COSINUS - Cryogenic Dark Matter searches with NaI crystals

Jochen Schieck
Institute of High Energy Physics (HEPHY) of the Austrian Academy of Sciences
and
Institute of Atomic and Subatomic Physics, TU Wien

for the COSINUS collaboration

www.cosinus.it

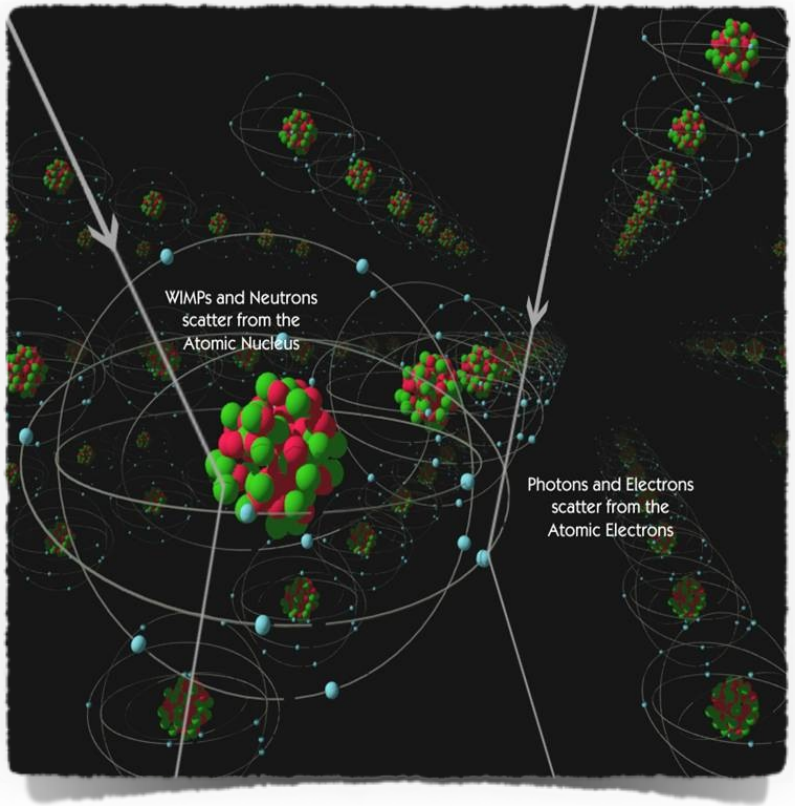
HEPHY
INSTITUTE OF HIGH ENERGY PHYSICS

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

TU WIEN TECHNISCHE UNIVERSITÄT WIEN Vienna | Austria

Search for Dark Matter

- clear evidence for dark matter on different scales
- observation of dark matter based on gravitational pull only
- undiscovered new particles as a well motivated candidate to explain dark matter
- **direct detection:** search for dark matter via elastic scattering of relic dark matter in the detector

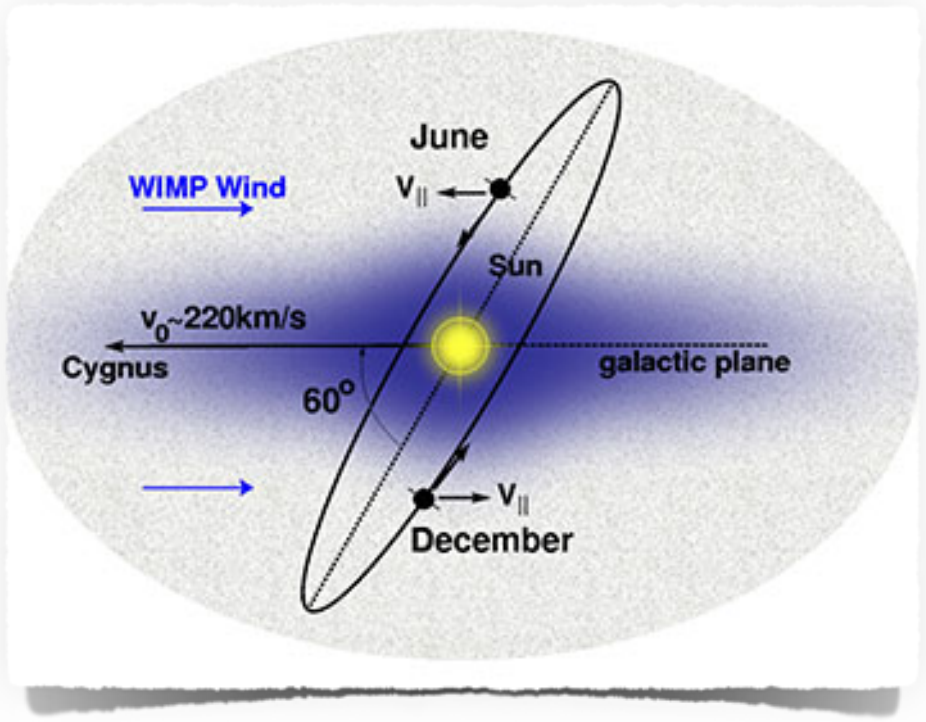


http://cdms.berkeley.edu/Education/DMpages/science/directDetection.shtml

Dark Matter searches by Annual Modulation

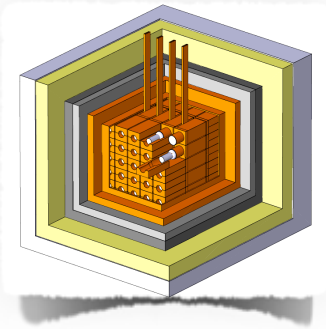
- small interaction rate of dark matter expected
- excellent knowledge of background required to identify dark matter signal
- movement of earth in dark matter wind leads to **annual modulation of dark matter signal**
  - size of **modulation amplitude ~10%** (threshold dependent)

(http://arxiv.org/abs/1209.3339)



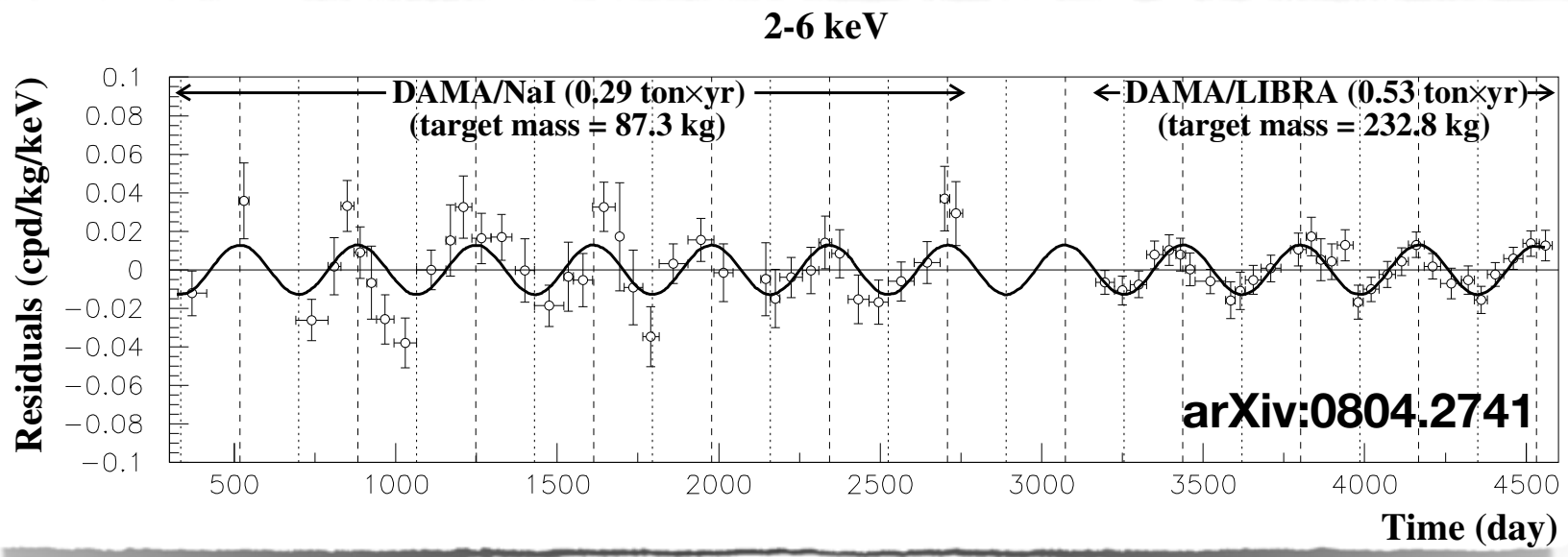
Annual Modulation of Dark Matter Interaction Rate

- DAMA/LIBRA experiment searches for dark matter via annual modulation of signal rate



- operation of radiopure NaI(Tl)-crystals and **detection of scintillation light from dark matter scattering**

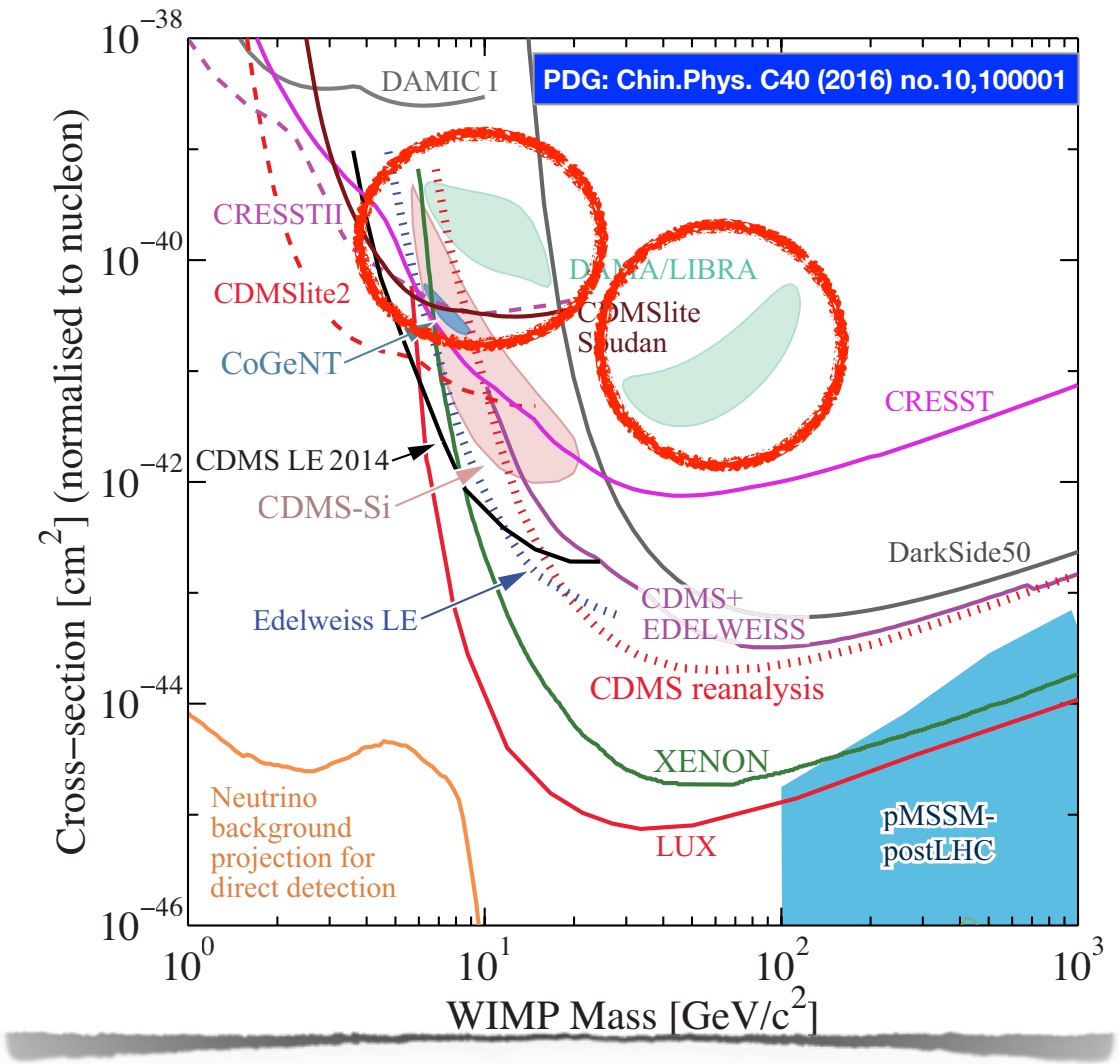
- **residual signal** shows clear sign for an **annual modulation** of interaction rate in the energy region of **2-6 keVee**



9.3σ

Interpretation of Annual Modulation as Dark Matter

valid for standard assumptions only



$m_X \approx 50$ GeV ; $\sigma_{Xn} \approx 7 \cdot 10^{-6}$ pb

$m_X \approx$ 6-10 GeV ; $\sigma_{Xn} \approx 10^{-3}$ pb

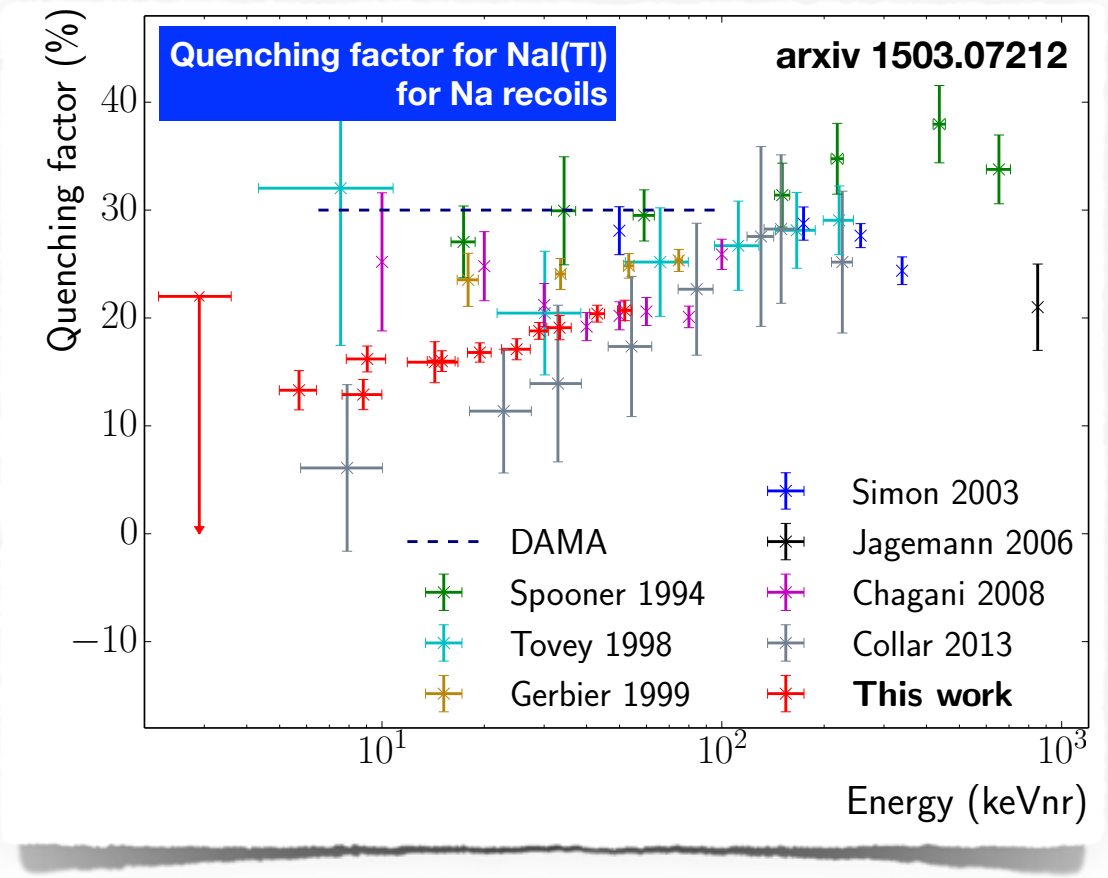
- **interpretation** of annual modulation as **dark matter** scattering
  arXiv:0808.3607
- standard astrophysical assumptions for WIMP density and velocity
- **preferred mass and cross-section area excluded by other dark matter experiments**

Annual Modulation - what do we know?

- statistically significant observation of annual modulated rate of events observed through NaI(Tl) scintillation light
  - **origin of underlying process is unknown**
- observation is **consistent** with expectation from **dark matter** scattering modulated by annual changes of dark matter relative velocity
- detailed systematic studies cannot explain annual fluctuation by background processes
- **assumptions:** quenched scintillation light, together with standard astrophysical assumption could explain signal modulation via dark matter-nucleus scattering

Measurement of Recoil Energy - Signal Quenching

- amount of **scintillation light** produced depends on underlying scattering process ("**quenching**")
- origin of scattering process unknown and size of **total deposited energy** undetermined
- origin of annual modulation hindered

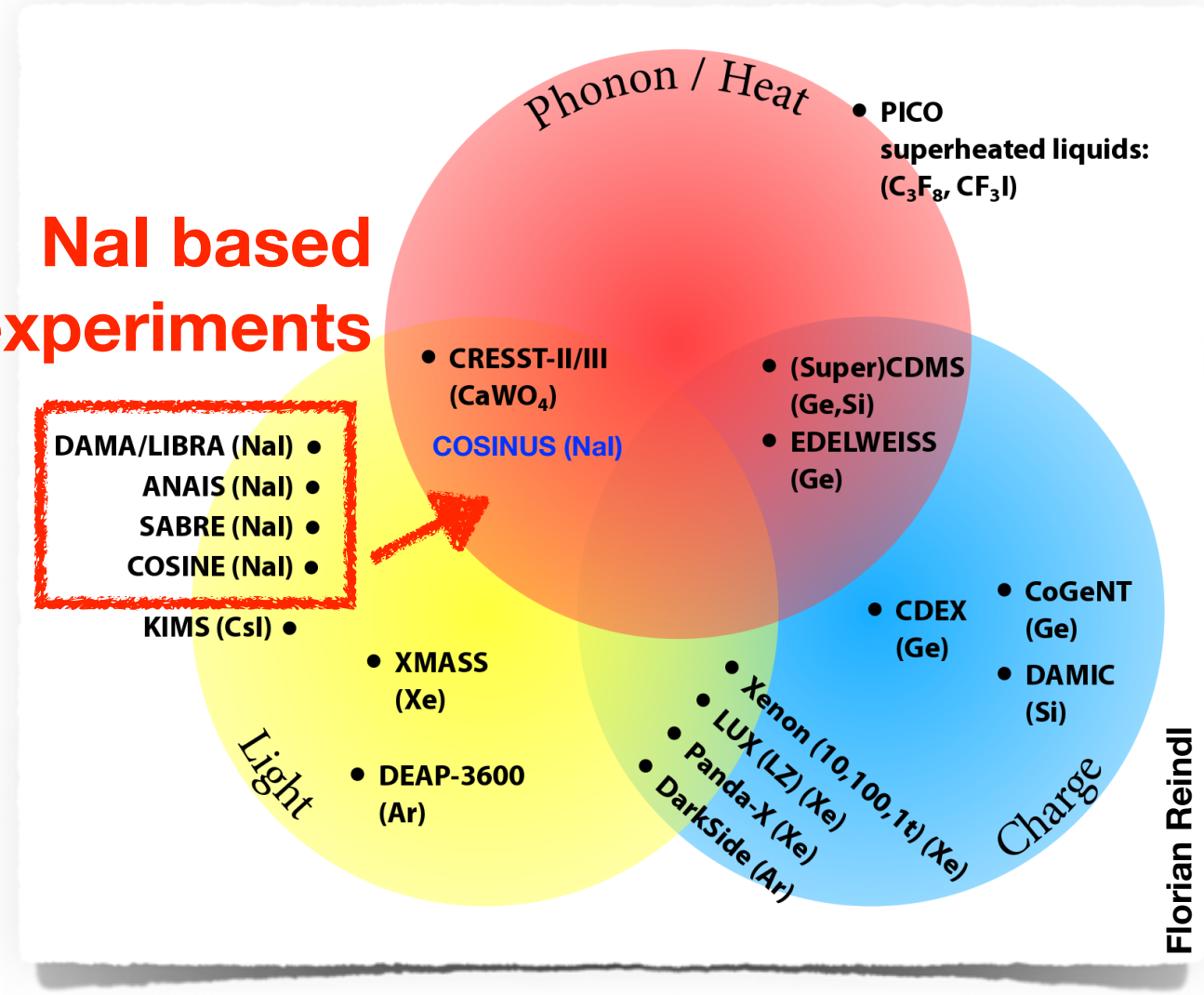


→measurement of total energy independent from scattering process

Detection of Dark Matter Scattering

- better understanding of underlying scattering process by **scintillation light independent energy measurement**

- **measurement of energy via phonon / heat channel**

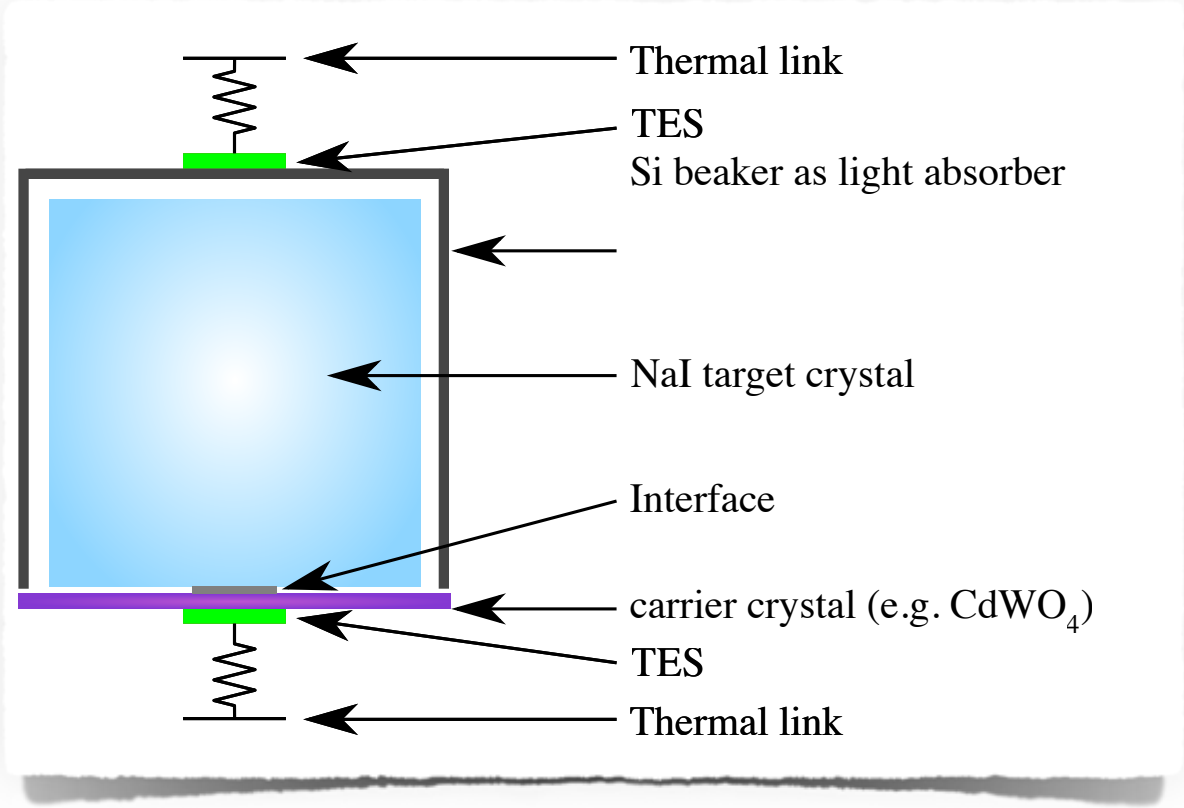


The Cosinus Collaboration

about 20 scientists from seven institutions from Germany, Italy and Austria:

i. Max-Planck-Institut für Physik- D-80805 München - Germany
ii. INFN - Sezione di Milano-Bicocca, I-20125 Milano - Italy
iii. Dipartimento di Fisica, Universita di Milano-Bicocca, I-20126 Milano - Italy
iv. Institut fur Hochenergiephysik, Österreichische Akademie der Wissenschaften, A-1050 Wien - Austria
v. Atominstitut, Technische Universität Wien, A-1020 Wien - Austria
vi. INFN - Laboratori Nazionale del Gran Sasso, I-67010 Assergi (AQ) - Italy
vii. Gran Sasso Science Institute, I-67100 L'Aquilla - Italy

The COSINUS Experiment - Detection Principle



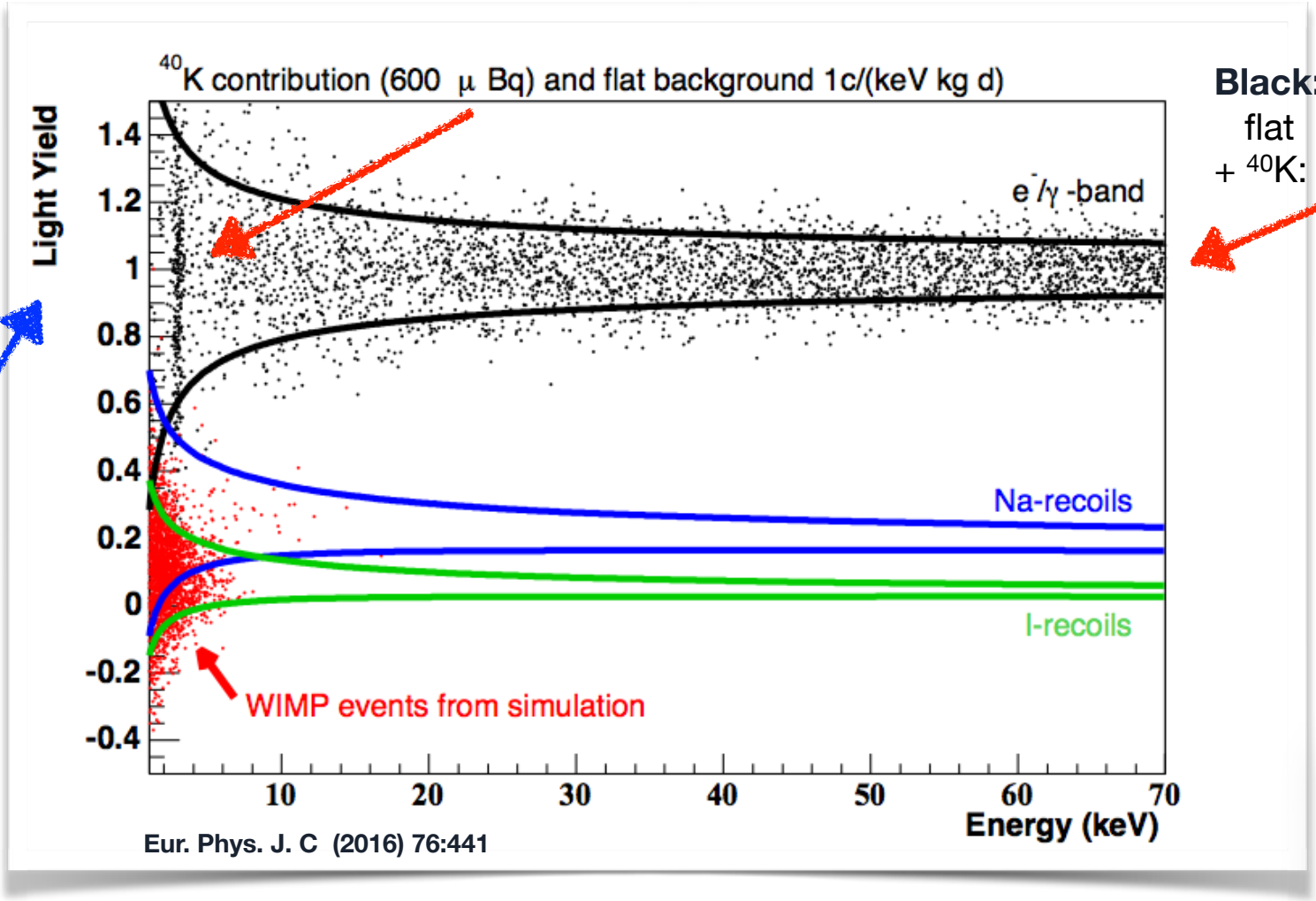
- **cryogenic operation of NaI-crystal**
- simultaneous read-out of
  - **phonon channel:** particle independent measurement of deposited energy (= nuclear recoil energy)
  - **(scintillation) light:** different response for signal and background events for background rejection ("quenching")

→separation between nuclear scattering and β/γ background events

Quenching factors by V. Tretyak, Astropart. Phys. 33, 40 (2010)

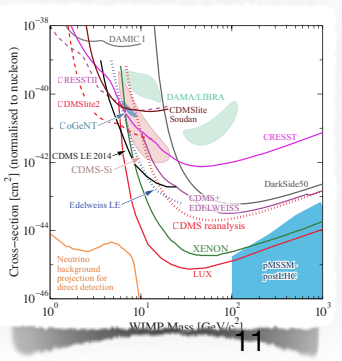
COSINUS - Expected Performance

separation between signal and background type events



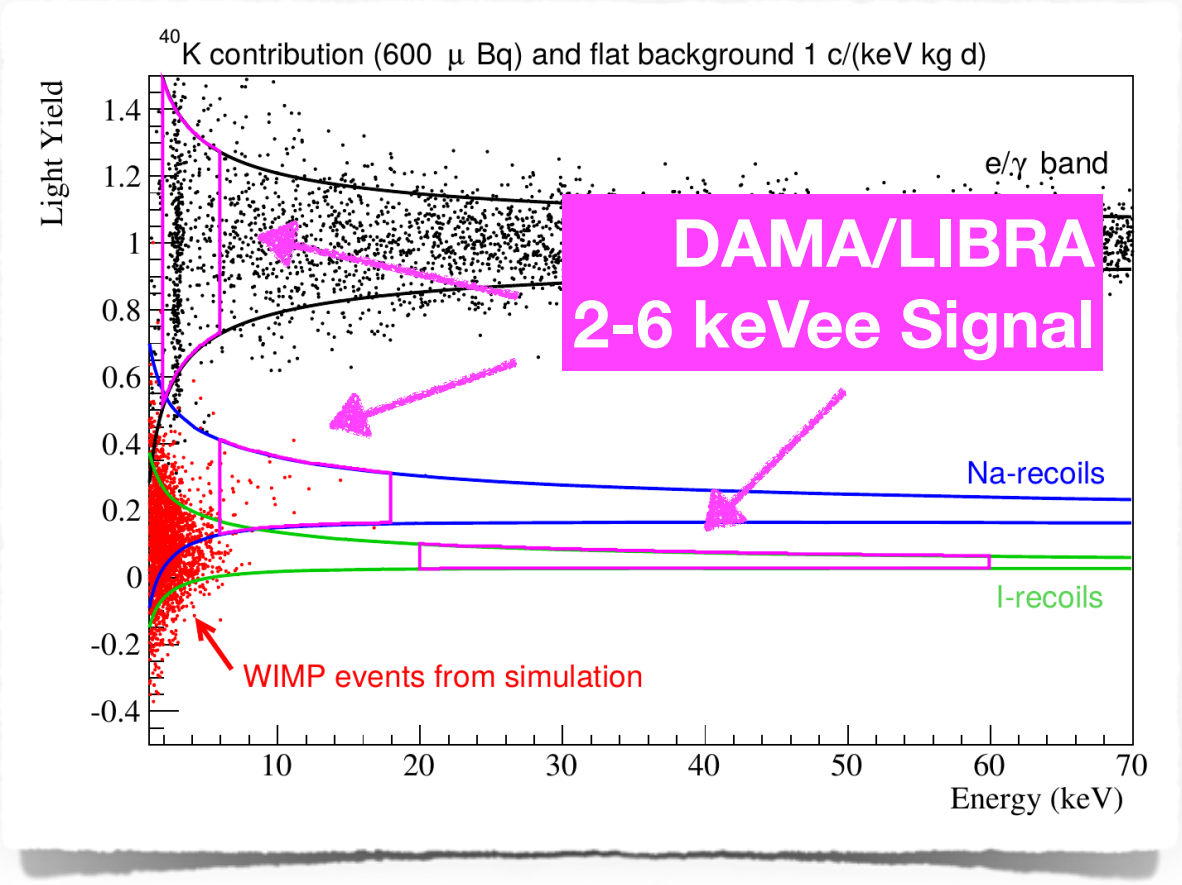
Black: β/γ-background
flat 1c /(keV kg day)
+ ^{40}K: 600μBq/kg

Red: 10 GeV/c^2 WIMP with 2 10^{-4} pb (Savage et al.)



Light yield = Light signal / Phonon signal

COSINUS - Expected Performance



Simulation of WIMP-events (100 kg d before cuts)

Energy	# Events	Fraction
1-2 keV	1078	45 %
2-6 keV	1262	53 %
> 6 keV	46	2 %
TOTAL	**2386**	**100 %**

DESIGN GOALS

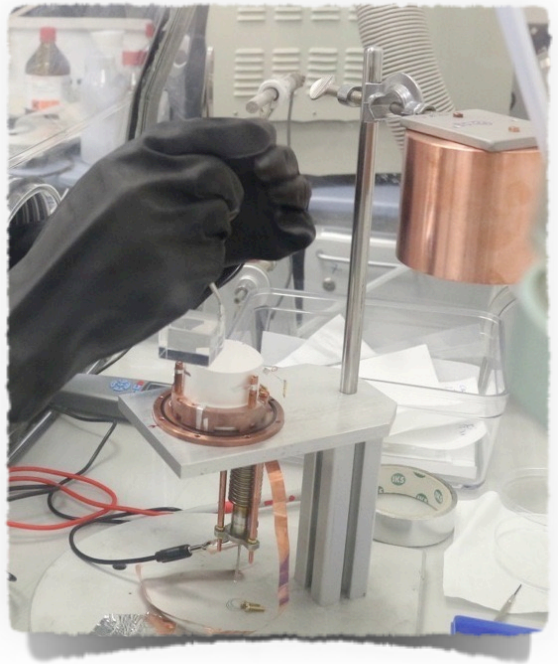
- **threshold of 1 keV nuclear recoil**
- **4% of deposited energy measured as scintillation light**

The COSINUS Experiment - Challenges

- NaI is hygroscopic
  → requires careful handling in glove box

- high contamination with ^{40}K
  emission of ~3 keV Auger electron possible

- small signal amplitude



$$\Delta T \propto \frac{\Delta Q}{c \cdot m}$$

c: specific heat capacity of the crystal

$$c \propto (T/\Theta_D)^3$$

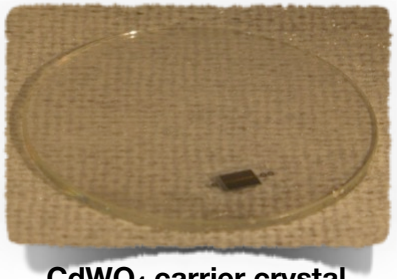
Θ_D:Debye temperature

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

First NaI-Prototype and Mounting in Cryostat

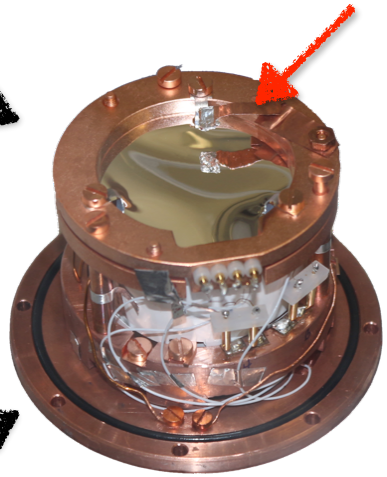
30x30x20 mm^3 (66g)

NaI phonon detector
(undoped)



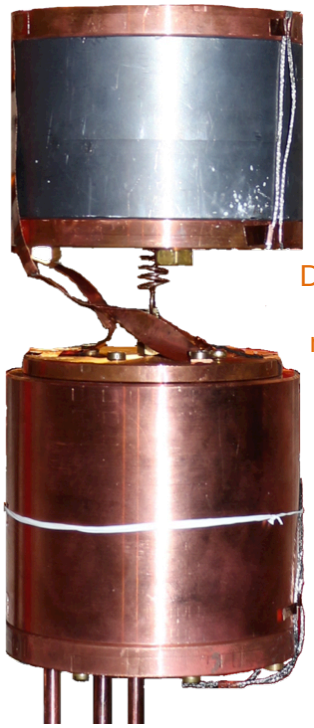
$CdWO_4$ carrier crystal

Light detector
(Silicon on Sapphire + TES)



surrounded by
reflecting foil

5 cm of Pb to shield radioactivity
from the dilution unit of the cryostat



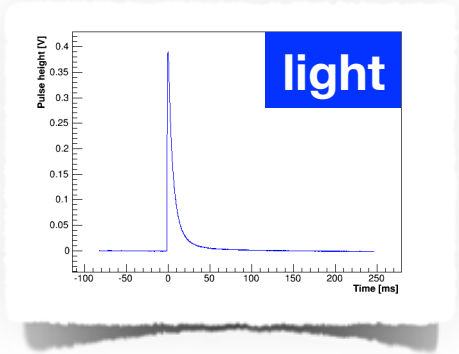
Copper
housing

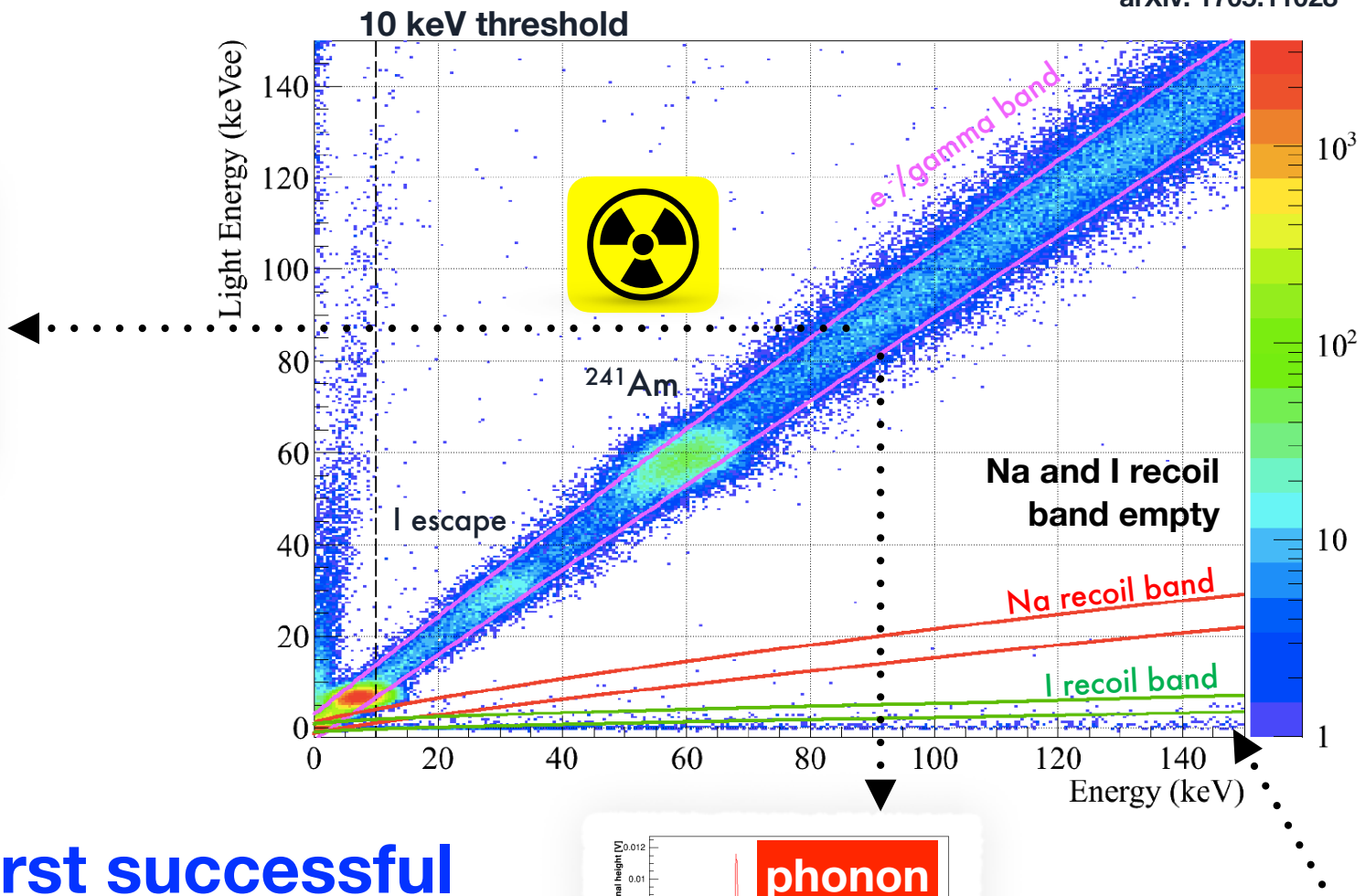
Decoupling system
to reduce
microphonic noise

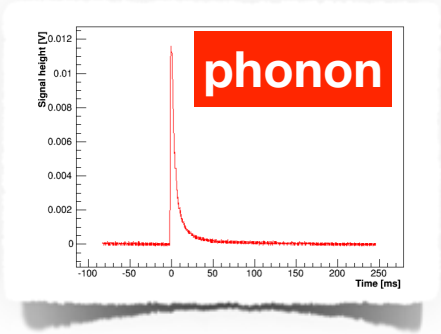
Construction and operation of first detector module for cryogenic operation

NaI-crystal - Prototype Performance

arXiv: 1705.11028







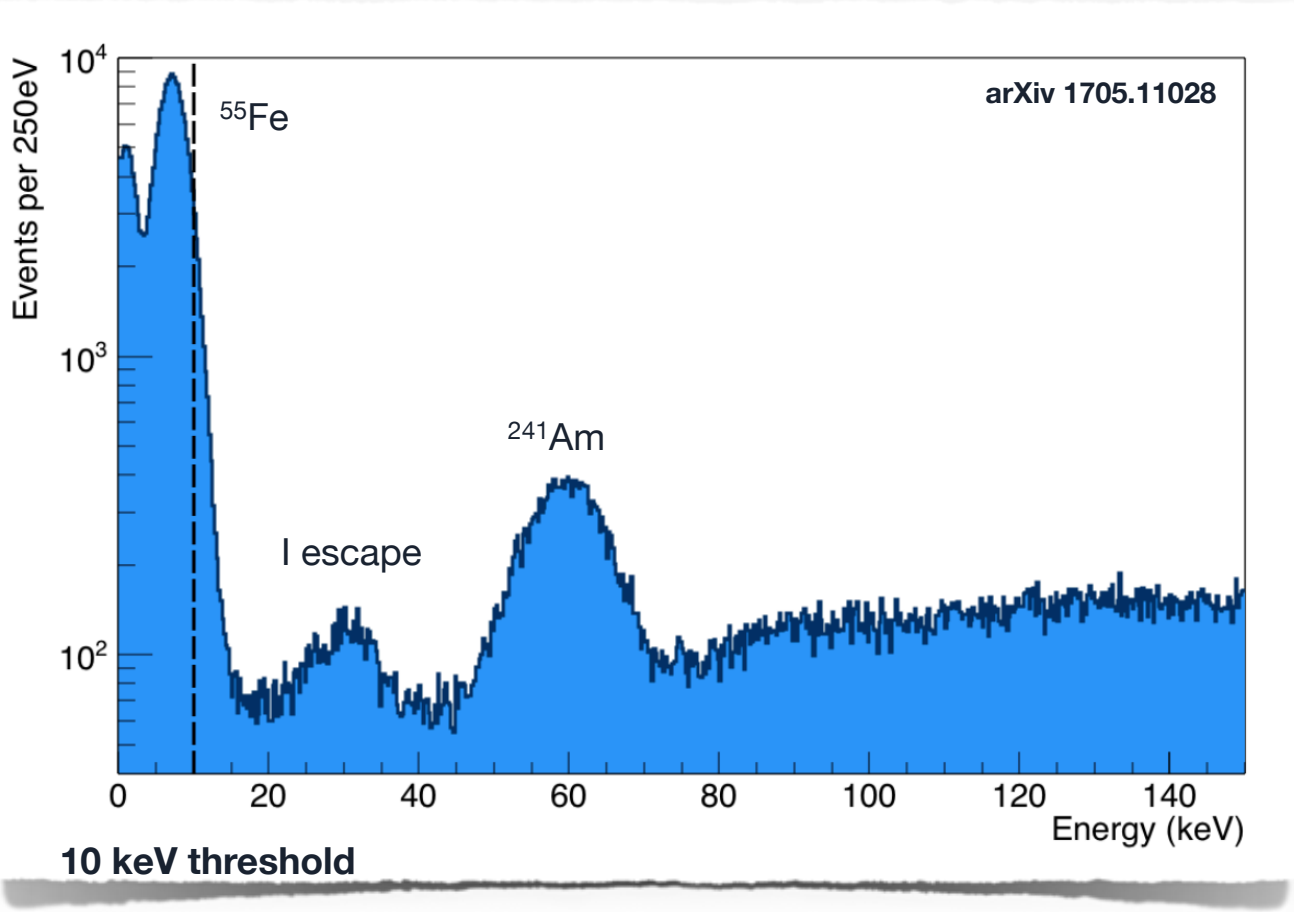
→first successful measurement of NaI crystal as cryogenic detector

hits of the $CdWO_4$ carrier

NaI-crystal - Prototype Performance

- energy threshold: 10 keV
- 3.7% of energy from γ/β-events deposited in detector is measured as scintillation light

exposure after cuts: 0.46 kg d

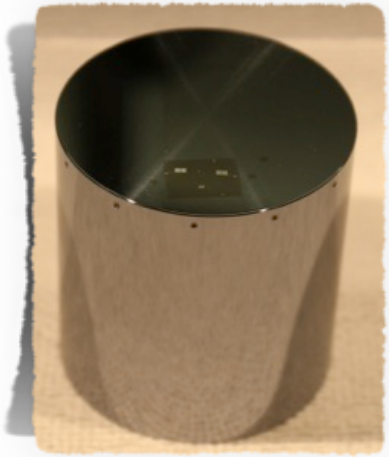


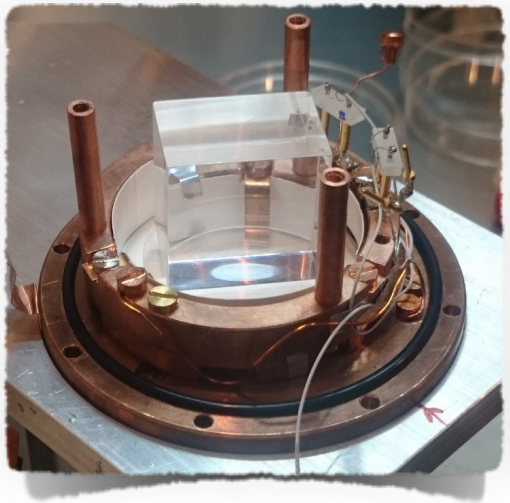
→improvement of detector performance needed

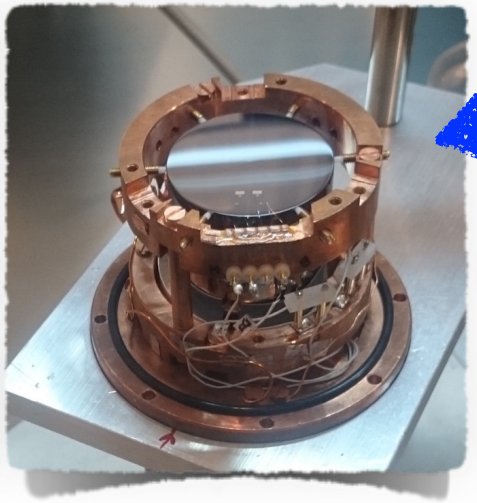
Future Plans

- optimisation of performance
  - improve light yield and lower threshold
- measurement of quenching factors
- new prototypes with improved light yield
  - proof of particle discrimination using neutrons

beaker shape light detector of high purity silicon
→improved light detection





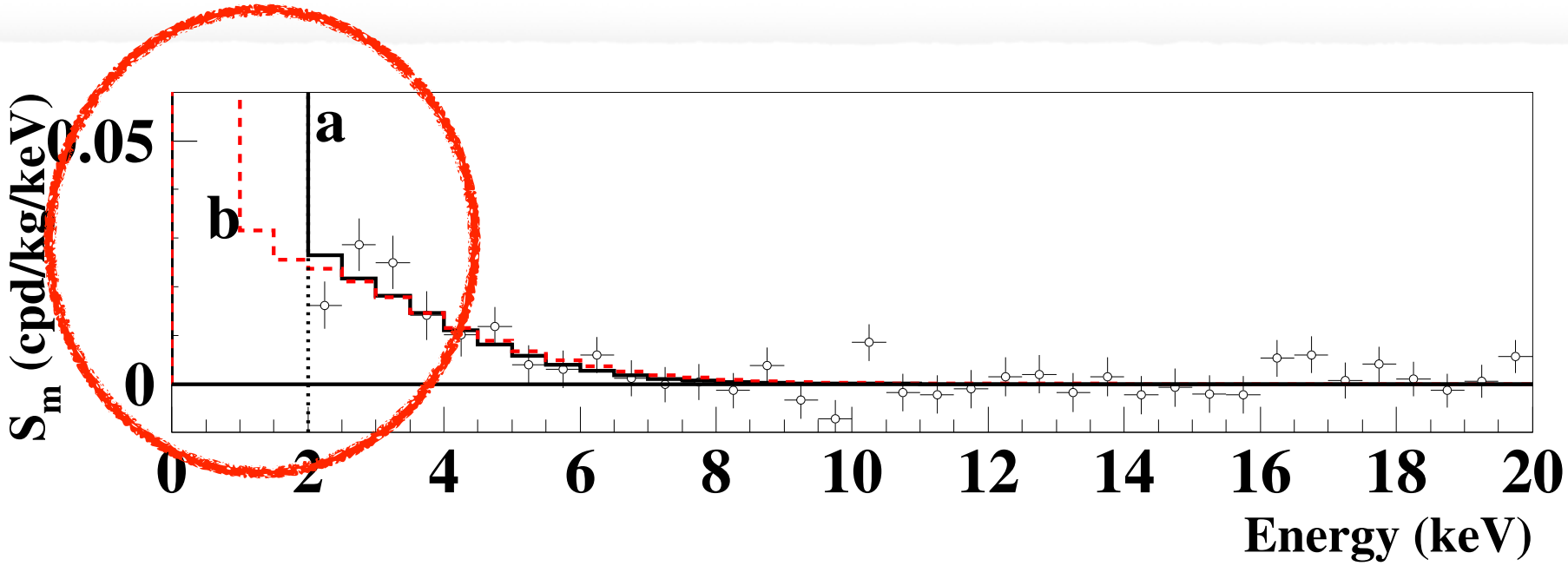


about 10 kg d needed to clarify if events originate from nuclear recoils

Summary and Conclusion

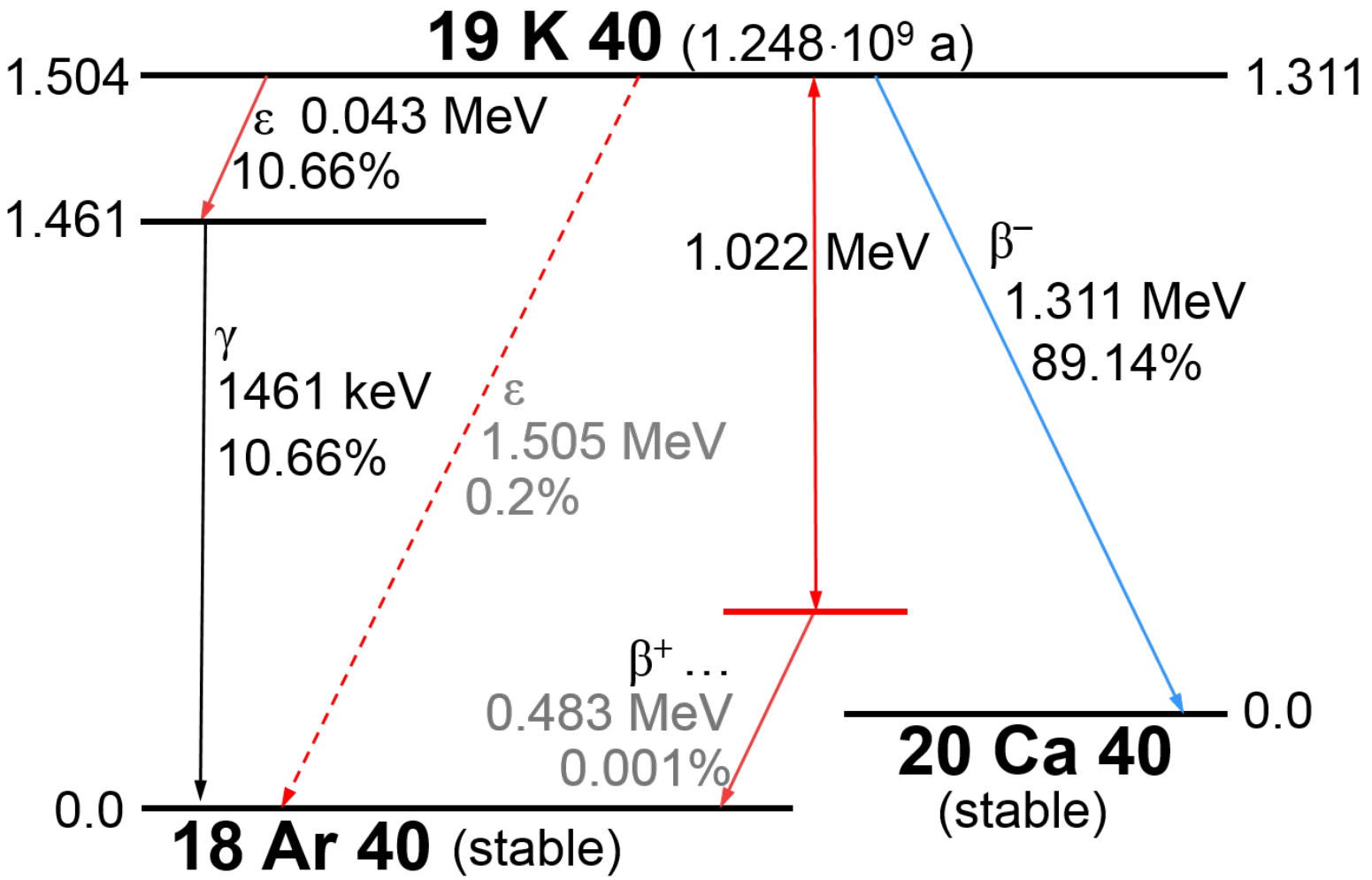
- DAMA/LIBRA experiment observes annual modulation of rate based on scintillation measurements from NaI(Tl)
- simultaneous measurement of phonon energy (= total energy) provides additional information on scattering process including γ/β-background rejection
- COSINUS is an R&D project aiming for cryogenic operation of NaI-crystals and measurement of total energy
- COSINUS achieved first successful measurement of NaI-crystal as a cryogenic calorimeter

Additional Material



arXiv:0804.2741

Typically high contamination with ^{40}K



3 keV Auger electron emitted together with the 1.46 MeV gamma quantum