

# Annual modulation of dark matter signals: Experimental results and new ideas

**Felix Kahlhoefer**

**Identification of Dark Matter, 18-22 July 2022, Vienna**

Many thanks to  
Govinda Adhikari, Ken-Ichi Fushimi,  
Ambra Mariani, Florian Reindl,  
Marisa Sarsa, Karoline Schaeffner  
and Madeleine Zurowski  
for providing material for this talk

# Reaction vs. scientific age

## Professor:

Ahh, those were the good old days, when we were still excited about DAMA. I was there, you know?

## Postdoc:

I. DON'T. WANT. TO. HEAR. ANOTHER. WORD. ABOUT. DAMA

## Grad student:

What is DAMA?



# Reaction vs. scientific age

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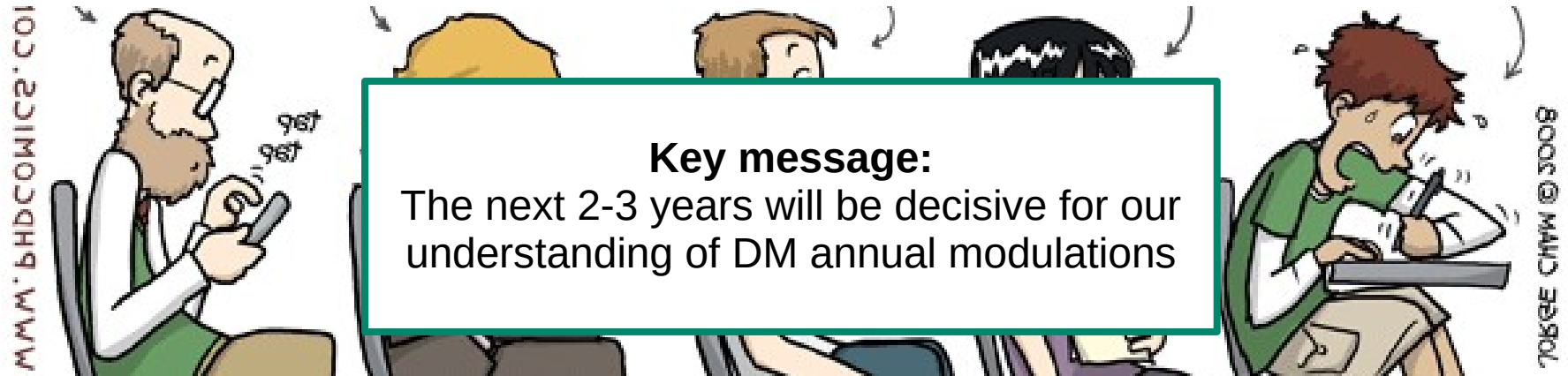
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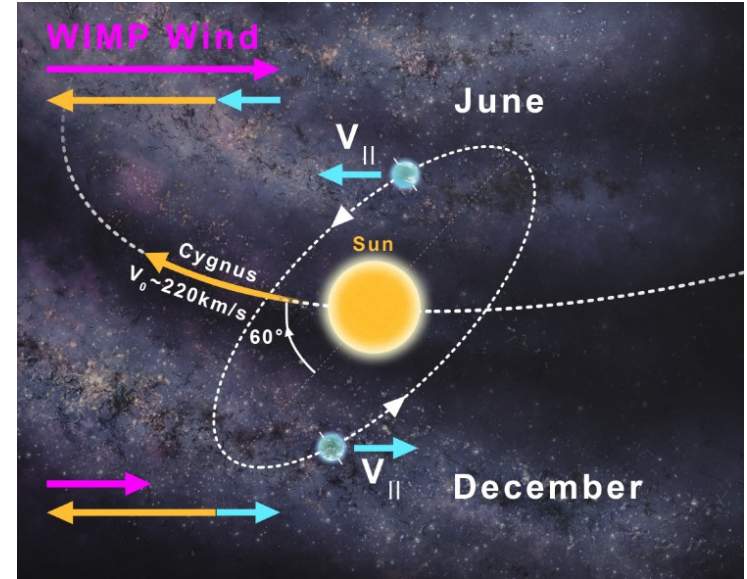
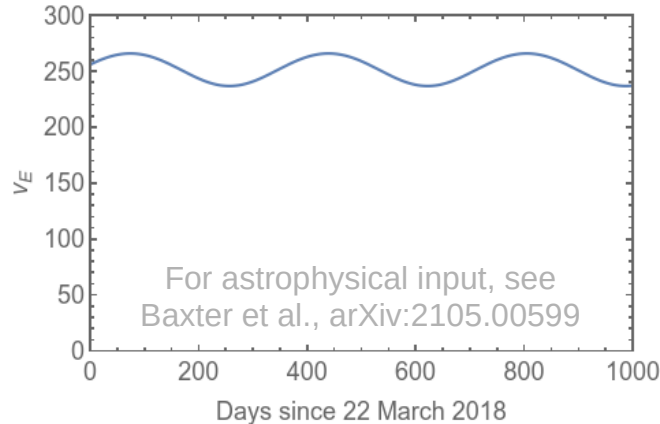
What is DAMA?



# Annual modulation of direct DM signals

- Consider DM particles at rest, Earth moving with velocity  $v_E$  through DM density  $\rho_{DM}$ :

$$R \propto \sigma v_E \rho_{DM}$$



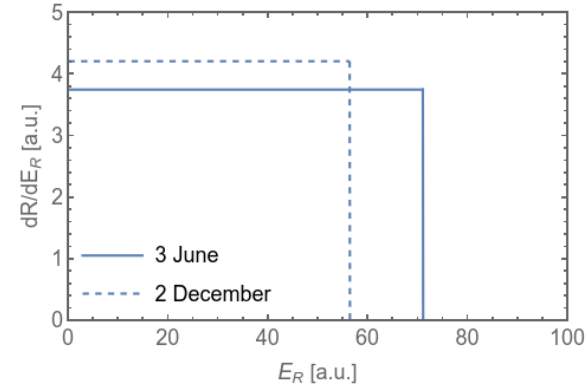
Froborg & Duffy, *Annual Modulation in Direct Dark Matter Searches*, arXiv:2003.04545

# Annual modulation of direct DM signals

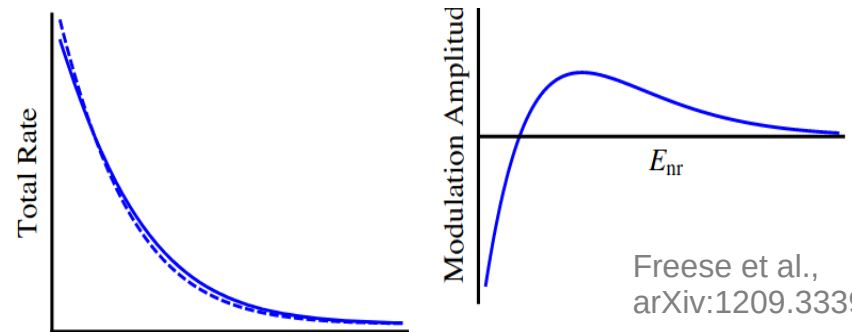
- Maximum possible recoil energy:

$$E_{R,\max} = \frac{p_{\max}^2}{2m_N} = \frac{2\mu^2 v_E^2}{m_N}$$

$$\Rightarrow \frac{dR}{dE_R} \propto \frac{\sigma \rho_{\text{DM}}}{v_E} \Theta(E_{R,\max} - E_R)$$



- Realistic DM velocity distribution (Maxwell-Boltzmann):
  - Recoil spectrum shifted to larger energies
  - “Anti-modulation” at low energies



Freese et al.,  
arXiv:1209.3339

# Search for annual modulations

$$\frac{dR(t)}{dE_R} \approx \left. \frac{dR}{dE_R} \right|_{v_E=0} + \vec{v}_E(t) \cdot \vec{\nabla}_{v_E} \frac{dR}{dE_R} = \frac{d\bar{R}}{dE_R} + \cos(\omega t + \phi) \frac{dA}{dE_R}$$

- Assuming time-independent backgrounds, significance of modulation is

$$\sqrt{\chi^2} \sim \frac{A}{\sqrt{\bar{R}_{\text{signal}} + \bar{R}_{\text{background}}}} \times \sqrt{\text{exposure}}$$

- Promising way to increase significance in the presence of unknown backgrounds
- Time dependence may serve as ultimate proof for DM origin of a signal

# Backgrounds

- Underground muon flux correlates with atmospheric temperature and hence varies with the seasons

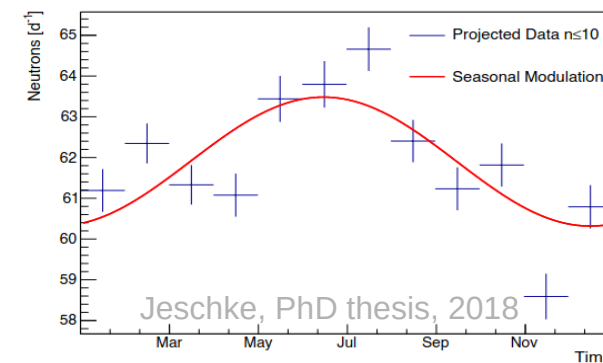
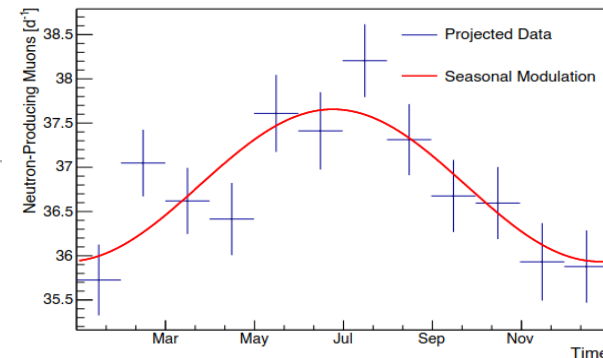
Blum, arXiv:1110.0857

- Modulating background from neutron scattering?

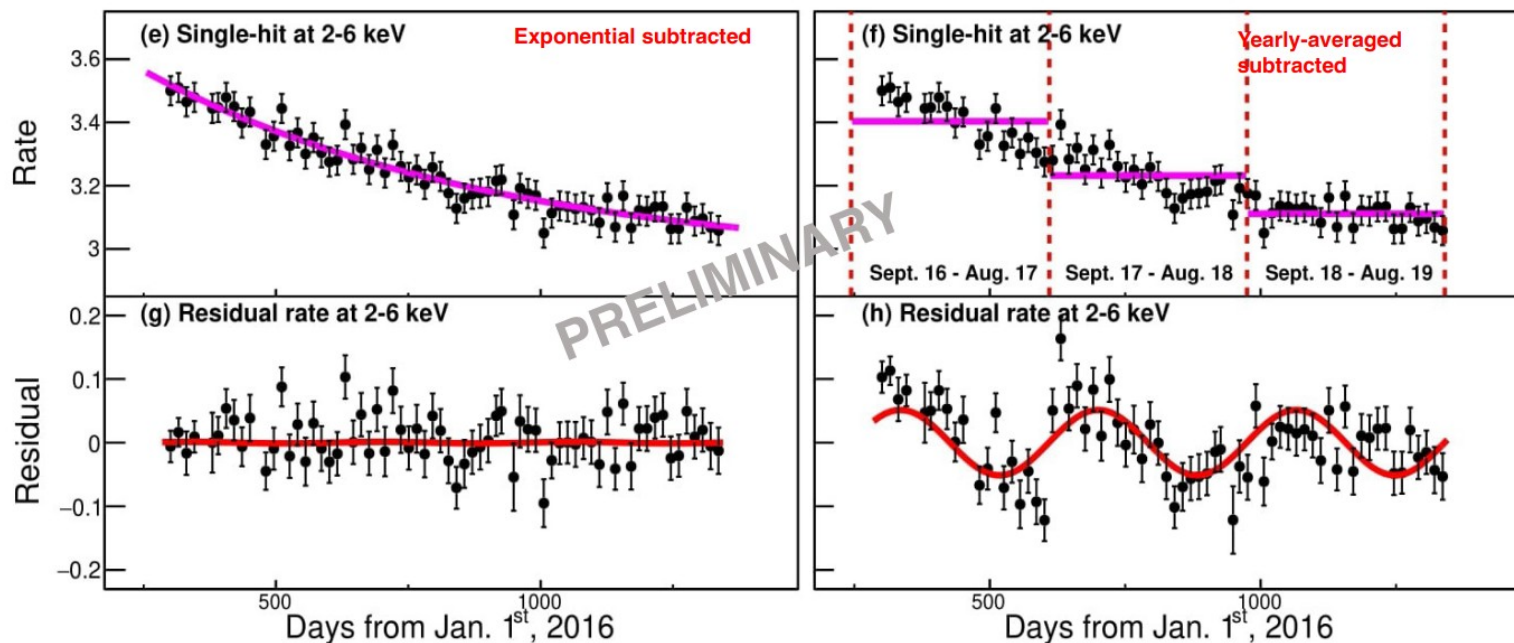
- Can be tested by searching for multiple scatters
- Phase depends on hemisphere

- **Careful:** Periodic subtraction of slowly varying backgrounds may mimic modulation signal

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



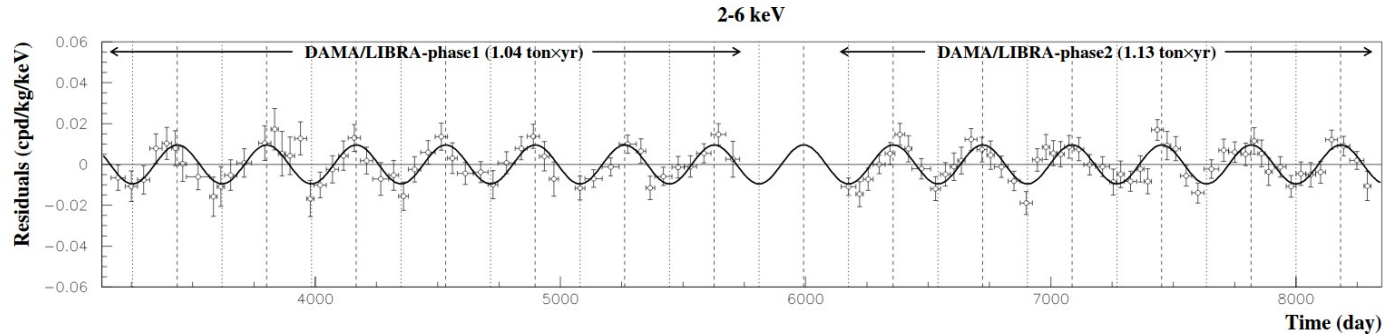
# Problematic analysis techniques



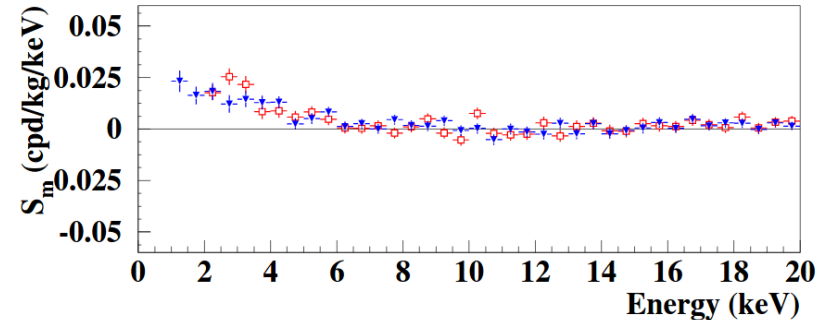
Hafizh Prihtiadi for the COSINE-100 collaboration, ICHEP 2022



# The Elephant in the Room: DAMA



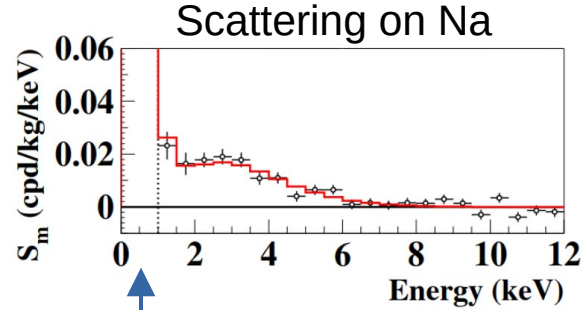
- The DAMA experiment observes evidence for a modulation in their (nuclear?) recoil data at a significance of  $\sim 13$  sigma
- Modulation phase consistent with the expectations for DM scattering



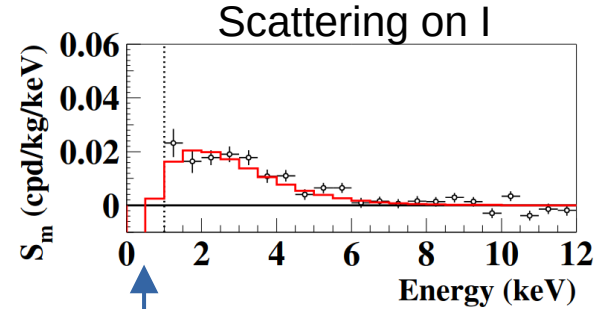
Bernabei et al., arXiv:1805.10486

# DM interpretation of the DAMA signal

- Energy dependence also agrees with expectation for the scattering of a 10-100 GeV WIMP



Contribution of I below threshold



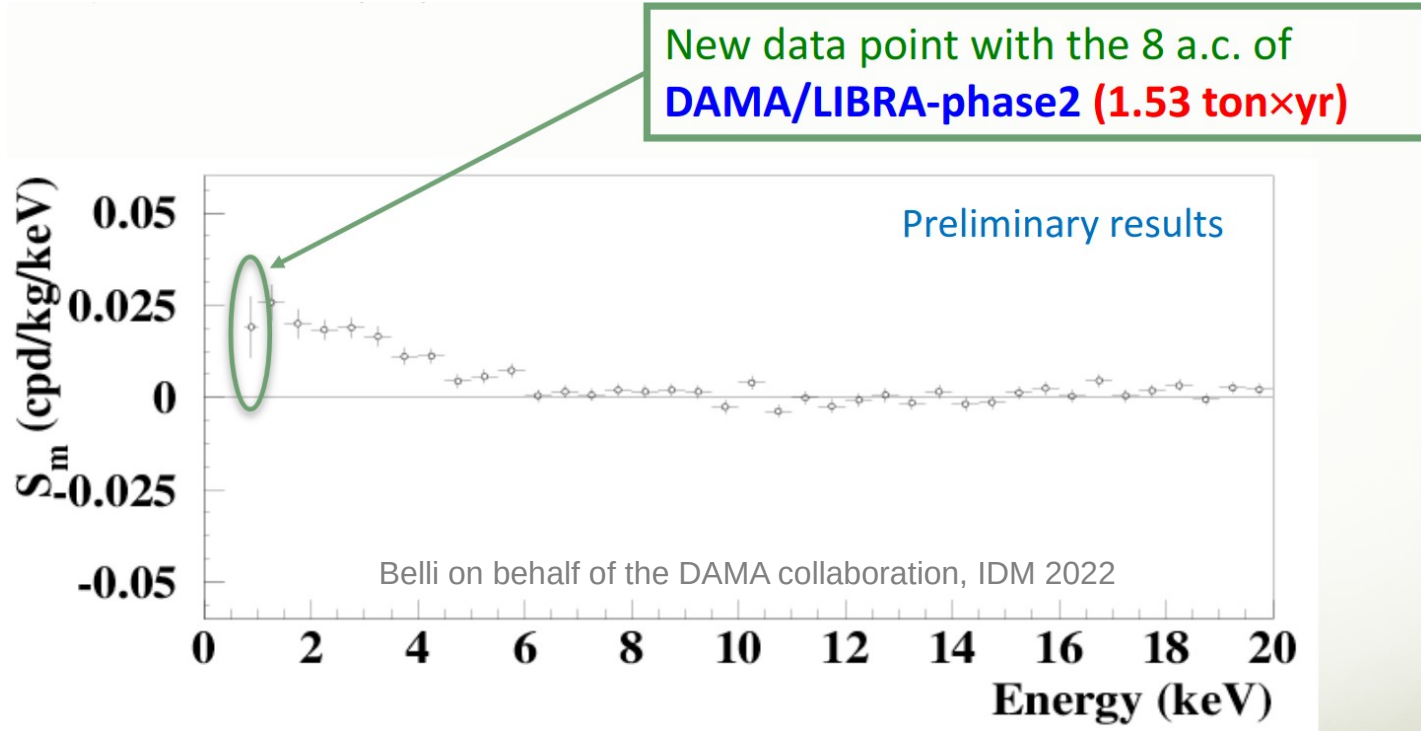
Anti-modulation below threshold

## ■ Notes:

Bernabei et al., arXiv:1907.06405

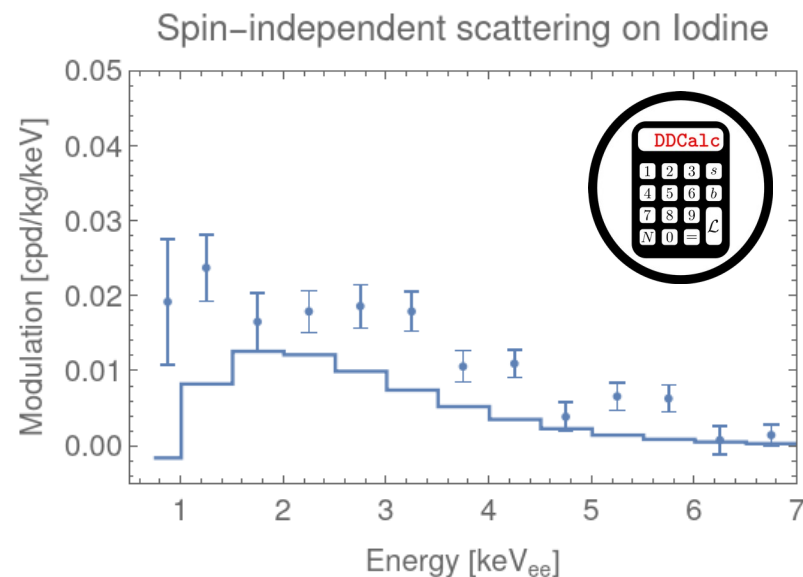
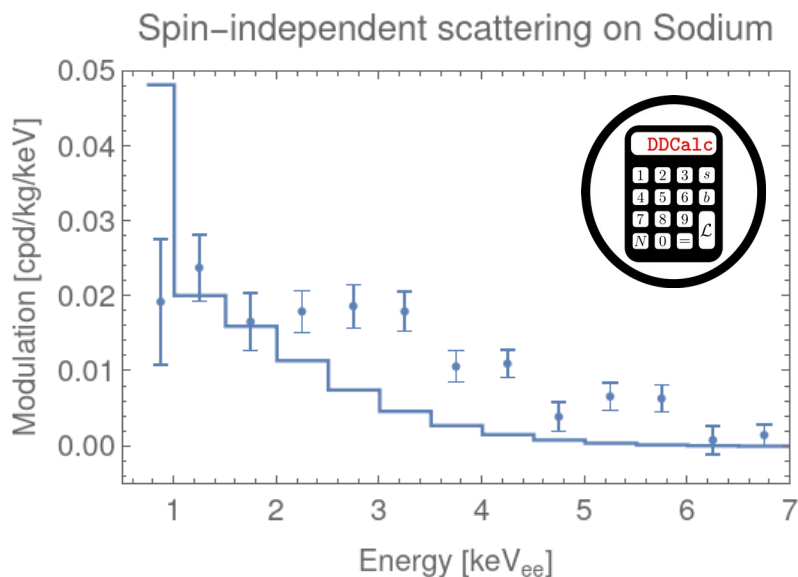
- Observed energy related to true nuclear recoil energy by quenching factor  $Q < 1$
- Difficult to accurately reproduce these figures independently, since energy resolution and acceptance of DAMA not public

# Breaking news: Threshold below 1 keV



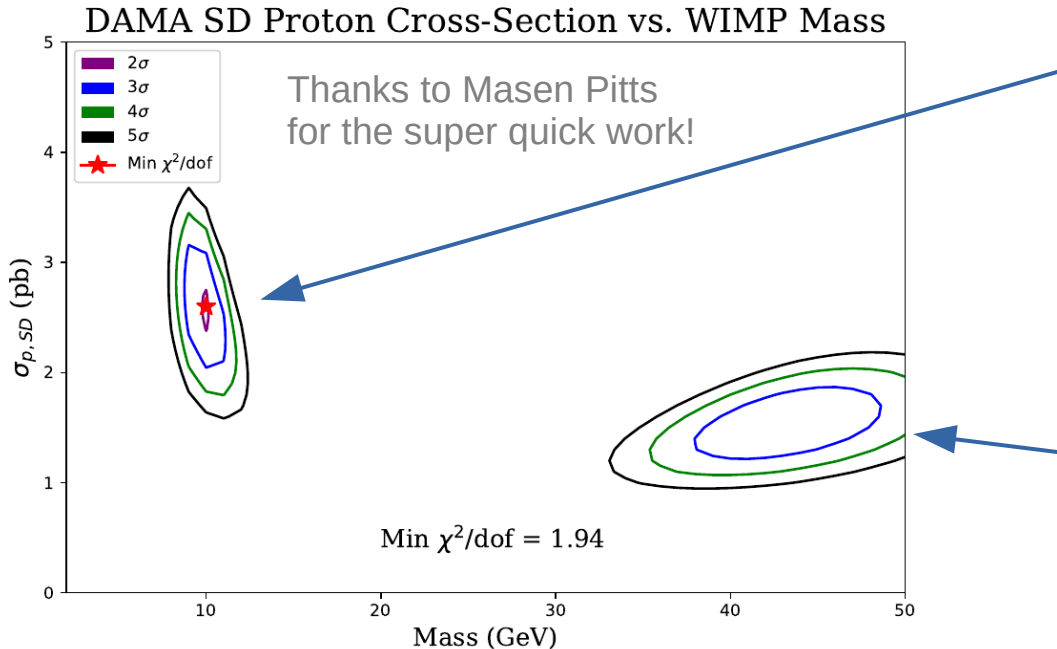
# Very preliminary interpretation

- Spin-independent scattering **no longer** gives a good fit!
- **Best-fit point:**  $\chi^2 \sim 42$  (11 d.o.f.)

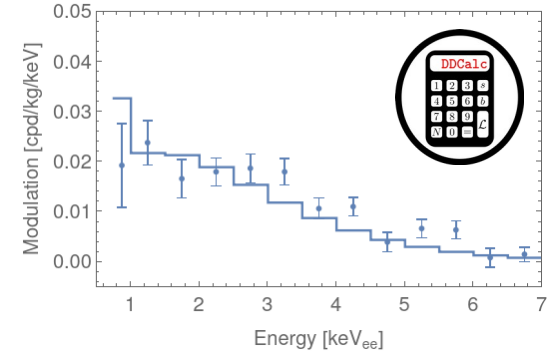


# Very preliminary interpretation

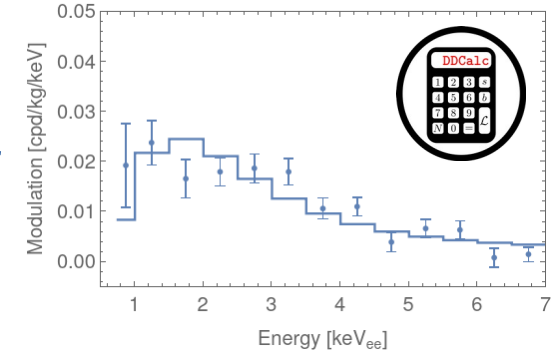
## Spin-dependent scattering still works alright



Spin-dependent scattering on Sodium

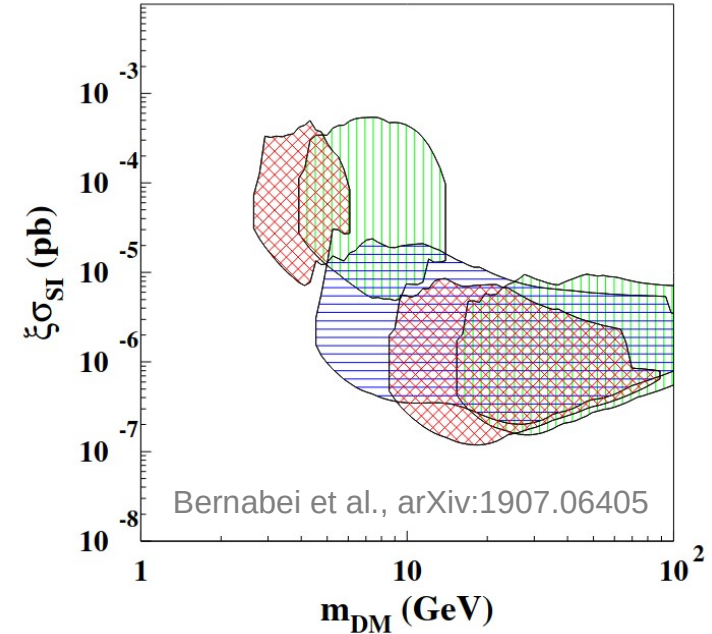


Spin-dependent scattering on Iodine



# DM interpretation of the DAMA signal

- No official interpretation of DAMA data under standard astrophysical assumptions
- Instead “marginalization” over different halo models and parameters
- Separate analyses for different (optimistic) assumptions on the quenching factors
- Many models considered, but no comparison to exclusion limits from other experiments

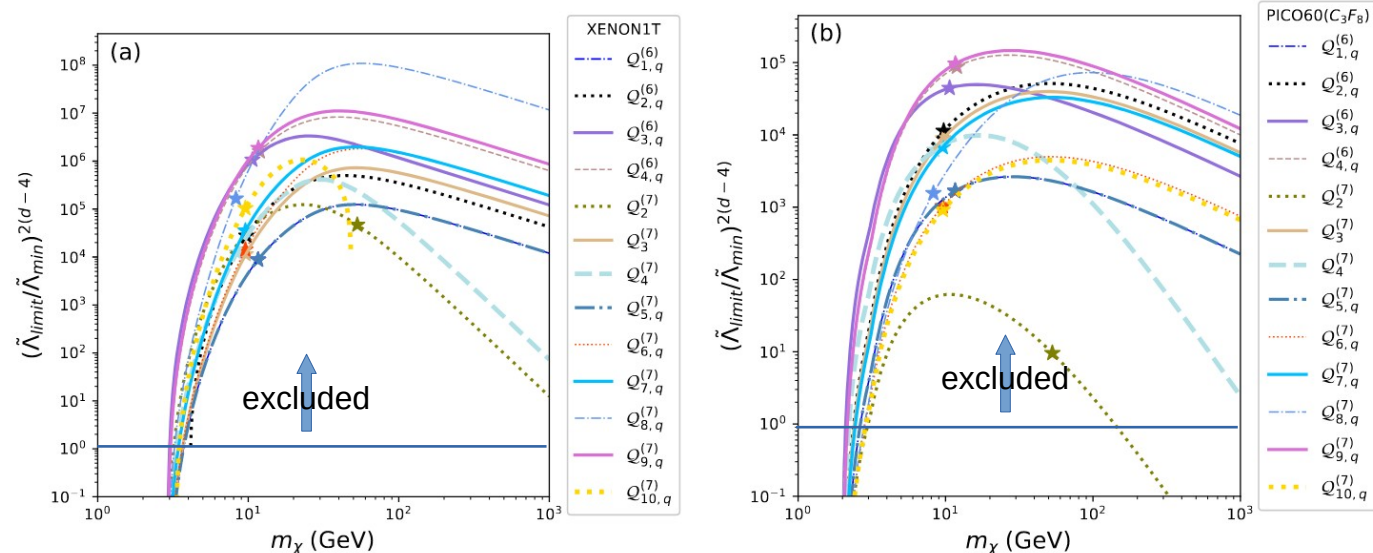


# (In)compatibility of DAMA and the rest

- Detailed comparison between DAMA and other experiments for various astrophysical assumptions performed in series of papers by Kang et al.

arXiv:1805.06113, arXiv:1808.04112, arXiv:1810.09674, arXiv:1902.09121, arXiv:1910.11569

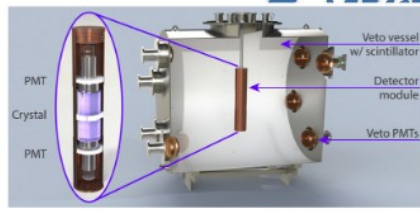
- Standard halo model: Any type of nuclear scattering excluded
- Elastic scattering: Excluded independent of astrophysical assumptions



# How to make progress?

- **Conclusion:** If the DAMA signal is due to DM, we are fundamentally wrong about its astrophysical distribution **and** fundamental interactions
- Need to find ways to test DAMA without the need for any assumptions
  - Need independent measurements with NaI detectors over same energy range (1-6 keV<sub>ee</sub>)
- **Challenge:** Achieve ultra-low background ( $\sim 1$  cpd/kg/keV) in region of interest
  - Need to improve crystal purity and remove radioactive contaminants

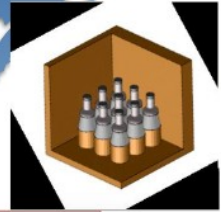




**DAMA/LIBRA @ LNGS**

**SABRE @ LNGS**

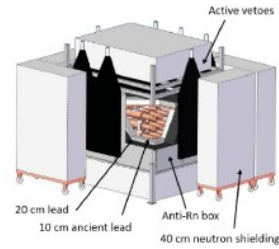
**COSINE-100 @ Y2L**



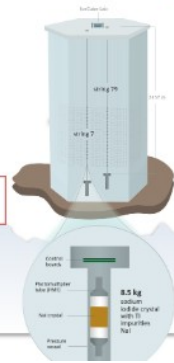
**PICO-LON @ Kamioka**

**ANAIS @ Canfranc**

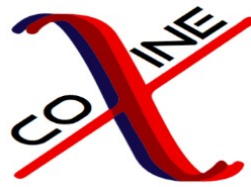
**SABRE @ Stawell**



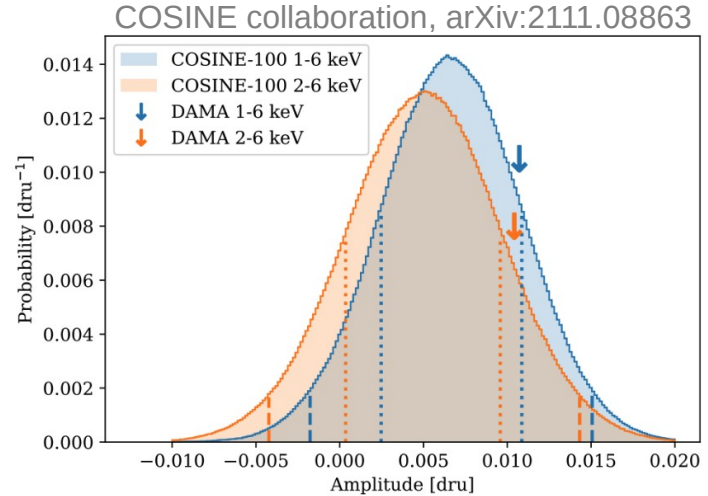
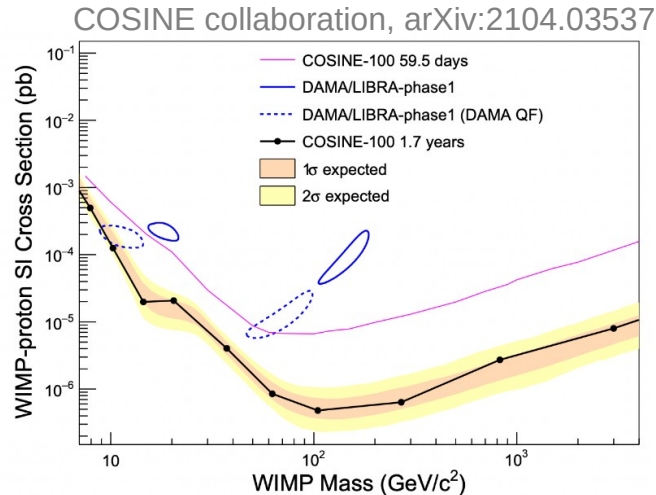
**DM-Ice17 @ South Pole**



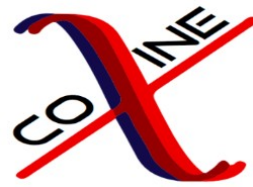
# COSINE-100



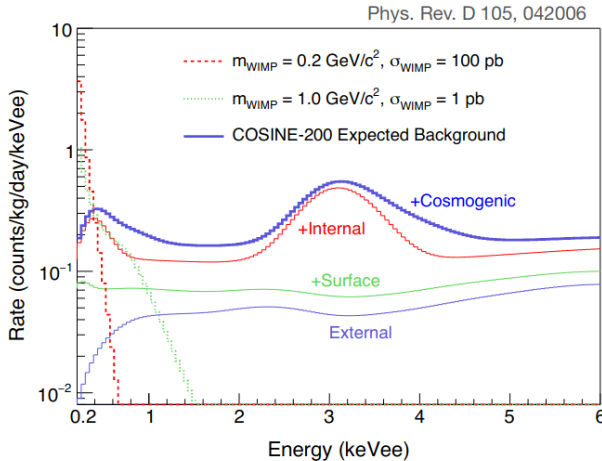
- Joint venture of KIMS and DM-Ice at Yangyang Underground Lab, South Korea
- Total rate achieved low enough to exclude DAMA for standard assumptions
- Search for annual modulation compatible with both DAMA and no modulation



# COSINE: Next steps



- Complete six years of data-taking in 2022

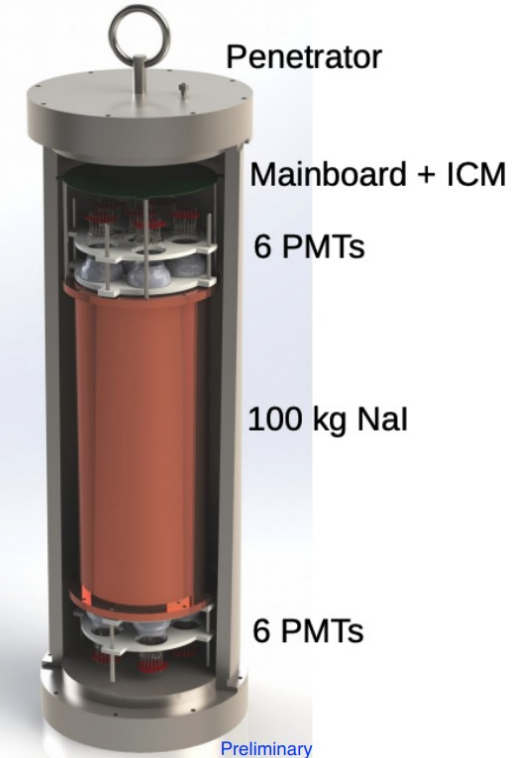


- COSINE-200: Lower background, deeper location, sub-keV threshold

- Data taking to start in 2023
- Conclusive test of DAMA modulation

- Ongoing R&D for DM-Ice 250

# DM-ICE

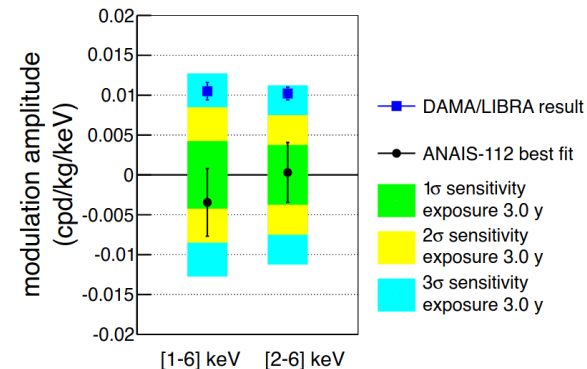
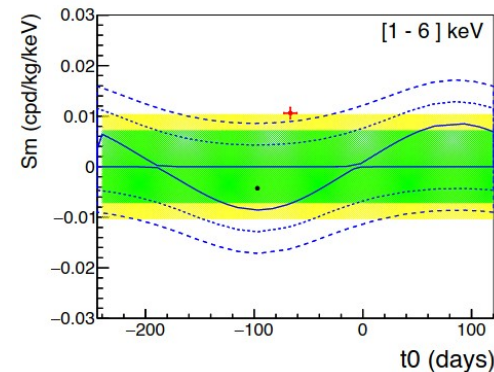


# ANAIS-112



- At Canfranc Underground Lab, Spain
- 112.5 kg of NaI with 1 keV analysis threshold
- Background level slightly higher than DAMA
  - Background decreases exponentially with time
  - Background model with nuisance parameters for every detector (up to 18 in total)
  - No evidence for modulation
- 3 years of data: ANAIS-112 and DAMA are incompatible at the level of  $3.3\sigma$
- 5 years of data by August 2022: Expect to test DAMA at  $4\sigma$  CL

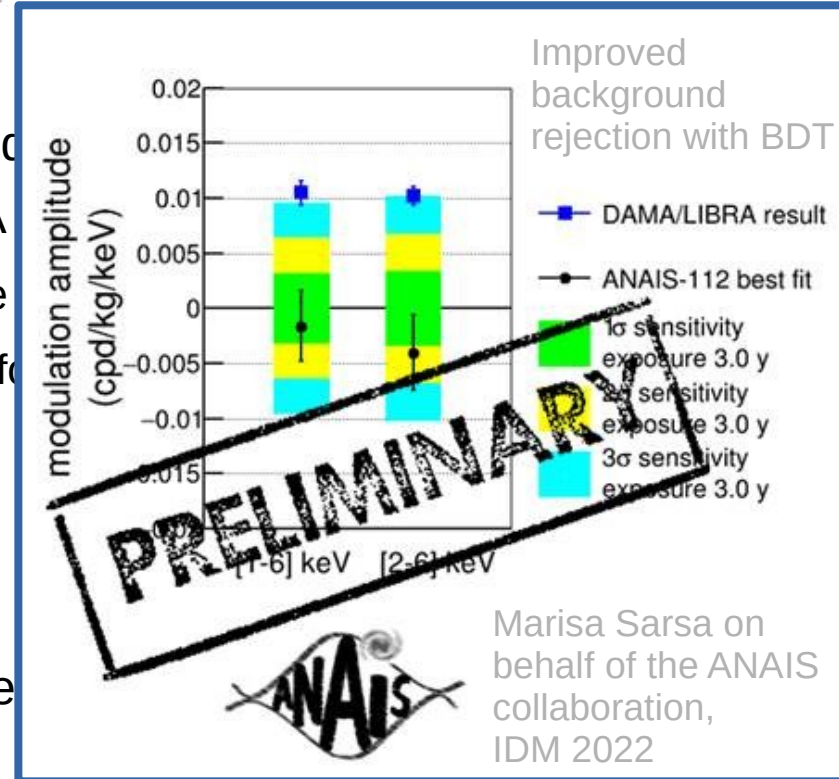
ANAIS collaboration,  
arXiv:2103.01175



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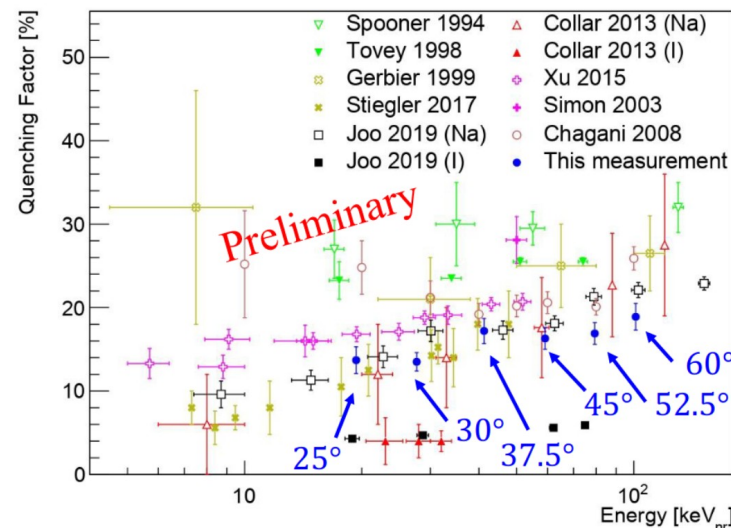


## ■ Successful manufacturing of high purity NaI(Tl) crystals

|   | DAMA/LIBRA<br>(NIM A592 (2008) 297.)        | Ingot #85<br>(2020)                 | Ingot #94<br>(This work) |
|---|---|-------------------------------------|--------------------------|
| Crystal size                            | $10.2 \times 10.2 \times 25.4 \text{ cm}^3$ | $7.62\phi \times 7.62 \text{ cm}^3$ |                          |
| $^{232}\text{Th}$ [ $\mu\text{Bq/kg}$ ] | 2~31  | $0.3 \pm 0.5$                       | $4.6 \pm 1.2$            |
| $^{226}\text{Ra}$ [ $\mu\text{Bq/kg}$ ] | 8.7~124                                     | $1.0 \pm 0.4$                       | $8.7 \pm 1.5$            |
| $^{210}\text{Po}$ [ $\mu\text{Bq/kg}$ ] | 5~30  | $< 5.7$                             | $28 \pm 5$               |

## ■ Need further reduction of noise below 3 keV<sub>ee</sub>

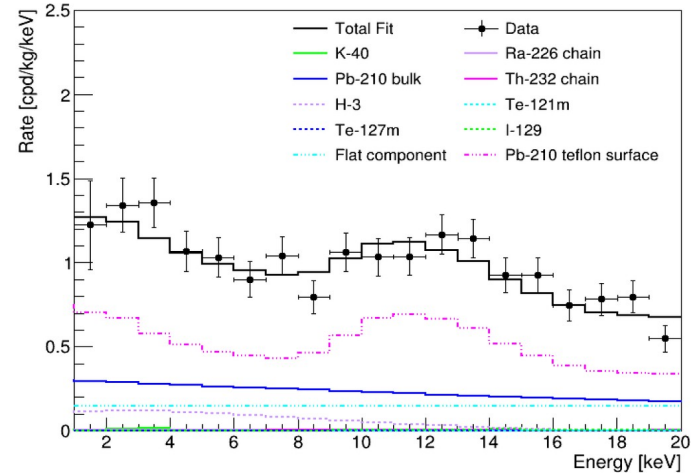
## ■ New measurement of Na quenching factor



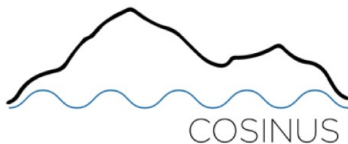
# SABRE North & South



- Particular focus on high radiopurity
  - Proof-of-principle achieved background level of 1.2 cpd/kg/keV (comparable to DAMA/LIBRA)
  - Further reduction of  $^{210}\text{Pb}$  should push background level down to 0.3 cpd/kg/keV
  - SABRE South: Active veto for further background rejection

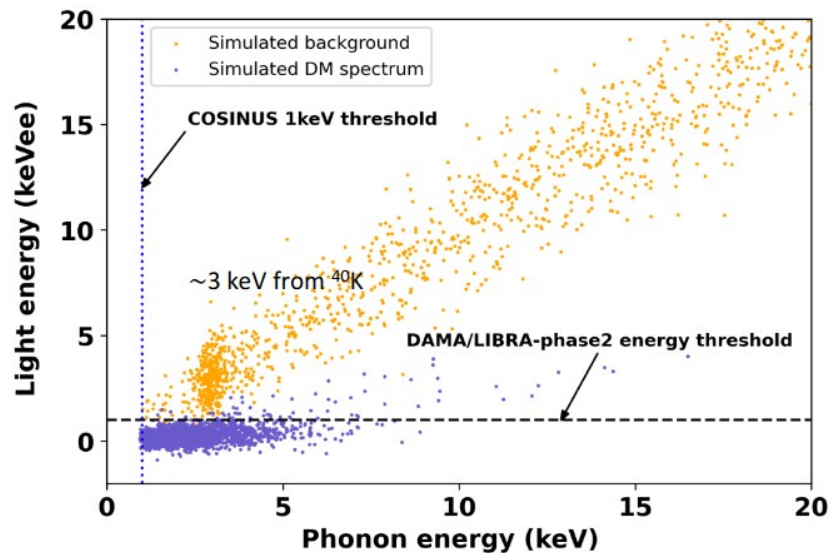
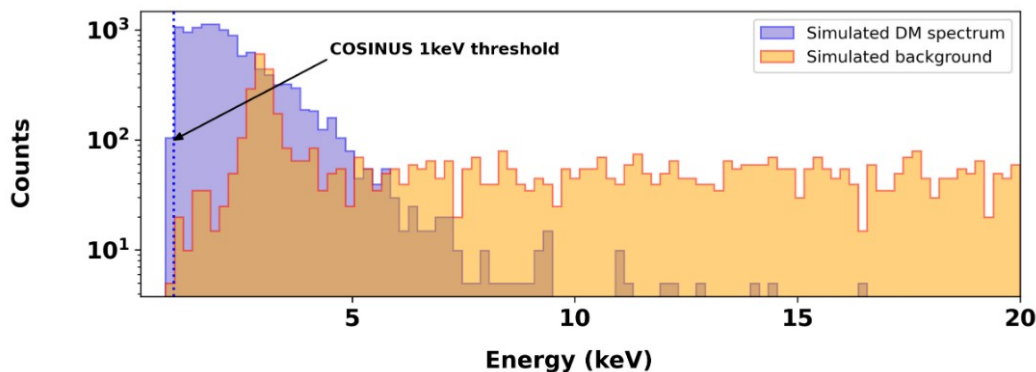


- Two sites: Gran Sasso, Italy and Stawell Underground Physics Lab, Australia
  - Data taking planned for 2023-24
  - Expect to test DAMA at  $3\sigma$  within 2-4 years of data taking



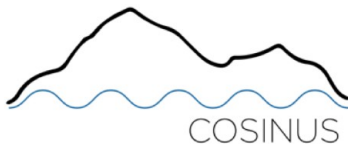
## ■ NaI as low-temperature calorimeter

- Phonon channel gives high energy resolution and low threshold (below 2 keV<sub>nr</sub>)
- Scintillation channel allows for discrimination between electron and nuclear recoil
- Strong background suppression





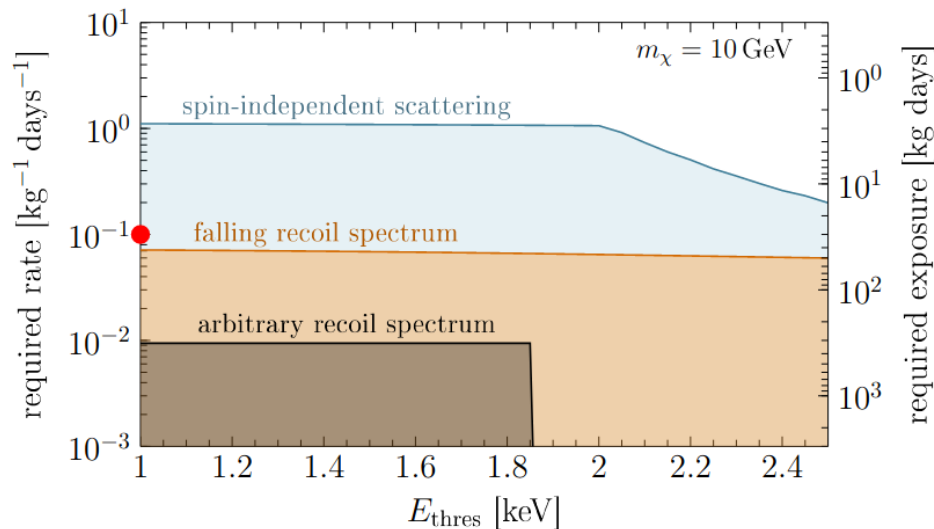
# COSINUS



- Low background makes it possible to test DAMA with a single annual cycle
- Idea: Modulation amplitude cannot be larger than (average) absolute rate
- Model-independent exclusion possible with 100 kg-days exposure in background-free environment

## ■ Current status:

- Experimental facility under construction at LNGS
- Data taking with  $\sim 1$  kg target mass in 2023

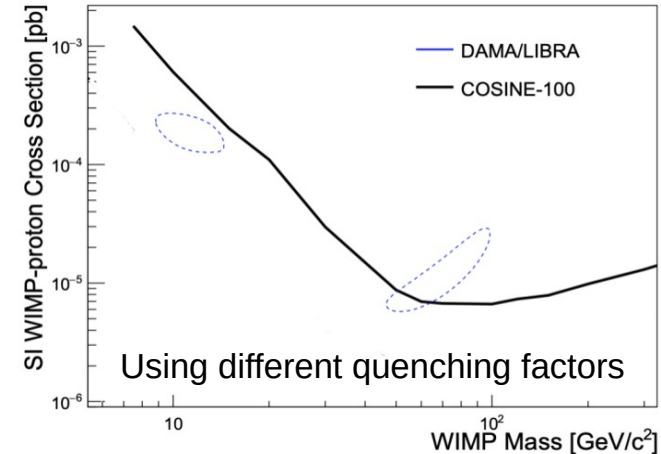


FK et al., arXiv:1802.10175

# Are these tests really model-independent?

- **Quenching factors:** Does the quenching of NaI crystals depend on the growth method or on the TI concentration?
  - If so, the energy range probed by DAMA may be different from the one probed by other experiments
  - Comparison becomes model-dependent

Talk by Madeleine Zurowski, IDM 2022



- **Energy resolution:** Is it possible that DAMA/LIBRA has very poor energy resolution and sees leakage from a signal that sits below threshold?
  - Newer detectors with better energy resolution might see nothing above threshold

# What if DAMA is confirmed?

- **Follow-up question:** How could we have been so wrong about DM?
- After 10+ years and hundreds of papers, there is **not a single model** that demonstrably gives a good fit to DAMA while evading all other constraints
- Need to **fundamentally re-think** the interactions of dark and visible matter and/or the distribution of dark matter in the Milky Way
- Attempts to explain DAMA have given rise to **many new ideas** that have turned out to be **fruitful in other contexts**

# Inelastic Dark Matter (IDM@IDM)

## ■ Proposed over 20 years ago to explain DAMA

Tucker-Smith & Weiner, hep-ph/0101138

### ■ Start with dark sector fermion with Dirac mass term $m_D$

See also talk by Sam Junius

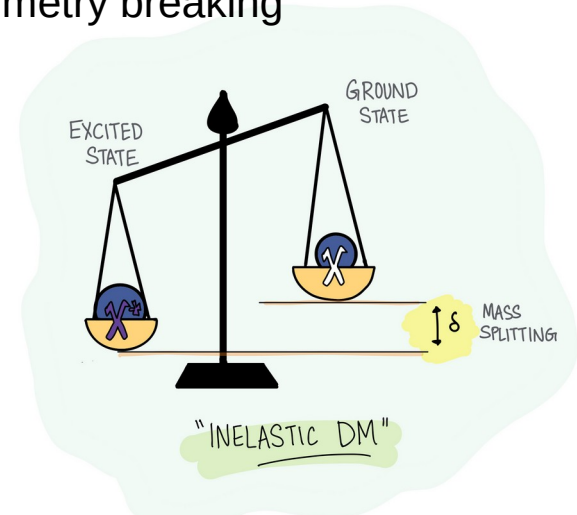
### ■ Majorana mass terms generated through spontaneous symmetry breaking

$$\mathcal{L}_\psi \supset -\frac{1}{2} \begin{pmatrix} \overline{\psi_L^c} & \overline{\psi_R} \end{pmatrix} \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \psi_L \\ \psi_R^c \end{pmatrix}$$

### ■ For $m_L = m_R \ll m_D$ end up with two nearly degenerate states $\chi$ and $\chi^*$ with mass splitting $\delta$

### ■ → Excited state long-lived, ground state stable (“inelastic” or “Pseudo-Dirac” dark matter)

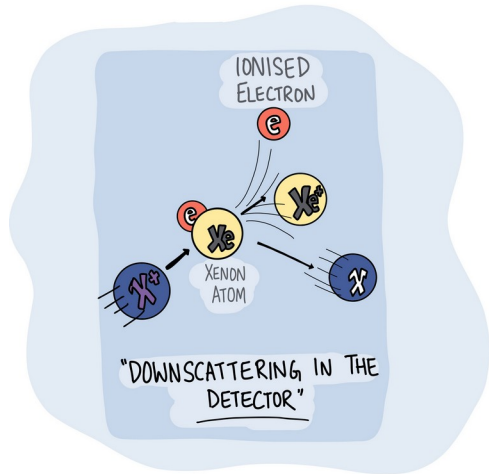
### → Couplings are off-diagonal: All interactions must involve transition $\chi \rightarrow \chi^*$ or $\chi^* \rightarrow \chi$



Doodles by Saniya Heeba

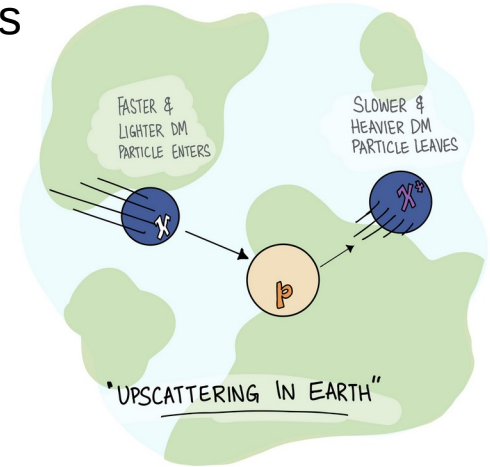
# Luminous & exothermic dark matter

- In IDM models, there may be a population of excited states
  - Cosmological relics Baryakhtar et al., arXiv:2006.13918
  - Upscattering on cosmic rays, the Sun or the Earth



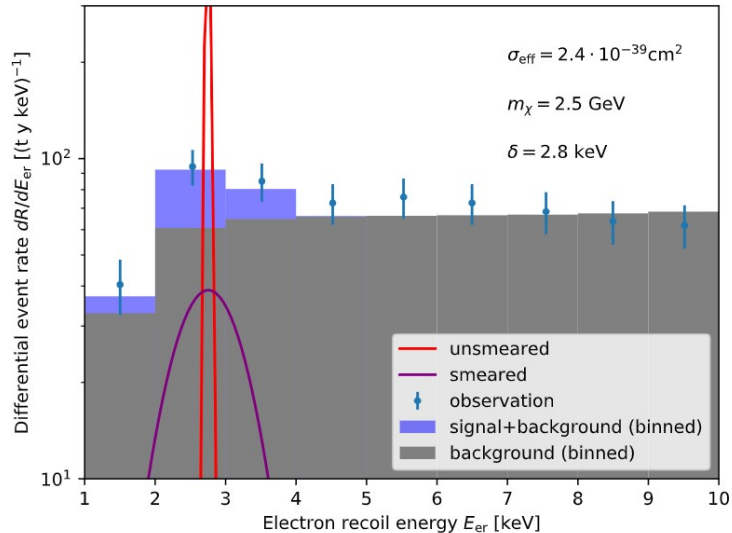
- Excited states can spontaneously decay in the detector ( $\chi^* \rightarrow \chi + \gamma$ )  
Feldstein & Rajendran, arXiv:1008.1988
- Excited states can down-scatter on electrons or nuclei

Graham et al., arXiv:1004.0937



# XENON1T excess

- Inelastic/exothermic/luminous DM **cannot** explain the DAMA annual modulation
- But it might explain another direct detection anomaly: The **XENON1T excess**

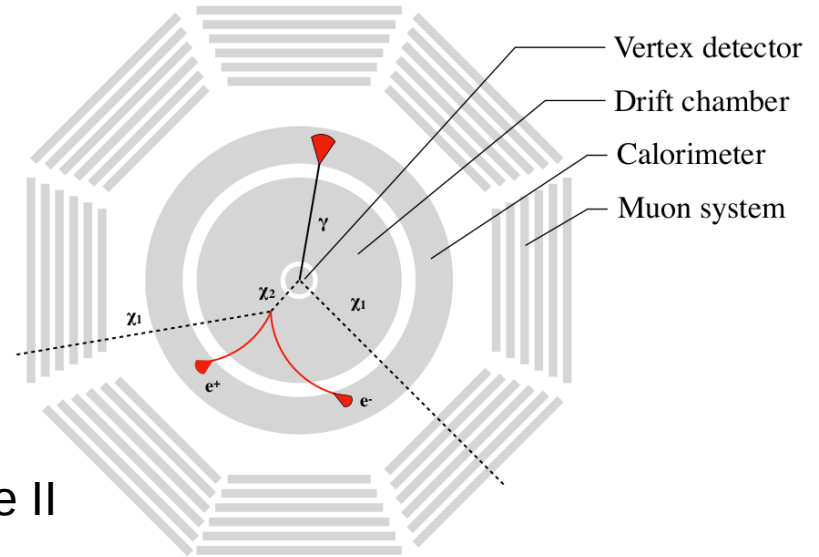
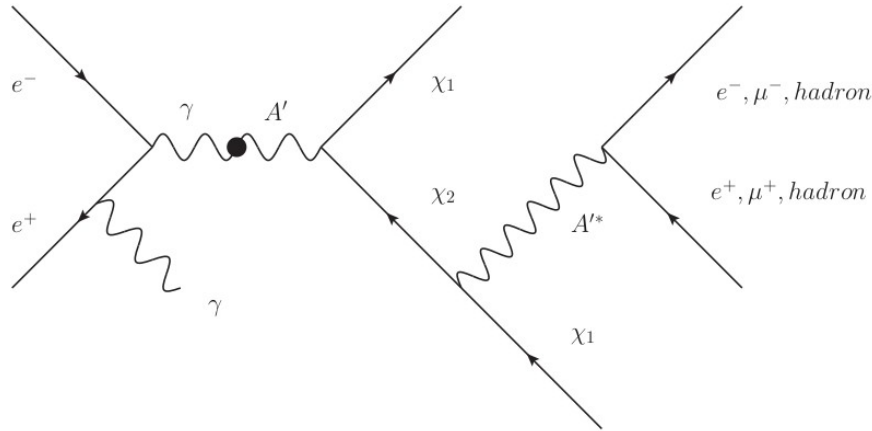


- **Exciting prediction:** Flux of excited states depends on orientation of detector relative to WIMP wind
- Daily modulation of event rate at level of 10%
- Testable in future experiments (if confirmed)

For further details, see talk by Jonas Frerick and Emken, FK et al., arXiv:2112.06930

# Accelerator searches for IDM

- We can also look for the production and subsequent decays of  $\chi^*$  at colliders

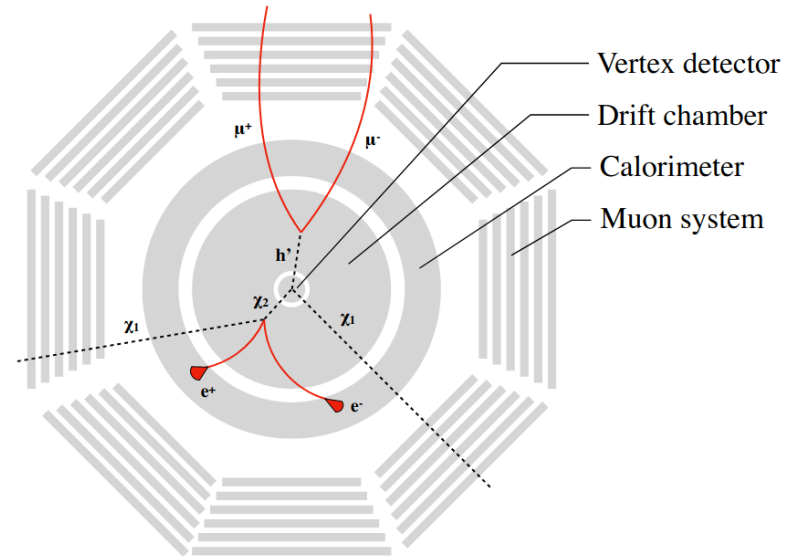
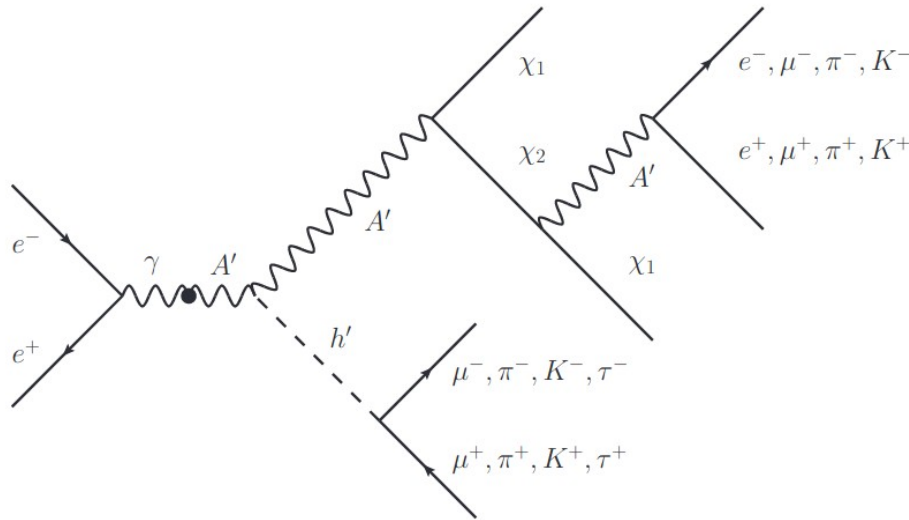


- **Promising:** Displaced vertex search at Belle II

Duerr, FK et al., arXiv:1911.03176

# Accelerator searches for IDM

- **Exciting signature:** Production of IDM in association with dark Higgs boson



- **Official Belle II analysis ongoing...**

Duerr et al., arXiv:2012.08595



# Conclusions

- Annually modulating event rates are **among the most striking predictions** for DM direct detection experiments
- DAMA annual modulation persists (even below 1 keV), but independent analyses are difficult and there is **no consistent interpretation**
- Essential to test DAMA signal with **independent NaI experiments**
  - Strong bounds on total rate from **COSINE** and on modulation amplitude from **ANAIS**
  - Upcoming ultra-pure detectors: **PICOLON** and **SABRE** (North & South)
  - New idea: **COSINUS** (NaI as low-temperature calorimeter)
- Confirmation of DAMA would be **groundbreaking**, but implications unclear
- Model-building for DAMA may inspire **new DM search strategies**