Effects of lattice defects in dark matter direct detection experiments

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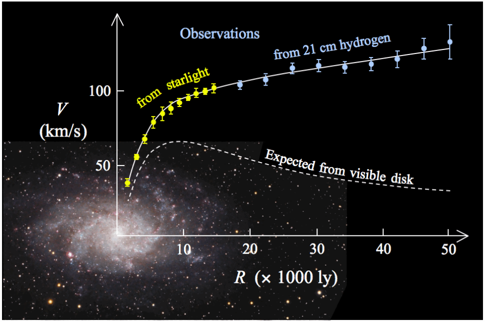
Contents

Introduction

- The existence of dark matter is confirmed via multiple independent observations:
  - Galactic rotation curves and velocity dispersions.
  - Gravitational lensing of galaxy clusters.
  - CMB power spectrum.
  - Structure formation.
- All of these observations are based on the **gravitational** interactions between DM and visible matter.



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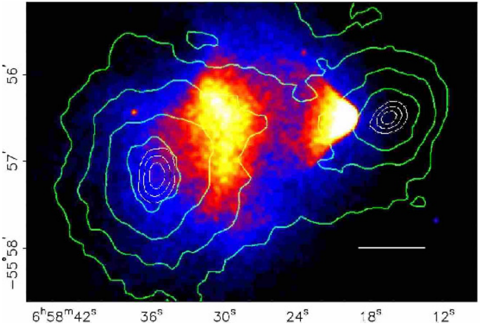

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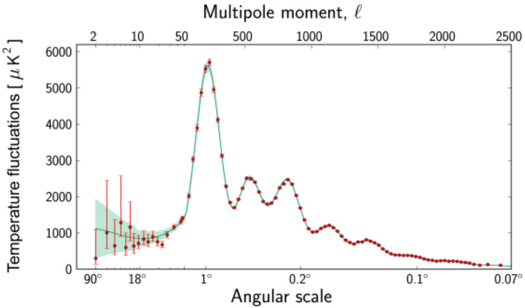

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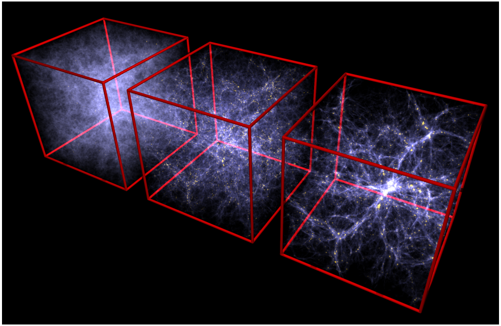
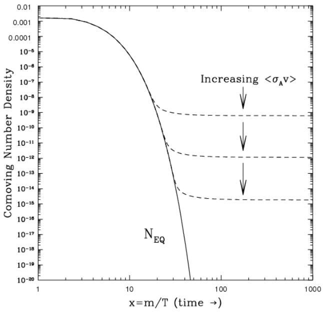
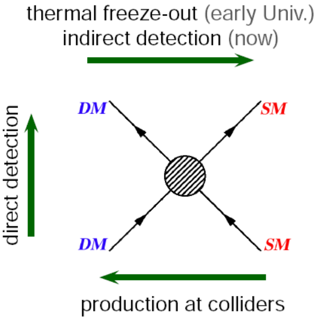


Introduction

- To understand the role of the DM particle in the context of particle physics theory, we would like to know something about its **non-gravitational** interactions.
- A nice feature of WIMPs is that their abundance is determined via their scattering with the SM particles.
- Therefore WIMPs should be observable with direct detection, indirect detection and collider experiments.





thermal freeze-out (early Univ.)
indirect detection (now)

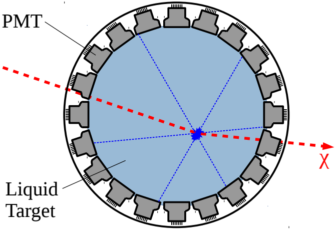
direct detection

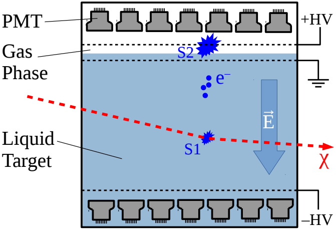
production at colliders

Direct detection

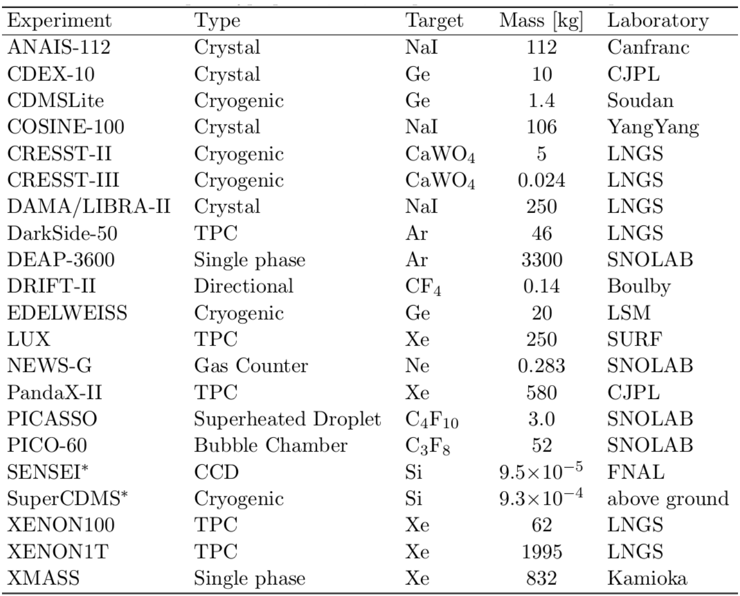
- Direct detection experiments look for DM scattering off the atoms of the target material, by detecting the recoil event (typically via scintillation light, electric signal or phonons).
- The event rate depends on the DM-nucleus scattering cross section, and the velocity distribution of DM:

$$\frac{dR}{dE_r} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_\mathrm{min}}^{v_\mathrm{esc}} v f(v) \frac{d\sigma}{dE_r} dv, \qquad v_\mathrm{min} = \sqrt{\frac{E_r m_N}{2\mu_{N\chi}^2}}, \; \mu_{N\chi} = \frac{m_N m_\chi}{m_N + m_\chi}.$$





Direct detection experiments

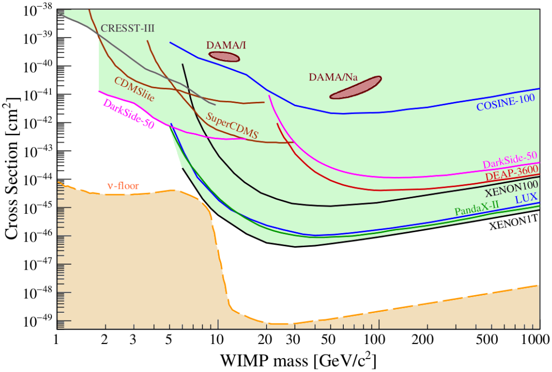


Experiment	Type	Target	Mass [kg]	Laboratory
ANAIS-112	Crystal	NaI	112	Canfranc
CDEX-10	Crystal	Ge	10	CJPL
CDMSLite	Cryogenic	Ge	1.4	Soudan
COSINE-100	Crystal	NaI	106	YangYang
CRESST-II	Cryogenic	$CaWO_4$	5	LNGS
CRESST-III	Cryogenic	$CaWO_4$	0.024	LNGS
DAMA/LIBRA-II	Crystal	NaI	250	LNGS
DarkSide-50	TPC	Ar	46	LNGS
DEAP-3600	Single phase	Ar	3300	SNOLAB
DRIFT-II	Directional	CF_4	0.14	Boulby
EDELWEISS	Cryogenic	Ge	20	LSM
LUX	TPC	Xe	250	SURF
NEWS-G	Gas Counter	Ne	0.283	SNOLAB
PandaX-II	TPC	Xe	580	CJPL
PICASSO	Superheated Droplet	C_4F_{10}	3.0	SNOLAB
PICO-60	Bubble Chamber	C_3F_8	52	SNOLAB
SENSEI*	CCD	Si	9.5×10^{-5}	FNAL
SuperCDMS*	Cryogenic	Si	9.3×10^{-4}	above ground
XENON100	TPC	Xe	62	LNGS
XENON1T	TPC	Xe	1995	LNGS
XMASS	Single phase	Xe	832	Kamioka

Direct detection

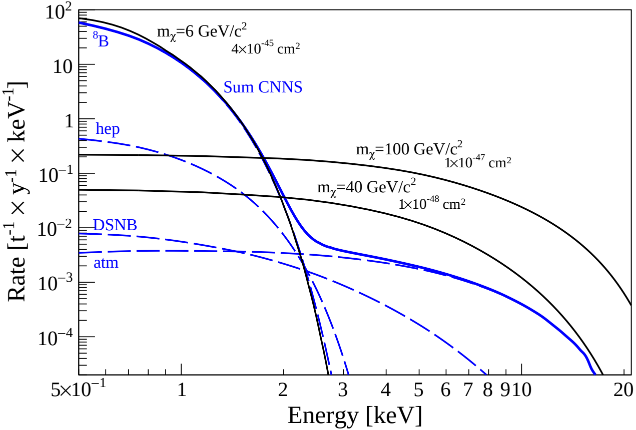
- The exclusion limit is typically presented in the $(m_\chi, \sigma_{\chi n})$-plane, where the cross section refers to a given scattering operator.
- The simplest operator is the scalar (Spin-Independent) operator. Arising from e.g. $\bar{\chi}\chi\bar{q}q$.

$$\frac{d\sigma}{dE_r} = \sigma_{\chi n} \frac{A^2 m_N}{2v^2 \mu_{n\chi}^2} F^2(E_r)$$



The neutrino floor

- Solar and cosmic neutrinos form an irreducible background for the standard direct detection experiments.
- DM-nucleon cross sections below the neutrino floor can not be probed with simple counting experiments.



Contents

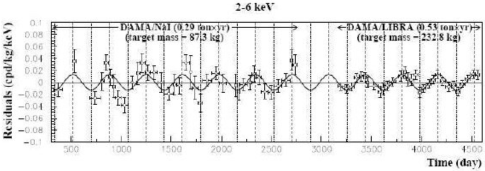
Modulation experiments

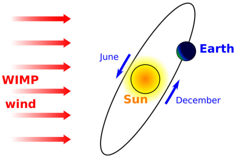
- To reach below the neutrino floor, the DM signal must somehow be differentiated from the neutrino background.
- The separation can be achieved via the modulation of the DM scattering event rate due to the motion of the earth in the Galactic rest frame: $f(\vec{v}) \to f(\vec{v} + \vec{v}_{\rm lab})$.

$$\vec{v}_{\rm lab} = \vec{v}_{\rm circ} + \vec{v}_{\rm sol} + \vec{v}_{\rm rev} + \vec{v}_{\rm rot}\,,$$

$v_{\rm circ} \sim 220\,{\rm km\,s^{-1}}$, $v_{\rm sol} \sim 18\,{\rm km\,s^{-1}}$, $v_{\rm rev} \sim 30\,{\rm km\,s^{-1}}$, $v_{\rm rot} \sim 0.5\,{\rm km\,s^{-1}}$.

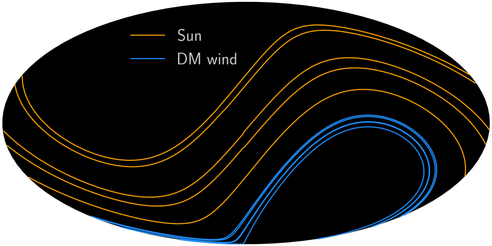
- Annual modulation (of order $\sim 5\%$) is expected due to the variation in $v_{\rm lab}$ as $\vec{v}_{\rm rev}$ and $\vec{v}_{\rm circ}$ are aligned/antialigned during the year.





Daily modulation

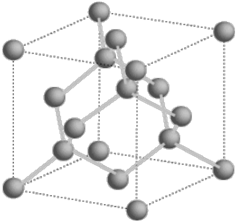
- The rotation speed v_{rot} is small compared to the other components, and the daily modulation induced by the variation of v_{lab} due to v_{rot} is negligible.
- However, the rotation changes the direction of $\vec{v}_{\mathrm{lab}}$ significantly during the day.

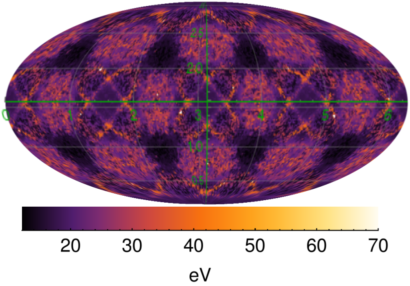


- If the target material is anisotropic, the scattering propability becomes a function of the recoil direction.
- As the direction of the DM wind changes throughout the day, the event rate modulates correspondingly.
- This effect is not present in isotropic targets, such as liquid Xenon.

Ionization energy threshold in Germanium

- Germanium crystal has a diamond lattice structure.
- The threshold energy for creating a lattice defect depends on the recoil direction. (It costs more energy to kick a nucleus towards another nucleus.)
- Conjecture: The threshold for creating an electron-hole pair has a similar directional dependency.
- This idea is supported by time dependent density functional theory (TDDFT) calculations, observational confirmation in progress.





DM event rate in Germanium

- In the experiment setup, the scattering events that fail to exite an electron-hole pair will not be detected.
- Thus the rate of observable events as a function of recoil direction is obtained by integrating the differential rate $d^2R/dEd\Omega$ over the recoil energy from $E_{\mathrm{min}} = E_{\mathrm{Threshold}}(\theta, \phi)$ to the cut-off energy E_{max} (or to infinity if no upper limit is set by the experimental setup).

$$\frac{dR}{d\Omega_q} = \frac{\rho_0}{2\pi m_{\mathrm{DM}}} \frac{1}{32\pi m_{\mathrm{N}}^2 m_{\mathrm{DM}}^2} \int_{E_{\mathrm{min}}(\Omega_q)}^{E_{\mathrm{max}}} dE \int d^3v\, |\mathcal{M}|^2 f(\vec{v}) \delta(\vec{v} \cdot \hat{\vec{q}} - v_{\mathrm{min}})$$

- In non-relativistic effective theory, the squared matrix element can be expanded as

$$|\mathcal{M}|^2 = a_1 1 + a_2 q^2 + a_3 q^4 + b_1 v_\perp^2 + b_2 q^2 v_\perp^2 + b_3 q^4 v_\perp^2 + \cdots$$

$$v_\perp^2 = v^2 - \frac{q^2}{4\mu_{\mathrm{DM,N}}^2}$$

DM event rate in Germanium

- The integral over the DM velocity $\vec{v}$ can be expressed in terms of the Radon transform and transverse Radon transform of $f(\vec{v})$:

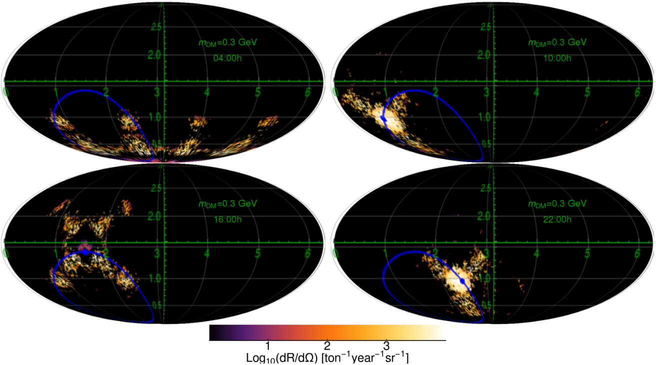
$$\hat{f}(v_{\rm min},\hat{q}) = \int d^3v\, f(\vec{v})\delta(\vec{v}\cdot\hat{\vec{q}} - v_{\rm min})$$

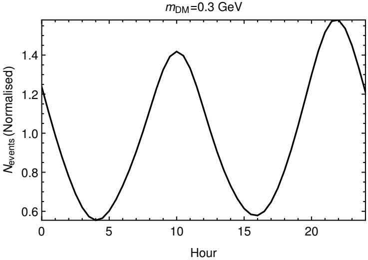
$$\hat{f}^{\rm T}(v_{\rm min},\hat{q}) = \int d^3v\, f(\vec{v})v_\perp^2\delta(\vec{v}\cdot\hat{\vec{q}} - v_{\rm min})$$

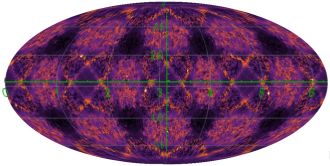
$$\frac{dR}{d\Omega_q} = \frac{\rho_0}{4\pi m_{\rm DM}}\frac{\sigma_0 A^2}{\mu^2_{\rm DM,n}}\int_{E_{\rm min}(\Omega_q)}^{E_{\rm max}} dE\,\Big((a_1 + a_2q^2 + \ldots)\hat{f}(v_{\rm min},\hat{q}) \\ + (b_1 + b_2q^2 + \ldots)\hat{f}^{\rm T}(v_{\rm min},\hat{q})\Big)$$

- For the commonly used DM velocity distribution (the standard halo model) $f_{\rm SHM}(v) = N_{\rm e}^{-1}(2\pi\sigma_v^2)^{-3/2}\exp(-v^2/2\sigma_v^2)\Theta(v_e - v)$, these integrals can be performed analytically.

DM event rate in Germanium

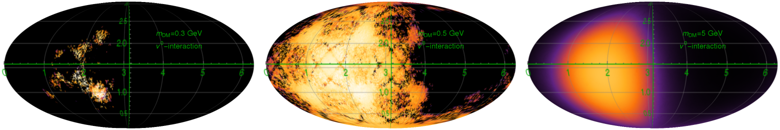


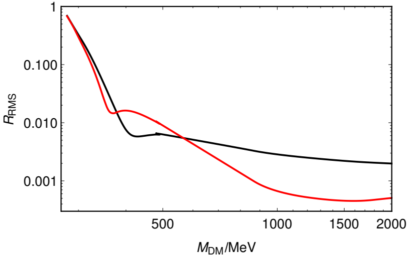




DM event rate in Germanium

- The modulation signal is strong for light DM.
- A heavy DM particle will have enough kinetic energy to exite the electron-hole pair regardless of the recoil direction, therefore suppressing the modulation signal.



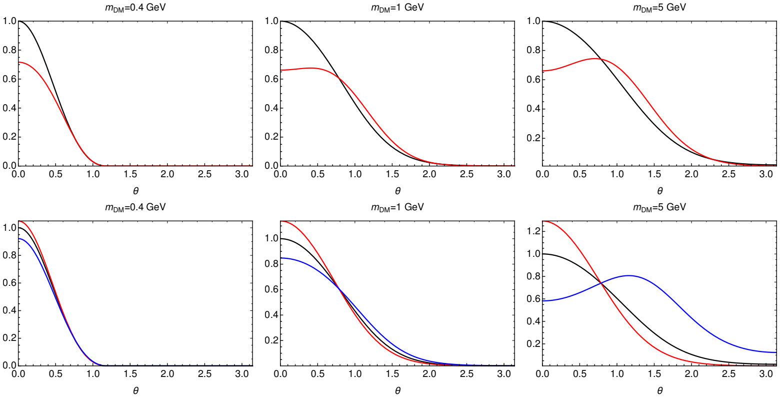


Identifying the DM-Nucleon coupling operator

- The stucture of the daily modulation signal depends on the type of the DM-nucleon coupling via the squared matrix element: Recall:

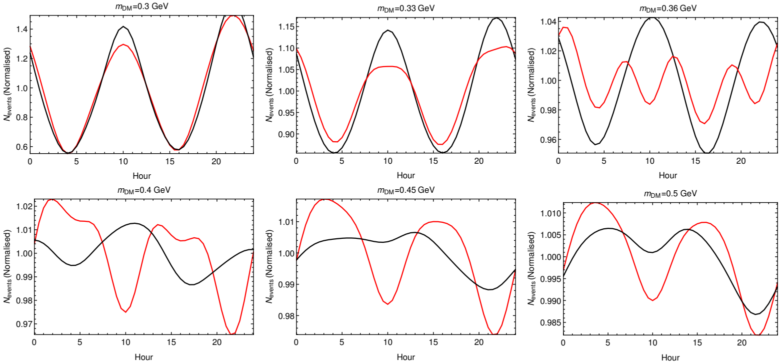
$$|\mathcal{M}|^2 = a_1 1 + a_2 q^2 + a_3 q^4 + b_1 v_\perp^2 + b_2 q^2 v_\perp^2 + b_3 q^4 v_\perp^2 + \cdots$$

- For small DM mass the directional scattering rate is similar for all operators, but for larger DM mass they begin to differ.



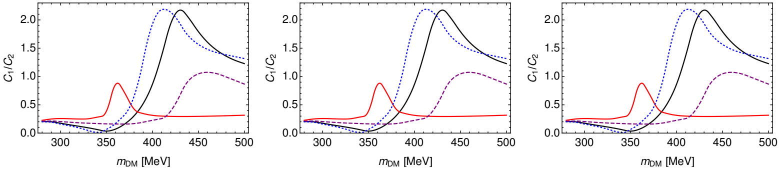
Identifying the DM-Nucleon coupling operator

The daily modulation of the event rate for the a_1 (unit) operator (black) and b_1 ($v_\perp^2$) operator (red):



Identifying the DM-Nucleon coupling operator

The ratios of the Fourier-components for the v^0-interaction (black line), $v_\perp^2$-interaction (red line), q^{-4}-interaction (purple dashed line) and q^2-interaction (blue dotted line):

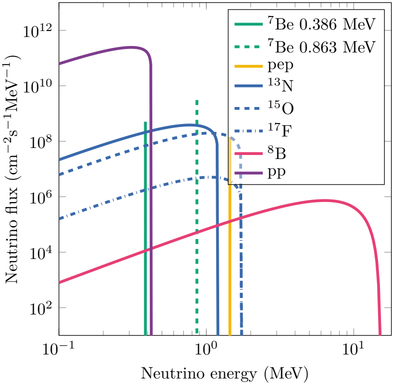


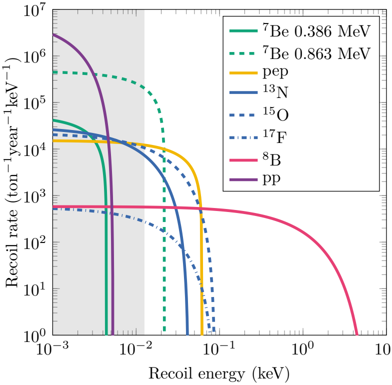
- With combination of the measurements of the recoil energy spectrum, the amplitude of the daily modulation, and the structure (Fourier-modes) of the daily modulation signal, both the DM mass and the type of DM-nucleon coupling could be determined.

Contents

Solar neutrino background

- The solar neutrino flux consists of components from various reactions.
- Left: Neutrino flux, Right: Recoil spectrum in Germanium





Solar neutrino background

- The event rate due to solar neutrinos is given by

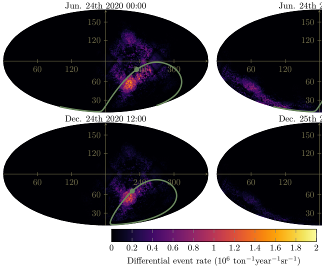
$$\frac{d^2R}{dE_r d\Omega_r} = \frac{1}{2\pi}\frac{A(t)}{\Delta t}\frac{\epsilon^2}{E_\nu^{\rm min}}\frac{d\sigma}{dE_r}(E_r,\epsilon)\frac{d\Phi}{dE_\nu}(\epsilon)\Theta(\cos\theta_\odot)$$

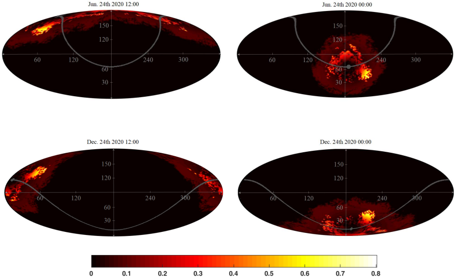
$$\frac{d\sigma}{dE_r}(E_r,E_\nu) = \frac{G_F^2}{4\pi}Q_W^2 m_N\left(1-\frac{m_N E_r}{2E_\nu^2}\right)$$

$$\epsilon = (\cos\theta_\odot/E_\nu^{\rm min} - 1/m_N)^{-1}, \quad E_\nu^{\rm min} = \sqrt{m_N E_r/2}$$

- The integral over the recoil energy E_r must again be performed from $E_{\rm min}(\theta,\phi)$ to $E_{\rm max}$.
- Since the neutrino flux has a preferred direction, also the neutrino event rate will exhibit daily modulation.
- The DM wind never points from the direction of the sun, therefore the modulation in DM event rate will have a different phase from the solar neutrino rate.

Solar neutrino background

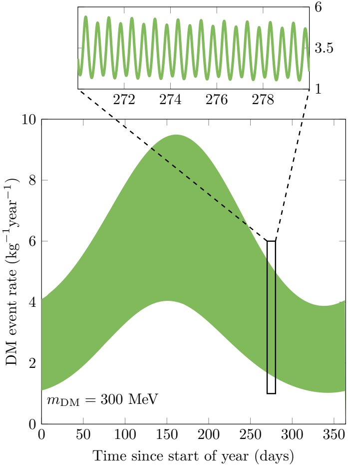


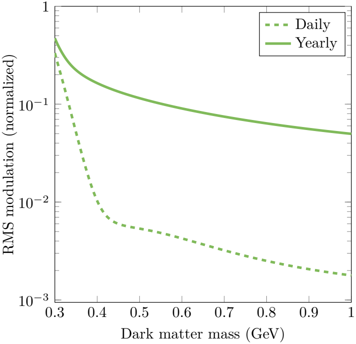


Differential event rate (10^4 ton^{-1} year^{-1} sr^{-1})

Daily and annual modulation

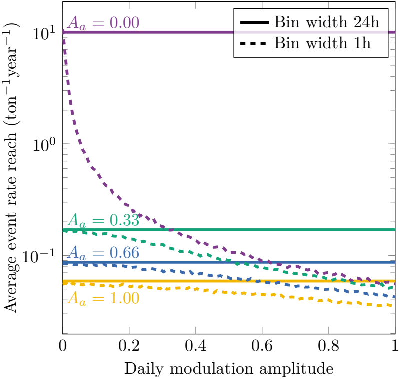
- The dark matter event rate contains both daily and yearly modulation features.
- For low mass DM close to detection threshold, also the yearly modulation amplitude grows.





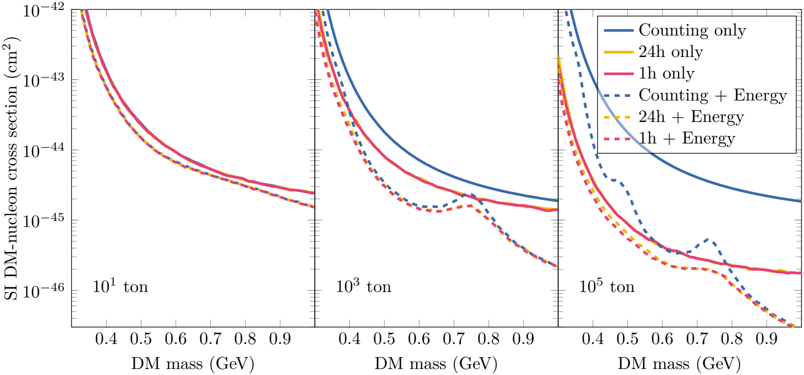
Daily and annual modulation

- In a statistical analysis we find that the daily modulation feature does not significantly increase the sensitivity vs background.
- This is because the annual modulation already contains enough information to identify the signal.
- However, the daily modulation alone provides similar improvement over static background, as demonstrated by a parametric model $R \sim (1 + A_a \sin(\Omega t))(1 + A_d \sin(\omega t))$.



Discovery reach

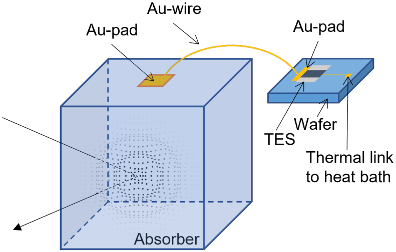
- The timing information becomes important for very large exposure, where the solar neutrino rate is significant.

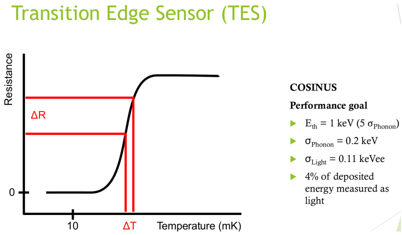


Contents

Calorimetric detectors

- In the above we discussed the ionization detector, where the defect creation (and the induced ionization) acts as a threshold for observable signal.
- In calorimetric detectors the recoil events can in principle be always detected (obviously there is some instrumental noise that sets the threshold for observable energy. The current limits are ~ 10 eV.)
- These detectors measure the kinetic energy deposited to the target crystal via monitoring the heat flux from the crystal to the surrounding thermal bath.





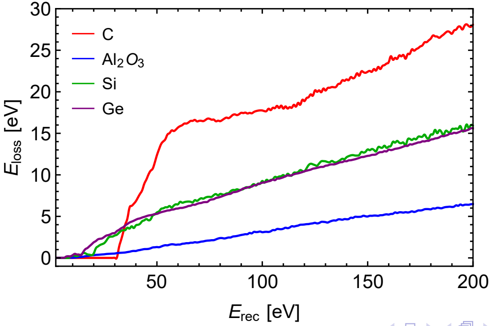
COSINUS

Performance goal

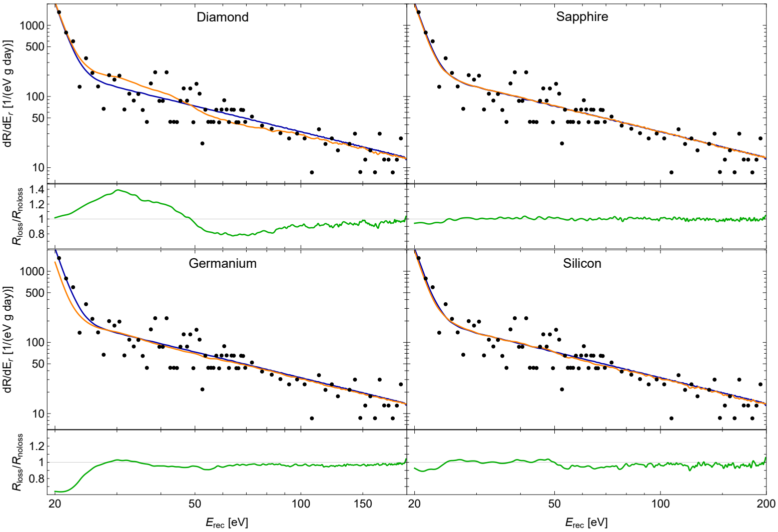
- $E_{th} = 1$ keV ($5\ \sigma_{Phonon}$)
- $\sigma_{Phonon} = 0.2$ keV
- $\sigma_{Light} = 0.11$ keVee
- 4% of deposited energy measured as light

Calorimetric detectors

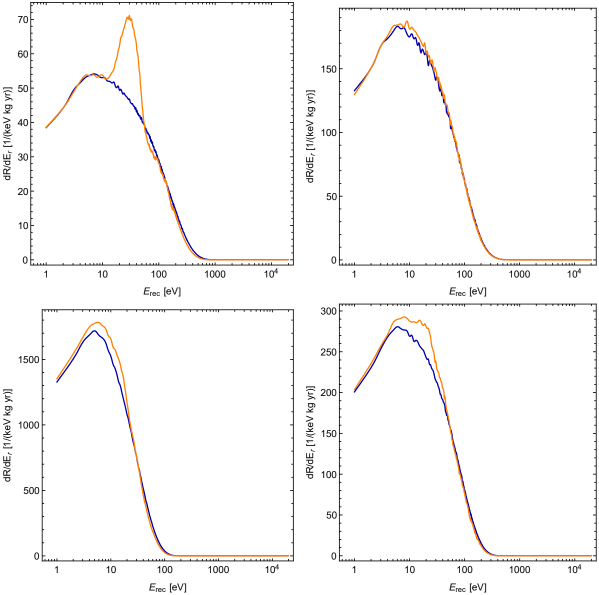
- However, if some energy is stored in the crystal, it will not be measured.
- The amount of energy that is lost to lattice defects varies significantly between different target materials.
- Consequently, experiments using different targets will measure different spectrum from the same underlying source.
- Since this feature is expected for nuclear recoils, but not e.g. for electron-recoils, this effect can be used to confirm that the observed events are due to nuclear recoils.



Spectrum in different materials: low energy background



Spectrum in different materials: dark matter



Conclusions

- For low-threshold solid state detectors, lattice defects play an important role in the formation of the signal.
- For ionization detectors, the ionization threshold is believed to correlate with the defect creation.
- The directional dependence of the threshold displacement energy then induces a daily modulation to the DM event rate for low mass DM.
- This can be used to identify the type of the DM-SM interaction, or to separate the DM signal from the neutrino background.
- For calorimetric detectors, defect creation modifies the observed energy spectrum.
- The shape and amplitude of the modification depends on the target material, comparing spectra measured with different targets can help to confirm that the events are due to nuclear recoils.