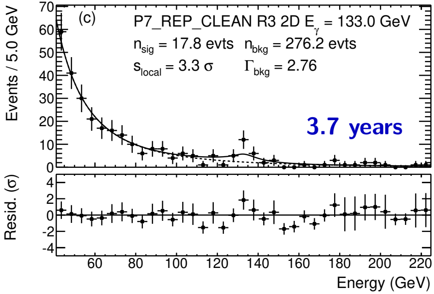
Fermi-LAT Official Results: Not Confirmed with More Data

3.7-year data

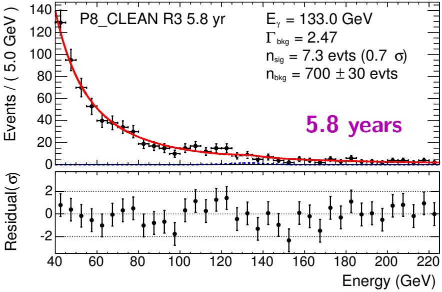
⚠️ The most significant fit occurred at $E_\gamma = 133$ GeV and had a **local significance** of 3.3σ, translating to a global significance of 1.6σ

5.8-year data

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



[Fermi-LAT Coll., 1305.5597, PRD]



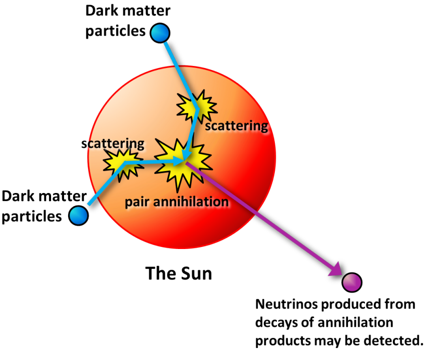
[Fermi-LAT Coll., 1506.00013, PRD]

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**:

$$\frac{\mathrm{d}N_\chi}{\mathrm{d}t} = C_\odot(\sigma_{\chi\mathrm{H}}, \sigma_{\chi\mathrm{He}}) - A_\odot(\sigma_{\mathrm{ann}})N_\chi^2$$

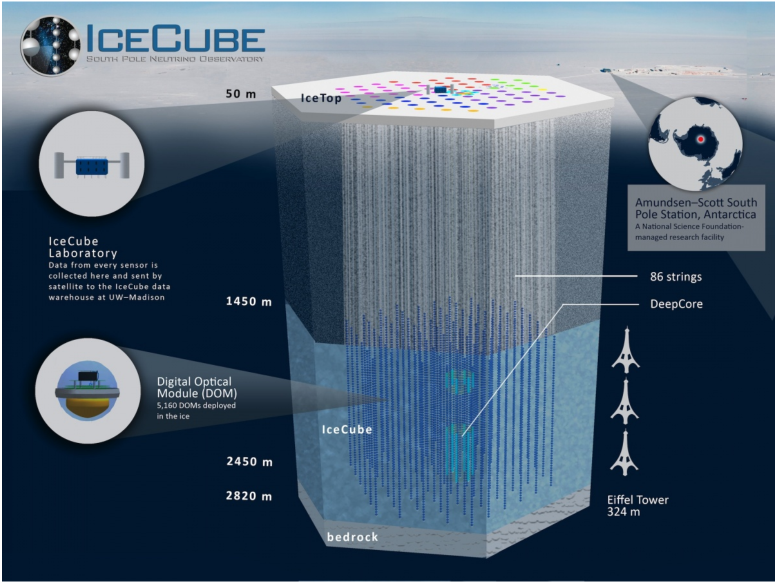


Capture rate $C_\odot$ depends on **DM scattering** on Hydrogen and Helium

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

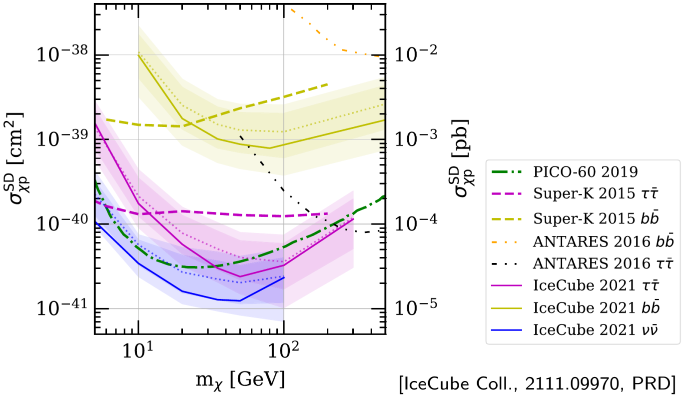
The **age** of the **Sun** is **long enough** (~ 4.6 billion years) to make the **capture** and **annihilation** processes reach **equilibrium:** $\mathrm{d}N_\chi/\mathrm{d}t = 0$

IceCube: South Pole Neutrino Observatory



Searches for Neutrinos from DM Annihilation within the Sun

- Using the **7-year IceCube data**, **no significant detection** of **neutrinos** with energies < 500 GeV from **DM annihilation** at the **solar core** is found
- Assuming **equilibrium** in the **capture** and **annihilation** processes, the constraints can be converted to those on the **DM scattering cross section**

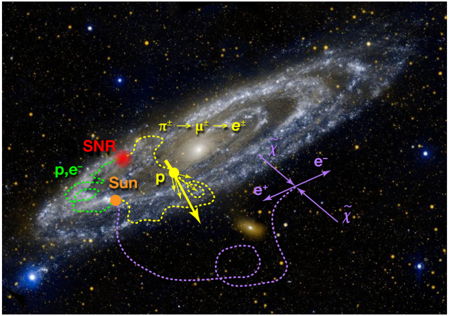


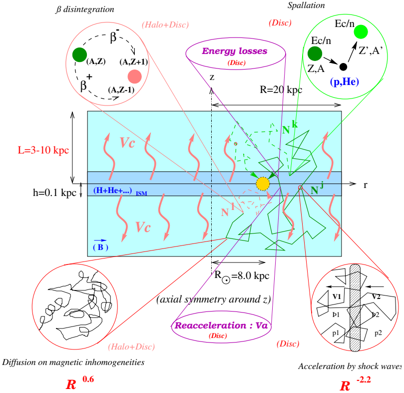
[IceCube Coll., 2111.09970, PRD]

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**

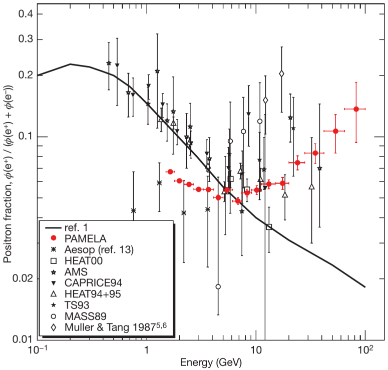




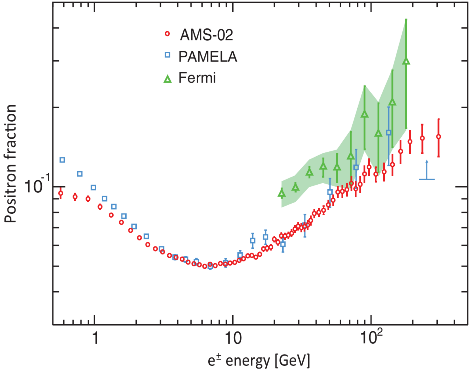
[Maurin *et al.*, astro-ph/0212111]

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**



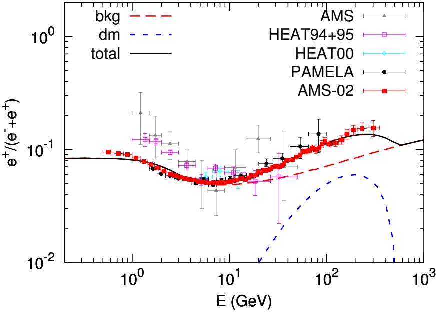
[PAMELA Coll., 0810.4995, Nature]



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

Interpretation: Dark Matter vs Pulsar

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



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

Interpretation: Dark Matter vs Pulsar

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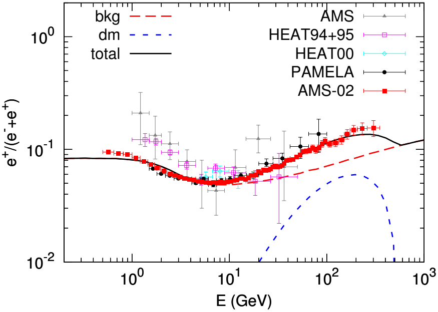
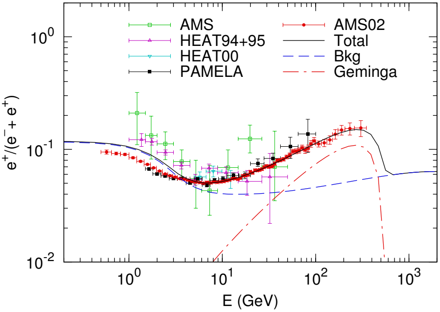


[Yuan, Bi, *et al.*, 1304.1482, APP]

🎾 Interpretation with the **nearby pulsar Geminga**



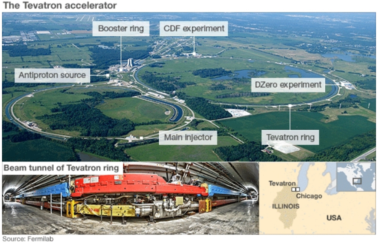
[Yin, **ZHY**, Yuan, Bi, 1304.4128, PRD]

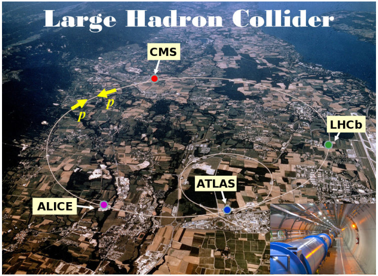
Past and Current High Energy Colliders

- **TEVATRON**: $p\bar{p}$ collider, 1987–2011
  Circumference: 6.28 km
  Collision energy: $\sqrt{s} = 1.96$ TeV
  Luminosity: $\mathcal{L} \sim 4.3 \times 10^{32}$ cm^{-2} s^{-1}
  Detectors: CDF, DØ

- **LEP**: e^+e^- collider, 1989–2000
  Circumference: 26.66 km
  Collision energy: $\sqrt{s} = 91\text{–}209$ GeV
  Luminosity: $\mathcal{L} \sim (2\text{–}10) \times 10^{31}$ cm^{-2} s^{-1}
  Detectors: ALEPH, DELPHI, OPAL, L3

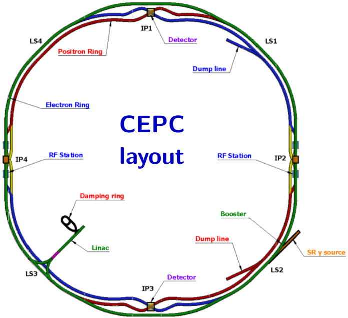
- **LHC**: pp ($p\mathrm{Pb}$, PbPb) collider, 2009–Now
  Circumference: 26.66 km
  Collision energy: $\sqrt{s} = 7, 8, 13, 14$ TeV
  Luminosity: $\mathcal{L} \sim (1\text{–}5) \times 10^{34}$ cm^{-2} s^{-1}
  Detectors: ATLAS, CMS, ALICE, LHCb





Future Projects

- **ILC**: International Linear Collider
  e^+e^- collider, $\sqrt{s} = 0.25$–1 TeV
  $\mathcal{L} \sim 1.5 \times 10^{34}$ cm^{-2} s^{-1}
  Detectors: SiD, ILD



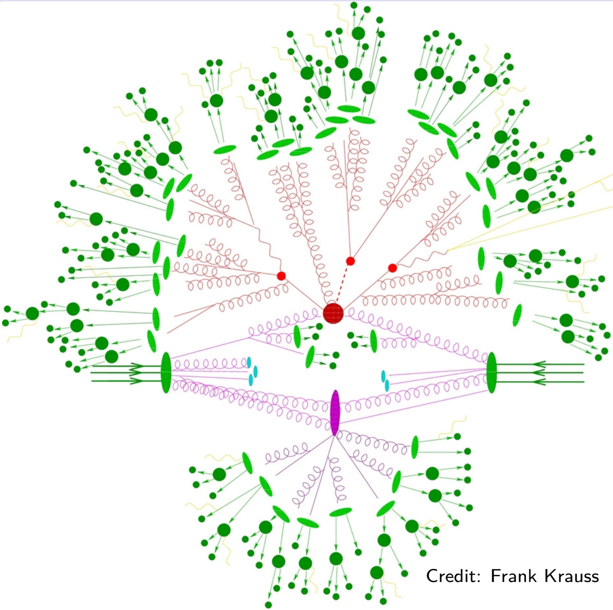
- **CEPC**: Circular Electron-Positron Collider (China)
  e^+e^- collider, $\sqrt{s} \sim 91$–350 GeV
  $\mathcal{L} \sim (0.5$–$100) \times 10^{34}$ cm^{-2} s^{-1}

- **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, $\sqrt{s} \sim 91$–350 GeV, $\mathcal{L} \sim (1$–$200) \times 10^{34}$ 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}

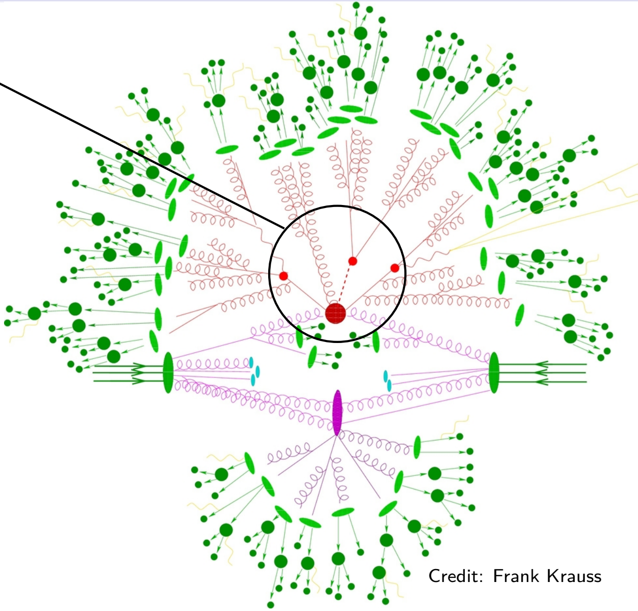
Typical Event in High Energy pp Collisions



Credit: Frank Krauss

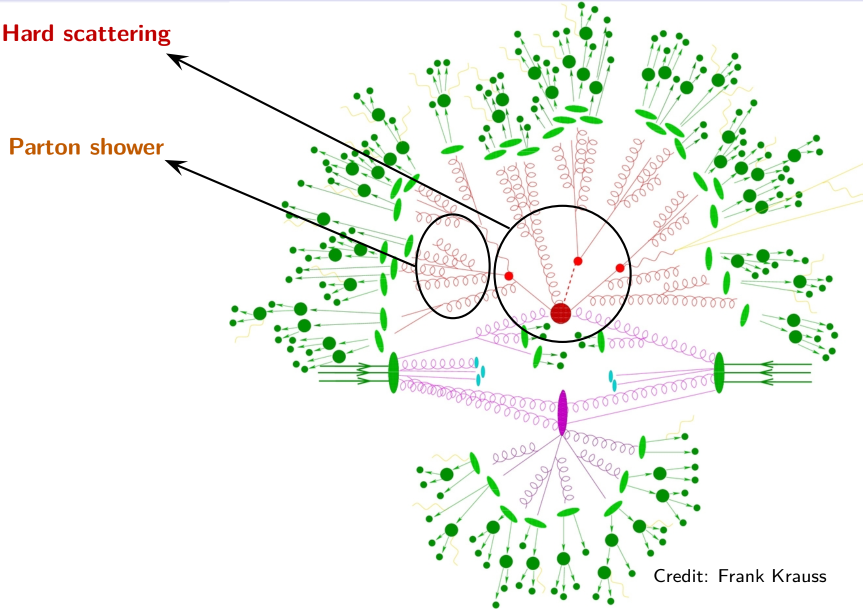
Typical Event in High Energy pp Collisions

Hard scattering



Credit: Frank Krauss

Typical Event in High Energy pp Collisions



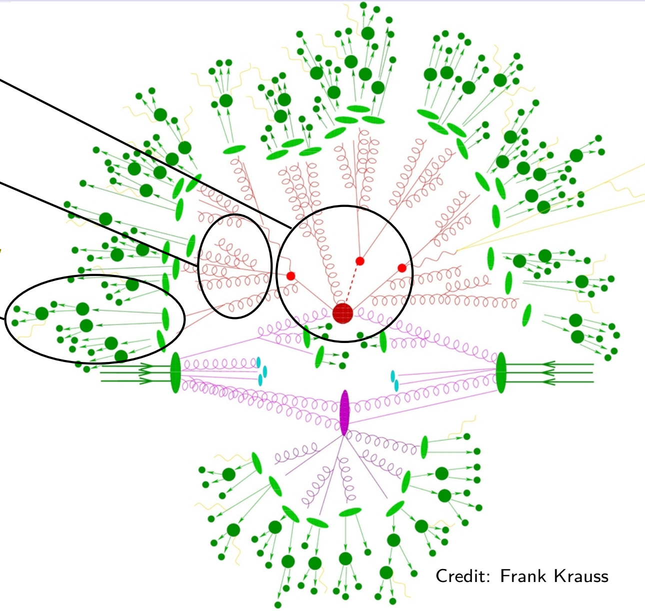
Credit: Frank Krauss

Typical Event in High Energy pp Collisions

Hard scattering

Parton shower

Hadronization and decay



Credit: Frank Krauss

Typical Event in High Energy pp Collisions

Hard scattering

Parton shower

Hadronization and **decay**

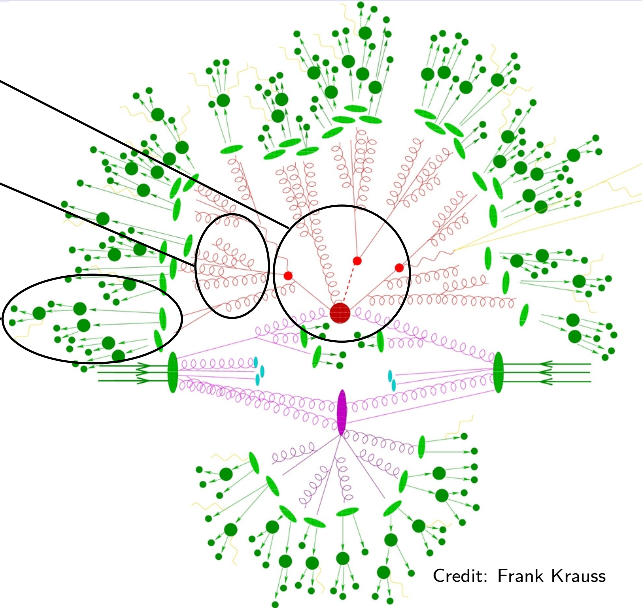
Collimated particles

⬇️

Jet

⬇️

Mimic a **hard parton**



Credit: Frank Krauss

Typical Event in High Energy pp Collisions

Hard scattering

Parton shower

Hadronization and **decay**

Collimated particles

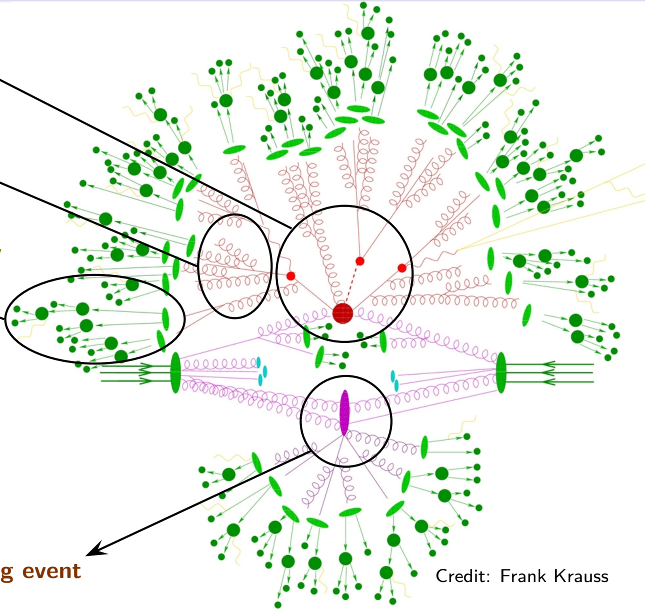
⬇

Jet

⬇

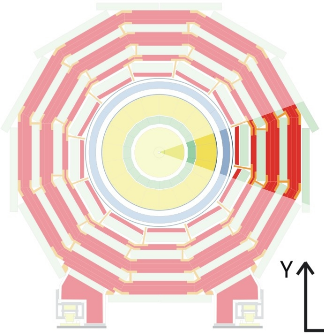
Mimic a **hard parton**

Underlying event

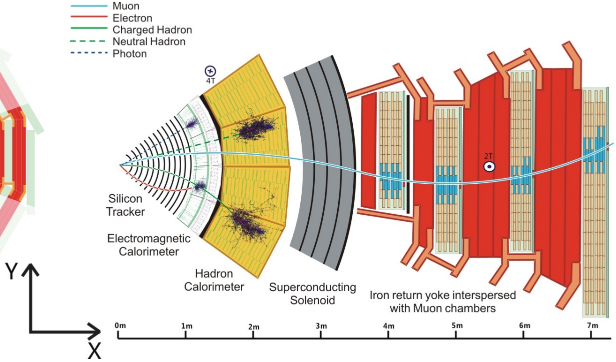


Credit: Frank Krauss

Particle Detectors at Colliders

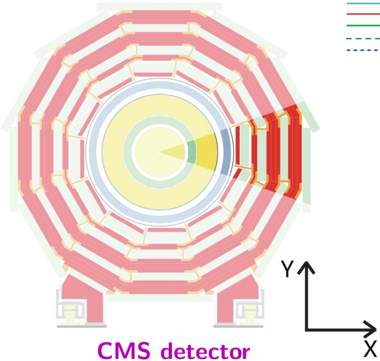


CMS detector

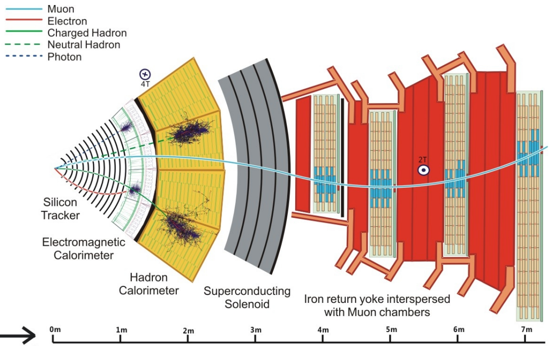


Sub-detectors	γ	$e^\pm$	$\mu^\pm$	Charged hadrons	Neutral hadrons	ν, DM
Tracker, $\lvert\eta\rvert \lesssim 2.5$	$\times$	$\surd$	$\surd$	$\surd$	$\times$	$\times$
ECAL, $\lvert\eta\rvert \lesssim 3$			$\surd$	$\surd$	$\times$	$\times$
HCAL, $\lvert\eta\rvert \lesssim 5$	$\times$	$\times$	$\times$		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

Particle Detectors at Colliders



CMS detector



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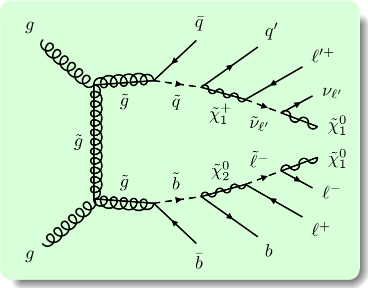
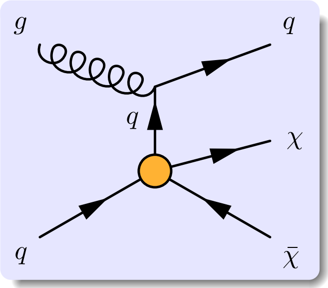
Tracker, $\lvert\eta\rvert \lesssim 2.5$	$\times$	$\surd$	$\surd$	$\surd$	$\times$	$\times$
ECAL, $\lvert\eta\rvert \lesssim 3$			$\surd$	$\surd$		$\times$
HCAL, $\lvert\eta\rvert \lesssim 5$	$\times$	$\times$	$\times$			$\times$
Muon detectors, $\lvert\eta\rvert \lesssim 2.4$	$\times$	$\times$	$\surd$	$\times$	$\times$	$\times$

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 + $\not{E}_{\mathrm{T}}$, ...)

Maverick dark matter

DM particle is the **only new particle**

reachable at the collision energy

Direct production

Mono-X $+ \not{E}_{\mathrm{T}}$ **final states**

(monojet, mono-γ, mono-W/Z, ...)

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:

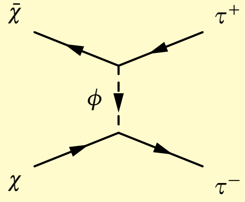
$$\mathcal{L}_\phi = \lambda\phi\bar{\tau}_\mathrm{R}\chi_\mathrm{L} + \mathrm{H.c.}$$

- **DFDM model:** χ is a Dirac fermion
- **MFDM model:** χ is a Majorana fermion

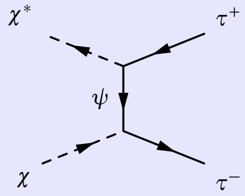
Spin-0 scalar boson χ, spin-1/2 mediator ψ:

$$\mathcal{L}_\psi = \kappa\chi\bar{\tau}_\mathrm{R}\psi_\mathrm{L} + \mathrm{H.c.}$$

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



DFDM: annihilation

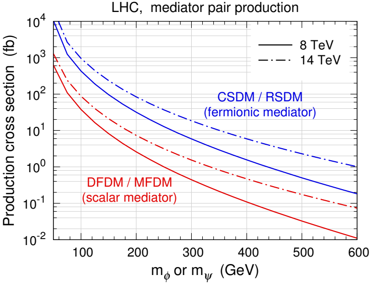


CSDM: annihilation

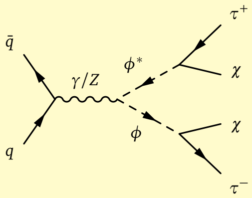
Mediator Pair Production at the LHC

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

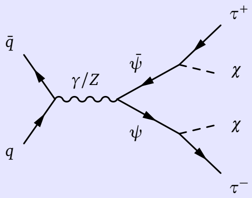
We found that the **8 TeV LHC data cannot explore the interesting regions** in these models, and went further to investigate the LHC sensitivity at $\sqrt{s} = 14$ TeV with **tight τ_h-tagging** techniques



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



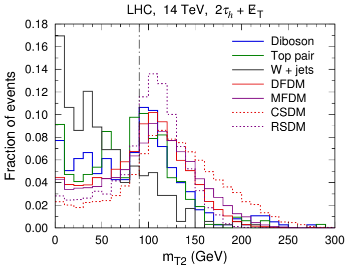
DFDM or **MFDM**



CSDM or **RSDM**

14 TeV LHC Searches for $pp \to \phi\phi^*/\psi\bar{\psi} \to \tau^+\tau^-\chi\chi$

🎃 $2\tau_\mathrm{h} + \not{E}_\mathrm{T}$ **channel:** two opposite-sign tau-jet (τ_h); without any other particle; $m_{\mathrm{T2}} > 90$ GeV



Signals:

DFDM model

$m_\phi = 225$ GeV

MFDM model

$m_\phi = 250$ GeV

CSDM model

$m_\psi = 300$ GeV

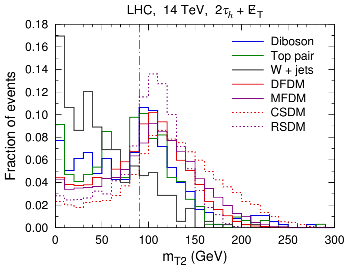
RSDM model

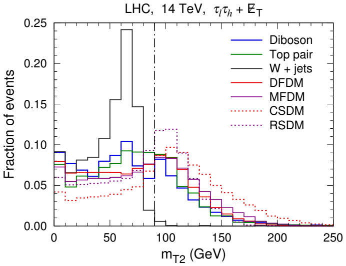
$m_\psi = 200$ GeV

14 TeV LHC Searches for $pp \to \phi\phi^*/\psi\bar{\psi} \to \tau^+\tau^-\chi\chi$

$2\tau_\mathrm{h} + \not{E}_\mathrm{T}$ channel: two opposite-sign tau-jet (τ_h); without any other particle; $m_{\mathrm{T2}} > 90$ GeV

$\tau_\ell\tau_\mathrm{h} + \not{E}_\mathrm{T}$ channel: one τ_h and one light lepton ($\ell = \mu, e$) with opposite signs; without any other particle; $m_{\mathrm{T2}} > 90$ GeV





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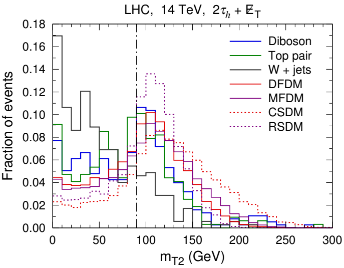
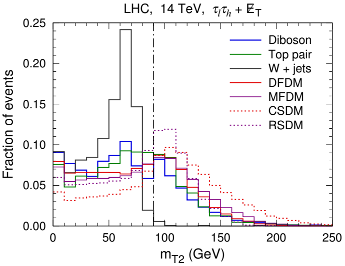
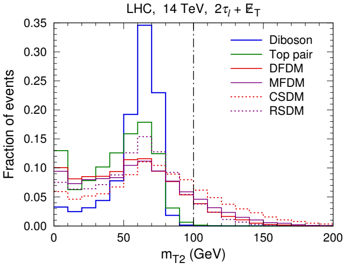


$2\tau_h + \not{E}_T$ channel: two opposite-sign tau-jet (τ_h); without any other particle; $m_{T2} > 90$ GeV

$\tau_\ell\tau_h + \not{E}_T$ channel: one τ_h and one light lepton ($\ell = \mu, e$) with opposite signs; without any other particle; $m_{T2} > 90$ GeV

$2\tau_\ell + \not{E}_T$ channel: two opposite-sign light leptons; $|m_{\ell\ell} - m_Z| > 10$ GeV for the same-favor case; without any other particle; $m_{T2} > 100$ GeV





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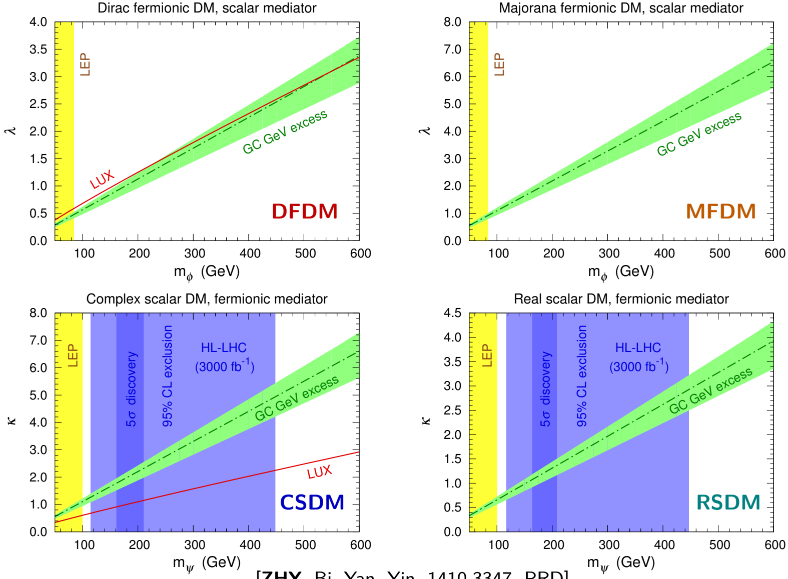
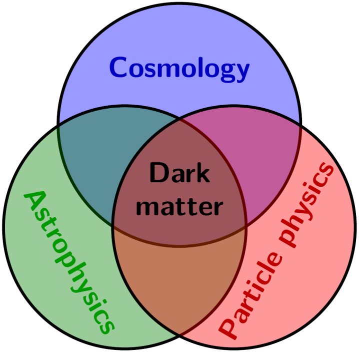
Sensitivity of the 14 TeV High-Luminosity LHC



[**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**, and it is promising to detect robust DM signals in the future



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Thank you!