

Introduction to Dark Matter

Zhao-Huan Yu (余钊煥)

School of Physics, Sun Yat-Sen University

<http://yzhxxzxy.github.io>



Guangzhou University, Guangzhou
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Dark Matter in the Universe

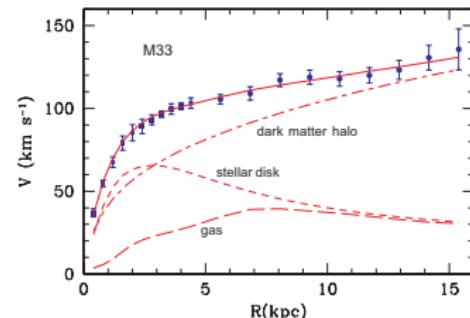
Dark matter (DM) makes up most of the matter component in the Universe, as suggested by astrophysical and cosmological observations



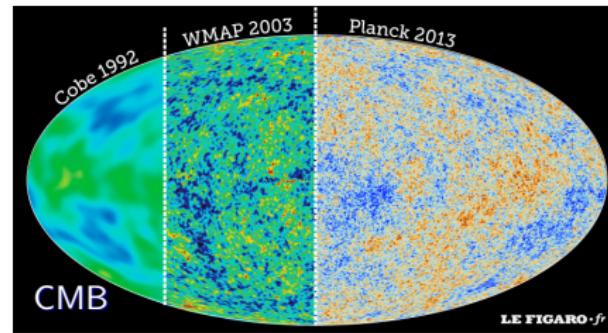
Bullet Cluster



Spiral galaxy M33



Cluster Abell 2218



Dark Matter

○●○○○○○○○○○○○○○○○○

Direct Detection

A horizontal row of 15 small circles, evenly spaced, used as a decorative element.

Indirect Detection

Collider Searches

○○○○○○○○○○

Coma Cluster (后发座星系团)



Dark Matter

○●○○○○○○○○○○○○○○○○

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Indirect Detection

Collider Searches

oooooooooooo

Coma Cluster (后发座星系团)



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Coma Cluster



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

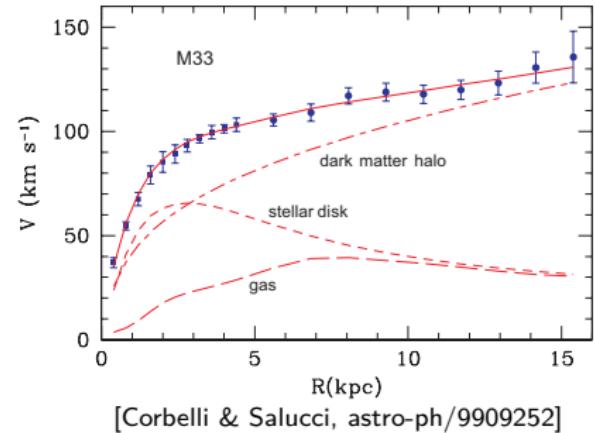
Mass-to-light ratio $\Upsilon_{\text{Coma}} \sim 260\Upsilon_\odot$
 [Kent & Gunn, 1982]

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

Spiral Galaxies: Rotation Curves



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



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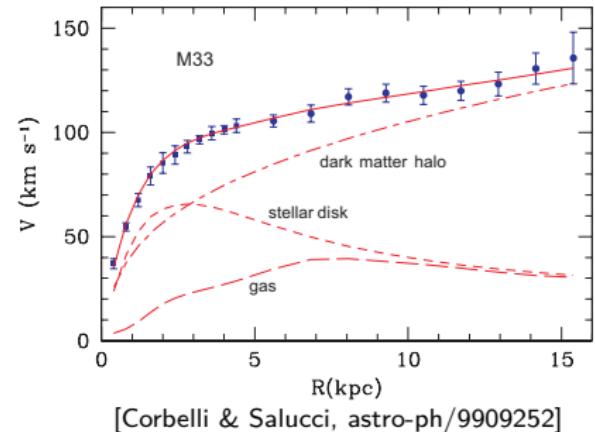


According to [Newton's law](#), the relation between the rotation velocity v and the mass $M(r)$ within radius r should be

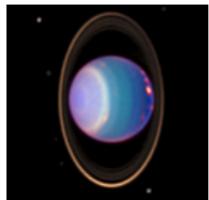
$$\frac{v^2}{r} = \frac{G_N M(r)}{r^2}$$

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

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

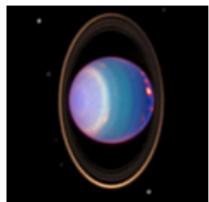


How Can We Explain an Anomalous Phenomenon?

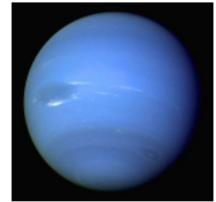


Unexpected movement of **Uranus**

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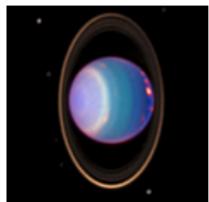


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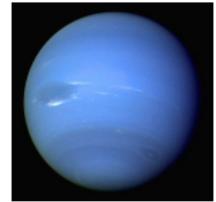


Perturbed by **Neptune** (discovered in 1846)

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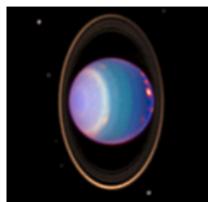


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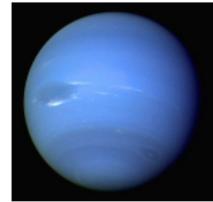


Search for new objects/substances responsible for it!

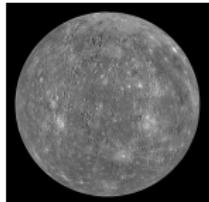
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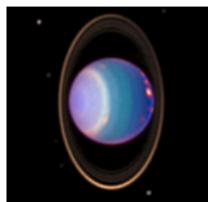


Anomalous perihelion precession of **Mercury**

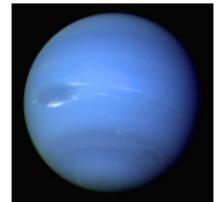


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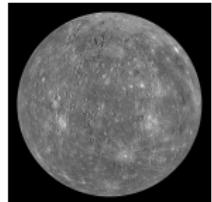
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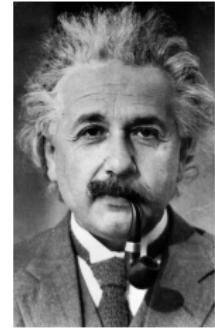
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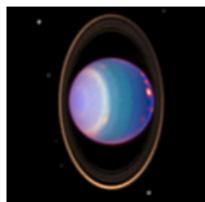
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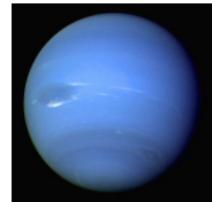
↓

Update Newtonian mechanics to **general relativity**

How Can We Explain an Anomalous Phenomenon?



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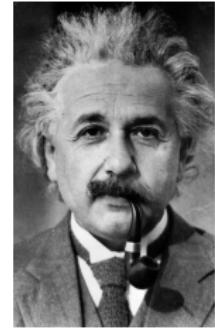
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Update Newtonian mechanics to **general relativity**



Modify known physical laws!

How about the Anomalous Phenomena Here?



Modify physical laws \Rightarrow 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 \Rightarrow **MAssive Compact Halo Objects (MACHOs)**

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

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

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

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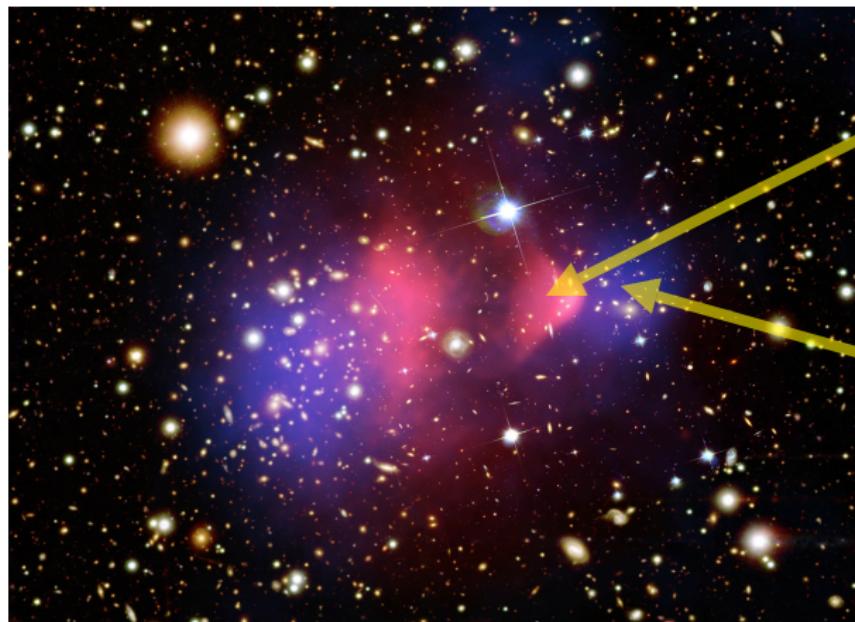
[EROS-2 coll., astro-ph/0607207]



Consider new substances \Rightarrow **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]

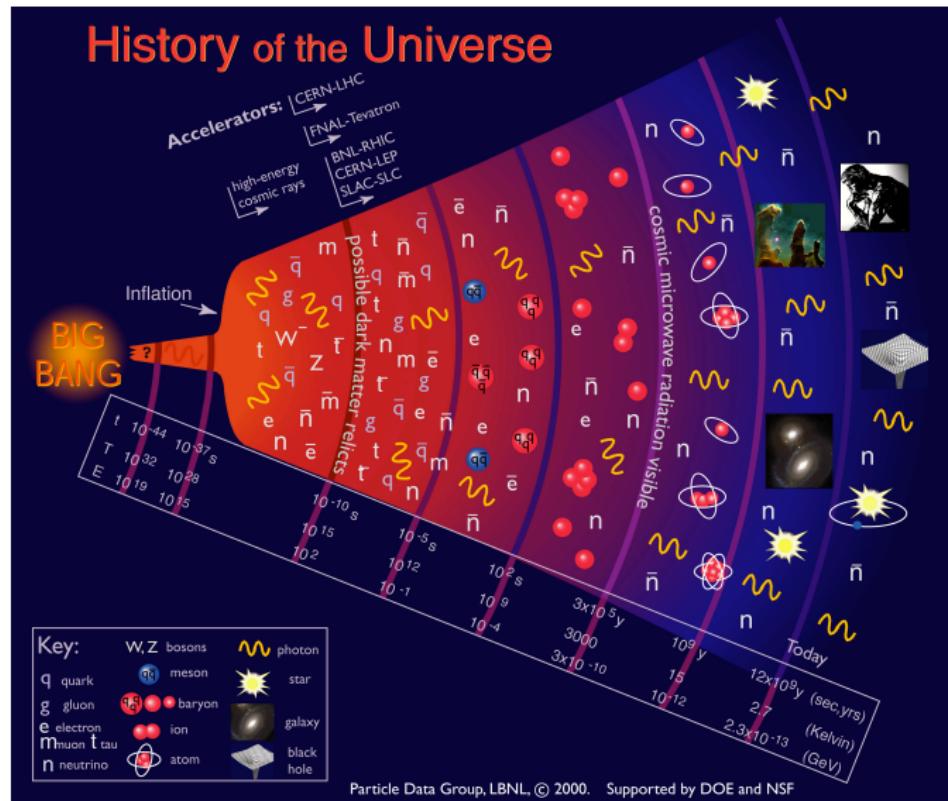
Big Bang Cosmology

~ 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

⇒ structure forms hierarchically (bottom-up)

Galaxies are older than clusters ⇒ Favors **cold dark matter theory**

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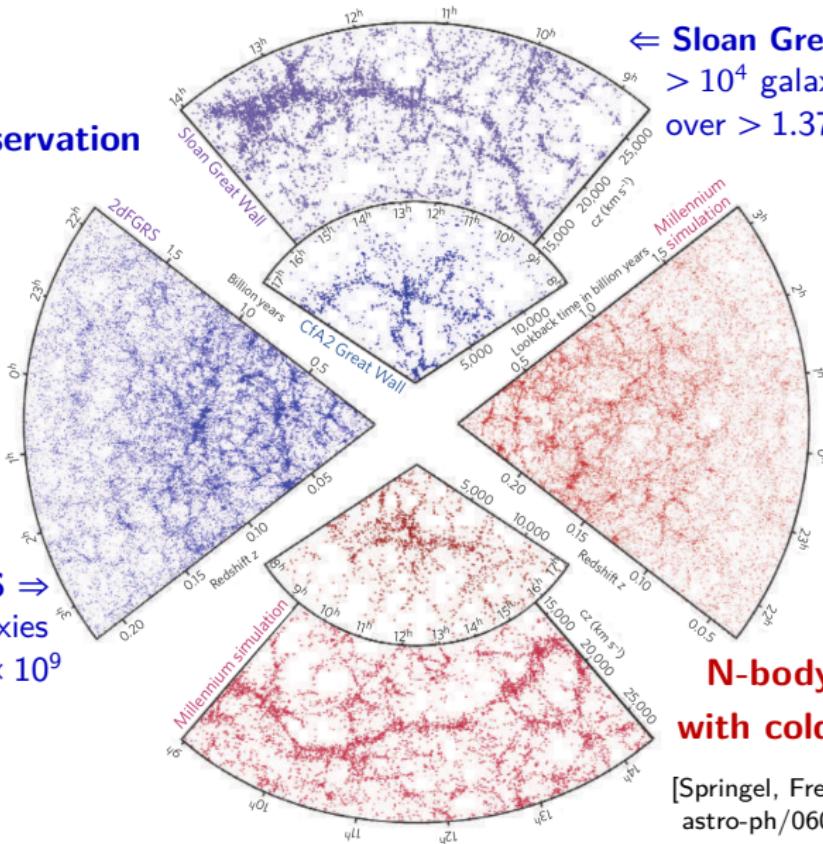
Galaxies are older than clusters ⇒ **Favors cold dark matter theory**

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



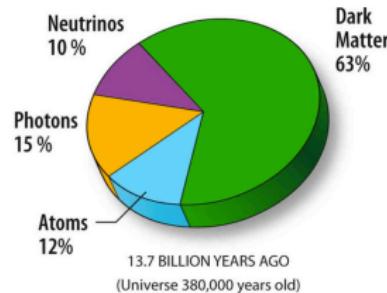
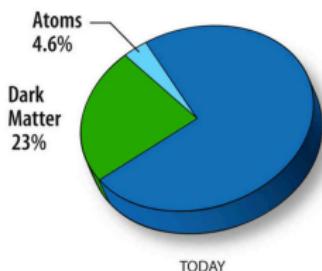
Standard Cosmology: Λ CDM Model

Λ CDM: the standard cosmological model

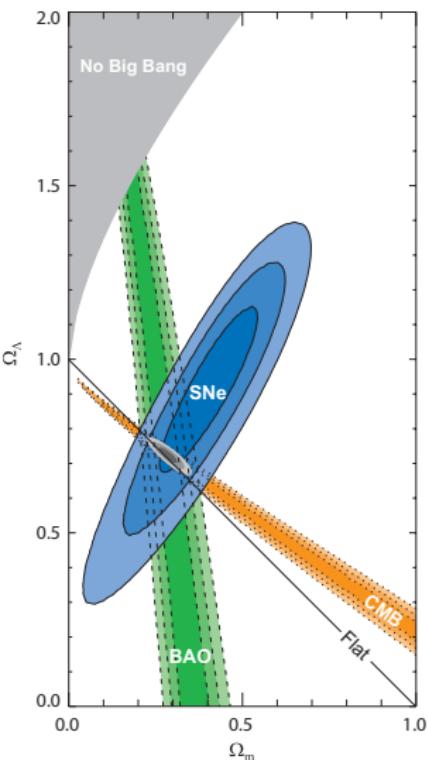
- **Cosmological constant Λ** (dark energy)
- **Cold dark matter** (CDM)

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

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



[WMAP Science Team]



[Kowalski et al., 0804.4142]

Cosmic Microwave Background (CMB)

$t \sim 380\,000$ yr, $T \sim 3000$ K

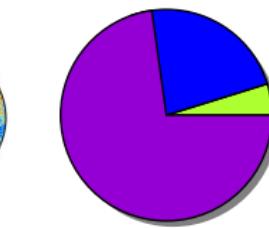
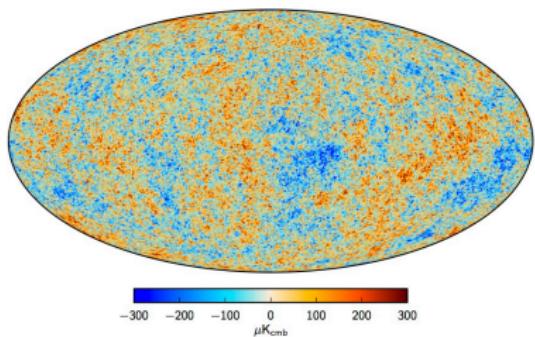
Electrons + Protons \rightarrow Hydrogen Atoms

Photons decoupled

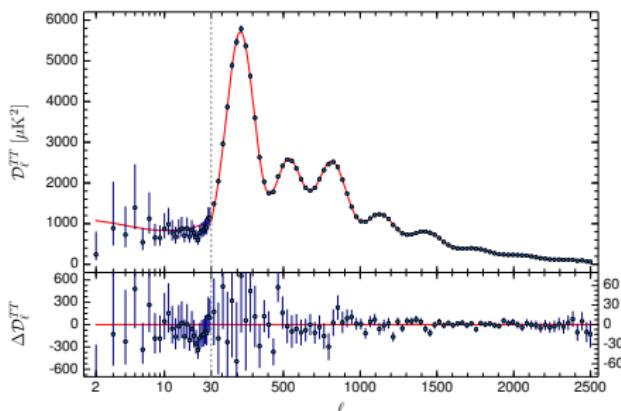
cools \downarrow down

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%)

$$\Omega_c h^2 = 0.1186 \pm 0.0020$$

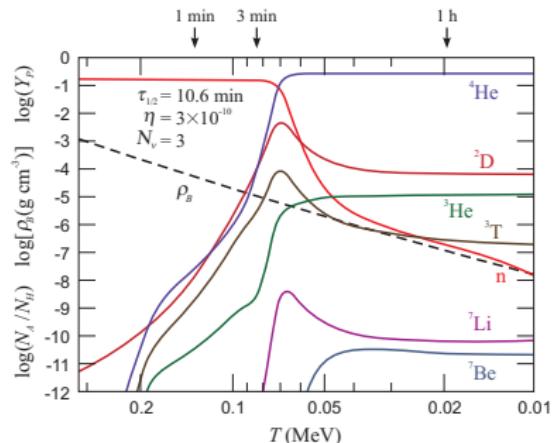
Baryons (4.8%)

$$\Omega_b h^2 = 0.02226 \pm 0.00023$$

Dark energy (69.3%)

$$\Omega_\Lambda = 0.692 \pm 0.012$$

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



[Kolb & Turner, *The Early Universe*]

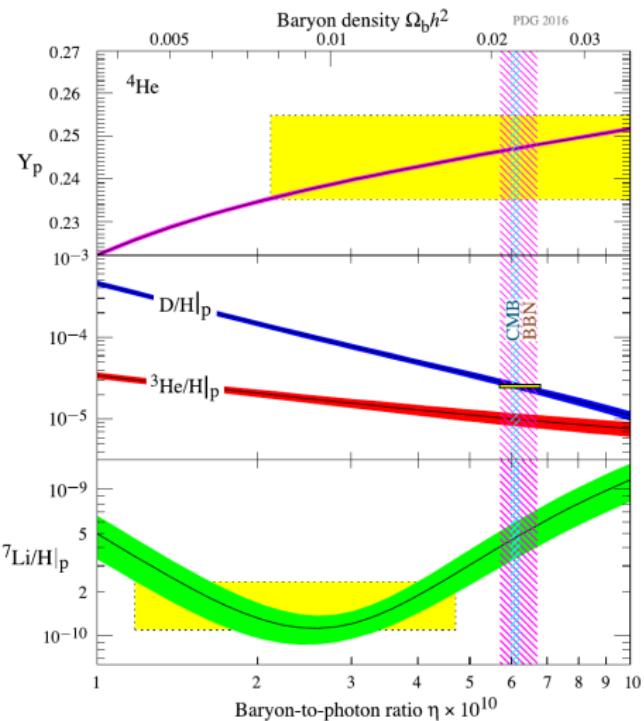
Primordial abundances of light elements



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



The majority of matter is **nonbaryonic**



[PDG 2016]

Inferred Properties of Dark Matter

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

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

Standard Model (SM) of Particle Physics

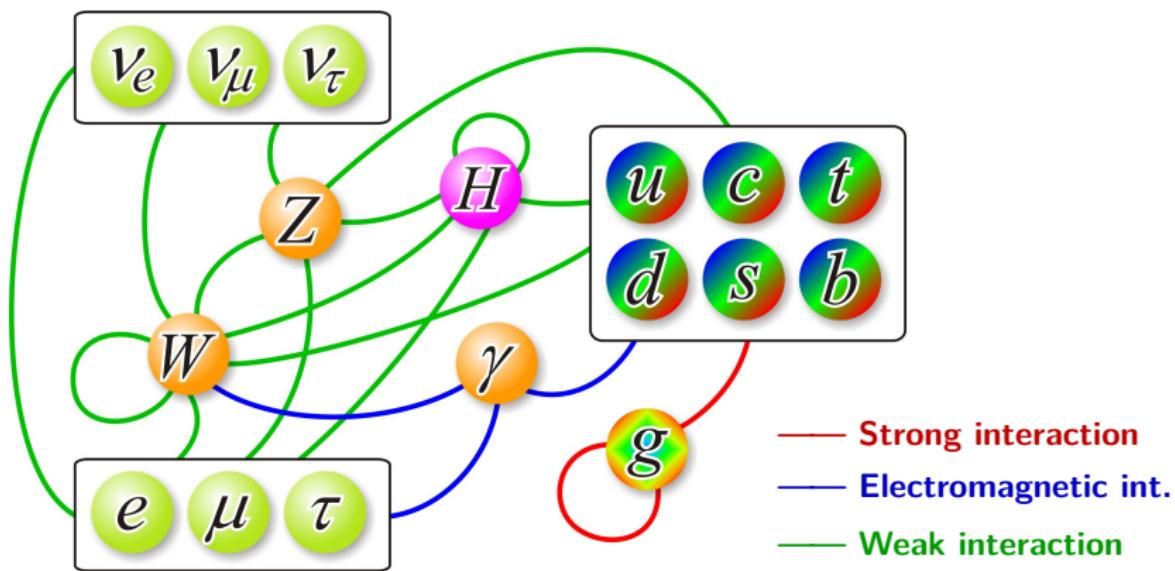
$SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry

↓ Englert-Brout-Higgs mechanism

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

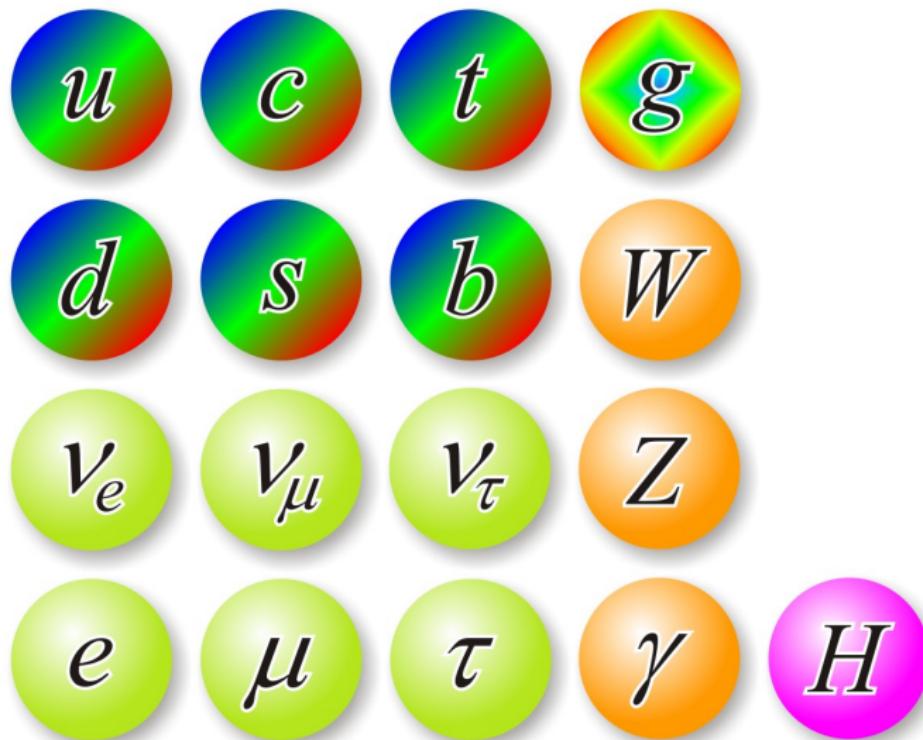
Fermion masses

Higgs boson

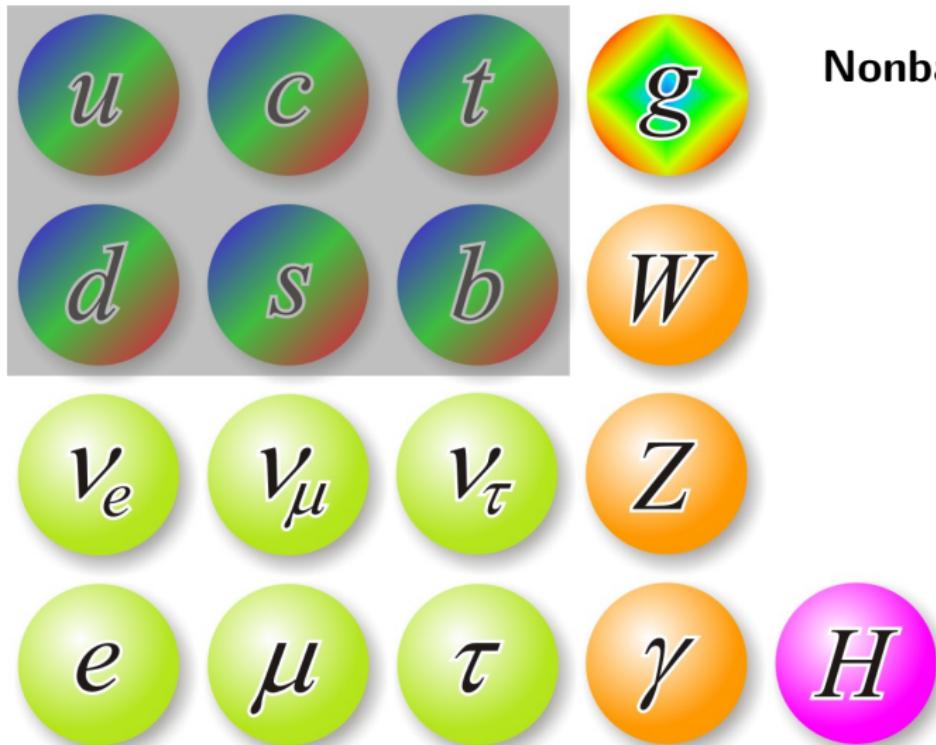


- Strong interaction
- Electromagnetic int.
- Weak interaction

Are There Dark Matter Candidates in the Standard Model?

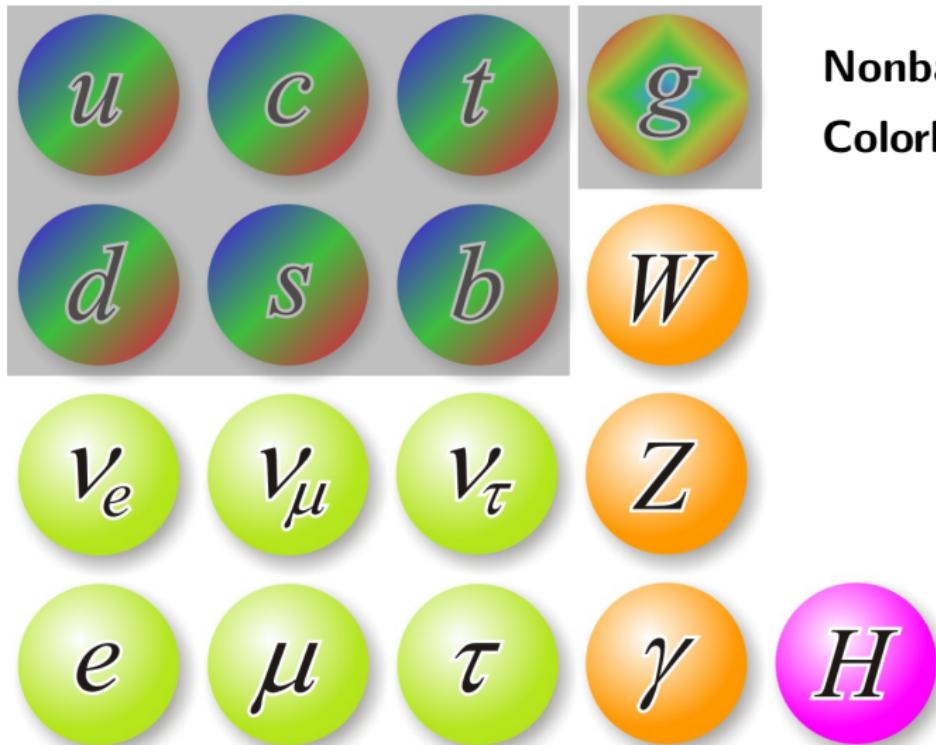


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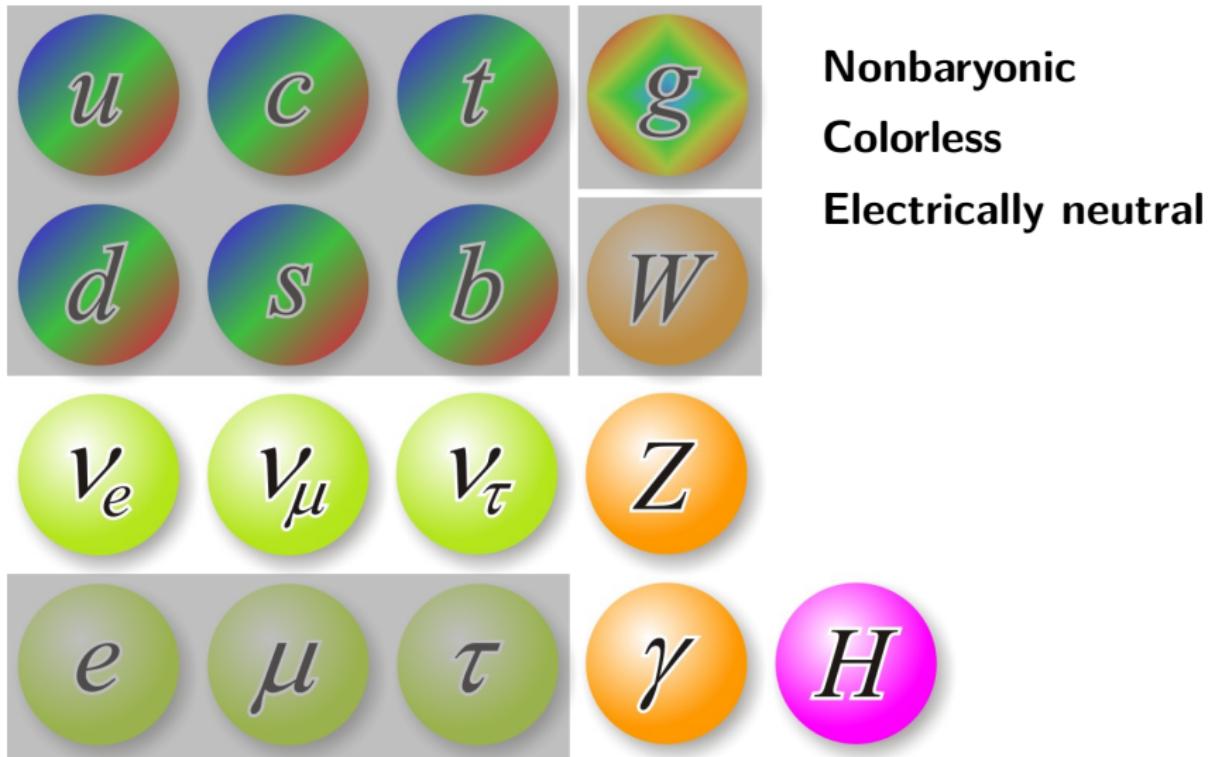
Nonbaryonic

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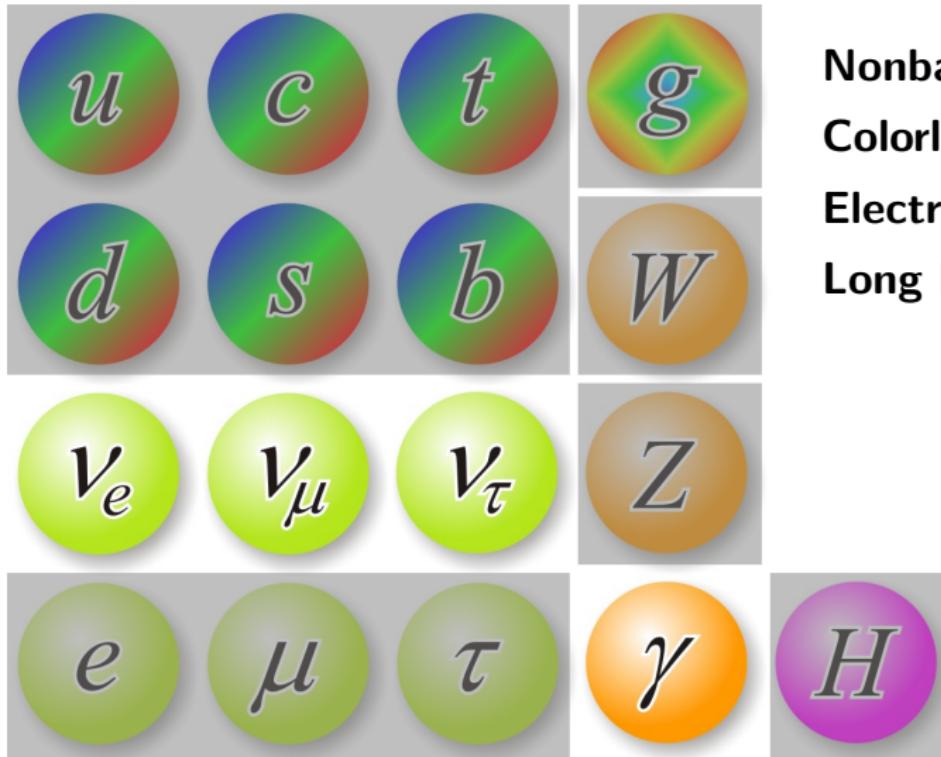


Nonbaryonic
Colorless

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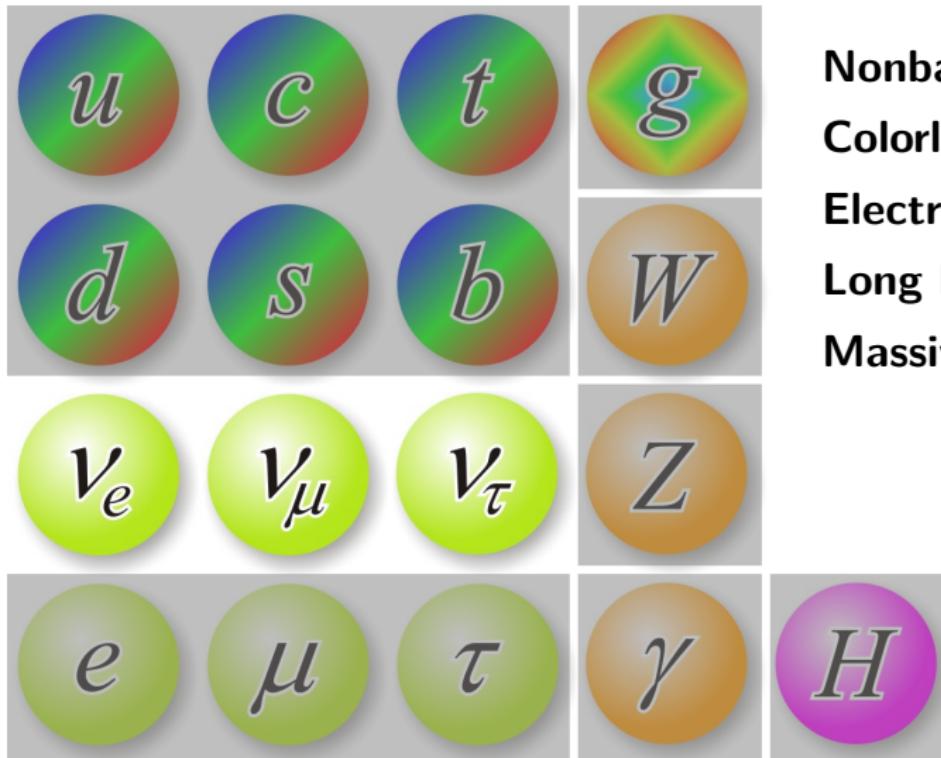


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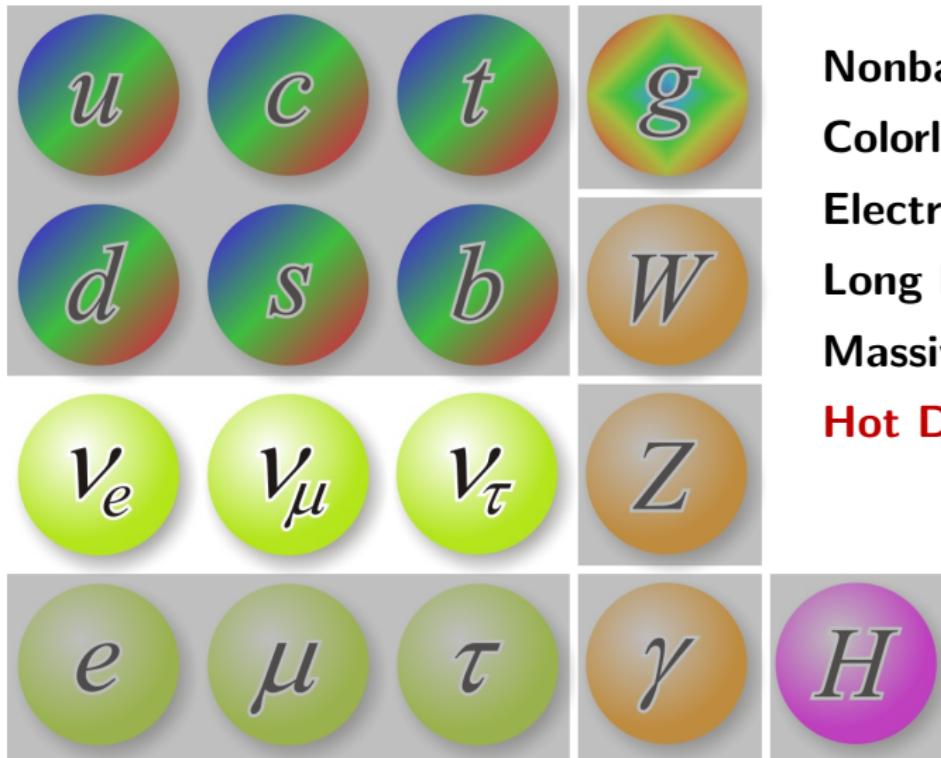
**Nonbaryonic
Colorless
Electrically neutral
Long lived**

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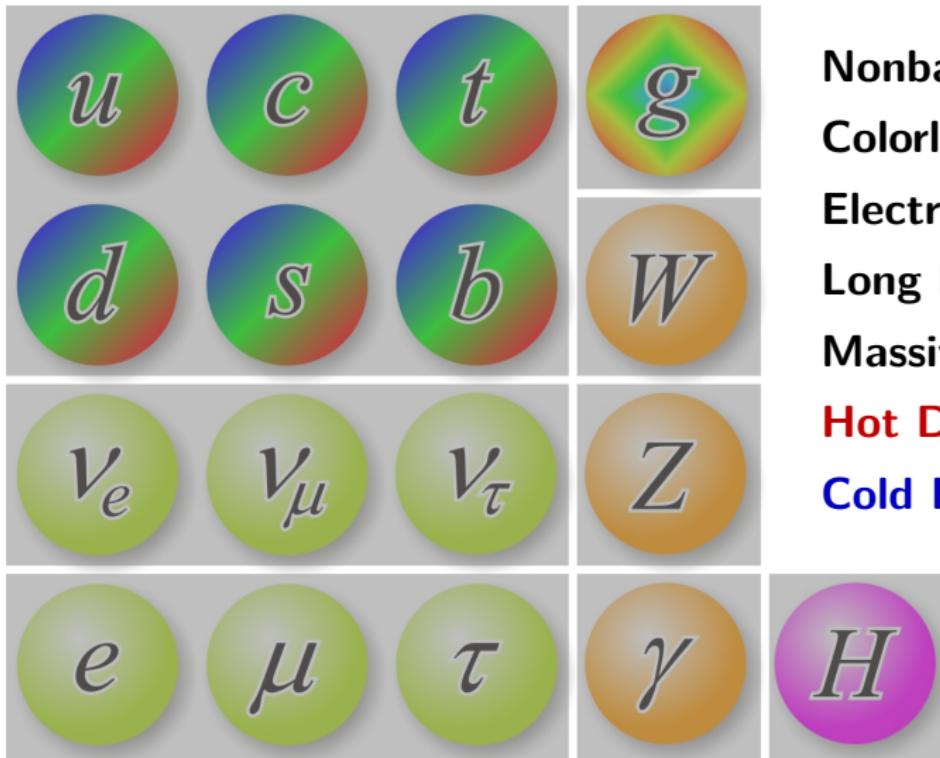


**Nonbaryonic
Colorless
Electrically neutral
Long lived
Massive**

Are There Dark Matter Candidates in the Standard Model?



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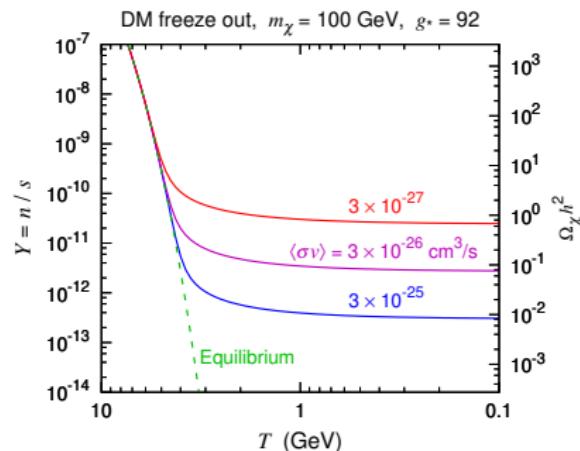
DM Relic Abundance

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

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

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

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



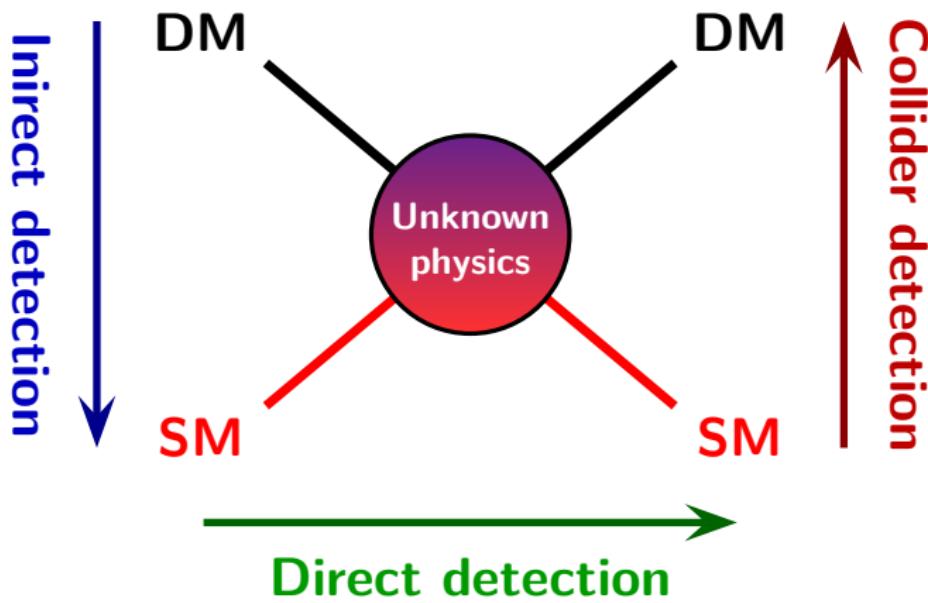
Assuming the annihilation process consists of two weak interaction vertices with the $SU(2)_L$ gauge coupling $g \simeq 0.64$, for $m_\chi \sim \mathcal{O}(\text{TeV})$ we have

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

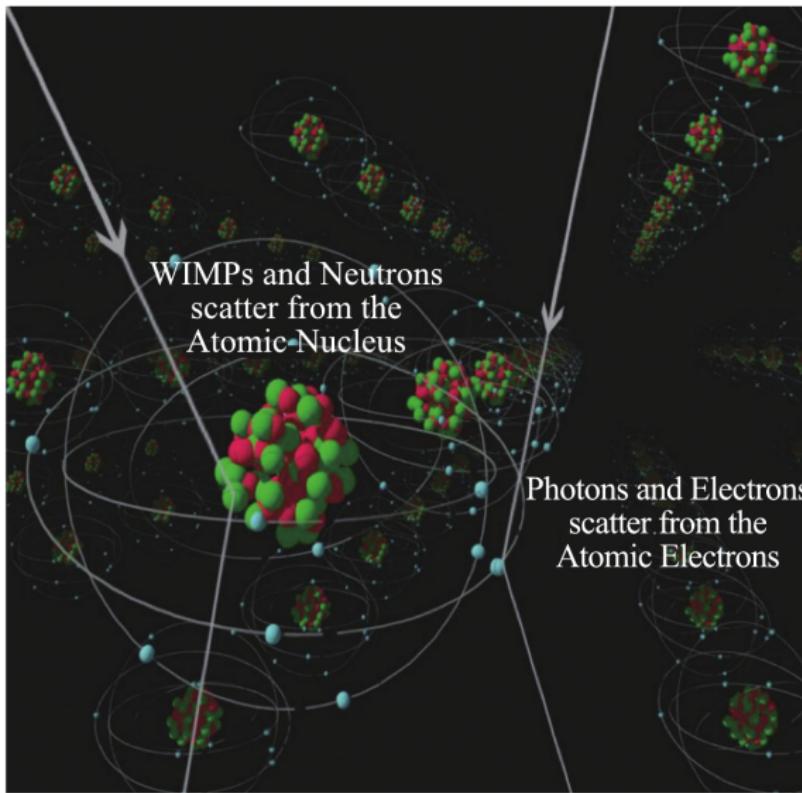
\Rightarrow A very attractive class of DM candidates:

Weakly interacting massive particles (WIMPs)

Experimental Approaches to Dark Matter

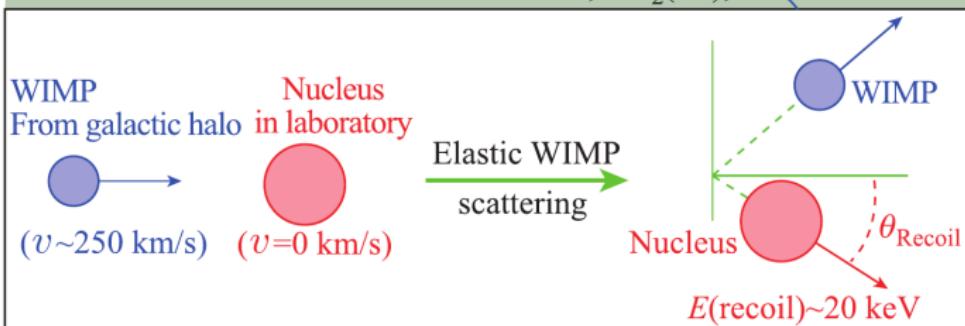
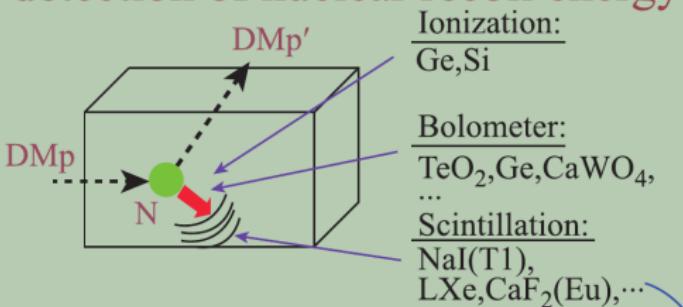


WIMP Scattering off Atomic Nuclei



Direct Detection

- Scatterings on nuclei
→ detection of nuclear recoil energy



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

WIMP Velocity Distribution

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

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

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

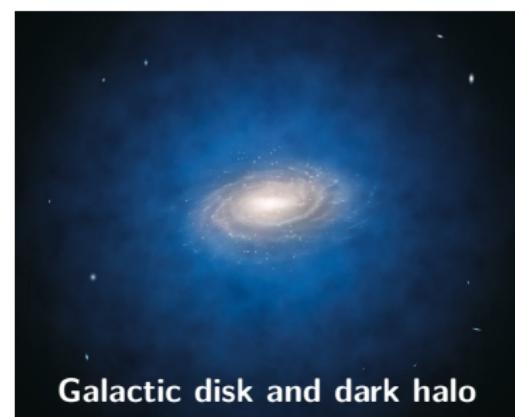
Speed distribution: $\tilde{f}(\tilde{v})d\tilde{v} = \frac{4\tilde{v}^2}{\sqrt{\pi}v_0^3} e^{-\tilde{v}^2/v_0^2} d\tilde{v}$

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]

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



Galactic disk and dark halo

[Credit: ESO/L. Calçada]

Earth Rest Frame

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

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

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

Speed distribution:

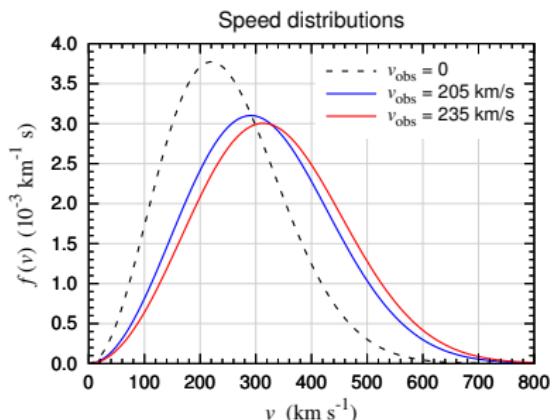
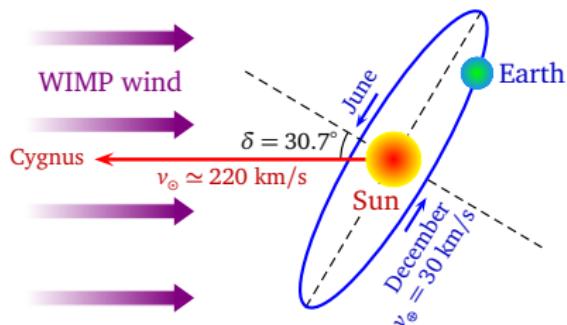
$$f(v)dv = \frac{4v^2}{\sqrt{\pi}v_0^3} \exp\left(-\frac{v^2 + v_{\text{obs}}^2}{v_0^2}\right) \times \frac{\tilde{v}_0^2}{2vv_{\text{obs}}} \sinh\left(\frac{2vv_{\text{obs}}}{v_0^2}\right) dv$$

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

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

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

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



Event Rate

Event rate per unit time per unit energy interval:

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

Astrophysics factors
Particle physics factors
Detector factors

N_A : target nucleus number

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

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

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

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

Maximal velocity v_{\max} : determined by the DM escape velocity v_{esc}

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

Cross Section Dependence on Nucleus Spin

There are two kinds of DM-nucleus scattering

Spin-independent (SI) cross section: $\sigma_{\chi A}^{\text{SI}} \propto \mu_{\chi A}^2 [ZG_p + (A-Z)G_n]^2$

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

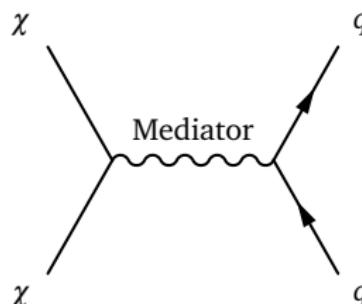
Nucleus properties: mass number A , atomic number Z , spin J_A ,
expectation value of the proton (neutron) spin content in the nucleus S_p^A (S_n^A)

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

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

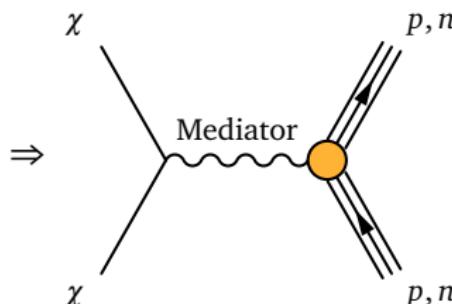
Three Levels of Interaction

DM-parton interaction



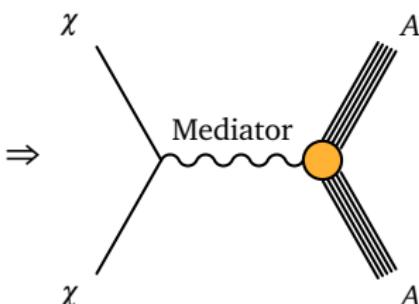
$$\mathcal{M}(\chi q \rightarrow \chi q)$$

DM-nucleon interaction



$$\mathcal{M}(\chi N \rightarrow \chi N)$$

DM-nucleus interaction

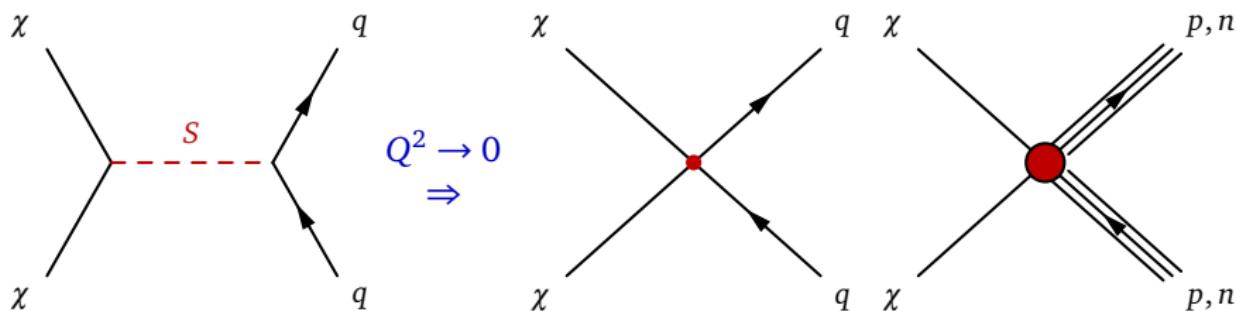


$$\mathcal{M}(\chi A \rightarrow \chi A)$$

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

Zero Momentum Transfer Limit

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



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

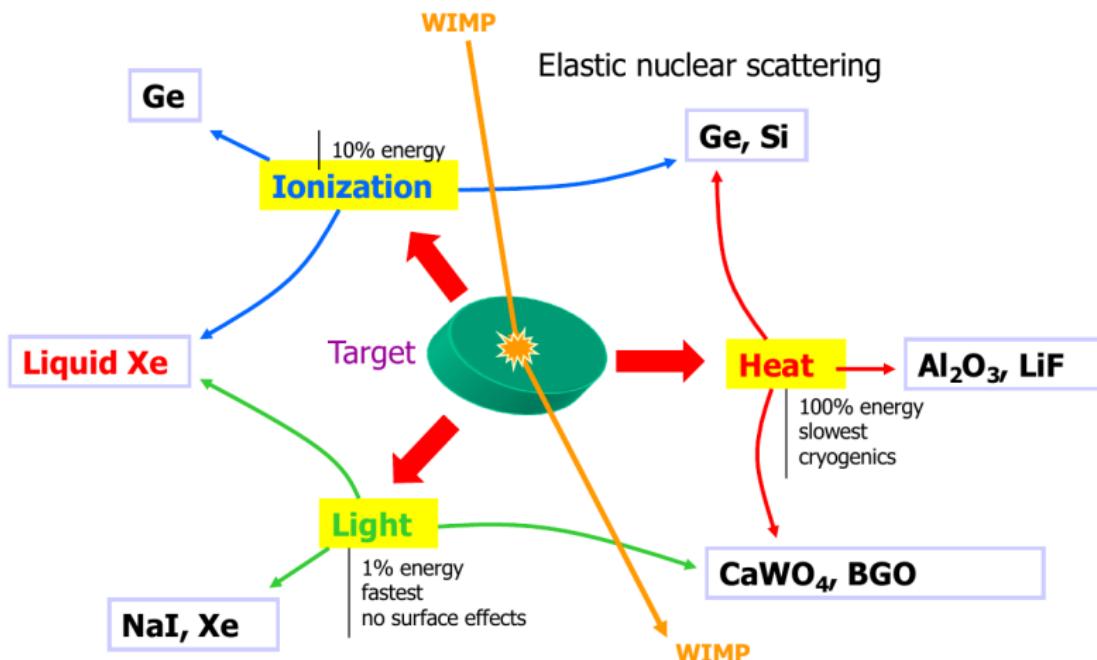
Lagrangian: $\mathcal{L}_{\text{int}} = g_\chi S \bar{\chi} \chi + g_q S \bar{q} q \Rightarrow \mathcal{L}_{\text{eff}} = G_{\text{eff}} \bar{\chi} \chi \bar{q} q, \quad G_{\text{eff}} = \frac{g_\chi g_q}{m_S^2}$

Effective Operators for DM-quark Interactions

	Spin-1/2 DM	Spin-0 DM
SI	$\bar{\chi}\chi\bar{q}q, \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$\chi^*\chi\bar{q}q, (\chi^*i\overleftrightarrow{\partial}^\mu\chi)\bar{q}\gamma_\mu q$
SD	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu\gamma_5 q, \bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	
$\sigma_{\chi N} \propto Q^2 $	$\bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5 q, \bar{\chi}\chi\bar{q}i\gamma_5 q$	$\chi^*\chi\bar{q}i\gamma_5 q$
	$\bar{\chi}i\gamma_5\chi\bar{q}q, \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma_5 q$	$(\chi^*i\overleftrightarrow{\partial}^\mu\chi)\bar{q}\gamma_\mu\gamma_5 q$
	$\bar{\chi}\gamma^\mu\gamma_5\chi\bar{q}\gamma_\mu q, \epsilon^{\mu\nu\rho\sigma}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\rho\sigma} q$	
	Spin-3/2 DM	Spin-1 DM
SI	$\bar{\chi}^\mu\chi_\mu\bar{q}q, \bar{\chi}^\nu\gamma^\mu\chi_\nu\bar{q}\gamma_\mu q$	$\chi_\mu^*\chi^\mu\bar{q}q, (\chi_\nu^*i\overleftrightarrow{\partial}^\mu\chi^\nu)\bar{q}\gamma_\mu q$
SD	$\bar{\chi}^\nu\gamma^\mu\gamma_5\chi_\nu\bar{q}\gamma_\mu\gamma_5 q, \bar{\chi}^\rho\sigma^{\mu\nu}\chi_\rho\bar{q}\sigma_{\mu\nu} q$ $i(\bar{\chi}^\mu\chi^\nu - \bar{\chi}^\nu\chi^\mu)\bar{q}\sigma_{\mu\nu} q$	$i(\chi_\mu^*\chi_\nu - \chi_\nu^*\chi_\mu)\bar{q}\sigma^{\mu\nu} q$ $\epsilon^{\mu\nu\rho\sigma}(\chi_\mu^*\overleftrightarrow{\partial}_\nu\chi_\rho)\bar{q}\gamma_\sigma\gamma_5 q$
$\sigma_{\chi N} \propto Q^2 $	$\bar{\chi}^\mu i\gamma_5\chi_\mu\bar{q}i\gamma_5 q, \bar{\chi}^\mu\chi_\mu\bar{q}i\gamma_5 q$	$\chi_\mu^*\chi^\mu\bar{q}i\gamma_5 q$
	$\bar{\chi}^\mu i\gamma_5\chi_\mu\bar{q}q, \bar{\chi}^\nu\gamma^\mu\chi_\nu\bar{q}\gamma_\mu\gamma_5 q$	$(\chi_\nu^*i\overleftrightarrow{\partial}^\mu\chi^\nu)\bar{q}\gamma_\mu\gamma_5 q$
	$\bar{\chi}^\mu\gamma^\mu\gamma_5\chi_\nu\bar{q}\gamma_\mu q, \epsilon^{\mu\nu\rho\sigma}i(\bar{\chi}_\mu\chi_\nu - \bar{\chi}_\nu\chi_\mu)\bar{q}\sigma_{\rho\sigma} q$ $\epsilon^{\mu\nu\rho\sigma}\bar{\chi}^\alpha\sigma_{\mu\nu}\chi_\alpha\bar{q}\sigma_{\rho\sigma} q, (\bar{\chi}^\mu\gamma_5\chi^\nu - \bar{\chi}^\nu\gamma_5\chi^\mu)\bar{q}\sigma_{\mu\nu} q$ $\epsilon^{\mu\nu\rho\sigma}(\bar{\chi}_\mu\gamma_5\chi_\nu - \bar{\chi}_\nu\gamma_5\chi_\mu)\bar{q}\sigma_{\rho\sigma} q$	$\epsilon^{\mu\nu\rho\sigma}(\chi_\mu^*\overleftrightarrow{\partial}_\nu\chi_\rho)\bar{q}\gamma_\sigma q$ $\epsilon^{\mu\nu\rho\sigma}i(\chi_\mu^*\chi_\nu - \chi_\nu^*\chi_\mu)\bar{q}\sigma_{\rho\sigma} q$

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

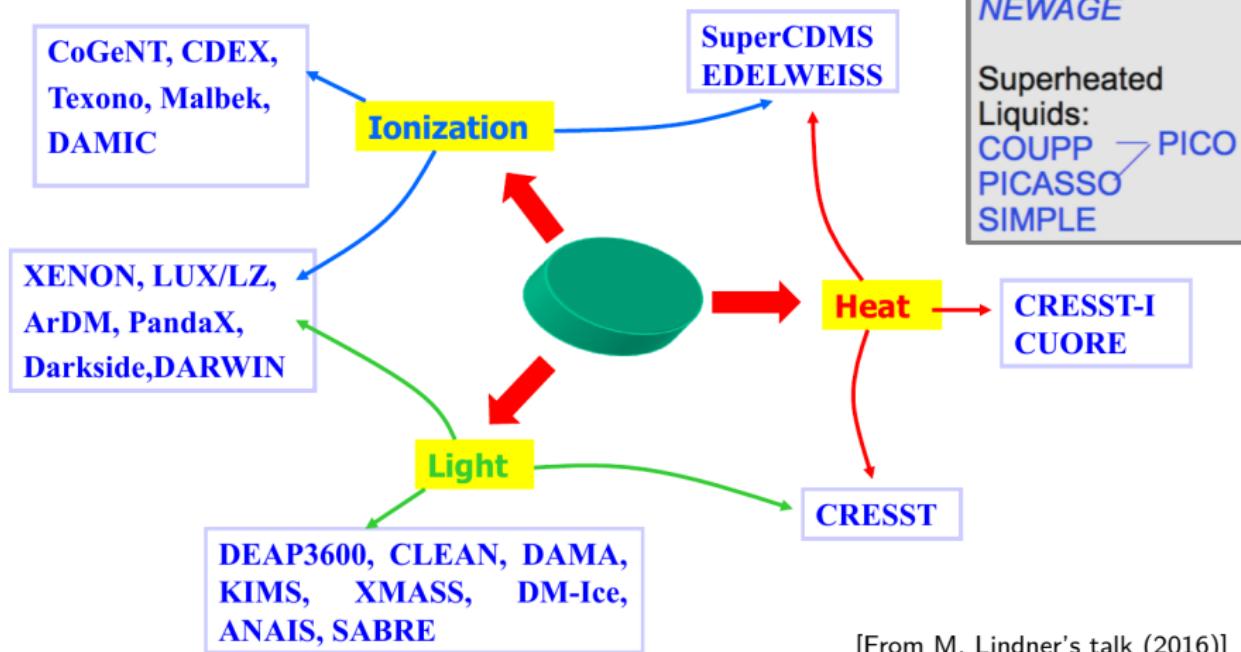
Technologies and Detector Material



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

Technologies and Detector Material

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



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

Example: Dual-phase Xenon Time Projection Chamber

Upper: **Xenon gas**

Lower: **Liquid Xenon**

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

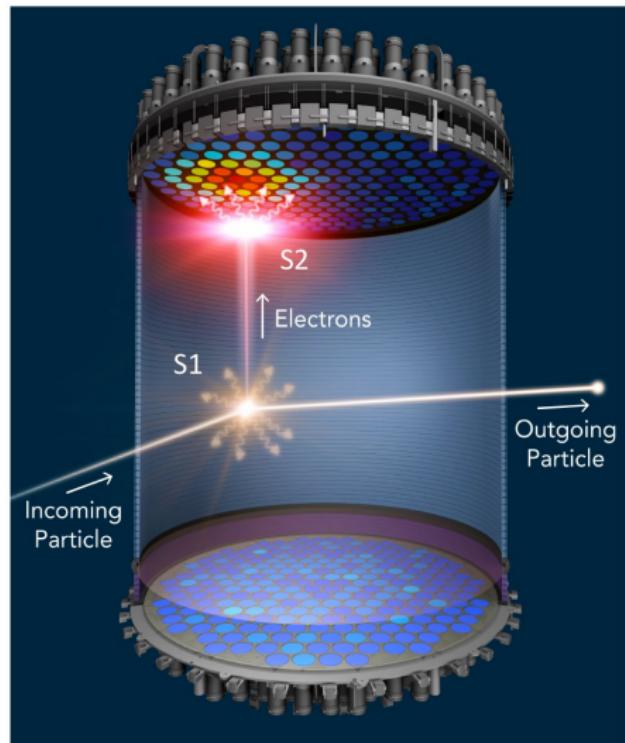
- **Primary scintillation (S1):**

Scintillation light promptly emitted from the interaction vertex

- **Secondary scintillation (S2):**

Ionization electrons emitted from the interaction are drifted to the surface and into the gas, where they emit proportional scintillation light

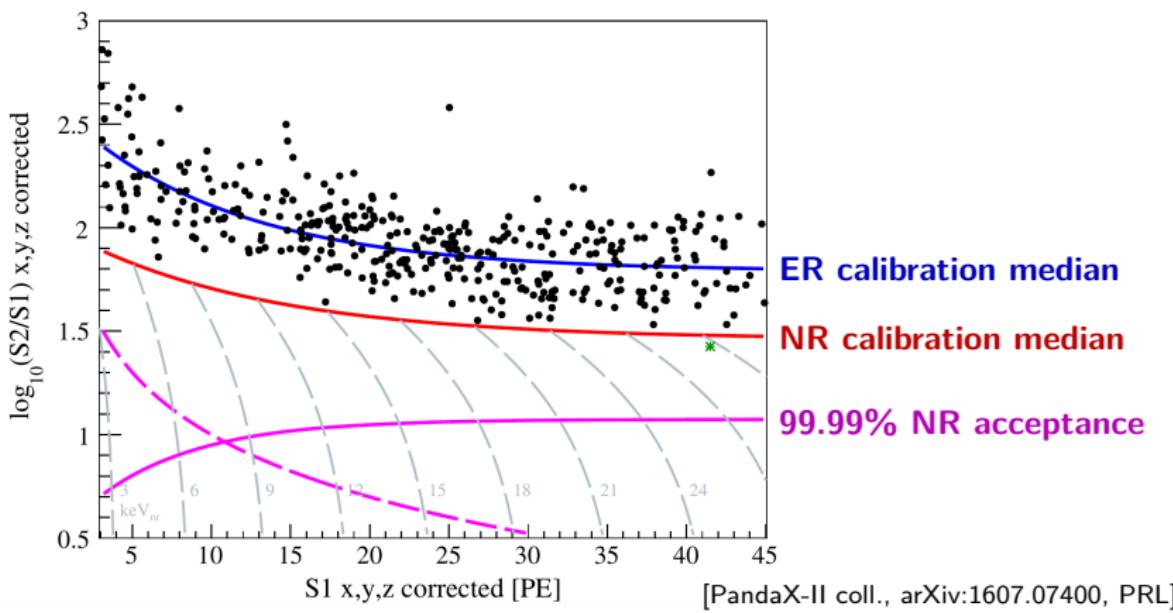
Experiments: XENON, LUX, PandaX



[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



Backgrounds

Background suppression:

Deep underground

Shielded environments

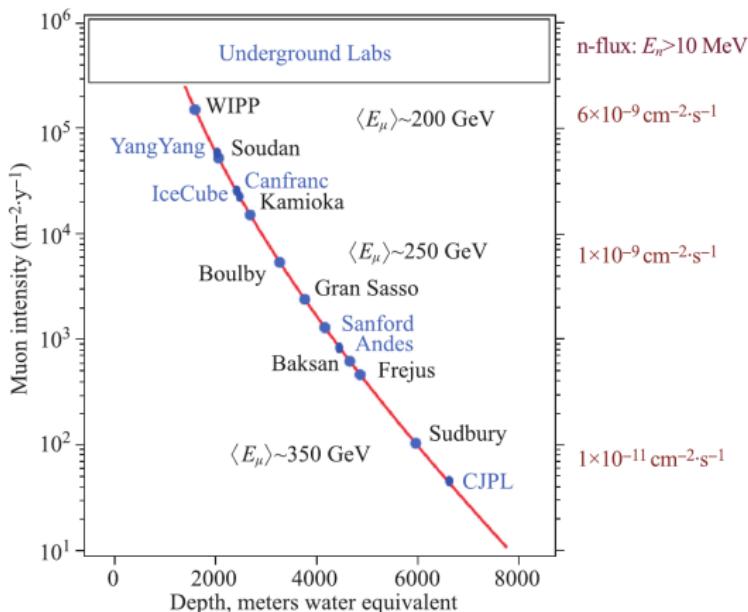
• Cosmogenic backgrounds:

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

• Radiogenic backgrounds:

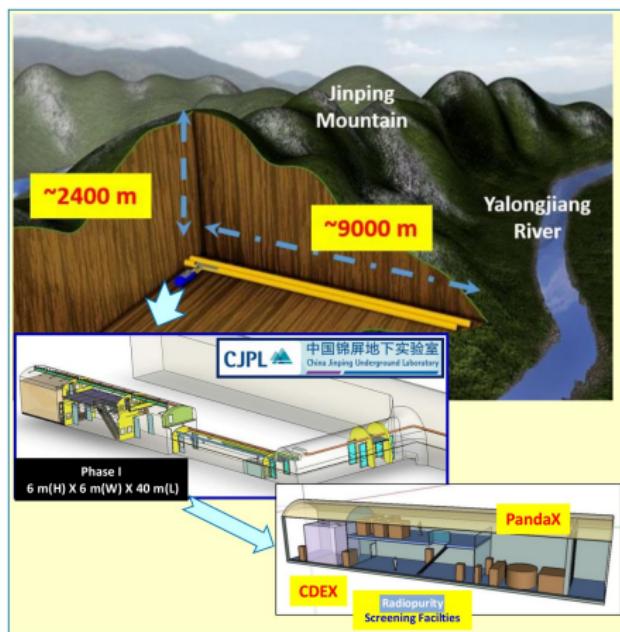
- External natural radioactivity: walls, structures of site, radon
- Internal radioactivity:

shield and construction materials, detector contamination in manufacture, naturally occurring radio-isotopes in target material



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

China JinPing Underground Laboratory (CJPL)

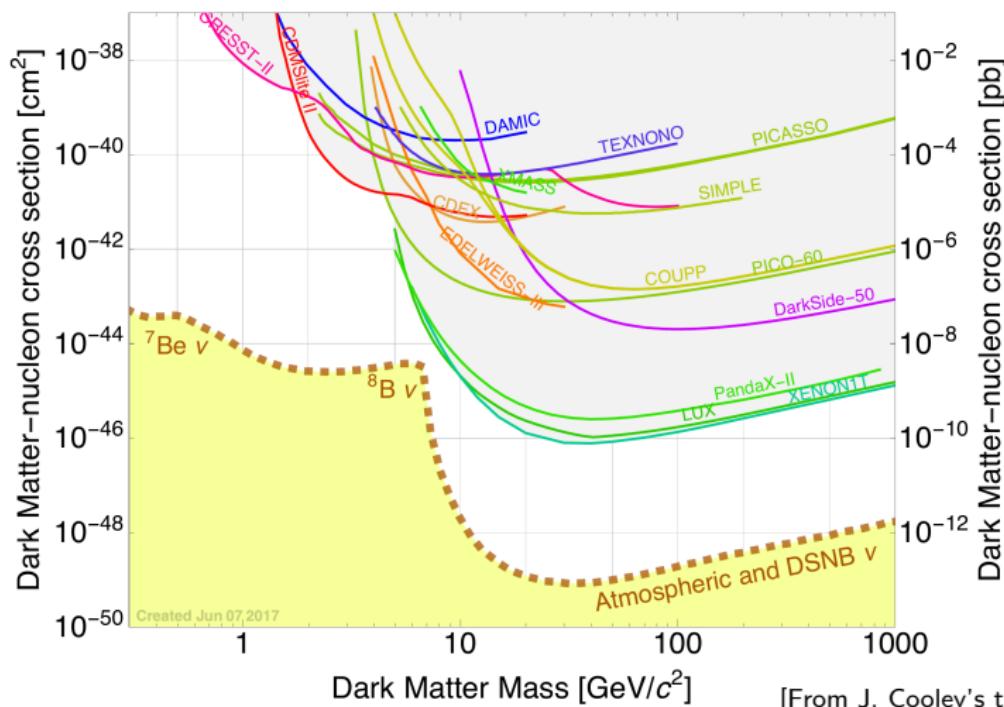


[Yue et al., arXiv:1602.02462]

Experiments: CDEX, PandaX

Exclusion Limits for SI Scattering

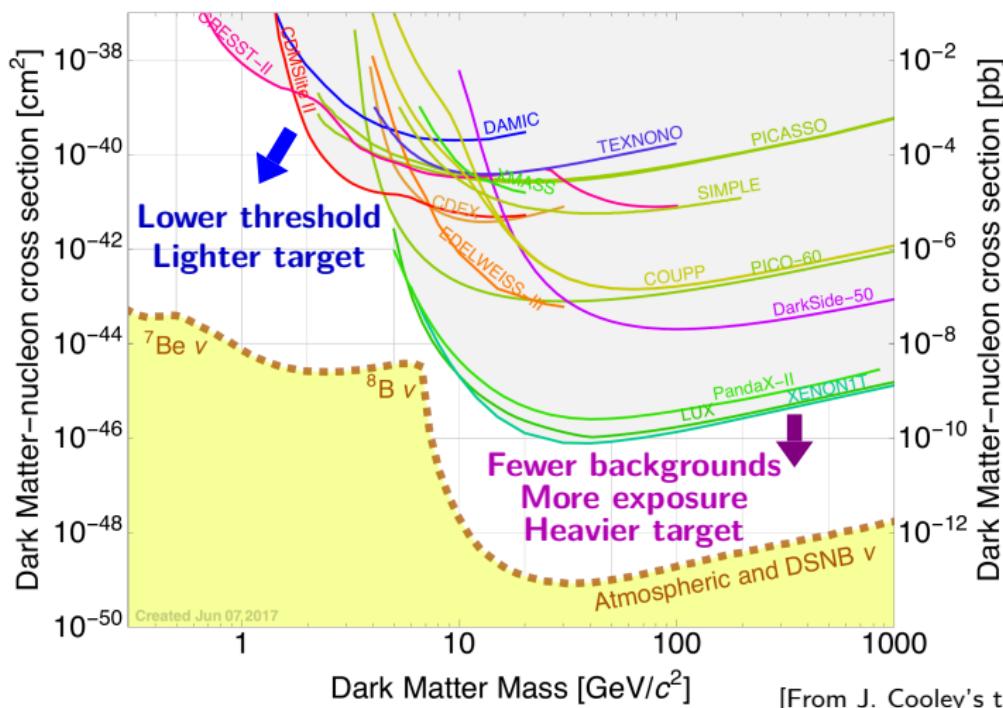
For **SI scattering**, the **coherent enhancement** allows us to treat protons and neutrons as the same species, “**nucleons**”



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

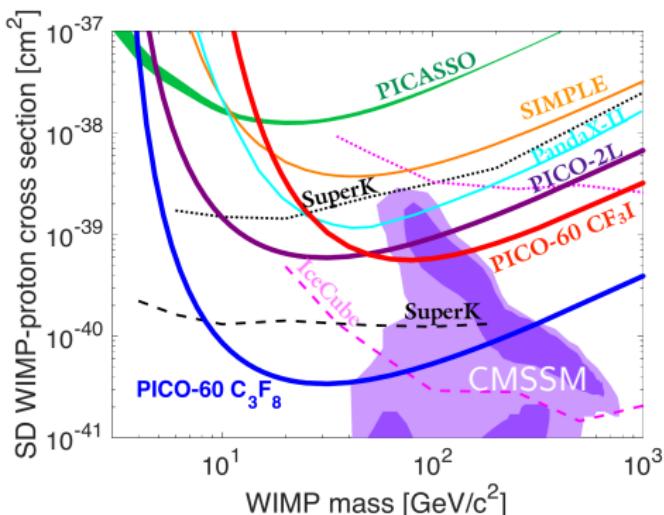
Exclusion Limits for SI Scattering

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

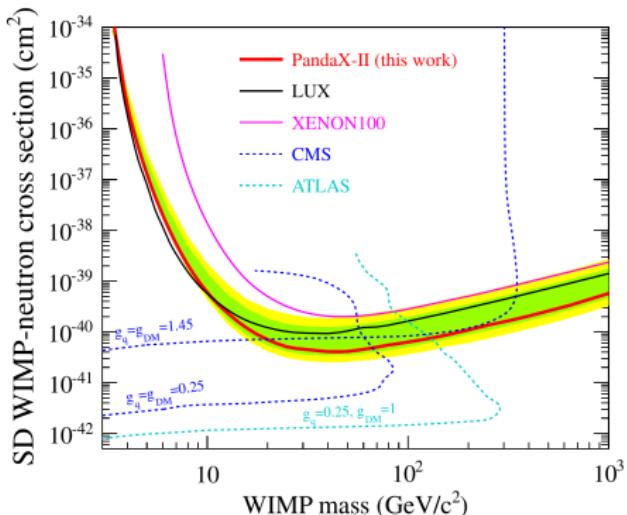


Exclusion Limits for SD Scattering

- 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**



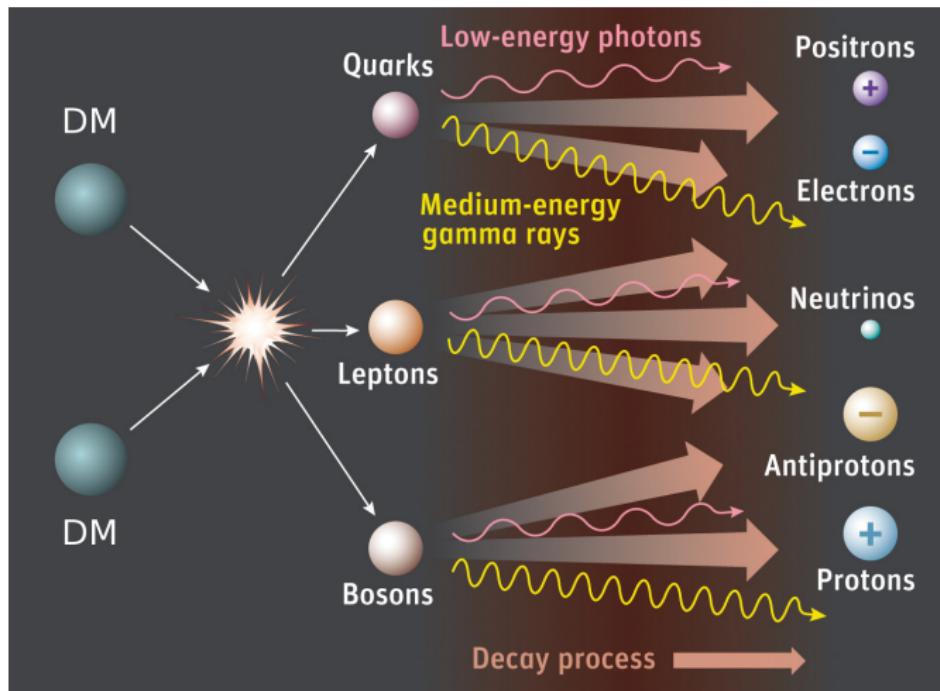
[PICO coll., arXiv:1702.07666, PRL]



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

Indirect Detection

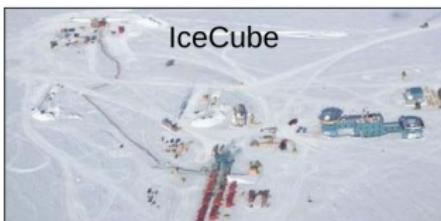
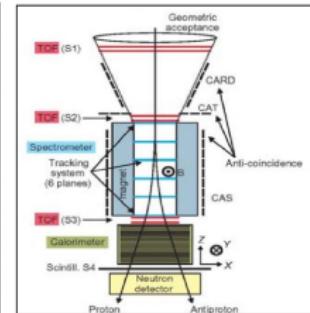
Indirect detection looks for stable products (γ rays, cosmic rays, neutrinos) from dark matter **annihilation** or **decay** (if DM is not totally stable) in space



Indirect Detection Experiments



PAMELA

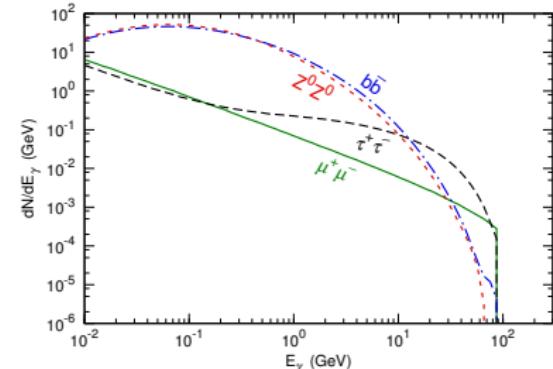


γ rays from DM: Continuous Spectrum

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



γ -ray emission from final state radiation or particle decays



- **Cut-off energy:**

m_χ for DM annihilation

$m_\chi/2$ for DM decay

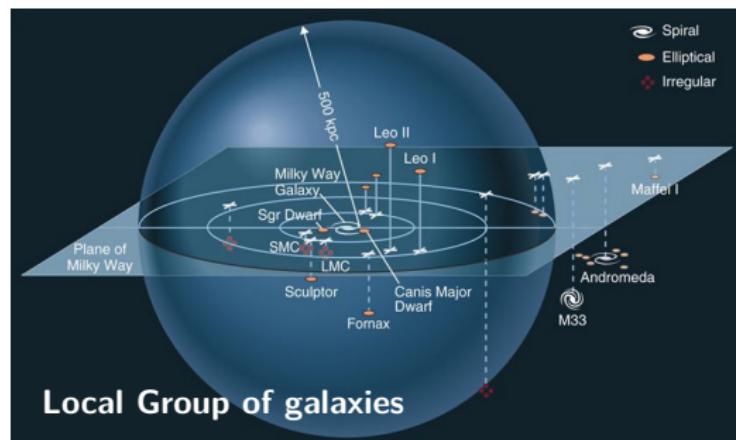
- More promising to look at
DM-dominated regions:

Galactic Center

Galactic halo

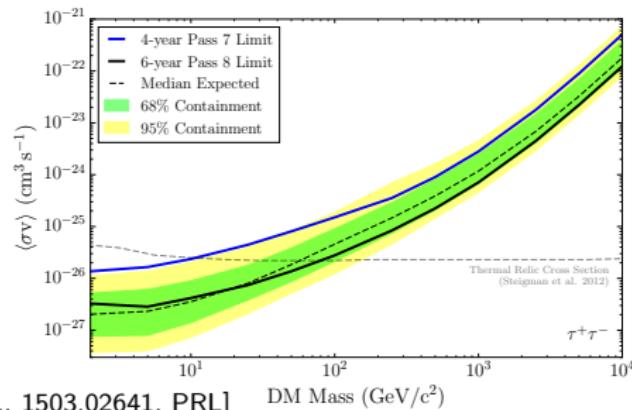
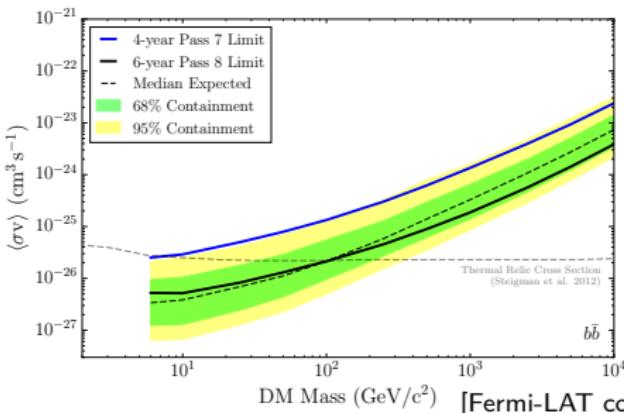
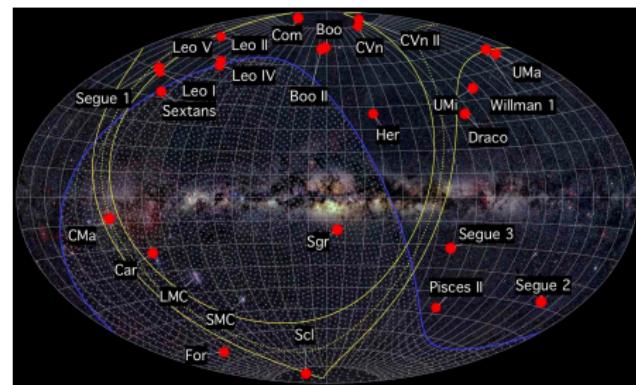
dwarf galaxies

clusters of galaxies



γ -ray Observation of Dwarf Galaxies

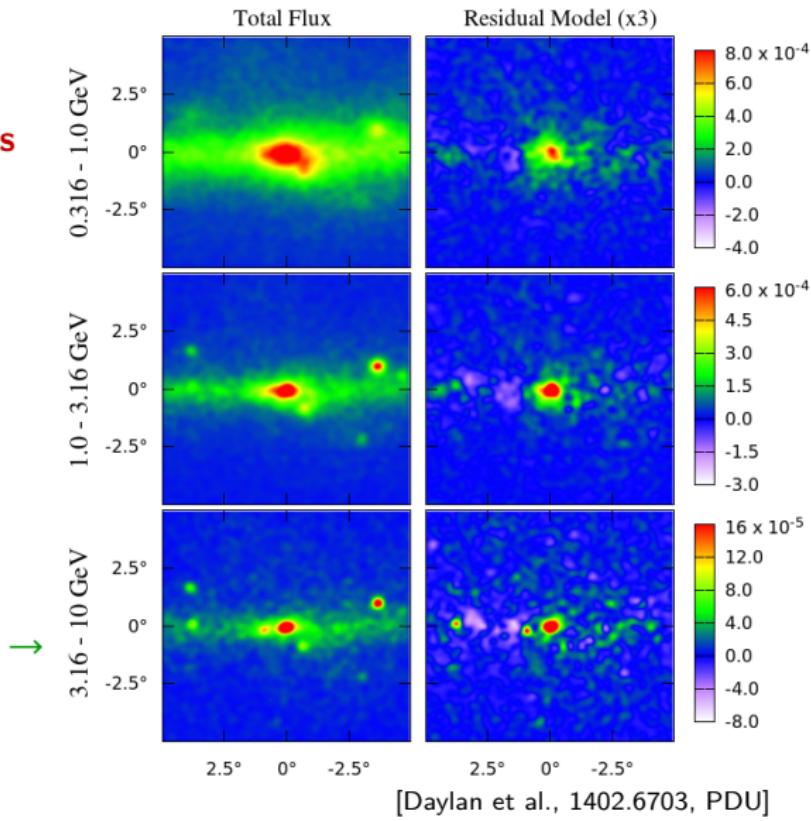
- The space experiment **Fermi-LAT** searched for γ -ray emission from **dwarf spheroidal satellite galaxies** of the Milky Way and found no significant signal
- Based on the 6-year data, upper limits on DM annihilation cross section are given



GeV Excess at the Galactic Center?

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

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



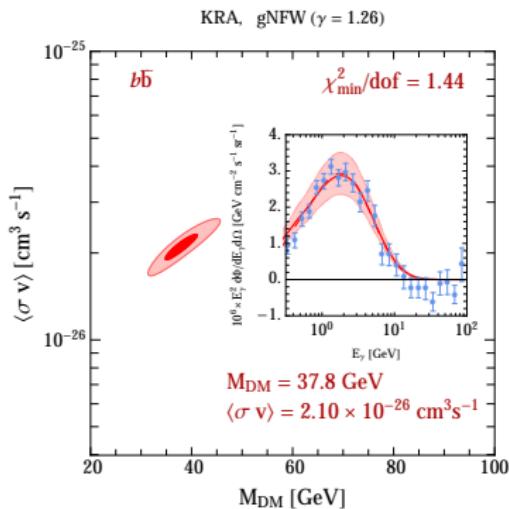
[Daylan et al., 1402.6703, PDU]

Interpretation with Dark Matter Annihilation

DM annihilation into $b\bar{b}$

$$m_\chi \simeq 30 - 40 \text{ GeV}$$

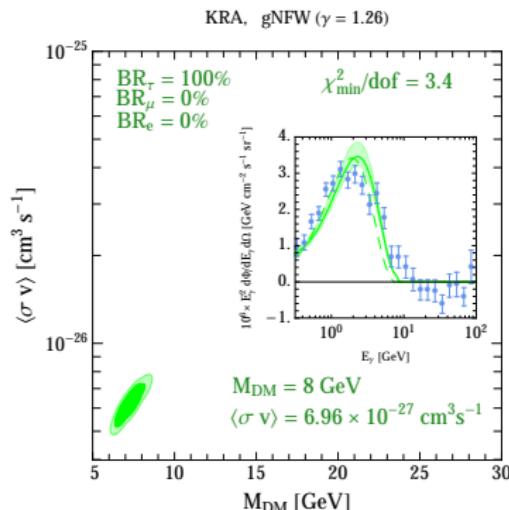
$$\langle \sigma_{\text{ann}} v \rangle \sim 10^{-26} \text{ cm}^3 \text{s}^{-1}$$



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

$$m_\chi \sim 9 \text{ GeV}$$

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



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

γ rays from DM: Line Spectrum

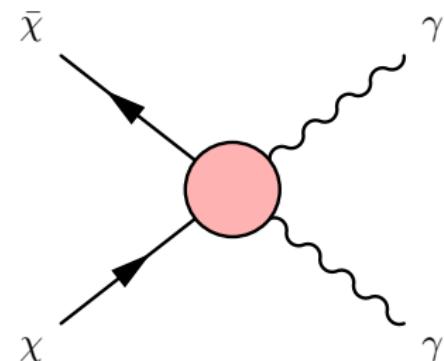
DM particles should **not have electric charge** and thus not directly couple to photons



DM particles may couple to photons via high order loop diagrams



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



γ rays from DM: Line Spectrum

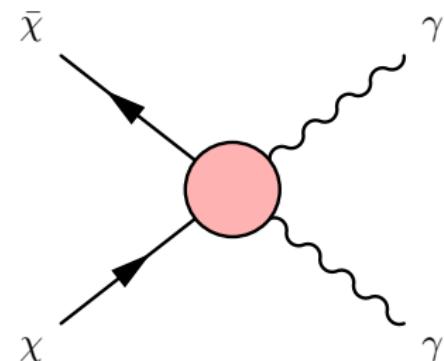
DM particles should **not have electric charge** and thus not directly couple to photons



DM particles may couple to photons via high order loop diagrams



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



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

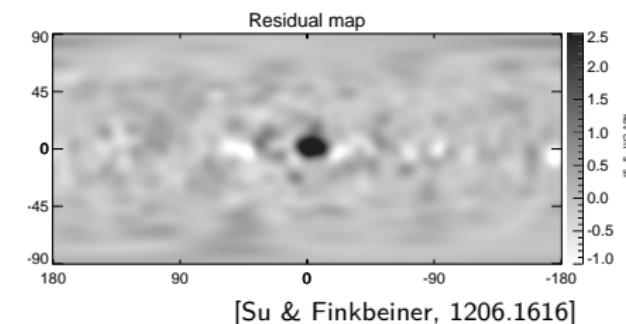
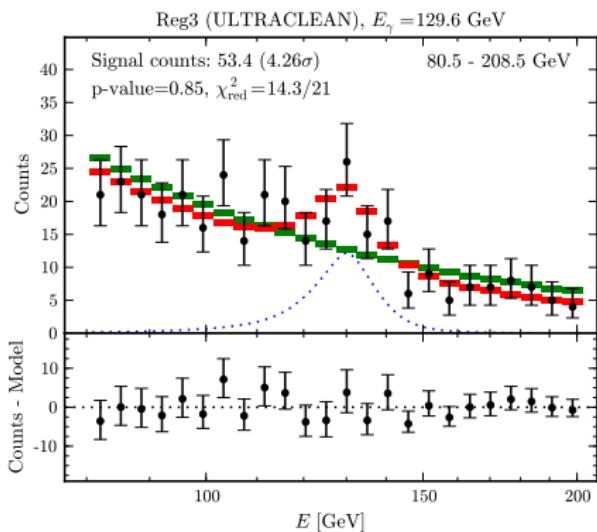


A γ -ray line at energy $\sim m_\chi$
("smoking gun" for DM particles)



A γ -ray Line Signal at the Galactic Center?

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



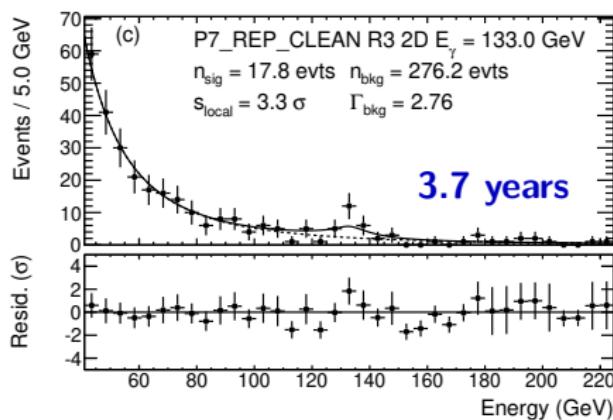
[Su & Finkbeiner, 1206.1616]

[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]

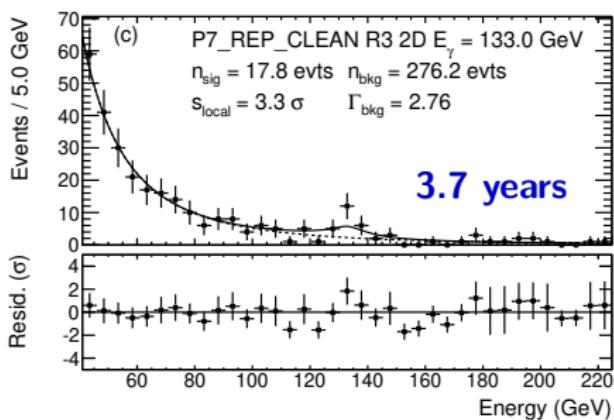
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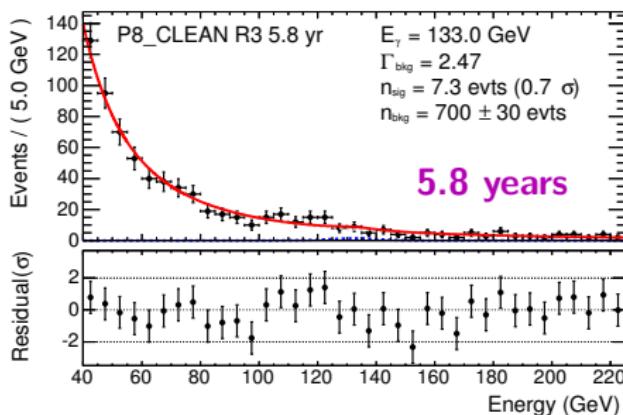
The most significant fit occurred at $E_\gamma = 133$ GeV and had a **local significance** of 3.3σ , translating to a global significance of 1.6σ

- **5.8-year data**

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



[Fermi-LAT Coll., 1305.5597, PRD]



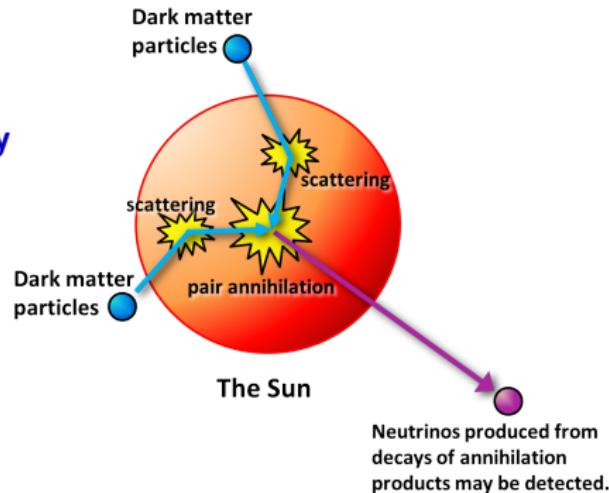
[Fermi-LAT Coll., 1506.00013, PRD]

Neutrinos from DM

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

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

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

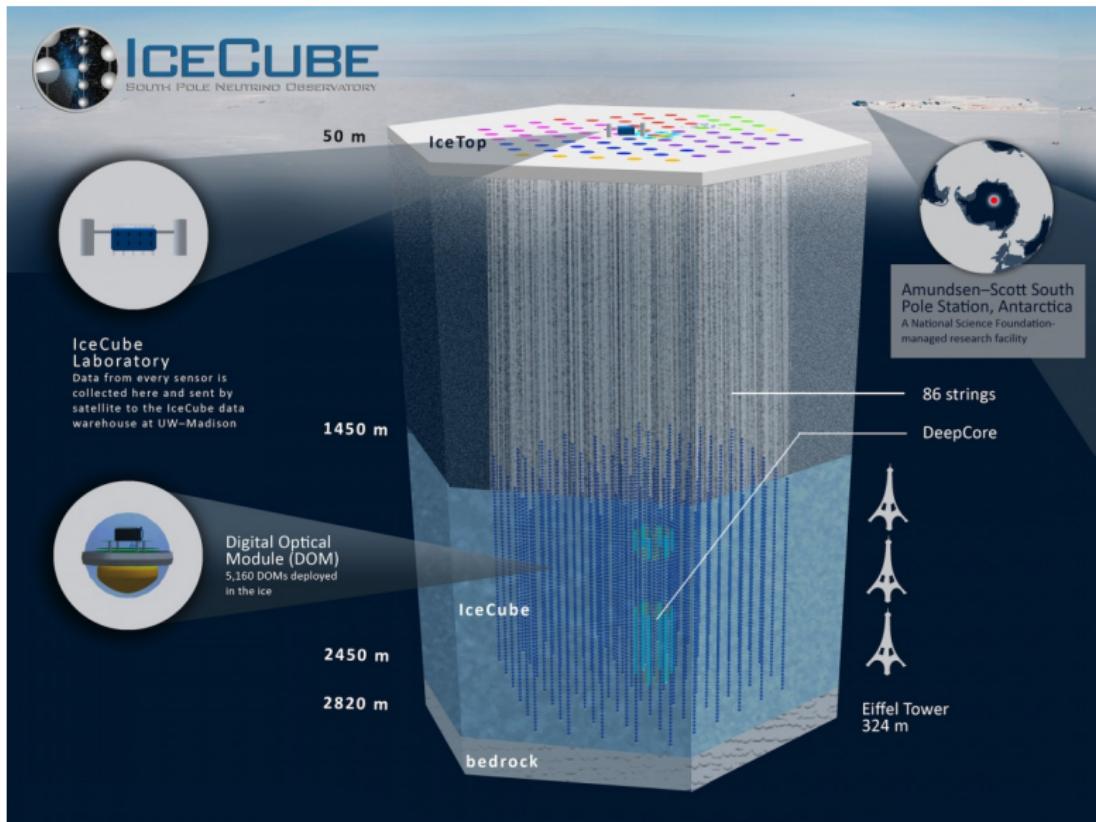


Capture rate C_\odot depends on DM scattering on Hydrogen and Helium

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

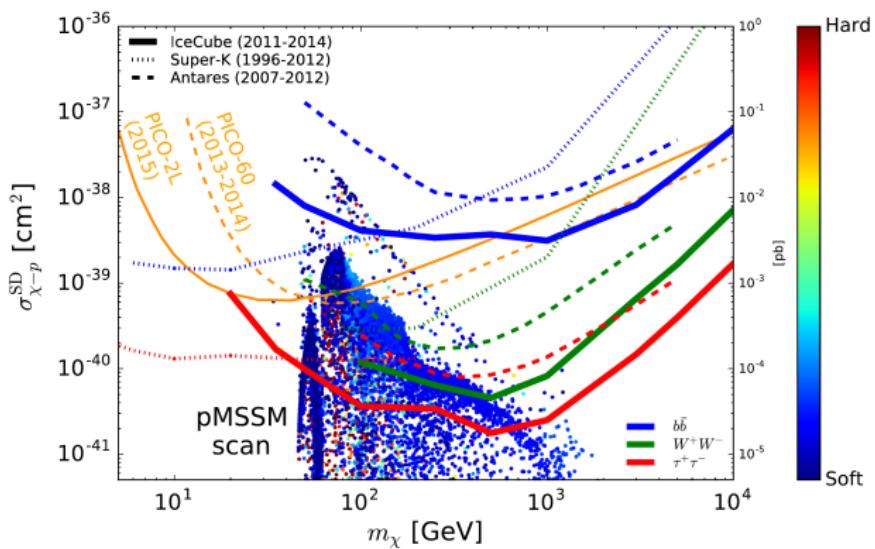
 The age of the Sun is long enough (~ 4.6 billion years) to make the capture and annihilation processes reach **equilibrium**: $dN_\chi/dt = 0$

IceCube: South Pole Neutrino Observatory



Searches for Neutrinos from DM Annihilation within the Sun

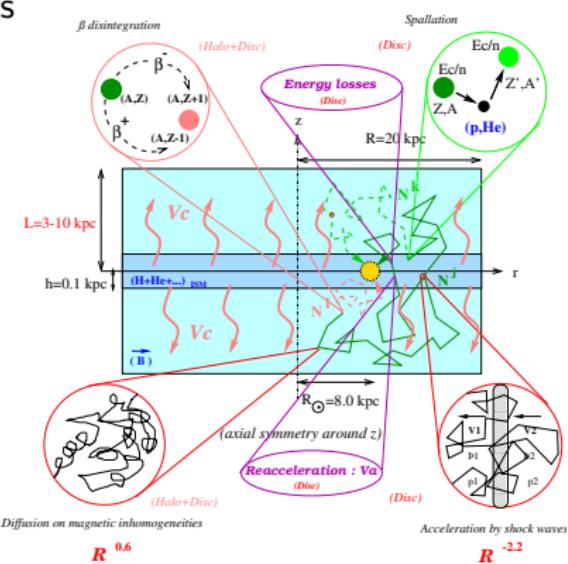
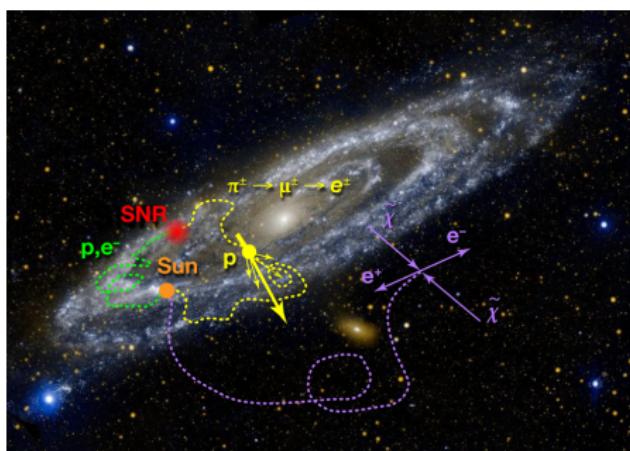
- **No signal detected** in searches for neutrinos with energies of GeV – TeV from DM annihilation at the solar core
- Assuming equilibrium in the capture and annihilation processes, the constraints can be converted to those on the **DM scattering cross section**



[IceCube Coll, 1612.05949, EPJC]

Cosmic Rays from DM

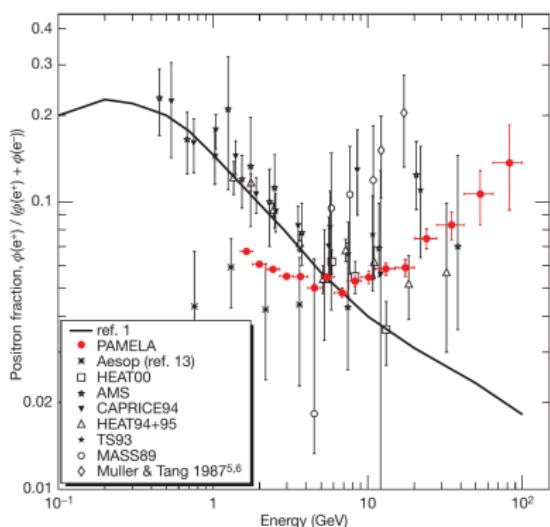
- After produced in sources, Galactic cosmic rays diffuse in the interstellar space, suffering from several **propagation effects** before they arrive at the Earth: diffusion, energy losses, convection, reacceleration, spallation, ...
- Unlike γ rays and neutrinos, cosmic rays **typically do not contain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



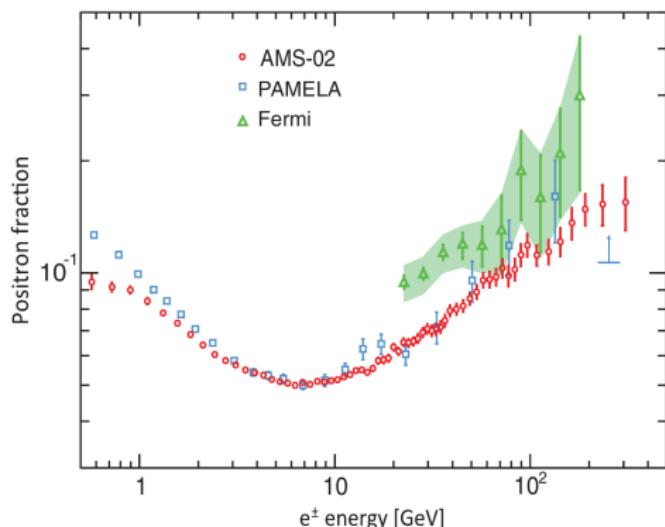
[Maurin et al., astro-ph/0212111]

Cosmic-ray 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



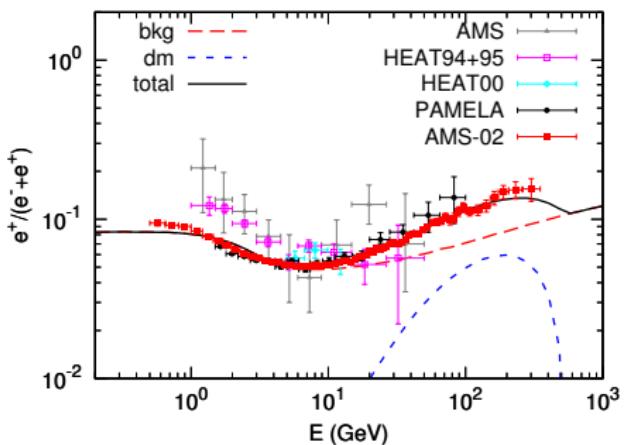
[PAMELA Coll., 0810.4995, Nature]



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

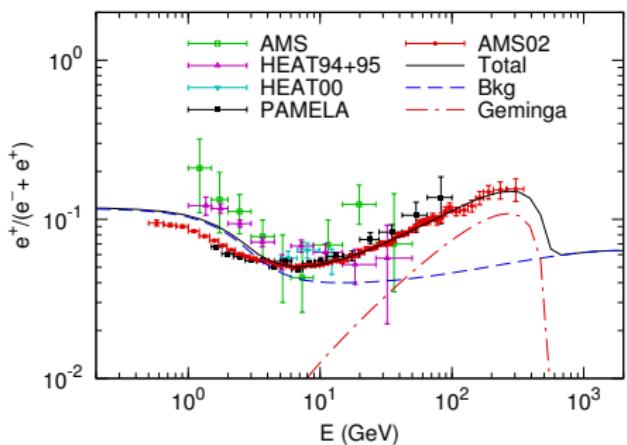
Interpretation: Dark Matter vs Pulsar

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



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

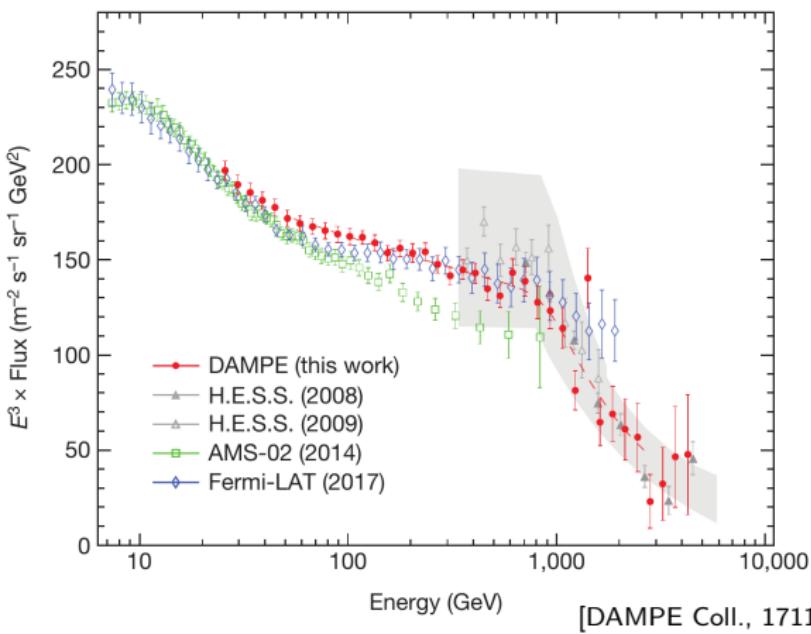
Interpretation with the
nearby pulsar Geminga



[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



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 ($p\text{Pb}$, PbPb) collider, 2009-

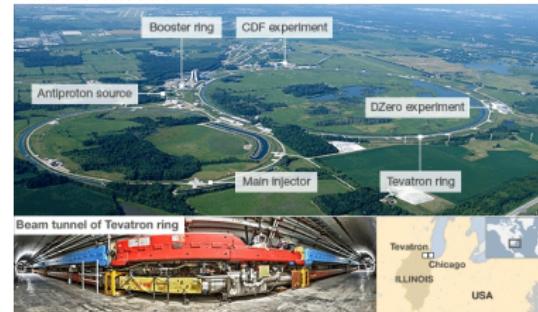
Circumference: 26.66 km

Collision energy: $\sqrt{s} = 7, 8, 13, 14$ TeV

Luminosity: $\mathcal{L} \sim (1 - 5) \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

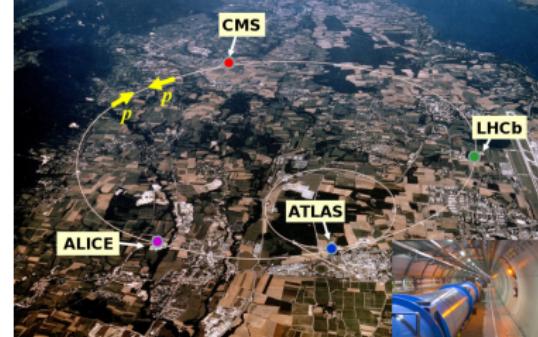
Detectors: ATLAS, CMS, ALICE, LHCb

The Tevatron accelerator



Source: Fermilab

Large Hadron Collider



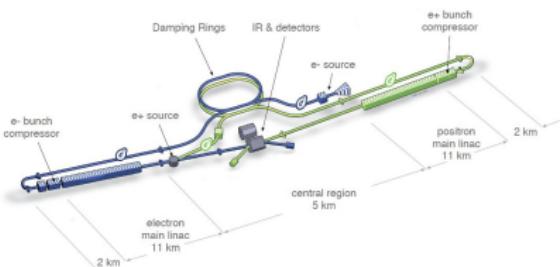
Future Projects

- **ILC:** International Linear Collider

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

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

Detectors: SiD, ILD



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

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

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

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

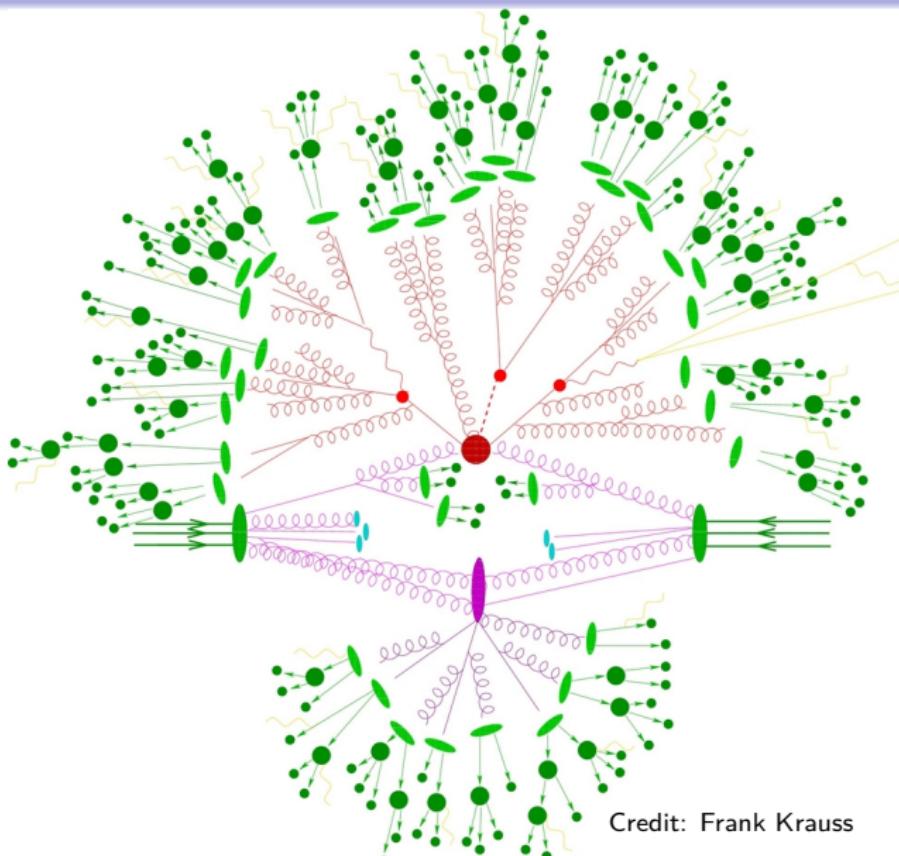
- **FCC:** Future Circular Collider (CERN)

- **FCC-ee:** e^+e^- collider, $\sqrt{s} \sim 90 - 350 \text{ GeV}$, $\mathcal{L} \sim 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

- **FCC-hh:** pp collider, $\sqrt{s} \sim 100 \text{ TeV}$, $\mathcal{L} \sim 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

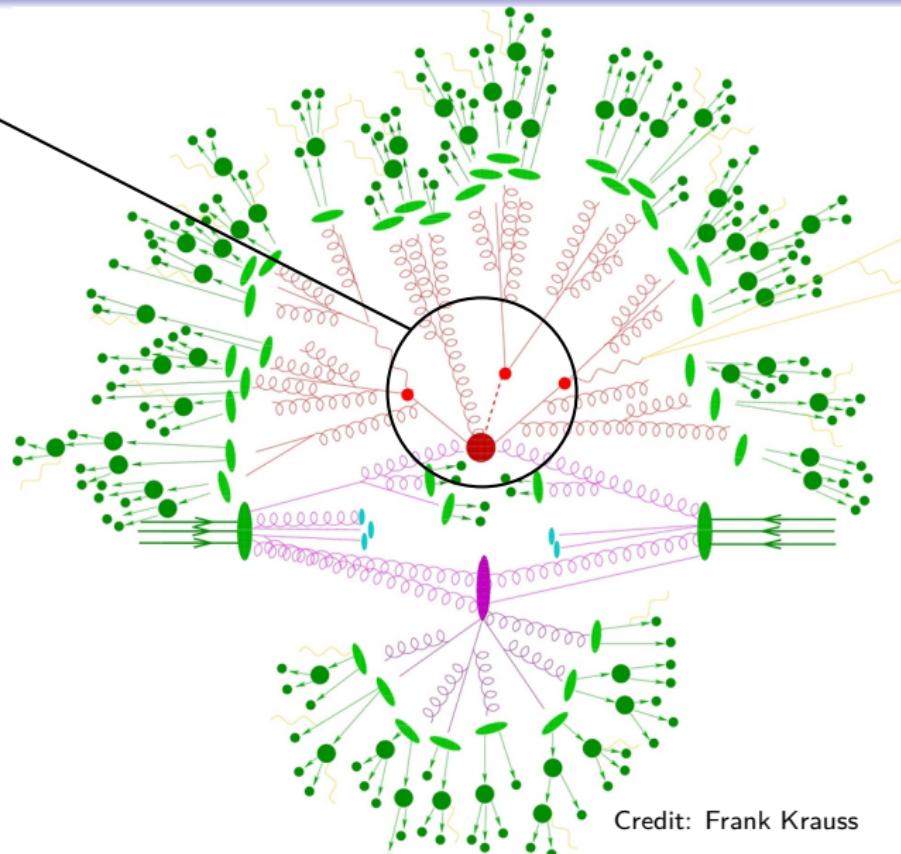
- **CLIC:** Compact Linear Collider, $\sqrt{s} \sim 1 - 3 \text{ TeV}$, $\mathcal{L} \sim 6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Typical Event in High Energy pp Collisions



Typical Event in High Energy pp Collisions

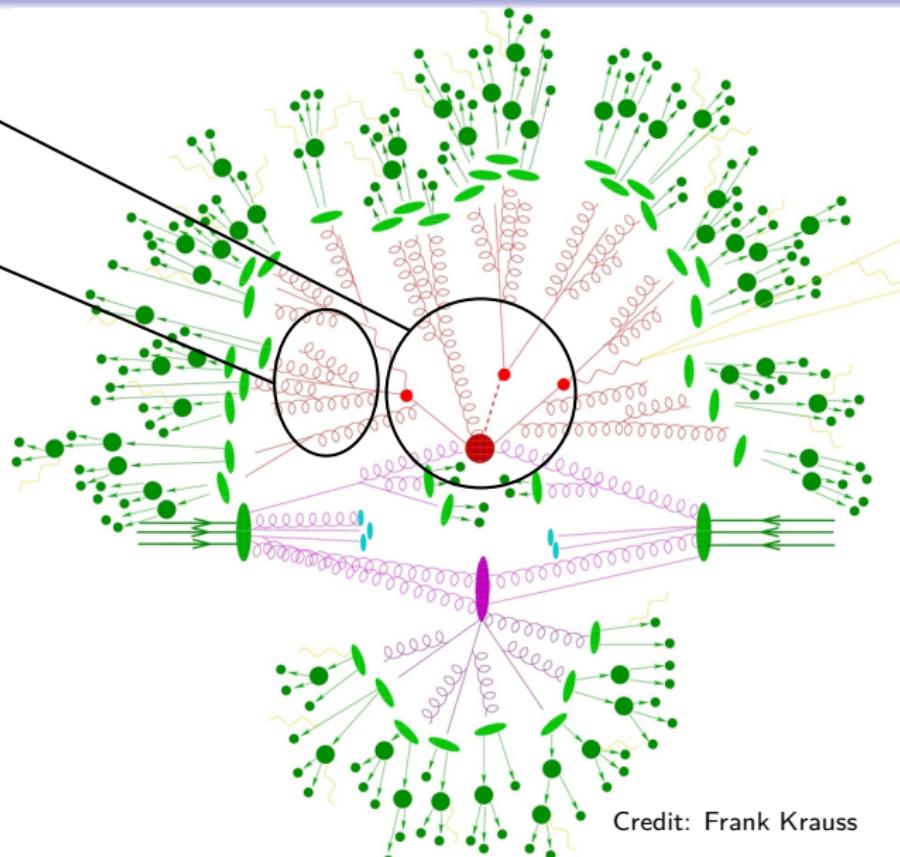
Hard scattering



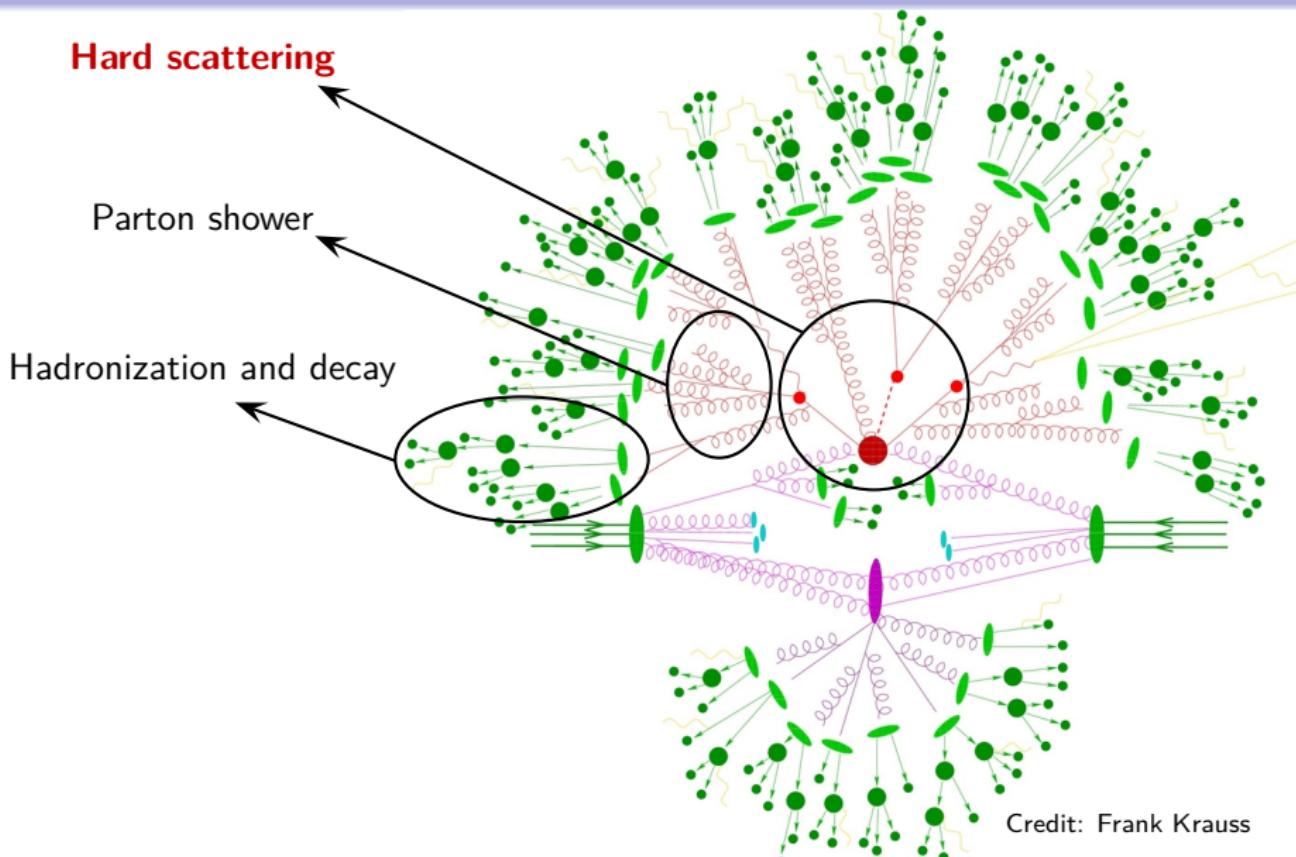
Typical Event in High Energy pp Collisions

Hard scattering

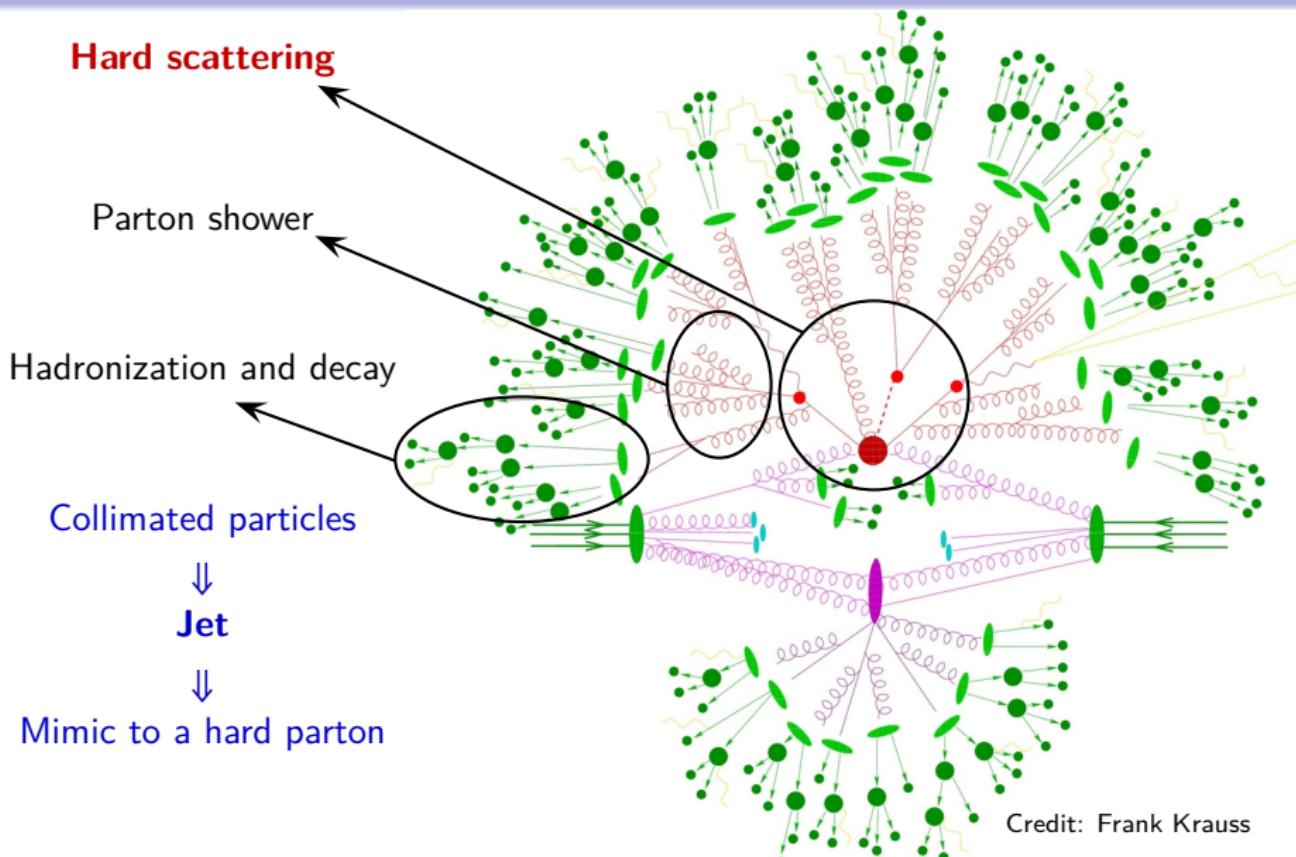
Parton shower



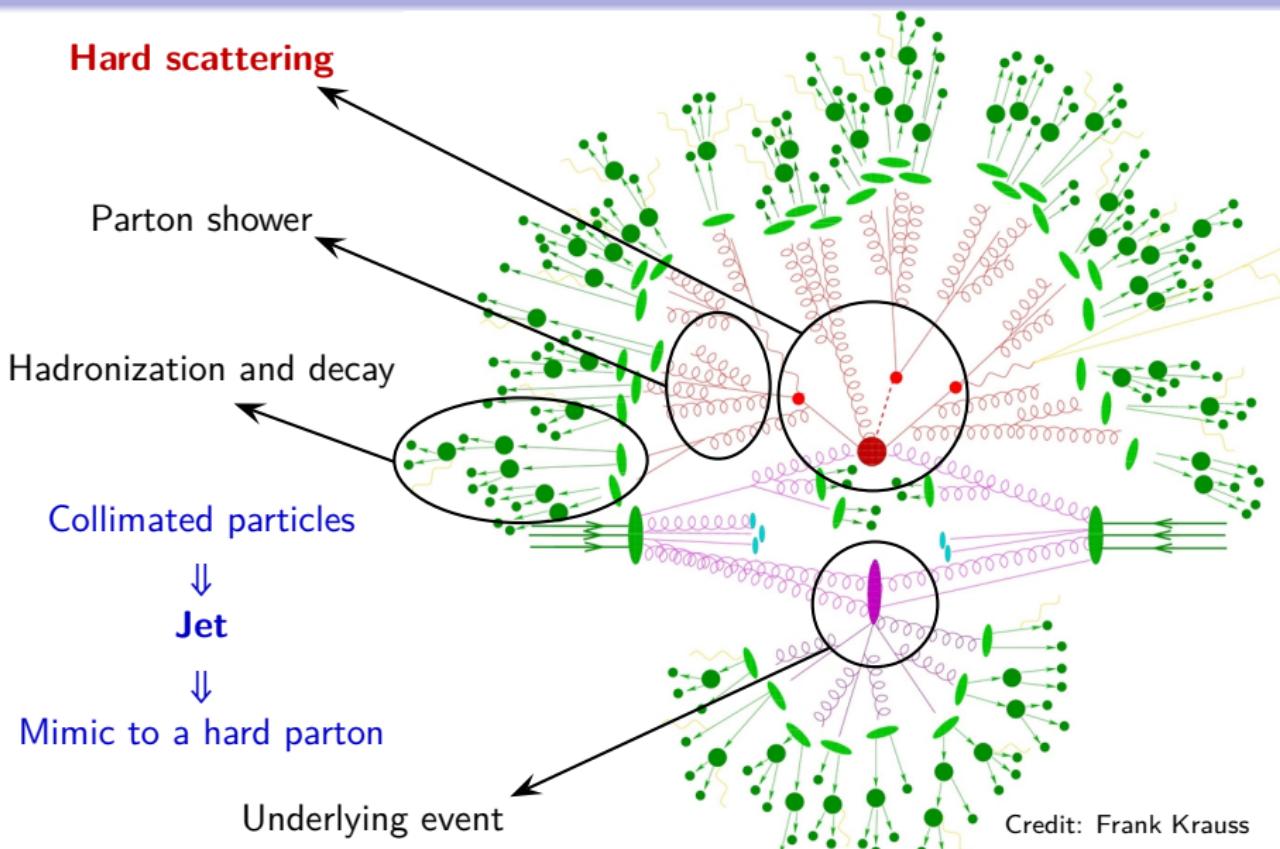
Typical Event in High Energy pp Collisions



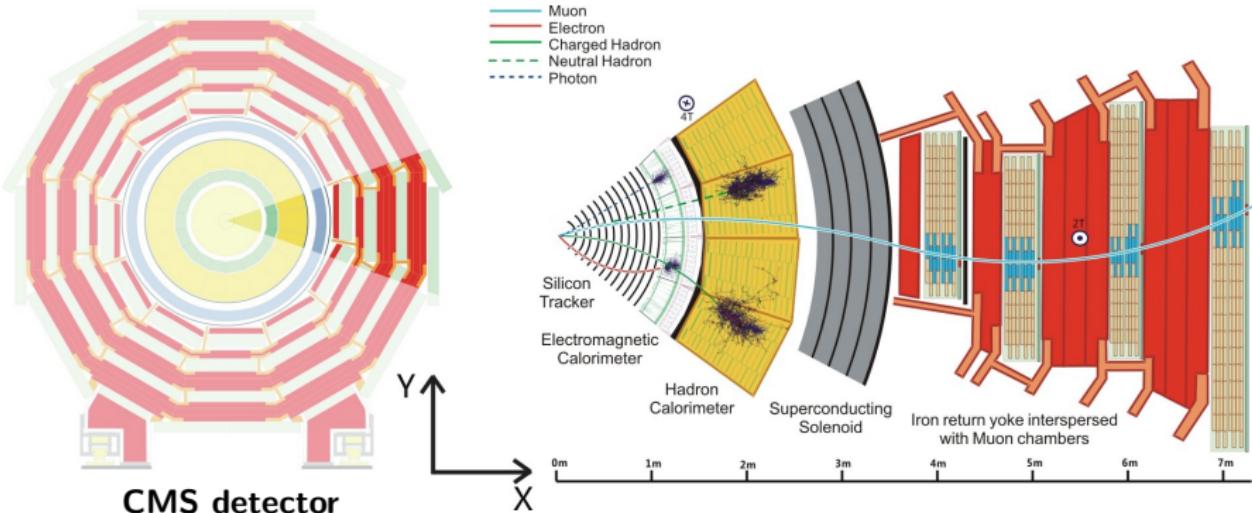
Typical Event in High Energy pp Collisions



Typical Event in High Energy pp Collisions

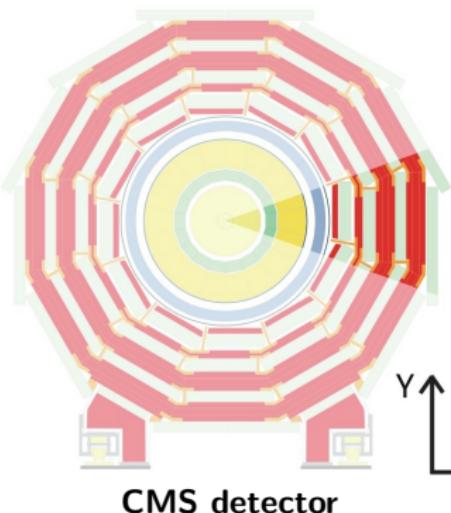


Particle Detectors at Colliders

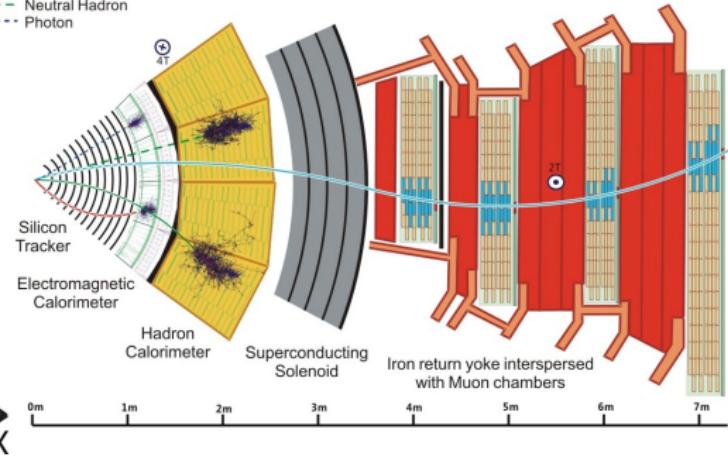


Sub-detectors	γ	e^\pm	μ^\pm	Charged hadrons	Neutral hadrons	ν , DM
Tracker, $ \eta \lesssim 2.5$	✗	✓	✓	✓	✗	✗
ECAL, $ \eta \lesssim 3$	●	●	✓	✓	✗	✗
HCAL, $ \eta \lesssim 5$	✗	✗	✗	●	●	✗
Muon detectors, $ \eta \lesssim 2.4$	✗	✗	✓	✗	✗	✗

Particle Detectors at Colliders



- Muon
- Electron
- Charged Hadron
- Neutral Hadron
- Photon

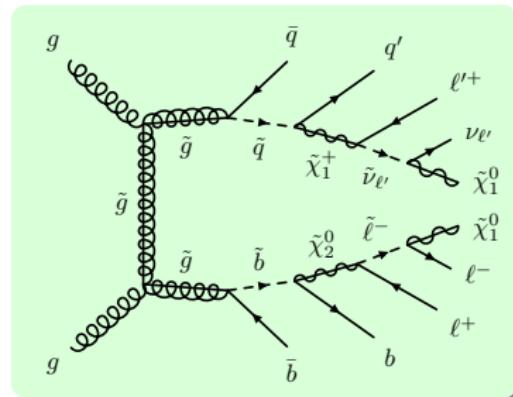


CMS detector

Sub-detectors	γ	e^\pm	μ^\pm	Charged hadrons	Neutral hadrons	ν , DM
Tracker, $ \eta \lesssim 2.5$	✗	✓	✓	✓		✗
ECAL, $ \eta \lesssim 3$	✗	✗	✓	✓		✗
HCAL, $ \eta \lesssim 5$	✗	✗	✗	✗		✗
Muon detectors, $ \eta \lesssim 2.4$	✗	✗	✓	✗		✗

Missing energy
 E_T

DM Production



Social dark matter

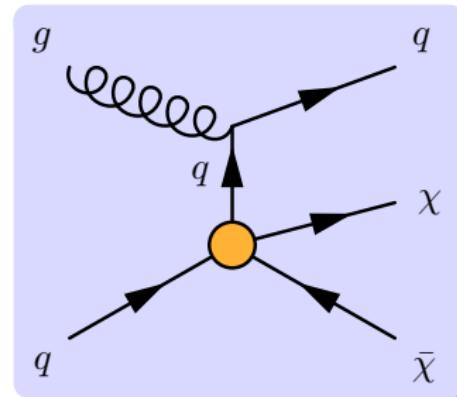
Accompanied by other new particles

Complicated decay chains

Decay products of other particles

Various final states

(jets + leptons + \cancel{E} , ...)



Maverick dark matter

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

Direct production

Mono-X + \cancel{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 :**

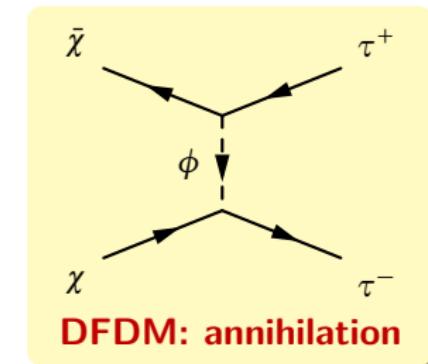
$$\mathcal{L}_\phi = \lambda \phi \bar{\tau}_R \chi_L + \text{h.c.}$$

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

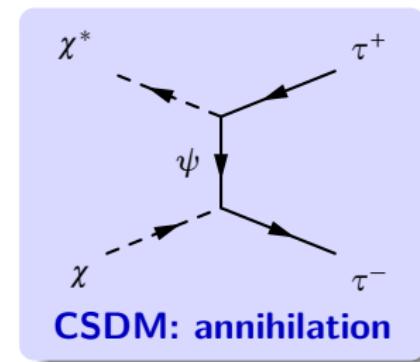
- Spin-0 scalar χ , spin-1/2 mediator ψ :**

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

- 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:

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

MFDM model:

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

CSDM model:

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

RSDM model:

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

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

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

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

CSDM model: Helicity suppression

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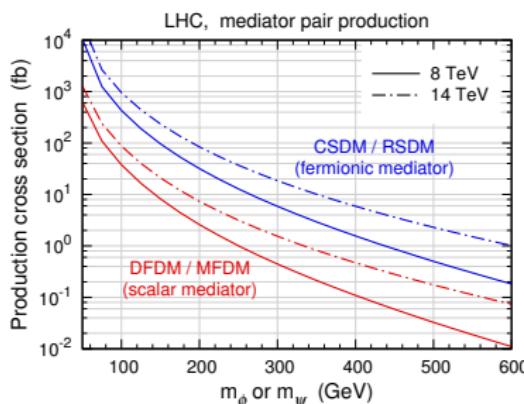
RSDM model: Helicity suppression

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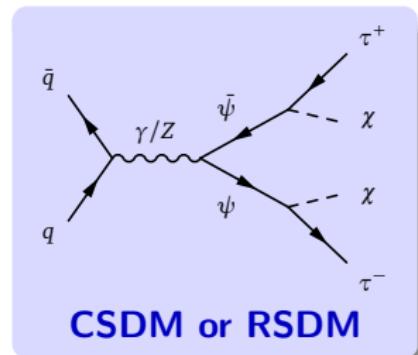
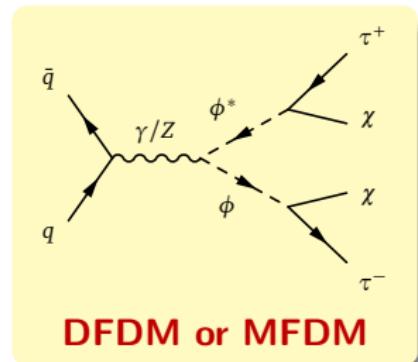
$(\beta_\tau \equiv \sqrt{1 - m_\tau^2/m_\chi^2}; \ m_\tau \ll m_\chi \ll m_\phi, m_\psi \text{ approximation})$

Mediator Pair Production at the LHC

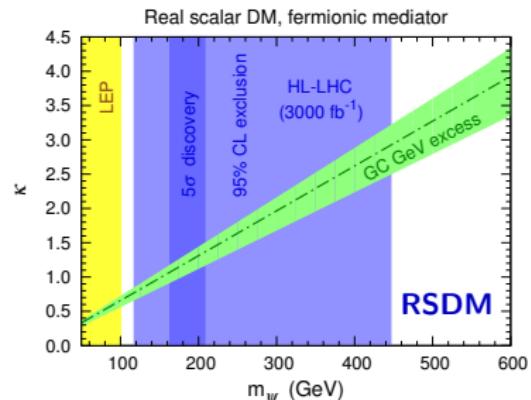
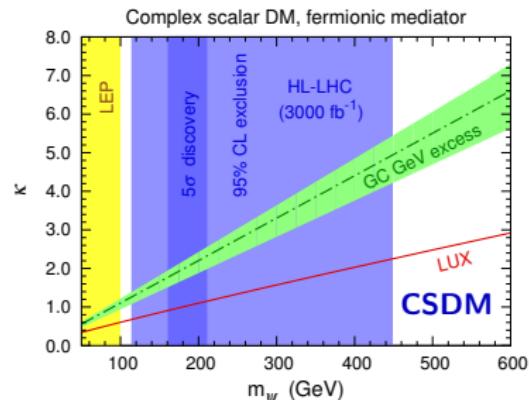
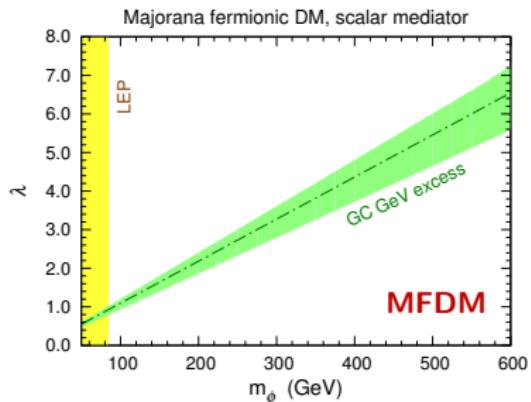
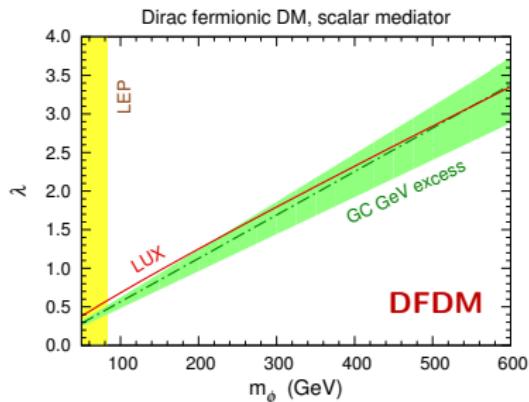
- The mediators ϕ and ψ could be produced at the LHC through **Drell-Yan processes** exchanging s -channel γ or Z , and then decay into τ^\pm and χ
- We found that the **8 TeV LHC data cannot explore the interesting regions** in these models, and went further to investigate the LHC sensitivity at $\sqrt{s}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



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



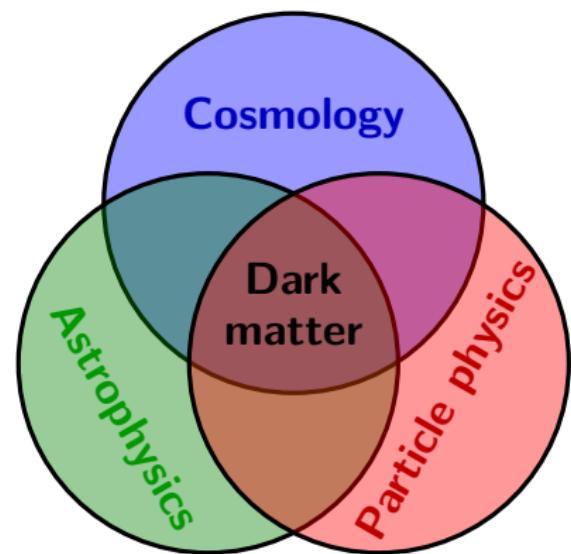
Sensitivity of the 14 TeV High-Luminosity LHC



[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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- **DM detection sensitivities are being improved quickly**; it is very promising to detect robust DM signals in the near future

Thank you!

