Astrophysics-insensitive methods for Dark Matter direct detection

LAPTH, Annecy, France, 25 Oct 2012

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Outline

Introduction
- DM direct detection general phenomenology

Present experimental situation
- Hints for a signal versus constraints

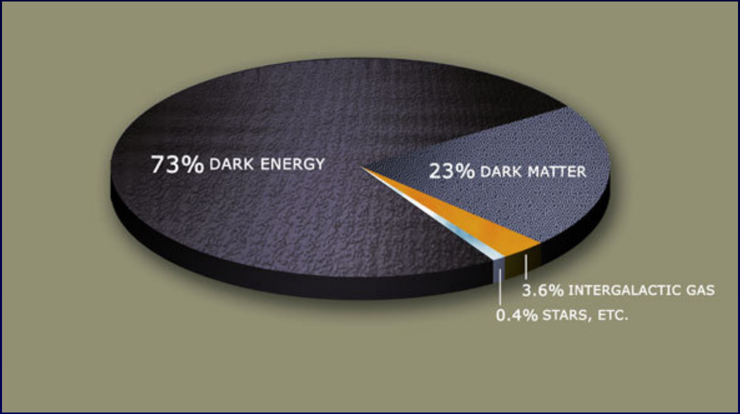
Astrophysics-independent methods

Annual modulation

Comments and outlook

Outline

Dark Matter in the Universe



WMAP 7yr + BAO + H_0: $\Omega_{\rm CDM} = 0.229 \pm 0.015$

(within ΛCDM paradigm)

Dark Matter in a Milkyway-like Galaxy

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Local Dark Matter flux

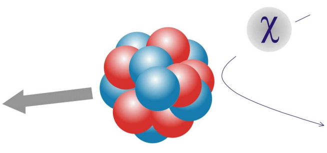
"standard halo model":

local DM density: $\rho_\chi \approx 0.389 \pm 0.025\,\mathrm{GeV\,cm}^{-3}$ Catena, Ullio, 0907.0018

typical DM velocity: $\bar{v} \simeq 220$ km/s

$\Rightarrow$ local DM flux: $\phi_\chi \sim 10^5\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{\rho_\chi}{0.4\,\mathrm{GeV\,cm}^{-3}}\right)$

assuming DM has non-gravitational interactions (“WIMP”)
look for recoil of DM-nucleus scattering M. Goodman, E. Witten, PRD 1985



PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

The signal

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

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

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

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for inelastic scattering $\chi + A \to \chi^* + A$ with $m_{\chi^*} = m_\chi + \delta$:

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

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:

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

The differential event rate

cnts / unit detector mass / keV recoil energy E_R:

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in many models for DM-nucleus interactions:

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

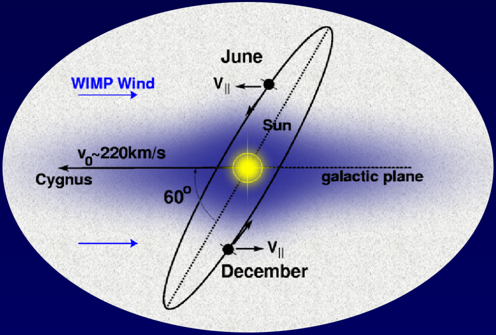
$$\boxed{\eta(v_{\min}, t) \equiv \int_{v > v_{\min}(E_R)} d^3v \, \frac{f_\oplus(\vec{v}, t)}{v}} \qquad = \langle \frac{1}{v} \rangle$$

DM velocity distribution

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

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

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



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

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

We don't know!

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

Often a truncated Maxwellian distribution is assumed:

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

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

(corresponds to an iso-thermal sphere)

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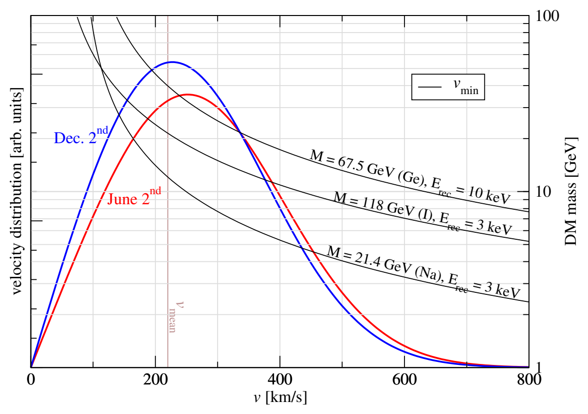
(corresponds to an iso-thermal sphere)

but most likely this is not the real distribution of DM

- 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 integral (Maxwellian)

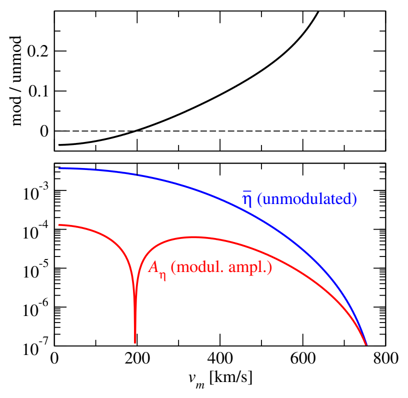
$$\eta(E_R, t) \propto \frac{1}{v_{\rm obs}(t)} \int_{v_{\rm min}(E_R)}^{\infty} dv \left[e^{-\left(\frac{v - v_{\rm obs}(t)}{\bar{v}}\right)^2} - e^{-\left(\frac{v + v_{\rm obs}(t)}{\bar{v}}\right)^2} \right]$$



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

$$v_{\rm obs}(t) = |\vec{v}_\odot + \vec{v}_\oplus(t)|$$

Size of the modulation (Maxwellian)



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

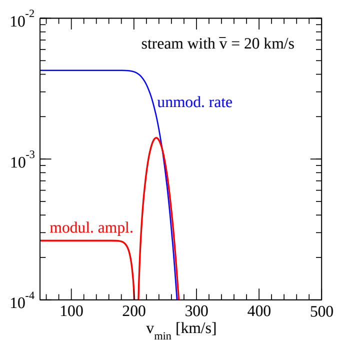
$$v_{\min} = \sqrt{\frac{m_A E_R}{2\mu^2}}$$

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

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

Non-Maxwellian modulation

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



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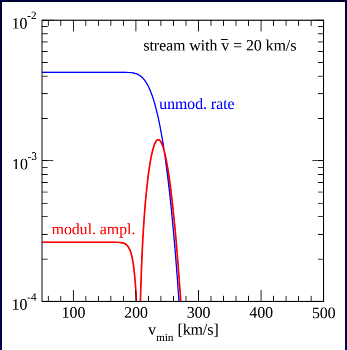
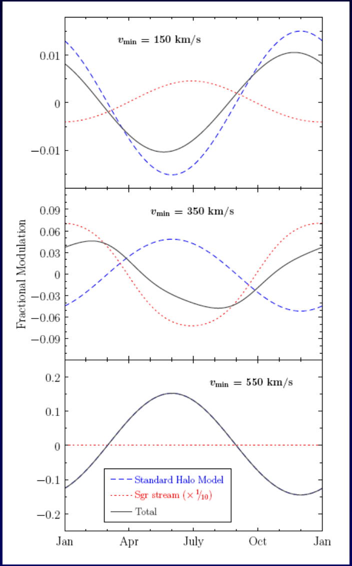




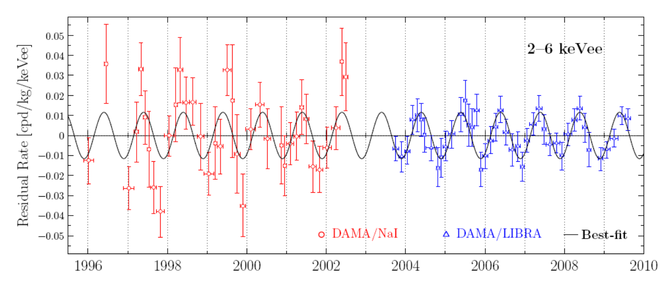
Freese, Lisanti, Savage, 12

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)
$\sim$ 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

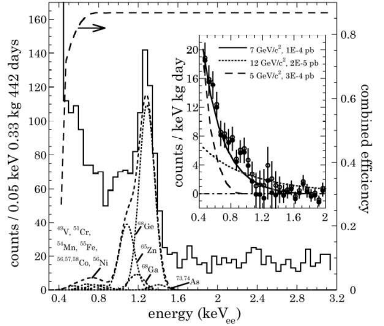


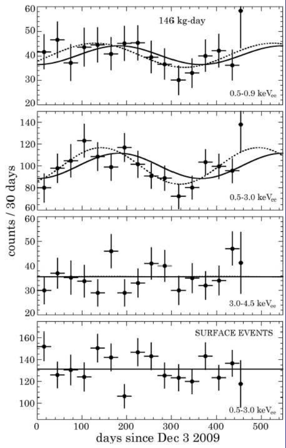
plot from Freese, Lisanti, Savage, 12

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
$0.4\,\mathrm{keVee} \approx 1.9\,\mathrm{keV}_{nr}$

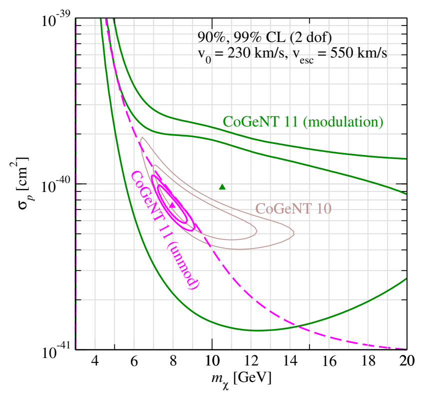




Aalseth et al, 1106.0650

2.8σ preference for modulation

Fitting CoGeNT with elastic SI scattering?



TS, Zupan, 11

see also: Fox, Kopp, Lisanti, Weiner, 11; Chang, Pradler, Yavin, 11; Arina, Hamann, Trotta, Wong, 11

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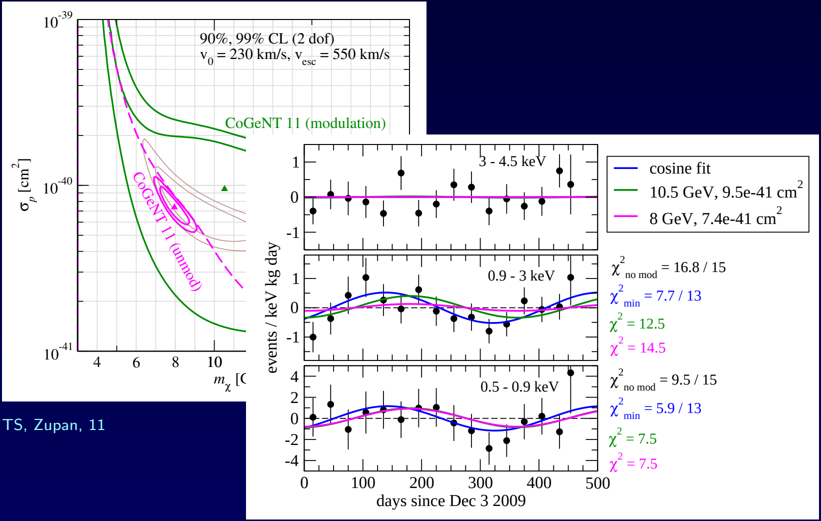
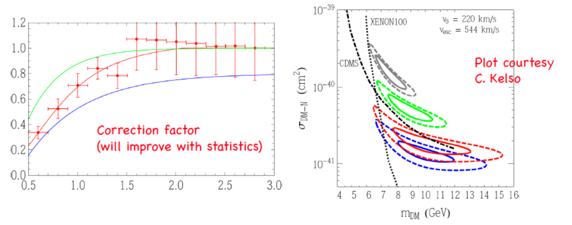


TS, Zupan, 11

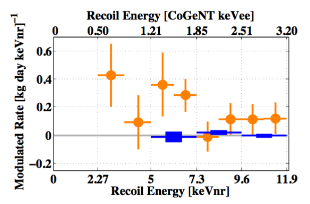
see also: Fox, Kopp, Lisanti, Weiner, 11; Chang, Pradler, Yavin, 11; Arina, Hamann, Trotta, Wong, 11

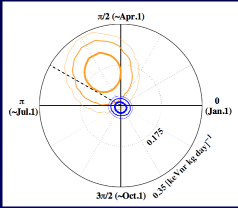
Problems with CoGeNT results?

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



- constraints from CDMS on modulation arXiv:1203.1309



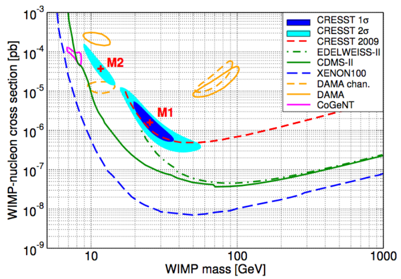


blue: CDMS, orange: GoGeNT; right: 68%, 95%, 99% CL

CRESST-II TAUP 2011, 1109.0702

$CaWO_4$ target, 8 detectors, 730 kg d

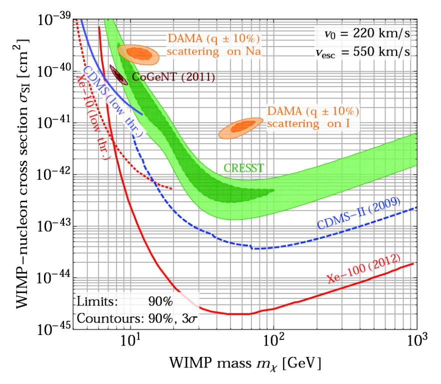
backgrounds: e/γ : 8, α : $\sim$ 11, neutrons: $\sim$ 7, Pb: $\sim$ 15
observe 67 events: likelihood fit gives $\sim$ 29 signal events at $> 4\sigma$



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

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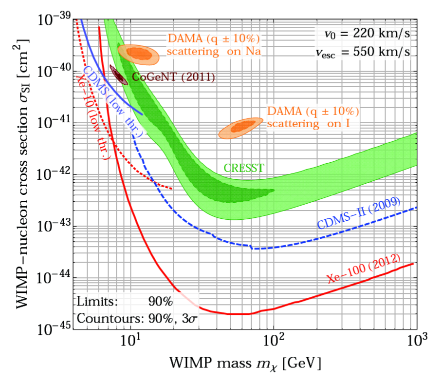


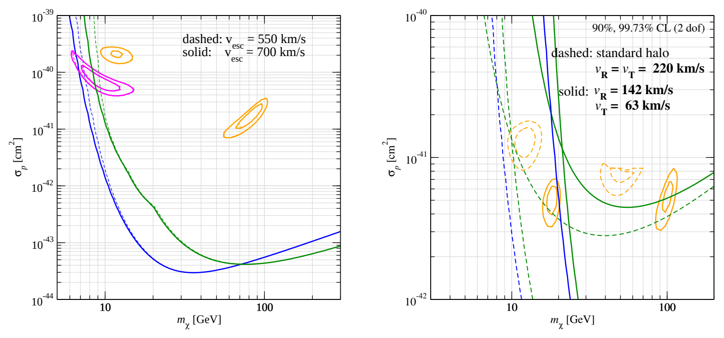
updated from Kopp, TS, Zupan, 11

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

Other types of DM-nucleus interactions

- spin-dependent interaction
- inelastic DM Tucker-Smith, Weiner, hep-ph/0101138
- inelastic SD Kopp, Schwetz, Zupan, 0912.4264
- mirror DM R. Foot; An, Chen, Mohapatra, Nussinov, Zhang, 1004.3296
- leptophilic DM Fox, Poppitz, 0811.0399; Kopp, Niro, Schwetz, Zupan, 0907.3159
- form factor DM Feldstein, Fitzpatrick, Katz, 0908.2991
- momentum dep. DM Scattering Chang, Pierce, Weiner, 0908.3192
- resonant Dark Matter Bai, Fox, 0909.2900
- luminous Dark Matter Feldstein, Graham, Rajendran, 1008.1988
- electro-magnetic DM interactions Masso, Mohanty, Rao, 0906.1979; Chang, Weiner, Yavin, 1007.4200; Barger, Keung, Marfatia, 1007.4345; Fitzpatrick, Zurek, 1007.5325; Banks, Fortin, Thomas, 1007.5515
- iso-spin violating SI scattering Chang, Liu, Pierce, Weiner, Yavin, 1004.0697; Feng, Kumar, Marfatia, Sanford, 1102.4331; Frandsen et al., 1105.3734
- more to come

Dependence on halo assumptions



left: value of $v_{\rm esc}$ 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

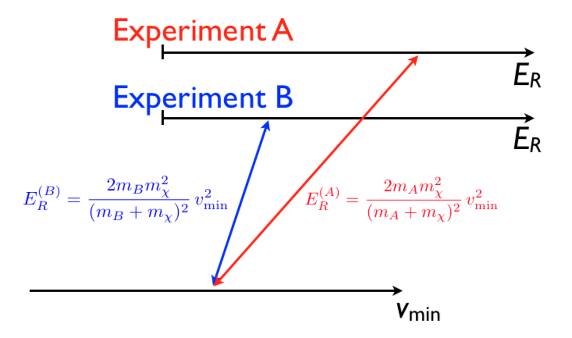
$$\frac{dN}{dE_R} = \frac{\rho_\chi \sigma_0 |F(E_R)|^2}{2 m_\chi \mu^2} \eta(v_{\min}) \quad \text{with} \quad \eta(v_{\min}) \equiv \int_{v > v_{\min}} d^3 v \, \frac{f_\oplus(\vec{v})}{v}$$

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)
- for fixed DM mass, can transform the experimentally observed spectrum (or bound on it) into a function of $v_{\min}$ by using the l.h.s. and $v_{\min} = \sqrt{E_R m_A / (2\mu^2)}$
- the comparison of different experiments is then possibly without specifying the r.h.s.

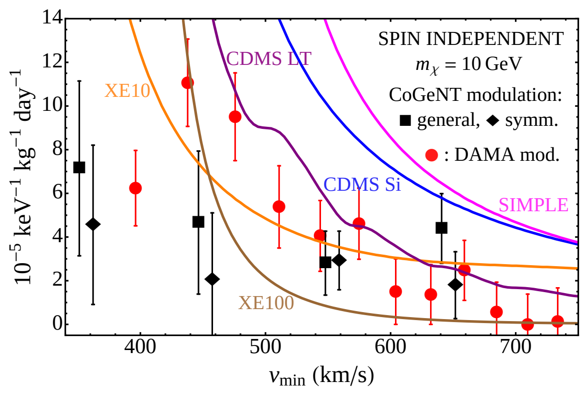
Working in $v_{\min}$ space Fox, Kribs, Tait 1011.1910; Fox, Liu, Weiner, 1011.1915



for fixed m_χ and interaction type the recoil energy in a given experiment can be mapped in $v_{\min}$

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

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



Herrero-Garcia, TS, Zupan, 1205.0134

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

Outline

A bound on the annual modulation

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

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

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

Under the assumption of time-independent $f_\odot(\vec{v})$ the only time dependence enters via $\vec{v}_\oplus(t)$.

A bound on the annual modulation

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

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

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

A bound on the annual modulation

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

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

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

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

A bound on the annual modulation

the modulating part:

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

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

with

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

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

A bound on the annual modulation

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using $g(v_m) \geq 0$ and $G(v_m) \geq 0$ we can bound the amplitude:

$$A_\eta(v_m) \leq v_\oplus [v_m g(v_m) + G(v_m)]$$

A bound on the annual modulation

it is easy to show that

$$g(v_m) \le -\frac{1}{v_m}\frac{d\overline{\eta}}{dv_m}\,, \qquad G(v_m) \le \frac{\overline{\eta}(v_m)}{v_m} - \int_{v_m} dv\,\frac{\overline{\eta}(v)}{v^2}$$

and we can bound the modulation amplitude in terms of the unmodulated rate:

$$\begin{aligned} A_\eta(v_m) &\le v_\oplus \left[v_m g(v_m) + G(v_m)\right] \\ &\le v_\oplus \left[-\frac{d\overline{\eta}}{dv_m} + \frac{\overline{\eta}(v_m)}{v_m} - \int_{v_m} dv\,\frac{\overline{\eta}(v)}{v^2}\right] \end{aligned}$$

or

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

A bound on the modulation with a "symmetric" halo

the modulating part:

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

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

with

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

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

A bound on the modulation with a "symmetric" halo

the modulating part:

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

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

with

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

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

let us assume that $\hat{v}_G = \hat{v}_g = \hat{v}_{\rm halo}$ independent of v_m

A bound on the modulation with a “symmetric” halo

$$\int_{v_1}^{v_2} dv\, A_\eta(v) \le v_\oplus \sin\alpha_\mathrm{halo} \left[\overline{\eta}(v_1) - v_1 \int_{v_1}^{v_2} dv \frac{\overline{\eta}(v)}{v^2}\right]$$

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

- α_halo is the angle between the DM direction $\hat{v}_\mathrm{halo}$ and a vector orthogonal to the ecliptic
- in many situations (static halo) $\hat{v}_\mathrm{halo}$ is the direction of the sun velocity, and in this case $\sin\alpha_\mathrm{halo} = 0.5$
- in general can use $\sin\alpha_\mathrm{halo} \le 1$

A bound on the modulation with a "symmetric" halo

Under which condidtions is the assumption of constant $\hat{v}_{\mathrm{halo}}$ fulfilled?

- 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)

A bound on the modulation with a "symmetric" halo

Under which condidtions is the assumption of constant $\hat{v}_{\rm halo}$ fulfilled?

- single-component halos
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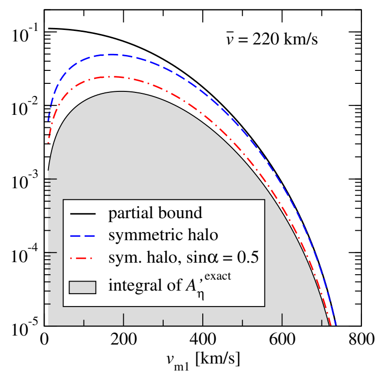
check directly in the data:

- 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

The bound for the Maxwellian halo

$$\int_{v_1}^{v_2} dv\, A_\eta(v) \le v_\oplus \sin\alpha_{\rm halo} \left[\overline{\eta}(v_1) - v_1 \int_{v_1}^{v_2} dv \frac{\overline{\eta}(v)}{v^2}\right]$$



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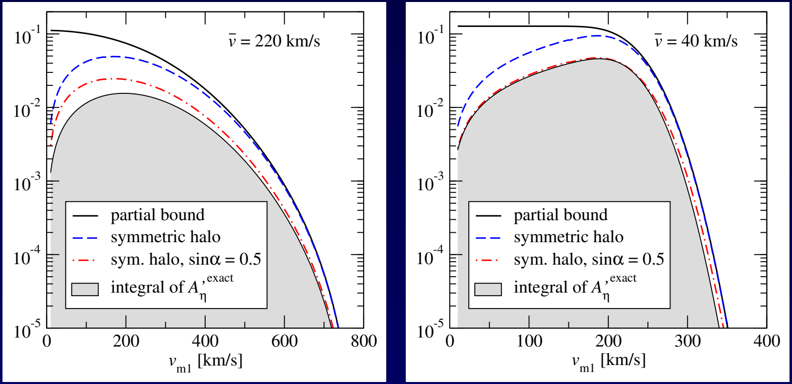


Numerical results

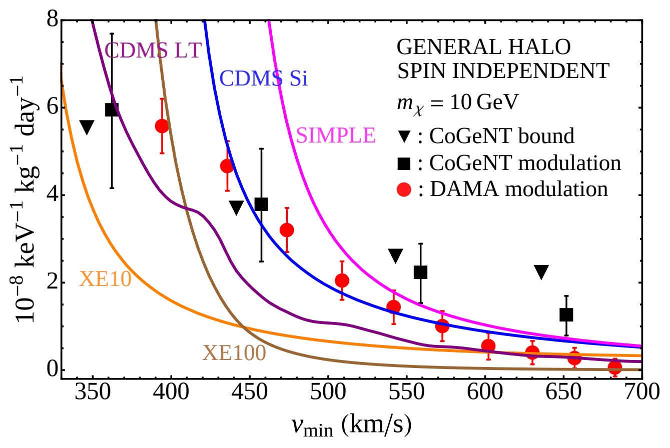
$$\text{general:} \quad \int_{v_1}^{v_2} dv\, A_\eta(v) \leq v_\oplus \left[\overline{\eta}(v_1) + \int_{v_1}^{v_2} dv \frac{\overline{\eta}(v)}{v} \right]$$

$$\text{symmetric:} \quad \int_{v_1}^{v_2} dv\, A_\eta(v) \leq 0.5\, v_\oplus\, \overline{\eta}(v_1)$$

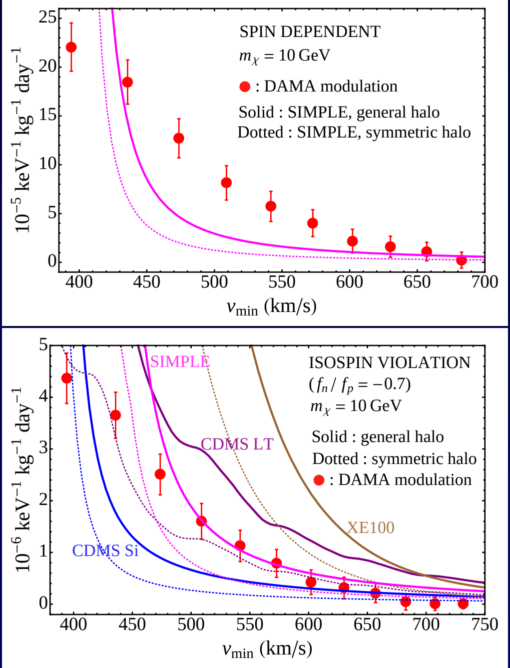
- choose a particle physics model and DM mass and map all data into v_m space
- take DAMA/CoGeNT data on modulation to calculate l.h.s
- take data from XENON, CDMS,... to bound $\overline{\eta}$ and get r.h.s.

Herrero-Garcia, TS, Zupan, PRL12

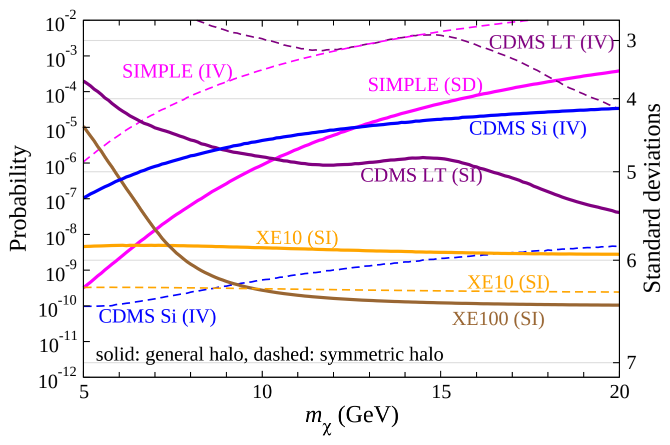
SI interaction



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



Outline

Discussion

We presented a powerful test, which any annual modulation signal has to pass if its origin is DM scattering

Discussion

We presented a powerful test, which any annual modulation signal has to pass if its origin is DM scattering

Assumptions:

- halo is constant on time scales of years and distant scales of the sun-earth distance
- for "symmetric" halos stronger bounds can be obtained (apply to a large class of halo models)
- combined with "$v_{\rm min}$ method" this leads to strong tension between current modulation signals and bounds from other experiments

Discussion

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Assumptions:

- 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)

Discussion

We presented a powerful test, which any annual modulation signal has to pass if its origin is DM scattering

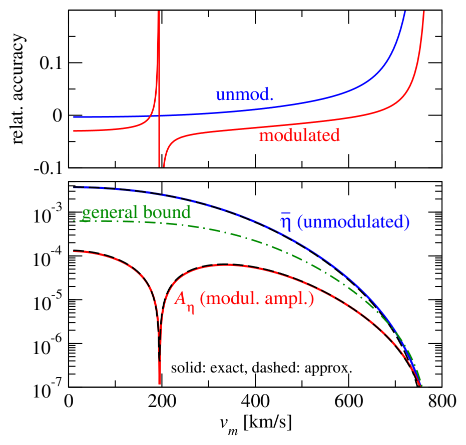
Assumptions:

- 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)
- bounds are still subject to experimental uncertainties (light-yield, quenching factors,...)

Expansion in $v_\oplus$

- the bounds are based on expanding the halo integral in the small quantity $v_\oplus / v_{\rm min}$
- this requires that $f_\odot(\vec{v})$ is "smooth" enough: variations small on the scale of $v_\oplus$
- might not be fulfilled at the edge of very cold streams

Accuracy of the expansion for the standard Maxellian halo:



Validity of the expansion in $v_\oplus$

- 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

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

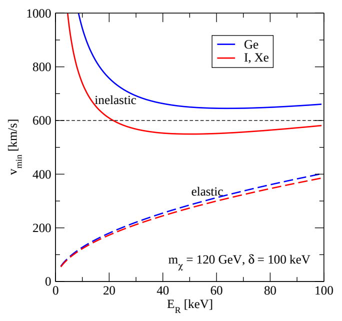
Outlook for future work

- take into account higher order corrections in the $v_\oplus$ expansion

Outlook for future work

- take into account higher order corrections in the $v_\oplus$ expansion
- generalize to inelastic scattering

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



  - $v_{\min} \leftrightarrow E_R$ mapping is no longer unique
  - sampling only tail of distribution, higher order in $v_{\min}$ may become important

Merci