Global interpretation of direct dark matter searches

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Johns Hopkins University, Feb 23, 2010

in collaboration with Viviana Niro, Thomas Schwetz-Mangold and Jure Zupan
arXiv:0912.4264 (JCAP **02** (2010) 014)
arXiv:0907.3159 (Phys. Rev. D **80** (2009) 083502)

Fermilab

Outline

1. Prologue: Phenomenology of Dark Matter interactions
   - WIMP-nucleus scattering
   - Leptophilic dark matter
2. Dramatis personae: Direct detection experiment
3. Act I: Global constraints on WIMP-nucleon interactions
4. Act II: Global constraints on leptophilic Dark Matter
   - Leptophilic Dark Matter in direct detection experiments
   - Leptophilic Dark Matter in the Sun
5. Epilogue: Summary and conclusions

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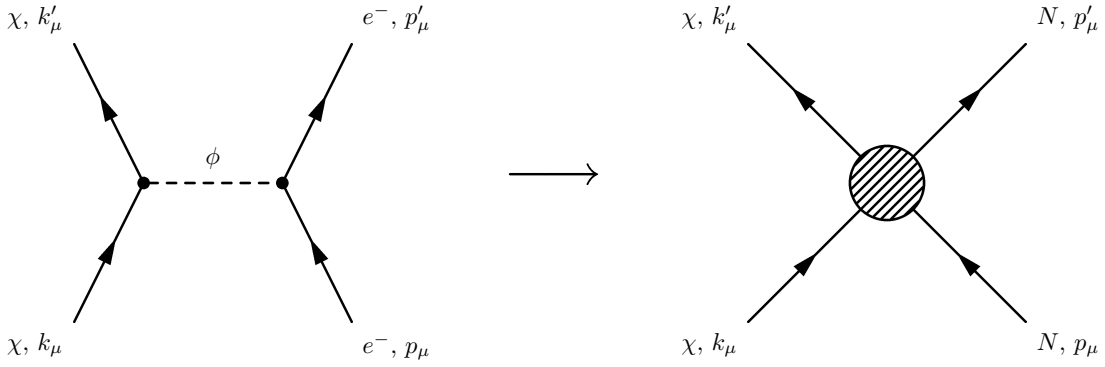
Elastic WIMP-nucleus scattering

The "standard" scenario: Scalar or fermionic (Dirac or Majorana) WIMP



$$\mathcal{L}_{\rm eff} = \sum_i G\,(\bar{\chi}\Gamma^i_\chi \chi)\,(\bar{q}\Gamma^i_q q) \qquad \text{with} \qquad G = \frac{g^2}{\Lambda^2}\,, \qquad \Lambda \sim 100 \text{ GeV ???}$$

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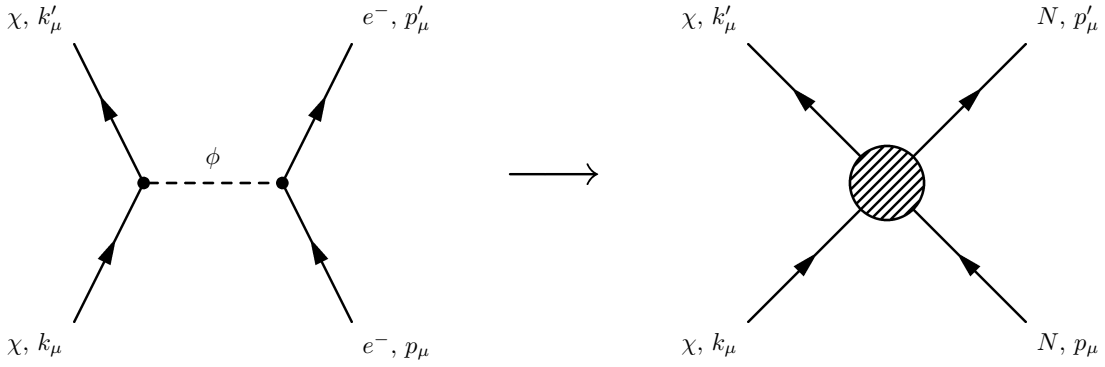

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Possible Lorentz structures:

scalar/pseudoscalar:	$\Gamma_\chi = c_S^\chi + i c_P^\chi \gamma_5,$	$\Gamma_q = c_S^q + i c_P^q \gamma_5,$
vector/axial vector:	$\Gamma_\chi^\mu = (c_V^\chi + c_A^\chi \gamma_5)\gamma^\mu,$	$\Gamma_{q\mu} = (c_V^q + c_A^q \gamma_5)\gamma_\mu,$
tensor/axial tensor:	$\Gamma_\chi^{\mu\nu} = (c_T + i c_{AT}\gamma_5)\sigma^{\mu\nu},$	$\Gamma_{q\mu\nu} = \sigma_{\mu\nu},$

Phenomenology of different Lorentz structures

$\Gamma_\chi \otimes \Gamma_q$	$\sigma(\chi N \to \chi N)/\sigma^0_{\chi N}$	
$S \otimes S$	1	spin-independent
$S \otimes P$	$\mathcal{O}(v^2)$	suppressed
$P \otimes S$	$\mathcal{O}(v^2)$	suppressed
$P \otimes P$	$\mathcal{O}(v^4)$	suppressed
$V \otimes V$	1	spin-independent
$V \otimes A$	$\mathcal{O}(v^2)$	suppressed
$A \otimes V$	$\mathcal{O}(v^2)$	suppressed
$A \otimes A$	3	spin-dependent
$T \otimes T$	12	spin-dependent
$AT \otimes T$	$\mathcal{O}(v^2)$	suppressed

see also: Momentum-dependent WIMP scattering: Chang, Pierce, Weiner, 0908.3192

Inelastic WIMP-nucleus scattering

- Spin-independent: E.g. Pseudo-Dirac fermion with vector interactions
  $\psi = (\eta, \bar{\xi})$

$$\mathcal{L} \supset \frac{1}{\Lambda^2} g \left[\bar{\psi}\gamma^\mu\psi\right] \left[\bar{q}\gamma_\mu q\right] + \delta\left(\eta\eta + \xi\xi\right), \qquad \delta \ll m_\chi$$

Mass eigenstates: $\chi_1 = i/\sqrt{2}(\eta - \xi)$, $\chi_2 = 1/\sqrt{2}(\eta + \xi)$

$$\Rightarrow \bar{\psi}\gamma_\mu\psi \simeq i(\bar{\chi}_1\bar{\sigma}_\mu\chi_2 - \bar{\chi}_2\bar{\sigma}_\mu\chi_1)$$

Tucker-Smith Weiner hep-ph/0101138
Cui Morrissey Poland Randall 0901.0557

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- Spin-dependent: E.g. Pseudo-Dirac fermion with tensor interaction

$$\mathcal{L} \supset \frac{1}{\Lambda^2} g \left[\bar{\psi}\Sigma_{\mu\nu}\psi\right] \left[\bar{q}\Sigma^{\mu\nu} q\right] + \delta\left(\eta\eta + \xi\xi\right), \qquad \delta \ll m_\chi$$

with $\Sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$.

$$\Rightarrow \bar{\psi}\Sigma_{\mu\nu}\psi \simeq -2i(\chi_2\sigma_{\mu\nu}\chi_1 + \chi_2^\dagger\bar{\sigma}_{\mu\nu}\chi_1^\dagger)$$

In the non-relativistic limit:

$$\langle N|\bar{q}S_i q|N\rangle(\chi_{2,s'}^\dagger\sigma_i\chi_{1,s})$$

$\Rightarrow$ inelastic interaction, proportional to nuclear spin

WIMP scattering rate

$$\frac{dR^0}{dE_d} \simeq \frac{\rho_0 \sigma_N}{2 m_\chi \mu_{\chi N}^2} F^2(E_d)\ I(v_{\rm min}^0)$$

where

$$I(v_{\rm min}^{\rm WES}) \equiv \int d^3 v \frac{f_\oplus(\vec{v})}{v} \theta(v - v_{\rm min}^{\rm WES}), \qquad v_{\rm min} = \frac{1}{\sqrt{2 m_N E_d}} \left(\frac{m_N E_d}{\mu_{\chi N}} + \delta \right),$$

ρ_0	Local WIMP density (0.3 GeV $\pm\mathcal{O}(100\%)$)
$\mu_{\chi N}$	WIMP-nucleus reduced mass
σ_N	WIMP-nucleus cross section (at $\vec{p} \to 0$)
$F^2(E_d)$	Nuclear form factor
	Depends on nuclear structure computations for SD scattering
$f_\oplus(\vec{v})$	WIMP velocity distribution

Jungman hep-ph/9506380

Nuclear structure: Bednyakov Simkovic hep-ph/0608097, Toivanen Kortelainen Suhonen Toivanen 2009

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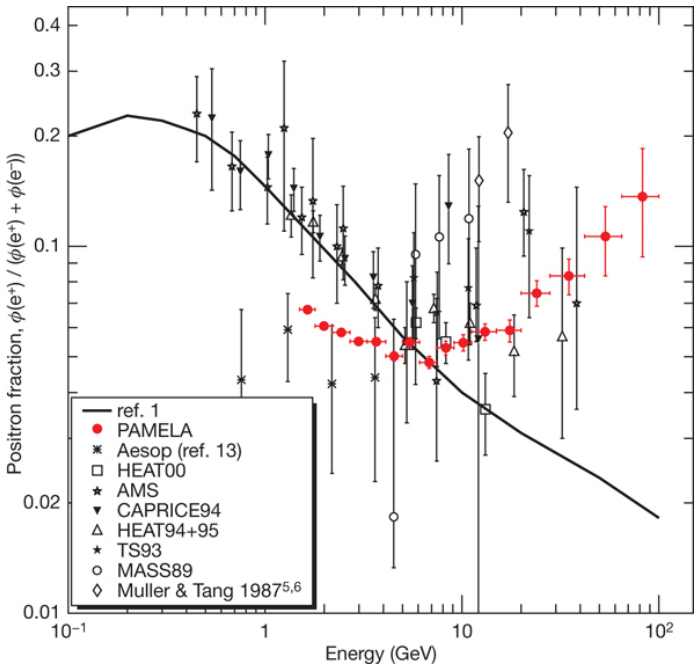
Why leptophilic Dark Matter?



Anomalies in cosmic e^+ and e^- fluxes (but not in $\bar{p}$ flux).

DM coupling predominantly to leptons?

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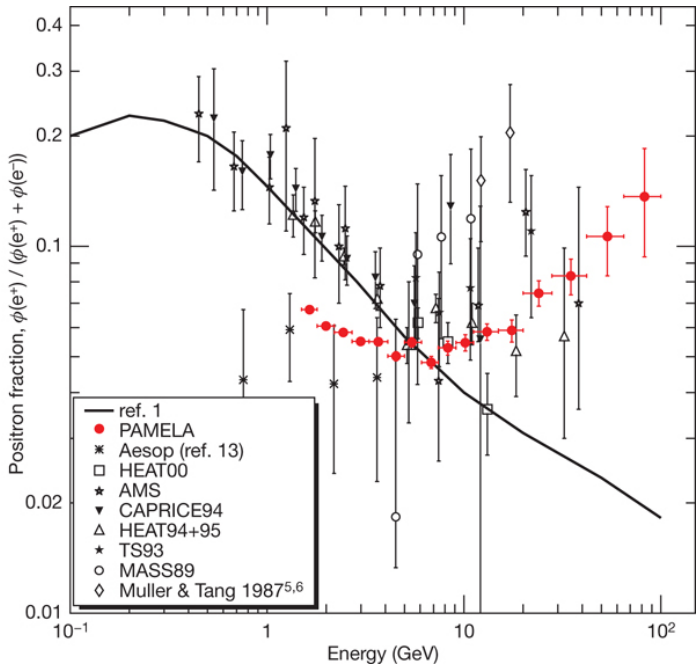

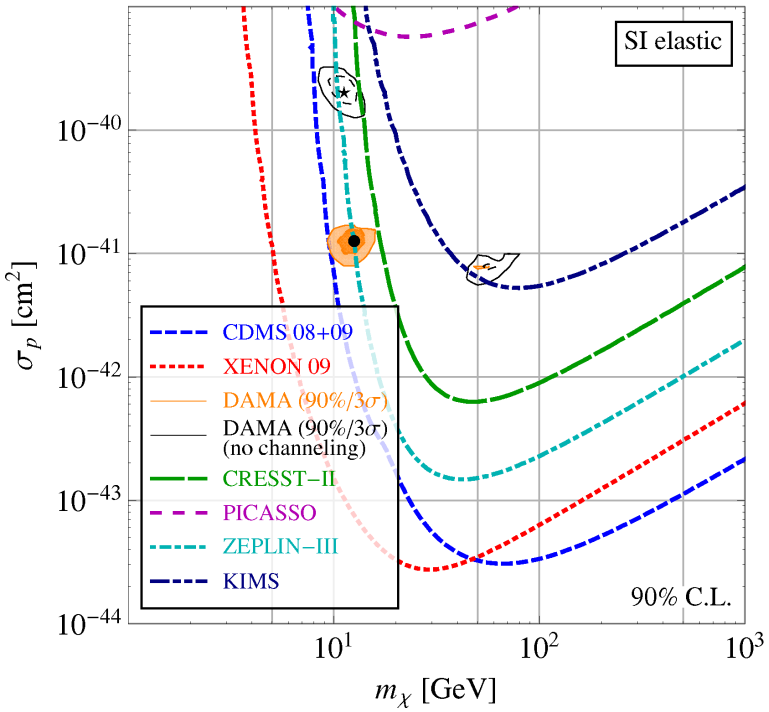

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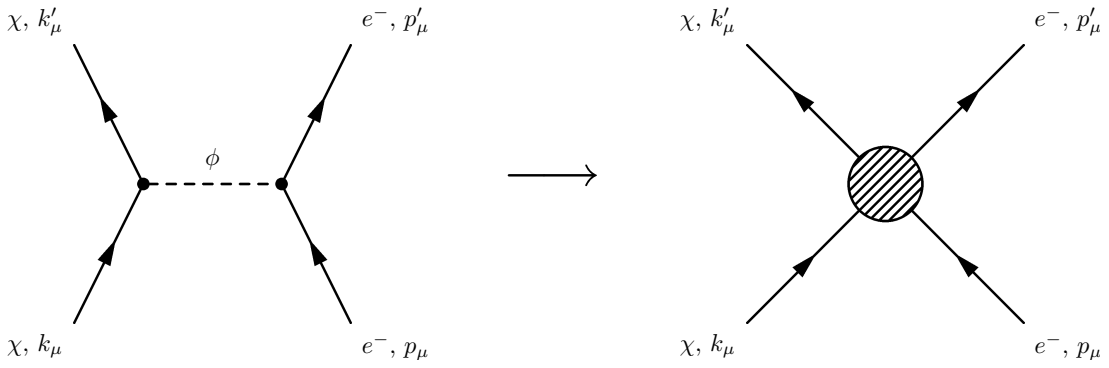
Conflict between DAMA (electron & nuclear recoils) and other experiments (nuclear recoils only).

Leptophilic DM formalism



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If electrons are *bound*, things start to get complicated . . .

4 things a leptophilic WIMP can do in a detector

- Scattering on an electron
  - Outer-shell electrons can be kicked out (WIMP-electron scattering)
  - Inner-shell electrons will remain bound (elastic WIMP-atom scattering) $\longrightarrow$ recoil transferred to nucleus
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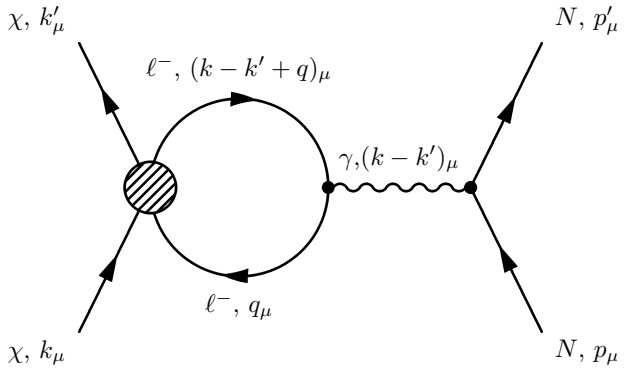
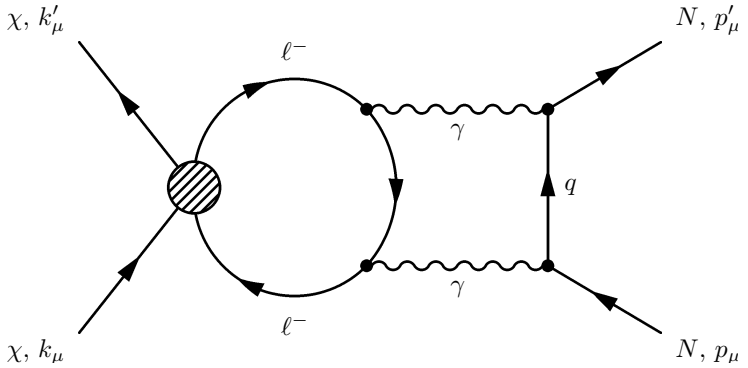
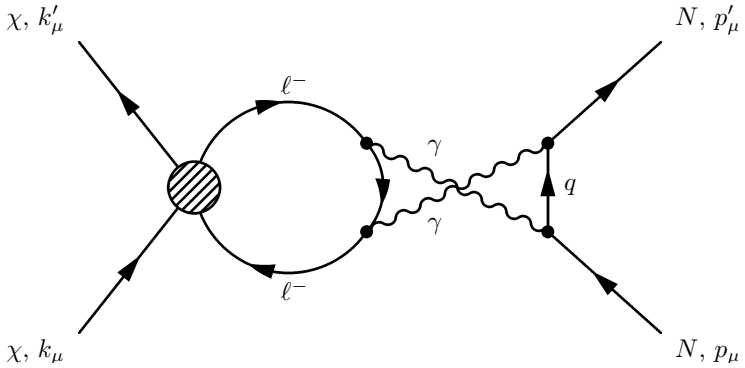
- Loop-induced scattering on the nucleus







WIMP-electron scattering

(Leptophilic DM, $A \otimes A$ interactions)

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- Bound electrons are in energy eigenstates, but not momentum eigenstates.
  $\rightarrow$ Include electron wave function $\chi_{nl}(p)$ in matrix element calculation
- Kinematics more complicated: bound electrons do not fulfill free-particle energy-momentum relation.
  $\rightarrow$ Phase space factors in $d\sigma/dE$ get more complicated.

Rate for WIMP-electron scattering

(Leptophilic DM, $A \otimes A$ interactions)

$$\frac{dR^{\rm WES}}{dE_d} \simeq \frac{3\rho_0 G^2}{4\pi m_\chi} \frac{m_e}{m_N} \sum_{nl} \sqrt{2m_e(E_d - E_{B,nl})}\,(2l+1) \int \frac{dp\,p}{(2\pi)^3} |\chi_{nl}(p)|^2\, I(v_{\rm min}^{\rm WES})$$

where

$$I(v_{\rm min}^{\rm WES}) \equiv \int d^3v \frac{f_\oplus(\vec{v})}{v}\,\theta(v - v_{\rm min}^{\rm WES})\,, \qquad v_{\rm min}^{\rm WES} \approx \frac{E_d}{p} + \frac{p}{2m_\chi}$$

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Compare to the formula for standard WIMPs:

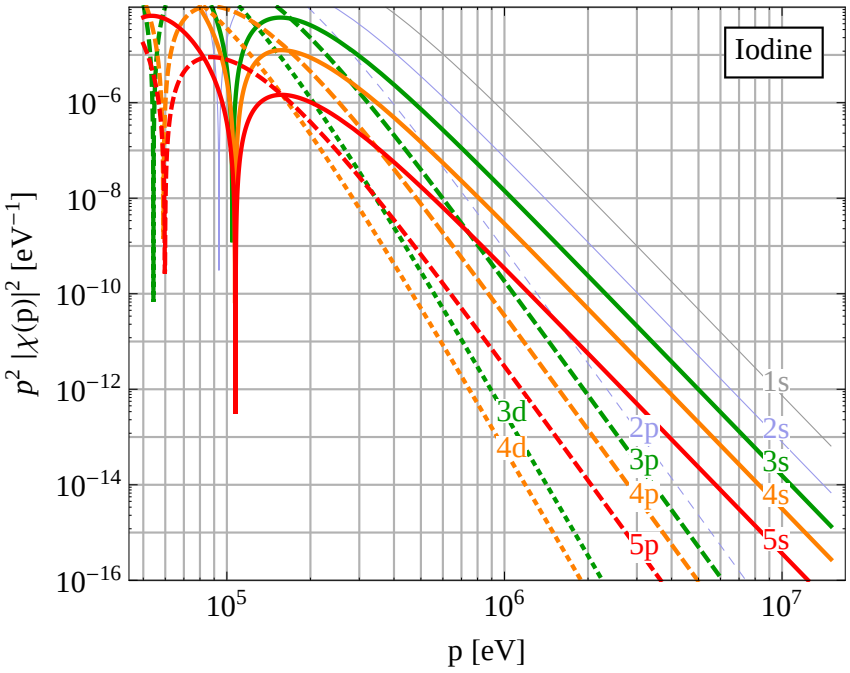
$$\frac{dR^0}{dE_d} \simeq \frac{3\rho_0 G^2}{2\pi m_\chi}\, I(v_{\rm min}^0) \qquad \text{with} \qquad v_{\rm min}^0 = \frac{m_\chi + m_N}{m_\chi}\sqrt{\frac{E_d}{2m_N}}$$

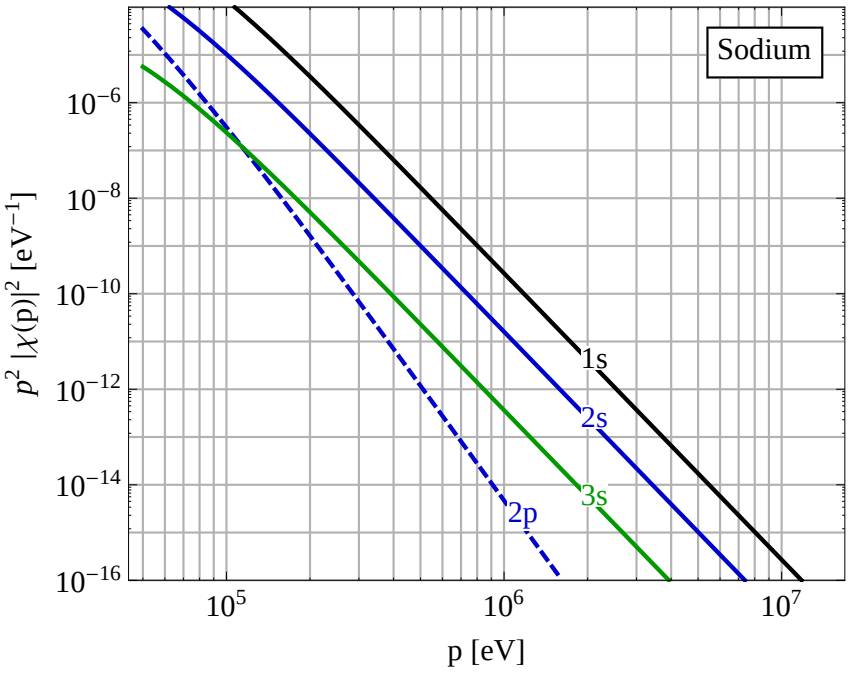
Discussion of WIMP-electron scattering

(Leptophilic DM, $A \otimes A$ interactions)

Suppression factor are:

- m_e/m_N: smallness of electron mass
- Smallness of $|\chi_{nl}(p)|^2$ at $p > 1$ MeV$/c$ (as required for $E_d \sim$ keV).





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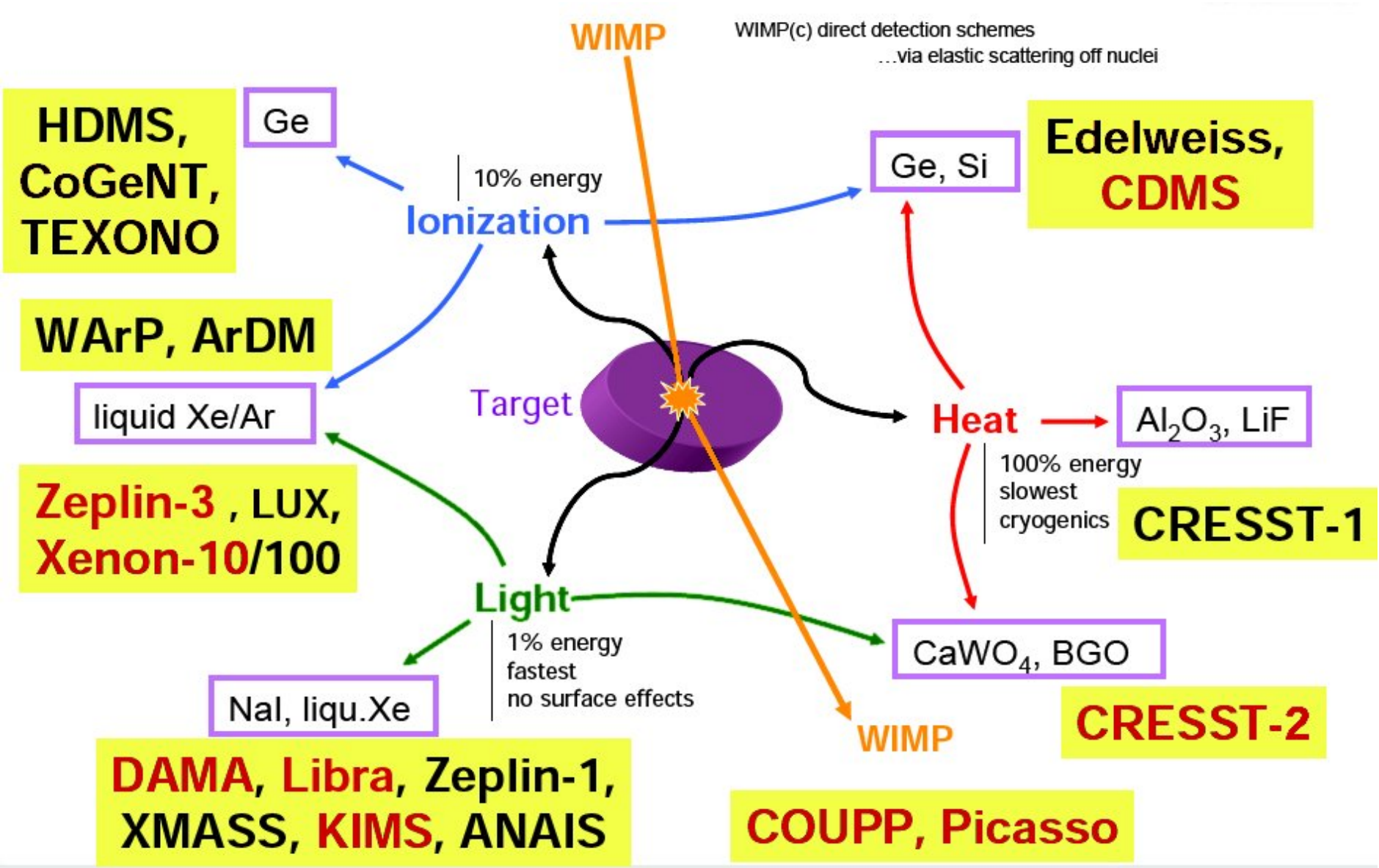
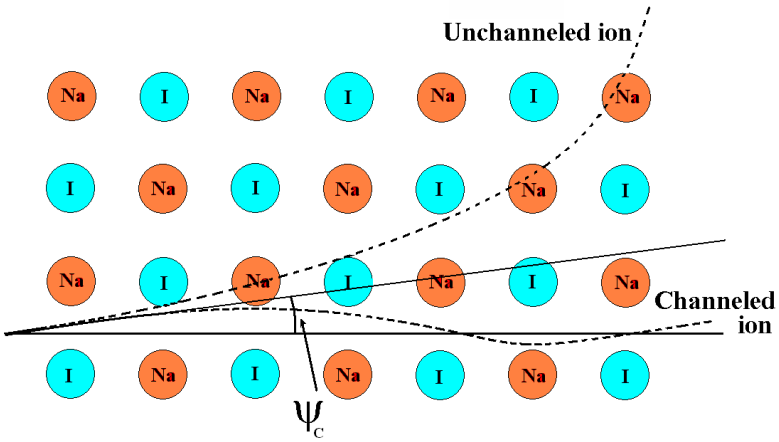
Direct detection experiments

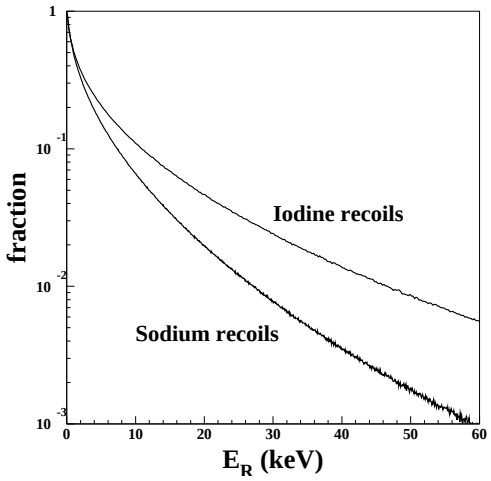


Slide courtesy of K. Eitel

The channeling effect in DAMA

Particles travelling along crystal planes loose their energy electronically
$\rightarrow$ below a critical impact angle ψ_c, there are no quenching factors





DAMA, 0710.0288

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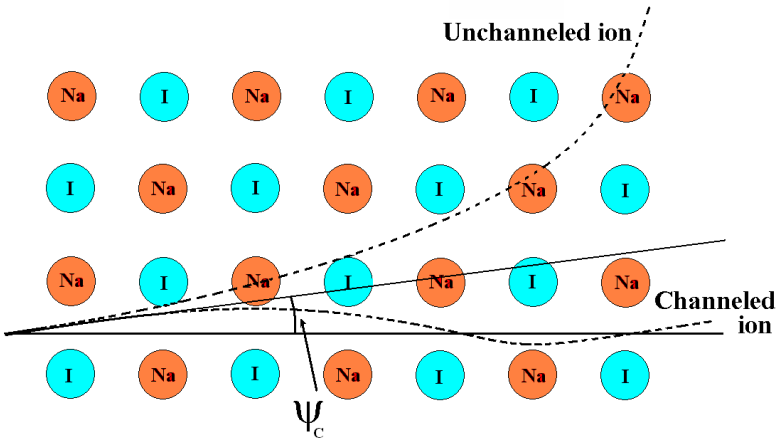

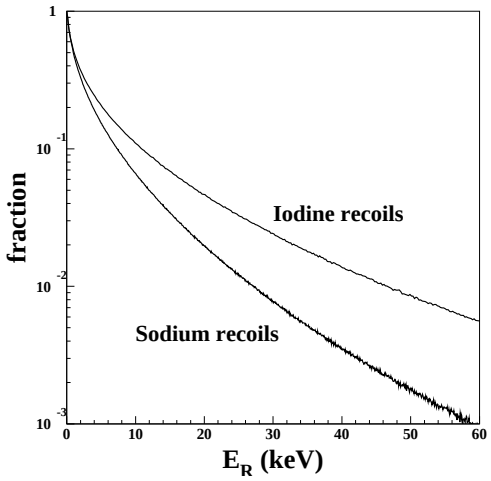

DAMA, 0710.0288

But: Recoil nuclei in a DM experiment start out *in one of the crystal planes*!
$\rightarrow$ for small ψ, nucleus will immediately crash into its nearest neighbor.
$\rightarrow$ channeling requires not only $\psi < \psi_c$, but also $\psi > \psi_{\rm min}$.
Conclusion: DAMA assumptions on channeling probably too optimistic

Graichen et al. Nucl. Instrum. Meth. A **485** (2002) 774, see also Gelmini, 0910.3032
see Feldstein, Fitzpatrick, Katz, Tweedie, 0910.0007 for a discussion of the phenomenology of reduced channeling

Fitting techniques

- DAMA, KIMS: Binned data
  - χ^2 analysis
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- COUPP, PICASSO: Event rates as function of T and p
  - χ^2 analysis including background model with 3 free parameters

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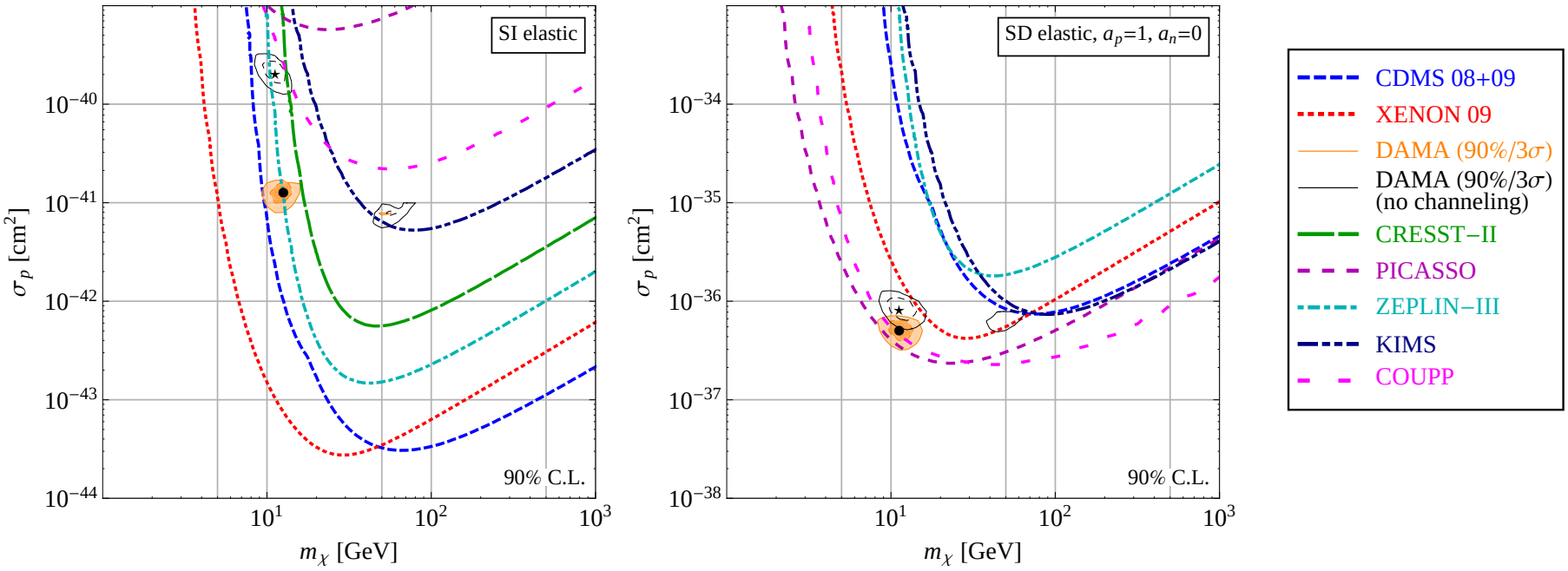
Elastic scattering

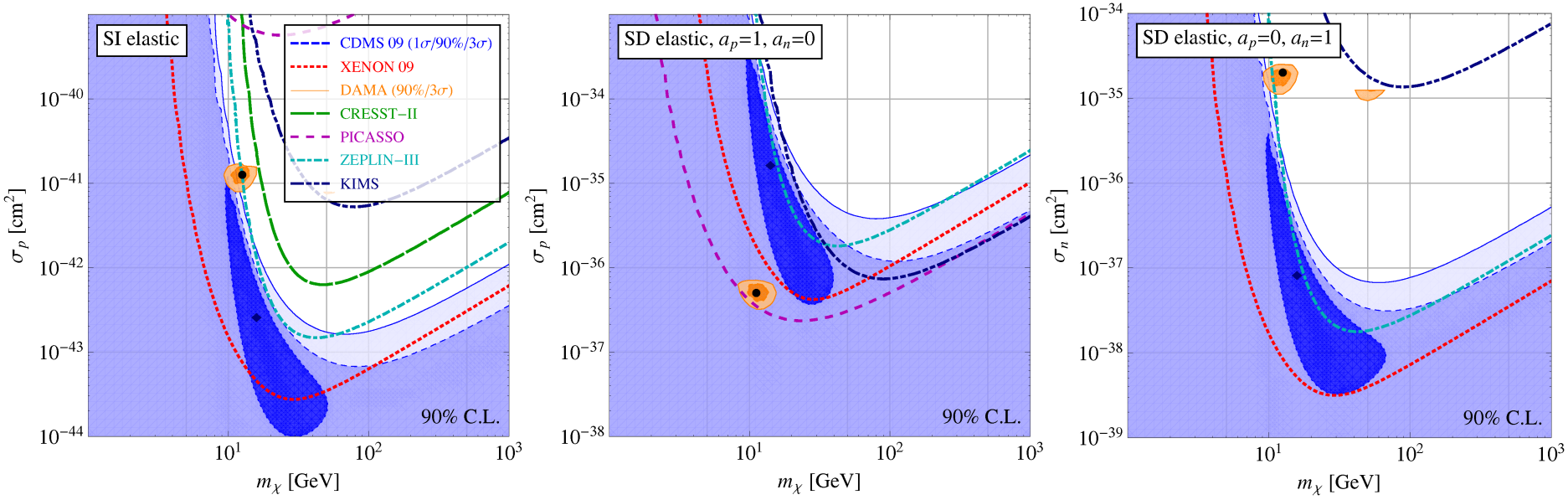


Results:

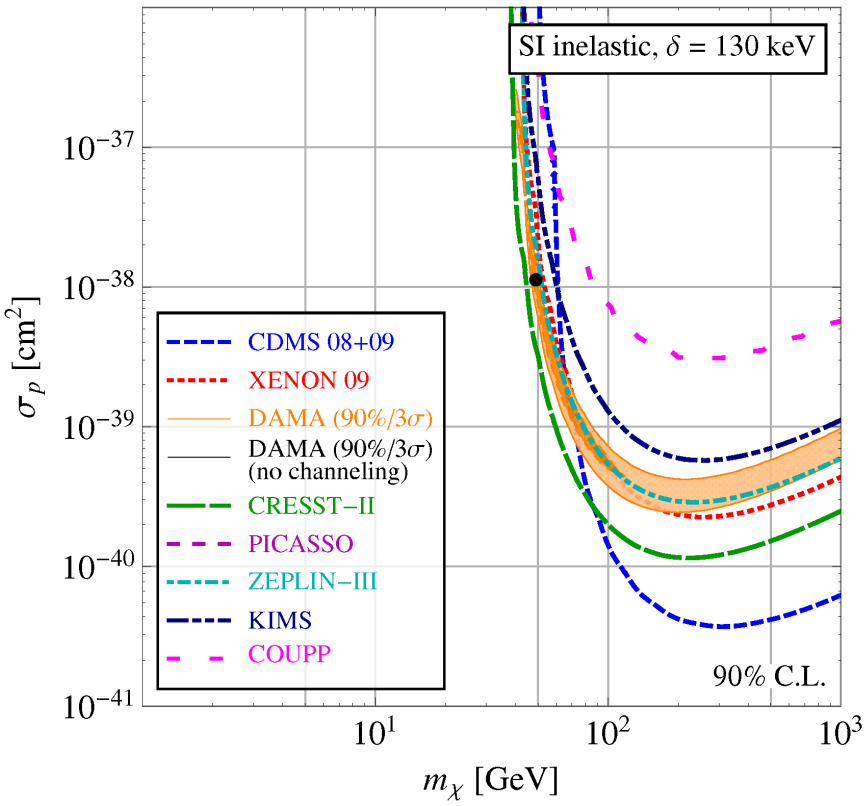
- DAMA-favored region ruled out
- Only a combination of different experiments can give best limits

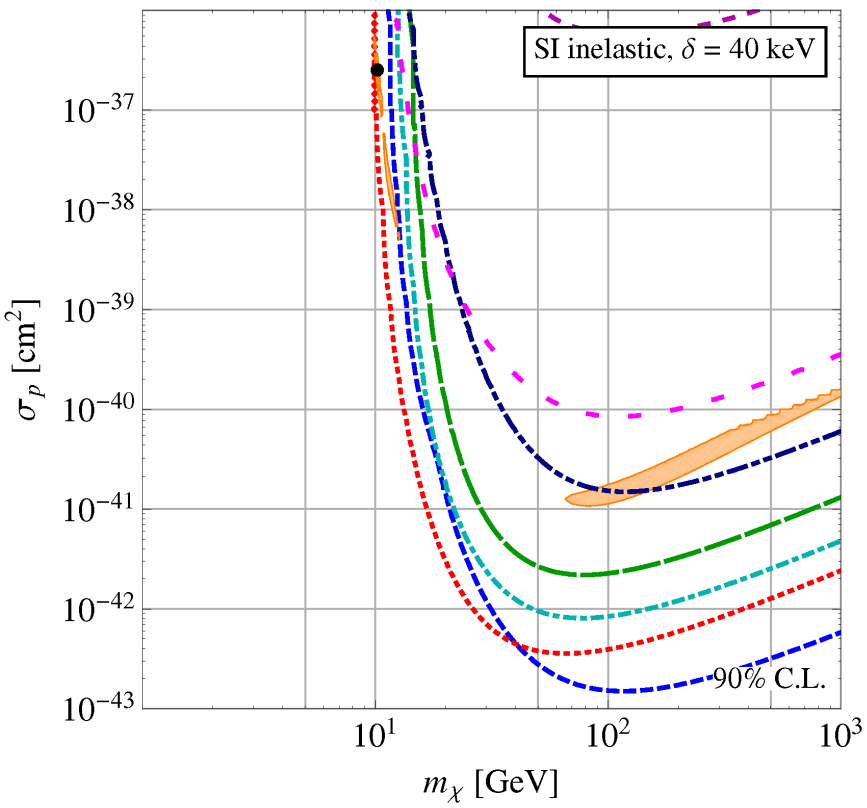
A signal in CDMS?

Pictures without words



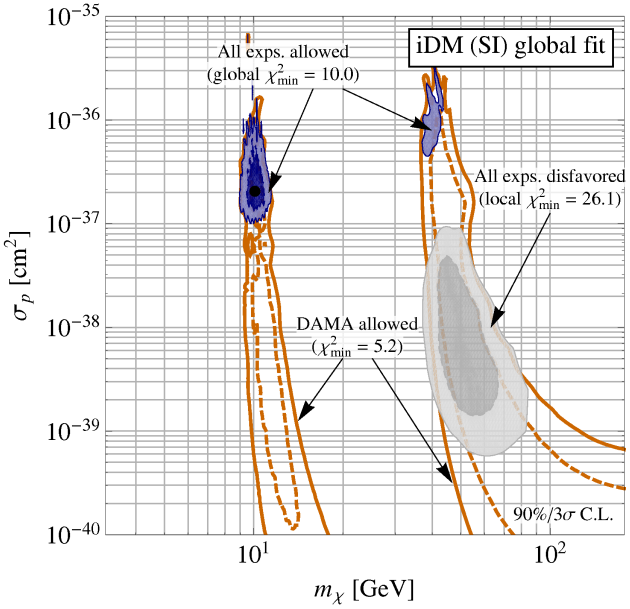
Inelastic SI scattering

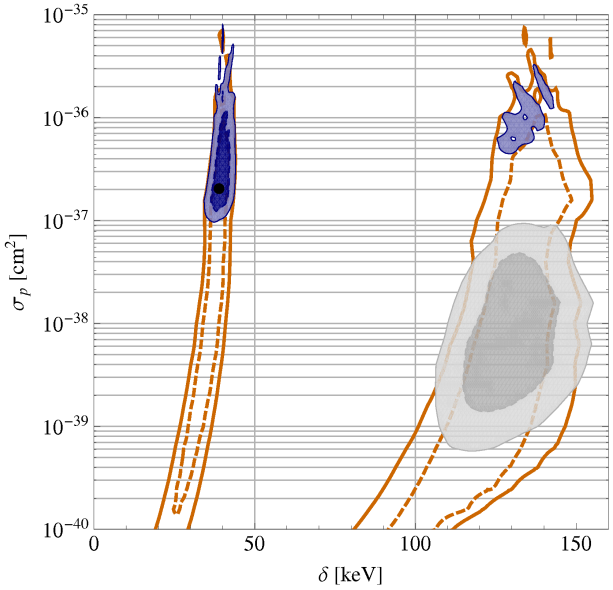


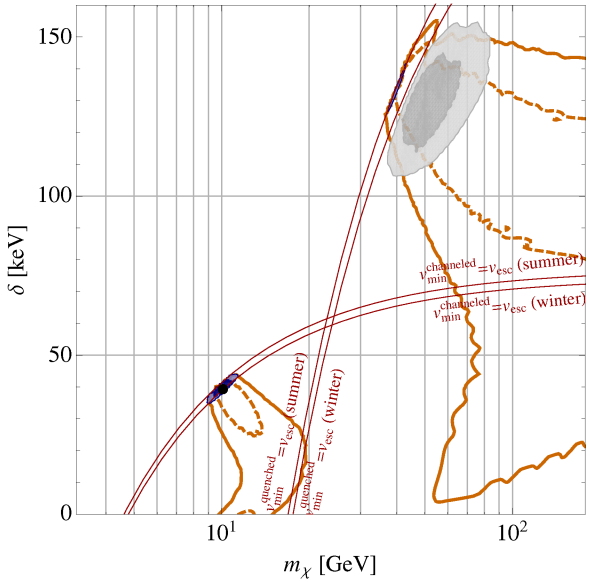


- DAMA marginally compatible with others in tiny region
- Extremely sensitive to the tail of the WIMP velocity distribution $f_\oplus(\vec{x})$

Inelastic SI scattering — Global fit

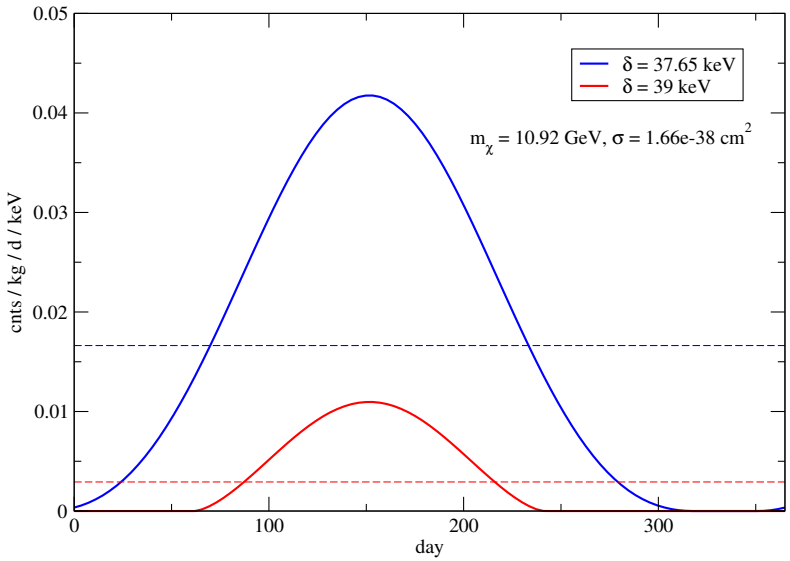






- Strong fine-tuning between particle physics parameters and halo profile.

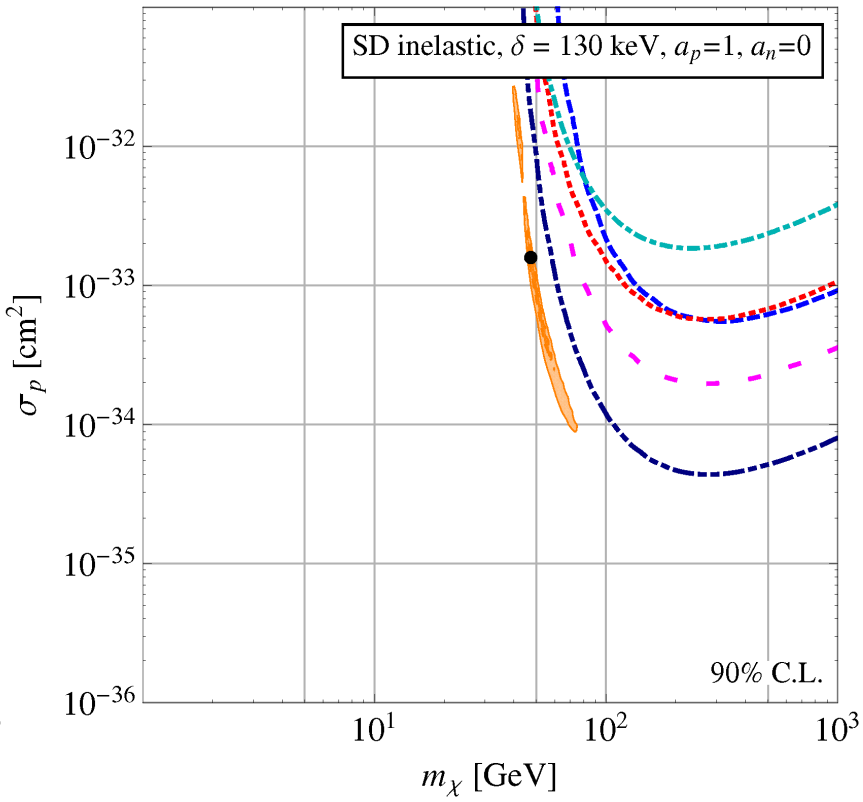
Inelastic SI scattering — Global fit (2)

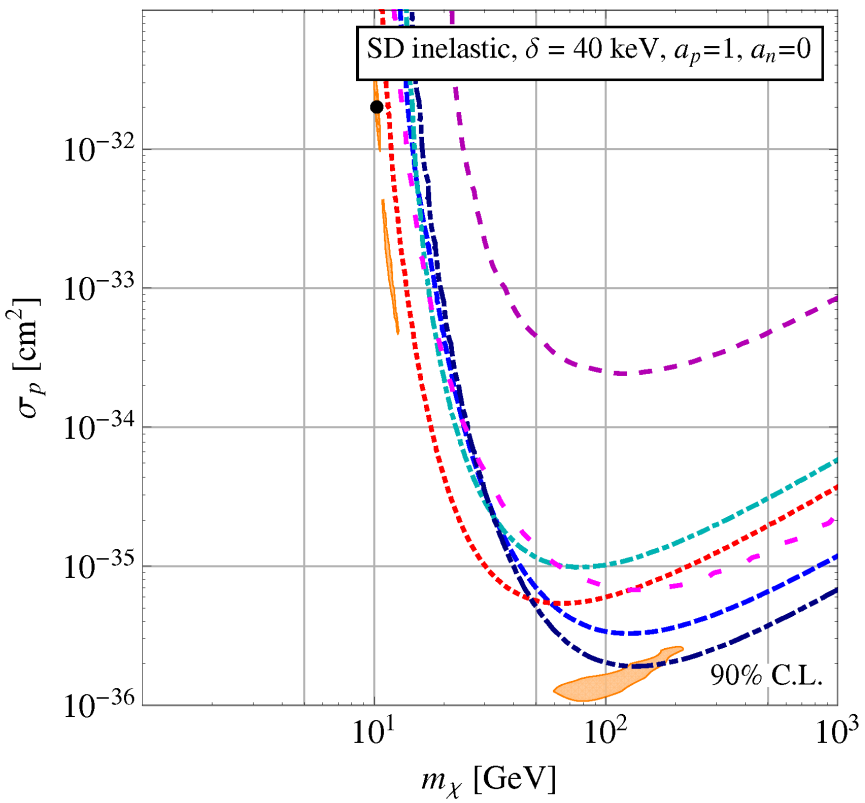


At the best fit point:

- Signal only in summer
- Cosine fit to DAMA no longer possible

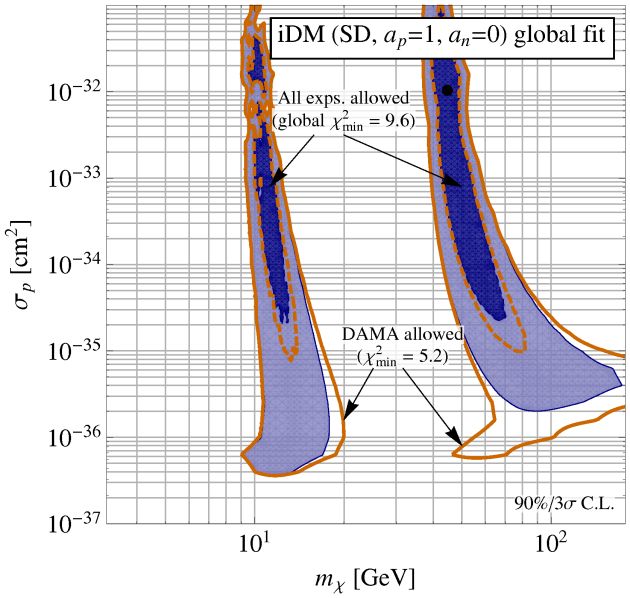
Inelastic SD scattering

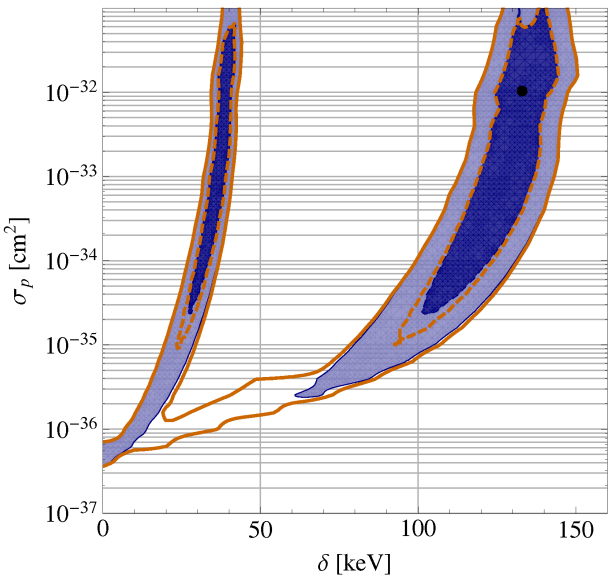


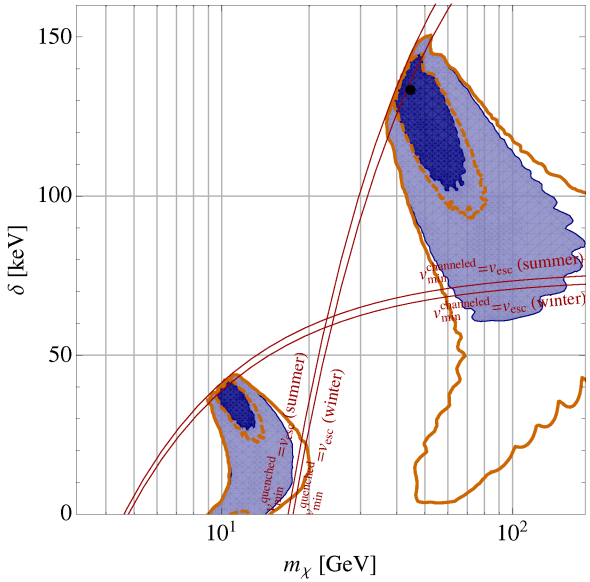


- Better compatibility between DAMA and the rest
- Still sensitive to the tail of the WIMP velocity distribution $f_\oplus(\vec{x})$

Inelastic SD scattering — Global fit

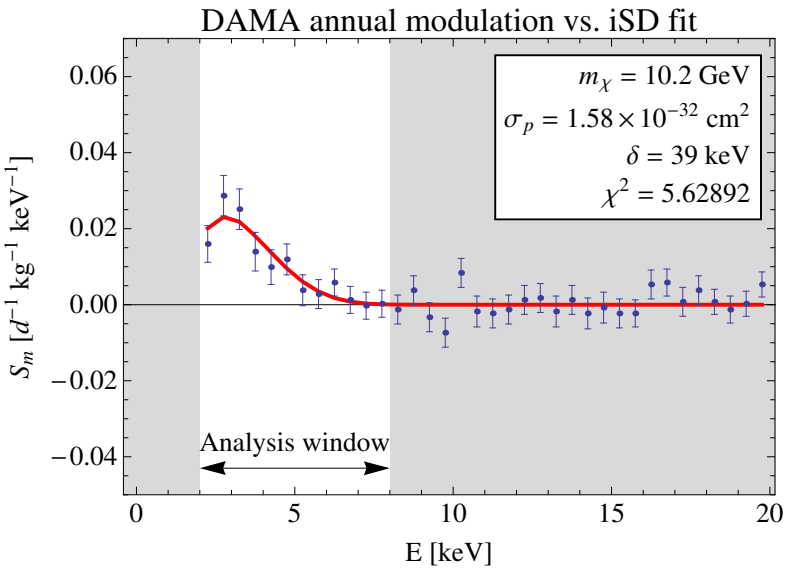


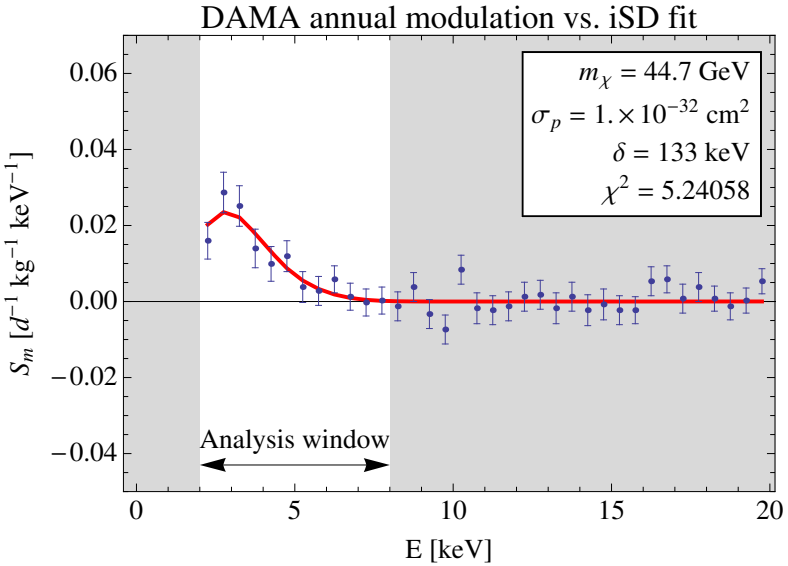




- No tuning between particle physics and astrophysics parameters
- DM experiments would have very good sensitivity to parameters (particle & astro)

Inelastic SD scattering — Quality of fit





- Excellent fit to the DAMA specrum

Outline

1. Prologue: Phenomenology of Dark Matter interactions
   - WIMP-nucleus scattering
   - Leptophilic dark matter
2. Dramatis personae: Direct detection experiment
3. Act I: Global constraints on WIMP-nucleon interactions
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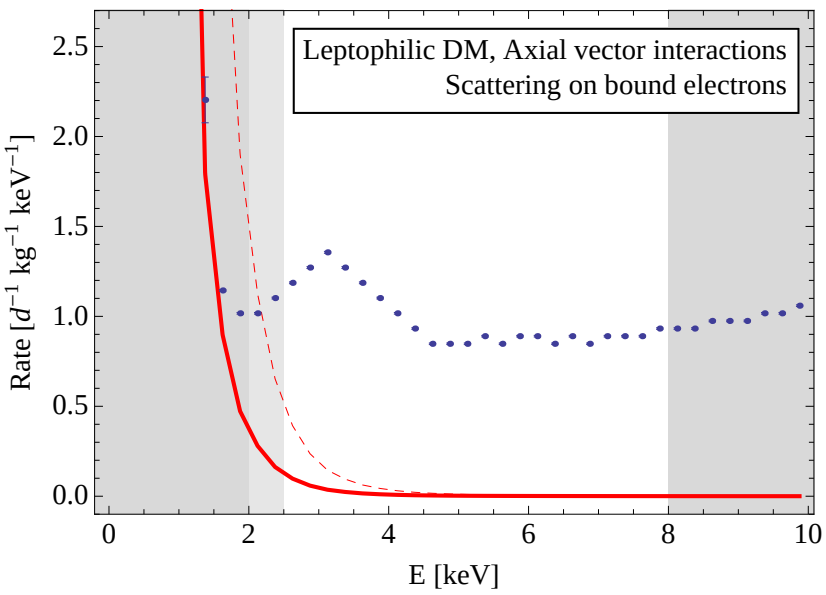
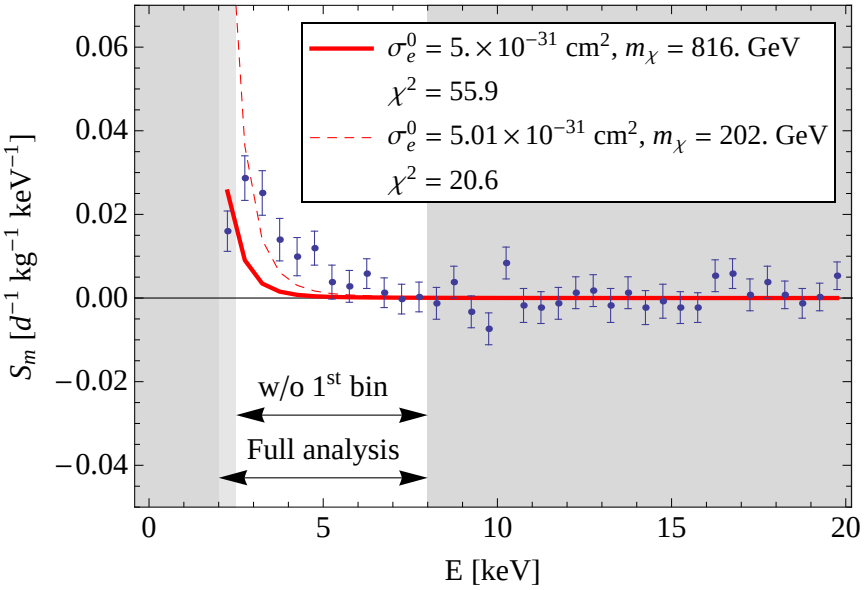
Leptophilic DM with $A \otimes A$ interactions

(Dominated by WIMP-electron scattering)

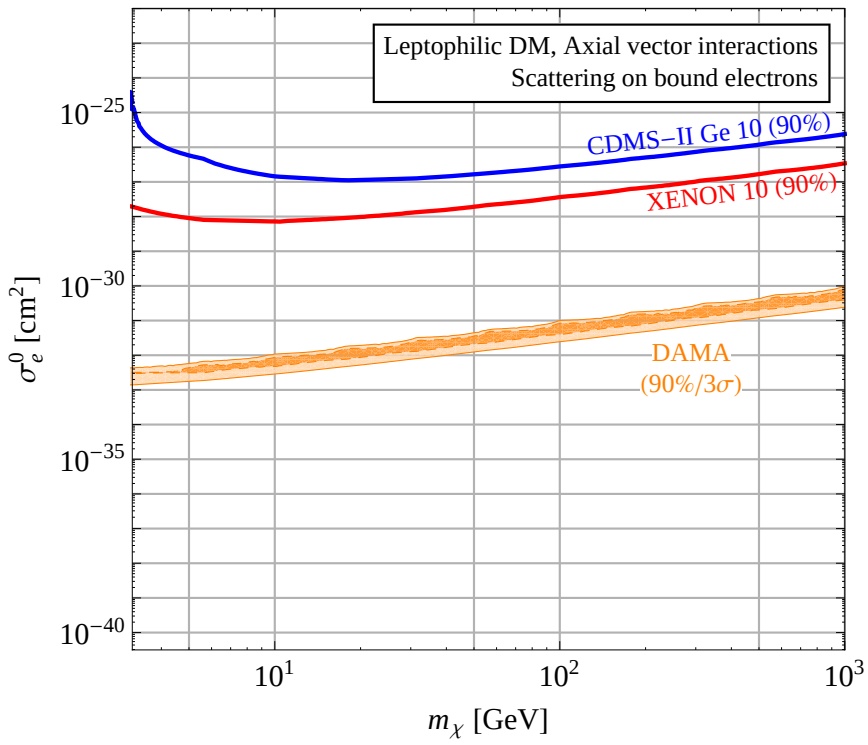




- Poor spectral fit
- Extremely high rates predicted at low energy
- Fit requires very large cross sections

Leptophilic DM with $A \otimes A$ interactions (2)

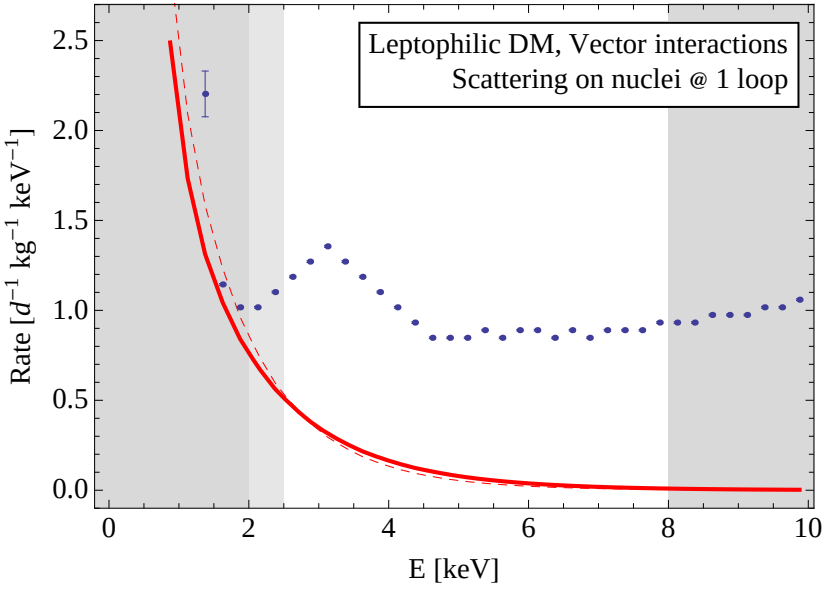
(Dominated by WIMP-electron scattering)

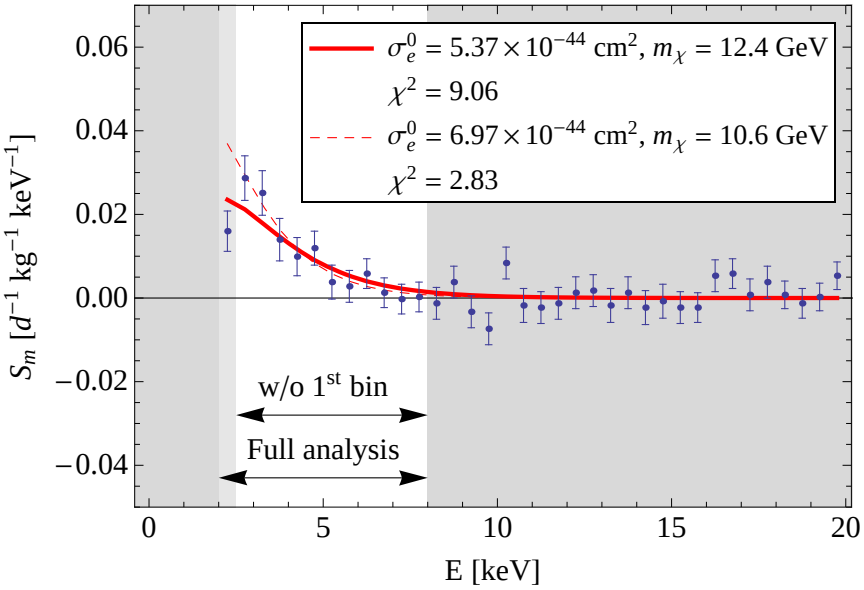


- Signal in DAMA from inelastic WIMP-electron scattering
- Signal in CDMS/XENON from inelastic WIMP-atom scattering
- Allowed region in $\Delta\chi^2$ fit, but remember poor quality of fit

Leptophilic DM with $V \otimes V$ interactions

(Dominated by WIMP-nucleus scattering)





- Same spectrum as for conventional WIMPs
- Cannot explain the lowest DAMA bin

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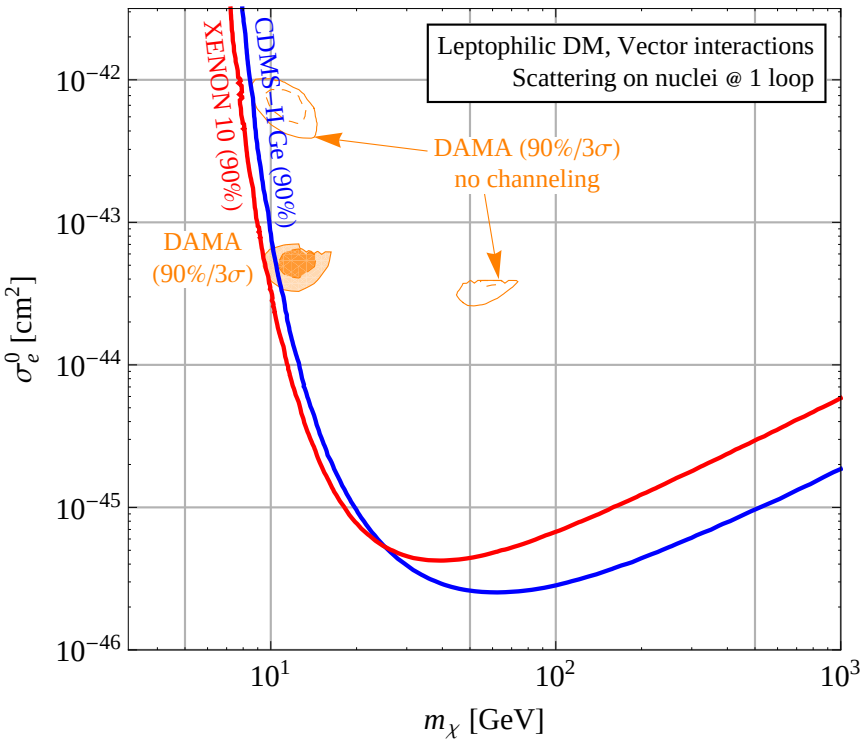

- Same situation as for conventional WIMPs: Conflict between DAMA and CDMS/XENON.

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Scattering of leptophilic Dark Matter in the Sun

- Tree level scattering on *free* electrons
  $\longrightarrow$ no suppression by wave function or atomic matrix elements
  $\longrightarrow$ But energy loss in each scattering process is small since $m_e \ll m_\chi$.

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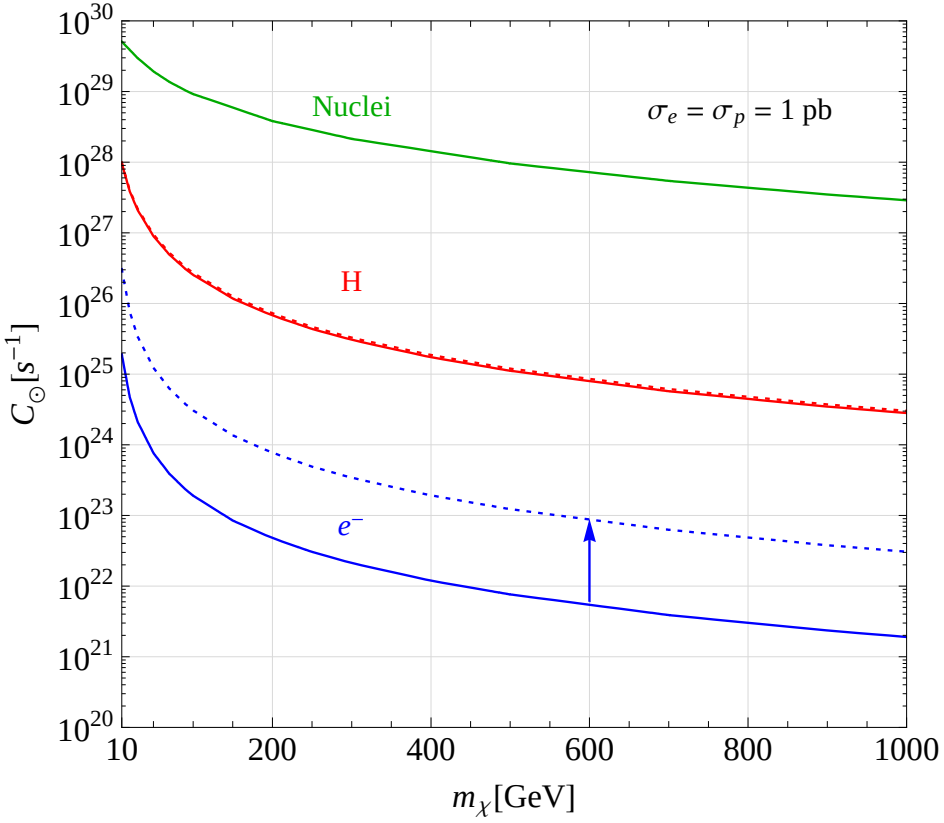

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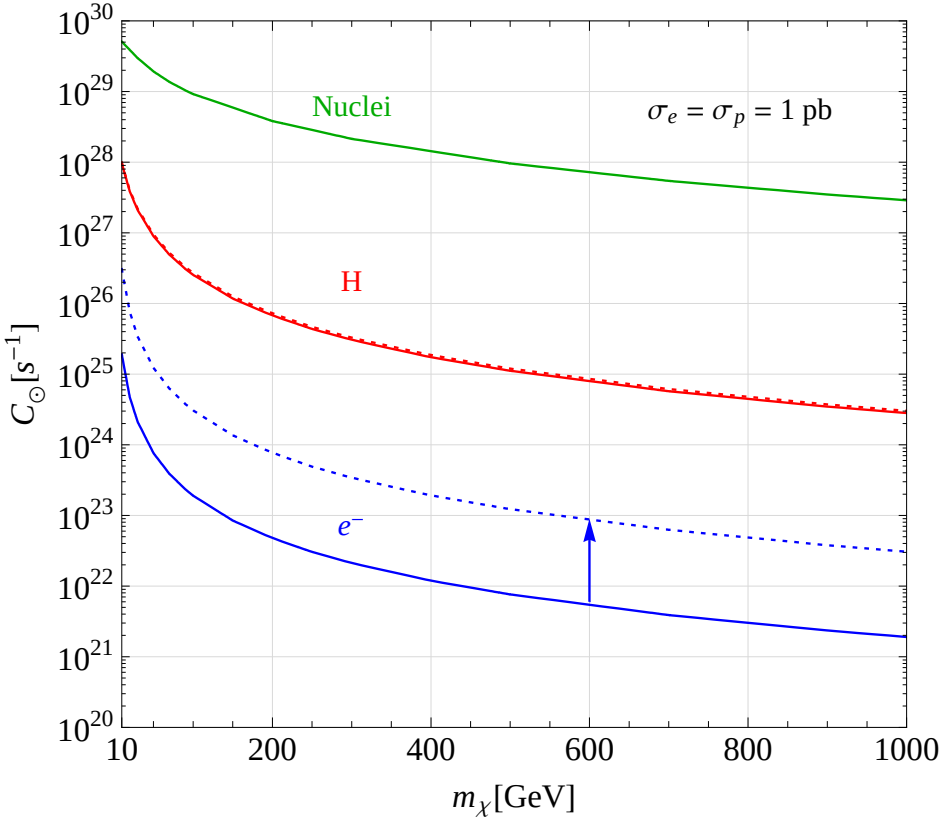
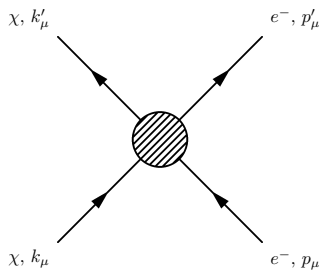


- Loop-induced scattering on heavy nuclei dominates if allowed (more efficient energy loss)

Neutrinos from annihilation of leptophilic Dark Matter



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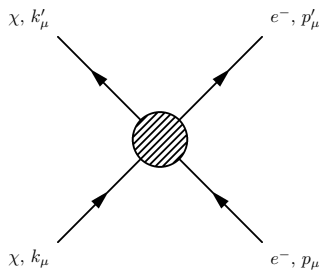

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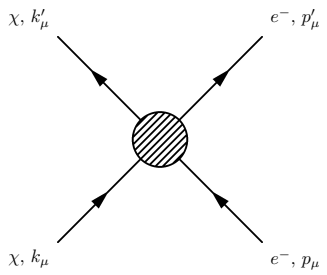

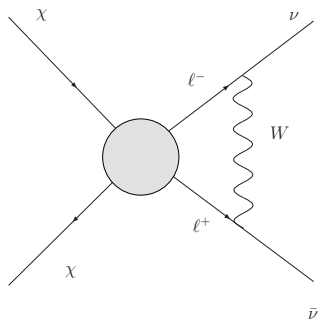

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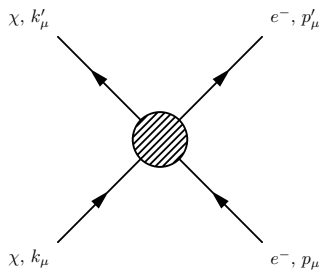

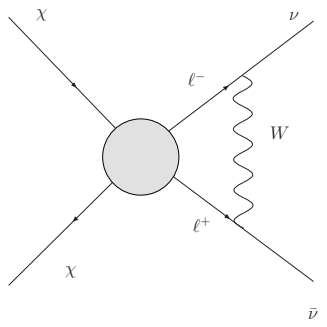

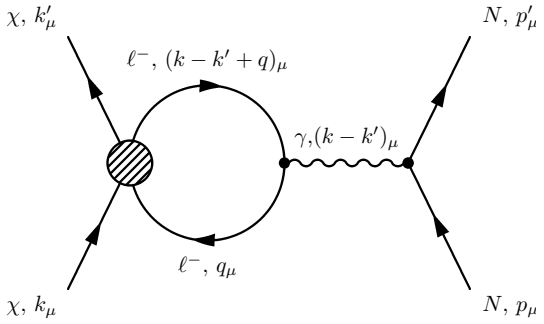

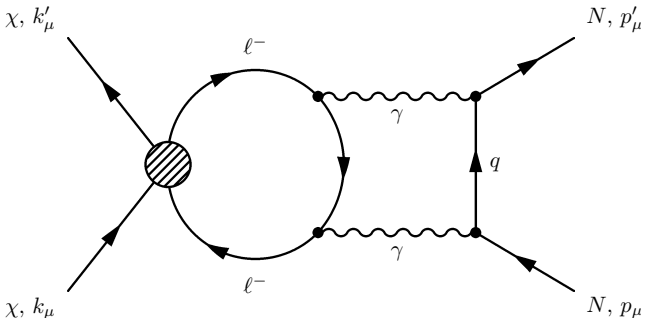

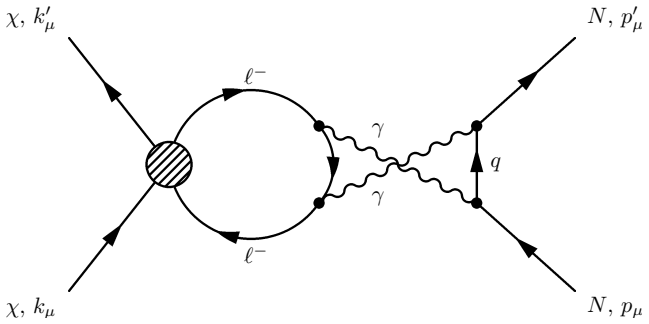

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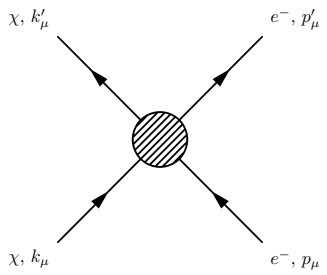
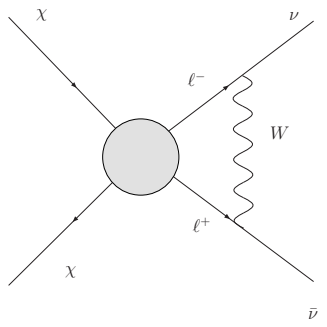
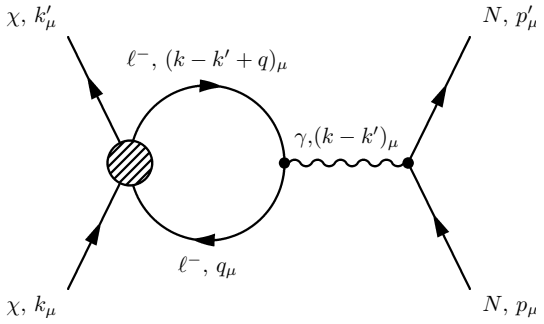
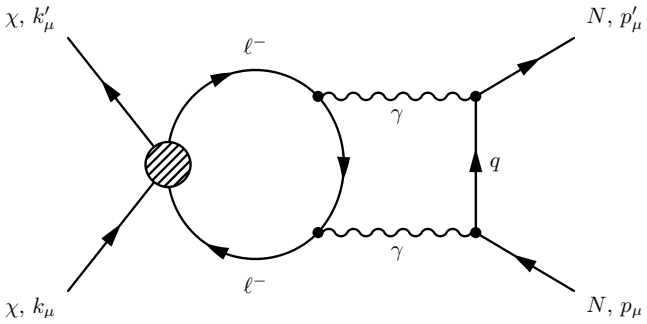
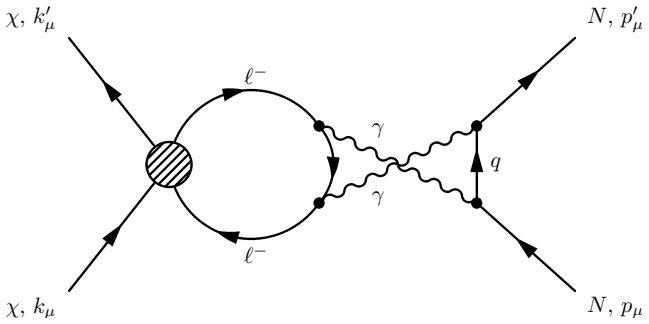








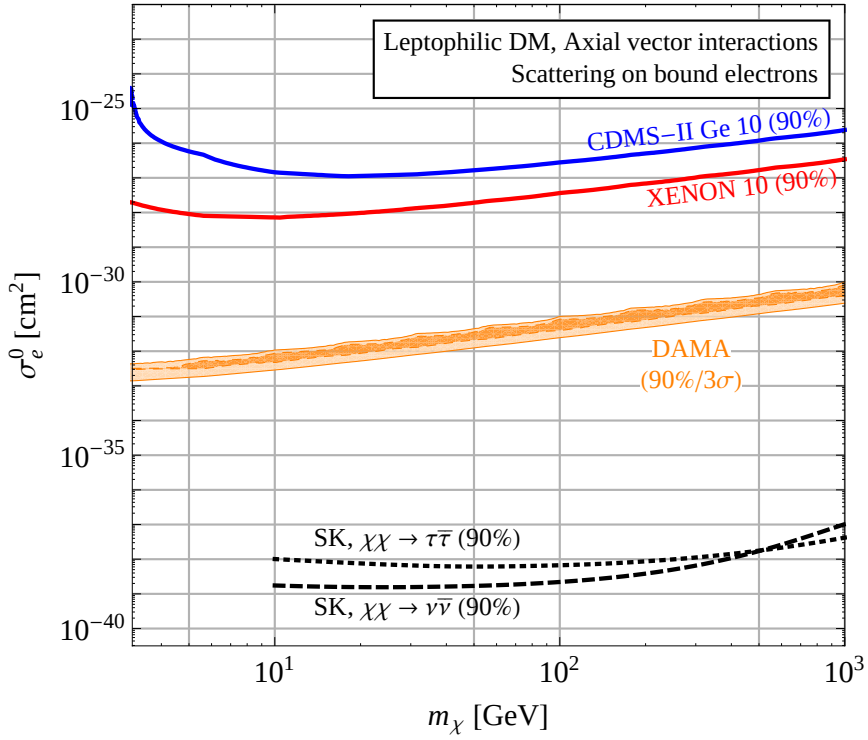


Only way to jeopardize interesting annihilation signals: χ-$\bar{\chi}$ asymmetry.

see e.g. Kaplan, Luty, Zurek, 0901.4117 for a recent work on asymmetric DM

Super-K bounds on leptophilic DM

$A \otimes A$



- Super-K by far the most sensitive experiment
- Excludes DAMA-favored region

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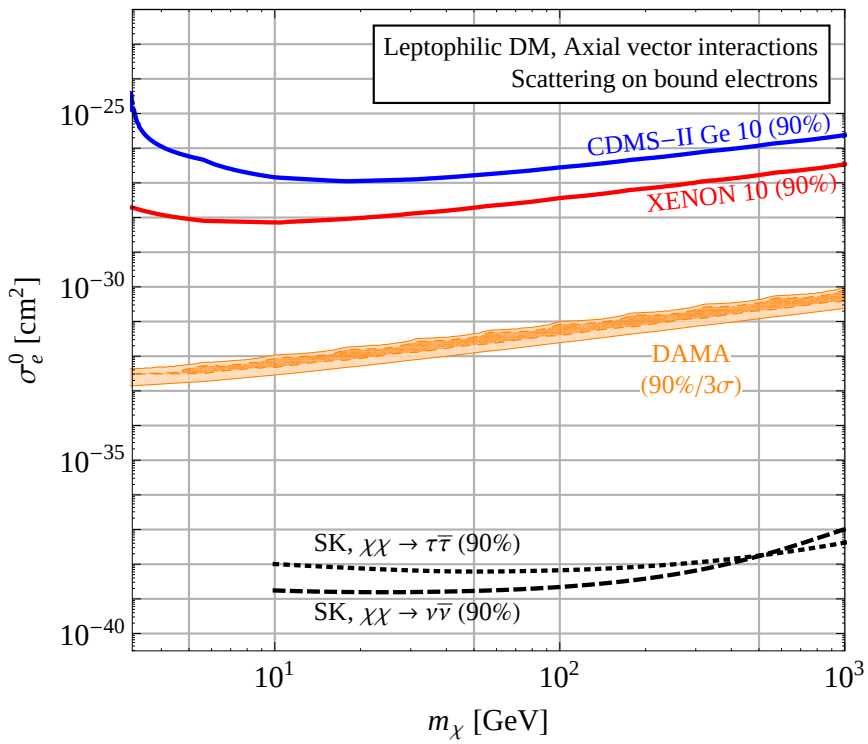

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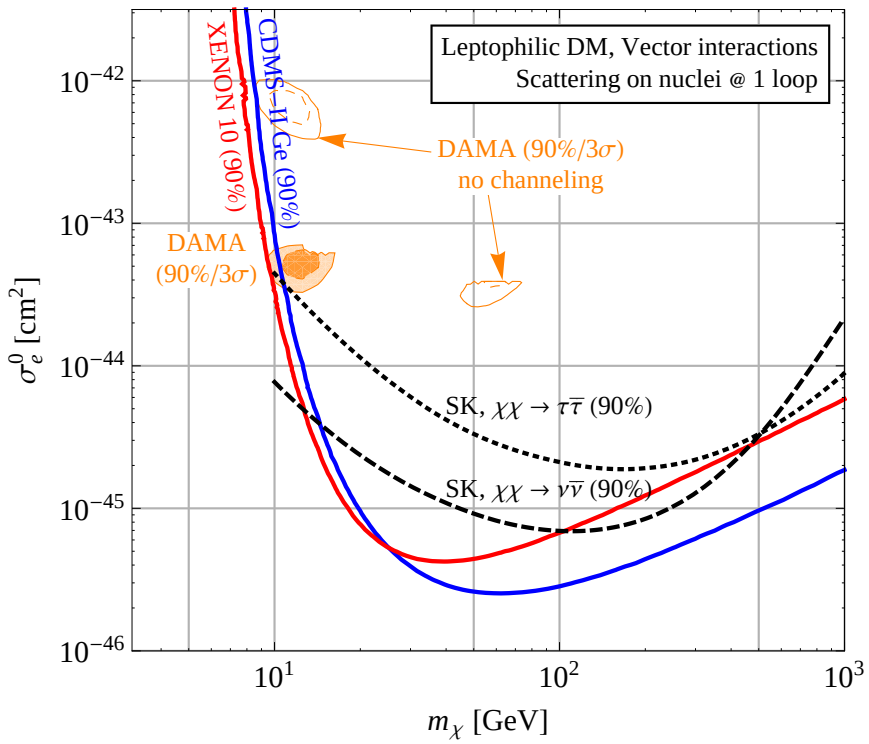

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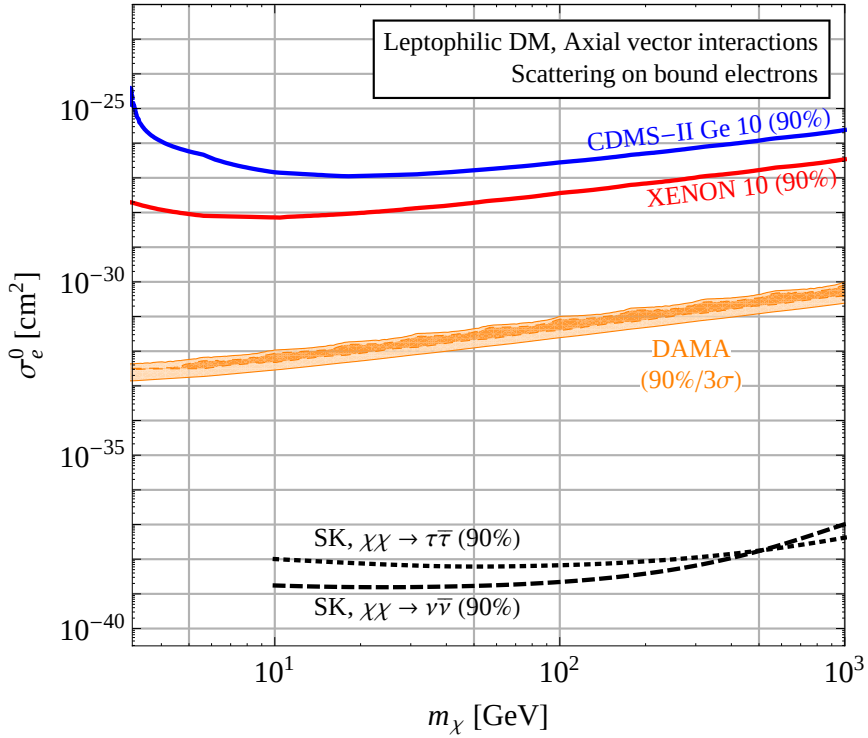

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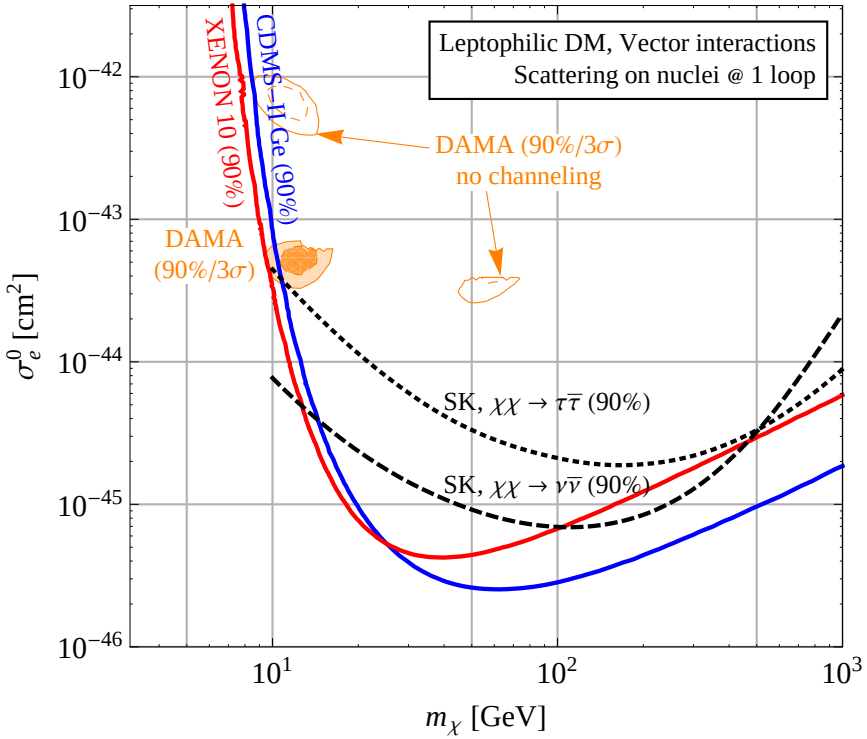

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but remember: Super-K not as model-independent as DAMA, CDMS, XENON

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- Inelastic spin-dependent scattering (iSD)
  - Can explain DAMA
  - If true, direct detection experiments have high sensitivity to model parameters
  - Only from tensor interactions

Summary II — Leptophilic DM

- Leptophilic DM well-motivated by recent data
- Rich phenomenology in direct detetcion experiments
  - WIMP-electron scattering
    $\longrightarrow$ strongly suppressed by smallness of e^- wave function at large p.
  - Elastic WIMP-atom scattering
    $\longrightarrow$ Even stronger suppression from electronic matrix elements (sometimes completely absent due to cancellations)
  - Inelastic WIMP-atom scattering
    $\longrightarrow$ Again, strong suppression from electronic matrix elements
  - WIMP-nucleus scattering (via loops)
    $\longrightarrow$ always dominant if allowed
- Leptophilic Dark Matter in the Sun
  - If scattering on e^- dominates, interesting finite-T effects.
  - Neutrino signals almost unavoidable (except if there is a χ-$\bar{\chi}$ asymmetry)
- Results:
  - Leptophilic DM constrained by CDMS, XENON, ...
  - Cannot explain DAMA
  - Strong bounds from Super-K.

Thank you!

Backup slides

Spin-independent elastic scattering (eSI)

$$\sigma_N^{\rm SI} = \frac{[Zf_p + (A-Z)f_n]^2}{f_p^2} \frac{\mu_{\chi N}^2}{\mu_{\chi p}^2} \sigma_p^{\rm SI}$$

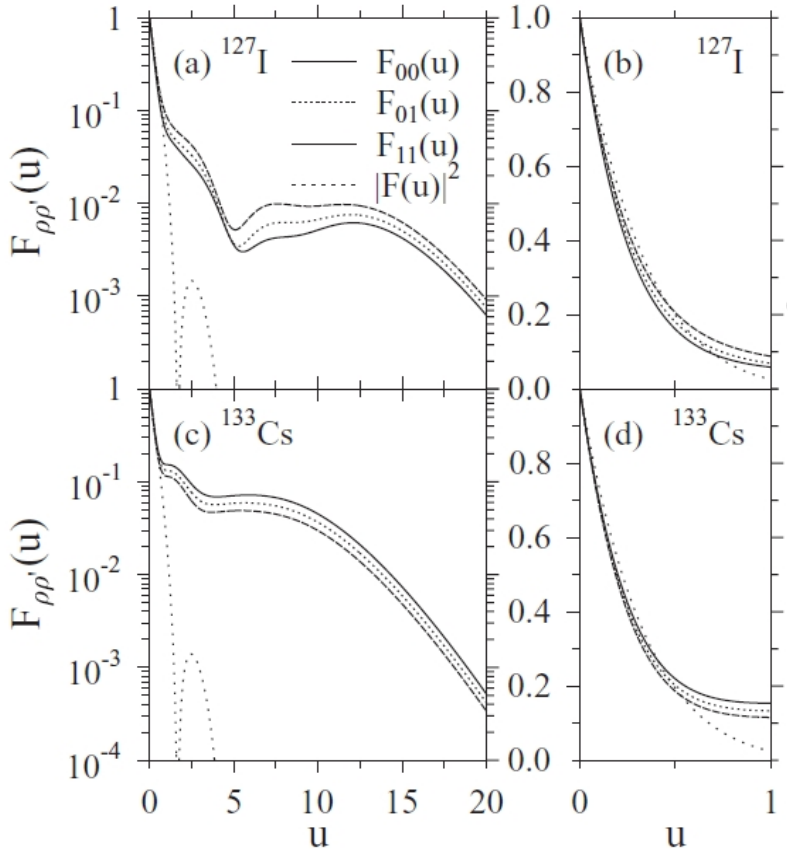
$f_{p,n}$ Coupling to protons/neutrons (usually $f_p = f_n$)

Spin-dependent elastic scattering (eSD)

- For a long time a possible explanation of the DAMA anomaly
- Fit requires spin-dependent structure functions $S(E_d)$

$$\sigma^{\rm SD} S(E_d) = \frac{4\mu_{\chi N}^2 \pi}{3\mu_{\chi p}^2 a_p^2 (2J+1)} [a_0^2 S_{00}(q) + a_0 a_1 S_{01}(q) + a_1^2 S_{11}(q)]\, \sigma_p^{\rm SD}$$

- . . . which have to be calculated from nuclear structure models (= large uncertainty)



8097, 2009

A leptophilic Dark Matter model

- $U(1)_{DS}$ dark sector
- Dark Matter is a Dirac fermion charged under $U(1)_{DS}$

$$\mathcal{L}_{DS} = -\frac{1}{4} F'^2_{\mu\nu} + \overline{\chi}\gamma^\mu D_\mu \chi + |D_\mu \phi|^2 - M_\chi \overline{\chi}\chi - V_{DS}(\phi) \ .$$

Fox, Poppitz, 0811.0399

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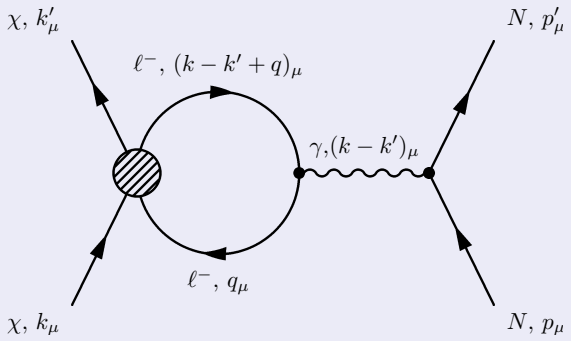
- $U(1)_{DS}$ exchange provides Sommerfeld enhancement

Fox, Poppitz, 0811.0399

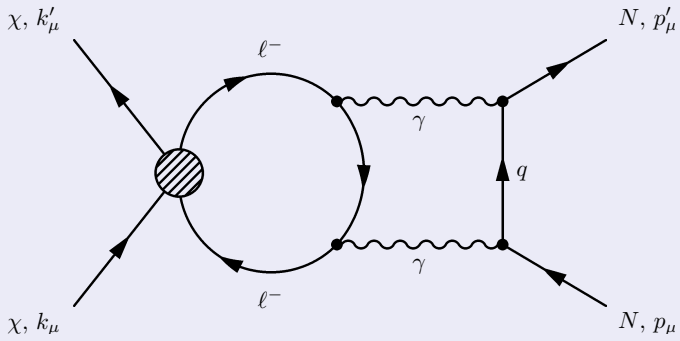
Loop-induced WIMP-nucleus scattering
(Leptophilic DM, $V \otimes V$ interactions)

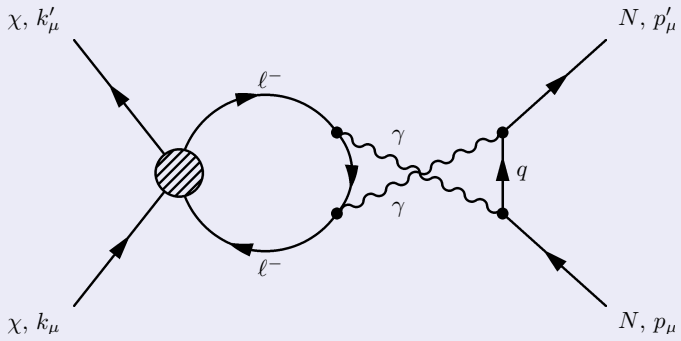
One-loop



- For $V \otimes V$, $A \otimes V$, $T \otimes T$, and $AT \otimes T$ Lorentz structures

Two-loop





(The lowest order diagrams for the $S \otimes S$ and $P \otimes S$ Lorentz structures)

Rate for loop-induced WIMP-nucleus scattering

(Leptophilic DM, $V \otimes V$ interactions, one-loop)

$$\frac{dR^{\rm WNS}}{dE_d} = \frac{\rho_0 G^2}{18\pi\, m_\chi} \left(\frac{\alpha Z}{\pi}\right)^2 F^2(q) \left[\log\left(\frac{m_\ell^2}{\mu^2}\right)\right]^2 I(v_{\rm min}^{\rm WNS})\,,$$

where

$$v_{\rm min}^{\rm WNS} = \frac{m_\chi + m_N}{m_\chi}\sqrt{\frac{E_d}{2m_N}}$$

Rate for loop-induced WIMP-nucleus scattering

(Leptophilic DM, $V \otimes V$ interactions, one-loop)

$$\frac{dR^{\rm WNS}}{dE_d} = \frac{\rho_0 G^2}{18\pi\, m_\chi} \left(\frac{\alpha Z}{\pi}\right)^2 F^2(q) \left[\log\left(\frac{m_\ell^2}{\mu^2}\right)\right]^2 I(v_{\rm min}^{\rm WNS})\,,$$

where

$$v_{\rm min}^{\rm WNS} = \frac{m_\chi + m_N}{m_\chi}\sqrt{\frac{E_d}{2m_N}}$$

Compare to the formula for standard WIMPs:

$$\frac{dR^0}{dE_d} \simeq \frac{3\rho_0 G^2}{2\pi m_\chi} I(v_{\rm min}^0) \qquad \text{with} \qquad v_{\rm min}^0 = \frac{m_\chi + m_N}{m_\chi}\sqrt{\frac{E_d}{2m_N}}$$

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→ Suppressed only by α^2

→ Loop-induced scattering on the nucleus will dominate whenever it is allowed!

Elastic WIMP-atom scattering

- Coherent scattering on all electrons
- Depends on atomic form factor, computable from the electron wave functions.

Rate for elastic WIMP-atom scattering

($A \otimes A$ case)

$$\frac{dR^{\mathrm{WAS-el}}}{dE_d} = \frac{3\rho_0 G^2}{2\pi\, m_\chi} \left| \sum_{nlms} \langle nlms | e^{i(\vec{k}-\vec{k}')\vec{x}} | nlms \rangle \right|^2 I(v_{\mathrm{min}}^{\mathrm{WAS-el}}) \,,$$

where

$$v_{\mathrm{min}}^{\mathrm{WAS-el}} = \frac{m_\chi + m_N}{m_\chi} \sqrt{\frac{E_d}{2m_N}}$$

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$\rightarrow$ Suppression by smallnes of matrix elements $\langle nlms | e^{i(\vec{k}-\vec{k}')\vec{x}} | nlms \rangle$ at large $|\vec{k} - \vec{k}'|$ (as required for $E_d \sim$ keV)

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→ For the $A \otimes A$ case, $\sum_s \bar{u}_e^s \gamma^\mu \gamma^5 u_e^s$ vanishes

Inelastic WIMP-atom scattering

- Electrons contribute incoherently
- Requires computation of electron transition matrix elements

Rate for inelastic WIMP-atom scattering

($A \otimes A$ case)

$$\frac{dR^{\mathrm{WAS-in}}}{dE_d} = \frac{3\rho_0 G^2}{2\pi\, m_\chi} \sum_{nlm} \sum_{n'l'm'} |\langle n'l'm'|e^{i(\vec{k}-\vec{k}')\vec{x}}|nlm\rangle|^2\, I(v_{\mathrm{min}}^{\mathrm{WAS-in}})\,,$$

where

$$v_{\mathrm{min}}^{\mathrm{WAS-in}} = \frac{E_d(m_\chi + m_N) - m_N \delta E_B}{m_\chi \sqrt{2 m_N (E_d - \delta E_B)}}\,,$$

Rate for inelastic WIMP-atom scattering

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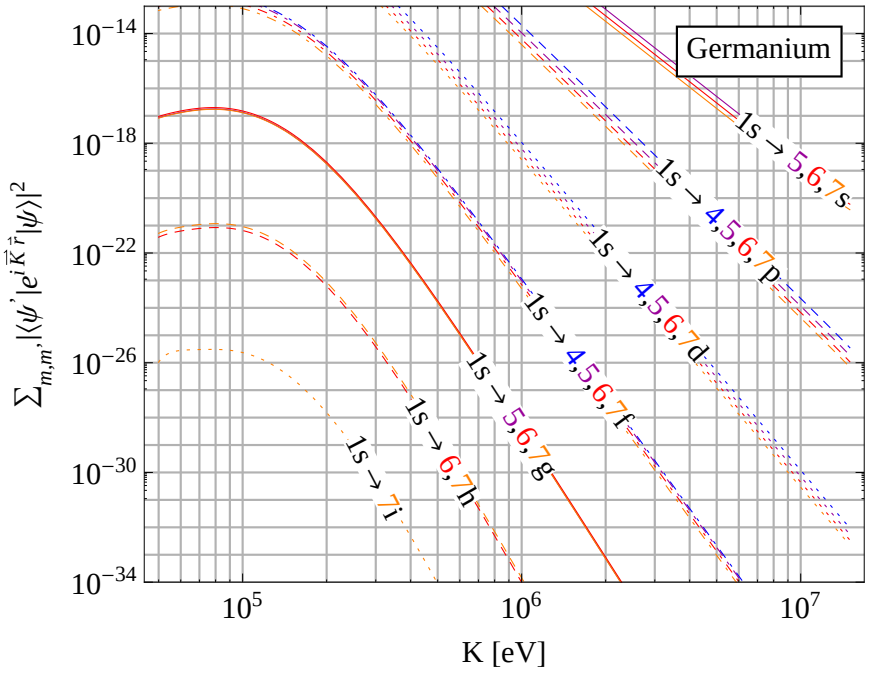
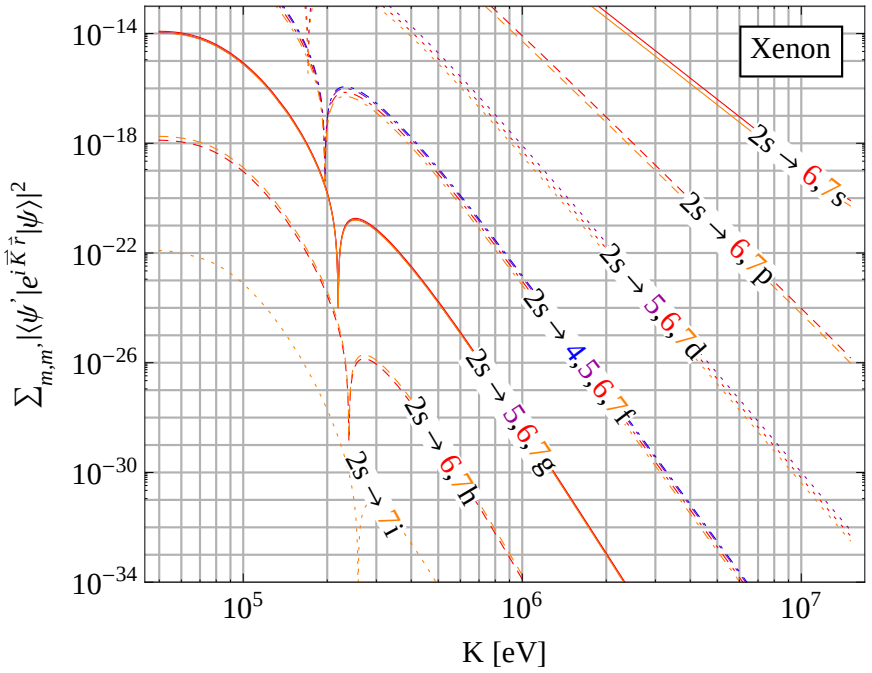
Compare to the formula for standard WIMPs:

$$\frac{dR^0}{dE_d} \simeq \frac{3\rho_0 G^2}{2\pi m_\chi}\, I(v_{\mathrm{min}}^0) \qquad \text{with} \qquad v_{\mathrm{min}}^0 = \frac{m_\chi + m_N}{m_\chi}\sqrt{\frac{E_d}{2m_N}}$$

Discussion of inelastic WIMP-atom scattering

- Supression due to smallness of matrix elements $\langle n' l' m' | e^{i(\vec{k}-\vec{k}')\vec{x}} | nlm \rangle$ at large $|\vec{k} - \vec{k}'|$ (as required for $E_d \sim$ keV)





Computation of matrix elements $\langle n' l' m' | e^{i\vec{K}\vec{x}} | nlm \rangle$

- Expand $e^{i\vec{K}\vec{x}}$ in spherical harmonics and carry out angular integration:

$$\langle n' l' m' | e^{i\vec{K}\vec{x}} | nlm \rangle = 4\pi \int dr\, r^2 R_{nl}(r)\, R_{n'l'}(r) \sum_{L,M} j_L(Kr)\, Y_{LM}(\theta_K, \phi_K)$$

$$\times \frac{(-1)^m}{\sqrt{4\pi}} \sqrt{(2l+1)(2l'+1)(2L+1)} \begin{pmatrix} l & l' & L \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} l & l' & L \\ m & m' & M \end{pmatrix}$$

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- Square this and use properties of Wigner-3j symbols

$$\sum_{mm'} \left| \langle n' l' m' | e^{i\vec{K}\vec{x}} | nlm \rangle \right|^2 = (2l+1)(2l'+1) \sum_L (2L+1) \left[\begin{pmatrix} l & l' & L \\ 0 & 0 & 0 \end{pmatrix} \right]^2$$
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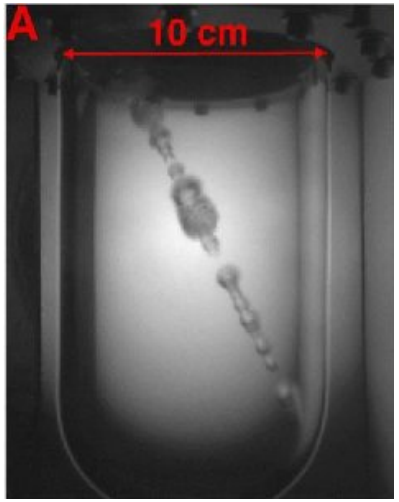
$$\times \left[\int dr\, r^2 R_{nl}(r)\, R_{n'l'}(r) j_L(Kr) \right]^2$$

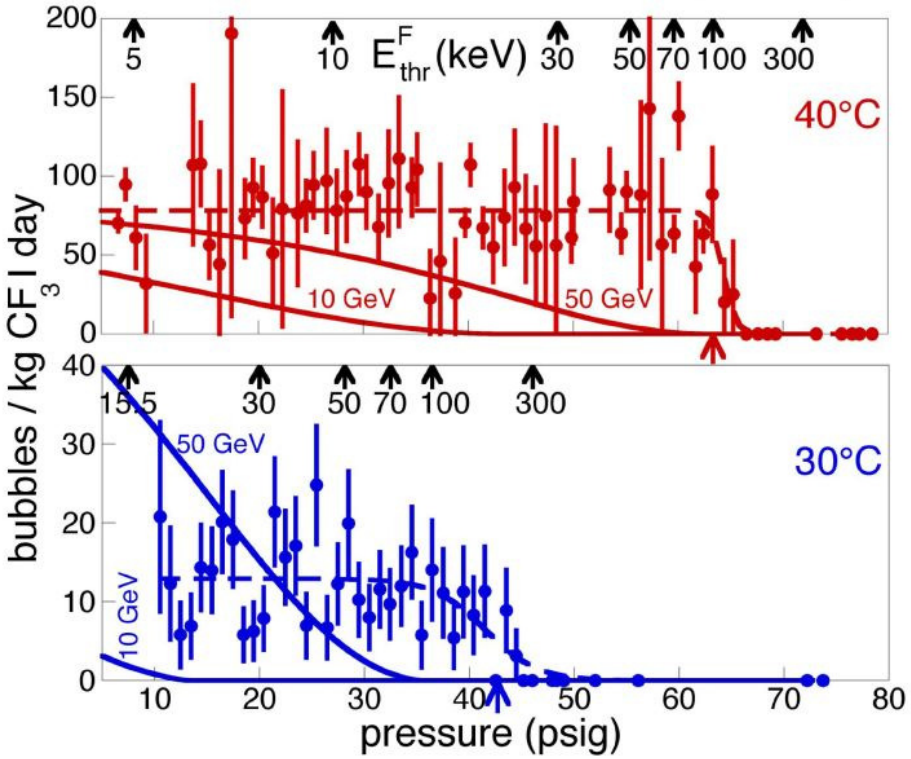
- Numerically tricky, but OK if done carefully (spherical Bessel transform)

Spherical Bessel transform: Sharafeddin et al., J. Comput. Phys. **100** (1992) 294
Radial wave functions $R_{nl}(r)$ taken from Bunge, Barrientos, Atom. Dat. Nucl. Dat. Tab. **53** (1993) 113

DM in bubble chambers: COUPP and PICASSO

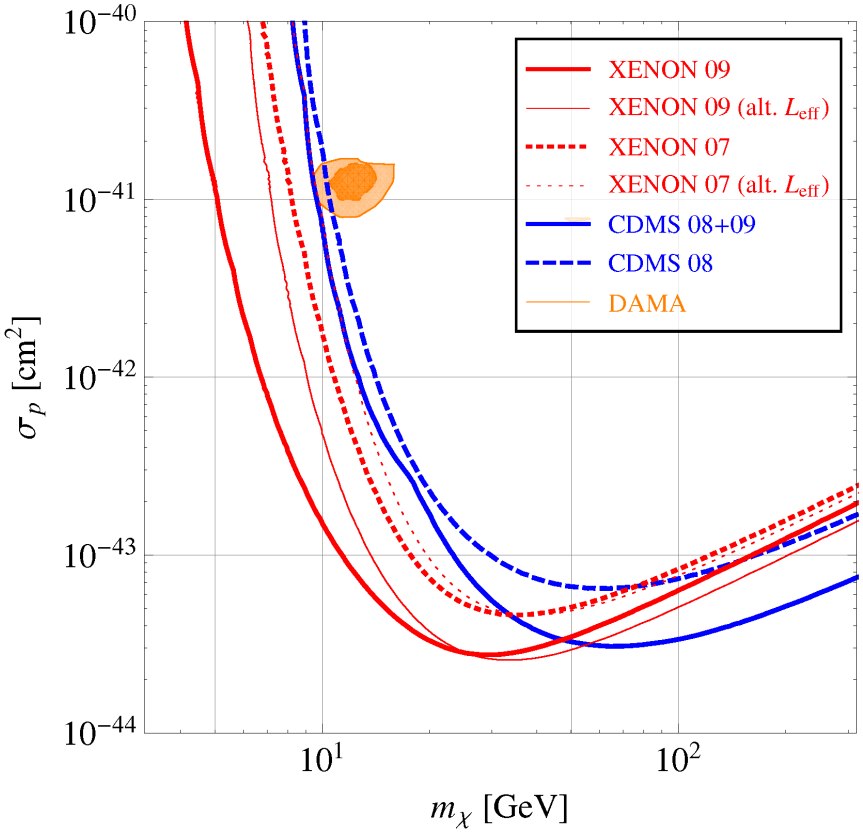
- Superheated liquid
- Localized energy deposit can lead to formation of visible gas bubble
- Bubble formation requires $dE/dx > dE_{\rm thr}(T,p)/dx$
  - By appropriate choie of T and p, muon, electron, photon backgrounds can be switched off.
  - Remaining background: monoenergetic α's from Rn-122 (flat, sharp threshold)
- DM signal: Slowly rising as $dE_{\rm thr}(T,p)/dx$ decreases
- Measure bubble formation rate at different T and/or p





COUPP Science 2008

Different data sets in CDMS and XENON



- XENON: Different data sets
  - 2007: Original analysis (0706.0039)
  - 2009: Reanalysis (0910.3698)
- XENON: Uncertainty in light yield (quenching factor) $L_{\rm eff}$
  - Uncertainty in energy reconstruction
- CDMS: Different data sets
  - 2008: First 5-tower data (0802.3530)
  - 2009: The much-anticipated two events (0912.3592)