Direct detection of light dark matter

Joachim Kopp

IDM 2012, Chicago

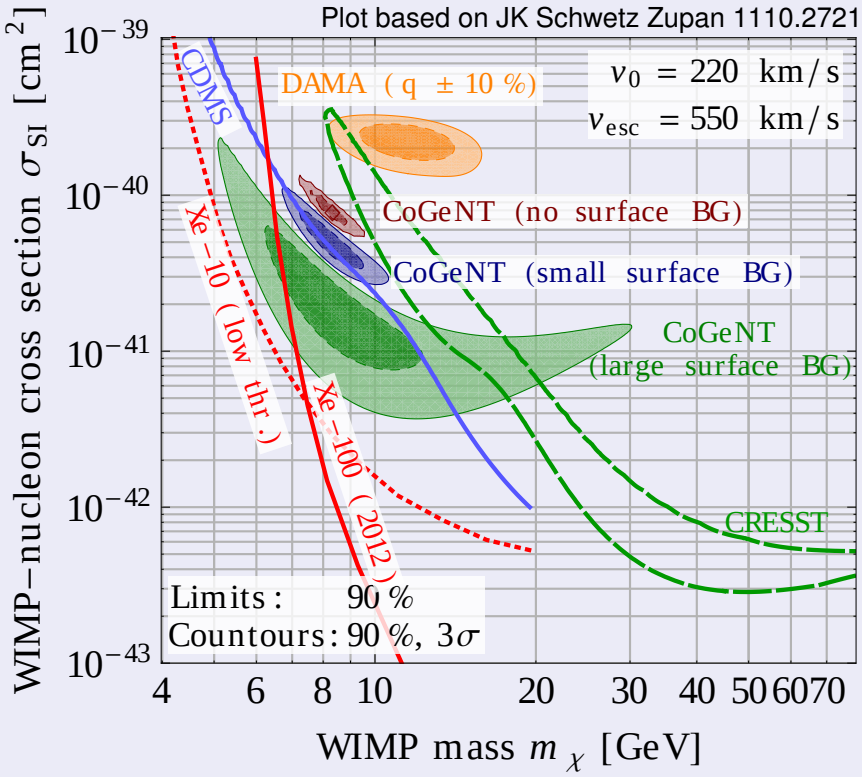
Fermilab

Outline

Outline

Hints for light dark matter

On the Earth . . .



- Several intriguing direct detection signals
- But severe tension with null results

Hints for light dark matter

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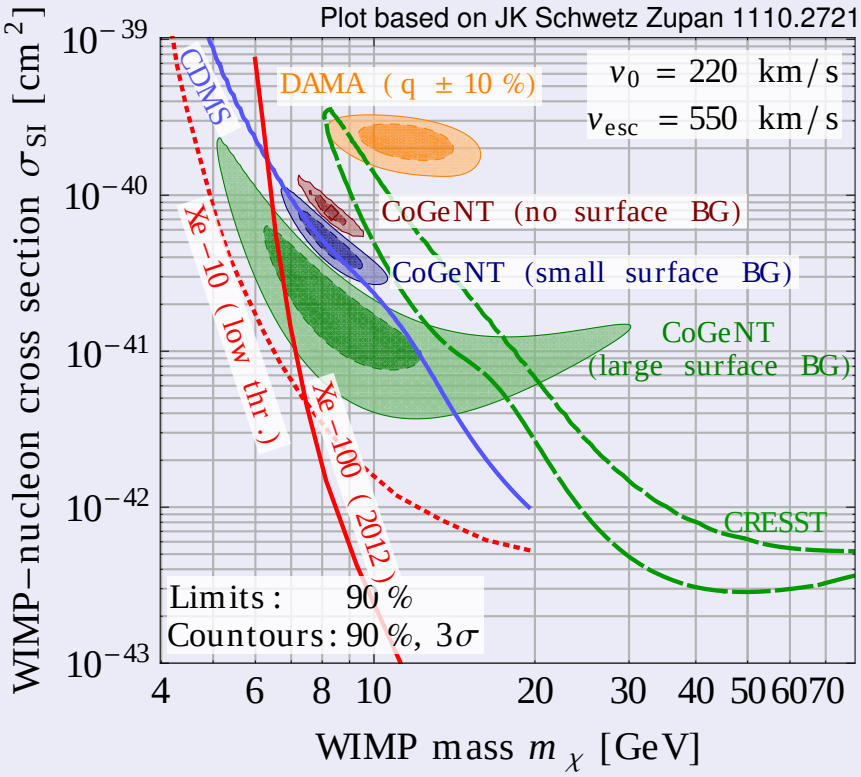

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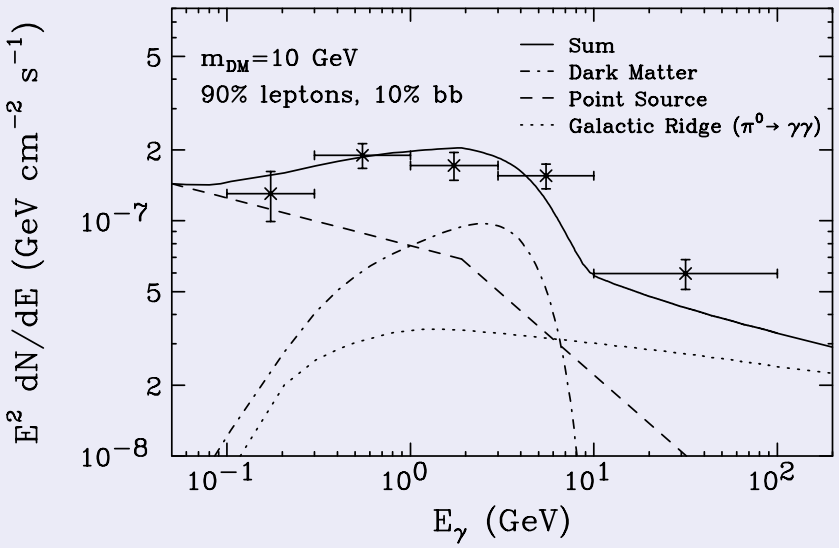
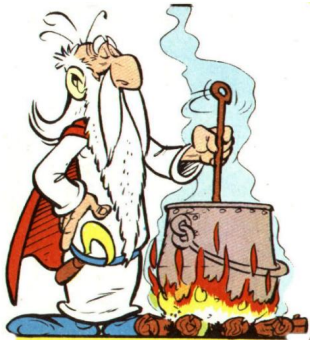
. . . and in the skies



- An tentative γ ray excess from the Galactic Center
  Hooper Goodenough 0912.2998, 1010.2752, 1201.1303
  - Morphology $\neq$ point source
- Radio filaments
  Linden Hooper Yusef-Zadeh 1106.5493
- Isotropic radio background
  Hooper Belikov Jeltema Linden Profumo Slatyer 1203.3547

Theoretical motivation for light DM



- Conventional DM paradigm: DM has electroweak scale mass, weak scale couplings $\rightarrow$ Thermal production
  $\rightarrow$ The WIMP Miracle
- But note: Thermal production also possible for lighter DM

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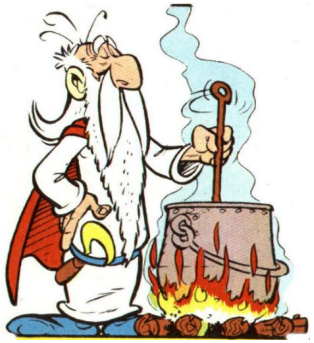

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- But note: Thermal production also possible for lighter DM
- An interesting alternative: Asymmetric dark matter
  - Based on the observation that $\Omega_{\rm DM} \simeq 5 \times \Omega_{\rm baryon}$
  - Suggests related production mechanisms
  - Baryon abundance determined by matter–antimatter asymmetry
  - If DM carries baryon number and $m_{\rm DM} \sim 10 m_p$, the observed $\Omega_{\rm DM}$ could be explained.
  - Many model-building and phenomenology papers related to this idea:

Kaplan Luty Zurek 0901.4117, Cai Luty Kaplan 0909.5499, Frandsen Sarkar Schmidt-Hober 1103.4350, Frandsen Sarkar 1003.4505, Feldstein Fitzpatrick 1003.5662, An Chen Mohapatra Nussinov Zhang 1004.3296, Cohen Phalen Pierce Zurek 1005.1655, Shelton Zurek 1008.1997, Haba Matsumoto 1008.2487, Davoudiasl Morrissey Sigurdson Tulin 1008.2399, Buckley Randall 1009.0270, Chun 1009.0983, Gu Lindner Sarkar Zhang 1009.2690, Blennow Dasgupta Fernandez-Martinez Rius 1009.3159, McDonald 1009.3227, Hall March-Russell West 1010.0245, Allahverdi Dutta Sinha 1011.1286, Dutta Kumar 1012.1341, Kouvaris Tinyakov 1012.2039, Falkowski Ruderman Volansky 1101.4936, Graesser Shoemaker Vecchi 1103.2771, McDermott Yu Zurek 1103.5472, Kouvaris Tinyakov 1104.0382, Buckley 1104.1429, Iminniyaz Drees Chen 1104.5548, Bell Petraki Shoemaker Volkas 1105.3730, Chang Goodenough 1105.3976, Cheung Zurek 1105.4612, Del Nobile Kouvaris Sannino 1105.5431, Masina Sannino 1106.3353, March-Russell McCullough 1106.4319, Davoudiasl Morrissey Sigurdson Tulin 1106.4320, Profumo Ubaldi 1106.4568, Cui Randall Shuve 1106.4834, Graesser Shoemaker Vecchi 1107.2666, Arina Sahu 1108.3967, Kane Shao Watson Yu 1108.5178, Buckley Profumo 1109.2164, Lewis Pica Sannino 1109.3513, Cirelli Panci Servant Zaharijas 1110.3809, Zentner Hearin 1110.5919, Lin Yu Zurek 1111.0293, Cui Randall Shuve 1112.2704, Kamada Yamaguchi 1201.2636, Tulin Yu Zurek 1202.0283, Walker 1202.2348, Davoudiasl Mohapatra 1203.1247, March-Russell Unwin West 1203.4854, Fan Yang Chang 1204.2564, Ellwanger Mitropoulos 1205.0673, Masina Panci Sannino 1205.5918, Okada Seto 1205.2844, Blennov Fernandez-Martinez Mena Redondo Serra 1203.5803, ...

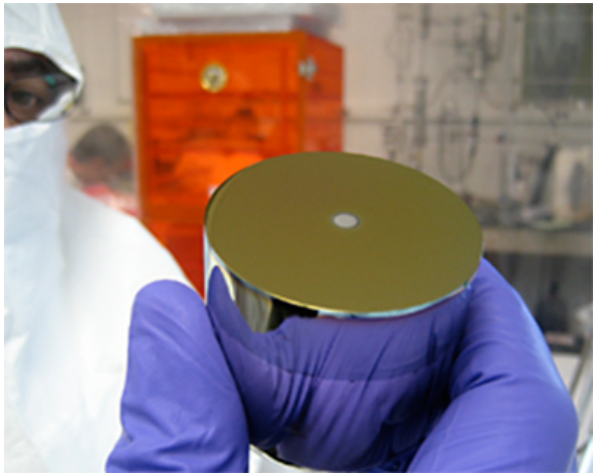
Outline

Semiconductor detectors

- Binding energy of electrons in semiconductor detectors is very small (3 eV in Ge)
  - Already a very feeble nuclear recoil leads to excitation
- Practical limitation: Electronic noise
- Possible solution: Reduce capacitance of the device
  - Make them smaller — for instance CCDs (DAMIC)

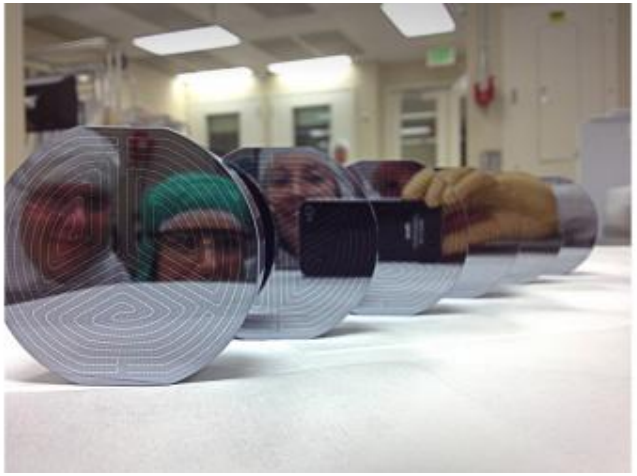
    DAMIC collaboration 1105.5191
  - Change the electrode geometry → Point-contact detectors (CoGeNT)

    Luke Goulding. Madden Pehl IEEE Trans. Nucl. Sci. 36 (1989) 926
    Barbeau Collar Tench nucl-ex/0701012



CoGeNT

$\longleftrightarrow$



Super-CDMS

Ionization (S2) signals in liquid Xenon

- Ionization energy in LXe: $\mathcal{O}(12\text{ eV})$

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- Actual experimental energy threshold depends on kinematics:
  - Threshold energy for WIMP–nucleus scattering depends on L_{eff}
    - ★ Difficult to measure (requires experiments with low-E neutrons)
    - ★ Difficult to calculate (interactions of primary recoil nucleus with other Xe atoms requires complicated many-body dynamics)

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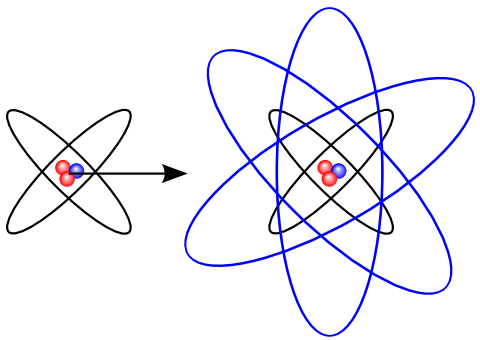
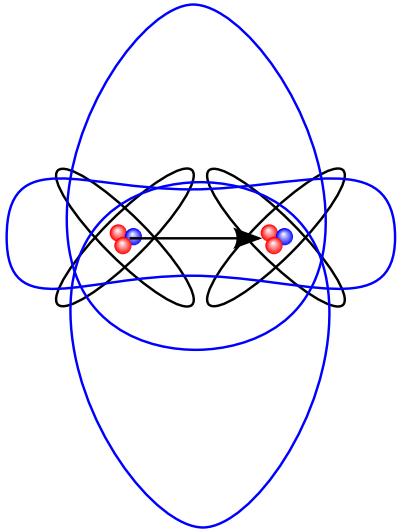


Primary recoil ion hits Xe atom at rest



Outer electrons rearrange themselves under the influence of both nuclei.

Some of them may end up in excited or unbound states

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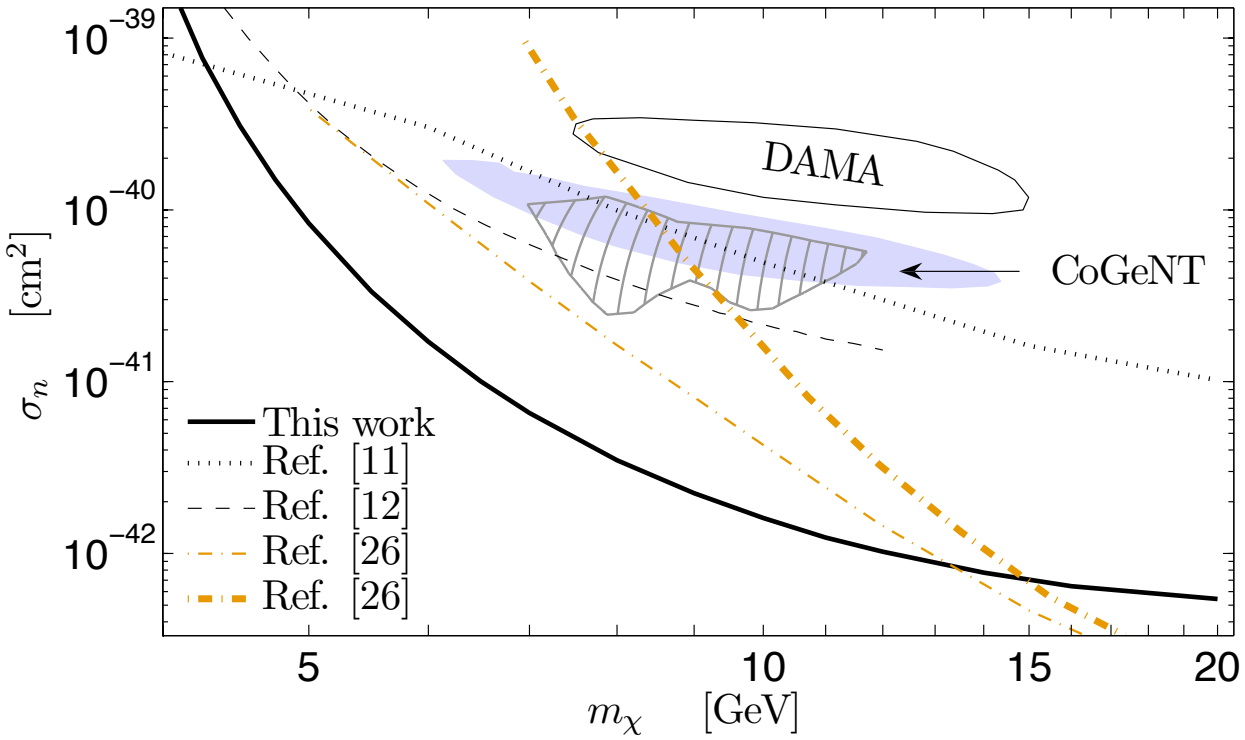

Xenon-10 1104.3088

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  - WIMP–electron scattering very inefficient for $\mathcal{O}(100\text{ GeV})$ dark matter

    JK Niro Schwetz Zupan 0907.3159

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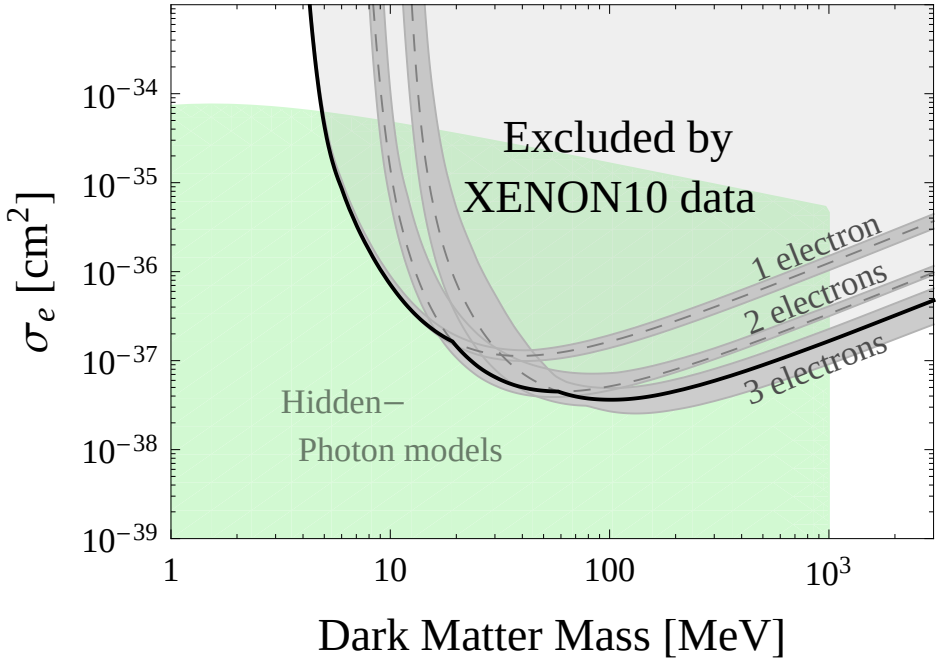
    JK Niro Schwetz Zupan 0907.3159
  - ... but an ideal process for MeV–GeV DM

    Essig Mardon Volansky 1108.5383, Essig Manalaysay Mardon Sorensen Volansky 1206.2644



Outline

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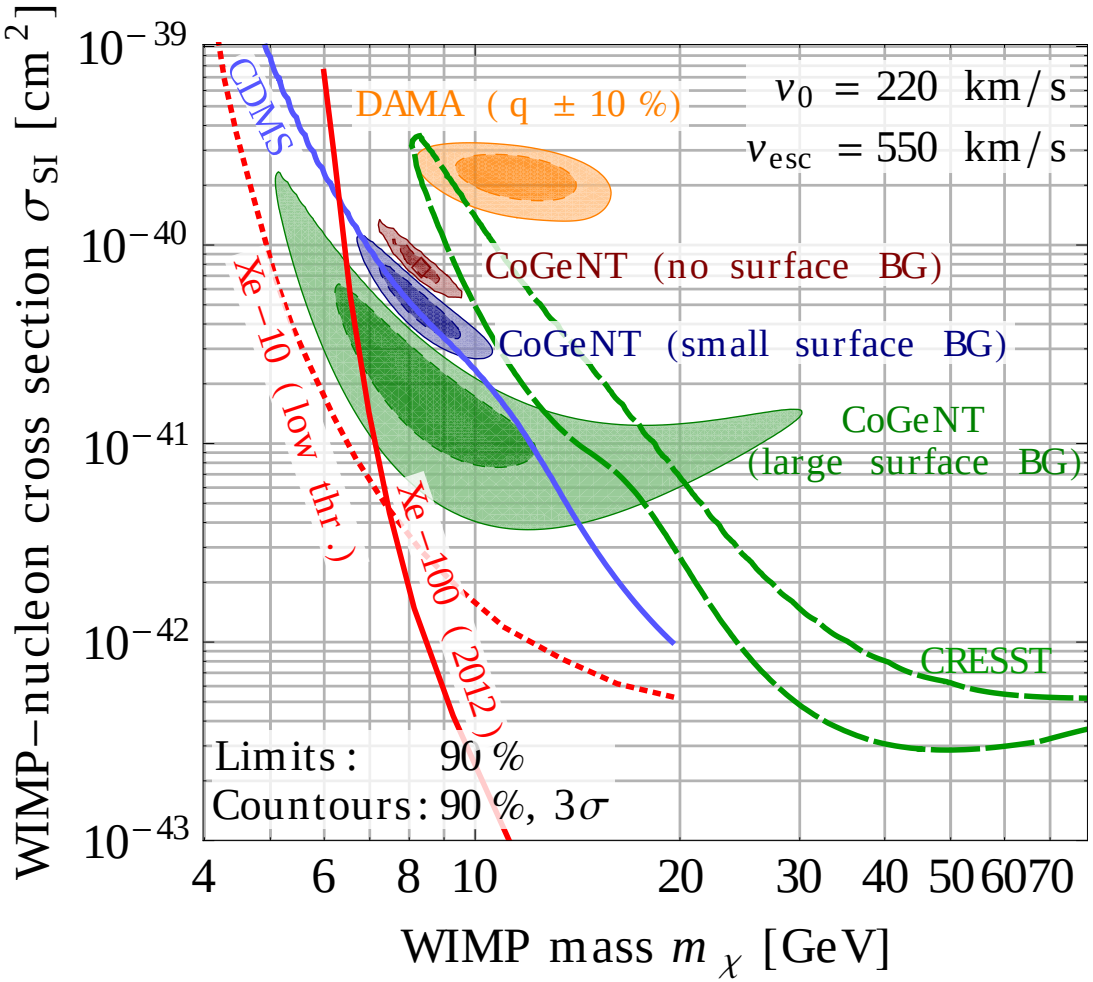
1. Why light WIMPs?
2. Experimental techniques for direct detection of light dark matter
3. Theoretical interpretation of direct detection data
   - Material-dependent scattering cross sections
   - Dependence on the WIMP velocity distribution
   - Light WIMPs and annual modulation
   - Neutrinos as WIMP impostors
4. Conclusions

Material-dependent scattering cross sections

How can the tension in the global data set — when interpreted in terms of dark matter scattering — be resolved?



Plot based on JK Schwetz Zupan 1110.2721

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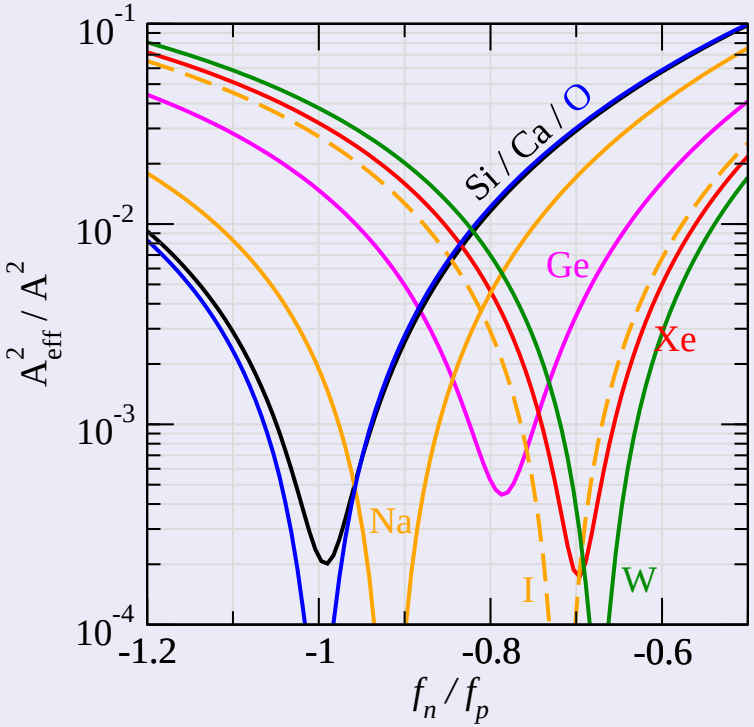
Isospin-violating DM

Feng Kumar Marfatia Sanford 1102.4331

Different couplings to protons and neutrons

$\longrightarrow$ "switch off" xenon



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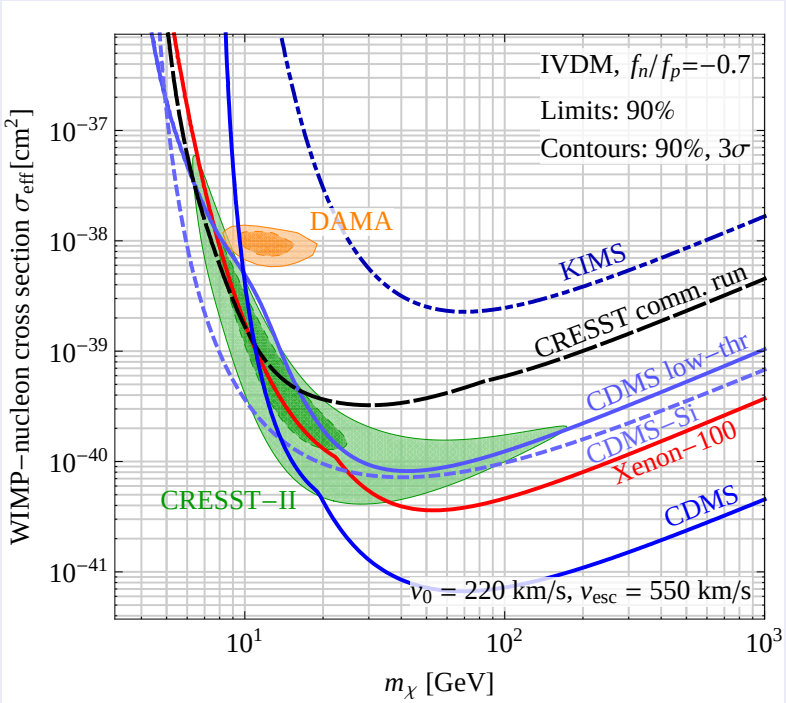

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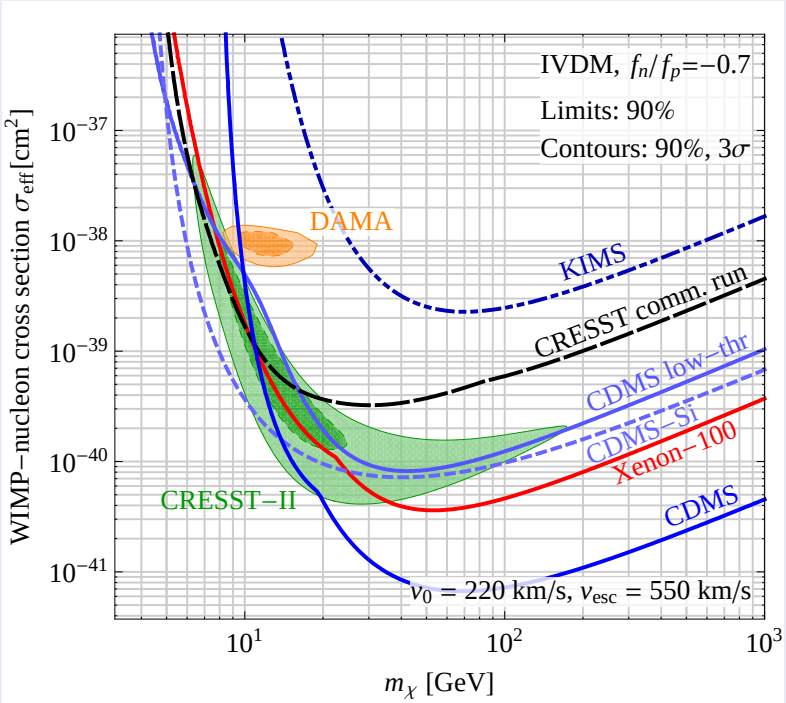

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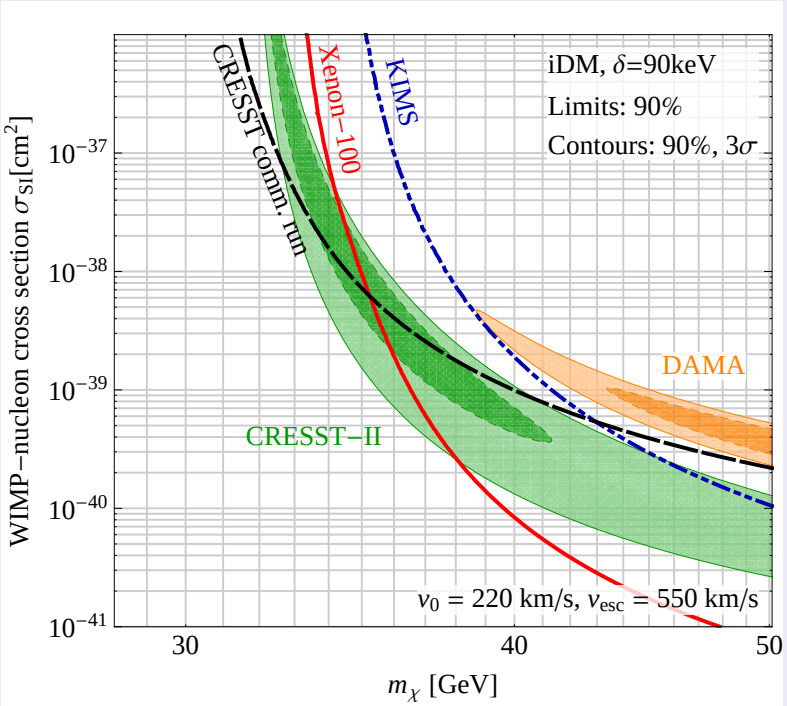
Inelastic DM

Tucker-Smith Weiner hep-ph/0101138

Inelastic scattering

→ prefers heavy targets (CRESST!)



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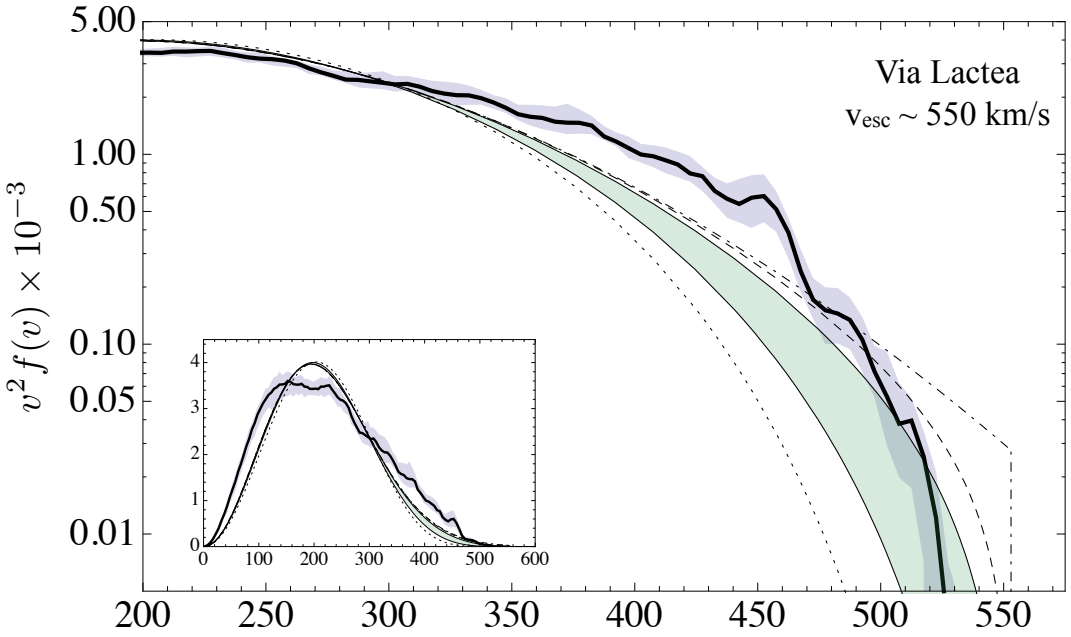
Outline

Dependence on the WIMP velocity distribution

Conventional assumption:

$$f(v) \propto \left(\exp\left[-v^2/v_0^2 \right] - \exp\left[-v_{\rm esc}^2/v_0^2 \right] \right) \Theta(v_{\rm esc} - v)$$

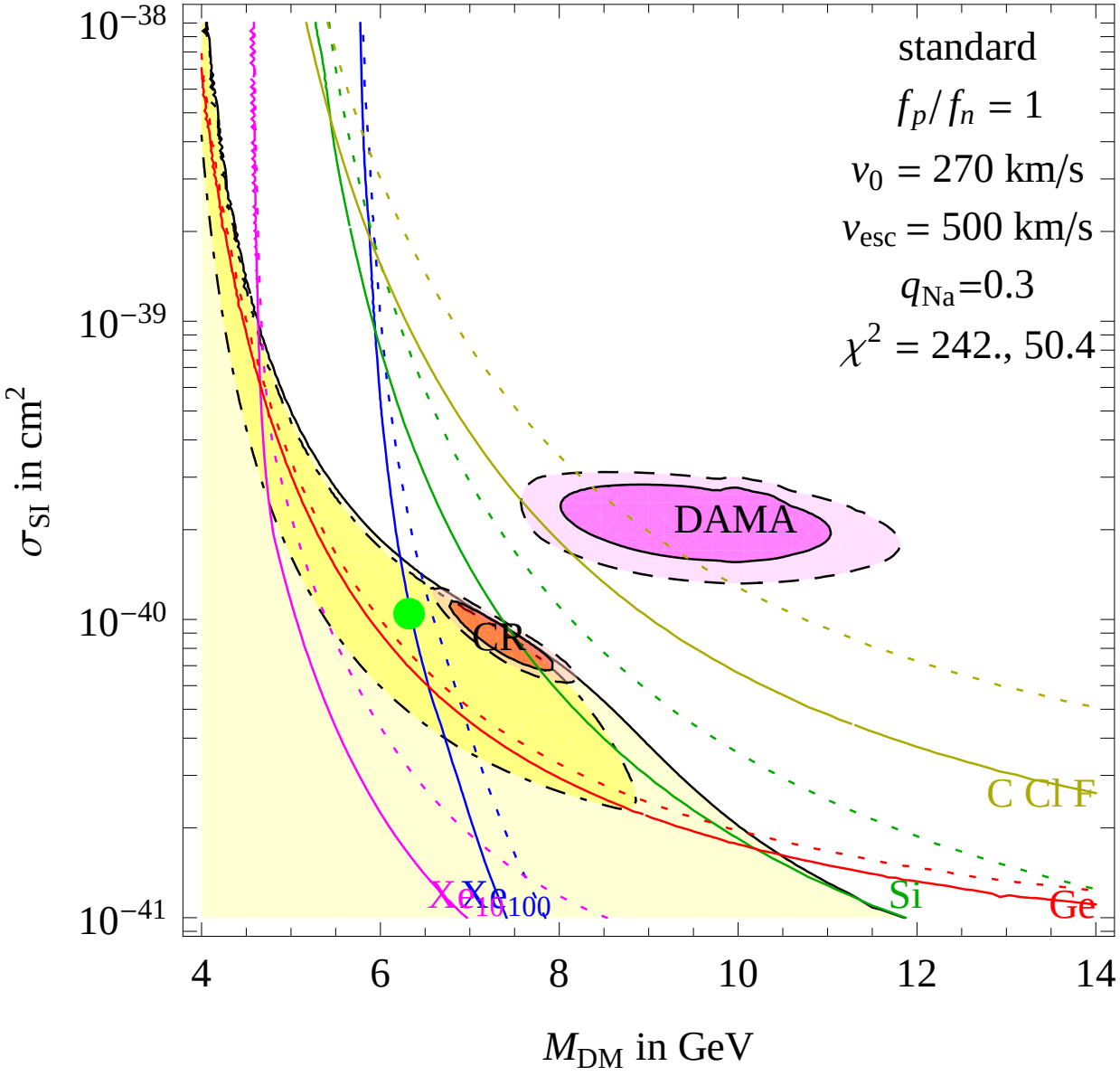
However, *N*-body simulations predict deviations from this simple form



Lisanti Strigari Wacker Wechsler 1010.4300

Also: Streams and debris flow Lisanti Spergel 1105.4166, Kuhlen Lisanti Spergel 1202.0007

Dependence on the WIMP velocity distribution



Farina Pappadopulo Strumia Volansky 1107.0715

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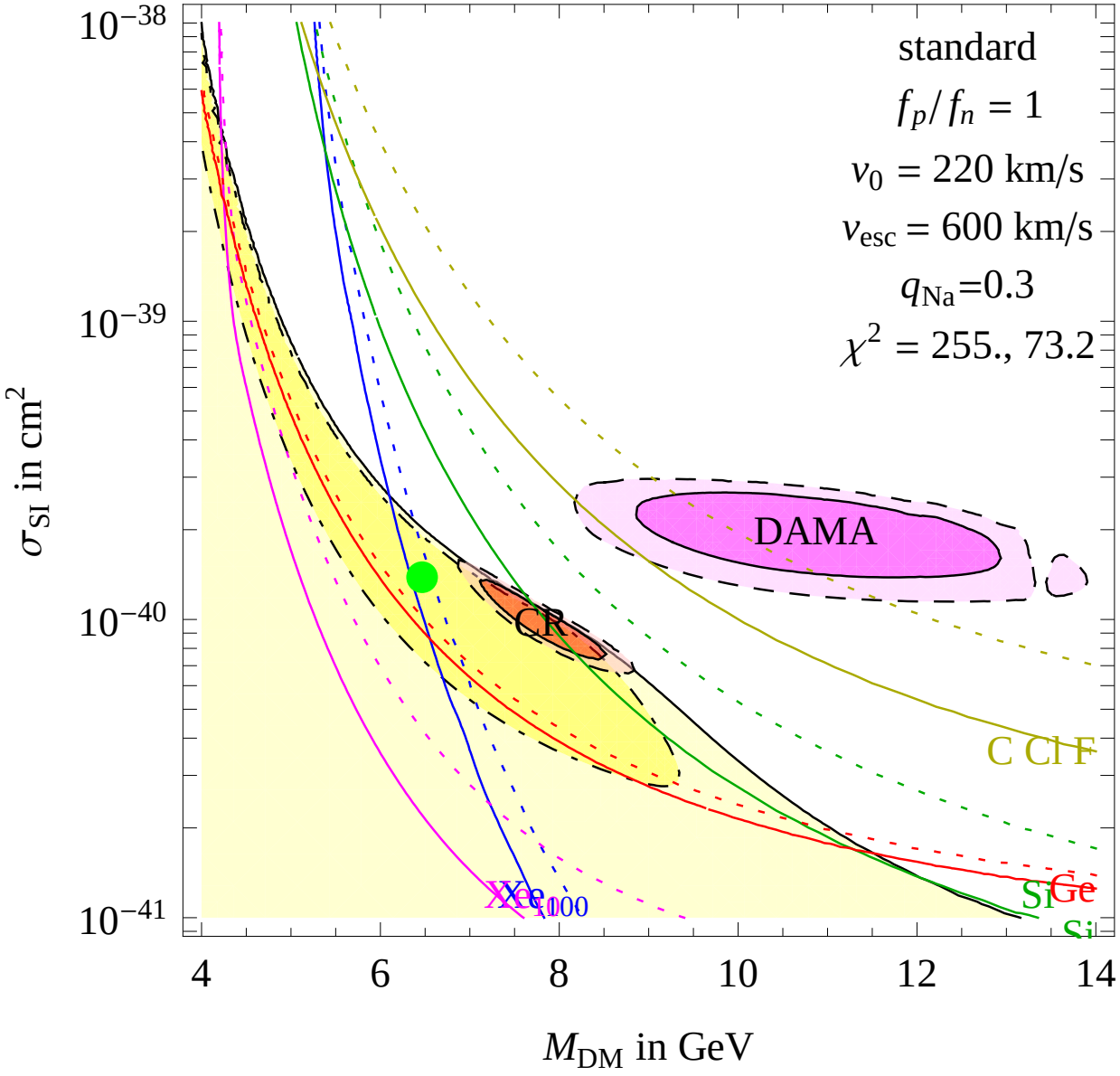

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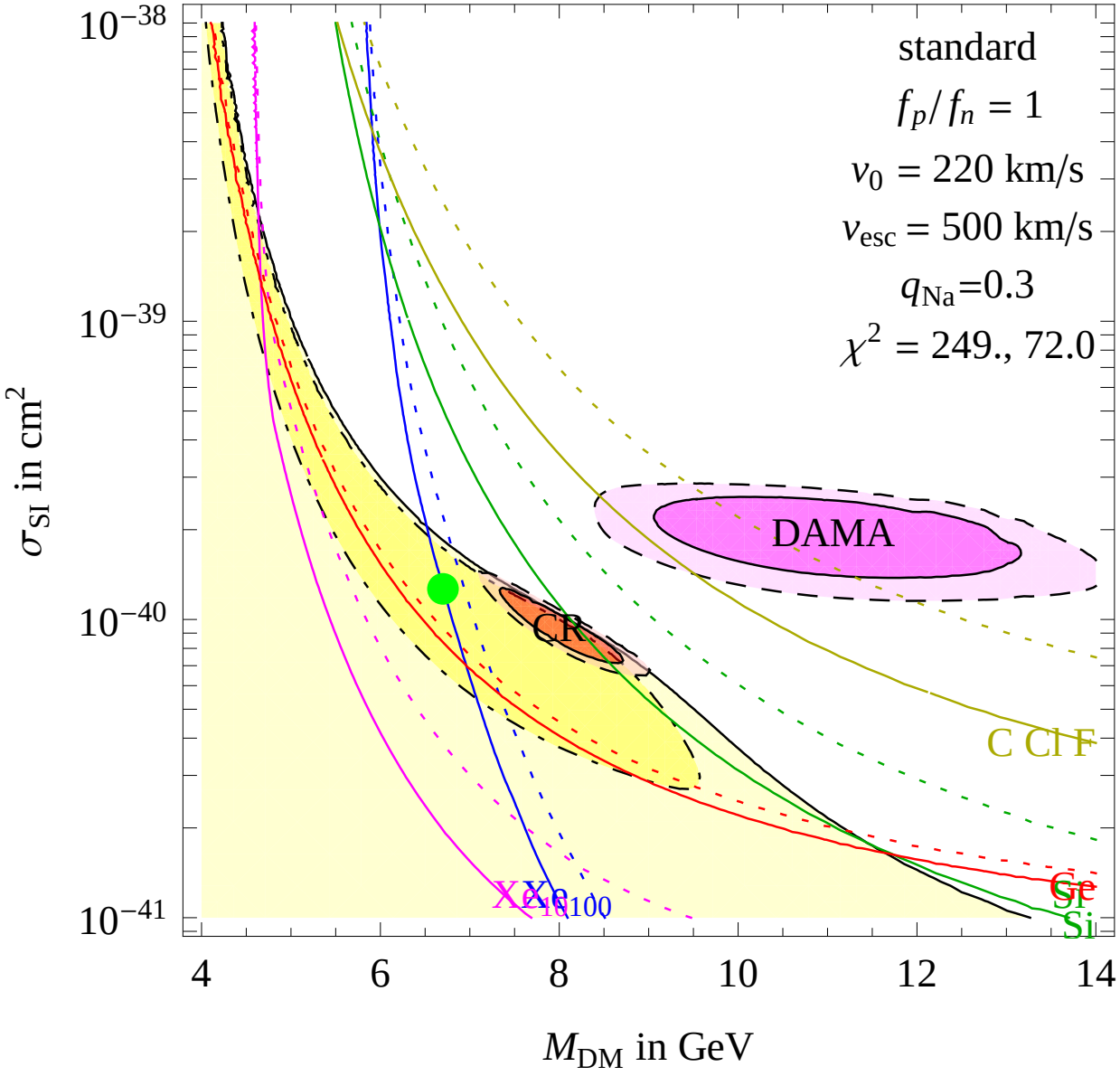

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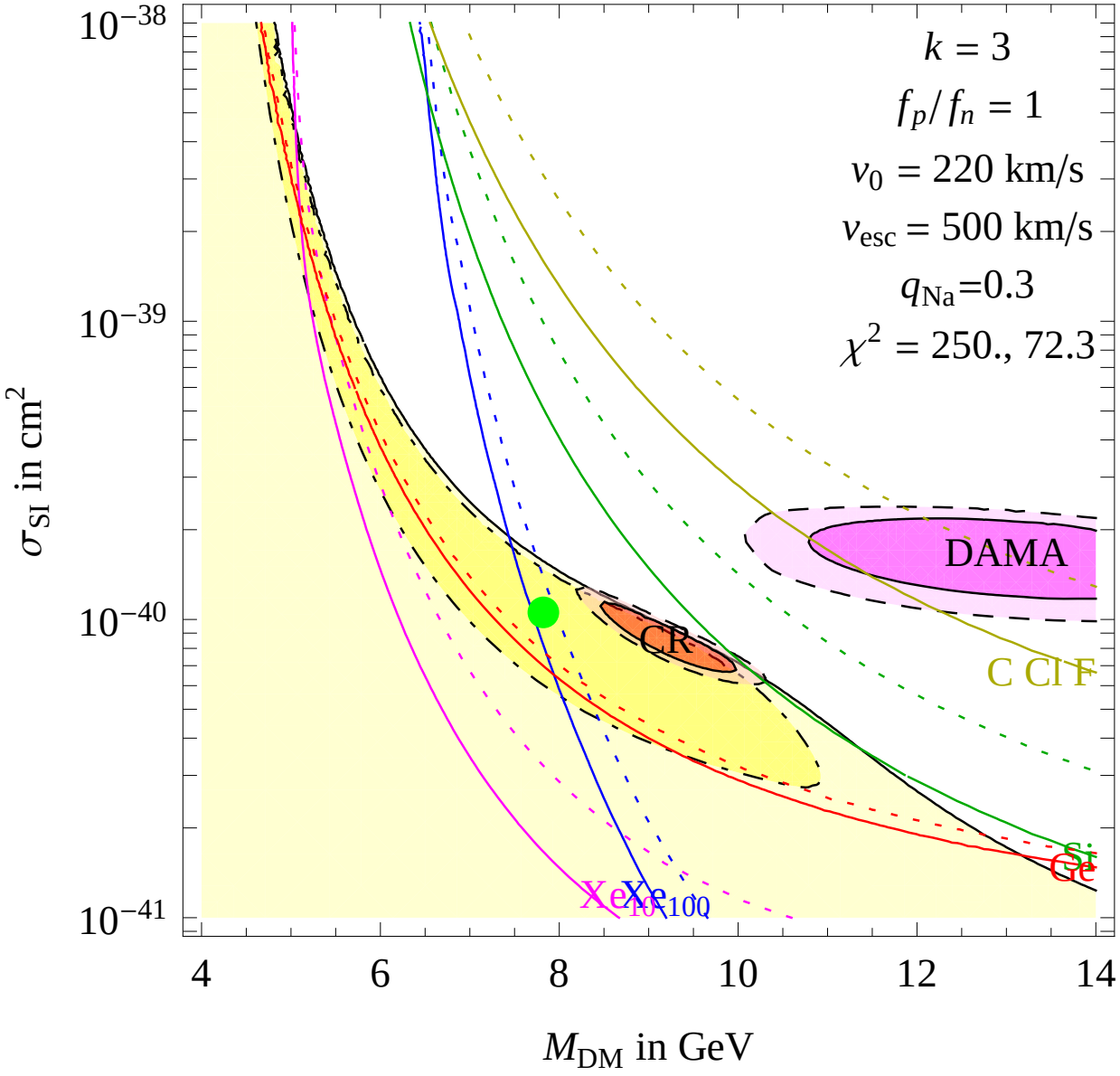

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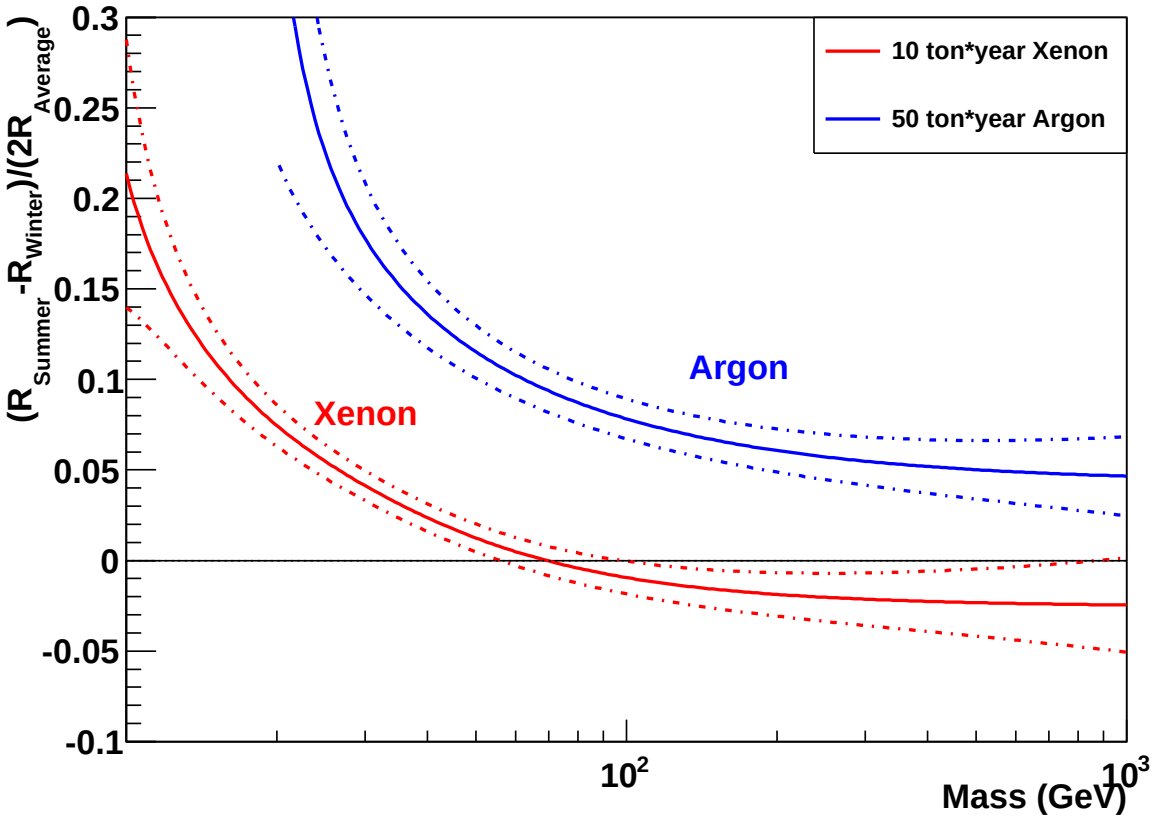
Light WIMPs and annual modulation

For light WIMPs, detectors are probing the tail of the velocity distribution
→ Larger fractional annual modulation expected



Arisaka et al. 1107.1295

Light WIMPs and annual modulation

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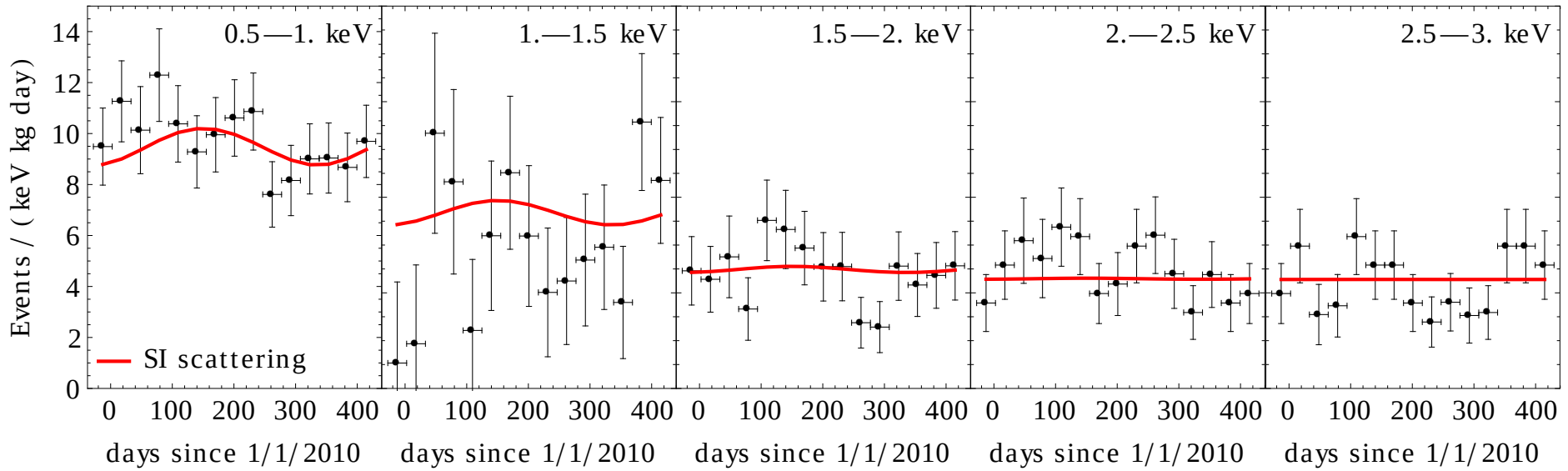
What would reduced annual modulation in the new CoGeNT data mean for the DM interpretation?

Plot based on Fox JK Lisanti Weiner 1107.0717 and JK Schwetz Zupan 1110.2721



Data points: CoGeNT, 1106.0650 (after subtraction of known cosmogenic peaks)
Red curve: Prediction (signal + BG @ best fit) for spin-independent scattering

Extra surface BG = $0\ \mathrm{keV}^{-1}\mathrm{day}^{-1} \times \exp\left(-E/0.3\mathrm{keV}\right)$
(signal fraction in 0.5–1 keV bin = 73%)

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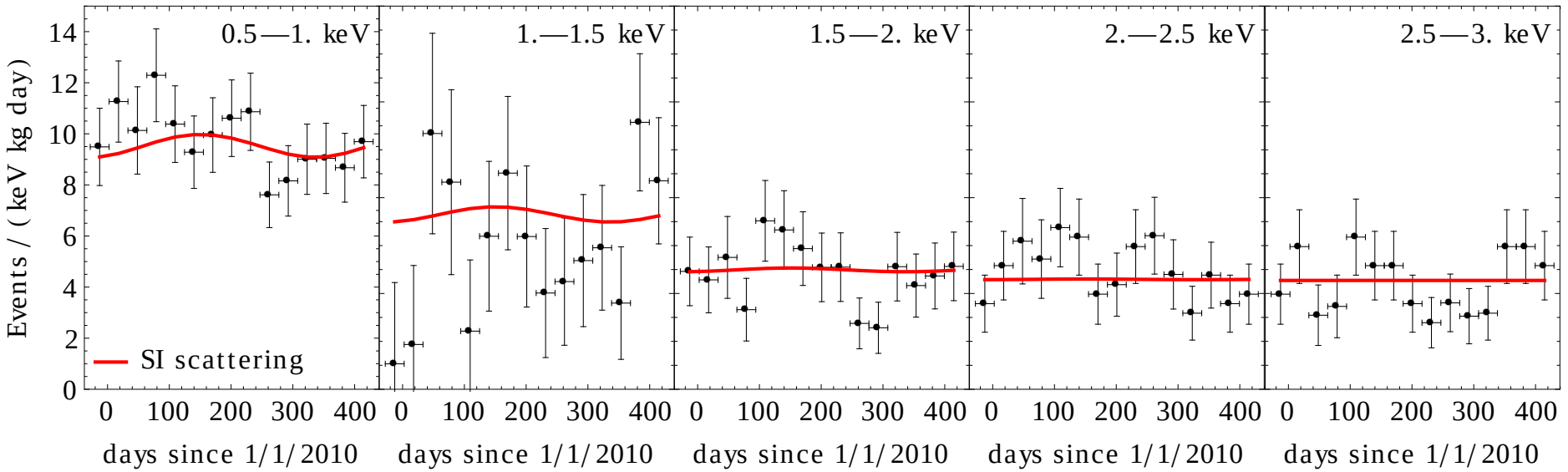

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Extra surface BG = $12\ \mathrm{keV}^{-1}\mathrm{day}^{-1} \times \exp\left(-E/0.3\mathrm{keV}\right)$
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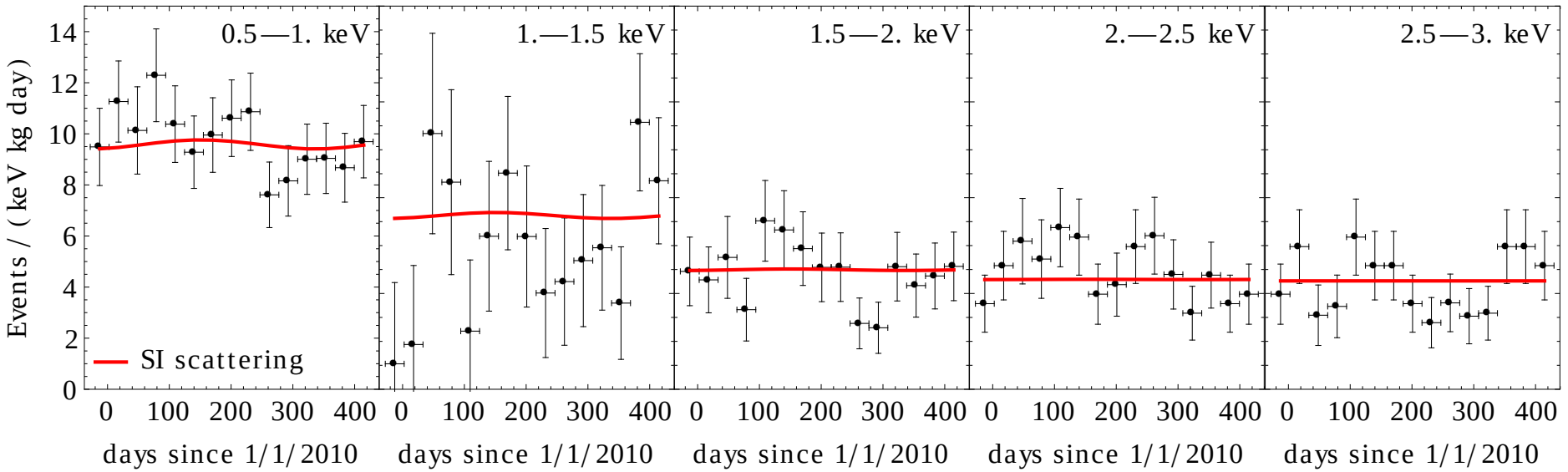

Data points: CoGeNT, 1106.0650 (after subtraction of known cosmogenic peaks)
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Extra surface BG = $24\ \mathrm{keV}^{-1}\mathrm{day}^{-1} \times \exp\left(-E/0.3\mathrm{keV}\right)$
(signal fraction in 0.5–1 keV bin = 30%)

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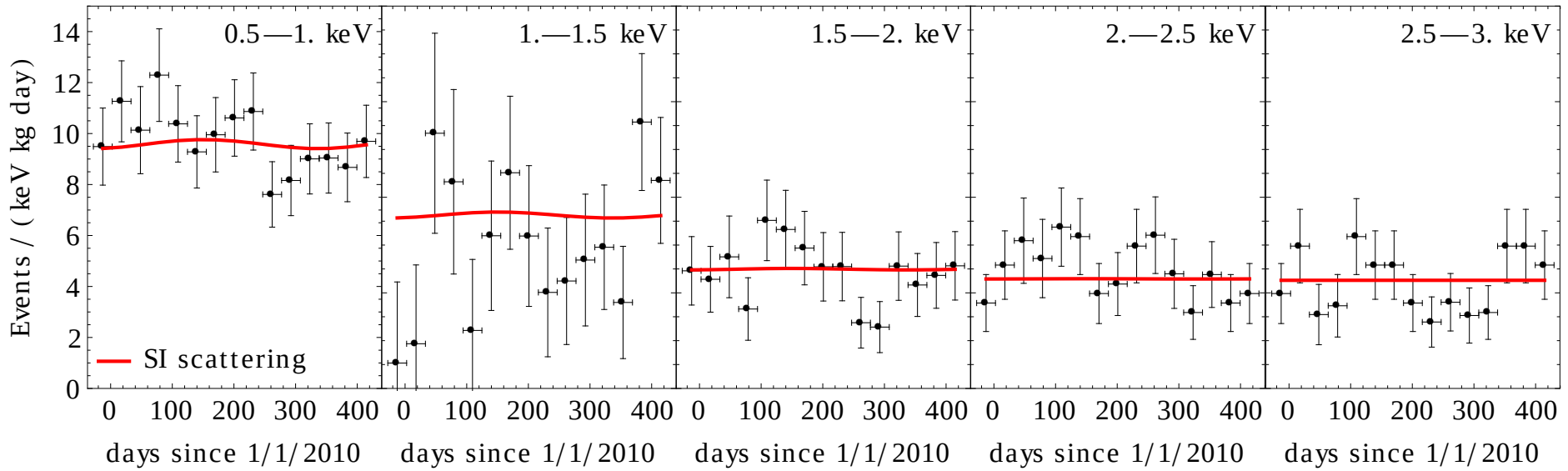

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When surface backgrounds are accounted for, reduced modulation in CoGeNT would make the data more consistent with a WIMP hypothesis

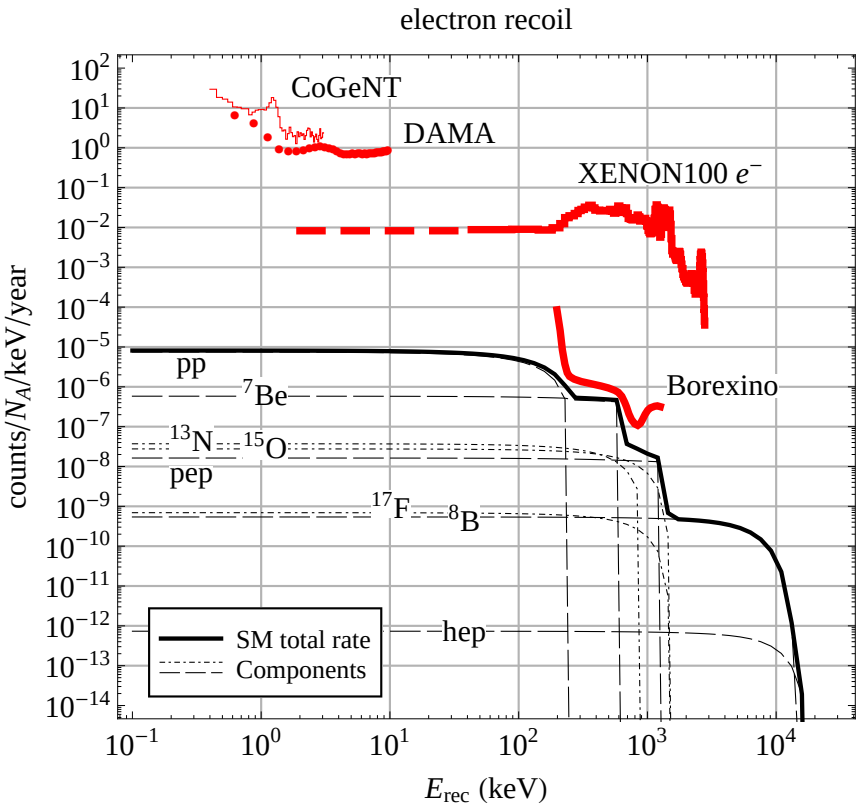
Outline

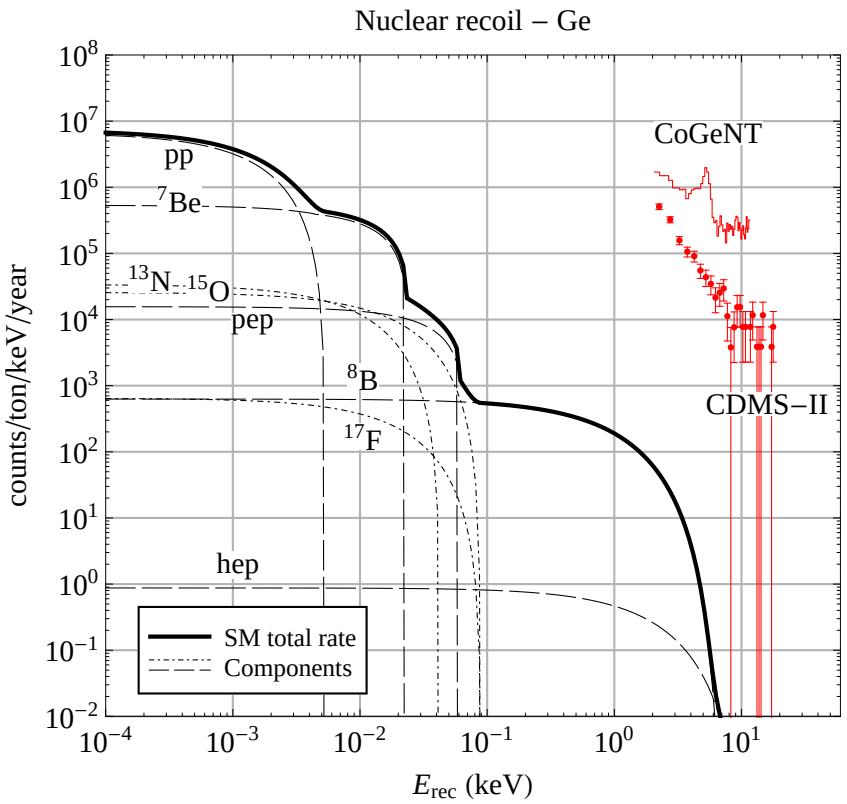
Neutrinos as WIMP impostors

Solar neutrinos are a well-known background to future direct DM searches:

see e.g. Gütlein et al. arXiv:1003.5530

$$\frac{d\sigma_{\rm SM}(\nu N \to \nu N)}{dE_r} = \frac{G_F^2 m_N F^2(E_r)}{2\pi E_\nu^2}\Big[A^2 E_\nu^2 + 2AZ(2E_\nu^2(s_w^2-1) - E_r m_N s_w^2)$$
$$+ 4Z^2(E_\nu^2 + s_w^4(2E_\nu^2 + E_r^2 - E_r(2E_\nu + m_N)) + s_w^2(E_r m_N - 2E_\nu^2))\Big],$$





Plots from Harnik JK Machado 1202.6073

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$$+ 4Z^2(E_\nu^2 + s_w^4(2E_\nu^2 + E_r^2 - E_r(2E_\nu + m_N)) + s_w^2(E_r m_N - 2E_\nu^2))\Big],$$

SM signal will only become sizeable in multi-ton detectors

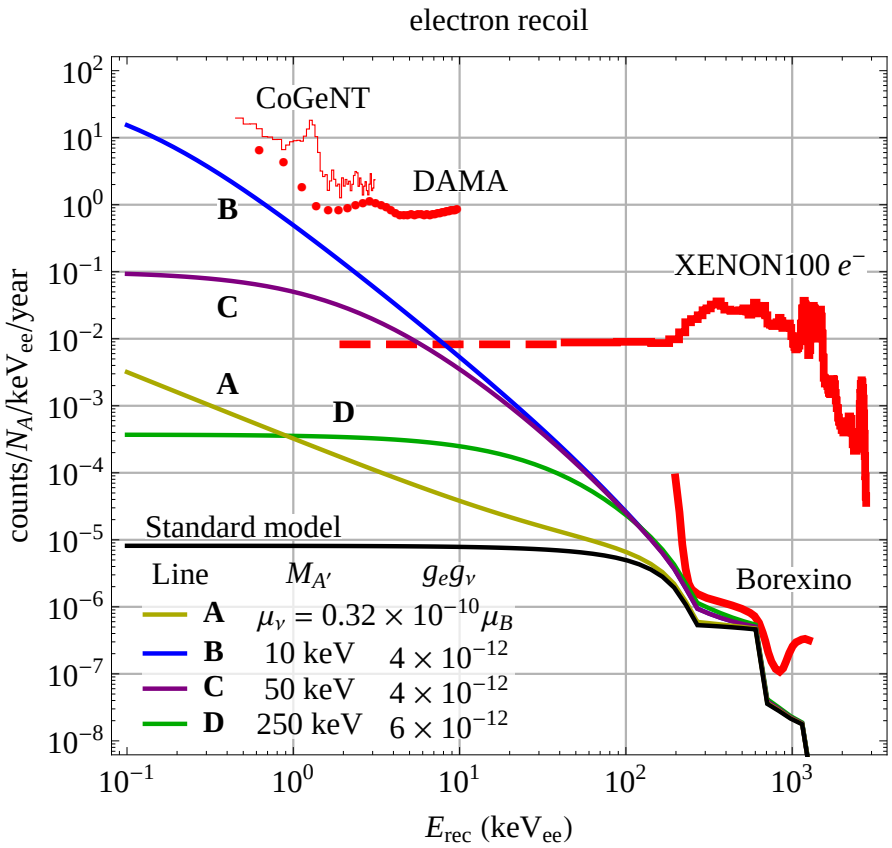
But: New physics can enhance the rate

$\Rightarrow$ New ν physics can be confused with a dark matter signal

$\Rightarrow$ DM detectors can search for new physics in the ν sector

Enhanced neutrino scattering from BSM physics

Harnik JK Machado 1202.6073



A: ν magnetic moment

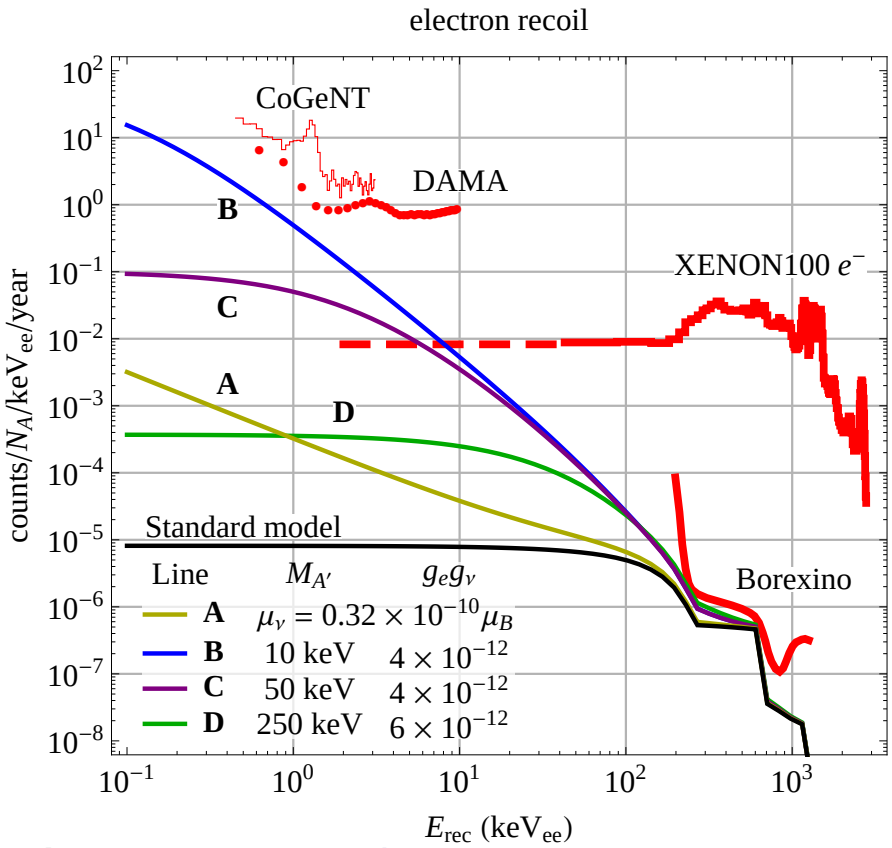
B, C, D: kinetically mixed A' + sterile ν_s:

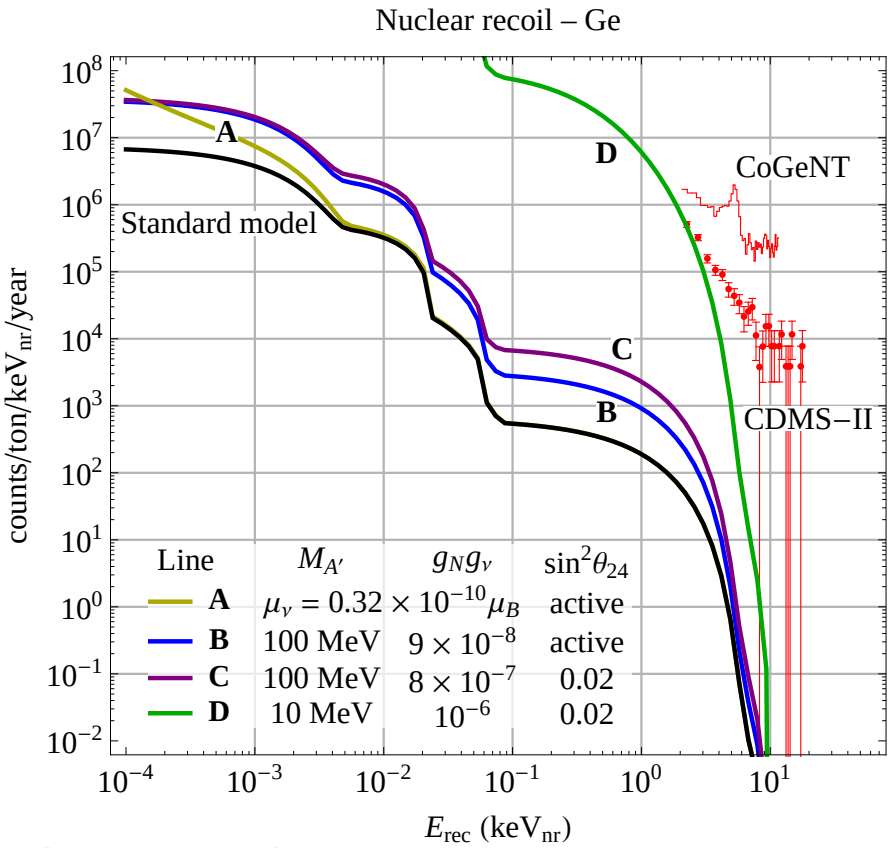
$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \epsilon F'_{\mu\nu} F^{\mu\nu}$$
$$+ \bar{\nu}_s i \partial\!\!\!/ \nu_s + g' \bar{\nu}_s \gamma^\mu \nu_s A'_\mu$$
$$- \overline{(\nu_L)^c} m_{\nu_L} \nu_L - \overline{(\nu_s)^c} m_{\nu_s} \nu_s - \overline{(\nu_L)^c} m_{\text{mix}} \nu_s$$

- Enhanced scattering at low E_r for light A'
- Negligible compared to SM scattering at energies probed in dedicated neutrino experiments
- Various mechanisms for daily and annual modulation Pospelov 1103.3261, Harnik JK Machado 1202.6073

Enhanced neutrino scattering from BSM physics

Harnik JK Machado 1202.6073





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B: $U(1)_{B-L}$ boson
C: kinetically mixed $U(1)'$ + sterile ν
D: $U(1)_B$ + sterile ν charged under $U(1)_B$

Pospelov 1103.3261, Pospelov Pradler 1203.0545

- Enhanced scattering at low E_r for light A'
- Negligible compared to SM scattering at energies probed in dedicated neutrino experiments
- Various mechanisms for daily and annual modulation Pospelov 1103.3261, Harnik JK Machado 1202.6073

Outline

Summary and conclusions

- Several intriguing experimental hints for $\lesssim$ 10 GeV DM
- Theoretical motivation in asymmetric DM scenarios, but can be accomodated in many popular DM models
- Direct detection of light dark matter requires new experimental techniques
- Currently, data from different experiments contradict each other
  - CoGeNT, DAMA, CRESST see unexplained signals
  - Strong exclusion from Xenon-100, CDMS, . . . (under standard assumptions)
  - Note: Reduced modulation removes tension within the CoGeNT data
- Ways out:
  - Material-dependent scattering cross sections? (isospin-violating DM, inelastic DM)
  - New physics in the neutrino sector can fake WIMP signals

Thank you!

Bonus slides

Example: A model with a 4th neutrino

Introduce a 4th neutrino ν_s and a light $U(1)'$ gauge boson A' (hidden photon)

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related model with gauged $U(1)_B$ first discussed by Pospelov 1103.3261
see also Pospelov Pradler 1203.0545

- ν_s charged under $U(1)'$ $\rightarrow$ direct coupling to A'
- SM particles couple to A' only through kinetic mixing

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu} + \bar{\nu}_s i\partial\!\!\!/\nu_s + g'\bar{\nu}_s\gamma^\mu\nu_s A'_\mu$$
$$- \overline{(\nu_L)^c} m_{\nu_L}\nu_L - \overline{(\nu_s)^c} m_{\nu_s}\nu_s - \overline{(\nu_L)^c} m_{\text{mix}}\nu_s$$

A small fraction of solar neutrinos can oscillate into ν_s

ν_s scattering cross section in the detector given by

$$\frac{d\sigma_{A'}(\nu_s e \rightarrow \nu_s e)}{dE_r} = \frac{\epsilon^2 e^2 g'^2 m_e}{4\pi p_\nu^2 (M_{A'}^2 + 2E_r m_e)^2}\left[2E_\nu^2 + E_r^2 - 2E_r E_\nu - E_r m_e - m_\nu^2\right]$$

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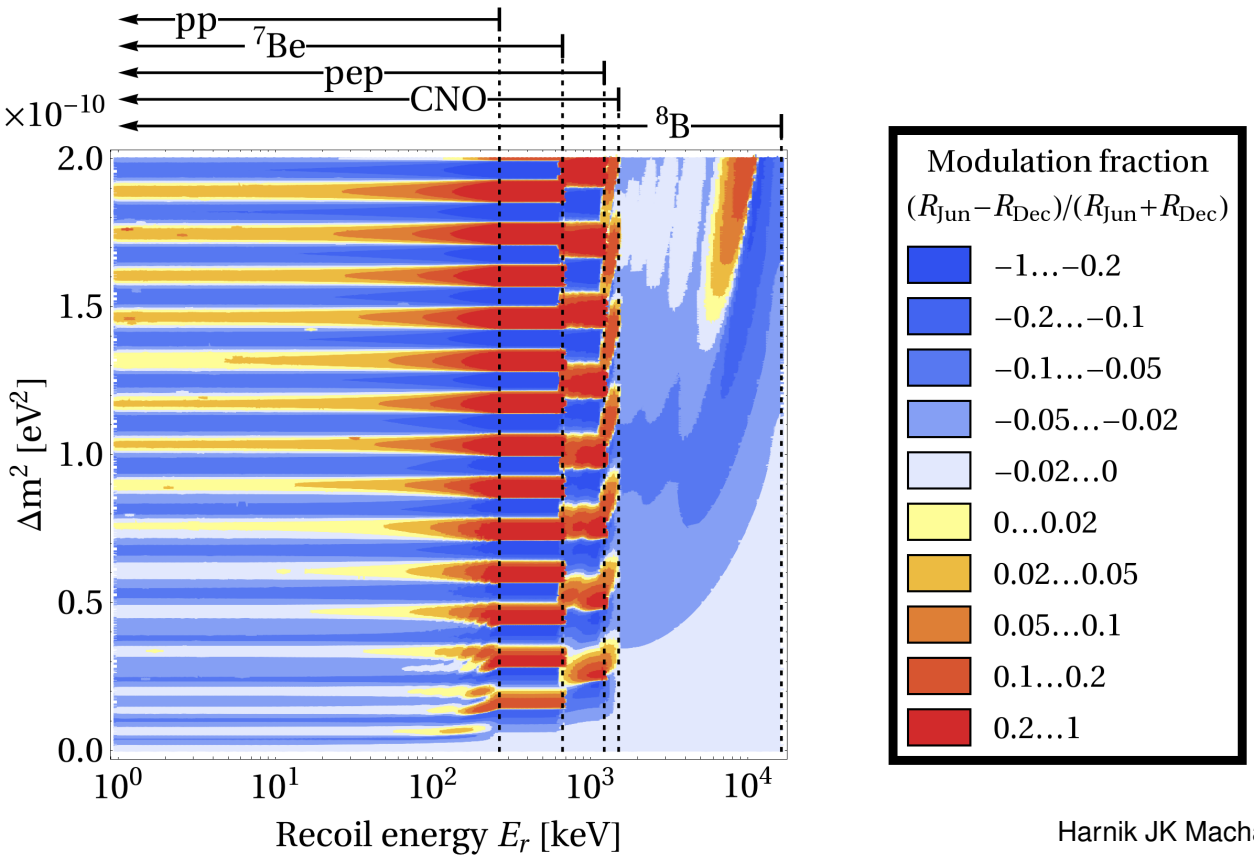

Harnik JK Machado, arXiv:1202.6073

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- Earth matter effects: An MSW-type resonance can lead to modified flux of certain neutrino flavors at night. And nights are longer in winter.

Hidden photons

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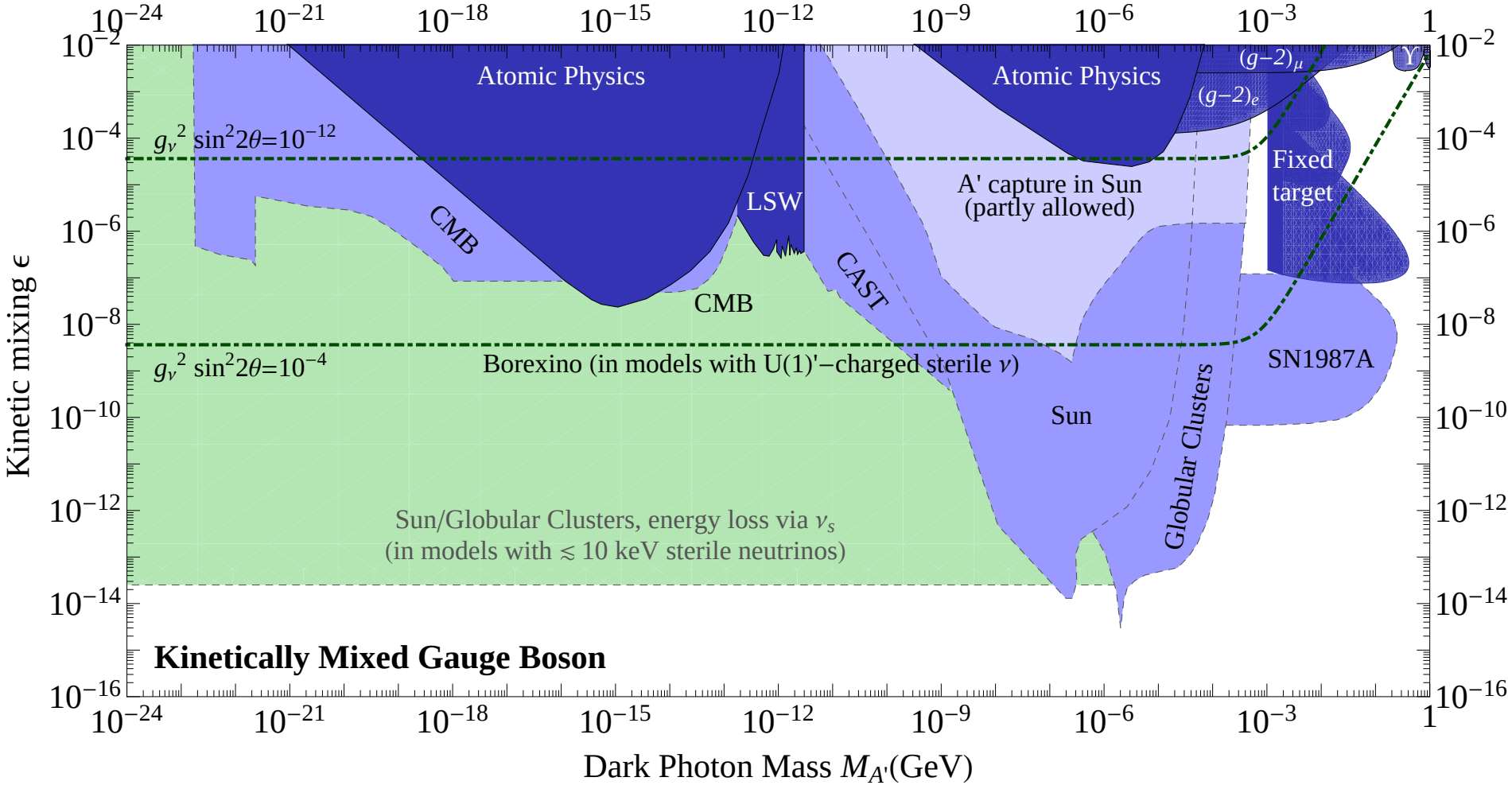

Constraints from Jaeckel Ringwald 1002.0329, Redondo 0801.1527,
Bjorken Essig Schuster Toro 0906.0580, Dent Ferrer Krauss 1201.2683, Harnik JK Machado 1202.6073