Bounds on annual modulation signal in dark matter direct detection

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based on Schwetz, JZ 1106.6241; Kopp, Schwetz, JZ 1110.2721;
Herrero-Garcia, Schwetz, JZ 1112.1627;
Lopez-Honorez, Schwetz, JZ 1203.2064

THREE TOPICS

- bounds on dark matter modulation signal in direct detection
- global fits to dark matter experiments
- time permitting: Higgs portal and DM

DM direct detection & modulation

THE QUESTION

- CoGeNT, DAMA, CRESST claim signals

Bernabei et al. [DAMA], 0804.2741
Aalseth et al. [CoGeNT], 1002.4703; 1106.0650
Angloher et al., [CRESST-II], 1109.0702

  - Is it (can it be) dark matter?
- the answer depends on
  - DM particle model
  - astrophysics assumed

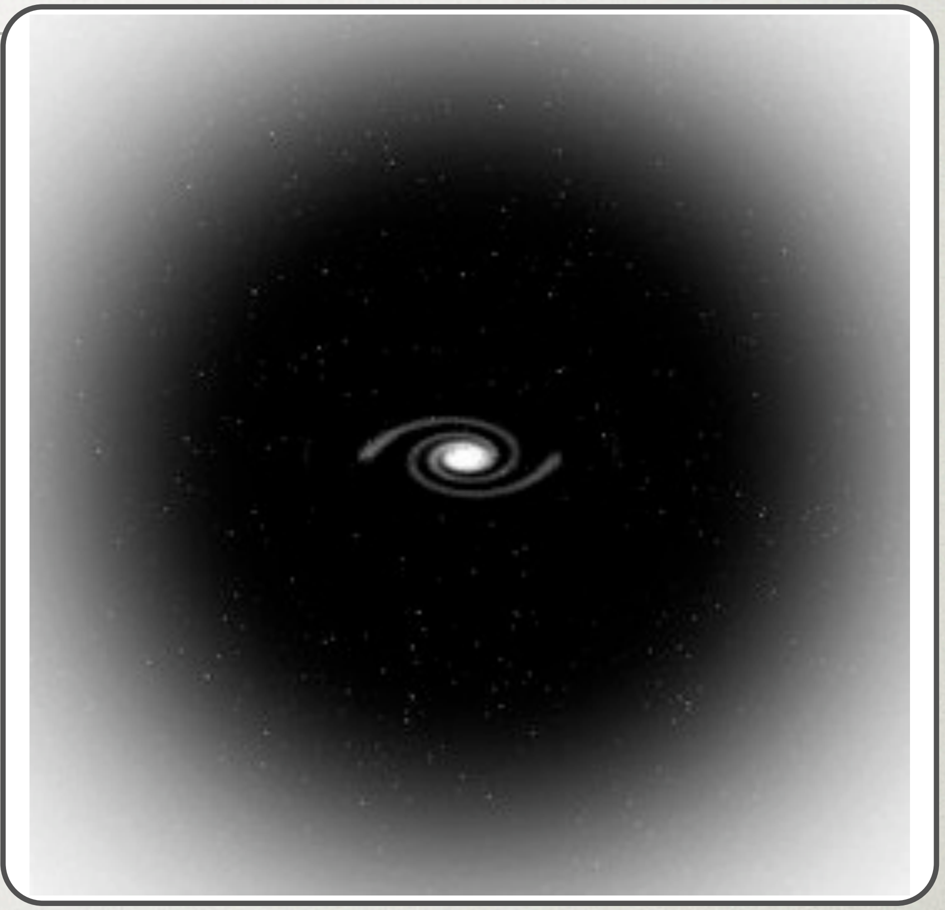
OUTLINE

- basics of direct dark matter detection
- elastic spin independent scattering
  - global (in)consistency of the experimental results
  - astrophysics independent bounds on annual modulation signal
- inelastic DM and isospin violating DM

basics of DM direct detection

DIRECT DM DETECTION

- WIMPS form DM halo
  - typical $v \sim 10^{-3}$
- scatters on target nuclei $\chi N \to \chi N$
  - leaves energy in the detector



$$E_d = 2\frac{\mu_\chi^2}{M_A} v^2 \sim 2\text{keV}\left(\frac{120GeV}{M_A}\right)\left(\frac{\mu_\chi}{10\text{GeV}}\right)^2\left(\frac{v}{10^{-3}}\right)^2$$

  - energy deposit measured through: ionization, scintillation light, phonons

RATE

- differential counting rate

$$\frac{dR}{dE_d} = \frac{\rho_0}{m_\chi}\frac{\eta}{\rho_{\rm det}} \int_{v>v_{\rm min}} d^3v \, \frac{d\sigma}{dE_d} \, v f_\odot(\vec{v})$$

$$\rho_0 = 0.3 \ \mathrm{GeV/cm^3}$$

- minimal velocity $\chi N \to \chi' N$

$$v_{\rm min} = \frac{1}{\sqrt{2m_N E_d}}\left(\frac{m_N E_d}{\mu_{\chi N}} + \delta\right)$$

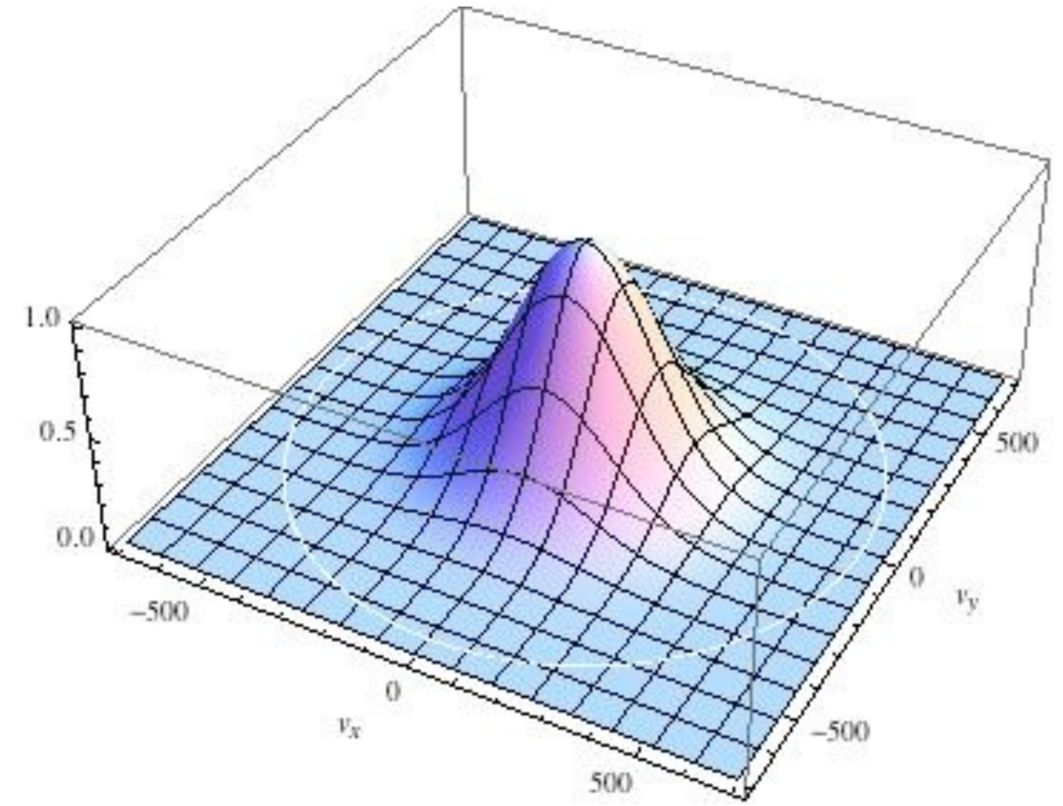
- for mass splitting large enough $v_{\rm min} > v_{\rm esc}$

RATE

- differential counting rate

$\frac{d}{d}$ … $(\vec{v})$

$$f_{\rm gal}(\vec{v}) \propto \exp(-\vec{v}^2/\bar{v}^2) - \exp(v_{\rm esc}^2/\bar{v}^2)$$



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- for … $\bar{v} = 220\,{\rm km\,s^{-1}}$ $\quad v_{esc} = 550~{\rm km~s^{-1}}$ …$_{\rm min} > v_{\rm esc}$

RATE

- differential counting rate

$$\frac{dR}{dE_d} = \frac{\rho_0}{m_\chi}\frac{\eta}{\rho_{\rm det}}\int_{v>v_{\rm min}} d^3v\, \frac{d\sigma}{dE_d}\, v f_\odot(\vec{v})$$

$$\rho_0 = 0.3\ {\rm GeV/cm^3}$$

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CROSS SECTIONS

- non-relativistic limit
  - DM can only couple to mass or spin
  - spin dependent (SD) or spin indep. (SI) scattering
  - keep only velocity unsupp. terms
- differential rate

$$\frac{d\sigma}{dE_d} = \frac{m_N}{2\mu_{\chi N}^2 v^2}\left(\sigma^{\rm SI} F^2(E_d) + \sigma^{\rm SD}\frac{S(E_d)}{S(0)}\right)$$

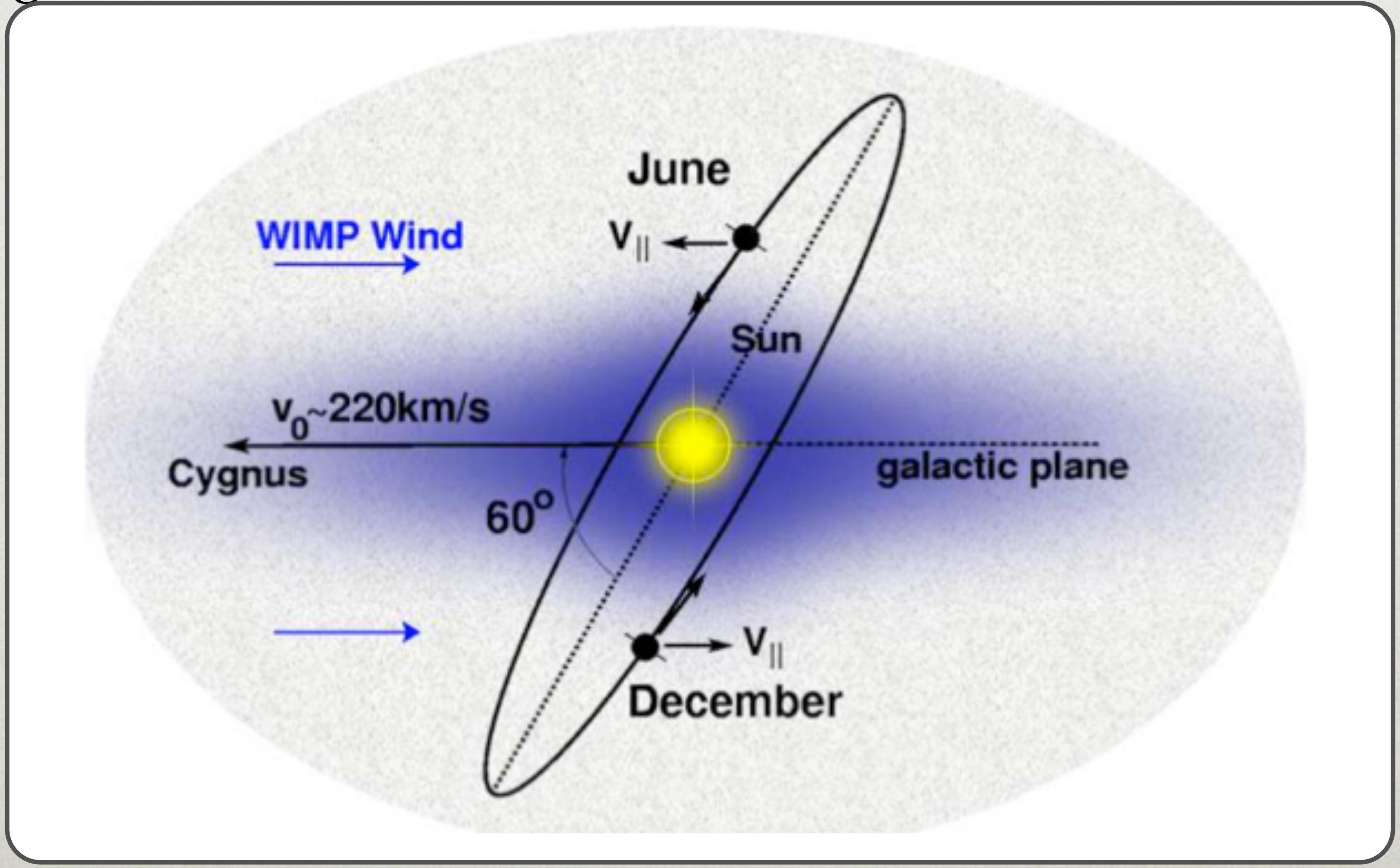
$$\sigma^{\rm SI} \propto (Z f_p + (A-Z) f_n)^2 \sigma_p^{\rm SI}/f_p^2$$

$$\sigma^{\rm SD} \propto (a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2 \sigma_p^{\rm SD}/a_p^2$$

EXPERIMENTAL SIGNALS

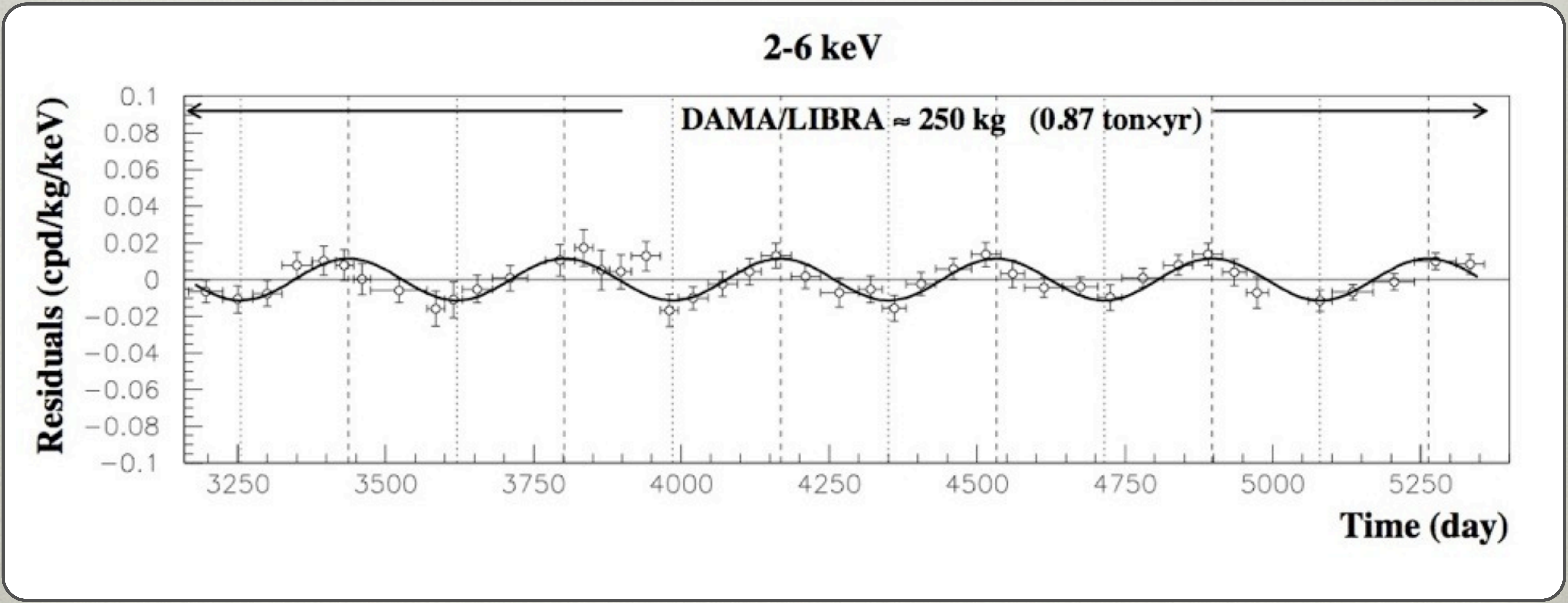
DAMA/LIBRA result

- impressive data sample from DAMA/NAI and DAMA/LIBRA: 1.14 ton year (1002.1028)
- see 8.9 sigma evidence for annual modulation
- target is Na and I



DAMA/LIBRA result

- phase agrees with DM interpretation: max @ day 146 ± 7 , expected June 2nd = day 152



CoGeNT

- germanium detector, low threshold — CoGeNT, Aalseth et al, 1002.4703
- sees a large rise of events at threshold
- a claim of modulation 2.8σ — Aalseth et al. [CoGeNT], 1106.0650
- recently: a bulk of the signal is due to surface events — J. Collar, talk at TAUP 2011
  - makes the modulation signal relatively larger
- CDMS also presented search for annual modulation — B. Serfass, talk at UCLA-DM 2012
  - incompatible with CoGeNT at *>95% CL*

CRESST

Angloher et al. [CRESST-II], 1109.0702

- $CaWO_4$ crystal, 730 kg days of data
- 67 events observed in the signal region
- background from e/γ events, α events, neutron events, Pb recoil
  - signal ~30±9 evnts (24±8 evnts)
- the significance of extra signal is >4σ

1109.0702

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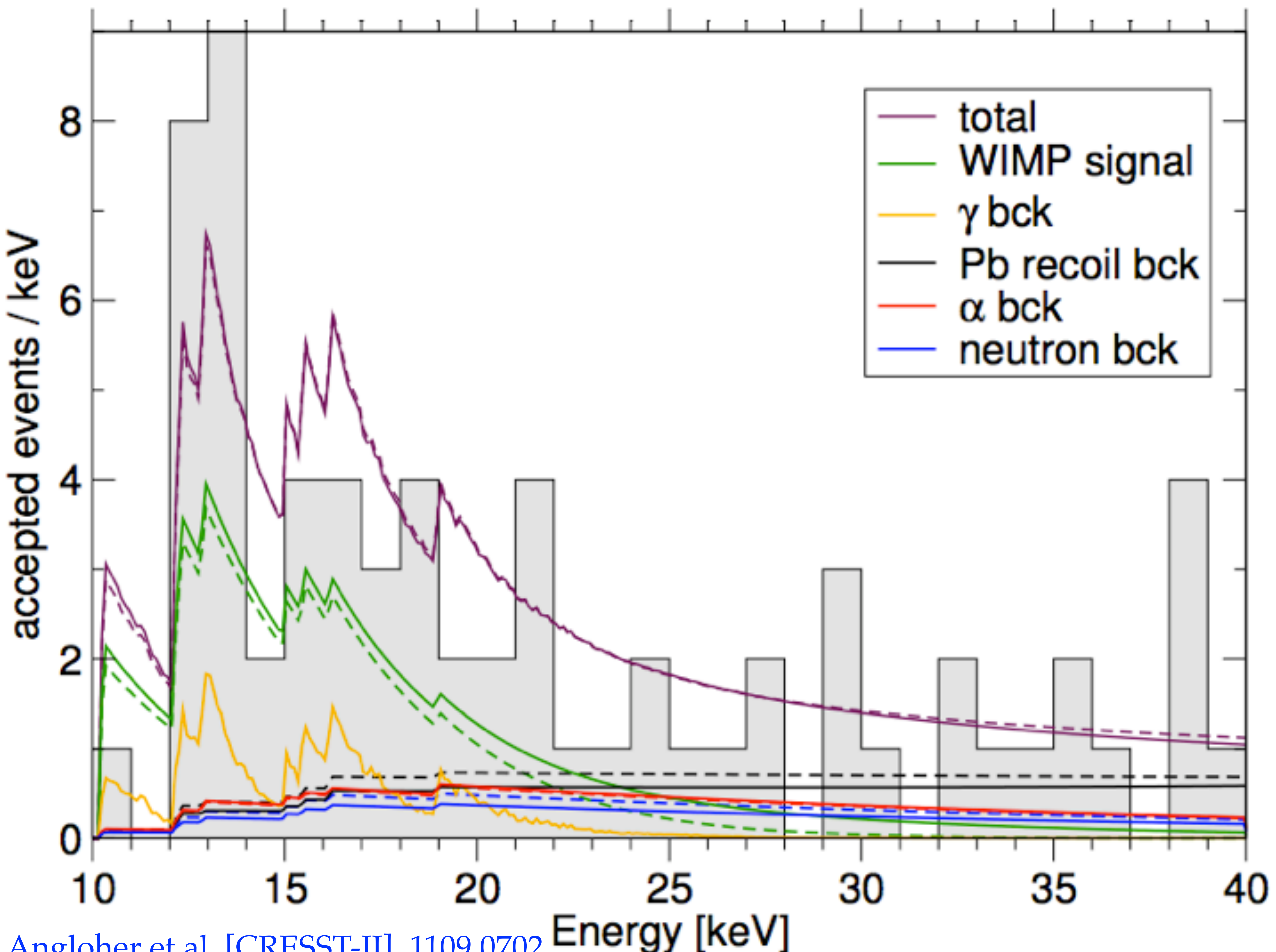

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SPIN INDEPENDENT SCATTERING

- in most DM models spin indep. scattering gives the dominant signal
  - for instance from scalar or vector interactions
- excluded by other direct detection searches

SPIN INDEPENDENT SCATTERING

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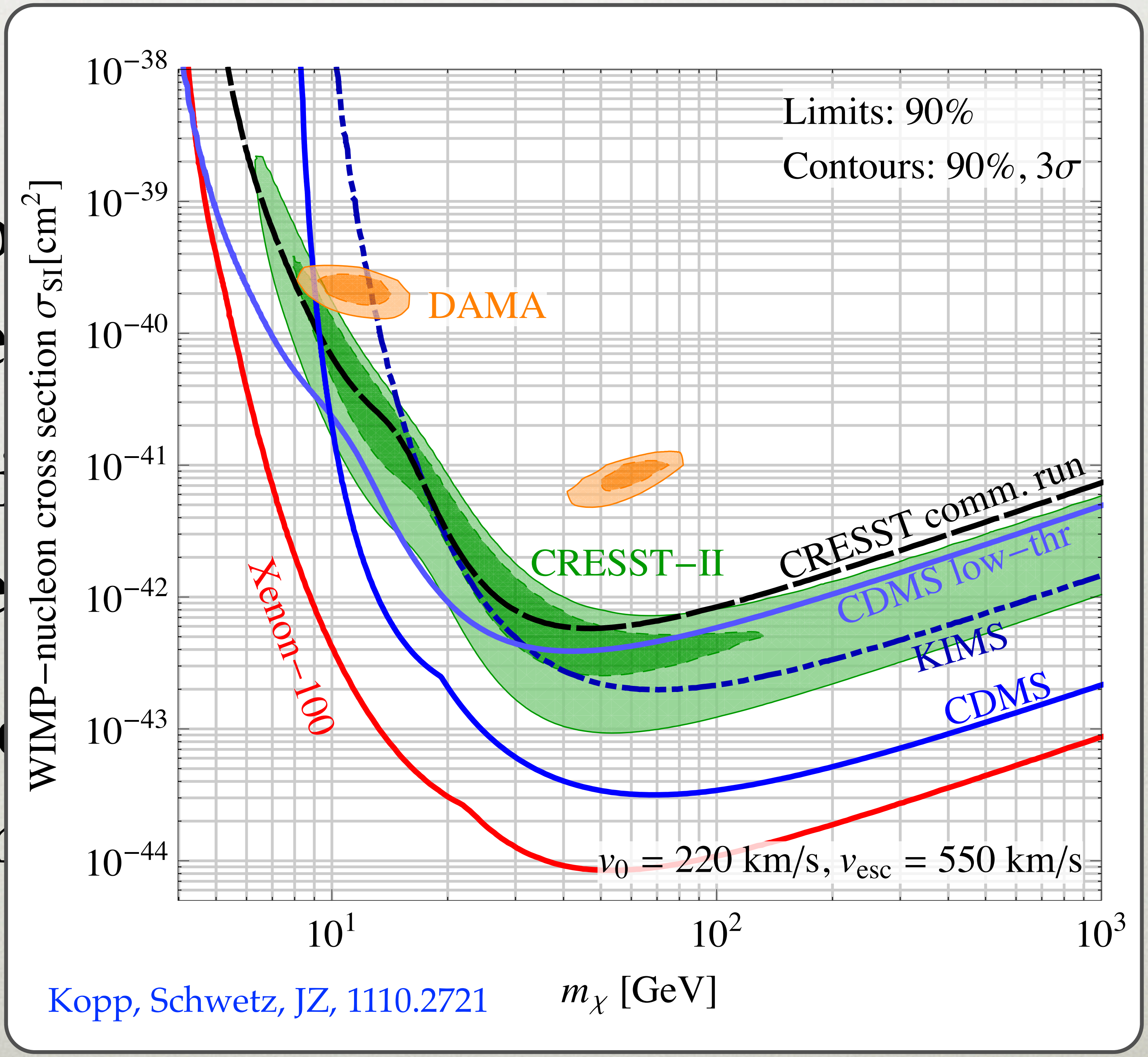

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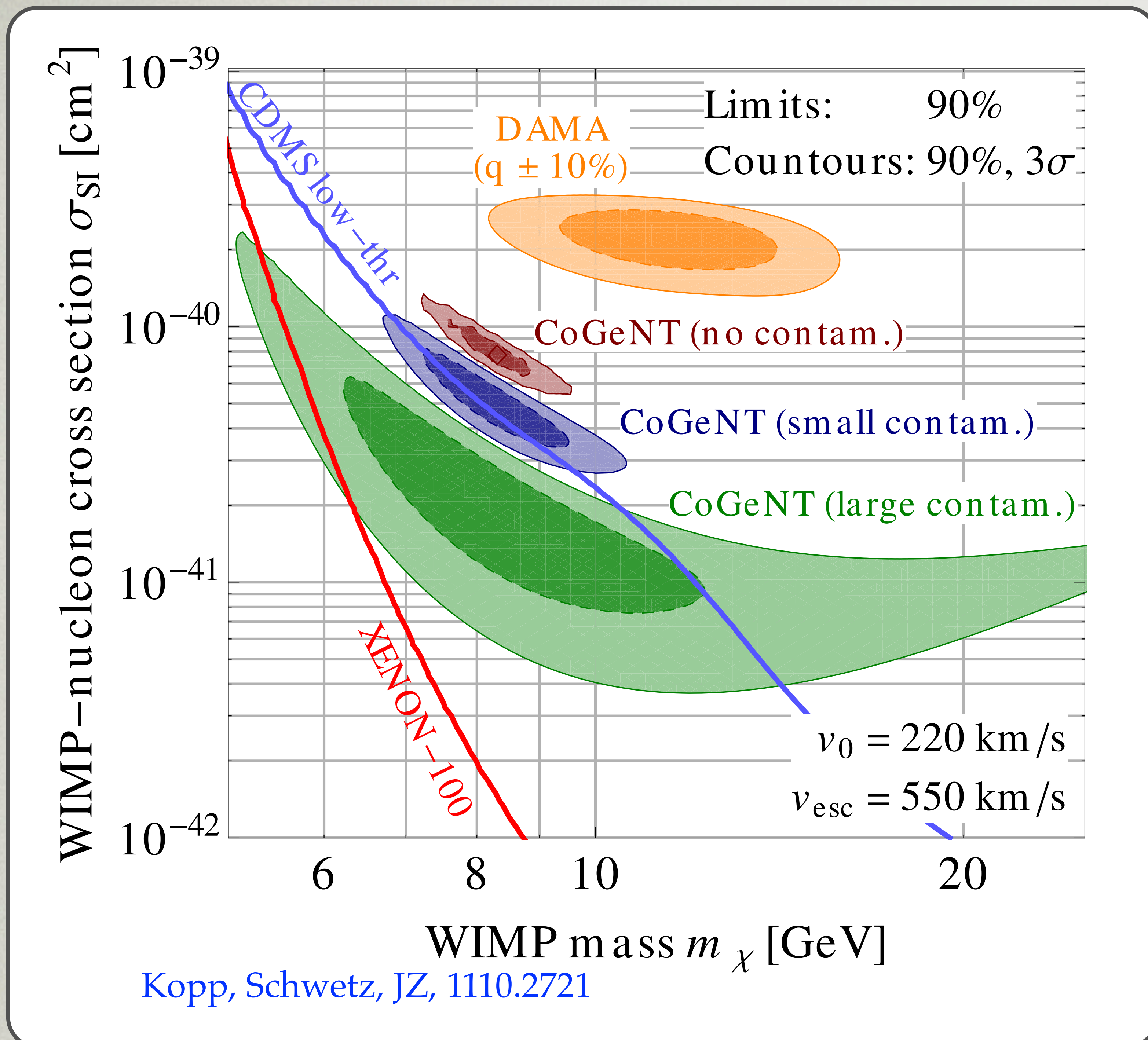
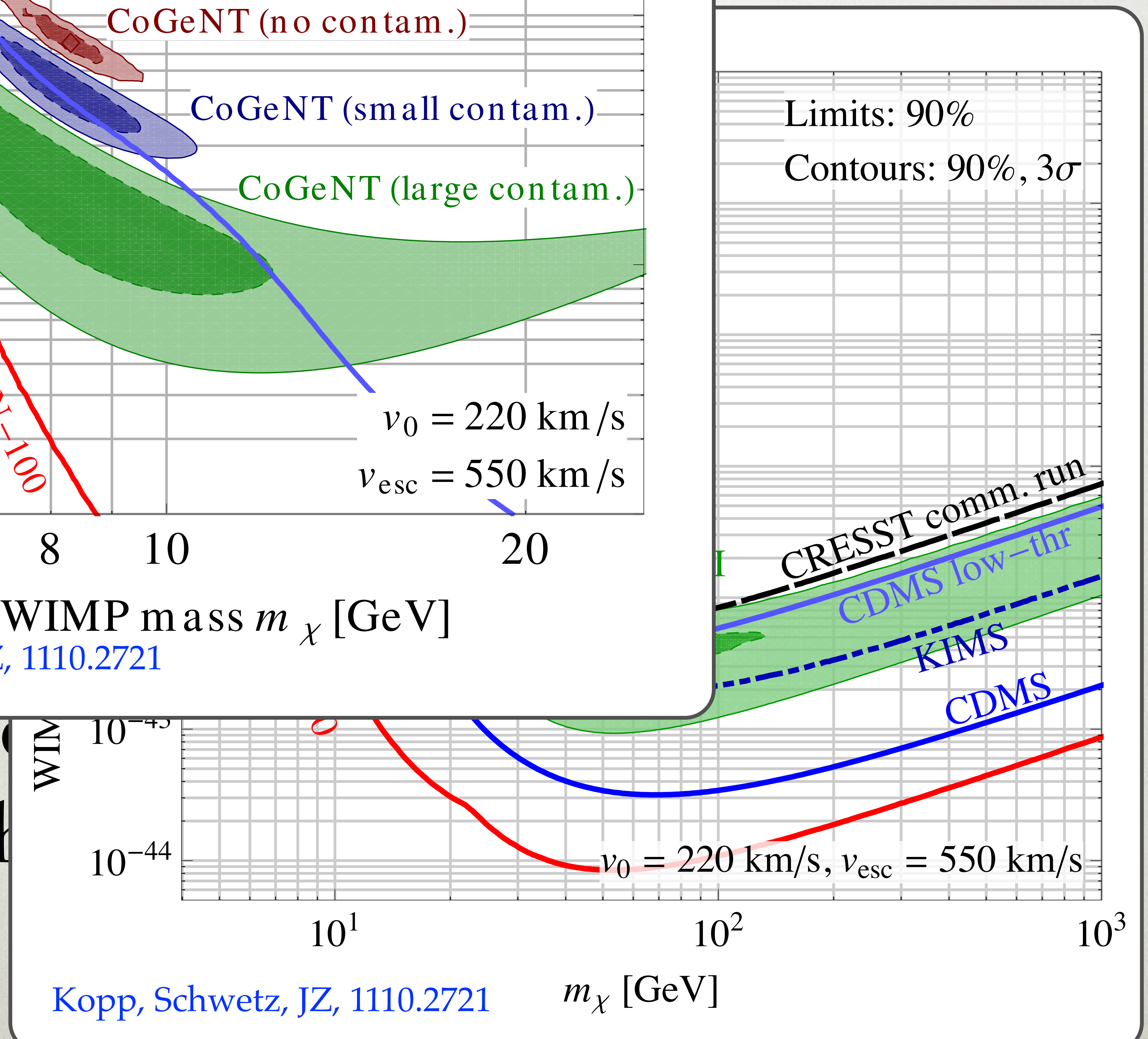




- exclu
search

UNCERTAINTIES?

- could this incompatibility be just due to errors?
  - nuclear uncertainties?
  - astrophysics uncertainties?
- can get rid (most) of both
  - through bounds on observed annual modulation

BOUNDS ON ANNUAL MODULATION

EXPANSION PARAMETER

Herrero-Garcia, Schwetz, JZ, 1112.1627

- there is an expansion parameter
  - $v_{earth} \simeq 30km/s \ll v_{sun} \simeq 230km/s$
- **Assumption 1:** only time dependence from $v_{earth}(t)$
- this implies
  - DM halo spatially constant at sun-earth scale
  - DM halo constant in time on scale of months
- very conservative assumptions
  - also, that we can expand in v_{earth}
  - this can be checked experimentally

EXPANSION

- the rate is

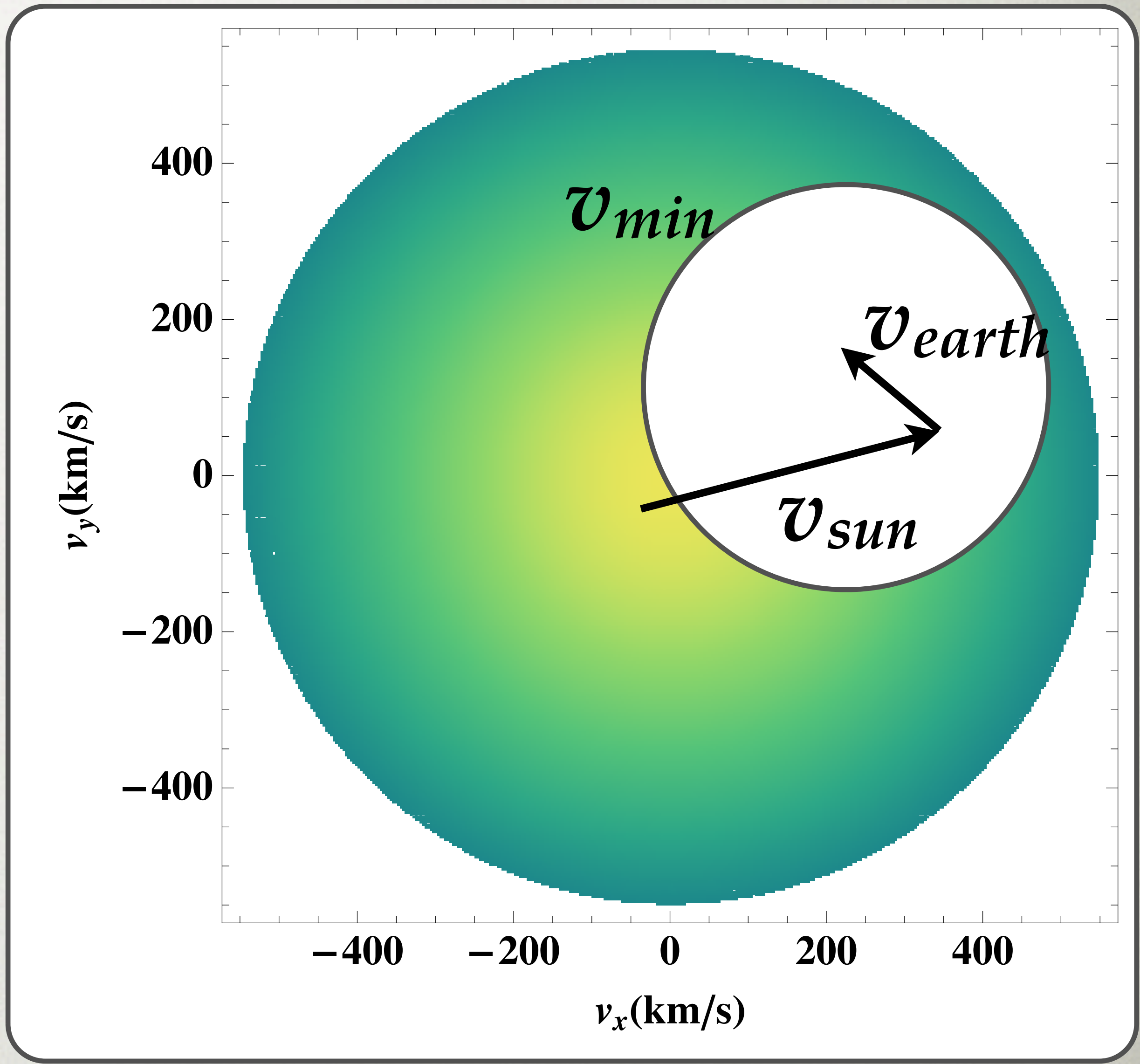
$$C = \frac{\rho_\chi \sigma_A^0}{2 m_\chi \mu_{\chi A}^2}$$

$$R(E_{nr}, t) = C\, F^2(E_{nr})\, \eta(v_m, t)$$

$$\eta(v_m, t) \equiv \int_{v > v_m} d^3 v f_{\text{det}}(\mathbf{v}, t)/v$$

- time modulation given by linear term in v_{earth}

$$R(E_{nr}, t) \propto \overline{\eta}(v_m) + \delta\eta(v_m, t)$$



$$\delta\eta(v_m, t) = A_\eta(v_m) \cos 2\pi[t - t_0(E_{nr})]$$

EXPANSION

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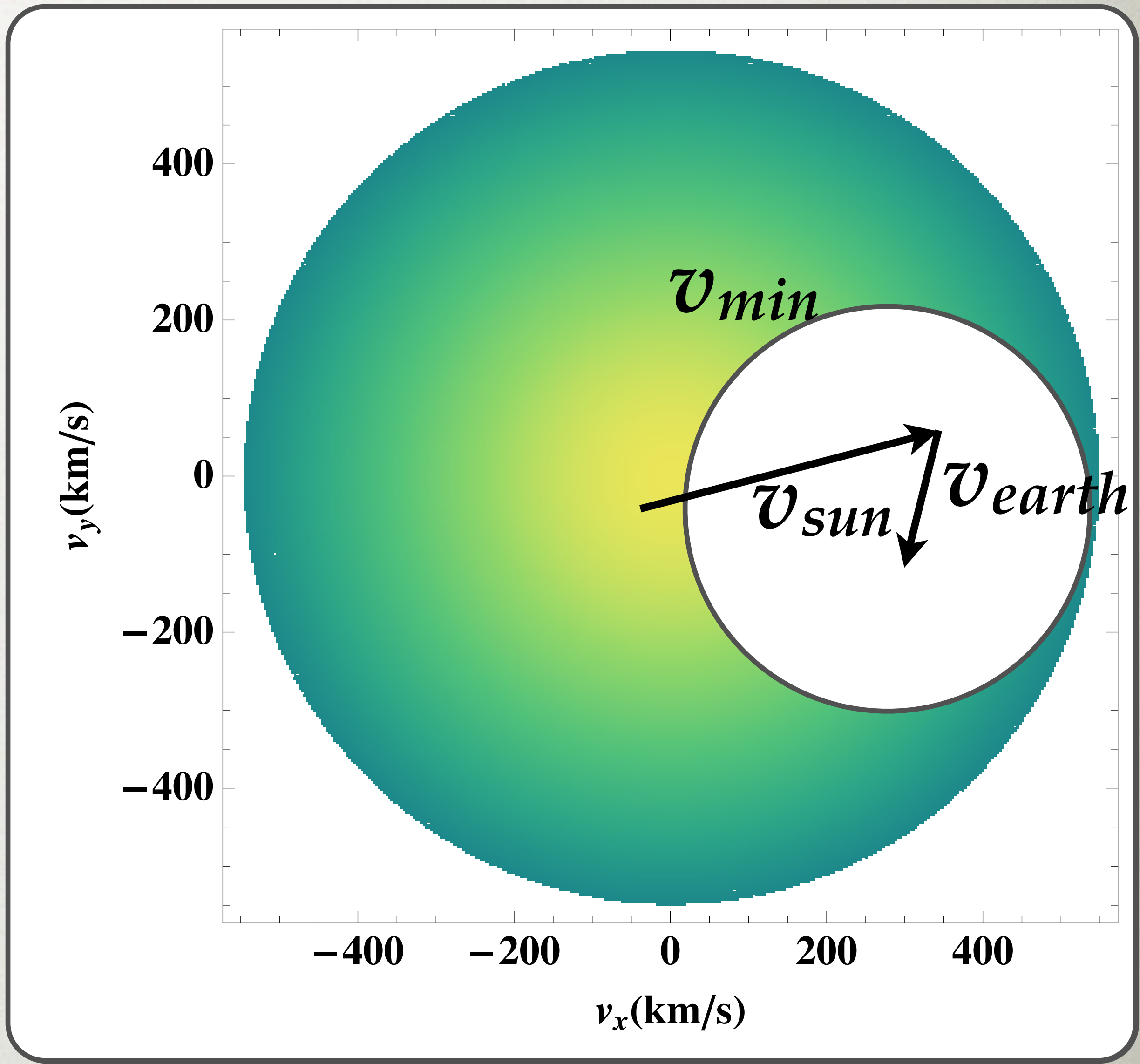

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EXPANSION

- expanding in v_{earth}

$$\eta(v_m,t)=\int_{|\mathbf{v}-\mathbf{v}_e|>v_m} d^3v\frac{f(\mathbf{v})}{|\mathbf{v}-\mathbf{v}_e|}$$
$$=\int_{v>v_m} d^3v\frac{f(\mathbf{v})}{v}+\int d^3v f(\mathbf{v})\frac{\mathbf{v}\cdot\mathbf{v}_e(t)}{v^3}\left[\Theta(v-v_m)-\delta(v-v_m)v_m\right]$$

- $\delta\eta(v_m,t)$ has surface and bulk contribs.

$$\delta\eta(v_m,t)=\mathbf{v}_e(t)\cdot\left[\hat{\mathbf{v}}_G(v_m)G(v_m)-\hat{\mathbf{v}}_g(v_m)v_m g(v_m)\right]$$

$$\hat{\mathbf{v}}_g(v_m)g(v_m)\equiv\int d^3v f(\mathbf{v})\frac{\mathbf{v}}{v^3}\delta(v-v_m)$$
$$\hat{\mathbf{v}}_G(v_m)G(v_m)\equiv\int d^3v f(\mathbf{v})\frac{\mathbf{v}}{v^3}\Theta(v-v_m)$$

- this leads to a bound

$$A_\eta(v_m)\le v_e\left[v_m g(v_m)+G(v_m)\right]$$

EXPANSION

- expanding in v_{earth}

$\bar{\eta}(v_m)$

$$\eta(v_m, t) = \int_{|\mathbf{v}-\mathbf{v}_e|>v_m} d^3v \frac{f(\mathbf{v})}{|\mathbf{v}-\mathbf{v}_e|}$$

$$= \int_{v>v_m} d^3v \frac{f(\mathbf{v})}{v} + \int d^3v f(\mathbf{v}) \frac{\mathbf{v}\cdot\mathbf{v}_e(t)}{v^3} \left[\Theta(v-v_m) - \delta(v-v_m)v_m\right]$$

- $\delta\eta(v_m,t)$ has surface and bulk contribs.

$$\delta\eta(v_m, t) = \mathbf{v}_e(t) \cdot \left[\hat{\mathbf{v}}_G(v_m)G(v_m) - \hat{\mathbf{v}}_g(v_m)v_m g(v_m)\right]$$

$$\hat{\mathbf{v}}_g(v_m)g(v_m) \equiv \int d^3v f(\mathbf{v}) \frac{\mathbf{v}}{v^3}\delta(v-v_m)$$

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$$A_\eta(v_m) \le v_e\left[v_m g(v_m) + G(v_m)\right]$$

THE BOUND

- the bound in terms of rate

$$A_\eta(v_m) \leq v_e \left[-\frac{d\overline{\eta}}{dv_m} + \frac{\overline{\eta}(v_m)}{v_m} - \int_{v_m} dv \frac{\overline{\eta}(v)}{v^2} \right]$$

  - r.h.s. can be expressed in terms of observed rates
  - the bound applies irrespective of modulation phase
  - is saturated for very nontrivial DM velocity distrib.
    - e.g. a strong cold stream that dominates at v_m
    - even then will not be saturated for different v_m

IMPROVED BOUNDS

- the bound can be improved, if additional assumptions
- **Assumption 2:** $\hat{v}_g$ is independent of v_m
- a simple relation for annual modulation

$$\delta\eta(v_m, t) = -\mathbf{v}_e(t) \cdot \hat{\mathbf{v}}_{\rm halo} \left[v_m g(v_m) - G(v_m) \right]$$

  - experimental indication would be that phase indep. of v_m
- is satisfied for symmetrical halos
  - standard Maxwellian halo, any other isotropic velocity distrib.
  - triaxial halos (up to subleading corrections due to the peculiar velocity of the sun)
  - dark streams parallel to v_{sun} (e.g. dark disk co-rotating with stellar disk)

IMPROVED BOUNDS

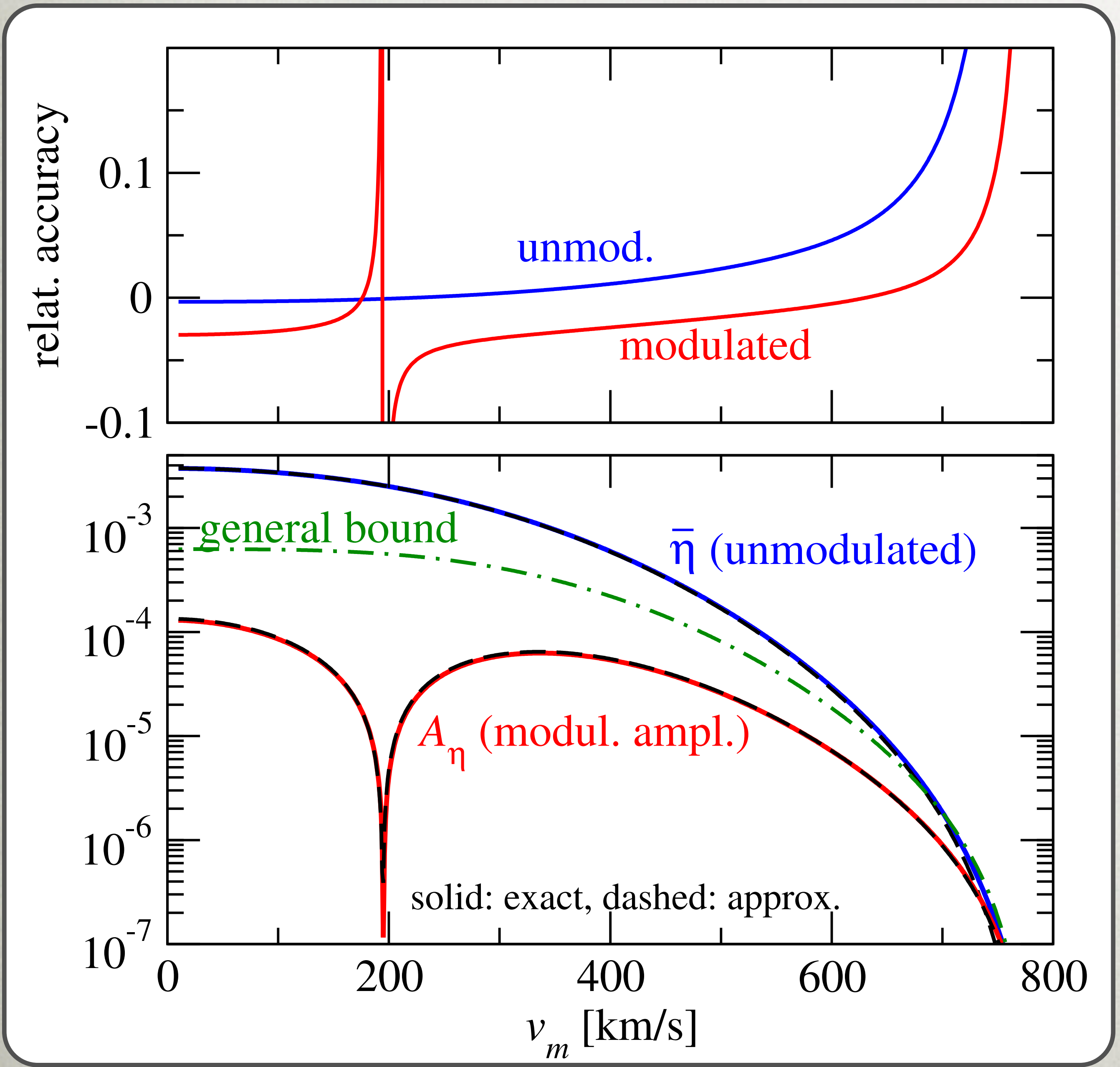
- an integral bound can be derived

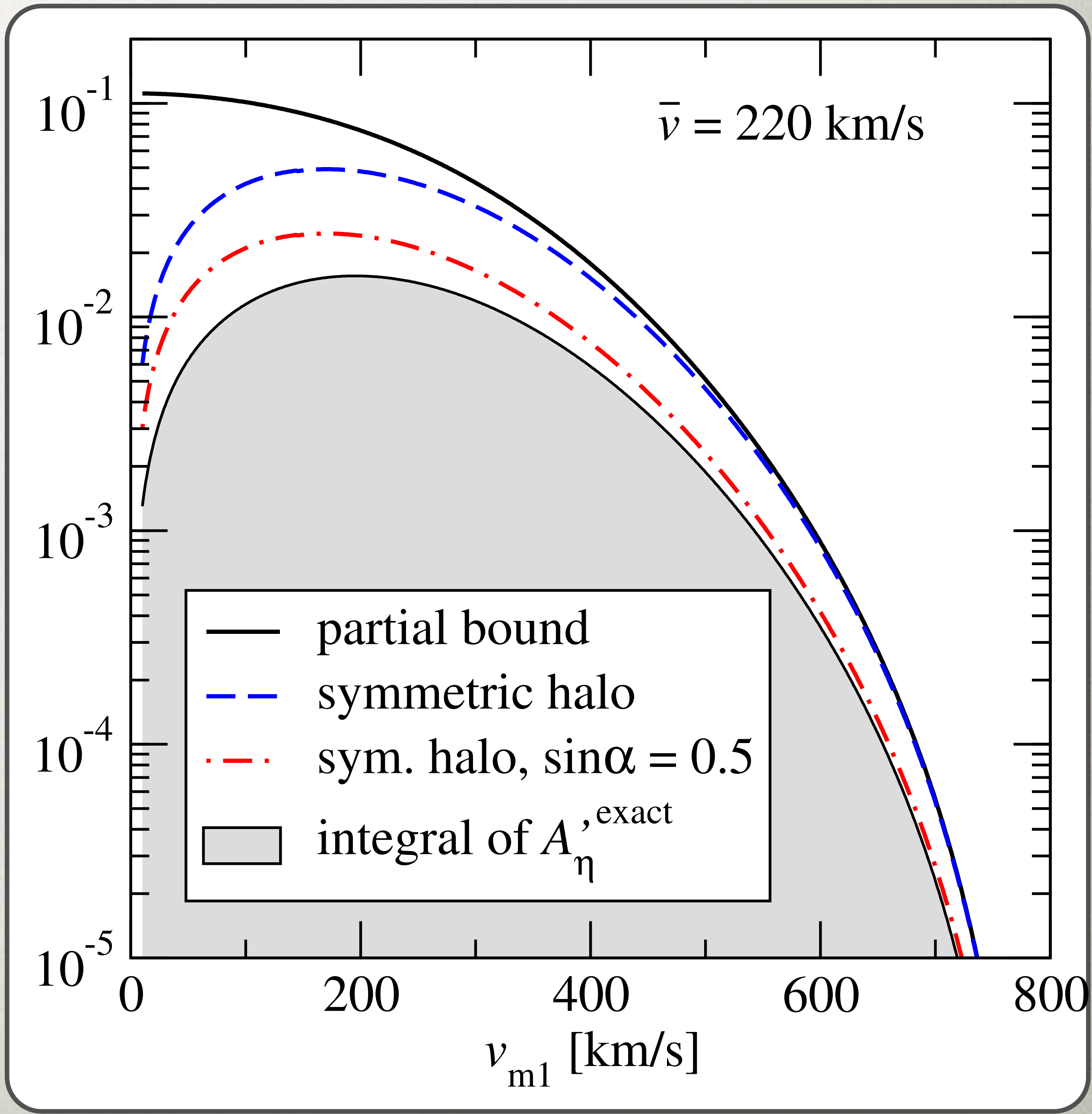
$$\int_{v_{m1}}^{v_{m2}} dv_m A'_\eta(v_m) \le v_e |\sin\alpha_{\rm halo}| \left[\overline{\eta}(v_{m1}) - v_{m1}\int_{v_{m1}} dv \frac{\overline{\eta}(v)}{v^2}\right]$$

- **Assumption 2:** $\hat{v}_g$ is independent of v_m
  - then $|sin(\alpha_{halo})| \to 1$
- **Assumption 2a:** $\hat{v}_g$ is also aligned with v_{sun}
  - then $|sin(\alpha_{halo})| \to 0.5$
  - true for all previous examples
  - this assumption fixes the phase to be around June 2nd

HOW GOOD ARE THE BOUNDS?

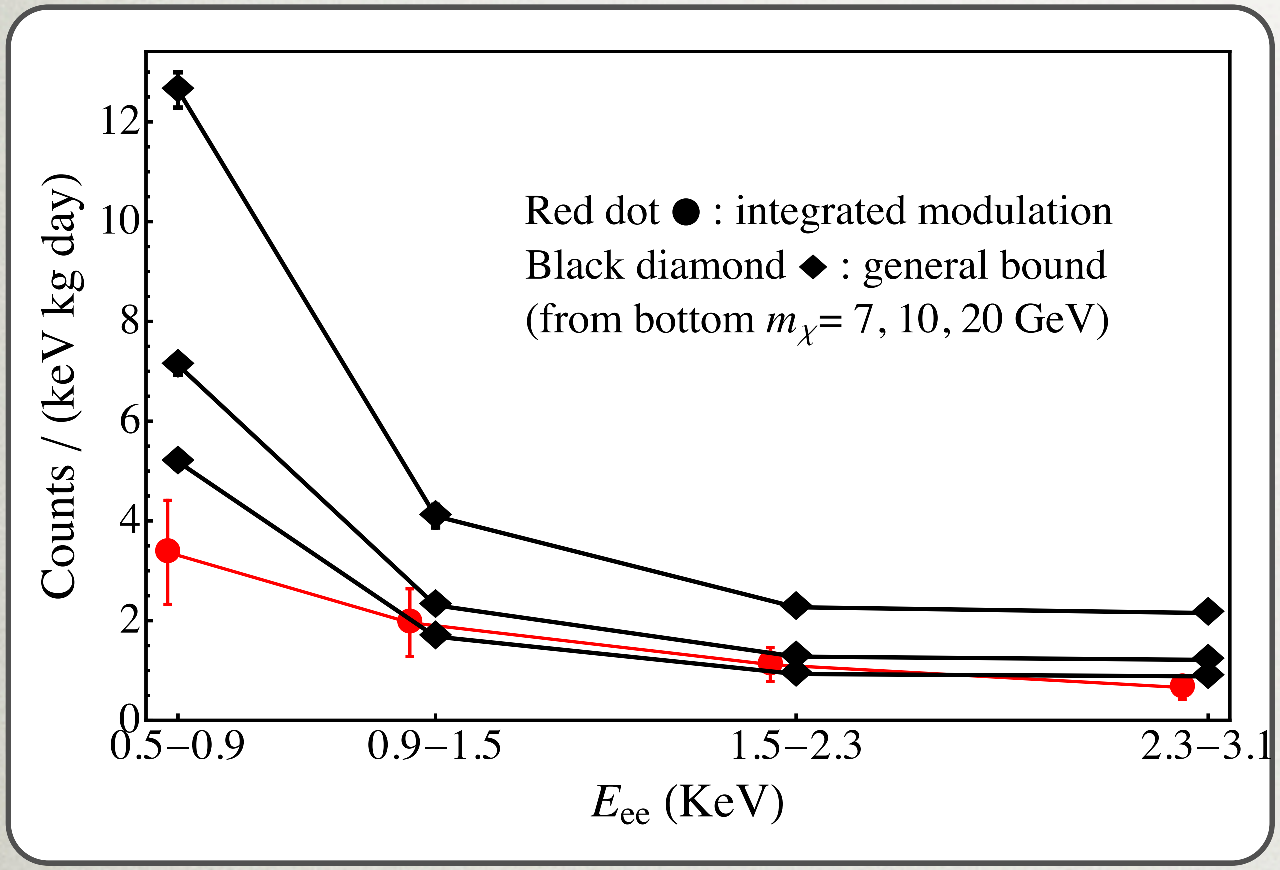
- assume Maxwellian halo, $\bar{v}$=220km/s

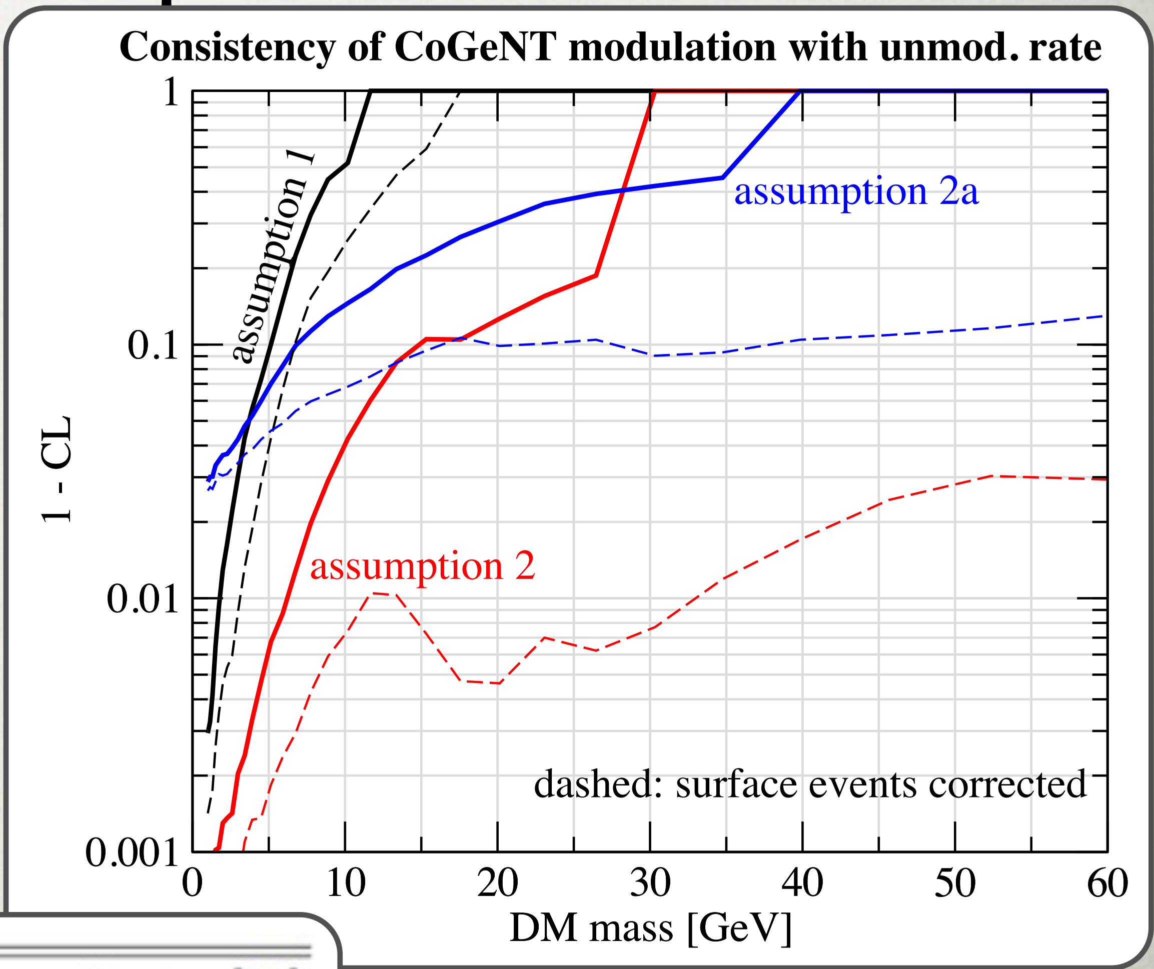




CoGeNT

- use CoGeNT as an example

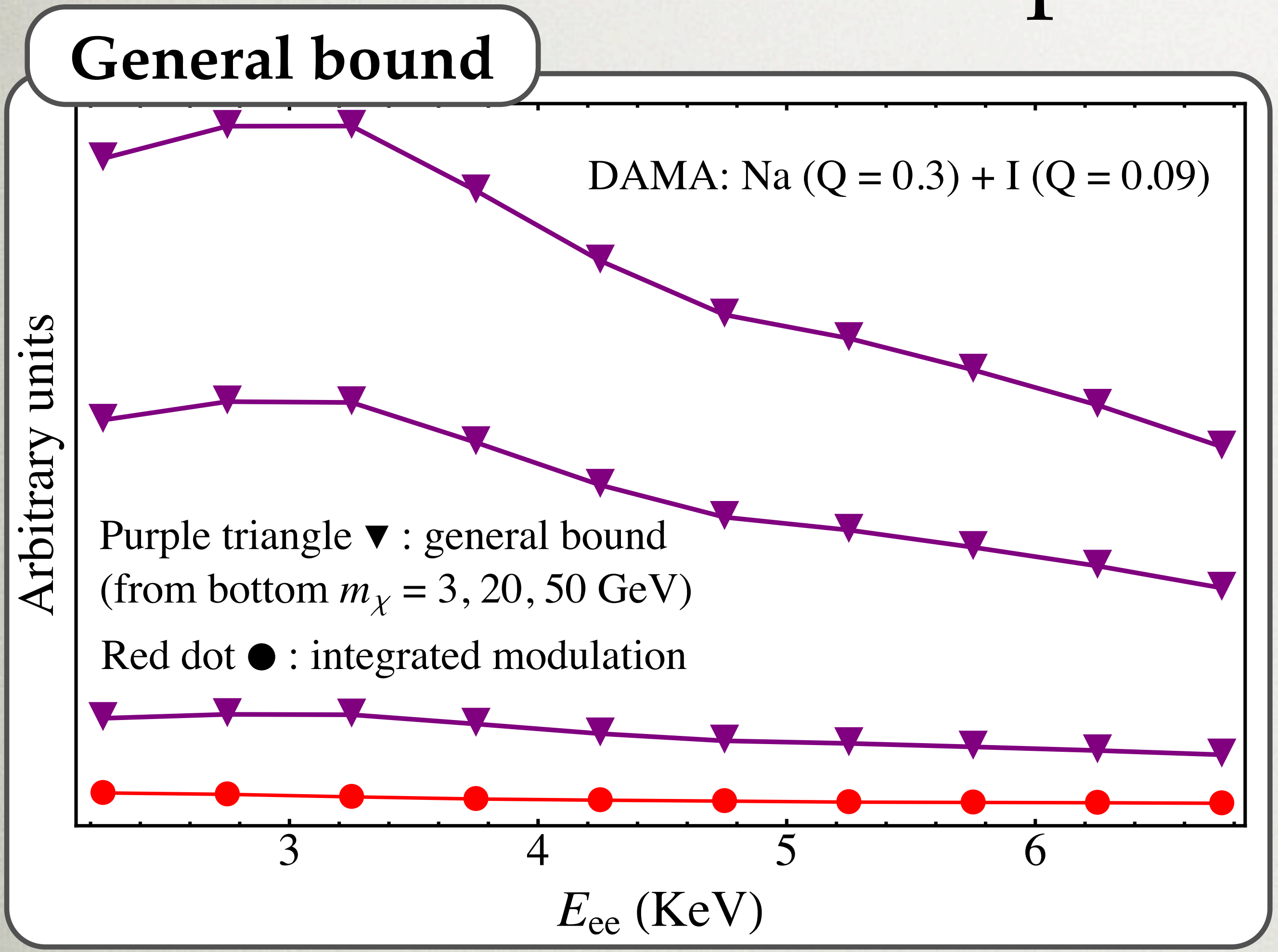


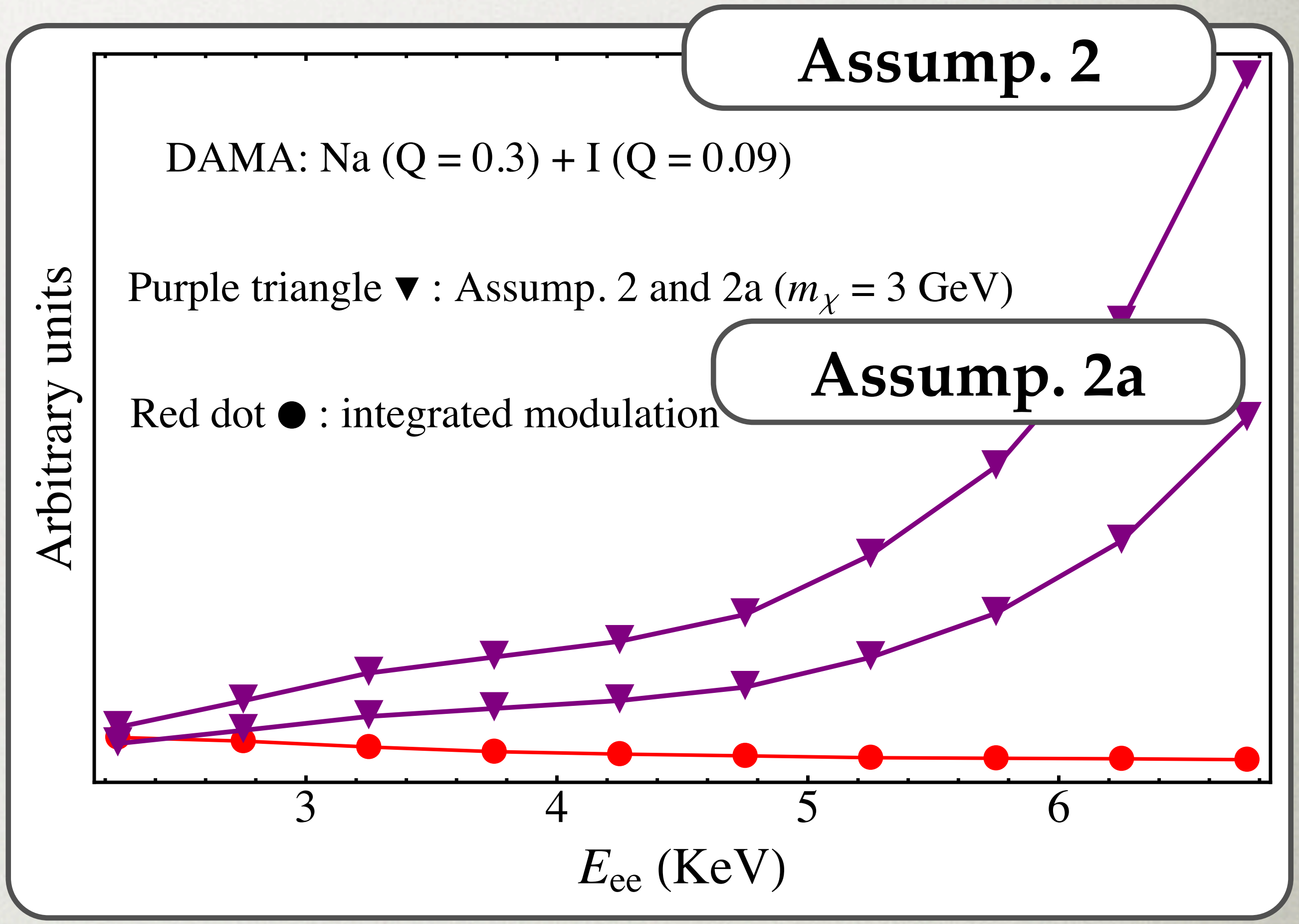


	unmodulated rate from [4]				corrected unmod. rate [21]			
	Mean	68%	95%	$X^2 \leq 1$	Mean	68%	95%	$X^2 \leq 1$
Ass. 1: general bound	8.5	6	3	7.3	10	6.5	3	10
Ass. 2: symmetric halo	24	14	6	18	43	25	12.5	37
Ass. 2a: sym. halo, $\sin\alpha = 0.5$	27.5	13.5	3.5	16	59.5	23	3	35

DAMA

- another example: DAMA





- no useful bound, modulation small enough

FURTHER COMMENTS

- the bounds avoid dependence on astrophysics
  - smoothness of halo used
  - spikes in velocity distrib. narrower than *30km/s* break the expansion
- to apply the bounds need to choose the particle physics model
- illustrated for elastic DM scattering
  - can be modified to inelastic case
  - also different velocity dependence
  - can be used for comparison between different experiments

Herrero-Garcia, Schwetz, JZ, work in progress

other DM models

QUESTIONS

- elastic spin-independent with standard halo: not a good fit to all experiments
  - could a nongeneric DM model be viable?

DARK MATTER VARIATIONS

- a number of variations on DM one can consider
  - isospin violating couplings

    Kamionkowski, Kurylov, hep-ph/0307185; Giuliani, hep-ph/0504157; Cotta et al., 0903.4409; Kang et al., 1008.5243; Feng et al., 1102.4331; Chang et al., 1004.0697; Frandsen et al., 1105.3734
  - velocity suppressed interactions
  - inelastic scattering
    - endothermic, exothermic

      Tucker-Smith, Weiner, hep-ph/0101138
      Graham, Harnik, Rajendran, Saraswat, 1004.0937
  - scattering through resonances

    Bai, Fox, 0909.2900
  - additional momentum dependence

    Feldstein, Fitzpatrick, Katz, 0908.2991; Chang, Pierce, Weiner, 0908.3192
    - light mediators, derivative interactions,...
  - leptophilic interactions

    Kopp, Niro, Schwetz, JZ, 0907.3159
  - spin dependent interactions
  - ...

OTHER UNCERTAINTIES

- astrophysical uncertainties
  - vary velocity profiles, v_{esc}, etc
  - can at least partially address model indep.
    - Fox, Liu, Weiner 1011.1915 Fox, Kribs, Tait, 1011.1910
    - "integrate them out" in comparing exp.
    - bounds on modulation from the same exp.
    - Herrero-Garcia, Schwetz, JZ, 1112.1627
- channeling Bozorgnia, Gelmini, Gondolo, 1006.3110; 1008.3676; 1009.3325
- nuclear and atomic physics
  - quenching factors, L_{eff} in S1, Q_y in Xenon S2
  - nuclear form factor uncertainties

TENSIONS

Schwetz, JZ 1106.6241; Farina, Pappadopulo, Strumia, Volansky 1107.0715;
Fox, Kopp, Lisanti, Weiner 1107.0717; Hooper, Kelso 1106.1066; McCabe 1107.0741

- a complete check for “old” CoGeNT and DAMA was done by four groups
- the bottom line:
  - none of the models can make both signals +other bounds work
  - including uncertainties
- focus on CRESST-II
  - could it be due to DM?

INELASTIC DARK MATTER

- CRESST target contains W, is heavy
- if scattering of DM inelastic
  - scattering on light nuclei no signal

$$v_{\min} = \frac{1}{\sqrt{2m_N E_d}}\left(\frac{m_N E_d}{\mu_{\chi N}} + \delta\right)$$

- W the heaviest, there is a solution, $\delta \sim 90$keV
- maybe tension with Xenon-100 (PG test values of 2%-20%)
- very dependent on astrophysics details
  - a coincidence problem

INELA

- CRESST ta
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  - scatterin

$v_{min} =$

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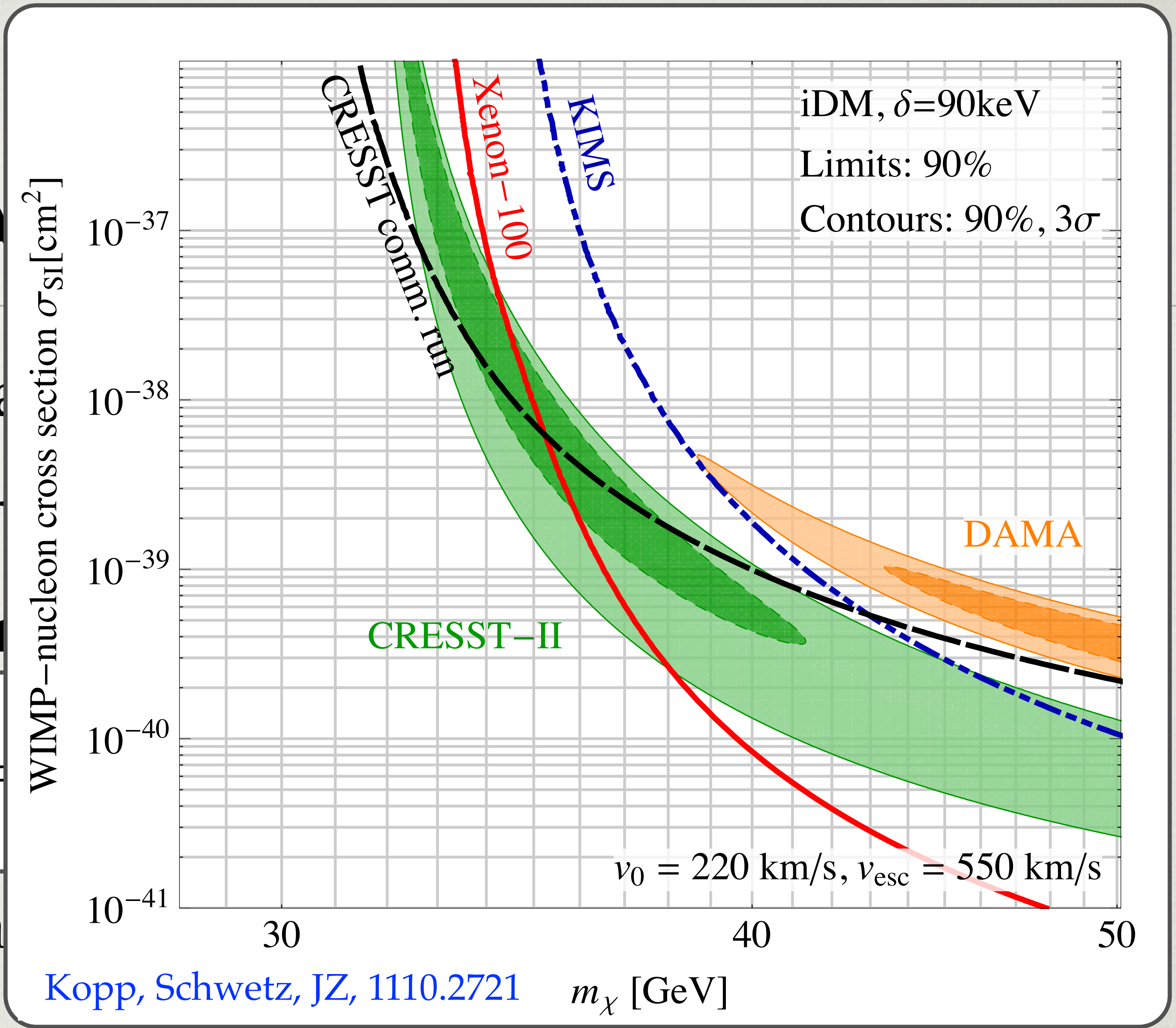

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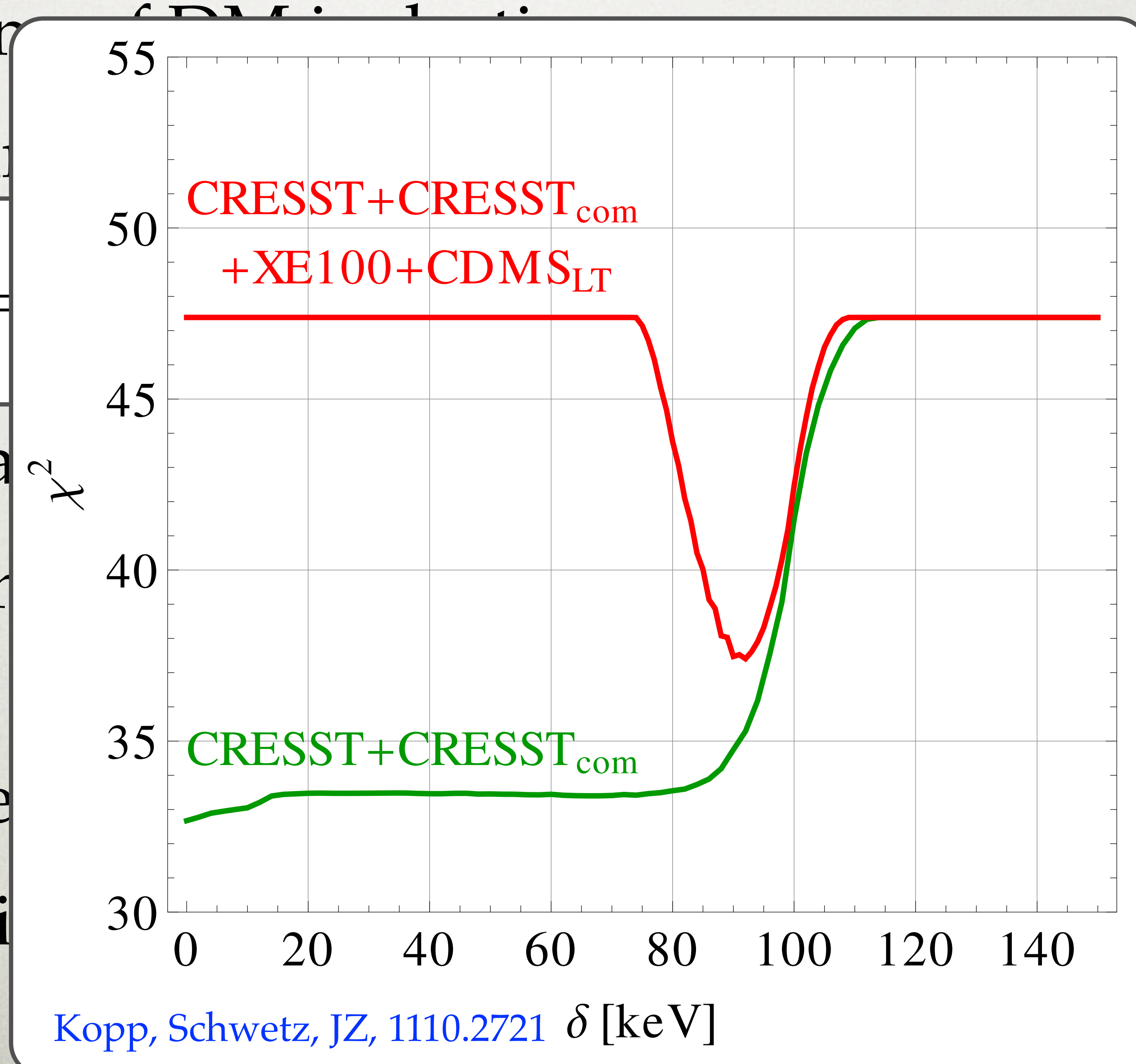

Kopp, Schwetz, JZ, 1110.2721

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ISOSPIN VIOLATING DM

- DM could couple differently to *p* than *n*
  - counter example: higgs mediated scattering
    - dominated by strangeness content
- if couplings to *u*, *d* dominate IVDM possible
- phenomenologically interesting if couplings such that scattering on Xe suppressed
- not possible to suppress it completely
  - in detector several isotopes

IVDM and CRESST

- define effective atomic number

$$A_{\text{eff}}^2 \equiv \sum_{i \in \text{isotopes}} 2r_i [Z\cos\theta + (A_i - Z)\sin\theta]^2$$

here $\tan\theta \equiv f_n/f_p$

- Xe suppressed for $f_n/f_p = -0.7$
  - but then Si, Ge large
  - also W suppressed, Ca and O large
  - in CRESST-II scattering exclusively on Ca an O now
    - 39% scattering on O, 61% on Ca
    - exactly opposite to iDM solution where only W

IVDM AND

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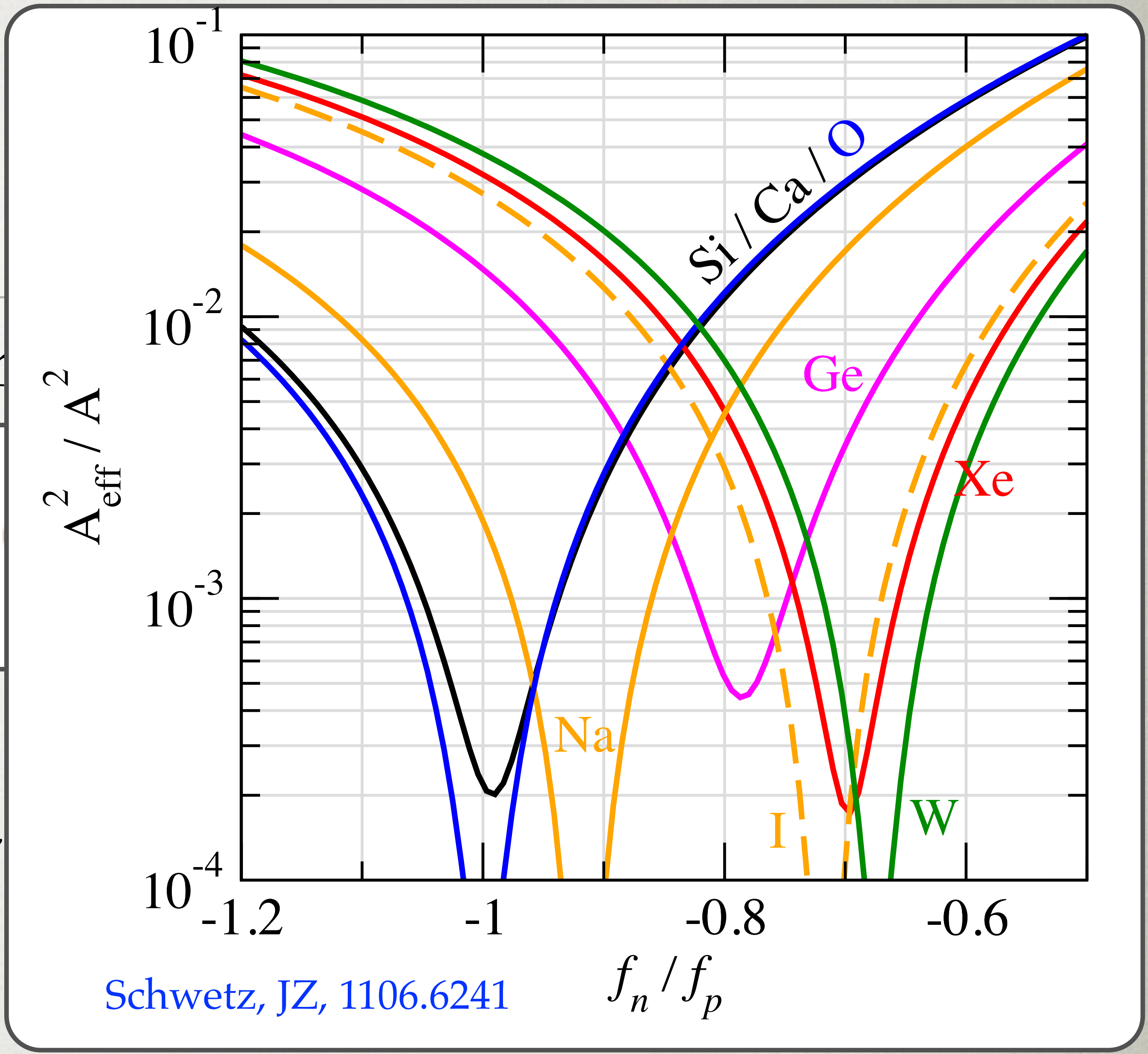
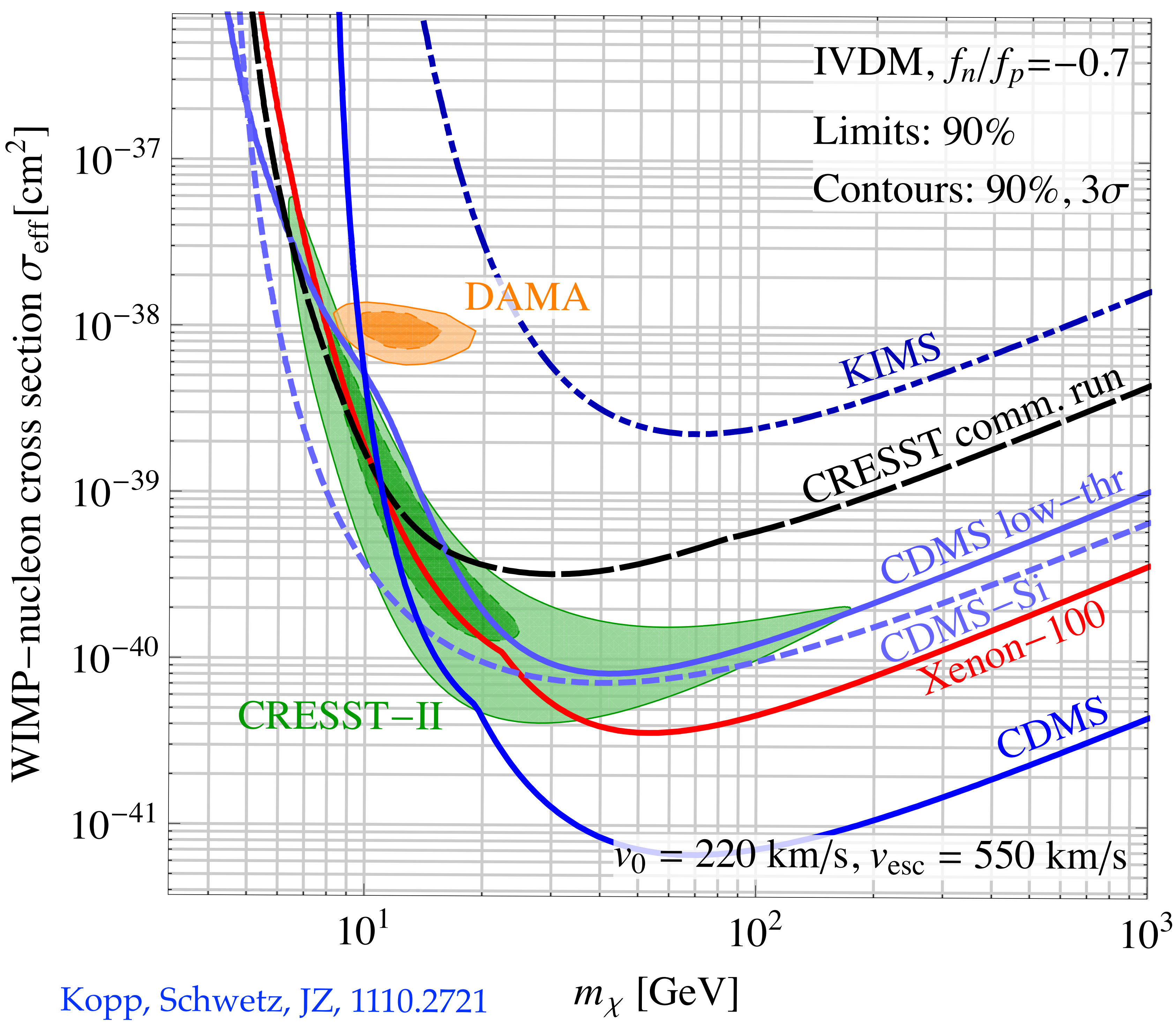
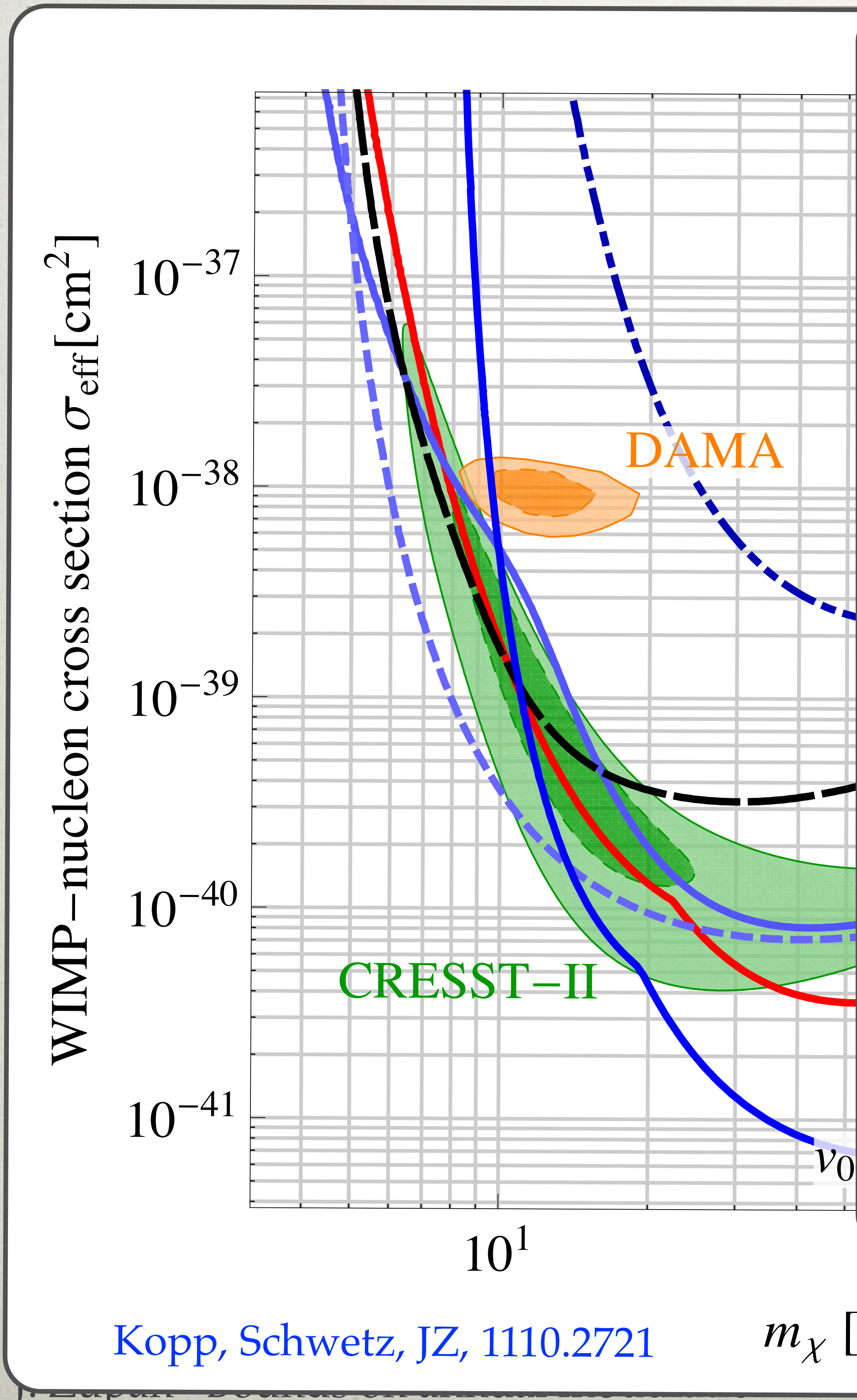


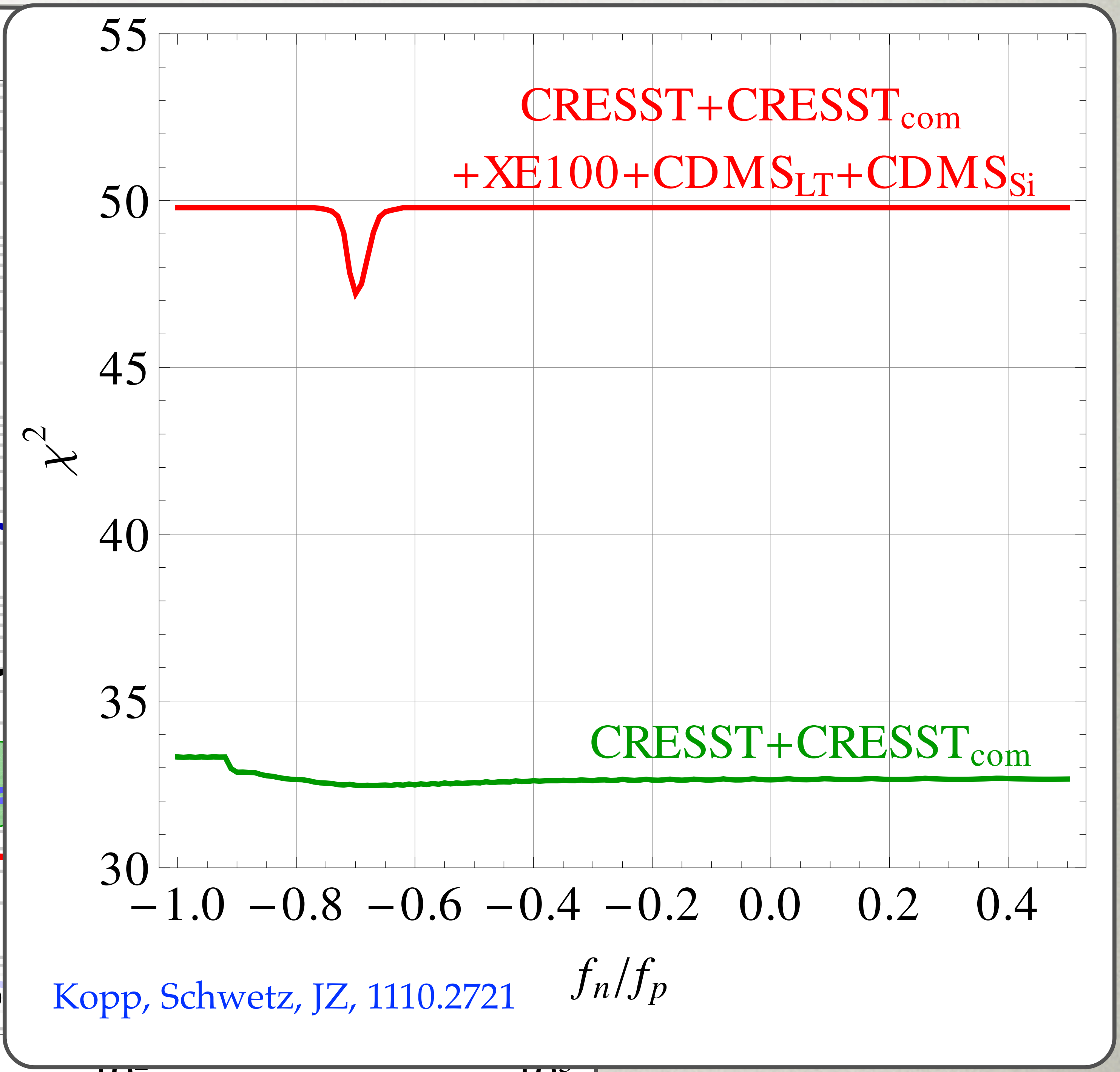
IVDM and CRESST



Kopp, Schwetz, JZ, 1110.2721

IVDM and CRESST





DARK MATTER AND THE HIGGS PORTAL

HIGGS AND DM

- first hints of SM-like Higgs* at the LHC and Tevatron
- what implications does this have for dark matter?
    - Higgs portal

- *SM-like Higgs for us:
    - m_H=*125* GeV, (xsec)x(Br) is the SM one ±*10%*

HIGGS PORTAL

- $(H^\dagger H)$-(dark sector) is (one of) the lowest dim. operator(s) connecting dark and visible sectors Patt, Wilczek, hep-ph/0605188; Kim, Lee, hep-ph/0611069....
  - renormalizable for scalar, vector DM
  - dim 5 for fermionic DM
- Higgs portal probed through
  - Higgs decays, and production
  - direct and indirect DM detection

DIRECT DETECTION BOUNDS

- assume only Higgs portal interactions for (DM)-(visible)
- for DM scalar or vector no useful bounds

Djouadi, Lebedev, Mambrini, Quevillon, 1112.3299

- for fermionic DM more interesting

Lopez-Honorez, Schwetz, JZ, 1203.2064

- will do first EFT, two dim=5 ops.

$$H_{\text{eff}} = \frac{1}{\Lambda_1} Q_1 + \frac{1}{\Lambda_5} Q_5$$

$$Q_1 = (H^\dagger H)(\bar{\chi}\chi)$$

$$Q_5 = i(H^\dagger H)(\bar{\chi}\gamma_5\chi)$$

DIRECT DETECTION BOUNDS

- nonrelativistic limit
  - the two operators behave differently in annihilation and DM-nucleon scattering

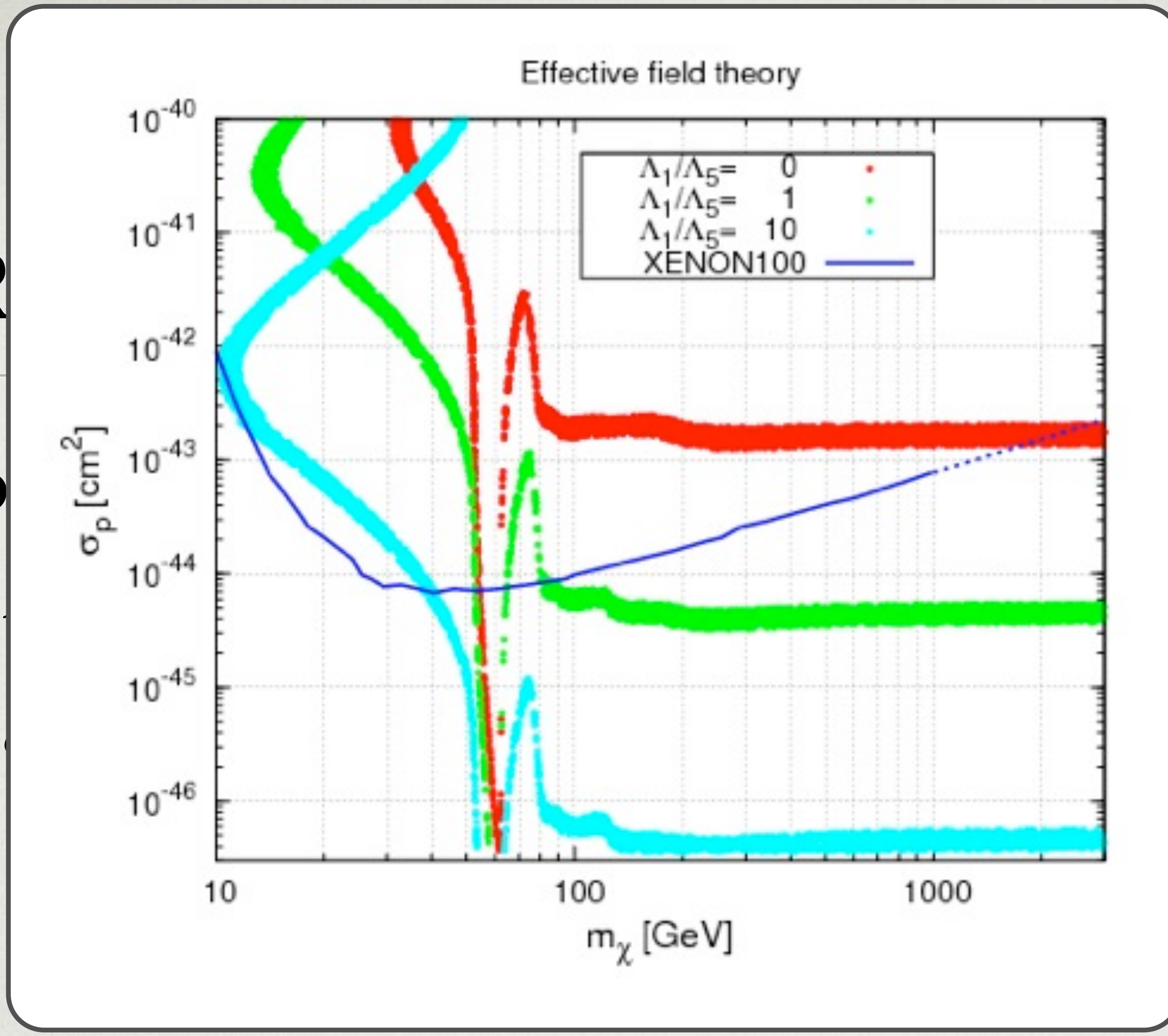
$$\sigma_{\rm ann} = \frac{1}{4\pi v}\left[\frac{v^2}{\Lambda_1^2} + \frac{1}{\Lambda_5^2}\right] f(m_\chi)$$

$$\sigma(\chi p \to \chi p) = \frac{2}{\pi}\left(\frac{2}{\Lambda_1^2} + \frac{v^2}{\Lambda_2^2}\right)\left(v_{\rm vev} g_{Hp}\right)^2 \left(\frac{m_{\rm red}}{m_h^2}\right)^2$$

- in EFT purely scalar coupling excluded to ~1TeV
  - i.e. parity conserving interactions excluded
- pseudoscalar (or mixed parity violating) allowed

DIR OUNDS

- no
  - ntly in
    ttering



$$\sigma(\chi p \to \chi p) = \frac{2}{\pi}\left(\frac{2}{\Lambda_1^2} + \frac{v^2}{\Lambda_2^2}\right)(v_{\rm vev} g_{Hp})^2 \left(\frac{m_{\rm red}}{m_h^2}\right)^2$$

- in EFT purely scalar coupling excluded to ~1TeV
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ON-SHELL REALIZATIONS

- this only in EFT
- when would EFT description break?
- light degrees of freedom below m_χ
  - s-channel resonant scattering
    - either through higgs or other resonances
  - light mediators form a thermal bath

PARITY CONSERVING INTERACTIONS

- for parity conserv. fermion DM Higgs portal 2 options
- show on toy model: Majorana DM +singlet scalar+SM
  - resonant Higgs portal
    - at decoupl. resonant annih. through Higgs

$$\chi\chi \to h \to X_{SM}$$

  - indirect Higgs portal
    - at decoupl. annih. through an extra mediator

$$\chi\chi \leftrightarrow \phi\phi \qquad \phi\phi \leftrightarrow X_{SM}$$

$$\sigma_{\chi\chi\to\phi\phi} = \frac{3 g_S^4 v}{32\pi m_\chi^2}$$

PARITY CONSERVING INTERACTIONS

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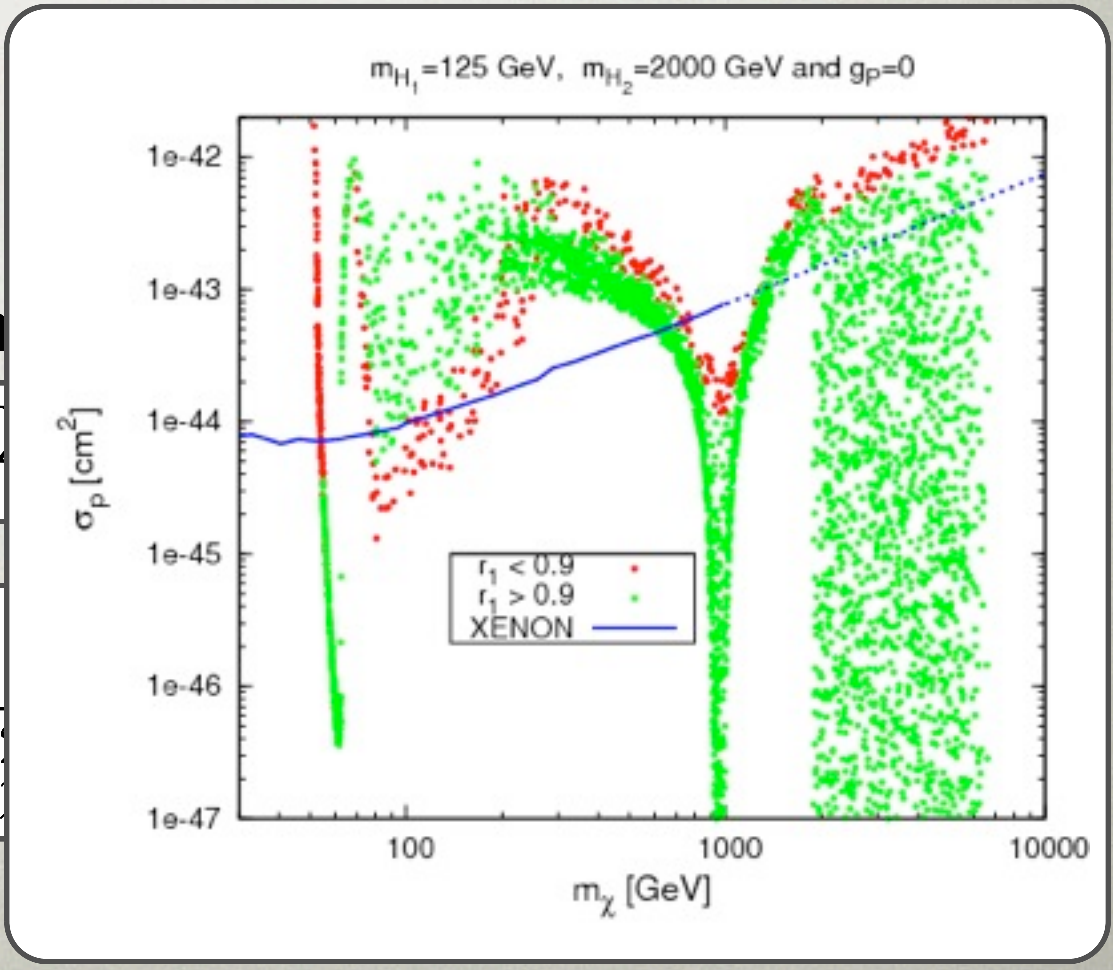
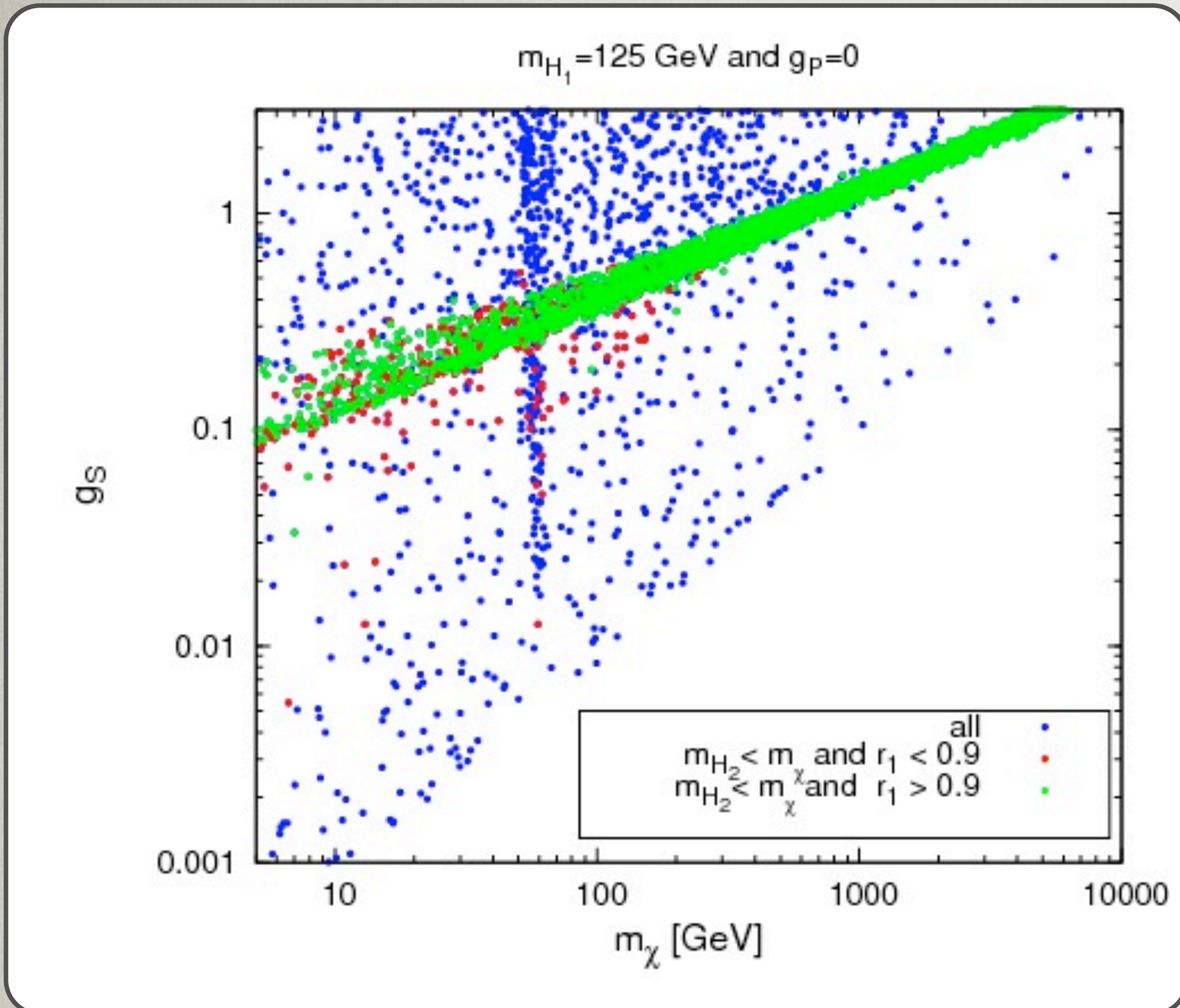


...NSERVING ...TIONS



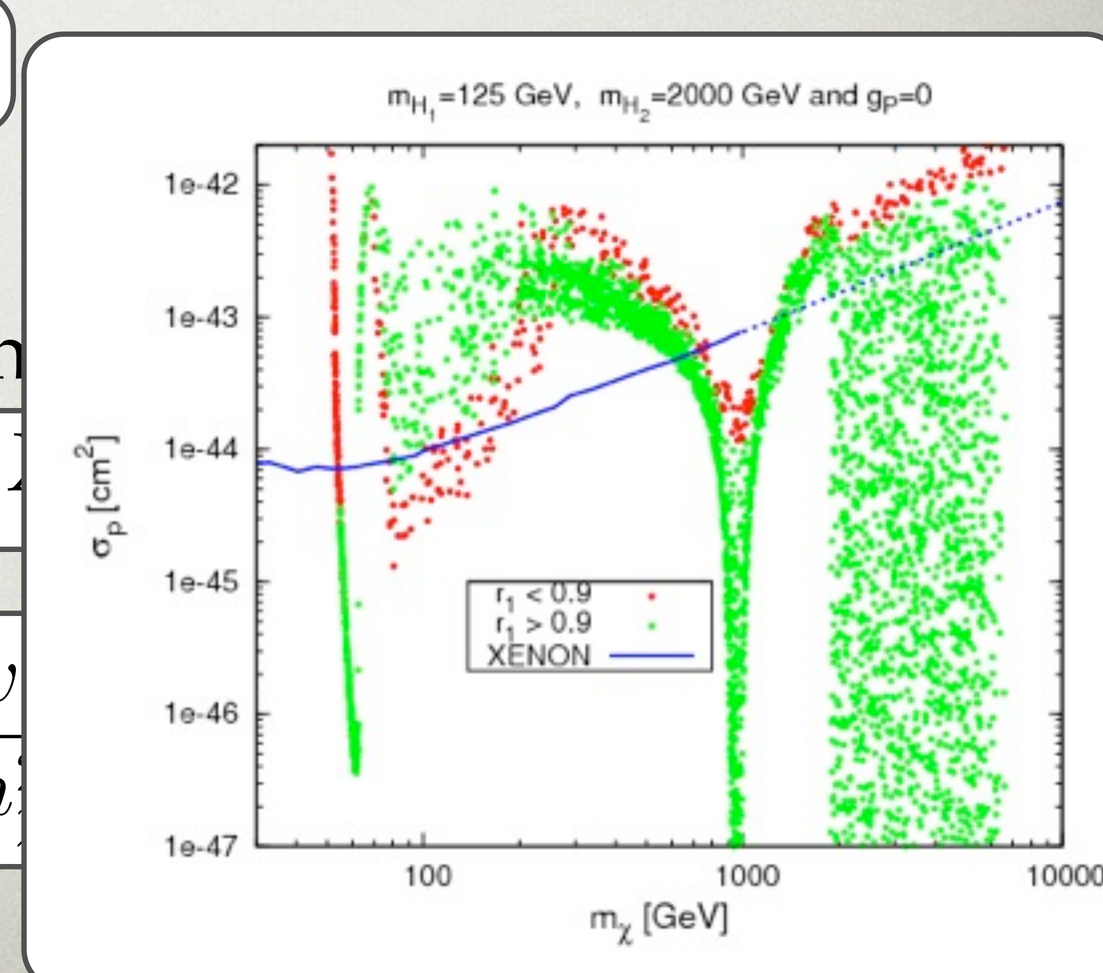
- ... DM Higgs portal 2 options
- ...ana DM +singlet scalar+SM
- ...nnih. through Higgs

...SM

- indirect Higgs portal
  - at decoupl. annih. through ...

$$\chi\chi \leftrightarrow \phi\phi \qquad \phi\phi \leftrightarrow ...$$

$$\sigma_{\chi\chi\to\phi\phi} = \frac{3g_S^4 v ...}{32\pi m ...}$$



CONCLUSIONS

- shown astrophysics indep. bounds on DM modulation signal
  - excludes eSI CoGeNT explanation
- CRESST could be a signal of DM, if scattering inelastic or isospin violating
- fermionic DM Higgs portal
  - parity conserving interactions and heavy mediator excluded by direct detection

BACKUP SLIDES