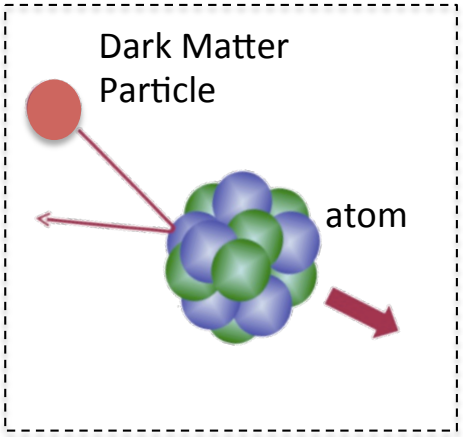
Improving Background Levels of $CaWO_4$ Detectors for CRESST

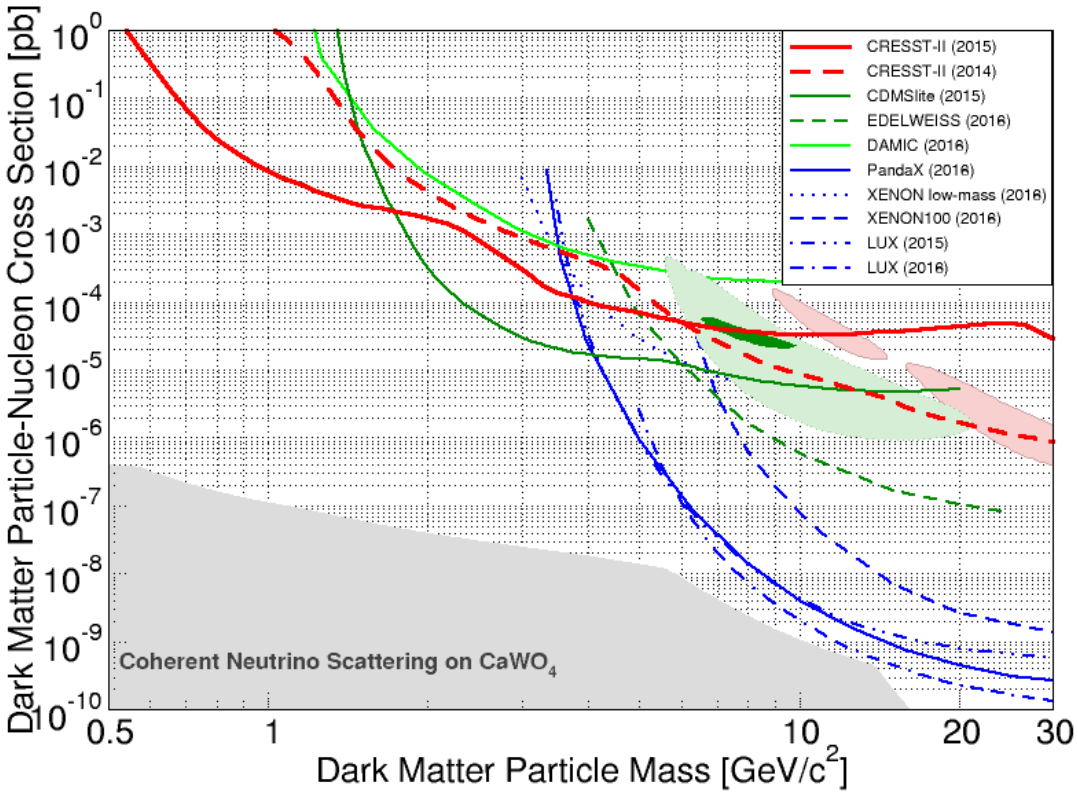
Raimund Strauss
MPI München

LRT 2017, Seoul,
25.05.2017

Direct Dark Matter Search



Search for nuclear recoils



G. Angloher et al. EPJ C76 (2016) no.1, 25

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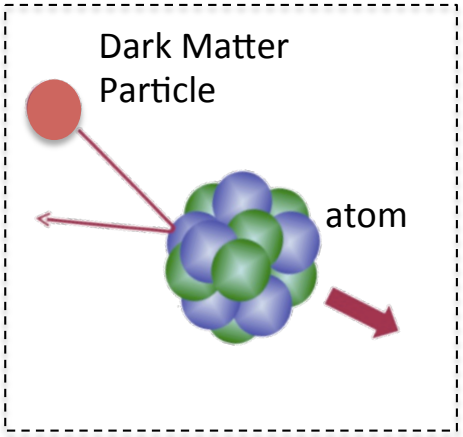

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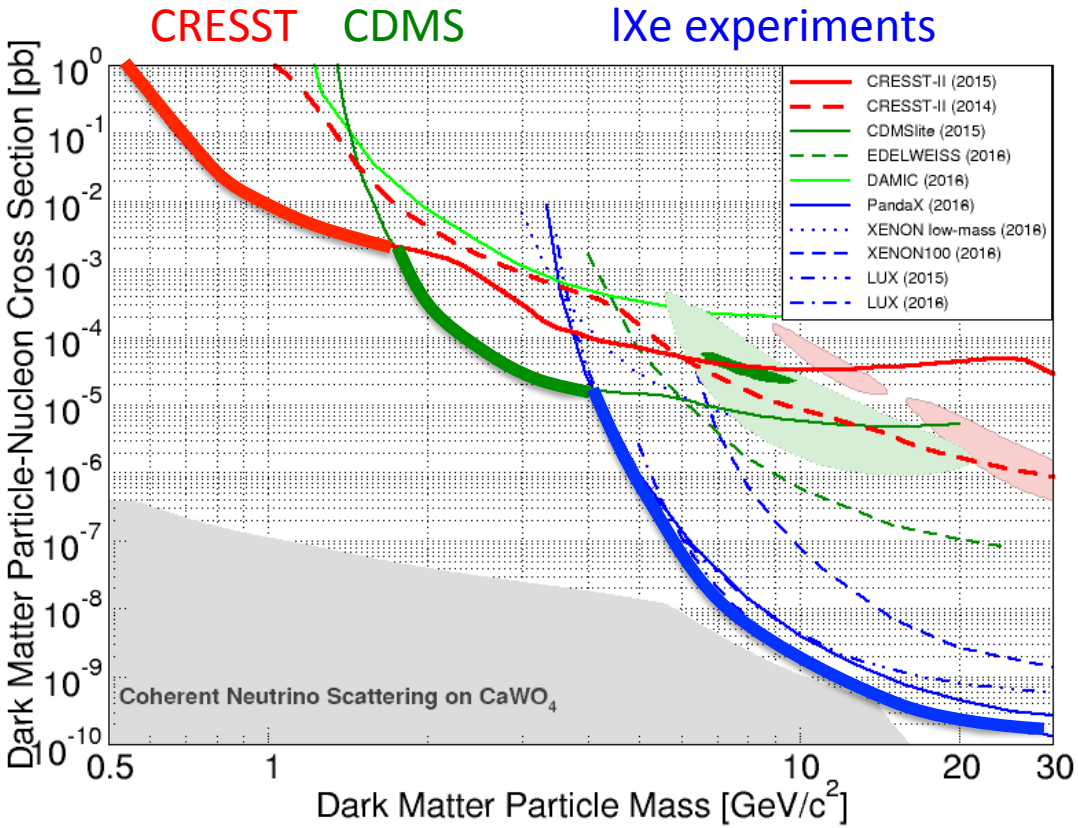
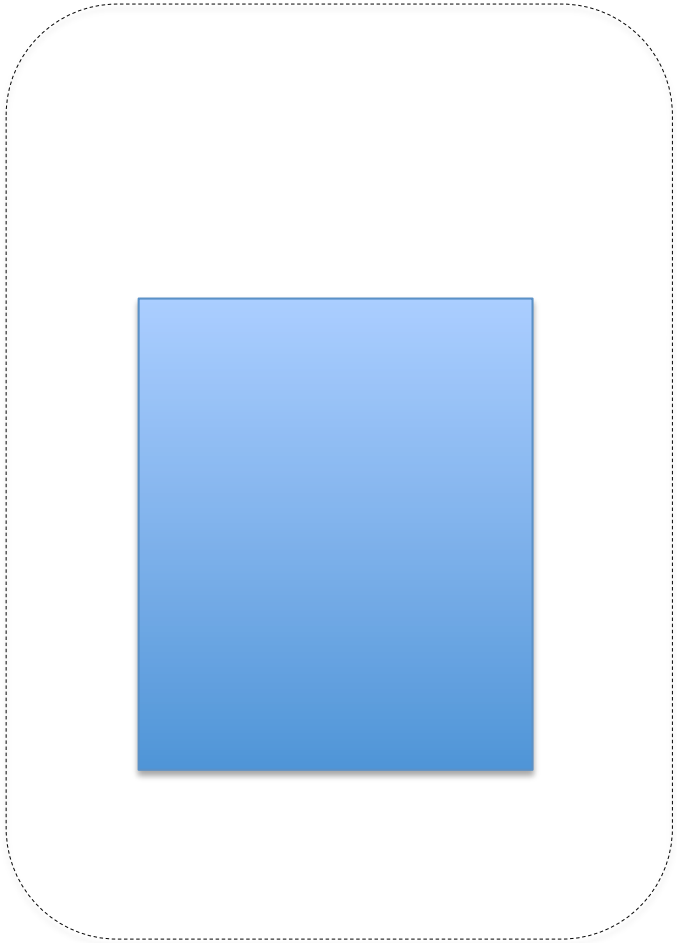


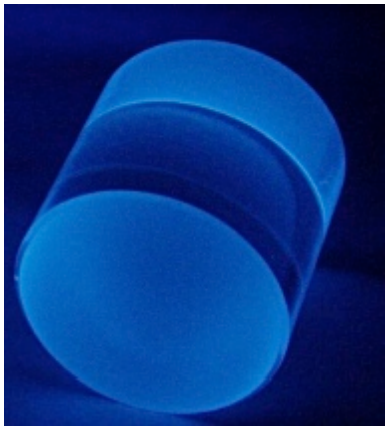
G. Angloher et al. EPJ C76 (2016) no.1, 25

The CRESST-II Detector Module

The CRESST-II Detector Module



$CaWO_4$ Target Crystal

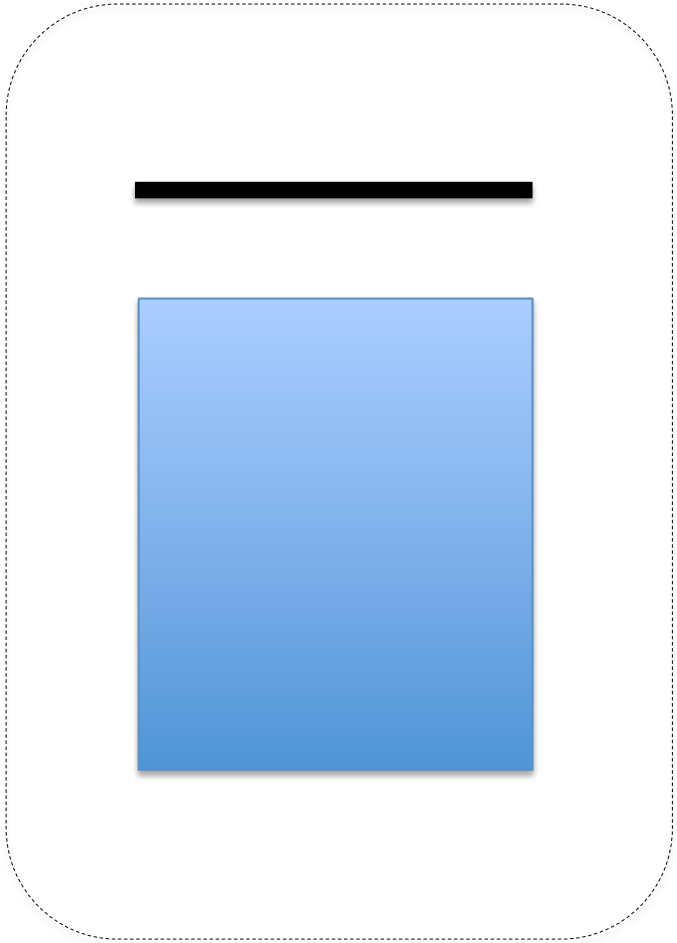


- scintillating
- multi-element target
- mass: 250 – 350 g

^{16}O ^{40}Ca ^{184}W

In-house production and processing at our institutes

The CRESST-II Detector Module

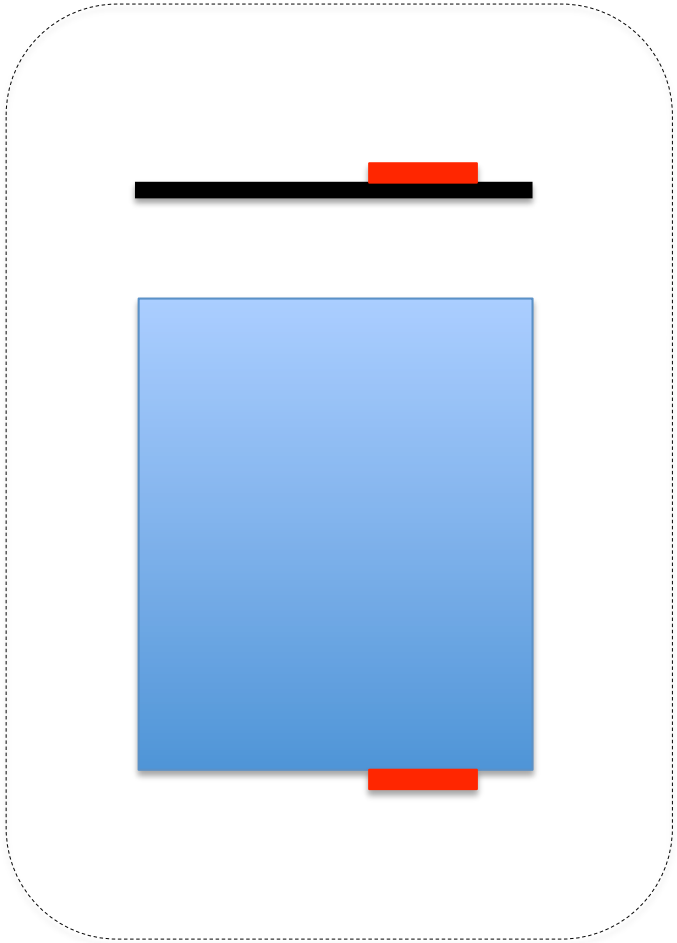


Light Absorber

for scintillation-light detection

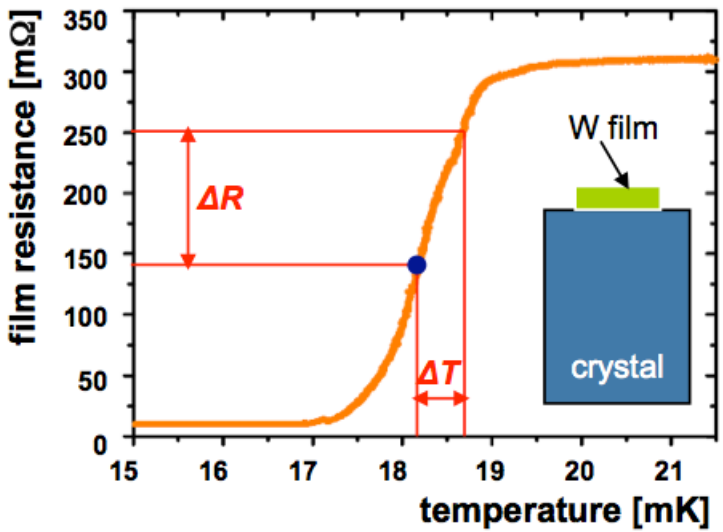
- silicon-on-sapphire disc
- diameter: 40mm
- thickness: 500µm

The CRESST-II Detector Module



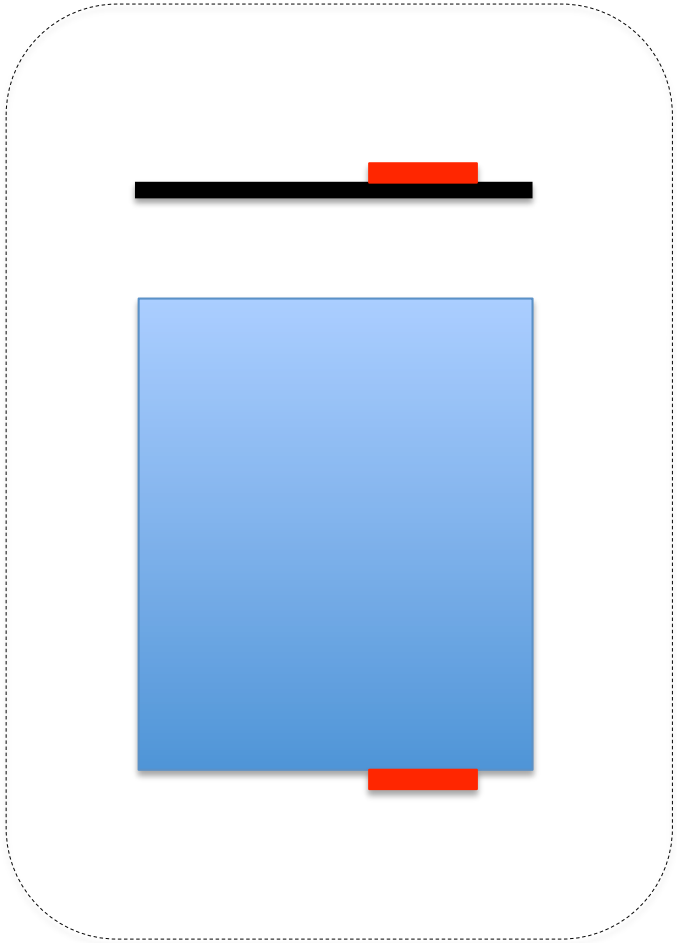
Transition-Edge-Sensors

→ 2 independent calorimeters



- mK temperatures
- calorimetric / bolometric operation
- read-out with SQUIDs

The CRESST-II Detector Module



Transition-**E**dge-**S**ensors

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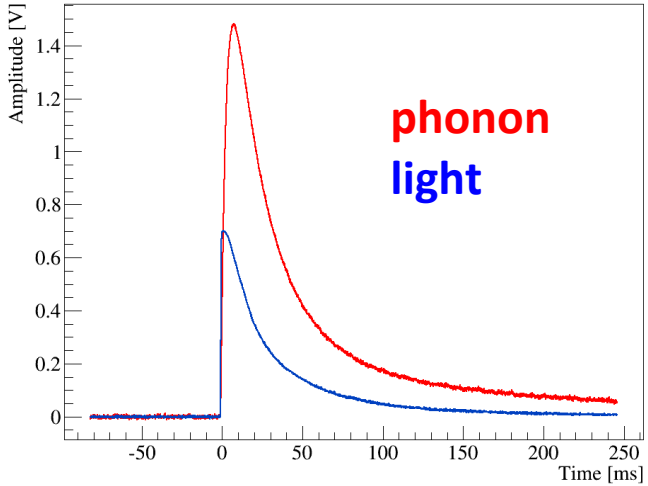


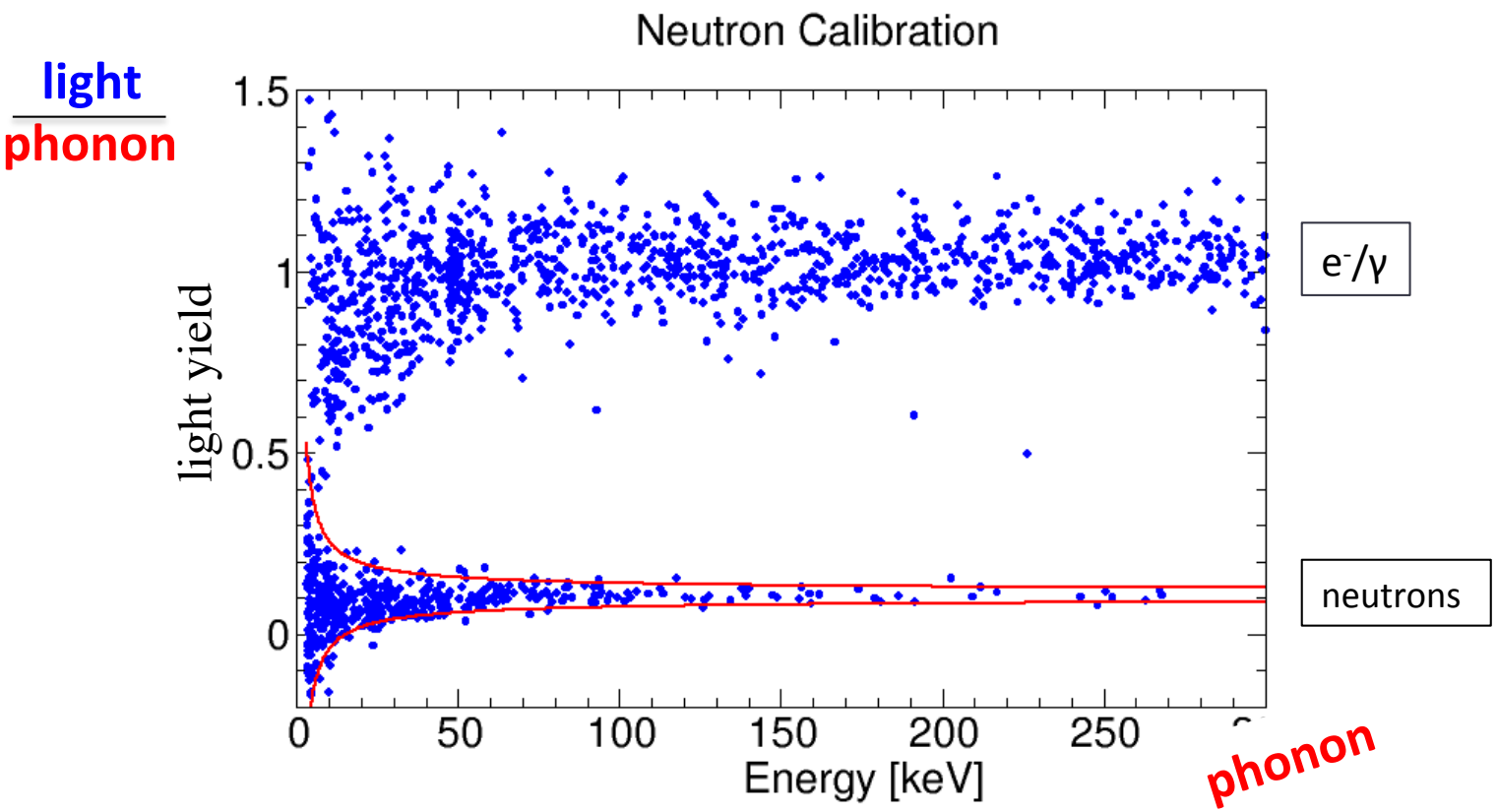
CRESST is leading the field of low-mass Dark Matter search!

World-best thresholds

- for 300g $CaWO_4$: E_{th} = 307 eV

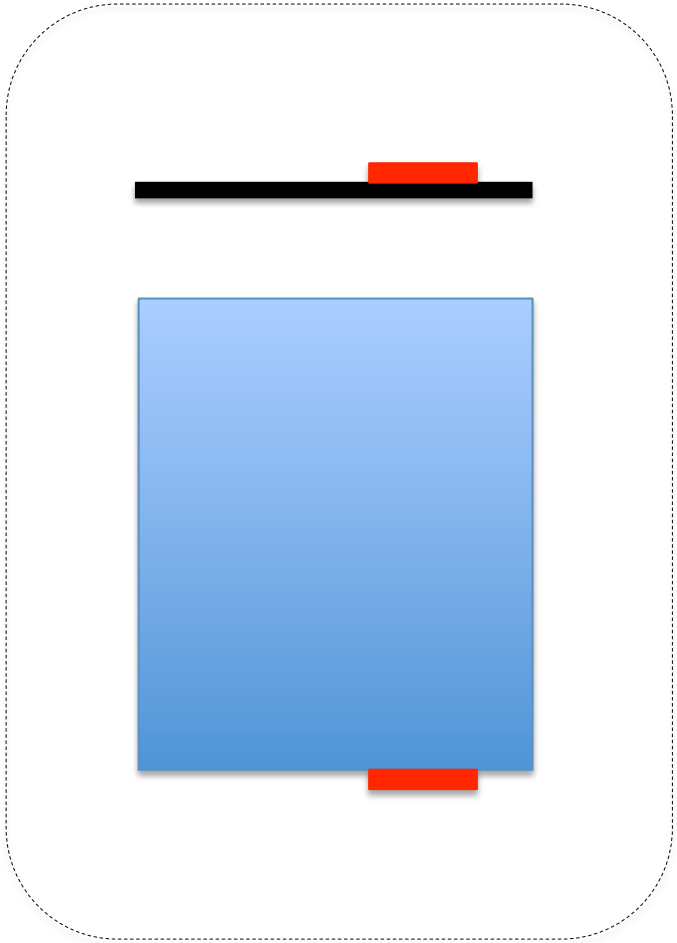
G. Angloher et al. EPJ C76 (2016) no.1, 25

Phonon-Light Technique



Reduced light output for highly-ionizing particles → Quenching

Outline



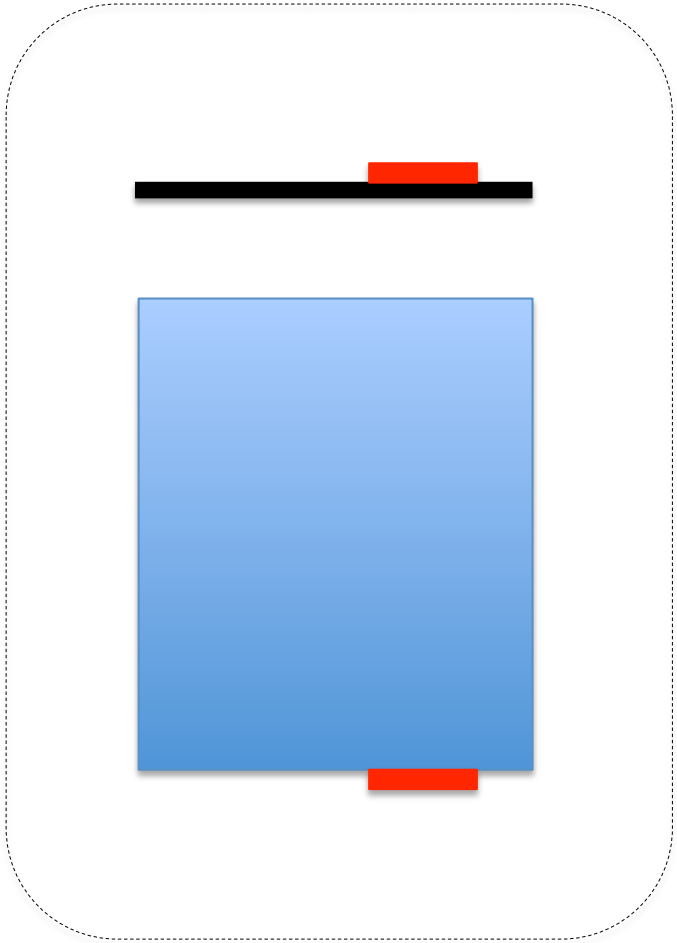
Background sources

1. External radiation
2. Surface backgrounds
3. Thermal stress/artefacts??
4. Intrinsic contamination

Physics case

1

Outline



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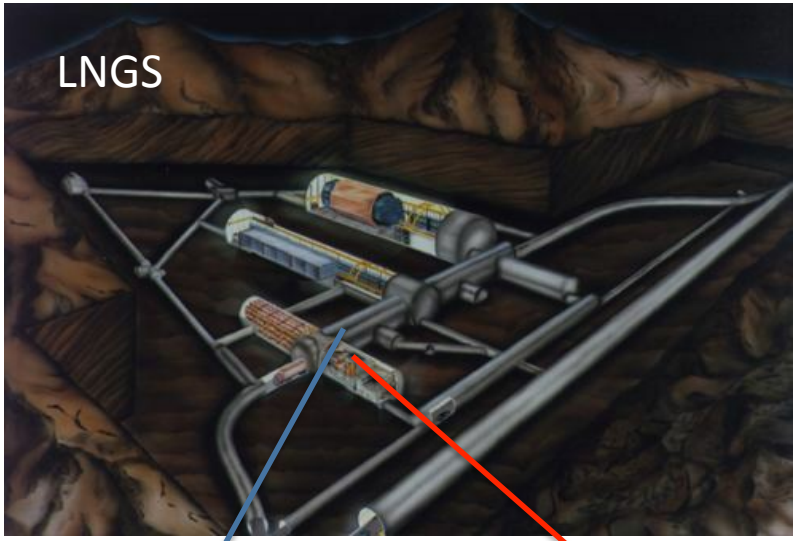
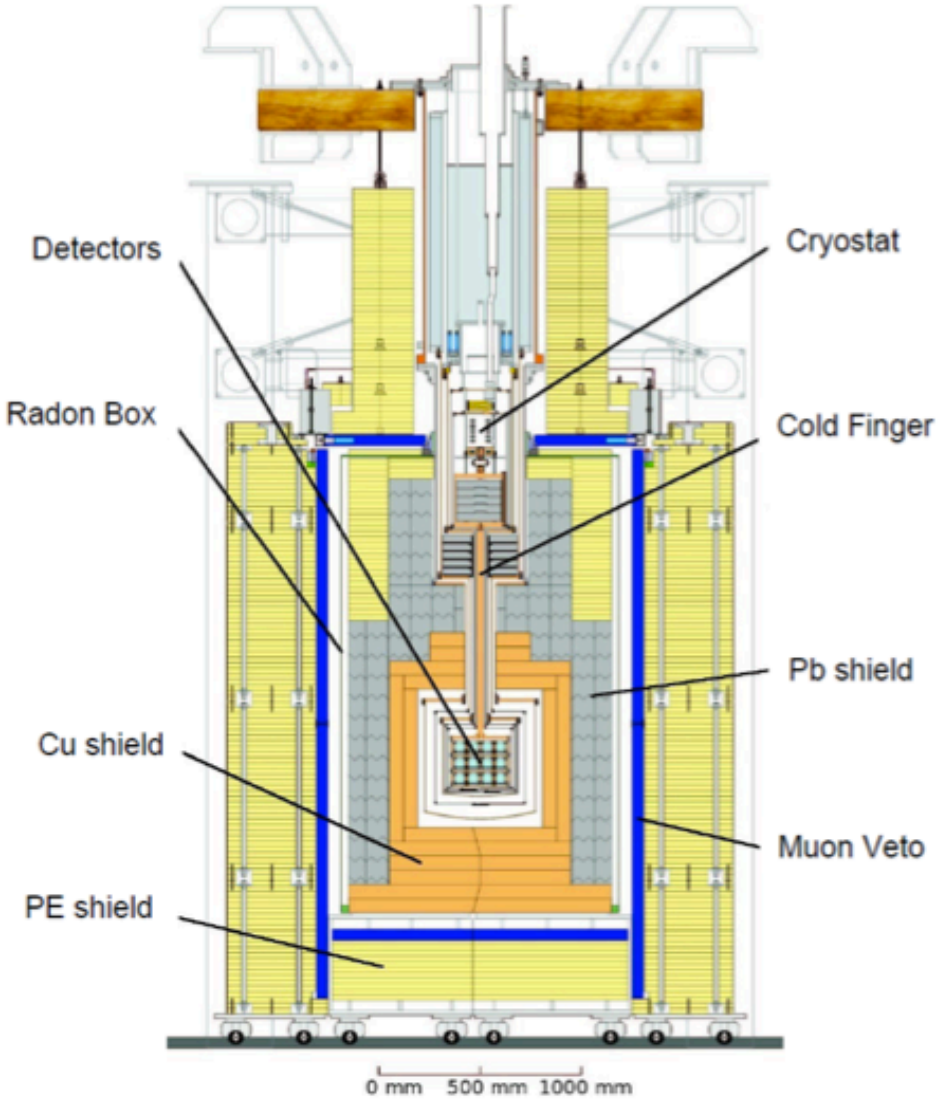
Physics case

The CRESST Experiment

Cryogenic Rare Event Search with Superconducting Thermometers





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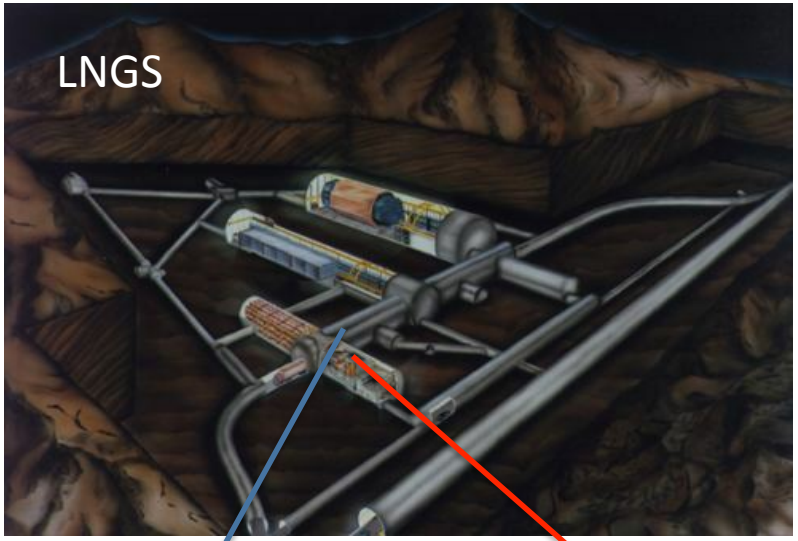

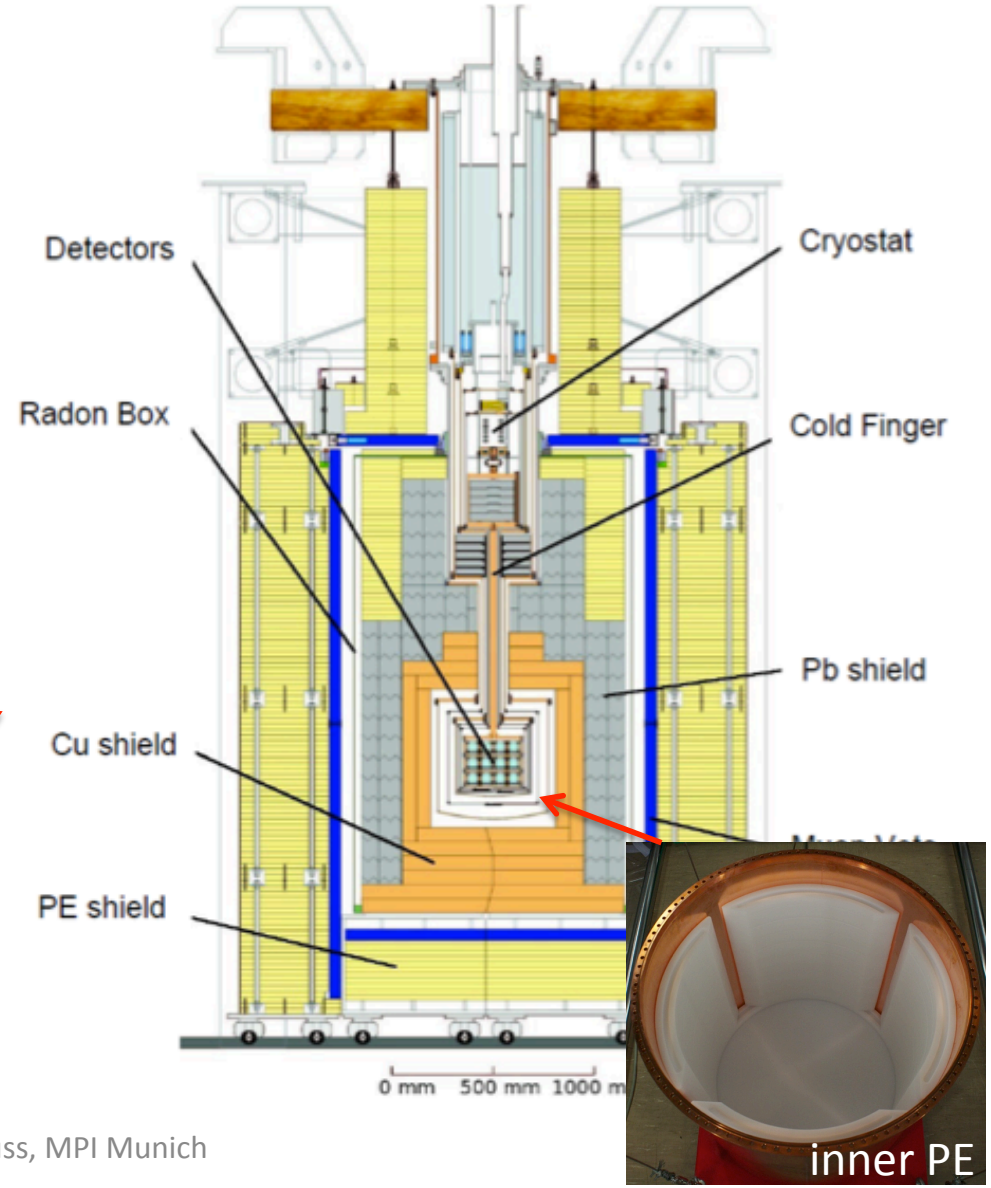

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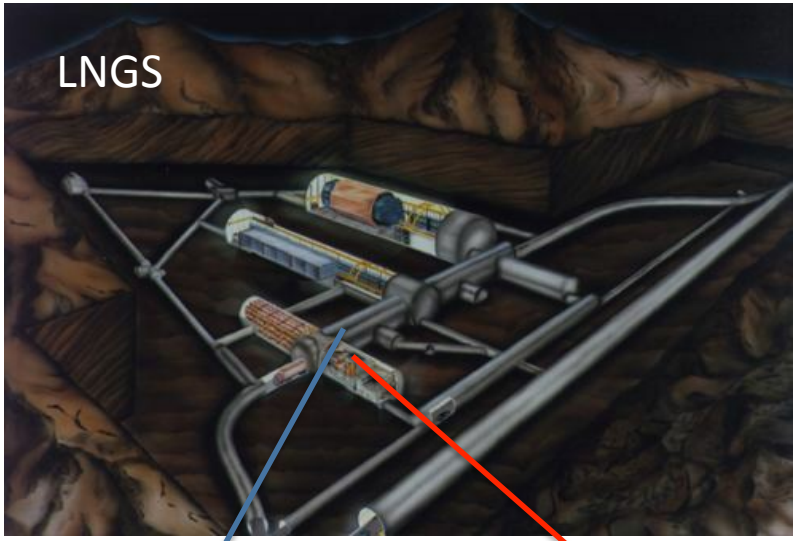
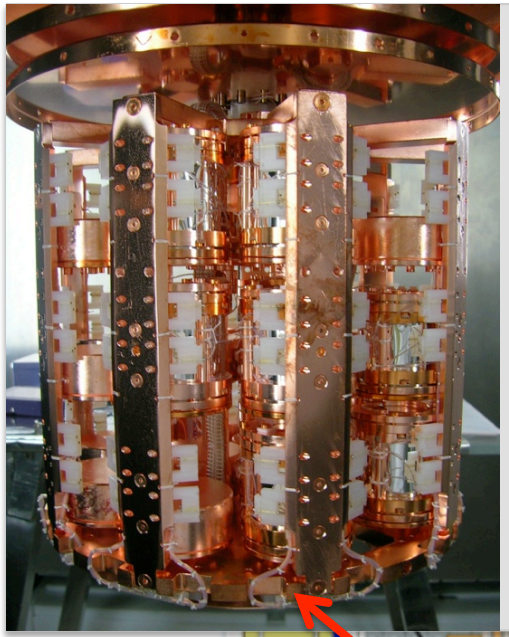
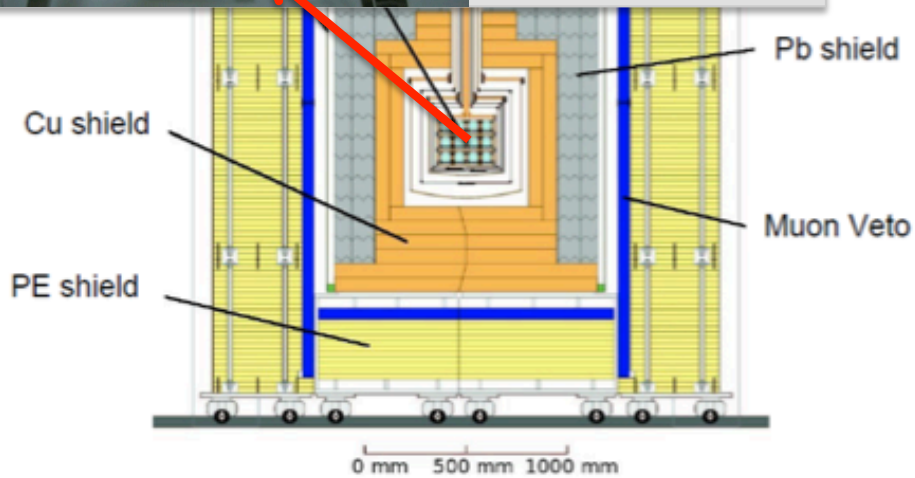




Detector "Carousel"

Currently 36 SQUID readout channels



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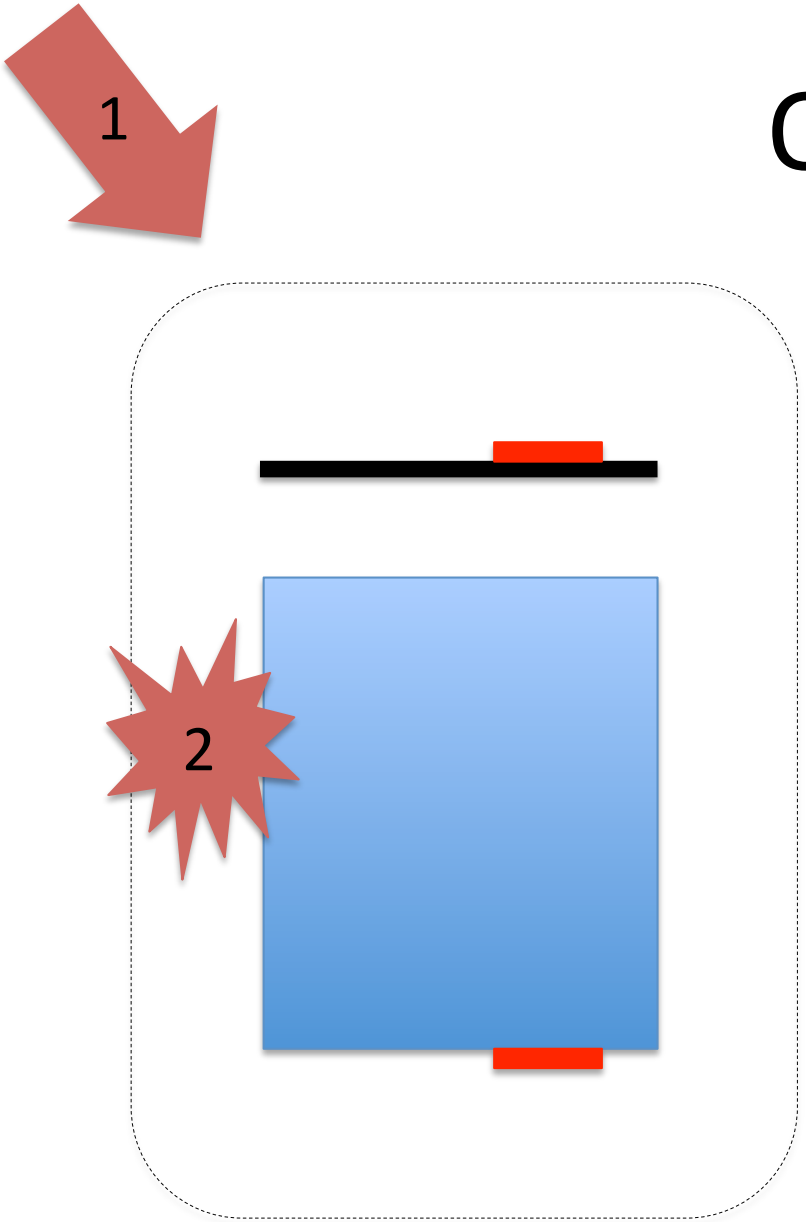

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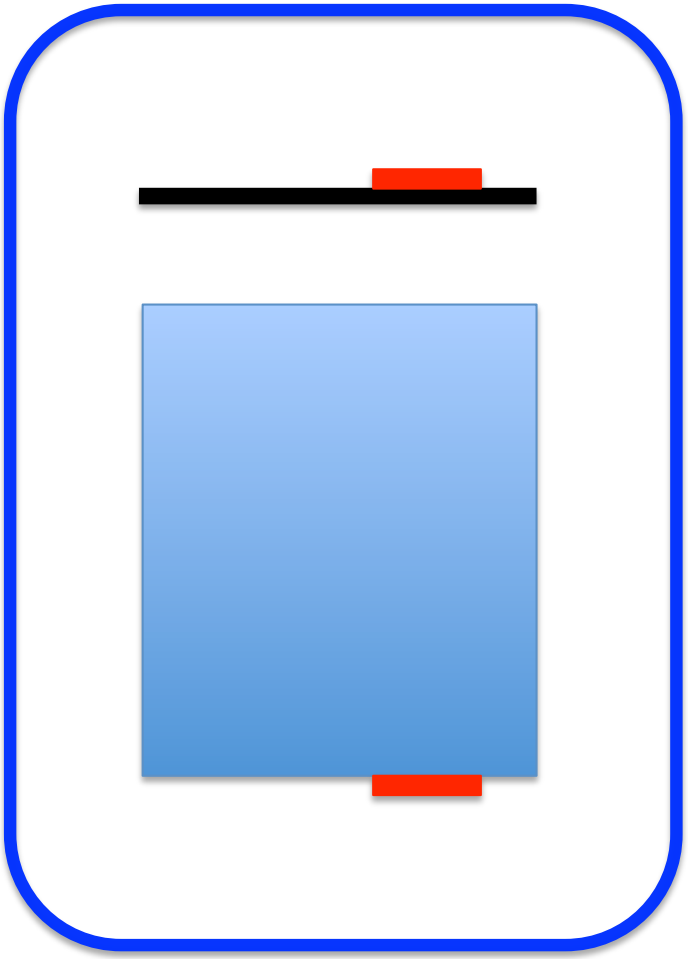
Physics case

The CRESST-II Detector Module



Polymeric Foil

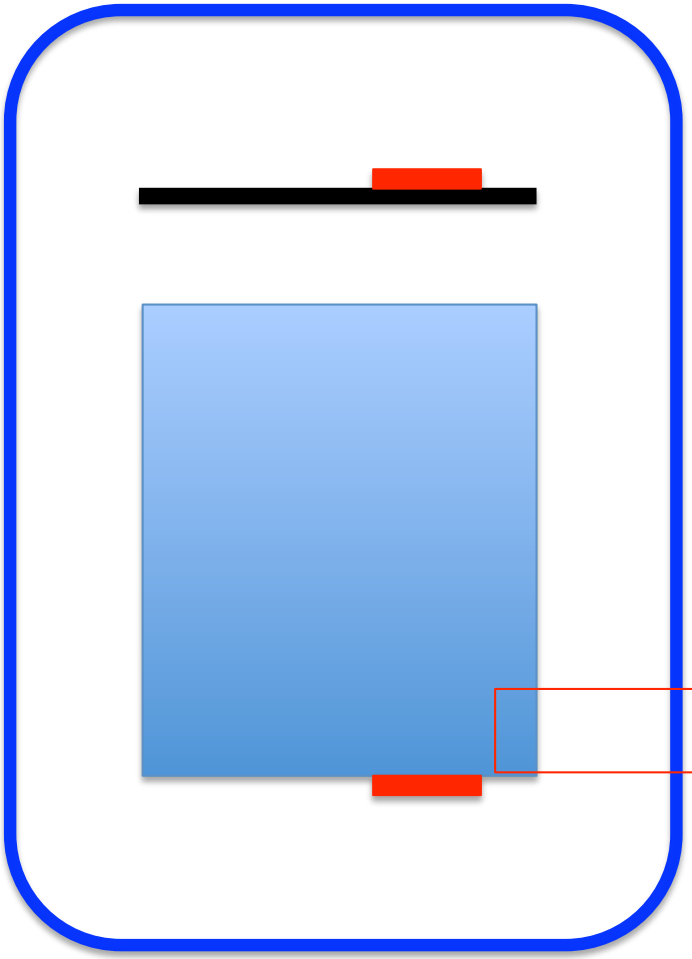
① Highly reflective

- ➢ light collection

② Scintillating

- ➢ rejection of surface events

The CRESST-II Detector Module



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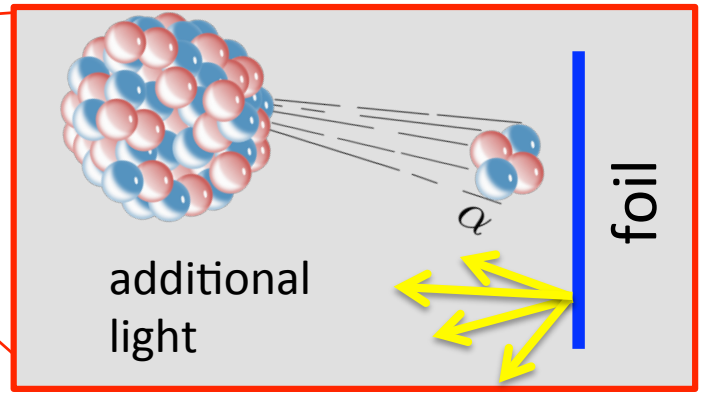

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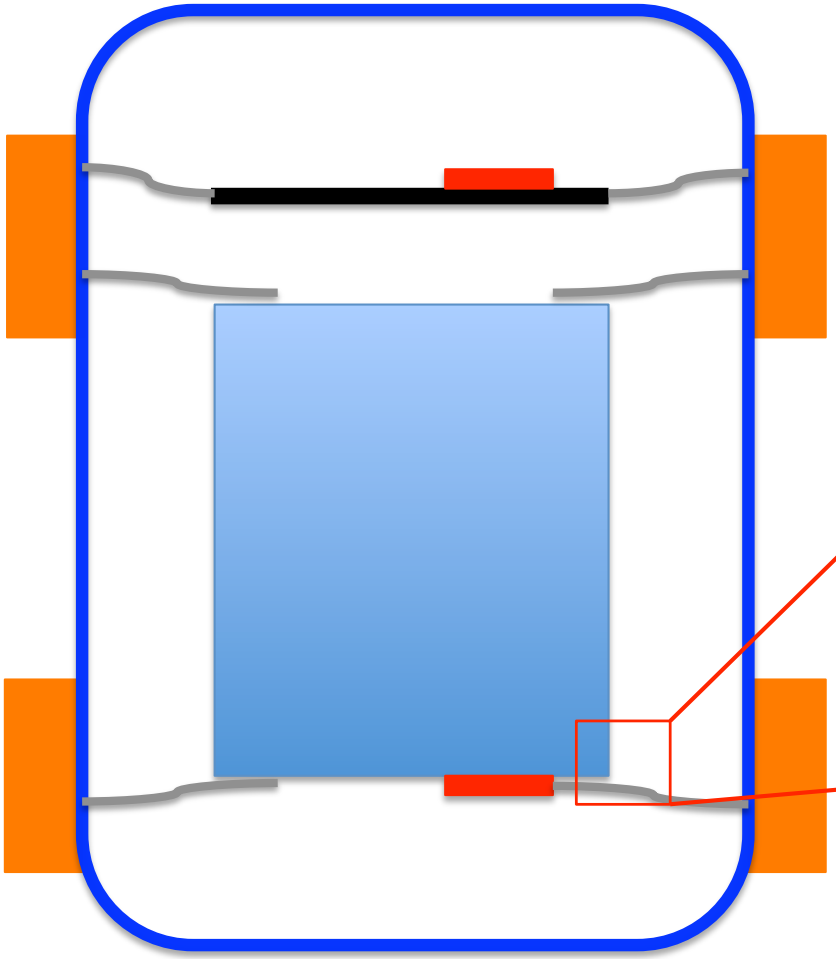
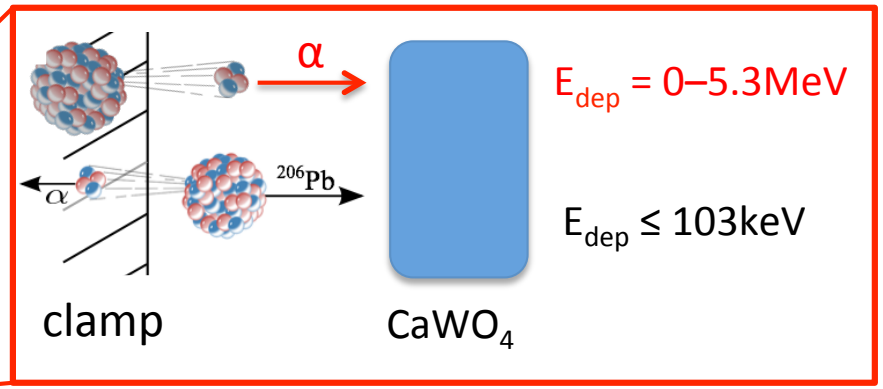


Dangerous Surface Backgrounds

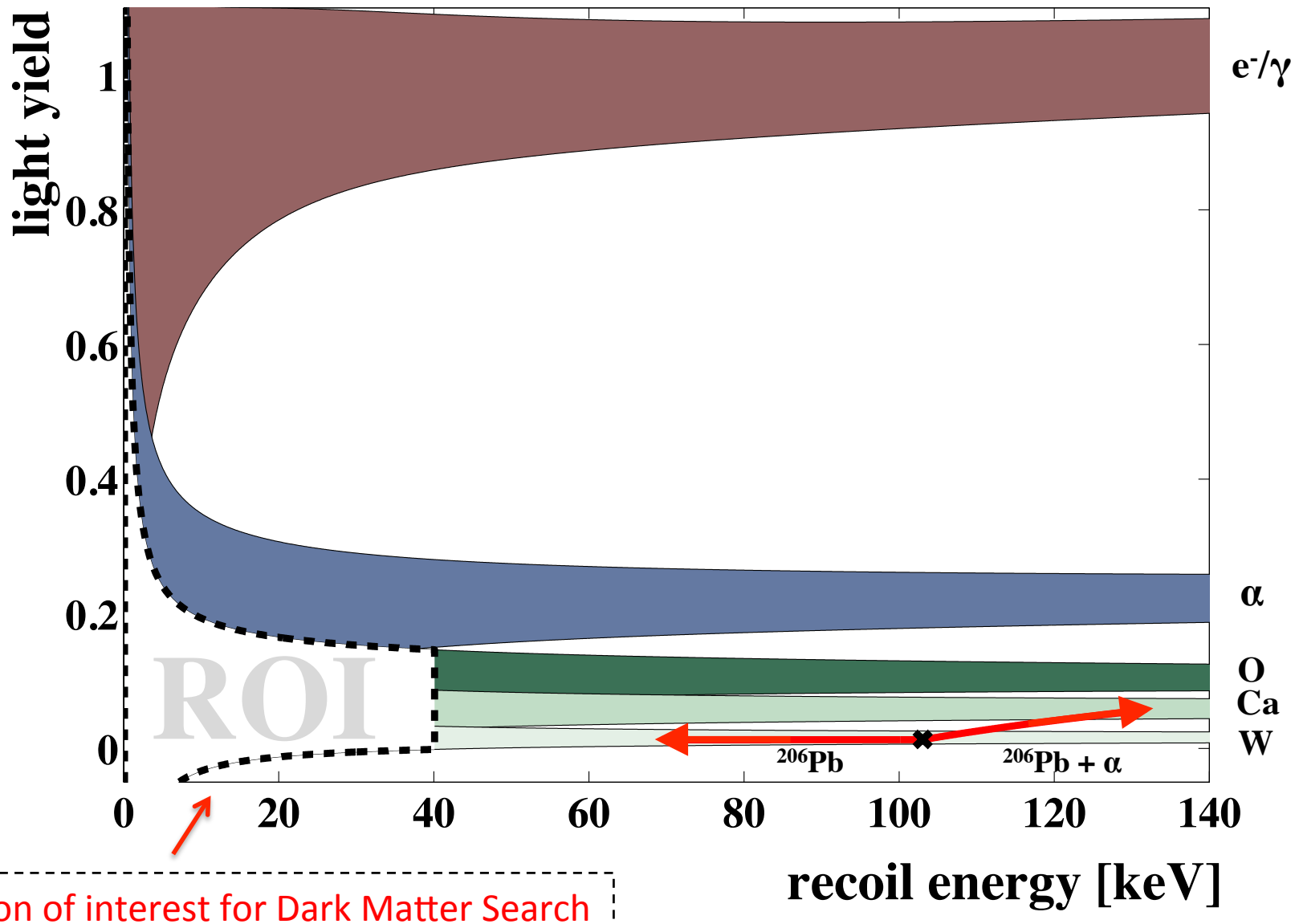
$^{210}Po \rightarrow {}^{206}Pb\ (103keV) + \alpha\ (5.3MeV)$



→ Lead/alpha recoils can mimic WIMPs

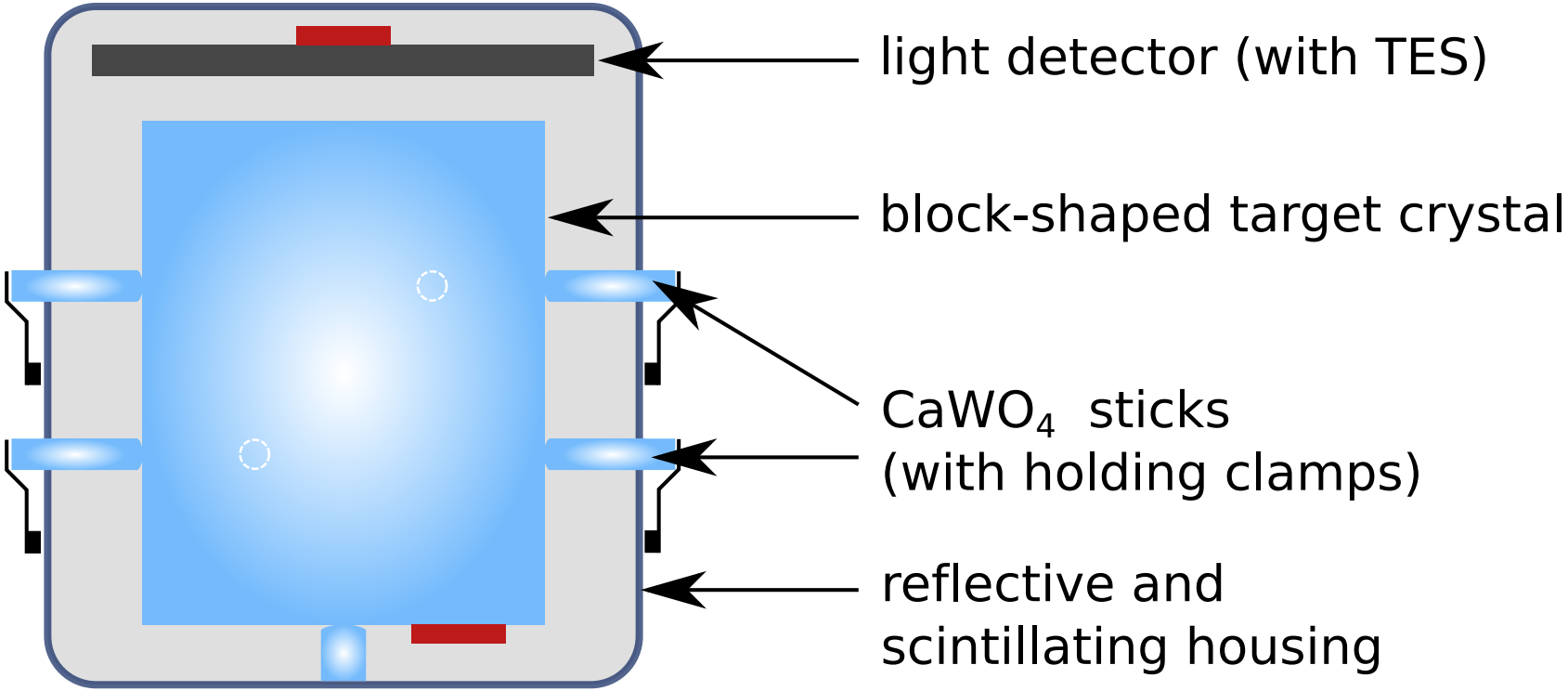
→ Avoid non-scintillating materials!

Efficient Veto of Surface-Alpha Backgrounds



Region of interest for Dark Matter Search

Fully-Scintillating Design



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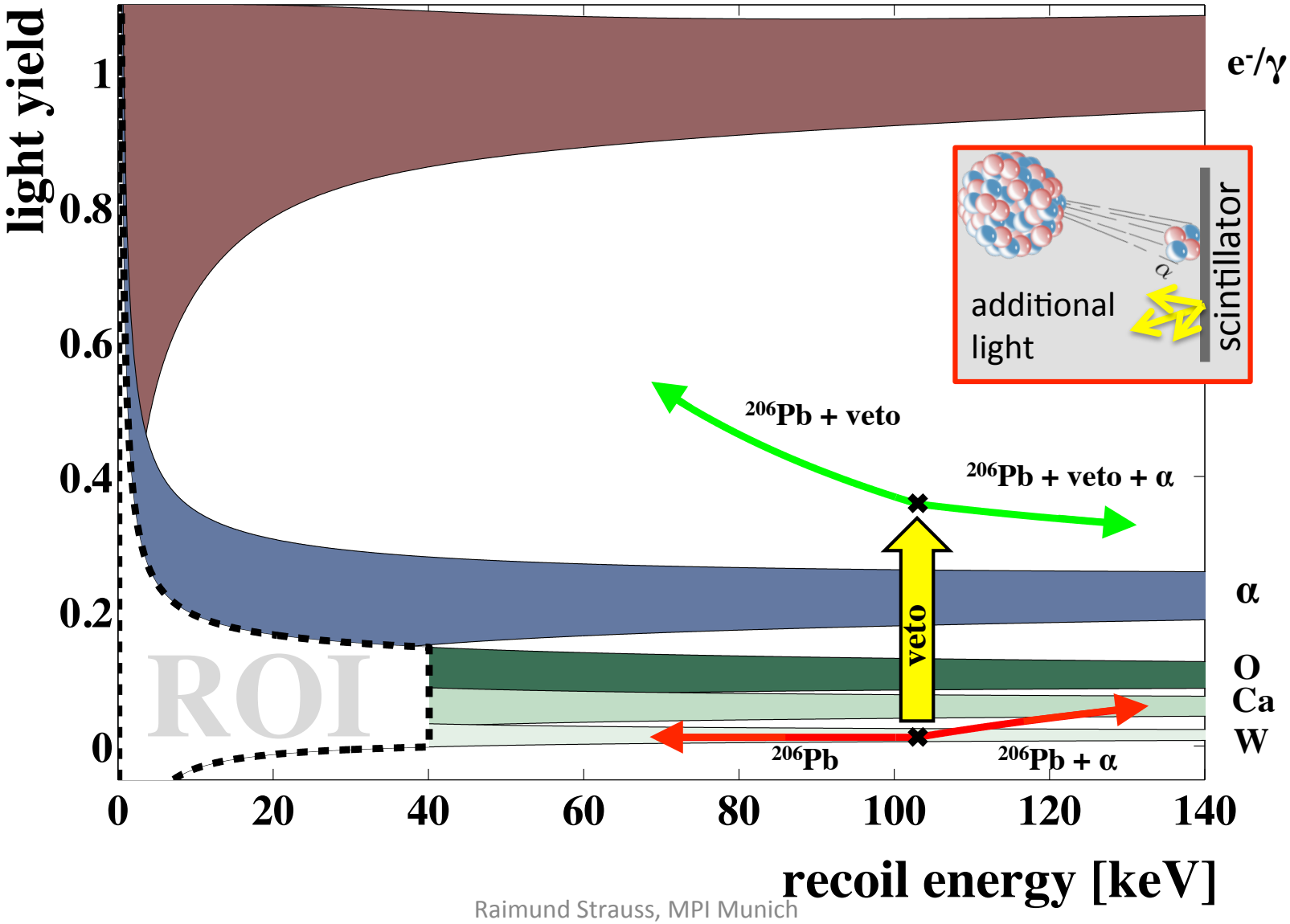
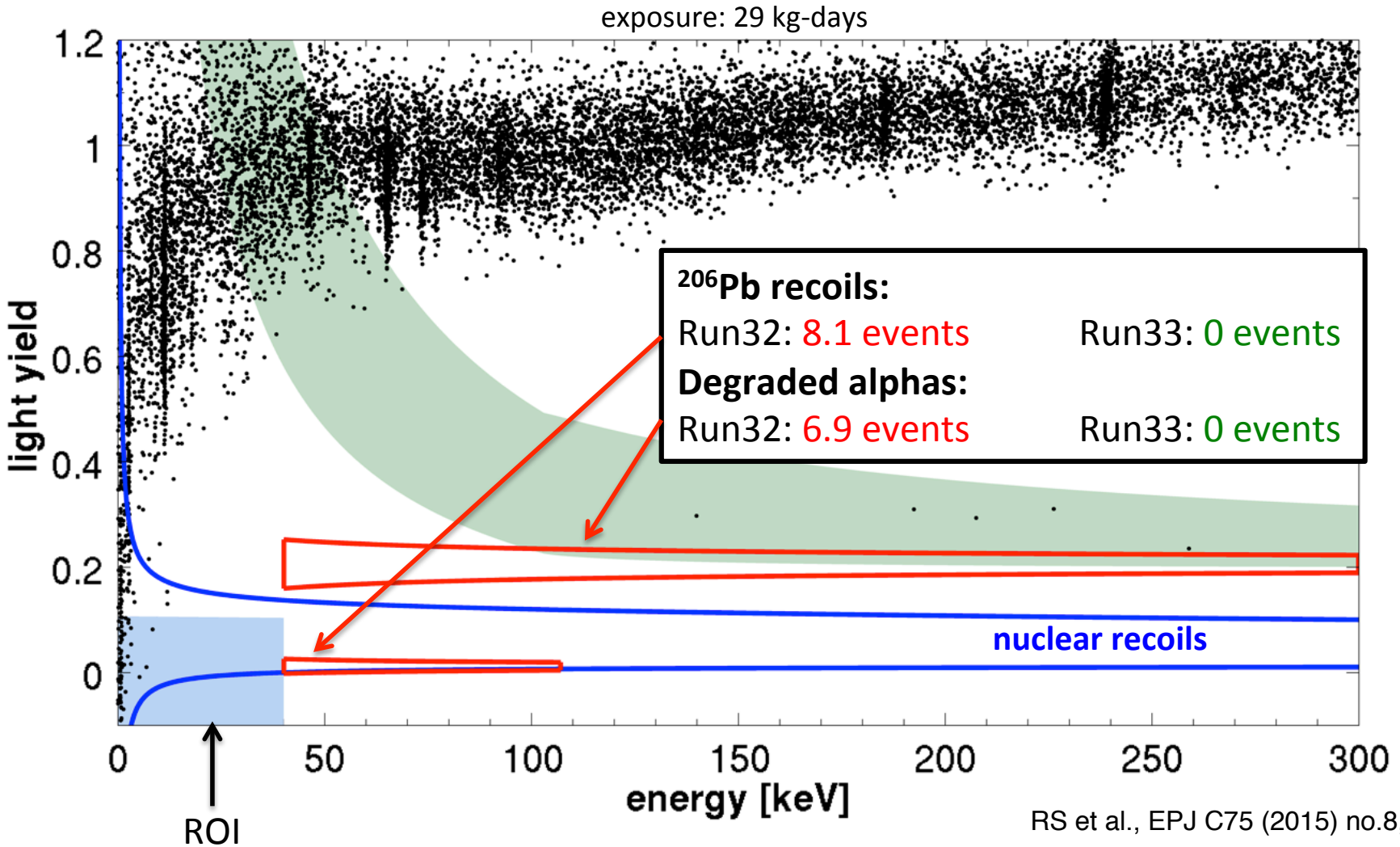
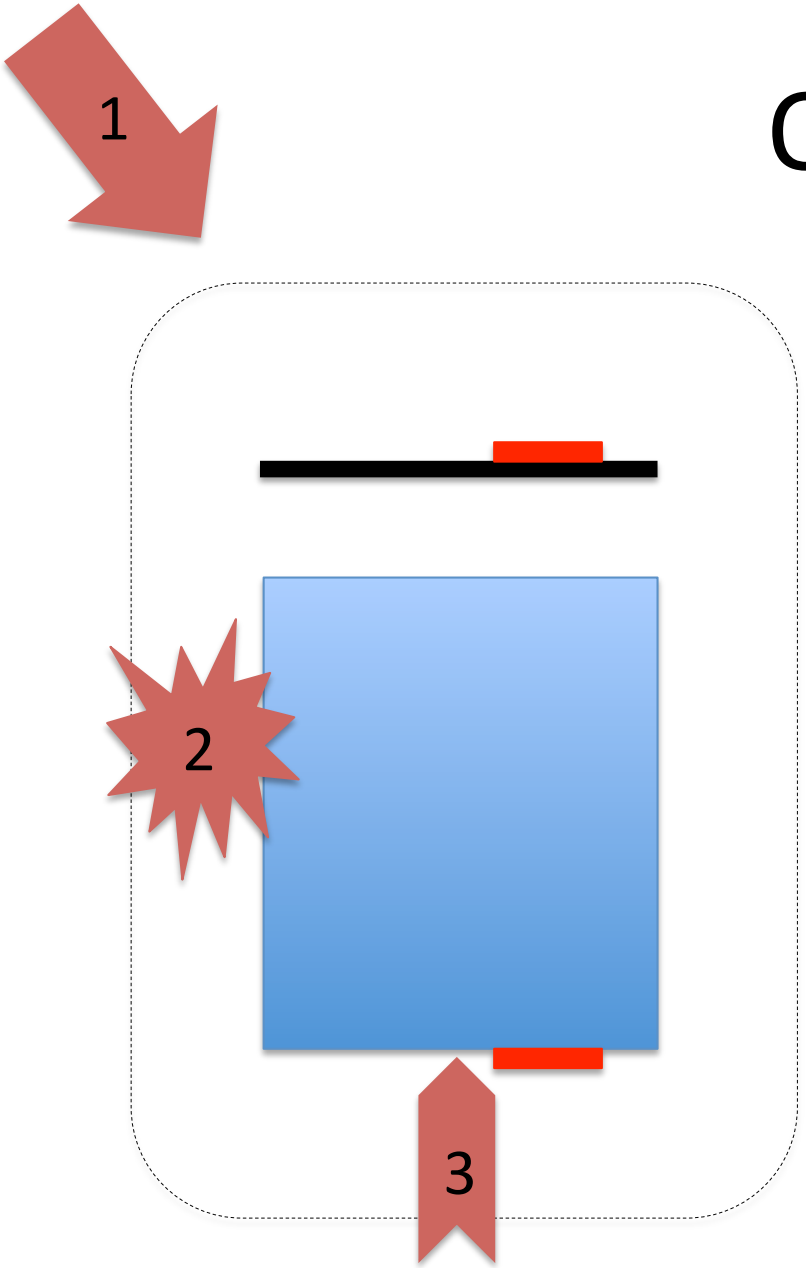


TUM-40: Surface-Alpha Backgrounds



RS et al., EPJ C75 (2015) no.8, 352

Outline

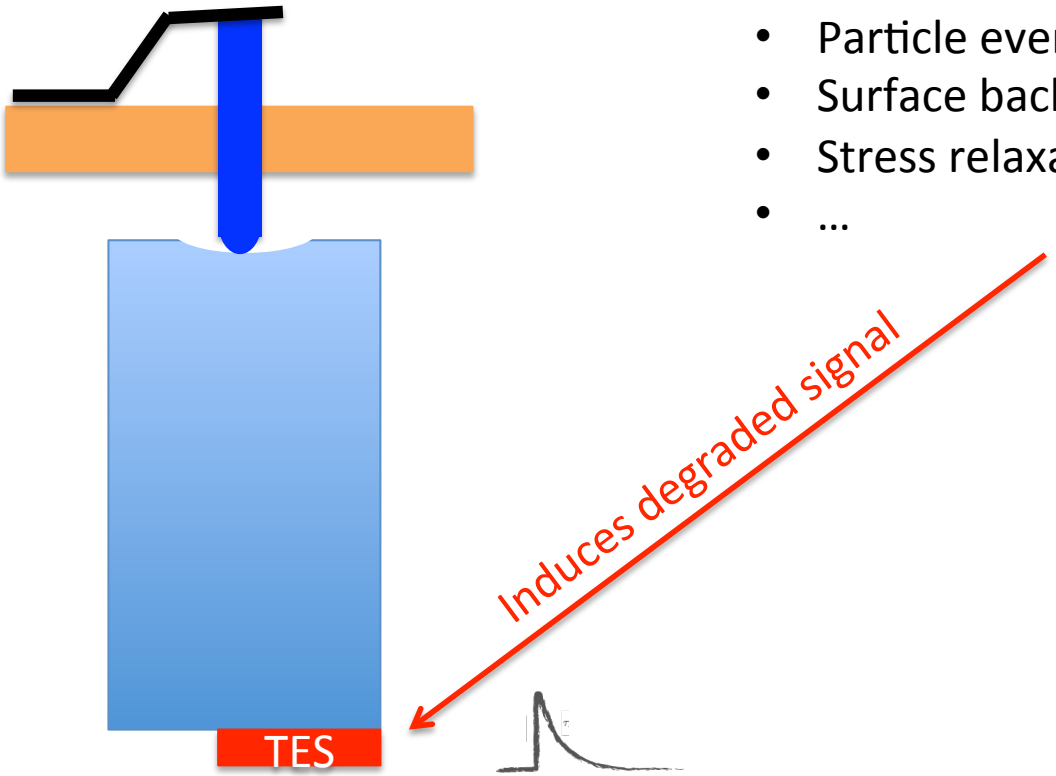


Background sources

1. External radiation
2. Surface backgrounds
3. Thermal stress/artefacts??
4. Intrinsic contamination

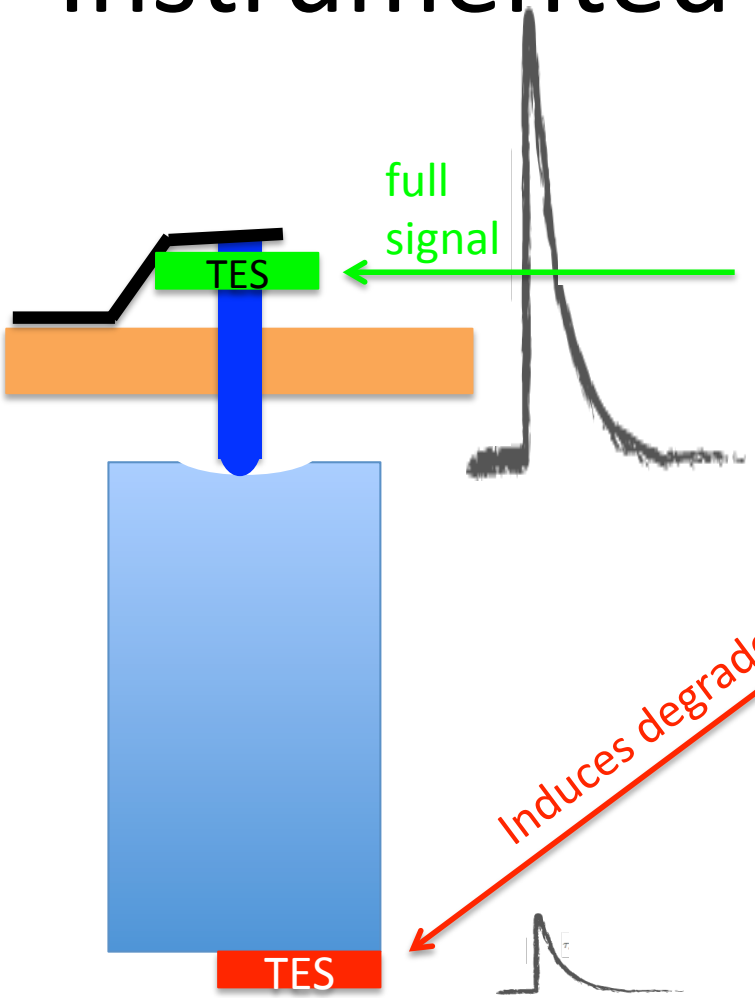
Physics case

Instrumented Holder - iSticks



- Particle events in sticks
- Surface backgrounds
- Stress relaxations
- …

Instrumented Holder - iSticks

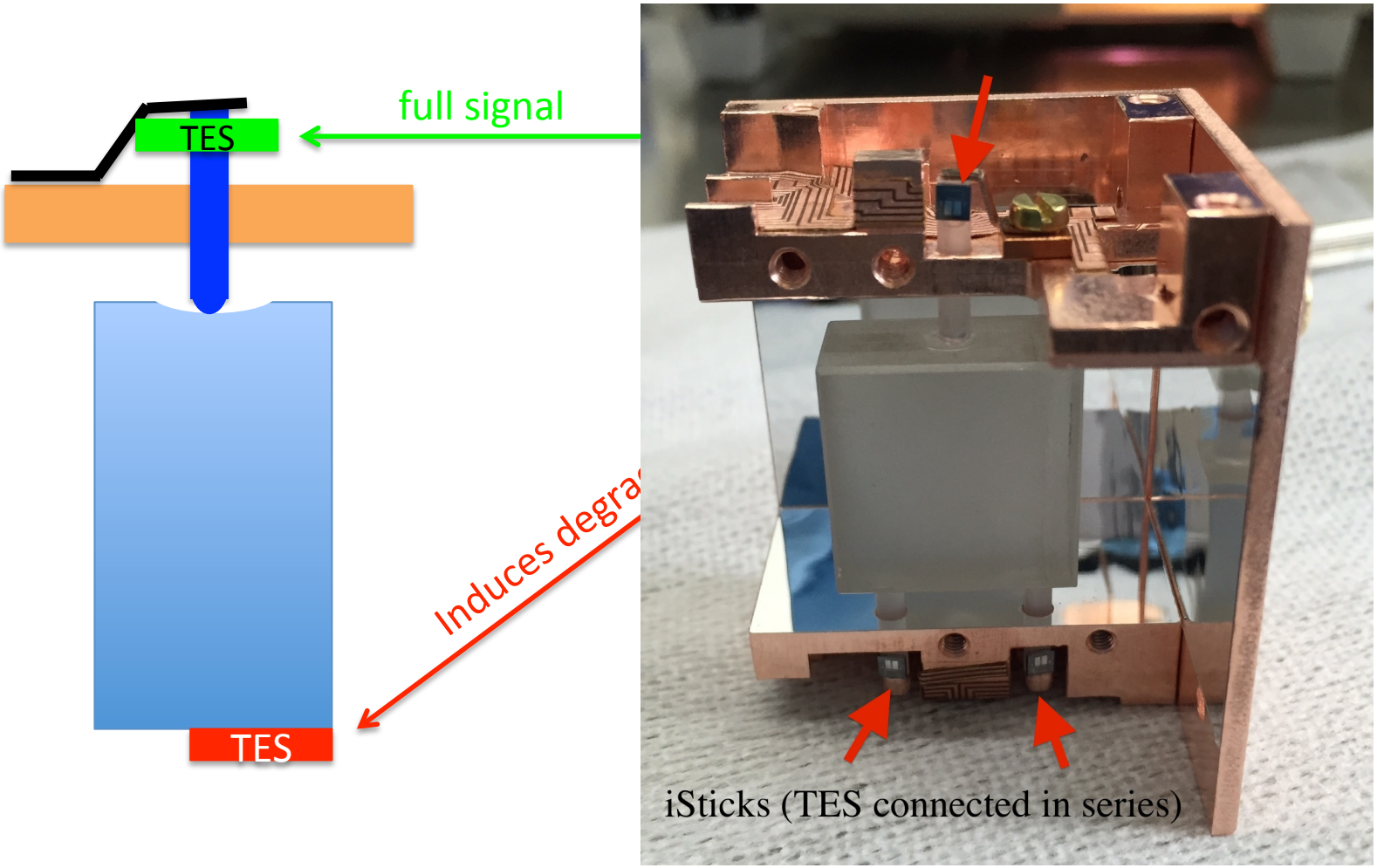


- Particle events in sticks
- Surface backgrounds
- Stress relaxations
- …

ratio $\frac{\text{stick}}{\text{absorber}}$

powerful tool to reject all kind of backgrounds related to holder!

Instrumented Holder - iSticks



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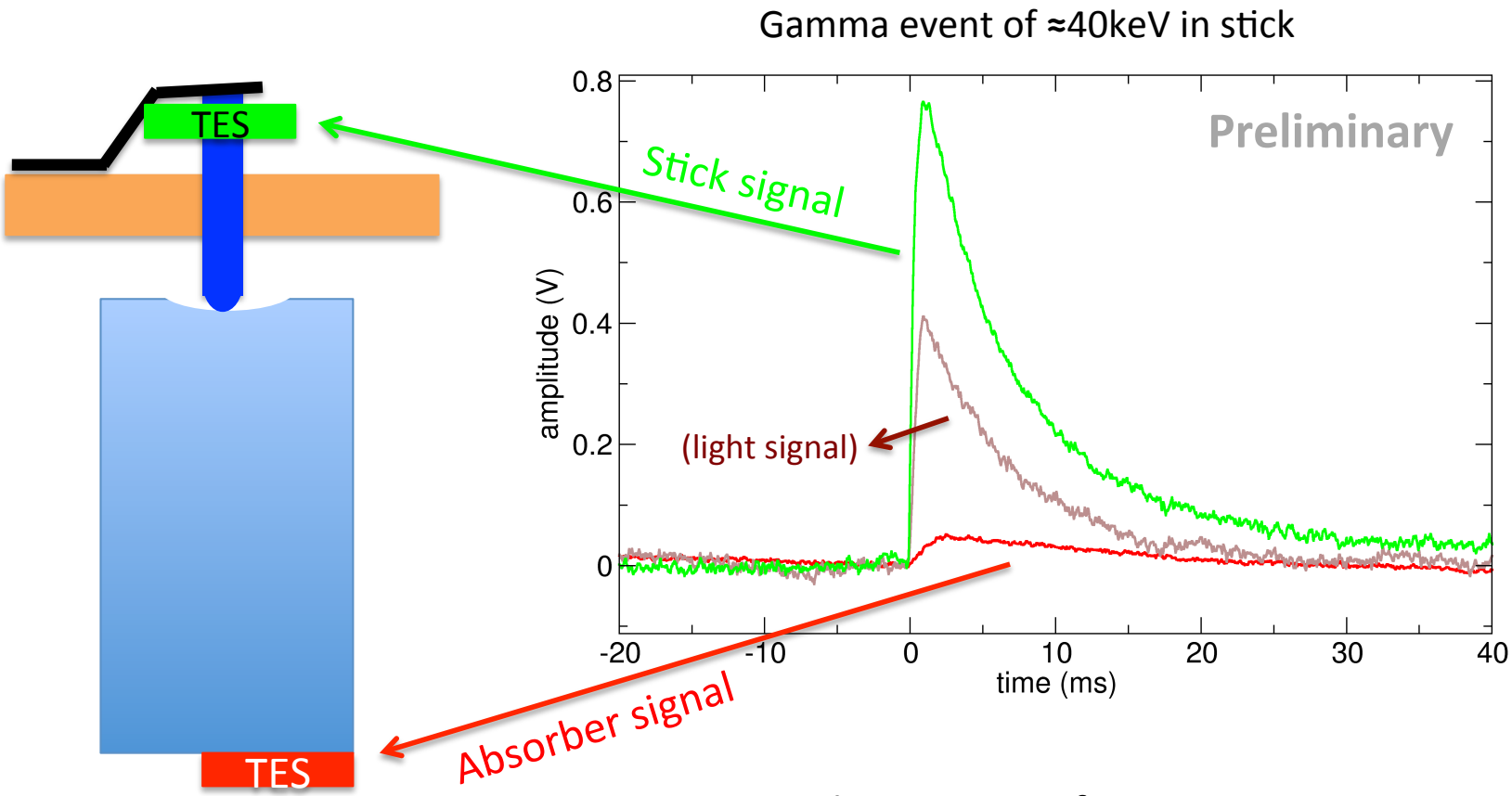
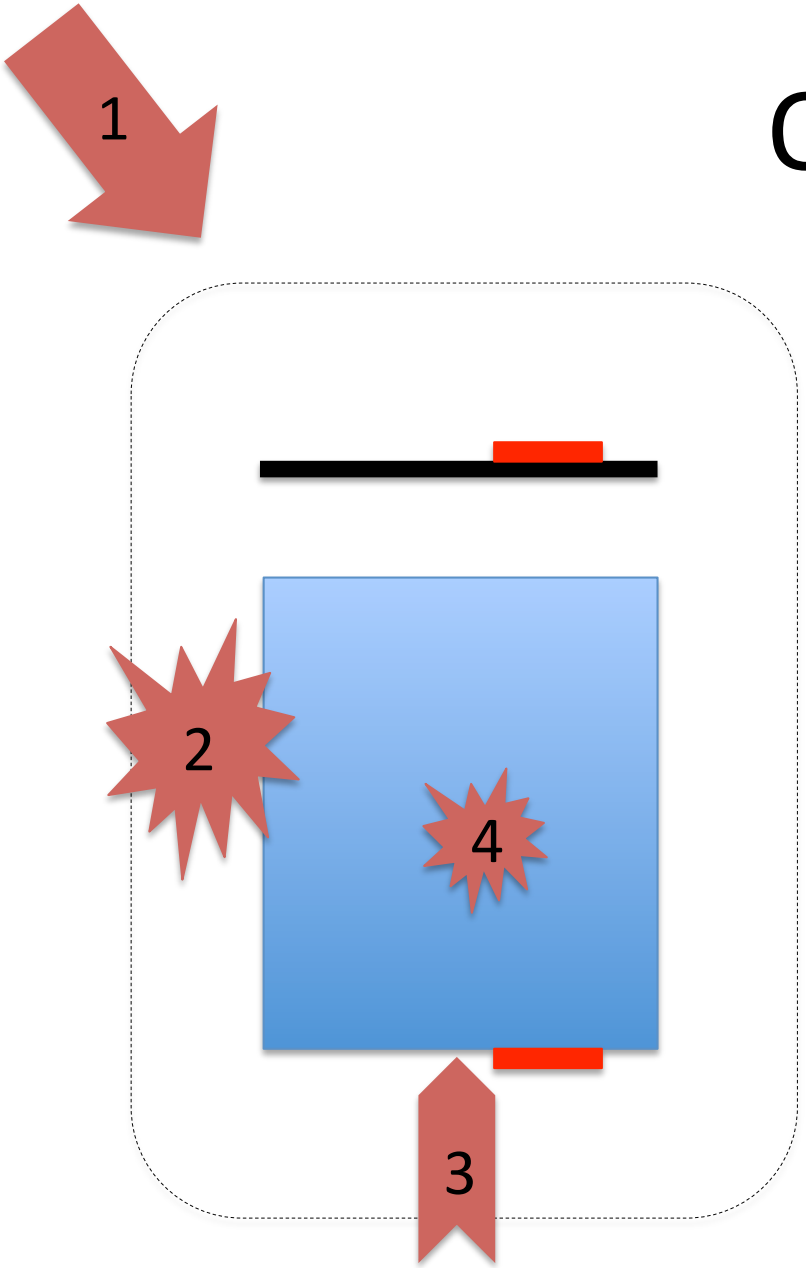


Implementation for CRESST-III

Outline



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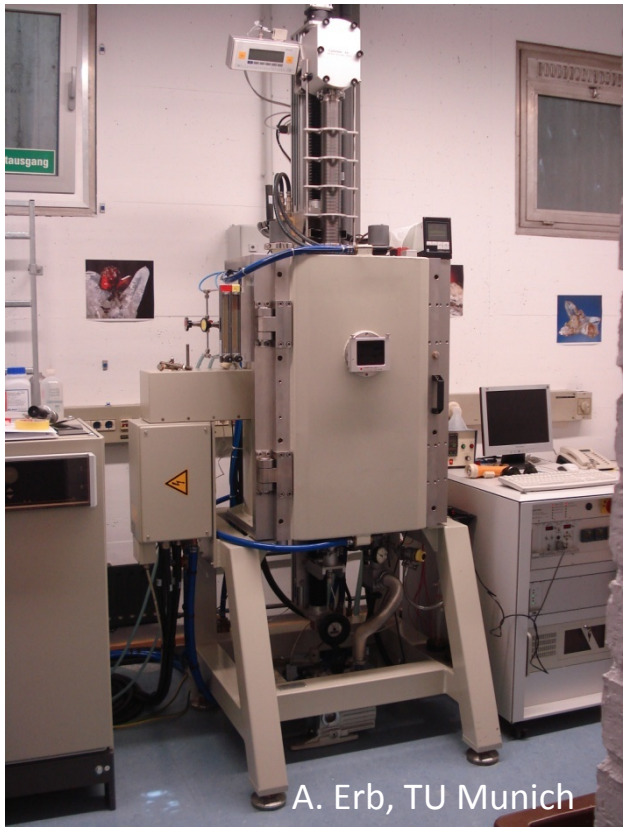
Physics case

$CaWO_4$ Crystal Production at TU Munich

Furnace for **Czochralski process**



A. Erb et al., *CrystEngComm*, 2013,**15**, 2301-2304
M. von Sivers et al., Opt. Mat. 34, 11 (2012) 1843-1848

Dedicated machine for CRESST:

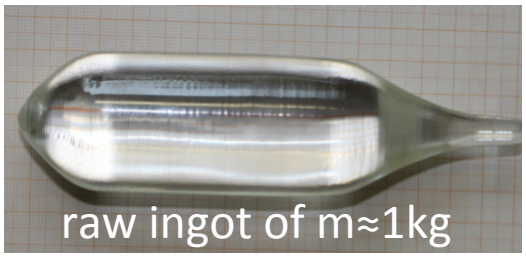
- All production steps under control
- Machining of crystals in-house

Goals :

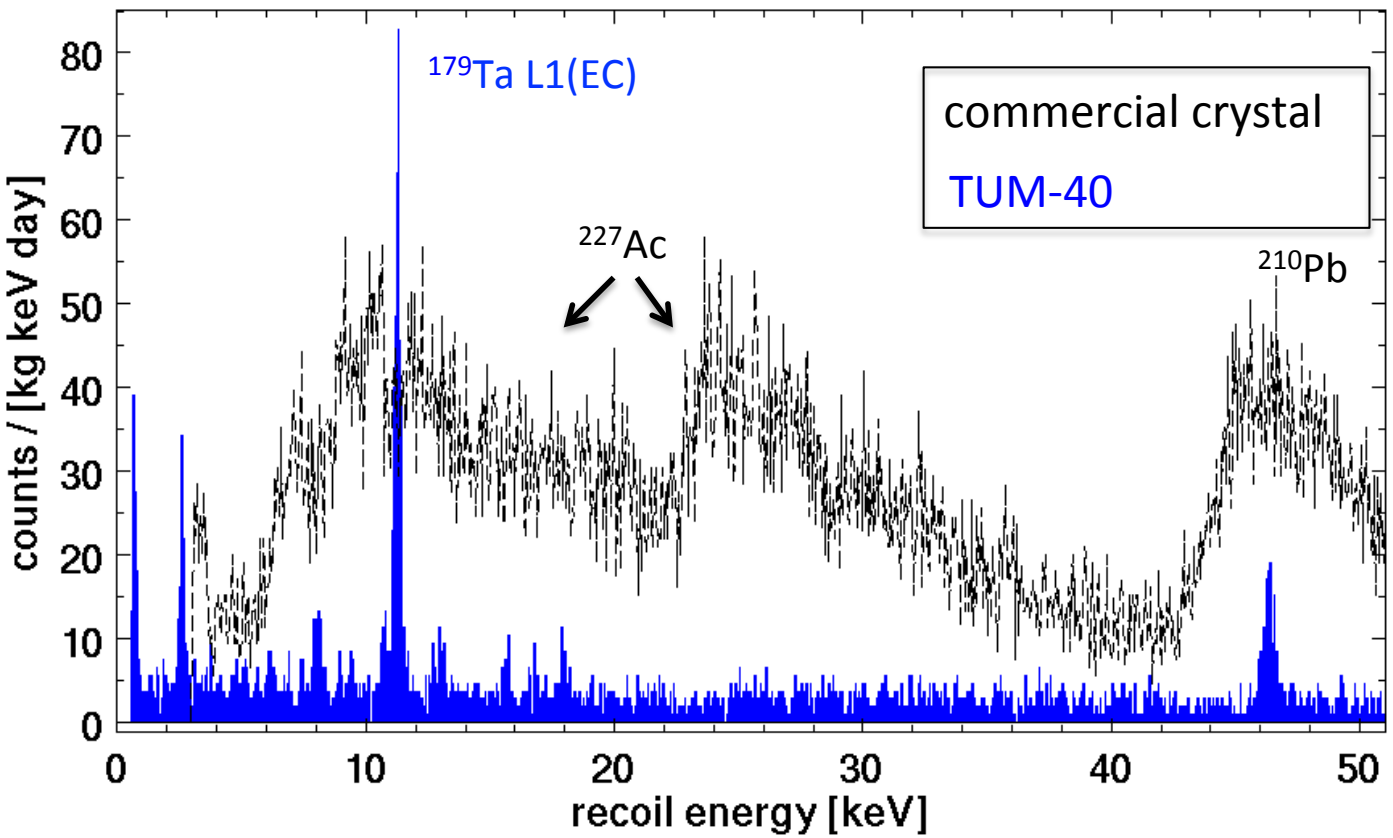
- Increase **radiopurity**
- Increase **light output**
- Ensure supply

Major achievements:

- Reproducible growth process
- Crystals of CRESST size
- Unprecedented intrinsic radiopurity



TUM-40: Radiopurity



Average rate:
~3.5 counts / [kg keV day]

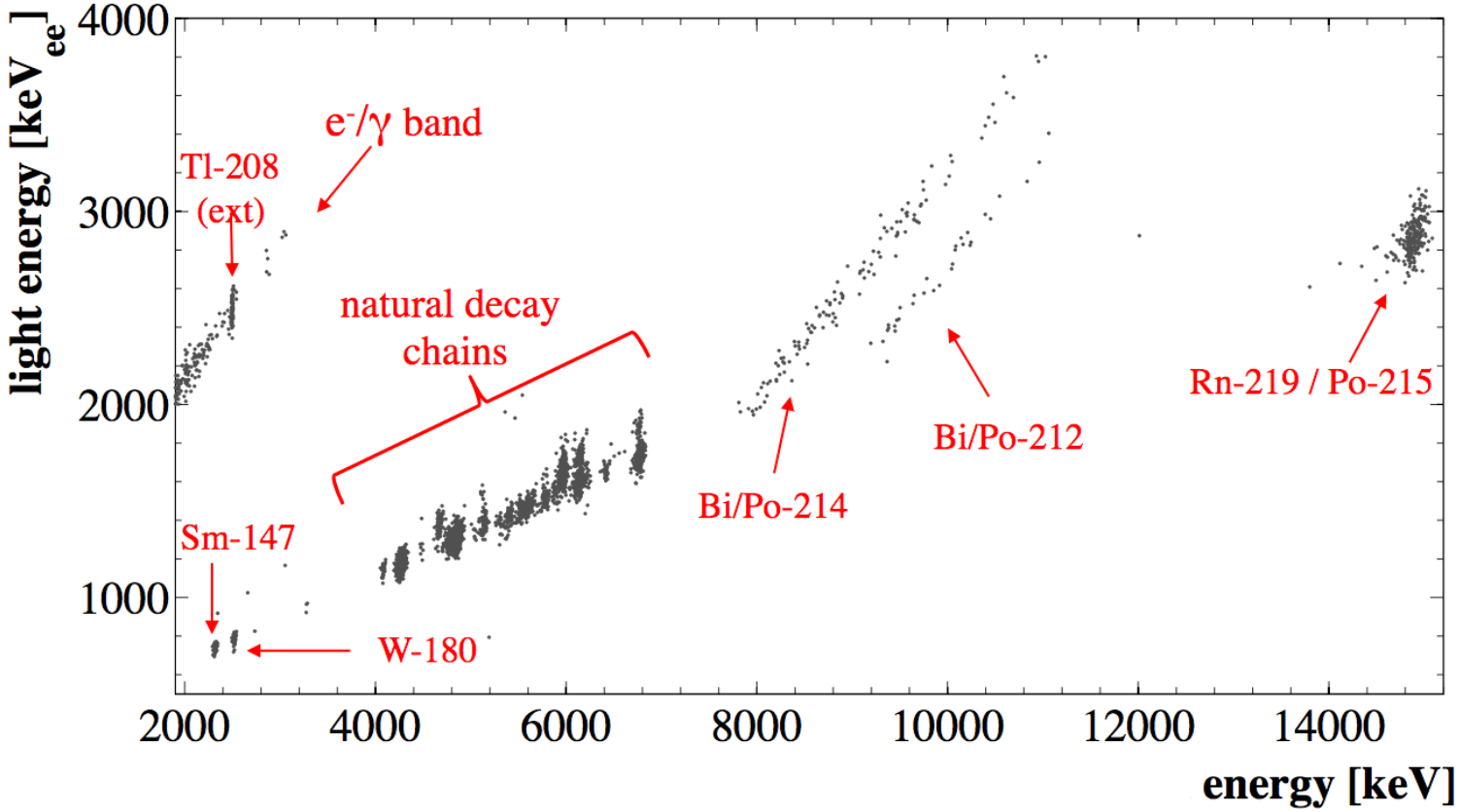
Gamma-lines from **cosmogenic activation**

Excellent resolution:
$\sigma \approx 100$eV

All gamma lines agree within < 5eV with tabulated values !!

Alpha analysis to understand low-energy backgrounds

RS, et al. JCAP 1506 (2015) no.06, 030



High dynamic range of CRESST detectors (300eV – 20 MeV)!

Derive individual alpha activities

chain	parent	mode	br [%]	half-life	E_{lit} [keV]	E_{obs} [keV]	A [μBq/kg]
^{238}U	^{238}U	α	100	$4.47 \cdot 10^9$ y	4270	4271	$(1.01\pm0.02)\cdot10^3$
	^{234}Th	β^-	100	24.1 d	273	0-273	(a)
	^{234}Pa*	β^-	100	1.17 min	2197	0-2197	(a)
	^{234}U	α	100	$2.45 \cdot 10^5$ y	4858	4853	$(1.08\pm0.03)\cdot10^3$
	^{230}Th	α	100	75.4 y	4770	4771	55.8±5.4
	^{226}Ra	α	100	1.60 y	4871	4853 (b)	43.0±9.9
	^{222}Rn	α	100	3.82 d	5590	5592	38.1±4.9
	^{218}Po	α	99.98	3.10 min	6115	6139	43.1±9.9
	^{214}Pb	β^-	100	26.8 min	1023	0-1023	(a)
	^{214}Bi	β^-	99.98	19.9 min	3272	7800-11000	47.4±4.9
	^{214}Po	α	100	0.164 ms (c)	7883		
	^{210}Pb	β^-	100	22.3 y	63.5	0-63.5	7^{+36}_{-7}
	^{210}Bi	β^-	100	5.01 d	1163	0-1163	(a)
	^{210}Po	α	100	138 d	5407	5403	17.8±4.0
^{235}U	^{235}U	α	100	$7.04 \cdot 10^8$ y	4678	4671	39.5±4.4
	^{231}Th	β^-	100	25.52 h	389.5	0-389.5	(a)
	^{231}Pa	α	100	$3.27 \cdot 10^4$ y	5150	5139	23.2±4.4
	^{227}Ac	β^-	98.62	21.8 y	44.8	0-44.8	98±20
	^{227}Th	α	100	18.7 d	6147	6139	105±19
	^{223}Ra	α	100	11.4 d	5979	5968	104±7
	^{219}Rn	α	100	3.96 s	6946	14900	107±7
	^{215}Po	α	100	1.78 ms (c)	7527		
	^{211}Pb	β^-	100	36.1 min	1373	0-1373	(a)
	^{211}Bi	α	100	0.51 s	6751	6771	105±7
	^{207}Tl	β^-	100	4.77 min	1423	0-1423	(a)
^{232}Th	^{232}Th	α	100	$1.40 \cdot 10^{10}$ y	4083	4084	9.2±2.3
	^{228}Ra	β^-	100	5.75 y	45.9	6.7-45.9	(a)
	^{228}Ac	β^-	100	6.15 h	2127	58-2127	(a)
	^{228}Th	α	100	1.91 y	5520	5518	15.2±4.1
	^{224}Ra	α	100	3.63 d	5789	5788	19.8±8.1
	^{220}Rn	α	100	55.6 s	6404	6414	8.4±3.4
	^{216}Po	α	100	0.145 s	6906	-	0
	^{212}Pb	β^-	100	10.64 h	573.7	0-573.7	(a)
	^{212}Bi	α	35.94	60.6 min	6208	6216	$7.7^{+8.9}_{-7.7}$
		β^-	64.06		2252	8900-11200	15.8±2.8
	^{212}Po	α	100	299 ns (c)	8955		
	^{208}Tl	β^-	100	3.01 min	5001	3197-5001	(a)

Full understanding of natural decay chains by detailed **in-situ** alpha measurement!

(a)=in equilibrium

chain	parent	mode	br [%]	half-life	E_{lit} [keV]	E_{obs} [keV]	A [μBq/kg]
^{238}U	^{238}U	α	100	$4.47 \cdot 10^9$ y	4270	4271	$(1.01\pm0.02)\cdot10^3$
	^{234}Th	β^-	100	24.1 d	273	0-273	(a)
	^{234}Pa*	β^-	100	1.17 min	2197	0-2197	(a)
	^{234}U	α	100	$2.45 \cdot 10^5$ y	4858	4853	$(1.08\pm0.03)\cdot10^3$
	^{230}Th	α	100	75.4 y	4770	4771	55.8±5.4
	^{226}Ra	α	100	1.60 y	4871	4853 (b)	43.0±9.9
	^{222}Rn	α	100	3.82 d	5590	5592	38.1±4.9
	^{218}Po	α	99.98	3.10 min	6115	6139	43.1±9.9
	^{214}Pb	β^-	100	26.8 min	1023	0-1023	(a)
	^{214}Bi	β^-	99.98	19.9 min	3272	7800-11000	47.4±4.9
	^{214}Po	α	100	0.164 ms (c)	7883		
	^{210}Pb	β^-	100	22.3 y	63.5	0-63.5	7^{+36}_{-7}
	^{210}Bi	β^-	100	5.01 d	1163	0-1163	(a)
	^{210}Po	α	100	138 d	5407	5403	17.8±4.0
^{235}U	^{235}U	α	100	$7.04 \cdot 10^8$ y	4678	4671	39.5±4.4
	^{231}Th	β^-	100	25.52 h	389.5	0-389.5	(a)
	^{231}Pa	α	100	$3.27 \cdot 10^4$ y	5150	5139	23.2±4.4
	^{227}Ac	β^-	98.62	21.8 y	44.8	0-44.8	98±20
	^{227}Th	α	100	18.7 d	6147	6139	105±19
	^{223}Ra	α	100	11.4 d	5979	5968	104±7
	^{219}Rn	α	100	3.96 s	6946	14900	107±7
	^{215}Po	α	100	1.78 ms (c)	7527		
	^{211}Pb	β^-	100	36.1 min	1373	0-1373	(a)
	^{211}Bi	α	100	0.51 s	6751	6771	105±7
	^{207}Tl	β^-	100	4.77 min	1423	0-1423	(a)
^{232}Th	^{232}Th	α	100	$1.40 \cdot 10^{10}$ y	4083	4084	9.2±2.3
	^{228}Ra	β^-	100	5.75 y	45.9	6.7-45.9	(a)
	^{228}Ac	β^-	100	6.15 h	2127	58-2127	(a)
	^{228}Th	α	100	1.91 y	5520	5518	15.2±4.1
	^{224}Ra	α	100	3.63 d	5789	5788	19.8±8.1
	^{220}Rn	α	100	55.6 s	6404	6414	8.4±3.4
	^{216}Po	α	100	0.145 s	6906	-	0
	^{212}Pb	β^-	100	10.64 h	573.7	0-573.7	(a)
	^{212}Bi	α	35.94	60.6 min	6208	6216	$7.7^{+8.9}_{-7.7}$
		β^-	64.06		2252	8900-11200	15.8±2.8
	^{212}Po	α	100	299 ns (c)	8955		
	^{208}Tl	β^-	100	3.01 min	5001	3197-5001	(a)

Derive individual alpha activities

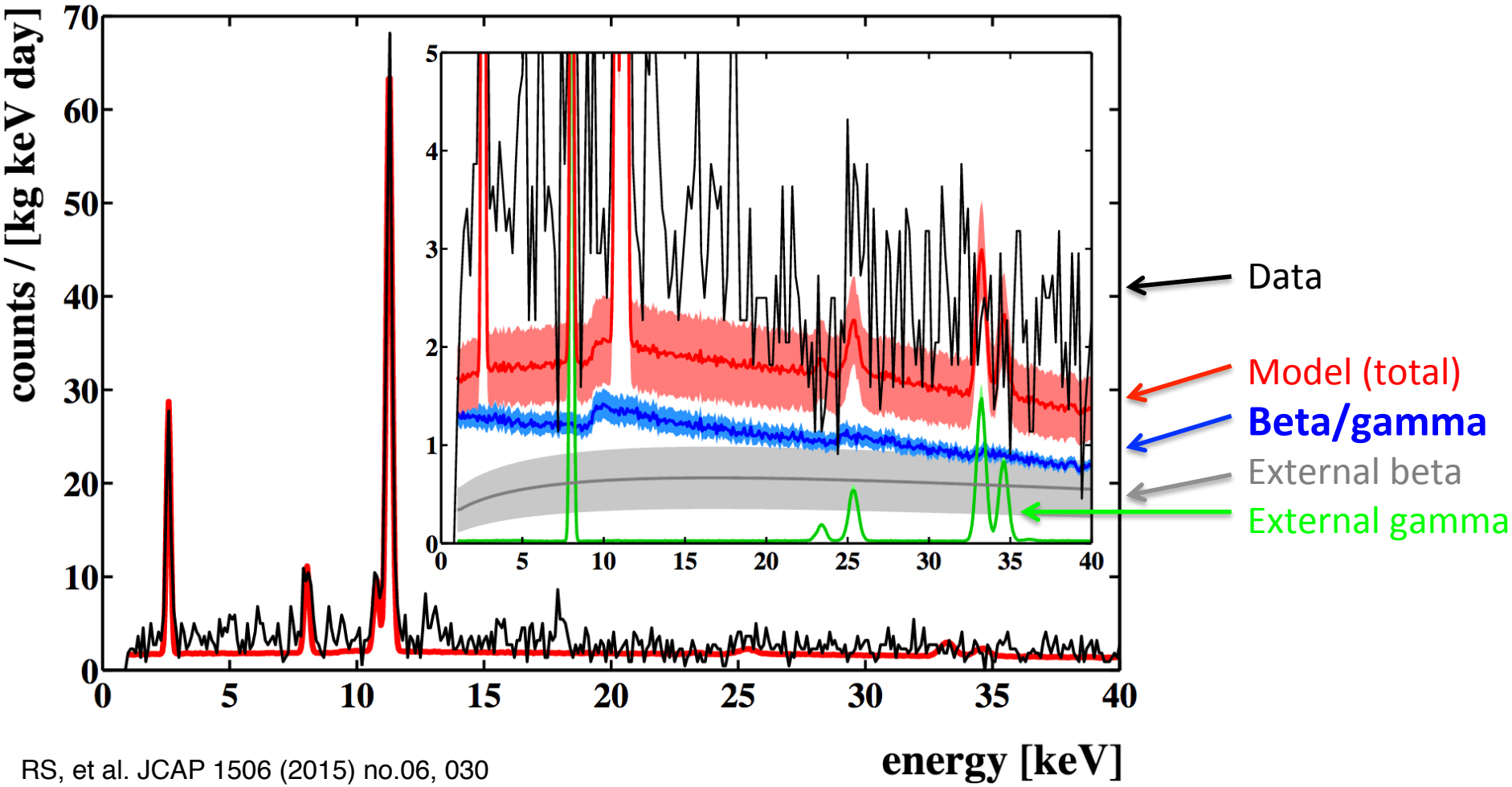
Full understanding of natural decay chains by detailed **in-situ** alpha measurement!

Impact on low energies?

- Calculation of beta/gamma spectra
- Dedicated MC simulation!

(a)=in equilibrium

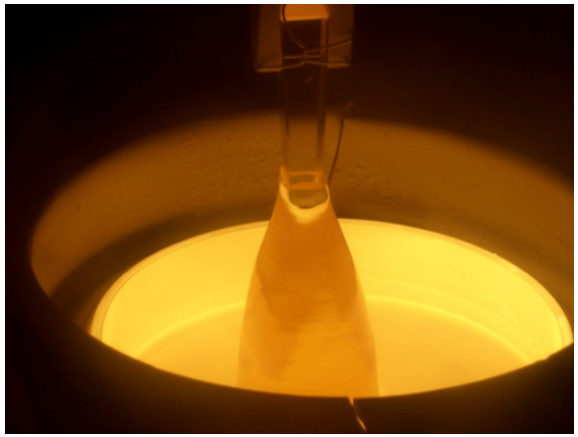
Low-energy backgrounds



RS, et al. JCAP 1506 (2015) no.06, 030

Beta/gammas from nat. decay chains dominate low-energy backgrounds!

Next Steps



Reduce intrinsic background level of crystals!

- Improvement by factor 10 already achieved
- Purification by crystal growth, e.g. multiple-crystalization
- Purification of raw materials, e.g. during production via precipitation

OUR GOAL FOR CRESST (within 2 years):

Reduction of background level to 10^{-2} counts /[kg keV day]
(2 orders of magnitude compared to present $CaWO_4$ crystals)

Raw Material Preparation

State-of-the-art:

Solid state reaction: $CaCO_3 + WO_3 \rightarrow \mathbf{CaWO_4} + CO_2$

Problems:

- Grinding of powders
- Heating of materials to 1200°C

→ Involved materials and machinery have to be extremly radiopure!

→ No possibility for purification

Precipitation Method

Raw materials from commercial suppliers: WO_3 and $CaCO_3$ (powders)

Dissolve powders → aqueous solutions

$$CaCO_3 + 2\,HNO_3 \rightarrow Ca(NO_3)_2 + H_2O + CO_2$$

$$WO_3 + 2NH_3 + H_2O \rightarrow (NH_4)_2WO_4$$

Courtesy of
A. Münter

Precipitation Method

Raw materials from commercial suppliers: WO_3 and $CaCO_3$ (powders)

Dissolve powders → aqueous solutions

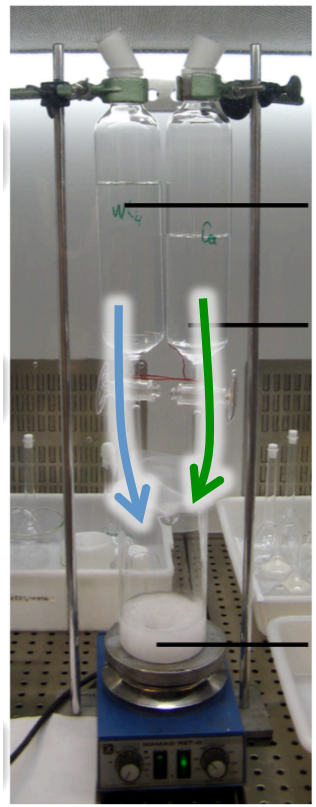
$$CaCO_3 + 2\,HNO_3 \rightarrow Ca(NO_3)_2 + H_2O + CO_2$$

$$WO_3 + 2NH_3 + H_2O \rightarrow (NH_4)_2WO_4$$

Mix solutions

$$Ca(NO_3)_2 + (NH_4)_2WO_4 \rightarrow CaWO_4 \downarrow + 2\,NH_4NO_3$$

Precipition ↓



Courtesy of A. Münter

Precipitation Method

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Mix solutions

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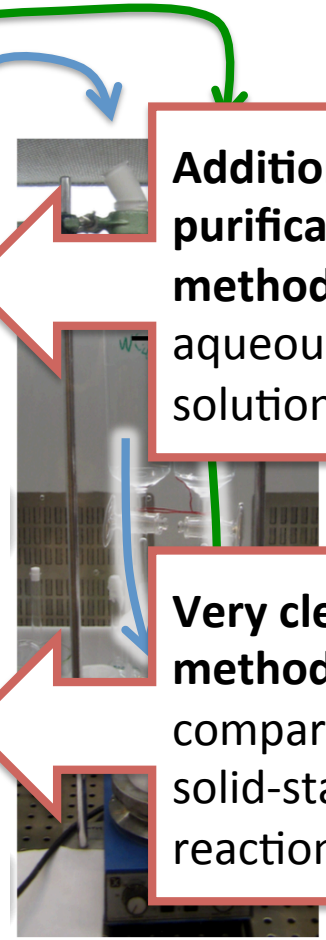
Precipition ↓

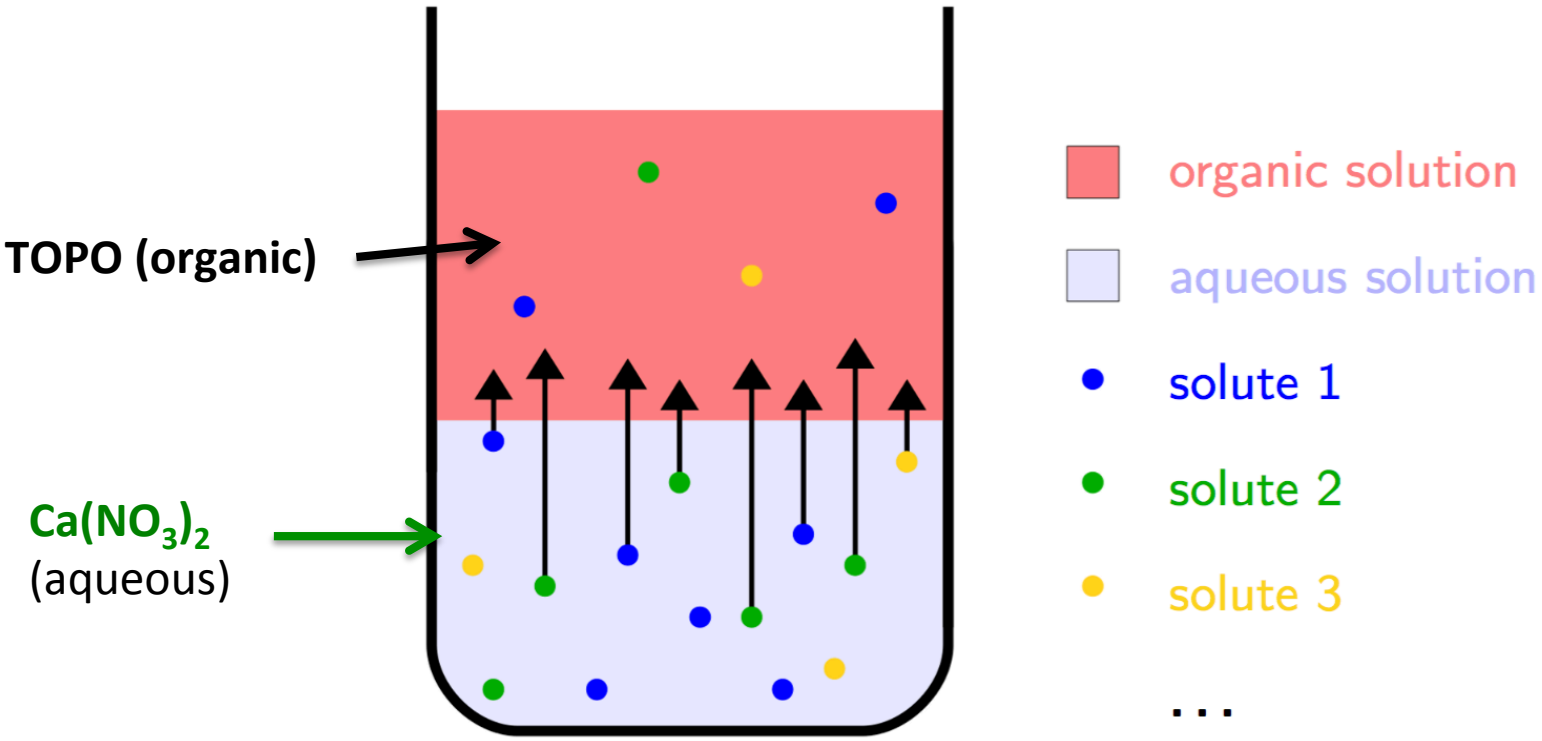


Additional purification methods for aqueous solutions

Very clean method compared to solid-state reaction

y of
A. Münter

Method 1: Liquid-liquid extraction

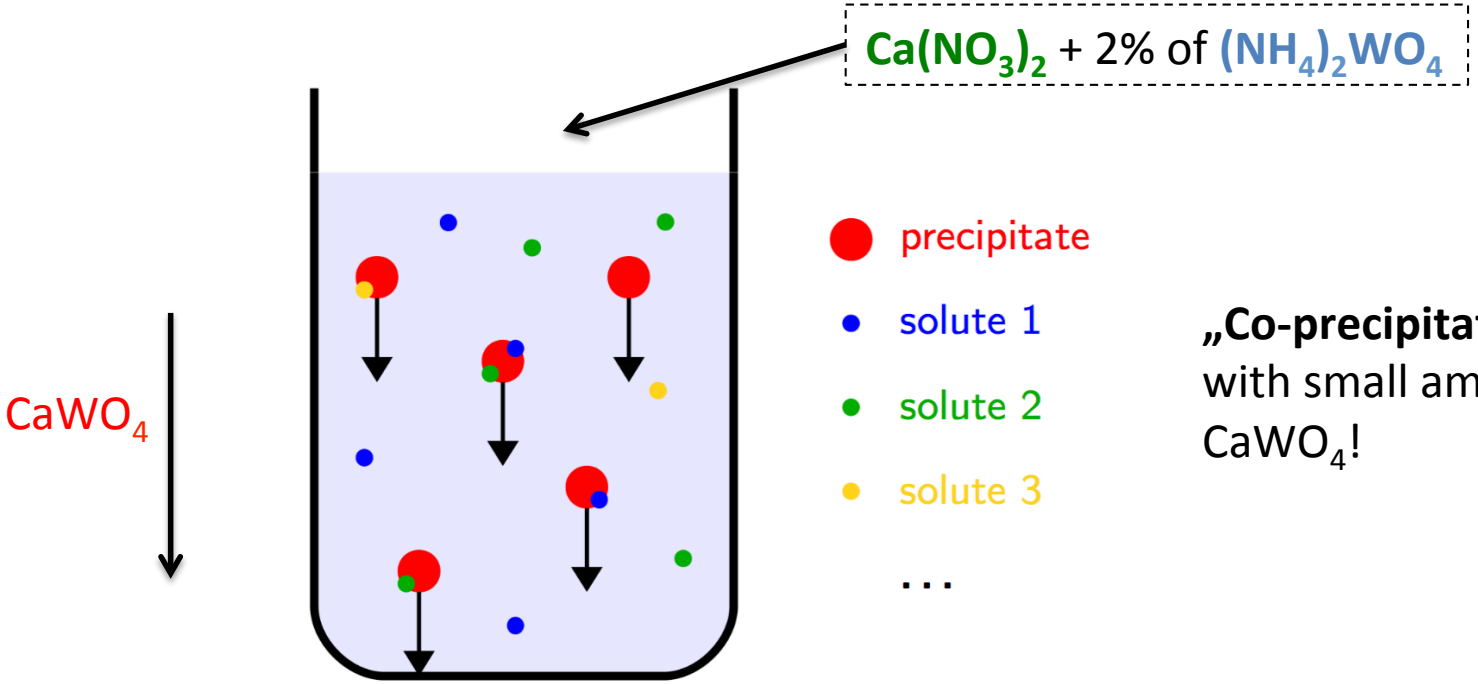


Extraction of **U and Th** by organic trioctylphosphineoxide (TOPO) from aqueous solution

Courtesy of A. Münter

Method 2: Co-Precipitation

Carrying down of (normally soluble) substances on a precipitate



„Co-precipitation“ with small amounts of $CaWO_4$!

→ $CaWO_4$ itself as precipitate for carrying down e.g. Sr, Pb isotopes

Courtesy of A. Münter

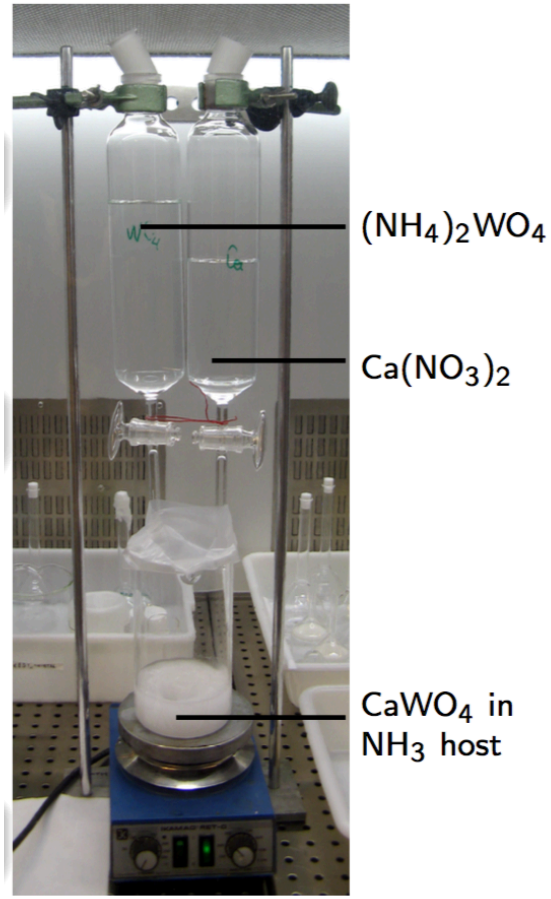
Precipitation Method

$$Ca(NO_3)_2 + (NH_4)_2WO_4 \rightarrow CaWO_4 \downarrow + 2\ NH_4NO_3$$

After precipitation reaction:
several cleaning steps (rinsing with water, decantantion, filtration, calcination)

→ Major effort for purifaction of raw materials

→ 1.5 kg $CaWO_4$ powder ready for crystal growth



Courtesy of A. Münter

First Promising Results (HPGe @LSC)

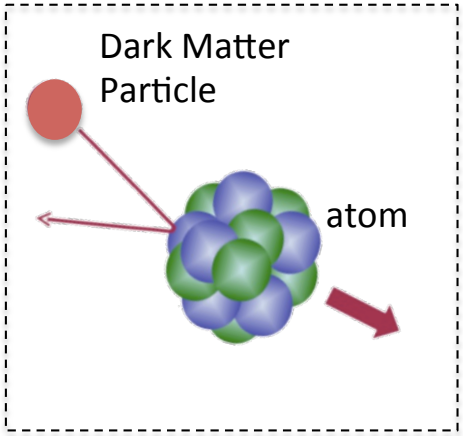
TECHNISCHE UNIVERSITÄT MÜNCHEN

isotope	Activity [mBq/kg]	
	$CaWO_4$ (1) not cleaned, solid state	$CaWO_4$ (2) cleaned, precipitation
^{228}Ra	< 4.5	< 1.4
^{228}Th	3.0 ± 0.9	< 0.71
^{232}Th (eq)	3.0 ± 0.9	< 0.75
^{238}U	< 55	< 17
^{235}U	< 3	< 0.78
^{226}Ra	4.7 ± 0.7	< 0.9
^{137}Cs	< 1.1	< 0.5
^{60}Co	< 0.8	< 0.09
^{40}K	109 ± 10	39 ± 3

preliminary

from A. Münter, H. Trinh Thi, et al.
(to be published)

CRESST-III

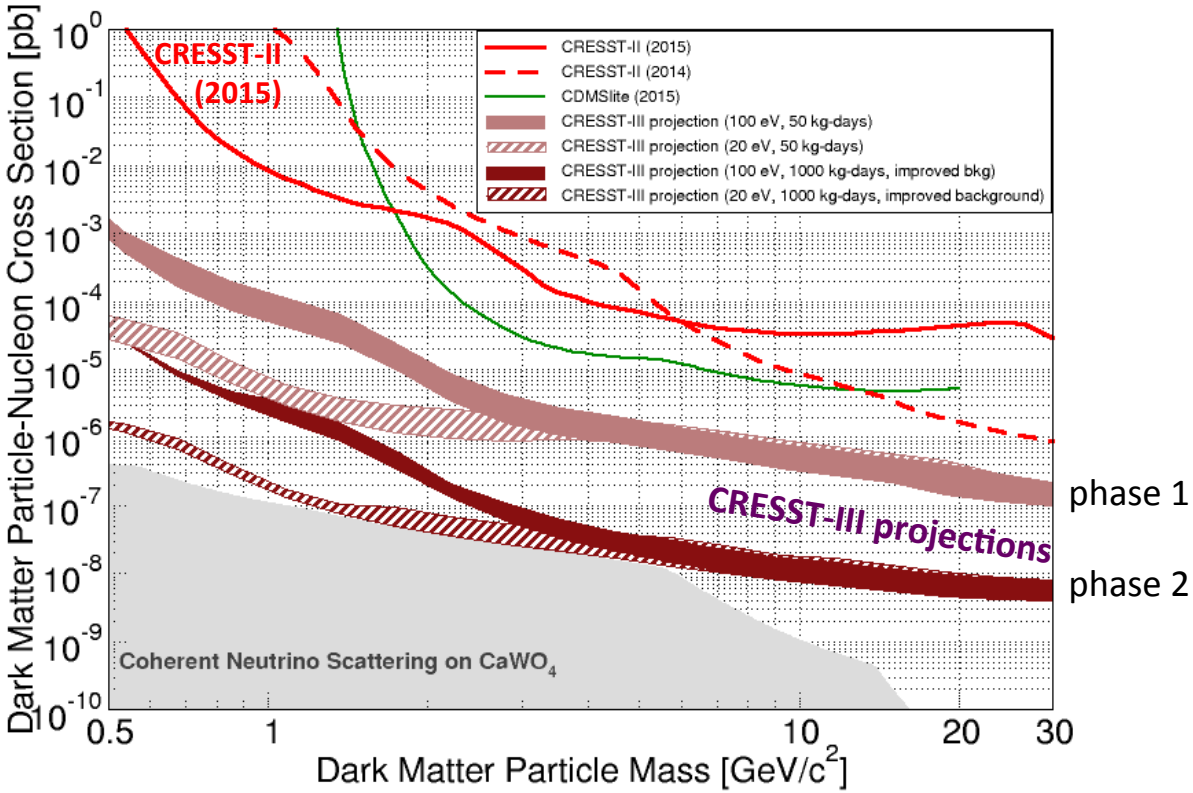


Phase 1: Currently taking data at Gran Sasso → First data at LTD and TAUP 2017

Phase 2: Upgrade to 300 channels + crystals of improved quality

CRESST-III Detector (24g $CaWO_4$)

RS et al., NIM A845 (2017) 414-417



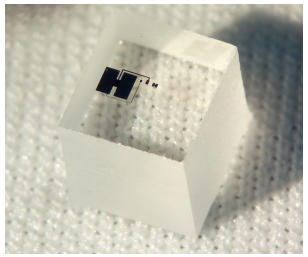
G. Angloher et al. , arXiv:1503.08065

Coherent neutrino-nucleus scattering (CNNS) with $CaWO_4$ detectors

Gram-scale cryogenic calorimeters

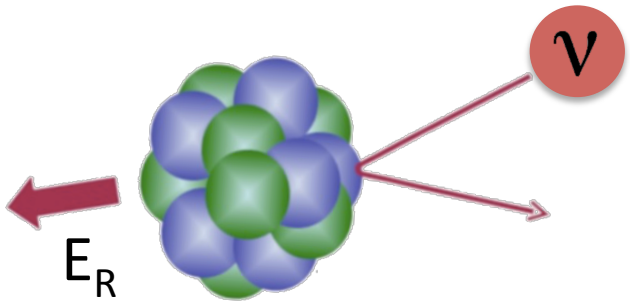
Best treshold for macroscopic devices:

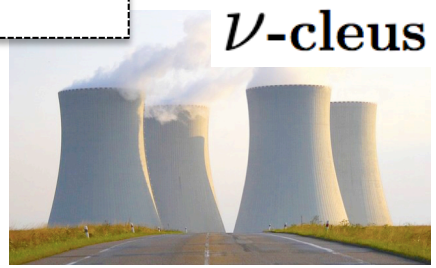
E_{th} = (19.7±0.1) eV



$(5mm)^3$ detector prototype

RS, J. Rothe et al. arXiv: 1704.04317





15-100m from a nuclear power plant

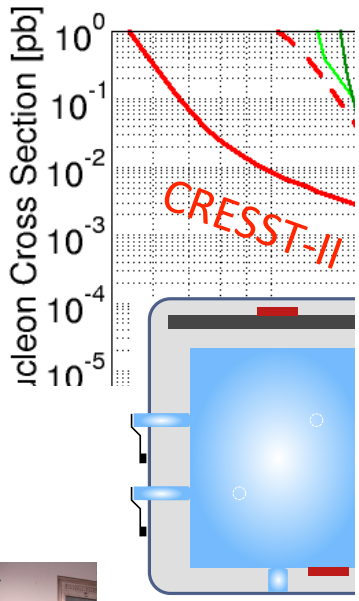
R&D for an experiment based on gram-scale $CaWO_4$ calorimeters

- 10g detector sufficient
- 5-sigma discovery within 2 weeks
- Future: exciting BSM physics

RS, J. Rothe et al. arXiv: 1704.04320

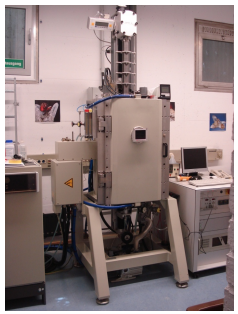
Initial funding

Conclusion



- CRESST experiment achieves lowest thresholds in the field and leads low-mass DM search

- Detailed in-situ alpha screening
- Implementation of passive and active systems for background reduction



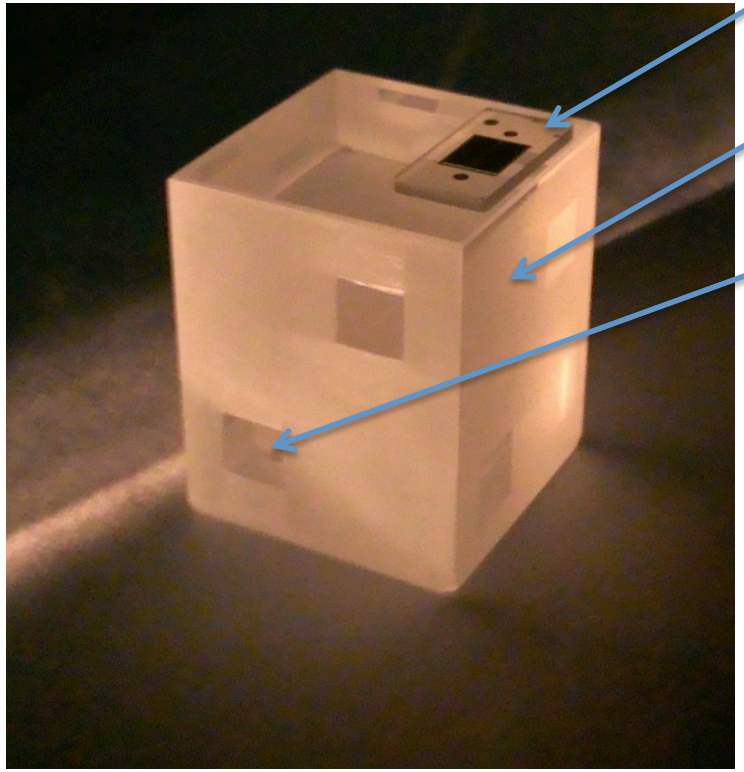
- $CaWO_4$ crystal growth at our institutes
- Chemical purification of raw materials established

- $CaWO_4$ is a promising target for future searches for DM and coherent neutrino scattering

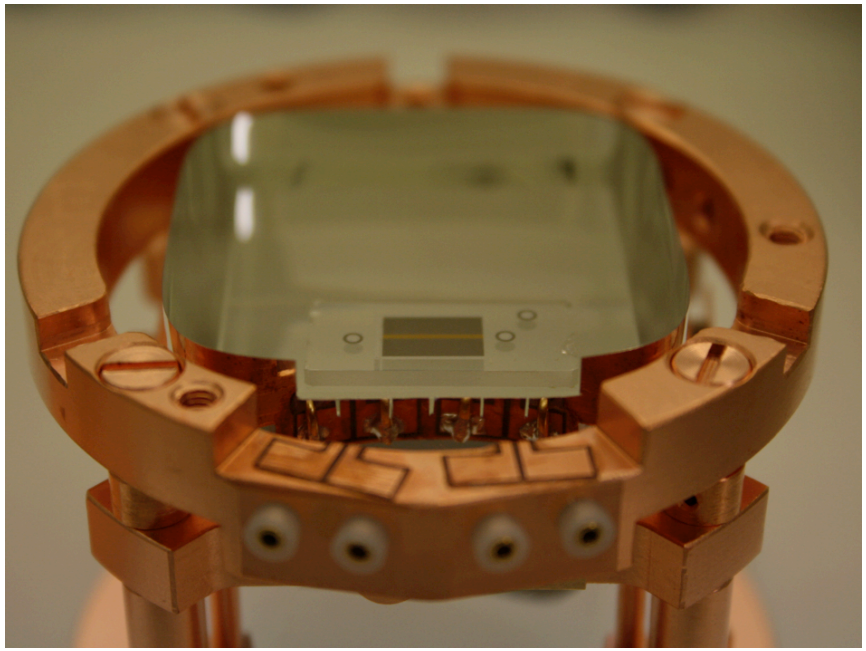
BACKUP

TUM-40

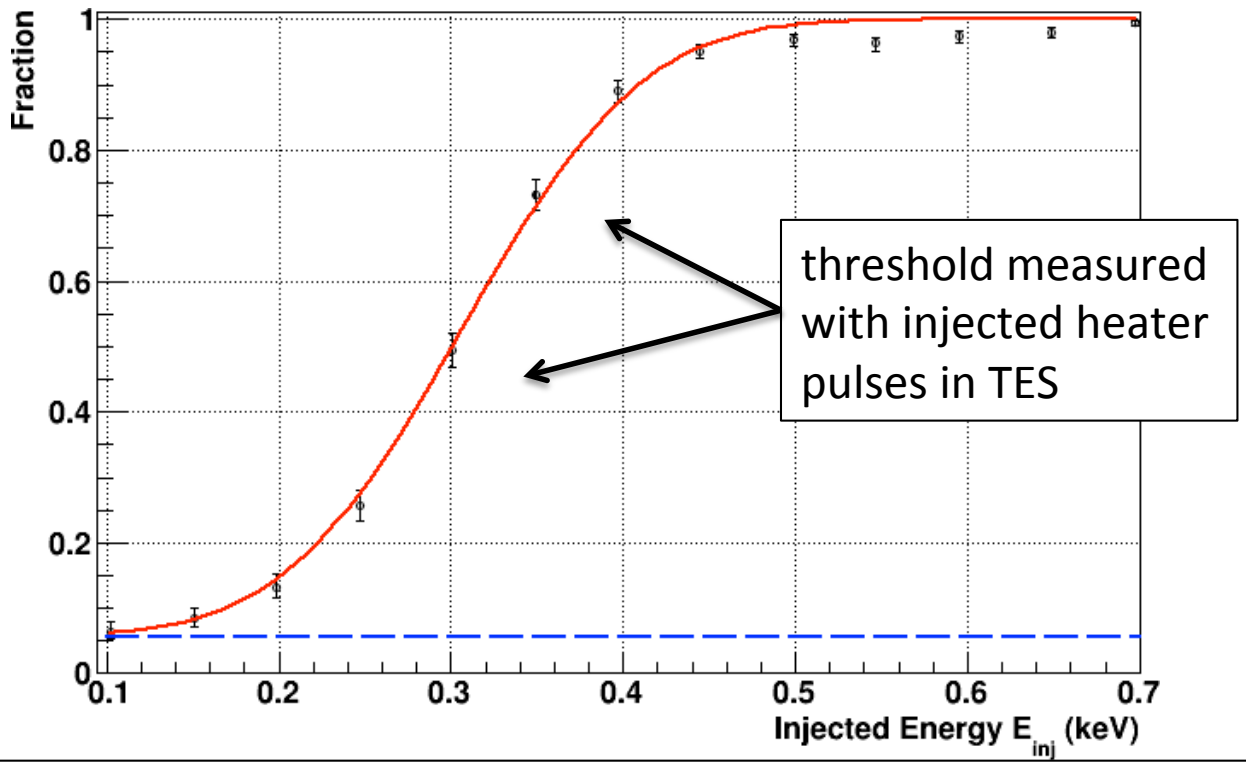
Self-grown crystal WILHELM I (TUM-40)



- equipped with a W TES
- roughened at 5 surfaces
  → maximum light output
- polished at areas where the sticks touch



“Lise”: Trigger Threshold

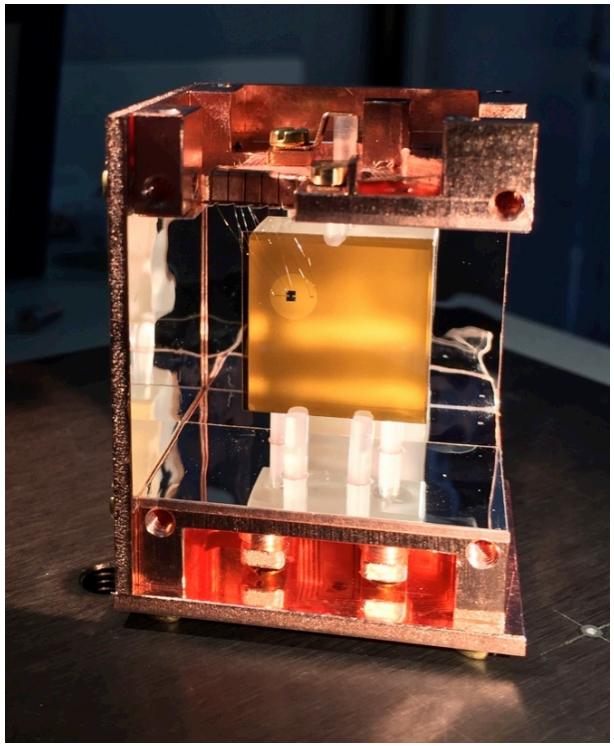


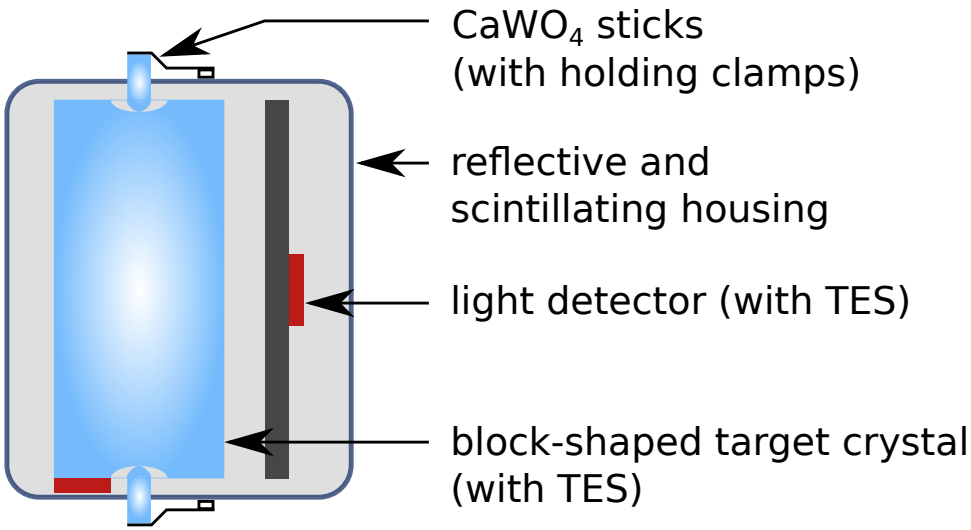
Lowest trigger threshold for nuclear recoils among all Dark Matter searches!

Direct measurement of nuclear-recoil energy with calorimetric detector!

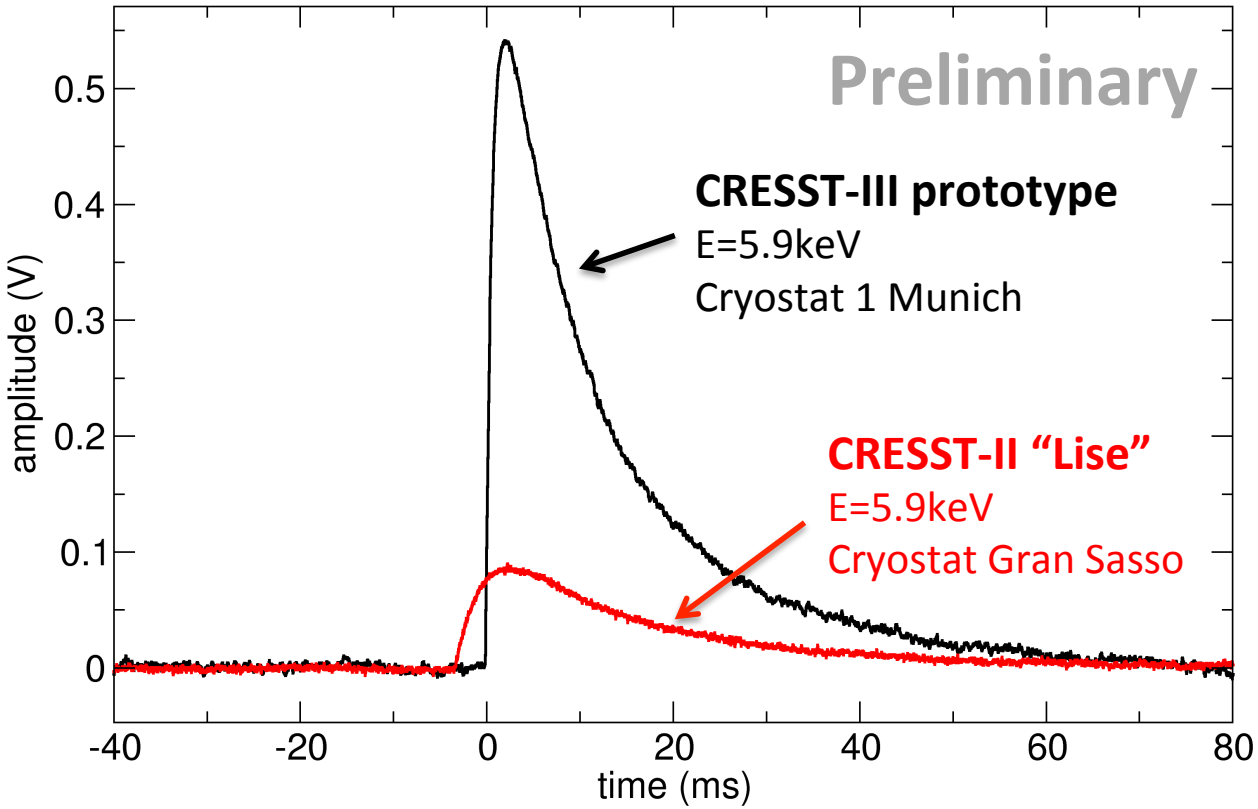
See: CRESST collab. G. Angloher et al. arXiv1509.01515

CRESST-III Detector Prototype





First Results of CRESST-III Detector



Promising results:

Improvement by **factor 6.2 (S/N)** compared to best CRESST-II detector (E_{th} = 307eV)

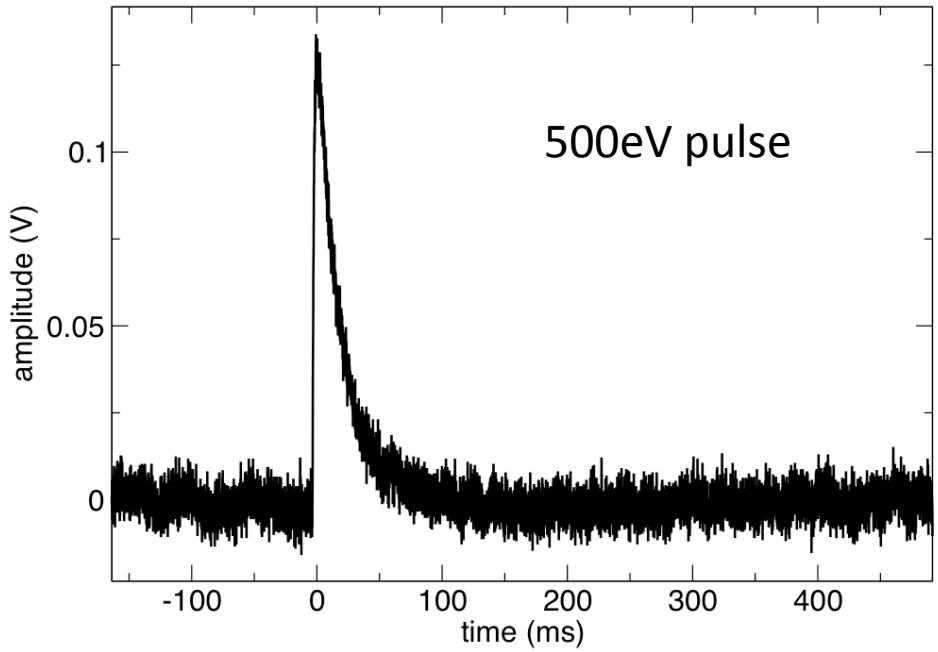
→ Baseline noise @GS 1.8-3.0mV RMS

→ **Threshold: E_{th}= 45-60eV**

Design goal (E_{th}=100eV) for **CRESST-III** Phase 1 probably exceeded!

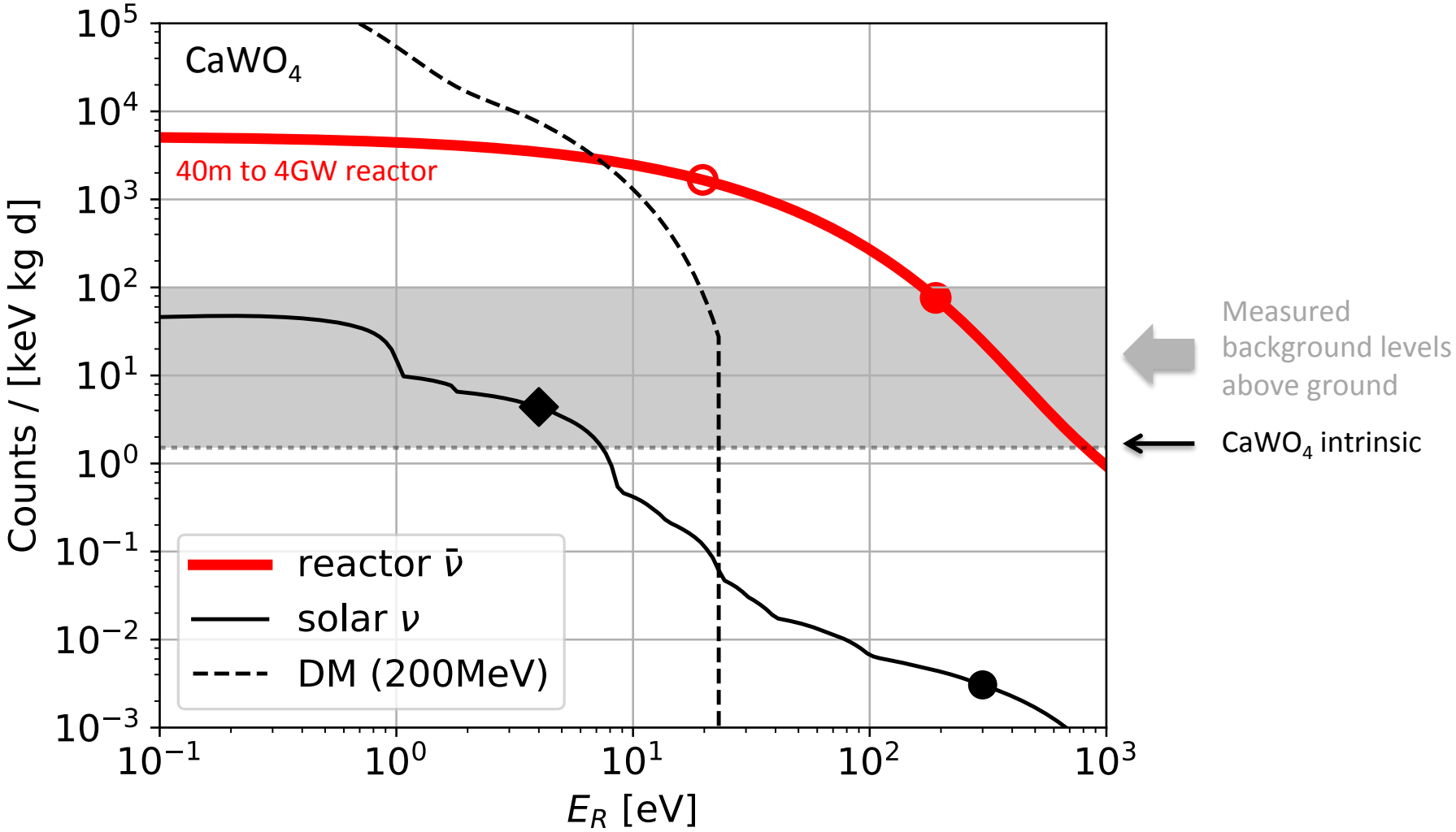
First Results of CRESST-III Phase 1

First preliminary data from CRESST-III @Gran Sasso

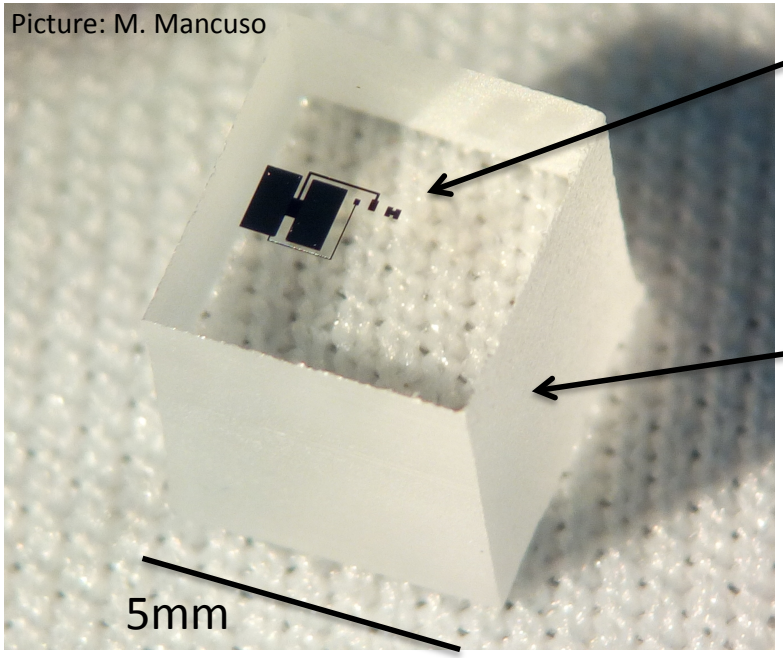


Design goal (E_{th}=100eV) for **CRESST-III** Phase 1 ~~pr~~ ~~ly~~ exceeded!

New approaches in rare-event search

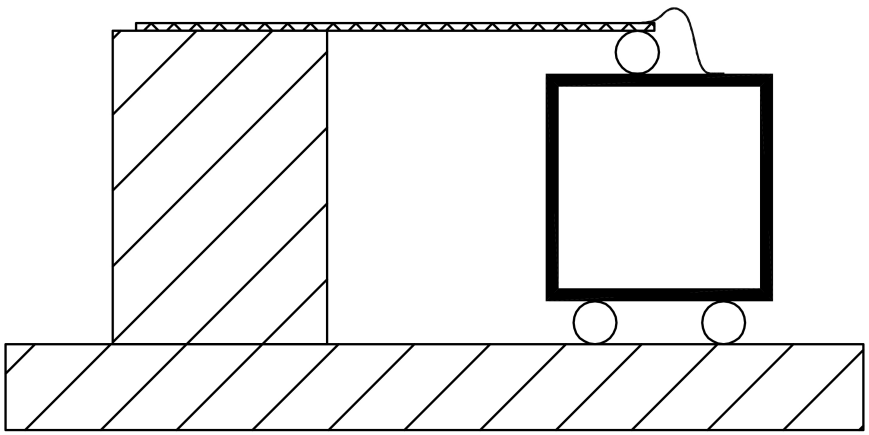


0.5g Sapphire Prototype

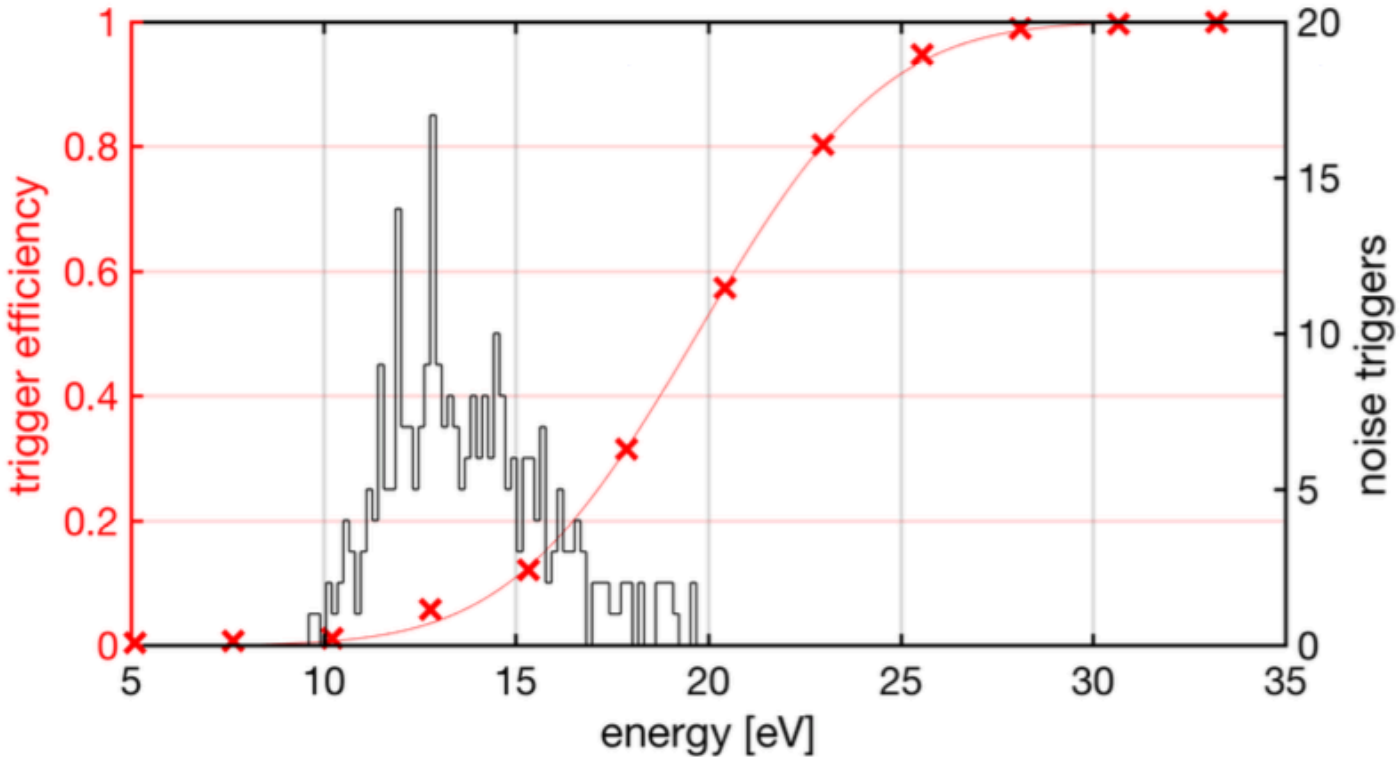


Transition-edge-sensor

Sapphire crystal 0.5g



Result on Threshold



Energy threshold: E_{th} = (19.7 +- 0.1) eV

„First try“