COSINUS

Status and results of the COSINUS project

Natalia Di Marco for the COSINUS Collaboration

LNGS - INFN

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SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN
Istituto Nazionale di Fisica Nucleare

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Max-Planck-Institut für Physik
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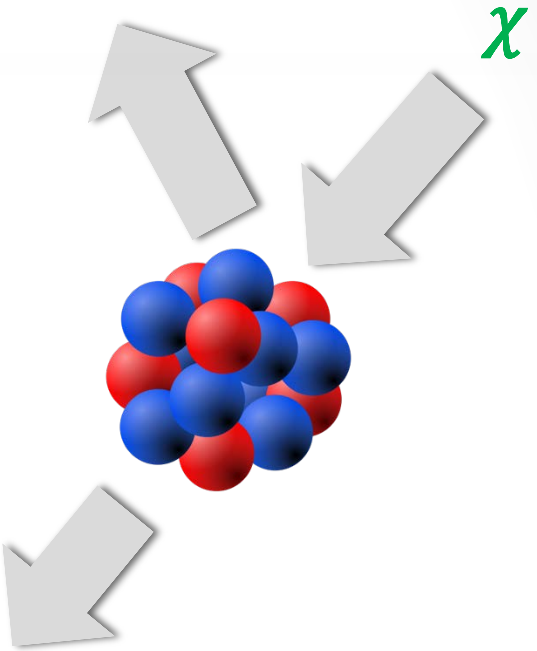
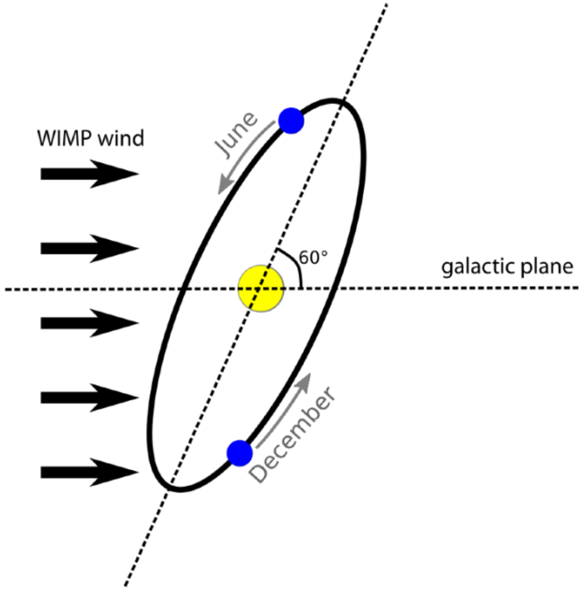
Dark Matter: direct search



Assumption
Dark matter particles (WIMPs) scatter off the nucleus and induce nuclear recoils

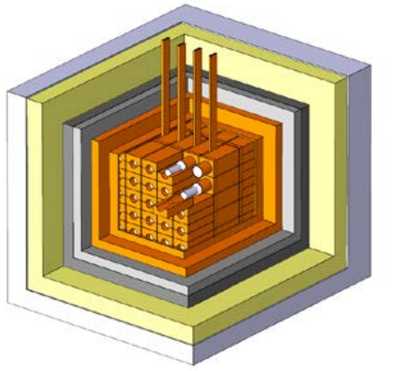


Signature

- Earth revolution gives ***seasonal modulation*** with a period of 1 year and a phase peaking at June the 2nd
- Due to the solar system movement in the galaxy, the **DM** flux is expected to be **anisotropic @earth** (***directionality***)

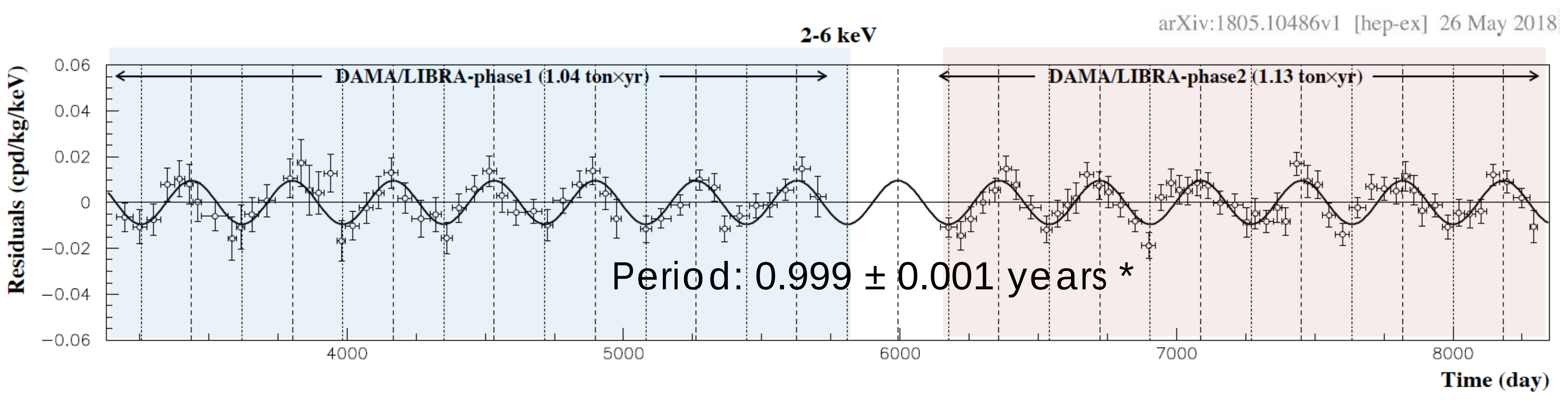
D. N. Spergel, Phys. Rev. D37 (1988)

The **DAMA/LIBRA** results



- 250 Kg NaI(Tl)
- Threshold 1 KeVee
- Running since 1996

Total exposure: 2.17 tonne years (phase 1 + 2)
Statistical significance: >11.9 σ
(combined with DAMA/NaI: 2.46 tonne years and 12.9σ !!!!)
Phase: 25th May +/- 5 days (cosine peaking June 2nd)



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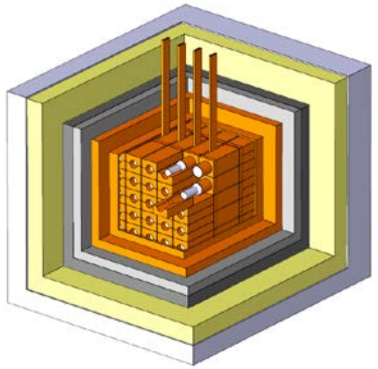

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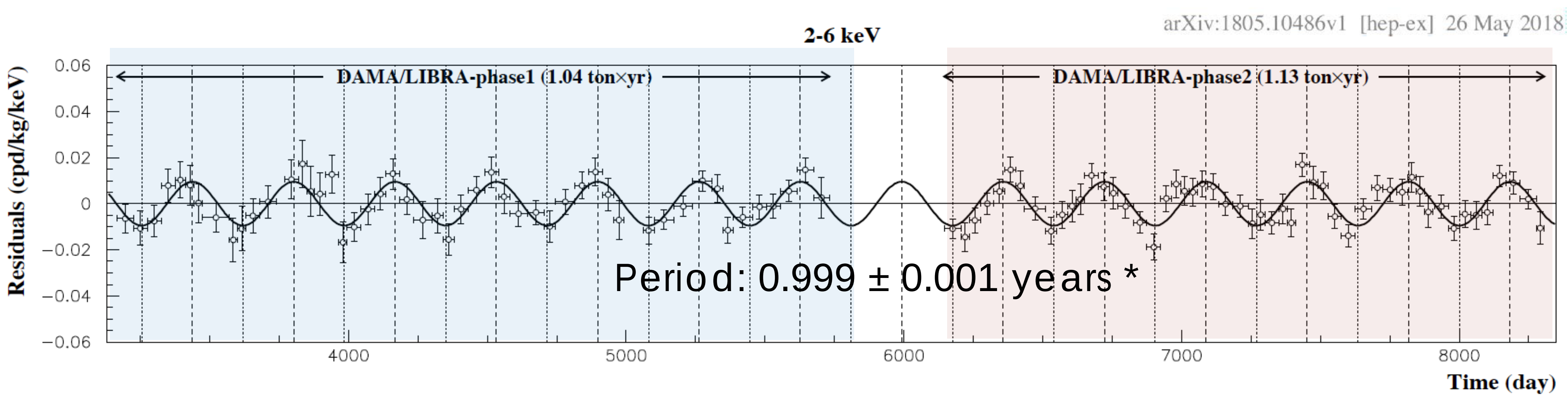


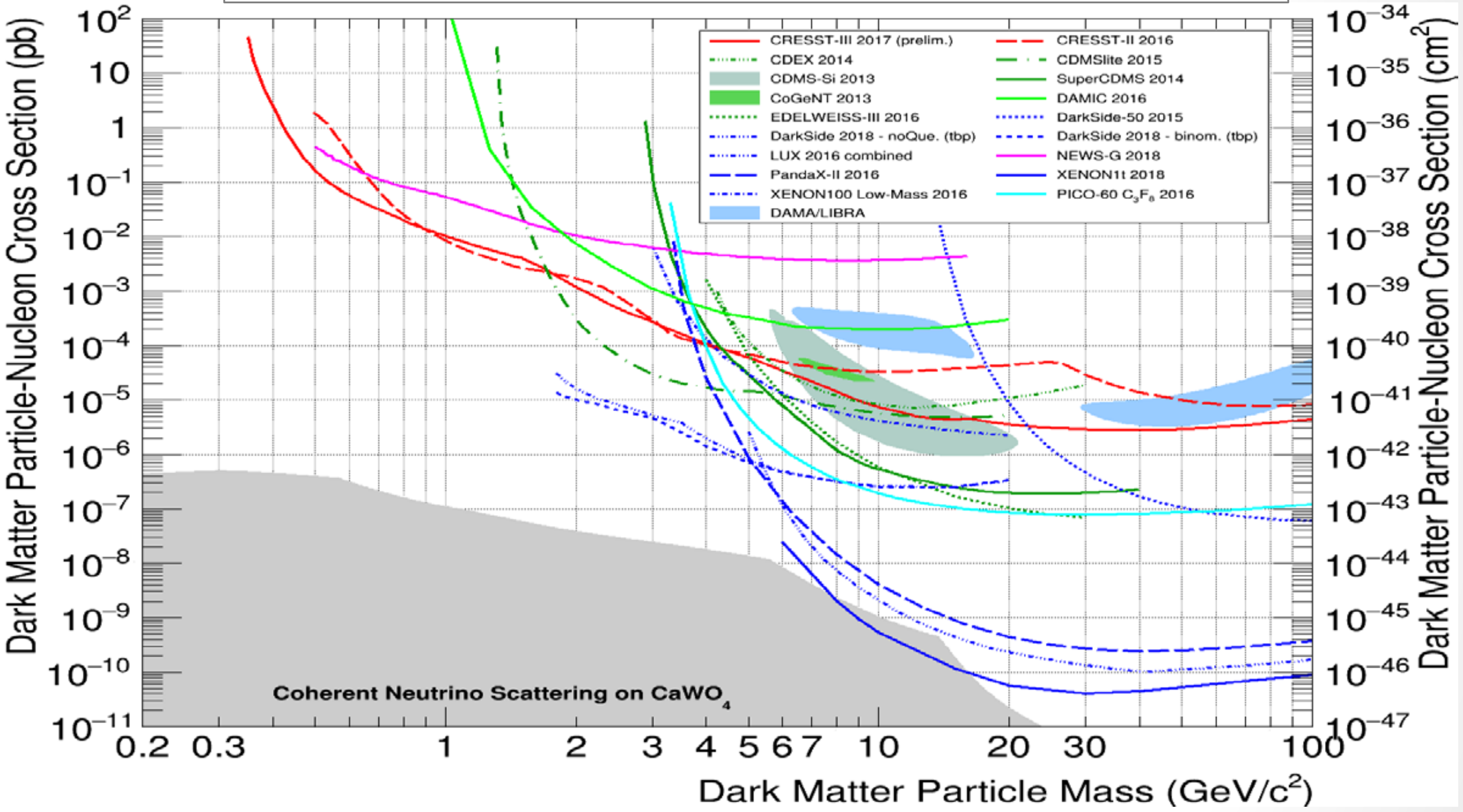
Positive evidence for the presence of DM particles in the galactic halo

GLOBAL LANDSCAPE OF DM Direct Search

CAVEAT: valid only under standard assumption!

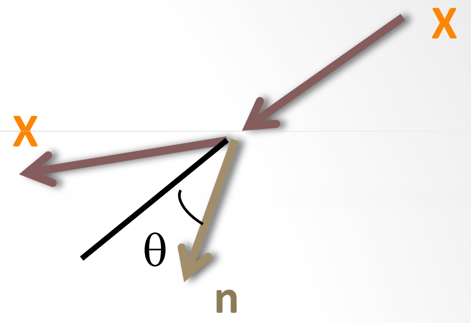
Null results shown as 90% C.L. upper limits on the spin-independent DM particle-nucleon cross section

DAMA/LIBRA:
3σ allowed parameter space



Long-reigning contradicting situation in the dark matter sector: the positive evidence for the detection of a dark matter modulation signal claimed by the DAMA/LIBRA collaboration is (under standard assumptions) **inconsistent with the null-results** reported by most of the other direct dark matter experiments (using different targets Xe, Ge, $CaWO_4$).

WHAT ARE THE **UNKNOWNS**?



$$\frac{dR}{dE_r} = N_N \frac{\rho_0}{m_\chi} \int_{v_{min}}^{v_{max}} d\vec{v}\, f(\vec{v}) v \frac{d\sigma}{dE_r}$$

N_N → number of target nuclei

ρ_0 → local WIMP density

$f(\vec{v})$ → WIMP velocity distribution

$v_{min} = \sqrt{\frac{m_N E_{th}}{2 m_r^2}}$

v_{max} → escape velocity

$\frac{d\sigma}{dE_r}$ → WIMP-nucleus differential cross section

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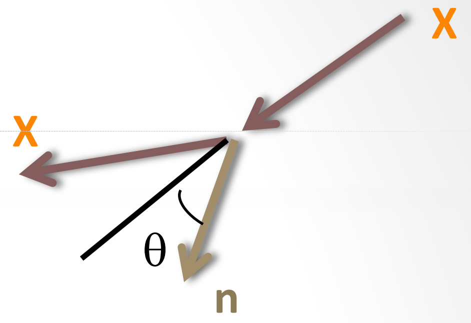

Astrophysics

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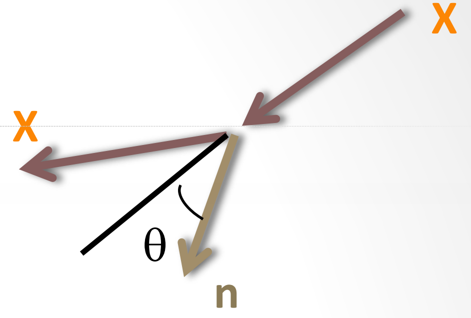

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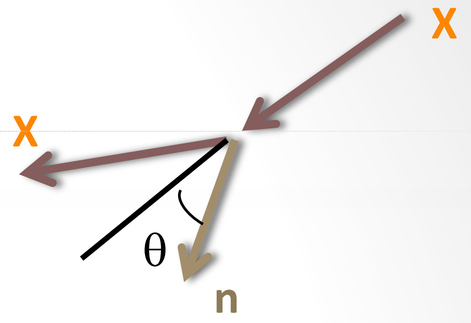

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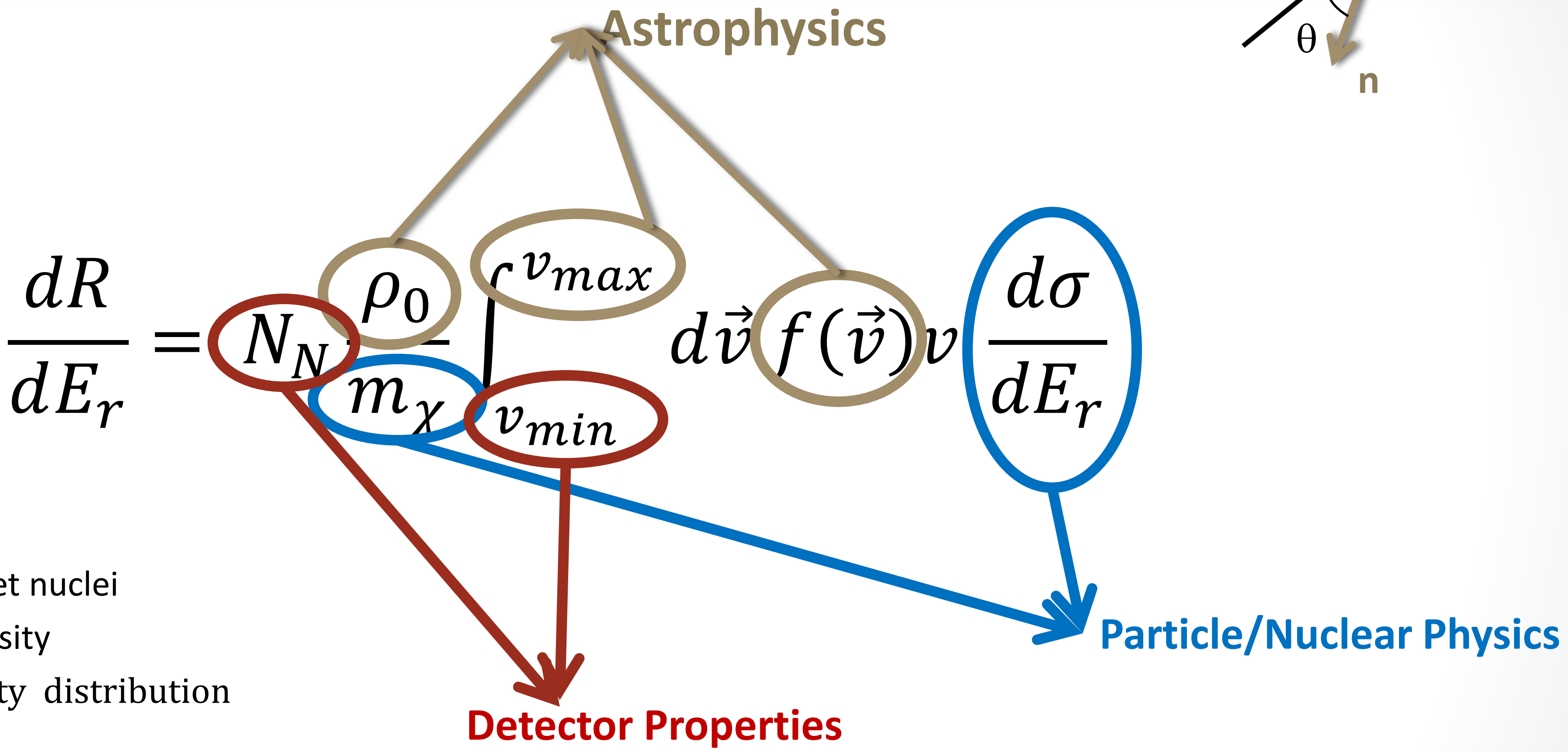

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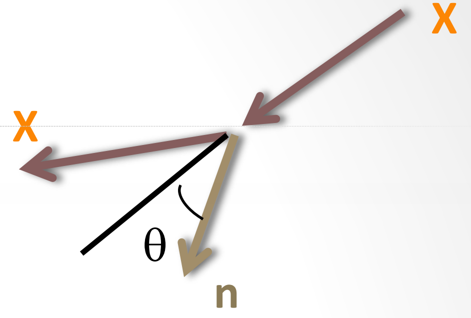

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Particle/Nuclear Physics

Detector Properties

N_N → number of target nuclei

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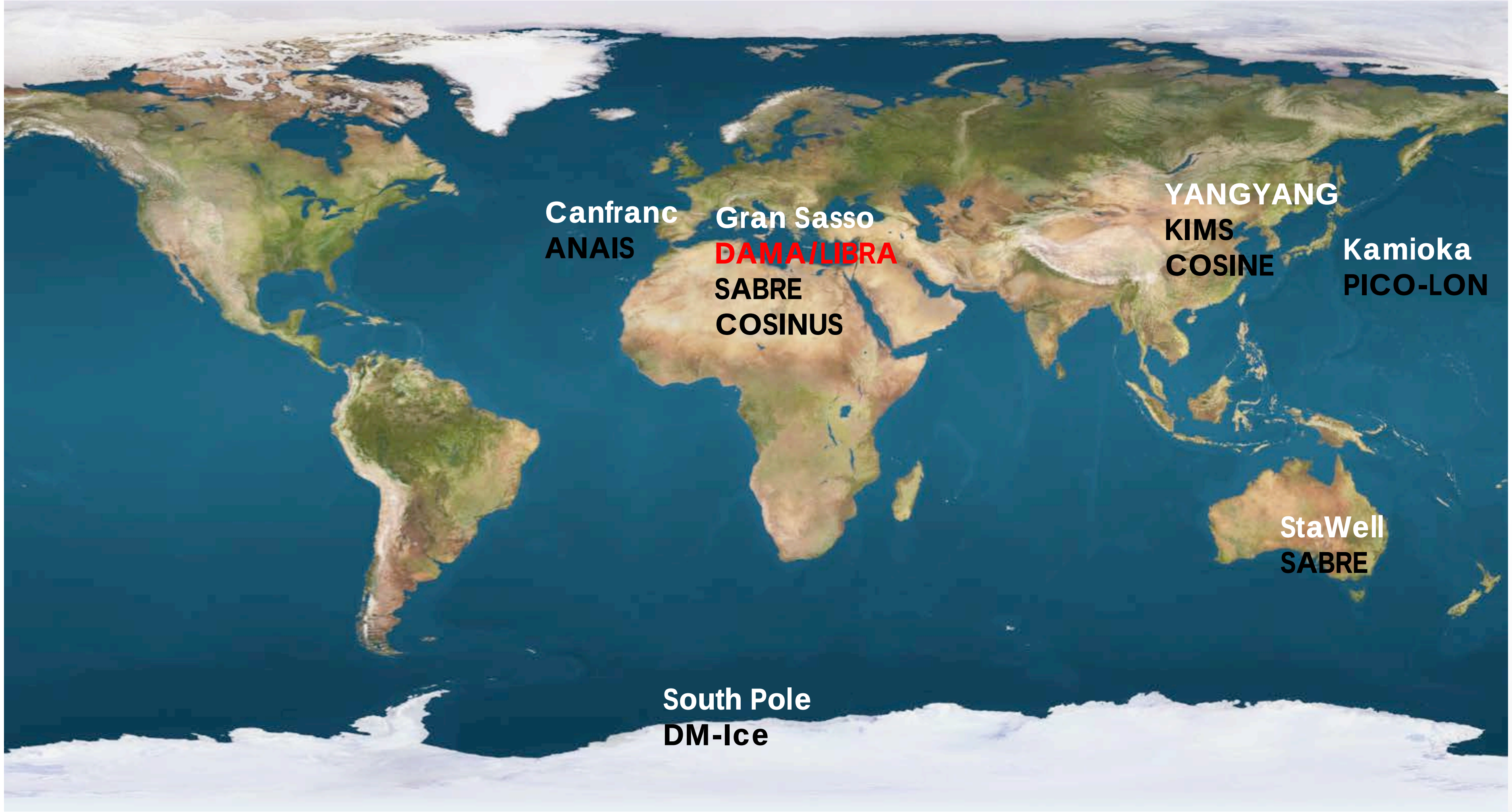
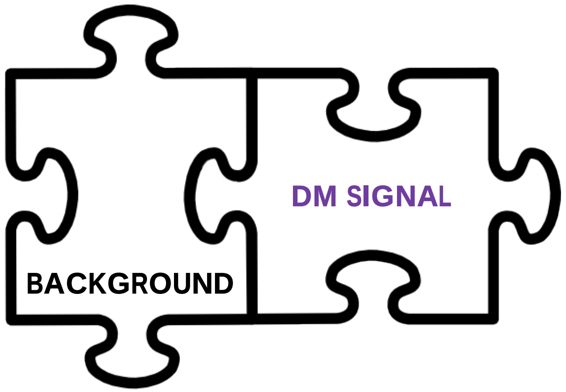
Target material dependence: test DAMA with NaI experiment(s)

GLOBAL NaI EFFORTS

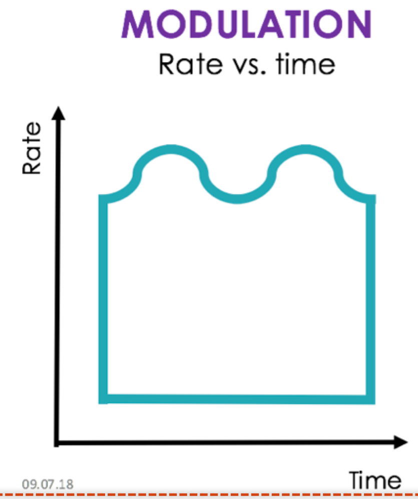


GLOBAL NaI SEARCHES

SINGLE CHANNEL



- **DAMA/LIBRA**
- **COSINE-100**
- **ANAIS-112**
- **SABRE**
- **PICO-lon**



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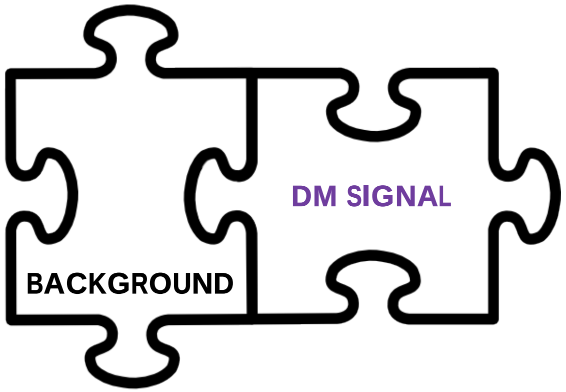

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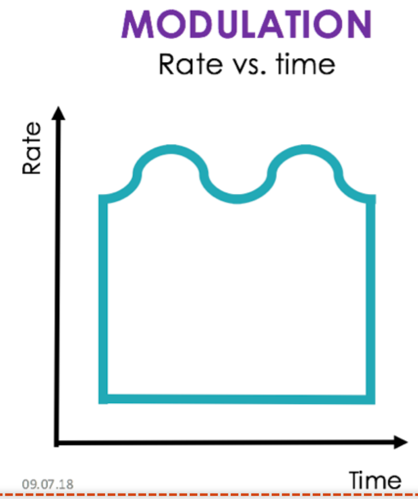
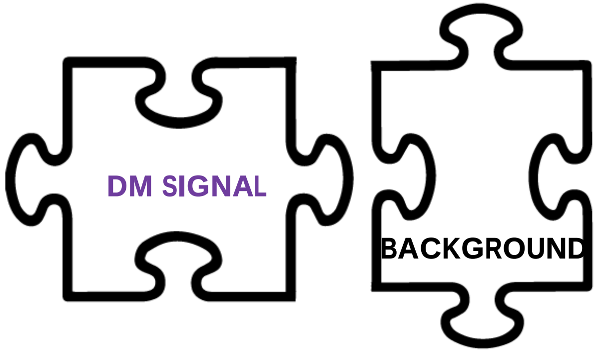


DUAL CHANNEL

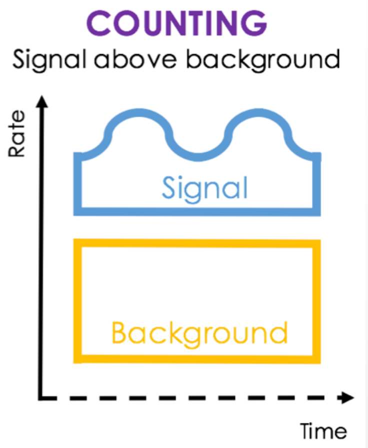


COSINUS

DISCRIMINATION

nuclear recoil events

to β/γ-events



COSINUS

www.cosinus.it

- 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 (MPRG) grant: duration 5 years, starting 2019**
- **prolongation for one year (2019) in CSN 5 requested**
- Eur. Phys. J. C (2016) 76:441

NEW

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INFN Istituto Nazionale di Fisica Nucleare

SICCAS Since 1928

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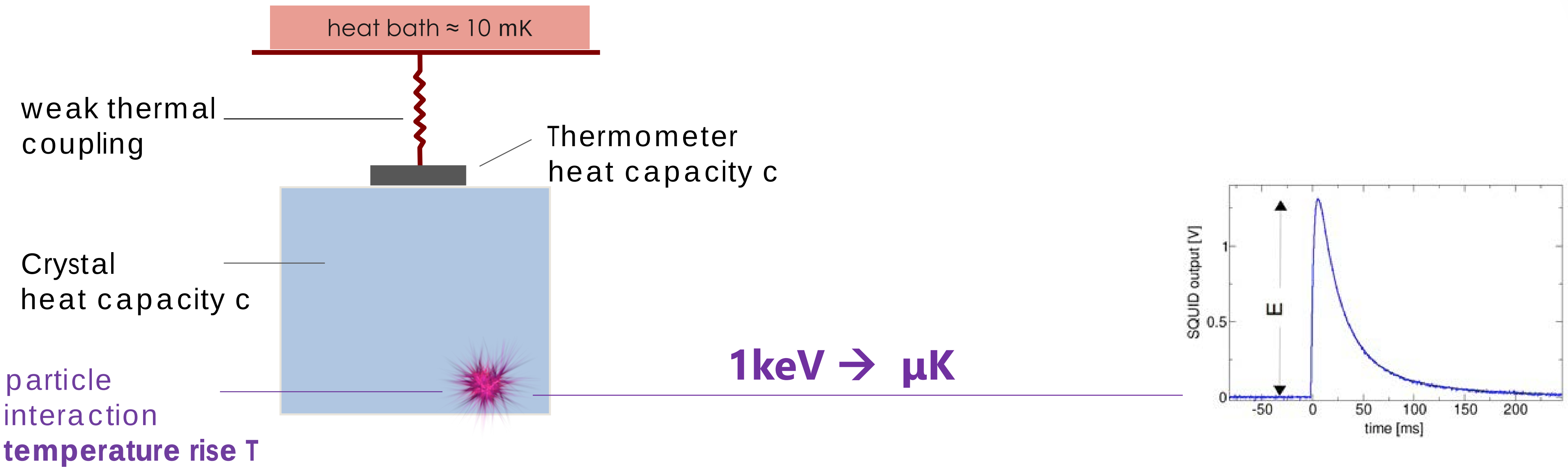
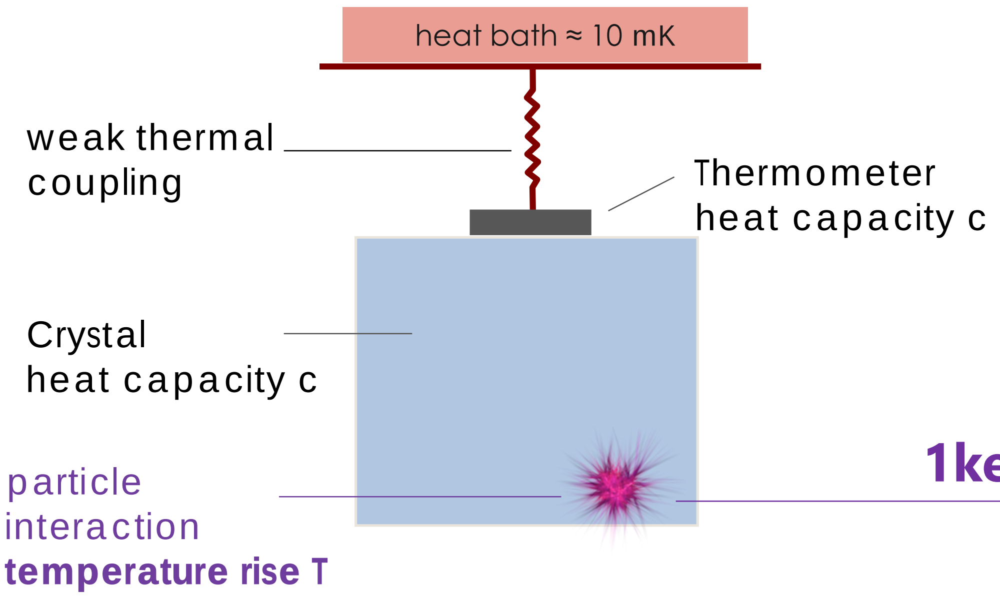
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

LOW-TEMPERATURE CALORIMETER



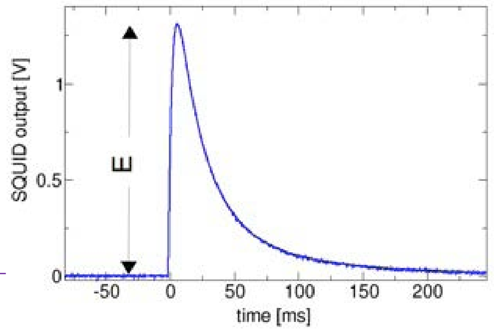
NaI-based **SCINTILLATING CALORIMETER**



Phonon signal (~ 90 %)

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

1keV → µK



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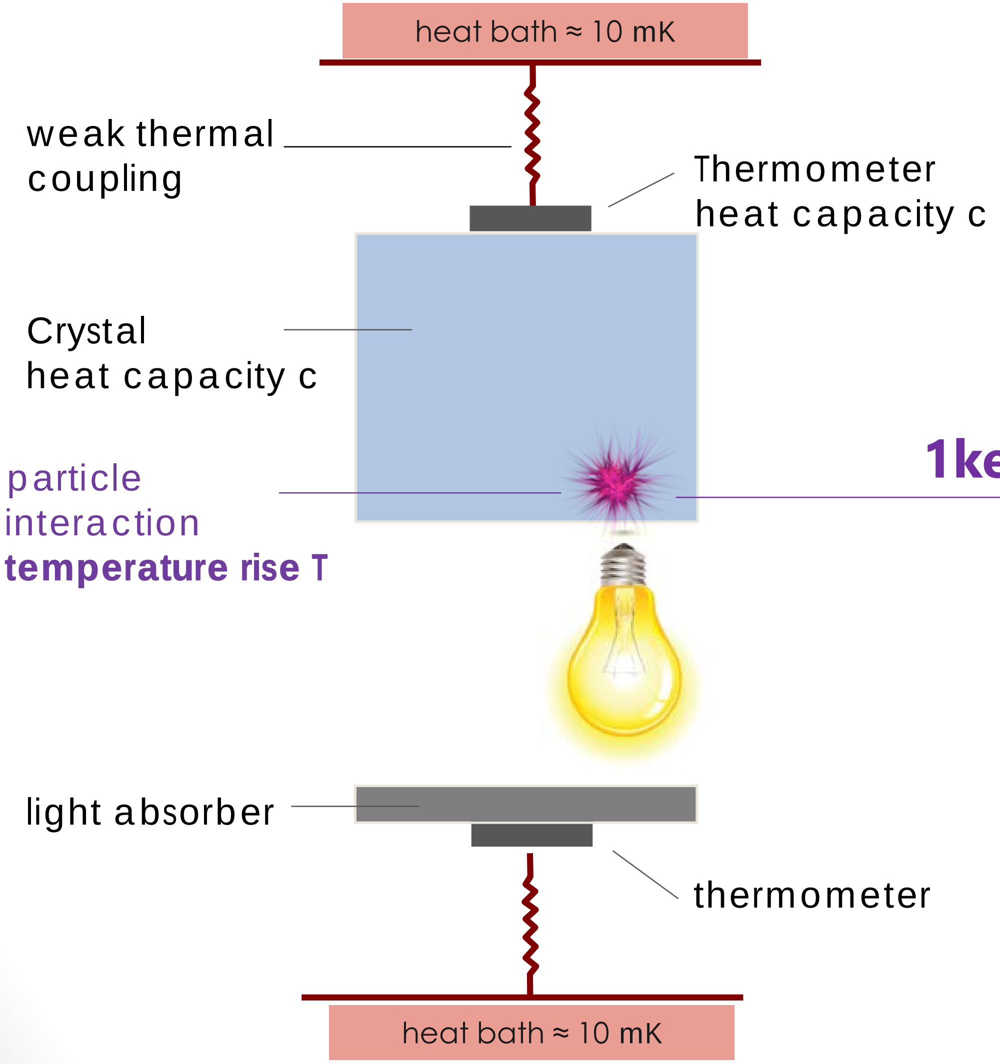

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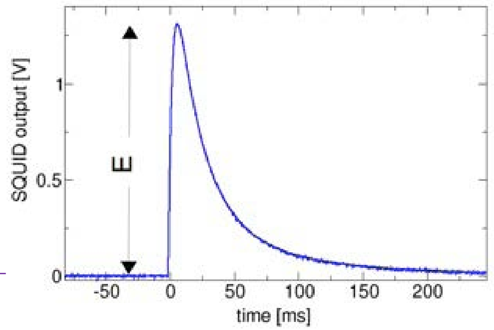

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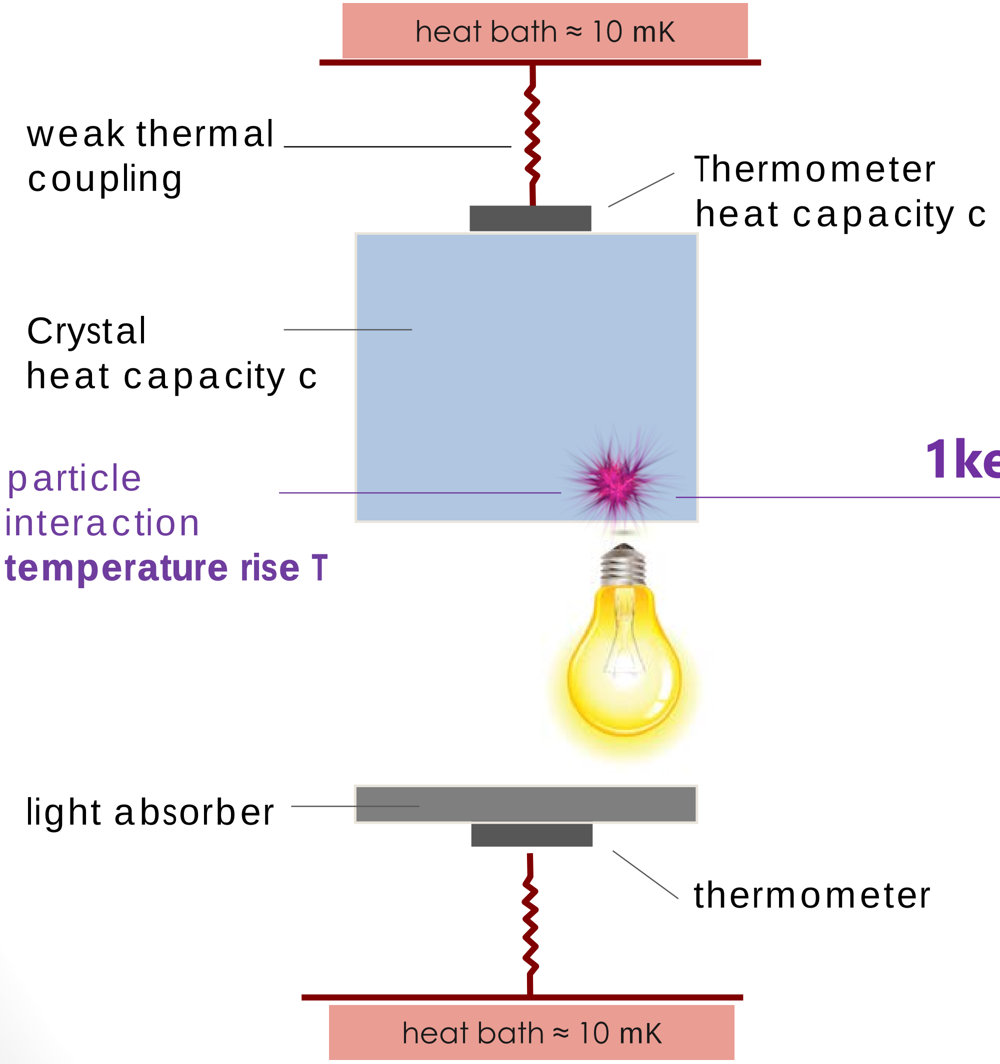

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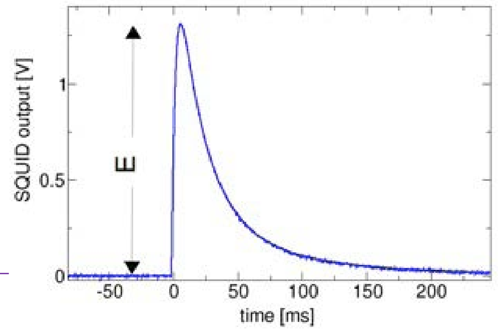
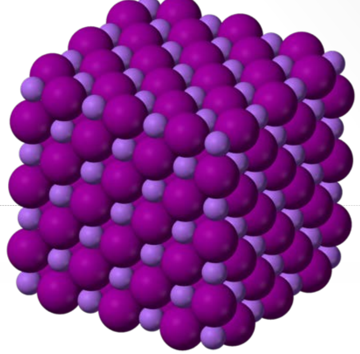


Scintillation light (few %)

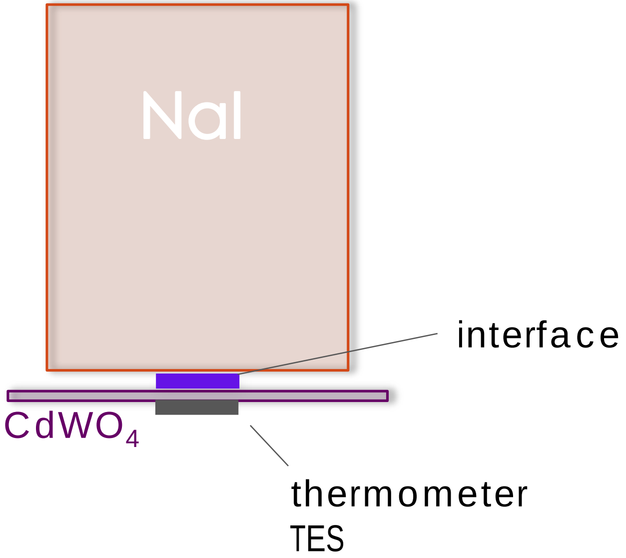
→ **add cryogenic light detector** for scintillation light detection

- amount of emitted light depends on particle type → LIGHT QUENCHING
- discrimination of interacting particle via the **ratio light to phonon signal** → ***LIGHT YIELD***

COSINUS DETECTOR DESIGN



^{11}Na 53



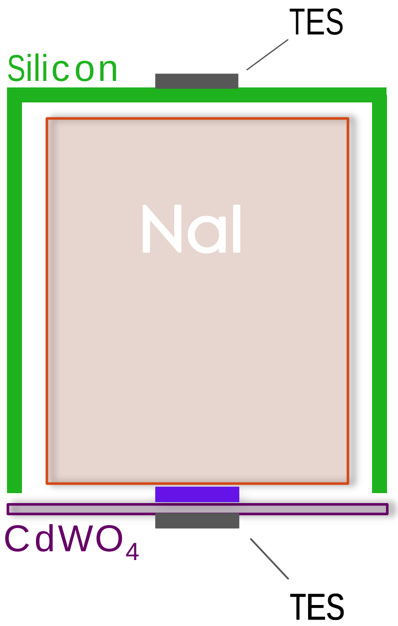
NaI Target Crystal

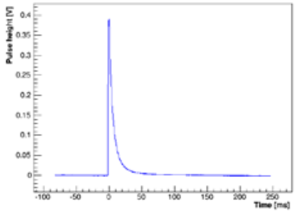
- scintillator
- multi-element target
- mass: ~ 30 – 200 g
- **hygroscopic**

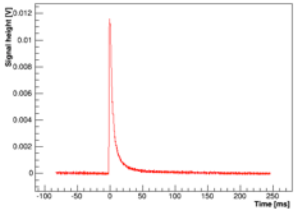
Carrier Crystal

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

COSINUS DETECTOR DESIGN







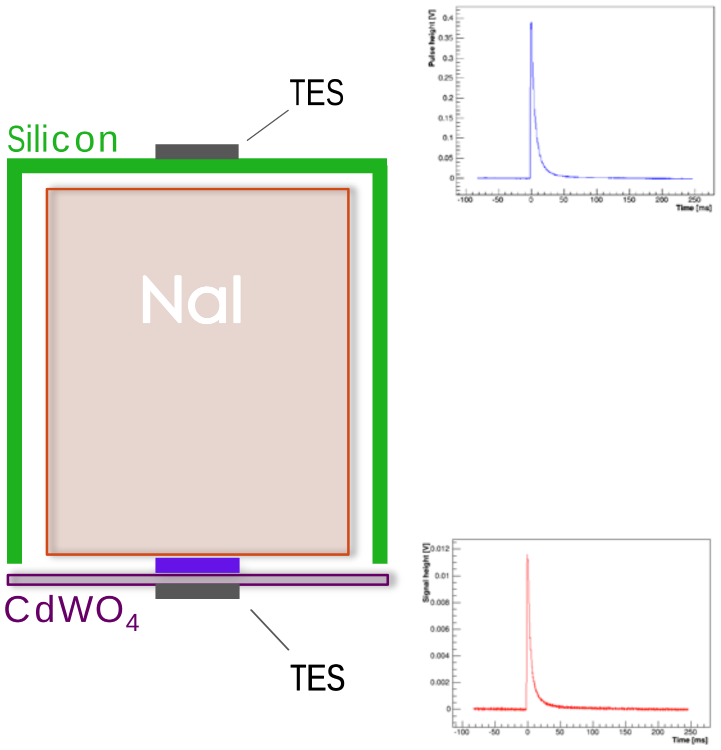
Light absorber

- 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 GOALS



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

NaI nuclear recoil energy threshold of 1 keV

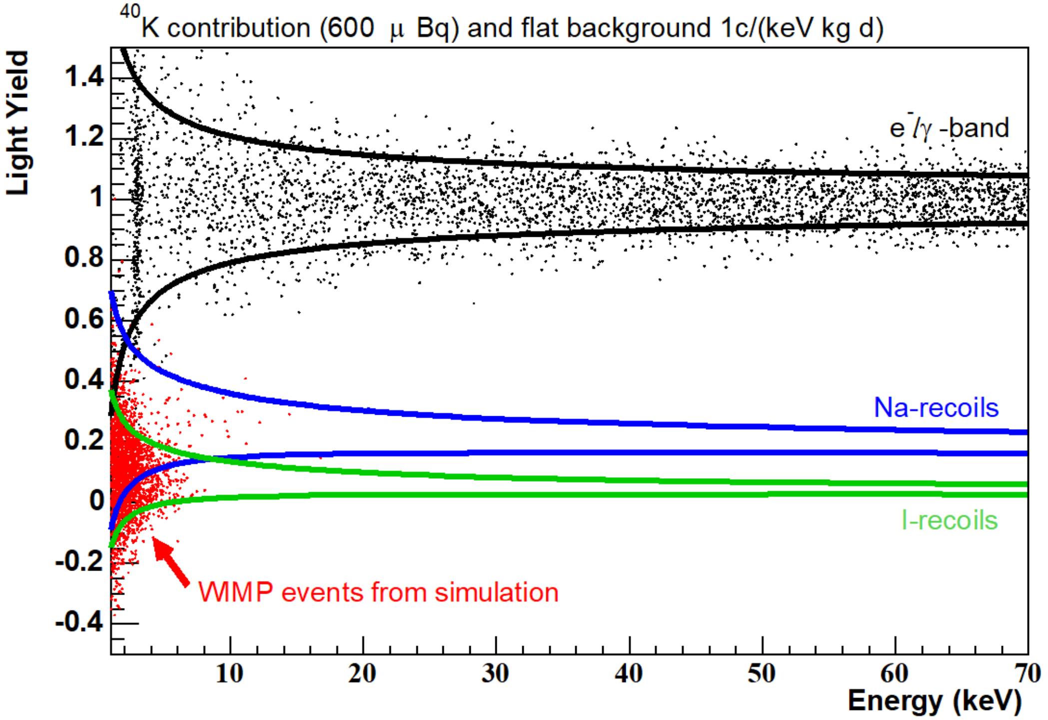
~ 4% of deposited energy detected in form of light

light detector baseline noise σ =10 eV

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

SIMULATED DATA

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



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

Exposure before cuts: 100 kg-days

- **black** events:
  flat background: 1 /(keV kg d)
  + ^{40}K background: 600μBq/kg

- **recoils off Na**
  → light quenching factor ~ 0.3

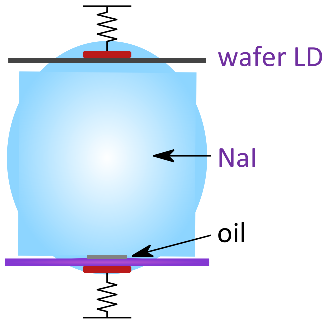
- **recoils off I**
  → light quenching factor ~ 0.1

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

- **Red:** 10 GeV/c^2 WIMP with 2E-04 pb as from Savage et al.

COSINUS R&D

1st PROTOTYPE (2016)



1st measurement of a NaI as cryogenic calorimeter

linear relation between light output and deposited energy

NaI threshold: 10 keV

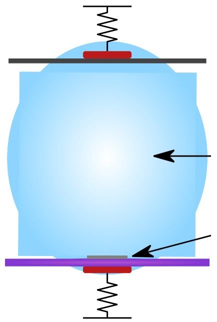
3.7% detected in light

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

COSINUS R&D

1st PROTOTYPE (2016)

2nd PROTOTYPE (2016/17)



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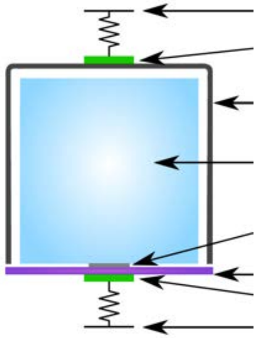


successful test of complete COSINUS detector design

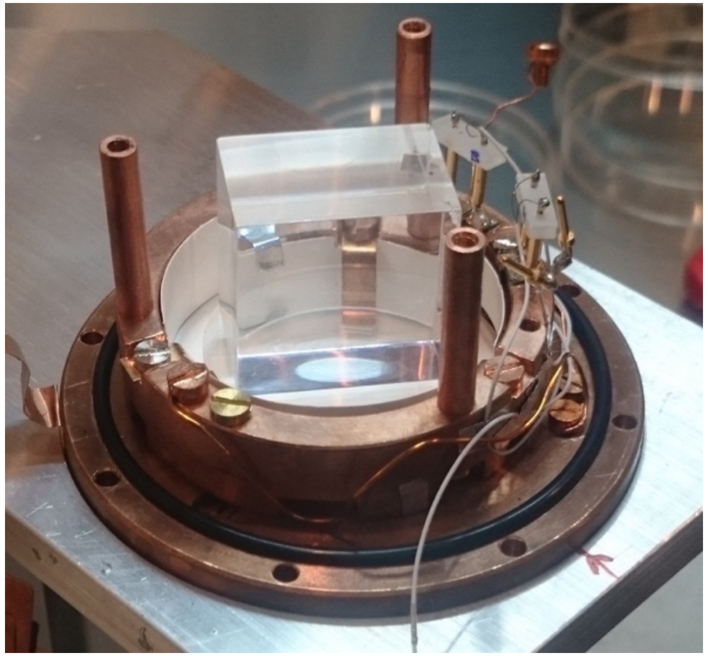
energy resolution at zero energy : 15 eV

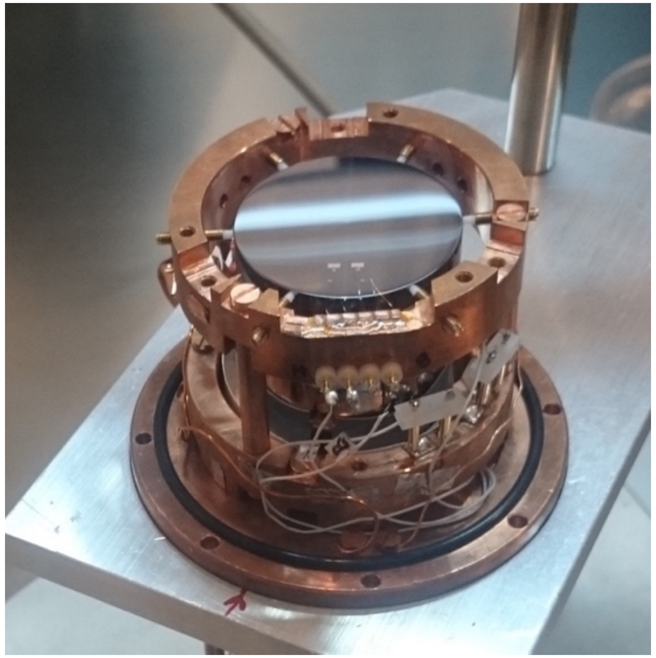
NaI threshold: 8.3 keV

13 % detected in light

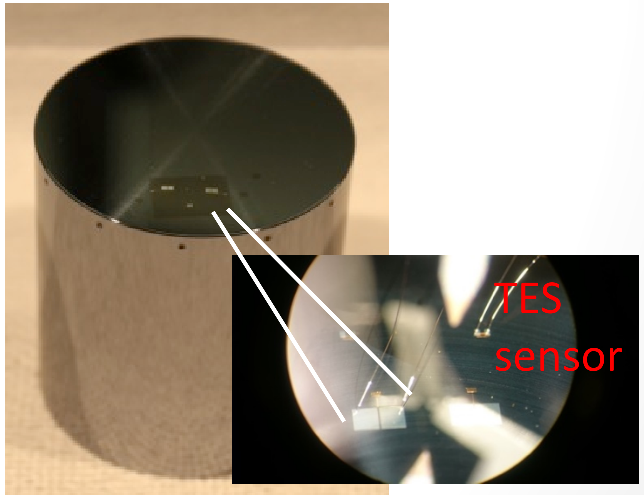
Schäffner, K. et al. J Low Temp Phys (2018). https://doi.org/10.1007/s10909-018-1967-3

2nd PROTOTYPE DETECTOR





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



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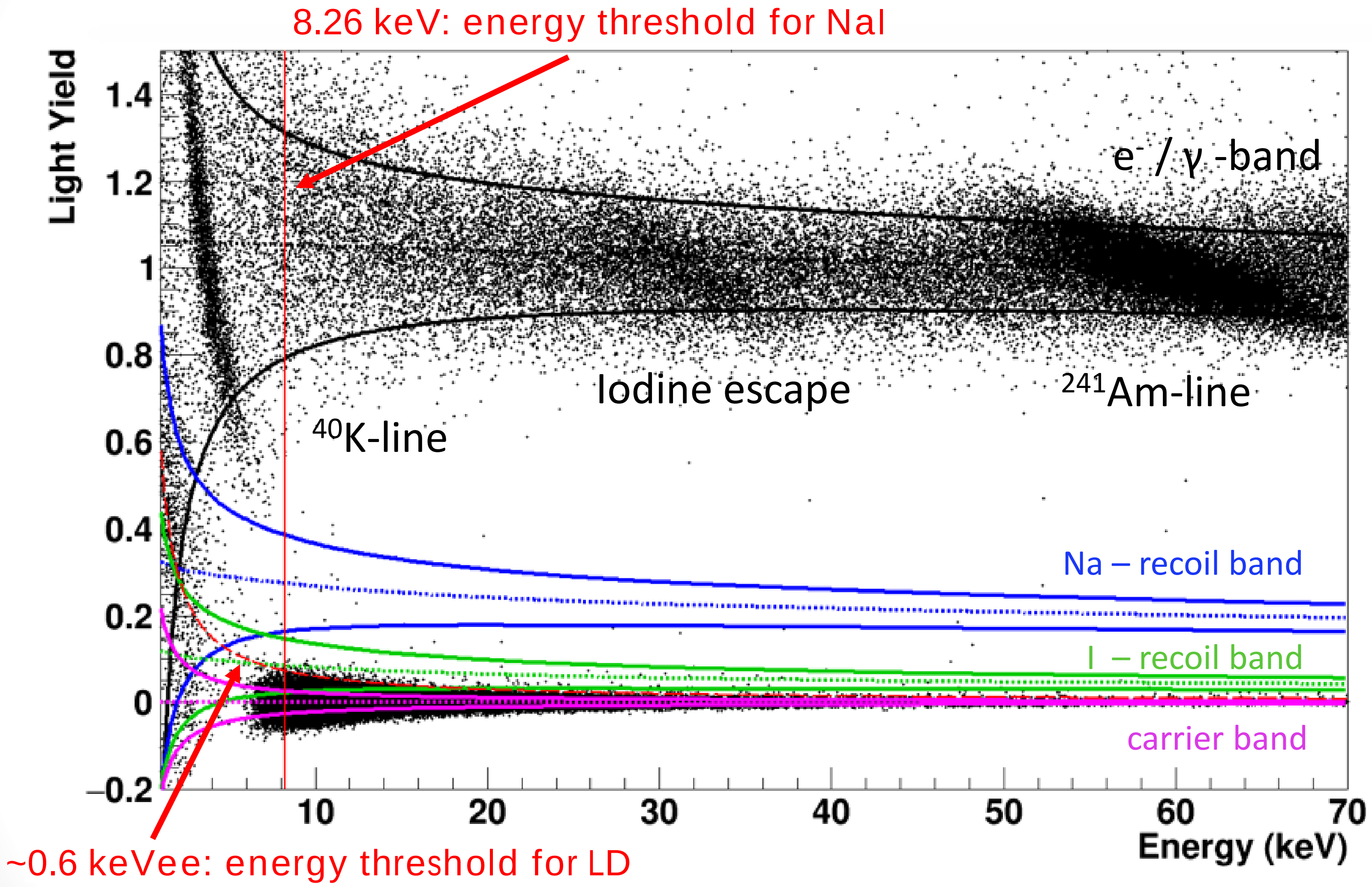


- NaI energy threshold is (8.26 ± 0.02 (stat.))keV
- width of the ^{241}Am peak is (4.508 ± 0.064 (stat.)) keV
- carrier events identified by pulse shape

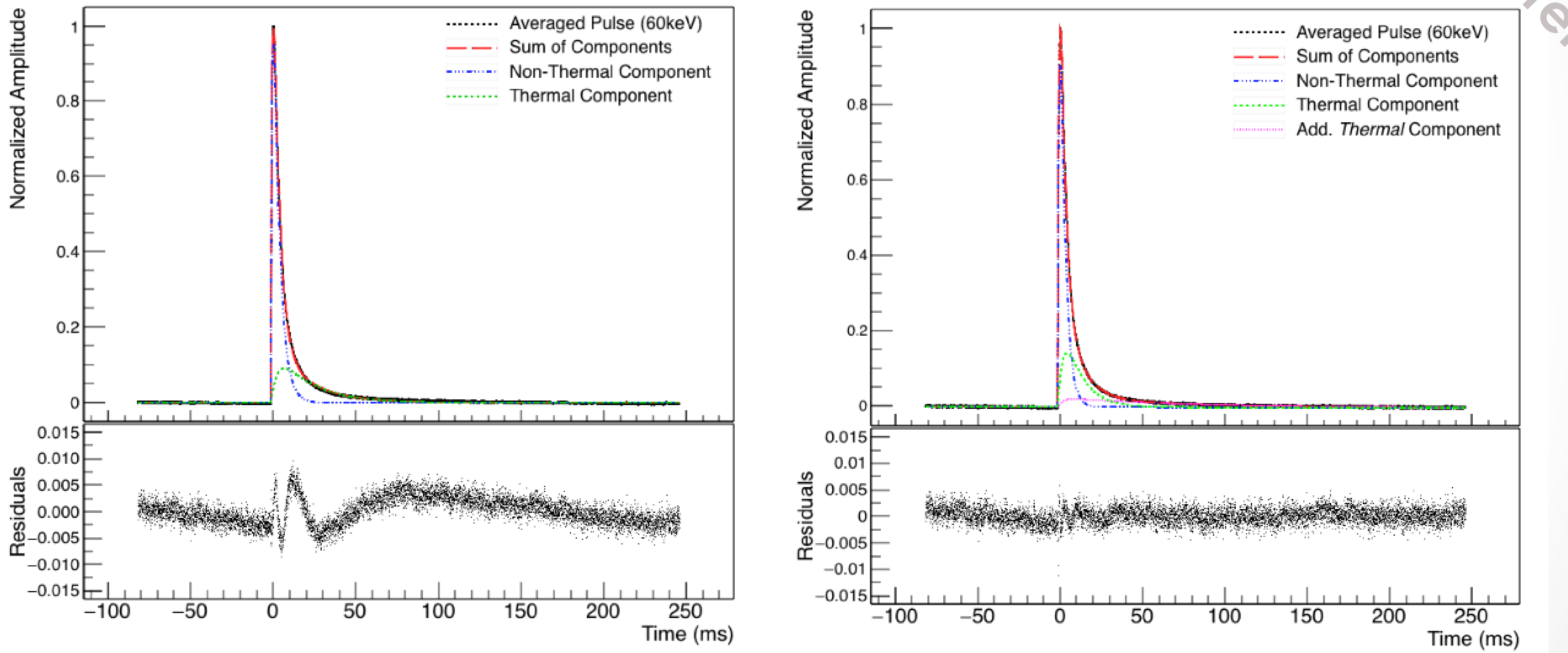
Schäffner, K. et al. J Low Temp Phys (2018).
https://doi.org/10.1007/s10909-018-1967-3

LONG DECAY TIMES – PULSE MODEL

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

all measurements observed in

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



(a)Two-component pulse model (b)Three-component pulse model

This example: 1st prototype: G. Angloher et al. JINST 12 P11007 (2017)
Same result: 2nd prototype: F. Reindl et al., arXiv 1711.01482

COSINUS R&D

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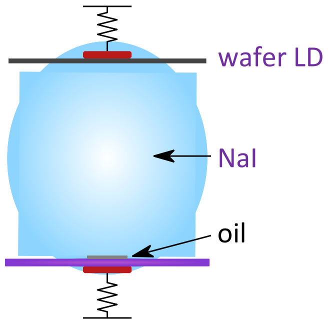

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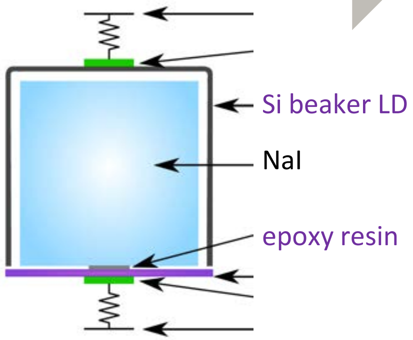
2nd PROTOTYPE (2016/17)



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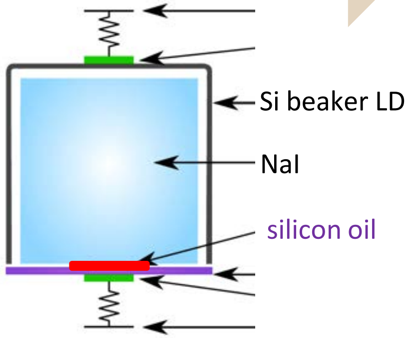
3rd PROTOTYPE (2017)



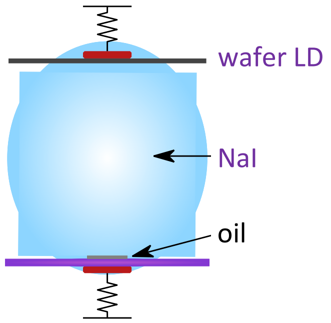
changed interface to thin layer of silicon oil

commissioning of:
in-house electronics
and DAQ from MIB

NaI threshold: 6.5 keV

COSINUS R&D

1st PROTOTYPE (2016)	2nd PROTOTYPE (2016/17)	3rd PROTOTYPE (2017)	4th → 7th PROTOTYPE (2017/18)



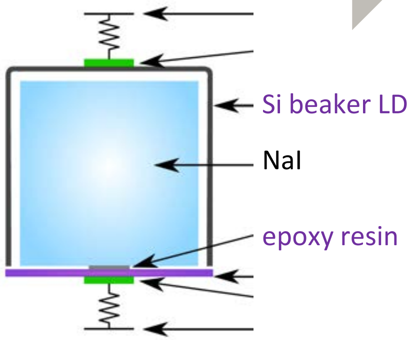
1st measurement of a NaI as cryogenic calorimeter

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)



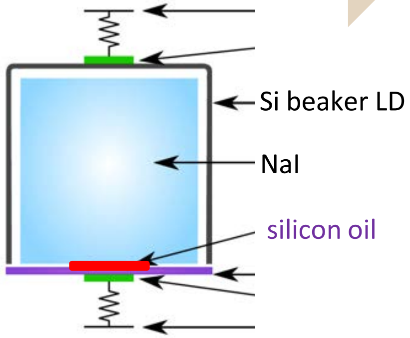
successful test of complete COSINUS detector design

energy resolution at zero energy : 15 eV

NaI threshold: 8.3 keV

13 % detected in light

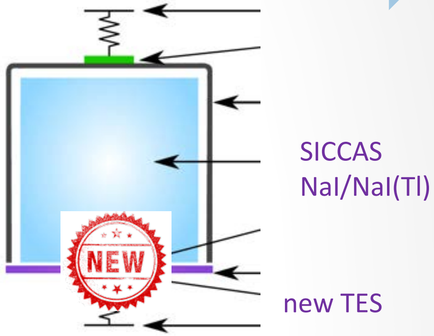
Schäffner, K. et al. J Low Temp Phys (2018). https://doi.org/10.1007/s10909-018-1967-3



changed interface to thin layer of silicon oil

commissioning of:
in-house electronics
and DAQ from MIB

NaI threshold: 6.5 keV



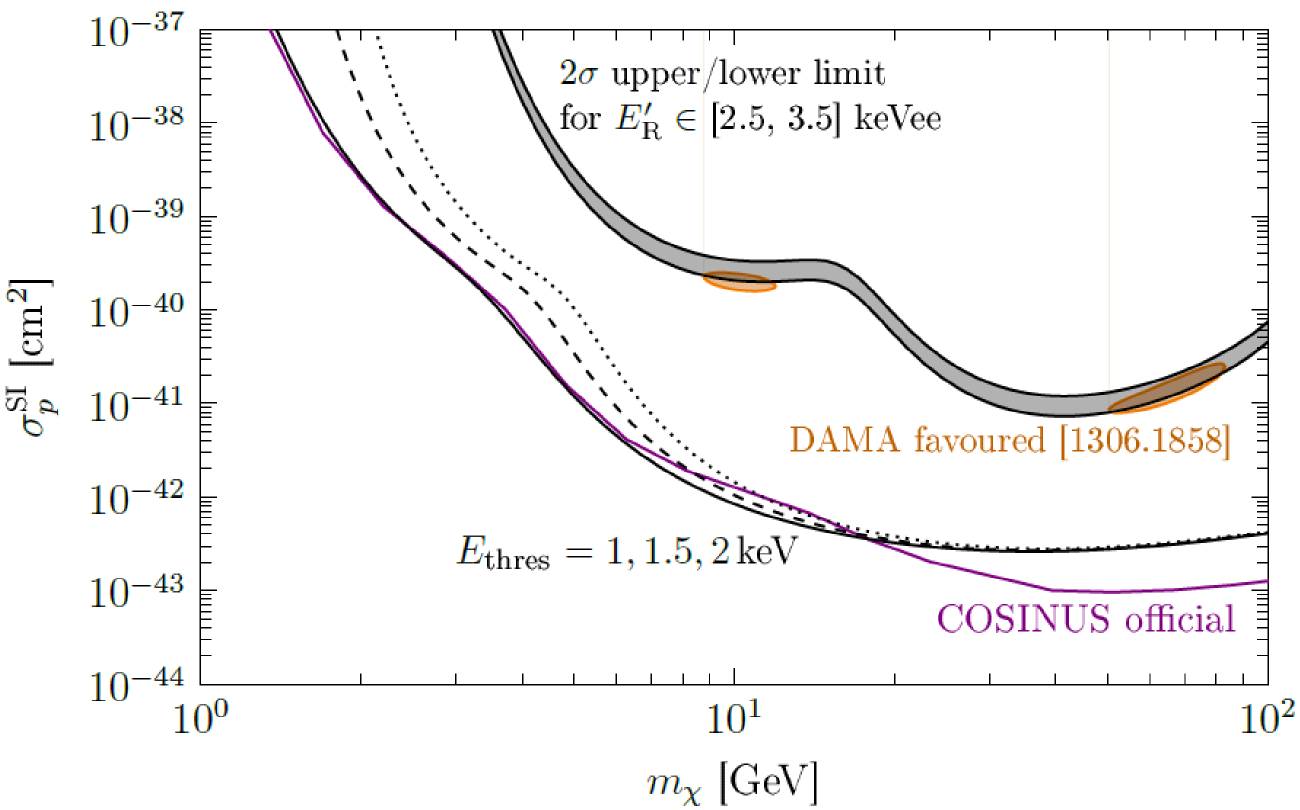
test of new batch of NaI/**NaI(Tl)** crystals from SICCAS

test of new TES-concept for the NaI crystal

Work ongoing!

COSINUS PHYSICS REACH

JCAP 1805 (2018) no.05, 074

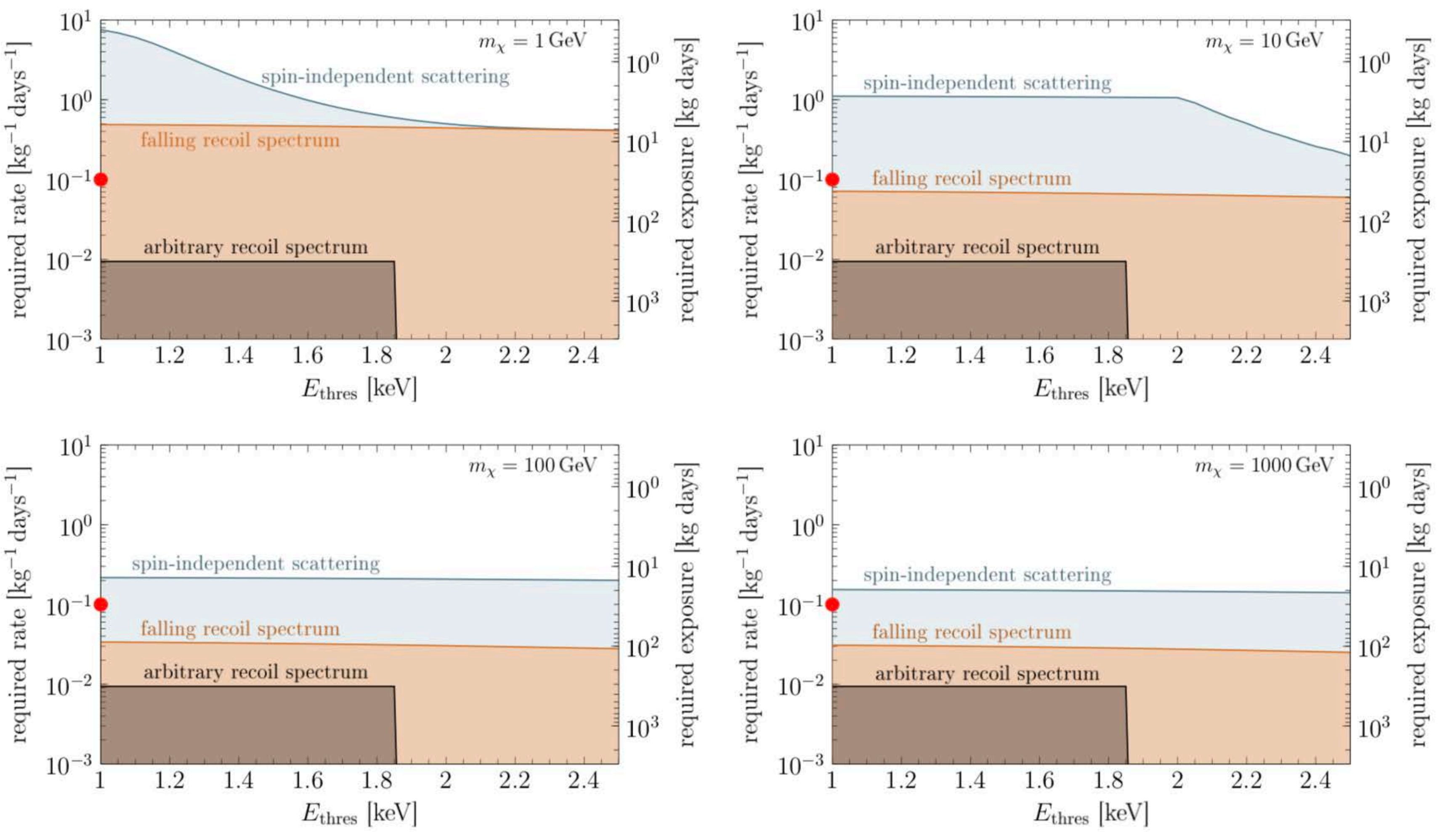


Assuming spin-independent interaction and a Maxwell-Boltzmann velocity distribution, COSINUS should be able to exclude the DAMA region by about two orders of magnitude in cross section with an exposure of 100 kg days

What about sensitivity in case of less restrictives assumptions?

COSINUS PHYSICS REACH

JCAP 1805 (2018) no.05, 074



COSINUS exclusion power, defined as the bound on the total rate (or equivalently the total exposure with zero observed events) that COSINUS must achieve for excluding DAMA in a halo-independent way, as a function of the assumed threshold in COSINUS for different DM masses.

COSINUS PHYSICS REACH

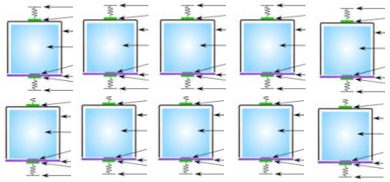
COSINUS has the unique potential to clarify a nuclear recoil origin of the DAMA/LIBRA signal

CONFIRM

\+ not **too exotic** dark matter

Good chance for exposure of $\mathcal{O}$ (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

Model-independent comparison of annual modulation and total rate with direct detection experiments

F. Kahlhoefer et al. **JCAP 1805 (2018) no.05, 074**

SUMMARY

COSINUS

www.cosinus.it

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

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

BACKUP

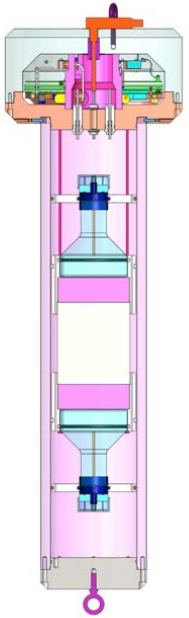
NaI EXPERIMENTS

DM-Ice17

South pole
17 kg NaI

energy: 4 keV_{ee}

3.5 y physics run
no hint

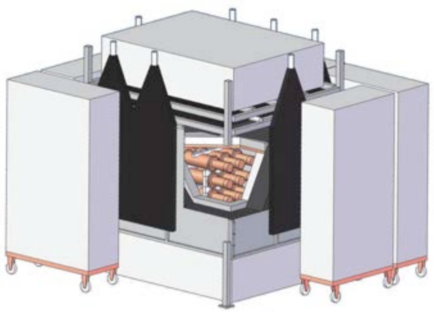


ANAIS-112

LSC - Spain
112.5 kg NaI

energy: < 1 keV_{ee}

spring 2017



COSINE-100

Y2L Korea
KIMS NaI + DM-Ice
106 kg

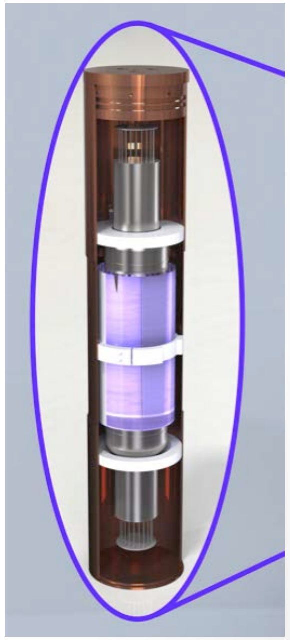
energy: ~ 2 keV_{ee}

since Sept. 2016

SABRE

Gran Sasso/Australia
40-50 kg NaI

construction phase
Proof of Principle in 2018



not complete list!

MUST HAVE TO PROOF DAMA/LIBRA

- energy threshold of < 2 keVee
- radiopure crystal: ~ 1 count / (keV kg day)
  → **in particular very low ^{40}K content**
- large detector mass $\mathcal{O}$ (10 kg)

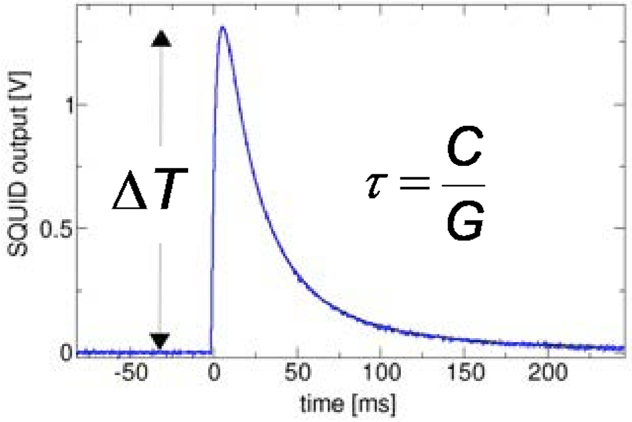
DAMA/LIBRA BACKGROUND

K	**< 20 ppb**
^{238}U	< 0.7-10 ppt
^{232}Th	< 0.5-7.5 ppt
^{210}Po	< 0.5 mBq/kg

- liquid scintillator veto to suppress ^{40}K background
- muon veto to reject muon-induced background
- particle discrimination
  (nuclear recoils – electron/gammas)

LIMITATIONS: thermodynamic fluctuations

Temperature pulse



N is the total excitations which have a mean energy $\mathbf{k_B T}$

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

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

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

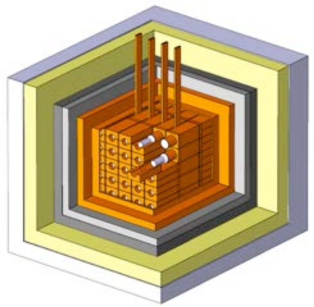
Ultimate energy resolution is determined by how well you can measure **T** against thermodynamic fluctuations:

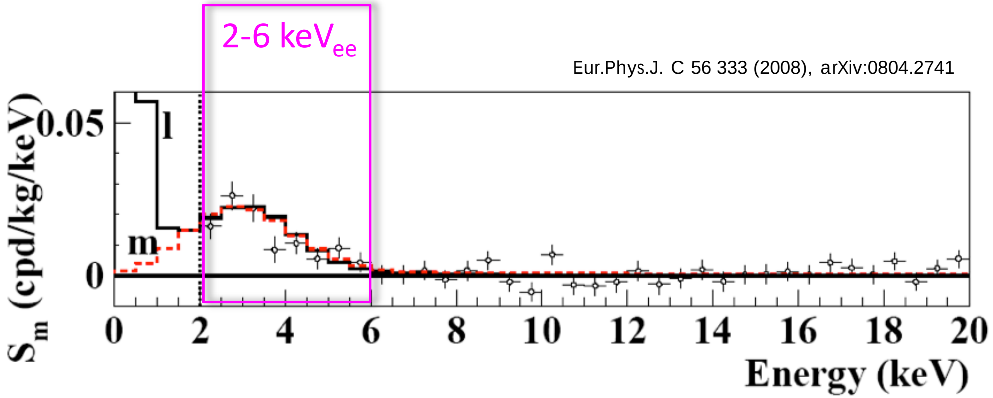
low temperatures → better energy sensitivity

low heat capacity → careful selection of materials with low C

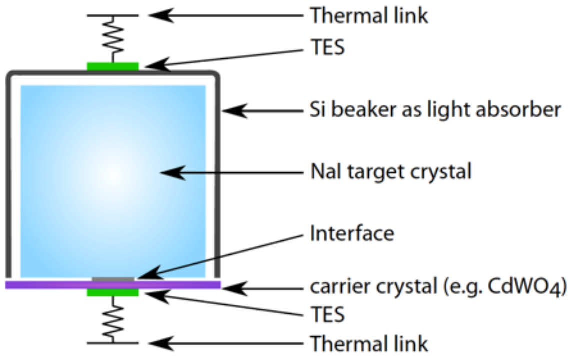
COMPARE DAMA TO COSINUS

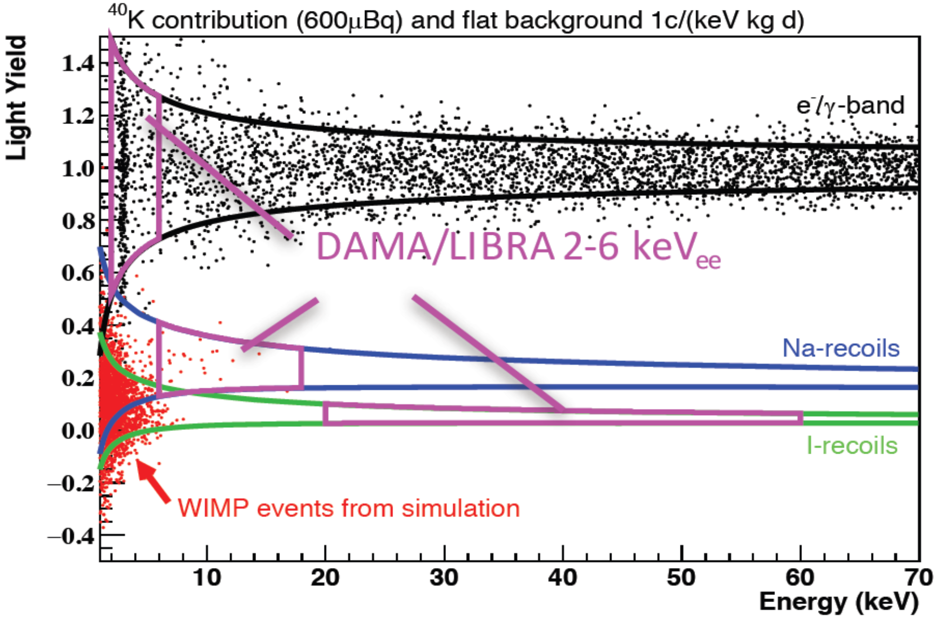
DAMA/LIBRA





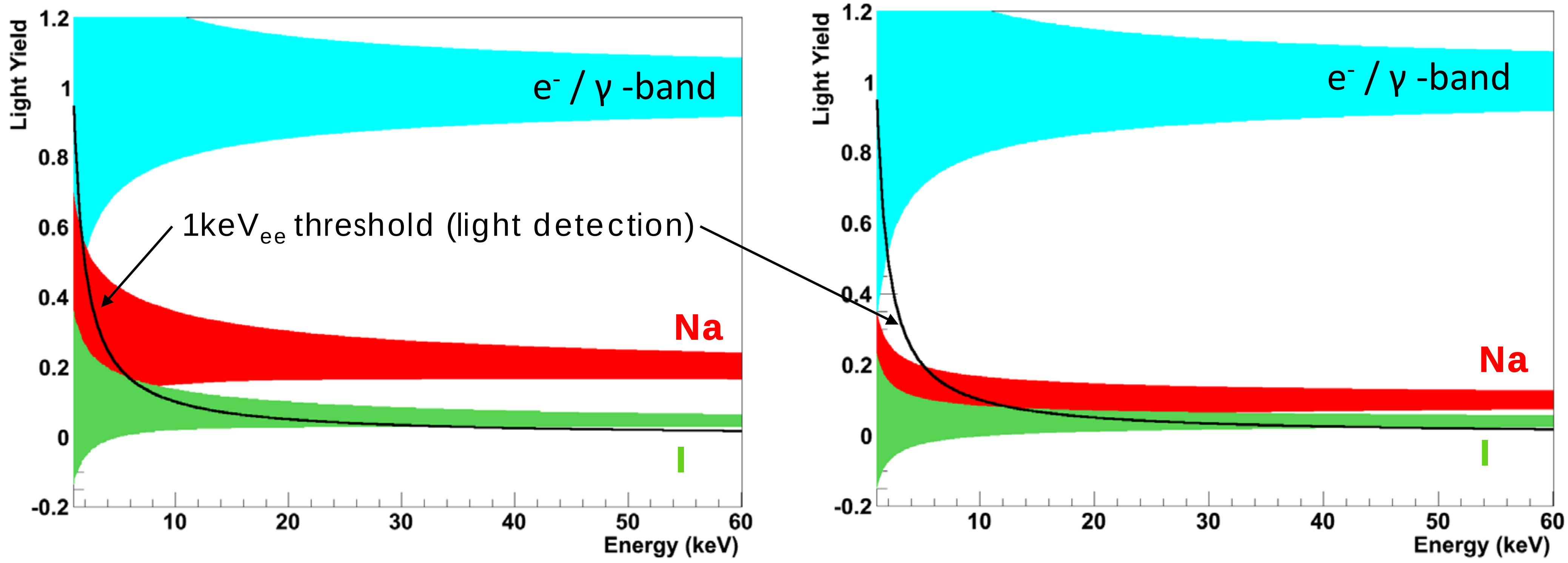
COSINUS





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

REMARK: QUENCHING FACTORS



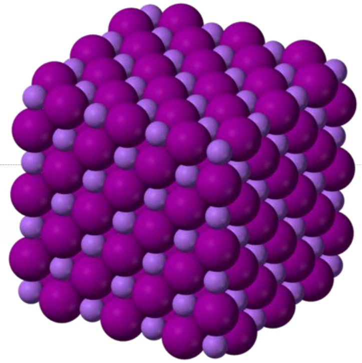
recoils off Na → factor ~ 0.3

recoils off I → factor ~ 0.1

recoils off Na → factor ~ 0.1

recoils off I → factor ~ 0.04

NaI as TARGET MATERIAL



^{11}Na ^{53}I

Sodium Iodide

- multi-target compound: **light Na** and **heavy I**
- very good scintillator at room temperature (> 15 p.e. / keV)
- NaI doped with thallium has suitable wavelength for Photomultipliers (PMTs)
- crystal is "easy" to grow and available as >10 kg blocks

… but NaI is not that NaIce!

- **hygroscopic nature**

handle in controlled atmosphere:

- glove box
- special container for cooldown in dilution refrigerator

- **low Debye temperature**

Properties	NaI(pure)	CsI(pure)	$CdWO_4$	$CaWO_4$
Density [g/cm^3]	3.67	4.51	7.9	6.12
Melting point [°C]	661	894	1598	1650
Structure	CsCl	CsCl	Wolframite	Scheelite
λ_{max} at 300 K [nm]	~300	~315	~475	420-425
Hygroscopic	yes	slightly	no	no
Θ_D [K]	169	125	-	335
Photons per keV at 3.4 K	19.5 ±1.0	58.9±5.6	-	-
Mean energy of emitted photon [eV]	3.3	3.9	-	3.14

PREPARE FOR:

small signal amplitudes

- develop highly sensitive W-TES
- surface of NaI optically polished

- **typically high contamination with ^{40}K**

dangerous background is the 3 keV Auger electrons emitted together with the 1.46 MeV gamma quantum

Contamination	DAMA/LIBRA crystal [ppb]
K	~ 13
Rb	< 0.35
U	0.5 – 7.5 x 10^{-3}
Th	0.7 – 10 x 10^{-3}

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)

CYRSTAL PROGRAM

- collaboration with **I. Dafinei** from INFN, Roma 1 in Italy
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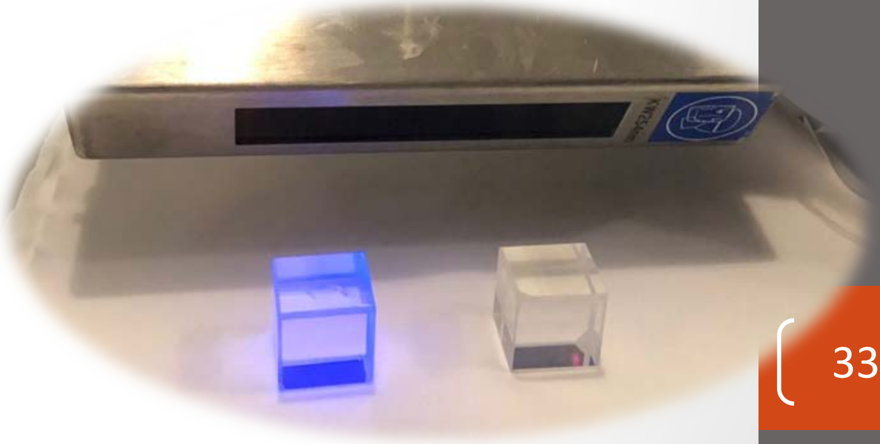
  NEW → **very promising radiopurity**:

  5-9 ppb of K at crystals' nose and 22-35 ppb at crystals' tail

  (3-inch crystal @ SICCAS)

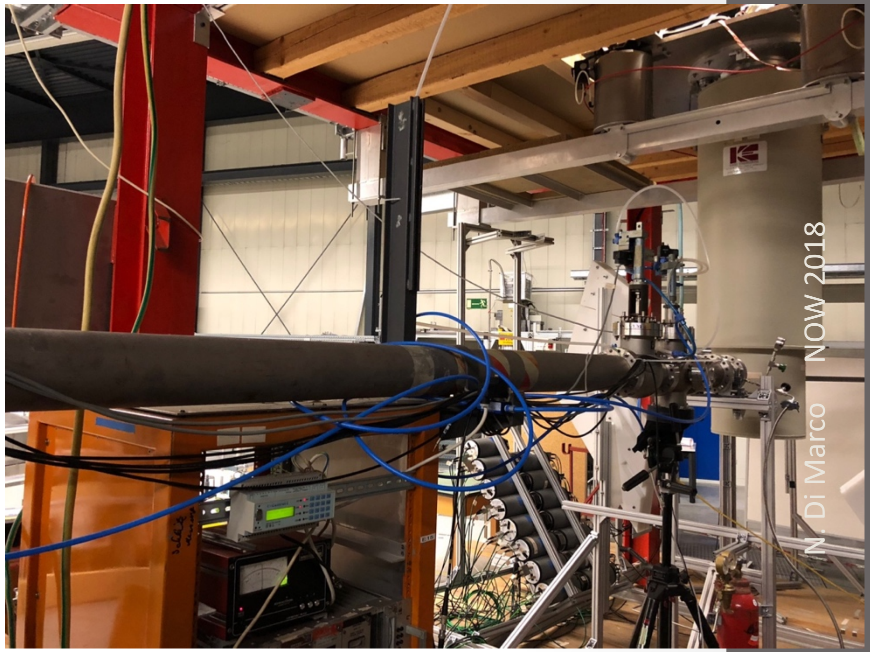
IN THE QUEUE:

- 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

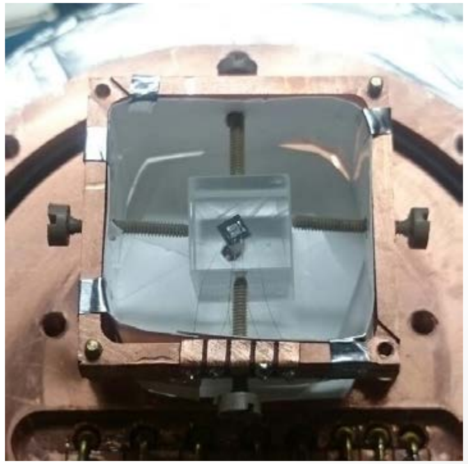
- Meier-Leibnitz Laboratorium - Tandem accelerator at Technical University in Munich
- 11 MeV mono-energetic neutrons
- dilution cryostat available
- small NaI scintillating cryogenic calorimeter

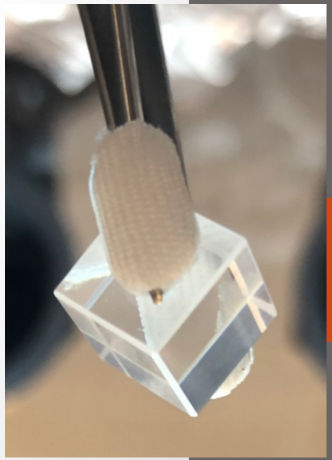


STATUS:

- successfully measured an undoped NaI crystal in April 2018
- measurement of a Tl-doped NaI scheduled for Nov. 2018

  → beam time already assigned!





DAMA/LIBRA PhaseII

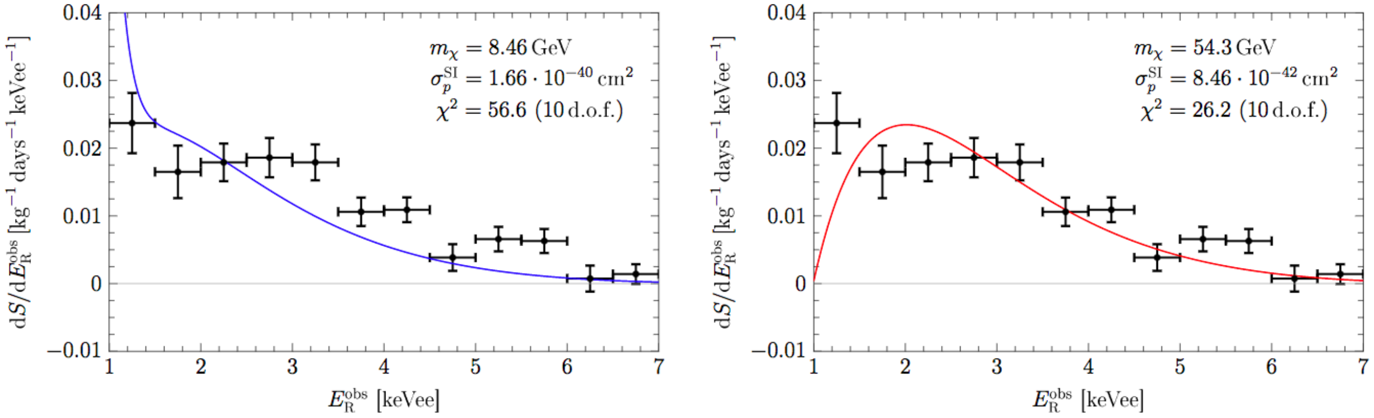


Figure 9. Best-fit recoil spectra in DAMA for low-mass DM (left), corresponding to scattering dominantly on sodium, and high-mass DM (right), corresponding to scattering dominantly on iodine. In both cases we have included the first twelve bins from the combined data sets of DAMA/NaI, DAMA/LIBRA-phase1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

arXiv:1802.10175v4

Any interpretation of the DAMA signal in terms of DM requires **non-standard interactions** or **non-standard astrophysical distributions** (or both), independently of (but already implied by) the exclusion bounds from other experiment

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

DAMA

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

F. Kahlhöfer, K. Schmidt-Hoberg, K. Schäffner, 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:

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

DAMA phase 1:

Best fit	$S = (2.34 \pm 0.28) \cdot 10^{-2}\,kg^{-1}\,days^{-1}$ (in [2.5keVee,3.5keVee])
Minimal Mod. Ampl. (95% C.L.)	$S = 1.78 \cdot 10^{-2}\,kg^{-1}\,days^{-1}$

F. Kahlhöfer, K. Schmidt-Hoberg, K. Schäffner, 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:

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

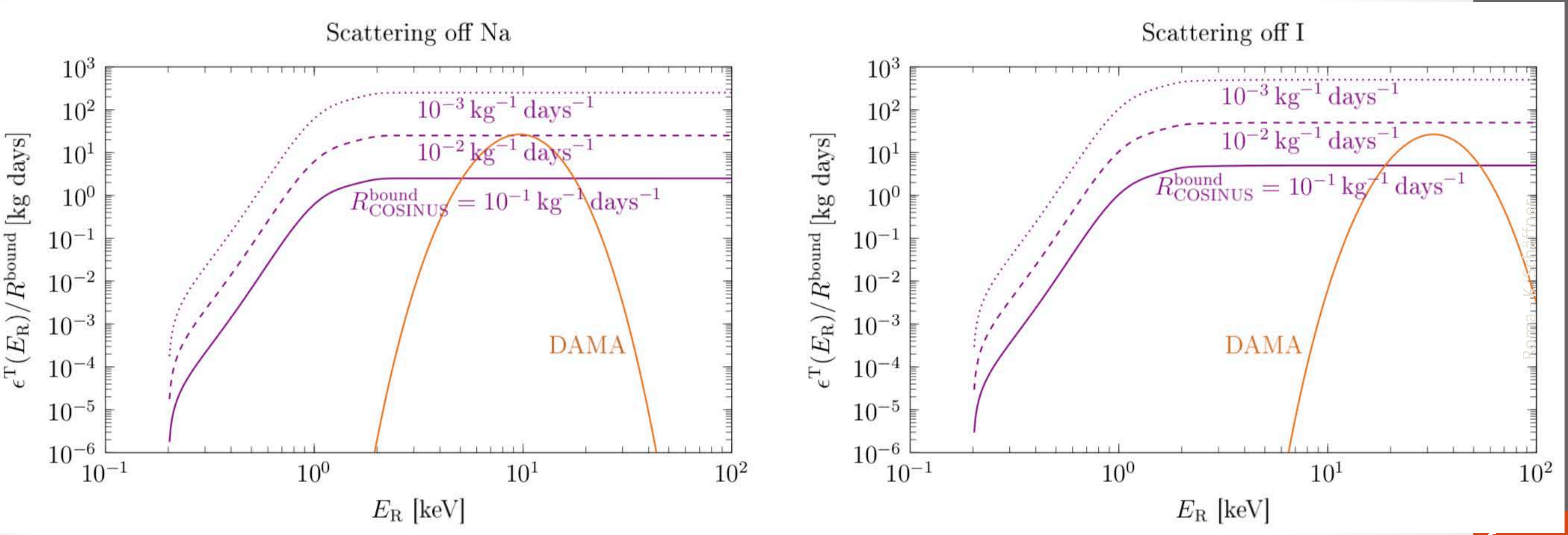
$$\frac{\epsilon^{T}_{\text{COSINUS}}(E_{\text{R}})}{R^{\text{bound}}_{\text{COSINUS}}} > \frac{\epsilon^{T}_{\text{DAMA}}(E_{\text{R}})}{S^{\text{bound}}_{\text{DAMA}}}$$

T: target nucleus
ϵ: efficiency to see nuclear recoils of energy E_R

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

MOST GENERAL CASE

$$\frac{\epsilon^{\mathrm{T}}_{\mathrm{COSINUS}}(E_{\mathrm{R}})}{R^{\mathrm{bound}}_{\mathrm{COSINUS}}} > \frac{\epsilon^{\mathrm{T}}_{\mathrm{DAMA}}(E_{\mathrm{R}})}{S^{\mathrm{bound}}_{\mathrm{DAMA}}}$$



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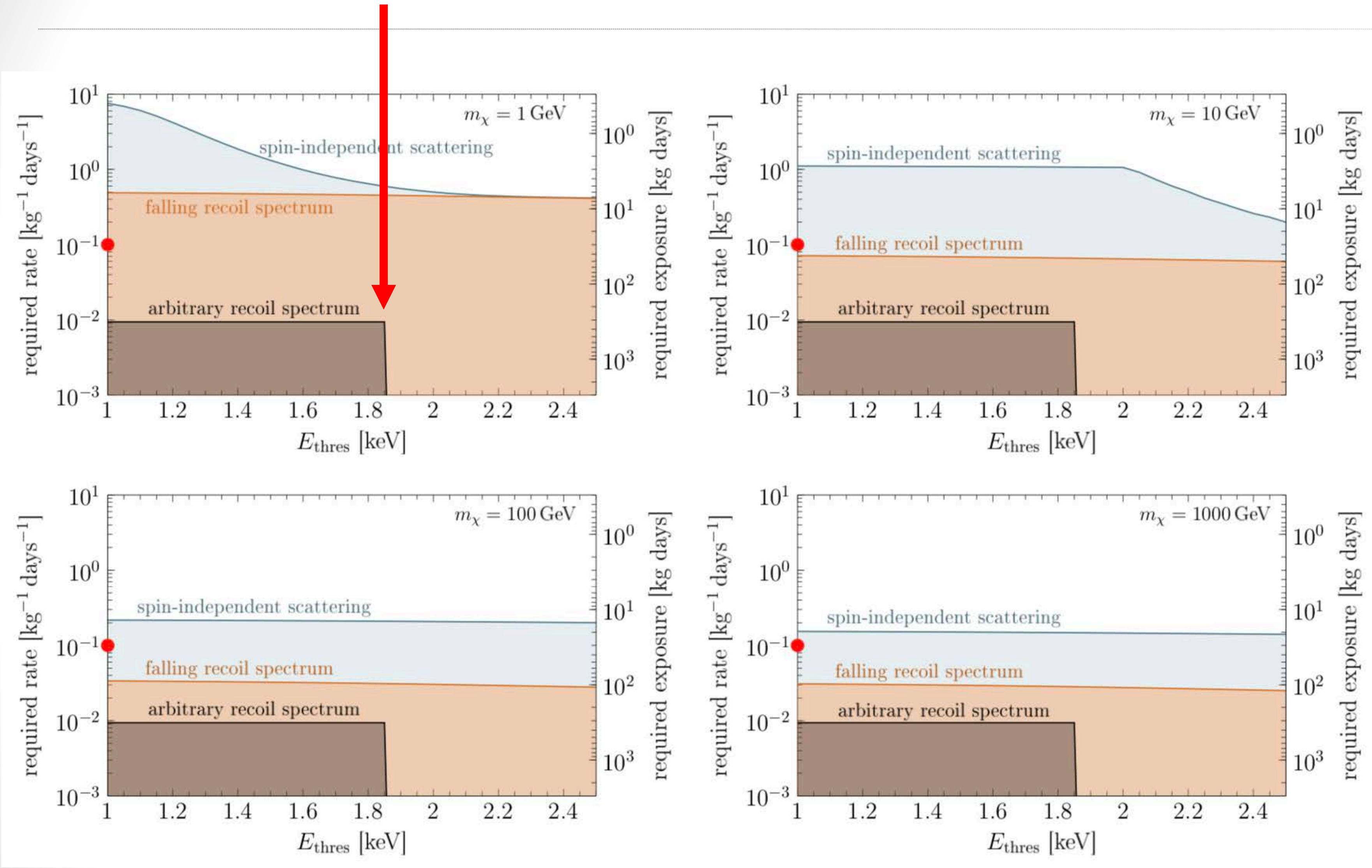
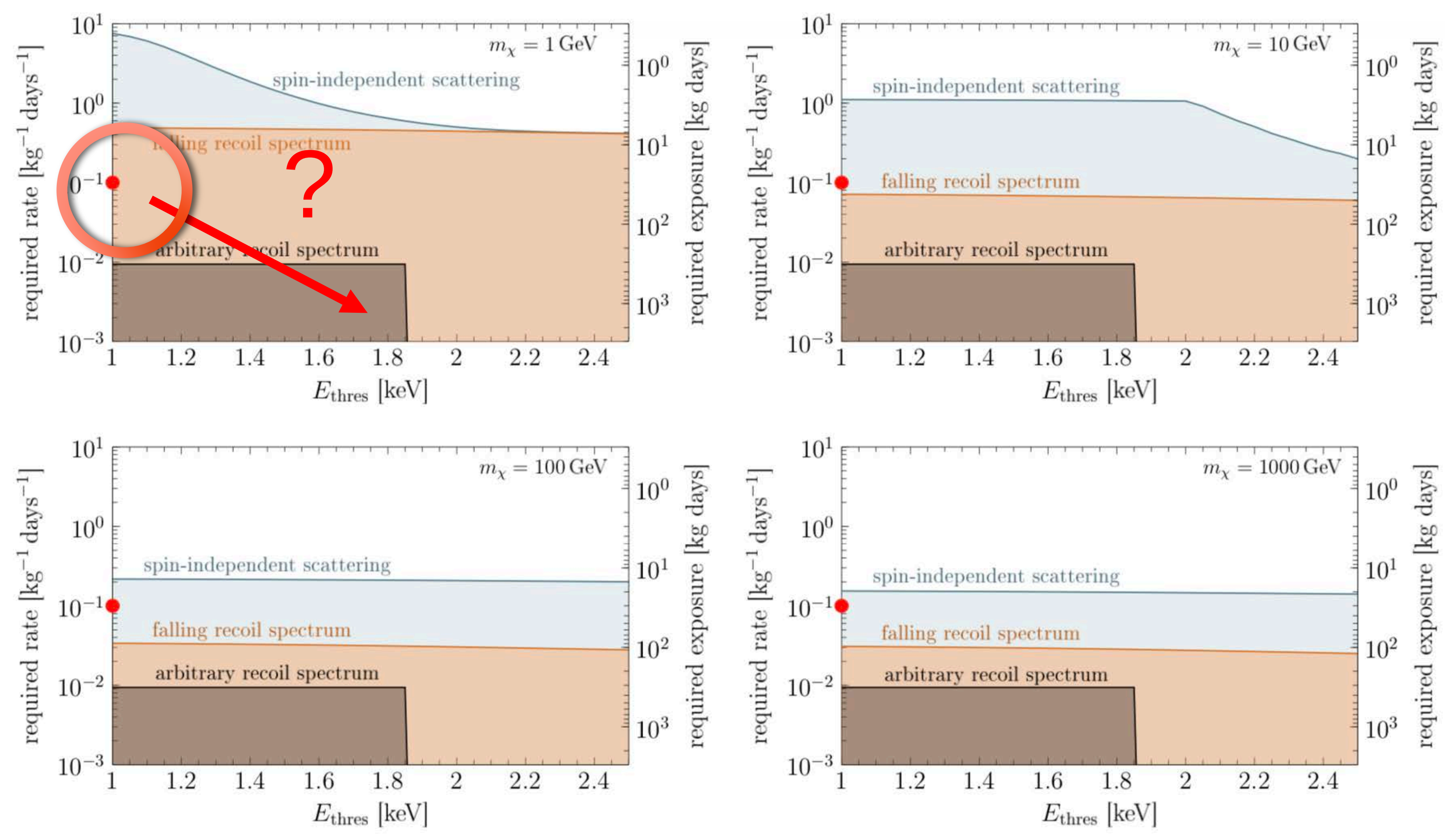
RESULT



Threshold:
1.8 keV sufficient

F. Kahlhöfer, K. Schmidt-Hoberg, K. Schäffner, 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

COSINUS PHYSICS REACH

Model-independent comparison of annual modulation and total rate with direct detection experiments

F. Kahlhoefer et al. **JCAP 1805 (2018) no.05, 074**

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

Assuming:

- a threshold of ~1.8keV with a resolution of 0.2keV
- a bound on the rate of 0.01 kg^{-1} $days^{-1}$

➢ Exclude DAMA/LIBRA signal in a model-independent way:
  - Halo-independent
  - For arbitrary nuclear recoil interactions

Outlook: Cut and count only → Make use of spectral information for potentially stronger bounds