Direct Detection of Dark Matter

Graciela Gelmini - UCLA

LNGS, October 21, 2014

Content of Lecture 1

- What we know about dark matter (avoid oversimplications)
- Introduction to direct detection of WIMPs:
  main elements of the expected event rate and their uncertainties

Subject is very vast, so idiosyncratic choice of subjects + citations disclaimer

The DARK MATTER problem has been with us since 1930's,

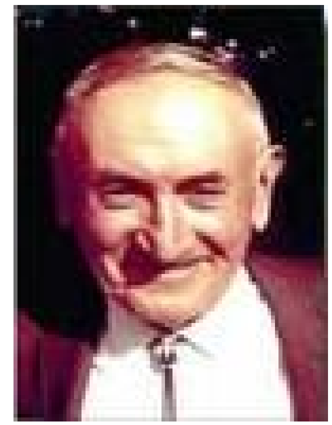
name coined by Fritz Swicky in Helvetica Physica Acta Vol6 p.110-127, 1933

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.



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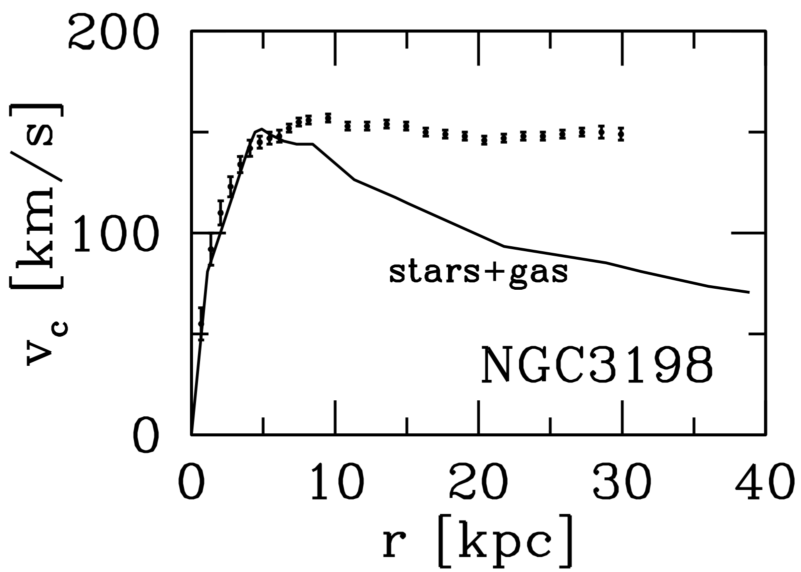
gr/cm³. Es ist natürlich möglich, dass leuchtende plus **dunkle (kalte) Materie** zusammengenommen eine bedeutend höhere Dichte ergeben, und der Wert $\bar{\varrho} \sim 10^{-28}$ gr/cm³ erscheint daher nicht

Used the Virial theorem in the Coma Cluster: found its galaxies move too fast to remain bounded by the visible mass only. J. Ostriker: in the first 40 y his seminal 1937 paper had 10 citations!

Dark Matter rediscovered

In 1970's Vera Rubin found that the rotation curves of galaxies ARE FLAT!



$$\frac{GMm}{r^2} = m\frac{v^2}{r} \Rightarrow v = \sqrt{\frac{GM(r)}{r}}$$

$$v = const. \Rightarrow M(r) \sim r$$

even where there is no light!

1 pc = 3.2 ℓy

Dark Matter dominates in galaxies e.g. in NGC3198

$$M = 1.6 \times 10^{11} M_\odot (r/30 \text{ kpc})$$

$$M_{stars+gas} = 0.4 \times 10^{11} M_\odot$$

$$\frac{M}{M_{vis}} > 4$$

We are going to concentrate on the DM in the Dark Halo of our own galaxy

After 80 years, what we know about DM:

- **Attractive gravitational interactions and stable (or lifetime $>> t_U$)**

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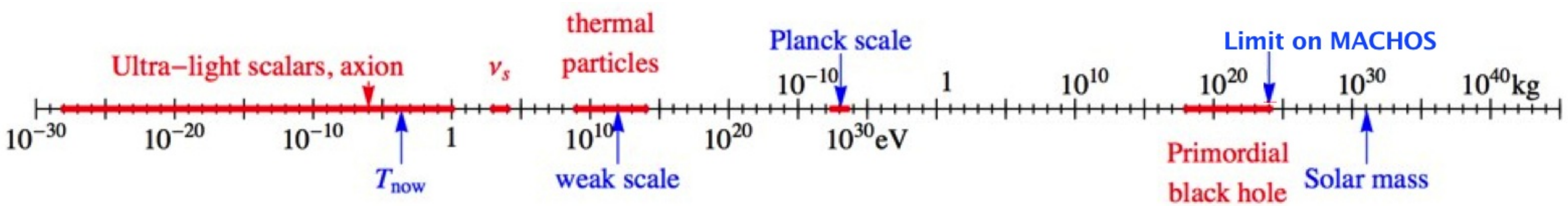
  ("Fuzzy DM", boson de Broglie wavelength= 1 kpc Hu, Barkana, Gruzinov, astro-ph/0003365)
  or 0.2-0.7 $\times 10^{-6}$ GeV$\leq$ mass (for particles which reached equilibrium - depending on boson-fermion and d.o.f. Tremaine-Gunn 1979; Madsen, astro-ph/0006074)

DM particle mass: 80 orders of magnitude!



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- **Dissipationless** i.e. cannot cool by radiating as baryons do to collapse in the center of galaxies- i.e. either neutral or charged but very heavy or with a very small electromagnetic coupling ("Milli-Charged DM", "electric" or "magnetic dipole DM", "anapole DM") but $<$ 10% could be:"Double Disk DM" (DDDM) Fan, Katz, Randall & Reece 1303.1521-1303.3271

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- **Collisionless?** with huge upper limit $\sigma_{self}/m \leq 1$ cm^2/g = 2 barn/GeV = $2{\times}10^{-24}$ cm^2/ GeV on self interactions (^{235}U-n cross section is a few barns!). Self Interacting DM (SIDM)?

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- **Collisionless?** Bullet cluster+non-sphericity of galaxy and cluster halos huge upper limit (SIDM) $\boldsymbol{\sigma_{self}/m} \leq$ 2 barn/GeV (^{235}U-n cross section is a few barns!).
- **Cold or Warm, thus not included in the Standard Model of EP**
- We need new particle candidates with the **right relic abundance** $\leq \Omega_{DM}$ (but not necessarily calculated with the "STANDARD" pre-BBN era assumptions). Among these are Weakly Interacting Massive Particles.

WIMPs require new physics at the EW scale

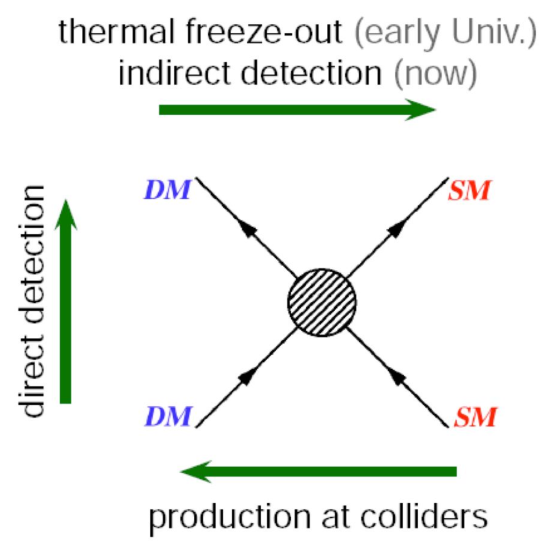
WIMPs: particles with GeV to 100 TeV mass and with weak scale interactions.

New physics is expected at O(TeV) scale because of Spontaneous Symmetry Breaking arguments (totally independently of the DM issue) BSM models such as Supersymmetry, Technicolor, large extra spatial dimensions (possibly warped), "Little Higgs" model...

But the new physics to explain DM may be different....,

e.g. many new models trying to account for "hints" of DM in direct and indirect DM searches ("boutique models") e.g. "secluded" or "intermediate state" models with DM charged under a broken hidden gauge symmetry and interacting with the SM through a light scalar ("dark photon")... Made to fit DM-not to solve the EW hierarchy (attest to the ingenuity of theorists to explain everything)... may or not provide novel signatures for the LHC

WIMP DM searches:

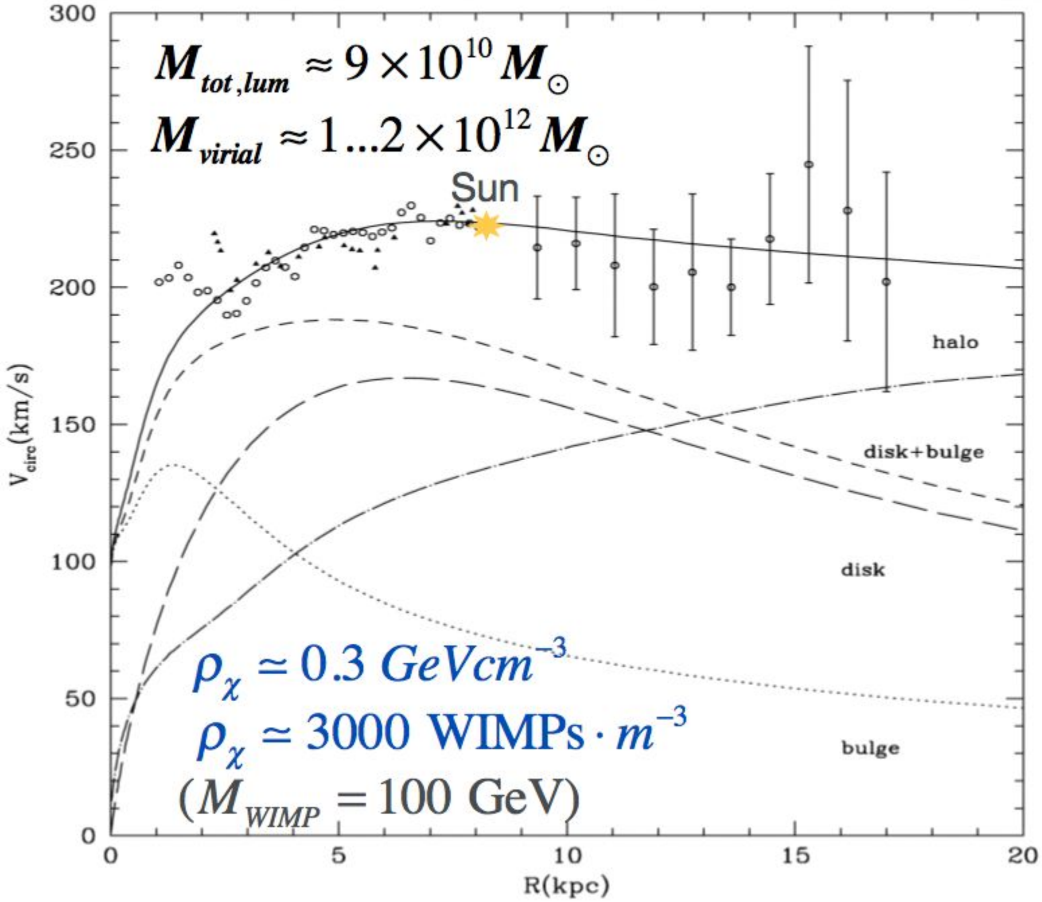


- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way. Could detect even a very subdominant WIMP component. (Caveat: the DM interaction might be too weak to detect)
- Indirect Detection- looks for WIMP annihilation (or decay) products. (Caveat: the DM may not annihilate)
- At colliders as missing transverse energy, mono-jet or mono-photon events (Caveat: the DM mass may be above 2 TeV or its signature hidden by backgrounds)

All three are independent and complementary to each other!

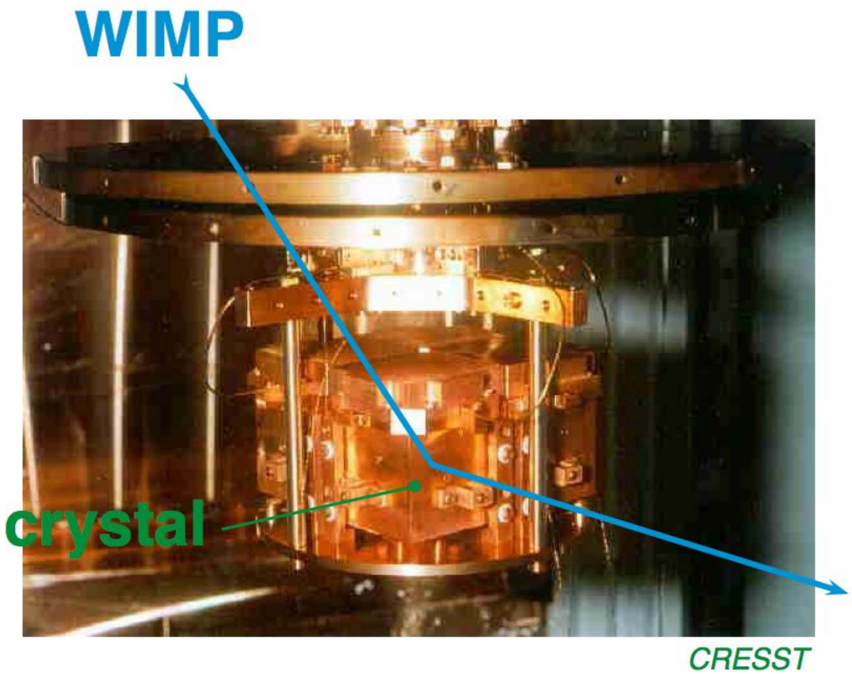
Even if the Large Hadron Collider finds a DM candidate, in order to prove that it is the DM we will need to find it where the DM is, in the haloes of our and other galaxies.

Milky Way's Dark Halo Fig. from L.Baudis; Klypin, Zhao and Somerville 2002



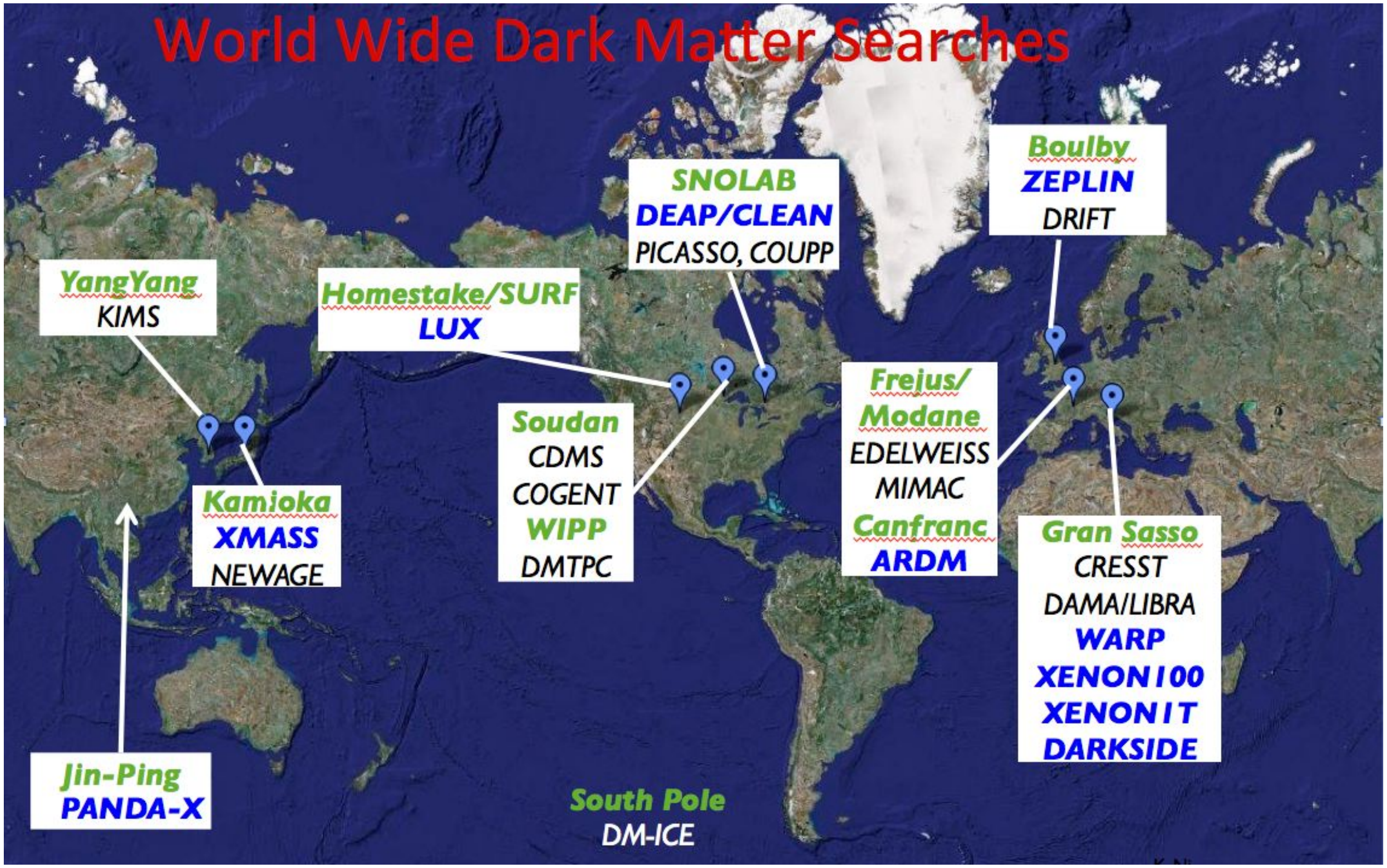
10^{10}(GeV/m_χ) WIMP's passing through us per cm^2 per second!

Direct DM Searches:



- Small $E_{Recoil} \leq 50$keV(m/100 GeV)
- Rate: depends on WIMP mass, cross section, dark halo model, nuclear form factors... typical... < 1 event/ 100 kg/day requires constant fight against backgrounds (need to go underground to shield from cosmic rays)
- Single hits: single scatters, uniform through volume of detector
- Annual flux modulation due to the rotation of the Earth around the Sun (few % effect)
- Most searches are non-directional but some in development are (try to measure the recoil direction)

Direct DM Searches: Many experiments!



WIMPs interact coherently with nuclei

WIMPs are not relativistic: $v \simeq 300\text{km/s} \simeq 10^{-3}$ c. Thus, for the typical momentum exchanged $q \simeq \mu v$ ($\mu = \frac{mM}{(m+M)}$ is the reduced mass, 1= 197 MeV fm; 1 femtometre, fm = 10^{-15} m)

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

e.g. for $m << M$ so $\mu = m$ or $m >> M$ so $\mu = M$

$$q \simeq MeV\left(\frac{m_\chi}{GeV}\right) \quad or \quad q \simeq AMeV$$

and WIMPs interact coherently with all the nucleons in a pointlike nucleus.

For larger q and heavier nuclei- A large- the loss of coherence is taken into account with a nuclear form factor $F(E) = \int e^{-iqr}\rho_{Nucleon}(r)dr$.

For Spin-Independent interactions conventional Helmi form factor :

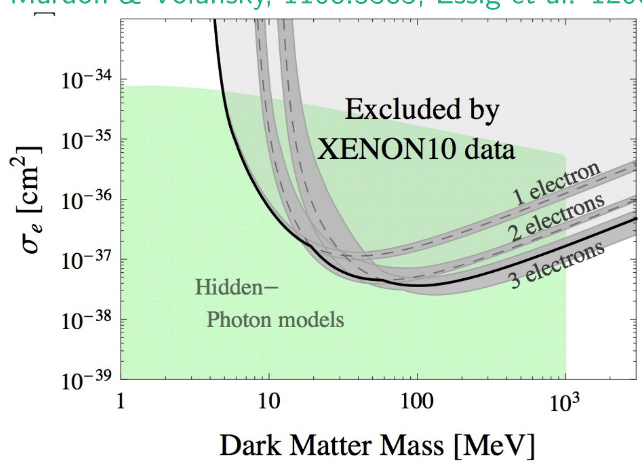
$F(E) = 3e^{-q^2 s^2/2}[\sin(qr) - qr\cos(qr)]/(qr)^3$,

with $s = 1$ fm, $r = \sqrt{R^2 - 5s^2}$, $R = 1.2A^{1/3}$ fm, $q = \sqrt{2ME}$.

Caveat: Sub-GeV "Light Dark Matter" (LDM) With mass $m \simeq$ MeV to GeV. For $m << M$, $\mu = m$, the maximum energy imparted in an elastic collision with the whole nucleus is below threshold for most experiments,

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

but the 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; Battel, Essig & Surujon 1406.2698



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

$$\frac{dR}{dE_R} = \sum_T \int \frac{C_T}{M_T} \times \frac{d\sigma_T}{dE_R} \times nv f(\vec{v}, t) d^3 v$$

- For a WIMP-nucleus contact differential cross section $d\sigma_T/dE_R = \sigma_T(E_R)\ M_T/2\mu_T^2 v^2$

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

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

- $\frac{C_T}{M_T}$= mass fraction × Number of nuclides T per unit target mass; $\mu_T = mM_T/(m + M_T)$

- $v_{min} = \left|\sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}}\right|$ ($\delta = m' - m << m$, $\delta = 0$ for elastic scattering)

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

- E.g. for contact spin-independent (SI) interactions $\sigma_T(E_R) = \sigma_{T0} F^2(E_R)$ where

$\sigma_{T0} = \left[Z + (A - Z)(f_n/f_p)\right]^2 (\mu_T^2/\mu_p^2)\sigma_p = A^2(\mu_T^2/\mu_p^2)\sigma_p$ for $f_p = f_n$

Given $\rho\eta(v_{min})$, **"Halo dependent" data comparison in the m, σ_p plane**

Fixing m, **"Halo Independent" data comparison in the $v_{min}, \rho\eta/m$ plane**

The recoil spectrum dR_T/dE_R is not directly accessible to experiments because of energy dependent energy resolution and efficiencies and because they often observe only a fraction $E^{'}$ for the recoil energy E_R.

Observed event rate:

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

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

$$\frac{dR_T}{dE_R} = \int \frac{d\sigma_T}{dE_R} \times \frac{1}{m} \rho v f(\vec{v}, t) d^3 v$$

[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); - $\varepsilon(E^{'})$: 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 (usually measured in a different experiment)
- The energy resolution $\sigma_E(E^{'})$ should be measured, but e.g. for Xe at low energies it is computed assuming Poisson fluctuations

Signal in Direct Searches: WIMPs interact with nuclei.

In crystals: most of the recoil energy goes usually to phonons,

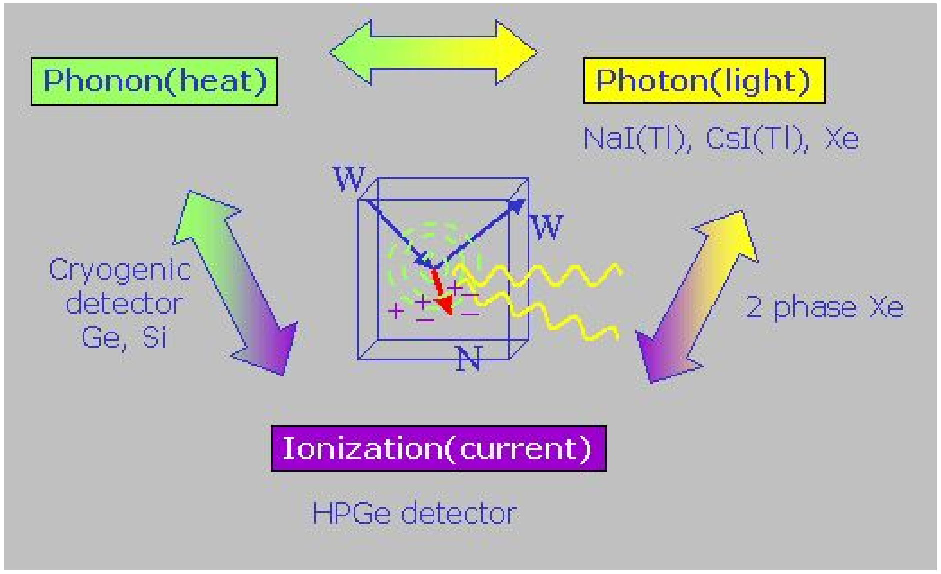
but a fraction Q goes into ionization/ scintillation, $Q_{Na} = 0.3$, $Q_I = 0.09$...

In Xe: L_{eff} measures scintillation efficiency of a WIMP (which is S1)

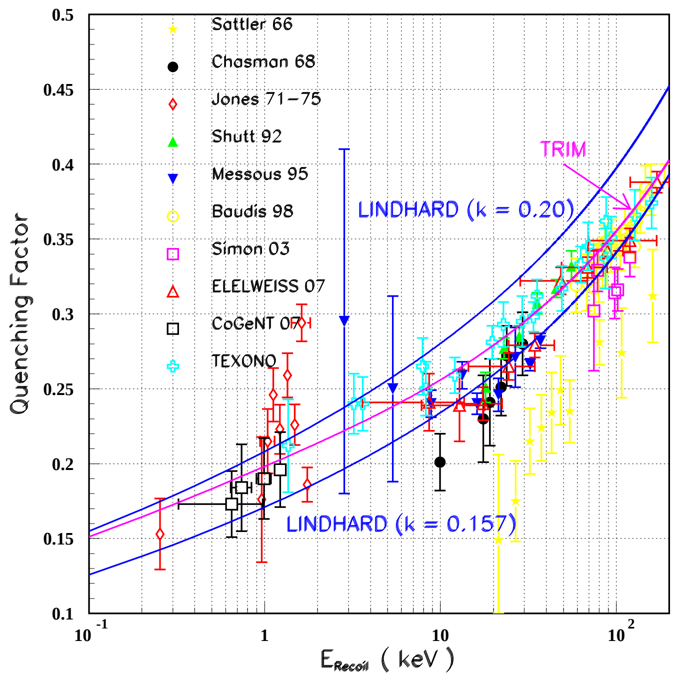
there is also delayed ionization (S2).

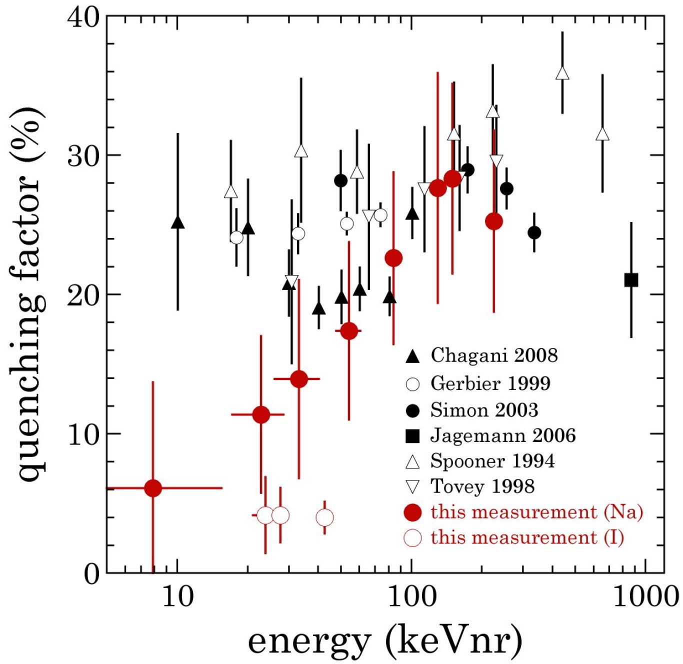
Q and L_{eff} have large uncertainties at low E.

Fig. from KIMS



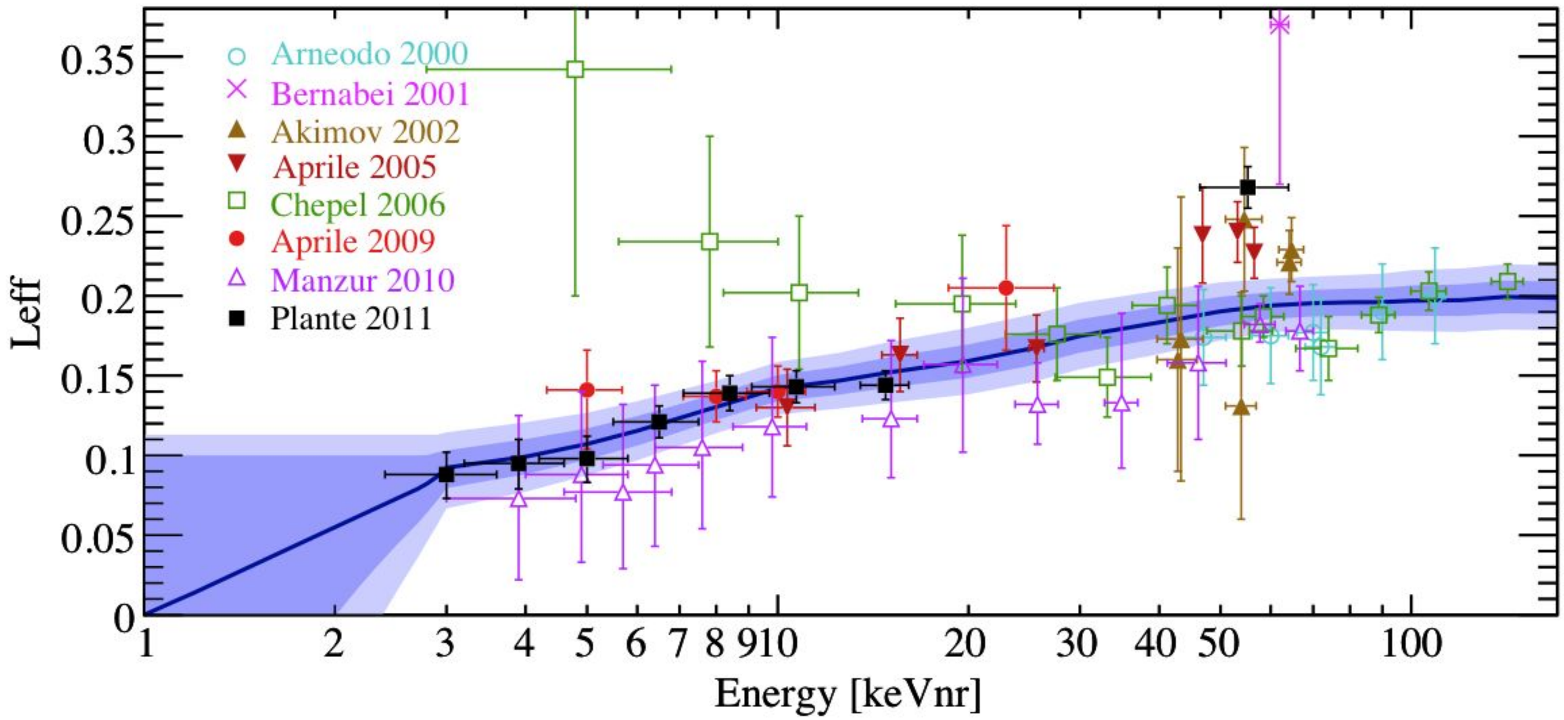
Large uncertainties in Q factors





Compilation of Q_{Ge} TEXONO 2007 and Q_{Na} Collar et al. 2013 measurements

Large uncertainties in L_{eff} of Xenon



Signal in Direct Searches:

- **Single Channel Techniques:**

  -Ionization (Ge, Si, CdTe): IGEX, HDMS, GENIUS, TEXONO, CoGeNT, C4

  -Scintillation (NaI, Xe, Ar, Ne, CsI): DAMA, NAID, DEAP, CLEAN, XMASS, **KIMS**

  -Phonons (Ge, Si, Al_2O_3, TeO_2): CRESST-I , Cuoricino, CUORE

  -Threshold detectors: PICASSO, SIMPLE, COUPP, PICO

  (superheated bubble chamber, bubbles of C_4F_10)

- **Hybrid detector techniques for discrimination:**

  (Xe, Ar, Ne are Liquid/Gas Detectors- others are crystal

  -Ionization + Phonons (Ge, Si): CDMS, SuperCDMS, EDELWEISS, EURECA?

  -Ionization + Scintillation(Xe, Ar, Ne):LUX, XENONZEPLIN,WARP,ArDM, DarkSide

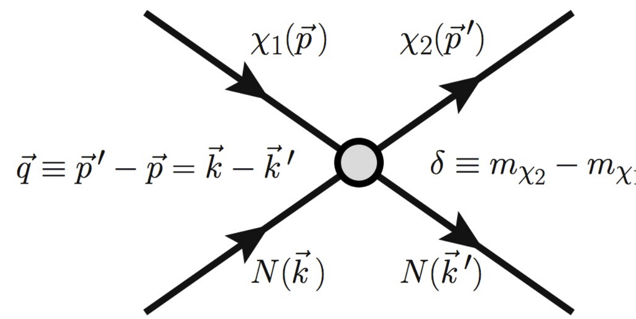
  -Scintillation+Phonons ($CaWO_4$, Al_2O_3): CREST, EURECA?, CRESST I

- **Directional low density gas TPCs(CS_2, CF_4):** DRIFT, DM-TPC, MIMAC, measure recoil $\vec{q}$, not well developed yet

Elements of the Event Rate

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

How does the DM particle couple to the nuclei?



- Starting with fundamental interactions, DM particles couple to quarks, and there are also uncertainties on how to pass from quarks to protons and neutrons
- besides the DM mass m, this is the only input of Particle Physics

Usual interactions

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

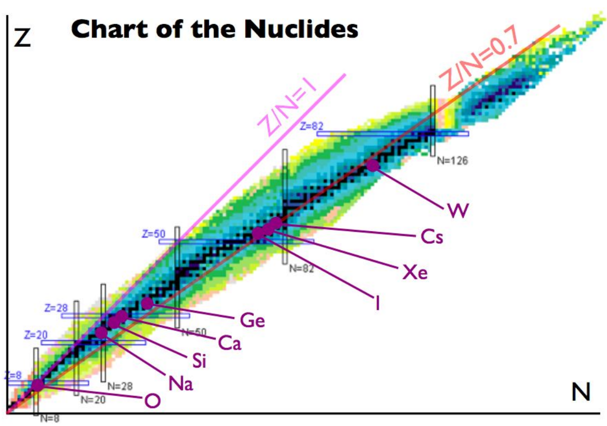
From scalar and vector couplings in the Lagrangian- $f_{p,n}$ effective couplings to p, n

$$\sigma_0 = \left[\langle Z f_p + (A - Z) f_n\right]^2 (\mu^2/\mu_p^2)\sigma_p = A^2(\mu^2/\mu_p^2)\sigma_p \text{ for } f_p = f_n \text{ for IC}$$

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

IV can make the coupling $\left[Z f_p + (A - Z) f_n\right] \simeq 0$ 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)

Usual interactions

- **Contact spin-dependent:** $\sigma^{SD}(q) = \frac{32\mu^2 G_F^2 (J_N+1)}{J_N} \left[\langle S_p \rangle a_p + \langle S_n \rangle a_n \right]^2$

From axial vector couplings in the Lagrangian- $a_{p,n}$ couplings to p, n Need non zero nuclear spin J_N, e.g. ^{29}Si (J_N = 1/2, 4.7%), ^{129}Xe (J_N = 1/2, 26.4%), ^{131}Xe (J_N = 1/2, 21.2%)

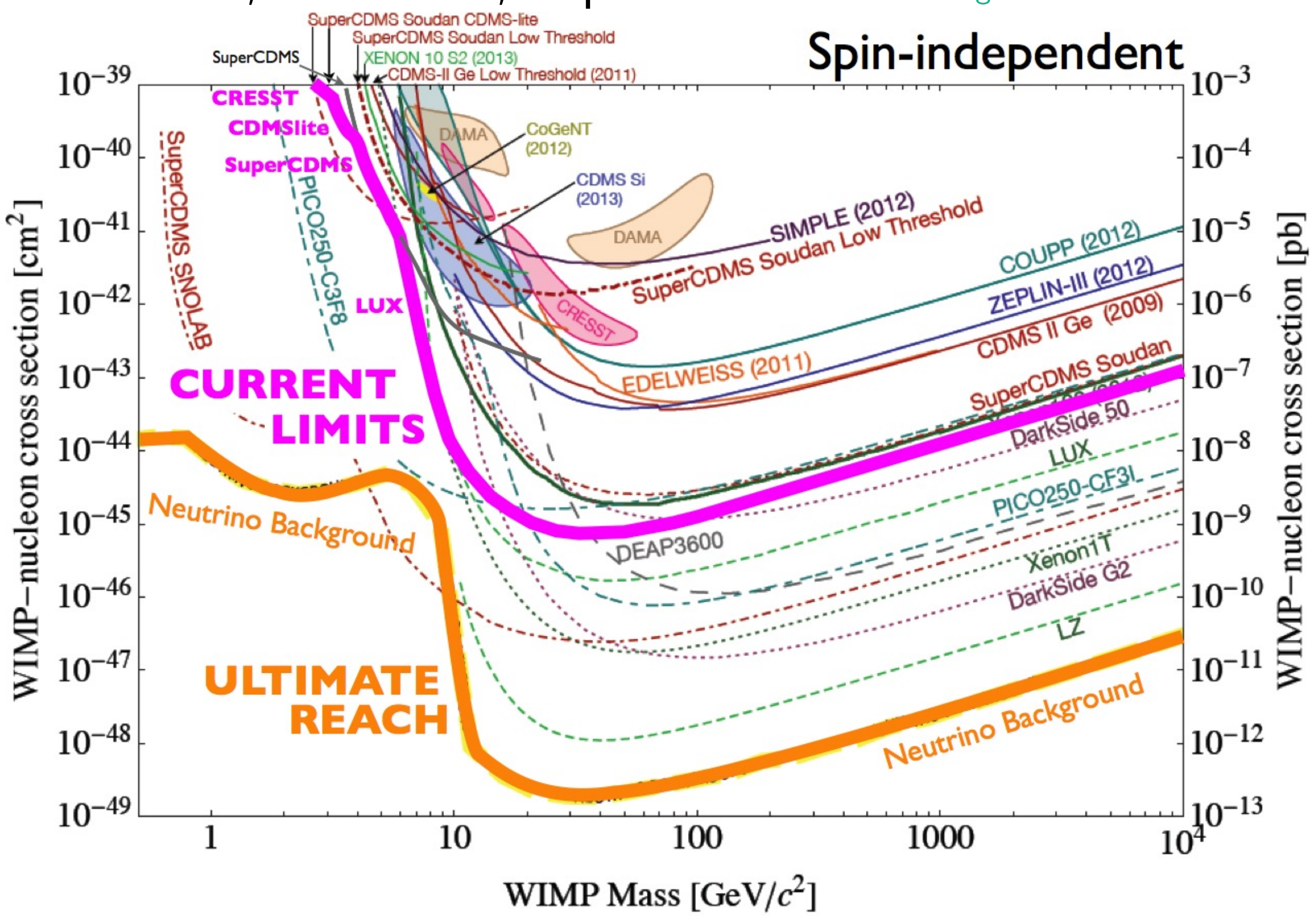
$\langle S_{p,n} \rangle$ expectation values of the spin content of p,n in the target nucleus due mostly to unpaired nucleon: - Na, I, F (DAMA, KIMS , COUPP, PICASSO, SIMPLE) have unpaired p,
- Xe, Ge (LUX, XENON, CDMS, CoGeNT) have unpaired n.
Example: ^{73}Ge (J_N = 9/2, 7.8% in isotopic composition) Single particle shell model: $\langle S_n \rangle =$ 0.5, $\langle S_p \rangle = 0$ (Odd-group model: 0.23, 0; Shell Model 0.488, 0.011)

- SD Form Factor is $O(1)$: $\sigma^{SI} \simeq A^2 \sigma^{SD}$ thus bounds on SI better that on SD.

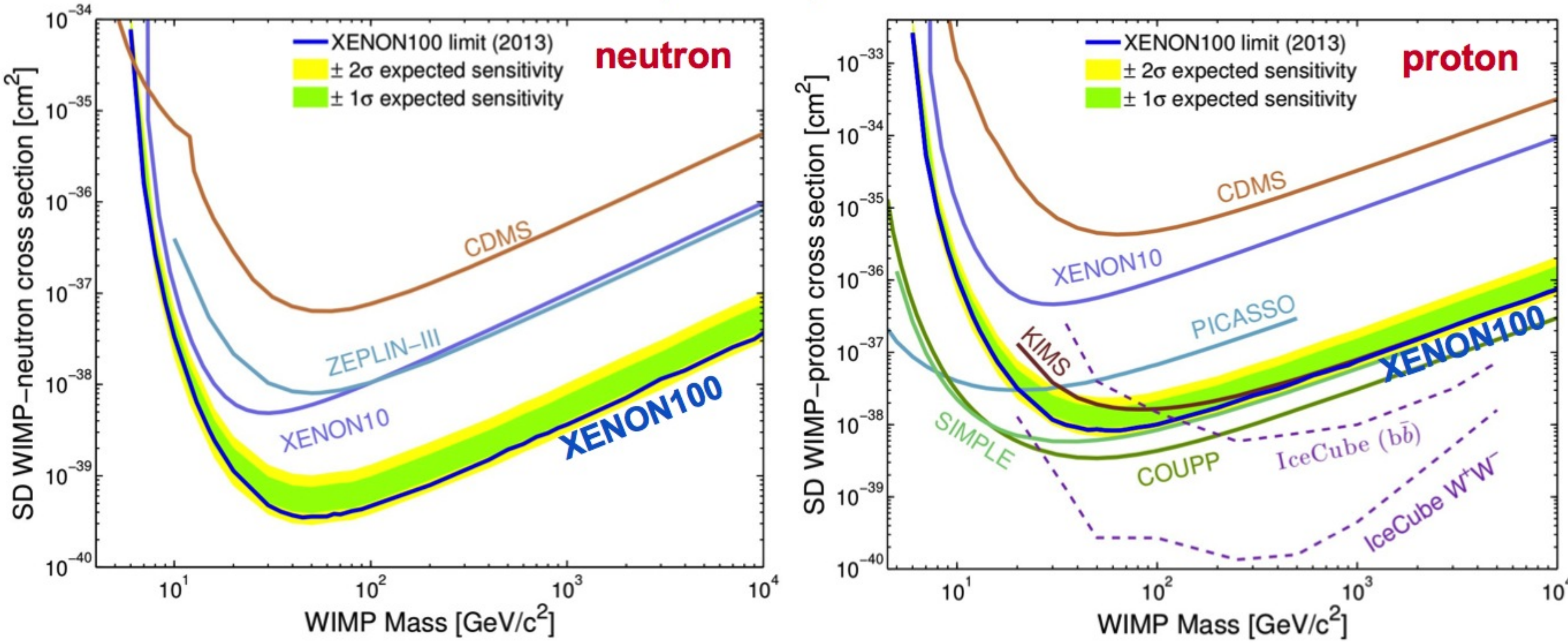
Experimentalist only use these two: SI and SD!

Present and future -IC SI and SHM

from Snowmass 2013, LUX 2013, SuperCDMS 2014- Fig. from P. Gondolo



Present bounds SD with n or p only and SHM



Many other possible interactions With fermionic DM Fitzpatrick et al 1203.3542; Barello, Chang, Newby 1409.0536

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

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

Many other possible interactions With scalar DM 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	$4\frac{m_\chi}{m_M}\left(\vec{v}^\perp_{\mathrm{inel}}-\frac{\delta}{\lvert\vec{q}\rvert^2}\vec{q}\right)\cdot\vec{S}_N$
$\frac{1}{m_M}\partial_\mu(\Phi_2\Phi_1)\bar{N}\gamma^\mu\gamma^5 N$		$-\frac{2i}{m_M}\vec{q}\cdot\vec{S}_N$
$\frac{1}{m_M}\left(i\Phi_2\overleftrightarrow{\partial}_\mu\Phi_1\right)Ni\sigma_{\mu\nu}\frac{q^\nu}{m_M}N$		$4i\frac{m_\chi}{m_M}\vec{v}^\perp_{\mathrm{inel}}\cdot\left(\frac{\vec{q}}{m_M}\times\vec{S}_N\right)+\frac{m_\chi}{m_N m_M^2}\lvert\vec{q}\rvert^2\mathbf{1}_\chi\mathbf{1}_N$
$\frac{i}{m_M}\left(i\Phi_2\overleftrightarrow{\partial}_\mu\Phi_1\right)Ni\sigma_{\mu\nu}\gamma^5\frac{q^\nu}{m_M}N$		$4i\frac{m_\chi}{m_M}\frac{\vec{q}}{m_M}\cdot\vec{S}_N$

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

Can have a rich "Dark Sector" similar to visible sector, with hidden gauge interactions and flavor Foot 2004, Huh at al 2008, Pospelov, Ritz, Voloshin 2008, Arkani-Hamed et al.,2009, Kaplan et al 0909.0753 and 1105.2073. . . "Atomic DM" Unbroken U'(1) hidden gauge symmetry that would give rise to bound states Goldberg Hall 1986; Feng, Kaplinghat, Tu 0905.3039; Ackerman 2009 DM must be asymmetric "Millicharged DM" with dark analogues of p, e, H coupled to a new U'(1) and "kinetic coupling"

$$\varepsilon F_{\mu\nu} F'^{\mu\nu}$$

Diagonalized gauge boson kinetic terms: em photon $A_\mu(J^\mu_{em} + \varepsilon g J^\mu_{dark})$ (g is U'(1) coupling). Need $\varepsilon \simeq 10^{-3}$, thus the DM acquires a millicharge $\varepsilon g = \varepsilon e$ under the usual e.m. Holdom 1986 , Burrage et al 0909.0649- Several versions too,

- γ mixed with massive dark vector boson that couples to the axial vector current of the DM D. E. Kaplan 0909.0753 1105.2073
- or γ mixed with massless dark vector boson γ' of the unbroken U(1) gauge symmetry Cline, Zuowei Liu, and Wei Xue 1201.4858

Dark Atoms may scatter elastically or inelastically depending of the choice of parameters e.g if the γ' gauge coupling is $\alpha' = 0.06$ and $m_e = m_p \simeq 3$ GeV, the hyperfine splitting is 15 keV, and $\varepsilon = 10^{-2}$ gives the right cross section for explaining candidate DM events reported by CoGeNT.

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!

Small electromagnetic couplings Besides "Millicharged DM", could be neutral and have

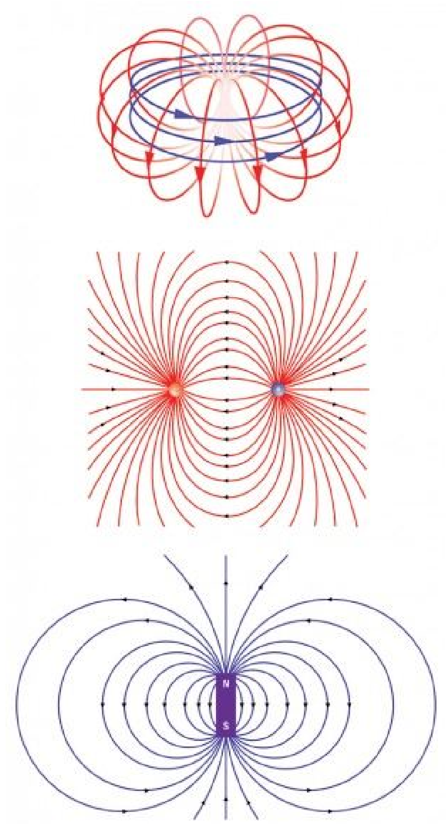
Magnetic (MDM) and Electric (EDM) Dipole Moment DM Pospelov & Veldhuis 2000, Sigurdson, Doran, Kurylov, Caldwell Kamionkowsky 2004, 2006, Maso, Mohanty, Rao 2009, Fortin, Tait 2012 many more

$$L = -(i/2)\bar{\psi}\sigma_{\mu\nu}(d_m + d_e\gamma_5)\psi F^{\mu\nu} \quad \rightarrow \quad H_{MDM} \sim d_m \vec{\sigma}.\vec{B}; \quad H_{EDM} \sim d_e \vec{\sigma}.\vec{E}$$

- For MDM, e.g. the cross section is (here $T =$ Target nucleus)

$$\frac{d\sigma_T}{dE_R} = \frac{\alpha d_m^2}{v^2}\left\{ Z_T^2 \frac{m_T}{2\mu_T^2}\left[\frac{v^2}{v_{min}^2} - \left(1 - \frac{\mu_T^2}{m^2}\right)\right] F_{SI,T}^2(E_R) + \frac{d_{mT}^2}{\mu_N^2}\frac{m_T}{m_p^2}\left(\frac{S_T+1}{3S_T}\right) F_{M,T}^2(E_R)\right\}$$

Dipole moments are zero for Majorana fermions (although transition moments are not) and the first non-zero moment is the Anapole Moment



Anapole moment DM (ADM) Ho-Scherrer 1211.0503

First proposed by Zel dovich in Sov. Phys. JETP 6, 1184 (1958): particles could have anapole moment that breaks C and P, but preserves CP - first measured experimentally in Cesium-133: C. S. Wood et al, Science 275, 1759 (1997)

$$L = \frac{g}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma_5\psi\partial^\nu F^{\mu\nu} \quad \rightarrow \quad H_{anapole} \sim \vec{\sigma} \times \vec{B}$$

Annihilation is purely p-wave- $\sigma_{scattering} \sim \alpha Z^2 \mu_T v^2$, again two dominant terms in the differential cross sections.

Each interaction requires its own nuclear Form Factor (FF)

Sometimes DM FF needed too!

Some are known (SI: Helmi charge FF, SD: known with uncertainties; many electric and magnetic form factors have been measured).

Recently all possible non-relativistic operators to $O(q^2)$ classified Fitzpatrick et al 1203.3542

$$\mathbf{1},\ \ \vec{S}_\chi \cdot \vec{S}_N,\ \ v^2,\ \ i(\vec{S}_\chi \times \vec{q}) \cdot \vec{v},\ \ i\vec{v} \cdot (\vec{S}_N \times \vec{q}),\ \ (\vec{S}_\chi \cdot \vec{q})(\vec{S}_N \cdot \vec{q}) \qquad i\vec{S}_N \cdot \vec{q},\ i\vec{S}_\chi \cdot \vec{q},$$

$$\vec{v}^\perp \cdot \vec{S}_\chi,\ \ \vec{v}^\perp \cdot \vec{S}_N,\ \ i\vec{S}_\chi \cdot (\vec{S}_N \times \vec{q}). \qquad (i\vec{S}_N \cdot \vec{q})(\vec{v}^\perp \cdot \vec{S}_\chi),\ (i\vec{S}_\chi \cdot \vec{q})(\vec{v}^\perp \cdot \vec{S}_N)$$

and six nuclear FF for single-nucleon operators classified and computed for some nuclei (F, Na, Ge, I, Xe) using the nuclear oscillator model Fitzpatrick, Haxton, Katz, Lubbers, Xu 1203.3542

Response $\times \left[\frac{4\pi}{2J_i+1}\right]^{-1}$	Leading Multipole	Long-wavelength Limit	Response Type
$\sum_{J=0,2,...}^{\infty} \lvert\langle J_i \vert\vert M_{JM} \vert\vert J_i\rangle\rvert^2$	$M_{00}(q\vec{x}_i)$	$\frac{1}{\sqrt{4\pi}}1(i)$	M_{JM} : Charge
$\sum_{J=1,3,...}^{\infty} \lvert\langle J_i \vert\vert \Sigma''_{JM} \vert\vert J_i\rangle\rvert^2$	$\Sigma''_{1M}(q\vec{x}_i)$	$\frac{1}{2\sqrt{3\pi}}\sigma_{1M}(i)$	L^5_{JM} : Axial Longitudinal
$\sum_{J=1,3,...}^{\infty} \lvert\langle J_i \vert\vert \Sigma'_{JM} \vert\vert J_i\rangle\rvert^2$	$\Sigma'_{1M}(q\vec{x}_i)$	$\frac{1}{\sqrt{6\pi}}\sigma_{1M}(i)$	T^{el5}_{JM} : Axial Transverse Electric
$\sum_{J=1,3,...}^{\infty} \lvert\langle J_i \vert\vert \frac{q}{m_N}\Delta_{JM} \vert\vert J_i\rangle\rvert^2$	$\frac{q}{m_N}\Delta_{1M}(q\vec{x}_i)$	$-\frac{q}{2m_N\sqrt{6\pi}}\ell_{1M}(i)$	T^{mag}_{JM} : Transverse Magnetic
$\sum_{J=0,2,...}^{\infty} \lvert\langle J_i \vert\vert \frac{q}{m_N}\Phi''_{JM} \vert\vert J_i\rangle\rvert^2$	$\frac{q}{m_N}\Phi''_{00}(q\vec{x}_i)$	$-\frac{q}{3m_N\sqrt{4\pi}}\vec{\sigma}(i) \cdot \vec{\ell}(i)$	L_{JM} : Longitudinal
	$\frac{q}{m_N}\Phi''_{2M}(q\vec{x}_i)$	$-\frac{q}{m_N\sqrt{30\pi}}[x_i \otimes (\vec{\sigma}(i) \times \frac{1}{i}\vec{\nabla})_1]_{2M}$	
$\sum_{J=2,4,...}^{\infty} \lvert\langle J_i \vert\vert \frac{q}{m_N}\tilde{\Phi}'_{JM} \vert\vert J_i\rangle\rvert^2$	$\frac{q}{m_N}\tilde{\Phi}'_{2M}(q\vec{x}_i)$	$-\frac{q}{m_N\sqrt{20\pi}}[x_i \otimes (\vec{\sigma}(i) \times \frac{1}{i}\vec{\nabla})_1]_{2M}$	T^{el}_{JM} : Transverse Electric

Table 1: The response dark-matter nuclear response functions, their leading order behavior, and the response type. The notation $\otimes$ denotes a spherical tensor product, while $\times$ is the conventional cross product.

Elements of the Event Rate

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

How many dark matter particles are passing through the detector and with which velocity distribution?

We will cover the astrophysical uncertainties in the rate in the following lecture.