Direct Dark Matter Searches: Fits to the WIMP Candidates

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Content:

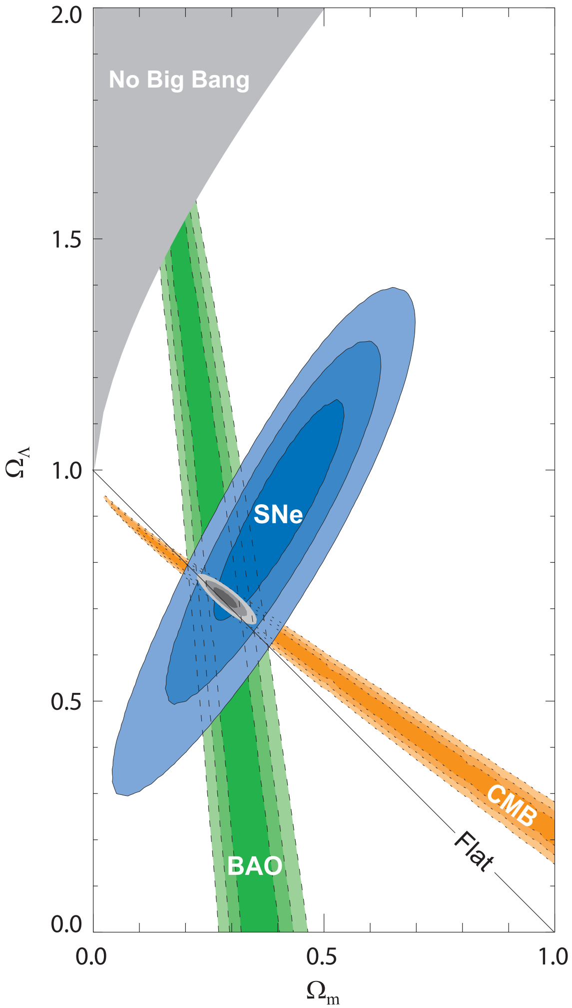
- Dark Matter: what we know
- WIMPs: earliest relics
- Hints and bounds on light WIMPs $m < 10$ GeV
- New bounds on Inelastic Dark Matter (IDM)
- Summary and Future Prospects

Dark Matter: We know a lot!

- We know its abundance in the Universe to a percent level
- We know most is not baryonic
- We know is it NOT explained by the Standard Model of EP

Dark Matter: not baryons

Fig: Kowalski et al 2008



$$\Omega = \rho/\rho_c \qquad\qquad \rho_c \simeq 5 \text{ keV/cm}^3$$

68.3%, 95.4%, 99.7%CL constraints on Ω_M and Ω_Λ obtained from Cosmic Background Radiation Anisotropy CMB (orange), Baryon Acoustic Oscillations BAO (green), and the Union Compilation of 307 Type Ia supernovae (SNe Ia) (blue); Ω_m =0.285$^{+0.020}_{-0.019}$(stat)$^{+0.011}_{-0.011}$(sys) assuming DE is a cosmological constant

WMAP7, BAO, SN1a: E. Komatsu, et al., 2010

$\Omega_\Lambda = 72.2 \pm 1.5\%$ $\Omega_m = 27.8 \pm 1.5\%$

where Ω_m is:

$\Omega_b = 4.61 \pm 0.15\%$ $\Omega_{DM} = 23.2 \pm 1.3\%$

Most of the Dark Matter: is cold or warm

i.e. is non-relativistic or semi-relativistic at galaxy formation ($T \simeq 1\text{keV}$)

No CDM or WDM in the SM! (active-ν are HDM)

But many in extensions of the SM!

- Warm dark matter: sterile neutrino, gravitino, non-thermal WIMPs...
- Cold dark matter: WIMPs (LSP or variants LKP, LZP, LTP), axion, WIMPZILLAs, solitons (Q-balls), SuperWIMPs (get their relic density from WIMPs which decay into them)...

Concentrate on WIMPs (Weakly Interacting Massive Particles)
Why WIMP's? The "WIMP" miracle....

WIMPs as Dark Matter

WIMPs are the earliest relics, from the pre-BBN era of the Universe, from which we have no data! So we must make assumptions...

With standard assumptions (few but powerful):

- Universe is radiation dominated when WIMP's relic number is fixed

-WIMPs produced only via interactions with the thermal bath

-WIMPs reached equilibrium before

- No entropy production during or after

- No Asymmetries

$$\Omega_{\rm std} \approx 0.2 \, \frac{3 \times 10^{-26} {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle}$$

Weak annihilation cross section $\sigma_{annih} \simeq 3 \times 10^{-26} {\rm cm}^3/{\rm s}$
for $\Omega = \Omega_{DM} \sim 0.2$!

If any of these standard pre-BBN cosmological assumptions do not hold, the WIMP relic density can be very different than what our standard computations indicate.

So no matter the properties of a DM particle candidate, we will not be sure that it constitutes the DM unless we find it in the dark halos of galaxies!

WIMP DM searches:Complementary to the LHC and to each other!

- Indirect Detection- looks for DM annihilation (or decay) products
- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way

Many DM "hints" in both.... I will concentrate on Direct Searches:
CDMS, CoGeNT, CRESST II, DAMA, XENON 10, XENON 100

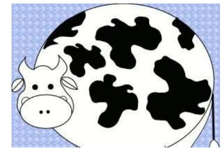
Recall event rate: events/(kg of detector)/(keV of recoil energy)

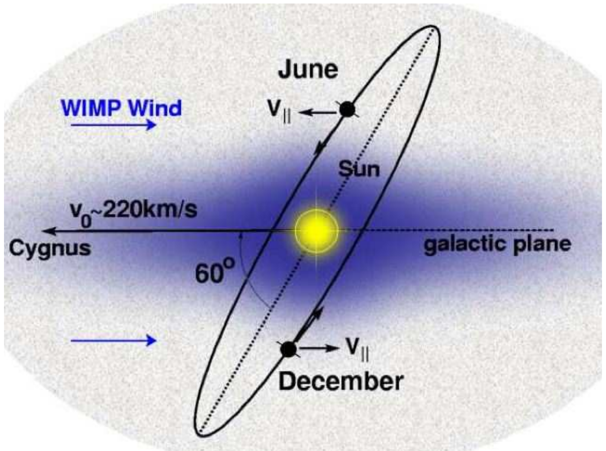
$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nvf(\mathbf{v},t)d^3v$$
$$= \frac{\rho\sigma(q)}{2m\mu^2}\int_{v>v_{\min}} \frac{f(\mathbf{v},t)}{v}d^3v$$

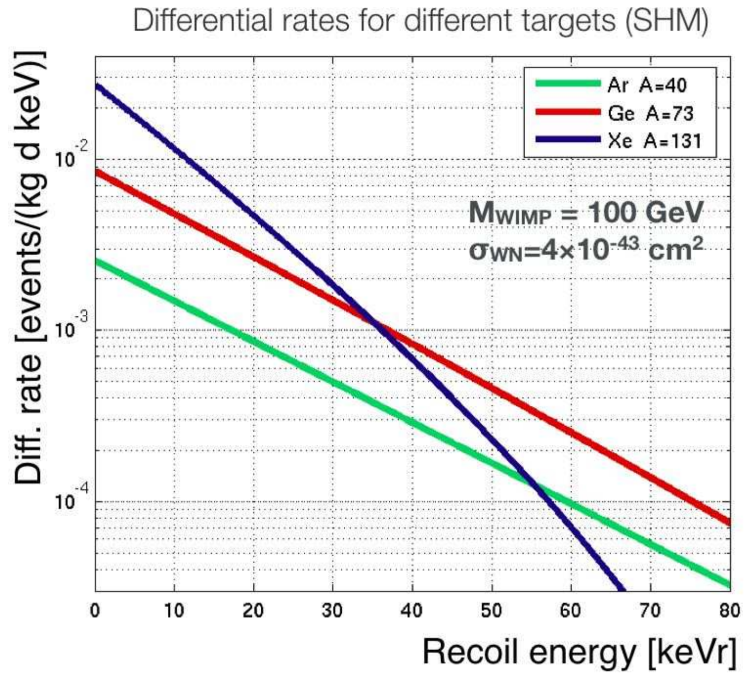
-$\frac{N_T}{M_T}$ = Avogadro's number per mol = Number of atoms per gram; $\mu = mM/(m+M)$
- For elastic scattering: $v_{\min} = \sqrt{ME/2\mu^2}$
-

- spin-independent (SI) $\sigma(q)= \sigma_0 F^2(q) = A^2(\mu^2/\mu_{\rm p}^2)\sigma_{\rm p}$ for $f_p = f_n$
$\sigma_0 = \left[\langle Z f_p + (A-Z) f_n\right]^2 (\mu^2/\mu_{\rm p}^2)\sigma_{\rm p}$
- spin-dependent (SD) $\sigma(q) = \frac{32\mu^2 G_F^2 (J_N+1)}{J_N}\left[\langle S_{\rm p}\rangle a_{\rm p} + \langle S_{\rm n}\rangle a_{\rm n}\right]^2$
I will concentrate on SI interactions, where most of the action has been in recent months....

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

Standard Halo Model (SHM) The  of halo models





- ρ: $\rho_{SHM} = 0.3$ GeV/cm^3
- $f(\mathbf{v}, t)$: Maxwellian $\vec{v}$ distribution

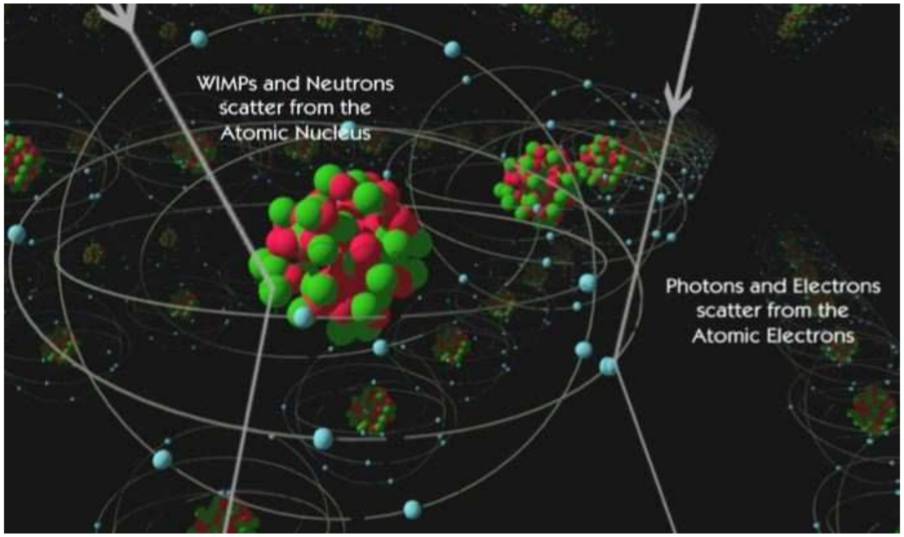
at rest with the Galaxy

$v_\odot \simeq$220 km/s, $v_{esc} \simeq$ 500 - 650 km/s

ANNUAL MODULATION: max in June, min in Dec.

Local ρ and velocity could be very different if the Earth is within a DM clump or stream or if there is a “Dark Disk”.

WIMPs vs photons



- WIMPs interact with nuclei. In crystals they produce mostly phonons and also ionization/scintillation.
- Photons and electrons interact mostly with electrons and all their energy goes into ionization/scintillation.

In crystals: quenching factor Q= fraction of E_{Recoil} that goes into ionization/scintillation.
$Q_{\rm Ge} \simeq 0.3$, $Q_{\rm Si} \simeq 0.25$, $Q_{\rm Na} \simeq 0.3$, $Q_{\rm I} \simeq 0.09$

In liquid Xe: $L_{\rm eff}$=scintillation efficiency of a WIMP relative to a γ

WIMP vs. photons Many experiments!

- **Single Channel Techniques:**
  -Ionization (Ge, Si, CdTe): IGEX, HDMS, GENIUS, TEXONO, CoGeNT
  -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 (bubbles of C_4F_10),
  COUPP (superheated bubble chamber)

- **Hybrid detector techniques for discrimination:**
  -Ionization + Phonons (Ge, Si): CDMS, SuperCDMS, EDELWEISS, EURECA
  -Ionization + Scintillation(Xe, Ar, Ne):XENON,LUX,ZEPLIN,WARP,ArDM, DarkSide
  -Scintillation+Phonons ($CaWO_4$, Al_2O_3): CREST-II, EURECA, CRESST I

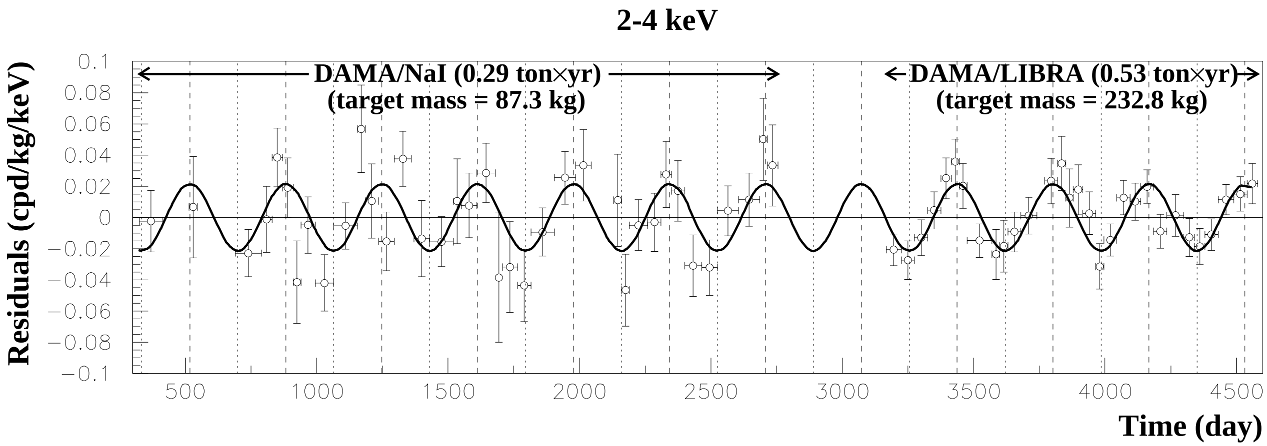
Direct DM Searches: Hints and negative results!

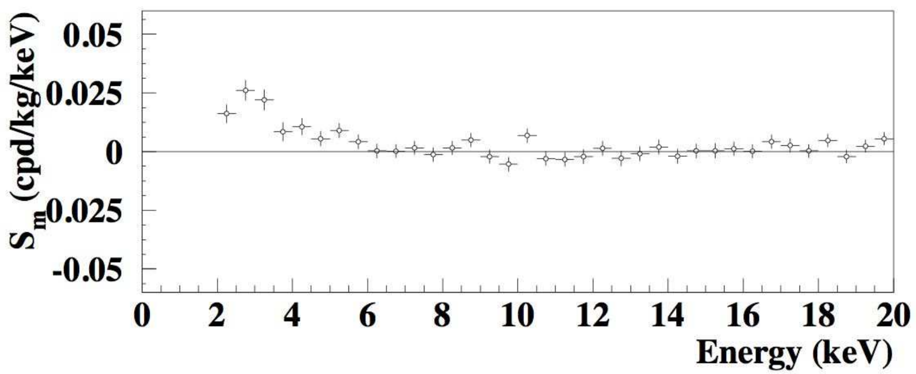
Let us start with the oldest "hint"...

Is the DAMA annual modulation signal (assuming due to DM) compatible with all other Direct DM searches?: Maybe for light (elastically scattering) WIMP's and inelastically scattering DM (IDM)...

Direct DM Searches: 2008 DAMA/LIBRA

25 NaI (TI) crystals of 9.5 kg each, 4y in LIBRA (11 years total), 0.83 ton × year, 8.2σ modulation signal. (Bernabei et al 0804.2741)

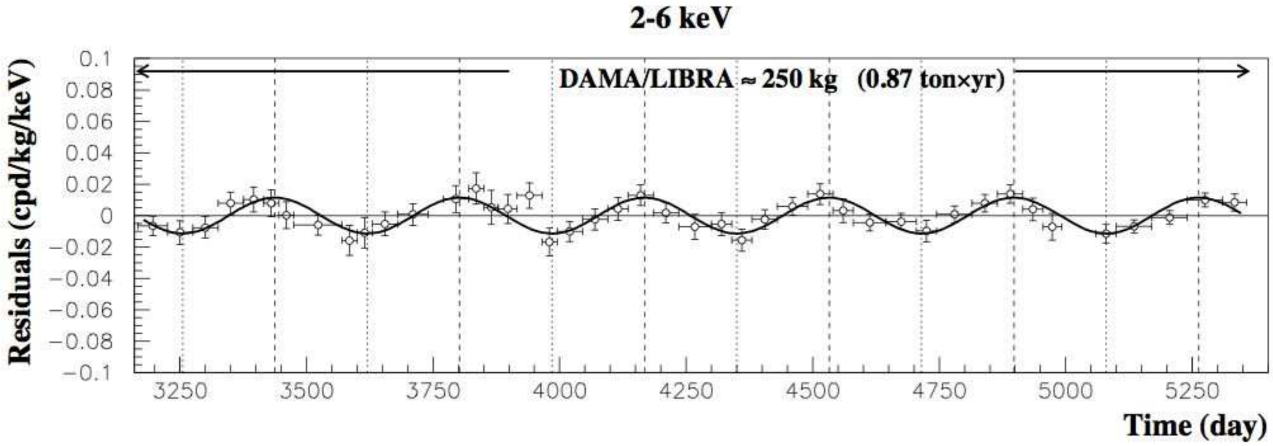


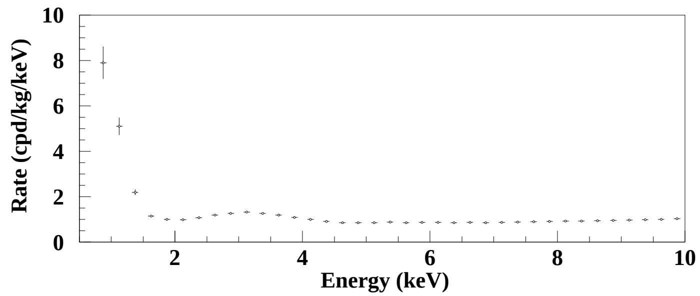


Rate

Direct DM Searches: 2010 DAMA/LIBRA

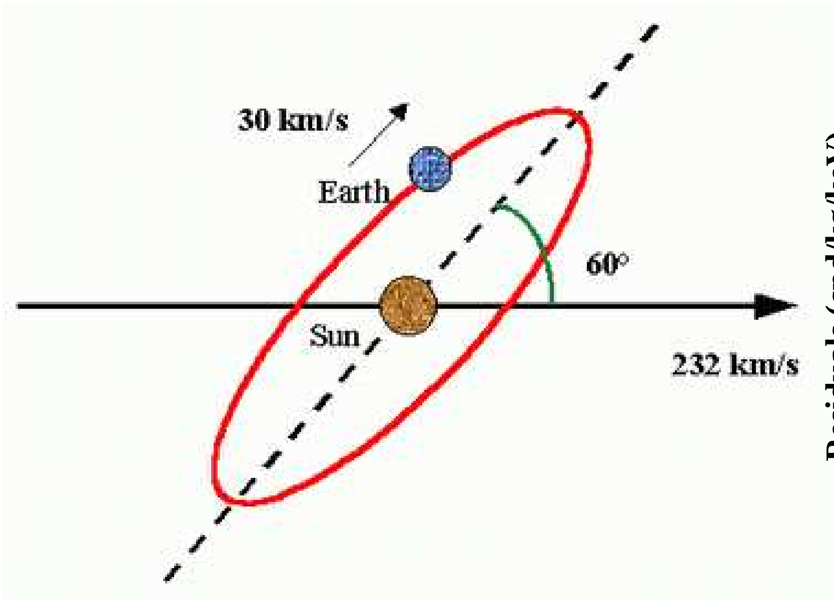
25 NaI (TI) crystals of 9.5 kg each, 6y in LIBRA (13 years total), 1.17 ton × year, 8.9σ modulation signal.(Bernabei et al 1002.1028)

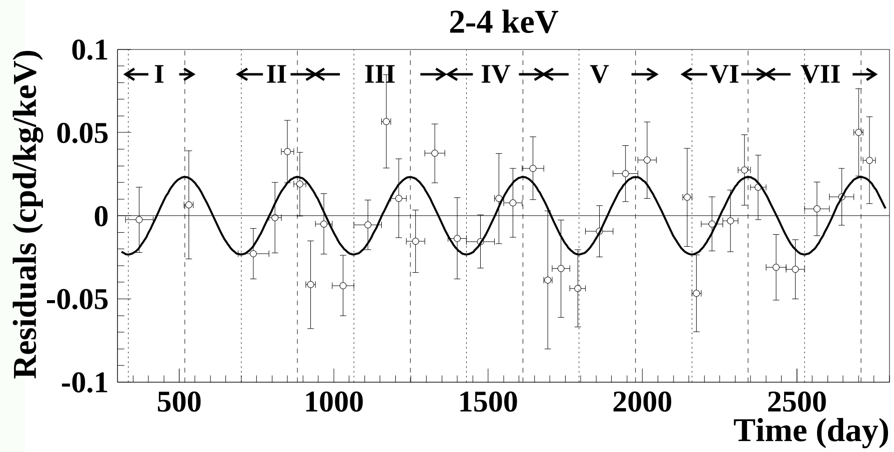




Rate

Old DAMA/NaI: DM signal?



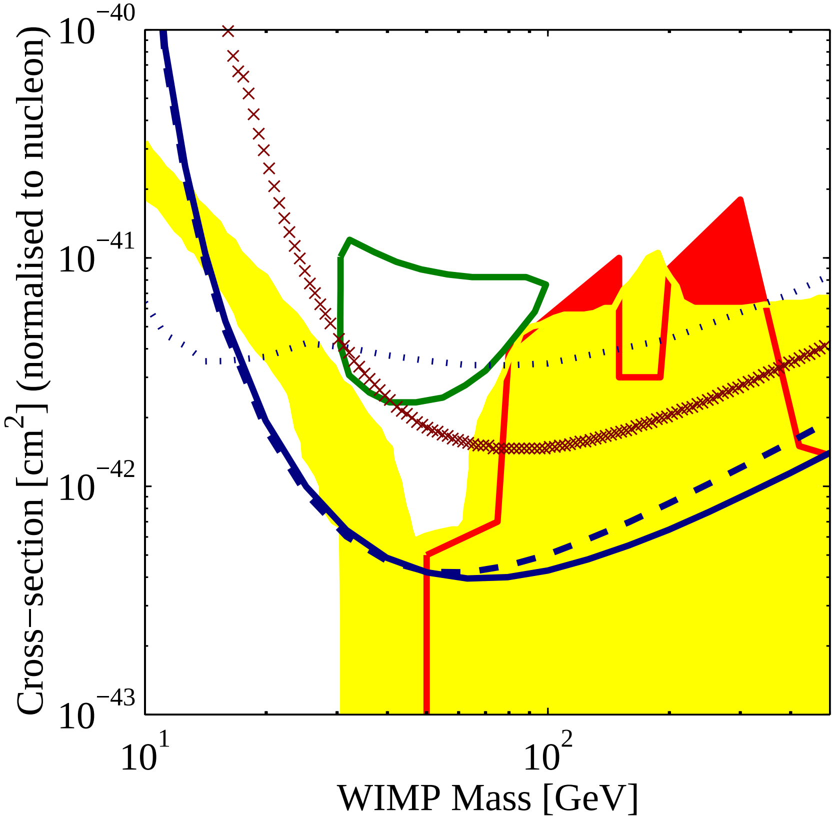


7 years of DAMA/NaI showed a 6σ modulation signal.

Old DAMA/NaI: Spin independent?

Theoretical prejudice in early DAMA analysis: DAMA region cut at 30GeV

which was excluded in 2004 by CDMS-Soudan and Edelweiss .



Bottino et al.

Baltz et al.

Old DAMA: Spin independent?

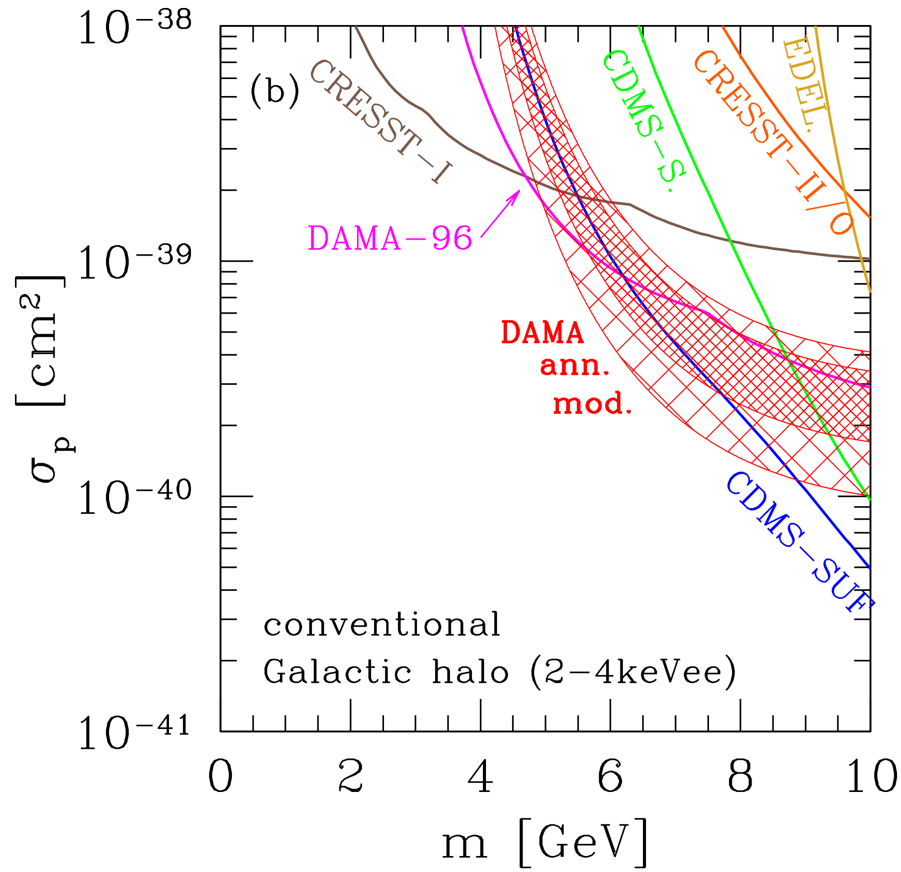
Gelmini, Gondolo 2004; Gondolo Gelmini 2005

In 2004 we found the DAMA signal still allowed for WIMP $m < 10$ GeV (with Standard Halo)

Due to its Na component, DAMA could see a signal that was under threshold for Ge in CDMS and EDELWEISS

(Example: uses 2-4 and 6-14 keVee DAMA bins)

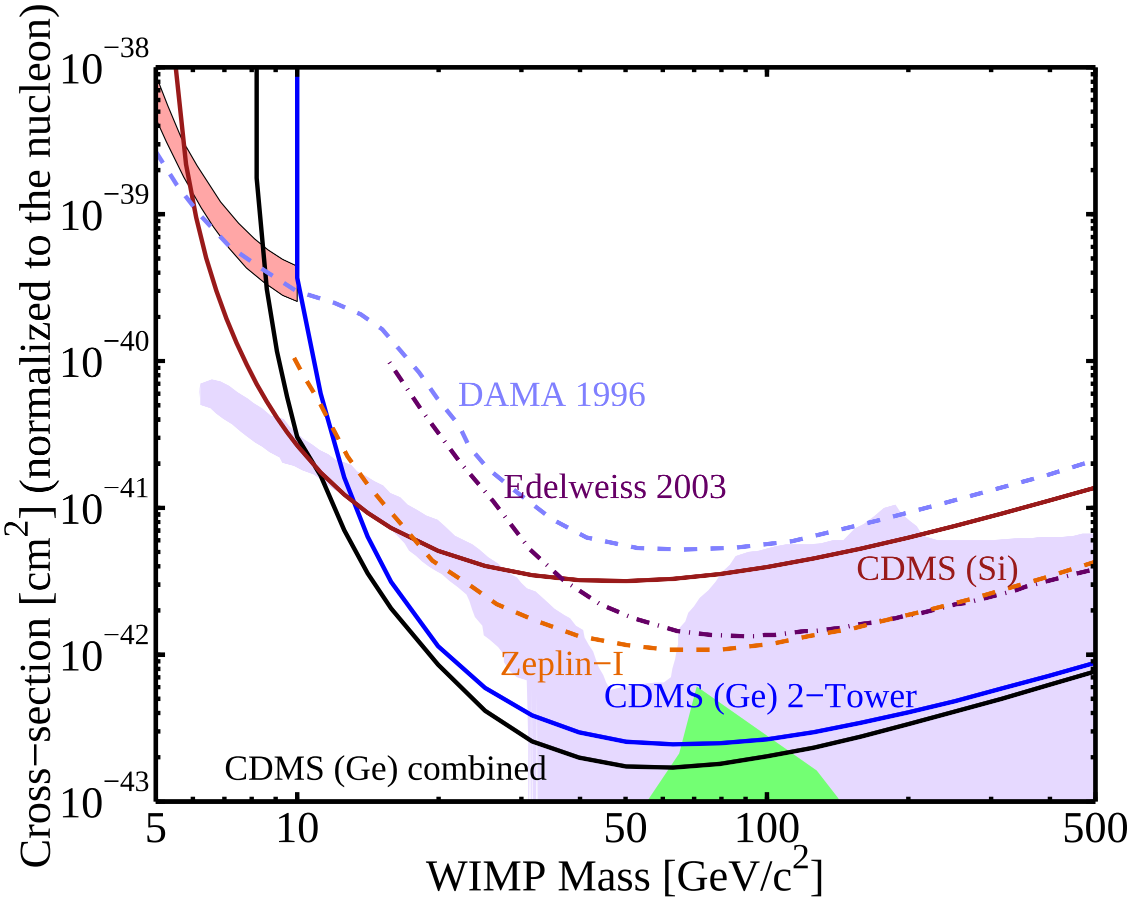
Only two data bins, so we used a "raster scan" in m...



2005 CDMS Si bound

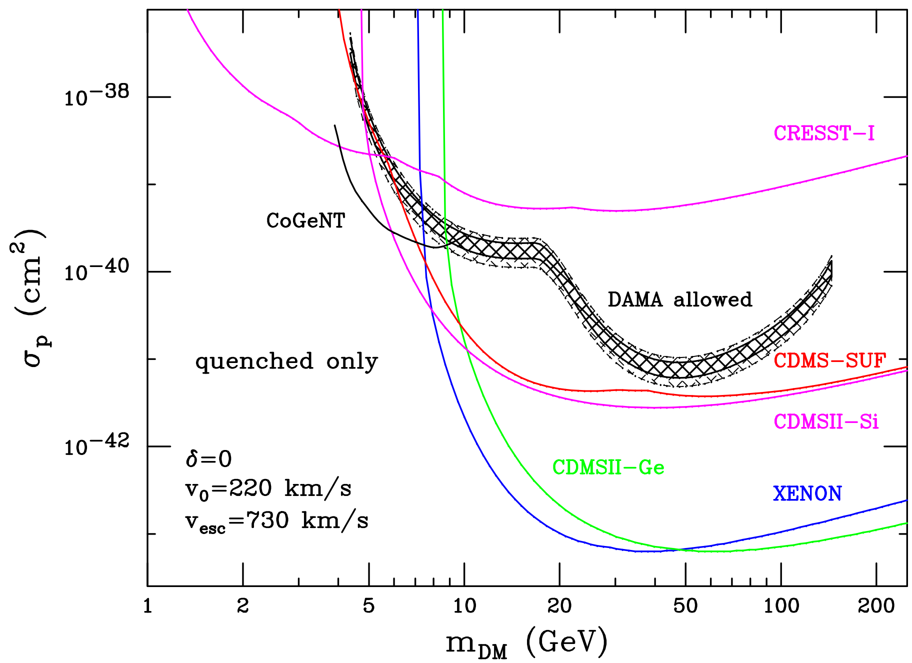
remained as the most restrictive bound on light WIMPs until recently

Small exposure 12 kg d , of Si and 7 keVnr threshold [astro-ph/0509259]



DAMA/LIBRA: Spin independent? Soon after 2008 data release Petriello and Zurek repeated Gondolo-Gelmini-2005 method with new data

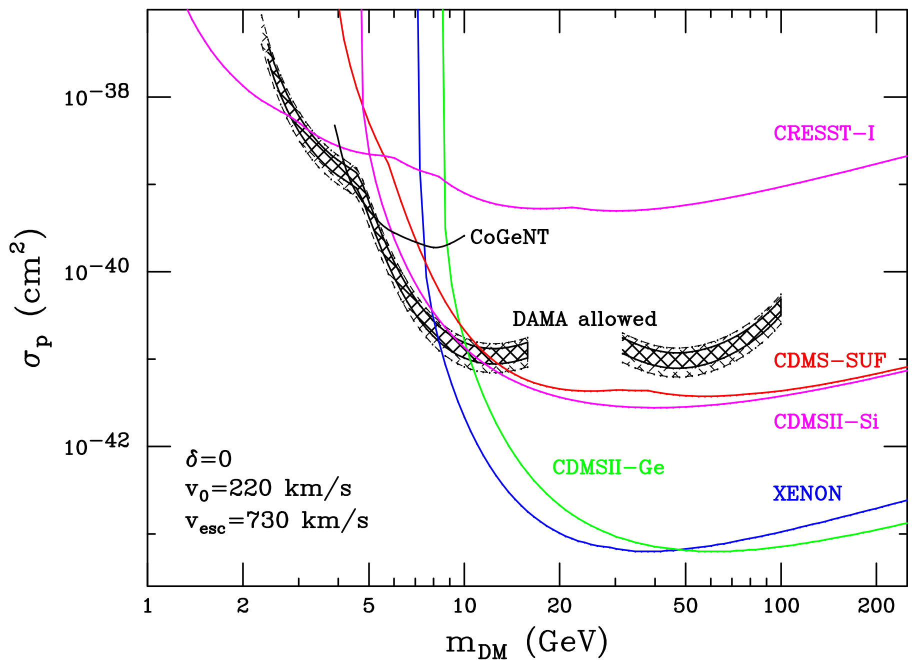
They concluded that
no allowed region remained
unless ion channeling was
important



DAMA/LIBRA: Spin independent? Soon after 2008 data release, Petriello and Zurek repeated Gondolo-Gelmini-2005 method with new data

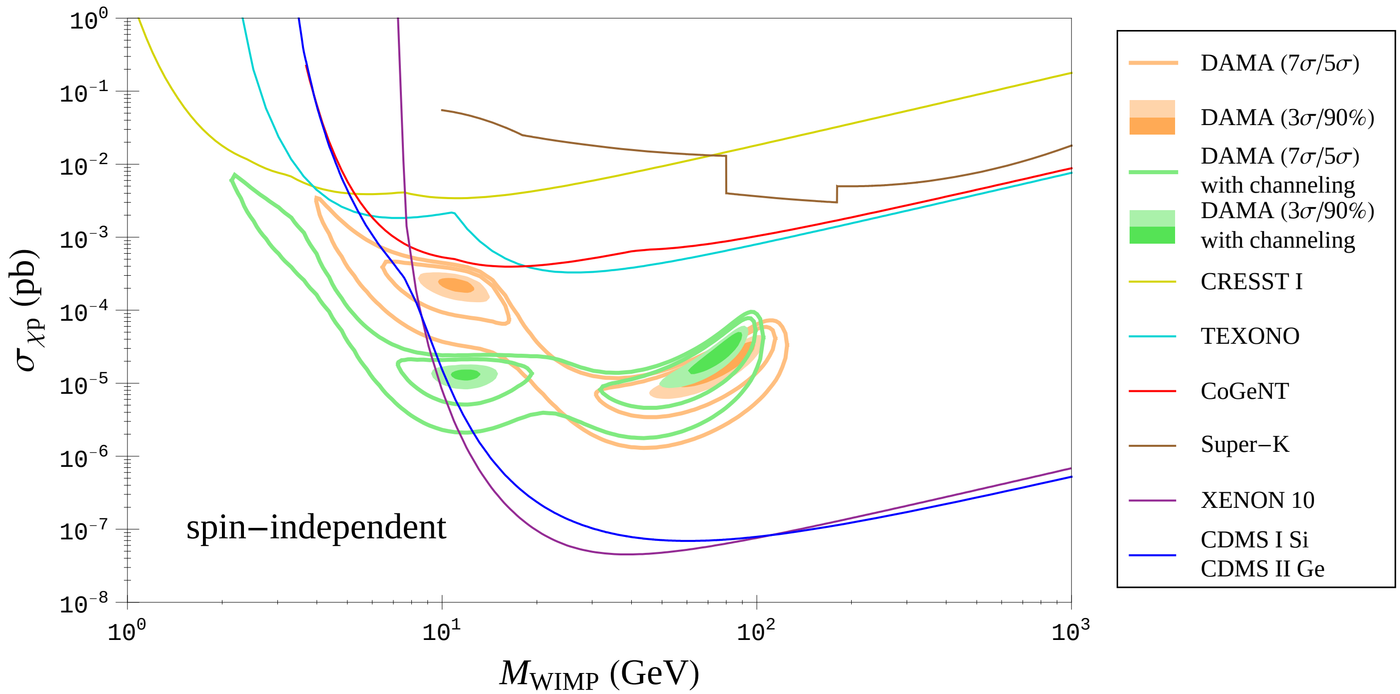
they concluded that with Ion-Channelling still region allowed!

But now 36 data bins, so "raster scan" was not justified...



Many papers examined the issue: Bottino Donato,Fornengo Scopel; Chang, Pierce Weiner; Fairbairn Schwetz; Hooper, Petriello, Zurek, Kamionkowski;...

SI, 36 bins (likelihood ratio 4param. fit) Savage, Gelmini, Gondolo and Freese, arXiv:0808.3607, JCAP 0904:010,2009 (Others reached similar conclusions...)

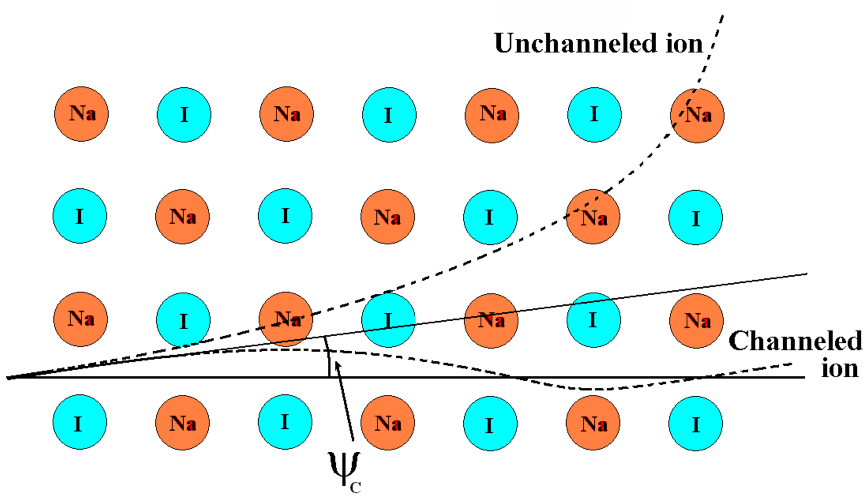


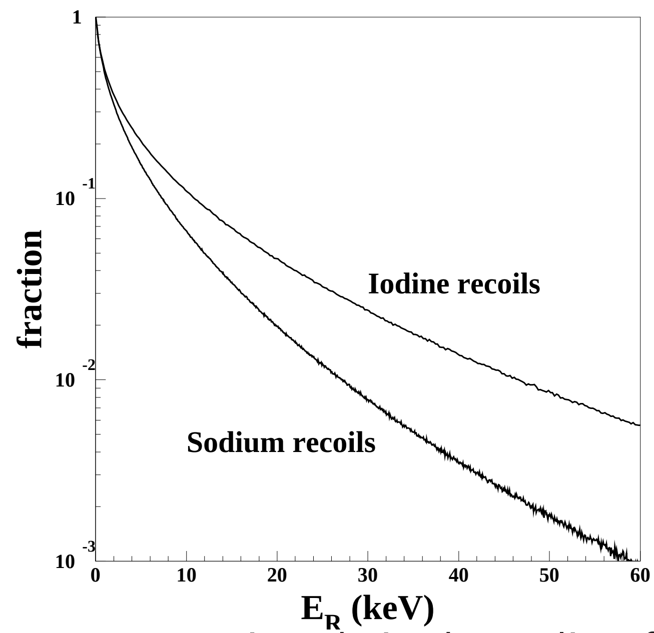
With the large channeling fraction DAMA estimated, light usual WIMPs, $m \simeq$ 7-10 GeV were a possible explanation (conflict with CDMS and XENON at the 2-3σ level)

DAMA channeling fraction: Drobyshevski, 0706.3095 suggested use in DM detection; DAMA coll. computed channeling fraction, Bernabei et al., 0710.0288

When ions recoiling after a collision with a WIMP move along crystal axes and planes, they give their energy to electrons, so $Q = 1$ instead of $Q_I = 0.09$ and $Q_{Na} = 0.3$

Calculated as if ions are incident on the crystal, i.e. start in the middle of the channel





Paper with $\simeq$ 90 citations, most from theory papers using their channeling fraction!

Channeling and Blocking Effects in Crystals depend on the initial position of the ion and the angle of incidence with respect to a lattice row or wall.

Channeling:

Ions moving in the crystal along symmetry axes and planes suffer a series of small-angle scattering that maintain them in the open "channels" (ions do not get close to lattice sites)

Blocking:

Reduction of the flux of ions **originating in lattice sites** along symmetry axis and planes

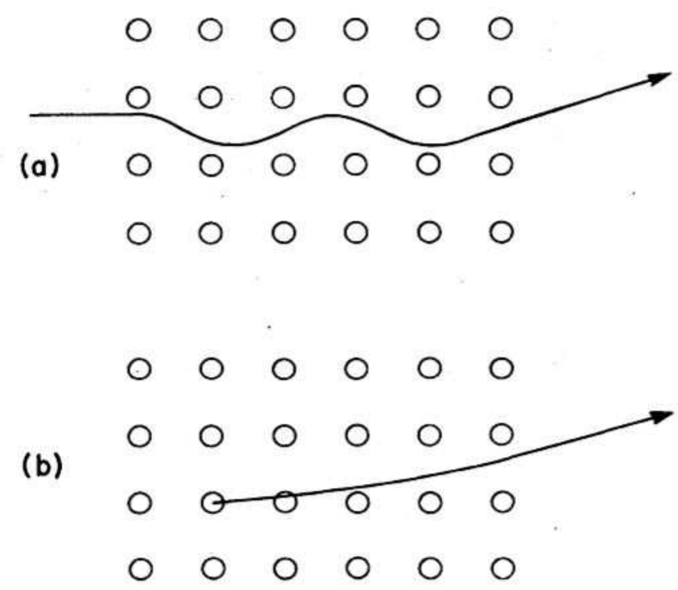
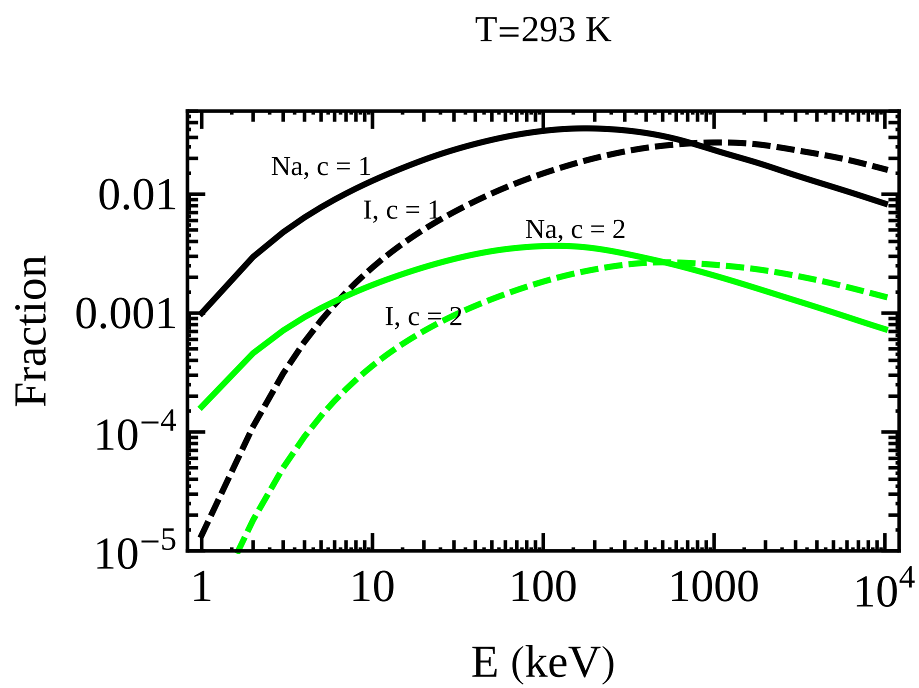


FIG. 1. Schematic illustration of (a) channeling and (b) blocking effects. The drawings are highly exaggerated. In reality, the oscillations of channeled trajectories occur with wavelengths typically several hundreds or thousands of lattice spacings.

(From D. Gemmell 1974, Rev. Mod. Phys. 46, 129)

Channeling fraction: (Bozorgnia, Gelmini, Gondolo 1006.3110)

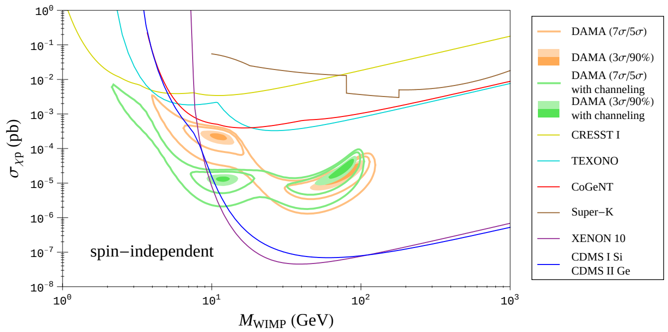
When colliding with WIMPs ions are ejected from lattice sites, **"blocking" is important and channeling fraction is reduced (in a perfect lattice would be zero)**- A generous upper bound on the fraction (using analytic channeling models) is given by $c = 1$ curve



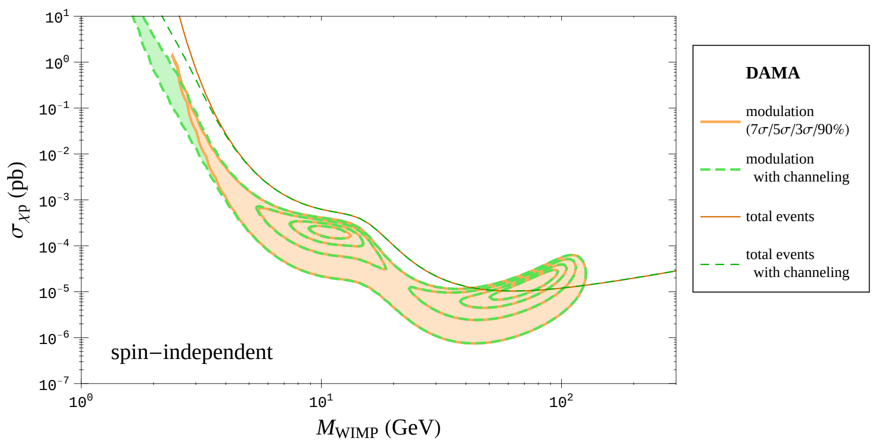
(c is a parameter between 1 and 2 which characterizes Temperature-effects)

DAMA/LIBRA WIMP region

Then (Savage, Gelmini, Gondolo, Freese JCAP 0904:010,2009)



and now (difference at 7σ)(Savage, Gelmini, Gondolo Freese, 1006.0972)



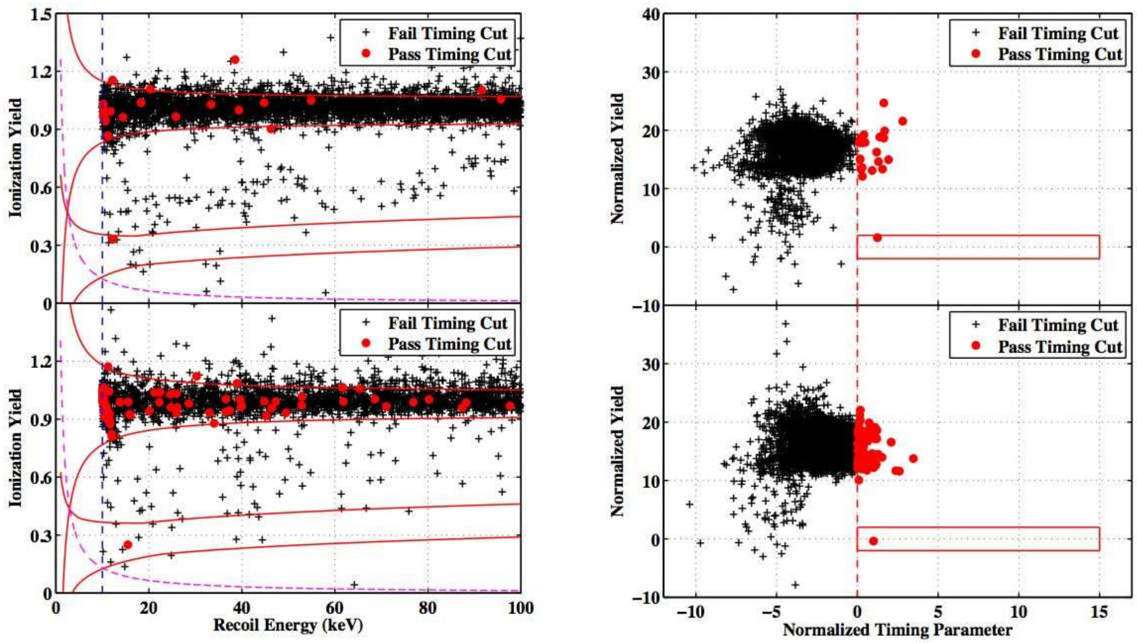
Higher region due to Na - Lower due to I rejected by at least 2 orders of magnitude

Another light WIMP hint or just background? background!

CDMS (Soudan Mine):19 Ge detectors (4.75 kg) and 11 Si (1.1 kg) ZIPs in 5 towers

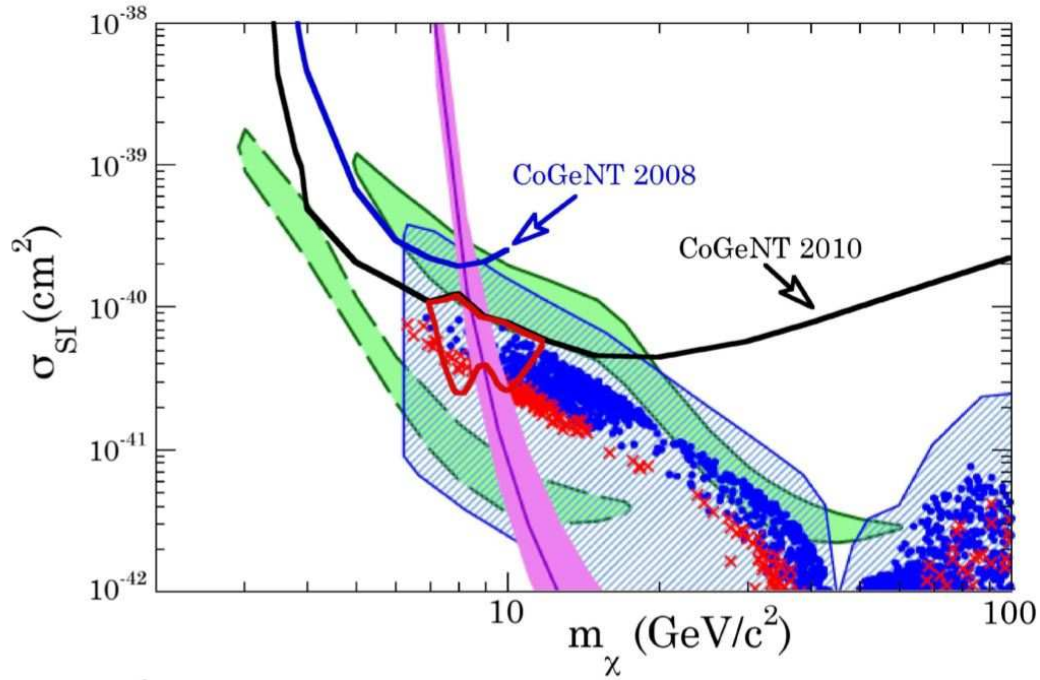
Rejection: ionization (Q= 0.3)-phonons and timing to discriminate surface vs bulk events

Dec 2009: arXiv:0912.3592, Science 327:1619-1621, Feb. 2010

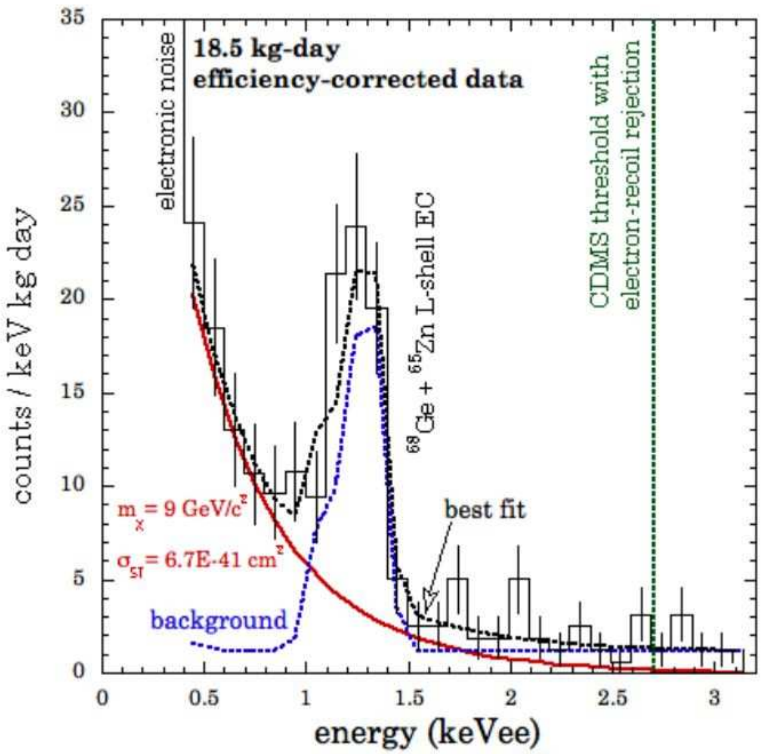


2 events- 0.9 backg. expected, in 612 kg d (prior set: 0 events, 0.6 expect., $\sim$ 400 kg d)

Another light WIMP hint or just background? CoGeNT (Soudan Mine): a 440g Ge detector with extremely low threshold, 0.4 keVee, 56 days of data, has excess "compatible" with the red-outlined irregular region for WIMPs with SI interactions
Feb. 2010: Aalseth et al. [CoGeNT collaboration], arXiv:1002.4703 [astro-ph.CO]



Light WIMP or just background? CoGeNT data



(Juan Collar DM-Marina del Rey, 2010):

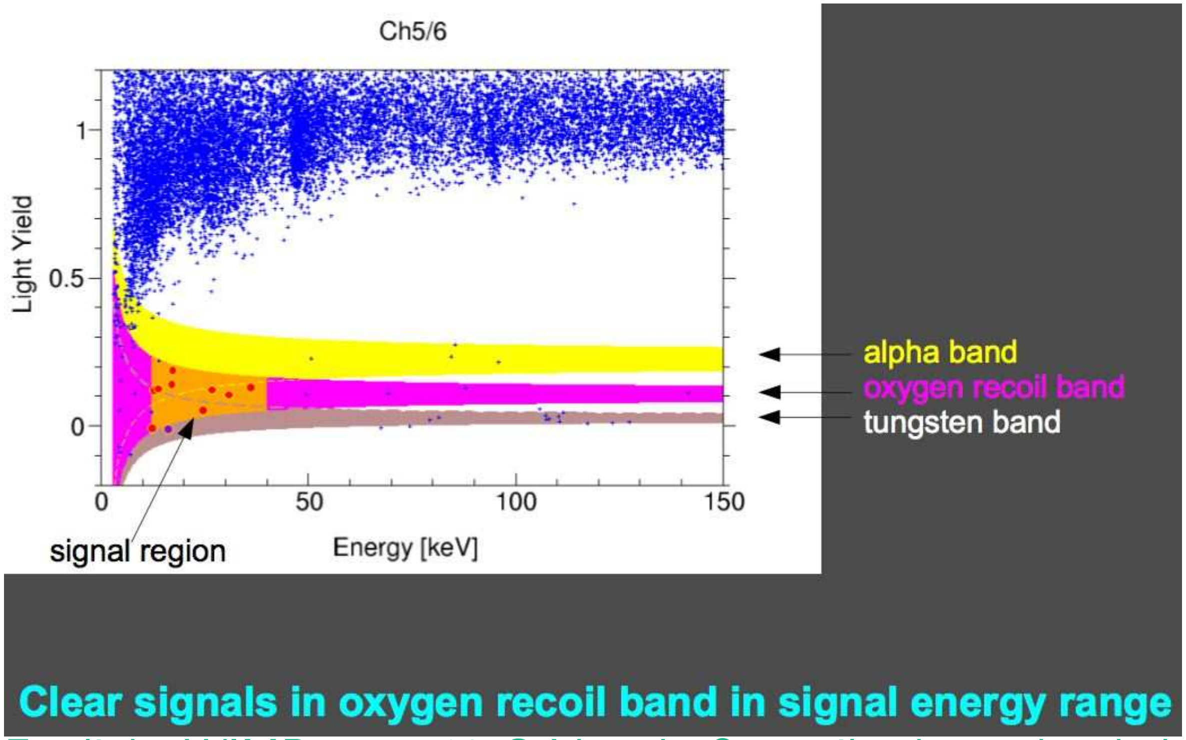
Quotable: The excess of irreducible bulk-like events in CoGeNT is compatible with the WIMP hypothesis in a region where CDMS, DAMA and (several) phenomenological models (good thermal relics) can coexist. It is also equally compatible with any exponential background.

WIMP region only if exponential background is "constrained" (Kopp, Schwetz, Zupan addition to 0912.4264; Fitzpatrick, Hooper, Zurek 1003.0014; Chang, Liu, Pierce, Weiner, Yavin 1004.0697; Hooper, Collar, Hall, McKinsey 1007.1005; Kelso Hooper 1011.3076;)

Another light WIMP hint or just background?

CREST II (LNGS): 564 kgd from 9 $CaWO_4$ crystals at 10-20 mK

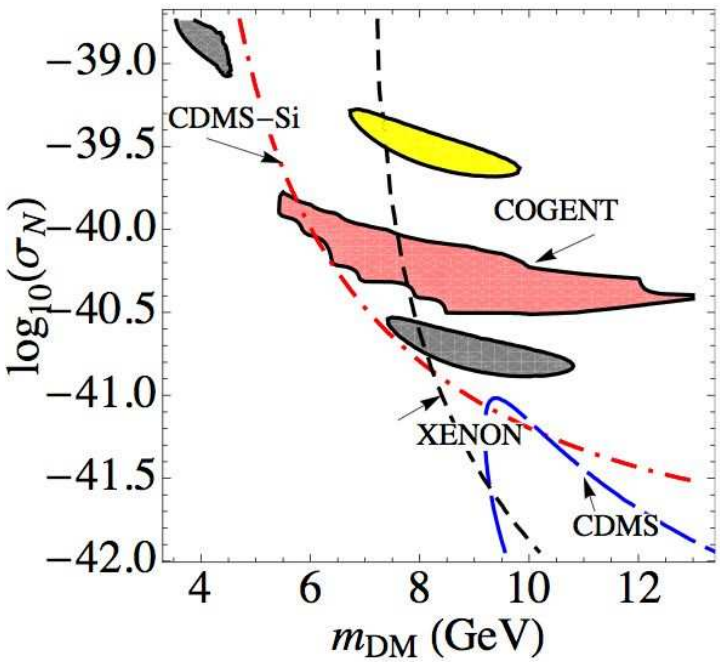
Feb 2010 Preliminary results,W.Seidel in WONDER, LNGS; Nov. F.Probst in Princeton



Total of 32 events in O band: could be from n, leakage of α's or low mass WIMPs - After removal of n, α and γ backgrounds:23.2 remain!

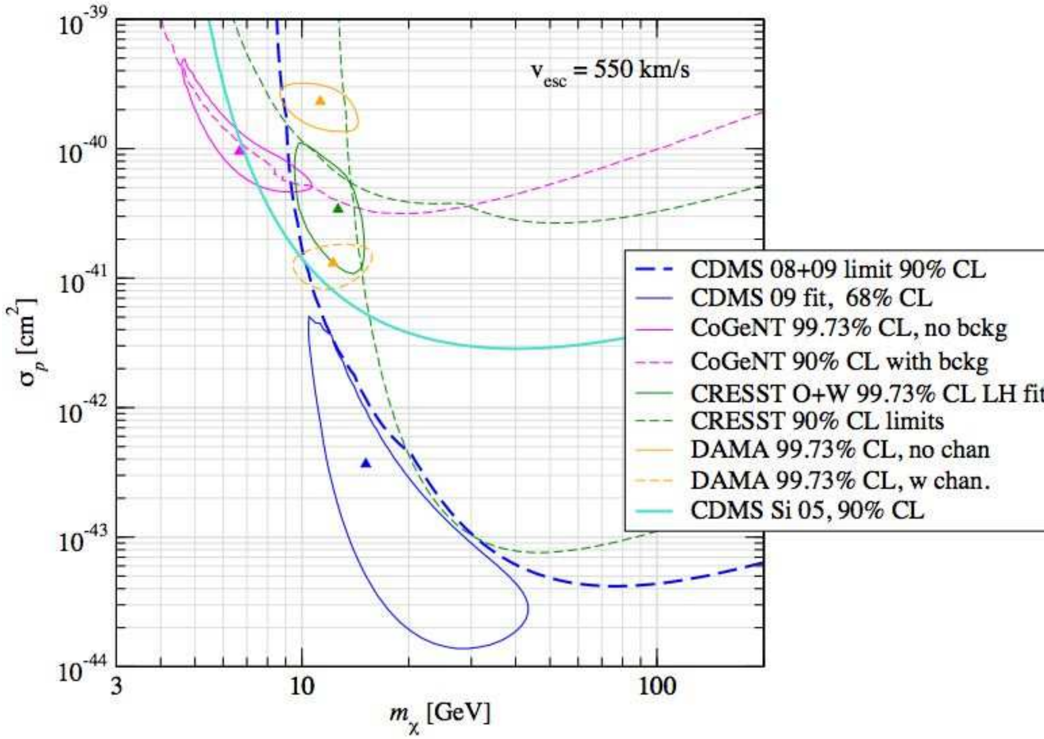
For light WIMPs m$<$ 10 GeV, only O recoils above threshold, Ca recoils for m$\simeq$ 10 GeV and W dominates for large m

Light WIMP's: (grey regions on left, dashed-yellow on right: channeling)



Fitzpatrick, Hooper, Zurek 1003.0014

"Constrained" exp. CoGeNT background



Schwetz, 4/2010

No CoGeNT exp. background

Light WIMP's: $m < 10$ GeV

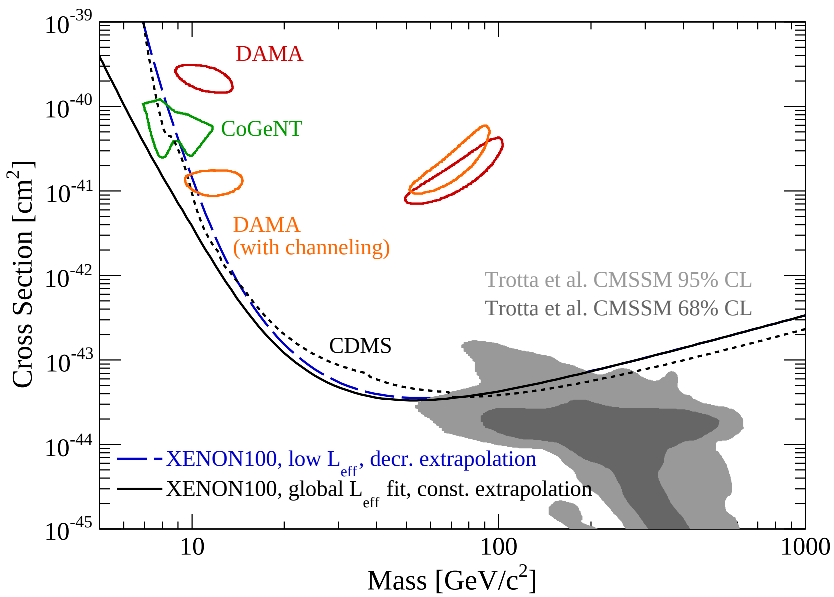
DAMA+ CoGeNT excess (and may be also CRESST excess) generated a new bust of light WIMP models, most need light bosons with GeV mass scale ...(e.g. Feldman et al. 1003.0437; Chang, Liu, Pierce, Weiner Yavin 10; Kufflic, Pierce Zurek, 1003.0682; Andreas et al 1003.2595; Essig, Schuster, Toro Wojtsekhowski, 1004.0691; Fitzpatrick, Hooper Zurek 1003.0014; Cline et al.1008.1796 Buckley Hooper Tait 1011.1499; Fitzpatrick Zurek 1007.5325; Kang et al 1008.5243; Buckley, Hooper Tait 1011.1499)

neutralinos in non-minimal SUSY models too...(e.g.Gunion, Belikov, Hooper 1009.2555; Belikov, Gunion, Hooper Tait 1009.0549)

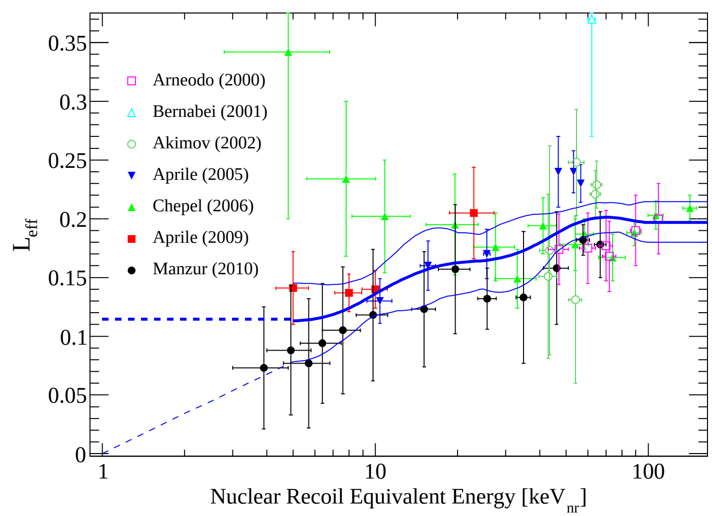
Important new bounds from XENON100 and 10, CDMS "low threshold" 2010 analyses

Light WIMP region Confronted to first 2010 XENON100 bounds-

PRL 105, 131302 (2010) 11.7 d, 40 kg fiducial, 230 kg d, 4PE threshold ($\simeq$ 9.5 keVnr)



XENON bounds depend crucially on L_{eff}

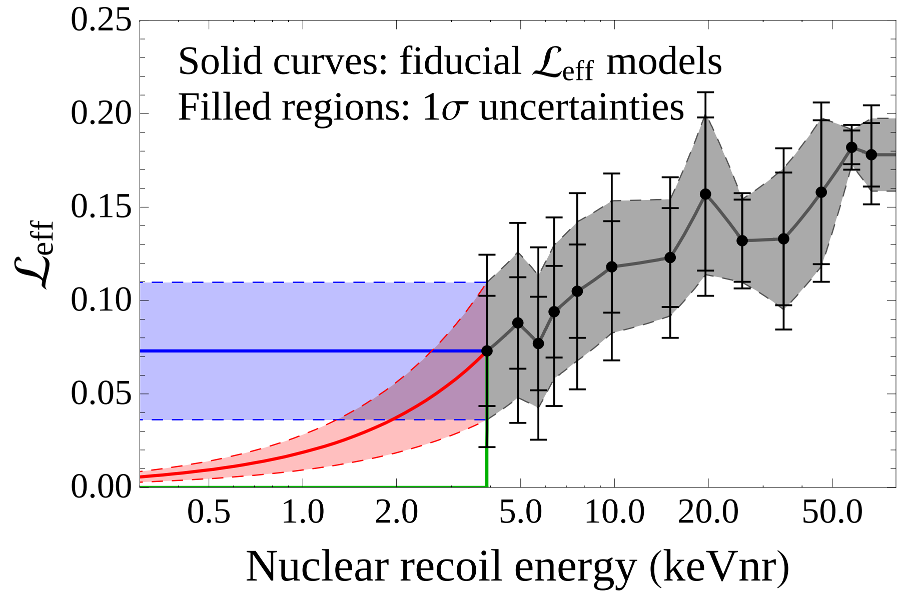


Orange "channeling regions" are not there

Light WIMP's: DAMA/LIBRA +CoGeNT vs XENON bounds

L_{eff} measures how much scintillation light is produced by a certain Xe recoil energy.

Conservative choice: data of Manzur et.al 09 extrapolated below 4 keVnr in three ways



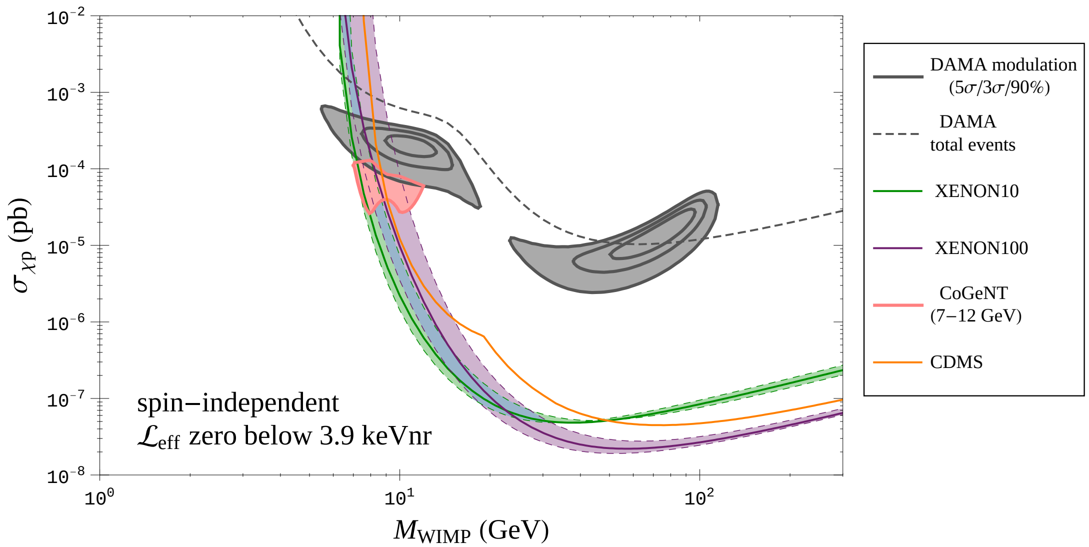
Savage, Gelmini, Gondolo, Freese 1006.0972

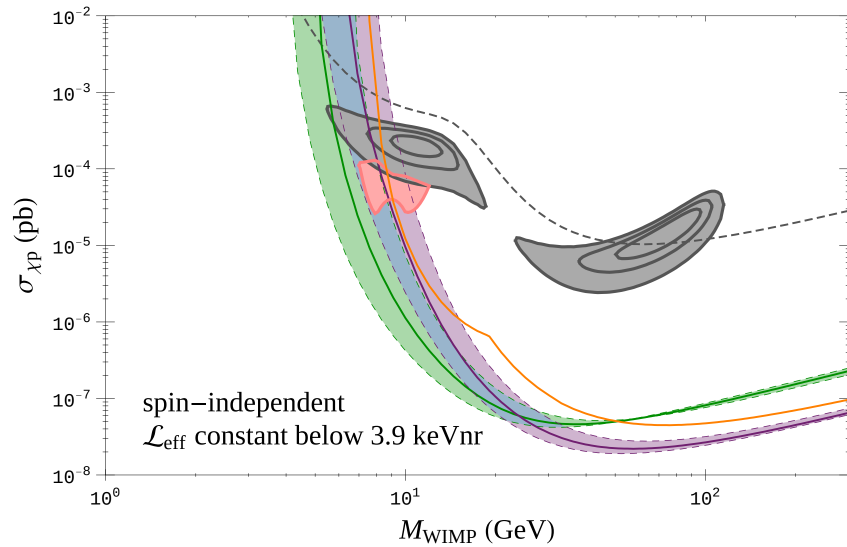
Light WIMP's:DAMA/LIBRA +CoGeNT vs XENON bounds

Data of Manzur et.al 09 extrapolated below 4 keVnr. Band: changes in 90%CL bound with 1σ in L_{eff}. Savage,Gelmini, Gondolo, Freese 1006.0972

Green: XENON10 (15 kg fiducial, 136 kg day, but low thres. 2PE $\simeq$ 4.6 keVnr thres.)

Purple: ZENON100 (4PE $\simeq$ 9.5keV thres.)





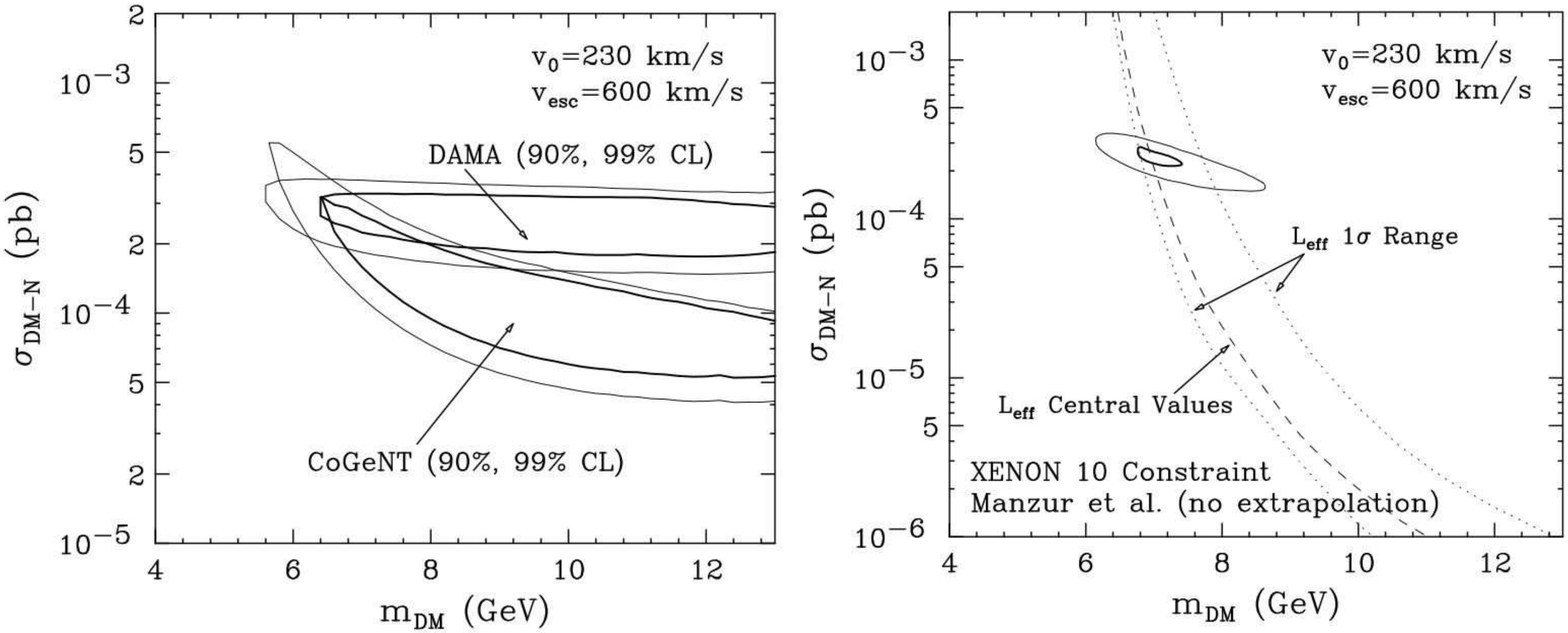
Zero L_{eff}

Constant L_{eff}

Light WIMP's: Can CoGeNT+ DAMA regions overlap?

No exp. background in CoGeNT+ $Q_{\rm Na}$ = 0.2 to 0.4 (instead of usual 0.3) regions overlap

Hooper, Collar, Hall, McKinsey 1007.1005 - XENON bounds from Savage et al. 1006.0972



(m_{DM} = 7.2 GeV and $\sigma_{DM-N} = 2.25 \times 10^{-4}$ pb good to fit CRESS hint too!)

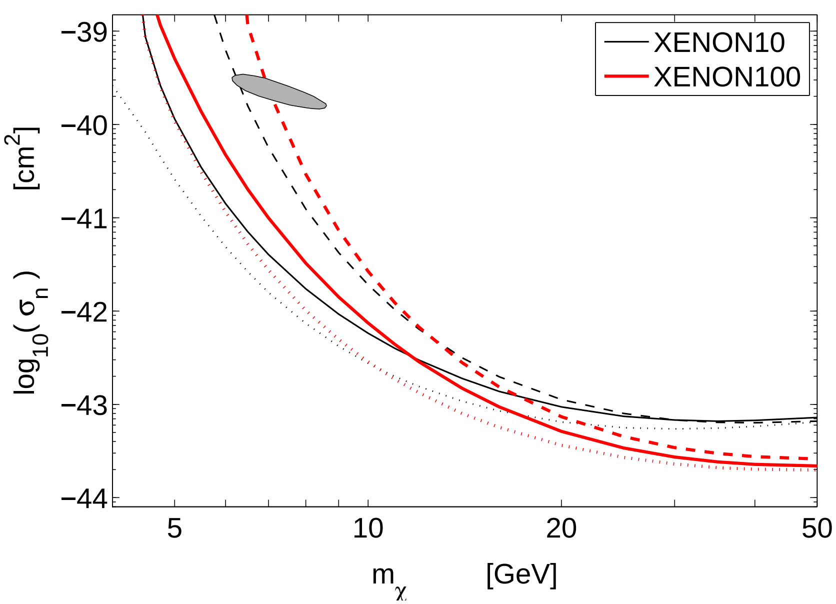
Light WIMP's: DAMA/LIBRA +CoGeNT vs new XENON bounds

S1 prompt scintillation signal, S2 later ionization signal

S2/S1 used as main signal but for low mass WIMPs S2 alone allows for a lower threshold

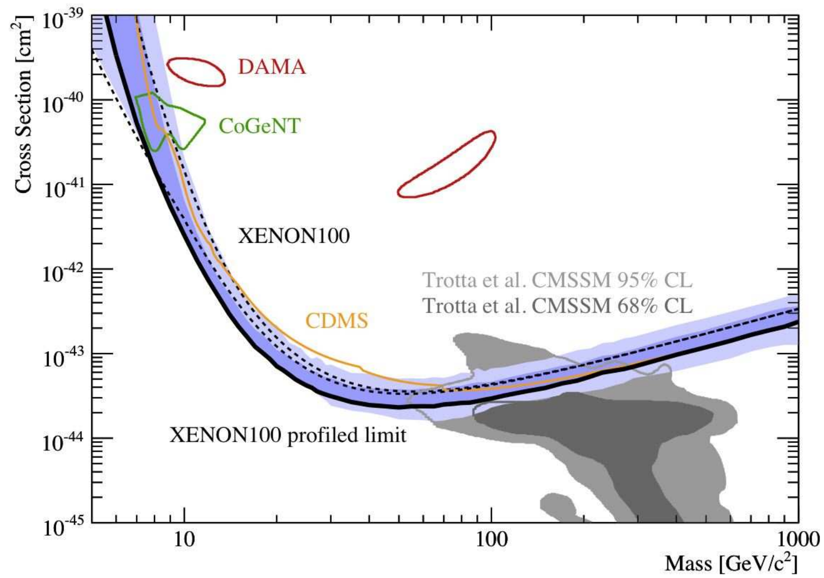
Sorensen 1007.3549

Using only S2 (ionization signal)



XENON100 1103.0303

Still only 11 d of data

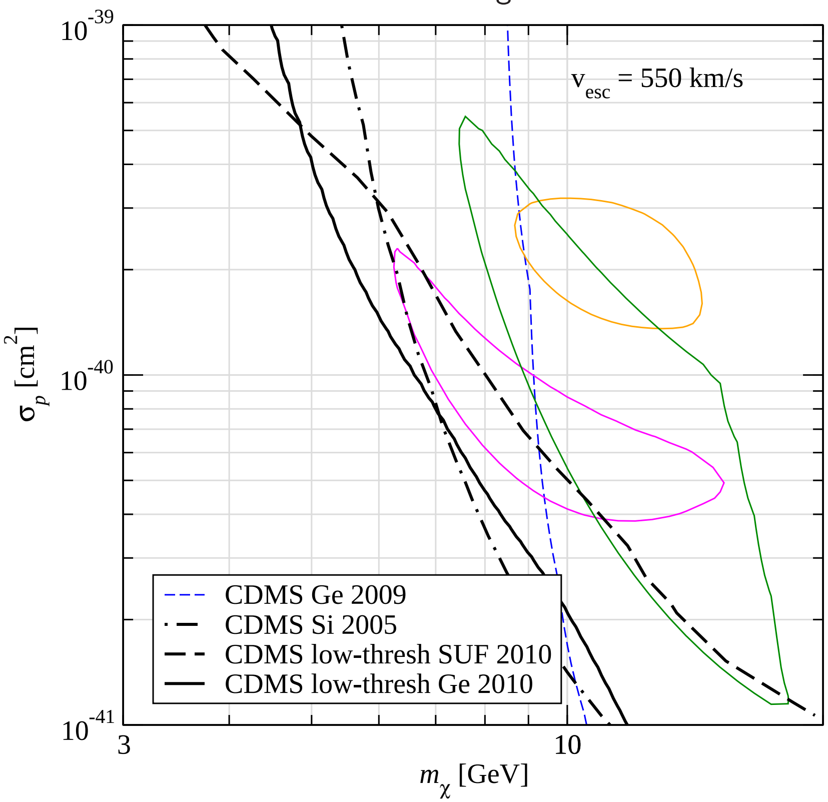


See talk of E. Aprile in this conference

Light WIMP's: New low threshold CDMS bounds

CDMS SUF Ge+Si1010.4290: 118 d in 2001-02 4 × 224g Ge + 2 × 105 g Si, higher bias voltage 2 keVnr threshold

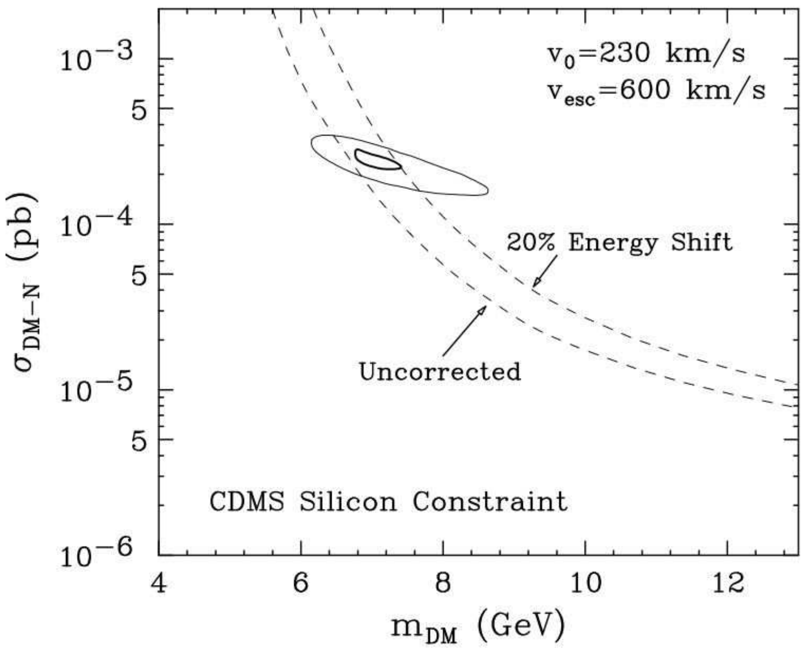
CDMS II Ge Low Threshold 1011.2482: 241 kg d and 2 keVnr threshold

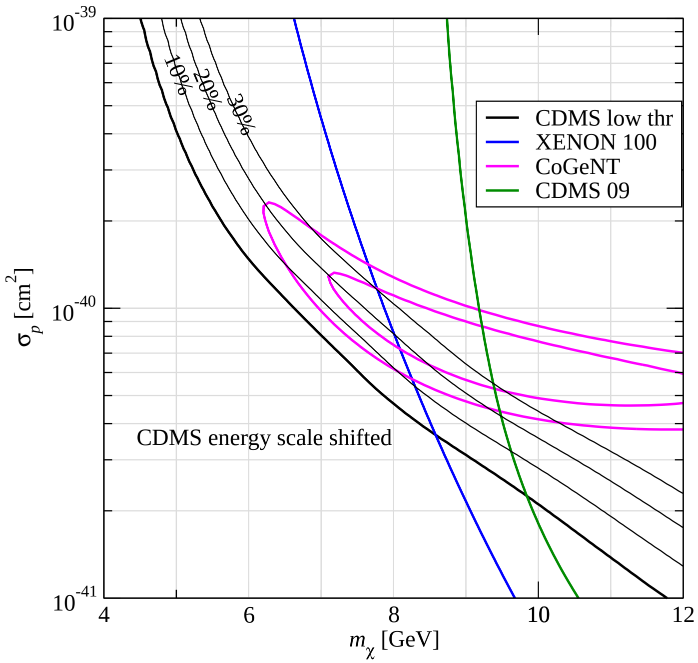


T. Schwetz 1011.5432 Q_{Na}=0.3- No exp. CoGeNT background.

Are Light WIMP's rejected by CDMS bounds?

Energy shift? Si 2005 bounds (left) and low threshold Ge bounds (right)





Hooper, Collar, Hall, McKinsey 1007.1005 Schwetz, arXiv:1011.5432

Other changes? halo model, larger $Q_{\rm Na}$... unlikely to change things much for CoGeNT, with Ge as CDMS and similar thresholds, but maybe for the DAMA low mass region? (see e.g. Chaudhury Bhattacharjee Cowsik, 1006.5588; Schwetz 1011.5432)

Inelastic DM (IDM):

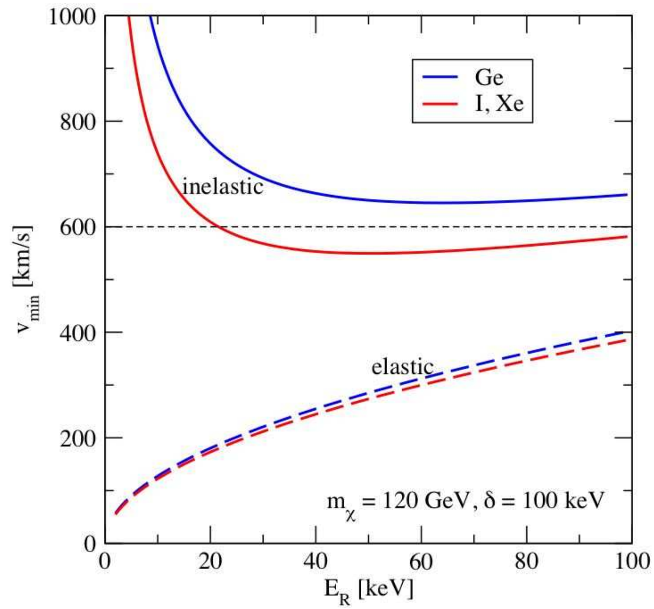
(Tucker-Smith, Weiner 01 and 04; Chang, Kribs, Tucker-Smith, Weiner 08; March-Russel, McCabe, McCullough 08; Cui, Morrisey, Poland, Randall 09; Arina, Ling, Tytgat 09; chmidt-Hoberg, Winkler 09; Shu, Yin, Zhu 10; McCullough, Fairbairn 10; Alves, Lisanti, Wacker 1005.5421)

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

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

Inelastic scattering $\chi + N \to \chi^* + N$ dominates over elastic.

Inelastic DM (fig from T. Schwetz)



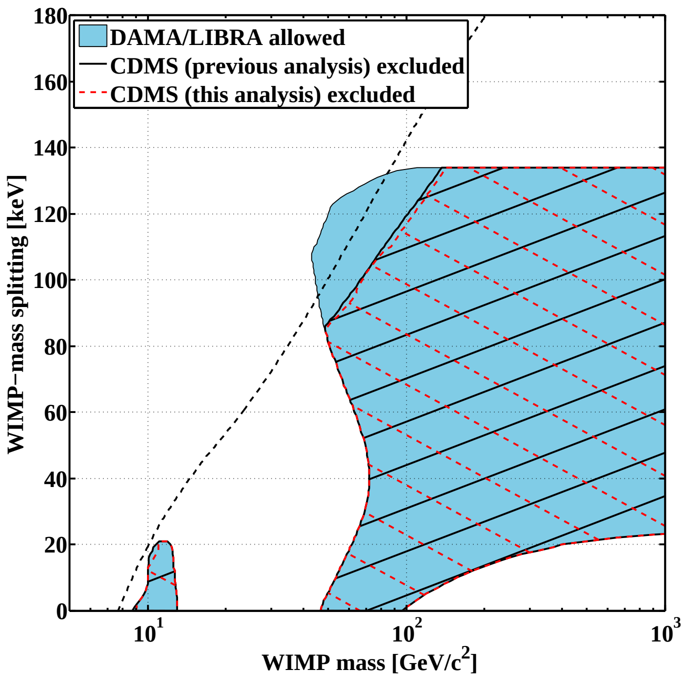
$$v_{min}^{inel} = \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}}$$

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

Only high-velocity DM particles have enough energy to up-scatter, and v_{min}^{inel} decreases with increasing target mass M, thus targets with high mass are favored (better I in DAMA than Ge in CDMS, but Xe and W are heavy too...). Notice no low E$_R$ events.

Leads to very different spectrum (no low E$_R$ events) The modulation of the signal is enhanced (the number of WIMPs changes more rapidly at high v)

IDM: for SI , CDMS new Dec 2010 bounds (1012.5078) leave very small room for compatibility with DAMA region, - above dotted line no events in Ge, but yes in I



Preliminary from CRESST II: with W has rejected the whole region F. Prost talk, Princeton Nov 2010

But IDM with Spin Dependent coupling to only p would survive (although not realistic model for it)(Kopp, Schwetz, Zupan, JCAP1002:014,2010; Chang et al. 1004.0697)

- SD coupling eliminates CRESST II, SD with only p eliminates XENON and CDMS bounds
- Inelasticity, eliminates PICASSO and COUPP (light targets)

For SD,coupling with nucleus is mainly with an unpaired nucleon but in CRESST W, O n-even and p-even

- DAMA, KIMS , COUPP, PICASSO and SIMPLE have unpaired p,
- XENON, ZEPLIN,CDMS and CoGeNT have unpaired n

SUMMARY - OUTLOOK

DM searches are advancing fast... Lots of data necessarily lead to many hints... hopefully at some point several of them will point to the same DM candidate!
So far, no firm DM signature found but more data will help clarify the situation

If the DAMA modulation is due to DM, a DM signal should be found by another experiment-
Light WIMP's and IDM were among the most promising candidates to make the DAMA annual modulation data compatible with all other negative searches

Light WIMPs signal would be close to threshold where background is difficult to understand
In the near future: CRESST II and CoGeNT will eventually understand better their background and check for annual modulation. Unless for some reason recent "low threshold Ge CDMS" bound is weakened, the CoGeNT region seems rejected- Better measurements of $L_{\rm eff}$ at low energies should clarify the XENON 10 and 100 bounds. Better measurements of the $Q_{\rm Na}$ would help greatly to clarify the situation too.

For IDM, CRESST II with its W should be able to test all the region of compatibility with DAMA (other "epicycles" of the idea may be very hard to test).

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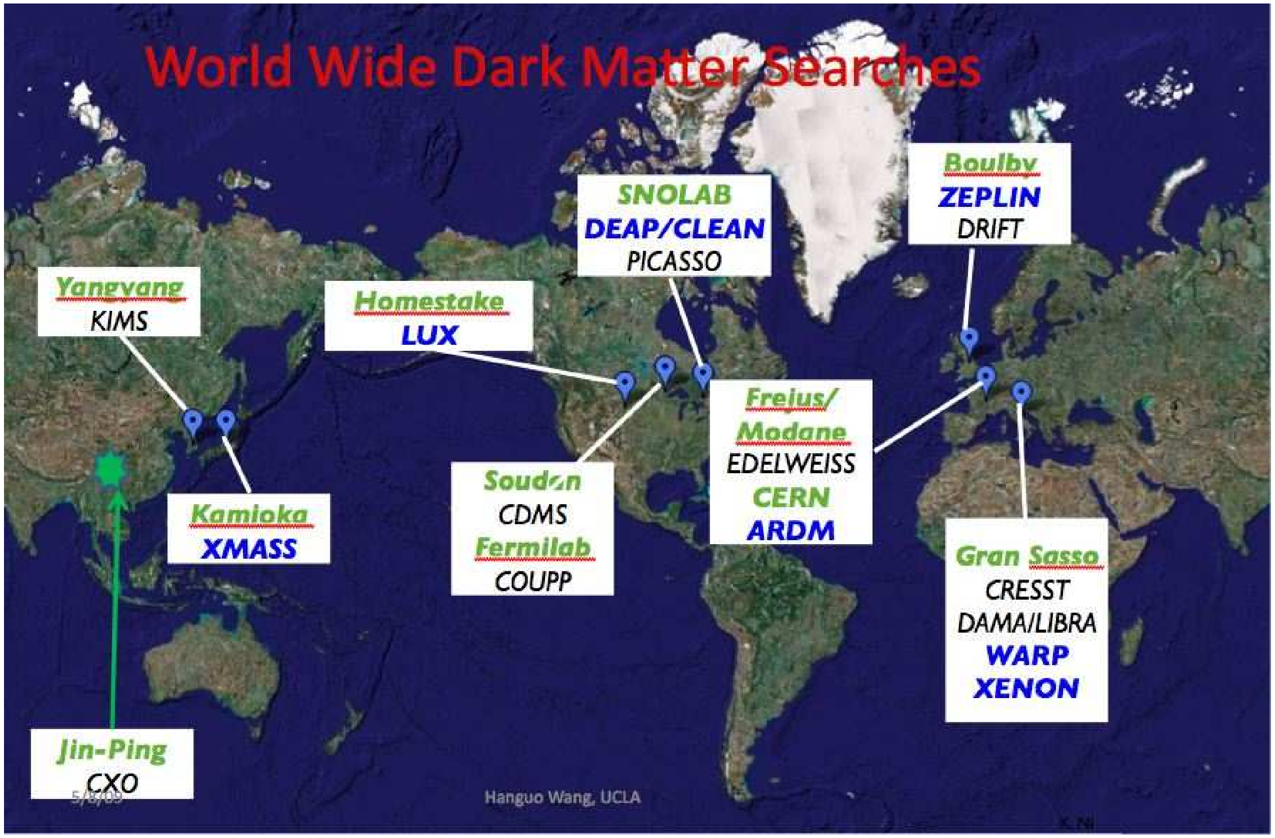
ANDES

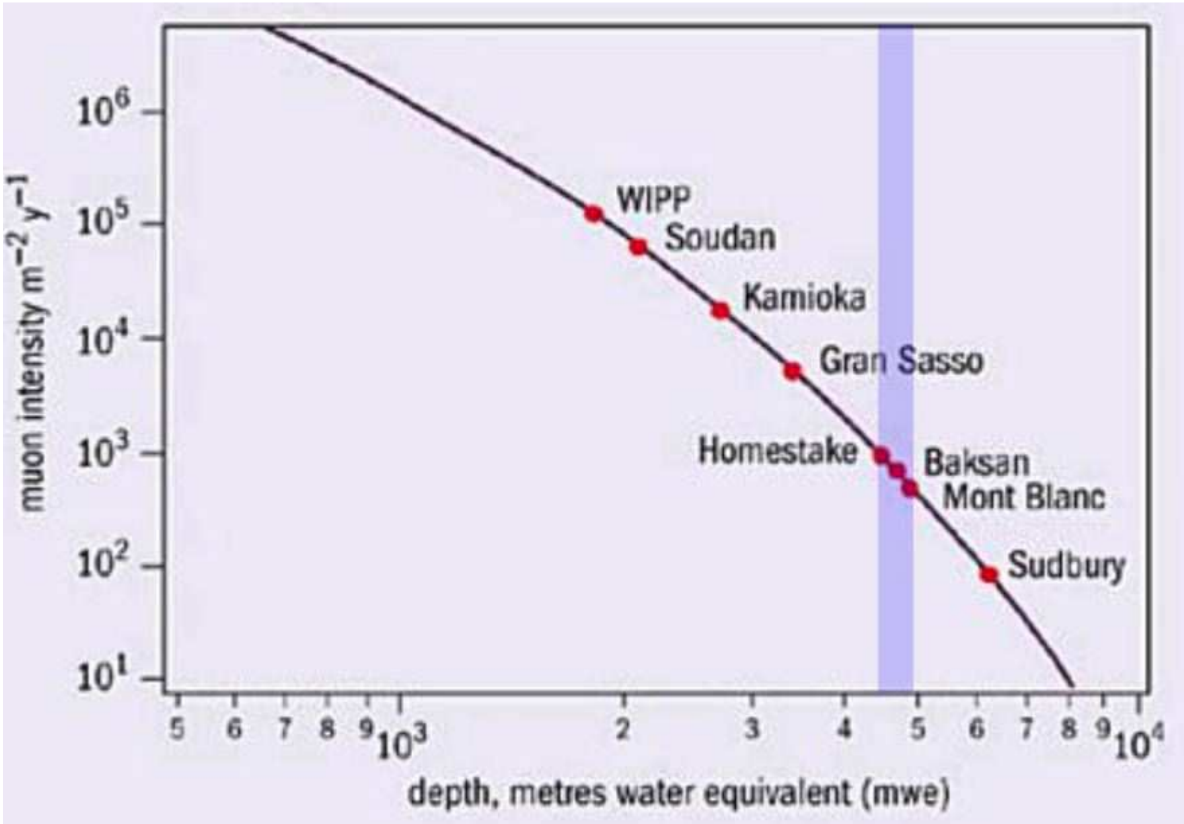
All underground labs are in the Northern Hemisphere



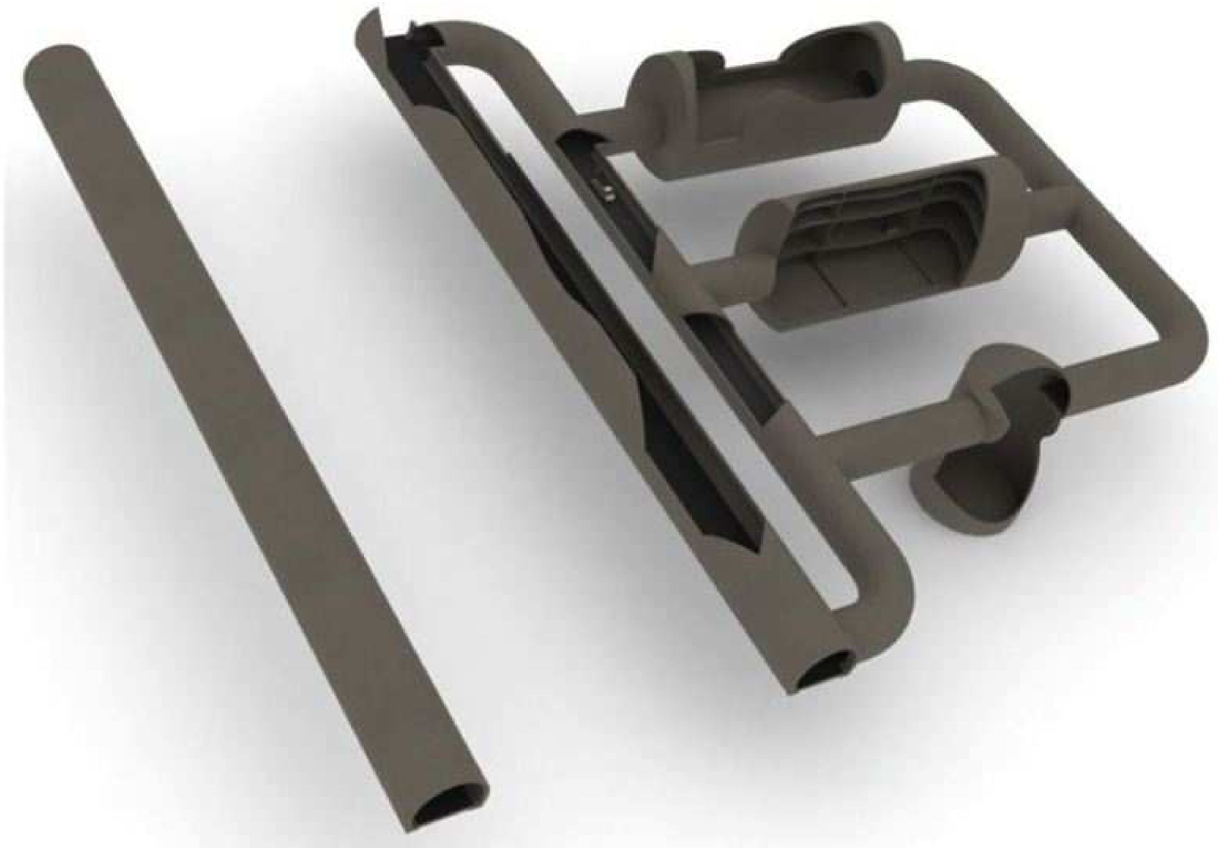
Opportunity to build one at the Agua Negra Tunnel

ANDES, an underground laboratory in the Agua Negra tunnel

- 2 tunnels, 12 m diameter, separated 60 m, 14 km long
- Entry in Argentina (close to the city of San Juan) at altitude 4085m, in Chile at 3600 m (close to La Serena)
- Cavities at $\simeq$ 3700m altitude
- Argentinian side at about 400 km N of Pierre Auger
- Rock: basalt, rhyolite; density $\simeq$ 2.7 g/cm^3
- Deepest point from surface at $\simeq$ 1750 m $\simeq$ 4500-4800 mwe, l
- Low radioactivity, T$\simeq$ 30-40^o


muon intensity m^{-2} y^{-1}
10^6
10^5
10^4
10^3
10^2
10^1
WIPP
Soudan
Kamioka
Gran Sasso
Homestake
Baksan
Mont Blanc
Sudbury
5 6 7 8 9 10^3 2 3 4 5 6 7 8 9 10^4
depth, metres water equivalent (mwe)

ANDES Laboratory concept



First International Workshop for the Design of the ANDES Underground Laboratory

Buenos Aires, Argentina 11-14 April 2011

SEE: http://particulas.cnea.gov.ar/andes/workshop/index.php?lang=es

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Project organizers: H. Asorey , X. Bertou , O. Civitarese , M. Gomez Berisso

More information about ANDES:

http://particulas.cnea.gov.ar/andes/