Electroweak Dark Matter and Direct Detection

David Cabo

Supervisors: Federico Mescia, Javier Virto

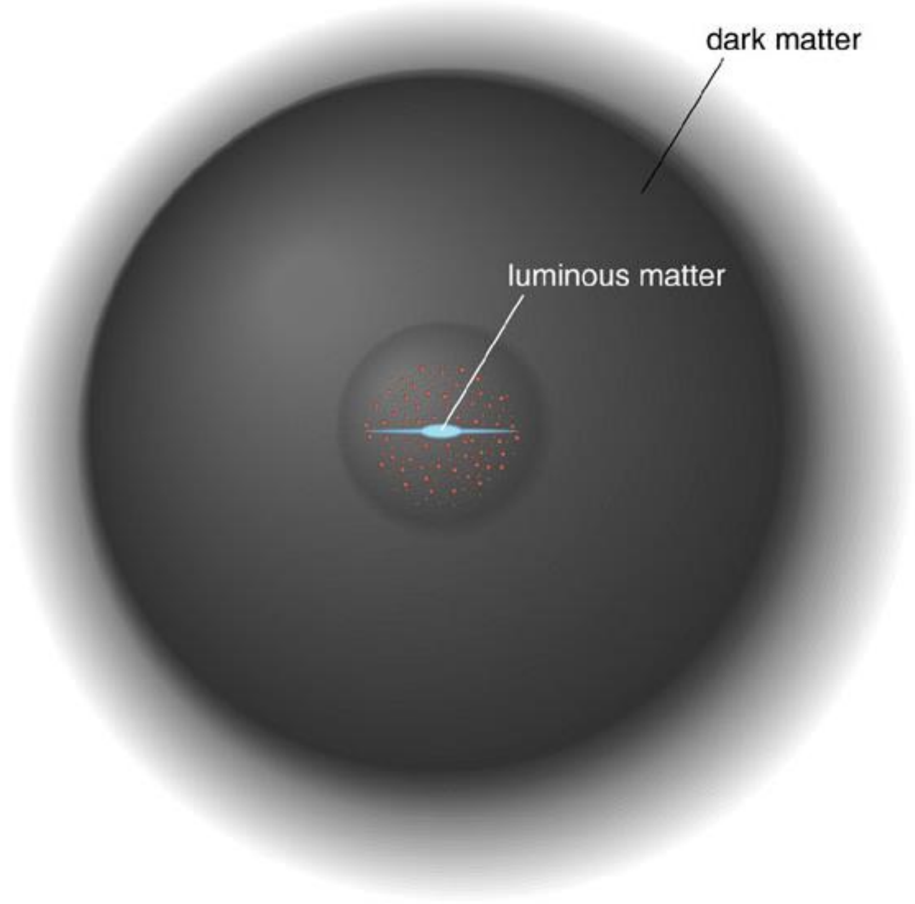
ICCUB

Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU 2020-2023

What is Dark Matter?

- All indications leads to the existence of **unobserved massive** matter
- The nature of this matter is yet a **mystery**
- If it interacts not only gravitationally the interaction would be **weak**



Evidence of Dark Matter

- **Rotation Curves:** Expected $\sim r^{-1/2}$ vs Observed constant

- **Dispersion Velocities of galaxies in clusters:** mismatch between observed and calculated mass of the galaxies using Virial theorem

- **Gravitational lensing:** analysis of the deflection patterns can be used to reconstruct the matter distribution of the lens.

- **Galaxy-cluster collisions:** give limits of the dark matter self-interaction

- **Cosmic microwave background:** spectrum fits with a 6-parameter model: ΛCDM (Λ cold dark matter) indicating that dark matter is a fundamental ingredient.

Planck collaboration $\Omega_{\mathrm{CDM}} h^2 = 0.1199 \pm 0.0022$

Candidates to Dark Matter

- **Massive Compact Halo Objects (MACHOS):** Black Holes, Neutron stars, Brown dwarfs…

- **Primordial Black Holes:** Hypothetical black holes formed soon after the Big Bang

- **Standard Model particles and beyond:**
  - **Massive:** Gravitational effects
  - **Neutral particle:** No electromagnetic interaction
  - **Stable:** did not decay until today
  - **Weak:** No strong interaction

Weakly Interactive Massive Particles

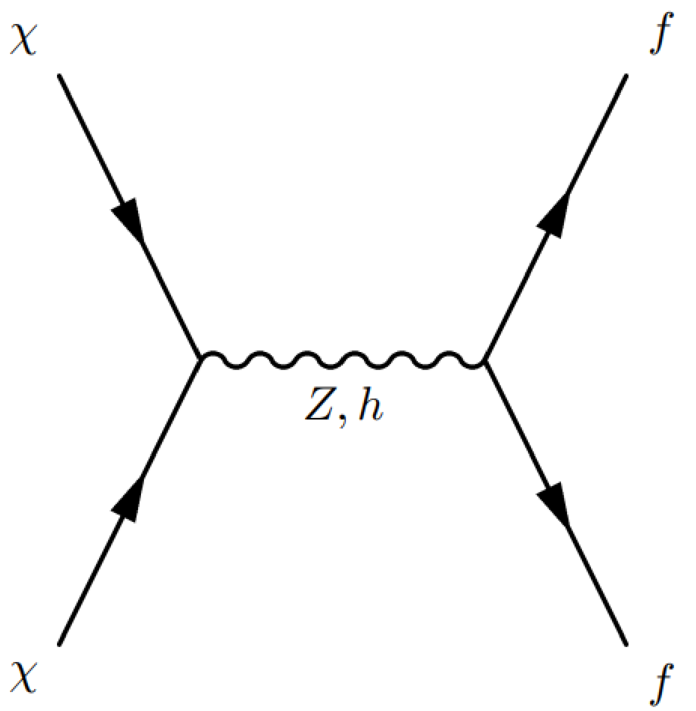
- Naturally have the right abundance to account for Dark Matter

$$m_\chi >> m_Z, m_h \;\Rightarrow\; \langle \sigma v \rangle \sim \frac{1}{m_\chi^2}$$

Weak interaction $\Rightarrow$ $\langle \sigma v \rangle \sim \frac{\alpha_W^2}{m_\chi^2}$

$$\Omega_\chi h^2 \sim 0,1$$

$$\Omega_{\mathrm{CDM}} h^2 = 0.1199 \pm 0.0022$$



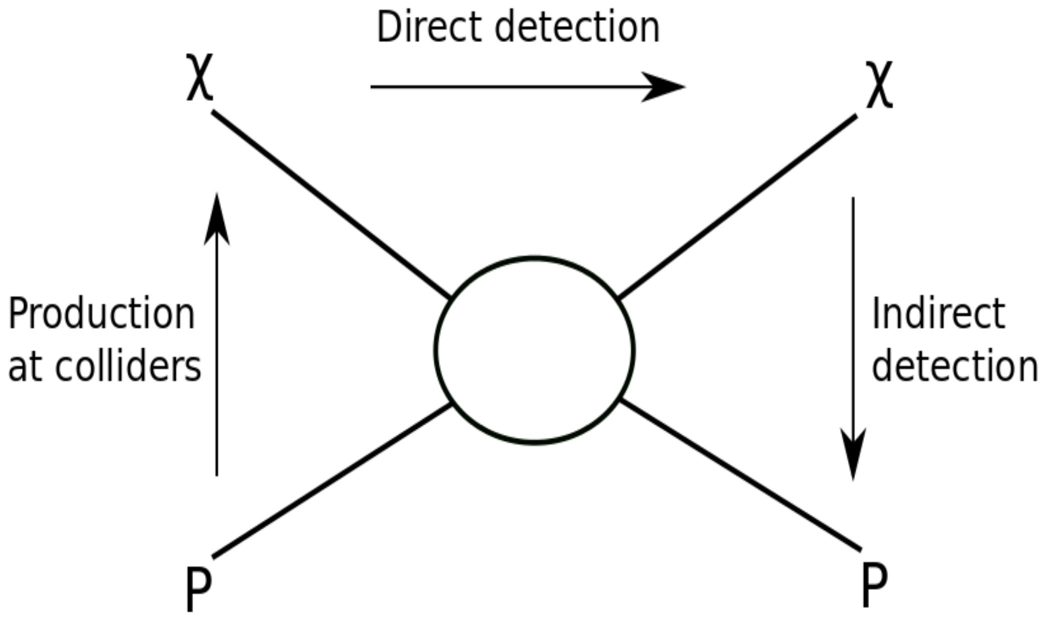
How we are looking for Dark Matter?

- **Direct Detection** the rate depends linearly on the DM density and contains integral over the velocity distribution

- **Indirect Detection** annihilation at galactic center, Milky Way satellite galaxies and close by galaxy-clusters

- **Collider Searches** invert annihilation process in the Early Universe. Search for invisible particles (missing E_T)

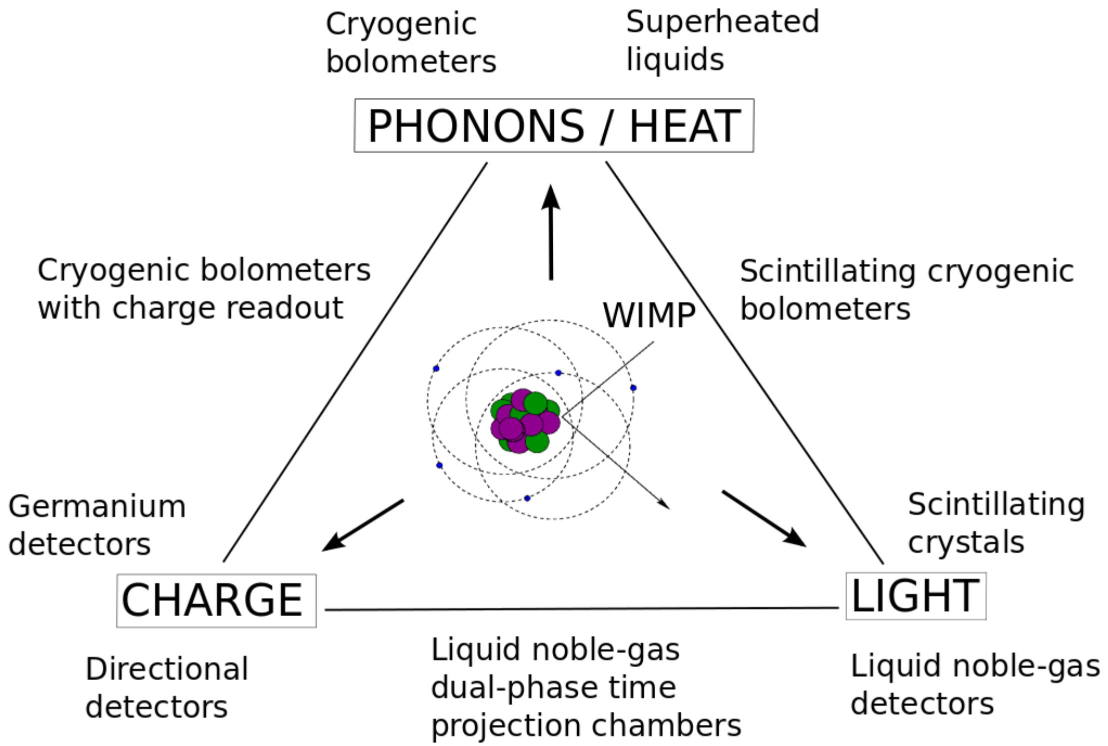
Make it!-Shake it!-Break it!



arXiv:1509.08767

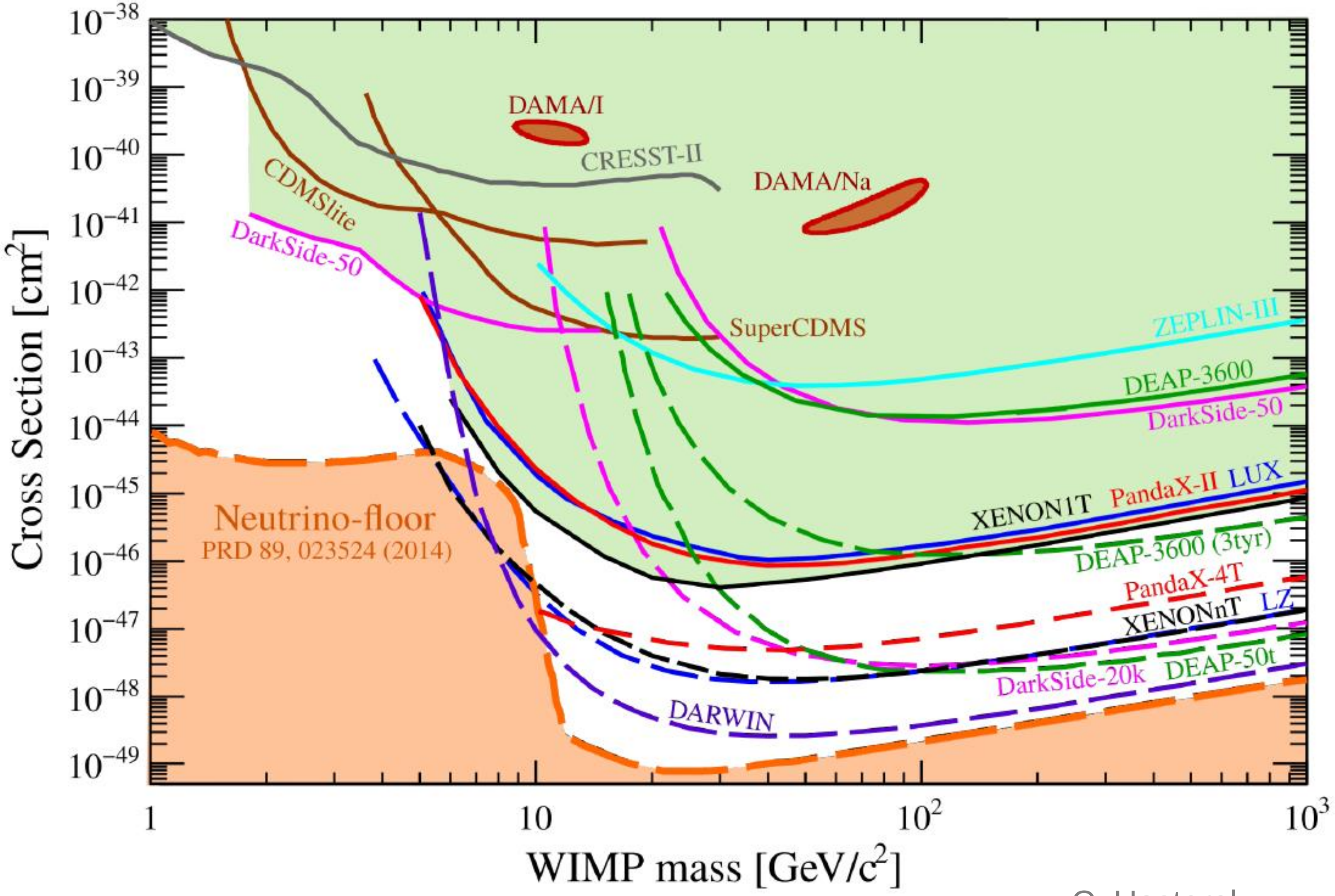
Direct Detection: Introduction

- WIMPs can scatter off Standard Model particles
- **Low cross-section** ($\sigma \sim 10^{-36} \mathrm{cm}^2$) few events by hour. Multiple interactions are negligible
- For (10- 1000) GeV/c^2 WIMP mass with velocities of standard halo model → **Nuclear recoils (1-100) KeV**
- Different forms of detection
  - **Ionization** (charge)
  - **Scintillation** (light)
  - **Heat** (phonons)
- Combination of different signals for **discrimination**



arXiv:1509.08767

Direct Detection: Overview



C. Hasterok.

Direct Detection: Scattering rate

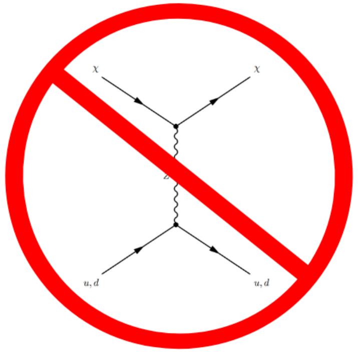
- Direct detection detects the nuclear recoil from the scattering of Dark Matter (DM) of the Galactic halo
- Not all DM has the same velocity ➡ $v_{DM} \rightarrow \int v f(\vec{v})\, d^3v$
- The distribution of the velocities can be approximated to a Maxwell-Boltzmann distribution
- Energy and momentum conservation ➡ $v > v_{min} = \sqrt{\frac{m_N E_R}{2\mu^2}}$
- The DM that escapes from the halo cannot be detected ➡ $f(v) = 0 \quad \text{for} \quad v > v_{esc}$
- Due to Astrophysical observation ➡ $\rho_{DM} \sim (0,2 - 0,5)\frac{\text{GeV}}{\text{cm}^3}$

$$\frac{dR}{dE_R}(E_R, t) = \frac{\rho_{DM}}{m_{DM} m_N} \int_{v_{min}}^{\infty} v f(\vec{v}, t) \frac{d\sigma}{dE_R}(E_R, v) \mathrm{d}^3 v$$

Model I: Minimal Model

- Colourless $(c, n, Y) \longrightarrow (1, n, Y)$
- At least one Neutral Component in the multiplet
- Not ruled out $Y \approx 0$

Multiplets of SU(2)= 1,3,5…



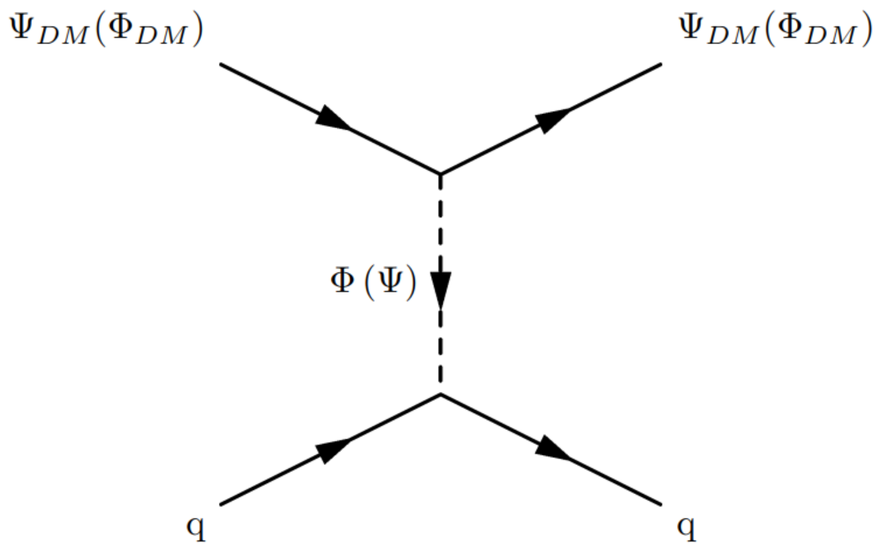
$$\mathcal{L}_{\mathcal{DM}} = \eta \begin{cases} \bar{\chi}(i\not{D} + M)\chi & \text{when } \chi \text{ is a spin } 1/2 \text{ fermionic multiplet} \\ |D_\mu \Phi_{\rm DM}|^2 - M^2 |\Phi_{\rm DM}|^2 - \lambda_{H,DM} |\Phi_{DM}|^2 |H|^2 & \text{when } \Phi_{\rm DM} \text{ is a spin 0 bosonic multiplet} \end{cases}$$

- Real scalar or Majorana fermion $\eta = 1/2$
- Complex scalar or Dirac fermion $\eta = 1$

Model II: t-Channel mediator

- Add the term:

$$\mathcal{L}_Y = \lambda_i \overline{f}_i P_R \Psi_{f_i} \Phi_{f_i} + \text{h.c.}$$



- Consider a new vector-like fermion or scalar which mediates between the SM and Dark sector

- Same constraints (SU(3),SU(2),U(1)$_Y$)

Quark Mediator		Lepton Mediator	
$\Phi_Q/\Psi_Q(DM)$	Ψ_Q/Φ_Q	$\Phi_\ell/\Psi_\ell(DM)$	$\Psi_\ell\Phi_\ell$
$(1,1,0)$	$(3,2,1/6)$	$(1,1,0)$	$(1,2,-1/2)$
$(1,3,0)$	$(3,2,1/6)$	$(1,3,0)$	$(1,2,-1/2)$

Justification for an EFT

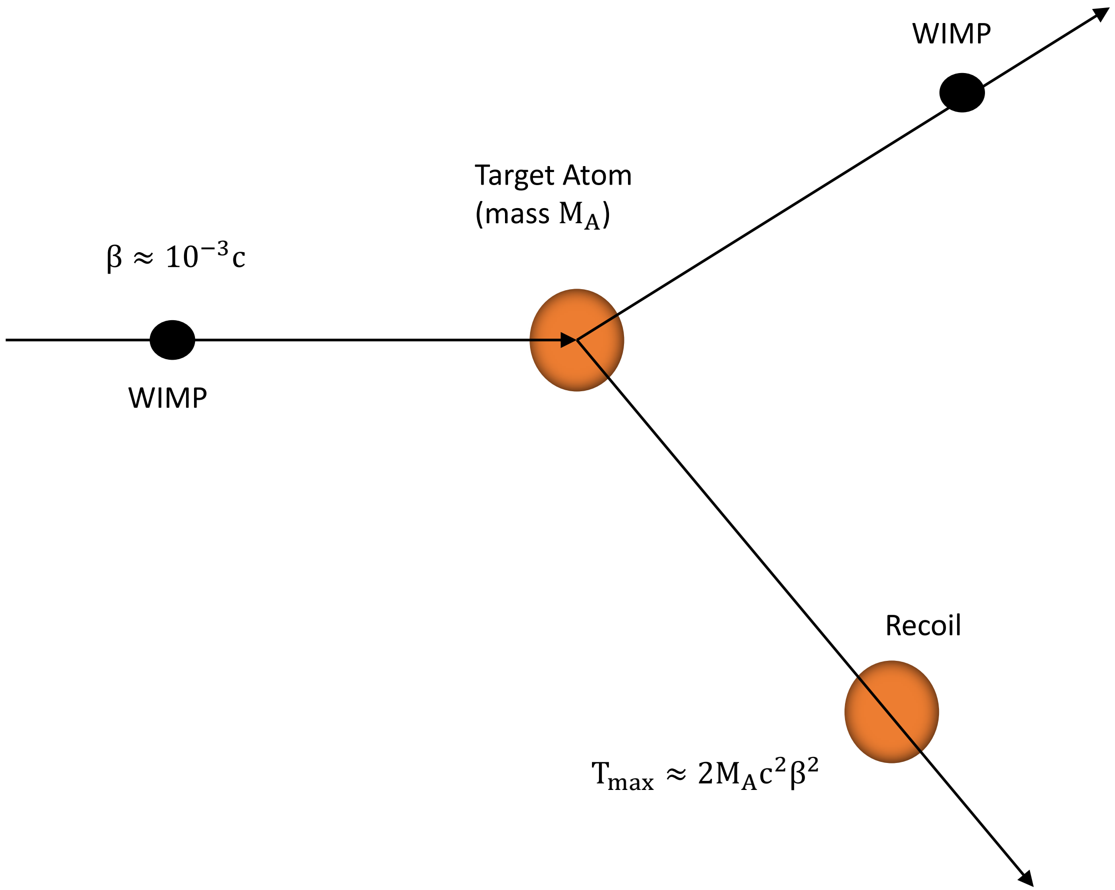
- Recoil Energy or Moment transfer

$$q = p_2 - p_1 = k_1 - k_2$$

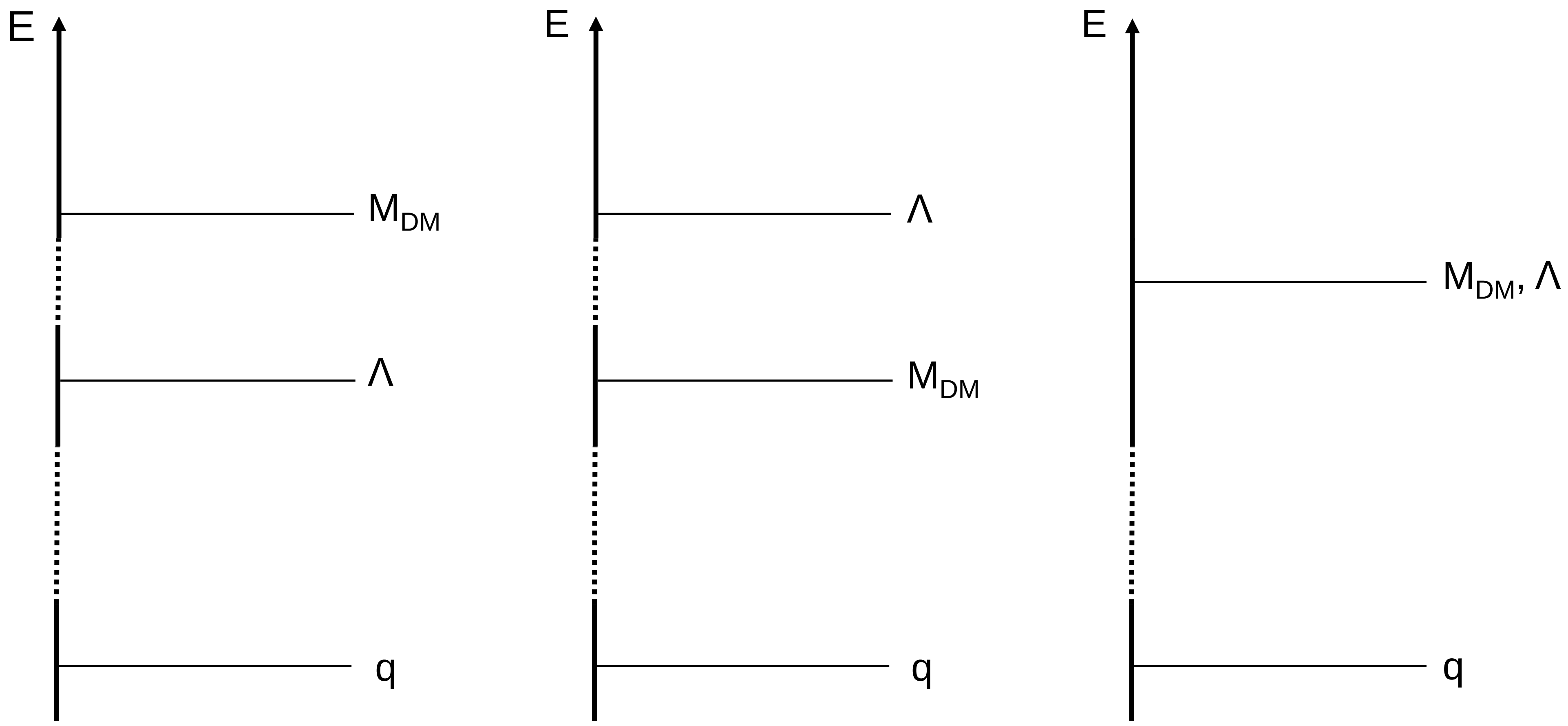
- DM low velocity $v_{DM} \sim 10^{-3}c$ → Low recoil

$$q \approx 0$$

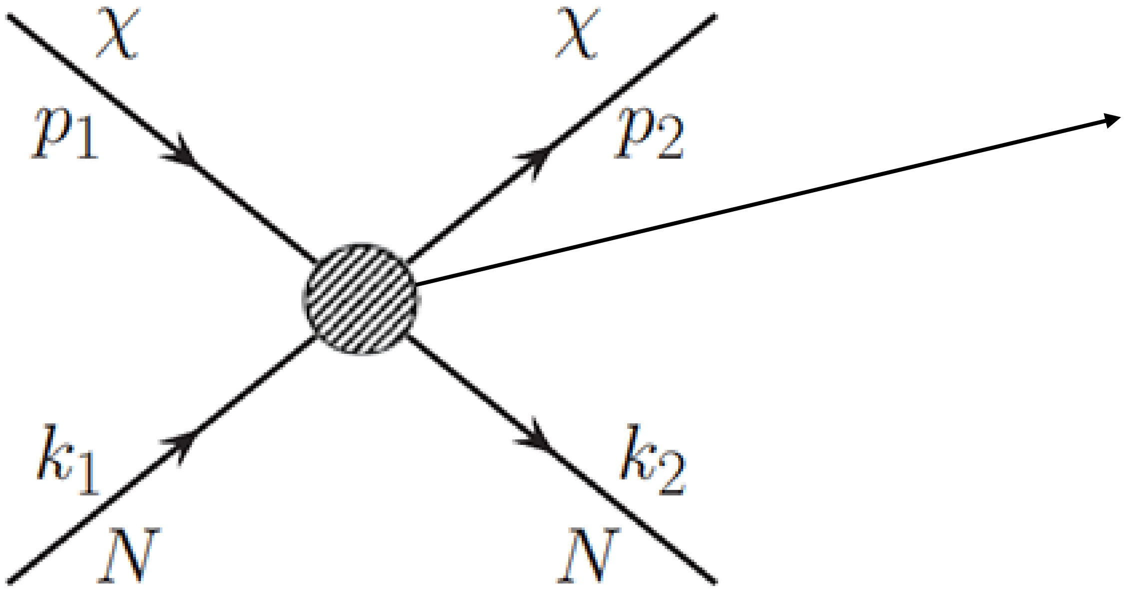
- Typically $q_{\max} \lesssim 200 \text{ MeV}$



Scales



Effective Theory



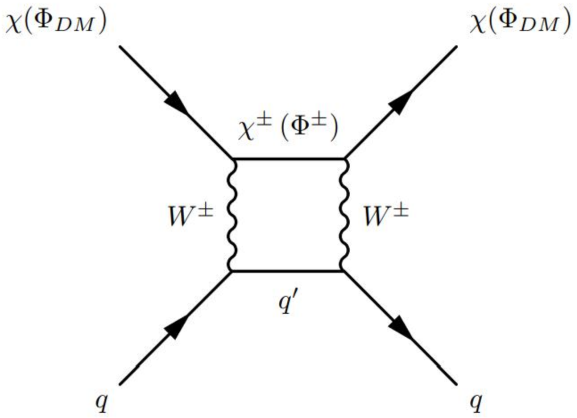
$$\mathcal{L}_{Int} = \sum_{d,m} \hat{\mathcal{C}}_a^{(d,m)} \mathcal{Q}_a^{(d,m)}$$

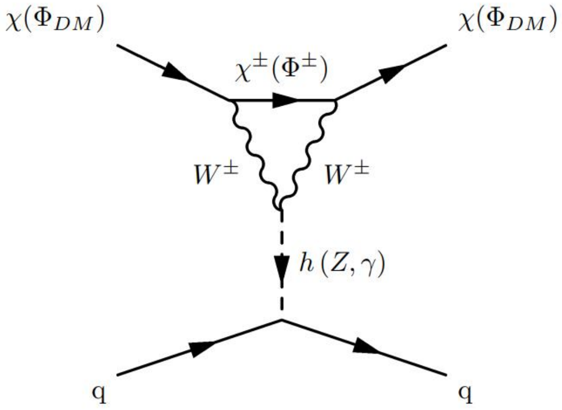
$$\text{where} \quad \hat{\mathcal{C}}_a^{(d)} = \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}}$$

The momentum transverse (q) is smaller compare to the scale of energy. We can integrate the heavy particles.

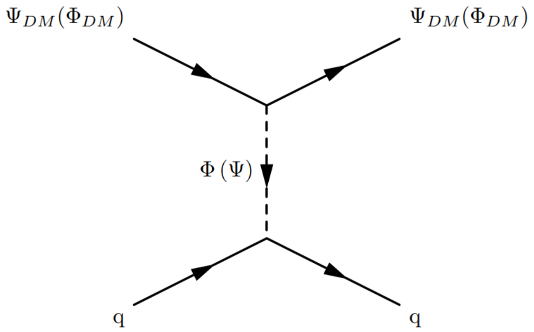
One-loop Matching Calculation

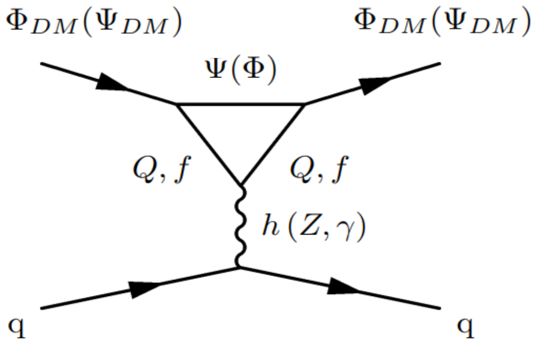
Minimal Model

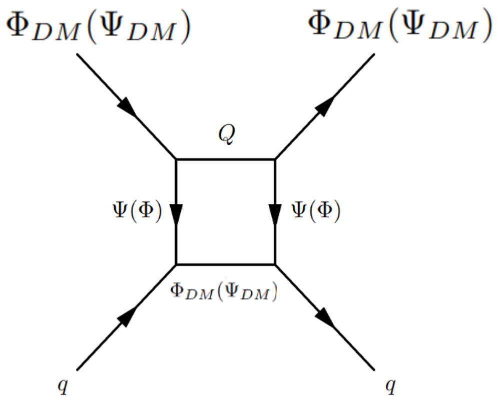


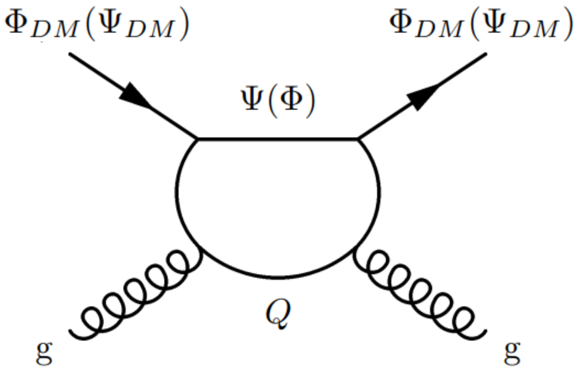


Mediator









Minimal Model: EFT Lagrangian

$$\mathcal{L}^{MF}_{q,\text{eff}} = \sum_{q=u,d,s} f_q \overline{\chi^0}\gamma^\mu\gamma_5\chi^0\bar{q}\gamma_\mu(1-\gamma_5)q + \sum_{q=u,d,s} d_q m_q \overline{\chi^0}\chi^0\bar{q}q$$
$$+ \sum_{q=u,d,s} f'_q \overline{\chi^0}\chi^0\bar{q}i\partial\!\!\!/(1-\gamma_5)q$$
$$+ \sum_{q=u,d,s} \frac{g_q^{(1)}}{M}\overline{\chi^0}i\partial^\mu\gamma^\nu\chi^0\mathcal{O}^{q,P_L}_{\mu\nu} + \sum_{q=u,d,s}\frac{g_q^{(2)}}{M^2}\overline{\chi^0}(i\partial^\mu)(i\partial^\nu)\chi^0\mathcal{O}^{q,P_L}_{\mu\nu}.$$

$$\mathcal{L}^{\text{RS}}_{q,\text{eff}} = \sum_{q=u,d,s} c^q\left(\Phi^\dagger_{\text{DM}} i \overleftrightarrow{\partial}_\mu \Phi_{\text{DM}}\right)\bar{q}\gamma^\mu q + \sum_{q=u,d,s}\lambda_{eff} M_q \Phi^\dagger_{\text{DM}}\Phi_{\text{DM}}\bar{q}q$$
$$+ \sum_{q=u,d,s} g_1^q \frac{\Phi_{\text{DM}}(i\partial^\mu)(i\partial^\nu)\Phi_{\text{DM}}\mathcal{O}^{q,P_L}_{\mu\nu}}{M^2}$$

Where: $$\mathcal{O}^{q,P_L}_{\mu\nu} = \bar{q}i\left(\frac{\partial_\mu\gamma_\nu + \partial_\nu\gamma_\mu}{2} - \frac{1}{4}g_{\mu\nu}\partial\!\!\!/\right)P_L q$$

Minimal Model: Majorana Results

$$f_q = -\frac{\alpha_2^2}{m_W^2}\left(\frac{1}{24 b_x}\sqrt{x}\left(8 - x - x^2\right)\tan^{-1}\left(\frac{2b_x}{\sqrt{x}}\right) - \frac{1}{24}x(2 - (3+x)\log(x))\right)$$

$$f'_q = 0$$

$$d_q = \frac{\alpha_2^2}{4 m_W m_h^2}\left(-\frac{2}{b_x}\left(2 + 2x - x^2\right)\tan^{-1}\left(\frac{2b_x}{\sqrt{x}}\right) + 2\sqrt{x}(2 - x\log(x))\right)$$

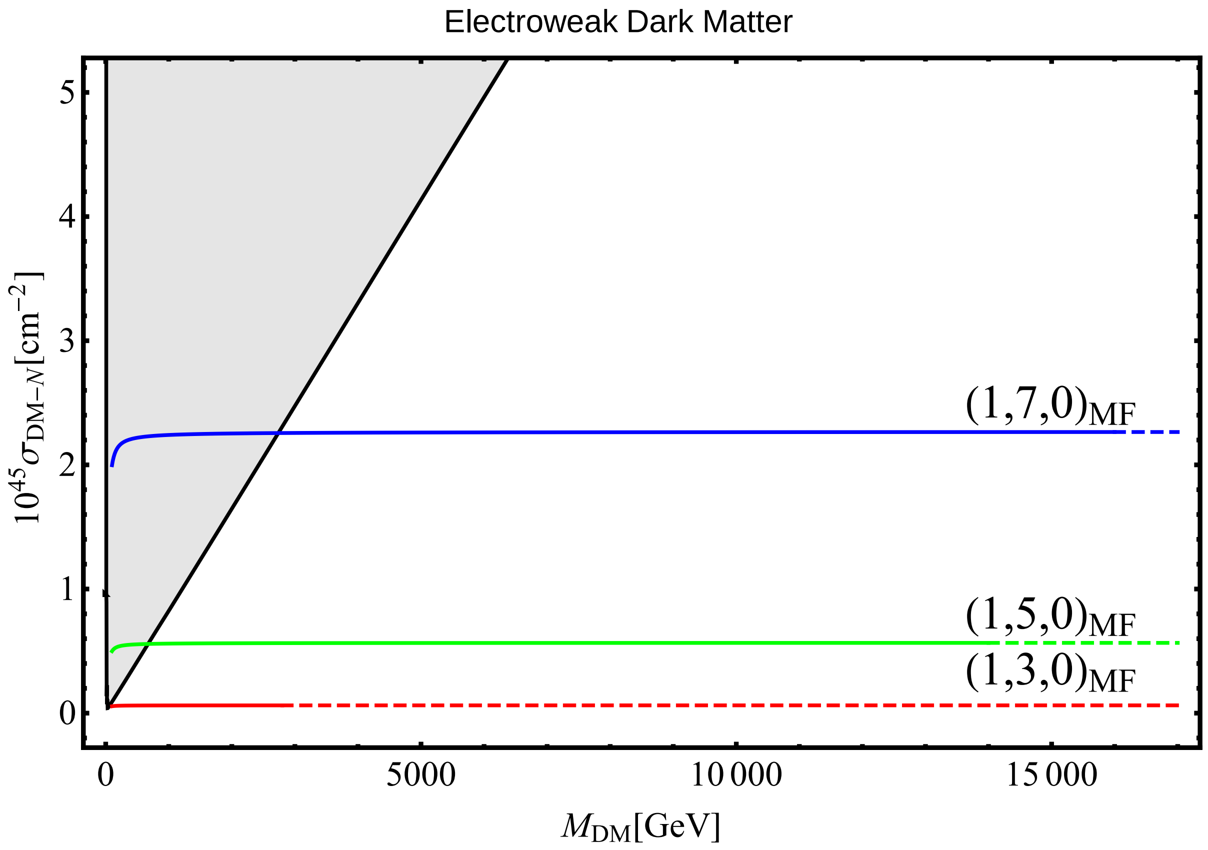
$$g_q^{(1)} = \frac{\alpha_2^2}{m_W^3}\left(\frac{1}{3}b_x\left(2 + x^2\right)\tan^{-1}\left(\frac{2b_x}{\sqrt{x}}\right) + \frac{1}{12}\sqrt{x}(1 - 2x - x(2-x)\log(x))\right)$$

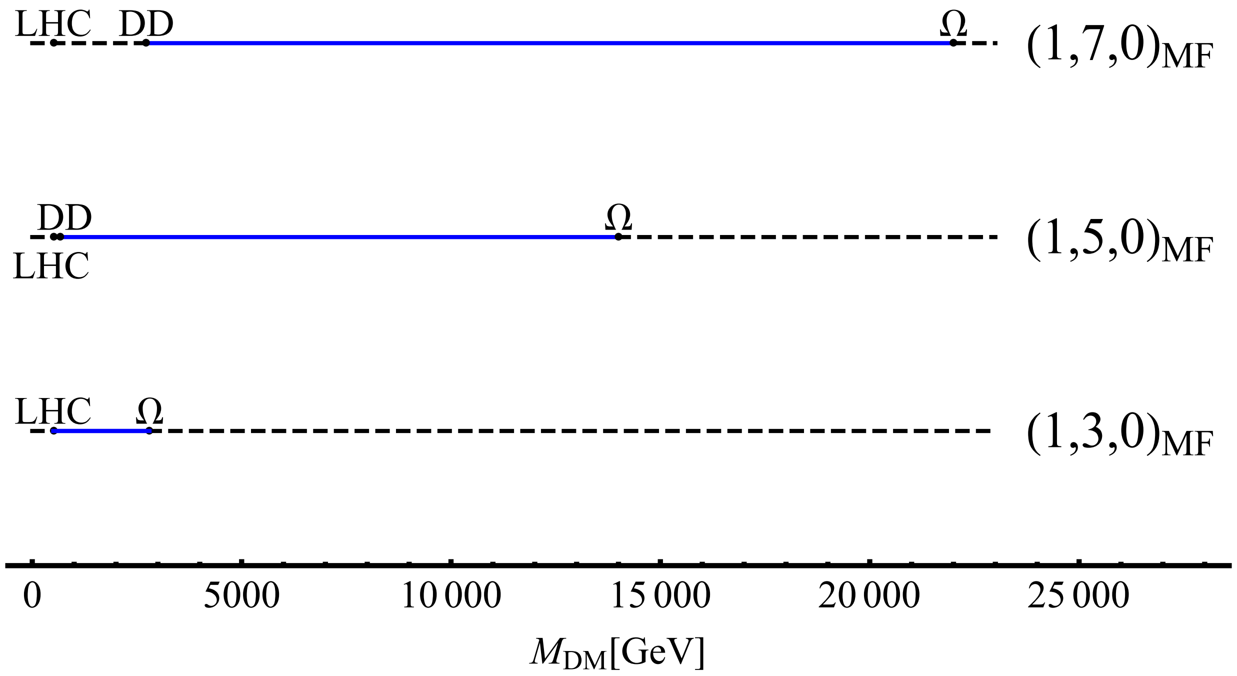
$$g_q^{(2)} = \frac{\alpha_2^2}{m_W^3}\left(\frac{1}{4b_x}x\left(2 - 4x + x^2\right)\tan^{-1}\left(\frac{2b_x}{\sqrt{x}}\right) - \frac{1}{4}\sqrt{x}(1 - 2x - x(2-x)\log(x))\right)$$

$$x \equiv m_W^2/m_{DM}^2 \qquad b_x \equiv \sqrt{1 - x/4}$$

- Real result $\langle\bar{\chi}\Gamma\chi\rangle = 2\bar{u}_\chi\Gamma u_\chi$ $\Rightarrow$ Complex results $\langle\bar{\chi}\Gamma\chi\rangle = \bar{u}_\chi\Gamma u_\chi$

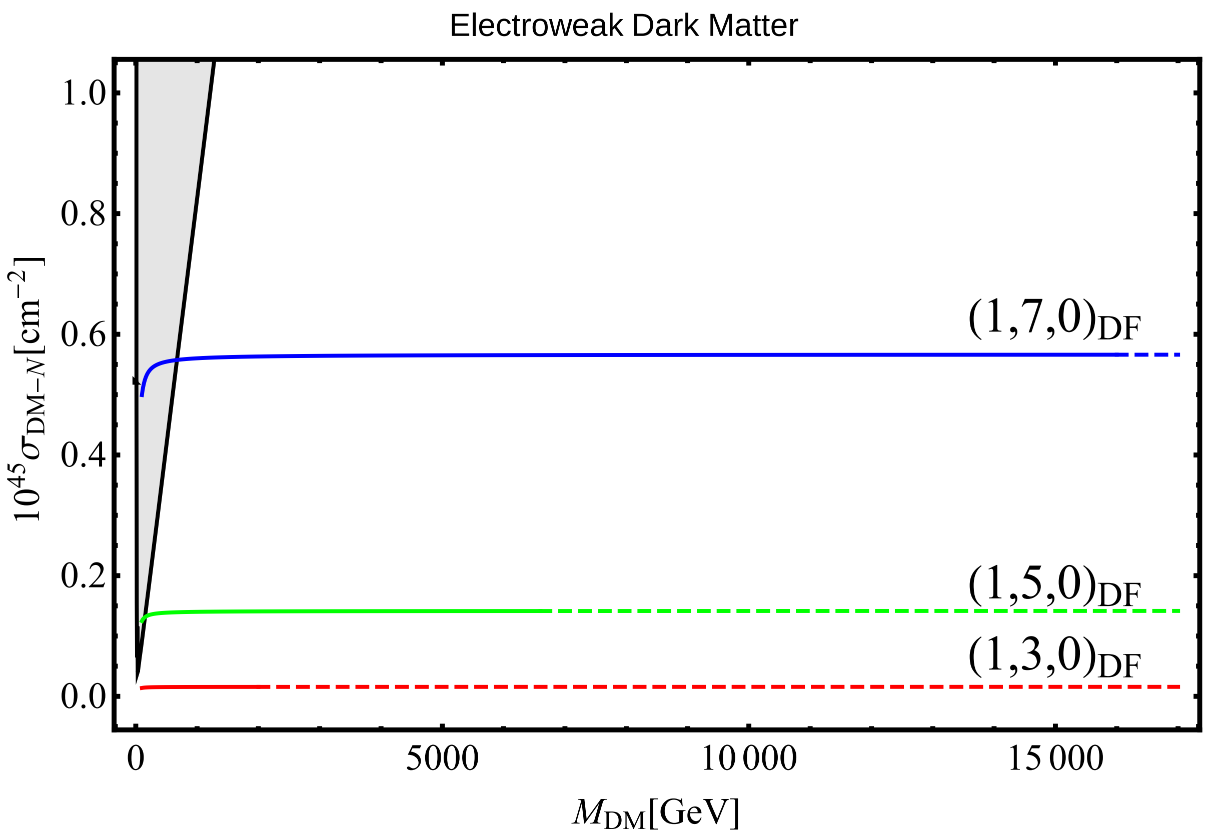
Phenomenological Results: Majorana

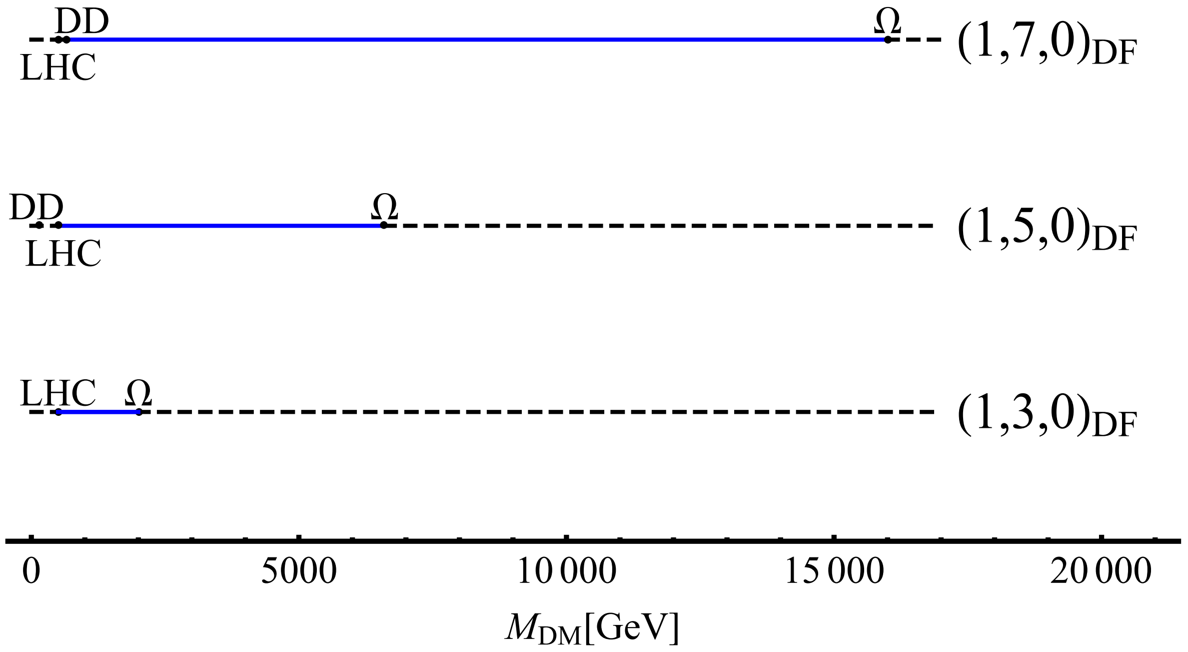




arXiv:1810.10993

Phenomenological Results: Dirac

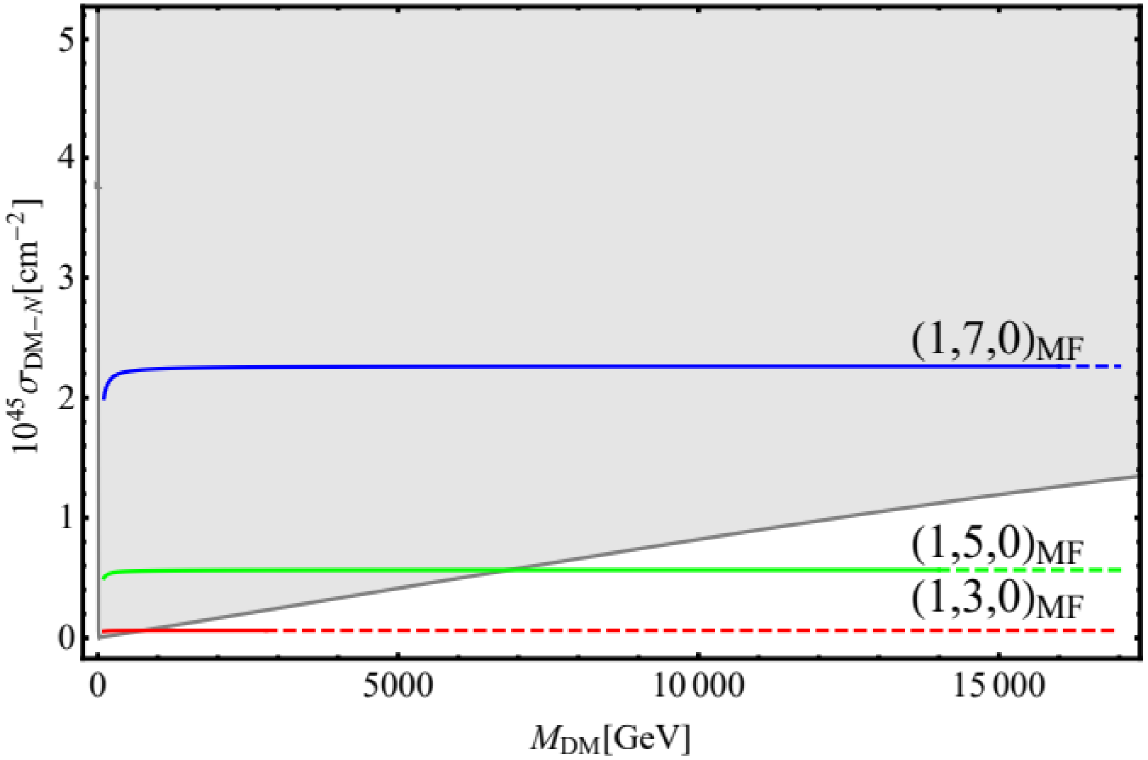




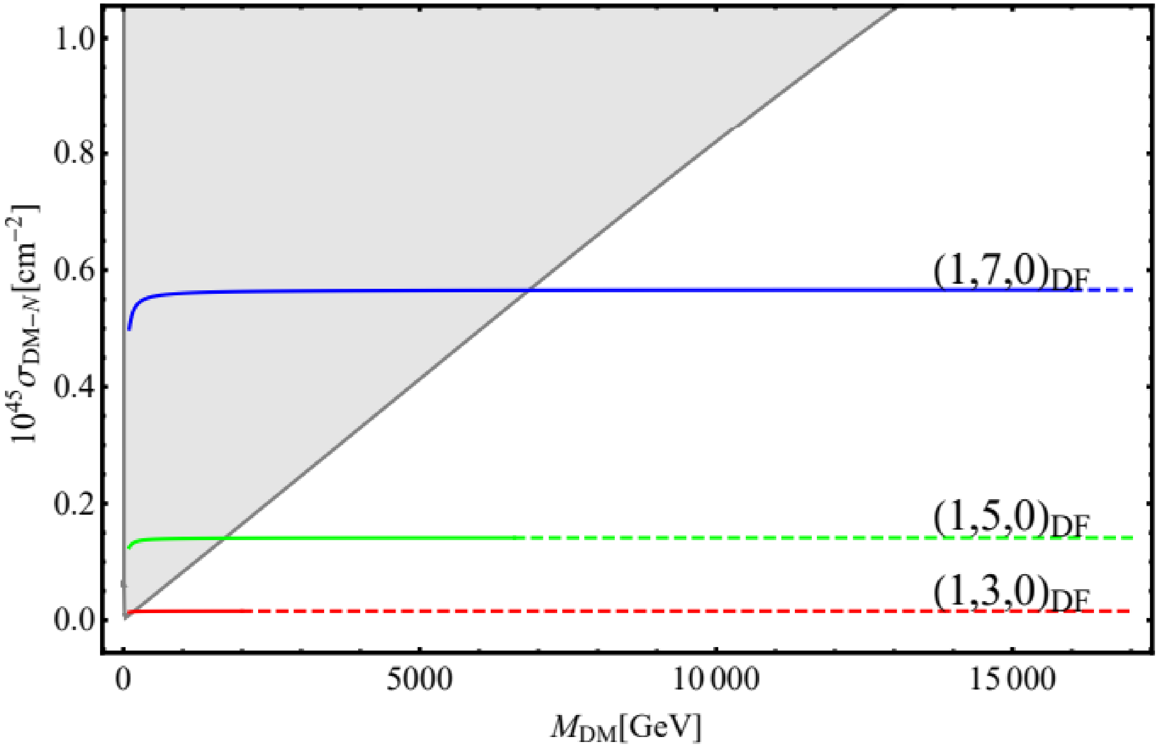
arXiv:1810.10993

Future Experiments: XENONnT

Majorana



Dirac



Comparison with earlier works

- **J.Hisano** → Disagreement with the paper published in 2005. Agreement with the Majorana calculated in the paper published in 2011 — arXiv:0407168, arXiv:1104. 0228

- **R.Essaig** → Agreement with $f'_q = 0$, but not with other coefficients — arXiv:0710.1668

- **Cirelli & Strumia** → Disagreement in all the coefficients — arXiv:hep-ph/0512090

Thank You!

Electroweak Dark Matter and Direct Detection

David Cabo

Supervisors: Federico Mescia, Javier Virto

ICCUB

Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU 2020-2023