Some aspects on the Dark matter direct detection

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Outline

- Basics
- Recent experiment results
- Theoretical explanations

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Direct Detection

DM-quark interaction

↓ form factor

DM-nucleon interaction

↓ form factor

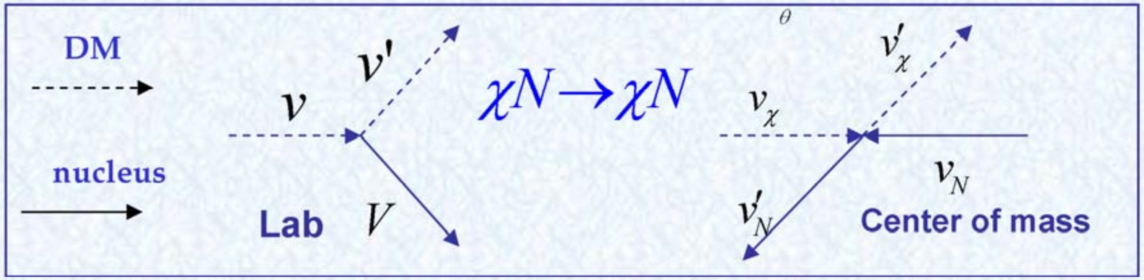
DM-nucleus interaction

↓ astrophysics factor

Nucleus recoil

↓ detector effect

Detectable events: phonon, ionization , scintillation



- Detect nucleus recoil signal induced by dark matter at underground detector
- If the DM mass is taken as O(100)GeV, typical recoil energy is O(10keV)
- The interaction may be spin independent or dependent, elastic or inelastic …
- Possible modulation signal due to the emotion of the earth in the Solar system.
- Possible to reconstruct the DM mass and the velocity distribution with large statistic.

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From quark to nucleon

scalar interaction

$$B_q \equiv \langle N | \bar{\psi}_q \psi_q | N \rangle = f_q^N m_N / m_q$$

$$f_N = \sum_{q=1-6} B_q f_q$$ **sum all the contributions**

$$f_Q^N = \frac{2}{27}(1 - \sum_{q=1-3} f_q^N)$$ **heavy quark contribution**

$$f_d^p = \frac{2\sigma_{\pi N}}{(1+m_u/m_d)m_p(1+a)} \qquad f_u^p = \frac{m_u}{m_d} a f_d^p \qquad f_s^p = \frac{\sigma_{\pi N} - \sigma_0}{(1+m_u/m_d)m_p} \frac{m_s}{m_d}$$

Uncertainties !

axial vector interaction

$$\Delta q^N = \langle N | \bar{\psi}_q \gamma^\mu \gamma^5 \psi_q | N \rangle / 2 s_N$$

$$\xi_N = \sum_{q=1,2,3} \Delta q^N \xi_q$$

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From nucleon to nucleus

- **non-relativistic limit**

$$u(p) \to \sqrt{E}\begin{pmatrix}\xi \\ \xi\end{pmatrix} + \frac{p}{2\sqrt{E}}\begin{pmatrix}-\xi \\ \xi\end{pmatrix} + O(p^2)$$

$$\bar{u}u \approx \bar{u}\gamma^0 u \to E\begin{pmatrix}\xi^+ & \xi^+\end{pmatrix}\begin{pmatrix} & 1 \\ 1 & \end{pmatrix}\begin{pmatrix}\xi \\ \xi\end{pmatrix} \simeq 2m\xi^+\xi = 2m\delta^{ss'} \qquad \bar{u}\gamma^5\gamma^i u \to 4m\xi^+\frac{\sigma_i}{2}\zeta = 4m\langle J_i\rangle^{ss'}$$

- **scalar interaction**

spin independent

$$L_{SI} = \lambda\overline{\Psi}_\chi\Psi_\chi\overline{\Psi}_N\Psi_N \qquad q^2 \to 0, F^2(q) \to 1$$

$$\sigma_0^{SI}F^2(q) = \left(\frac{\mu}{\mu_{\chi p}}\right)^2\left(Z + \frac{f_n}{f_p}(A-Z)\right)^2 \sigma_p^{SI}\ F^2(q)$$

For $f_n \sim f_p$, proportional to A^2

- **axial vector interaction**

spin dependent

$$L_{SD} = \xi\overline{\Psi}_\chi\gamma^5\gamma_\mu\Psi_\chi\overline{\Psi}_N\gamma^5\gamma^\mu\Psi_N$$

$$\sigma_0^{SD}F^2(q) = \frac{4\mu^2\pi}{3\mu_{\chi p}^2 a_p^2(2J_N+1)}\left(a_0^2S_{00}(q) + a_1^2S_{11}(q) + a_0a_1S_{01}(q)\right)\sigma_p^{SD}$$

Nucleus's spin is carried by unpaired nucleon, only nucleus with odd mass number has contribution

COUPP:CF_3I, PICASSO:C_4F_{10}, KIMS:CsI,…

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Event rate

$$\frac{dR}{dE_R} = \frac{1}{m_N}\frac{\rho_\chi}{m_\chi}\int_{v_{\min}}^{v_{\max}} d^3v f(\vec{v}) v \frac{d\sigma(\vec{v}, E_R)}{dE_R}$$

count/kg/day

Astrophysics factor

DM velocity distribution
Maxwell-Boltzmann in the Galaxy

DM local density
0.3~0.4 GeV/cm^3

DM velocity in the solar system
~220km/s~0.001c

Particle Physics factor

DM-nucleus differential cross section
Spin independent or Spin dependent
elastic or inelastic
……

Recoil energy

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Recoil energy

DM kinetic energy

$$E_R = \frac{1}{2} m_\chi v^2 \times \frac{4\mu^2}{m_\chi m_N} \times \frac{1}{2}(1-\cos\theta)$$

Nucleus recoil energy

velocity cut

$$v_{\min} = \sqrt{\frac{2E_{\min}}{m_\chi}} = \sqrt{\frac{E_R m_N}{2\mu^2}}$$

$v_{\max} \sim 544\text{km/s}$ galactic escape velocity

$$\frac{d\sigma}{dE_R} = \frac{m_N \sigma_0}{2\mu^2 v^2} F^2(q)$$

Point like limit, DM-nucleus cross section

form factor

$$\lim_{point\,like} \frac{d\sigma}{d\cos\theta} = cons$$

assumption

mass cut

$$m_N \gg m_\chi \quad \frac{m_\chi^2}{m_N} \rightarrow \frac{1}{1-\cos\theta} \frac{E_R}{v^2} \geq \frac{E_{thresh}}{2v_{\max}^2}$$

$$m_N \ll m_\chi \quad E_R \rightarrow m_N (1-\cos\theta) v^2$$

low sensitivity for very light and heavy DM

$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_\chi}{2m_\chi \mu^2} F^2(q) \int_{v_{\min}}^{v_{\max}} \frac{f(\vec{v})}{v} d^3 v$$

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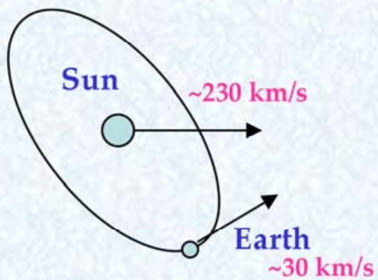
Velocity distribution

- Assume **Maxwell-Boltzmann** distribution for DM in the Galactic reference frame

$$f(v')d^3v' = \left(\frac{3}{2\pi v_0}\right)^{\frac{3}{2}} \exp\left(-\frac{3v'^2}{2v_0^2}\right)d^3v'$$

$$\vec{v}' = \vec{w} + \vec{v}$$

- $\vec{v}'$: DM velocity in the Galaxy
- $\vec{v}$: DM velocity in the Earth
- $\vec{w}$: Earth velocity in the Galaxy, related to earth velocity in the solar system. important for **modulation**



$$\frac{v_c^2}{v_0^2} = \frac{2}{3}$$

- v_c: local circular velocity 220km/s
- v_0: Local DM rms velocity in the Galaxy 270 km/s

assume thermal equilibrium

$$\int_{v_{\min}}^{\infty} \frac{f(\vec{v})}{v} d^3\vec{v} = \frac{1}{2w}\left[erf(x_{\min}+\eta) - erf(x_{\min}-\eta)\right]$$

$$x^2 \equiv v^2 / v_c^2 \qquad \eta^2 \equiv w^2 / v_c^2$$

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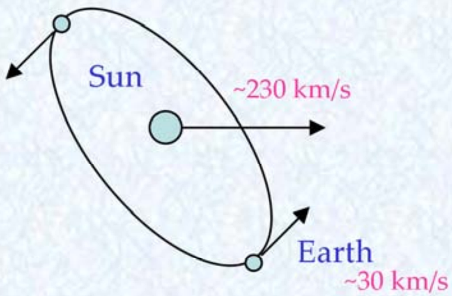
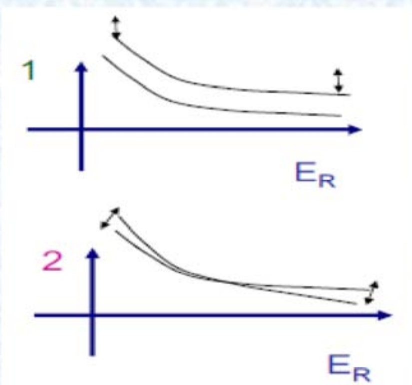
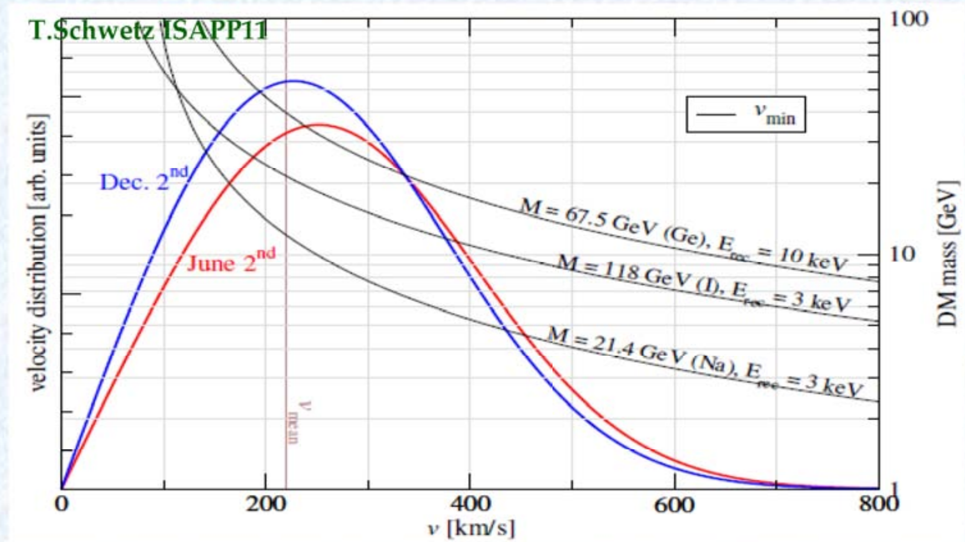
DM annual modulation



Earth velocity in the Galaxy

expected event rate





$$w = \eta v_c \sim (1 + 0.07\cos[2\pi(t - 156)/365]) \times 230$$

$$\frac{dR}{dE} \approx S(t) + \frac{dS(t)}{d\eta}\Delta\eta \approx S_0(E) + S_m(E)\cos\omega(t - t_0)$$

average total rate (S_0) — **modulation amplitude** (S_m)

$$S_m(E) = \frac{1}{E_2 - E_1}\int_{E_1}^{E_2} dE\,\frac{1}{2}\left[\frac{dR}{dE}(June) - \frac{dR}{dE}(Dec)\right]$$

DAMA results $S_m / S_0 \approx 5\%$

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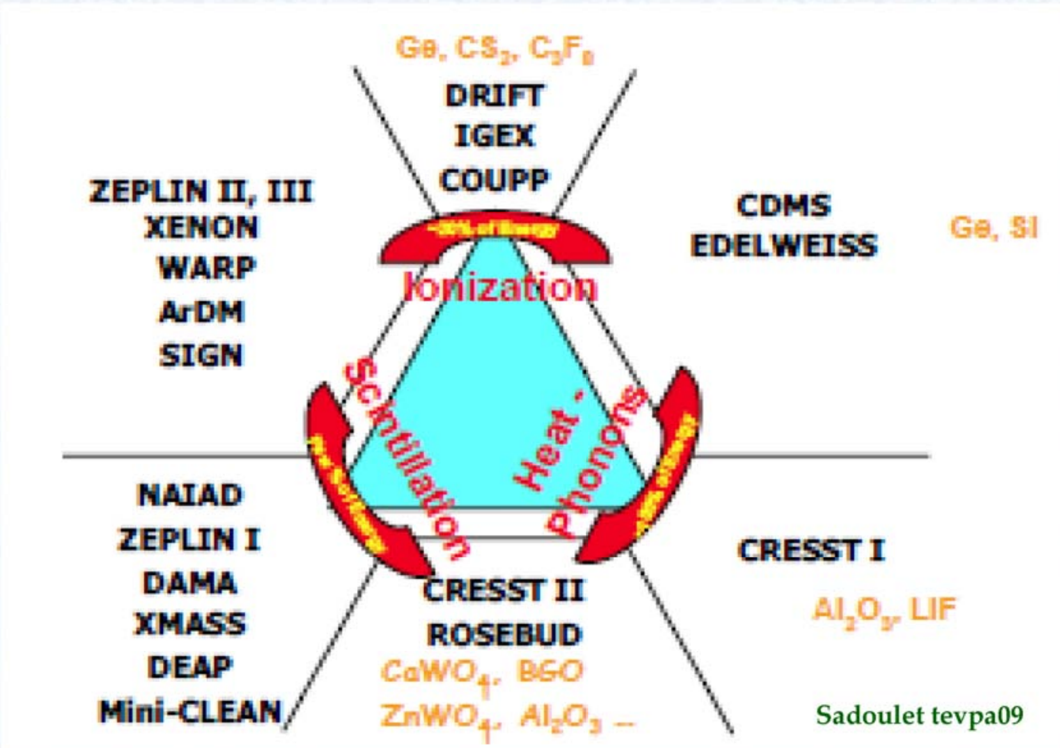
Detector effects



$$R = \int dE\, \varepsilon(QE)\, \Phi(QE) \frac{dR}{dE}$$

Energy response function

selection efficiency

$$Q = E_{\rm det} / E_R$$

quenching factor (keVee/keVnr)

- Underground experiment to shield cosmic rays
- Special shielding from radioactive contaminations

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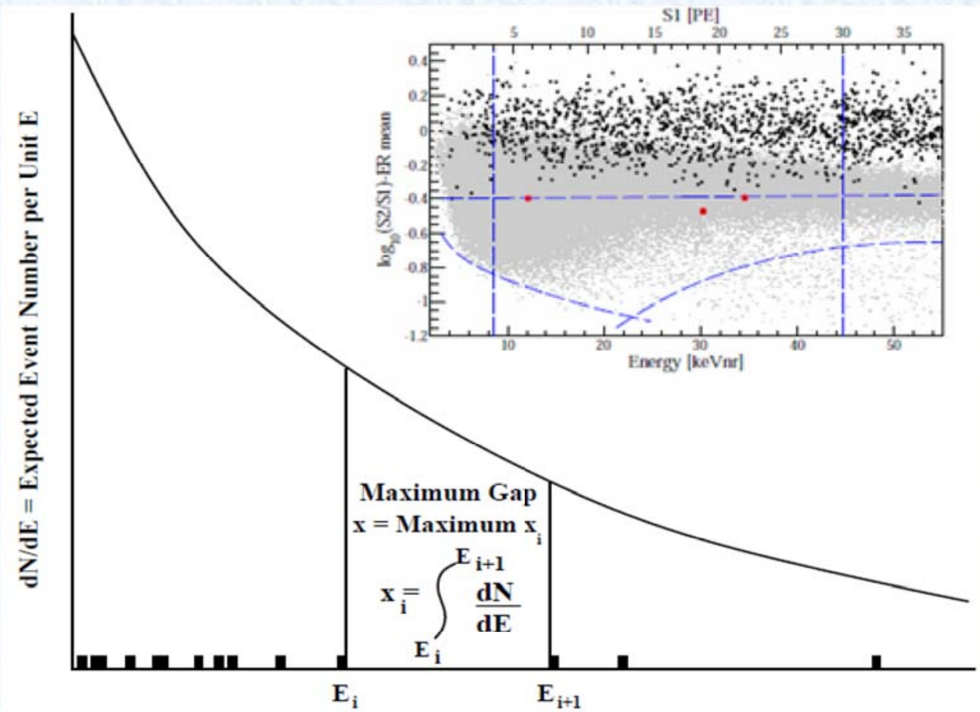
Statistic methods

- If detect signals, just do the χ^2 fit
- If not, set the limits
  - If background is well handled, likelihood method. For simplicity, if we know the total events N_t and background number N_b, we can get the signal number upper-limit $N_s < f(N_t, N_b)$ by using some methods (e.g. Feldman-Cousins, physics/9711021)
  - If not, use so-called "maximum gap" method (Yellin, physics/0203002)



- use the event distribution, find maximum gap
- The probability that the maximum gap being smaller than a given value x and total event number μ

$$C_0(x,\mu) = \sum_{k=0}^{m} \frac{(kx-\mu)^k e^{-kx}}{k!}\left(1 + \frac{k}{\mu - kx}\right)$$

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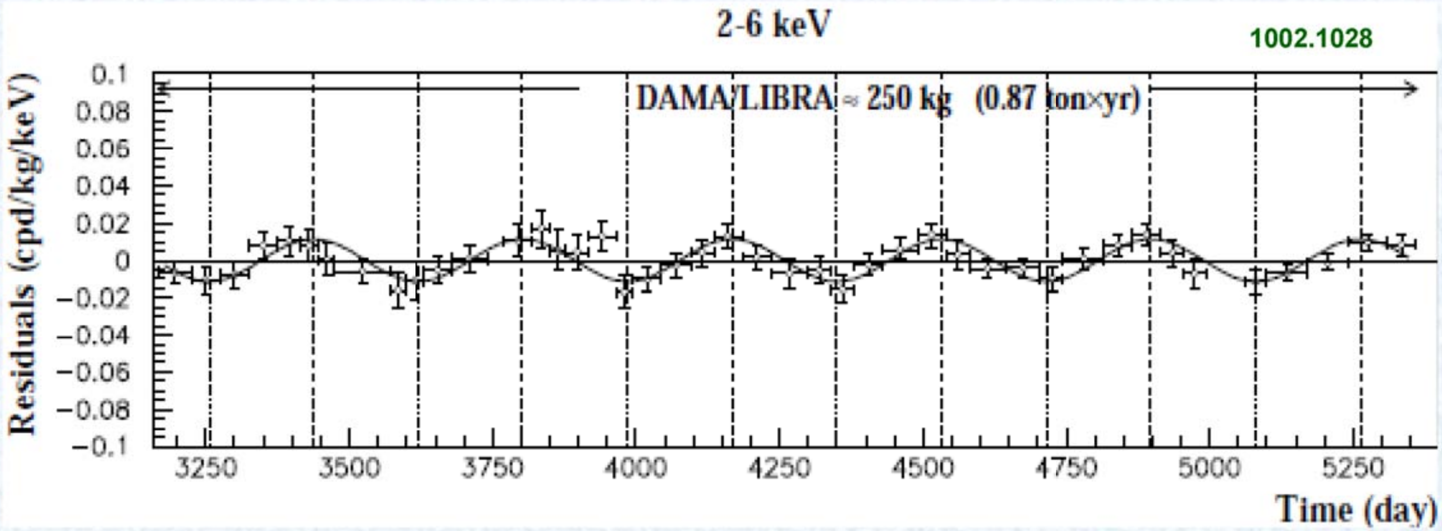
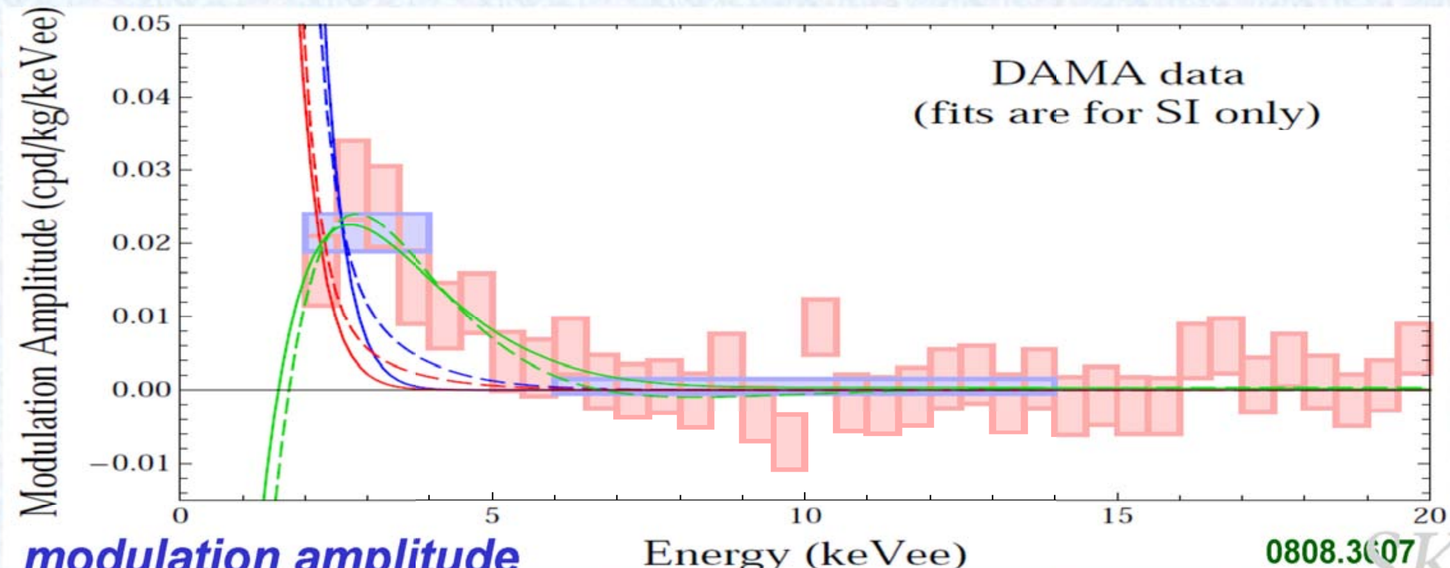
World wide DM direct detection experiments

DAMA modulation





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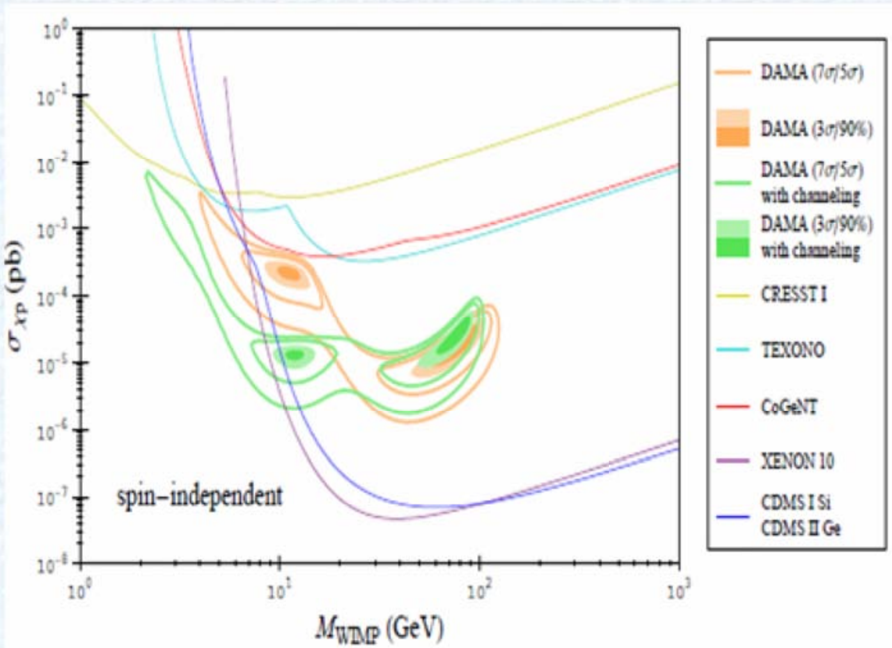
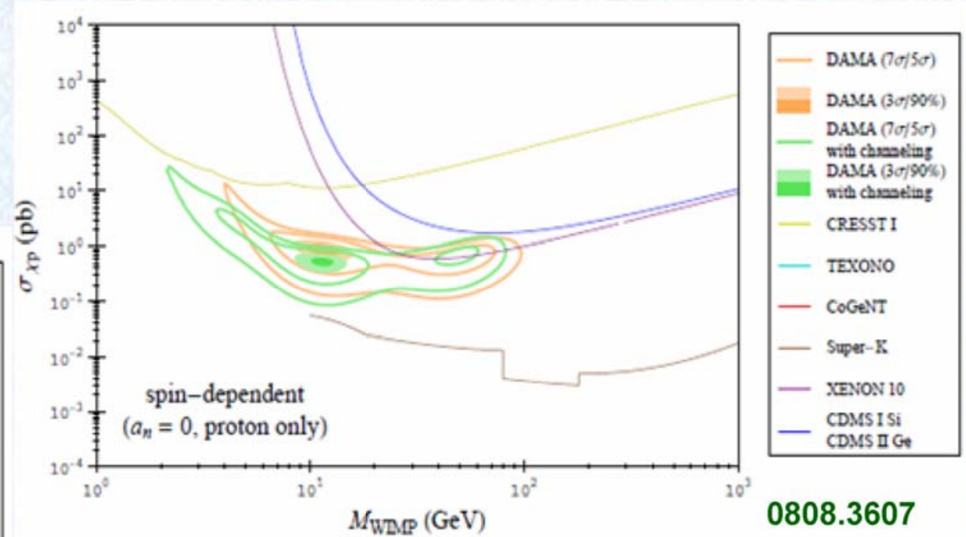
Data fit

- **Typical SI DM:**
  m~10GeV, σ~10^{-4} pb





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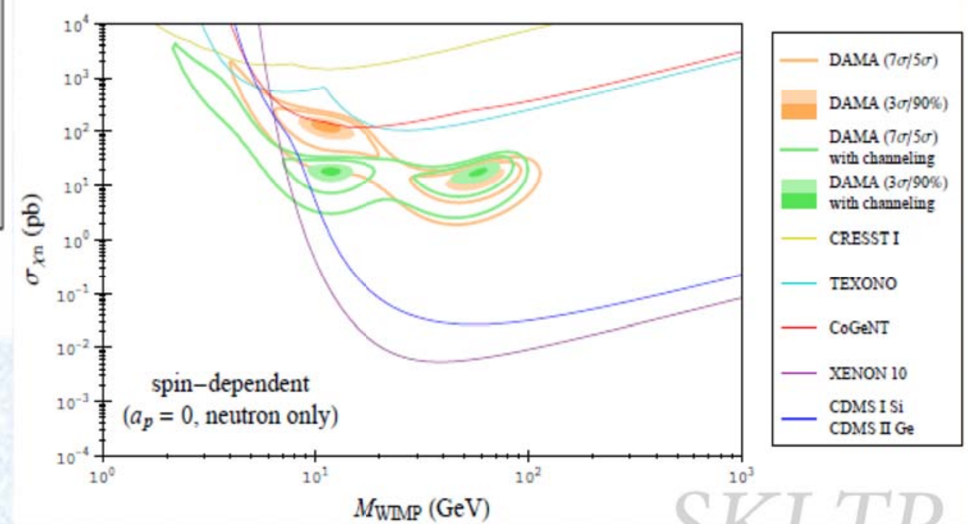

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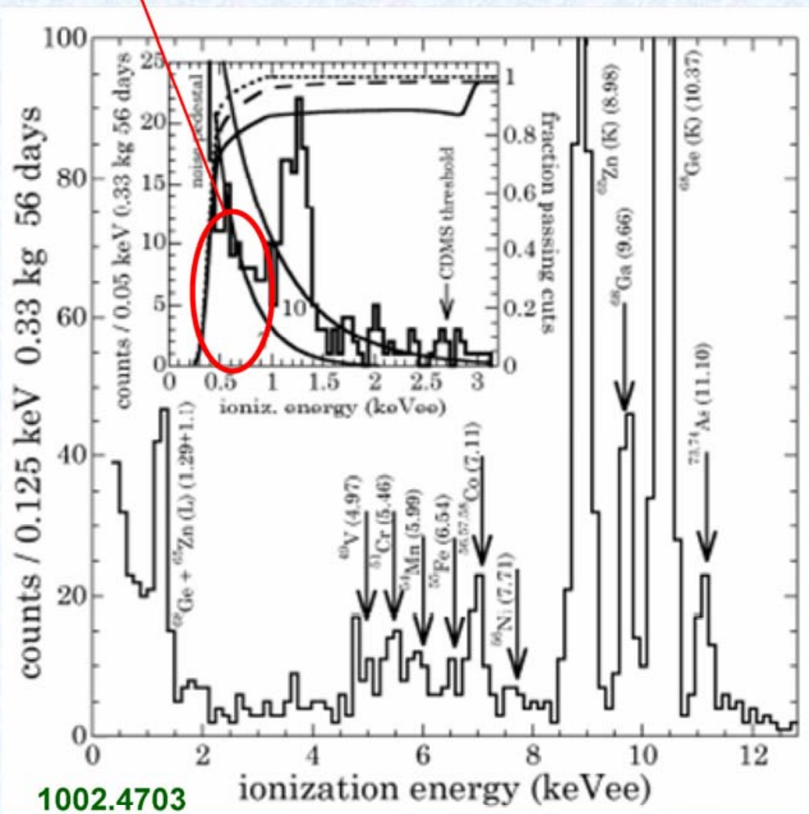
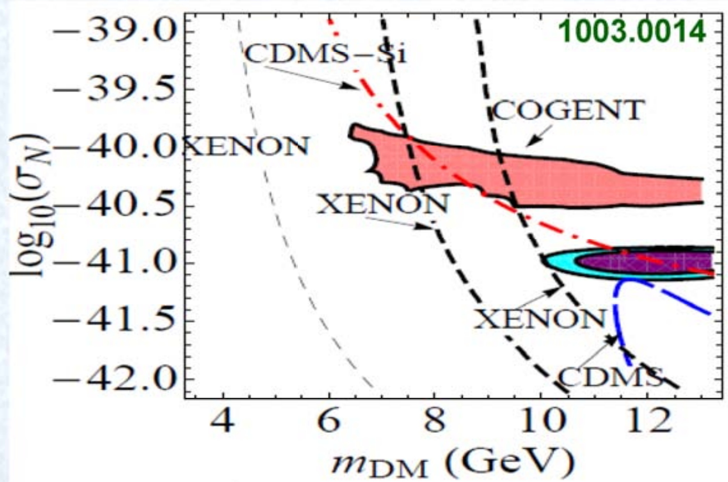
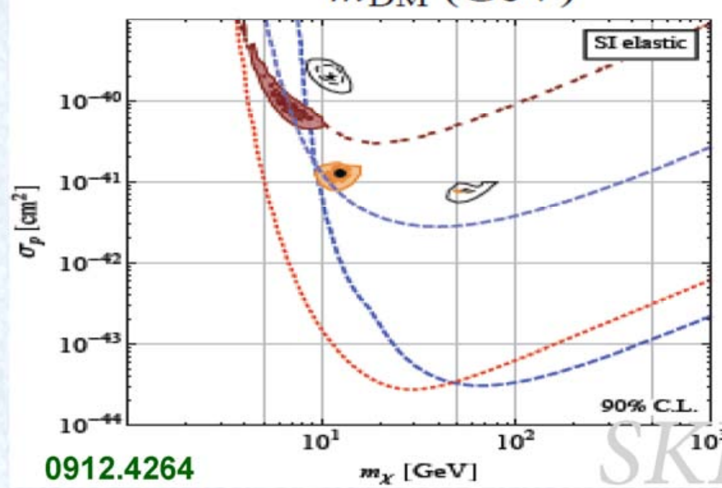
CoGeNT: low energy events

- Germanium detector in the Soudan mine,
  energy threshold~0.4keVee
  ~100 unknown events in the 0.4~3.2keVee (0.33kg, 56days results)







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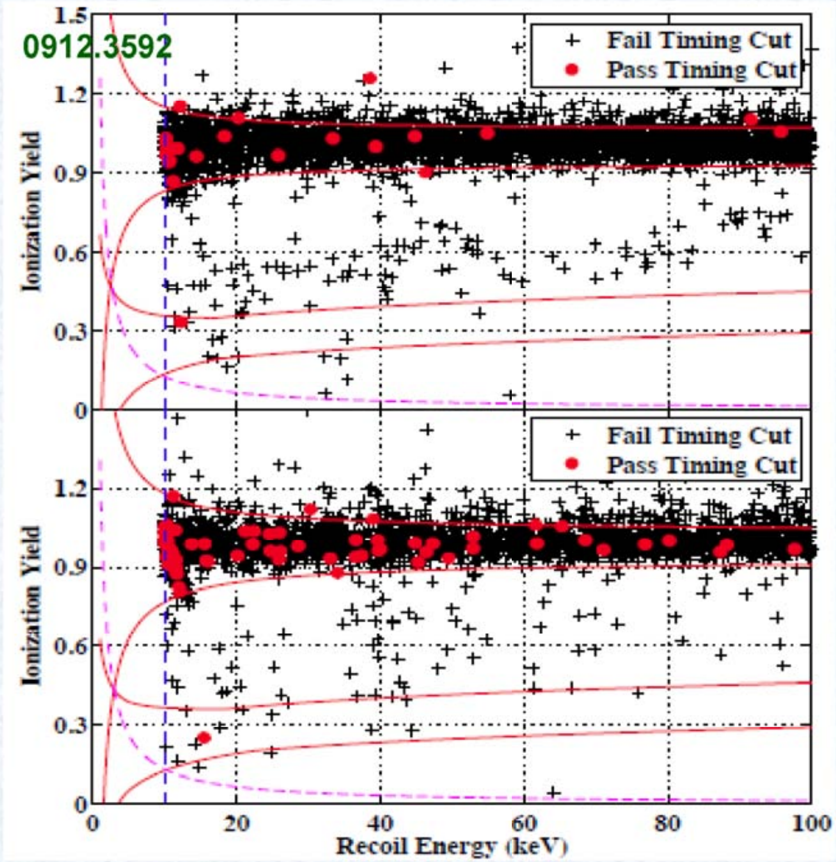
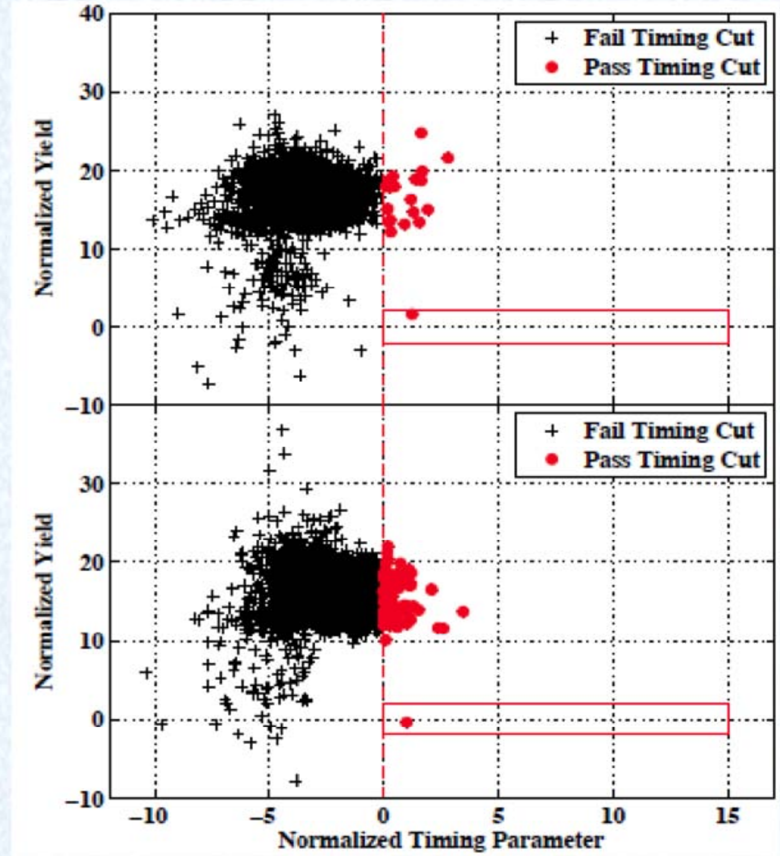
CDMSII: two events





- exposure for 60GeV DM, 612kg-day
- cosmic ray muon induced neutron ~0.04
  material U induced neutron ~0.03-0.06
  misidentified surface events ~0.8

- 12.3keV and 15.5keV
- near the surface-event rejection threshold
- 23% probability to be background

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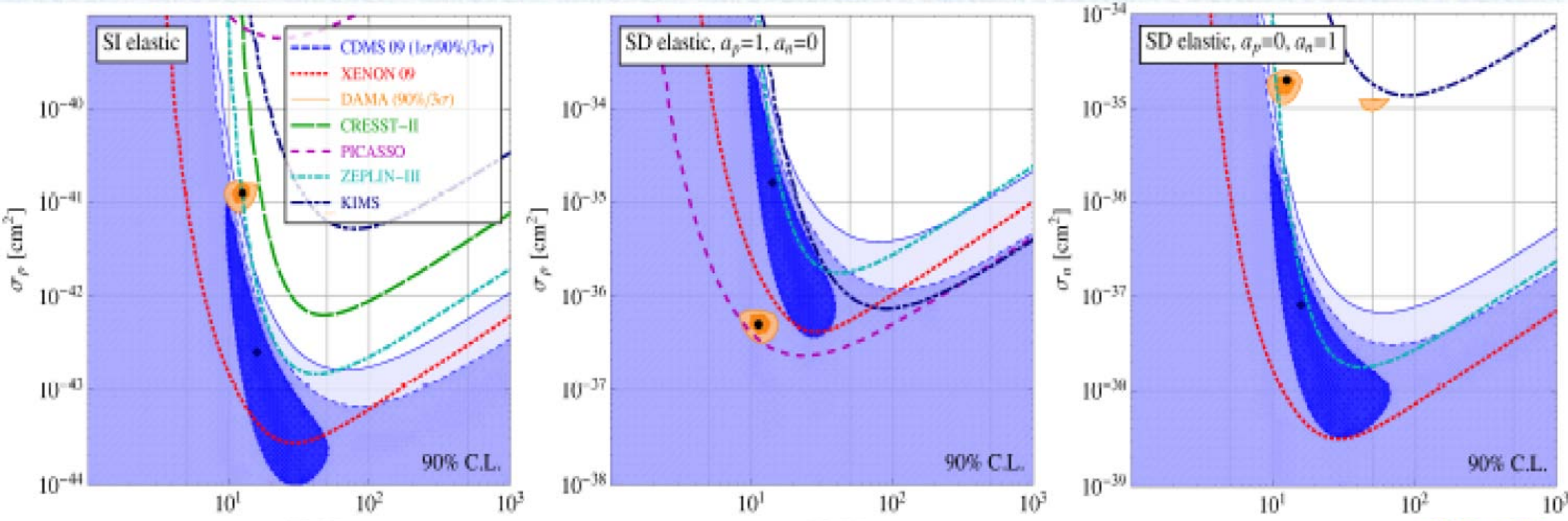
Data fit



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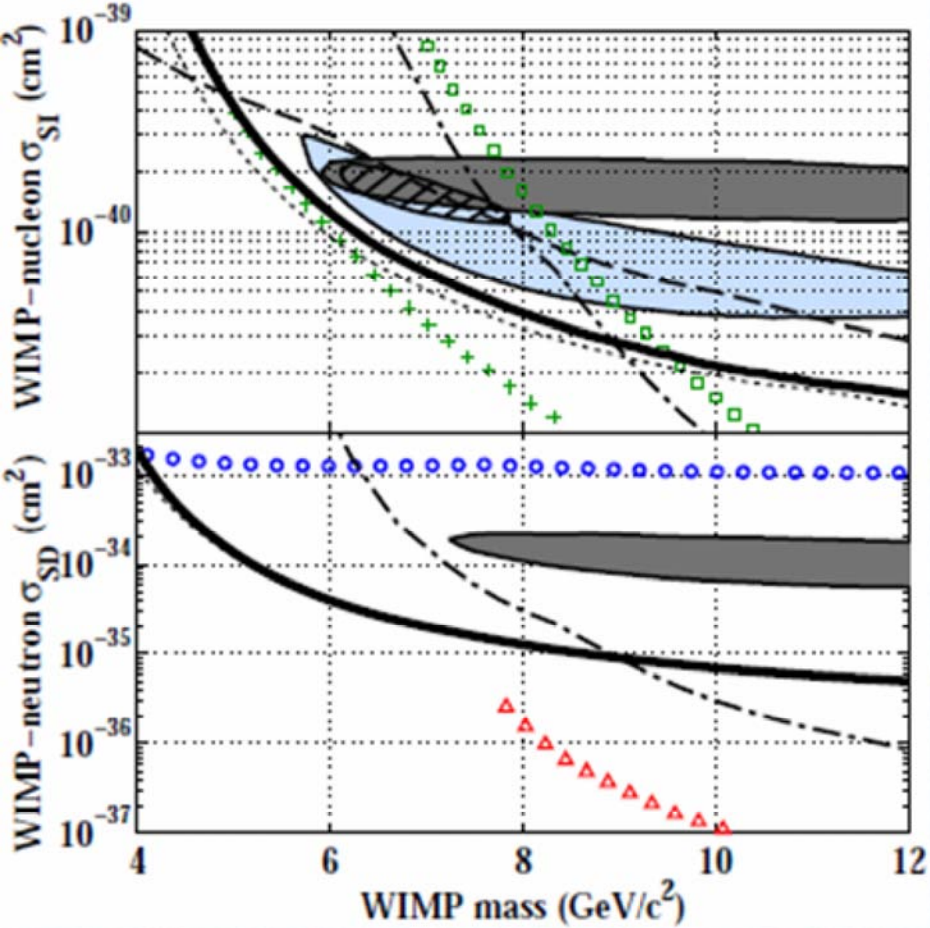
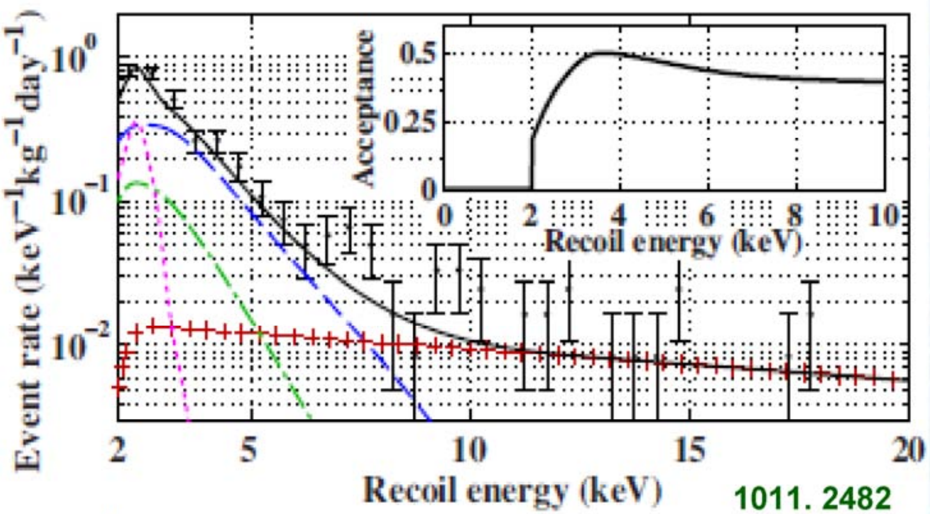
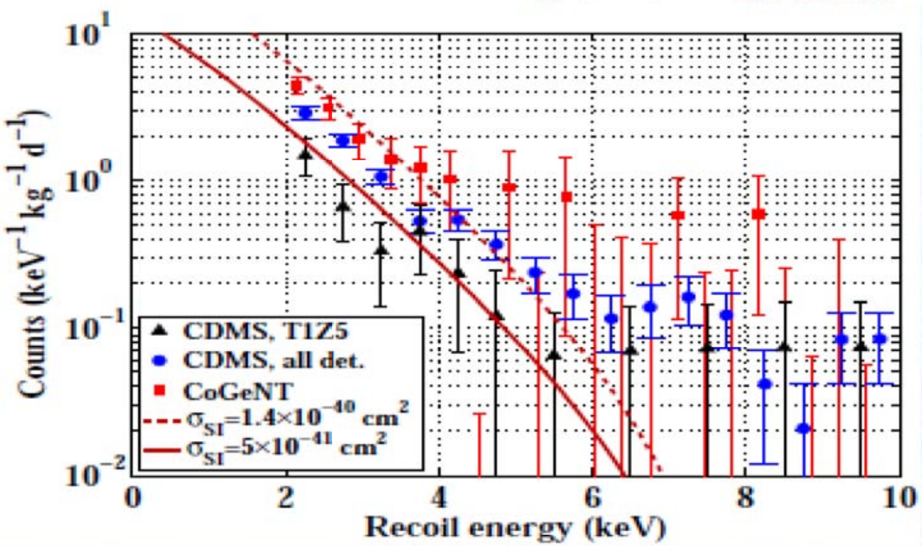
CDMS II : low-threshold





1011. 2482



- Re-analyze previous results of 241 kg day
- Decrease threshold to 2 keVnr

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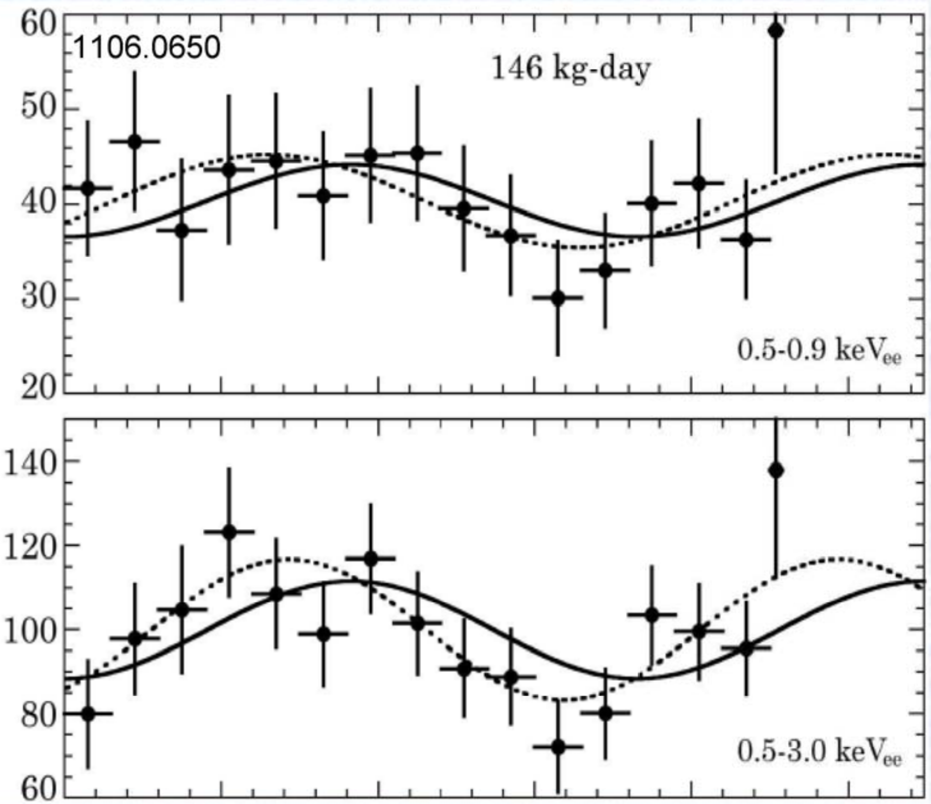
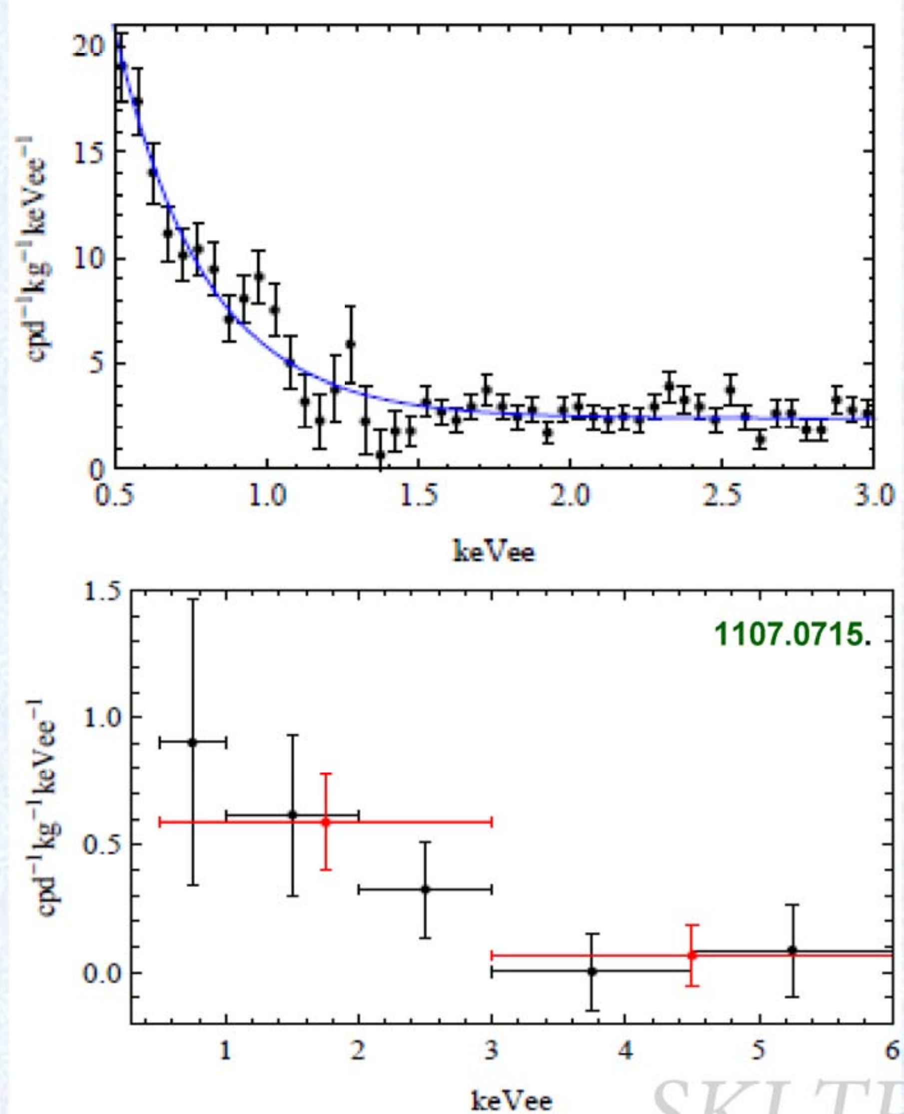
CoGeNT : modulation





- New modulation results in 2011.06
- 0.33kg, 442days

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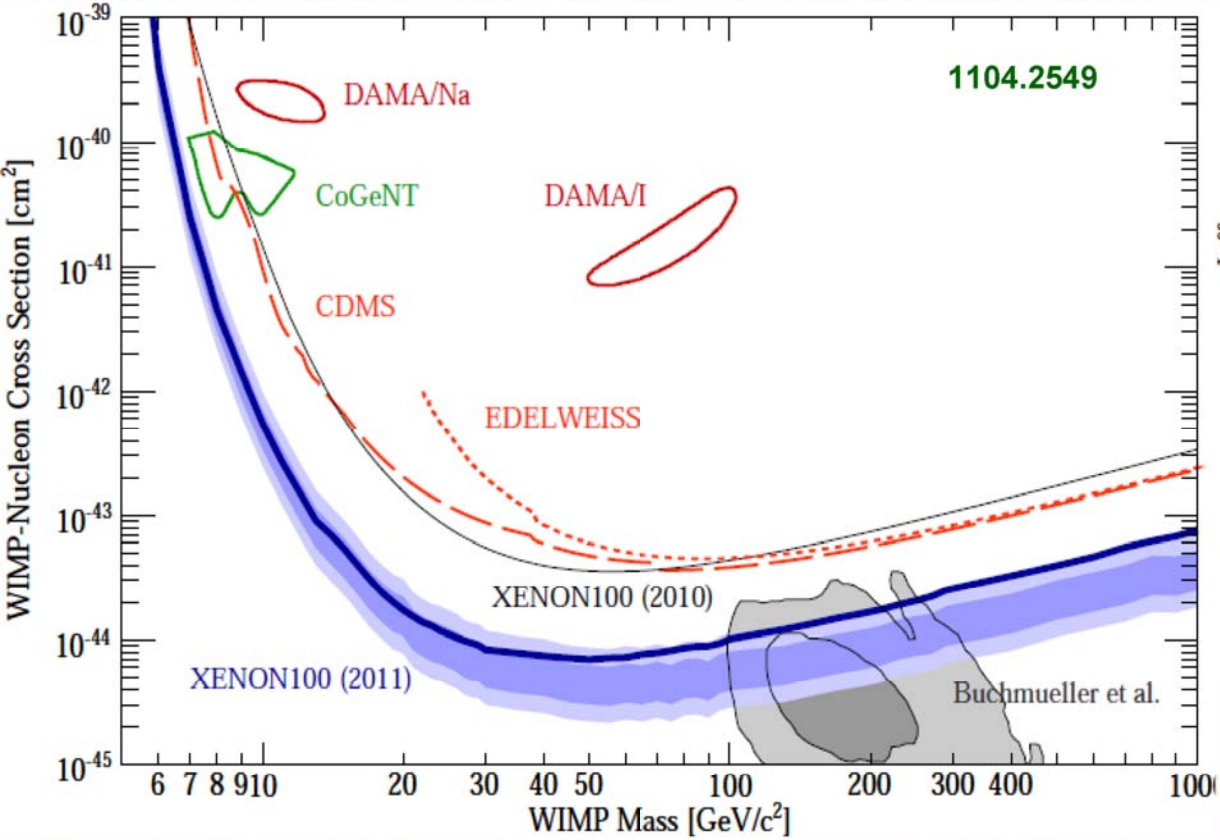
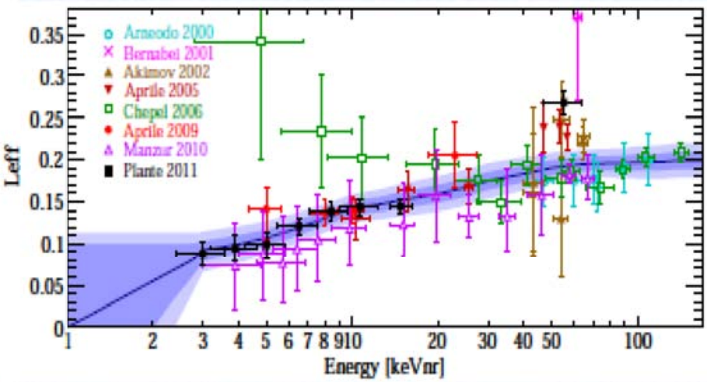
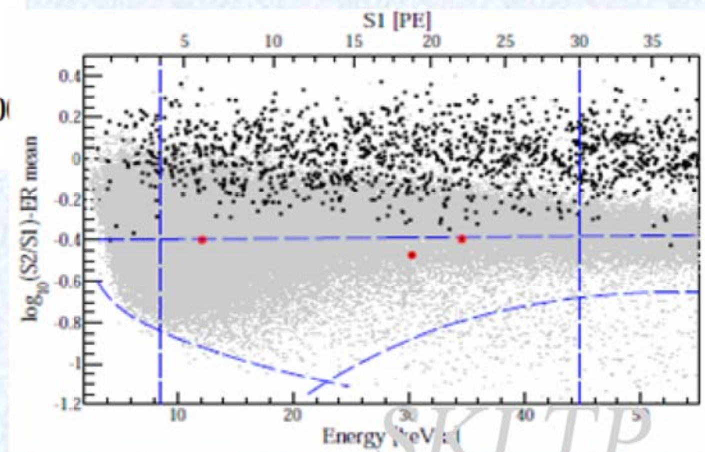
XENON 100



- Scintillation efficiency



- 3 observed events, expected background is $1.8^{+}_{-}0.6$



- 48 kg, 100.9days
- Most stringent constraints on SI cross section

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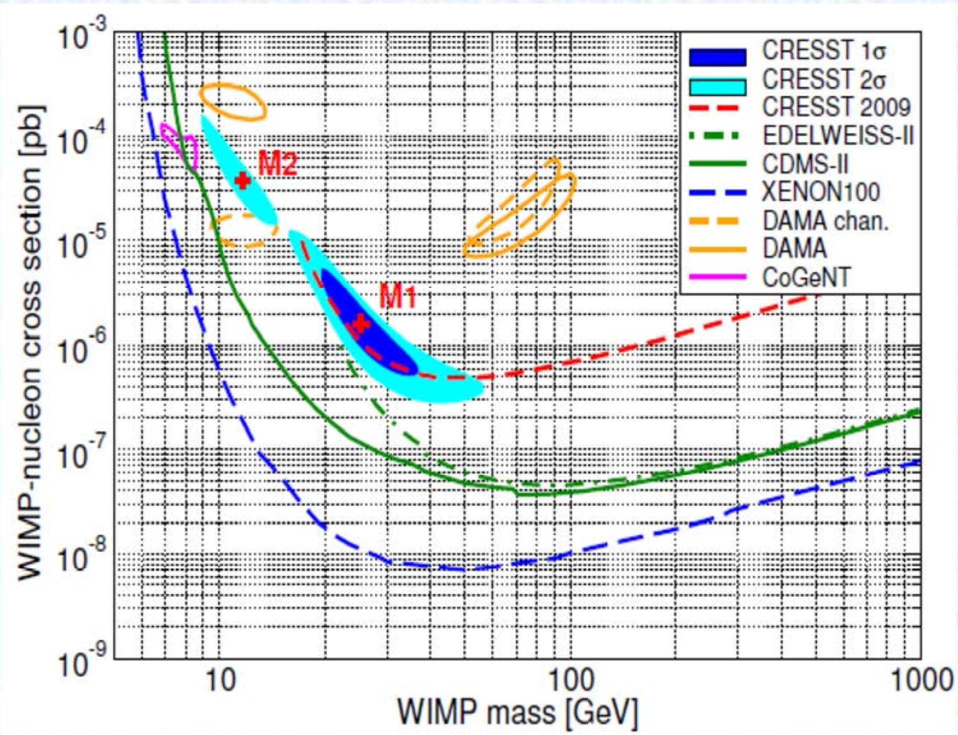
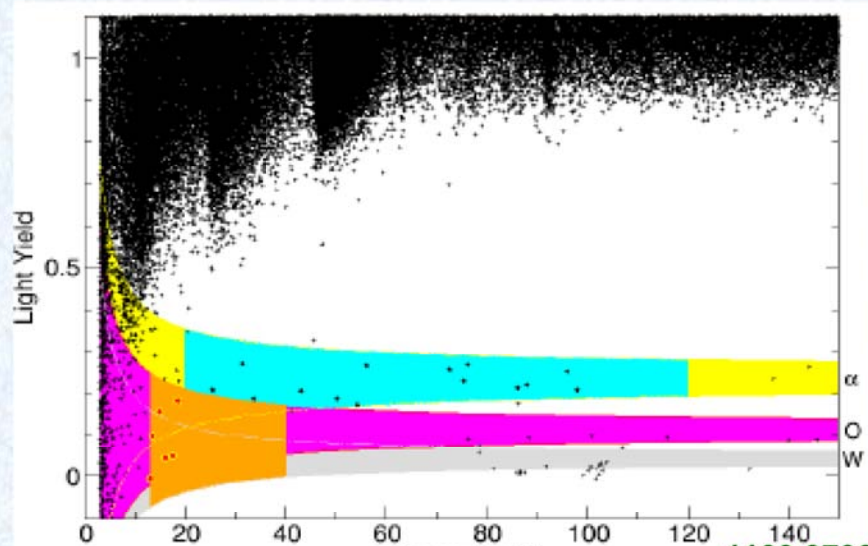
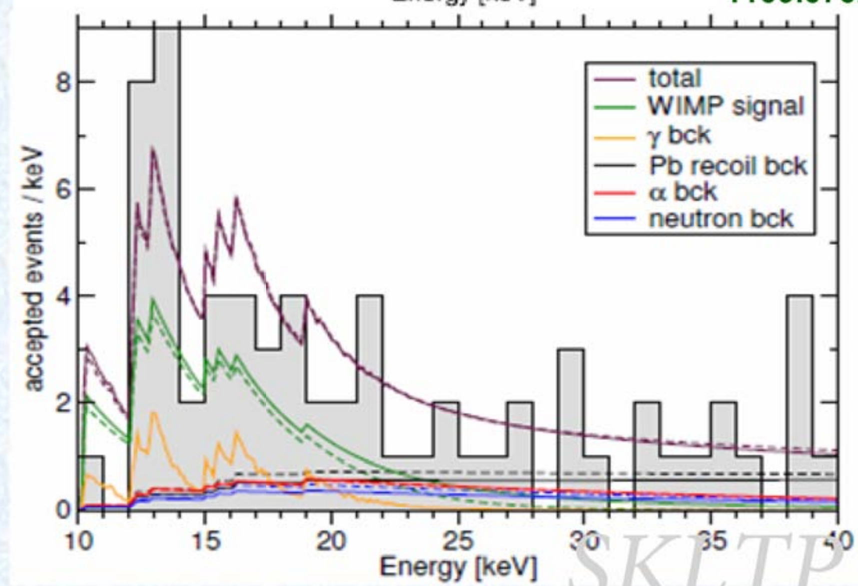
CRESST II

- CaWO4 crystals, 730 kg day, 8 modules
- 67events, singal events~29.4, 24.2
  (for two fit methods)







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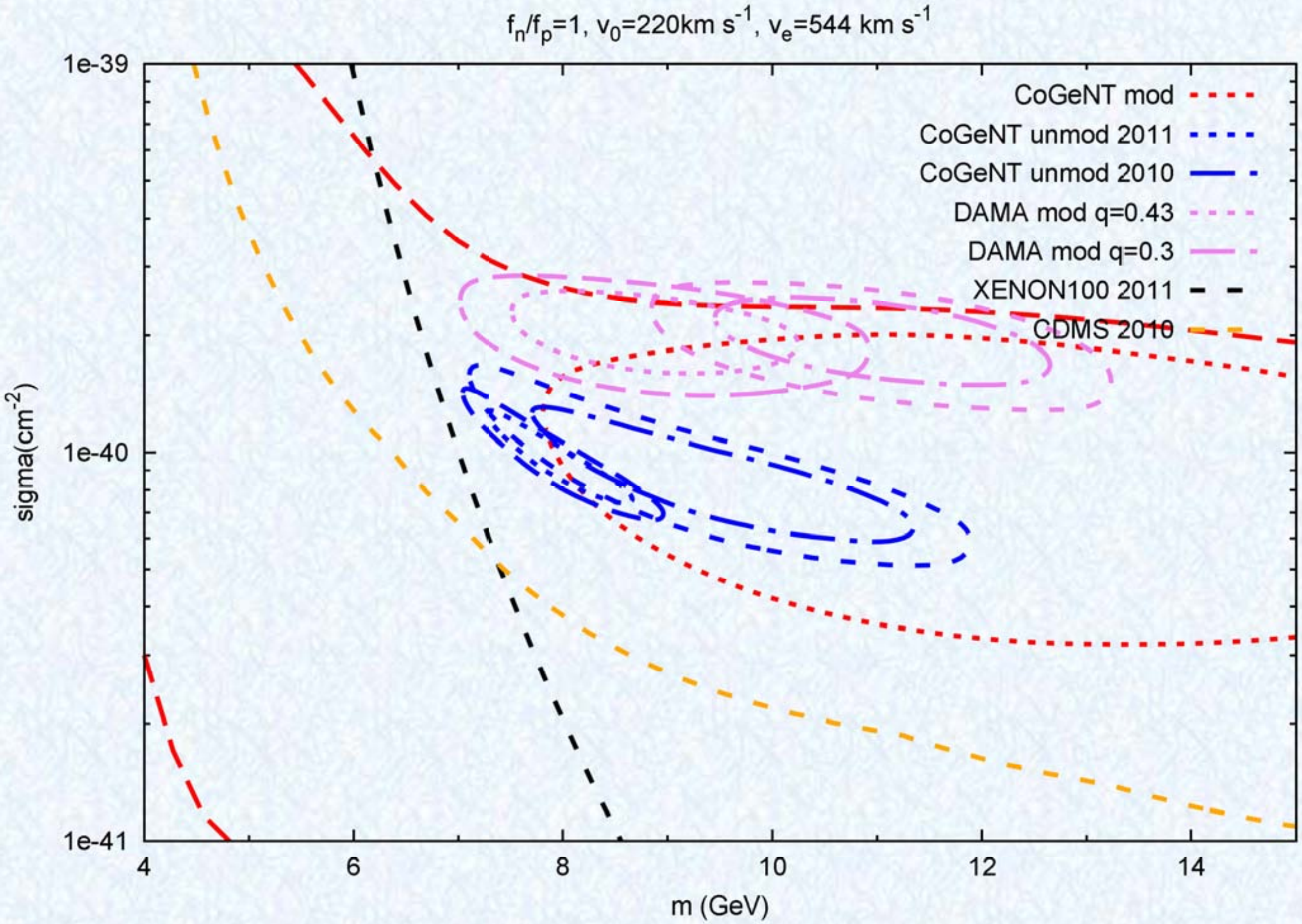
How to explain everything or something?

- Experimental uncertainties?
- Velocity distribution?
- New interaction between DM and nucleon?



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Experimental uncertainties

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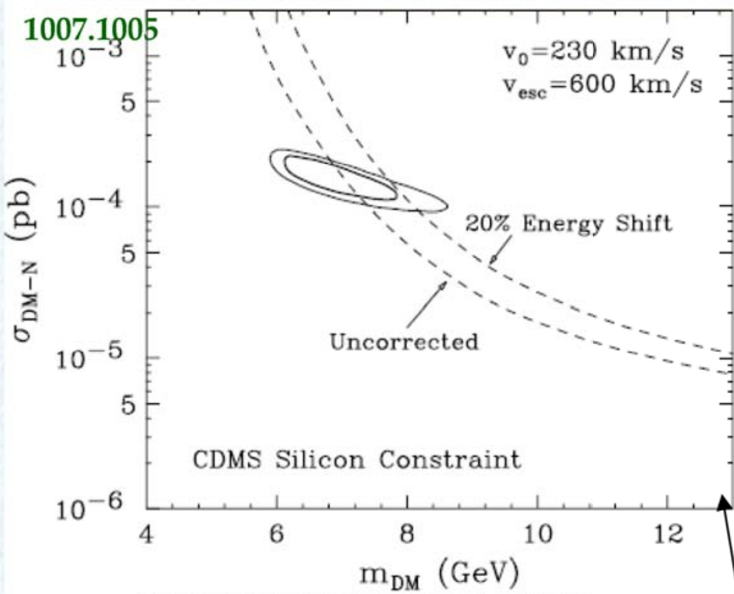

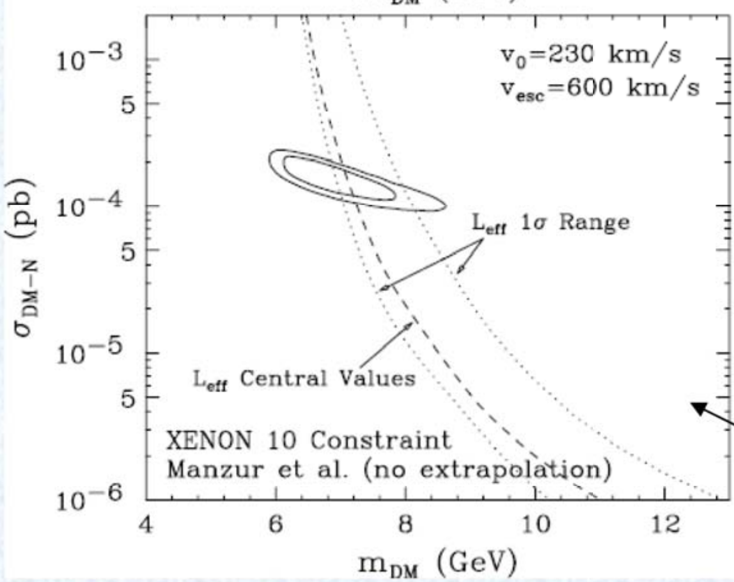

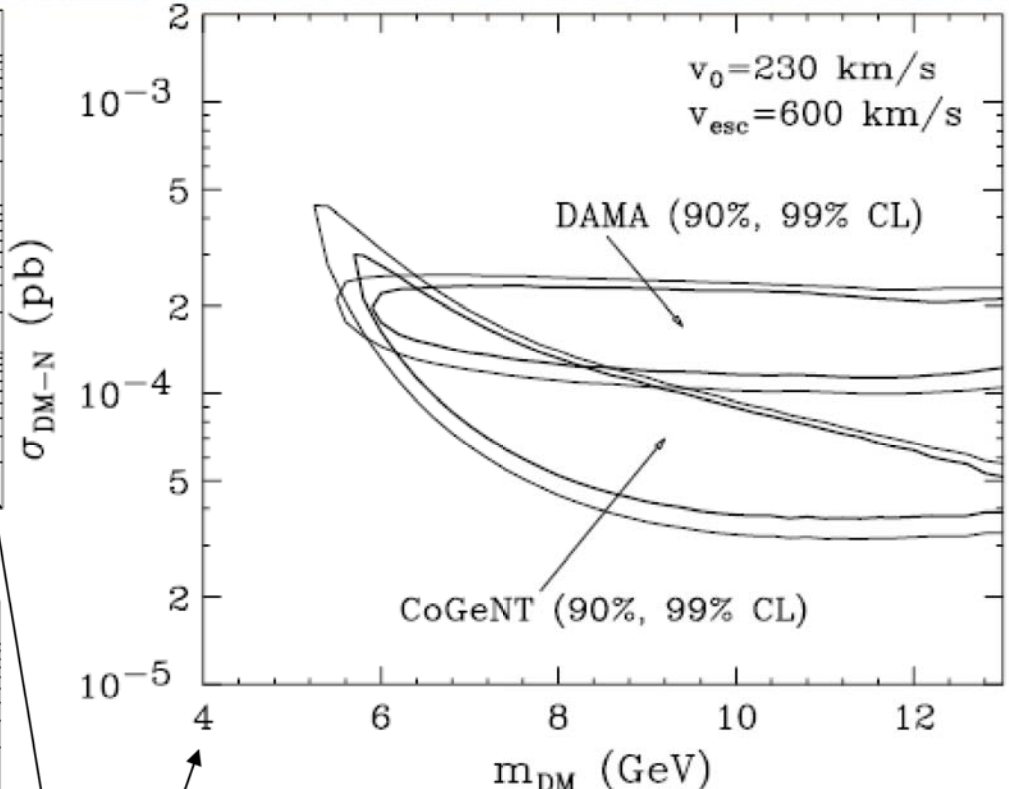

However, in order to get a consistent picture we need to assume that

- CDMS made a major calibration error (in Ge and Si),
- the XENON S2 analysis is completely wrong,
- there is a serious problem with L_{eff} in Xenon, and
- major error in the Na quenching factor determination for DAMA

T.Schwetz ISAPP11

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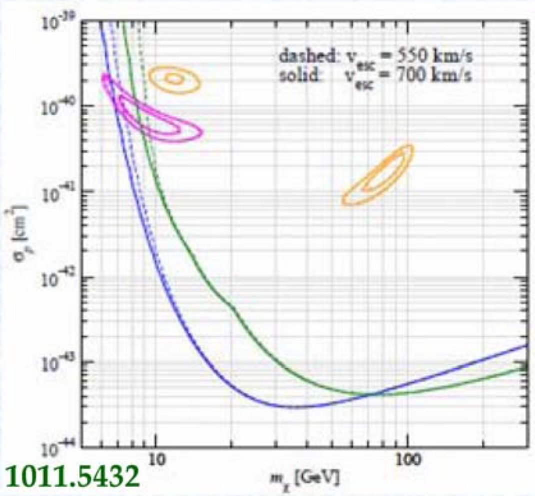
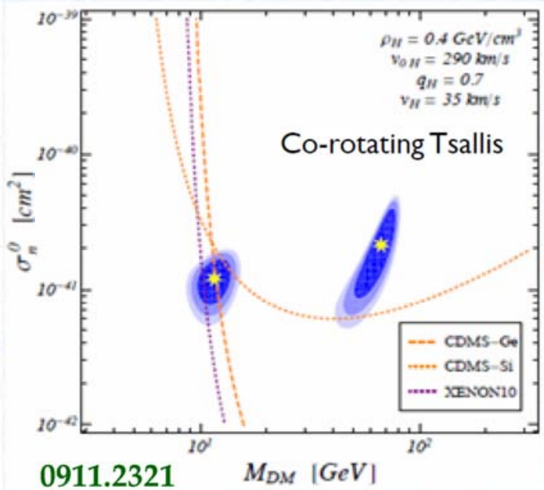
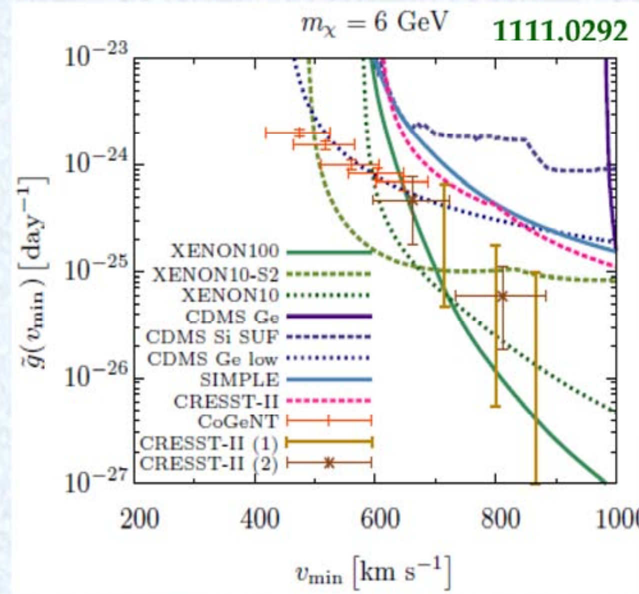
Astrophysics factor

- The values of v_{sun}, v_{esc} can not affect the results seriously
- Some extremely non-standard halo model may work ?







- Integrate out astrophysics factor (1011.1915)

Remember we can set

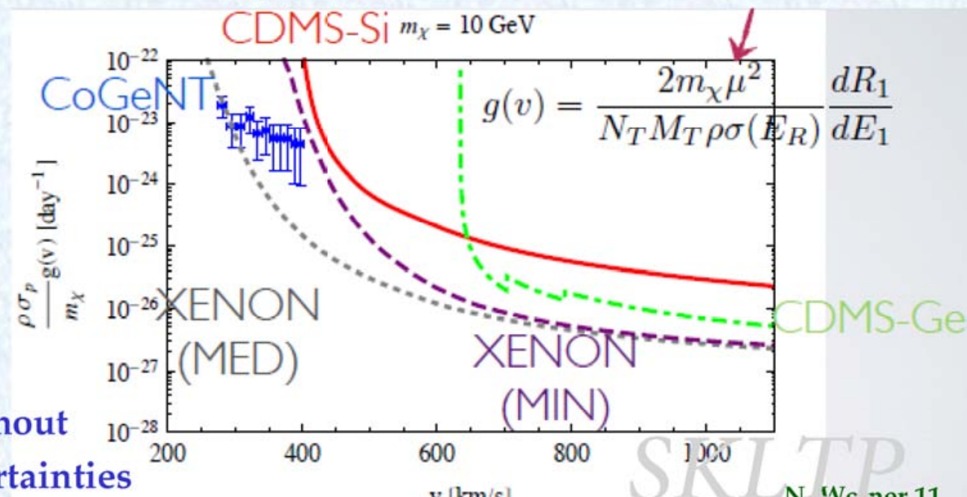
$$\frac{dR}{dE_R} = \frac{N_T M_T \rho}{2 m_\chi \mu^2} \sigma(E_R)\, g(v_{min})$$

For two different experiments

$$[E^{(1)}_{low}, E^{(1)}_{high}] \Longleftrightarrow [v^{low}_{min}, v^{high}_{min}] \Longleftrightarrow [E^{(2)}_{low}, E^{(2)}_{high}]$$

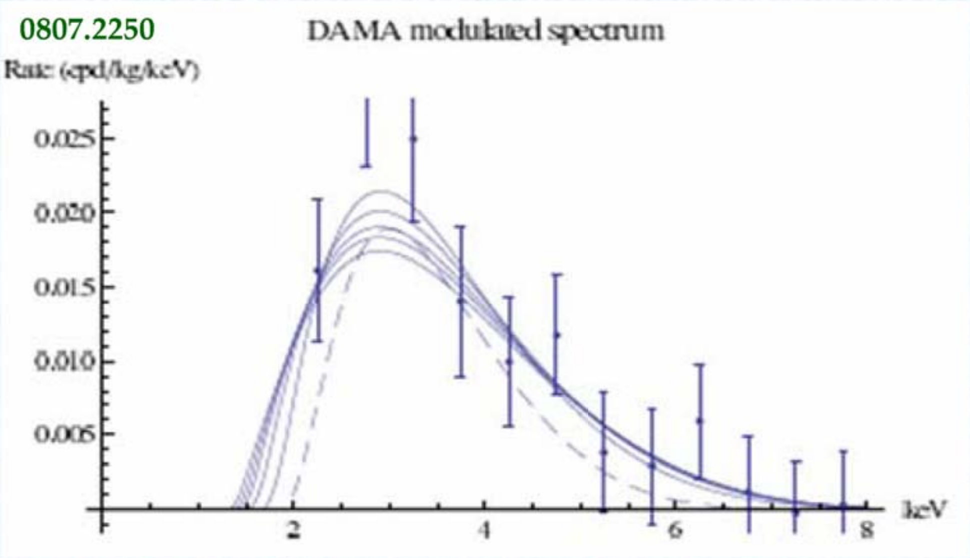
$$\frac{dR_1}{dE_1} \Longleftrightarrow g(v_{min}) \Longleftrightarrow \frac{dR_2}{dE_2}$$

Can set limits without astrophysics uncertainties



N. Weiner 11

Inelastic DM

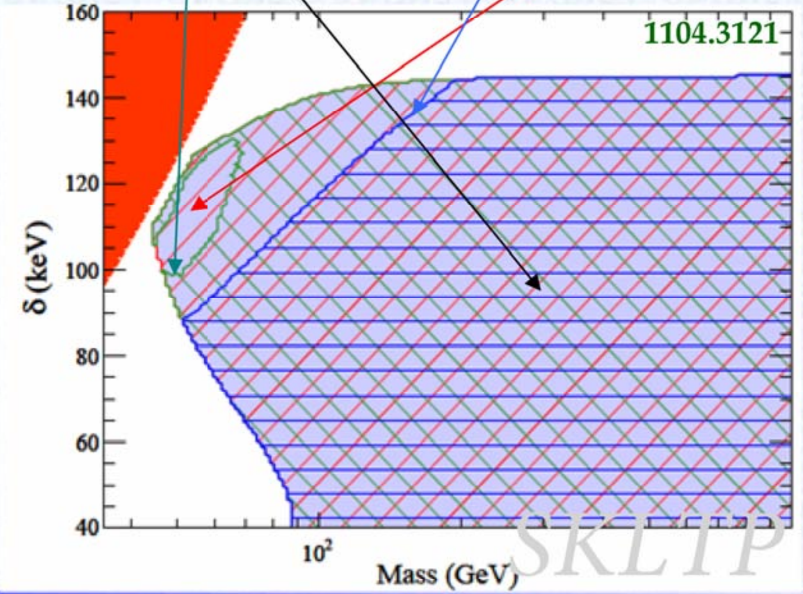


$$\chi N \to \chi^* N$$

$$\delta = m_{\chi^*} - m_\chi \approx m_\chi \beta^2$$

$$v_{min} = \sqrt{\frac{1}{2m_N E_R}}\left(\frac{m_N E_R}{\mu} + \delta\right)$$

- Large parameter space to explain DAMA is excluded by CDMS and ZEPLIN-III (standard SI inelastic DM)
- Totally excluded by XENON100

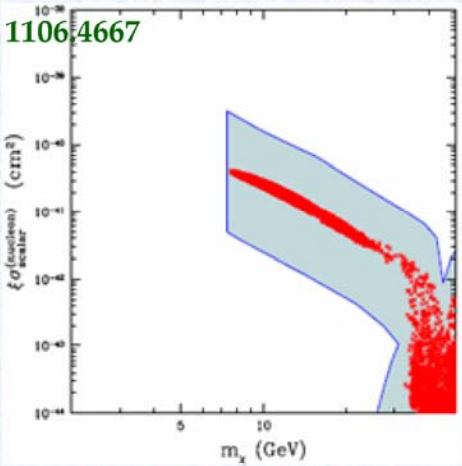


- Higher velocity cut, require heavier target
- Sensitive for high velocity region, event number changed rapidly with velocity varying, the modulation effect is enhanced
- Change low energy spectrum, there is a peak in the spectrum

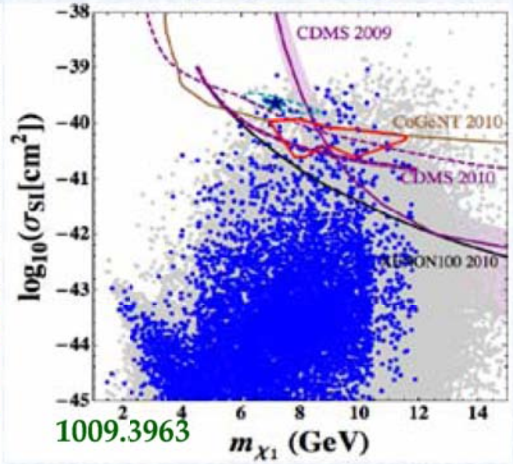
Light DM and others…

Light neutralino in MSSM or NMSSM

Non-universal gauginos



very light Higgs

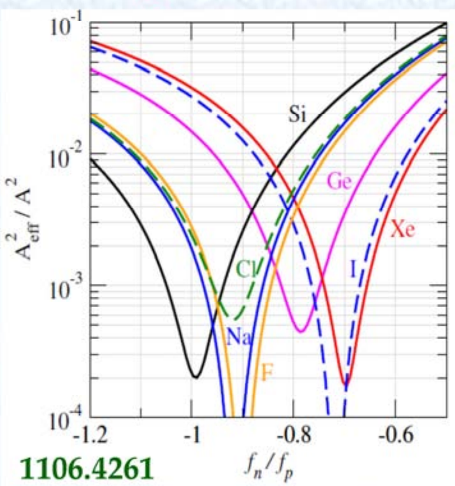


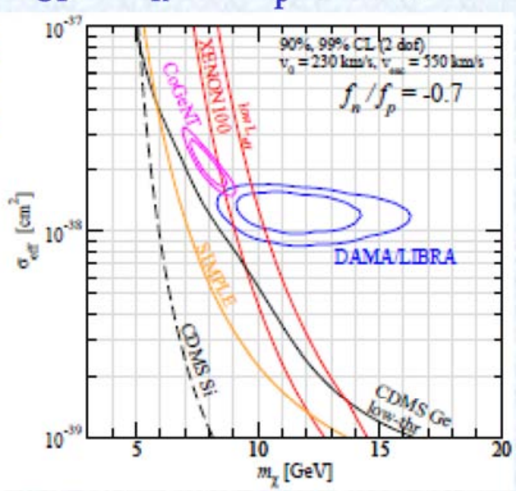
Asymmetric DM

Relate DM production to the baryogenesis. DM and baryon genesis might have common origin

$n_{DM} \sim n_B$ -> $m_{DM} = m_B\, \Omega_{DM}/\Omega_B \sim 5$GeV

Iso-spin violation $\sigma_{SI} \sim (f_n A + f_p (A-Z))^2$





Others

Down scattering inelastic DM, iso-spin violation inelastic DM, Magnetic inelastic DM, mirror DM, asymmetric mirror DM, leptophilic DM, form factor DM, resonant DM, luminous DM, electric-dipole DM, magnetic-dipole DM….

Too many works, I am very sorry for ignoring more works..

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Why explain everything?

The model builder's last refuge…

---------Neal Weiner

My suggestion: pay theorists more, so they do not need to work so hard

---------Paolo Gondolo

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DM induced solar neutrinos : another direct detection

DM is free in the Galaxy with MB distribution

↓ attracted by solar system's gravitation

DM-nucleon scatter in the Sun

↓ DM loss energy

DM is trapped in the core of Sun

↓ reach equilibrium

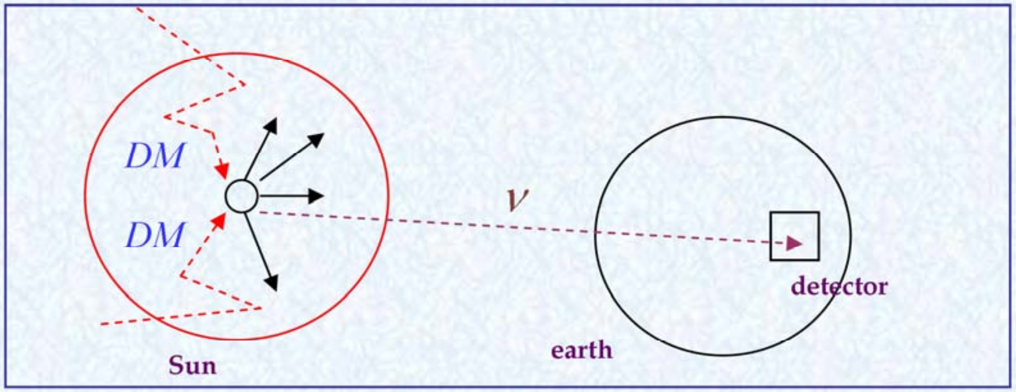
DM annihilate in the Sun

↓ neutrinos escape, propagate to the earth

Neutrinos interact with matter near the detector

↓ produce muons

Detect Cherenkov light induced by muons



- Detect Spin-dependent DM-nucleon cross section and branching ratio of DM annihilating to neutrinos
- DM annihilate rate is determined by capture rate and then DM-nucleon scattering
- Constrain DM annihilate channel to WW, ZZ, tt $\tau\tau$ and $\nu\nu$
- Main backgrounds are atmospheric neutrinos induced by cosmic rays
- Favor heavy DM

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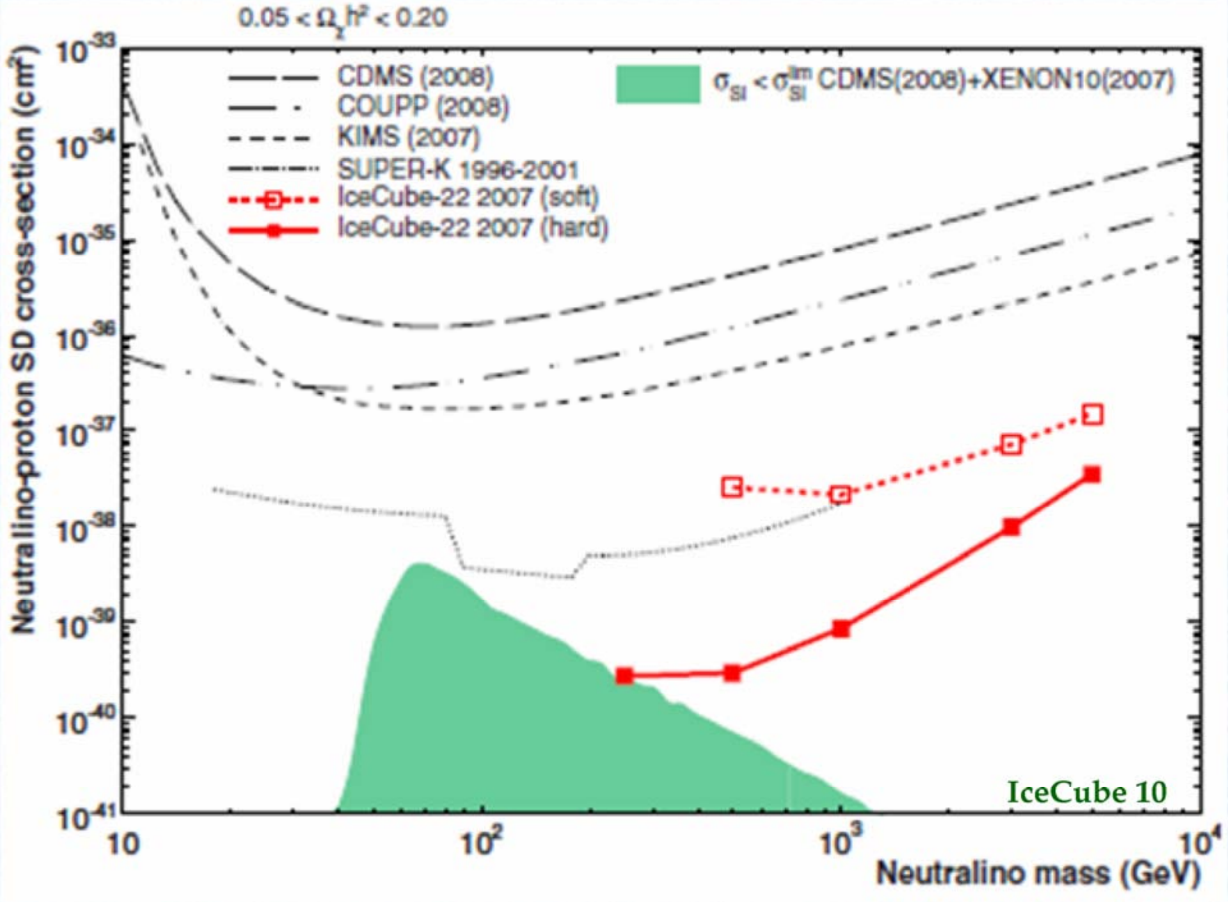
Constraints on SD interaction



To be continued…

- DAMA and CoGeNT *unknown* modulation events
- CRESSTII *unknown* events
- *Null results* from XENON, CDMS and other experiments
- Exotic interactions between DM and nucleon ? *Still difficult…*
- SD constraints might come from other experiments and neutrino telescopes
- China DM direct detection can play an important role. *Good luck !*

Thank you

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