Solar gravitational focusing and WIMP direct detection

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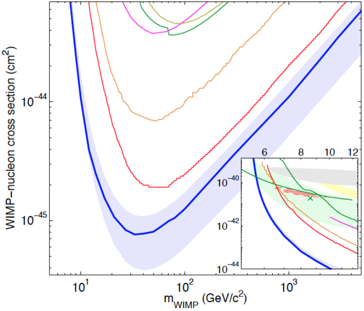
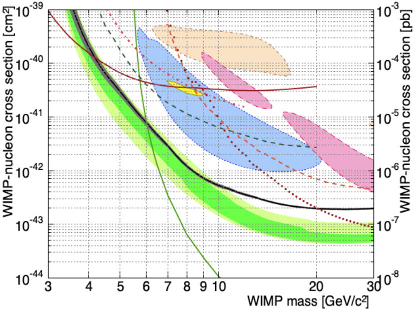
Based on work done with T. Schwetz [1405.2340]

Direct dark matter detection

- Assuming elastic spin-independent scattering, strong tension between hints for a signal and exclusion limits:



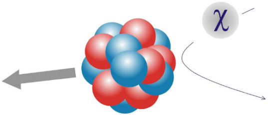
LUX Collaboration, 1310.8214



SuperCDMS Collaboration, 1402.7137

Direct dark matter detection

- Look for energy deposited in low-background detectors by the scattering of WIMPs in the dark halo of our galaxy.
- WIMP-nucleus collision:



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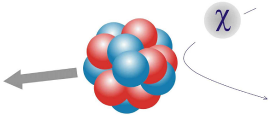

- Minimum WIMP speed required to produce a recoil energy E_R:

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

The differential event rate

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

$$R(E_R, t) = \frac{\rho_\chi}{m_\chi} \frac{1}{m_A} \int_{v>v_m} d^3v \frac{d\sigma_A}{dE_R}\ v\ f_{\rm det}(\mathbf{v}, t)$$

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

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

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

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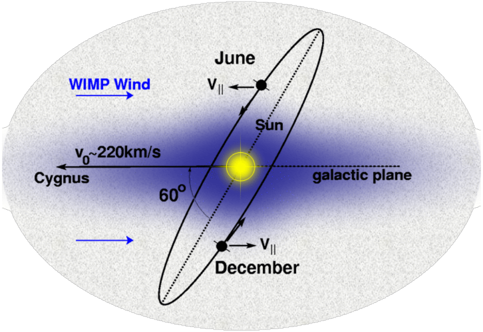
- The time dependence of $R(E_R, t)$ due to the velocity of the Earth around the Sun, $\mathbf{v}_e(t)$.

Annual modulation

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

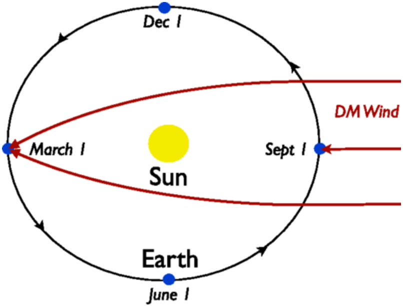
Max in June
Min in Dec



Gravitational focusing

- Sun's gravitational potential changes the phase space density of galactic dark matter particles at Earth.

Max in March
Min in Sep



Griest, PRD 1988
Sikivie and Wick, astro-ph/0203448
Alenazi and Gondolo, astro-ph/0608390
Lee, Lisanti, Peter, Safdi, 1308.1953

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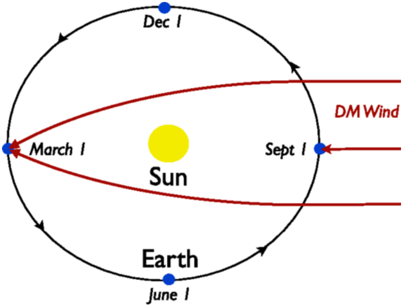

- The net modulation comes from an interplay of the annual modulation and gravitational focusing (GF).

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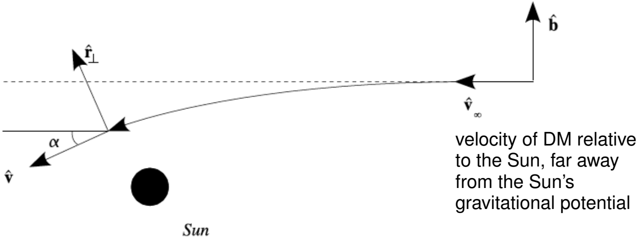
Gravitational focusing

- Due to Liouville's theorem, the phase-space density of DM is constant in time along trajectories.

$$\rho_\chi\ f_{\rm gal}(\mathbf{v}_s+\mathbf{v}+\mathbf{v}_e(t)) = \rho_\infty\ f_{\rm gal}(\mathbf{v}_s+\mathbf{v}_\infty[\mathbf{v}+\mathbf{v}_e(t)])$$

r.h.s measured *near the Solar System*, but *far away from the Sun*, such that Sun's gravitational potential is small.
$\rho_\infty = 0.3$ GeV/cm^3



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The halo integral

$$R(E_R, t) = \frac{\rho_\infty}{m_\chi} \frac{1}{m_A} \int_{v > v_m} d^3v \, \frac{d\sigma_A}{dE_R} \, v \, f_{\rm gal}(\mathbf{v}_s + \mathbf{v}_\infty[\mathbf{v} + \mathbf{v}_e(t)])$$

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

$$\frac{d\sigma_A}{dE_R} = \frac{m_A A^2}{2\mu_{\chi p}^2 v^2} \, \sigma_{\rm SI} \, F^2(E_R)$$

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$$R(E_R,t)=\underbrace{\frac{A^2\sigma_{\rm SI}F^2(E_R)}{2m_\chi\mu_{\chi p}^2}}_{\rm particlephysics}\;\underbrace{\rho_\infty\eta(v_m,t)}_{\rm astrophysics}$$

where

$$\eta(v_m,t)\equiv\int_{v>v_m} d^3v\;\frac{f_{\rm gal}(\mathbf{v}_s+\mathbf{v}_\infty[\mathbf{v}+\mathbf{v}_e(t)])}{v}$$

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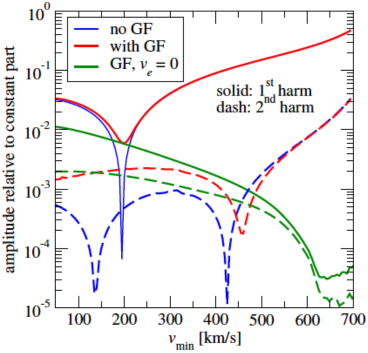
$$\eta(v_m, t) \equiv \int_{v > v_m} d^3v \, \frac{f_{\rm gal}(\mathbf{v}_s + \mathbf{v}_\infty[\mathbf{v} + \mathbf{v}_e(t)])}{v}$$

- The time variation of $\eta(v_m, t)$ is independent of particle physics, DM mass, and experimental configuration.

Time dependence of the halo integral

- Assuming the Standard Halo Model, calculate $\eta(v_m, t)$.
- For a fixed v_m, perform a Fourier decomposition in time.



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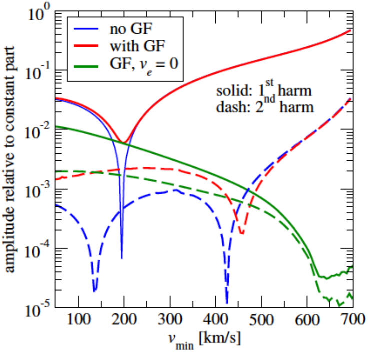
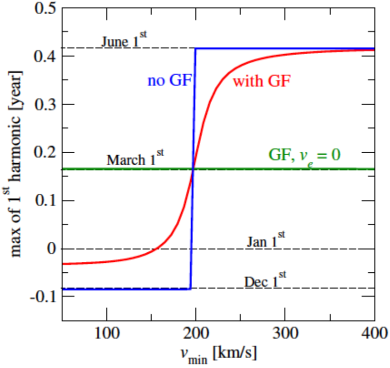


- Amplitude of first harmonic hardly affected by GF, except close to the phase flip.
- Amplitude of 2nd harmonic significantly affected by GF. $\Rightarrow$ disappearance of one of the phase flips.

Time dependence of the halo integral



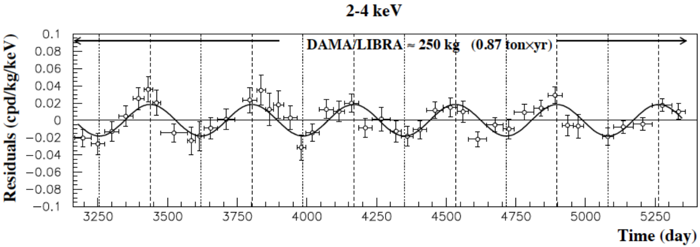
- Significant distortion of the maximum of the first harmonic around and below the phase flip. ⇒ results in agreement with Lee *et al.*, 1308.1953.
- Date of maximum moves smoothly from around Dec 20 at very low v_m to beginning of June for large v_m.

Our analysis

- We focus on the first harmonic which is easier to observe.
- Main effect of GF is the modification of the phase, especially for $v_m \lesssim 250$ km/s [Lee *et al.*, 1308.1953].
- We perform numerical studies of the statistical significance of GF in (semi)realistic experimental situations.
- Investigate the effect of GF for extracting dark matter parameters.

GF and the DAMA signal

- Data are presented either binned in time or in energy.
- Main effect of the GF is a change in the time behavior of the signal. $\Rightarrow$ we use time binned data.



DAMA/LIBRA Collaboration, 1002.1028

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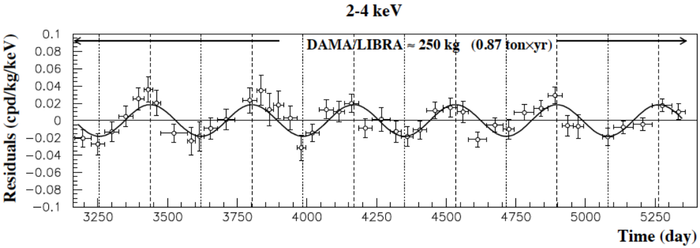
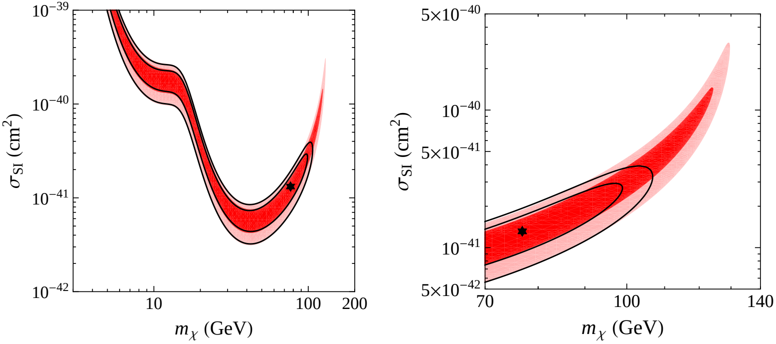


DAMA/LIBRA Collaboration, 1002.1028

- Construct a χ^2 function to fit the DAMA data:

$$\chi^2_{\rm DAMA}(m_\chi, \sigma_{\rm SI}) = \sum_{i=1}^{i=43} \left(\frac{A_i^{\rm pred}(m_\chi, \sigma_{\rm SI}) - A_i^{\rm obs}}{\sigma_i} \right)^2$$

GF and the DAMA signal



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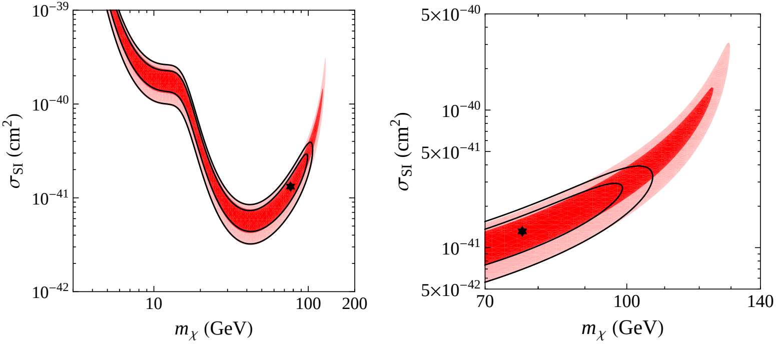

- limited information on the energy dependence of the signal. $\Rightarrow$ allowed region appears as a degenerate band.
- GF makes the preferred DAMA region smaller, excluding large DM masses.
- Large m_χ corresponds to small v_m $\Rightarrow$ phase shift induced by GF becomes relevant.

GF in a future Xe experiment

Simulation Details:

- Assume dark matter is just below the current best limit from LUX.
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- Gaussian energy resolution with width: $0.1\sqrt{E_{nr}/E_{thr}}$ keV.
- Assume a reference value $\sigma_{\rm SI} = 10^{-45}$ cm^2.

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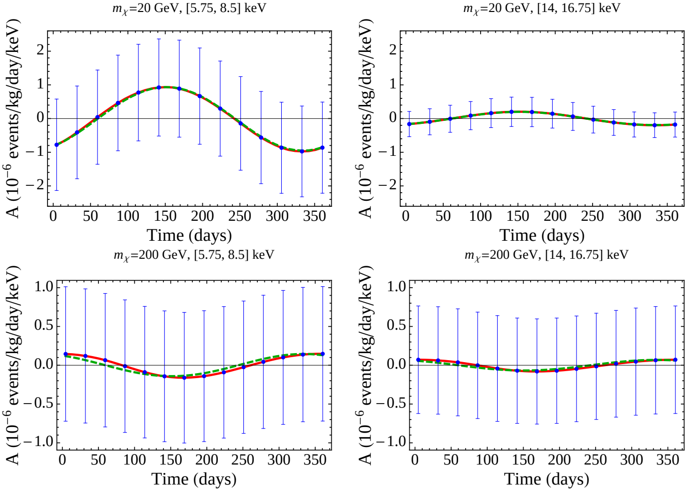
DM mass [GeV]	20	50	80	100	200
# events (no GF)	11305	21094	16974	14514	8058
# events (with GF)	11525	21418	17213	14712	8162

- Effect of GF on the total number of events is very small.

Annual modulation with and without GF



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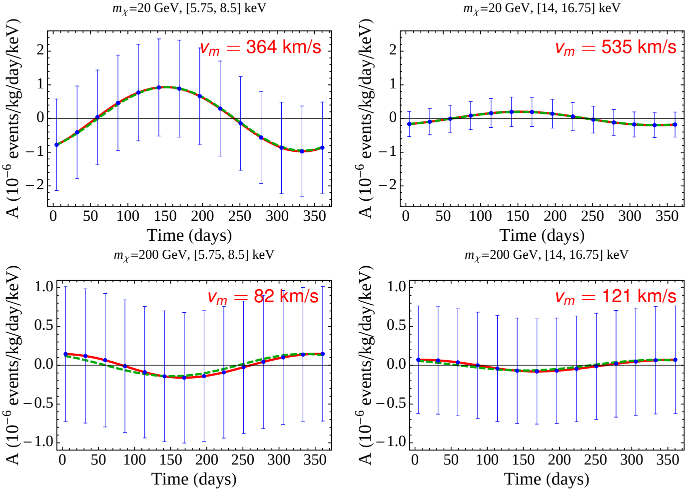

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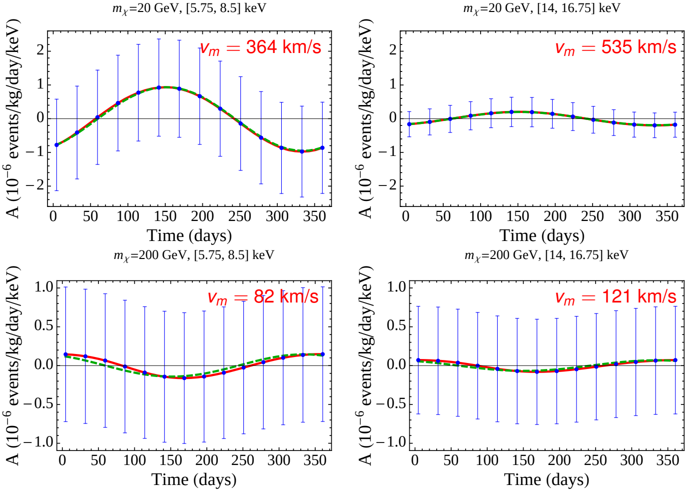

- Large error bars $\Rightarrow$ establishing GF or annual modulation at high significance would be hard.

Statistical significance

- Estimate the achievable statistical significance for the annual modulation signal and GF for our hypothetical Xe detector.

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- Construct a χ^2 function:

$$\Delta\chi^2(m_\chi, \sigma_{\rm SI};\, m_\chi^0, \sigma_{\rm SI}^0) = \sum_{i,j} \left(\frac{A_{ij}^{\rm pred}(m_\chi, \sigma_{\rm SI}) - A_{ij}^{\rm obs}(m_\chi^0, \sigma_{\rm SI}^0)}{\sigma_{ij}} \right)^2$$

  The sum is over both time and energy bins.
- $A_{ij}^{\rm obs}$ plays the role of the future "data". $\Rightarrow$ take the predicted modulation amplitude including GF for particular "true" parameter values $(m_\chi^0, \sigma_{\rm SI}^0)$ with $\sigma_{\rm SI}^0 = 10^{-45}$ cm^2.

Statistical significance

Significance of the annual modulation:

- To measure significance of the modulation, set $A_{ij}^{\rm pred} = 0$ and fit "data" with a prediction constant in time $\Rightarrow \Delta\chi^2_{\rm mod}$.
- $\sqrt{\Delta\chi^2_{\rm mod}}$ gives the number of Gaussian standard deviations.

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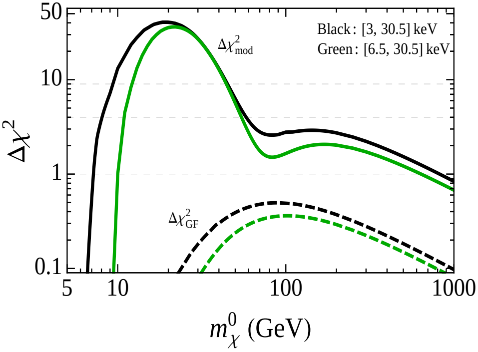
Significance of GF:

- Hypothesis test: presence of GF is the null hypothesis which we want to test against the alternative hypothesis of the absence of GF.
- Calculate the "data" A_{ij}^{obs} with GF and A_{ij}^{pred} without GF. $\Rightarrow \Delta\chi^2_{\mathrm{GF}}$.
- $\sqrt{\Delta\chi^2_{\mathrm{GF}}}$ corresponds to the number of standard deviations with which the median experiment can reject the alternative hypothesis.

Statistical significance



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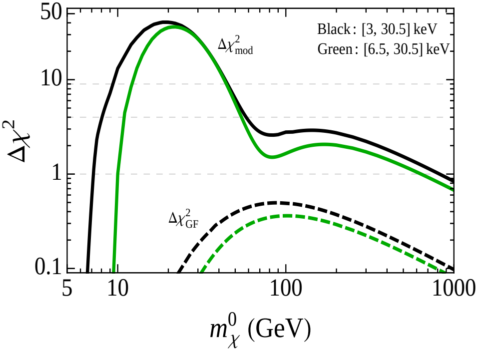
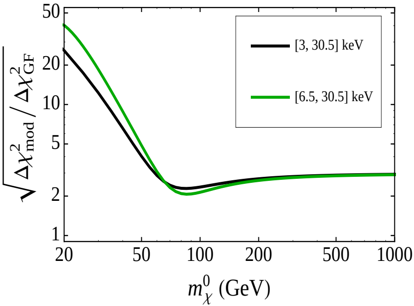


- **Annual modulation**: Only in the mass range $m_\chi \lesssim 40$ GeV can obtain a significant ($> 3\sigma$) signal. For larger DM masses only a hint below 2σ can be reached.
- **GF:** The significance never reaches the 1σ level.

Statistical significance

- Our analysis based on statistical errors. $\Rightarrow$ χ^2 values scale linearly with exposure MT and $\sigma^0_{\rm SI}$. Curves can easily be translated to any other exposure and/or cross section.

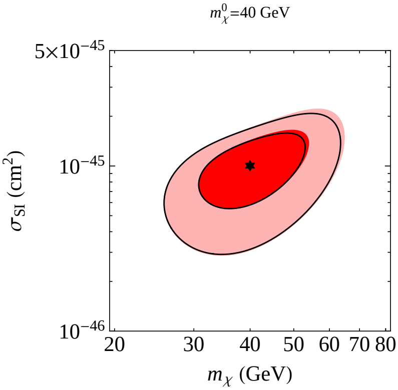
$\xi \equiv \sqrt{\Delta\chi^2_{\rm mod}/\Delta\chi^2_{\rm GF}}$

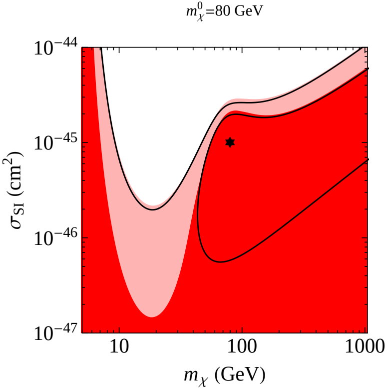


- Assume a future experiment established annual modulation at $n\sigma$ significance. $\Rightarrow$ GF will be detected at a significance of $(n/\xi)\sigma$
- (n/ξ) largest at $m^0_\chi \sim 70 - 90$ GeV

Preferred regions at 1σ and 2σ

- Calculate the "data" A_{ij}^{obs} with GF for two example values of m_χ^0.





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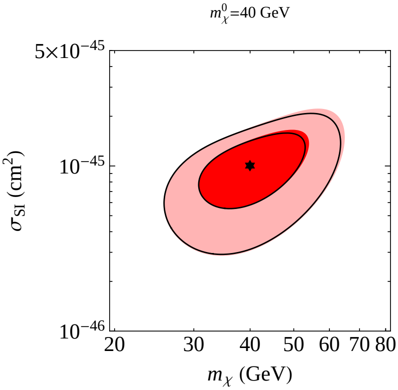

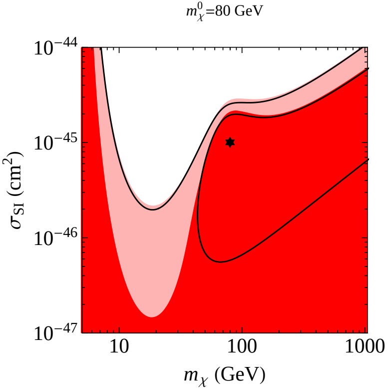

- GF affects only marginally the region at 40 GeV.
- Large difference for the 1σ region at 80 GeV, but not statistically meaningful. At 2σ regions with and without GF are similar.

Inelastic scattering

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- **Inelastic scattering:** DM particle χ scatters to a new state χ' with mass difference $\delta = m_{\chi'} - m_\chi$.
- Minimum velocity for inelastic scattering

$$v_m = \frac{1}{\sqrt{2m_A E_R}} \left| \frac{m_A E_R}{\mu_{\chi A}} + \delta \right|$$

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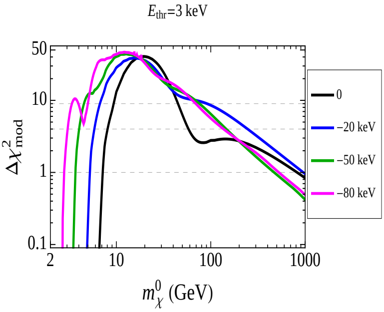
- Endothermic scattering: $\delta > 0$, up-scattering. Scattering off heavy target nuclei is favored. v_m is larger compared to elastic case $\Rightarrow$ GF becomes less important.
- Exothermic scattering: $\delta < 0$, down-scattering. We probe region of smaller v_m $\Rightarrow$ GF can be important.

Inelastic scattering



- The significance of detecting GF can reach values above 1σ for $|\delta| \gtrsim$ 20 keV.

GF and light DM searches

- Experiments such as CDMSlite probe low energies where GF is relevant even for light WIMPs.
- Considered a Ge detector with similar threshold and energy range as CDMSlite.
- Assume $\sigma_{\rm SI} = 10^{-45}$ cm^2, and $MT = 270$ ton yr.

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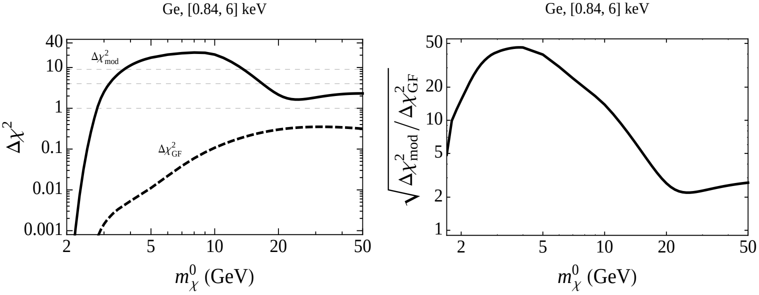

- At **4 GeV**, we can assume $\sigma_{\rm SI} = 10^{-40}$ cm^2. To observe GF at $\sim 3\sigma$, we need $MT \sim 5$ ton yr $\sim 3 \times 10^5$ larger than current exposure of CDMSlite.

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- Sun's Gravitational focusing can distort the DM phase space distribution. $\Rightarrow$ may potentially lead to a significant change of the time dependence of the count rate.
- Performed a fit to the time dependent DAMA data. Allowed DM parameter range is more restricted for large DM masses if GF is taken into account.
- Considered very large Xe detector (270 ton yr):
    - Annual modulation can be established at $\gtrsim 3\sigma$ only for $m_\chi \lesssim 40$ GeV. For such small masses, v_m is large $\Rightarrow$ GF is small.
    - For larger DM masses, where GF may be potentially observable, the annual modulation is not significant.
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  - For larger DM masses, where GF may be potentially observable, the annual modulation is not significant.
  - For inelastic exothermic scattering, GF is slightly larger because of lower v_m.
- Our conclusions hold for lighter target nuclei. We obtain similar results for hypothetical Ar and Ge detectors.

Backup slides

Events and modulation amplitude

- The number of events in an energy interval $[E_1, E_2]$ and at a given time t is

$$N_{[E_1,E_2]}(t) = MT \int_0^\infty dE_{nr} G_{[E_1,E_2]}(E_{nr}) R(E_{nr}, t)$$

- The annual modulation signal in a given energy interval (in events/keV):

$$A_{[E_1,E_2]}(t) = \frac{N_{[E_1,E_2]}(t) - \langle N_{[E_1,E_2]}(t) \rangle_t}{E_2 - E_1}$$

where $\langle N_{[E_1,E_2]}(t) \rangle_t$ is the number of events averaged over one year in the given energy bin.

Gravitational focusing

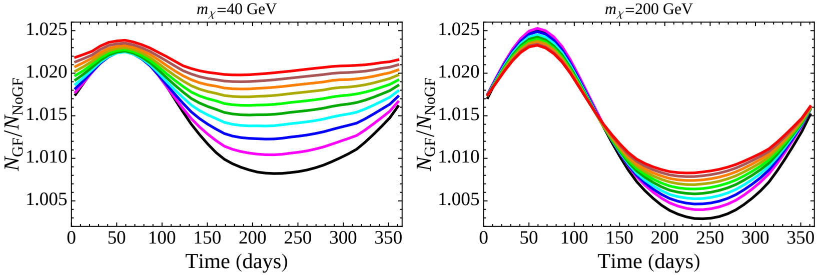
$$\rho_\chi\, f_{\rm gal}(\mathbf{v}_s + \mathbf{v} + \mathbf{v}_e(t)) = \rho_\infty\, f_{\rm gal}(\mathbf{v}_s + \mathbf{v}_\infty[\mathbf{v} + \mathbf{v}_e(t)])$$

$$\mathbf{v}_\infty[\mathbf{v}] = \frac{v_\infty^2 \mathbf{v} + v_\infty u_{\rm esc}^2 \hat{\mathbf{r}}_s/2 - v_\infty \mathbf{v}(\mathbf{v}\cdot\hat{\mathbf{r}}_s)}{v_\infty^2 + u_{\rm esc}^2/2 - v_\infty(\mathbf{v}\cdot\hat{\mathbf{r}}_s)}$$

With:

- $v_\infty^2 = v^2 - u_{\rm esc}^2$
- $u_{\rm esc} = \sqrt{2GM_\odot/r_{\rm A.U.}} \simeq 40$ km/s is the escape velocity from the Sun near the Earth's orbit.
- $\hat{\mathbf{r}}_s$ is the unit vector pointing in the direction of the Earth from the center of the Solar System.

Events with and without GF



- The 10 colored lines correspond to 10 energy bins of equal size in the interval $[3, 30.5]$ keV.
- The effect of GF is smaller for $m_\chi = 40$ GeV compared to 200 GeV. For both masses $N_{\rm GF}/N_{\rm NoGF}$ is close to 1.