GGI Conference The DM Connection: Theory & Experiment

DM direct detection data and speculations on the low-mass WIMP region

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on-going collaboration with Joachim Kopp and Jure Zupan

Outline

- “low-mass” WIMPs: $5\,\mathrm{GeV} \lesssim m_\chi \lesssim 50\,\mathrm{GeV}$
  χ should not couple to Z^0 (LEP)
  see talks by N. Fornengo, T. Hambye for example models which can do it
- Hints for low-mass WIMPs from: (alphabetical order)
  CDMS?, CoGeNT?, CRESST?, DAMA?
- constraints from XENON10,100, CDMS-Si
- focus on elastic spin-independent scattering
- comment briefely on spin-dependent
  and inelastic scattering

Elastic spin-independent scattering

Event spectrum

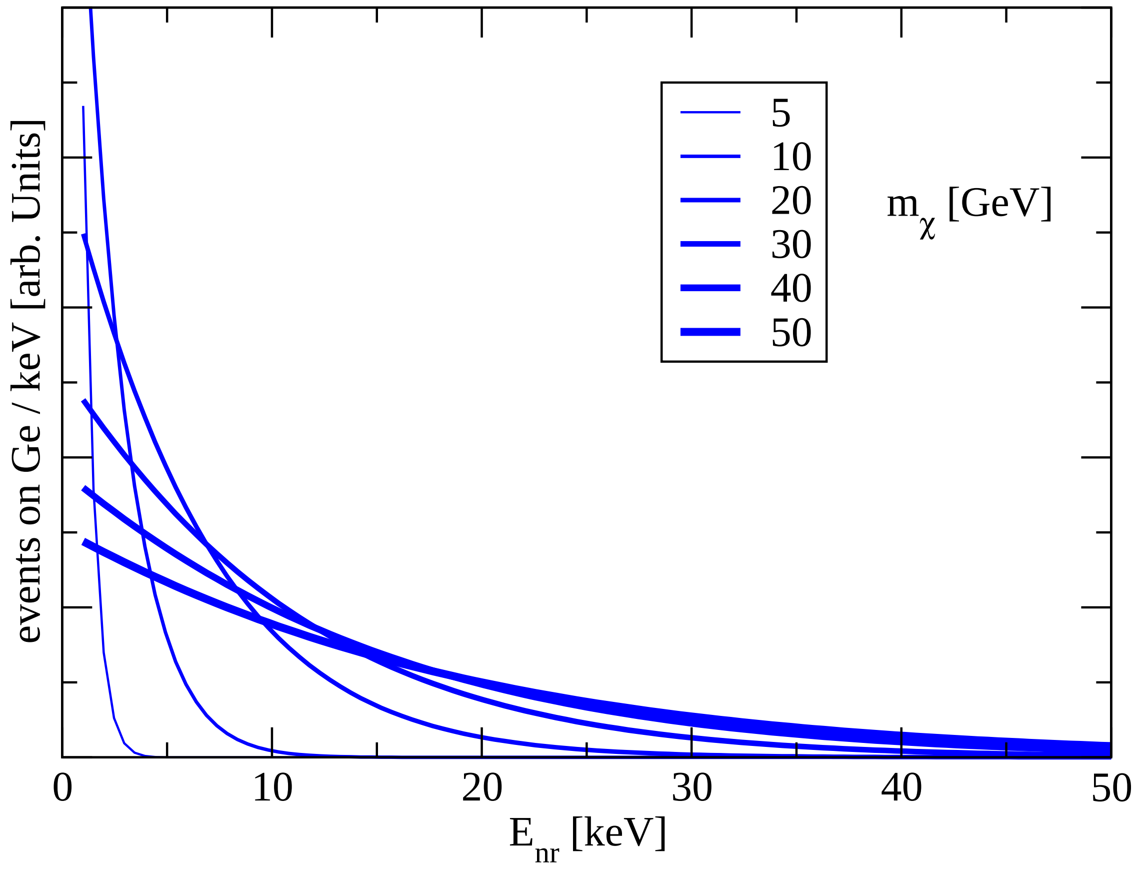
$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi}\,\frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2} \int_{v>v_{\min}(E_R)} d^3v\, \frac{f_\oplus(\vec{v},t)}{v}$$

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

$$v_{\min} = \frac{m_\chi + M}{m_\chi}\sqrt{\frac{E_R}{2M}} \quad \Rightarrow \quad m_\chi \ll M \; : \qquad v_{\min} \approx \frac{\sqrt{M E_R/2}}{m_\chi}$$

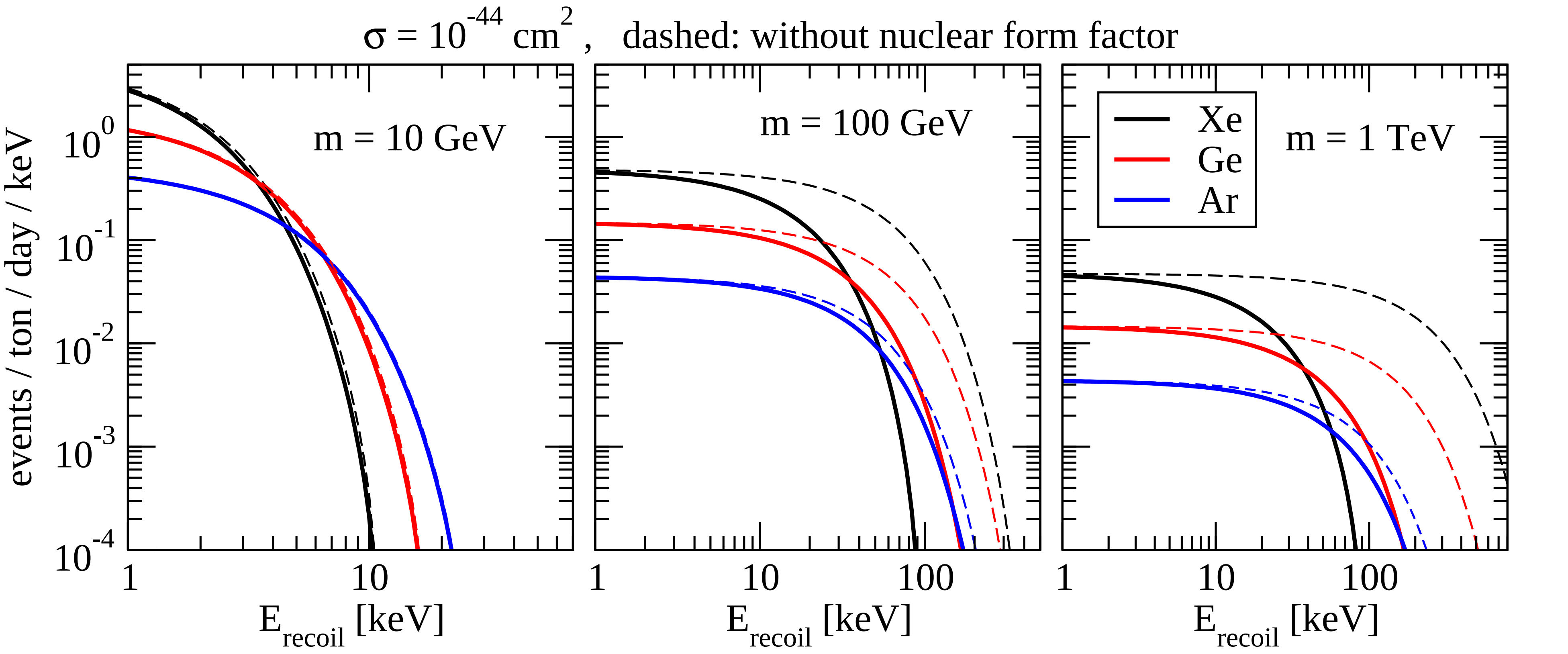
need light target and/or low threshold on E_R to see light WIMPs

Event spectrum



spectrum gets shifted to low energies for low WIMP masses $\Rightarrow$energy threshold is crucial

Event spectrum



nuclear form factor is less important for low mass WIMPs

low-mass WIMP hints

CDMS-II

CoGeNT

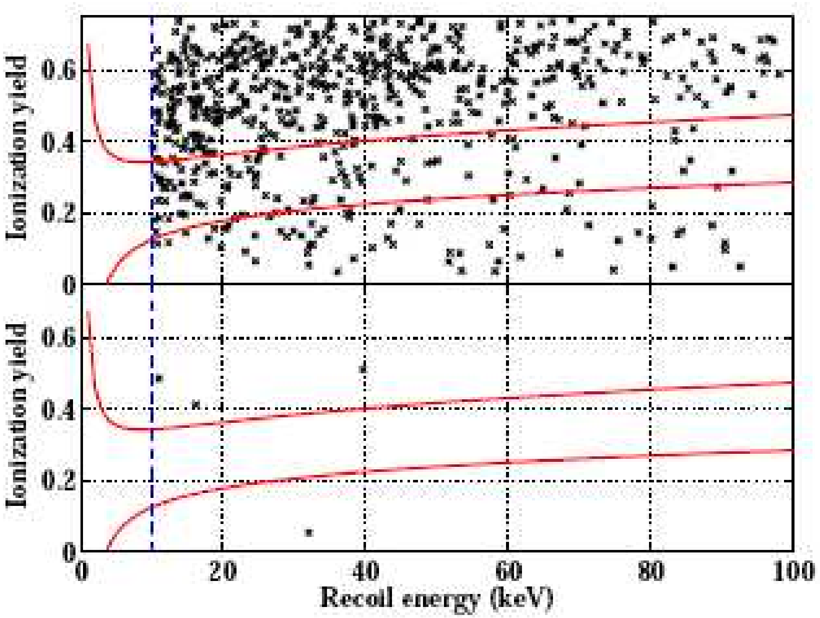
CRESST-II

DAMA

CDMS-II

Germanium detector, recoil energy range 10–100 keV

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

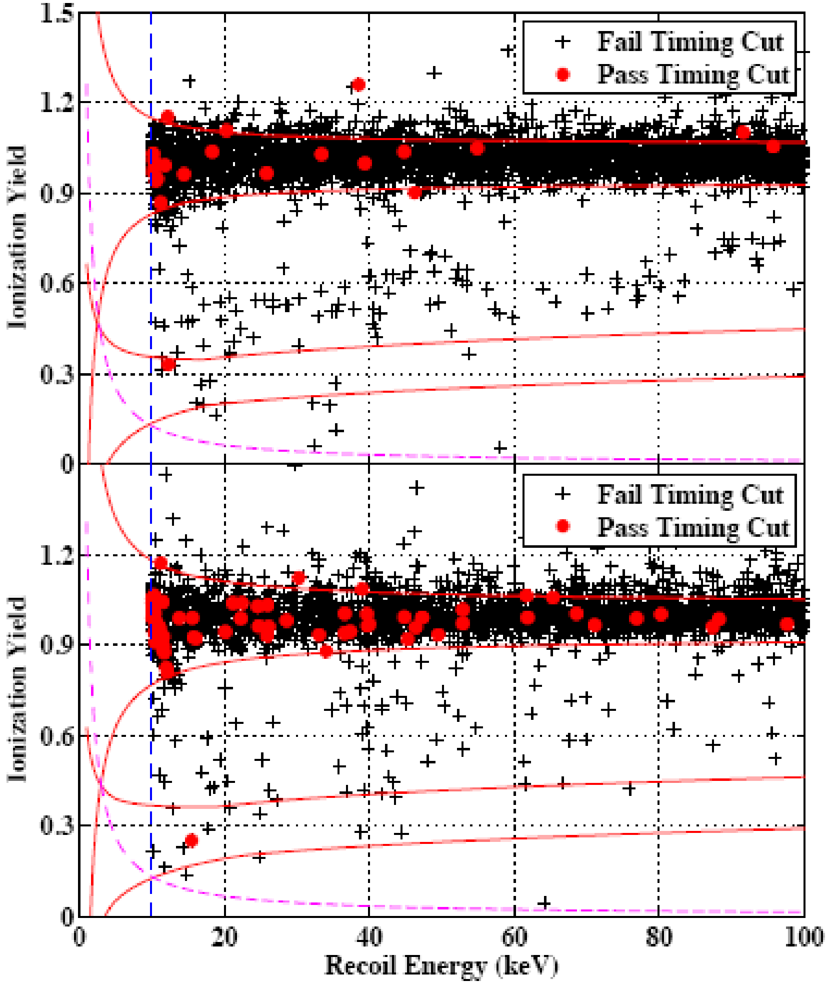


nuclear recoil signal region before (top) and after (bottom) timing cut

CDMS-II

Germanium detector, recoil energy range 10–100 keV

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

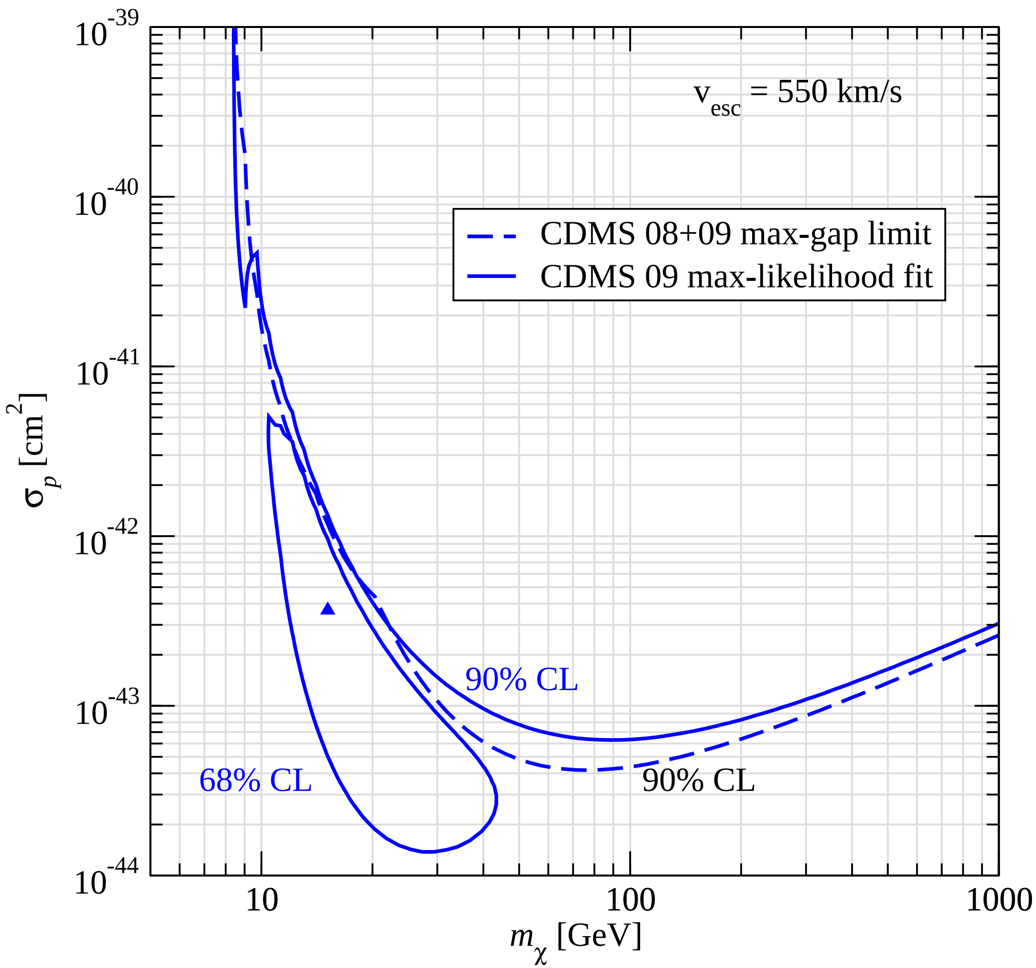


electron and nucl. recoil regions for two different detectors

candidates:
12.3 keV and 15.5 keV

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

CDMS-II



assuming a shape for the distribution of the 0.8 background events based on the event distr. shown in fig. 3 of 0802.3530 and performing a maximum likelihood fit to the two observed events (no uncert. on bckg number and shape included)

Kopp, Schwetz, Zupan, 0912.4264

low-mass WIMP hints

CDMS-II

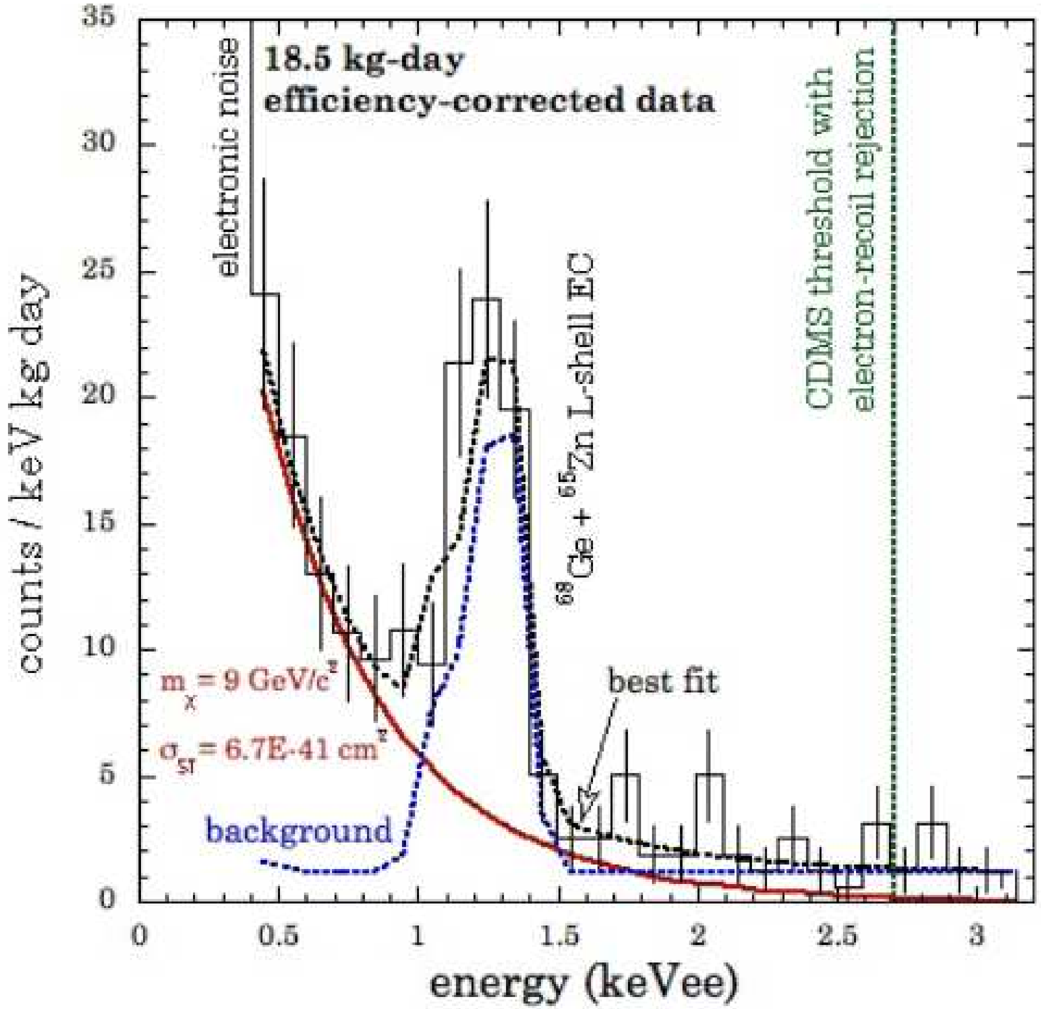
CoGeNT

CRESST-II

DAMA

CoGeNT

Germanium detector with extremely low threshold of 0.4 keVee

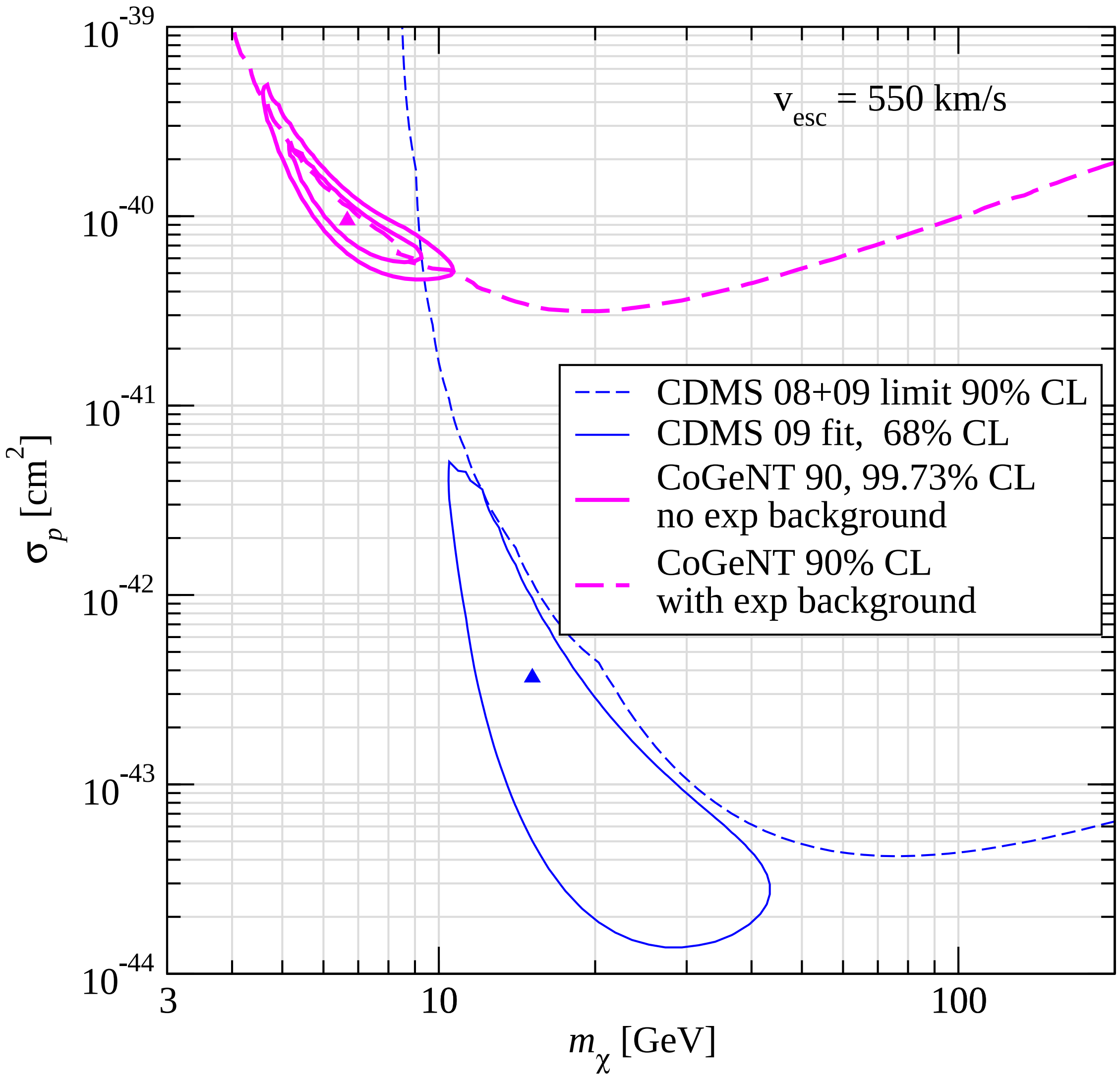


exponential rise of events at low energies

claim that it cannot be electronic noise

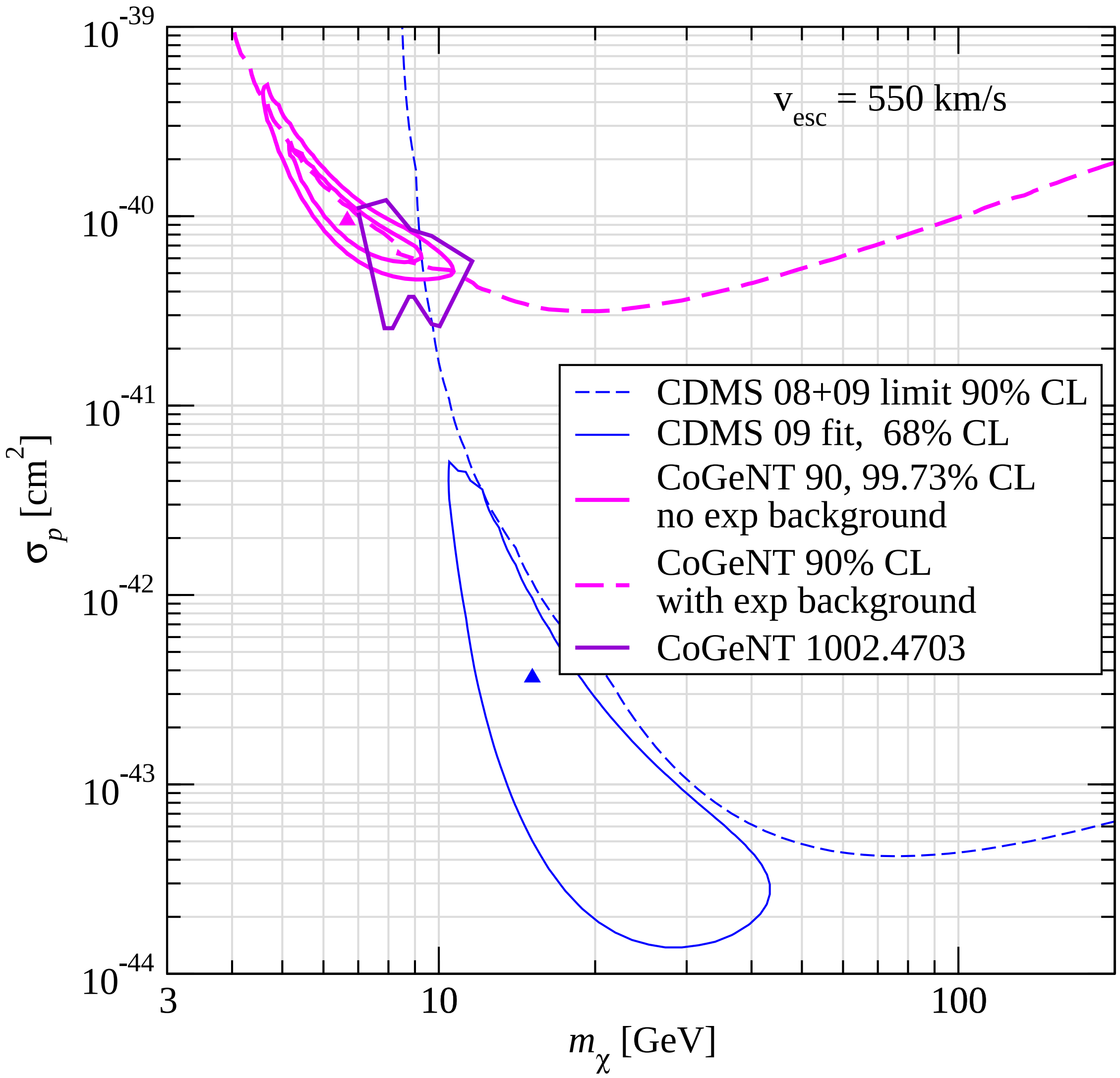
Aalseth et al., 1002.4703

CoGeNT



v_{esc} = 550 km/s
CDMS 08+09 limit 90% CL
CDMS 09 fit, 68% CL
CoGeNT 90, 99.73% CL
no exp background
CoGeNT 90% CL
with exp background
σ_p [cm^2]
m_χ [GeV]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
3
10
100

CoGeNT



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10^{-39}
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σ_p [cm^2]
3
10
100
m_χ [GeV]

low-mass WIMP hints

CDMS-II

CoGeNT

CRESST-II

DAMA

CRESST-II

Talk by W. Seidel @ WONDER 2010, March 22 to 23, Gran Sasso:

Present run

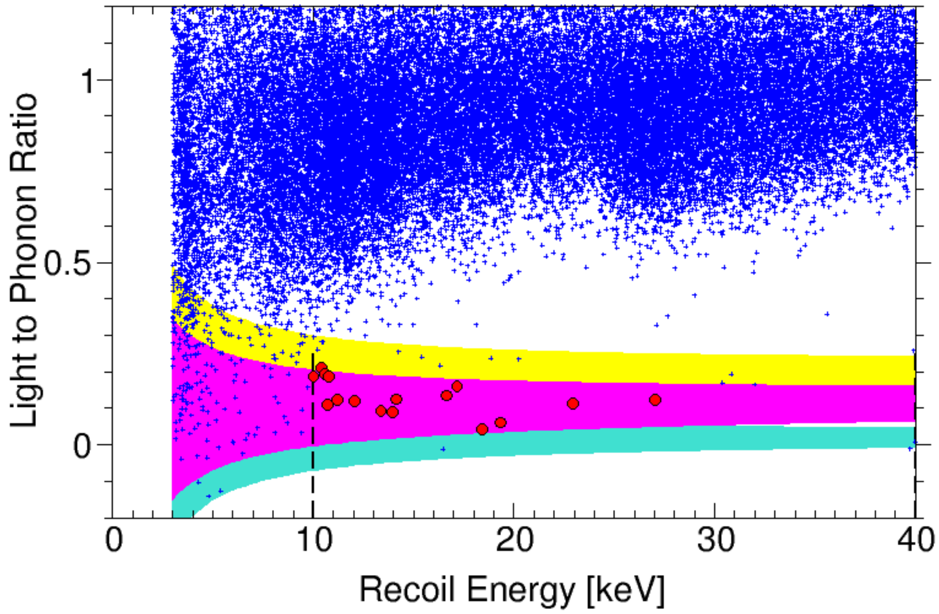
All results preliminary

- running since summer 2009
- 10 detectors running (1 $ZnWO_4$)
- Clamps not covered with scintillator
- data analysis is still in progress
- No neutron calibration yet
- Data discussed are from 9 $CaWO_4$ detectors (333 kgd)

CRESST data

Talk by W. Seidel @ WONDER 2010, March 22 to 23, Gran Sasso

see also talk by J. Jochum



- α-band (yellow)
- 1 event in W-band (cyan)
- 16 single-scatter events in O-band (magenta)

$\Rightarrow$ WIMPs ??

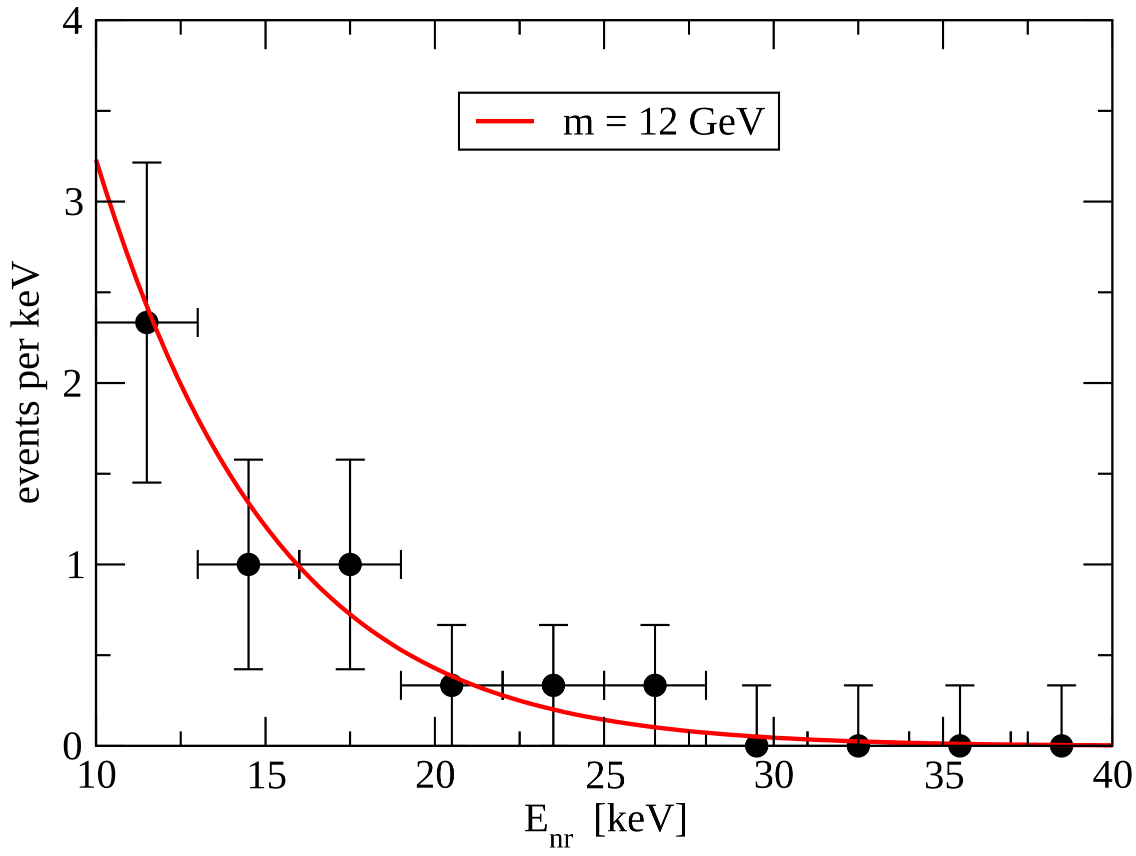
analysis is ongoing, some of the events (all?) are from neutrons

neutron calibration measurments are being carried out

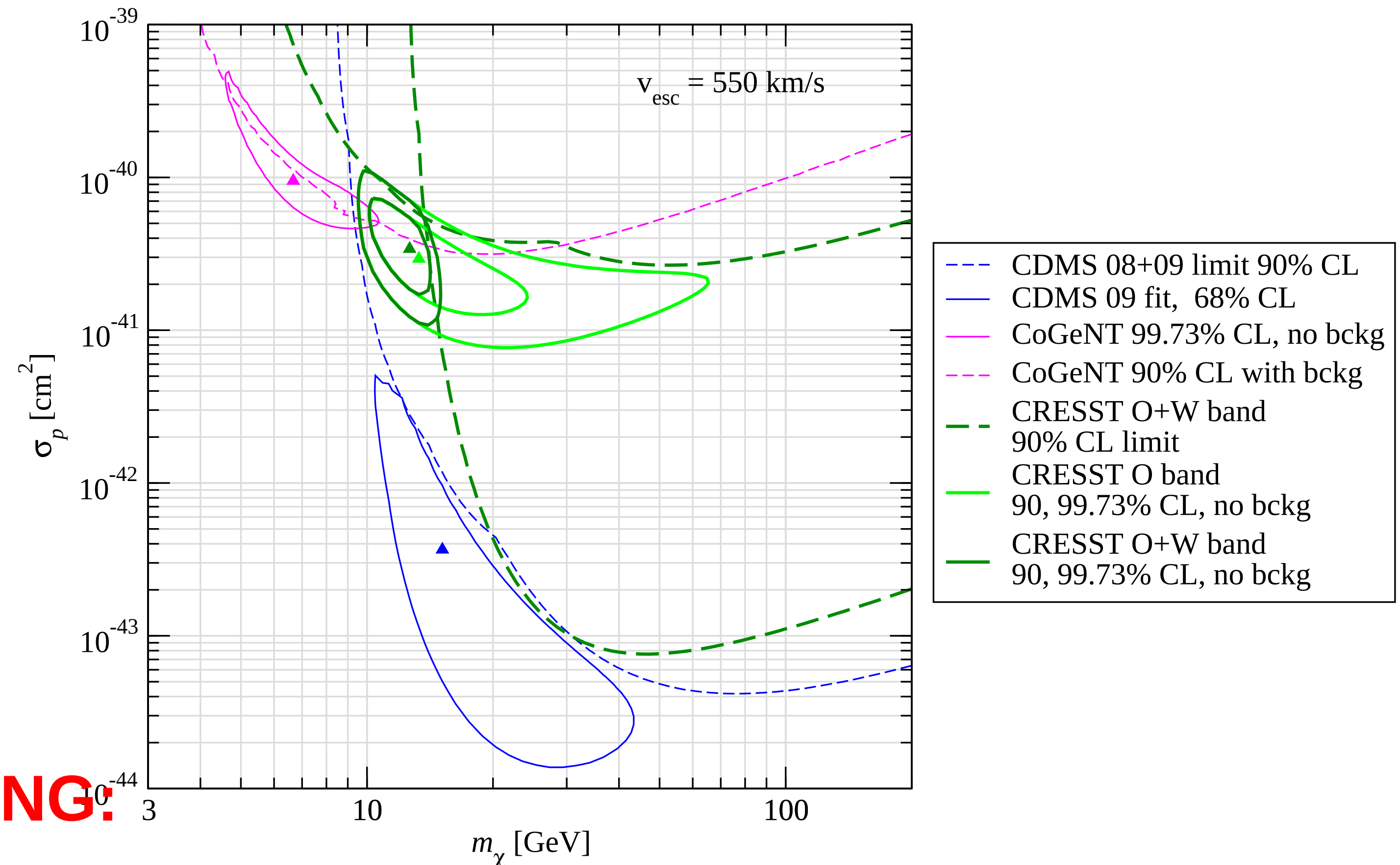
(measure the fraction of single scatter events from neutrons)

CRESST O-band

Can the events in the oxygen band be explained by (light) WIMPs?



CRESST vs CoGeNT vs CDMS



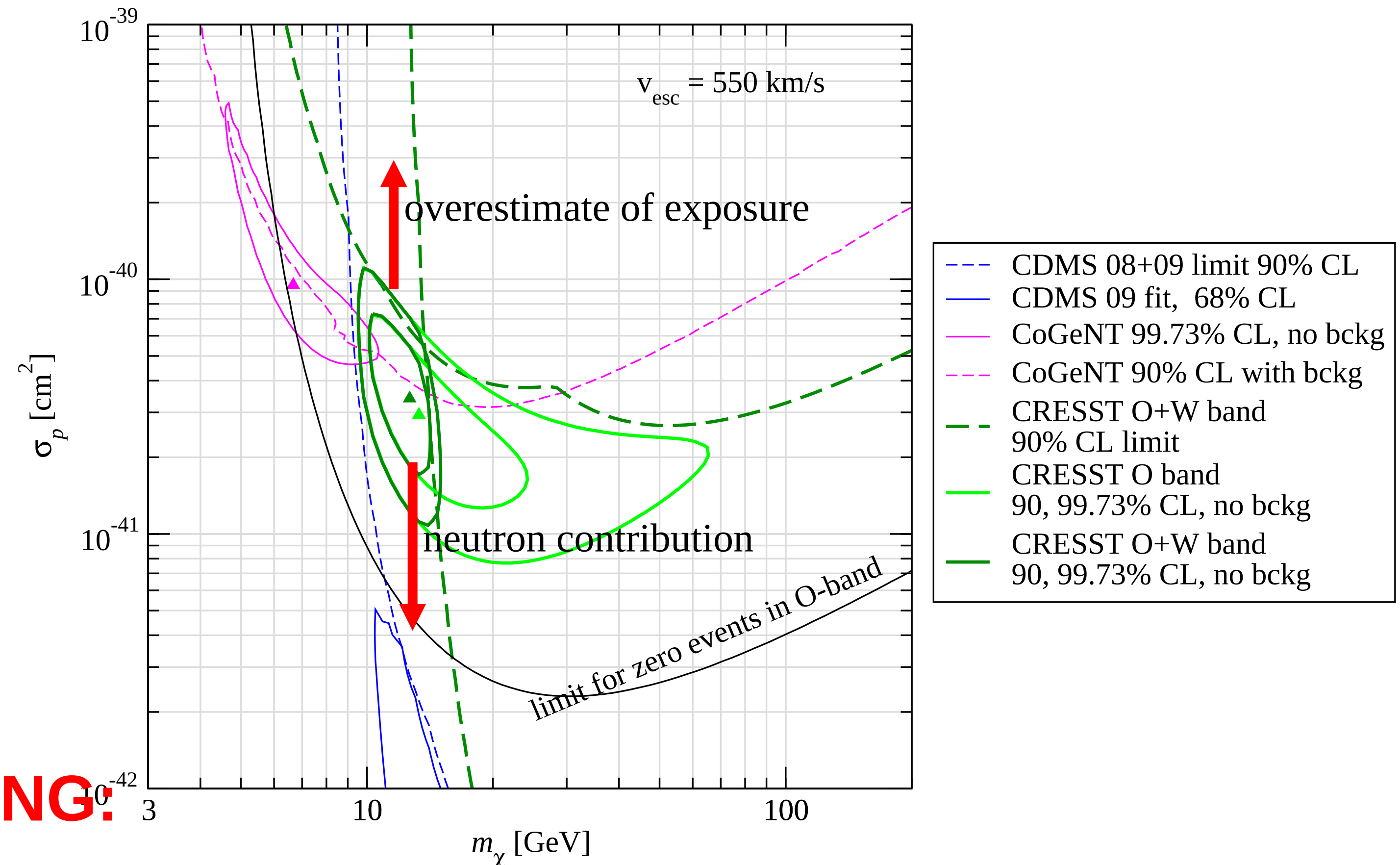
WARNING:

max-LH fit to O-band ev. assuming that ALL come from WIMPs

real effective exposure not public: take 333 kg day exposure with 100% efficiency

$\Rightarrow$ regions may shift

CRESST vs CoGeNT vs CDMS



WARNING:

max-LH fit to O-band ev. assuming that ALL come from WIMPs

real effective exposure not public: take 333 kg day exposure with 100% efficiency

⇒ regions may shift ⇒ wait for final results from CRESST

low-mass WIMP hints

CDMS-II

CoGeNT

CRESST-II

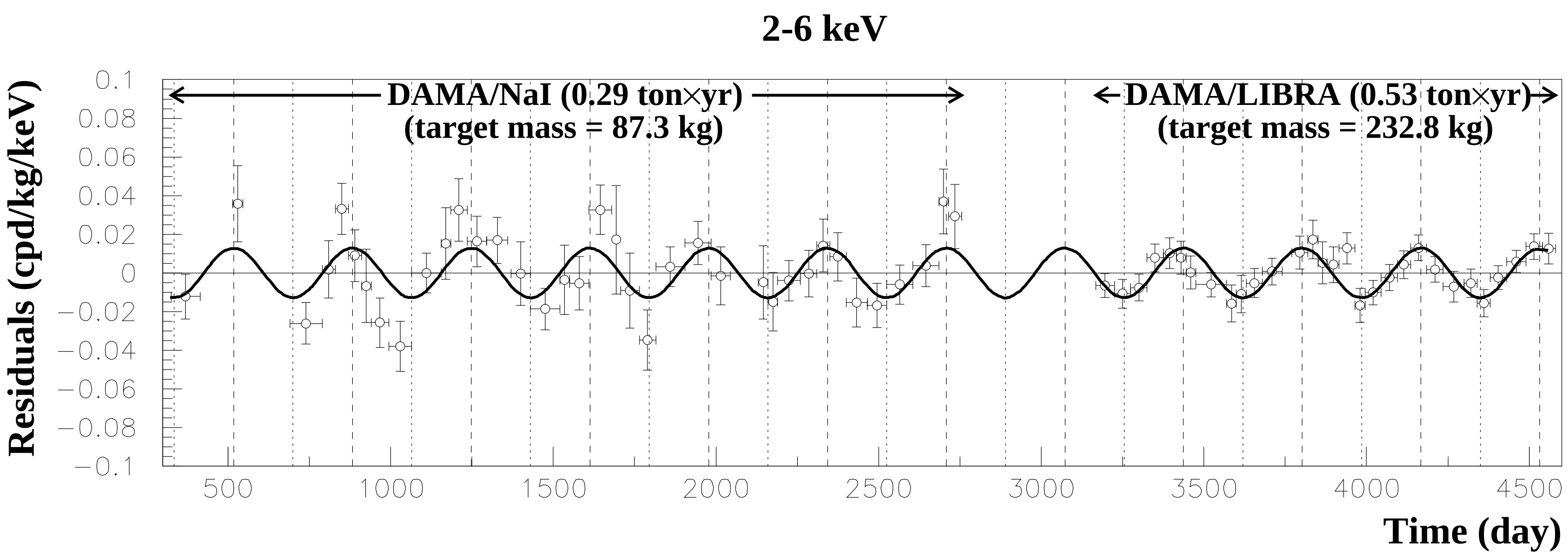
DAMA

DAMA/LIBRA annual modulation signal

Scinitillation light in NaI detector, 1.17 t yr exposure (13 yrs)

~ 1 cnts/d/kg/keV $\quad \rightarrow \quad \sim 4 \times 10^5$ events/keV in DAMA/LIBRA

$\sim 8.9\sigma$ evidence for an annual modulation of the count rate with maximum at day 146 ± 7 (June 2nd: 152) Bernabei et al., 1002.1028



Talk by P. Belli, Bernabei et al., 0804.2741

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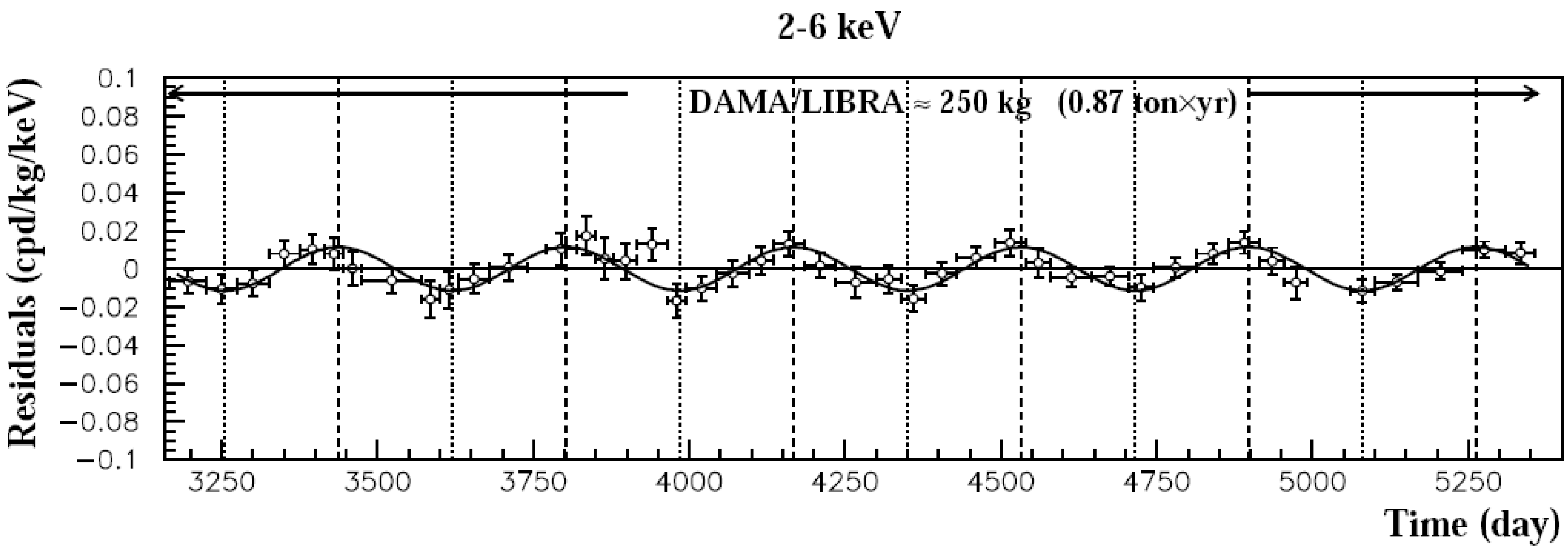

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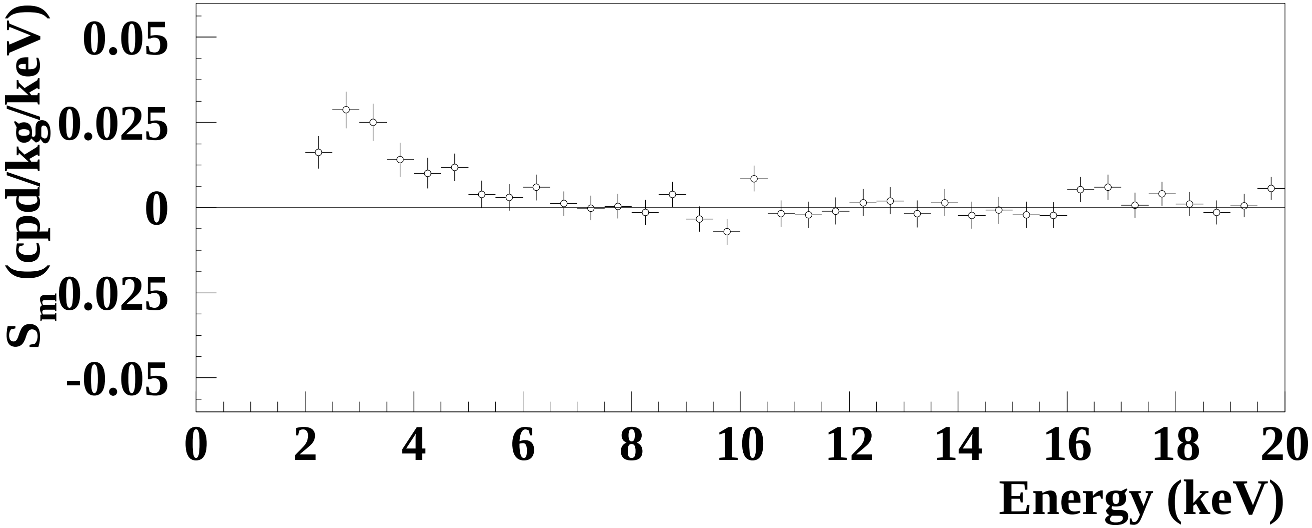


energy shape of modulation is important for constraining params

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

Quenching

DAMA measures energy in
"electron equivalent" (keVee)

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

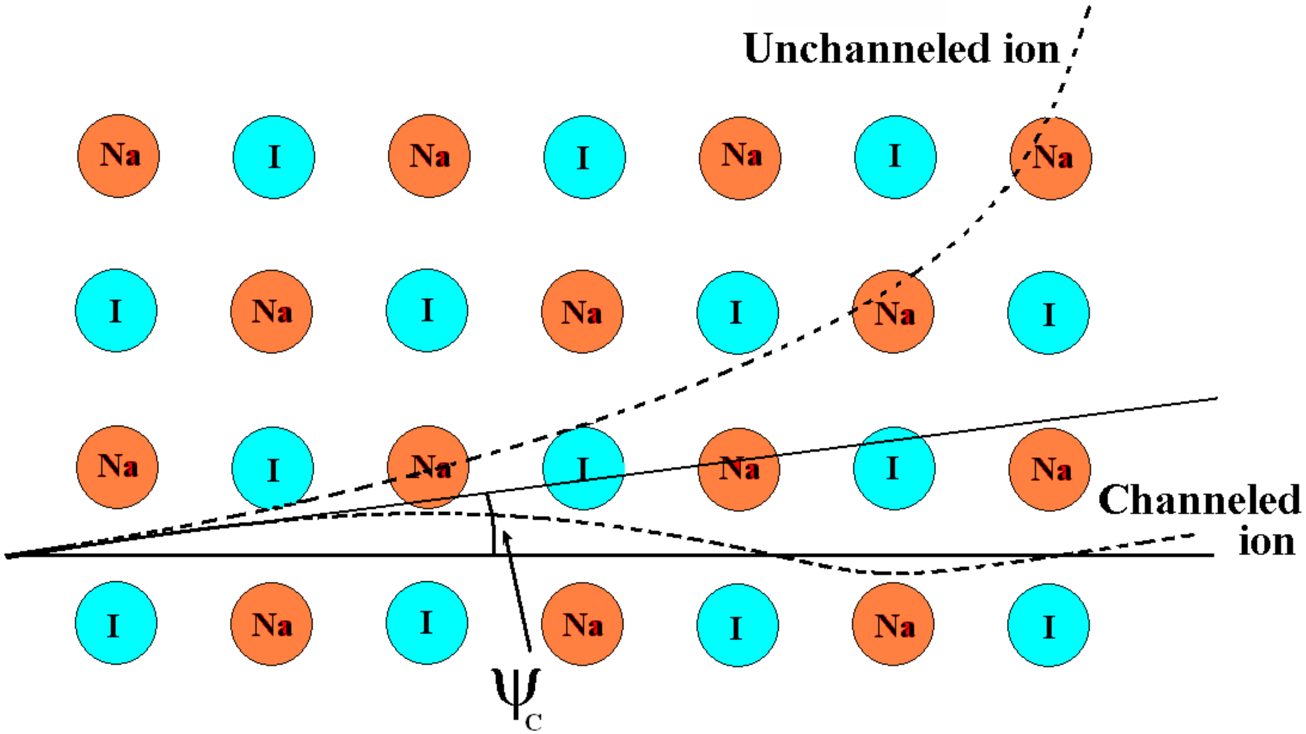
$$E_{\rm obs} = q \times E_R$$

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.

Channeling

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 $q \approx 1$

Channeling and DAMA

there are four types of events in the NaI of DAMA:

$$R_{\rm DAMA}(E) = \sum_{x={\rm Na,I}} \frac{M_x}{M_{\rm Na}+M_{\rm I}} \Big\{ \underbrace{[1-f_x(E/q_x)]R_x(E/q_x)}_{\text{quenched}} + \underbrace{f_x(E)R_x(E)}_{\text{channeled}} \Big\}$$

$f_x(E_R)$: fraction of channeled events on $x =$ Na, I

Channeling and DAMA

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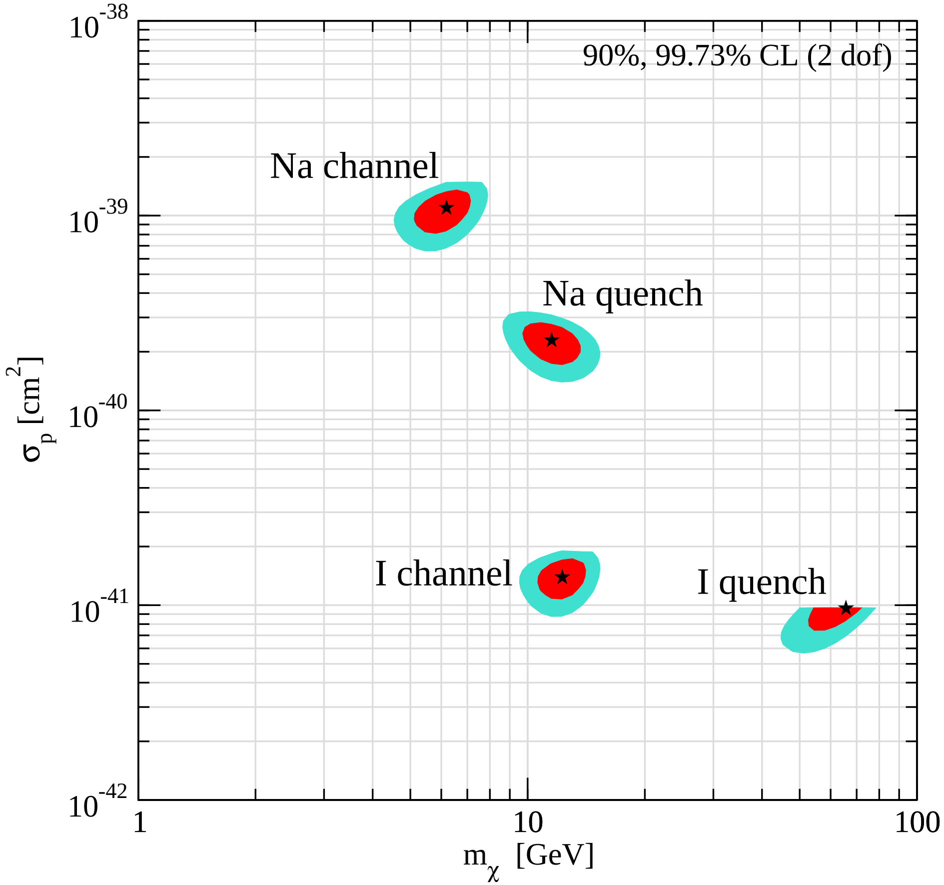
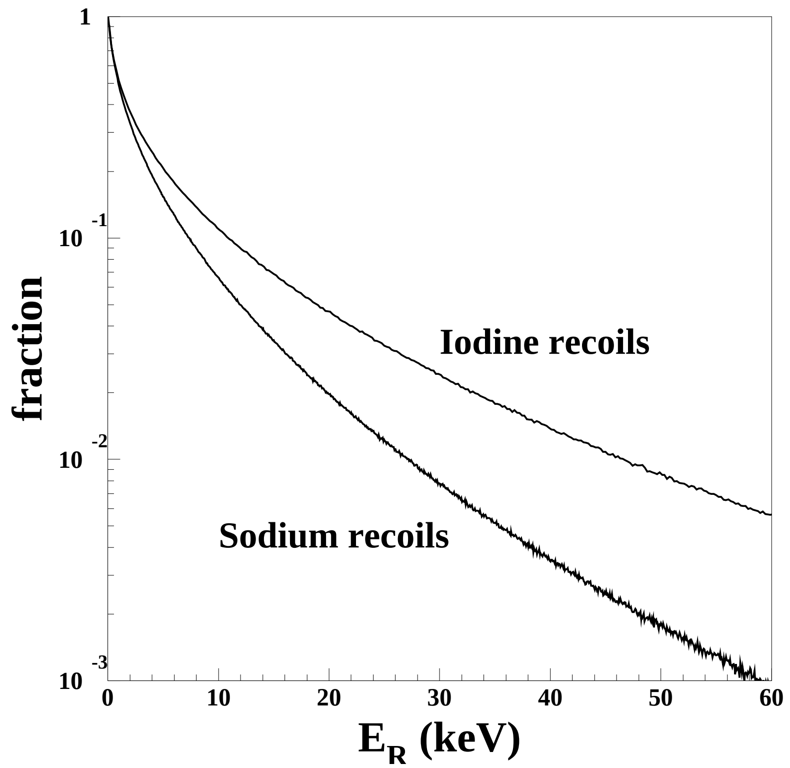


fitting DAMA requires

$$v_{\min} = \frac{m_\chi + M}{m_\chi}\sqrt{\frac{E_R}{2M}}$$
$$\approx 400\,\text{km/s}$$

$\Rightarrow$

How large is the fraction of channeled events?



Bernabei et al., 0710.0288

HOWEVER:

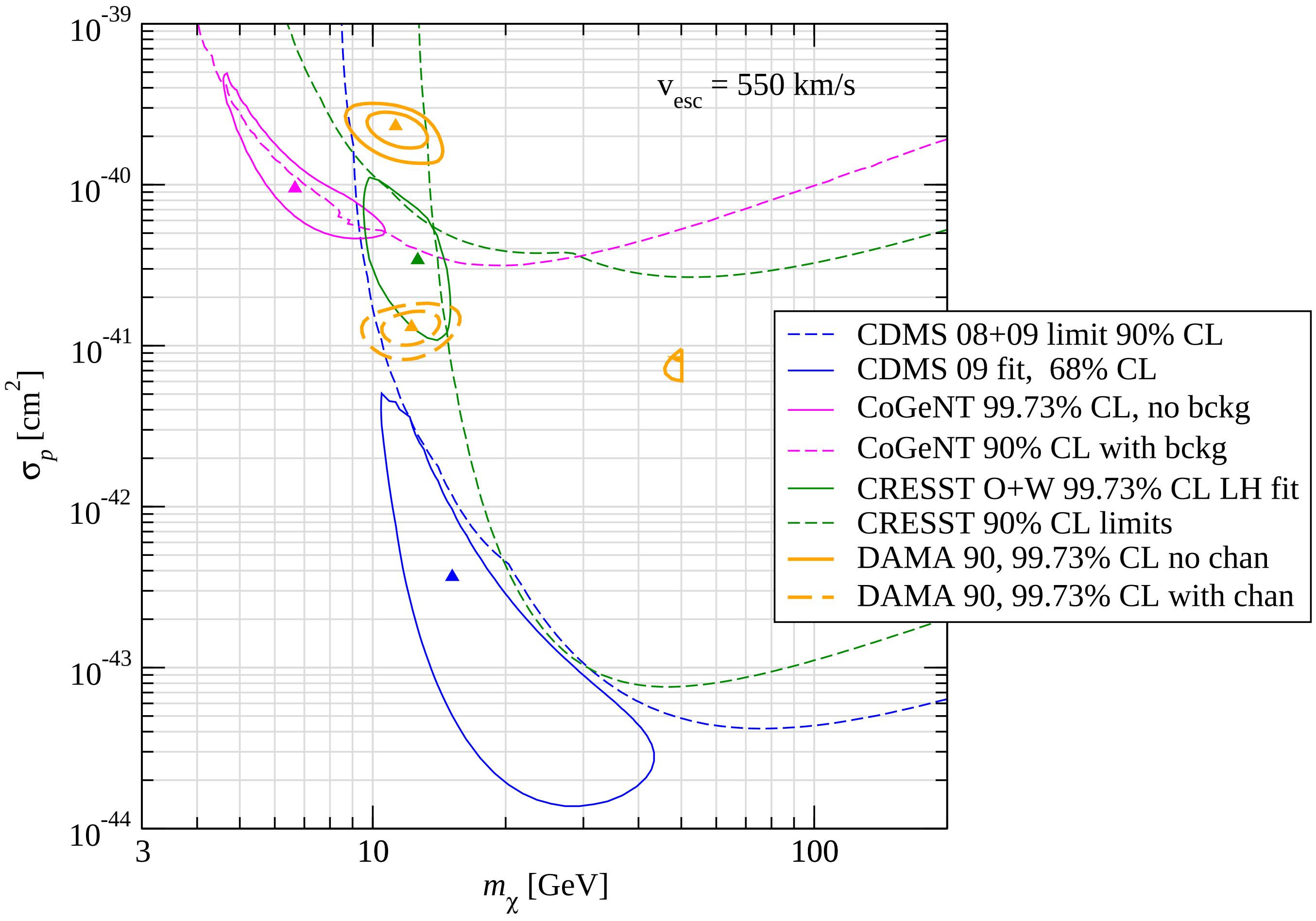
prelim. calculations of Bozorgnia, Gelmini, Gondolo suggest that

$$f_{\rm Na} \lesssim 3 \times 10^{-3}$$
$$f_{\rm I} \lesssim 10^{-4}$$

in the relevant energy range

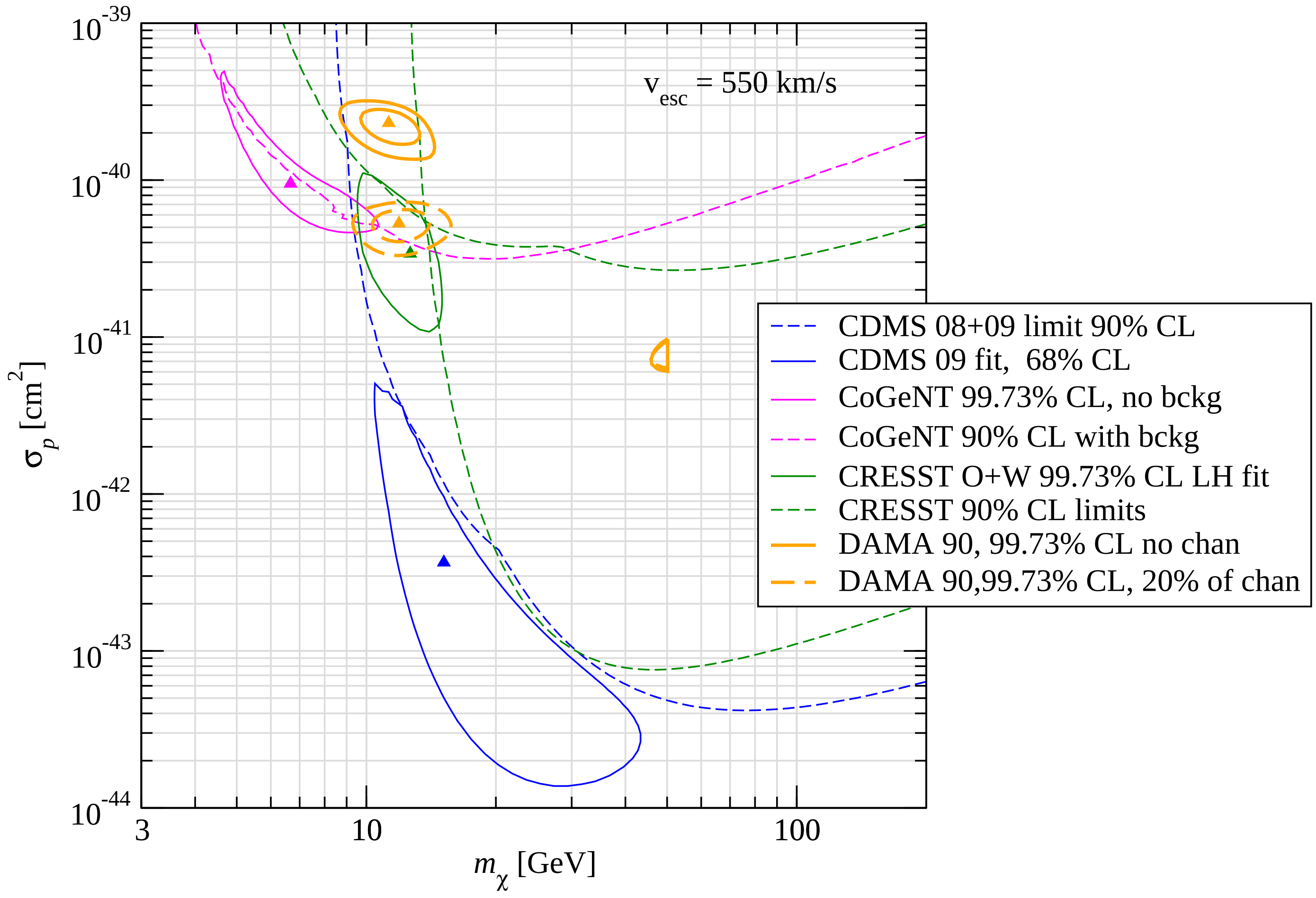
see talk by G. Gelmini for detailed discussion

Fitting DAMA



DAMA region with channeling assumes fraction of chan. events according to Bernabei et al., 0710.0288

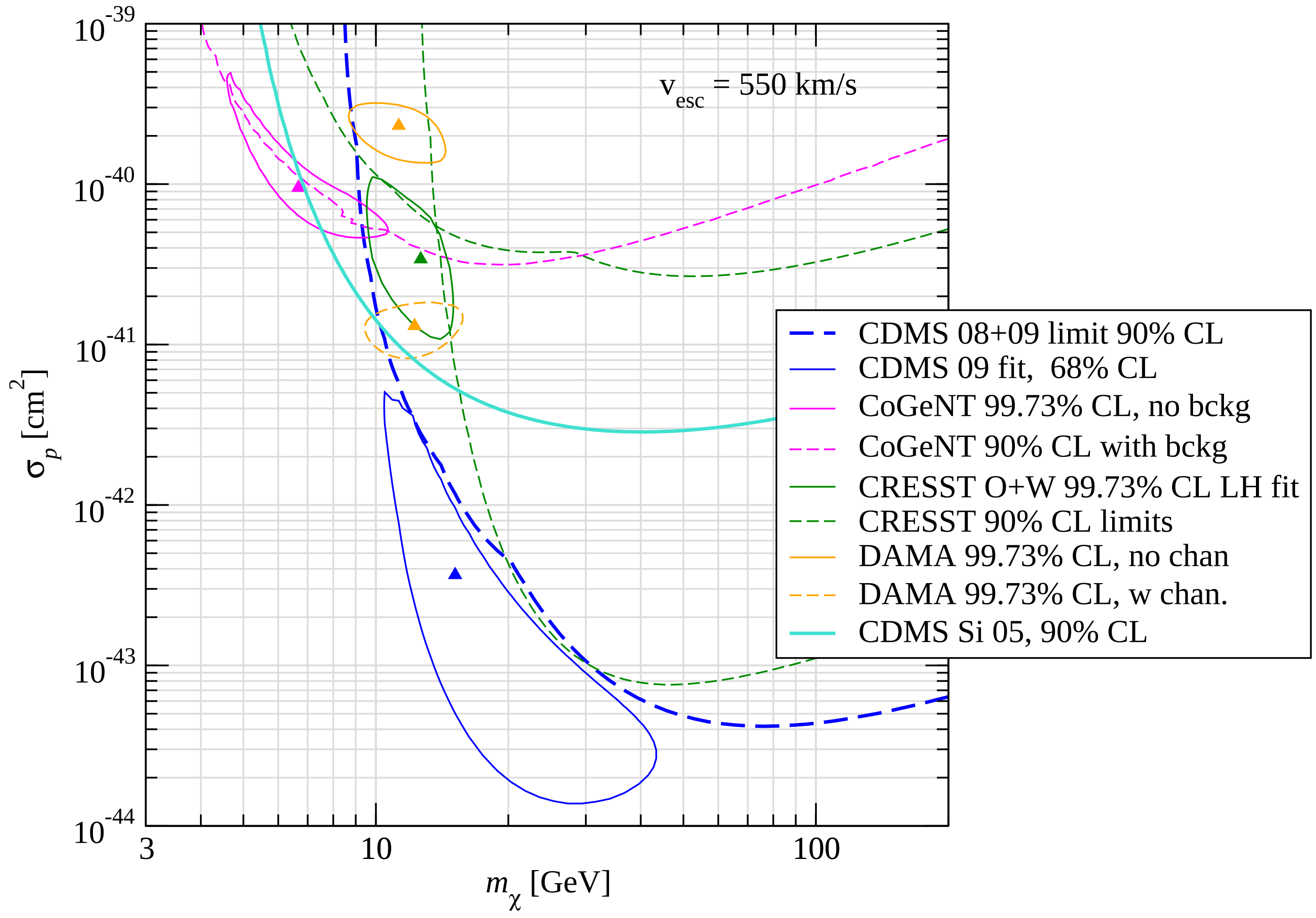
Fitting DAMA



reducing artificially the fraction of chan. events from Bernabei et al., 0710.0288, by a factor 5 (keeping the energy dependence)

Constraints from CDMS and XENON

CDMS constraints



CDMS data on Si (astro-ph/0509259): 12 kg day, 7 keV threshold

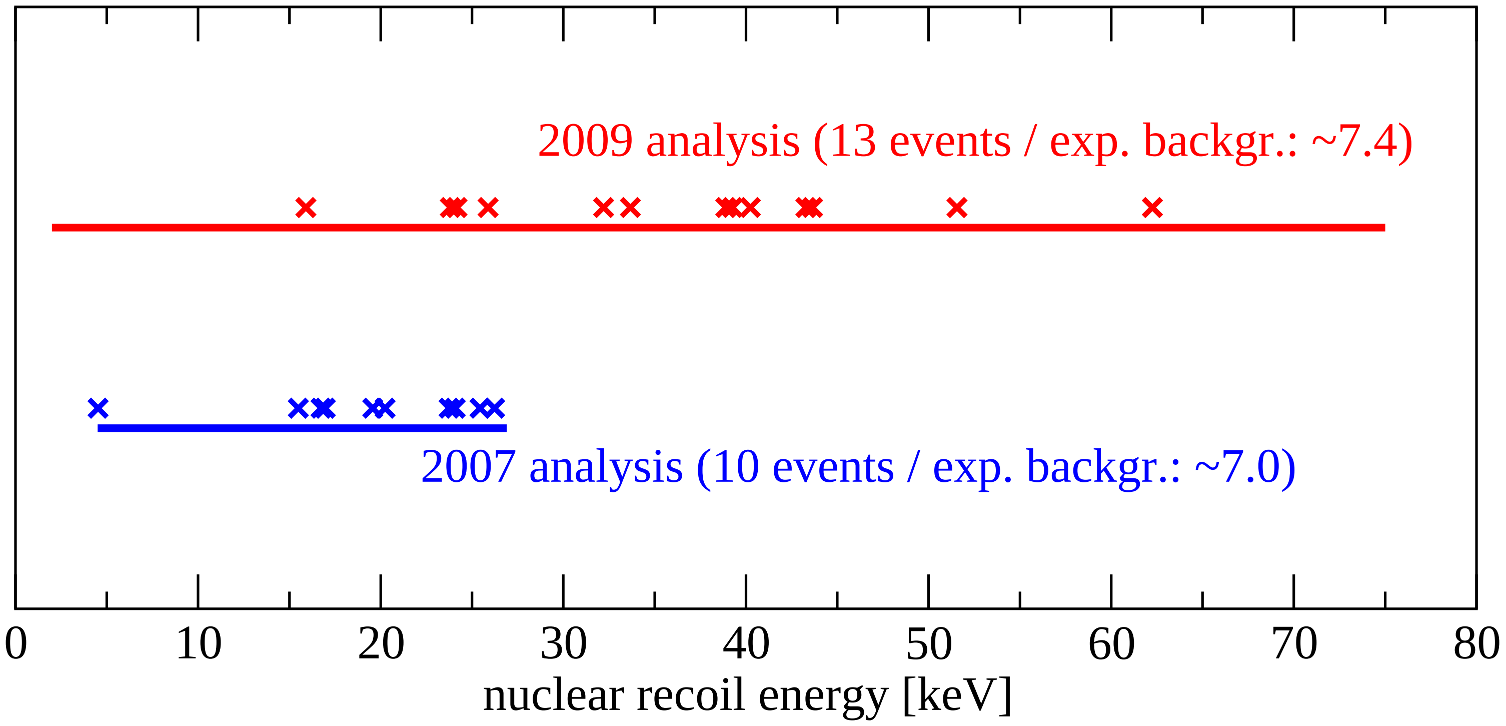
more data on tape

XENON-10

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

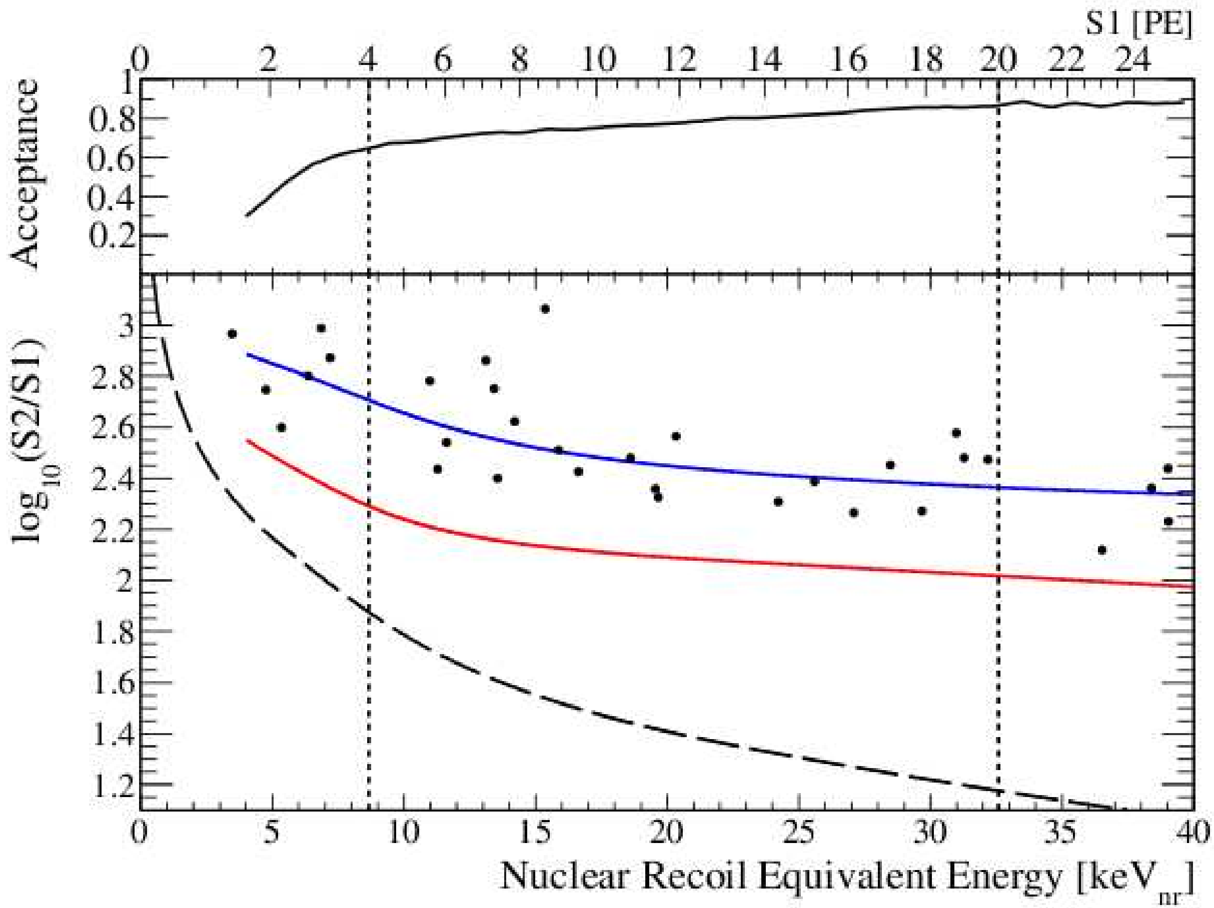
0706.0039: original blind analysis: 10 events

0910.3698: revised cuts: 13 events, extended energy window



XENON-100

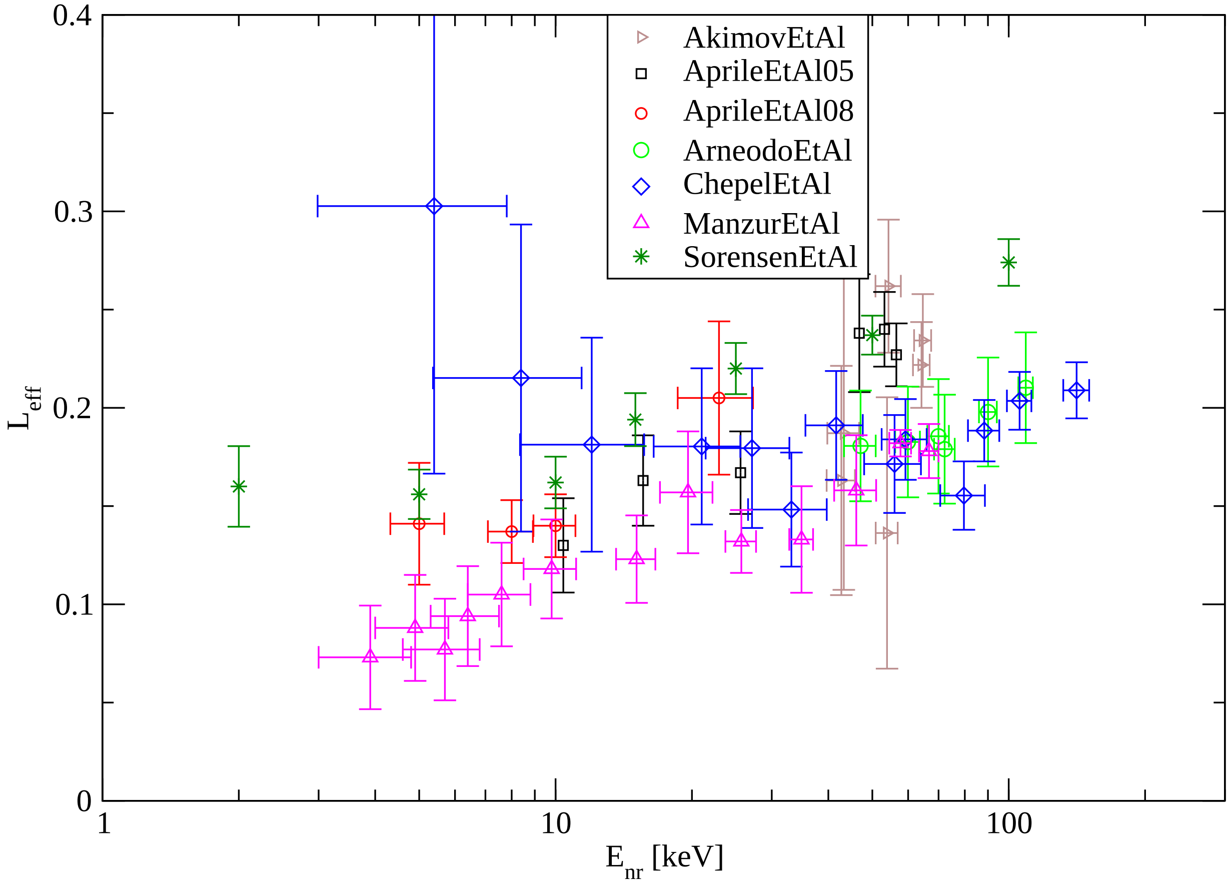
11.7 days, 40 kg fid., $\sim$ 230 kg day effective exp.



1005.0380; talk by E. Aprile

L_{eff}

translate $S1$ signal [PE] into E_{nr} [keV]: $E_{nr} = \frac{S1}{L_{eff}(E_{nr})} \frac{1}{L_y} \frac{S_e}{S_n}$



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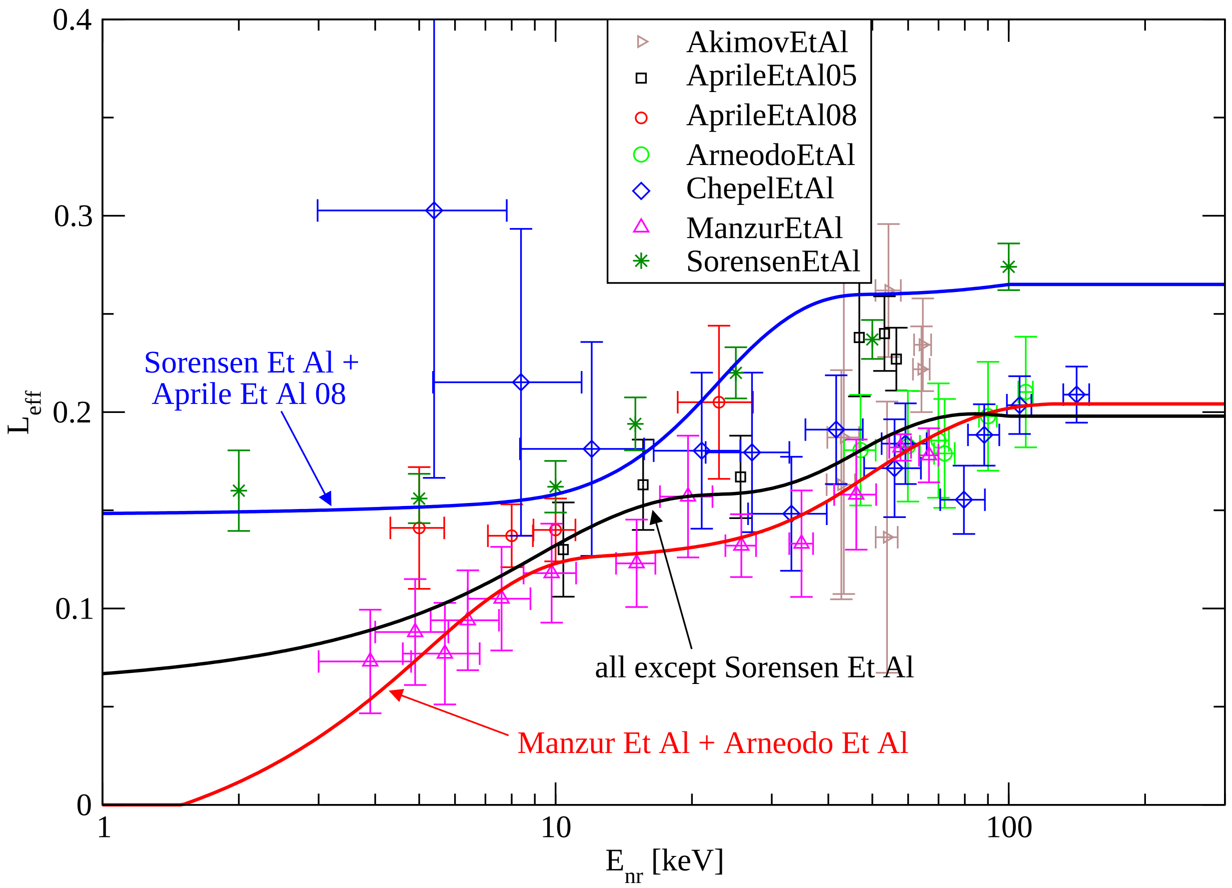
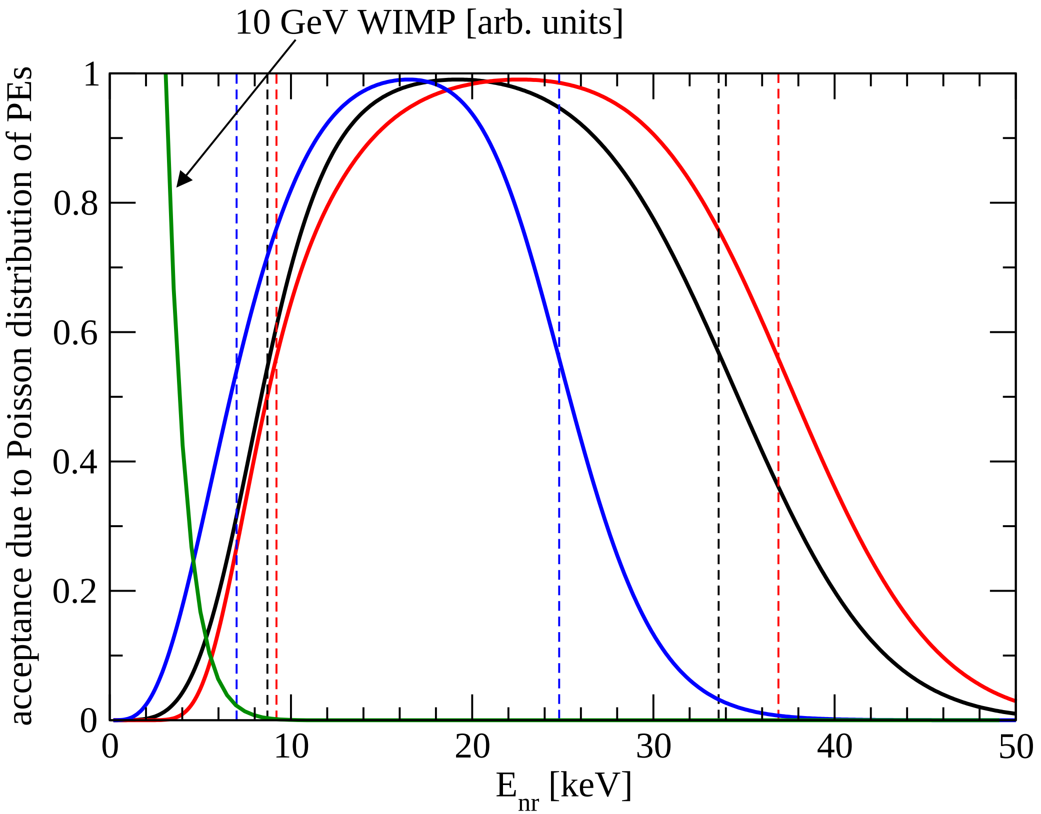


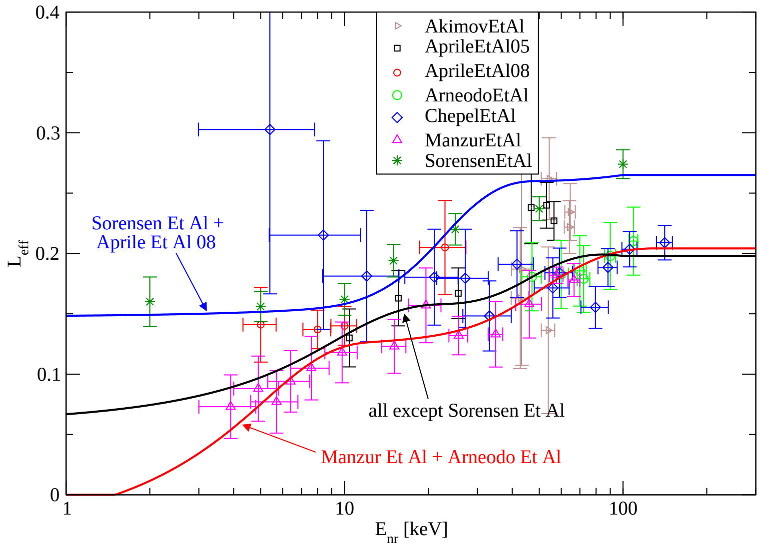
3 exemplary fits, extrapolating with straight lines at low energies

Acceptance window in XENON100

the acceptance window is defined as S1 between 4 and 20 PEs

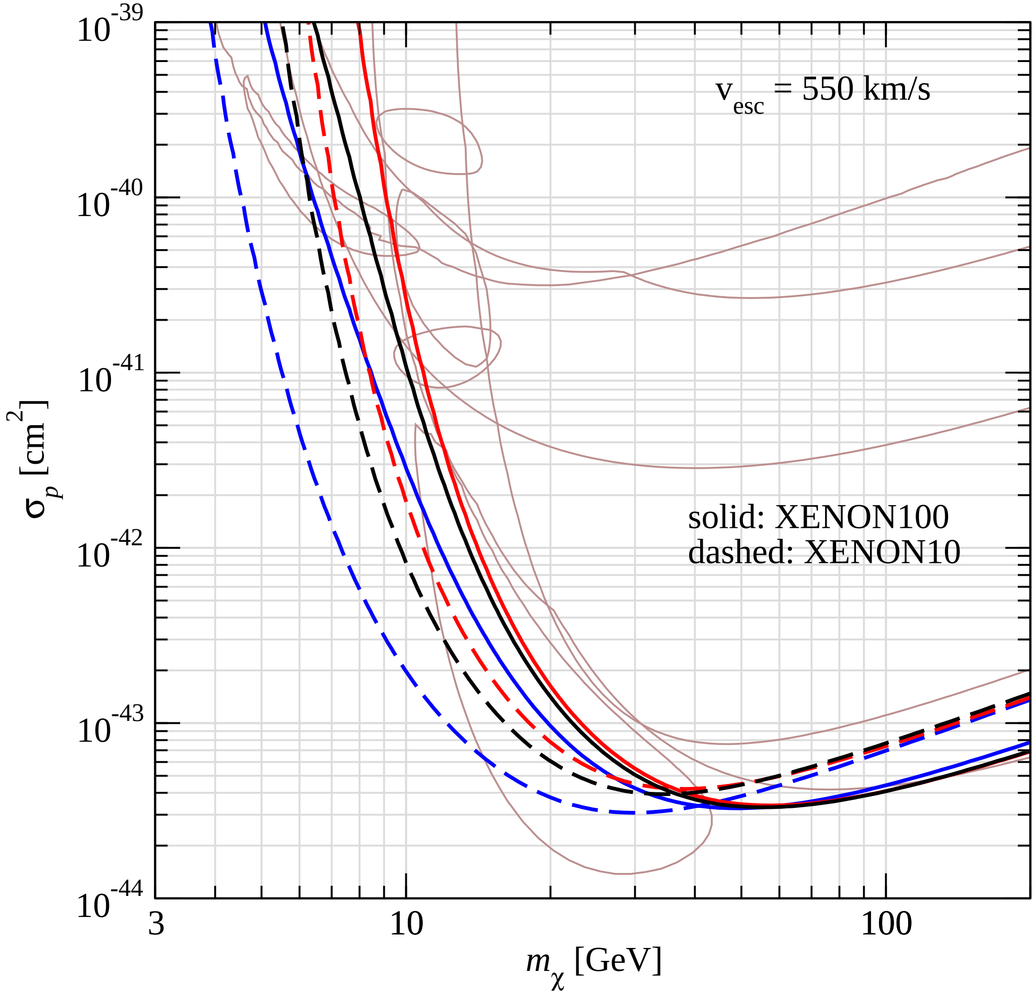
- this translates into window in E_{nr} according to L_{eff}
- Poisson statistics of PEs implies smearing of the thresholds

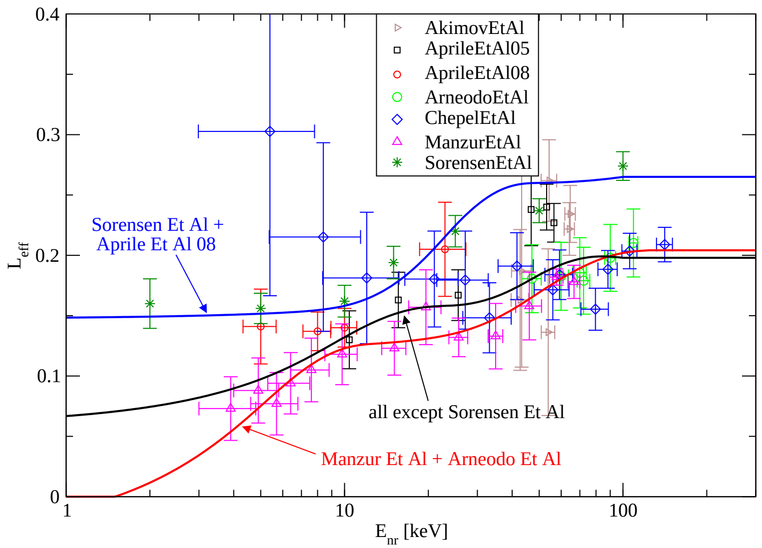




same color coding

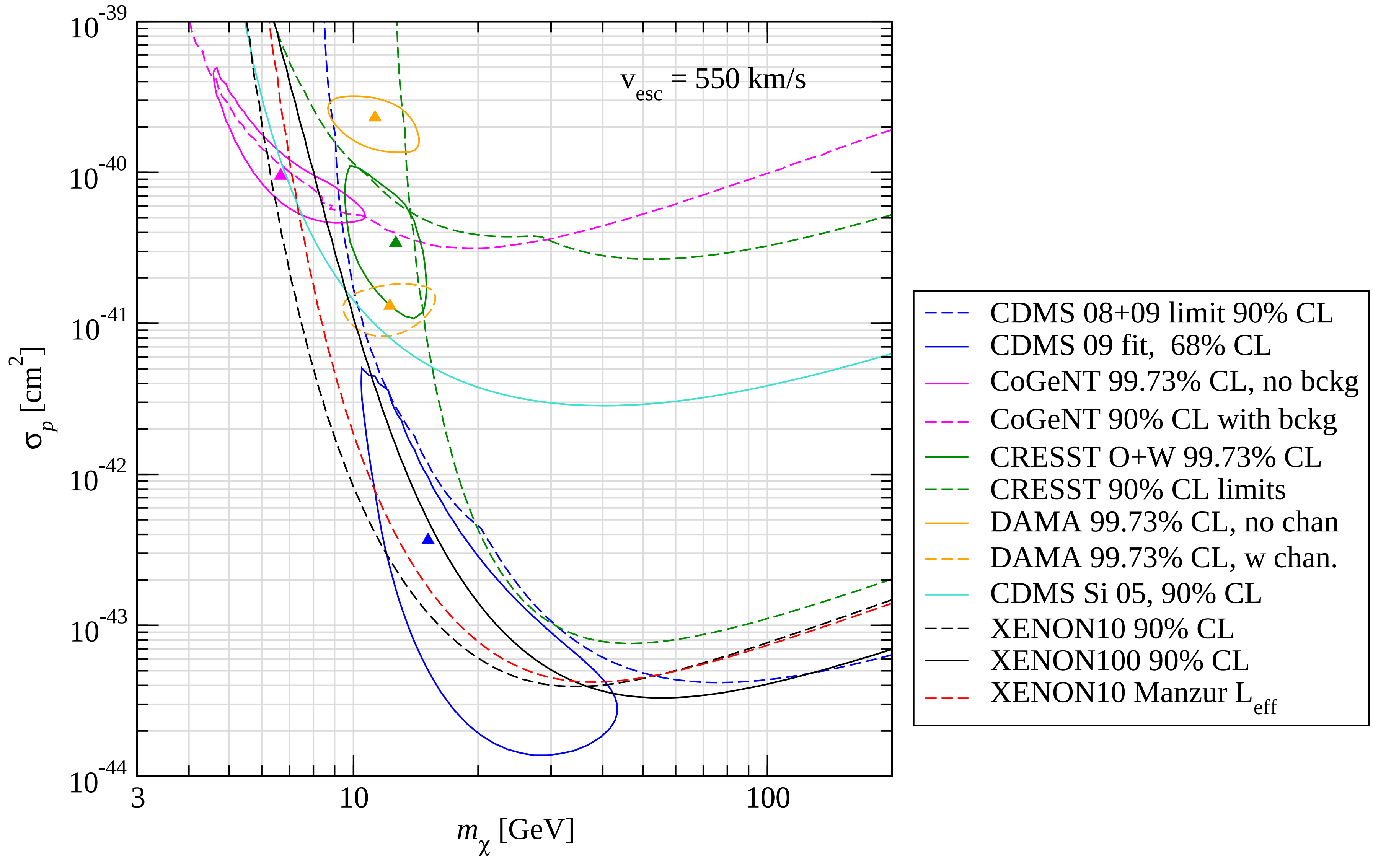
L_{eff} and the XENON bounds





same color coding

Summary elastic SI scattering



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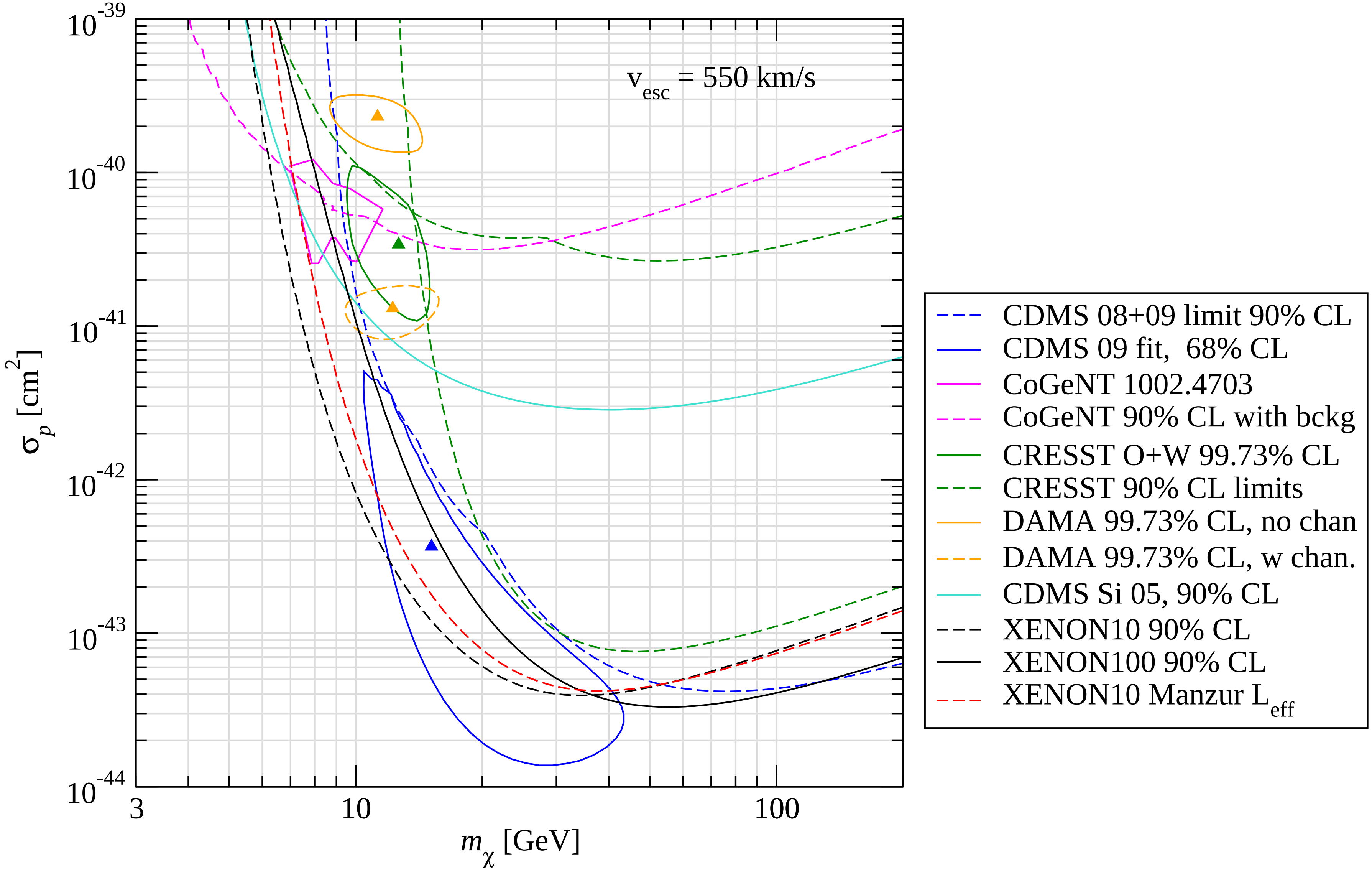


elastic spin-dependent (eSD) scattering

Spin-dependent scattering

coupling mainly to an un-paired nucleon:

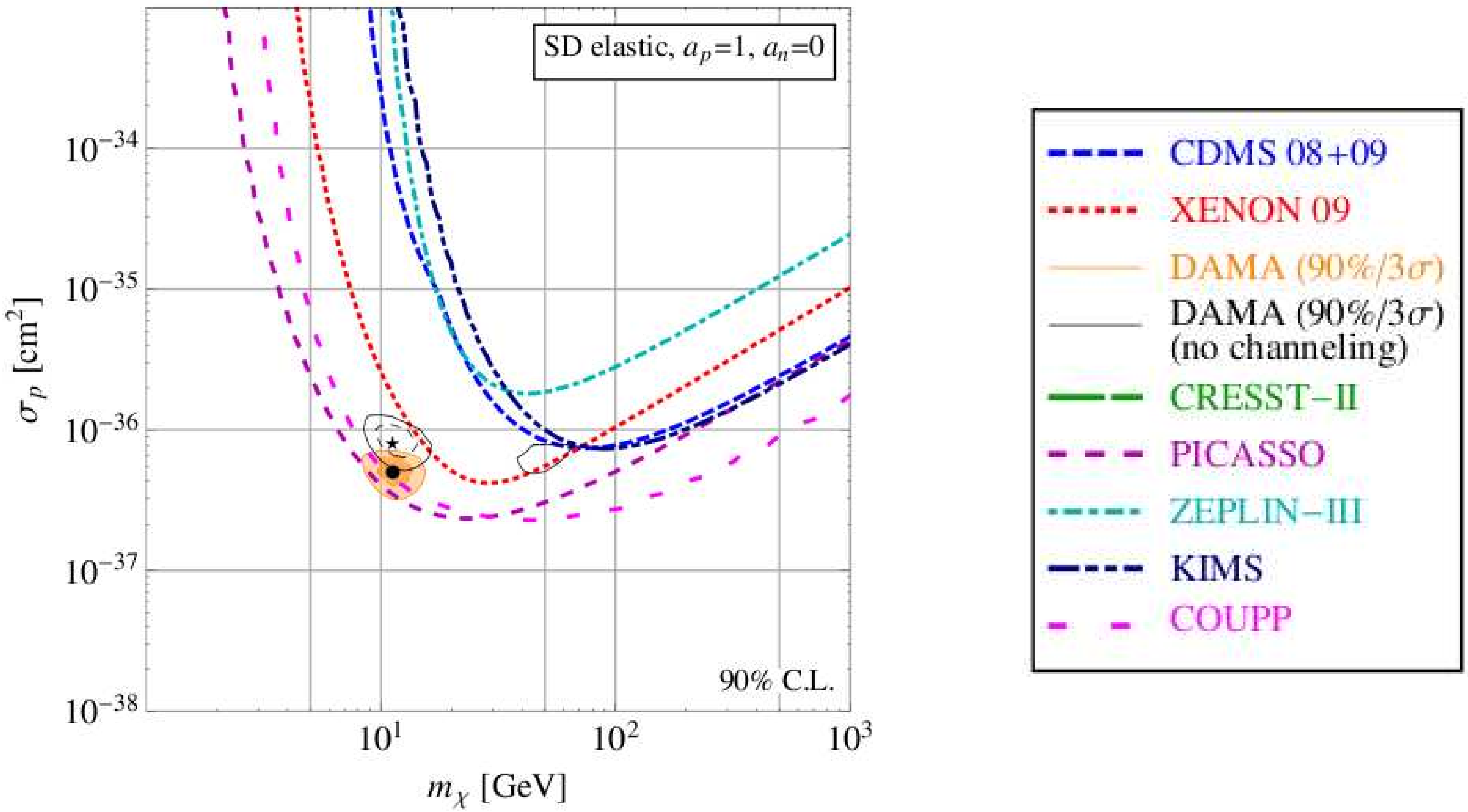
		neutron	proton
DAMA	$^{23}_{11}$Na	even	odd
DAMA, KIMS, COUPP	$^{127}_{53}$I	even	odd
SIMPLE	$^{35}_{17}$Cl, $^{35}_{17}$Cl	even	odd
XENON, ZEPLIN	$^{129}_{54}$Xe, $^{131}_{54}$Xe	odd	even
CDMS, CoGeNT	$^{73}_{32}$Ge	odd	even
PICASSO, COUPP, SIMPLE	$^{19}_{9}$F	even	odd
CRESST	$^{A}_{74}$W, $^{16}_{8}$O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

coupling with proton promising for DAMA vs CDMS/XENON

BUT: severe bounds from COUPP, KIMS, PICASSO, SIMPLE

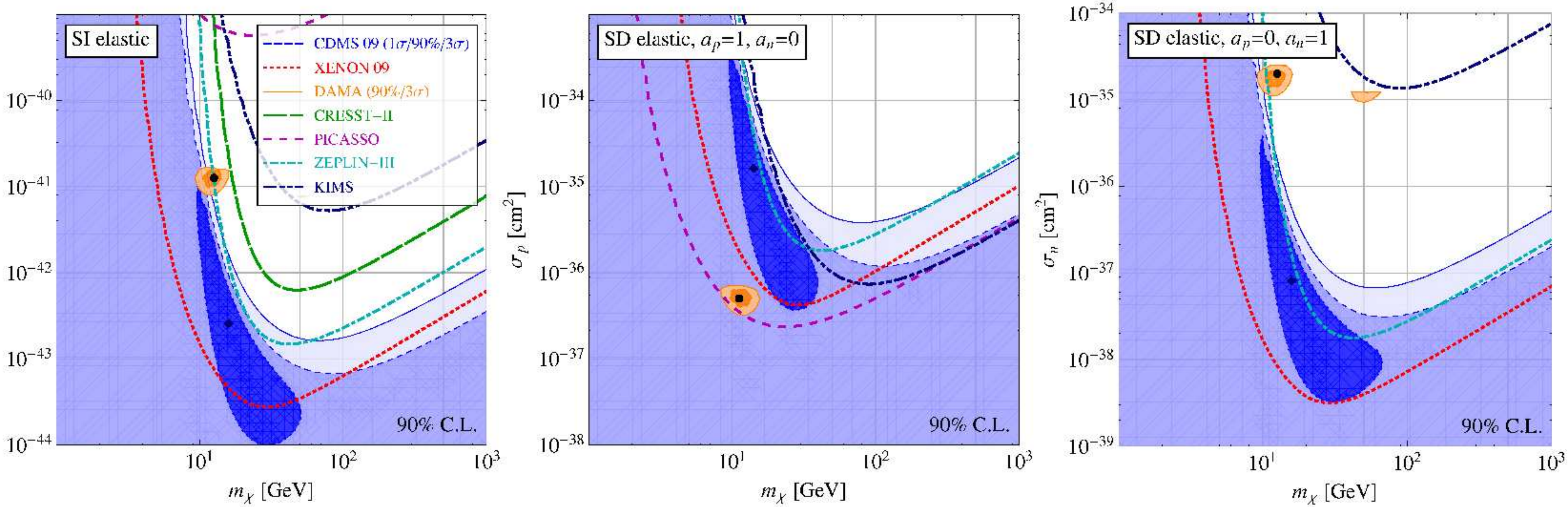
and neutrino constraints from annihilations in the sun

DAMA and eSD off protons



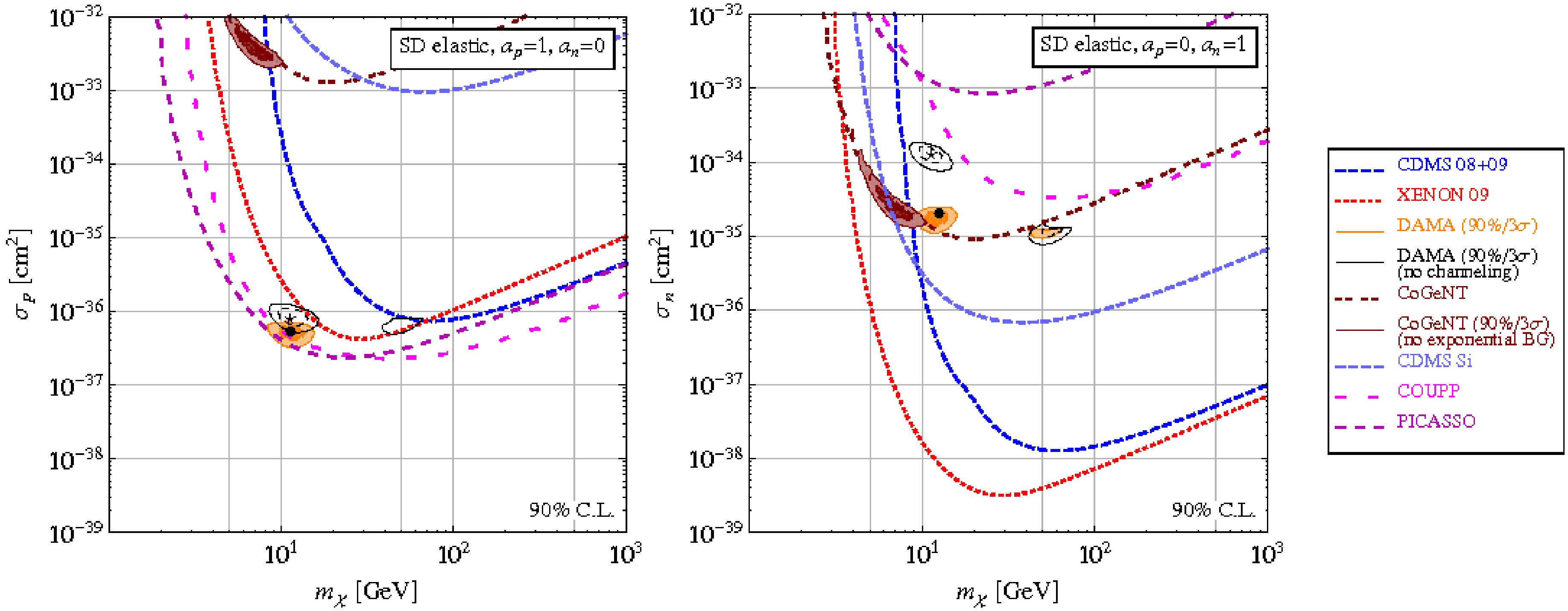
Kopp, Schwetz, Zupan, 0912.4264

CDMS and eSD



Kopp, Schwetz, Zupan, 0912.4264

CoGeNT and eSD



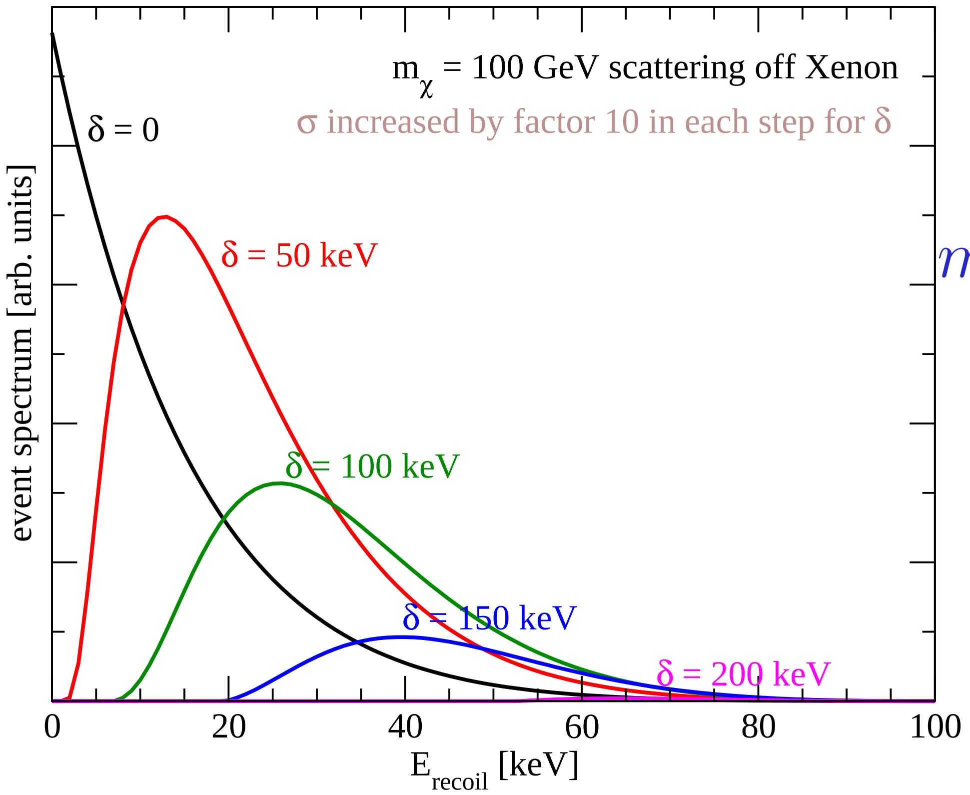
Kopp, Schwetz, Zupan, 0912.4264

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

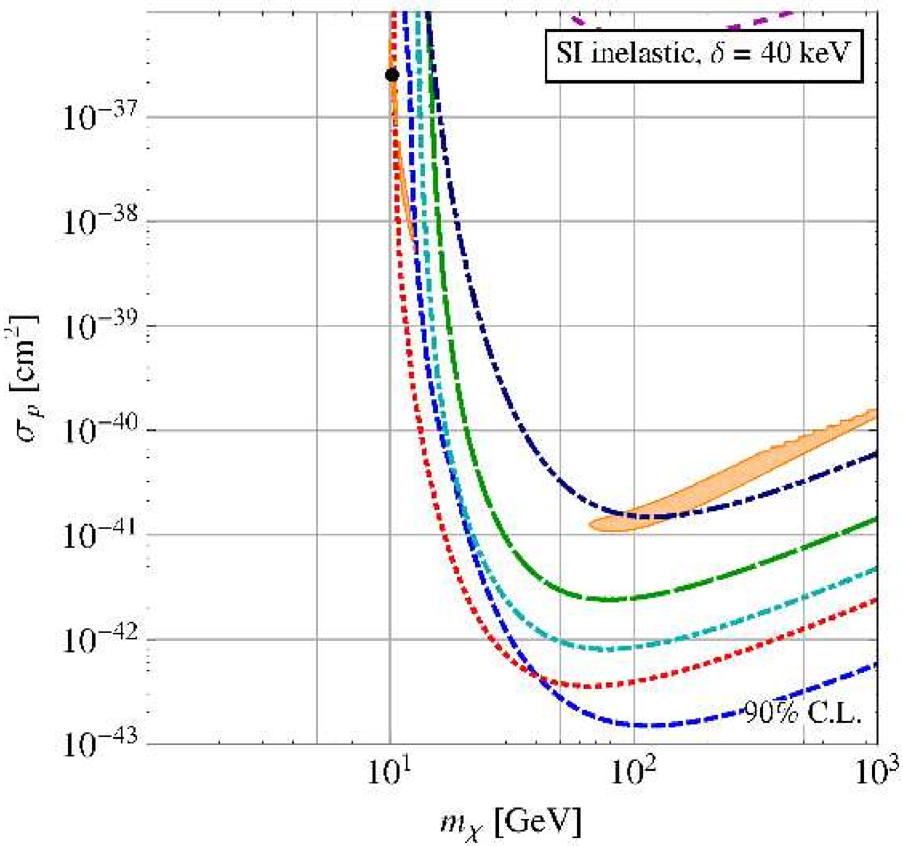


$$m_{\chi^*} - m_\chi = \delta \simeq 100\,\text{keV} \sim 10^{-6} m_\chi$$

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

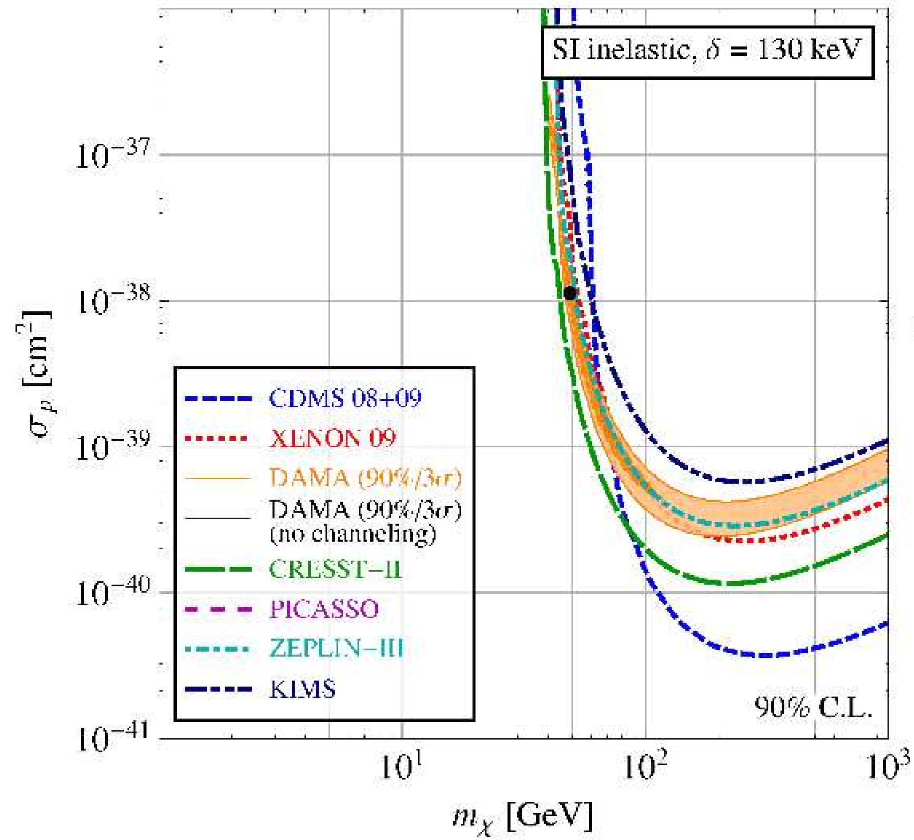
- sampling only high-velocity tail of velocity distribution
- no events at low recoil energies
- targets with high mass are favoured

iSI



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

from channeled events

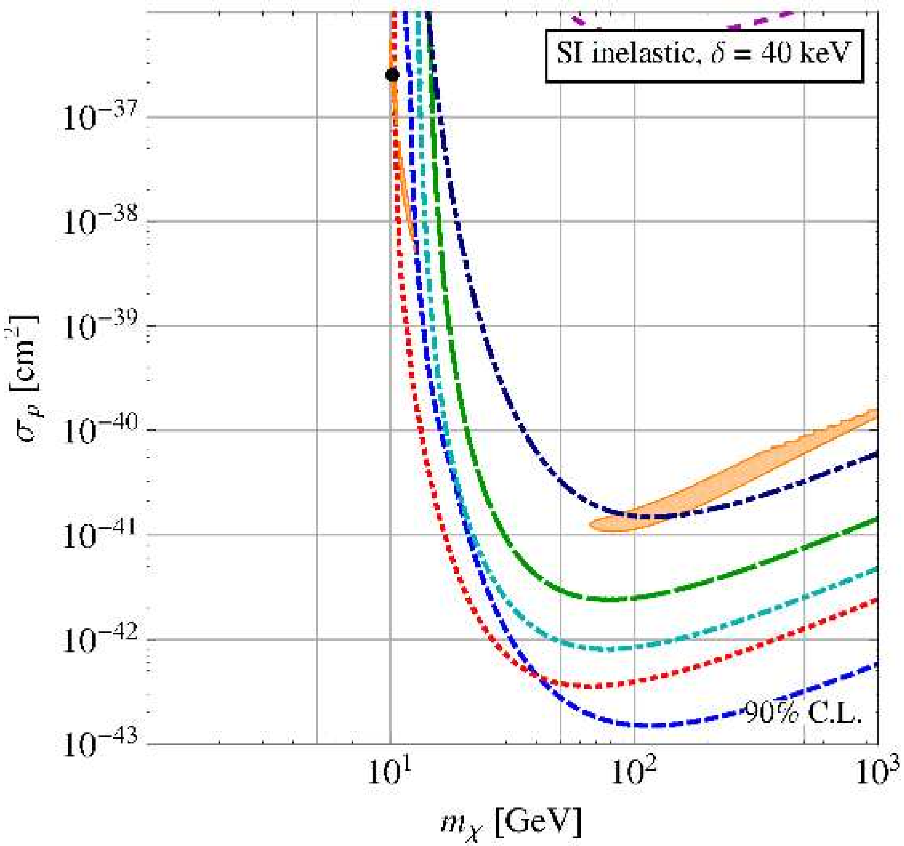


$m_\chi \simeq 50\,\mathrm{GeV}$, $\delta \simeq 130\,\mathrm{GeV}$

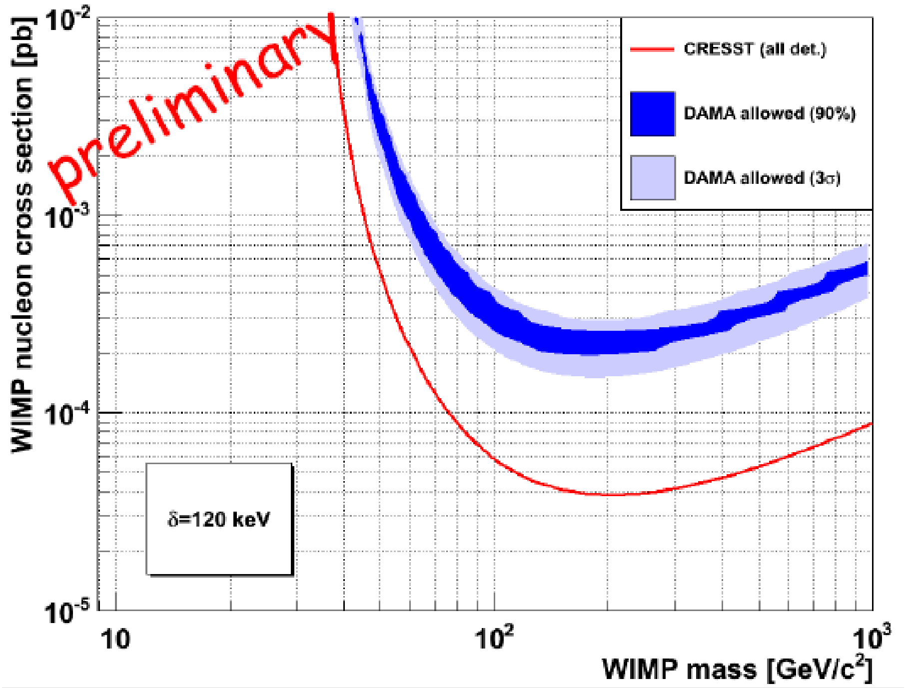
quenched events

disfavored by CRESST (tungsten)

iSI



talk by W. Seidel @ WONDER 2010



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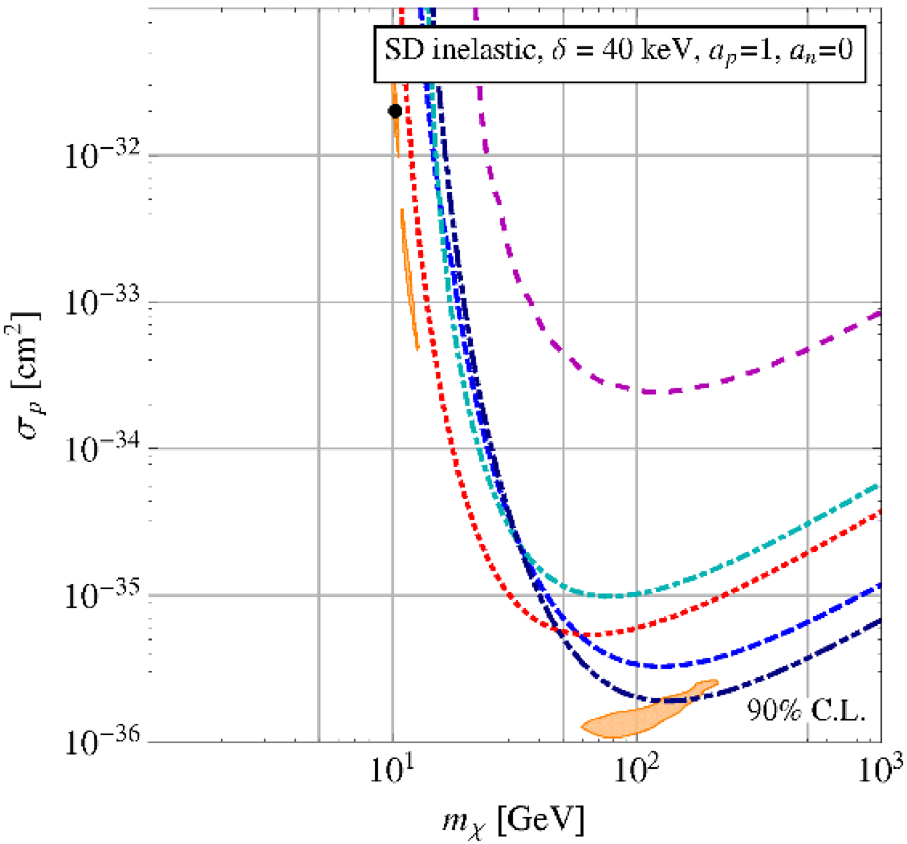
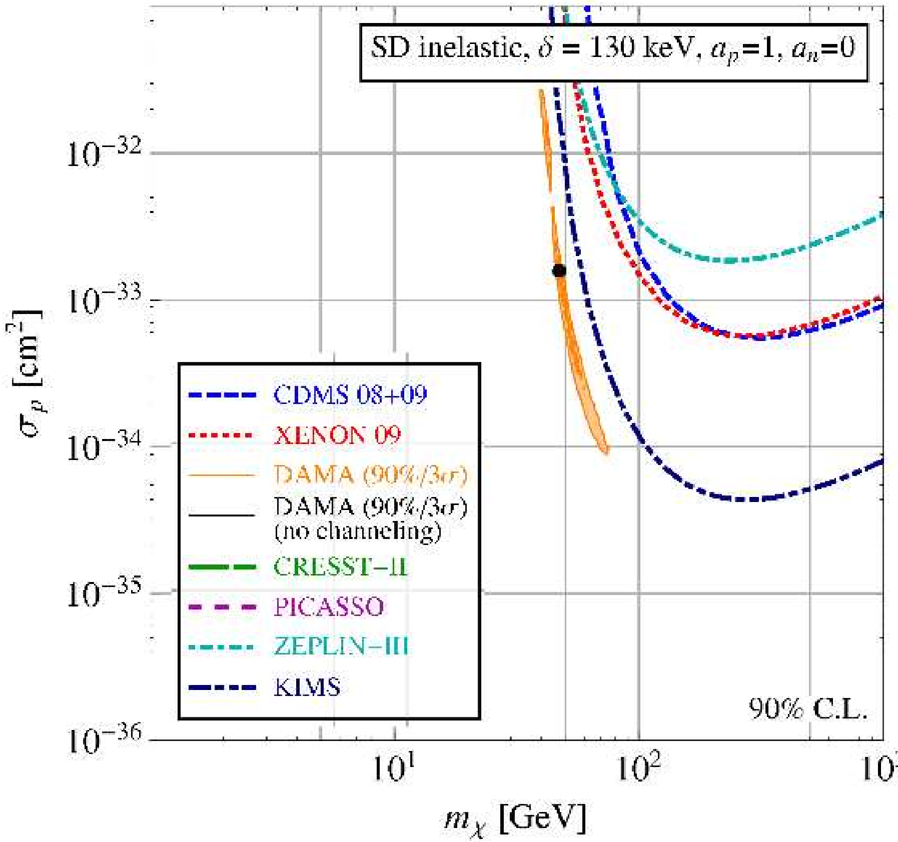
inelastic spin-dependent (iSD) scattering

Kopp, Schwetz, Zupan, 0912.4264

iSD on protons





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from channeled events

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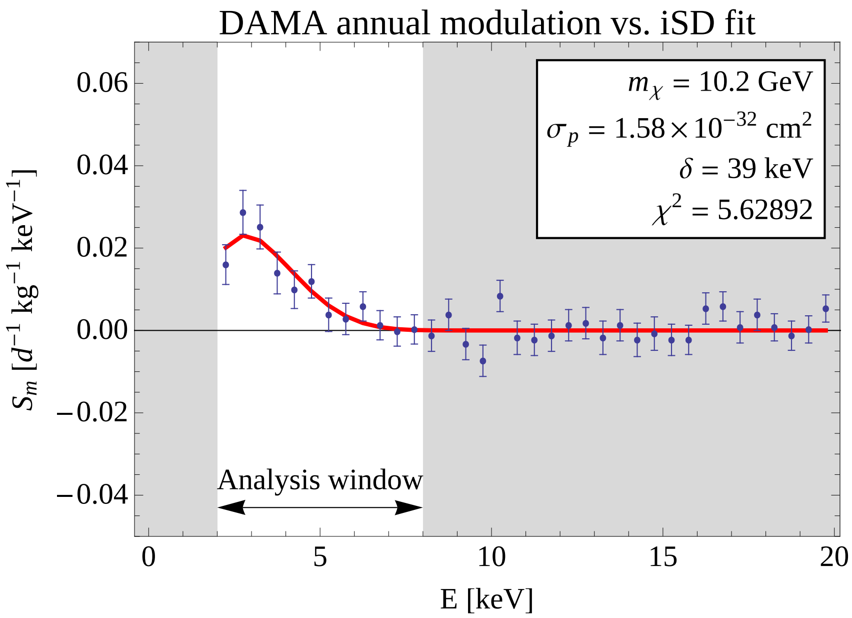
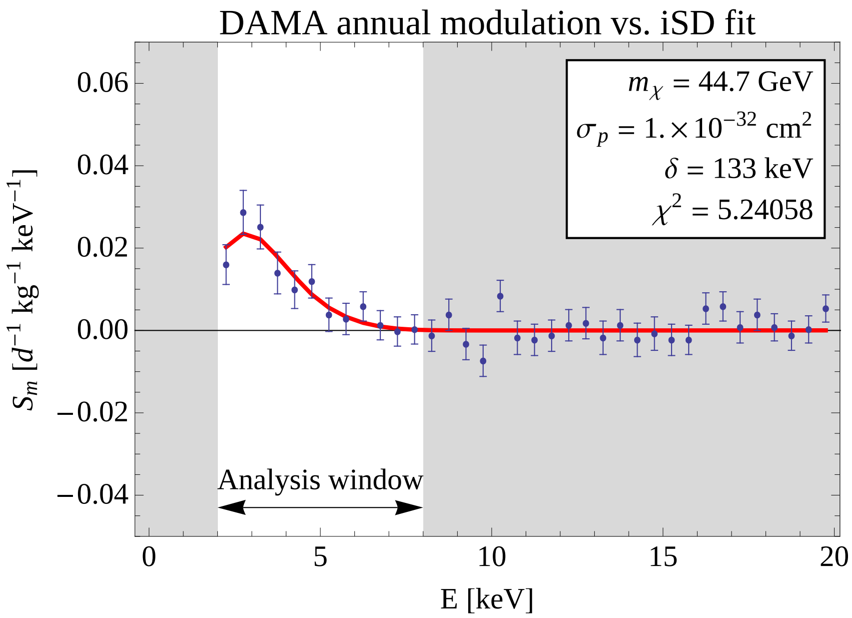
quenched events

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)

Conclusions

Conclusions

There are a few hints in the low mass region, BUT:

- mostly not consistent with each other
- region(s) strongly constrained (excluded?) by various bounds
- under some assumptions also collider constraints

  talk by T. Tait

$\Rightarrow$ we are speaking about a challenging region on the edge of the capabilities of detectors

Conclusions

maybe we are not seeing DM now,. . .

but this situation is typical for the DM field:
any claimed signal has to be cross checked / re-discovered / excluded by several complementary experiments

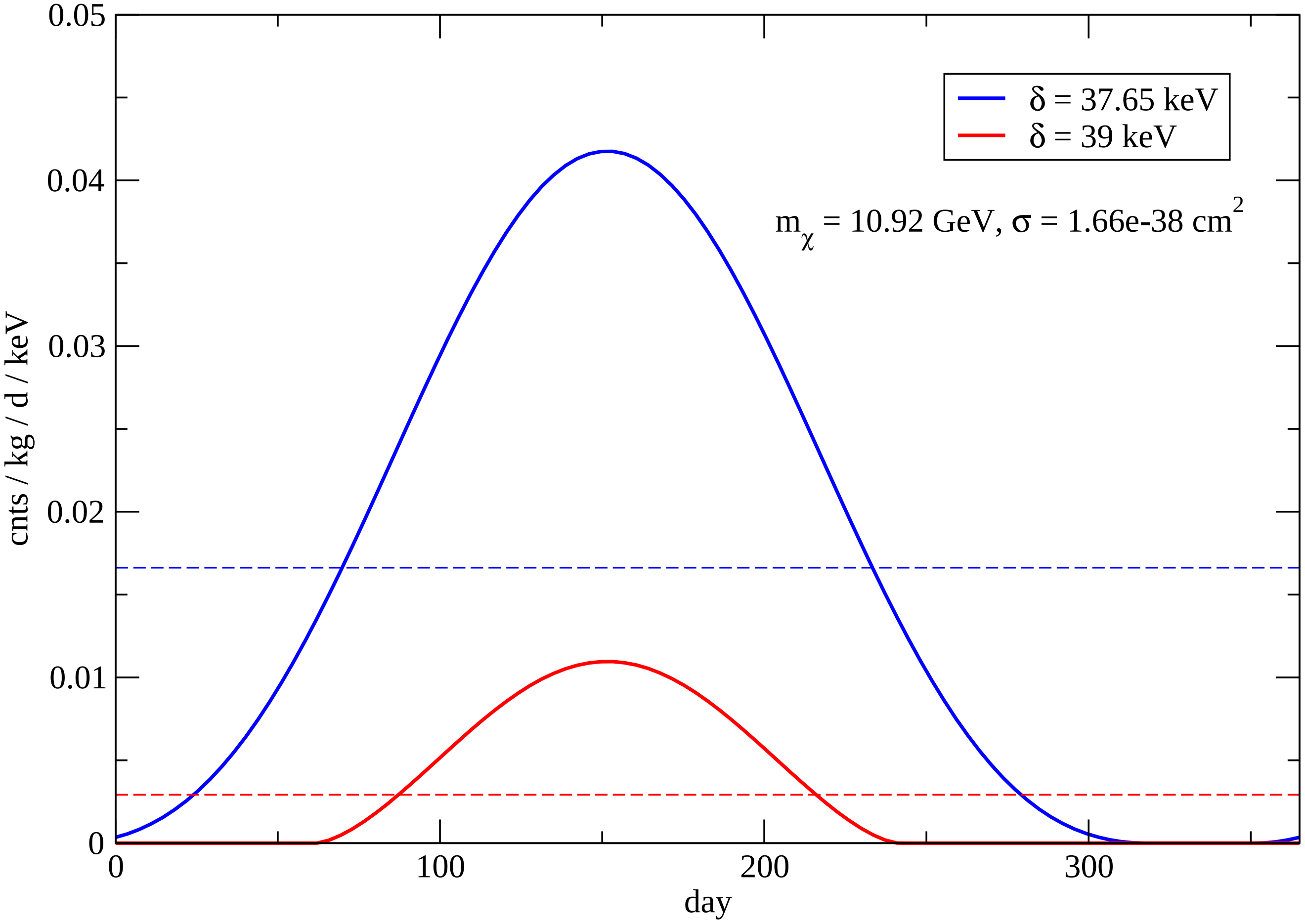
similar situation as recent cosmic ray "DM signals"

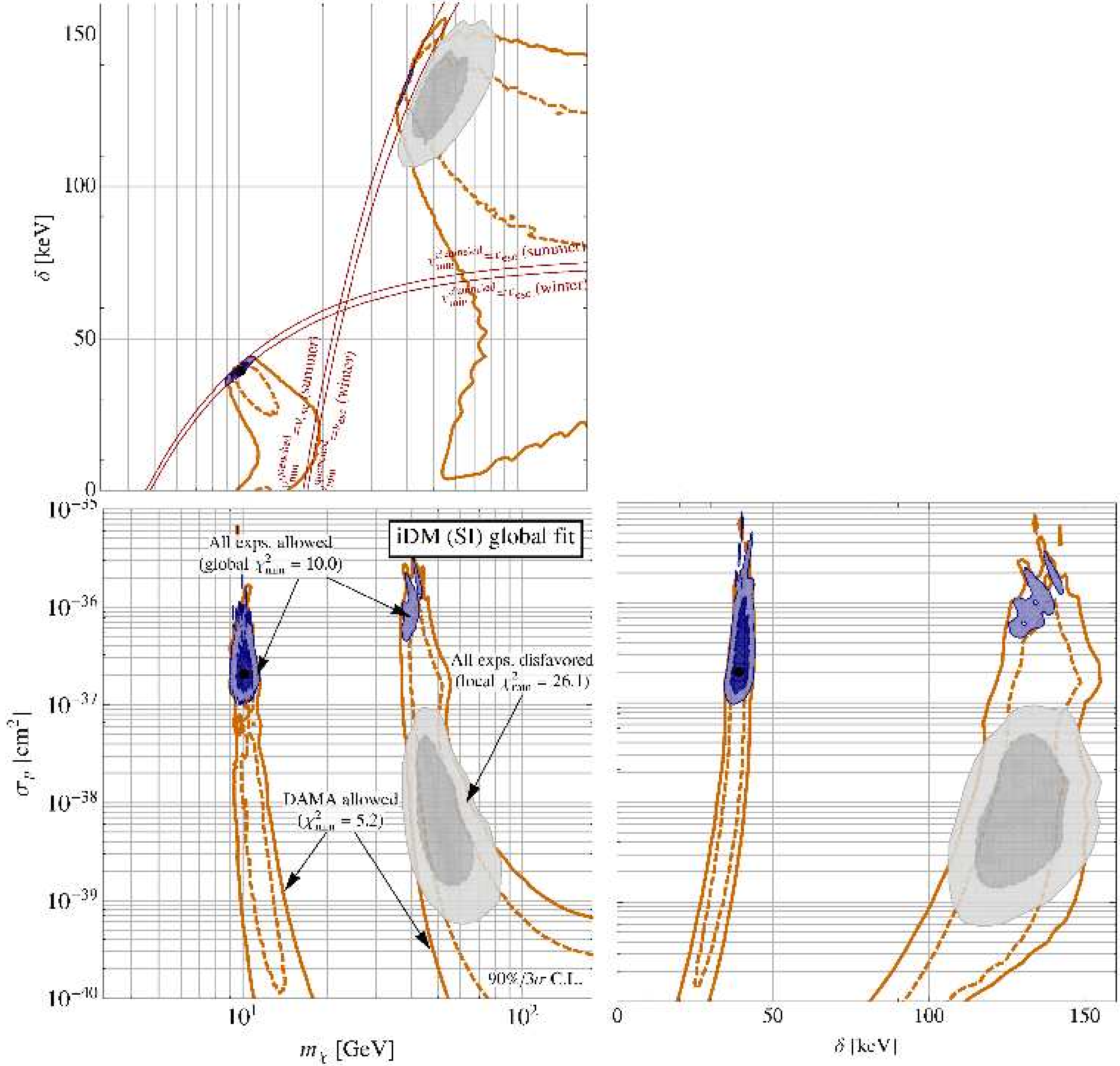
at some point "hints" will converge (hopefully)!

Additional slides

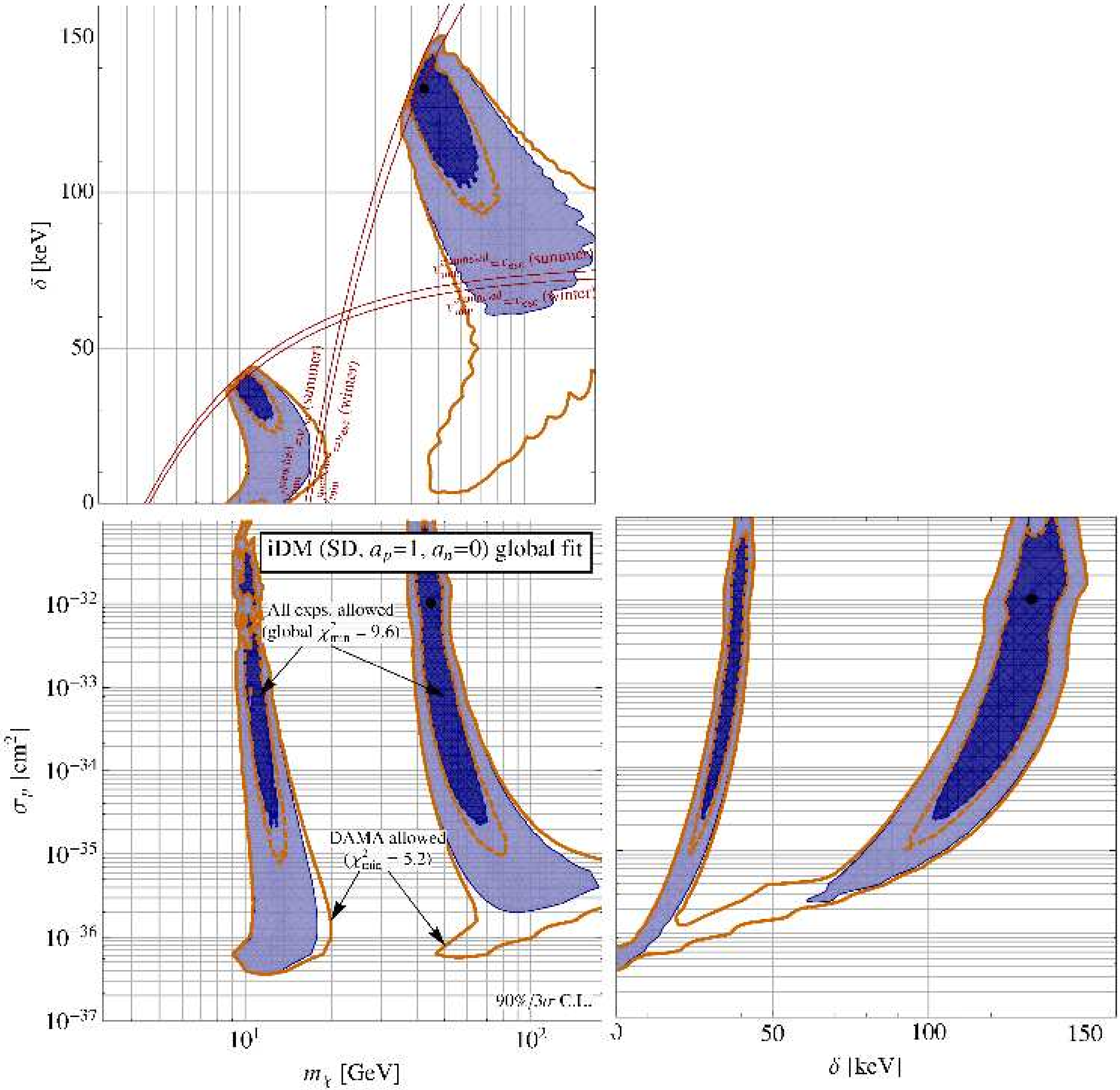
iSI

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





δ [keV]
150
100
50
0
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
σ_p [cm^2]
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.
10^1
10^2
m_χ [GeV]
0
50
100
150
δ [keV]



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]
(summer)
(winter)

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 $m \pm \delta$ ($\delta_\eta = \delta_\xi = \delta \ll m$):

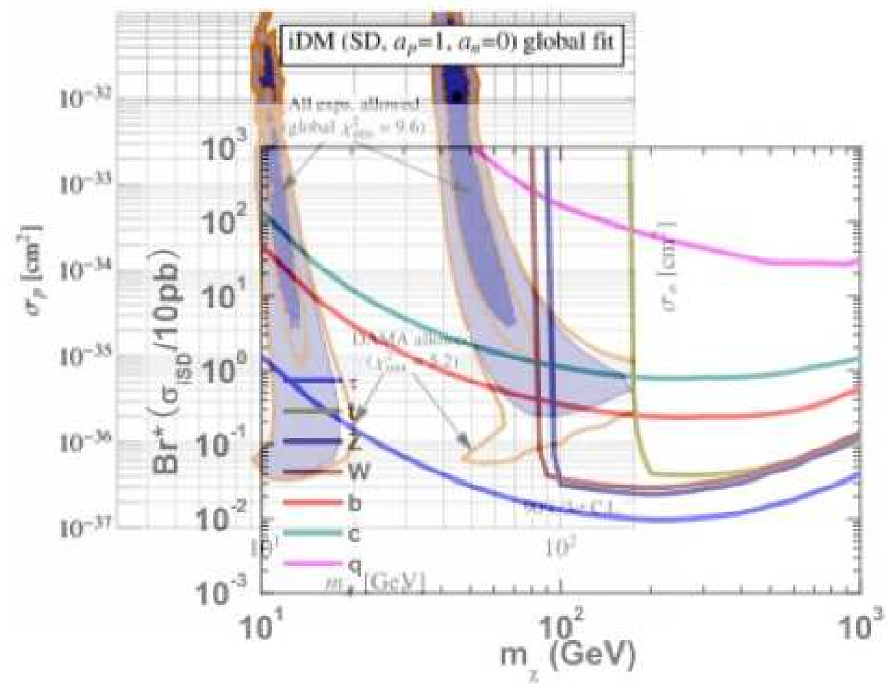
$$\chi_1 = i(\eta - \xi)/\sqrt{2}, \qquad \chi_2 = (\eta + \xi)/\sqrt{2}$$

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

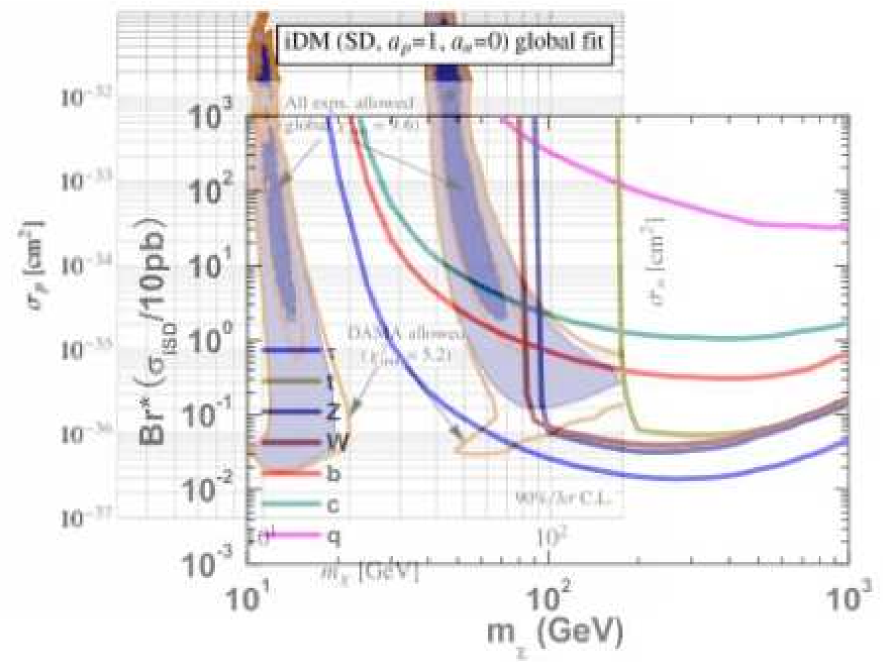
- inelastic scattering for $\delta \neq 0$
- $T \otimes T$ leads to spin dependent scattering in the non-rel. limit

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