Global interpretation of Dark Matter direct detection searches

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M. Fairbairn, TS, 0808.0704

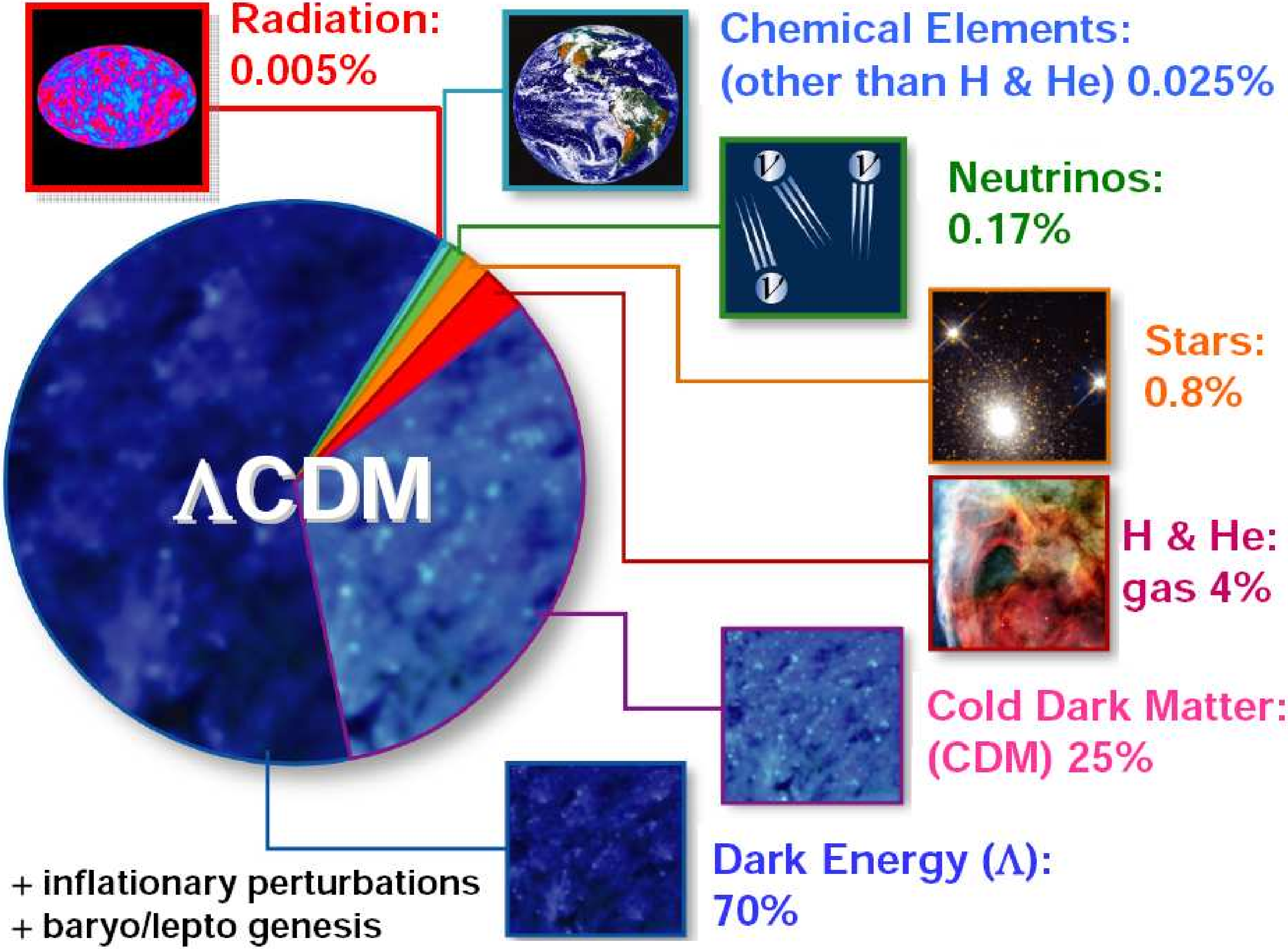
J. Kopp, V. Niro, TS, J. Zupan, 0907.3159

J. Kopp, TS, J. Zupan, 0912.4264

Outline

- Introduction
- DM direct detection
- News from CDMS-II and XENON10
- The DAMA annual modulation signal
- (in)elastic spin-(in)dependent scattering
- Conclusions

The "concordance model" of cosmology



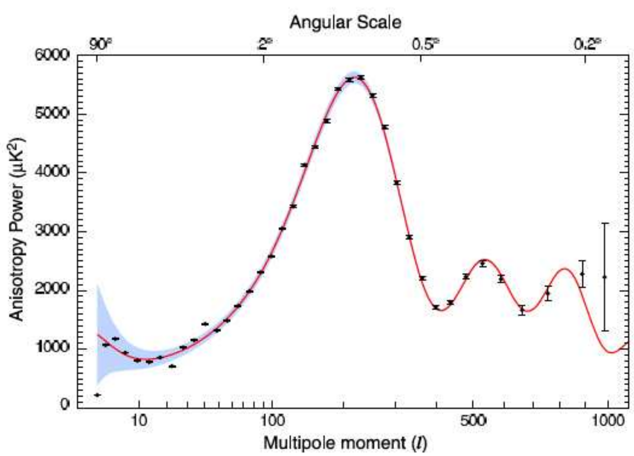
+ inflationary perturbations
+ baryo/lepto genesis

Global fit to cosmological data

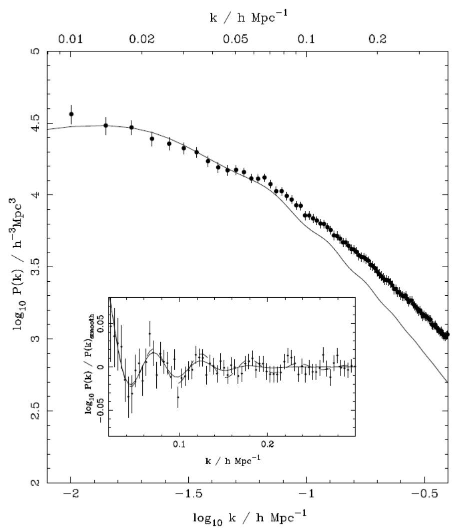
$$\Omega_\Lambda = 0.726 \pm 0.015$$
$$\Omega_{\mathrm{CDM}} = 0.228 \pm 0.013$$
$$\Omega_{\mathrm{baryon}} = 0.0456 \pm 0.0015$$

arXiv:0803.0547

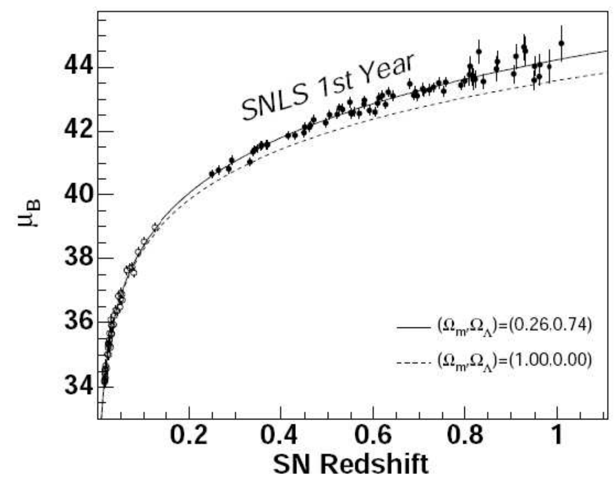
CMB (WMAP)



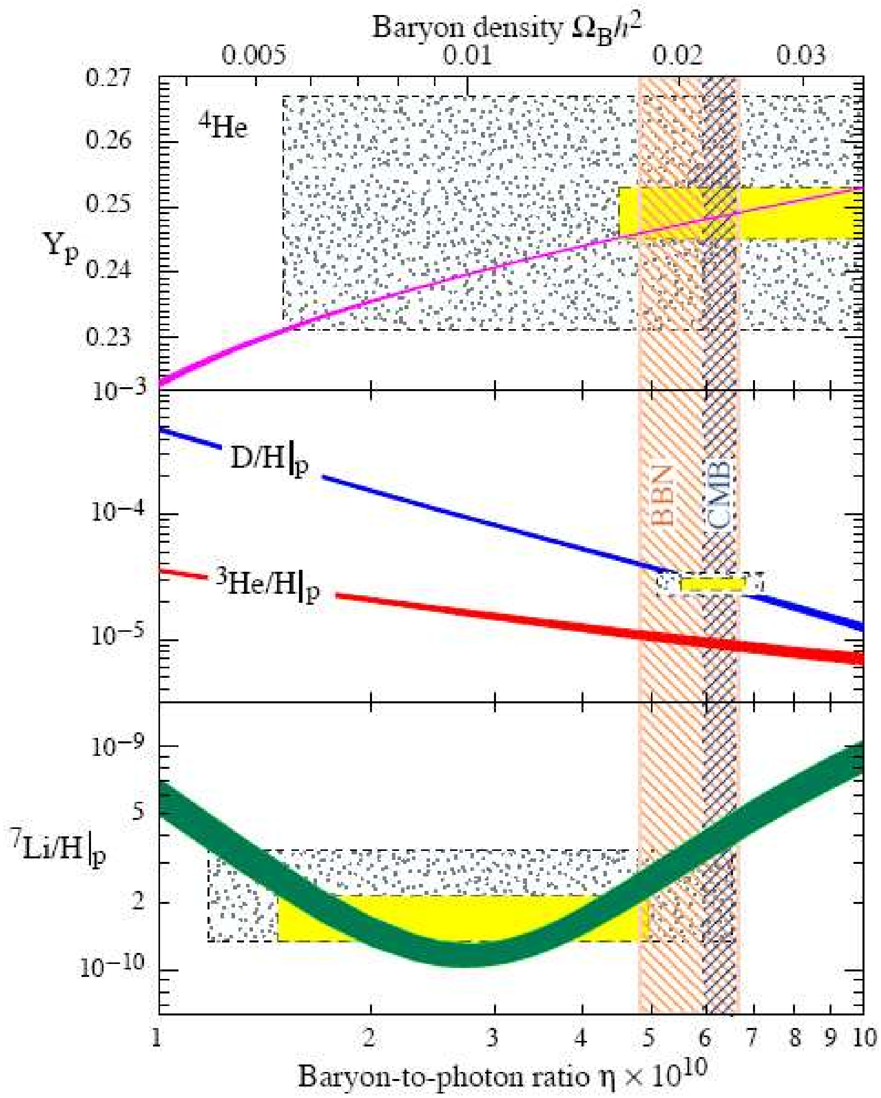
BAO



SN Ia



Density of “normal matter”



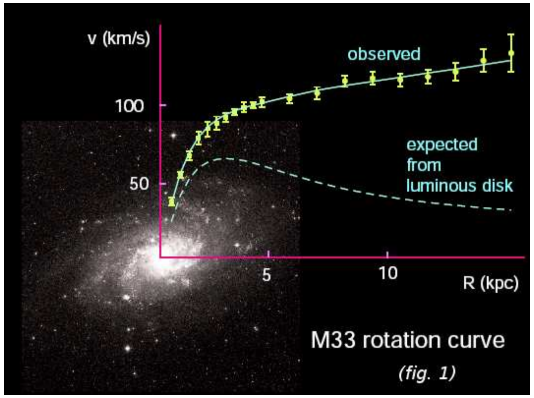
determinations of the baryon density from Big Bang Nucleosythesis and CMB are in perfect agreement:

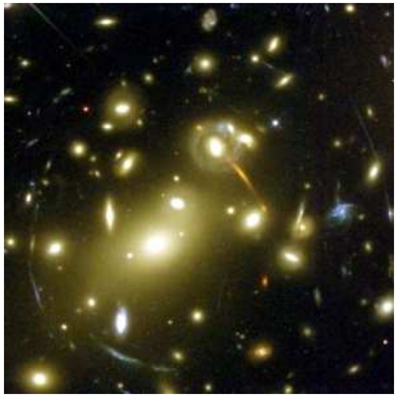
$$\Omega_b h^2 = 0.0214 \pm 0.0020 \quad \text{(BBN)}$$

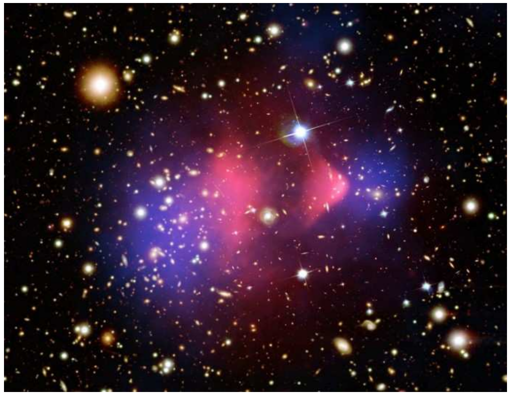
$$\Omega_b h^2 = 0.0227 \pm 0.0006 \quad \text{(CMB)}$$

The scale of galaxies and clusters of galaxies

- rotation curves
- gravitational lensing
- bullet clusters



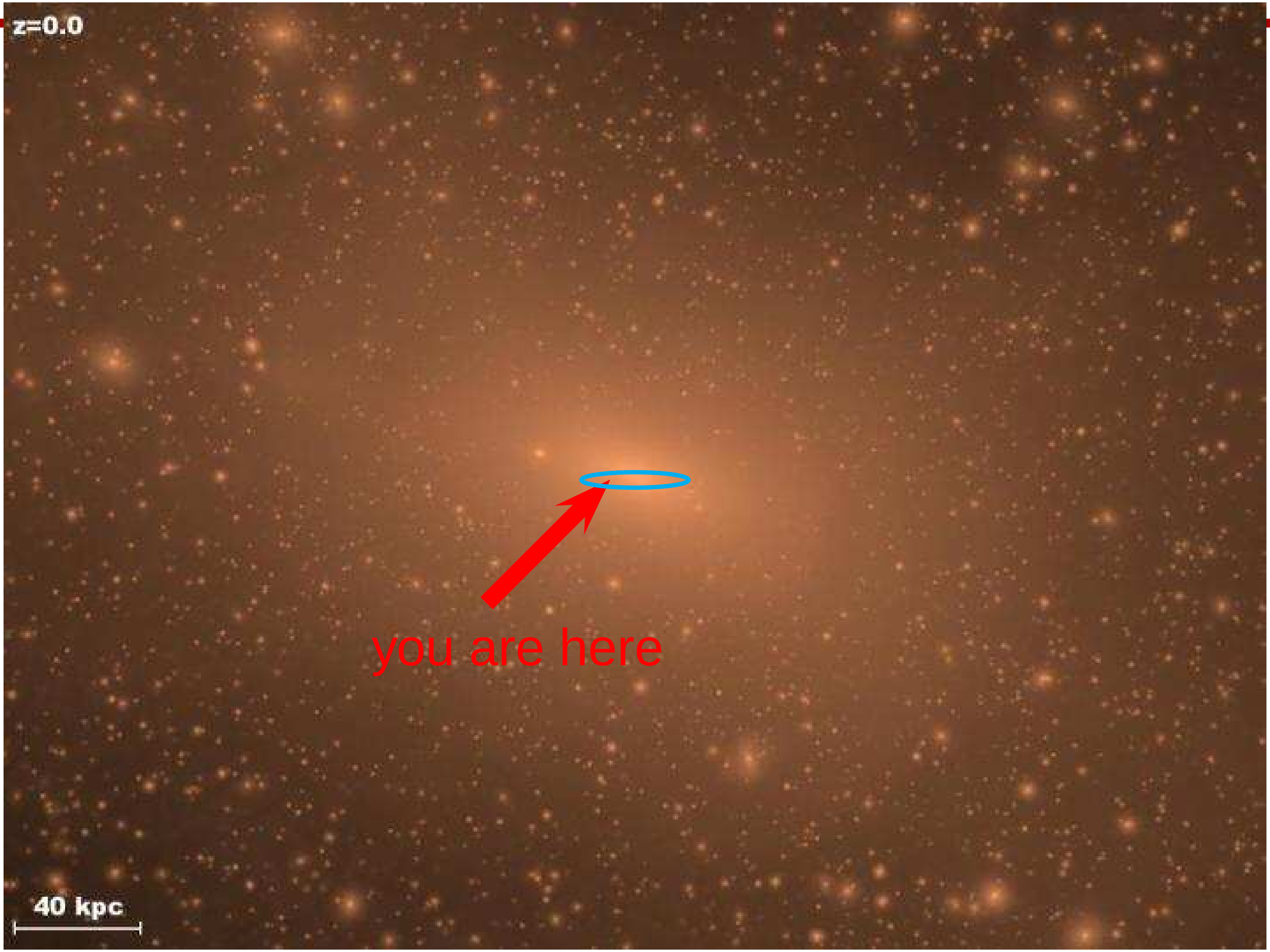




- virial theorem applied to galaxies and clusters
- X-rays from clusters of galaxies

$\Rightarrow$ Many independent observations are consistent with the hypothesis that the dominating gravitating component of the Universe cannot be the matter we know.

Dark Matter in a Milkyway-like Galaxy



Via Lactea N-body DM simulation Diemand, Kuhlen, Madau, astro-ph/0611370

Dark Matter distribution

"standard halo model":

local DM density $\rho_\chi \approx 0.3\,\mathrm{GeV\,cm^{-3}} \quad \Rightarrow$

$$n_\chi \approx 3000\,\mathrm{m}^{-3}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)$$

Maxwellian velocity distribution (in halo rest frame)

$$f_{\mathrm{gal}}(\vec{v}) \approx \begin{cases} N\exp\left(-v^2/\bar{v}^2\right) & v < v_{\mathrm{esc}} \\ 0 & v > v_{\mathrm{esc}} \end{cases}$$

with $\bar{v} \simeq 220$ km/s and $v_{\mathrm{esc}} \simeq 650$ km/s

DM direct detection

Assuming DM has non-gravitational interactions ("WIMP"):

Look for recoil of DM-nucleus scattering:

M. Goodman, E. Witten, PRD 1985

$$\chi + N \to \chi + N$$

cnts / keV recoil energy E_R:

$$\frac{dN}{dE_R}(t) \propto \frac{\rho_\chi}{m_\chi} \int_{v>v_{\rm min}} d^3v \, \frac{d\sigma}{dE_R} \, v \, f_\oplus(\vec{v}, t)$$

$v_{\rm min}$: minimal DM velocity required to produce recoil energy E_R

DM nucleon scattering cross section

in general the interaction between χ and a nucleus can be spin-independent (SI) and/or spin-dependent (SD):

DM nucleon scattering cross section

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Example: fermionic DM $\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2} \left(\bar\chi_q \Gamma_{\rm dark} \chi_q\right) \left(\bar\psi \Gamma_{\rm vis} \psi\right)$

	S	P	V	A	T	AT
$\Gamma_{\rm dark,vis}$	γ_0	$\gamma_0\gamma_5$	γ_μ	$\gamma_\mu\gamma_5$	$\sigma_{\mu\nu}$	$\sigma_{\mu\nu}\gamma_5$

$\Rightarrow$ in the non-relativistic limit:

- $(S \otimes S), (V \otimes V)$: spin-independent interaction
- $(A \otimes A), (T \otimes T)$: spin-dependent interaction
- other combinations are suppressed by $\mathcal{O}(v^2) \sim 10^{-6}$

e.g., A. Kurylov, M. Kamionkowski, hep-ph/0307185

DM nucleon scattering cross section

in general the interaction between χ and a nucleus can be spin-independent (SI) and/or spin-dependent (SD):

$$\sigma_{\rm SI} = \sigma_p \frac{\mu_{\chi N}^2}{\mu_{\chi p}^2} \frac{[Z f_p + (A-Z) f_n]^2}{f_p^2} |F(q)|^2 \quad \propto A^2 \quad \text{for } f_n \approx f_p$$

$$\sigma_{\rm SD} = \frac{32 \mu_{\chi N}^2 G_F^2}{2J+1} \left[a_p^2 S_{pp}(q) + a_p a_n S_{pn}(q) + a_n^2 S_{nn}(q) \right]$$

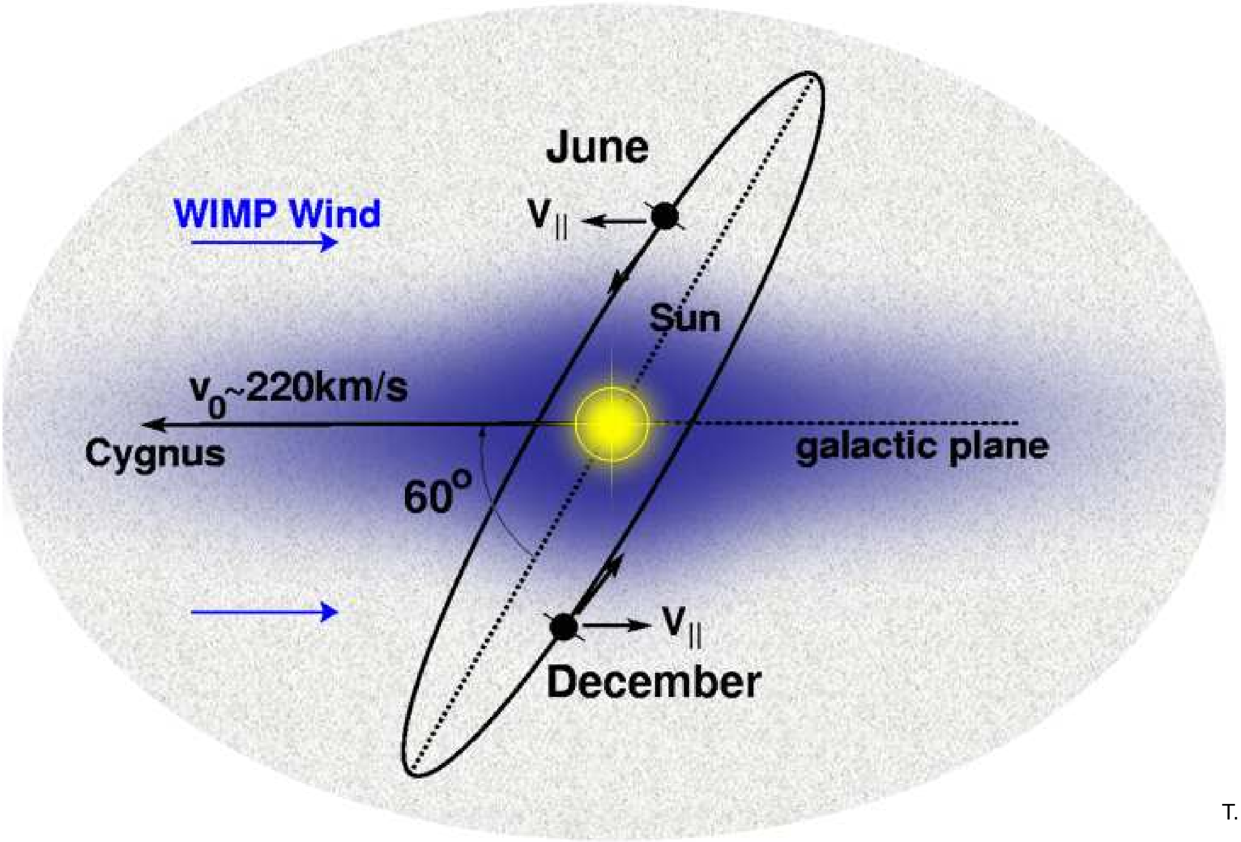
$\mu_{\chi N}$ ($\mu_{\chi p}$):	DM-nucleus(proton) reduced mass
f_p, f_n, a_p, a_n:	couplings to proton and neutron
$F(q), S_{pp}(q), S_{pn}(q), S_{nn}(q)$:	nuclear structure functions

DM velocity distribution

$$f_\oplus(\vec{v}, t) = f_{\rm gal}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t)) \qquad f_{\rm gal}(\vec{v}) \propto \exp(v^2/\bar{v})$$

sun velocity: $\vec{v}_\odot = (0, 220, 0) + (10, 13, 7)$ km/s

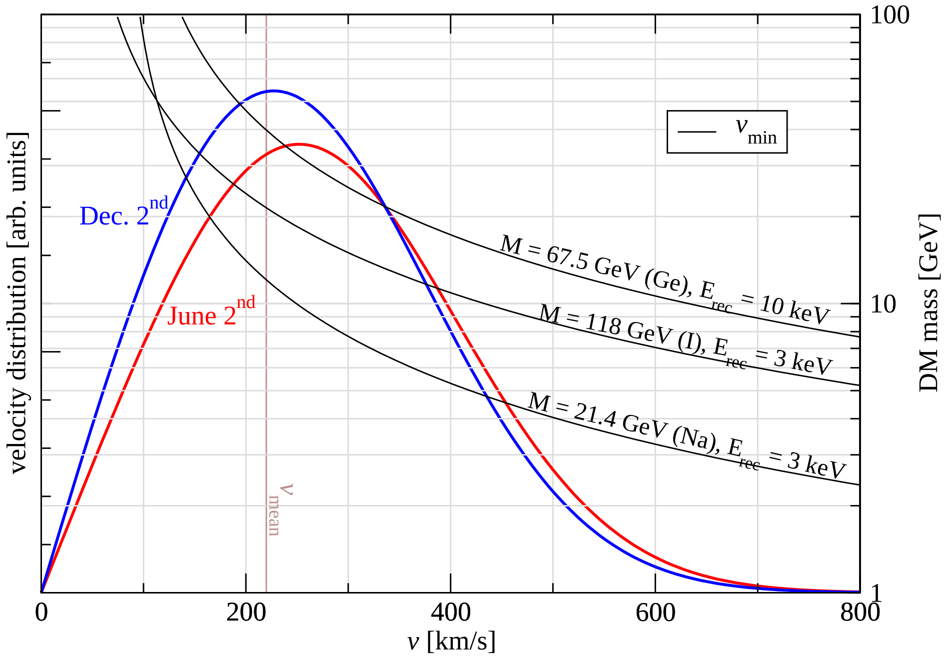
earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30$ km/s



Velocity distribution integral

$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi}\frac{\sigma(E_R)}{2\mu_\chi^2}\underbrace{\int_{v>v_{\min}} d^3v\,\frac{f_\oplus(\vec{v},t)}{v}}_{\eta(E_R,t)=\langle 1/v\rangle}$$

$$\eta(E_R,t) \propto \frac{1}{v_{\rm obs}(t)}\int_{v_{\min}(E_R)}^{\infty} dv\left[e^{-\left(\frac{v-v_{\rm obs}(t)}{\bar v}\right)^2} - e^{-\left(\frac{v+v_{\rm obs}(t)}{\bar v}\right)^2}\right]$$

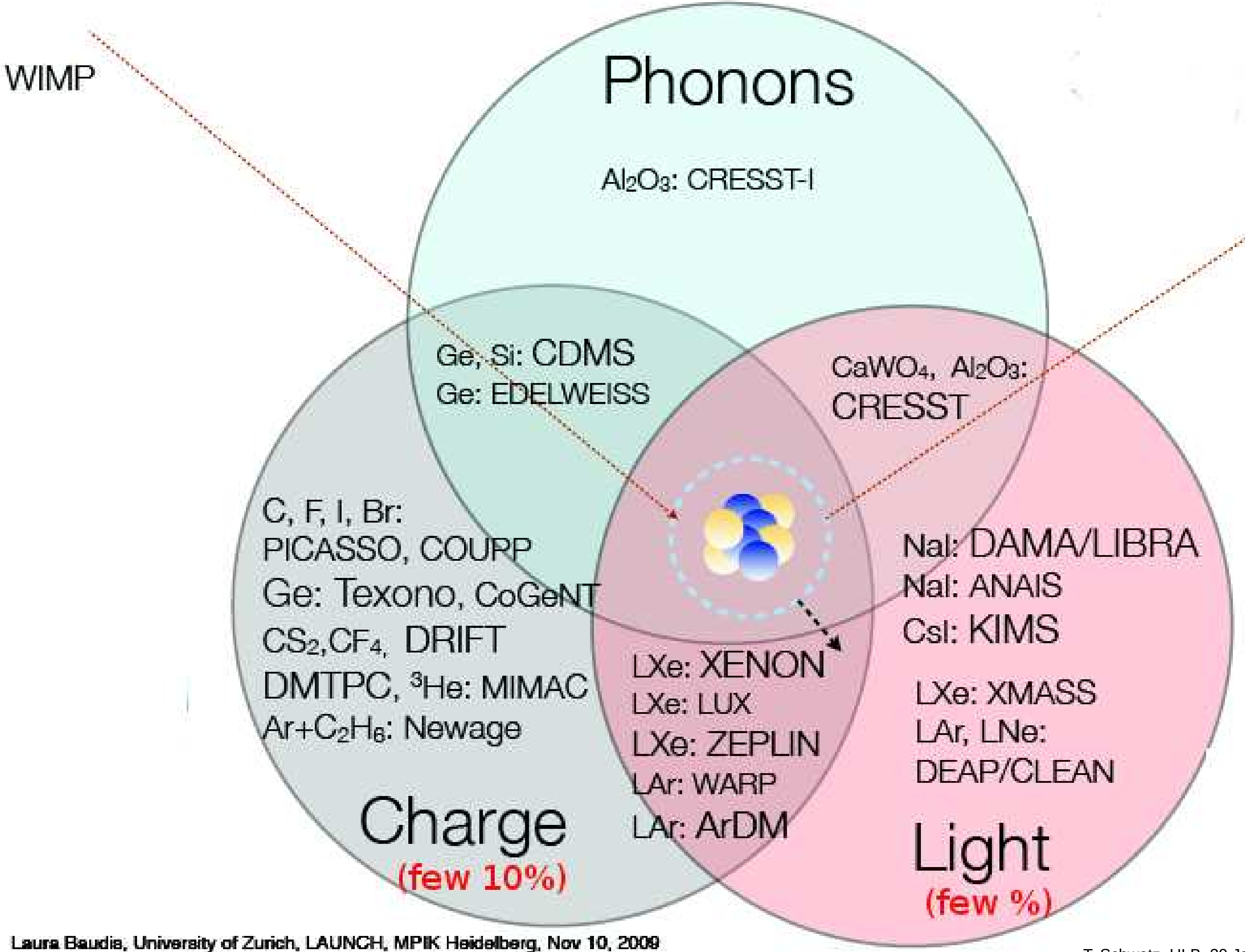


$$v_{\rm min,el} = \sqrt{\frac{M E_R}{2\mu_\chi^2}}$$

$$v_{\rm obs}(t) = |\vec{v}_\odot + \vec{v}_\oplus(t)|$$

Direct detection experiments

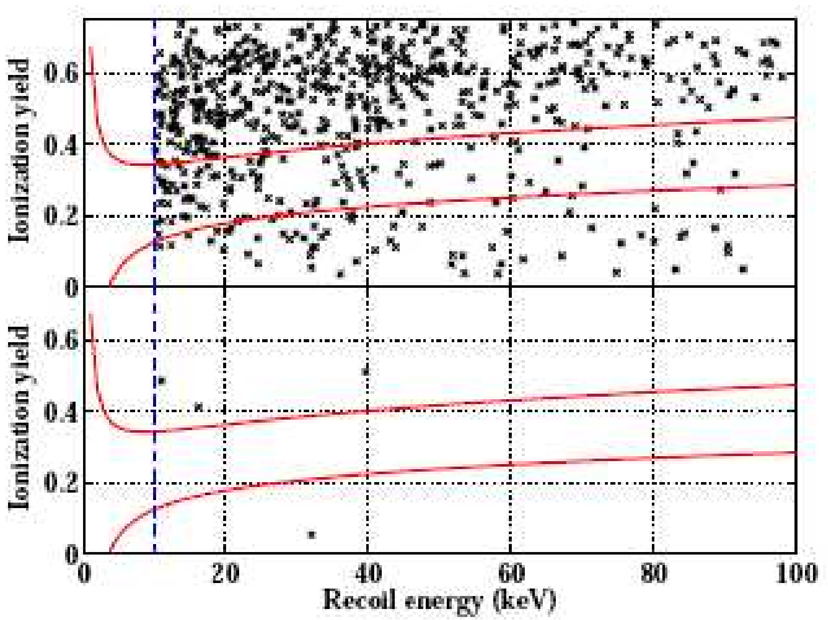
Direct Detection Techniques



CDMS-II

Germanium detector, recoil energy range 10–100 keV

- 0802.3530 Oct 2006-July 2007, 398 kg day: zero events

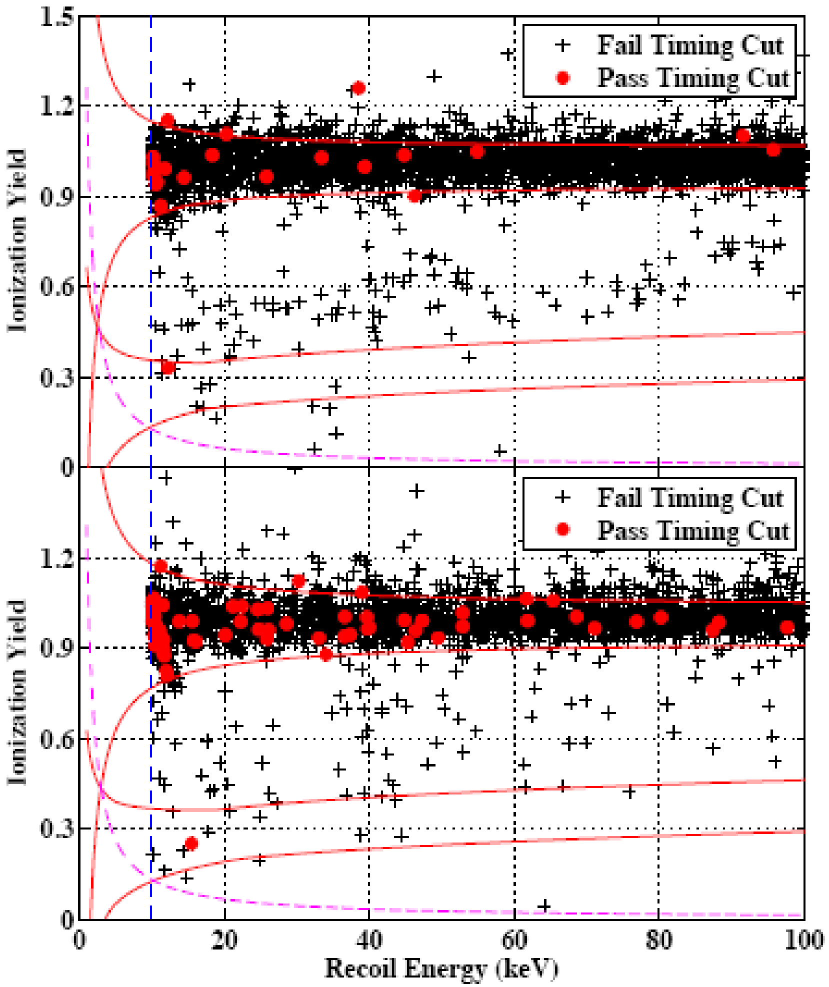


nuclear recoil signal region before (top) and after (bottom) timing cut

CDMS-II

Germanium detector, recoil energy range 10–100 keV

- 0912.3592 July 2007-Sep 2008, 612 kg day: 2 candidate ev.



electron and nucl. recoil regions for two different detectors

candidates:
12.3 keV and 15.5 keV

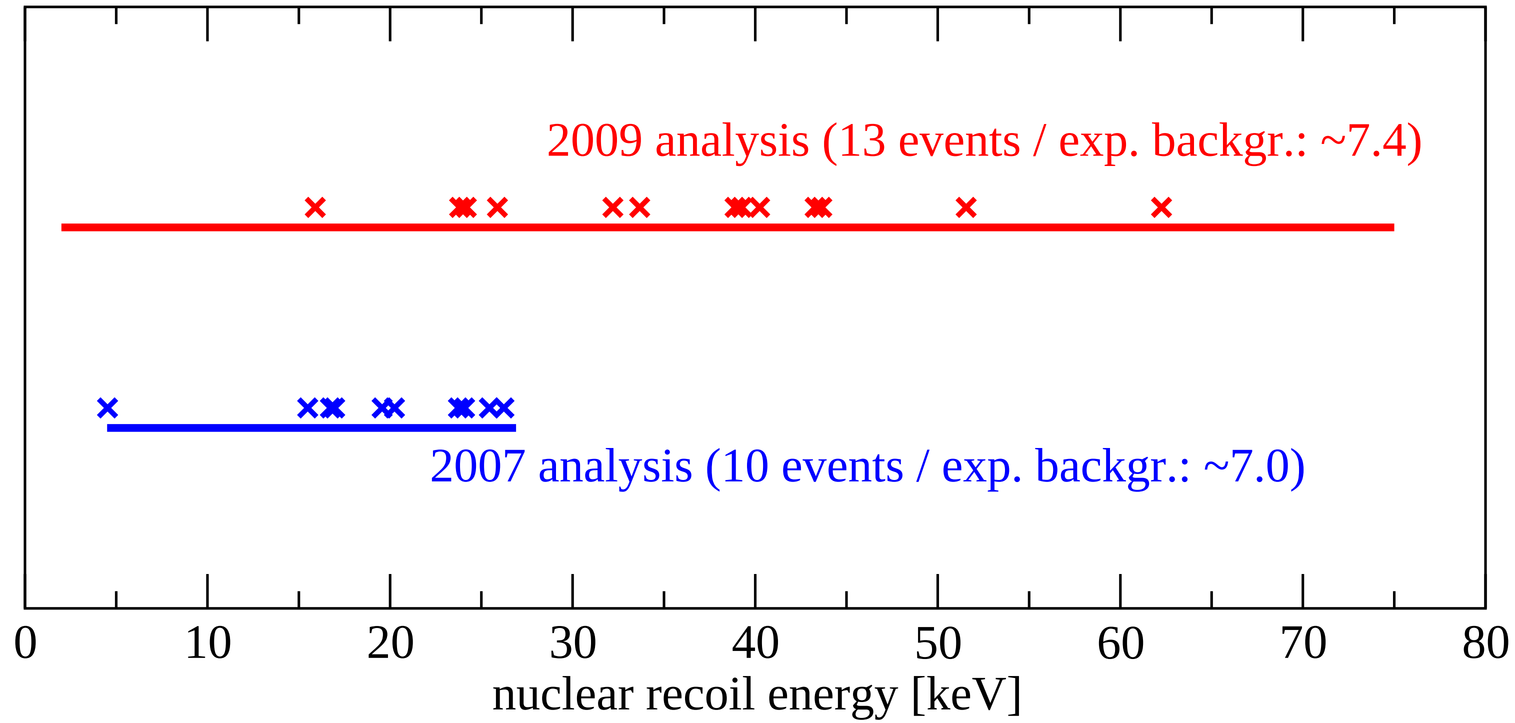
background: $0.8 \pm 0.1 \pm 0.2$
probablitly for >= 2 ev: 23%

XENON-10

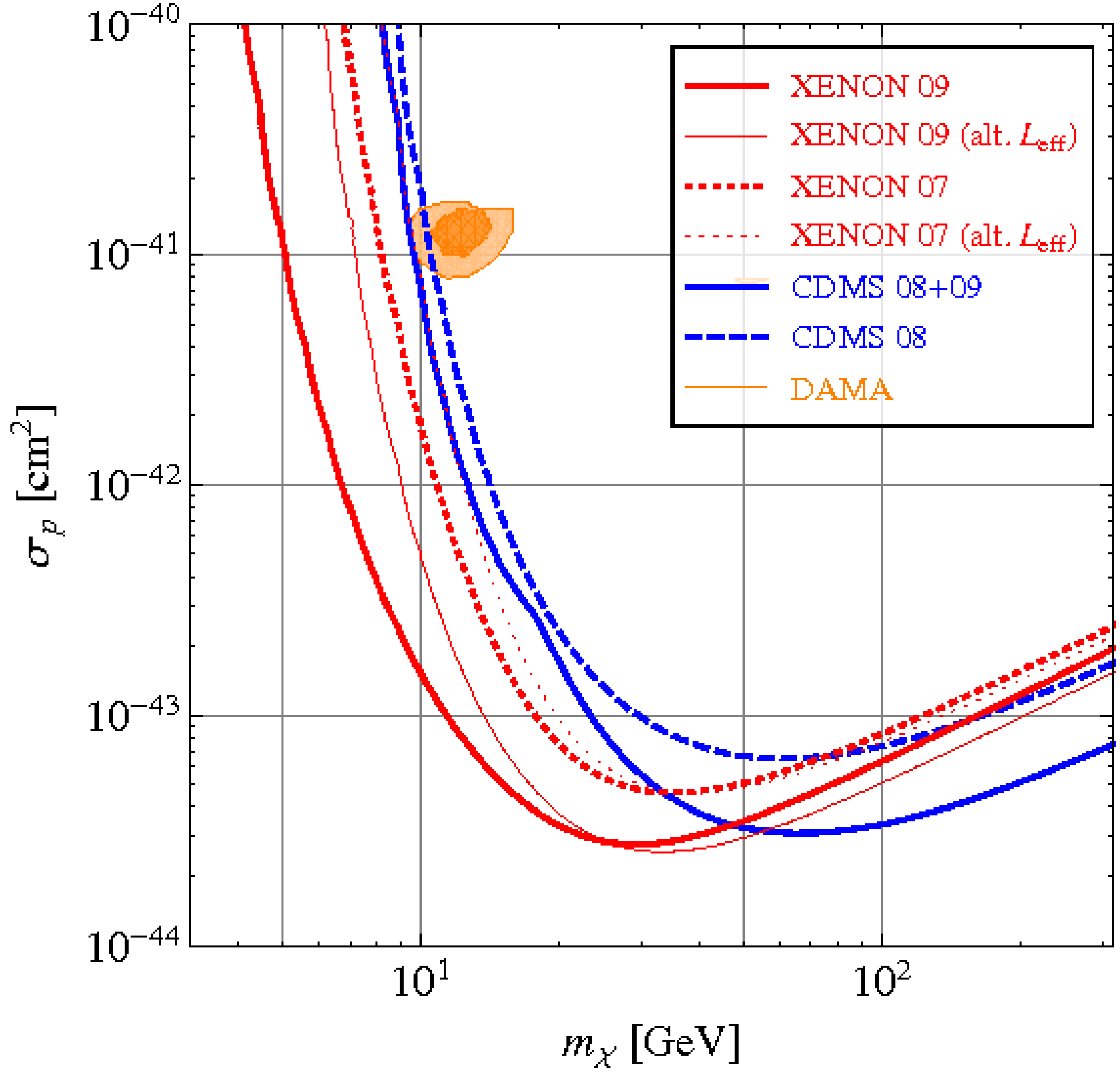
2 phase (gas/liquid) Xenon detector @ Gran Sasso
Oct 2006 - Feb 2007, 316 kg day exposure

0706.0039: original blind analysis: 10 events

0910.3698: revised cuts: 13 events, extended energy window



New CDMS and XENON results

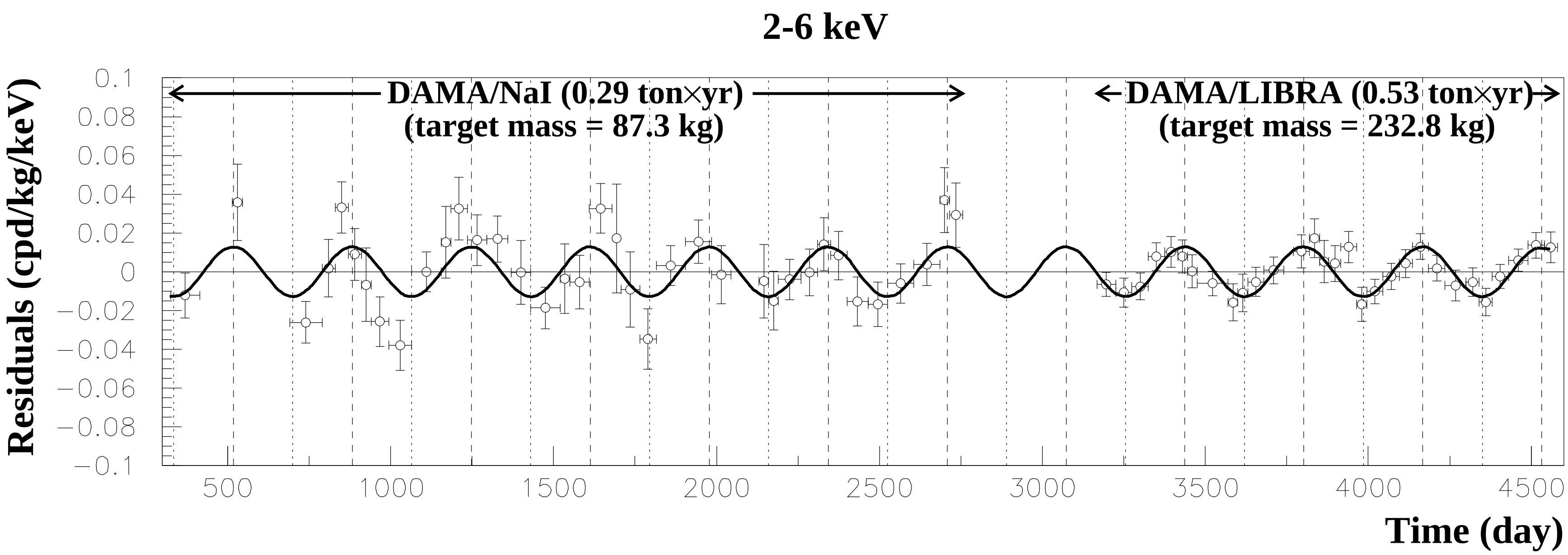


DAMA/LIBRA annual modulation signal

Scinitillation light in NaI detector, 0.82 t yr exposure

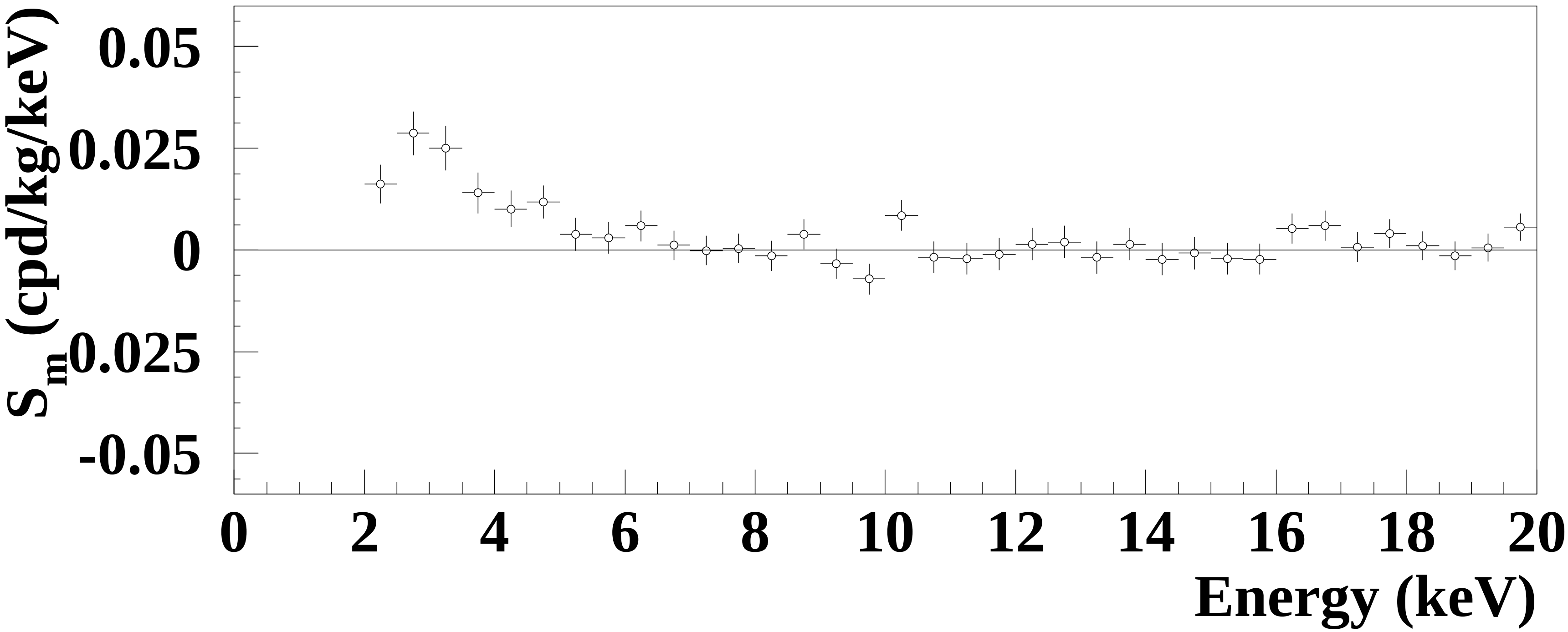
~ 1 cnts/d/kg/keV $\quad\rightarrow\quad \sim 2\times 10^5$ events/keV in DAMA/LIBRA

8.2σ evidence for an annual modulation of the count rate with maximum at day 144 ± 8 (June 2nd: 152)



Bernabei et al., 0804.2741

Energy dependence of the modulation signal



modulation signal at $2 - 6$ keV

above 6 keV consistent with no modulation

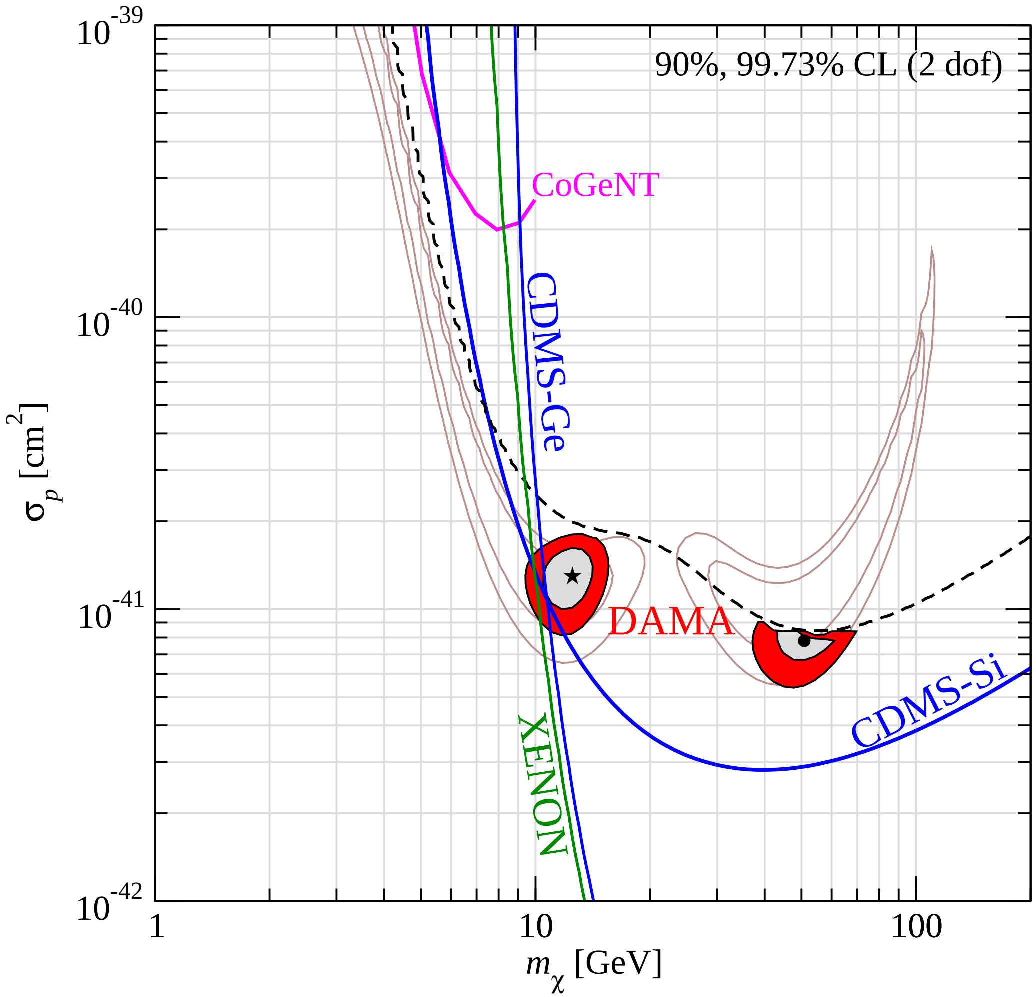
Can this be explained by DM?

Can this be explained by DM?

- Yes, the DAMA signal can be explained,
  spin-independent, spin-dependent, inelastic scattering, . . .
- but it is difficult to reconcile it with constraints from other experiments.

elastic spin-independent (eSI) scattering

DAMA vs CDMS/XENON (08/2008)



Fairbairn, Schwetz, 0808.0704

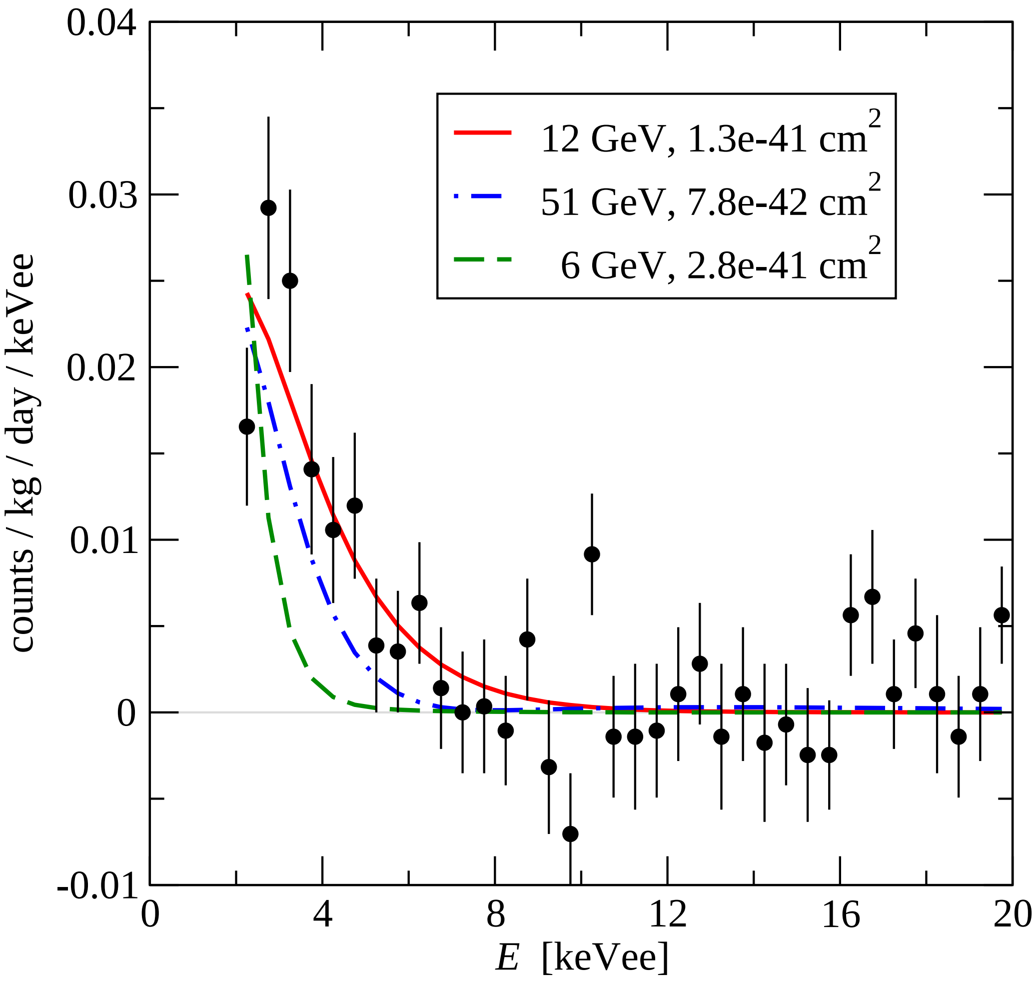
DAMA 90% CL region excluded by 90% CL XENON, CDMS bounds

$\chi^2_{\rm min,glob} = 59.3/(45-2)$ $(P \approx 5\%)$

consistency check:

$P_{\rm PG} = 1.2 \times 10^{-5}$

Energy spectrum of the modulation



energy shape of the modulation is important

Chang, Pierce, Weiner, 0808.0196
Fairbairn, TS, 0808.0704

The Channeling effect

Quenching:

DAMA observes scintillation light $\Rightarrow$ measures energy in “electron equivalent” (keVee)

only a fraction q of nuclear recoil energy E_R is observable as scintillation signal in DAMA:

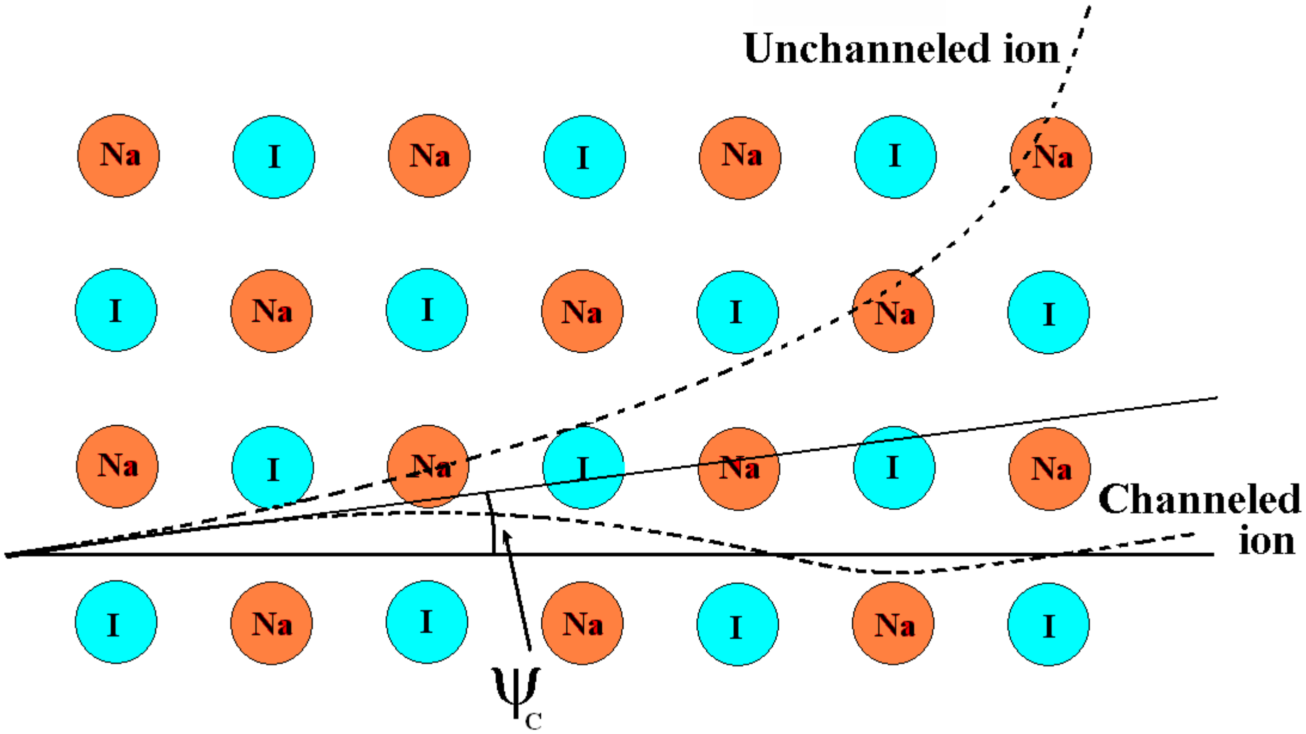
$$E_{\rm obs} = q \times E_R$$

with $q_{\rm Na} = 0.3, \; q_{\rm I} = 0.09$

$\Rightarrow$ the energy threshold of 2 keVee implies a threshold in E_R of 6.7 keV for Na and 22 keV for I.

The Channeling effect

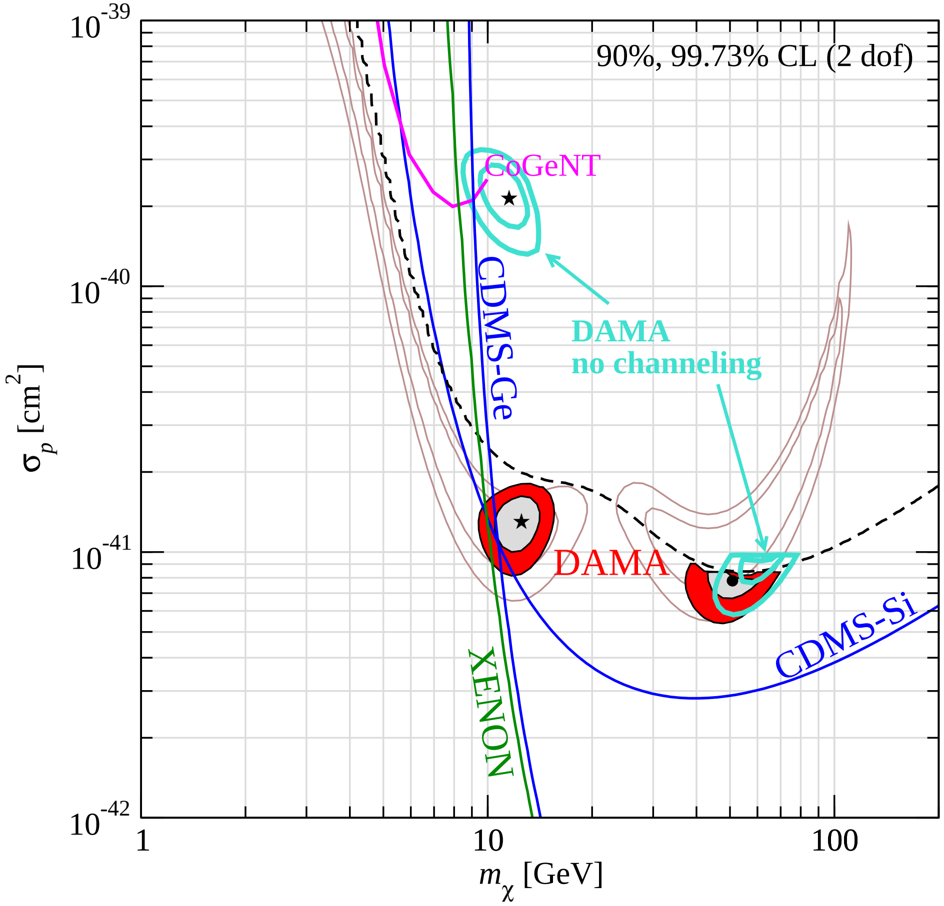
Drobyshevski, 0706.3095; Bernabei et al., 0710.0288



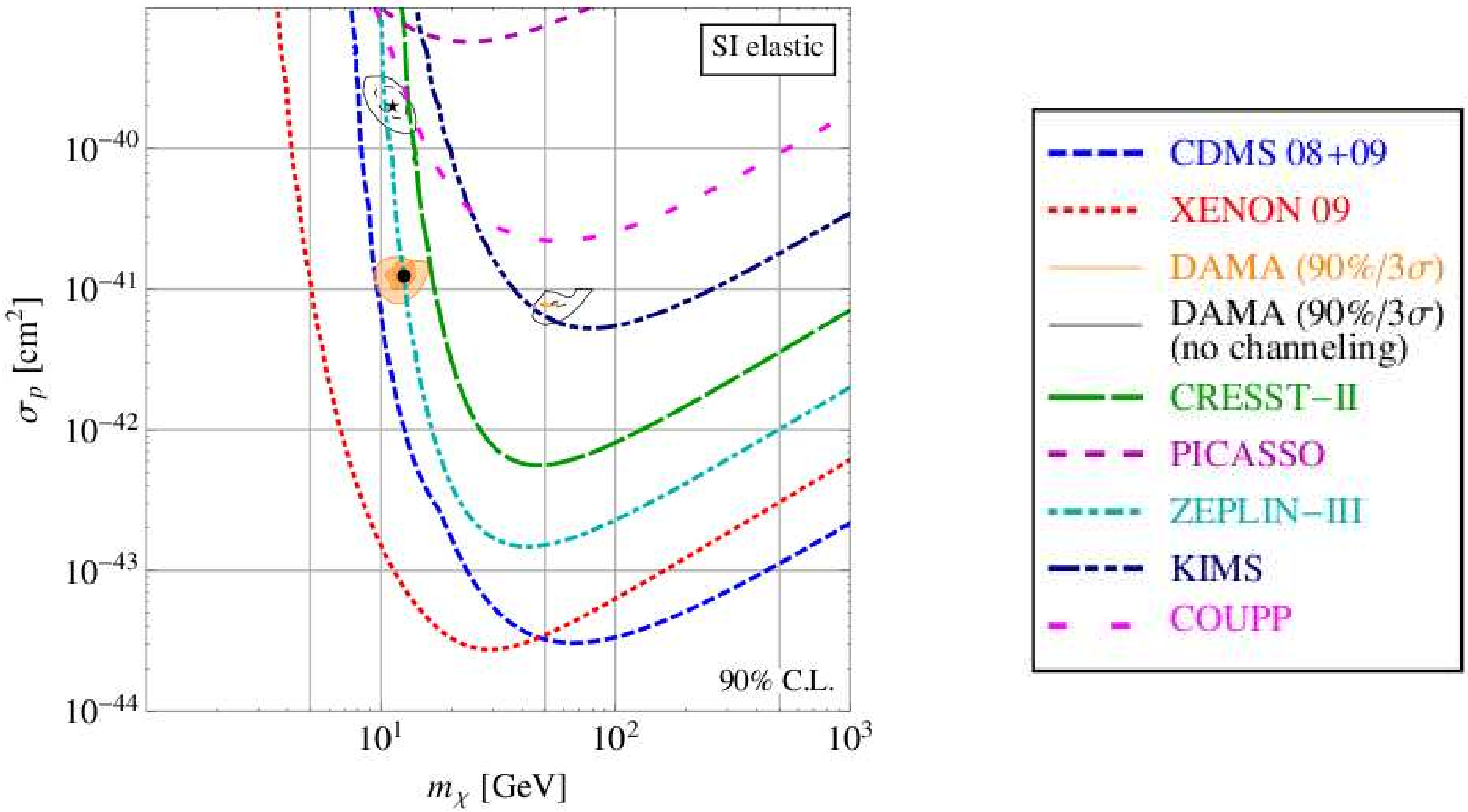
with a certain probability a recoiling nucleus will not interact with the crystal but loose its energy only electro-magnetically

for such "channeled" events $q \approx 1$

The Channeling effect



eSI (Jan 2010)



Kopp, Schwetz, Zupan, 0912.4264

elastic spin-dependent (eSD) scattering

Spin-dependent scattering

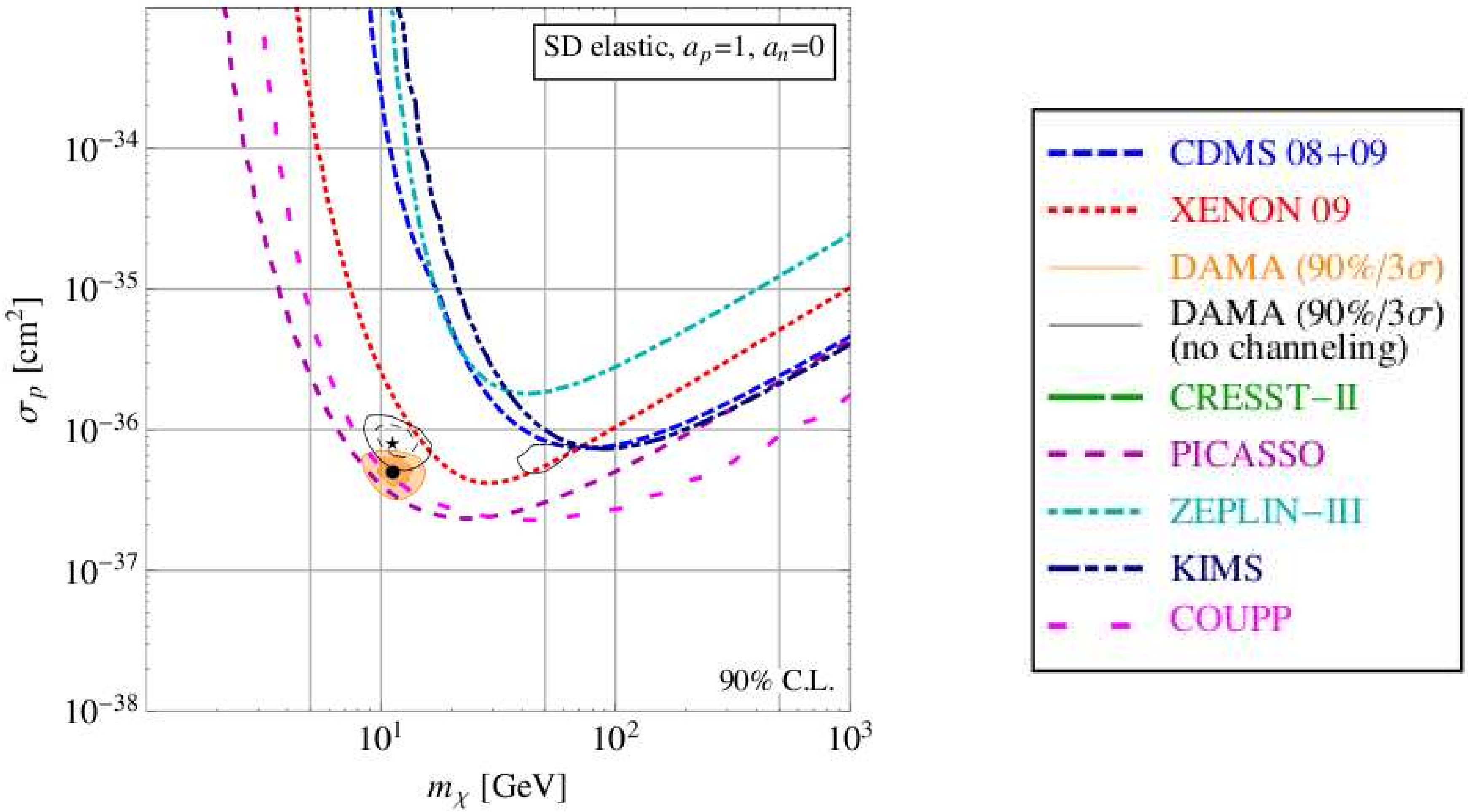
coupling mainly to an un-paired nucleon:

		neutron	proton
DAMA	$^{23}_{11}$Na	even	odd
DAMA, KIMS, COUPP	$^{127}_{53}$I	even	odd
XENON, ZEPLIN	$^{129}_{54}$Xe, $^{131}_{54}$Xe	odd	even
CDMS	$^{73}_{32}$Ge	odd	even
PICASSO, COUPP	$^{19}_{9}F$	even	odd

coupling with proton promising for DAMA vs CDMS/XENON

BUT: severe bounds from COUPP, KIMS, PICASSO

eSD off protons

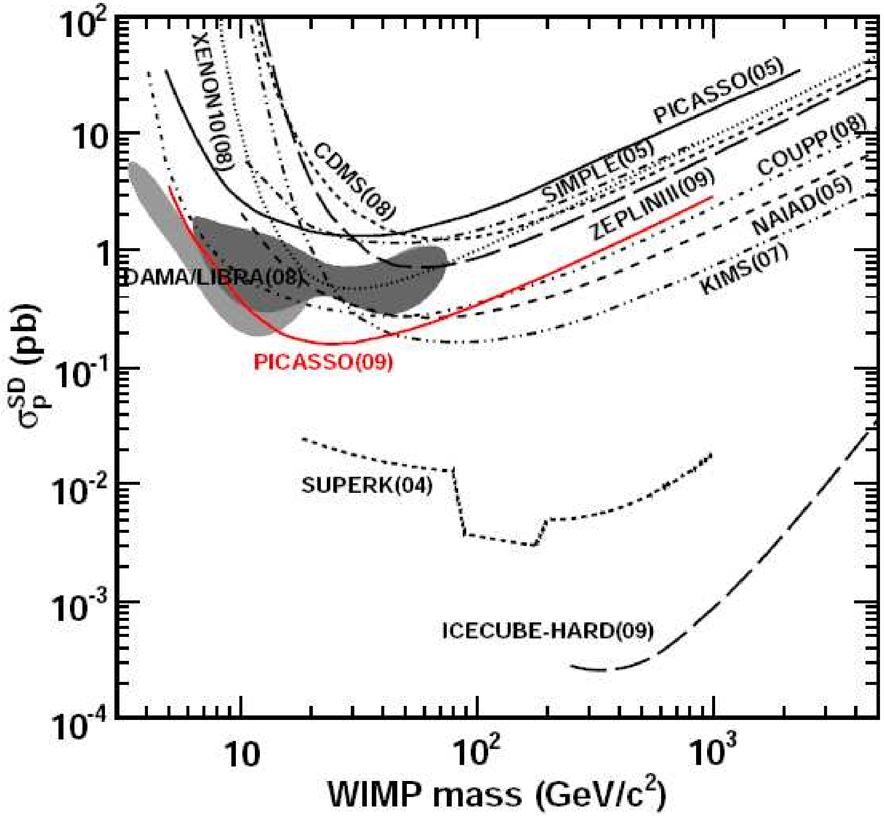


Kopp, Schwetz, Zupan, 0912.4264

Neutrino constraints on eSD

bounds on neutrinos from DM annihilations in the sun from Super-Kamiokande / IceCube

Savage, Gelmini, Gondolo, Freese, 0808.3607
Hooper, Petriello, Zurek, Kamionkowski, 0808.2464



S. Archambault et al., 0907.0307

A signal in CDMS?

Signal in CDMS?

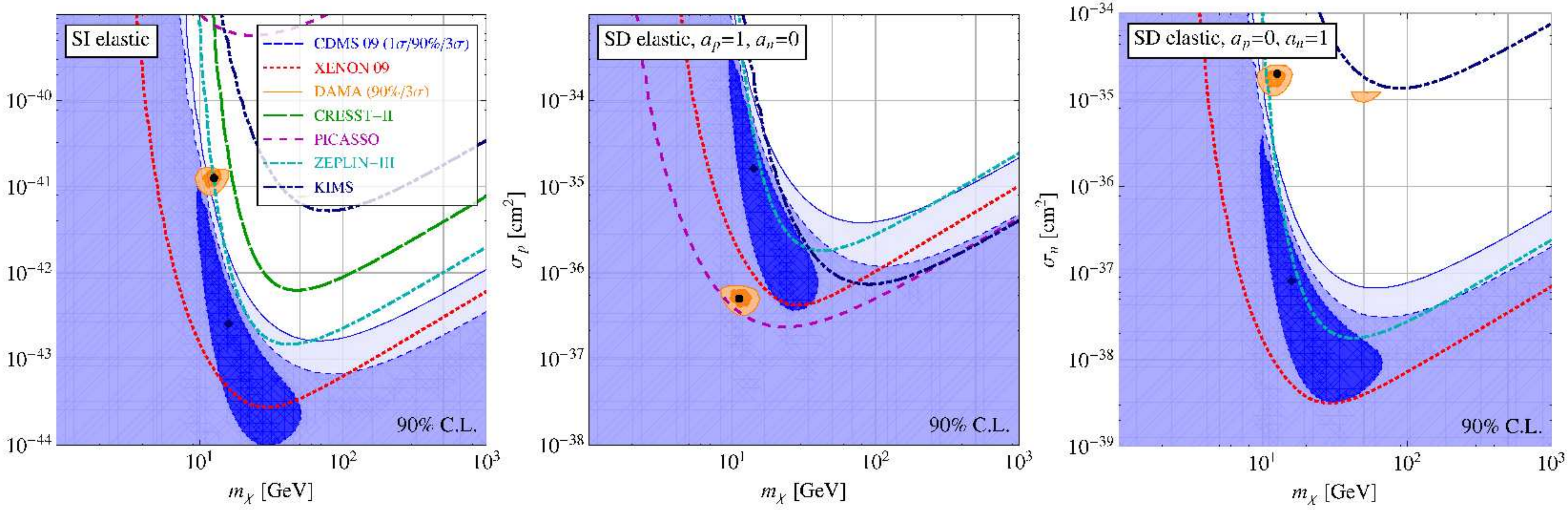
Sofar we haved used CDMS only to set an upper bound ("maximum gap method").

Let us assume for a moment that the two observed events are due to a DM signal

+ a spectral shape for the expected background

$\Rightarrow$ perform a maximum-likelihood fit to CDMS data

Signal in CDMS?



closed region only at 68% CL
disfavoured by XENON10 (PICASSO)
in combined fit no closed contour even at 68% CL

we will know very soon from XENON100

inelastic scattering

Tucker-Smith, Weiner, hep-ph/0101138

many studies:
Tucker-Smith, Weiner, hep-ph/0402065;
Chang, Kribs, Tucker-Smith, Weiner, 0807.2250;
March-Russell, McCabe, McCullough, 0812.1931;
Cui, Morrissey, Poland, Randall, 0901.0558;
Arina, Ling, Tytgat, 0907.0430;
Schmidt-Hoberg, Winkler, 0907.3940;
Kopp, Schwetz, Zupan, 0912.4264;
Shu, Yin, Zhu, 1001.1076;
McCullough, Fairbairn, 1001.2737; . . .

Inelastic DM scattering

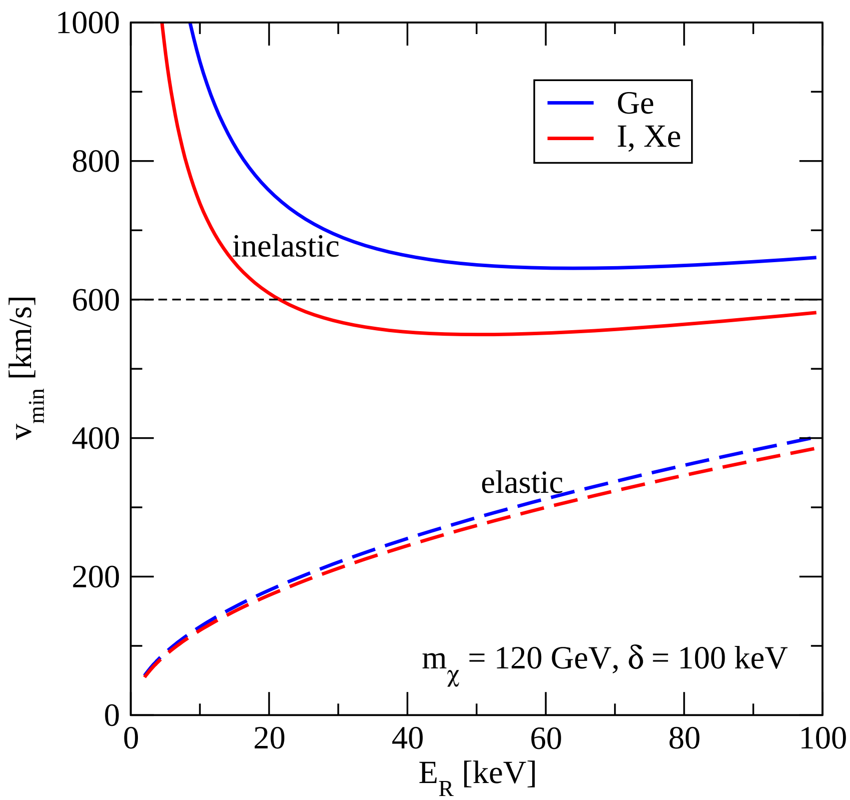
- in addition to the DM χ there exists an excited state χ^*, with a mass splitting

$$m_{\chi^*} - m_\chi = \delta \simeq 100\,\text{keV} \sim 10^{-6} m_\chi$$

- elastic scattering $\chi + N \to \chi + N$ is suppressed with respect to inelastic scattering

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

iDM kinematics

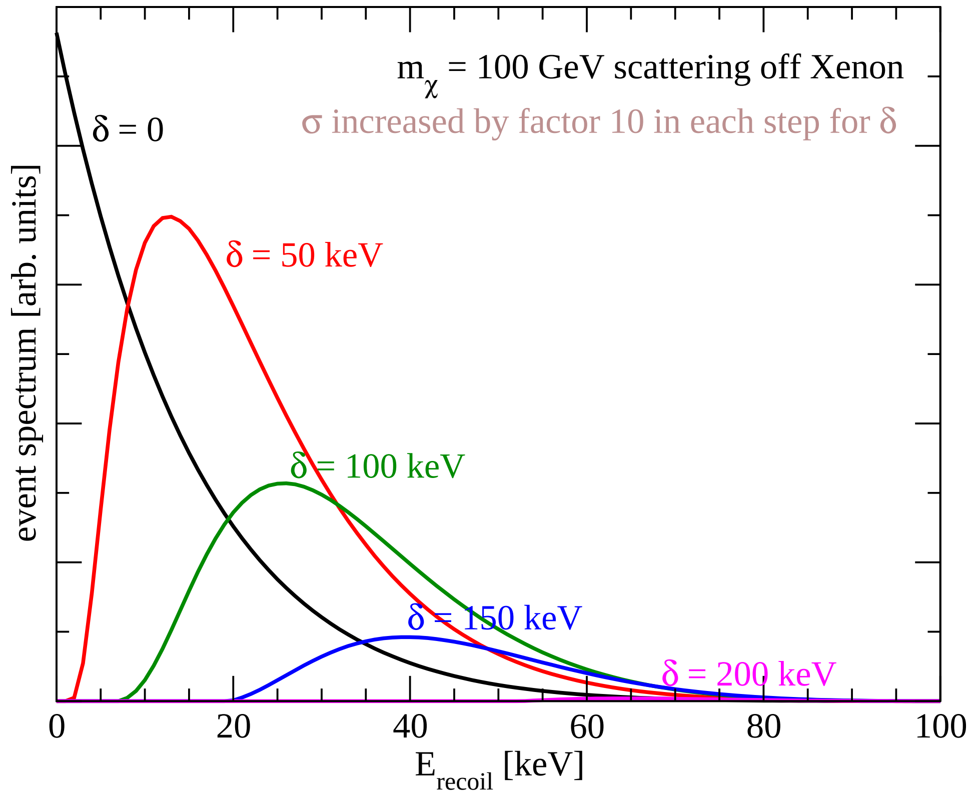


$$v_{\text{min}}^{\text{inel}} = \frac{1}{\sqrt{2ME_R}}\left(\frac{ME_R}{\mu_\chi} + \delta\right)$$

$$v_{\text{min}}^{\text{el}} = \sqrt{\frac{ME_R}{2}}\frac{1}{\mu_\chi}$$

- sampling only high-velocity tail of velocity distribution
- no events at low recoil energies
- targets with high mass are favoured

iDM kinematics

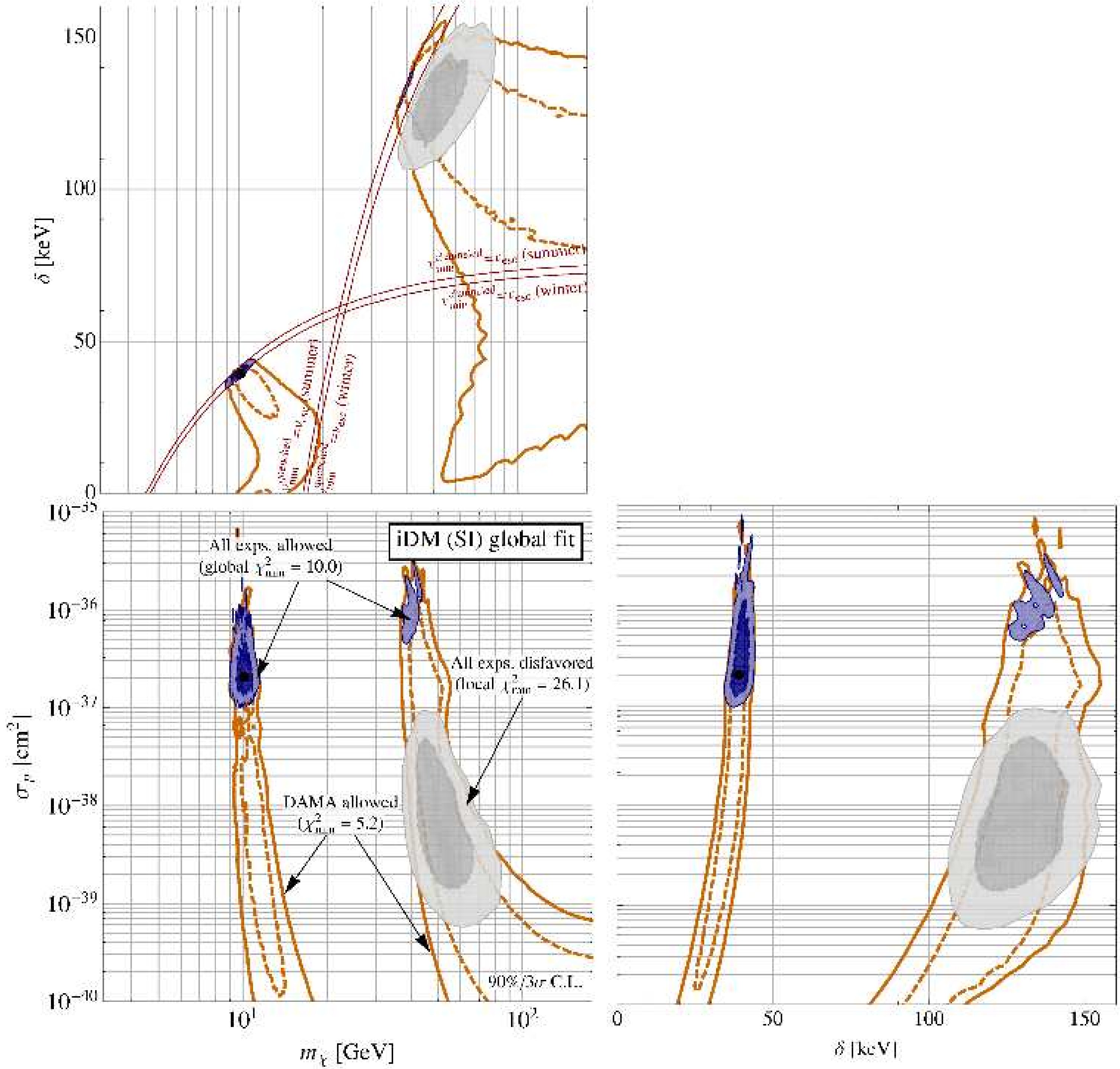


$$v_{\min}^{\rm inel} = \frac{1}{\sqrt{2ME_R}}\left(\frac{ME_R}{\mu_\chi} + \delta\right)$$

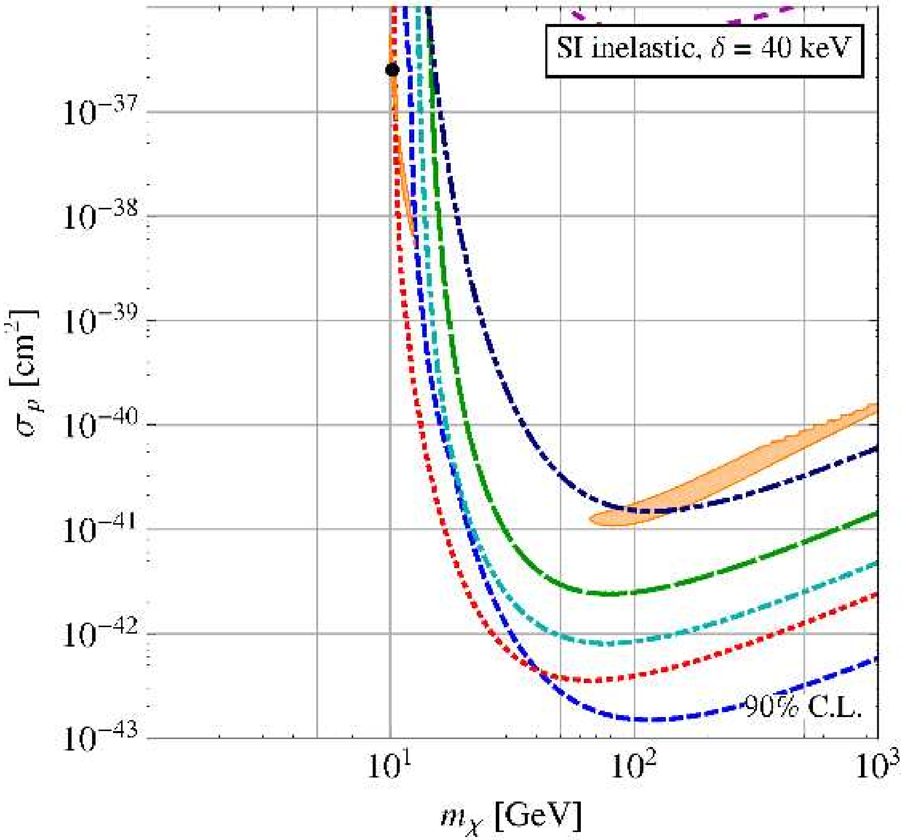
$$v_{\min}^{\rm el} = \sqrt{\frac{ME_R}{2}\frac{1}{\mu_\chi}}$$

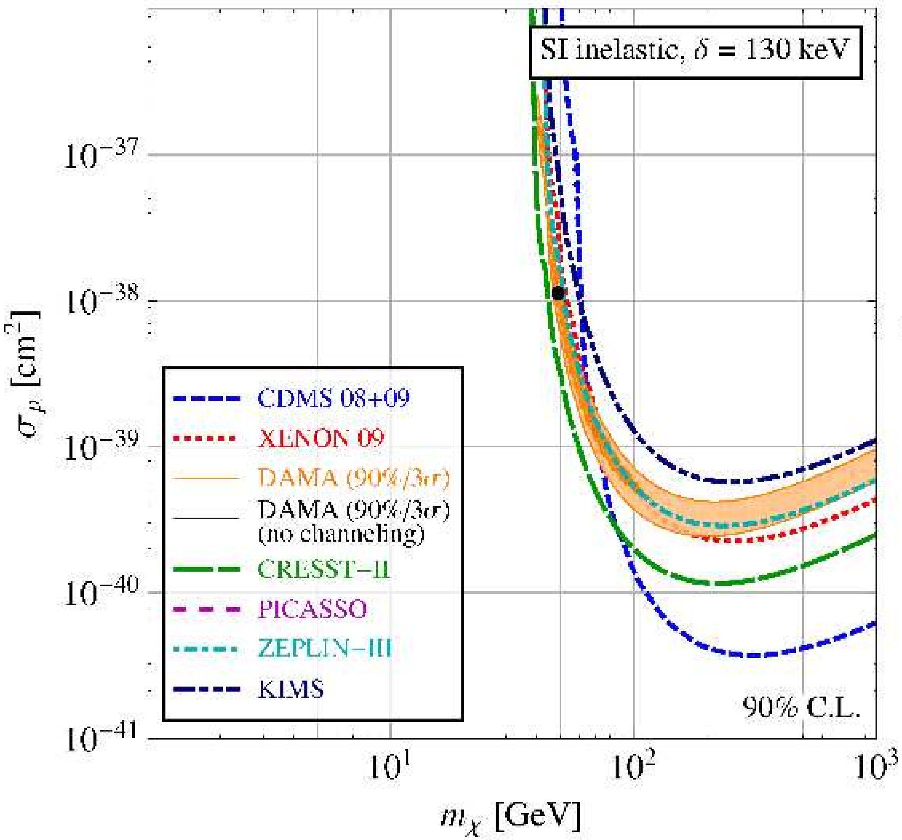
- sampling only high-velocity tail of velocity distribution
- no events at low recoil energies
- targets with high mass are favoured

inelastic spin-independent (iSI) scattering


iDM (SI) global fit
All exps. allowed
(global χ^2_{min} = 10.0)
All exps. disfavored
(local χ^2_{min} = 26.1)
DAMA allowed
(χ^2_{min} = 5.2)
90%/3σ C.L.
(summer)
(winter)
δ [keV]
σ_p [cm²]
m_χ [GeV]

iSI





$m_\chi \simeq 10\,\mathrm{GeV}$, $\delta \simeq 40\,\mathrm{keV}$

from channeled events

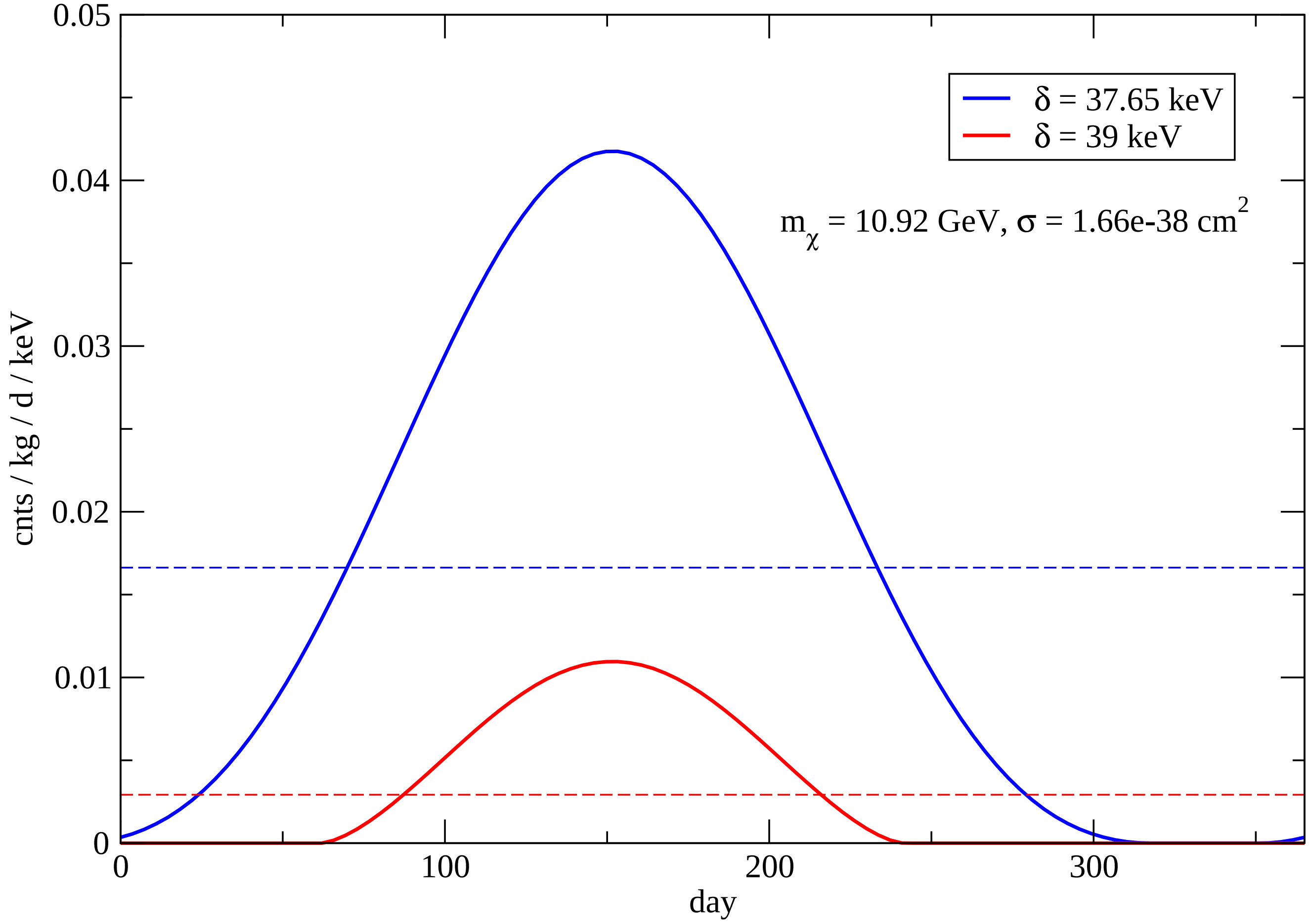
$m_\chi \simeq 50\,\mathrm{GeV}$, $\delta \simeq 130\,\mathrm{GeV}$

quenched events

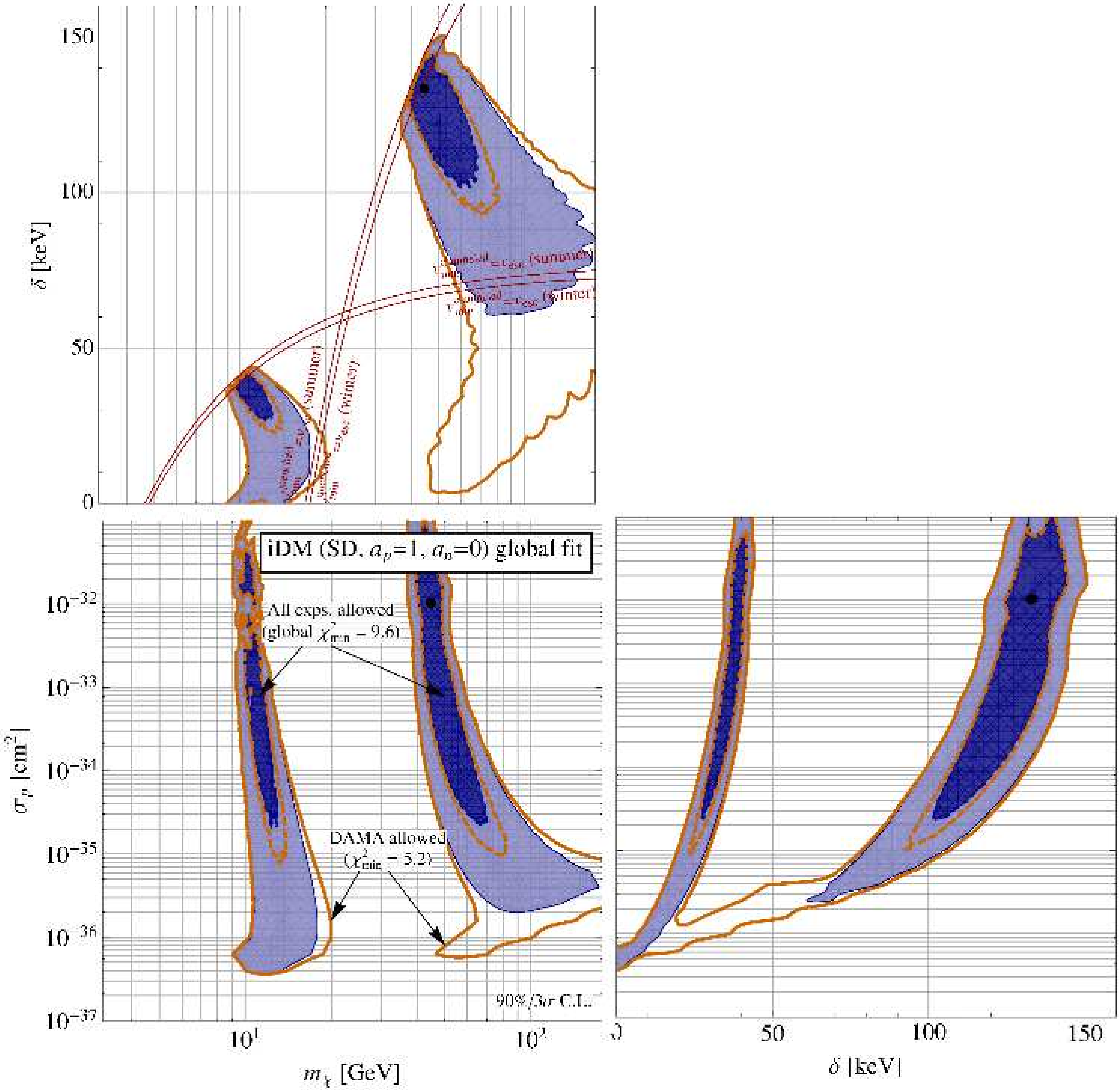
disfavored by CRESST (tungsten)

iSI

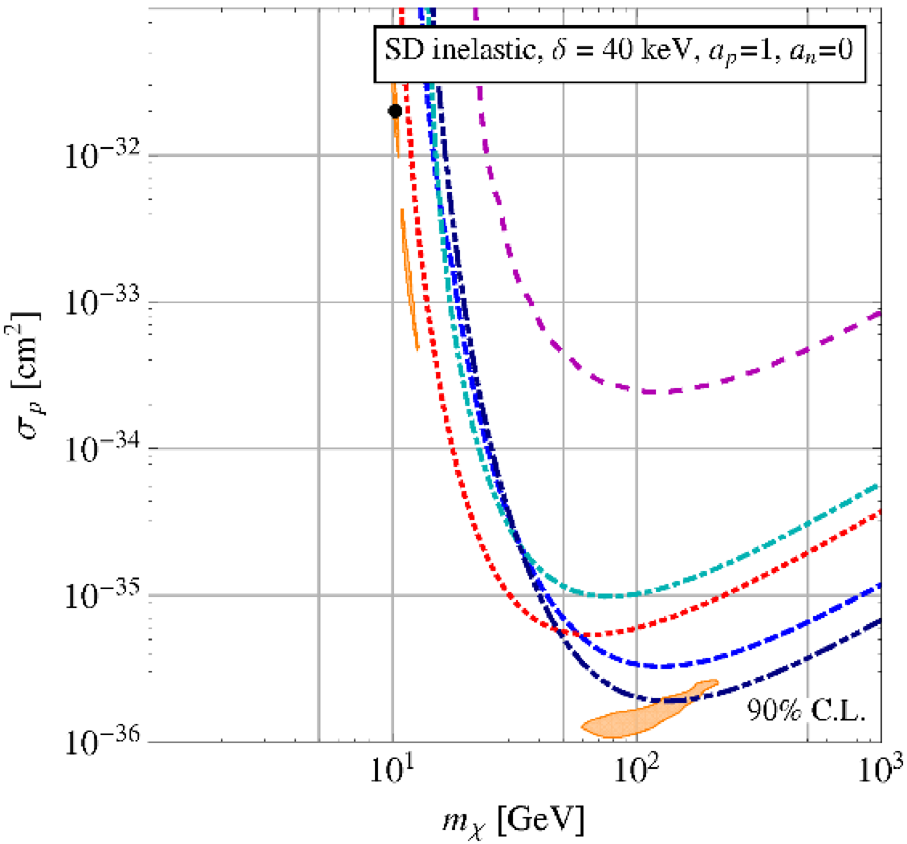
$v_{\rm min}$ relevant for the DAMA signal is tuned exactly to the galactic escape velocity:

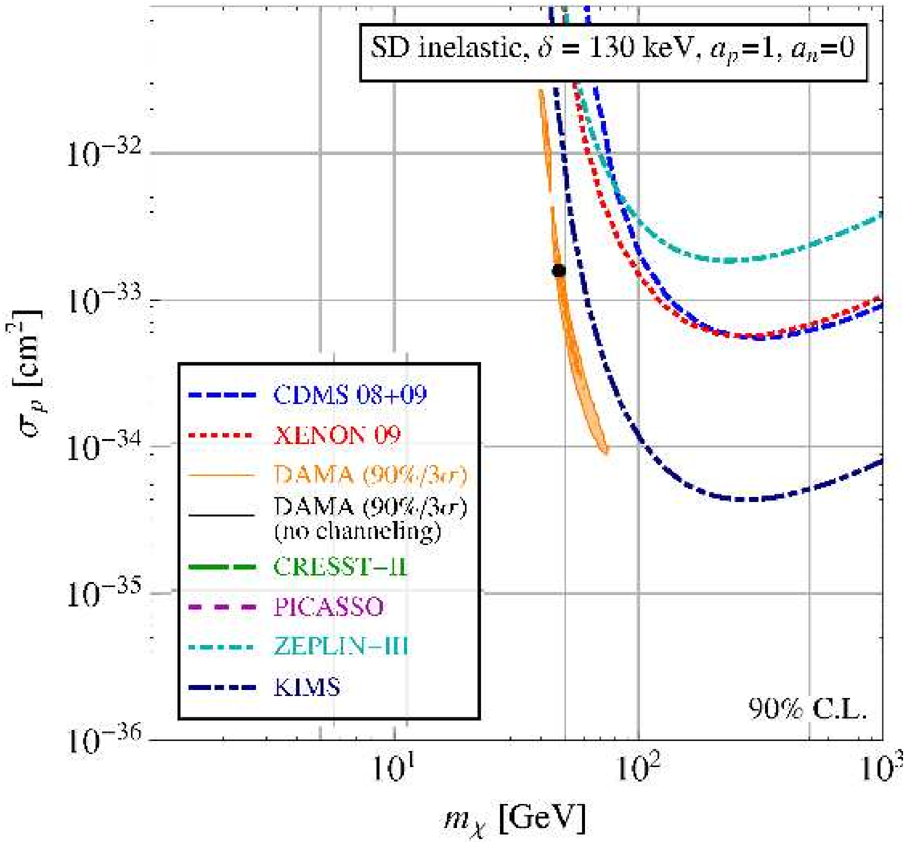


inelastic spin-dependent (iSD) scattering


iDM (SD, a_p=1, a_n=0) global fit
All exps. allowed
(global χ^2_{min} = 9.6)
DAMA allowed
(χ^2_{min} = 5.2)
90%/3σ C.L.
δ [keV]
σ_p [cm^2]
m_χ [GeV]
δ [keV]

iSD on protons





$m_\chi \simeq 10\,\mathrm{GeV}$, $\delta \simeq 40\,\mathrm{keV}$

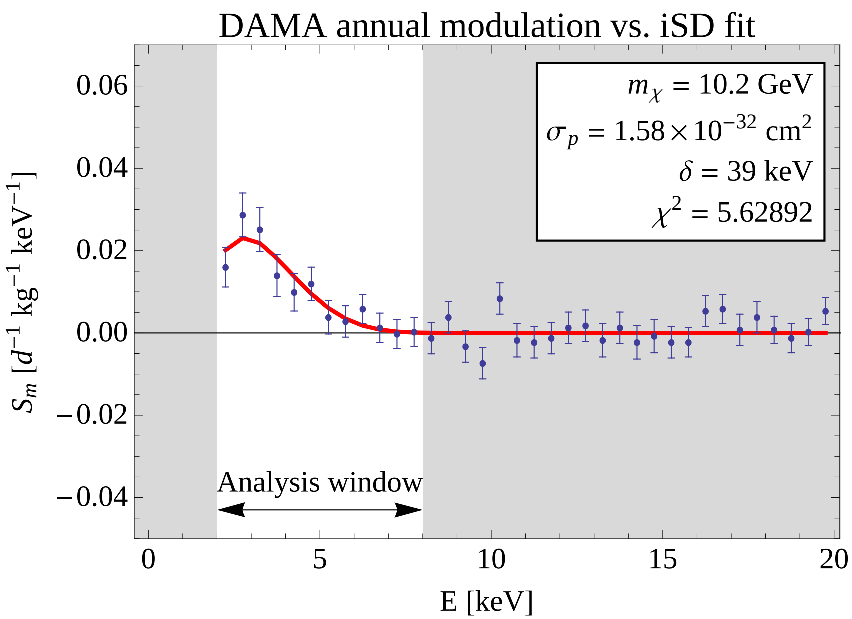
from channeled events

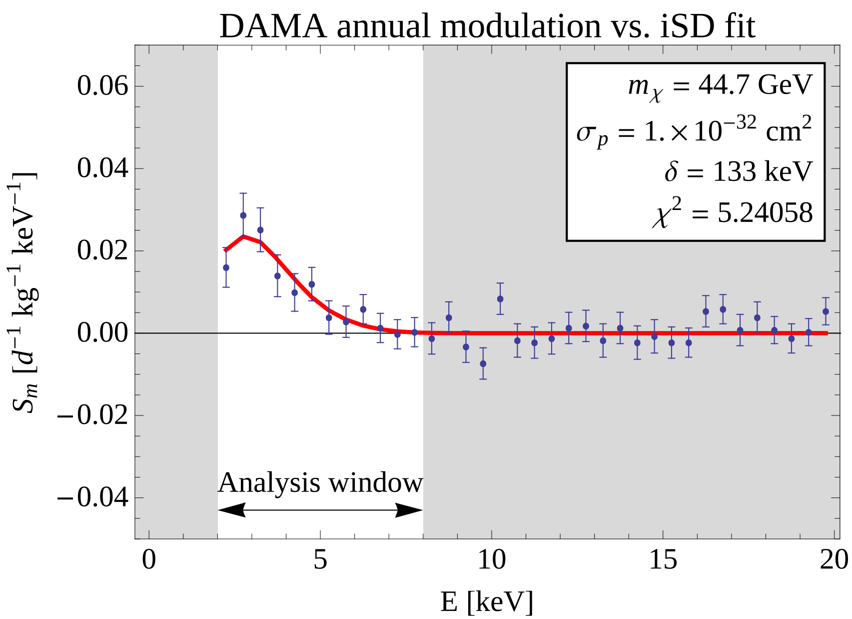
$m_\chi \simeq 50\,\mathrm{GeV}$, $\delta \simeq 130\,\mathrm{GeV}$

quenched events

iSD on protons

- good fit to DAMA spectrum:

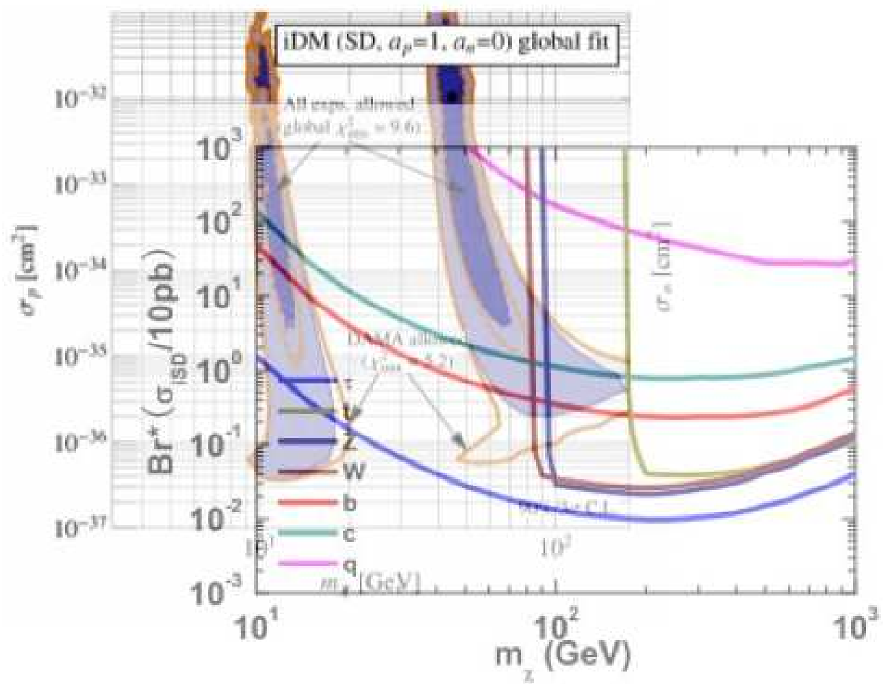




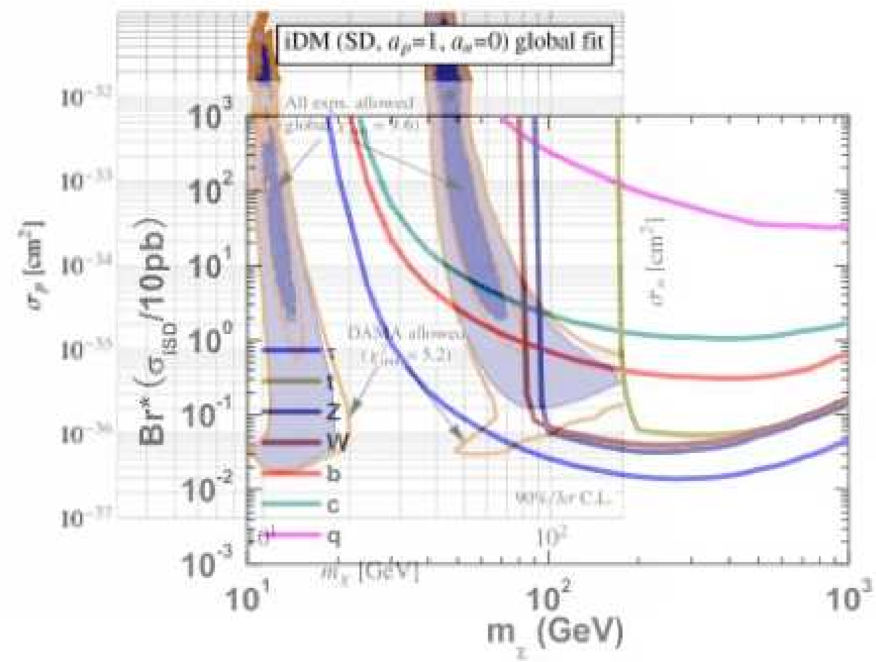
- no tuning wrt to $v_{\rm esc}$ needed
- SD coupling to proton gets rid of XENON/CDMS/CRESST bounds (no unpaired proton)
- inelastic scatt. gets rid of PICASSO/COUPP (light target)

iSD on protons - neutrino constraints

$\delta = 40\,\mathrm{keV}$



$\delta = 130\,\mathrm{keV}$



Shu, Yin, Zhu, 1001.1076

constraints from SuperK on high-energy neutrinos from DM annihilations inside the sun

iSD - toy model

generalize idea of Tucker-Smith, Weiner, hep-ph/0101138 to SD couplings:

assume 4-Fermi interaction with $T \otimes T$ structure:

$$\mathcal{L}_{\rm int} = \frac{C_{\rm T}}{\Lambda^2} \left[\bar\psi \Sigma_{\mu\nu} \psi\right] \left[\bar q \Sigma^{\mu\nu} q\right] , \qquad \Sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$$

$\psi = (\eta, \xi^\dagger)$ with Dirac $m\bar\psi\psi$ and Majorana mass $(\delta_\eta \eta\eta + \delta_\xi \xi\xi)/2$

$\Rightarrow$ two Majorana fermions with masses $m \pm \delta$ ($\delta_\eta = \delta_\xi = \delta \ll m$):

$$\chi_1 = i(\eta - \xi)/\sqrt{2}, \qquad \chi_2 = (\eta + \xi)/\sqrt{2}$$

$$\Rightarrow \quad \bar\psi \Sigma_{\mu\nu} \psi = -2i(\chi_2 \sigma_{\mu\nu} \chi_1 + \chi_2^\dagger \bar\sigma_{\mu\nu} \chi_1^\dagger) ,$$

- inelastic scattering for $\delta \neq 0$
- $T \otimes T$ leads to spin dependent scattering in the non-rel. limit

more ideas to reconsile DAMA?

More ideas

astro physics:

- non-standard halos
  Fairbairn, Schwetz, 0808.0704; March-Russell, McCabe, McCullough, 0812.1931
- DM streams
  Gondolo, Gelmini, hep-ph/0504010; Chang, Pierce, Weiner, 0808.0196

particle physics:

- mirror DM Foot, 0804.4518
- DM with electric/magn. moments Masso, Mohanty, Rao, 0906.1979
- resonant DM scattering Bai, Fox, 0909.2900
- momentum dep. DM scattering Chang, Pierce, Weiner, 0908.3192
- form factor DM Feldstein, Fitzpatrick, Katz, 0908.2991
- leptophilic DM Bernabei et al., 0712.0562; Kopp, Niro, Schwetz, Zupan, 0907.3159
- . . .

More ideas

astro physics:

- non-standard halo…
  Fairbairn, Sch… …04; March-Russell, McCabe, McCullough, 0812.1931
- D… …eams
  Gondolo, Gelmini, hep-ph/0504010; Chang, Pierce, Weiner, 0808.0196

only modest improvement by extreem assumptions on astro physics

particle physics:

- mirror DM Foot, 0804.4518
- DM with electric/magn. moment… …ohanty, Rao, 0906.1979
- resonant DM scatteri… …x, 0909.2900
- momentu… …DM scattering Chang, Pierce, Weiner, 0908.3192
- …actor DM Feldstein, Fitzpatrick, Katz, 0908.2991
- leptophilic DM Bernabei et al., 0712.0562; Kopp, Niro, Schwetz, Zupan, 0907.3159
- . . .

most of these ideas work only marginally - at best . . .

leptophilic DM?

DM scattering off electrons

- DAMA looks for the annual modulation of their (relat. large) count rate from scintillation light
  $\Rightarrow$ pure electron events fully contribute
- CDMS, XENON10, CRESST, KIMS, ZEPLIN,. . .
  reject electron events to perform a low background search for nuclear recoils.

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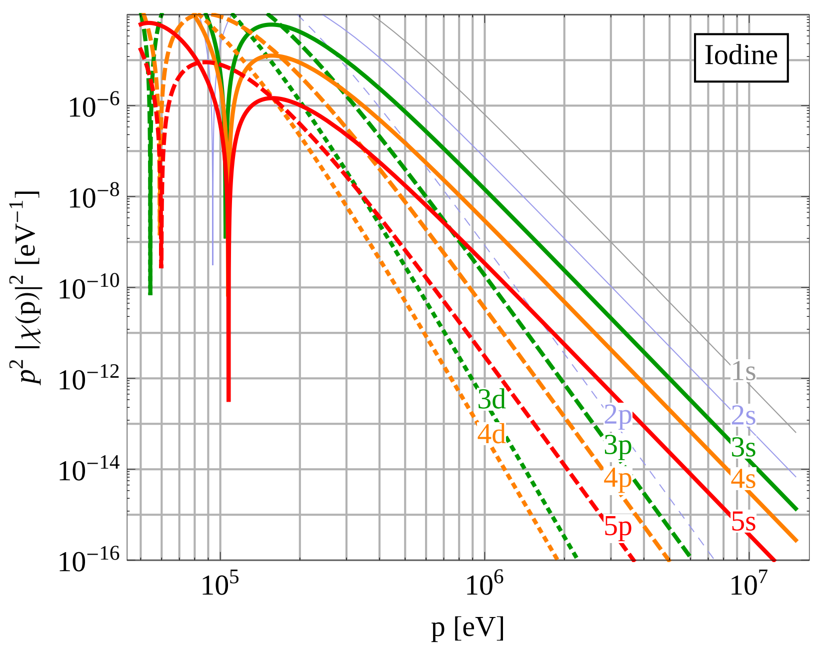
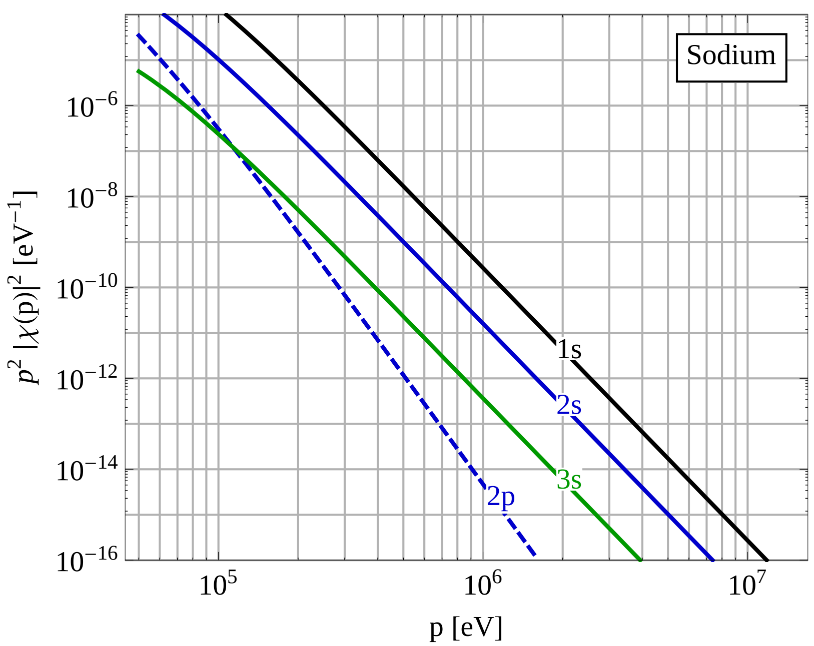
- PAMELA, ATIC, FERMI see an anomaly in cosmic electrons/positrons, but not in anti-protons
  $\Rightarrow$ Has DM a special affinity to leptons?

DM scattering off electrons

DM scattering off electrons at rest: recoils of order $m_e v^2 \sim$ eV cannot account for the DAMA signal at few keV

$\Rightarrow$ bound electrons with $p \sim$ MeV, Bernabei et al., 0712.0562

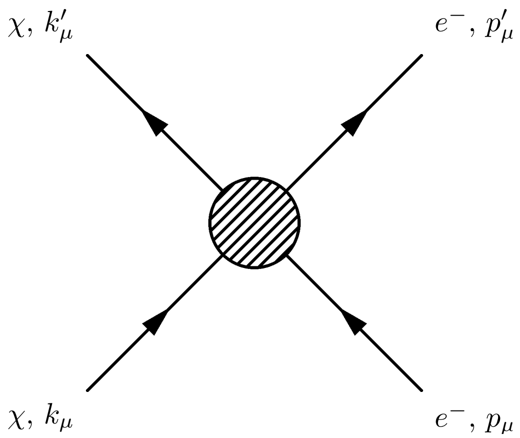




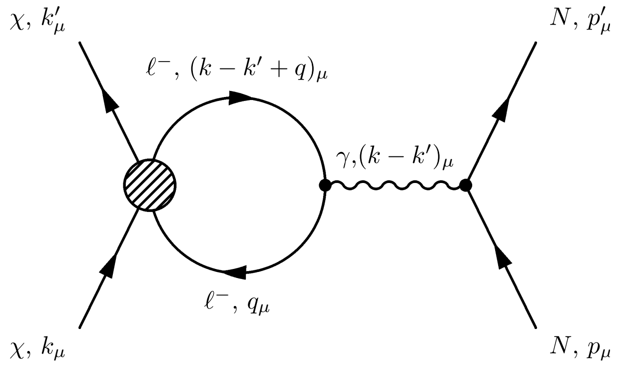
wave function suppression of count rate $\sim 10^{-6}$

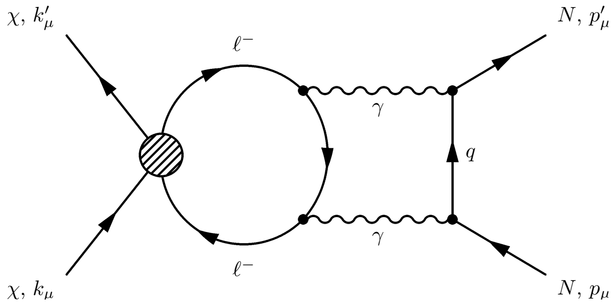
Loop induced DM-nucleus scattering

suppose an effective interaction of DM with electrons:



this will induce DM-nucleus interactions at loop level:





Kopp, Niro, Schwetz, Zupan, 0907.3159

Electron vs Loop scattering

Whenever loop-induced DM-nucleon scattering is present (at 1 and 2-loop) it will dominate over scattering off electrons because of the wave function suppression

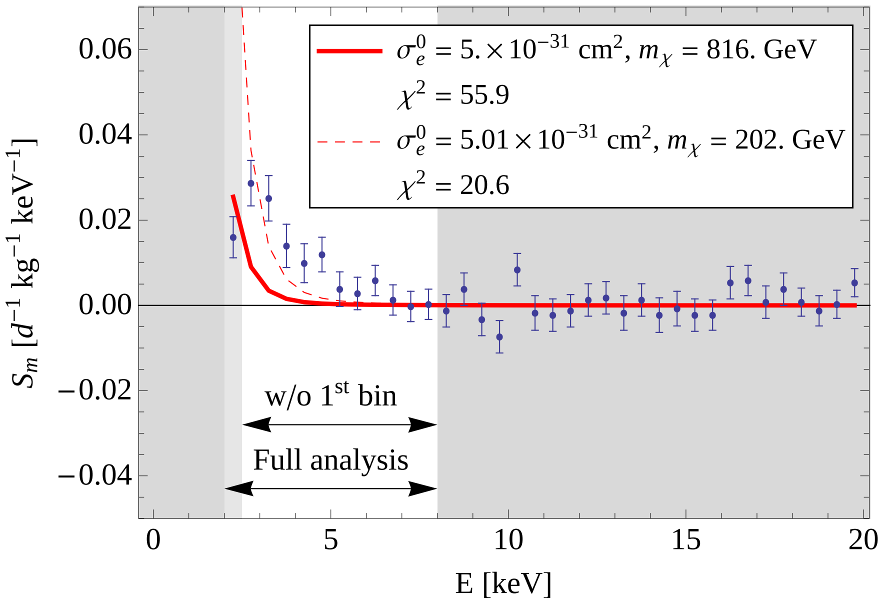
$\Rightarrow$ Have to forbid loop diagrams!

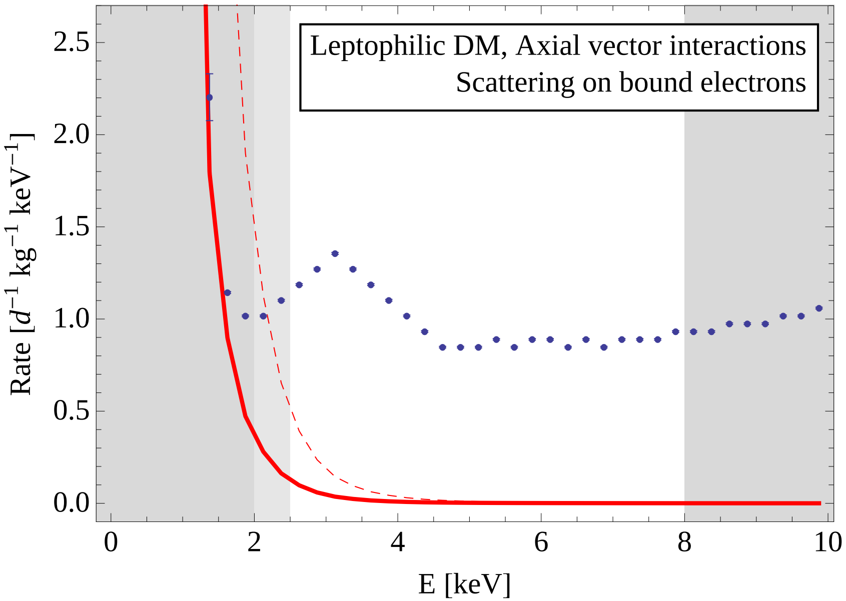
example: fermionic DM with axial-vector coupling

$$\mathcal{L}_{\rm eff} = G\,(\bar{\chi}\gamma_\mu\gamma_5\chi)\,(\bar{\ell}\gamma^\mu\gamma_5\ell) \qquad \text{with} \qquad G = \frac{1}{\Lambda^2}$$

Axial coupling without loop

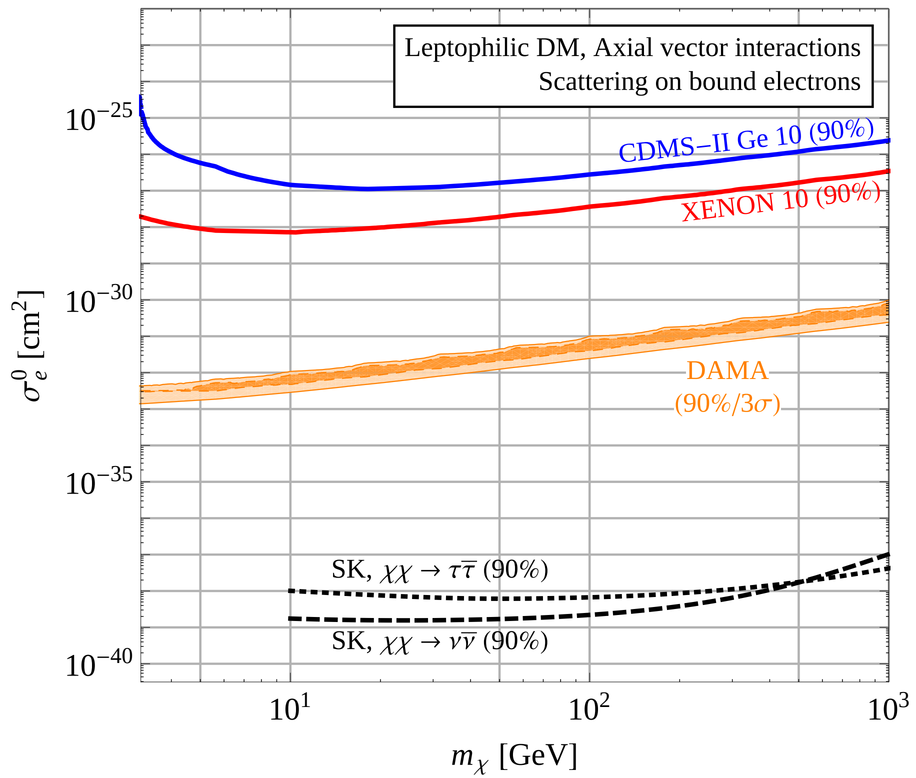
Best fit prediction for the modulated and unmodulated spectrum in DAMA from DM-electron scattering





$\Rightarrow$ disfavoured by spectral shape and constraint from unmodulated event rate

Axial coupling without loop



Kopp, Niro, TS, Zupan, 0907.3159

- very "large" cross sec:
  $\sigma^0_{\chi e} \sim 10^{-31}\,\mathrm{cm}^2 \times \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)$ requires $\Lambda \lesssim 0.1\,\mathrm{GeV}$
- excluded by SuperK constraints on neutrinos from DM annihilations in the sun

Conclusions

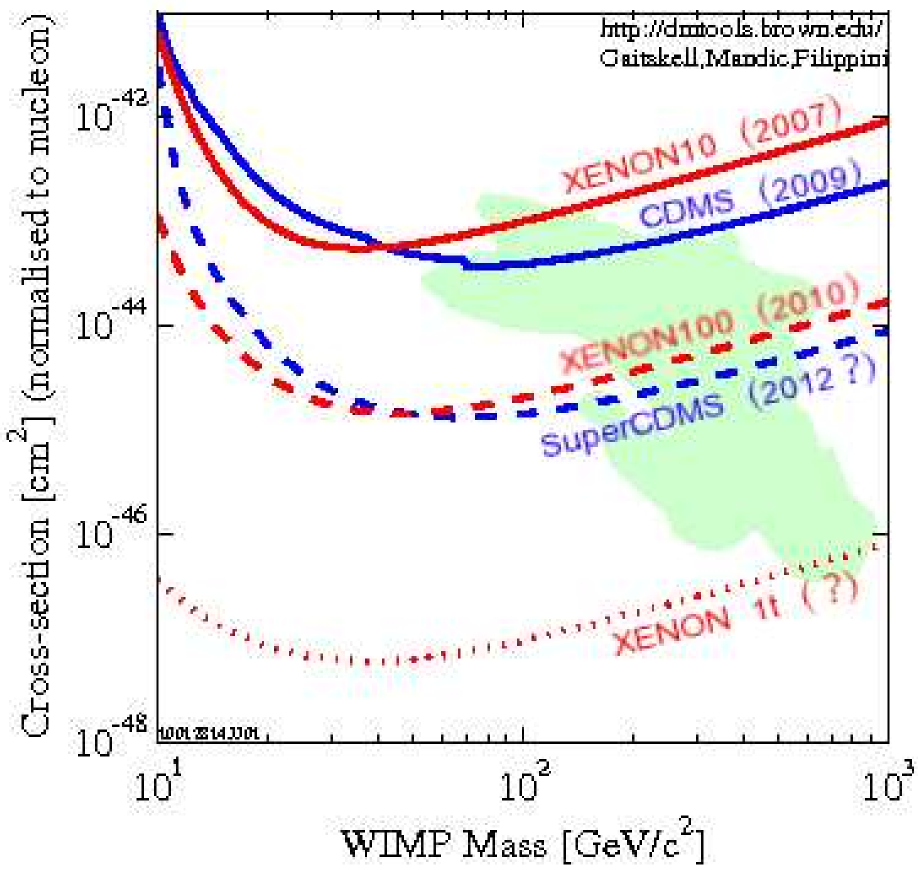
Conclusions

- Recent developements in direct DM detection:
  no conclusive signal (yet)
  CDMS: 2 events (background with 23% prob.)

- status of DAMA annual modulation:
  - eSI: disfavoured by XENON re-analysis
  - eSD: disfavoured by PICASSO/COUPP
  - iSI: disfavoured by CRESST, channeling, tuning wrt $v_{\rm esc}$
  - iSD: seems to work!

Outlook

significant improvement expected very soon from XENON100:




Thank you for your attention!