The COSINUS experiment

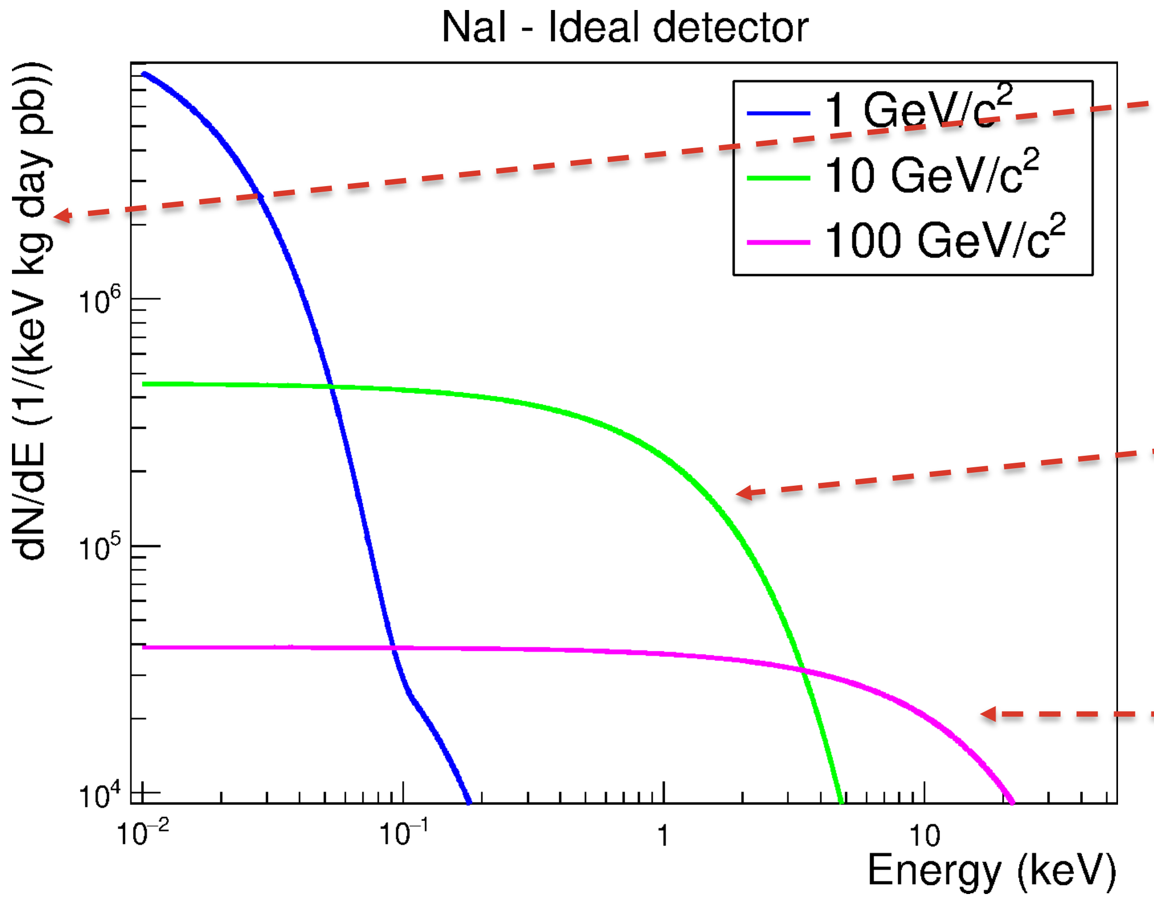
A cryogenic direct dark matter search with NaI target

ICHEP 2020 conference
Virtual, 30.07.2020

Discussion room (together with J. Schieck (CRESST)):
Friday, 31. July 14:30
https://cern.zoom.us/j/94156181934

Florian Reindl,
HEPHY & TU Vienna

EXPERIMENTAL CHALLENGES
THE DARK MATTER RECOIL SPECTRUM



Very rare

current limit*

$\mathcal{O}$(0.01) counts/tonne/day

Featureless spectrum

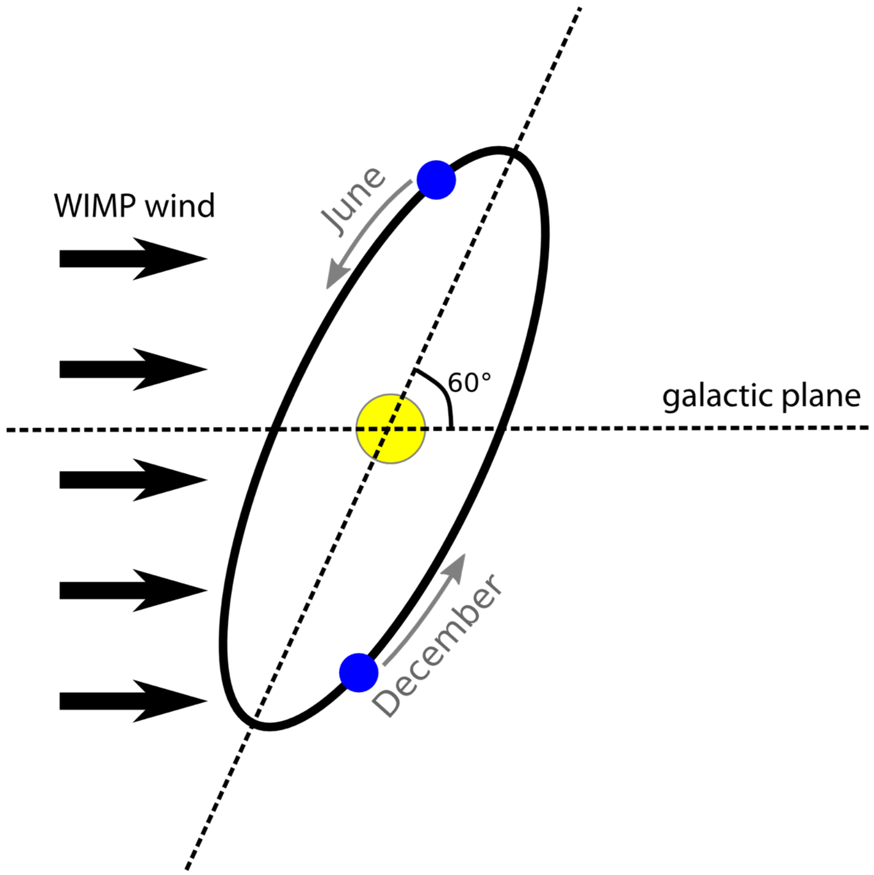
Small recoil energies

~keV range

* Xenon1t: PRL 119, 181301 (2017)

THE RELATIVE VELOCITY MODULATES

AND SO SHOULD THE INTERACTION RATE

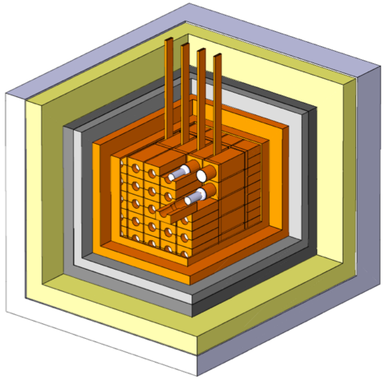


Period: 1 year

Phase: cosine peaking June 2nd

The smoking gun evidence?

DAMA/LIBRA

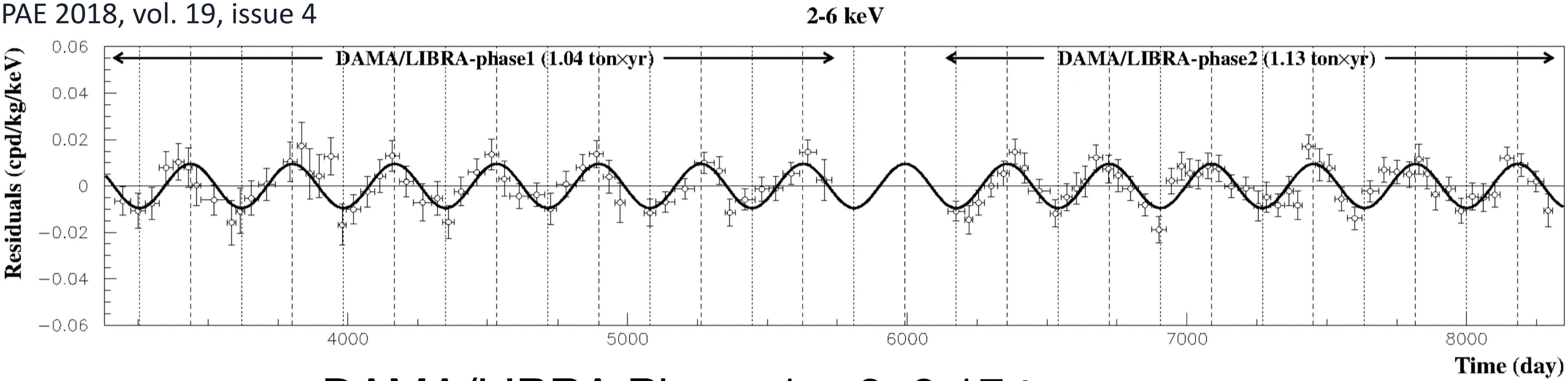


Material	250kg of NaI (Tl)
Signal(s)	Light (PMTs)
Location	LNGS
β/γ-discrimination	no
Taking data	since 1996
Threshold	1keVee

2018: NEW LOWER THRESHOLD

DAMA/LIBRA MODULATION SIGNAL
TIME DISTRIBUTION

NPAE 2018, vol. 19, issue 4

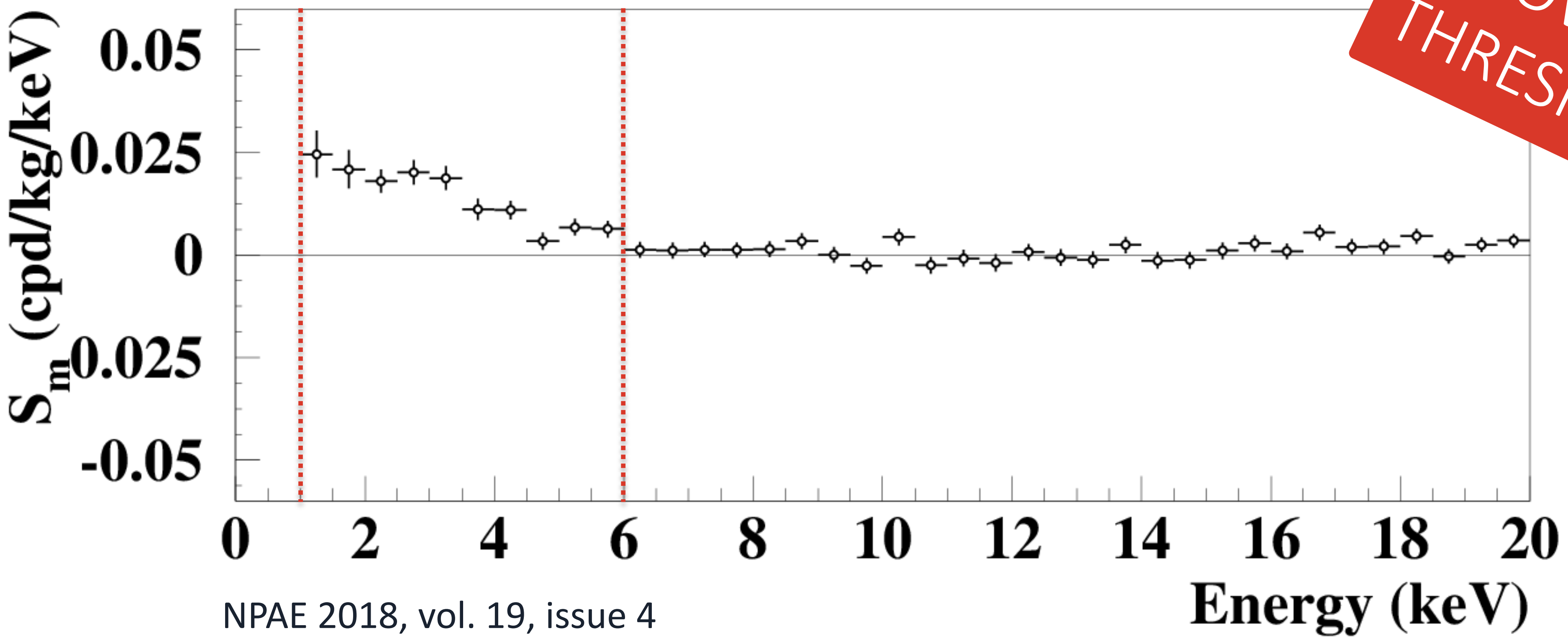


DAMA/LIBRA Phase 1 + 2: 2.17 tonne years
Statistical significance: 11.9σ

Combined with DAMA/NaI: 2.46 tonne years, 12.9σ

DAMA/LIBRA MODULATION SIGNAL

ENERGY DISTRIBUTION



NPAE 2018, vol. 19, issue 4

2018: NEW LOWER THRESHOLD

A DARK MATTER SIGNAL?

Statistics: 12.9σ ✓

Period: 0.999 ± 0.001* ✓

Phase: 25th May +/- 5 days ✓

(cosine peaking June 2nd)

Convincing non-DM explanation ✗

*in (2-6)keVee interval

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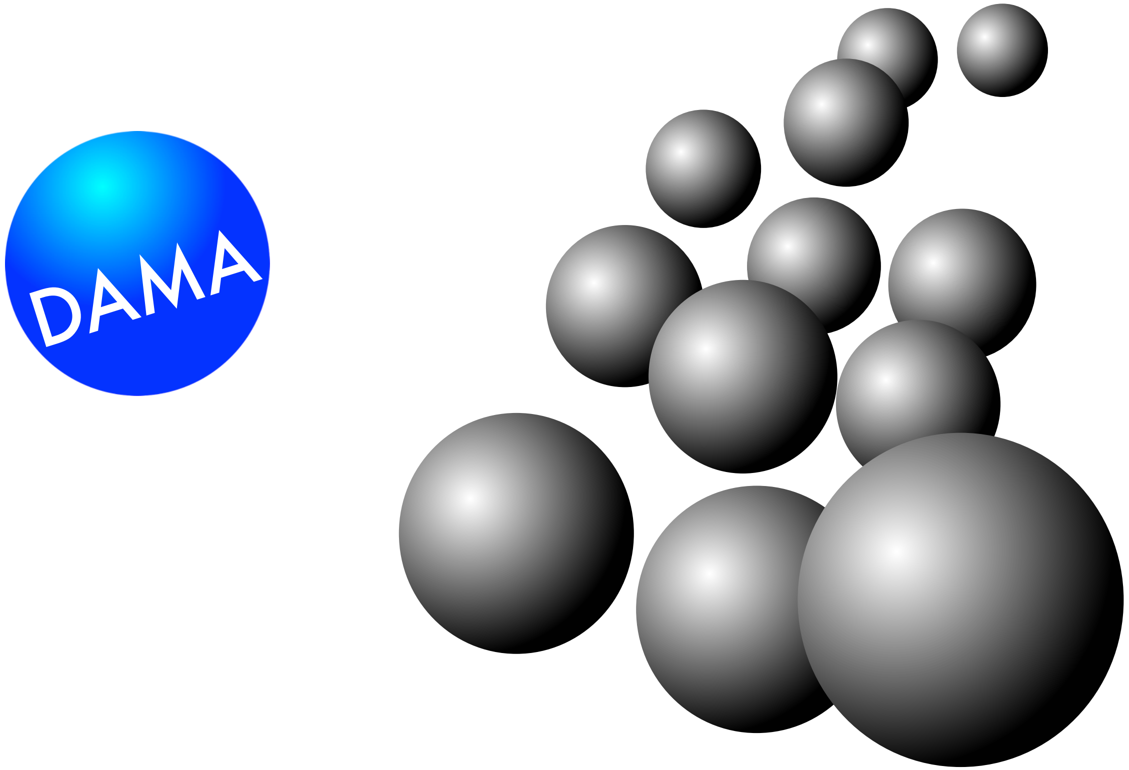
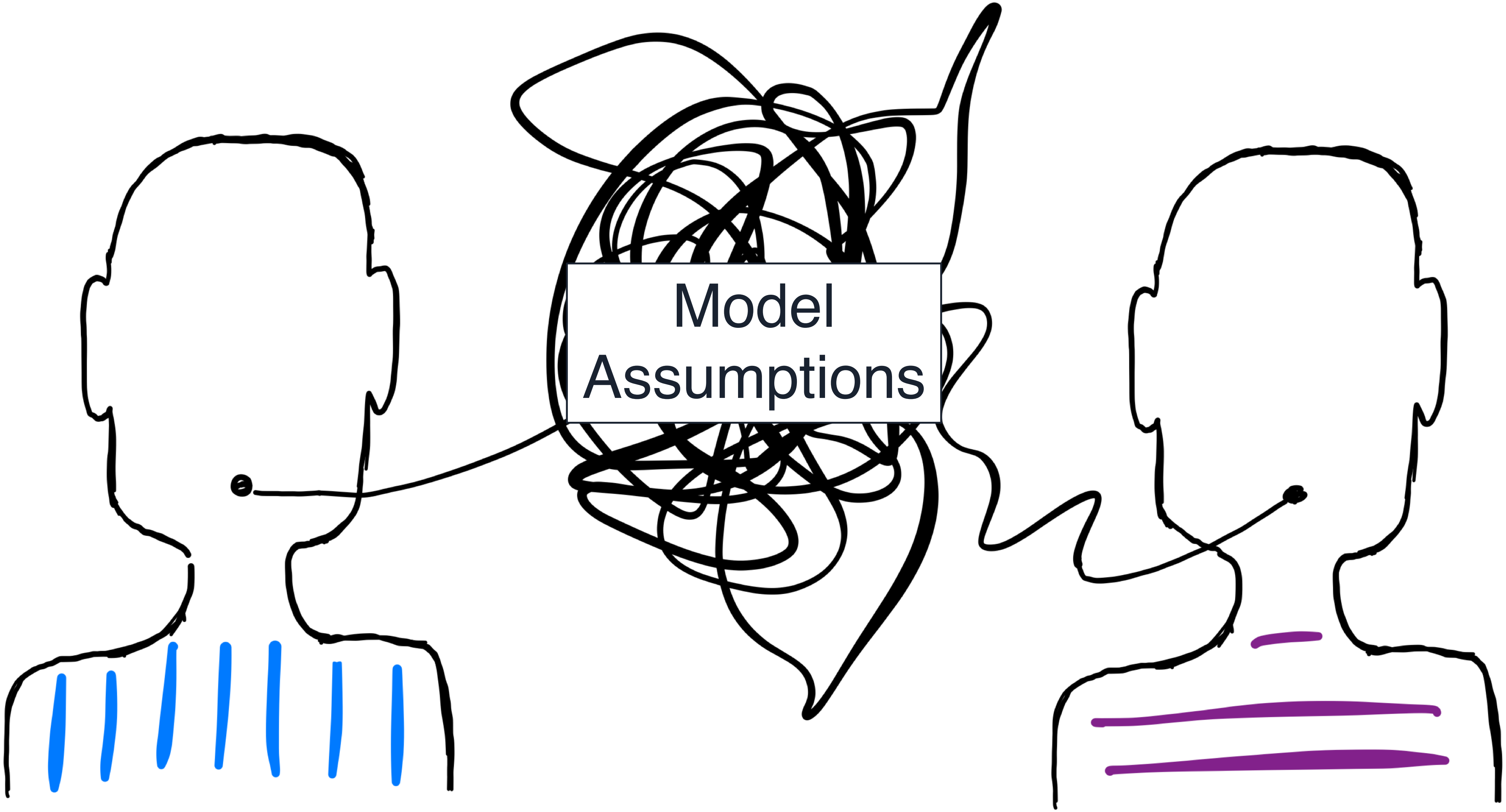


(All) other direct DM searches

*in (2-6)keVee interval

Comparison to other experiments



WHAT ARE THE UNKNOWNS?

Astro physics

Dark matter halo ←→

Velocity distribution

Particle physics

Interaction mechanism

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

galactic escape velocity

velocity distribution

WIMP-nucleon cross section

minimal velocity to produce a recoil above E_R

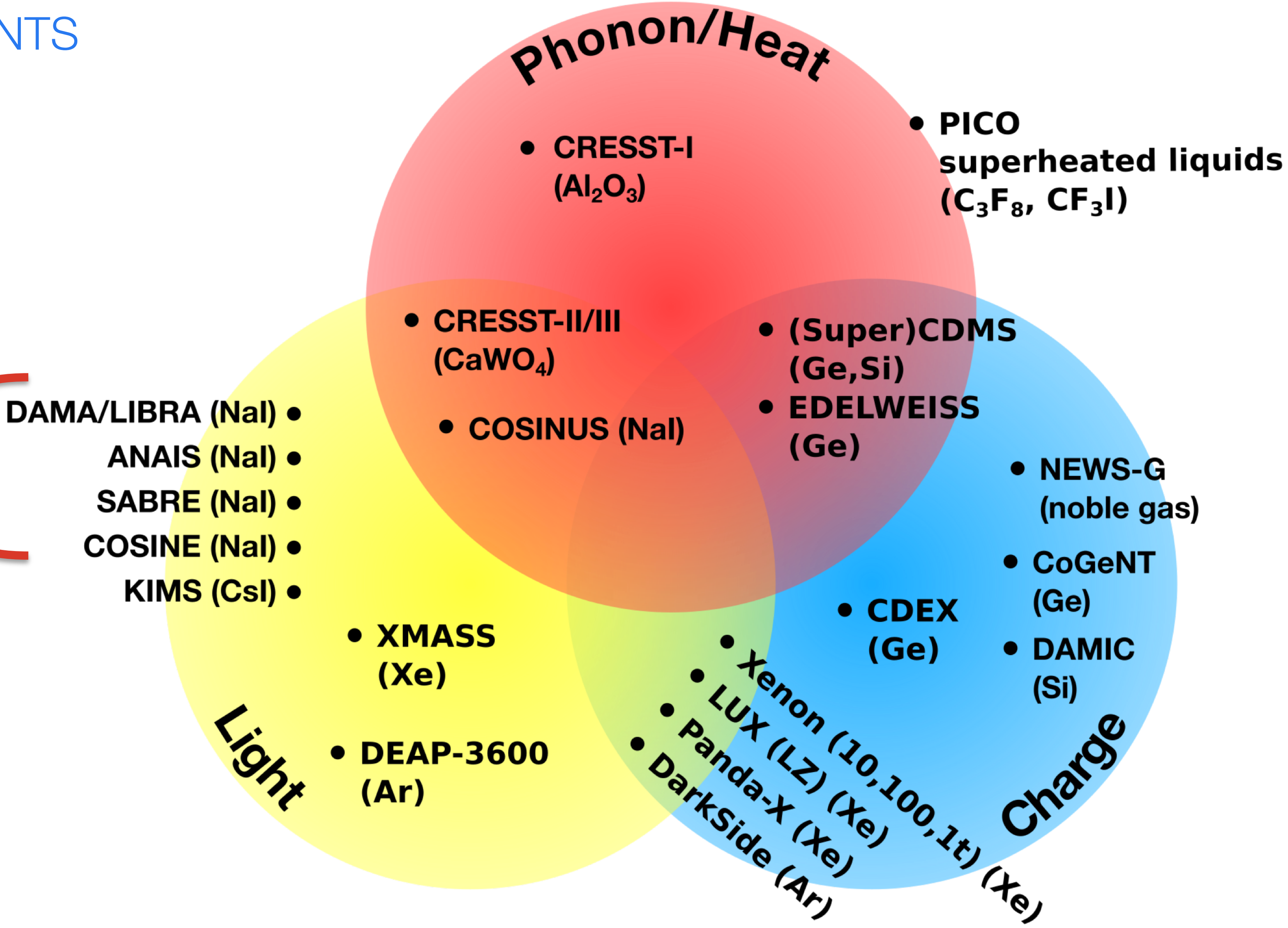
~ A^2
~ form factor

→ Target material dependence
→ → Test DAMA with NaI experiment(s)

Direct detection

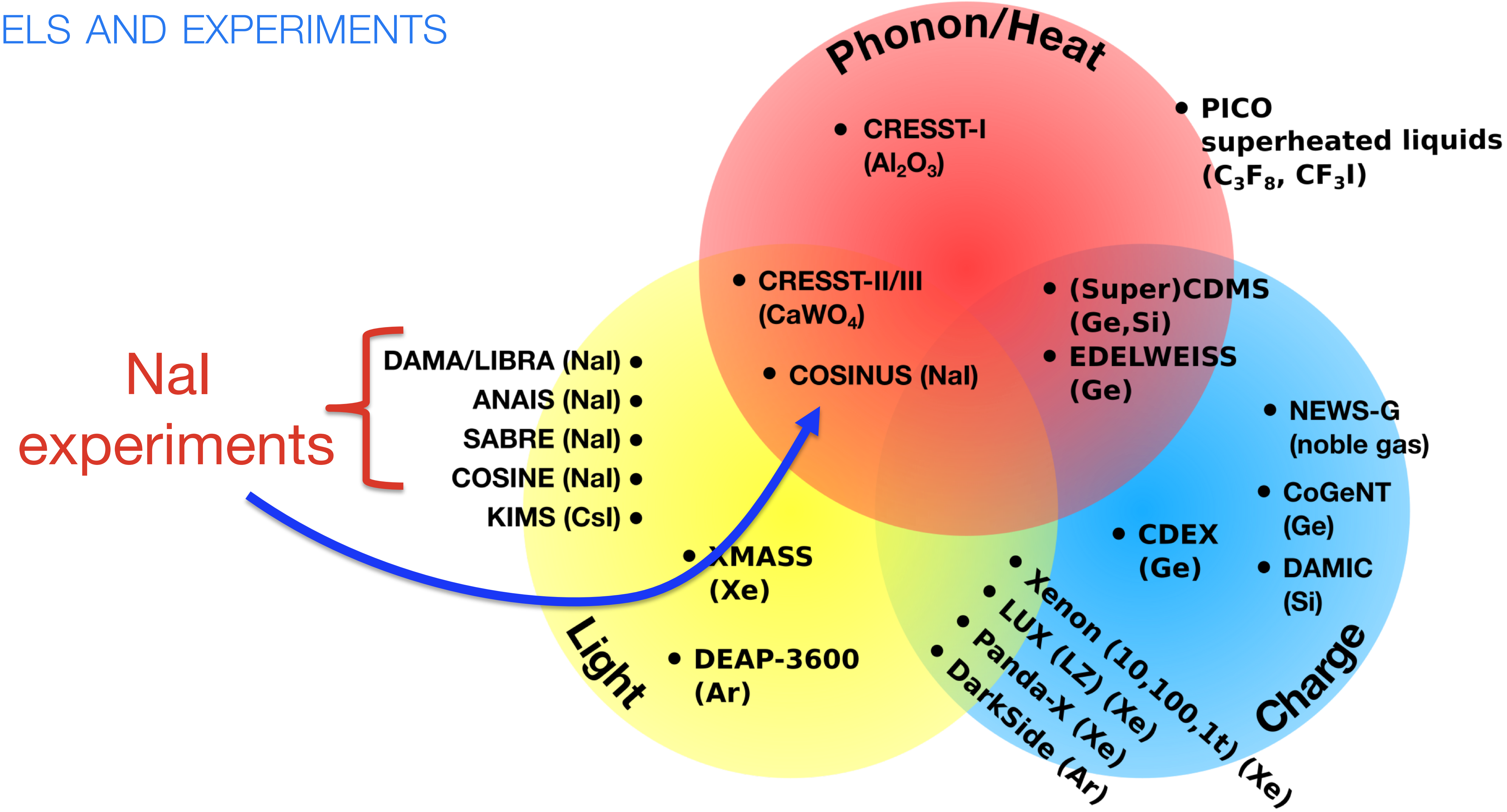
Channels and experiments

NaI experiments



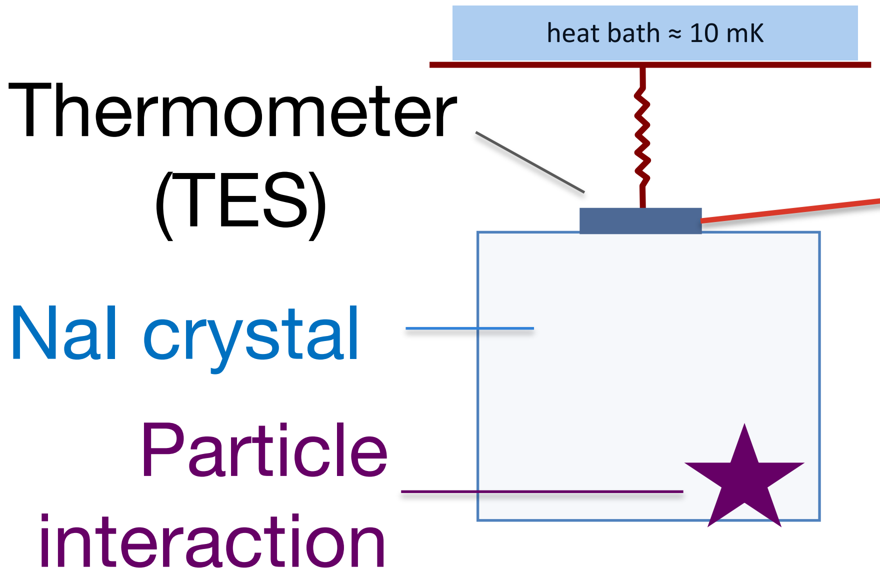
Incomplete compilation!

Direct detection
Channels and experiments

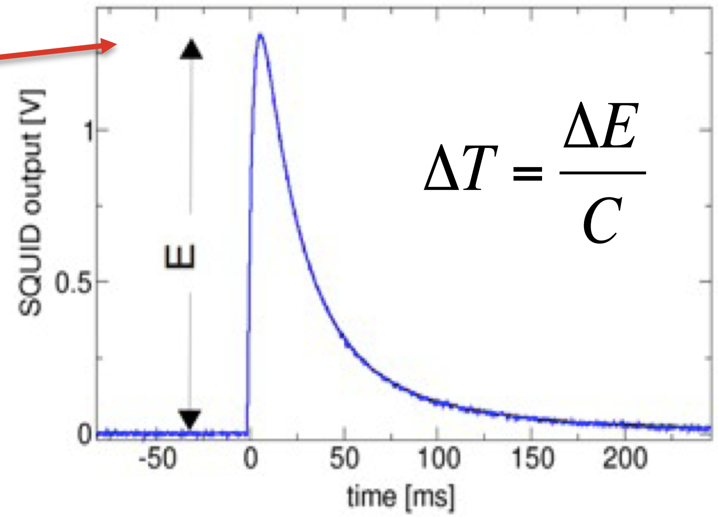


Incomplete compilation!

CRYOGENIC DETECTOR



Temperature pulse

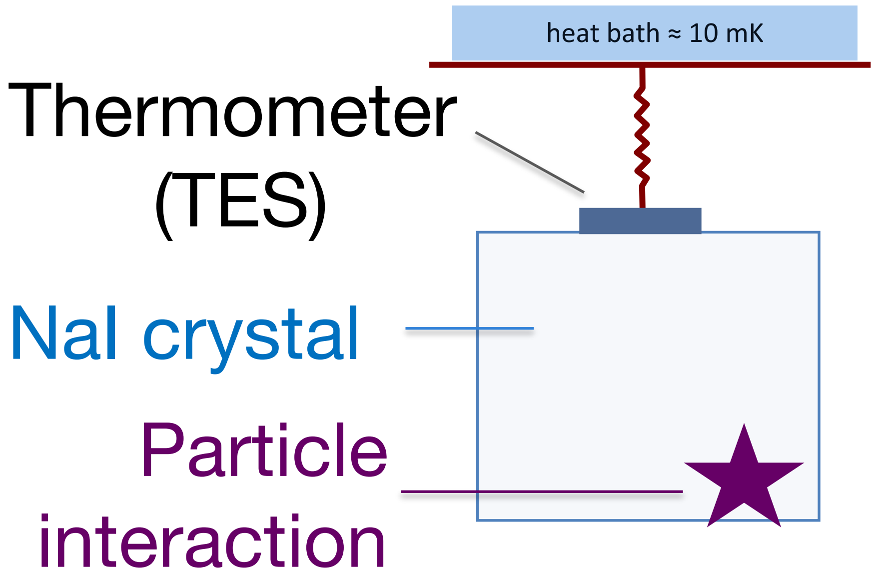


$$\Delta T = \frac{\Delta E}{C}$$

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

Low temperature
Low heat capacity } High sensitivity

CRYOGENIC DETECTOR

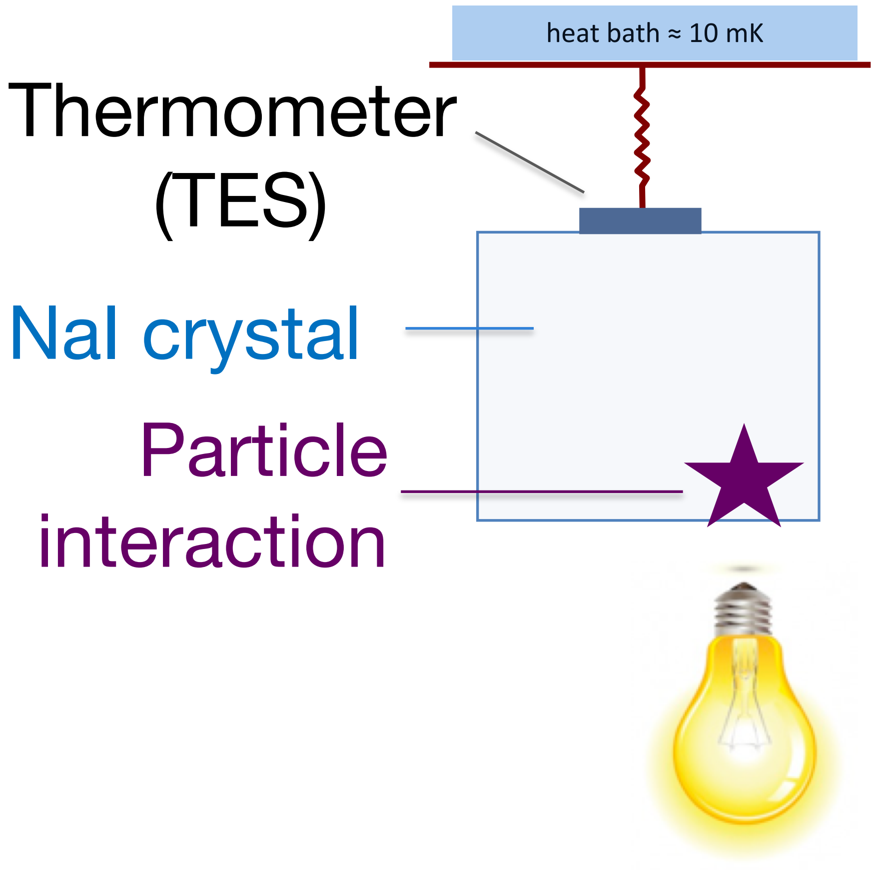


Phonon signal (~90 %)

(Almost) independent of particle type

Precise measurement of the deposited energy

SCINTILLATING CALORIMETER



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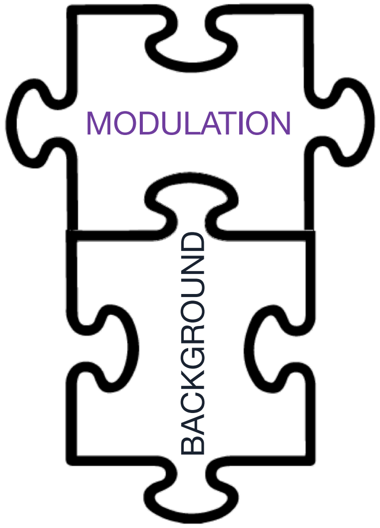
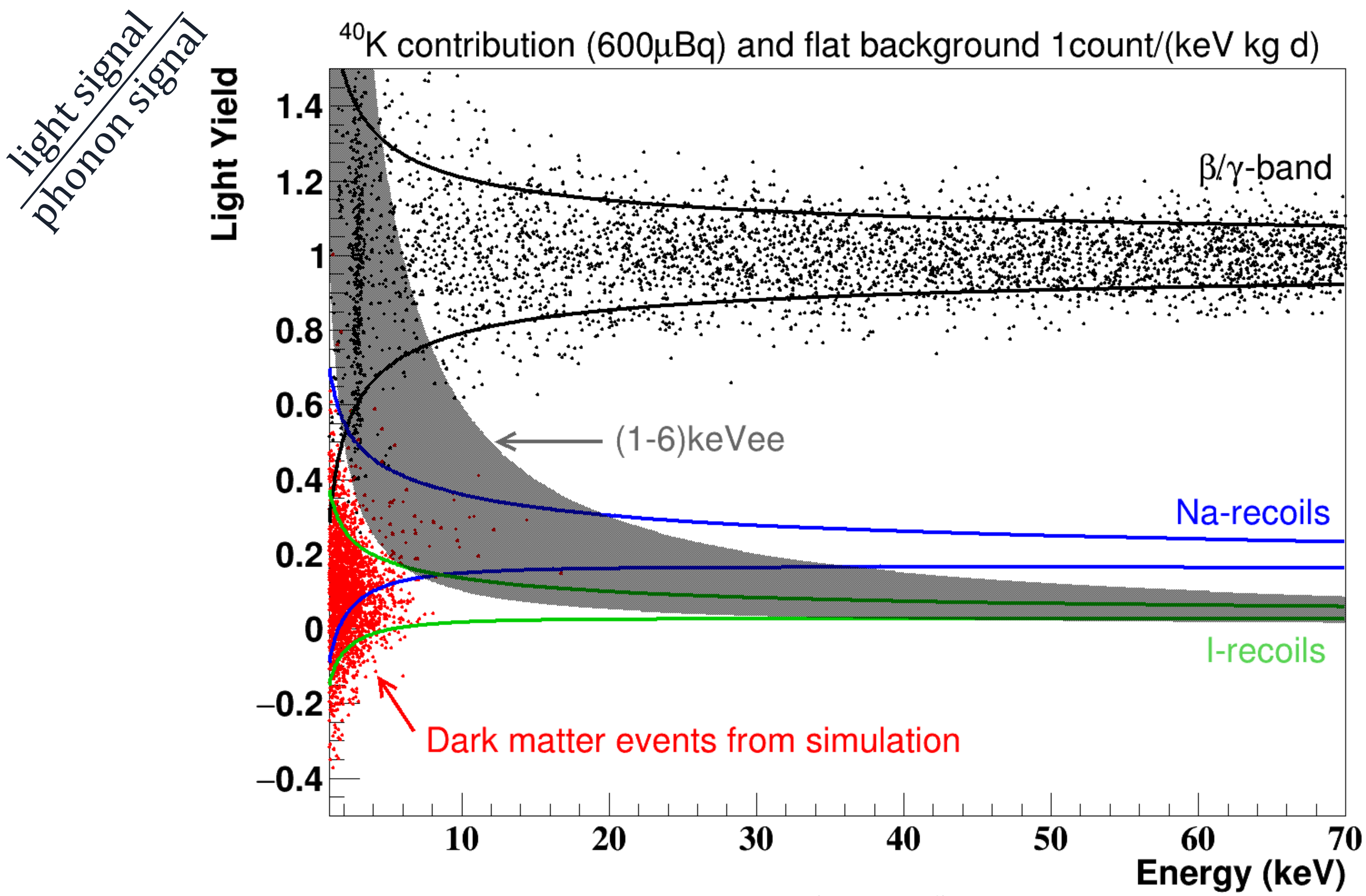


Scintillation light (few %)

Particle-type dependent
→ LIGHT QUENCHING

Simulation

100 kg-days before cuts
1keV nuclear recoil threshold



(1-6)keVee
=
modulation signal in DAMA

PHYSICS REACH

On the way to Corno Grande (2912m)
30. Sep 2018

Rate vs. Modulation Amplitude

Felix Kahlhoefer, FR, et al JCAP05(2018)074

Mean rate
COSINUS

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

Modulation Amplitude
DAMA

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

RATE VS. MODULATION AMPLITUDE

Felix Kahlhoefer, FR, et al JCAP05(2018)074

Mean rate
COSINUS

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

Modulation Amplitude
DAMA

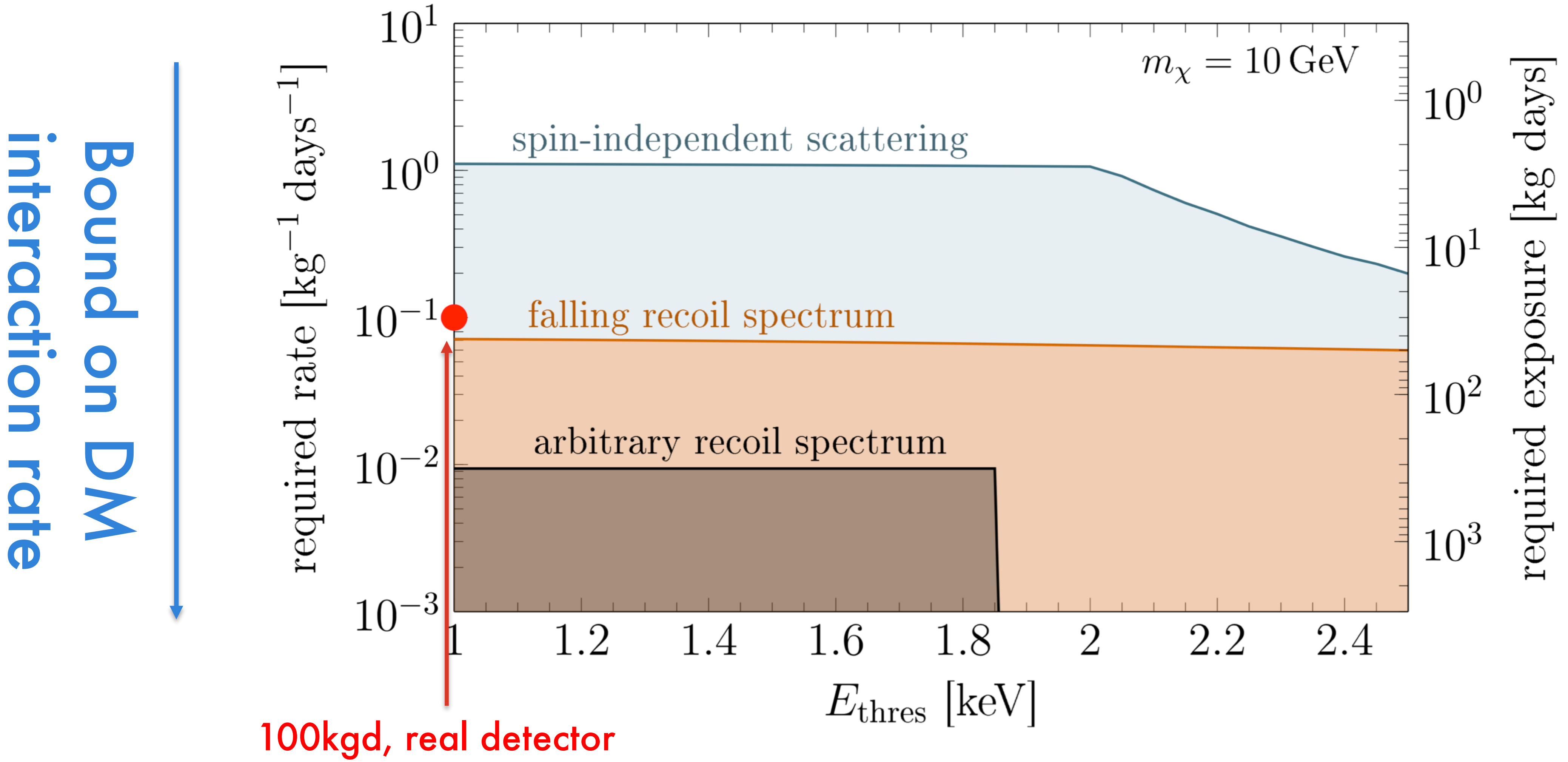
$$S = \frac{1}{2}\left[R(t = \text{June } 1^{st}) - R(t = \text{Dec. } 1^{st})\right]$$

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

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

RESULT

Felix Kahlhoefer, FR, et al JCAP05(2018)074



CONCLUSIONS

If COSINUS achieves

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

Warning: Not updated for new DAMA result with 1keVee threshold

➢ 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

A CRYOGENIC NAI DETECTOR PROVIDES

- particle identification on event-by-event basis
- a low(er) threshold for nuclear recoils
- → a model-independent test of DAMA

A Cryogenic NaI detector provides

- particle identification on event-by-event basis
- a low(er) threshold for nuclear recoils
- → a model-independent test of DAMA

COSINUS

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

INFN Istituto Nazionale di Fisica Nucleare

TU WIEN

GRAN SASSO SCIENCE INSTITUTE SCHOOL OF ADVANCED STUDIES Scuola Universitaria Superiore

SICCAS Since 1928

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

cosinus.it

COSINUS TIME SKETCH

Year	Phase	Activity
2017-19	R&D	Detector prototype development
2020-22	Construction	Build up experimental setup (at LNGS)
2023	1π	Test nuclear recoil origin of the DAMA signal
≥2024	2π	Test annual modulation

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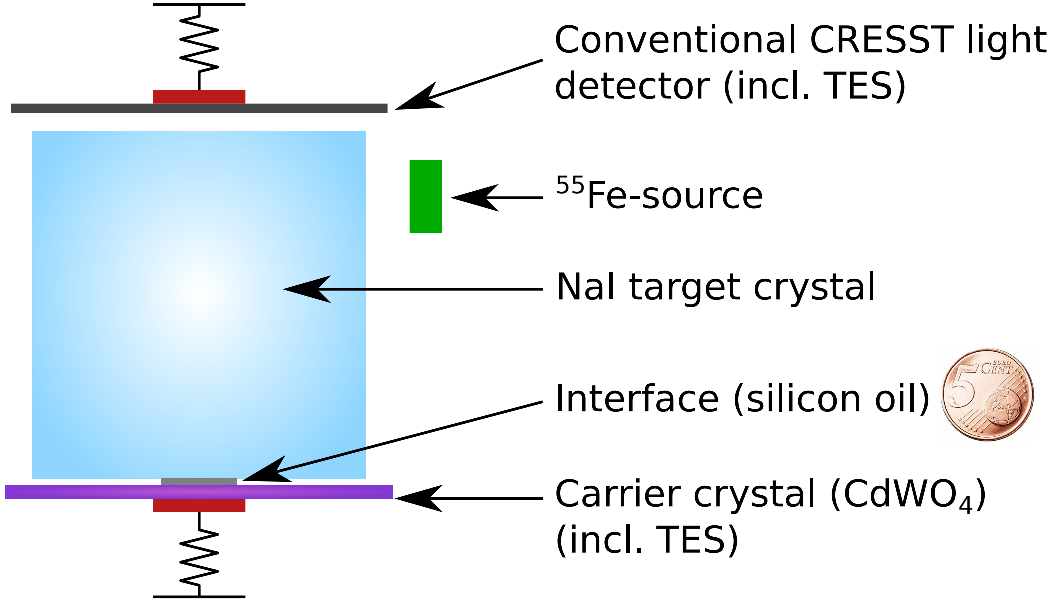
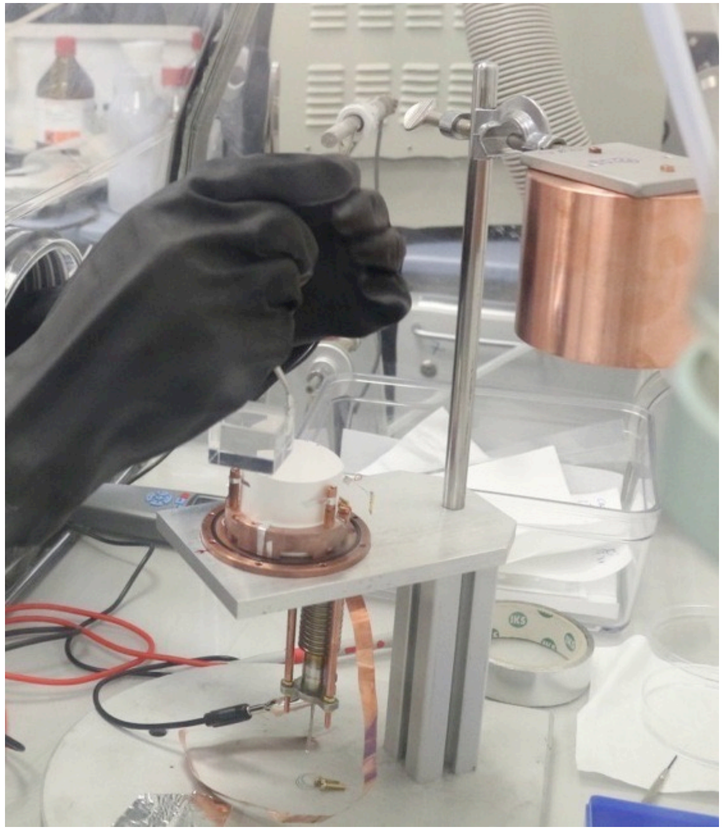
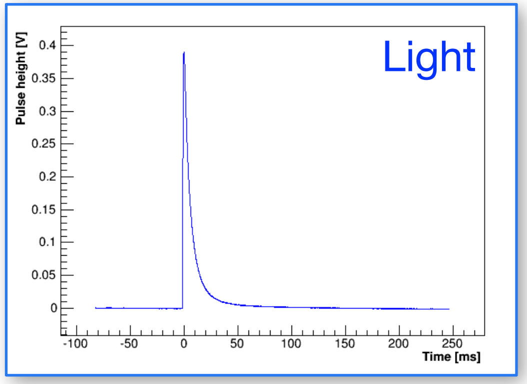
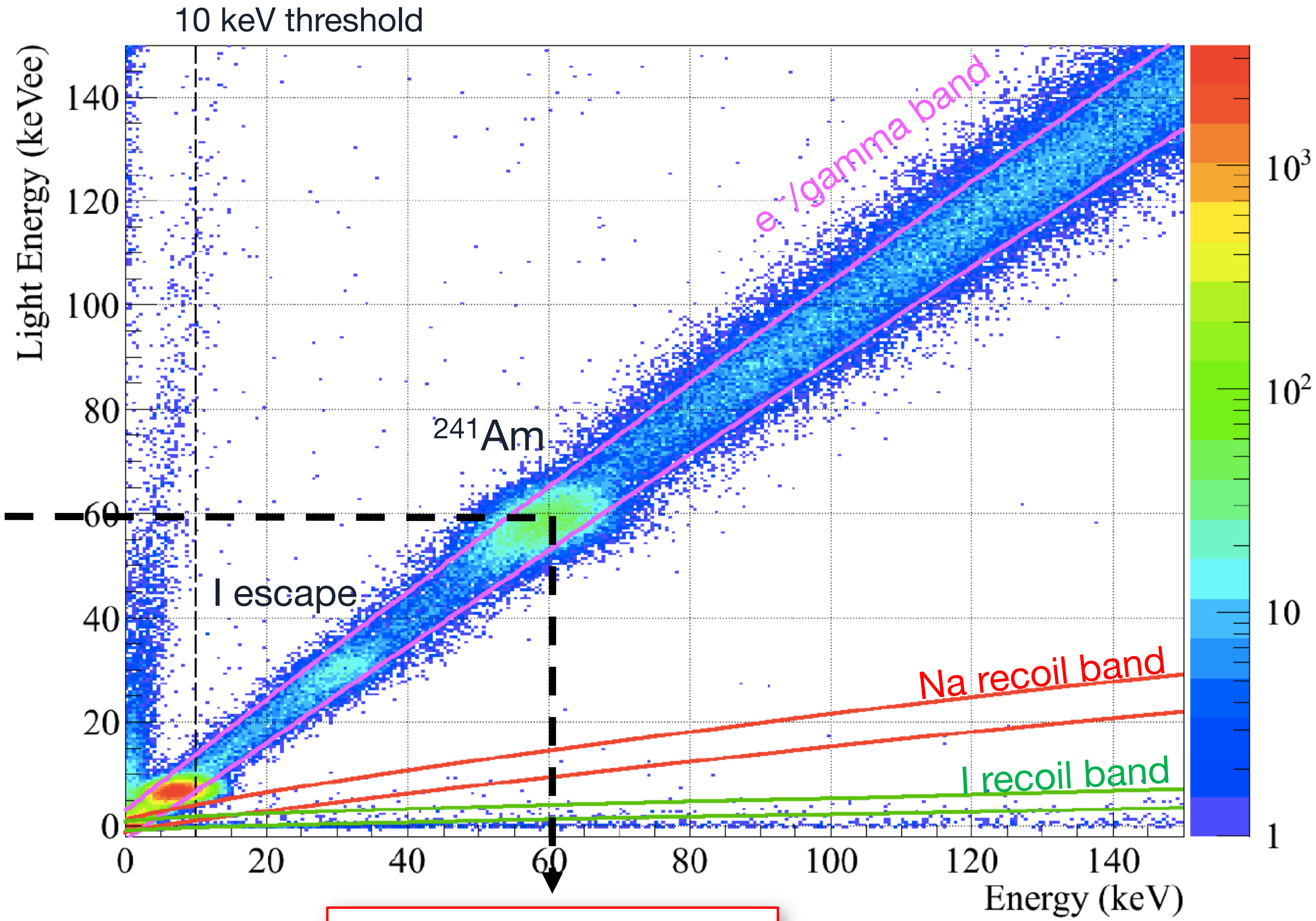
First NaI prototype

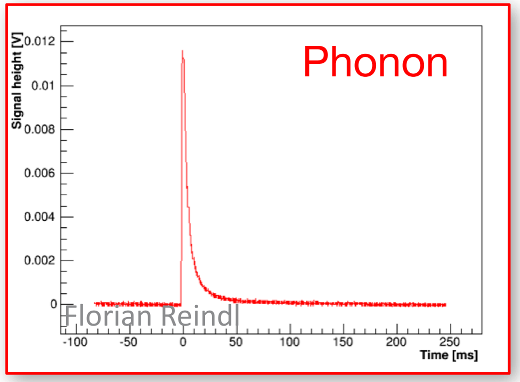




DATA FROM 1ST PROTOTYPE







plot: G. Angloher et al. JINST 12 P11007 (2017)
QF from Tretyak, Astropart. Phys. 33, 40 (2010)

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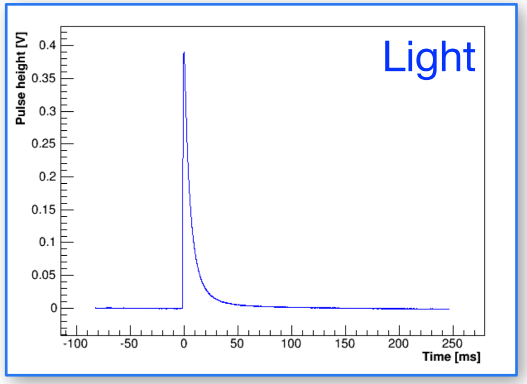

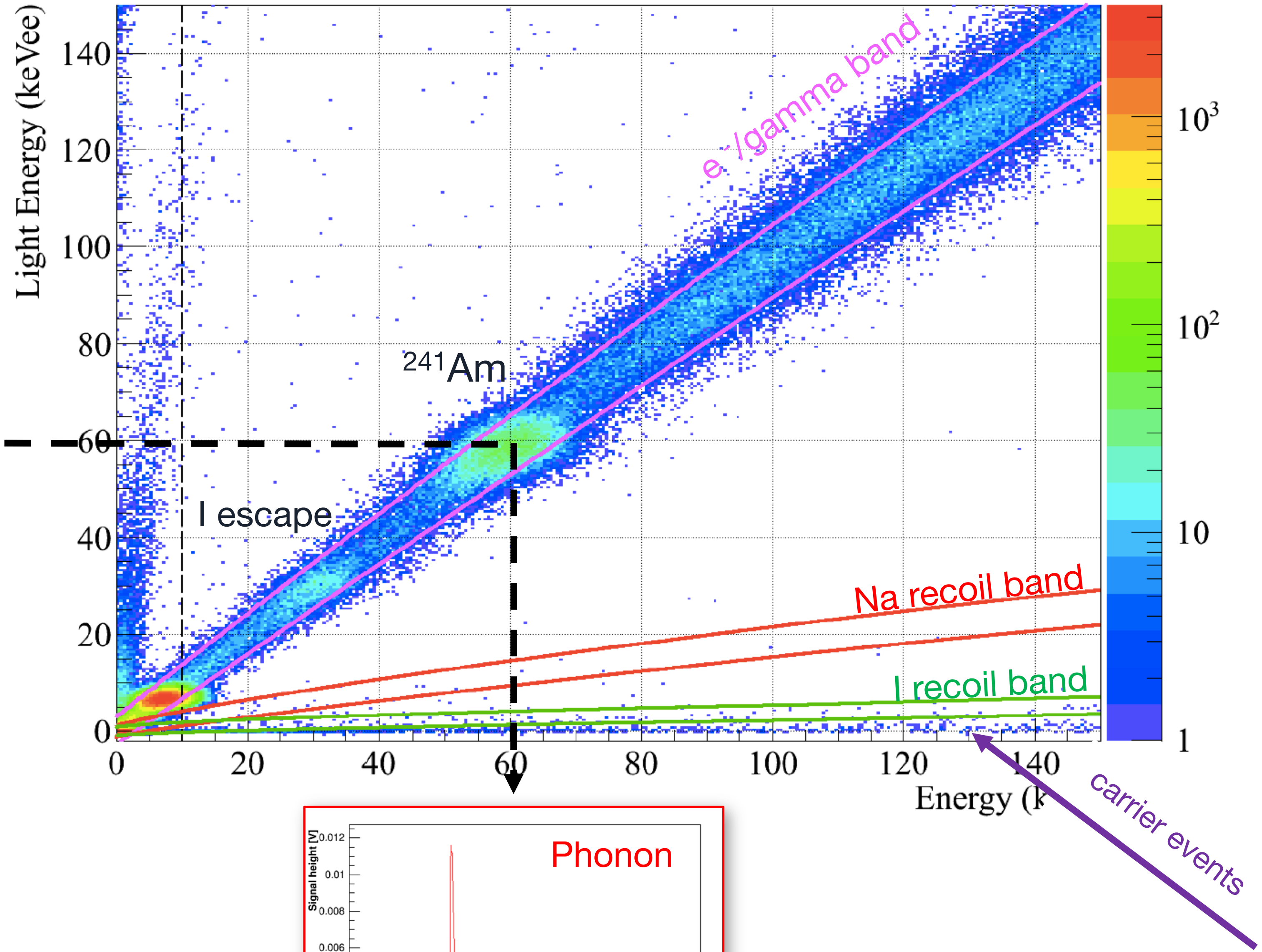

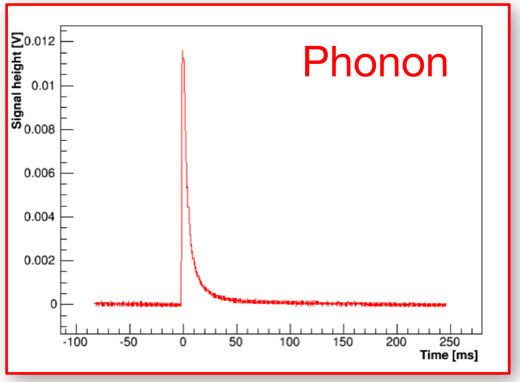

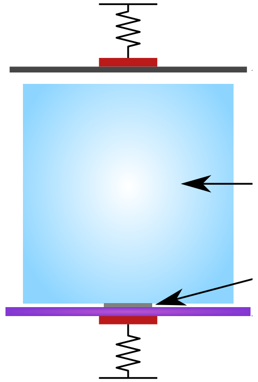

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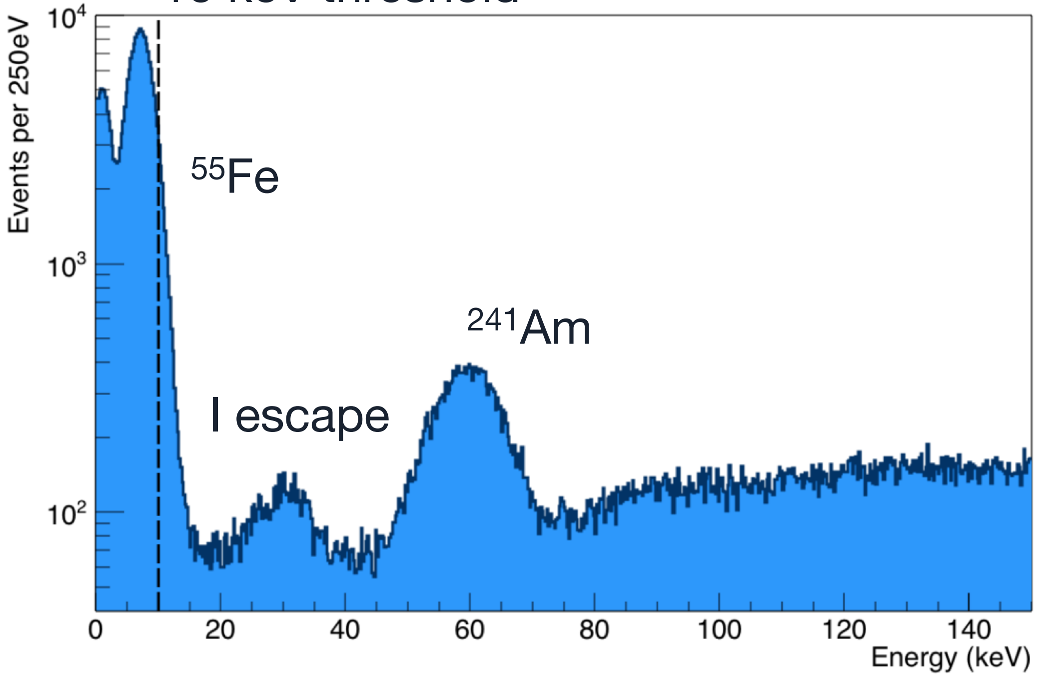

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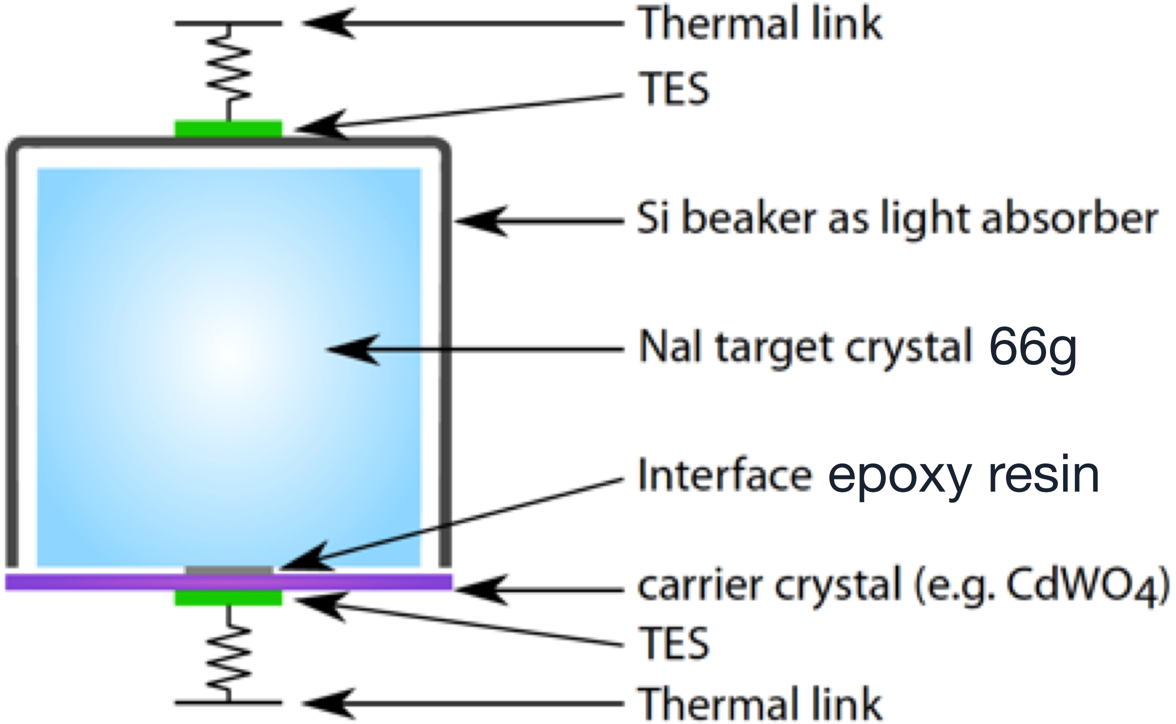
QF from Tretyak, Astropart. Phys. 33, 40 (2010)

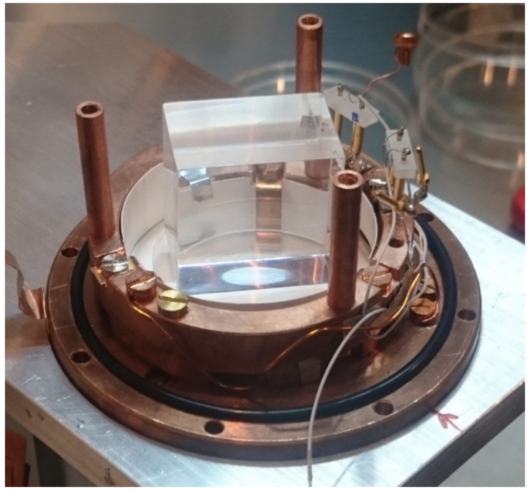
- Energy threshold: 10 keV
- For β/γ-events:
  3.7% of the energy deposited in the NaI crystal is measured by the light detector (design goal 4%)

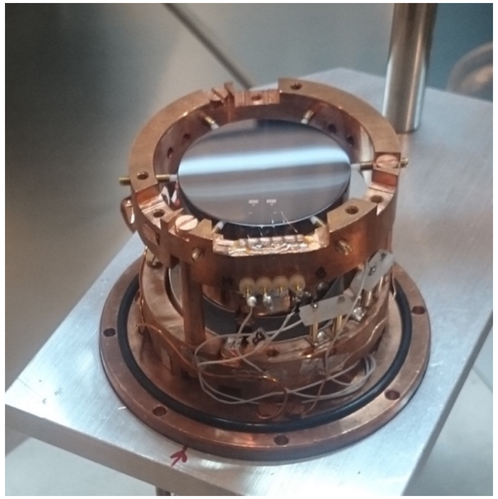
First successful measurement of a NaI crystal as cryogenic detector

Improve detector performance

PROOF-OF-PRINCIPLE OF FINAL DETECTOR DESIGN
2ND PROTOTYPE (2016/17)



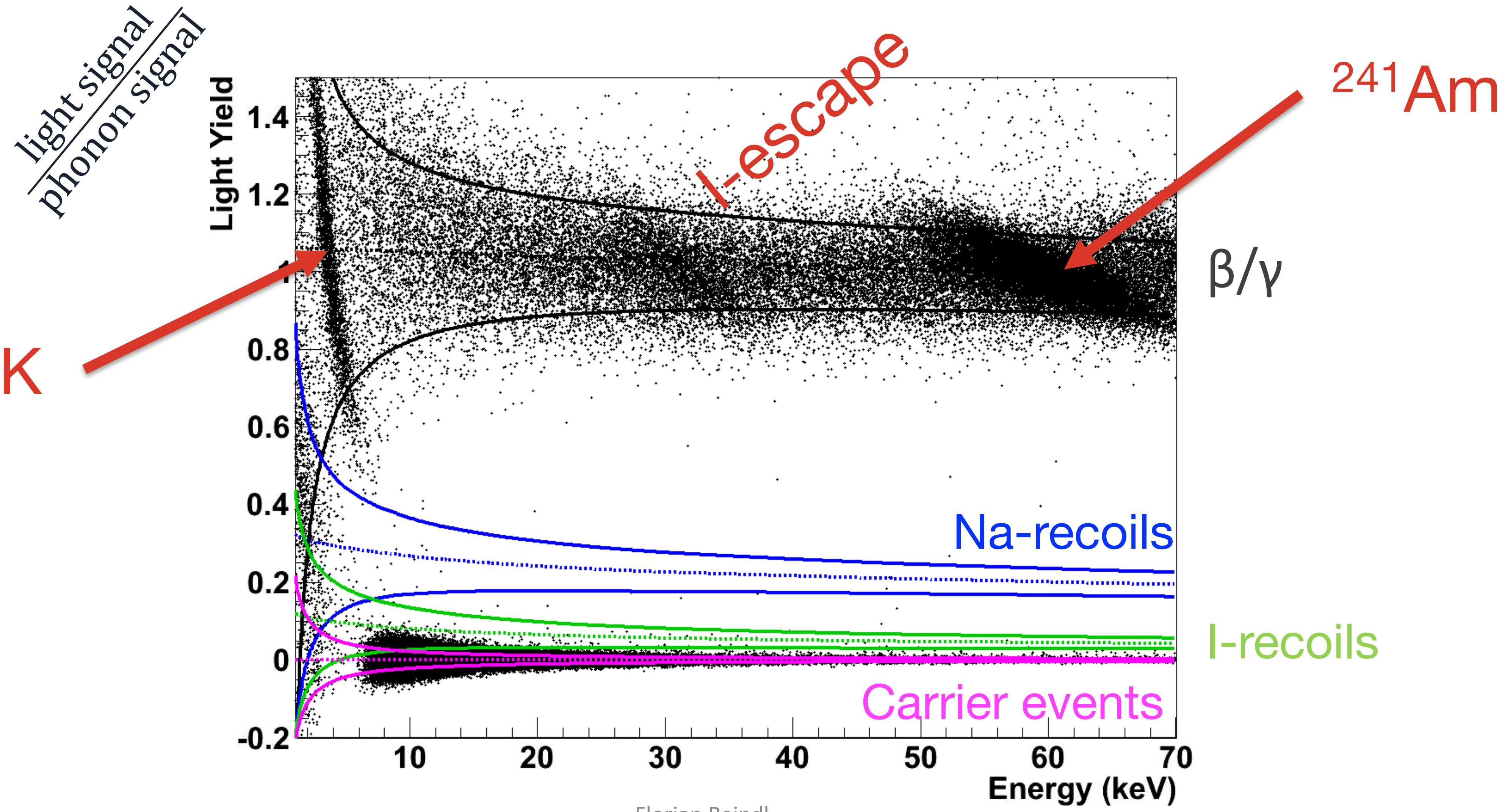




^{241}Am Gamma calibration Data 2ND prototype (2016/17)

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

F. Reindl et al., arXiv 1711.01482



QF from Tretyak, Astropart. Phys. 33, 40 (2010

PERFORMANCE OF THE 2ND PROTOTYPE

- Phonon detector resolution (at zero energy): 1.0keV
- Absolute light yield for a β/γ-event: **13 %**

👍 Successful test of detector concept

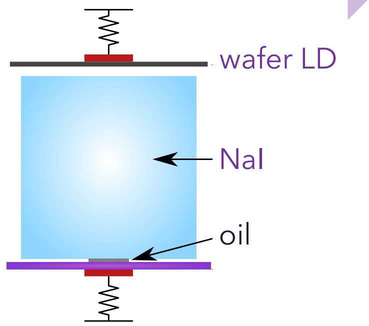
👍 Undoped NaI is an excellent scintillator at low temperatures

👎 Further improvement of phonon detector performance required

👎 205ppm of ^{40}K in the HILGER crystal

COSINUS R&D TIMELINE

1st PROTOTYPE (2016)



1st measurement of a NaI as cryogenic calorimeter

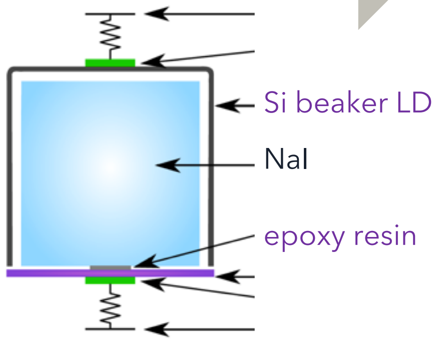
linear relation between light output and deposited energy

NaI threshold: 10 keV

3.7% detected in light

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

2nd PROTOTYPE (2016/17)



successful test of complete COSINUS detector design

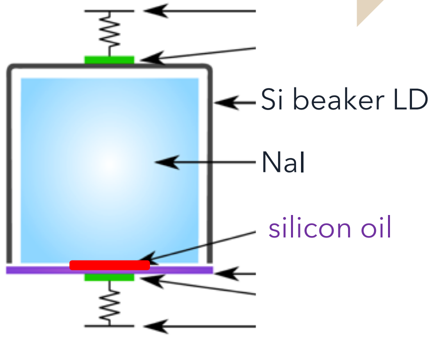
energy resolution at zero energy : 15 eV

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

3rd PROTOTYPE (2017)



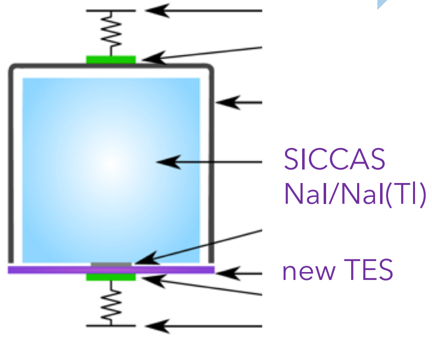
changed interface to thin layer of silicon oil

commissioning of:
in-house electronics
and DAQ from INFN Milano

NaI threshold: 6.5 keV

AmBe calibration campaign

4th→ 14th PROTOTYPE (17-19)



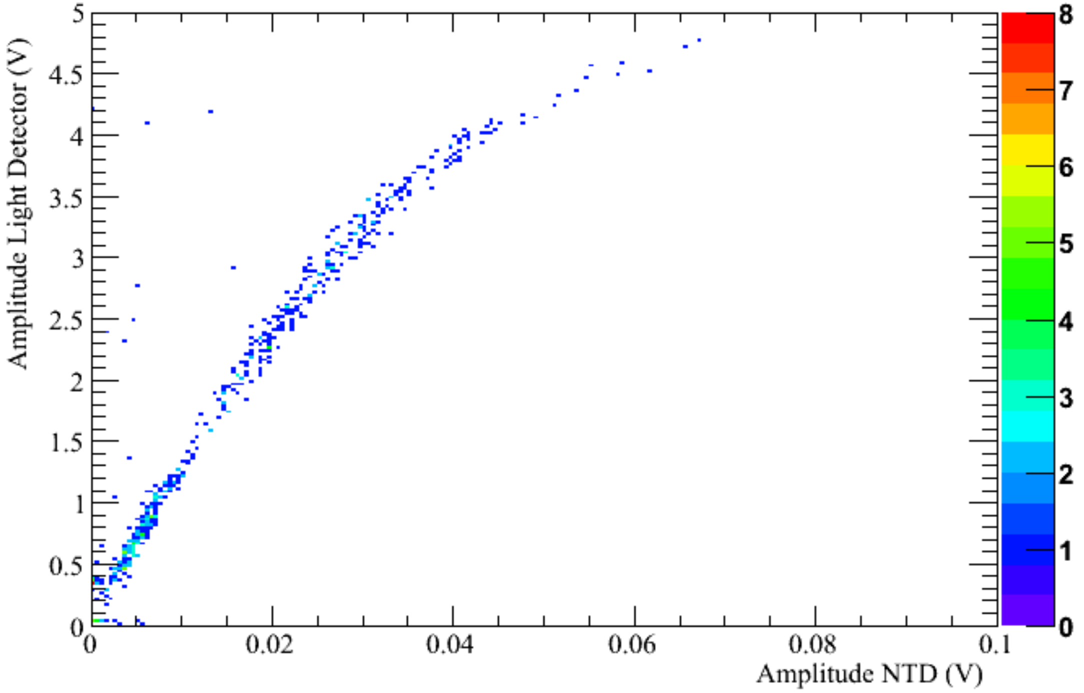
test of new batch of NaI/**NaI(Tl)** crystals from SICCAS

test of new TES-concept for the NaI crystal

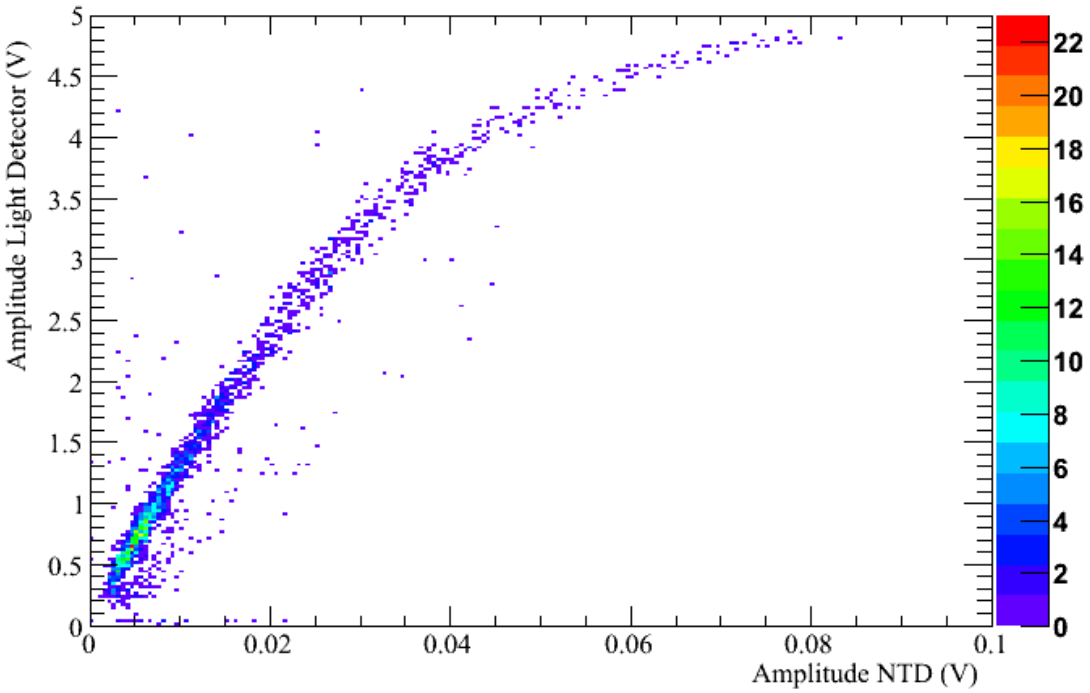
Work ongoing!

NaIce6 – Particle discrimination

Background data (~20h)



Neutron data (~20h)



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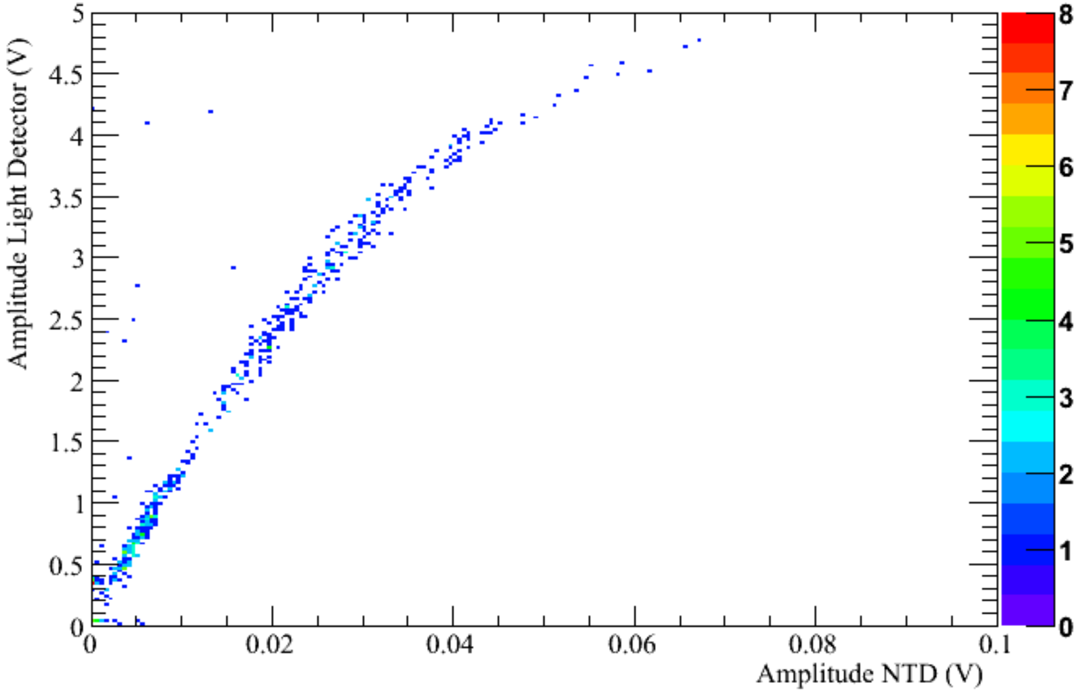
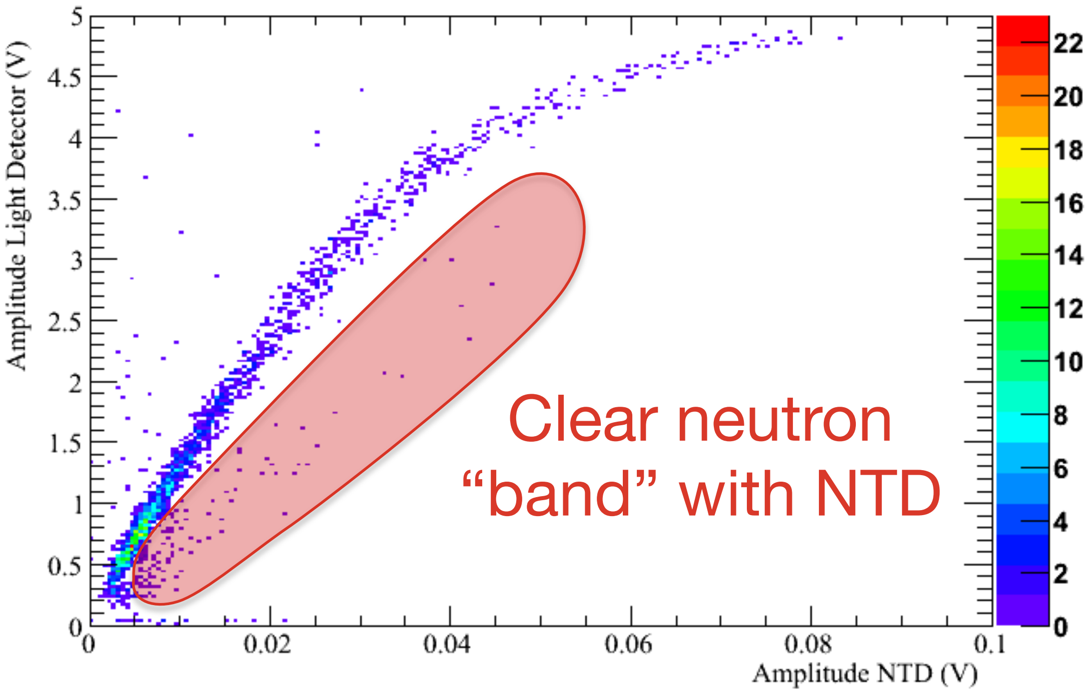


Neutron data (~20h)



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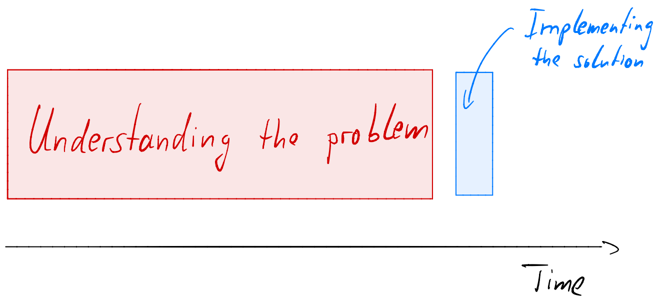
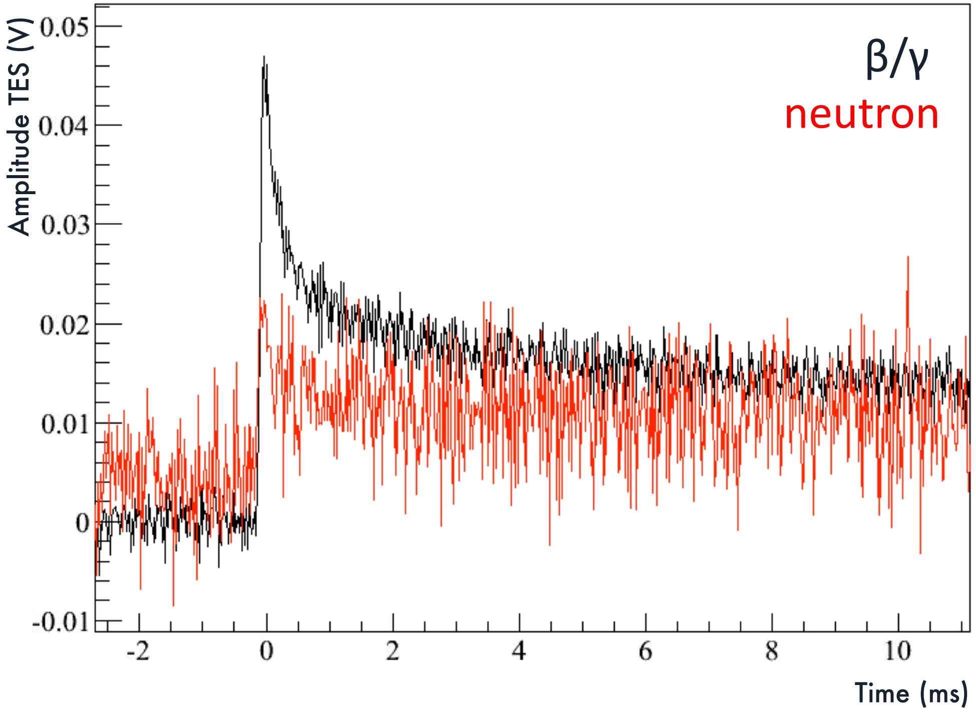


Now looking at the TES



- Different pulse-shapes for neutron and β/γ-events, NOT observed for other materials (CRESST, $CaWO_4$)
- TES not yet well adapted to slow phonon signals of NaI

➢ TES Optimization

➢ Simulation/study of phonon signal pulse formation (solid state physics, l'Aquila university)

TODO LIST FOR A COSINUS DM MODULE

✓ Operate NaI as cryogenic detector

✓ Beaker-shaped light detector

✓ Clean (enough) NaI crystals: Grown by SICCAS*

❑ Phonon threshold of 1keV: 10keV→8.5 keV→6.5keV

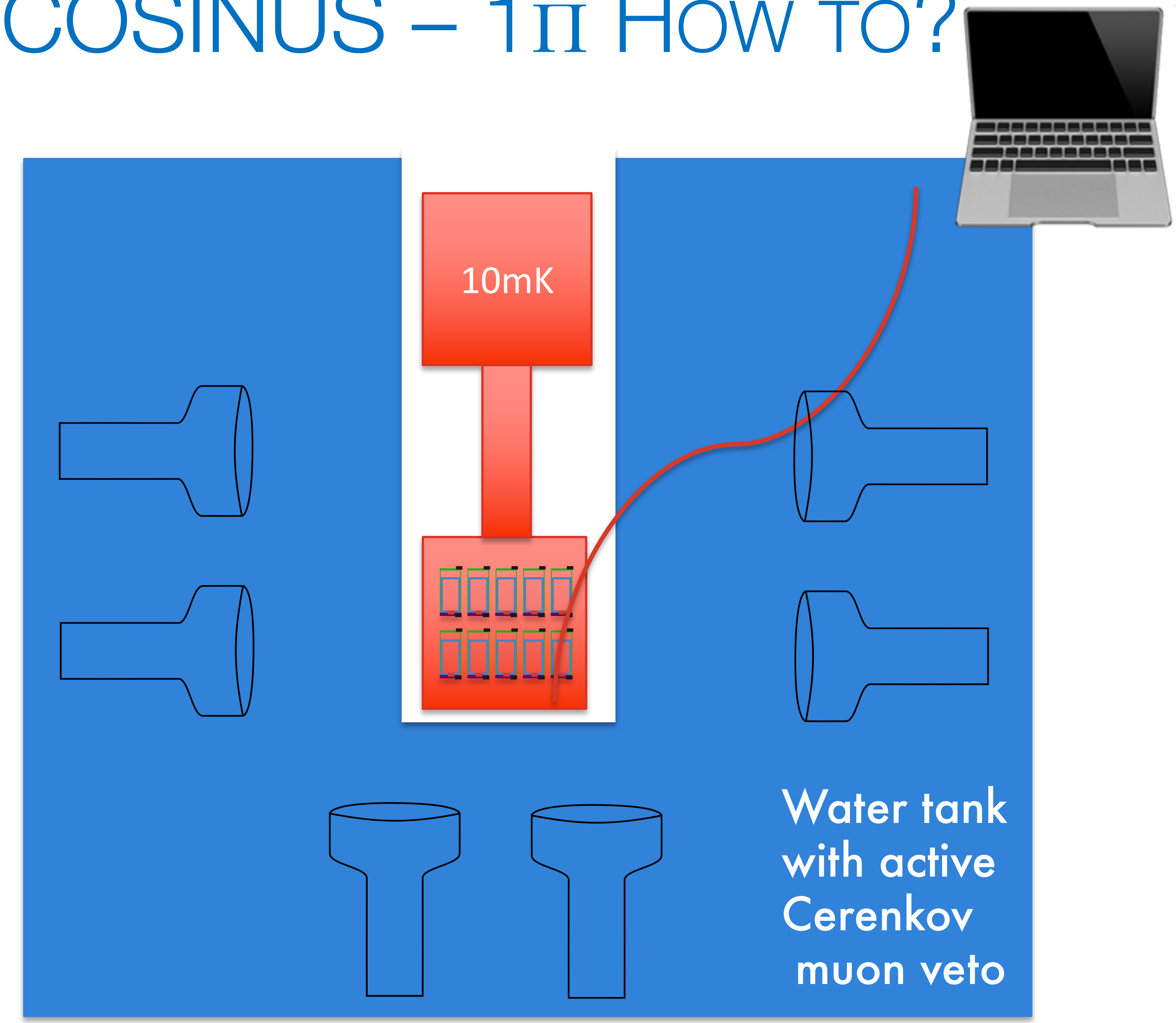
❑ Particle discrimination:

- ❑ Phonon pulse formation: Under investigation
- ❑ In-Situ measurement with TES

Prototype measurement results:
G. Angloher et al. JINST 12 P11007 (2017)
F. Reindl et al., arXiv 1711.01482
Schäffner, K. et al. J Low Temp Phys (2018)

* ICP-MS measurement results in backup

COSINUS – 1π How to?



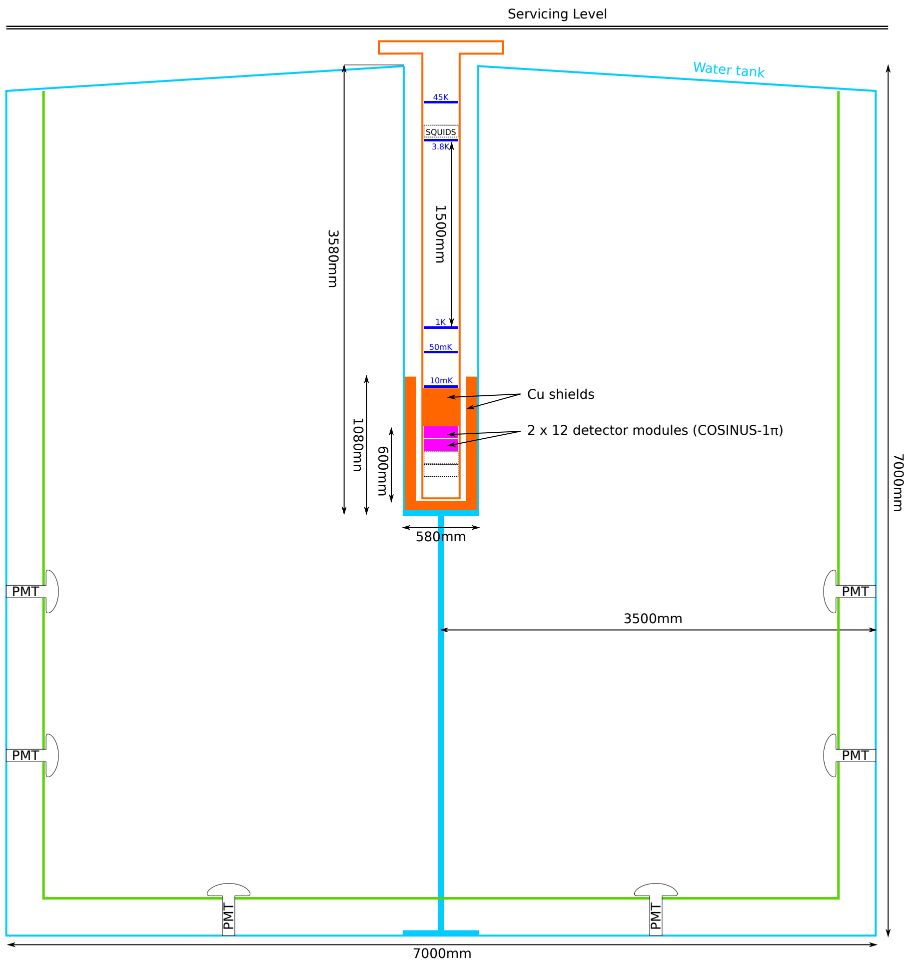
Detectors

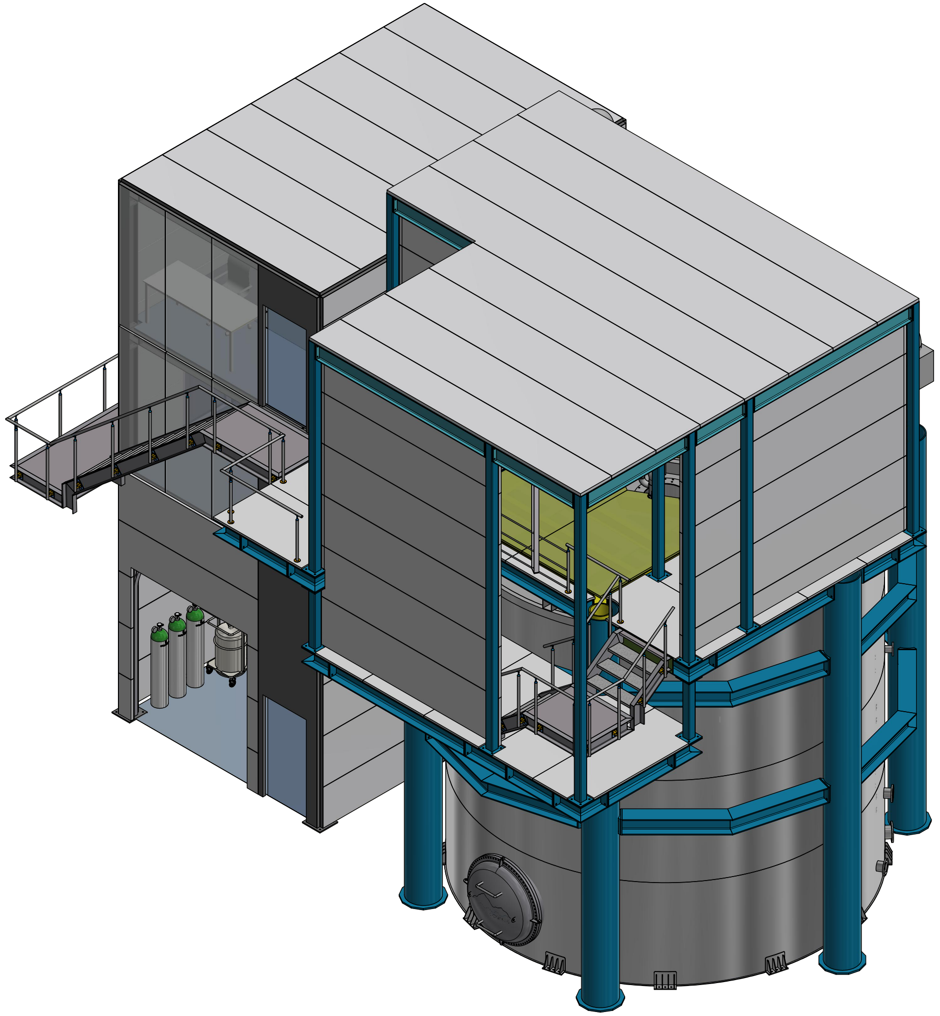
Cryostat

Water tank

DAQ Electronics

PLANNED EXPERIMENTAL SETUP AT LNGS





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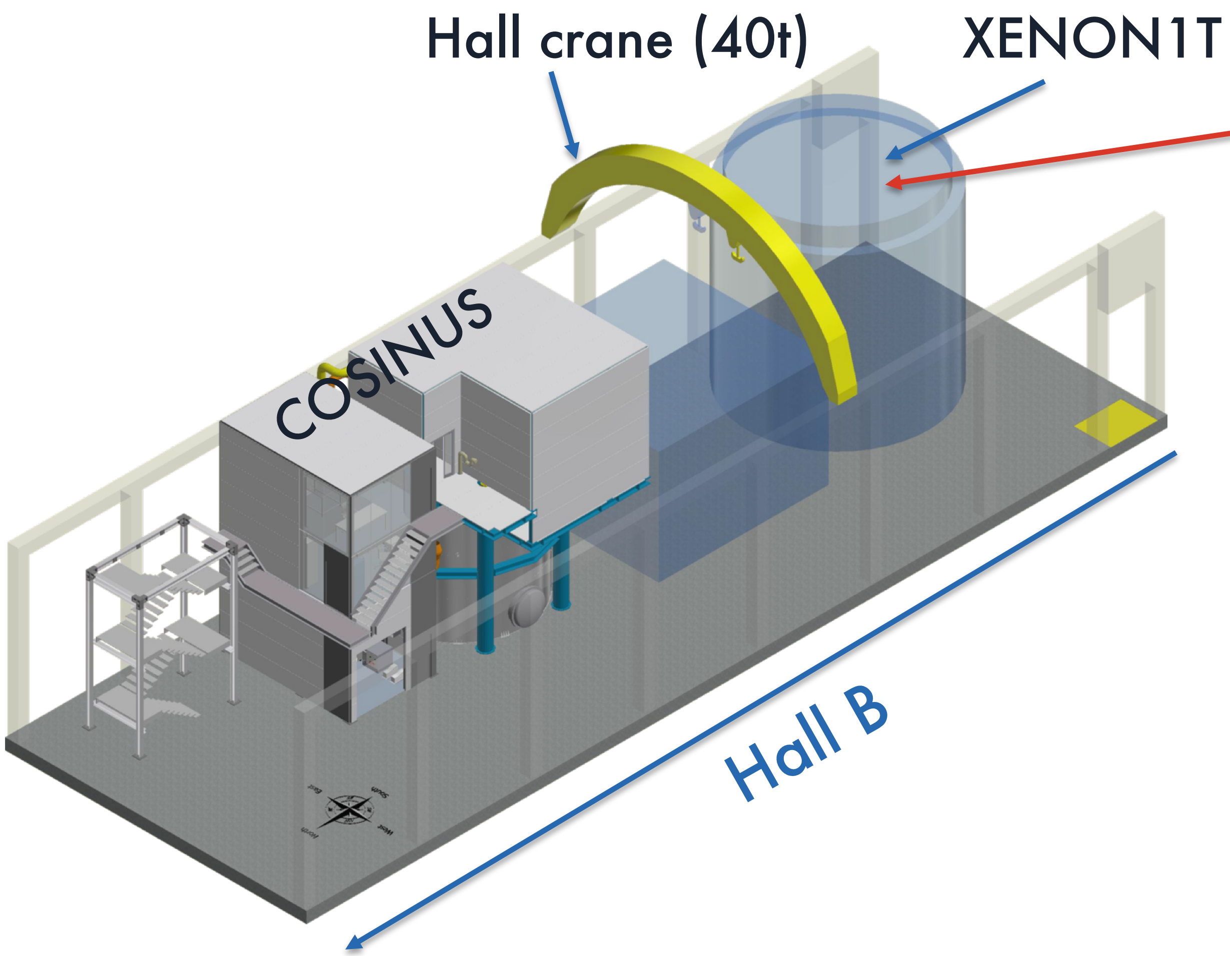
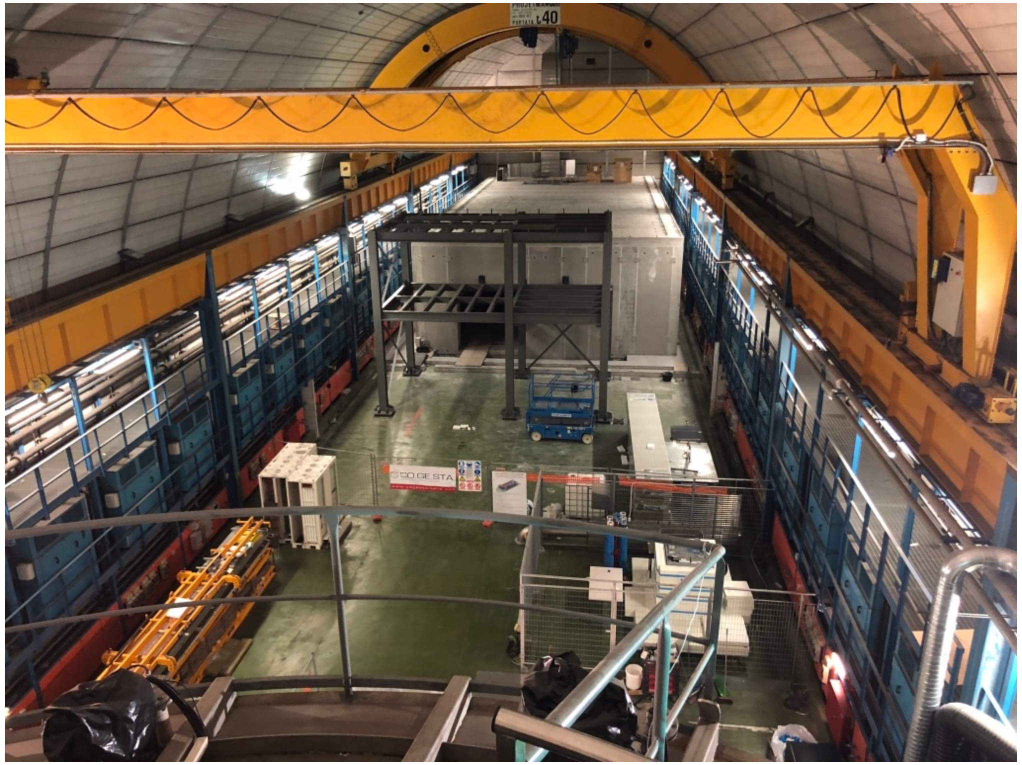
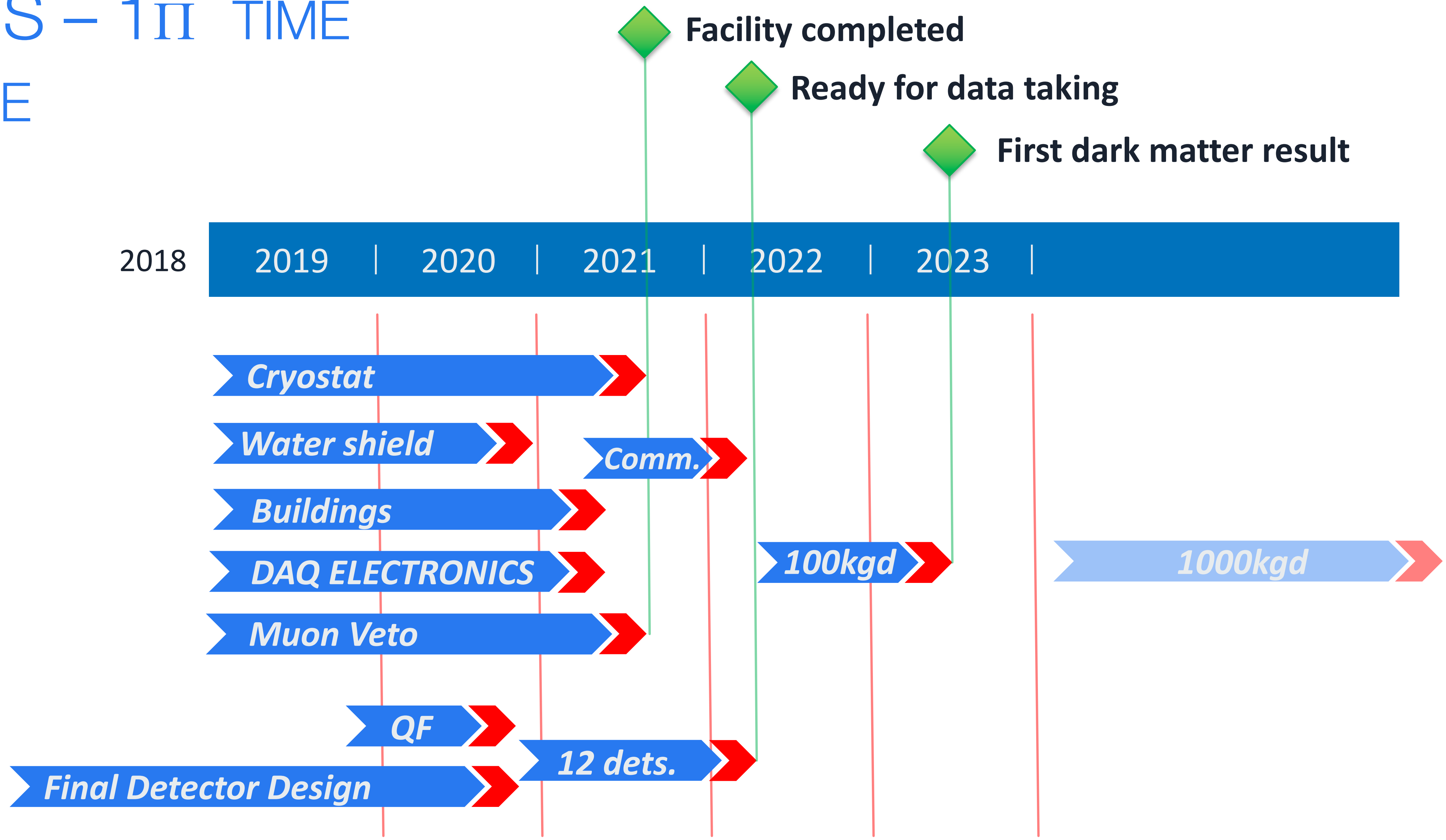


Picture taken from here in direction of hall B



COSINUS – 1π TIME SCHEDULE



Funding and contributors:
The COSINUS family is growing

INFN LNGS

Funding for R&D [2016 – 2019]

Funding for experiment: >= 2020

MPRG MPI Munich

Lion's share for funding of experimental setup

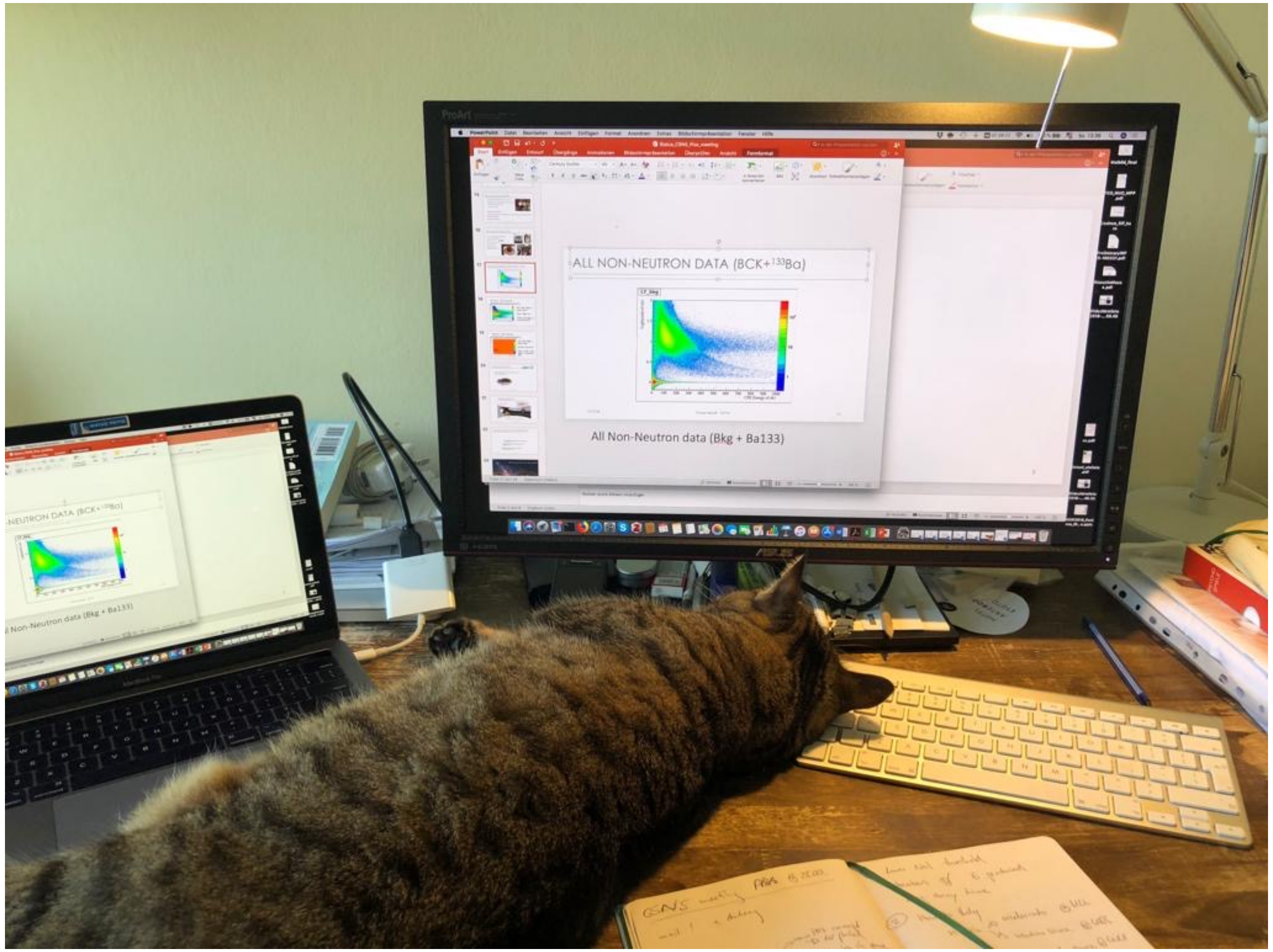
HEPHY/ TU Vienna

Funding for DAQ & setup

...

...

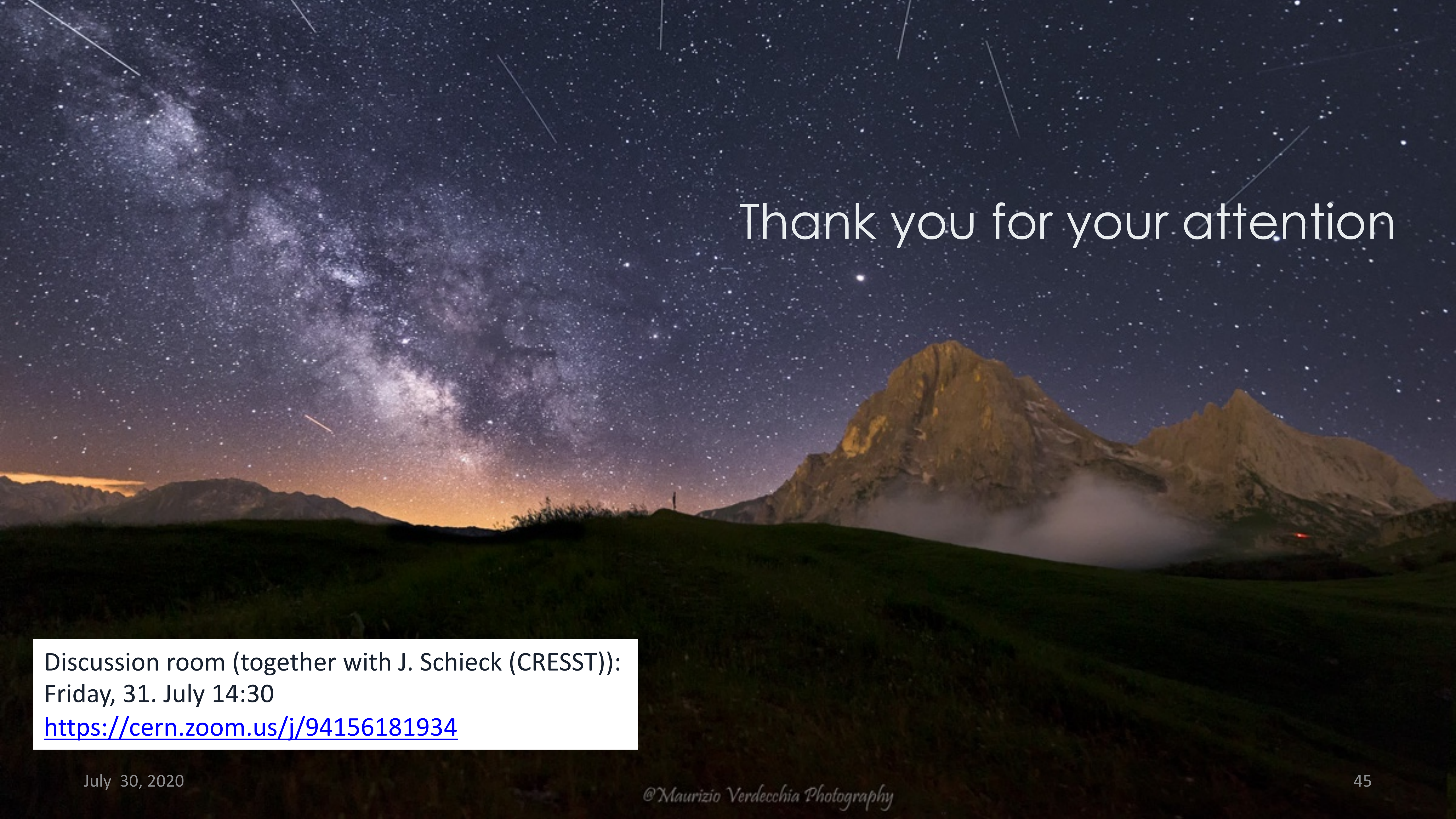
WE SEARCH FOR COLLABORATORS



We already have Fermi* on board

But:
He cannot do everything

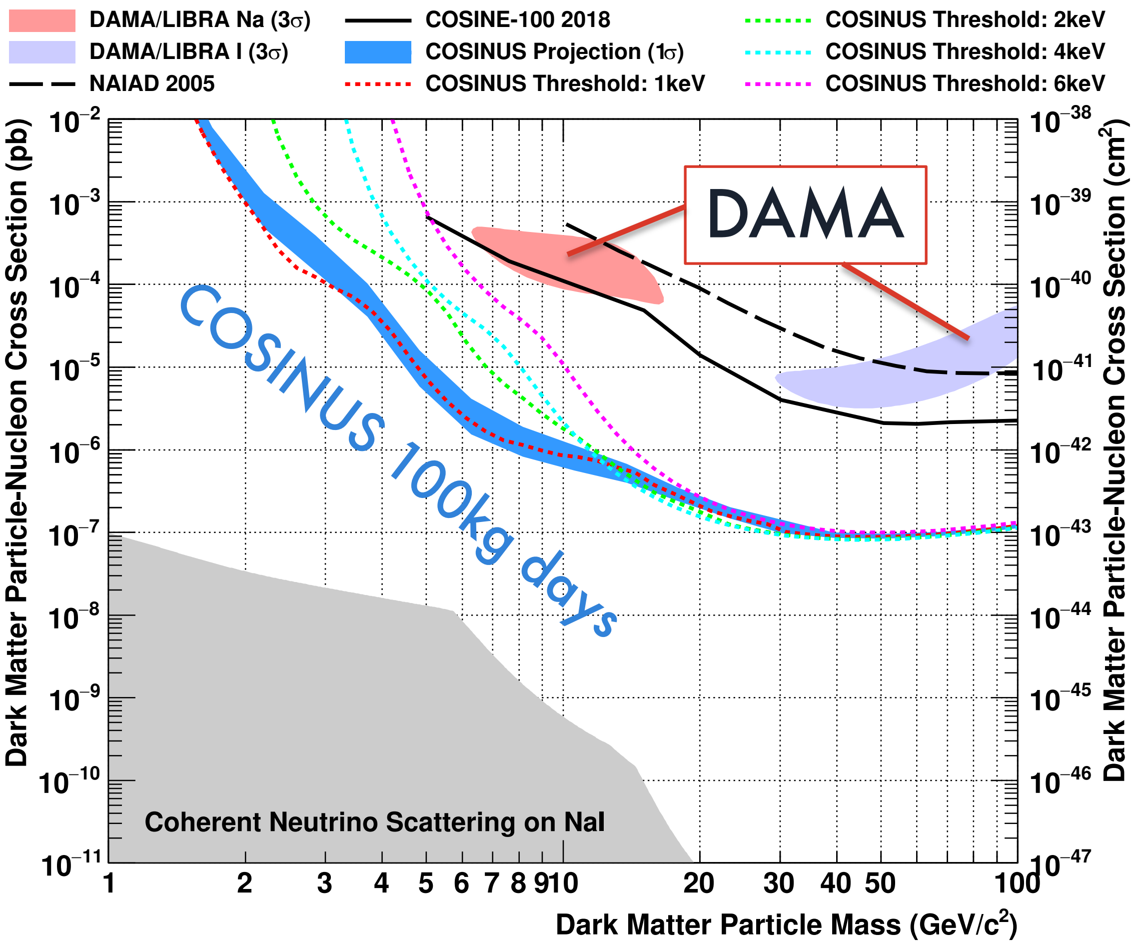
*yes, the cat's name is really Fermi



Thank you for your attention

Discussion room (together with J. Schieck (CRESST)):
Friday, 31. July 14:30
https://cern.zoom.us/j/94156181934

COSINUS IN THE STANDARD SCENARIO

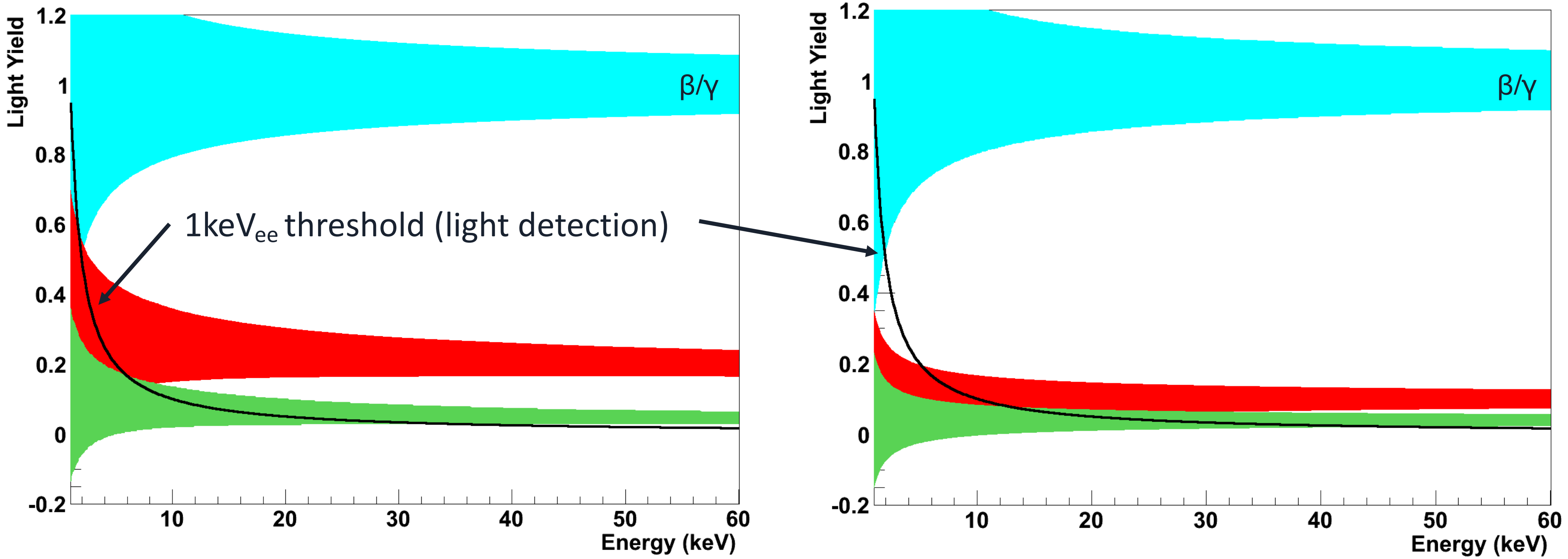


Standard dark matter halo
Fixed quenching factors:
QF_{Na}=0.3, QF_{I}=0.09

Blue band: COSINUS projection (incl. stat. fluctuation) for 100kg days and 1keV nuclear recoil threshold

Dotted lines: Exemplary COSINUS projections for 100kg days and thresholds as in legend

QUENCHING FACTORS



recoils off Na → factor ~ 0.3

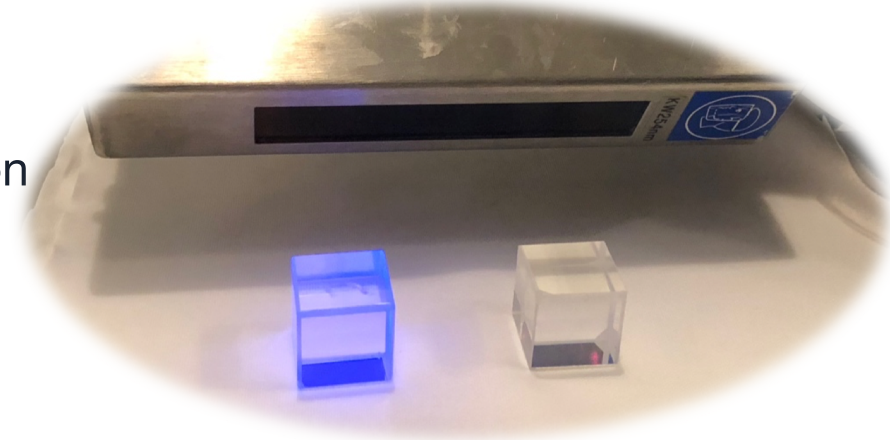
recoils off I → factor ~ 0.1

recoils off Na → factor ~ 0.1

recoils off I → factor ~ 0.04

CRYSTAL PROGRAM

Since 1928 SICCAS



- Collaboration with I. Dafinei from Roma 1 (MAECI project)
- Yong Zhu from SICCAS is member of the COSINUS collaboration
- Different batches of crystals tested in the last months
  - NaI / NaI(Tl) grown from SICCAS powder (> 3rd prototype) (3 g – 30 g crystals)

- <u>Crystals that will be/ are tested in the upcoming runs:</u>

NEW

  - NaI / NaI(Tl) grown from Astrograde-powder
    → promising radiopurity: 5-9 ppb at crystals' nose and 22-35 ppb at the tail (3-inch crystal @ SICCAS)
  - NaI / NaI(Tl) grown with internal samarium ”contamination” to study alpha quenching factor
  - NaI(Tl) with different amount of thallium dopant

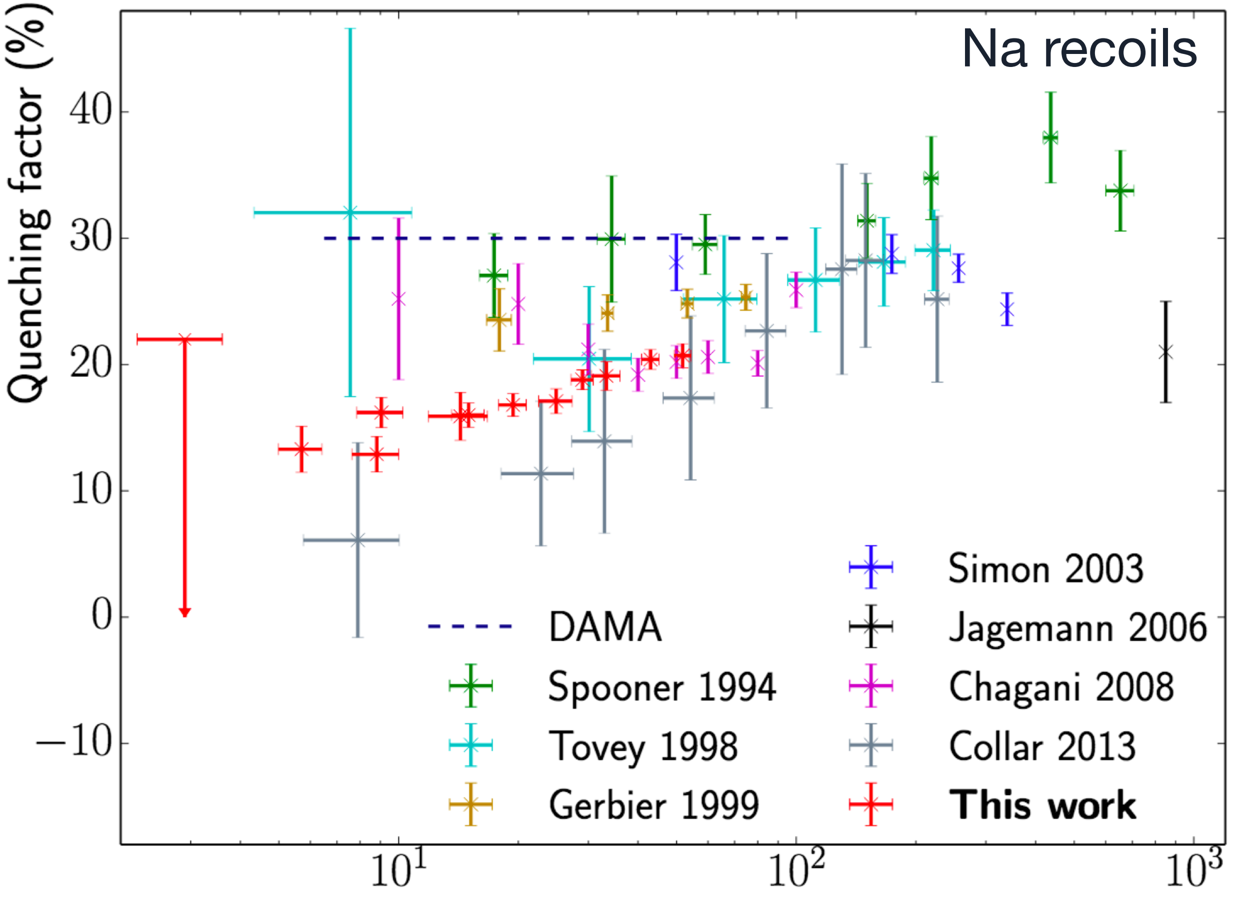
NaI crystal radiopurity
Preliminary ICP-MS Results S. Nisi (LNGS)

Sample	Powder	Crystal Grower	K	Rb	Pt	Tl	Th	U
			ppb	ppb	ppb	ppm	ppb	ppb
MLL_V1	SICCAS	SICCAS	28000	8	<0.6	2.5	<0.015	<0.015
MLL_V2	SICCAS	SICCAS	1100	<3	6	180	<0.015	<0.015
NaI 4_1_1	Astrograde	SICCAS	350	<3	250	1800	0.1	0.2
DAMA/LIBRA crystal*			~13	<0.35			$0.7 – 10 \times 10^{-3}$	$0.5 – 7.5 \times 10^{-3}$

* Bernabei et al., NIM A592 (2008) 297-315

“DAMA-LIKE” SETUPS - INTERPRETATION

BACKGROUND MODULATION



Phys. Rev. C 92, 015807 (2015)

Quenching factors are uncertain
→
Uncertainty on nuclear recoil energy scale

CRYSTAL RADIOPURITY

Powder

Element	Astrograde	SICCAS	DAMA
K [ppb]	<15	100	<20
U [ppt]	<10	<5	0.7-10
Th [ppt]	<10	<10	0.5-7.5

Crystal

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

Bernabei et al., NIM A592 (2008) 297-315

Sample	K [ppb]
NaI powder	30±10
NaI-ingot (nose)	18±7
NaI-ingot (tail)	25±8

WHAT COSINUS CAN DO WITH A DM MODULE

DAMA (&COSINE,SABRE …?) signal

COSINUS has the unique potential to clarify a nuclear recoil origin

Confirm

O(100kgd) most probably sufficient

Rule-out

O(100kgd): Strong statement

O(1000kgd): Fully model-independent statement possible

(Felix Kahlhoefer, FR, et al JCAP05(2018)074)

COSINUS – 1π GOAL

GOAL: Collect O(100kg days)

10 modules @ 50g for 1 year
with 50% overall efficiency*:

91kgd net exposure

04/2019

Conceptual design report
handed to the scientific
committee of the LNGS
underground laboratory

→

full endorsement for COSINUS

*includes: cryostat refills, calibration campaigns, cuts

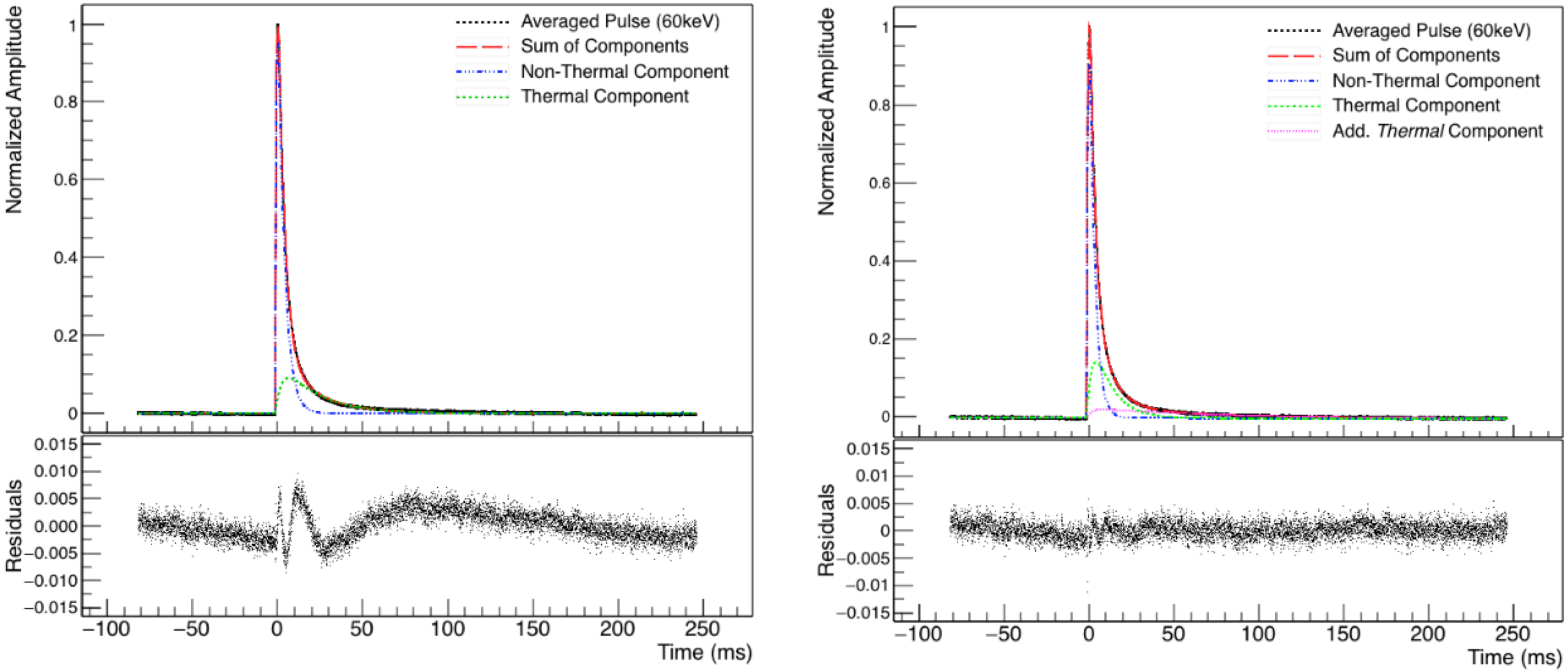
LONG DECAY TIMES – PULSE MODEL

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

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



(a)Two-component pulse model

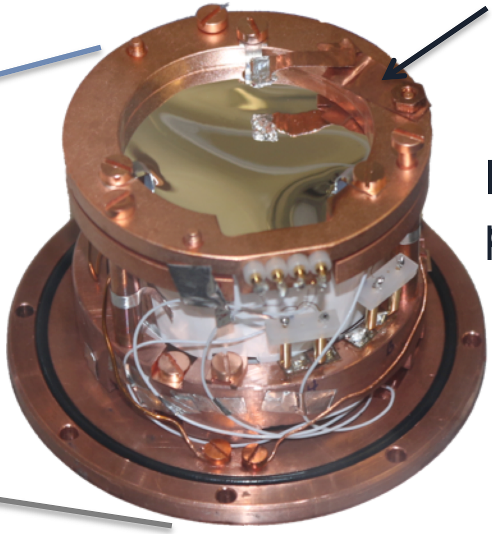
(b)Three-component pulse model

MOUNTING IN CRYOSTAT

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

Decoupling system
to reduce microphonic noise

Copper
housing

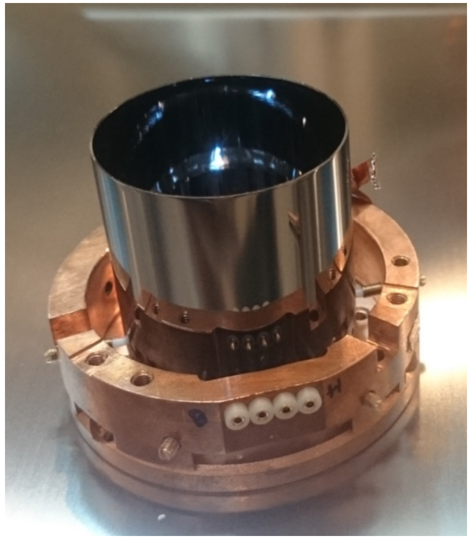


Light detector

NaI
phonon detector

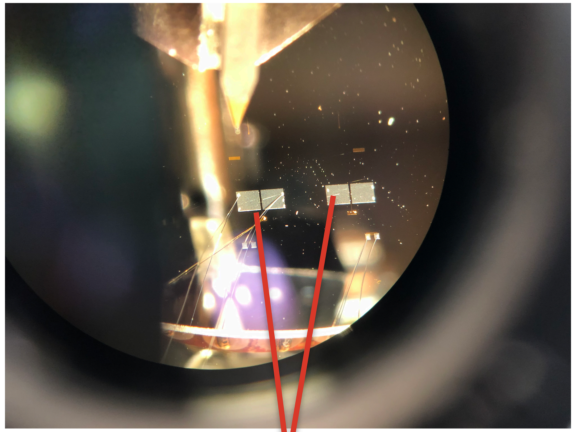
FINAL BEAKER-SHAPED LIGHT DETECTOR
2ND PROTOTYPE (2016/17)

- From OPTEC company with perfect surface quality
- Diameter: 40mm
- Height: 38mm
- Mass: 4g



38mm

40mm



TESs