Introduction to Dark Matter

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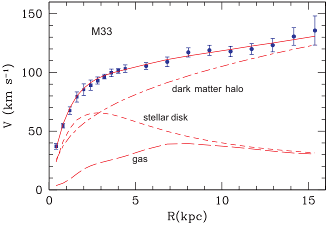
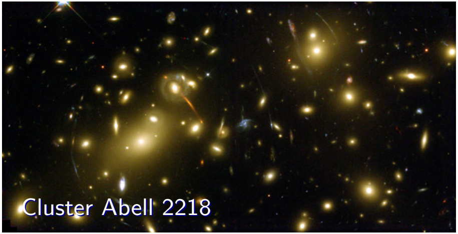
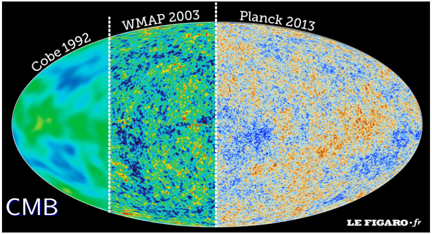
Dark Matter in the Universe

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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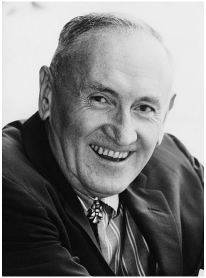


In 1933, Fritz Zwicky found that the **velocity dispersion** of galaxies in the Coma cluster was far too large to be supported by the luminous matter

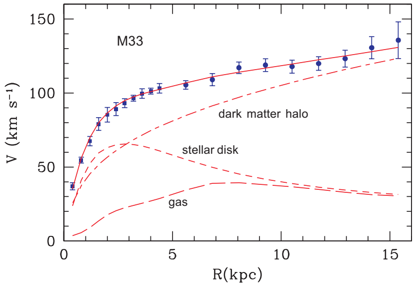
Mass-to-light ratio $\Upsilon_{\mathrm{Coma}} \sim 260\Upsilon_\odot$

[Kent & Gunn, 1982]

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

Spiral Galaxies: Rotation Curves

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



[Corbelli & Salucci, astro-ph/9909252]

Spiral Galaxies: Rotation Curves

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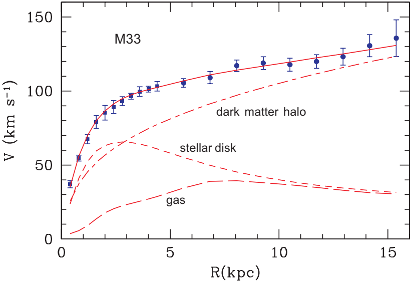
According to Newton's law, the relation between the rotation velocity v and the mass $M(r)$ within radius r should be

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

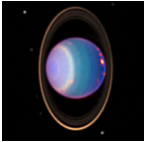
$$M(r) = \text{constant} \quad \Rightarrow \quad v \propto r^{-1/2}$$

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



[Corbelli & Salucci, astro-ph/9909252]

How Can We Explain an Anomalous Phenomenon?



Unexpected movement of **Uranus**

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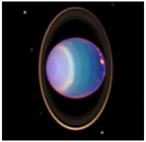

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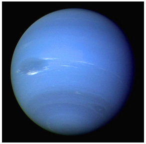
⇓

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



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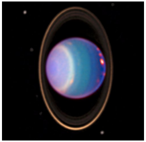

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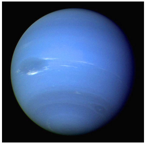

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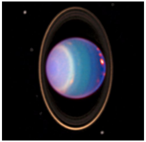

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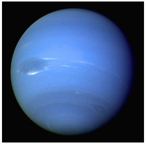

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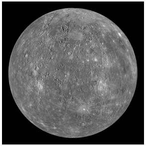

Anomalous perihelion precession of **Mercury**

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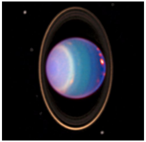

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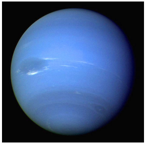

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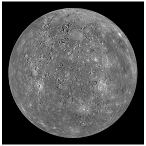

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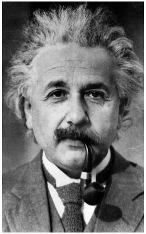
Update Newtonian mechanics to **general relativity**



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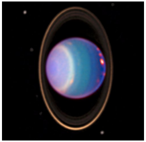

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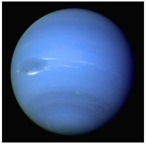

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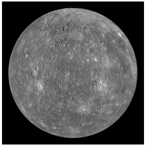

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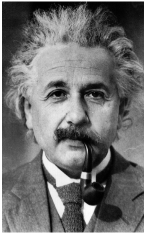

Modify known physical laws!

How about the Anomalous Phenomena Here?

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

[Milgrom, ApJ, 1983]

Difficult to coherently explain data at all scales with one model

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

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

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

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

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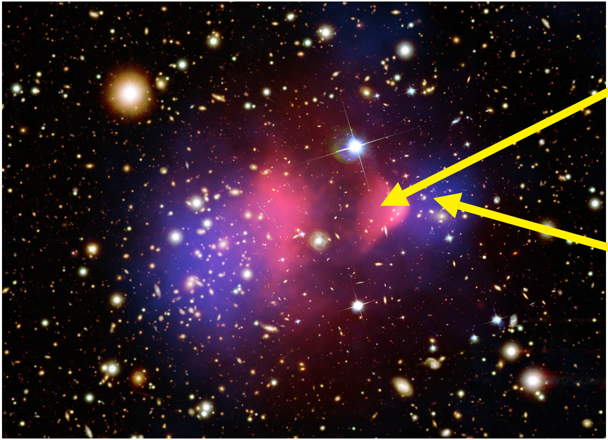
Consider new substances ⇒ **Nonbaryonic Dark Matter**

(not constituted by baryons)

Bullet Cluster: Disfavor MOND



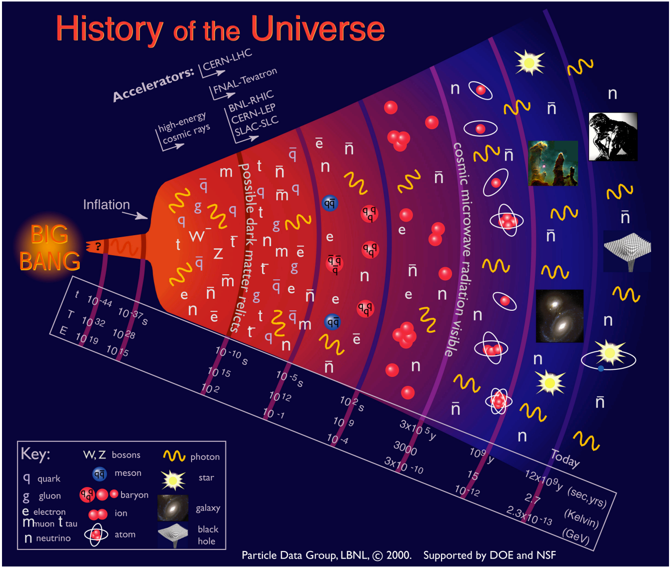
Fluid-like X-ray emitting plasma, *i.e.*, gas (visible matter)

Mass distribution observed by weak gravitational lensing (DM dominated)

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

Big Bang Cosmology

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



Structure Formation: Hot, Cold, and Warm Dark Matter

Small initial fluctuations + Gravitational instability
⇒ 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

⇒ structure forms by fragmentation (top-down)

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

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Galaxies are older than clusters ⇒ Favors cold dark matter theory

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

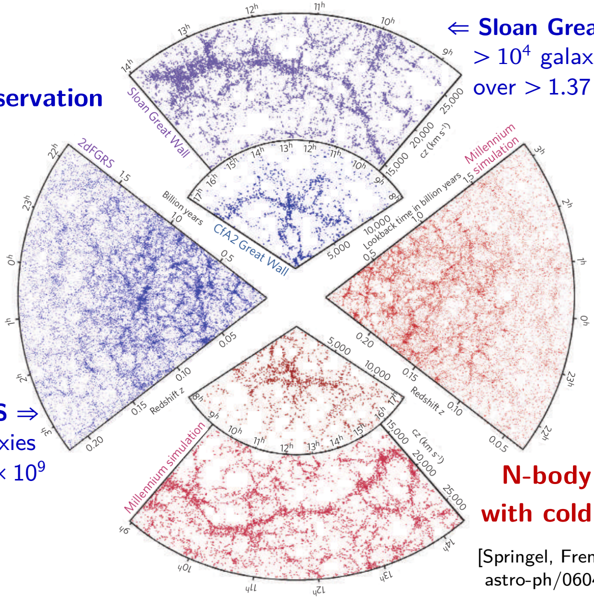
"Missing satellites problem" ⇒ A component of **warm dark matter**?

Galaxy Distribution: Observation vs Simulation

Observation

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

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



N-body simulation with cold dark matter

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

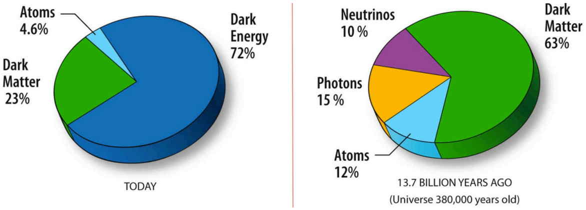
Standard Cosmology: ΛCDM Model

ΛCDM: the standard cosmological model

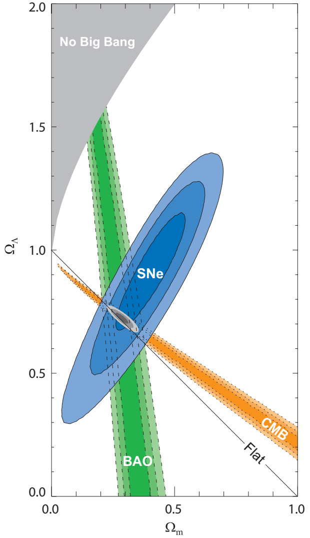
- **Cosmological constant** Λ (dark energy)
- **Cold dark matter** (CDM)

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

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



[WMAP Science Team]



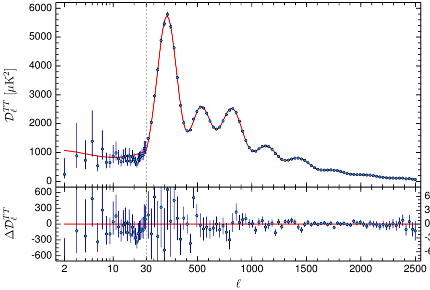
[Kowalski *et al.*, 0804.4142]

Cosmic Microwave Background (CMB)

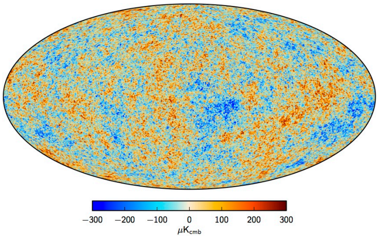
$t \sim 380\,000$ yr, $T \sim 3000$ K
Electrons + Protons → Hydrogen Atoms
Photons decoupled

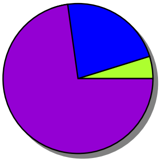
cools ⇓ down

Today, ~2.7 K microwave background



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





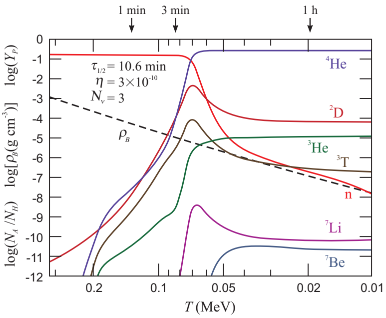
Planck 2015
[1502.01582, 1502.01589]

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

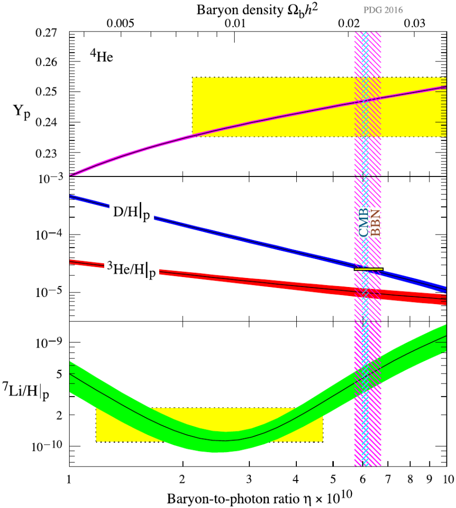
Baryons (4.8%)
$\Omega_b h^2 = 0.02226 \pm 0.00023$

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

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



[Kolb & Turner, *The Early Universe*]



[PDG 2016]

Primordial abundances of light elements

⇓

Infer the **baryon density Ω_b**
(consistent with CMB observations)

⇓

The majority of matter is **nonbaryonic**

Inferred Properties of Dark Matter

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

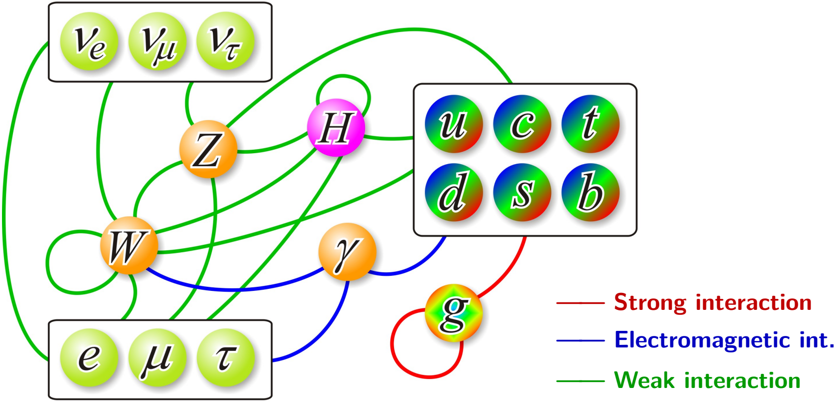
$$\rho_{\mathrm{DM}} \sim 0.3 - 0.4\ \mathrm{GeV/cm^3}\ \text{near the earth}$$

Standard Model (SM) of Particle Physics

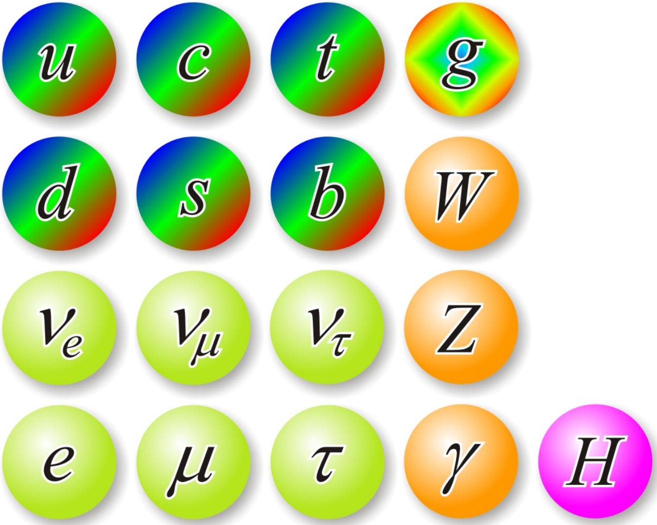
$\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ **gauge symmetry** ↗ Fermion masses

⇓ **Englert-Brout-Higgs mechanism**

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



Are There Dark Matter Candidates in the Standard Model?



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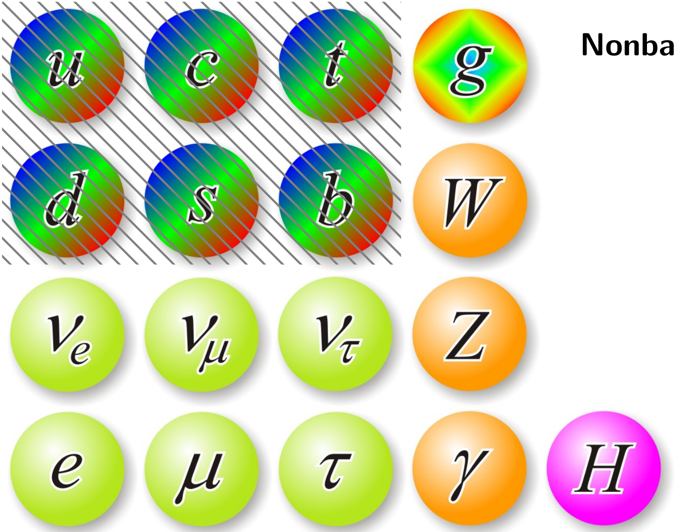

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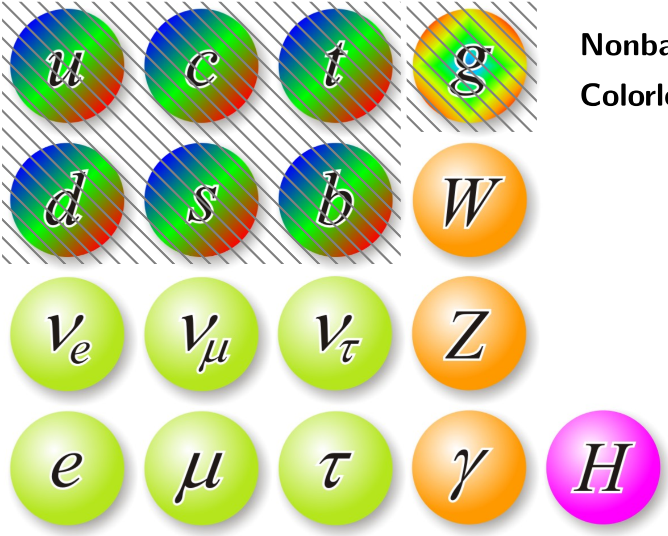

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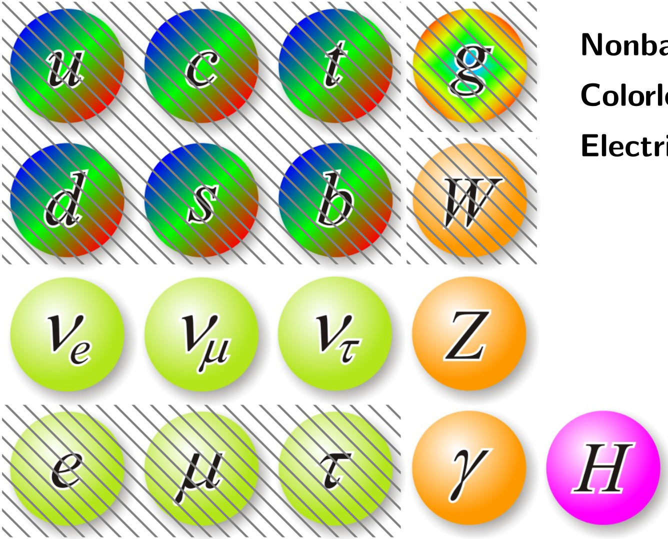

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Electrically neutral

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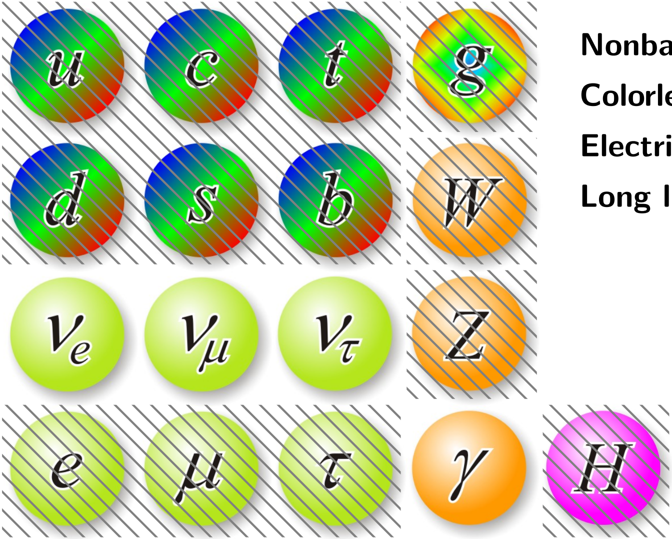

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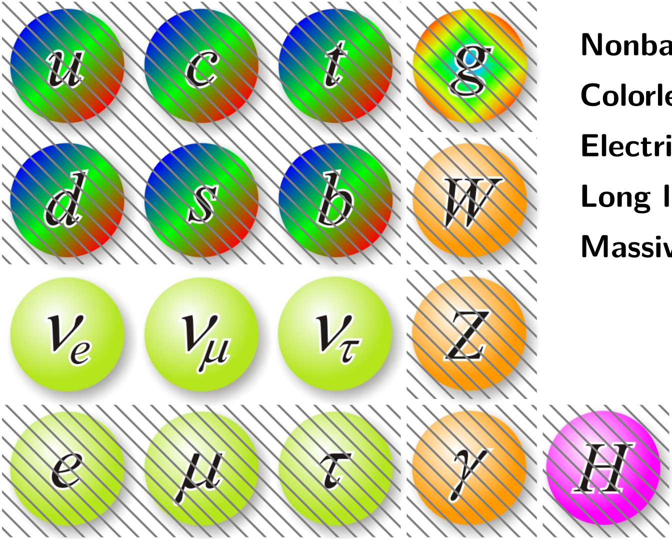

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Massive

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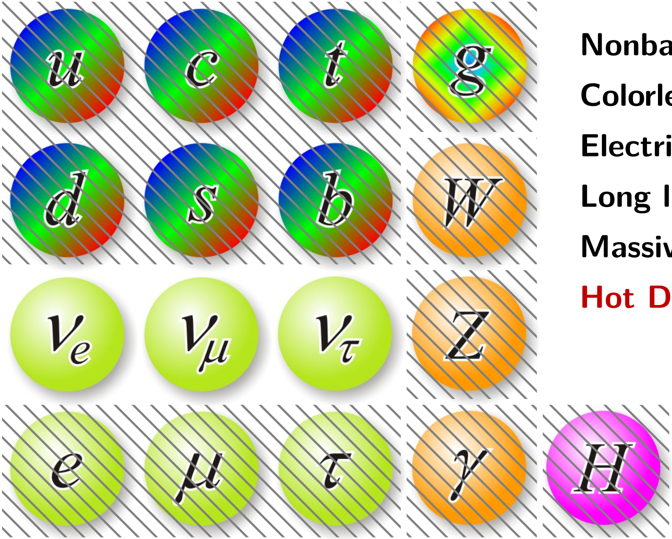

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Hot DM: neutrinos

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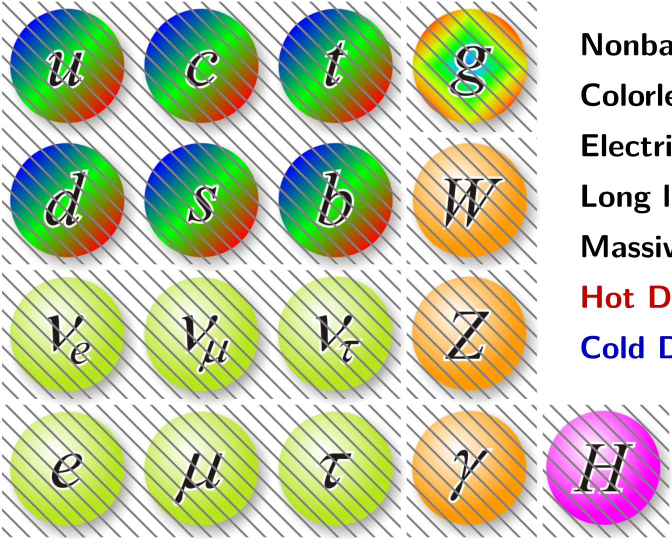

Nonbaryonic

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Electrically neutral

Long lived

Massive

Hot DM: neutrinos

Cold DM: none

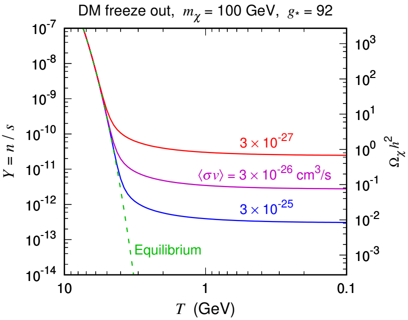
DM Relic Abundance

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

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

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

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



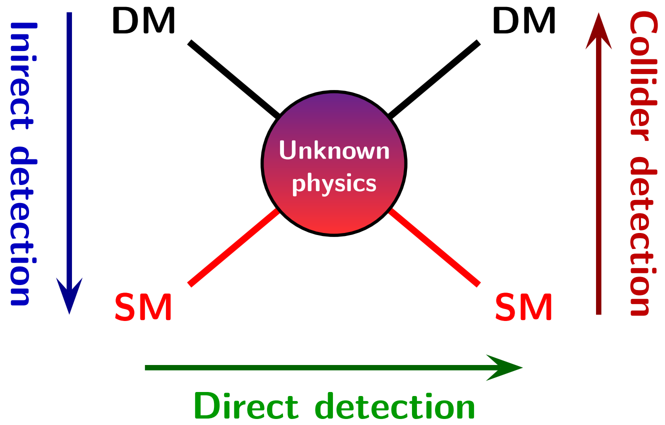
Assuming the annihilation process consists of two weak interaction vertices with the $\mathrm{SU(2)_L}$ gauge coupling $g \simeq 0.64$, for $m_\chi \sim \mathcal{O}(\text{TeV})$ we have

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

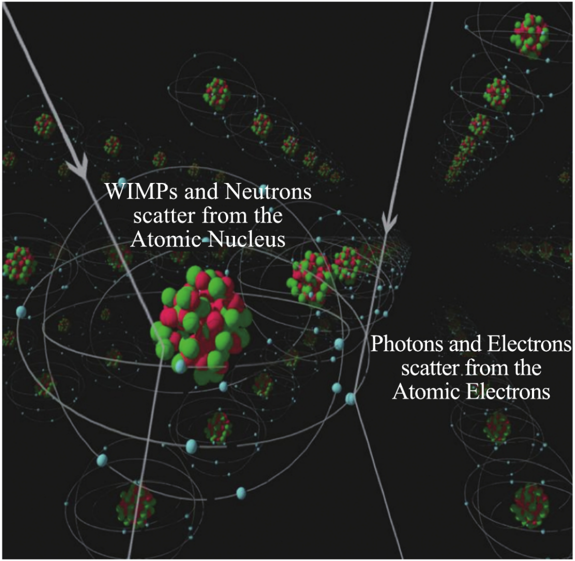
$\Rightarrow$ A very attractive class of DM candidates:

Weakly interacting massive particles (WIMPs)

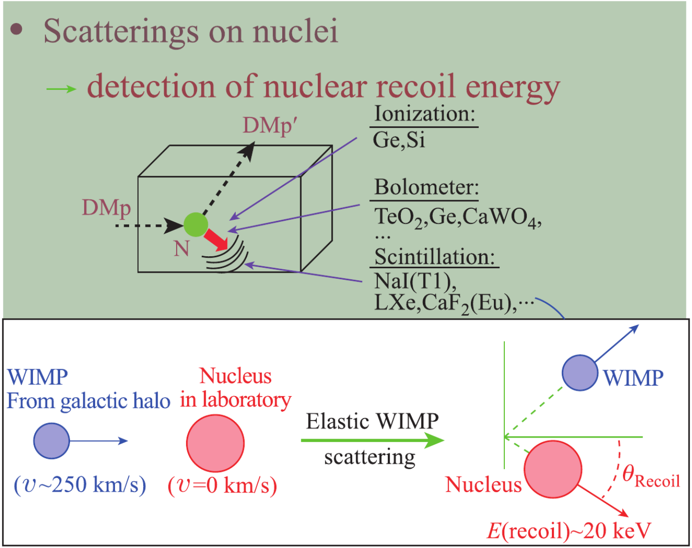
Experimental Approaches to Dark Matter



WIMP Scattering off Atomic Nuclei



Direct Detection



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

WIMP Velocity Distribution

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

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

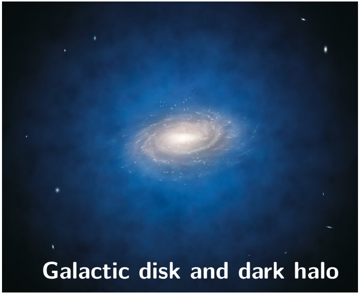
$$\langle \tilde{\mathbf{v}} \rangle = \int \tilde{\mathbf{v}} \tilde{f}(\tilde{\mathbf{v}}) d^3\tilde{v} = \mathbf{0}, \quad \langle \tilde{v}^2 \rangle = \int \tilde{v}^2 \tilde{f}(\tilde{\mathbf{v}}) d^3\tilde{v} = \frac{3}{2} v_0^2$$

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

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

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

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



Galactic disk and dark halo

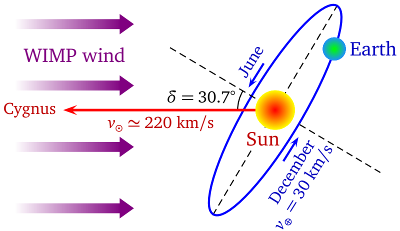
[Credit: ESO/L. Calçada]

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

Earth Rest Frame

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

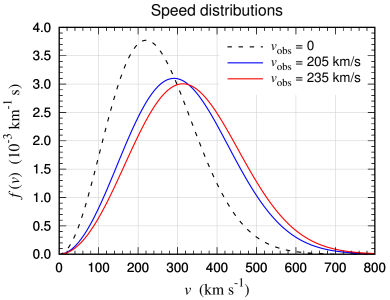
$$\tilde{\mathbf{v}} = \mathbf{v} + \mathbf{v}_{\text{obs}}, \quad \mathbf{v}_{\text{obs}} = \mathbf{v}_{\odot} + \mathbf{v}_{\oplus}$$



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

Speed distribution:

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



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

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

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

Event Rate

Event rate per unit time per unit energy interval:

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

Astrophysics factors
Particle physics factors
Detector factors

N_A: **target nucleus number**

$\rho_\oplus \simeq 0.4$ GeV/cm^3: DM **mass density** around the Earth

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

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

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

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

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

Cross Section Dependence on Nucleus Spin

There are two kinds of DM-nucleus scattering

Spin-independent (SI) cross section: $\sigma^{\mathrm{SI}}_{\chi A} \propto \mu^2_{\chi A}[Z G_p + (A - Z) G_n]^2$

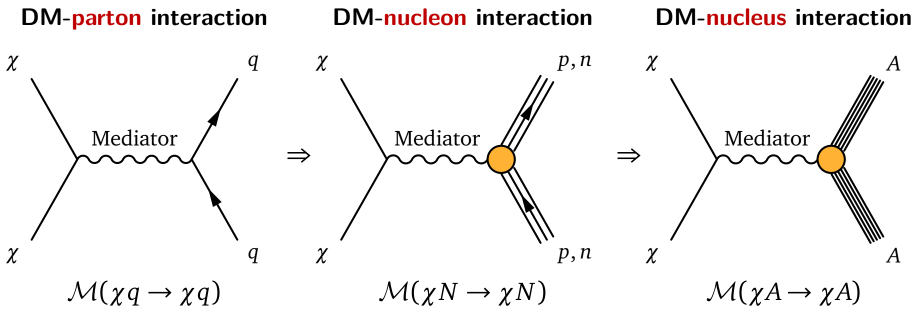
Spin-dependent (SD) cross section: $\sigma^{\mathrm{SD}}_{\chi A} \propto \mu^2_{\chi A} \frac{J_A + 1}{J_A} (S^A_p G'_p + S^A_n G'_n)^2$

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

$G^{(\prime)}_p$ and $G^{(\prime)}_n$: **DM effective couplings** to the proton and the neutron

- $Z \simeq A/2 \;\Rightarrow\; \sigma^{\mathrm{SI}}_{\chi A} \propto A^2[(G_p + G_n)/2]^2$
  Strong **coherent enhancement** for **heavy** nuclei
- Spins of nucleons tend to **cancel out** among themselves:
  - $S^A_N \simeq 1/2$ ($N = p$ or n) for a nucleus with an **odd** number of N
  - $S^A_N \simeq 0$ for a nucleus with an **even** number of N

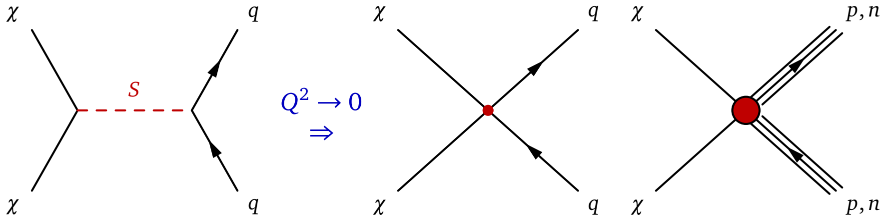
Three Levels of Interaction



- As a variety of target nuclei are used in direct detection experiments, results are usually compared with each other at the **DM-nucleon level**
- The DM-nucleon level is related to the DM-parton level via **form factors**, which describe the probabilities of finding partons inside nucleons
- Relevant partons involve not only valence quarks, but also **sea quarks and gluons**

Zero Momentum Transfer Limit

- As the momentum transfer is typically much smaller than the underlying energy scale (*e.g.*, mediator mass), the **zero momentum transfer limit** is a good approximation for calculation
- In this limit, the mediator field can be integrated out, and the interaction can be described by **effective operators** in **effective field theory**



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

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

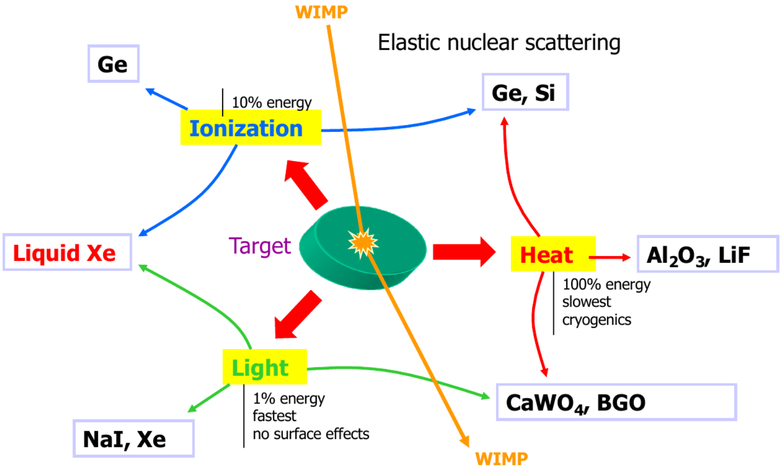
Effective Operators for DM-quark Interactions

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

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

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

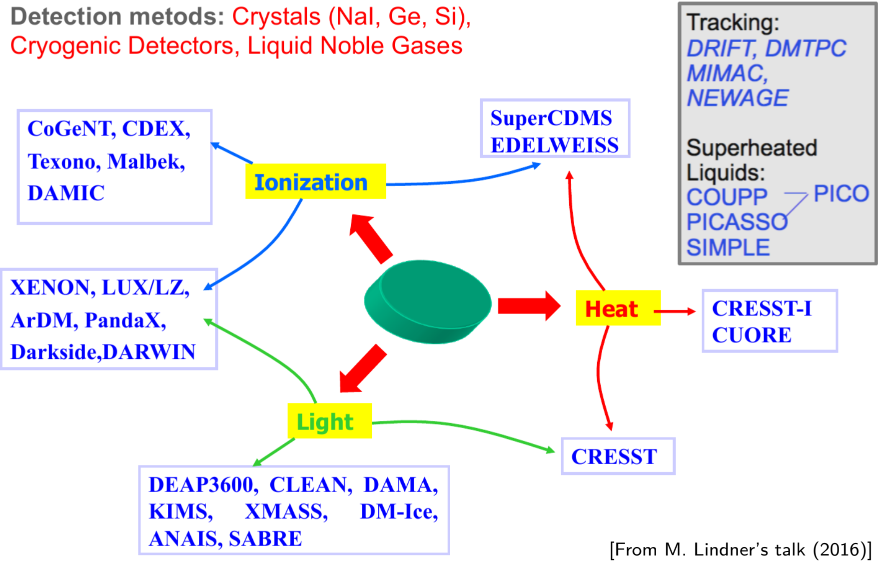
Technologies and Detector Material



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

Technologies and Detector Material

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



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

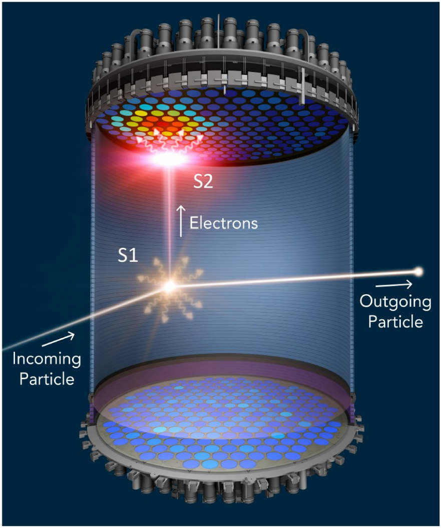
Example: Dual-phase Xenon Time Projection Chamber

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

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

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

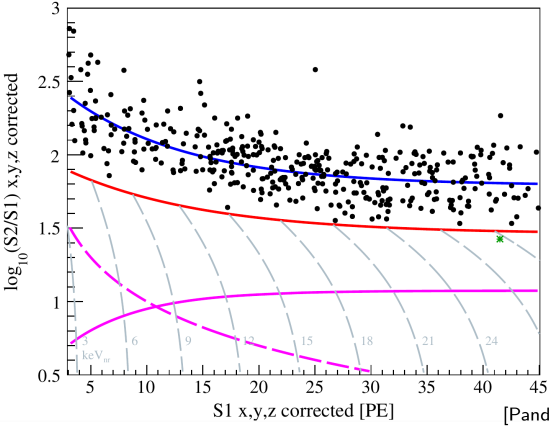
Experiments: XENON, LUX, PandaX



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

PandaX-II Real Data: S1 versus S2

- S1 and S2: characterized by numbers of **photoelectrons (PEs)** in PMTs
- The γ **background**, which produces **electron recoil (ER)** events, can be distinguished from **nuclear recoil (NR)** events using the S2-to-S1 ratio



ER calibration median

NR calibration median

99.99% NR acceptance

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

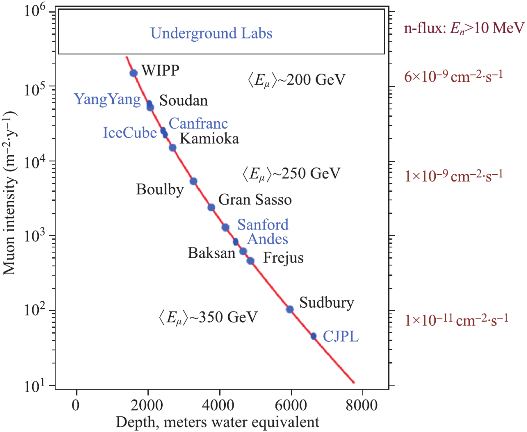
Backgrounds

Background suppression:

Deep underground

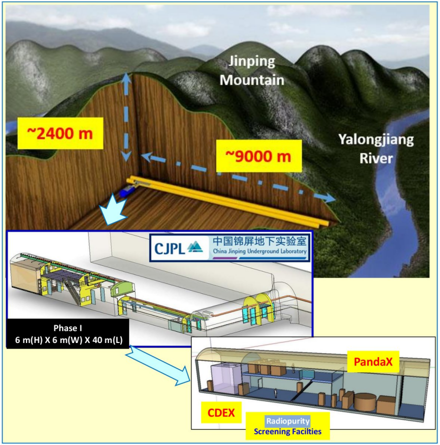
Shielded environments

- **Cosmogenic backgrounds:**
  - Cosmic rays and secondary reactions
  - Activation products in shields and detectors
- **Radiogenic backgrounds:**
  - External natural radioactivity: walls, structures of site, radon
  - Internal radioactivity: shield and construction materials, detector contamination in manufacture, naturally occurring radio-isotopes in target material



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

China JinPing Underground Laboratory (CJPL)

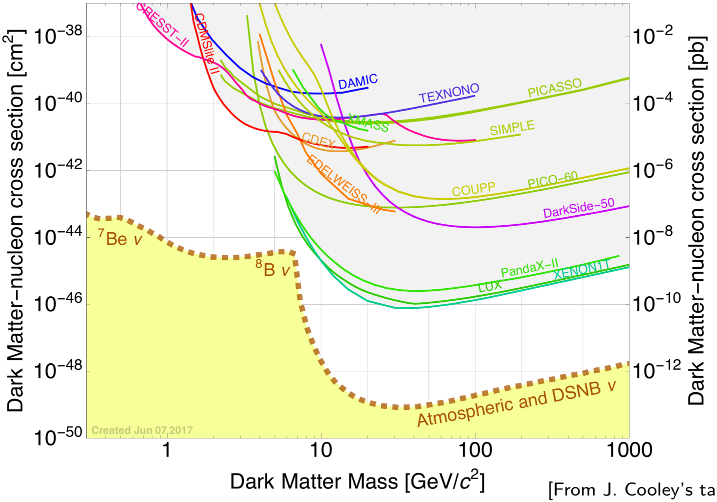


[Yue *et al.*, arXiv:1602.02462]

Experiments: CDEX, PandaX

Exclusion Limits for SI Scattering

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



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

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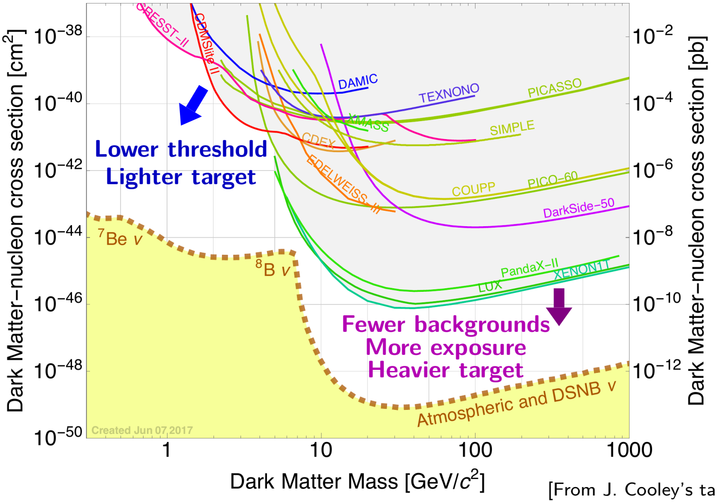
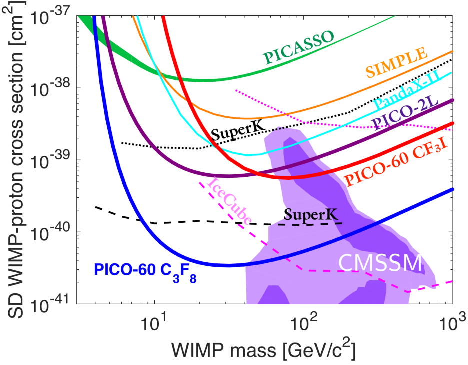


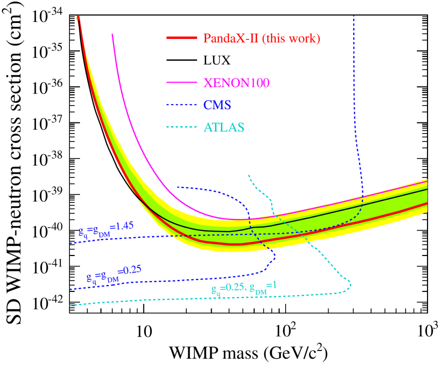
[From J. Cooley's talk (2017)]

Exclusion Limits for SD Scattering

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



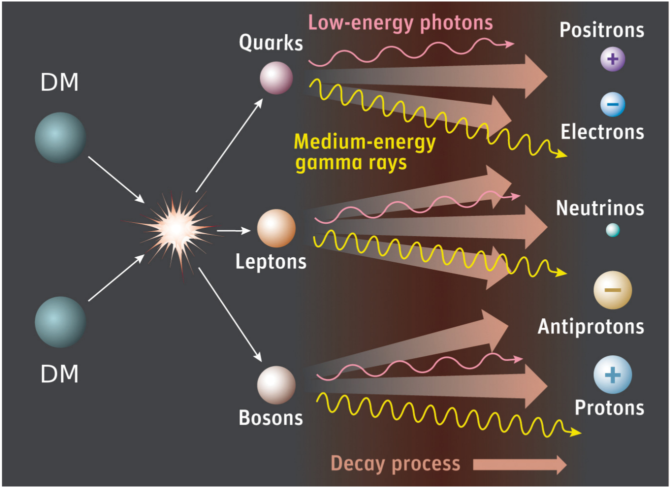
[PICO coll., arXiv:1702.07666, PRL]



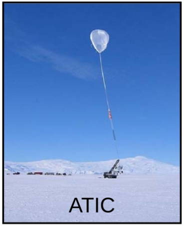
[PandaX-II coll., arXiv:1611.06553, PRL]

Indirect Detection

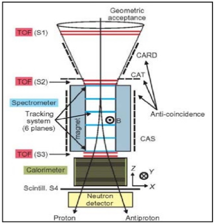
Indirect detection looks for stable products (γ **rays, cosmic rays, neutrinos**) from dark matter **annihilation** or **decay** (if DM is not totally stable) in space

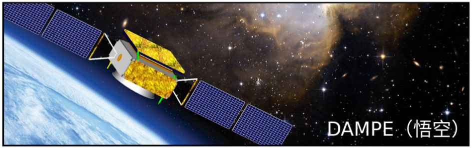


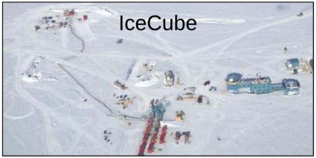
Indirect Detection Experiments



PAMELA





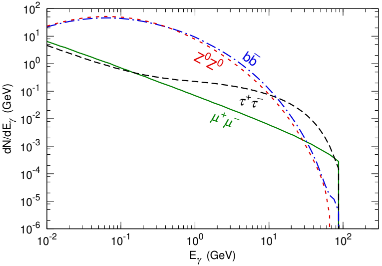


γ rays from DM: Continuous Spectrum

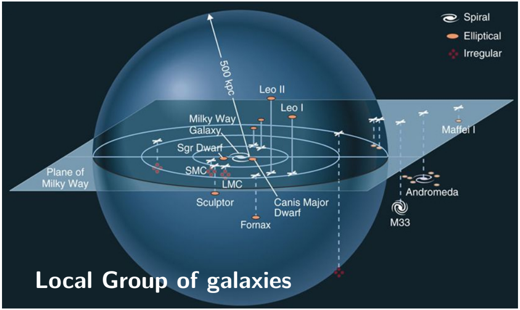
DM pair annihilation or decay into e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, W^+W^-, Z^0Z^0, h^0h^0

$\Downarrow$

γ-ray emission from final state radiation or particle decays

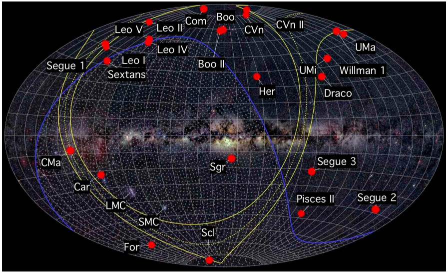


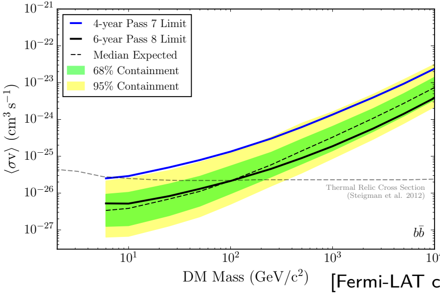
- **Cut-off energy**:
  m_χ for DM annihilation
  $m_\chi/2$ for DM decay
- More promising to look at **DM-dominated regions**:
  - Galactic Center
  - Galactic halo
  - dwarf galaxies
  - clusters of galaxies

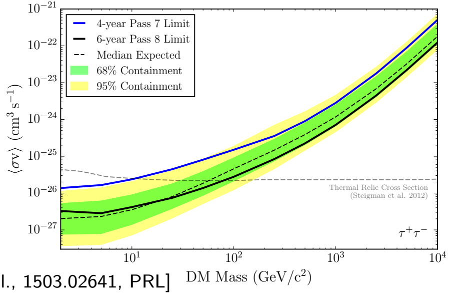


γ-ray Observation of Dwarf Galaxies

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







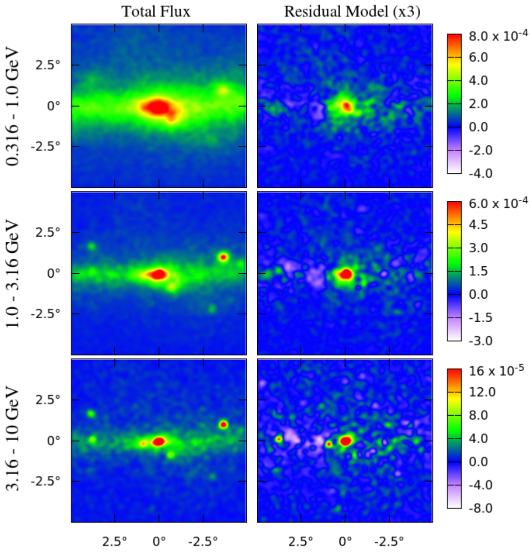
[Fermi-LAT coll., 1503.02641, PRL]

GeV Excess at the Galactic Center?

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

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

→



[Daylan et al., 1402.6703, PDU]

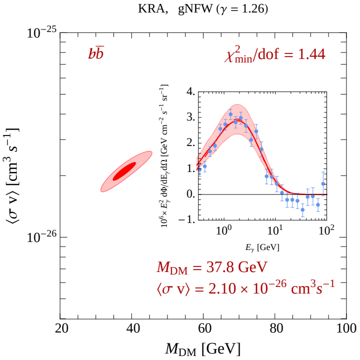
Interpretation with Dark Matter Annihilation

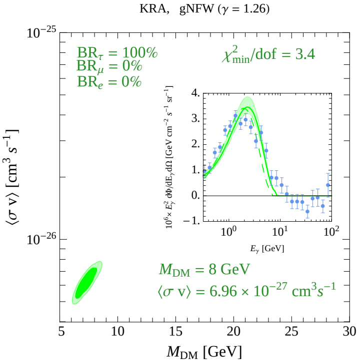
DM annihilation into $b\bar{b}$

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

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

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





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

γ rays from DM: Line Spectrum

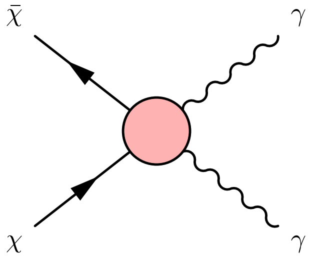
DM particles should **not have electric charge** and thus not directly couple to photons

$\Downarrow$

DM particles may couple to photons via high order loop diagrams

$\Downarrow$

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



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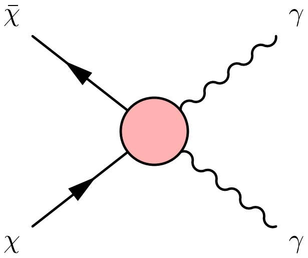


For **nonrelativistic** DM particles in space, the photons produced in $\chi\chi \to \gamma\gamma$ would be **mono-energetic**

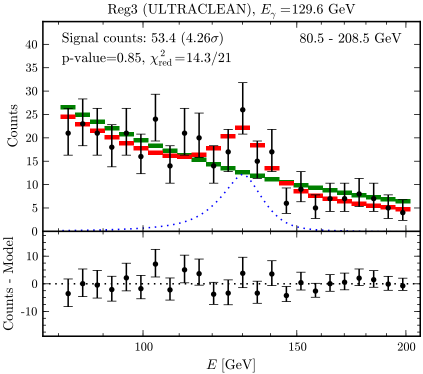
$\Downarrow$

A γ-ray line at energy $\sim m_\chi$

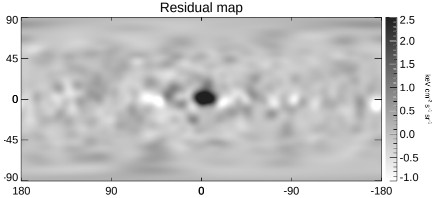
(**"smoking gun"** for DM particles)

A γ-ray Line Signal at the Galactic Center?

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



[Weniger, 1204.2797, JCAP]

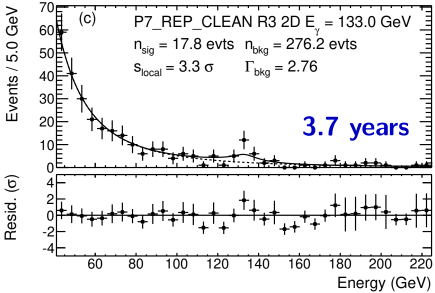


[Su & Finkbeiner, 1206.1616]

Fermi-LAT Official Results: Not Confirmed with More Data

- **3.7-year data**

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



[Fermi-LAT Coll., 1305.5597, PRD]

Fermi-LAT Official Results: Not Confirmed with More Data

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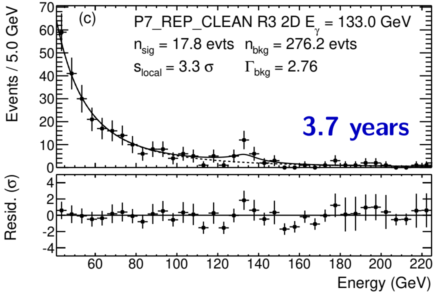
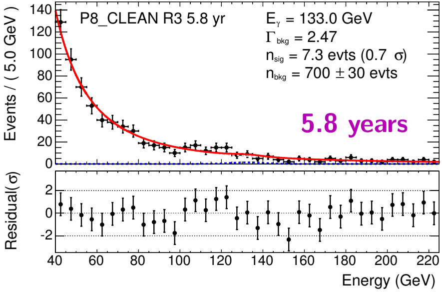
- **5.8-year data**

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



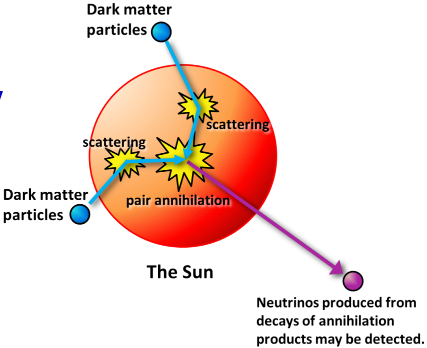
[Fermi-LAT Coll., 1305.5597, PRD]



[Fermi-LAT Coll., 1506.00013, PRD]

Neutrinos from DM

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



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

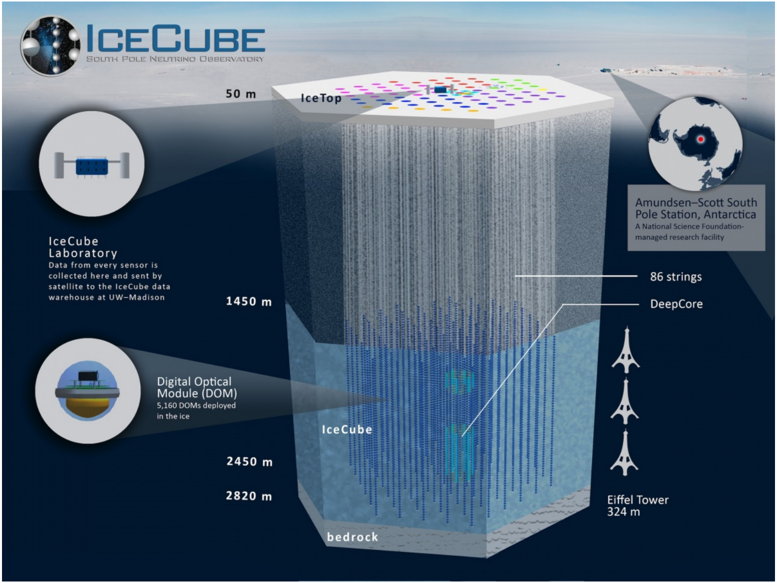
$$\frac{dN_\chi}{dt} = C_\odot(\sigma_{\chi\mathrm{H}}, \sigma_{\chi\mathrm{He}}) - A_\odot(\sigma_{\mathrm{ann}})N_\chi^2$$

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

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

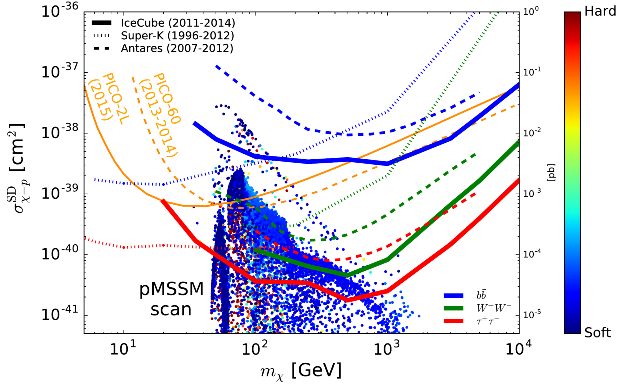
✨ The age of the Sun is long enough ($\sim$ 4.6 billion years) to make the capture and annihilation processes reach **equilibrium:** $dN_\chi/dt = 0$

IceCube: South Pole Neutrino Observatory



Searches for Neutrinos from DM Annihilation within the Sun

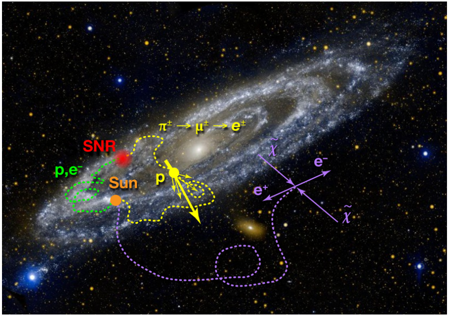
- **No signal detected** in searches for neutrinos with energies of GeV − TeV from DM annihilation at the solar core
- Assuming equilibrium in the capture and annihilation processes, the constraints can be converted to those on the **DM scattering cross section**

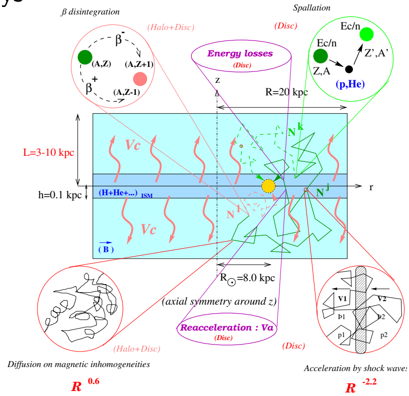


[IceCube Coll, 1612.05949, EPJC]

Cosmic Rays from DM

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

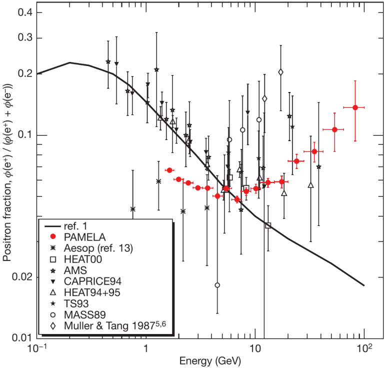




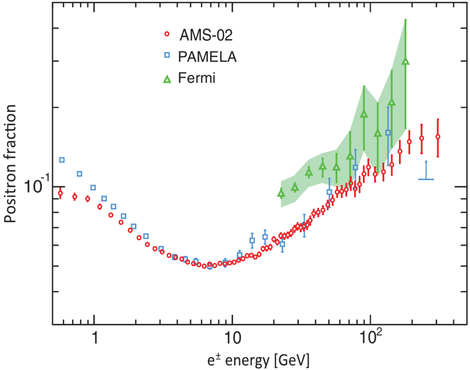
[Maurin *et al.*, astro-ph/0212111]

Cosmic-ray Positron Excess

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



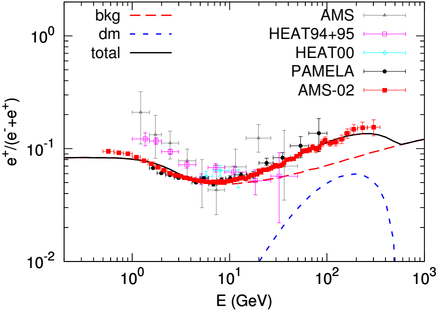
[PAMELA Coll., 0810.4995, Nature]



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

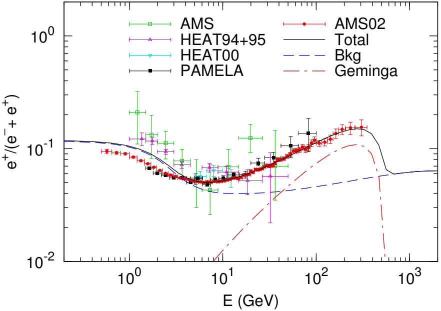
Interpretation: Dark Matter vs Pulsar

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



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

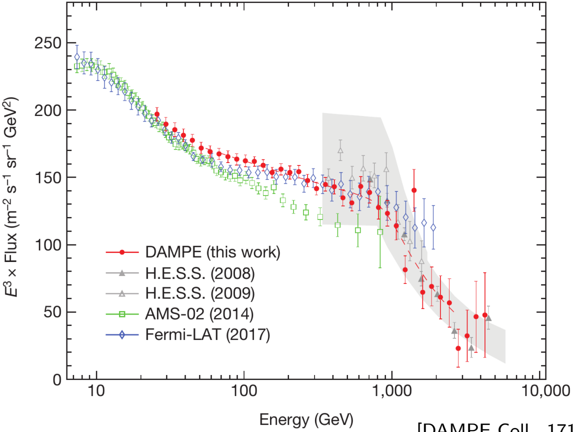
Interpretation with the **nearby pulsar Geminga**



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

First Result from DAMPE

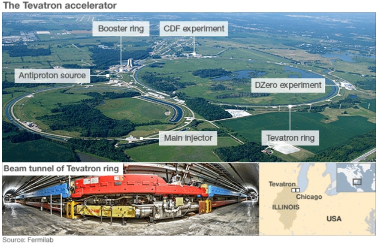
- In November 2017, **DAMPE (悟空)** collaboration released their first measurement of the cosmic-ray spectrum of **electrons and positrons**
- This measurement found a **spectral break** at ~ 0.9 TeV

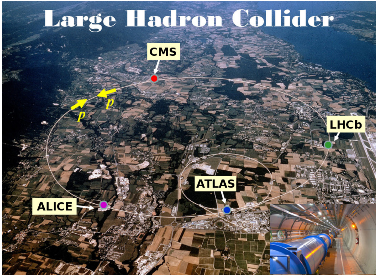


[DAMPE Coll., 1711.10981, Nature]

Past and Current High Energy Colliders

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





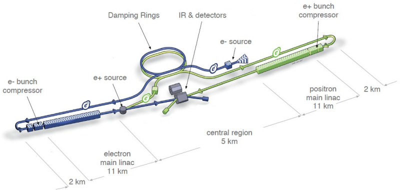
Future Projects

- **ILC**: International Linear Collider

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

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

  Detectors: SiD, ILD



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

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

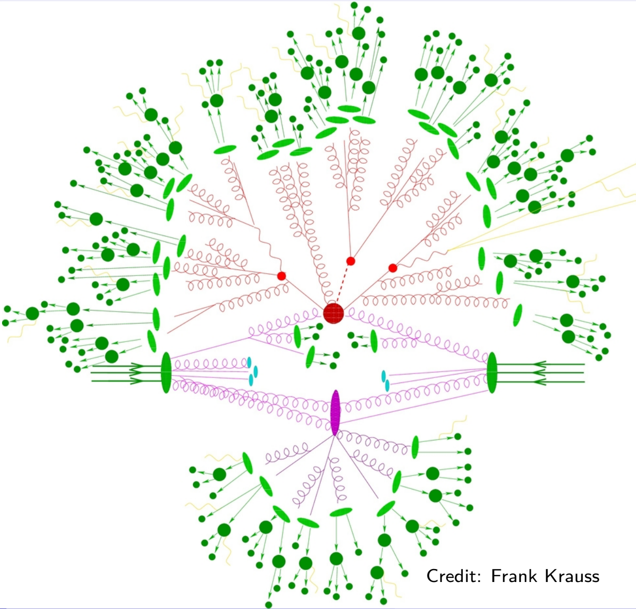
- **SPPC**: Super Proton-Proton Collider (China)

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

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

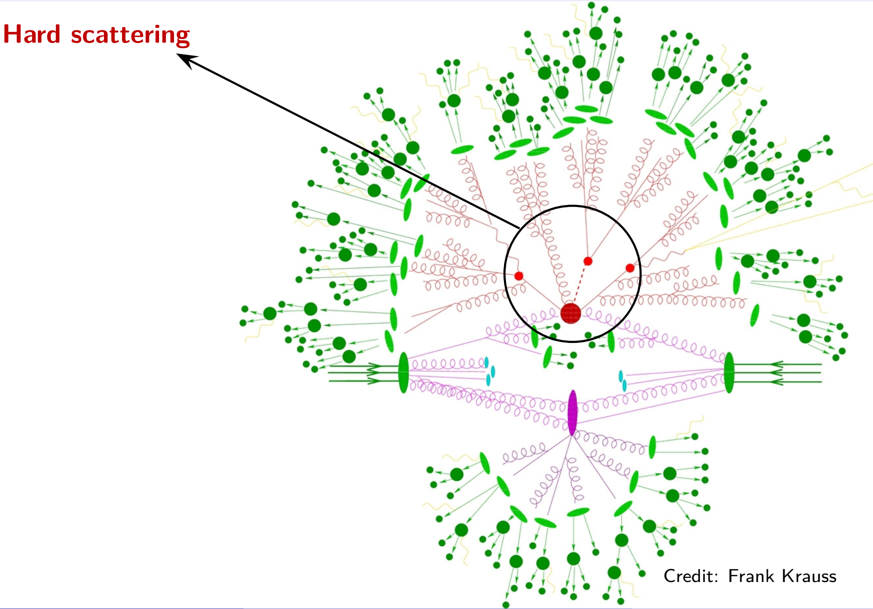
- **CLIC**: Compact Linear Collider, $\sqrt{s} \sim 1 - 3$ TeV, $\mathcal{L} \sim 6 \times 10^{34}$ cm^{-2} s^{-1}

Typical Event in High Energy pp Collisions



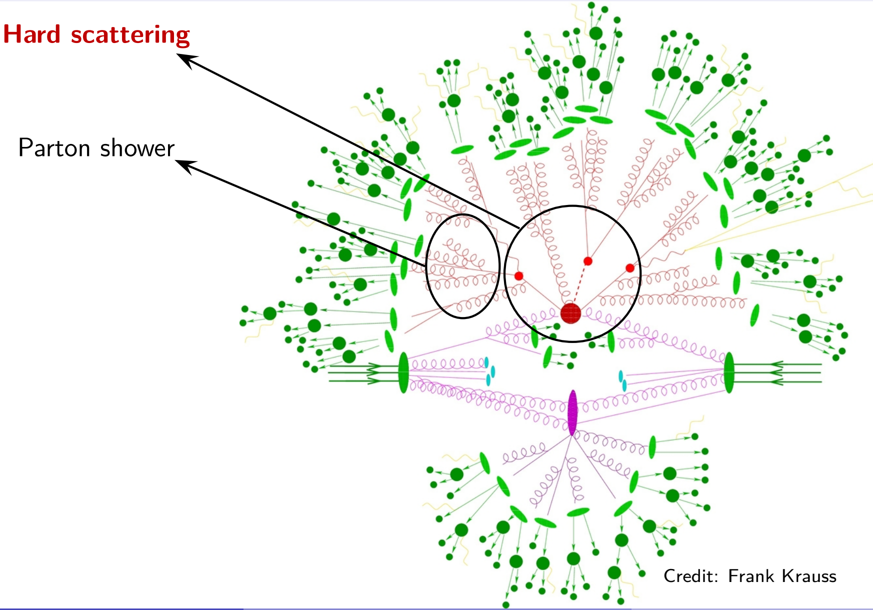
Credit: Frank Krauss

Typical Event in High Energy pp Collisions



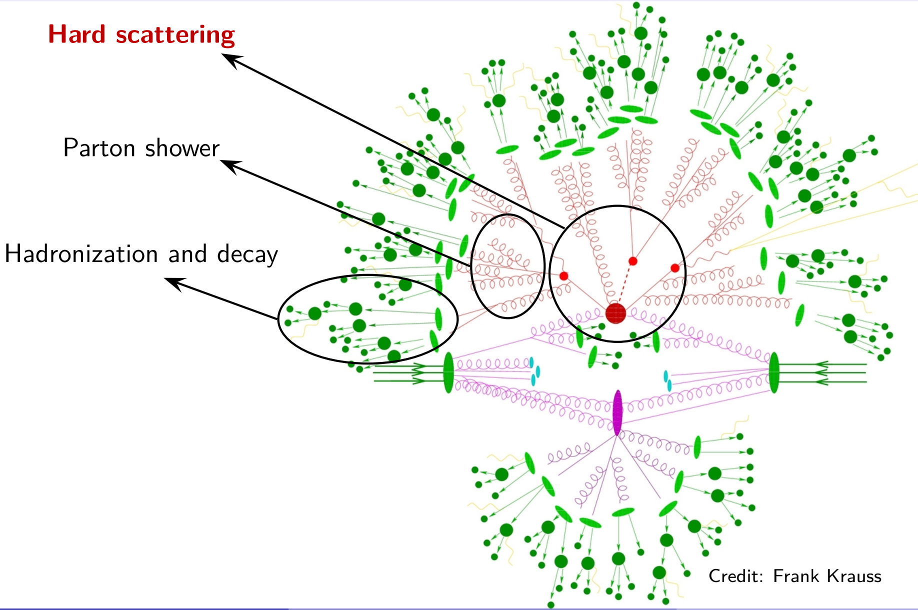
Credit: Frank Krauss

Typical Event in High Energy pp Collisions



Credit: Frank Krauss

Typical Event in High Energy pp Collisions



Credit: Frank Krauss

Typical Event in High Energy pp Collisions

Hard scattering

Parton shower

Hadronization and decay

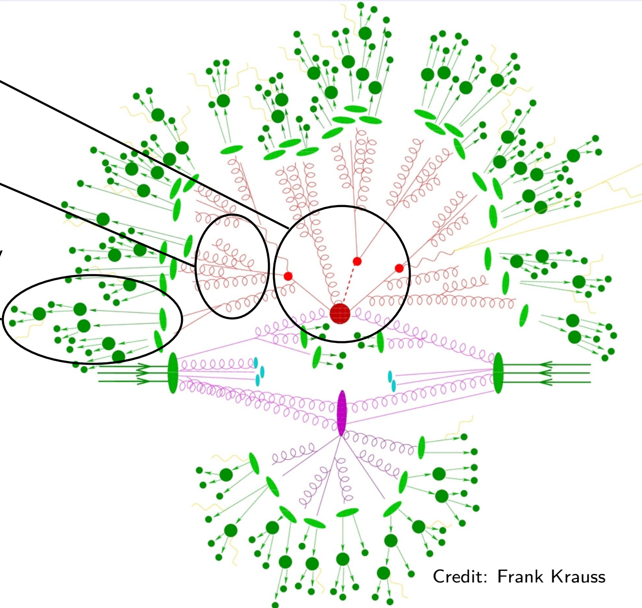
Collimated particles

⇓

Jet

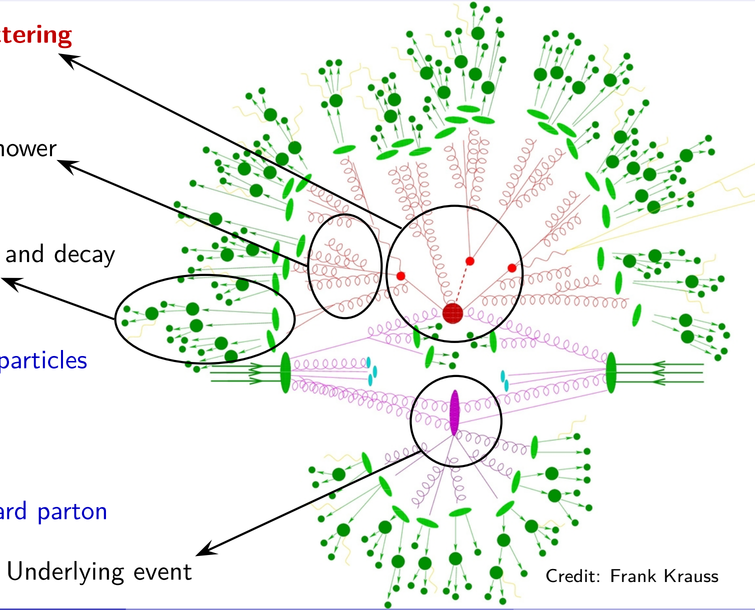
⇓

Mimic to a hard parton



Credit: Frank Krauss

Typical Event in High Energy pp Collisions



Collimated particles

⇓

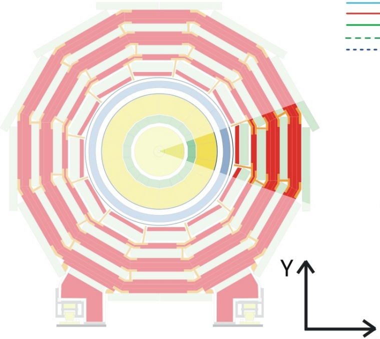
Jet

⇓

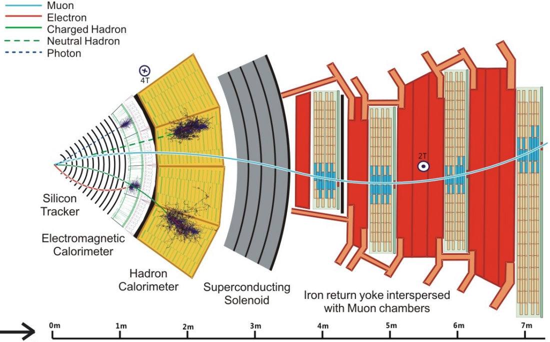
Mimic to a hard parton

Credit: Frank Krauss

Particle Detectors at Colliders

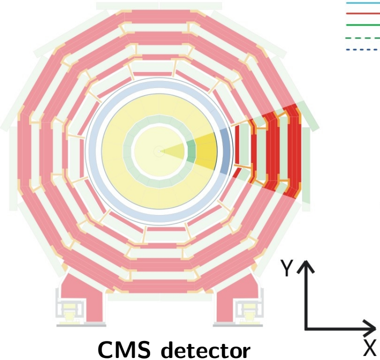


CMS detector

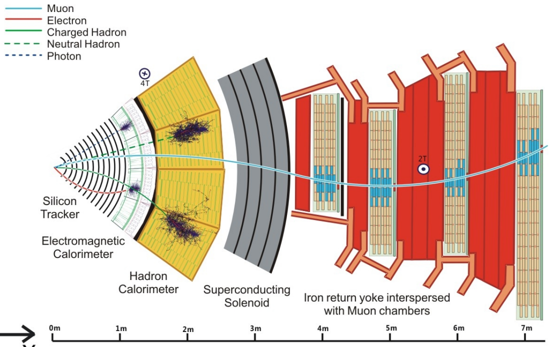


Sub-detectors	γ	$e^\pm$	$\mu^\pm$	Charged hadrons	Neutral hadrons	ν, DM
Tracker, $\lvert\eta\rvert \lesssim 2.5$	$\times$	$\surd$	$\surd$	$\surd$	$\times$	$\times$
ECAL, $\lvert\eta\rvert \lesssim 3$			$\surd$	$\surd$	$\times$	$\times$
HCAL, $\lvert\eta\rvert \lesssim 5$	$\times$	$\times$	$\times$		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

Particle Detectors at Colliders



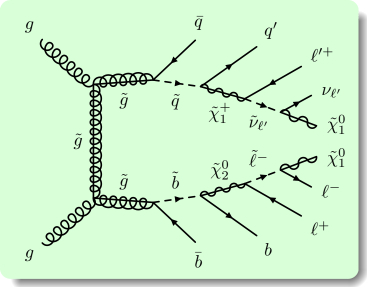
CMS detector



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

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

DM Production



Social dark matter

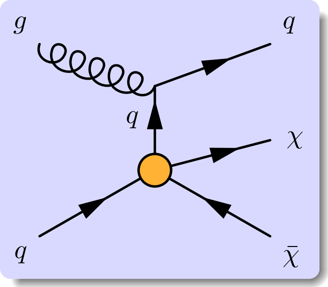
Accompanied by other new particles

Complicated decay chains

Decay products of other particles

Various final states

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



Maverick dark matter

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

Direct production

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

(monojet, mono-γ, mono-W/Z, ...)

[From Rocky Kolb's talk]

τ-portal Simplified DM Models

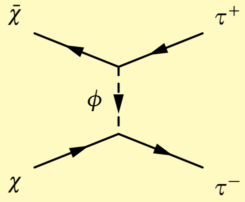
- We studied four **τ-portal simplified models** involving a mediator with additive quantum numbers identical to the right-handed τ^-
- We interpreted the **GC GeV excess signal** as DM annihilation into $\tau^+\tau^-$, and discussed **how to test this interpretation at the LHC**
- **Spin-1/2 fermion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

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

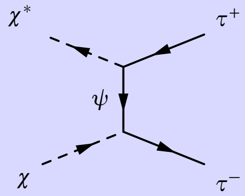
  - **DFDM model:** χ is a Dirac fermion
  - **MFDM model:** χ is a Majorana fermion
- **Spin-0 scalar χ, spin-1/2 mediator ψ:**

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

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



DFDM: annihilation



CSDM: annihilation

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

DFDM model:

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

MFDM model:

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

CSDM model:

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

RSDM model:

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

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

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

DFDM model:

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

MFDM model: **Helicity suppression**

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

CSDM model: **Helicity suppression**

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

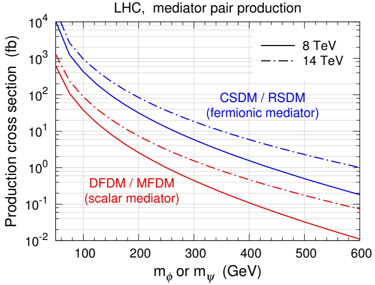
RSDM model: **Helicity suppression**

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

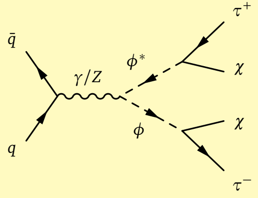
$$\left(\beta_\tau \equiv \sqrt{1 - m_\tau^2/m_\chi^2};\quad m_\tau \ll m_\chi \ll m_\phi, m_\psi\ \text{approximation}\right)$$

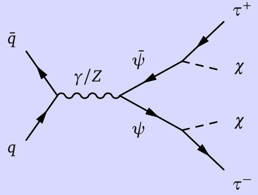
Mediator Pair Production at the LHC

- 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

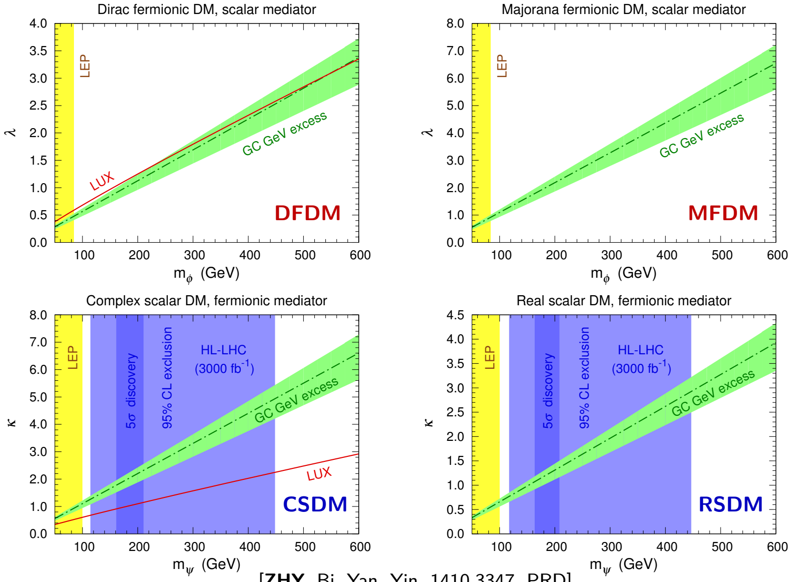


[**ZHY**, Bi, Yan, Yin, 1410.3347, PRD]





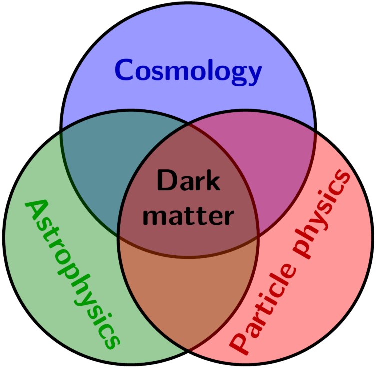
Sensitivity of the 14 TeV High-Luminosity LHC



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

Summary

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



Summary

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Thank you!