Astrophysics independent bounds on the annual modulation of dark matter signals

HAP Dark Matter 2013

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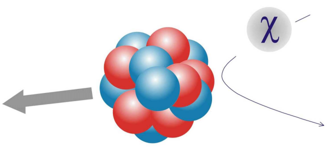
Outline

- Introduction
  - DM direct detection general phenomenology
  - The annual modulation signal
- Hints for a signal?
  - DAMA/LIBRA, CoGeNT, CRESST
- Astrophysics-independent methods
  - A bound on the annual modulation amplitude
- Summary

Dark Matter in a Milkyway-like Galaxy

Dark Matter in the Universe

Dark Matter direct detection



colliding a DM particle ($m_\chi \sim 100$ GeV) with a nucleus ($m_A \sim 100$ GeV) and DM velocity: $v \sim 10^{-3}$c $\Rightarrow$ non-relativistic

$$\text{(elastic) recoil energy:} \quad E_R = \frac{2\mu^2 v^2}{m_A} \cos^2\theta_{\text{lab}} \sim 10\,\text{keV}$$

$\mu \equiv m_\chi m_A/(m_\chi + m_A)$

minimal DM velocity required to produce recoil energy E_R:

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

The differential event rate

cnts / unit detector mass / keV recoil energy E_R:

$$\frac{dN}{dE_R}(t) = n_\chi \frac{1}{m_A} \langle \frac{d\sigma}{dE_R} v \rangle$$
$$= \frac{\rho_\chi}{m_\chi} \frac{1}{m_A} \int_{v > v_{\min}(E_R)} d^3 v \, \frac{d\sigma}{dE_R} \, v \, f_\oplus(\vec{v}, t)$$

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in many models for DM-nucleus interactions:

$$\frac{d\sigma}{dE_R} = \frac{m_A}{2\mu^2 v^2} \sigma_0 |F(E_R)|^2$$

(|scattering amplitude|^2 independent of v)

The differential event rate

cnts / unit detector mass / keV recoil energy E_R:

$$\frac{dN}{dE_R}(t) = n_\chi \frac{1}{m_A} \langle \frac{d\sigma}{dE_R} v \rangle = \frac{\rho_\chi}{m_\chi} \frac{1}{m_A} \int_{v > v_{\min}(E_R)} d^3 v \, \frac{d\sigma}{dE_R} \, v \, f_\oplus(\vec{v}, t)$$

in many models for DM-nucleus interactions:

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

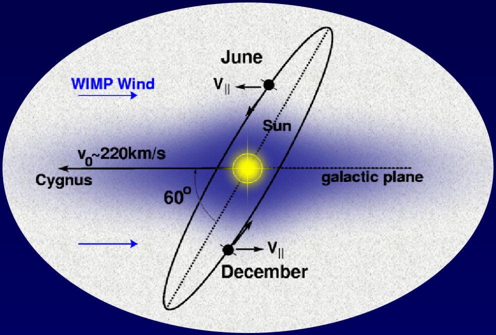
$$\boxed{\eta(v_{\min}, t) \equiv \int_{v > v_{\min}(E_R)} d^3 v \, \frac{f_\oplus(\vec{v}, t)}{v}} = \langle \frac{1}{v} \rangle$$

Annual modulation

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

sun velocity: $\vec{v}_\odot \approx (0, 220, 0) + (10, 13, 7)\,\mathrm{km/s}$

earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30\,\mathrm{km/s}$



What is $f_{\mathrm{gal}}(\vec{v})$?

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We don't know!

What is $f_{\rm gal}(\vec{v})$?

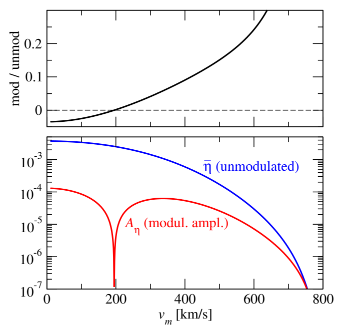
Often a truncated Maxwellian distribution is assumed:

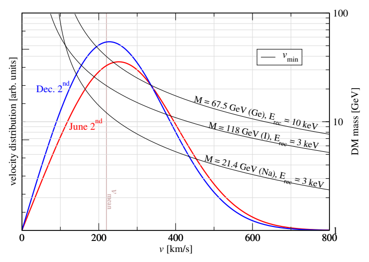
$$f_{\rm gal}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

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

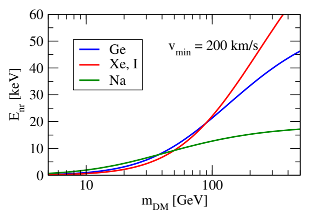
(corresponds to an iso-thermal sphere)

Velocity distribution integral (Maxwellian)





E_{nr} of the phase flip:



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

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

$$A_\eta = \frac{1}{2}[\eta(2 \text{ June}) - \eta(2 \text{ Dec})]$$

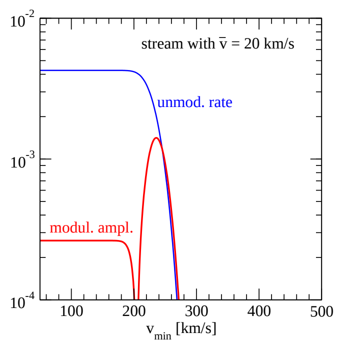
What is $f_{\mathrm{gal}}(\vec{v})$?

Most likely the DM distribution is NOT Maxwellian

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

Non-Maxwellian modulation

cold stream: $f_{\rm gal}(\vec{v}) \propto \delta^3(\vec{v} - \vec{v}_0)$



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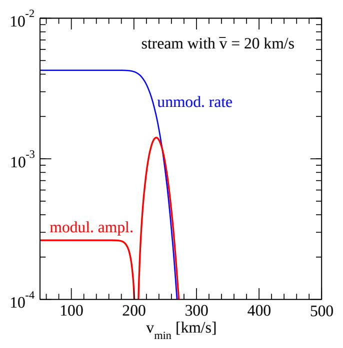
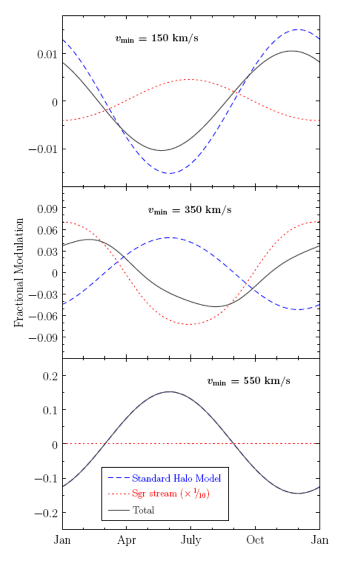




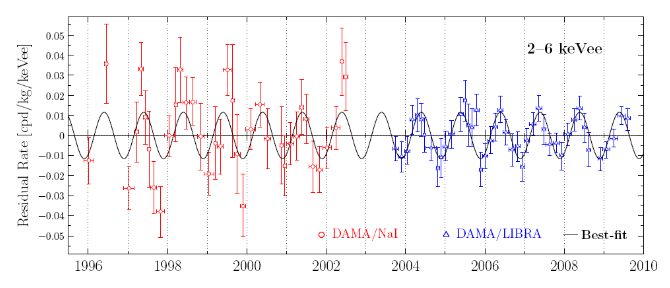
Freese, Lisanti, Savage, 12

in the presence of several halo components the phase as well as the cos-shape of the modulation may be modified e.g., Fornengo, Scopel, 03; Green, 03

Outline

DAMA/LIBRA annual modulation signal

Scintillation light in NaI detector, 1.17 t yr exposure (13 yrs)
~ 1 cnts/d/kg/keV $\quad\rightarrow\quad \sim 4\times 10^5$ events/keV in DAMA/LIBRA
$\sim 8.9\sigma$ evidence for an annual modulation of the count rate with maximum at day 146 ± 7 (June 2nd: 152) **Bernabei et al., 0804.2741, 1002.1028**

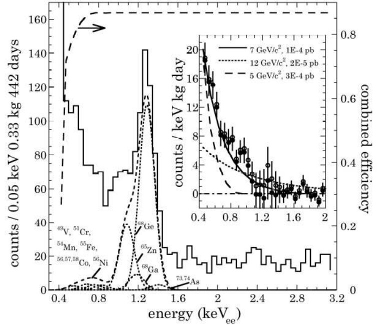


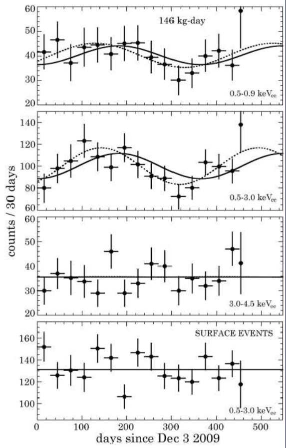
plot from Freese, Lisanti, Savage, 12

consistent with DM interpretation with $m_\chi \sim 10$ GeV or 60 GeV

CoGeNT: exponential event excess and hint for modulation

Germanium detector with very low threshold of
$0.4\,\text{keVee} \approx 1.9\,\text{keV}_{nr}$





Aalseth et al, 1106.0650

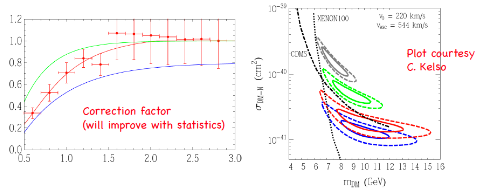
2.8σ preference for modulation

Some comments on CoGeNT results

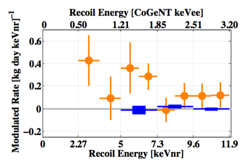
- modulation amplitude “too large” and “too early”

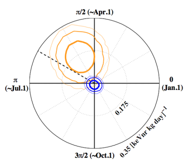
  e.g., TS, Zupan, 11; Fox, Kopp, Lisanti, Weiner, 11; Farina, Pappadopulo, Strumia, Volansky, 11; Chang, Pradler, Yavin, 11; Arina, Hamann, Trotta, Wong, 11

- CoGeNT surface event rejection near threshold **J. Collar @ TAUP 2011**



- constraints from CDMS on modulation **arXiv:1203.1309**



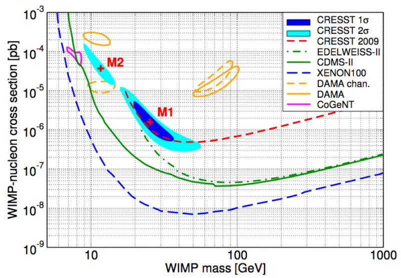


blue: CDMS, orange: GoGeNT; right: 68%, 95%, 99% CL

CRESST-II TAUP 2011, 1109.0702

$CaWO_4$ target, 8 detectors, 730 kg d

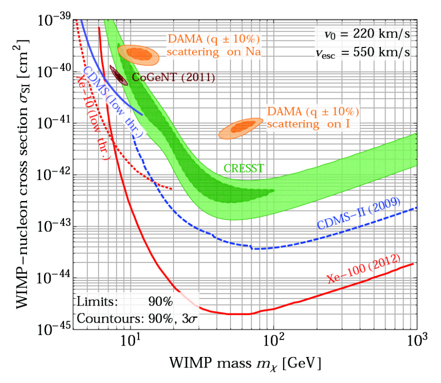
backgrounds: e/γ : 8, α : $\sim$ 11, neutrons: $\sim$ 7, Pb: $\sim$ 15
observe 67 events: likelihood fit gives $\sim$ 29 signal events at $> 4\sigma$



M1: $m_\chi = 25.3$ GeV, significance: 4.7σ (signal: 69% W, 25% Ca, 7% O)
M2: $m_\chi = 11.6$ GeV, significance: 4.2σ (signal: 52% O, 48% Ca)

Constraints from CDMS, XENON, . . .

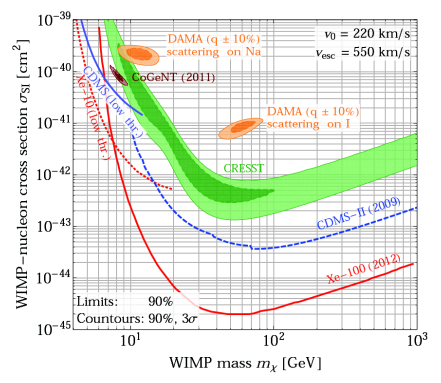
strong tension between hints and various bounds



updated from Kopp, TS, Zupan, 11

Constraints from CDMS, XENON, ...

strong tension between hints and various bounds

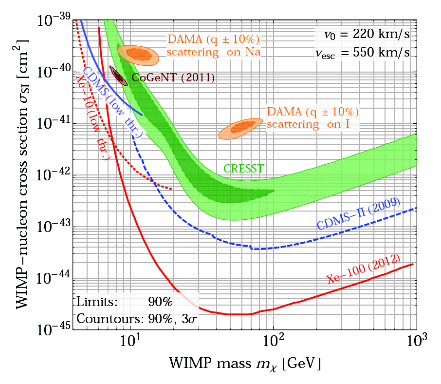


updated from Kopp, TS, Zupan, 11

$\sim$ 10 GeV region is experimentally challenging:
energy scale (DAMA q_{Na}, XENON: L_{eff}), threshold effects (XENON), backgrounds (CoGeNT surface ev., CRESST?),...

Constraints from CDMS, XENON, ...

strong tension between hints and various bounds

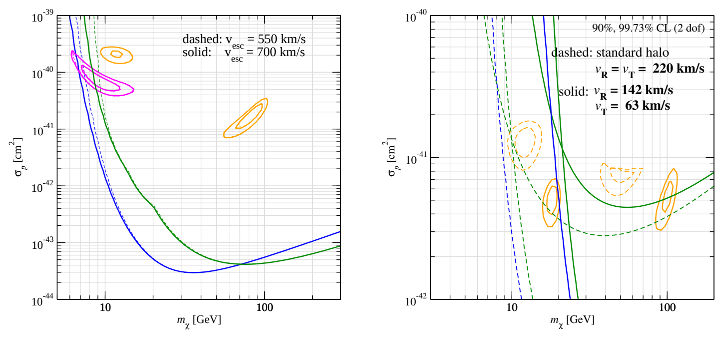


updated from Kopp, TS, Zupan, 11

WARNING: these type of plots assume

- the most simple minded DM-nucleus interaction and
- the most simple minded DM halo!

Dependence on halo assumptions



left: value of v_{esc} **TS, 1011.5432**; right: asymmetric velocity distr. **Fairbairn, TS 0808.0704**

- Conclusions on consistency of different experiments may depend significantly on the assumptions on the halo model.
- Sensitivity to astrophyiscs may also vary depending on the particle physics model.

Outline

Methods independent of halo assumptions

- reconstructing DM properties and halo shape from data

  Drees, Shan, astro-ph/0703651; 0803.4477

- comparison of experiments in $v_{\min}$ space

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

  applied e.g., in **McCabe 1107.0741; Frandsen et al., 1111.0292; Gondolo, Gelmini, 1202.6359**

- halo independent constraints on the modulation amplitude

  Herrero-Garcia, TS, Zupan, 1112.1627, 1205.0134

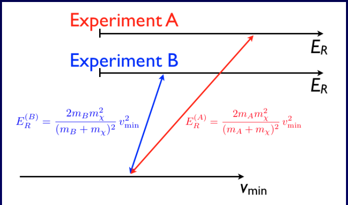
Working in $v_{\min}$ space Fox, Kribs, Tait 1011.1910; Fox, Liu, Weiner, 1011.1915

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

consider now

$$\boxed{\frac{2 m_\chi \mu^2}{\sigma_0 |F(E_R)|^2} \frac{dN}{dE_R} = \rho_\chi \, \eta(v_{\min})}$$

- r.h.s. is independent of experiment (target nucleus)
- fix DM mass, transform observed spectrum into function of $v_{\min}$ using the l.h.s. and $v_{\min} = \sqrt{E_R m_A / (2\mu^2)}$
- comparison of experiments possible without specifying r.h.s.



An upper bound on $\eta(v_{\min})$

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

$$N^{\rm pred}_{[E_1,E_2]} = \mathcal{C} \int_0^\infty dE_{nr} F_A^2(E_{nr}) G_{[E_1,E_2]}(E_{nr})\, \eta(v_{\min}(E_{nr}))$$

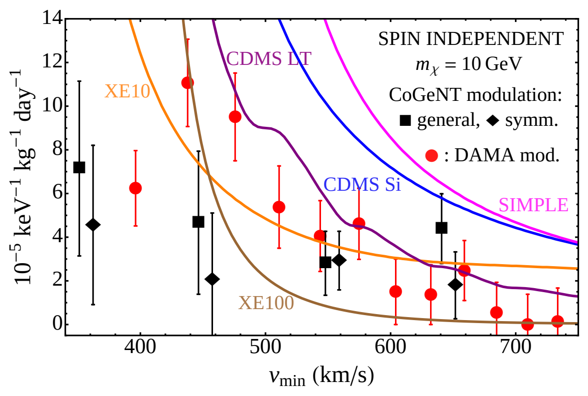
$G_{[E_1,E_2]}(E_{nr})$: detector response function

use that η is a monotonically decreasing function:
at a given $v_{\min}$ the minimal number of events is obtained for a step function $\eta(v) = C\Theta(v_{\min} - v)$

$$N^{\rm pred}_{[E_1,E_2]} \geq \mathcal{C}\, \eta(v_{\min}) \int_0^{E_{nr}(v_{\min})} dE_{nr} F_A^2(E_{nr}) G_{[E_1,E_2]}(E_{nr})$$

obtain an upper bound on $\eta(v_{\min})$ from the # observed events in XENON100, CDMS,...

Limits in $v_{\rm min}$ space



Herrero-Garcia, TS, Zupan, 1205.0134

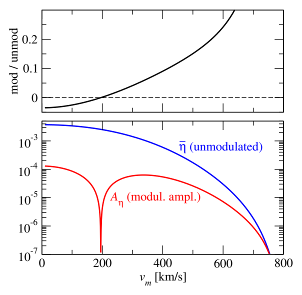
see also, McCabe 1107.0741; Frandsen et al., 1111.0292; Gondolo, Gelmini, 1202.6359

A bound on the annual 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 $\vec{v}_\oplus(t)$.

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

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



"surface term" and "volume term" are competing and lead to the cancellation/phase shift in the modulation

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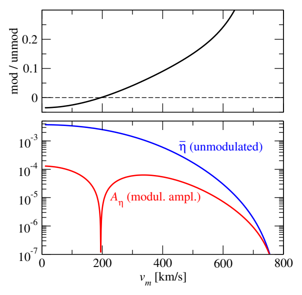

$$\eta(v_{\rm min}, t) = \int_{v>v_{\rm min}} d^3v \, \frac{f_\odot(\vec{v} + \vec{v}_\oplus(t))}{v}$$

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

expand in the small Earth velocity $v_\oplus$:

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

A bound on the annual modulation

the modulating part:

$$\delta\eta(v_m, t) = \vec{v}_\oplus(t) \cdot [\hat{v}_g v_m g(v_m) - \hat{v}_G G(v_m)]$$

$$= A_\eta(v_m) \cos 2\pi[t - t_0(v_m)]$$

where $g(v_m)$ and $G(v_m)$ are known functions of $f_\odot(v)$

$$\int d^3v\, f_\odot(\vec{v}) \frac{\vec{v}}{v^3} \delta(v - v_m) \equiv \hat{v}_g(v_m) g(v_m)$$

$$\int d^3v\, f_\odot(\vec{v}) \frac{\vec{v}}{v^3} \Theta(v - v_m) \equiv \hat{v}_G(v_m) G(v_m)$$

A bound on the annual modulation

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$$= A_\eta(v_m) \cos 2\pi[t - t_0(v_m)]$$

where $g(v_m)$ and $G(v_m)$ are known functions of $f_\odot(v)$

after some algebra **Herrero, TS, Zupan, 11**

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

A bound on the modulation with a "symmetric" halo

A stronger bound can be obtained by assuming that there is only one preferred direction of the DM flow, indep. of v_m, with an angle $\alpha_{\rm halo}$ wrt to the ecliptic.

- single-component halos
- isotropic velocity distributions
- up to the peculiar velocity of the sun also for tri-axial halos
- holds also for streams parallel to motion of sun (dark disc)

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check directly in the data:

- phase of the modulation needs to be constant in energy
- if $\sin \alpha_{\rm halo} = 0.5$ the phase has to be on June 2nd

Numerical results

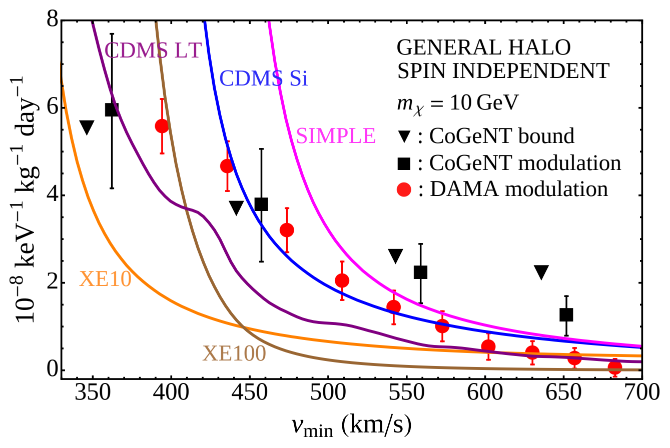
$$\text{general:} \quad \int_{v_1}^{v_2} dv A_\eta(v) \leq v_\oplus \left[\overline{\eta}(v_1) + \int_{v_1}^{v_2} dv \frac{\overline{\eta}(v)}{v} \right]$$

$$\text{symmetric:} \quad \int_{v_1}^{v_2} dv A_\eta(v) \leq \sin \alpha_{\rm halo} \, v_\oplus \, \overline{\eta}(v_1)$$

- choose a particle physics model and DM mass and map all data into v_m space
- take DAMA/CoGeNT data on modulation to calculate l.h.s
- take data from XENON, CDMS,... to bound $\overline{\eta}$ and get r.h.s.

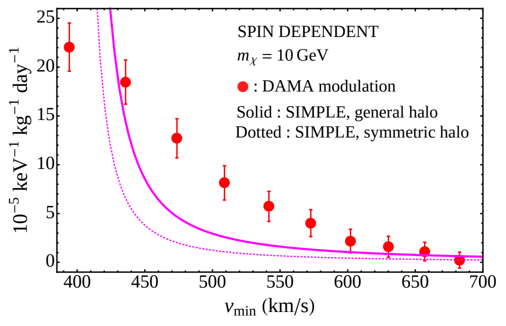
Herrero-Garcia, TS, Zupan, PRL12

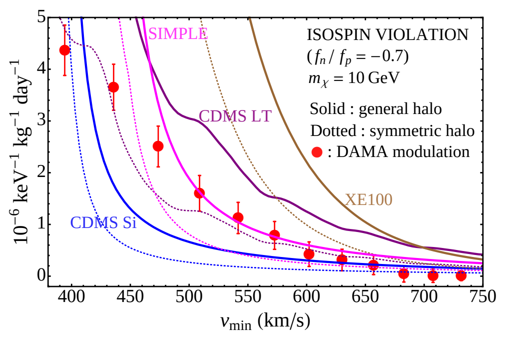
SI interaction



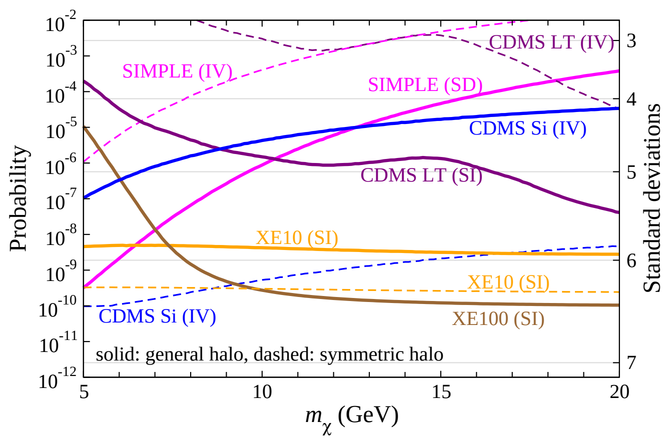
XENON100 limit from 2011

SD/IV


SPIN DEPENDENT
$m_\chi = 10$ GeV
● : DAMA modulation
Solid : SIMPLE, general halo
Dotted : SIMPLE, symmetric halo
10^{-5} keV^{-1} kg^{-1} day^{-1}
v_{min} (km/s)


ISOSPIN VIOLATION
$(f_n / f_p = -0.7)$
$m_\chi = 10$ GeV
Solid : general halo
Dotted : symmetric halo
● : DAMA modulation
SIMPLE
CDMS LT
XE100
CDMS Si
10^{-6} keV^{-1} kg^{-1} day^{-1}
v_{min} (km/s)

exclusion CL of DAMA modulation signal



Expansion in $v_\oplus$

- expanding halo integral in $v_\oplus$ requires that $f_\odot(\vec{v})$ is "smooth" enough: variations should be small on the scale of $v_\oplus$

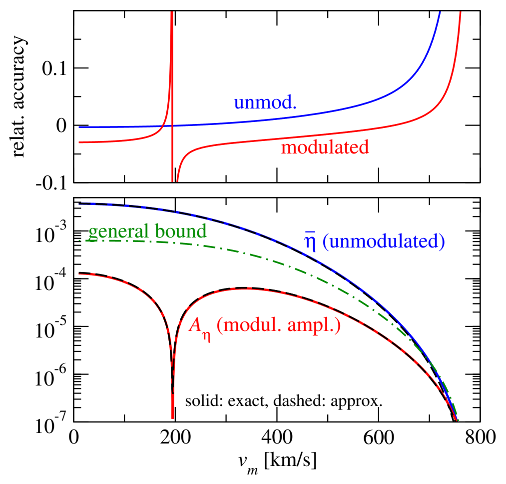
- very strong variations of $f_\odot(\vec{v})$ should also lead to striking features in the modulation signature (e.g., sharp edges in energy, effects on modulation phase)

- higher order terms in the $v_\oplus$ expansion would show up as higher harmonics in a Fourier analysis of the modulation signal

$\rightarrow$ can check the validity of the expansion on the data

Expansion in $v_\oplus$

accuracy for Maxellian:



Expansion in $v_\oplus$

re-write the bound $\int_{v_1}^{v_2} dv A_\eta(v) \leq v_\oplus \, \overline{\eta}(v_1)$ as

$$\int_{v_1}^{v_2} dv A_\eta(v) \leq 2 \frac{v_\oplus}{\Delta} \int_{v_1}^{v_2} dv \overline{\eta}(v) \,, \qquad \Delta \approx v_2 - v_1$$

- the expansion parameter is actually $v_\oplus/\Delta$
- expect the expansion to break down for $v_\oplus \sim \Delta$
  - Δ becomes small for large DM masses $\gtrsim$ several 100 GeV
  - at the edge of the velocity distribution
  - inelastic scattering
- higher harmonics become important

work in progress, Bozorgnia, Herrero, TS, Zupan

Outline

Summary

- The interpretation of results from DM direct detection experiments requires some assumptions about the galactic DM distribution
- It is important to develop and apply methods largely independent of such assumptions
- Comparison of different experiments is possible in an astro-physics independent way

Bound on annual modulation amplitude...

- ...provides powerful test, which any annual modulation signal has to pass if its origin is DM scattering
- combined with "$v_{\rm min}$ method" this leads to strong tension between modulation signals from DAMA/CoGeNT and bounds from other experiments
- a particle physics model has to be specified (showed results for elastic SI, SD, IV interactions)
- bounds are obtained for fixed m_χ but independent of size of DM–nucleon cross section (and also ρ_χ) item bounds are subject to experimental uncertainties (light-yield, quenching factors, backgrounds,...)

Thank You!