Modulation of Dark Matter Signals

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Identification of Dark Matter 2020
Online
20 July 2020

Including results from
arXiv:1802.10175 with Florian Reindl, Karoline Schaeffner, Kai Schmidt-Hoberg and Sebastian Wild
arXiv:1910.02091 with Matthias Geilhufe and Martin Winkler

Emmy Noether-Programm
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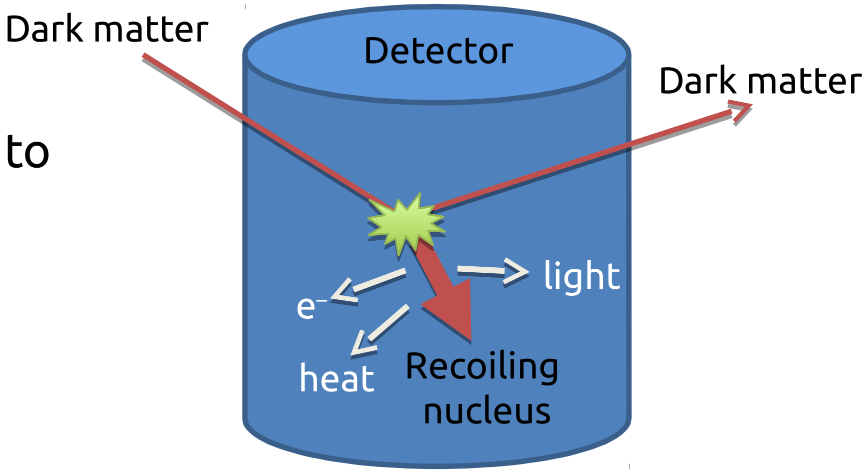
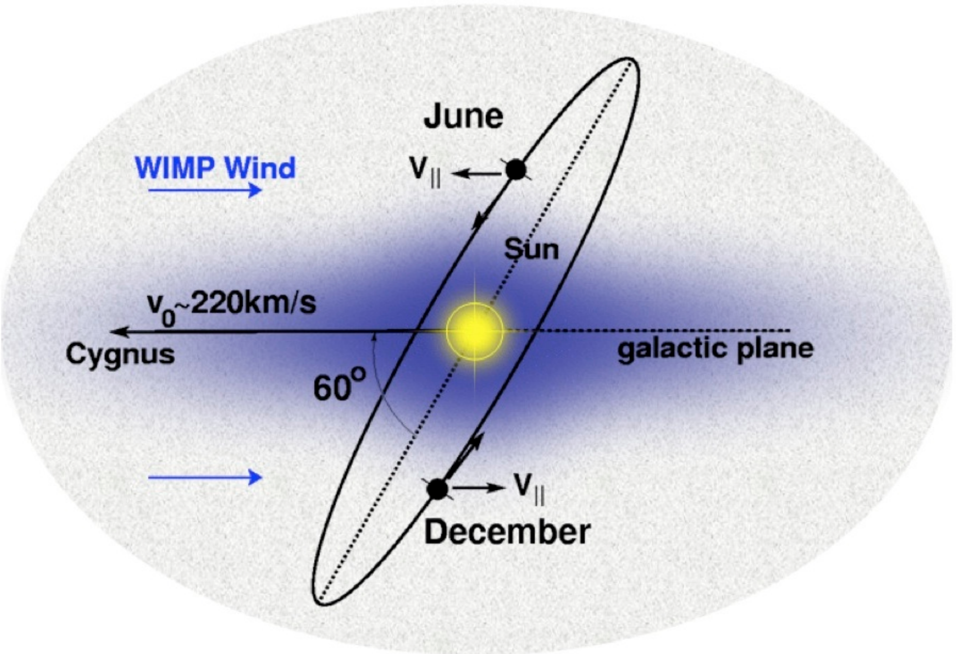
Introduction: Why look for modulation?



- Many DM signals have a **characteristic time dependence**, while backgrounds are expected to be time-independent (or non-periodic)
- Time dependence offers a promising way to **discriminate signal from background**
- Even periodic backgrounds may be eliminated by rotating experiment or moving it to different location
- Possibility to **increase exposure** and/or **lower threshold** in face of non-negligible background rate
- **Ultimate goal:** Time dependence as conclusive proof for the DM origin of a signal

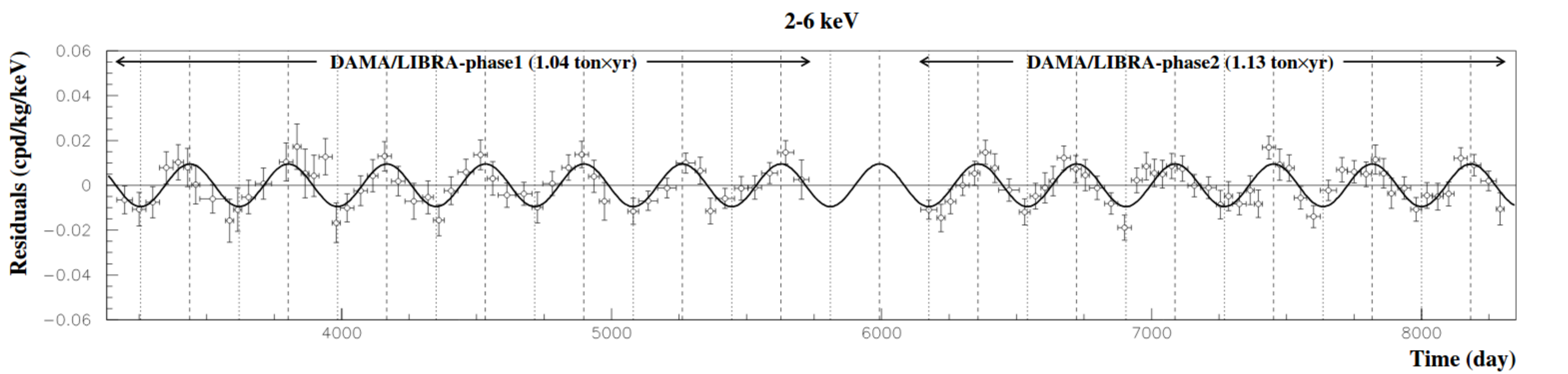
Part 1: Annual modulations

- The Sun moves through the Milky Way with a velocity of about $v_S \sim 220$ km/s, leading to a **boost of the DM velocity** distribution in the laboratory frame
- "WIMP Wind" coming from the direction of Cygnus
- The Earth moves around the Sun with a velocity of about $v_E \sim 30$ km/s, **increasing the boost in summer** and **decreasing it in winter**
- Result: Larger (and more energetic) WIMP flux in summer than in winter

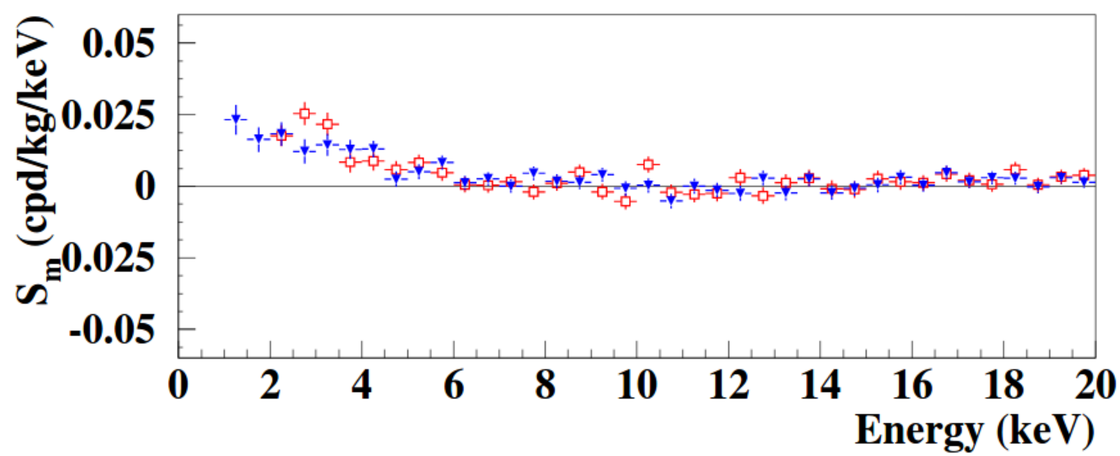


- Magnitude of the effect expected to be of the order of $v_E / v_S \sim 15\%$, but **larger modulations possible** close to threshold

The DAMA signal



- The DAMA experiment observes **evidence for such a modulation** in their (nuclear?) recoil data at a significance of ~13 sigma
- Phase and energy dependence of the modulation are (roughly) consistent with the expectations for a **10–100 GeV WIMP**

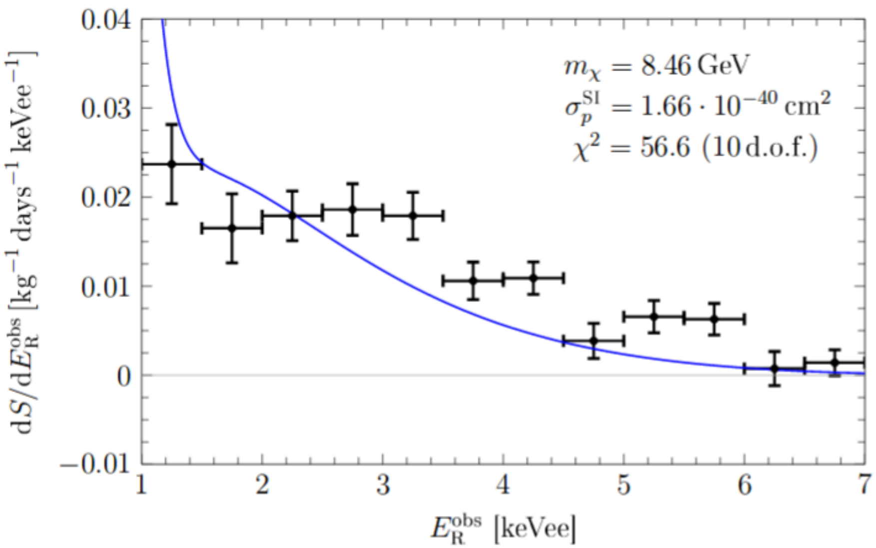


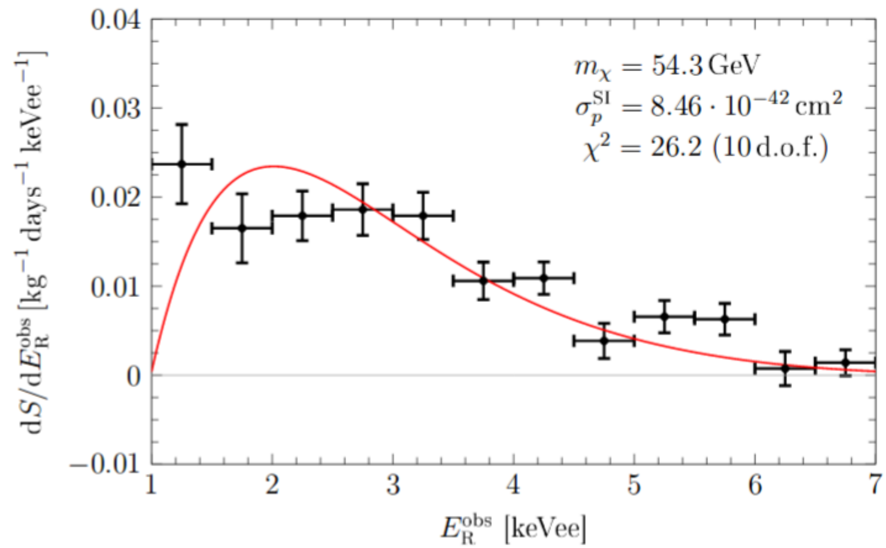
Bernabei et al., arXiv:1805.10486

DAMA: Elastic DM-nucleus scattering

- Upon closer inspection the energy dependence of the new DAMA data **does not agree with expectation** for DM-nucleus scattering

Baum et al., arXiv:1804.01231
FK et al., arXiv:1802.10175



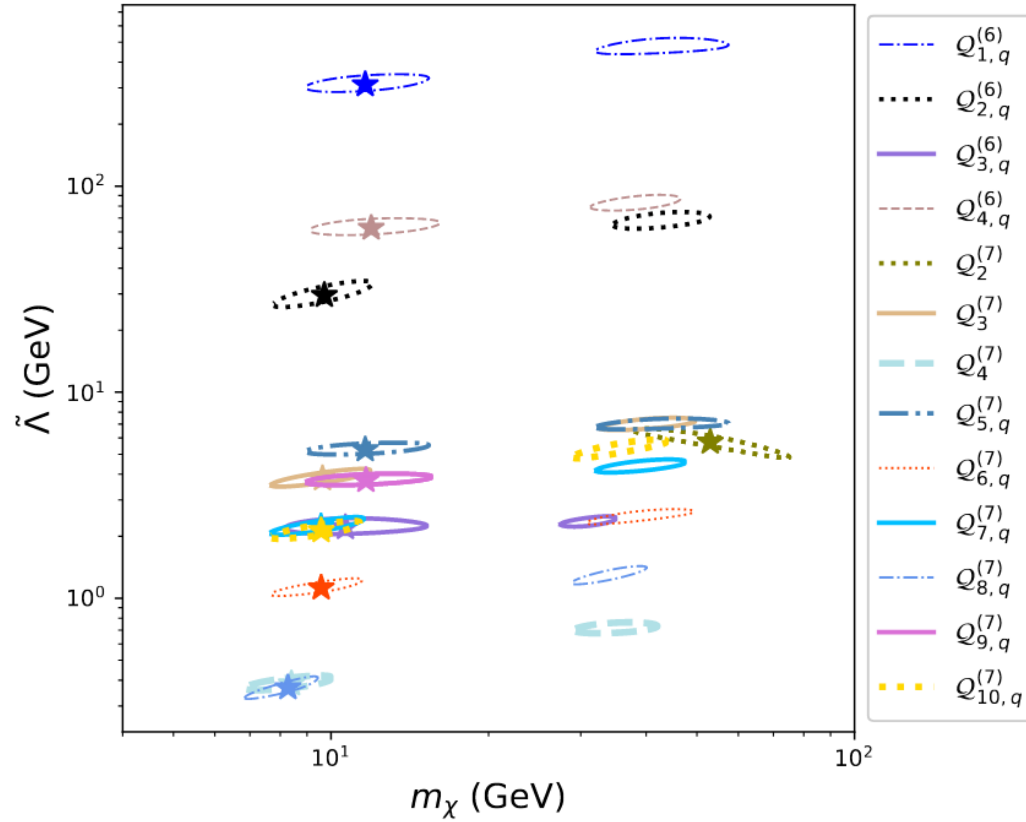


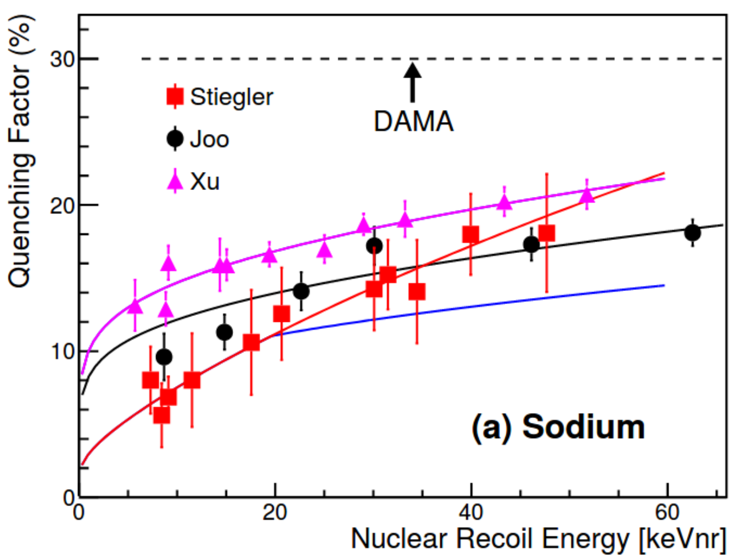
- DAMA disputes this claim (arXiv:1907.06405)
- Possible explanation: different assumptions on **energy resolution** close to threshold (information not public)

DAMA: Elastic DM-nucleus scattering

- Moreover, any best-fit point is in **vast tension** with other direct detection experiments
- "For all the minima the corresponding predicted number of events exceeds by more than three orders of magnitude the upper bounds from XENON1T and/or PICO–60."

Kang et al., arXiv:1910.11569





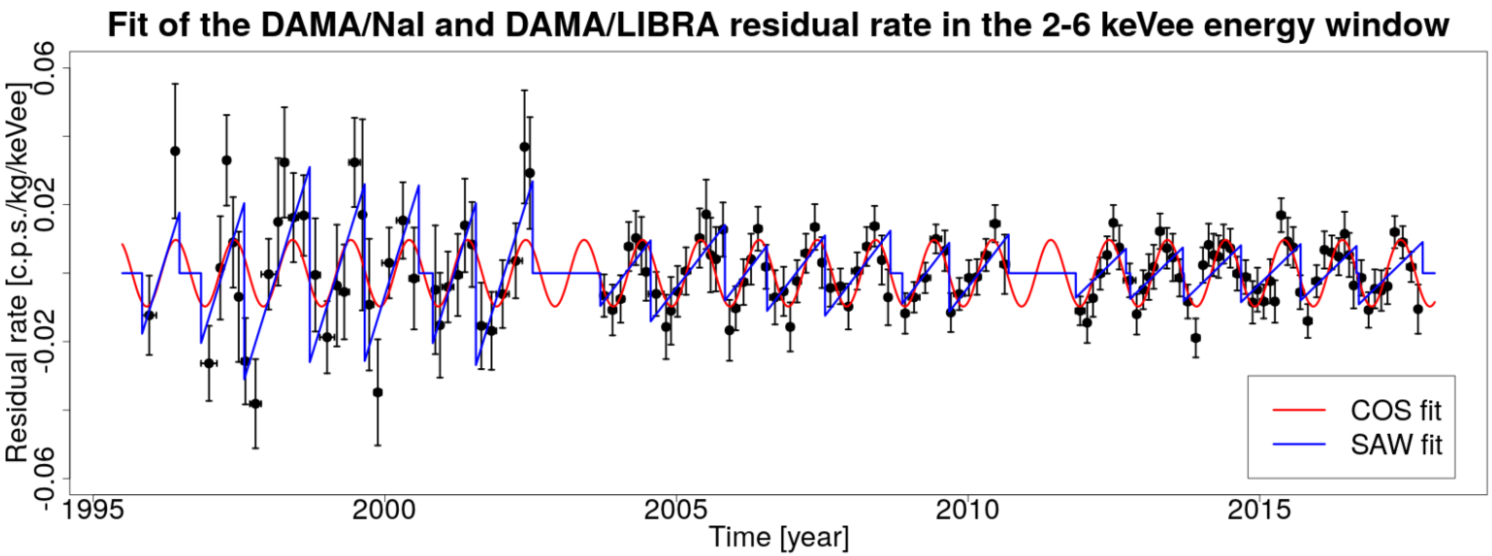
- **Uncertainties in quenching factors** are insufficient to change this conclusion

COSINE-100 Collaboration, arXiv:1907.04963

DAMA: Backgrounds?

- **No known background** explains the DAMA modulation
- Recent suggestions: Annual modulation as artifact of **subtracting a slowly varying total rate**

Buttazzo et al., arXiv:2002.00459
Messina et al., arXiv:2003.03340



- In principle easy for DAMA collaboration to confirm/refute

What next?

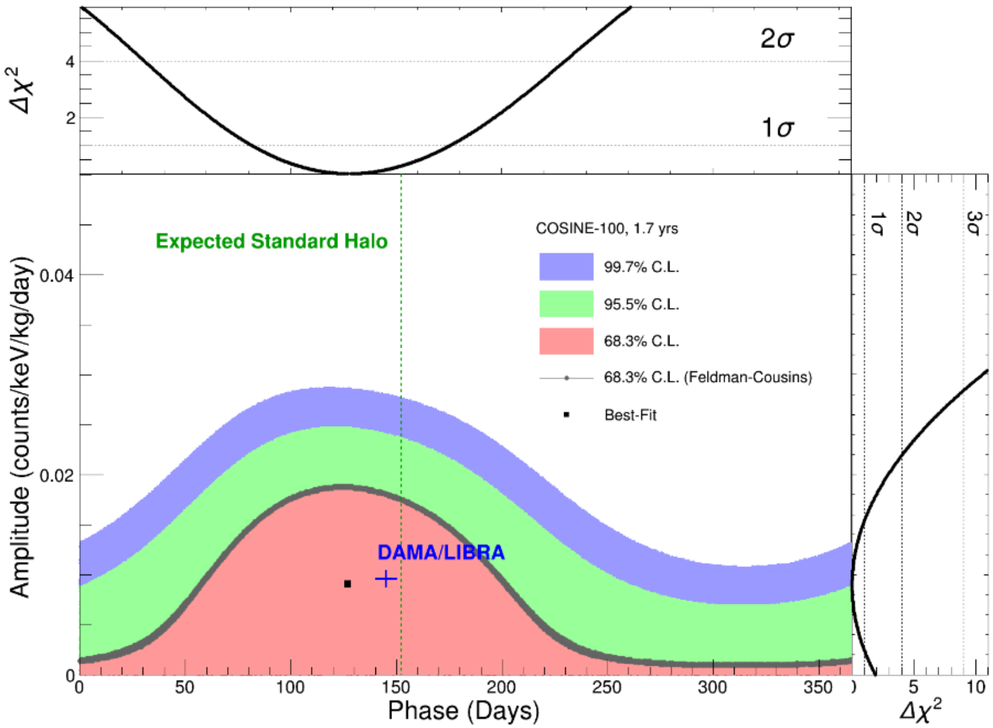
- We need to entertain the possibility that the DAMA signal is due to **unknown type of DM interaction** that **scales in an unknown way** for different detector materials

- To settle the controversy around DAMA, need **independent experiments employing the same target material** (NaI)

- Ongoing experiments repeating DAMA:
  - COSINE (@ Yangyang, South Korea)
  - ANAIS (@ Canfranc, Spain)

- More experiments under development:
  - SABRE (@ LNGS, Italy & Stawell, Australia)
  - COSINUS (@ LNGS, Italy)
  - PICO-LON (@ Kamioka, Japan)

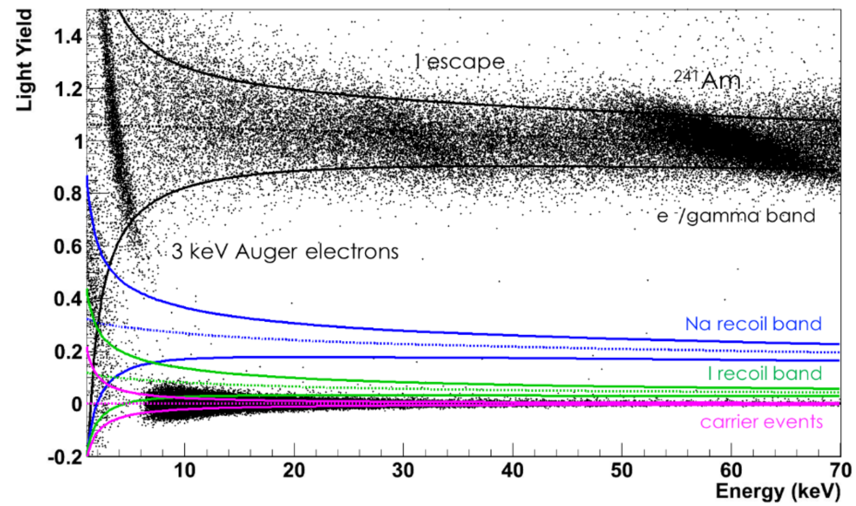
COSINE-100, arXiv:1903.10098

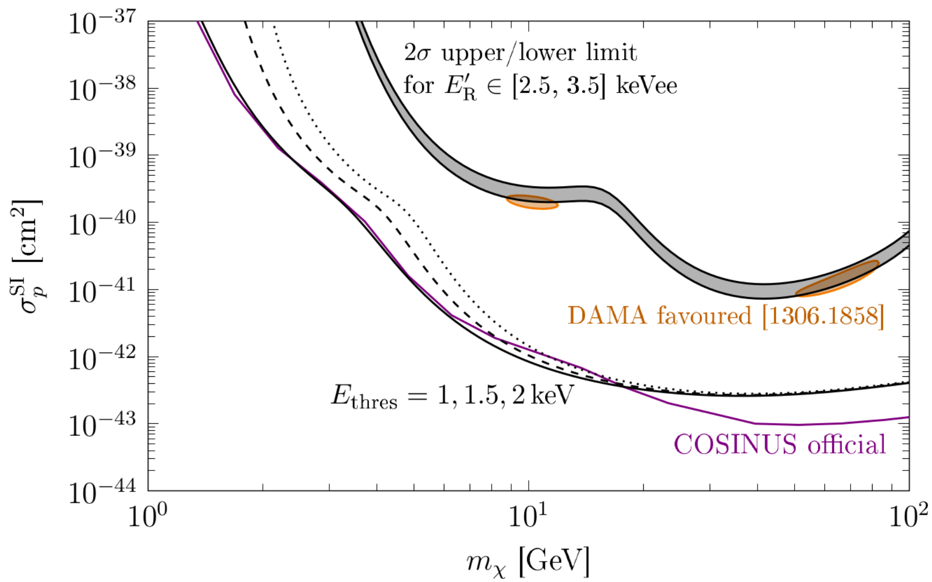


Comparing total rate and annual modulation

- Searching for annual modulations requires **lots of statistics**
- Can we instead test the DAMA signal based on the **total rate**?
- Promising strategy: COSINUS
  - Cryogenic NaI crystals allow for simultaneous detection of scintillation light and phonons
  - Ability to discriminate between nuclear recoils and electron recoils
  - Substantial reduction of background and much lower threshold
- Rather than searching for annual modulations, COSINUS can potentially **place a strong bound on the total event rate** of nuclear recoils in NaI

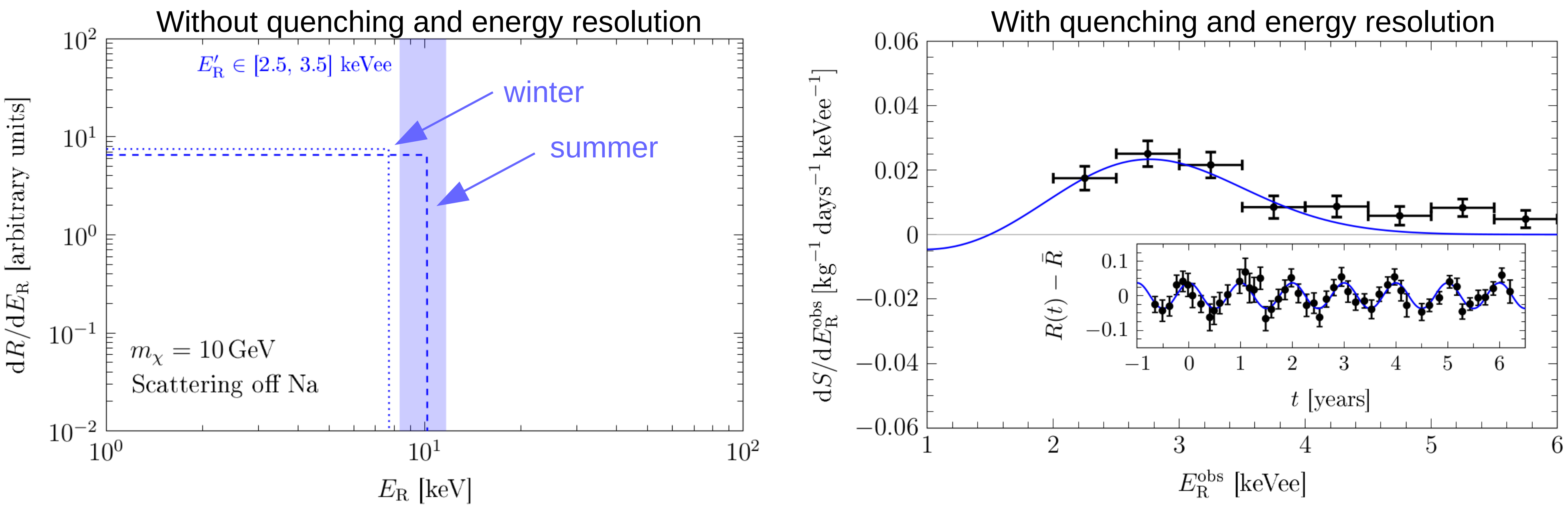
COSINE prototype – Angloher et al., arXiv:1603.02214





Astrophysical uncertainties

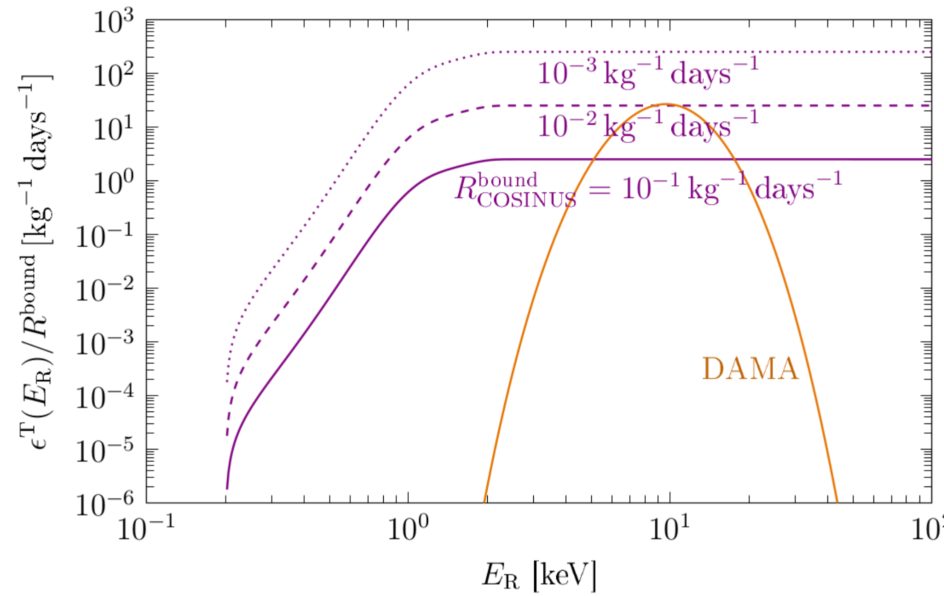
- Problem: The comparison of total rate and modulation amplitude **re-introduces model-dependence**, in particular regarding the assumed DM velocity distribution
- For example, the DAMA signal could be due to a **single DM stream** right at the DAMA energy threshold

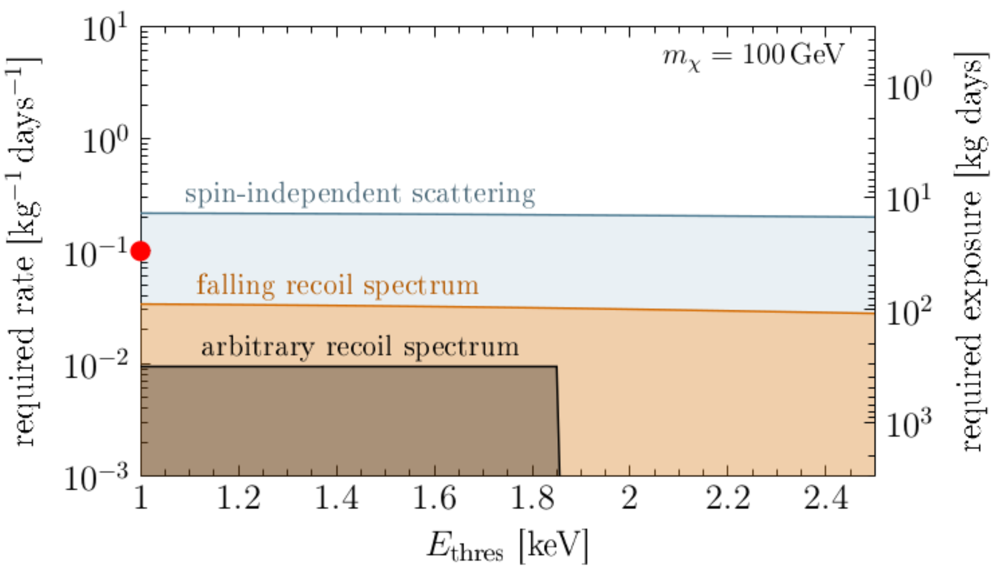


- Essential for COSINUS to **achieve lower threshold** than DAMA!

Model-independent comparison

- For a fully model-independent test of DAMA it is necessary to achieve a **total rate smaller than the modulation amplitude** in DAMA
- This requires a total rate < 10^{-2} kg^{-1} days^{-1}
- **Very ambitious goal** - likely need to make some additional assumptions

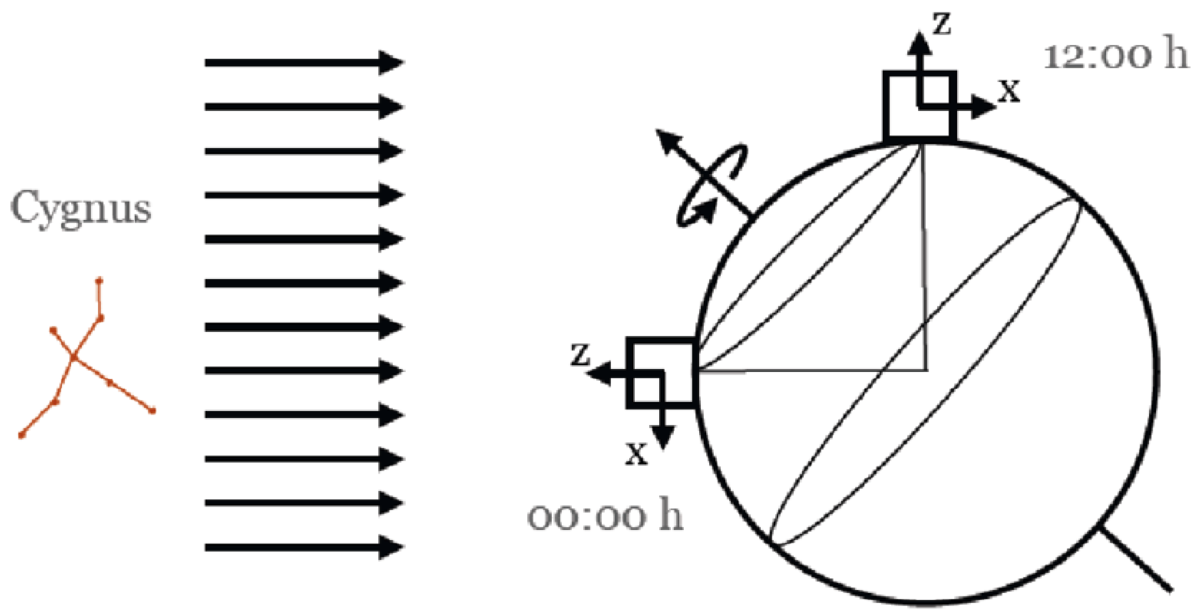




- To exclude spin-independent scattering for **any DM velocity distribution**, it is sufficient to achieve a total rate < 0.2 kg^{-1} days^{-1}
- For comparison: COSINE-100 has a rate of about 5 kg^{-1} days^{-1} (for 2 < E_R / keVee < 6)

Part 2: Daily modulations

- Crucial observation: the DM flux is **not isotropic** in the laboratory frame
- Direction of the WIMP wind **changes by almost 90 degrees** over the course of 12h



Part 2: Daily modulations

- Crucial observation: the DM flux is **not isotropic** in the laboratory frame
- Direction of the WIMP wind **changes by almost 90 degrees** over the course of 12h
- This change of direction can lead to detectable effects if

a) The probability for DM particles to reach the detector depends on how far they must travel through the Earth

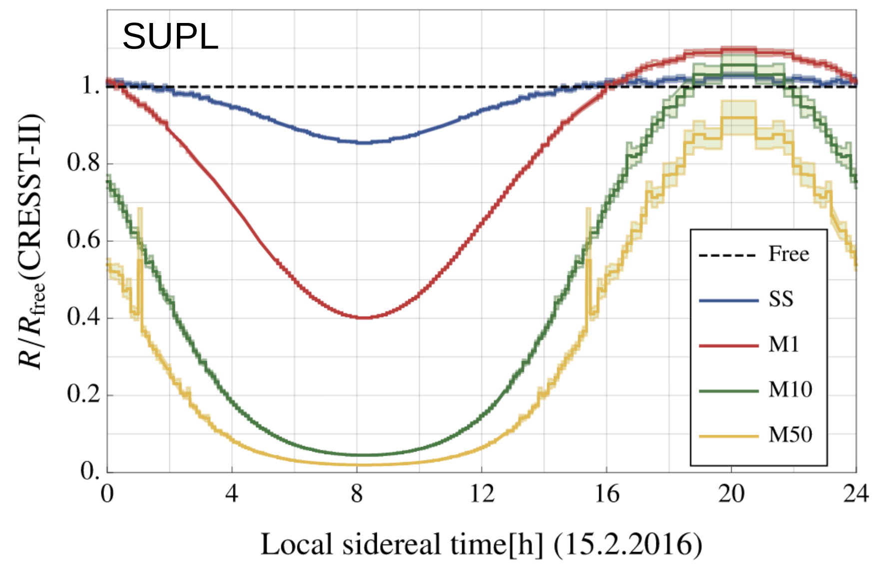
b) The probability for a DM particle to scatter depends on the orientation of the detector relative to the incoming particle

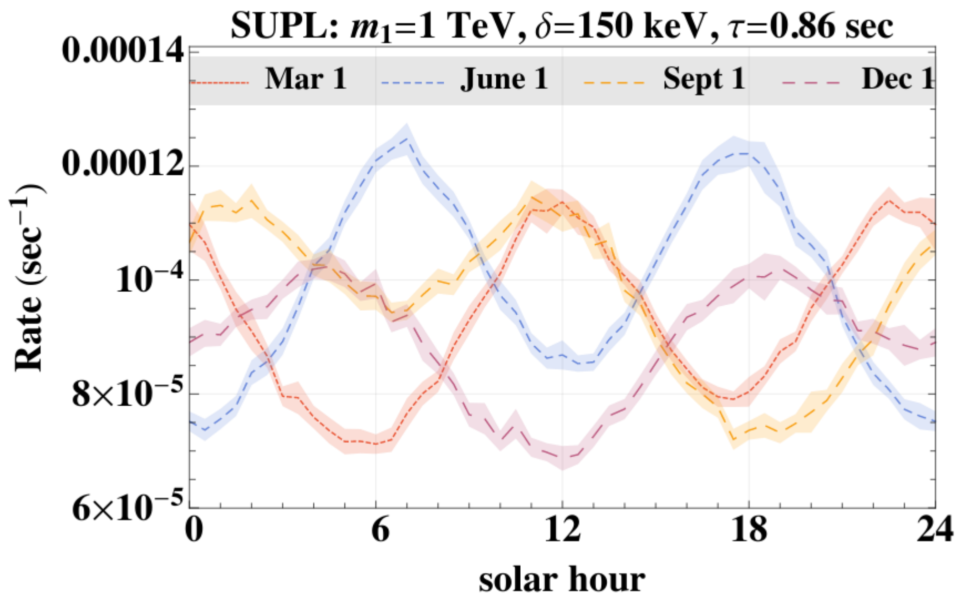
c) The detector response is sensitive to the direction of the recoiling particle

Diurnal modulation from scattering in the Earth

- **Option 1:** DM particles have such strong interactions that they scatter on the way through the Earth and lose energy

Emken & Kouvaris: arXiv:1706.02249



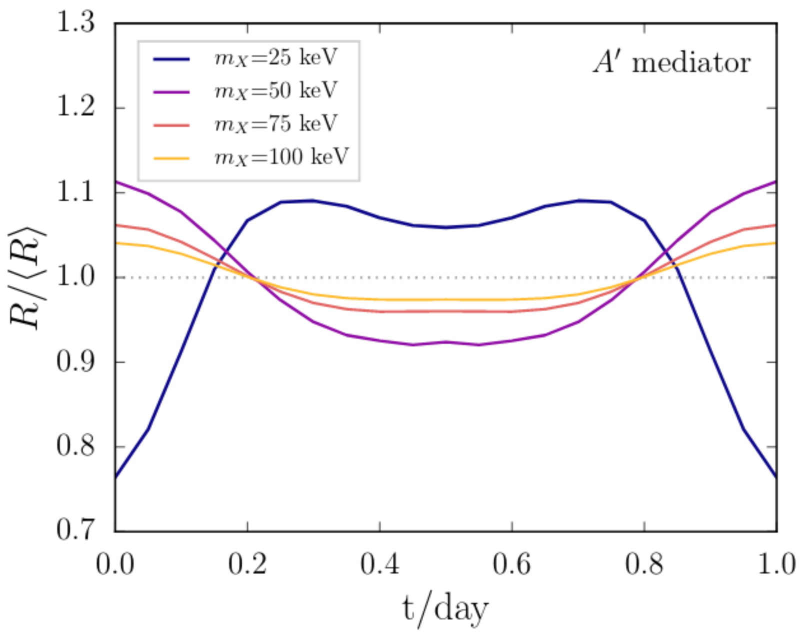


- **Option 2:** DM particles can upscatter into an excited state and then release the energy in the detector

Eby et al., arXiv:1904.09994

Diurnal modulation from scattering probability

- Conventional detector materials are **approximately isotropic**, such that the scattering probability is independent of the direction of the incoming DM particle
- Many new detector concepts have been **proposed recently**, in particular with the aim to **lower the energy threshold** and extend sensitivity to smaller DM masses
- Many such materials exhibit sizable **anisotropy**
- Diurnal modulation can help to **suppress backgrounds** from impurities and thermal noise
- Example: Optical photons in polar crystals like GaAs or Al_2O_3



Knapen et al., arXIv:1712.06598

Griffin et al., arXiv:1807.10291

Dirac materials

- Materials in which elementary excitations can be described by **Dirac equation**

- Energy-momentum relation: $E_{\mathbf{k}}^{\pm} = \pm\sqrt{v_{\mathrm{F}}^2\,\mathbf{k}^2 + \Delta^2}$

  k: lattice momentum

  v_F: Fermi velocity (replacing speed of light)

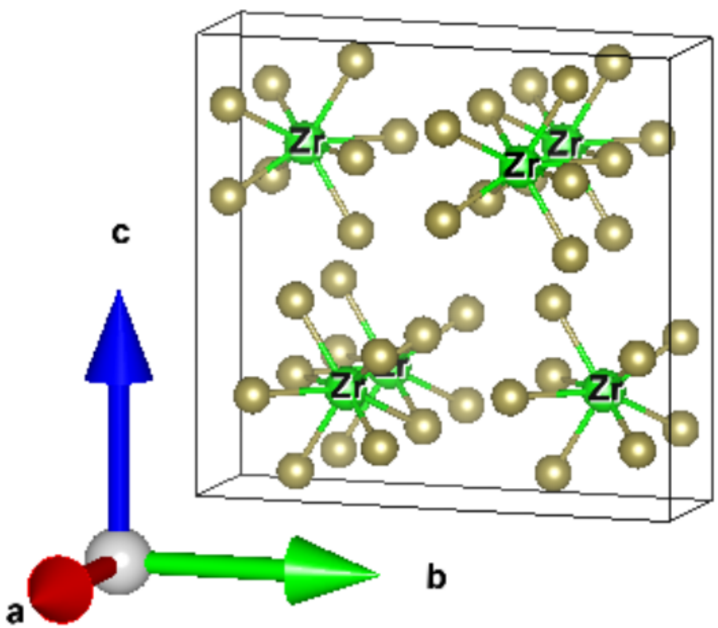
  2Δ: Band gap (replacing rest mass)

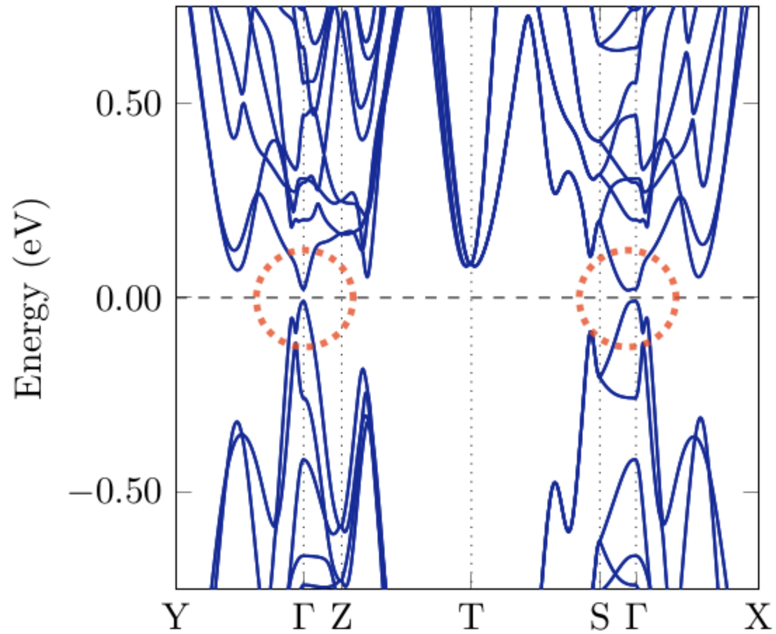
- For k >> Δ dispersion relation becomes linear → electrons behave like free relativistic fermions

- **Crucial advantage:** Δ can be as small as 10 meV

Hochberg et al., arXiv:1708.08929
Coskuner et al., arXiv:1909.09170

Example: $ZrTe_5$





- Band structure calculated with density functional theory + structural optimisation

	v_{Fx}	v_{Fy}	v_{Fz}	Δ [meV]
Theory	1.1e-3	9.1e-4	4.4e-4	15.6
Experiment	1.3e-3	1.6e-3	6.5e-4	11.75

Calculating event rates

- Various ingredients are necessary to calculate scattering rate

In-medium effects — Astrophysics

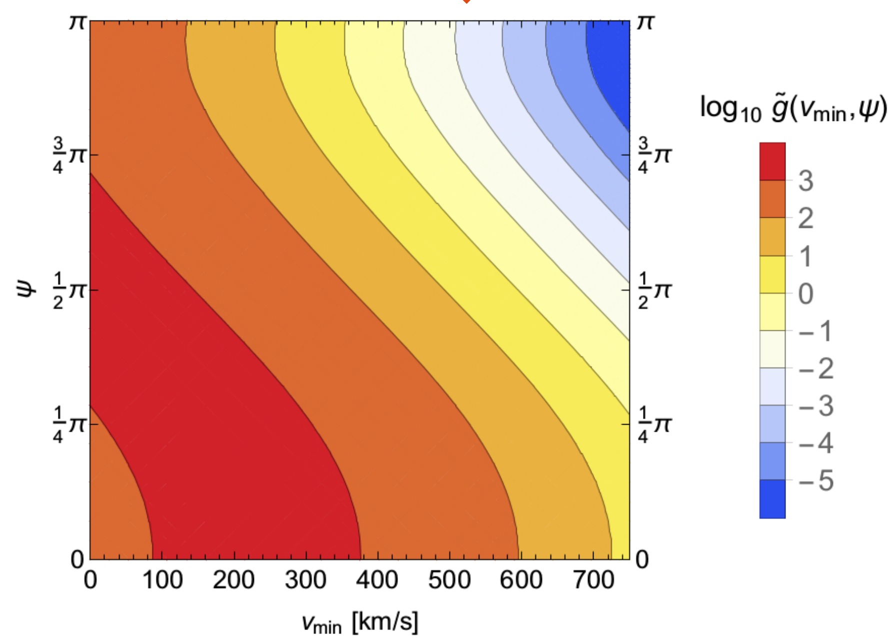
$$R_{\mathbf{k}\to\mathbf{k}'} = \frac{\rho_\chi}{m_\chi}\frac{\bar{\sigma}_e}{8\pi\mu_{\chi e}^2}\int d^3q\,|F_{\rm DM}(q)|^2|\mathcal{F}_{\rm med}(q)|^2|f_{\mathbf{k}\to\mathbf{k}'}(q)|^2\frac{\tilde{g}(v_{\rm min},\psi)}{|\mathbf{q}|}$$

Particle physics — Transition probability

Requires knowledge of dielectric tensor and polarisation tensor

$$\mathcal{F}_{\rm med}(q) = \frac{1}{1+\left(q_x^2\frac{v_{{\rm F},z}^2}{\kappa_{xx}} + q_y^2\frac{v_{{\rm F},y}^2}{\kappa_{yy}} + q_z^2\frac{v_{{\rm F},z}^2}{\kappa_{zz}}\right)\frac{\pi(\tilde{q}^2)}{q^2}}$$

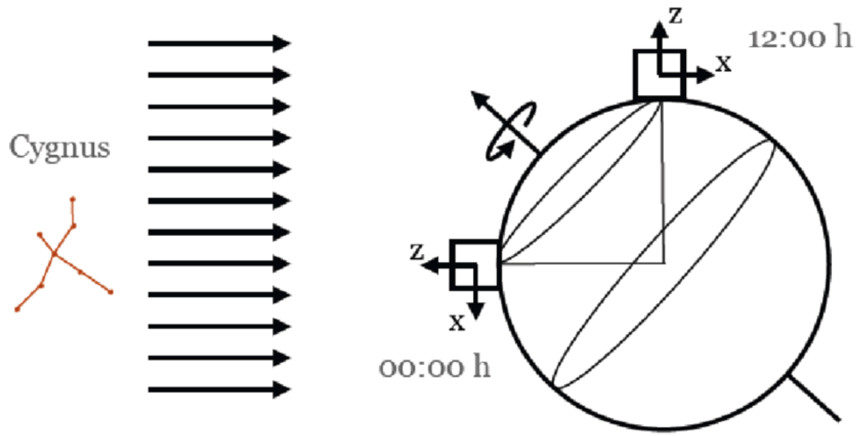
$$\pi(\tilde{q}^2) = -\frac{g\,e^2}{24\pi^2\,v_{{\rm F},x}v_{{\rm F},y}v_{{\rm F},z}}\left(\log\left|\frac{4\tilde{\Lambda}^2}{\tilde{q}^2}\right| + i\pi\Theta\left(\tilde{q}^2\right)\right)$$



Directional detection from anisotropies

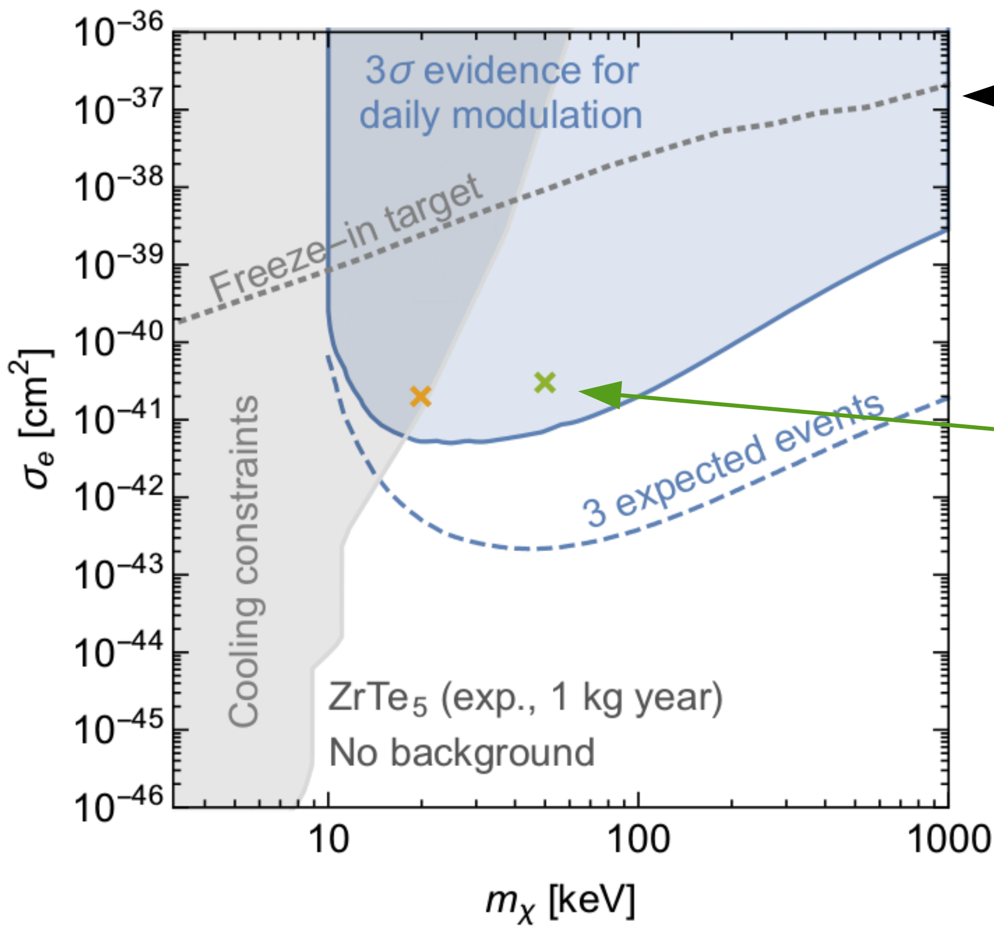
- **Observation 1:** Scattering in Dirac materials is possible only if the velocity of the incoming DM particle is larger than the Fermi velocity
- **Observation 2:** The Fermi velocities in Dirac materials exhibit significant anisotropies!

	v_{Fx}	v_{Fy}	v_{Fz}	Δ [meV]
Theory	1.1e-3	9.1e-4	4.4e-4	15.6
Experiment	1.3e-3	1.6e-3	6.5e-4	11.75

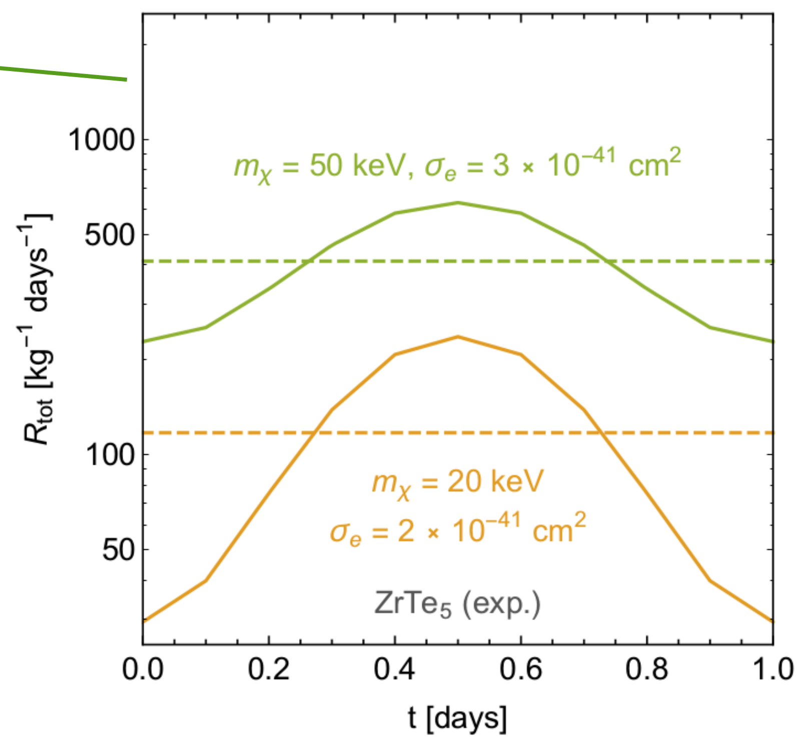


- Scattering is **suppressed** when the Fermi velocity pointing towards the WIMP wind is large

Sensitivity estimates



Dirac materials have **enormous potential** for testing the freeze-in mechanism for keV-scale DM



- **Also promising:** Organic Dirac materials like BNQ-TTF

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Interested in DM direct detection?
Try DDCalc!

DDCalc v2

Dark matter direct detection phenomenology package

DDCalc is a software package for performing various dark matter direct detection calculations, including signal rate predictions and likelihoods for several experiments.

A full description of this package and the physics framework behind it can be found in the GAMBIT DarkBit paper:

- T Bringmann, J Conrad, JM Cornell, LA Dal, J Edsjö, B Farmer, F Kahlhoefer, A Kvellestad, A Putze, C Savage, P Scott, C Weniger, M White & S Wild 2017, EPJC 77 (2017) 831, arXiv:1705.07920

A description of the new features in DDCalc v2 can be found in

- P Athron , C Balazs, A Beniwal, S Bloor, JE Camargo-Molina, JM Cornell, B Farmer, A Fowlie, TE Gonzalo, F Kahlhoefer, A Kvellestad, GD Martinez, P Scott, AC Vincent, S Wild, M White & AG V 2018, EPJC 79 (2019) 38, arXiv:1808.10465

If you write a paper that uses DDCalc, please cite both papers.

Version history:

- `v2.2.0 - February 2020`: Added implementation of PICO-60 (2019), DarkSide-50 (S2-only) and CRESST-III.
- `v2.1.0 - September 2018`: Added python support and interface with DirectDM for automated RGE evolution and matching of effective operators.
- **`v2.0.0 - June 2018`:** Support for full set of non-relativistic operators with general momentum and velocity dependence, new features for the definition of complex experiments with several signal regions and/or target elements, improved user interface including several new example files, new results from XENON1T (2018).

Coming soon
DDCalc v3.0
including annular modulation for arbitrary non-relativistic effective operators

Conclusions

- DM flux in the laboratory is predicted to **vary in magnitude and energy** over the course of the year and **in direction** over the course of each day
- As a result, many DM signals are expected to **exhibit annual or daily modulations**, which may enable us to distinguish them from backgrounds
- **Annual modulations:** DAMA signal remains mysterious, but new experiments are on their way to comprehensively test the DM interpretation
- Model-independent tests require similar set-up and techniques for comparing **modulation amplitude and total rate**
- **Daily modulations** can arise from a number of different effects and can vary greatly in terms of amplitude and phase
- **Interesting idea:** Daily modulation from anisotropic scattering probability in Dirac materials
- Promising strategy for **testing DM models with tiny couplings** in the face of unknown backgrounds