

# COSINUS

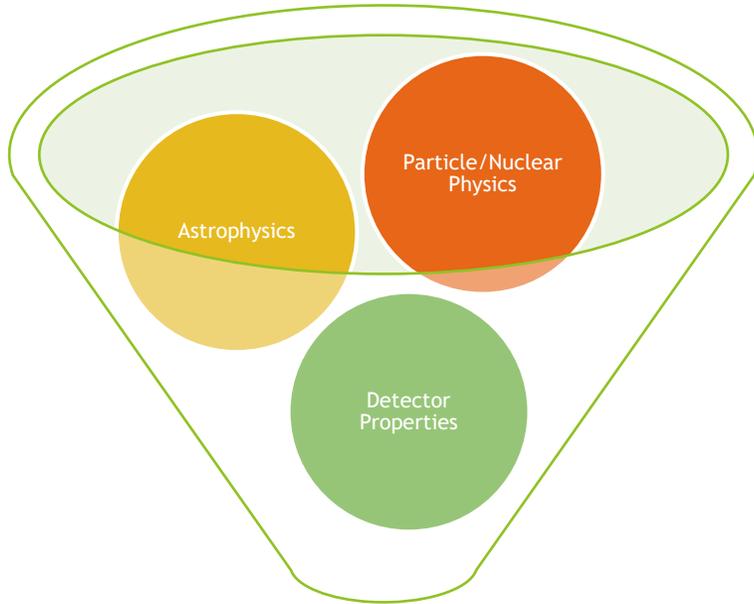
## a NaI-based experiment for DM search

Natalia Di Marco

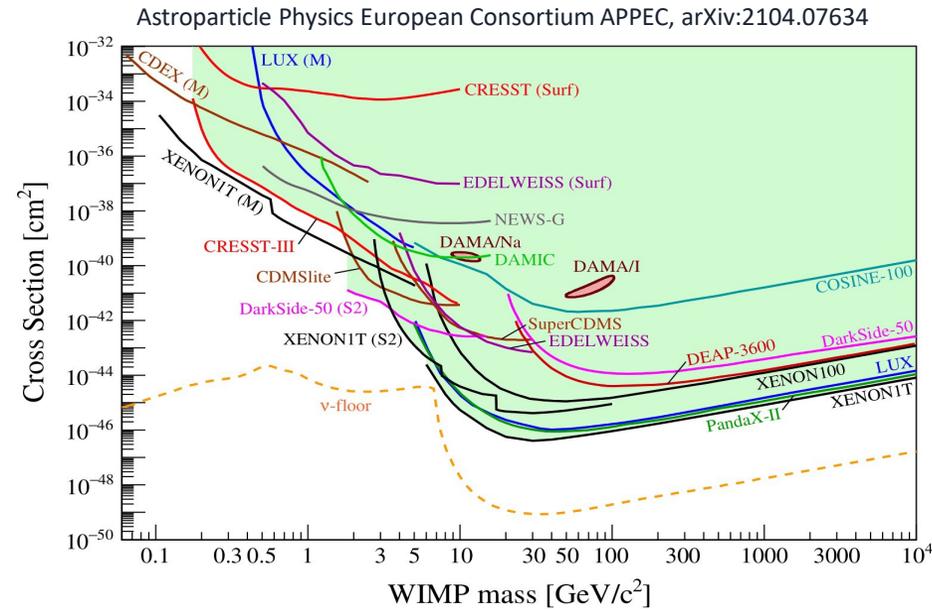
GSSI & INFN

on behalf of the COSINUS Collaboration

# Direct DM detection landscape



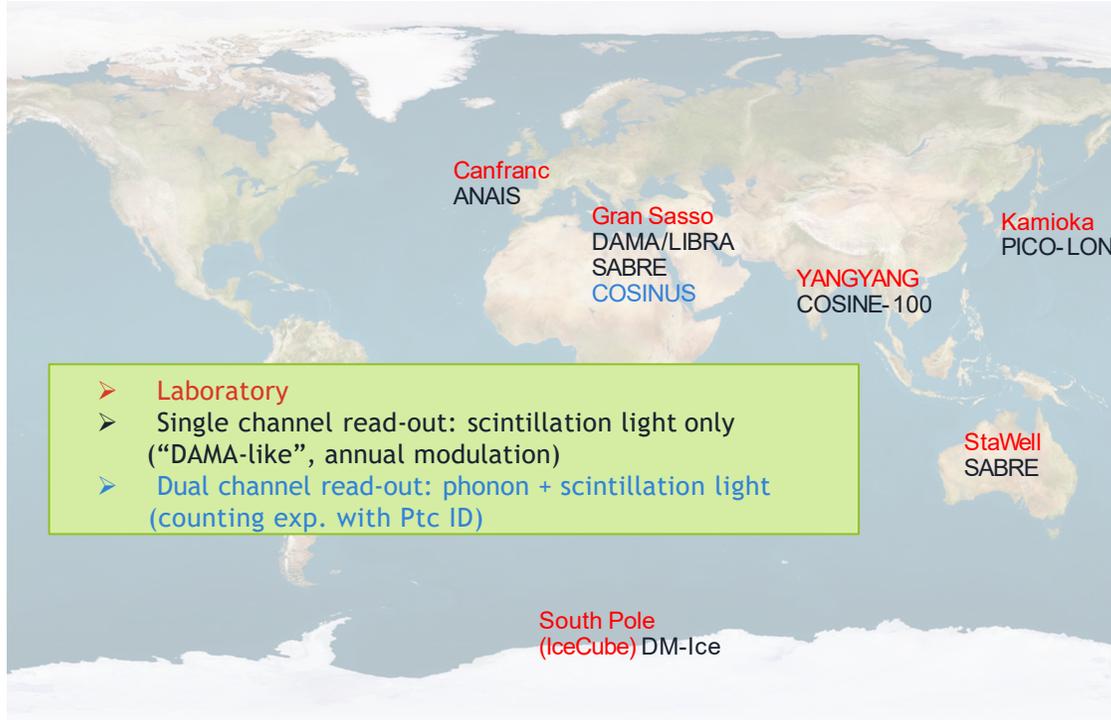
$$\frac{dR}{dE_r} = N_N \frac{\rho_0}{m_\chi} \int_{v_{min}}^{v_{max}} d\vec{v} f(\vec{v}) v \frac{d\sigma}{dE_r}$$



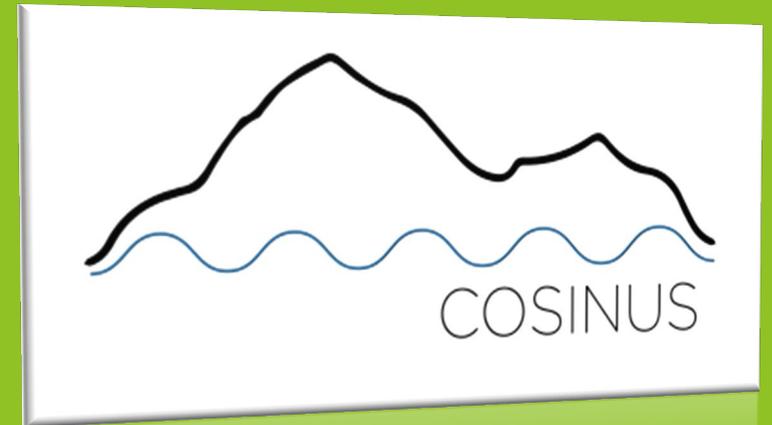
Astroparticle Physics European Consortium (APPEC)  
Recommendation:

*“The long-standing claim from DAMA/LIBRA [...] needs to be independently verified using the same target material.”*

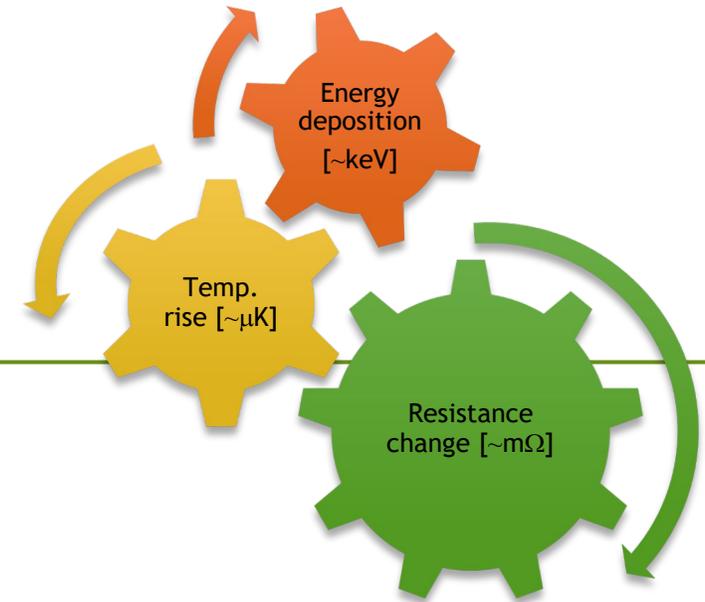
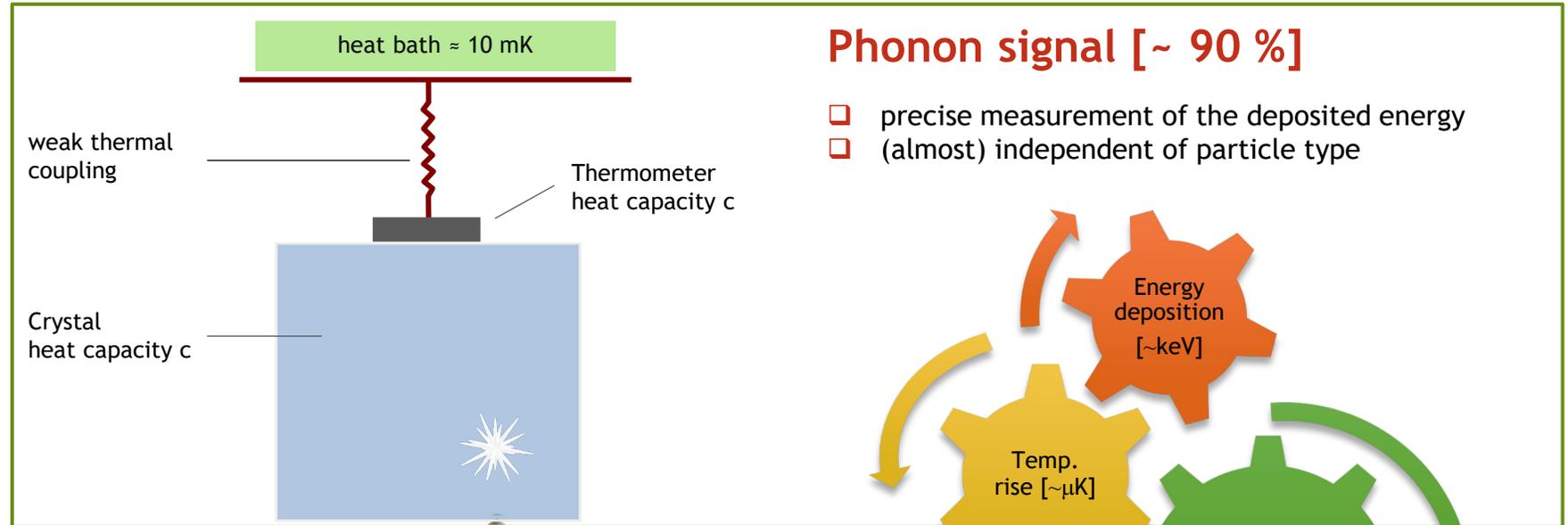
# Nal-based DM search



- **Laboratory**
- Single channel read-out: scintillation light only (“DAMA-like”, annual modulation)
- Dual channel read-out: phonon + scintillation light (counting exp. with Ptc ID)



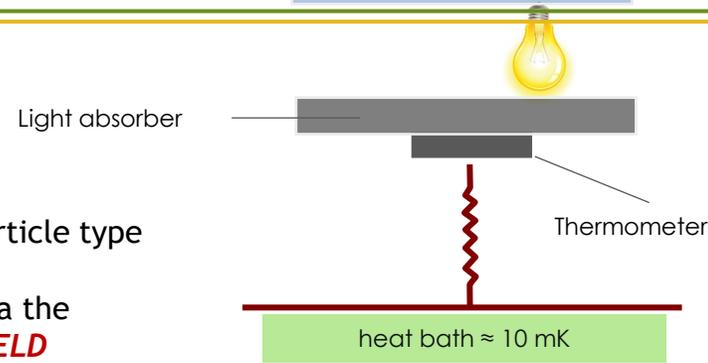
# COSINUS detection principle



## Scintillation light [0(1-10%)]

### Cryogenic light detector

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

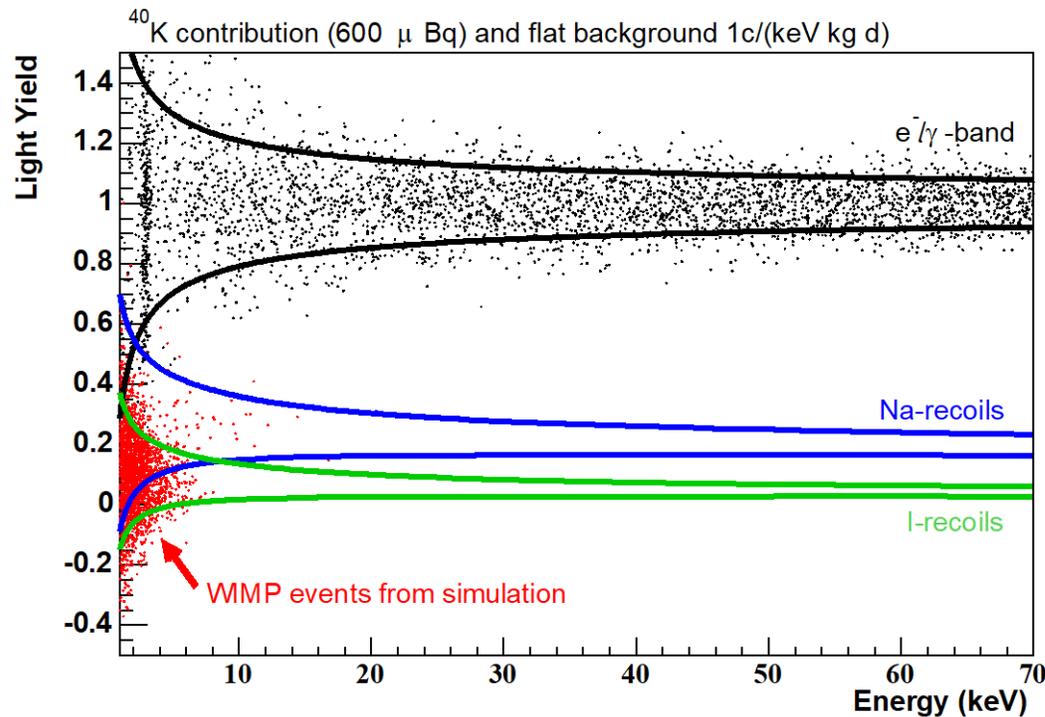


G. Angloher et al., EPJ C 76:441 (2016)

# COSINUS detection principle

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

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



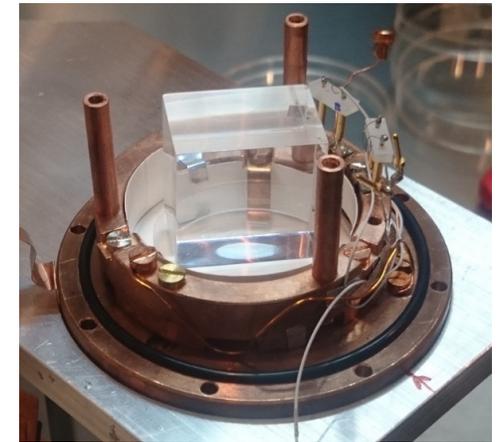
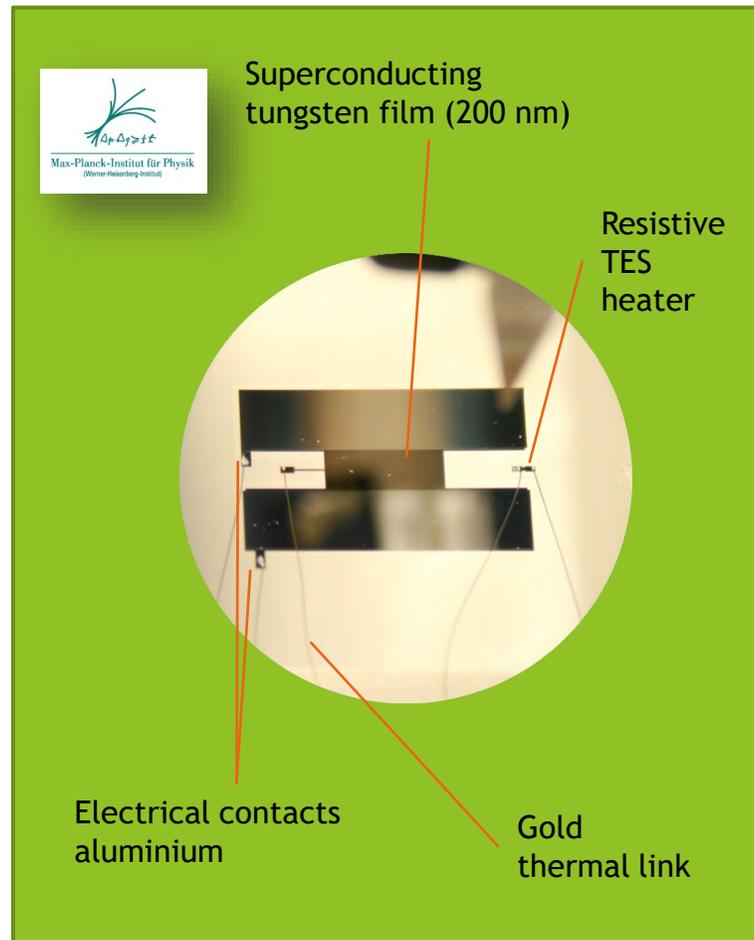
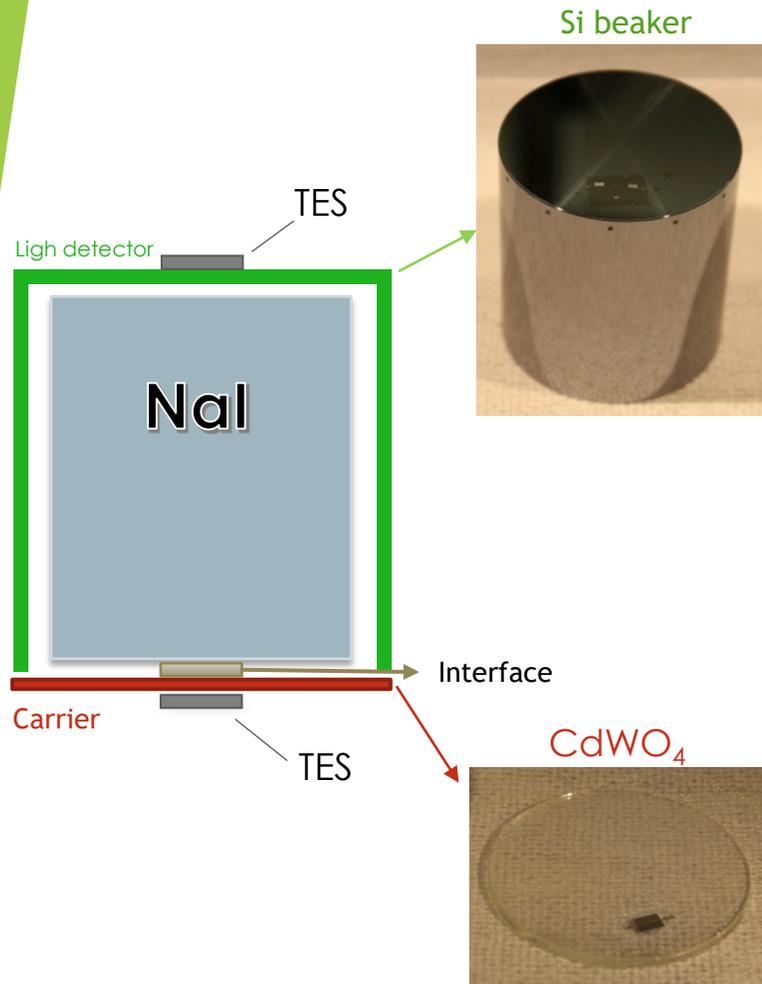
Exposure before cuts: 100 kg-days

- ▶ flat background: 1 / (keV kg d) + <sup>40</sup>K background: 600mBq/kg
- ▶ recoils off Na: light quenching factor ~ 0.3
- ▶ recoils off I: light quenching factor ~ 0.1
- ▶ Red: 10 GeV/c<sup>2</sup> WIMP with 2E-04 pb as from Savage et al.



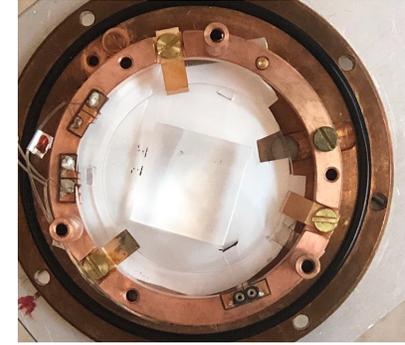
(QF from Tretyak, Astropart. Phys. 33, 40 (2010))

# COSINUS detector unit



# Nal crystal

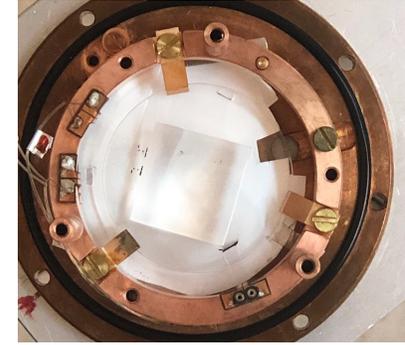
- ▶ Highly hygroscopic:  
handling in controlled ( $N_2$ ) atmosphere  
need for a carrier crystal for TES



Material	Debye Temp. [K]
$Al_2O_3$	1040
$MgF_2$	620
$CdWO_4$	360
Nal	169

# NaI crystal

- ▶ Highly hygroscopic:
  - handling in controlled (N<sub>2</sub>) atmosphere
  - need for a carrier crystal for TES
- ▶ Typically, high contamination with <sup>40</sup>K:
  - COSINUS crystals produced in collaboration with SICCAS
    - ▶ modified Bridgman technique using platinum foil crucibles
    - ▶ Astrograde powder from MERCK Company



Material	Debye Temp. [K]
Al <sub>2</sub> O <sub>3</sub>	1040
MgF <sub>2</sub>	620
CdWO <sub>4</sub>	360
NaI	169

NaI Powder

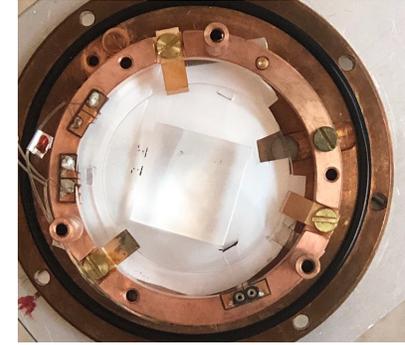
Element	Astrograde	SICCAS	DAMA
K [ppb]	<15	100	<20
U [ppt]	<10	<5	0.7-10
Th [ppt]	<10	<10	0.5-7.5

NaI cristal from SICCAS

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

# Nal crystal

- Highly hygroscopic:
  - handling in controlled ( $N_2$ ) atmosphere
  - need for a carrier crystal for TES
- Typically, high contamination with  $^{40}K$ :
  - COSINUS crystals produced in collaboration with SICCAS
    - modified Bridgman technique using platinum foil crucibles
    - Astrograde powder from MERCK Company
- Low Debye temperature:
  - small amplitude signal
- Large band gap due to the mass difference between NaI and I ions:
  - long decay time



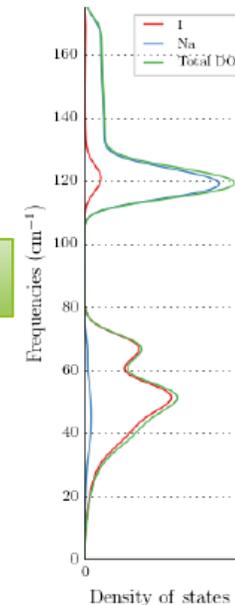
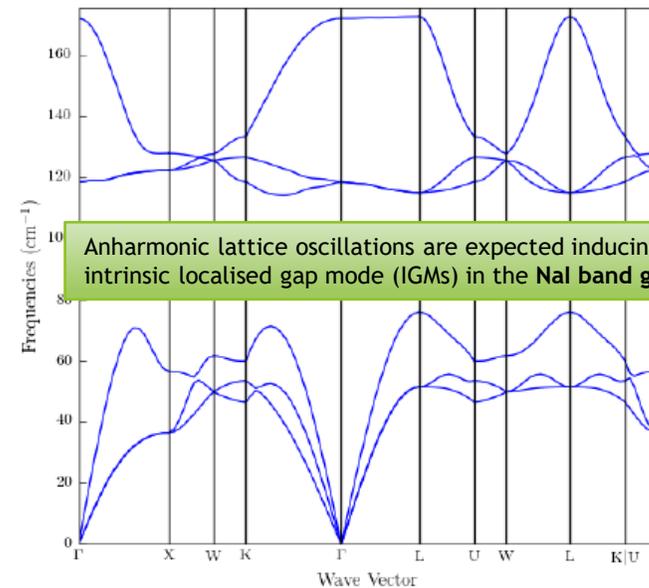
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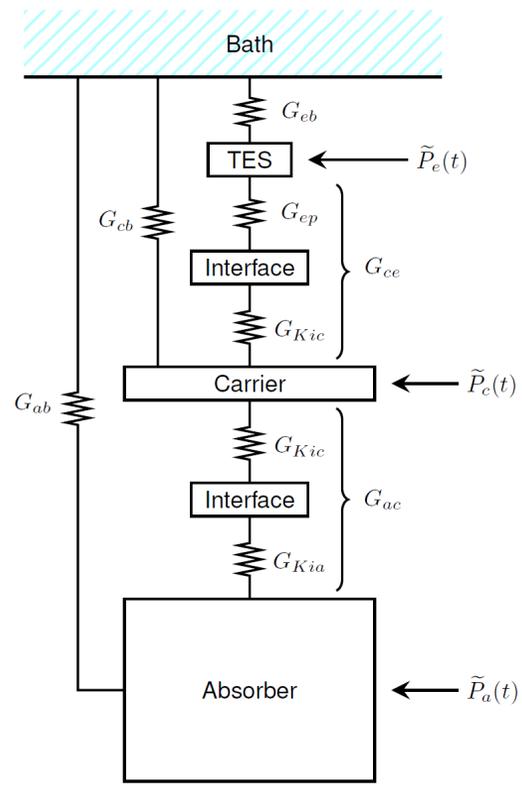
NaI cristal from SICCAS

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



IGM localisation of energy could cause a non thermal phonon transmission delay through the absorber - carrier interface

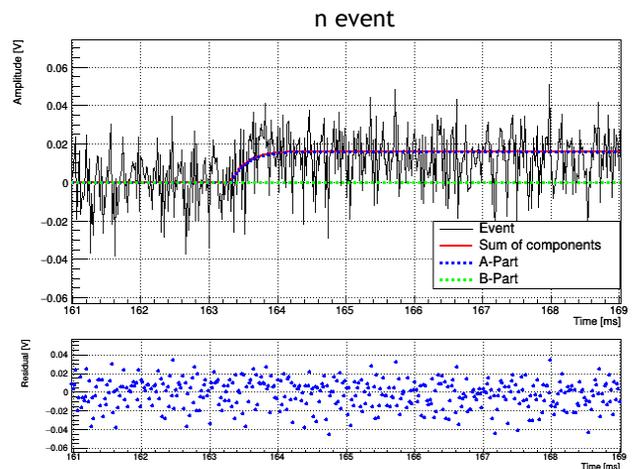
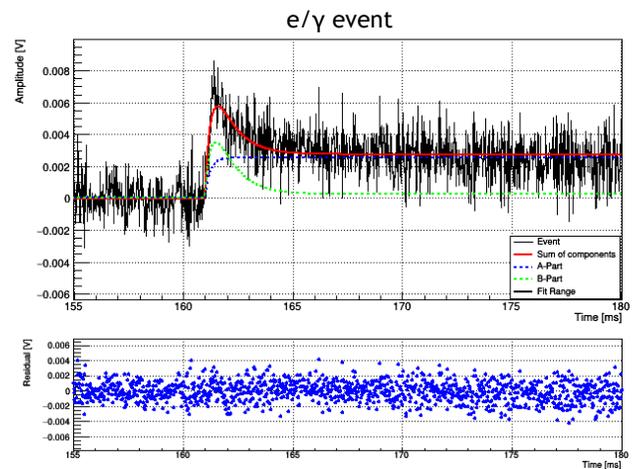
# Nal(ce) detector response model



$$\Delta T_e(t) = \underbrace{\sum_{i=1}^3 A_i [e^{\lambda_i t} - e^{-t/\tau'_n}]}_{\text{A-components}} + \underbrace{\sum_{i=1}^3 B_i [e^{\lambda_i t} - e^{-t/\tau_l}]}_{\text{B-components}}$$

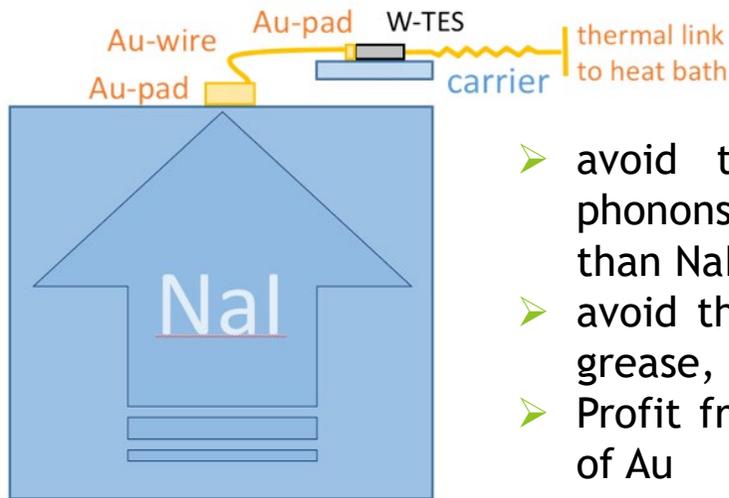
**A-Part** is proportional to the power input related to the phonons transmitted from the NaI-absorber to the TES → small amplitude, long tail

**B-part** is proportional to the power input related to the phonons produced in the carrier by the NaI-scintillation light absorption → large pulse height amplitudes and fast decay time



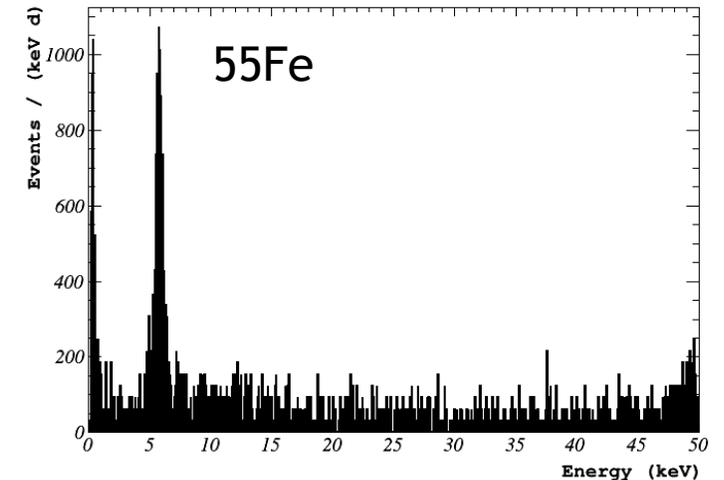
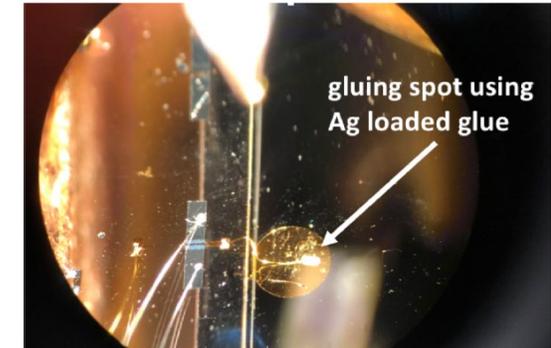
# Nal(ce) detector phonon sensor (R&D)

RemoTES (Originally proposed in M. Pyle et al., arXiv:1503.01200 (2015))

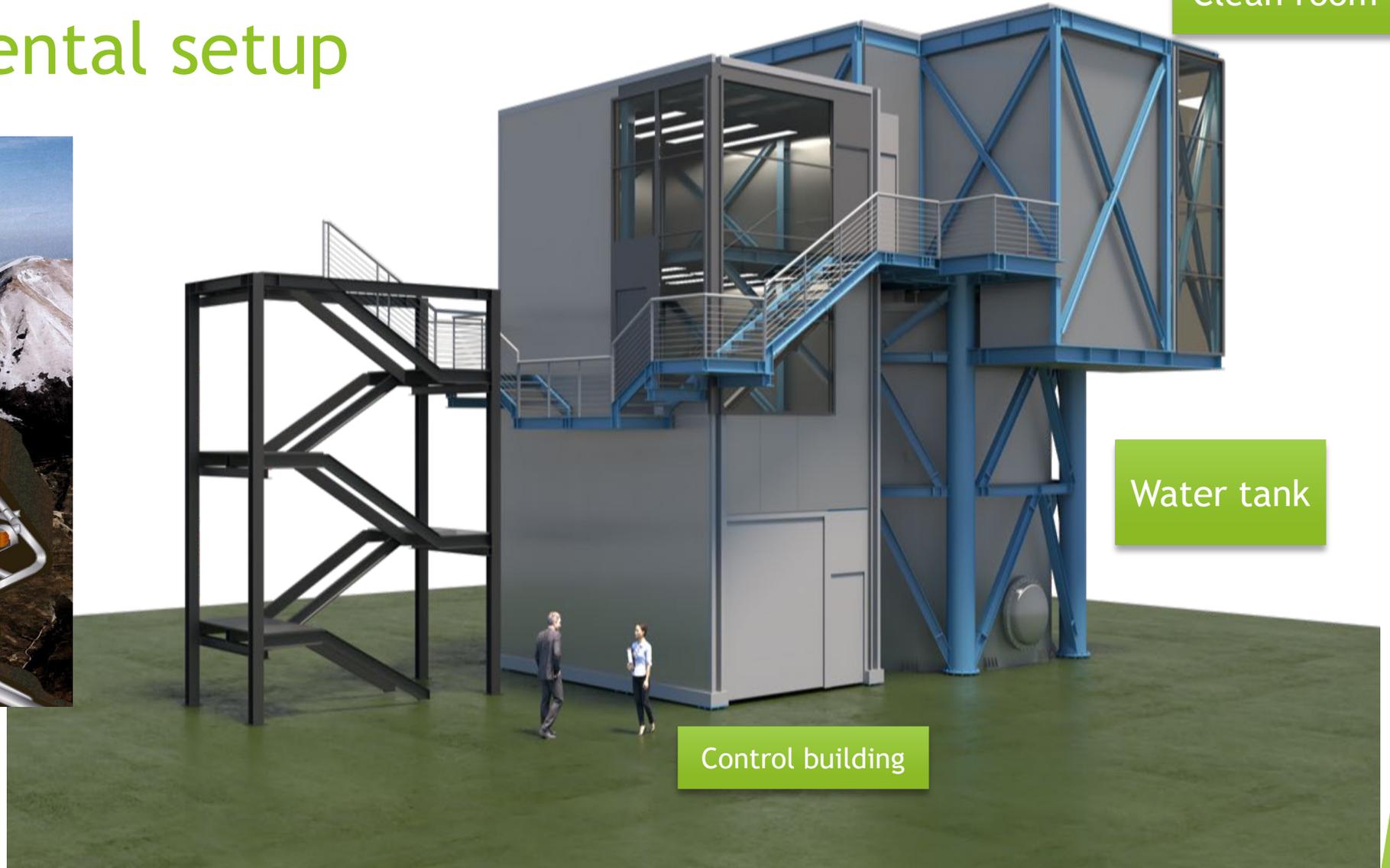
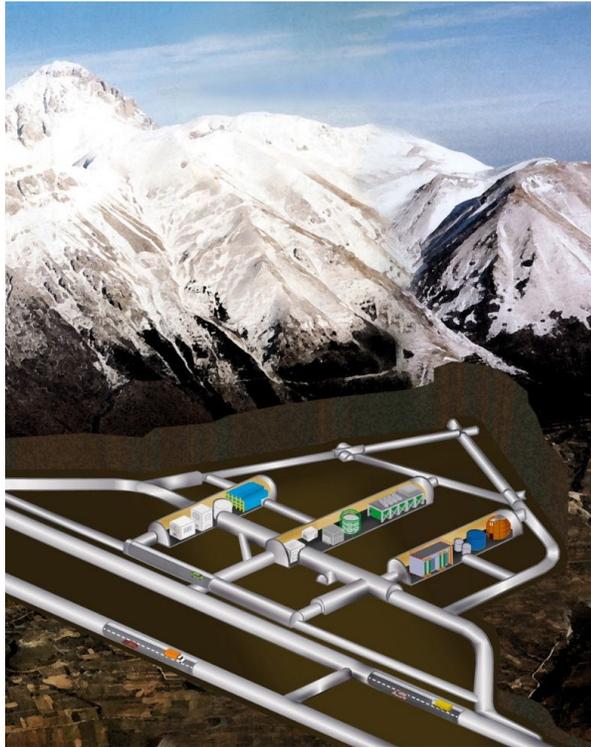


- avoid the carrier crystal, (thus avoid phonons passing through another material than NaI)
- avoid the amorphous interface (e.g. glue, grease, oil, ...)
- Profit from good electron-phonon coupling of Au
- above-ground measurements using Si and TeO<sub>2</sub> absorbers: successful operation of first remo-TES detectors

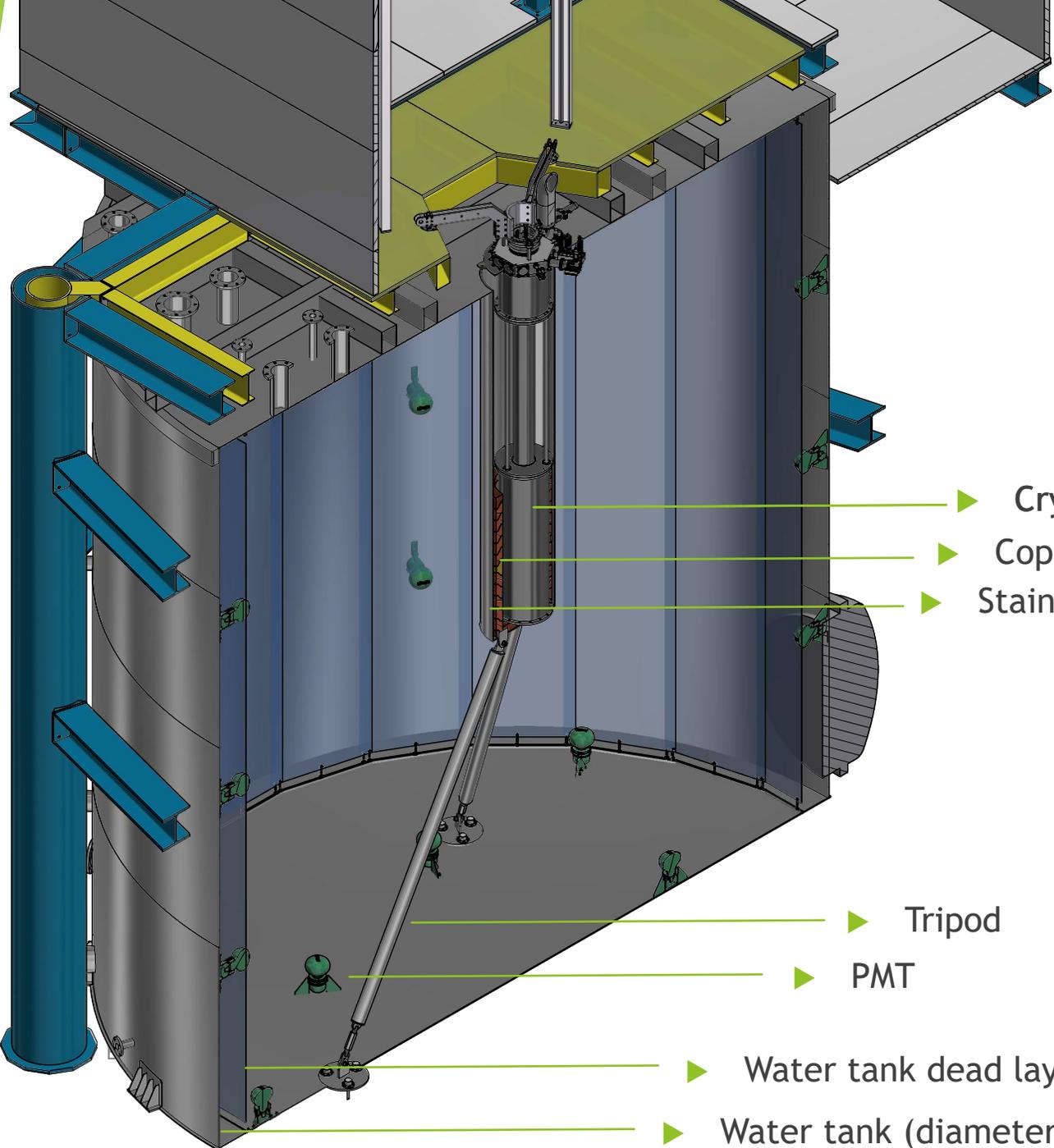
Threshold = 323 eV with a Si absorber (20x10x5 mm<sup>3</sup>)



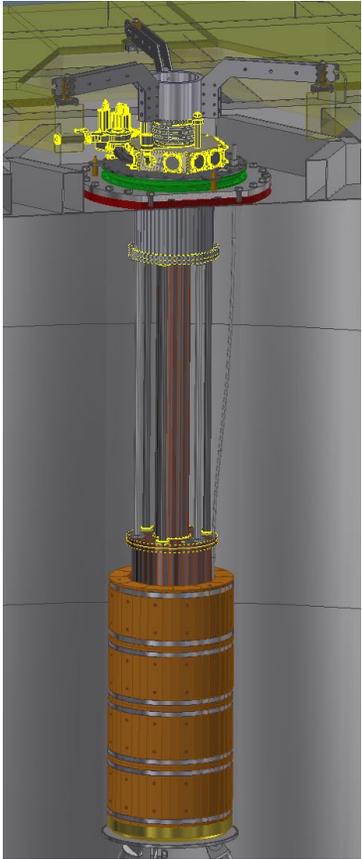
# Experimental setup



# Experimental setup



- ▶ Cryostat
- ▶ Copper shield (8 cm)
- ▶ Stainless steel dry - well
- ▶ Tripod
- ▶ PMT
- ▶ Water tank dead layer
- ▶ Water tank (diameter=7m, height=7 m)

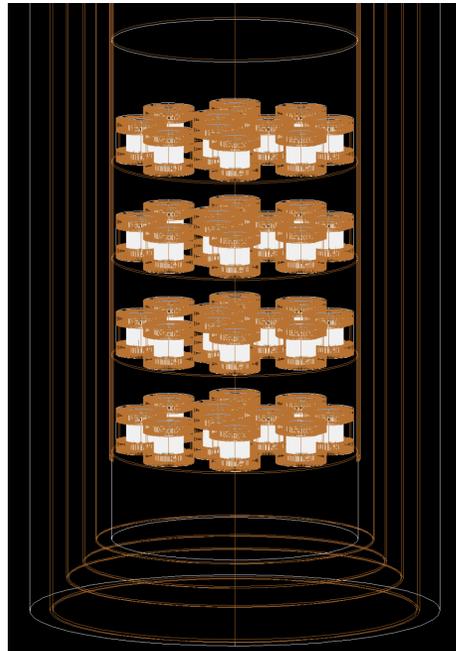


# Experimental setup

## DRY DILUTION REFRIGERATOR

- Design and manufacturing from Cryoconcept
- UQT technology
- Custom length of 3500 mm
- Additional decoupling at the detector stage

- 12 modules/layer
  - 70 mm/module
  - up to 0(150 gr) crystal
- Experimental volume thickness: 600 mm
  - 1 layer thickness: 100 mm
  - up to 6 layers (72 modules)



# Physics reach

## COSINUS-1 $\pi$

Exclusion (95% C.L.) without presuming any model on the dark matter halo or interaction properties except for the assumption that dark matter induces nuclear recoils.

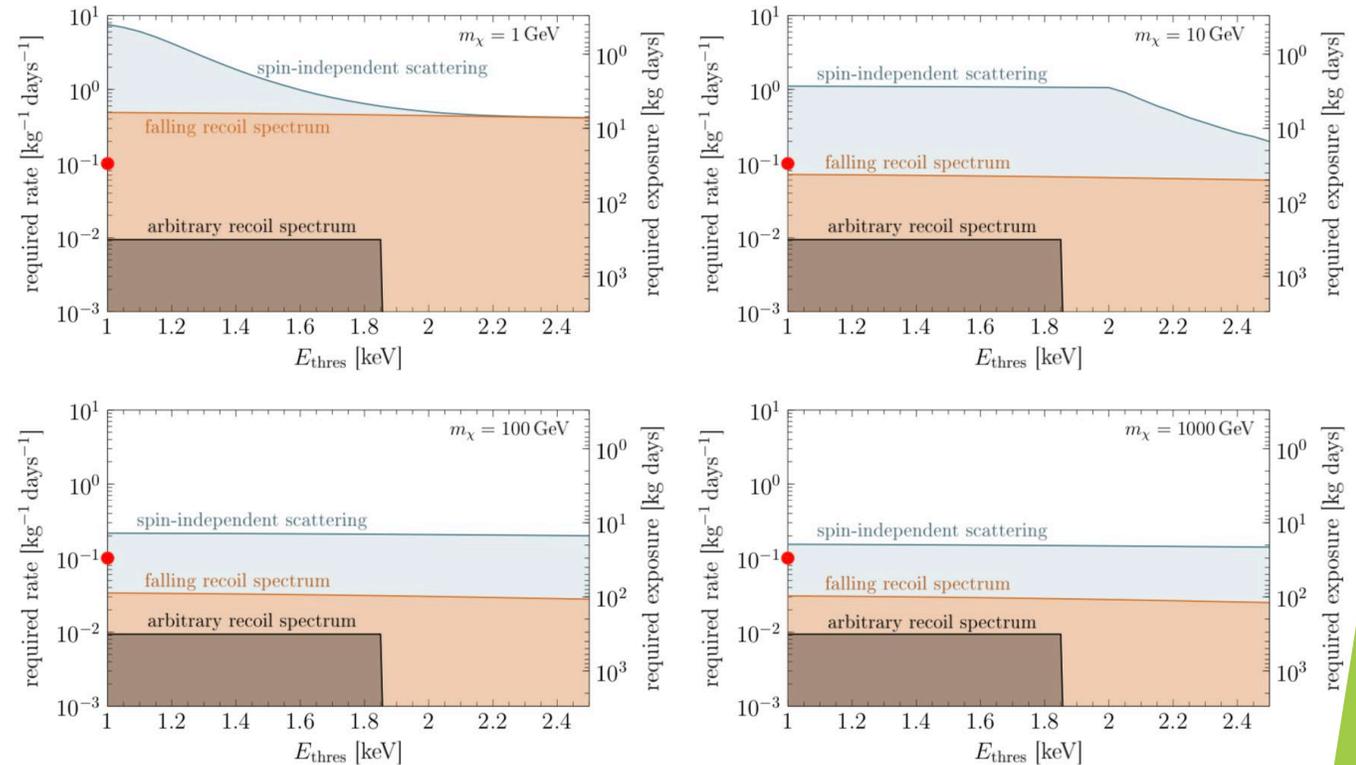
- 1.8 keV nuclear recoil threshold
- exposure 1000 kg days before cuts

20 crystals, 50 gr each  $\rightarrow$  3 year of data taking,  
20 crystals, 150 gr each  $\rightarrow$  1 year of data taking

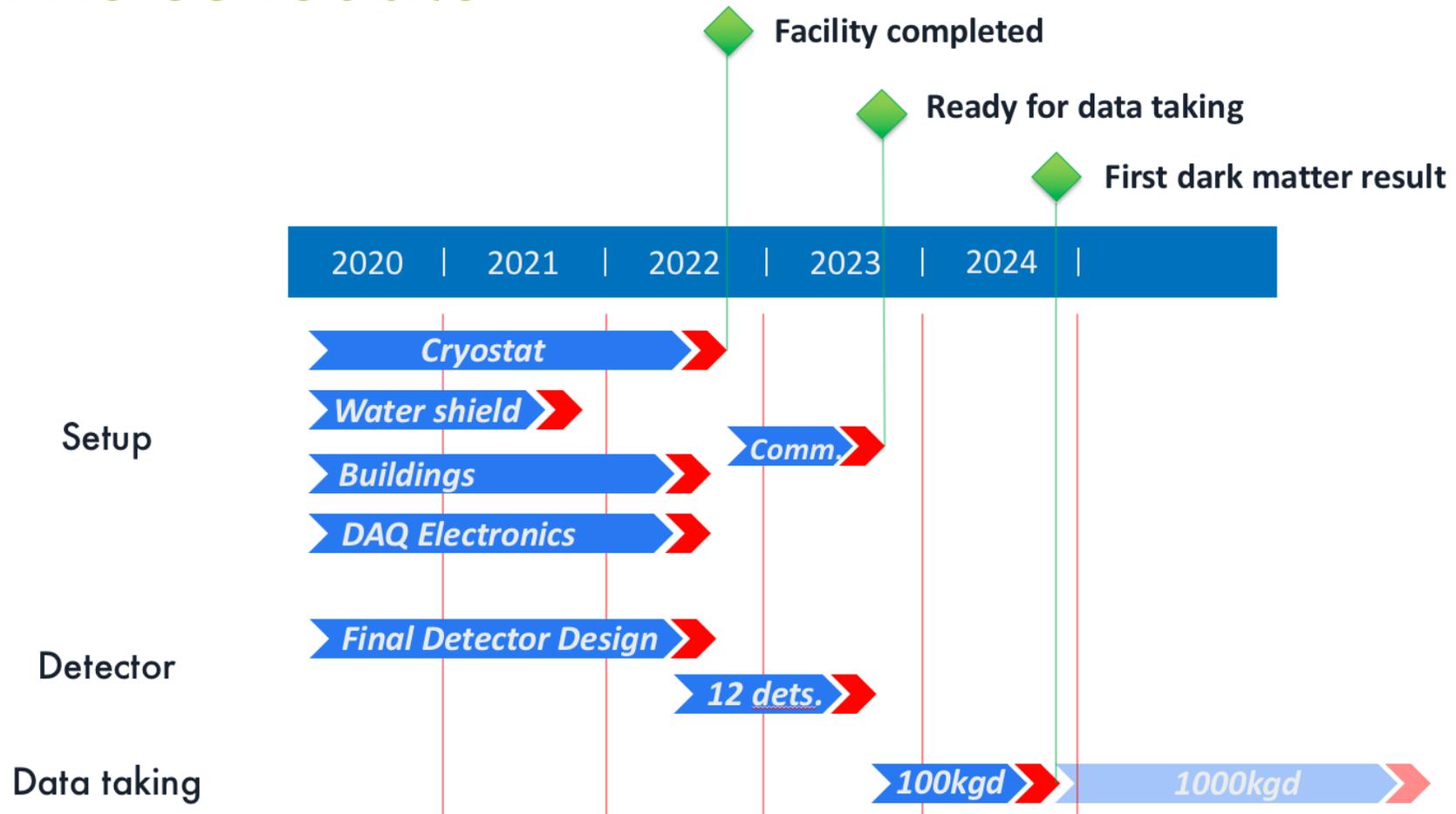
## COSINUS - 2 $\pi$

Investigate annual modulation signature with COSINUS

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



# Time schedule



# Crystal characterization

- ▶ Crystals produced with increasing TI concentration (from 0.1% to 0.9%) in powder



- ▶ Detailed ICP-MS measurements
- ▶ EXAFS test beam @ Diamond Facility (UK) in 2020 (analysis on going)
- ▶ Neutron test beam @ TUNL (USA) scheduled for August 2021
- ▶ LY measurement @ LNGS (analysis on going)
- ▶ Simulation of realistic lattice dynamics

# Conclusion

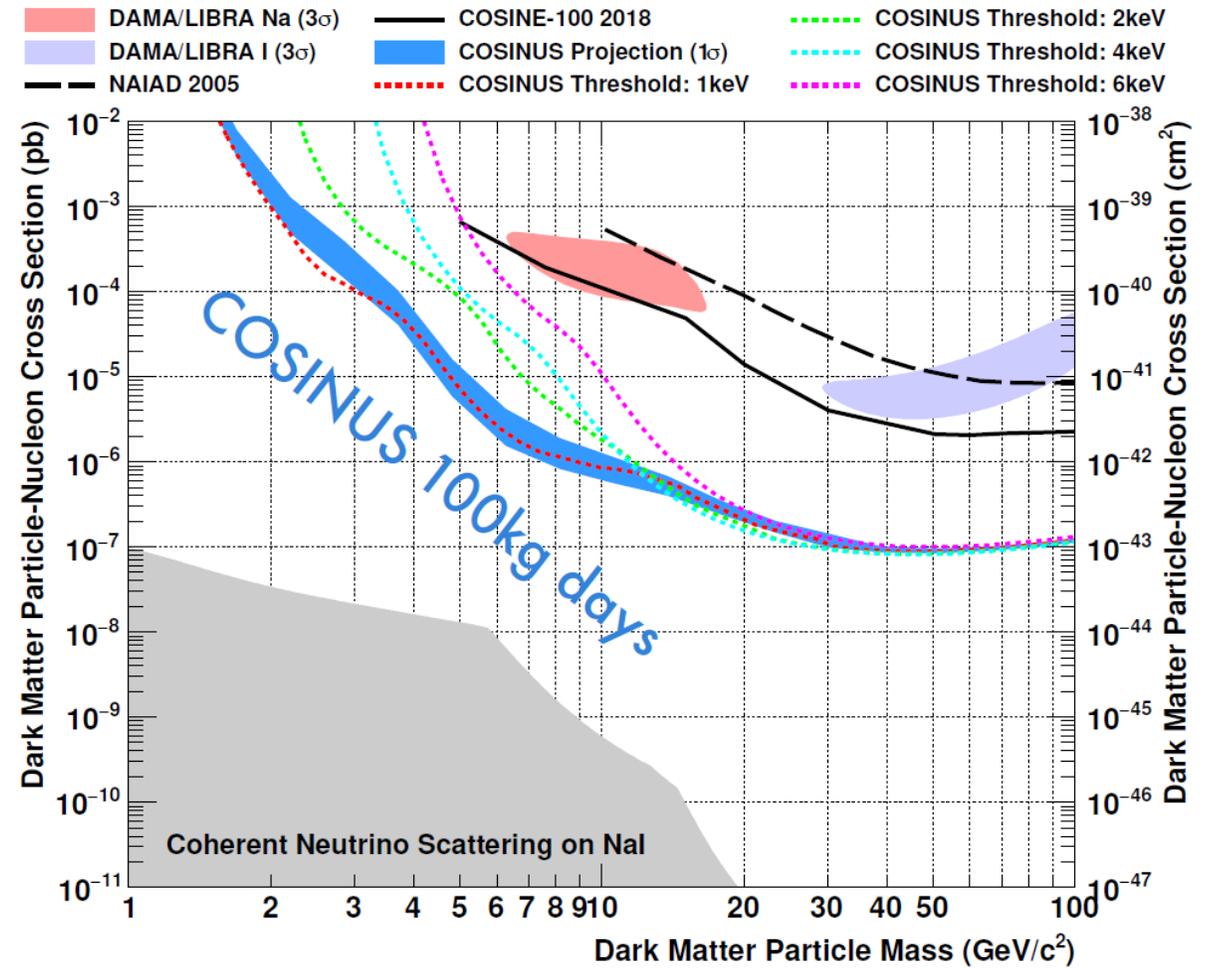
- ▶ Extensive studies of NaI crystal properties:
  - ▶ LY and QF measurements vs TI concentration at both room and cryogenic temperatures
  - ▶ EXAFS test beam
  - ▶ Lattice dynamics simulation for phonon propagation studies
- ▶ Production of highly radiopure crystals
- ▶ NaI crystals operated as cryogenic calorimeter
- ▶ Dual channel read-out allowing for particle identification on event-by-event basis
- ▶ Model-independent cross-check of DAMA/LIBRA claim using the same target material (NaI)
- ▶ Construction of COSINUS facilities coming soon:  $t_0$  in Autumn 2021
- ▶ First data expected in 2023

# backup

# Physics reach

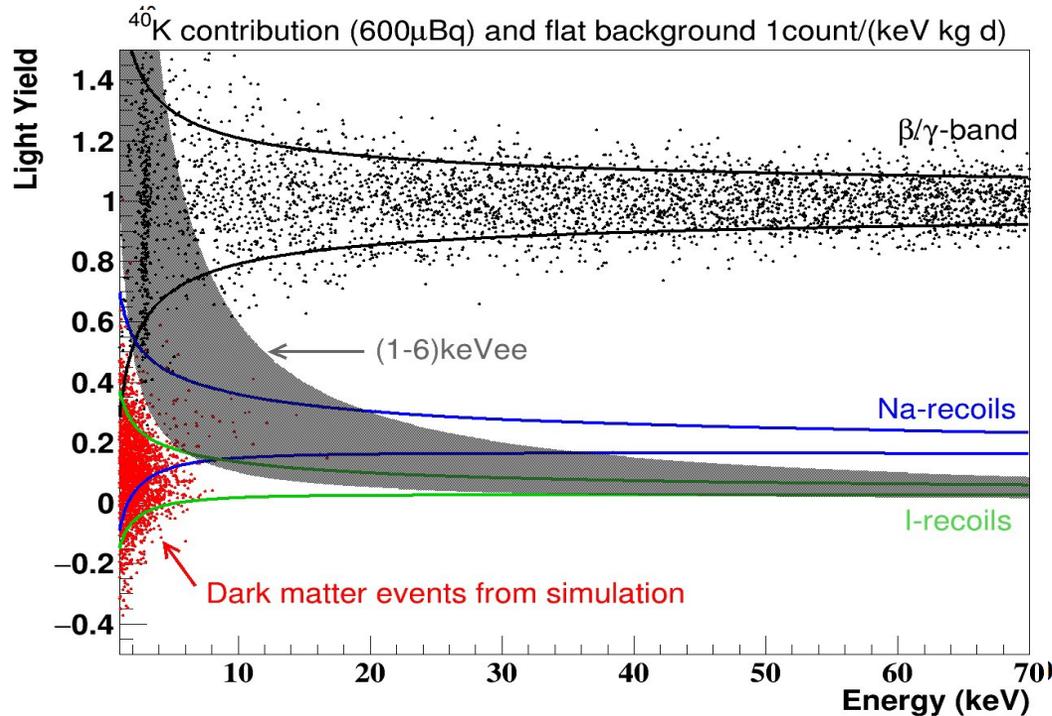
Standard scenario (SHM, spin independent interaction, elastic scattering)

100 kg days  
 10 crystals, 50 gr each → 1 year of data taking



# COSINUS detection principle

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



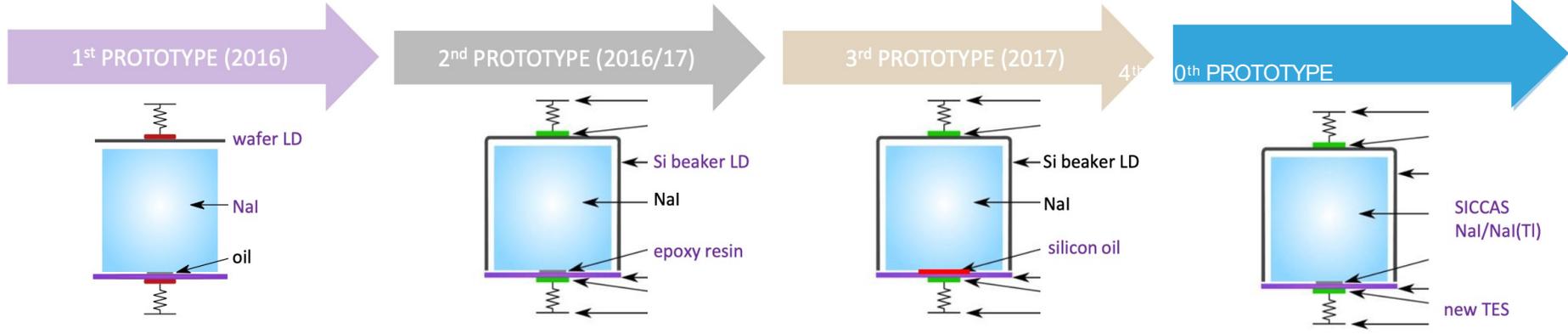
Exposure before cuts: 100 kg-days

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- ▶ recoils off Na: light quenching factor ~ 0.3
- ▶ recoils off I: light quenching factor ~ 0.1
- ▶ Red: 10 GeV/c<sup>2</sup> WIMP with 2E-04 pb as from Savage et al.



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

# R&D



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)

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

F. Reindl, TAUP 2017

tests with high-purity NaI/NaI(Tl) crystals from SICCAS

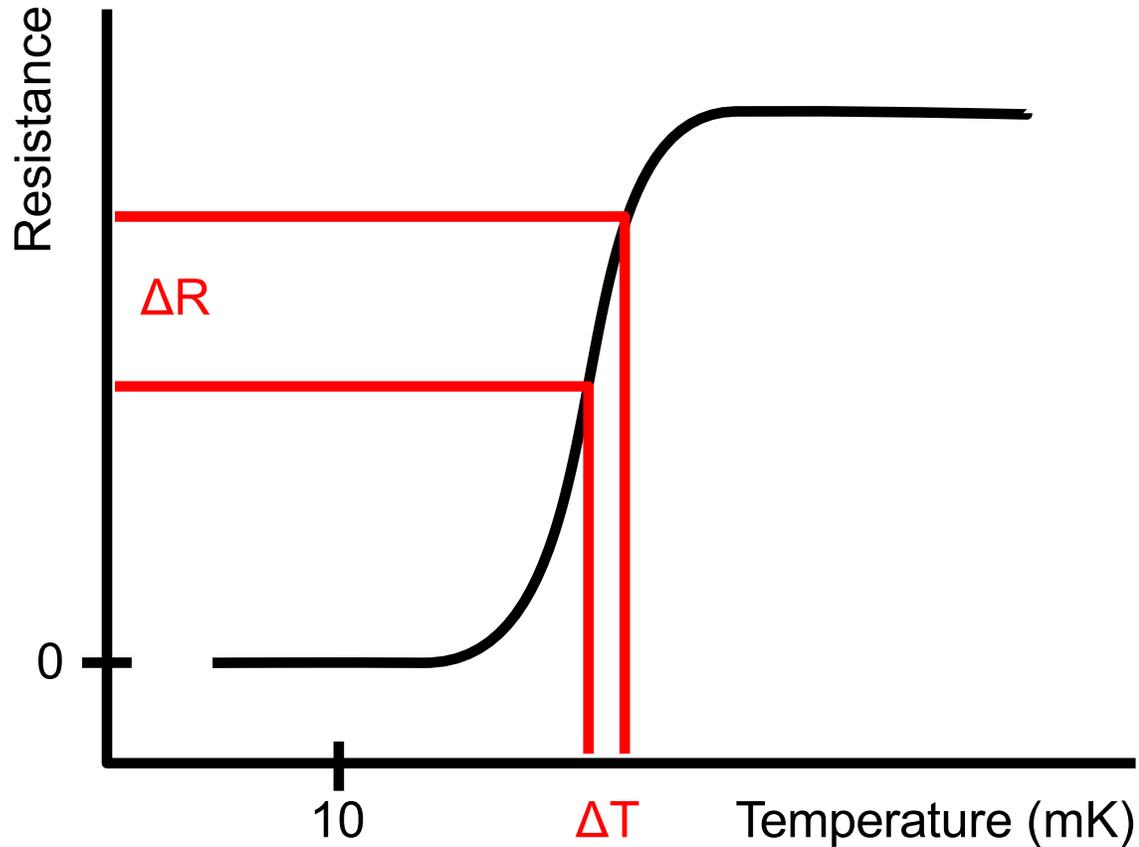
Tests of different TES-concepts for the NaI crystal, optimization of beaker design

**Work ongoing!**

➔ **Performance goal: 1 keV**

➔ **Performance goal: 4 %**

# Transition Edge Sensor (TES)

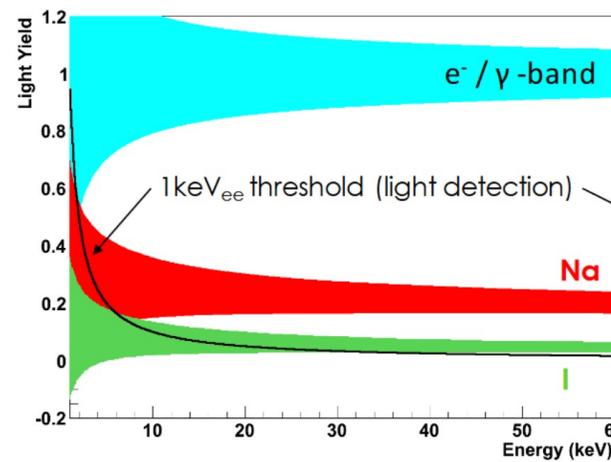
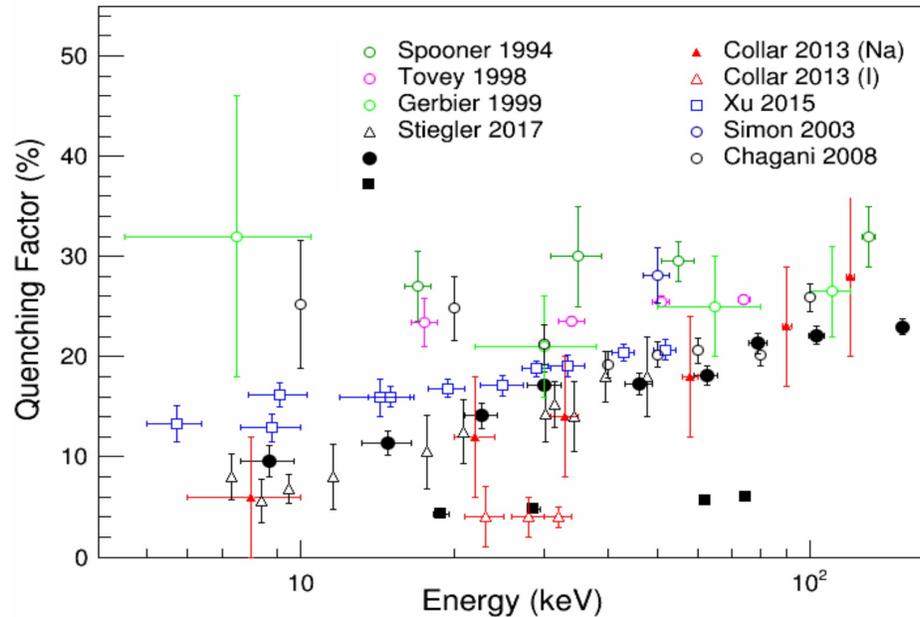


## COSINUS

### Performance goal

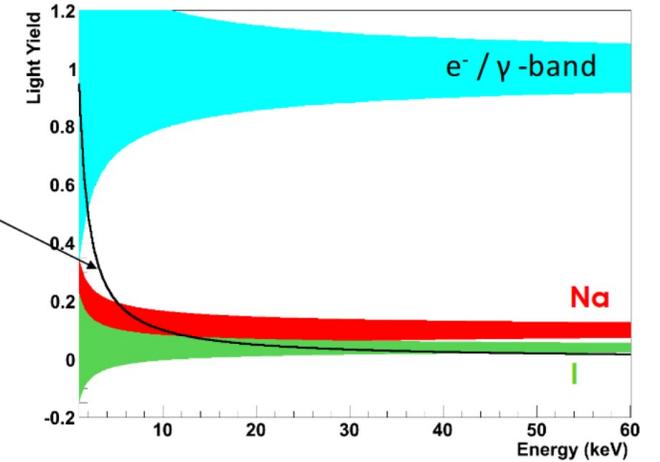
- ▶  $E_{th} = 1 \text{ keV} (5 \sigma_{\text{Phonon}})$
- ▶  $\sigma_{\text{Phonon}} = 0.2 \text{ keV}$
- ▶  $\sigma_{\text{Light}} = 0.11 \text{ keVee}$
- ▶ 4% of deposited energy measured as light

# Quenching Factor effect



recoils off Na → factor ~ 0.3

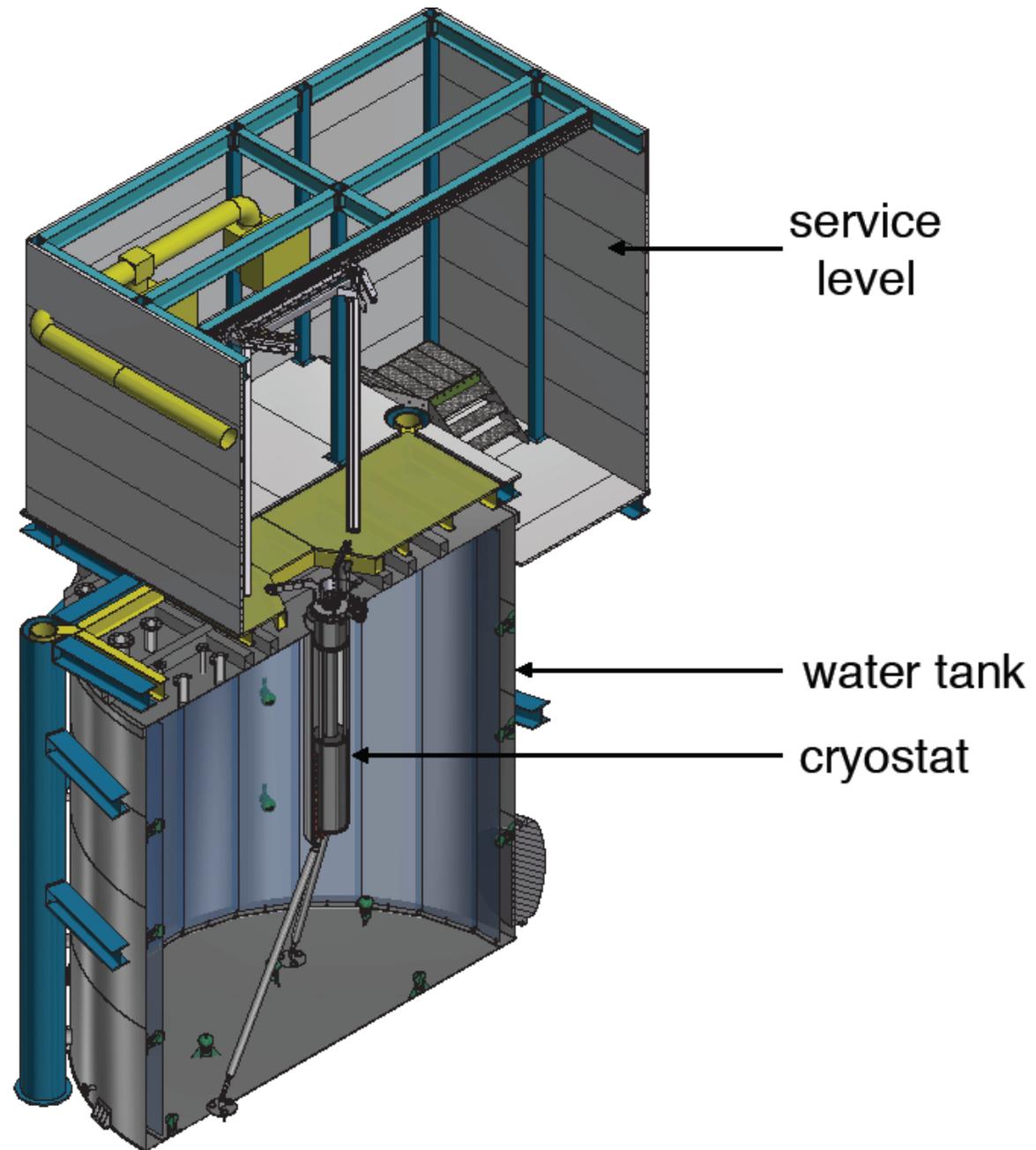
recoils off I → factor ~ 0.1



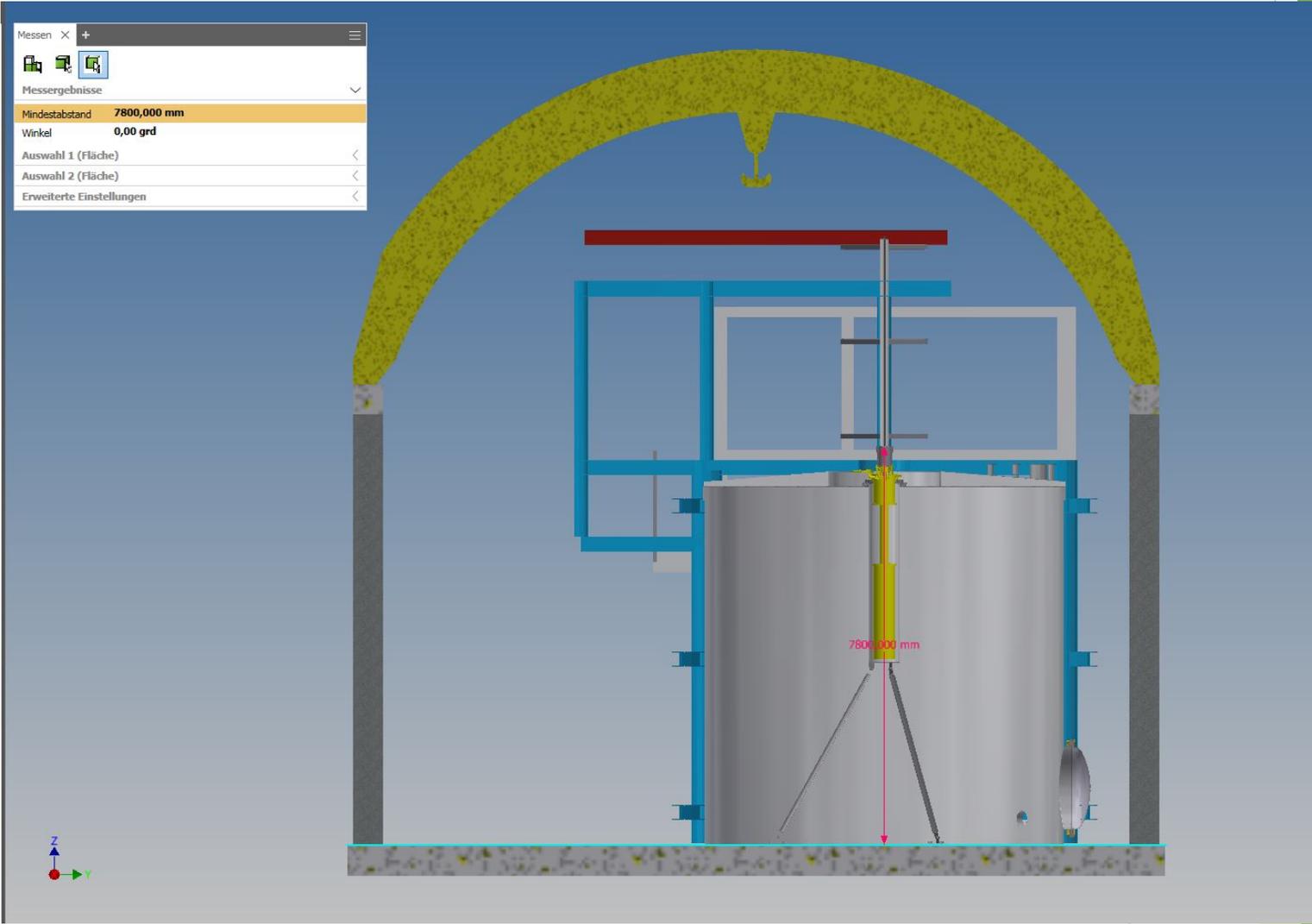
recoils off Na → factor ~ 0.1

recoils off I → factor ~ 0.04

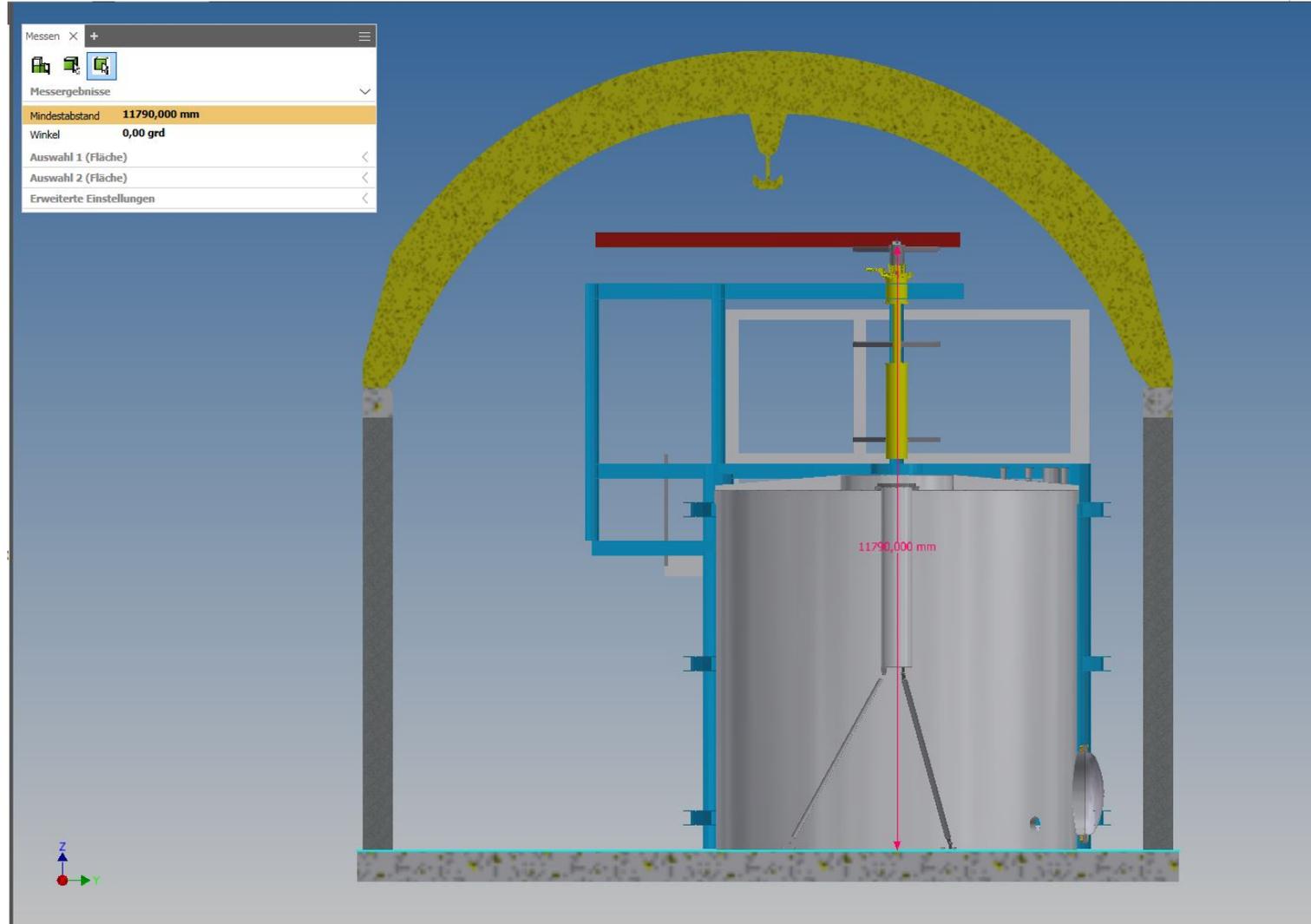
- Measurements of quenching factors (QF) at room temperature disagree
- In particular, role of TI is unclear (usually crystals are doped)
- Strong influence of QF on signal interpretation on nuclear recoil energy scale of scintillation-only experiments



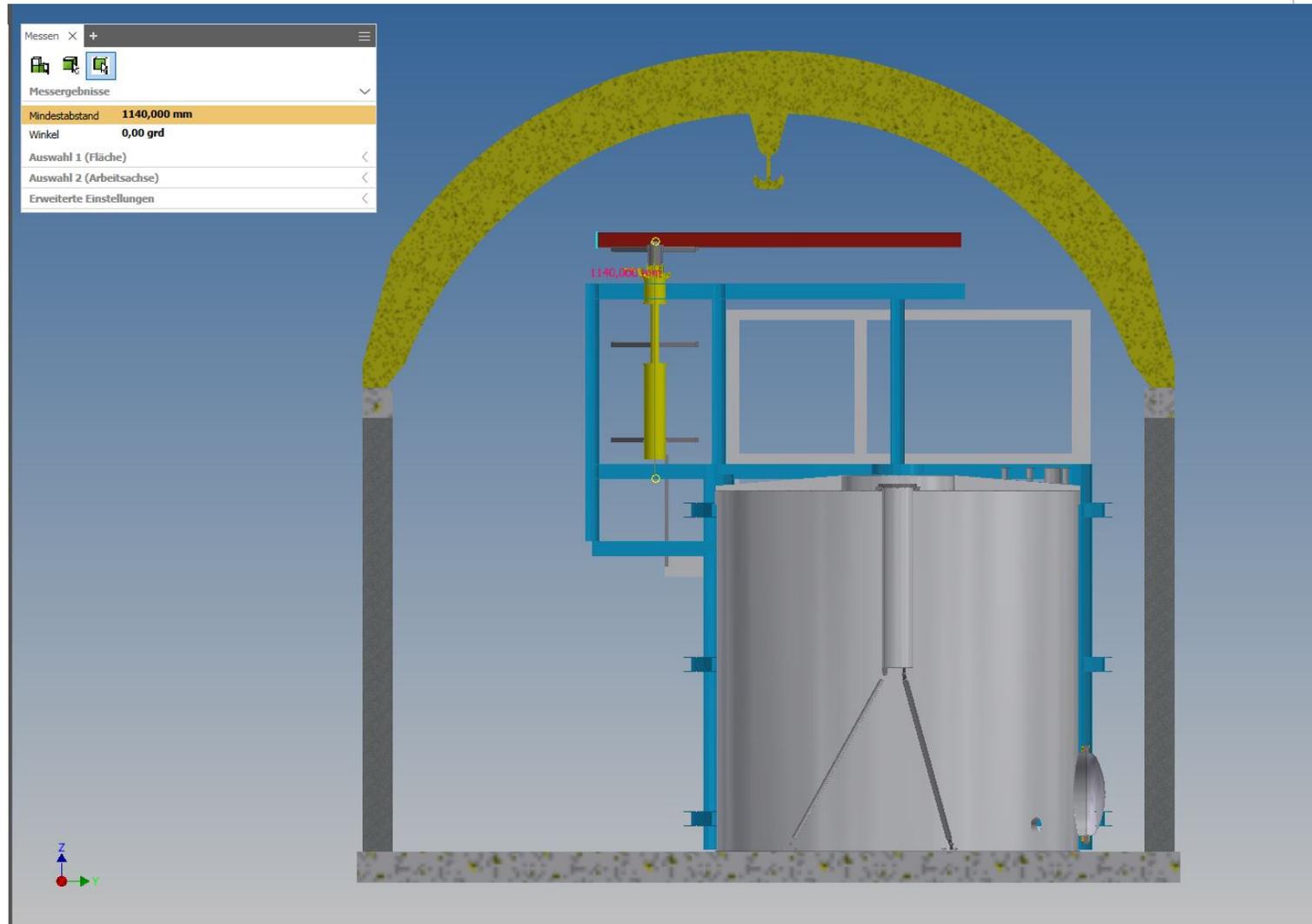
# Cryostat in working-position



## Cryostat moved out (movement in vertikal 3990mm)



Cryostat moved to parking-position (movement in horizontal 4700mm)



## Cryostat parked on the floor (movement in vertikal 1600mm)

