# Status of Direct Detection Fits

## (part 2)

Jure Zupan
U. of Cincinnati

part 1: Kai Schmidt-Hoberg

uses results from T. Schwetz, JZ 1106.6241;
M. Farina, Pappadopulo, Strumia, Volansky 1107.0715;
P.J. Fox, J. Kopp, M. Lisanti, N. Weiner 1107.0717;
D. Hooper, C. Kelso 1106.1066; McCabe 1107.0741

# QUESTIONS

- CoGeNT, DAMA claim signals

  Bernabei et al. [DAMA], 0804.2741

  Aalseth et al. [CoGeNT], 1002.4703; 1106.0650

  - also annual modulation
- Is it (can it be) dark matter?
  - constraints from other experiments
  - elastic spin-independent with standard halo: not a good fit to all experiments

    see talk by Kai Schmidt-Hoberg
  - could a nongeneric DM model be viable?
  - could nuclear and astrophysical uncertainties make a big difference?

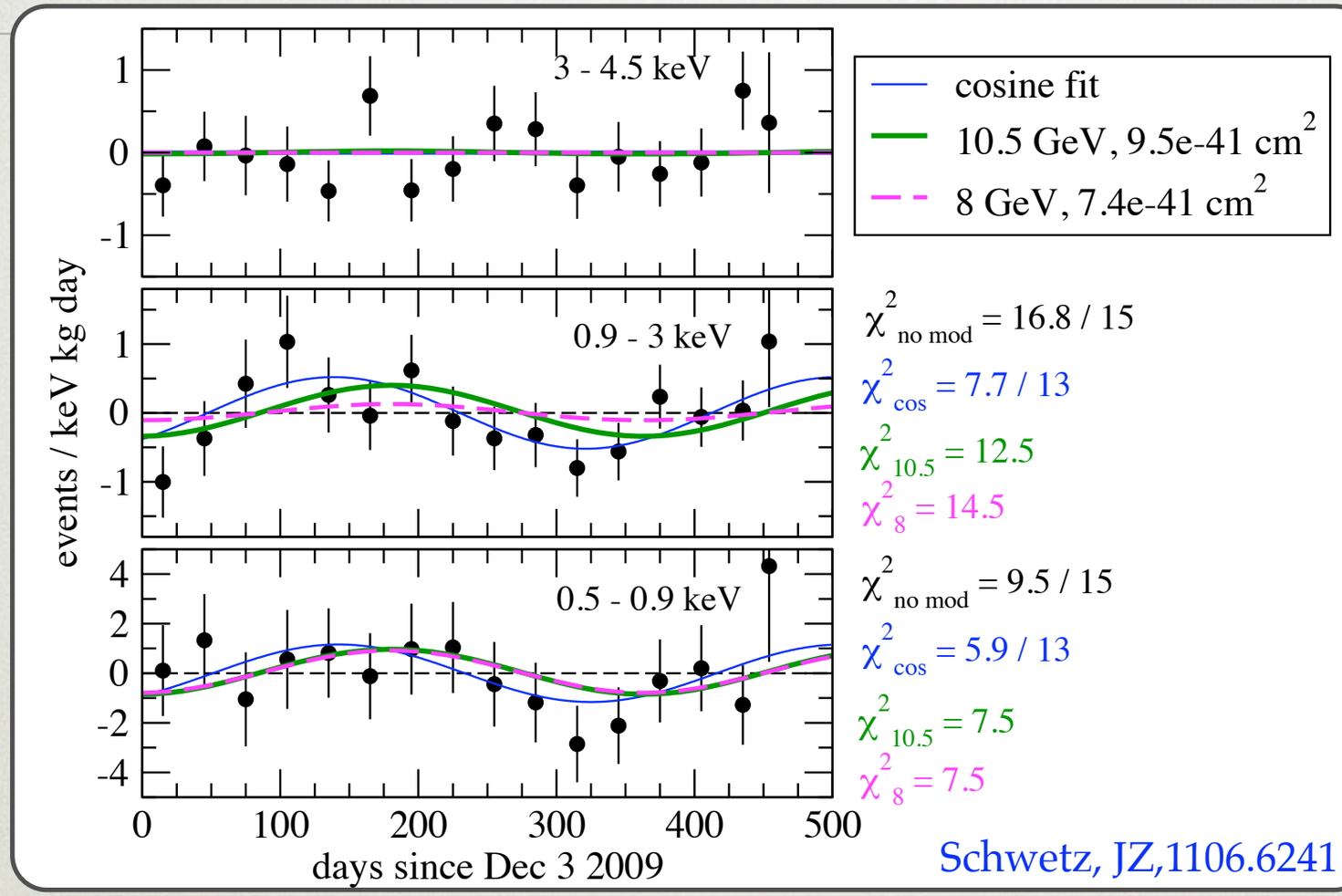
# DARK MATTER VARIATIONS

- 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 — see talk by A. Green
  - vary velocity profiles, $v_{esc}$, etc
  - "integrate them out" — Fox, Liu, Weiner 1011.1915; Fox, Kribs, Tait, 1011.1910
- 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

# MODULATION IN COGENT?



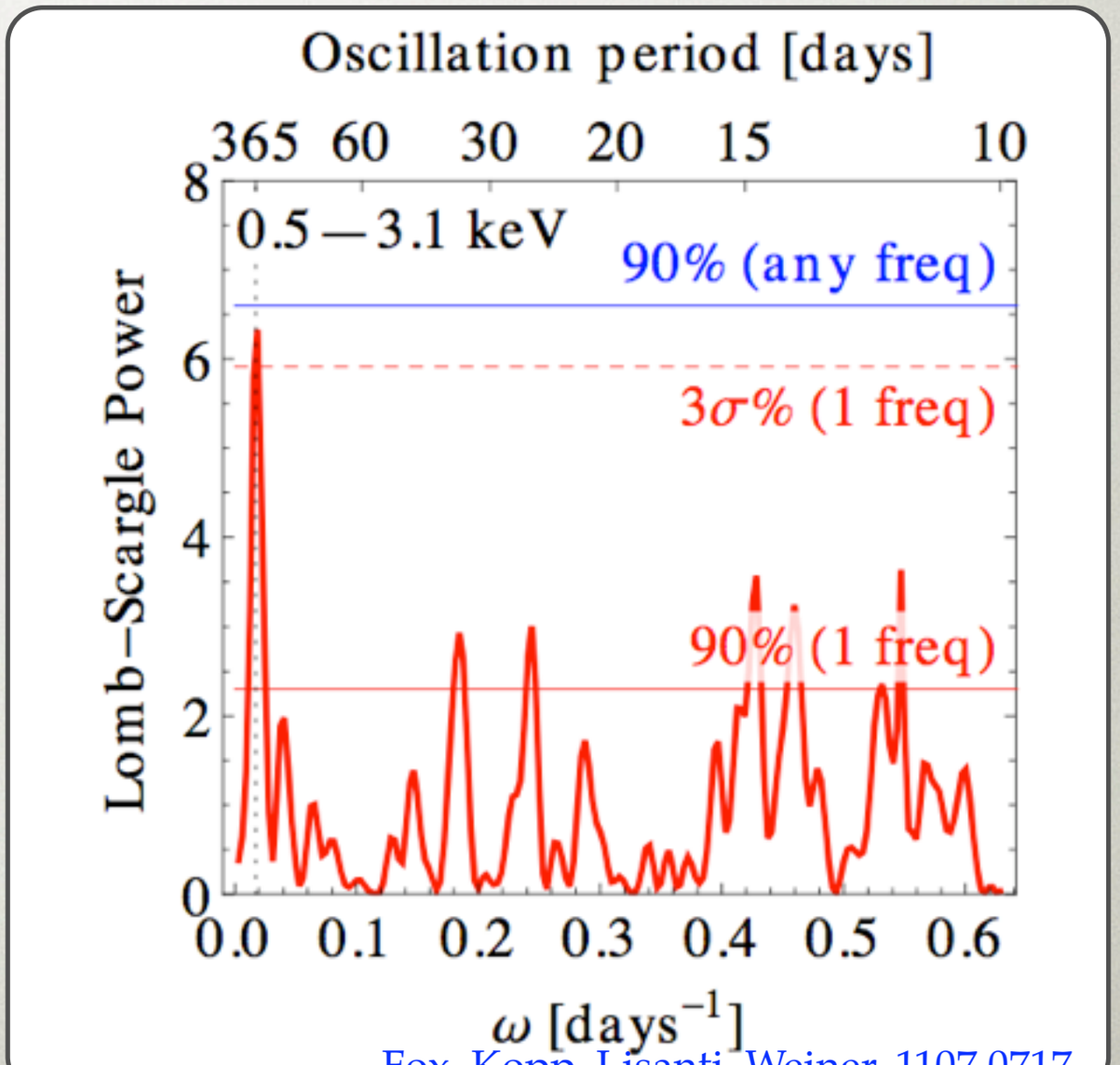

- fit with no modulation has acceptable goodness-of-fit:
  - $\chi^2_{\text{no mod}}$ is 9.5, 16.8, 11.7 for 15 d.o.f. for 3 eng. bands
  - $\chi^2_{\text{no mod}}$=20 for 15 d.o.f. for 0.5-3 keV (17%)
- 2.8σ preference for modulation Aalseth et al. [CoGeNT], 1106.0650

# OSCILLATION PERIOD

- CoGeNT 442 days of live data in 458 day long run
- what is the oscillation period?

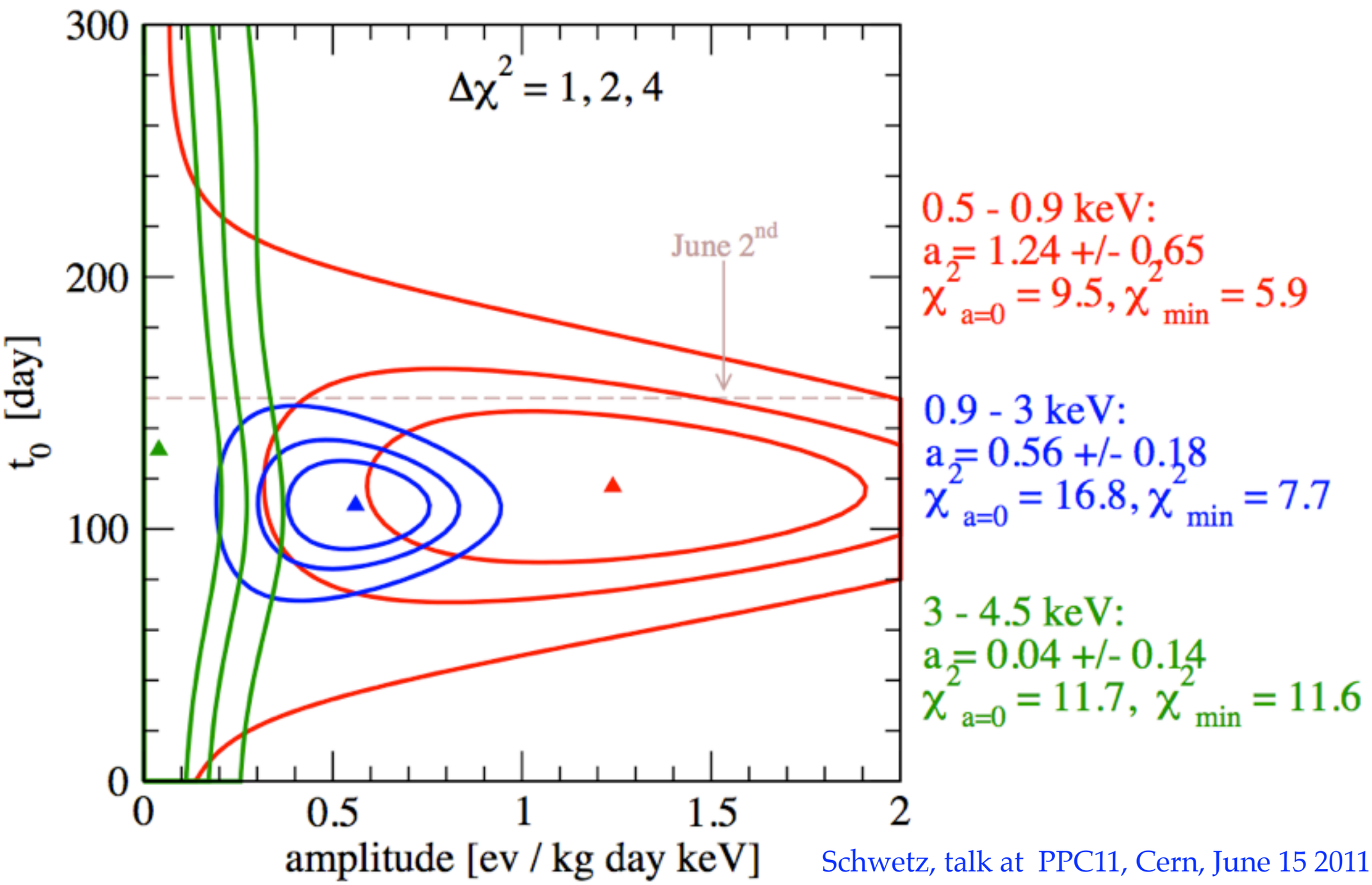
Fox, Kopp, Lisanti, Weiner, 1107.0717

- analysis using Lomb-Scargle periodogram in 0.5-3.1keVee
- strongest at 365 days
- no evidence for diurnal oscillation

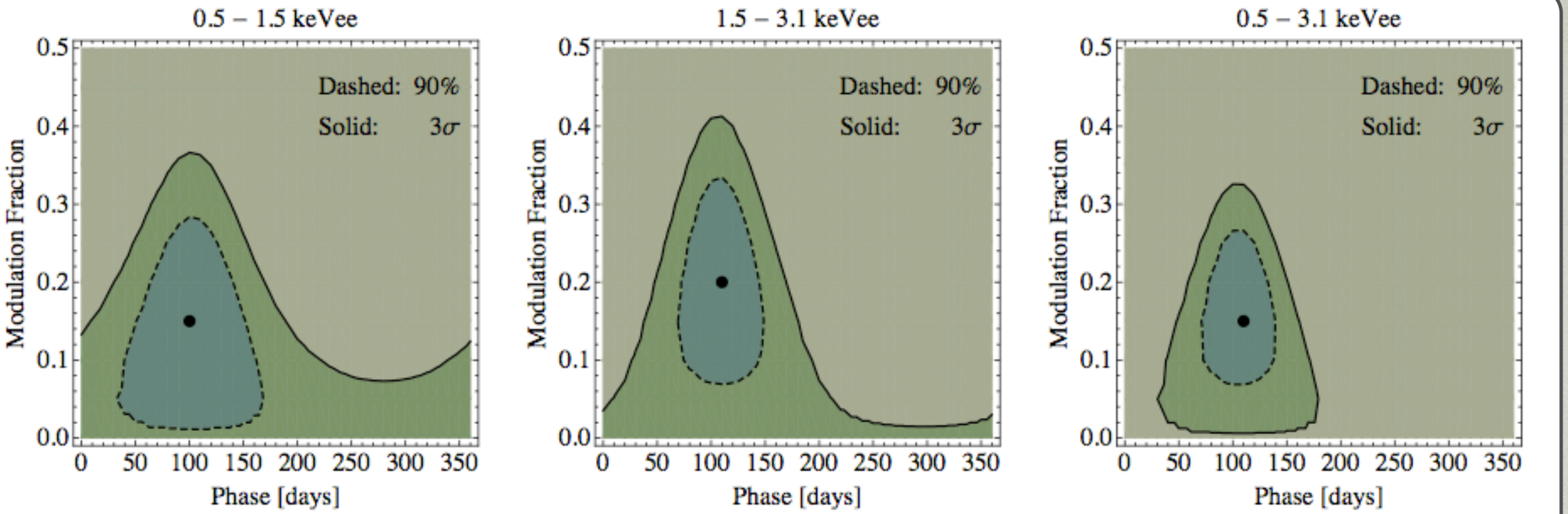



Fox, Kopp, Lisanti, Weiner, 1107.0717

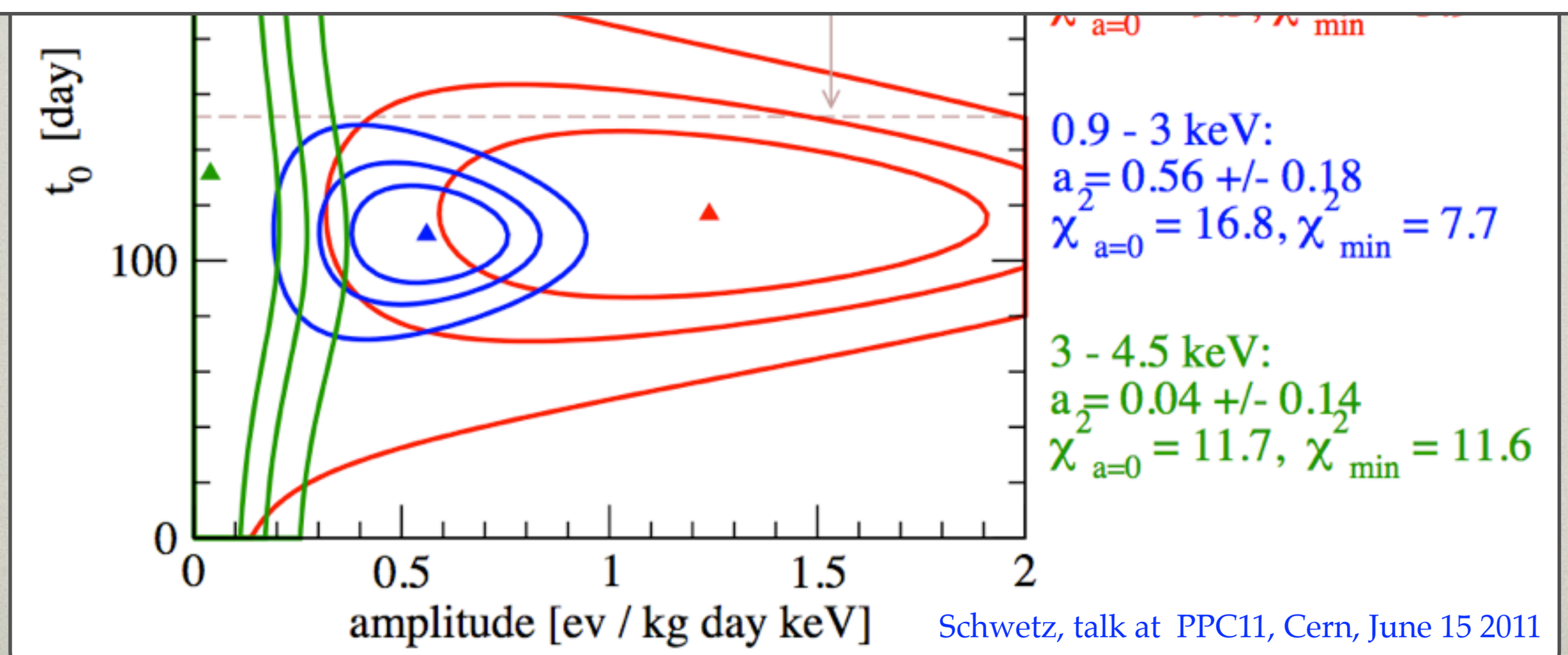
# PHASE OF THE MODULATION




Schwetz, talk at PPC11, Cern, June 15 2011



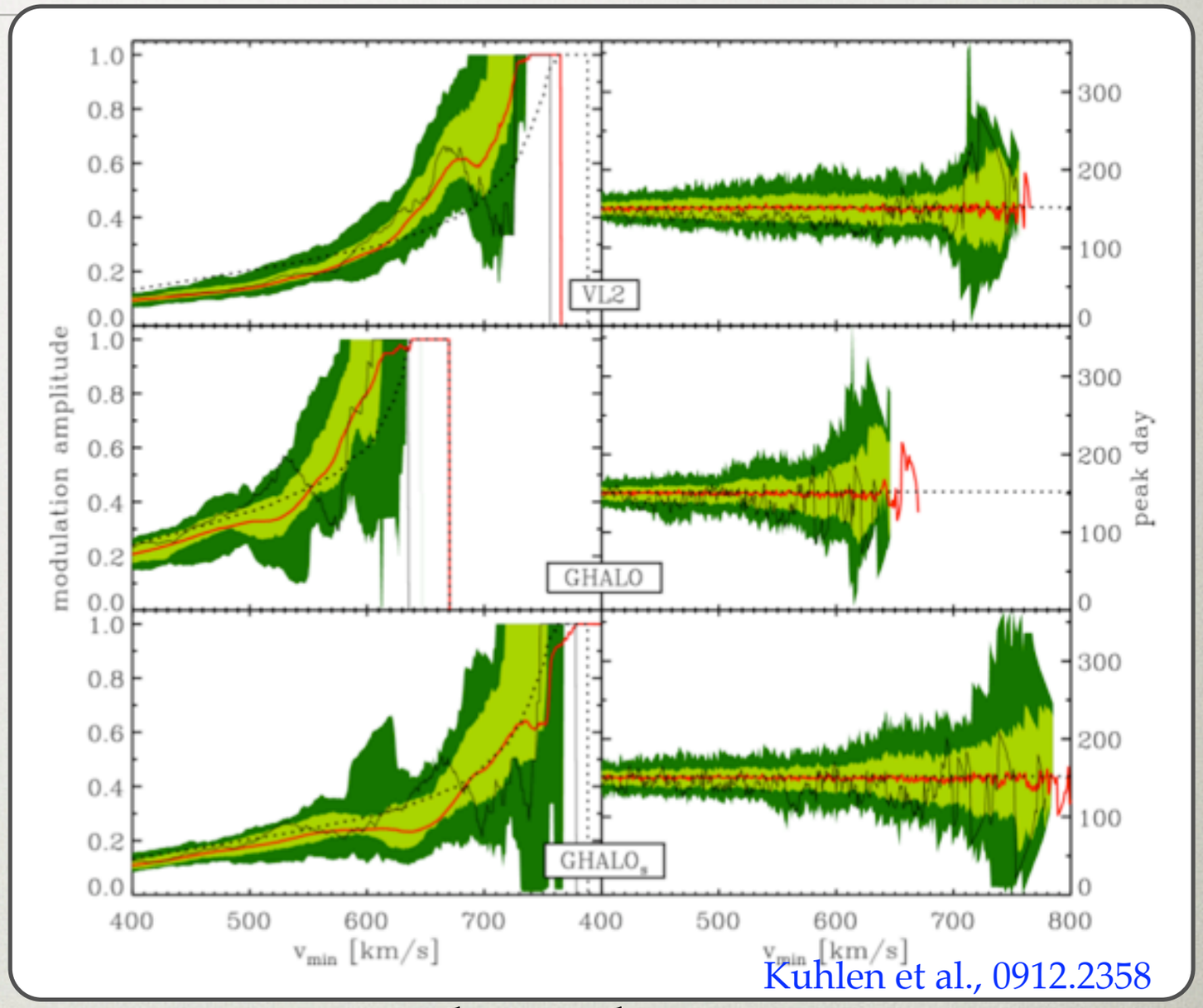

Fox, Kopp, Lisanti, Weiner, 1107.0717




Schwetz, talk at PPC11, Cern, June 15 2011

# VARIATIONS OF PHASE

- peak at day 152 in standard halo model only
- variations especially pronounced for light DM

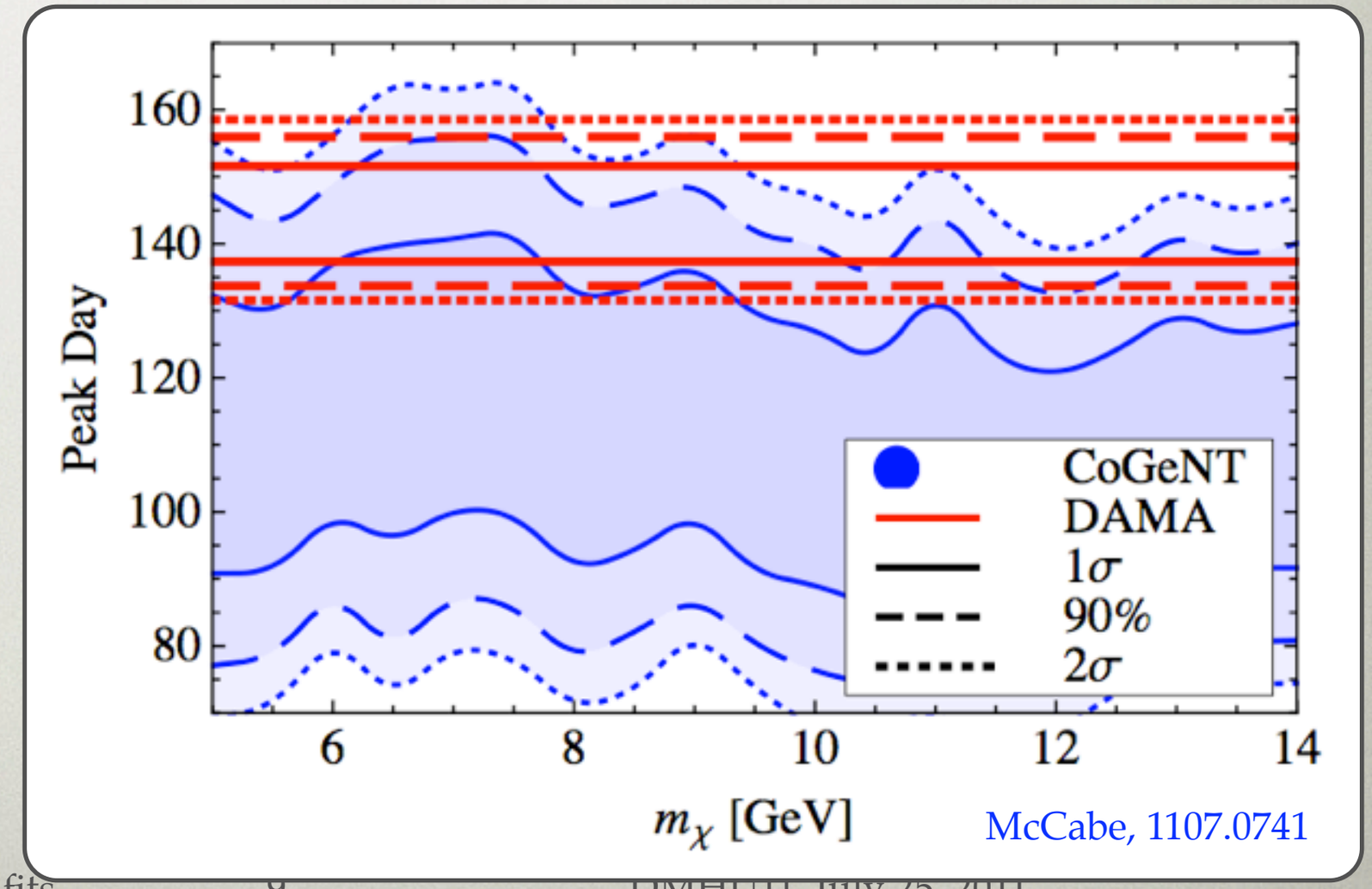



Kuhlen et al., 0912.2358

- if experiments compared within the same $v_{min}$ range the phase should be the same

# PHASE OF THE MODULATION

- integrating out astrophysical uncertainties
- comparing only the same regions in $v_{min}$ for DAMA [2-6 keVee] and CoGeNT
- assumes elastic scattering



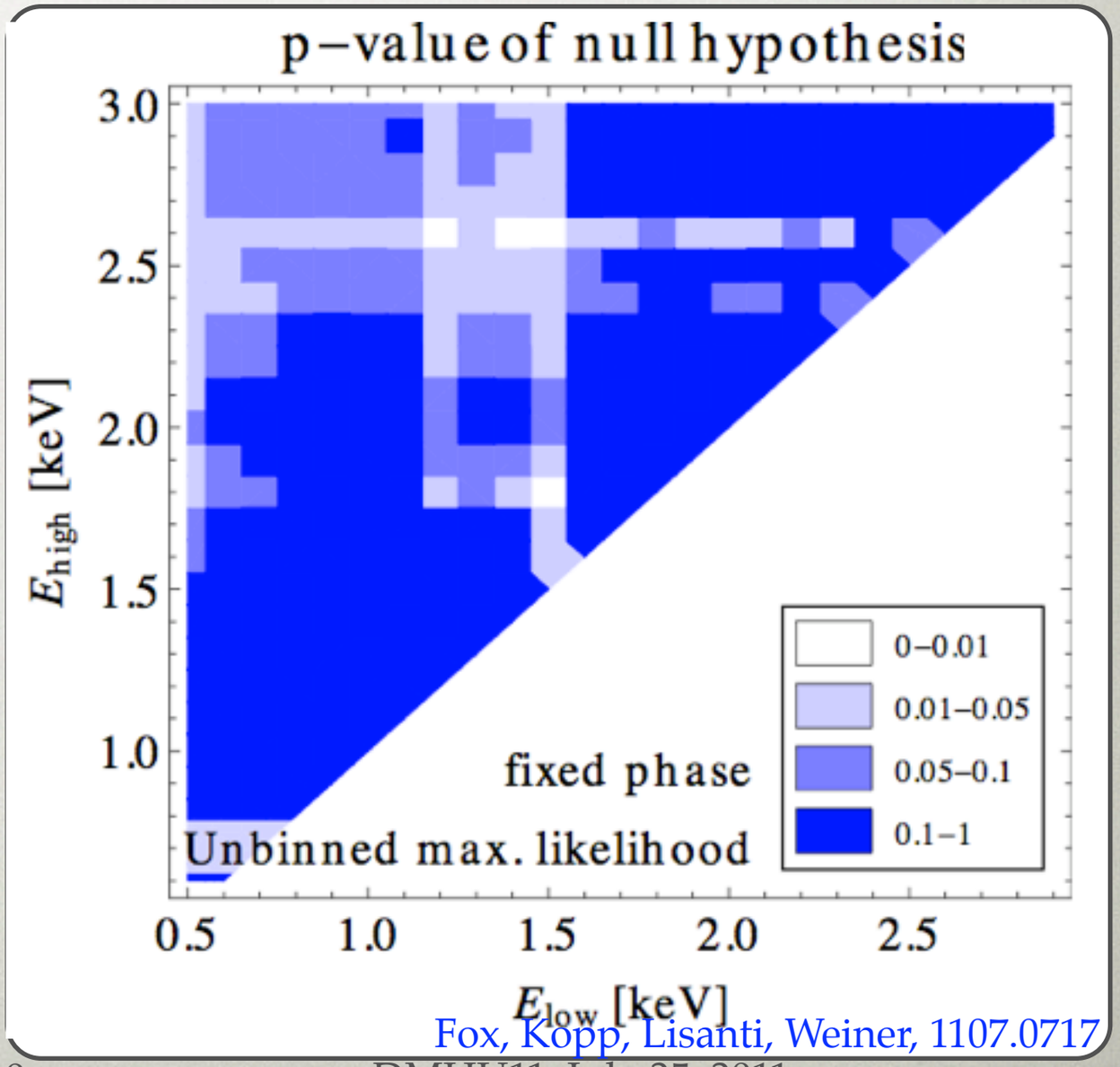

McCabe, 1107.0741

# WHERE IS THE MODULATION SIGNAL?

- most modulation signal significance comes from high energy bins, above 1.5 keVee

Fox, Kopp, Lisanti, Weiner, 1107.0717

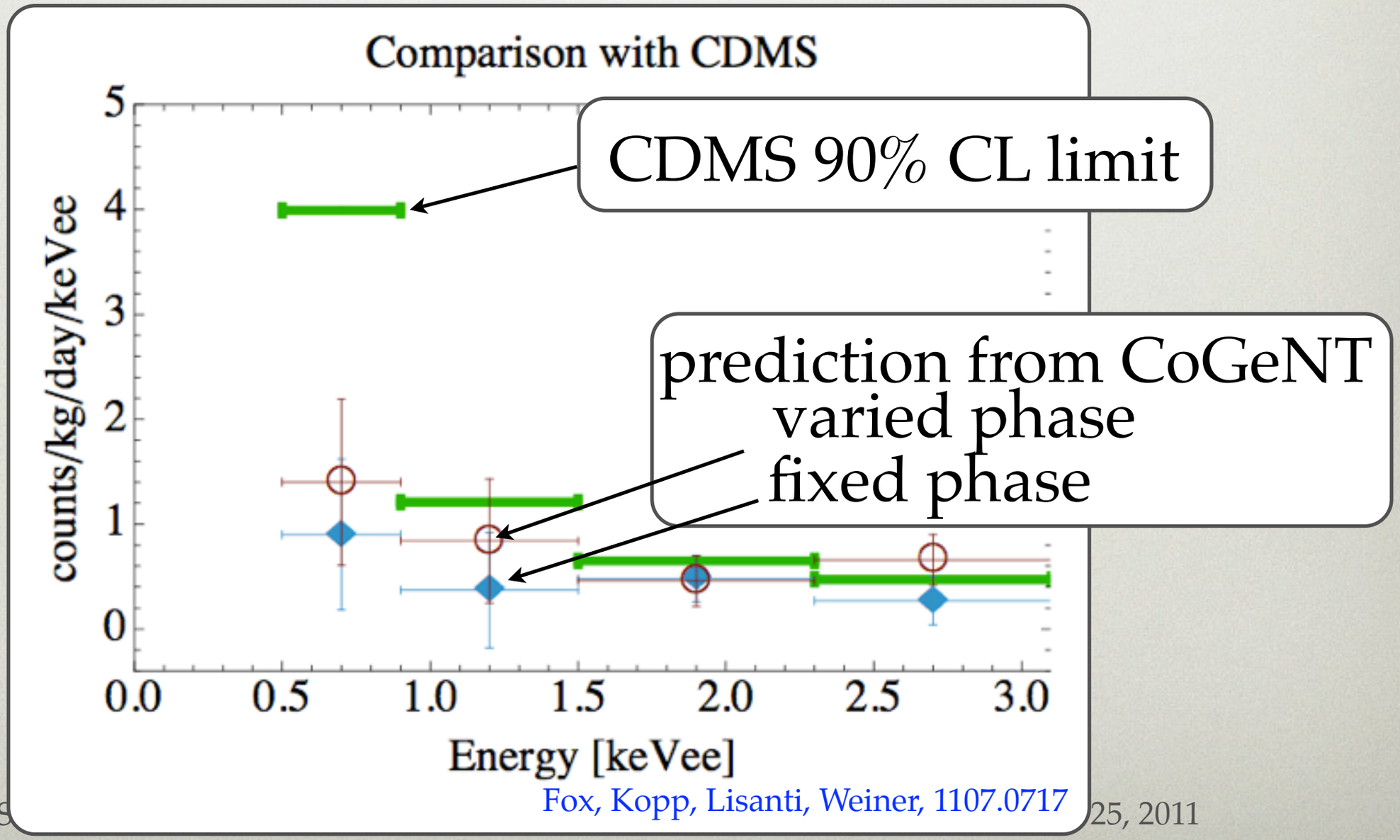
- shown on the right: propability of null modulation signal to fluctuate
- from elastic DM would expect most signal in low eng. bins




Fox, Kopp, Lisanti, Weiner, 1107.0717

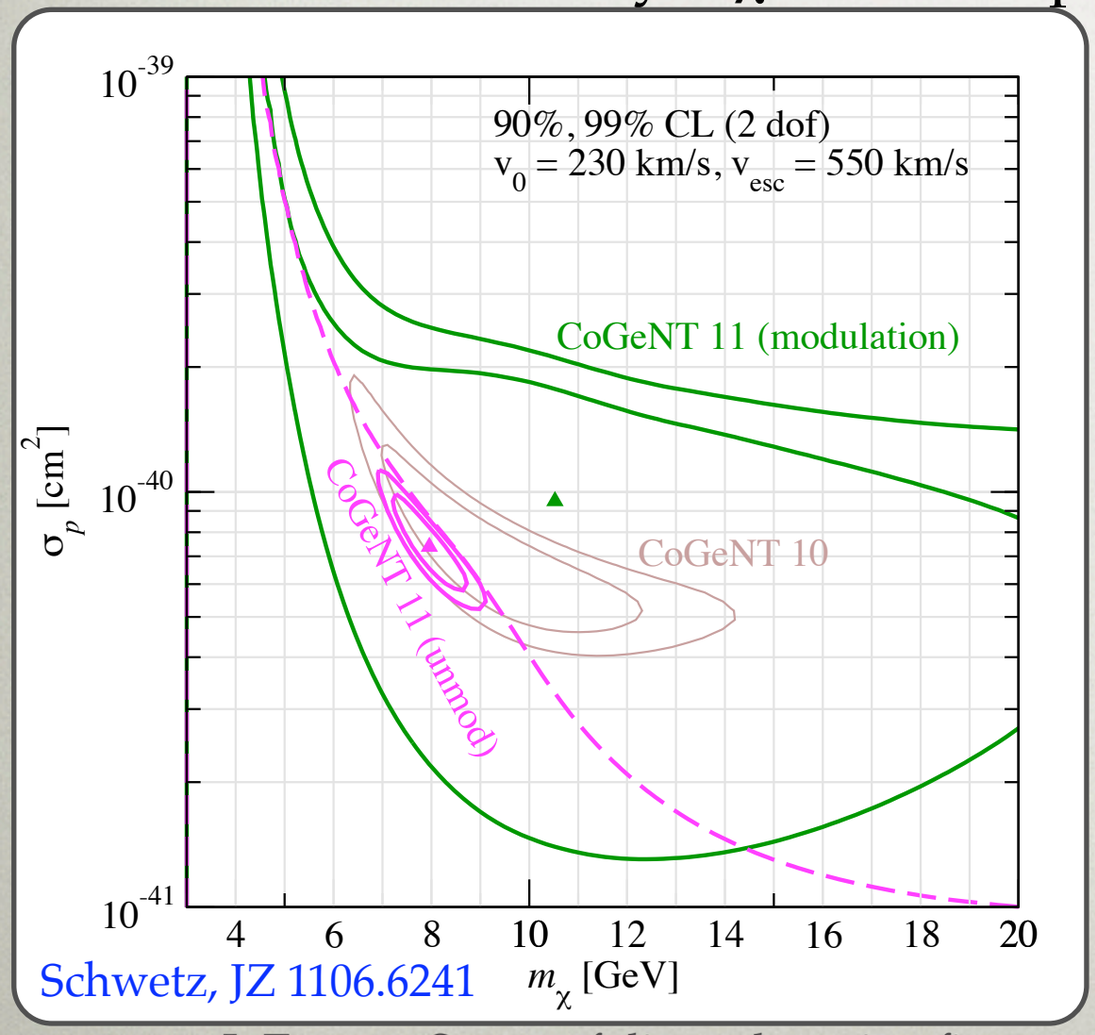
# COMPARISON WITH CDMS

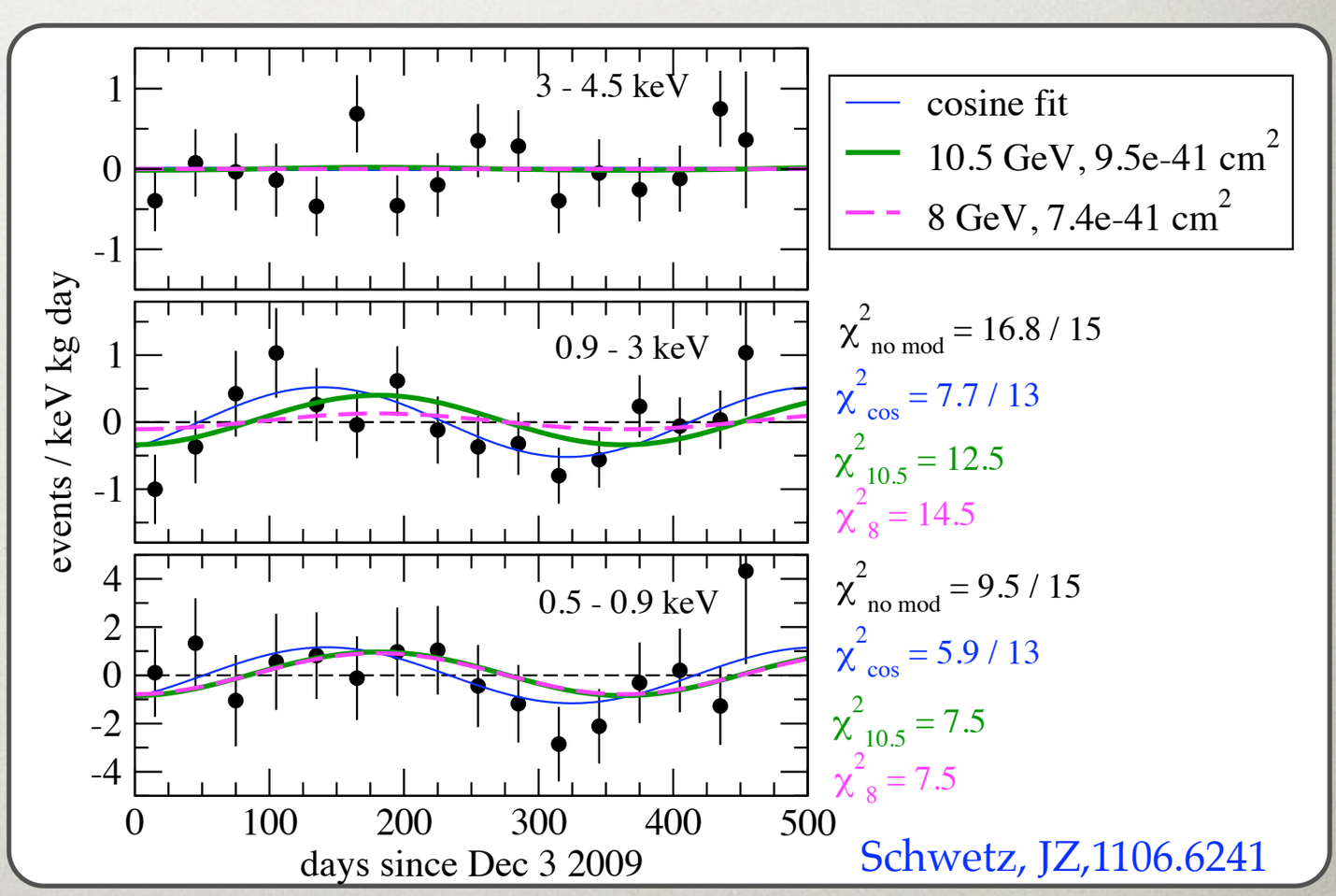
- direct comparison can be made to CDMS since both Ge



# ELASTIC SPIN INDEPENDENT

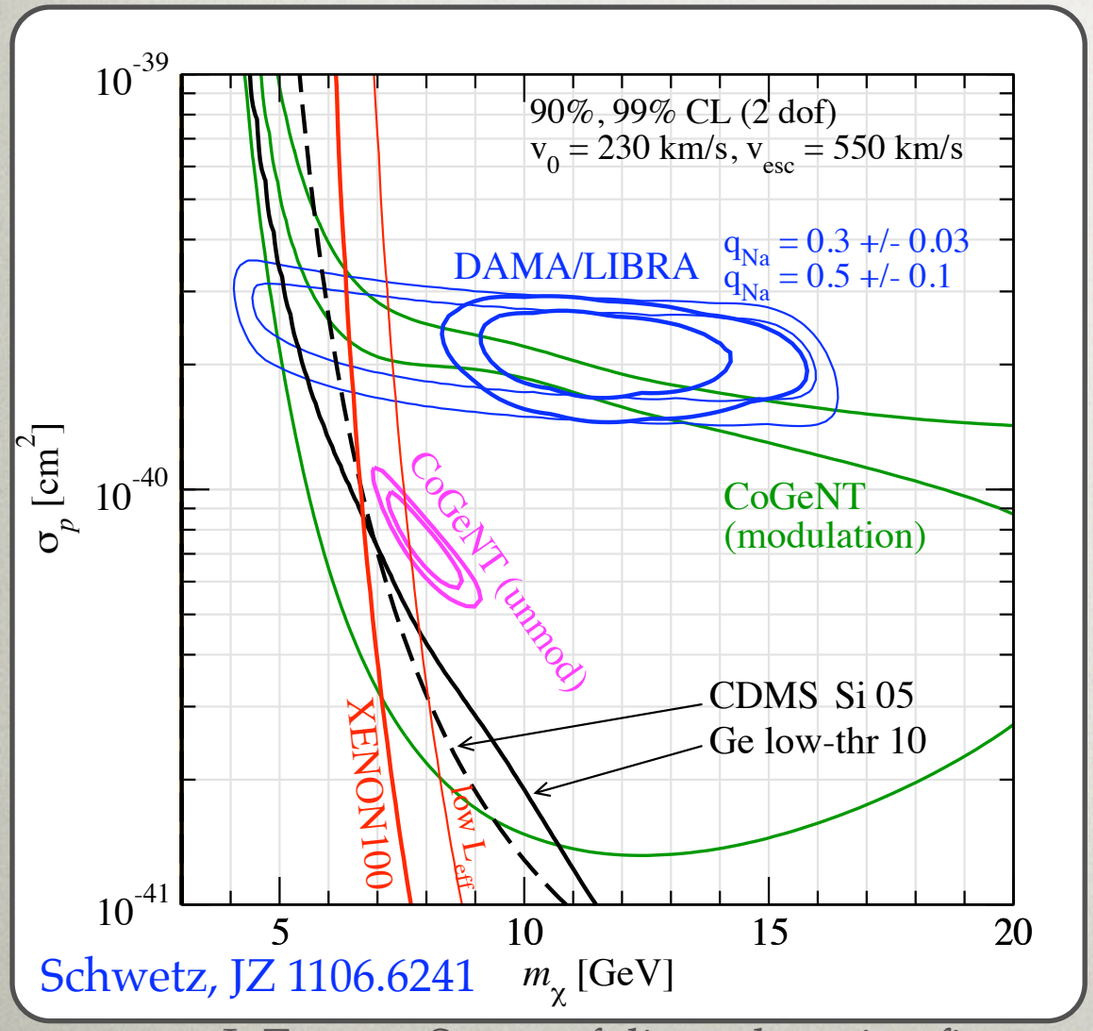
- tension between modulated and unmodulated rates in CoGeNT
  - best fit point to modulation excluded by total rate
  - best fit point to total rate almost no modulation in [0.9-3]keV
  - has only $\Delta\chi^2=2.3$ compared to null hypothesis

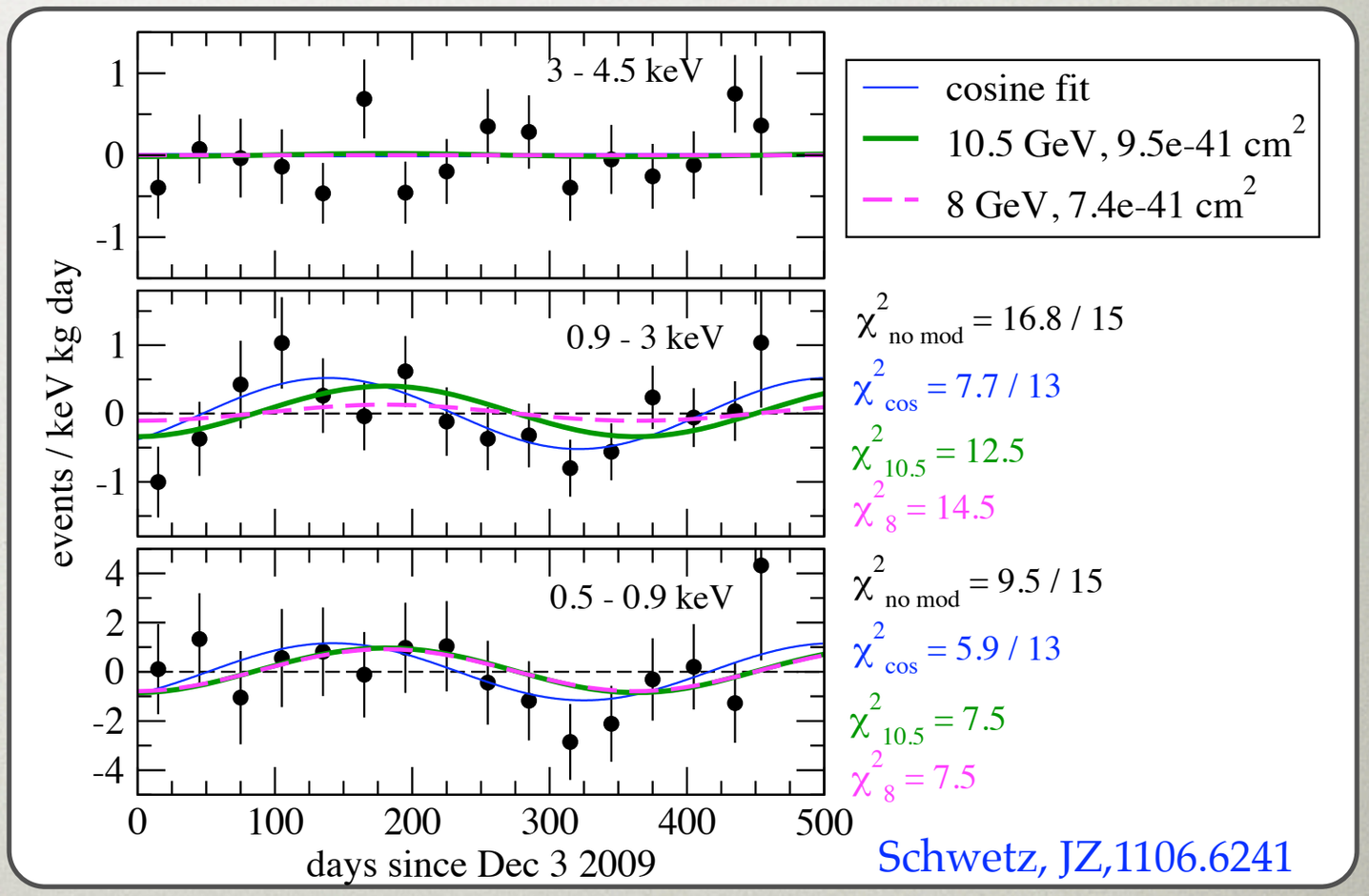


# ELASTIC SPIN INDEPENDENT

- tension between CoGeNT and other experiments



# QUENCHING FACTORS

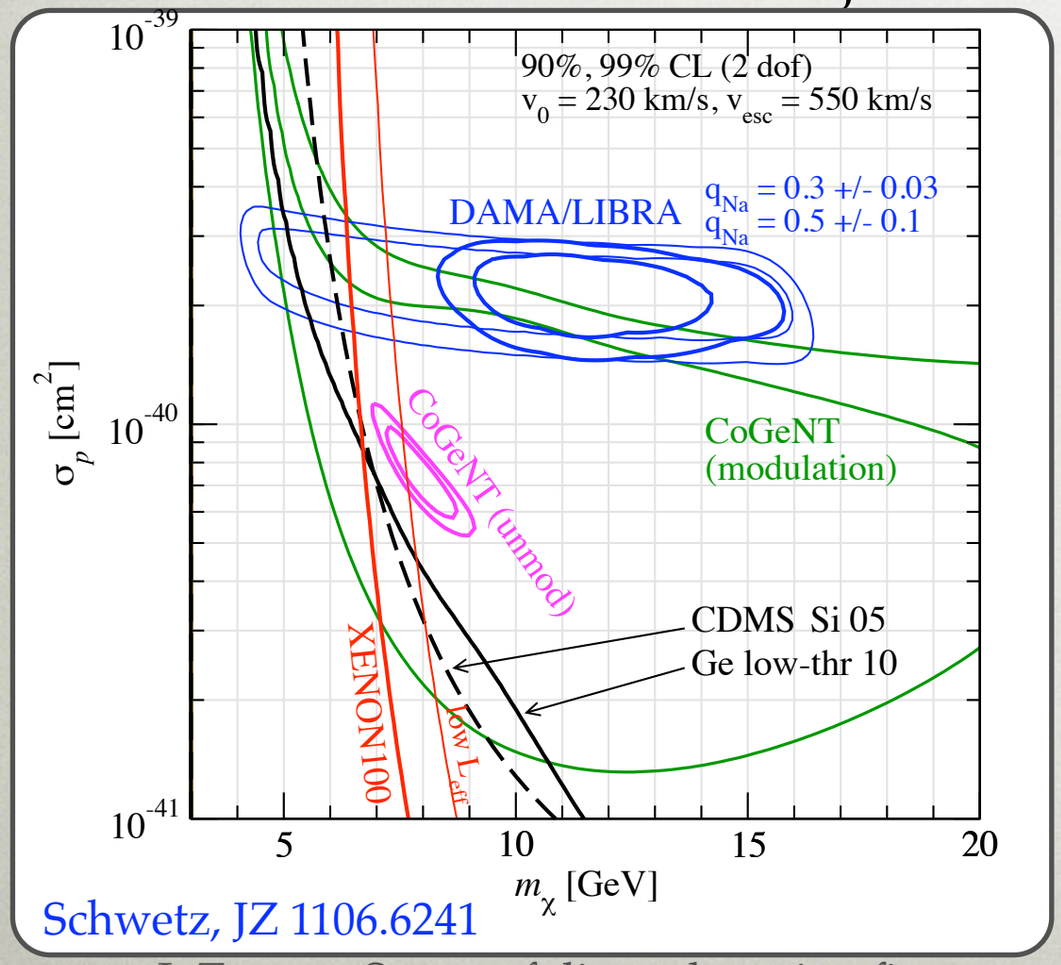
- for eSI CoGeNT (and DAMA) to be consistent with the rest one would need

see talk by J. Collar

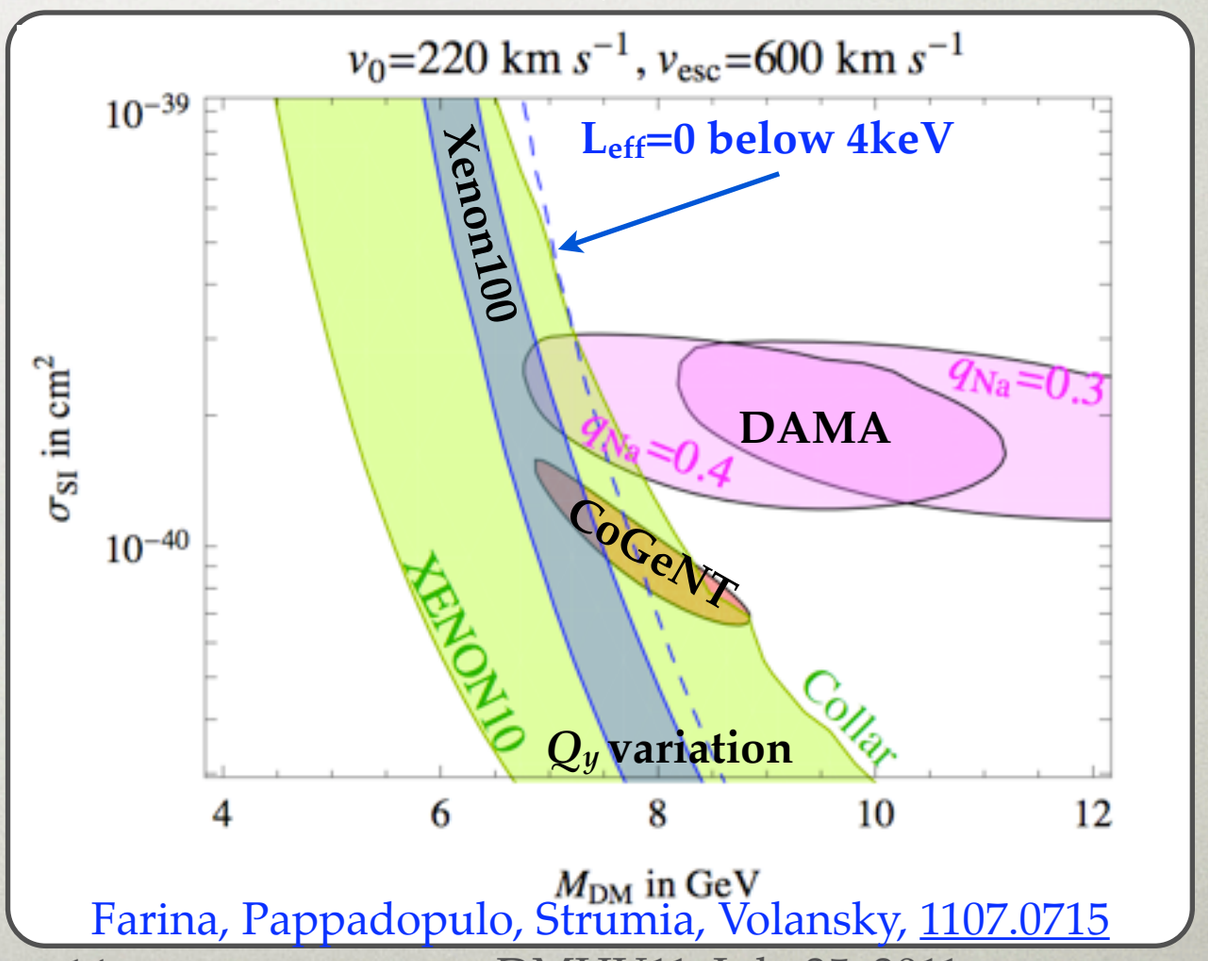
  - $L_{eff}$ drop to zero below measurements
  - $q_{Na}$ should be significantly larger

Hooper, Collar, Hall, McKinsey, 1007.1005;
Hooper, Kelso, 1106.1066

  - energy calibration of Xenon10 S2 analysis needs to be off
  - CDMS made a major calibration error (in Ge and Si)



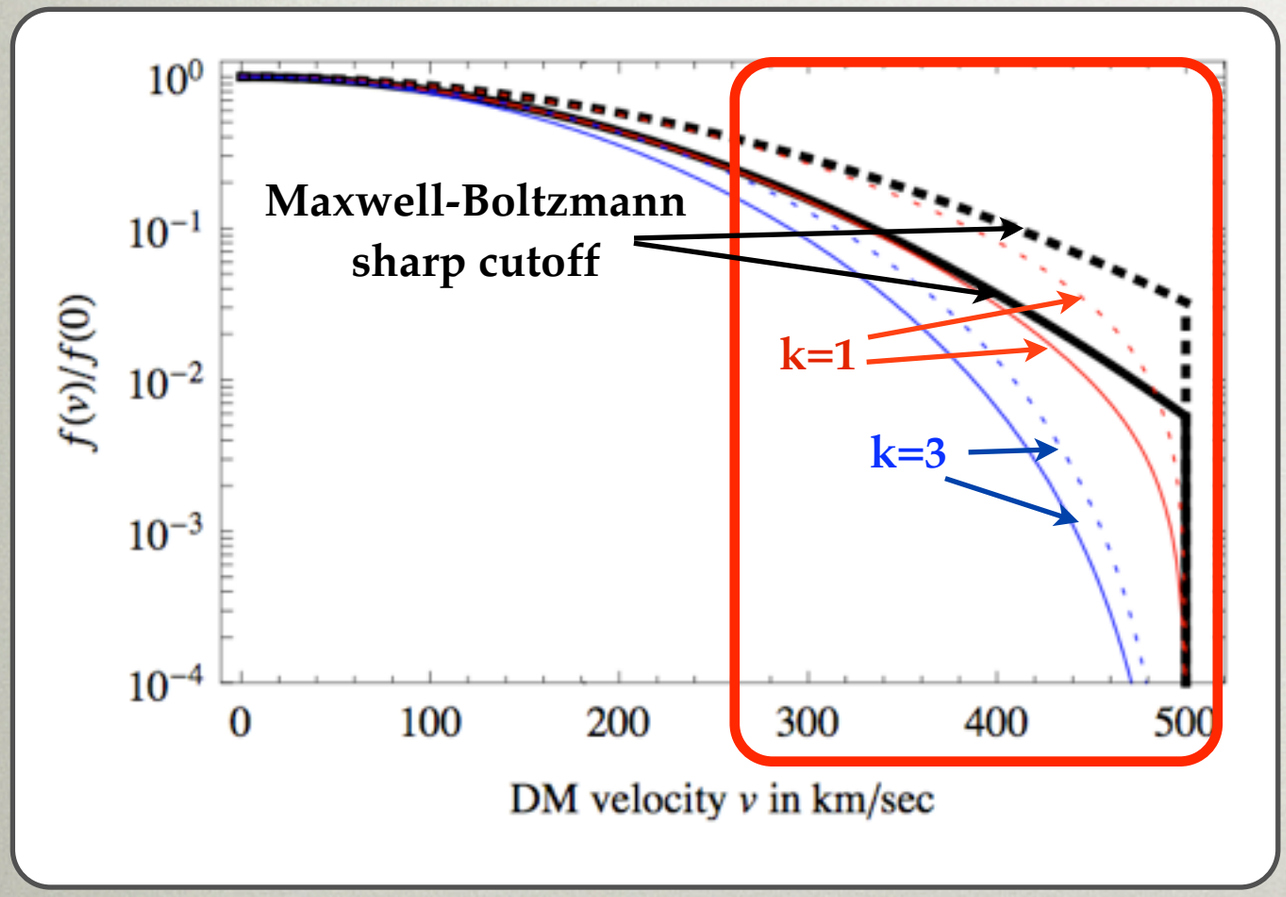

Schwetz, JZ 1106.6241

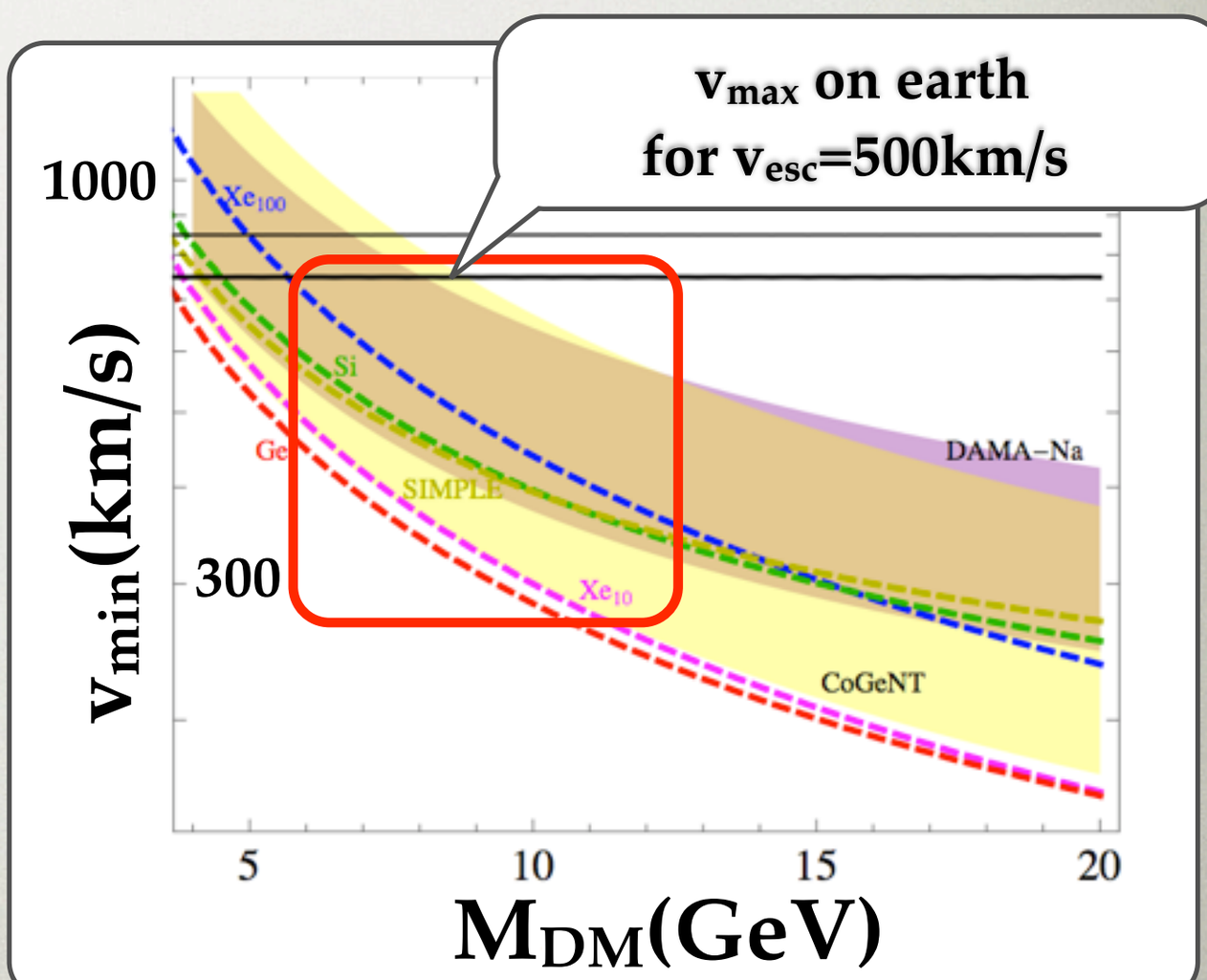



Farina, Pappadopulo, Strumia, Volansky, 1107.0715

# ASTROPHYSICAL UNCERTAINTIES

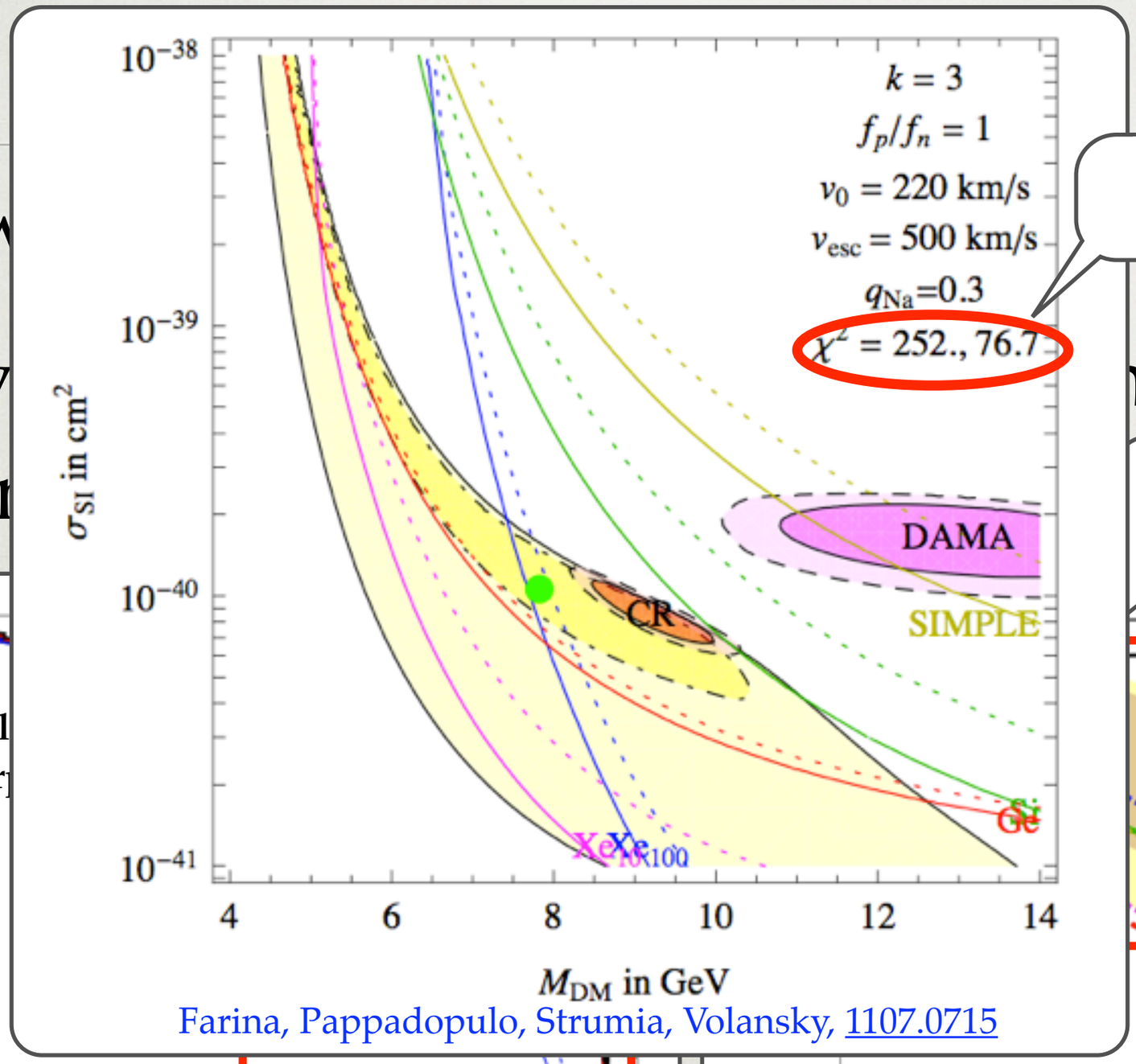
- with light DM probing high velocities
- varying velocity profiles does not improve fits



# ASTROPHYSICAL

- w
- v
- i

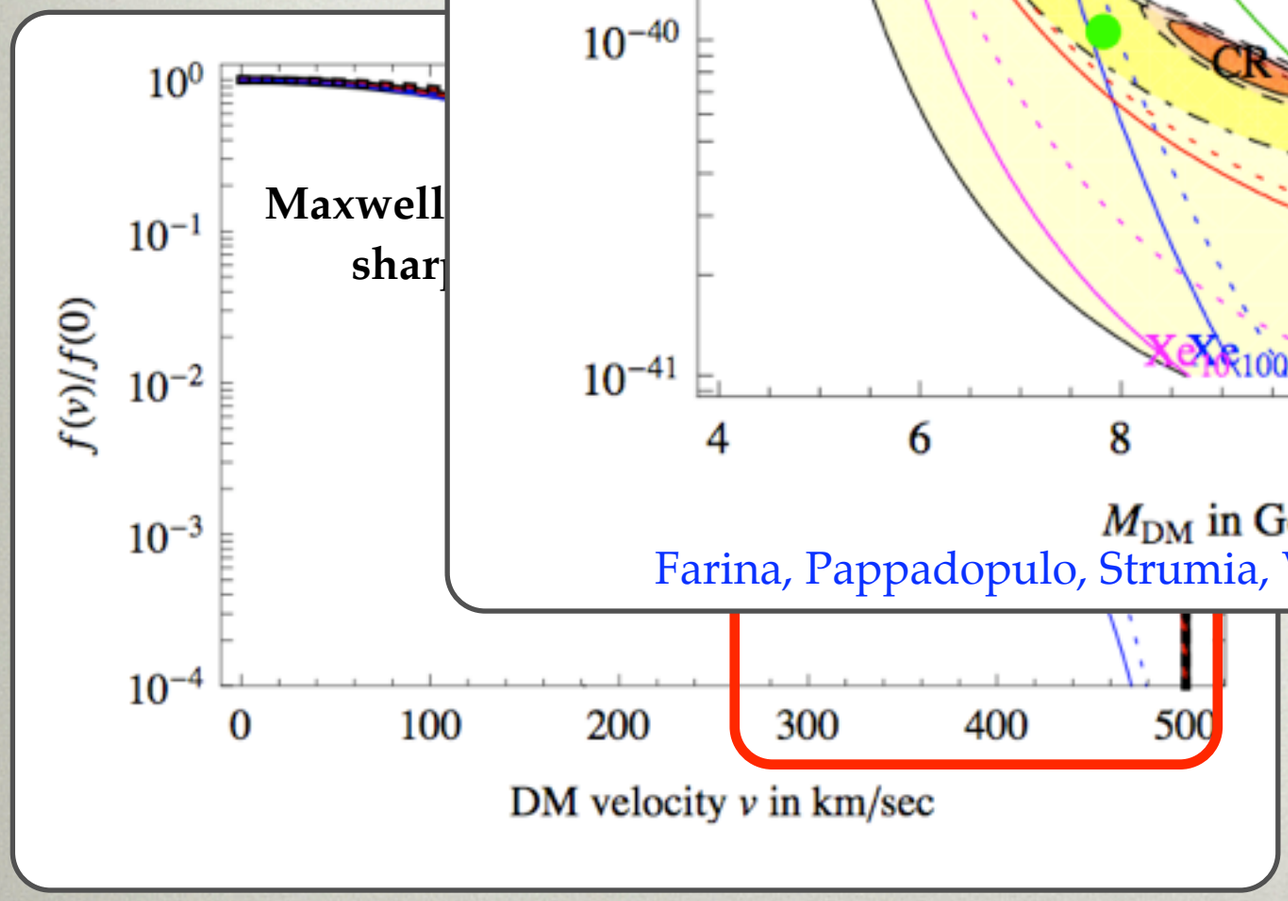



Farina, Pappadopulo, Strumia, Volansky, 1107.0715

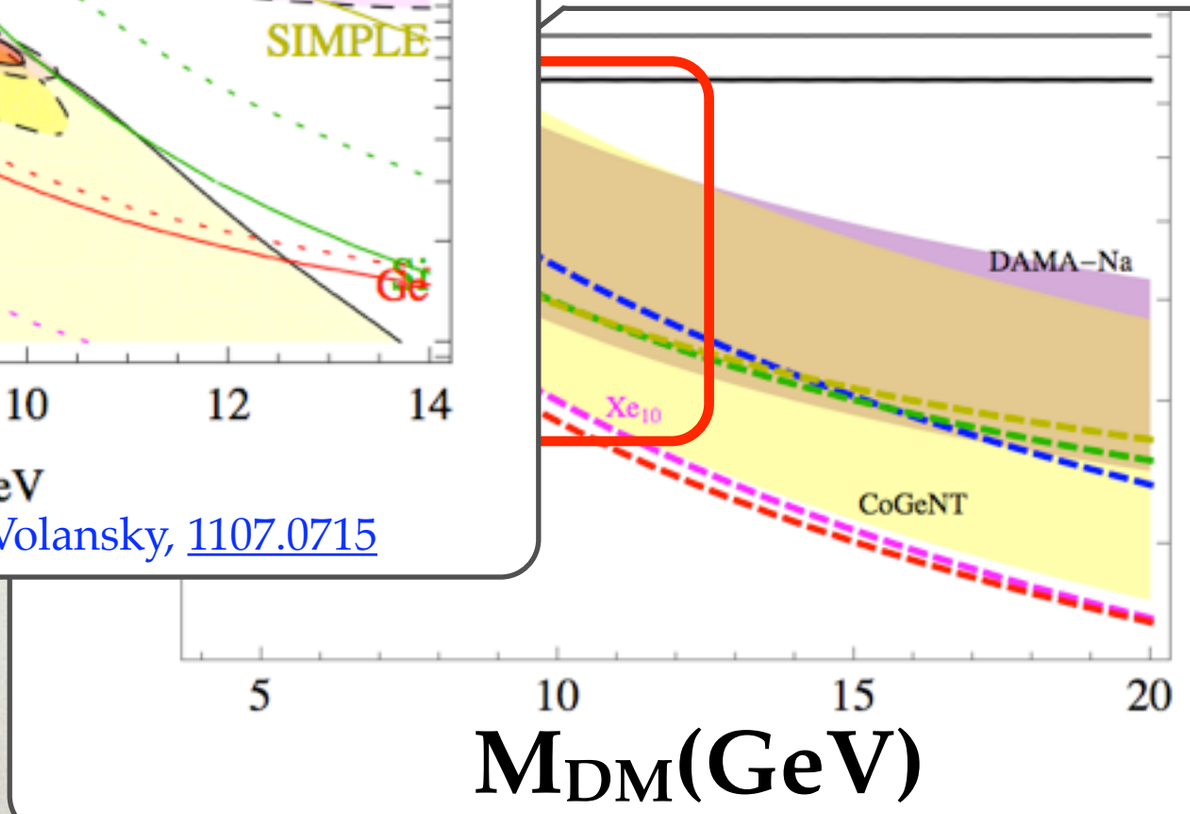
no CoGeNT rate
expect $\chi^2$~8

$\chi^2 = 252., 76.7$

all data: expect $\chi^2$~43

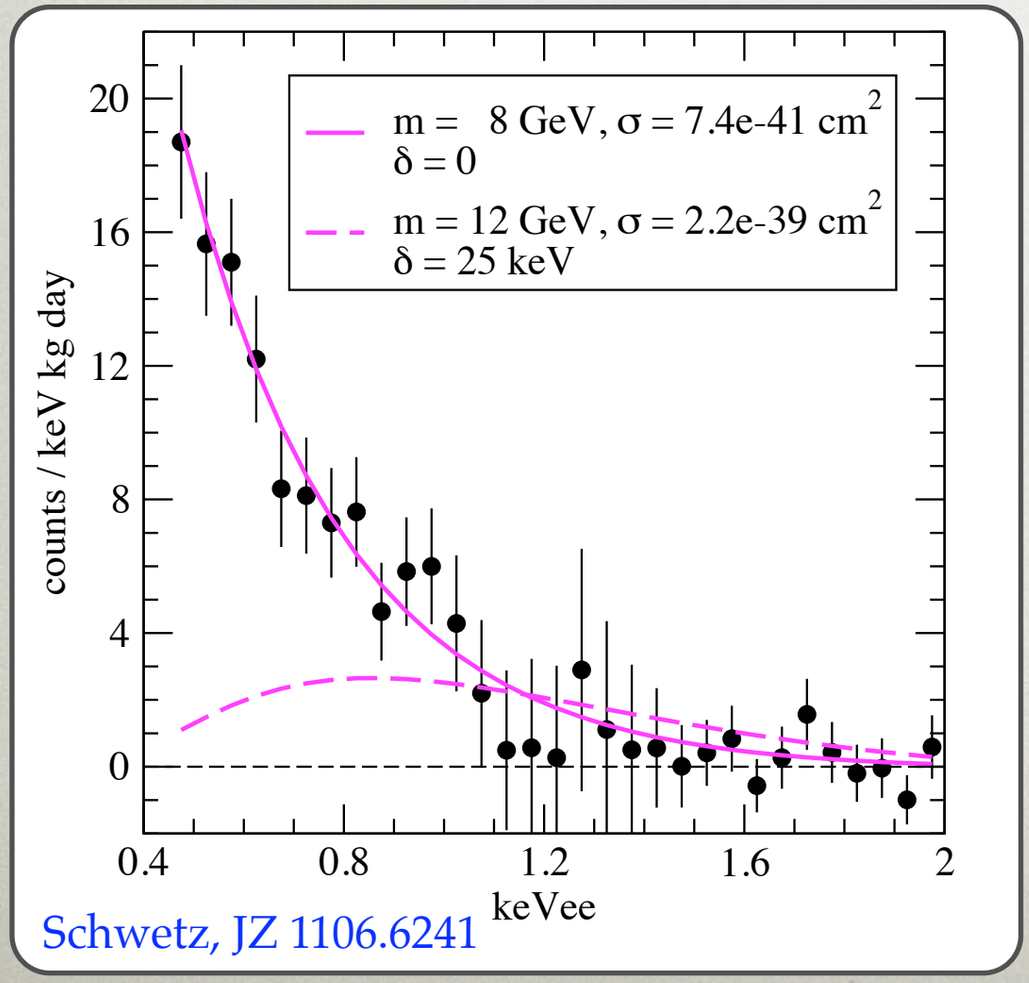



**$v_{max}$ on earth**
**for $v_{esc}$=500km/s**



# INELASTIC SCATTERING

- best fit modulation spectrum the same as for eSI
- total rate very different from the measured one
  - would need nontrivial background
- mismatch between CoGeNT and DAMA persists (assuming $f_n=f_p$)
- tension with CDMS low-threshold, Xenon100, CoGeNT total rate

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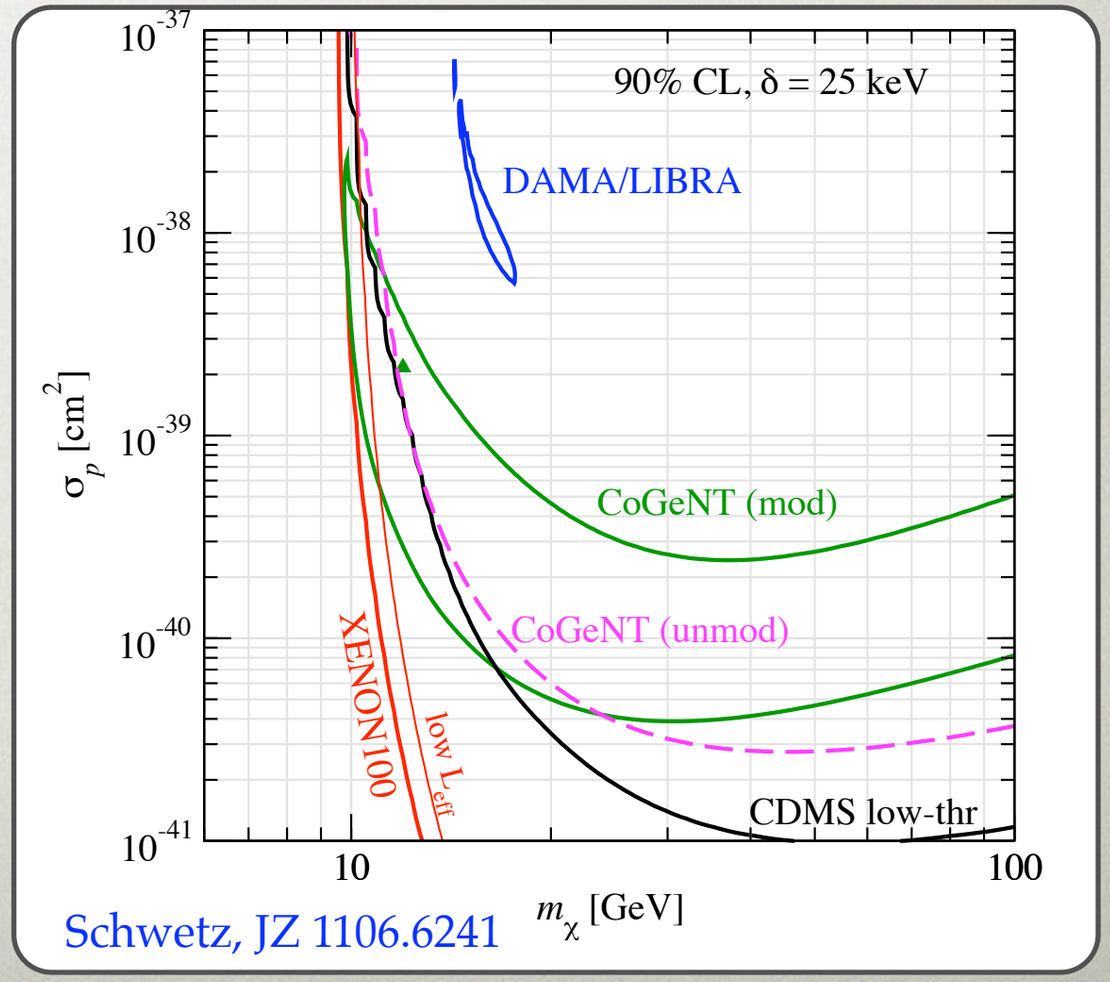



Schwetz, JZ 1106.6241

# ISOSPIN VIOLATING ELASTIC SPIN-INDEPENDENT

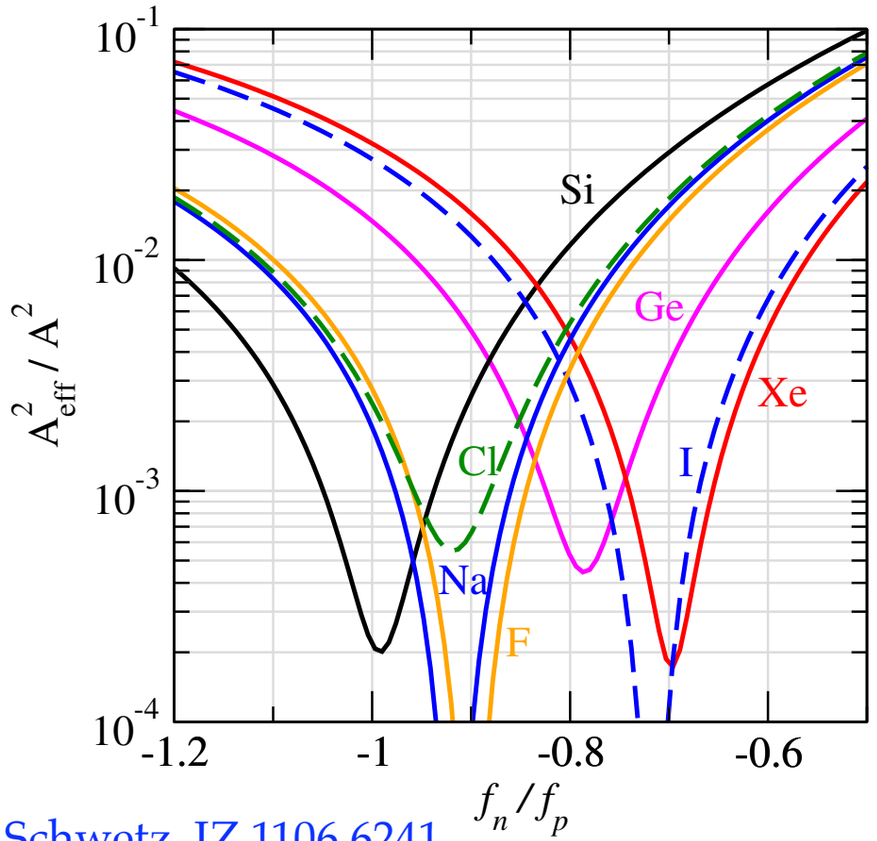
- arrange coupling to $n$ and $p$ to cancel contribs, e.g. to Xe

see talk by F. Kahlhoefer

- cannot cancel all elements, if Xe smaller Si larger

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

$$\tan\theta \equiv \frac{\lambda_n}{\lambda_p}$$

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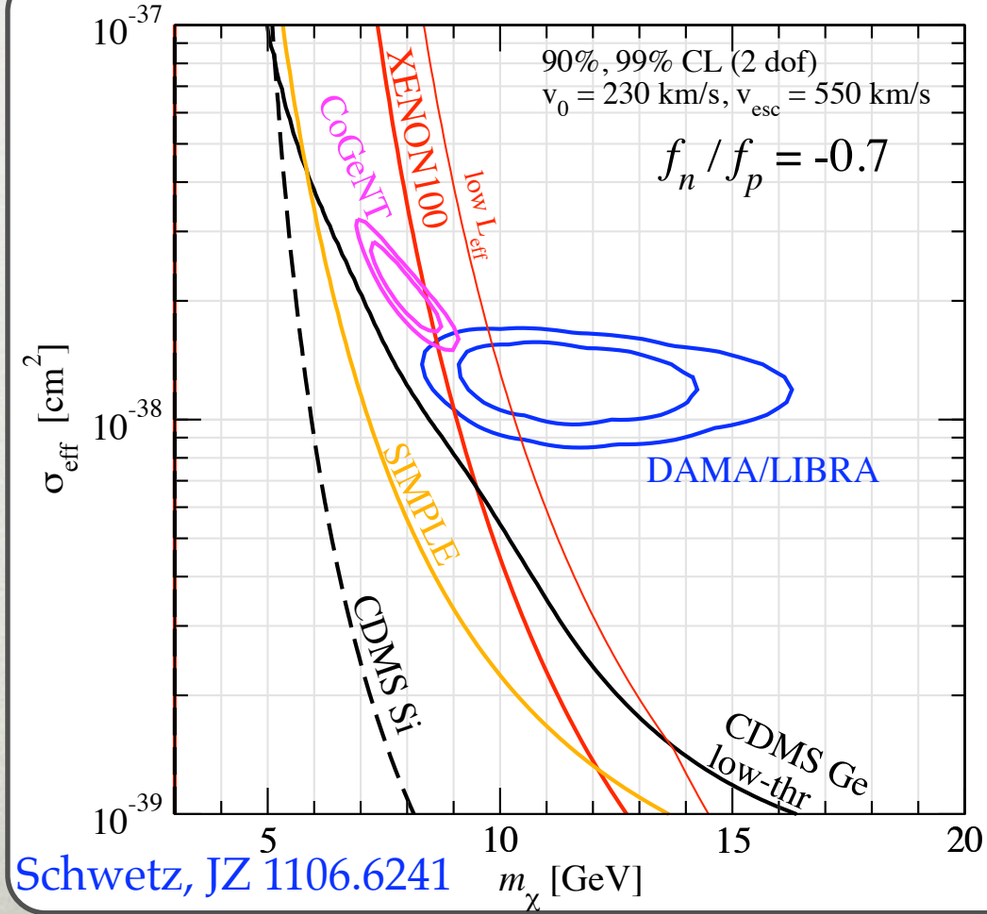


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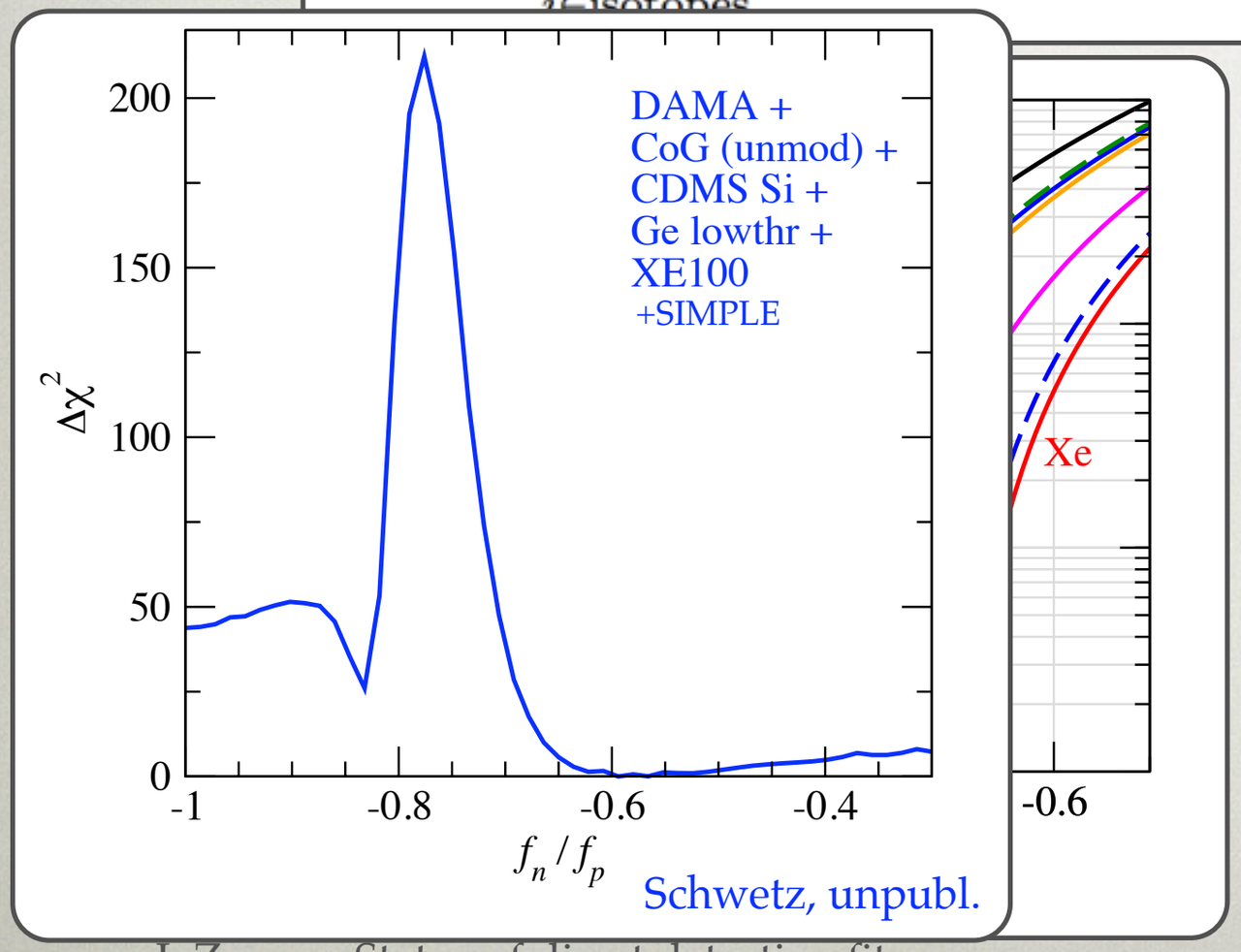
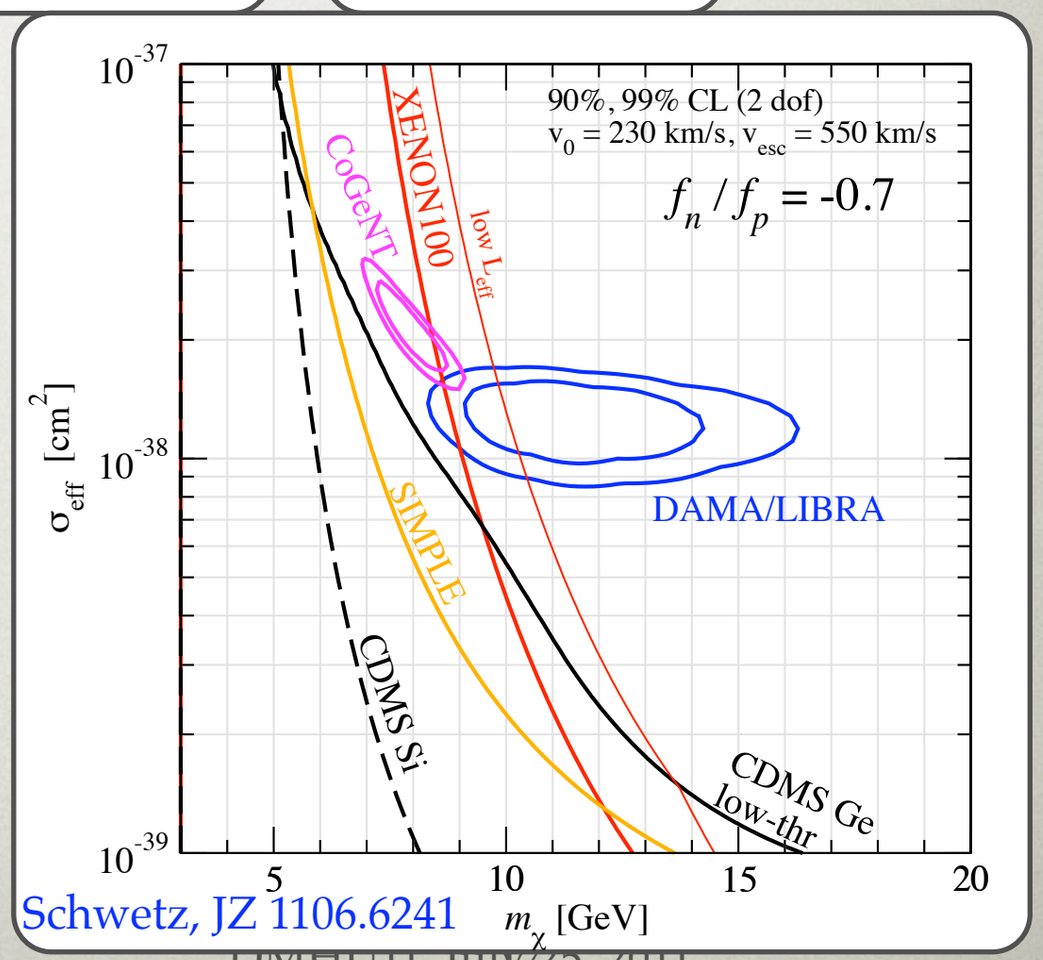
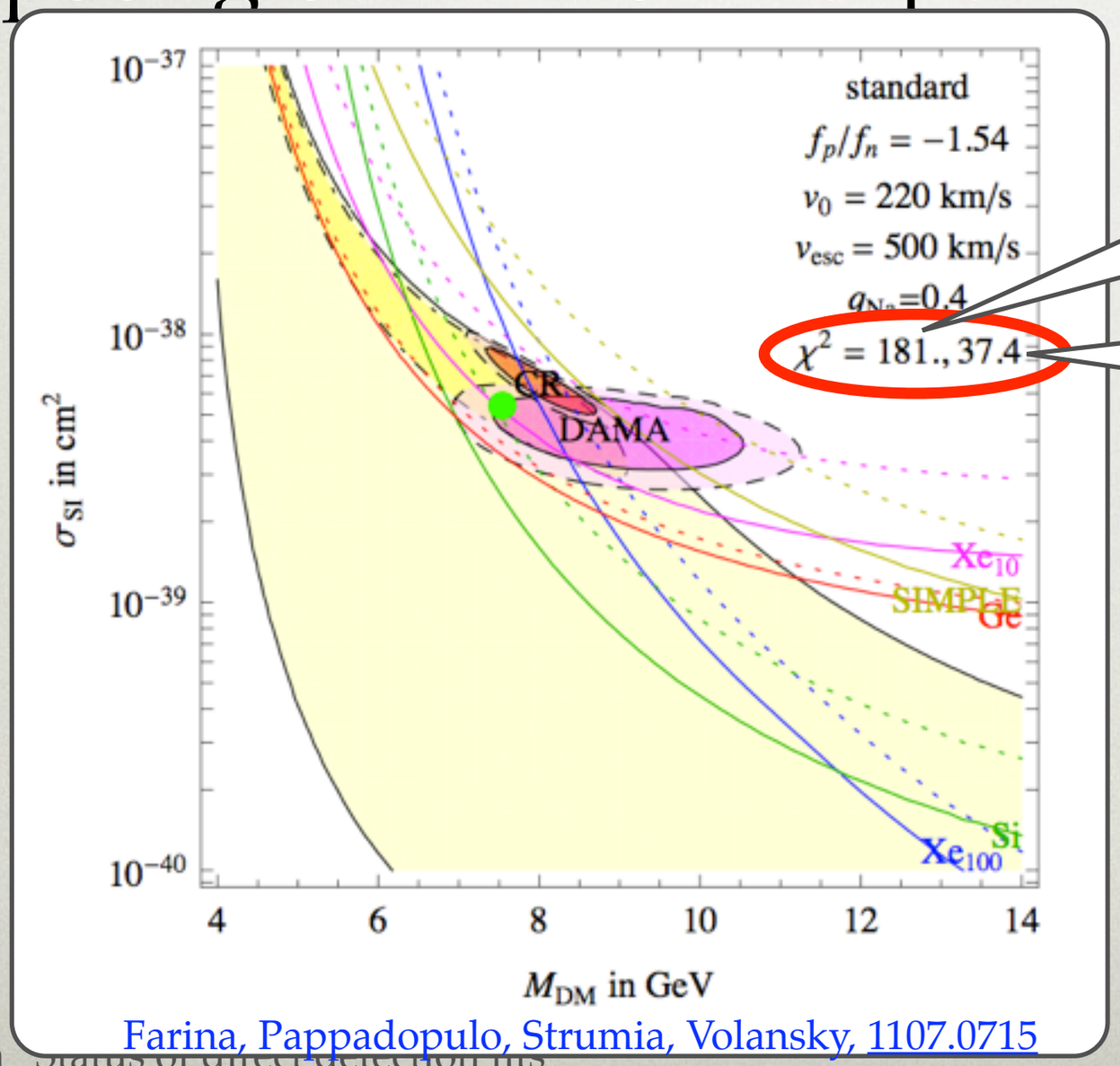


# ISOSPIN VIOLATING ELASTIC SPIN-INDEPENDENT

- CoGeNT and DAMA can be made to agree
- poor global fit to all experiments

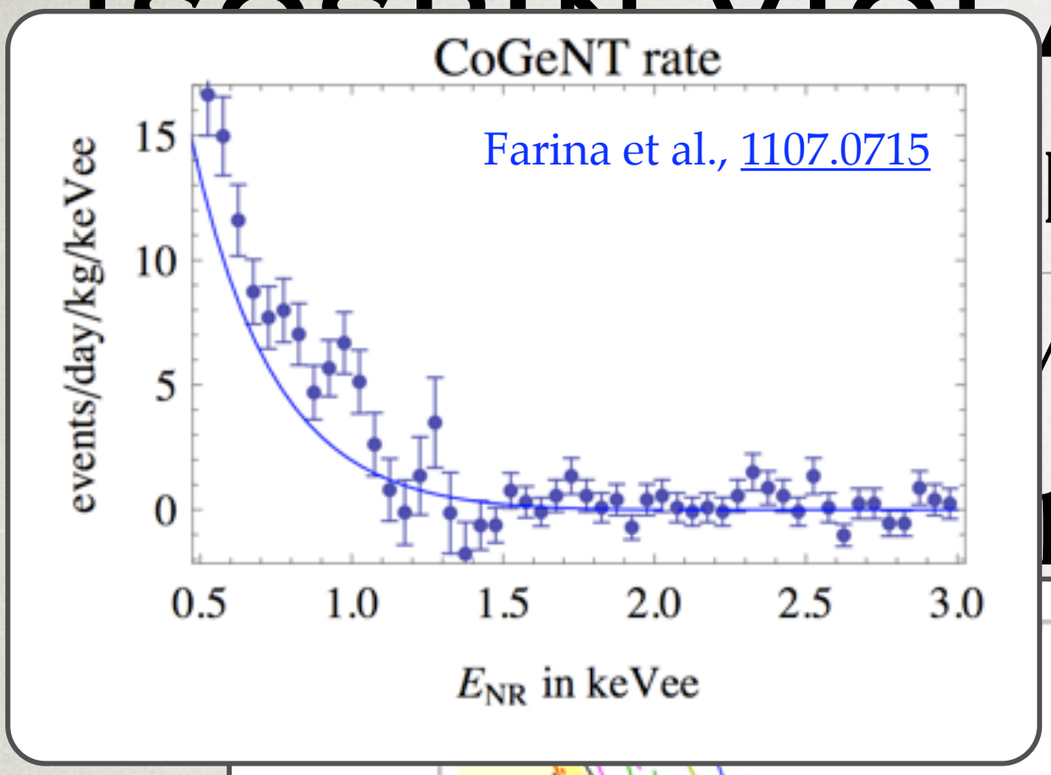


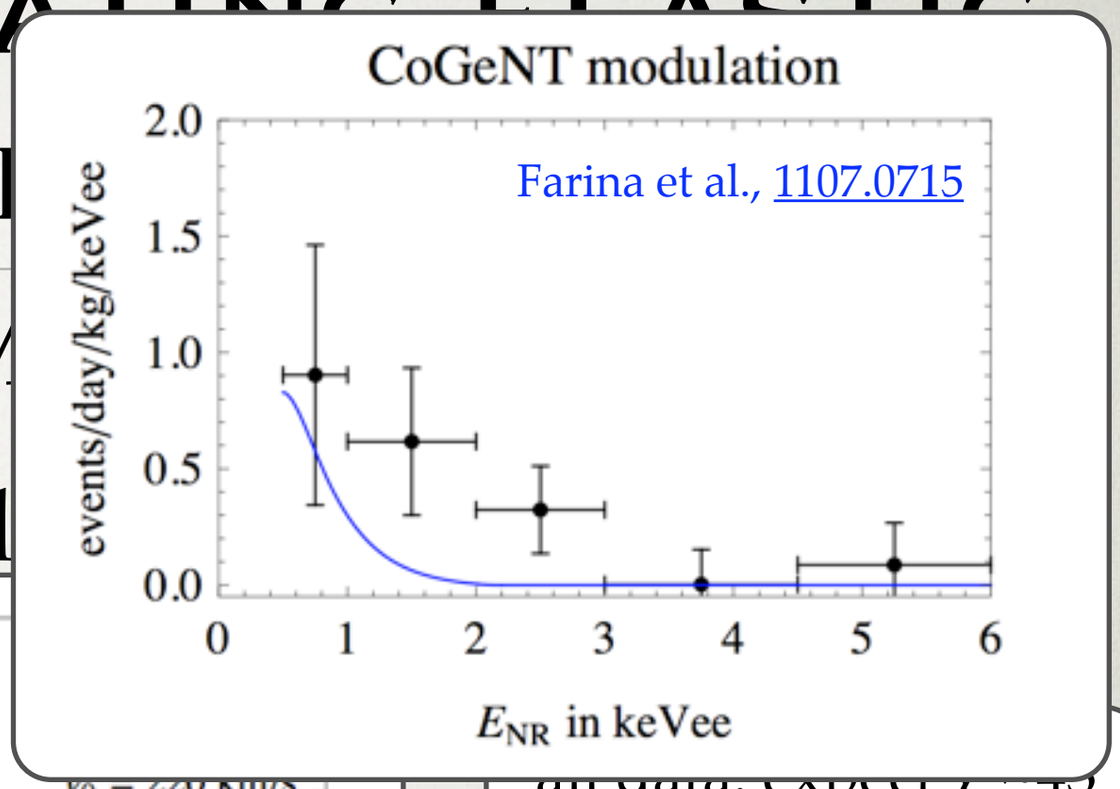

all data: expect $\chi^2$~43

no CoGeNT rate expect $\chi^2$~8

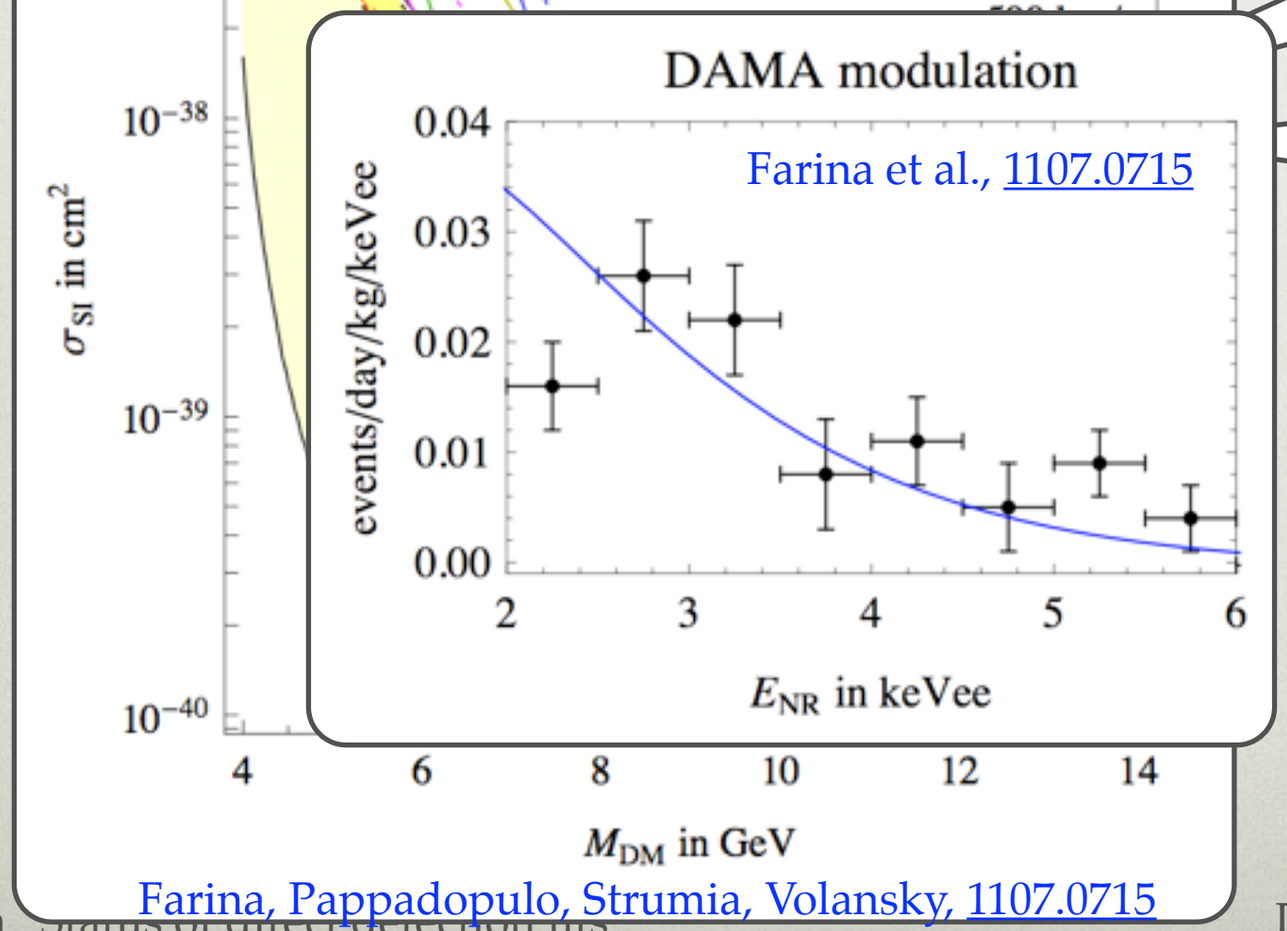
Farina, Pappadopulo, Strumia, Volansky, 1107.0715

# ISOSPIN VIOLATING ELASTIC




all data: expect $\chi^2$~45

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Farina, Pappadopulo, Strumia, Volansky, 1107.0715

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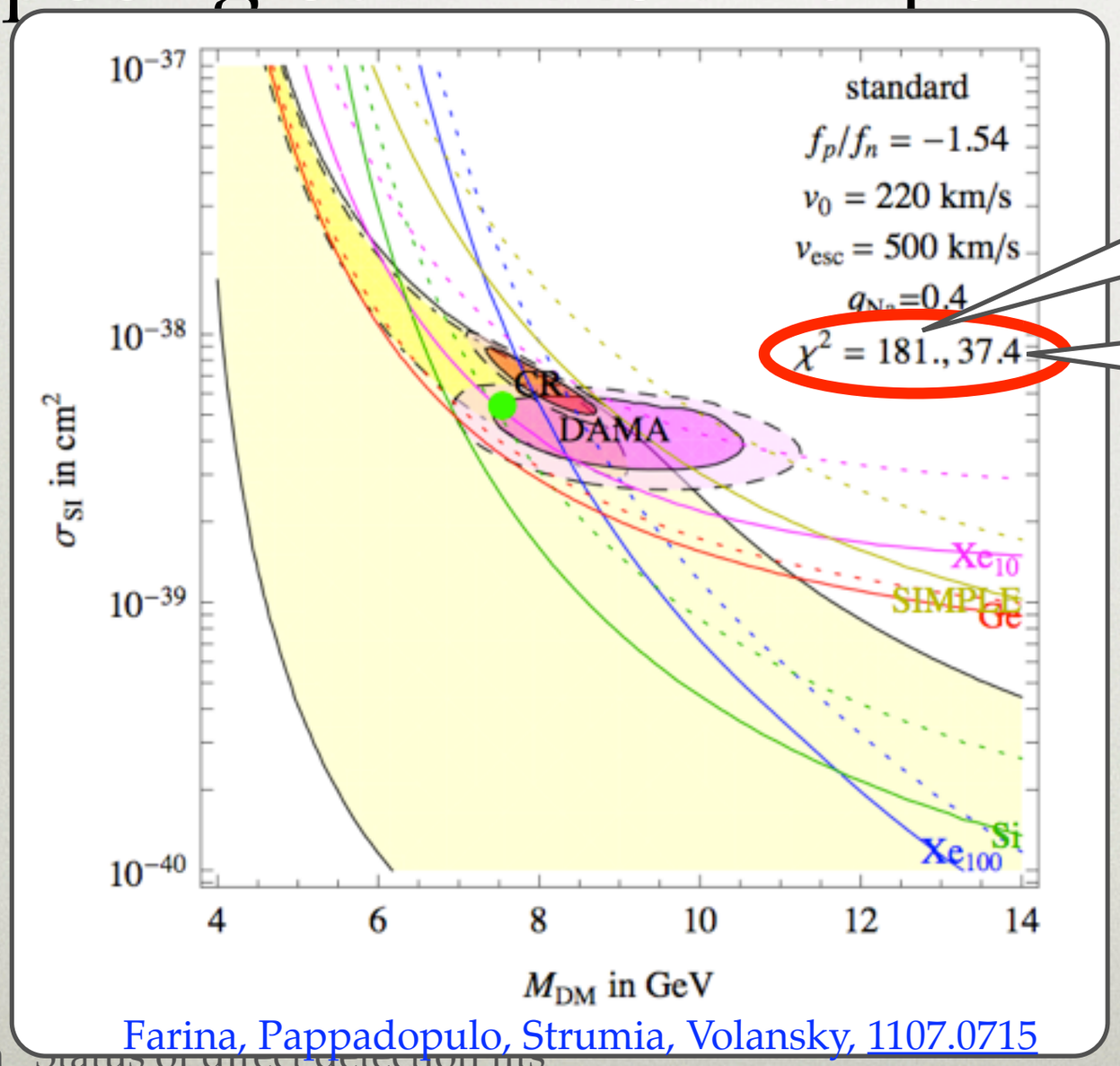


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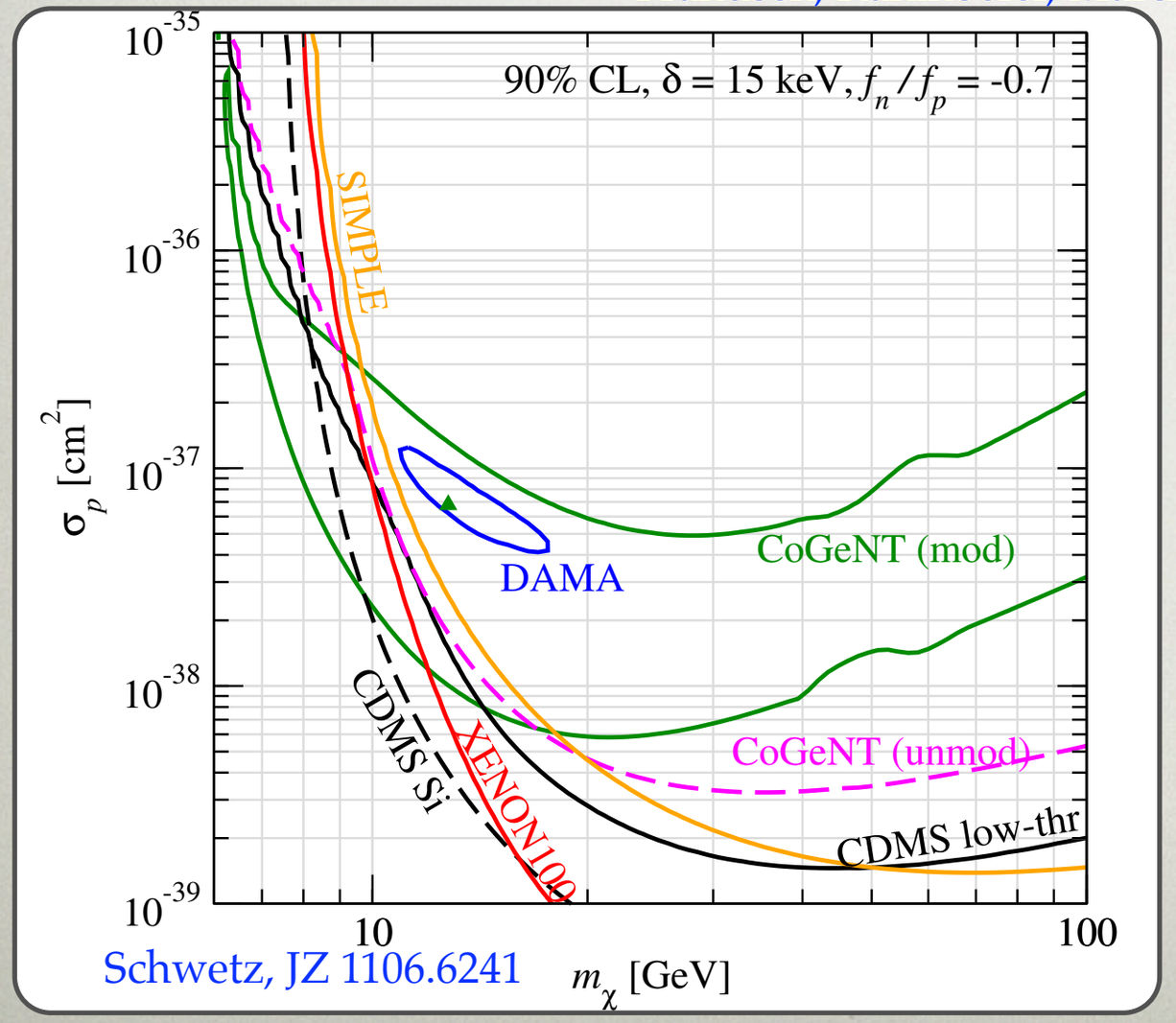
Farina, Pappadopulo, Strumia, Volansky, 1107.0715

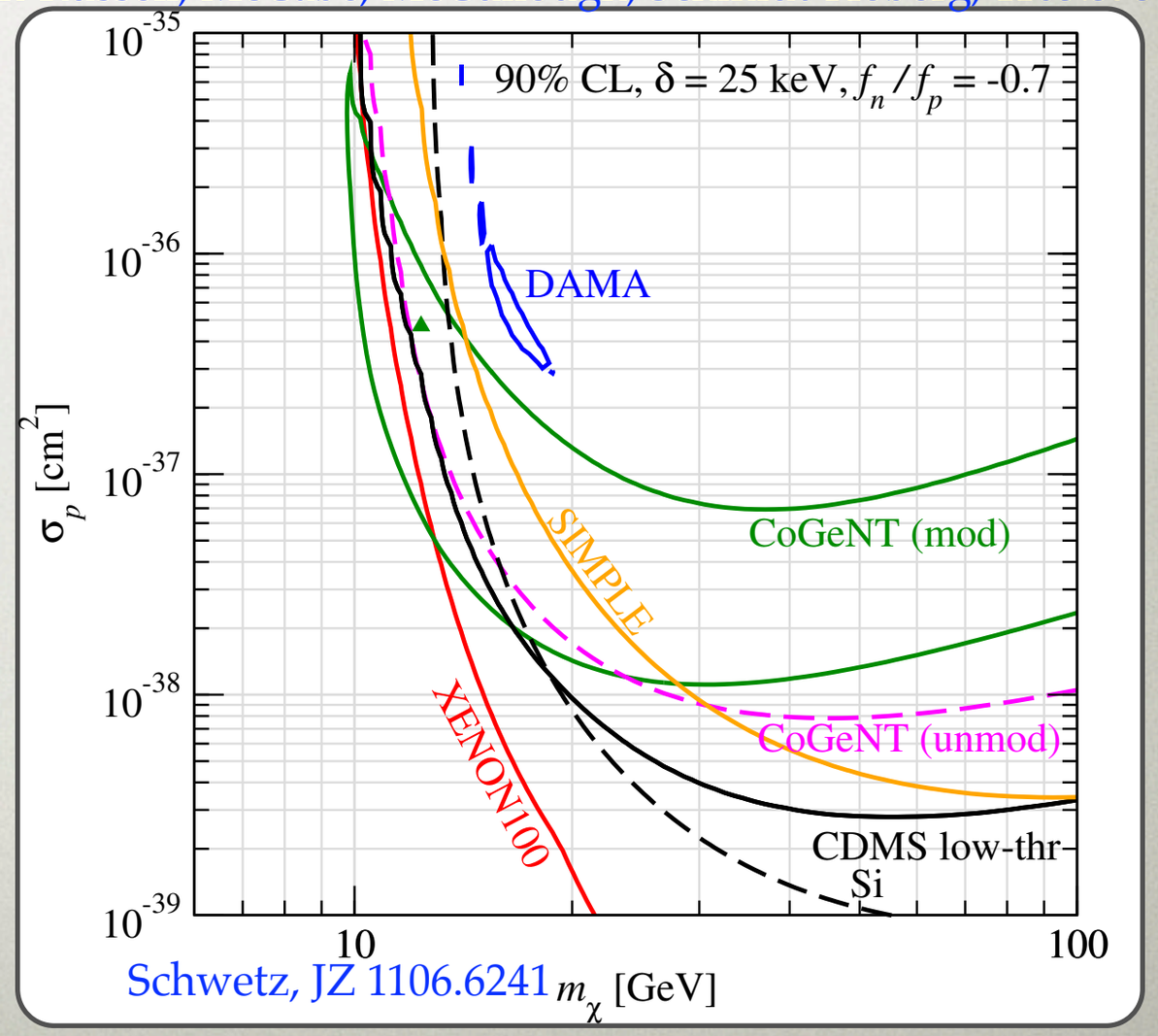
# ISOSPIN VIOLATING DM-INELASTIC

- $\delta>0$ no good fit to total CoGeNT rate possible
  - below treat it as upper bound only
- allowed region opens up

Frandsen, Kahlhoefer, March-Russell, McCabe, McCullough, Schmidt-Hoberg, 1105.3734




Schwetz, JZ 1106.6241



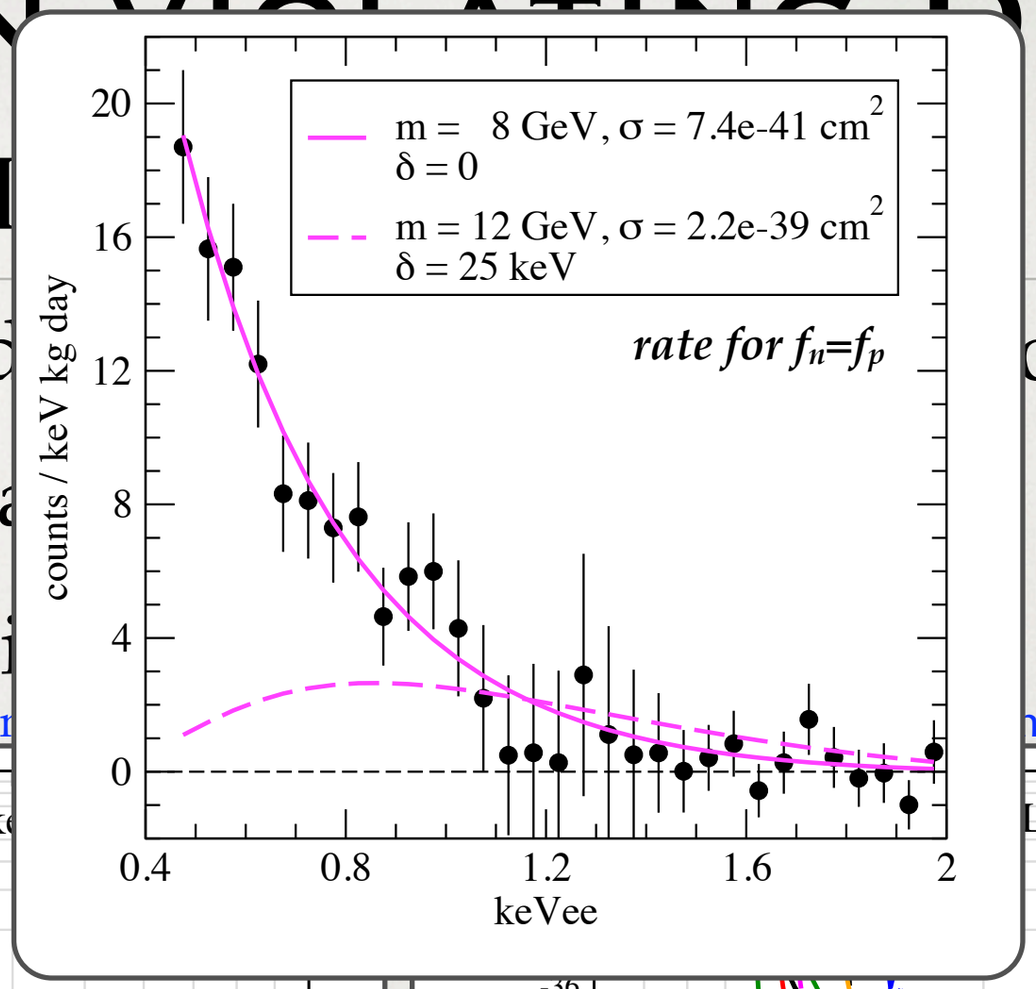

Schwetz, JZ 1106.6241

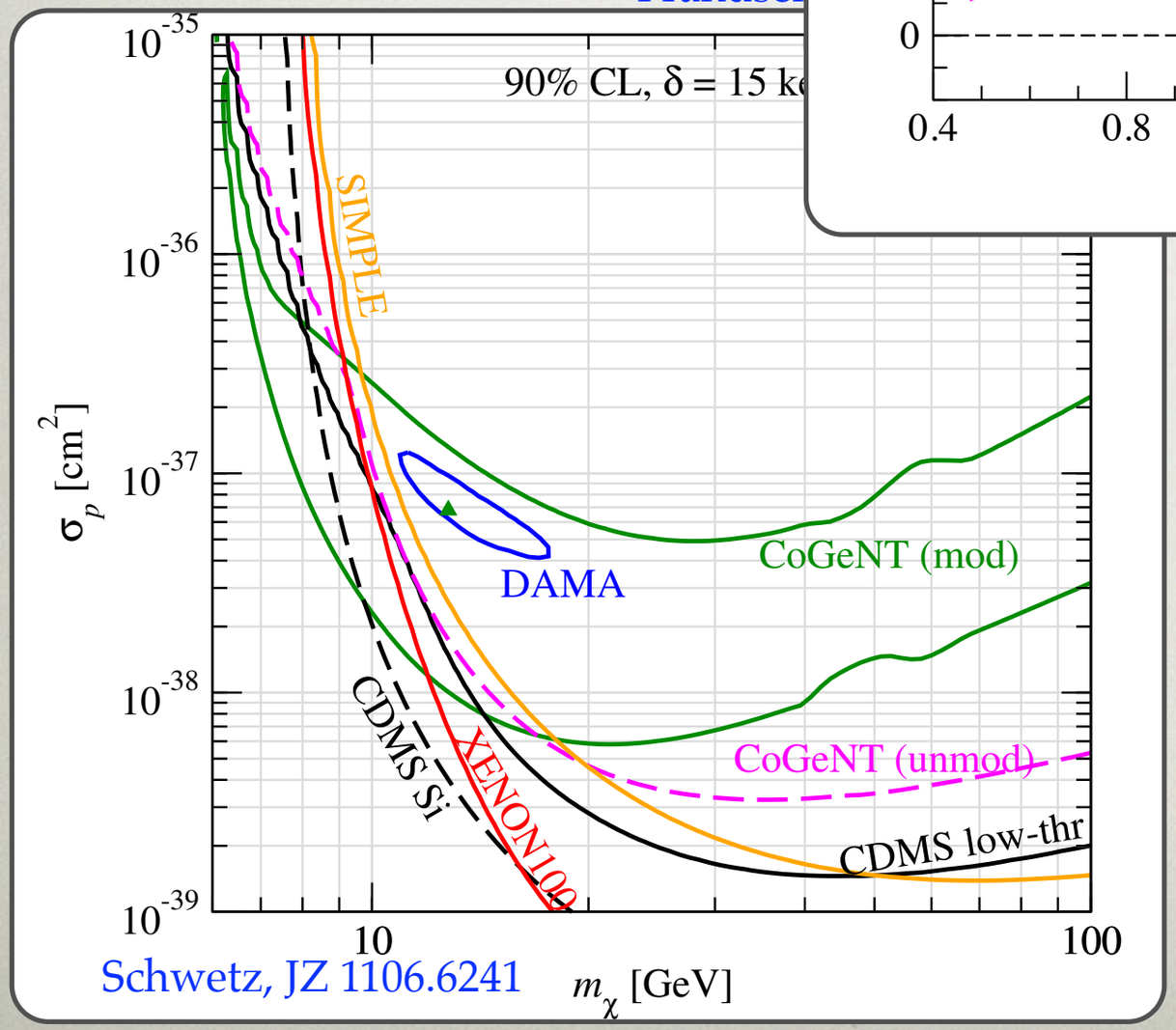
# ISOSPIN VIOLATING DM-

# I

- δ>0 no good … ossible
  - below trea…
- allowed regi…

Frandsen … n, Schmidt-Hoberg, 1105.3734

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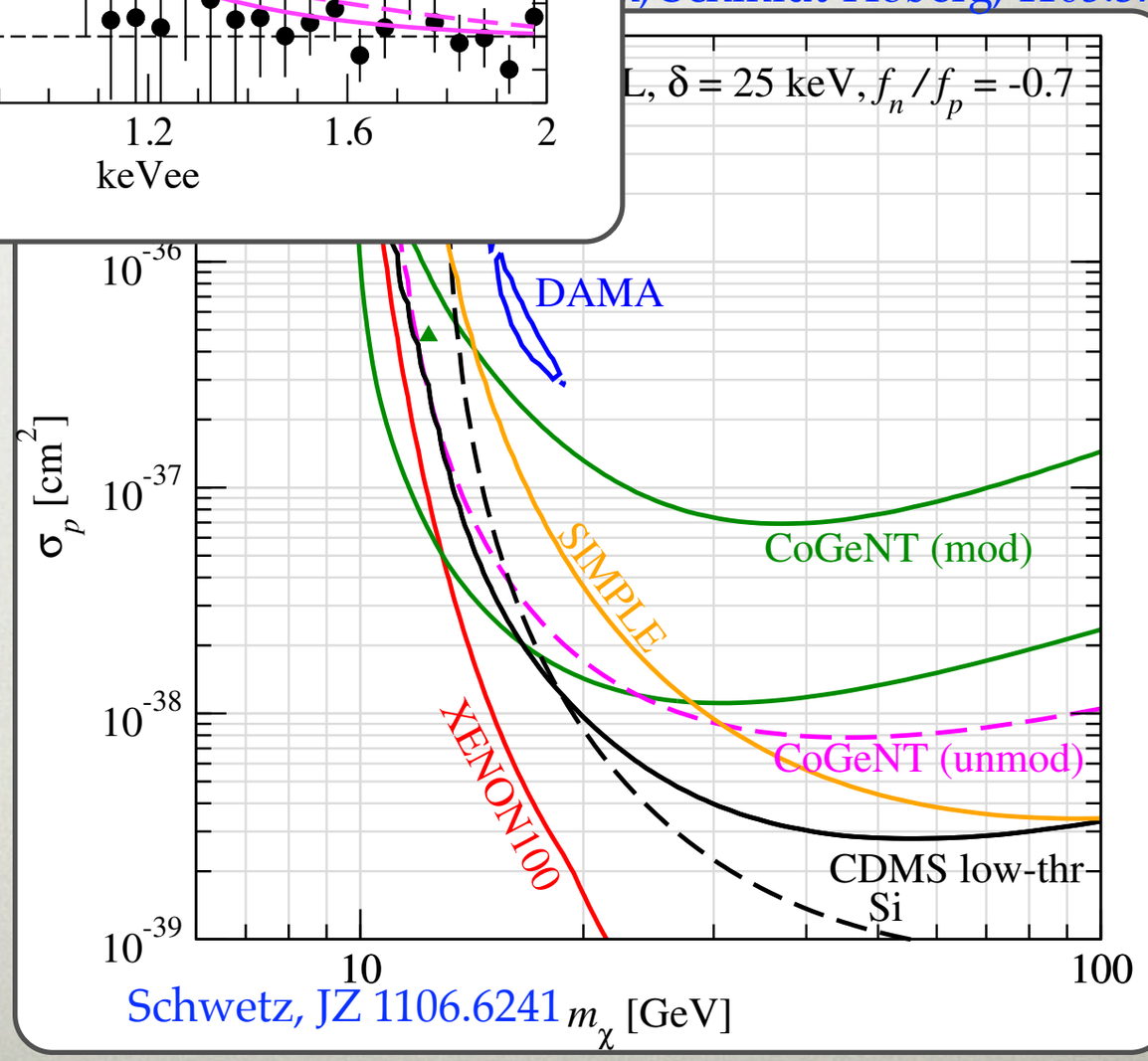
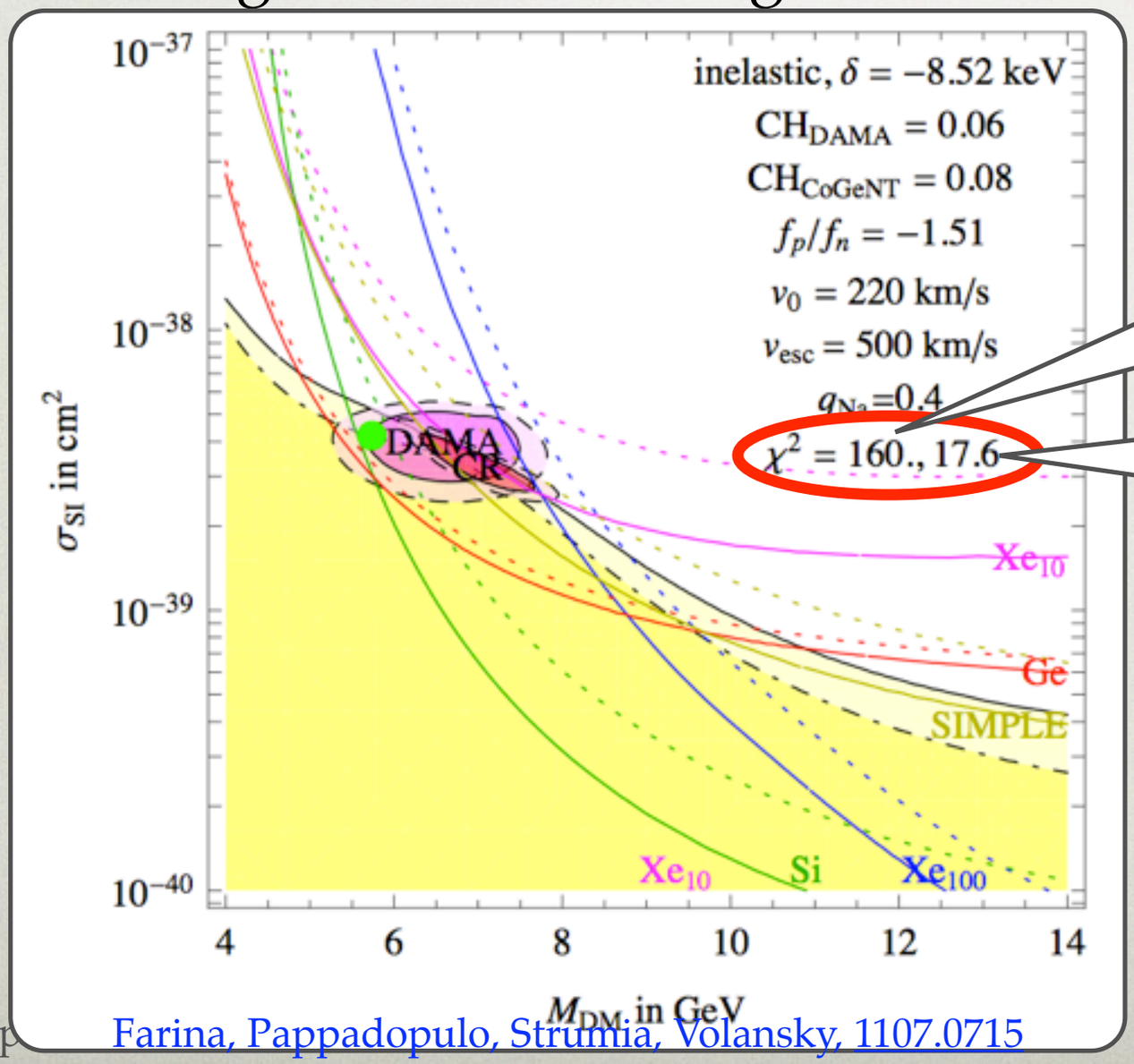



Schwetz, JZ 1106.6241

# ISOSPIN VIOLATING DM-INELASTIC

- an option with some channeling in DAMA and CoGeNT + exothermic iDM considered
- the global fit still not good

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Farina, Pappadopulo, Strumia, Volansky, 1107.0715

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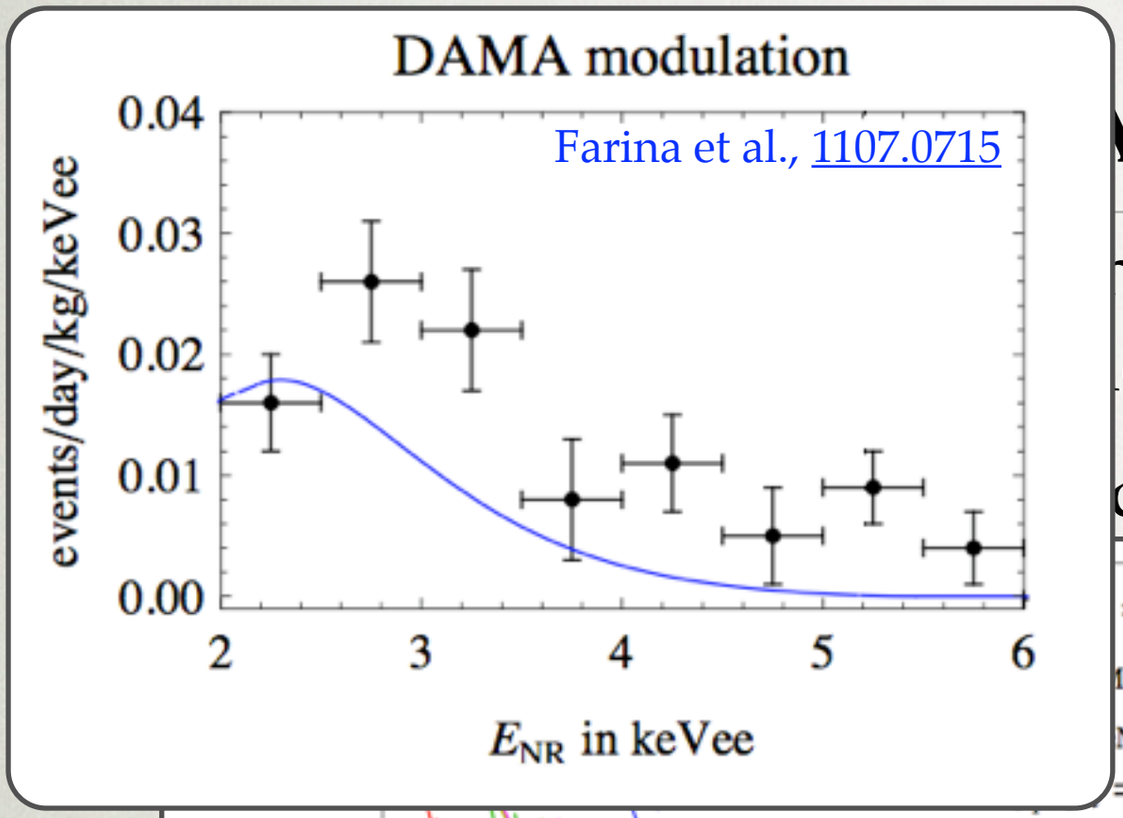


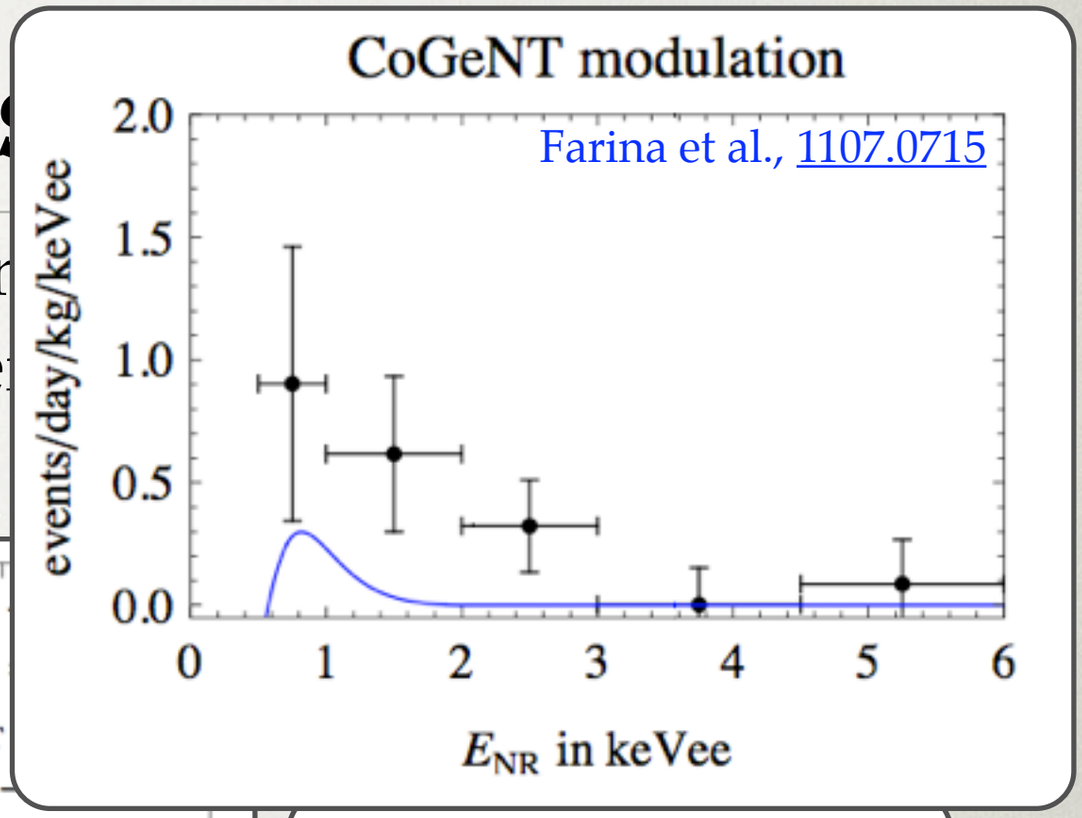


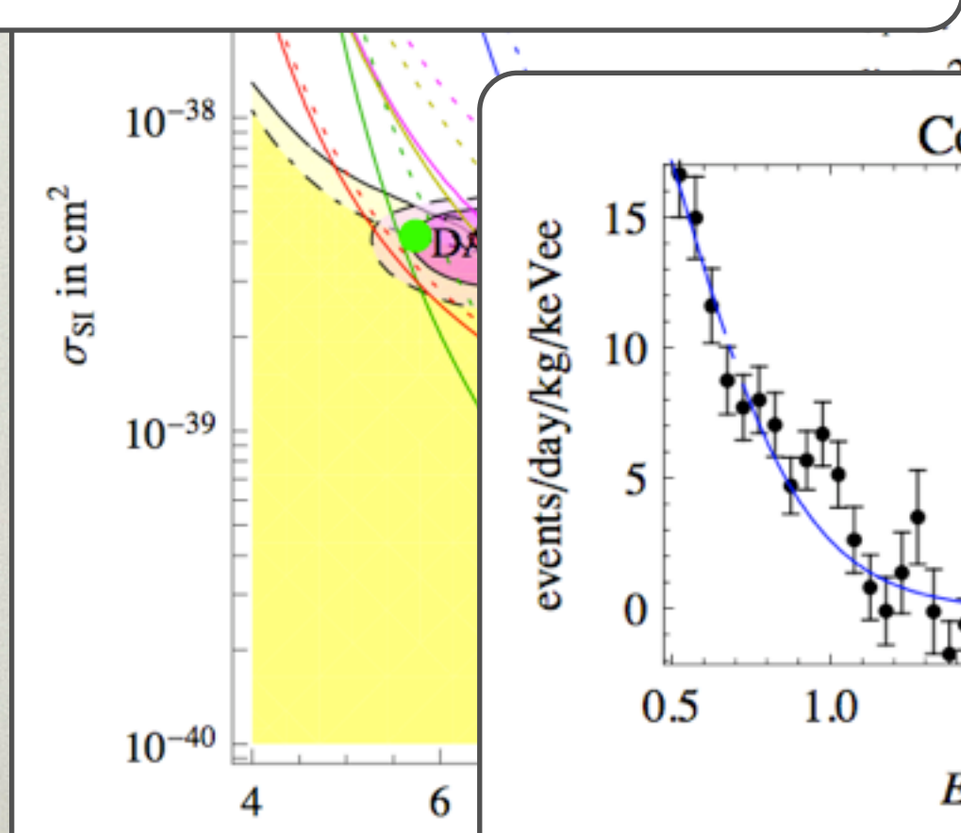


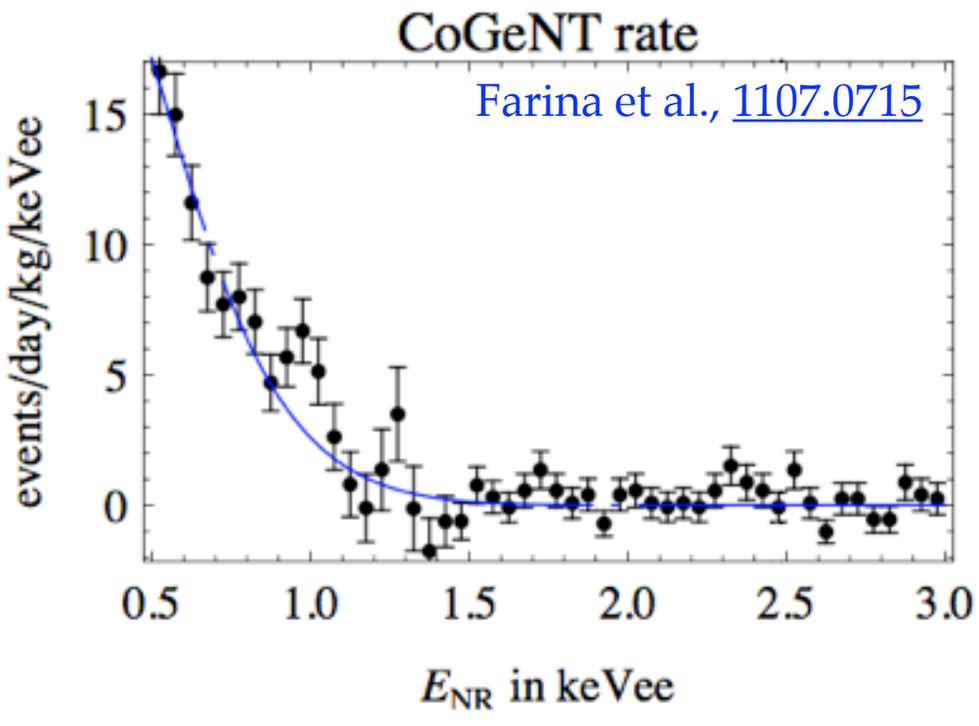


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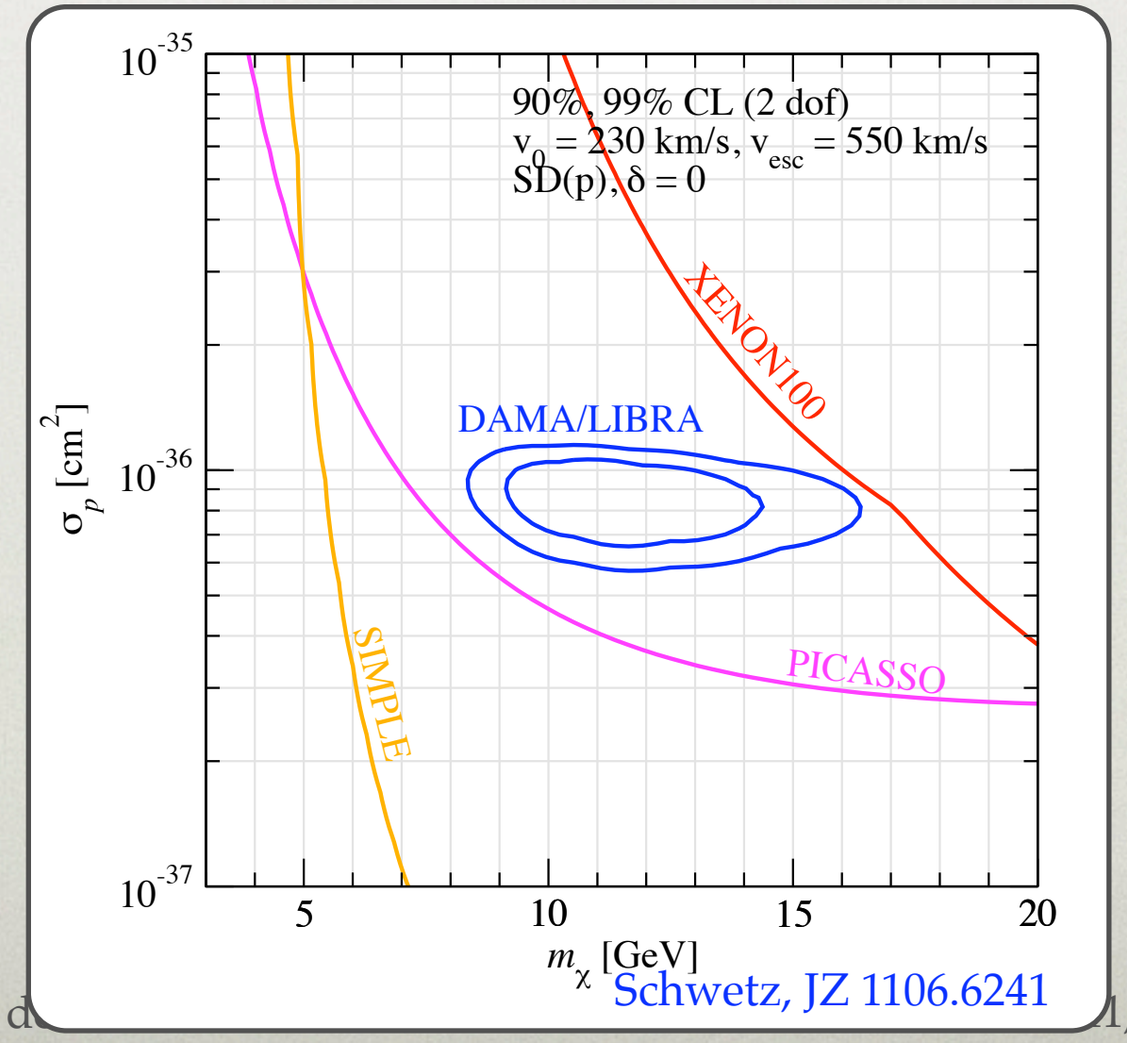
Farina, Pappadopulo, Strumia, Volansky, 1107.0715

# SPIN DEPENDENT - ON PROTONS

- for SD interactions the sensitivities of experiments change drastically
- depends crucially whether coupling mostly to *p* or *n*
- if mostly on protons: CoGeNT no signal, but signal in DAMA
- for inelastic SD a viable space opens up for DAMA Kopp, Schwetz, Zupan, 0912.4264




Schwetz, JZ 1106.6241

# SPIN DEPENDENT - ON PROTONS

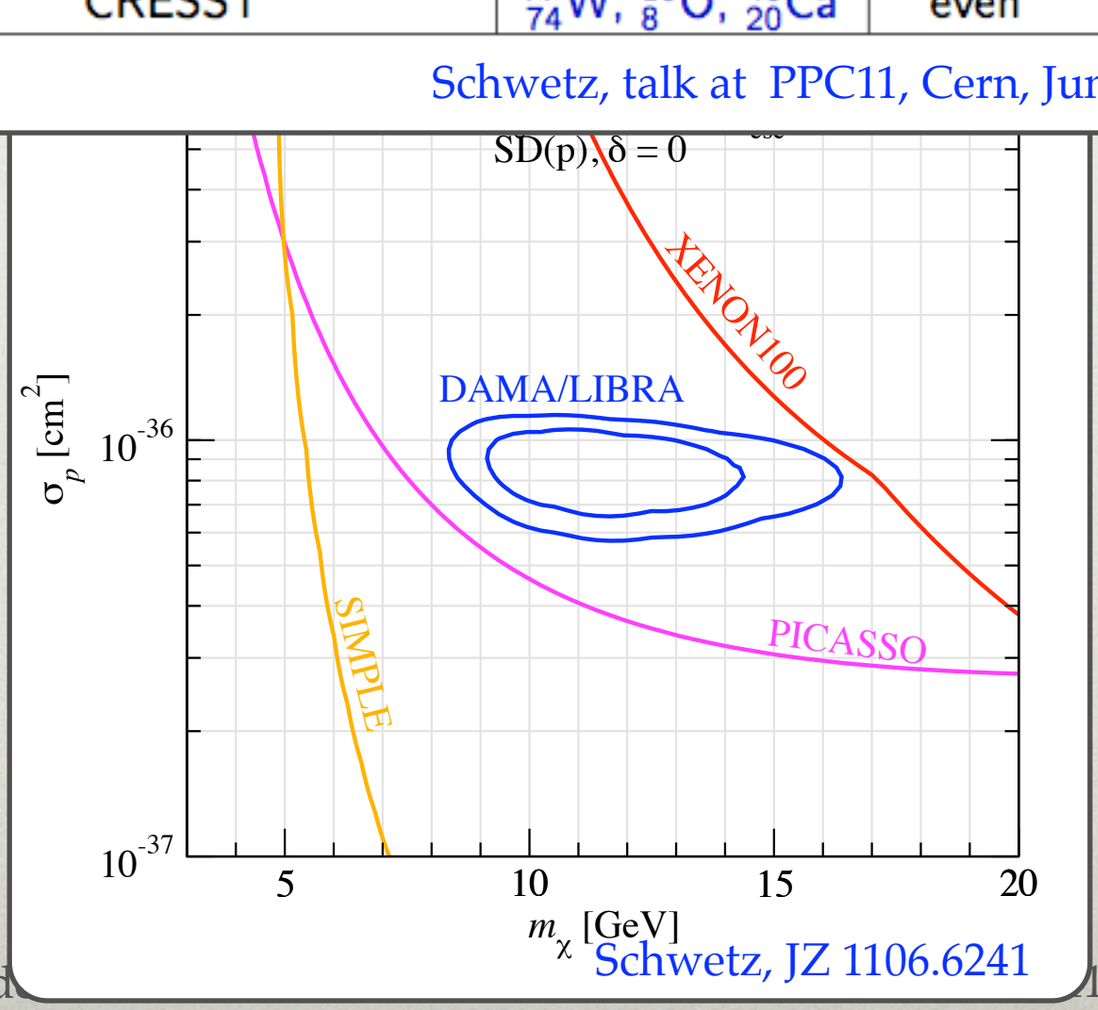
- for … cally
- de…
- if r…
- for…

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, $^{37}_{17}$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, $^{40}_{20}$Ca | even | even |

Schwetz, talk at PPC11, Cern, June 15 2011

Zupan, 0912.4264




Schwetz, JZ 1106.6241

# SPIN DEPENDENT - ON PROTONS

- for SD interactions the sensitivities of experiments change drastically
- depends crucially whether coupling mostly to *p* or *n*
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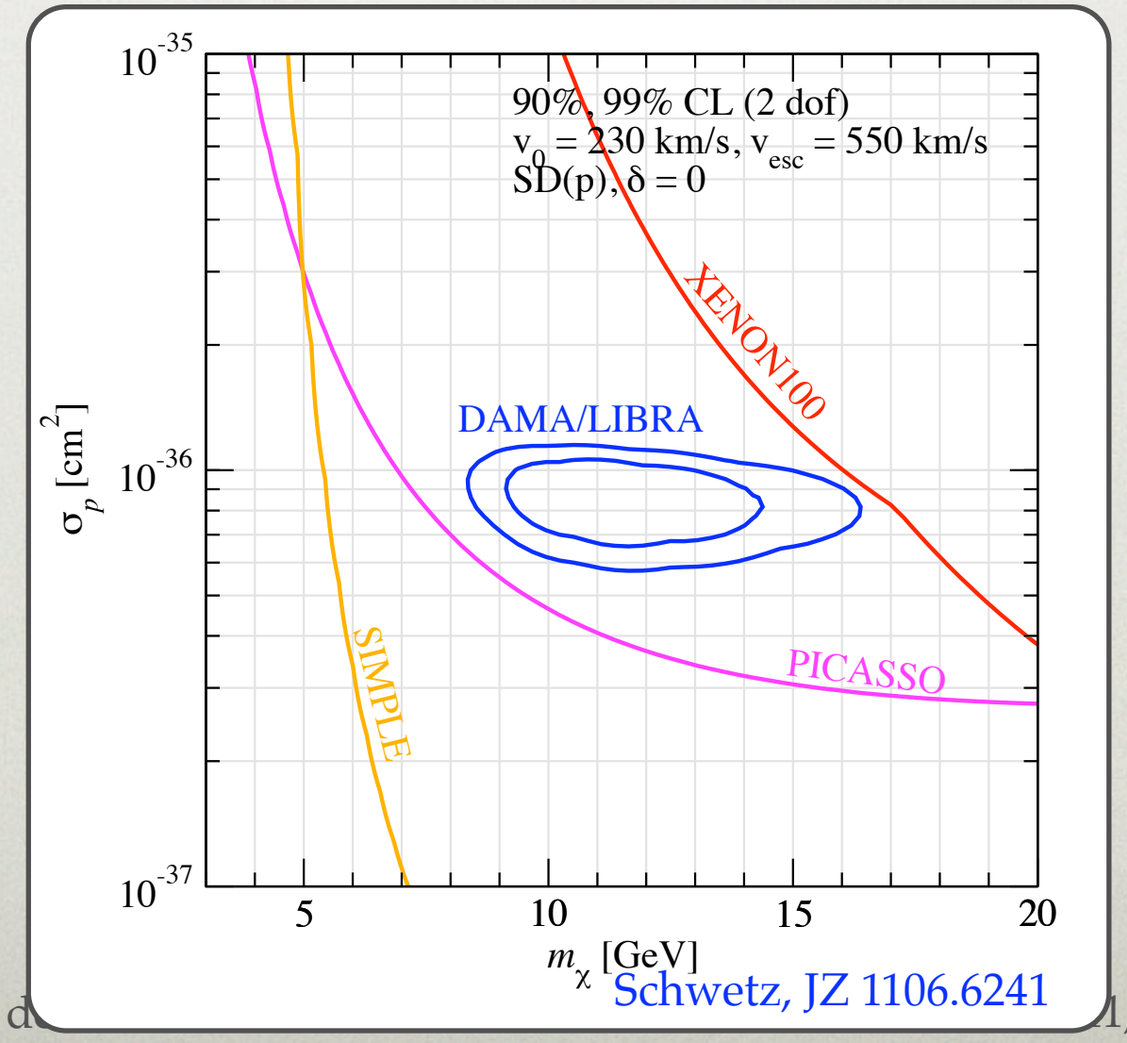


Schwetz, JZ 1106.6241

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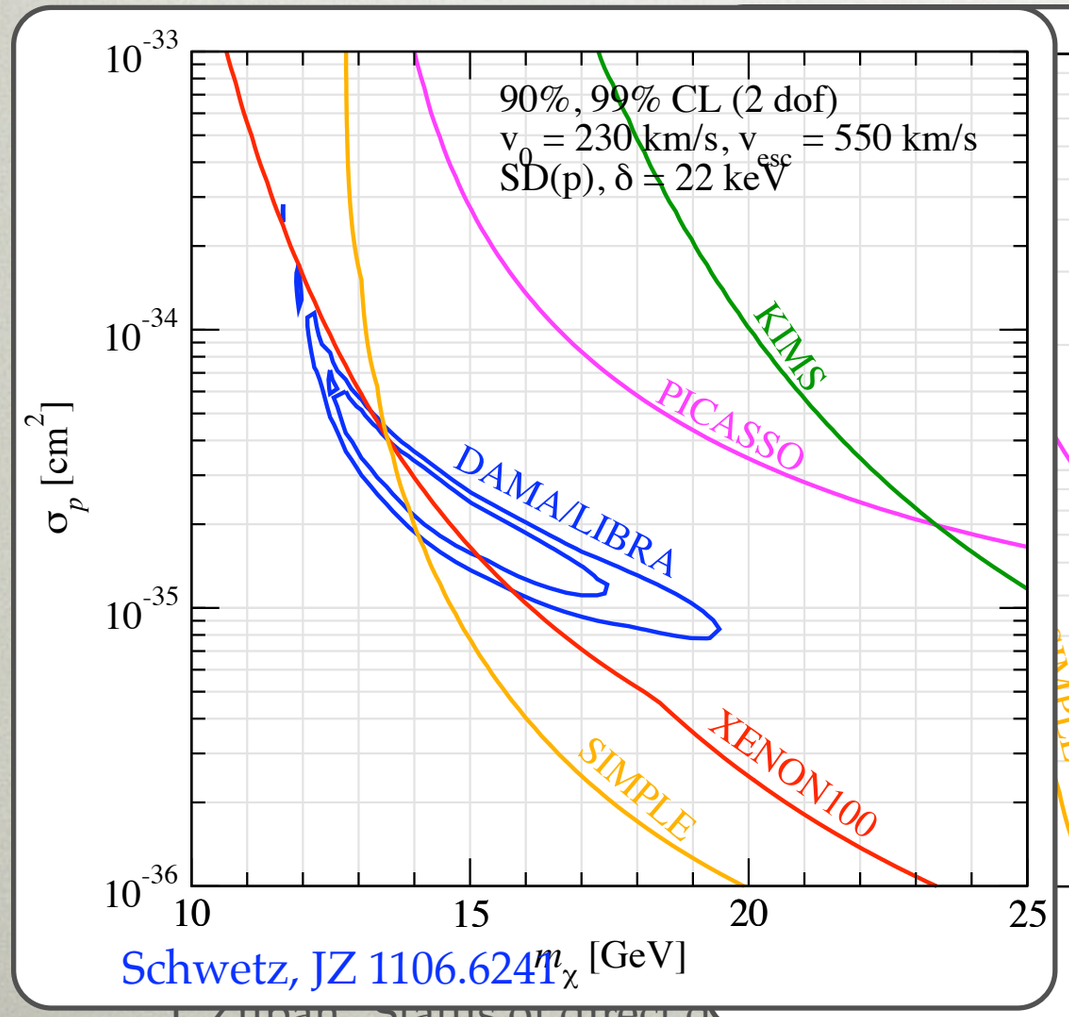
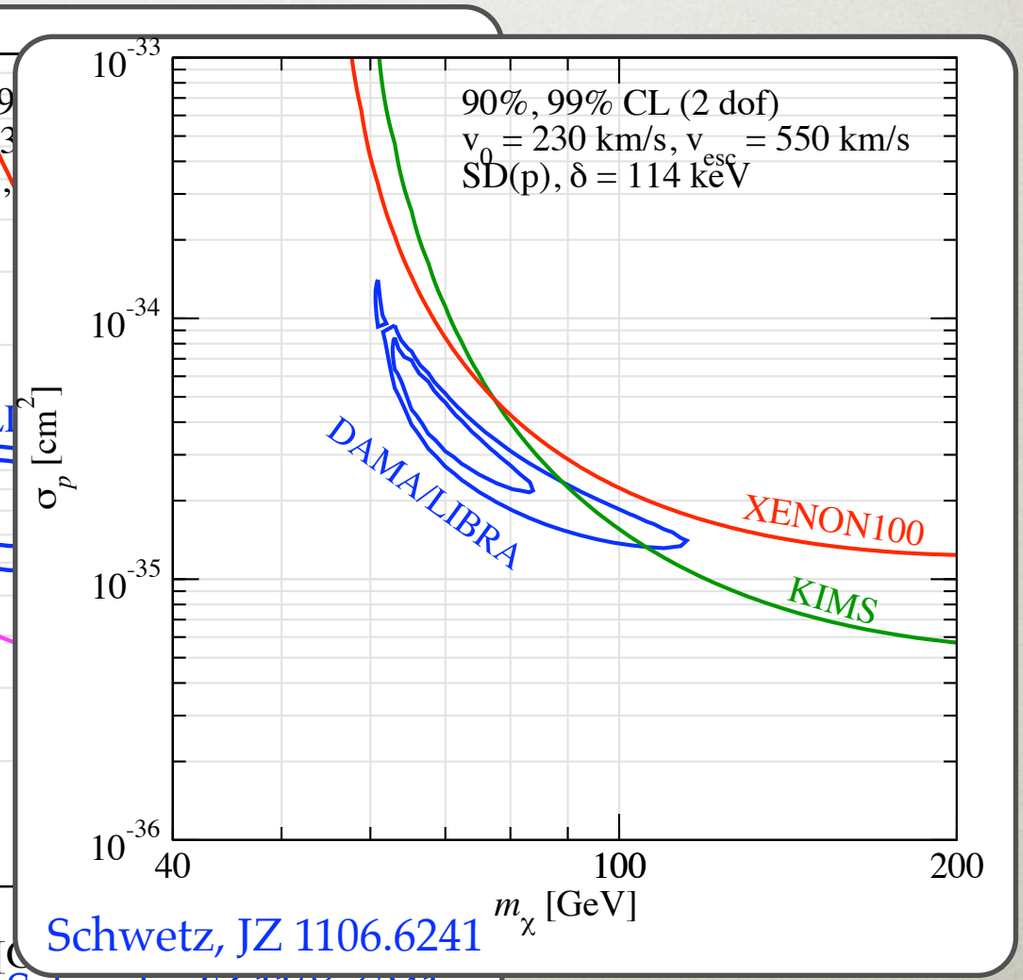


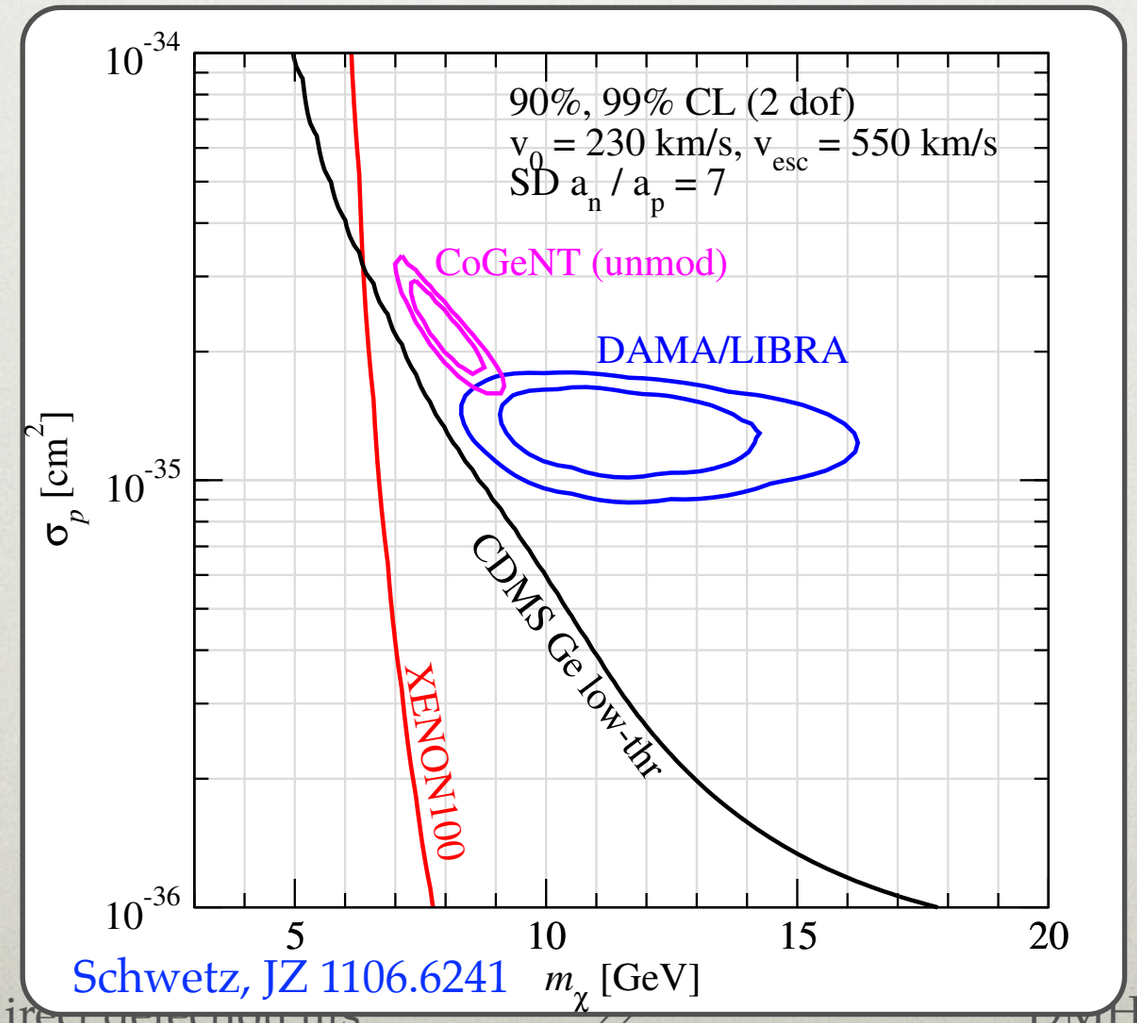
Schwetz, JZ 1106.6241



Schwetz, JZ 1106.6241

# SPIN DEPENDENT - OFF NEUTRONS

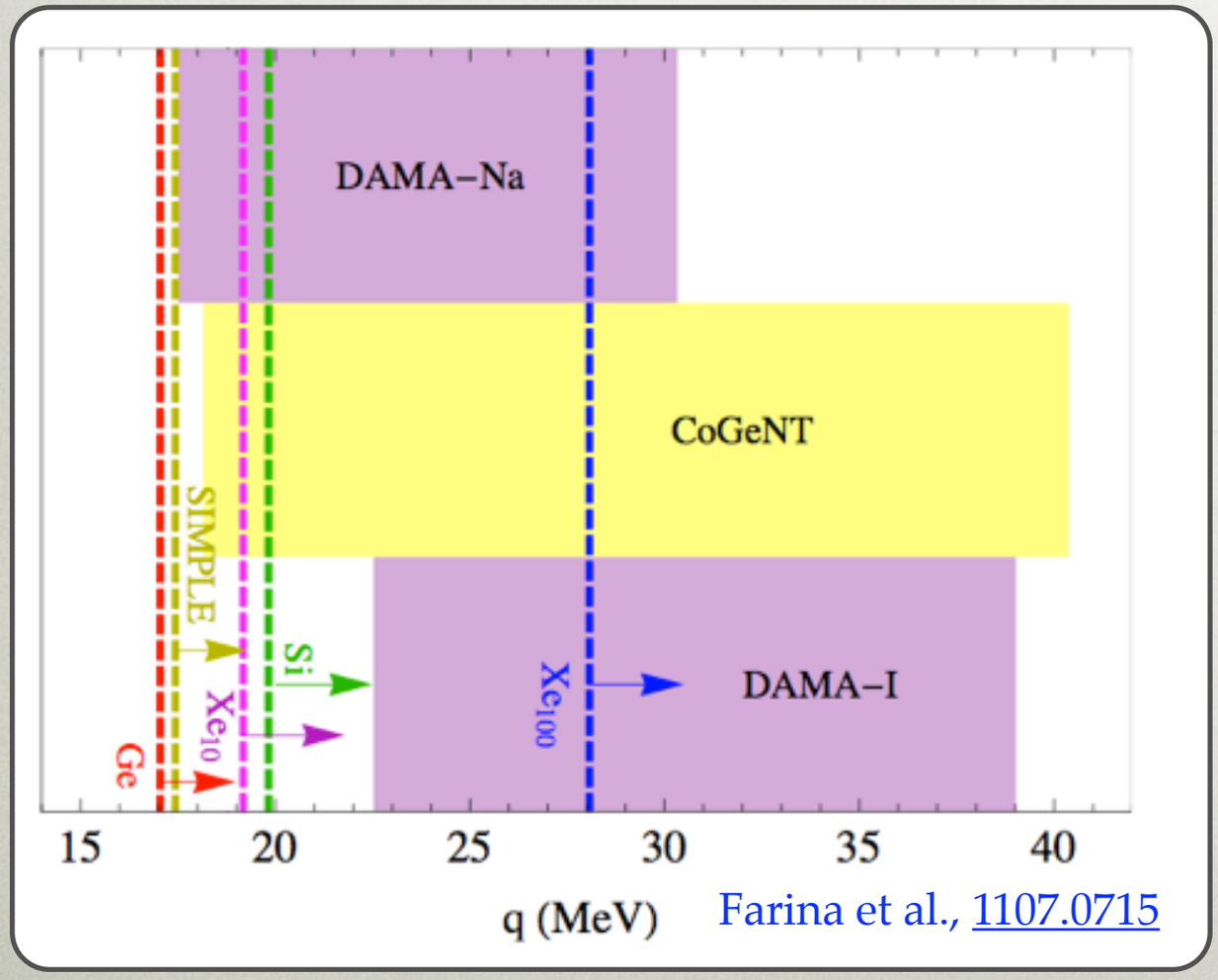
- for Ge in CoGeNT the spin dominated by *n*
- excluded by CDMS Ge low-threshold
- also excl. by Xenon100 from $^{129}$Xe and $^{131}$Xe



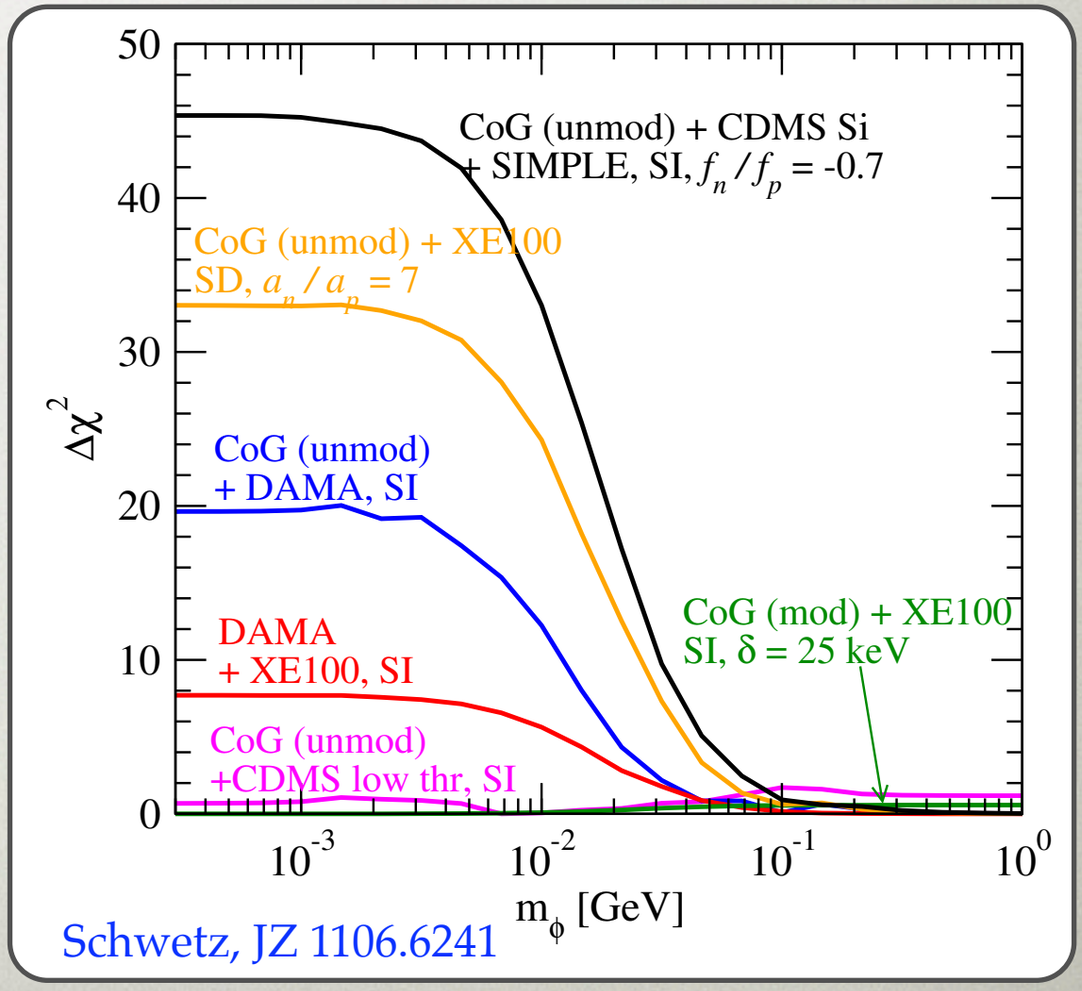

Schwetz, JZ 1106.6241

# LIGHT MEDIATORS

- additional q dependence if light mediators ($m<40$ MeV)
- $\sigma \sim 1/(m^2+q^2)^2$
- no improvement in global fits



Farina et al., 1107.0715



Schwetz, JZ 1106.6241

# MOMENTUM DEPENDENT SCATTERING

- even in EFT depending on operator can gave additional $q$ and $v$ dependence

$$\begin{aligned}
\mathcal{A}_1 &\propto 1, & \sigma &\propto 1\,, \\
\mathcal{A}_2 &\propto \vec{s}_{\rm DM}\cdot\vec{q}, & \sigma &\propto q^2\,, \\
\mathcal{A}_3 &\propto \vec{s}_{\rm DM}\cdot\vec{v}, & \sigma &\propto v^2\,, \\
\mathcal{A}_4 &\propto \vec{s}\cdot\vec{q}\times\vec{v}, & \sigma &\propto q^2 v^2
\end{aligned}$$

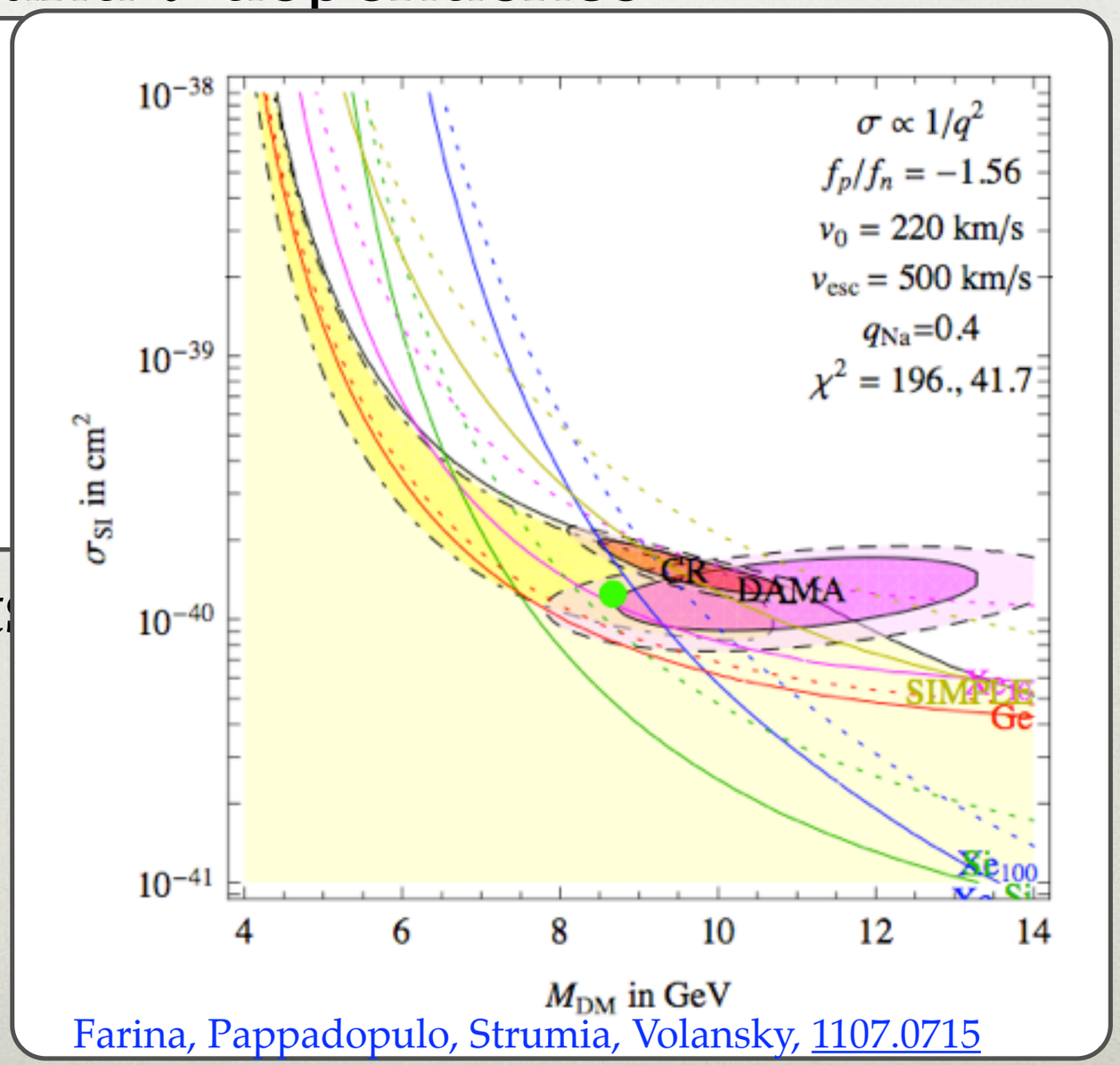
the global fits still do not have good $\chi^2$

# MOMENTUM DEPENDENT SCATTERING

- even in EFT depending on operator can gave additional $q$ and $v$ dependence

$\mathcal{A}_1$
$\mathcal{A}_2$
$\mathcal{A}_3$
$\mathcal{A}_4$

the global fits




Farina, Pappadopulo, Strumia, Volansky, 1107.0715

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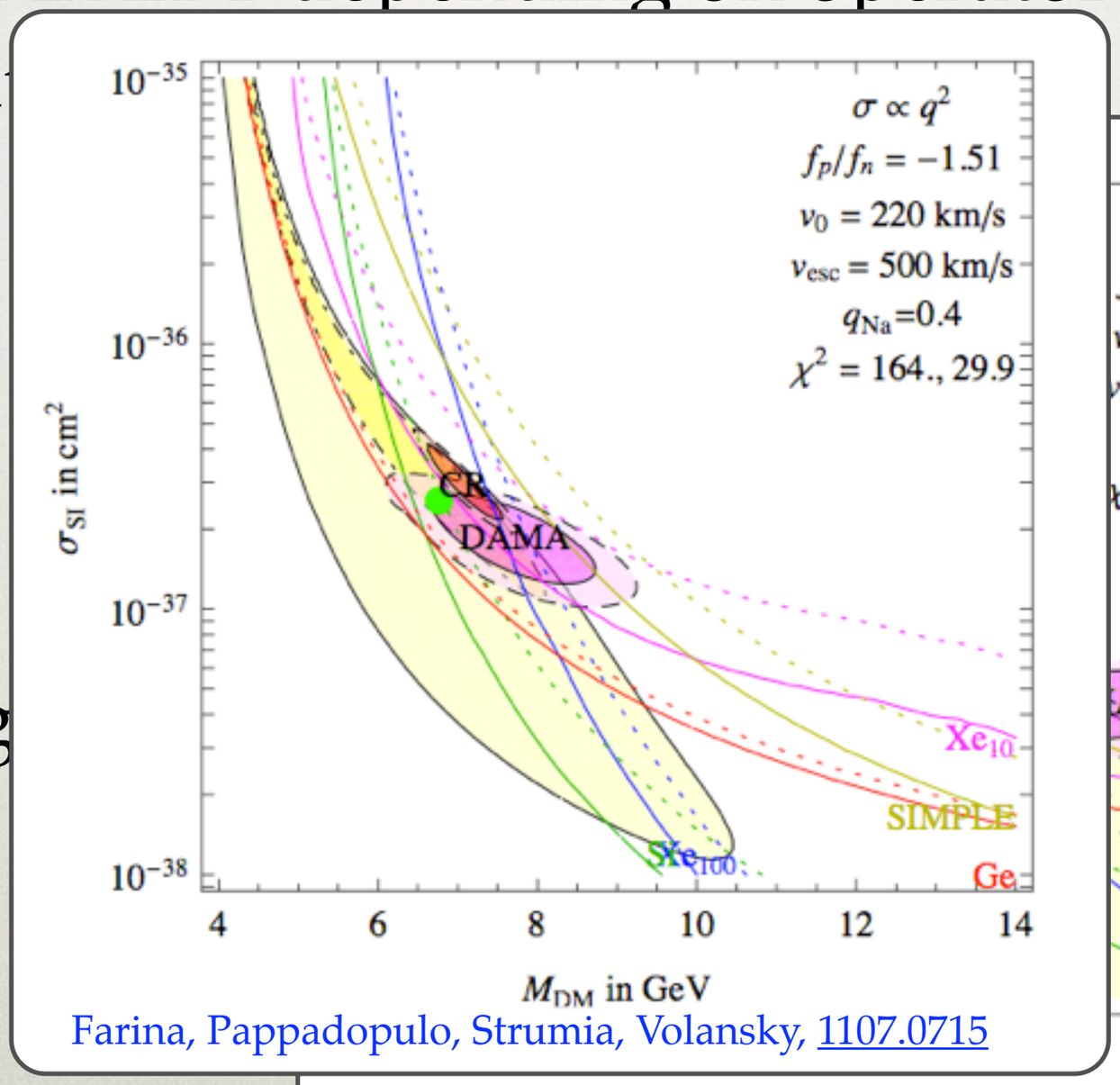


Farina, Pappadopulo, Strumia, Volansky, 1107.0715

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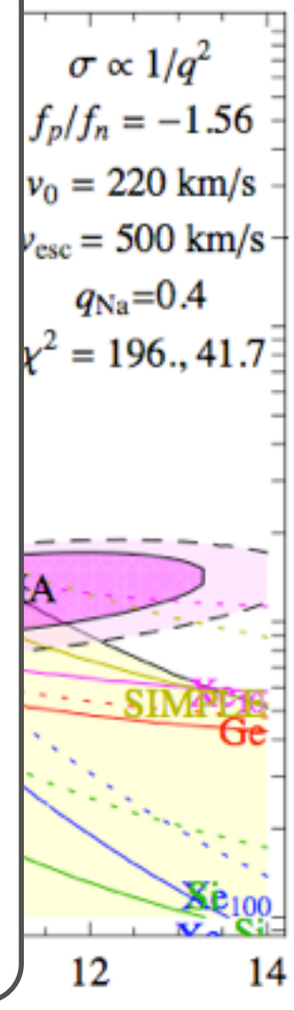
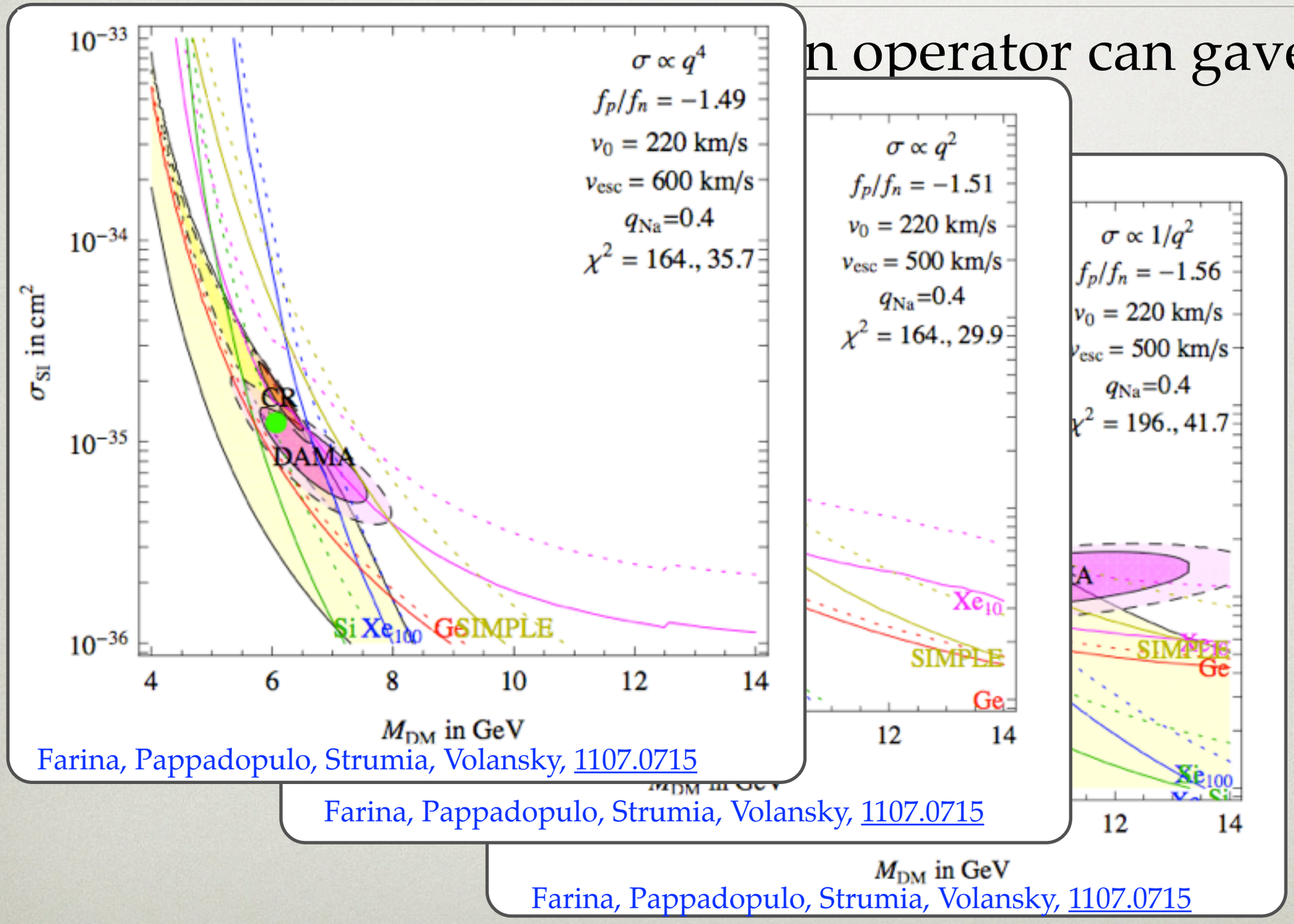



Farina, Pappadopulo, Strumia, Volansky, 1107.0715

# MOMENTUM DEPENDENT SCATTERING

n operator can gave




Farina, Pappadopulo, Strumia, Volansky, 1107.0715

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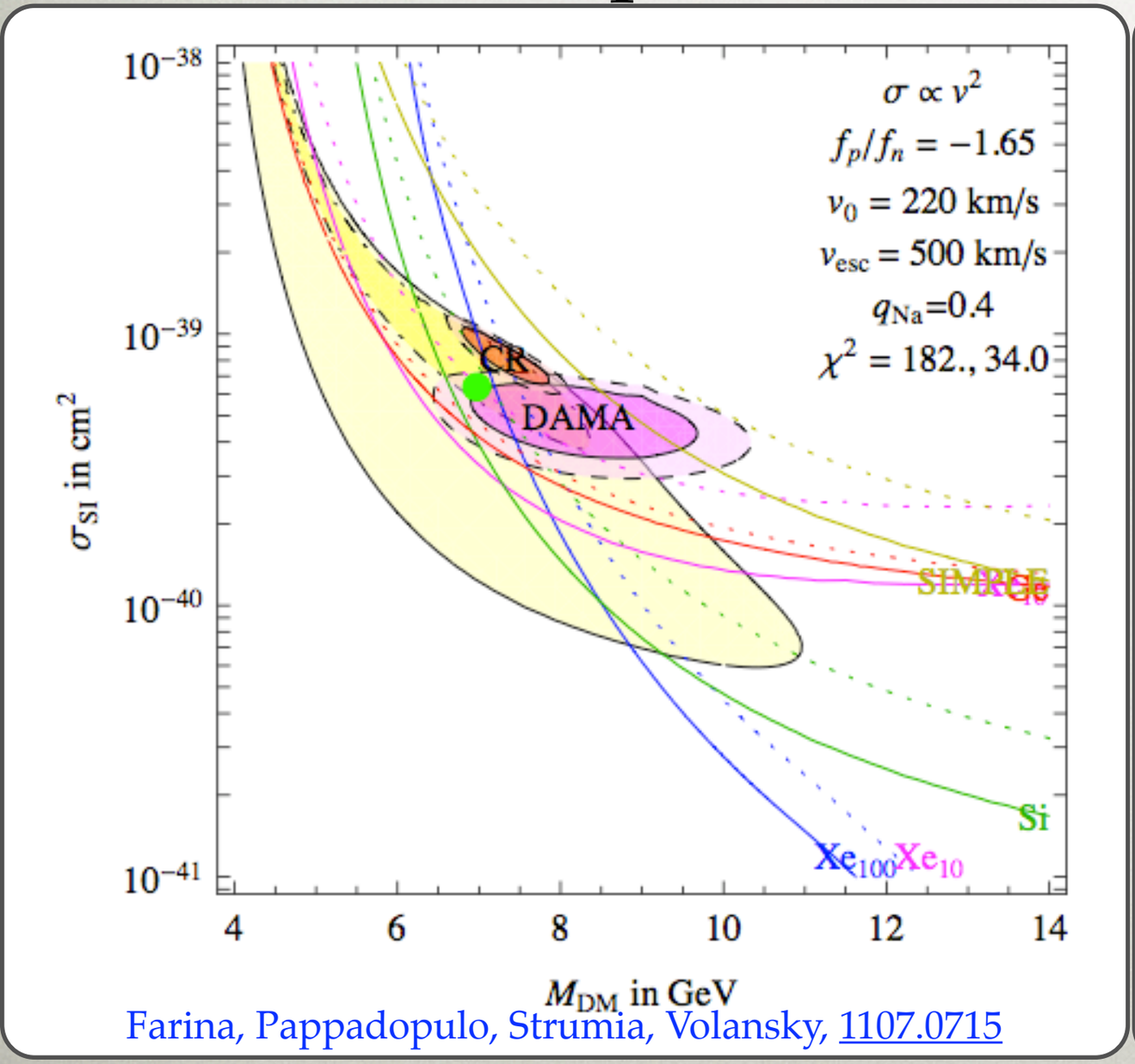
# VELOCITY DEPENDENT

- no improvement, if velocity dependent

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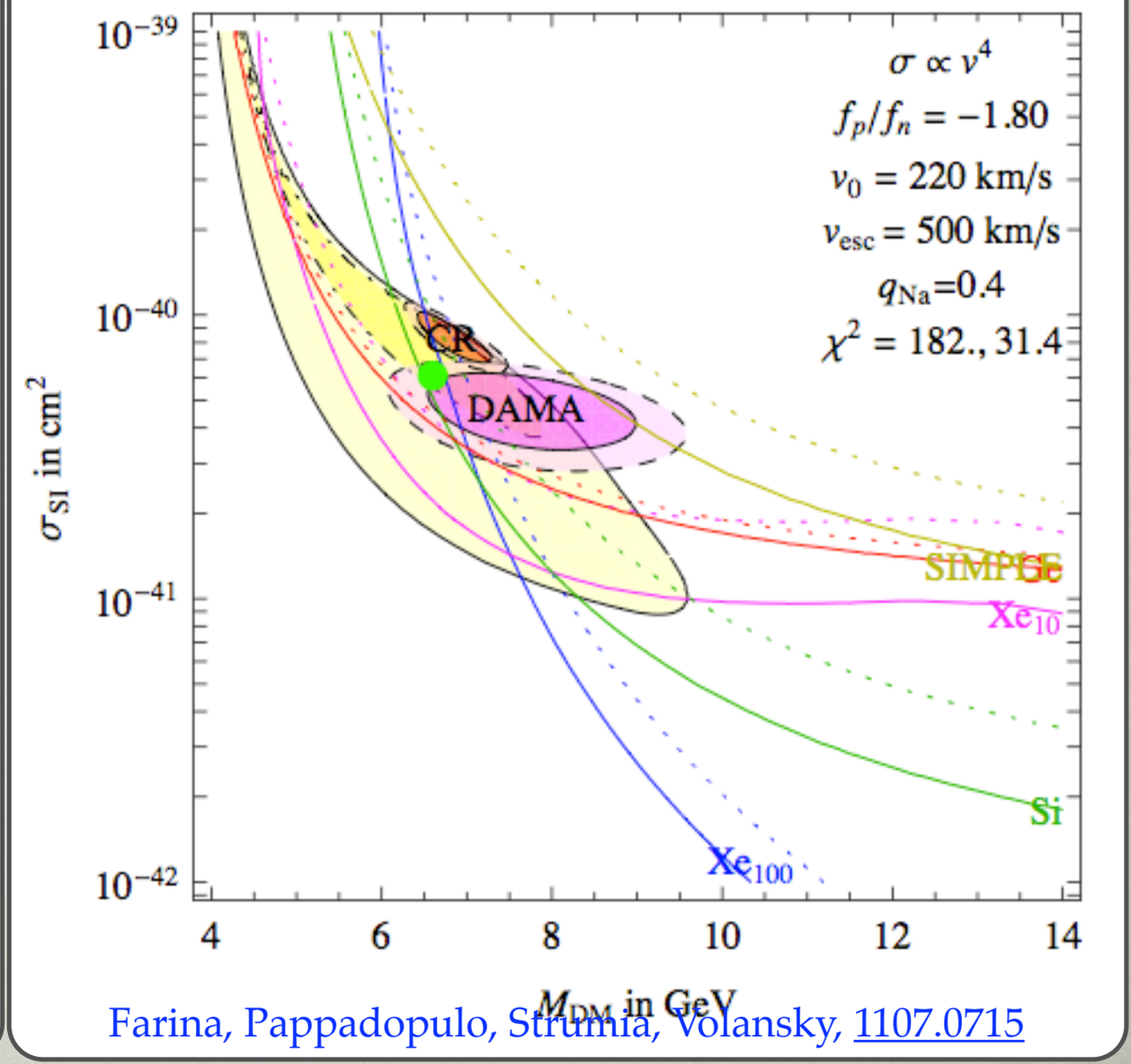



Farina, Pappadopulo, Strumia, Volansky, 1107.0715

# CONCLUSIONS

- none of the DM models fit all the data well
- would be very interesting to see modulation data from CDMS low threshold

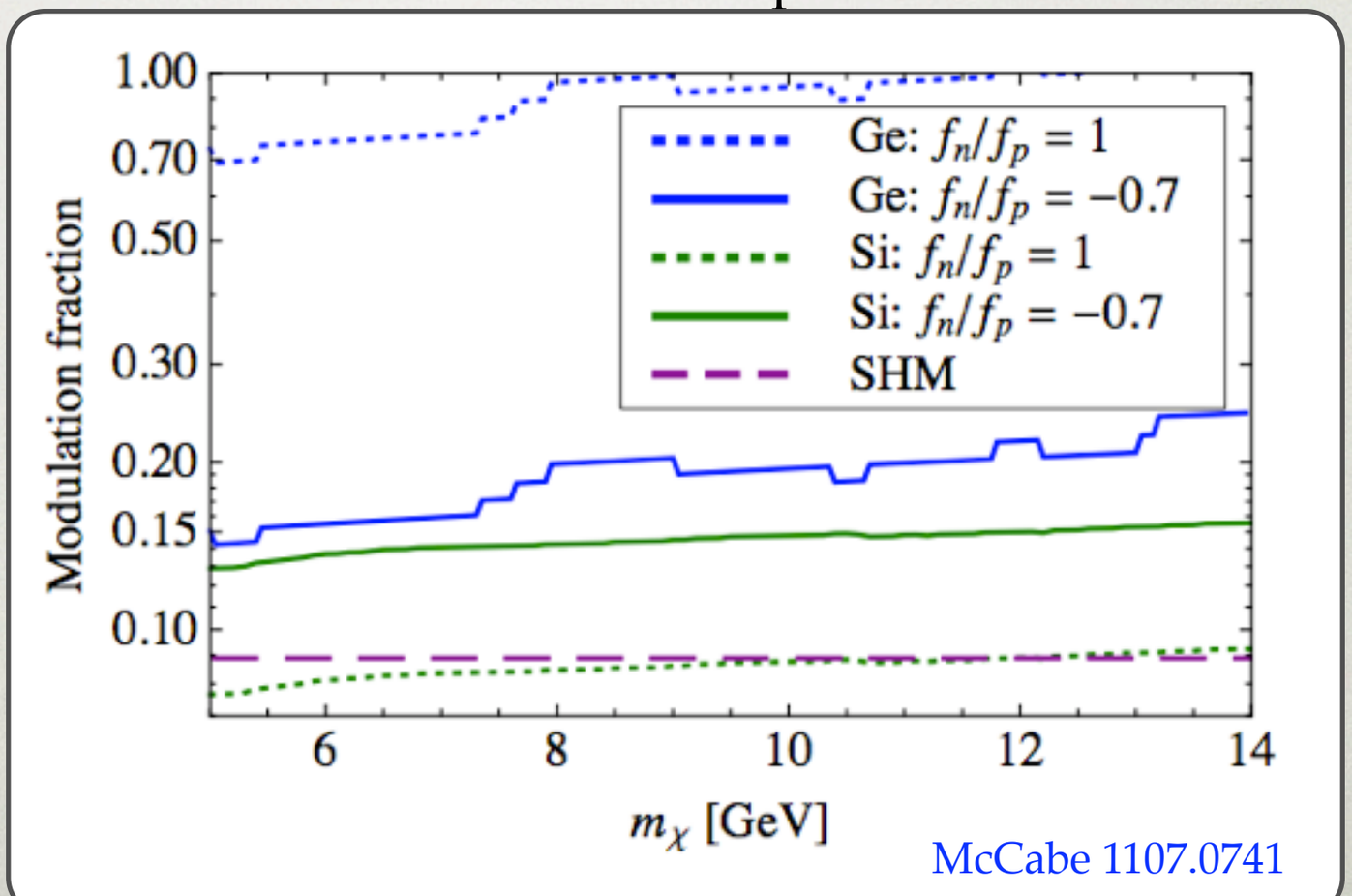
# BACKUP SLIDES

# MORE COMPARING WITH COGENT

- integrating out astrophysical uncertainties can translate CoGeNT modulation rate to other exp.

$$\frac{dR_2}{dE_R}(E_2) = \frac{C_T^{(2)}}{C_T^{(1)}} \frac{F_2^2(E_2)}{F_1^2\left(\frac{\mu_1^2 M_T^{(2)}}{\mu_2^2 M_T^{(1)}} E_2\right)} \frac{dR_1}{dE_R}\left(\frac{\mu_1^2 M_T^{(2)}}{\mu_2^2 M_T^{(1)}} E_2\right)$$

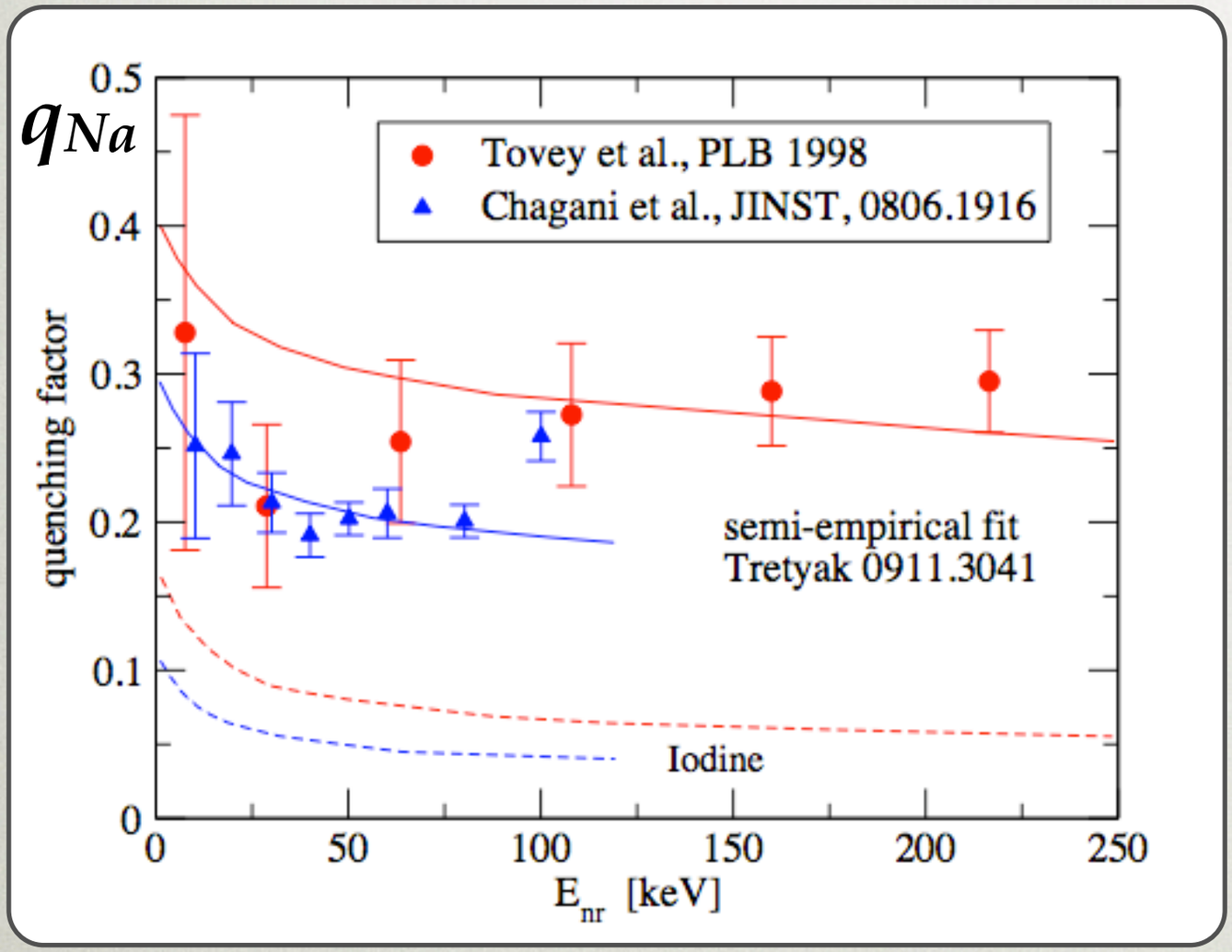
- below required modulation fraction to be compatible with CDMS-Ge and CDMS-Si




McCabe 1107.0741

# QUENHING FACTORS

- How well do we know $q_{Na}$,$L_{eff}$?



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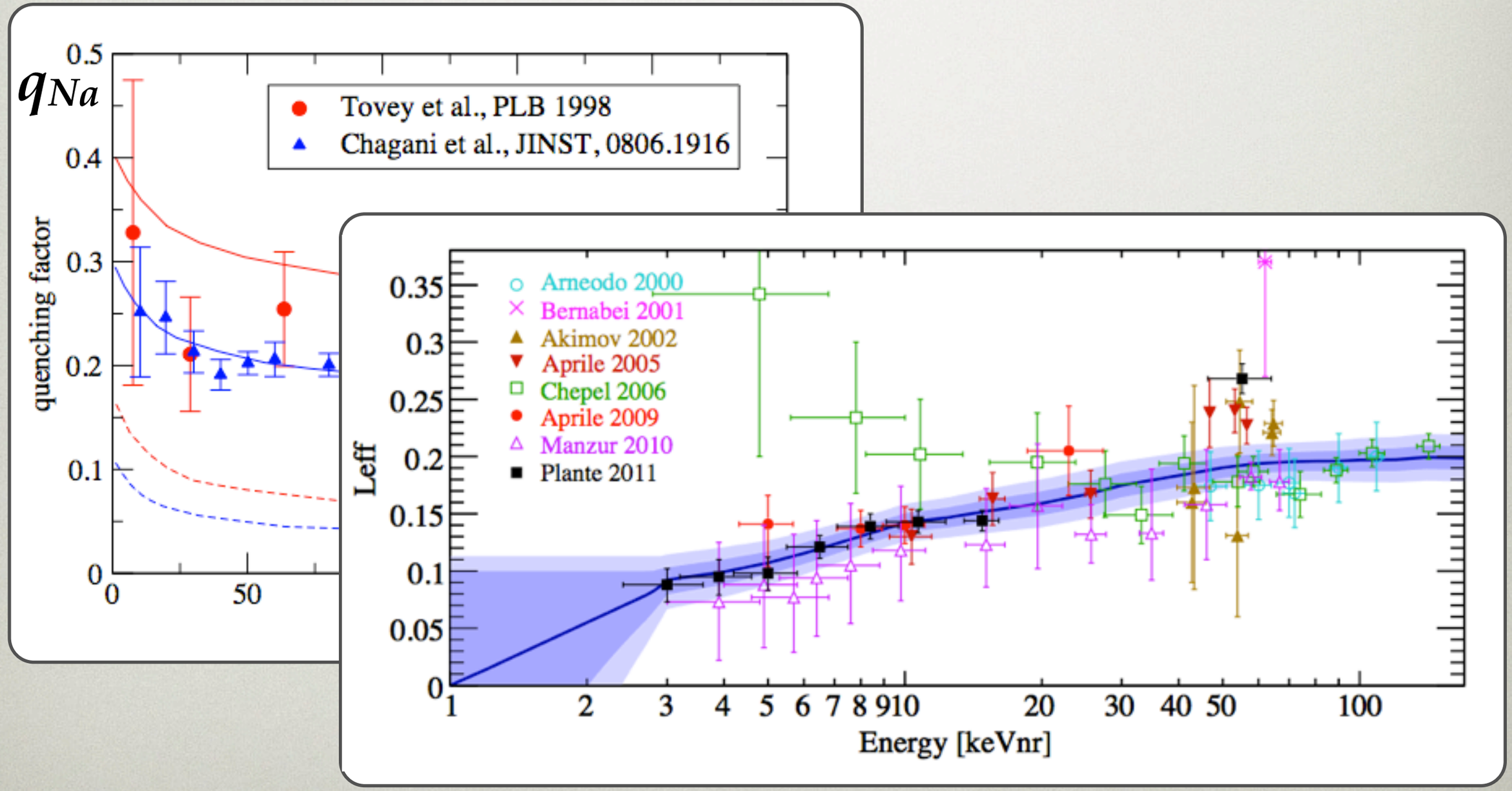


# COMPARING COGENT AND DAMA

- comparison of modulation amplitudes without astrophysical uncert.

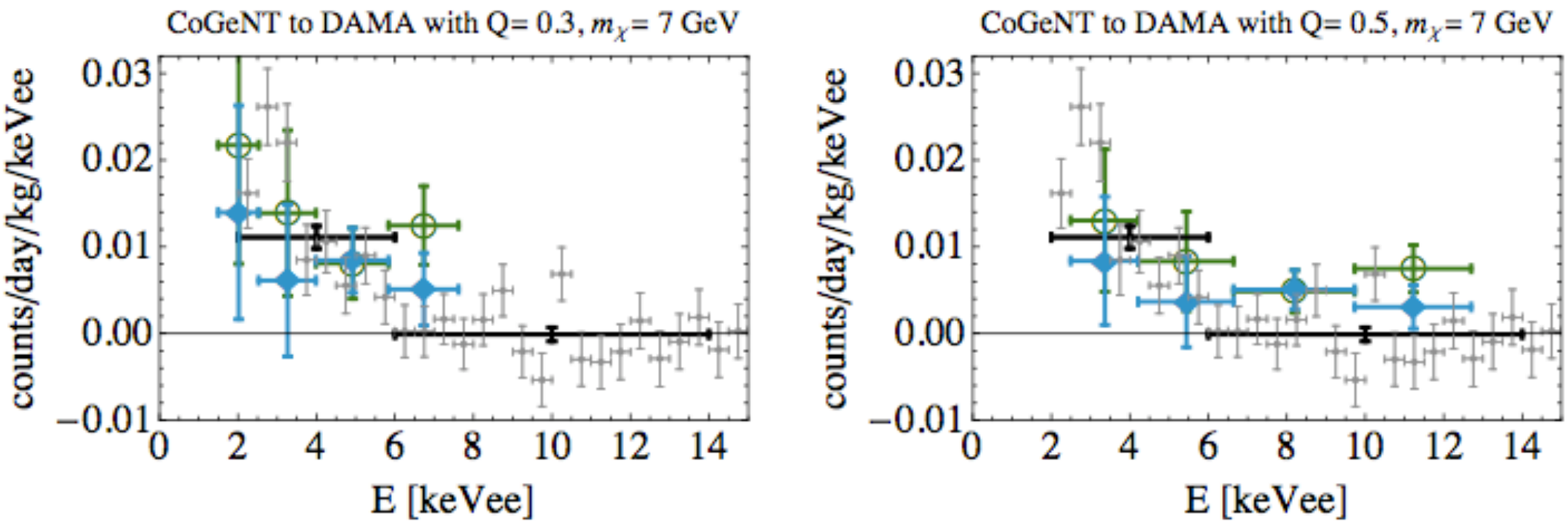
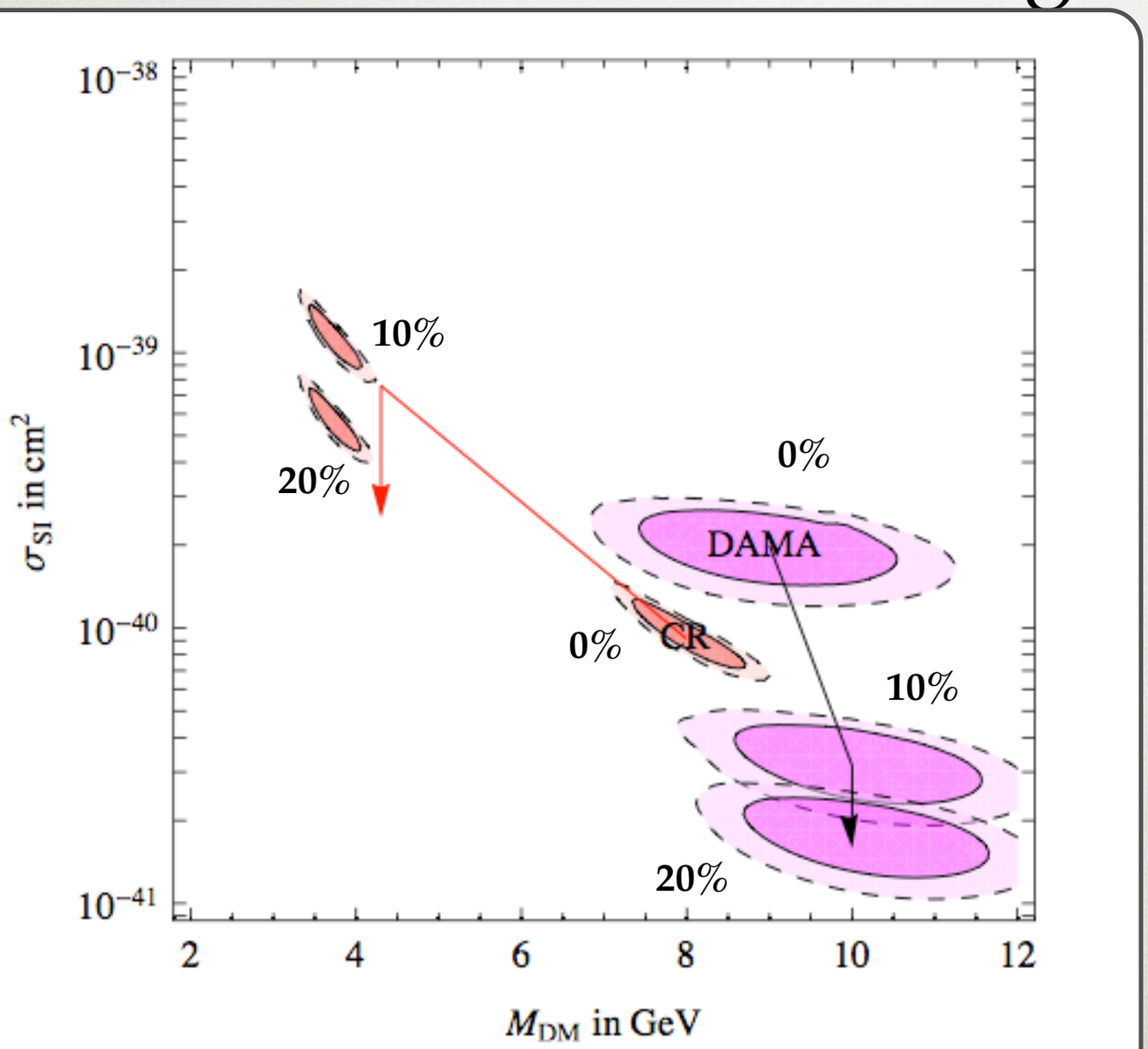



**Figure 14:** Astrophysics independent comparison of CoGeNT and DAMA modulation amplitudes.

# CHANNELING

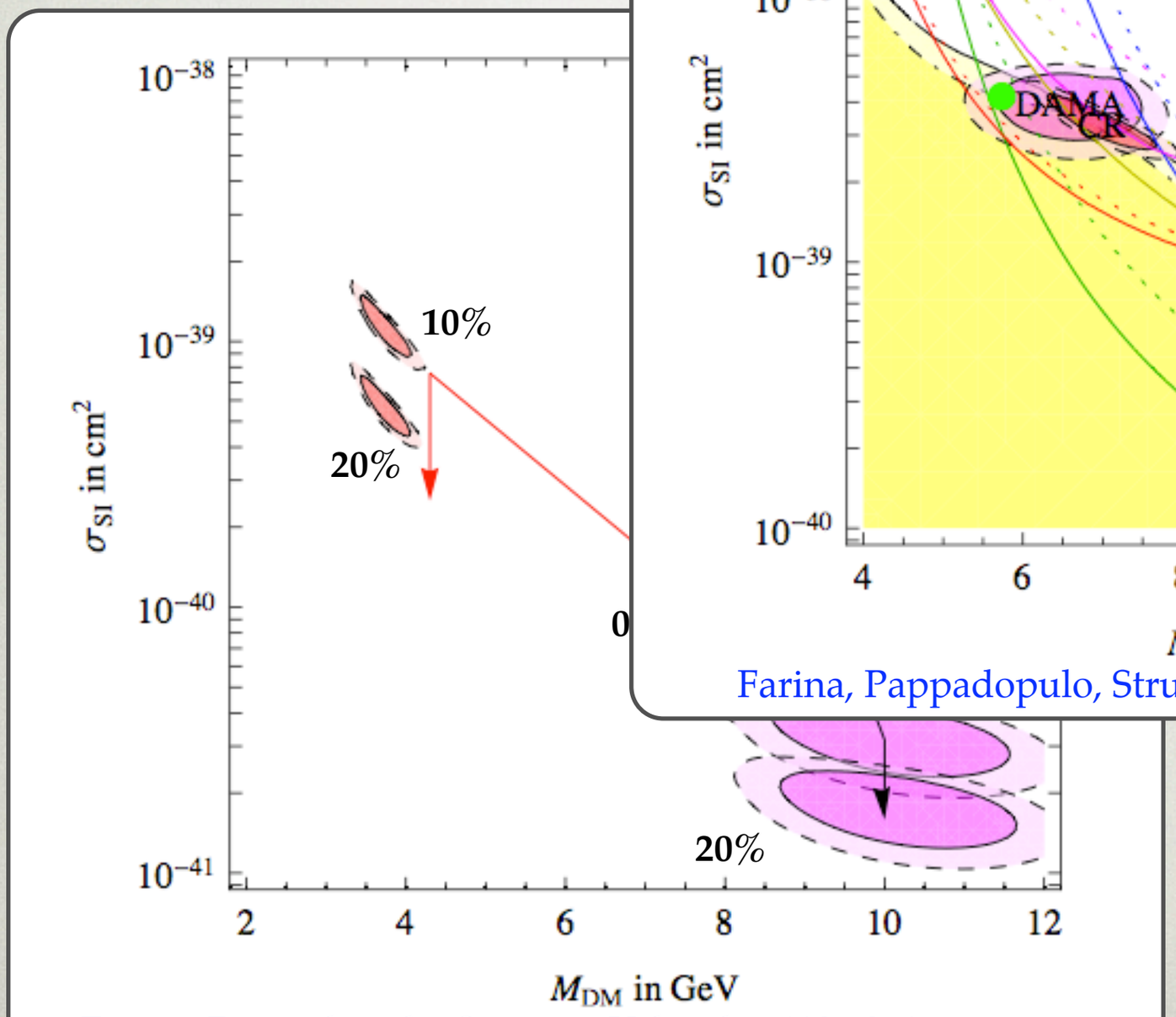
- the effect of channeling




Farina, Pappadopulo, Strumia, Volansky, 1107.0715

# CH

- the effect of

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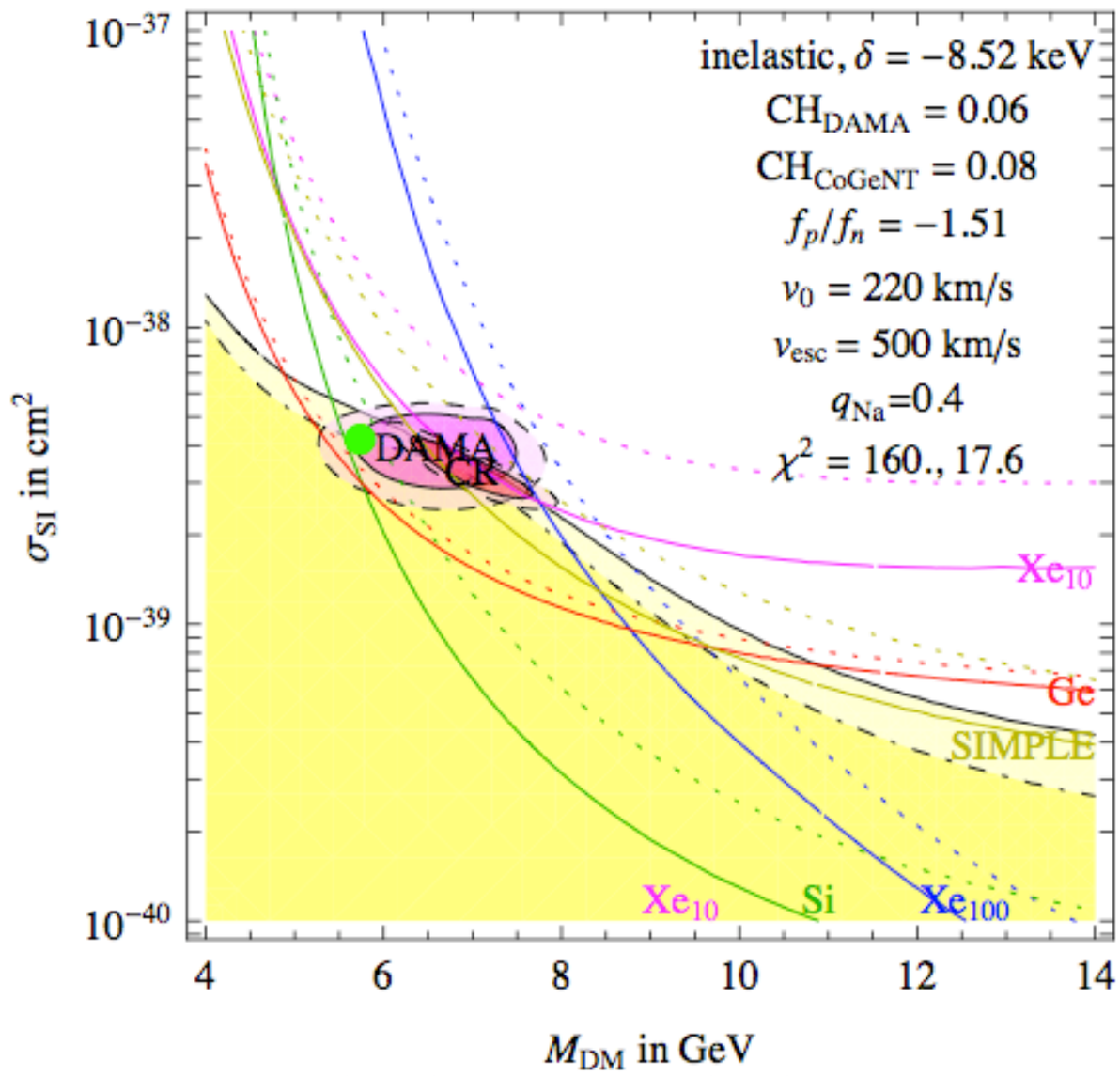


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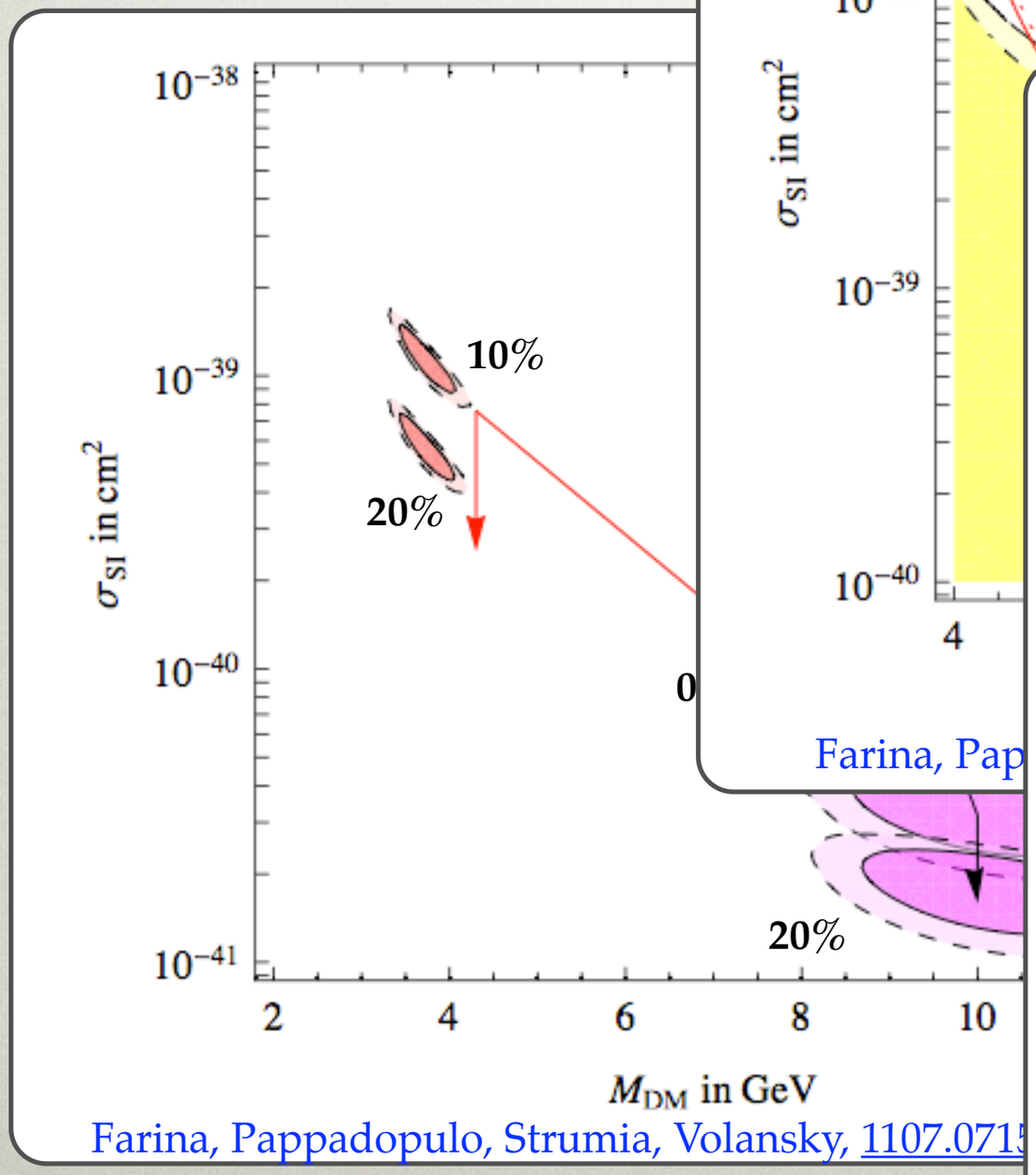


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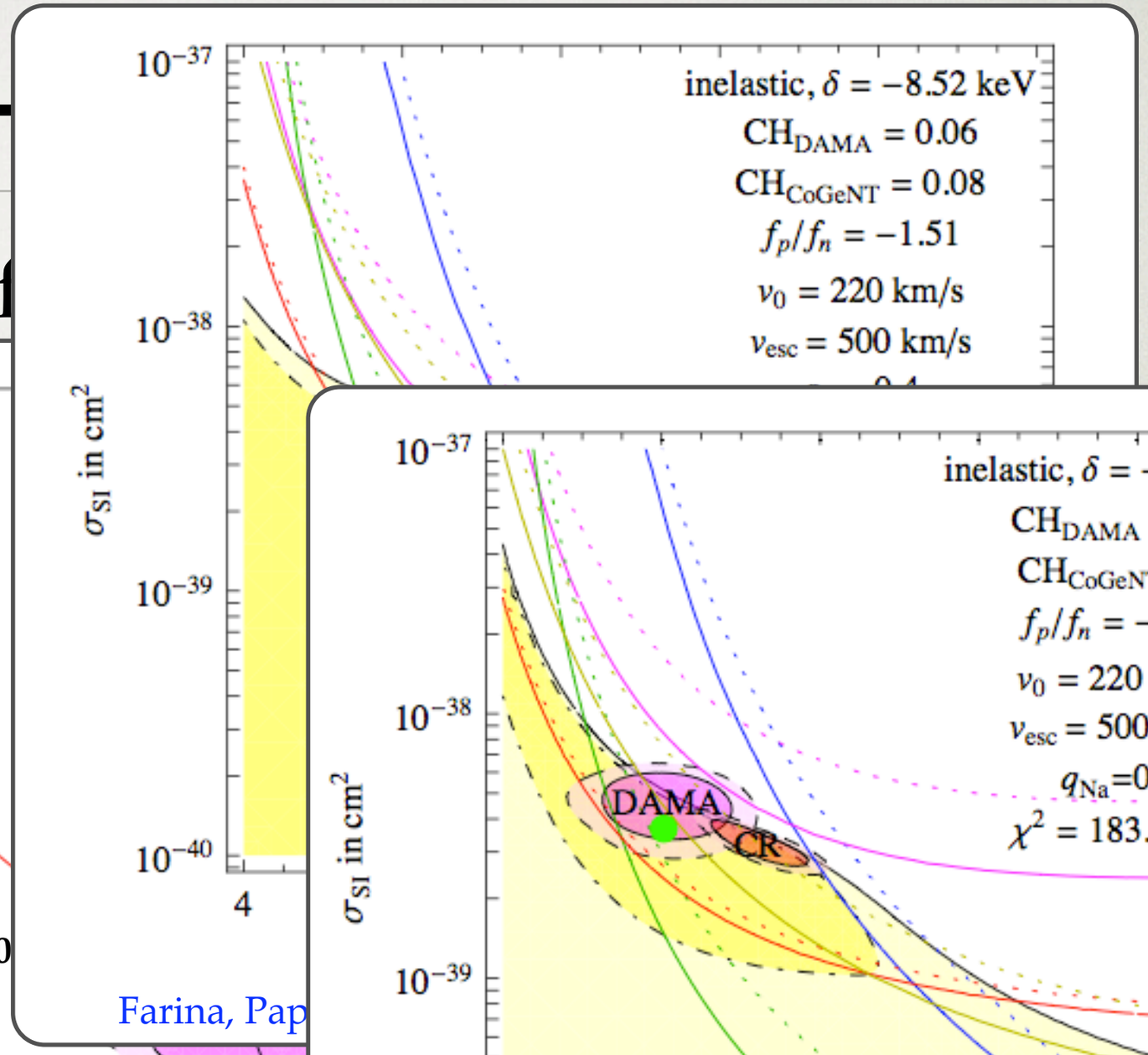


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Farina, Pappadopulo, Strumia, Volansky, 1107.0715