Bounds on the dark matter annual modulation signal

invisibles
neutrinos, dark matter & dark energy physics

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Based on work in progress with J. Herrero-Garcia, T. Schwetz, and J. Zupan

Outline

- Direct dark matter detection
- Hints for a signal versus constraints
- Astrophysics-independent methods
  - A bound on the annual modulation amplitude
  - Higher harmonics in the annual modulation
- Summary

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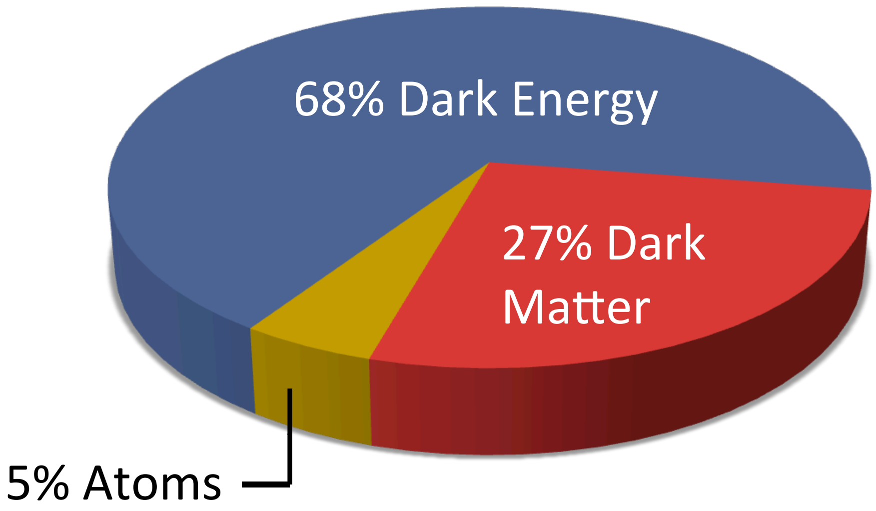
Why dark matter?

- The nature of dark matter (DM) is one of the major problems in physics and cosmology.
- Cosmological evidence suggests non-baryonic DM constituting most of the universe's mass density.
- Evidence for DM:
  - Big bang nucleosynthesis
  - CMB data
  - Supernova surveys
  - Galaxy surveys
  - …



Planck 2013

Why dark matter?

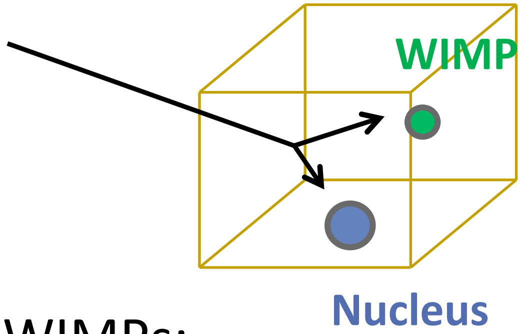
- Weakly Interacting Massive Particle (WIMP) is one of the preferred candidates for DM: *neutral stable particles which interact through the weak nuclear force, and have mass in the range of GeV-10 TeV.*
  ⇨ predicted by many theoretical extensions to the Standard Model of particle physics.

- DM halo in the local neighborhood most likely dominated by a smooth component.

- **"Standard Halo Model"**: isothermal sphere with an isotropic Maxwell-Boltzmann velocity distribution.
  - local DM density: $\rho_\chi \sim 0.4 \ \mathrm{GeV\ cm^{-3}}$
  - typical DM velocity: $\bar{v} \simeq 220 \ \mathrm{km/s}$

Direct dark matter detection

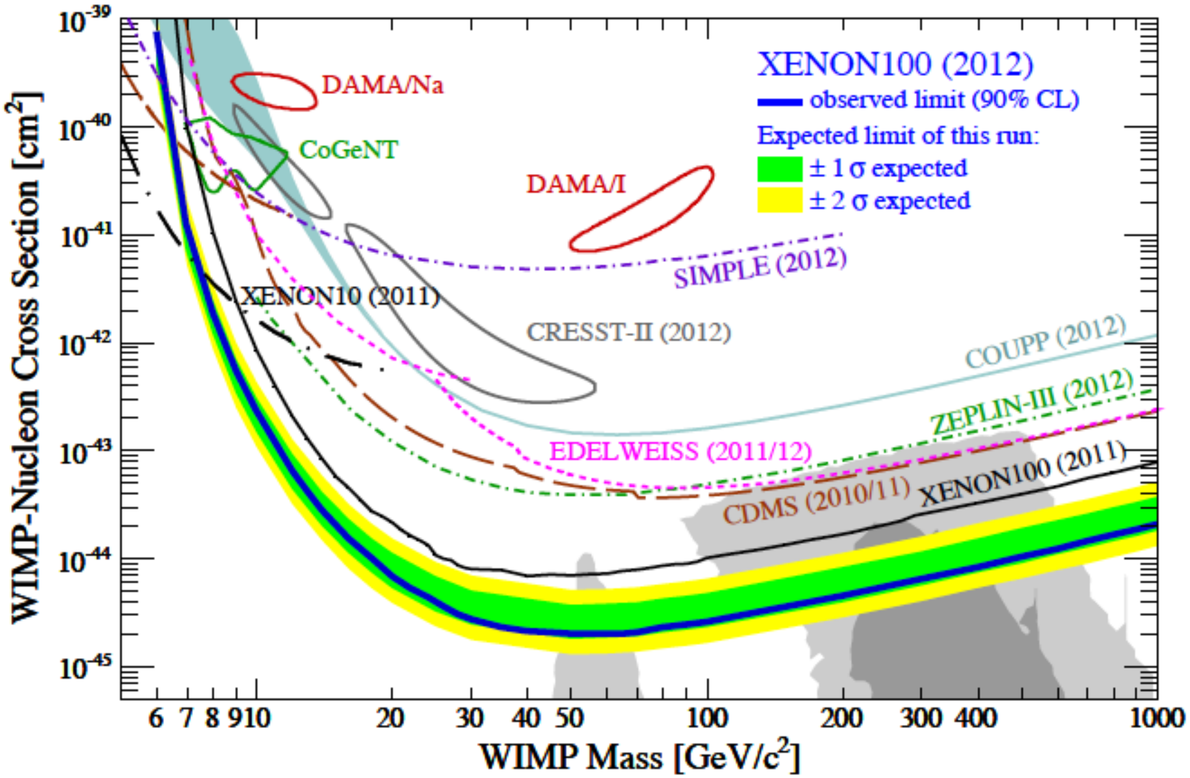
- Look for energy deposited in low-background detectors by the scattering of WIMPs in the dark halo of our galaxy.
  - Many experiments: **DAMA, XENON, CDMS, CoGeNT, CRESST, Edelweiss, ZEPLIN, LUX...**
- WIMPs interact with nuclei and produce:
  - **phonons, scintillation, or ionization**



- Data from four experiments pointing to light WIMPs:
  - **DAMA:** scintillation (NaI)
  - **CoGeNT:** ionization (Ge)
  - **CRESST:** scintillation + phonons ($CaWO_4$)
  - **CDMS-II:** ionization + phonons (Ge, Si)

Direct dark matter detection

- Strong tension between hints and XENON100 bound:



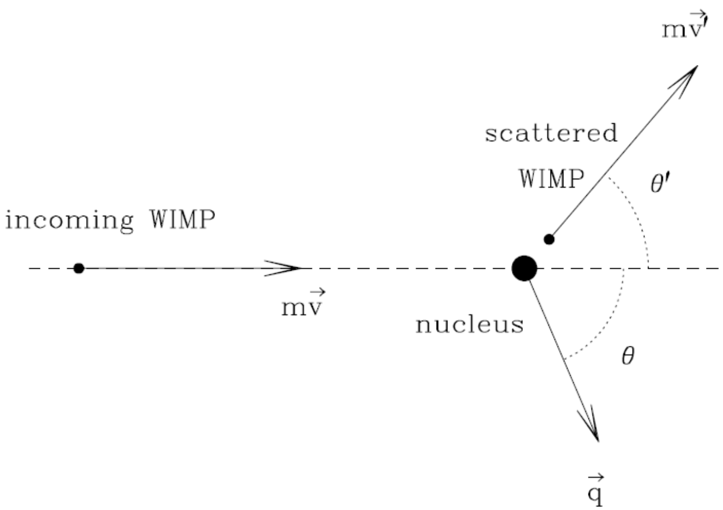
XENON100 Collaboration, 1207.5988

Direct dark matter detection

- WIMP-nucleus collision for a WIMP of mass $m_\chi \sim$ 100 GeV and a nucleus of mass $m_A \sim$ 100 GeV and DM velocity $v \sim$ 10^{-3} c
  ⇨ non-relativistic

- (elastic) recoil energy

$$E_R = \frac{2\mu^2 v^2}{m_A} \cos^2\theta \sim 10 \text{ keV}$$



- Minimum WIMP speed required to produce a recoil energy E_R :

$$v_{\min} = \sqrt{\frac{E_R m_A}{2\mu^2}}$$

The differential event rate

- The differential event rate (event/keV/kg/day):

$$\frac{dR}{dE_R}(t) = \frac{\rho_\chi}{m_\chi}\frac{1}{m_A}\int_{v>v_{\rm min}} d^3v\ \frac{d\sigma}{dE_R}\ v\ f_{\rm det}(\mathbf{v},t)$$

- For the standard spin-independent and spin-dependent scattering:

$$\frac{dR}{dE_R}(t) = \frac{\rho_\chi \sigma_0 F^2(E_R)}{2m_\chi \mu^2}\eta(v_{\rm min},t)$$

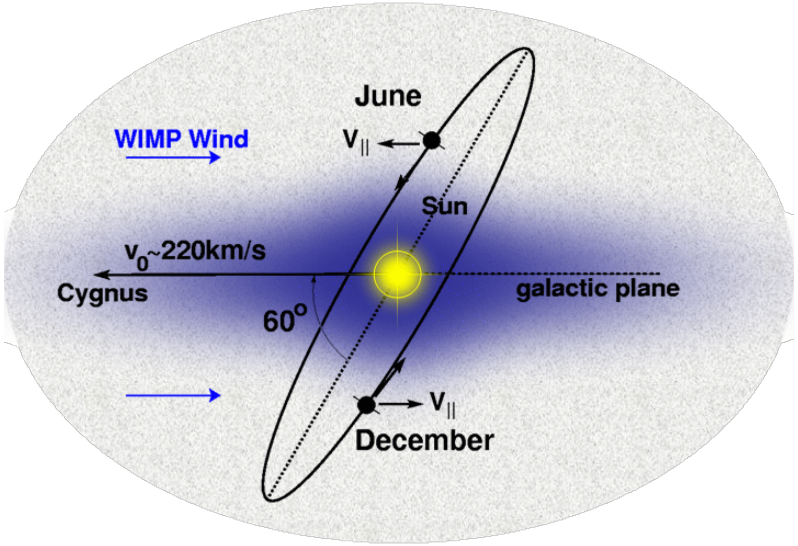
where

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

Annual modulation

- Due to the motion of the Earth around the Sun, the velocity distribution in the Earth's frame changes in a year.

Max in June
Min in Dec



$$f_{\rm det}(\mathbf{v}, t) = f_{\rm sun}(\mathbf{v} + \mathbf{v}_e(t)) = f_{\rm gal}(\mathbf{v} + \mathbf{v}_s + \mathbf{v}_e(t))$$

Sun's velocity wrt the Galaxy: $\mathbf{v}_s \approx (0, 220, 0) + (10, 13, 7)\ \mathrm{km/s}$

Earth's velocity: $v_e \approx 30\ \mathrm{km/s}$

Velocity distribution $f_{\rm gal}(\mathbf{v})$?

- The velocity distribution depends on the halo model.
- In the SHM, a truncated Maxwellian velocity distribution is assumed

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

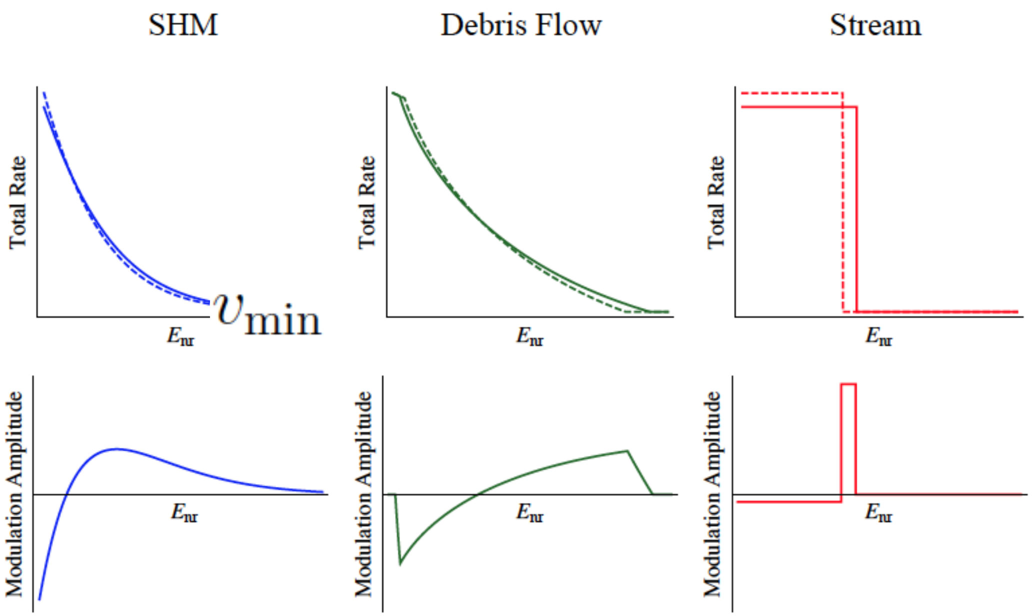
with $\bar{v} \simeq 220\ \mathrm{km/s}$, $v_{\rm esc} \simeq 550\ \mathrm{km/s}$

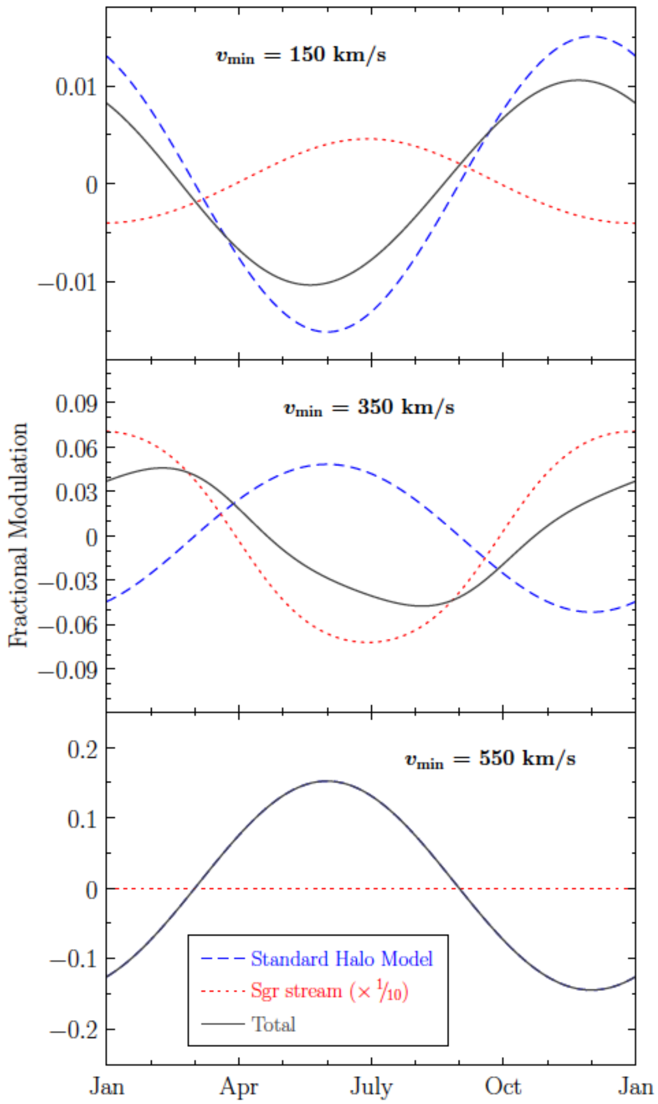
- DM distribution could be very different from Maxwellian:
  - Most likely both smooth and un-virialized (streams and debris flows) components.
  - the smooth component may not be Maxwellian

Modulation amplitude

- Annual modulation amplitude (SHM):

$$A_R = \frac{1}{2}\left[\frac{dR}{dE_R}(\text{June}) - \frac{dR}{dE_R}(\text{Dec})\right]$$





Freese, Lisanti, Savage, 1209.3339

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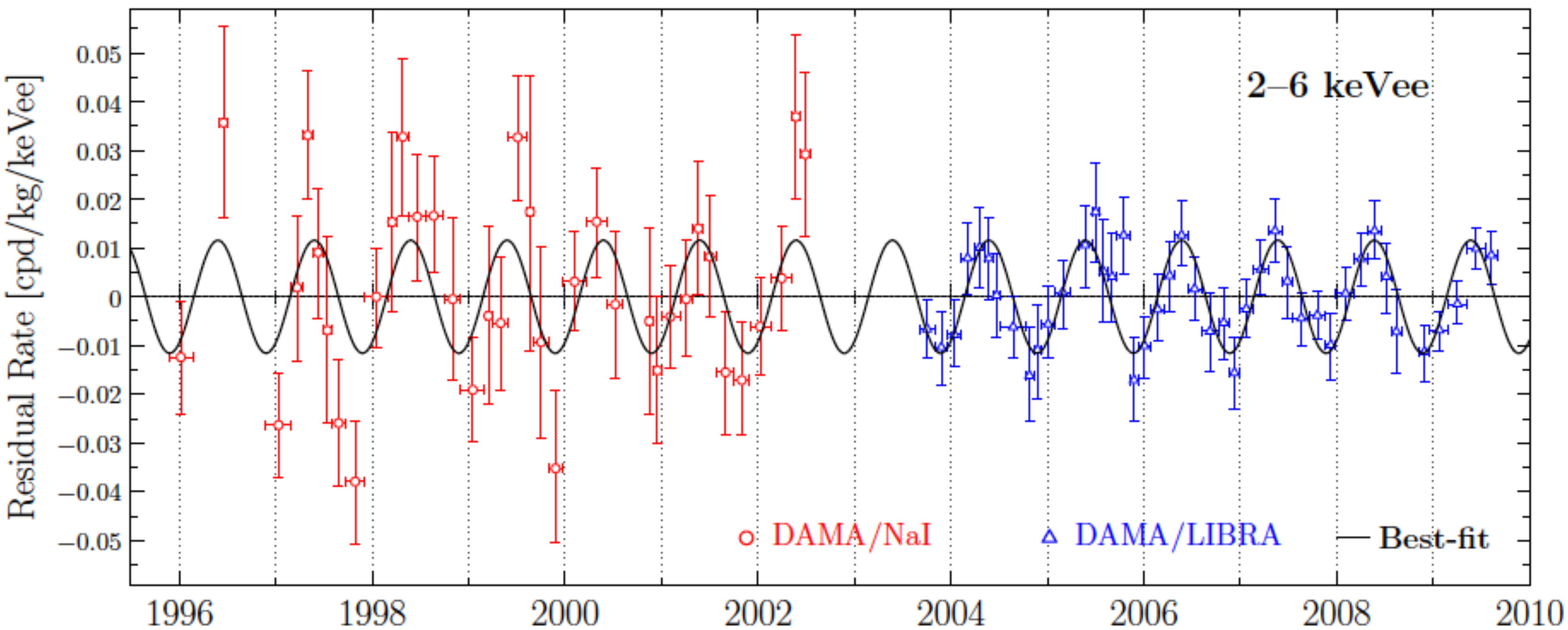
DAMA annual modulation signal

- NaI detectors, 8.9 σ modulation signal; 1.17 ton-yr (13 yrs)

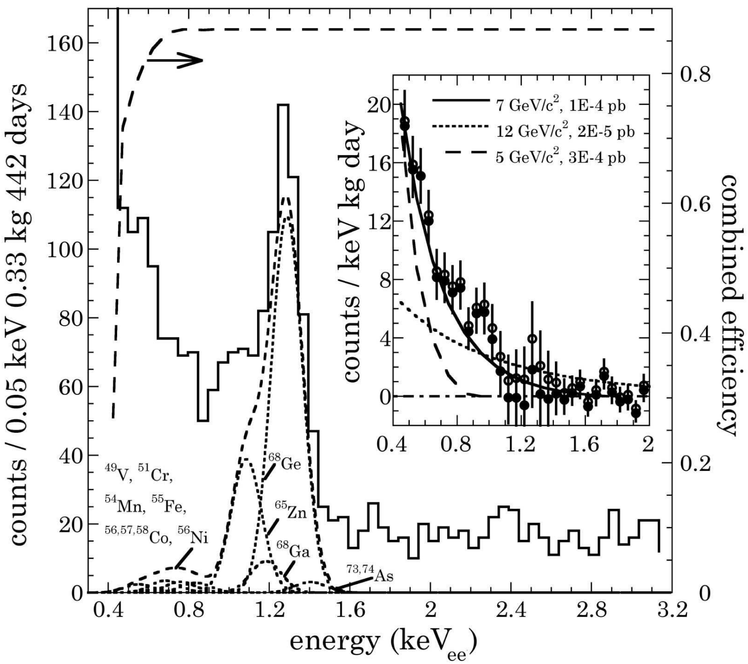


Freese, Lisanti, Savage, 1209.3339

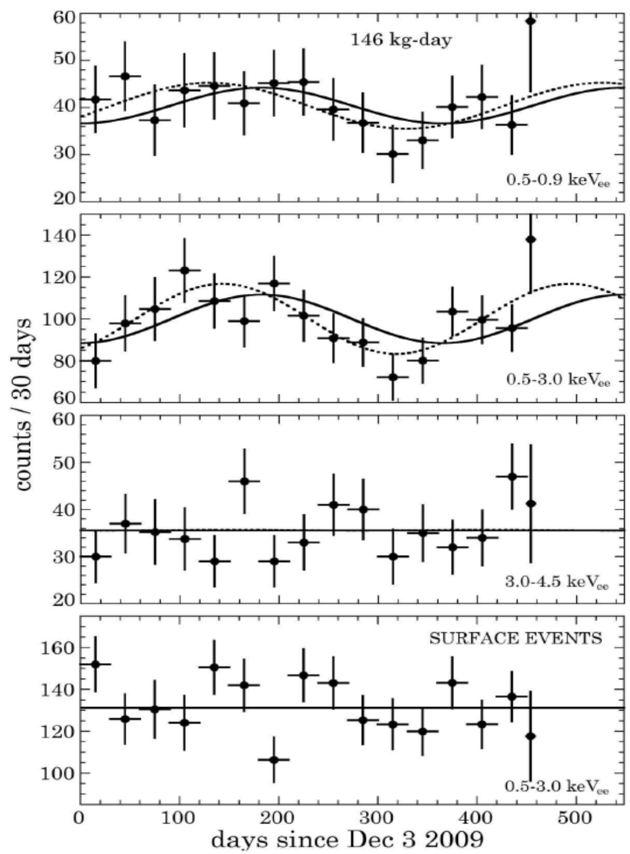
- Two possible WIMP masses: $m_\chi \sim 10$ GeV , $m_\chi \sim 80$ GeV

CoGeNT

- 440 gram Ge detector with extremely low threshold, 0.4 keVee
- With 56 days of exposure, an excess of low energy events above background, consistent with $m_\chi \sim 10\ \mathrm{GeV}$
- 2.8 σ annual modulation

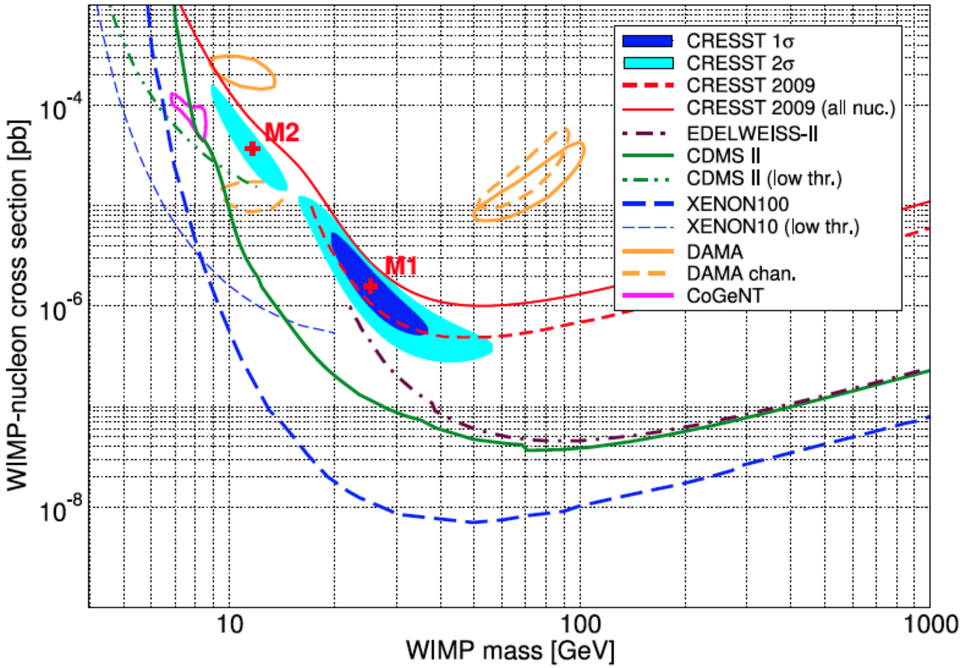


Aalseth et al,1106.0650



CRESST-II

- $CaWO_4$ crystal target, 730 kg-day exposure

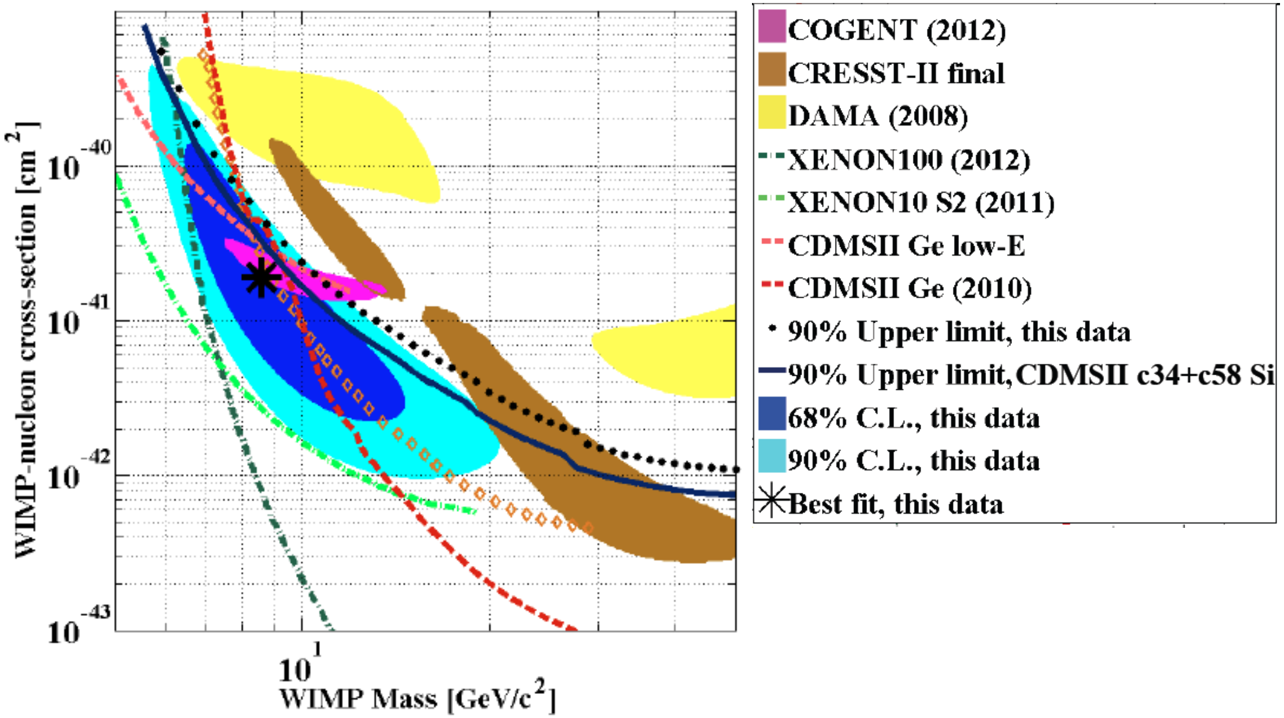


Angloher et al, Eur. Phys. J. C (2012) 72:1971

- **M1:** $m_\chi = 25.3\ \mathrm{GeV}$, significance: 4.7$\sigma$
- **M2:** $m_\chi = 11.6\ \mathrm{GeV}$, significance: 4.2$\sigma$

CDMS-II

- 140.2 kg-days in 8 Si detectors; 3 events against expected background of <0.7 events.

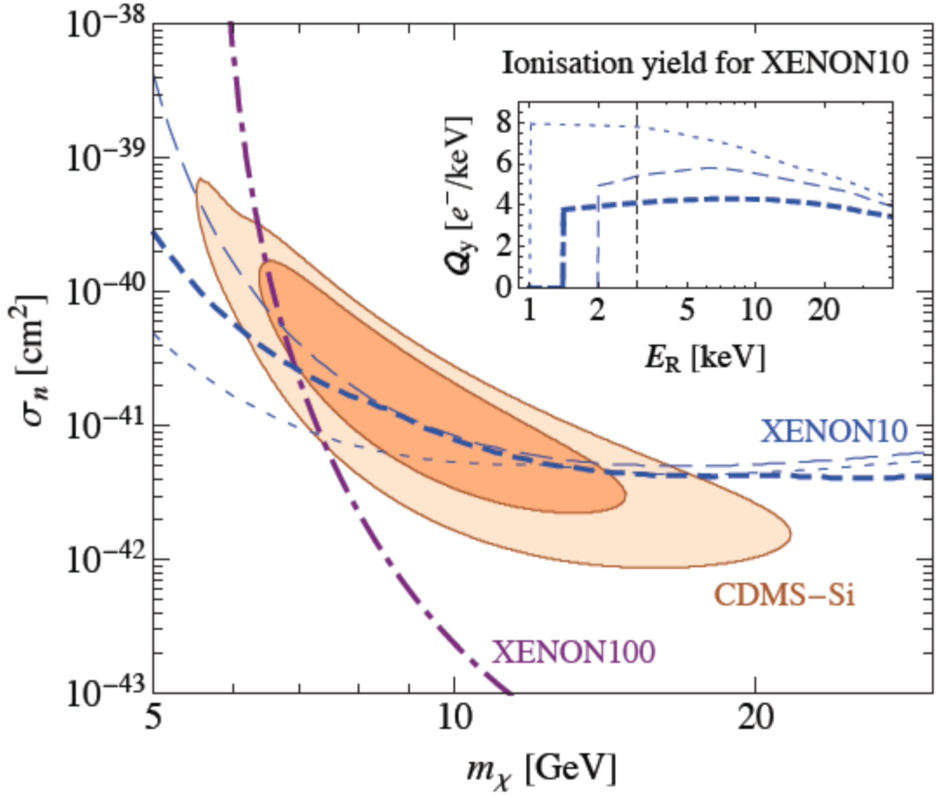


Agnese et al, 1304.4279

- Maximum likelihood at $m_\chi = 8.6\ \mathrm{GeV}$

Constraints from XENON

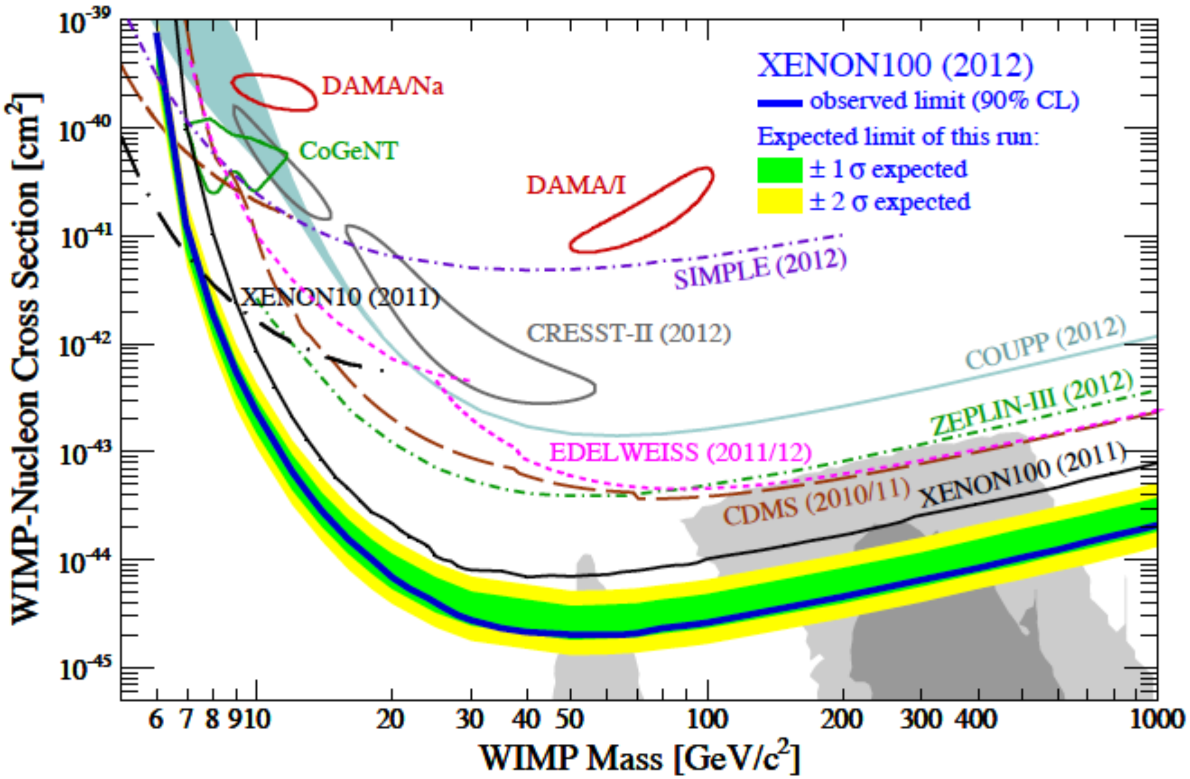
- New analysis of XENON10 data does not rule out light WIMPs. Bounds ***weaker*** by a factor 10 than the published value.



Frandsen et al, 1304.6066

Constraints from XENON

- Strong tension between hints and XENON100 bound:



XENON100 Collaboration, 1207.5988

- **These kind of plots assume SHM and specific DM-nucleus interaction.**

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Astrophysics-independent methods

- Are different experiments consistent? The answer depends significantly on the halo model assumptions.

- Sensitivity to astrophysics may also vary depending on the particle physics model.

Herrero-Garcia, Schwetz, Zupan, 1205.0134

- Give a general method that avoids astrophysical uncertainties when comparing DM modulation signals with the bounds on the time averaged DM scattering rates from different experiments.

- Translate the bound on the *DM scattering rate* in one experiment into a bound on the *annual modulation amplitude* in a different experiment.

Comparison of experiments in v_{min} space

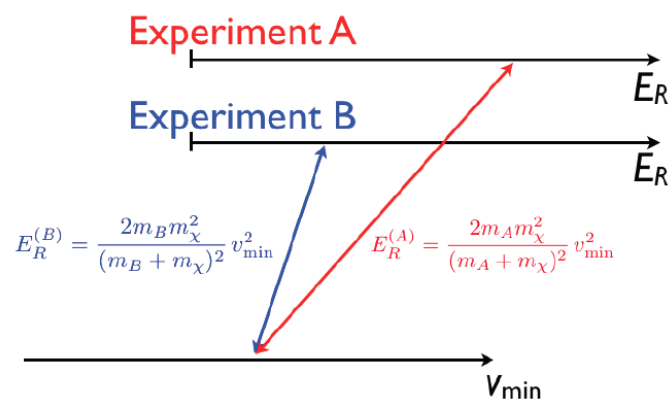
Fox, Kribs, Tait, 1011.1910; Fox, Liu, Weiner, 1011.1915

$$\frac{dR}{dE_R} = \frac{\rho_\chi \sigma_0 F^2(E_R)}{2 m_\chi \mu^2} \eta(v_{\mathrm{min}}) \quad \text{with} \quad \eta(v_{\mathrm{min}}) \equiv \int_{v>v_{\mathrm{min}}} d^3v \, \frac{f_{\mathrm{det}}(\mathbf{v})}{v}$$

- consider now

$$\boxed{\frac{2 m_\chi \mu^2}{\sigma_0 F^2(E_R)} \frac{dR}{dE_R} = \rho_\chi \; \eta(v_{\mathrm{min}})}$$

- r.h.s. is independent of experiment
- transform observed spectrum into function of v_{min} using the l.h.s and $v_{\mathrm{min}} = \sqrt{E_R m_A / 2\mu^2}$



- compare experiments without specifying r.h.s.

General bound on the annual modulation

- Write the halo integral as

$$f_{\rm det}(\mathbf{v},t) = f_{\rm sun}(\mathbf{v}+\mathbf{v}_e(t))$$

$$\eta(v_{\rm min},t) = \int_{v>v_{\rm min}} d^3v\, \frac{f_{\rm sun}(\mathbf{v}+\mathbf{v}_e(t))}{v}$$
$$= \int_{|\mathbf{v}-\mathbf{v}_e(t)|>v_{\rm min}} d^3v\, \frac{f_{\rm sun}(\mathbf{v})}{|\mathbf{v}-\mathbf{v}_e(t)|}$$

- Assume the DM velocity profile in the rest frame of the Sun, $f_{\rm sun}(\mathbf{v})$ is constant on ***timescales of 1 yr***, and on the ***scale of the Sun-Earth distance***. ⇨ Only time dependence due to $\mathbf{v}_e(t)$.

- Expand in the small Earth velocity v_e to ***first order***:

$$\eta(v_{\rm min},t) \approx \underbrace{\int_{v>v_{\rm min}} d^3v\, \frac{f_{\rm sun}(\mathbf{v})}{v}}_{\bar\eta(v_{\rm min})} + \underbrace{v_e \left.\frac{d\eta(v_{\rm min},t)}{dv_e}\right|_{v_e=0}}_{\delta\eta(v_{\rm min},t)}$$

General bound on the annual modulation

$$\eta(v_{\rm min}, t) = \bar{\eta}(v_{\rm min}) + \delta\eta(v_{\rm min}, t)$$

- The modulating part:

$$\delta\eta(v_{\rm min}, t) = A_\eta^{(1)}(v_{\rm min}) \cos 2\pi(t - t_1)$$

after some algebra ***(Herrero-Garcia, Schwetz, Zupan, 1112.1627)***:

$$\boxed{\int_{v_1}^{v_2} dv\, A_\eta^{(1)}(v) \leq v_e \left[\bar{\eta}(v_1) + \int_{v_1}^{v_2} dv \frac{\bar{\eta}(v)}{v}\right]}$$

- The annual modulation amplitude $A_\eta^{(1)}$ is bounded in terms of the unmodulated halo integral $\bar{\eta}$.

Bound for “symmetric” halo

- We can obtain a stronger bound if we assume that there is a preferred constant direction of the DM flow, independent of v_{min}, with an angle $\alpha_{\rm halo}$ with the direction normal to the ecliptic.
- This assumption is fulfilled for:
  - isotropic velocity distributions (e.g. Maxwellian)
  - tri-axial halos (up to the peculiar velocity of the Sun)
  - streams parallel to the motion of the Sun (e.g. dark disc)
- Can check directly in the data:
  - phase of the modulation has to be constant in energy
  - If the preferred direction is aligned with the motion of the Sun, $\sin\alpha_{\rm halo} = 0.5$, and phase fixed on June 2nd.

Applying the bounds to data

General: $$\int_{v_1}^{v_2} dv A_\eta^{(1)}(v) \leq v_e \left[\bar{\eta}(v_1) + \int_{v_1}^{v_2} dv \frac{\bar{\eta}(v)}{v}\right]$$

Symmetric: $$\int_{v_1}^{v_2} dv A_\eta^{(1)}(v) \leq \sin\alpha_{\text{halo}} v_e \bar{\eta}(v_1)$$

- The bounds depend on m_χ, $q(E_R)$, and $F^2(E_R)$, but ***not*** on ρ_χ, σ_p, and v_{esc}.
- A particle physics model has to be specified.
- The l.h.s and r.h.s can refer to different experiments.
- Calculate the l.h.s using modulation data from DAMA or CoGeNT
- Calculate the r.h.s using the bound on $\bar{\eta}$ from XENON, CDMS, …

Herrero-Garcia, Schwetz, Zupan, 1205.0134

Upper bound on $\bar{\eta}$

- The expected number of events in a recoil energy interval $[E_1, E_2]$:

$$N^{\rm pred}_{[E_1,E_2]} = C \int_0^\infty dE_R F^2(E_R) \underbrace{G_{[E_1,E_2]}(E_R)}_{\text{detector response function}} \bar{\eta}(v_{\rm min}(E_R))$$

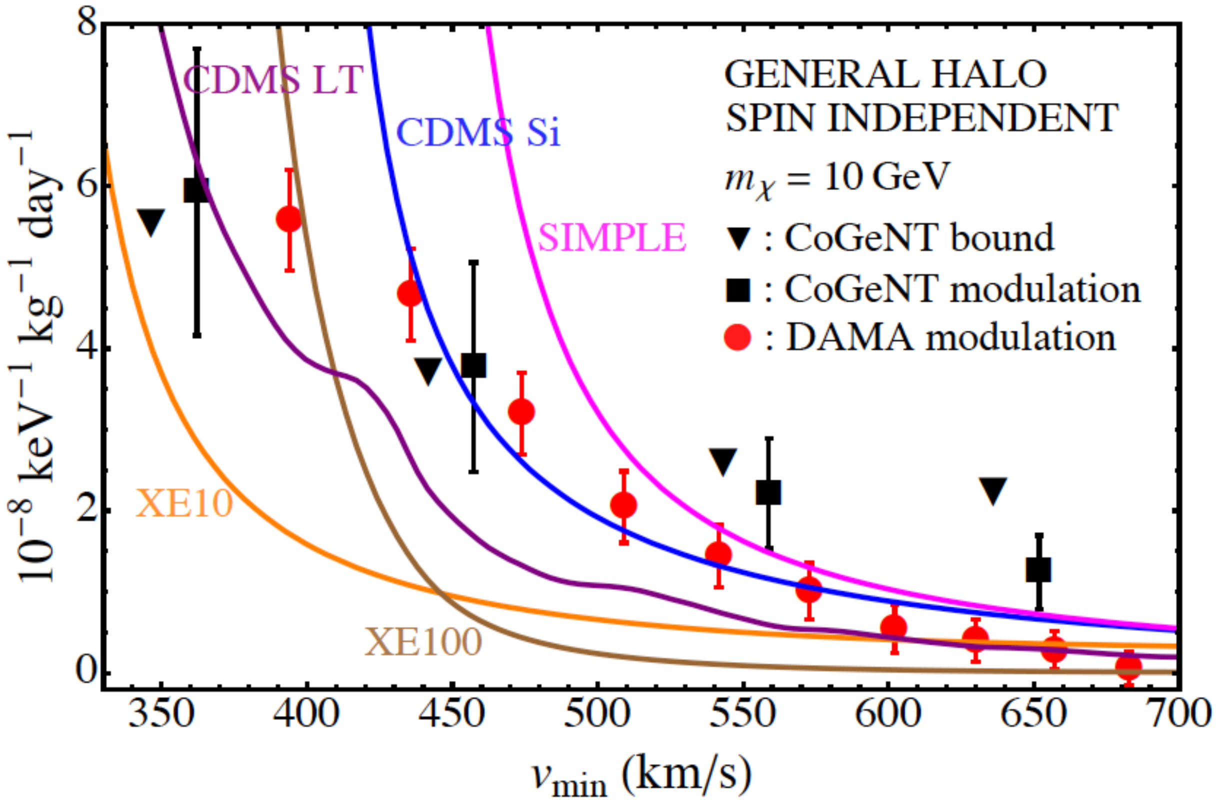
- Since $\bar{\eta}$ is a decreasing function, at a given $v_{\rm min}$ the minimum number of events is obtained for $\bar{\eta}(v) = \bar{\eta}(v_{\rm min})\Theta(v_{\rm min} - v)$

$$N^{\rm pred}_{[E_1,E_2]} \geq C \bar{\eta}(v_{\rm min}) \int_0^{E_R(v_{\rm min})} dE_R F^2(E_R) G_{[E_1,E_2]}(E_R)$$

- We can obtain an upper bound on $\bar{\eta}(v_{\rm min})$ from the observed number of events in XENON100, CDMS, …

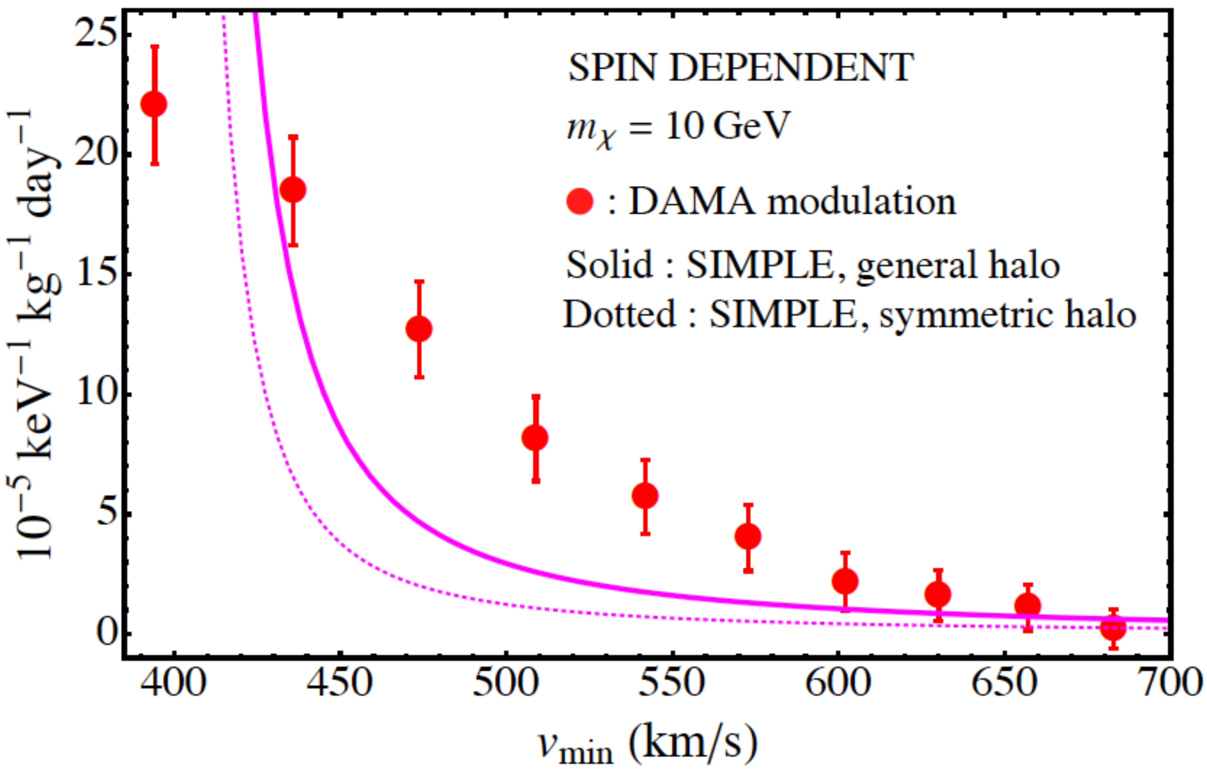
General halo, Spin independent

- Integrated modulation signals from DAMA and CoGeNT compared to the 3 σ upper bounds for the general halo.



Herrero-Garcia, Schwetz, Zupan, 1205.0134

Spin dependent



Herrero-Garcia, Schwetz, Zupan, 1205.0134

- The bound from SIMPLE in strong disagreement with the DAMA modulation signal, due to the presence of Fluorine in their target.

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Validity of the expansion in v_e

- The expansion in v_e requires that $f_{\rm sun}(\mathbf{v})$ is "smooth" enough
  ⇨ variations must be small on the scale of v_e .

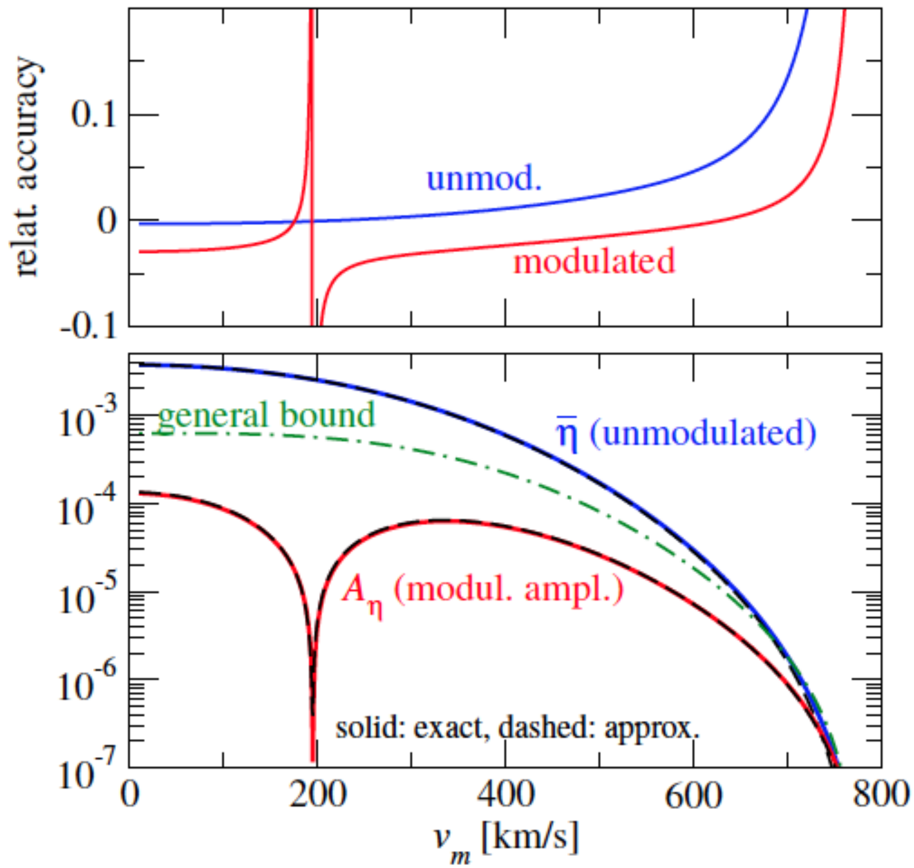
- Extreme features of the halo (like very sharp spikes or edges) should have other observable consequences, such as surprising spectral features or strong energy dependence of the modulation phase.

- Higher order terms in the v_e expansion would show up as higher harmonics in a Fourier analysis of the modulation signal.

  ⇨ can check the validity of the expansion on the data.

Validity of the expansion in v_e

- Accuracy for the Maxwellian:



Herrero-Garcia, Schwetz, Zupan, 1112.1627

Validity of the expansion in v_e

- An important parameter in dimensional analysis is the DM velocity range probed by the experiment, Δv
- The expansion parameter is actually: $v_e/\Delta v$
- So far the expansion was applied to the case of ***elastic*** DM scattering with DM masses ~10 GeV where the expansion is expected to be well-behaved. Typically $\Delta v \sim v_m \gg v_e$
- Expect the expansion to break down for $v_e \sim \Delta v$:
  - for elastic scattering for large DM masses > several 100 GeV.
  - at the edge of the velocity distribution
  - for inelastic scattering
- Higher harmonics become important.

Inelastic scattering

- In ***inelastic*** scattering:

  DM-nucleon interactions require the transition between two DM states of slightly different mass.

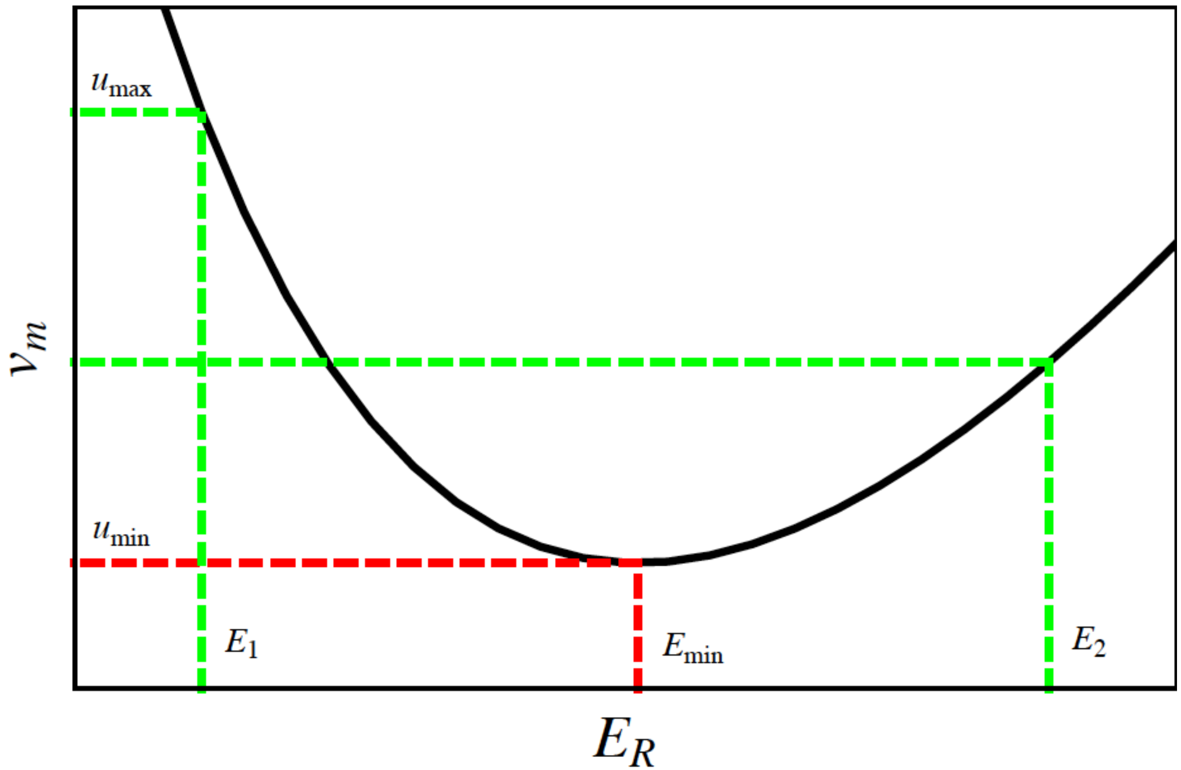
$$v_{\rm min} = \sqrt{\frac{1}{2 m_A E_R}} \left(\frac{m_A E_R}{\mu} + \delta \right)$$

  δ : mass splitting between the two DM states.

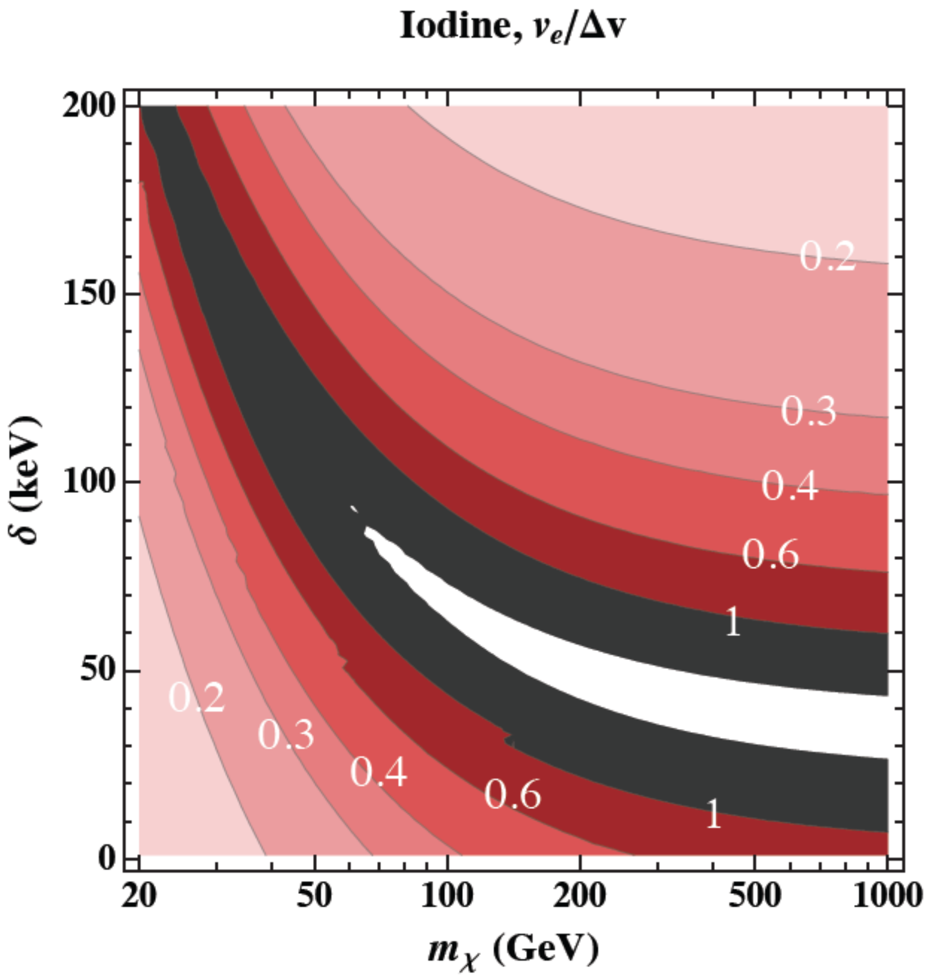
- In inelastic scattering explanations of DAMA or CRESST, the min velocity $v_{\rm min}$ required to deposit the *threshold* energy in the detector is already close to the galactic escape velocity.
  ⇒ The experiment probes the tails of the DM velocity distribution.

Inelastic scattering

- v_m has a minimum in E_R. ➡ No one-to-one correspondence between v_m and E_R. ➡ Should be taken into account when translating from v_m to E_R.



Inelastic scattering



- The expansion breaks down for $v_e/\Delta v \gtrsim 1$

Higher harmonics

- Consider the expansion of the halo integral ***in Earth velocity***:

$$\eta(v_m, t) = \sum_{n=0} v_e^n \, \eta_n(v_m, t)$$

- Also consider the ***Fourier expansion*** of the time dependence of the halo integral:

$$\eta(v_m, t) = \sum_{n=0} A_\eta^{(n)}(v_m) \cos 2n\pi(t - t_n)$$

$A_\eta^{(0)} \equiv \bar{\eta}(v_m)$: time averaged rate

$A_\eta^{(1)}$: annual modulation amplitude

$A_\eta^{(2)}$: semi-annual modulation amplitude

Higher harmonics

- Each amplitude $A_\eta^{(n)}$ can again be expanded in v_e.
- We observe that each amplitude $A_\eta^{(n)}$ receives contributions starting from v_e^n with powers increasing in steps of 2.

$$A_\eta^{(n)}(v_m) = \sum_{i=0} v_e^{n+2i} a_{n+2i}^{(n)}(v_m)$$

The unmodulated rate:

$$\bar{\eta}(v_m) = A_\eta^{(0)}(v_m) = \underbrace{a_0^{(0)}(v_m)}_{\eta_0(v_m)} + v_e^2 a_2^{(0)}(v_m) + \ldots.$$

First harmonic:

$$A_\eta^{(1)}(v_m) = v_e a_1^{(1)}(v_m) + v_e^3 a_3^{(1)}(v_m) + \ldots$$

➡ No corrections at order v_e^2.

Higher harmonics

- In the expansion to first order: $A_{\eta}^{(1)} < v_e \mathcal{O}(\eta_0)$
- The first corrections to those inequalities enter at order v_e^3.
- We derive the astrophysics independent bound on the annual modulation amplitude including terms of order v_e^3.
- The goal is to investigate under which conditions higher order terms are small, as expected for a well-behaved expansion.

Higher harmonics

- We obtain a bound on the integral of $A_\eta^{(1)}(v)$ in terms of an integral of η_0 at first order:

$$\int_{v_1}^{v_2} dv A_\eta^{(1)}(v)(v-v_1) < \frac{v_e}{2}\left(3-\frac{v_1^2}{v_2^2}\right)\int_{v_1}^{v_2} dv\eta_0 + \mathcal{O}(v_e^3)$$

- Estimating: $\Delta v = v_2 - v_1$

$$\int_{v_1}^{v_2} dv A_\eta^{(1)}(v)(v-v_1) \sim \Delta v \int_{v_1}^{v_2} dv A_\eta^{(1)}(v)$$

and neglecting $\mathcal{O}(1)$ coefficients, we can show explicitly that the expansion parameter is $v_e/\Delta v$.

$$\int_{v_1}^{v_2} dv A_\eta^{(1)}(v) \lesssim \frac{v_e}{\Delta v}\int_{v_1}^{v_2} dv\eta_0$$

Higher harmonics

- Formulate conditions on the halo integral which ensure that v_e^3 terms remain small compared to leading order terms.

$$\frac{v_e}{\Delta v}\frac{v_e}{v_1}\eta(v_1) \ll \langle\eta_0\rangle$$

$$\frac{v_e}{\Delta v}v_e\left.\frac{d\eta}{dv}\right|_{v_1,v_2} \ll \langle\eta_0\rangle$$

$$v_e^2\left.\frac{d^2\eta}{dv^2}\right|_{v_2} \ll \langle\eta_0\rangle$$

where $\langle\eta_0\rangle = \frac{1}{\Delta v}\int_{v_1}^{v_2} dv\,\eta_0(v)$

- These conditions imply that the variations of $\eta_0(v_m)$ relative to its mean value should be small on the scale of v_e .

Higher harmonics

$$\int_{v_1}^{v_2} dv A_\eta^{(1)}(v)(v - v_1) < \frac{v_e}{2}\left(3 - \frac{v_1^2}{v_2^2}\right)\int_{v_1}^{v_2} dv \eta_0 + \mathcal{O}(v_e^3)$$

- If the conditions on the halo integral are fulfilled, higher order contributions to the modulation amplitude and $\bar{\eta}$ are small:
  - can use the observed modulation amplitude A_η^{obs} as a determination of the lhs.
  - can use the observed upper bound on the unmodulated rate, η_{bnd} , to constrain η_0 on the rhs.

$$\boxed{\int_{v_1}^{v_2} dv A_\eta^{\mathrm{obs}}(v)(v - v_1) < \frac{v_e}{2}\left(3 - \frac{v_1^2}{v_2^2}\right)\int_{v_1}^{v_2} dv \eta_{\mathrm{bnd}}}$$

Bounds for inelastic scattering

- We present halo independent tests of the tension between the DAMA annual modulation signal and the XENON100 bound in the framework of inelastic scattering.
- In regions where our expansion breaks down, we can use a "trivial bound": the amplitude of the annual modulation has to be smaller than the unmodulated rate:

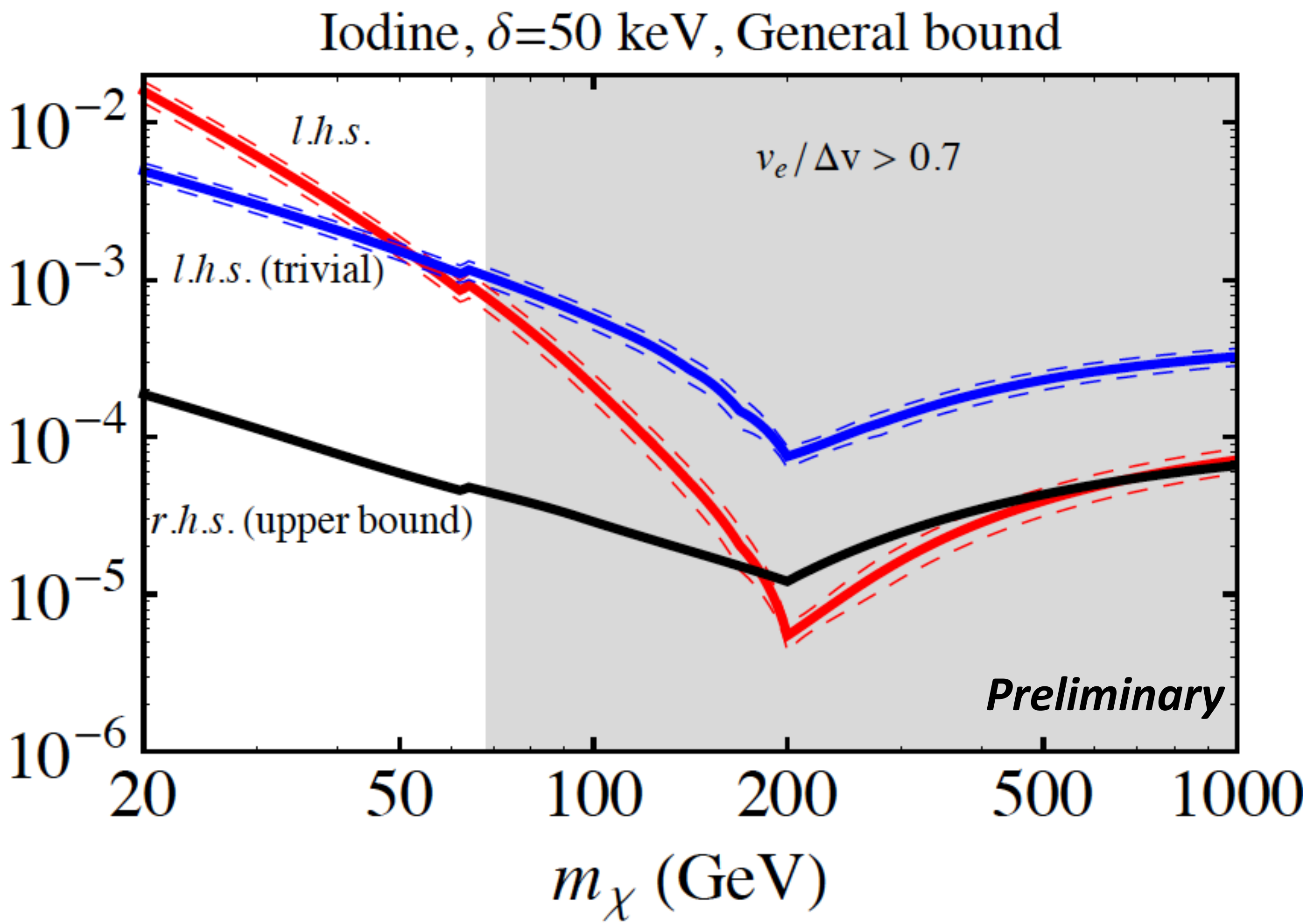
$$\int_{v_1}^{v_2} dv A_\eta^{\mathrm{obs}}(v) < \int_{v_1}^{v_2} dv \eta_{\mathrm{bnd}}(v)$$

$$\frac{v_e}{2}\left(3 - \frac{v_1^2}{v_2^2}\right) \int_{v_1}^{v_2} dv A_\eta^{\mathrm{obs}}(v) < \frac{v_e}{2}\left(3 - \frac{v_1^2}{v_2^2}\right) \int_{v_1}^{v_2} dv \eta_{\mathrm{bnd}}$$

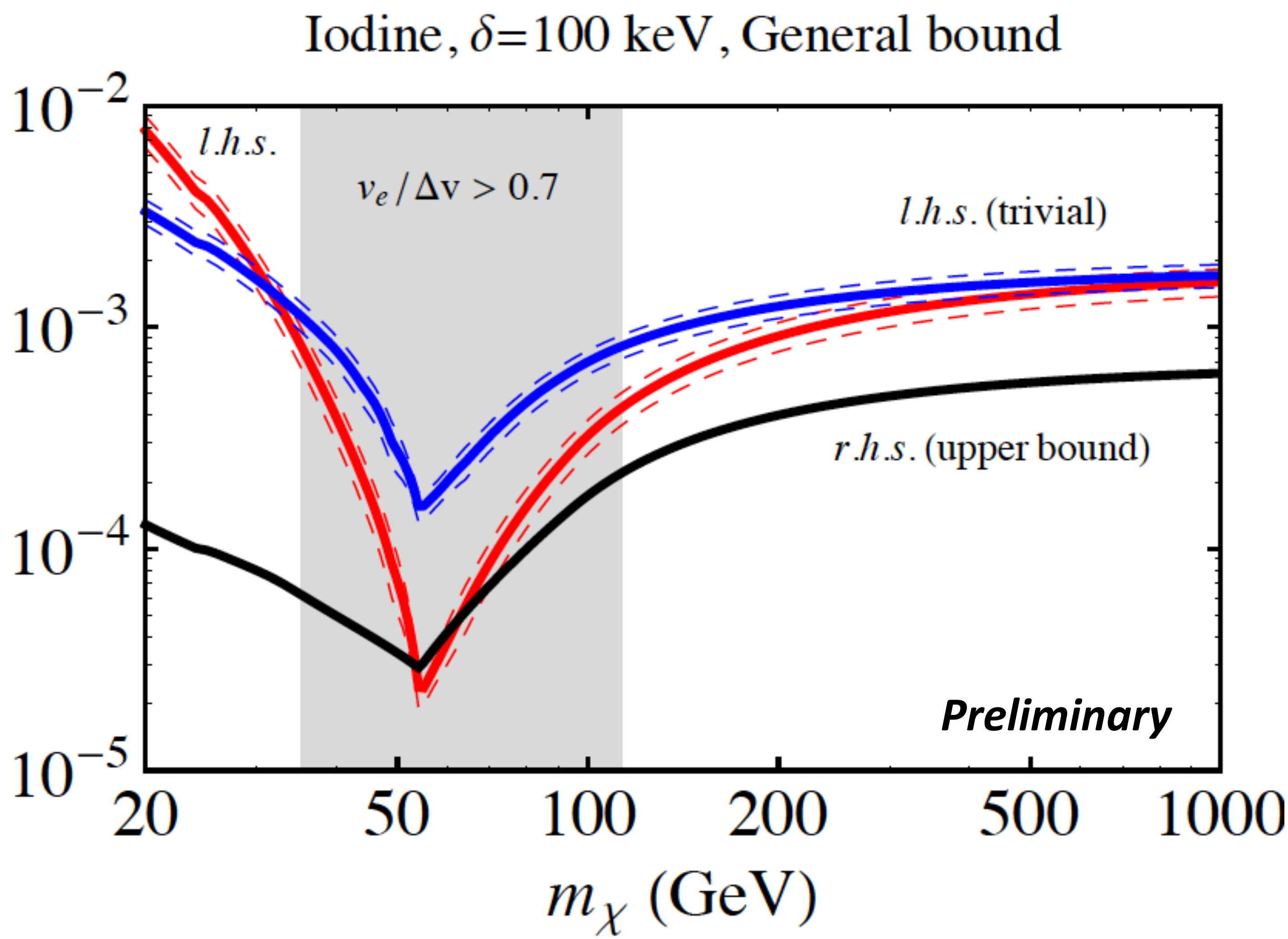
- Clearly this bound is independent of any expansion parameter and is valid in the full parameter space.

Numerical results

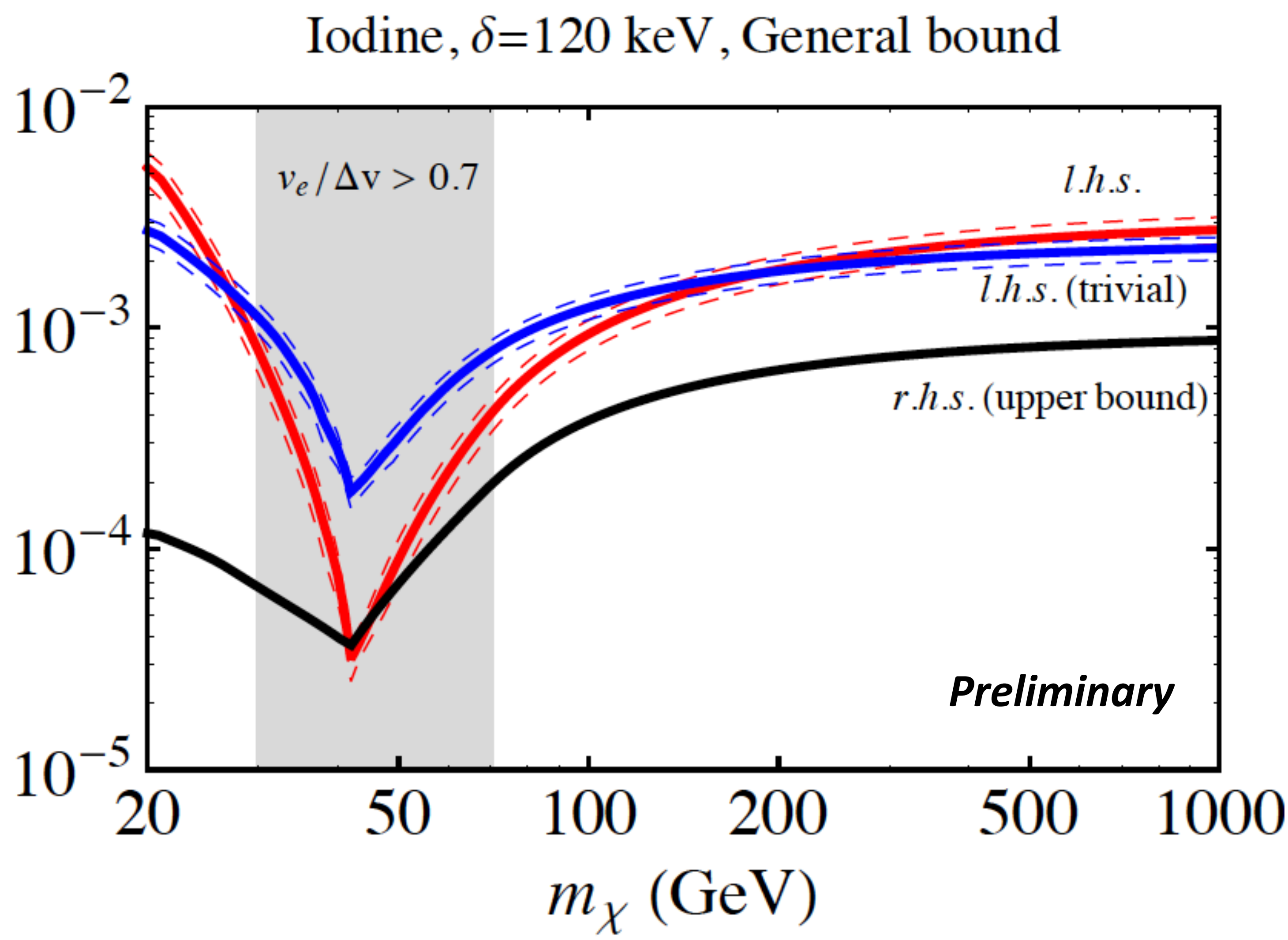
$$\boxed{\int_{v_1}^{v_2} dv A_\eta^{\rm obs}(v)(v - v_1) < \frac{v_e}{2}\left(3 - \frac{v_1^2}{v_2^2}\right)\int_{v_1}^{v_2} dv\eta_{\rm bnd}}$$



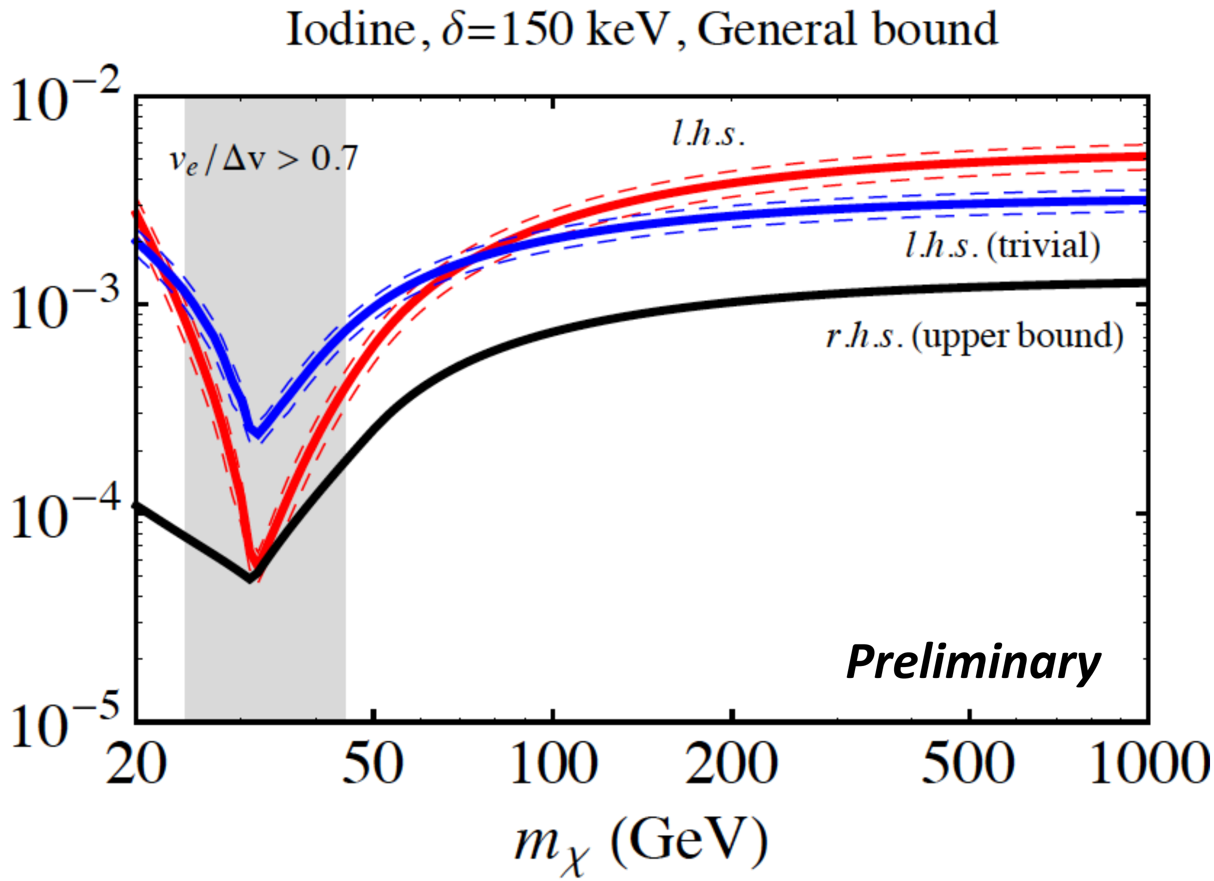
Numerical results



Numerical results



Numerical results



- In most regions of the parameter space, the bound is strongly violated, disfavoring an inelastic scattering interpretation of the DAMA signal halo independently.

Outline

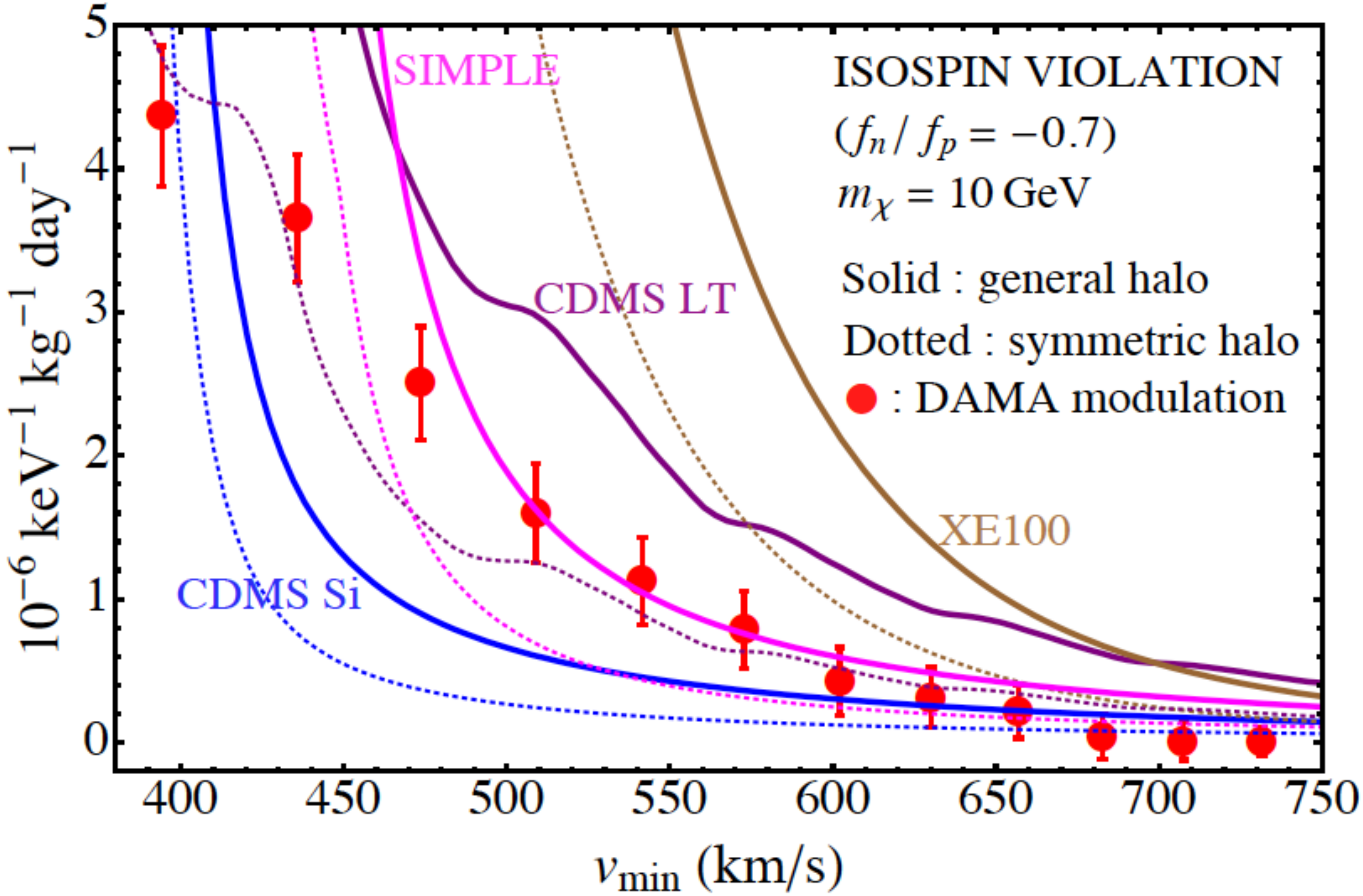
- Direct dark matter detection
- Hints for a signal vs. constraints
- Astrophysics-independent methods
  - A bound on the annual modulation amplitude
  - Higher harmonics in the annual modulation
- Summary

Summary

- Discussed methods to compare different experiments independent of assumptions on DM distribution.
- Can derive astrophysics independent bounds on the annual modulation signal by expanding in v_e .
- The expansion had been applied to the case of ***elastic*** DM scattering for low WIMP mass where the expansion is well-behaved. Strong tension between DAMA and other experiments independent of the DM halo.
- We developed similar methods for the case of inelastic scattering, and confirmed in a halo independent way that the ***inelastic*** scattering explanation of the DAMA signal is in tension with the XENON100 bound.

Additional

Isospin violation



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