Direct Detection and Collider Searches of Dark Matter Lecture 2

Graciela Gelmini - UCLA

Dark Matter School, Lund, Sept. 26-30, 2016

Content of Lecture 2

- Introduction to WIMP dark matter searches, direct detection world wide efforts.
- Main elements of the expected event rate in direct detection experiments: detector response, cross section and halo model
- Uncertainties related to detector response and particle DM physics
- Uncertainties related to DM particle physics

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

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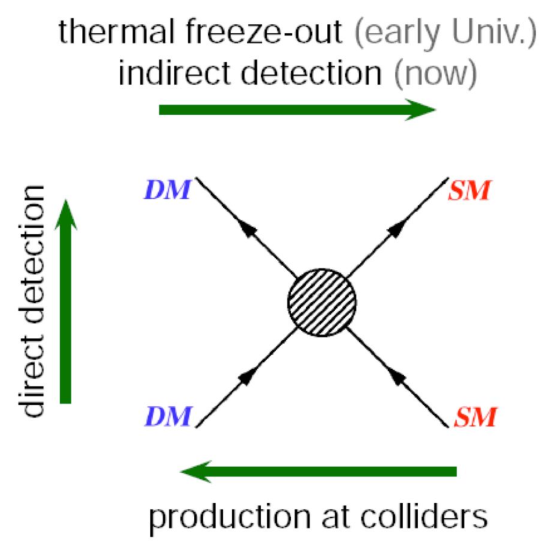
WIMP DM searches
Direct detection world-wide efforts

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 or decay)

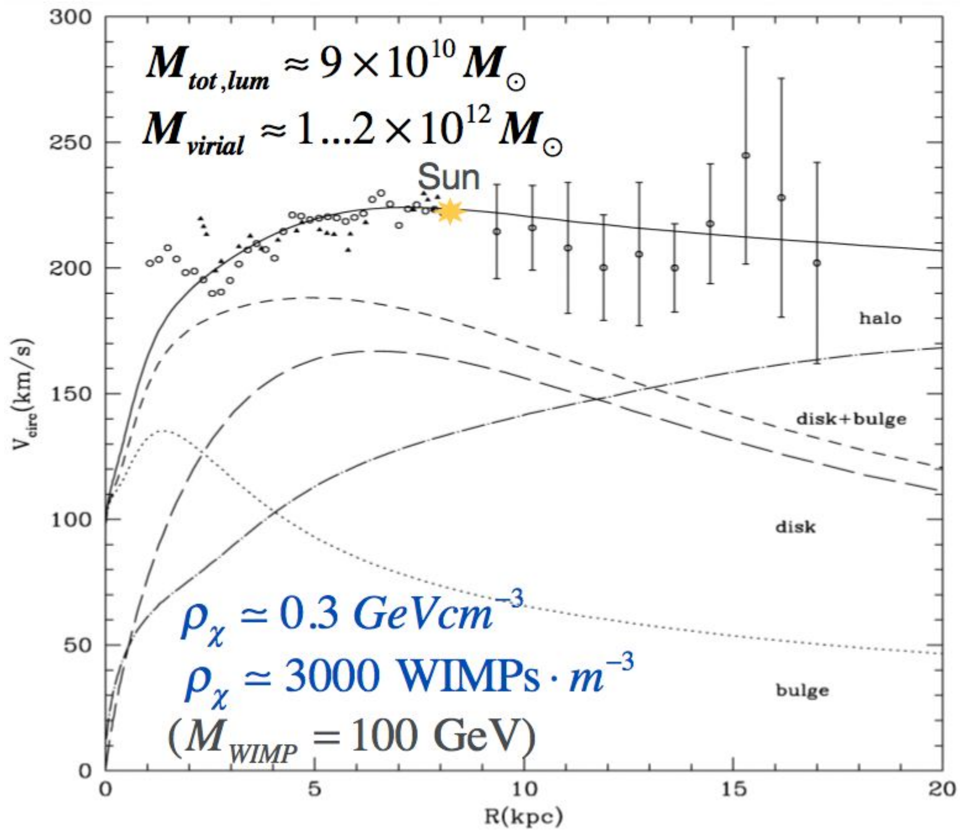
- At colliders (the LHC) as missing transverse energy, mono-jet or mono-photon events (Caveat: the DM mass may be above 2 TeV or its signature hidden by backgrounds)

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 galaxy and other galaxies.

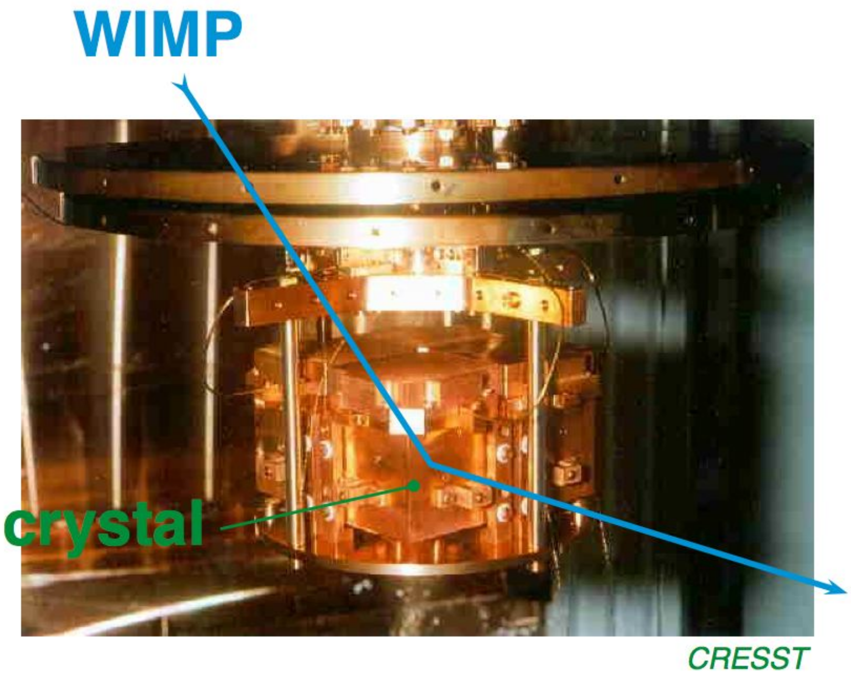
Milky Way's Dark Halo

Fig. from L.Baudis; Klypin, Zhao and Somerville 2002



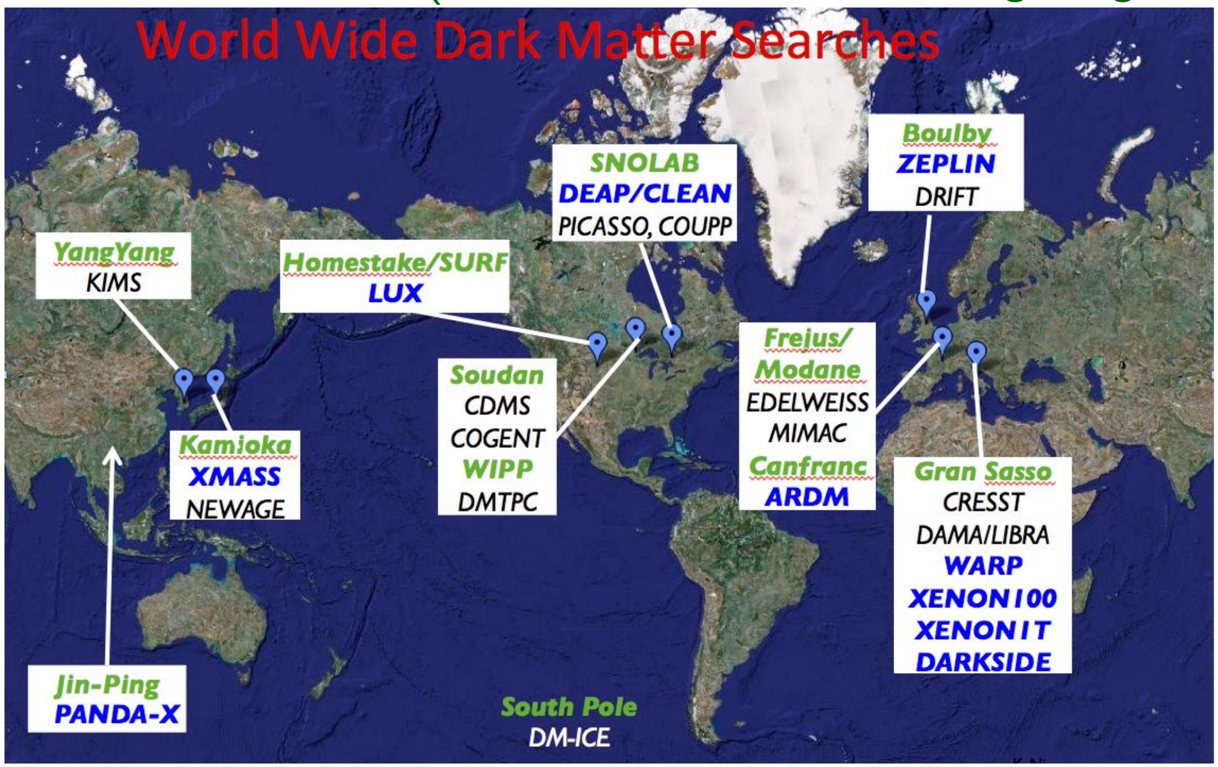
The Sun moves in the Dark Halo of our Galaxy. We have DM "wind" on Earth.
$10^7(\text{GeV}/m_\chi)$ WIMP's passing through us per cm^2 per second! (* See exercise)

Direct DM Searches:



- WIMP typically interacts with a nucleus in the detector which recoils
- Small $E_{Recoil} \leq 50\text{keV}(m/100\ \text{GeV})$
- Rate: depends on WIMP mass, cross section, dark halo model, nuclear form factors... typical... <1 event/ 100 kg/day requires constant fight against backgrounds, must be underground to shield from cosmic rays.
- Annual rate 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! in mines (Soudan, Boulby, Kamioka) or mountain tunnels (Gran Sasso, Modane, YangYang, Jin-Ping)



Sensitivity:

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

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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*

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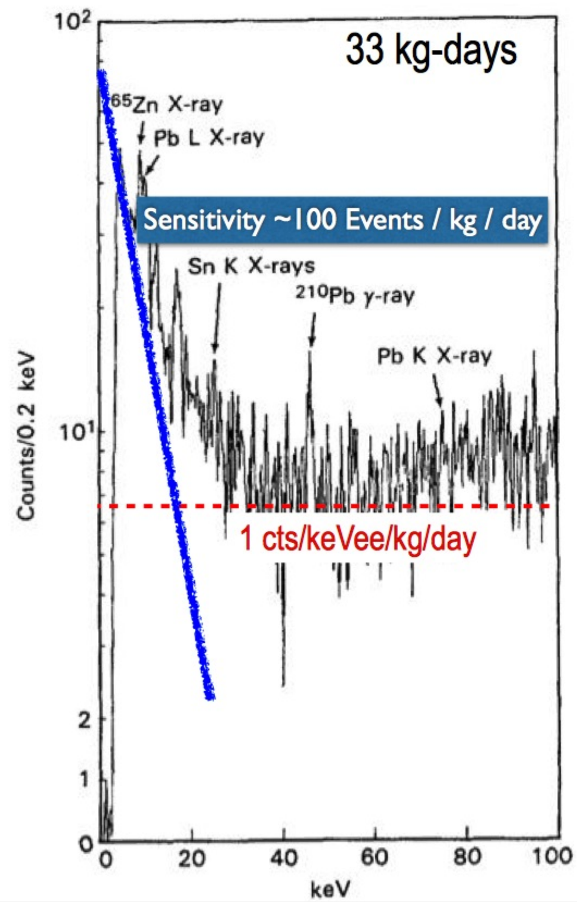
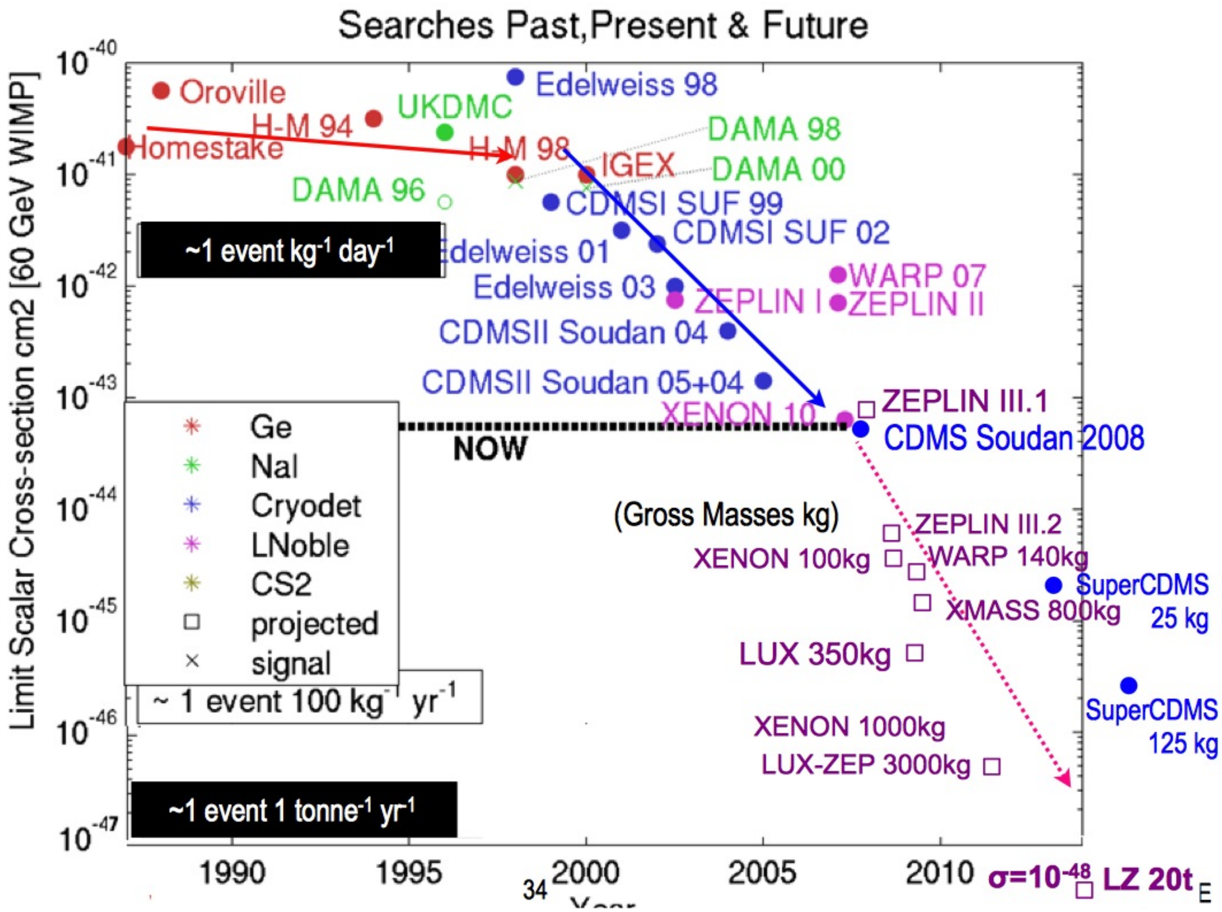
An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy Using a realistic model for the galactic halo, large regions of the mass–cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy 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.



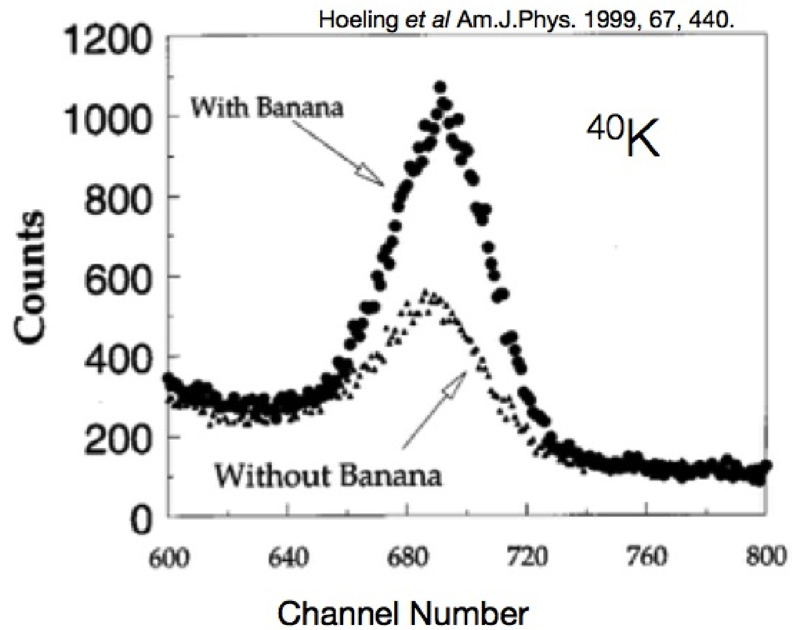
Sensitivity:



Backgrounds in Direct DM detectors:

Everything is radioactive! Some examples:

- In your body 4000 ^{14}C decay/s and 4000 ^{40}K decays/s (e^-, γ, ν_e),
- 7000 radon atoms escape of the ground per m^2 per s,
- There are 10^7 plutonium atoms in1 kg of soil (from transmutation of ^{238}U by fast cosmic ray neutrons, the soil contains 1 - 3 mg of U per kg)



So, no bananas in the lab!

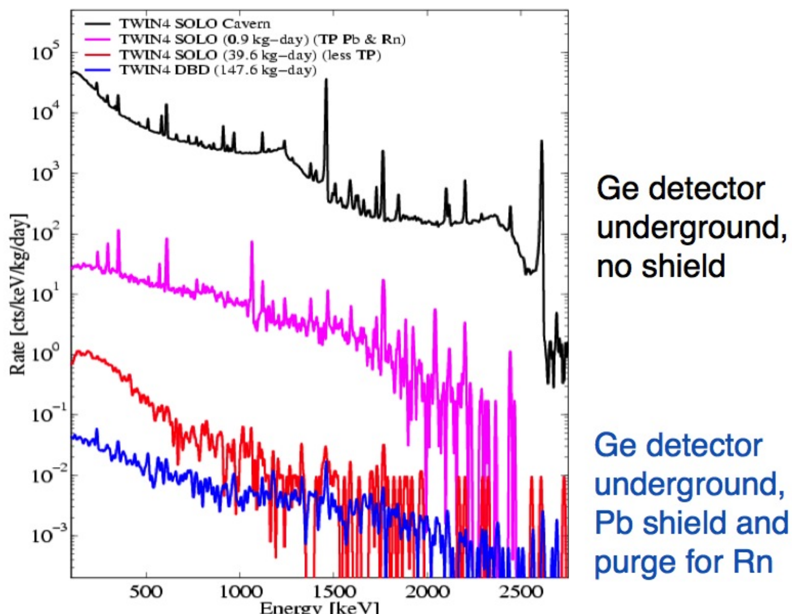
Backgrounds in Direct DM detectors:

- 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) require either

passive shields: Pb against the gammas, polyethylene/water against neutrons or

active shields: large water Cherenkov detectors or scintillators for gammas and neutrons



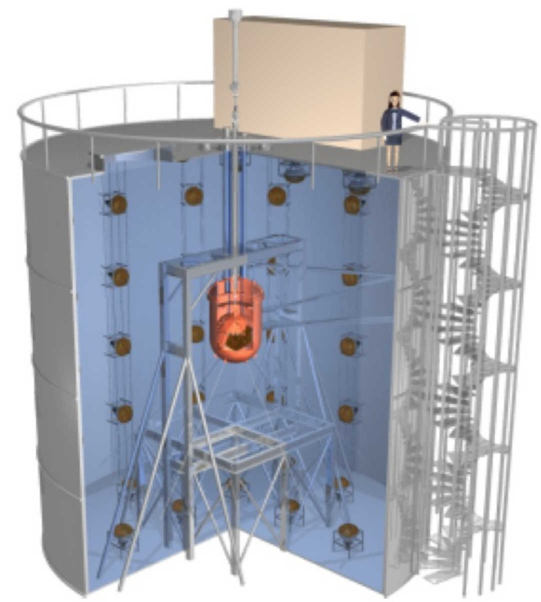


Fig. from L. Baudis- Right: XMASS (Xe at Kamioka, Japan)

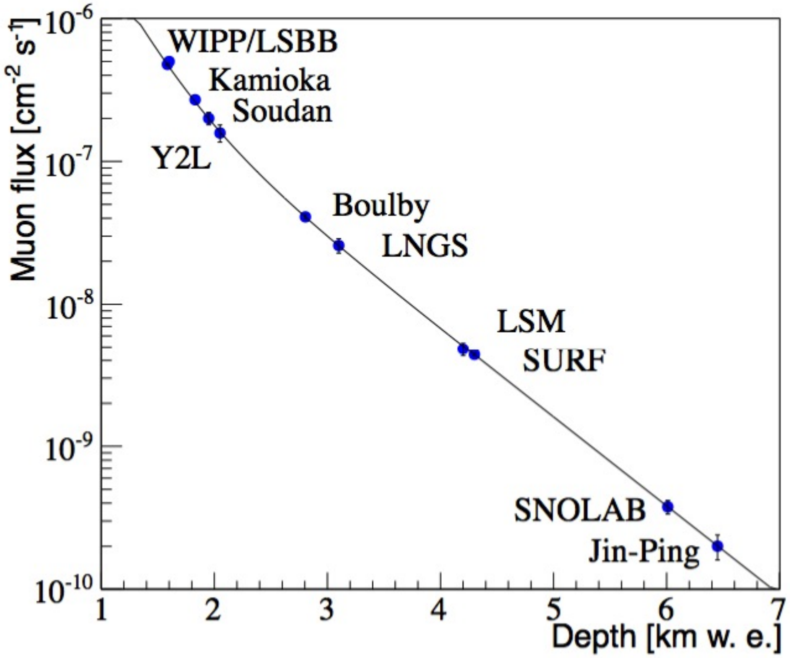
Backgrounds in Direct DM detectors:

-2- Internal radioactivity of detector and shield materials

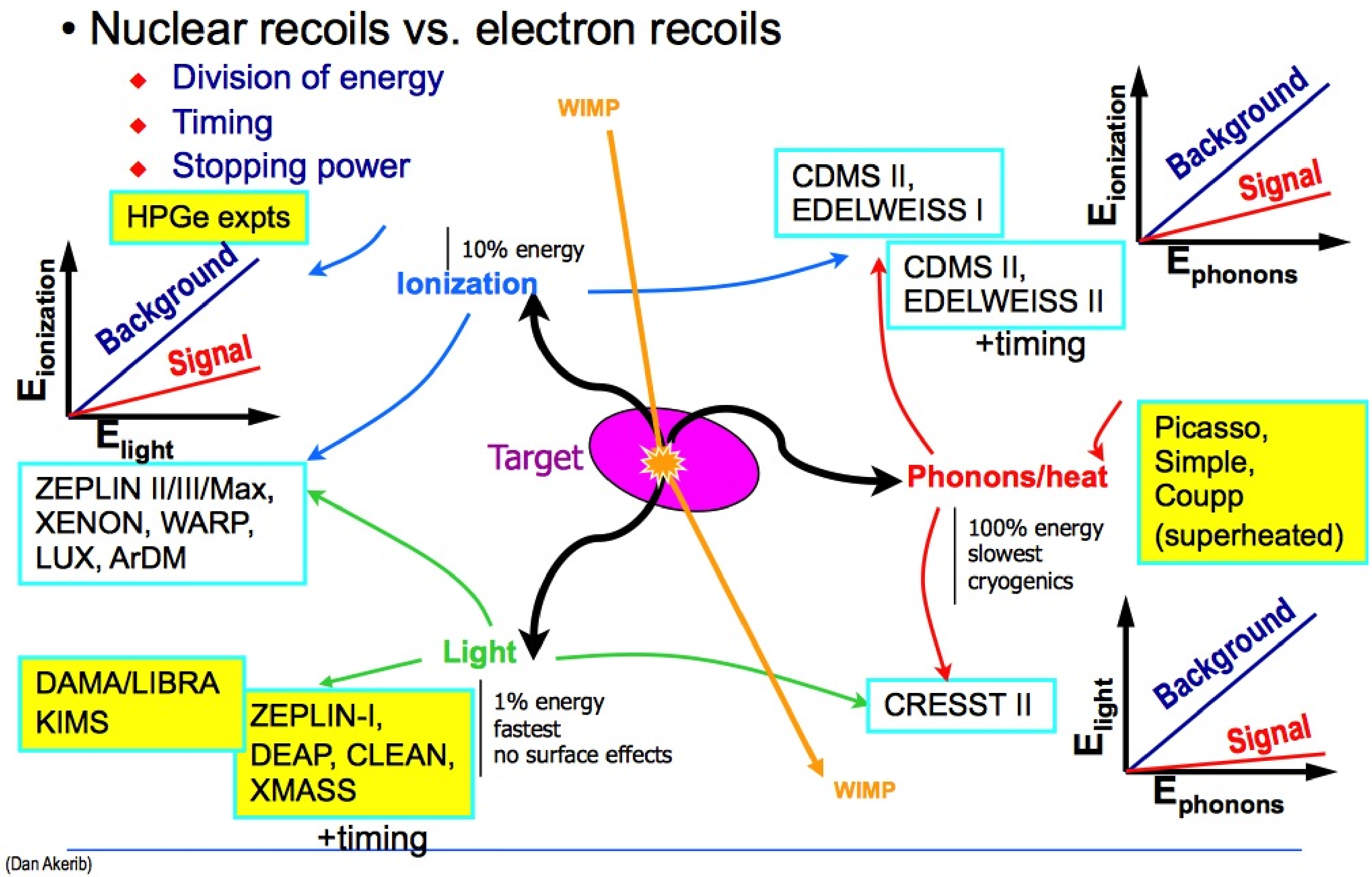
Many strategies to use material with very low radioactivity. E.g. ultra-pure Ge spectrometers are used to screen the materials before using them in a detector, down to ≤ parts-per-billion (ppb) levels

- 3- Cosmic rays and secondary reactions

Must go underground.



Signal in Direct Searches: Fig. from D. Akerib



Signal in Direct Searches: (In red: had signal claims)

- **Single Channel Techniques:**

  -Ionization (Ge, Si): CDEX, DAMIC, CoGeNT, C4

  -Scintillation (NaI, CsI // single phase noble-gas): DAMA/LIBRA, ANAIS, DM-Ice, KIMS, SABRE // DEAP, MiniCLEAN, XMASS,

  -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 crystals

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

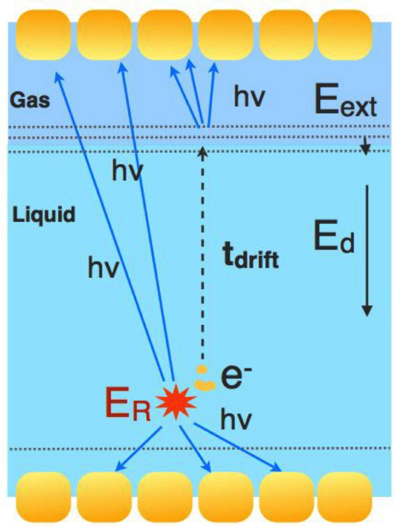
  -Ionization + Scintillation(Xe, Ar, Ne): XENON, LUX, PandaX, DarkSide, ArDM

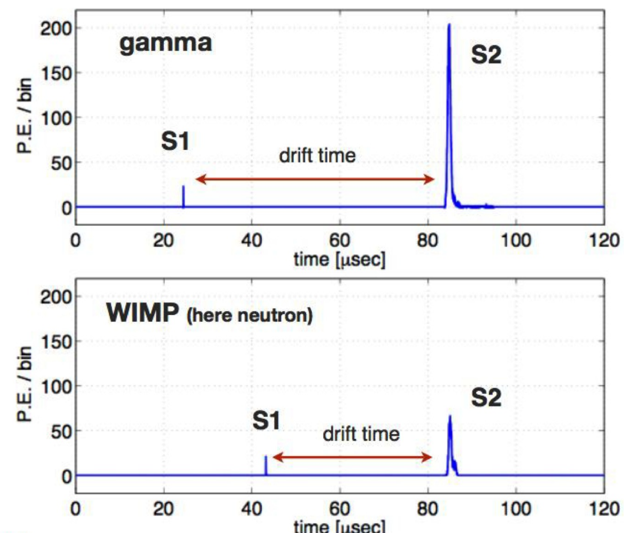
  -Scintillation+Phonons ($CaWO_4$, Al_2O_3): CREST-II, EURECA?

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

Example: Noble Liquid detectors: Either single phase (scintillation) or double phase (ionization/ scintillation) act as their own veto, up-scalable to multi-tonnes

- Single-Phase: Scintillation
  XMASS (Xe,Japan, Kamioka), DEAP/ MiniCLEAN (Ar/Ne,US/Canada, SNOLab)
- Two-phase liquid and gas: Scintillation and ionization seen as light pulses (one delayed)

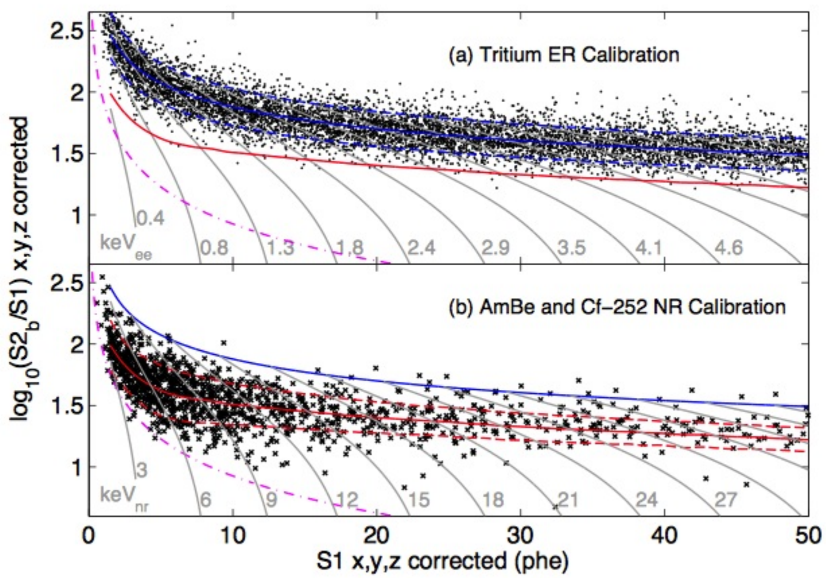


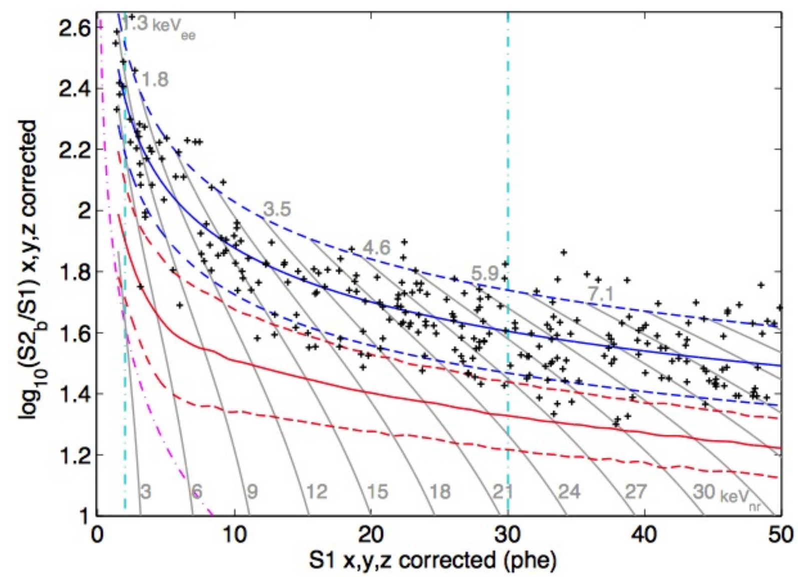


XENON1T/nT (Xe, US/Switzerland/Germany/France/Portugal/Italy/Japan/China, LNGS), LUX/LZ (Xe, US/UK, Sanford Lab), DarkSide (Ar, US/Europe, LNGS), WARP (Ar, Italy/US, LNGS), ZEPLIN (Xe, UK/US, Boulby), ArDM (Ar, Switzerland/Spain/UK, Canfranc)

Example of two-phase Xe: LUX

S_2/S_1 versus S_1 plots. Calibration data and actual data (2013)





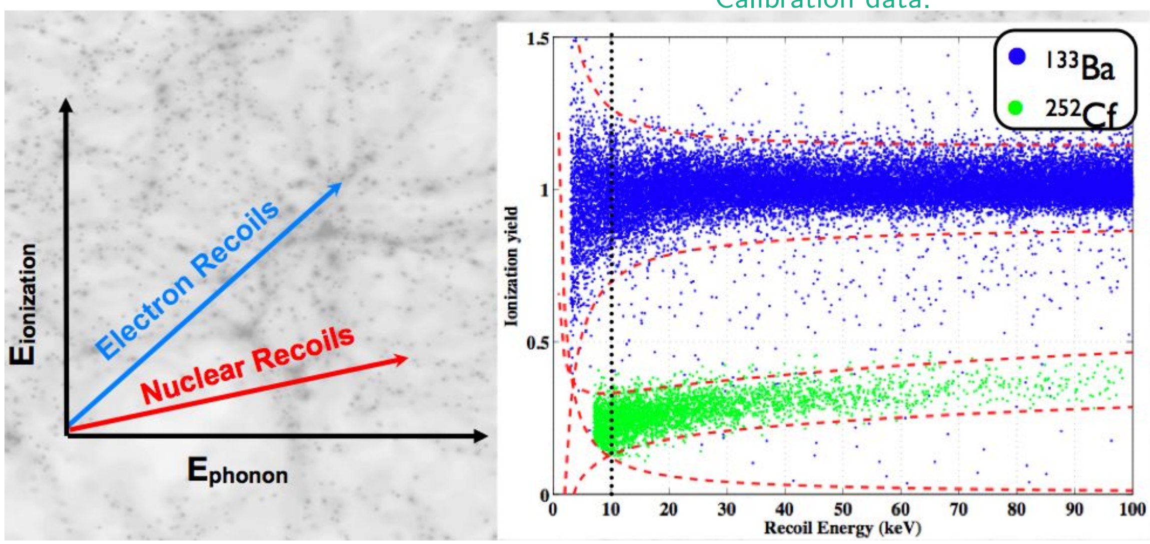
Actual data: neutral recoils expected in red band (evens compatible with backgrounds).

Example: CDMS and SuperCDMS (Ge and Si crystals)

- DM particles and neutrons produce nuclear recoils: only a fraction Q of energy deposited in a nucleus goes into ionization (Q is called "quenching factor") $Q_{Ge} \simeq 0.3$, $Q_{Si} \simeq 0.25$, bulk goes into phonons, thus "Ionization yield"$= Q$

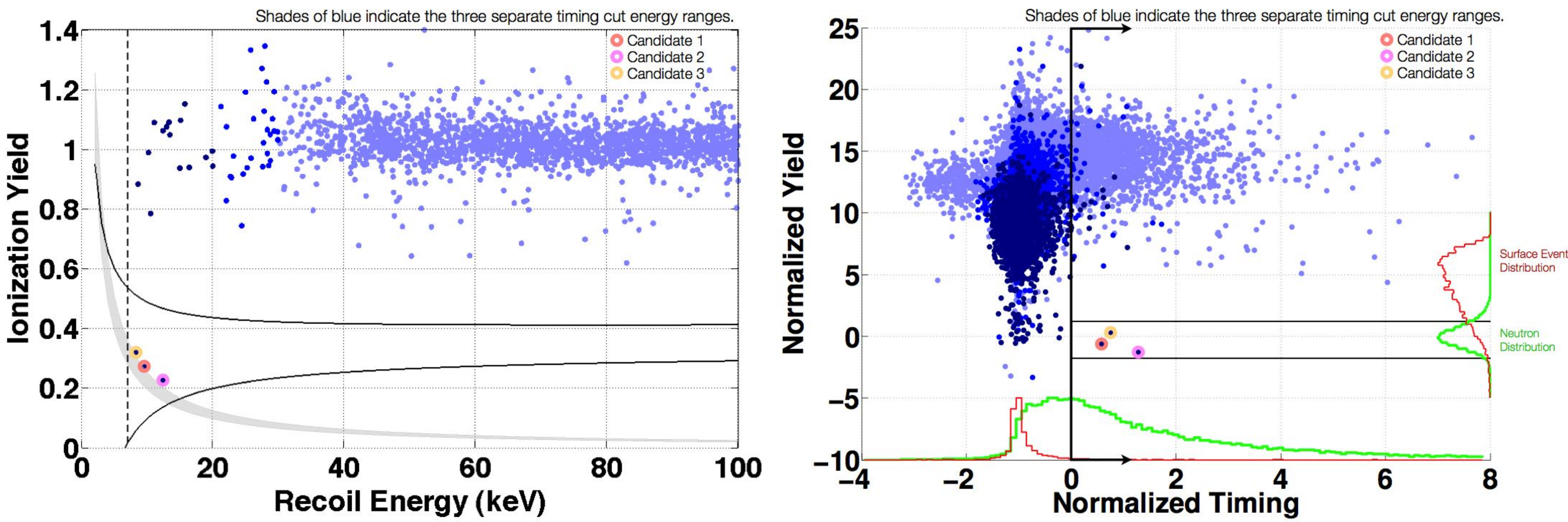
- Photons interact with electrons: All energy deposited into electrons goes into ionization: "Ionization yield"$= 1$

Calibration data.



CDMS-II three candidate events in Si

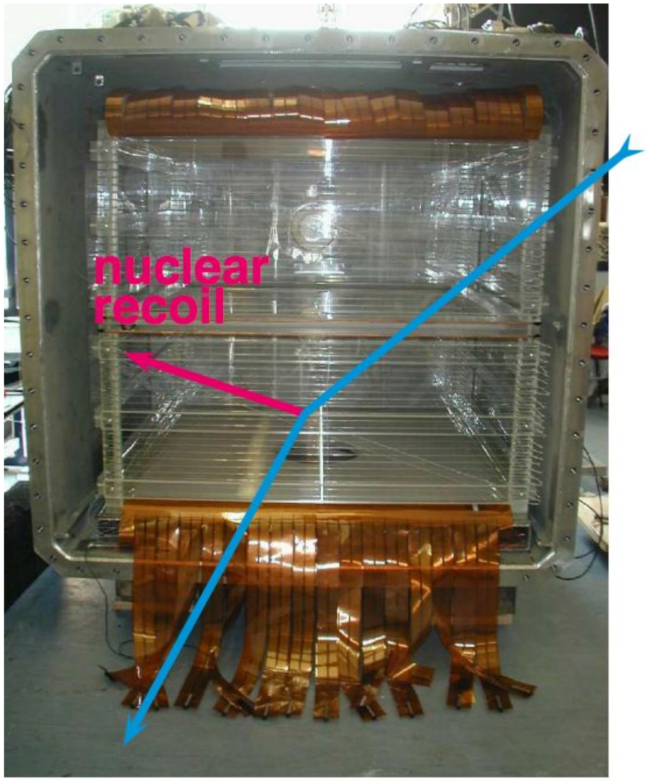
Data taken from July 2007 to Sep.2008- results published in 2013



Directional detectors: low density gas TPCs

DRIFT at Boulby (CS_2) and DM-TPC at MIT-WIPP (CF_4)

Measure direction of recoil- track reconstructed through drift of e



DRIFT

$m \geq$GeV WIMPs interact coherently with nuclei

WIMPs are not relativistic, $v \simeq 300$km/s $\simeq 10^{-3}$ the de Broglie wavelength of the mediator, $\frac{1}{q}$, where $\vec{q}$ is the momentum transfer and $q = |\vec{q}|$, is

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

(* You will prove this in an exercise)
(1= 197 MeV fm; 1 femtometre, fm (or Fermi) $= 10^{-15}$ m) e.g. for $m << M$

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

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

For larger q 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 one uses conventional the Helmi form factor (this is a charge form factor, i.e. for p, assumed to hold also for n), $F(E) = 3e^{-q^2 s^2/2}[sin(qd) - qd \ cos(qd)]/(qd)^3$, with $s = 1$ fm, $d = \sqrt{R^2 - 5s^2}$, $R = R_{Nucleus} \simeq 1.2 A^{1/3}$ fm, $q = \sqrt{2ME}$.

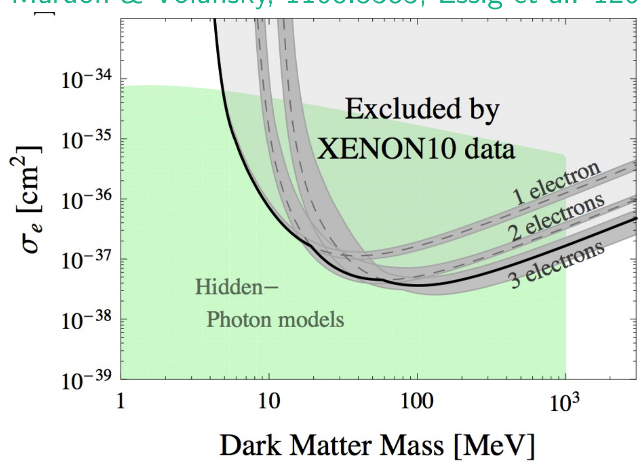
Caveat: Sub-GeV "Light Dark Matter" (LDM)

$m \simeq$ keV to 0.1GeV<< M, thus the maximum energy imparted in an elastic collision with the whole nucleus is below threshold for most experiments ($E_{thres} >$ 0.1 keV)

$$E_{max}^{elastic-Nuclei} \simeq 20eV \left(\frac{m}{100MeV}\right)^2 \left(\frac{10GeV}{M}\right) \qquad (^*)$$

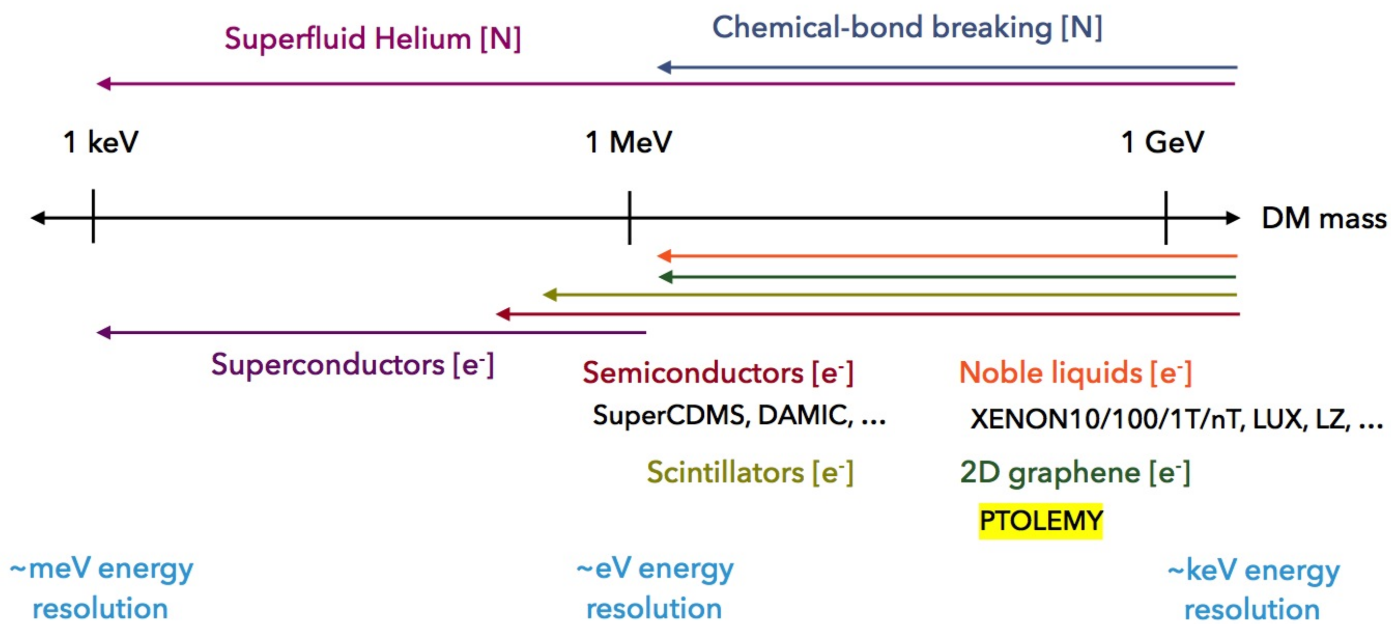
(* You will prove this in an exercise)

but LDM could deposit enough energy, 1 to 10 eV, interacting with electrons (electron ionization, electronic excitation, 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)

Will concentrate on $m >$ GeV WIMPs and nuclear recoils

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Main elements of the expected event rate

Event rate:

$dR = N_T \times \sigma \times \{$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

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

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

-E_R: nuclear recoil energy- T: each target nuclide (elements and isotopes)
- $\frac{C_T}{M_T}$= mass fraction of nuclide T× Number of nuclides T per kg=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 differential cross section (for momentum transfer and velocity-independent interaction operators)

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

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

-$\rho = nm$, $f(\vec{v},t)$: 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, σ_{ref} plane ("Halo-Dependent" analysis)

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

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

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

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Uncertainties in detector response

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,

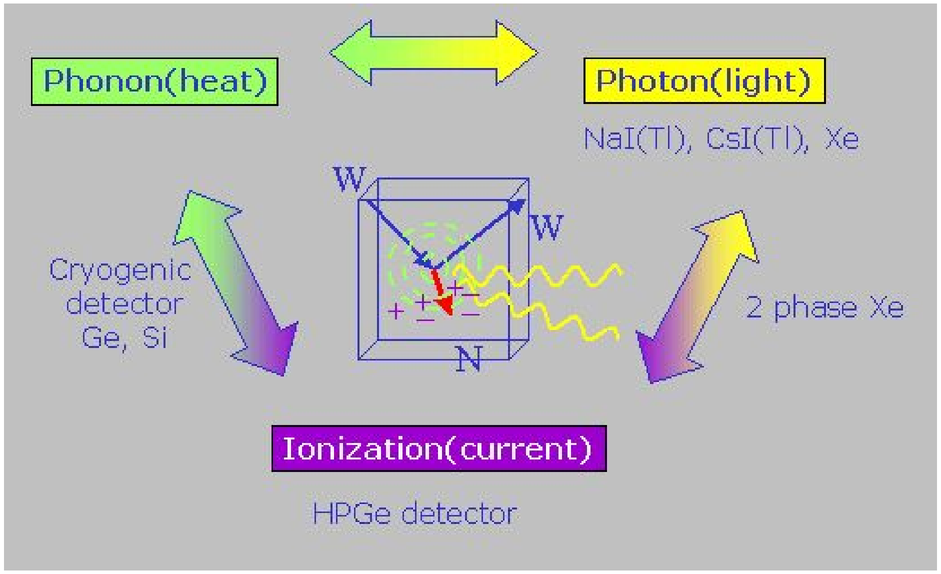
but a fraction Q goes into ionization/ scintillation, $Q_{Na} = 0.3$, $Q_I = 0.09$...

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

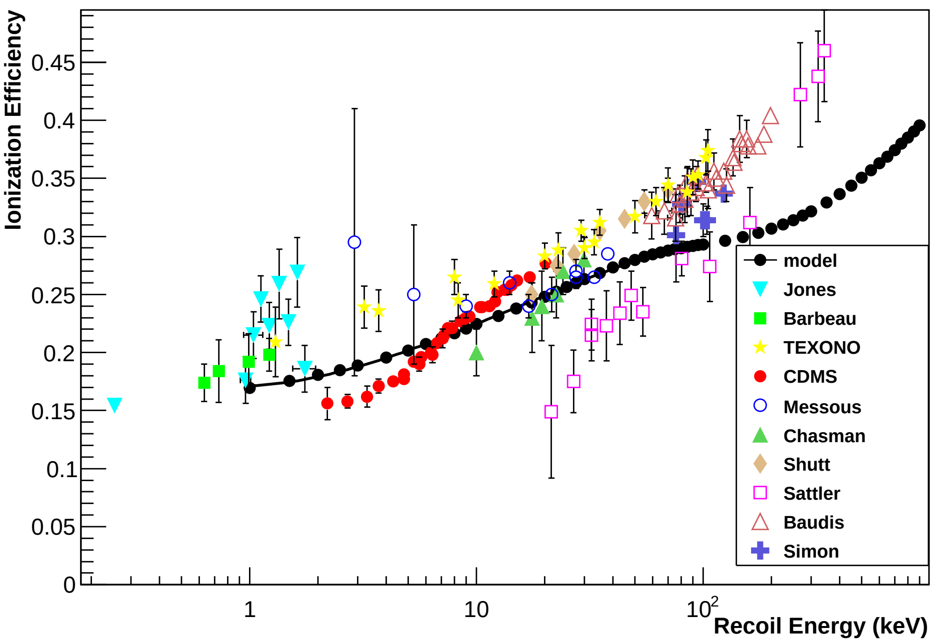
there is also delayed ionization (S2).

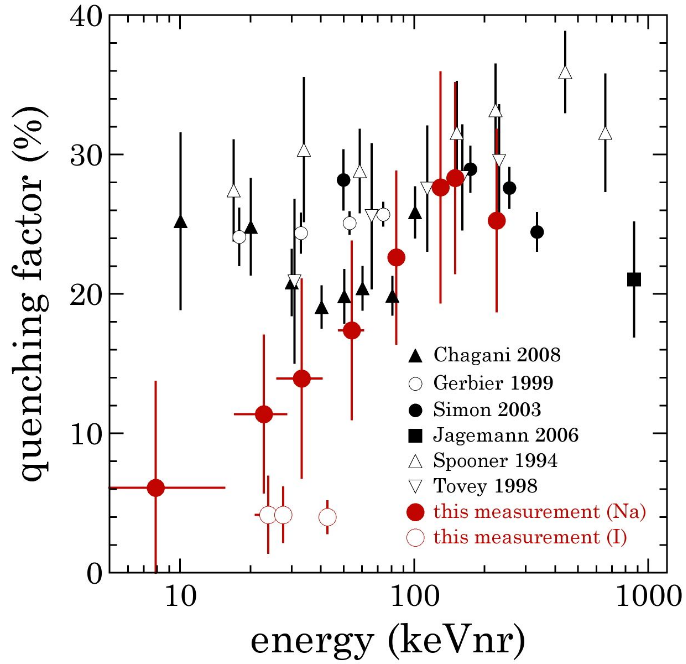
Q and L_{eff} have large uncertainties at low E.

Fig. from KIMS



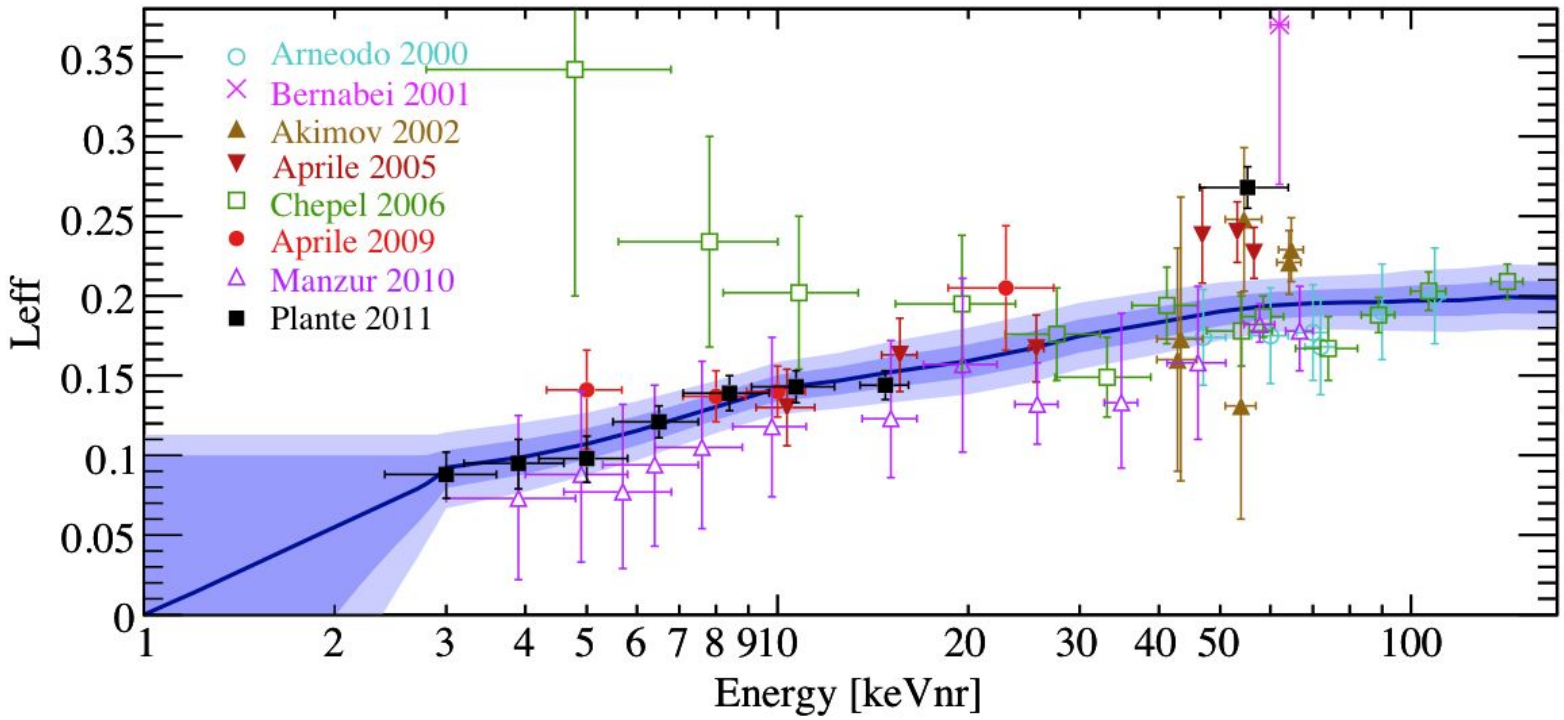
Large uncertainties in Q factors





Compilation of Q_{Ge} Barker, Mei 2012 and Q_{Na} Collar et al. 2013 measurements

Large uncertainties in L_{eff} of Xenon



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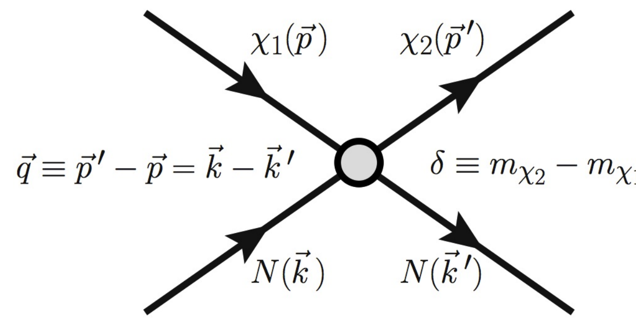
Uncertainties in the DM particle physics event rate

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: $\sigma^{SI}(q) = \sigma_0 F^2(q)$

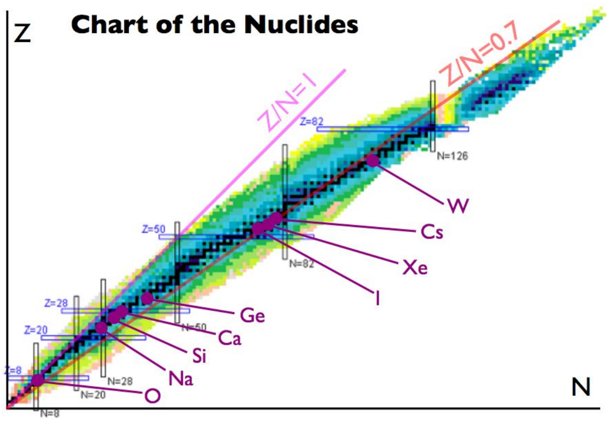
From scalar and vector couplings in the Lagrangian- $f_{p,n}$ effective couplings to p, n

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

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)

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

Usual interactions

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

From axial vector couplings-$a_{p,n}$ 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%)

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

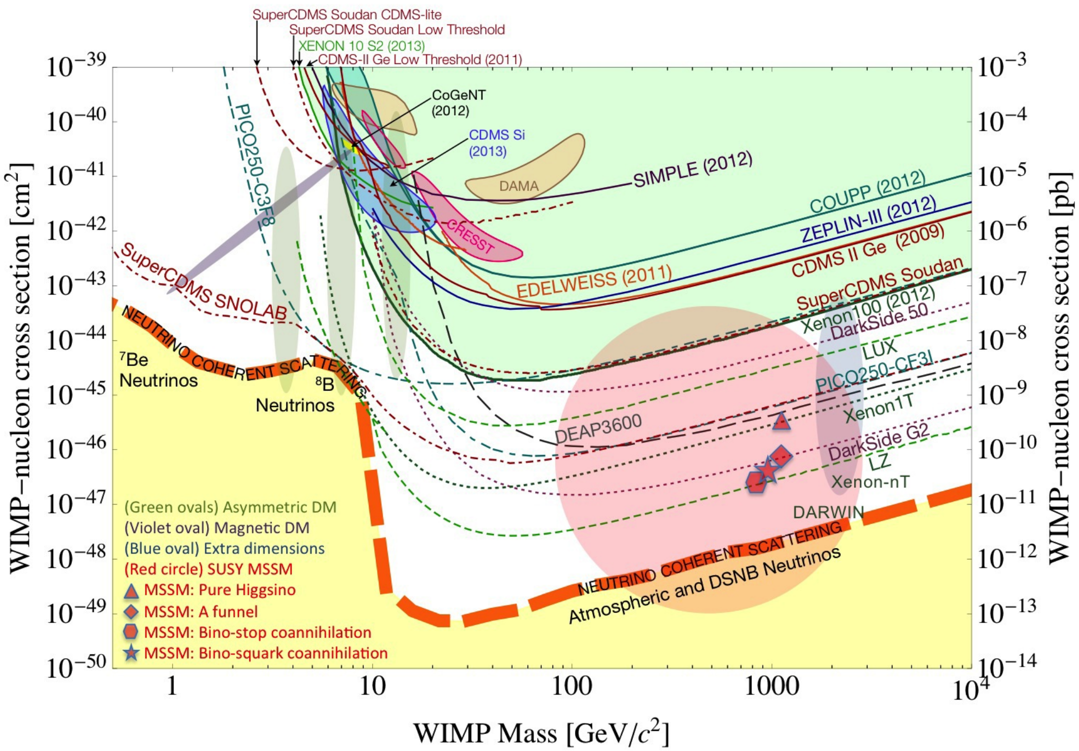
- **Na, I, F have unpaired** p (DAMA, KIMS, COUPP, PICASSO, SIMPLE) ,
- **Xe, Ge have unpaired** n (LUX, XENON, CDMS, CoGeNT) .

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)

Experimentalists only use these two:
Isospin-Conserving (IC) SI and SD!

Present and future for IC SI and SHM (Standard Halo Model)

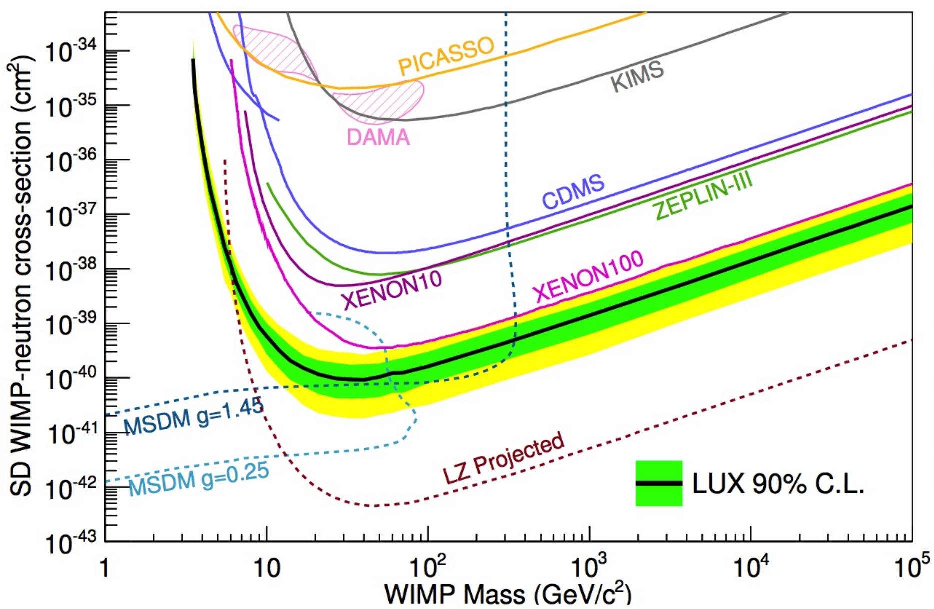
from Snowmass 2013- Best upper limits now from LUX, SuperCDMS, CRESST-II



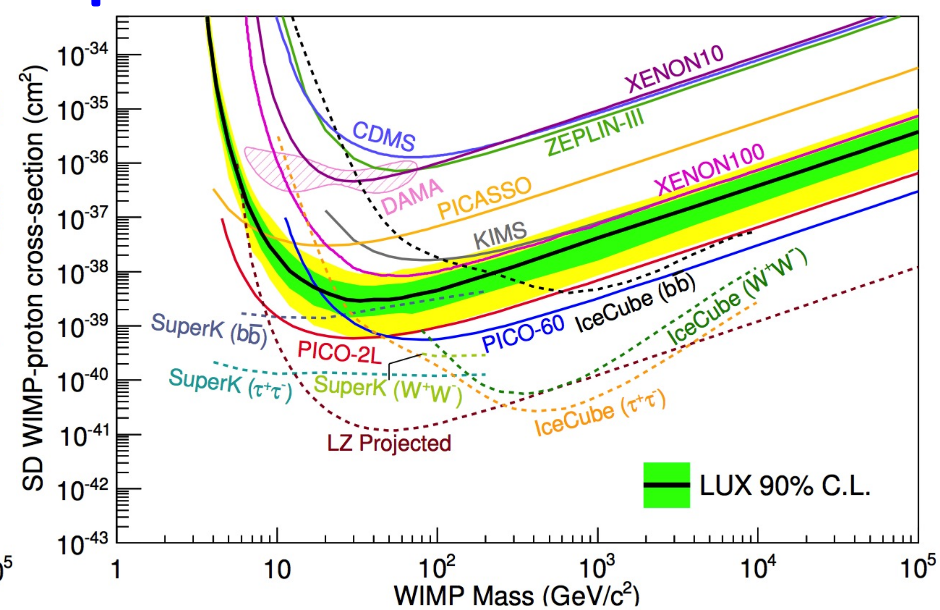
Present bounds for SD with n or p only and SHM

LUX collaboration 2016, 1602.03489

neutron



proton



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	$1_\chi 1_N$
	$i\bar{\chi}_2\chi_1\bar{N}\gamma^5 N$		$i\frac{\vec{q}}{m_N}\cdot\vec{S}_N$
	$i\bar{\chi}_2\gamma^5\chi_1\bar{N}N$		$-i\frac{\vec{q}}{m_\chi}\cdot\vec{S}_\chi$
	$\bar{\chi}_2\gamma^5\chi_1\bar{N}\gamma^5 N$	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.	$-4\vec{S}_\chi\cdot\vec{S}_N$
	$i\bar{\chi}_2\gamma^\mu\gamma^5\chi_1\bar{N}i\sigma_{\mu\nu}\frac{q^\nu}{[illegible]}\gamma^5 N$		$4i\frac{\vec{q}}{[illegible]}\cdot\vec{S}_N\left(\vec{v}^\perp_{[illegible]} - \frac{\delta}{[illegible]}\vec{q}\right)\cdot\vec{S}_\chi$

(* You will prove this in an exercise)

Graciela Gelmini-UCLA

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

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. . .

"Millicharged DM" Unbroken U$_{dark}$(1) hidden gauge symmetry that would give rise to bound states"kinetic coupling"

$$\varepsilon F_{\mu\nu} F^{\mu\nu}_{dark}$$

Diagonalized gauge boson kinetic terms: em photon $A_\mu(J^\mu_{em} + \varepsilon g J^\mu_{dark})$ (g is U$_{dark}$(1) coupling).

Holdom 1986 , Burrage et al 0909.0649 D. E. Kaplan 0909.0753 1105.2073 Cline, Zuowei Liu, and Wei Xue 1201.4858

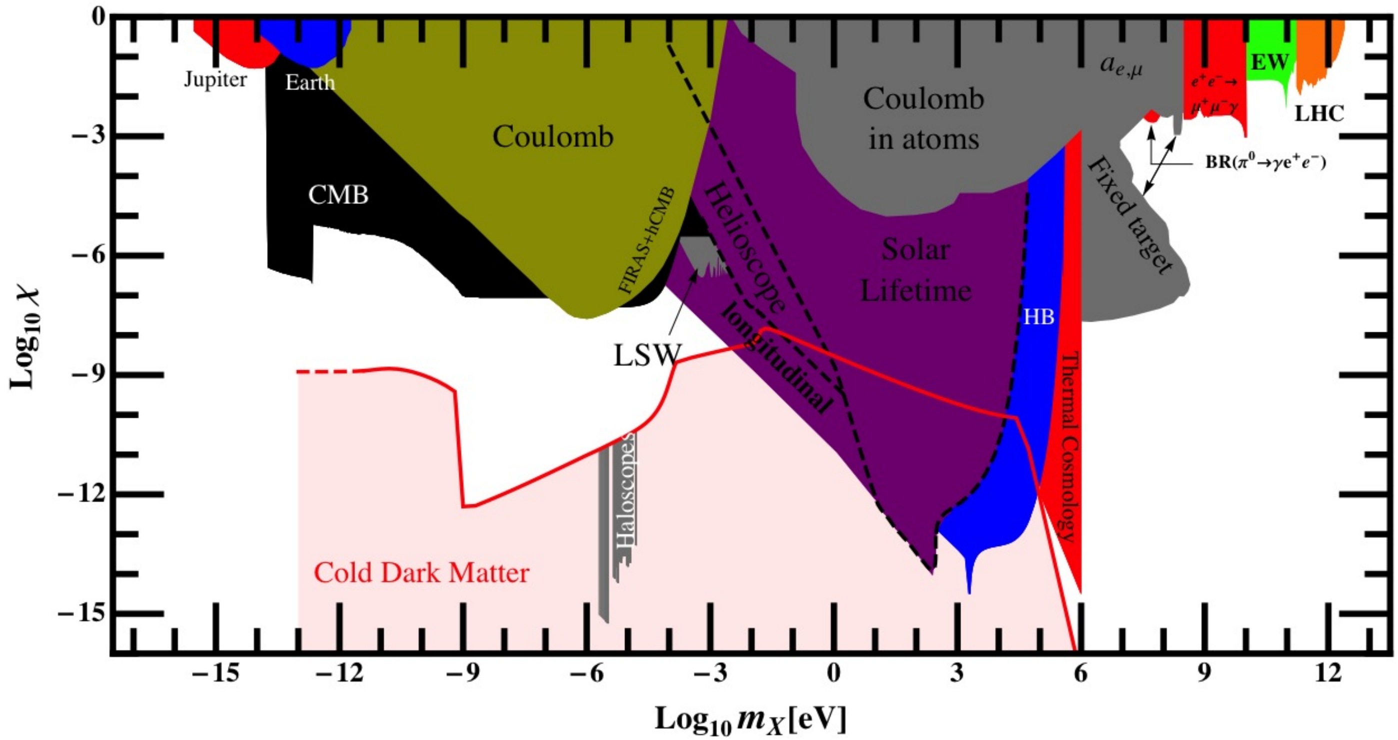
"Atomic DM" with dark analogues of p, e, H coupled to a new U'(1) and Dark Atoms may scatter elastically or inelastically depending of the choice of parameters Goldberg Hall 1986; Feng, Kaplinghat, Tu 0905.3039; Ackerman 2009. . .

"Dark" or "Hidden"-Photons (HP) themselves can be the DM- but LDM or lighter

Pospelov, Ritz& Voloshin 0807.3279; Arias etal1201.5902

Limits of Hidden-Photons (HP) Compilation in Jaeckel 1303.1821

HP's can be very light CDM (LDM or lighter). χ is here the mixing ε in $\varepsilon F_{\mu\nu} F^{\mu\nu}_{dark}$ and m_χ is the HP mass.



Besides "Millicharged DM", DM could be neutral and have

Small electromagnetic couplings

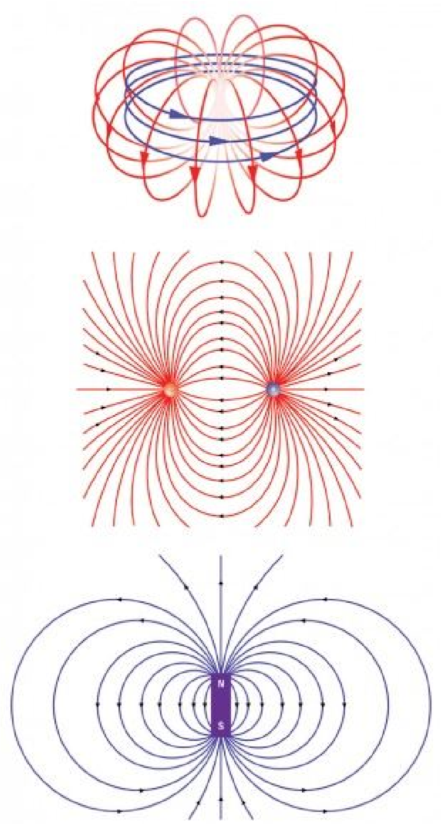
Magnetic (MDM) and Electric (EDM) Dipole Moment DM Pospelov & Veldhuis 2000, Sigurdson, Doran, Kurylov, Caldwell Kamionkowsky 2004, 2006, Maso, Mohanty, Rao 2009, Fortin, Tait 2012 many more

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

- 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.

Correct relic abundance and XENON bounds for 10MeV< m <80 GeV for 2.2 GeV< Λ < 340 GeV respect. $(g = 1)$.

Coupling cannot be with the em photon for $m\neq 0$- so use "kinetic mixing"

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

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

(* You will prove this in an exercise)

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!

Besides the interaction with quarks itself, there are uncertainties in passing from quarks to nucleons to nuclei.

Each interaction requires its own nuclear Form Factor

Some are known (SI: Helm charge form factor, SD: known with uncertainties; many electric and magnetic form factors have been measured) for many there are only estimates.

Sometimes DM Form Factors needed too (for composite DM)!

Instead of "The Fifty Shades of Gray" we have here "The 500 Shades of Dark"...