MPIK Seminar

Dark Matter direct detection and speculations on low-mass WIMPs

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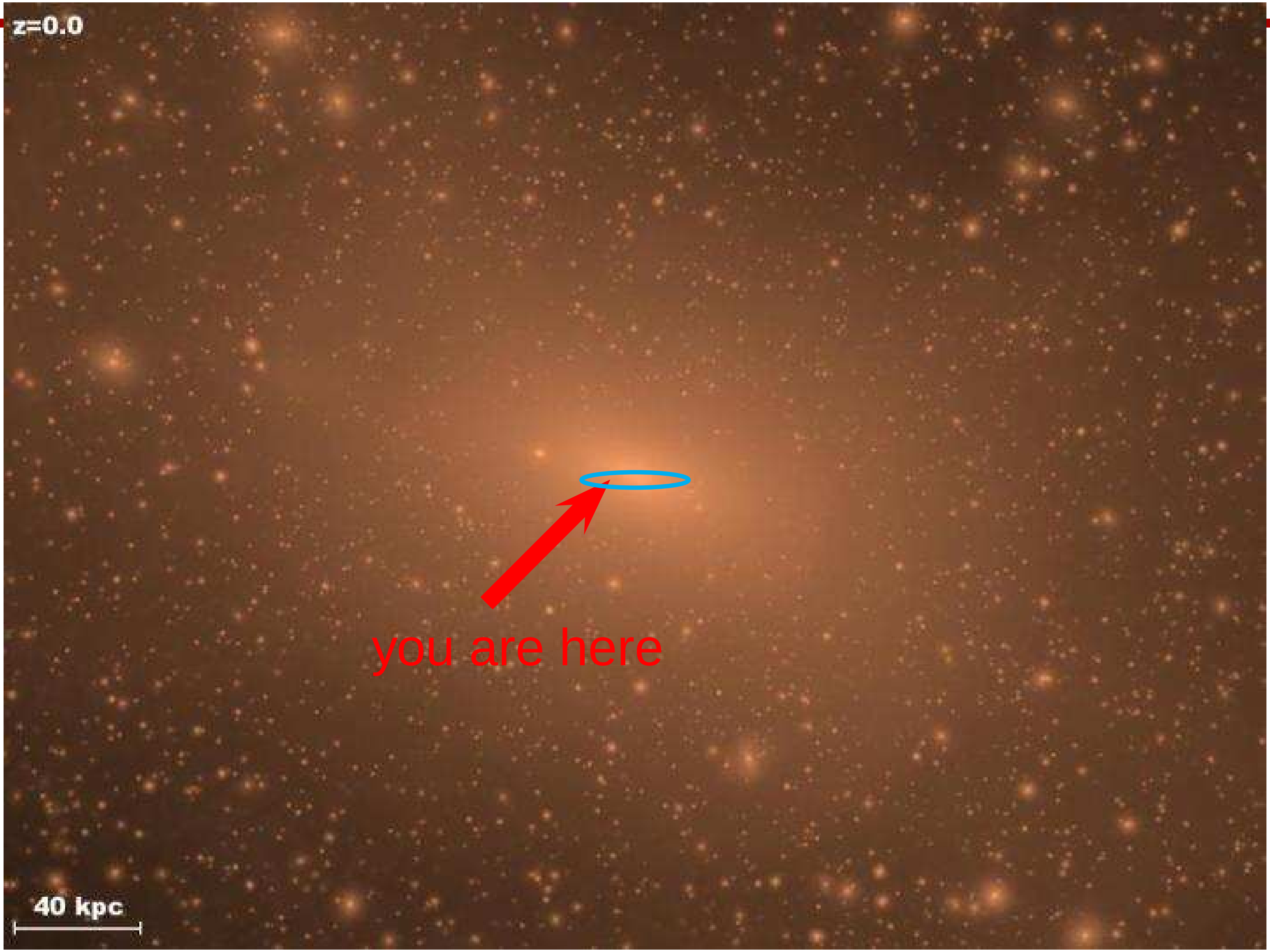
Dark Matter in a Milkyway-like Galaxy



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

Dark Matter distribution

“standard halo model”:

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

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

Maxwellian velocity distribution (in halo rest frame)

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

with $\bar{v} \simeq 220$ km/s and $v_{\rm esc} \simeq 600$ km/s

DM direct detection

. . . assuming DM has non-gravitational interactions (“WIMP”):

DM direct detection M. Goodman, E. Witten, PRD 1985

Look for recoil of DM-nucleus scattering:

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

cnts / keV recoil energy E_R:

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

$v_{\min}$: 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

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

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

$\mu_{\chi N}$ $(\mu_{\chi p})$:	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

SI: A^2 enhancement $\longrightarrow$ (heavy nuclei)

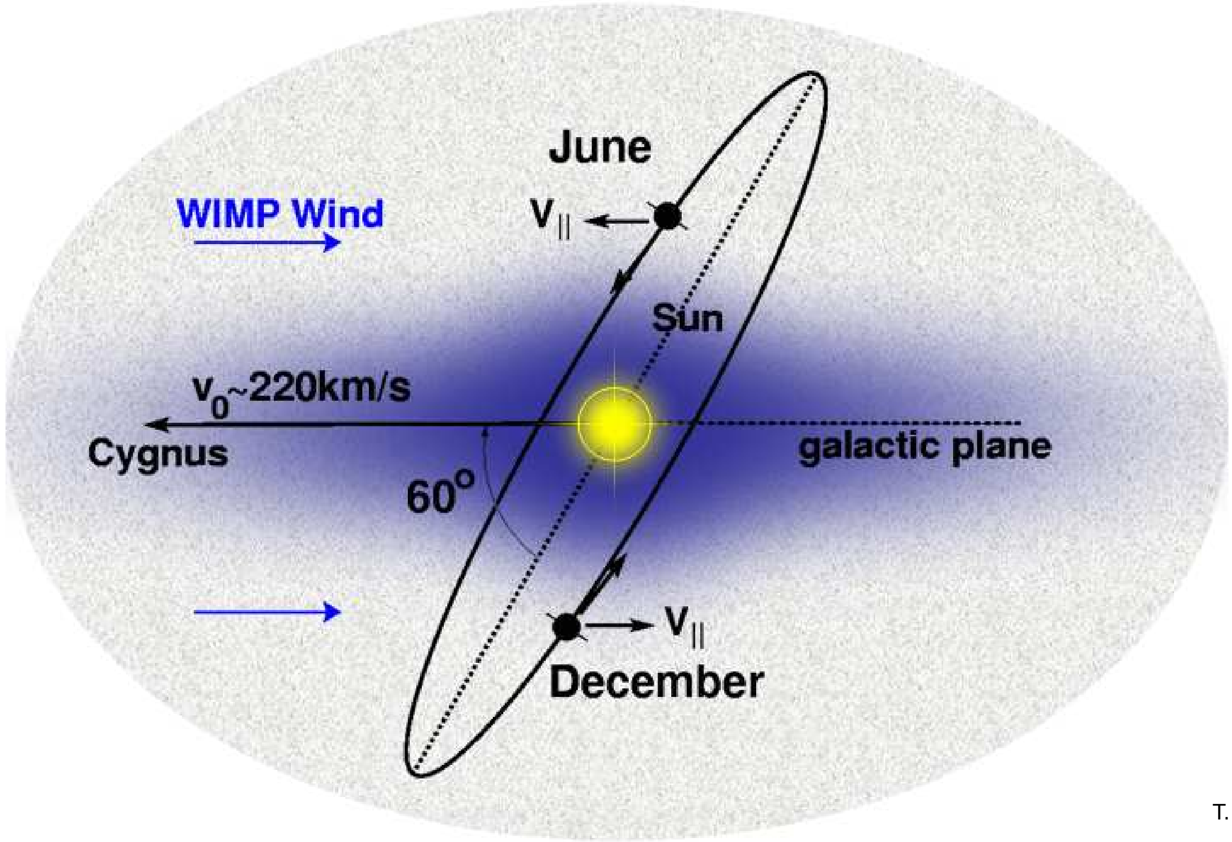
SD: coupling mainly to unpaired n or p

DM velocity distribution

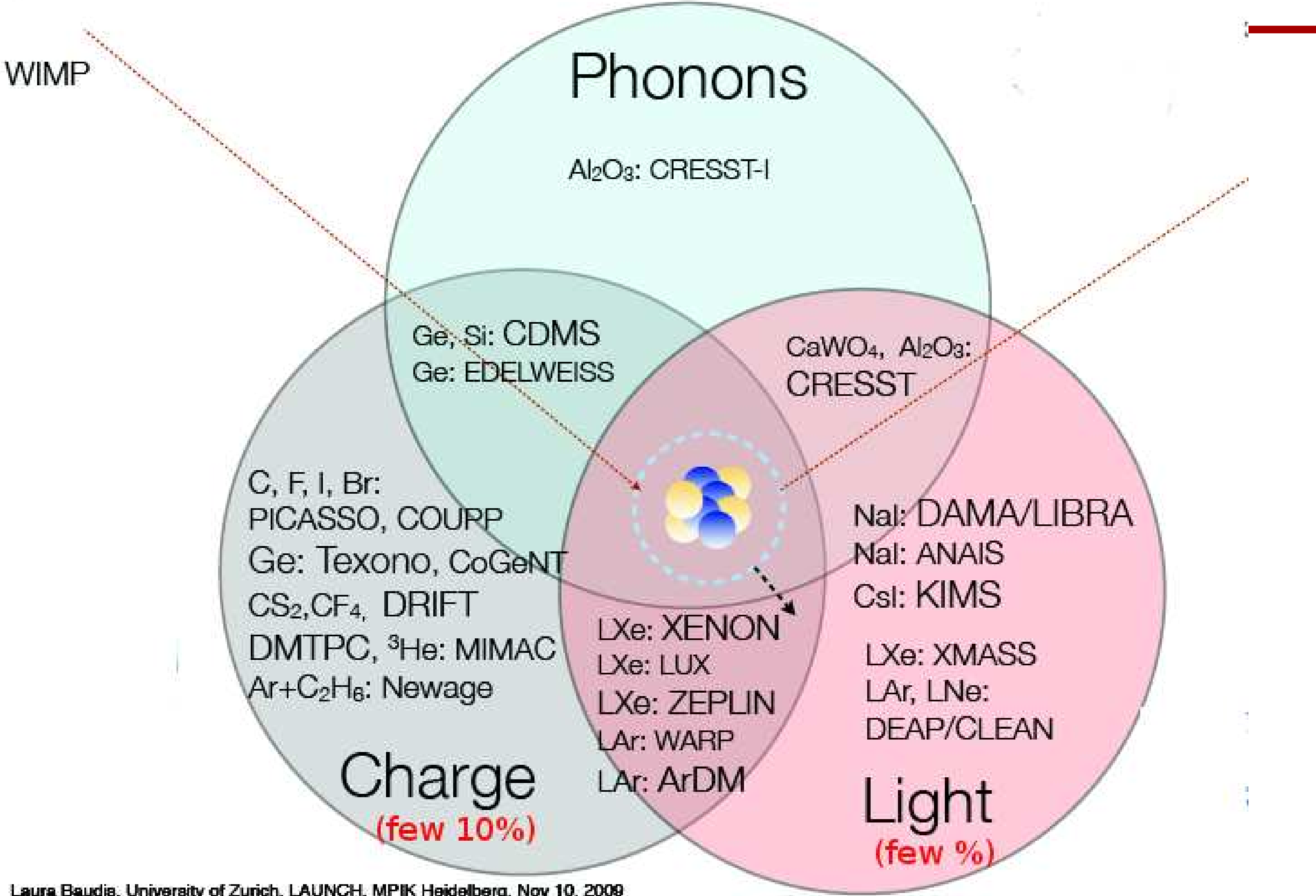
$$f_\oplus(\vec{v},t) = f_{\rm gal}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t)) \qquad f_{\rm gal}(\vec{v}) \propto \exp(v^2/\bar{v})$$

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



Direct Detection Techniques



Outline

- 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 briefely on spin-dependent
  and inelastic scattering
- “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 which can do it (even neutralino)

Elastic spin-independent scattering

Event spectrum for low-mass WIMPs

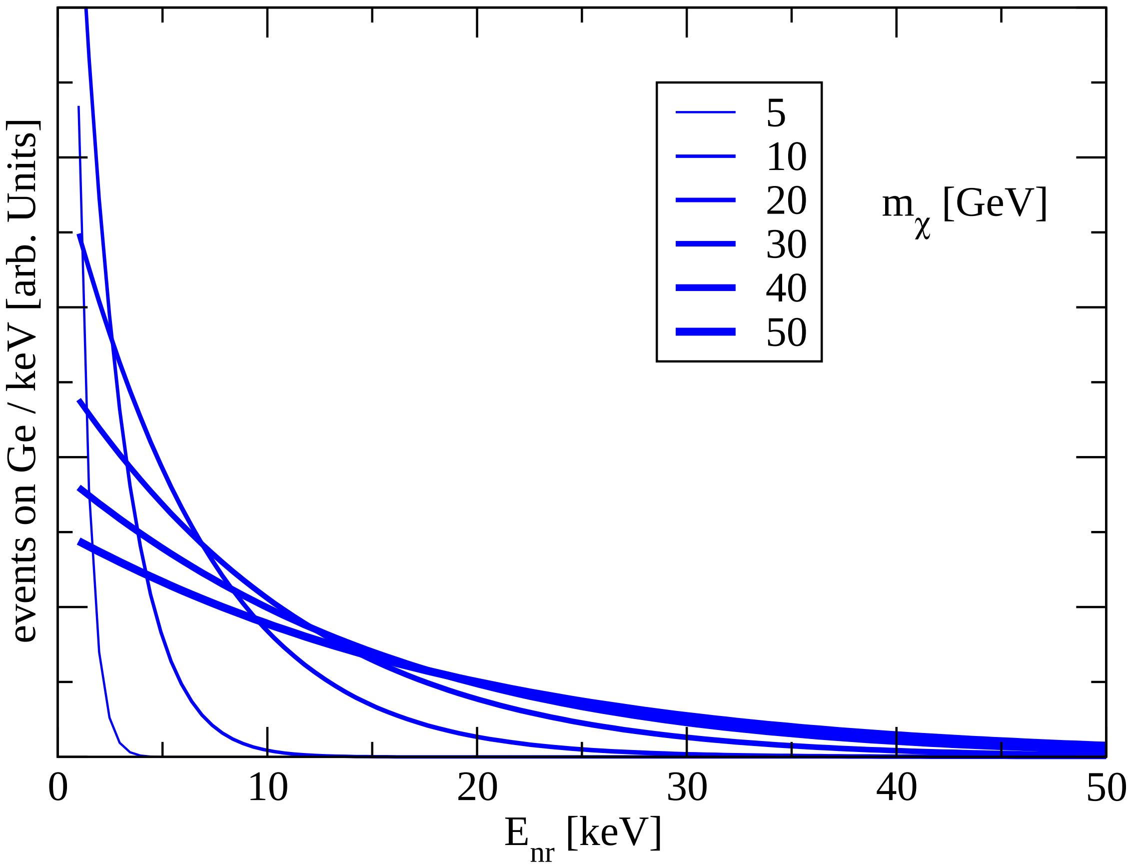
$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi} \frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2} \int_{v>v_{\min}(E_R)} d^3v \, \frac{f_\oplus(\vec{v}, t)}{v}$$

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

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

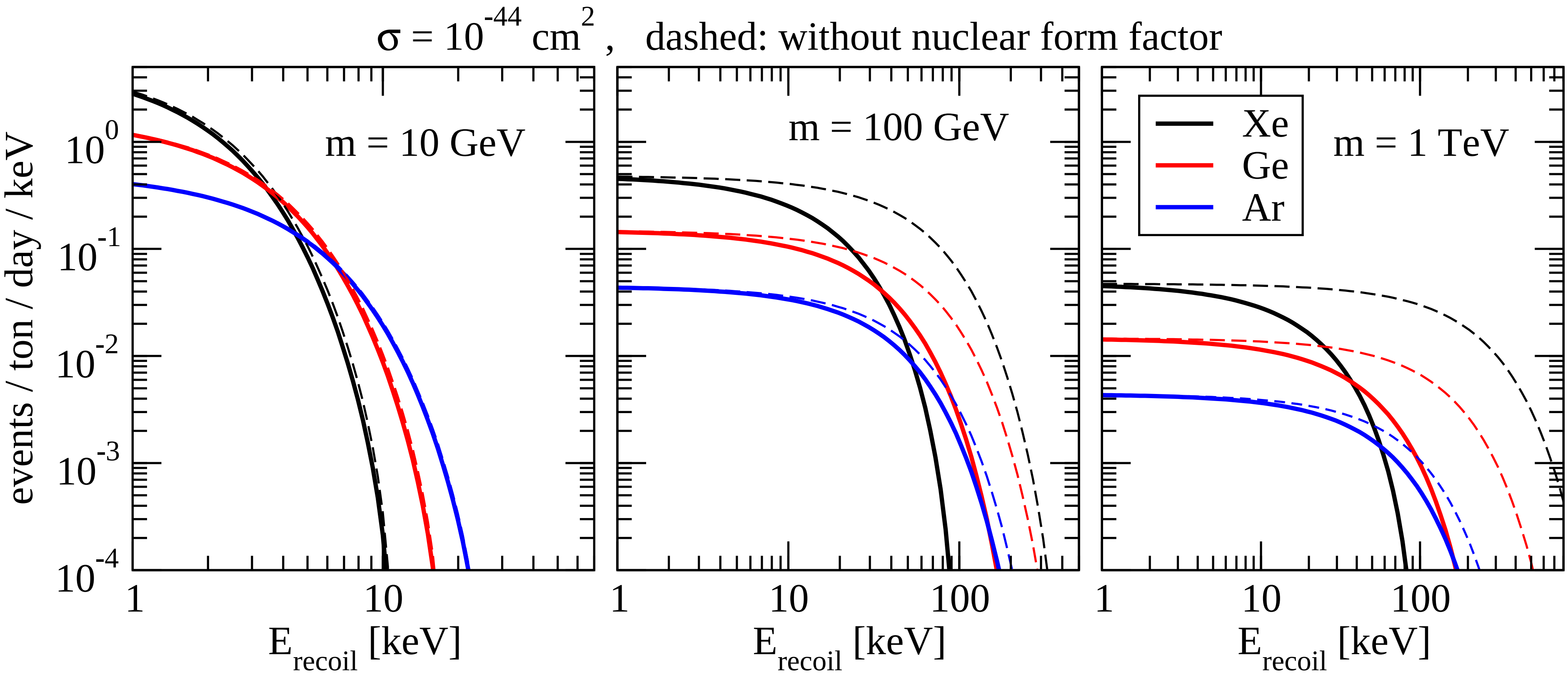
need light target and/or low threshold on E_R to see light WIMPs

Event spectrum for low-mass WIMPs



spectrum gets shifted to low energies for low WIMP masses ⇒energy threshold is crucial

Event spectrum for low-mass WIMPs



nuclear form factor is less important for low mass WIMPs

low-mass WIMP hints

CDMS-II

CoGeNT

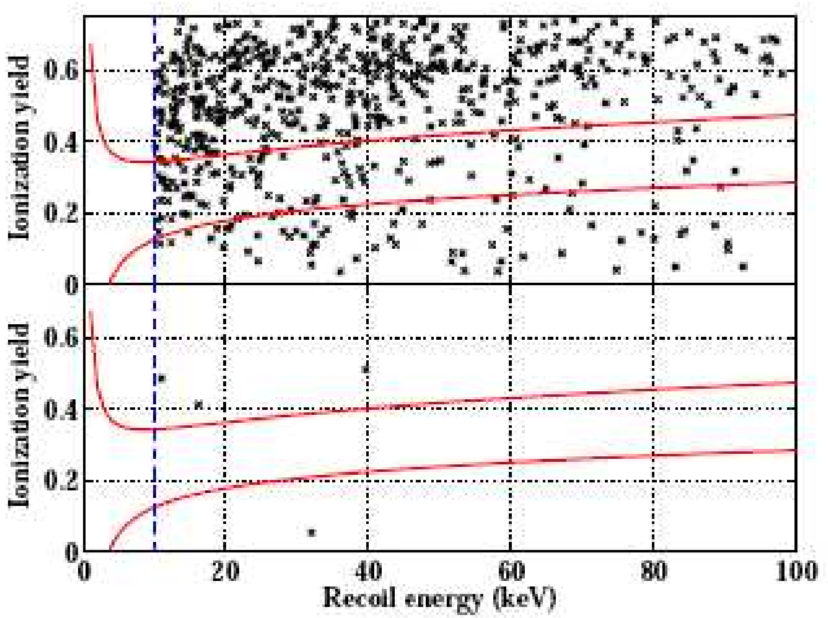
CRESST-II

DAMA

CDMS-II

Germanium detector, recoil energy range 10–100 keV

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

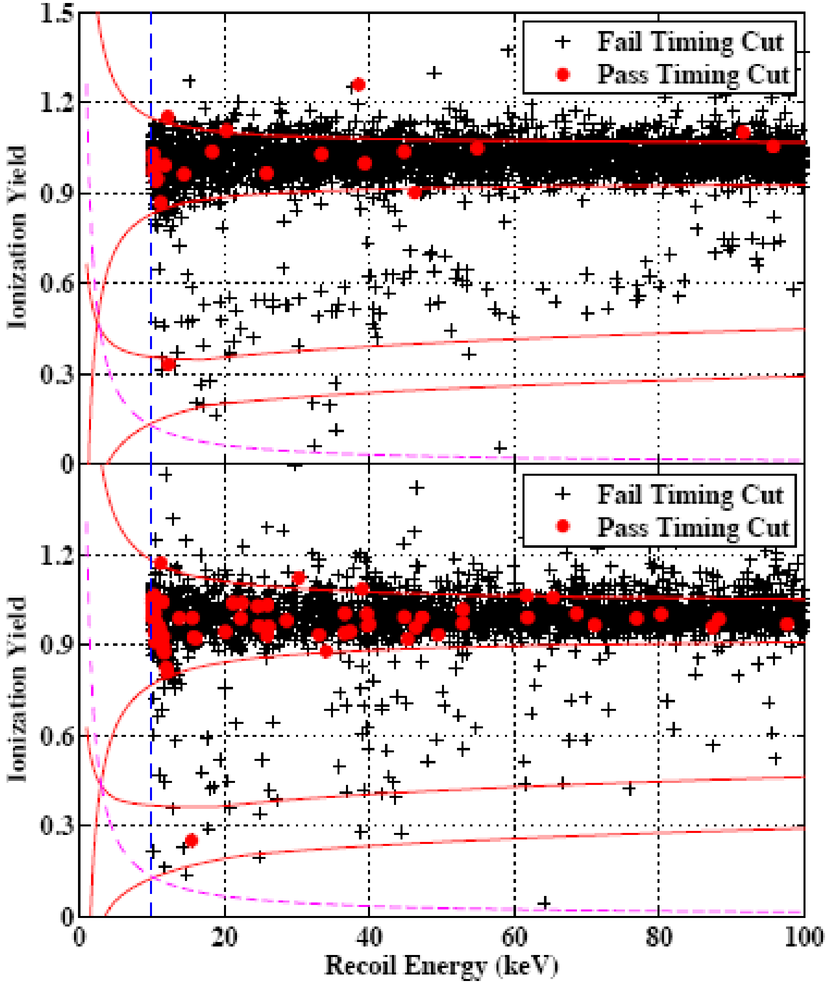


nuclear recoil signal region before (top) and after (bottom) timing cut

CDMS-II

Germanium detector, recoil energy range 10–100 keV

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

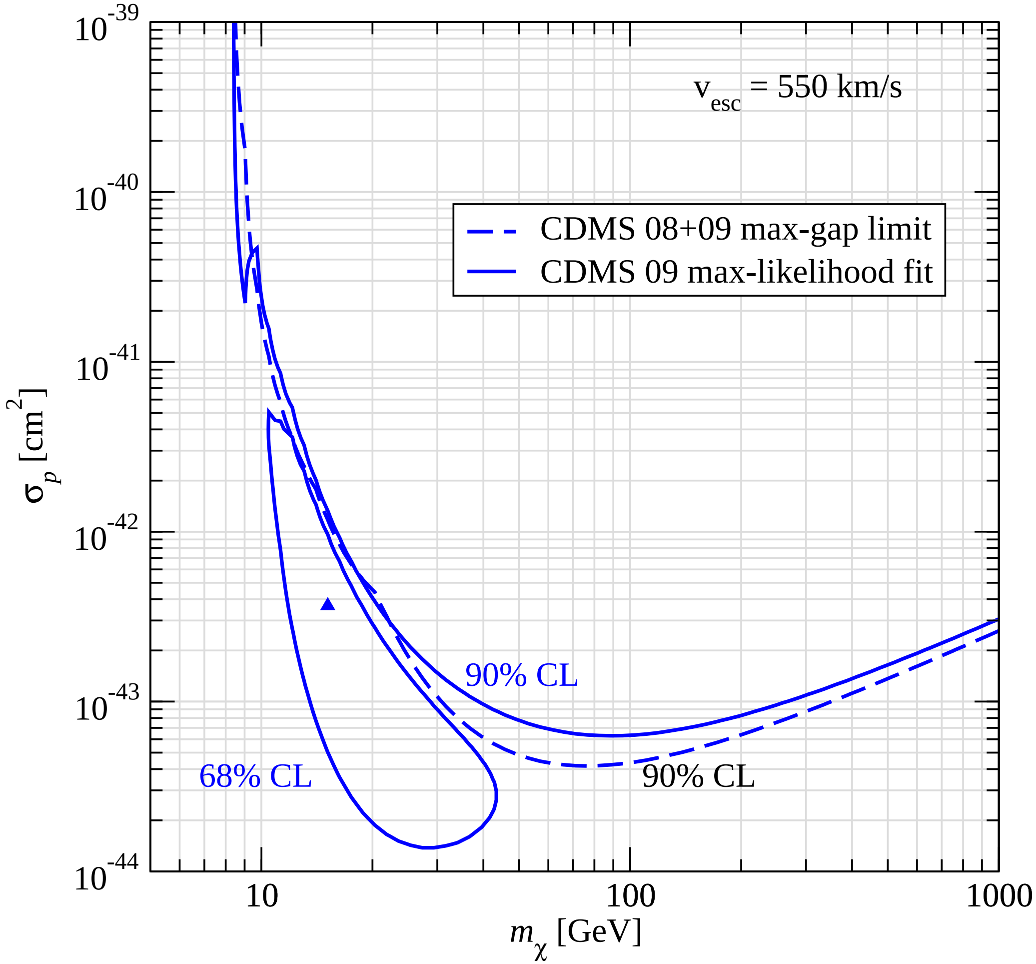


electron and nucl. recoil regions for two different detectors

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

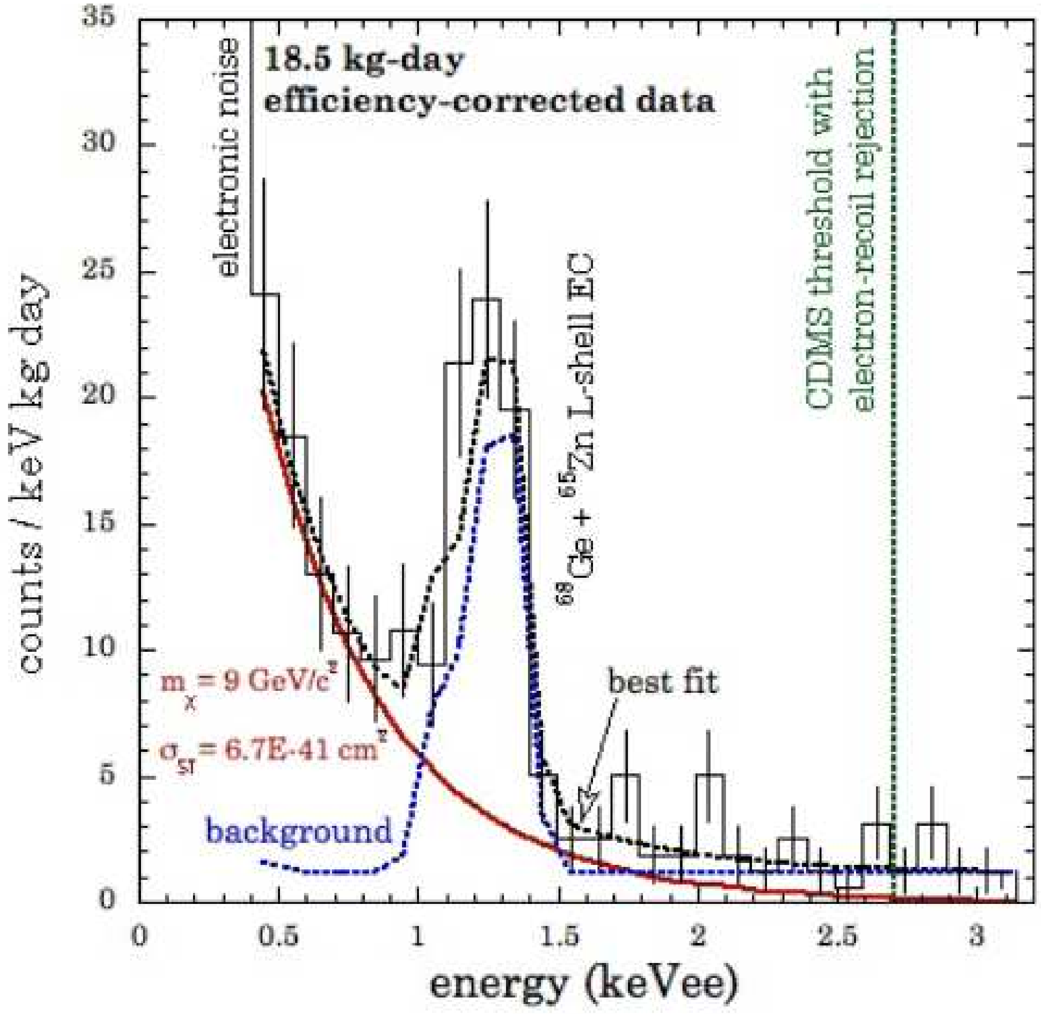
CoGeNT

CRESST-II

DAMA

CoGeNT

Germanium detector with extremely low threshold of 0.4 keVee

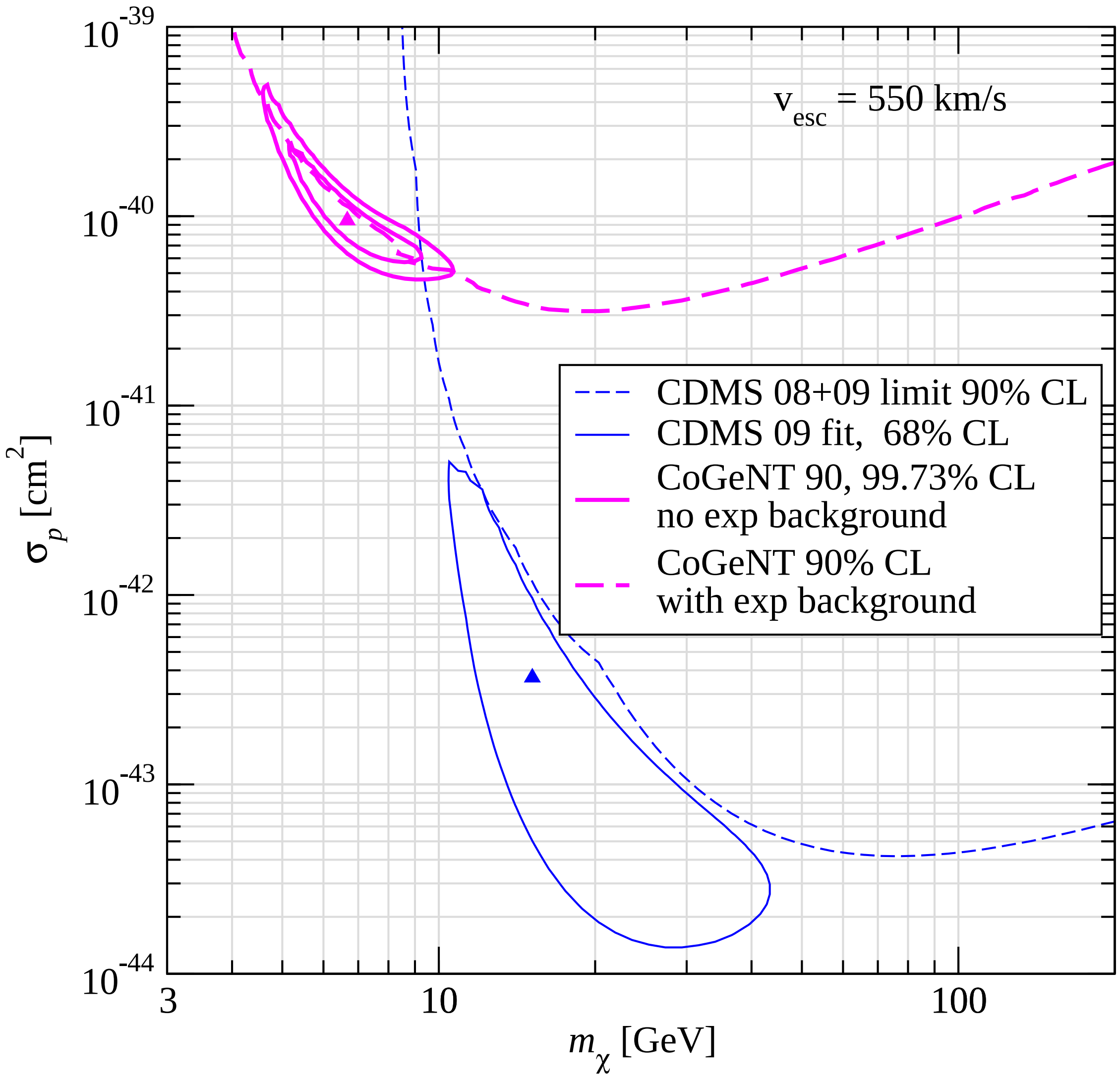


exponential rise of events at low energies

claim that it cannot be electronic noise

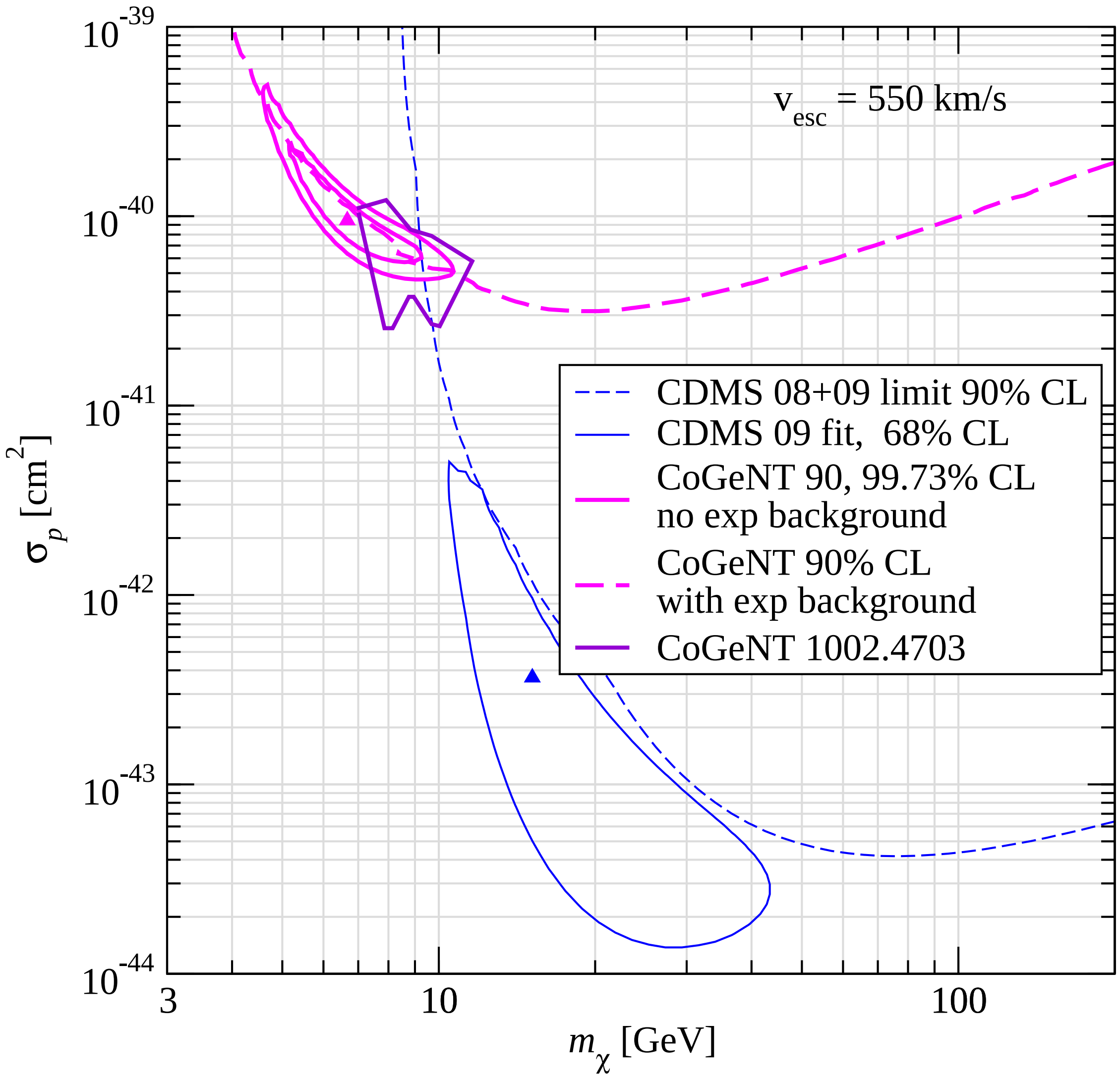
Aalseth et al., 1002.4703

CoGeNT



10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
3
10
100
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]

CoGeNT



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CoGeNT 1002.4703

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

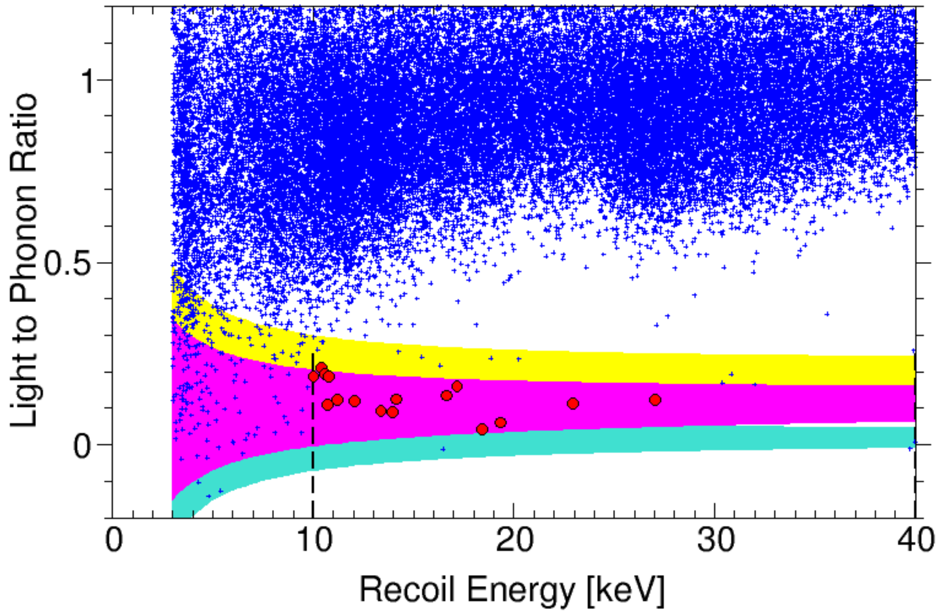
All results preliminary

- 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 Kolloquium by F. Proebst tomorrow at Univ. HD



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

$\Rightarrow$ WIMPs ??

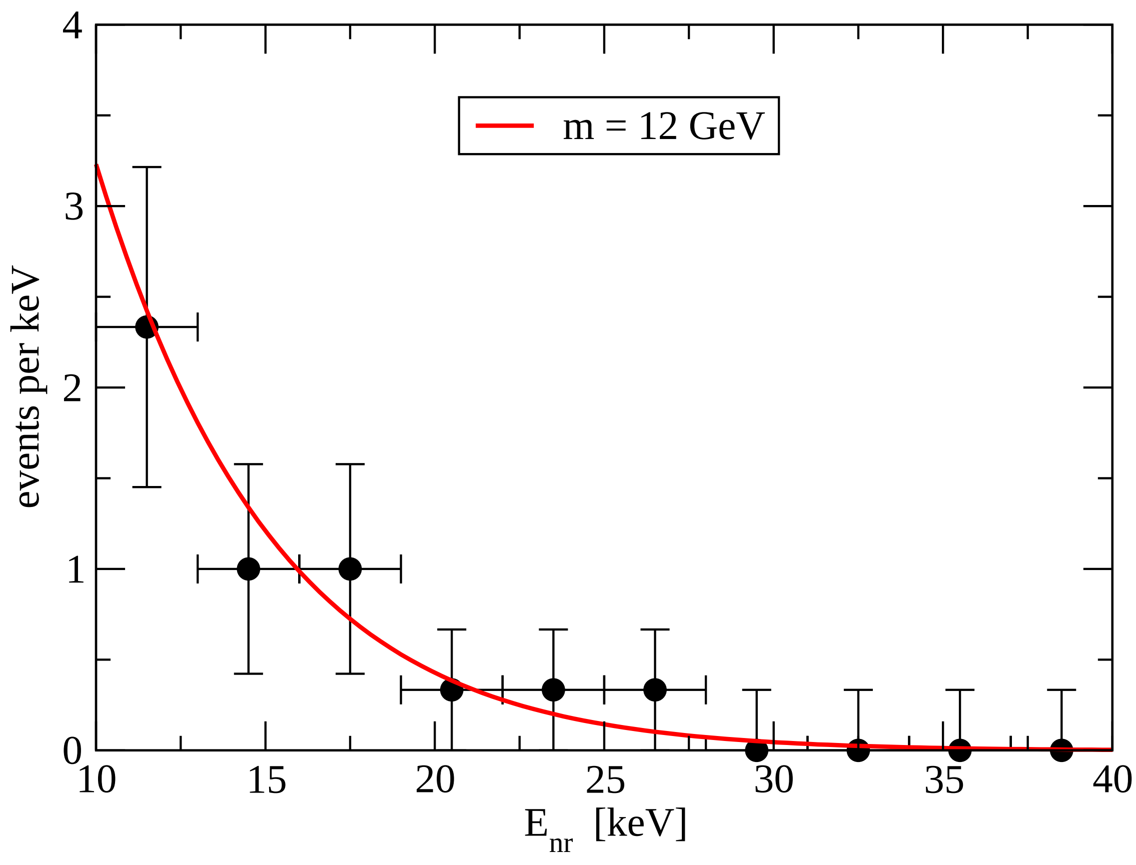
analysis is ongoing, some of the events (all?) are from neutrons

neutron calibration measurments are being carried out

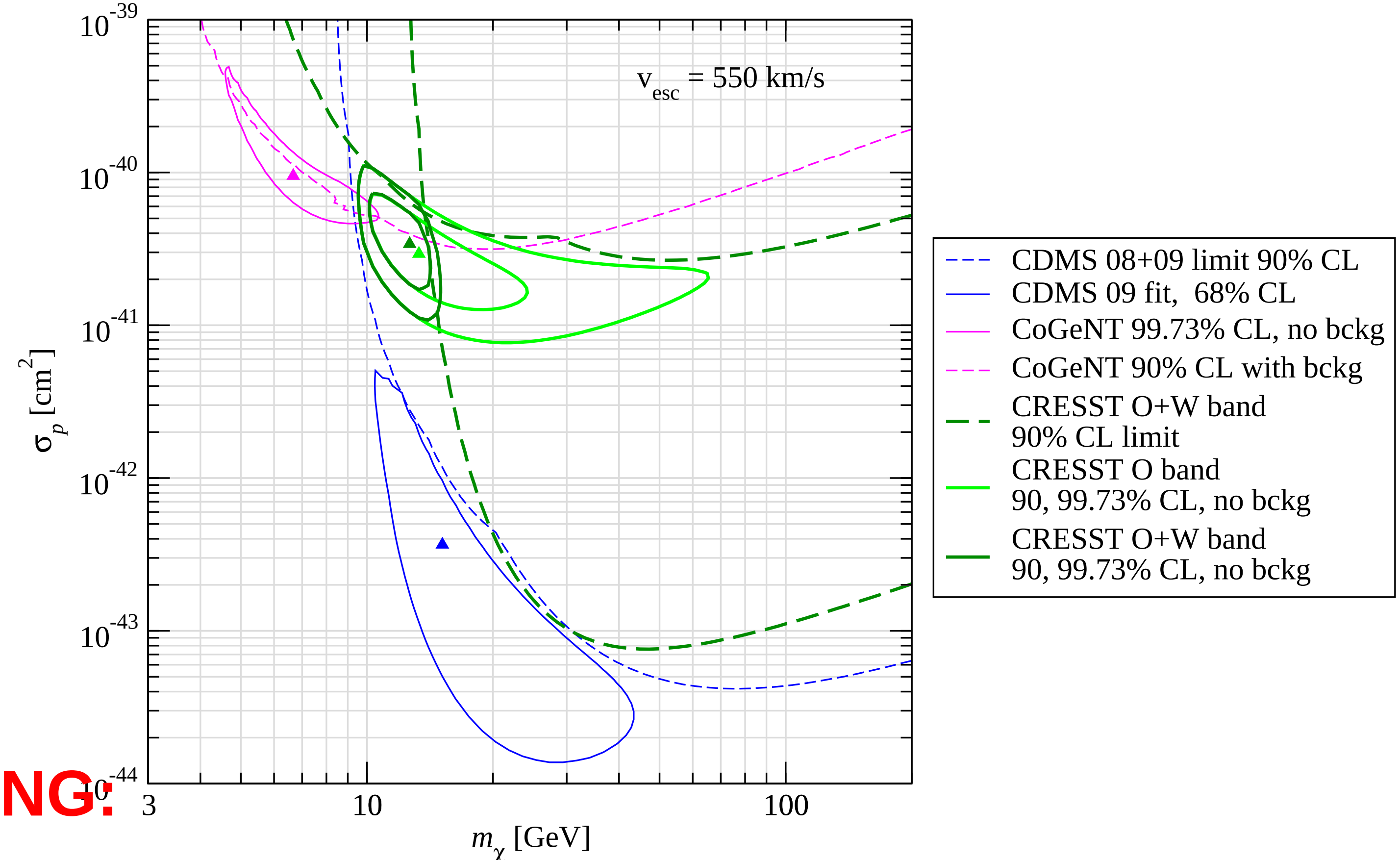
(measure the fraction of single scatter events from neutrons)

CRESST O-band

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



CRESST vs CoGeNT vs CDMS



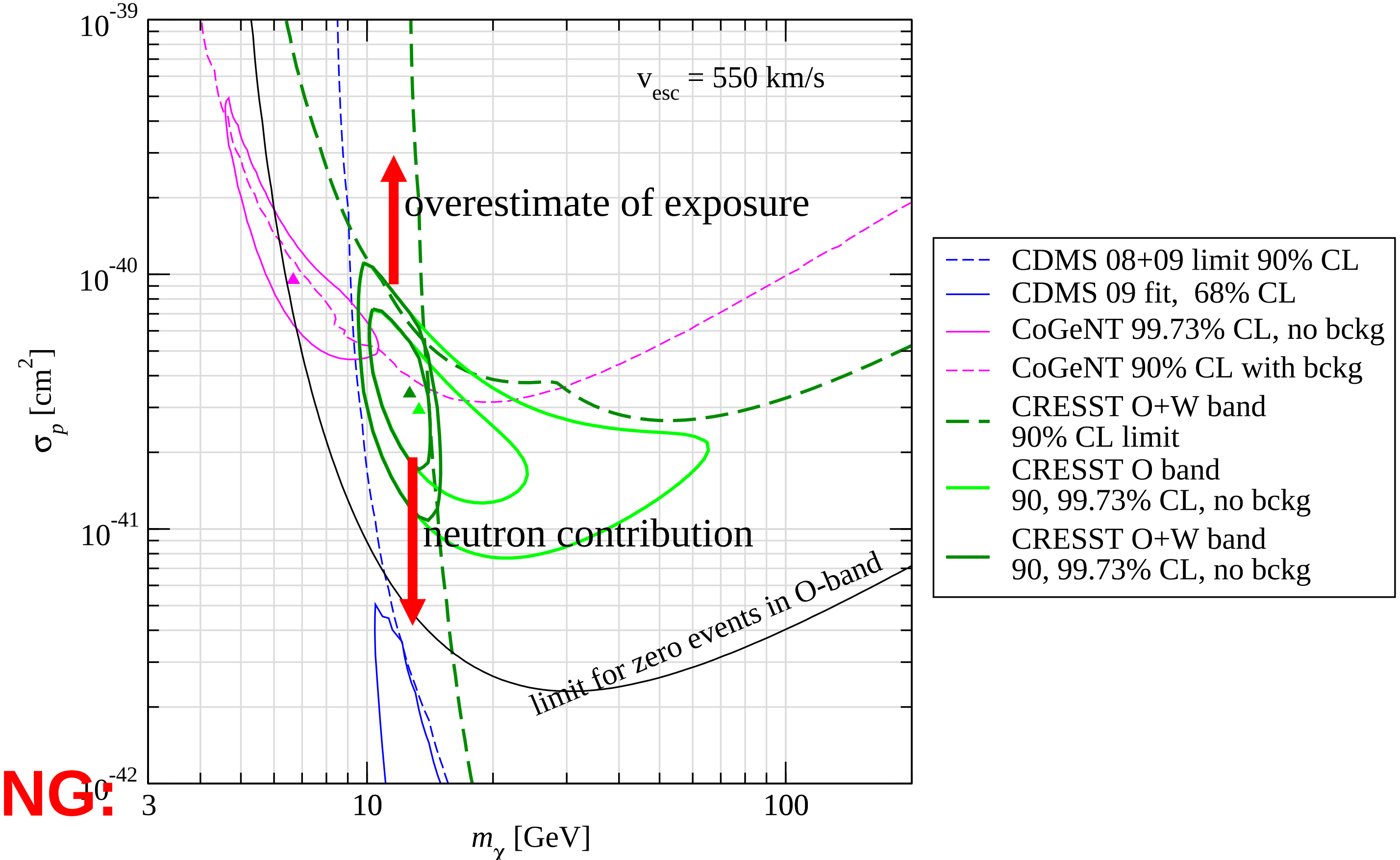
WARNING:

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

$\Rightarrow$ regions may shift $\Rightarrow$ wait for final results from CRESST

low-mass WIMP hints

CDMS-II

CoGeNT

CRESST-II

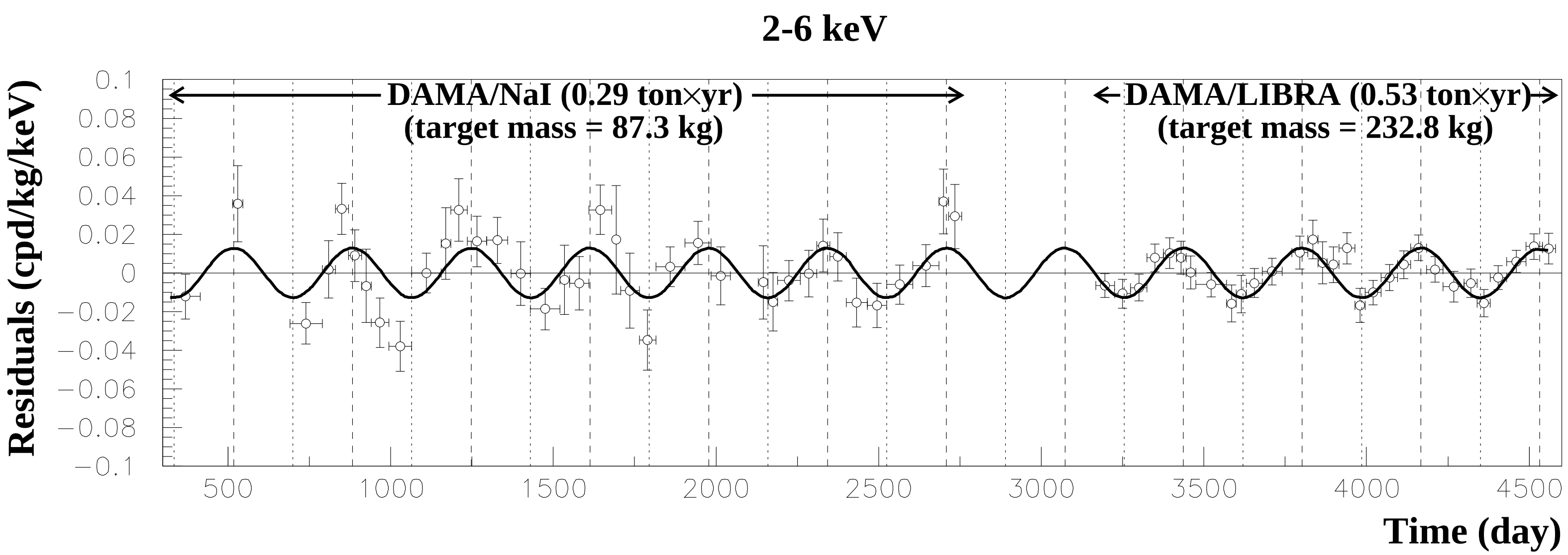
DAMA

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



Bernabei et al., 0804.2741

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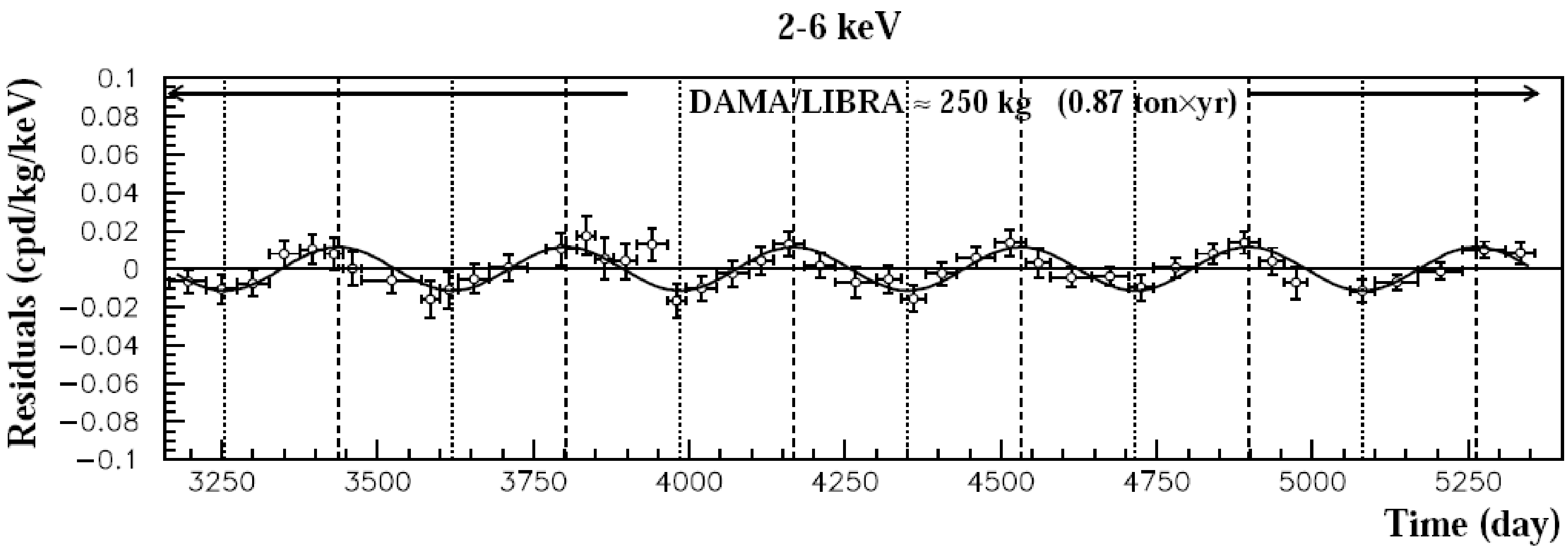

Bernabei et al., 1002.1028

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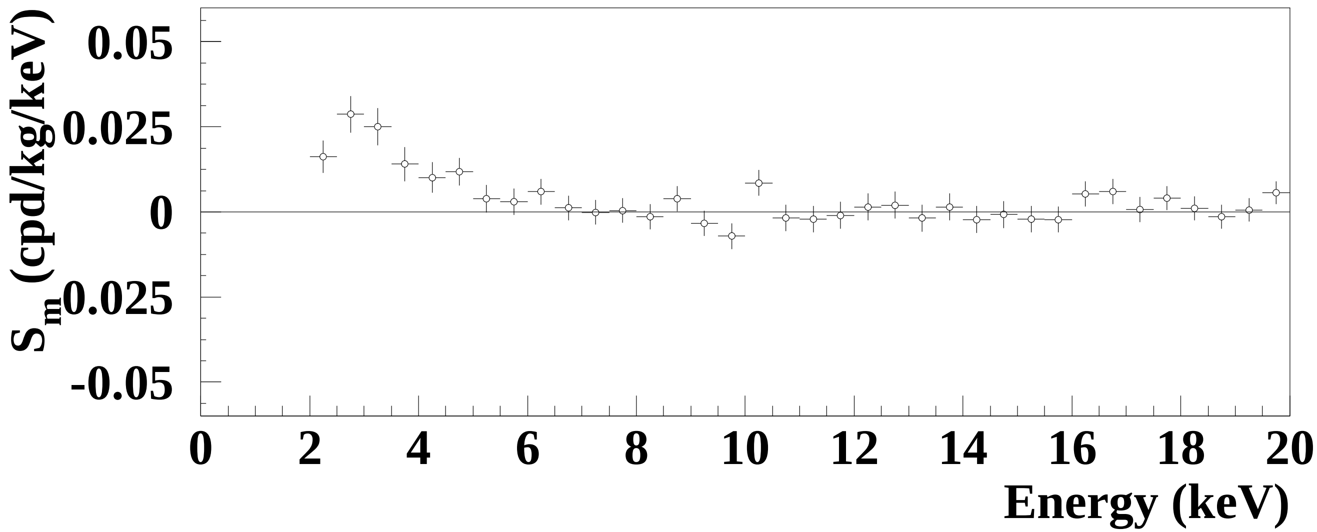


energy shape of modulation is important for constraining params

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:

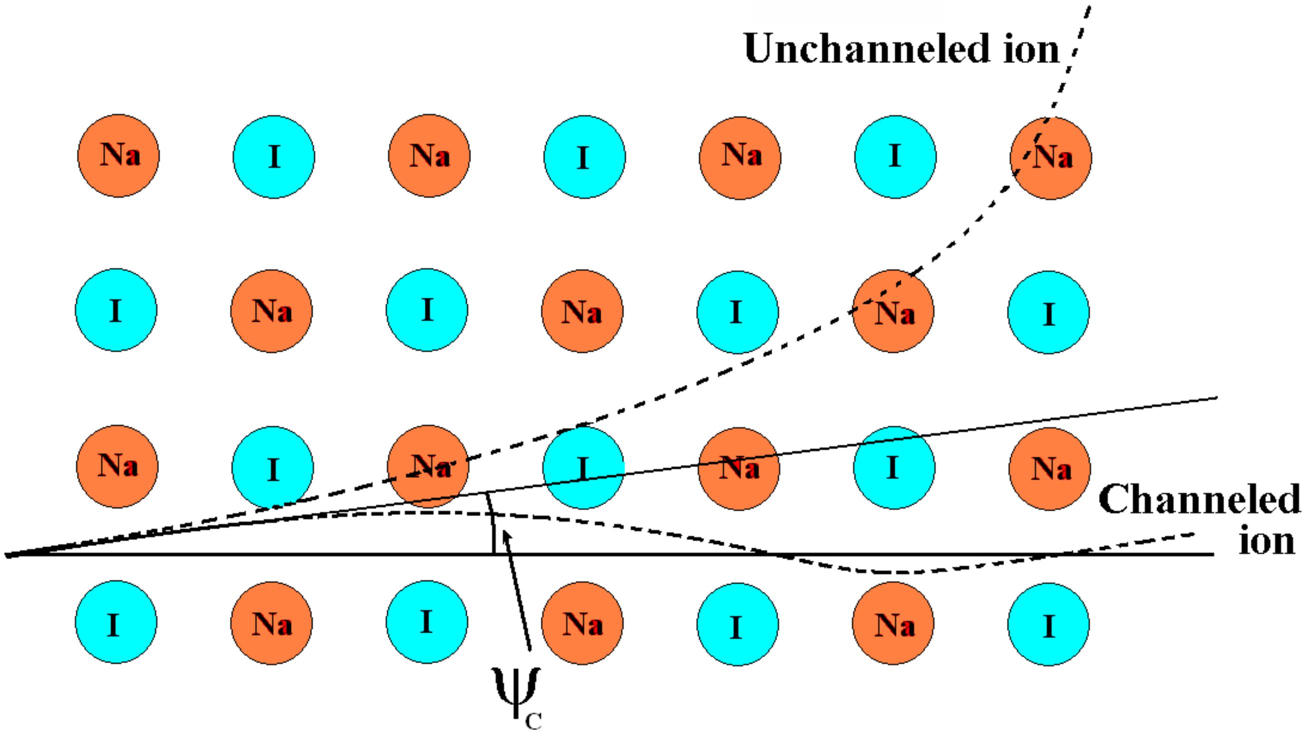
$$E_{\rm obs} = q \times E_R$$

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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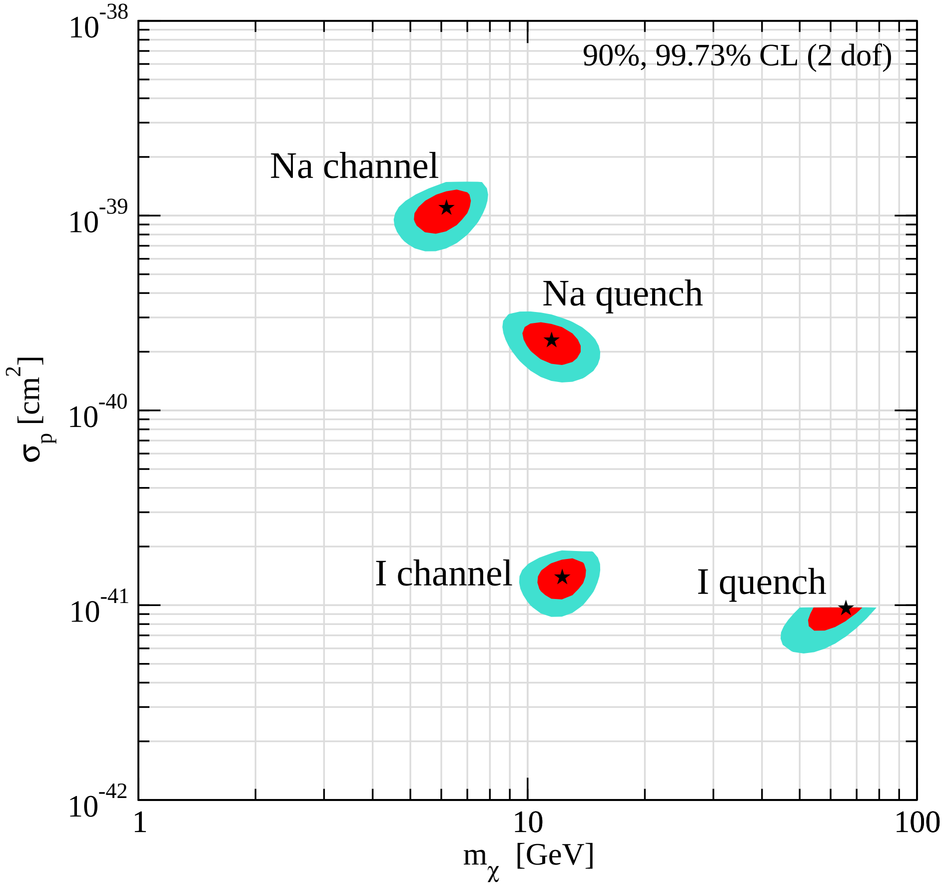
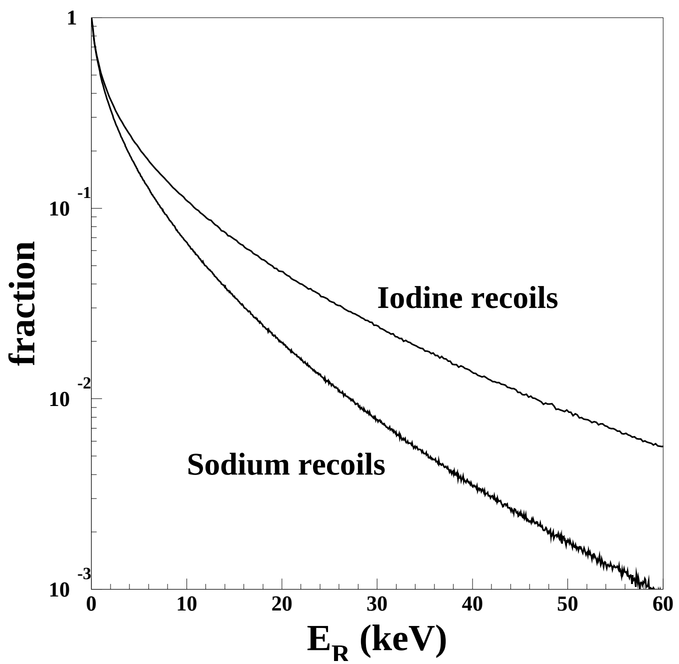


fitting DAMA requires

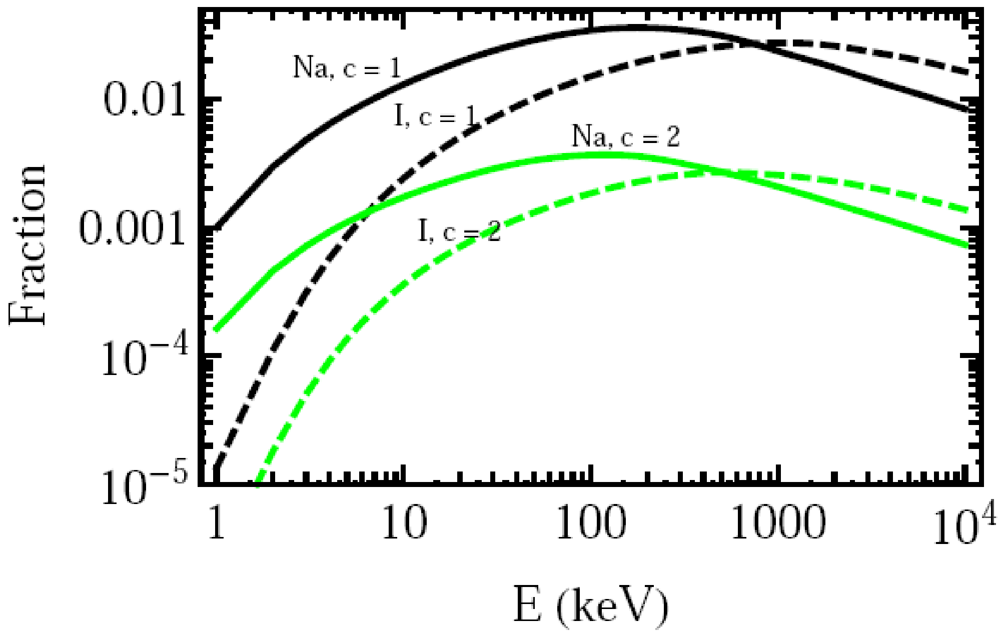
$$v_{\min} = \frac{m_\chi + M}{m_\chi}\sqrt{\frac{E_R}{2M}} \approx 400\,\text{km/s}$$

$\Rightarrow$

How large is the fraction of channeled events?



Bernabei et al., 0710.0288



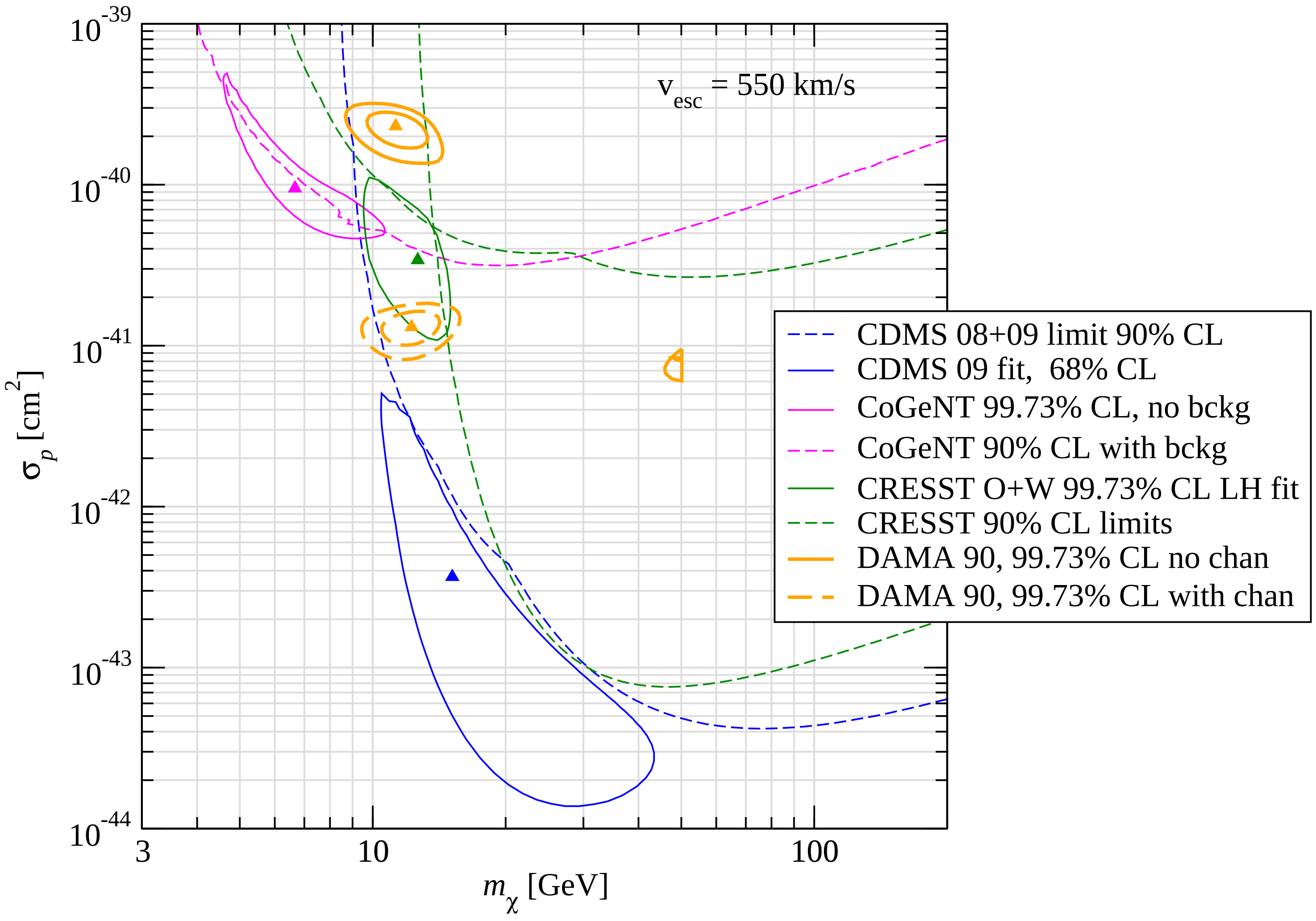
Savage et al., 1006.0972

Bozorgnia, Gelmini, Gondolo, in prep.

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

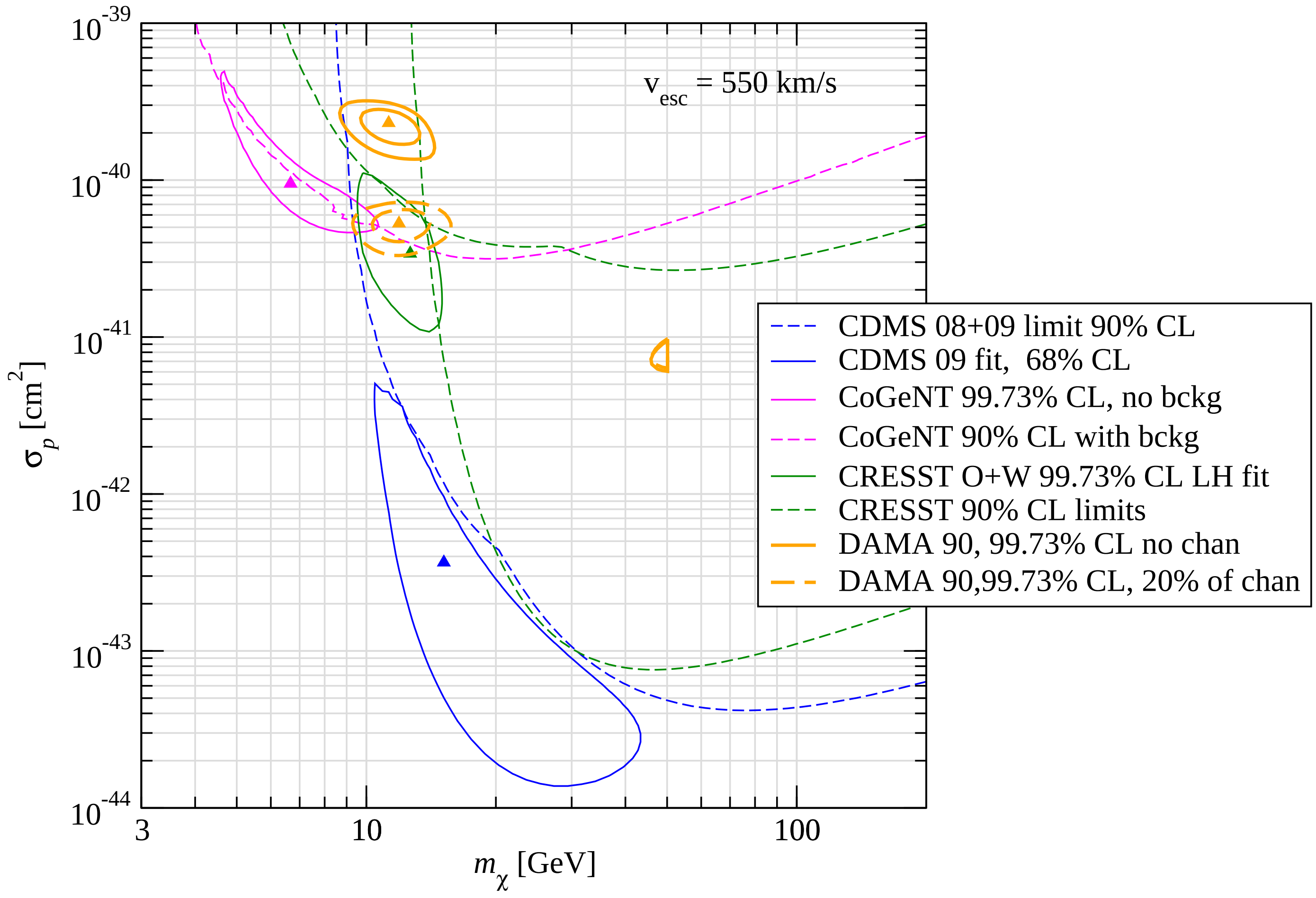
results of Bozorgnia, Gelmini, Gondolo suggest that channeling is not important $\Rightarrow$ BUT: should be measured !!

Fitting DAMA



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

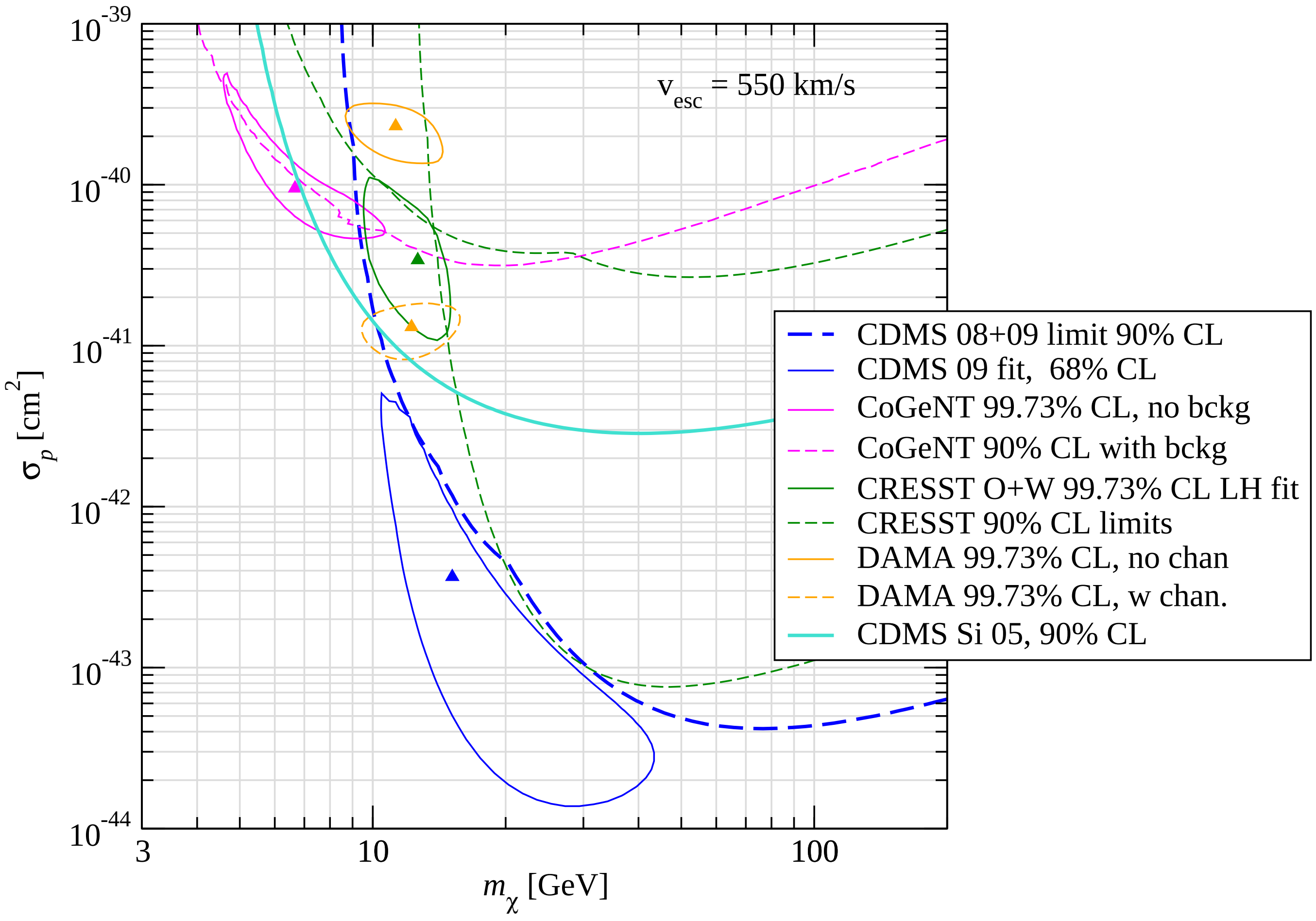
Fitting DAMA



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

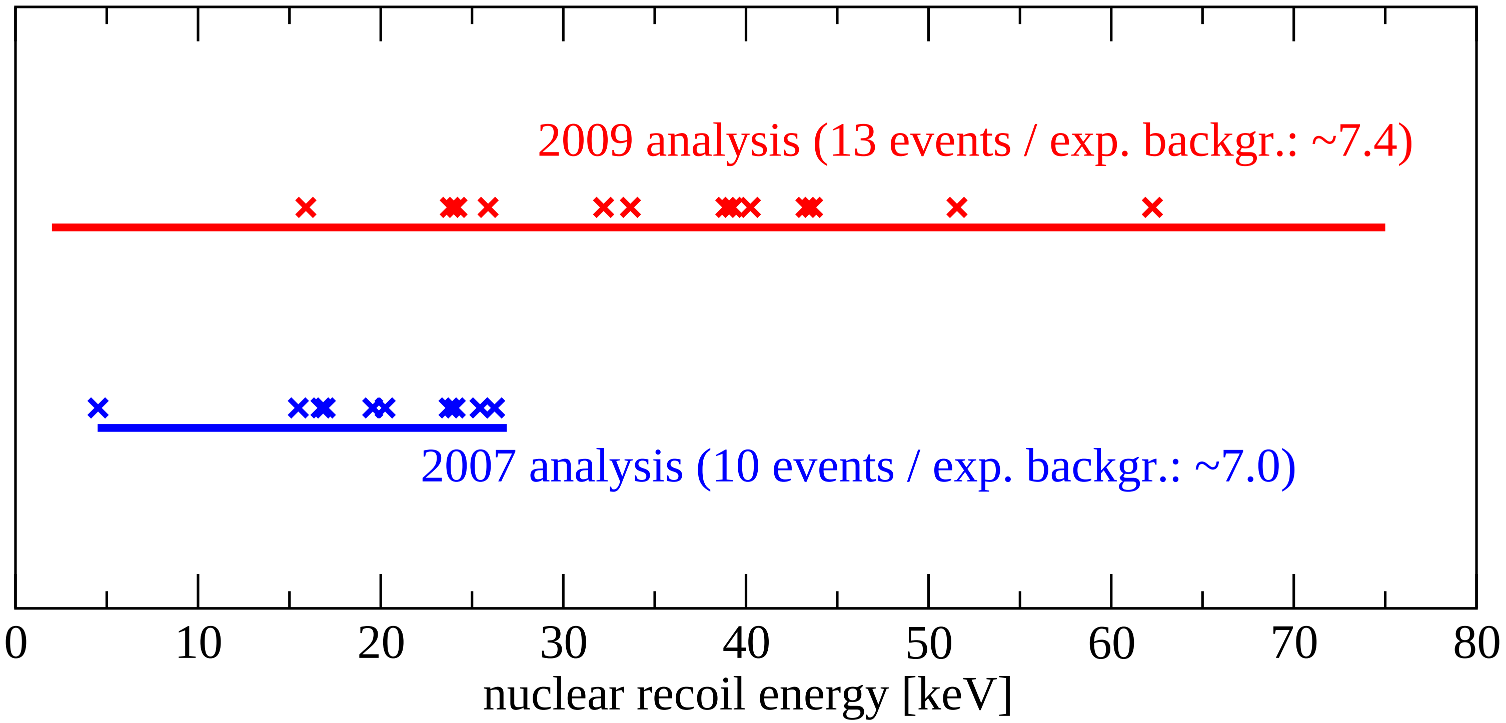
more data on tape

XENON-10

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

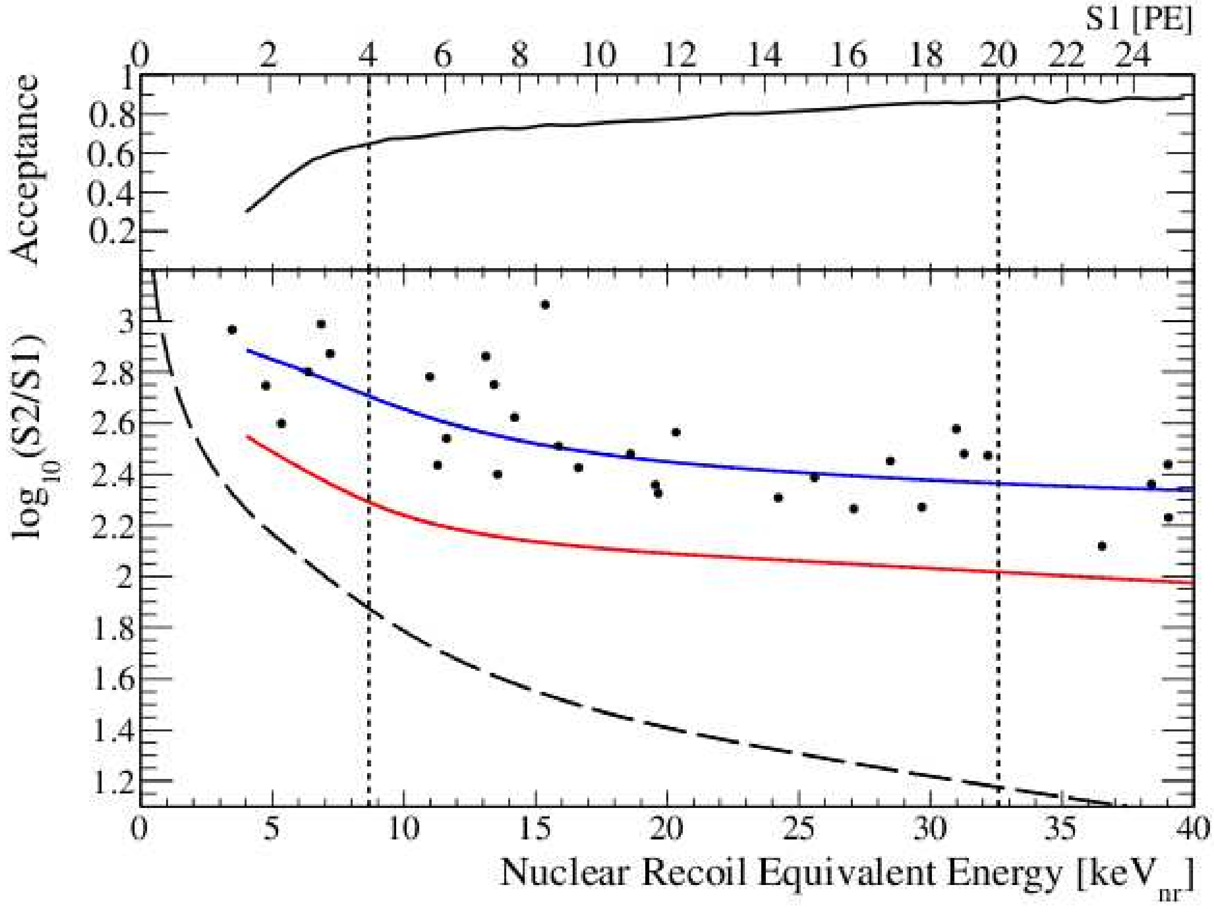
0706.0039: original blind analysis: 10 events

0910.3698: revised cuts: 13 events, extended energy window



XENON-100

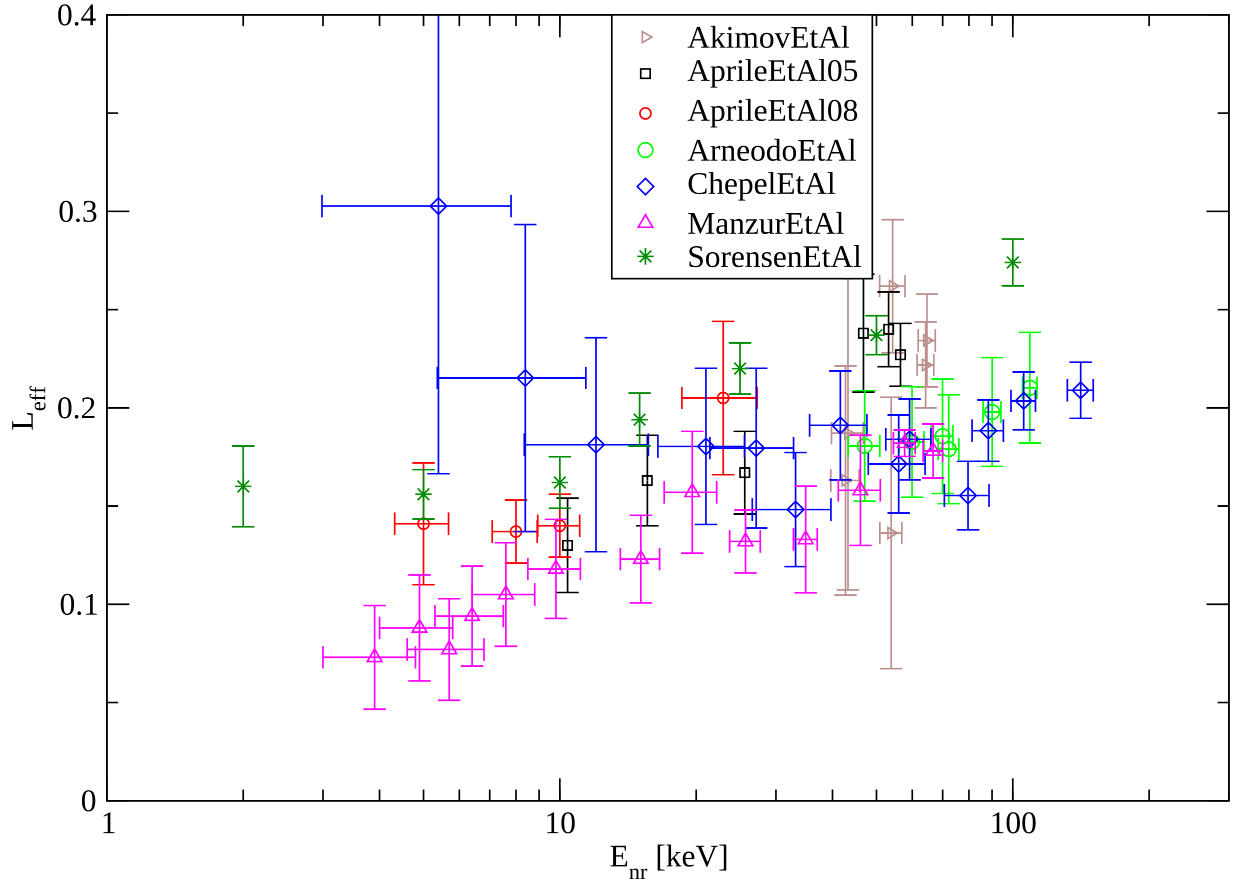
11.7 days, 40 kg fid., $\sim$ 230 kg day effective exp.



XENON100 coll., 1005.0380

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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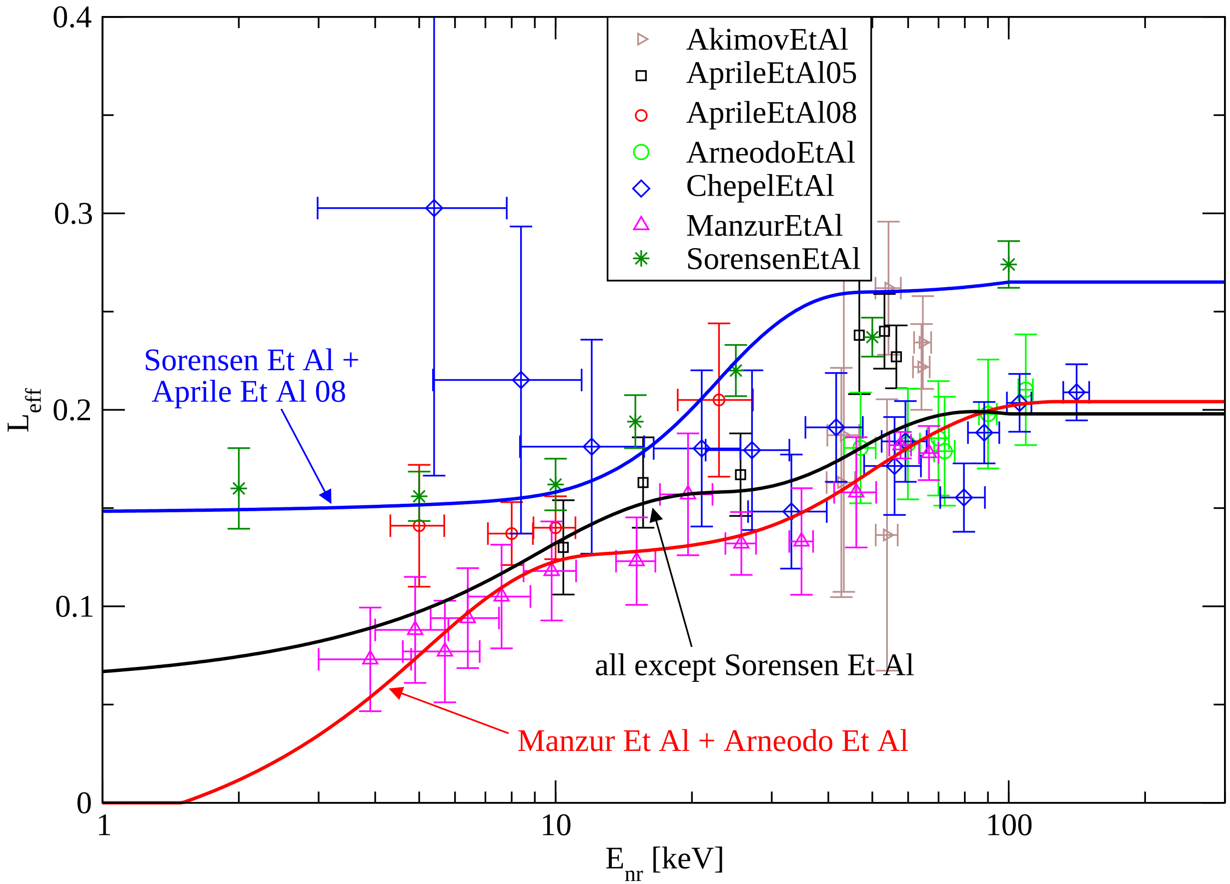
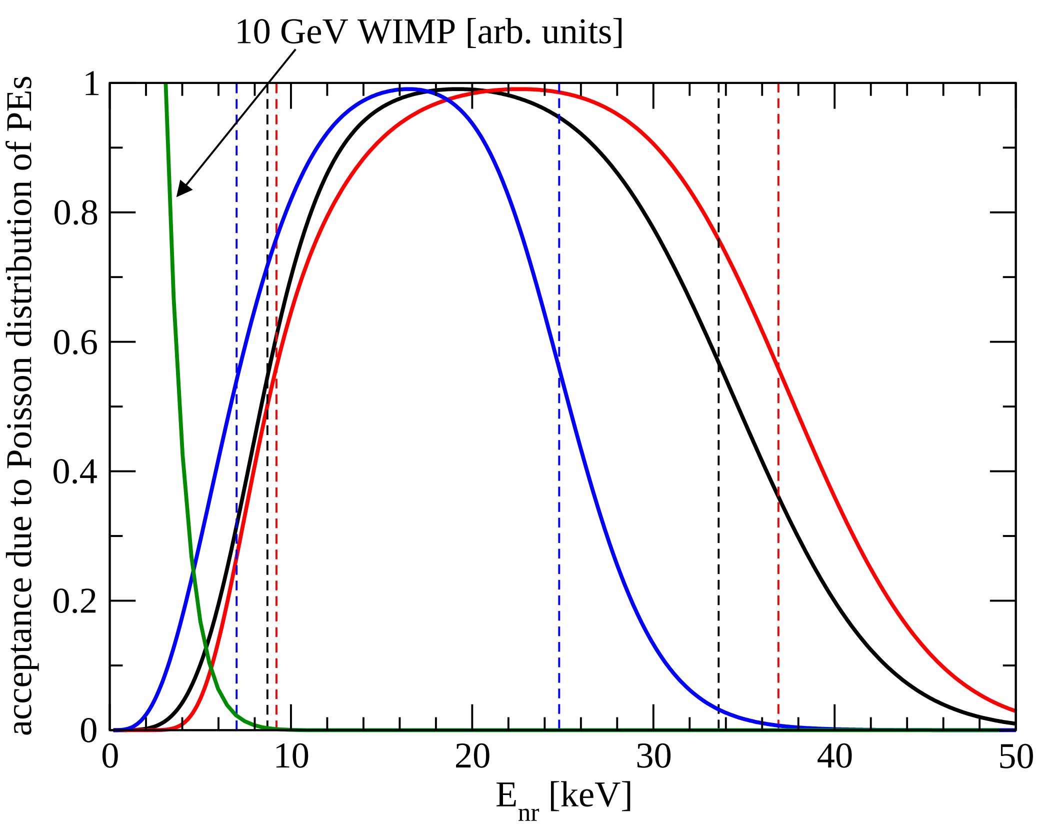


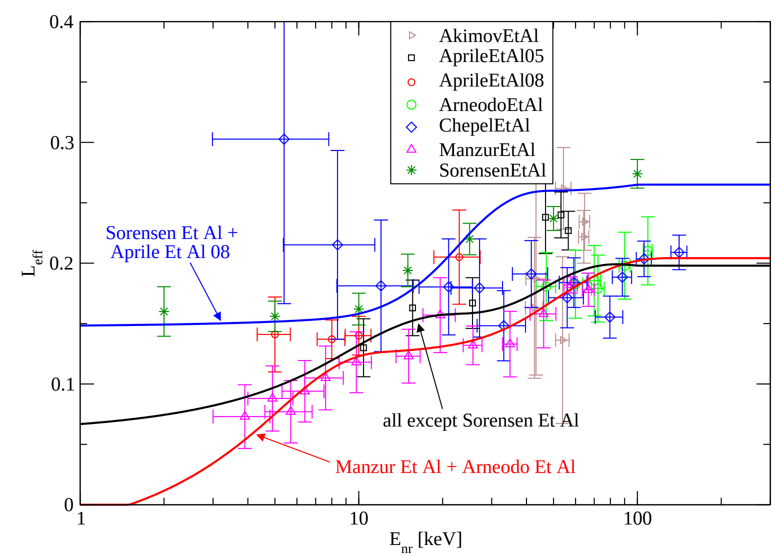
3 exemplary fits, extrapolating with straight lines at low energies

Acceptance window in XENON100

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

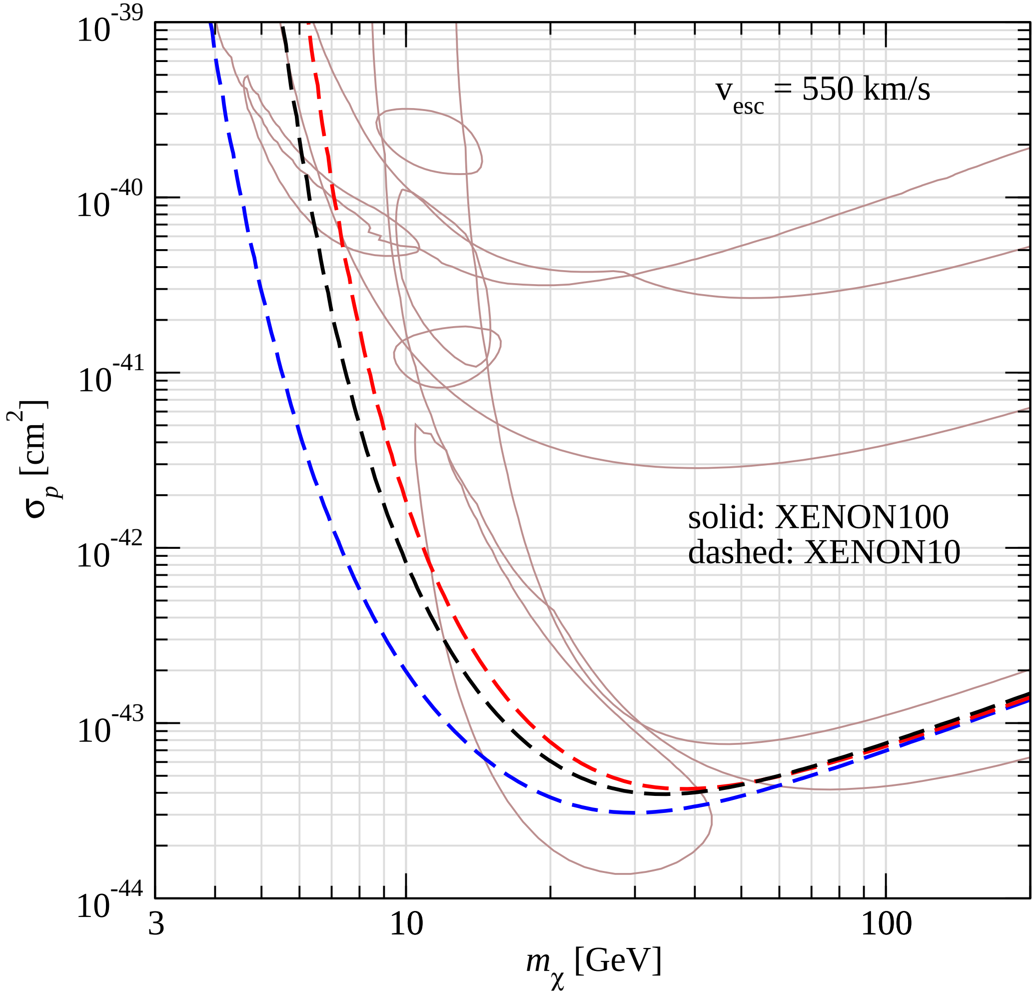
- this translates into window in E_{nr} according to L_{eff}
- Poisson statistics of PEs implies smearing of the thresholds

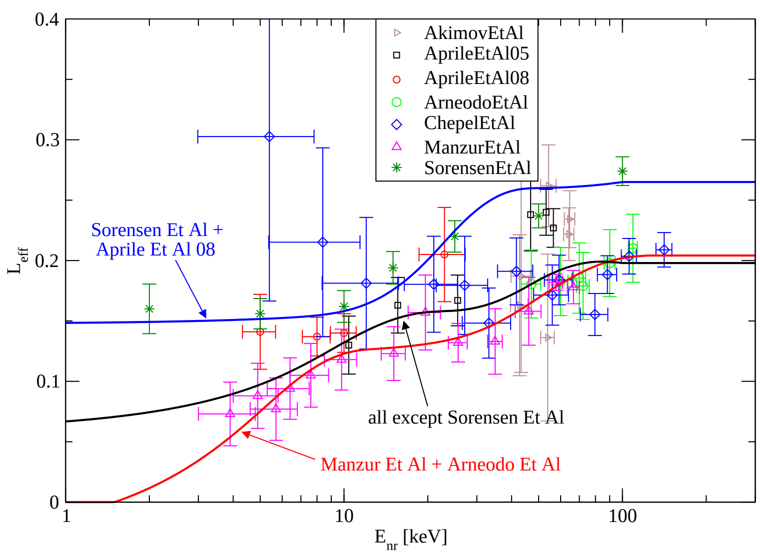




same color coding

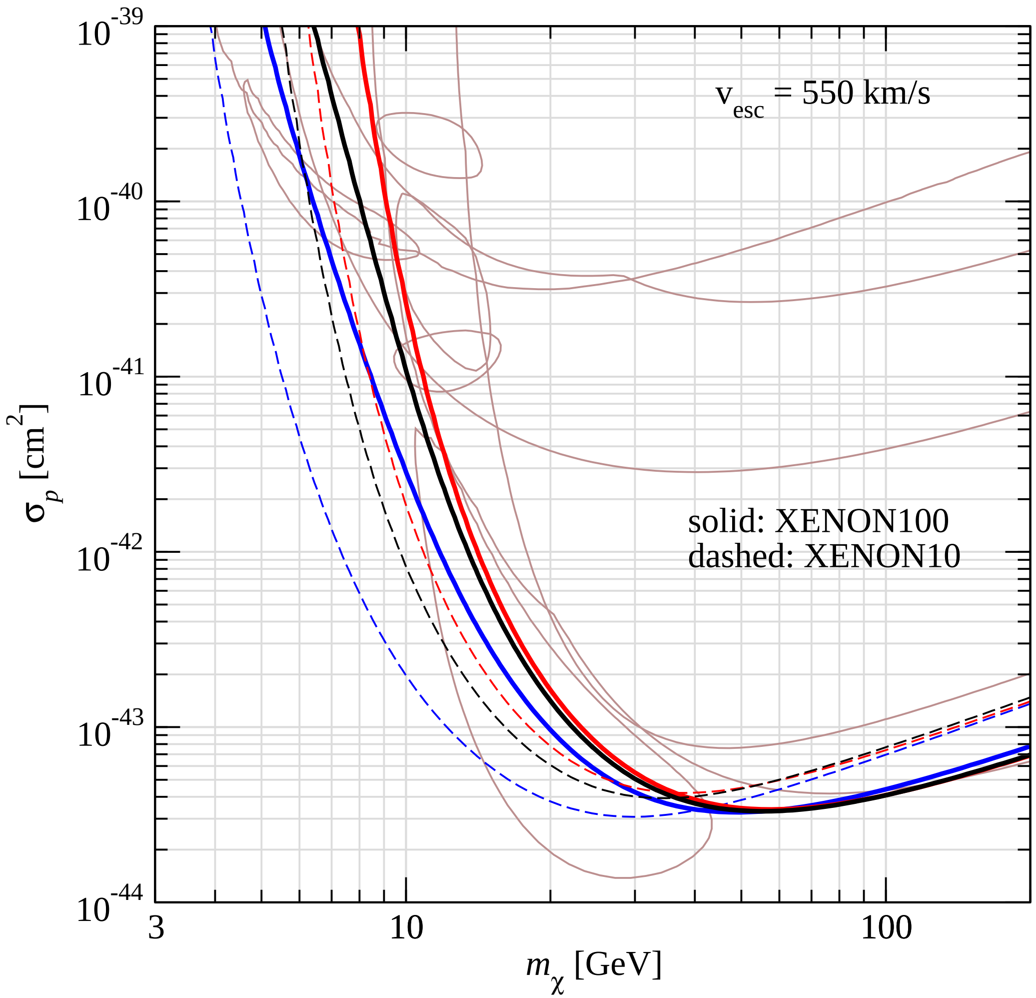
L_{eff} and the XENON10 bounds

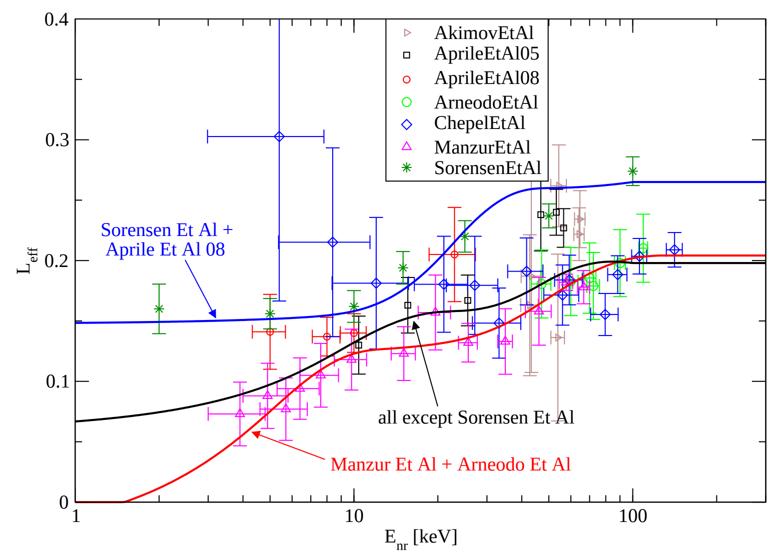




same color coding

L_{eff} and the XENON10/100 bounds





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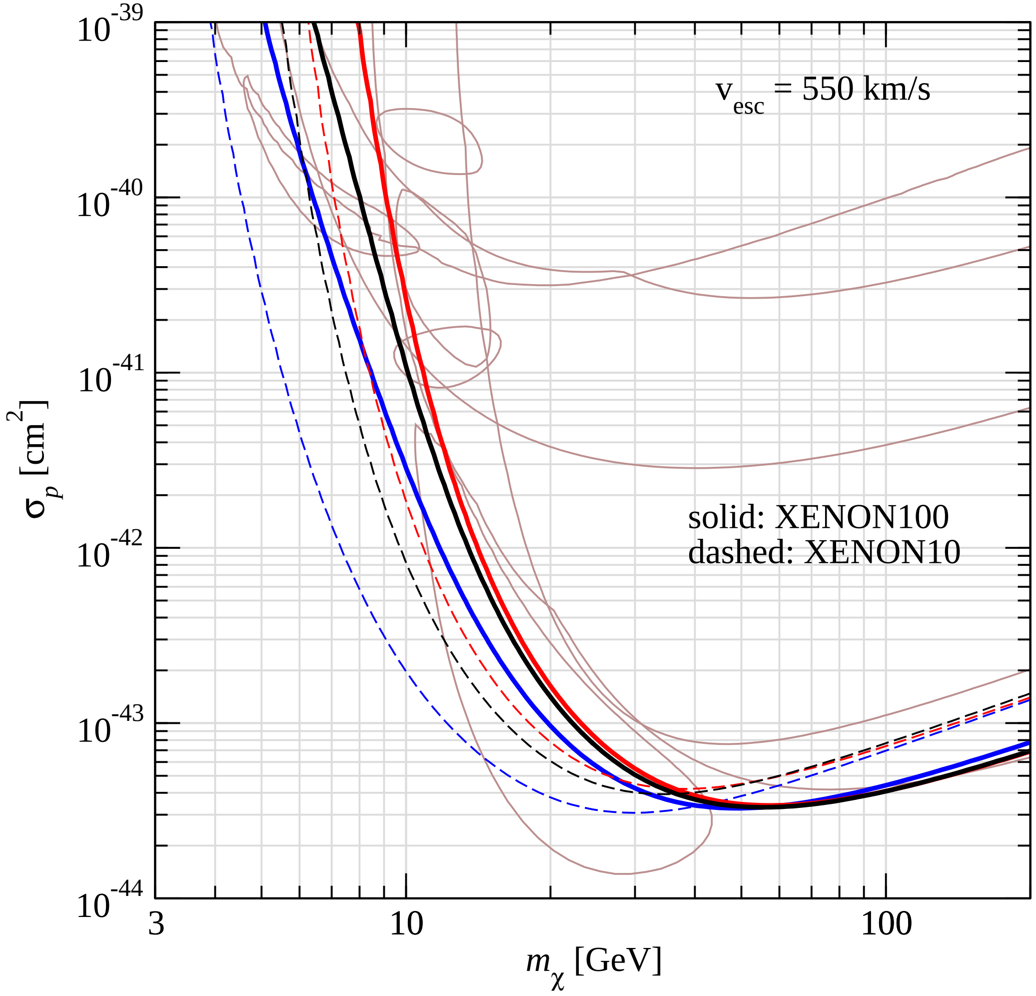


heated discussion:

Collar, McKinsey, 1005.0838

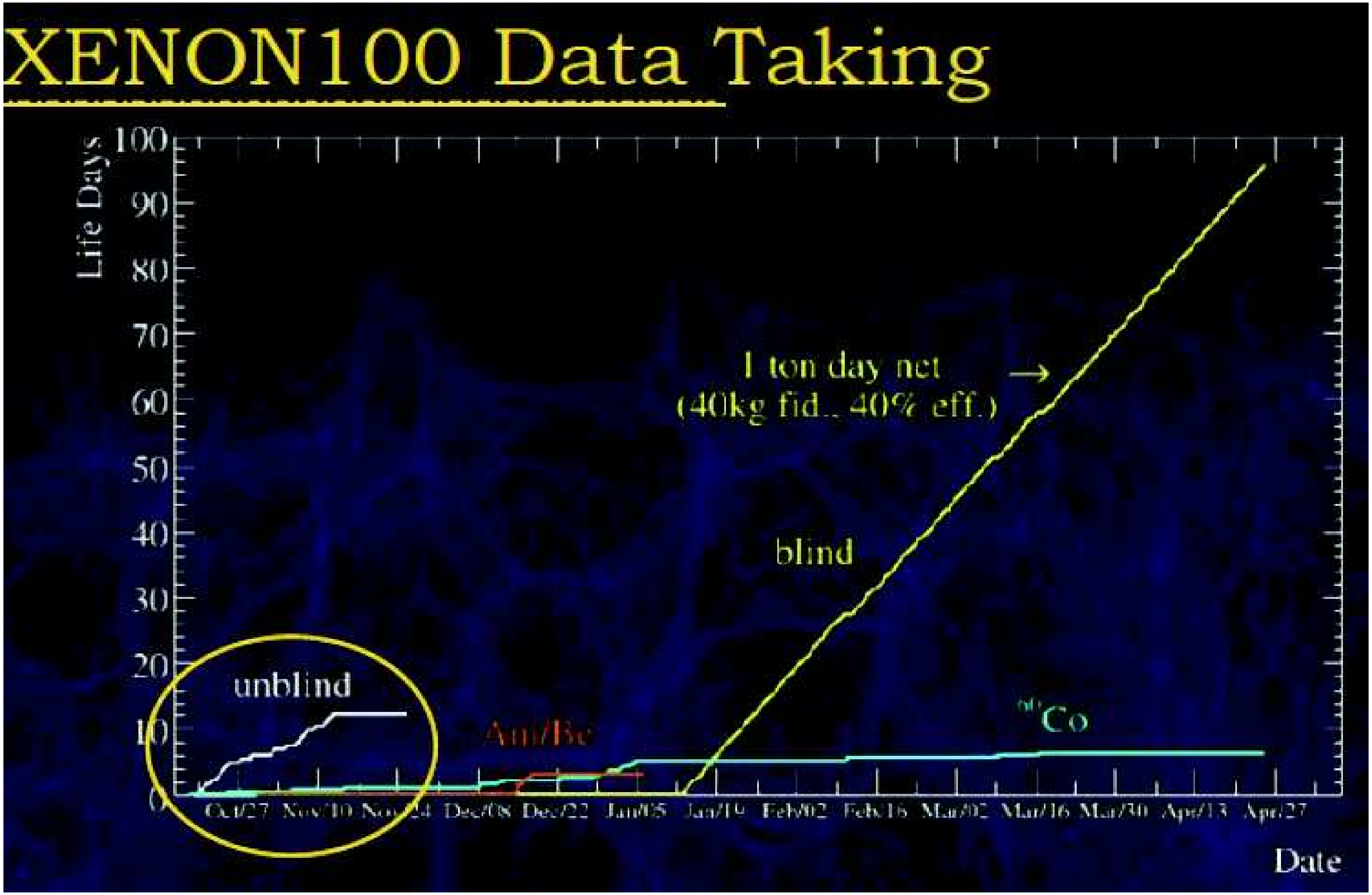
XENON100, 1005.2615

Collar, McKinsey, 1005.2615

Savage et al., 1006.0972

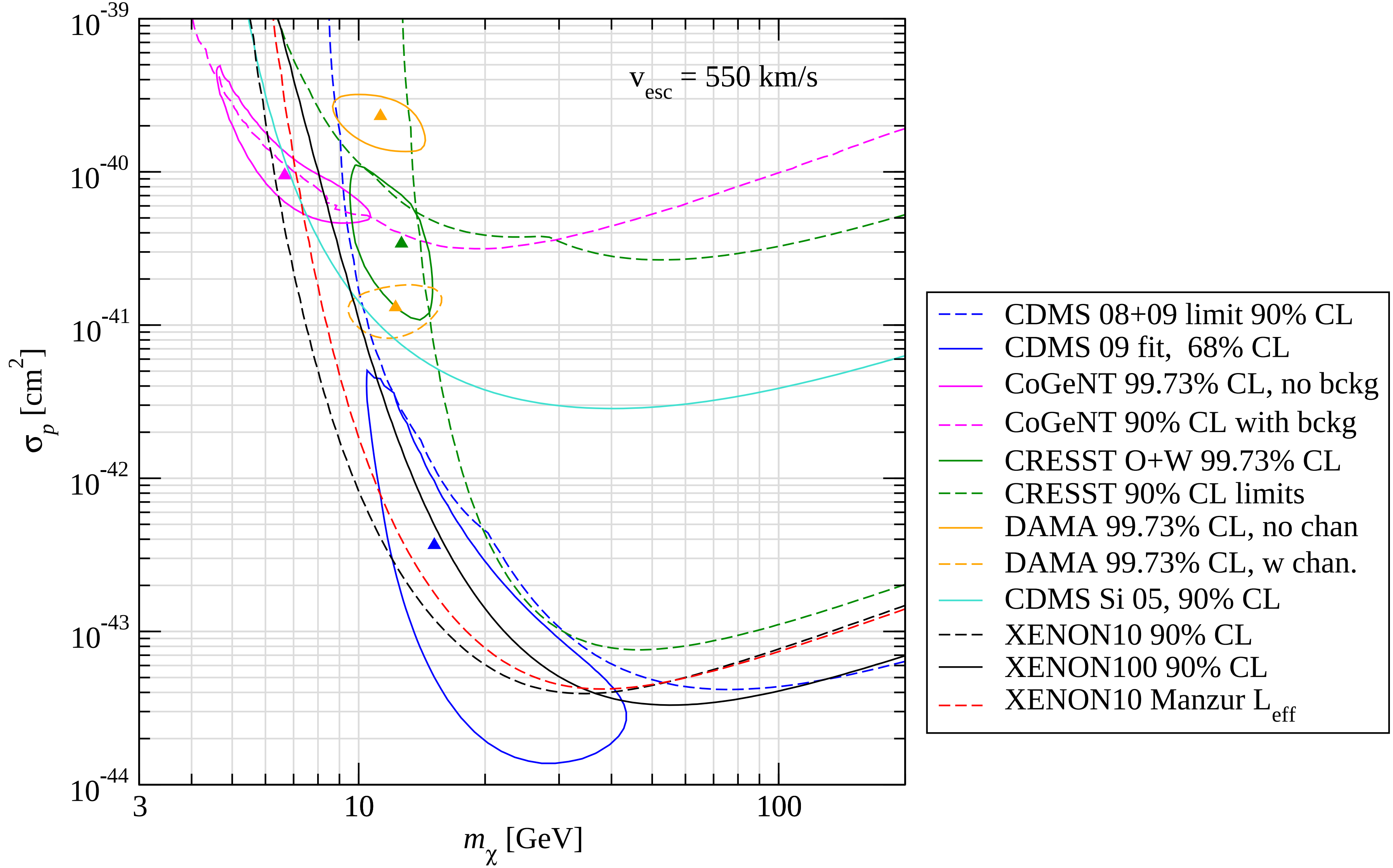
Collar, 1006.2031

XENON-100 exposure

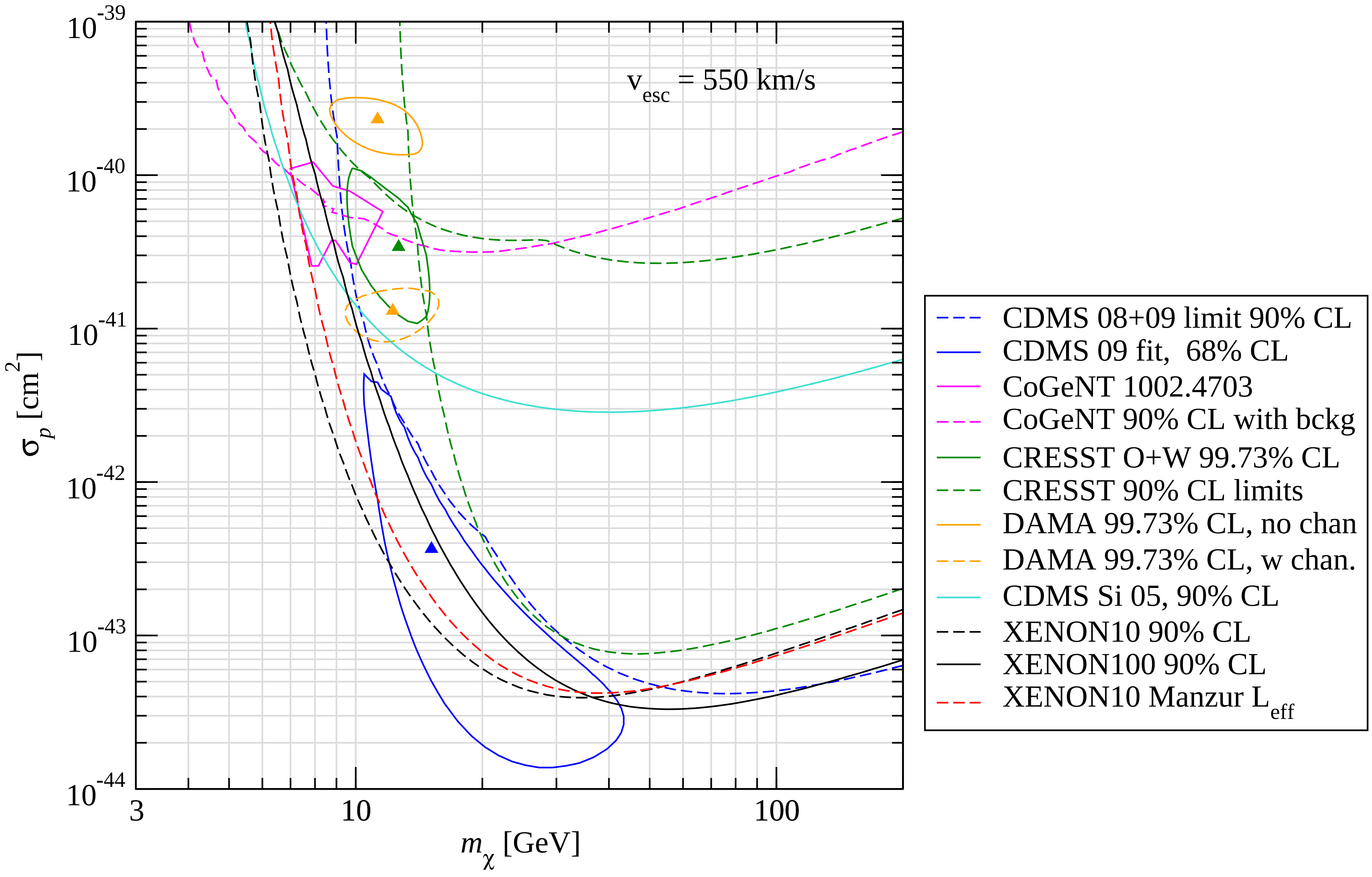


Talk by E. Aprile, GGI conference, 19 May 2010

Summary elastic SI scattering



Summary elastic SI scattering



elastic spin-dependent (eSD) scattering

Spin-dependent scattering

coupling mainly to an un-paired nucleon:

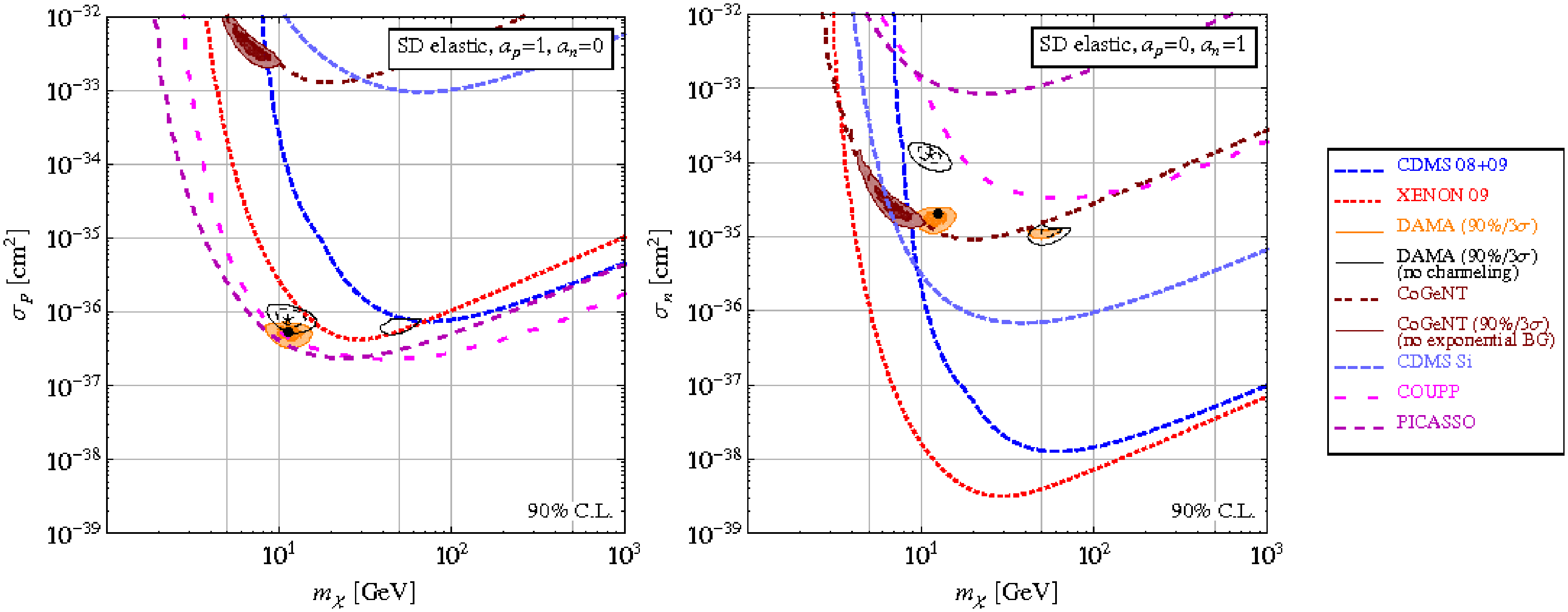
		neutron	proton
DAMA	$^{23}_{11}$Na	even	odd
DAMA, KIMS, COUPP	$^{127}_{53}$I	even	odd
SIMPLE	$^{35}_{17}$Cl, $^{35}_{17}$Cl	even	odd
XENON, ZEPLIN	$^{129}_{54}$Xe, $^{131}_{54}$Xe	odd	even
CDMS, CoGeNT	$^{73}_{32}$Ge	odd	even
PICASSO, COUPP, SIMPLE	$^{19}_{9}$F	even	odd
CRESST	$^{A}_{74}$W, $^{16}_{8}$O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

coupling with proton promising for DAMA vs CDMS/XENON

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

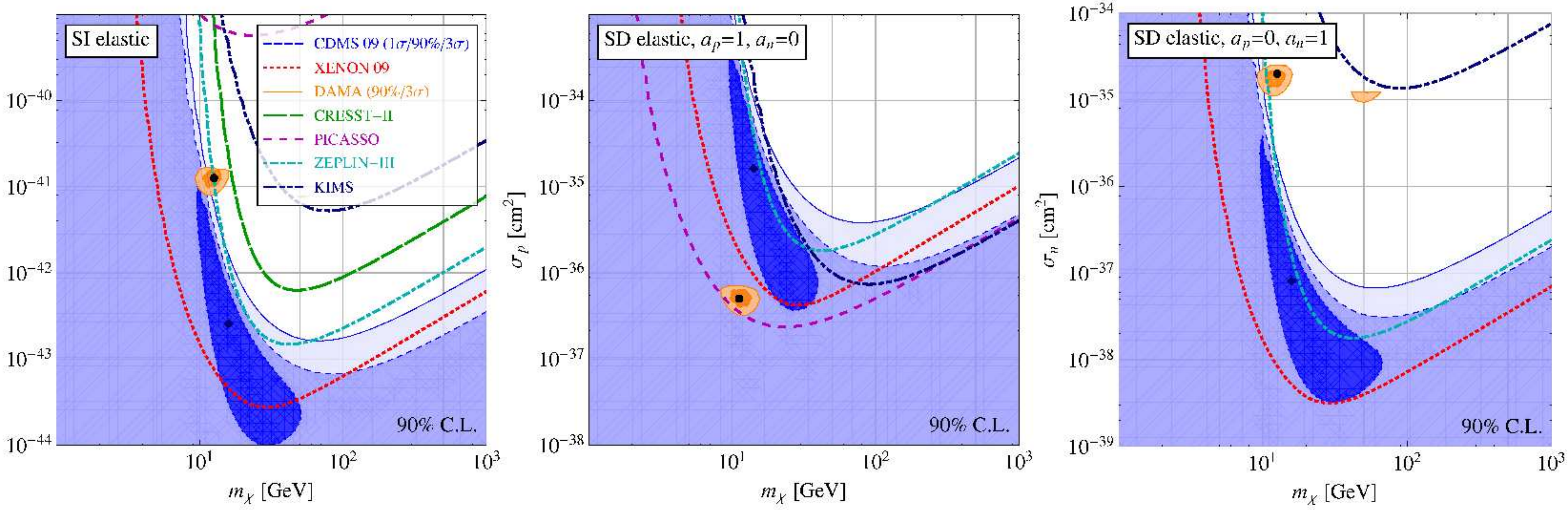
and neutrino constraints from annihilations in the sun

DAMA vs CoGeNT and eSD



Kopp, Schwetz, Zupan, 0912.4264

CDMS and eSD



Kopp, Schwetz, Zupan, 0912.4264

Constraints from Tevatron

assume effective quark DM interaction:

$$\frac{g}{\Lambda^2}(\bar{q}\gamma_5\gamma_\mu q)(\bar{\chi}\gamma_5\gamma^\mu\chi)$$

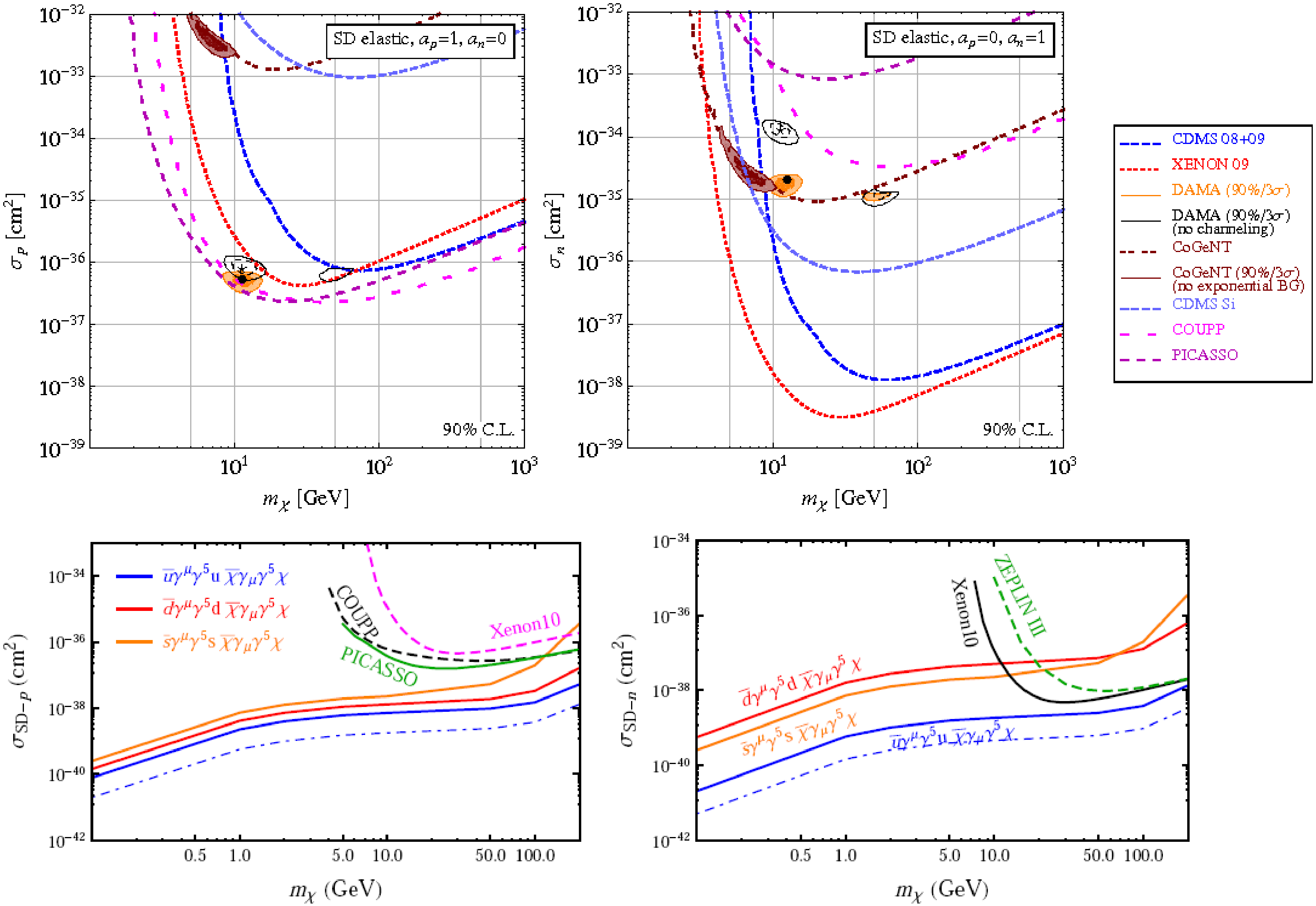
$$\Rightarrow \qquad pp \to \bar{\chi}\chi + j$$

constraints from mono-jet searches at Tevatron

e.g., Feng, Su, Takayama, hep-ph/0503117;

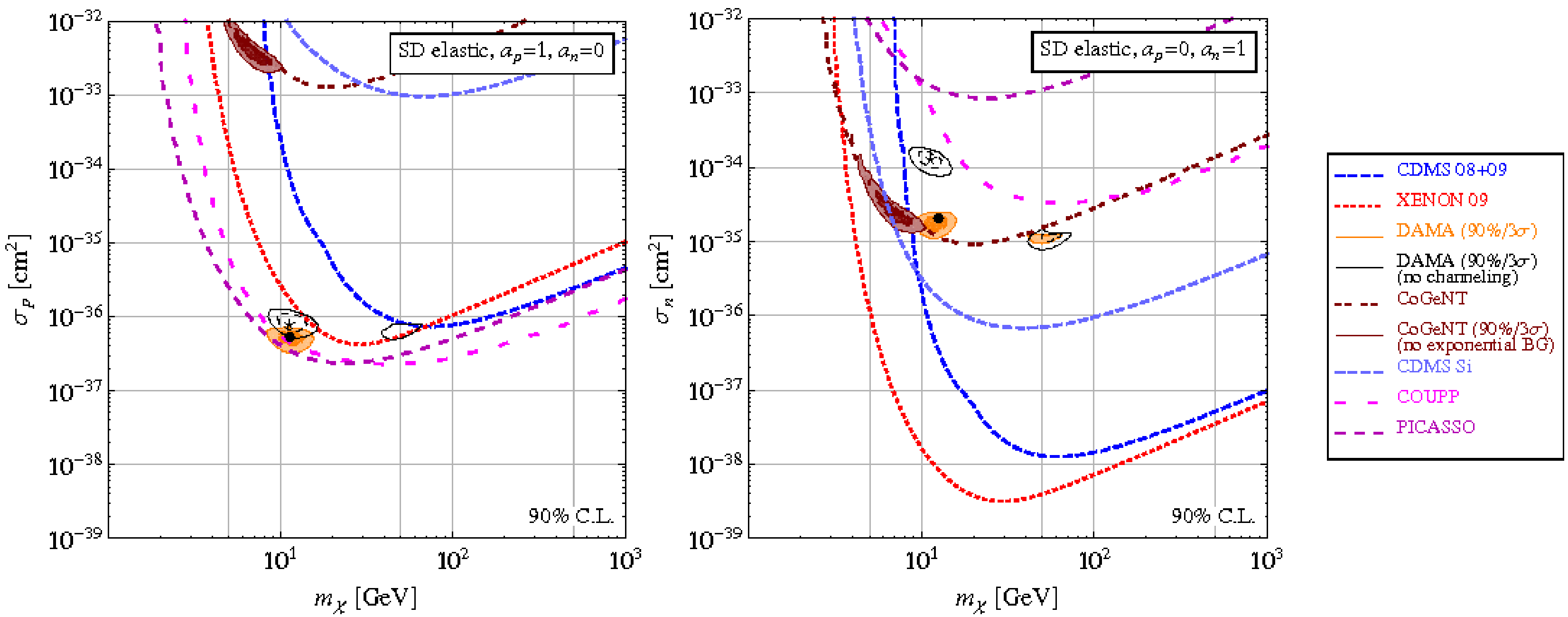
Beltran et al., 1002.4137; Goodman et al., 1005.1286; Bai, Fox, Harnik, 1005.3797

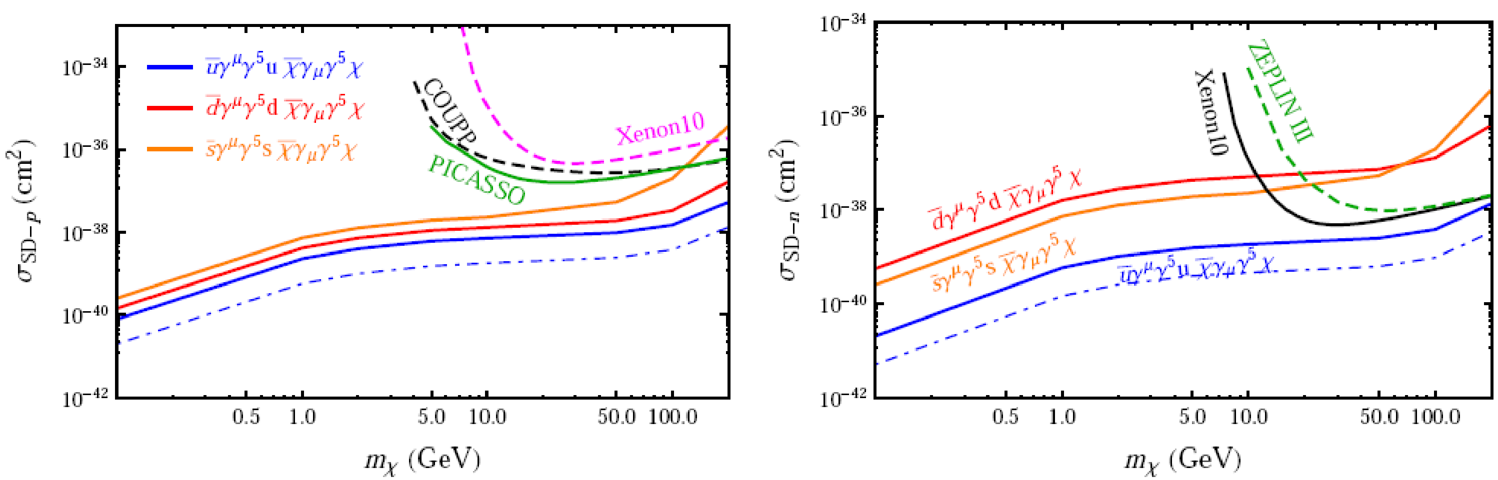
SD and constraints from Tevatron



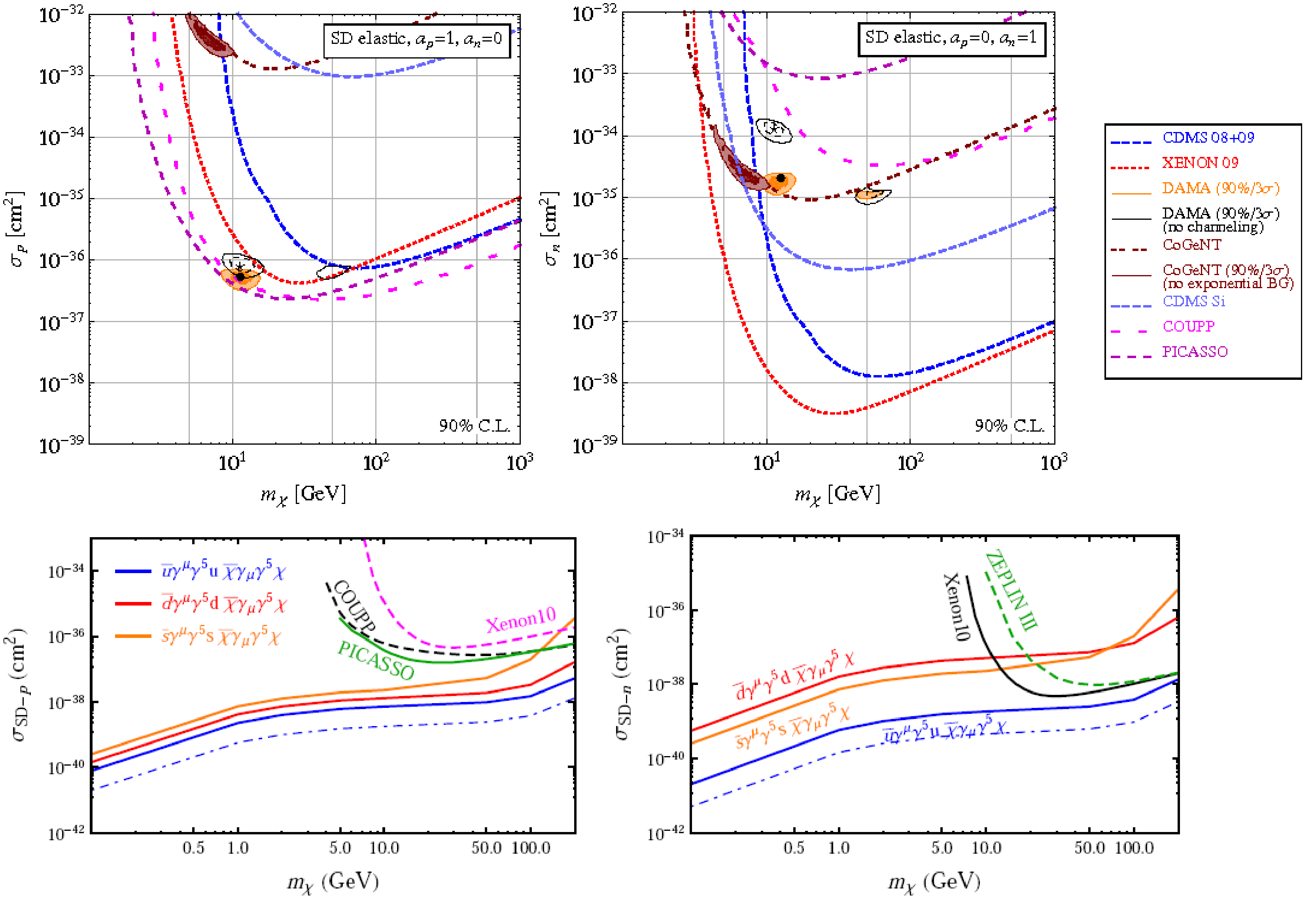
Bai, Fox, Harnik, 1005.3797

SD and constraints from Tevatron and neutrinos





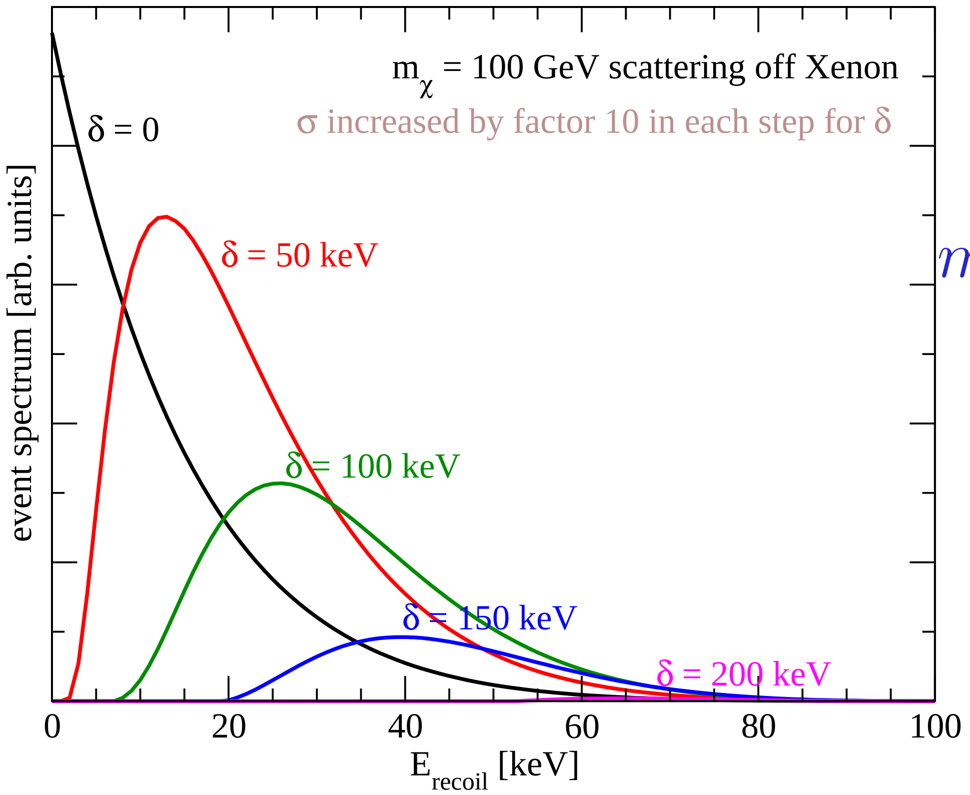
SD and constraints from Tevatron and neutrinos



inelastic scattering

Tucker-Smith, Weiner, hep-ph/0101138

Inelastic DM scattering

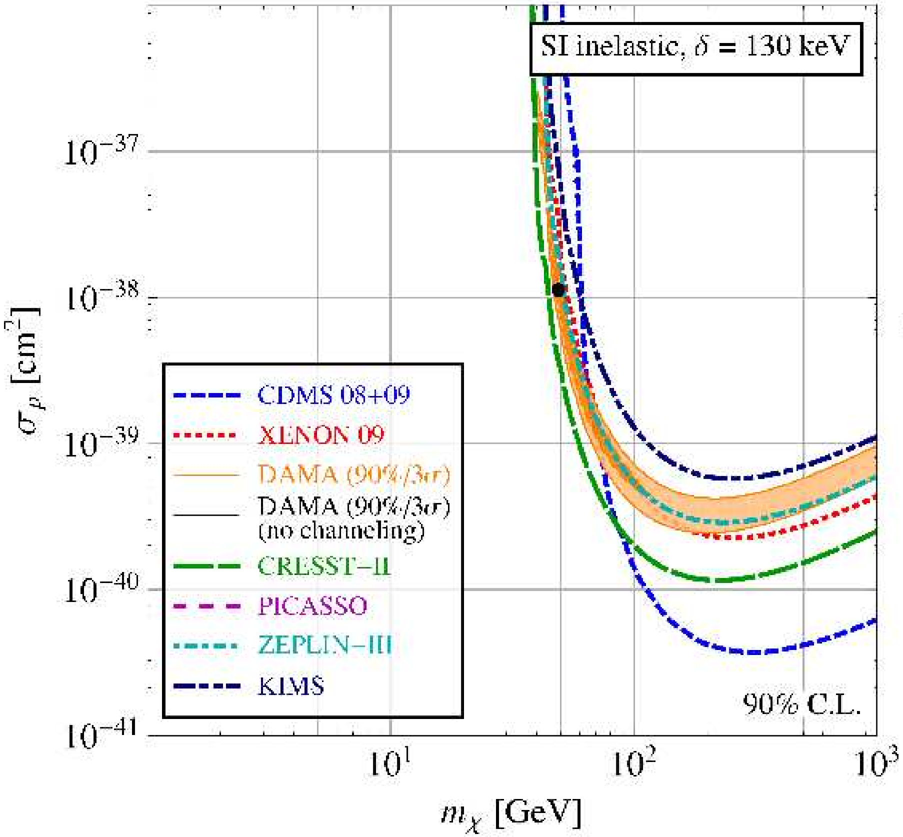


$$m_{\chi^*} - m_\chi = \delta \simeq 100\,\text{keV} \sim 10^{-6} m_\chi$$

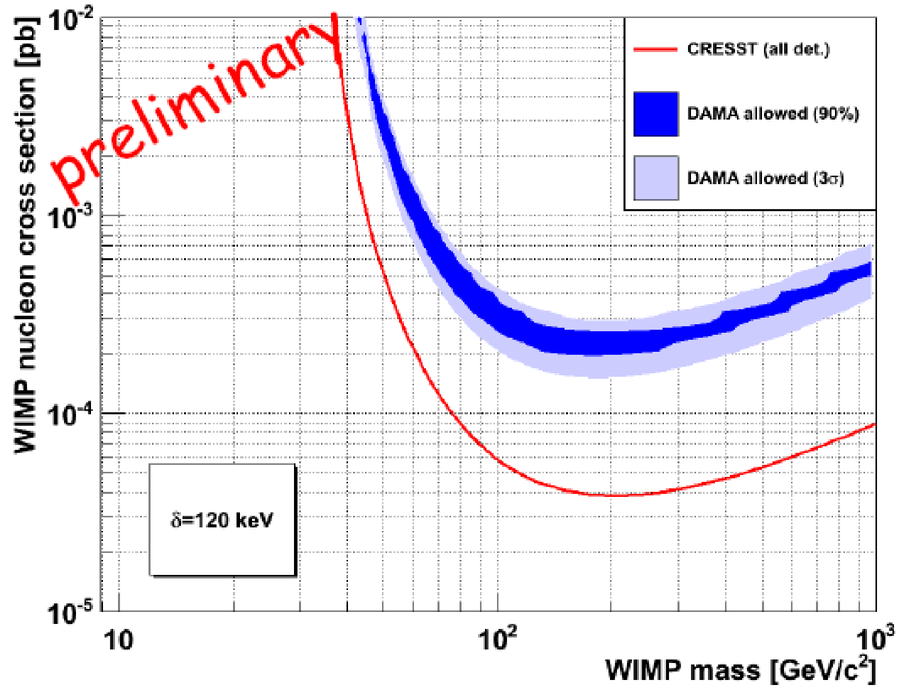
$$v_{\rm min}^{\rm inel} = \frac{1}{\sqrt{2ME_R}}\left(\frac{ME_R}{\mu_\chi} + \delta\right)$$

- 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 @ WONDER 2010



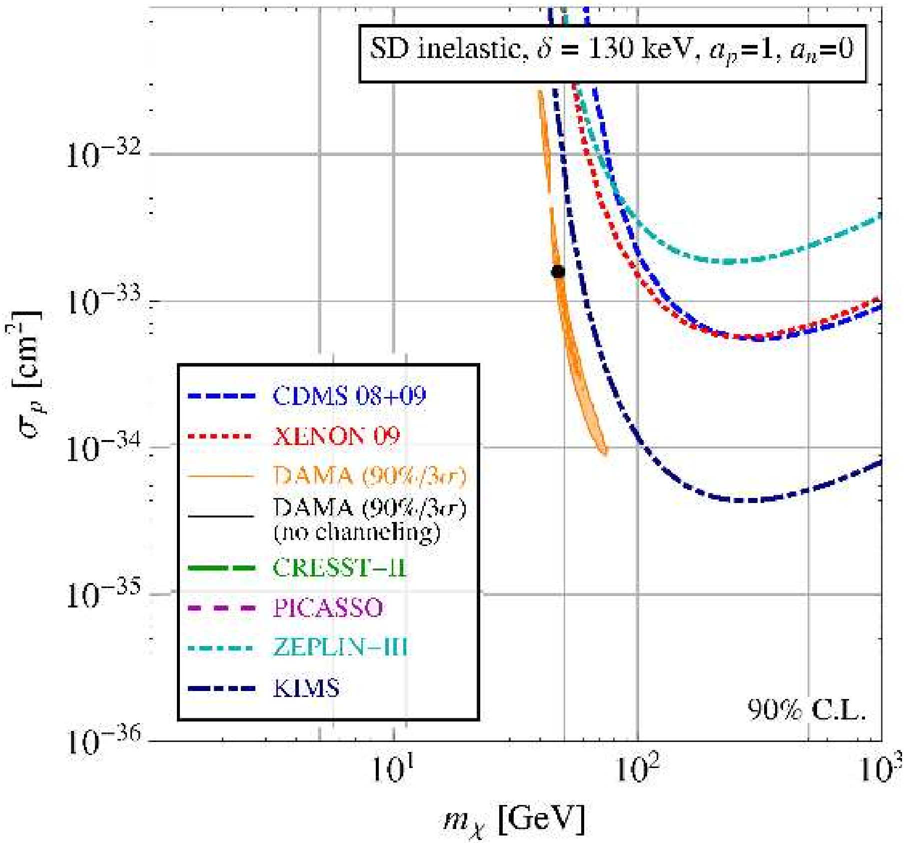
$m_\chi \simeq 50\,\mathrm{GeV}$, $\delta \simeq 130\,\mathrm{GeV}$

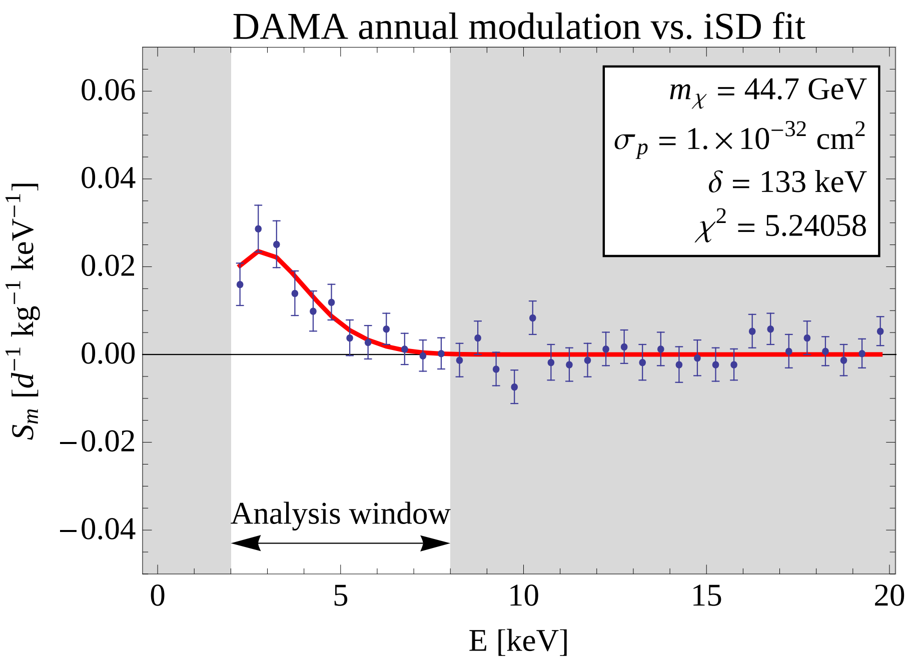
disfavored by CRESST (tungsten)

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)

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)

BUT:

- 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

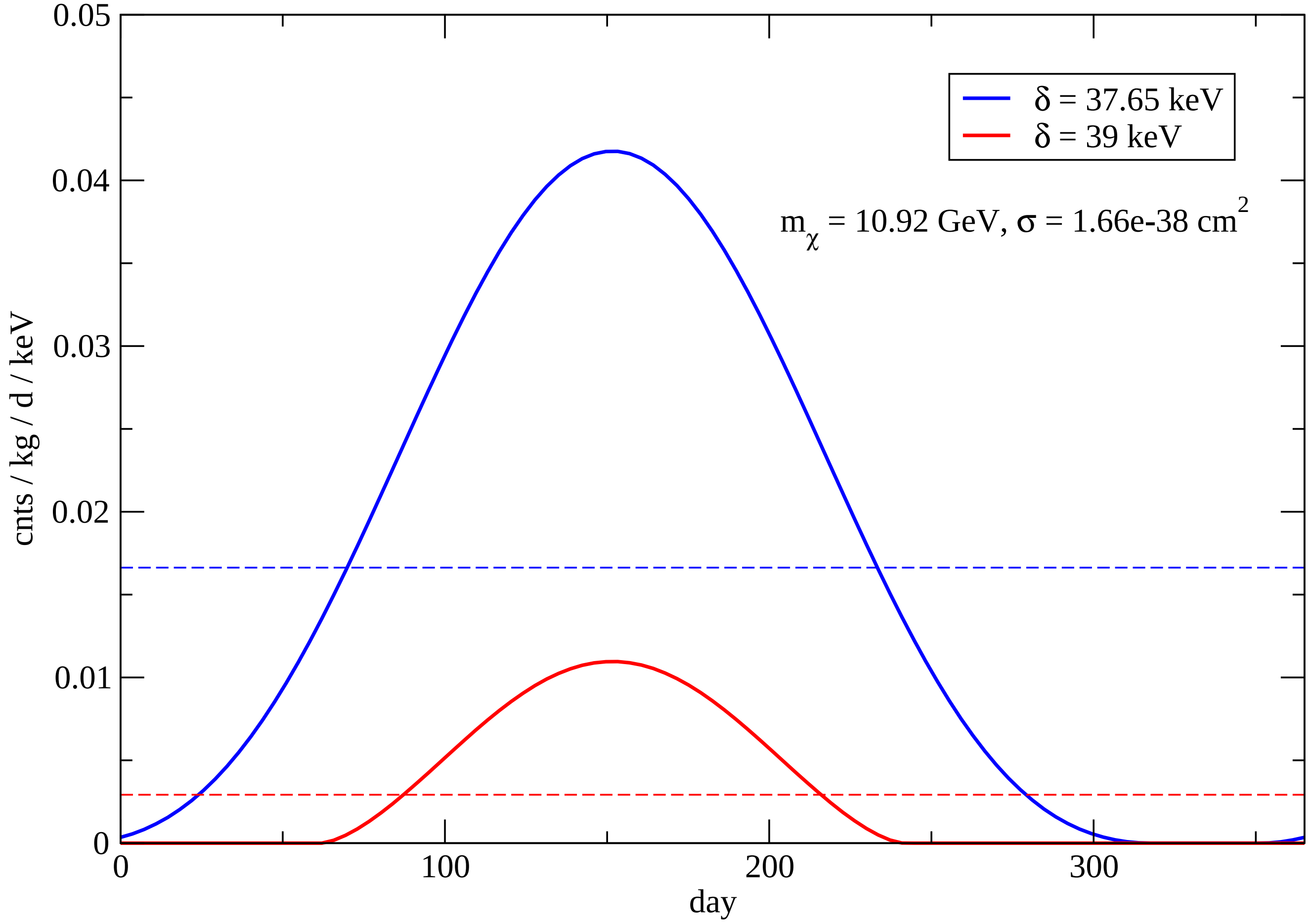
similar situation as recent cosmic ray “DM signals”

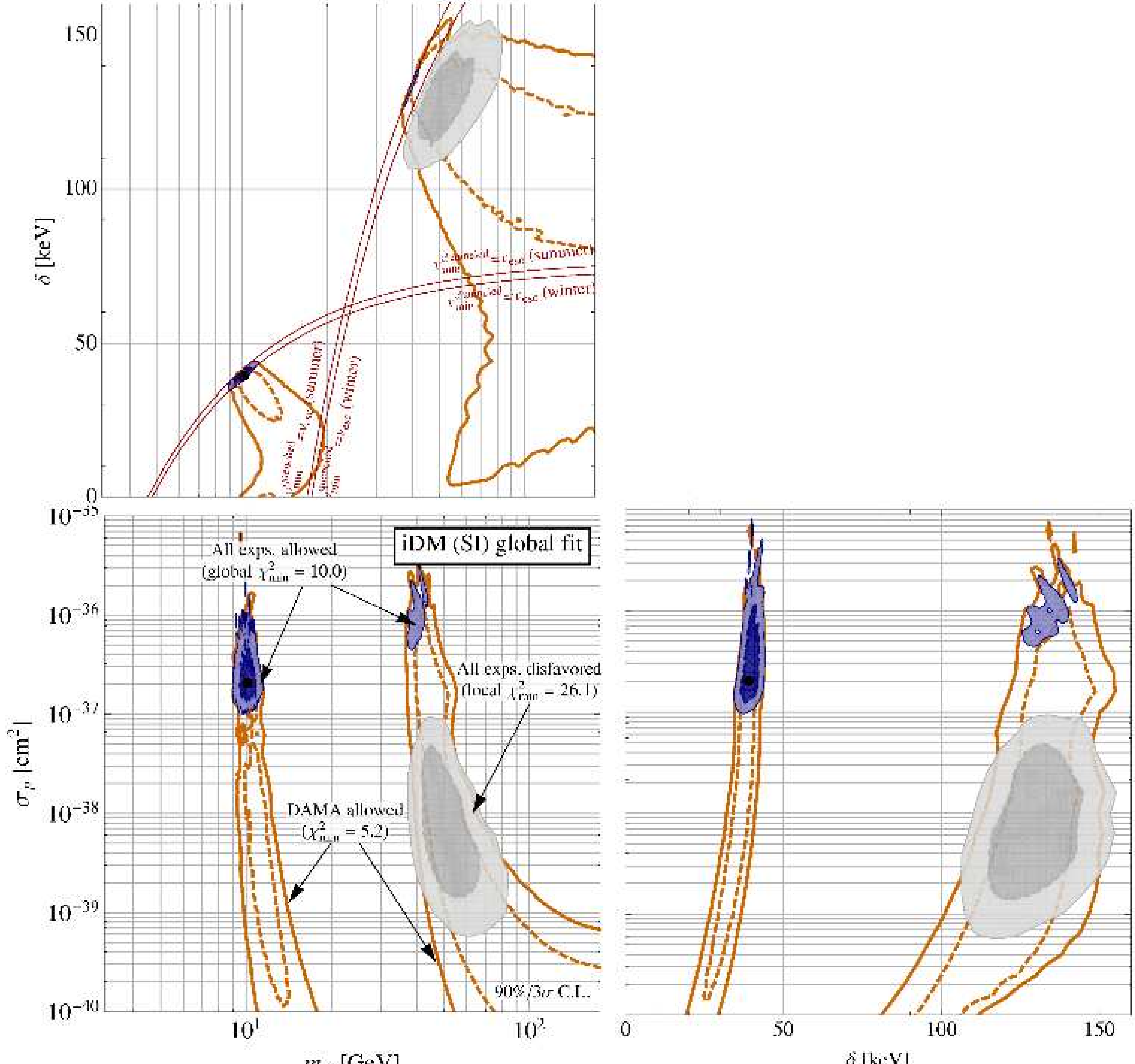
at some point “hints” will converge (hopefully)!

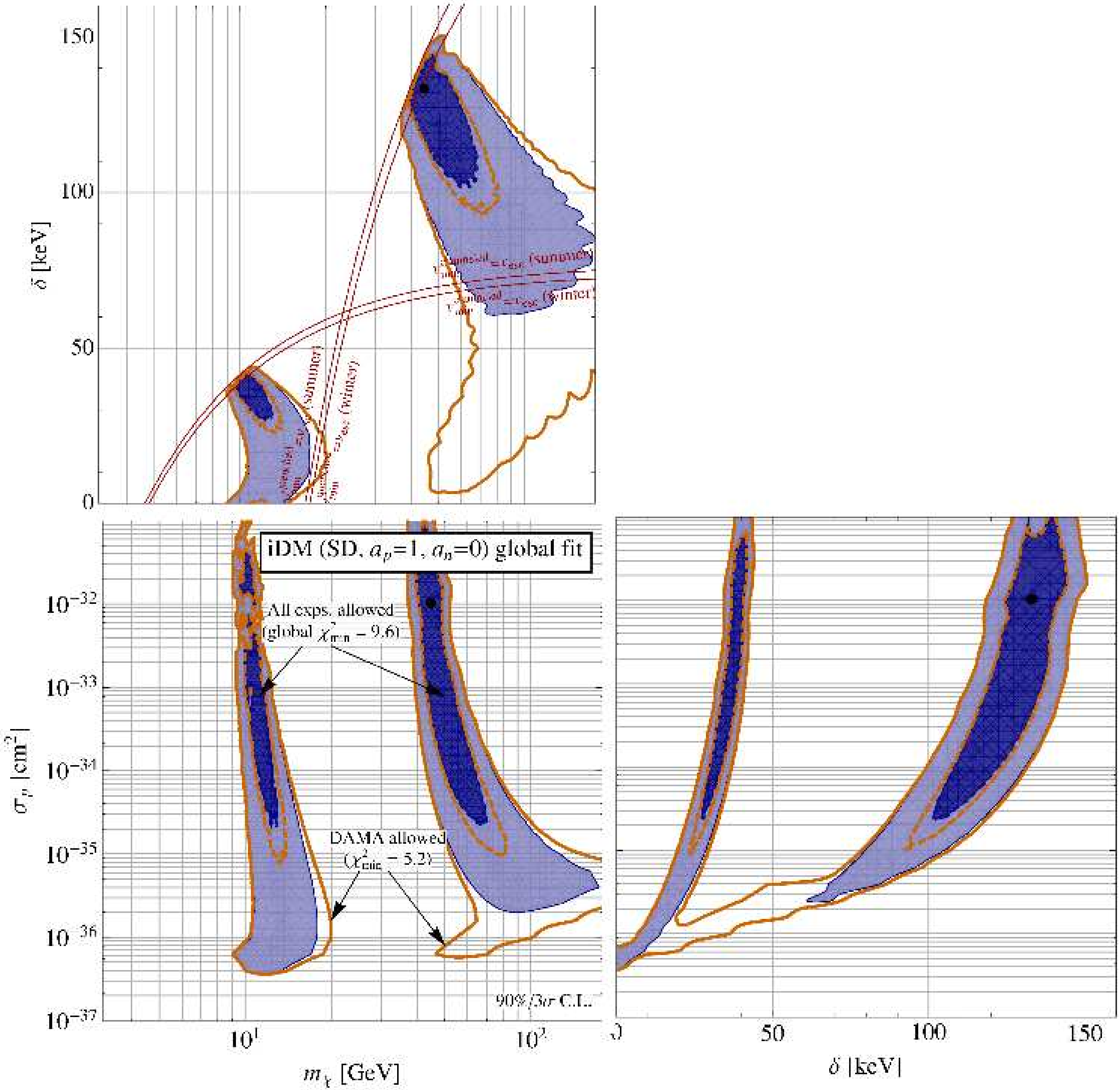
Additional slides

iSI

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



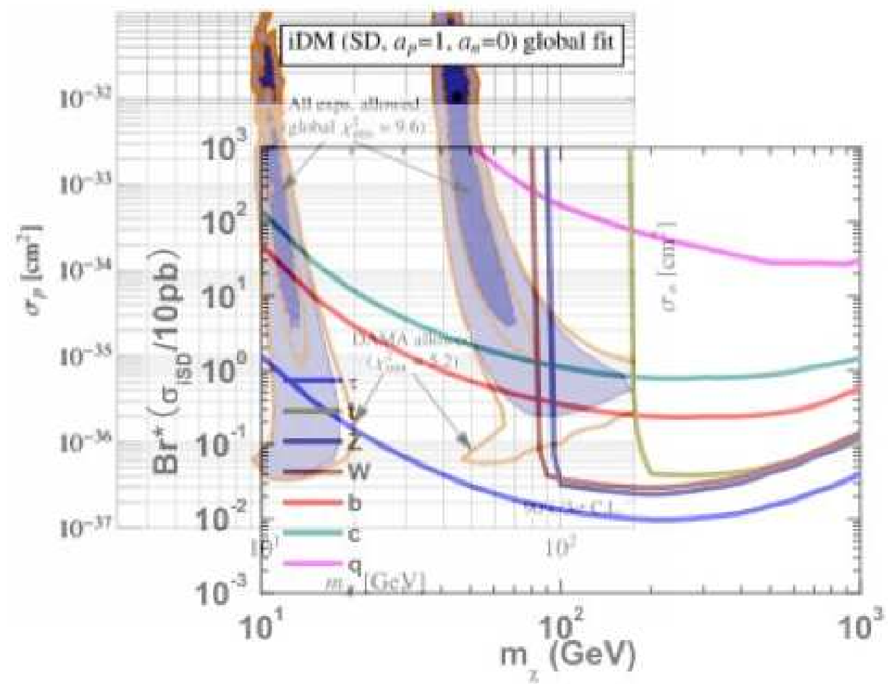

iDM (SI) global fit
All exps. allowed
(global χ^2_{min} = 10.0)
All exps. disfavored
(local χ^2_{min} = 26.1)
DAMA allowed
(χ^2_{min} = 5.2)
90%/3σ C.L.
δ [keV]
m_χ [GeV]
σ_p [cm^2]
δ [keV]



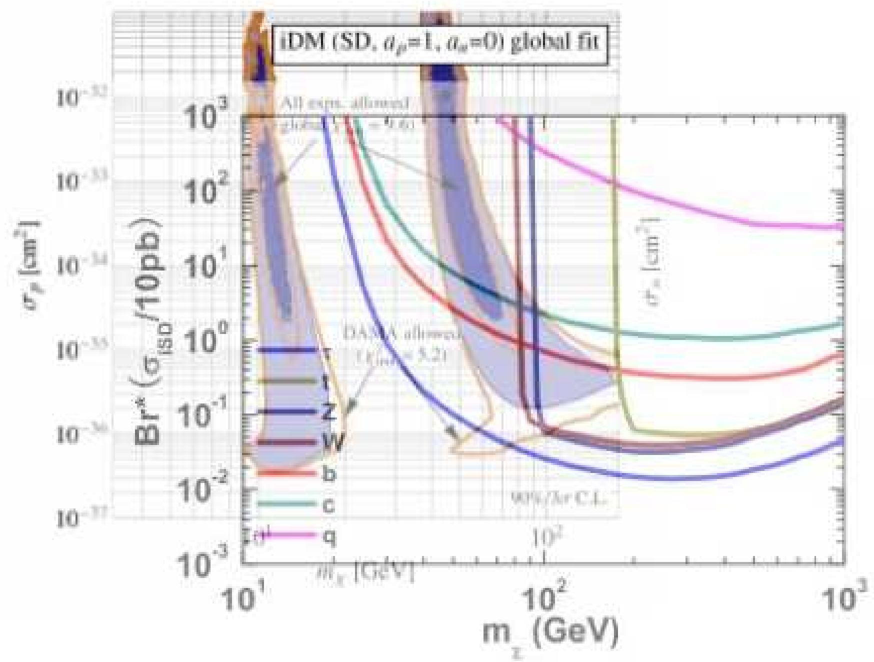
iDM (SD, a_p=1, a_n=0) global fit
All exps. allowed
(global χ^2_{min} = 9.6)
DAMA allowed
(χ^2_{min} = 5.2)
90%/3σ C.L.
δ [keV]
σ_p [cm^2]
m_χ [GeV]
δ [keV]

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