Introduction to Dark Matter

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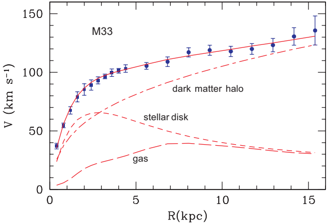
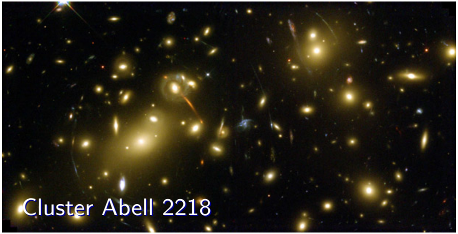
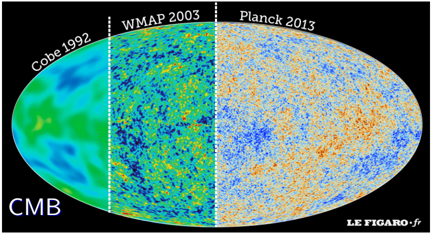
Dark Matter in the Universe

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







Coma Cluster (后发座星系团)

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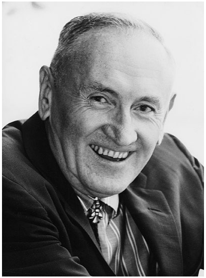


✨ In 1933, **Fritz Zwicky** found that the **velocity dispersion** of **galaxies** in the **Coma cluster** was **far too large** to be supported by the **luminous matter**

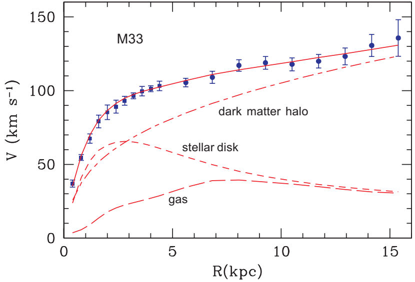
🌨️ **Mass-to-light ratio** $\Upsilon_{\mathrm{Coma}} \sim 240\Upsilon_{\odot}$

[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**



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

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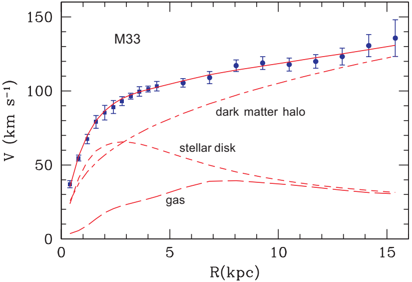
Triangulum galaxy M33

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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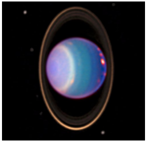
How Can We Explain an Anomalous Phenomenon?



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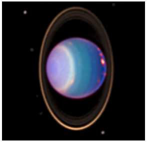

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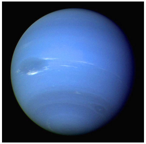

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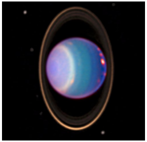

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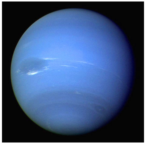

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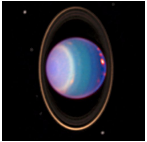

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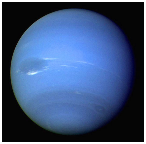

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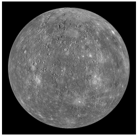

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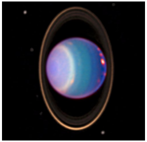

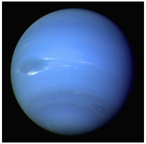

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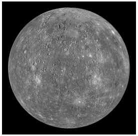

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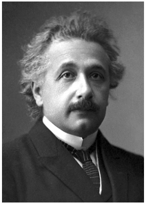
🚀 Update Newton's laws to **general relativity** (1915)



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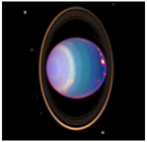

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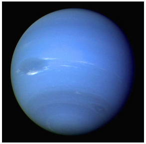

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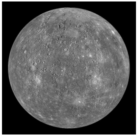

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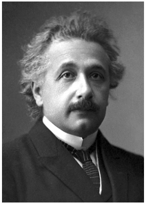
💣 **Modify known physical laws!**



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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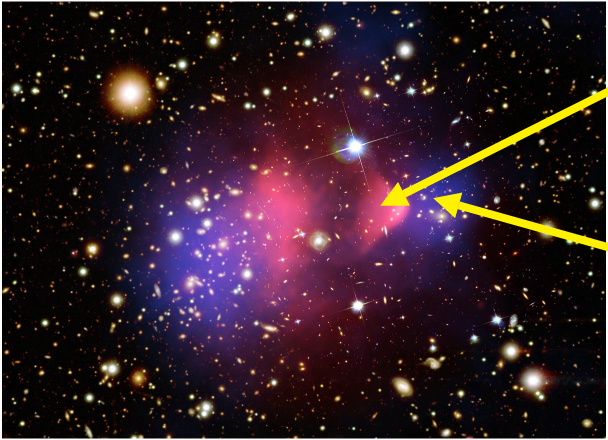
Consider new substances 👉 **Nonbaryonic Dark Matter**

(not constituted by baryons)

Bullet Cluster: Disfavor MOND



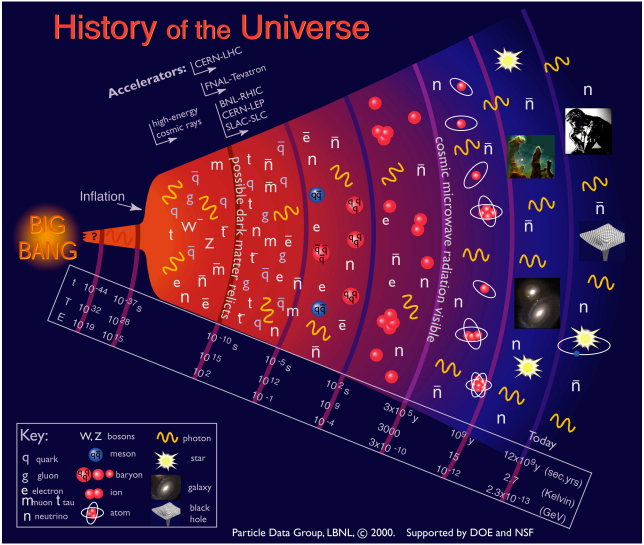
Fluid-like X-ray emitting plasma, *i.e.*, gas (luminous matter)

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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- **Hot dark matter** (such as neutrinos): **relativistic** when it decoupled
  - Structures are formed by **fragmentation** (**top-down**)
- **Cold dark matter (CDM)**: **nonrelativistic** when it decoupled
  - Structures are formed **hierarchically** (**bottom-up**)
- The observation that **galaxies** are **older** than **clusters** favors **cold dark matter**

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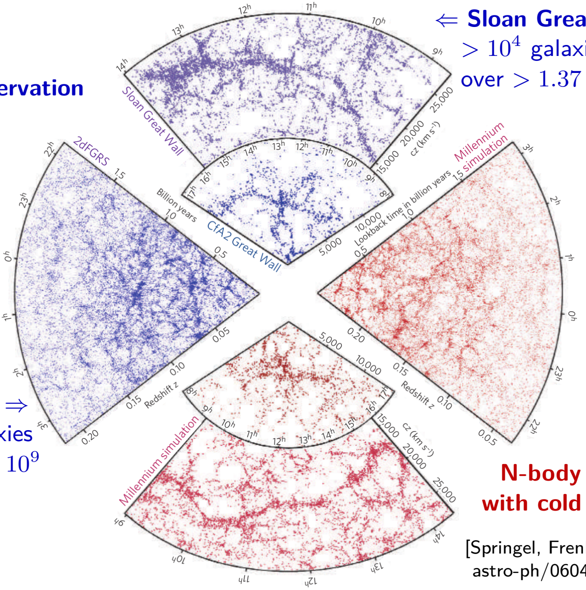
🛰 **Milky Way dwarf satellites**: ~ 60 **(observed)** vs. ~ 500 **(CDM predicted)**

☕ **"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]

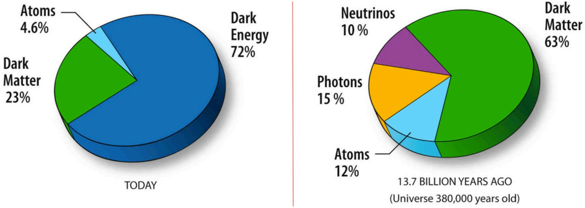
Standard Cosmology: ΛCDM Model

ΛCDM: the **standard cosmological model**

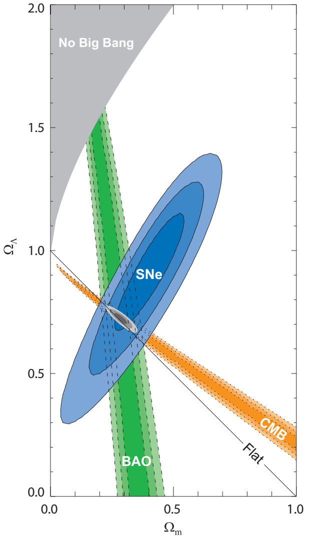
- **Cosmological constant** Λ (dark energy)
- **Cold dark matter** (CDM)

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

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



[WMAP Science Team]



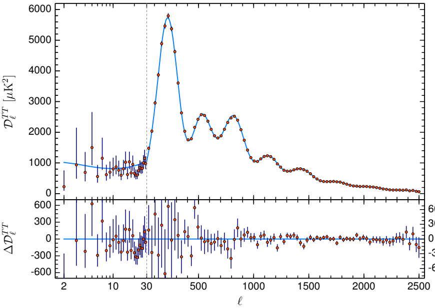
[Kowalski *et al.*, 0804.4142, ApJ]

Cosmic Microwave Background (CMB)

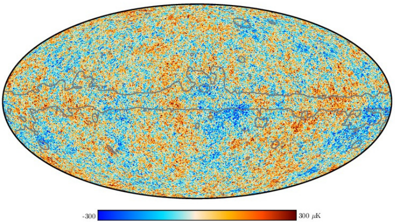
$t \sim 380\ 000$ yr, $T \sim 3000$ K
Electrons + Protons → Hydrogen Atoms
Photons decoupled

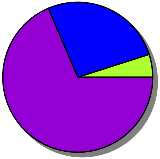
Cools ⇓ down

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**

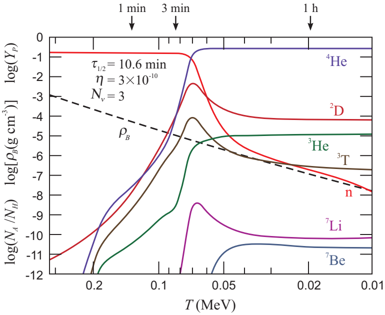




Planck 2018
[1807.06205, 1807.06209]

Cold DM (26.5%)
$\Omega_c h^2 = 0.1200 \pm 0.0012$
Baryons (4.9%)
$\Omega_b h^2 = 0.02237 \pm 0.00015$
Dark energy (68.6%)
$\Omega_\Lambda = 0.6847 \pm 0.0073$

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



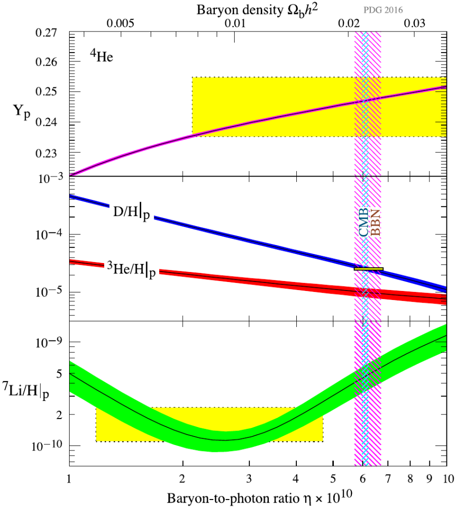
[Kolb & Turner, *The Early Universe*]

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

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

Standard Model (SM) of Particle Physics

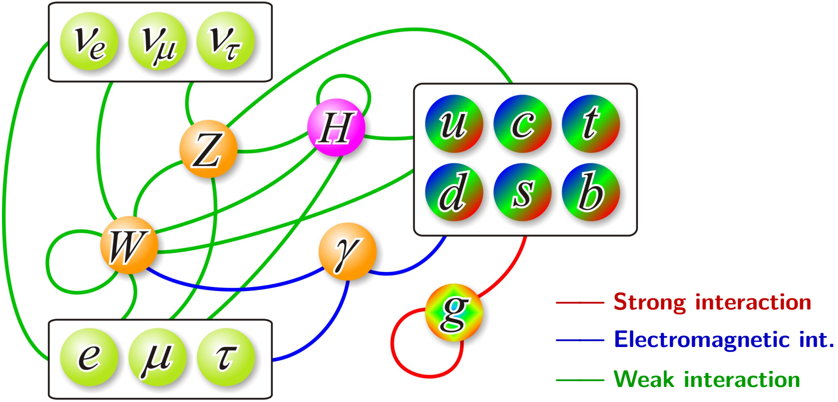
$\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ gauge symmetry

Englert-Brout-Higgs mechanism

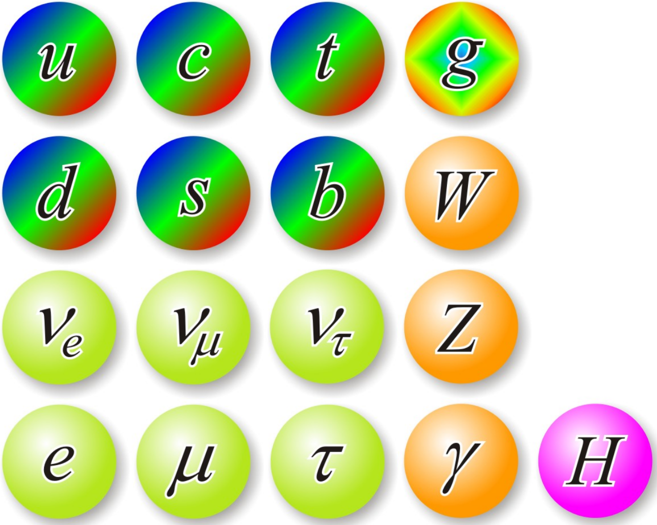
$\mathrm{SU(3)_C \times U(1)_{EM}}$ gauge symmetry

Fermion masses

Higgs boson



Are There Dark Matter Candidates in the Standard Model?



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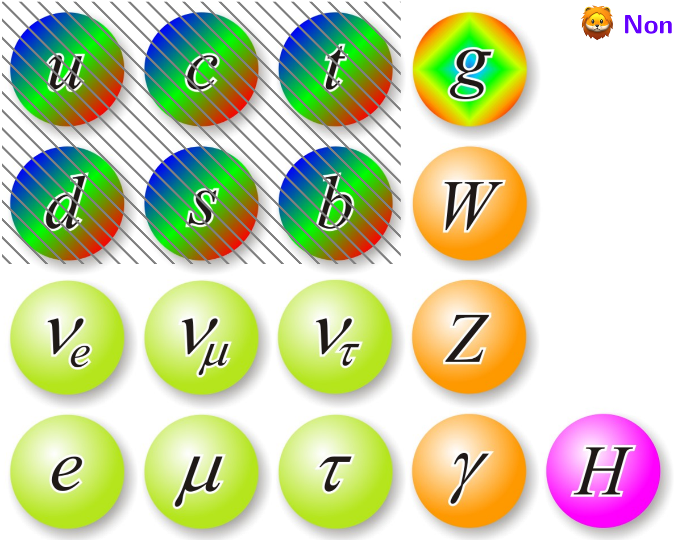

Nonbaryonic

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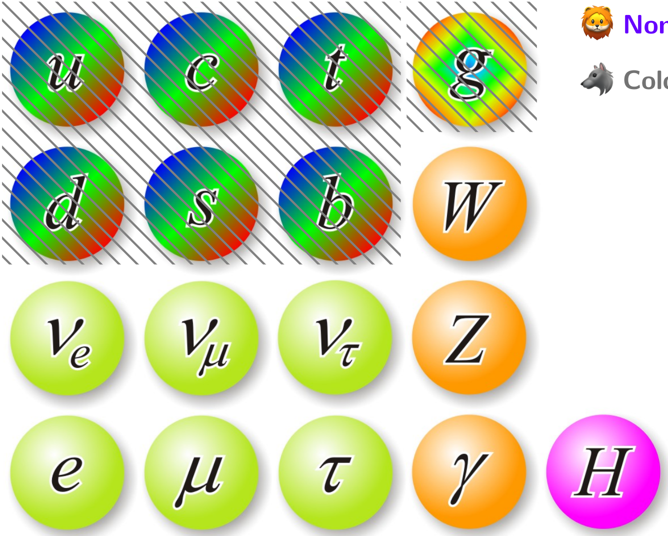

- Nonbaryonic
- Colorless

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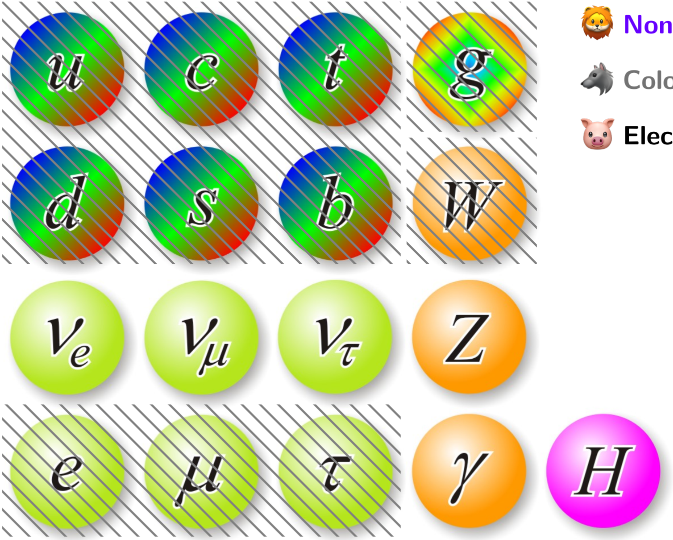

- Nonbaryonic
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- Electrically neutral

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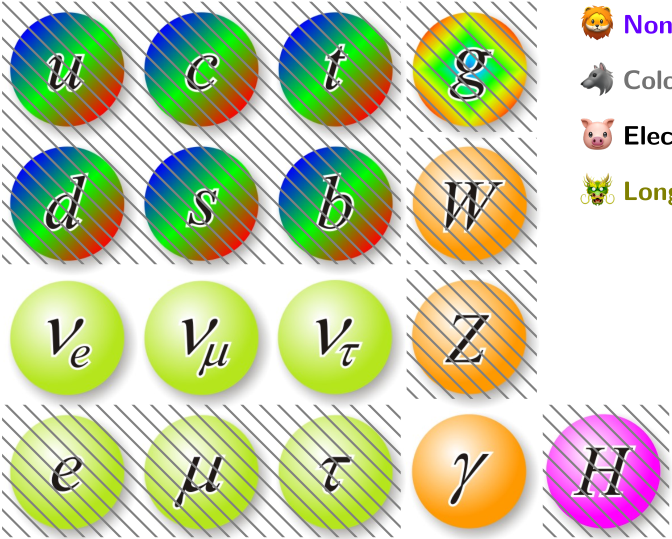

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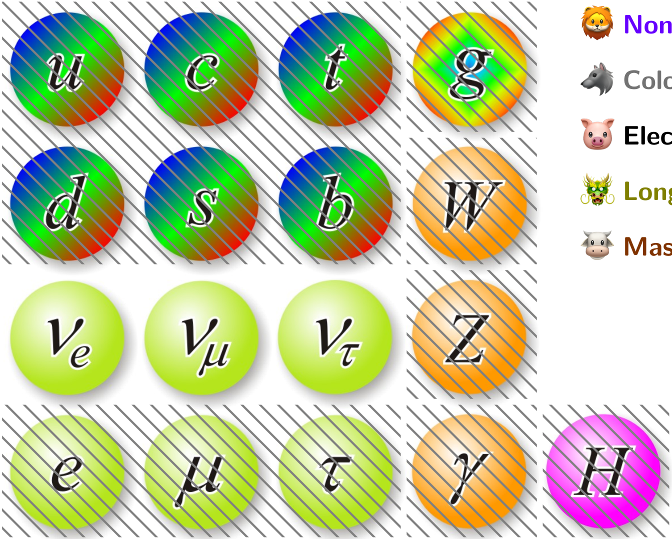

- Nonbaryonic
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- Massive

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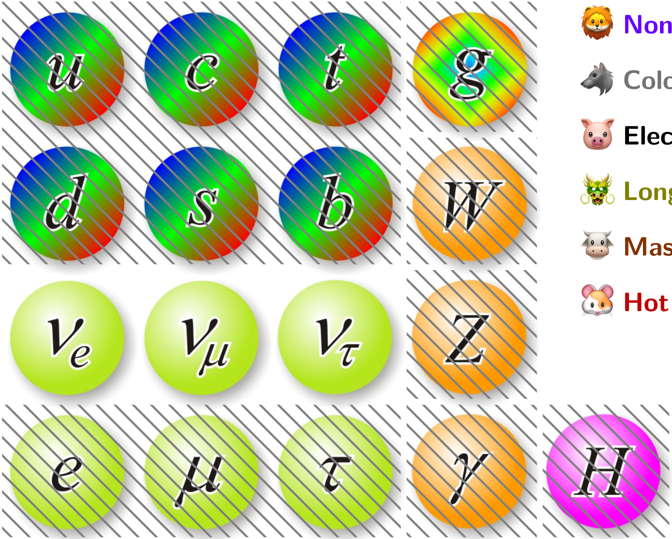

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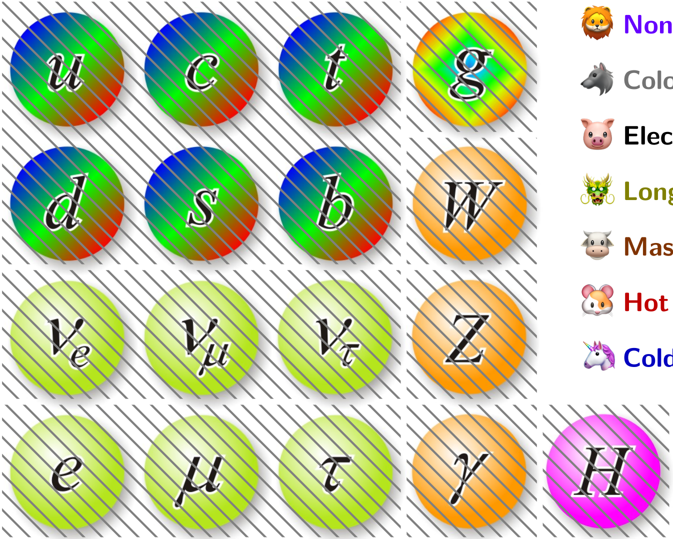

- Nonbaryonic
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- Long lived
- Massive
- Hot DM: neutrinos
- Cold DM: none

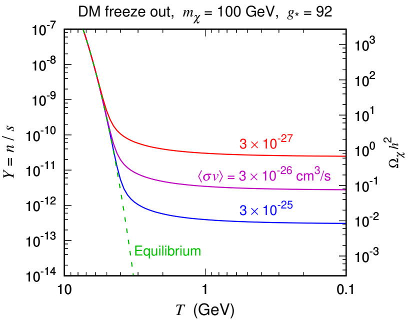
DM Relic Abundance from Thermal Production

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

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

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

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



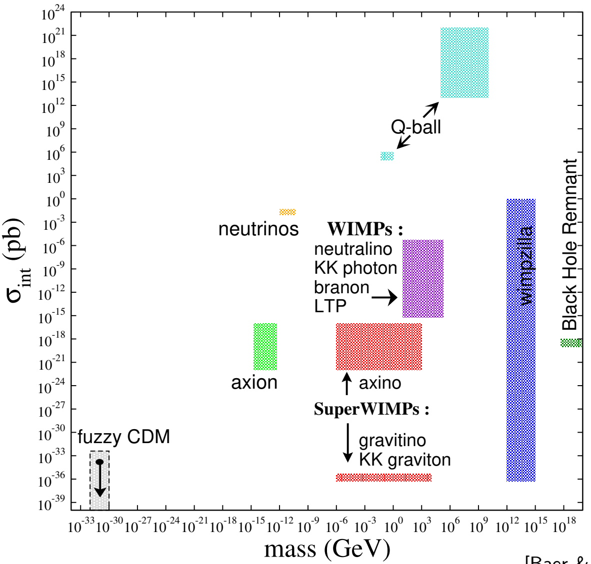
Assuming the **annihilation** process consists of two **weak interaction vertices** with the $\mathrm{SU}(2)_{\mathrm{L}}$ **gauge coupling** $g \simeq 0.64$, for $m_\chi \sim \mathcal{O}(\mathrm{TeV})$ we have

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

A very attractive class of DM candidates:

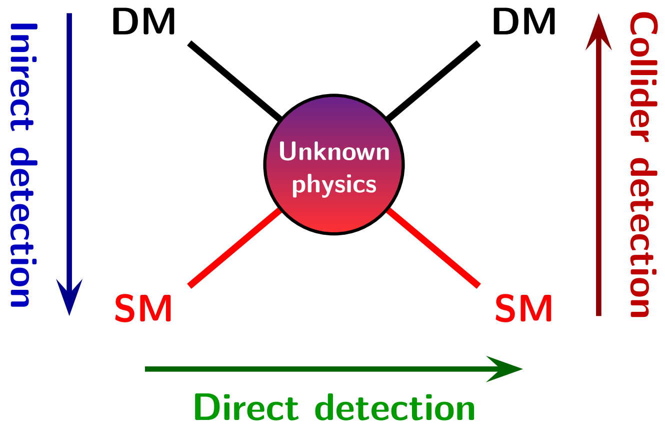
Weakly interacting massive particles (WIMPs)

DM Particle Candidates

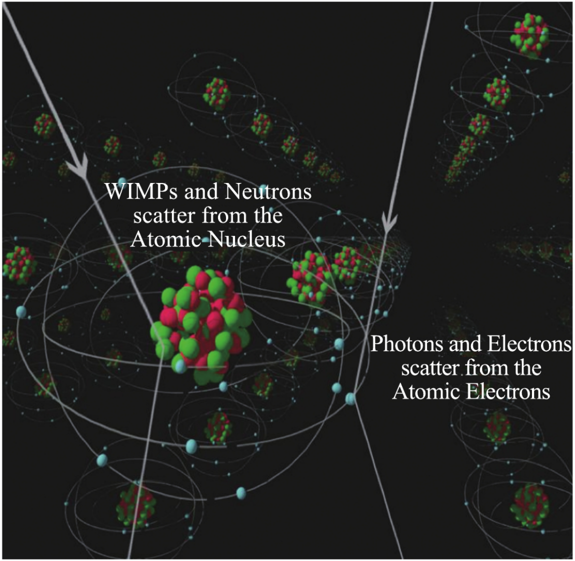


[Baer & Tata, 0805.1905]

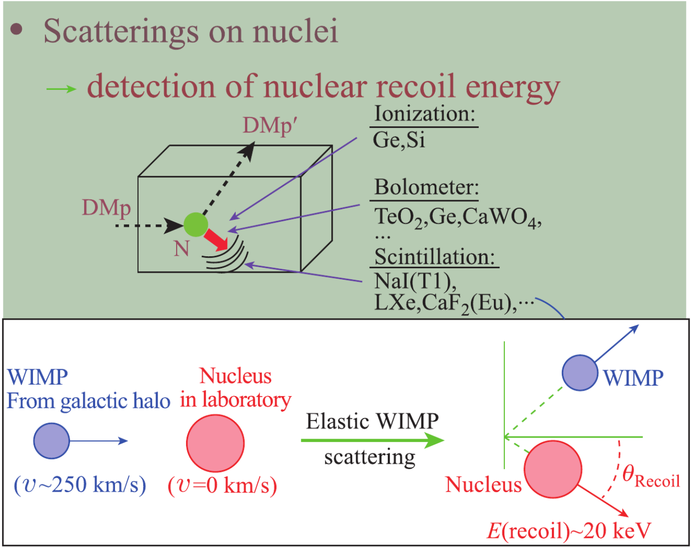
Experimental Approaches to Dark Matter



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


Galactic disk & dark halo

[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**

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

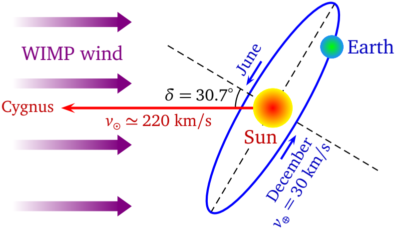
🦓 **Velocity distribution:** $f(\mathbf{v}) = \tilde{f}(\mathbf{v} + \mathbf{v}_{\mathrm{obs}})$

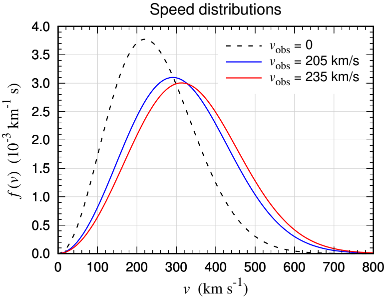
🦌 **Speed distribution:**

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

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

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





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

Nuclear Recoil

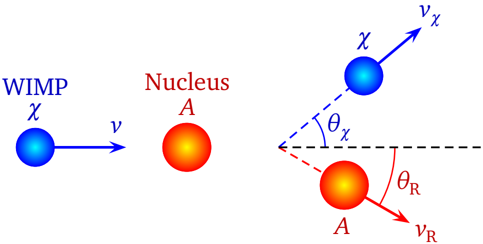
Energy conservation:

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

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 $\mu_{\chi A} \equiv \dfrac{m_\chi m_A}{m_\chi + m_A} = \begin{cases} m_A, & \text{for } m_\chi \gg m_A \\ \dfrac{m_\chi}{2}, & \text{for } m_\chi = m_A \\ m_\chi, & \text{for } m_\chi \ll m_A \end{cases}$

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

Nuclear Recoil

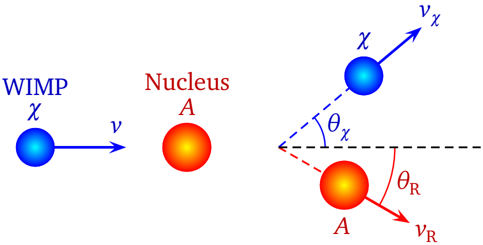
Energy conservation:

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

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

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

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

Cross Section Dependence on Nucleus Spin

There are two kinds of **DM-nucleus scattering**

- **Spin-independent (SI)** cross section $\sigma_{\chi A}^{\text{SI}} \propto \mu_{\chi A}^2 [Z G_p + (A - Z) G_n]^2$
- **Spin-dependent (SD)** cross section $\sigma_{\chi A}^{\text{SD}} \propto \mu_{\chi A}^2 \dfrac{J_A + 1}{J_A} (S_p^A G'_p + S_n^A G'_n)^2$

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**

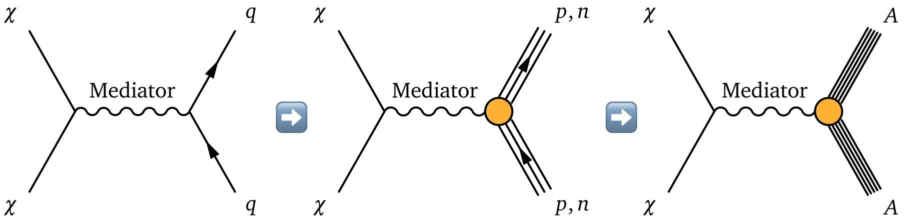
- $Z \simeq A/2$ 👉 $\sigma_{\chi A}^{\text{SI}} \propto A^2 [(G_p + G_n)/2]^2$

  ❗ Strong **coherent enhancement** for **heavy nuclei**

- **Spins** of nucleons tend to **cancel out** among themselves
  - $S_N^A \simeq 1/2$ ($N = p$ or n) for a nucleus with an **odd number** of N
  - $S_N^A \simeq 0$ for a nucleus with an **even number** of N

Three Levels of Interaction

DM-parton interaction → **DM-nucleon interaction** → **DM-nucleus interaction**



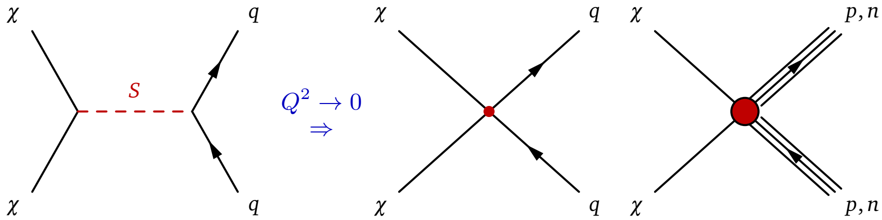
$\mathcal{M}(\chi q \to \chi q)$ $\mathcal{M}(\chi N \to \chi N)$ $\mathcal{M}(\chi A \to \chi A)$

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

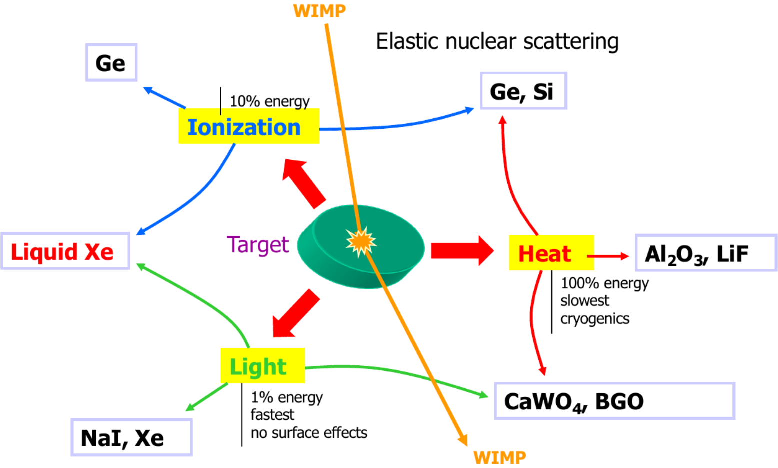
Effective Operators for DM-quark Interactions

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

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

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

Technologies and Detector Material



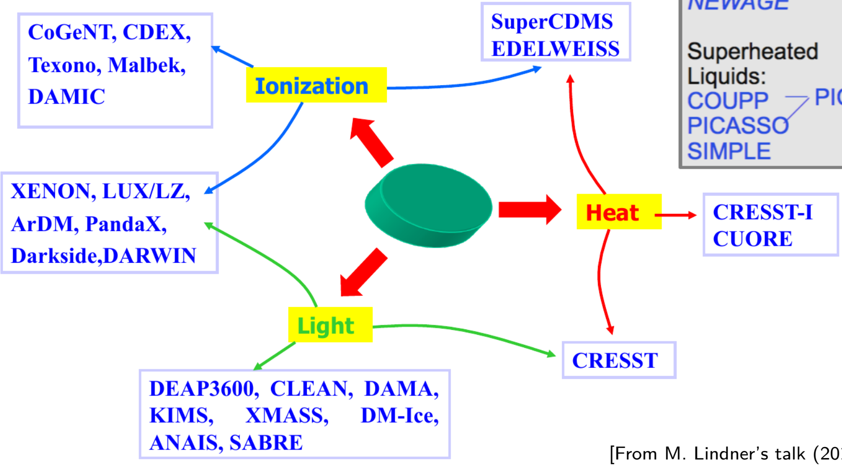
[From M. Lindner's talk (2016)]

Technologies and Detector Material

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

Tracking:
DRIFT, DMTPC
MIMAC,
NEWAGE

Superheated Liquids:
COUPP
PICASSO
SIMPLE
PICO



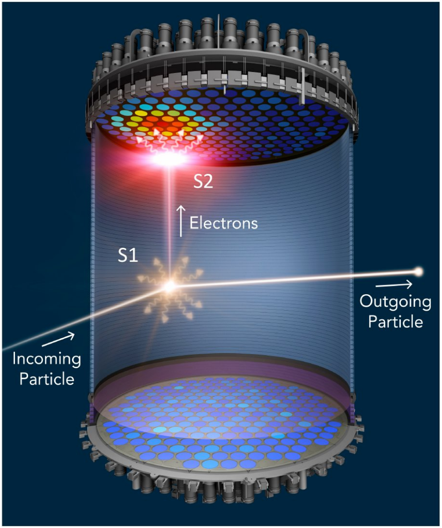
[From M. Lindner's talk (2016)]

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**

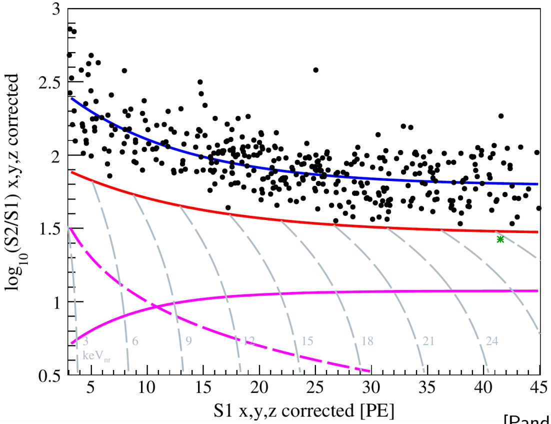
🏎️ **Experiments:** **PandaX**, **XENON**, **LZ**



[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**



ER calibration median

NR calibration median

99.99% NR acceptance

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

Backgrounds

Background suppression:

Deep underground

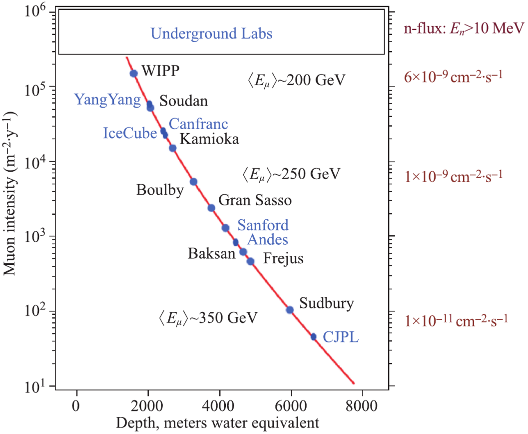
Shielded environments

Cosmogenic backgrounds

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

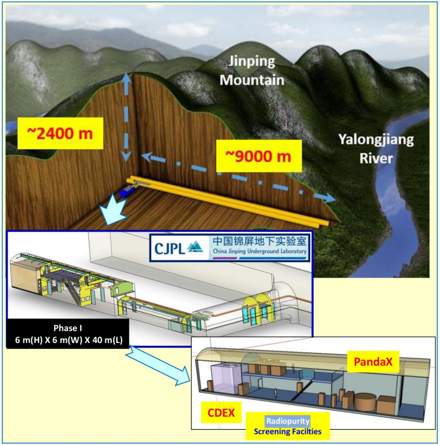
Radiogenic backgrounds

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



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

China JinPing Underground Laboratory (CJPL)

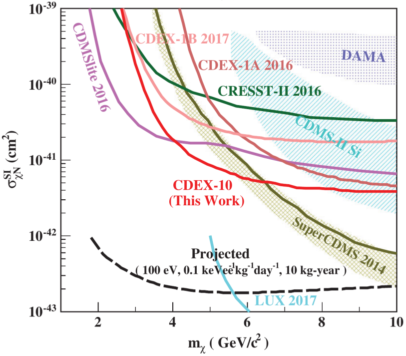


[Yue *et al.*, arXiv:1602.02462]

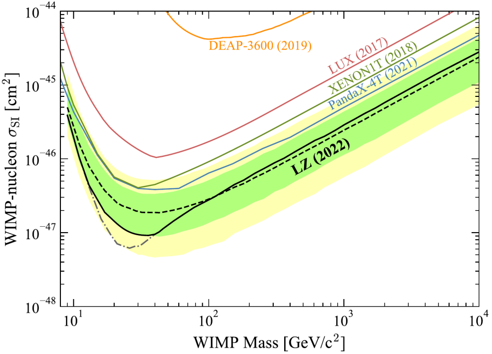
Experiments: CDEX, PandaX

Exclusion Limits for SI Scattering

- 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]

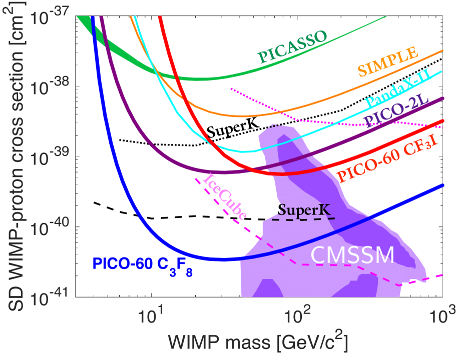


[LZ Coll., arXiv:2207.03764, PRL]

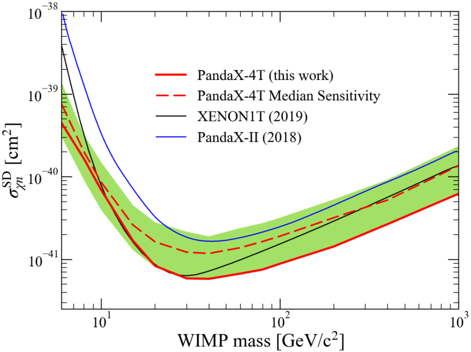
Exclusion Limits for SD Scattering

🚞 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**



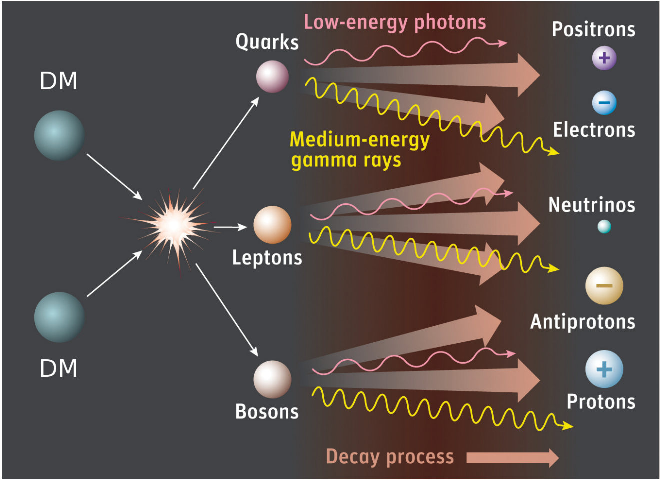
[PICO coll., arXiv:1702.07666, PRL]



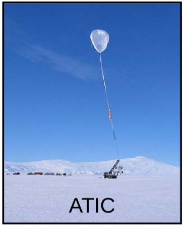
[PandaX-4T coll., arXiv:2208.03626, PLB]

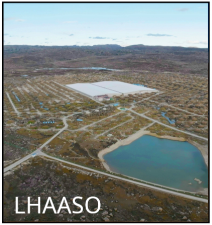
Indirect Detection

🔭 **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**

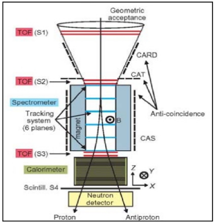


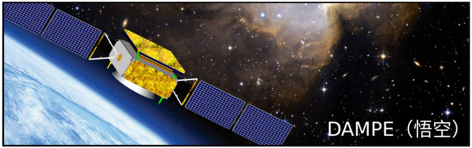
Indirect Detection Experiments

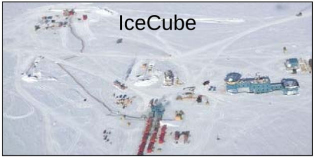




PAMELA







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

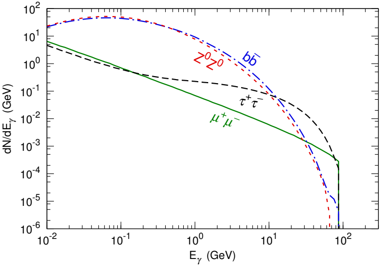
- $\rho(\mathbf{x})$: **DM mass density** at the source position $\mathbf{x}$
- $(\mathrm{d}N/\mathrm{d}E)_i$: **number per unit energy interval** from a single event in the **channel** i
- $\langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{tot}}$: thermal average of the total **annihilation cross section** 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
- $\tau_\chi \equiv 1/\Gamma_\chi$: 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 **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**

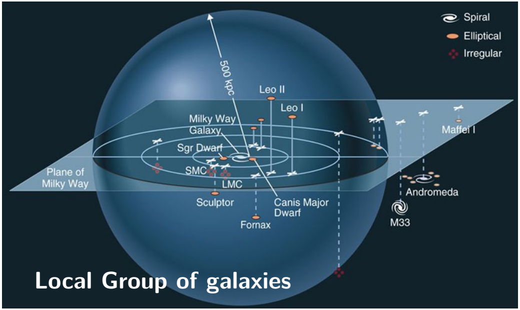
🔍 More promising to look at **DM-dominated regions**:

👑 **Galactic Center**

🎩 **Galactic halo**

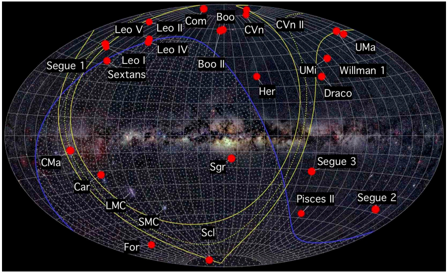
👒 **dwarf galaxies**

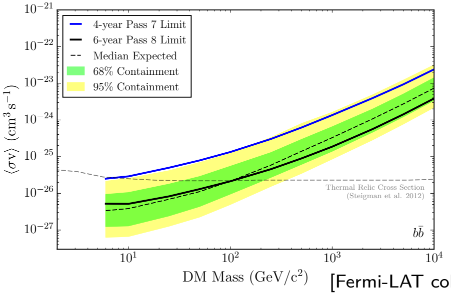
🧢 **clusters of galaxies**

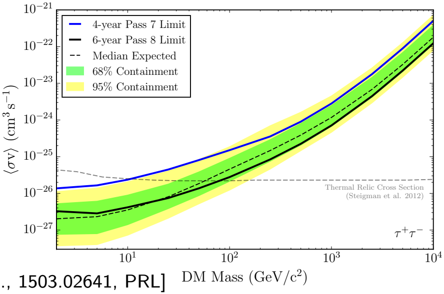


γ-ray Observation of Dwarf Galaxies

- 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]

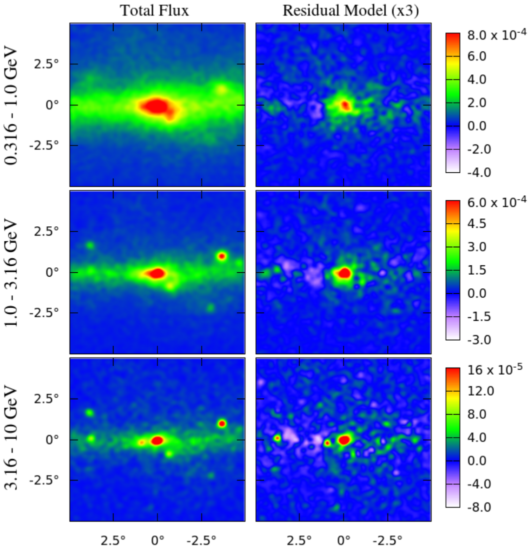
GeV Excess at the Galactic Center?

🏮 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]

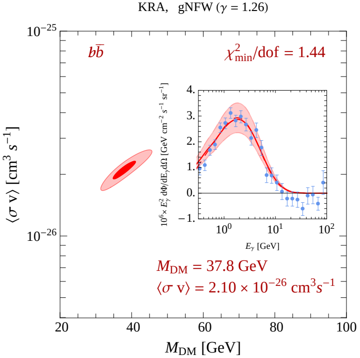
Interpretation with Dark Matter Annihilation

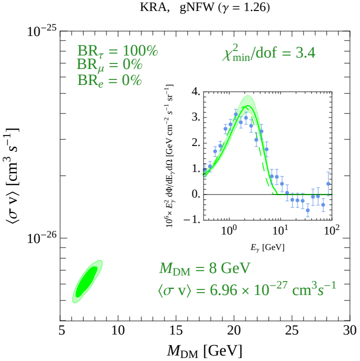
DM annihilation into $b\bar{b}$

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

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]

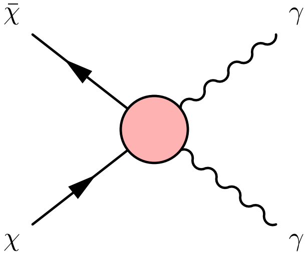
γ rays from DM: Line Spectrum

🧤 **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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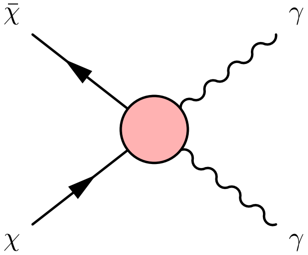


Highly suppressed: the $\chi\bar{\chi} \to \gamma\gamma$ **branching fraction** may be only $\sim 10^{-4} - 10^{-1}$

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

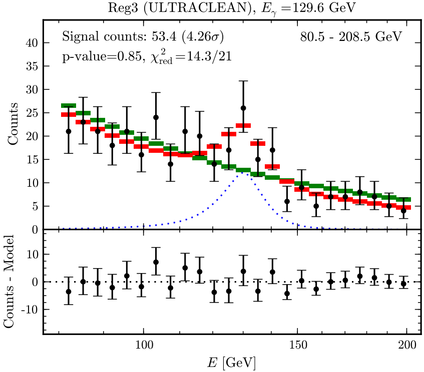
A γ-ray line at energy $\sim m_\chi$

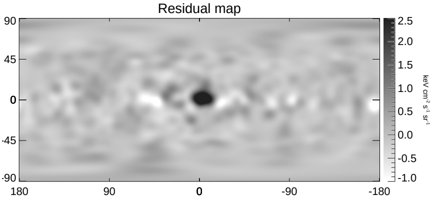
(**"smoking gun"** for DM particles)

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





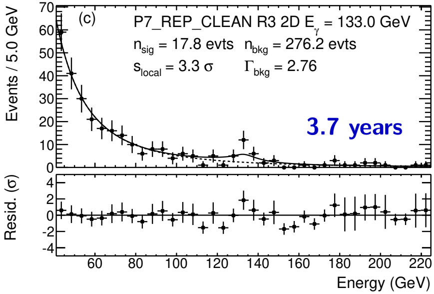
[Su & Finkbeiner, 1206.1616]

[Weniger, 1204.2797, JCAP]

Fermi-LAT Official Results: Not Confirmed with More Data

3.7-year data

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



[Fermi-LAT Coll., 1305.5597, PRD]

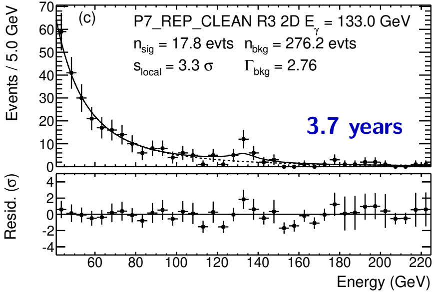
Fermi-LAT Official Results: Not Confirmed with More Data

3.7-year data

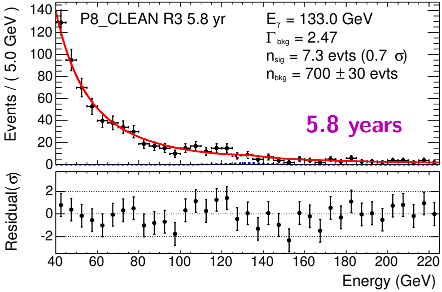
⚠️ The most significant fit occurred at $E_\gamma = 133$ GeV and had a **local significance** of 3.3σ, translating to a global significance of 1.6σ

5.8-year data

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



[Fermi-LAT Coll., 1305.5597, PRD]



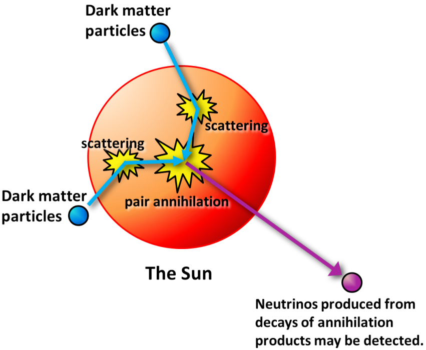
[Fermi-LAT Coll., 1506.00013, PRD]

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**:

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

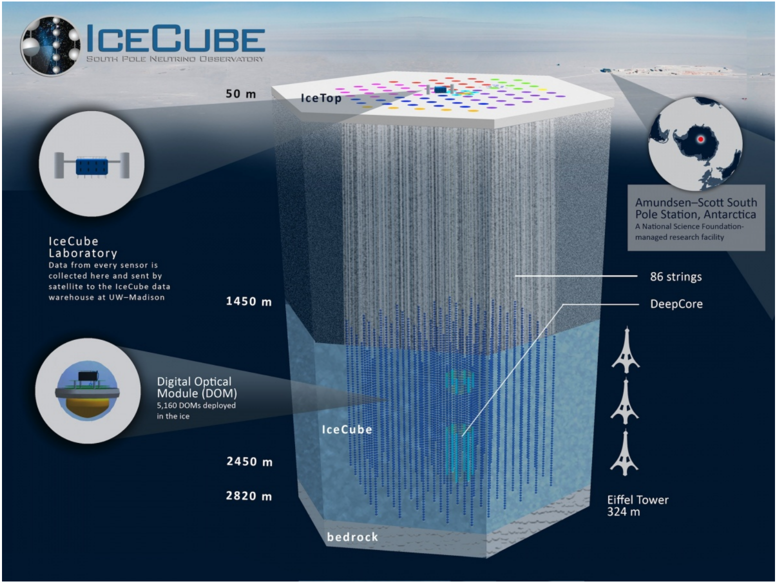


Capture rate $C_\odot$ depends on **DM scattering** on Hydrogen and Helium

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:** $\mathrm{d}N_\chi/\mathrm{d}t = 0$

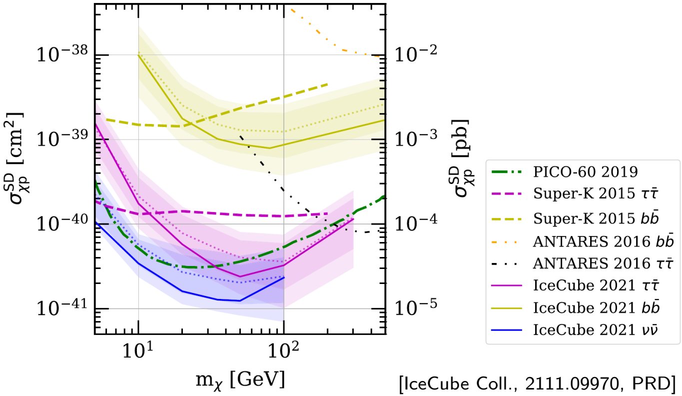
IceCube: South Pole Neutrino Observatory



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**

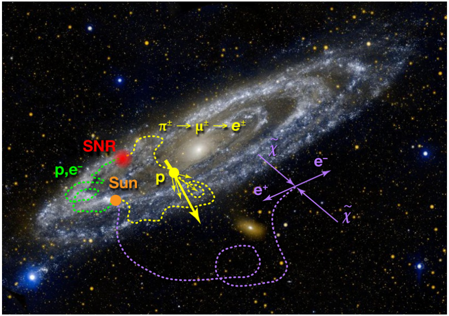


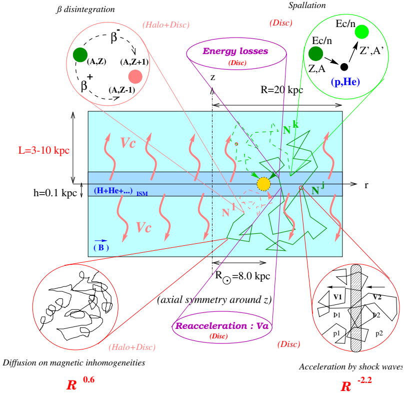
[IceCube Coll., 2111.09970, PRD]

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**

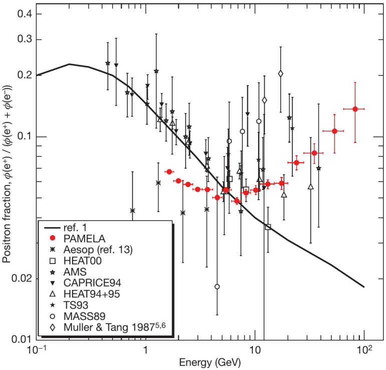




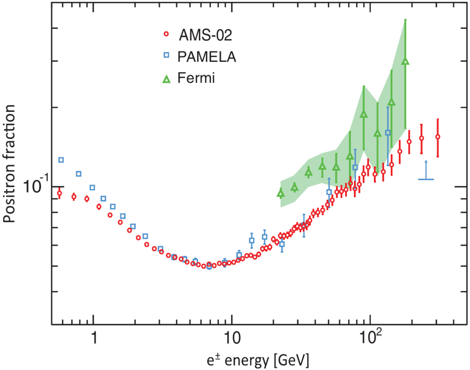
[Maurin *et al.*, astro-ph/0212111]

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**



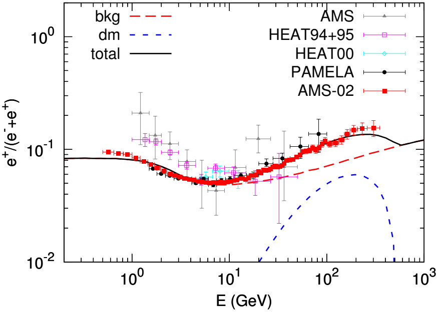
[PAMELA Coll., 0810.4995, Nature]



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

Interpretation: Dark Matter vs Pulsar

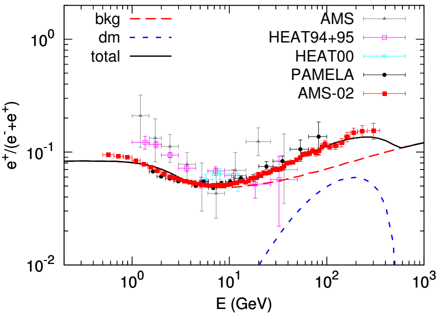
Interpretation with Galactic **DM annihilation** into $\tau^+\tau^-$



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

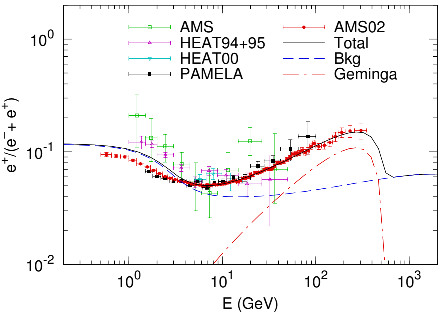
Interpretation: Dark Matter vs Pulsar

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



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

Interpretation with the **nearby pulsar Geminga**



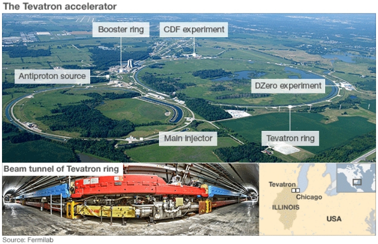
[Yin, **ZHY**, Yuan, Bi, 1304.4128, PRD]

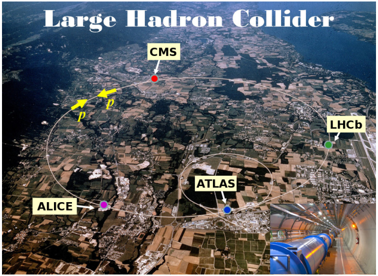
Past and Current High Energy Colliders

- **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: $\sqrt{s} = 91$–209 GeV
  Luminosity: $\mathcal{L} \sim (2$–$10) \times 10^{31}$ cm^{-2} s^{-1}
  Detectors: ALEPH, DELPHI, OPAL, L3

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





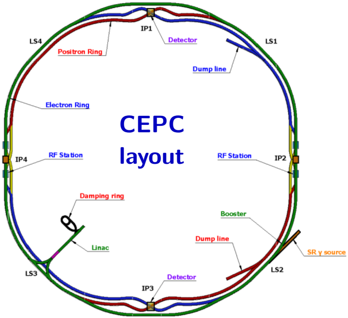
Future Projects

- **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}

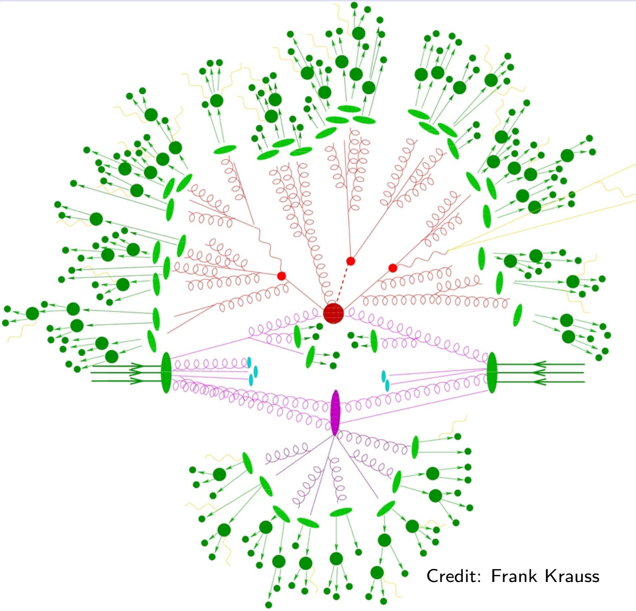
- **SPPC**: Super Proton-Proton Collider (China)

  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}

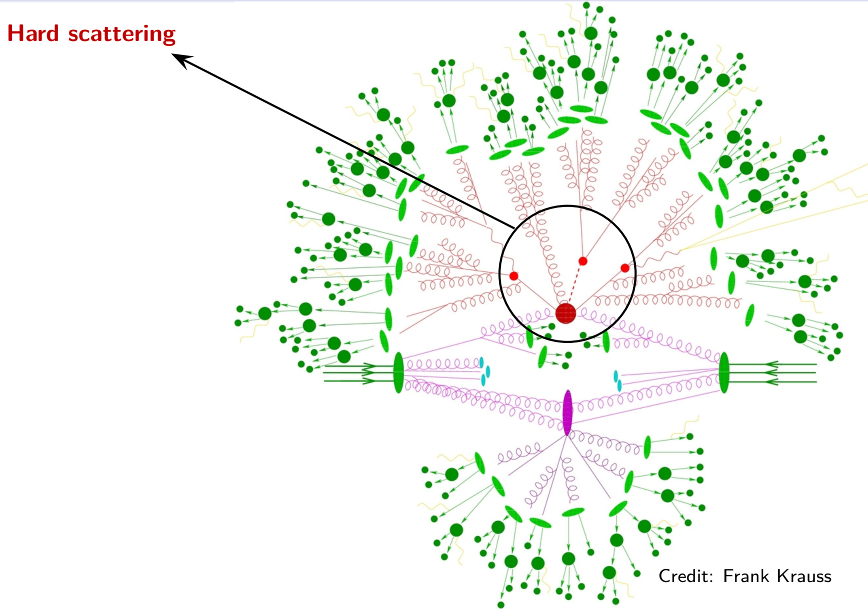
- **CLIC**: Compact Linear Collider, $\sqrt{s} \sim 1$–3 TeV, $\mathcal{L} \sim 6 \times 10^{34}$ cm^{-2} s^{-1}

Typical Event in High Energy pp Collisions



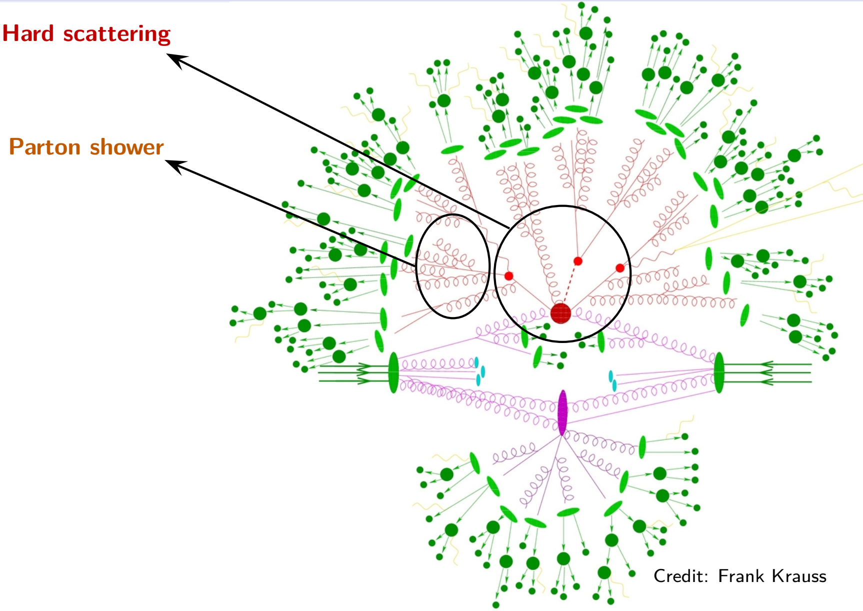
Credit: Frank Krauss

Typical Event in High Energy pp Collisions



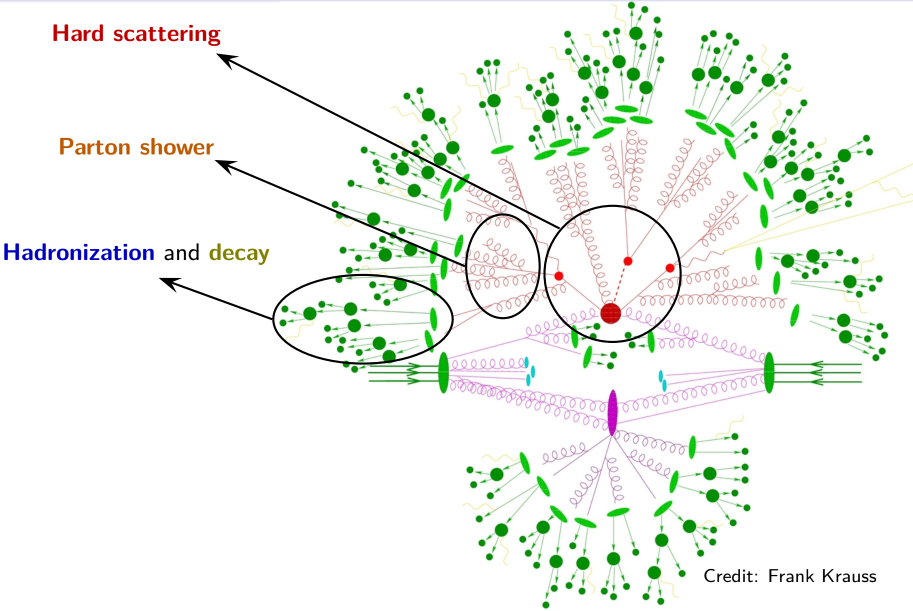
Credit: Frank Krauss

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

Hard scattering

Parton shower

Hadronization and **decay**

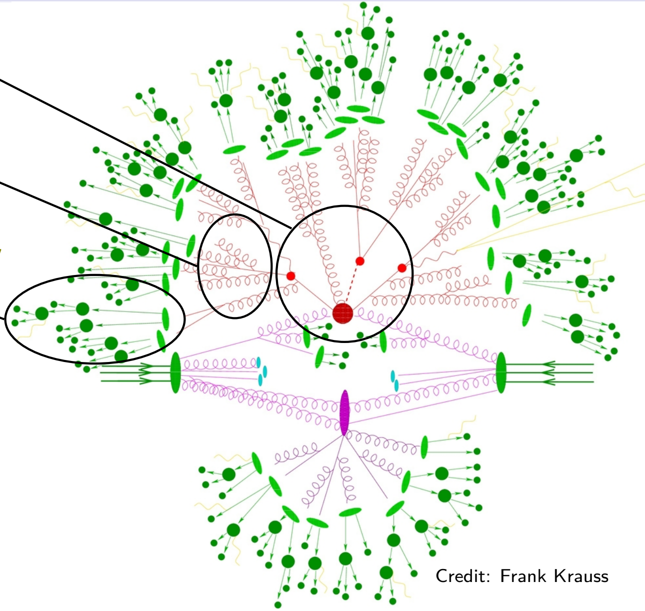
Collimated particles

⬇️

Jet

⬇️

Mimic a **hard parton**



Credit: Frank Krauss

Typical Event in High Energy pp Collisions

Hard scattering

Parton shower

Hadronization and **decay**

Collimated particles

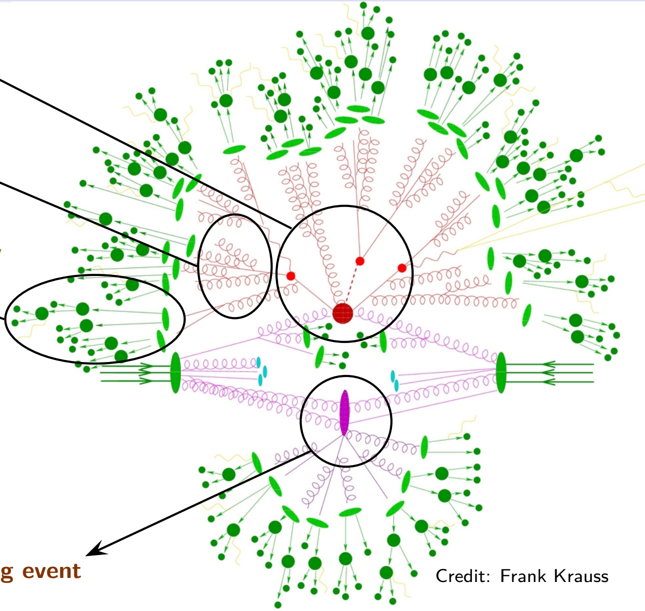
⬇️

Jet

⬇️

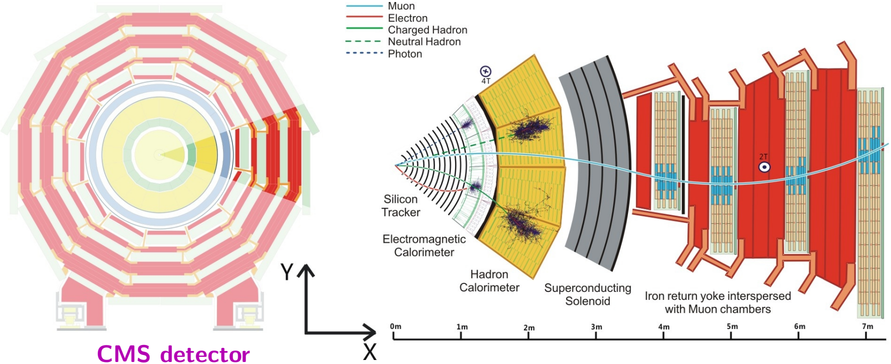
Mimic a **hard parton**

Underlying event



Credit: Frank Krauss

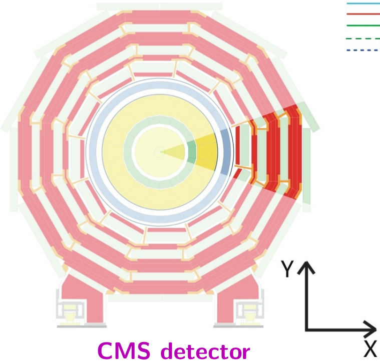
Particle Detectors at Colliders



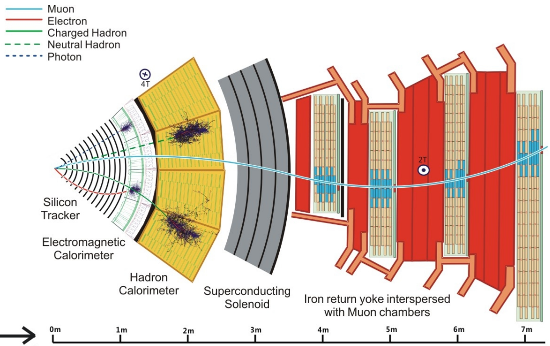
CMS detector

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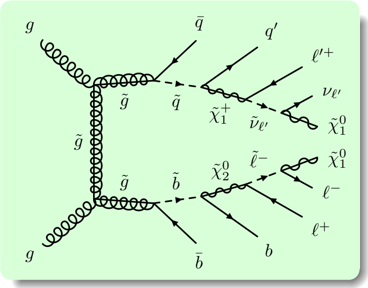
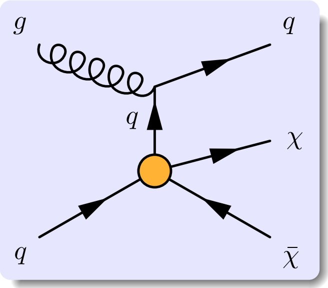
ECAL, $\lvert\eta\rvert \lesssim 3$			$\surd$	$\surd$		$\times$
HCAL, $\lvert\eta\rvert \lesssim 5$	$\times$	$\times$	$\times$			$\times$
Muon detectors, $\lvert\eta\rvert \lesssim 2.4$	$\times$	$\times$	$\surd$	$\times$	$\times$	$\times$

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:

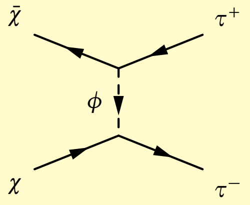
$$\mathcal{L}_\phi = \lambda\phi\bar{\tau}_\mathrm{R}\chi_\mathrm{L} + \mathrm{H.c.}$$

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

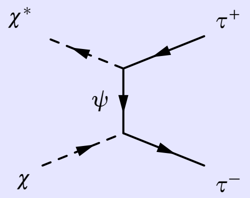
Spin-0 scalar χ, spin-1/2 mediator ψ:

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

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



DFDM: annihilation

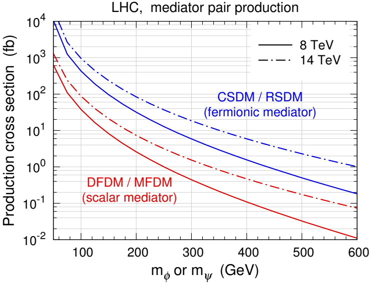


CSDM: annihilation

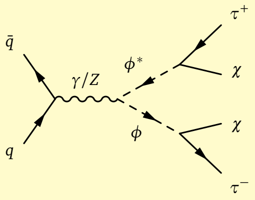
Mediator Pair Production at the LHC

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

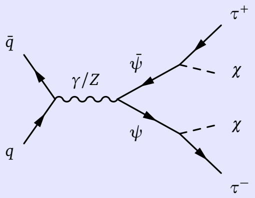
We found that the **8 TeV LHC data cannot explore the interesting regions** in these models, and went further to investigate the LHC sensitivity at $\sqrt{s} = 14$ TeV with **tight τ_h-tagging** techniques



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



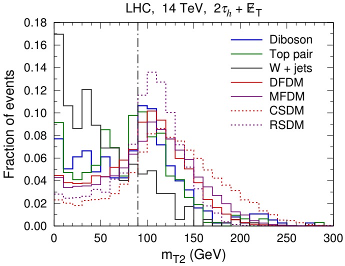
DFDM or **MFDM**



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 $pp \to \phi\phi^*/\psi\bar{\psi} \to \tau^+\tau^-\chi\chi$

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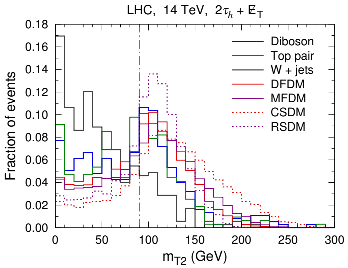
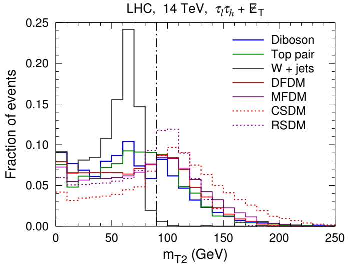
$\tau_\ell\tau_\mathrm{h} + \not{E}_\mathrm{T}$ **channel:** one τ_h and one light lepton ($\ell = \mu, e$) with opposite signs; without any other particle; $m_{\mathrm{T2}} > 90$ GeV





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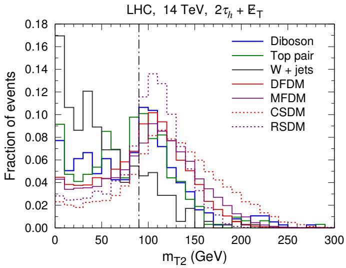
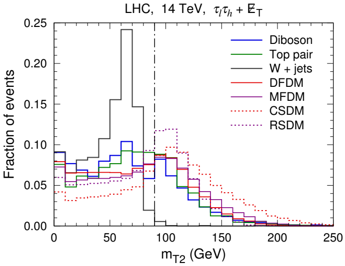
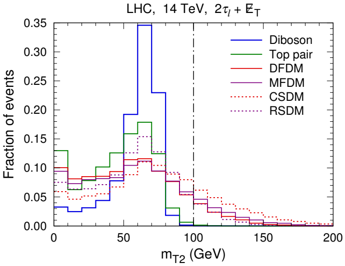
$2\tau_\ell + \not{E}_\mathrm{T}$ channel: two opposite-sign light leptons; $|m_{\ell\ell} - m_Z| > 10$ GeV for the same-favor case; without any other particle; $m_{\mathrm{T2}} > 100$ GeV







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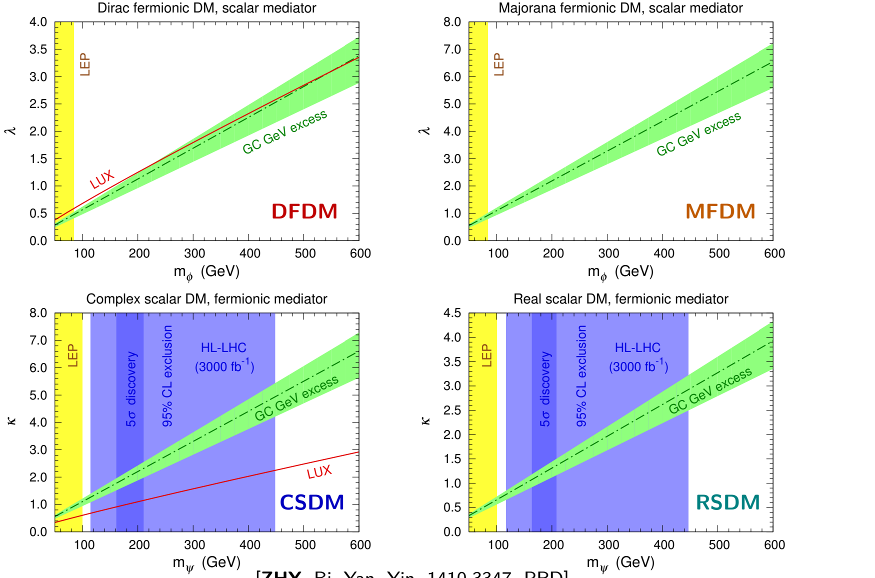
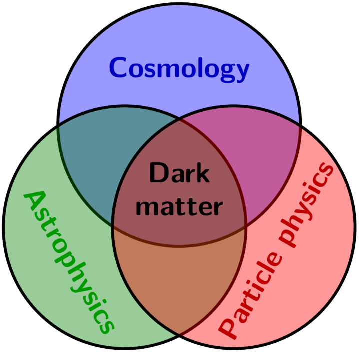
Sensitivity of the 14 TeV High-Luminosity LHC



[**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!