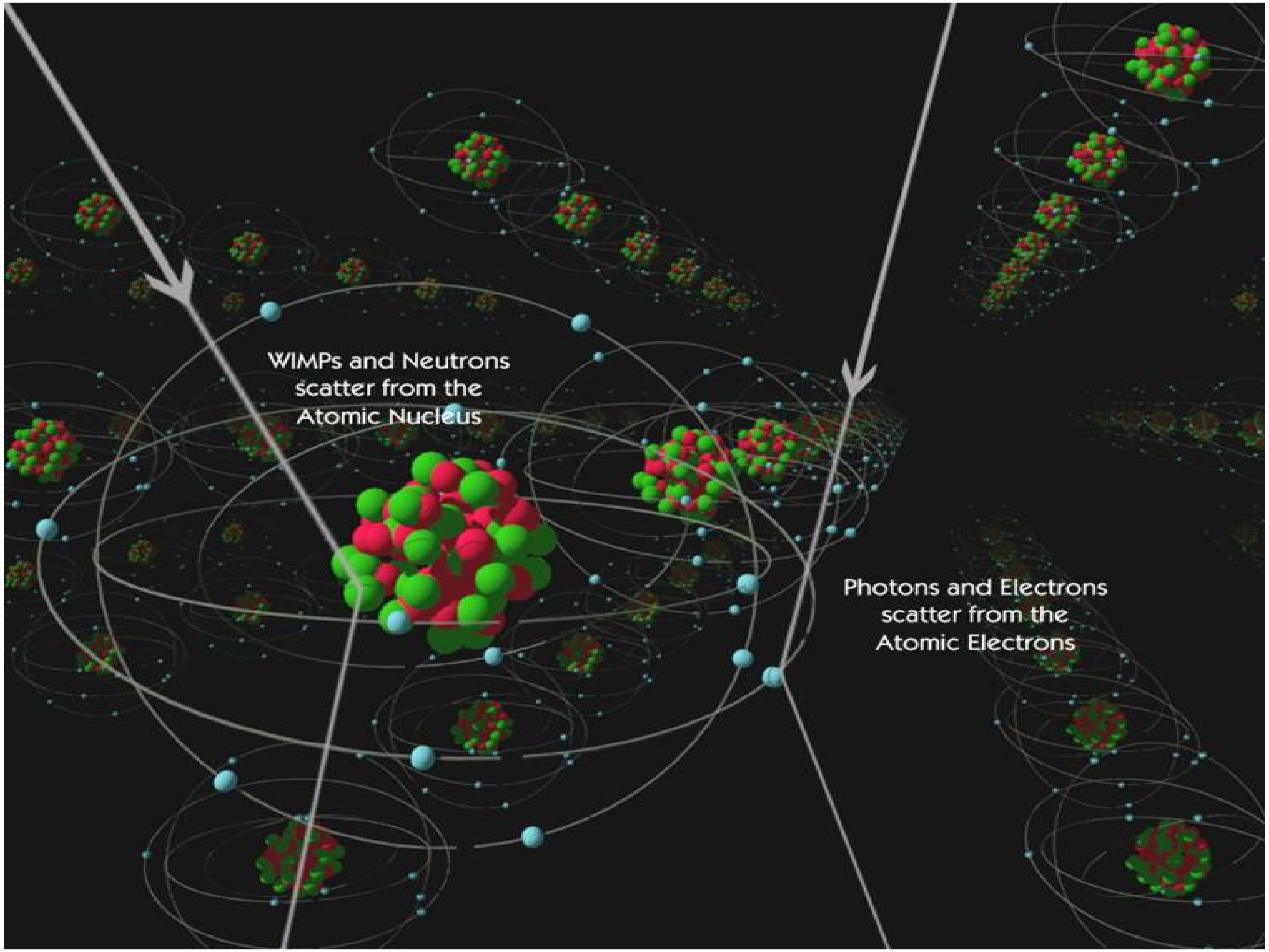
Implications of the CDMS Results on Invisible Higgs Decay

KC, Tzu-Chiang Yuan 0912.4599 (PLB) CPS Jan 2011

References

- CDMS Collaboration, arXiv:0912.3592 (Science), 1011.2482
- Xenon Collaboration, arXiv:1005.0380
- Cheung, Yuan, arXiv: 0912.4599 (PLB)

Schematics of Direct Detection

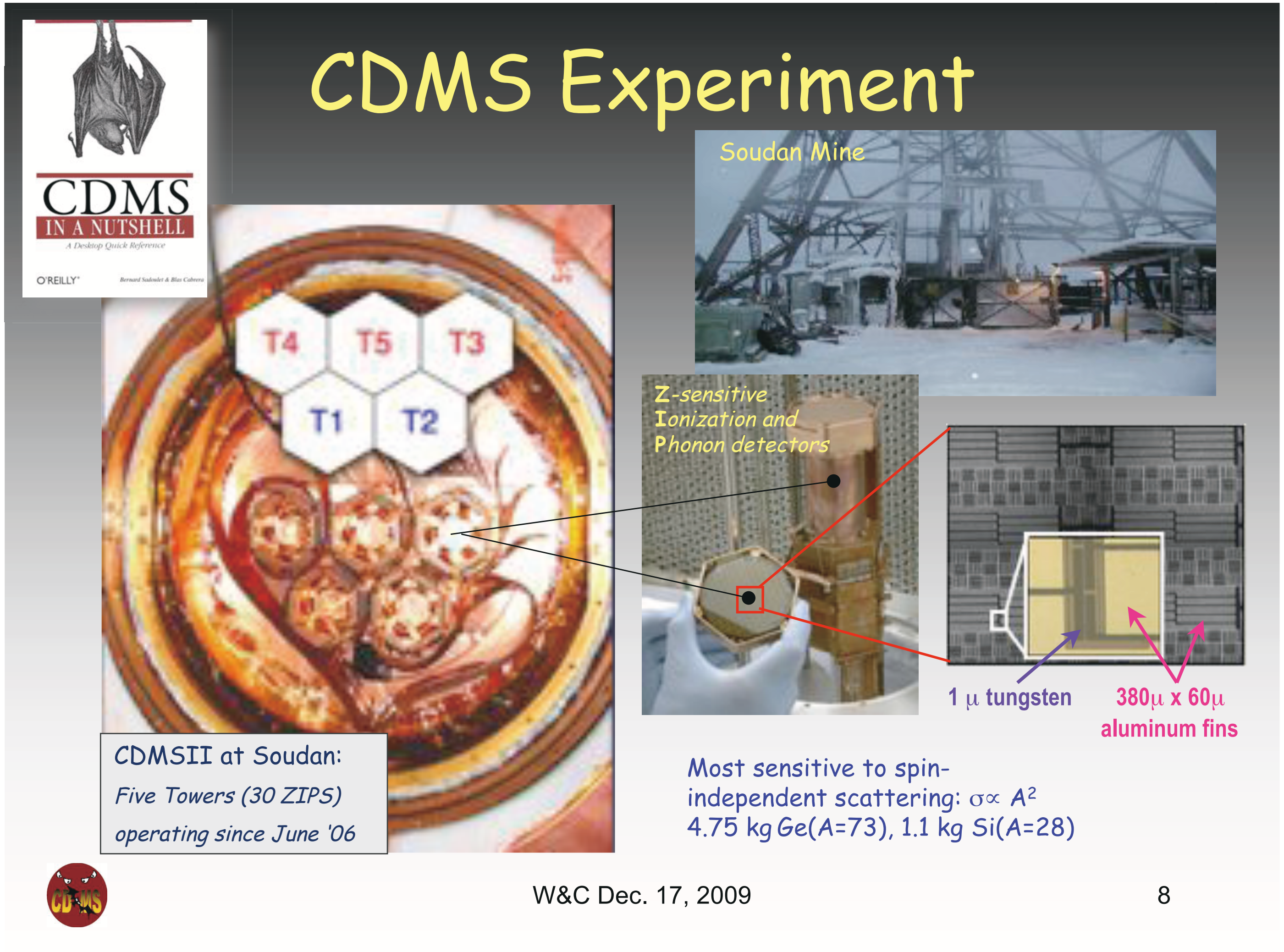


Direct Detection Methods

- Must be able to distinguish background particles, which scatter off electrons, from the dark matter particles which scatter off nuclei.
- One technology: cryogenic detectors, operate at temperatures below 100 mK. Detect the heat (phonon) when the WIMP hits an atom in a crystal absorber, e.g., Ge. Examples: CDMS, CRESST, EDELWEISS, EURECA.
- Another technology: noble liquid detectos, detect flash of scintillation light produced by a particle collision in liquid xenon or argon. Examples are ZEPLIN, XENON, ArDM, LUX.
- Some uses ionization, because electron charged may be liberated.
- All need a background-free environment, like a deep mine or under a mountain.

Kinematics of Direct Detection

- Relative velocity of DM particle ~ 270 km s$^{-1} \simeq 10^{-3}c$, with a gaussian tail.
- Average kinetic energy of the DM particle $\sim \frac{1}{2}mv^2 \simeq 0.5m$ keV (m in GeV); of order 50 keV for a 100 GeV DM particle.
- Energy transfer to nucleus is therefore the total or part of the k.e., ie., recoil spectrum $\langle E \rangle \sim 50$ keV.


CDMS Experiment
CDMS
IN A NUTSHELL
A Desktop Quick Reference
O'REILLY
Soudan Mine
T4
T5
T3
T1
T2
Z-sensitive
Ionization and
Phonon detectors
1 μ tungsten
380μ x 60μ
aluminum fins
CDMSII at Soudan:
Five Towers (30 ZIPS)
operating since June '06
Most sensitive to spin-
independent scattering: σ∝ A²
4.75 kg Ge(A=73), 1.1 kg Si(A=28)
W&C Dec. 17, 2009
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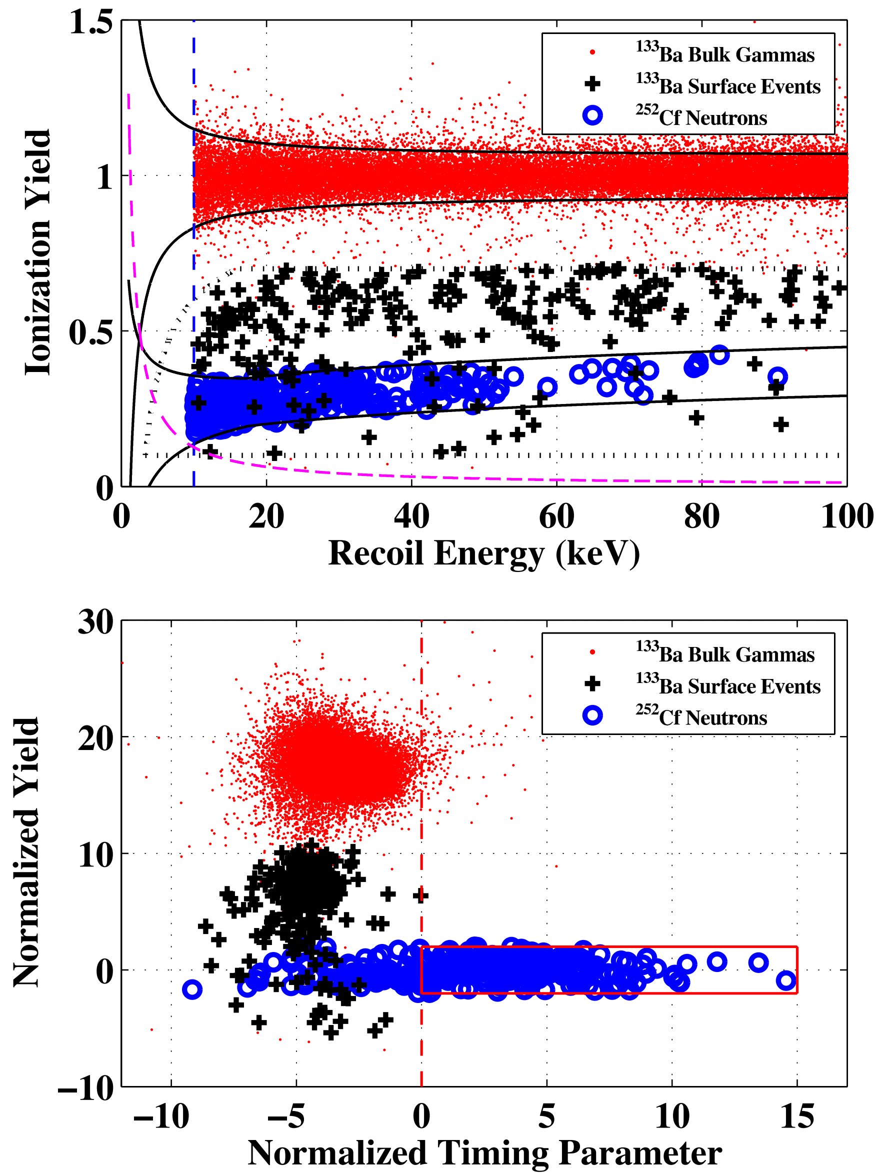
CDMS Detectors

- Use 19 Ge ($\sim$ 230 g) and 11 Si ($\sim$ 100 g) particle detectors at cryogenic temperatures ($<$ 50 mK).
- Deep in the Soudan Underground Lab.
- Particle interactions in the detectors deposit energy in form of phonons and ionization.
- Phonon sensors measure the recoil energy and the position of the event; phonon sensors are also the ground reference for ionization measurements.
- The ratio of ionization to recoil energy (ionization yield) provides event-by-event rejection of electron recoil events.
- Combining with phonon timing electron recoils are reject at $< 10^{-6}$ level.

- The efficiencies of the cuts are developed using neutron source.
- The WIMP signal is expected to a single-scatter event. Neutrons of several MeV are indistinguishable from WIMP.
- Neutron background includes cosmic-ray muons interacting nearby, radioactive contamination, environmental radioactivity.
- Use a blind analysis. The number of background events is 0.8 ± 0.1 (stat) ± 0.2 (syst) in the signal region.


1.5
1
0.5
0
Ionization Yield
0
20
40
60
80
100
Recoil Energy (keV)
133Ba Bulk Gammas
133Ba Surface Events
252Cf Neutrons
30
20
10
0
−10
Normalized Yield
−10
−5
0
5
10
15
Normalized Timing Parameter
133Ba Bulk Gammas
133Ba Surface Events
252Cf Neutrons

The 2009 year-end CDMS II Results

CDMS (0912.3592)

- Open the black box there are 2 events in the WIMP acceptance region. Recoil energies are 12.3 and 15.5 keV.
- The chance that these 2 events are due to background fluctuation is 23%.
- The upper limit on the WIMP-nucleon elastic scattering cross section based on standard galactic halo assumption is then, from this analysis

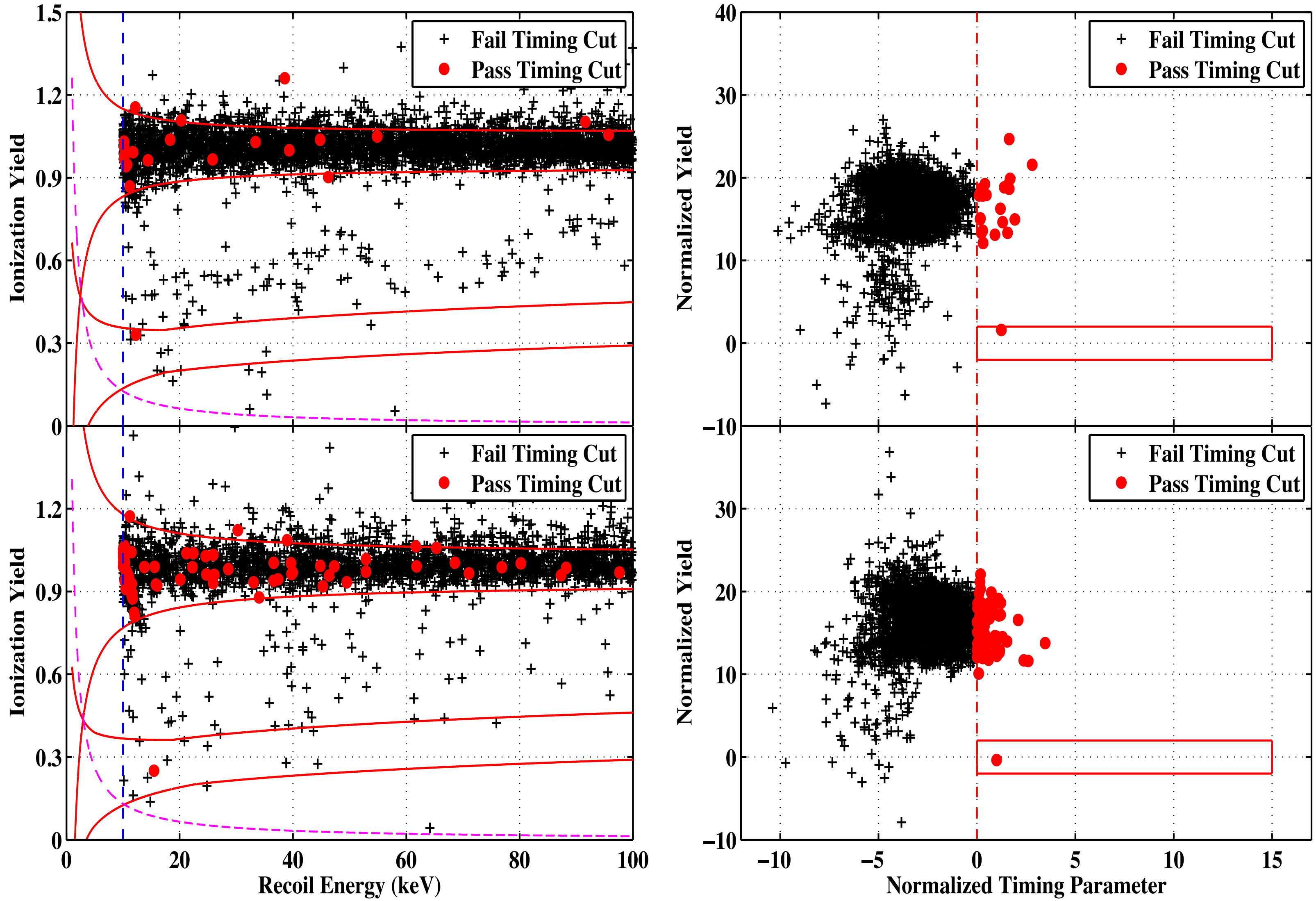
  $$7.0 \times 10^{-44}\ \mathrm{cm}^2$$

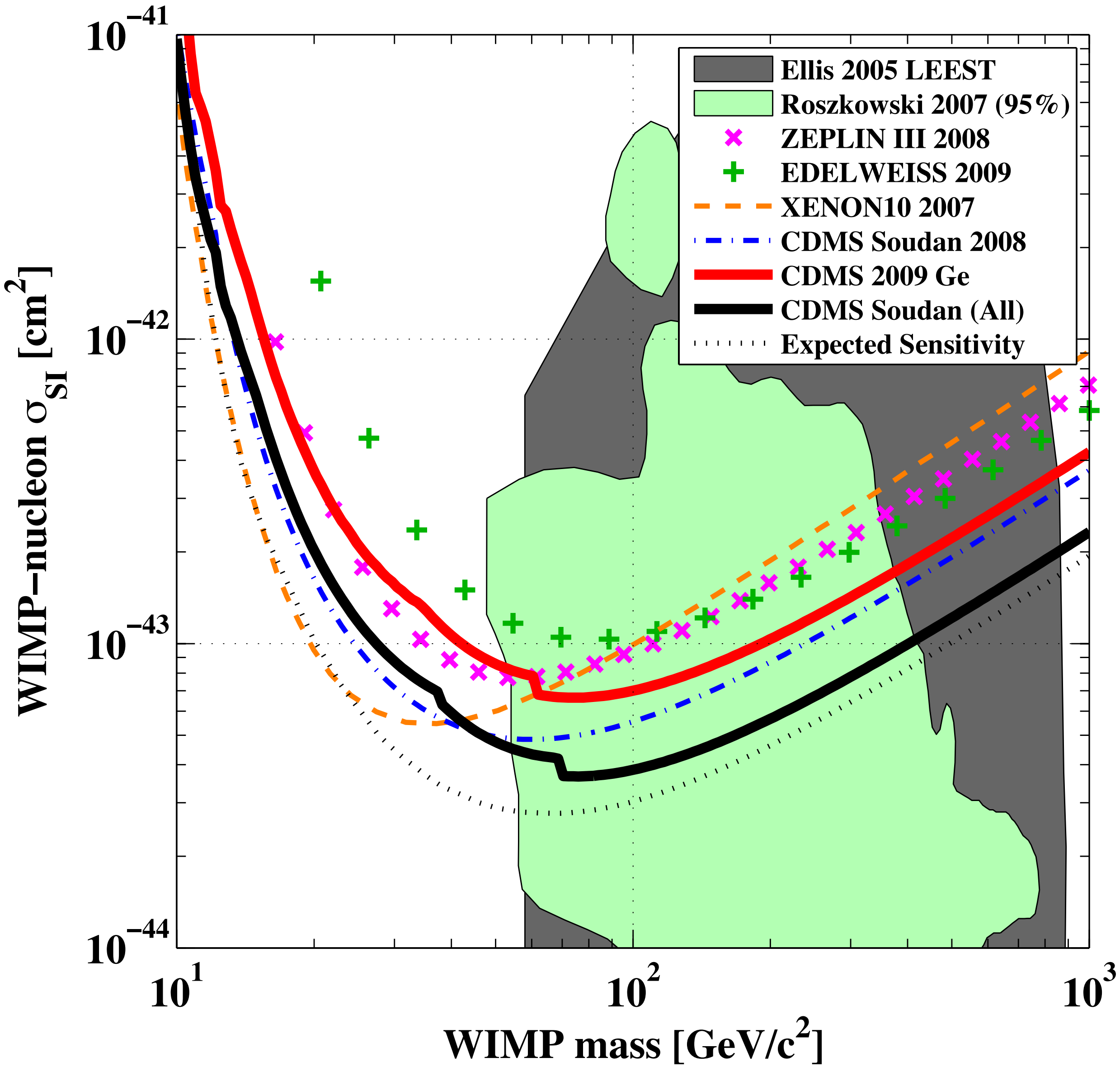
  and combined with previous results

  $$3.8 \times 10^{-44}\ \mathrm{cm}^2$$

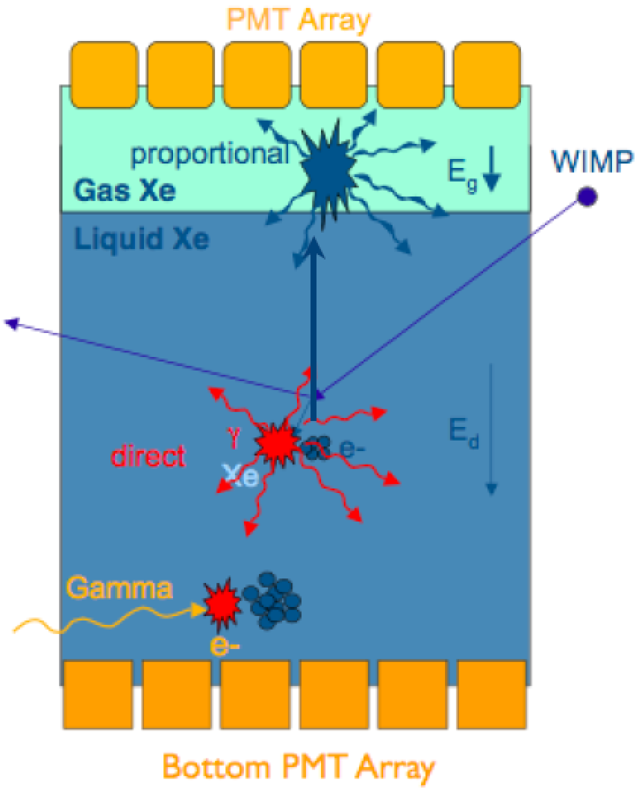
  for a WIMP of mass 70 GeV.
- If the 2 events are real signal, the $\sigma_{\chi N}^{\mathrm{SI}} \sim 10^{-44}\ \mathrm{cm}^2$.

CDMS (0912.3592)

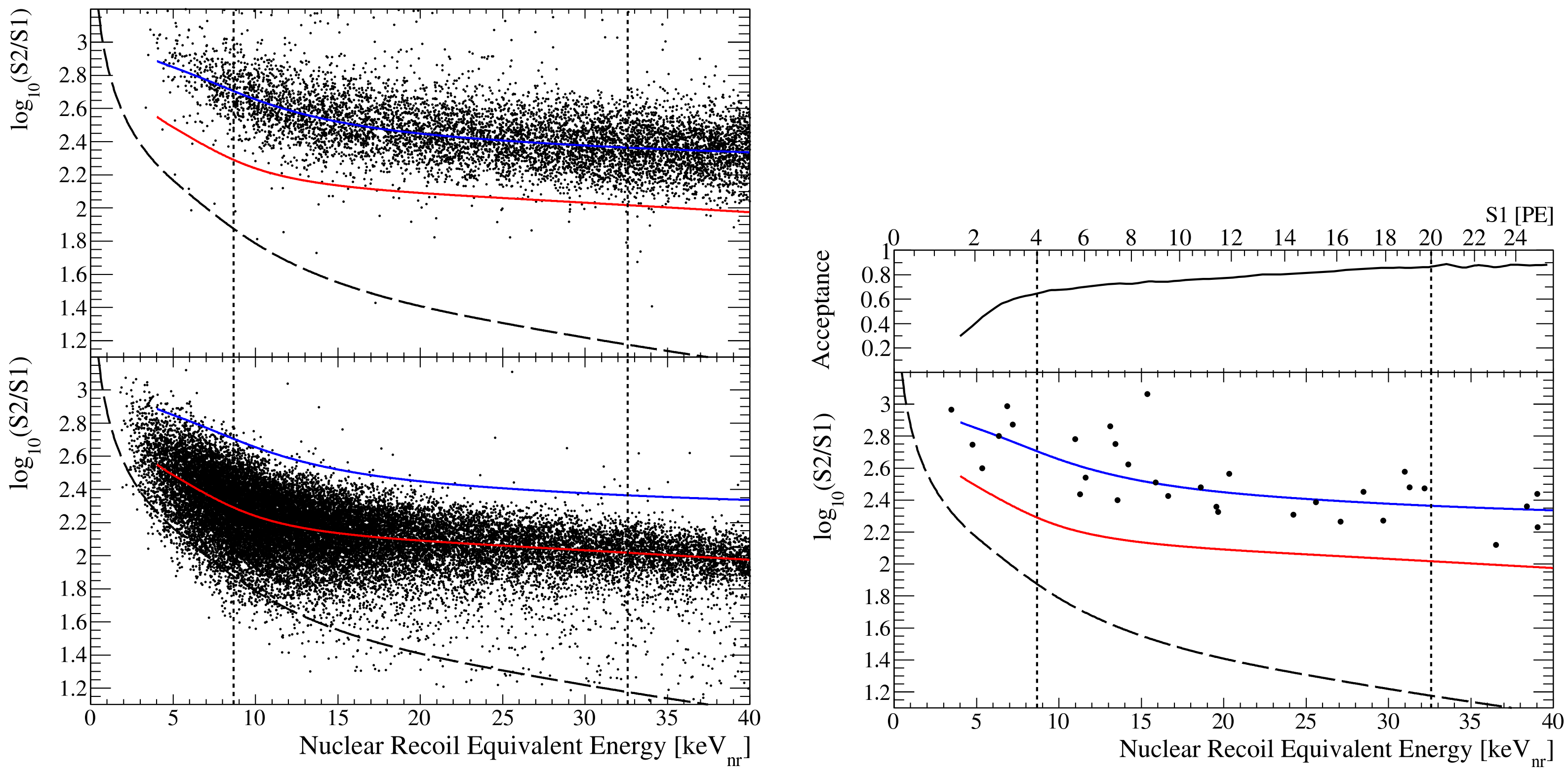



Ellis 2005 LEEST
Roszkowski 2007 (95%)
ZEPLIN III 2008
EDELWEISS 2009
XENON10 2007
CDMS Soudan 2008
CDMS 2009 Ge
CDMS Soudan (All)
Expected Sensitivity
WIMP-nucleon σ_SI [cm^2]
WIMP mass [GeV/c^2]
10^-41
10^-42
10^-43
10^-44
10^1
10^2
10^3

Xenon 100 (1005.0380)

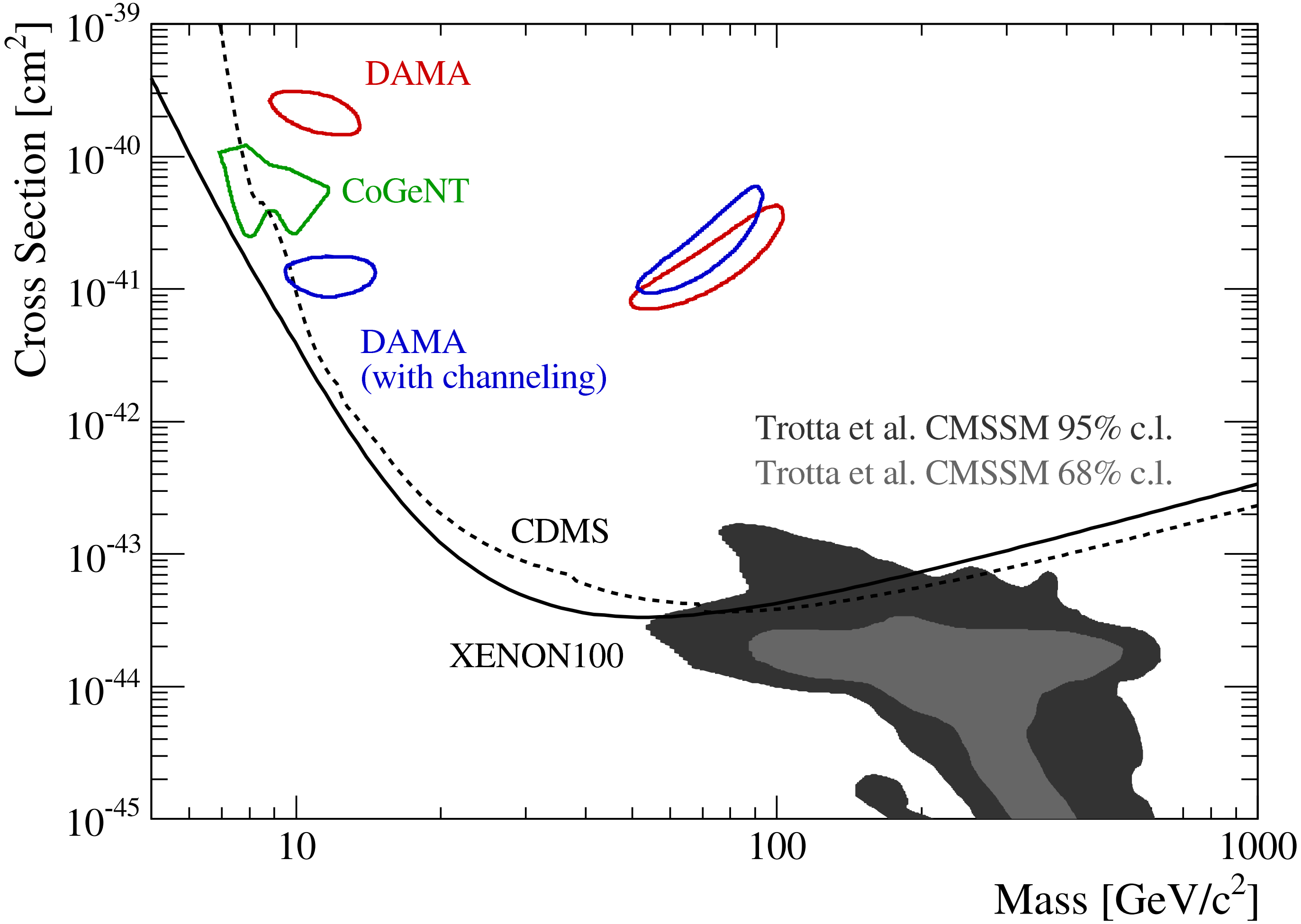


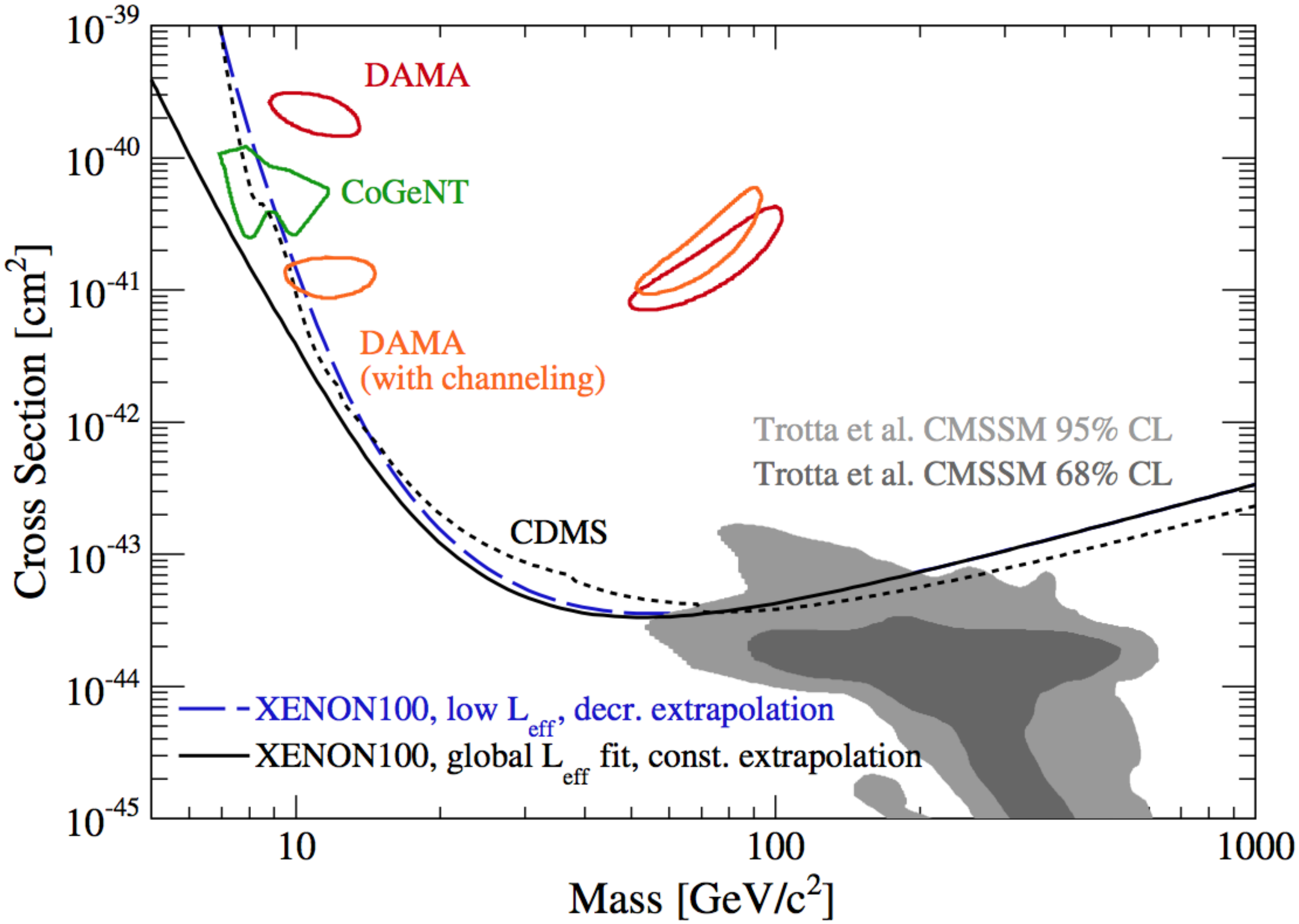
Two arrays of photomulipliers (PMT) below and above the field are used to detect both, the direct scintillation light (S1) in the liquid Xe and ionization, via proportional scintillation in the Xe gas phase (S2).



blue: median of electronic band

red: median of nuclear band


Cross Section [cm^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
DAMA
CoGeNT
DAMA
(with channeling)
Trotta et al. CMSSM 95% c.l.
Trotta et al. CMSSM 68% c.l.
CDMS
XENON100
10
100
1000
Mass [GeV/c^2]

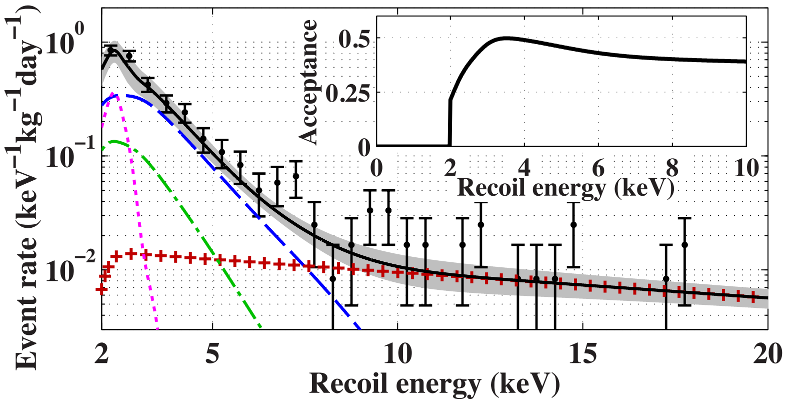

DAMA
CoGeNT
DAMA
(with channeling)
Trotta et al. CMSSM 95% CL
Trotta et al. CMSSM 68% CL
CDMS
XENON100, low L_eff, decr. extrapolation
XENON100, global L_eff fit, const. extrapolation
Cross Section [cm^2]
Mass [GeV/c^2]
10^-39
10^-40
10^-41
10^-42
10^-43
10^-44
10^-45
10
100
1000

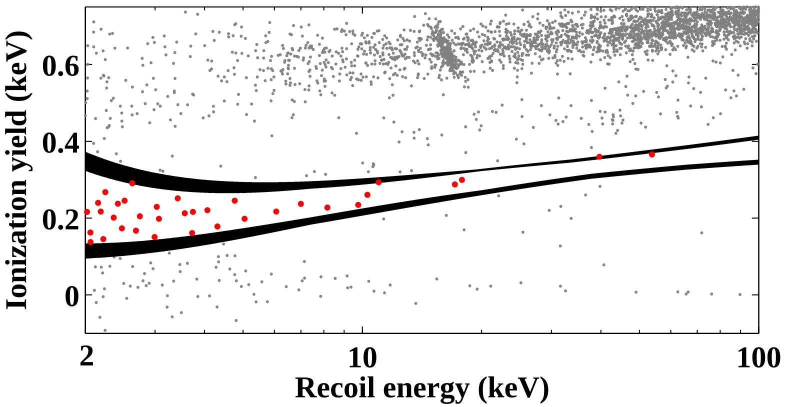
The 2010 year-end CDMS II Results

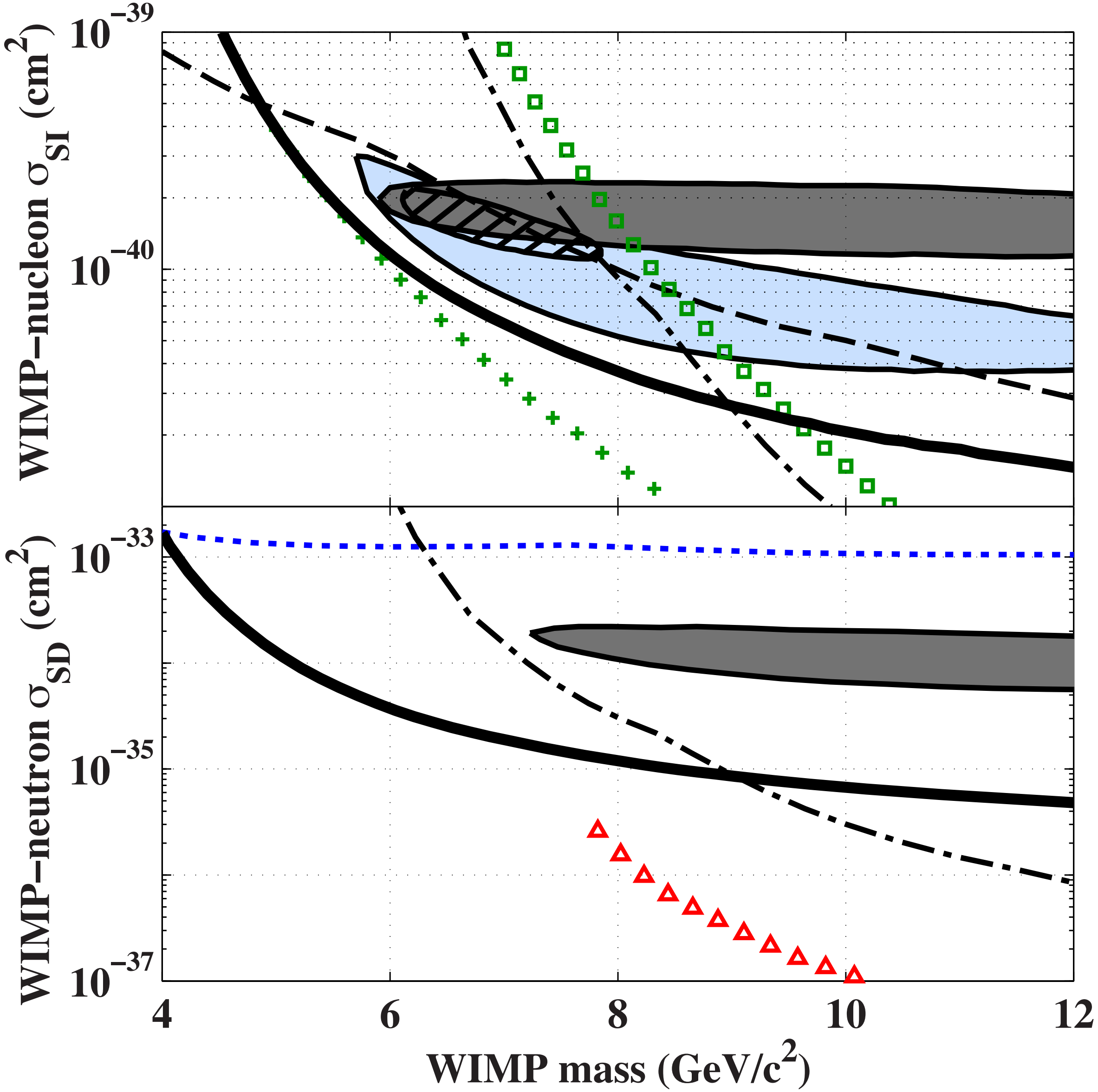
CDMS (1011.2482)

- Focus on low mass region, motivated by DAMA/LIBRA and CoGeNT positive results (WIMP mass < 10 GeV and $\sigma^{SI} \sim 10^{-40}$ cm^2.)
- Reanalyze data taken between Oct 2006 and Sept 2008 using eight Ge detectors with a lowered, 2 keV recoil-energy threshold. It can bring more sensitivity to WIMP below 10 GeV.
- Typically, the nuclear-recoiled events have lower ionization yield than electron-recoiled ones. But some near-surface events or "zero-charge" events can have rather low ionization yield.
- Candidate events are consistent with the electron-recoil background. See the figure. However, since the background model involves sufficient extrapolation that the systematic errors are difficult to quantify, they did not subtract this background but instead set

upper limits on the allowed WIMP-nucleon cross section by assuming all observed events could be from WIMPs.







WIMP–nucleon σSI (cm2)
WIMP–neutron σSD (cm2)
WIMP mass (GeV/c2)

Implications to $h - \chi\chi$ coupling and Higgs invisible width

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The spin-independent (SI) cross section between DM particle and nucleon is

$$\sigma^{\rm SI}_{\chi N} = \frac{\mu^2_{\chi N}}{\pi} \left| G^N_s \right|^2 ,$$

where $\mu_{\chi N} \simeq m_p$ and

$$G^N_s = \sum_{q=u,d,s,c,b,t} \langle N | \bar{q} q | N \rangle \left(\frac{1}{2} \sum_q \frac{g_{L\tilde{q}q} g_{R\tilde{q}q}}{m^2_{\tilde{q}}} - \frac{g_{h\chi\chi} g_{hqq}}{m^2_h} - \frac{g_{H\chi\chi} g_{Hqq}}{m^2_H} \right)$$

- In general the squarks are heavy and contributions ignored. The light Higgs is SM-like.
- We also assume the heavy Higgs contribution is small compared with the light Higgs in normal parameter space region.

- The matrix element

$$\langle N|\bar{q}q|N\rangle = f^T_{Tq} m_N/m_q$$

with typical values

$$f^p_{Tu} = 0.023,\quad f^p_{Td} = 0.034,\quad f^p_{Ts} = 0.14,\quad f^p_{Tc} = f^p_{Tb} = f^p_{Tt} = \frac{2}{27} f^p_{Tg} = 0.0595\ ,$$

$$f^n_{Tu} = 0.019,\quad f^n_{Td} = 0.041,\quad f^n_{Ts} = 0.14,\quad f^n_{Tc} = f^n_{Tb} = f^n_{Tt} = \frac{2}{27} f^n_{Tg} = 0.0592$$

- The Yukawa coupling for a SM-like Higgs boson:

$$g_{hqq} = \frac{g m_q}{2M_W}$$

The factor m_q cancels the factor of m_q in the matrix element.

- Taking the average between proton and neutron:

$$-G^N_s \simeq g_{h\chi\chi} \frac{g m_p}{2m_W} \frac{1}{m_h^2} (0.3766)\ .$$

- The SI cross section per nucleon is

$$\sigma^{\rm SI}_{\chi N} \approx \frac{g^2 m_p^4}{4\pi m_W^2} \frac{1}{m_h^4}\, g^2_{h\chi\chi} (0.3766)^2\ .$$

Implications on $g_{h\chi\chi}$

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- Taking the upper limit

$$\sigma^{\rm SI}_{\chi N} < 3.8 \times 10^{-44}\ {\rm cm}^2$$

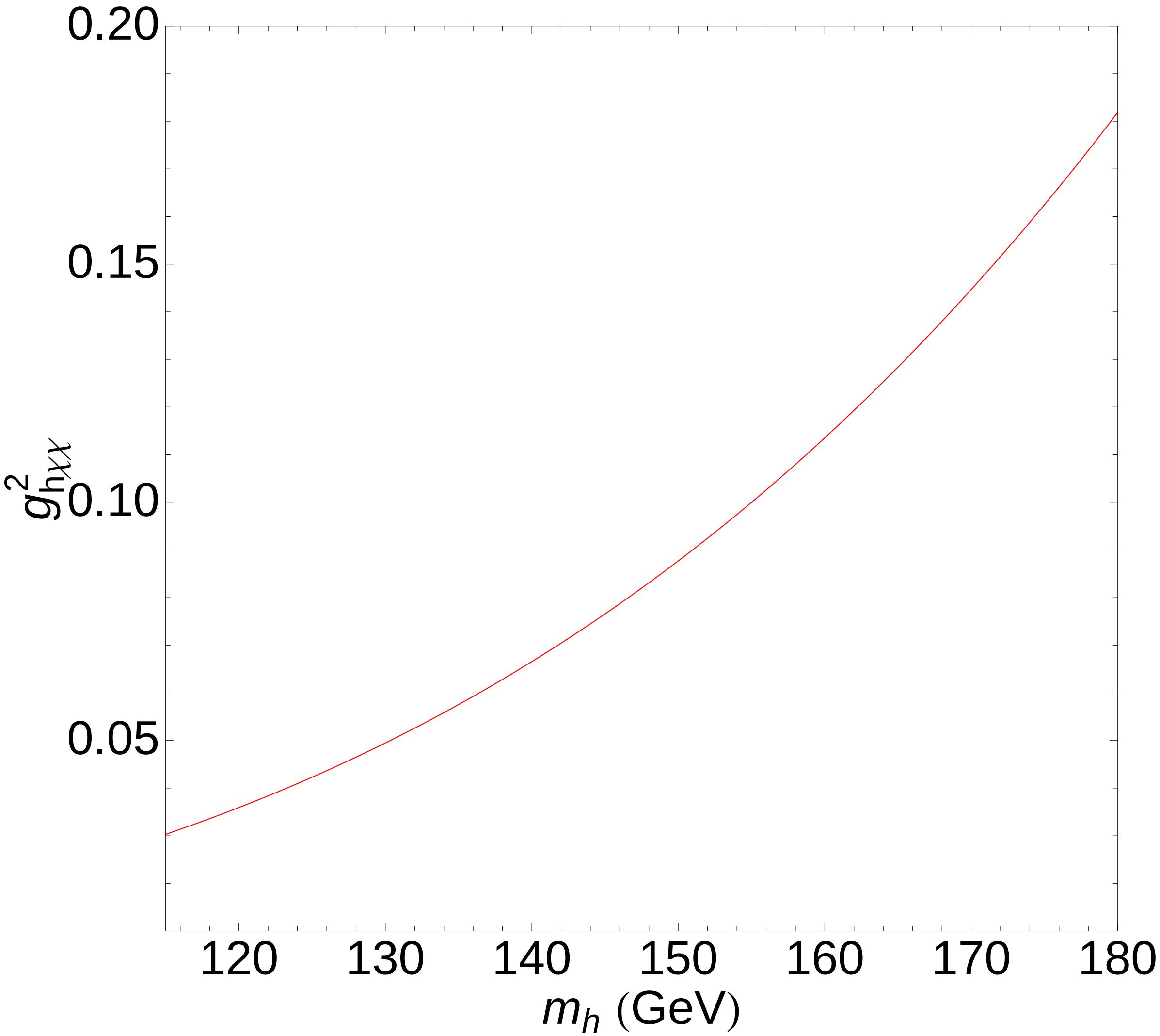
  The corresponding cross section for 2-event signal is

$$O(10^{-44}\ {\rm cm}^2)$$

- In most SUSY models $m_h = 115 - 180$ GeV, (Split-SUSY can give a large m_h), we obtain

$$g^2_{h\chi\chi} \lesssim 0.03 - 0.18$$

- In CDMS figure, the upper limits on $\sigma^{\rm SI}_{\chi N}$ around 100 GeV are all around $3.8 - 5 \times 10^{-44}$ cm^2. So the lower limits on $g^2_{h\chi\chi}$ are about the same.


0.20
0.15
0.10
0.05
$g^2_{h\chi\chi}$
120
130
140
150
160
170
180
m_h (GeV)

Implications on Invisible Higgs decay

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- If the Higgs boson is heavy enough, say 150 – 180 GeV and the neutralino is less than 75 GeV, then the Higgs boson can decay into a pair of neutralinos.
- Decay width of $h \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$

$$\Gamma_{\rm inv} = \frac{g_{h\chi\chi}^2 m_h}{16\pi} \left(1 - \frac{4m_\chi^2}{m_h^2} \right)^{3/2} \quad ,$$

- Numerically, for $m_h \approx 180$ GeV

$$\Gamma_{\rm inv} < 20 - 120 \text{ MeV} \; .$$

- If the 2-event signal cross section give $\sigma_{\chi N}^{\rm SI} \simeq 10^{-44}$ cm^2, the implied invisible Higgs decay width is

$$\Gamma_{\rm inv} < 10 - 50 \text{ MeV} \; .$$

Effects on Higgs boson search

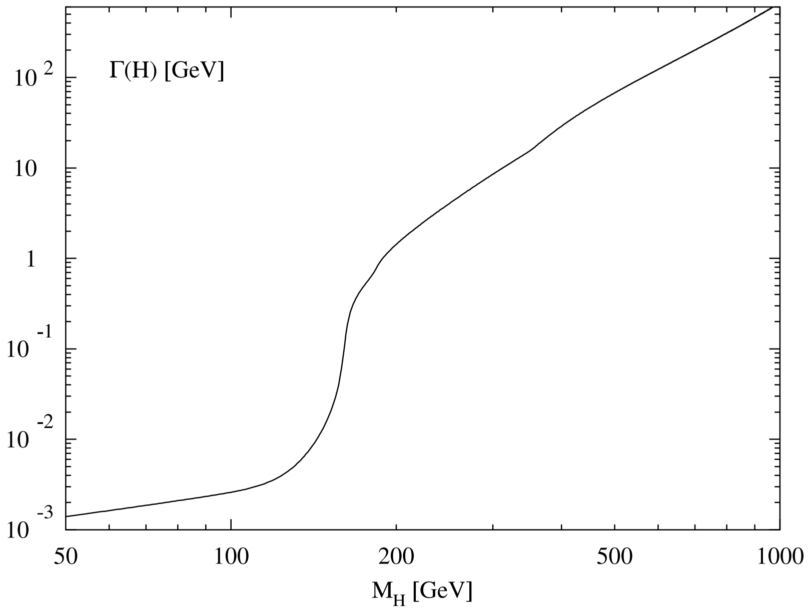
- The LSP is probably the light SUSY particle that the Higgs boson can decay into.
- The dominant modes for an intermediate-mass SM-like Higgs boson are $b\bar{b}$ and WW^*.
- The discovery modes are

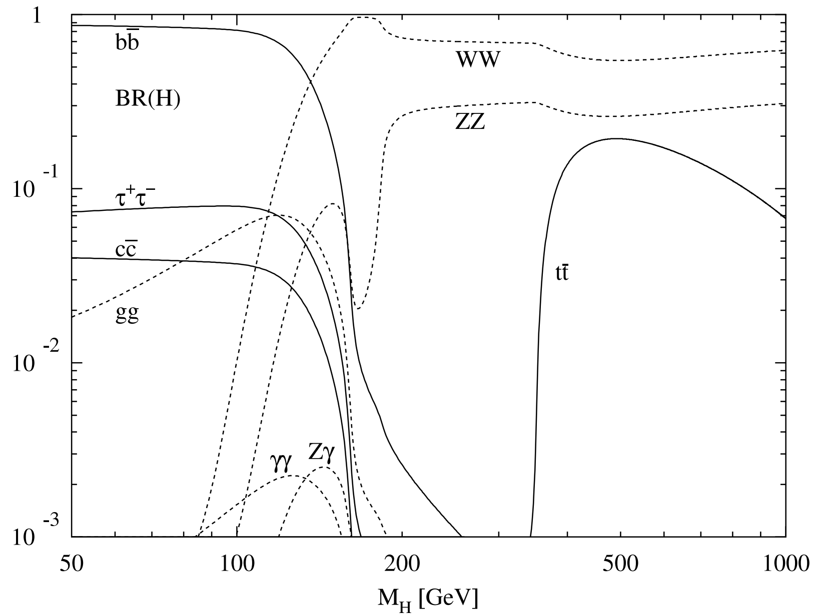
$$gg \to h \to \gamma\gamma$$

$$q\bar{q}' \to Wh \to (\ell\nu)\, b\bar{b}$$

- If the 2 events are signals of WIMP, the implied Higgs invisible width is of order $O(10-50)$ MeV.
- The total width of the SM-like Higgs boson is just a few MeV at 120 GeV, and quickly rises to 1 GeV at 180 GeV.

- The effect of the new invisible width is significant at lower mass range, say below 140–150 GeV, where the WW^* mode is not important.
- The search at the LHC for $m_h \approx 120 - 130$ GeV depends on $\gamma\gamma$ ($BR \sim 10^{-3}$). The invisible mode would largely dilute the branching ratio into $\gamma\gamma$.
- The search using $Wh \to (\ell\nu)b\bar{b}$ would also be affected because the $BR(h \to b\bar{b})$ also decreases with the invisible width.
- The search for heavier Higgs $m_h > 140$ GeV is less affected because of the opening of the WW^* mode.
- One can, on the other hand, search for the invisible mode of the Higgs boson, using say $Zh \to (\ell^+\ell^-)\chi\chi$.


Γ(H) [GeV]
10 2
10
1
10 -1
10 -2
10 -3
50
100
200
500
1000
M_H [GeV]


bb̄
BR(H)
τ+τ−
cc̄
gg
WW
ZZ
tt̄
γγ
Zγ
1
10 -1
10 -2
10 -3
50
100
200
500
1000
M_H [GeV]

Hdecay

Invisible Higgs search at the LHC

- Through the WW fusion: $qq \to q'q'W^*W^* \to q'q'h$. Two energetic forward jets with large invariant mass and with large PT-missing (Eboli, Zeppenfeld hep-ph/0009158).
- Associated production with a Z boson: $pp \to Zh$. But we cannot use the kinematics of the Z boson to get the recoil mass.
- Association production with a pair of heavy quarks: $pp \to t\bar{t}h$.
- Decay of heavier particles into the Higgs boson needs details of the model.

Conclusions

- The CDMS 2 events may just be background fluctuations. If not it is the first time that a concrete signal is detected on Earth.
- The implied signal cross section is $O(10^{-44})$ cm^2.
- The Higgs boson invisible width can be substantial given the CDMS result. It affects the standard search at low intermediate mass range.
- Search for an invisible Higgs at the LHC is challenging, but not impossible.
- Axion, gravitino, and any other Super-WIMP dark matter candidates are ruled out.