(Direct) dark matter searches

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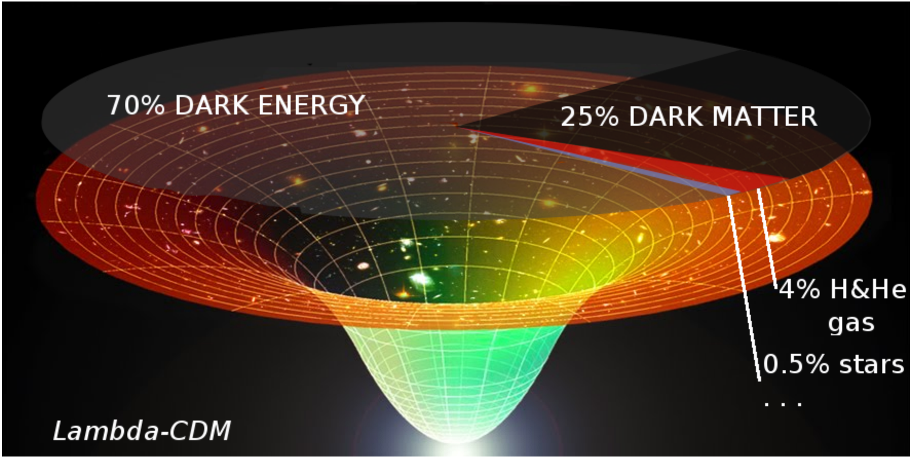
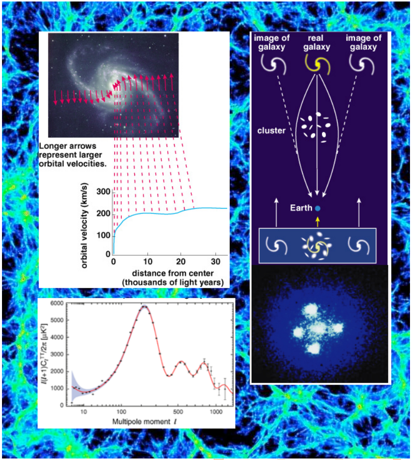
CDM



What do we know about Dark Matter

Interacts via gravitational action +
Dark + Massive + Still around today + (Quasi)Stable

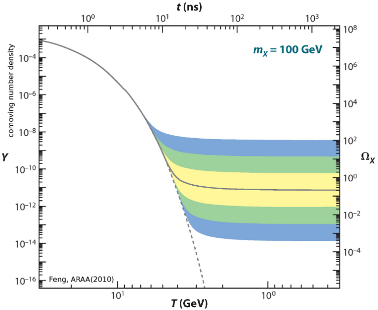
DM is a manifestation of physics beyond the Standard Model.
Wide variety of candidates : Axion, WIMP, superWIMP, Exotics, ...
A symmetry (at least approx.) is needed to prevent DM particles from decaying.
WIMPs are one of most attractive proposals. Why?



Why WIMP?

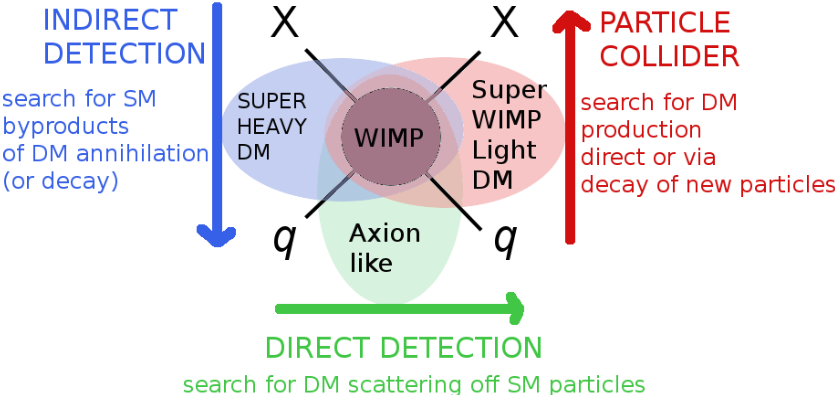
Assumption: DM in equilibrium with the SM plasma at early times

1. WIMP miracle an attractive picture explaining the density of DM in the Universe today as thermal relic DM density for particles with masses and coupling strengths at the electroweak scale.



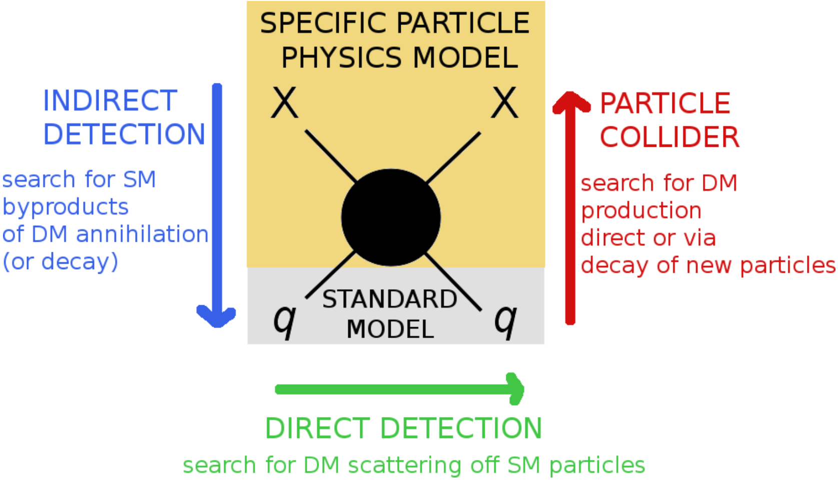
2. WIMPs automatically occur in many models of physics beyond the Standard Model, such as i.e. supersymmetric extensions.
3. WIMPs interacting with SM particles allow us to use particle physics experimental techniques to search for them.

First goal: measure WIMP interactions with the SM compute mass and cross section then check the relic density.



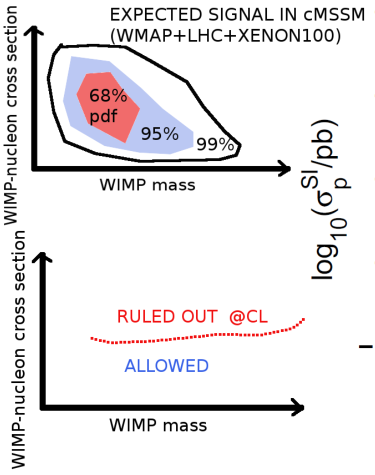
How WIMP

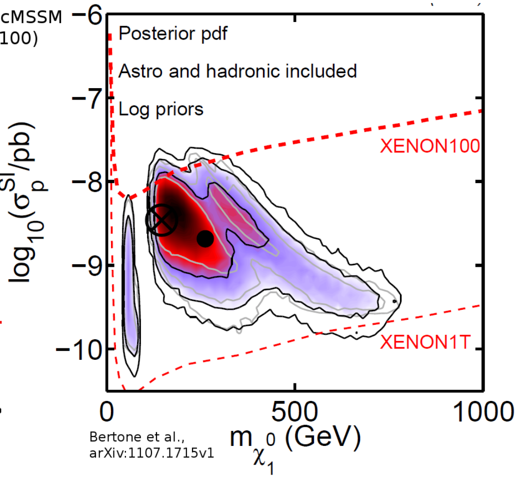
First goal: measure WIMP interactions with the SM compute mass and cross section check the relic density.



The constrained Minimal Supersymmetric Standard Model

simple SUSY model with predictive power (4+1 independent parameters).





Direct dark matter detection

Astrophysics: Earth within the solar system is ‘flying‘ through a halo of WIMPs with $V_{\oplus} \sim 220 km/s$.

A non-relativistic WIMP (χ) striking a nucleus (N) will induce:

$$E_{recoil} = \frac{m_\chi^2 m_N}{(m_\chi + m_N)^2} V^2 (1 - \cos\theta) \sim 100 keV \; (m_\chi >> m_N)$$

1.Detector with low energy threshold.
2.$\exists$ $V_{min} = \sqrt{m_N E_{recoil}/2\mu^2}$ required to produce E_{recoil}.

Coherent SI elastic scattering of WIMP:

$$\sigma_{SI} = (\mu_N^2/\mu_{nucleon}^2)^2 A^2 \sigma_{SI}^{nucleon} F^2(E_r, A)$$, μ-reduced mass

3. Target material with high A.
4. $\exists$ loss of coherence (Form factor) when $\lambda_{deBroglie} < (R_N \propto A^{1/3})$.

Direct dark matter detection

Astrophysics (Standard halo model):
Local WIMP density $\rho_\chi \sim 0.3\, GeV/cm^3$.
WIMPs form $\sim$ isothermal halo around the galaxy with Maxwellian velocity distribution with V_0 ~220km/s and a cut-off due to the escape velocity from the galaxy of $V_{esc} = 650$ km/s.

counts/day/kg/keV:

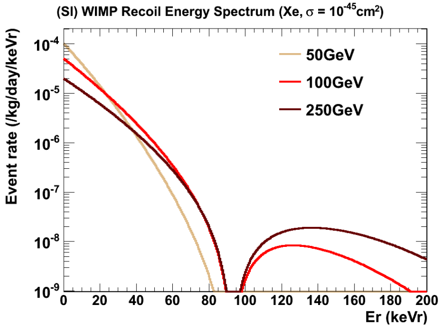
$$\frac{dRate}{dE_{recoil}} = \frac{\rho_\chi \sigma_{SI}^{nucleon}}{2 m_\chi \mu_{nucleon}^2} \mathbf{A}^2 F^2(E_r, \mathbf{A}) \underbrace{\mathcal{F}(V_{min}(E_{recoil}, \mathbf{A}, m_\chi), V_{esc}, V_0)}_{\text{velocity distribution}} ,$$

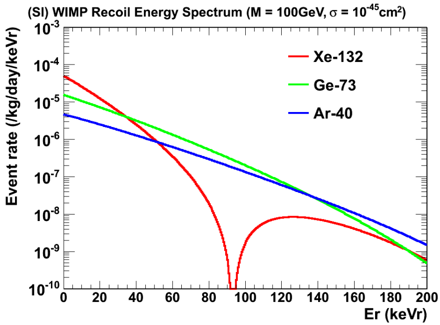
5. $\exists\ \rho_\chi \sigma_{SI}^{nucleon}/m_\chi$ degeneracy. Several energy bins and/or targets (A).
6. $\exists$ kinematic limit: $m_\chi >> m_N \Longrightarrow V_{min} = \sqrt{E_{recoil}/2m_N}$.
7. Astrophysics uncertainties affect all DDM experiments equally.

Complementarity of targets

Signature of dark matter

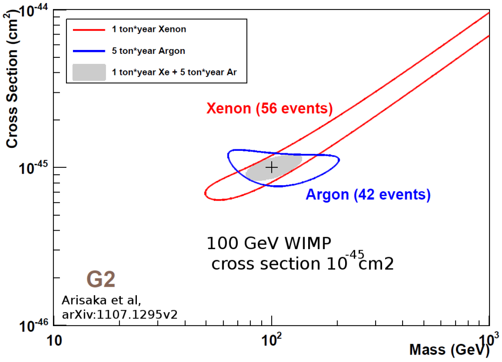
$\forall m_\chi$ quasi-exponential spectral shape dependent on A.

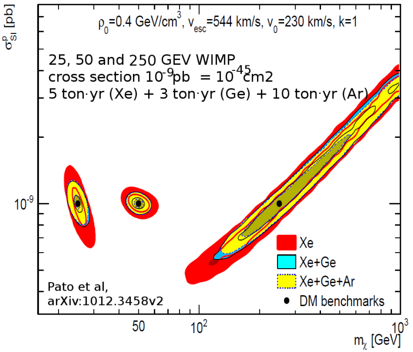




Complementarity of targets

Choose WIMP benchmark case : $\sigma_{SI}^{nucleon}$ and m_χ.
Generate mock counts according to experimental capabilities.
Reconstruct the mock data in $m_\chi - \sigma_{SI}^{nucleon}$



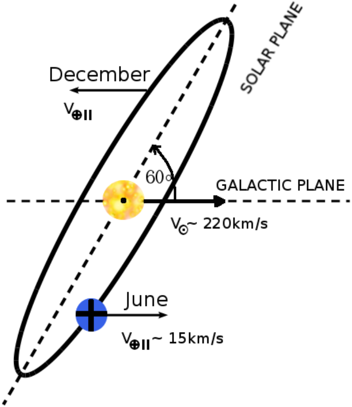


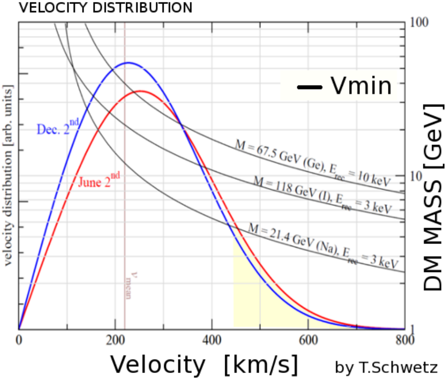
Annual modulation

Signature of dark matter

$\forall m_\chi \& E_{recoil}$ modulation in DM scattering rate dependent on A, $E_{treshold}$.

$$\mathcal{F}(V_{min}(E_{recoil}, A, m_\chi), V_{esc}, V_0) = \int_{V_{min}}^{V_{esc}} \frac{f_\oplus(\vec{V}, \mathbf{t})}{V} d^3V, \; V_{min} = \sqrt{m_N E_{recoil}/2\mu_N^2}$$





by T.Schwetz

But what is the background ?

Gammas & betas → electronic recoils

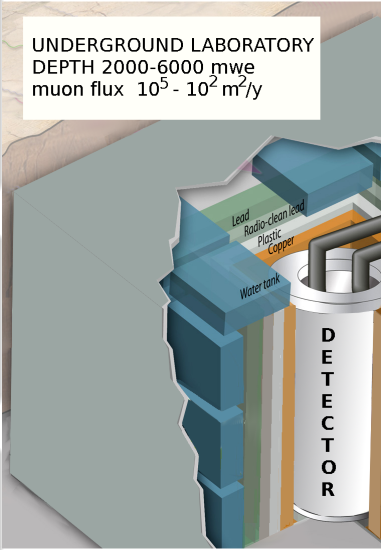
From: CR, natural radioactivity and cosmogenic activation of the detector and shields, ^{222}Rn
Reduction via: low-activity Pb, Co, H_2O, noble liquids (active), IN_2 purge, purification (liquids) and active background discrimination.

Neutrons → nuclear recoils

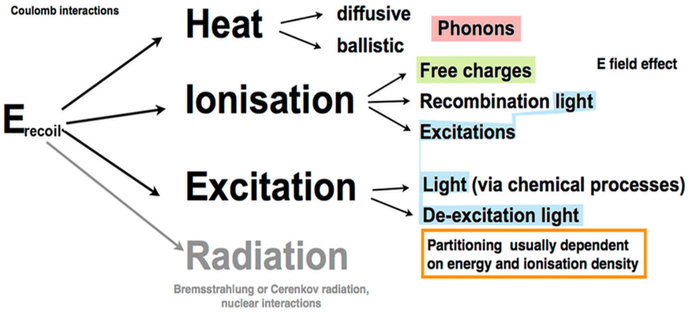
From: (α, n) and spontaneous fission (concrete, rock, etc.). Neutrons from CR muons
Reduction via: n-moderator (PE, paraffin, ...), n-veto, μ-veto, multiple hit.

Alphas interact both with e^- and nuclei

From: Rn daughters decays, intrinsic contamin.
Reduction: active background discrimination.



Direct DM Detectors: Detection channels



Electronic recoil and nuclear recoil events have different energy sharing. This allows for active discrimination of electromagnetic background via two detection channels. But this is not the only way.

Direct DM detectors

LIGHT
- DAMA/LIBRA
- NAIAD
- KIMS
- ANAIS
- ZEPLIN-I
- XMASS
- CLEAN
- DEAP
- DM-ICE

HEAT VIA NUCLEATION
- SIMPLE
- PICASSO
- COUPP

PHONONS& CHARGE
- EDELWEISS
- CDMS

CHARGE
- CoGeNT
- IGEX
- TEXONO
- DRIFT-I-II
- NEWAGE
- MIMAC

PHONONS
- CRESST-I

PHONONS & LIGHT
- CRESST-II
- ROSEBUD

LIGHT& CHARGE
- XENON10-100
- ZEPLIN-II-III
- WARP
- ArDM
- DarkSide10
- LUX
- DMTPC-direct

Direct DM detectors

LIGHT

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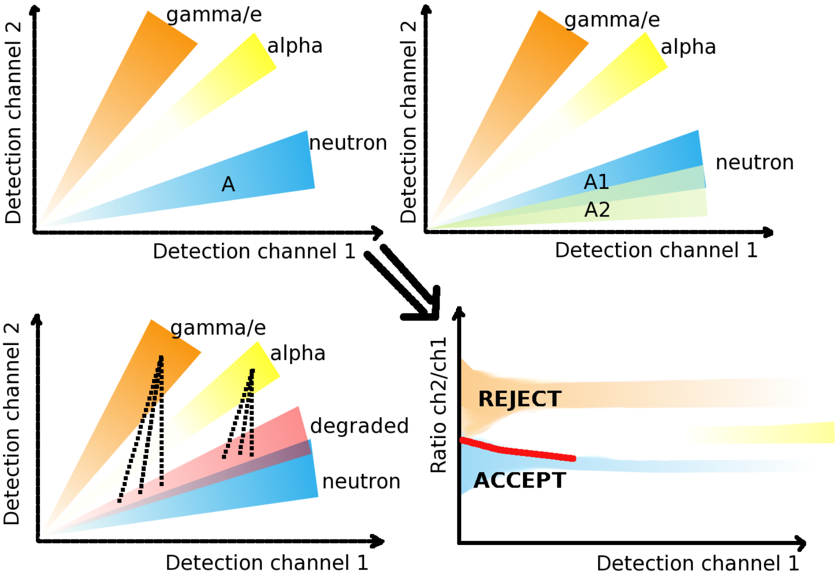
- ArDM
- DarkSide10
- LUX
- DMTPC

Active background discrimination: dual channel detection



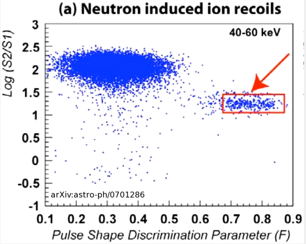
Active background discrimination

Fiducialization

Surface sees most of environmental background + radioactive deposits on the surface + "edge" effect lead to signal losses.
Requires: partitioning of the signal readout or position dependent response.
Many of experiments. 1:> 10^2 ER rejection.

Pulse shape discrimination

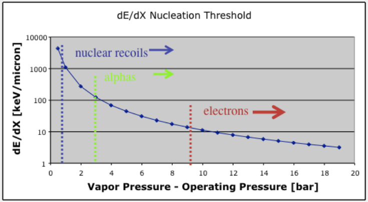
Electronic and nuclear recoil events produce light with different timing.
Requires: Timings sufficiently different.
Enough photons.
LAr detectors: $\tau_{fast} =\sim 6ns$ and $\tau_{slow} =\sim 1.6\mu s$. 1:> 10^8 ER rejection.
* α-nuclear recoil acoustic discrimination 1:> 10^3 rejection in nucleation detectors.



Active background discrimination

Nucleation threshold

Superheated liquid - nucleation occurs when enough energy to create a bubble with critical radius is deposited.
Tune by operating P and T to measure only NR.
$1{:}> 10^{10}$ ER rejection.

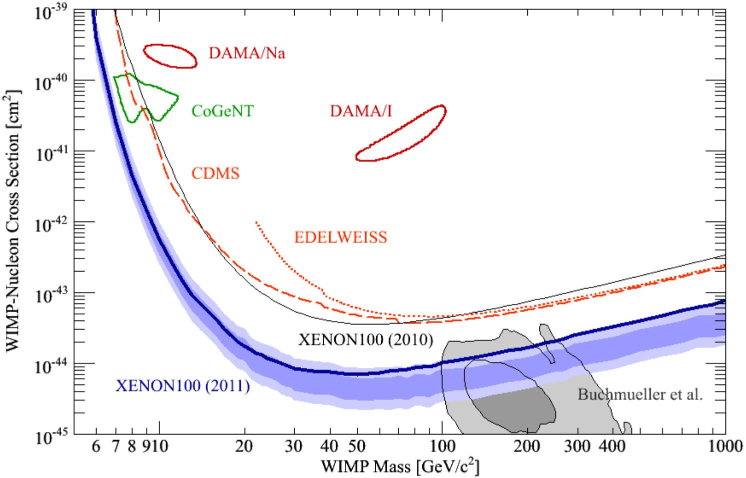


Multiple scatter rejection

Mean free path of gamma's $<$ m.f.p of neutrons $\ll$ m.f.p WIMPs.
Requires: Multiple modules or big detector with many readout channels or active veto.
All experiments.

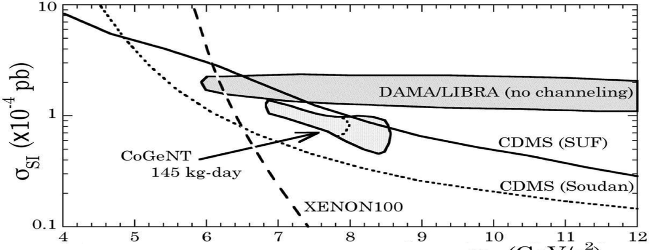
Status of SI DM search

Theory driven : most experiments are designed to achieve the best sensitivity in the 50GeV-1TeV range. No WIMP only exclusion plots.

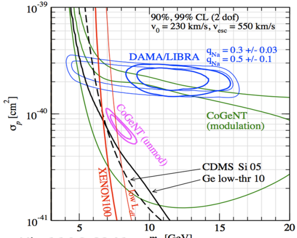


Status of SI DM search

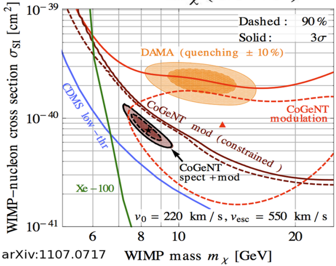
Data driven : some experiments report "hints" for WIMP interaction.



arXiv:1106.0650



arXiv:1106.6241

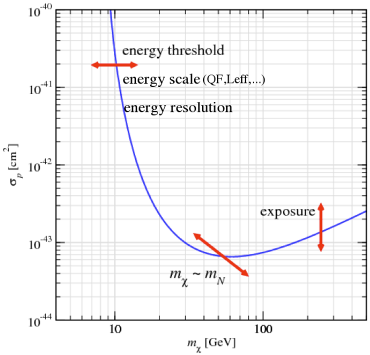


arXiv:1107.0717

Status of SI DM search: Conflicting results

DAMA/LIBRA, CoGeNT and CRESST (?) see low energy events excess.
DAMA/LIBRA and CoGeNT see the signal modulation.
Light WIMP (<15GeV) scenario individually fits all of the them.
Questions raised:
Some exotic DM model?
Does it has to do with DM at all?
Is it the same DM?

XENON10/100, CDMS-II exclude these region at 95% CL.
Questions raised:
How certain are these exclusion?



Nuclear recoil energy scale

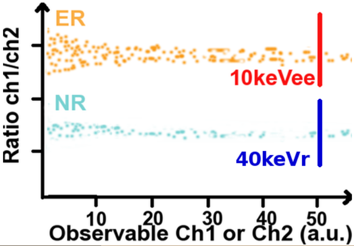
Most of recoil energy eventually becomes heat. Heat detection channel measure true recoil energy for both ER and NR i.e. keVee=keVr=keV.

Fraction of total recoil energy transferred to charge/light is different for NR and ER.
Expressed by **energy dependent quenching factor for NR**:

$$\text{QF} := E_{NR}^{CHARGE/LIGHT} / E_{NR}^{TOT} \;, \; QF \in \{0,1\}$$

$\text{QF}_{ER} := 1$ defined by calibration.

$E_{NR}^{TOT}[keVr] = E_{ER}^{TOT}[keVee]/QF,$
Example:
QF=0.25 at 10keV.
10keV by γ: = 10keVee.
10keVee/0.25= 40keVr.



Noble liquids: Nuclear recoil energy scale

QF_{NR}^{LIGHT} = absolute NR scintillation efficiency = Linhard factor

Interaction in LXe (or LAr) produce N_i ionized and N_{ex} excited atoms.
Recombining ions contribute to the scintillation light production.

$n_\gamma \propto N_{ex} + rN_i$

Sum is independent of recombination: $N_i + N_{ex} = n_\gamma + n_{electron}$

$$QF = \mathcal{L}(NR) = \frac{\epsilon(N_i + N_{ex})}{E_{NR}^{TOT}} = \frac{\epsilon(n_\gamma + n_{electron})}{E_{NR}^{TOT}}$$

$QF_{ER} := 1$ defined by calibration.

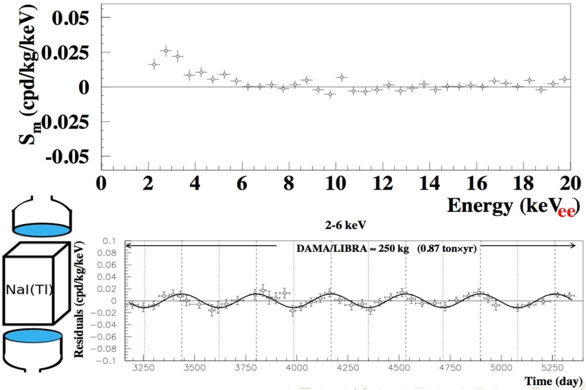
Relative NR scintillation efficiency = Effective Linhard factor

L_{eff} is zero-field ratio of light yields of nuclear recoils and electronic recoils at defined energy (122keVee).

$$\mathcal{L}_{eff}(NR) = \frac{L_y(E_{NR})}{L_y(ER{=}122keVee)},$$ where $\mathcal{L}_{eff}(NR) \neq \mathcal{L}(NR)$

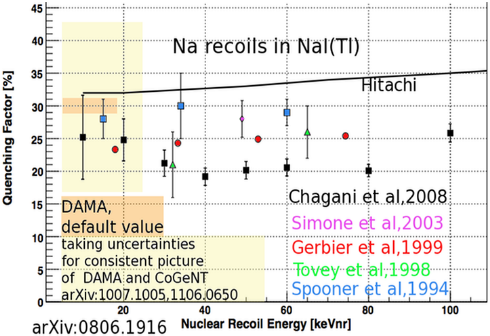
Measures scintillation light from 25 x 9.7kg NaI(Tl). 2PMTs in coincidence per crystal.
With 13yr and 1.17t$\times$yr:
Sees modulation signal (only singles) in 2-6keVee at $\sim$8.9 σ CL with period 1yr and phase 146$\pm$7days. $\sim$2% modulation amplitude.

Resolution $\sim$32%@2keVee.
Mutiple scatter cut.
R. Bernabei et al., Eur. Phys. J. C67, 39 (2010)

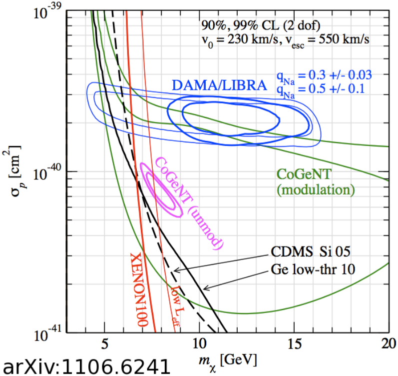


DAMA/LIBRA

$QF(Na)_{def} = \langle 0.3 \pm 0.01 \rangle_{6.5-97keV} \Rightarrow 2keVee \sim 6.7keVr$



arXiv:0806.1916



arXiv:1106.6241

QF(Na) >0.3 allows for compatibility between DAMA and CoGeNT allowed regions.

Measures ionization from one 440g PPC HPGe with one readout channel.

With 442live d and ~145kg×yr:

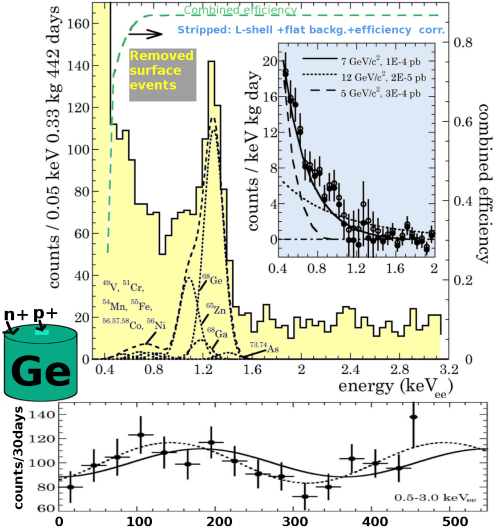
Sees modulation signal (only singles) in 0.5-3keVee at ~2.8σ CL with period 347±29 days and minimum in Oct. 16±12d. 16.6±3.8% modulation amplitude.

Energy resolution ~14%@0.5keVee.

Multiple scatter cut.

Surface events cut = rise time cut.

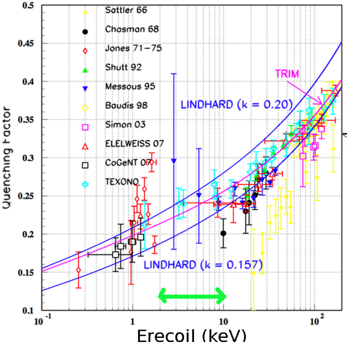
Background subtraction.

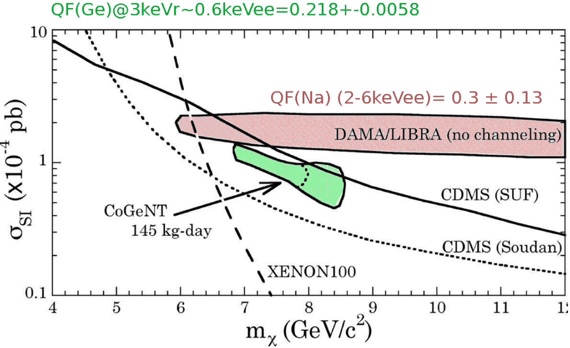


arXiv:1106.0650

CoGeNT

$QF(Ge)_{0.6keVee} = 0.218 \pm 0.0058 \Rightarrow 0.5keVee \sim 2.3keVr.$





CDMS

Measures heat and ionization from 30 modules: 230g Ge /100g Si. Per module: 4 phonon (x-y position) and 2 ionization (r cut) readouts per module.

With ∼2y and ∼191kg×yr.

In 10-100keV:

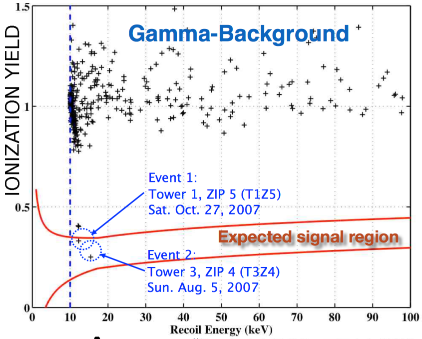
Expected surface ev = 0.8±0.1(stat)±0.2(syst).

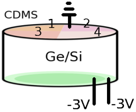
Expected n = 0.1±0.05(syst).

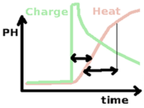
Observed: 2 events

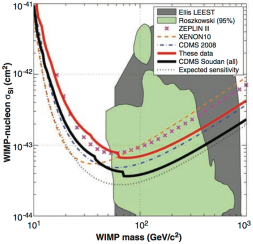
Cuts: veto, multiple scatter, fiducial volume, ionization yield, phonon timing, 2σ n-band

Resolution@10.37keV: 3% for ionization, 5% for phonon.







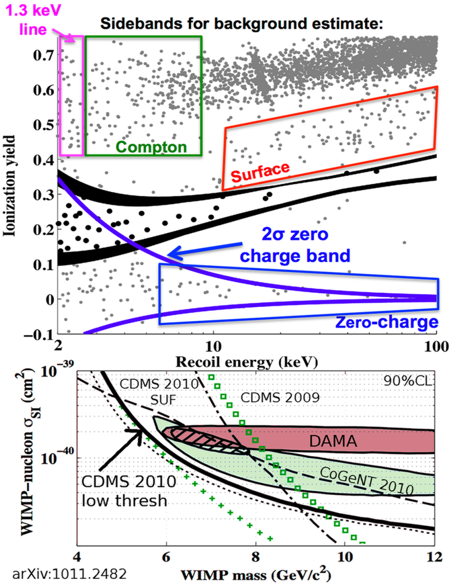


CDMS: Low threshold analysis

1. CDMS SUF data reanalysis with 1keV threshold

2. 2006-2008 Ge data reanalysis with 2keVr threshold.
Loose the ER/NR discrimination accept some background.
Tighten NR band (+1.25,-0.5) σ
No phonon timing cut.
No background subtraction.

Energy scale uncertainty?



arXiv:1011.2482

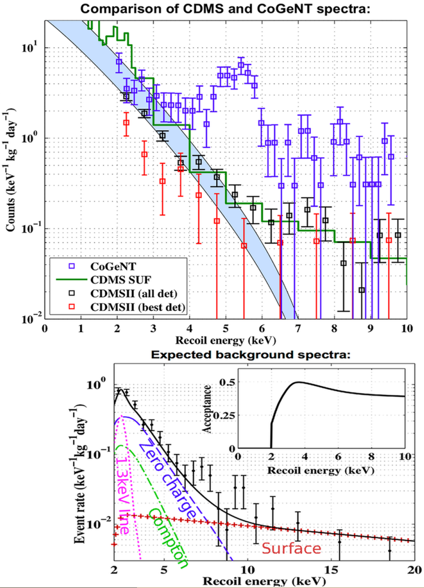
CDMS and CoGeNT comparison

Directly compare the rates (same target). Energy resolution are similar O(10%)@1keV.

Rate in CDMS inconsistent with 7GeV WIMP.

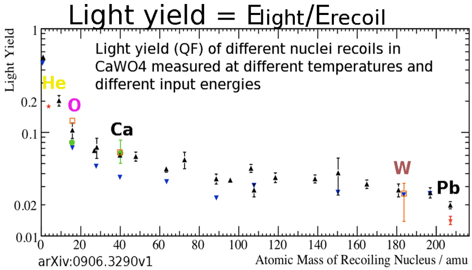
CDMS fairly understands the spectrum. CoGeNT excludes neutrons, noise, contamination.

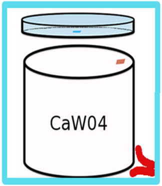
Comparison not really apples to apples: NR scale is wrong for ER events in case not full energy is recorded. See 1.3keV line at two different locations. !

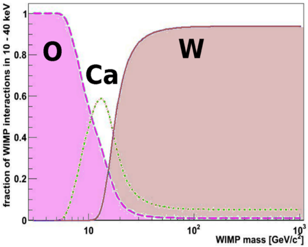


CRESST-II

Measures phonon and light from 9 300g CaWO4 crystals.
With ∼1y and 730kgd (not published)
In 10-40keV
Excess of events!
Composite target: additional active discrimination via selection of one type of nuclei.
For WIMP <10 GeV only O recoils above threshold.
For large masses W dominates.







CRESST-II

$E_{recoil} = E_{phonon}$

Light yield $= E_{light}/E_{recoil} \Rightarrow$

1:10^4 rejection via O recoils

1:>10^5 rejection via W recoils.

Resolution@3.6keVee: 8% for phonon.

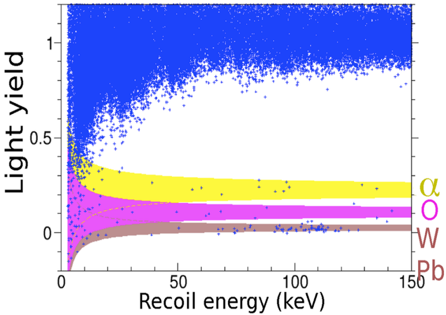
No surface dead layer.

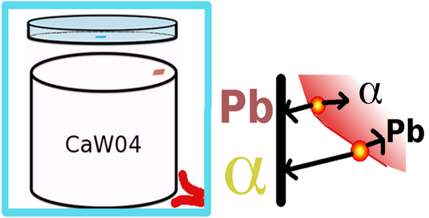
Degraded α and ^{206}Pb recoils from:

$^{210}Pb \rightarrow ^{206}Pb(103keV) + \alpha(5.3MeV)$

Non-scintillating clamps contamination.

Preliminary: From ~50 events in O band, 40% not explained by background. Possible solution with ~13GeV WIMP and $\sigma \sim 10^{-5}$pb





XENON100

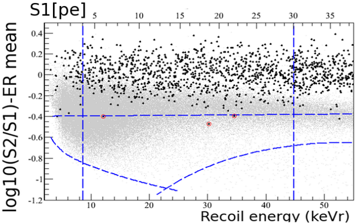
Measures light and ionization from 62kg of LXe with 178 PMTs. With 100.9 live d and 1471kg$\times$d

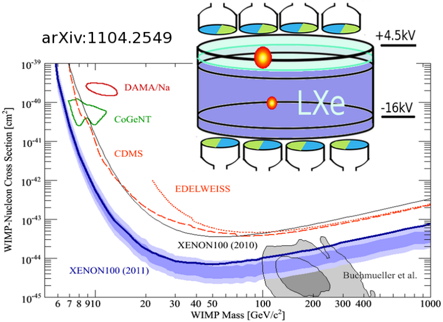
In 8.4-44.6keVr (4-30pe):

Expected bck = 1.8$\pm$0.6

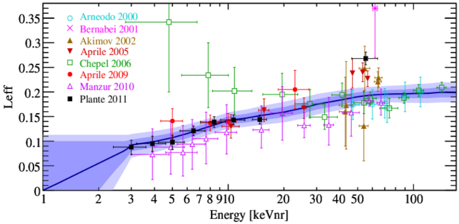
Observed: 3 events

Cuts: veto(LXe), multiple scatter, fiducial volume, S2/S1 cut, from 99.75% ER rejection to -3σ n-band, pattern cut, posterior noise cut.

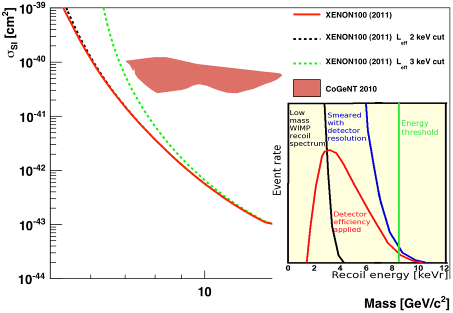




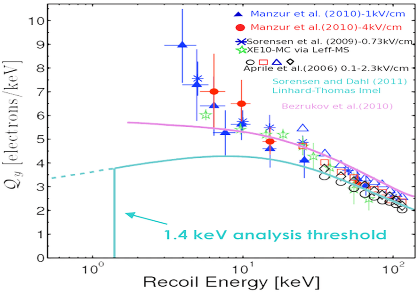
XENON100: Uncertainties at low masses



The nuclear recoil scale determined down to 3keVr. Below the trend is logarithmically extrapolated to 0@1keVr. XENON100 energy threshold is 8.4keVr.



Sensitivity to low masses is only due to energy resolution of the detector.
Even with the cut of L_{eff}@3keVr, does not affect the result compared to CoGeNT 2010 data.



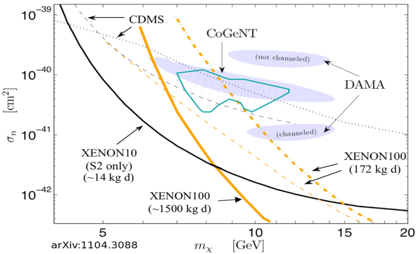
Avoid debate over L_{eff} reconstruct nuclear recoil scale from ionization signal (S2)

$$Enr = \frac{S2}{G_g \times \mathcal{Q}_y},$$

S2 - charge signal in pe.

G_g - gas gain in pe/e$^-$

$\mathcal{Q}_y$- NR charge yield in e$^-$/keVr



Reanalysis of 12.5 live days of XENON10 data with 1.4keVr threshold.

Lose: light signal S1, most of z positioning and ER/NR discrimination.

Do a tight radial cut.

Status of SI DM search: Conflicting results

DAMA/LIBRA and CoGeNT see modulated low energy events excess.

XENON10/100, CDMS-II exclude these regions at 95% CL.

- Can it be the same DM for CoGeNT and DAMA? Yes, but with QF(Na) higher than what is expected. (1106.1066)
- Some exotic DM model/halo model ? Yes, for some models, signal by DAMA or CoGeNT, is consistent with or not excluded by others. (1106.6241, 1107.0717)
- Some exotic DM model for all of them? No simultaneous explanation of CoGeNT and DAMA compatible with others. (1106.6241)
- Does it has to do with DM at all? Difficult to say (1102.0815, 1006.5255)
- How certain are the exclusions? To get a consistent picture $\Rightarrow$ major errors in understanding of CDMS and XENON10/100 detectors.

Results and experiments about to come ...

Analysing

CRESST-II
ZEPLIN-III (SSR $\sim 560kgd$)

Data taking

DAMA/LIBRA
COUPP - 4kg
XENON100 ($> 100ld$)
DM-ICE ($\sim$15kg)

Commissioning

XMASS - LXe SP - 100kg FV
WARP - 140kg LAR DP TPC.

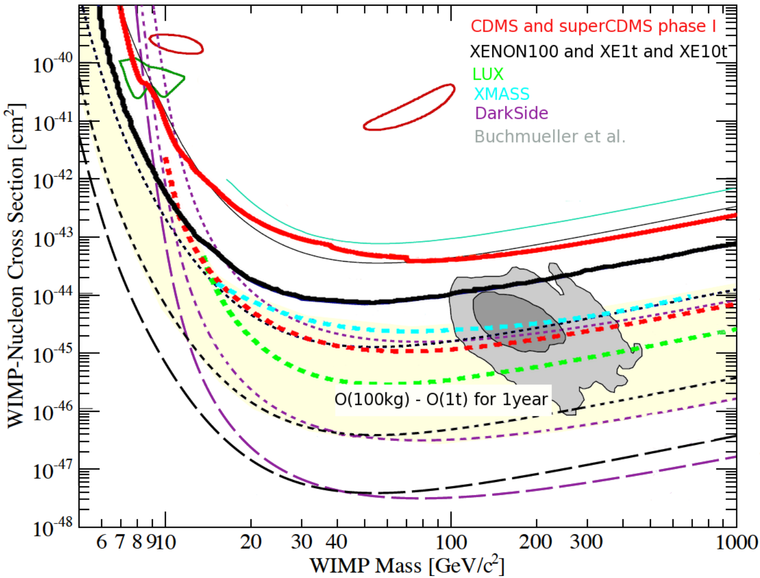
Installation/ construction/R&D

CoGeNT-4 - 10x mass.
CRESST-II -improved modules.
EDELWEISS-II - 40$\times$FID800
LUX350- LXe DP TPC
ArDM -850kg LAr DP TPC
DM-ICE -250kg.
COUPP- 60kg.
MiniClean 500kg LAr SP
DEAP-3600 3.6t LAr SP (1t FV)
DarkSide50-50kg LAr DP TPC
SuperCDMS-10kg
Directional DM ...

Future

XENON1t, SuperCDMS 100kg, PANDA-X, DarkSide5T, EURECA, DARWIN, MAX ...

Sensitivity goal



Summary: MORE DATA WILL TELL

Majority of Direct DM searches is theory driven.
Is it χ? About to probe it for many SS models.

Is it light DM? Still unresolved. More results very soon by CRESST!
More experiments will search for modulation: DM-ICE.

ER/NR background reduction and rejection strategies are being improved.
Understanding background? Not completely, need to **dig more !**.

Ongoing effort around the world for better precision measurements of QF down to lower energies. Will **reduce uncertainties in the energy scale**.

THANK YOU !

EDELWEISS with interleaved electrodes

Measures heat and ionization from 10 modules: ∼400g Ge . Per module: 1 phonon and 6 ionization (r-z cut) readouts per module. With ∼ 1.5y and ∼384kg×yr:

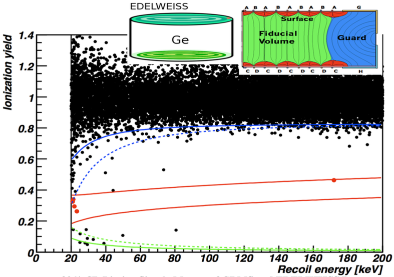
In 20-200keV.

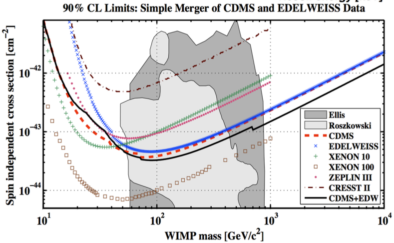
Expected bck = 3.

Observed: 5 events

Combined limits with CDMS.

Cuts: veto, multiple scatter, fiducial volume, surface events (ID), ionization yield, 1.64σ n-band





CDMS: Energy scale and rejection

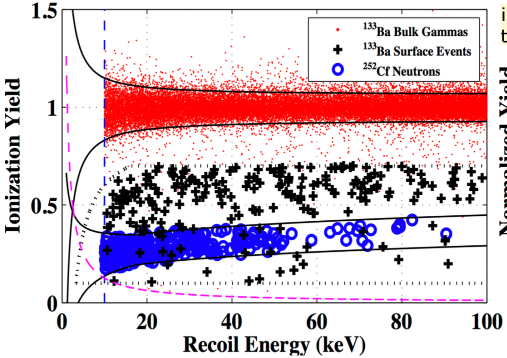
Phonon energy measures full recoil energy minus ER/NR "drift heating".

$E_{recoil} = E_{phonon} - E_{ionization} eV_{bias}/\varepsilon_{e-hole}$

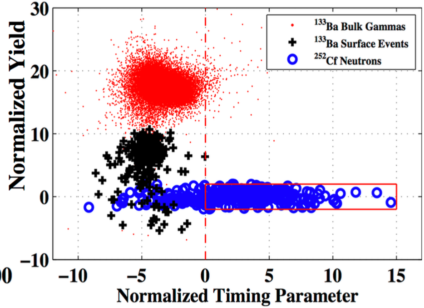
Ionization yield $= E_{ionization}/E_{recoil} \Rightarrow 1 : 10^4 rejection$

Timing cut = 1:∼200 rejection.

Resolution@10.37keV: 3% for ionization, 5% for phonon.



ionization yield 1:10^4ER rejection
timing cut 1: ∼200 surface ER rejection



XENON100: Nuclear recoil scale using L_{eff}

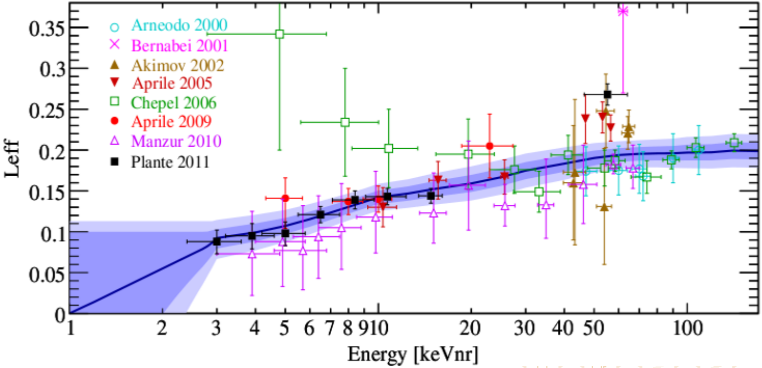
L_{eff} sets the scale between measured S1 (pe) and keVr

$$Enr = \frac{S1}{L_y(122KeVee)} \times \frac{S_{ee}}{S_{nr}} \times \frac{1}{L_{eff}},$$

$L_y(122KeVee)$ = light yield for 122 KeVee in pe.
S_{ee} and S_{nr} = quenching of scintillation yield for ERr and NRs due to field.

XENON100 values

$L_y(122\text{keVee}) = 2.20 \pm 0.09$ pe/keV
S_e=0.58, S_r=0.95
$L_{eff} = f(E_{nr})$.



IDM: DM scatters into an excited state (Tucker-Smith and Weiner, Phys. Rev. D64, 043502 (2001))

$\chi + N \Rightarrow \chi^* + N$, where

$m_{\chi^*} - m_{\chi^*} = \delta \sim 100 keV$

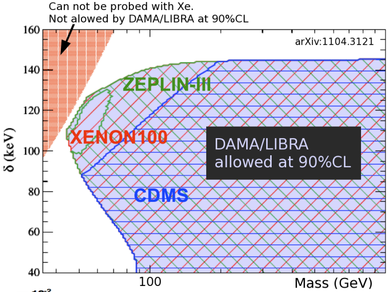
Modified kinematics:

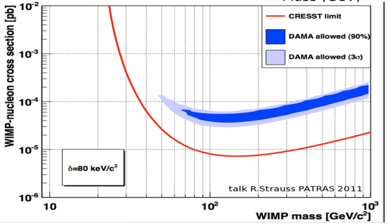
$V_{min} = (m_N E_{recoil}/\mu_N + \delta)/\sqrt{2 m_N E_{recoil}}$

High mass target favoured

$V_{min}(W) < V_{min}(Xe) < V_{min}(I) < V_{min}(Ge)$

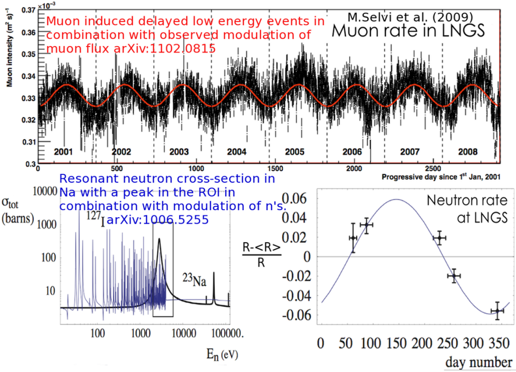
DAMA/LIBRA signal as IDM disfavoured by CRESST-II, XENON100 ...





Comments on Cogent/DAMA

DAMA/LIBRA has checked that following can not explain low energy excess of events: Radon, temperature, noise, shifts in energy scale over time, time dependent efficiency, background, muon flux variation.



CoGeNT has checked that following can not explain low energy excess of events: Radon on passivated surfaces, neutrons, electronic noise, microphonics and is checking other possibilities.

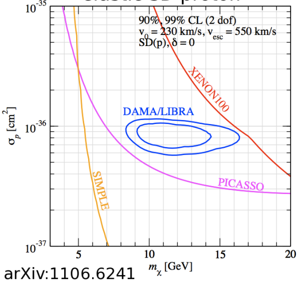
Possibility pointed in arXiv:1006.5255: Auger M-photoelectrons from 8.5keV X-ray produced by decay of metastable ^{73}Ge from low energy neutron captures ^{72}Ge(n,γ) combined with underestimated neutron rate.

Spin Dependent DM

Coupling mainly to an un-paired nucleon. Coupling with proton promising for DAMA vs CDMS/XENON but severe bounds from COUPP, KIMS, PICASSO, SIMPLE.

		neutron	proton
DAMA	$^{23}_{11}Na$	even	odd
DAMA, KIMS, COUPP	$^{127}_{53}I$	even	odd
SIMPLE	$^{35}_{17}Cl$, $^{37}_{17}Cl$	even	odd
XENON, ZEPLIN	$^{129}_{54}Xe$, $^{131}_{54}Xe$	odd	even
CDMS, CoGeNT	$^{73}_{32}Ge$	odd	even
PICASSO, COUPP, SIMPLE	$^{19}_{9}F$	even	odd
CRESST	$^{A}_{74}W$, $^{16}_{8}O$, $^{40}_{20}Ca$	even	even

elastic SD proton



arXiv:1106.6241

elastic SD mainly neutron