Halo-independent methods for Dark Matter detection

KBFI, Tallinn, Estonia, 23 April 2015

Thomas Schwetz

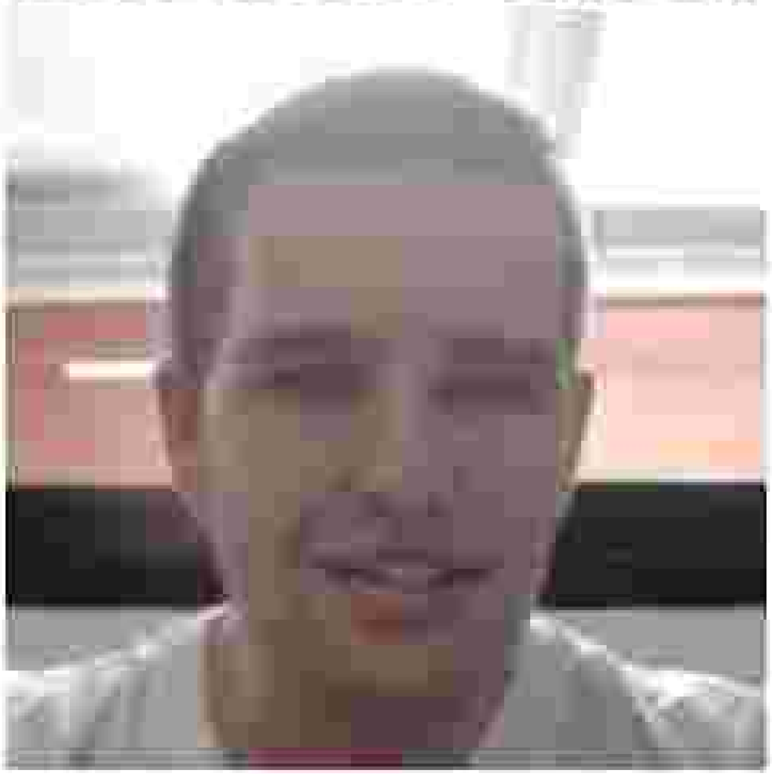
Stockholms universitet

Oskar Klein centre

Halo-independent methods for Dark Matter detection

based on work in collaboration with

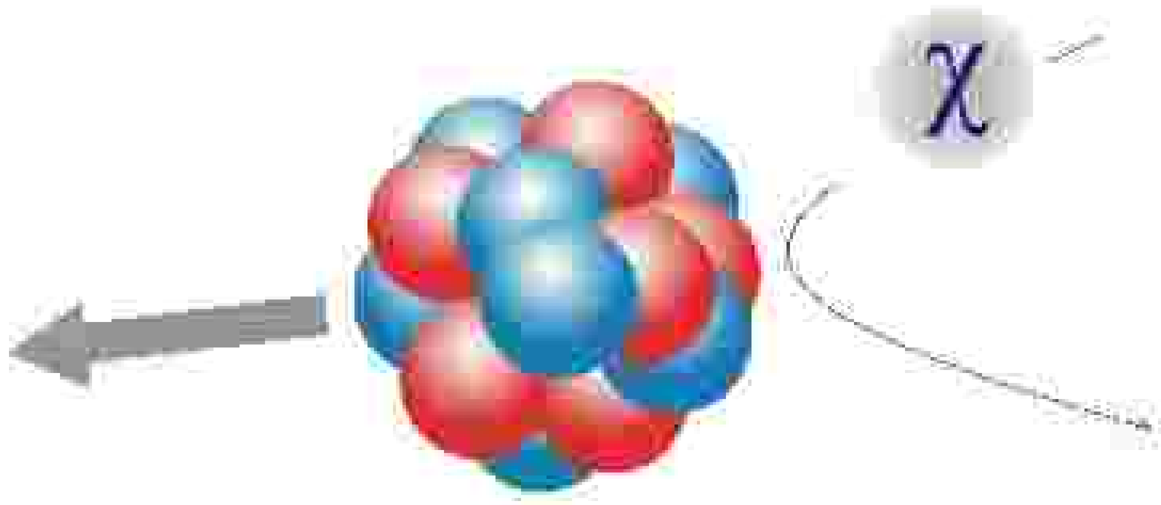
Juan Herrero-Garcia



Nassim Bozorgnia

Jure Zupan

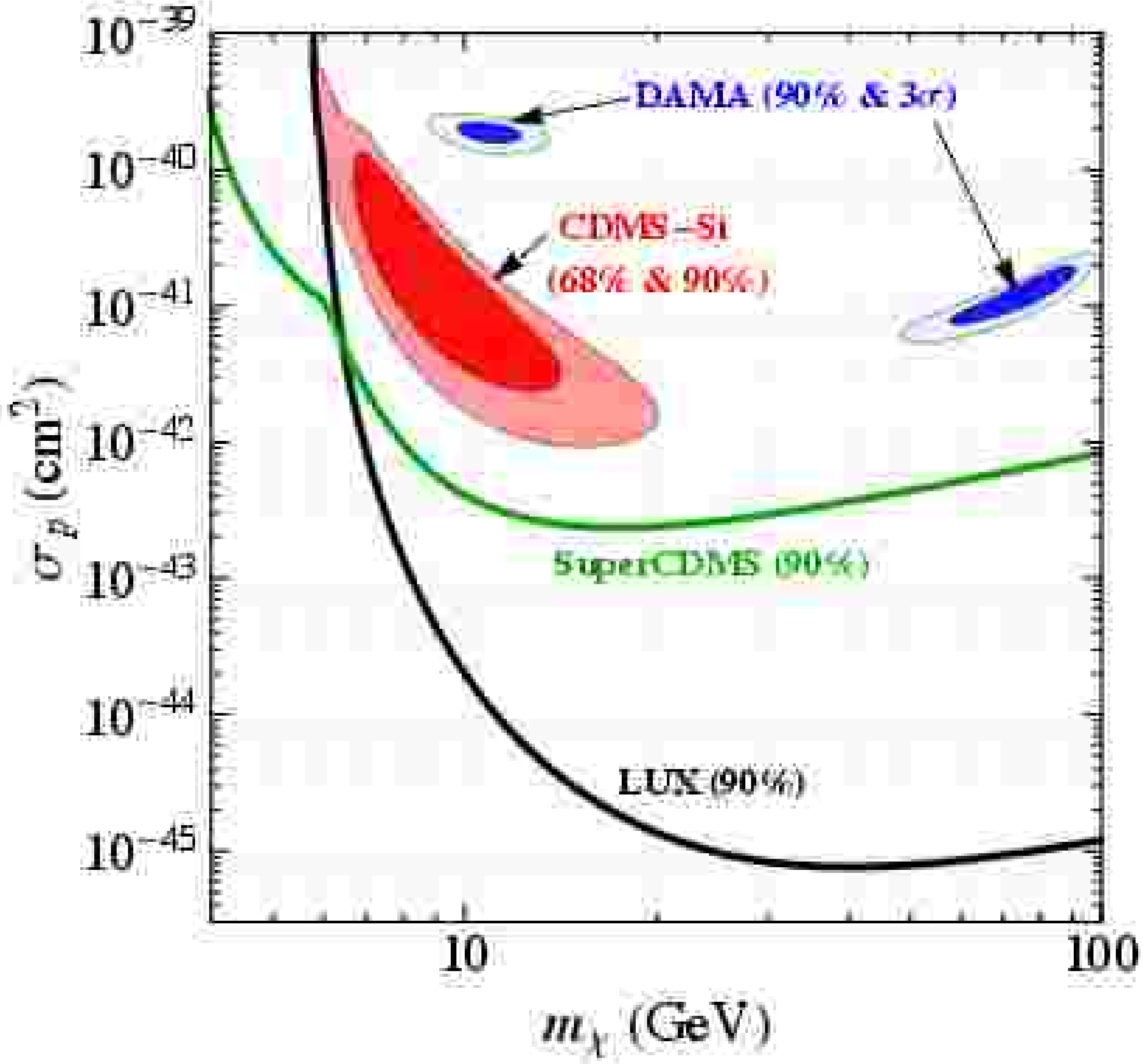
Dark Matter direct detection



Goodman, Witten, 1985

“Signals” versus exclusions

- *DAMA annual modulation at 9 sigma*
- *CDMS-Si: 3 events (exp. backgr. 0.62 ev.)*
- *limits from LUX (Xenon) and SuperCDMS (Ge)*



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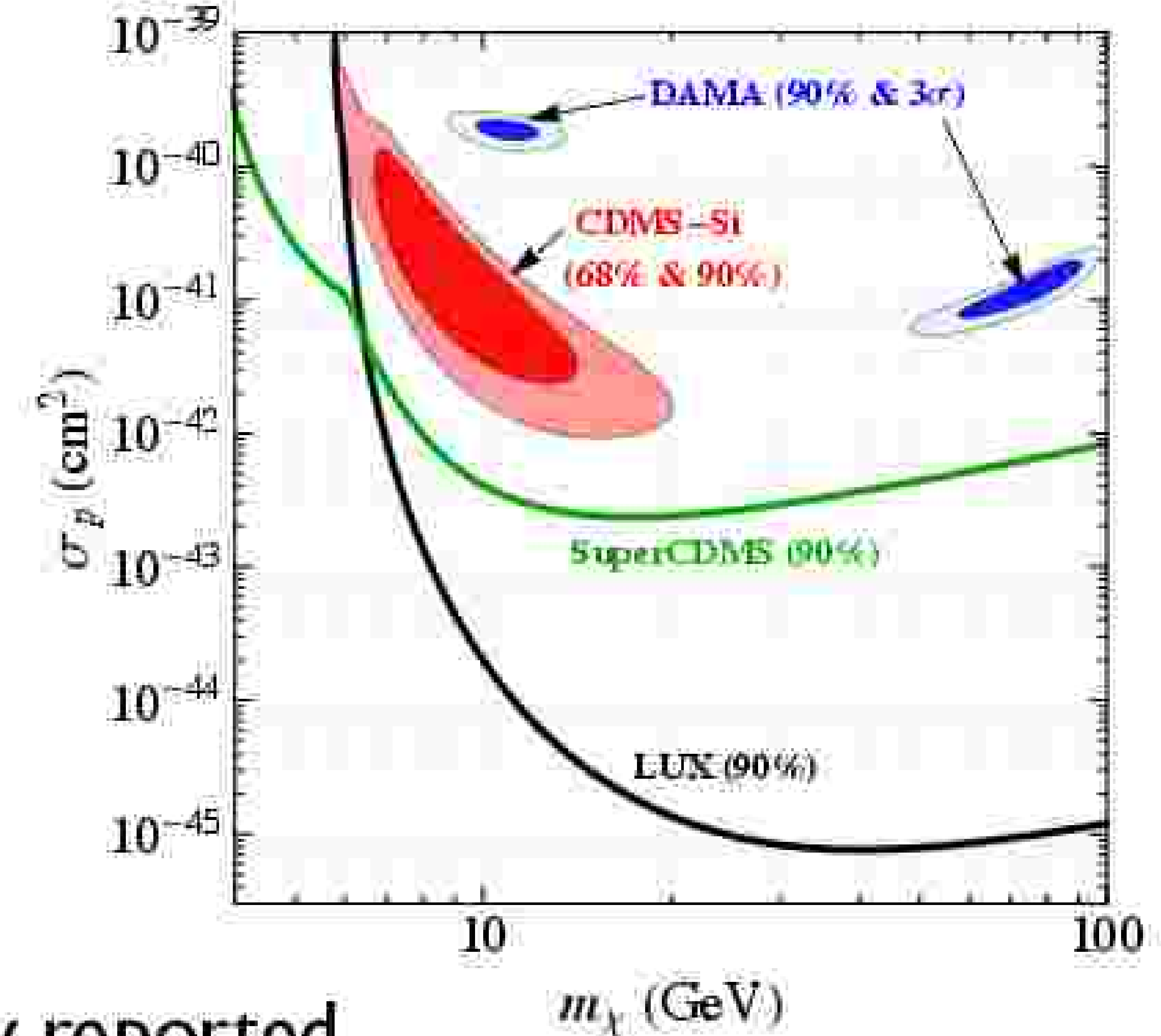

CoGeNT & CRESST: previously reported excesses have been identified as background

Bellis, Collar, Fields, Kelso, talk at Astroparticle 2014, Amsterdam also: Aalseth et al., 1401.6234; Davis, McCabe, Boehm, 1405.0495; Angloher et al., 1407.3146

"Signals" versus exclusions

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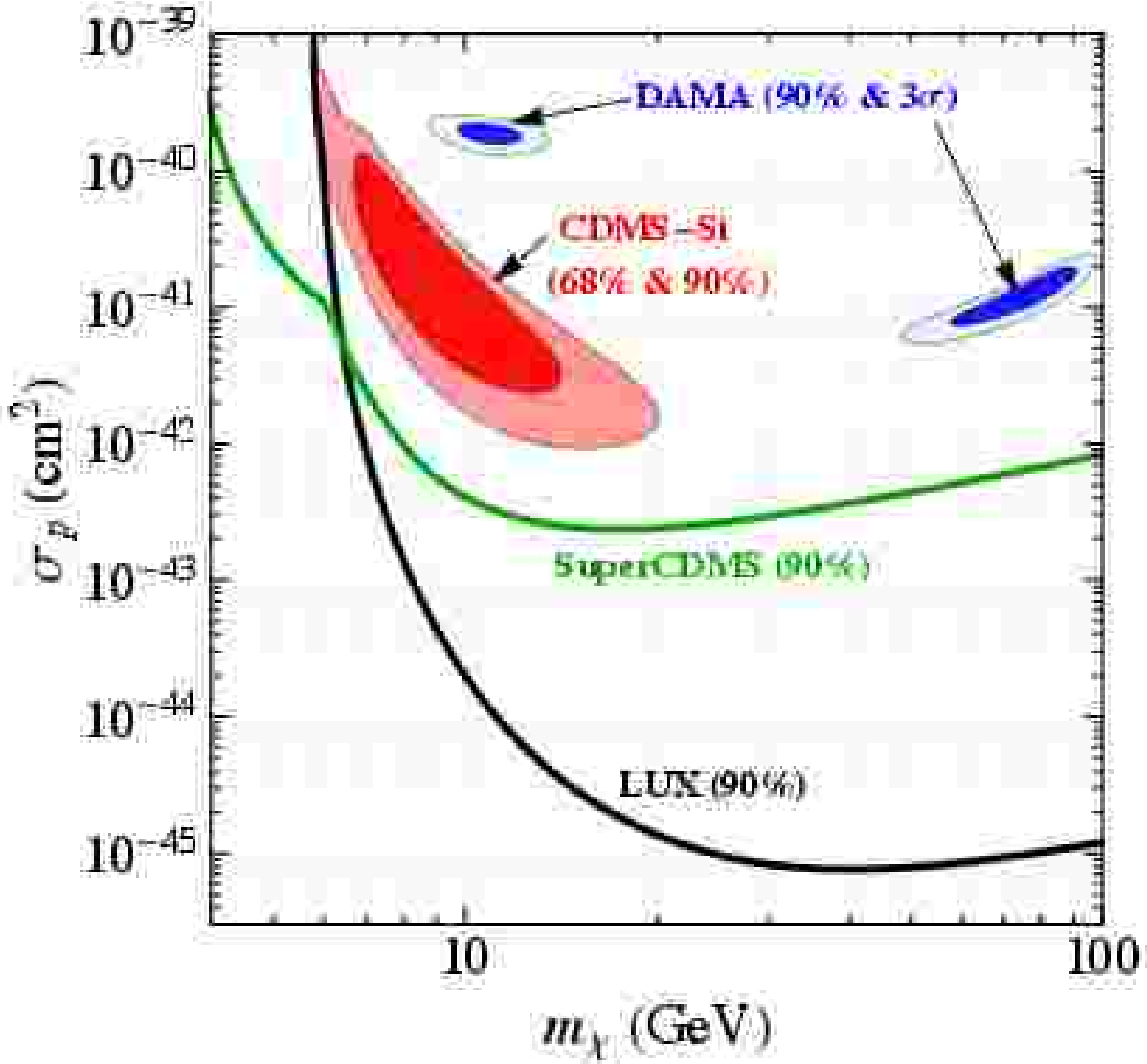


assume particle physics model (SI interactions)
assume "standard halo model"

Outline

- *Halo-independent comparison of direct detection experiments*
- *Upper bound on the annual modulation signal*
- *Halo-independent comparison of DM direct detection experiments and neutrinos from DM annihilation in the Sun*

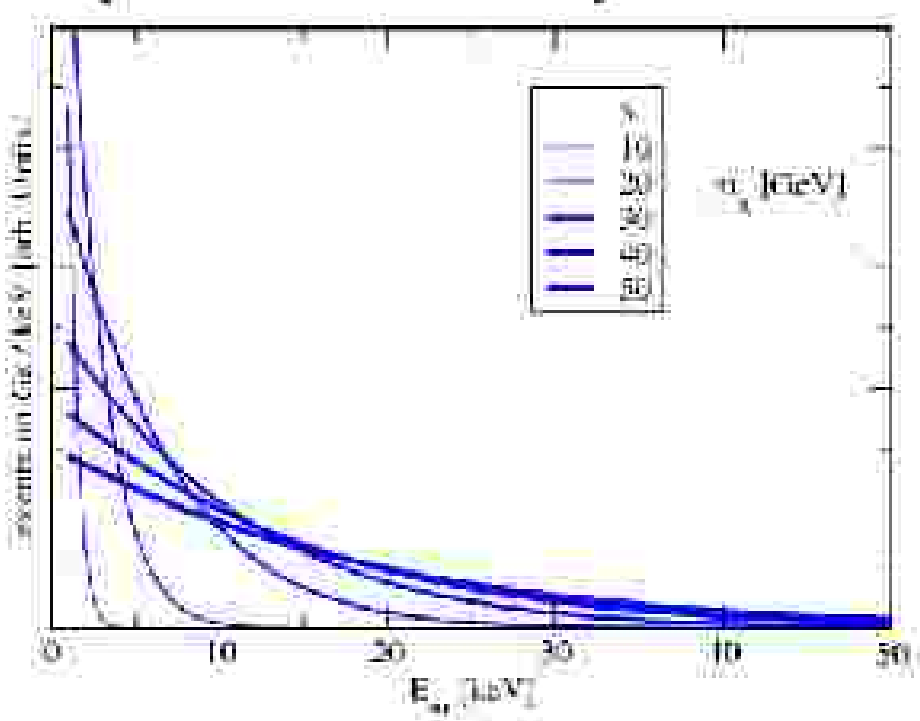
Direct detection - signature

events / keV :

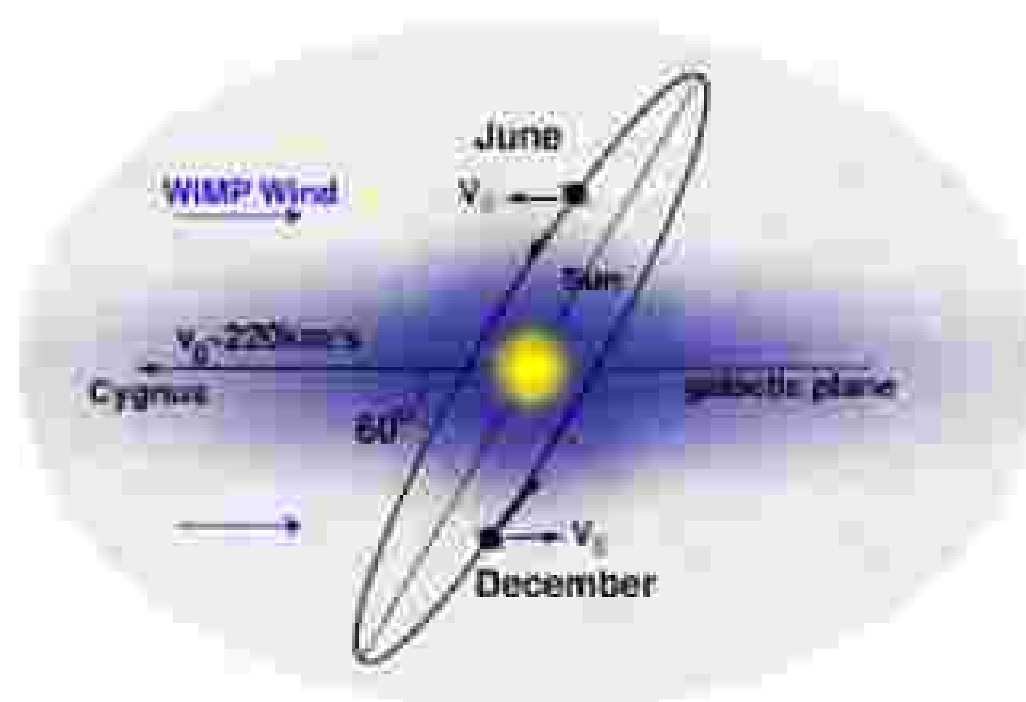
$$\frac{dN}{dE_R} \propto \frac{\rho_{\rm DM}}{m_{\rm DM}} \int_{v>v_{\rm min}} d^3v \frac{d\sigma}{dE_R} v f_\oplus(\vec{v},t)$$

$$f_\oplus(\vec{v},t) = f(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t))$$

exponential spectrum



annual modulation



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ex.: SI contact interaction, equal couplings to neutron and proton:

$$\frac{d\sigma}{dE_R} = \frac{m_A \sigma^p A^2}{2\mu_{\chi p}^2 v^2} F_A^2(E_R)$$

Event rates in DD experiments

One can define the halo integral as

$$\eta(v_m, t) \equiv \int_{v>v_m} d^3v \frac{f_{\rm det}(\mathbf{v}, t)}{v}, \qquad (3.5)$$

where $f_{\rm det}(\mathbf{v}, t)$ is the DM velocity distribution in the detector rest frame. Then the event rate can be written as

$$R(E_{nr}, t) = \frac{A^2 \sigma_p \rho_\chi}{2 m_\chi \mu_{\chi p}^2} F^2(E_{nr}) \eta(v_m, t). \qquad (3.6)$$

The halo integral $\eta(v_m, t)$ parametrizes the astrophysics dependence of the event rate.

minimal velocity required to give nuclear recoil energy E_{nr}

$$v_m = \sqrt{\frac{m_A E_{nr}}{2\mu_{\chi A}^2}},$$

What is the DM velocity distribution in the galaxy?

What is the DM velocity distribution in the galaxy?

my daughters answer (age of 6)

What is the DM velocity distribution in the galaxy?

Aquarius N-body simulation

What is the DM velocity distribution in the galaxy?

spherical cow approximation:

Truncated Maxwellian distribution:

$$f_{\rm gal}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

$$\bar{v} \simeq 220\,{\rm km/s} \qquad v_{\rm esc} \simeq 550\,{\rm km/s}$$

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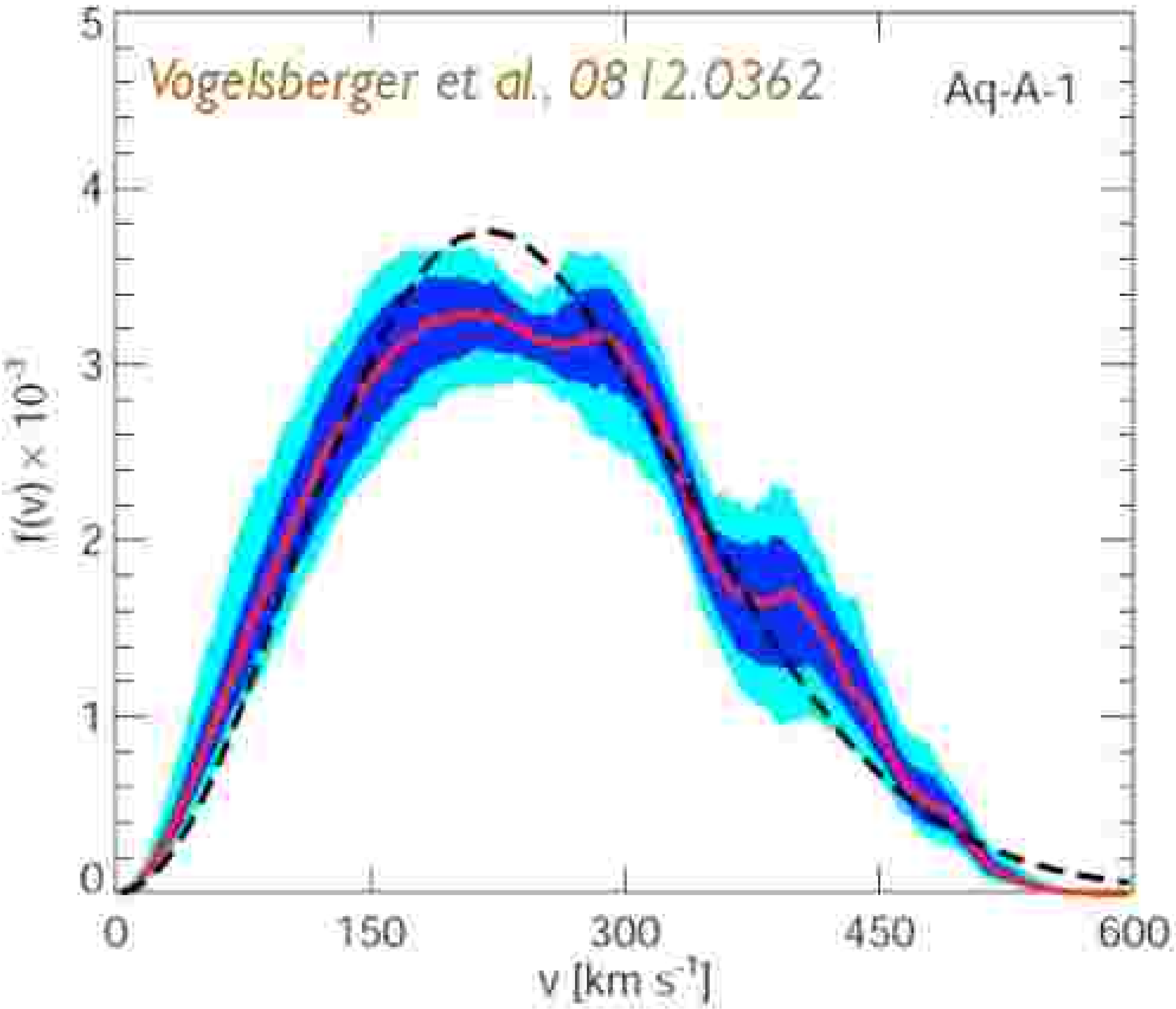
Most likely too simplistic:

- *expect smooth (virialized) and un-virialized (streams, debris flows) components*
- *the smooth component will most-likely not be Maxwellian expect different dispersions in radial and tangential directions*

Velocity distribution from N-body simulations



Halo-independent comparison of experiments

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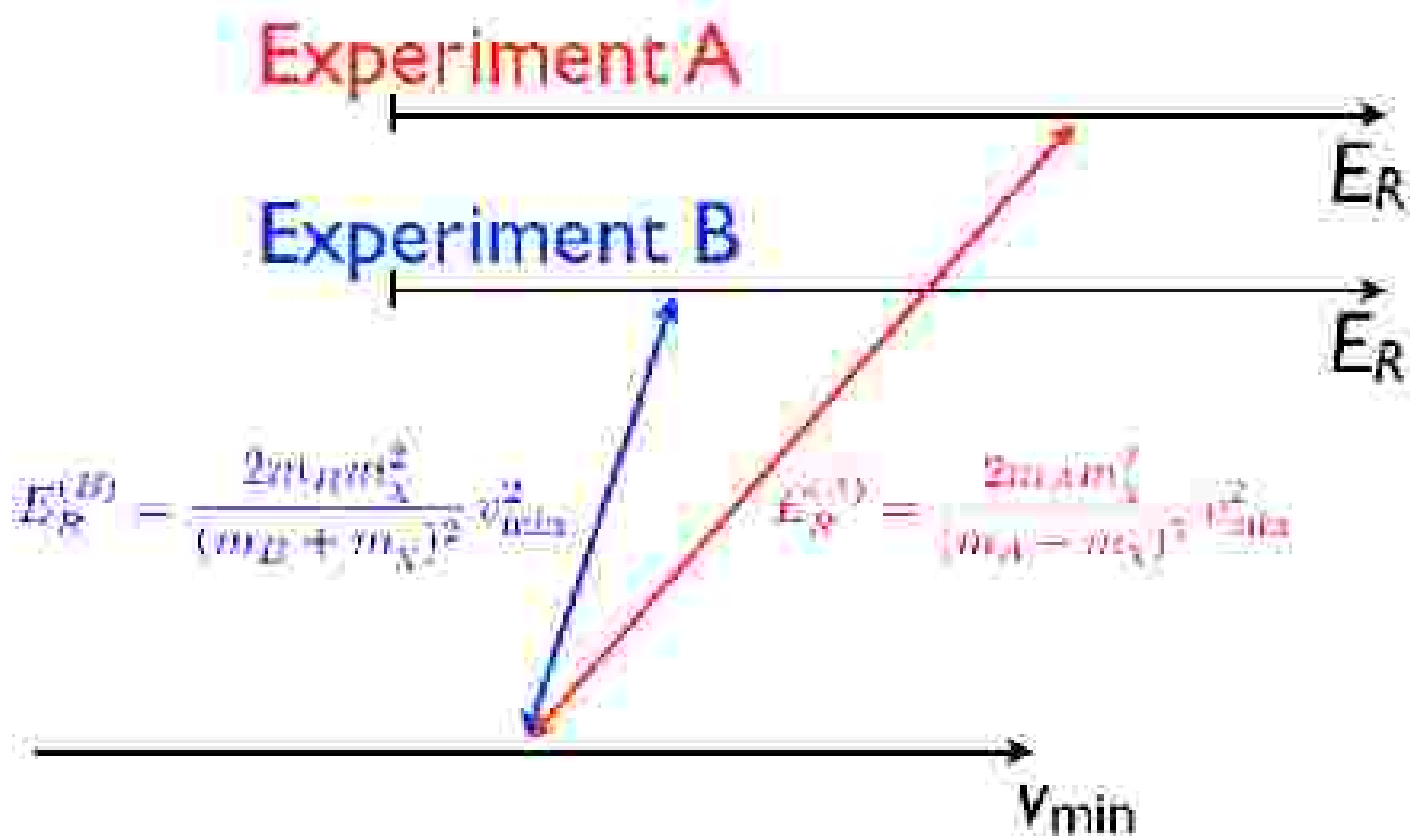
DM-halo independent comparison of experiments

$$\frac{2m_\chi \mu_{\chi p}^2}{A^2 \sigma_p} \frac{R(E_{nr},t)}{F^2(E_{nr})} = \rho_\chi \eta(v_m, t) \qquad v_m = \sqrt{\frac{m_A E_{nr}}{2\mu_{\chi A}^2}},$$

independent of experiment



Fox, Kribs, Tait 1011.1910
Fox, Liu, Weiner, 1011.1915

Upper bound on halo integral

$$N^{\text{pred}}_{[E_1,E_2]} = MTA^2 \int_0^\infty dE_{nr} F^2(E_{nr}) G_{[E_1,E_2]}(E_{nr}) \tilde{\eta}(v_m)$$

$\eta(v_m)$ is a decreasing function, step-function gives smallest number of events

$$N^{\text{pred}}_{[E_1,E_2]} > \mu(v_m) = MTA^2 \tilde{\eta}(v_m) \int_0^{E(v_m)} dE_{nr} F_A^2(E_{nr}) G_{[E_1,E_2]}(E_{nr}). \qquad (4.1)$$

Let μ_{CL} be the solution of the following equation for μ:

observed # events (e.g. zero events in LUX)

$$e^{-\mu} \sum_{n=0}^{N^{\text{obs}}} \frac{\mu^n}{n!} = 1 - \text{CL}.$$

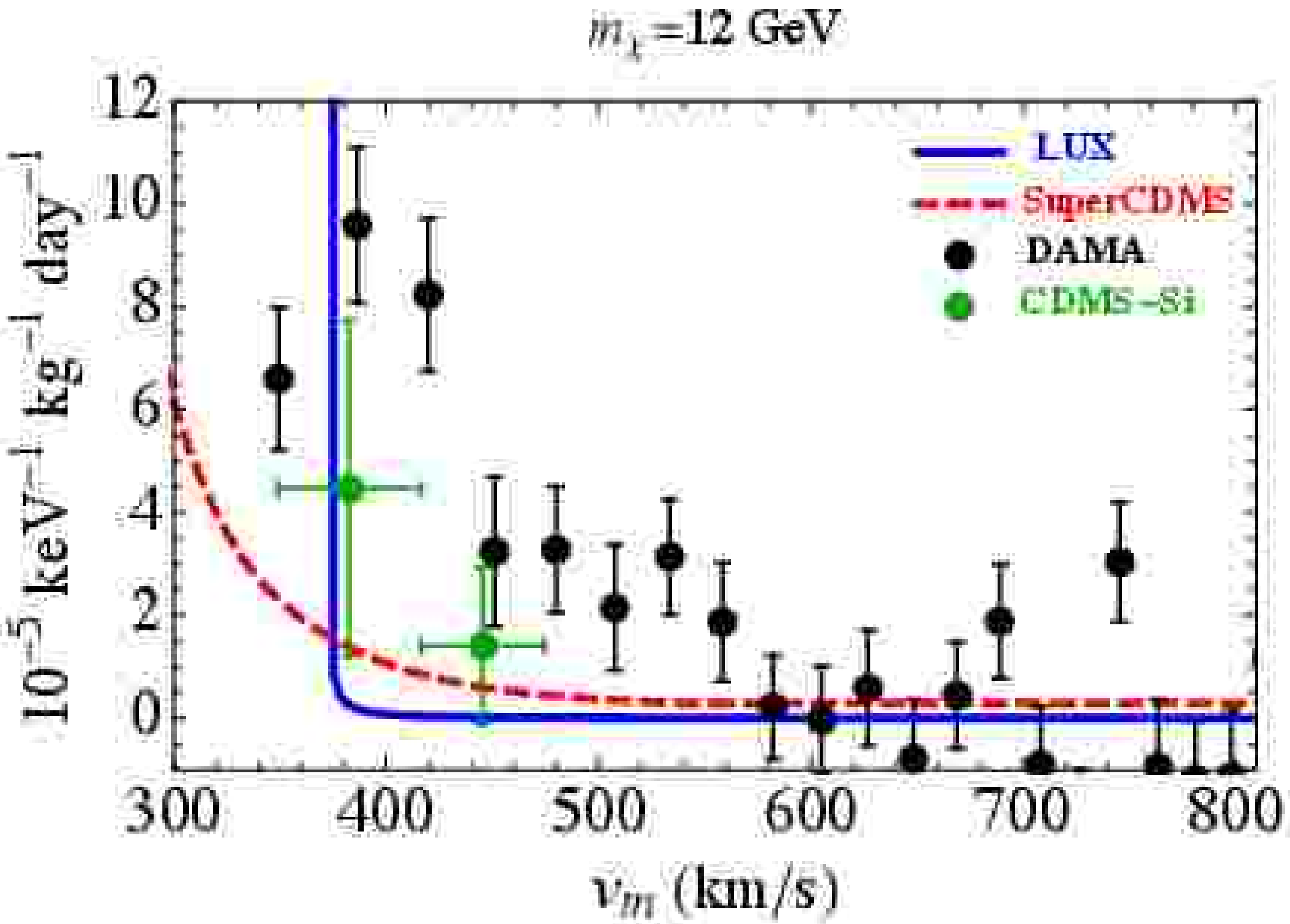
Then an upper bound on $\tilde{\eta}(v_m)$ at the confidence level CL is obtained from Eq. (4.1)

$$\tilde{\eta}_{\text{bnd}}(v_m) = \frac{\mu_{\text{CL}}}{MTA^2 \int_0^{E(v_m)} dE_{nr} F_A^2(E_{nr}) G_{[E_1,E_2]}(E_{nr})}.$$

Compare bound to positive signal

obs. # events expected background

$$\langle \tilde{\eta}(v_m^i) \rangle = \frac{N_i^{\rm obs} - \beta_i}{MTA^2 \int_0^{E(v_m)} dE_{nr} F_A^2(E_{nr}) G_i(E_{nr})}.$$



Bozorgnia, Schwetz, 1410.6160

s. also delNobil, Feldstein, Fox, Frandsen, Gelmini, Gondolo, Kahlhöfer, Harnik, McCabe, Sarkar, ...

Joint probability of pos (A) and neg (B) signals

derive bound on $\eta(v_m)$ from exp B at CL = 1 - p_B
gives an upper bound on the expected signal in exp A

$$N^{\text{bnd},A}_{[E_1,E_2]} = MTA^2 \int_0^\infty dE_{nr} F^2(E_{nr}) G_{[E_1,E_2]}(E_{nr}) \tilde{\eta}^B_{\text{bnd}}(v_m).$$

$$\mu^A_{\text{bnd}} = N^{\text{bnd},A}_{[E_1,E_2]} + \beta^A_{[E_1,E_2]}.$$

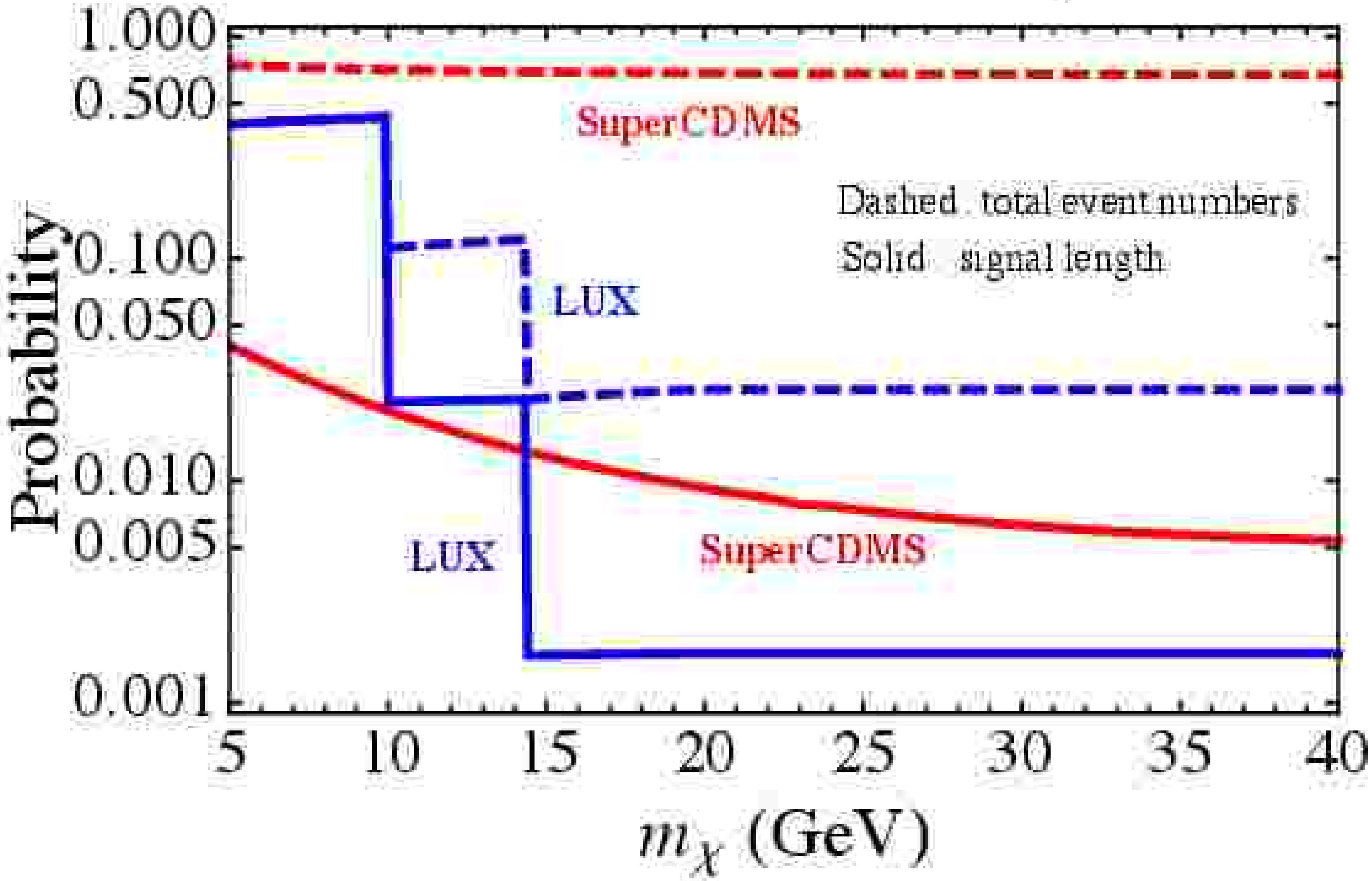
prob. to obtain N^{obs} events in exp A given the bound:

$$p_A = e^{-\mu^A_{\text{bnd}}} \sum_{n=N^{\text{obs},A}}^{\infty} \frac{(\mu^A_{\text{bnd}})^n}{n!}.$$

joint probability: $$p_{\text{joint}} = \max_{p_B} \left[p_A(p_B)\, p_B\right]$$

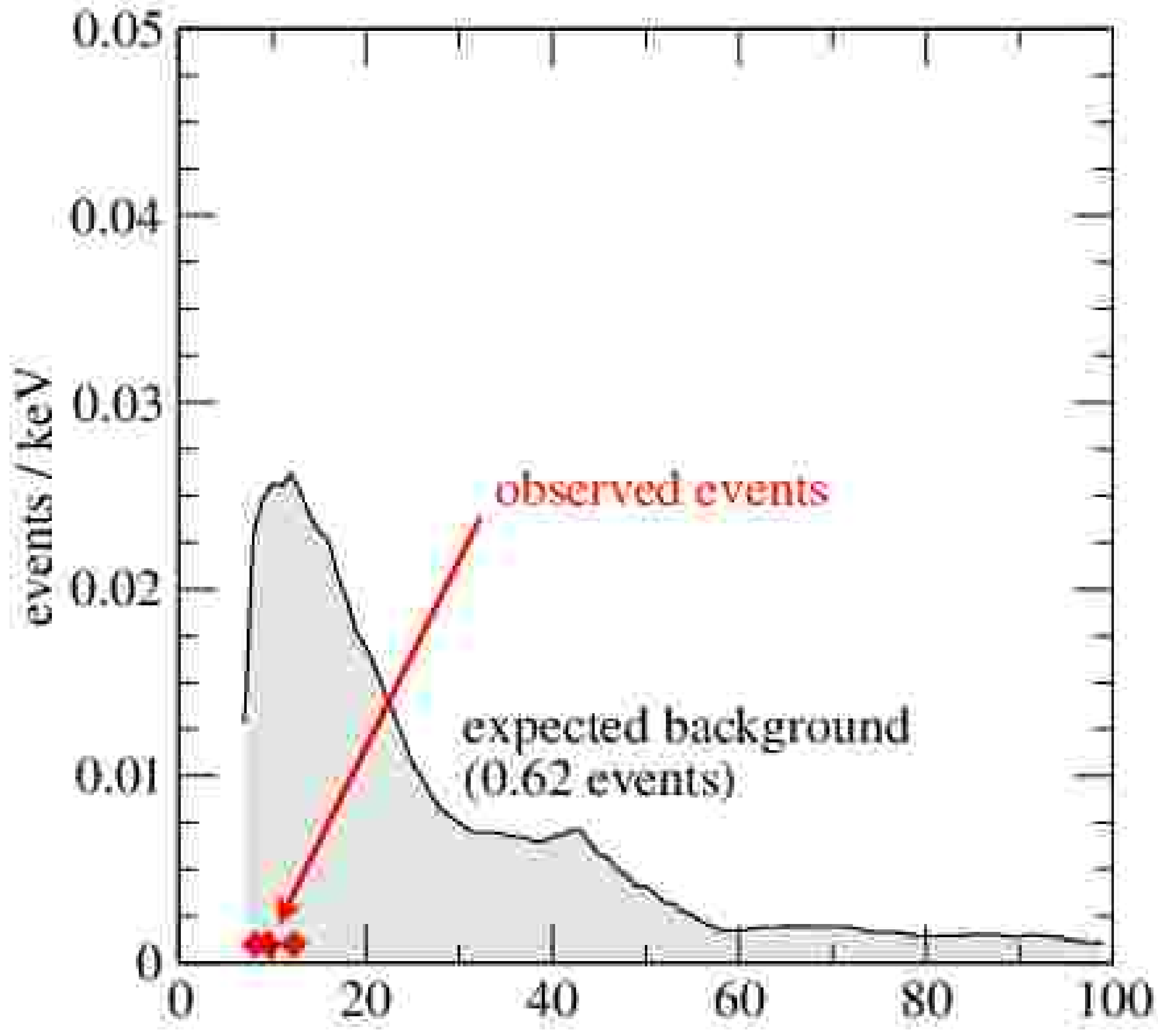
Joint probability of pos (A) and neg (B) signals

CDMS-Si vs LUX or SuperCDMS

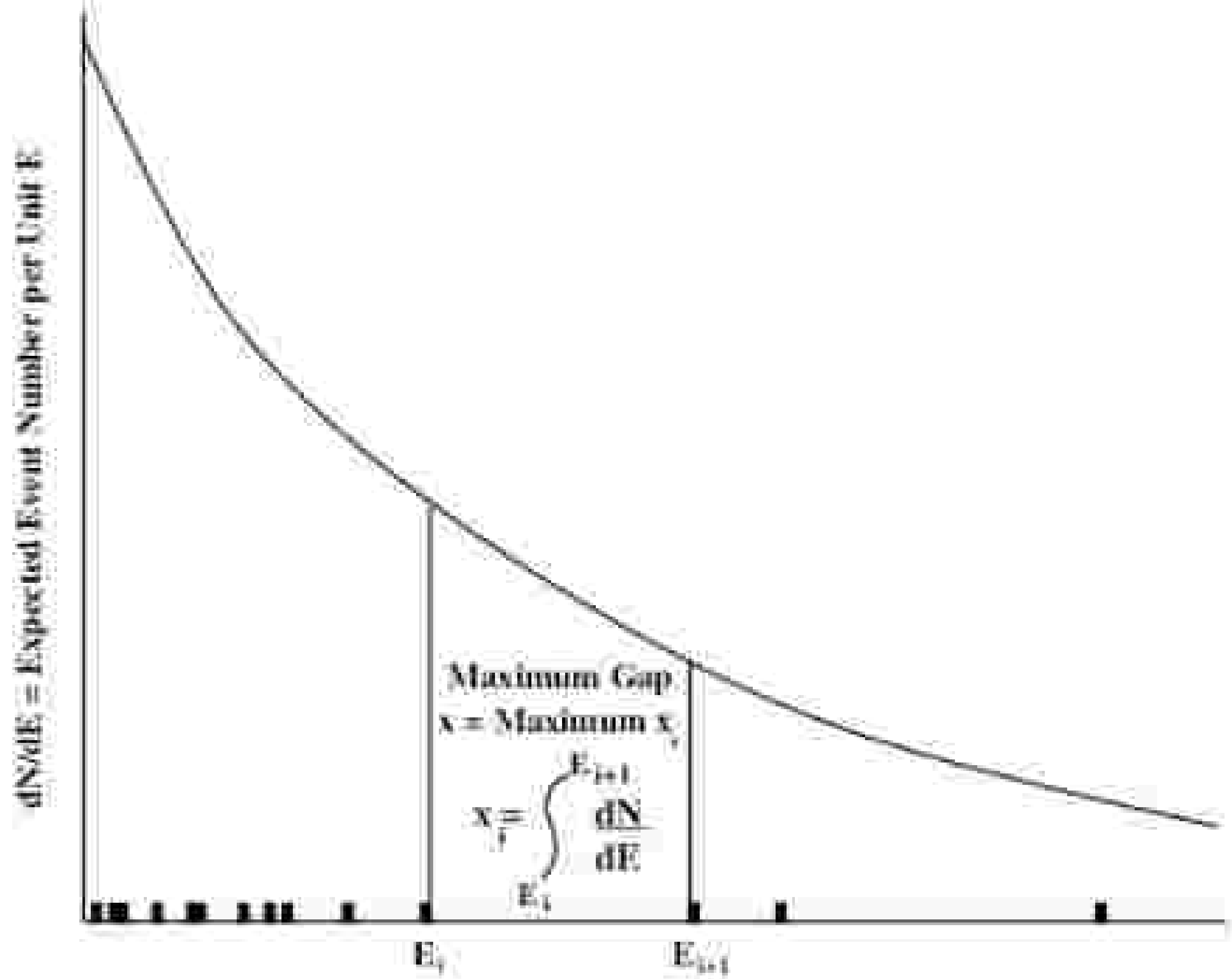


dashed curves: using only total event number gives only weak constraint

Taking into account energy information



Maximum gap method to set upper limit



Yellin, physics/0203002

Signal length method Bozorgnia Schwetz 1410.6160

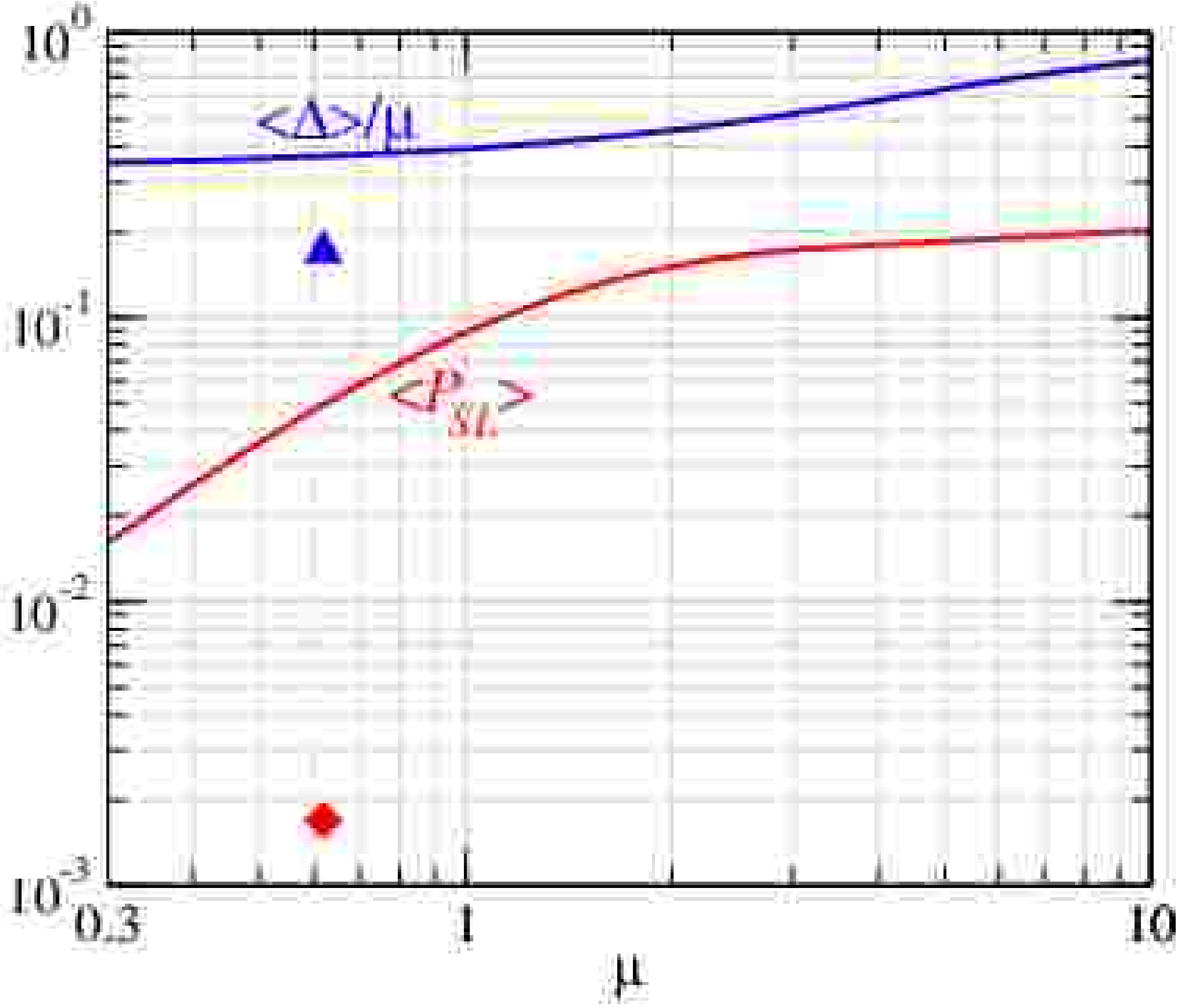
define "signal length":

$\Delta \equiv$ expected number of events in the energy interval between the two events with the lowest and highest energy.

for given Poisson mean μ consider probability to obtain equal or more events than obs. &
a signal length Δ equal or smaller than observed:

$$P_{\rm SL}(N^{\rm obs}, \Delta|\mu) = e^{-\mu} \sum_{n=N^{\rm obs}}^{\infty} \frac{1}{n!}[n\mu\Delta^{n-1} - (n-1)\Delta^n]$$

Expectation for P_{SL}



If for given data P_{SL} comes out much smaller than ~0.2 this experimental outcome is quite unlikely under the assumed hypothesis.

Comparison of SL and ML for CDMS-Si

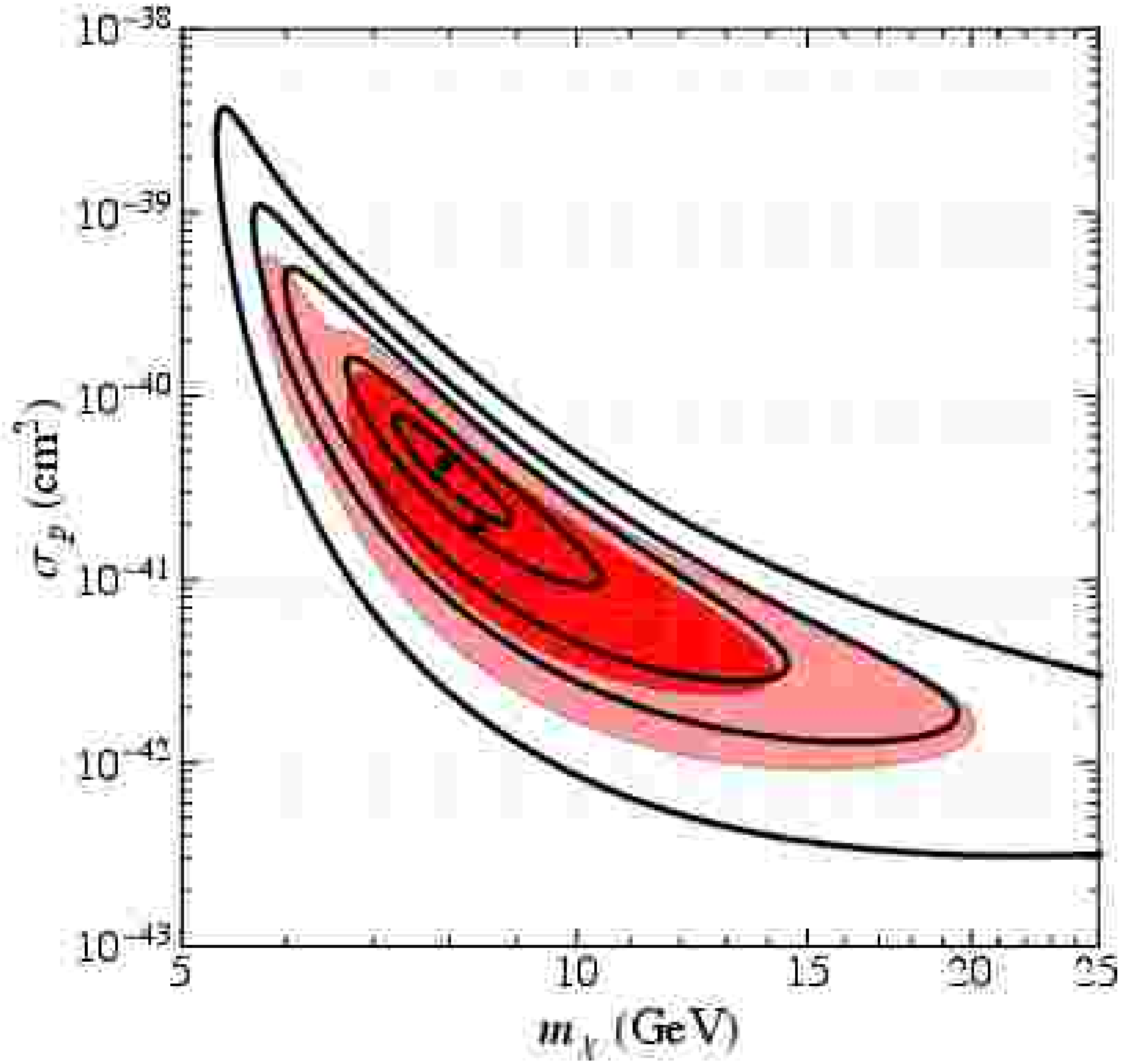


Figure 5. Regions in the plane of DM mass and scattering cross section from CDMS-Si data assuming the so-called standard halo model. The black curves show equal probability contours using the signal length method corresponding to $P_{\rm SL} = 0.01, 0.05, 0.1, 0.2, 0.25$, from outer to inner contours. The black dot indicates the point of highest probability. The shaded regions (black triangle) correspond to 68% and 90% CL regions (best fit point) using an extended maximum likelihood analysis.

The SL method

- *provides a goodness-of-fit test for a specified hypothesis in the case of very few events (but at least 2)*
- *does not require binning*
- *pdf has to be specified*
- *energy information is condensed into two numbers:* μ *and* Δ
- *not very useful for "many" events*

Can use SL also if only a bound is available for the hypothesis to be tested

maximize P_{SL} over allowed range for Δ and μ

$$b \le \Delta \le \Delta_{\rm bnd},$$

$$\mu_{\rm lo}(\Delta) \le \mu \le \mu_{\rm bnd},$$

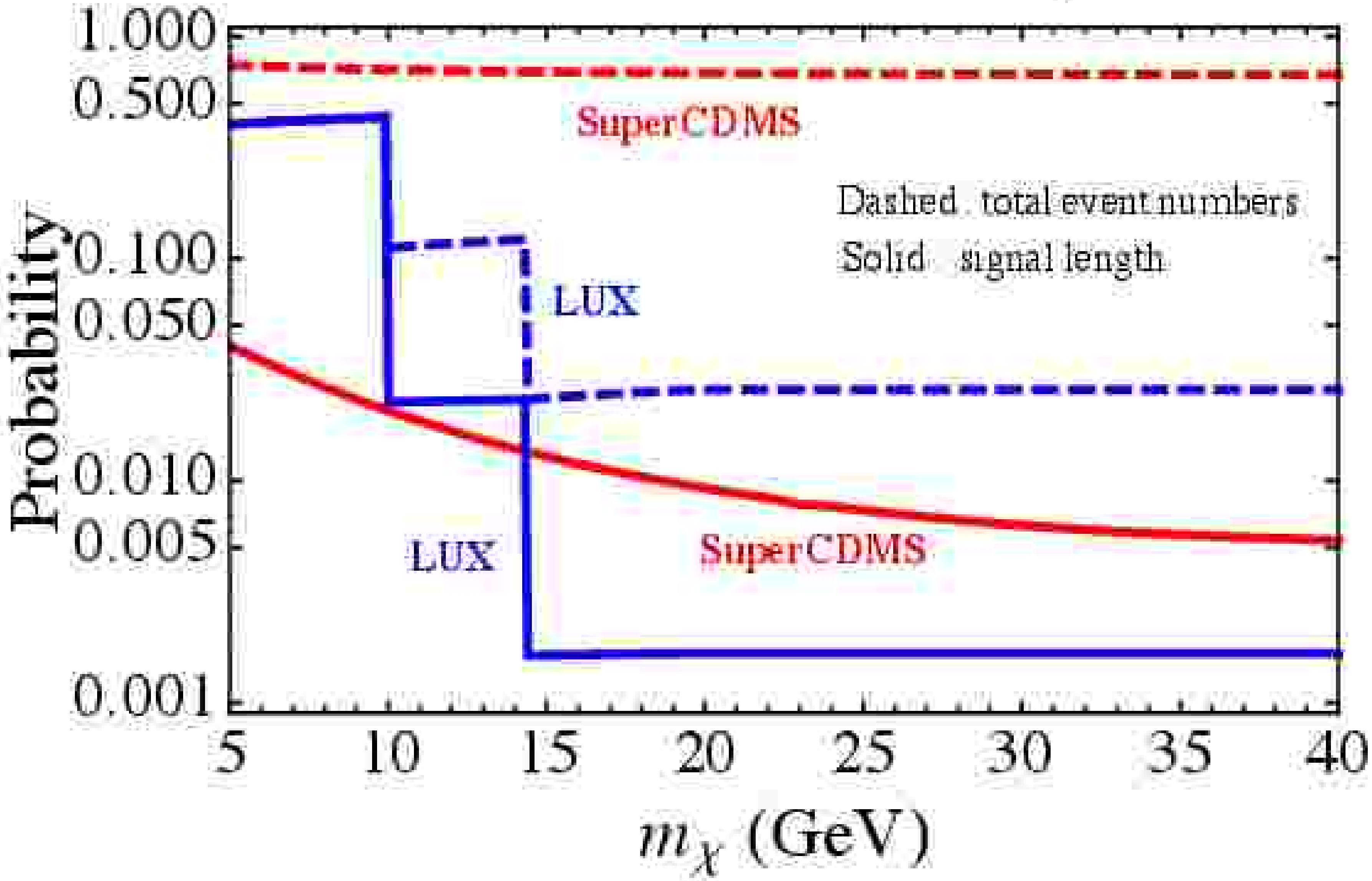
upper bound provided by null-result experiment

maximum joint probability:

$$p_{\rm joint} = \max_{p_B} \left[P_{\rm SL}(N^{\rm obs}, \Delta_{\rm bnd} | \mu_{\max})\; p_B \right]$$

Joint probability of pos (A) and neg (B) signals

CDMS-Si vs LUX or SuperCDMS



solid curves: using energy information via SL method leads to much stronger tension

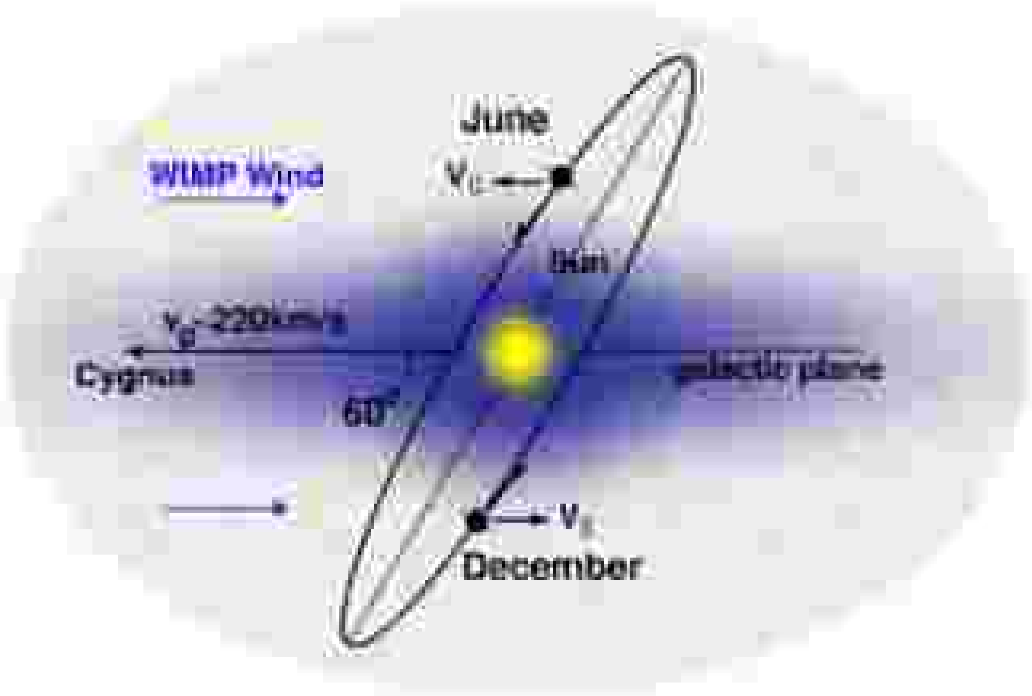
Method of Feldstein & Kahlhöfer

1409.5446

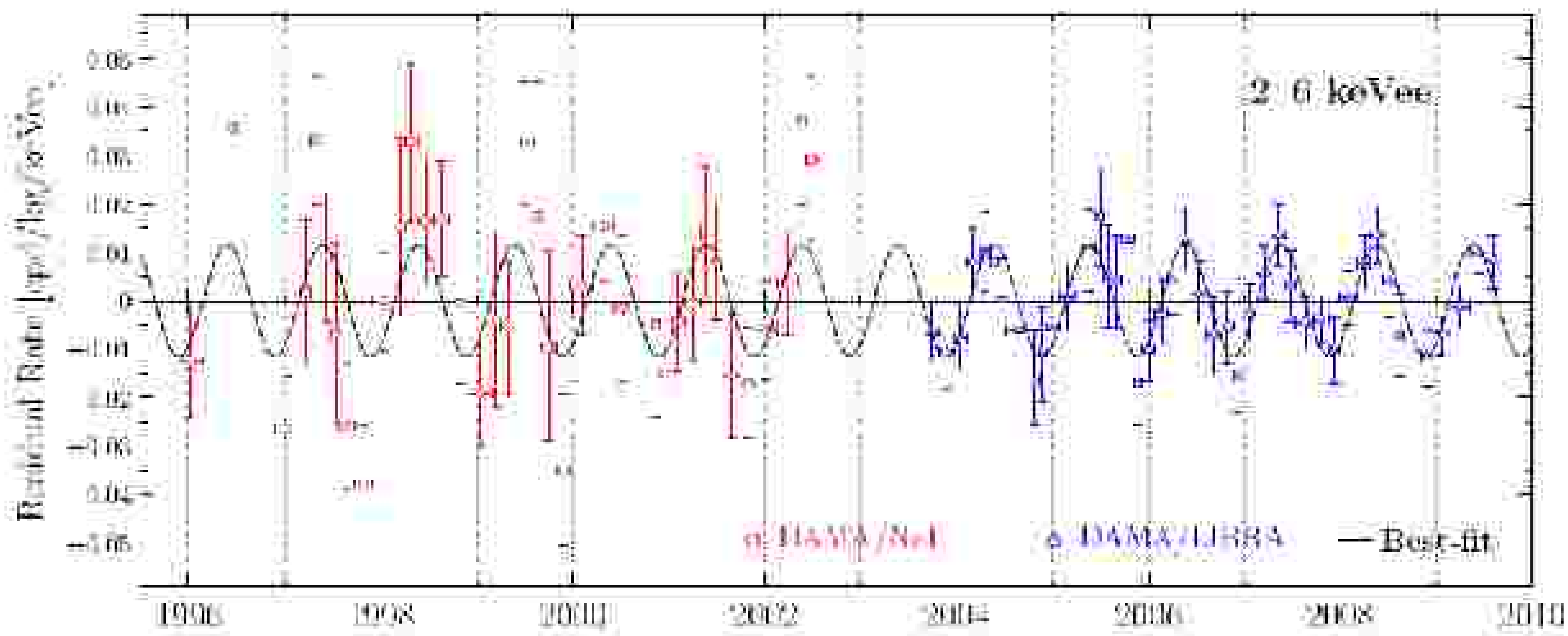
- *discretize the halo integral in step-functions in v_m space*
- *consider the joint LH of all data and maximize wrt to DM parameters and halo*
- *consider test statistic and determine distribution by Monte Carlo*
- *find p-value of 0.44% for CDMS-Si + LUX + SuperCDMS (best fit at DM mass = 5.7 GeV)*

Halo-independent bound on annual modulation

Annual modulation

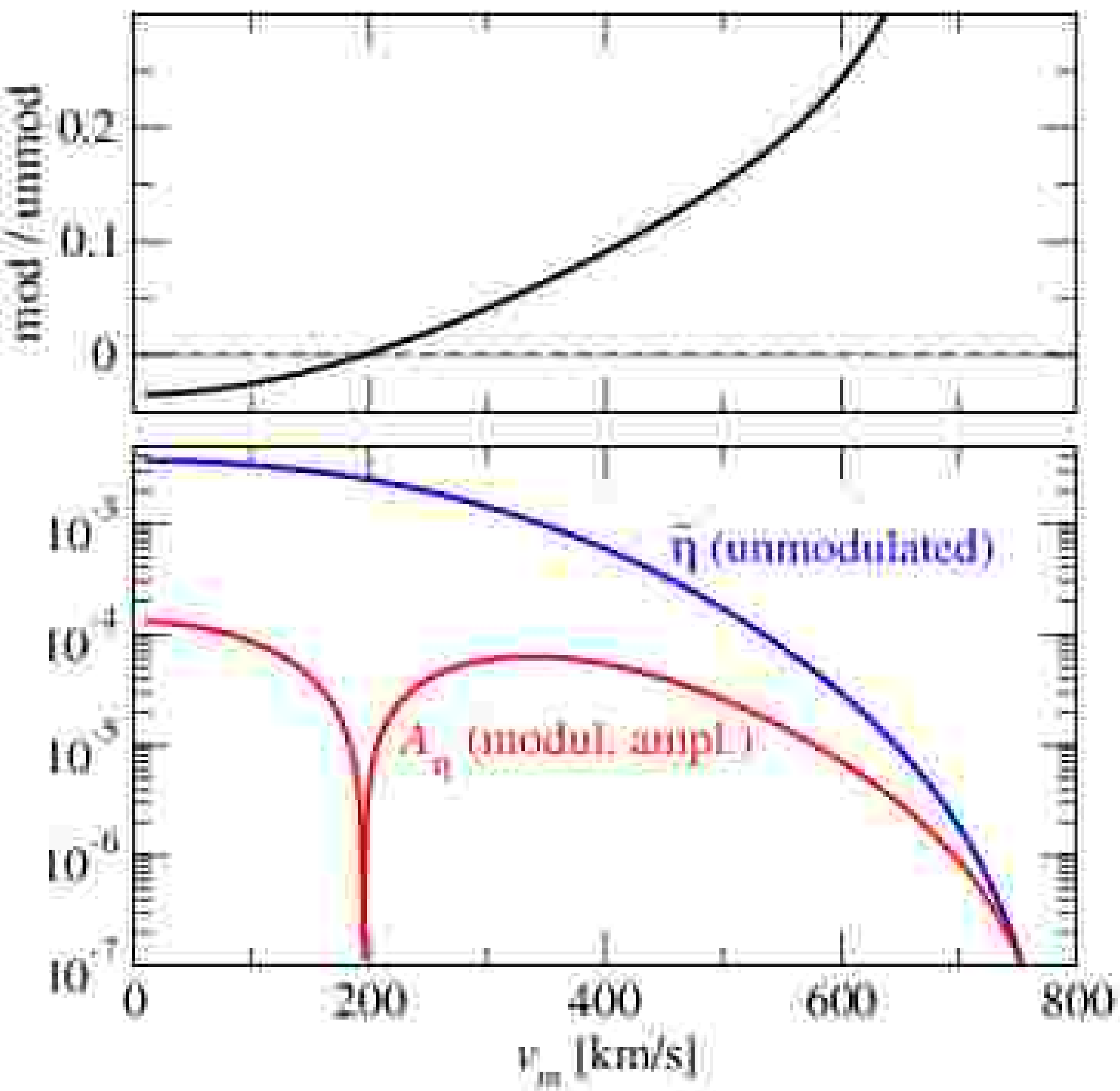


DAMA/LIBRA: 1.17 t yr exposure (13 yr)
~9σ evidence for modulation
maximum consistent with June 2nd

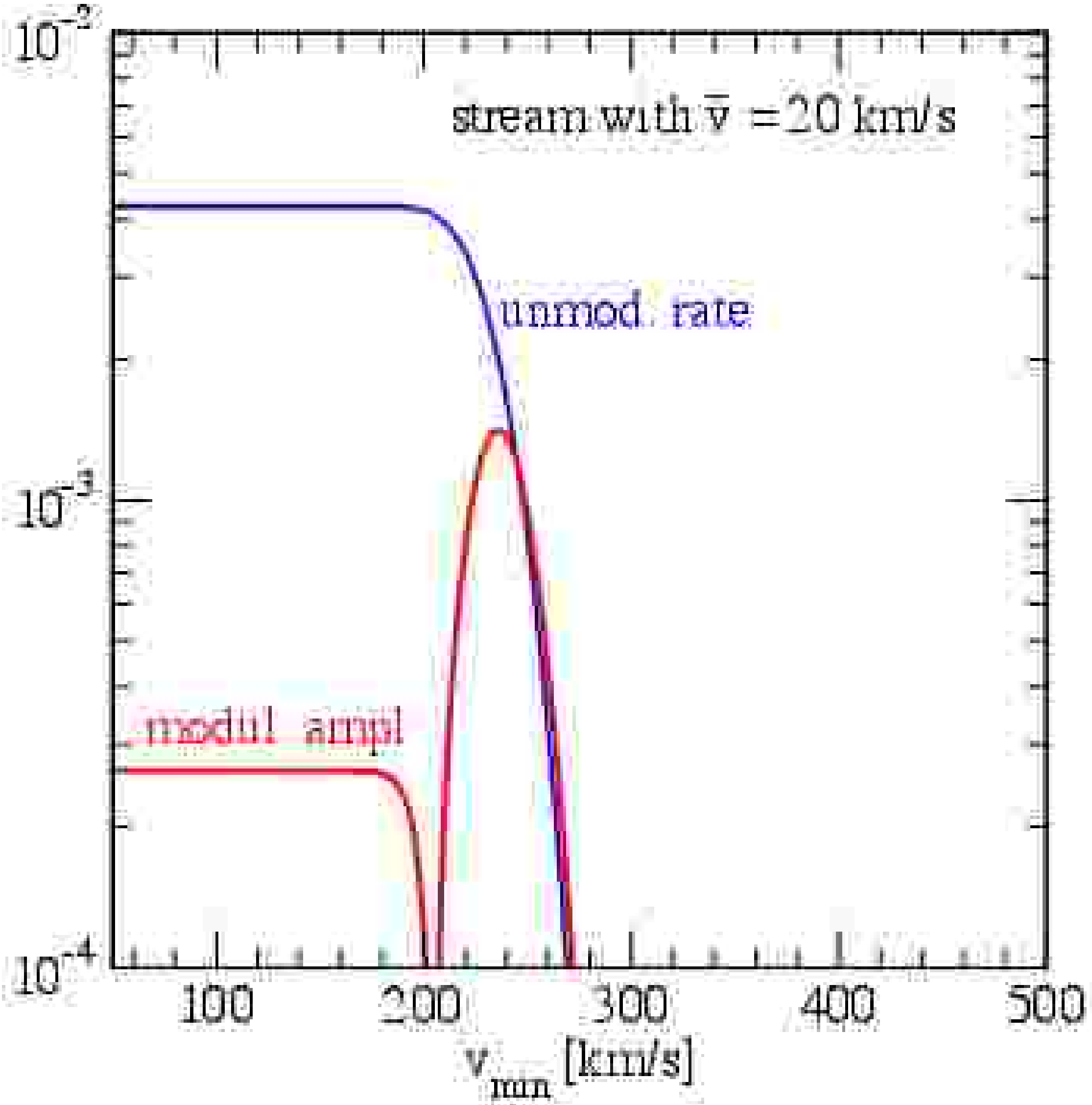


The size of the modulation amplitude

Maxwellian halo



stream

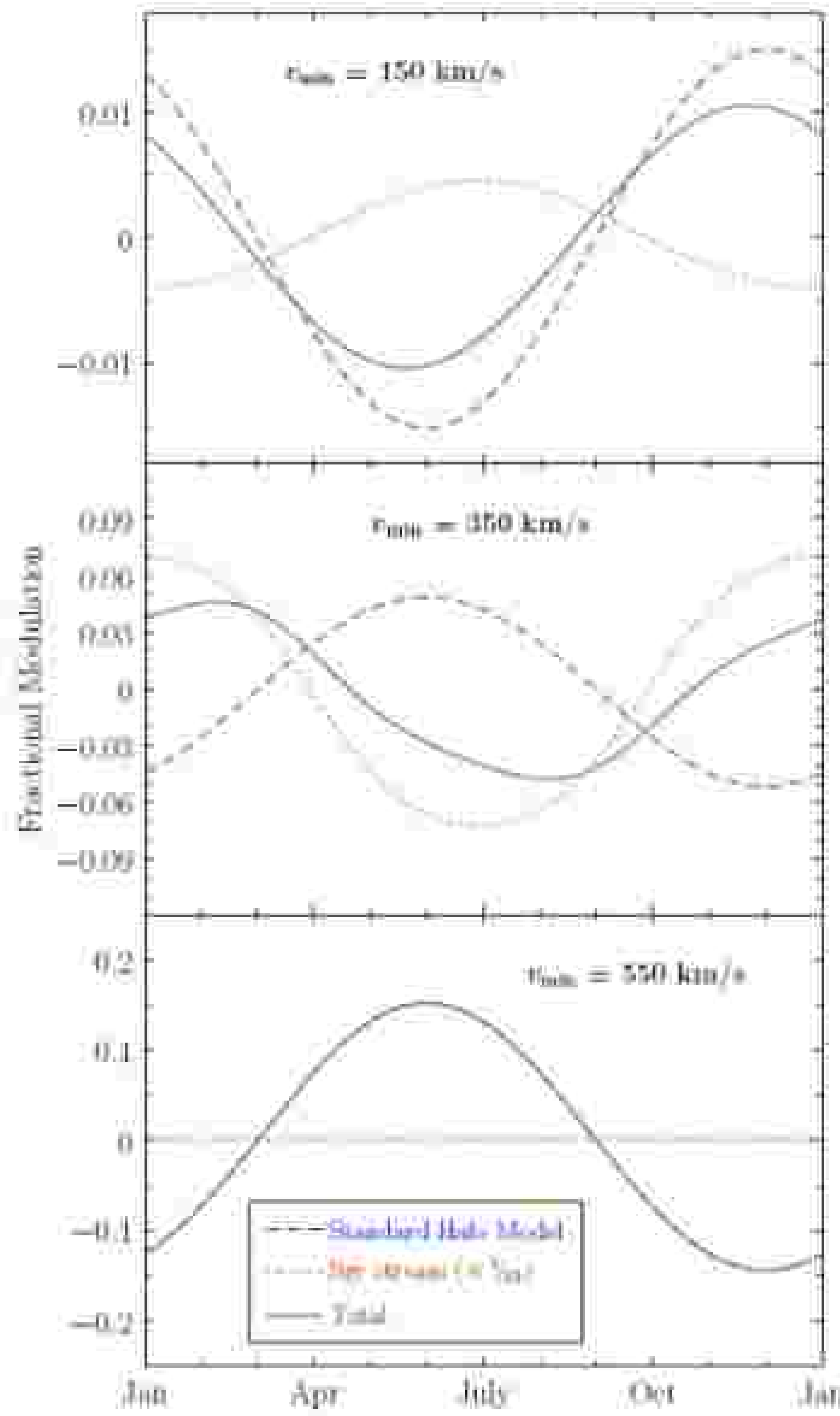


Non-Maxwellian modulation

for several halo components the phase and the cos-shape of the modulation signal may be strongly modified

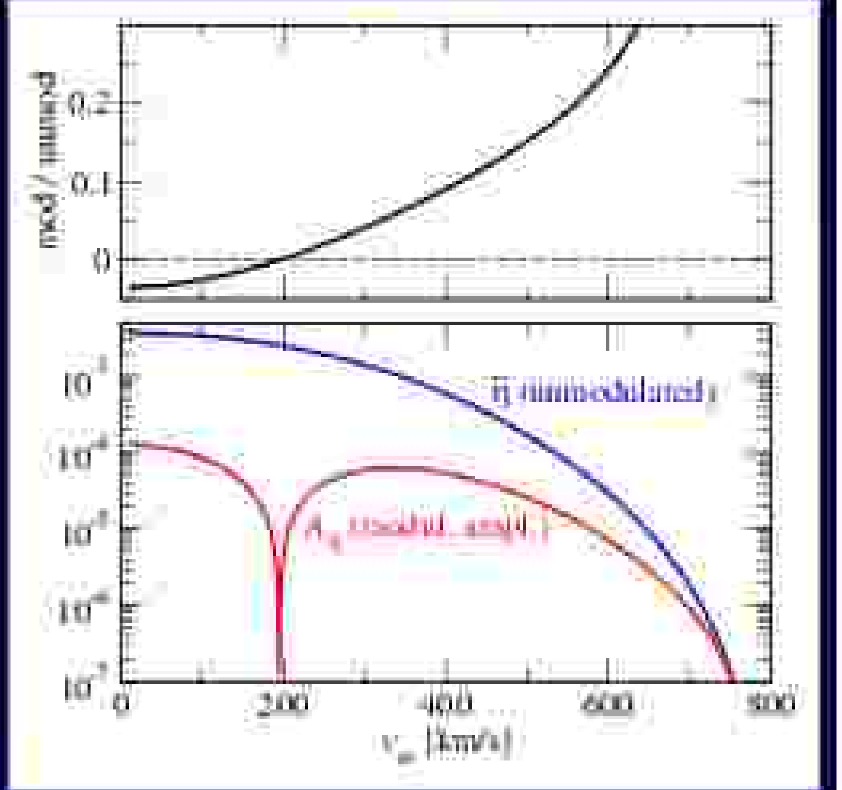
e.g. Green 03
Fornengo, Scopel, 03

Freese, Lisanti, Savage, 12



Halo-independent bound on the modulation

Assume time-indep. $f_\odot(\vec{v})$: halo const. on sun-earth distance and on timescales of 1 yr $\Rightarrow$ only time dependence due to $\vec{v}_\oplus(t)$.



$$\eta(v_{\rm min}, t) = \int_{v > v_{\rm min}} d^3 v \, \frac{f_\odot(\vec{v} + \vec{v}_\oplus(t))}{v}$$

$$= \int_{|\vec{v} - \vec{v}_\oplus(t)| > v_{\rm min}} d^3 v \, \frac{f_\odot(\vec{v})}{|\vec{v} - \vec{v}_\oplus(t)|}$$

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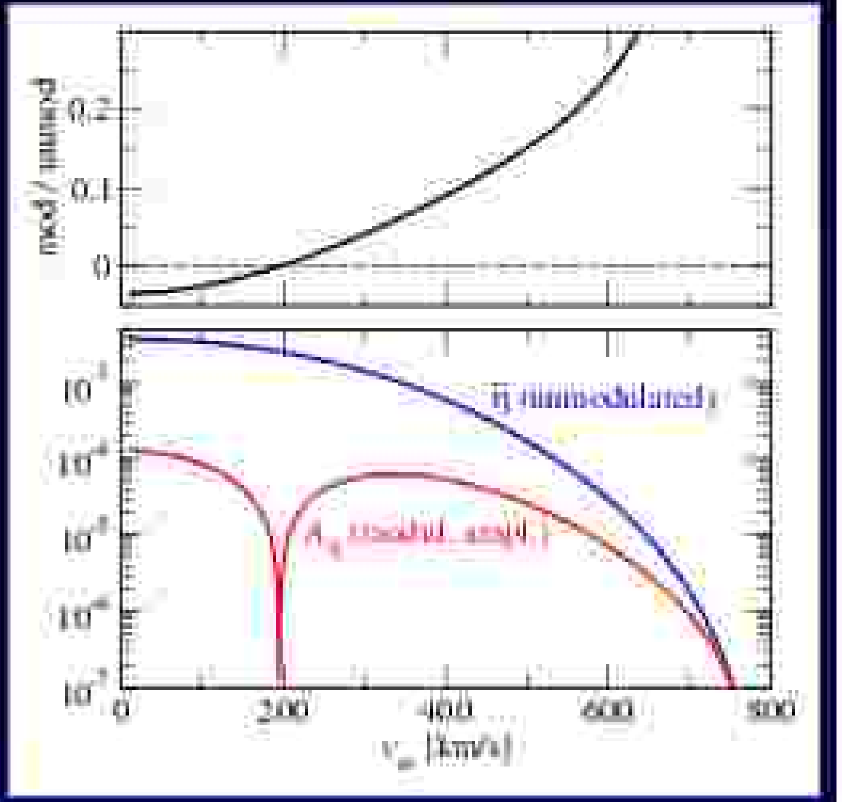

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surface term

volumn term

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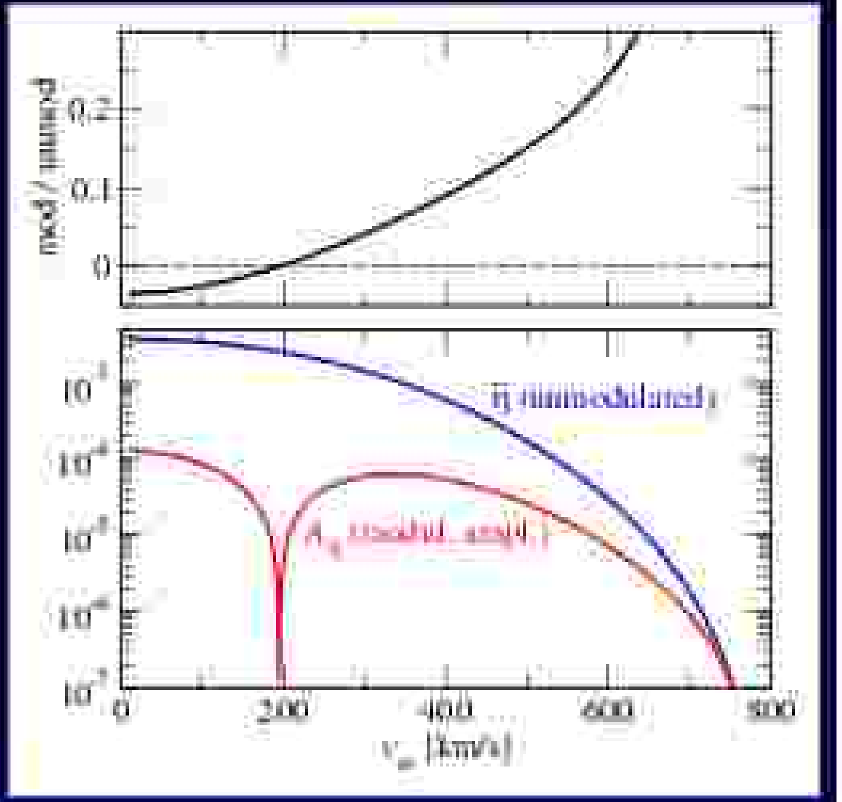

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expand in the small number $v_\oplus / v_{\min}$:

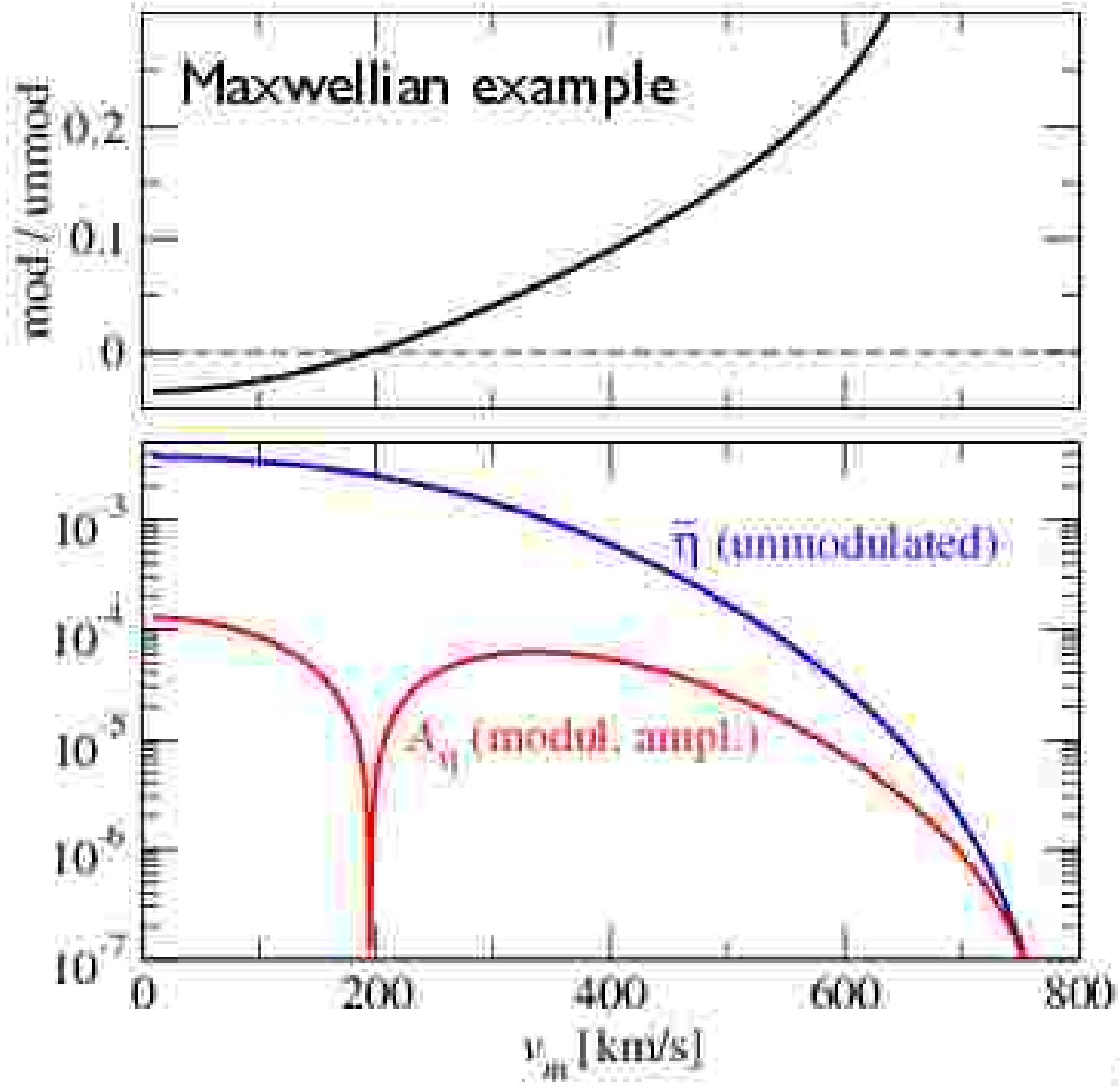
$$\eta(v_{\min}, t) \approx \underbrace{\int_{v > v_{\min}} d^3v \, \frac{f_\odot(\vec{v})}{v}}_{\overline{\eta}(v_{\min})} + \underbrace{v_\oplus \, \frac{d\eta(v_{\min}, t)}{dv_\oplus}\Big|_{v_\oplus = 0}}_{\delta\eta(v_{\min}, t)}$$

Halo-independent bound on the modulation

Herrero-Garcia, Schwetz, Zupan, 11, 12

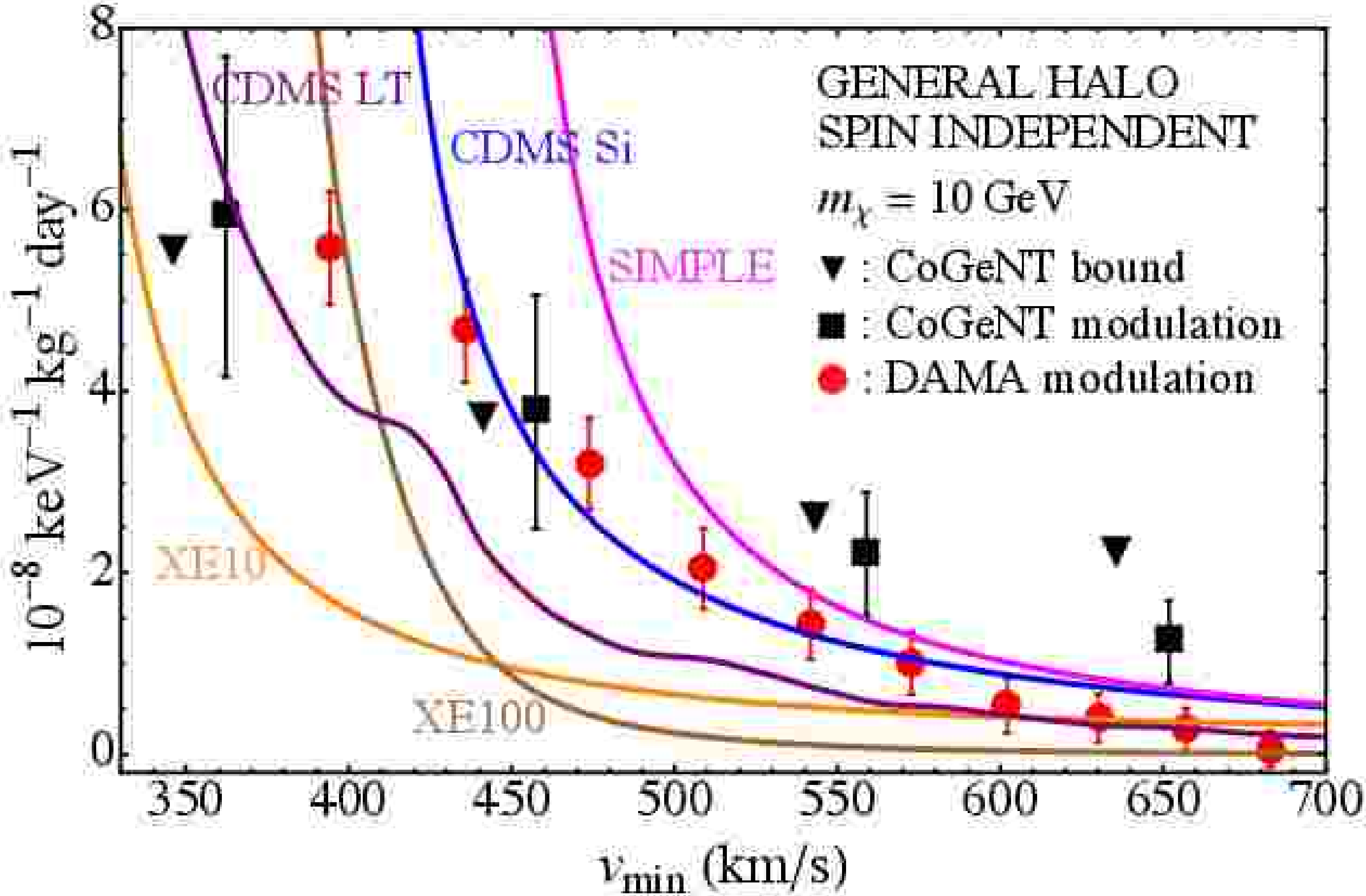
$$\int_{v_1}^{v_2} dv A_\eta(v) \leq v_\oplus \left[\overline{\eta}(v_1) + \int_{v_1}^{v_2} dv \frac{\overline{\eta}(v)}{v}\right]$$

upper bound on modulation amplitude in terms of unmodulated event rate under very modest assumptions about halo properties



DAMA signal highly disfavoured halo independently

Herrero-Garcia, Schwetz, Zupan, PRL12



using 2011 XENON100 data

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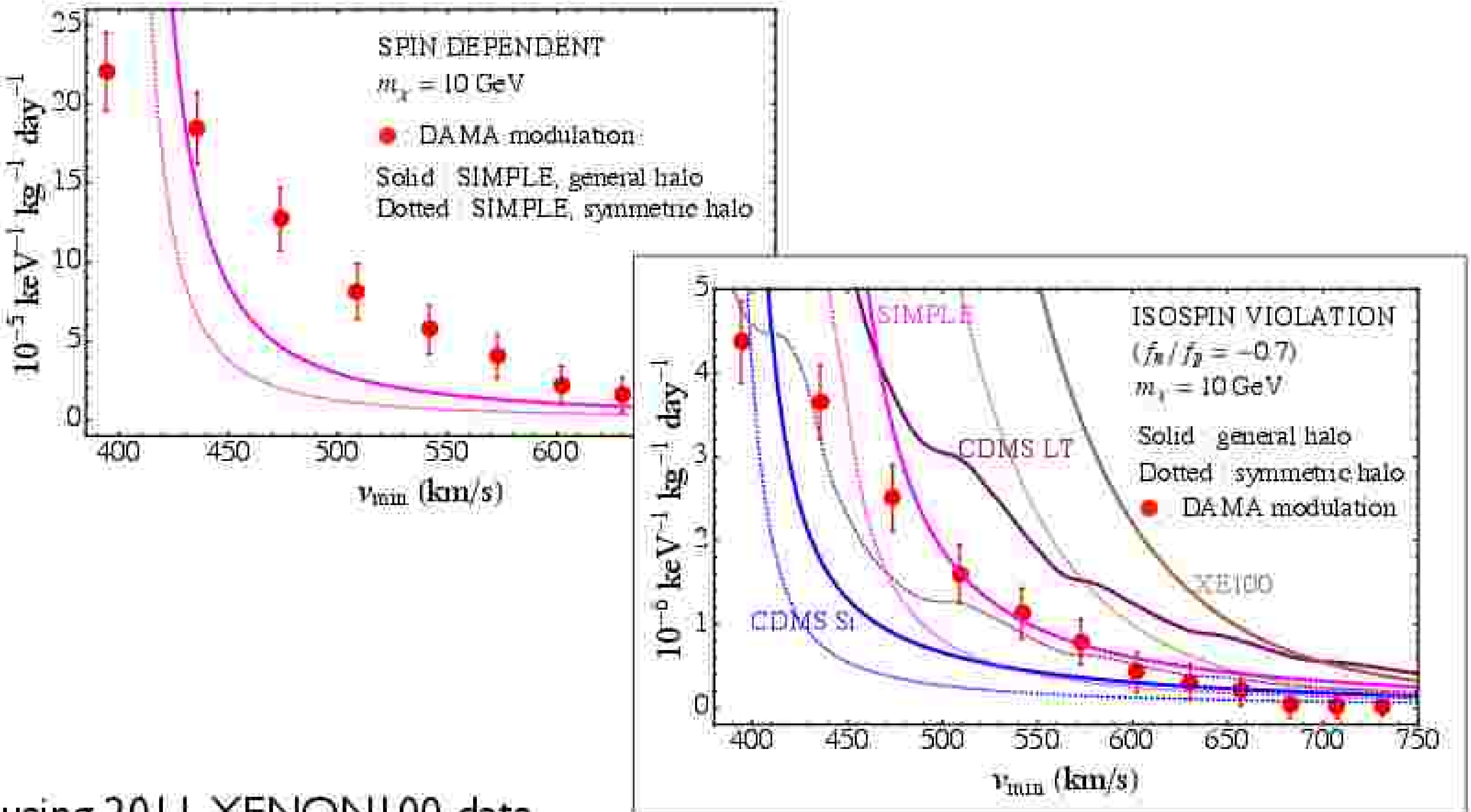

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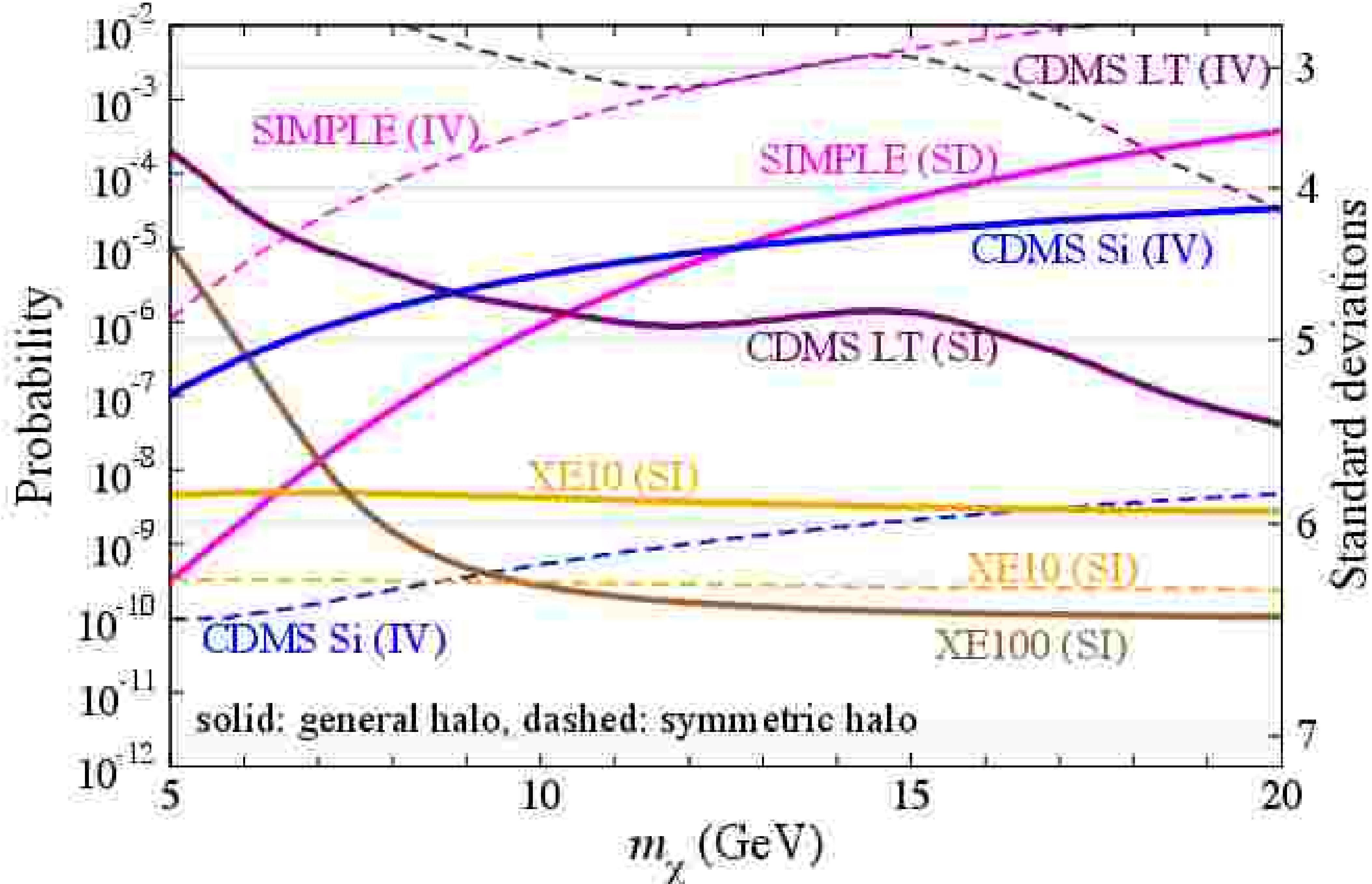

using 2011 XENON100 data

Halo-independent relation between direct detection and neutrinos from the Sun

Blennow, Herrero-Garcia, Schwetz, 1502.03342

Neutrinos from DM annihilations in the Sun

- *When a DM particle scatters on a nucleus inside the Sun it may loose enough energy to be gravitationally bound to the Sun.*
- *It will re-scatter and DM will accumulate in the centre of the Sun and start to annihilate.*
- *Annihilation products generically produce high-energy neutrinos → potential signal in SuperK, IceCube*

DM capture in the Sun vs DD

DM capture rate in the Sun:

$$C_{\rm Sun} = 4\pi \, \frac{\rho_\chi \sigma_\chi^p}{2 m_\chi \mu_{\chi p}^2} \sum_A A^2 \int_0^R dr r^2 \rho_A(r) \int_0^{v_{\rm cross}^A} dv \tilde{f}(v)\, v \int_{E_{\rm min}(v)}^{E_{\rm max}(v)} F_A^2(E_R) dE_R$$

DM direct detection:

$$R_{DD} = \frac{\rho_\chi \sigma_\chi^p}{2 m_\chi \mu_{\chi p}^2} A^2 F_A^2(E_R) \int_{v_m} dv\, v \tilde{f}(v)$$

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same pre-factor, including cross section and local DM density

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same velocity distribution
(per assumption)

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Sun probes low-velocity part,

DM direct detection:

DD sensitive to high-velocity tail

$$R_{DD} = \frac{\rho_\chi \sigma_\chi^p}{2 m_\chi \mu_{\chi p}^2} A^2 F_A^2(E_R) \int_{v_m} dv\, v \tilde{f}(v)$$

$$v_m = \sqrt{\frac{m_A E_R}{2\mu_{\chi A}^2}}$$

DM capture in the Sun vs DD

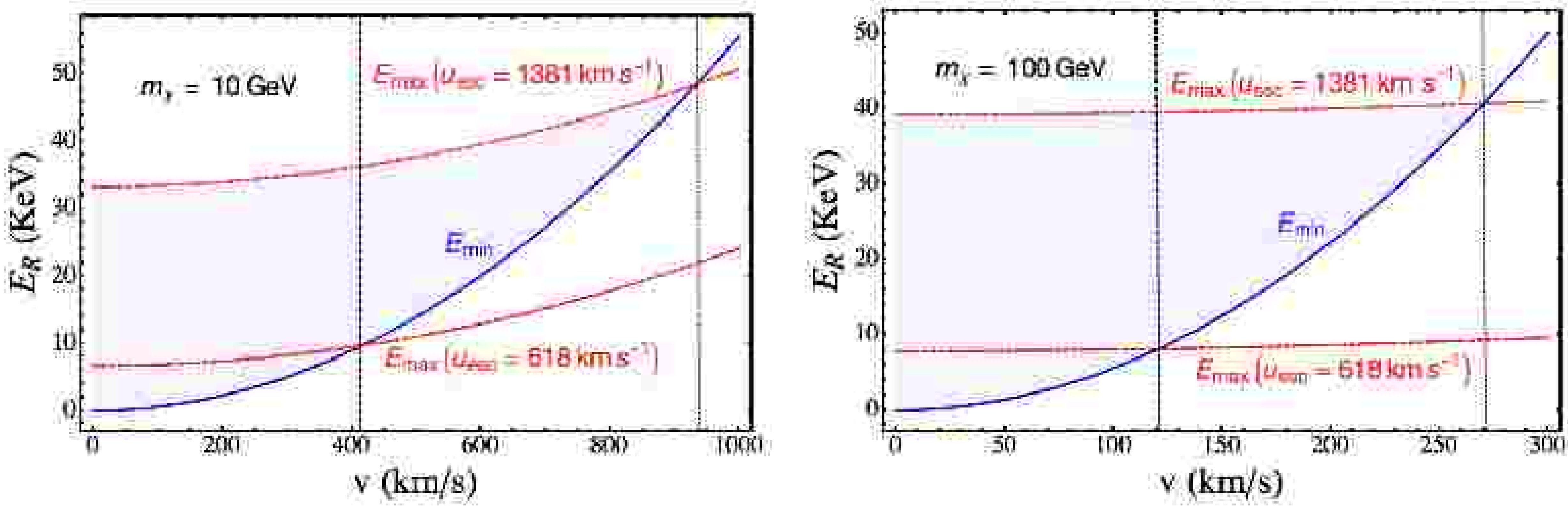

Figure 1. For hydrogen (SD), we show in blue the lower bound on the energy for DM capture in the Sun, $E_{\rm min}$, and in red the energy upper limits, $E_{\rm max}(r)$, for the two extreme escape velocities, versus the velocity v, for $m_\chi = 10\,(100)$ GeV, left (right). The points were they cross (indicated by the vertical dotted lines) are the maximum velocities of the DM particles, $v^p_{\rm cross}(r)$.

DM capture in the Sun vs DD

overlap region in the probed velocity space

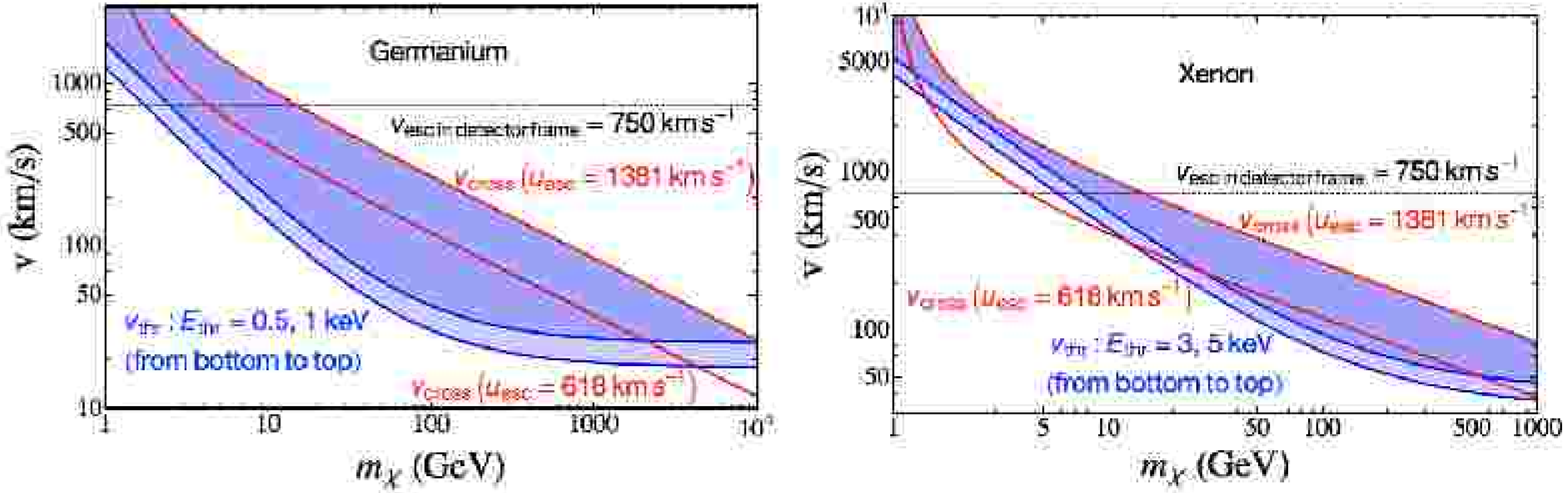

Figure 2. In blue we show the minimum velocity $v_{\rm thr}(E_{\rm thr})$ probed in a direct detection experiment versus m_χ, assuming different threshold energies $E_{\rm thr}$ and using a Ge (left) and a Xe (right) target. In red we show the maximum velocity relevant for DM capture in the Sun for scattering on hydrogen, $v^{p}_{\rm cross}$, for the two extreme values of $u_{\rm esc} = 1381\,\mathrm{km\,s^{-1}}$ in the centre of the Sun and $u_{\rm esc} = 618\,\mathrm{km\,s^{-1}}$ at the surface. The shaded area shows the overlap region assuming scattering in the centre of the Sun. The horizontal black line indicates approximately the galactic escape velocity in the detector rest frame.

Lower bound on the DM capture rate

consider only the overlap region between capture and DD

$$C_{\rm Sun} = 4\pi \frac{\rho_\chi \sigma_\chi^p}{2 m_\chi \mu_{\chi p}^2} \sum_A A^2 \int_0^R dr r^2 \rho_A(r) \int_0^{v_{\rm cross}^A} dv \tilde{f}(v)\, v \int_{E_{\rm min}(v)}^{E_{\rm max}(v)} F_A^2(E_R) dE_R$$

$$\geq 4\pi \frac{\rho_\chi \sigma_\chi^p}{2 m_\chi \mu_{\chi p}^2} \sum_A A^2 \int_0^R dr r^2 \rho_A(r) \int_{v_m^{\rm thr}}^{v_{\rm cross}^A} dv \tilde{f}(v)\, v \int_{E_{\rm min}(v)}^{E_{\rm max}(v)} F_A^2(E_R) dE_R$$

threshold of DD exp in v-space

DM capture in the Sun vs DD

$$R_{DD} = \frac{\rho_\chi \sigma_\chi^p}{2 m_\chi \mu_{\chi p}^2} A^2 F_A^2(E_R) \int_{v_m} dv\, v \tilde{f}(v)$$

For a high-statistics signal in DM direct detection we can extract the v-distribution from data: Drees, Shan, 07

$$\frac{\rho_\chi \sigma_\chi^p}{2 m_\chi \mu_{\chi p}^2} \tilde{f}(v) = -\frac{1}{v A^2} \frac{d}{dv} \left(\frac{R_{DD}(E_R)}{F_A^2(E_R)} \right)$$

DM capture in the Sun vs DD

$$R_{DD} = \frac{\rho_\chi \sigma_\chi^p}{2 m_\chi \mu_{\chi p}^2} A^2 F_A^2(E_R) \int_{v_m} dv\, v \tilde{f}(v)$$

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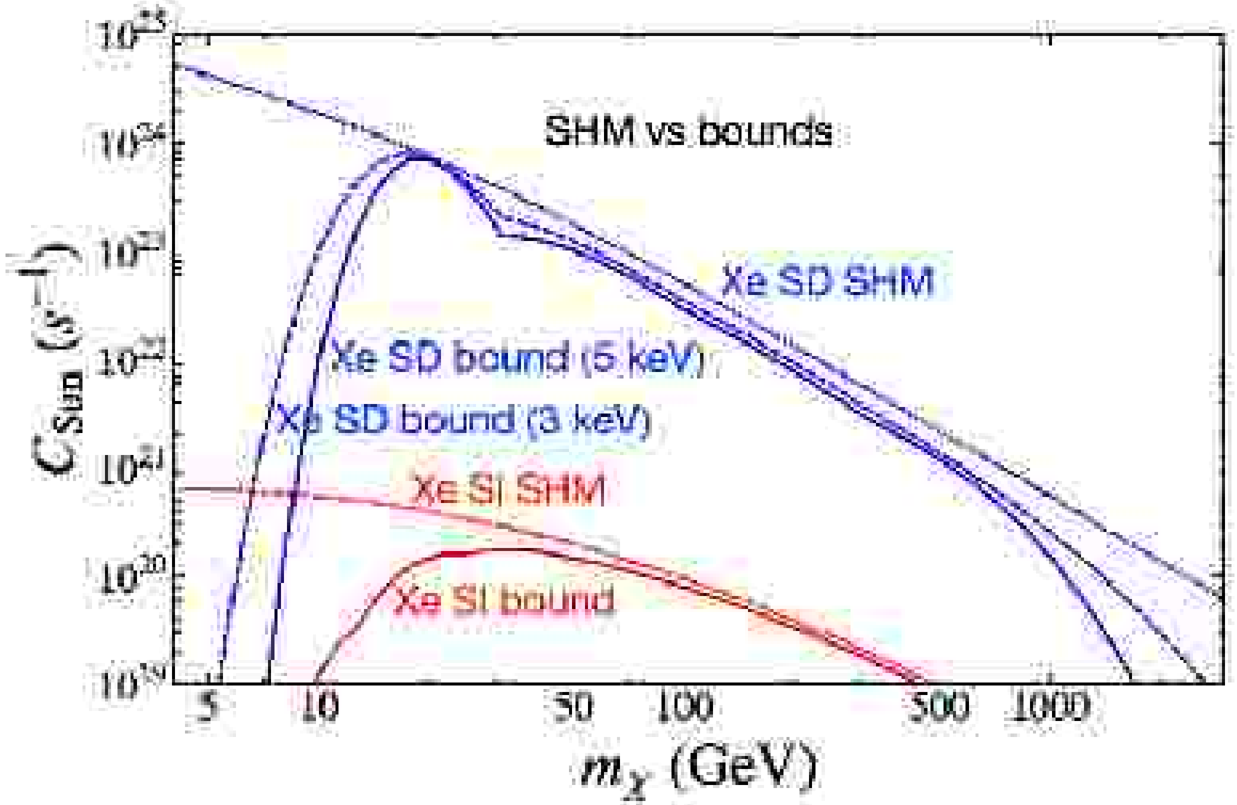
lower bound on C_{Sun} in terms of observable quantities in DD

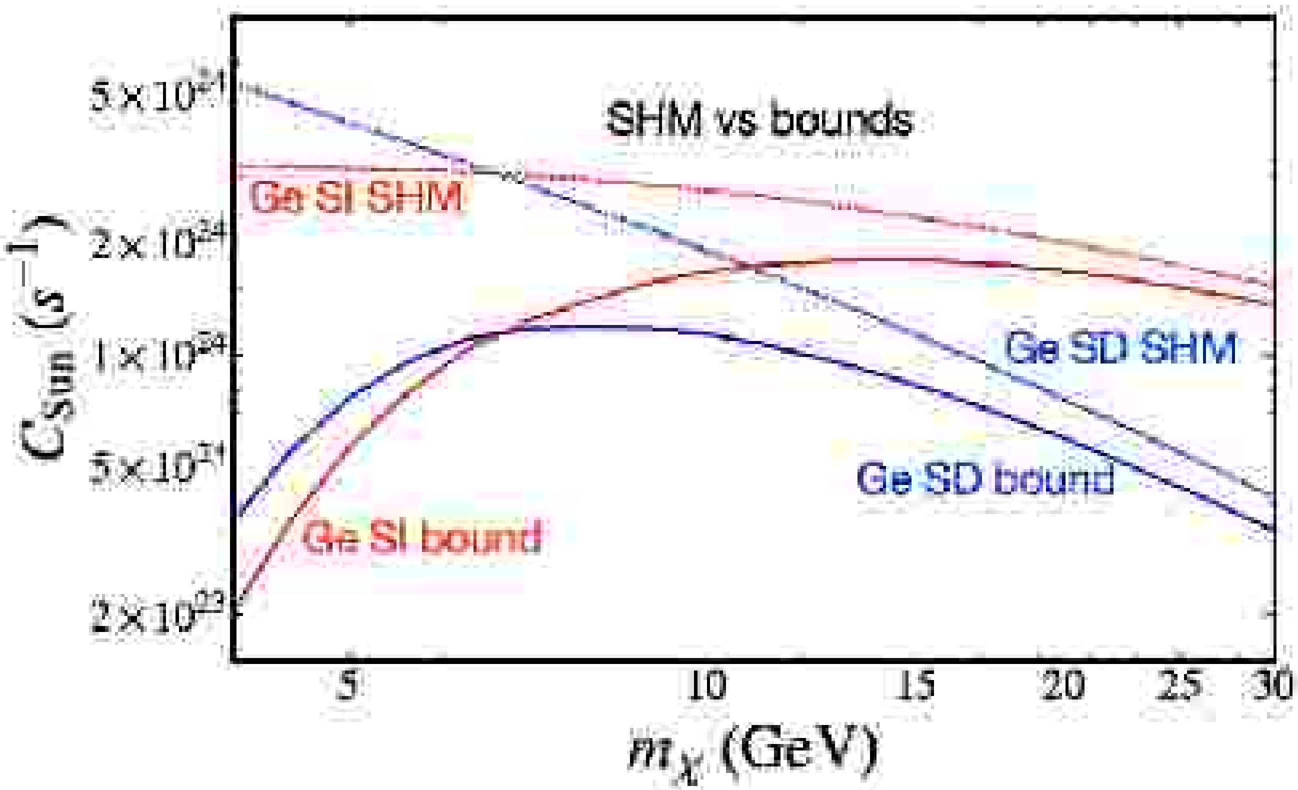
$$C_{\rm Sun} \geq 4\pi \frac{\rho_\chi \sigma_\chi^p}{2 m_\chi \mu_{\chi p}^2} \sum_A A^2 \int_0^R dr r^2 \rho_A(r) \int_{v_m^{\rm thr}}^{v_{\rm cross}^A} dv \tilde{f}(v)\, v \int_{E_{\rm min}(v)}^{E_{\rm max}(v)} F_A^2(E_R) dE_R$$

Mock data for direct detection

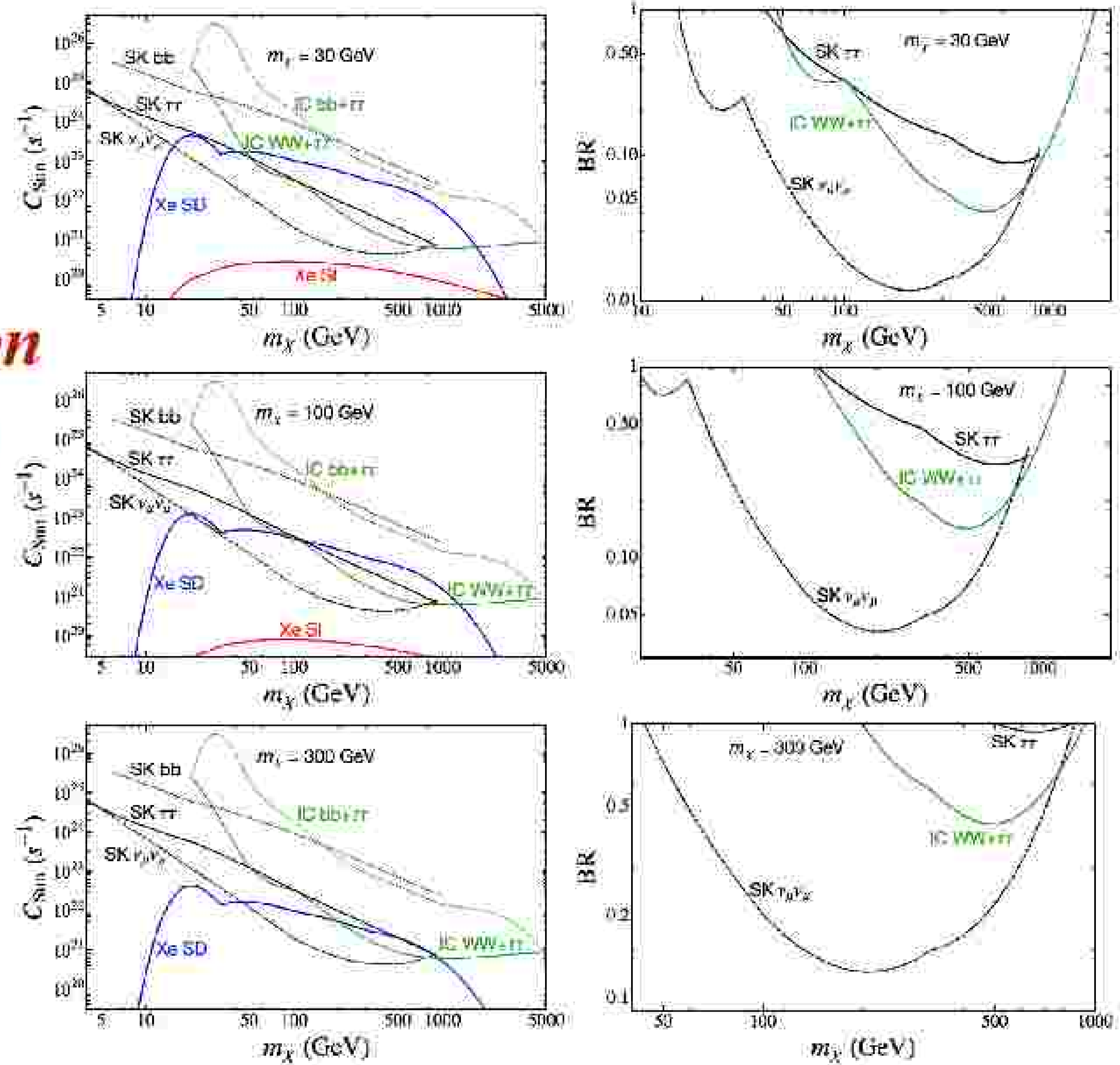
- Assume truncated Maxwellian halo (SHM)
- Xenon experiment: threshold of 3 or 5 keV
  SI (SD) cross sec of 10^{-45} (10^{-40}) cm^2
  equal couplings to protons and neutrons
  154 (267) events in the energy range 5 − 45 keV for SI (SD) for m_χ = 100 GeV and 1 ton yr
- Germanium experiment: threshold of 1 keV
  SI (SD) cross sec of 5×10^{-42} (2×10^{-40}) cm^2
  equal couplings to protons and neutrons
  15 000 (3) events in the energy range 1 − 100 keV for SI (SD) for m_χ = 6 GeV and 100 kg yr

Numerical results for mock data

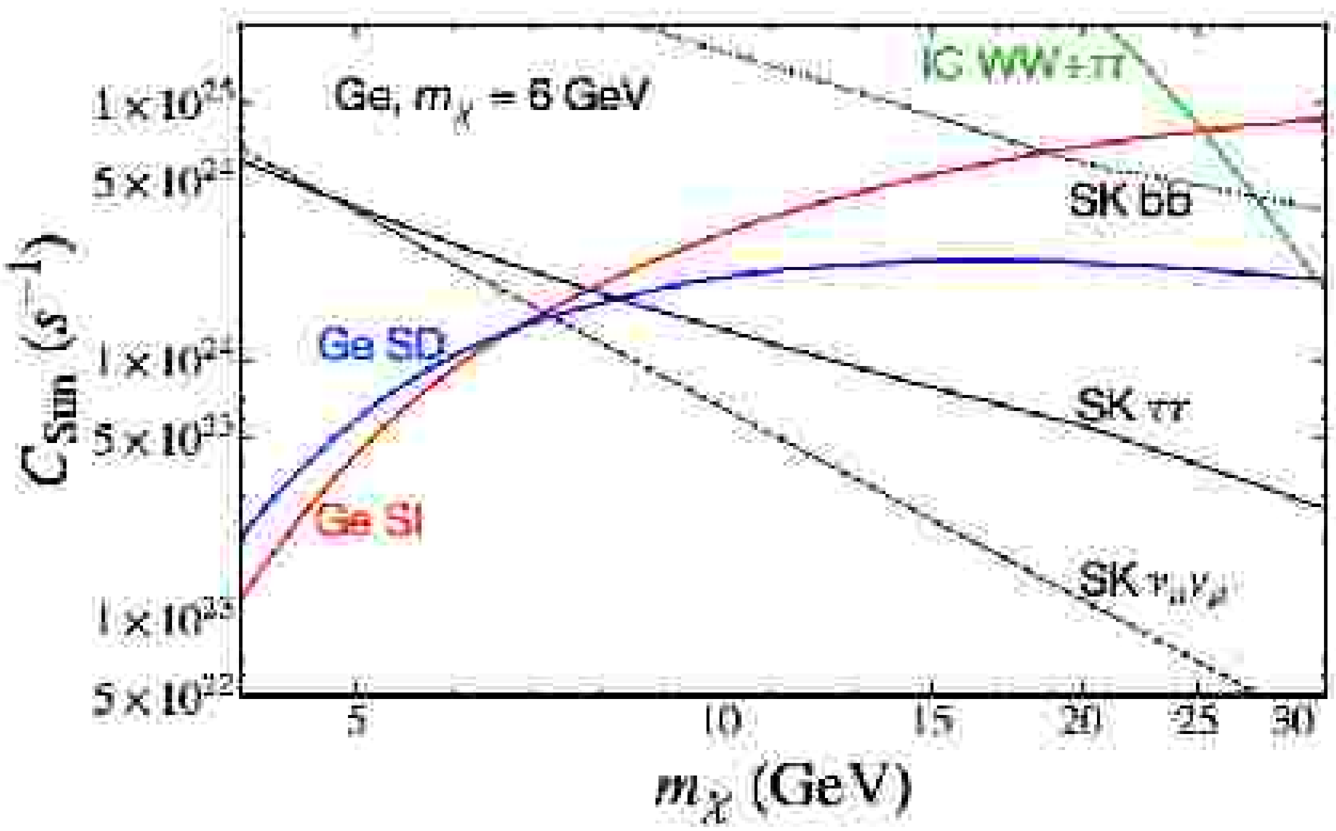


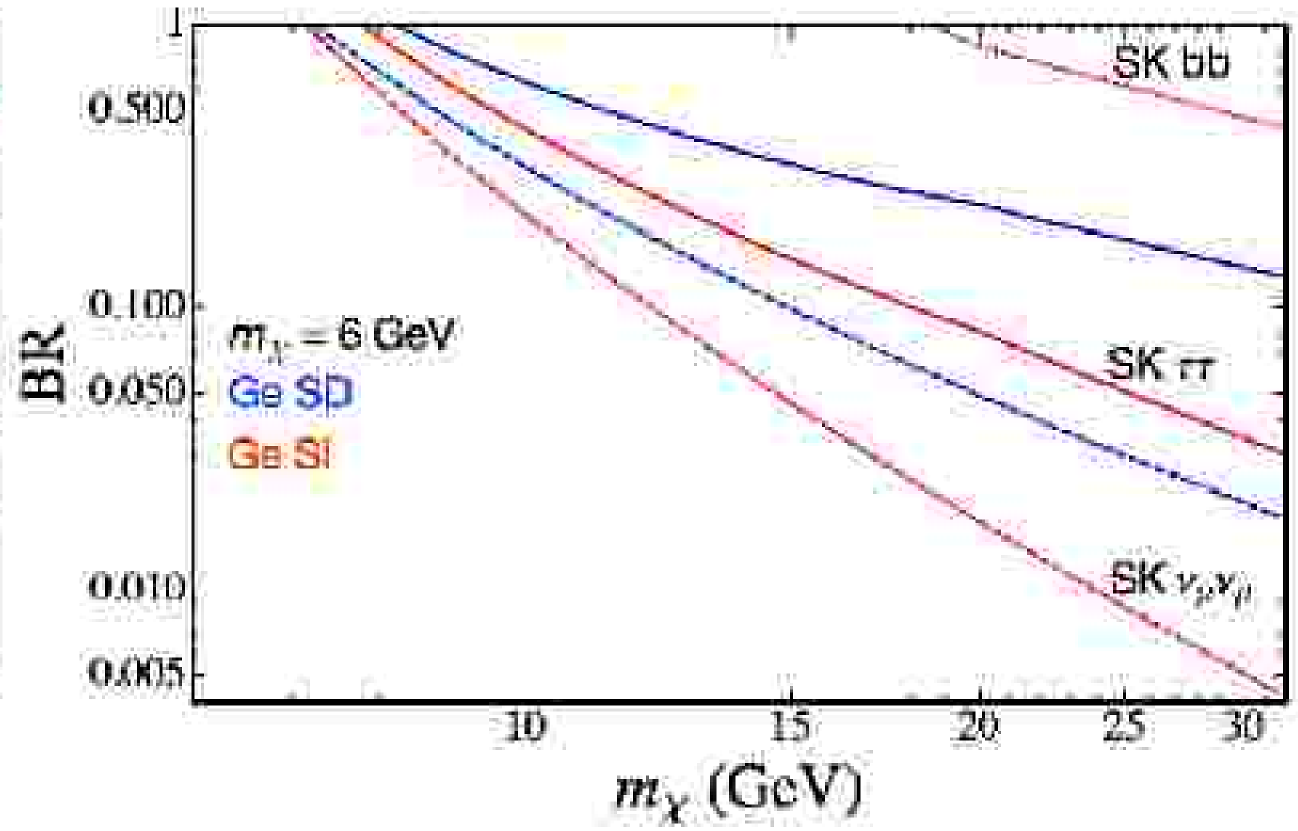


Comparison with limits from SK and IC



Comparison with limits from SK and IC





Conclusions

halo-independent methods to use data from DM direct detection experiments:

- *Comparison of positive and negative results*
- *Bounds on annual modulation*
- *Lower bound on the DM capture rate in the Sun*

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- *Comparison of positive and negative results*
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Outlook: extend to DD comparison with

- *LHC bounds*
- *thermal abundance*

Thank you!