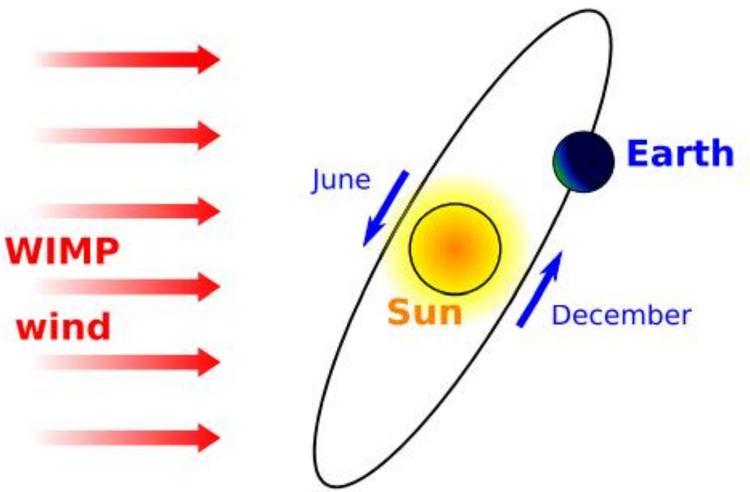
remoTES: The COSINUS sensor design

Speaker: Moritz Kellermann

Outline:
1. COSINUS motivation
2. Measuring principle
3. Facilities
4. remoTES

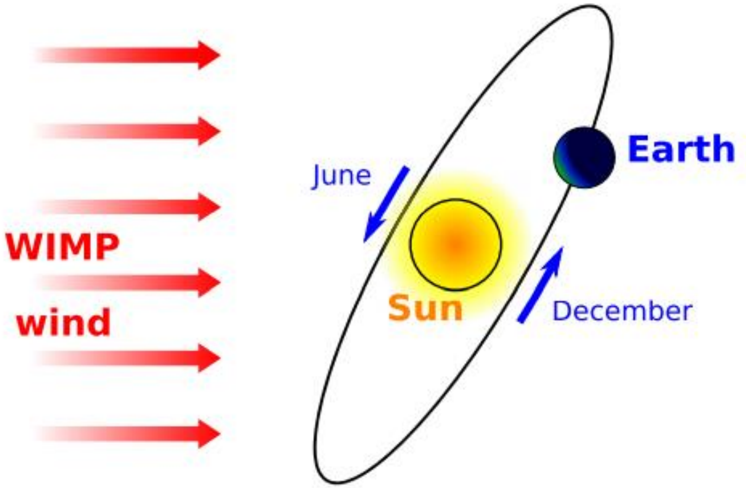
Dark matter in our galaxy

- Dark matter (DM) is expected to be distributed as halo around the galaxy
- Assume DM to be particle-like and interacting with standard model particles
- Motion of Earth causes a modulation of relative velocities



Dark matter in our galaxy

- Dark matter (DM) is expected to be distributed as halo around the galaxy
- Assume DM to be particle-like and interacting with standard model particles
- Motion of Earth causes a modulation of relative velocities

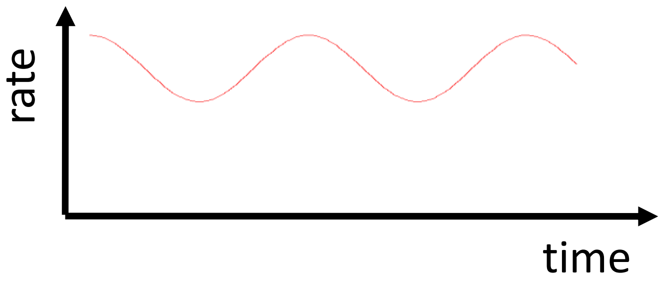


$$\mathbf{v}_{gal}^{det}(t) = \mathbf{v}_{gal}^{\odot} + \mathbf{v}_{\odot}^{det}(t)$$

$\rightarrow f(\mathbf{v}_{\chi}^{gal}(t))$ period 1 year

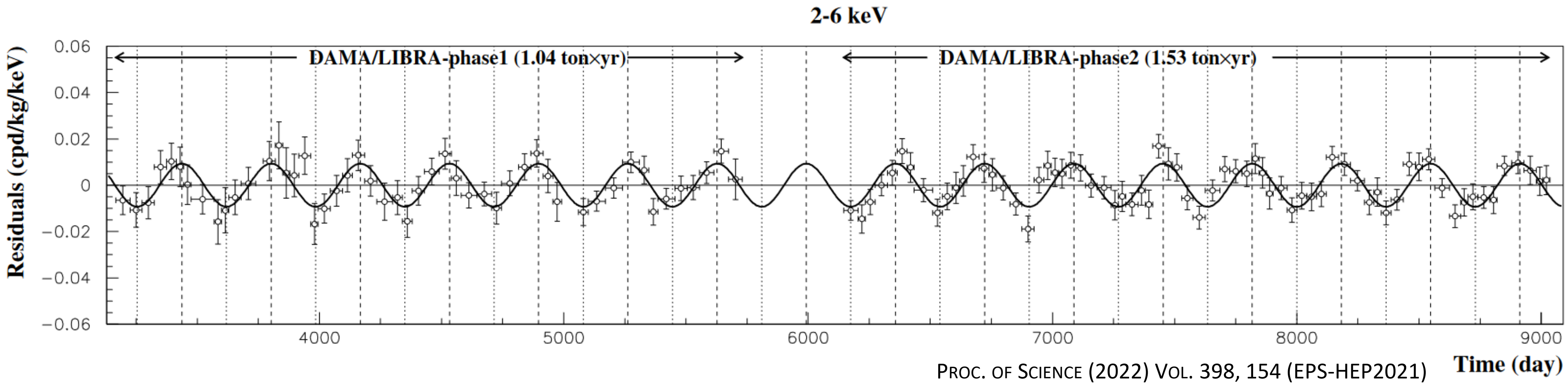
$$\frac{\mathrm{d}R(t)}{\mathrm{d}E_R} = A_0 + \sum_{n=1}^{\infty} A_n \cos n\omega(t-t_0) + \sum_{n=1}^{\infty} B_n \sin n\omega(t-t_0)$$

Interaction rate of DM-particles interacting with a detector should show a yearly modulation



DAMA/LIBRA experiment

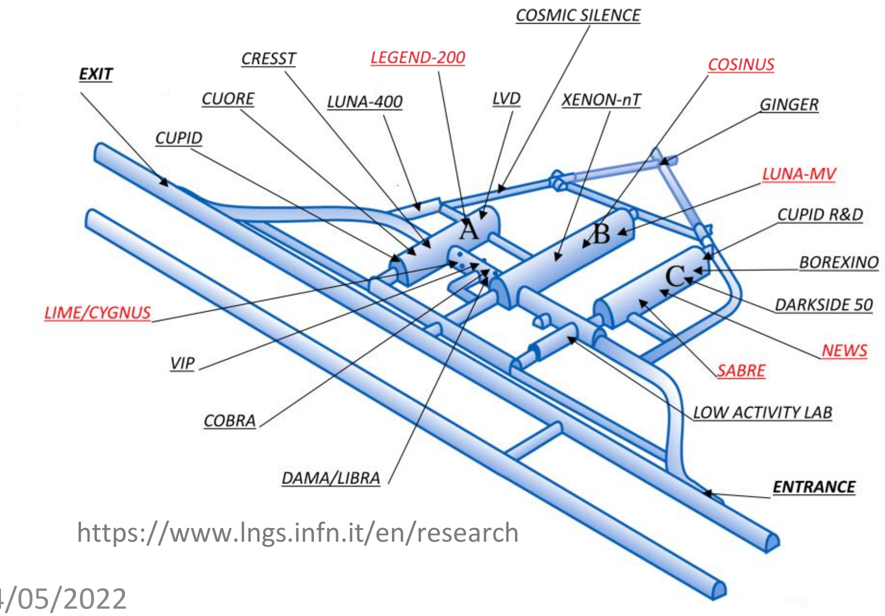
- DAMA/LIBRA measured a modulation using scintillating NaI since 1996 with
  - Period of 0.998 ± 0.001 years (at 2-6 keV)
  - High significance of 13.7 σ
  - Phase peaking on 22nd May ± 5 days
  - **No confirmation by other experiments**



PROC. OF SCIENCE (2022) VOL. 398, 154 (EPS-HEP2021)

COSINUS

- COSINUS is a direct dark matter experiment that will cross-check the results of DAMA/LIBRA
  - It uses the same target material (NaI) operated as low-temperature scintillating calorimeters
  - It will be the first DAMA-like experiment with **particle discrimination**
  - It will be located at the same underground lab as DAMA/LIBRA (LNGS)



https://www.lngs.infn.it/en/research

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut) · HEPHY INSTITUTE OF HIGH ENERGY PHYSICS · TU WIEN · INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso · GSSI · HELSINKI INSTITUTE OF PHYSICS · SICCAS Since 1928

Direct detection methods

Ionization Detectors

Targets: Ge, Si, CS_2, CdTe

GENIUS, HDMS, IGEX NEWAGE, CoGeNT, CDEX, DAMIC, SENSEI, DANAE, NEWS-G (noble gas mixture)

Light and Ionization Detectors

Targets: Xe, Ar, CS_2

WARP, ZEPLIN-II, ZEPLIN-III, Panda-X, LUX/LZ, DRIFT-I, DRIFT-II, XENON100, XENON1T, XENONnT, DarkSide-50, DarkSide-20k, ARDM, DARWIN

(cold, ~LN_2 temperature)

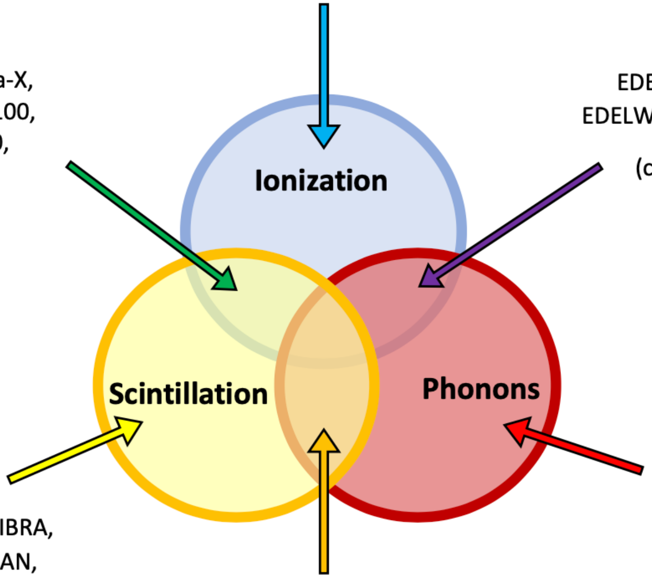
Heat and Ionization Bolometers

Targets: Ge, Si

EDELWEISS-I, EDELWEISS-II, EDELWEISS-III, CDMS, SuperCDMS

(cryogenic, T<50mK)

*list not complete



Scintillators

Targets: NaI, CsI, Xe, Ar

ZEPLIN-I, KIMS, NAIAD, DAMA/LIBRA, ANAIS, DEAP-3600, XMASS, CLEAN, SABRE, COSINE, KIMS, DM-Ice, PICO-LON

Bolometers

Targets: Al_2O_3, TeO_2

CRESST-I, CUORE

(cryogenic, T<50mK)

Light and Heat Bolometers

Targets: $CaWO_4$, BGO, Al_2O_3, NaI, CsI, Li_2MoO_4

ROSEBUD, CRESST-II, CRESST-III, COSINUS, CUPID

(cryogenic, T<50mK)

Emulsion

Targets: NIT (silver halides)

NEWSdm

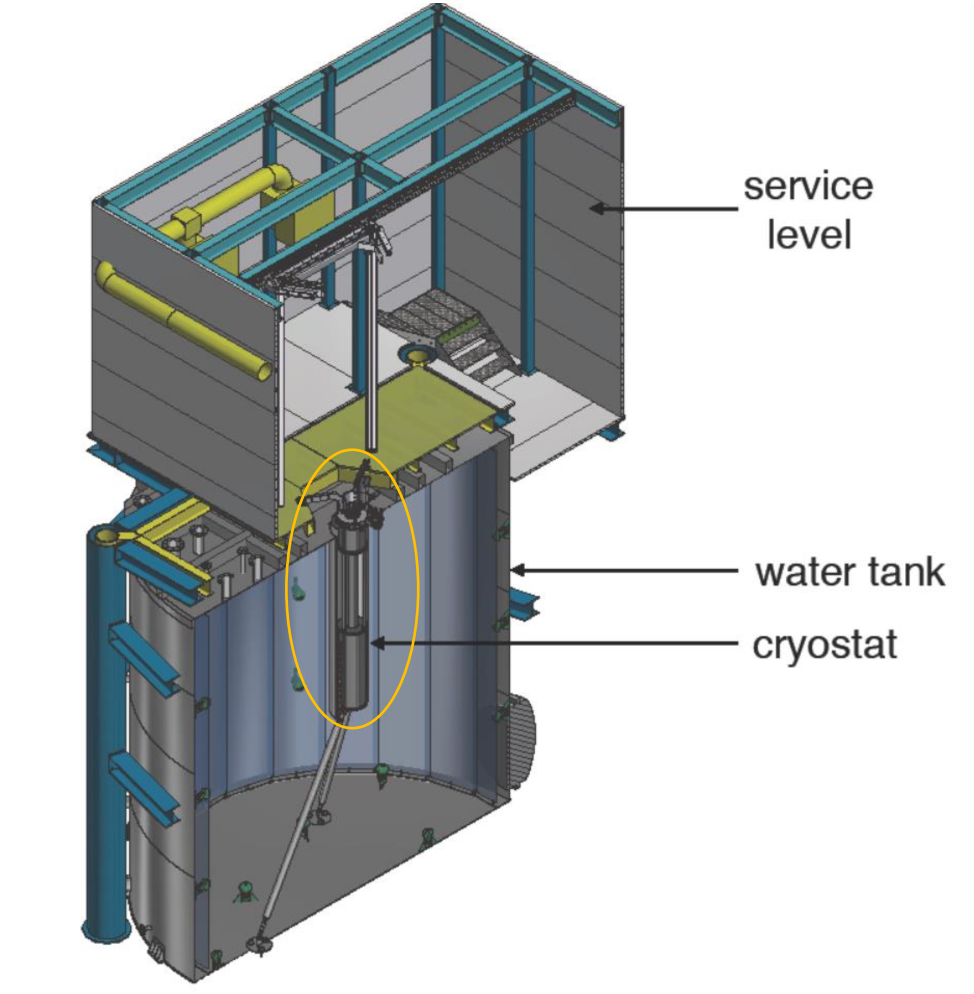
Bubbles and Droplets

Targets: CF_3Br, CF_3I, C_3F_8, C_4F_{10}

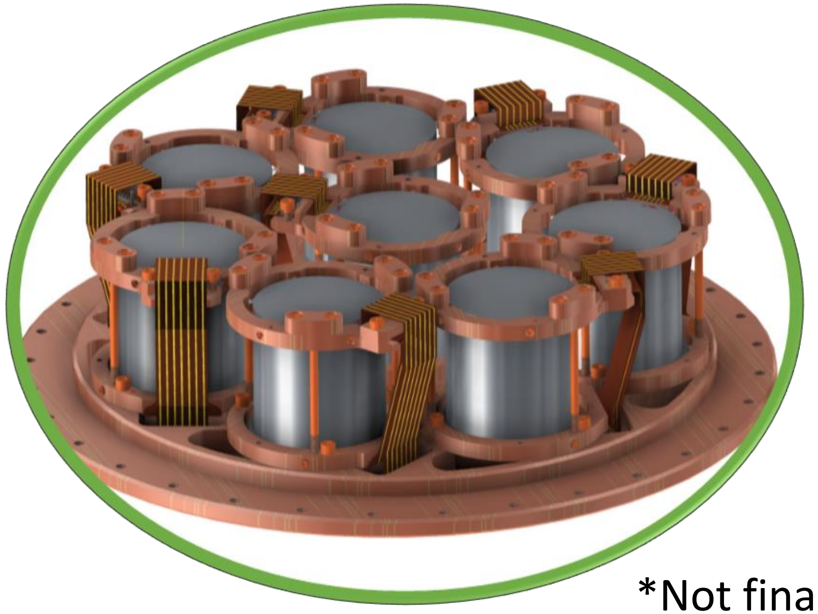
COUPP, PICASSO, SIMPLE, PICO-2L, PICO-60, PICO-250

M. Stahlberg (2020), https://doi.org/10.34726/hss.2021.45935

COSINUS Setup



3x



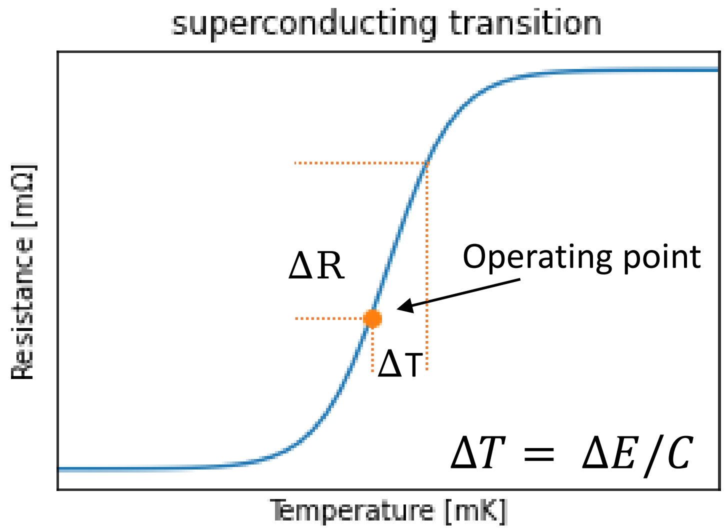
*Not final

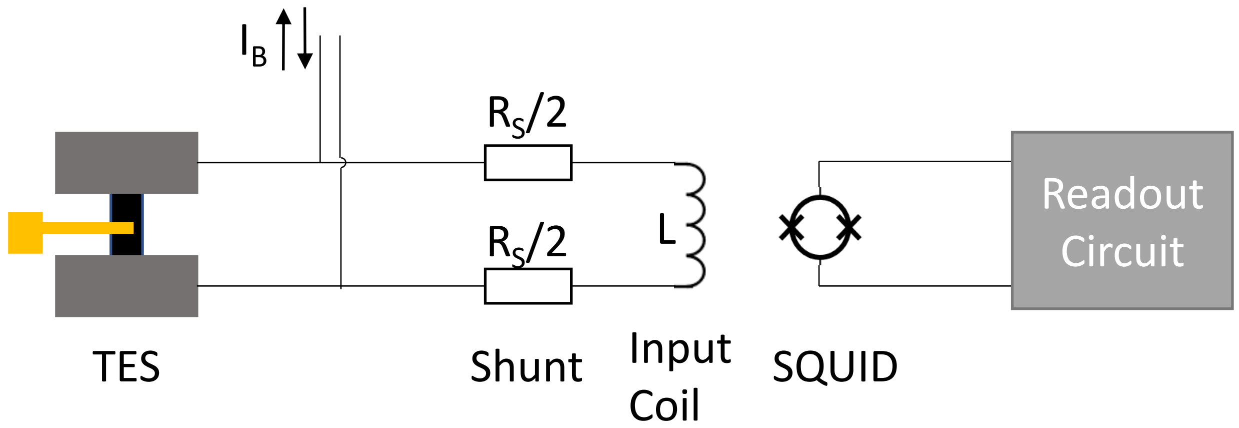
Status & Goal

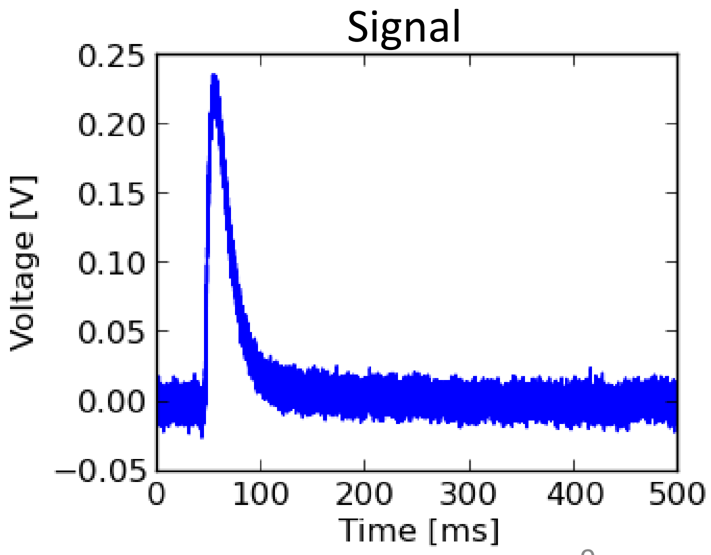
Most complicated part is done!

Operation of superconducting thermometers

- Measurement of µK-temperature differences with tungsten transition edge sensors (TES)
- Energy deposition leads to change in temperature and thus film resistance
- Electrical readout using "superconducting quantum interference devices" (SQUIDs) as amplifiers



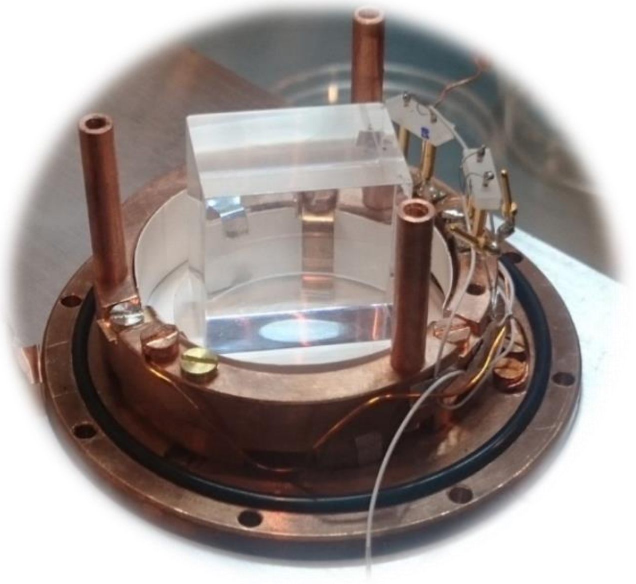


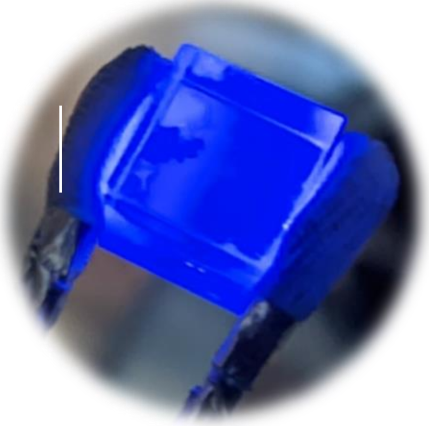


Sodium iodide

23.0	126.9
$_{11}$Na	$_{53}$I
Sodium	Iodine

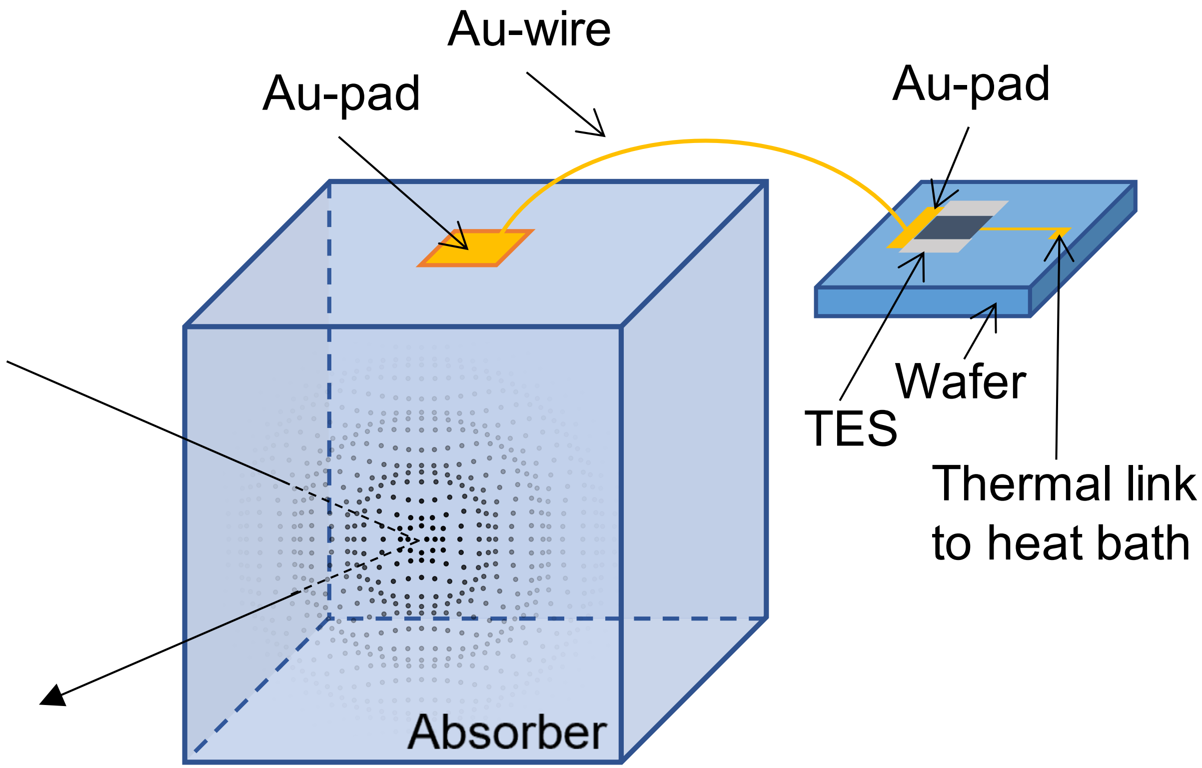
Material	NaI (COSINUS)	$CaWO_4$ (CRESST)
Density	3.67 g cm^{-3}	6.06 g cm^{-3}
Melting point	661 °C	1620 °C
Heat capacity @20 mK	91.3 x 10^{-6} µJ cm^{-3} K^{-1}	28.4 x 10^{-6} µJ cm^{-3} K^{-1}
Absorber mass	~90 g	~24 g
	Extremely hygroscopic !	
	Extremely soft !	

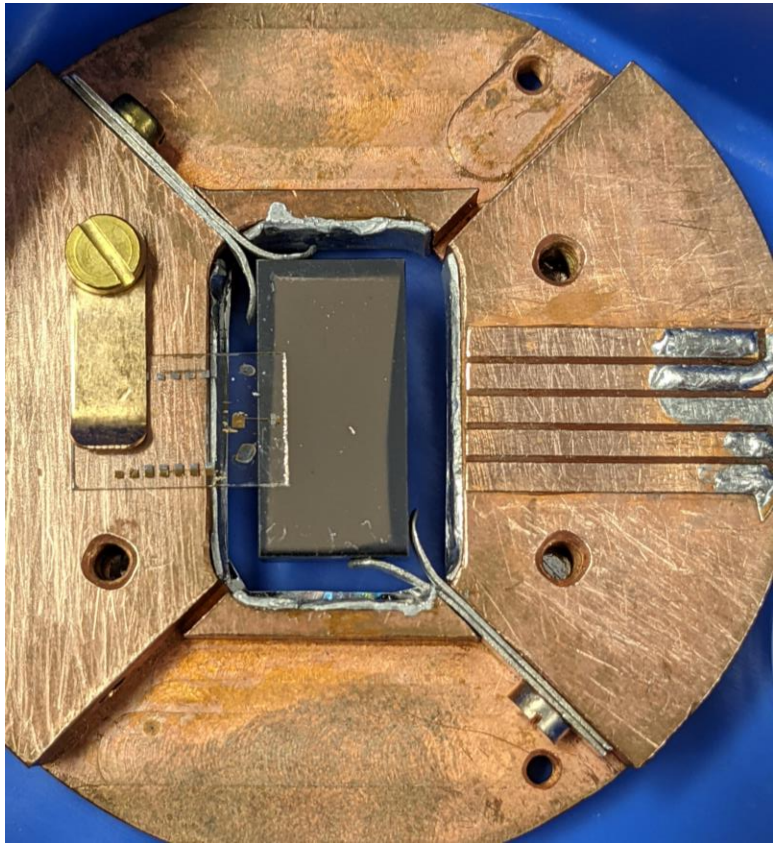




- NaI can not survive most of the common deposition processes

remoTES design





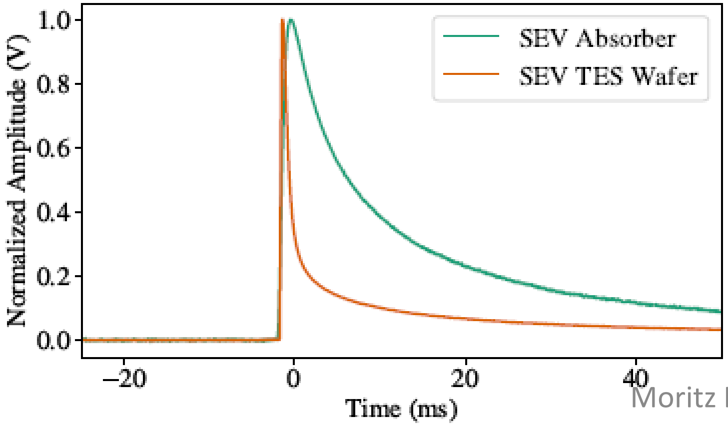
remoTES – first results

Absorber material	Absorber volume (mm^3)	Au-pad properties	Au-wire properties	TES	Energy resolution (eV)
Si	20x10x5 (2.23g)	200nm sputtered RRR=3.79	17 µm glued on pad	W-TES on Al_2O_3	87.8 ± 5.6
TeO_2	20x10x2 (2.27g)	400nm foil glued RRR=15	17 µm 2 wedge bonds	W-TES on Al_2O_3	193.5 ± 3.1

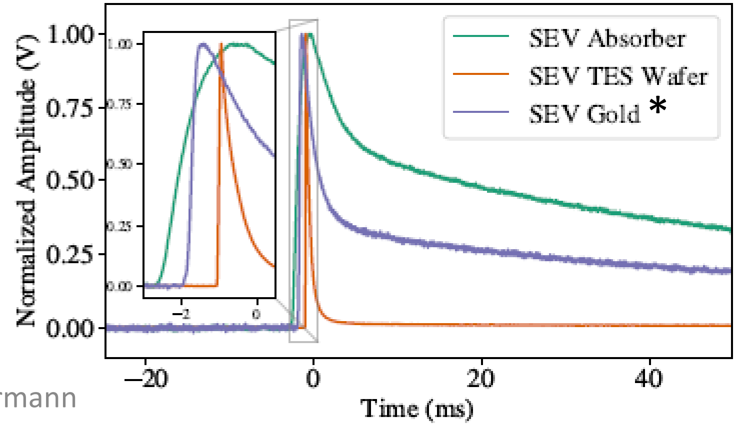
https://arxiv.org/abs/2111.00349

- Test measurements with TeO_2 and Si successful
- Energy resolution calibrated by using ^{55}Fe-sources
- Event types can be discriminated by pulse shape

Silicon

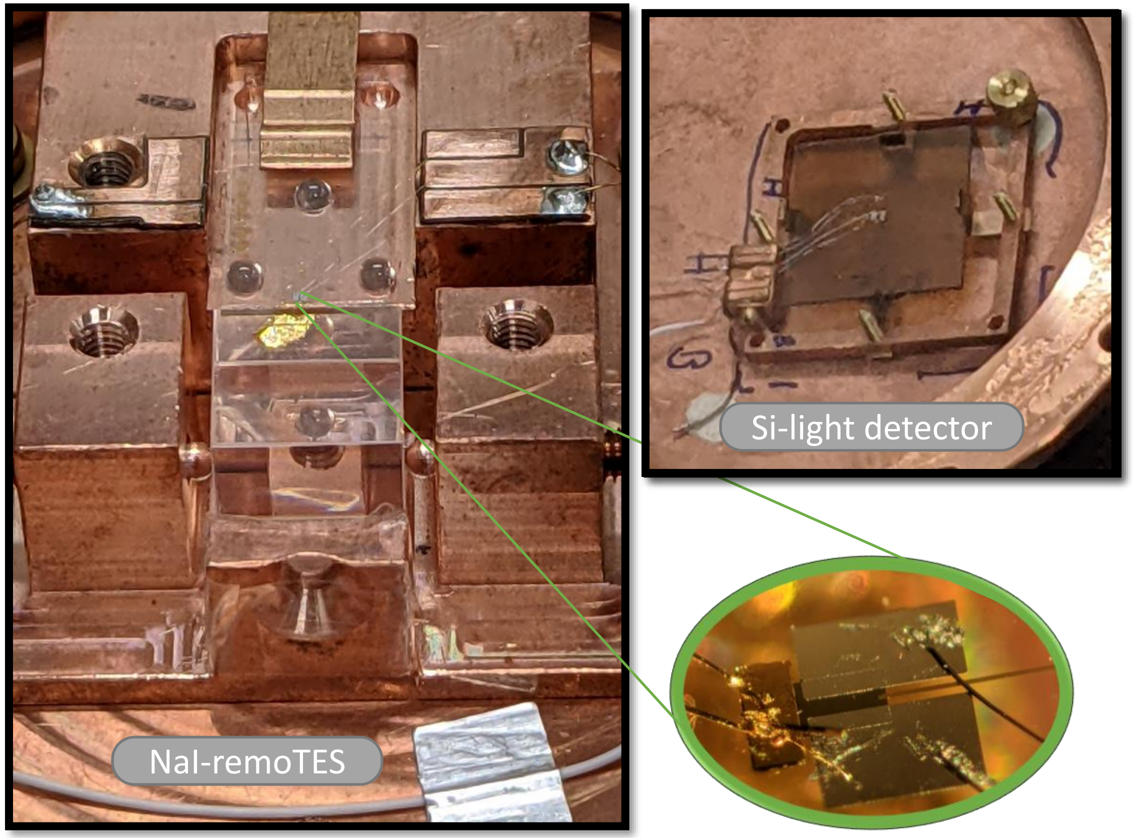


TeO_2



*additional ^{55}Fe source near Au-pad for TeO_2

remoTES – NaI-version

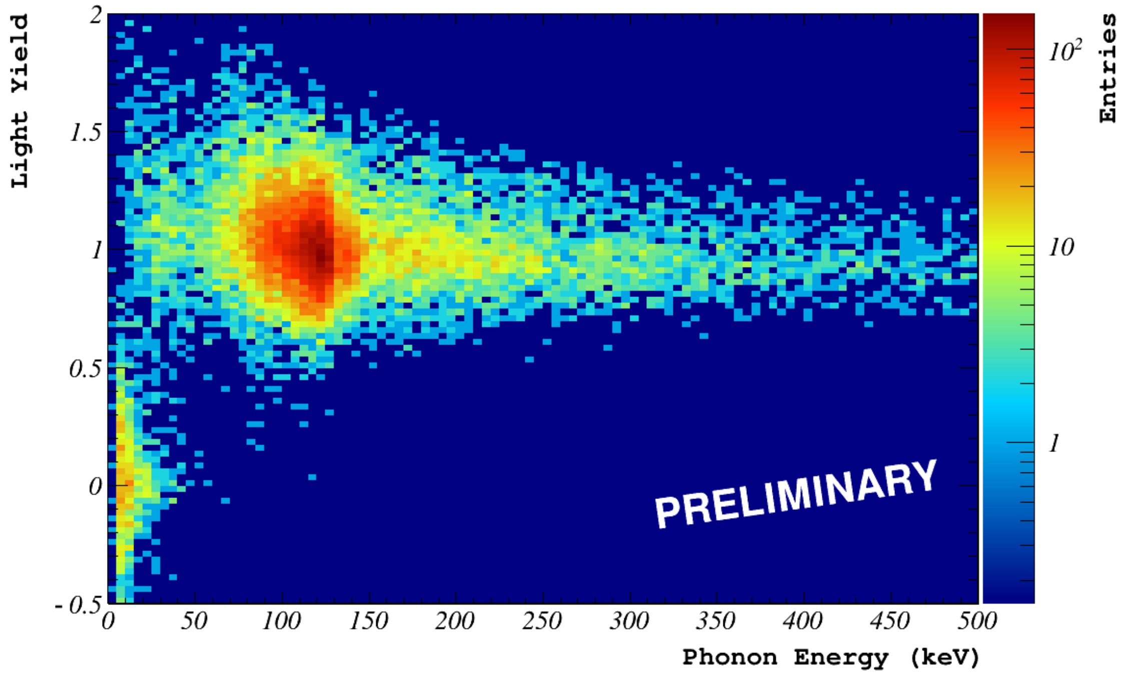


- December 2021: first fully functional remoTES of NaI
  - 1x1x1 cm^3 NaI-cube of 3.6 g
  - 1µm thick glued gold foil for phonon collection
  - 2 Au-wires with ⌀ 17 µm connecting absorber and TES
- Energy resolution in low keV range
- Neutron calibration with Am/Be source
  - **First neutron discrimination with a NaI-remoTES detector**

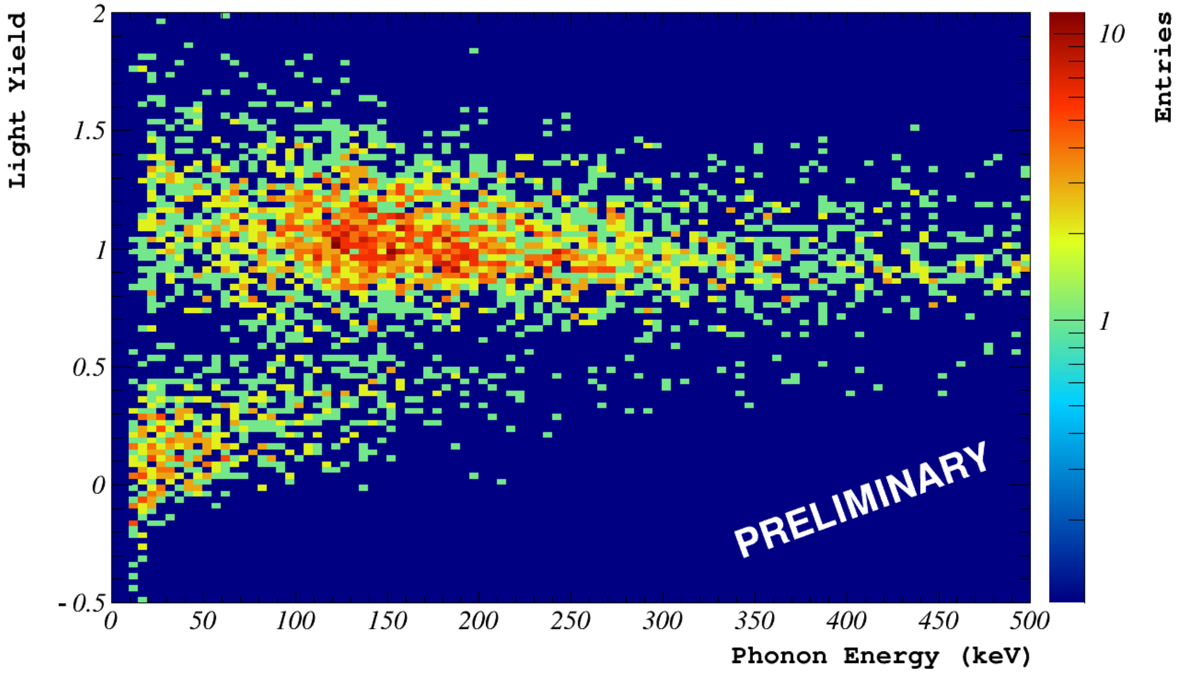
Particle discrimination

Stay tuned for the paper!

With ^{57}Co γ-source (122 keV)

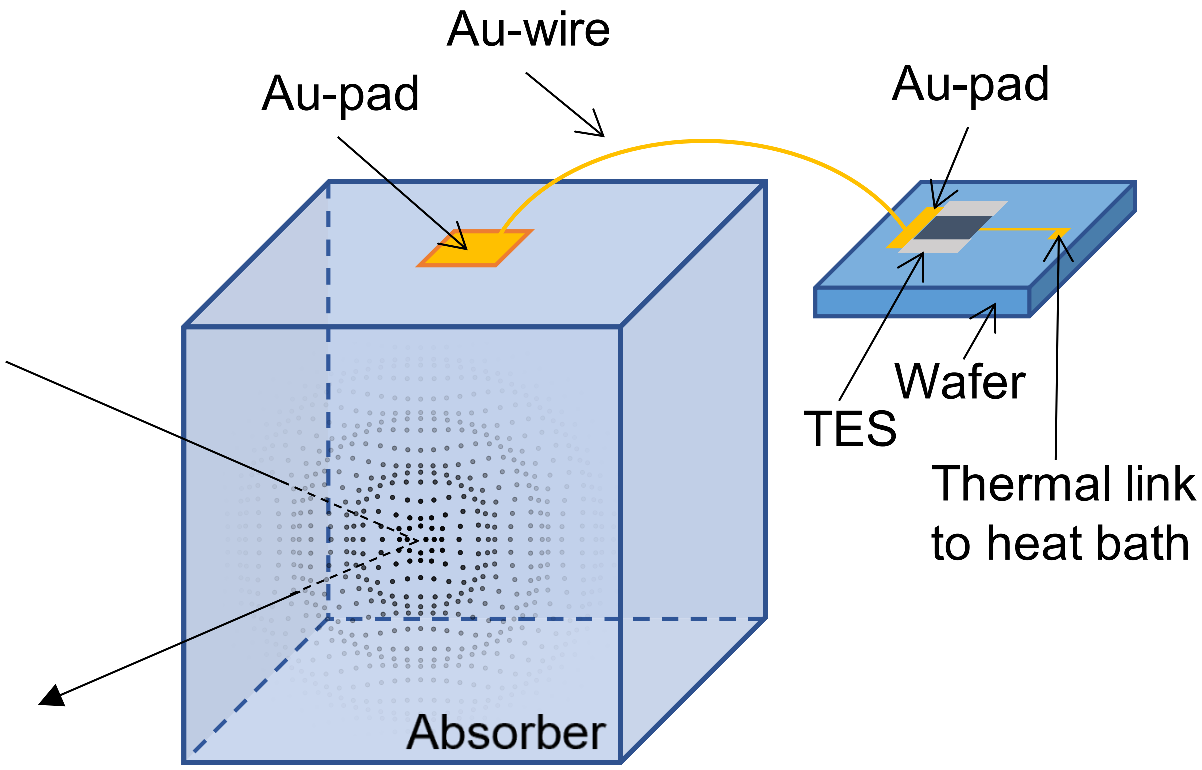


With ^{241}Am/Be n-source

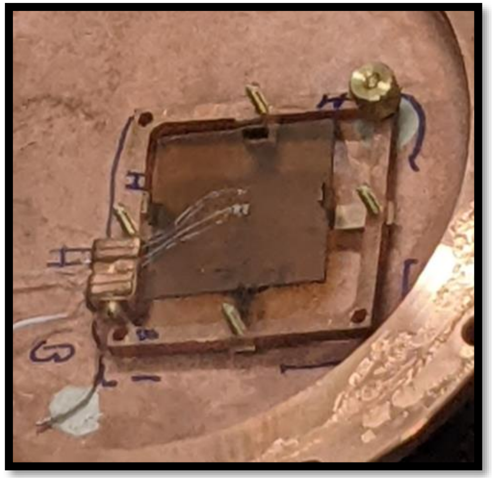


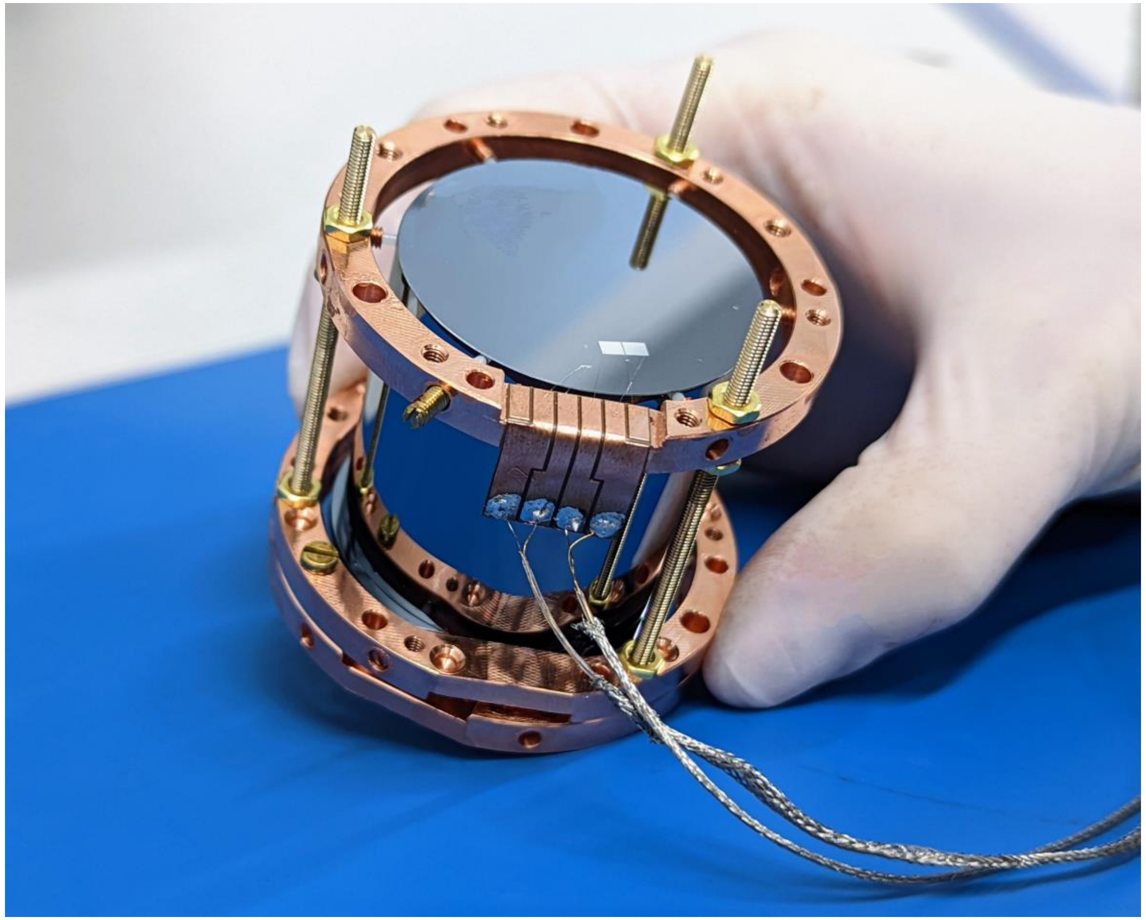
How to improve threshold

- Glue thickness and reproducibility?
- Gold pad properties
  - Dimensions + geometry? Quality?
- Gold bond properties
  - Thickness? Number? Type?
- Materials
  - Superconducting collector?
- Heat capacity
- Light collection
- …



Light detectors



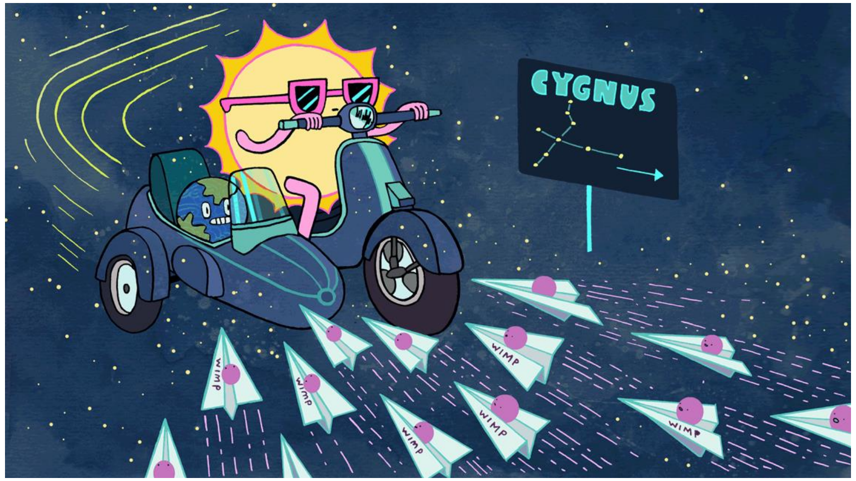


Better light collection will lead to a better particle discrimination

Status of COSINUS today

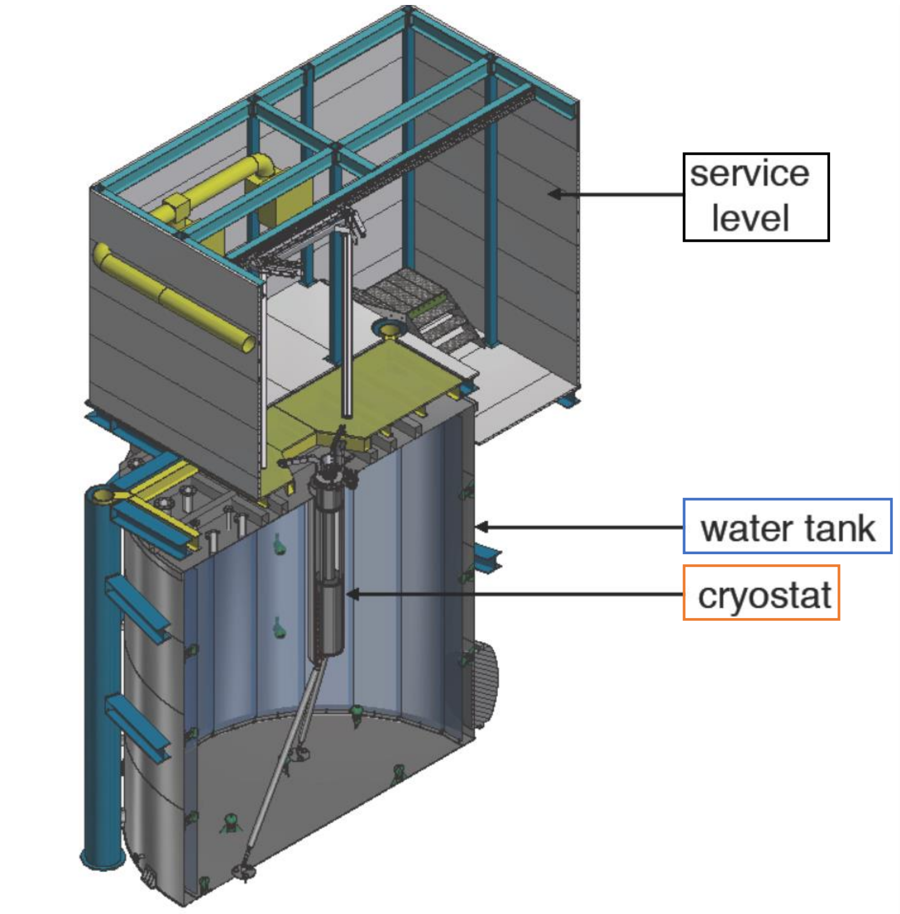
- A lot of progress in COSINUS:
  - Construction of facilities is going on smoothly
  - **remoTES-Sensor design is tested and working!**
  - Development of detector design including light detectors ongoing
- Big upcoming milestones:
  - August 2022: facilities finished
  - Late 2022: delivery and commissioning of new COSINUS cryostat
  - Mid 2023: COSINUS commissioning

Picture: symmetry magazine
Artwork by Sandbox Studio, Chicago with Corinne Mucha



Backup slides

COSINUS facilities

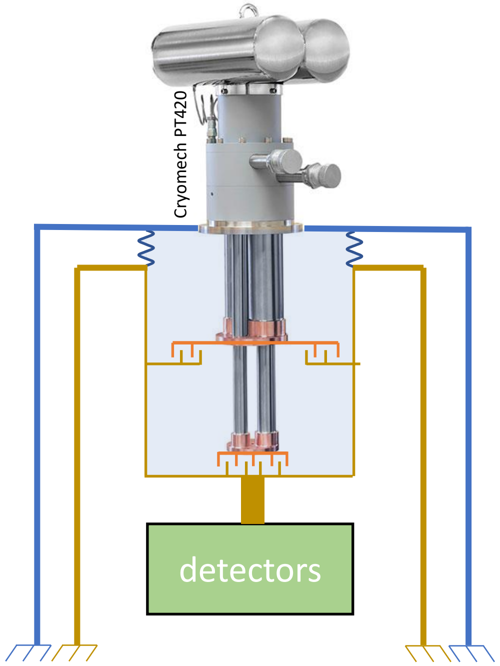


The COSINUS facilities can be divided into 4 units:

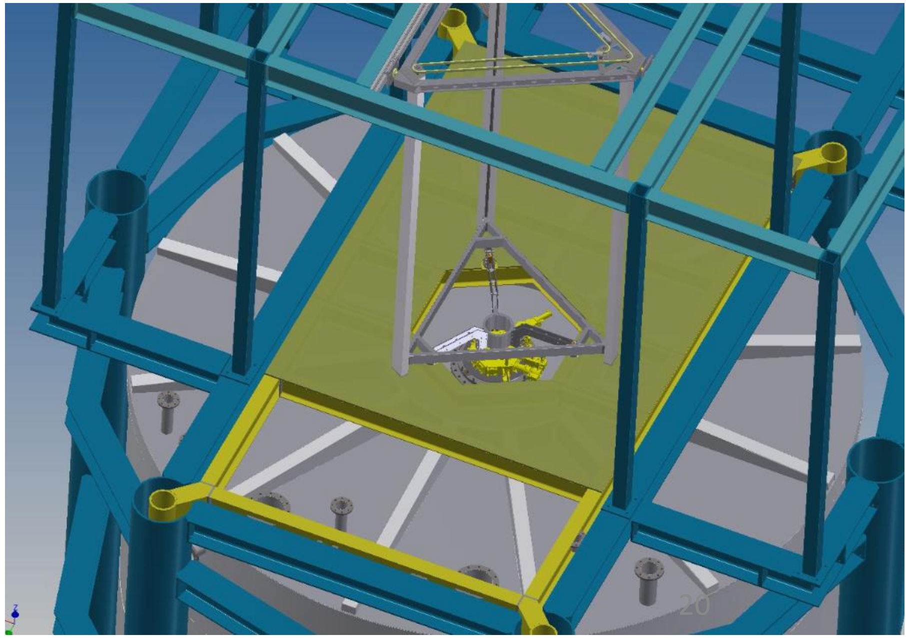
- Service level for mounting and dismounting detectors
  - Cleanroom conditions
  - Low vibration area
- Water tank for radiation shielding and muon tagging
  - Volume of 269 m^3
  - Contains up to 28 PMTs
- Cryostat area in a drywell inside of the water tank
  - Consists of the cryostat and an 8 cm external copper shielding
- Control building
  - Next to water tank (not shown in this depiction)
  - 3 floors equipped with infrastructure for working underground

Vibration mitigation

- COSINUS will use a dry dilution refrigerator to reach mK-temperatures
  - ➢ Trade-off between lower cost and higher vibration level
- Cryoconcept „ultra quiet technology“ allows for decoupling from machine noise
  - Use separate frames for noisy machines (e.g. pumps) and cryostat
  - No physical contact between both frames
  - Exchange gas for thermalization
  - @LNGS: build separate building structures instead
- Additional spring-based passive decoupling at the detector stage

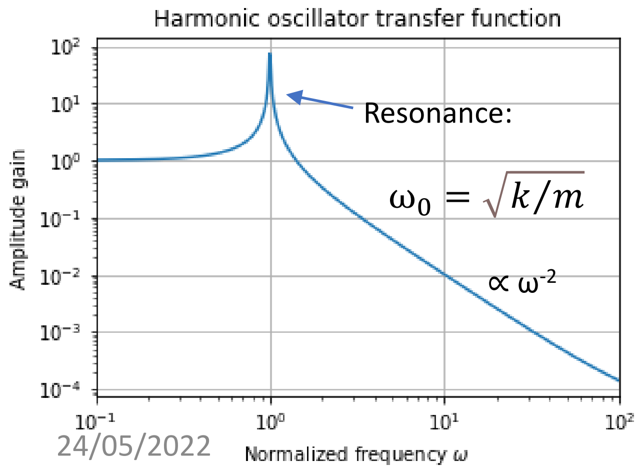


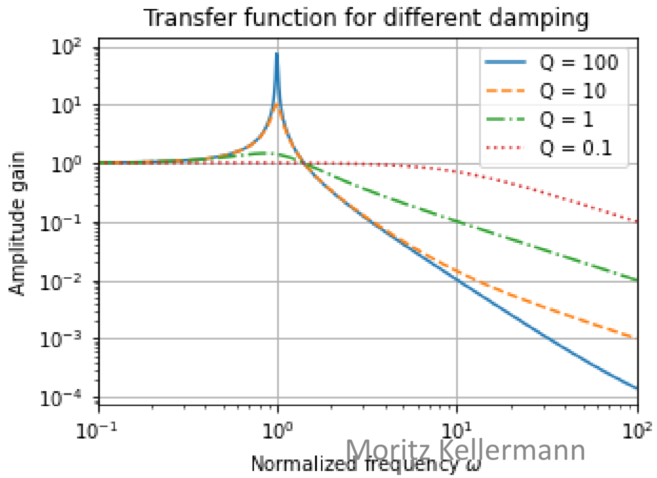
https://cryoconcept.com/product/the-ultra-quiet-technology/

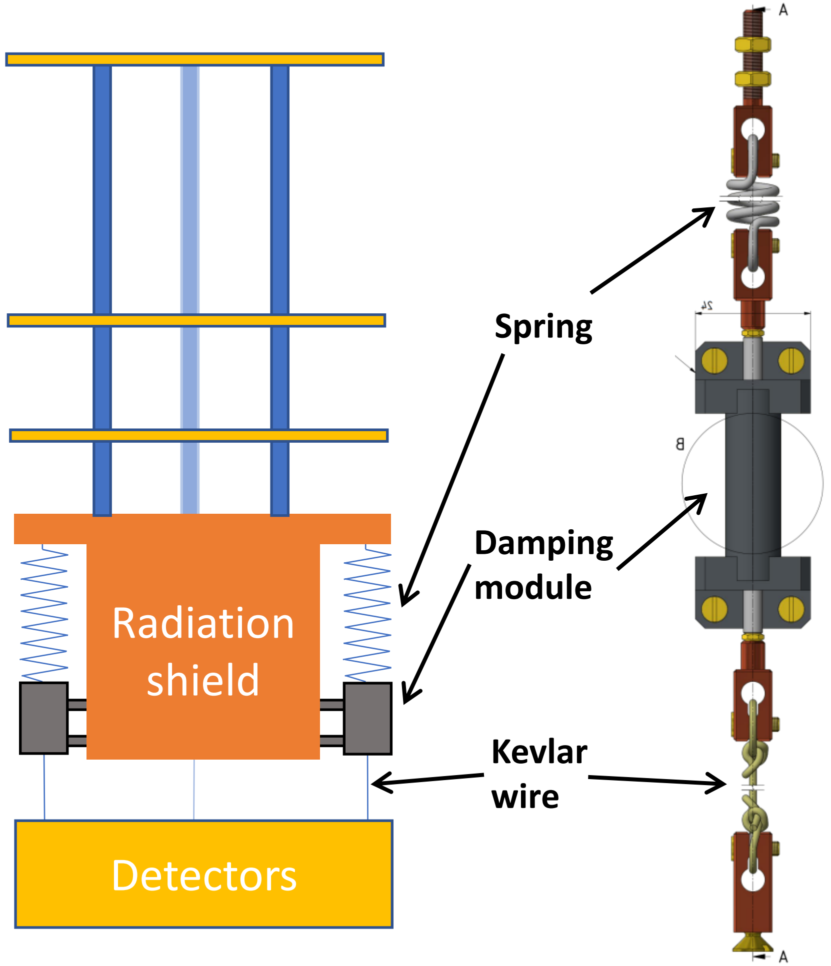


Spring-based passive decoupling

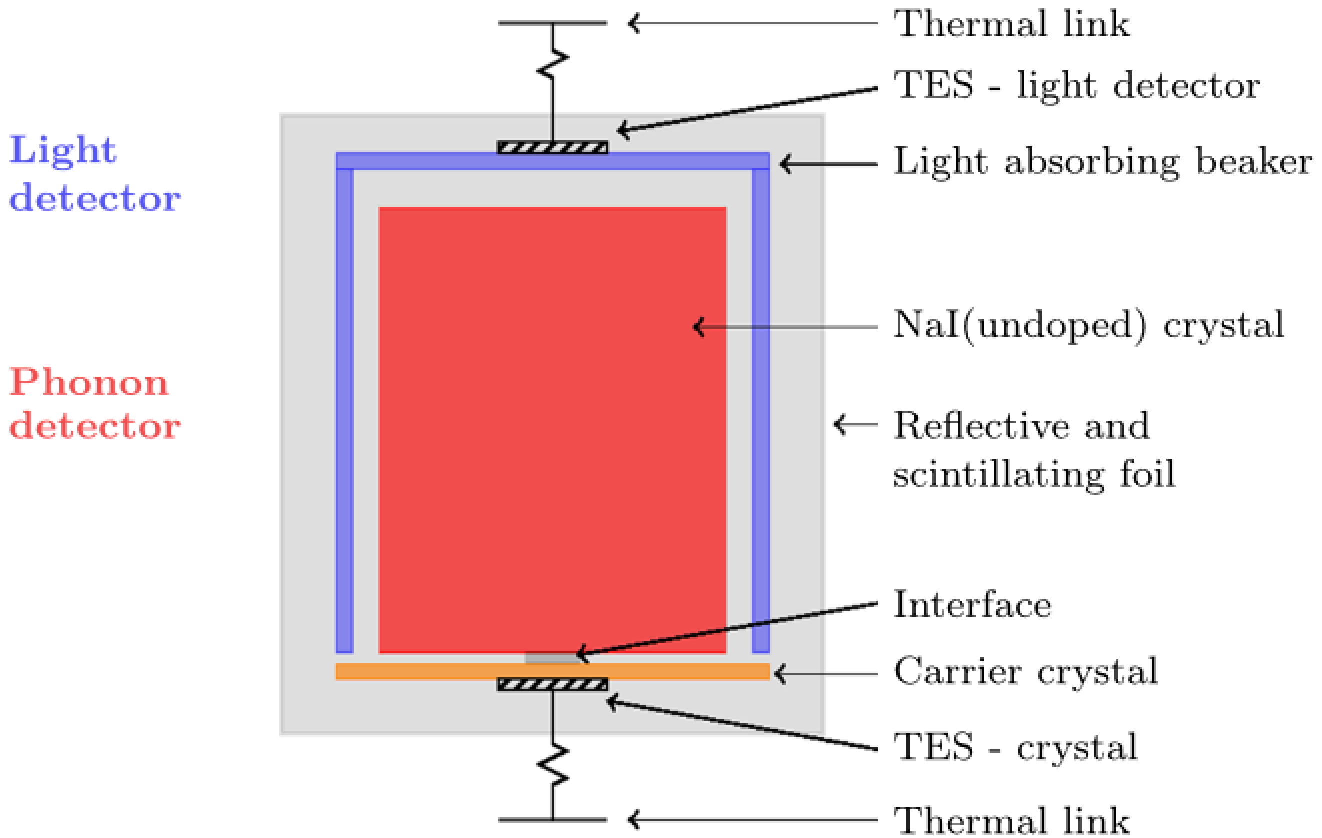
- Use the radiation shield for fixation:
  - ➢ High mass allows for a quiet starting point
  - ➢ Cooling power for the Cu-shield is high
- Decoupling system consists of 3 parts:
  1. Springs to decouple vertical motions
  2. ~10 cm for damping modules
  3. Kevlar to decouple horizontal motions and for thermal decoupling from the detectors



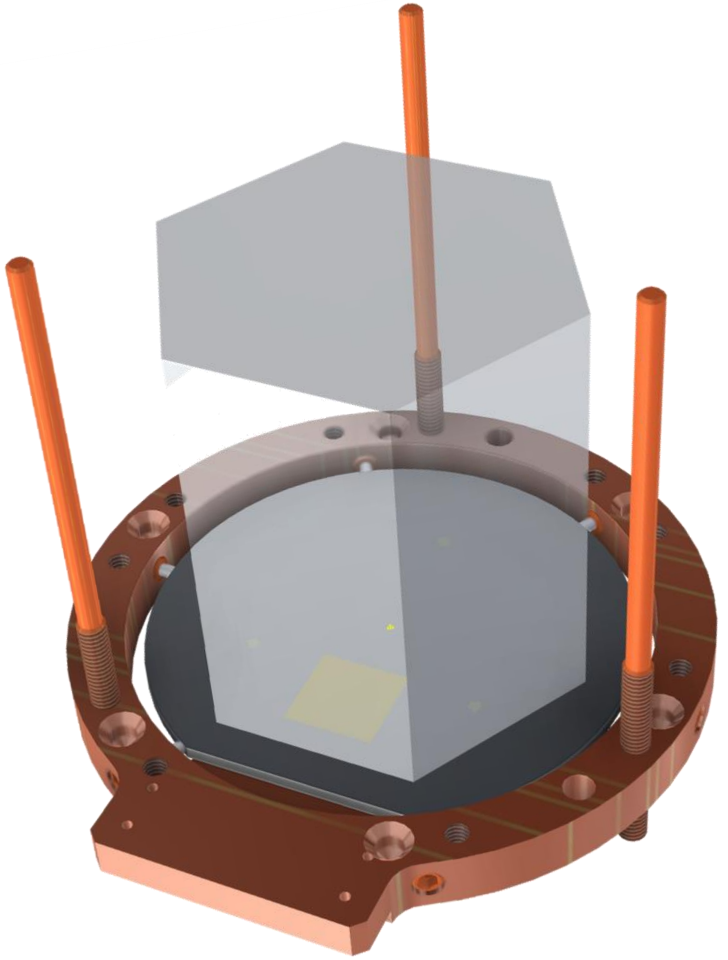


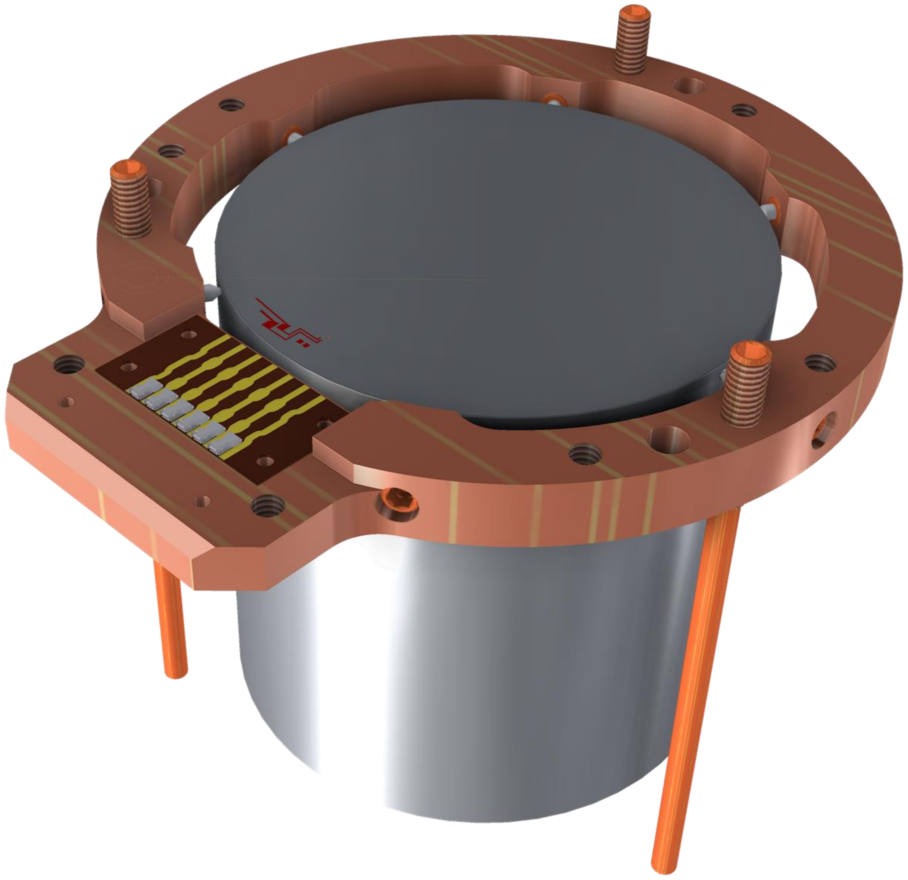


Backup – the abandoned baseline design

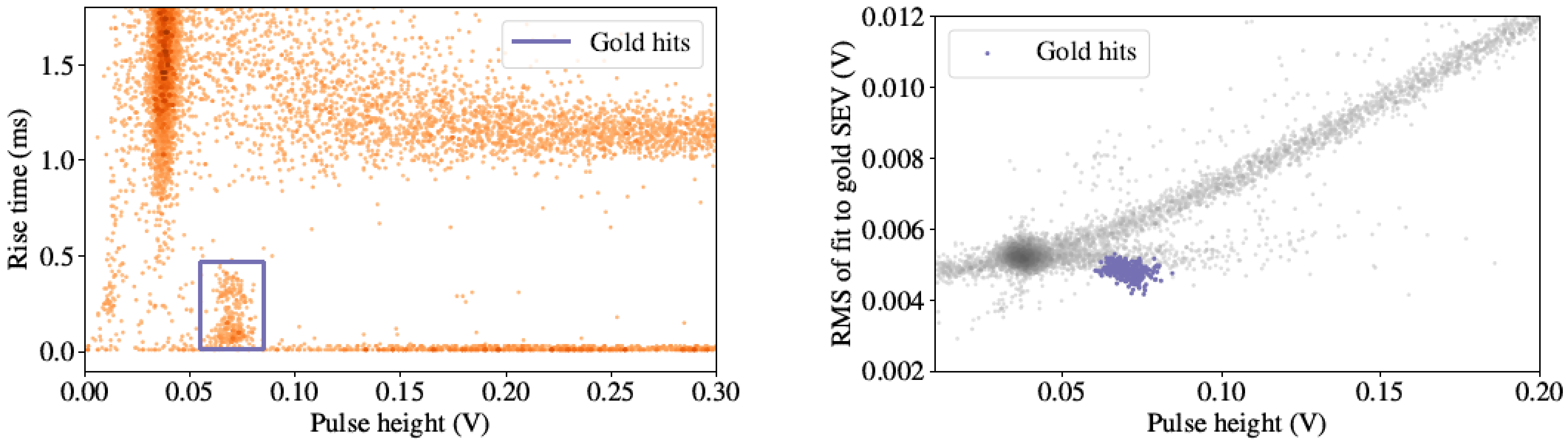


Backup – COSINUS detector module





Backup - PSD



(a) (b)

FIG. 3: TeO_2-*remoTES* data set: (a) Rise time versus moving average pulse height distribution. The violet box encloses the events in the gold foil produced by the collimated ^{55}Fe- source. (b) Fit RMS for the gold SEV as a function of the pulse height distribution. The events from the violet box in panel (a) are tagged and depicted in violet.

Backup – PSD 2

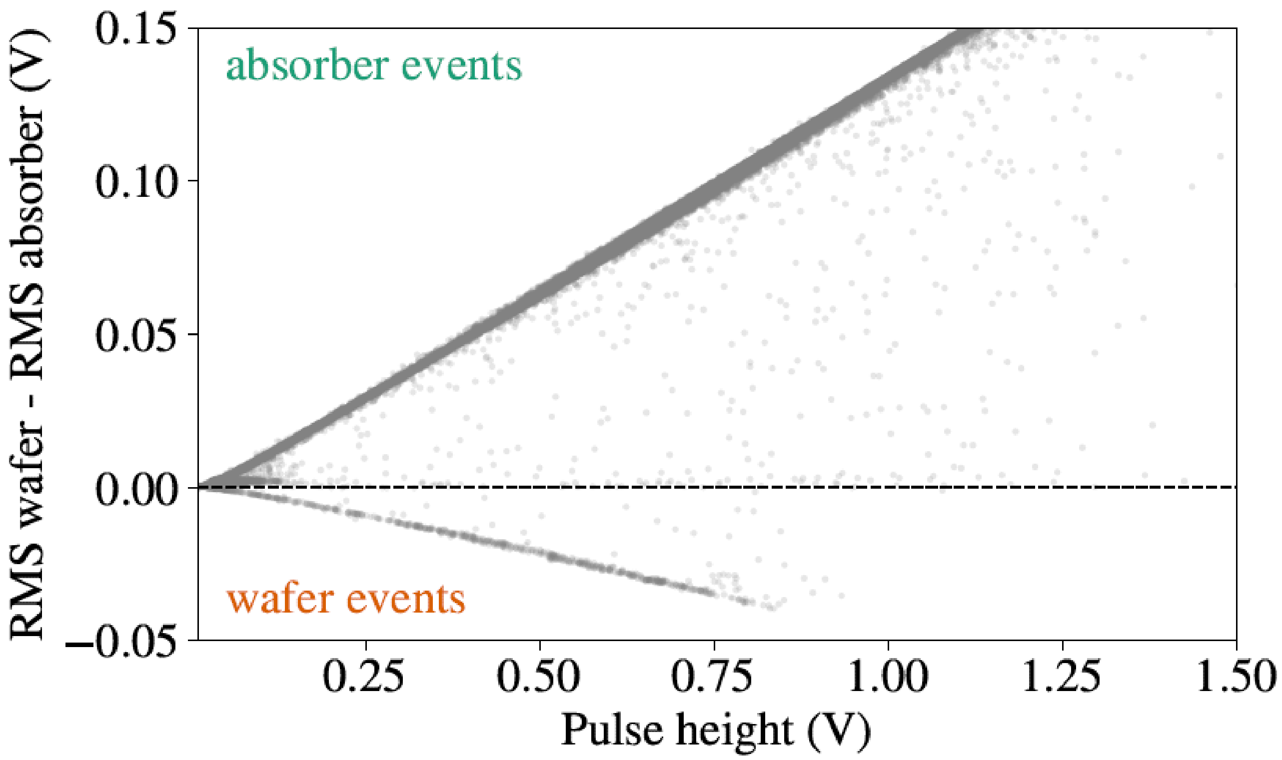
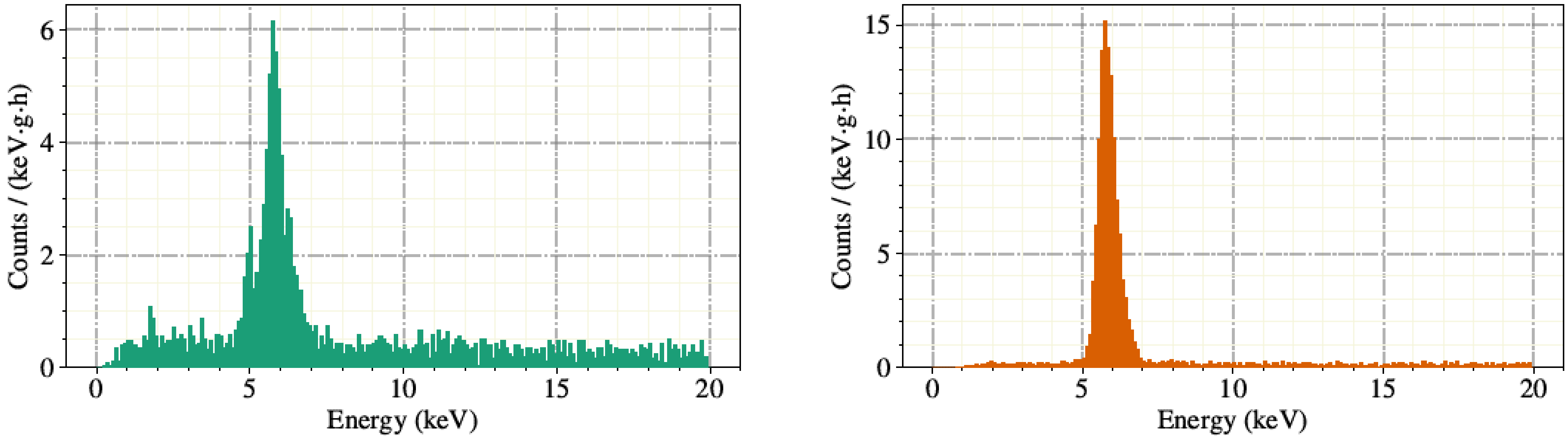


FIG. 4: Difference between RMS values from the wafer SEV fit and the absorber SEV fit as a function of moving-average pulse height for the TeO_2 prototype; different event bands corresponding to the different classes are visible. The event population between the absorber and the wafer band corresponds to the Au hits; its pulse shape is a mixture of the former two classes, and their shapes match it equally well.

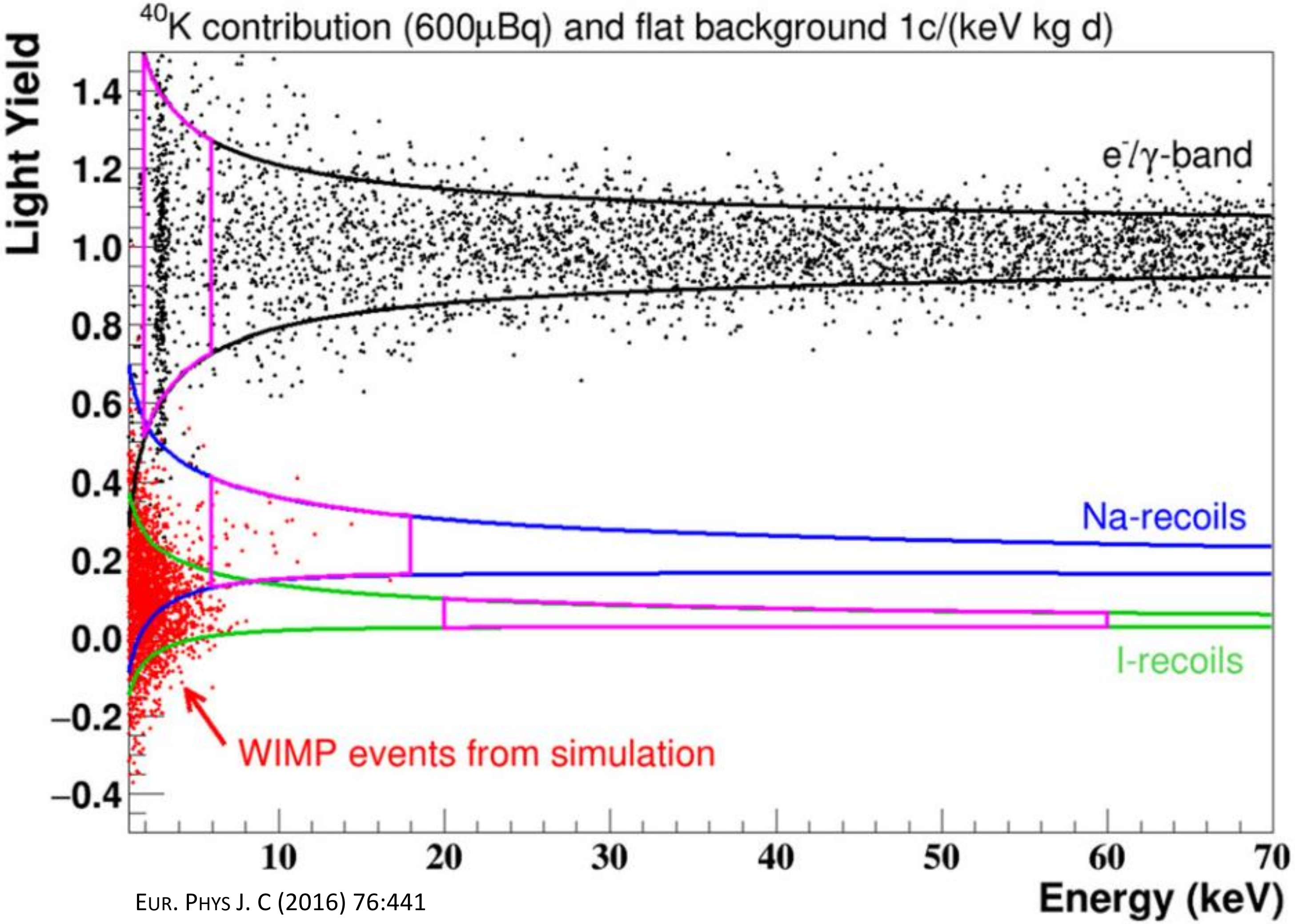
Backup - Energy-calibration



(a) (b)

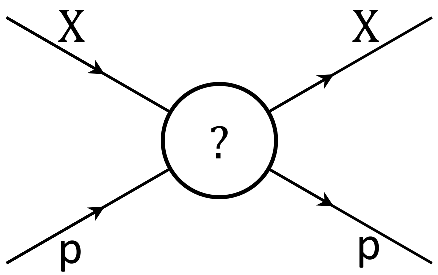
FIG. 5: The energy spectra of the two prototype detectors: (a) Si absorber and (b) TeO_2 absorber. The intensity of the ^{55}Fe-source producing X-rays of 5.89 keV (K_α) and 6.49 keV (K_β) was significantly stronger for (b). The additional peaks in the Si detector (∼1.8 keV and ∼5 keV) are consistent with x-ray emission from the K-shell of Si (1.84 keV), and an escape line from Cu (L1 at 1.10 keV).

Backup – simulated band-fit



EUR. PHYS J. C (2016) 76:441

Direct dark matter detection



Timescale:	**Nuclear recoils:**	**Electron recoils**
ns	• Inital recoil energy	• Initial recoil energy
µs	• Ionization (~30 %) • Athermal phonons	• Ionization (100 %)
ms	• (Scintillation) • Thermal phonons (Heat)	• Scintillation • Thermal phonons (Heat)