IDM, Montpellier, France

Direct detection data and possible hints for low-mass WIMPs

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in collaboration with Joachim Kopp and Jure Zupan, 0912.4264

Outline

- "low-mass" WIMPs: $5\,\mathrm{GeV} \lesssim m_\chi \lesssim 50\,\mathrm{GeV}$
  χ should not couple to Z^0 (LEP)
  many examples for models, e.g., couple to Higgs
- Hints for low-mass WIMPs from: (alphabetical order)
  CDMS?, CoGeNT?, CRESST?, DAMA?
- constraints from CDMS-Si, XENON10,100
- focus on elastic spin-independent scattering
- comment briefly on spin-dependent
  and inelastic scattering

Elastic spin-independent scattering

Event spectrum

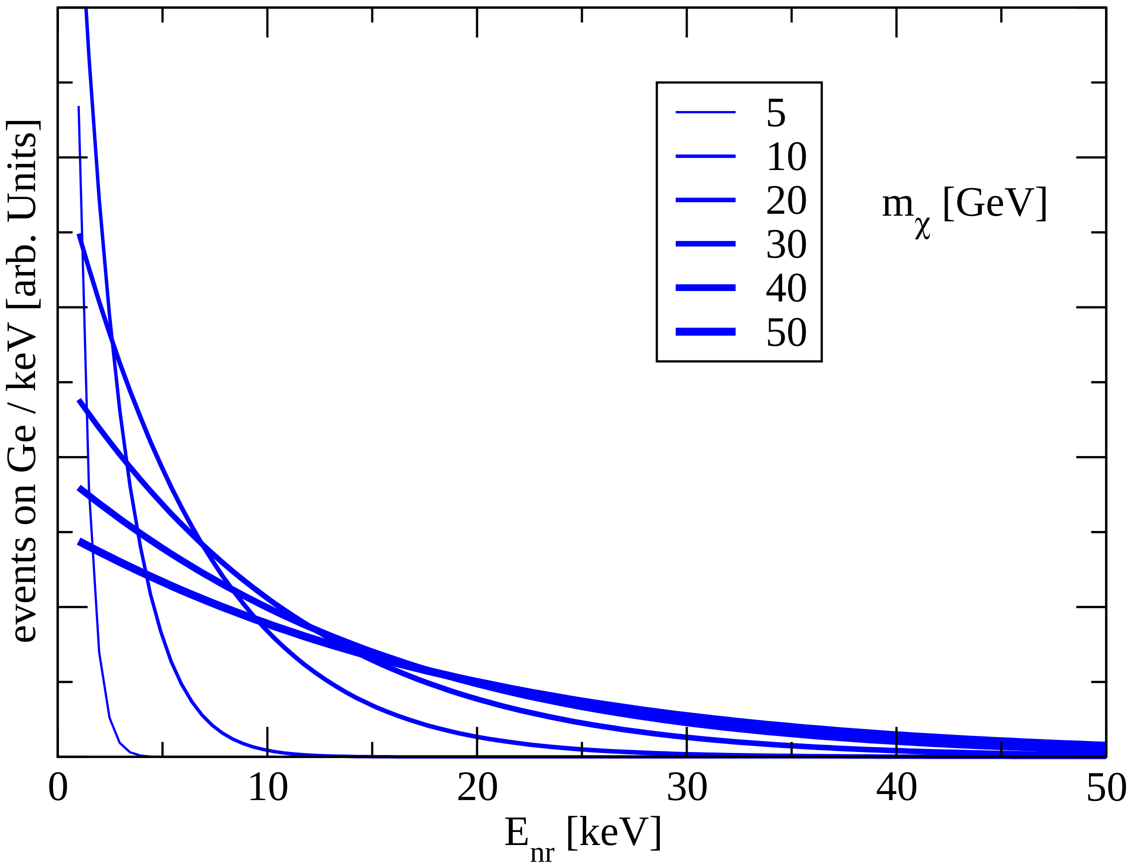
$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi} \; \frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2} \int_{v > v_{\min}(E_R)} d^3v \, \frac{f_\oplus(\vec{v}, t)}{v}$$

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

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

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 ⇒energy threshold is crucial

low-mass WIMP hints

CDMS-II

CoGeNT

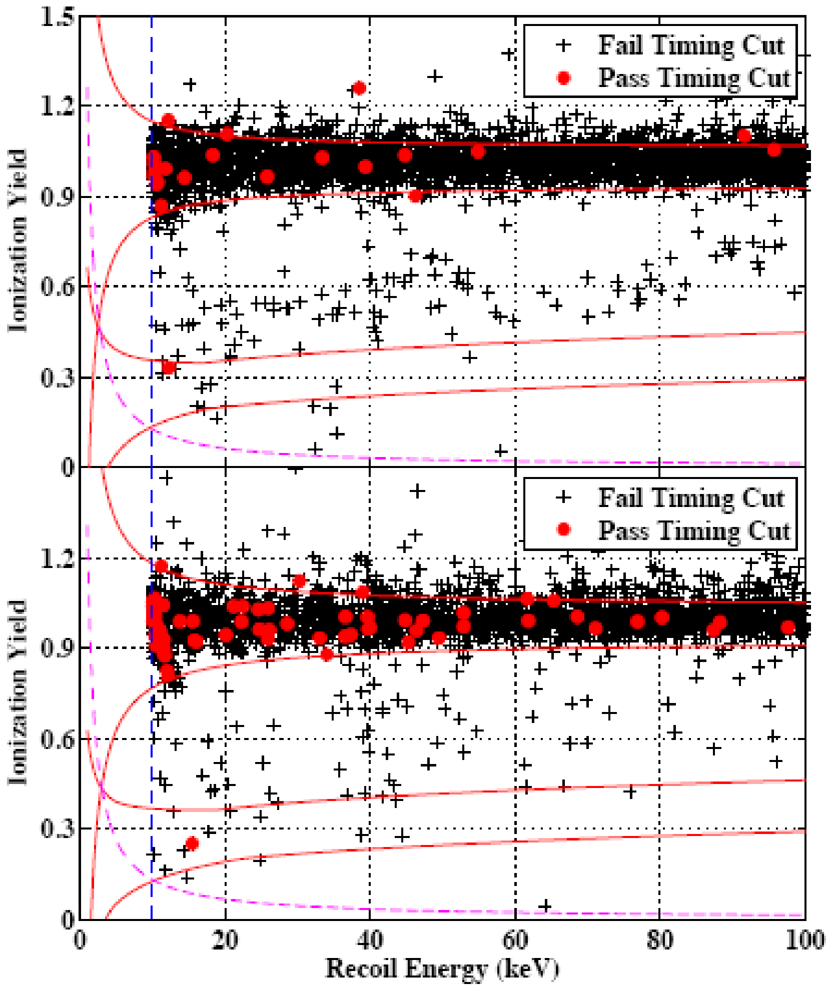
CRESST-II

DAMA

CDMS-II

Germanium detector, recoil energy range 10–100 keV

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

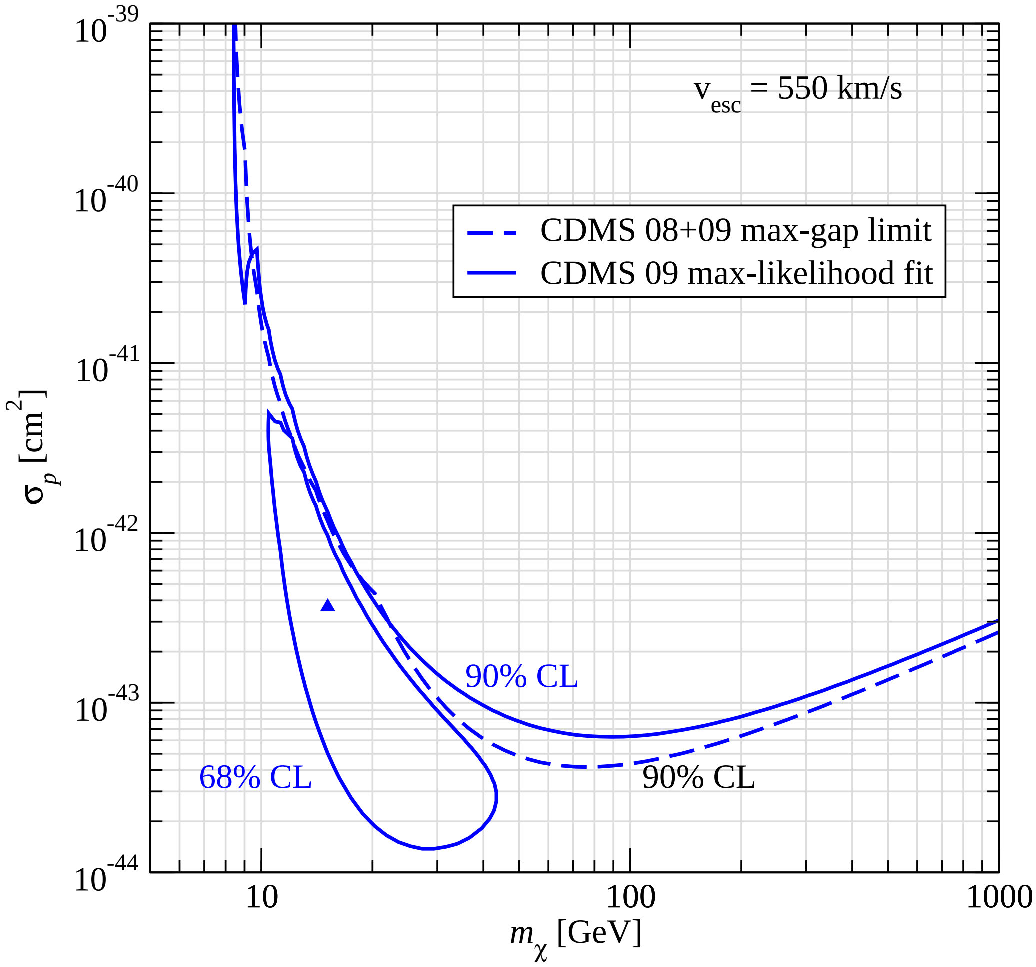


electron and nucl. recoil regions for two different detectors

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)

low-mass WIMP hints

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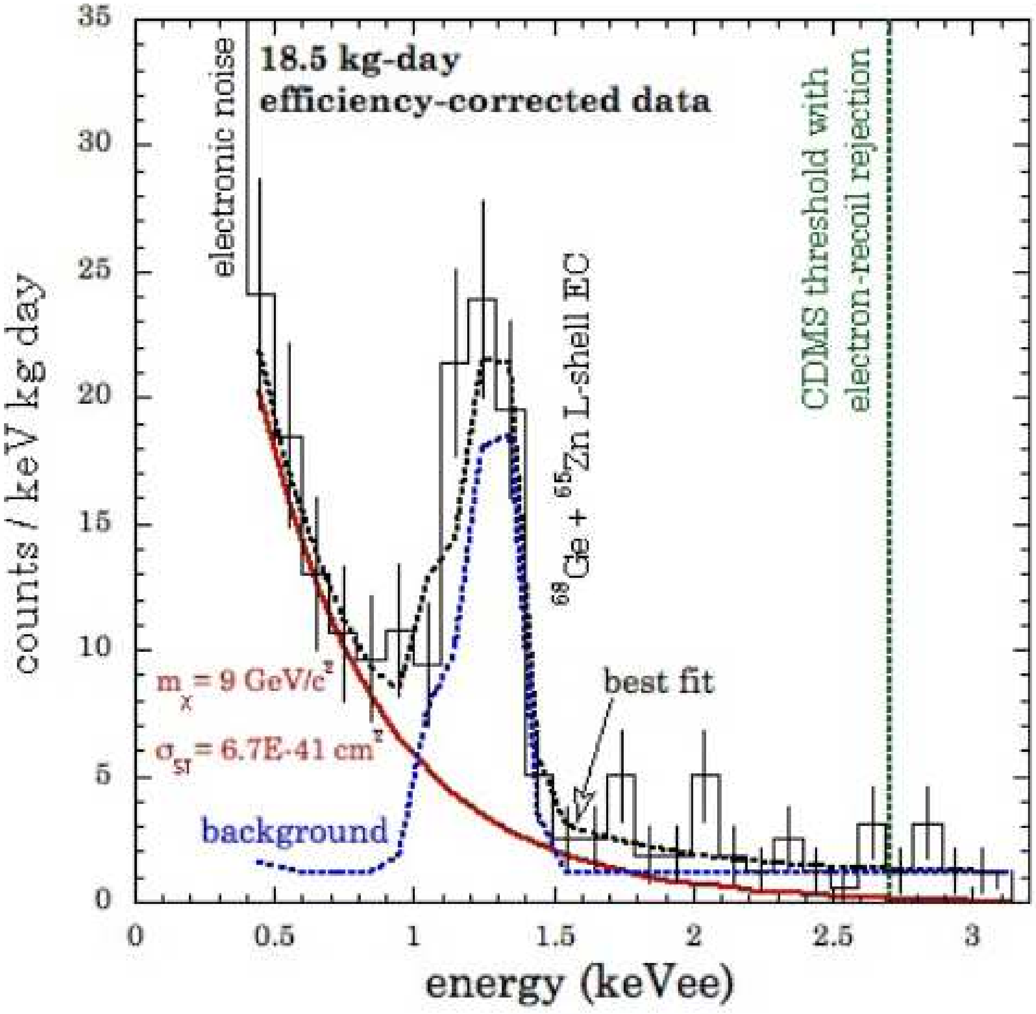
CoGeNT

CRESST-II

DAMA

CoGeNT

Germanium detector with extremely low threshold of 0.4 keVee

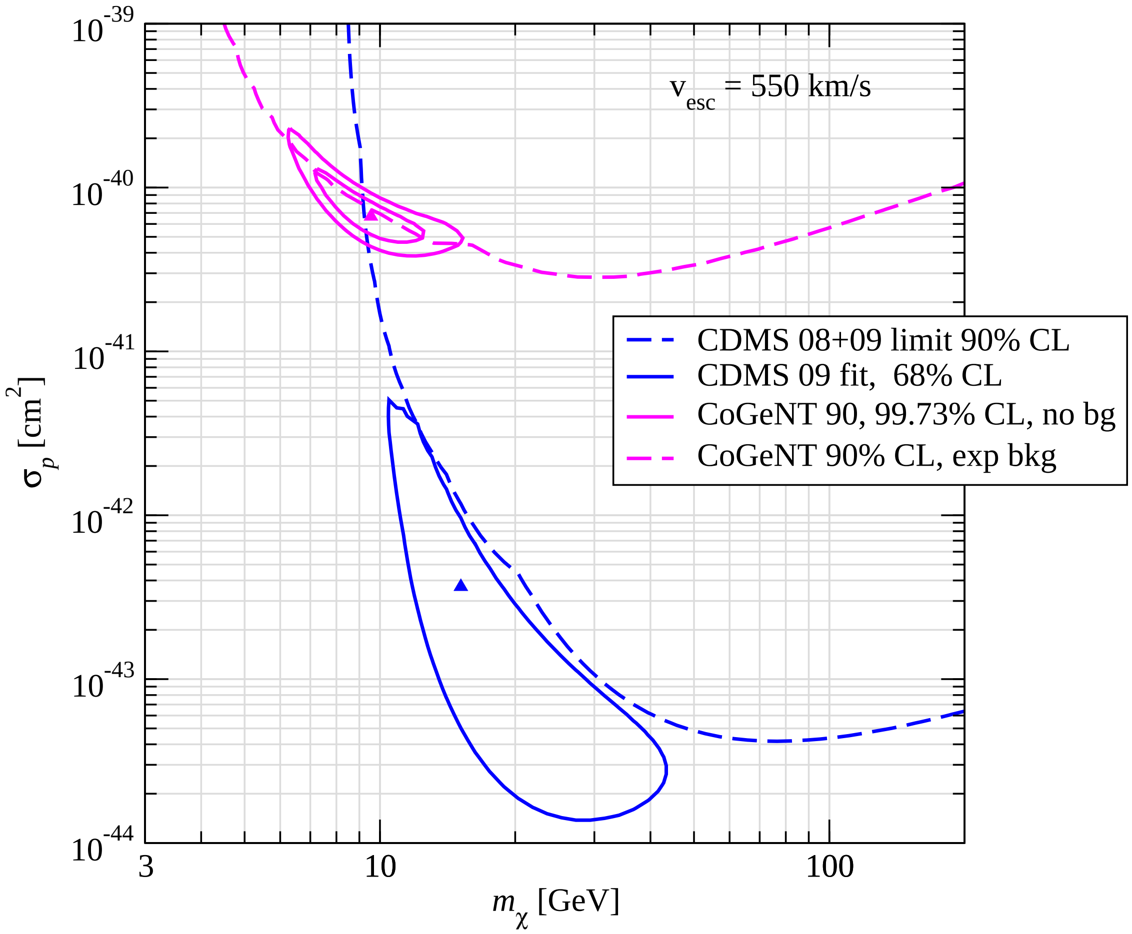


exponential rise of events at low energies

claim that it cannot be electronic noise

Aalseth et al., 1002.4703

CoGeNT



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

low-mass WIMP hints

CDMS-II

CoGeNT

CRESST-II

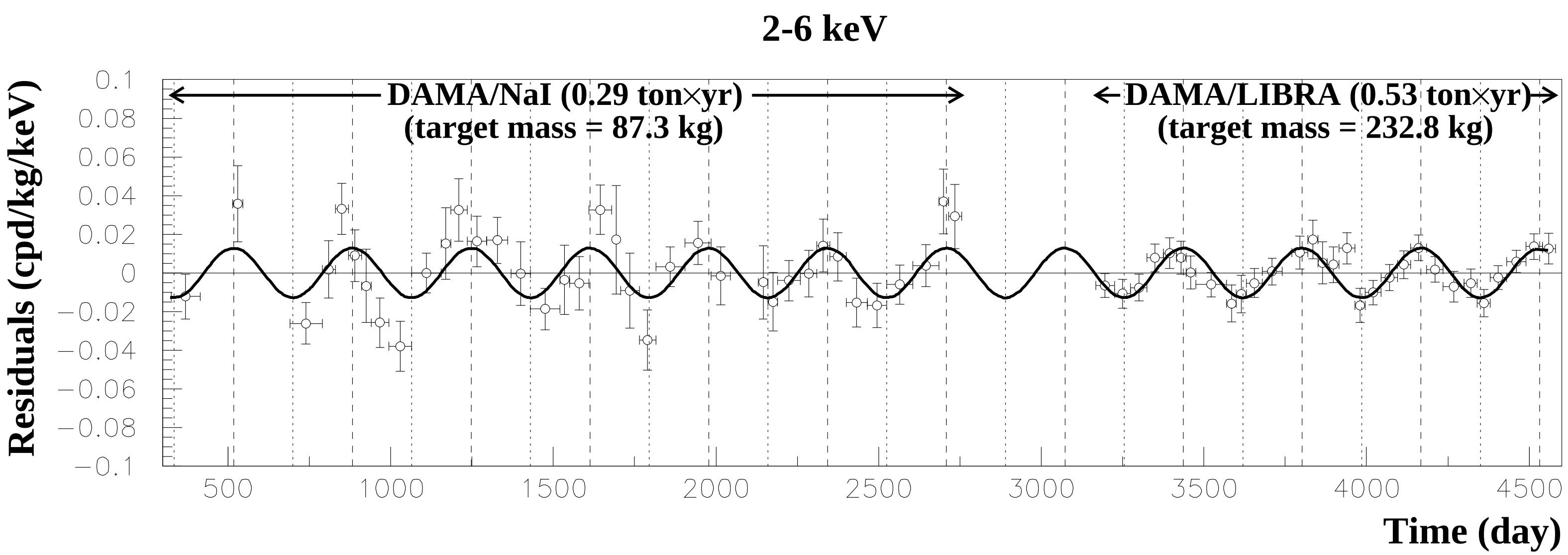
DAMA

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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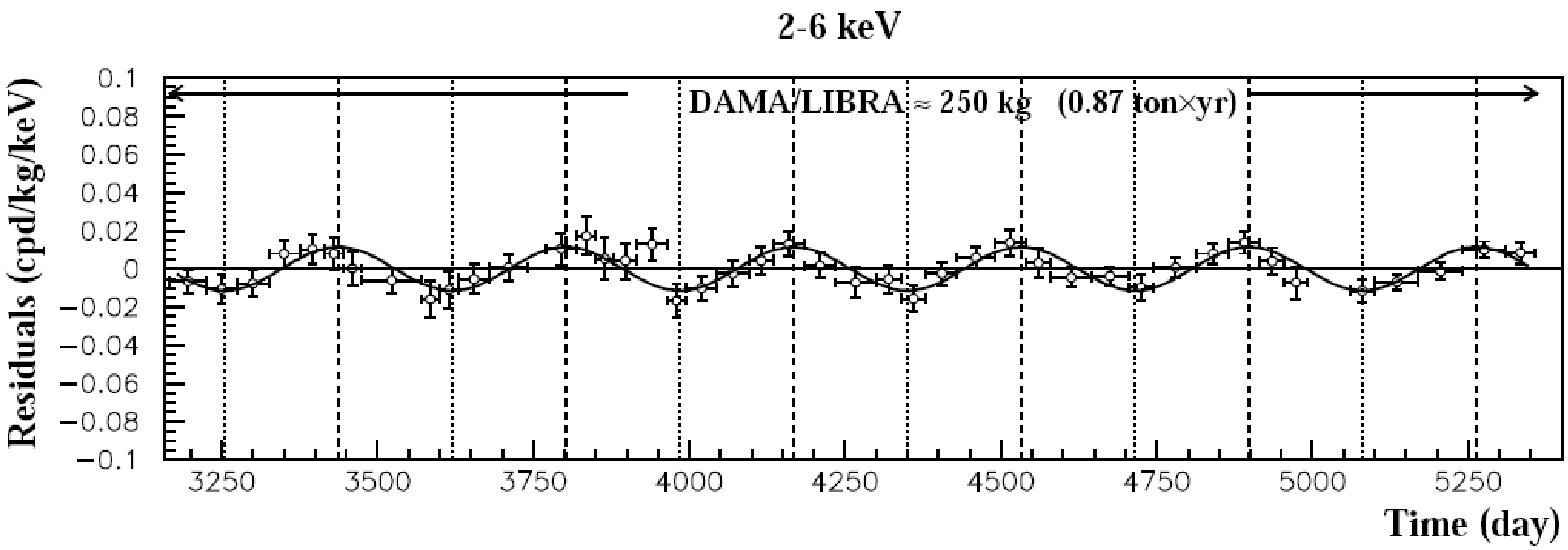

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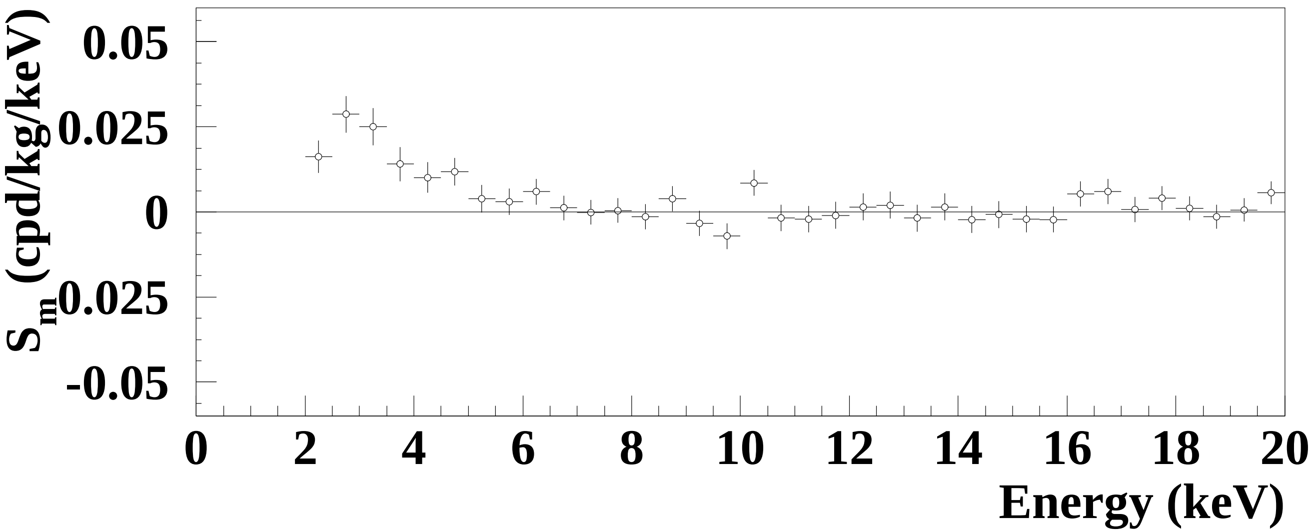


energy shape of modulation is important for constraining params

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:

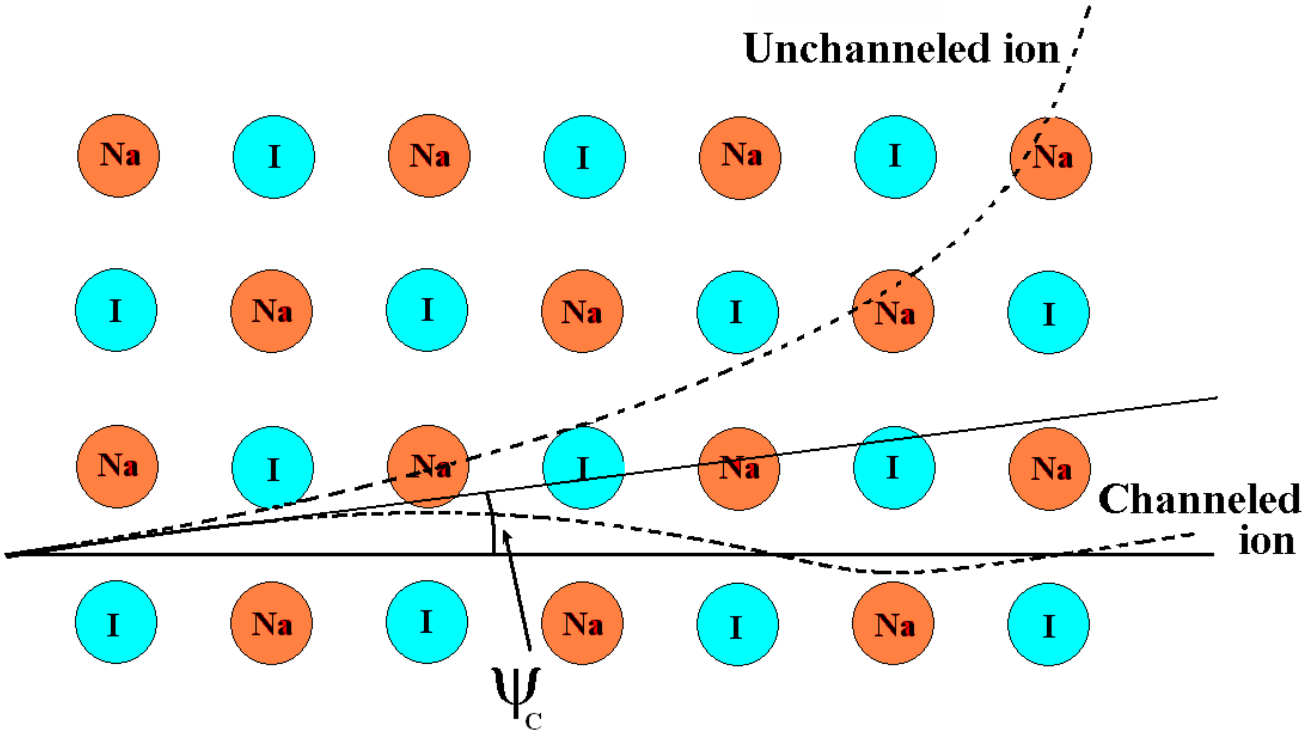
$$E_{\rm obs} = q \times E_R$$

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

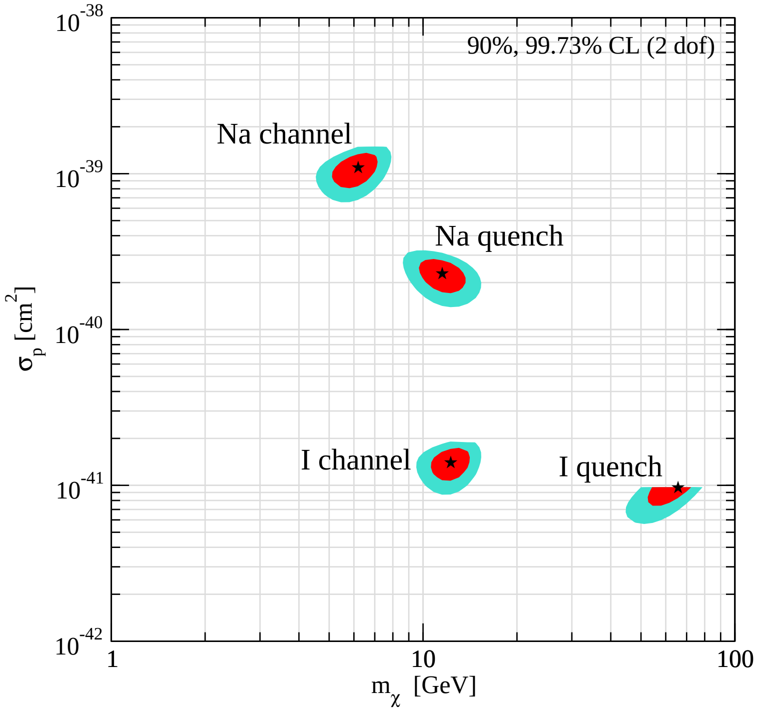
for such “channeled” events $q \approx 1$

Channeling and DAMA

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

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

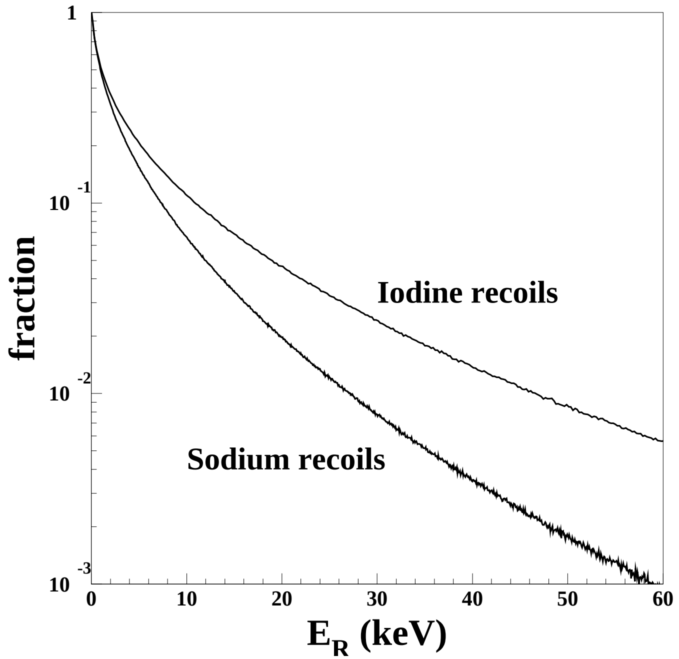
$f_x(E_R)$: fraction of channeled events on $x =$ Na, I



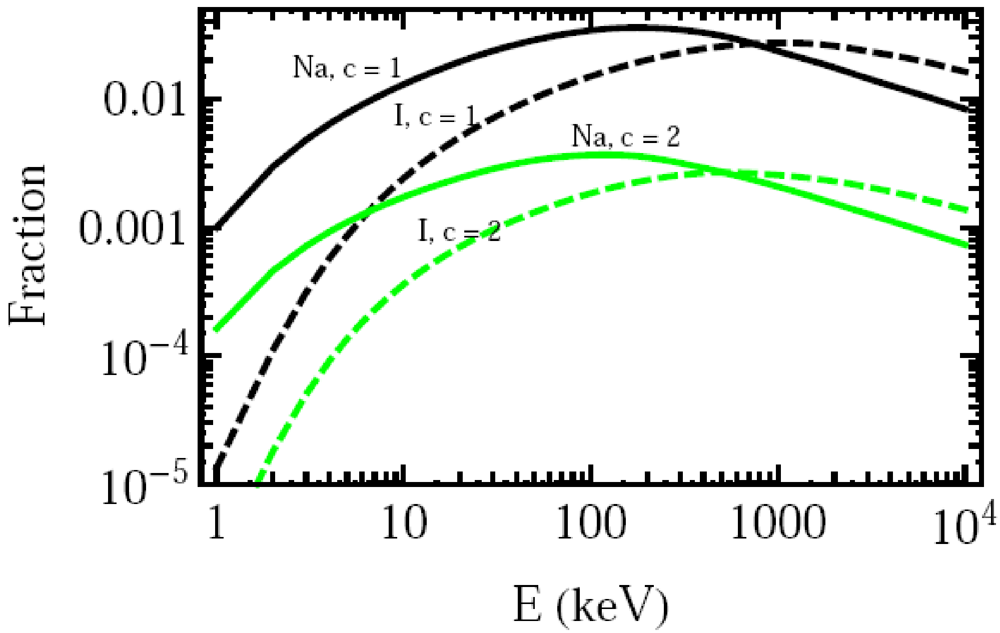
fitting DAMA requires

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

How large is the fraction of channeled events?



Bernabei et al., 0710.0288



Bozorgnia, Gelmini, Gondolo, 1006.3110

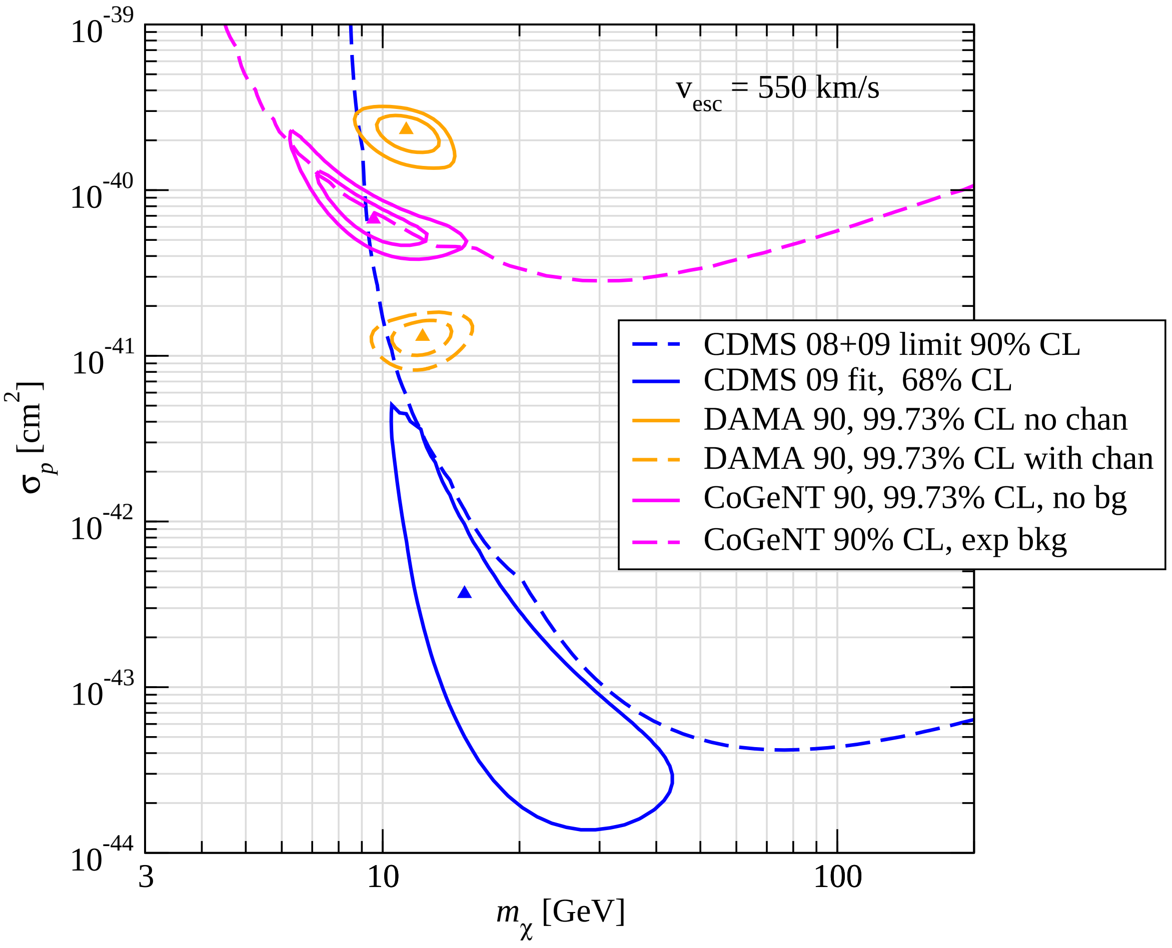
($c = 1, 2$ diff. temperature models)

see talk by G. Gelmini for detailed discussion

suggest that channeling is not important

$\Rightarrow$ BUT: should be measured !!

Fitting DAMA



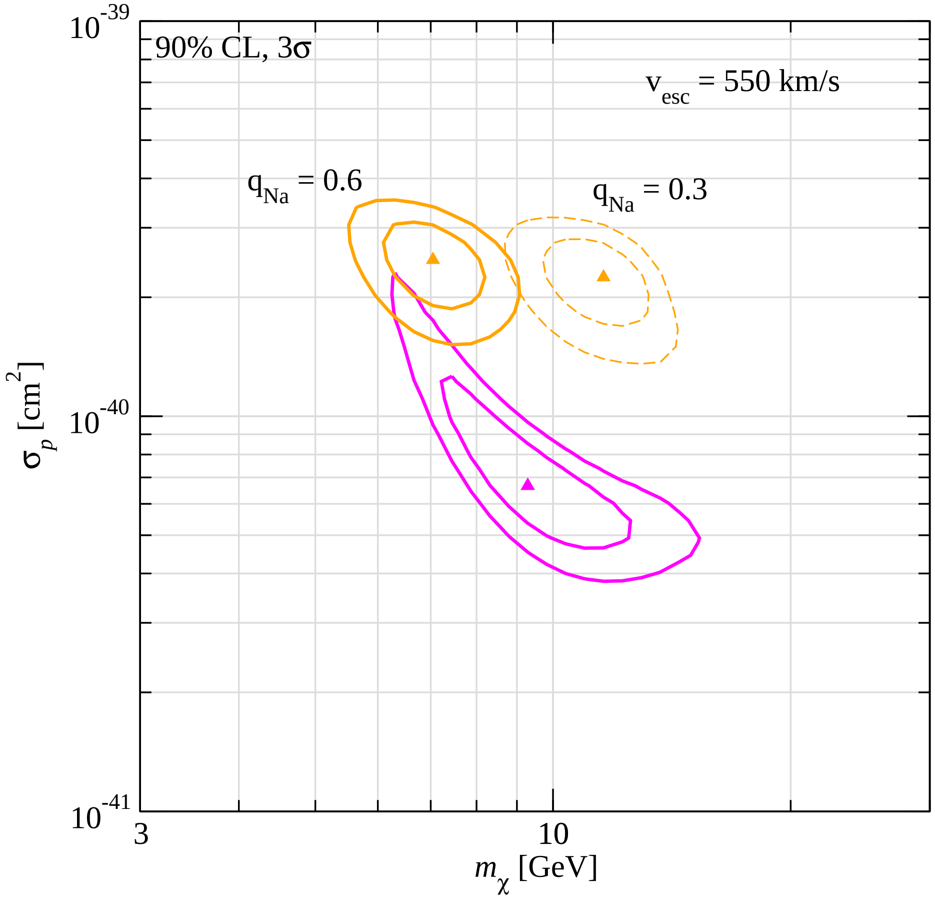
region with channeling assumes fraction of chan. according to Bernabei et al., 0710.0288

DAMA vs CoGeNT

can we make CoGeNT and DAMA consistent?

Hooper, Collar, Hall, McKinsey, 1007.1005

How well do we know the quenching factor of Na?



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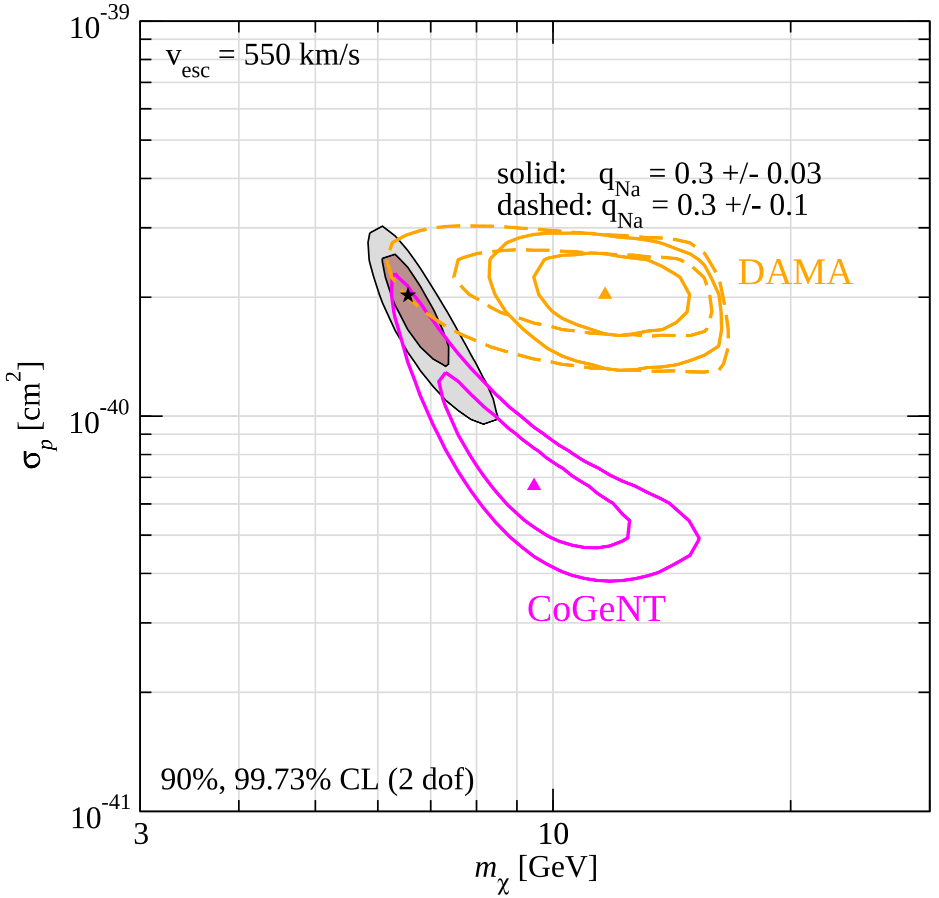


$$\chi^2_{\rm DAMA} = 8.2/(12-2) \quad (61\%)$$
$$\chi^2_{\rm CoG} = 46/(56-4) \quad (71\%)$$

$$\chi^2_{\rm glb,0.1} = 75/(68-4) \quad (1.6\%)$$
$$\chi^2_{\rm glb,0.03} = 95/(68-4) \quad (0.7\%)$$

low-mass WIMP hints

CDMS-II

CoGeNT

CRESST-II

DAMA

CRESST-II

Talk by W. Seidel on monday: $CaWO_4$ target, about 400 kg d

Events:

Detector	E0.1[keV]	events
5	12.35	5
20	11.85	2
29	11.65	4
33	15.55	2
43	15.55	4
45	19.15	2
47	17.35	4
51	9.65	6
55	22.25	3
total		32

Alpha background

Detector	Nfound	Nproj
5	4	1.05
20	2	0.51
29	4	1.02
33	3	0.76
43	5	1.06
45	2	0.55
47	2	0.53
51	4	0.98
55	3	0.46
total		6.93

Neutron background 0.9
Alpha background: 6.9
Leakage from gamma band: 0.9

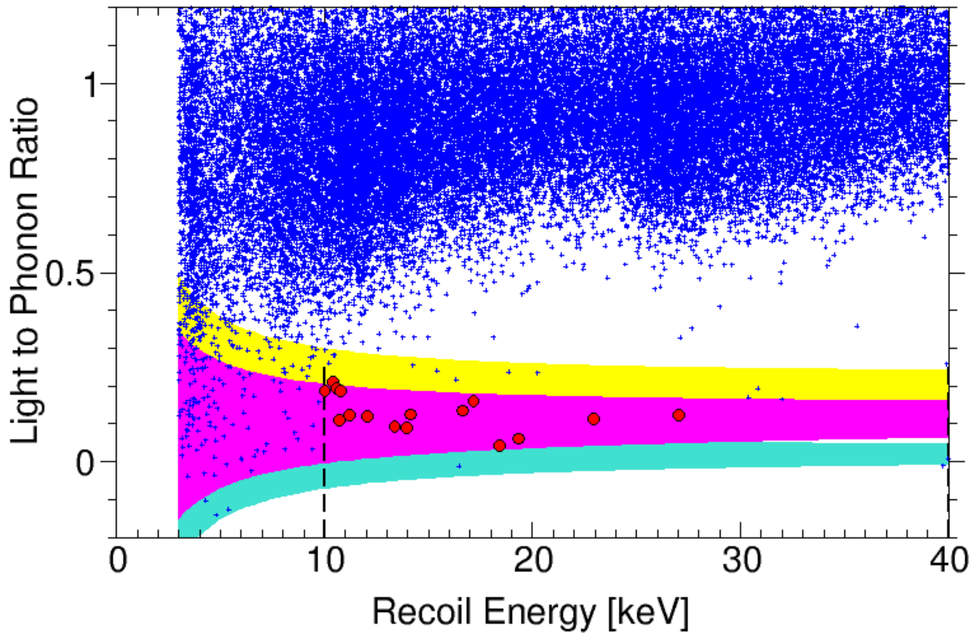
Sum of background estimates: 8.7

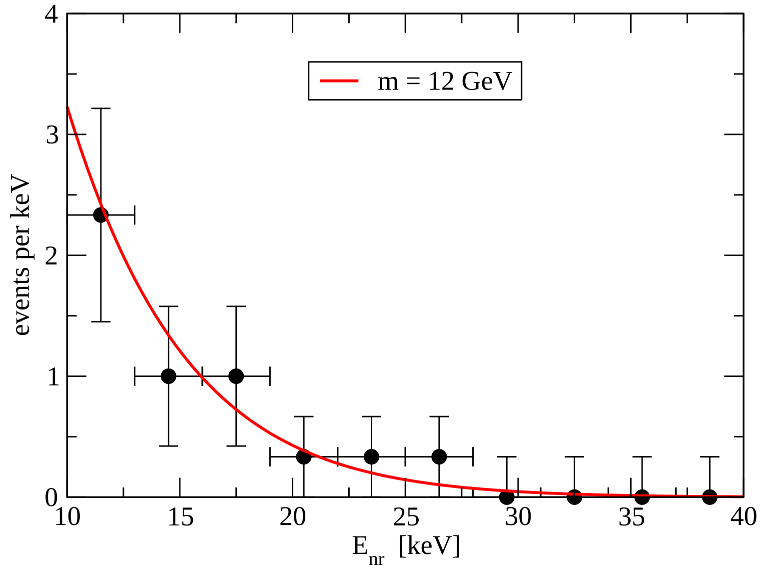
background estimate of 8.7 ± 1.4 not enough to explain observed 32 signals,

CRESST data

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

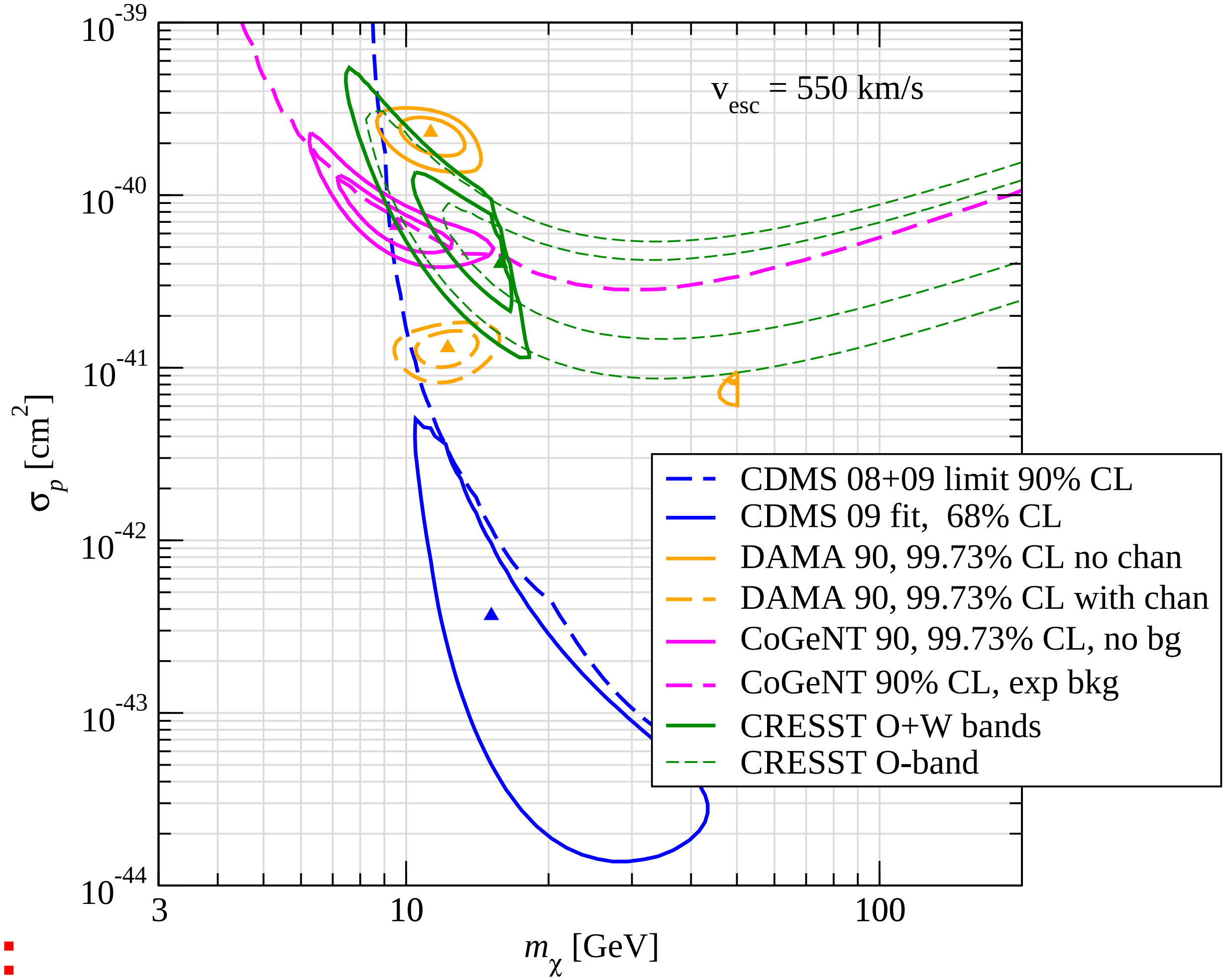
16 single-scatter events in O-band (magenta)





shape agrees with $\sim$ 10 GeV WIMP

Attempt CRESST O band fit

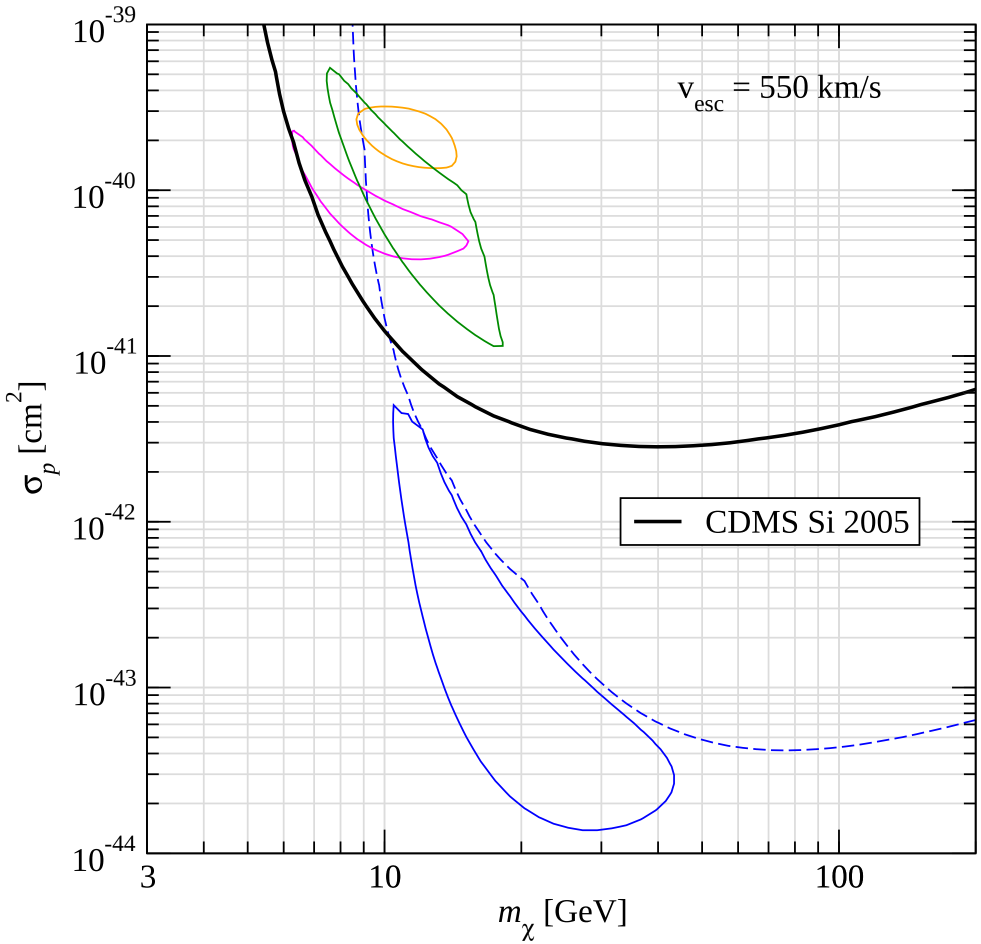


WARNING:

Do not take too serious - very speculative! ⇒ regions will shift/shrink/go away (?) when detailed information on CRESST events and background becomes available

Constraints from CDMS and XENON

CDMS Si constraints



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

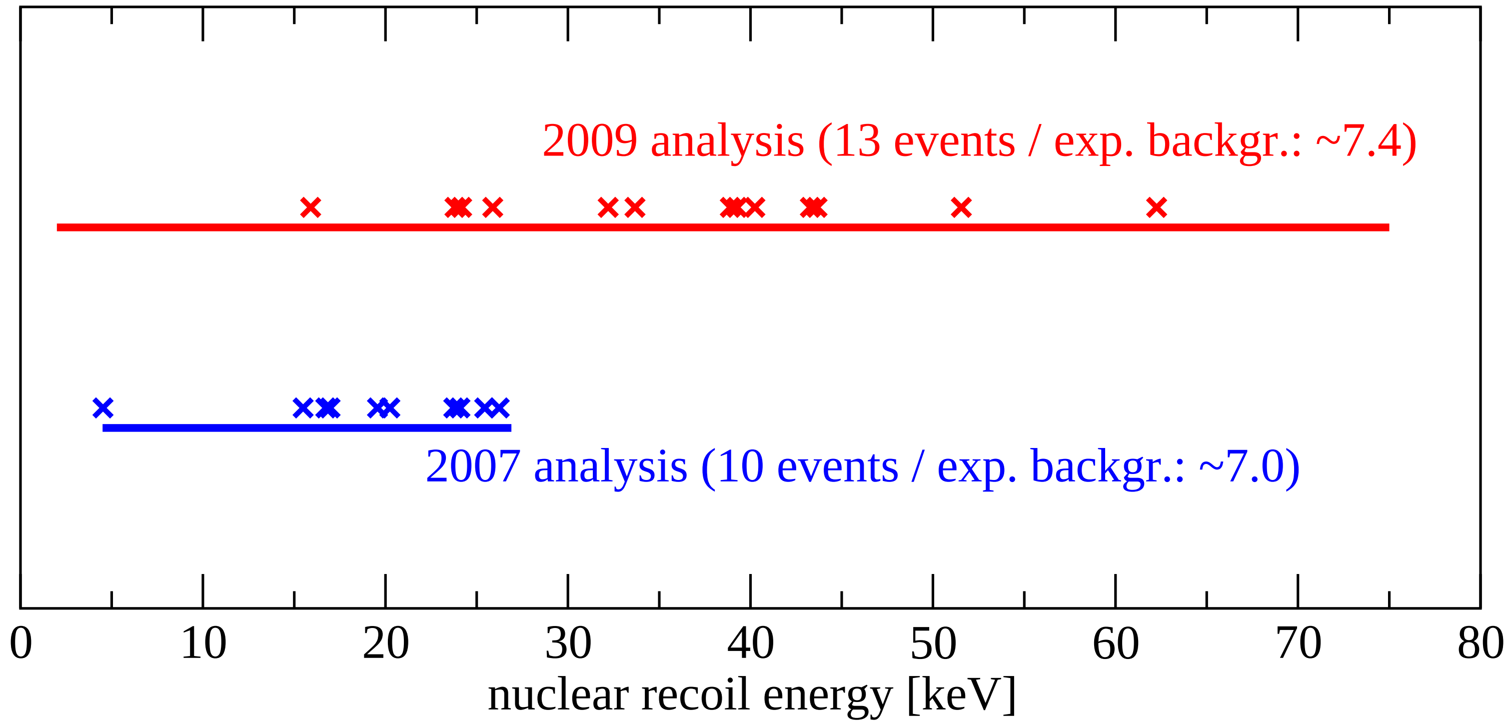
more data on tape

XENON-10

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

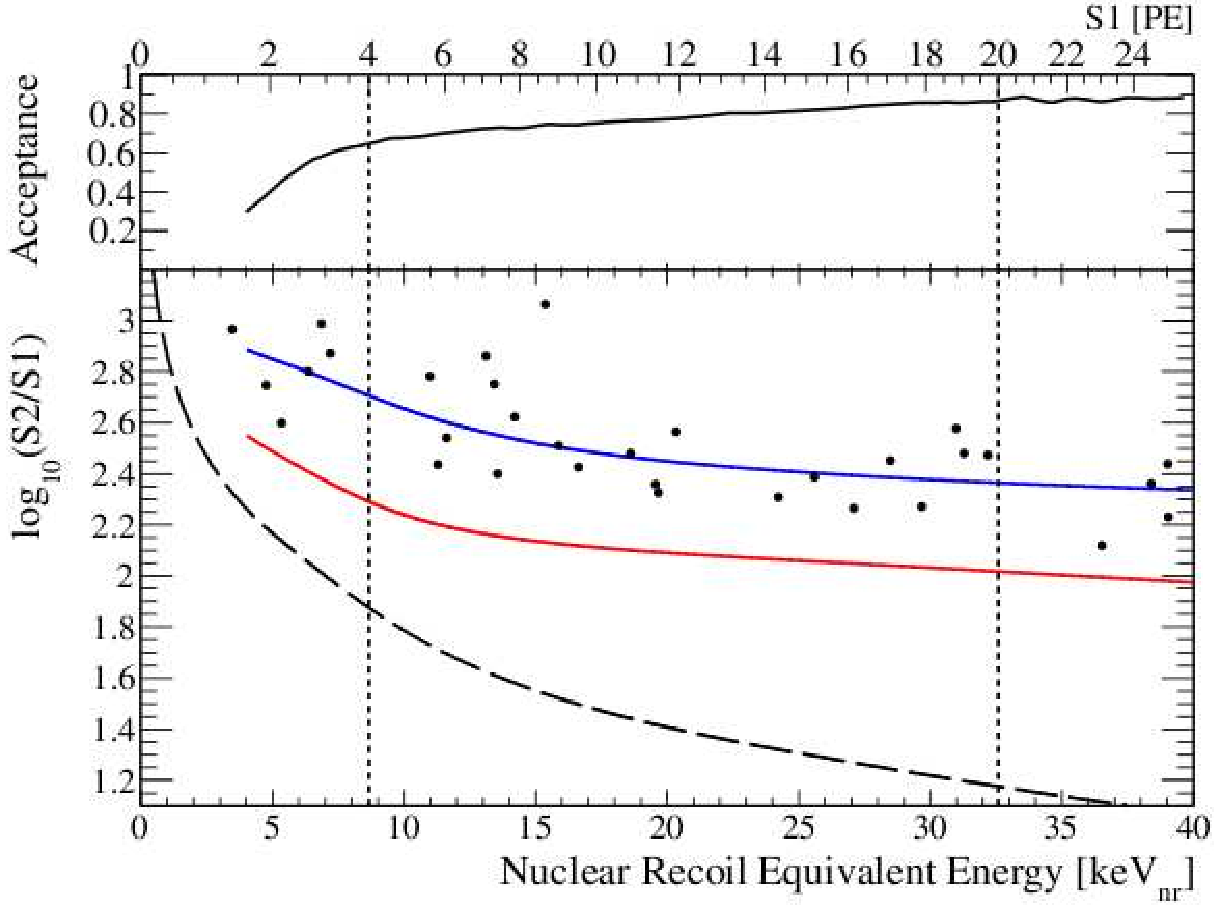
0706.0039: original blind analysis: 10 events

0910.3698: revised cuts: 13 events, extended energy window



XENON-100

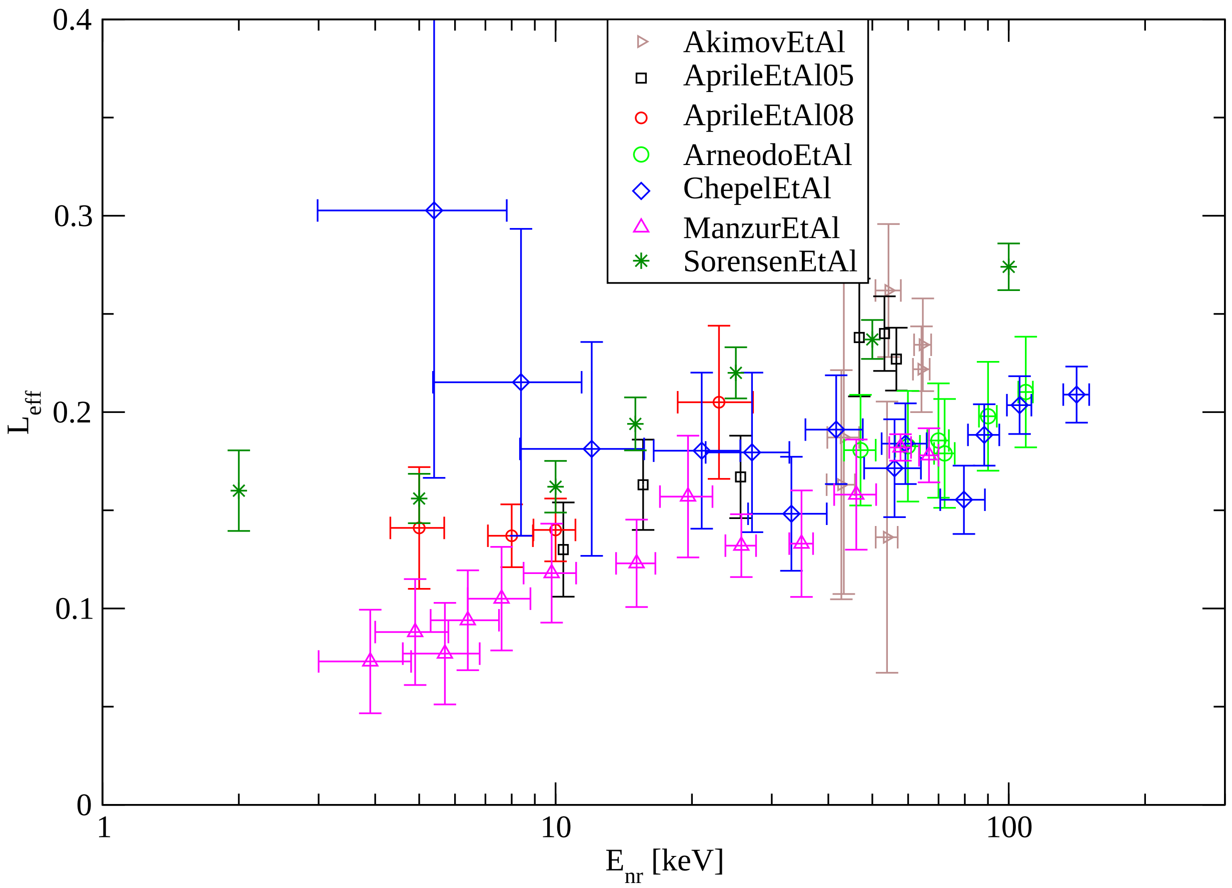
11.7 days, 40 kg fid., $\sim$ 230 kg day effective exp.



1005.0380; talk by M. Schumann

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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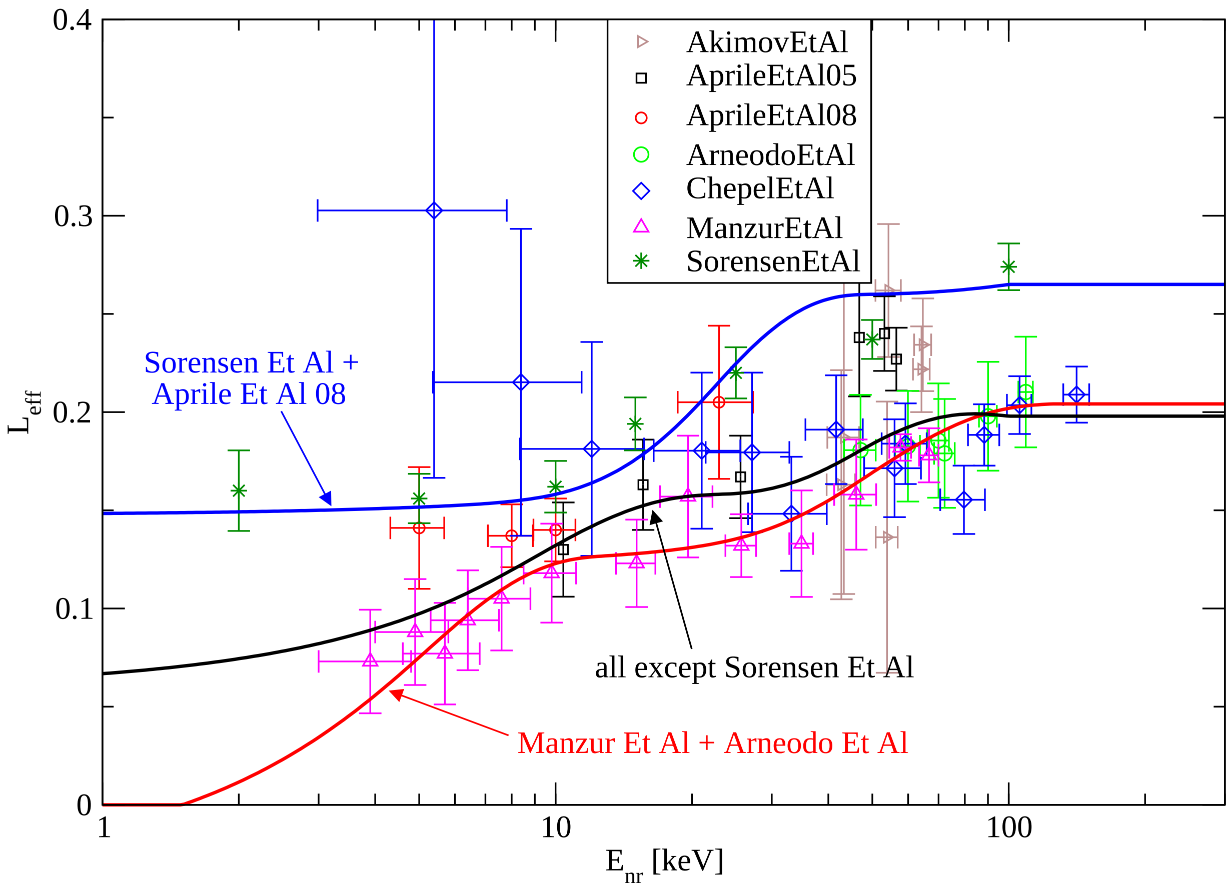
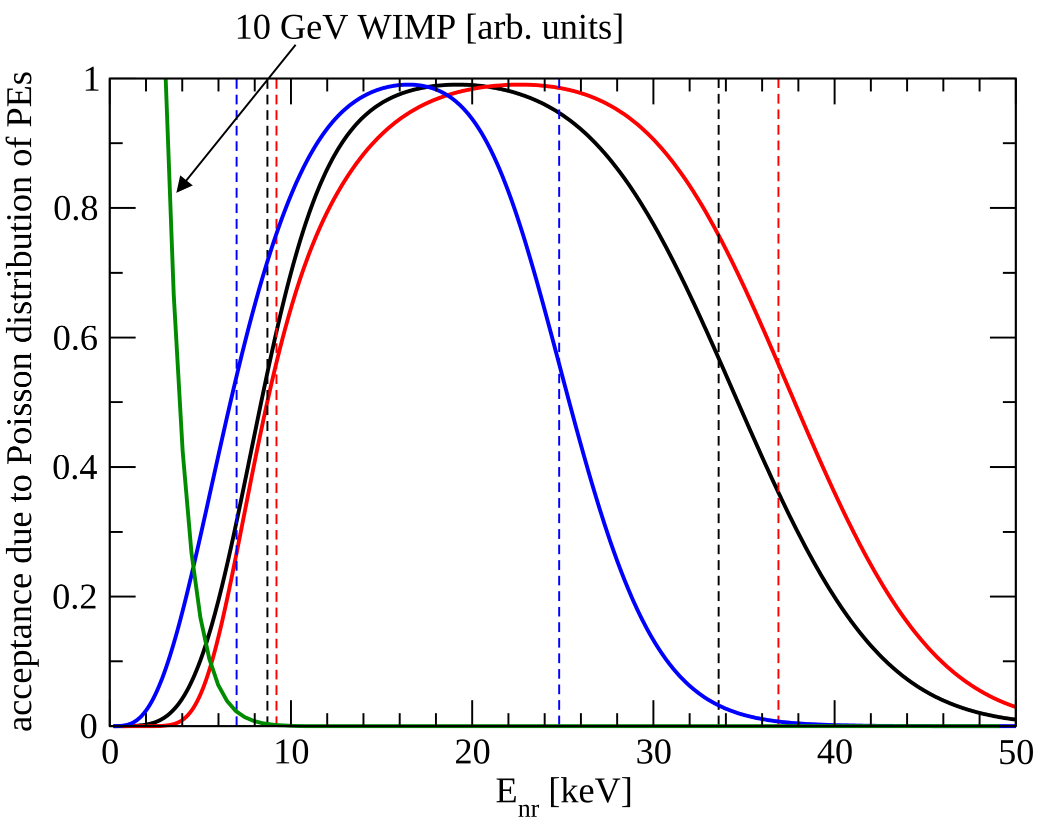


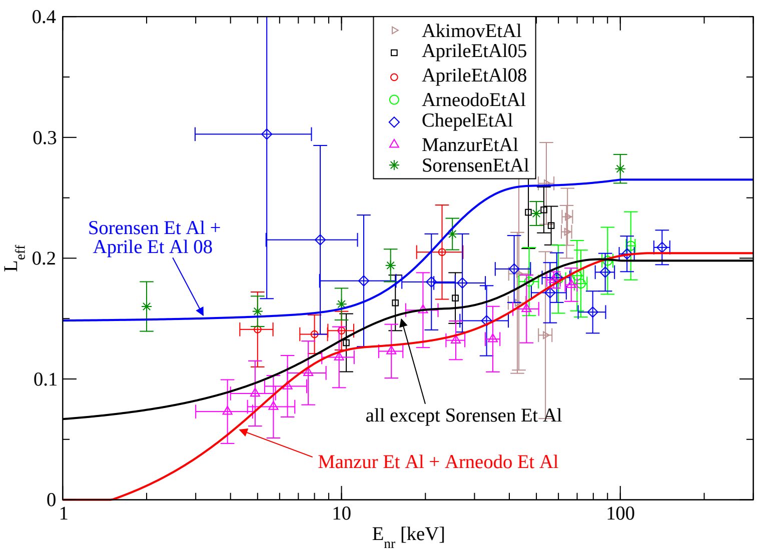
3 exemplary fits, extrapolating with straight lines at low energies

Acceptance window in XENON100

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

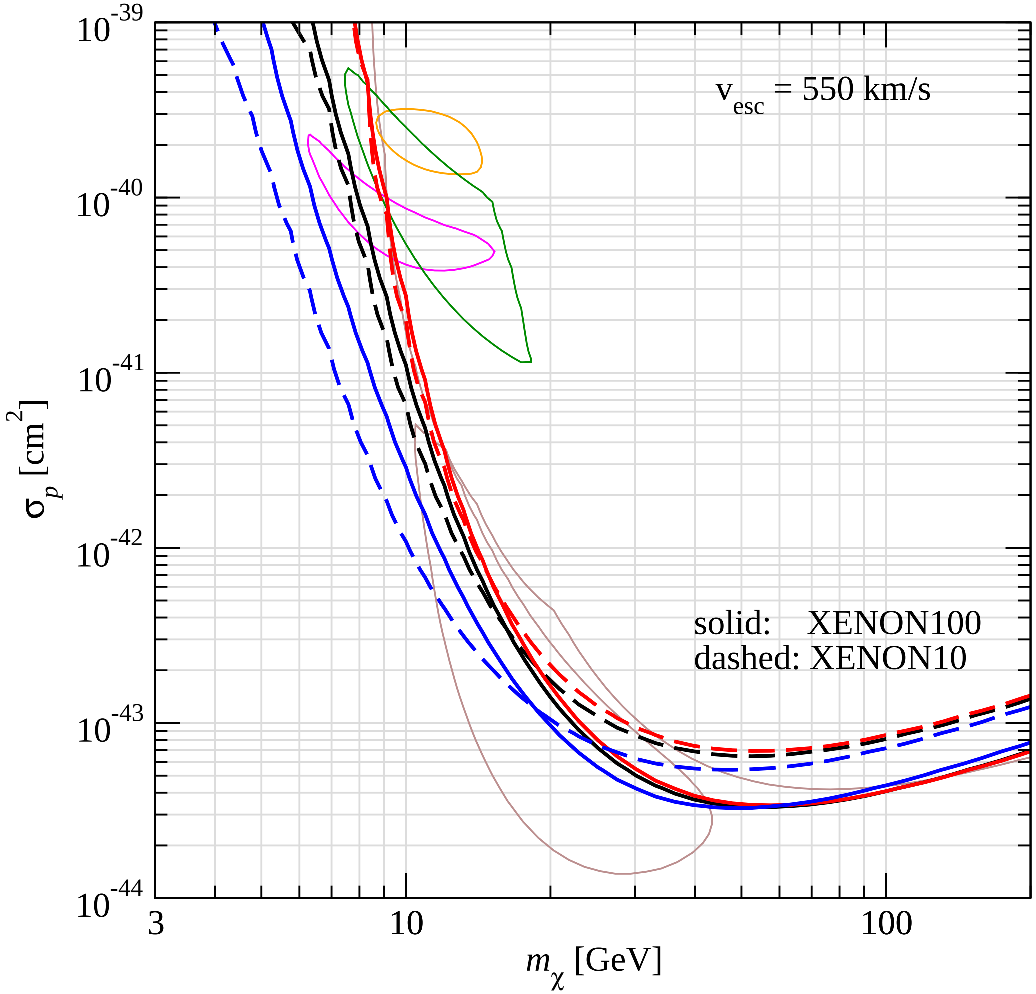
- this translates into window in E_{nr} according to L_{eff}
- Poisson statistics of PEs implies smearing of the thresholds

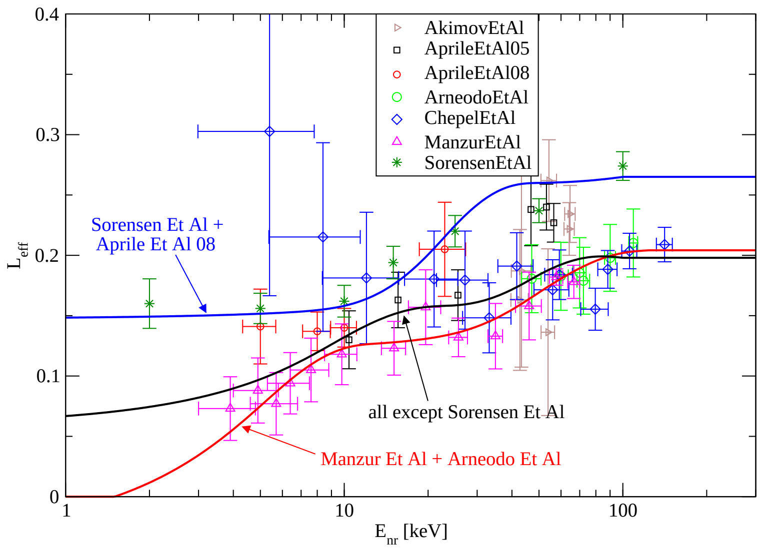




same color coding

L_{eff} and the XENON bounds





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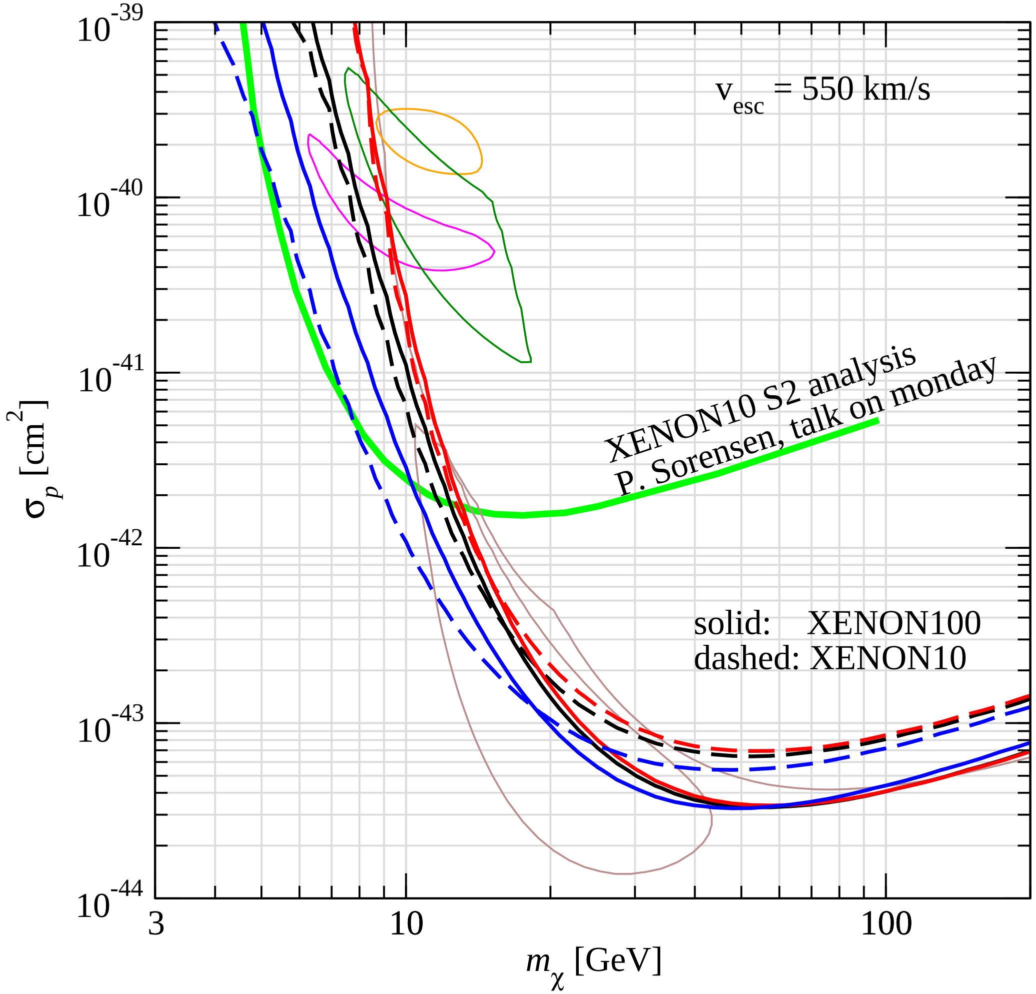
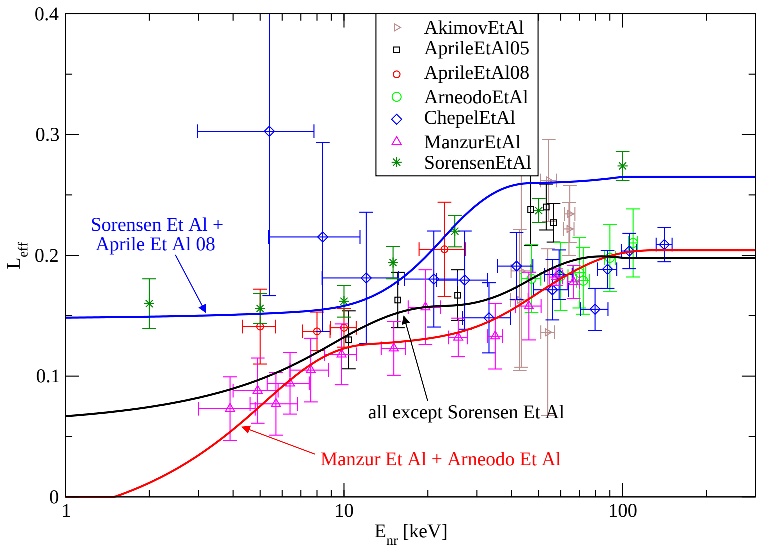
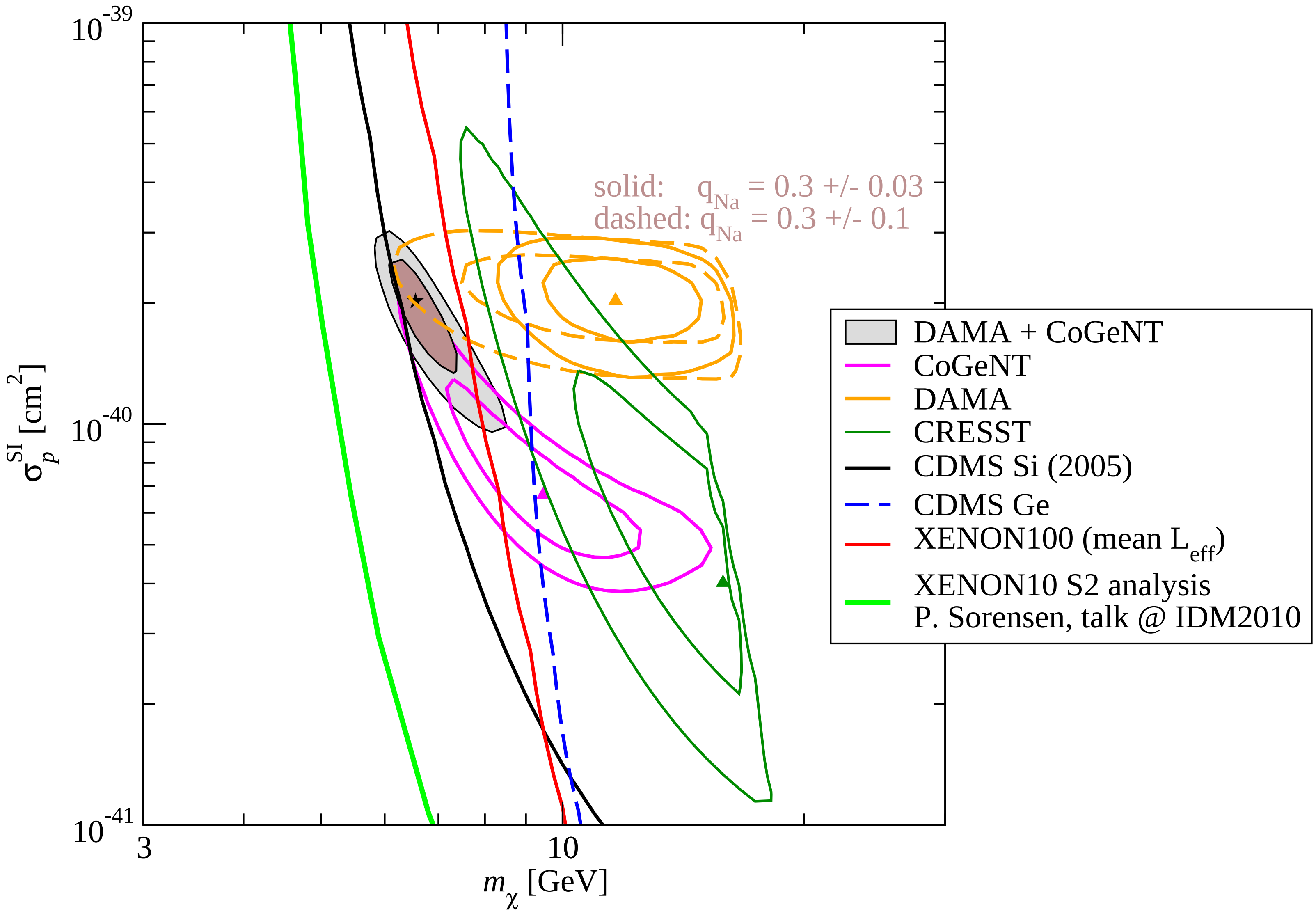




same color coding

Summary elastic SI scattering



How to reconcile?

- experimental issues?

  ~ 10 GeV region is experimentally challenging

  systematic uncertainties on quenching factors, energy scale, threshold effects, backgrounds… have to be understood and taken into account before making strong statements

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- modify astrophysics?

  changing $\bar{v}, v_{\rm esc}$ has little impact on consistency
  non-standard halos (asymmetric, streams, dark disc) require extreem params Fairbairn, Schwetz, 0808.0704, and others

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- more exotic particle physics? spin-dep., inelast., momentum-dep. scatt., leptophilic DM,...

  see talks by Neil Weiner, Joachim Kopp

elastic spin-dependent (eSD) scattering

Spin-dependent scattering

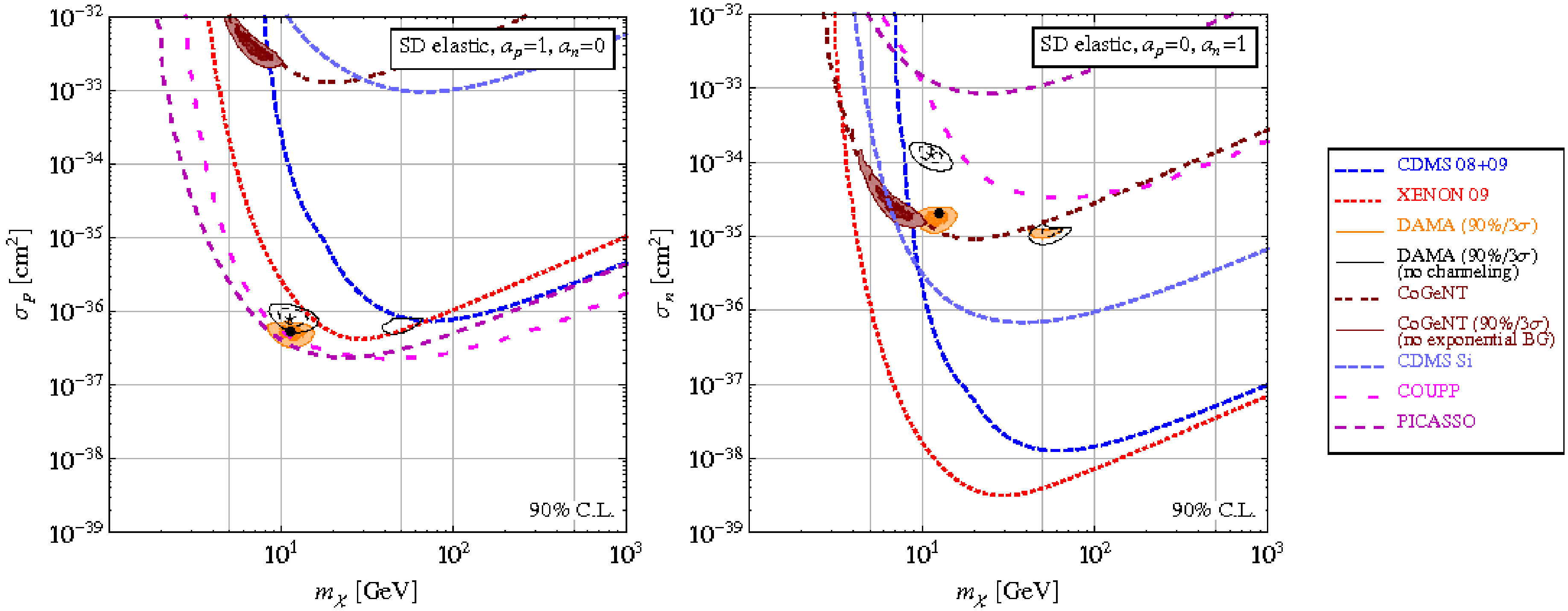
coupling mainly to an un-paired nucleon:

		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

eSD

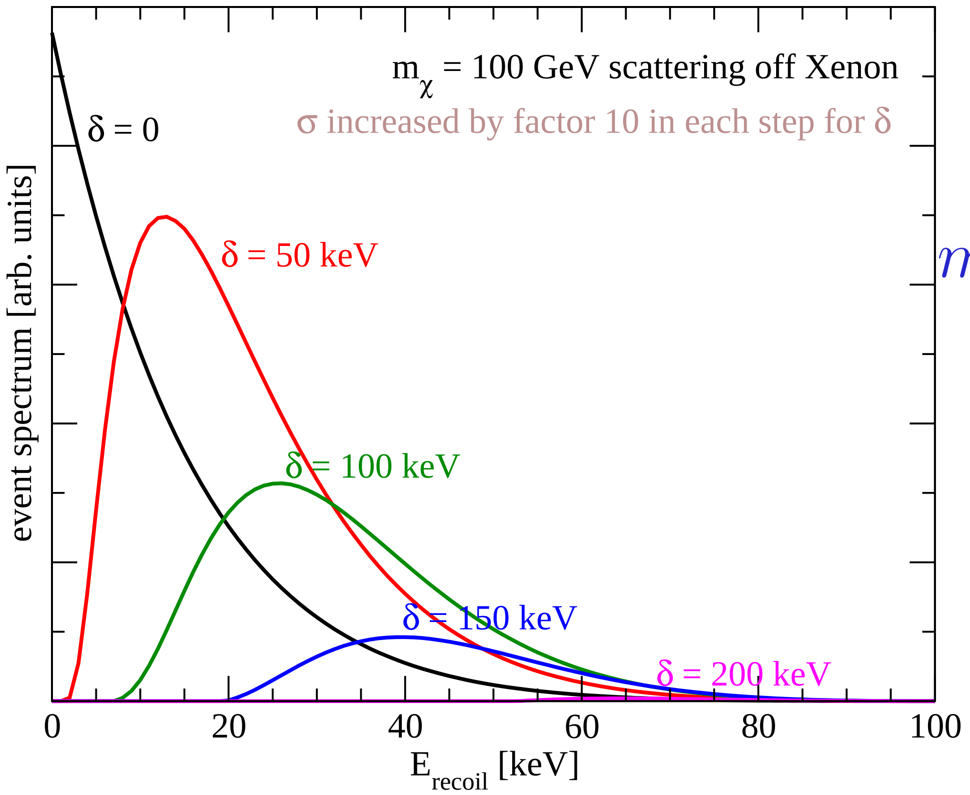


Kopp, Schwetz, Zupan, 0912.4264

inelastic scattering

Tucker-Smith, Weiner, hep-ph/0101138

Inelastic DM scattering

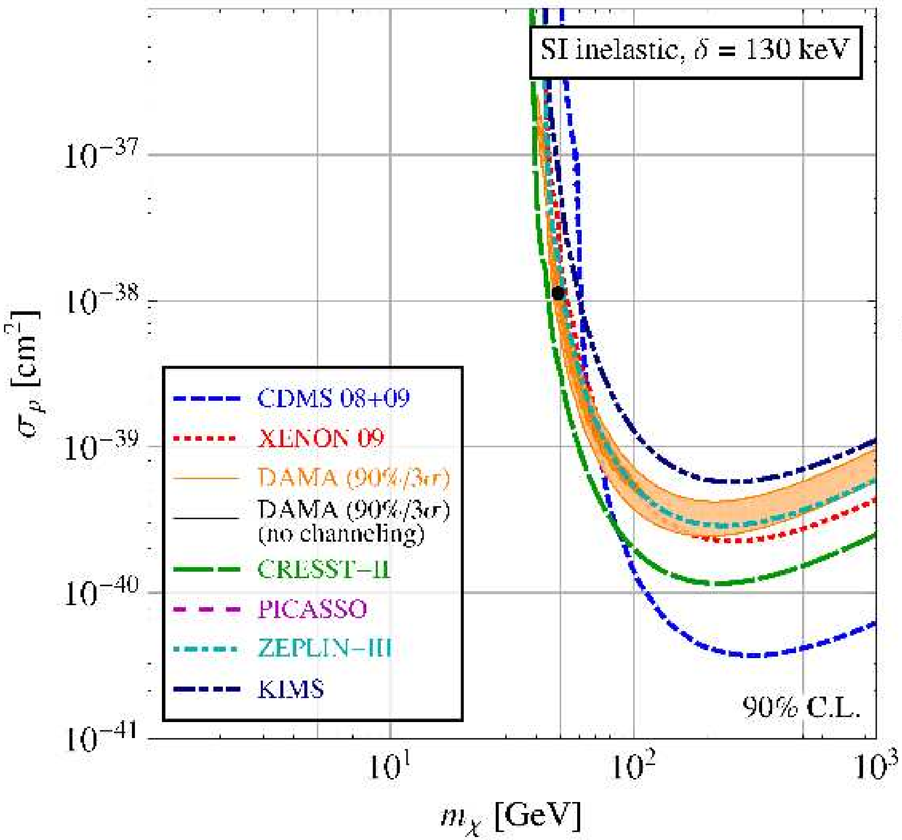


$$m_{\chi^*} - m_\chi = \delta \simeq 100\,\text{keV} \sim 10^{-6} m_\chi$$

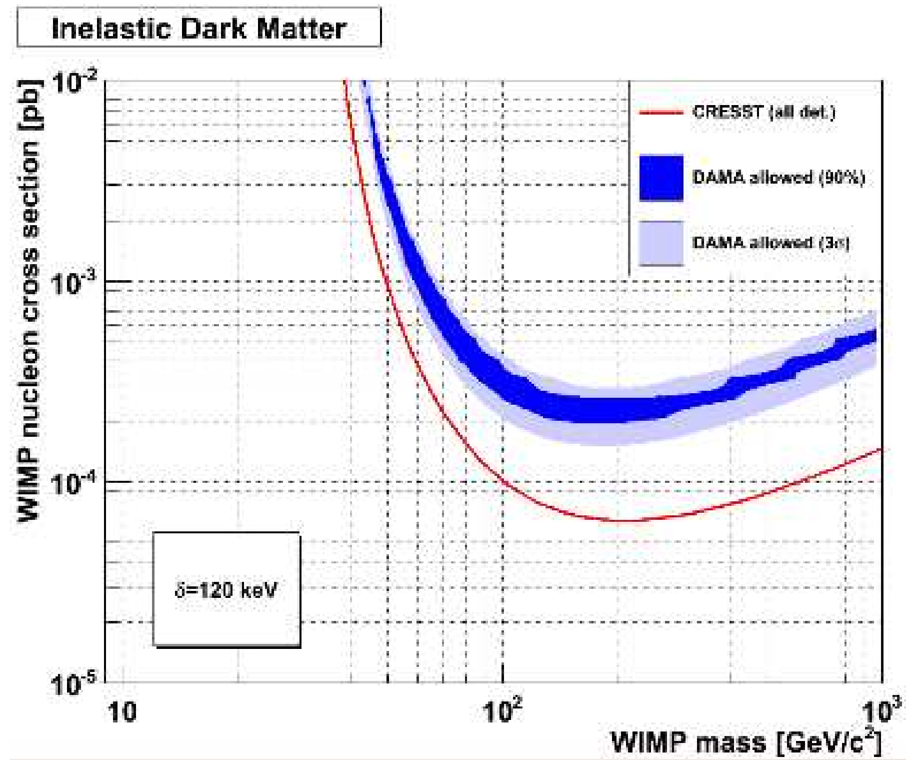
$$v_{\min}^{\text{inel}} = \frac{1}{\sqrt{2ME_R}} \left(\frac{ME_R}{\mu_\chi} + \delta \right)$$

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

iSI



talk by W. Seidel @ IDM 2010



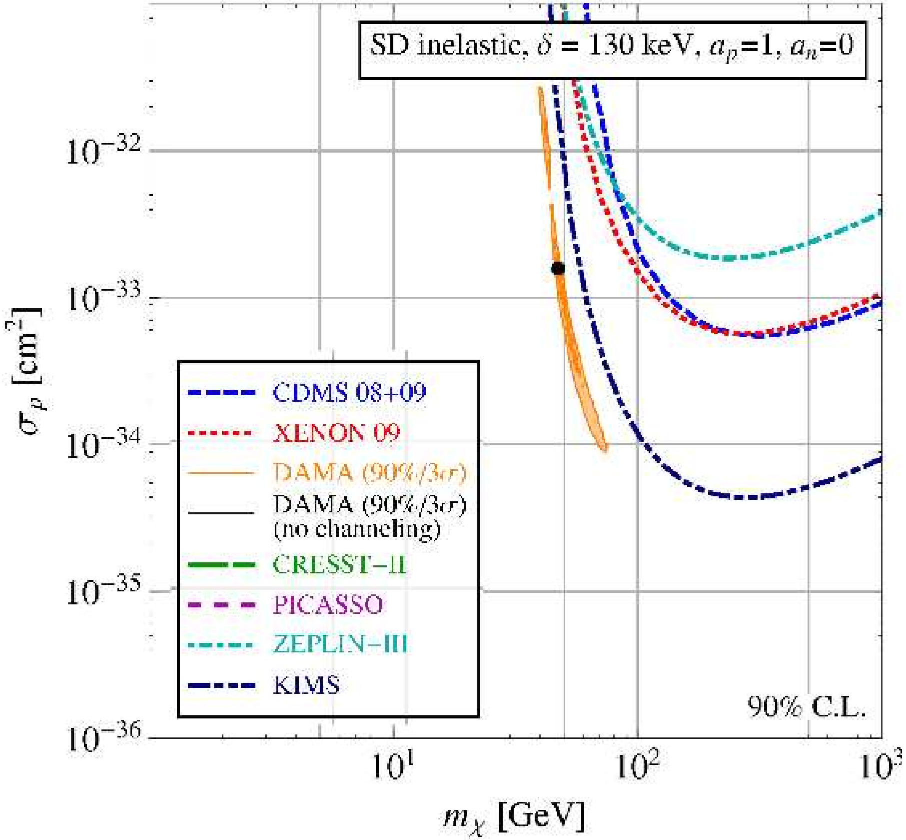
$m_\chi \simeq 50\,\mathrm{GeV}$, $\delta \simeq 130\,\mathrm{GeV}$

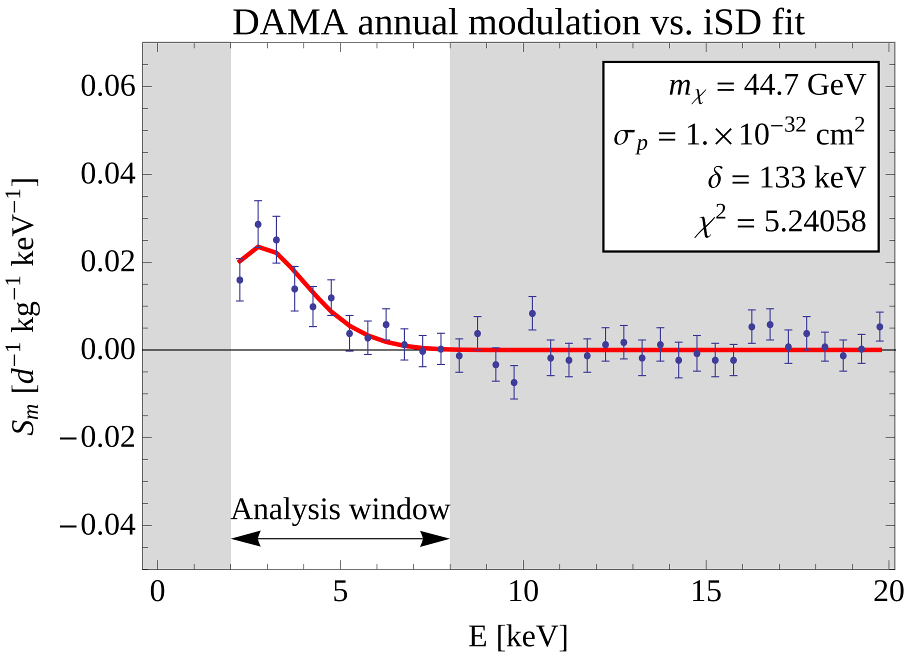
disfavored by CRESST (tungsten)

iSD on protons

inelastic spin-dependent scattering

Kopp, Schwetz, Zupan, 0912.4264





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

iSD on protons

- 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)

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BUT:

- cannot explain CoGeNT
- neutrino constraints from annihilations in the sun depend on annihilations channels (light quarks, μ, e still OK)

  Shu, Yin, Zhu, 1001.1076
- probably mono-jet bounds from Tevatron apply

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

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

$\Rightarrow$ 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

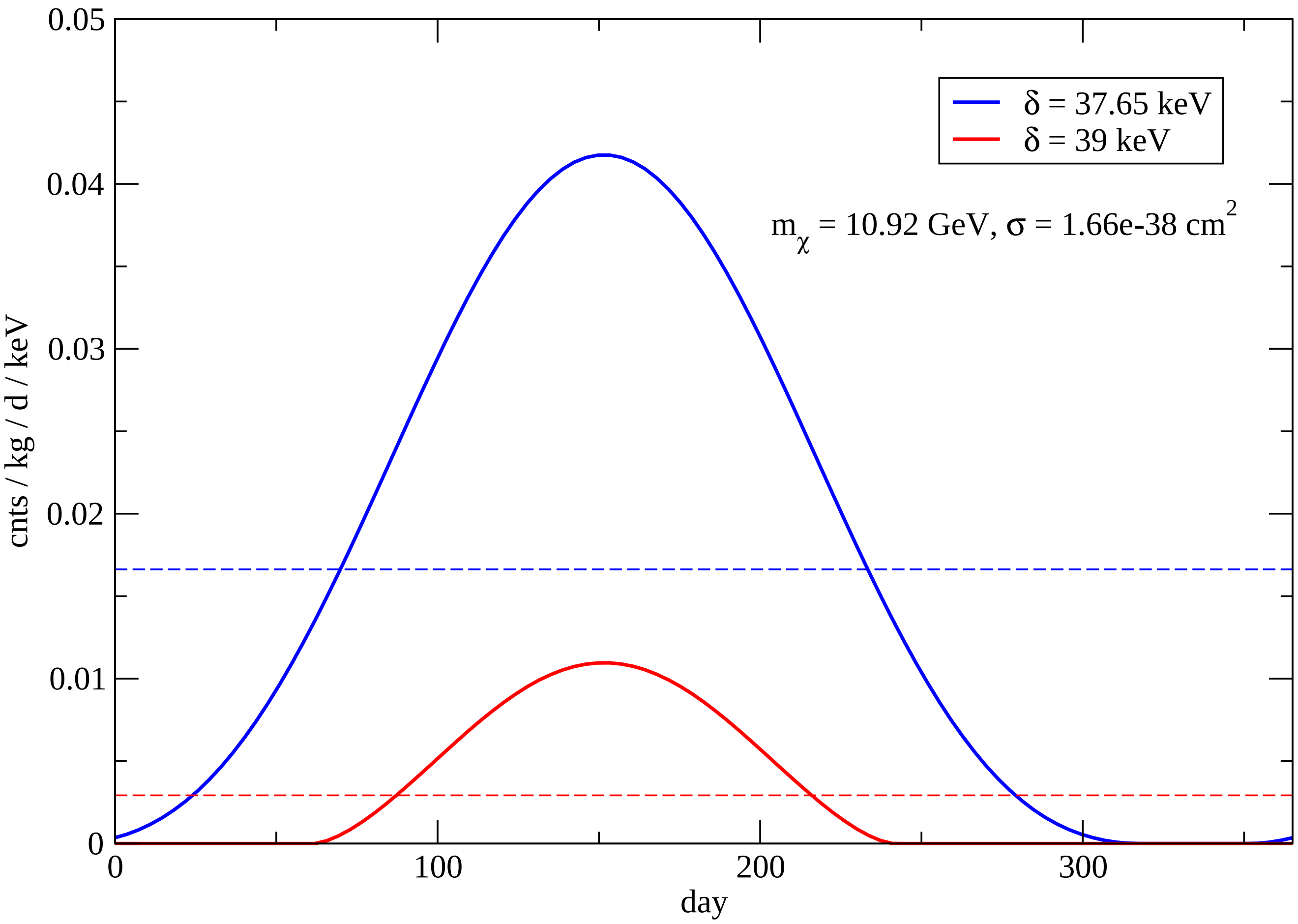
similar situation as recent cosmic ray “DM signals”

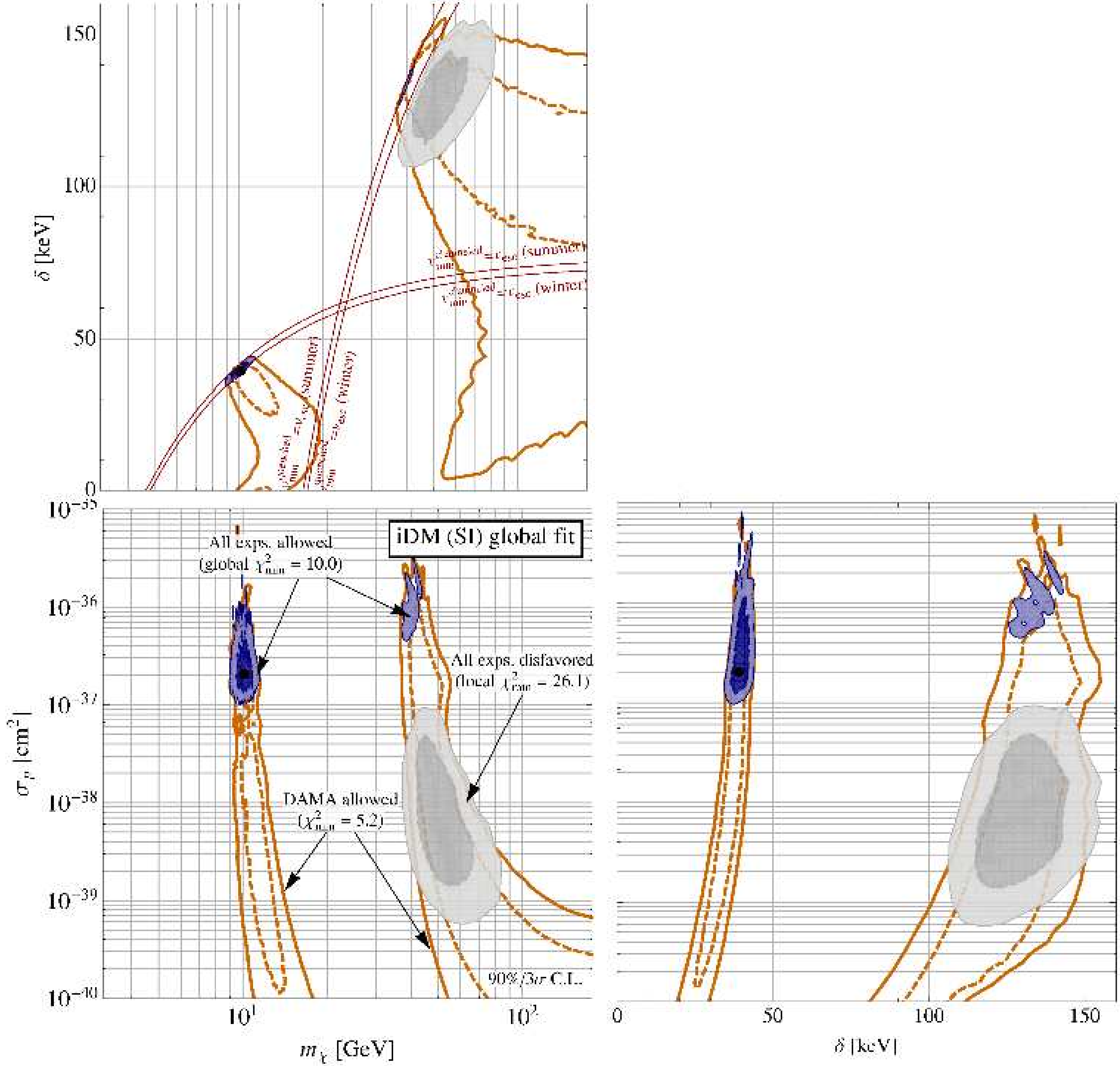
at some point “hints” will converge (hopefully)!

Additional slides

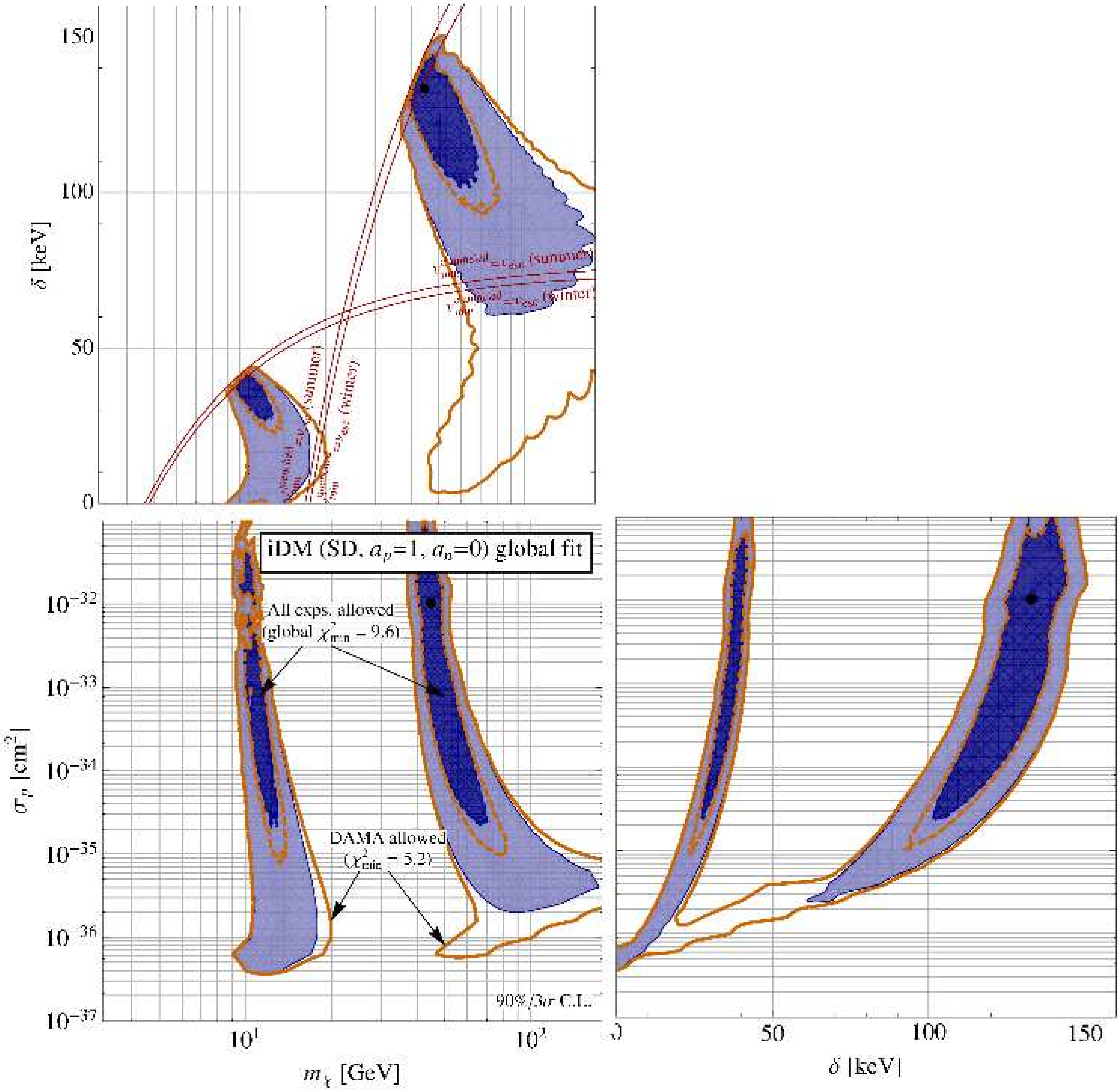
iSI

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





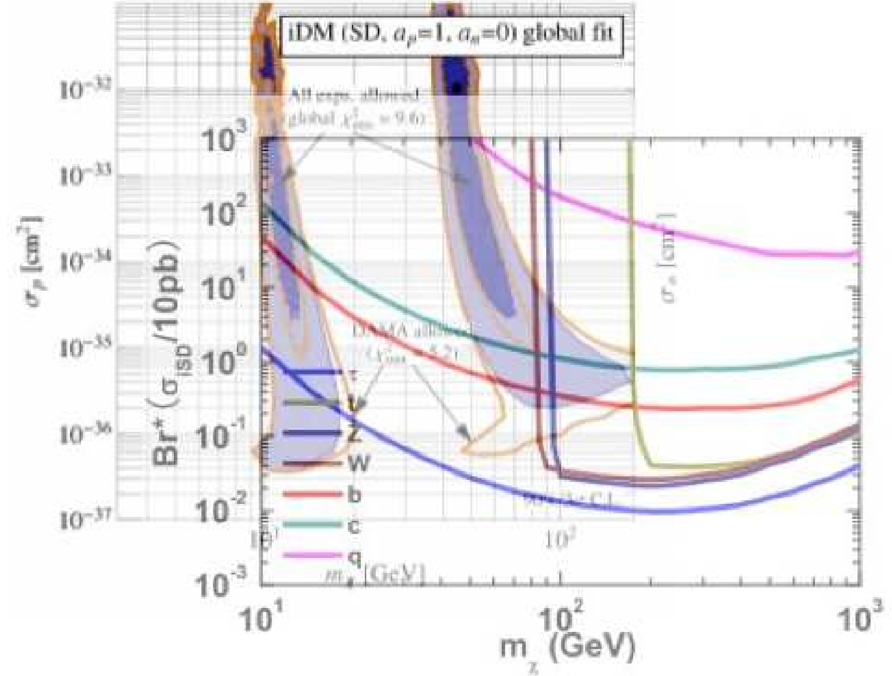
iDM (SI) global fit
All exps. allowed
(global χ^2_{min} = 10.0)
All exps. disfavored
(local χ^2_{min} = 26.1)
DAMA allowed
(χ^2_{min} = 5.2)
90%/3σ C.L.
$v_{min}^{channel} = v_{esc}$ (summer)
$v_{min}^{channel} = v_{esc}$ (winter)
δ [keV]
σ_p [cm^2]
m_χ [GeV]

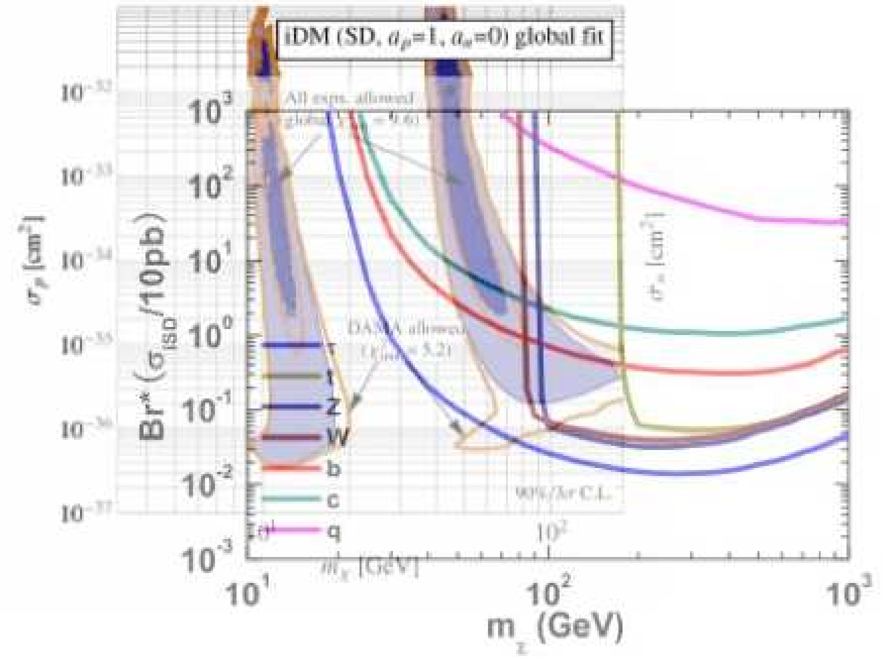


iDM (SD, a_p=1, a_n=0) global fit
All exps. allowed (global χ^2_{min} = 9.6)
DAMA allowed (χ^2_{min} = 5.2)
90%/3σ C.L.
δ [keV]
σ_p [cm^2]
m_χ [GeV]
(summer)
(winter)

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