GoranFest, Split, Croatia

Dark Matter and news from direct detection data

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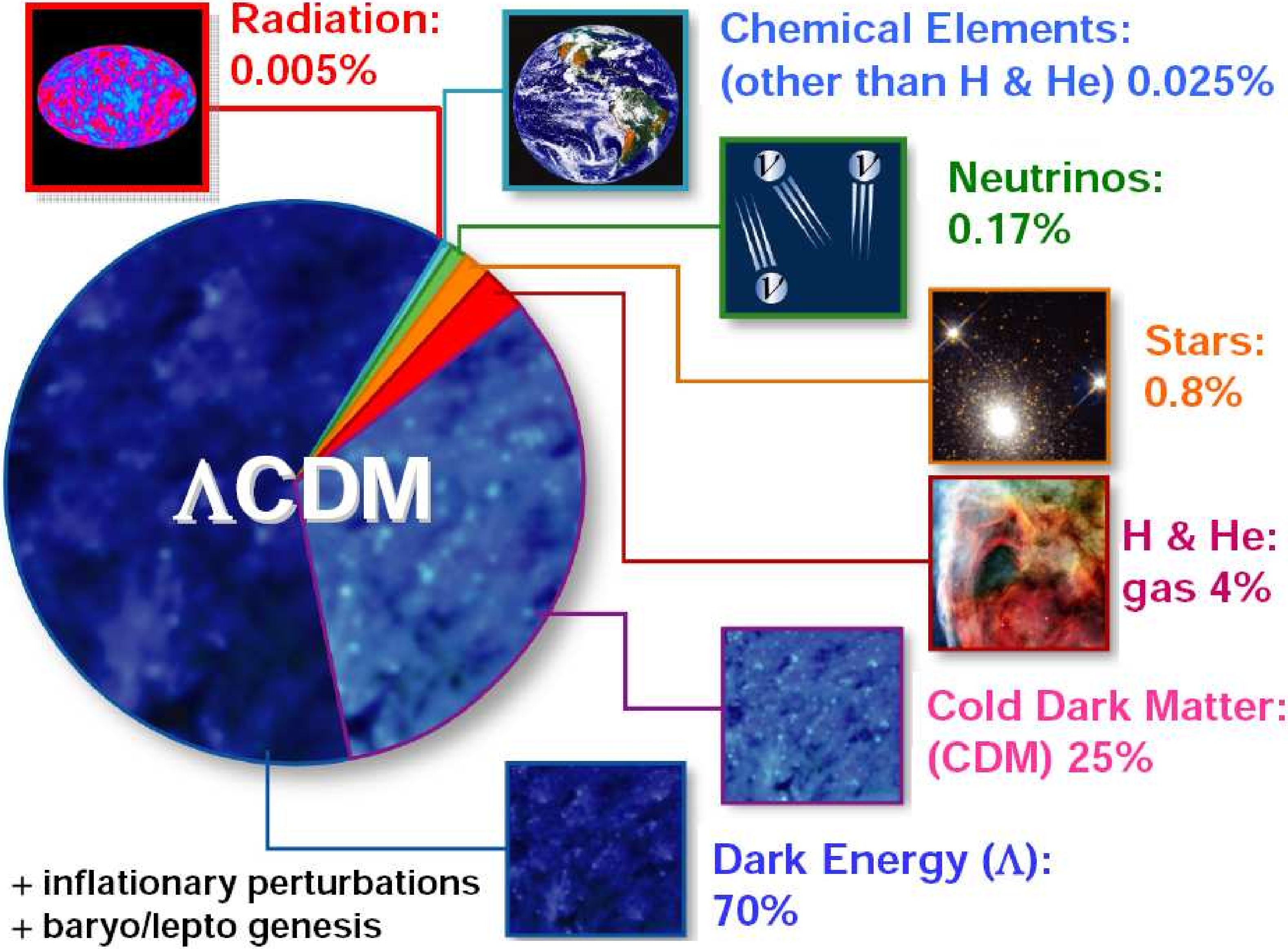
We have no clue what the Universe is made of. . .



+ inflationary perturbations
+ baryo/lepto genesis

Let's assume Dark Matter is a particle

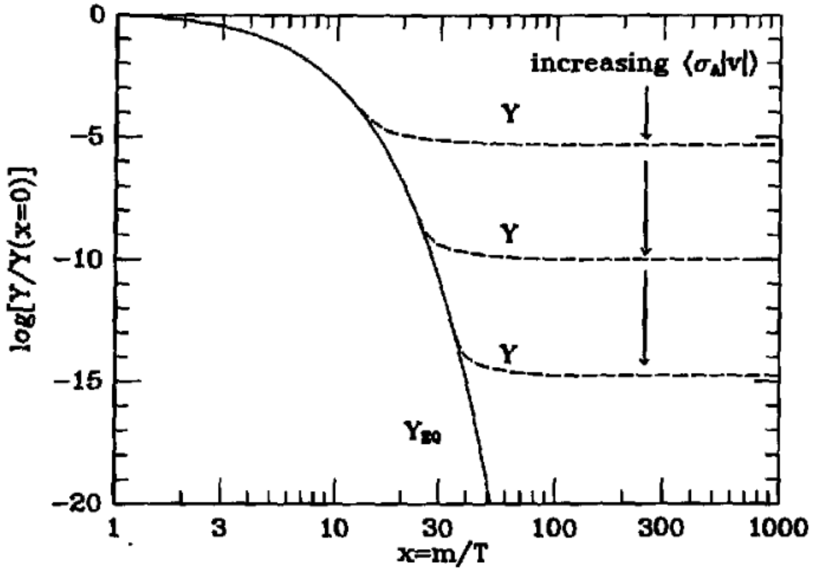
We need a particle which has

- the correct abundance to give $\Omega_{\text{CDM}} \approx 0.23$
  - production mechanism in the early Universe
  - has to be stable on the scale of the age of the Universe
- to be (electrically) neutral
- to fulfill constraints on
  interactions with matter (direct detection), self-interactions, searches for annihilation/decay products (gamma rays)
- to be consistent with structure formation
  $\longrightarrow$ "cold DM"
- no candiate within SM $\Rightarrow$ physics BSM!

The "WIMP miracle"

thermal freeze-out:

$$\Omega_X h^2 \simeq \frac{10^{-37}\mathrm{cm}^2}{\langle \sigma_{\mathrm{annih}} v \rangle}$$



WMAP:

$$\Omega_{\mathrm{CDM}} h^2 \simeq 0.11$$

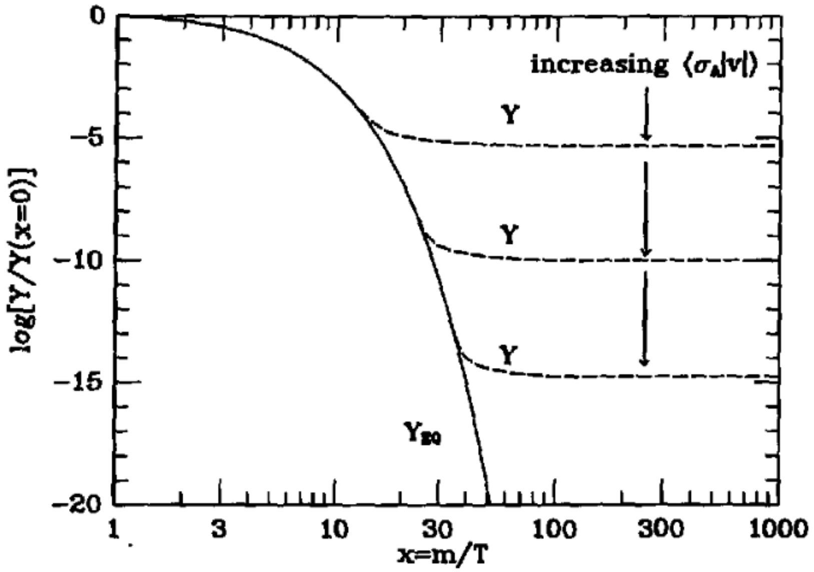
s-wave annihilations of a particle with mass m_X due to new physics at a scale Λ:

$$\langle \sigma_{\mathrm{annih}} v \rangle \sim \frac{g^4}{2\pi} \frac{m_X^2}{\Lambda^4} \simeq 6 \times 10^{-37}\mathrm{cm}^2\, g^4 \left(\frac{m_X}{100\,\mathrm{GeV}} \right)^2 \left(\frac{\Lambda}{1\,\mathrm{TeV}} \right)^{-4}$$

The “WIMP miracle”

thermal freeze-out:

$$\Omega_X h^2 \simeq \frac{10^{-37}\mathrm{cm}^2}{\langle \sigma_{\mathrm{annih}} v \rangle}$$

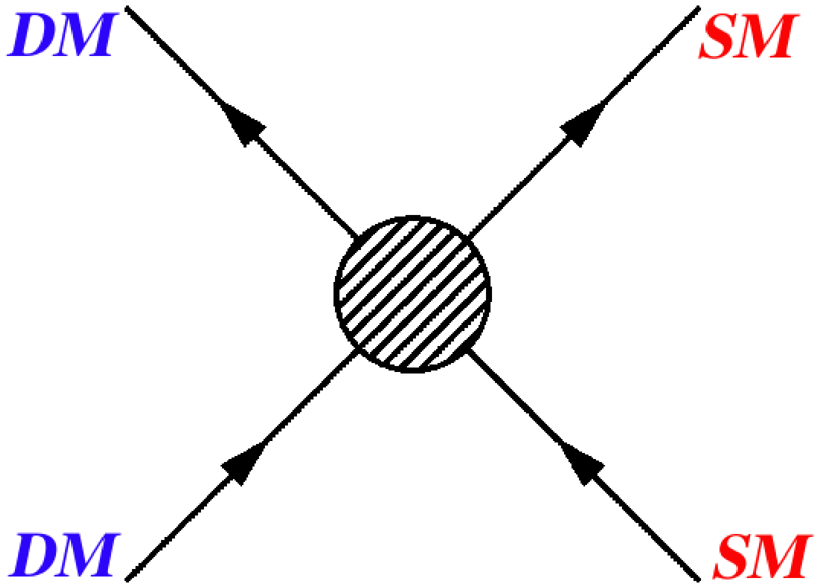


WMAP:

$$\Omega_{\mathrm{CDM}} h^2 \simeq 0.11$$

The new physics expected at the TeV scale may provide a DM candidate, and “typical” TeV scale cross sections will lead to a thermal abundance roughly of the correct size.

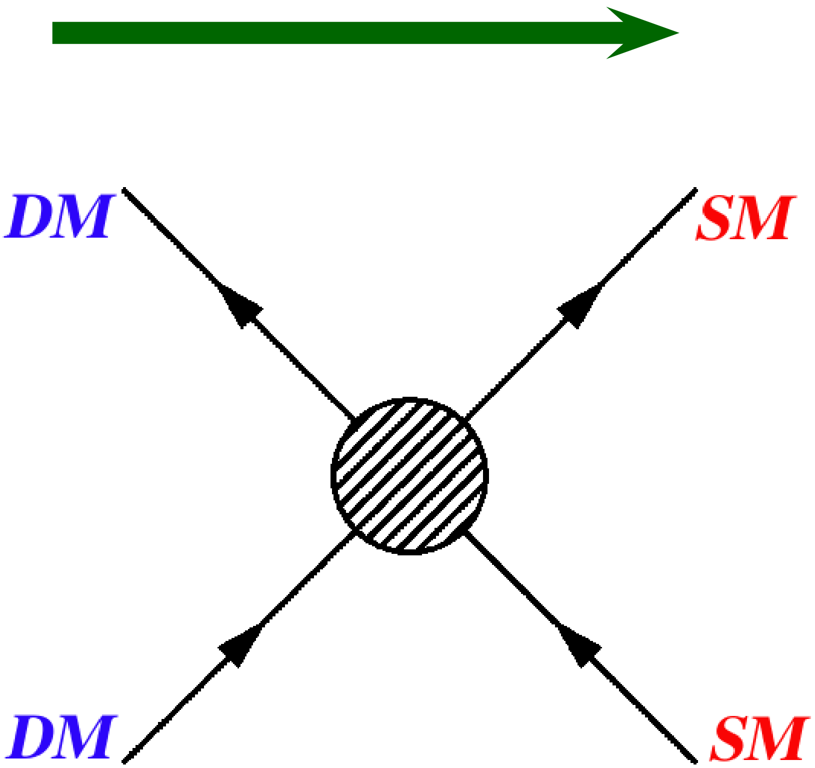
Testing WIMP models



Testing WIMP models

thermal freeze-out (early Univ.)

indirect detection (now)



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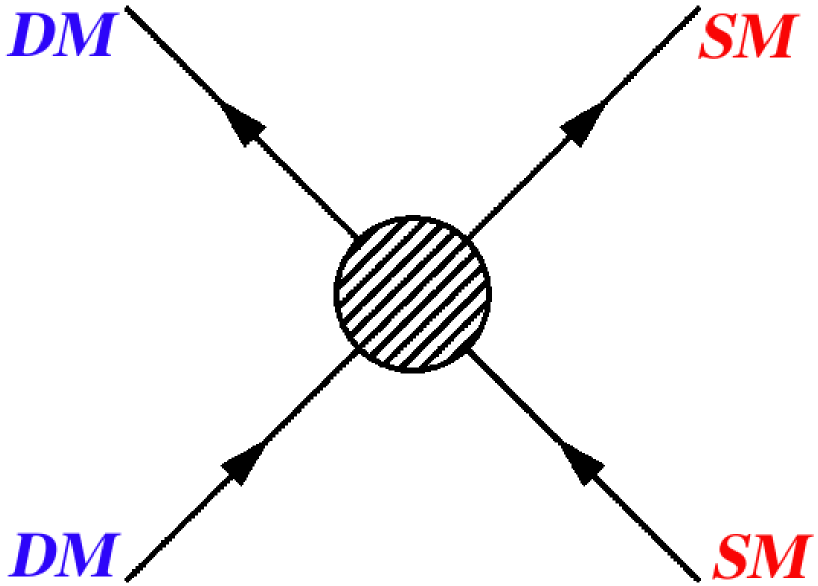

Testing WIMP models

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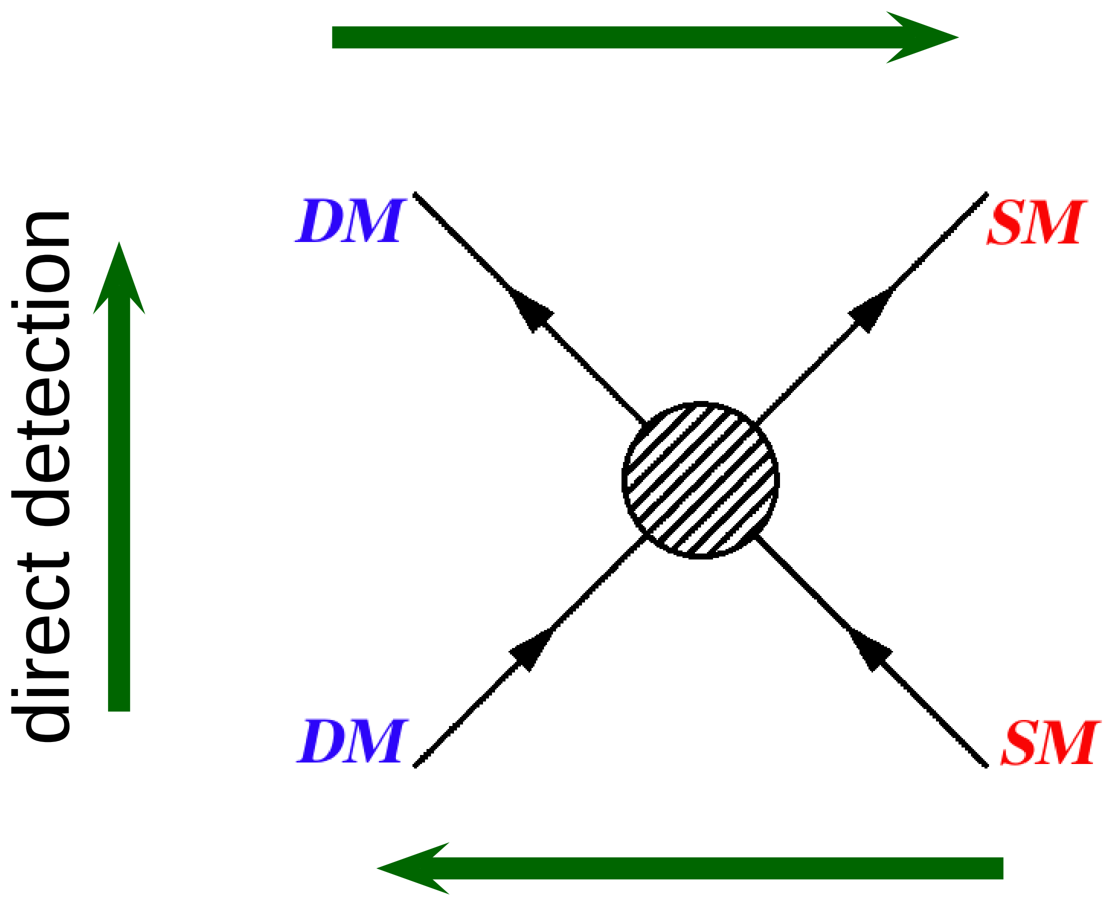
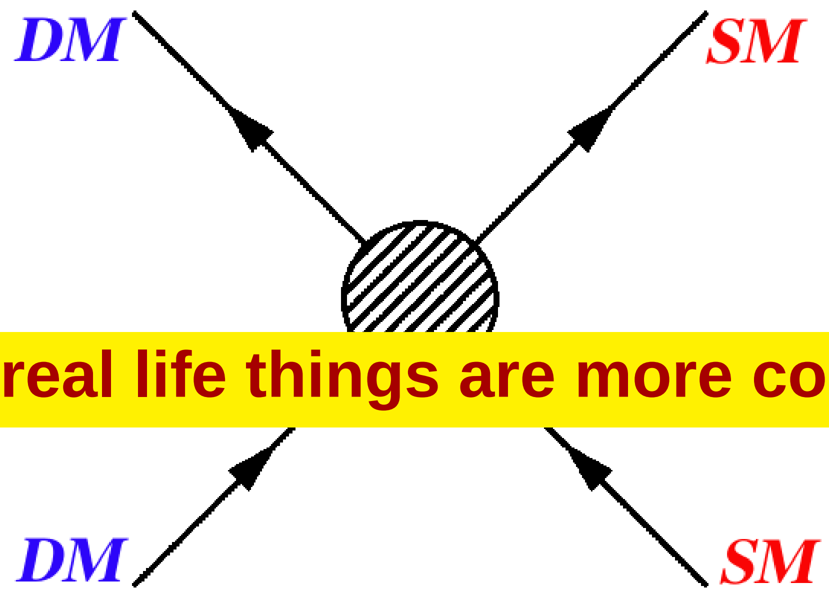


production at colliders

Testing WIMP models

thermal freeze-out (early Univ.)
indirect detection (now)



dire detection

Warning: in real life things are more complicated!

production at colliders

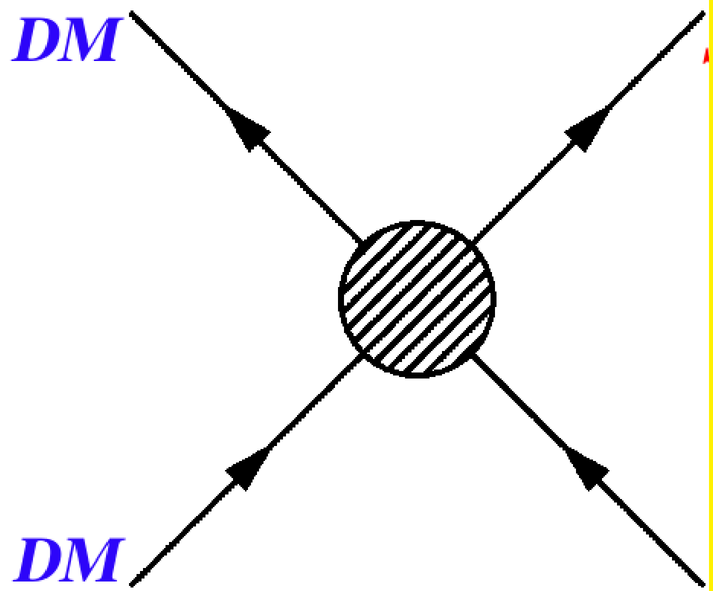
Testing WIMP models

PAMELA, FERMI, (AMS-II), IceCube

indirect detection (now)

XENON100, LUX, SuperCDMS, WARP,
DEAP/CLEAN, COUPP, EURECA,...

direct detection



In all three methods significant progress is expected soon!

production at colliders **LHC**

Testing WIMP models

PAMELA, FERMI, (AMS-II), IceCube

indirect detection (now)

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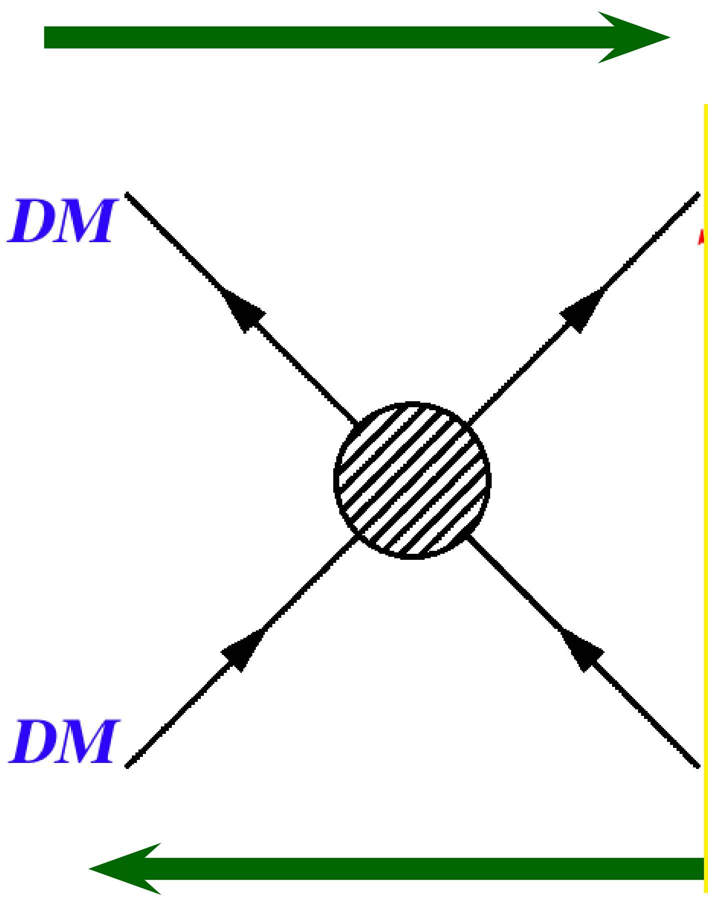


In all three methods significant progress is expected soon!

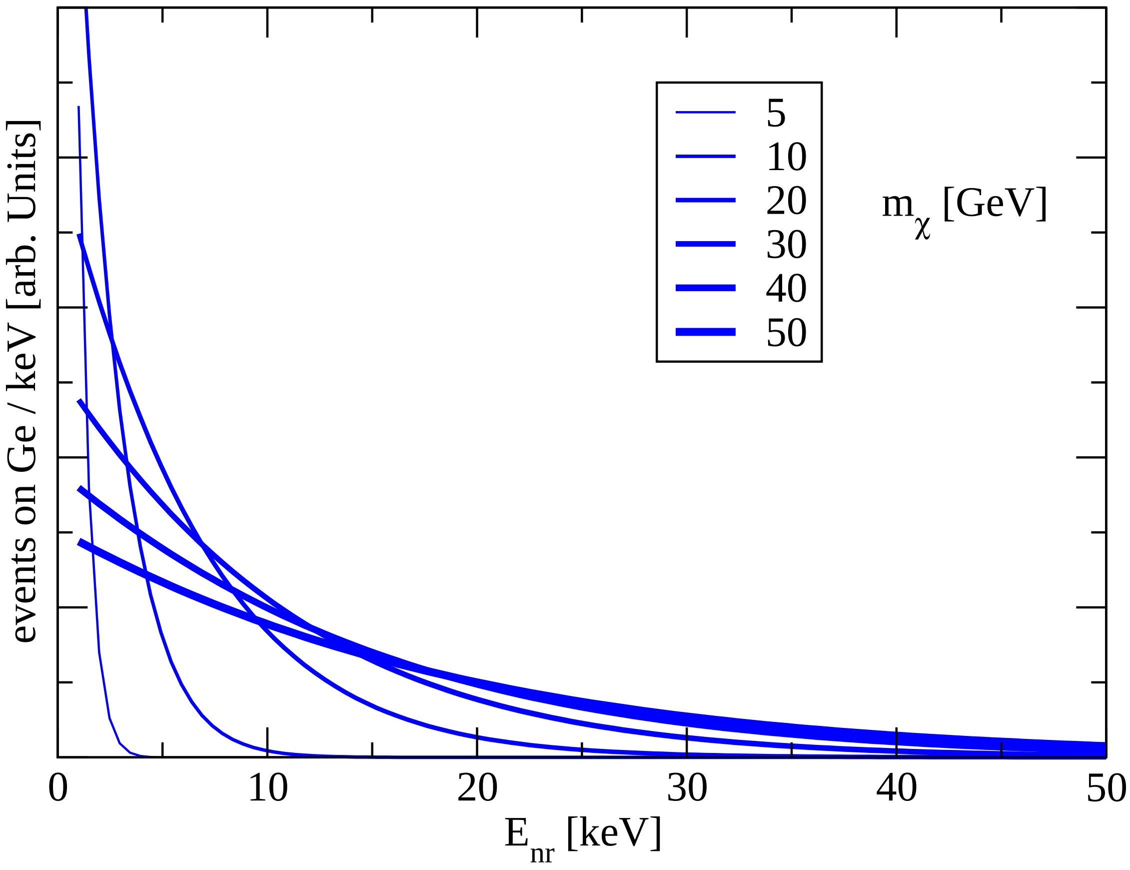
But indications will be weak and indirect ⇒ cross checks of different methods are essential

production at colliders **LHC**

Direct detection and hints for low-mass WIMPs

- Hints for low-mass WIMPs from: (alphabetical order)
  CDMS?, CoGeNT?, CRESST?, DAMA?
- constraints from CDMS-Si, XENON10,100
- "low-mass" WIMPs: $5\,\mathrm{GeV} \lesssim m_\chi \lesssim 50\,\mathrm{GeV}$
  χ should not couple to Z^0 (LEP)

Event spectrum for elastic scattering



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

low-mass WIMP hints

CDMS-II

CoGeNT

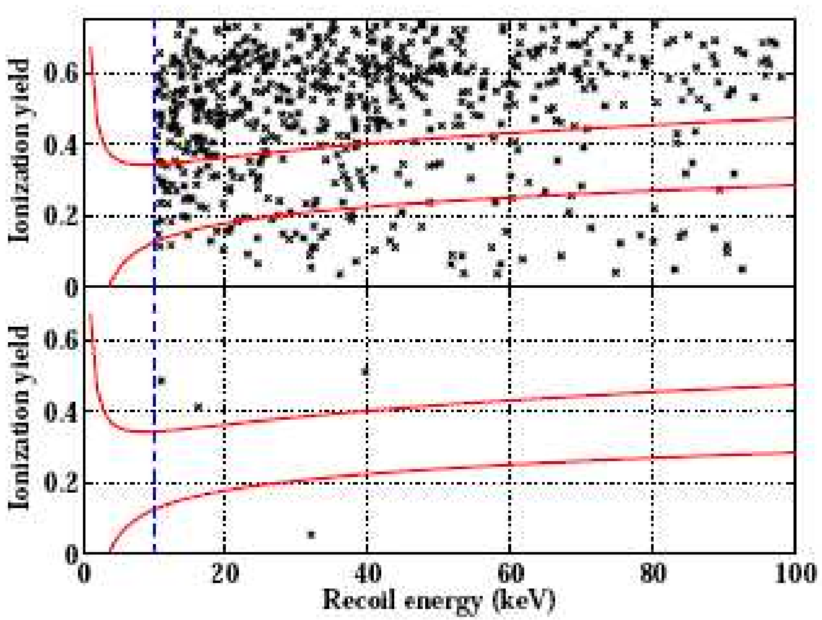
CRESST-II

DAMA

CDMS-II

Germanium detector, recoil energy range 10–100 keV

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

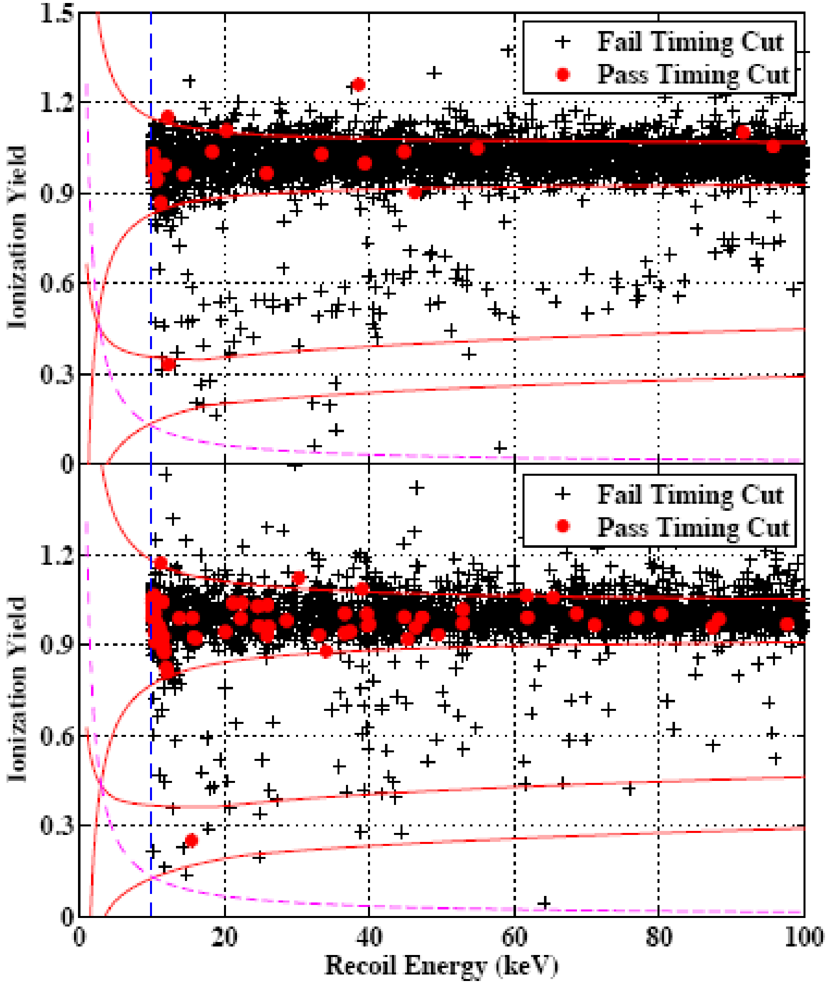


nuclear recoil signal region before (top) and after (bottom) timing cut

CDMS-II

Germanium detector, recoil energy range 10–100 keV

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

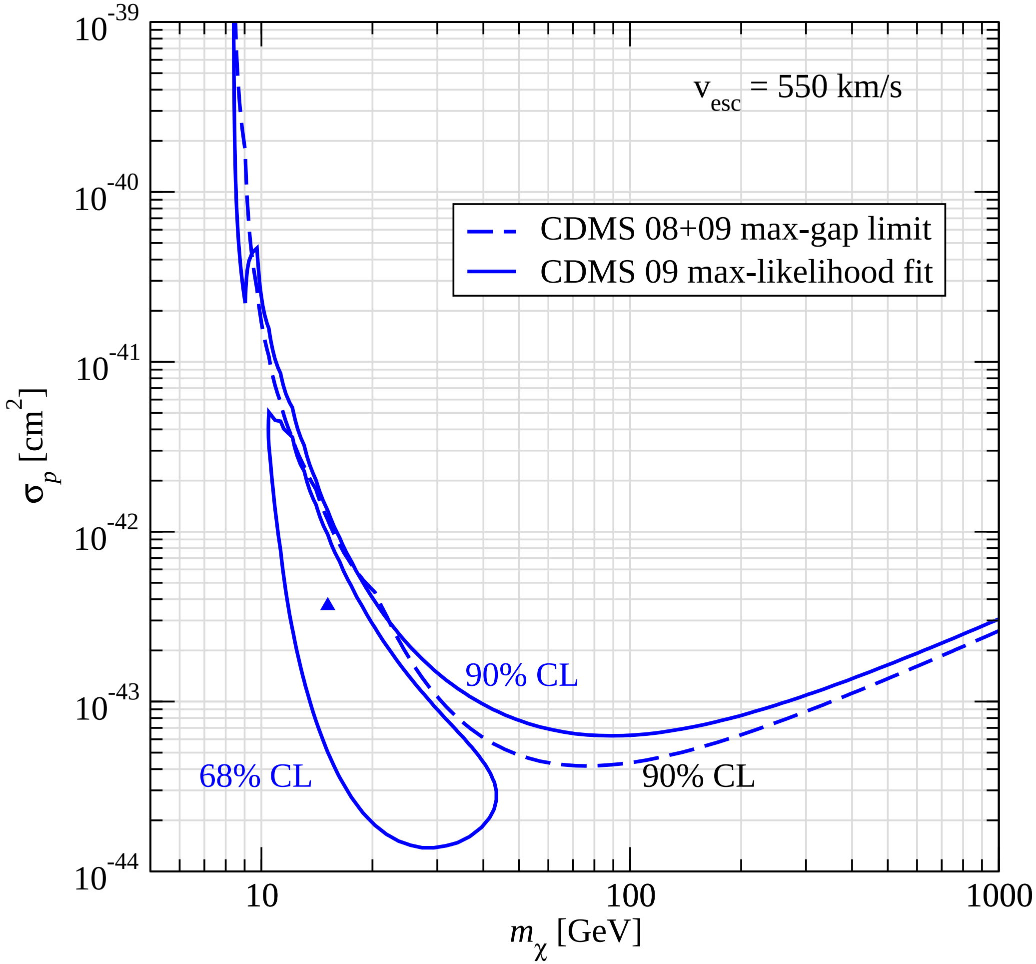


electron and nucl. recoil regions for two different detectors

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

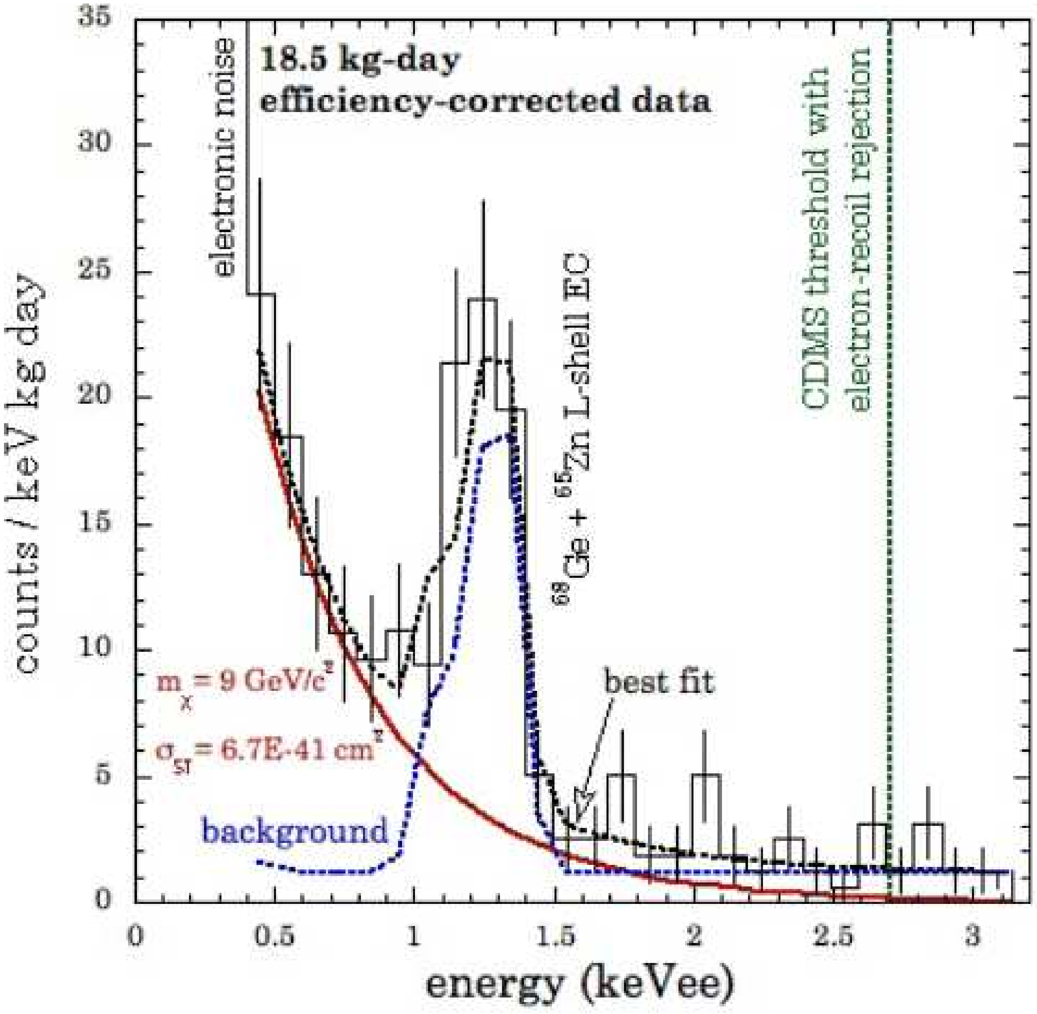
CoGeNT

CRESST-II

DAMA

CoGeNT

Germanium detector with extremely low threshold of 0.4 keVee

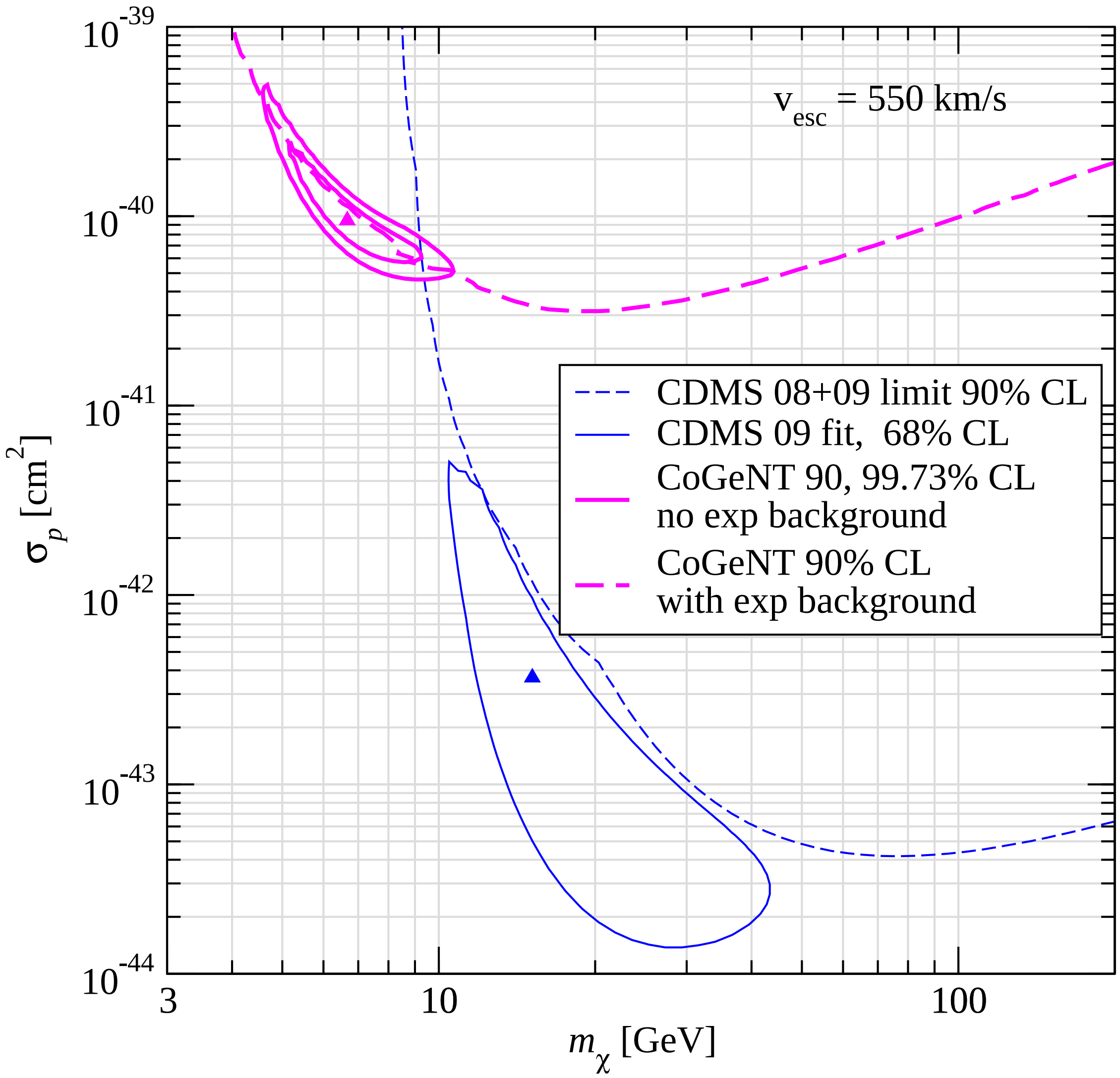


exponential rise of events at low energies

claim that it cannot be electronic noise

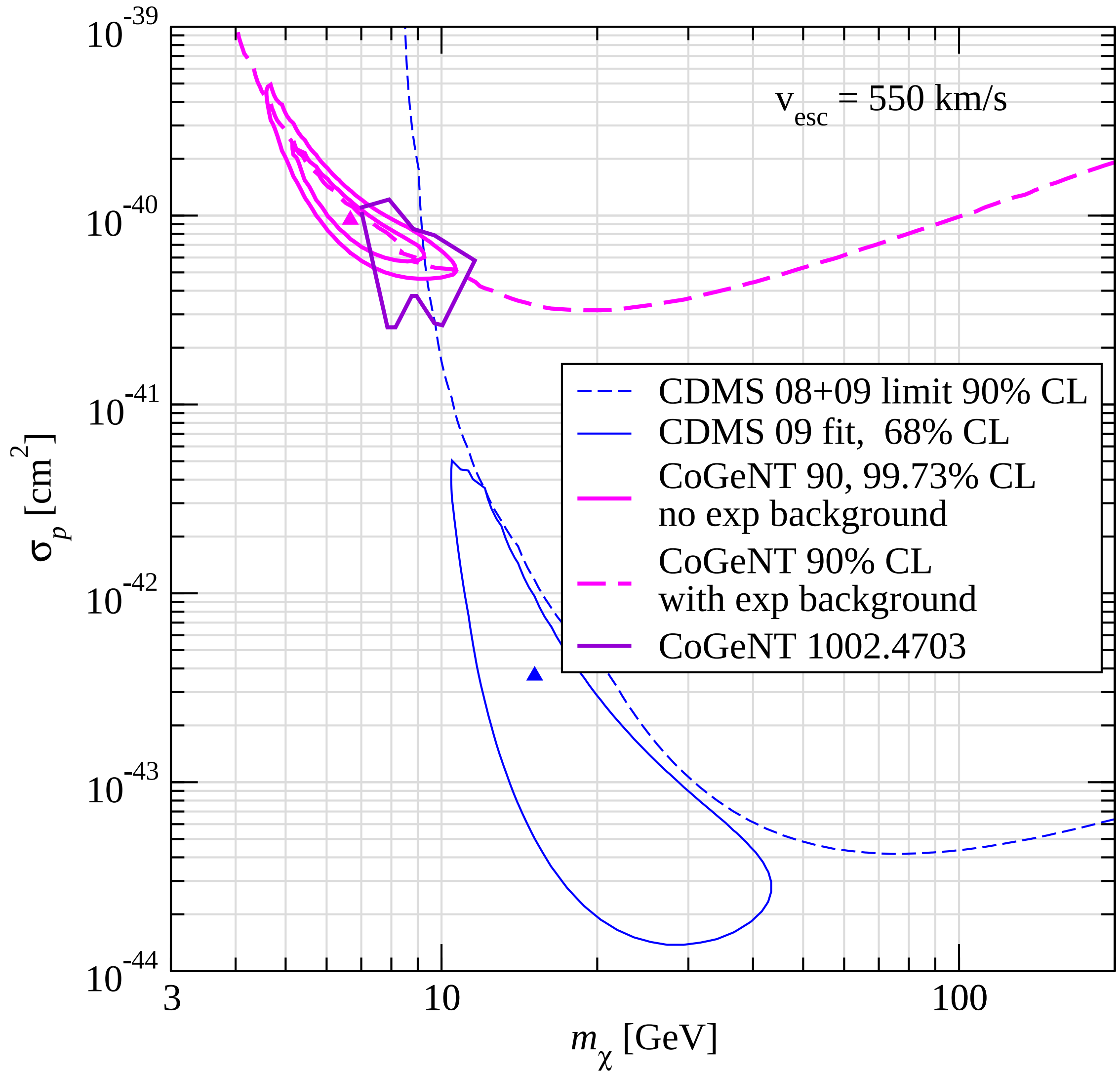
Aalseth et al., 1002.4703

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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CoGeNT 1002.4703
σ_p [cm^2]
m_χ [GeV]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
3
10
100

low-mass WIMP hints

CDMS-II

CoGeNT

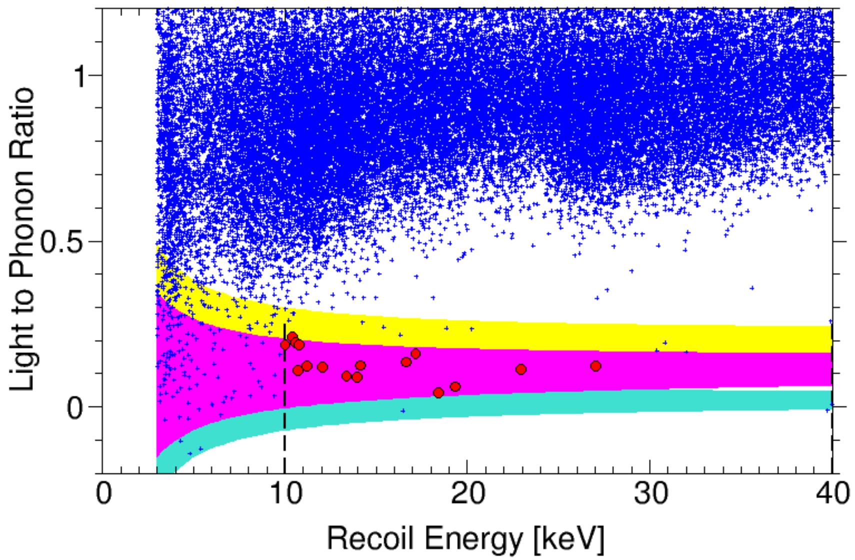
CRESST-II

DAMA

CRESST data

Preliminary results from present run (since summer 2009)

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



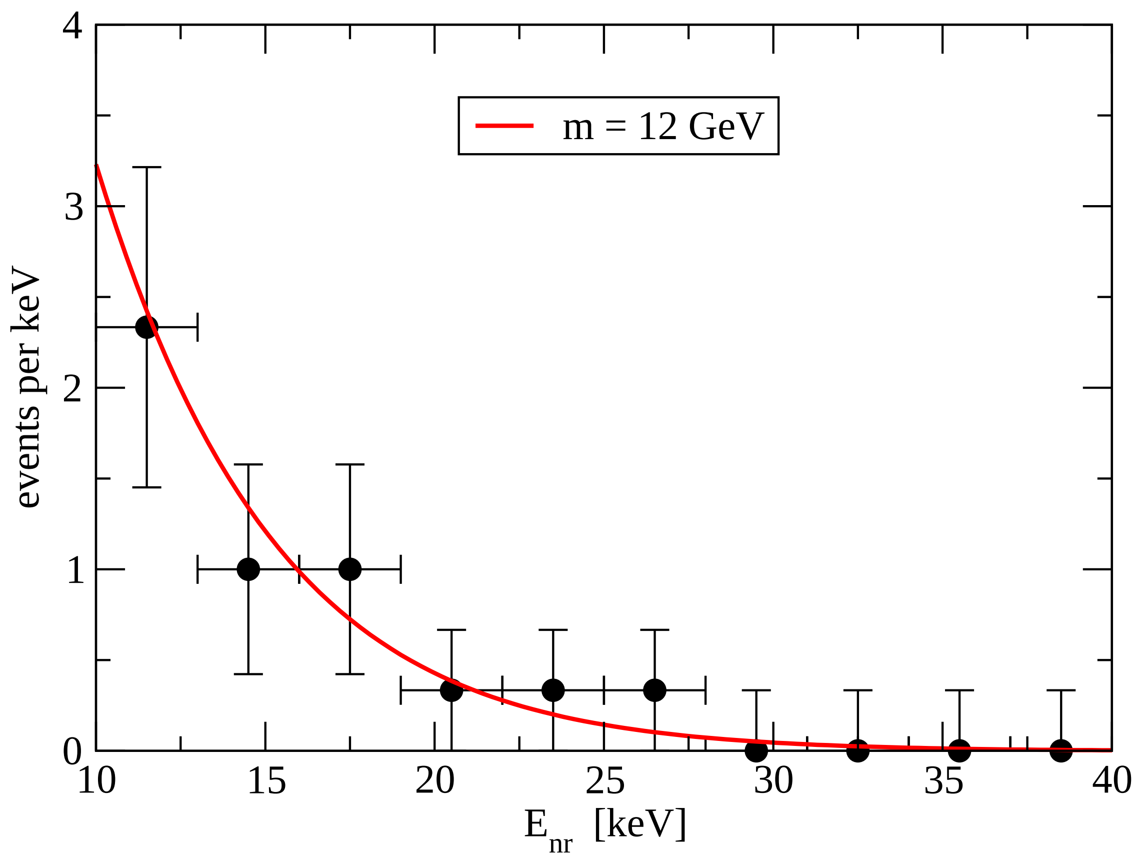
- α-band (yellow)
- 1 event in W-band (cyan)
- 16 single-scatter events in O-band (magenta)

$\Rightarrow$ WIMPs ??

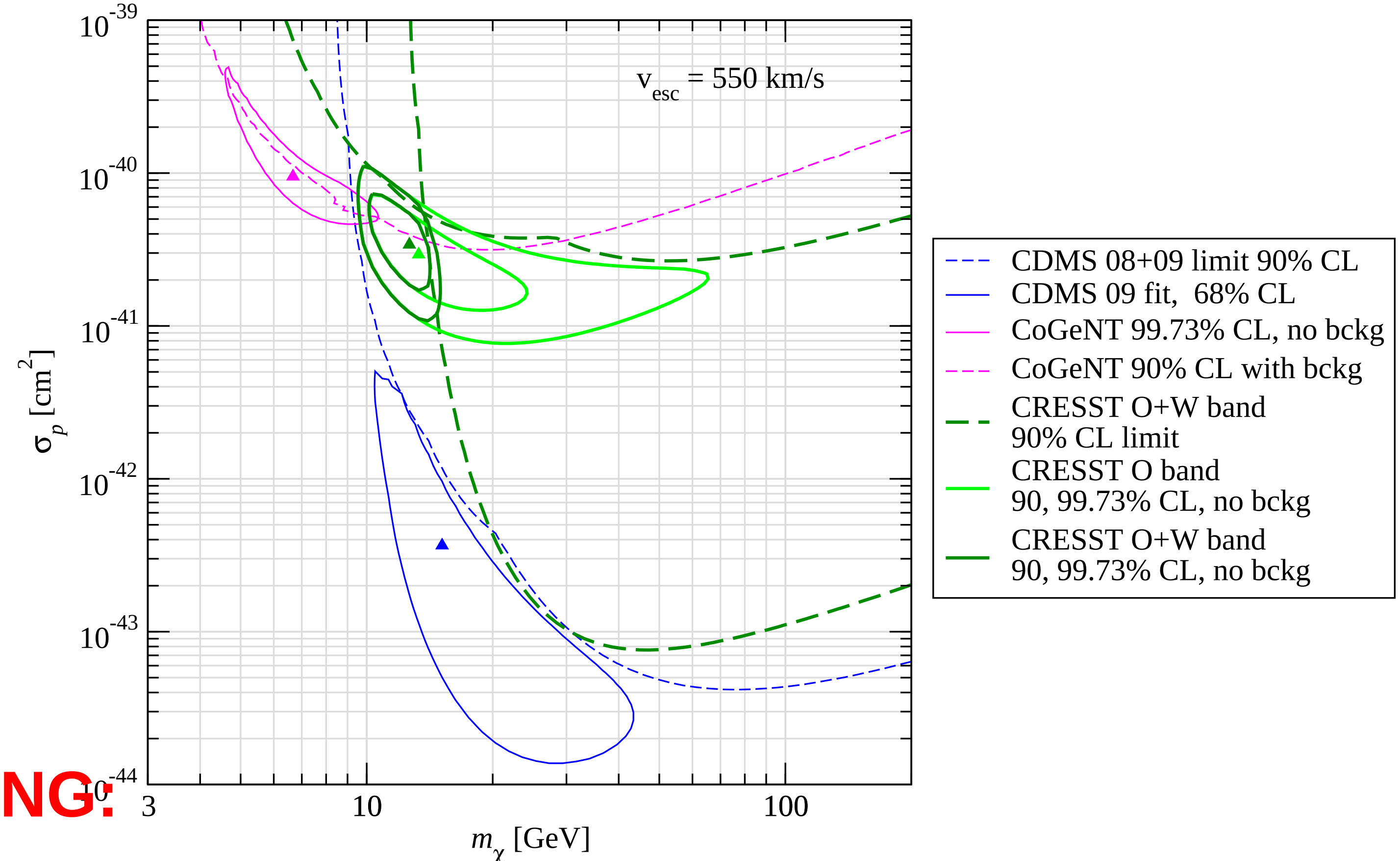
analysis is ongoing, some of the events (all?) are from neutrons
neutron calibration measurments are being carried out
(measure the fraction of single scatter events from neutrons)

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

⇒ regions may shift ⇒ wait for final results from CRESST

low-mass WIMP hints

CDMS-II

CoGeNT

CRESST-II

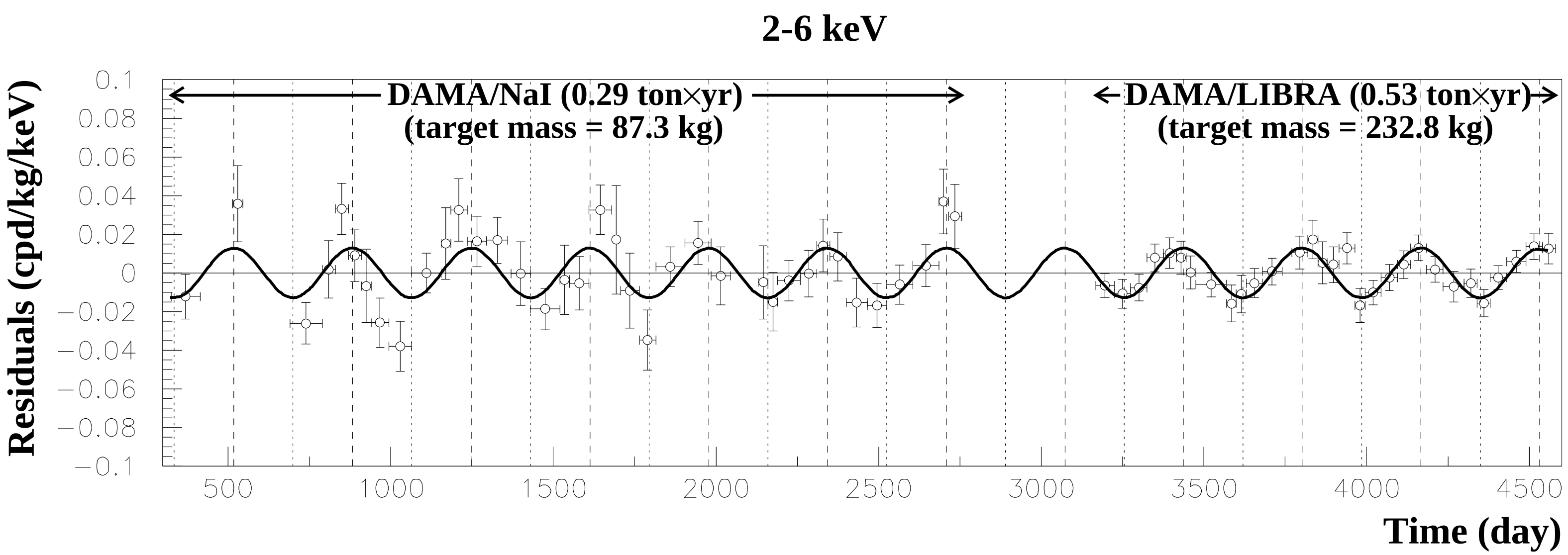
DAMA

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



Bernabei et al., 0804.2741

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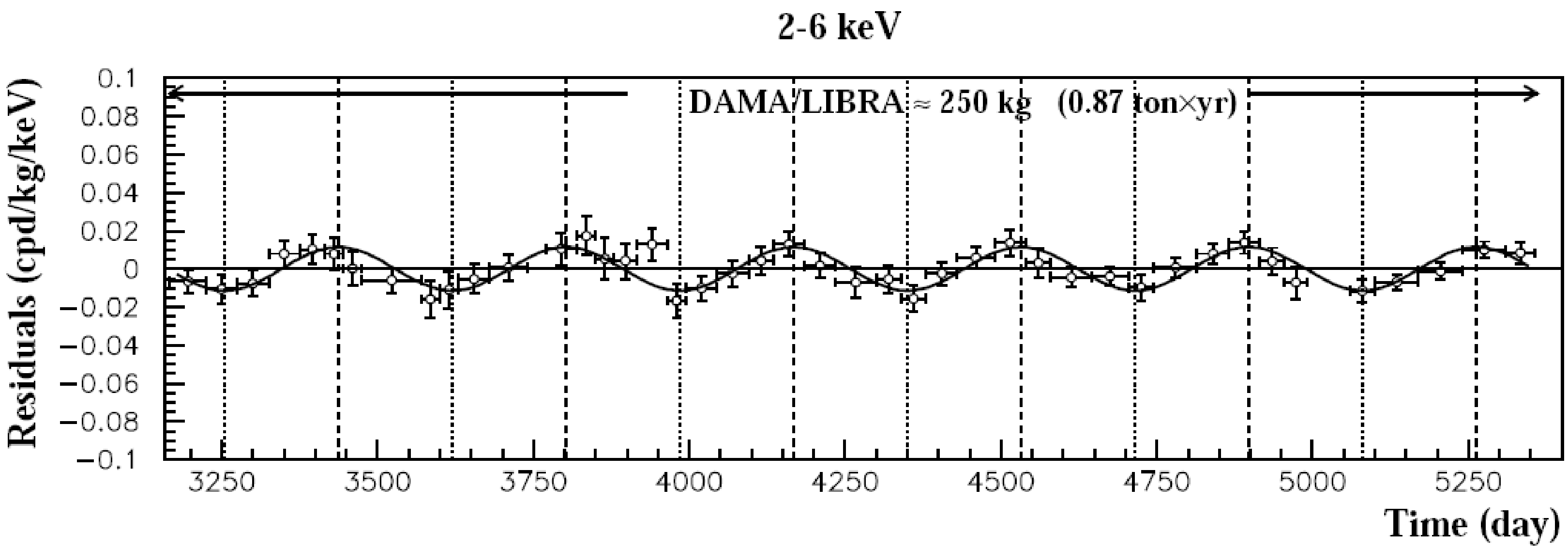

Bernabei et al., 1002.1028

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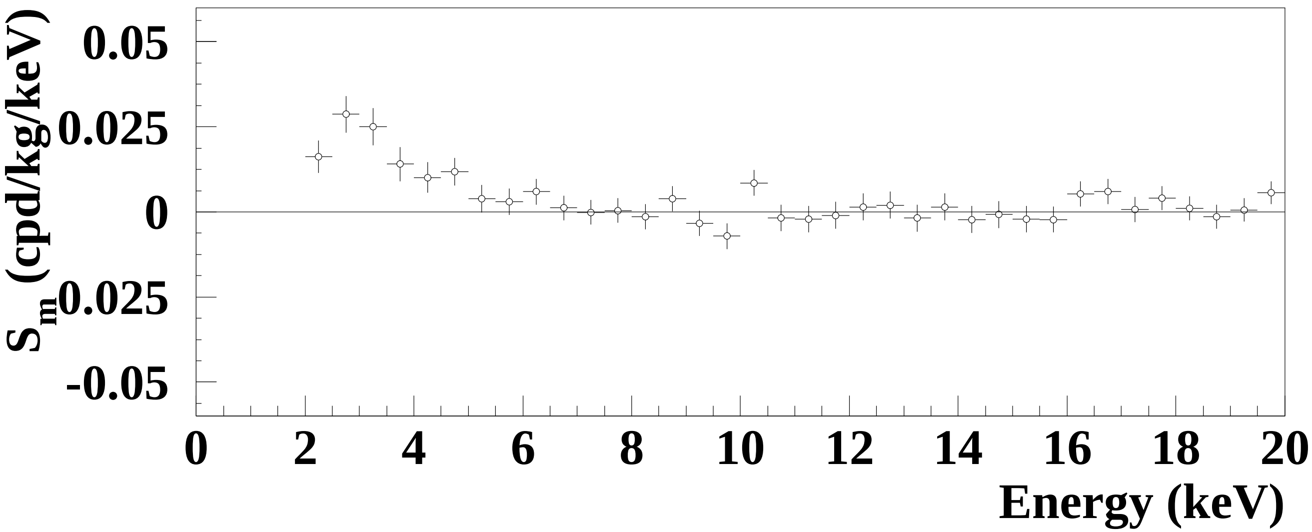


energy shape of modulation is important for constraining params

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:

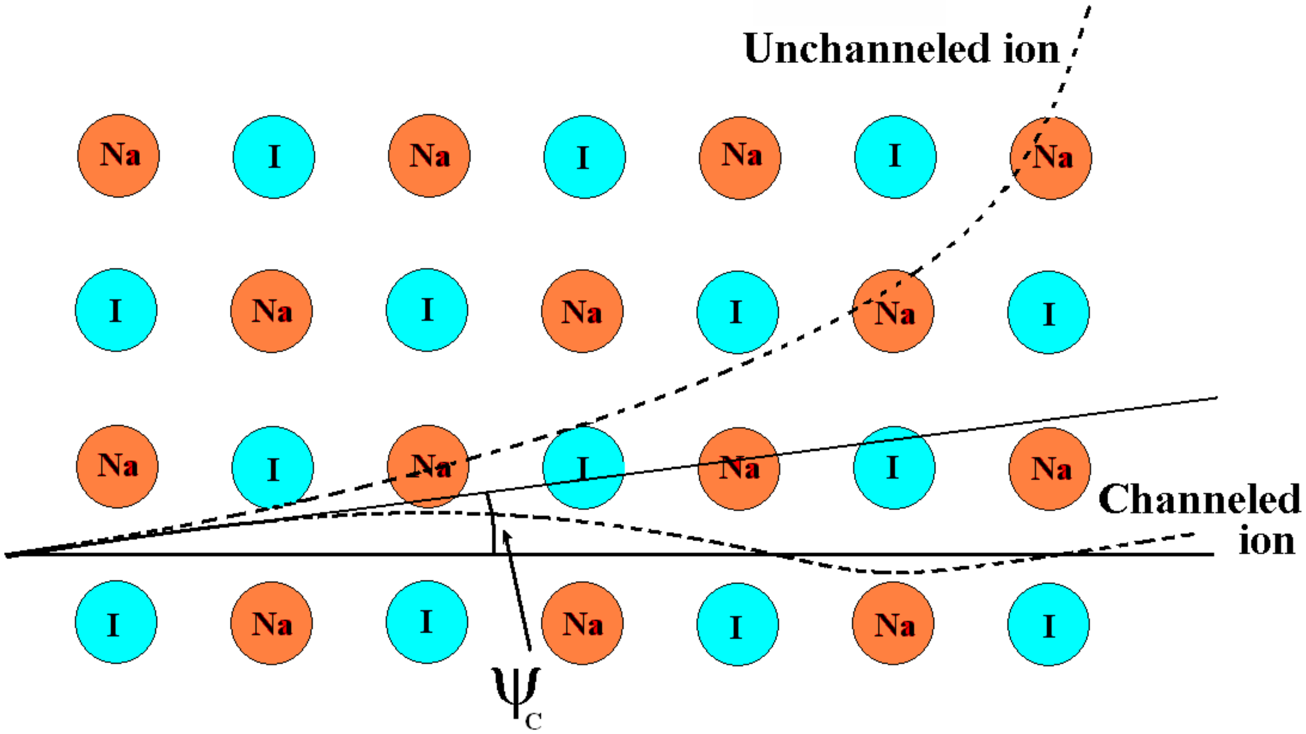
$$E_{\rm obs} = q \times E_R$$

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

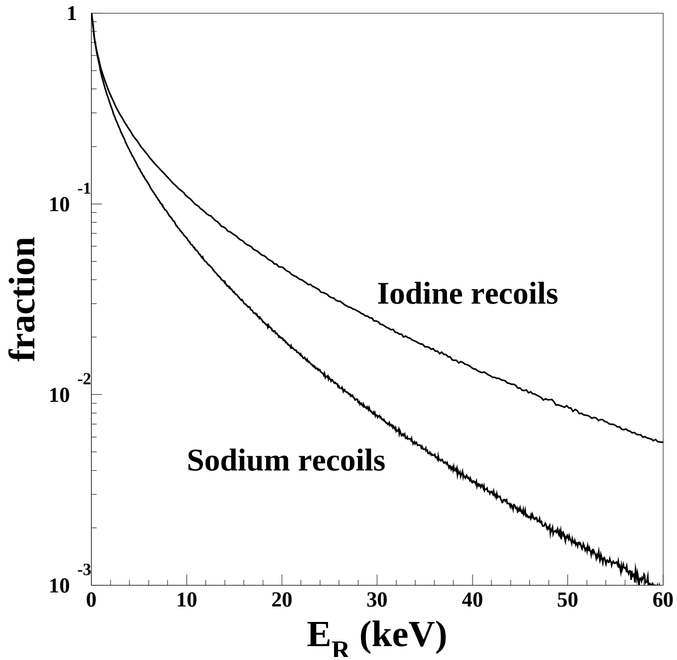
Drobyshevski, 0706.3095; Bernabei et al., 0710.0288



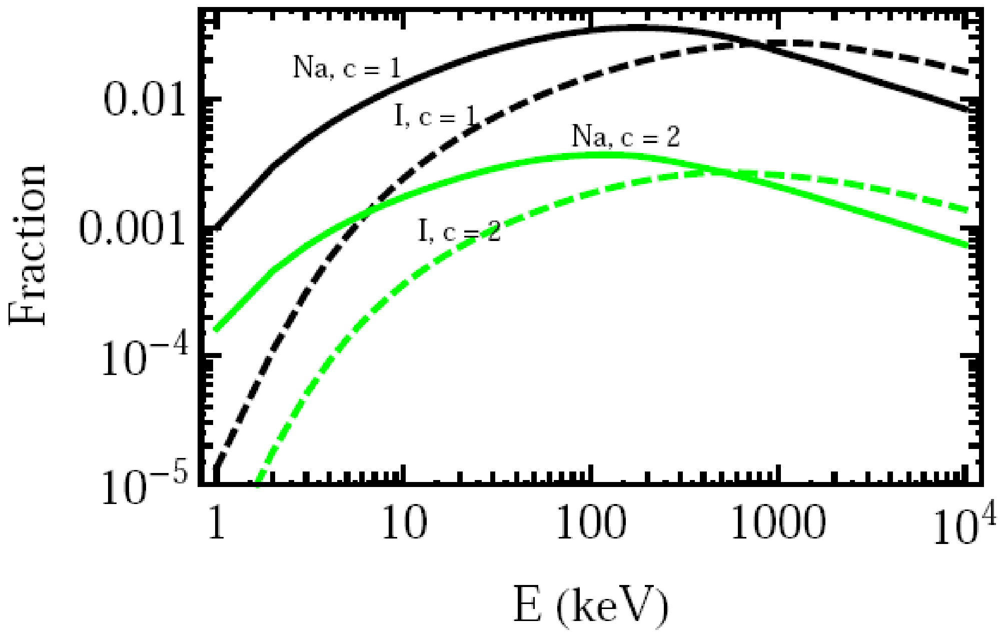
with a certain probability a recoiling nucleus will not interact with the crystal but loose its energy only electro-magnetically

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

How large is the fraction of channeled events?



Bernabei et al., 0710.0288



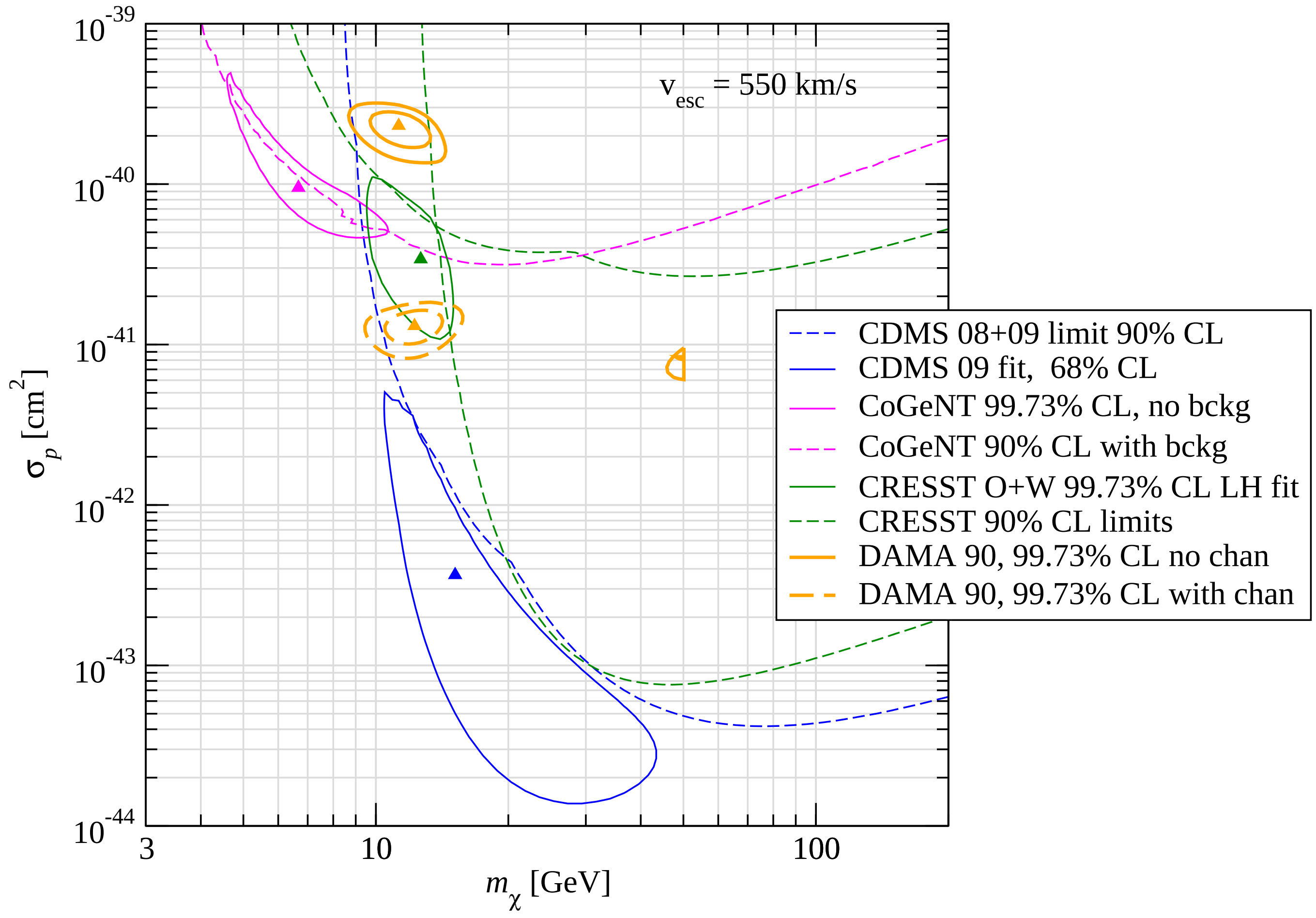
Savage et al., 1006.0972

Bozorgnia, Gelmini, Gondolo, in prep.

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

results of Bozorgnia, Gelmini, Gondolo suggest that channeling is not important

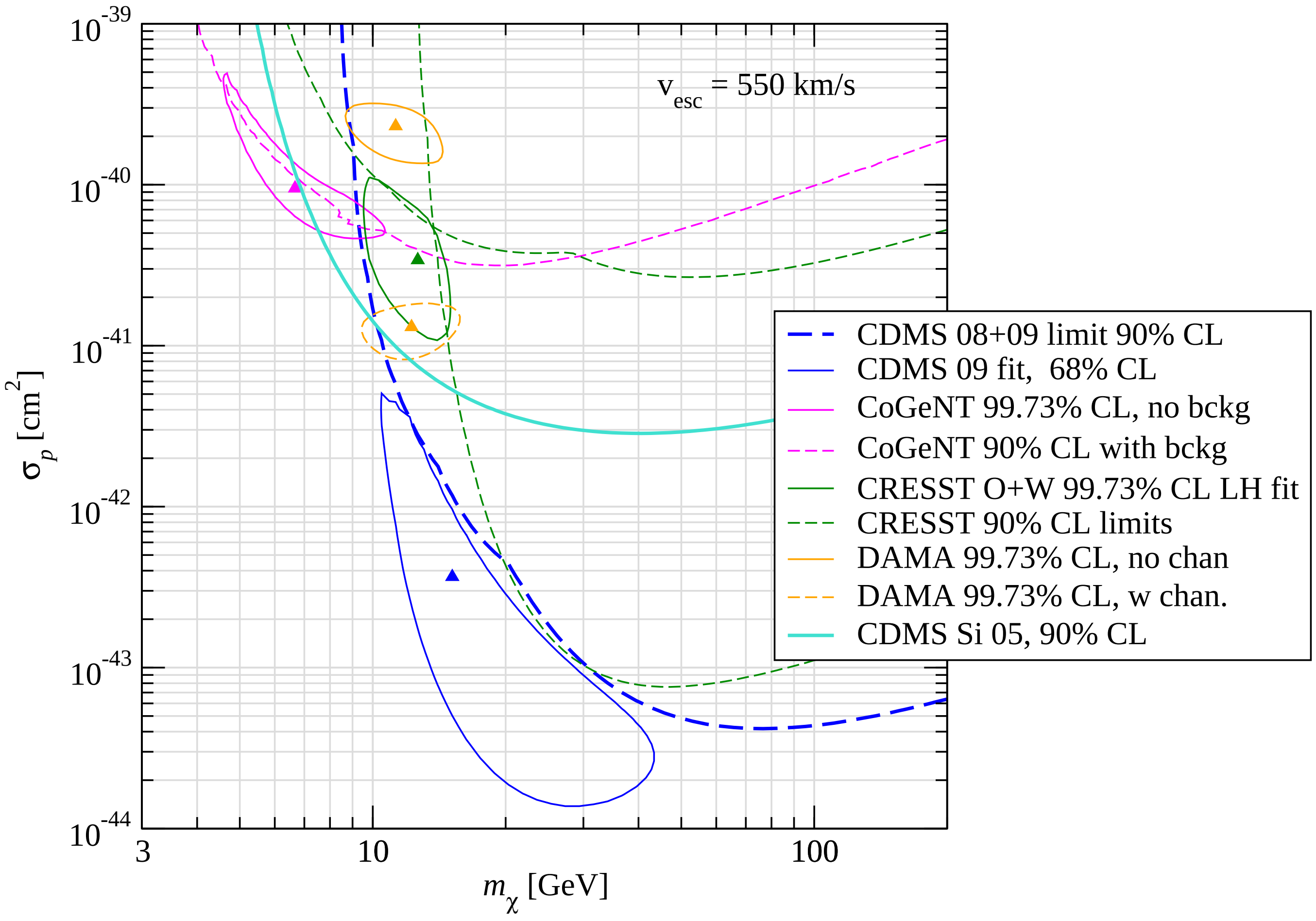
Fitting DAMA



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

Constraints from CDMS and XENON

CDMS constraints



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

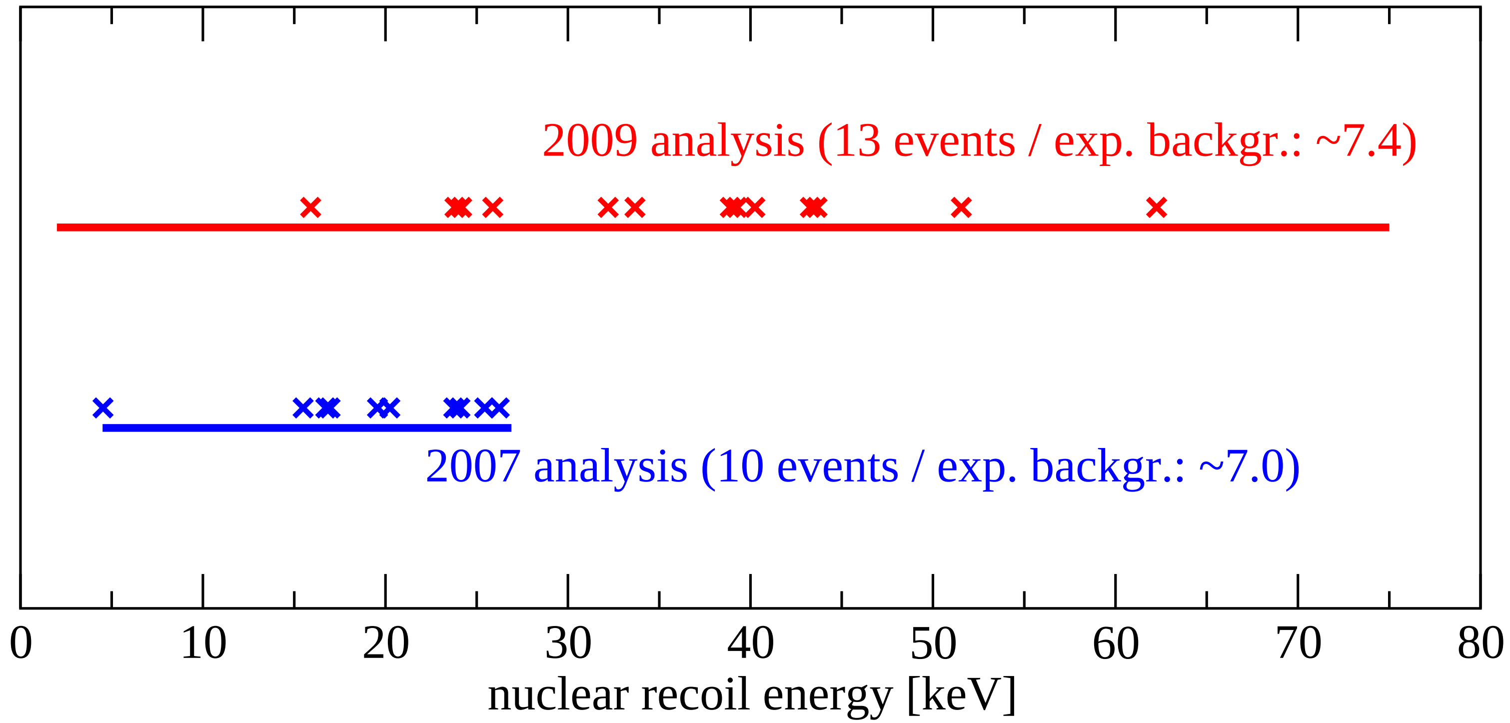
more data on tape

XENON-10

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

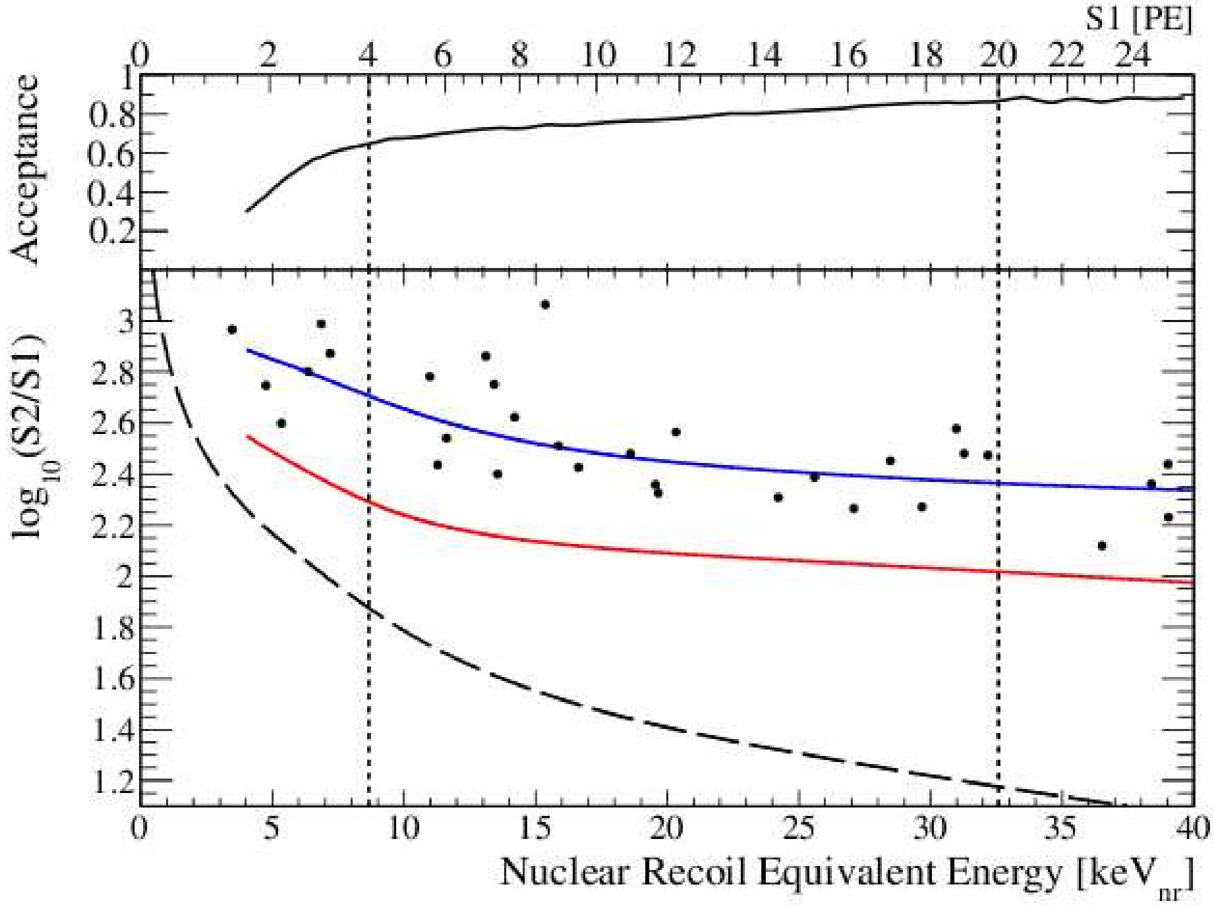
0706.0039: original blind analysis: 10 events

0910.3698: revised cuts: 13 events, extended energy window



XENON-100

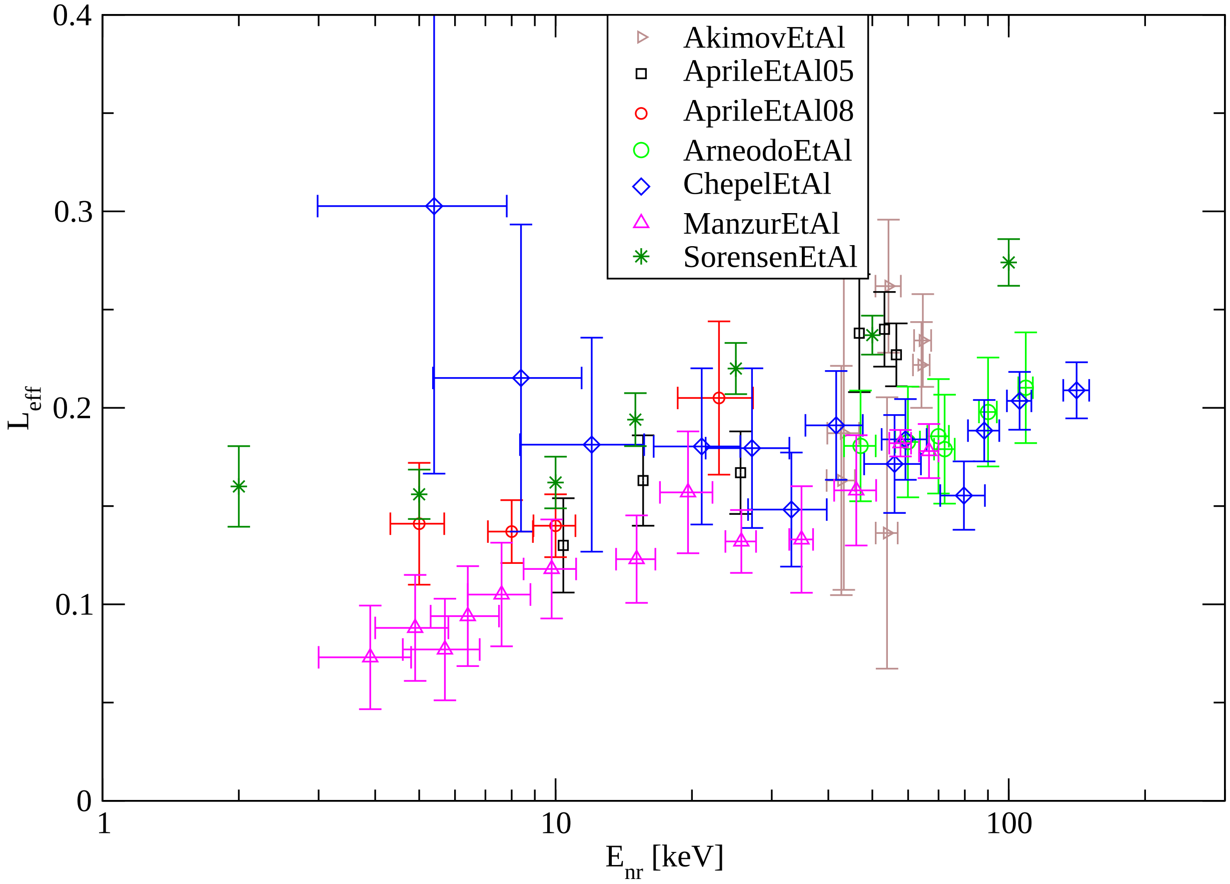
11.7 days, 40 kg fid., $\sim$ 230 kg day effective exp.



1005.0380

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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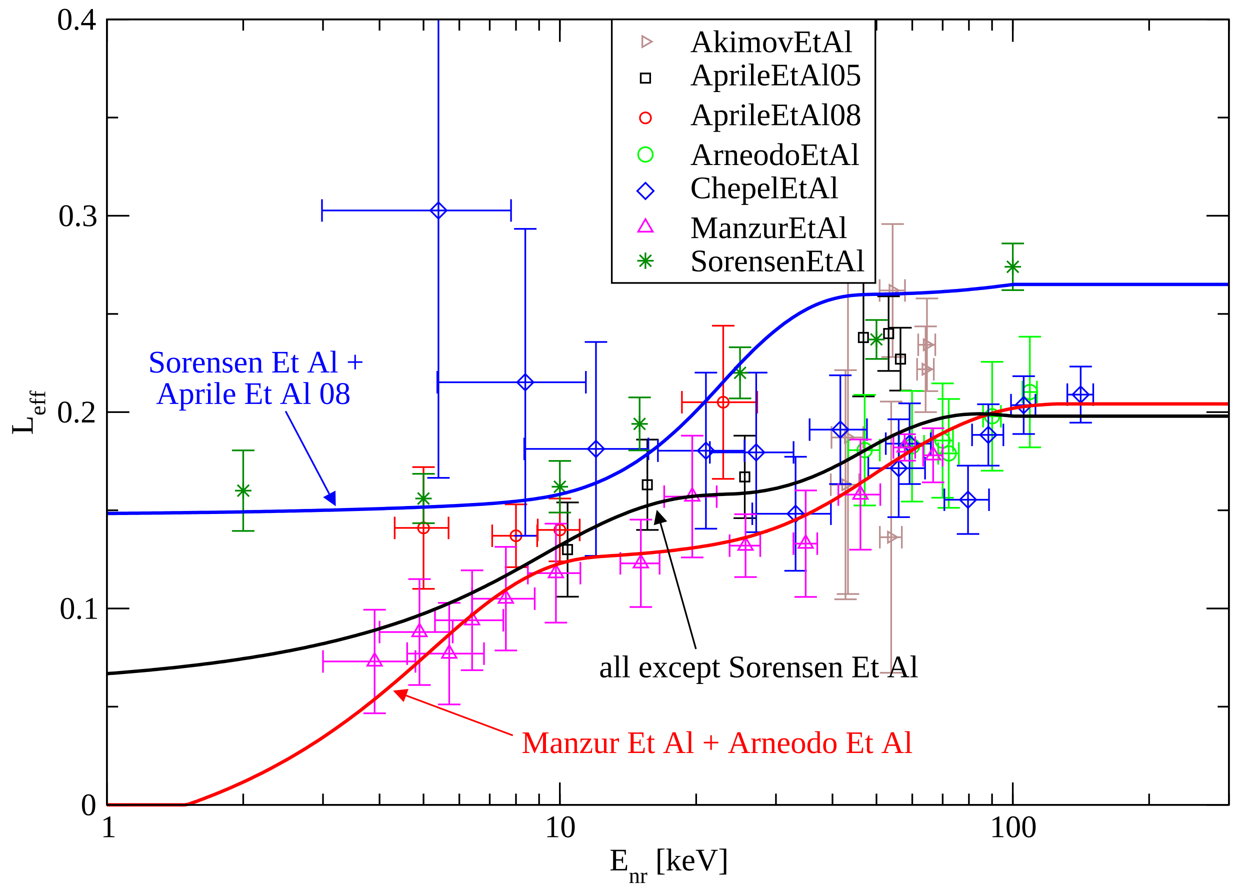
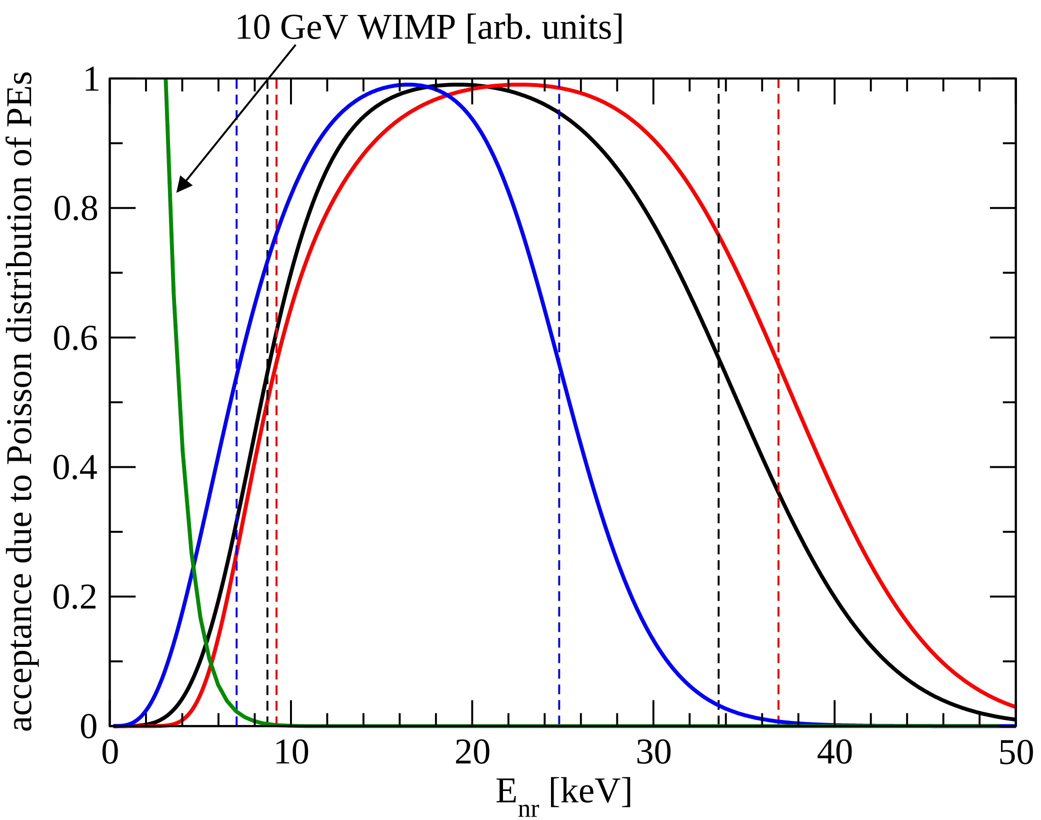


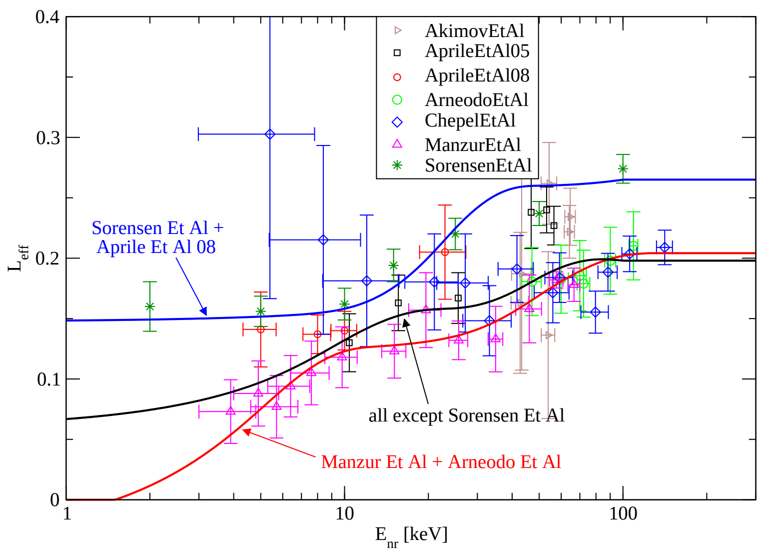
3 exemplary fits, extrapolating with straight lines at low energies

Acceptance window in XENON100

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

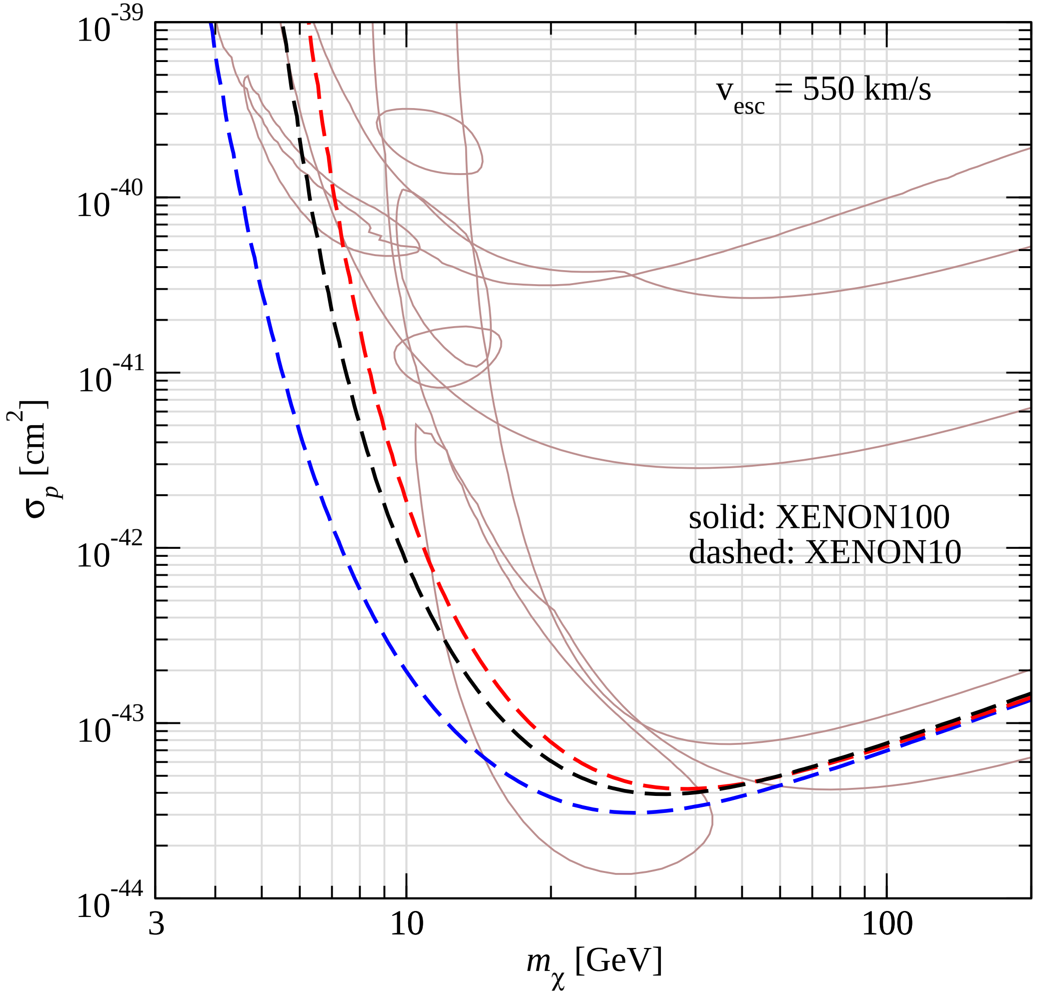
- this translates into window in E_{nr} according to L_{eff}
- Poisson statistics of PEs implies smearing of the thresholds

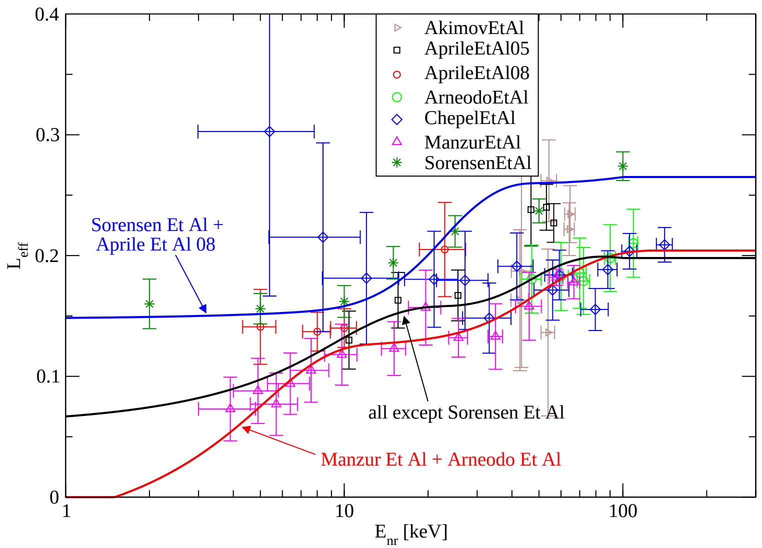




same color coding

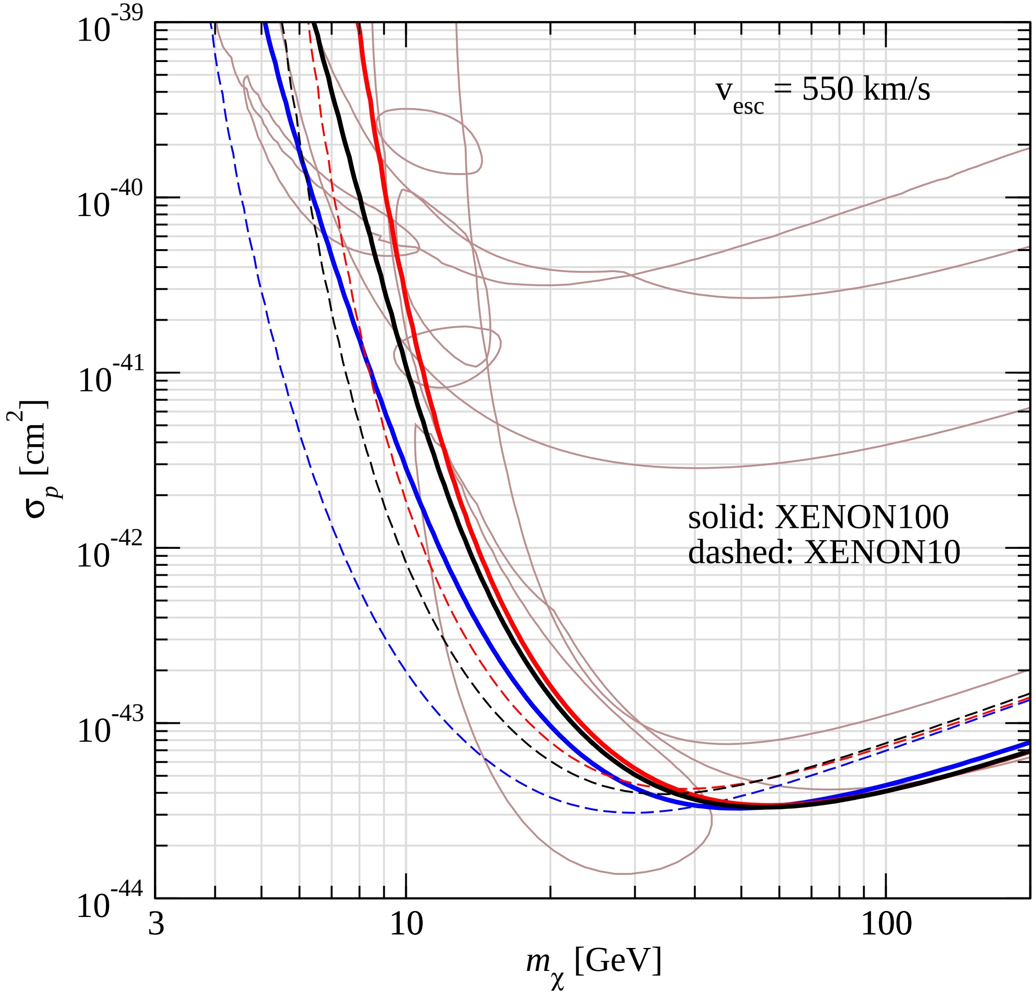
L_{eff} and the XENON10 bounds

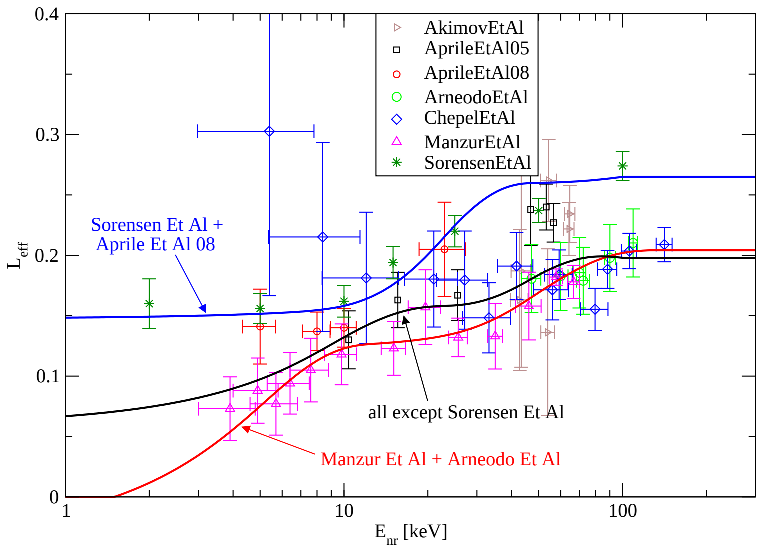




same color coding

L_{eff} and the XENON10/100 bounds





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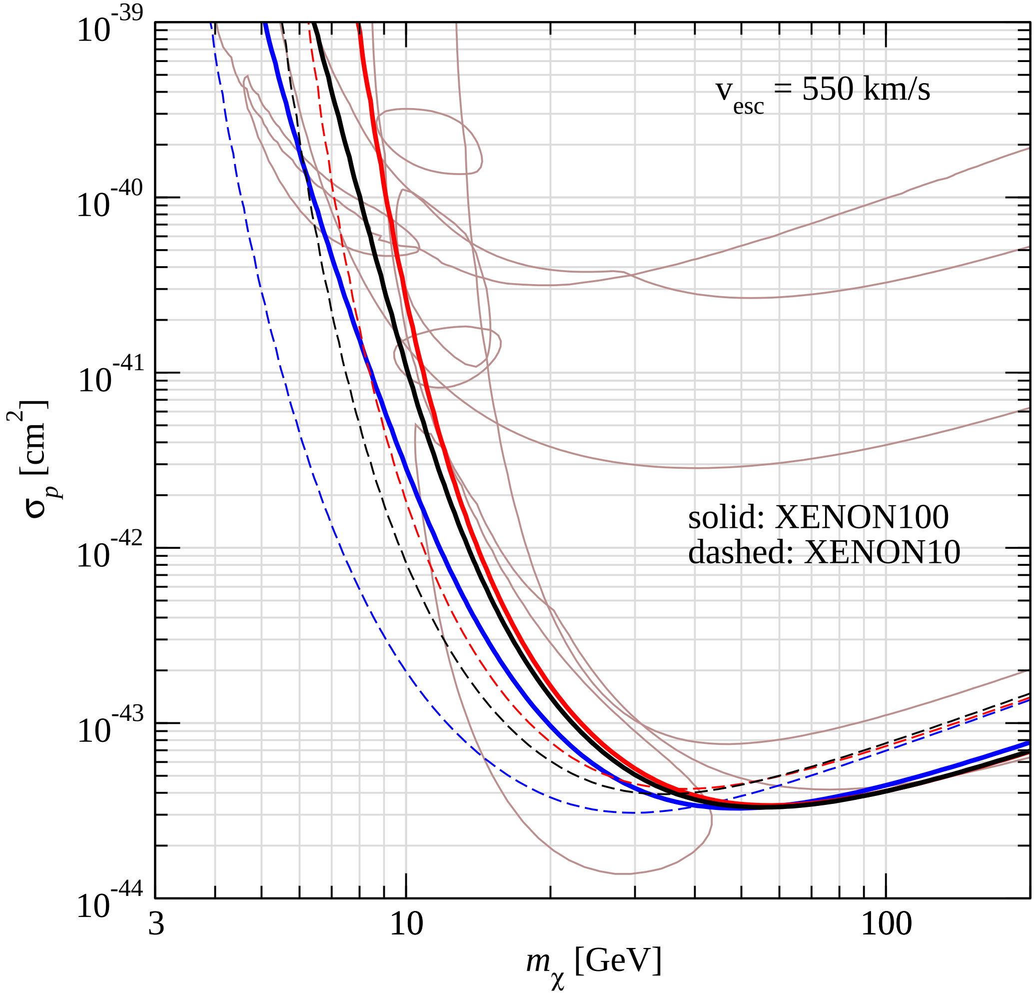


heated discussion:

Collar, McKinsey, 1005.0838

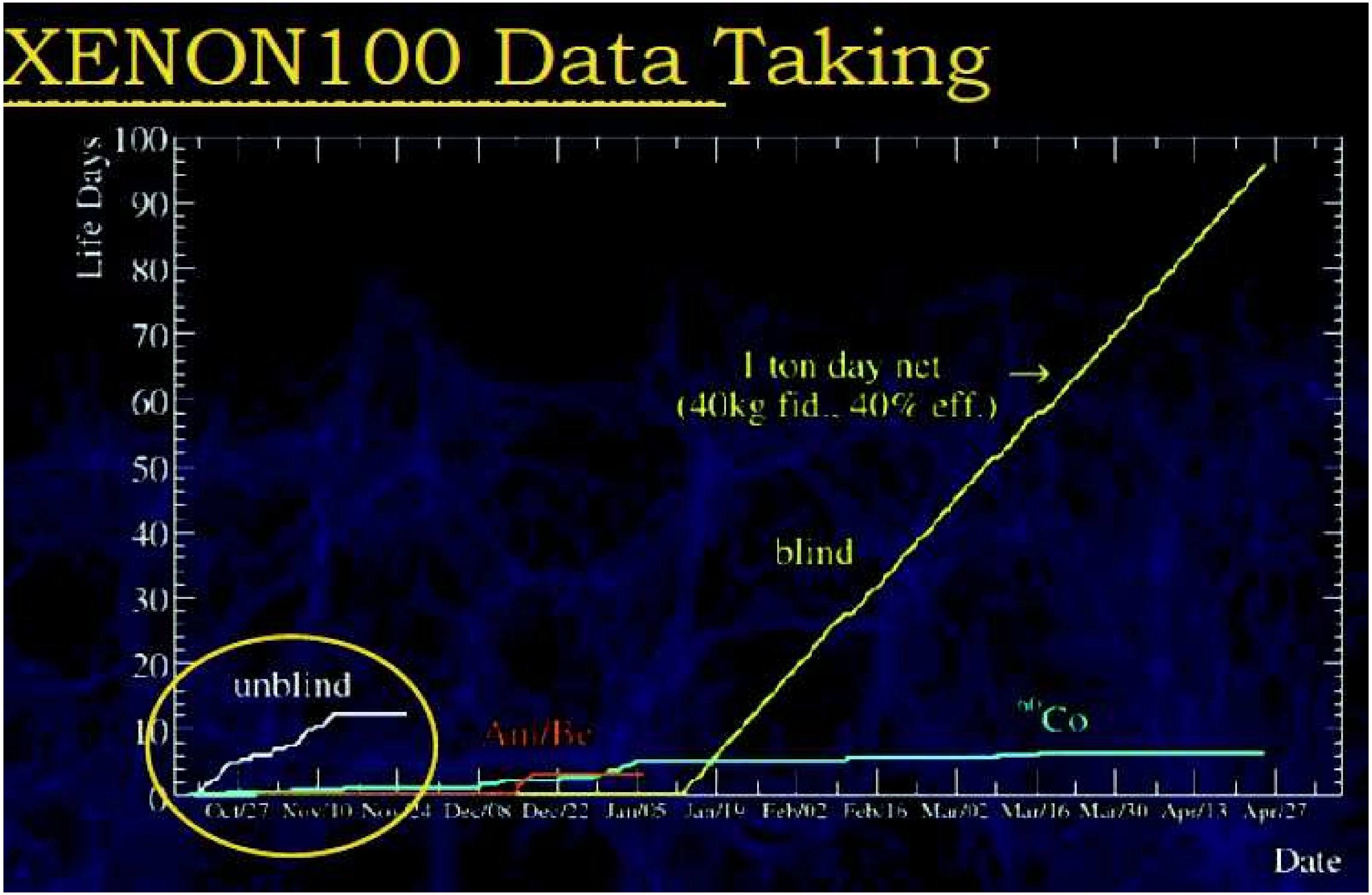
XENON100, 1005.2615

Collar, McKinsey, 1005.2615

Savage et al., 1006.0972

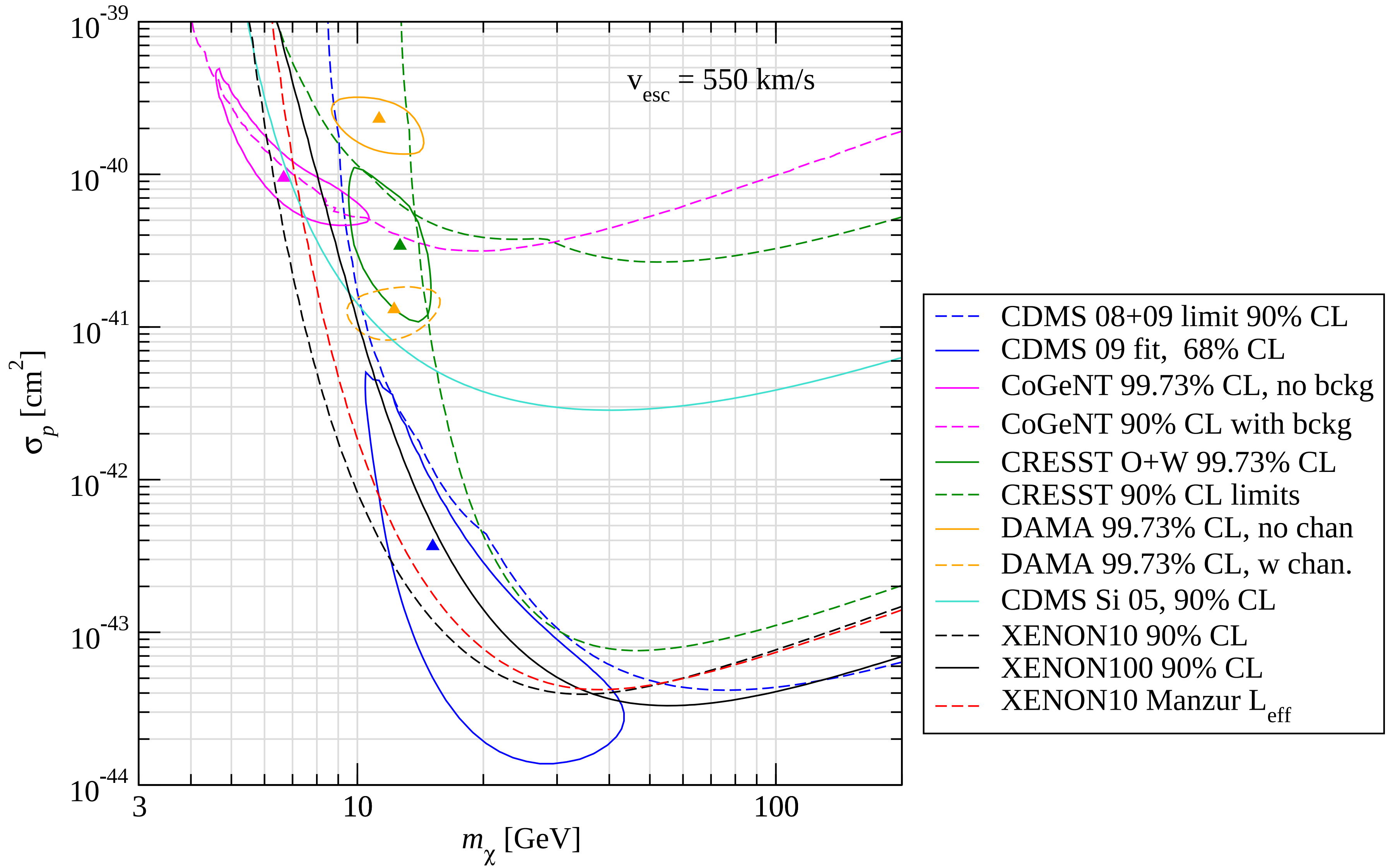
Collar, 1006.2031

XENON-100 exposure

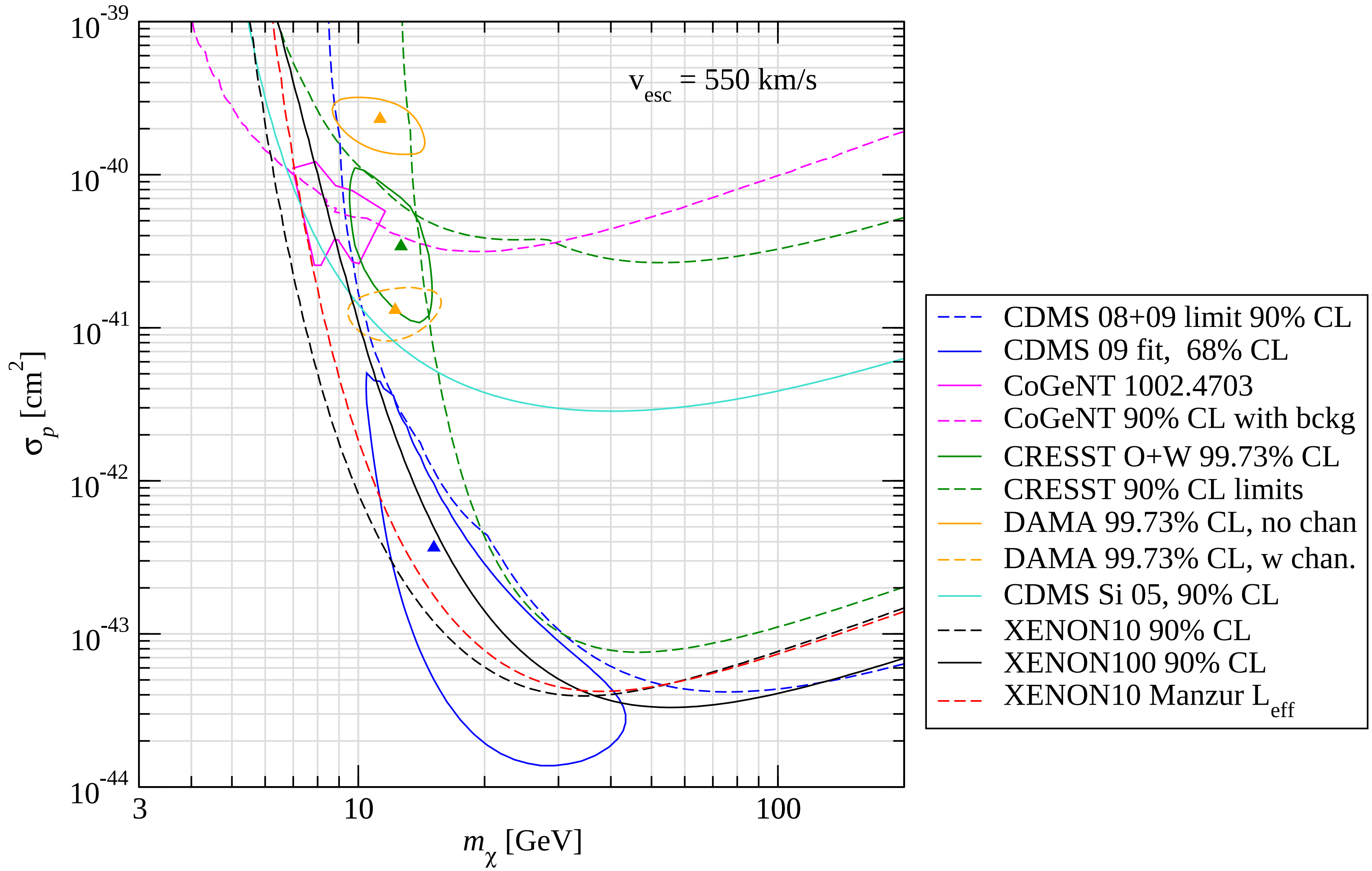


Talk by E. Aprile, GGI conference, 19 May 2010

Summary elastic SI scattering



Summary elastic SI scattering



elastic spin-dependent (eSD) scattering

Spin-dependent scattering

coupling mainly to an un-paired nucleon:

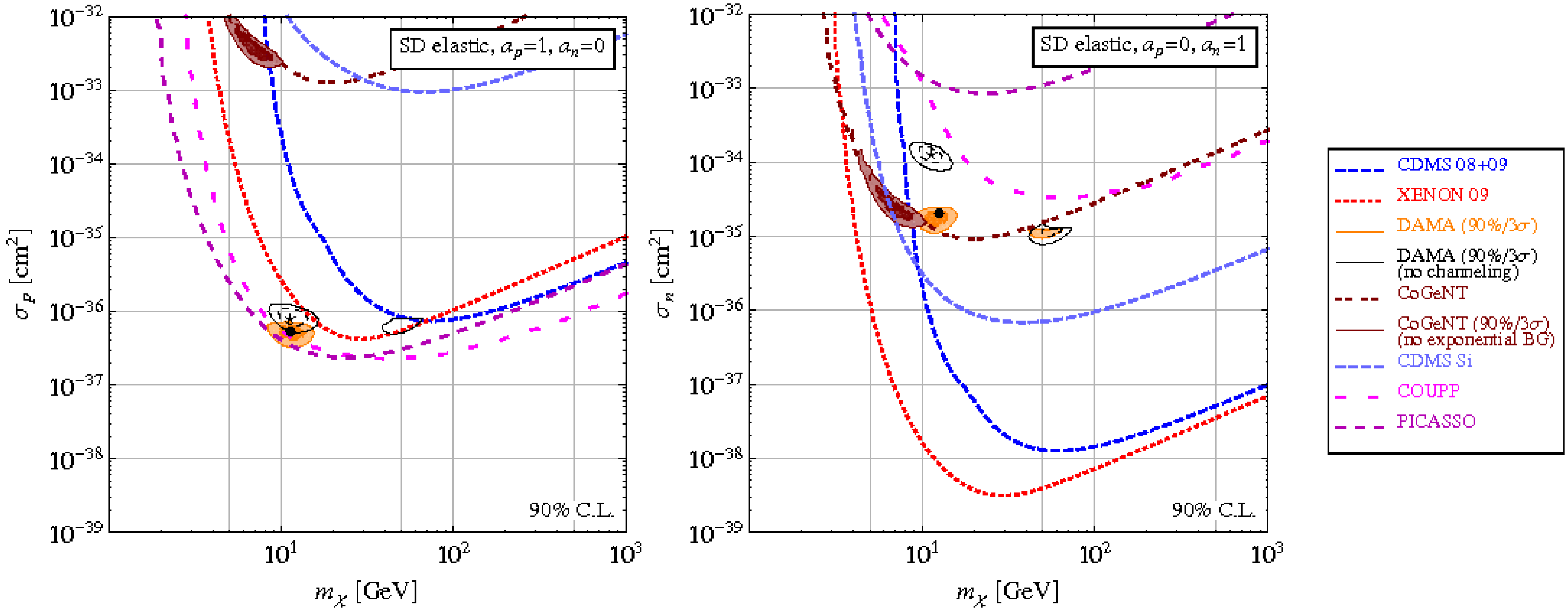
		neutron	proton
DAMA	$^{23}_{11}$Na	even	odd
DAMA, KIMS, COUPP	$^{127}_{53}$I	even	odd
SIMPLE	$^{35}_{17}$Cl, $^{35}_{17}$Cl	even	odd
XENON, ZEPLIN	$^{129}_{54}$Xe, $^{131}_{54}$Xe	odd	even
CDMS, CoGeNT	$^{73}_{32}$Ge	odd	even
PICASSO, COUPP, SIMPLE	$^{19}_{9}$F	even	odd
CRESST	$^{A}_{74}$W, $^{16}_{8}$O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

coupling with proton promising for DAMA vs CDMS/XENON

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

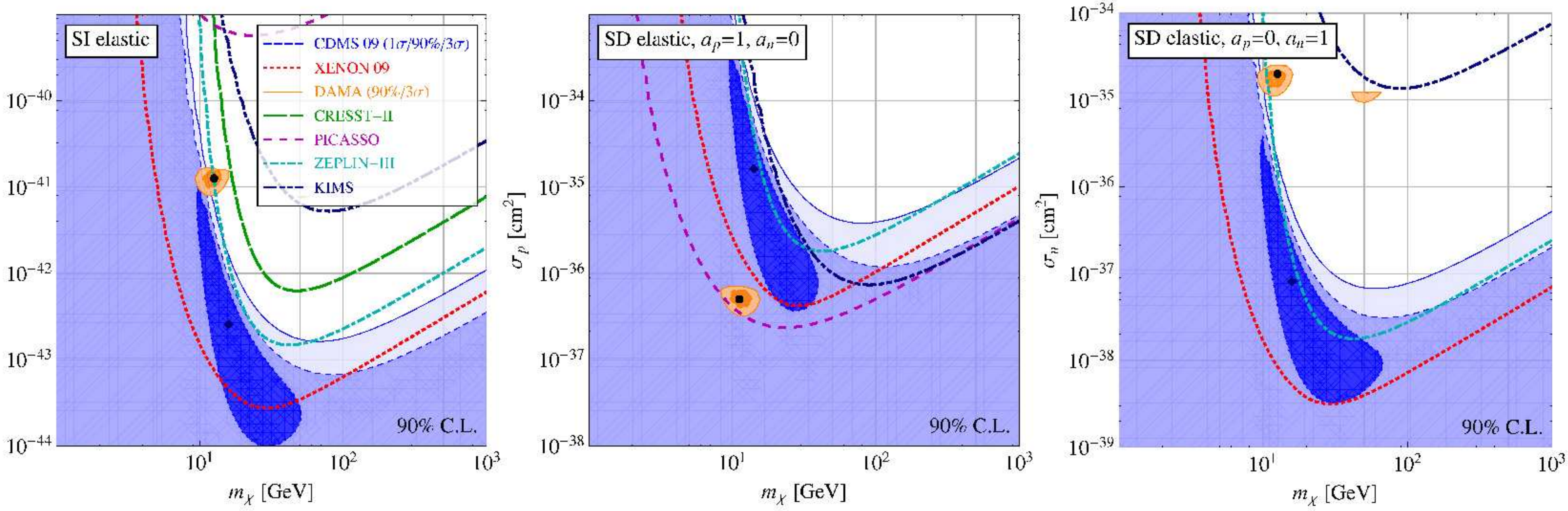
and neutrino constraints from annihilations in the sun

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:

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

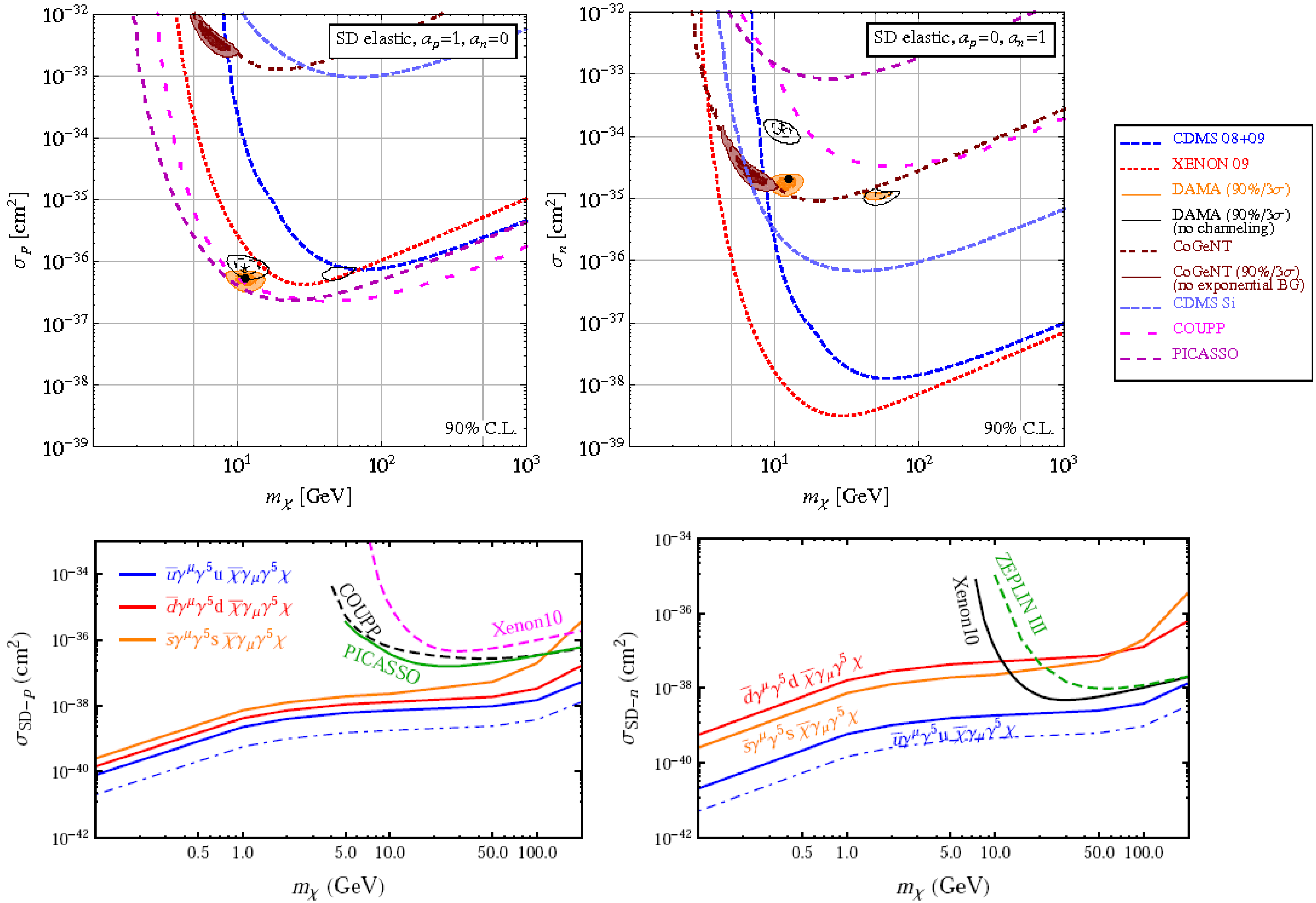
$$\Rightarrow \qquad pp \to \bar{\chi}\chi + j$$

constraints from mono-jet searches at Tevatron

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

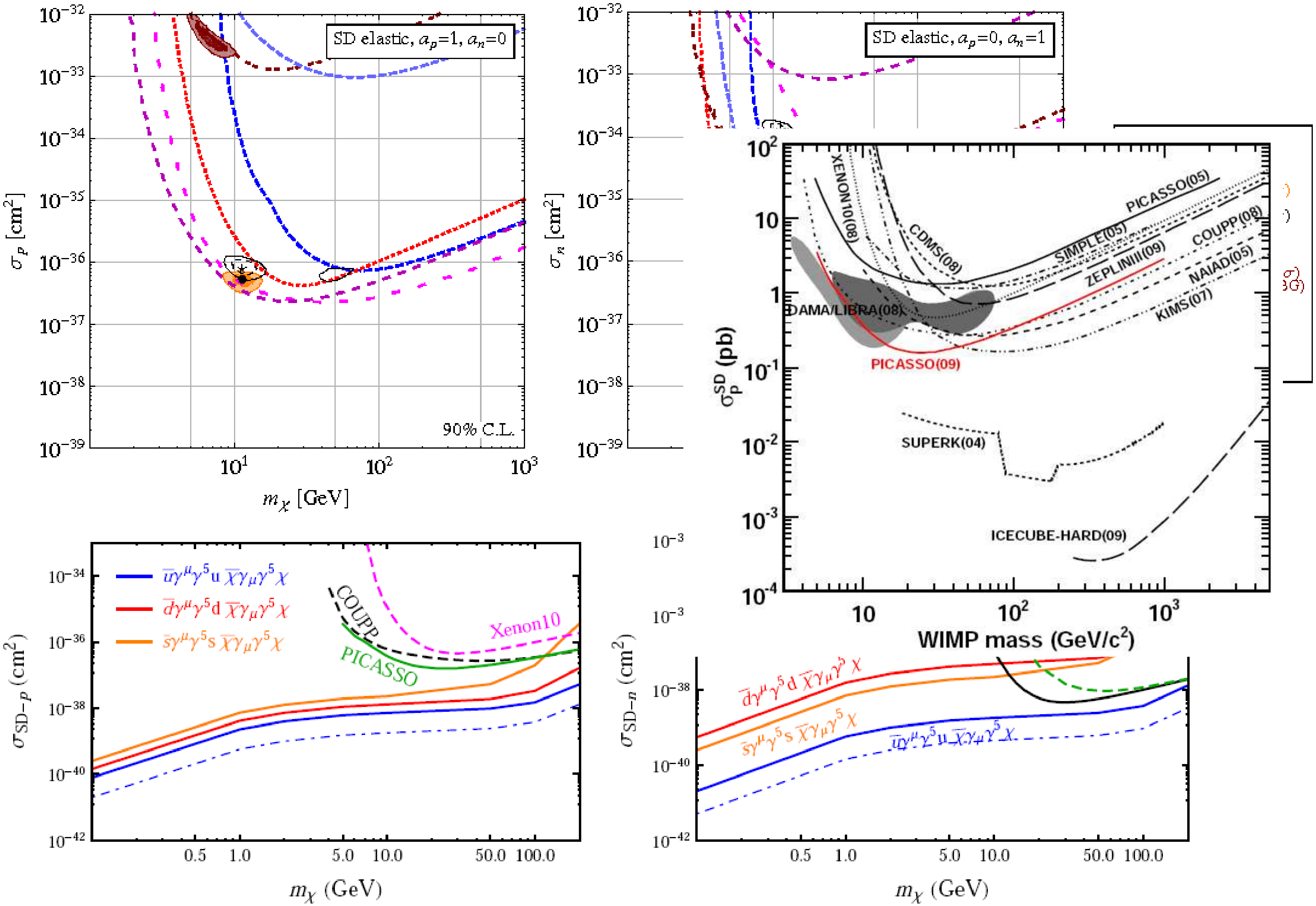
Beltran et al., 1002.4137; Goodman et al., 1005.1286; Bai, Fox, Harnik, 1005.3797

SD and constraints from Tevatron

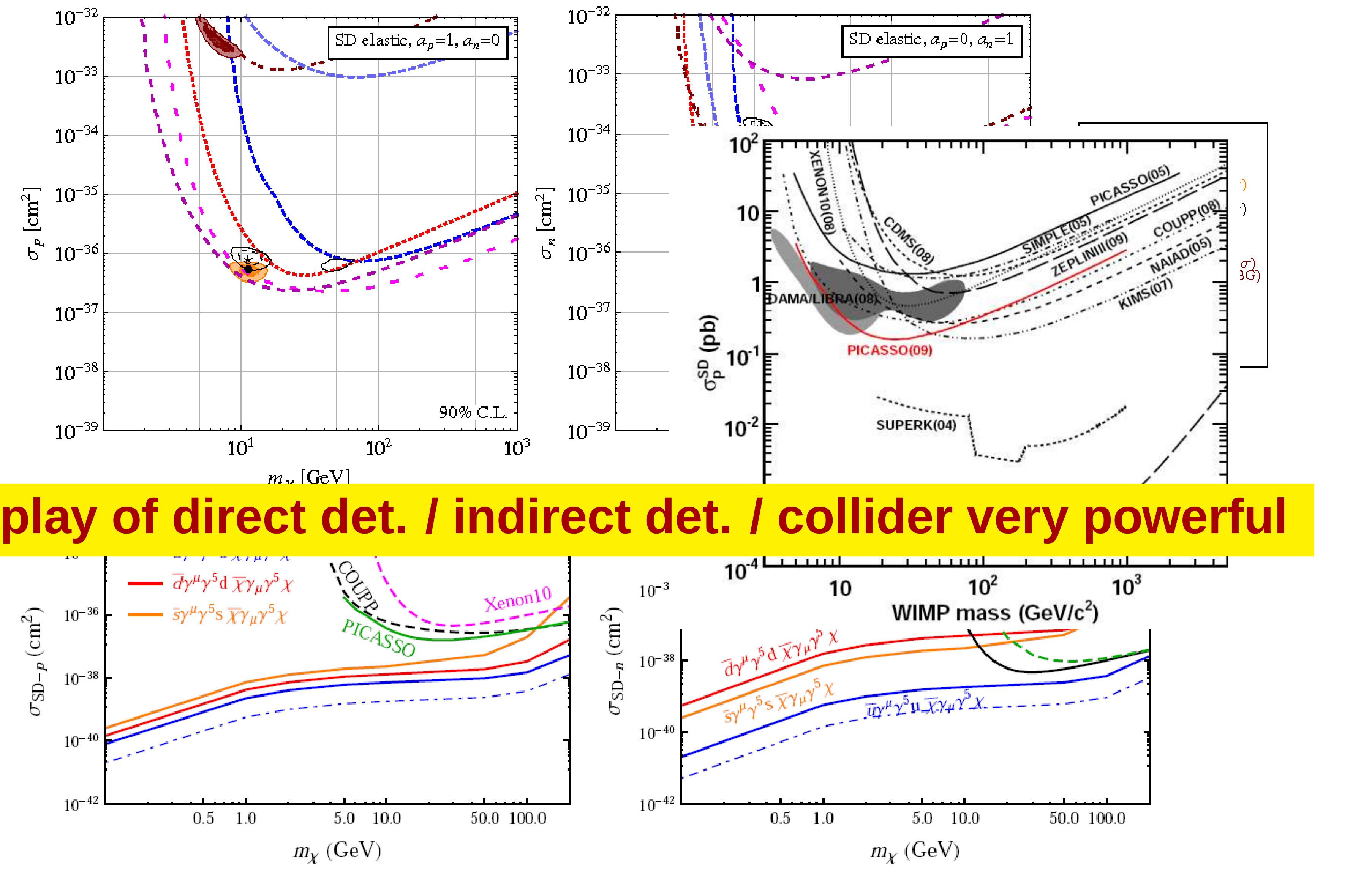


Bai, Fox, Harnik, 1005.3797

SD and constraints from Tevatron and neutrinos



SD and constraints from Tevatron and neutrinos

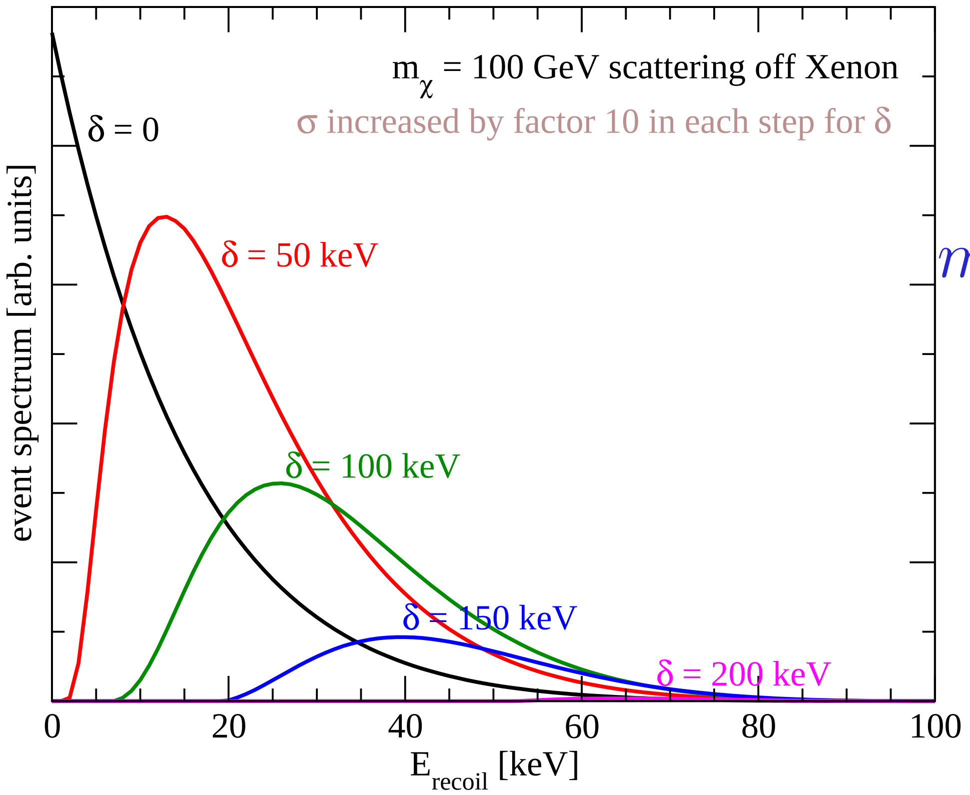


Interplay of direct det. / indirect det. / collider very powerful

inelastic scattering

Tucker-Smith, Weiner, hep-ph/0101138

Inelastic DM scattering

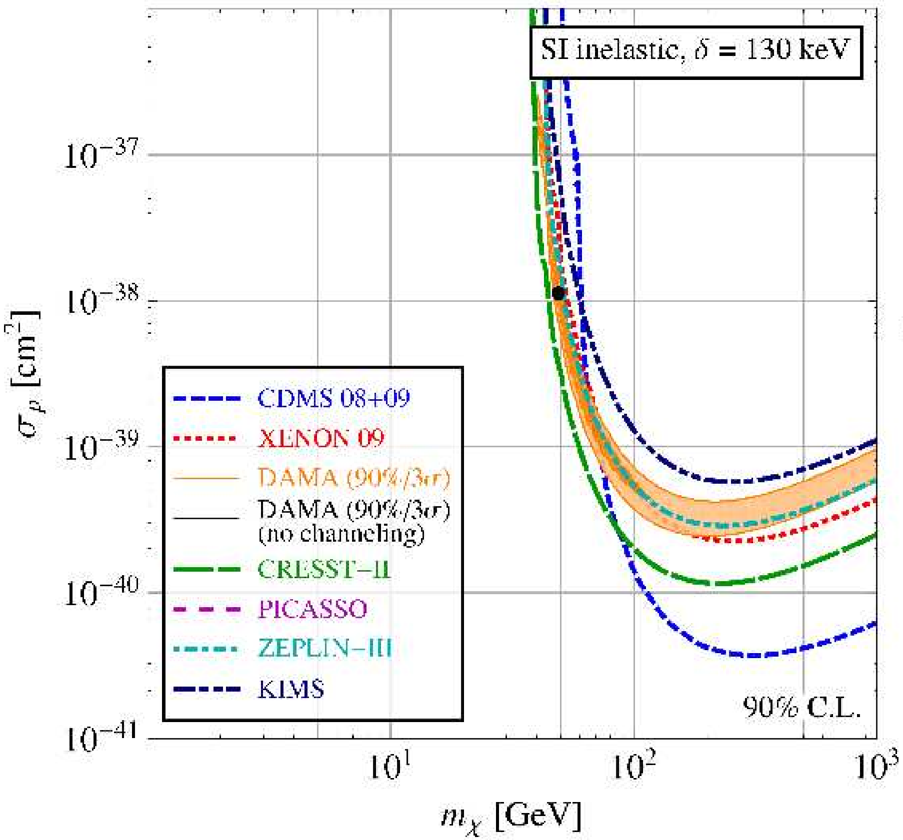


$$m_{\chi^*} - m_\chi = \delta \simeq 100\,\text{keV} \sim 10^{-6} m_\chi$$

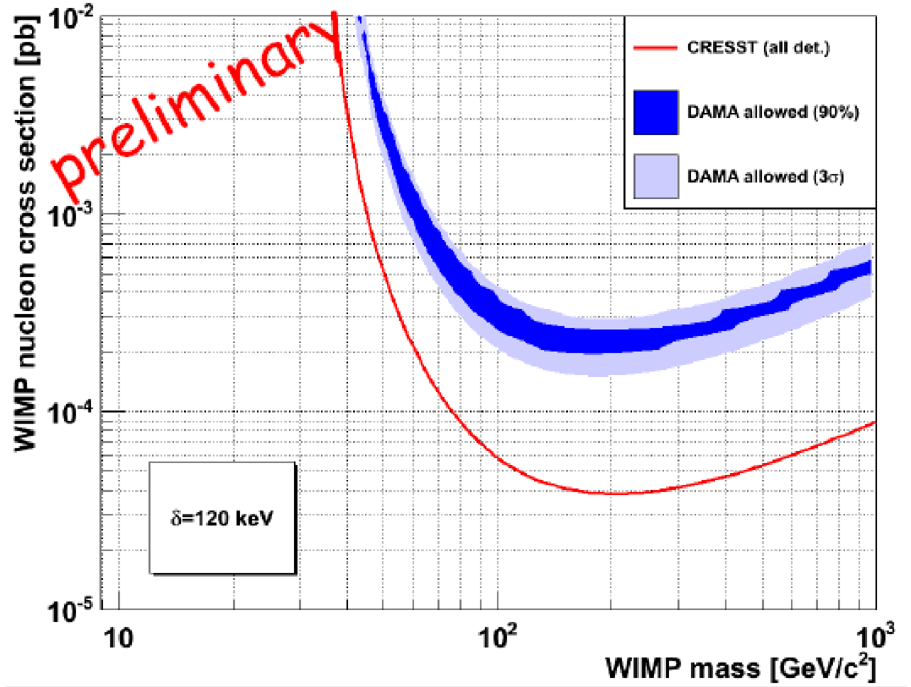
$$v_{\min}^{\text{inel}} = \frac{1}{\sqrt{2ME_R}} \left(\frac{ME_R}{\mu_\chi} + \delta \right)$$

- 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 @ WONDER 2010



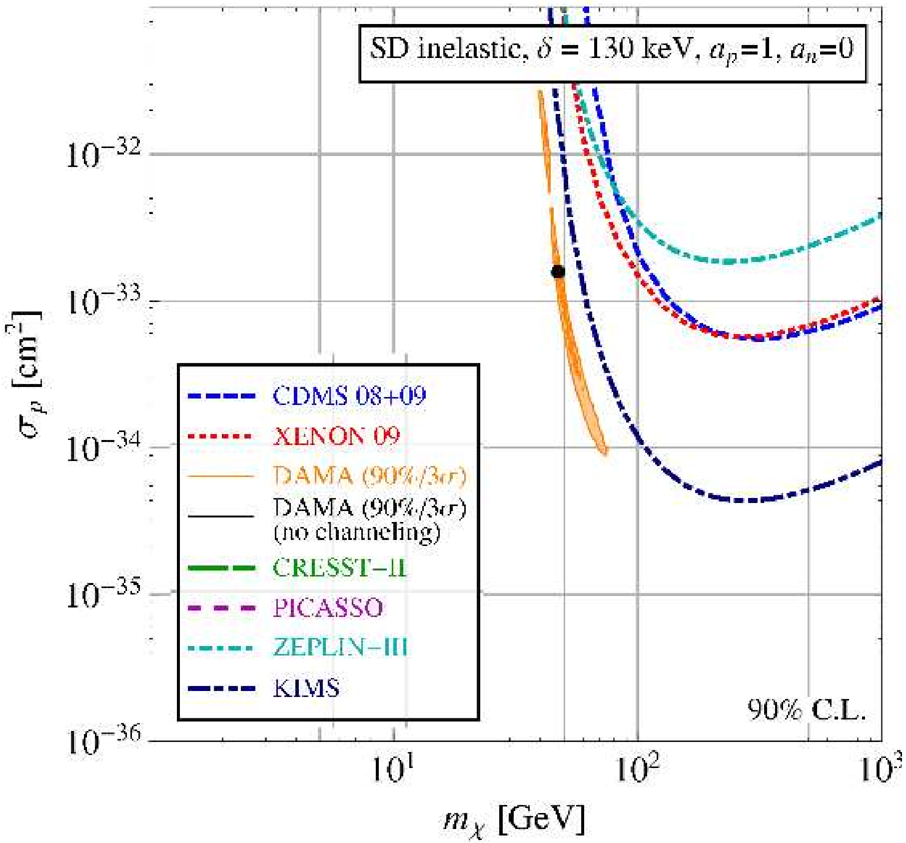
$m_\chi \simeq 50\,\mathrm{GeV}$, $\delta \simeq 130\,\mathrm{GeV}$

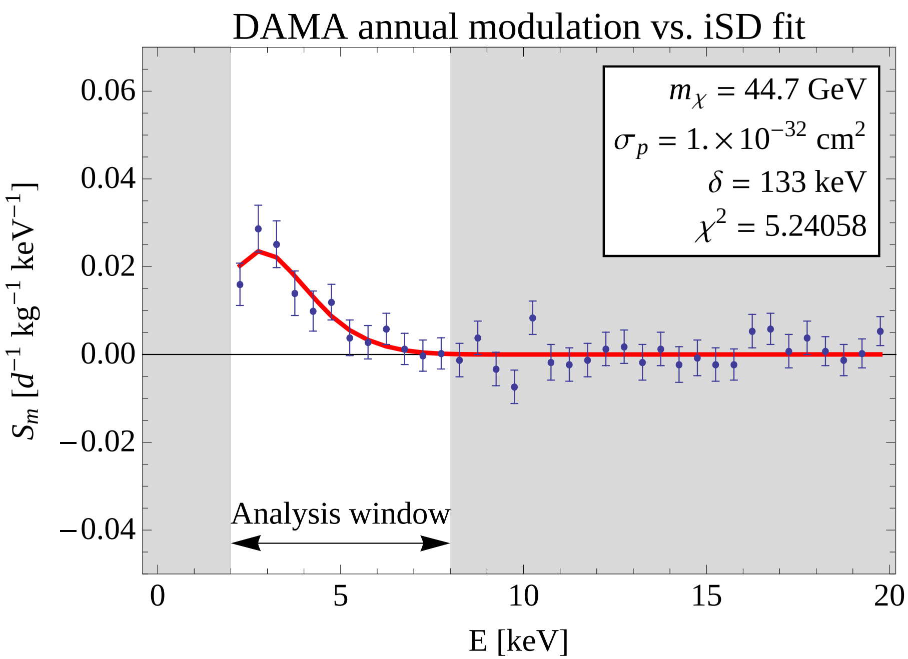
disfavored by CRESST (tungsten)

iSD on protons

inelastic spin-dependent scattering

Kopp, Schwetz, Zupan, 0912.4264





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

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

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

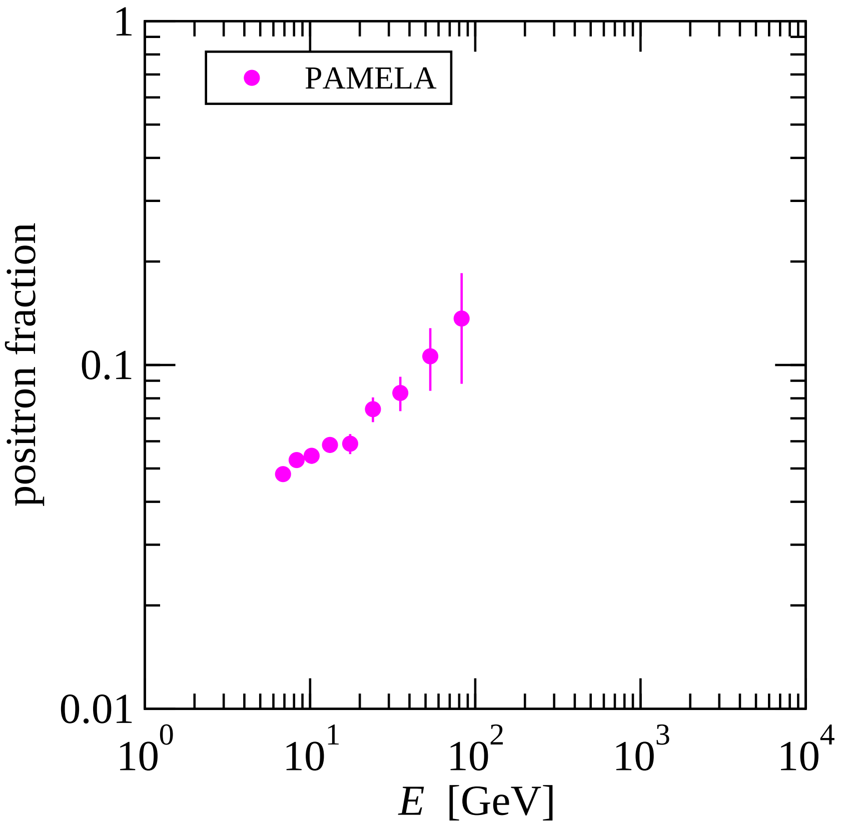
$$\chi_1 = i(\eta - \xi)/\sqrt{2}, \qquad \chi_2 = (\eta + \xi)/\sqrt{2}$$

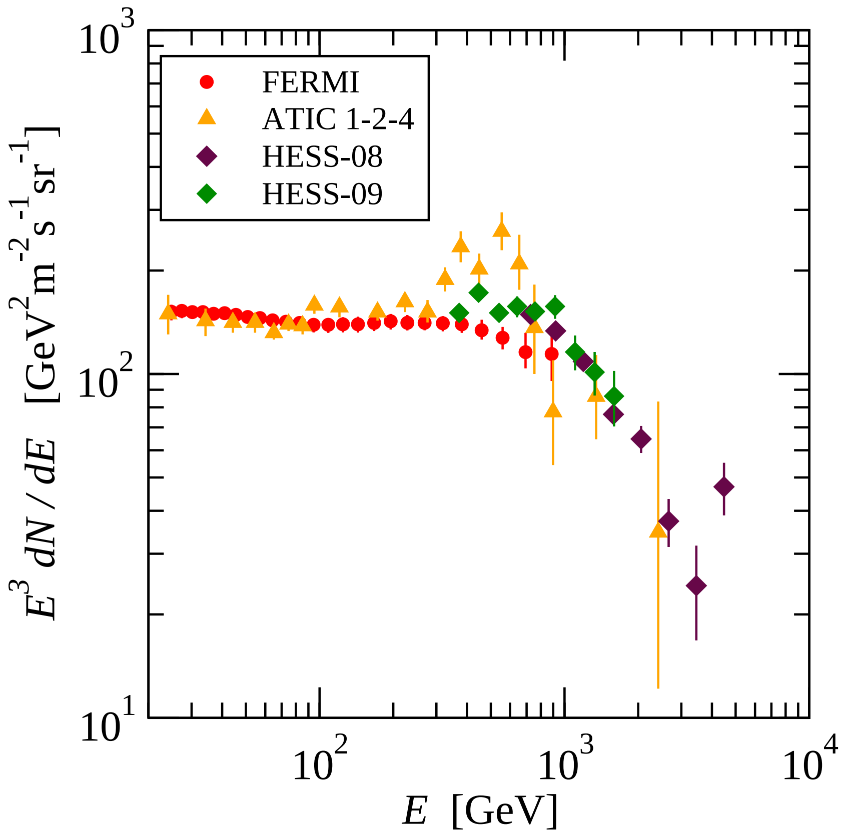
$$\Rightarrow \quad \bar\psi \Sigma_{\mu\nu} \psi = -2i(\chi_2 \sigma_{\mu\nu} \chi_1 + \chi_2^\dagger \bar\sigma_{\mu\nu} \chi_1^\dagger) ,$$

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

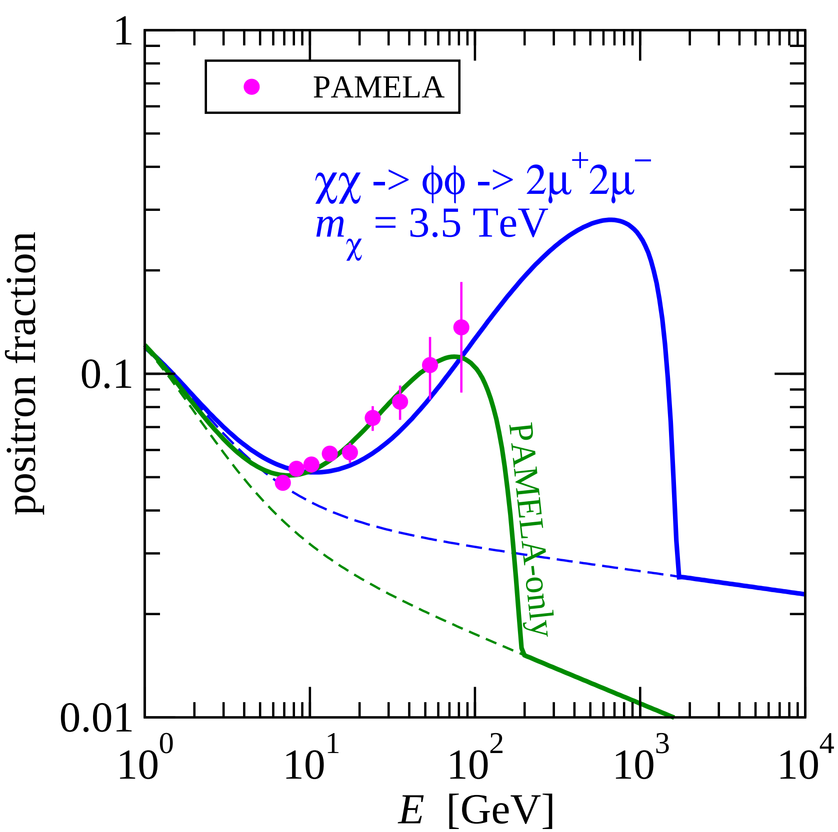
Indirect detection

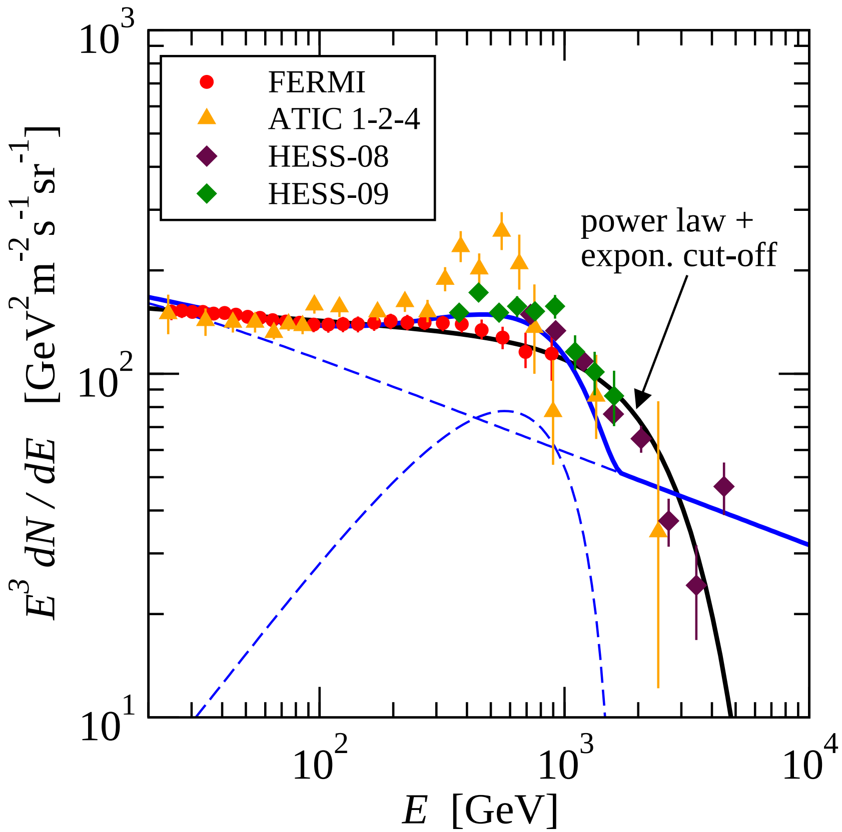
Anomalies in $e^{\pm}$ cosmic ray flux





Anomalies in $e^{\pm}$ cosmic ray flux





Anomalies in $e^{\pm}$ cosmic ray flux

- solar physics (heliospheric B-field)? Roberts, 1005.4668
- new source of primary e^{+} ?
  Is it DM or astro-physics (pulsars, SN remnants)?

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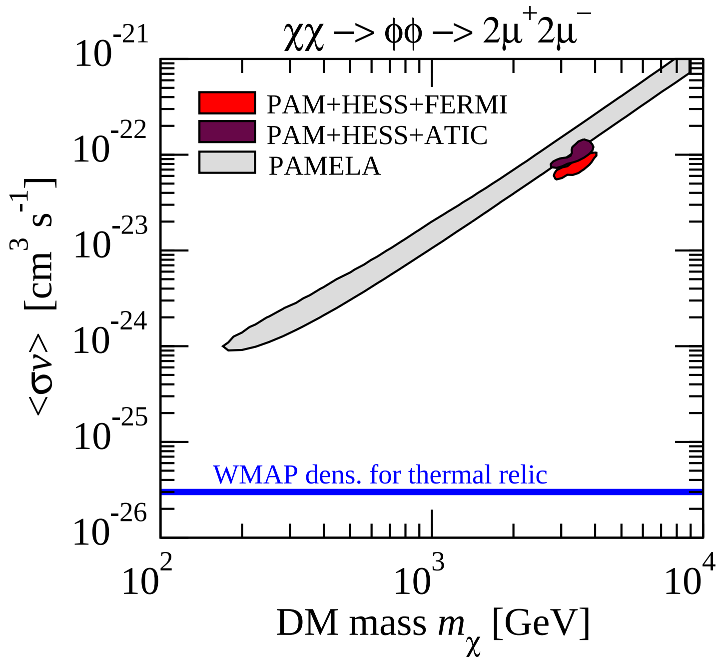

Rothstein, TS, Zupan
0903.3116

Anomalies in $e^{\pm}$ cosmic ray flux

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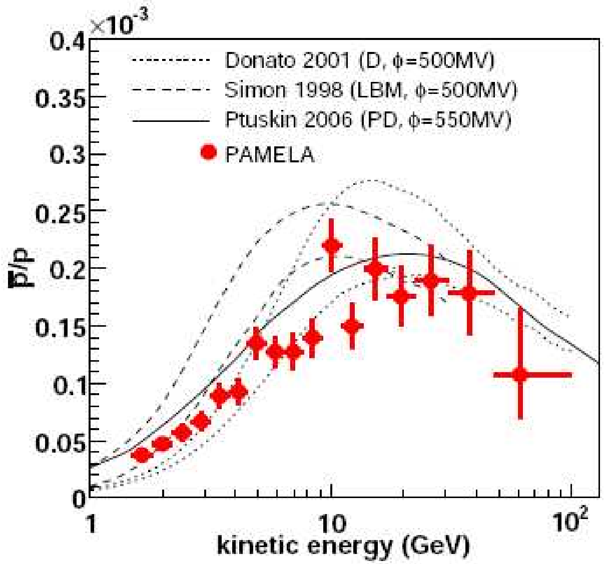

PAMELA, 0810.4994

Anomalies in $e^{\pm}$ cosmic ray flux

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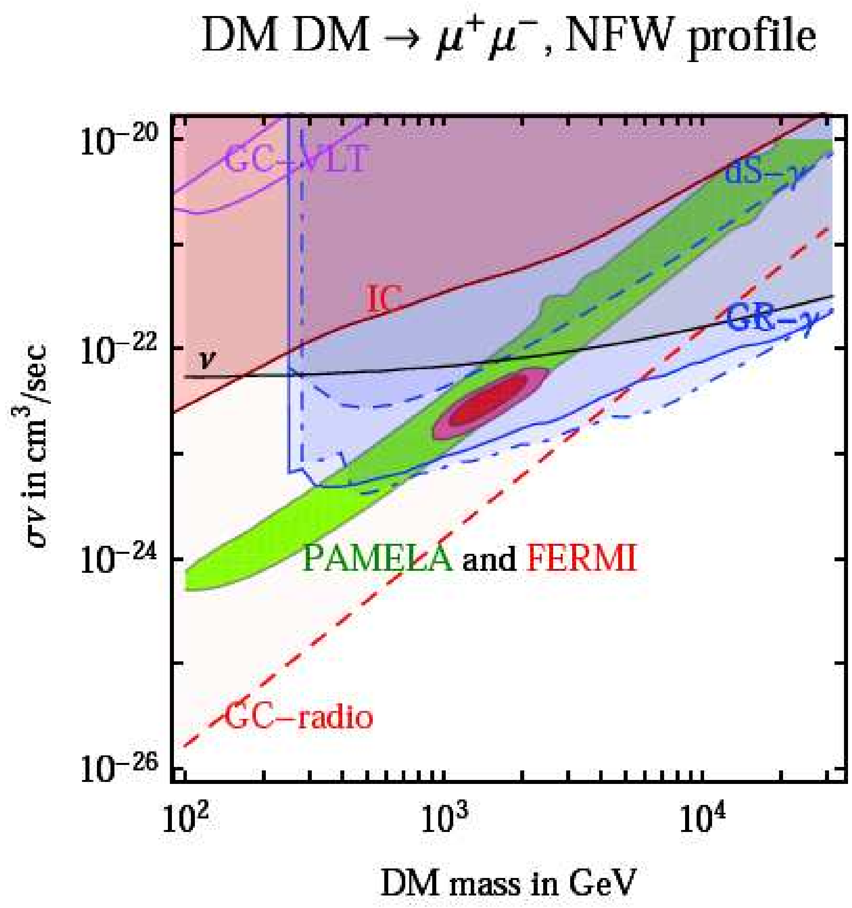
... it has very unexpected properties!

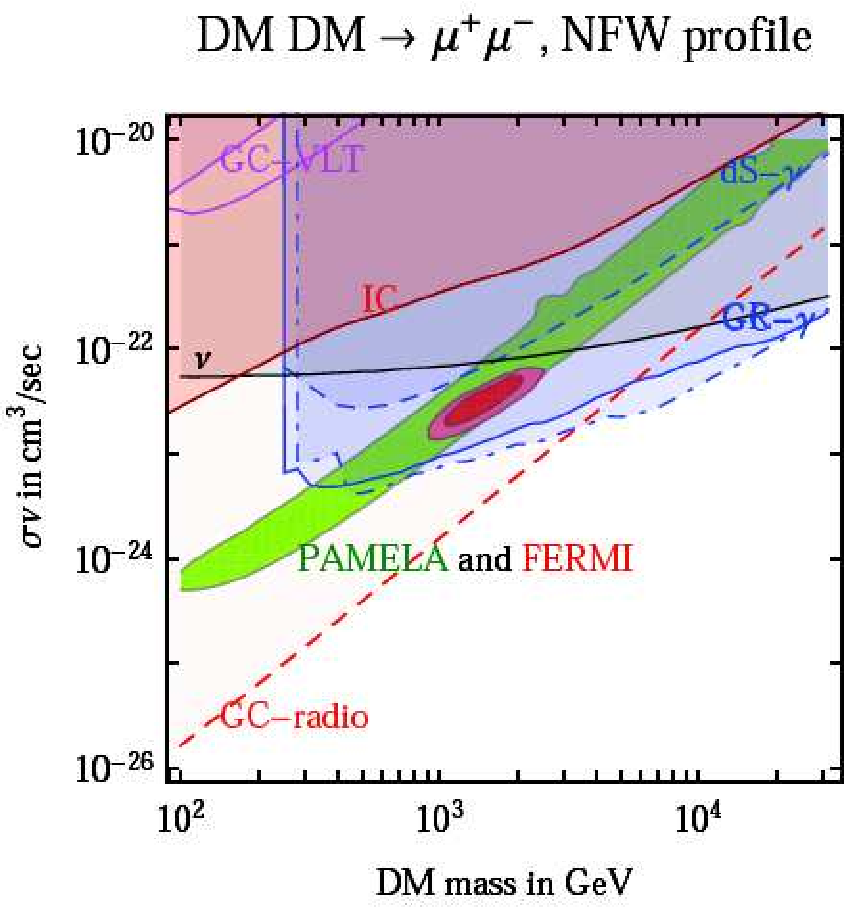
“multi-messenger” constraints

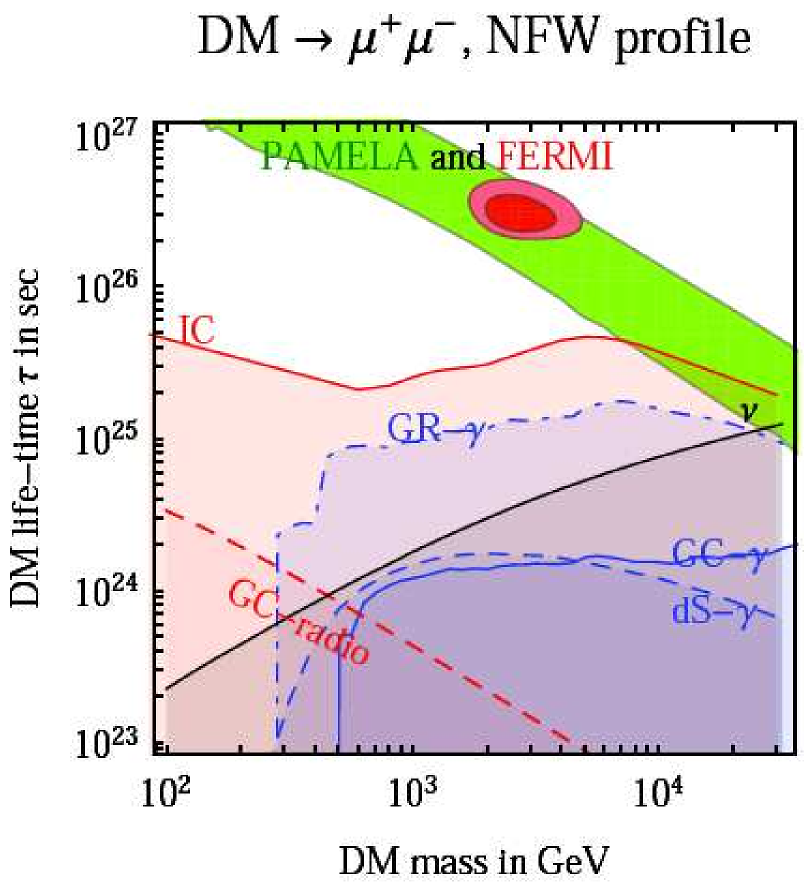


Meade, Papucci, Strumia, Volansky, 0905.0480

dependence on halo model, annihilation mode

“multi-messenger” constraints





Meade, Papucci, Strumia, Volansky, 0905.0480

DM decay typically is less constrained ($\propto \rho$ instead of ρ^2)

DM decay?

- Gravitino DM
  decay due to R-parity violation

  many papers; see talk by Borut Bajc

- decay rate from dim-6 operator:

$$\Gamma \sim \frac{m_\chi^5}{\Lambda^4} \sim 10^{25}\,\mathrm{s}^{-1} \left(\frac{m_\chi}{1\,\mathrm{TeV}}\right)^5 \left(\frac{\Lambda}{10^{16}\,\mathrm{GeV}}\right)^{-4}$$

$\Rightarrow$ GUT suppressed dim-6 operator roughly provides the right decay rate to explain the PAMALA anomaly due to DM decay

Arvanitaki et al., 0812.2075

Conclusions

Conclusions

- Exciting times for DM, lots of new data coming up
  LHC, XENON100, FERMI, IceCube,. . .
- There may be hints for DM in recent data from direct detection and cosmic rays
- if true, DM has “unexpected” properties
  $\Rightarrow$ new ideas for DM candidates are being explored

BUT:

- no consistent picture emerging yet
- hints are in tension with various constraints . . .

Look to the future

. . . so, maybe we are not seeing DM now,

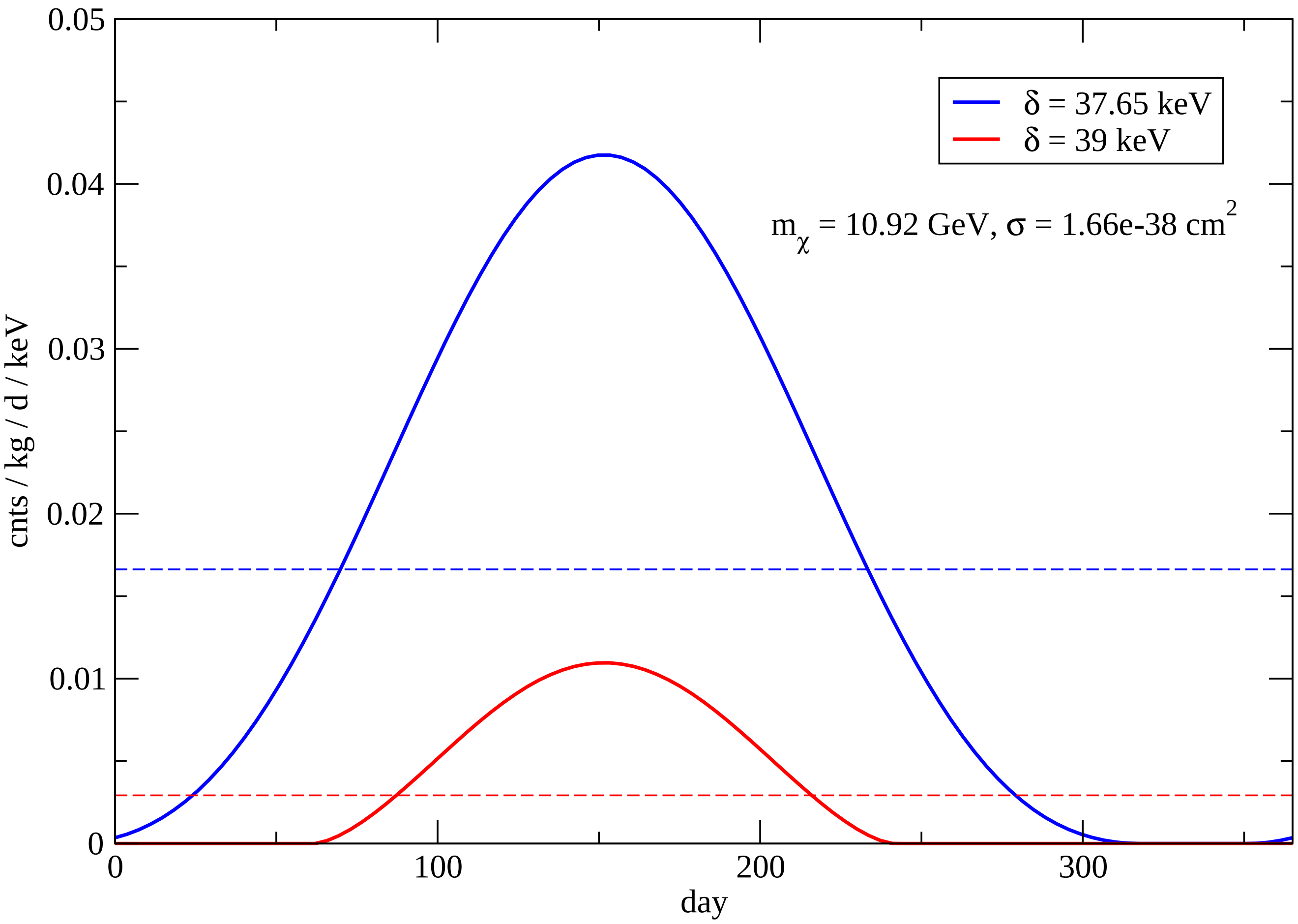
but this situation is typical for the DM field:
any claimed signal has to be cross checked /
re-discovered / excluded by several complementary
experiments

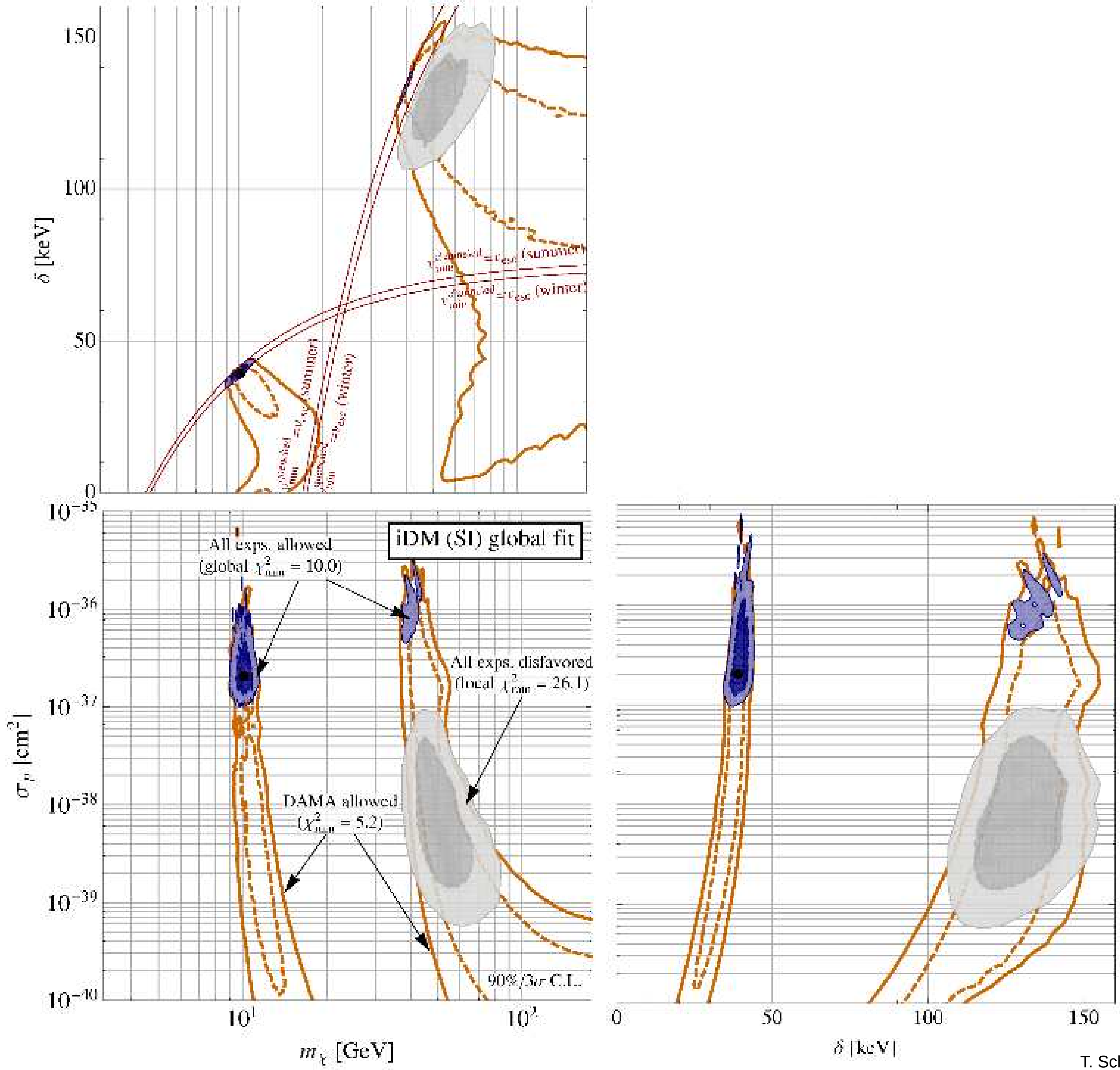
at some point “hints” will converge (hopefully)!

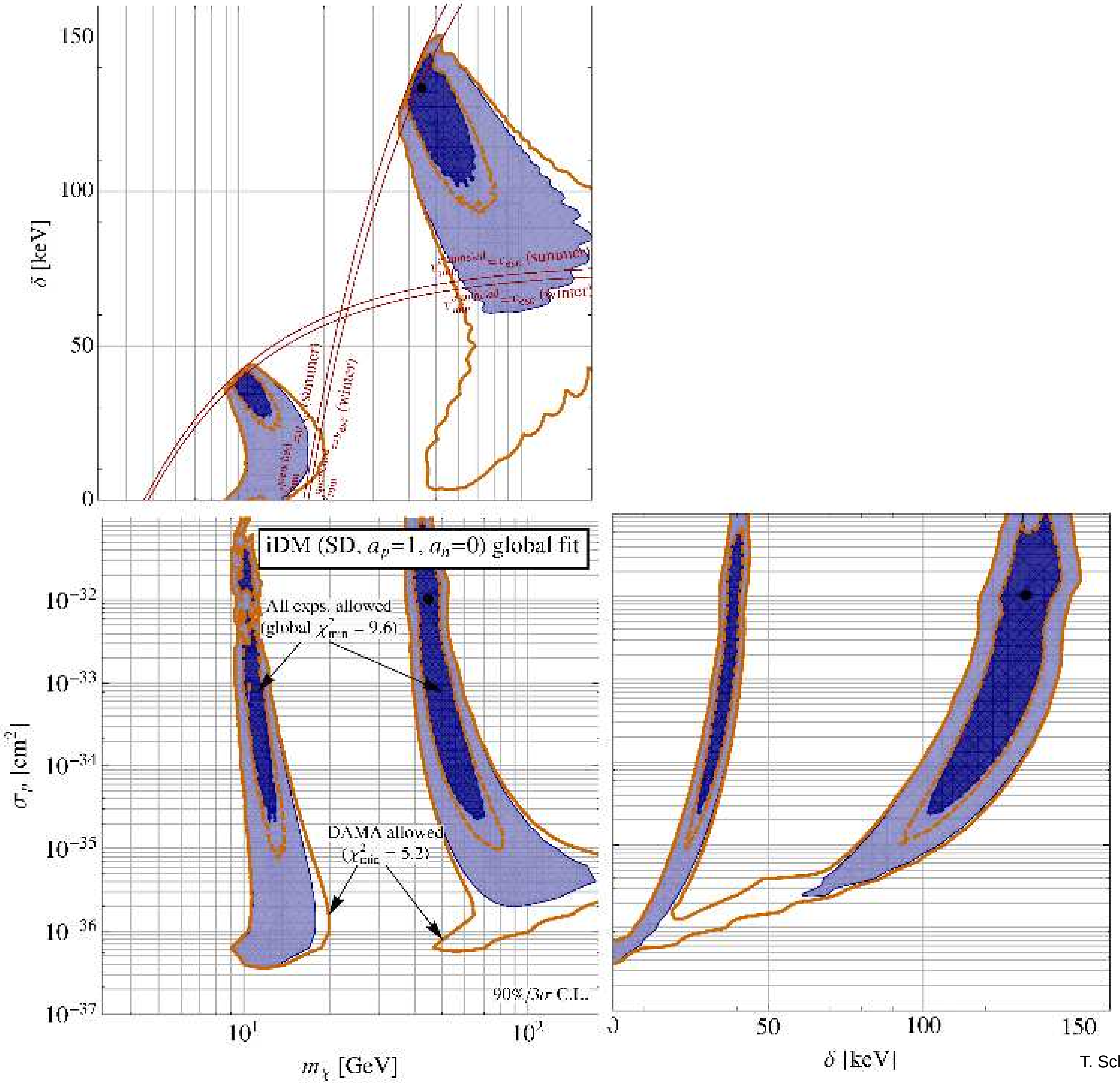
Additional slides

iSI

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



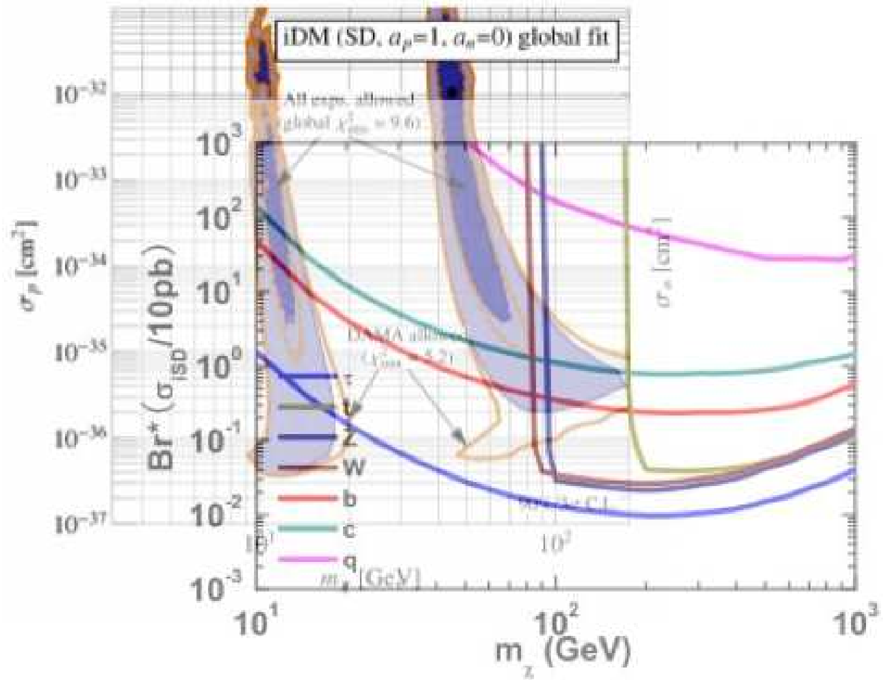

iDM (SI) global fit
All exps. allowed
(global χ^2_{min} = 10.0)
All exps. disfavored
(local χ^2_{min} = 26.1)
DAMA allowed
(χ^2_{min} = 5.2)
90%/3σ C.L.
m_χ [GeV]
δ [keV]
σ_p [cm^2]



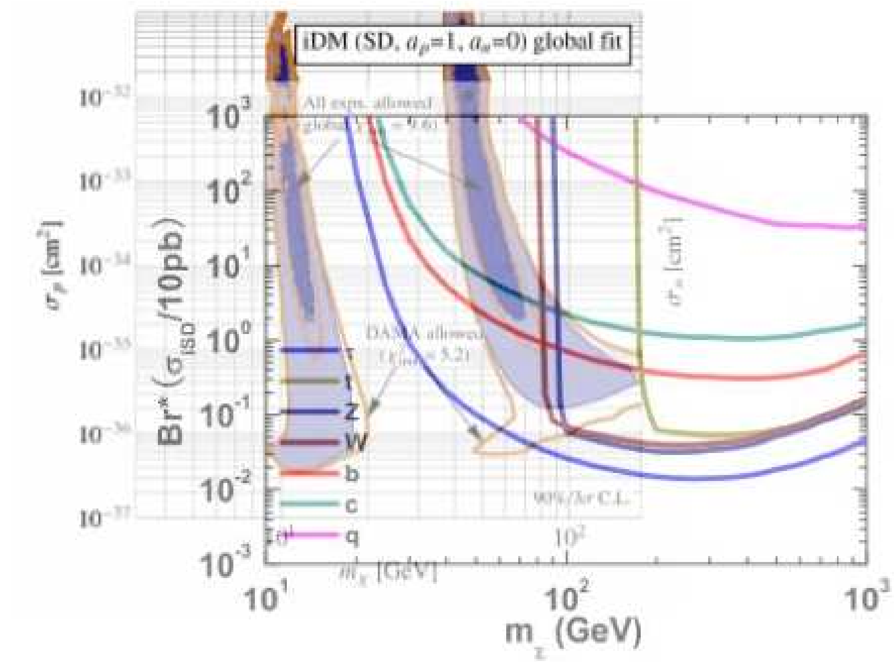
iDM (SD, a_p=1, a_n=0) global fit
All exps. allowed
(global χ^2_{min} = 9.6)
DAMA allowed
(χ^2_{min} = 5.2)
90%/3σ C.L.
δ [keV]
σ_p [cm^2]
m_χ [GeV]
δ [keV]

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

Event spectrum

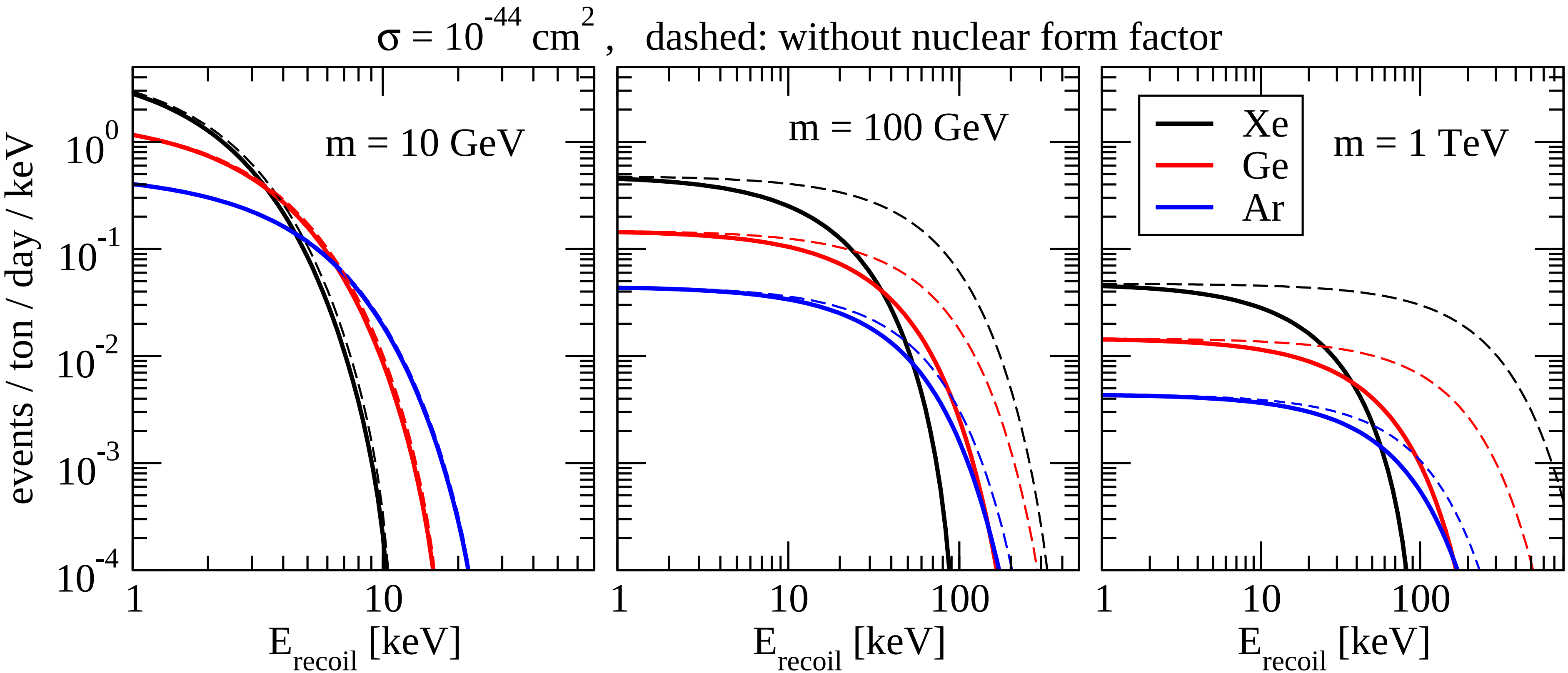
$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi} \frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2} \int_{v>v_{\rm min}(E_R)} d^3v \, \frac{f_\oplus(\vec{v},t)}{v}$$

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

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

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

Event spectrum



nuclear form factor is less important for low mass WIMPs

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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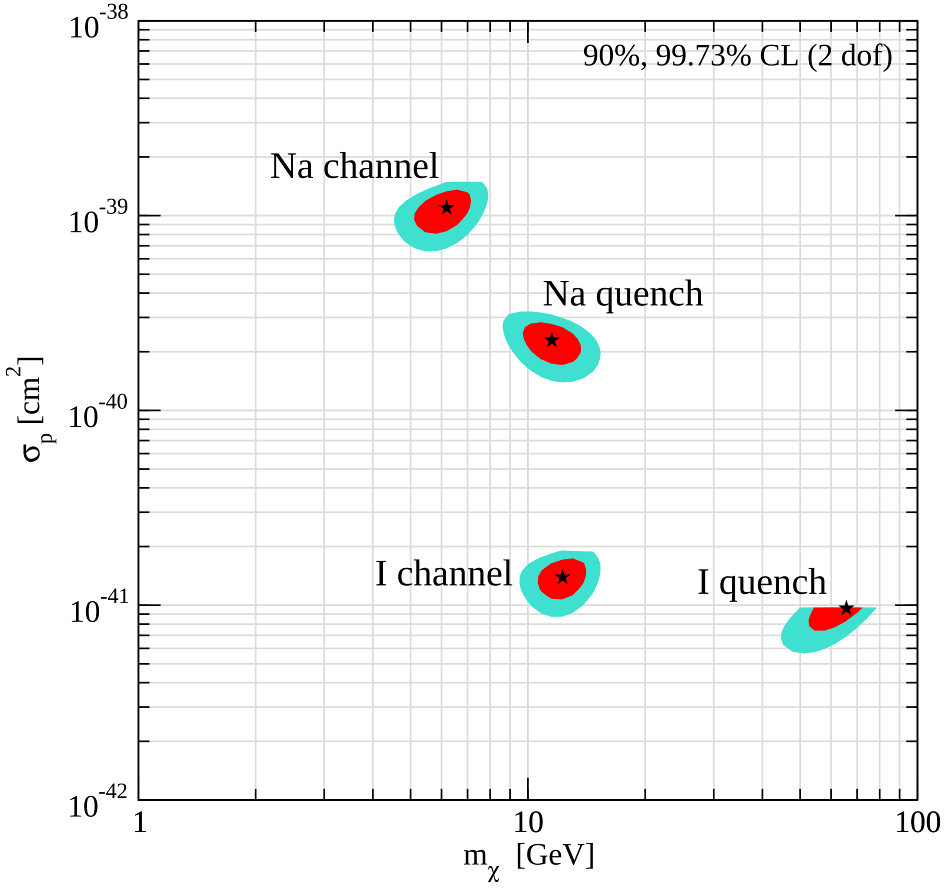

fitting DAMA requires

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

$\Rightarrow$