Particle Dark Matter Direct Detection

Lecture 2

Graciela Gelmini - UCLA

U.S. DEPARTMENT OF ENERGY | Office of Science DE-SC0009937

Theory Meets Experiments 2025, GGI, Florence, Nov 10-21 2025

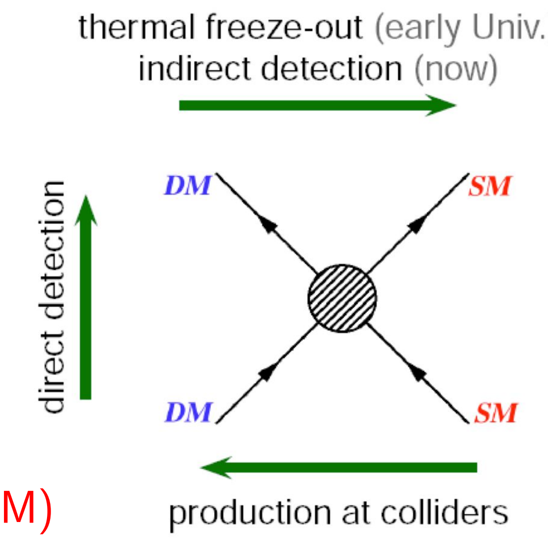
Direct Detection

- Lecture 1:
  - Brief review of the observational evidence for Dark Matter (DM)
  - What we know about DM and implications for DM candidates mass and interaction (PBH or particles? CDM, WDM, PIDM, DDDM, SIDM? Millicharge DM, kinetic mixing, Hidden (or Dark) Photons (HP or DP), Atomic DM, Mirror DM, WIMPs, FIMPs, SIMPs, ELDERs, Axions, ALPs, WISPs, FIPs...)
  - The Standard Halo Model (SHM) and its main parameters
- Lecture 2:
  - Introduction to DM Direct Detection (DD)
  - Non-directional DD of WIMPs
- Lecture 3:
  - Halo-Independent Data Analysis, – Directional DD
- Lecture 4:
  - DD of Light Dark Matter

Disclaimer: idiosyncratic choice of subjects and not complete lists of citations

WIMP DM searches:

- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way.
- Indirect Detection- looks for WIMP annihilation (or decay) products.
  (Caveat: dark matter may be stable (no decays) and may not annihilate either, as with Asymmetric DM)

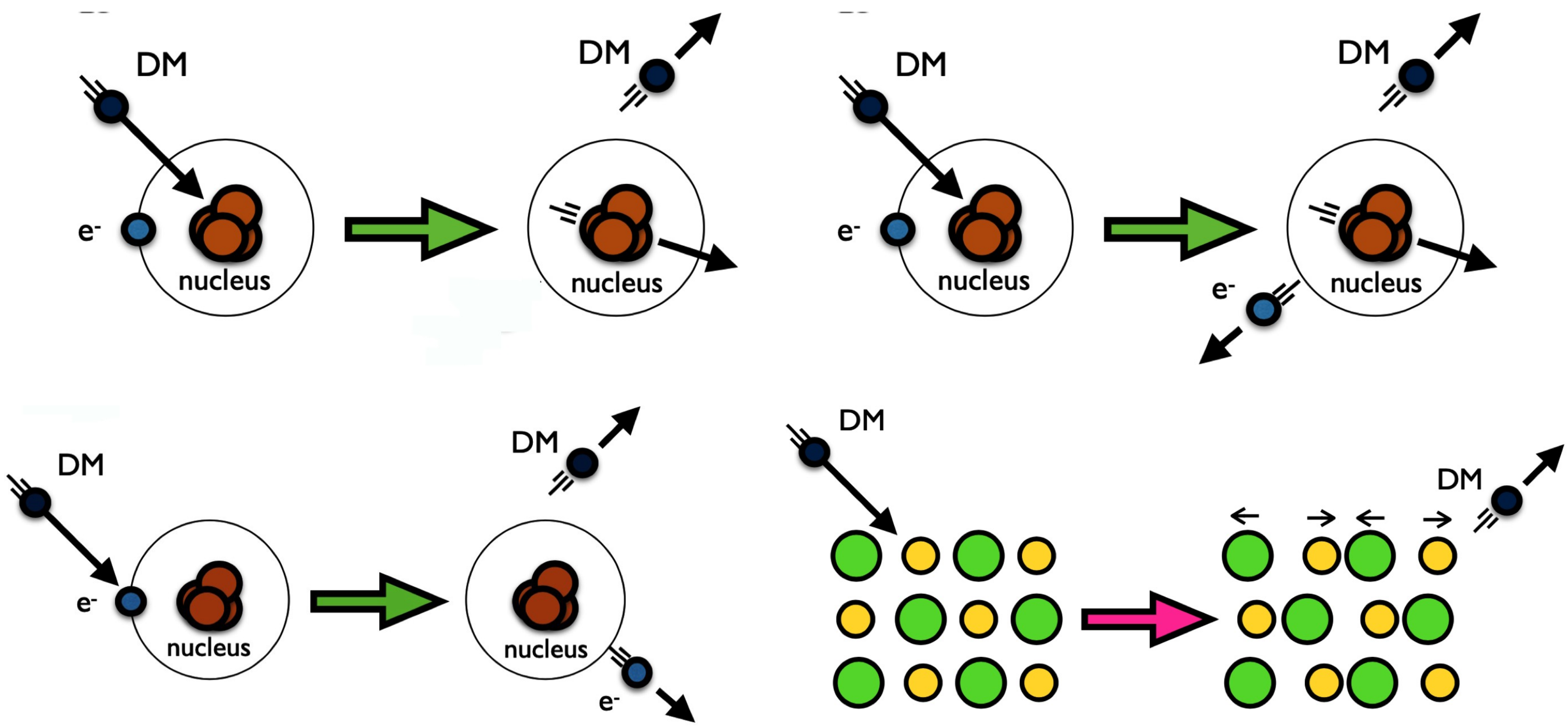


- At accelerators as missing transverse energy, mono-jet or mono-photon ... events
  (Caveats: - Reach of LHC is about 2 TeV, the DM may be heavier or its signature hidden by backgrounds. - Cannot prove particles found are stable (extrapolate from $\tau \simeq 10^{-7}$ s to $\tau \simeq 10^{17}$). - Even if a DM candidate is found in accelerator experiments, in order to prove that it is the DM we will need to find it where the DM is, in the haloes of galaxies.

All three are independent and complementary to each other!

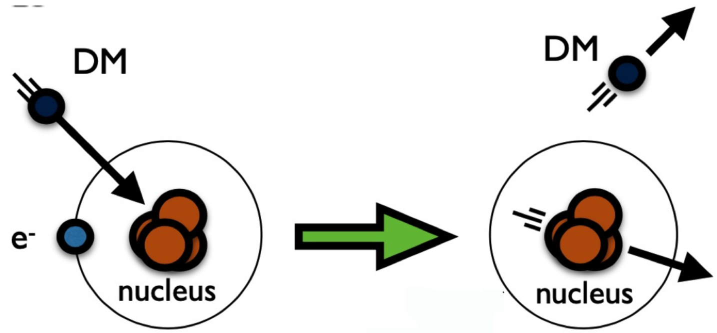
Direct DM searches: (Figs from Rouven Essig)

Looks for energy deposited within a detector through scattering or absorption of DM particles in the Dark Halo of the Milky Way ($v \simeq 10^{-3}$). Which process?

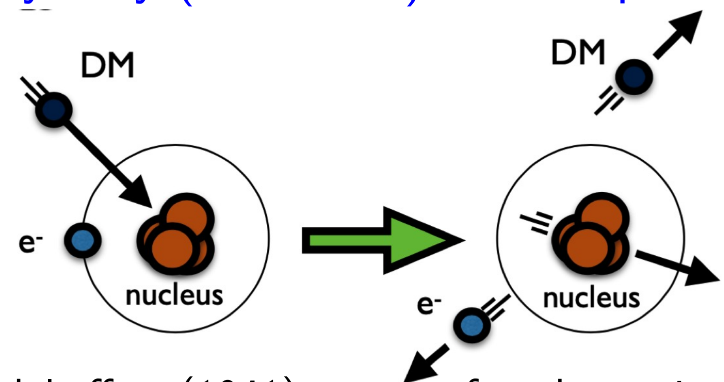


Direct DM searches: (Figs from Rouven Essig)

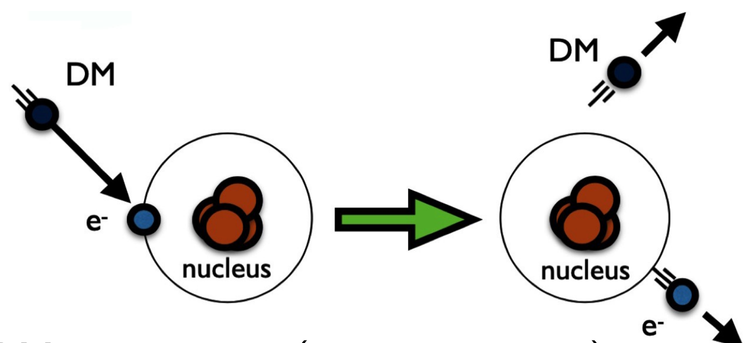
Looks for energy deposited within a detector through scattering or absorption of DM particles in the Dark Halo of the Milky Way ($v \simeq 10^{-3}$). Which process?



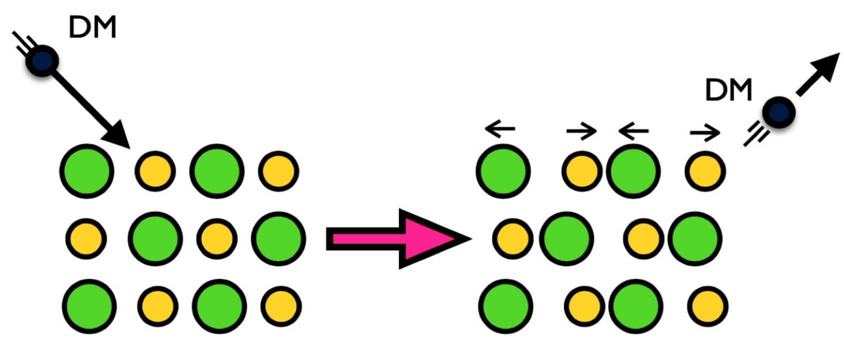
Elastic DM-Nucleus scattering



Migdal effect (1941)- not yet found experimentally



DM-e scattering (atom ionization)



DM-collective excitation scattering

For $m \geq$GeV WIMPs interact coherently with nuclei

In a non relativistic elastic collision, maximum nuclear recoil energy is $E_{max} = 2\mu^2 v^2/M$, $E \simeq$ keV (m/GeV) for $v \simeq 10^{-3}$, and for the typical momentum exchanged $q = |\vec{q}| \simeq \mu v$ with $\mu = mM/(m+M)$

$$\frac{1}{q} > R_{\rm Nucleus} \simeq 1.25 \text{ fm } A^{1/3} \quad \text{or} \quad q < 1/R_{\rm Nucleus} \simeq \text{MeV}\left(\frac{160}{A^{1/3}}\right)$$

(1=197 MeV fm; 1 femtometre, 1 fm (or Fermi)=10^{-15}m) e.g. for $m << M_{\rm Nucleus}$

$$q \simeq \text{MeV}\left(\frac{m}{\text{GeV}}\right)$$

thus WIMPs interact coherently with all the nucleons in a pointlike nucleus: A^2 enhancement in the cross section

For larger q the loss of coherence is taken into account with a nuclear form factor. E.g. for Spin-Independent interactions: conventional Helm form factor (is a charge form factor, i.e. for p, assumed to hold also for n), $F(E) = \int e^{-iqr} \rho_{\rm Nucleon}(r) dr =$
$= 3e^{-q^2 s^2/2}[\sin(qd) - qd\, \cos(qd)]/(qd)^3$, with $s = 1$ fm, $d = \sqrt{R^2 - 5s^2}$,
$R = R_{\rm Nucleus} \simeq 1.2 A^{1/3}$ fm, $q = \sqrt{2ME}$.

- Difference between WIMPs and "Light DM" (LDM) This is a recent distinction: in DM DD, WIMPs scattering on nuclei deposits enough energy to be detected ($E_{\text{threshold}} \simeq$ keV). LDM does not.

Elastic non-relativistic DM-Nucleus collision: the maximum recoil energy imparted to a nucleus by a WIMP moving with v is

$$E_{max} = 2\mu^2 v^2 / M$$

$\mu = \dfrac{mM}{(m+M)}$: reduced mass, m: WIMP mass, M: is the nucleus mass.

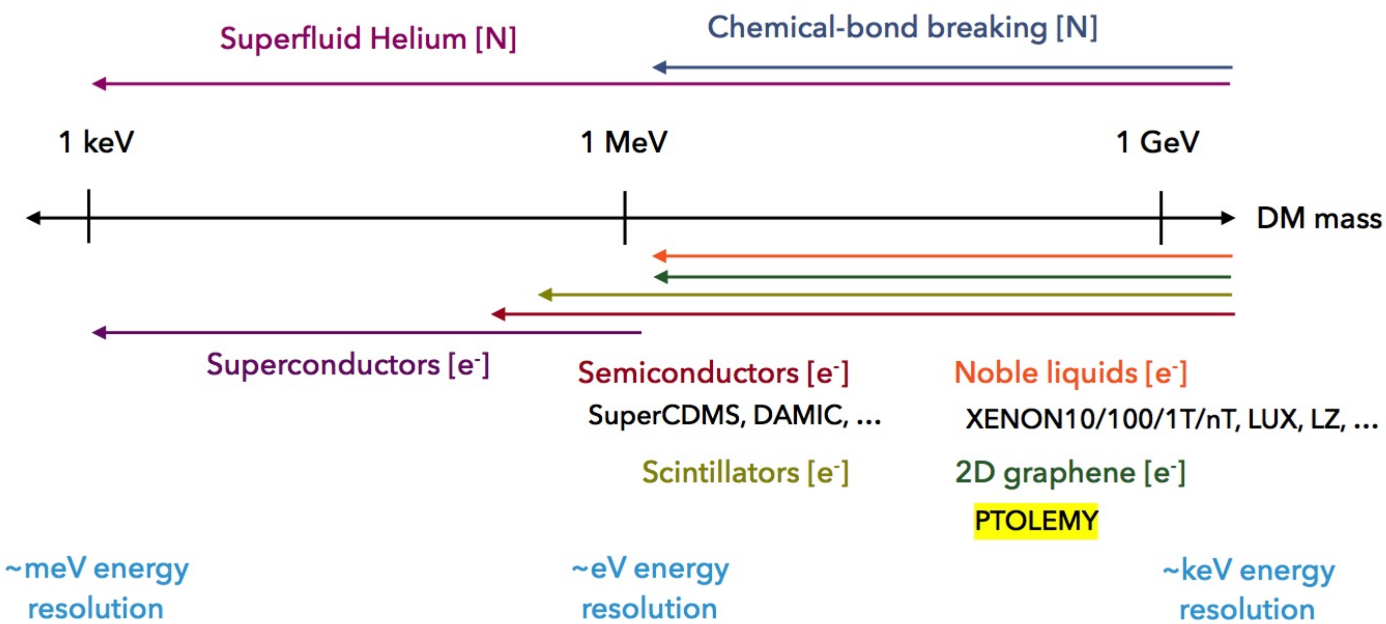
For LDM with mass $m \simeq$ keV to GeV E_{max} for $v \simeq 10^{-3}$ is below a keV threshold: e.g. for $m << M$, $\mu \simeq m$, thus

$$E_{max} = 2\mu^2 v^2 / M \simeq 20\text{eV} \left(\frac{m}{100\text{MeV}}\right)^2 \left(\frac{10\text{GeV}}{M}\right)$$

but LDM could deposit enough energy, 1 to 10 eV, interacting with electrons (electron ionization or electronic excitation or molecular dissociation...) Bernabei et al. 0712.0562; Kopp et al. 0907.3159; Essig, Mardon & Volansky, 1108.5383; Essig et al. 1206.2644; Batell, Essig & Surujon 1406.2698...

Sub-GeV "Light Dark Matter" (LDM) direct detection

Dark Sector Workshop, 1608.08632

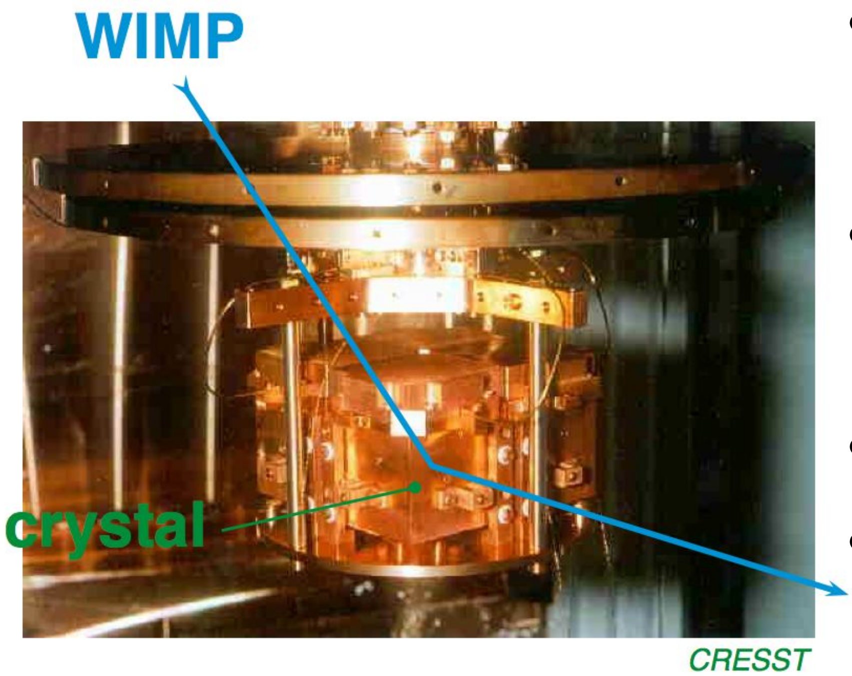


Materials that could be used to probe LDM, by scattering off electrons [e^-] or inelastic scattering nuclei [N] (photon emission in the nuclear recoil, breaking of chemical bonds in molecules or crystals, multi-phonon processes in superfluid helium or insulating crystals)

Concentrate first on $m >$ GeV WIMPs and nuclear recoils

WIMP direct DM searches :

WIMPs from the dark halo of our Galaxy would interact coherently with nuclei in a detector and produce a nuclear recoil



- Most searches are non-directional (but some in development are) (try to measure the recoil direction)
- Signature in non-directional searches is an annual rate modulation due to the rotation of the Earth around the Sun (few to 10's % effect)
- Small $E_{\rm Recoil} \leq 50$keV(m/100 GeV)
- Rate: <1 event/ kg/day for Light WIMPs and <1 event/ 100 kg/day for 60 GeV WIMPs must be underground to shield from cosmic rays.

Many direct DM experiments: most in the northern hemisphere! - southern hemisphere: Stawell UPL in a mine (and ANDES? in a mountain tunnel)

Sensitivity: (Fig. from R. Gaitskell)

- 1986 operating a 0.8 kg Ge ionization detector at Homestake Mine, SD (adjacent to Ray Davis's operating Solar Neutrino Experiment)

Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

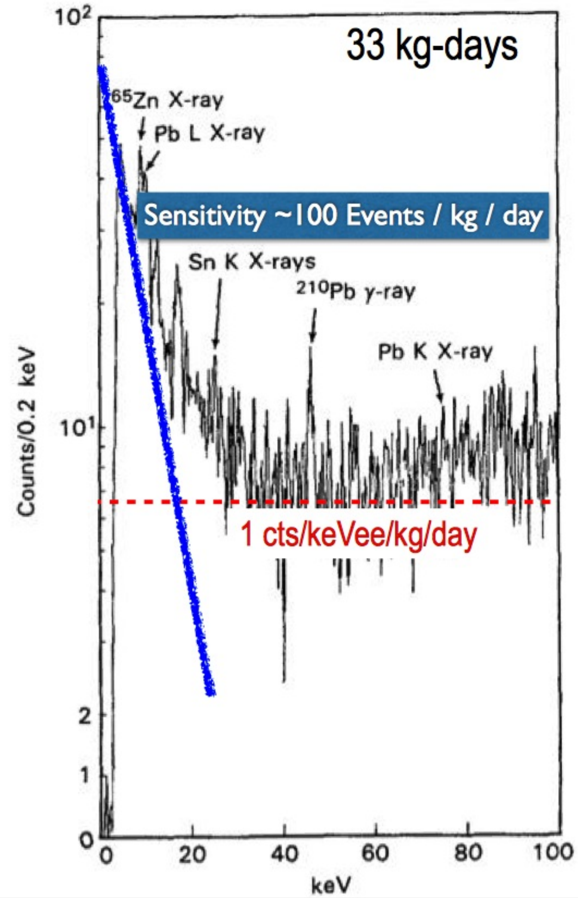
LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]

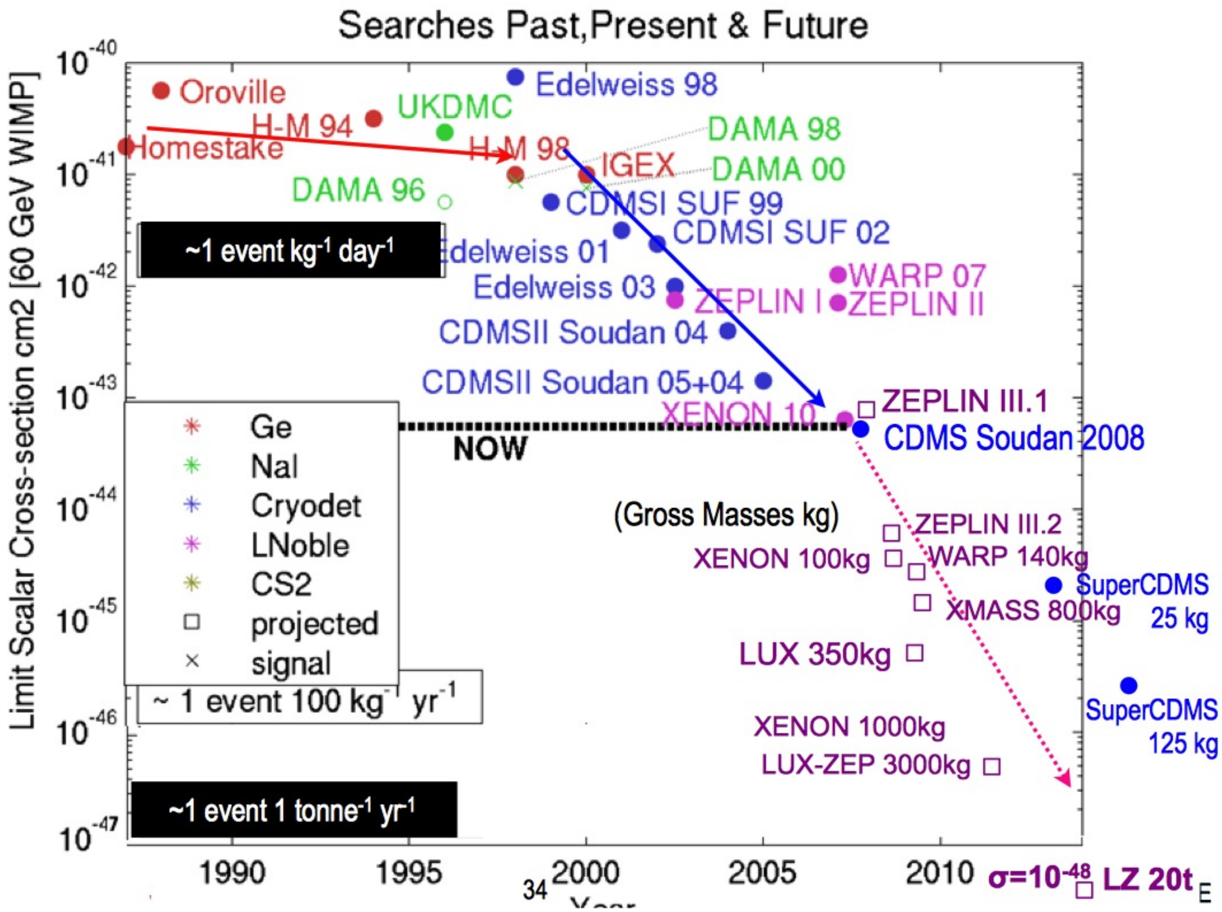
[a] *Department of Physics, Boston University, Boston, MA 02215, USA*
[b] *Department of Physics, University of South Carolina, Columbia, SC 29208, USA*
[c] *Pacific Northwest Laboratory, Richland, WA 99352, USA*
[d] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[e] *Applied Research Corp., 8201 Corporate Dr., Landover MD 20785, USA*
[f] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[g] *The Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[h] *Institute for Advanced Study, Princeton, NJ 08540, USA*

Received 5 May 1987

An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy Using a realistic model for the galactic halo, large regions of the mass–cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent Z^0 exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is <0.4 GeV/cm^3 for masses between 17.5 GeV and 2 5 TeV, at the 68% confidence level.



Sensitivity: (Fig. from R. Gaitskell)

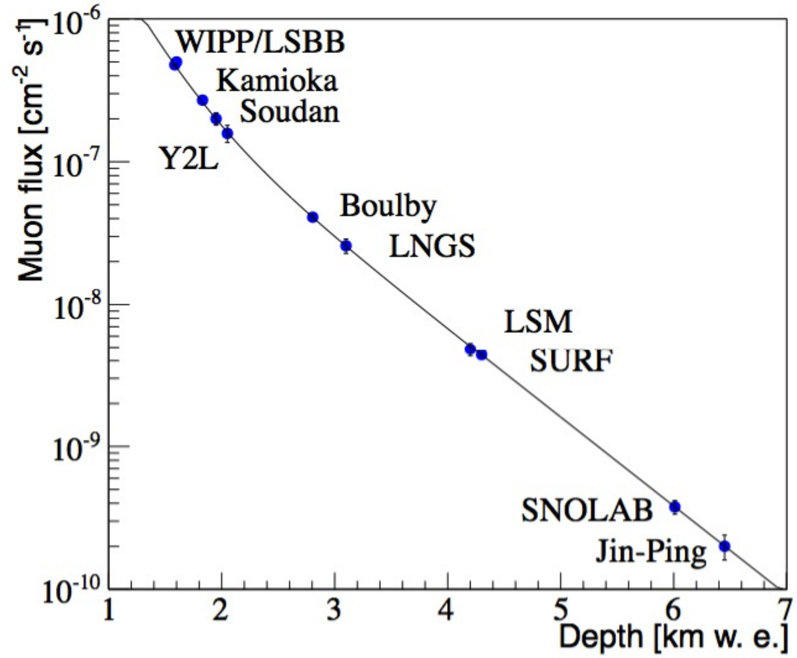


Backgrounds in Direct DM detectors:

-1- Radioactivity of surroundings. Natural radioactivity of ^{238}U, ^{238}Th, ^{40}K decays in rock and walls of the laboratory produce mostly gammas and neutrons, radon decay in the air

-2- Internal radioactivity of detector and shield materials. Many strategies to use materials with very low radioactivity.

-3- Cosmic rays and secondary reactions. Must go underground.



-4- Background of multi-ton experiments: neutrino-nucleous coherent scattering.

The only one I will talk about.

Event rate: Like the classical scattering of ping-pong and billiard balls.

$dR = N_T \times \sigma \times$ flux of projectiles with speed v

$N_T =$ number of targets

$\sigma =$ interaction cross section Thus $N_T \times \sigma =$ total area presented by targets to the projectiles

$\{$Flux of projectiles with speed $v\} = \{v\, dn(v)\} = \{[v\ (dt$ area$)\ dn(v)]/$ (area $dt)\}$ = number of projectiles with speed v reaching the detector per unit time per unit area

$$dn(v) = n f(\vec{v}, t) d^3v$$

with the velocity distribution $f(\vec{v}, t)$ normalized to 1:

$$\int f(\vec{v}, t) d^3v = 1$$

n is the total number density = number of projectiles per unit volume

Elements of the direct detection event rate

Event rate: events/(unit mass of detector)(keV of recoil energy)day

$$\frac{dR}{dE_R} = \sum_T \int_{v>v_{\min}} N_T \times \frac{d\sigma_T}{dE_R} \times n v f(\vec{v},t) d^3v$$

-E_R: nuclear recoil energy

- T: each target nuclide (elements and isotopes)

- $N_T = C_T/M_T$= Number of nuclides T in the detector = (mass fraction $\times$ Number of nuclides T per unit target mass);

- $v_{\min}$ min WIMP speed to impart E_R to the target T, $v_{\min}(E_R) = \frac{1}{\sqrt{2M_T E_R}}\left|\frac{M_T E_R}{\mu_T} + \delta\right|$
$\mu_T = mM_T/(m + M_T)$, reduced mass; $\delta = m' - m$ for DM inelastic scattering

-$\rho = nm$, $f(\vec{v},t)$: local DM density and $\vec{v}$ distribution depend on halo model.

Inelastic DM scattering

Tucker-Smith, Weiner 01 and 04; Chang, Kribs, Tucker-Smith, Weiner 08; March-Russel, McCabe, McCullough 08; Cui, Morrisey, Poland, Randall 09, many more. . .

In addition to the DM state χ with mass m_χ there is an excited state χ^* with mass m_{χ^*}

$$m_{\chi^*} - m_\chi = \delta$$

and inelastic scattering $\chi + N \to \chi^* + N$ dominates over elastic. Thus

$$v_{min}^{inel} = \left| \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}} \right| \qquad \text{instead of } v_{min}^{el} = \sqrt{\frac{ME_R}{2\mu^2}}$$

Inelastic Endothermic DM (iDM) i.e. Inelastic with $\delta > 0$

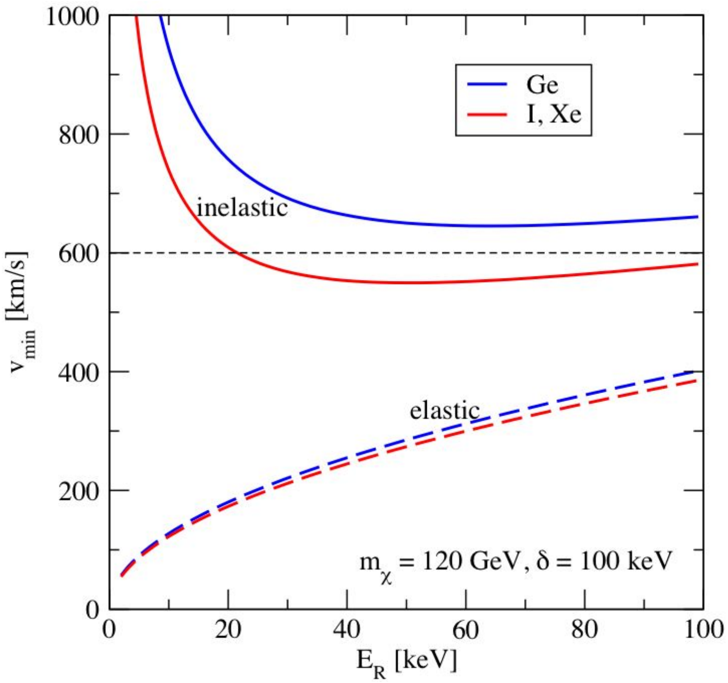
This was the initial idea. Favors heavy materials (I in DAMA over Ge in CDMS) and enhances the annual modulation amplitude

Inelastic Exothermic DM (ieDM) i.e. Inelastic with $\delta < 0$

Favors light materials (Si in CDMS over Xe in LUX and XENON) and reduces the annual modulation amplitude Graham, Harnik, Rajendran, Saraswat 1004.0937

Problem: make the excited state sufficiently long lived to be still present!

Inelastic Endothermic DM (IDM) $\delta > 0$ (fig from T. Schwetz)

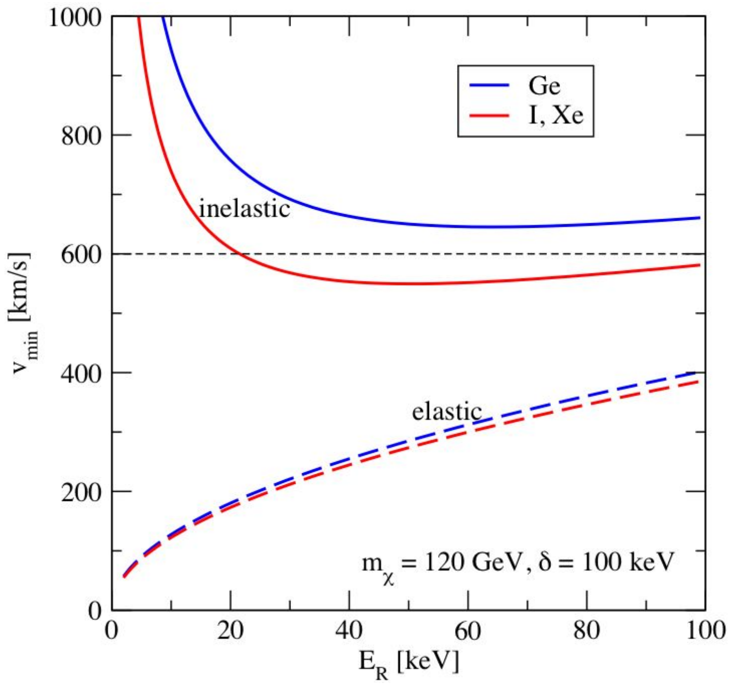


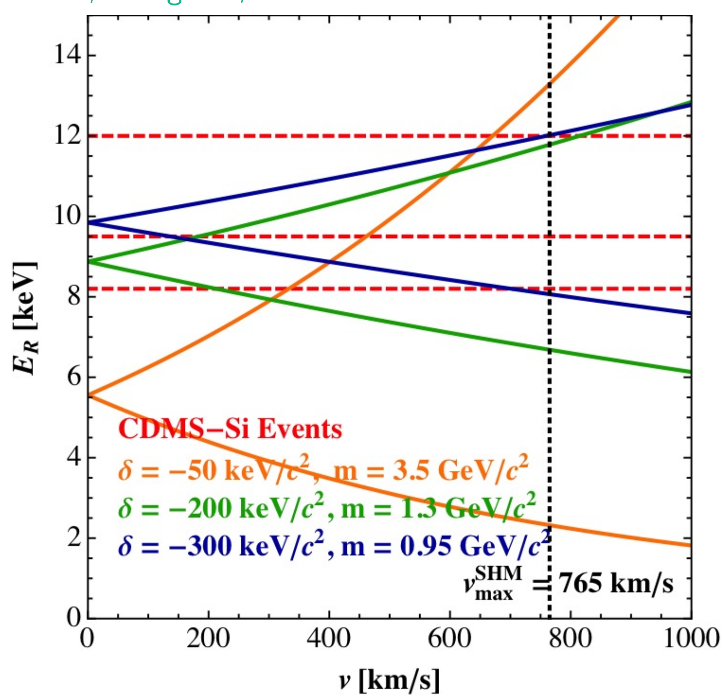
$$v_{\rm min}^{\rm inel} = \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}}$$

$$v_{\rm min}^{el} = \sqrt{\frac{ME_R}{2\mu^2}}$$

Only high v DM particles have enough energy to up-scatter, and $v_{\rm min}^{\rm inel}$ decreases with increasing target mass M, thus targets with high mass are favored (better I, Xe than Ge, Si...).
Notice no low E$_R$ events.

Inelastic Scattering Left:T. Schwetz, Right: GG, Georgescu, Huh 1404.7484





LEFT: Endothermic, only high v particles have enough energy to up-scatter, and v_{min}^{inel} decreases with increasing target mass M_T, thus targets with high mass are favored (better I than Ge...)
RIGHT: Exothermic, Characteristic recoil energy is at $v_{\rm min}$=0, $E_R = \mu_\chi \delta / M_T \simeq m_\chi \delta / M$ for $m_\chi << m_T$, which is larger for smaller M_T (for larger M_T it may be below threshold).

Event rate: usually in events/kg of detector/keV of recoil energy/day

$$\frac{dR}{dE_R} = \sum_T \int_{v>v_{\min}} \frac{C_T}{M_T} \times \frac{d\sigma_T}{dE_R} \times n v f(\vec{v},t) d^3v$$

-E_R: nuclear recoil energy- T: each target nuclide (elements and isotopes)

- $\frac{C_T}{M_T}$ =Number of nuclides T per kg in the detector
- $v_{\min}$ min WIMP speed to impart E_R to the target T - $\mu_T = mM_T/(m+M_T)$

- For a WIMP-nucleus contact interaction and momentum transfer and velocity-independent interaction cross section (operators), e.g. for Spin-Independent and Spin-Dep. interactions

$$\frac{d\sigma_T}{dE_R} = \frac{\sigma_T(E_R)\; M_T}{2\mu_T^2 v^2} \qquad \sigma_T(E_R) \sim \sigma_{\rm ref}$$

$$\frac{dR}{dE_R} = \sum_T \frac{\sigma_T(E_R)}{2m\mu_T^2}\, \rho\eta(v_{\min}) \qquad \text{where} \qquad \eta(v_{\min}) = \int_{v>v_{\min}} \frac{f(\vec{v},t)}{v} d^3v$$

-$\rho = nm$, $f(\vec{v},t)$: local DM density and $\vec{v}$ distribution depend on halo model.

Thus, given $\rho\eta(v_{\min})$ and the particle model, the plots are in the $m, \sigma_{\rm ref}$ plane ("Halo-Dependent" analysis)

The recoil rate dR/dE_R is not directly accessible to experiments, they observe only a proxy E' for the recoil energy E_R with E'-dependent energy resolutions/efficiencies.

Observed event rate:

$$\frac{dR}{dE'} = \epsilon(E') \int_0^{\infty} dE_R \sum_T G_T(E_R, E') \frac{dR_T}{dE_R}$$

- E': detected energy (in keVee or number of PE), C_T: mass fraction in target nuclide T;
- $\epsilon(E')$: counting efficiency or cut acceptance; $G_T(E_R, E')$: energy response function

$$\frac{dR_T}{dE_R} = \frac{C_T}{M_T} \int_{v>v_{\min}} \frac{d\sigma_T}{dE_R} \times \frac{\rho}{m} v f(\vec{v}, t) d^3v$$

Elements of the rate: Each with its own uncertainties

[Event Rate] = [Detector Response] x [Cross Section] x [Halo Model]

Elements of the Event Rate

[Event Rate] = [Detector Response] x [Cross Section] x [Halo Model]

Is a particular recoil event with recoil energy E_R observable in the detector?

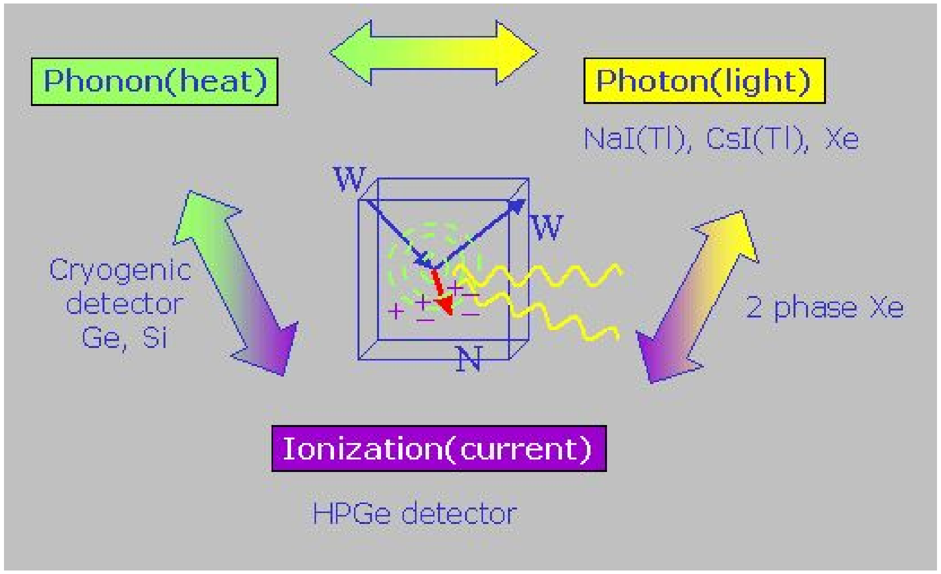
- E': detected energy (in keVee or number of PE);
- $\epsilon(E')$: counting efficiency or cut acceptance
- $G_T(E_R, E')$: effective energy response function $=$ probability of observing and event with energy E' when a collision with energy E_R occurred. Includes the energy resolution $\sigma_E(E')$ and the mean value $\langle E' \rangle = E_R Q_T(E_R)$
- Q_T: quenching factor of nuclide T
- $L_{\rm eff}$: relative scintillation efficiency w.r.t an electron recoil in LXe and LAr.

Signals in Direct Searches:

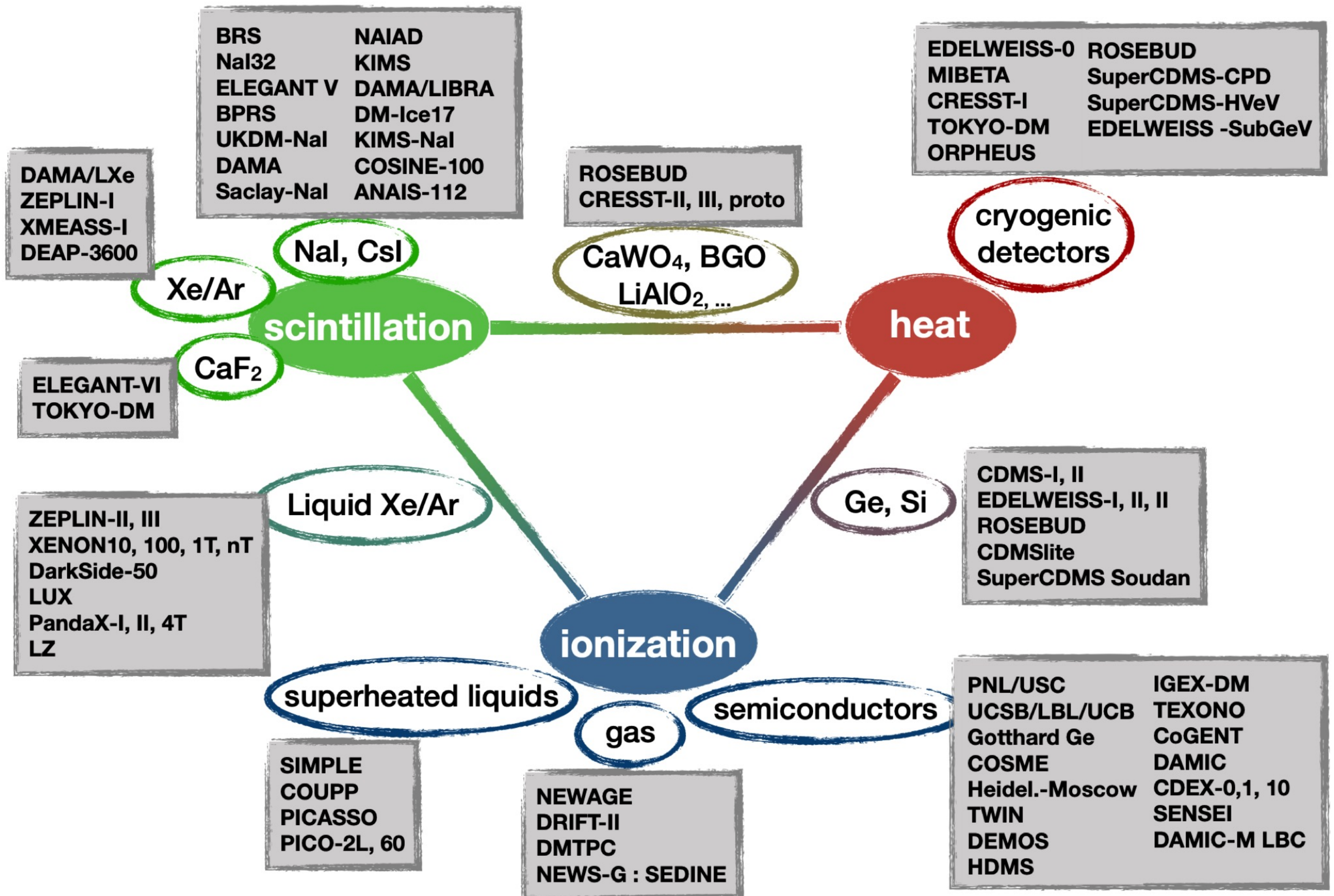
In crystals: most of the recoil energy goes usually to phonons, but a fraction Q goes into ionization/ scintillation, $Q_{\rm Na} = 0.3$, $Q_{\rm I} = 0.09$...

In LXe, LAr: $L_{\rm eff}$ measures scintillation (S1) and there is also delayed ionization (S2).

Fig. from KIMS



Signals in Direct Searches: Cirelli, Strumia, Zupan 2406.01705

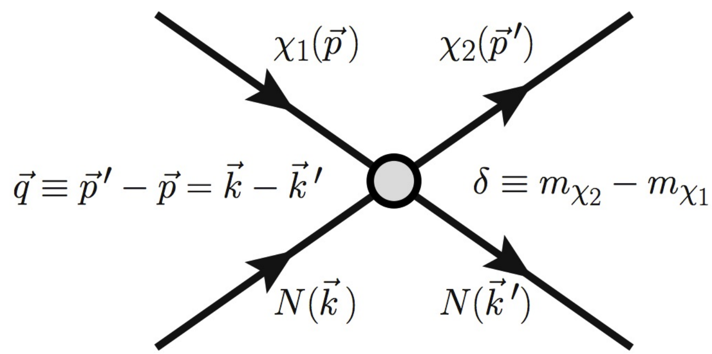


I leave this issue for experimentalists...

Elements of the Event Rate

[Event Rate] = [Detector Response] x [Cross Section] x [Halo Model]

How does the DM particle couple to the nuclei?
Besides the DM mass m, this is the only input
of Particle Physics



Two types of DM-baryon interaction models:
- Starting with fundamental interactions DM particles couple to quarks, and need to pass from quarks to nucleons $N = p, n$, and then to nuclei
- Phenomenologically, can start with couplings to N, and then nuclei.

Usual interactions

- Contact Spin-Independent (SI): $\sigma^{SI}(q) = \sigma_0 F^2(q)$

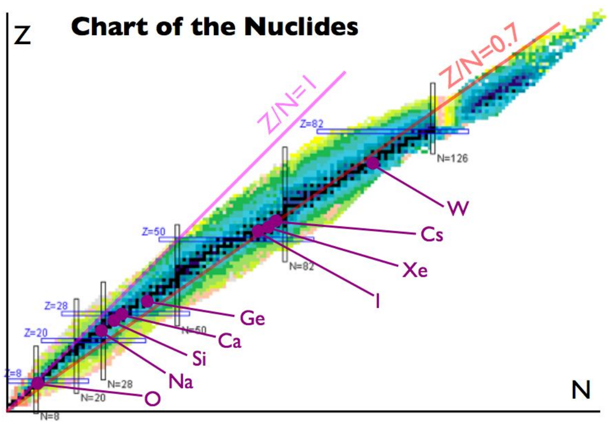
From scalar and vector couplings in the Lagrangian- $f_{p,n}$ effective couplings to p, n

$$\sigma_0 = [\langle Z f_p + (A-Z) f_n]^2 (\mu^2/\mu_{\rm p}^2)\sigma_{\rm p} = A^2(\mu^2/\mu_{\rm p}^2)\sigma_{\rm p} \text{ for } f_p = f_n \text{ for IC}$$

Isospin conserving (IC) or violating (IV) spin independent?

IV can make the coupling $[Z f_p + (A-Z) f_n] \simeq 0$ for $f_n/f_p \simeq -Z/N$, not exactly zero because of isotopic composition

Kurilov, Kamionkowski 2003; Giuliani 2005; Cotta et al 2009; Chang et al 2010; Kang et al 2010, Feng et al 2011...



$f_n/f_p \simeq -0.7$ disfavors Xe maximally
$f_n/f_p \simeq -0.8$ disfavors Ge maximally
(and changes the couplings of all other materials too)

Particle models exists, e.g. Del Nobile, Kouvaris and Sannino, "Interfering Composite Asymmetric Dark Matter", 1105.5431

Usual interactions

- **Contact Spin-Dependent:** $\sigma^{SD}(q) = \dfrac{32\mu^2 G_F^2 (J_N+1)}{J_N}\left[\langle S_{\rm p}\rangle a_{\rm p} + \langle S_{\rm n}\rangle a_{\rm n}\right]^2$

From axial vector couplings-$a_{p,n}$ couplings to p, n. Need non zero nuclear spin J_N

Examples: ^{29}Si ($J_N = 1/2$, 4.7%), ^{129}Xe ($J_N = 1/2$, 26.4%), ^{131}Xe ($J_N = 1/2$, 21.2%)

$\langle S_{\rm p,n}\rangle$ are expectation values of the spin content of p,n in the target nucleus. It is due mostly to an unpaired nucleon:

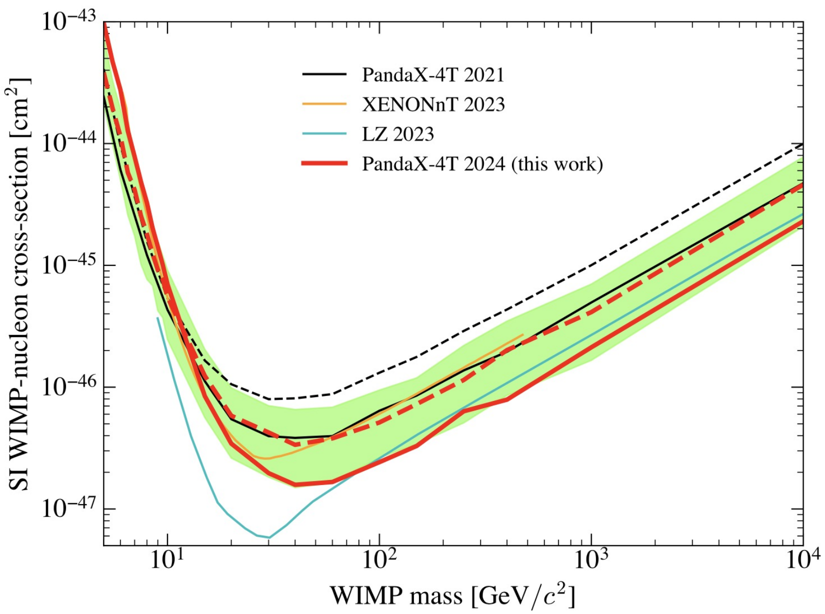
- **Na, I, F have unpaired** p (DAMA, KIMS..) ,
- **Xe, Ge have unpaired** n (XENON, LZ, LUX, PandaX, XLZD, CDMS...) ,
- **Ar does not have spin** (DarkSide, GADMC...) .

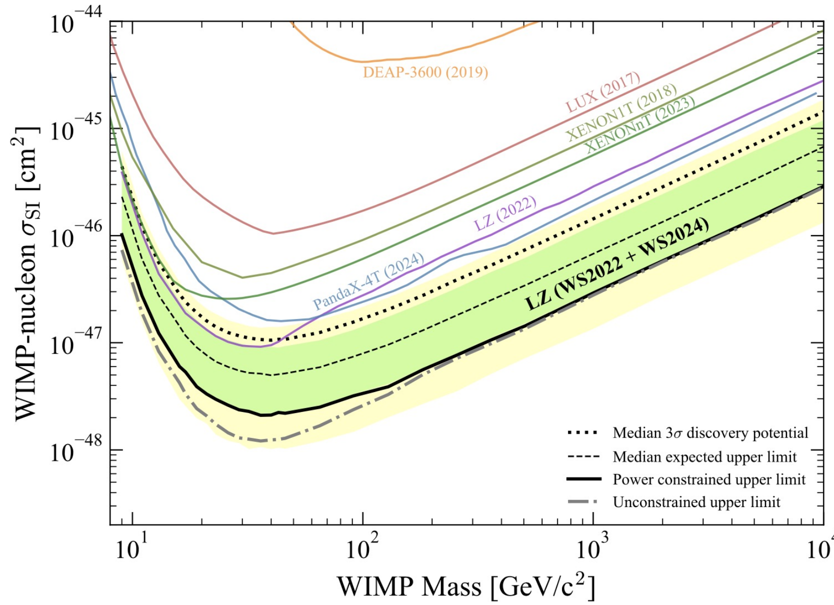
Example: ^{73}Ge ($J_N = 9/2$, 7.8% in isotopic composition) Single particle shell model: $\langle S_{\rm n}\rangle =$ 0.5, $\langle S_{\rm p}\rangle = 0$ (Odd-group model: 0.23, 0; Shell Model 0.488, 0.011)

Experimentalists mostly use Isospin-Conserving (IC) SI and SD to give limits

Recent SI WIMP limits

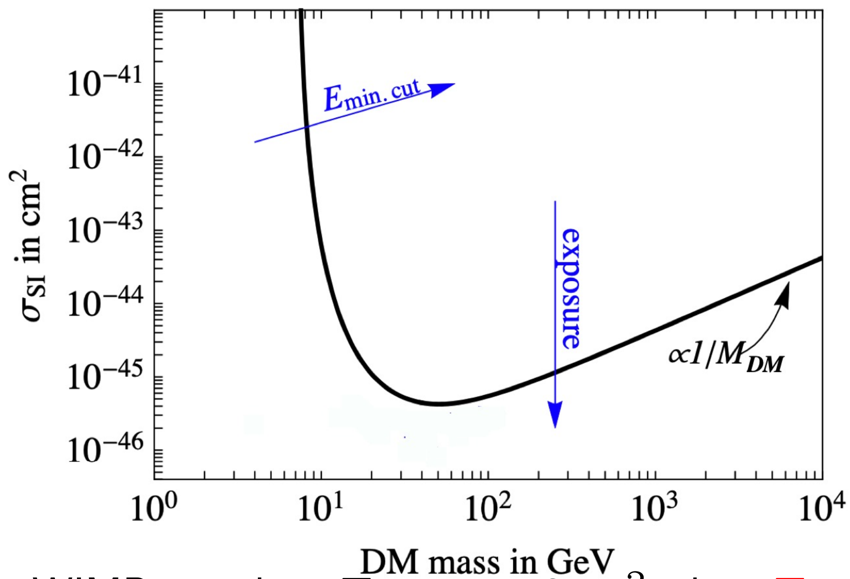
From PandaX-4T (for 1.54 tonne-year) 2408.00664 and LZ (4.2±0.1 tonne-year) 2410.17036





SI interactions, 90% CL upper limits

Shape of exclusion plots



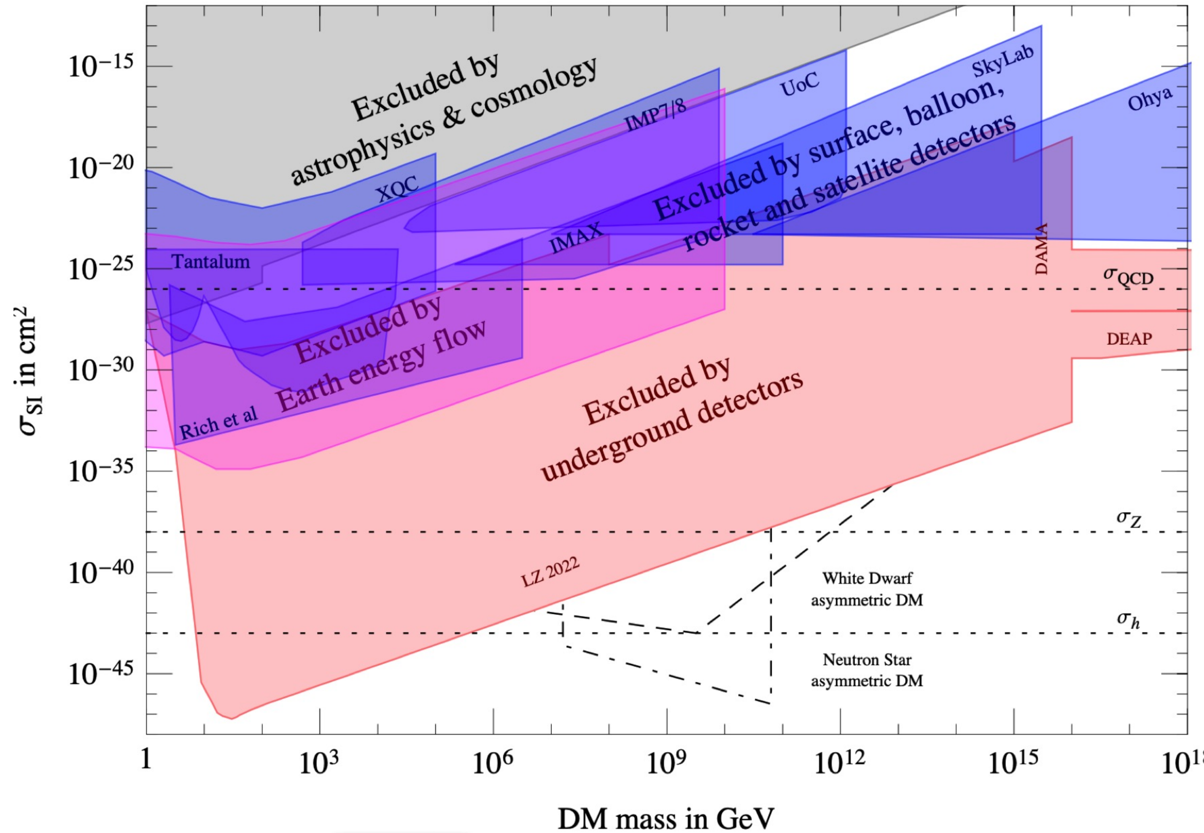
- Left boundary: given a WIMP speed v, $E_{\rm R-max} = 2\mu v^2$, thus $E_{\rm R-threshold} = \mu_{\rm min} v^2_{\rm max}$ gives the lowest $M_{\rm DM}$ reach (e.g. if $m_{\rm DM} << M_{\rm Target}$, $\mu = M_{\rm DM}$, thus $\mu_{\rm min} = M_{\rm DM-min}$)

- Lower boundary: Number of events $\propto$ exposure$\times\sigma \leq$ fixed limit, exposure$\times\sigma_{\rm min} =$ fixed limit ($\sigma_{\rm min}$ decreases as the exposure increases).

- Right boundary: Rate $\propto n_{\rm DM} = \rho_{\rm DM}/M_{\rm DM}$, where $\rho_{\rm DM}$ is a constant, Rate $\propto 1/M_{\rm DM}$ (for large $M_{\rm DM}$, DM particles become too rare to contribute to the rate)

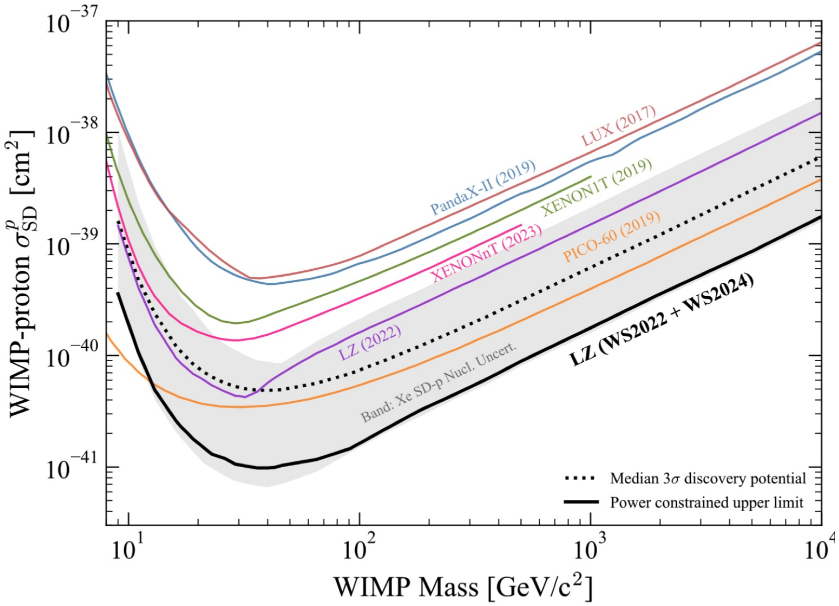
Limits continue to higher cross sections for which DM does not reach an underground detector, or lead to multiple scattering within one (usually rejected events)

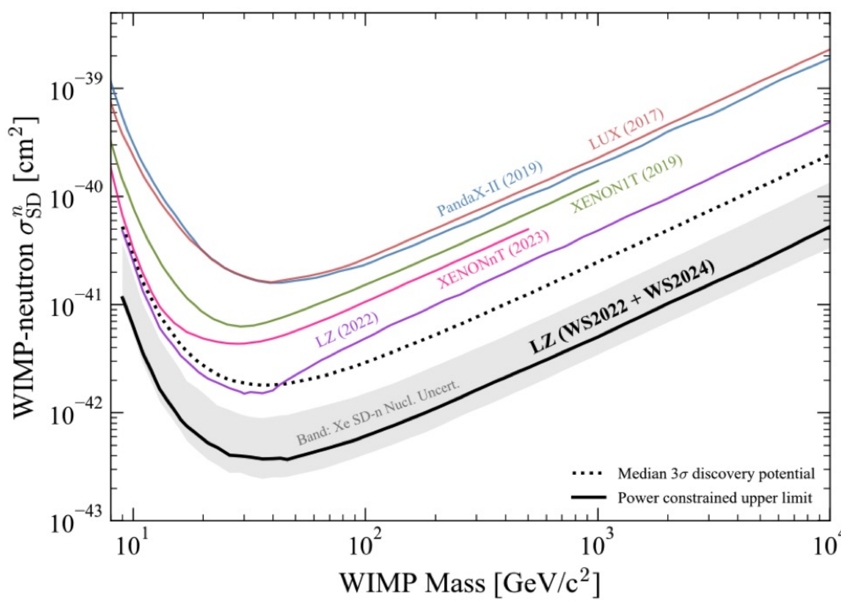
Fig. from Cirelli, Strumia, Zupan 2406.01705



Recent SD WIMP limits

LZ (4.2±0.1 tonne-year) 2410.17036





SD interactions with protons (left) and neutrons (right), 90% CL upper limits

Many other possible interactions E.g. with fermionic DM

from Fitzpatrick et al 1203.3542; Barello, Chang, Newby 1409.0536

Relativistic Operator	Nonrelativistic Limit $\times \frac{1}{4 m_N m_\chi}$
$\bar\chi_2\chi_1\bar N N$	$\mathbf{1}_\chi \mathbf{1}_N$
$i\bar\chi_2\chi_1\bar N\gamma^5 N$	$i\frac{\vec q}{m_N}\cdot\vec S_N$
$i\bar\chi_2\gamma^5\chi_1\bar N N$	$-i\frac{\vec q}{m_\chi}\cdot\vec S_\chi$
$\bar\chi_2\gamma^5\chi_1\bar N\gamma^5 N$	$-(\frac{\vec q}{m_\chi}\cdot\vec S_\chi)(\frac{\vec q}{m_N}\cdot\vec S_N)$
$\bar\chi_2\gamma^\mu\chi_1\bar N\gamma_\mu N$	$\mathbf{1}_\chi \mathbf{1}_N$
$\bar\chi_2\gamma^\mu\chi_1\bar N i\sigma_{\mu\nu}\frac{q^\nu}{m_M}N$	$\frac{\lvert\vec q\rvert^2}{2m_N m_M}\mathbf{1}_\chi\mathbf{1}_N$ $+2\left(\frac{\vec q}{m_\chi}\times\vec S_\chi+i\vec v^\perp_{\rm inel}\right)\cdot\left(\frac{\vec q}{m_M}\times\vec S_N\right)$
$\bar\chi_2\gamma^\mu\chi_1\bar N\gamma_\mu\gamma^5 N$	$-2\vec S_N\cdot(\vec v^\perp_{\rm inel}-\frac{\delta}{\lvert\vec q\rvert^2}\vec q)$ $+2i\vec S_\chi\cdot(\vec S_N\times\frac{\vec q}{m_\chi})$
$i\bar\chi_2\gamma^\mu\chi_1\bar N i\sigma_{\mu\nu}\frac{q^\nu}{m_M}\gamma^5 N$	$2i\frac{\vec q}{m_M}\cdot\vec S_N$
$\bar\chi_2 i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi_1\bar N\gamma_\mu N$	$-\frac{\lvert\vec q\rvert^2}{2m_\chi m_M}\mathbf{1}_\chi\mathbf{1}_N$ $-2\left(\frac{\vec q}{m_N}\times\vec S_N+i\vec v^\perp_{\rm inel}\right)\cdot\left(\frac{\vec q}{m_M}\times\vec S_\chi\right)$
$\bar\chi_2 i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi_1\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}N$	$4\left(\frac{\vec q}{m_M}\times\vec S_\chi\right)\cdot\left(\frac{\vec q}{m_M}\times\vec S_N\right)$
$\bar\chi_2 i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi_1\bar N\gamma_\mu\gamma^5 N$	$4i\left(\frac{\vec q}{m_M}\times\vec S_\chi\right)\cdot\vec S_N$
$i\bar\chi_2 i\sigma^{\mu\nu}\frac{q_\nu}{m_M}\chi_1\bar N i\sigma_{\mu\alpha}\frac{q^\alpha}{m_M}\gamma^5 N$	$-\left[i\frac{\lvert\vec q\rvert^2}{m_\chi m_M}-4\vec v^\perp_{\rm inel}\cdot\left(\frac{\vec q}{m_M}\times\vec S_\chi\right)\right]\frac{\vec q}{m_M}\cdot\vec S_N$
$\bar\chi_2\gamma^\mu\gamma^5\chi_1\bar N\gamma_\mu N$	$2\left(\vec v^\perp_{\rm inel}-\frac{\delta}{\lvert\vec q\rvert^2}\vec q\right)\cdot\vec S_\chi$ $+2i\vec S_\chi\cdot\left(\vec S_N\times\frac{\vec q}{m_N}\right)$
$\bar\chi_2\gamma^\mu\gamma^5\chi_1\bar N i\sigma_{\mu\nu}\frac{q^\nu}{m_M}N$	$4i\vec S_\chi\cdot\left(\frac{\vec q}{m_M}\times\vec S_N\right)$
$\bar\chi_2\gamma^\mu\gamma^5\chi_1\bar N\gamma_\mu\gamma^5 N$	$-4\vec S_\chi\cdot\vec S_N$
$i\bar\chi_2\gamma^\mu\gamma^5\chi_1\bar N i\sigma_{\mu\nu}\frac{q^\nu}{m_M}\gamma^5 N$	$4i\frac{\vec q}{m_M}\cdot\vec S_N\left(\vec v^\perp_{\rm inel}-\frac{\delta}{\lvert\vec q\rvert^2}\vec q\right)\cdot\vec S_\chi$

Relativistic Operator	Nonrelativistic Limit $\times \frac{1}{4 m_N m_\chi}$
USUAL SI $\bar{\chi}_2 \chi_1 \bar{N} N$ SCALAR MEDIATOR	$1_\chi 1_N$
$i\bar{\chi}_2 \chi_1 \bar{N} \gamma^5 N$	$i \frac{\vec{q}}{m_N} \cdot \vec{S}_N$
$i\bar{\chi}_2 \gamma^5 \chi_1 \bar{N} N$	$-i \frac{\vec{q}}{m_\chi} \cdot \vec{S}_\chi$
$\bar{\chi}_2 \gamma^5 \chi_1 \bar{N} \gamma^5 N$ PSEUDOSCALAR MED.	$-(\frac{\vec{q}}{m_\chi} \cdot \vec{S}_\chi)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
USUAL SI $\bar{\chi}_2 \gamma^\mu \chi_1 \bar{N} \gamma_\mu N$ VECTOR MEDIATOR	$1_\chi 1_N$
$\bar{\chi}_2 \gamma^\mu \gamma^5 \chi_1 \bar{N} i \sigma_{\mu\nu} \frac{q^\nu}{m_M} N$	$4i \vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_M} \times \vec{S}_N \right)$
USUAL SD $\bar{\chi}_2 \gamma^\mu \gamma^5 \chi_1 \bar{N} \gamma_\mu \gamma^5 N$ AXIAL-VECTOR MEDIAT.	$-4 \vec{S}_\chi \cdot \vec{S}_N$
$i\bar{\chi}_2 \gamma^\mu \gamma^5 \chi_1 \bar{N} i \sigma_{\mu\nu} \frac{q^\nu}{m_M} \gamma^5 N$	$4i \frac{\vec{q}}{[illegible]} \cdot \vec{S}_N \left(\vec{v}^\perp [illegible] - \frac{\delta}{[illegible]} \vec{q} \right) \cdot \vec{S}_\chi$

Notice these are DM-Nucleon (N=p,n) interactions

Many other possible interactions E.g. with scalar DM

from Fitzpatrick et al 1203.3542; Barello, Chang, Newby 1409.0536

Relativistic Operator		Nonrelativistic Limit $\times \frac{1}{2m_N}$
$\Phi_2\Phi_1\bar{N}N$	SCALAR MEDIATOR	$\mathbf{1}_\chi\mathbf{1}_N$
$\Phi_2\Phi_1 i\bar{N}\gamma^5 N$	PSEUDOSCALAR MEDIATOR	$i\frac{\vec{q}}{m_N}\cdot\vec{S}_N$
$\frac{1}{m_M}\left(i\Phi_2\overleftrightarrow{\partial}_\mu\Phi_1\right)\bar{N}\gamma^\mu N$	VECTOR MEDIATOR	$2\frac{m_\chi}{m_M}\mathbf{1}_\chi\mathbf{1}_N$
$\frac{1}{m_M}\left(i\Phi_2\overleftrightarrow{\partial}_\mu\Phi_1\right)\bar{N}\gamma^\mu\gamma^5 N$	AXIAL–VECTOR MEDIATOR	$4\frac{m_\chi}{m_M}\left(\vec{v}^\perp_{\rm inel}-\frac{\delta}{\lvert\vec{q}\rvert^2}\vec{q}\right)\cdot\vec{S}_N$
$\frac{1}{m_M}\partial_\mu(\Phi_2\Phi_1)\bar{N}\gamma^\mu\gamma^5 N$		$-\frac{2i}{m_M}\vec{q}\cdot\vec{S}_N$
$\frac{1}{m_M}\left(i\Phi_2\overleftrightarrow{\partial}_\mu\Phi_1\right)Ni\sigma_{\mu\nu}\frac{q^\nu}{m_M}N$		$4i\frac{m_\chi}{m_M}\vec{v}^\perp_{\rm inel}\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_N\right)+\frac{m_\chi}{m_N m_M^2}\lvert\vec{q}\rvert^2\mathbf{1}_\chi\mathbf{1}_N$
$\frac{i}{m_M}\left(i\Phi_2\overleftrightarrow{\partial}_\mu\Phi_1\right)Ni\sigma_{\mu\nu}\gamma^5\frac{q^\nu}{m_M}N$		$4i\frac{m_\chi}{m_M}\frac{\vec{q}}{m_M}\cdot\vec{S}_N$

Each different nucleon coupling needs it own nuclear form factor

And the mediators could be "heavy" or "light", i.e. with $M >> q$, contact interaction, or $M < q$ so keep propagator $\sigma \sim |q^2 - M^2|^{-2}$.

Cross sections can be very different: e.g. SI and Magnetic Dipole

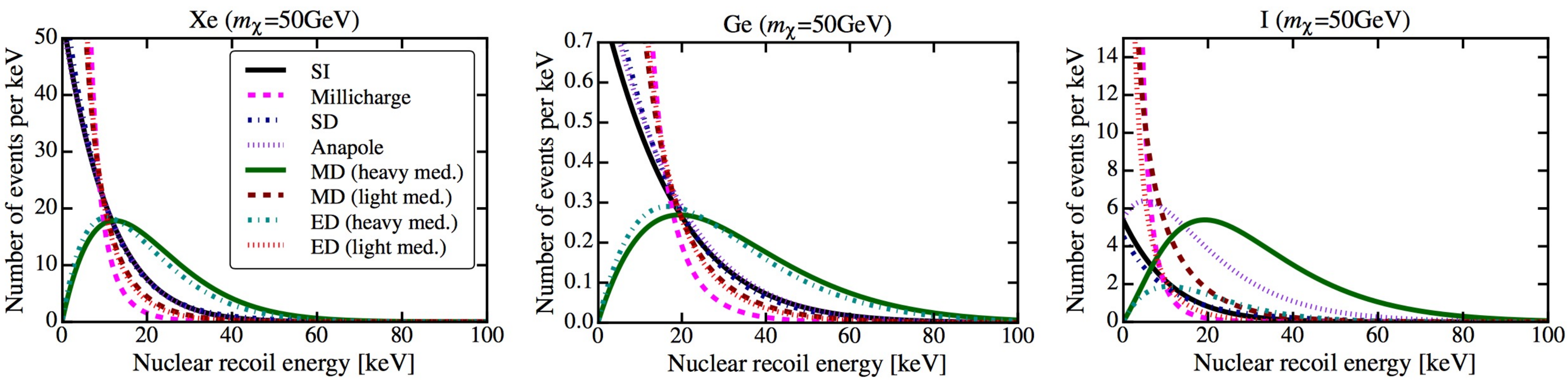
$$\frac{d\sigma_T^{\rm SI}}{dE_R} = \sigma_{\rm ref}^{\rm SI}\frac{|\vec{q}_{\rm ref}|^4}{M^4}\frac{m_T}{2\mu_N^2 v^2}\Big[A_T\Big]^2 F^2_{{\rm SI},T}$$

$|\vec{q}|$ independent, T : nucleus, N : nucleon

$$\frac{d\sigma_T^{\rm MD}}{dE_R} = \sigma_{\rm ref}^{\rm MD}\frac{|\vec{q}_{\rm ref}|^2}{M^4}\frac{m_T^2}{4v^2\mu_N^2}\left[Z_T^2\left(4v^2|\vec{q}|^2 - |\vec{q}|^4\left\{\frac{1}{\mu_T^2}-\frac{1}{m_\chi^2}\right\}\right)F^2_{\rm E,T} + 2\frac{|\vec{q}|^4}{m_N^2}\frac{\lambda_T^2}{\lambda_N^2}\left(\frac{J_T+1}{3J_T}\right)F^2_{\rm M,T}\right]$$

Rates can be very different than for SI

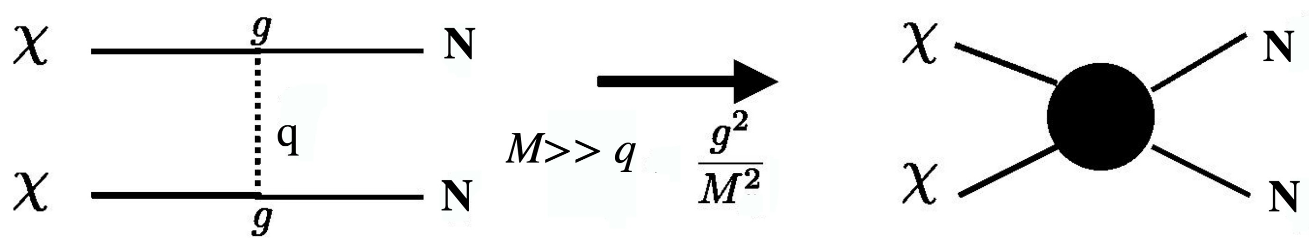
Fig. from Gluscevic et al. 1506.04454



EFT approach from DM-Nucleon interactions

When we write the Lorentz-invariant DM-N couplings above, we are assuming that each interaction is mainly mediated by one only mediator, and extract its propagator. This is done in the Effective Field Theory (EFT) approach

-"Heavy mediators" with $M >> q$ (in DD $q \lesssim 200$ MeV), we get "contact interactions".



- Then for "Light mediators" $M \lesssim q$ (since mediators are necessarily color neutral- non-strongly interacting) the point interaction is replaced by a long range interaction by multiplying the amplitude by $\dfrac{M^2}{q^2+M^2} \simeq \dfrac{M^2}{q^2}$

Each interaction requires its own Nuclear Form Factor

Some were known with uncertainties (e.g. SI: Helm charge form factor, SD: known with uncertainties; electric and magnetic form factors have been measured) for many there are calculations done for different EFT operators

Two formalisms currently frequently used for nuclear form factors:

Non-Relativistic Effective Field Theory (NREFT)

Fan, Reece, Wang 1008.1591; Fitzpatrick, Haxton, Katz, Lubbers, Xu, 1203.3542, 1211.2818; Anand, Fitzpatrick, Haxton 1308.6288.....

Chiral Effective Field Theory (ChEFT)

Bishara, Brod, Grinstein, Zupan 1611.00368; Hoferichter, Klos, Menéndez, Schwenk,1903.11075; Criado, Djouadi, Pérez-Victoria, Santiago 2104.14443...

Good reference for overview of current EFT approaches to DM interactions, Snowmass Process white paper Baumgart, Bishara, Brod, Cohen, Fitzpatrick, Reece, Zupan et al. 2203.08204

NREFT approach from nucleons to nuclei

Fan, Reece, Wang 1008.1591; Fitzpatrick, Haxton, Katz, Lubbers, Xu, 1203.3542, 1211.2818; Anand, Fitzpatrick, Haxton 1308.6288

Non-Relativistic EFT: $v_{\rm DM} \simeq 10^{-3}$ and $v_N \simeq 0.1$ for nucleons $(N = p, n)$

$$\mathcal{L}_{\rm NR} = \sum_{i,N} c_i^N(q^2)\ \mathcal{O}_i^N$$

constructed from Galilean-invariant quantities Dent et al 1505.0311:

- $\vec{q}/m_N$ momentum transfer divided N mass
- $\vec{v}^{\perp} \equiv \vec{v} - \vec{q}/2\mu_N$ component perpendicular to $\vec{q}$ of the relative DM-nucleon velocity where $\mu_N = m_\chi m_N/(m_\chi + m_N)$
- $\vec{S}_\chi, \vec{S}_N$ DM and nucleon spins

$$\begin{aligned}
&\mathcal{O}_1 = 1_\chi 1_N, \quad \mathcal{O}_2 = \left(v^\perp\right)^2, \quad \mathcal{O}_3 = i\vec{S}_N \cdot \left(\tfrac{\vec{q}}{m_N} \times \vec{v}^\perp\right),\\
&\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N, \quad \mathcal{O}_5 = i\vec{S}_\chi \cdot (\tfrac{\vec{q}}{m_N} \times \vec{v}^\perp),\\
&\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \tfrac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \tfrac{\vec{q}}{m_N}\right), \quad \mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp,\\
&\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp, \quad \mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \tfrac{\vec{q}}{m_N}\right),\\
&\mathcal{O}_{10} = i\vec{S}_N \cdot \tfrac{\vec{q}}{m_N}, \quad \mathcal{O}_{11} = i\vec{S}_\chi \cdot \tfrac{\vec{q}}{m_N},\\
&\mathcal{O}_{12} = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}^\perp\right), \quad \mathcal{O}_{13} = i\left(\vec{S}_\chi \cdot \vec{v}^\perp\right)\left(\vec{S}_N \cdot \tfrac{\vec{q}}{m_N}\right)\\
&\mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \tfrac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \vec{v}^\perp\right),\\
&\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \tfrac{\vec{q}}{m_N}\right)\left(\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \tfrac{\vec{q}}{m_N}\right).
\end{aligned}$$

Nuclear response functions

Fitzpatrick, Haxton, Katz, Lubbers, Xu, 1203.3542, 1211.2818; Anand, Fitzpatrick, Haxton 1308.6288 Assuming single nucleon (1-body) interactions, compute the products of the nuclear matrix elements

$$\left|\mathcal{M}\right|^2 = \sum_{i,j} \sum_{N,N'} c_i^N c_j^{N'} \langle T|\mathcal{O}_i^N|T\rangle \langle T|\mathcal{O}_j^{N'}|T\rangle,$$

where $\langle T|\mathcal{O}_j^N|T\rangle$ depend only on nuclear physics. Schematically, $\mathcal{M}$ averaged over nuclear spins,

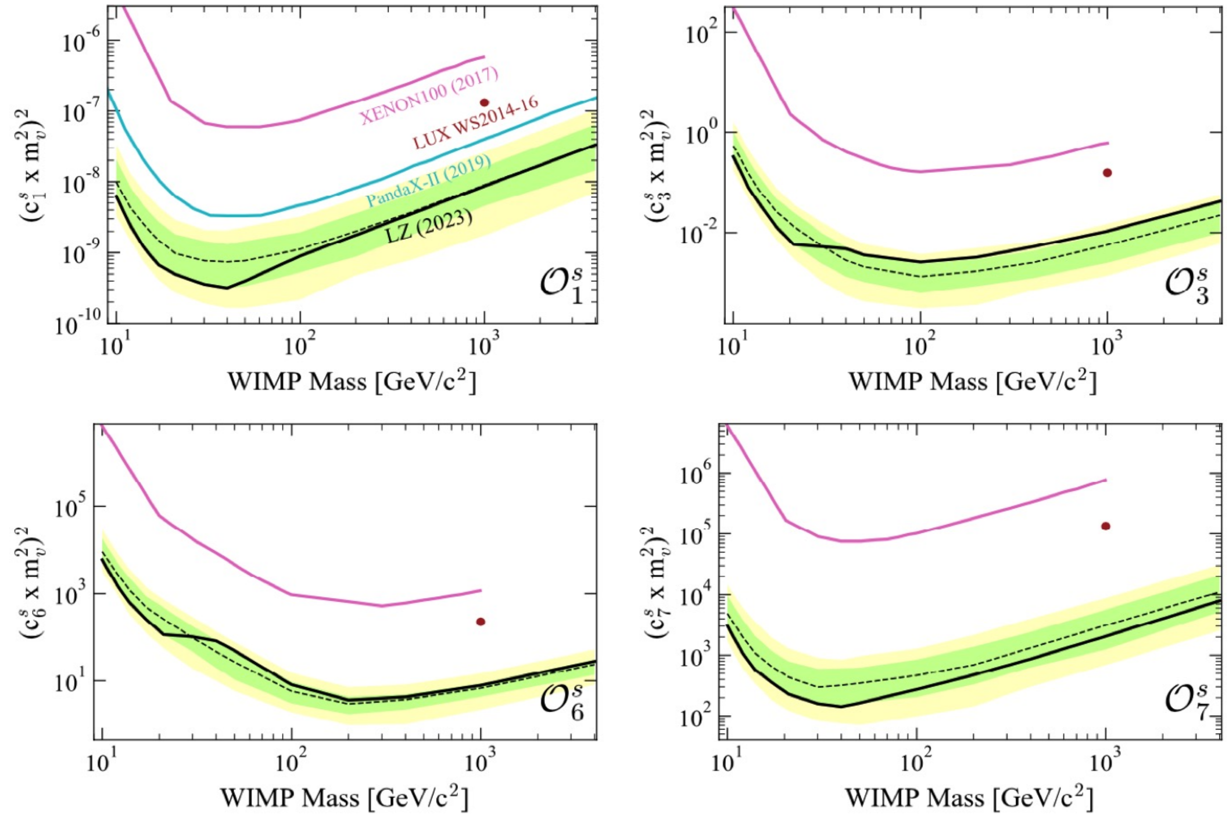
$$\frac{1}{2J_\chi + 1} \frac{1}{2J_T + 1} \sum_{\text{spins}} |\mathcal{M}|^2 \equiv \frac{m_T^2}{m_N^2} \sum_{i,j} f_{ij} \, F_{ij}^T(v^2, q^2)$$

where the factors f_{ij} contain the c_i^N coefficients. For unpolarized nuclei there are 8 F_{ij}^T functions of $|\vec{q}| = q$. Recall the differential cross section (θ is the scattering angle)

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{(2J_\chi + 1)} \frac{1}{(2J_T + 1)} \sum_{\text{spins}} \frac{1}{32\pi} \frac{|\mathcal{M}|^2}{(m_\chi + m_T)^2}$$

and for elastic DM scattering one can change variables using $d\cos\theta = m_T/\mu_T^2 v^2$ (with θ defined in the center of mass frame) and obtain the differential cross-section $d\sigma/dE_R$.

Using separate NREFT operators As a way to search for DM in a totally model-independent way. E.g. done by LZ (here only a few shown) 2312.02030



How to characterize interactions at the nucleon level: NREFT or relativistic Lorentz invariant coupling?

There is not a one-to-one correspondence between NREFT operators and relativistic DM-nucleon interactions through a single mediator in the NR limit (which I think is a more physically meaningful description). For some there is:
E.g. for an axial vector mediator

$$\mathcal{A}_{\rm int} = c\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\bar{N}\gamma_{\mu}\gamma^{5}N$$

χ and N: DM and nucleon spinors, which have the NR limit (Bjorken and Drell)

$$\chi(p) = \sqrt{\frac{E+m_\chi}{2m_\chi}}\begin{pmatrix} \xi \\ \frac{\vec{\sigma}\cdot\vec{p}}{E+m_\chi}\xi \end{pmatrix} \rightarrow \begin{pmatrix} \xi \\ \frac{\vec{\sigma}\cdot\vec{p}}{2m_\chi}\xi \end{pmatrix}$$

(same for $N(p)$); ξ is a two-component spinor, and $\vec{S} = \xi'^{\dagger}(\sigma/2)\xi$, thus

$$\mathcal{A}_{\rm int} = -4c\,\vec{S}_\chi\cdot\vec{S}_N \equiv -4c\,\mathcal{O}_4$$

So, AxialVector-AxialVector coupling (AV-AV) corresponds to: $\mathcal{O}_4$.
Also SI: $\mathcal{O}_1$, SD: $\mathcal{O}_4$, PseudoScalar-Scalar (PS-S): $\mathcal{O}_{11}$, S-PS: $\mathcal{O}_{10}$, PS-PS: $\mathcal{O}_6$, Electric-Dipole (ED): $\mathcal{O}_{11}$

From DM-nucleon interactions to NREFT operators

Many DM-N interactions are dominated in the NR limit by one NREFT operator, but not Magnetic Dipole (MD), Anapole, AxialVector-Vector(AV-V) couplings.

E.g. for a Magnetic Dipole coupling

$$\mathcal{A}_{\rm MD} \propto m_N Q_N (|\vec{q}|^2 \mathcal{O}_1 + 4 m_\chi m_N \mathcal{O}_5) + \frac{\lambda}{e/2m_N} 4 m_\chi (|\vec{q}|^2 \mathcal{O}_4 - m_N^2 \mathcal{O}_6)$$

Here m_N, Q_N, λ=mass, charge, magnetic moment of nucleon N,
$e/2m_N$= nuclear magneton

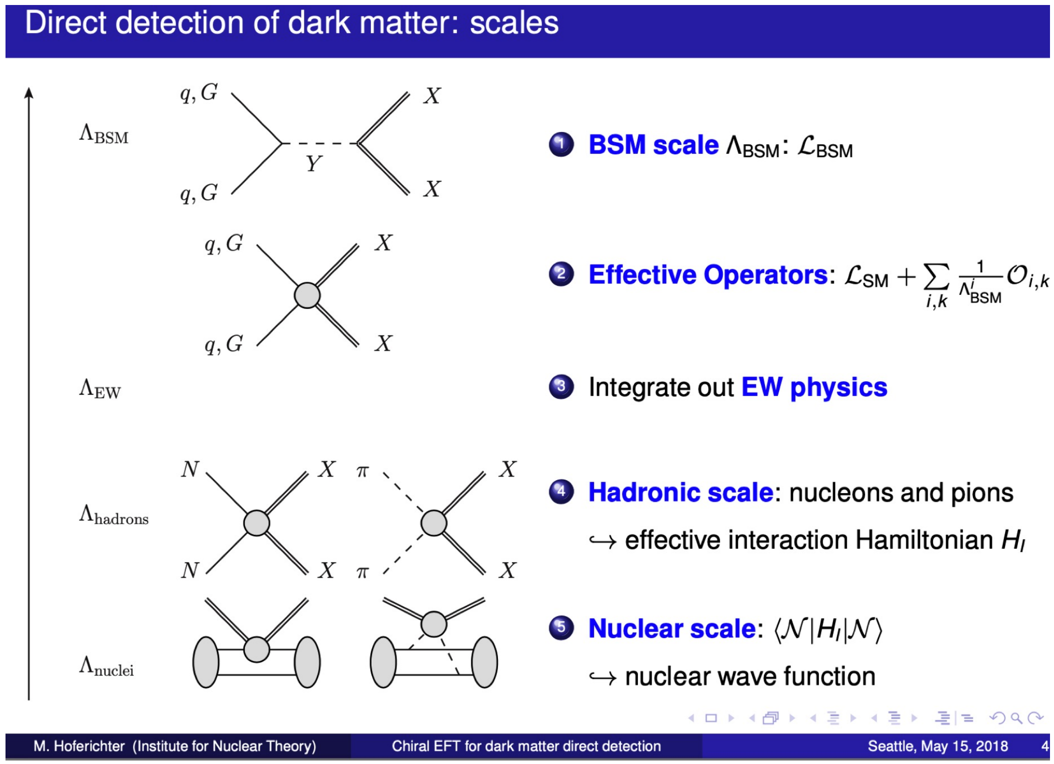
When several $\mathcal{O}_i$ appear in the amplitude their coefficients are T dependent, so different $\mathcal{O}_i$ may dominate for different T in a particular energy range. This is lost when using NREFT operators separately.

EFT approach from DM-quark and gluon interactions (from M. Hoferichter)

"heavy mediators" with $M >> q$ i.e. "contact interactions".

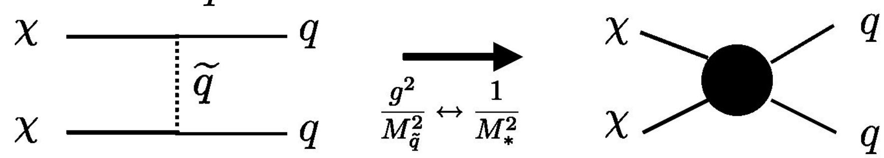
Aims: - remain agnostic to fundamental interactions, and

- make contact with accelerator and indirect DM searches



EFT approach from DM-quark and gluon interactions

-"heavy mediators" with $M >> q$ i.e. "contact interactions".



E.g. for a Dirac neutral DM χ, operators with dim 6 with q and dim 7 with gluons

$$\mathcal{O}_1^q = \bar{\chi}\chi\, \bar{q}q\ , \qquad \mathcal{O}_2^q = \bar{\chi}\, i\gamma^5\chi\, \bar{q}q\ ,$$
$$\mathcal{O}_3^q = \bar{\chi}\chi\, \bar{q}\, i\gamma^5 q\ , \qquad \mathcal{O}_4^q = \bar{\chi}\, i\gamma^5\chi\, \bar{q}\, i\gamma^5 q\ ,$$
$$\mathcal{O}_5^q = \bar{\chi}\gamma^\mu\chi\, \bar{q}\gamma_\mu q\ , \qquad \mathcal{O}_6^q = \bar{\chi}\gamma^\mu\gamma^5\chi\, \bar{q}\gamma_\mu q\ ,$$
$$\mathcal{O}_7^q = \bar{\chi}\gamma^\mu\chi\, \bar{q}\gamma_\mu\gamma^5 q\ , \qquad \mathcal{O}_8^q = \bar{\chi}\gamma^\mu\gamma^5\chi\, \bar{q}\gamma_\mu\gamma^5 q\ ,$$
$$\mathcal{O}_9^q = \bar{\chi}\,\sigma^{\mu\nu}\chi\, \bar{q}\,\sigma_{\mu\nu} q\ , \qquad \mathcal{O}_{10}^q = \bar{\chi}\, i\,\sigma^{\mu\nu}\gamma^5\chi\, \bar{q}\,\sigma_{\mu\nu} q\ ,$$
$$\mathcal{O}_1^g = \frac{\alpha_s}{12\pi}\, \bar{\chi}\chi\, G^a_{\mu\nu}G^a_{\mu\nu}\ , \qquad \mathcal{O}_2^g = \frac{\alpha_s}{12\pi}\, \bar{\chi}\, i\gamma^5\chi\, G^a_{\mu\nu}G^a_{\mu\nu}$$
$$\mathcal{O}_3^g = \frac{\alpha_s}{8\pi}\, \bar{\chi}\chi\, G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\ , \qquad \mathcal{O}_4^g = \frac{\alpha_s}{8\pi}\, \bar{\chi}\, i\gamma^5\chi\, G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}$$

- "Light mediators" $M \lesssim q$ are necessarily color neutral- non-strongly interacting- thus point interaction is just replaced by a long range interaction, i.e. the expansion coefficients get multiplied by $\dfrac{M^2}{q^2 + M^2} \simeq \dfrac{M^2}{q^2}$

EFT from quarks/gluons to nucleons

The effective Lagrangian DM- quark/gluon is

$$\mathcal{L}_{\rm eff} = \sum_{k=1}^{10} \sum_{q} c_k^q \mathcal{O}_k^q + \sum_{k=1}^{4} c_k^g \mathcal{O}_k^g$$

c_k^q and c_k^g are real dimensionful ($[\text{mass}]^{-2}$ and $[\text{mass}]^{-3}$) coefficients.

These operators induce an effective Lagrangian at nucleon level, by computing their matrix elements between Nucleon states: $\langle N|\bar{q}\ \Gamma\ q|N\rangle$ with Γ either $1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}$ or $\sigma^{\mu\nu}\gamma^5$, and $\langle N|G^a_{\mu\nu}G^a_{\mu\nu}|N\rangle$ and $\langle N|G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}|N\rangle$, using experimental data or lattice calculations. This has been done since the 1970's on, but with recent progress using Chiral EFT (ChEFT).

$$\mathcal{L}_{\rm eff} = \sum_{k=1} \sum_{N=p,n} c_k^N \mathcal{O}_k^N$$

where the c^N are linear combinations of the c^q and c^g

Current approaches to nuclear response functions in DD Introduce different uncertainties.

NREFT nuclear response functions use the "shell model", where a frozen core of nucleons is surrounded by valence nucleons which occupy energy and angular momentum states in close analogy with atomic electrons The degrees of freedom included are only nucleons, and only 1-particle interactions

Fitzpatrick, Haxton, Katz, Lubbers, Xu, 1203.3542, 1211.2818; Anand, Fitzpatrick, Haxton 1308.6288...

ChiralEFT nuclear response functions Include also mesons, thus it is valid below the QCD scale. $E < GeV$, anduses the global symmetries of QCD to provide:
- a systematic power counting scheme to organize WIMP-nucleon interactions, including pions,
- improved coefficients of the MREFT operators
- effects of 2-particle WIMP-nucleon interactions,
- includes WIMP-virtual pion interactions...

Bishara, Brod, Grinstein, Zupan 1611.00368; Hoferichter, Klos, Menéndez, Schwenk,1903.11075;...