

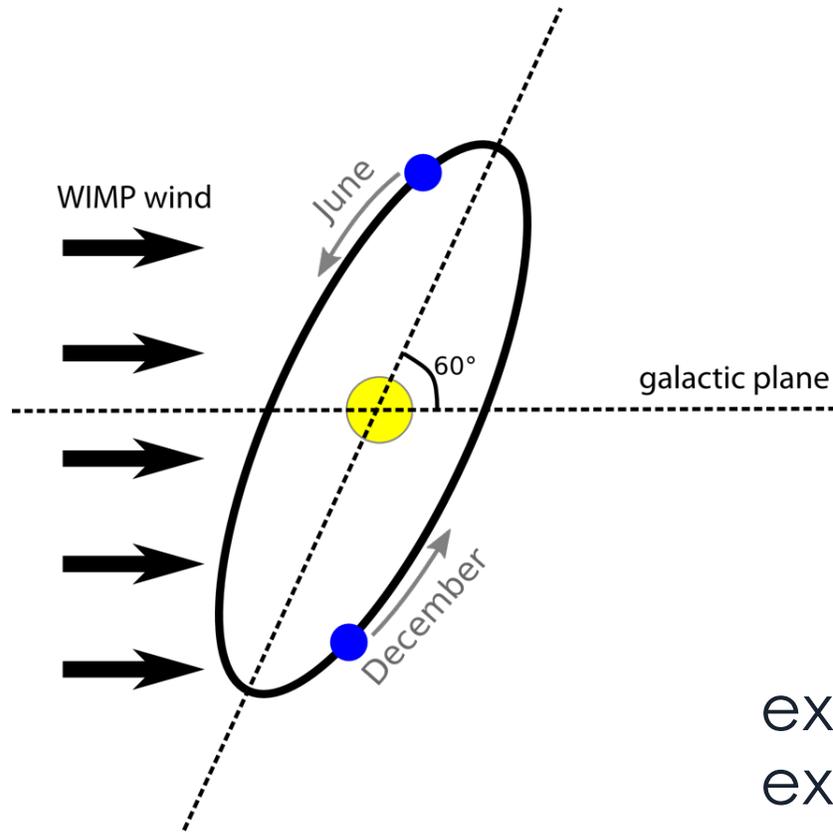
# COSINUS

probing the DAMA/LIBRA claim  
with NaI-based cryogenic detectors

Karoline Schöffner  
for the COSINUS collaboration

# DARK MATTER MODULATION SIGNAL

---



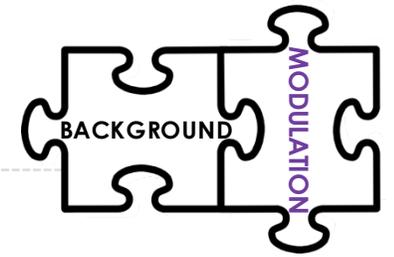
motion of the Earth causes  
relative modulation of velocity

→ **annual variation in the rate**

expected period: **1 year**

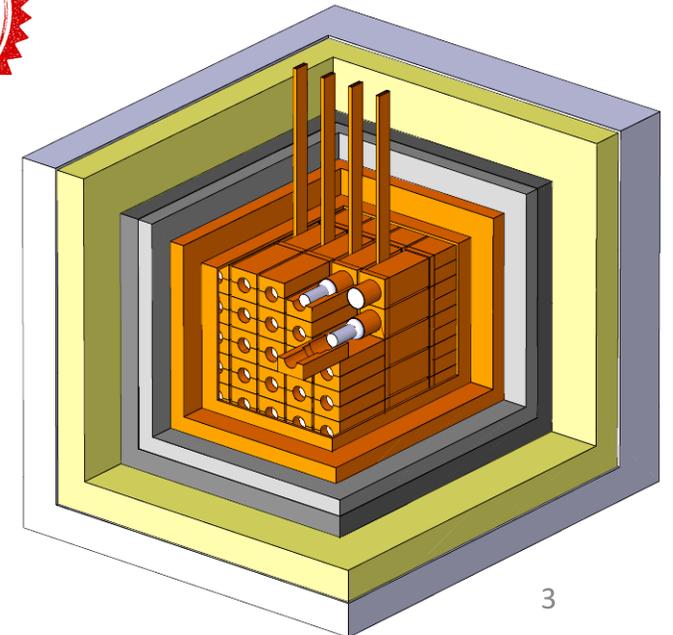
expected phase: **cosine peaking June 2<sup>nd</sup>**

# DAMA/LIBRA experiment



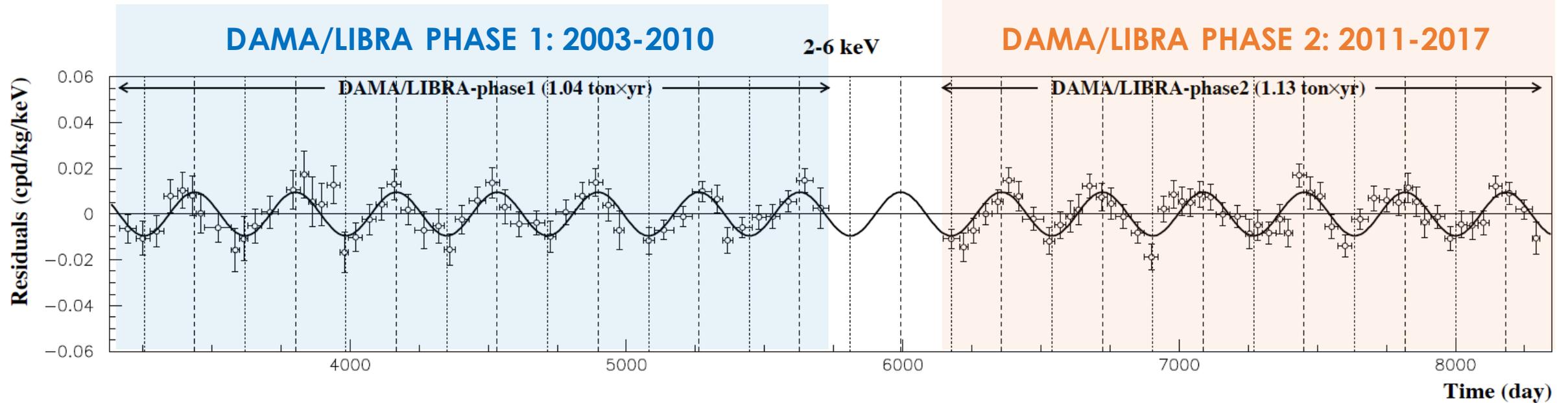
<b>MATERIAL</b>	250 kg NaI(Tl)
<b>SIGNAL(s)</b>	Light (PMTs)
<b><math>\beta/\gamma</math>-DISCRIMINATION</b>	no
<b>ENERGY THRESHOLD</b>	<b>1 keVee</b>
<b>DATA TAKING</b>	since 1996
<b>EVIDENCE</b>	yes

ChristianImages123.com



# DAMA/LIBRA: TIME DISTRIBUTION

arXiv:1805.10486v1 [hep-ex] 26 May 2018



Total exposure: 2.17 tonne years (phase 1 + 2)

Statistical significance:  $>11.9 \sigma$

combined with DAMA/NaI: 2.46 tonne years and  $12.9\sigma$  !!!!

**positive evidence** for the presence of DM particles in the galactic halo

# THE SMOKING GUN EVIDENCE?

---

Statistics:  $> 12 \sigma$  ✓

Period:  $0.999 \pm 0.001$  years \* ✓

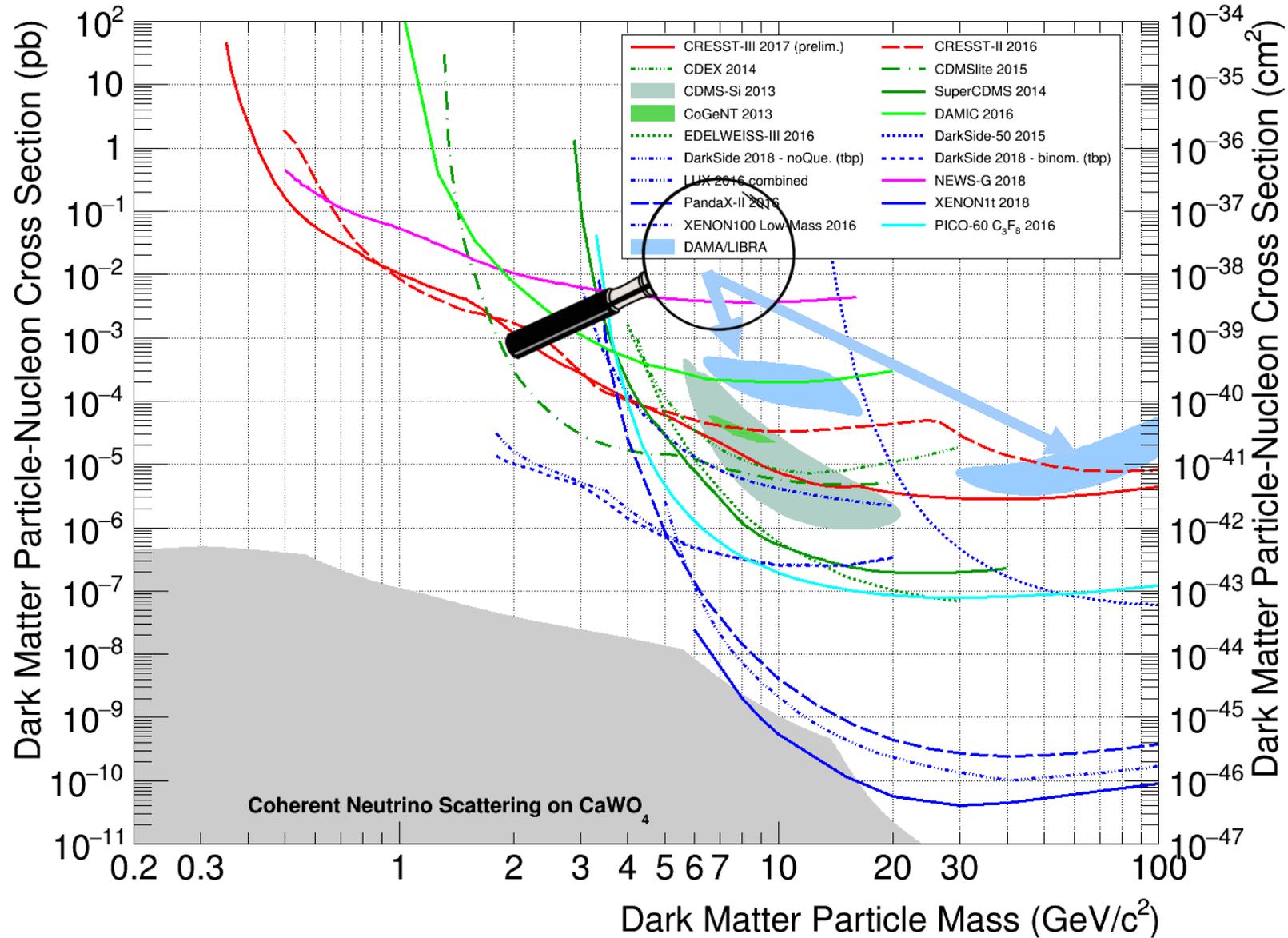
Phase: 25<sup>th</sup> May +/- 5 days ✓  
(cosine peaking June 2<sup>nd</sup>)

Convincing non-DM explanation ✗

\*in (2-6) keVee interval

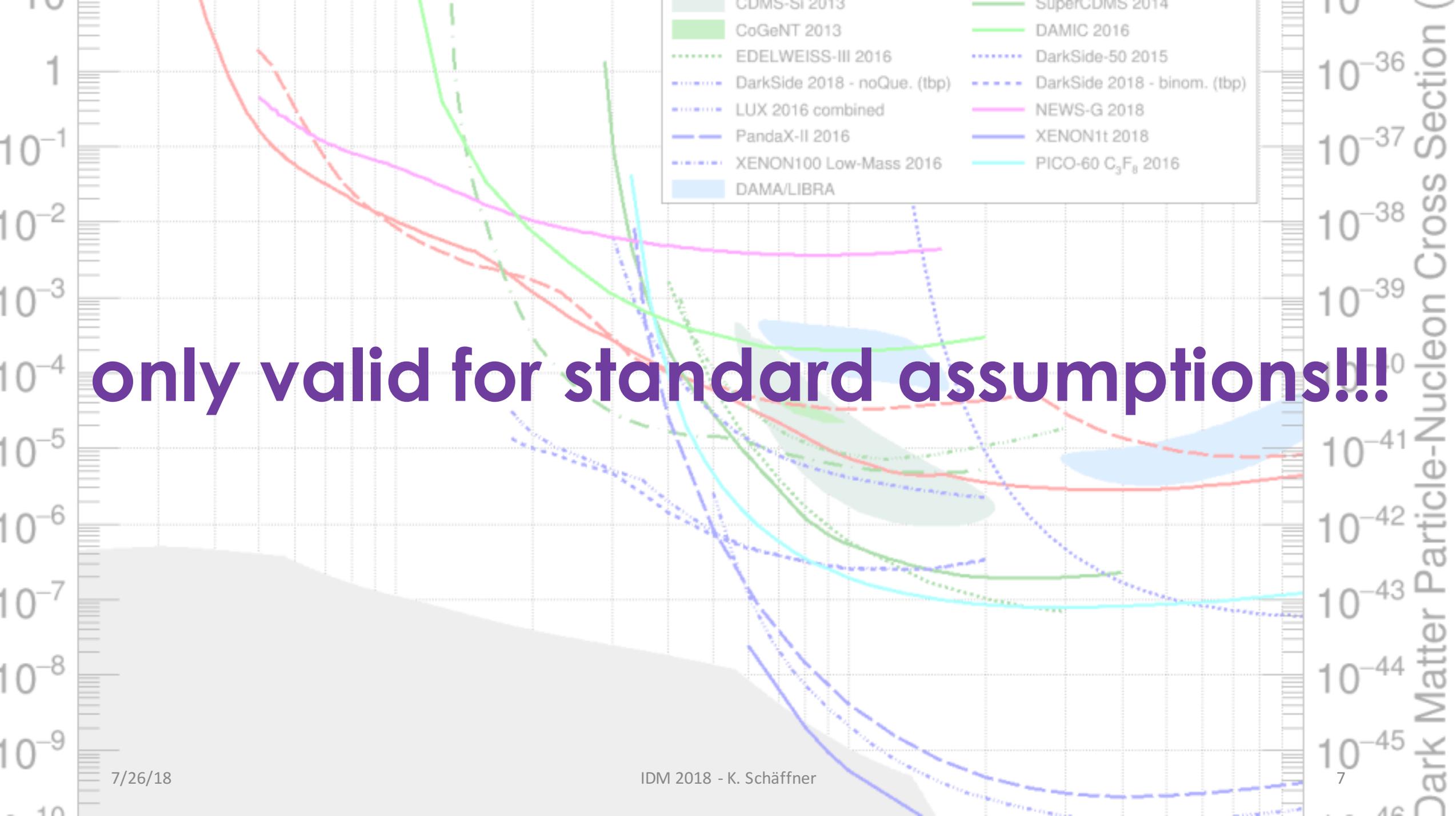


# DARK MATTER LANDSCAPE



Null results shown as:  
90% C.L. upper limits on the  
spin-independent DM  
particle-nucleon cross  
section

DAMA/LIBRA:  
 $3\sigma$  allowed parameter  
space



# WHAT ARE THE **UNKNOWN**S?

---

$$\frac{dR}{dE_r} = \frac{\rho_\chi}{m_N m_\chi} \cdot \int_{v_{min}}^{v_{esc}} d^3 v f(\vec{v}) v \frac{d\sigma(\vec{v}, E_r)}{dE_r}$$

galactic escape velocity

velocity distribution

DM-nucleus cross-section

minimal velocity to produce a recoil of energy  $E_r$

$\sim A^2$

$\sim$  form factor

## **Astro physics**

dark matter halo  
velocity distribution

## **Particle physics**

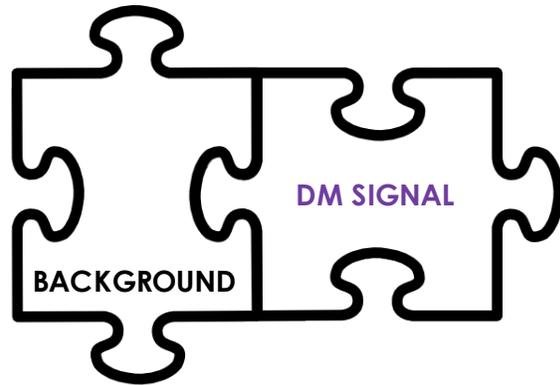
interaction mechanism

We have a dependence on the target material

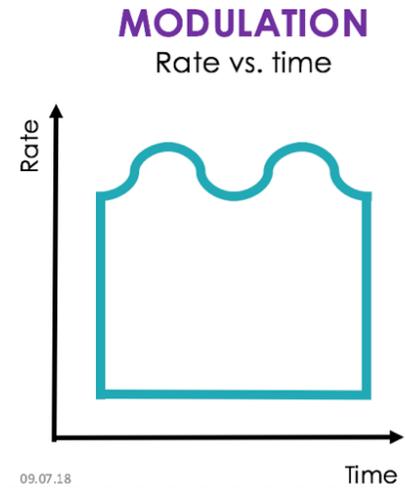
→ cross-check DAMA/LIBRA signal with **same-target experiment**

# GLOBAL NaI SEARCHES

SINGLE CHANNEL

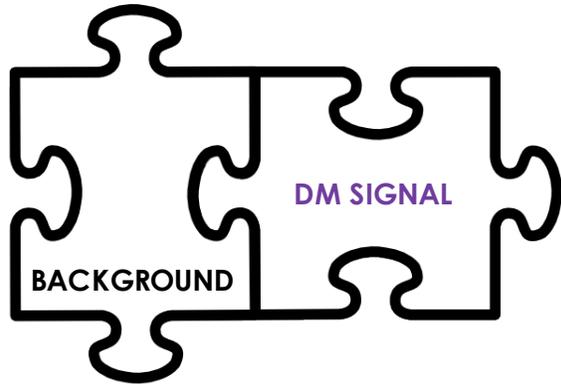


- DAMA/LIBRA
- COSINE-100
- ANAIS-112
- SABRE
- PICO-Ion

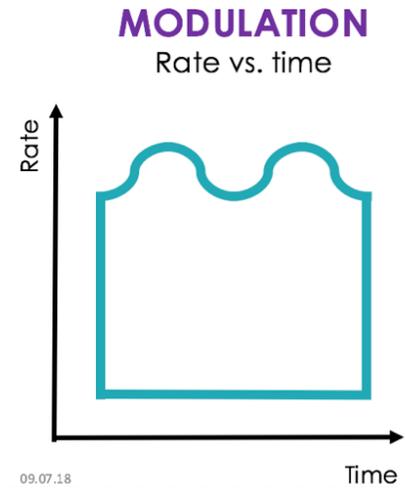


# GLOBAL $N_{\alpha I}$ SEARCHES

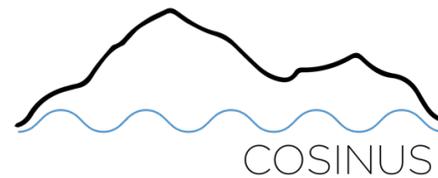
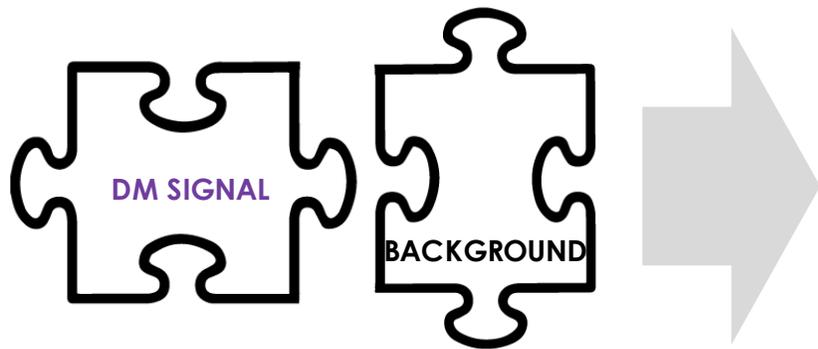
SINGLE CHANNEL



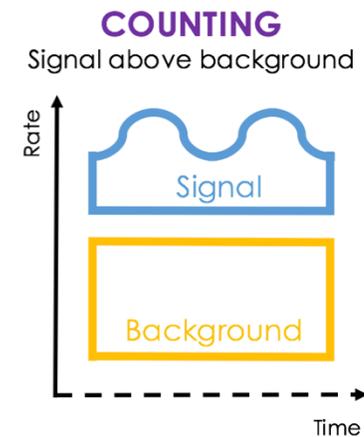
- DAMA/LIBRA
- COSINE-100
- ANAIS-112
- SABRE
- PICO-Ion

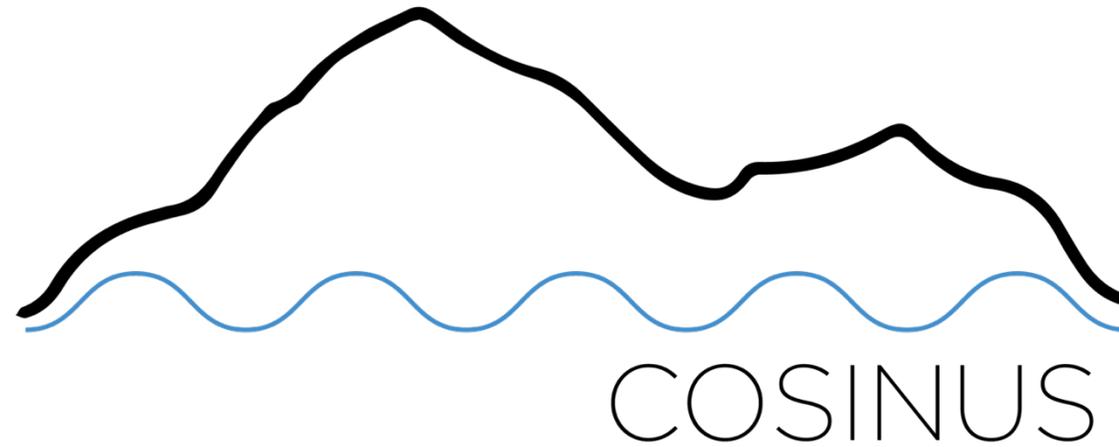


DUAL CHANNEL



**DISCRIMINATION**  
nuclear recoil events  
to  $\beta/\gamma$ -events

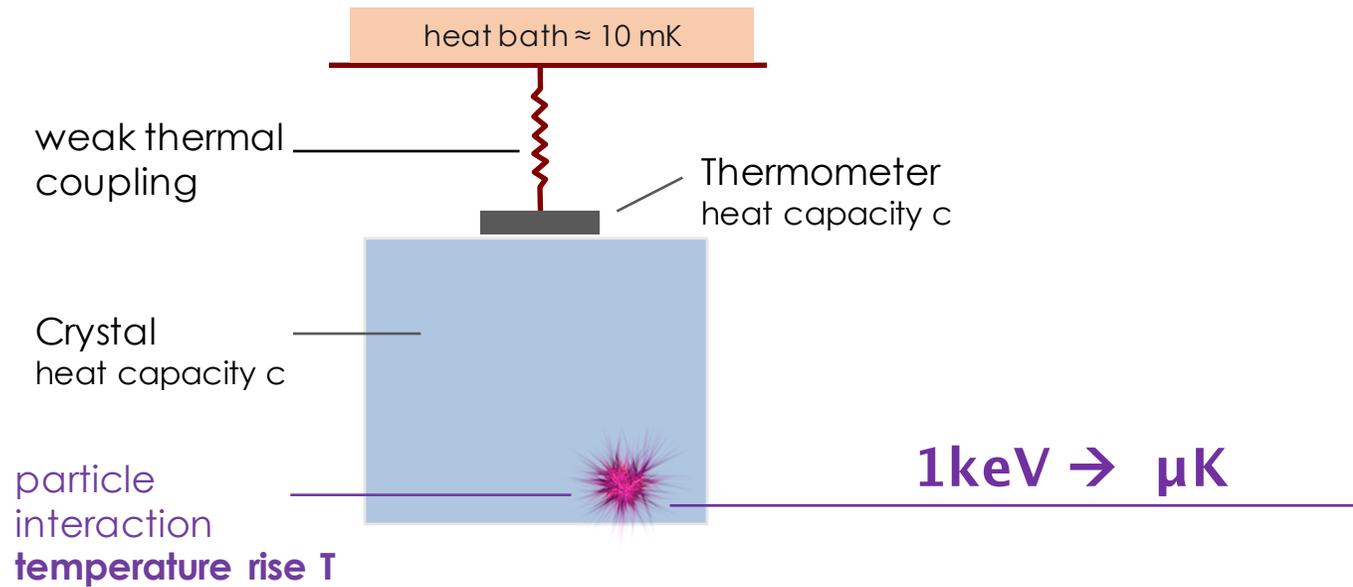




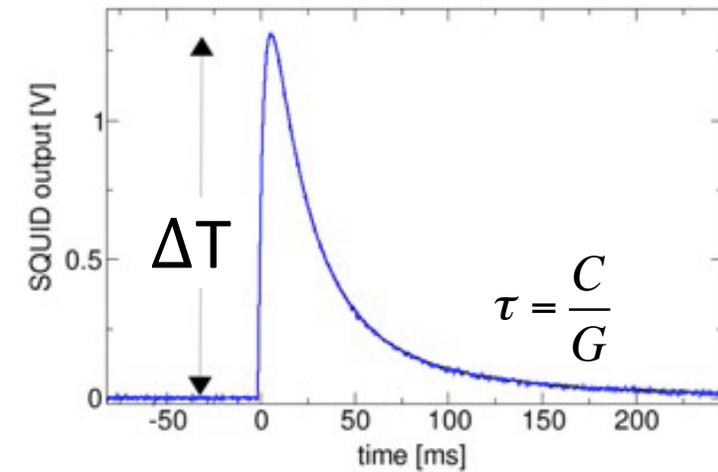
- R&D project
- funded by the “CSN 5” of Istituto Nazionale di Fisica Nucleare (INFN, Italy)
- 3 years for prototype development [2016 – 2018]
- **Max-Planck Research Group leader grant: duration 5 years, starting 2019**
- **prolongation for one year in CSN 5 requested**
- [Eur. Phys. J. C \(2016\) 76:441](#)



# LOW-TEMPERATURE CALORIMETER

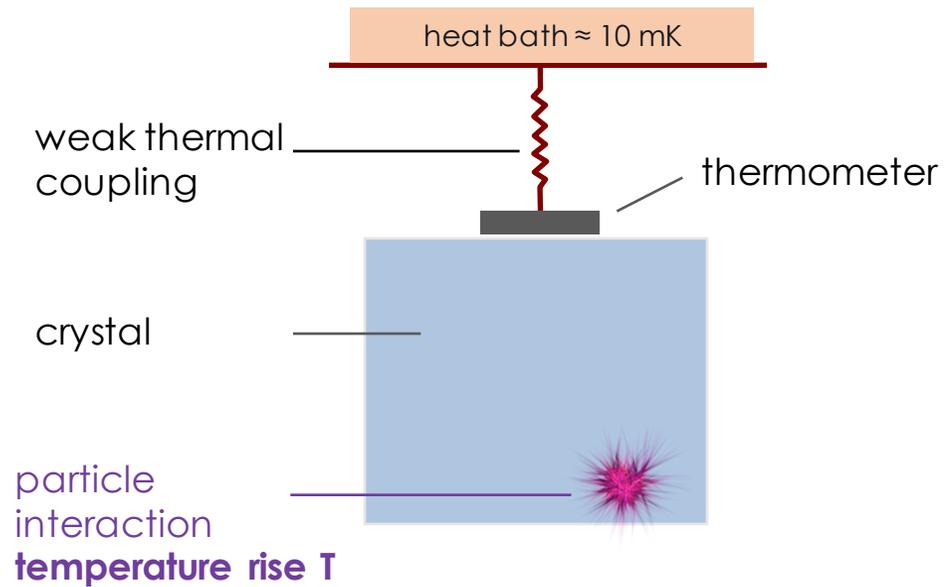


### Temperature pulse



# LOW-TEMPERATURE CALORIMETER

---

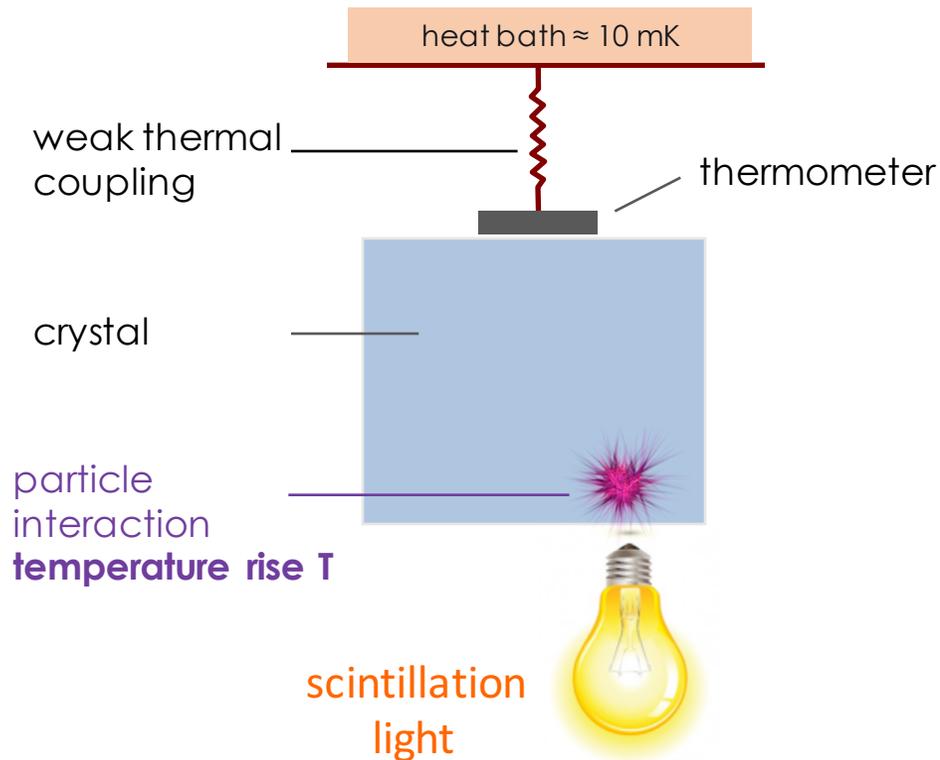


## Phonon signal ( $\sim 90\%$ )

- (almost) independent of particle type
- precise measurement of the deposited energy

# NaI-based SCINTILLATING CALORIMETER

---



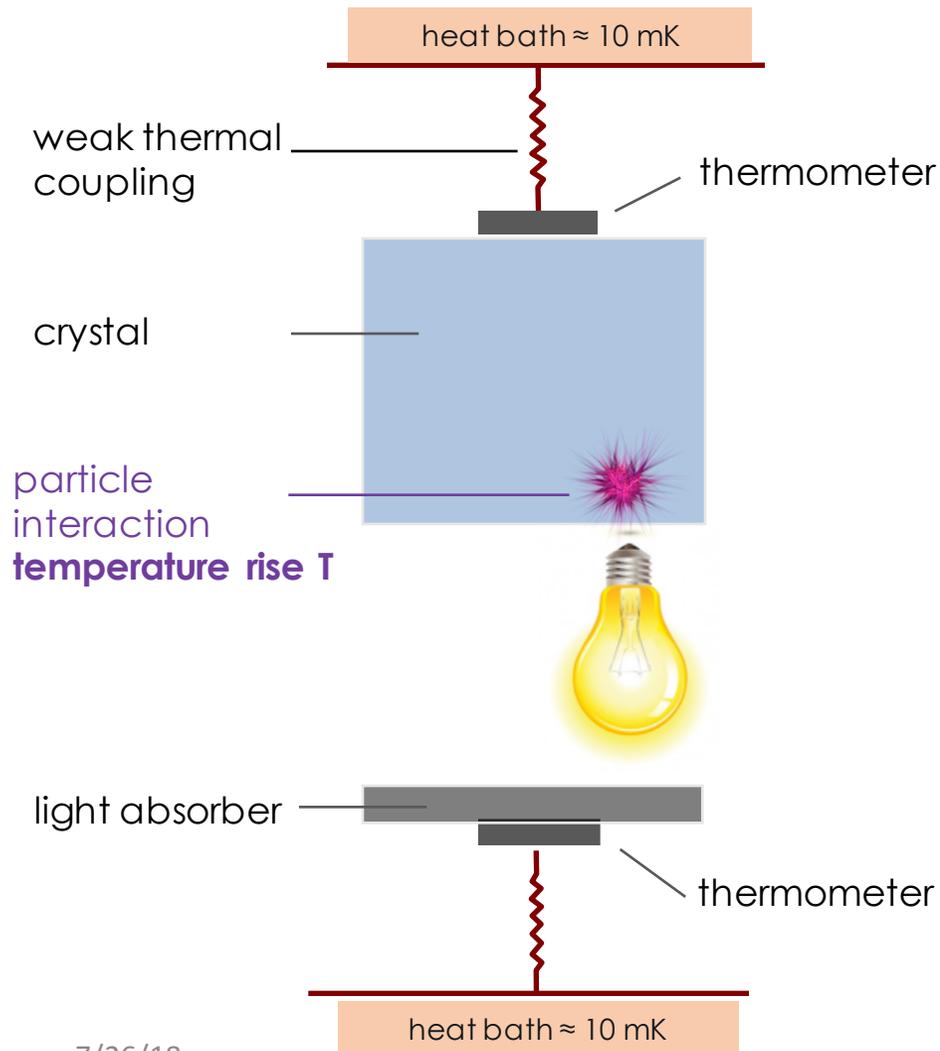
## Phonon signal ( $\sim 90\%$ )

- (almost) independent of particle type
- precise measurement of the deposited energy

## Scintillation light (few %)

- amount of emitted light depends on particle type  
→ LIGHT QUENCHING

# NaI-based SCINTILLATING CALORIMETER



## Phonon signal ( $\sim 90\%$ )

- (almost) independent of particle type
- precise measurement of the deposited energy

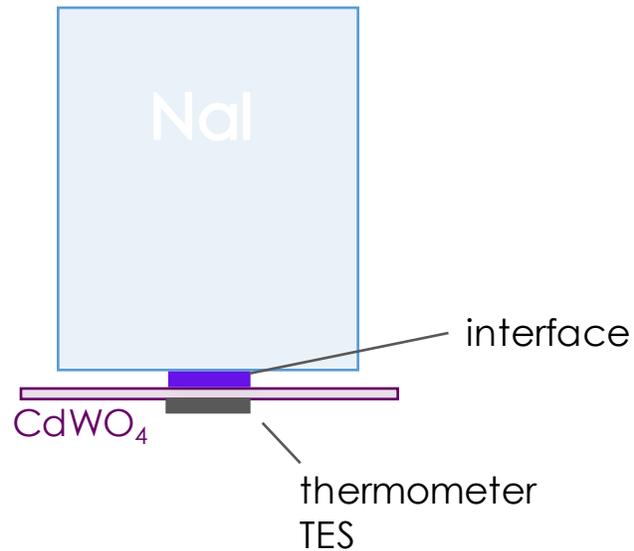
## Scintillation light (few %)

- amount of emitted light depends on particle type  
→ LIGHT QUENCHING

→ **add cryogenic light detector** for scintillation light detection

- discrimination of interacting particle via the **ratio light to phonon signal** → LIGHT YIELD

# COSINUS DETECTOR DESIGN



## NaI Target Crystal

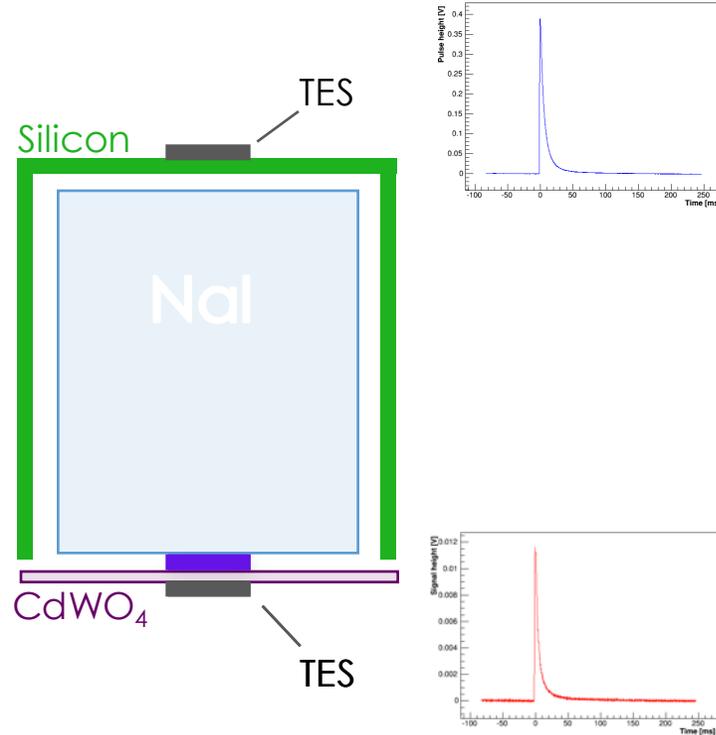
- scintillator
- multi-element target
- mass: ~ 30 – 200 g
- **hygroscopic**



## Carrier Crystal

- carries the thermometer (TES)
- glue/oil as interface and link for phonons

# COSINUS DETECTOR DESIGN



## Light absorber

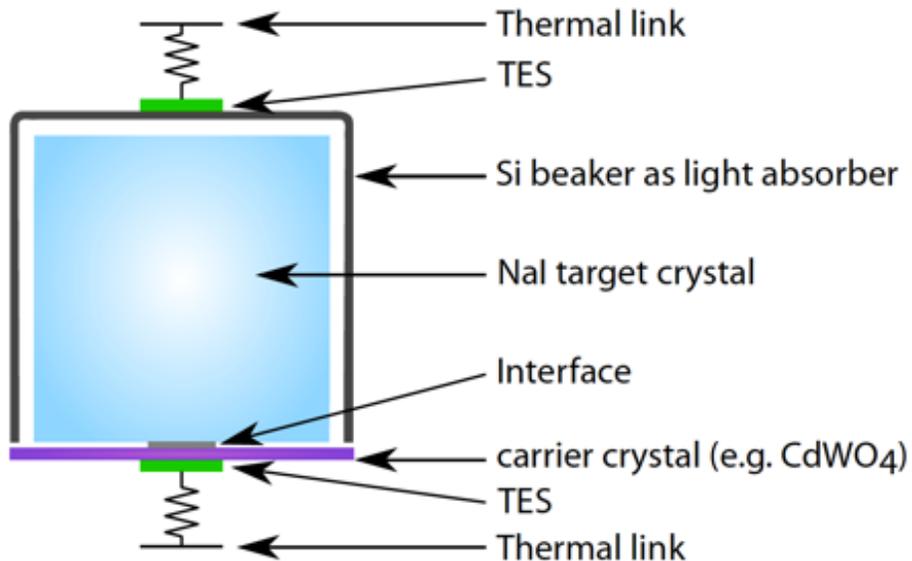
- beaker-shaped HP silicon
- 40 mm diameter & height
- equipped with TES optimized for light detection

→ high light collection efficiency

→ fully active veto to reject surface backgrounds

(e.g. alpha-induced nuclear recoils)

# PERFORMANCE GOAL



**NaI nuclear recoil energy threshold of 1 keV**

~ 4% of deposited energy detected in form of light

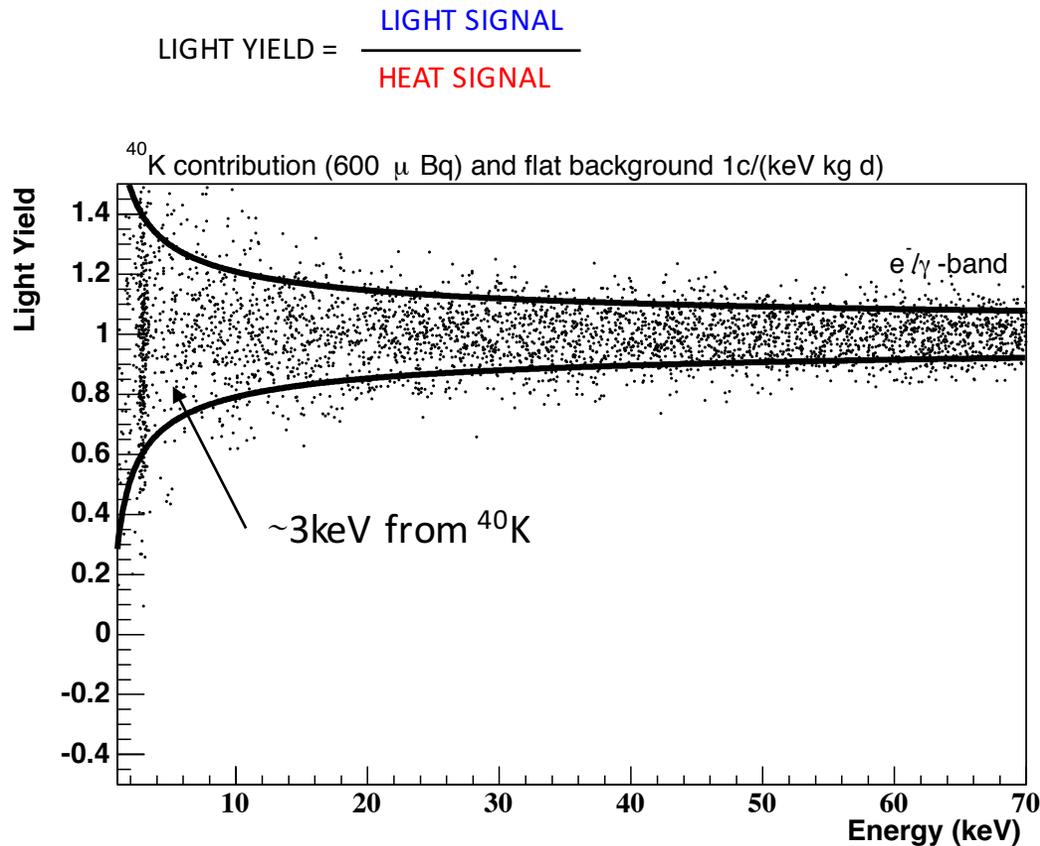
light detector baseline noise  $\sigma = 10$  eV

**Bring NaI-based cryogenic detectors to level of existing ones ( e.g. dark matter search CRESST-II )**

*Eur. Phys. J. C (2016) 76:441*

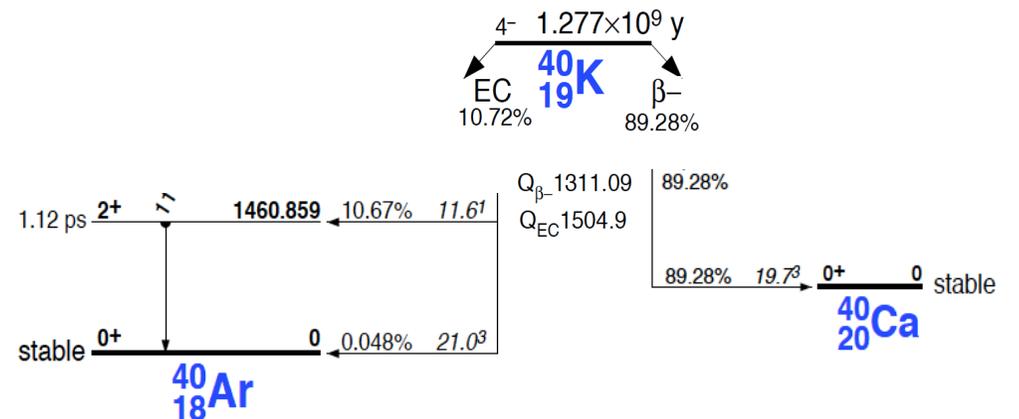
# SIMULATED DATA

# SIMULATED DATA FOR 100 kg days (gross-exposure)



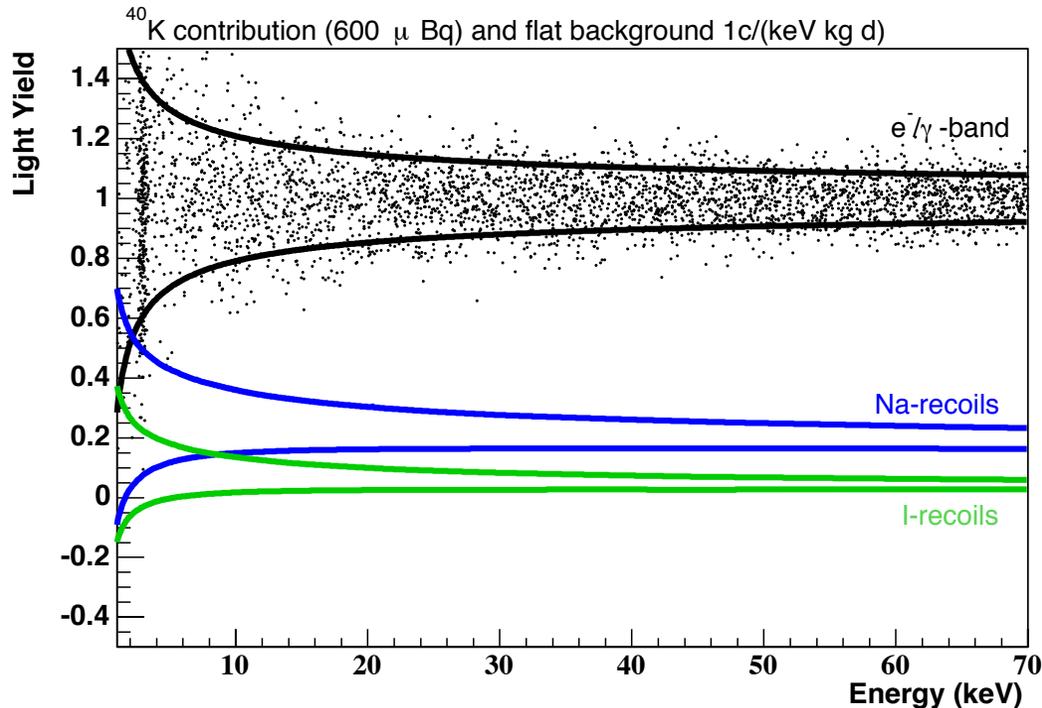
Eur. Phys. J. C (2016) 76:441  
 DOI 10.1140/epjc/s10052-016-4278-3

- **black events:**  
 flat background: 1 c / (keV kg day)  
 + <sup>40</sup>K background: 600 μBq/kg = DAMA
- **gross exposure: 100 kg-days**
- **solid lines: 80% band**



# SIMULATED DATA FOR 100 kg days (gross-exposure)

$$\text{LIGHT YIELD} = \frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$$

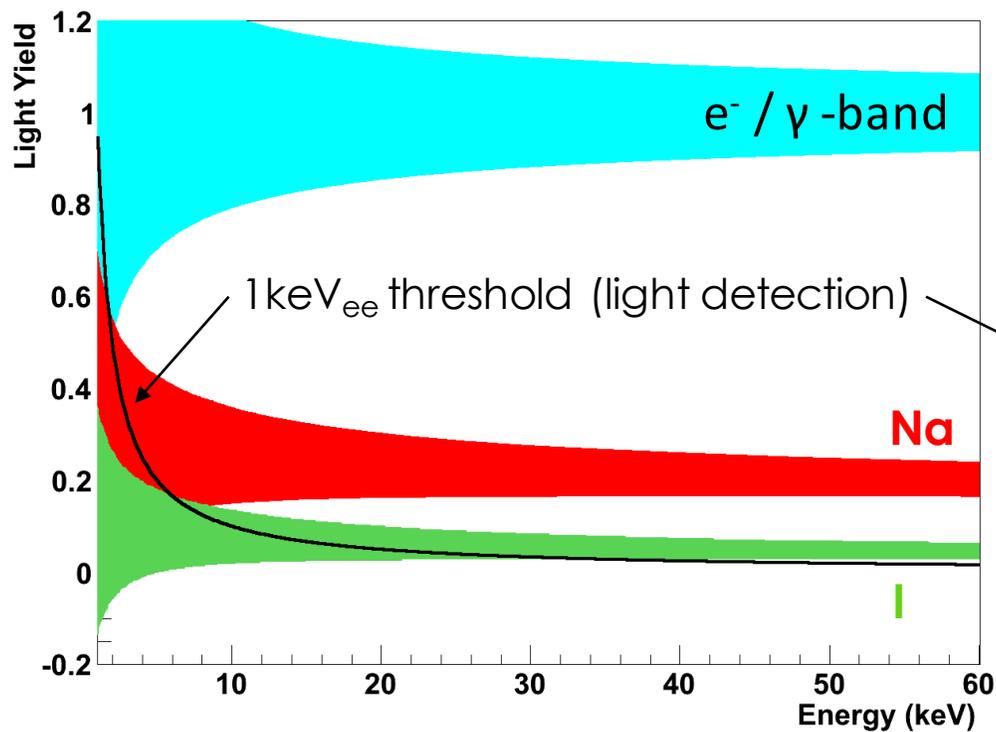


Eur. Phys. J. C (2016) 76:441  
DOI 10.1140/epjc/s10052-016-4278-3

- black events:  
flat background: 1 / (keV kg d)  
+ <sup>40</sup>K background: 600uBq/kg
- exposure before cuts: 100 kg-days
- recoils off Na  
→ light quenching factor ~ 0.3
- recoils off I  
→ light quenching factor ~ 0.1

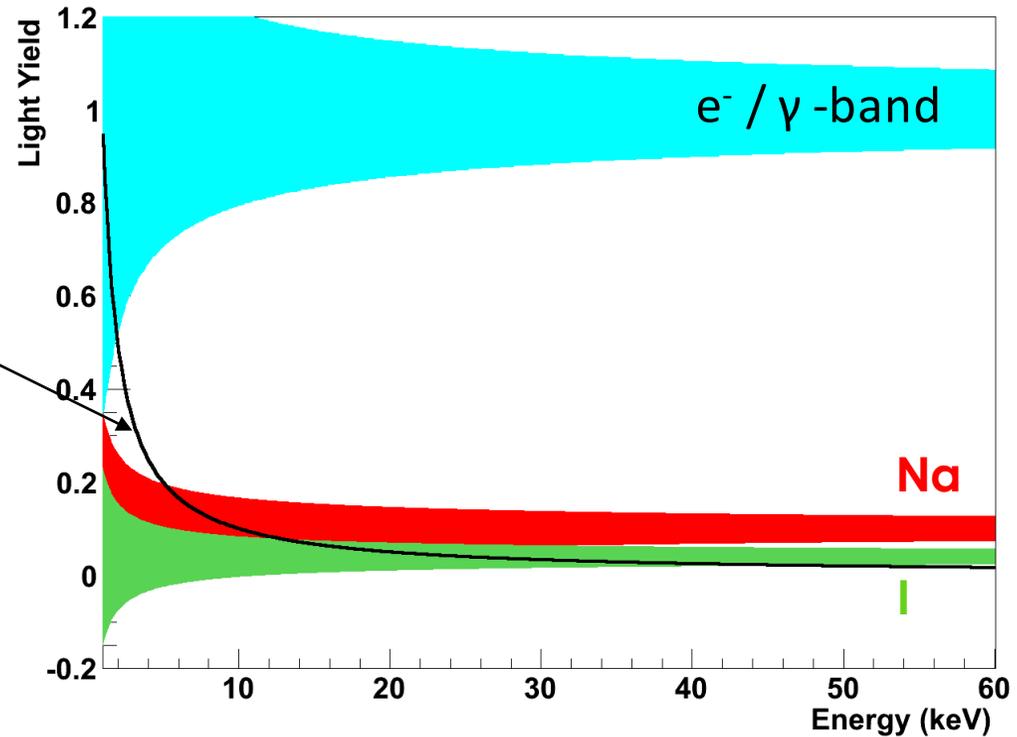
**values for quenching factors** from:  
Tretyak, Astropart. Phys. 33, 40 (2010)

# REMARK: QUENCHING FACTORS



recoils off Na  $\rightarrow$  factor  $\sim 0.3$

recoils off I  $\rightarrow$  factor  $\sim 0.1$



recoils off Na  $\rightarrow$  factor  $\sim 0.1$

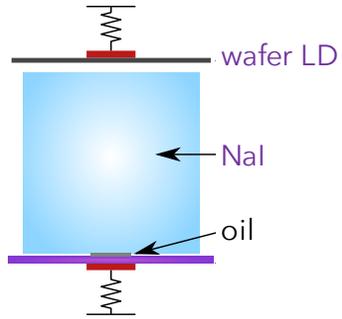
recoils off I  $\rightarrow$  factor  $\sim 0.04$

# PRESENT STATUS

# COSINUS R&D

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1<sup>st</sup> PROTOTYPE (2016)



1<sup>st</sup> measurement of a NaI as cryogenic calorimeter

linear relation between light output and deposited energy

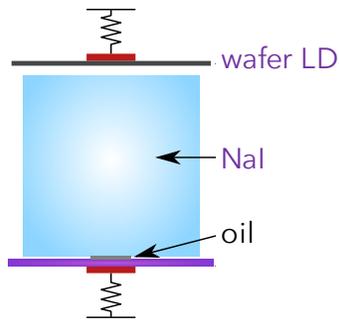
NaI threshold: 10 keV

3.7% detected in light

*G. Angloher et al. JINST 12 P11007 (2017)*

# COSINUS R&D

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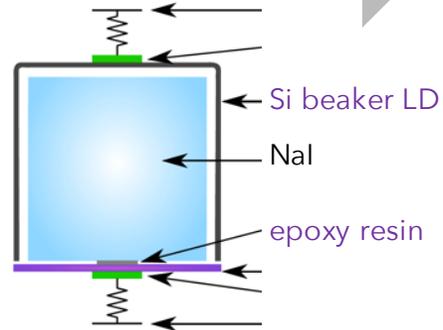
NaI threshold: 10 keV

3.7% detected in light

G. Angloher et al. JINST 12 P11007 (2017)

7/26/18

2<sup>nd</sup> PROTOTYPE (2016/17)



successful test of complete COSINUS detector design

LD energy resolution at zero energy : 15 eV

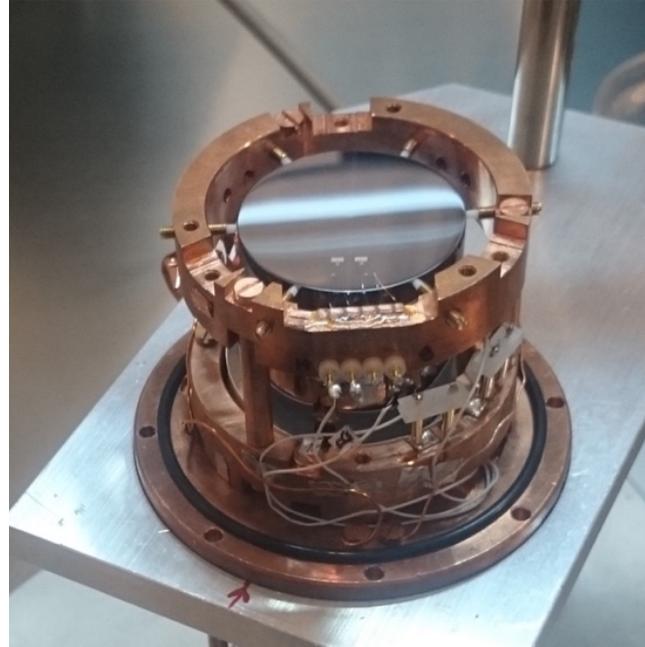
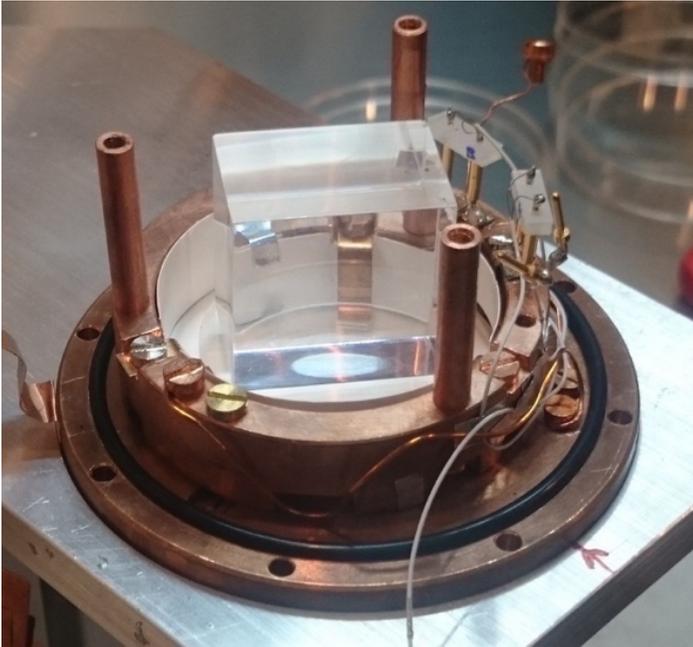
NaI threshold: 8.3 keV

13 % detected in light

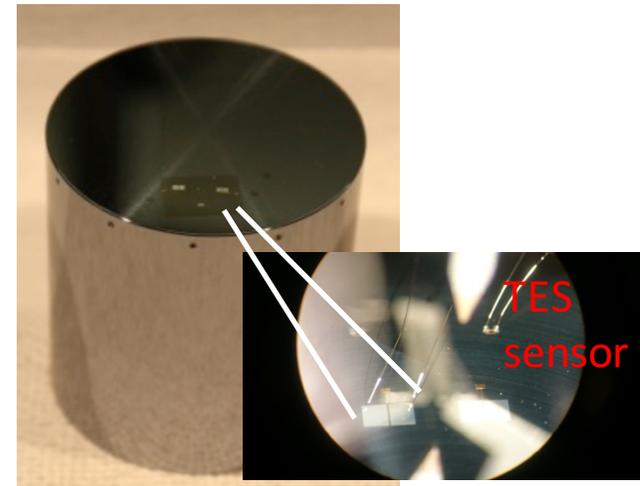
Schäffner, K. et al. J Low Temp Phys (2018).  
<https://doi.org/10.1007/s10909-018-1967-3>

IDM 2018 - K. Schäffner

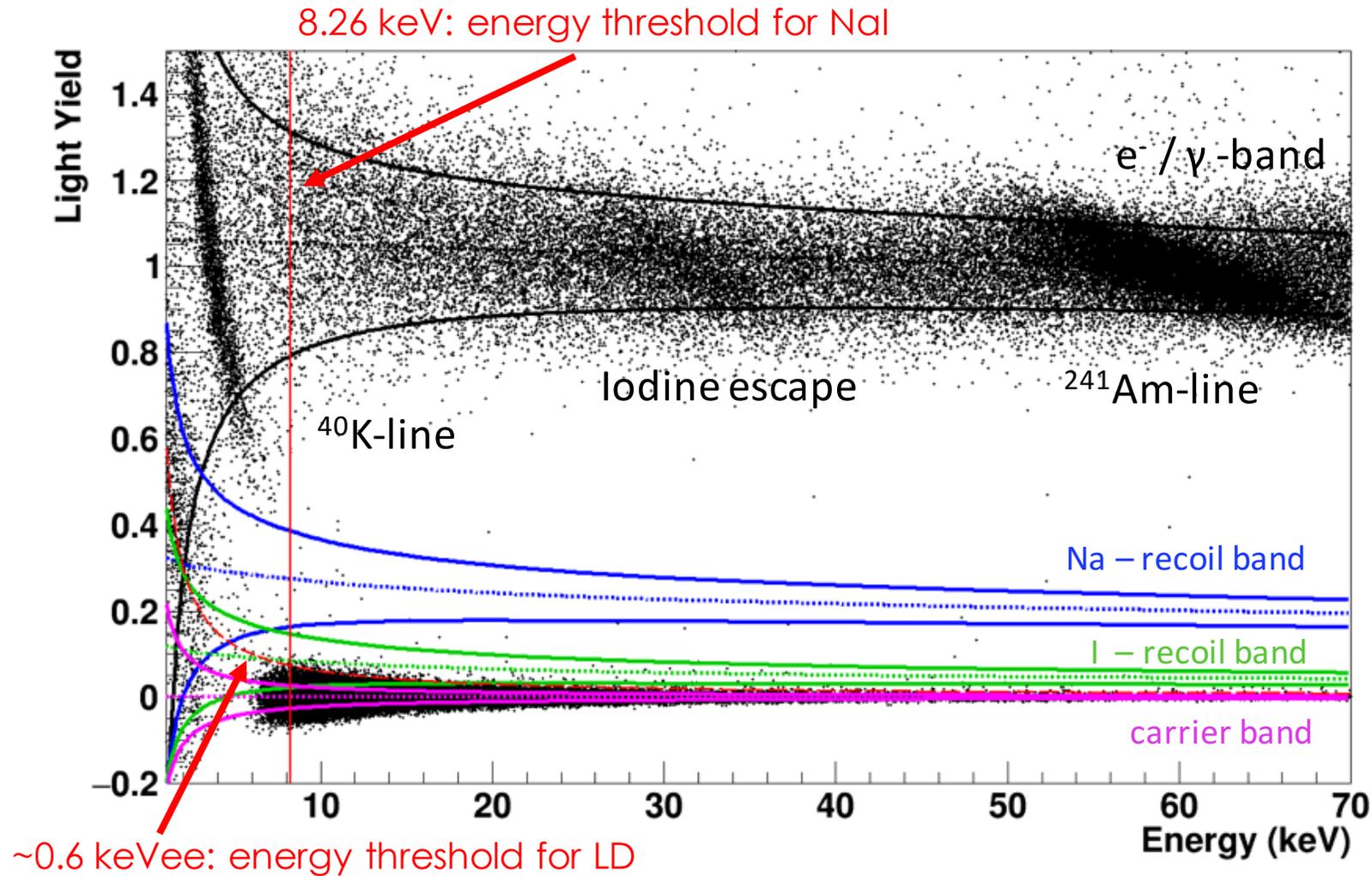
# 2<sup>nd</sup> PROTOTYPE DETECTOR



- interface: epoxy resin
- beaker-shaped Si light absorber
- NaI crystal: 66 g



# 2<sup>nd</sup> PROTOTYPE DETECTOR



- NaI energy threshold is  $(8.26 \pm 0.02 \text{ (stat.)}) \text{ keV}$
- width of the  $^{241}\text{Am}$  peak is  $(4.508 \pm 0.064 \text{ (stat.)}) \text{ keV}$
- carrier events identified by pulse shape

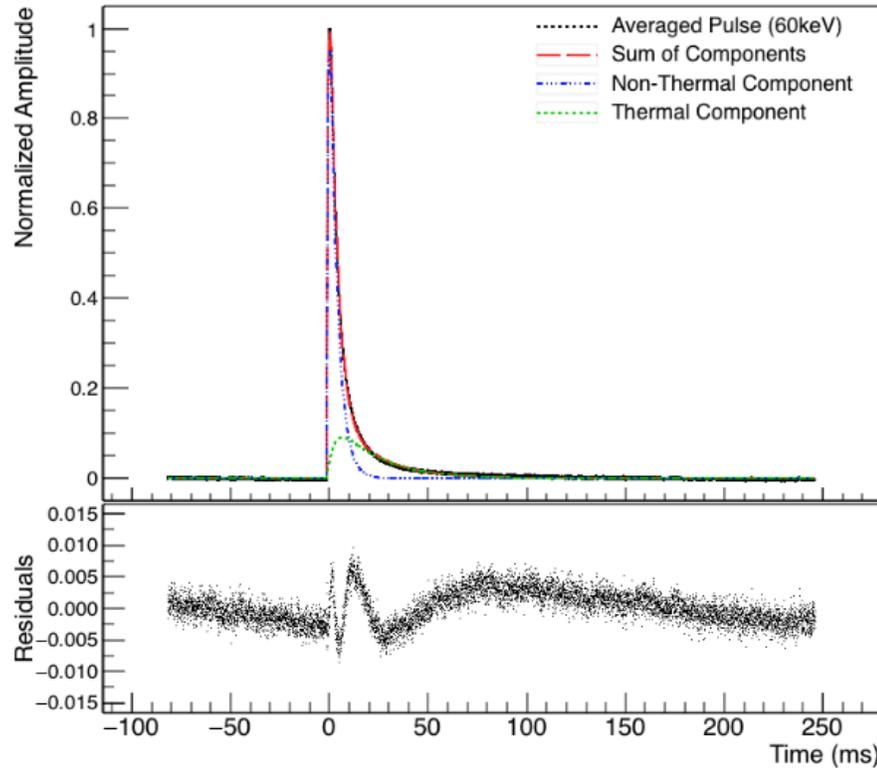
Schäffner, K. et al. J Low Temp Phys (2018).  
<https://doi.org/10.1007/s10909-018-1967-3>

# LONG DECAY TIMES – PULSE MODEL

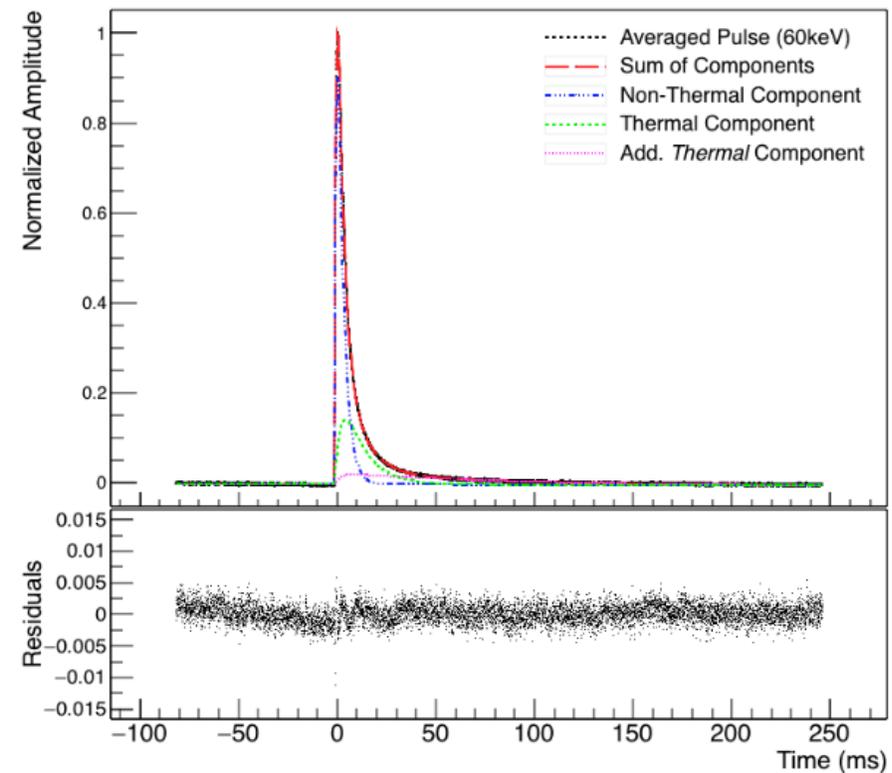
F. Pröbst et al., J. Low Temp. Phys. 100, 69 (1995):

$$\Delta T_e(t) = \Theta(t)[A_n(e^{-t/\tau_n} - e^{-t/\tau_{in}}) + A_t(e^{-t/\tau_t} - e^{-t/\tau_n})]$$

observed in  
all measurements



(a) Two-component pulse model

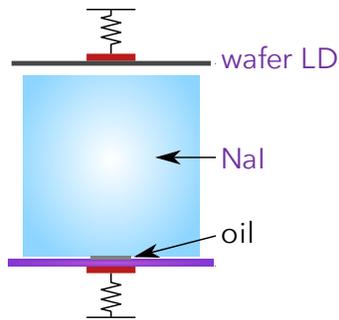


(b) Three-component pulse model

This example: 1<sup>st</sup> prototype: G. Angloher et al. JINST 12 P1 1007 (2017)  
Same result: 2<sup>nd</sup> prototype: F. Reindl et al., arXiv 1711.01482

# COSINUS R&D

## 1<sup>st</sup> PROTOTYPE (2016)



1<sup>st</sup> measurement of a NaI as cryogenic calorimeter

linear relation between light output and deposited energy

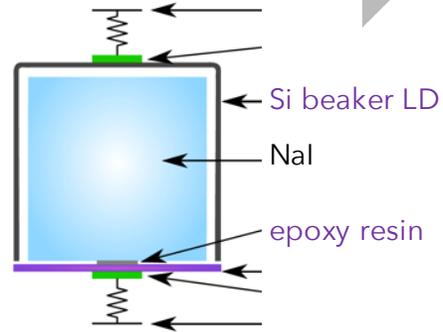
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successful test of complete COSINUS detector design

energy resolution at zero energy : 15 eV

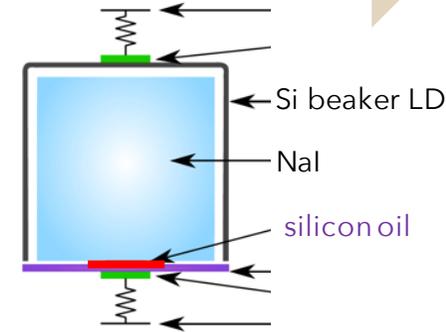
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Schäffner, K. et al. J Low Temp Phys (2018).  
<https://doi.org/10.1007/s10909-018-1967-3>

IDM 2018 - K. Schäffner

## 3<sup>rd</sup> PROTOTYPE (2017)



changed interface to thin layer of silicon oil

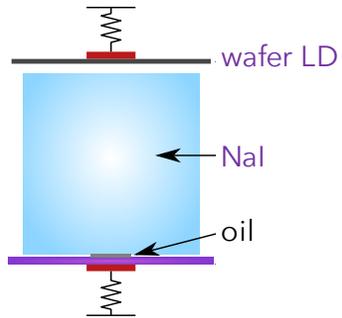
commissioning of:  
in-house electronics  
and DAQ

NaI threshold: **6.5 keV**



# COSINUS R&D

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linear relation between light output and deposited energy

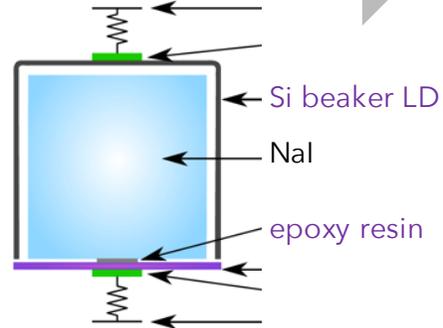
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7/26/18

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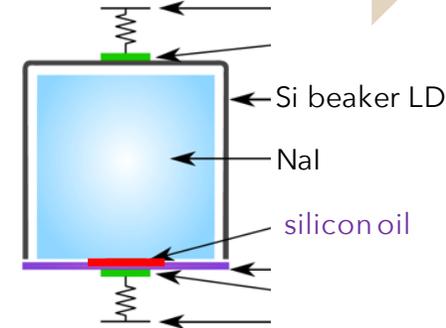
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IDM 2018 - K. Schäffner

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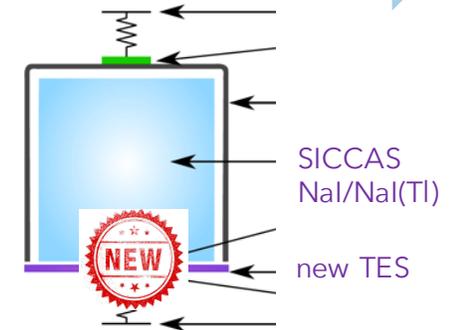


changed interface to thin layer of silicon oil

commissioning of: in-house electronics and DAQ from MIB

NaI threshold: 6.5 keV

## 4<sup>th</sup> → 7<sup>th</sup> PROTOTYPE (2017/18)



test of new batch of NaI/**Na(Tl)** crystals from SICCAS

test of new TES-concept for the NaI crystal

**Work ongoing!**

# CYRSTAL PROGRAM

---

- collaboration with **I. Dafinei** from INFN, Roma 1 in Italy
- **Yong Zhu** from SICCAS joined the COSINUS collaboration
- NaI / NaI(Tl) grown from **Astrograde-powder** at SICCAS:



→ **very promising radiopurity:**

5-9 ppb of K at crystals' nose and 22-35 ppb at crystals' tail  
(3-inch crystal @ SICCAS)



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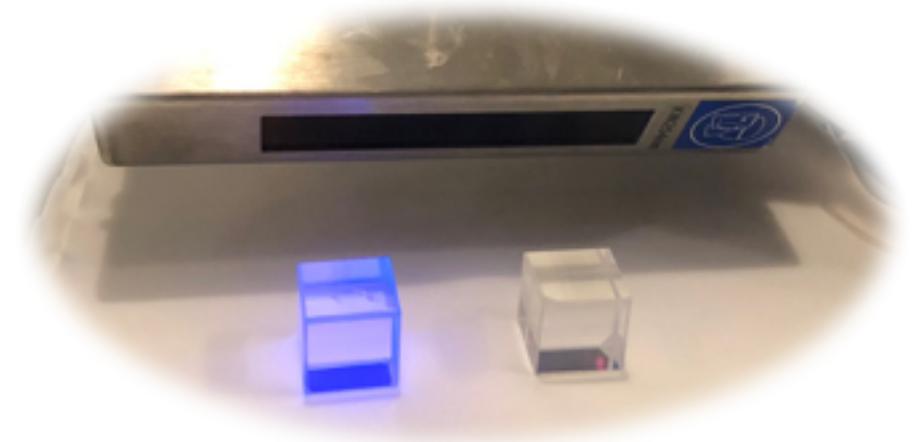


→ **very promising radiopurity:**

5-9 ppb of K at crystals' nose and 22-35 ppb at crystals' tail  
(3-inch crystal @ SICCAS)

## IN THE QUEUE:

- NaI(Tl) grown with internal samarium "contamination" to study alpha quenching factor
- NaI(Tl) with different amount of thallium dopant to study nuclear quenching factors



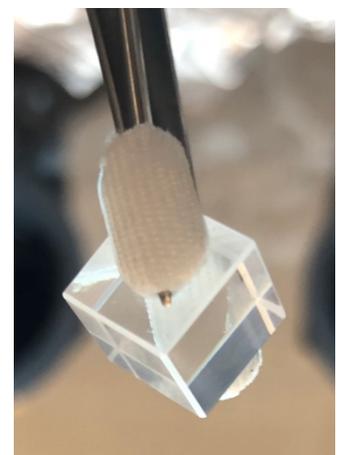
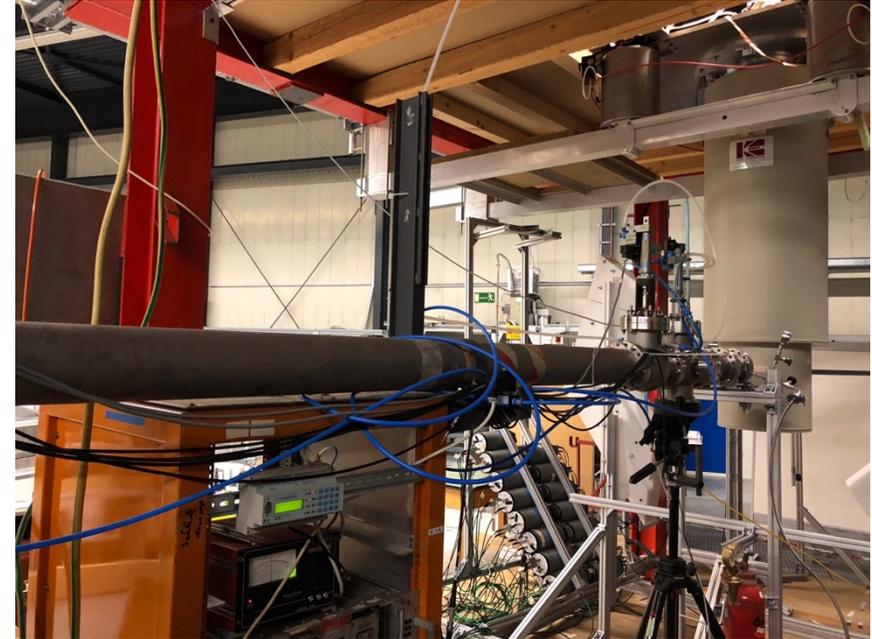
# QUENCHING FACTOR MEASUREMENT

---

- Meier-Leibnitz Laboratorium - Tandem accelerator at Technical University in Munich
- 11 MeV mono-energetic neutrons
- dilution cryostat available
- small NaI scintillating cryogenic calorimeter

## STATUS:

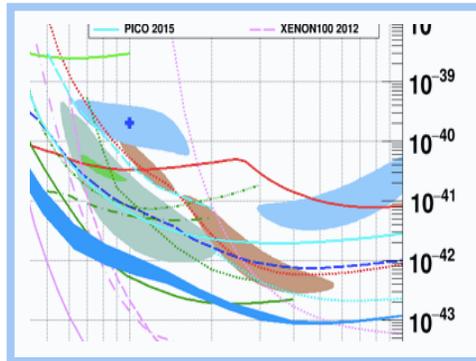
- successfully measured an undoped NaI crystal in April 2018
  - measurement of a Tl-doped NaI scheduled for Nov. 2018
- beam time already assigned!



# PHYSICS REACH

# STANDARD SI-INTERACTION

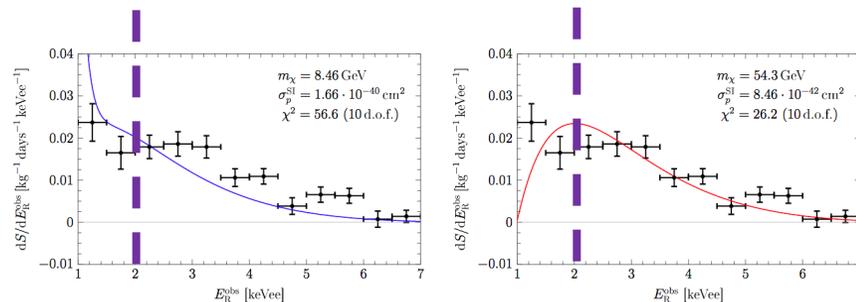
## Standard scenario



10 GeV/c<sup>2</sup> WIMP with  
2E-04 pb (Savage et al.)

**RULED OUT**

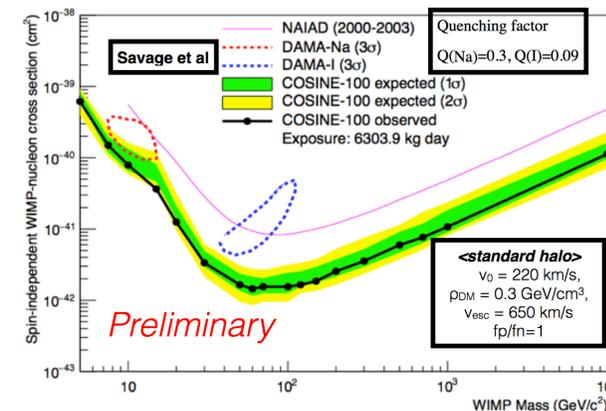
- DAMA/LIBRA PHASE 2 data**



**Figure 9.** Best-fit recoil spectra in DAMA for low-mass DM (left), corresponding to scattering dominantly on sodium, and high-mass DM (right), corresponding to scattering dominantly on iodine. In both cases we have included the first twelve bins from the combined data sets of DAMA/NaI, DAMA/LIBRA-phase1 and DAMA/LIBRA-phase2.

Plot: arXiv:1802.10175

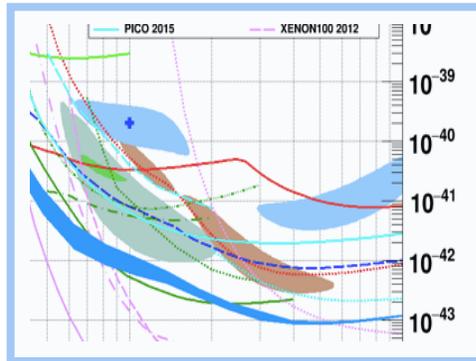
- First COSINE-100 data (6303.9 kg days)**



Chang Hyon Ha, ICHEP conference

# STANDARD SI-INTERACTION

## Standard scenario



10 GeV/c<sup>2</sup> WIMP with  
2E-04 pb (Savage et al.)

**RULED OUT**

DAMA signal requires

non-standard  
interactions or  
non-standard  
astrophysical  
distributions or both

# COSINUS PHYSICS REACH

---

**COSINUS has the unique potential to clarify a nuclear recoil origin of the DAMA/LIBRA signal**

**CONFIRM**

+ not **too exotic** dark matter

**Good chance for exposure of  $\varnothing$  (100 kg days)**



# COSINUS PHYSICS REACH

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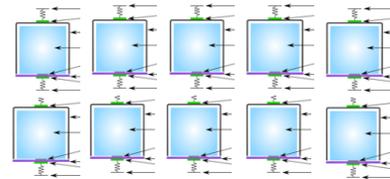
**COSINUS has the unique potential to clarify a nuclear recoil origin of the DAMA/LIBRA signal**

## CONFIRM

+ not **too exotic** dark matter

**Good chance for exposure of  $\varnothing$  (100 kg days)**

10 detector modules  
about 50 g each



1 year of data taking

50% overall efficiency (cryostat refills, calibration, cuts, ...)

Low-background cryogenic facility

underground lab, passive shields, dilution refrigerator



# THE TWO SIDES OF A COIN

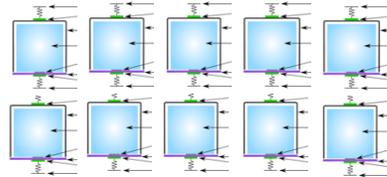
**COSINUS has the unique potential to clarify a nuclear recoil origin of the DAMA/LIBRA signal**

## CONFIRM

+ not **too exotic** dark matter

**Good chance for exposure of  $\mathcal{O}$  (100 kg days)**

10 detector modules  
about 50 g each



1 year of data taking

50% overall efficiency (cryostat refills, calibration, cuts, ...)

**Low-background cryogenic facility**

underground lab, passive shields, dilution refrigerator



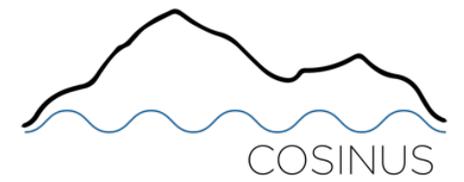
## RULE-OUT

$\mathcal{O}$  (100 kg days): strong statement

$\mathcal{O}$  (1000 kg days): fully model-independent

**Comparing annual modulation and total rate with same-target experiments**

Felix Kahlhoefer,<sup>a</sup> Florian Reindl,<sup>b</sup> Karoline Schaeffner,<sup>c</sup>  
Kai Schmidt-Hoberg<sup>d</sup> and Sebastian Wild<sup>d</sup>



- 1997: DAMA presents at TAUP first evidence for the modulation  
→ after more than 20 years the DAMA/LIBRA observation is **still not cross-checked** by a same-target experiment
- numerous NaI-based experiments *à la DAMA* in data taking or being set up  
→ **radiopure NaI crystals is still the key-issue for all DAMA-like experiments**
- COSINUS develops the first NaI dark matter detector with **particle discrimination**
- COSINUS is on a good way to achieve the performance goals. If we succeed:

**COSINUS-1 $\pi$** : comparatively little exposure ( $\mathcal{O}(100\text{kg days})$ ) is needed to give insight whether **DAMA sees a nuclear recoil signal**, or not

**COSINUS-2 $\pi$** : with a significantly increased target mass the COSINUS technique is also able to include the possibility for modulation detection

Thank you for your attention!

# RATE vs. MODULATION AMPLITUDE in NaI searches

**Central idea: The modulation amplitude  
(in a given experiment) cannot exceed the mean rate:**

$$\bar{R} \geq S$$

**COSINUS**

Mean rate

$$\bar{R} = \frac{1}{2} [R(t = \text{June } 1^{\text{st}}) + R(t = \text{Dec. } 1^{\text{st}})]$$

**DAMA**

Modulation Amplitude

$$S = \frac{1}{2} [R(t = \text{June } 1^{\text{st}}) - R(t = \text{Dec. } 1^{\text{st}})]$$

# RATE vs. MODULATION AMPLITUDE

**Central idea: The modulation amplitude  
(in a given experiment) cannot exceed the mean rate:**

$$\bar{R} \geq S$$

## DAMA phase 1:

Best fit  $S = (2.34 \pm 0.28) \cdot 10^{-2} \text{ kg}^{-1} \text{ days}^{-1}$  (in [2.5keVee,3.5keVee])

Minimal Mod. Ampl. (95% C.L.)  $S = 1.78 \cdot 10^{-2} \text{ kg}^{-1} \text{ days}^{-1}$

*F. Kahlhöfer, K. Schmidt-Hoberg, K. Schöffner, F. Reindl and S. Wild , JCAP 1805 (2018) no.05, 074*

# RATE vs. MODULATION AMPLITUDE

**Central idea: The modulation amplitude  
(in a given experiment) cannot exceed the mean rate:**

$$\bar{R} \geq S$$

$$\frac{\epsilon_{\text{COSINUS}}^{\text{T}}(E_{\text{R}})}{R_{\text{COSINUS}}^{\text{bound}}} > \frac{\epsilon_{\text{DAMA}}^{\text{T}}(E_{\text{R}})}{S_{\text{DAMA}}^{\text{bound}}}$$

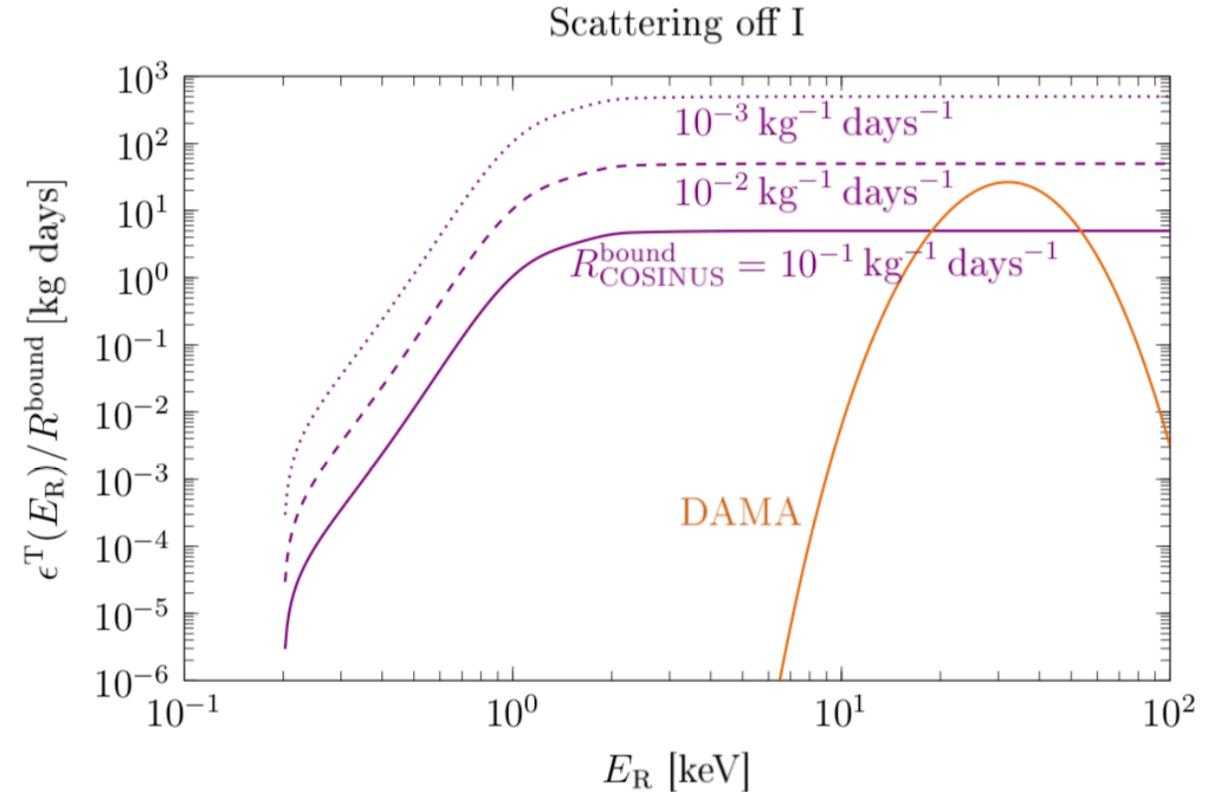
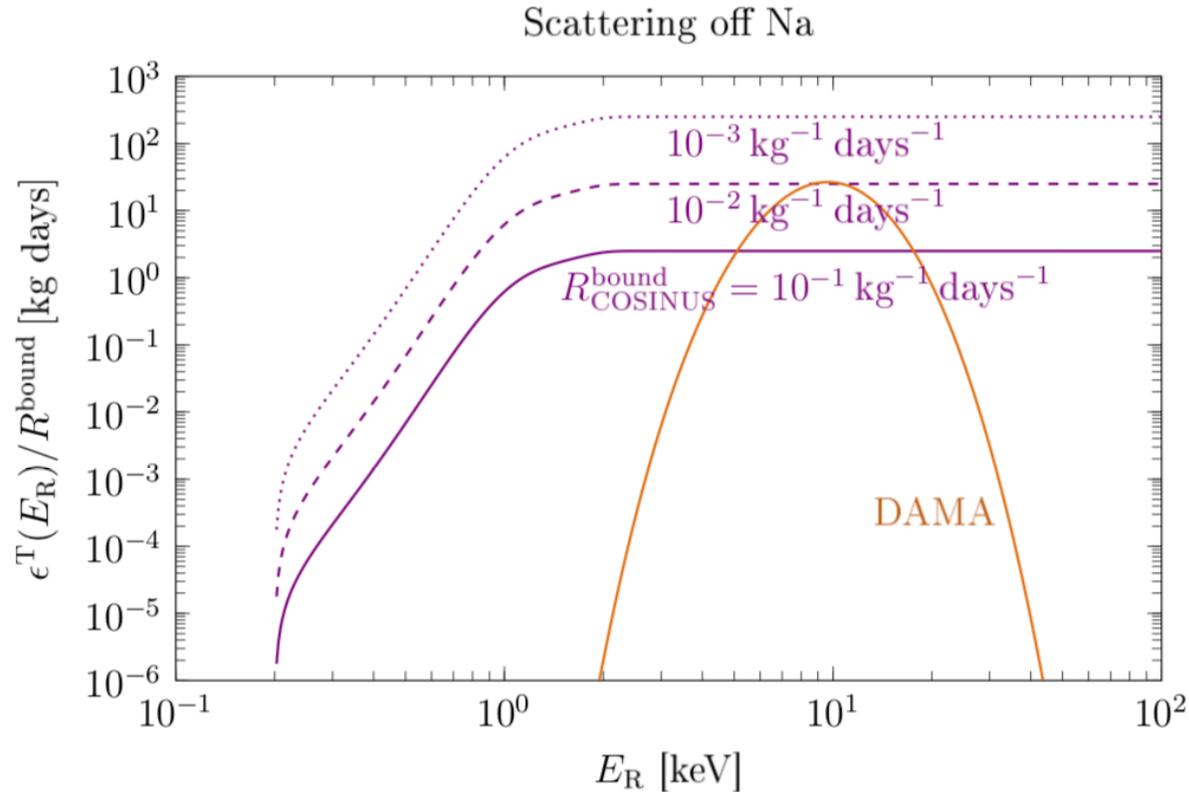
**T: target nucleus**

**$\epsilon$ : efficiency to see nuclear recoils of energy  $E_{\text{R}}$**

*F. Kahlhöfer, K. Schmidt-Hoberg, K. Schöffner, F. Reindl and S. Wild , JCAP 1805 (2018) no.05, 074*

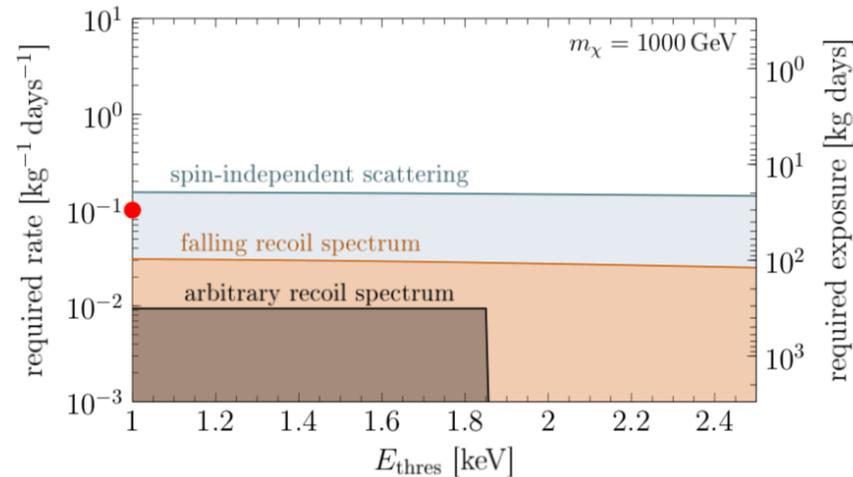
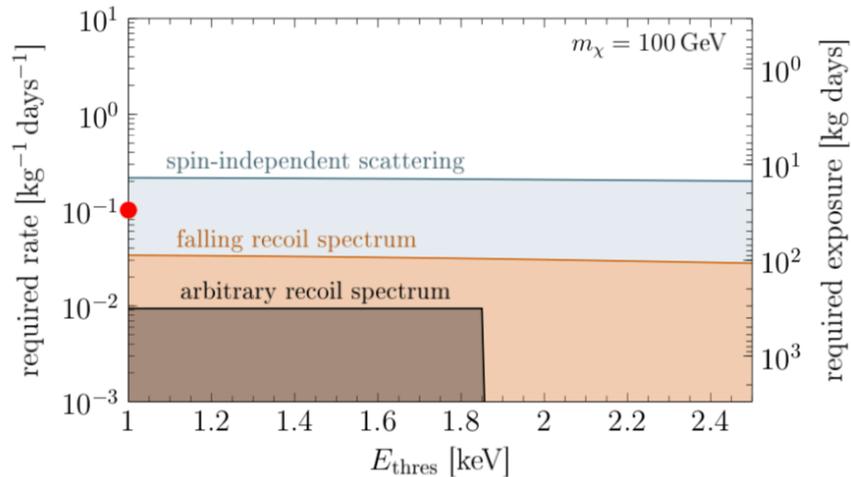
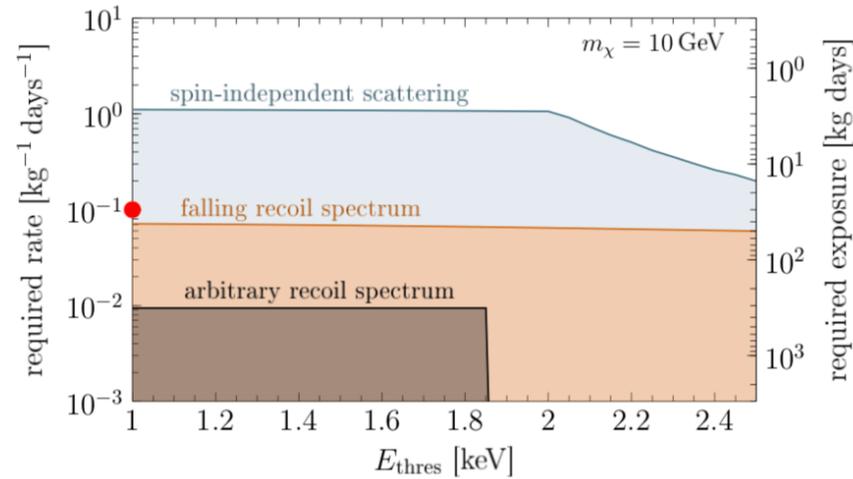
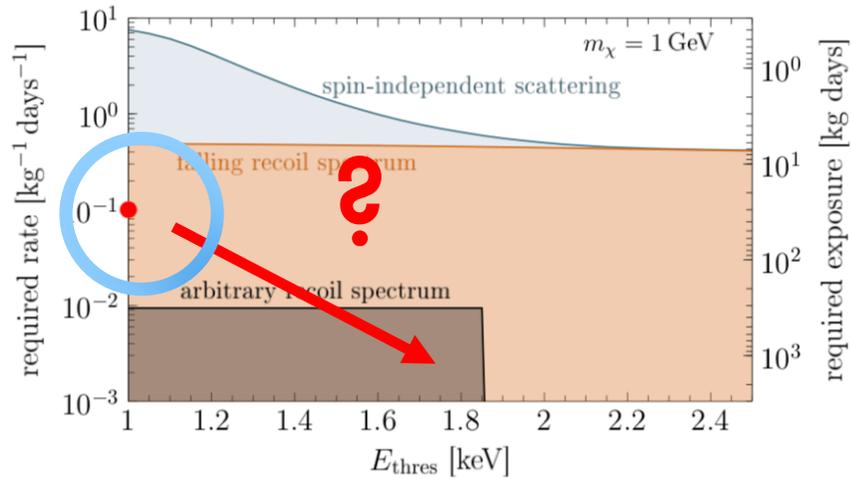
# MOST GENERAL CASE

$$\frac{\epsilon_{\text{COSINUS}}^{\text{T}}(E_{\text{R}})}{R_{\text{COSINUS}}^{\text{bound}}} > \frac{\epsilon_{\text{DAMA}}^{\text{T}}(E_{\text{R}})}{S_{\text{DAMA}}^{\text{bound}}}$$



*F. Kahlhöfer, K. Schmidt-Hoberg, K. Schöffner, F. Reindl and S. Wild, JCAP 1805 (2018) no.05, 074*

# RESULT



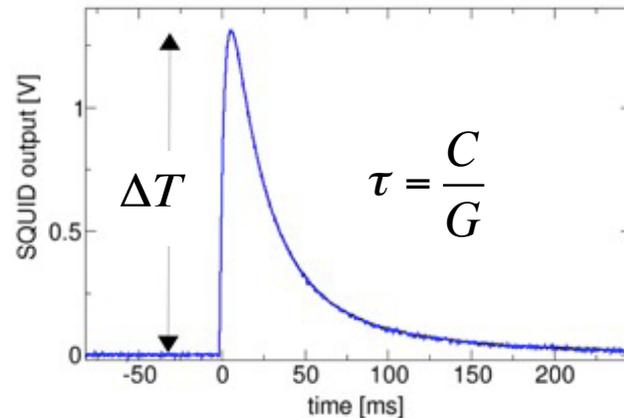
Threshold:  
1.8 keV sufficient

optimize rather  
exposure (mass)  
than threshold?

*F. Kahlhöfer, K. Schmidt-Hoberg, K. Schäffner, F. Reindl and S. Wild, JCAP 1805 (2018) no.05, 074*

# LIMITATIONS: thermodynamic fluctuations

## Temperature pulse



$N$  is the total excitations which have a mean energy  $k_B T$

$$N \propto CT / k_B T \quad \text{and} \quad \delta N = \sqrt{N}$$

$$\delta E = \delta N k_B T = \sqrt{k_B T^2 C}$$

noise comes from **irreducible random thermodynamic fluctuations** in energy due to transport across the thermal link

Ultimate energy resolution is determined by how well you can measure  $T$  against thermodynamic fluctuations:

low temperatures  $\rightarrow$  better energy sensitivity

low heat capacity  $\rightarrow$  careful selection of materials with low  $C$