The CRESST Experiment

Search for Low-Mass Dark Matter

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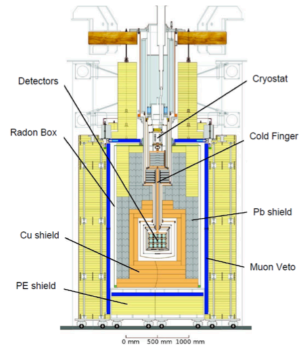
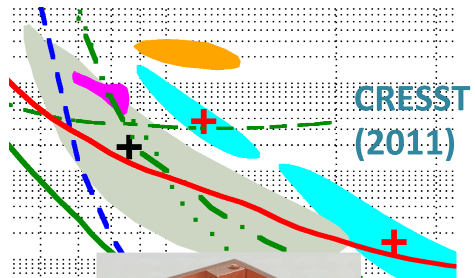
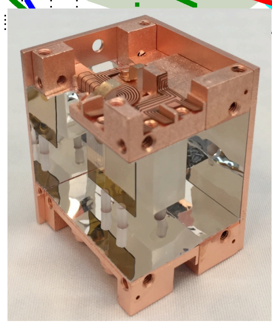
München,
Seminar CEA Saclay,
08.02.2016

Outline

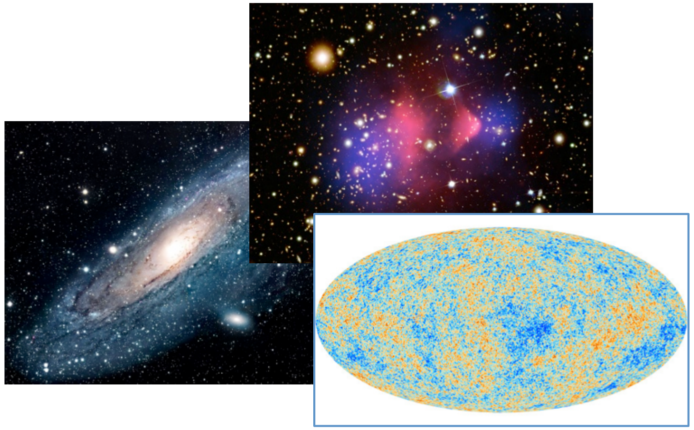
- Dark Matter and Direct Detection
- Principle of Cryogenic Detectors
- The CRESST Experiment
- Recent Results from CRESST-II
- Beyond that: CRESST-III







Dark Matter



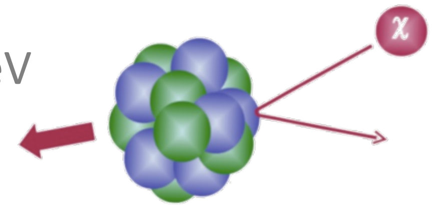
Dark Matter exists in the Universe!

WIMPs

Weakly Interacting Massive Particles

Particles are a well-motivated interpretation

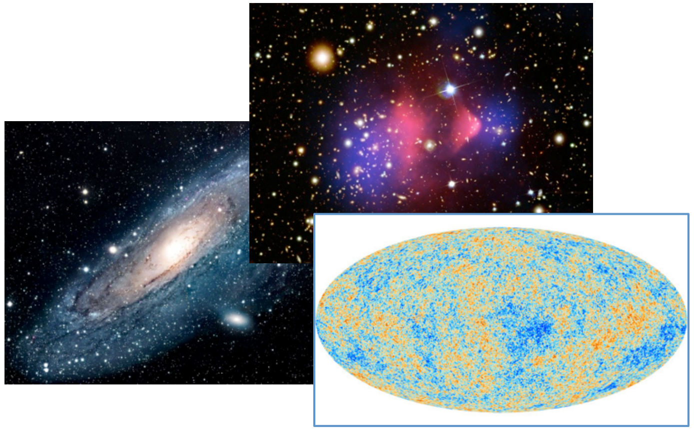
$E_r \approx keV$



Elastic WIMP-nucleus scattering

Direct detection with Earth-bound experiments

Dark Matter



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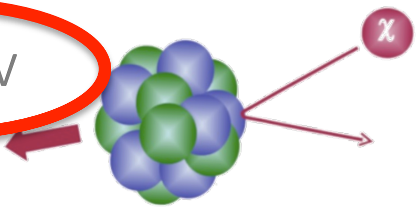


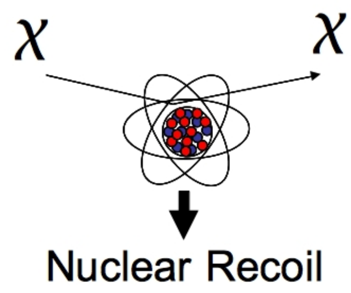
Elastic WIMP-nucleus scattering

Direct detection with Earth-bound experiments

challenging!

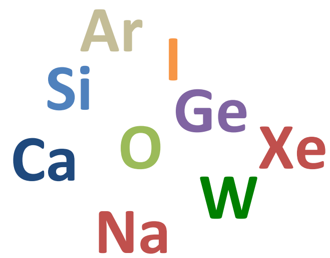
How does a possible WIMP signal look like??

- WIMP interactions via elastic scattering
  - Nuclear recoils (few keV)
  - Single scatters
  - Uniformly distributed in detector

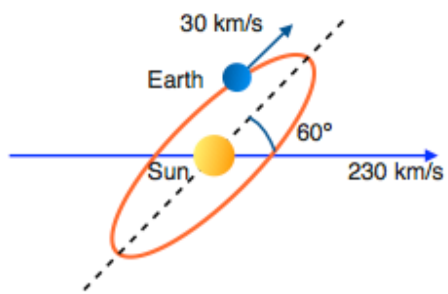


- Spectral shape
  - Exponential towards lower energies (similar to background)

- Dependence on material
  - Coherent scattering (A^2 - dependency)
  - Nuclear form factors
  - ➢ Consistency checks between experiments



- Annual flux modulation
  - Small effect (~ 3%)



WIMP Signals in Dark Matter Detectors

$$\boxed{\frac{\partial R}{\partial E_R} \propto N F^2(\vec{q}) \frac{\rho_D}{M_D} \sigma_\chi e^{-\frac{E_R}{E_0}}}$$

R measured rate in detector

N number of target nuclei

E_R recoil energy of target nucleus

M_D mass of WIMP

ρ_D WIMP density @Earth

F^2 nuclear form factor

σ_χ WIMP nucleus cross section

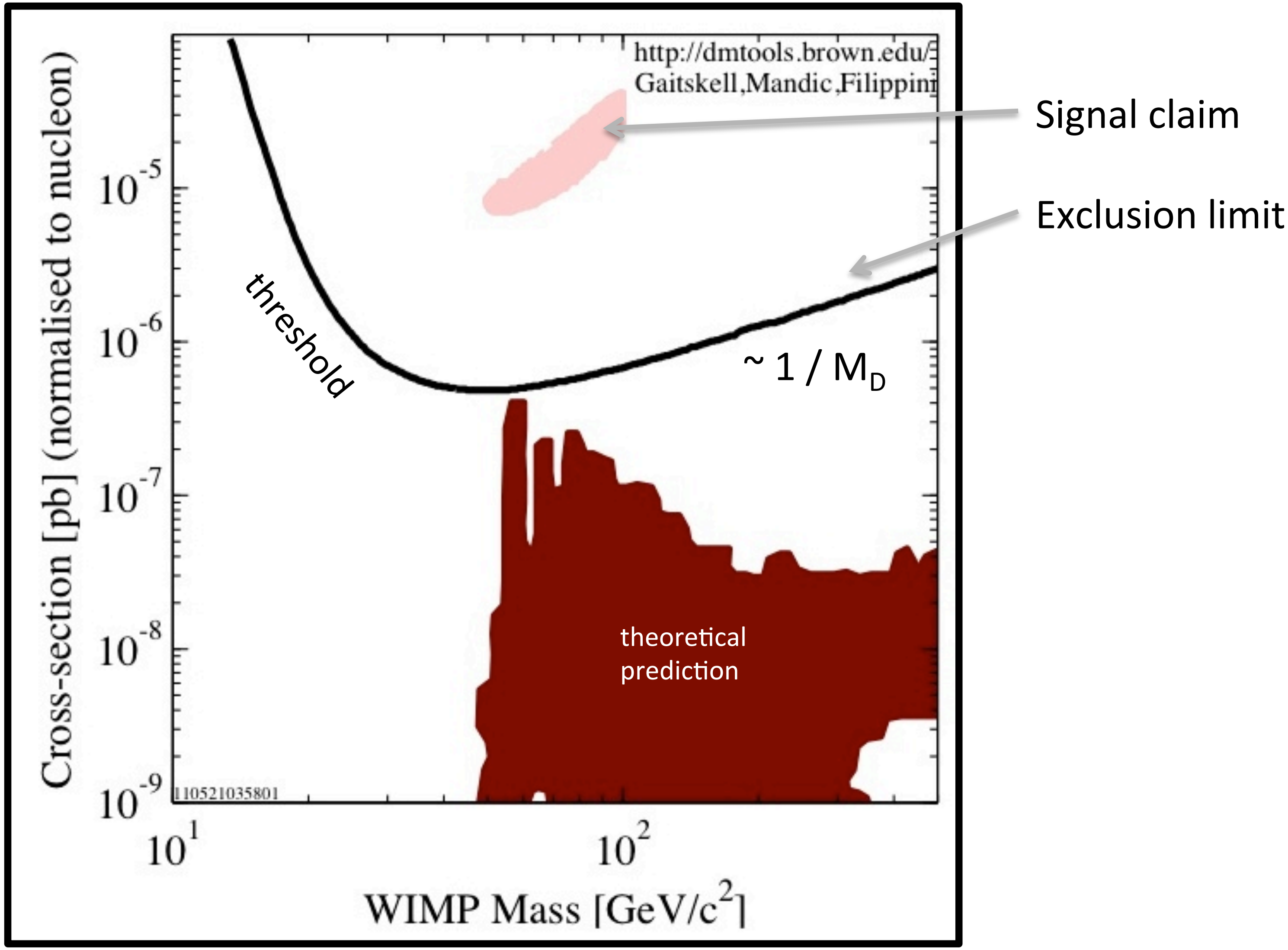
- mean value: ~0.3 $GeVcm^{-3}$
- 3000 ($100GeV/M_D$) WIMPs per m^3
- mean flux: 10^5 ($100GeV/M_D$) $cm^{-2}\,s^{-1}$

Usual (very basic) assumption:

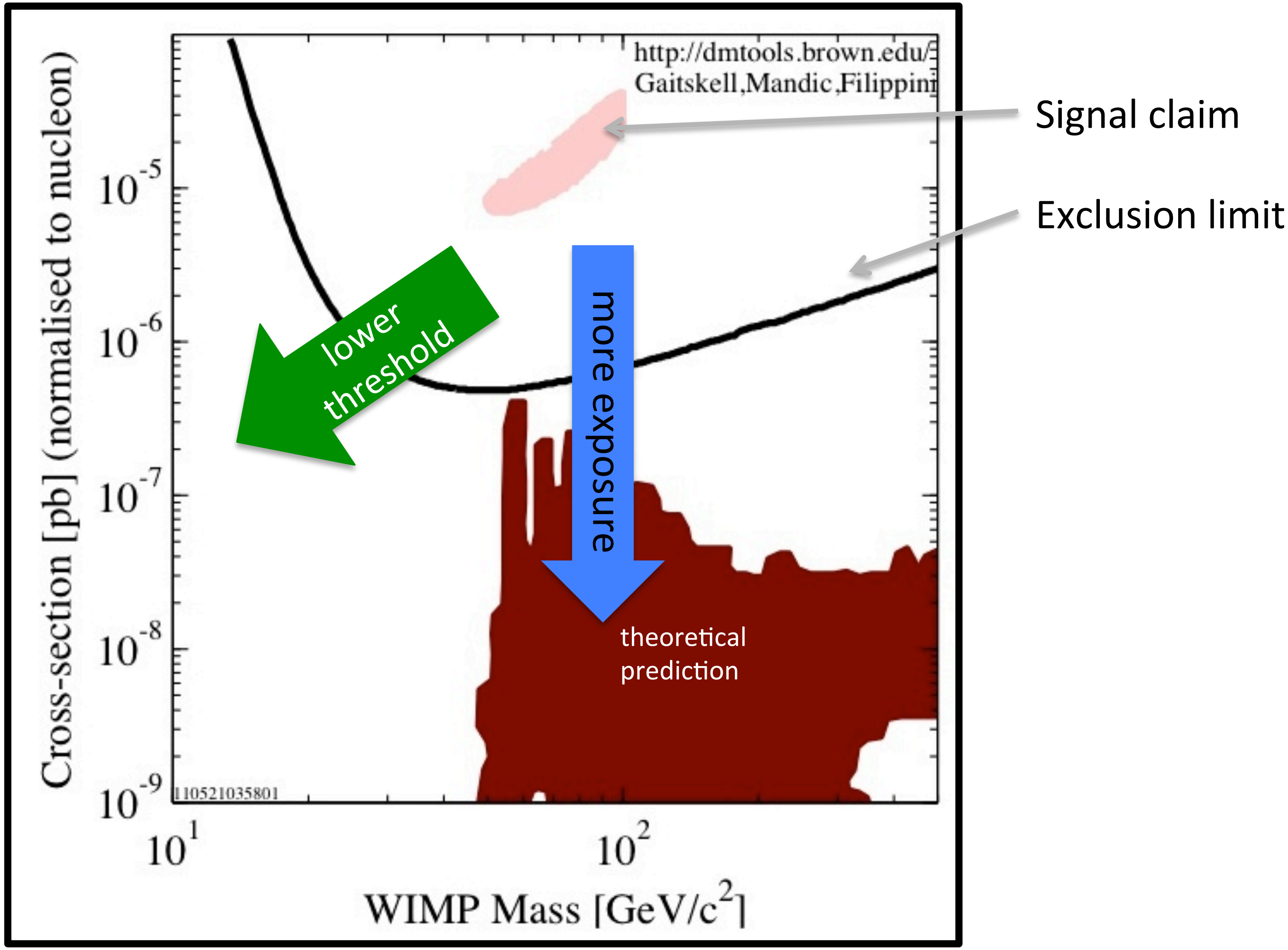
- Coherent scattering
- Scattering amplitudes add up in phase

➢ $\sigma_\chi \sim A^2$

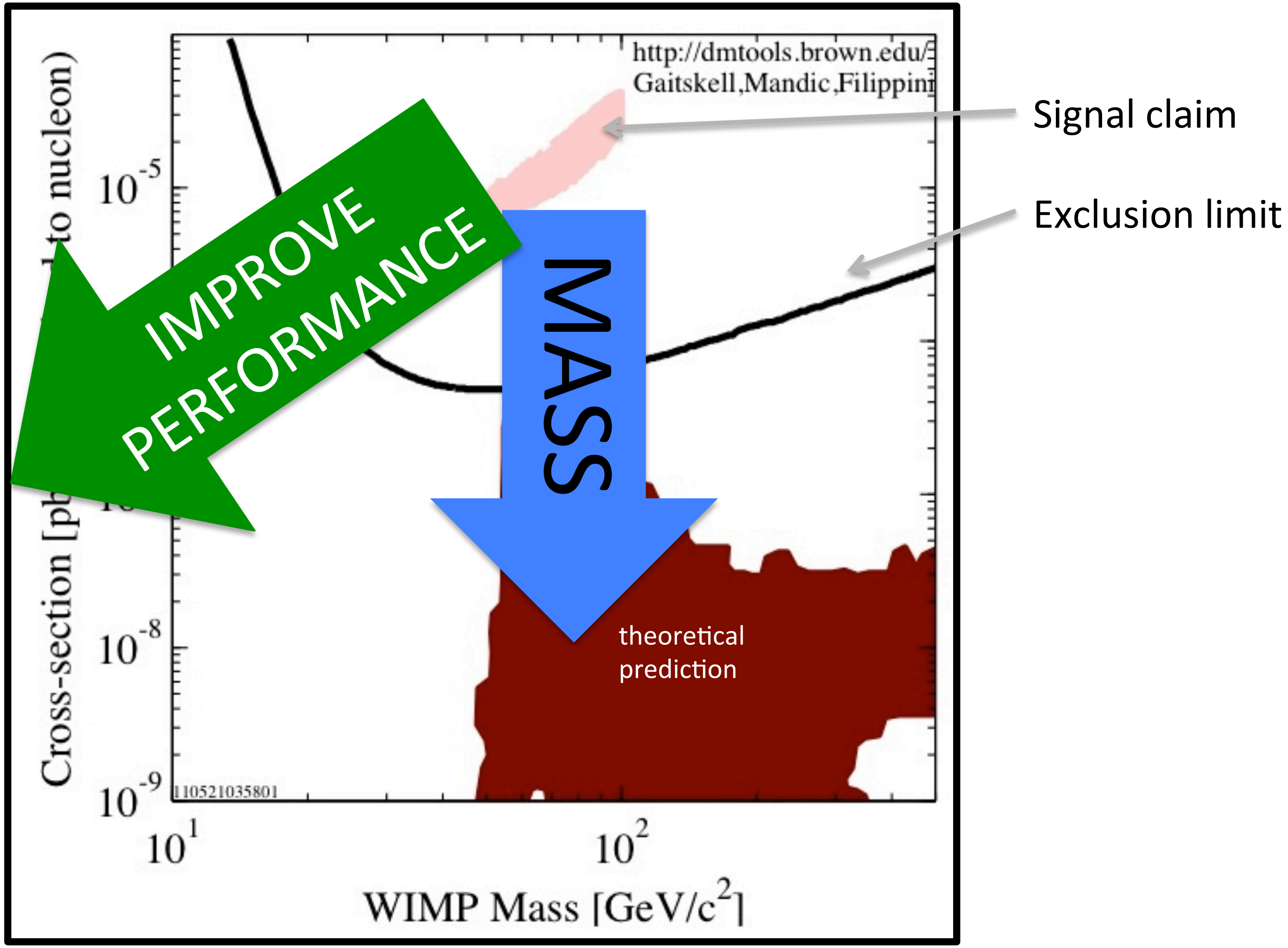
Exclusion Plot – Comparison of Results



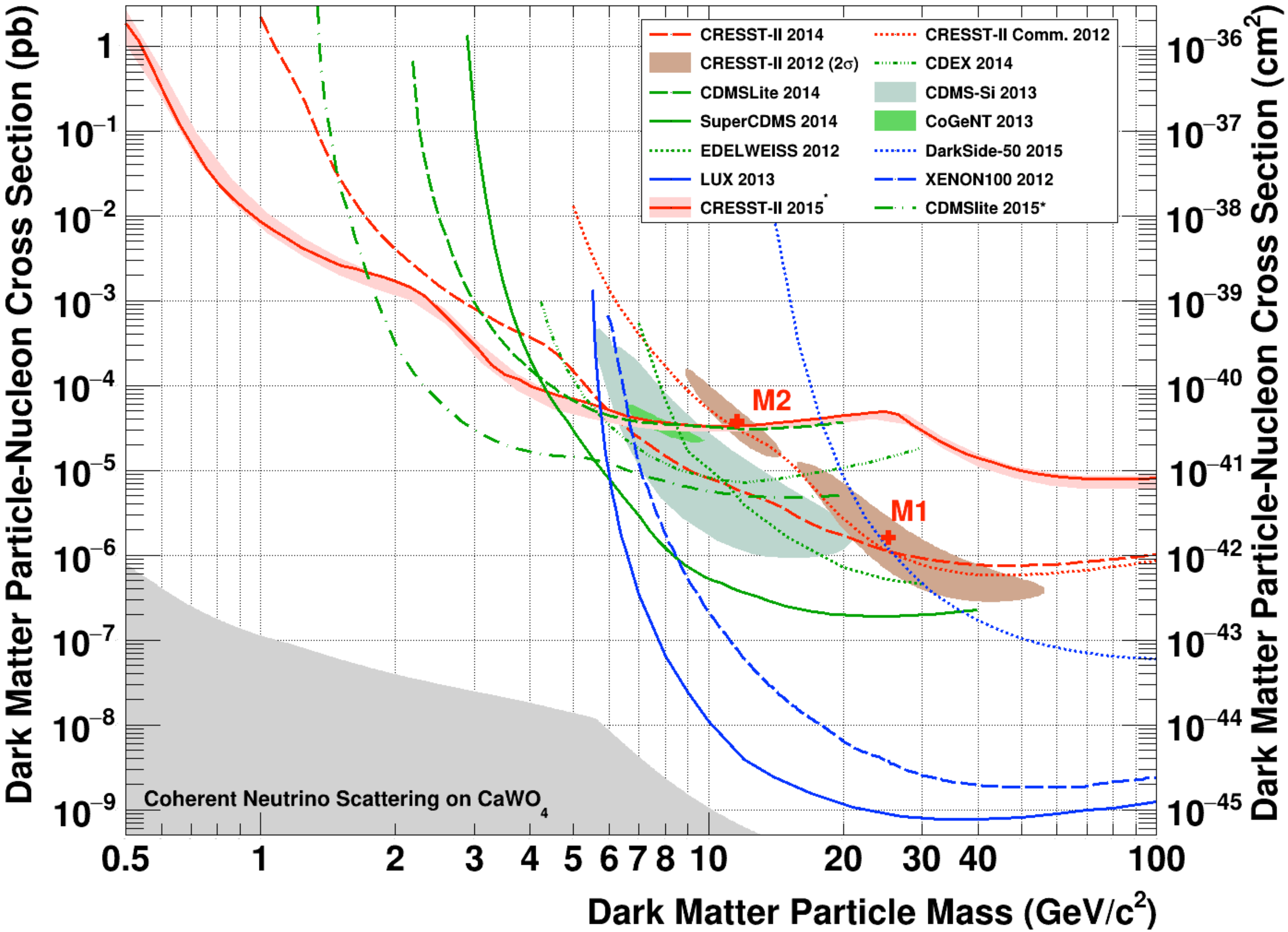
Exclusion Plot – Comparison of Results



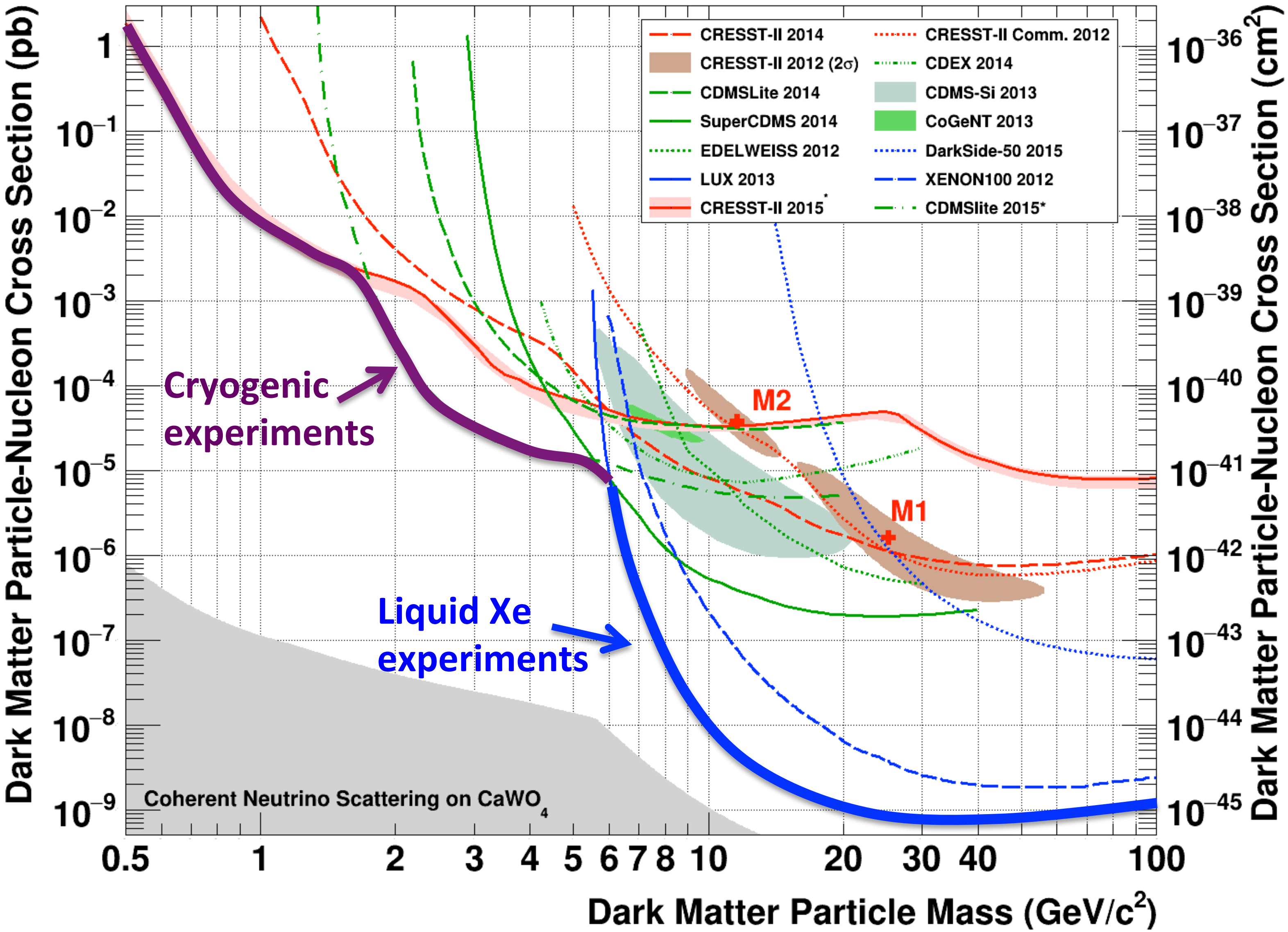
Exclusion Plot – Comparison of Results



Current Status of Direct Dark Matter Searches



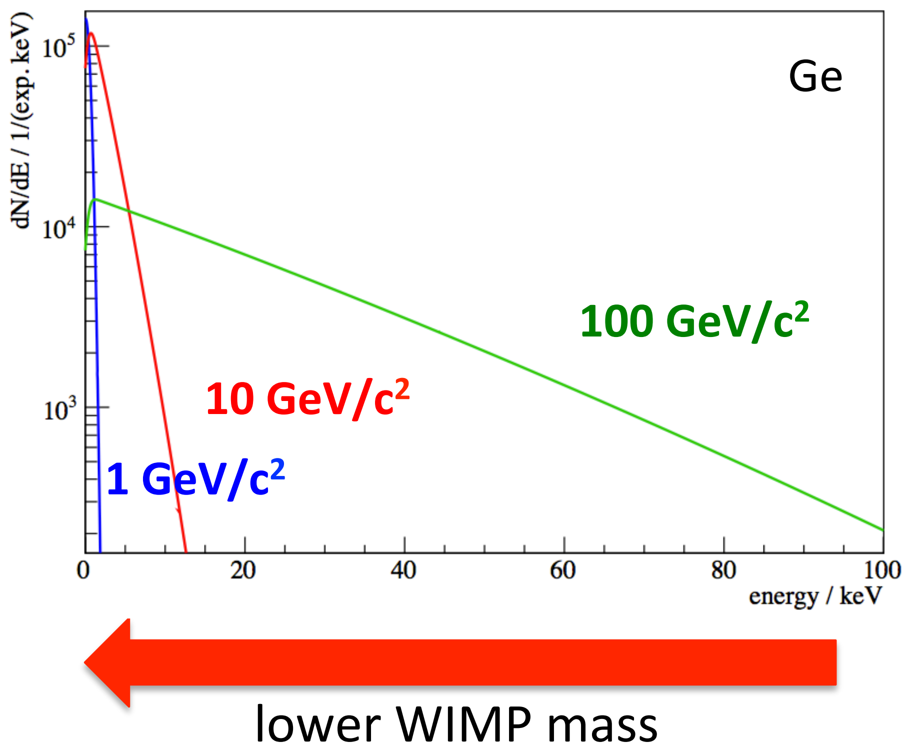
Current Status of Direct Dark Matter Searches



Potential of Cryogenic Detectors

*Why are cryogenic detectors particularly sensitive to **low-mass WIMPs** ?*

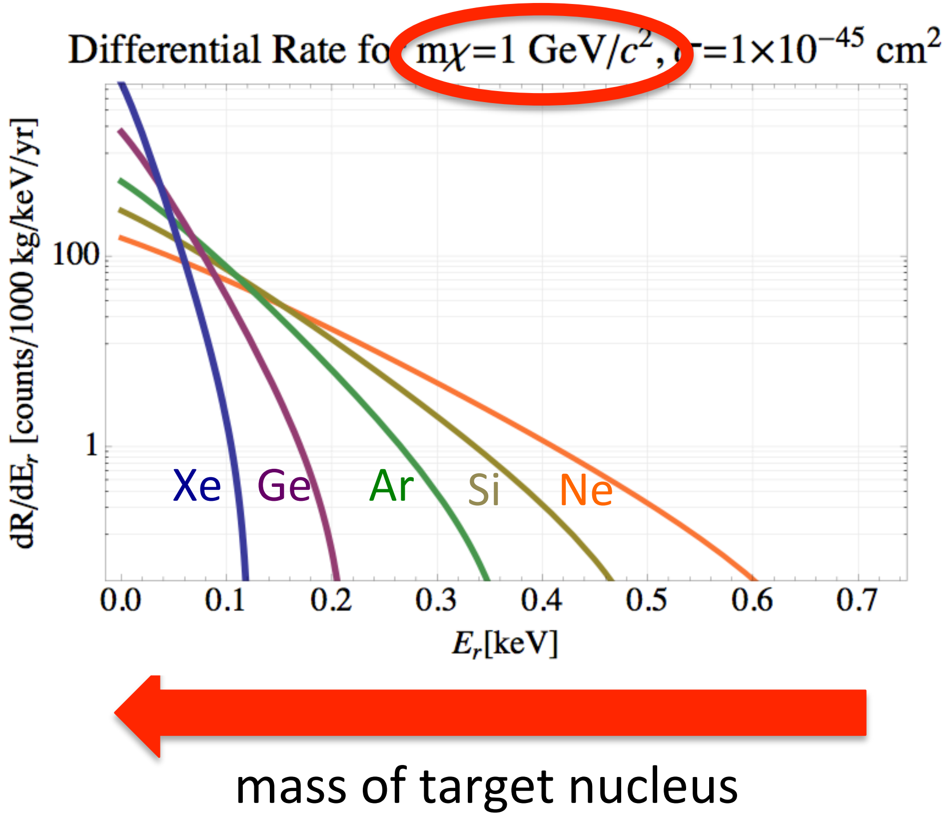
- **Low energy threshold**



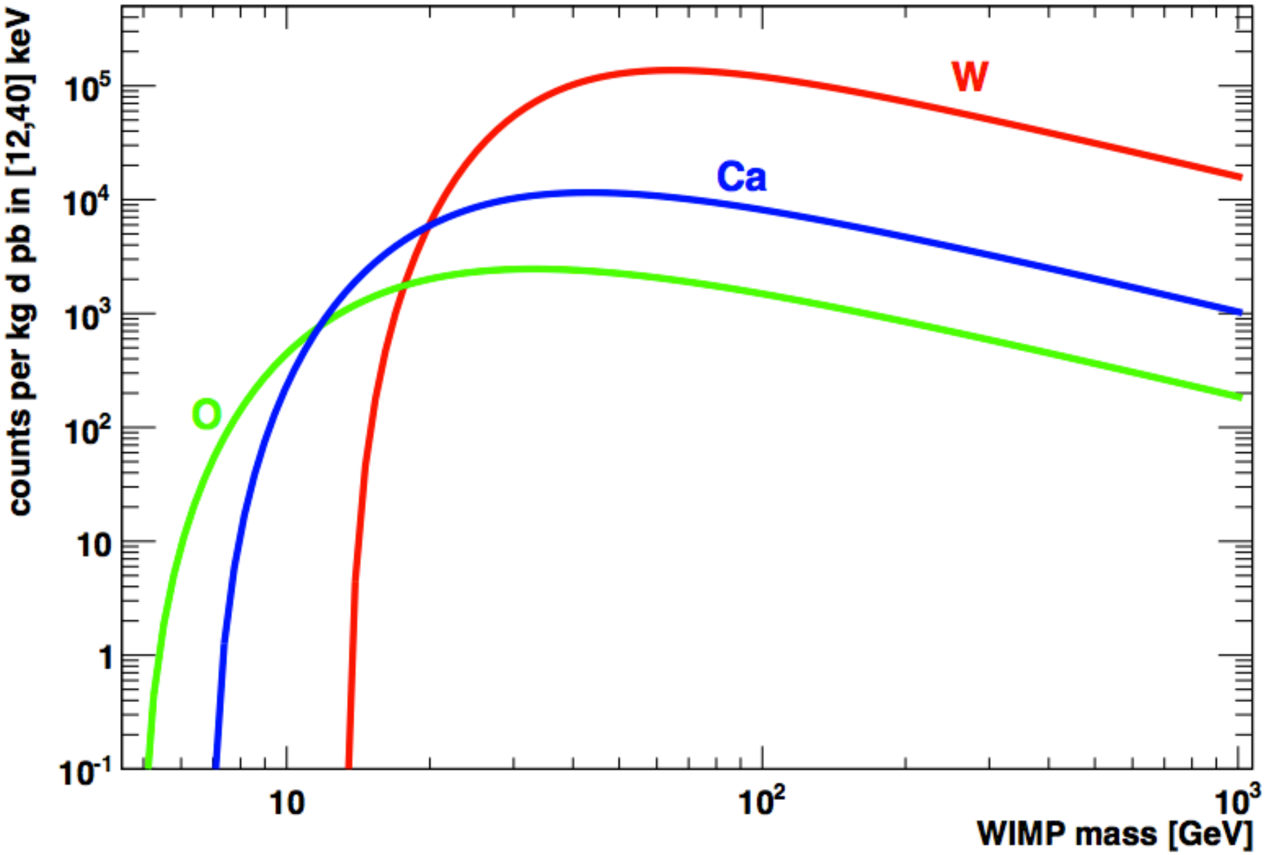
Potential of Cryogenic Detectors

*Why are cryogenic detectors particularly sensitive to **low-mass WIMPs** ?*

- Low energy threshold
- **Light elements**

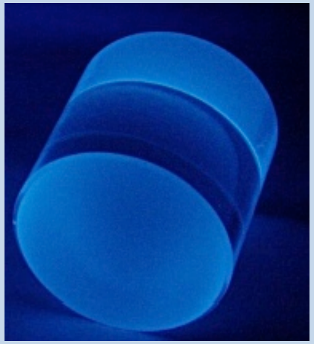


CRESST – Multi-Element Target



Example:

$CaWO_4$ target



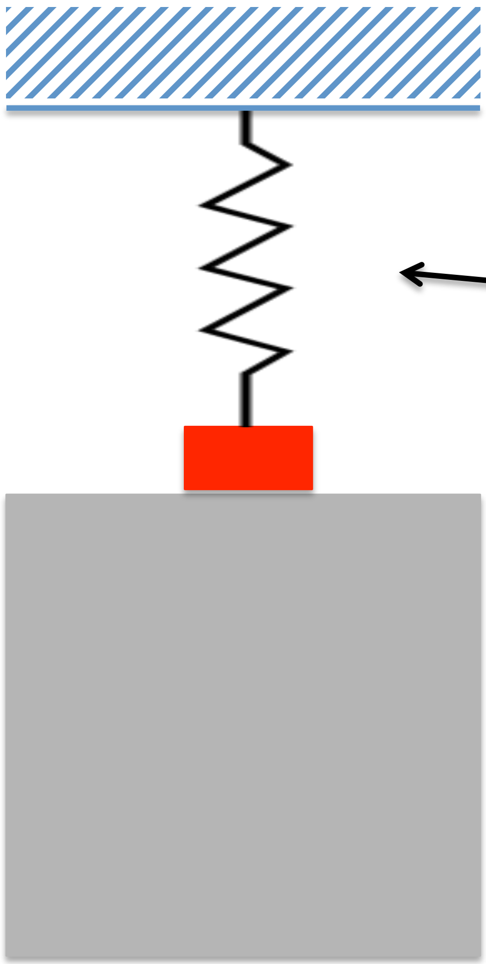
Threshold: 12keV
Cross-section: 1pb

$$\frac{\partial R}{\partial E_R} \propto \sigma_{\chi n} A^2 e^{-\frac{E_R}{E_0}}$$

Direct Search for Dark Matter

PRINCIPLE OF CRYOGENIC DETECTORS

Cryogenic Detector



heat bath ($T \approx 10mK$)

temperature $\mathbf{T_0}$

weak thermal link

conductance **G**

thermometer

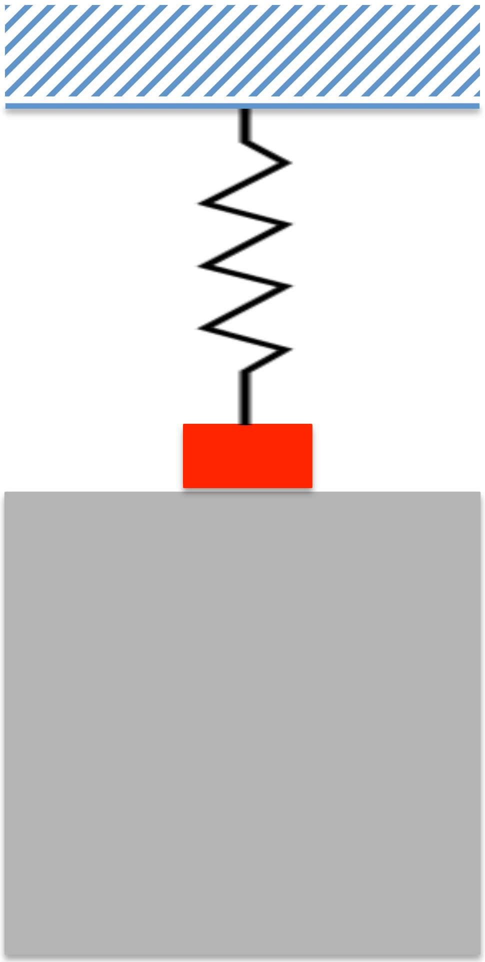
+

absorber material

heat capacity **C**

temperature **T**

Cryogenic Detector



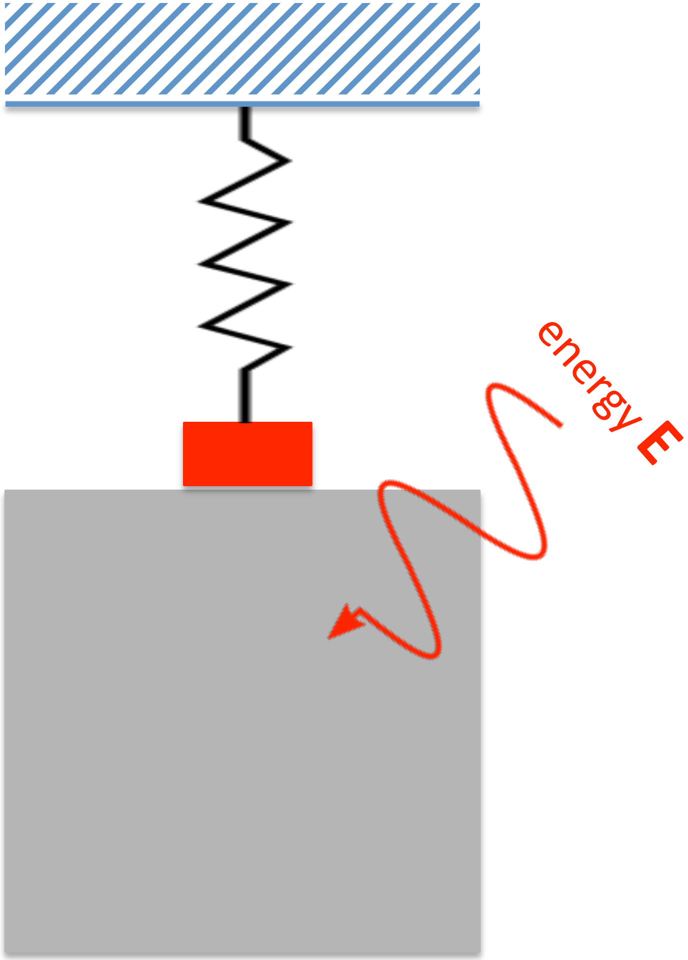
Irreducible thermal fluctuations:

$$\left\langle \Delta E^2 \right\rangle = k_B T^2 C$$

Need:

- Low temperature
- Low heat capacity

Cryogenic Detector



Irreducible thermal fluctuations:

$$\left\langle \Delta E^2 \right\rangle = k_B T^2 C$$

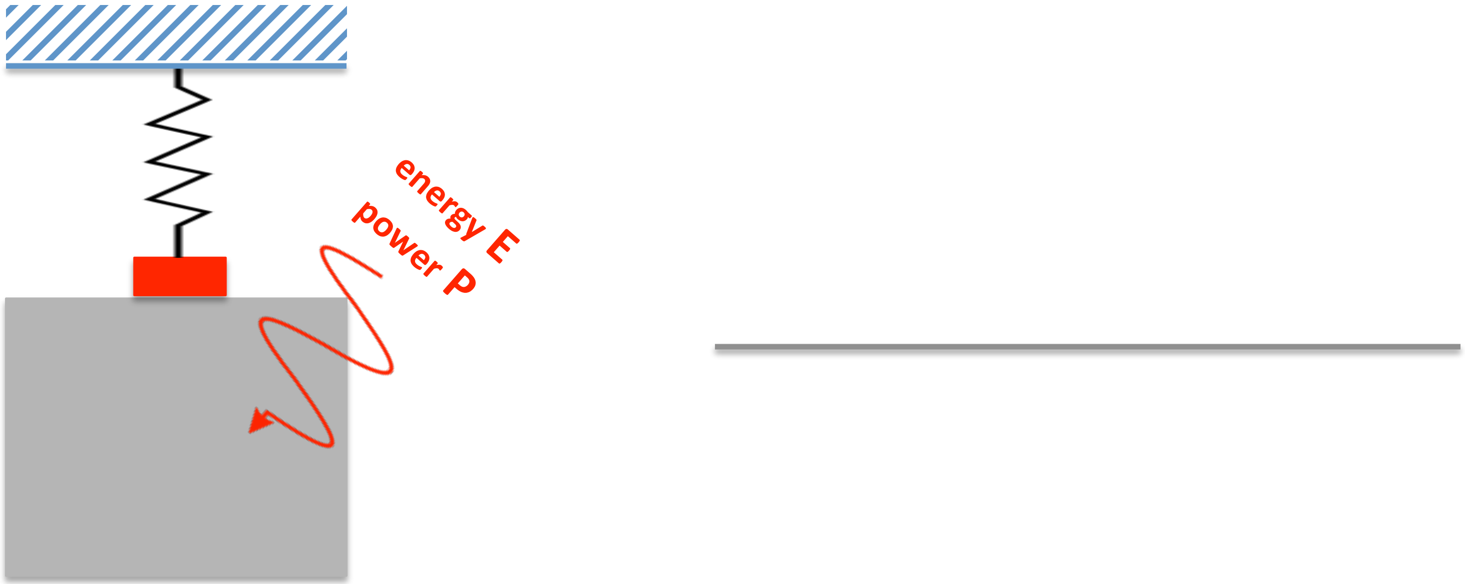
Need:

- Low temperature
- Low heat capacity

Operation at mK:

Temperature increase from particles interactions can be measured!
(1keV → µK)

Calorimetric Mode



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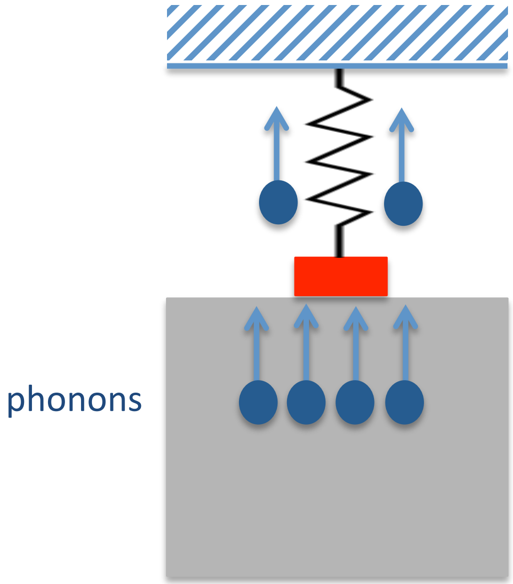
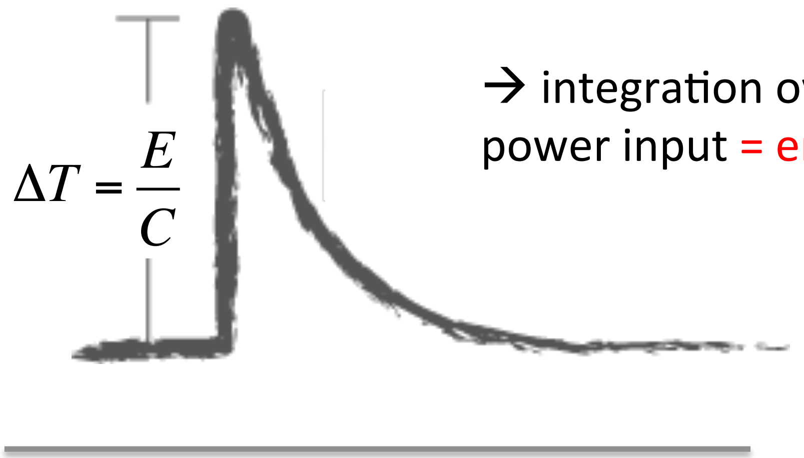
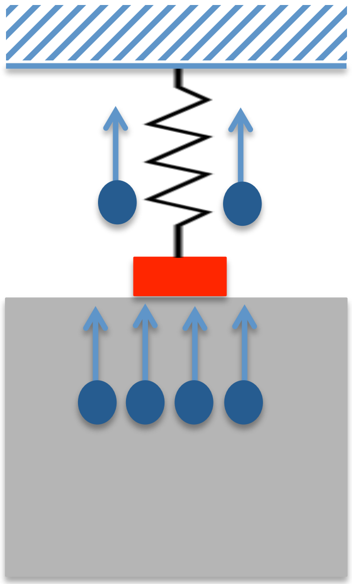




→ integration over power input = energy

“phonons flow into the thermometer more quickly than out of it !”

Calorimetric Mode



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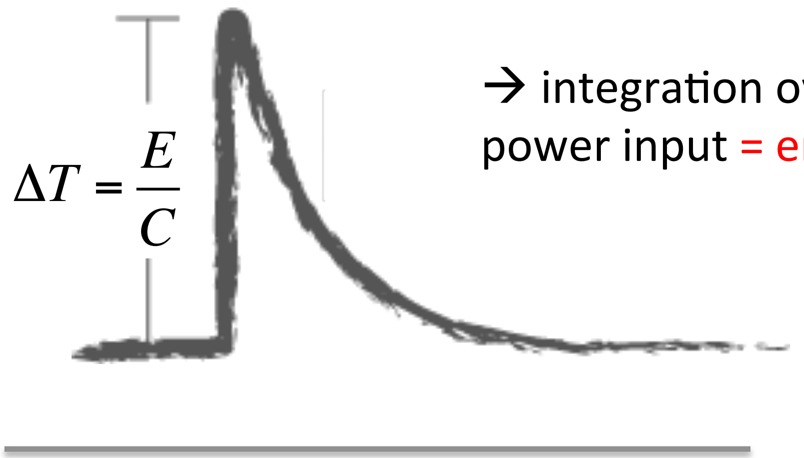
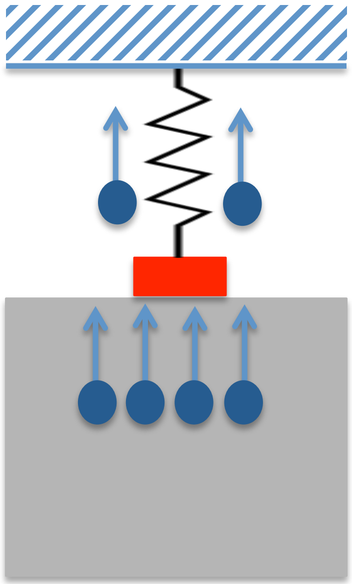


→ integration over power input = energy

← measure filling level

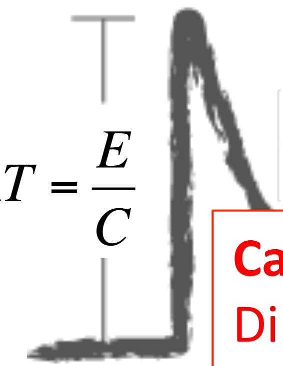
Calorimetric Mode

phonons



“phonons flow into the thermometer more quickly than out of it !”

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



→ integration over power input = energy

Calorimeter

Direct measurement of total deposited energy!

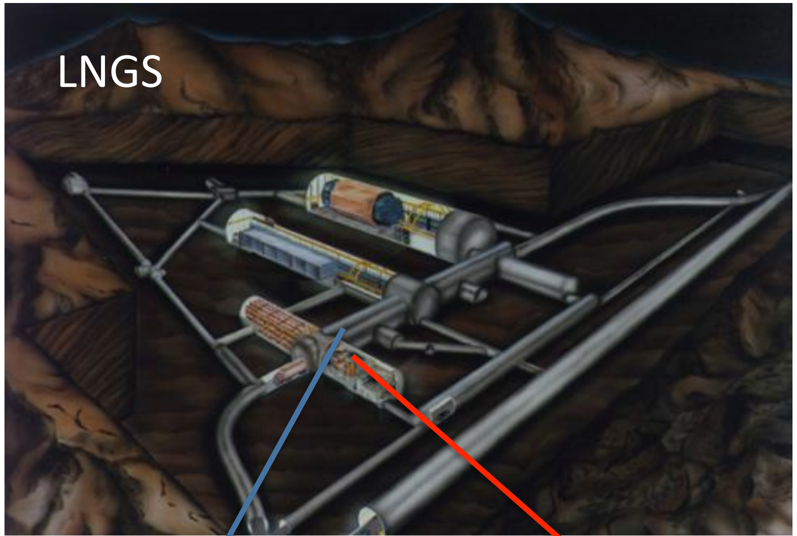
← measure filling level

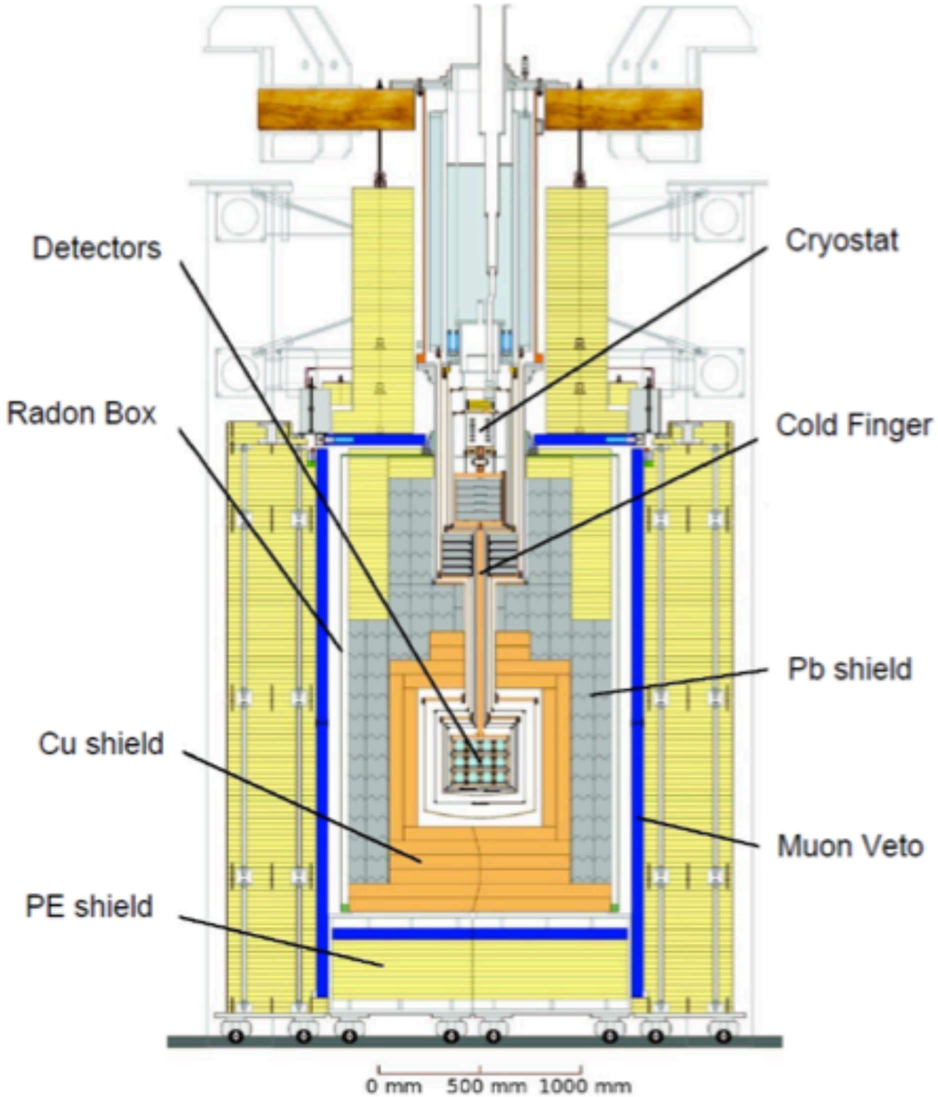
Experimental Basics

THE CRESST EXPERIMENT

The CRESST Experiment

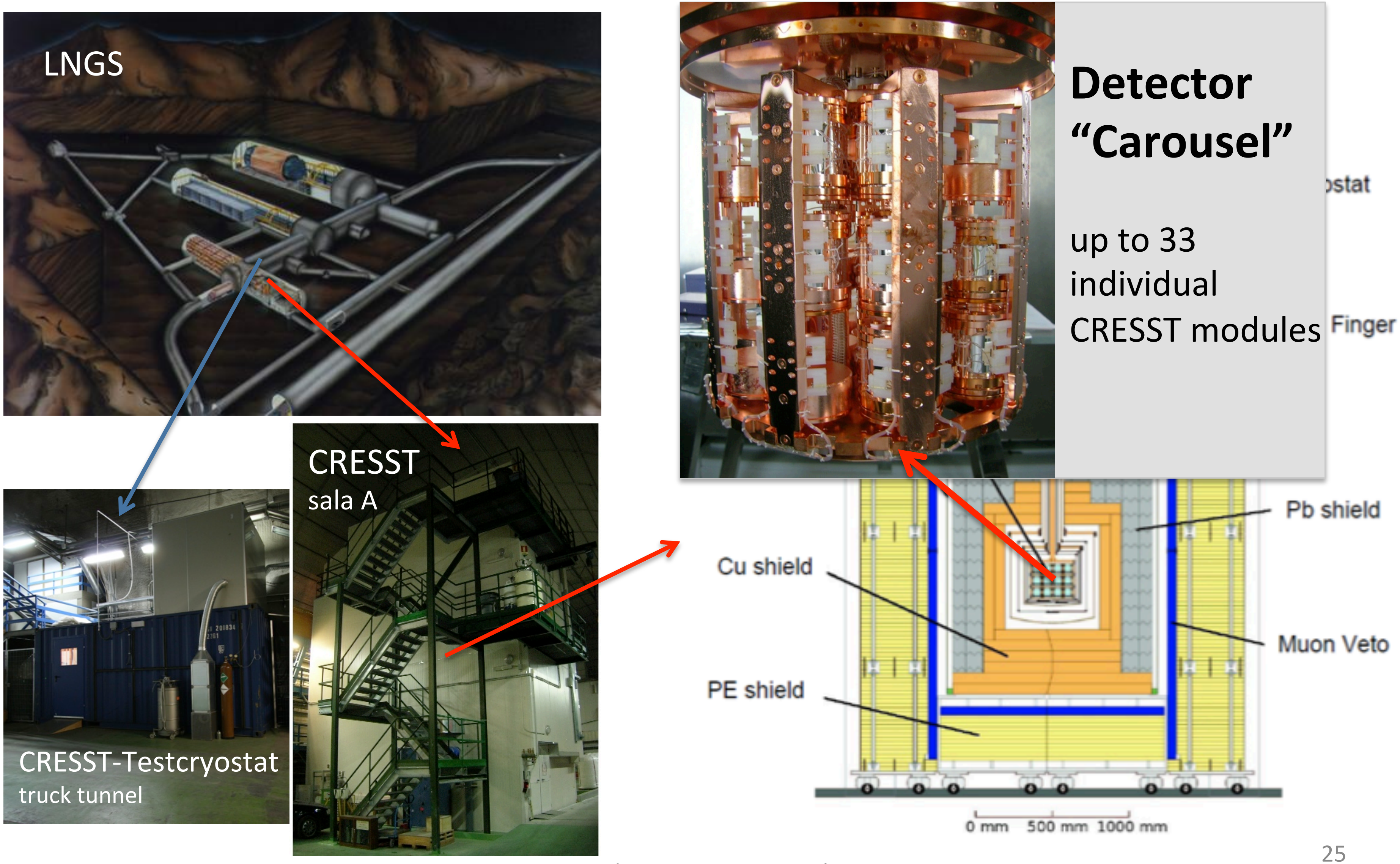
Cryogenic Rare Event Search with Superconducting Thermometers





The CRESST Experiment

Cryogenic Rare Event Search with Superconducting Thermometers



The CRESST-II Detector Module

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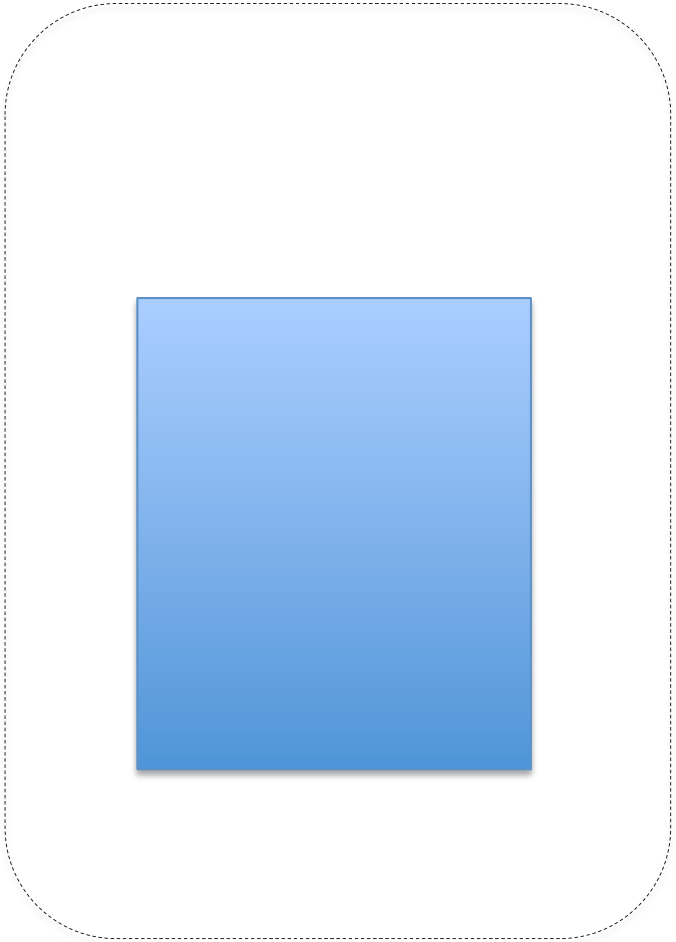
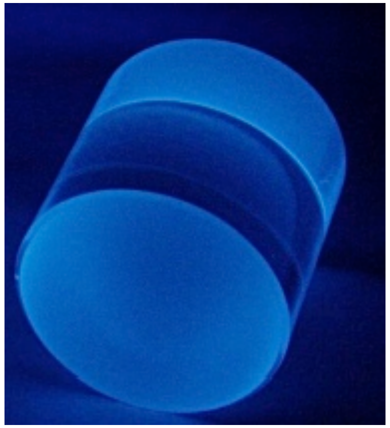


$CaWO_4$ Target Crystal

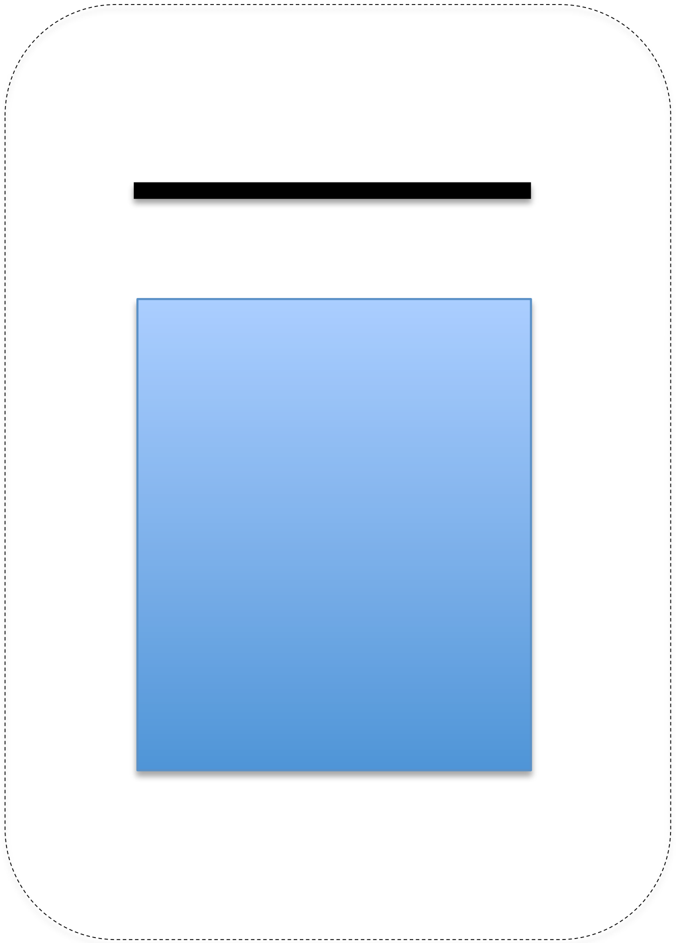


- scintillating
- multi-element target
- mass: 250 – 350 g

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

In-house production and processing at our institutes

The CRESST-II Detector Module

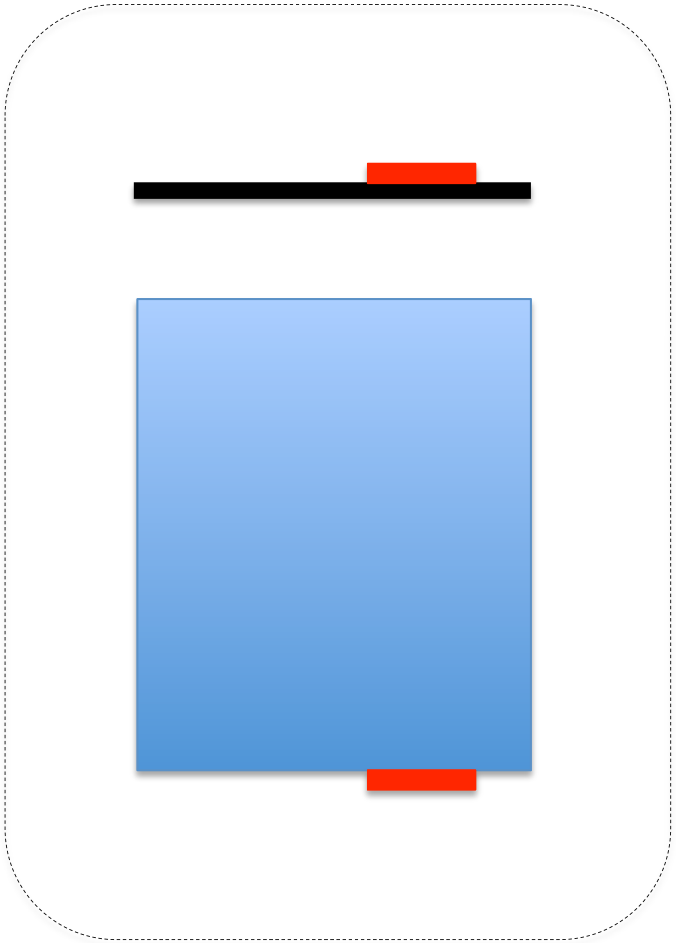


Light Absorber

for scintillation-light detection

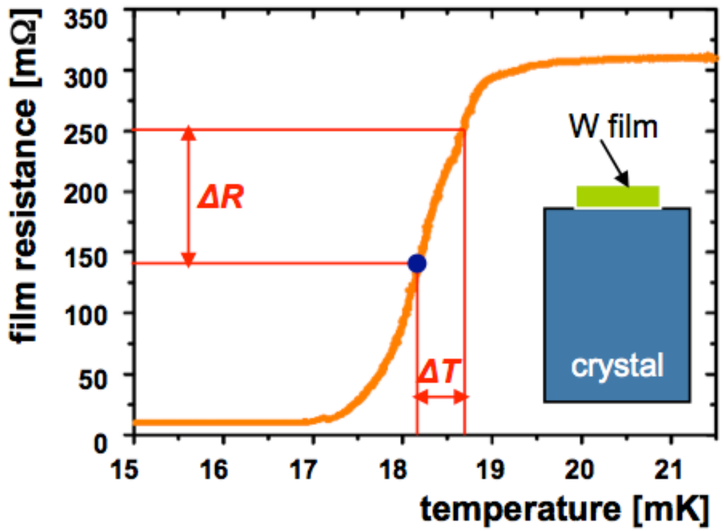
- silicon-on-sapphire disc
- diameter: 40mm
- thickness: 500µm

The CRESST-II Detector Module



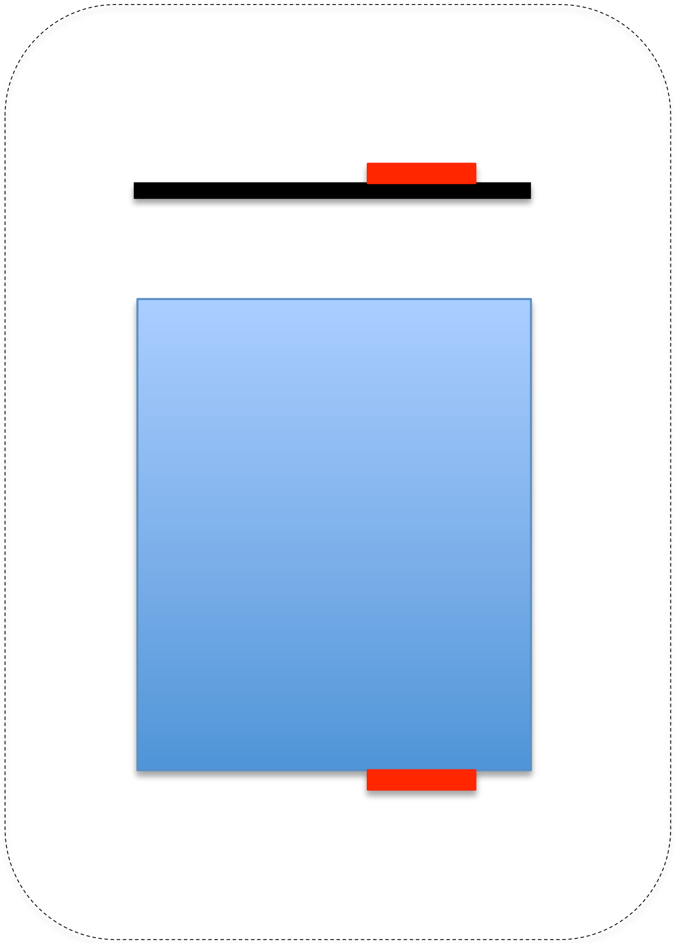
Transition-Edge-Sensors

→ 2 independent calorimeters



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

The CRESST-II Detector Module



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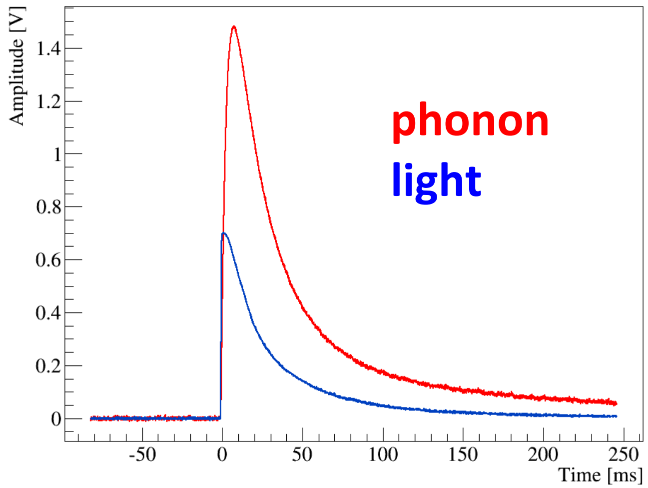


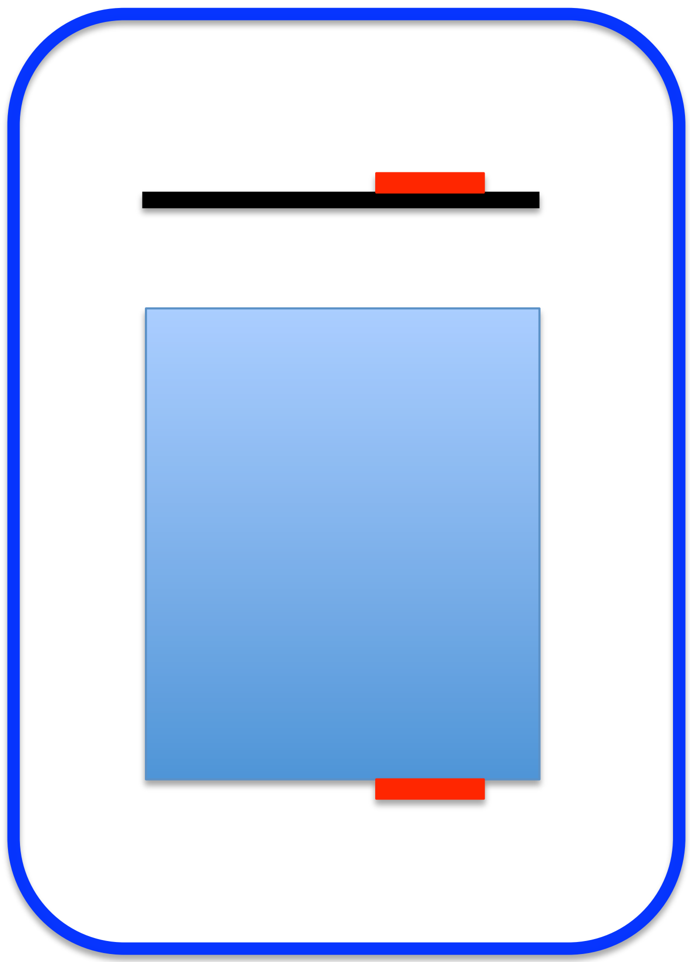
Phonon detector ($CaWO_4$)

- Threshold: $E_{th} \lesssim$ 1keV
- Resolution: $\sigma \approx$100-200 eV

Light detector (SOS)

- Baseline noise $\sigma \approx$ 5eV

The CRESST-II Detector Module



Polymeric Foil

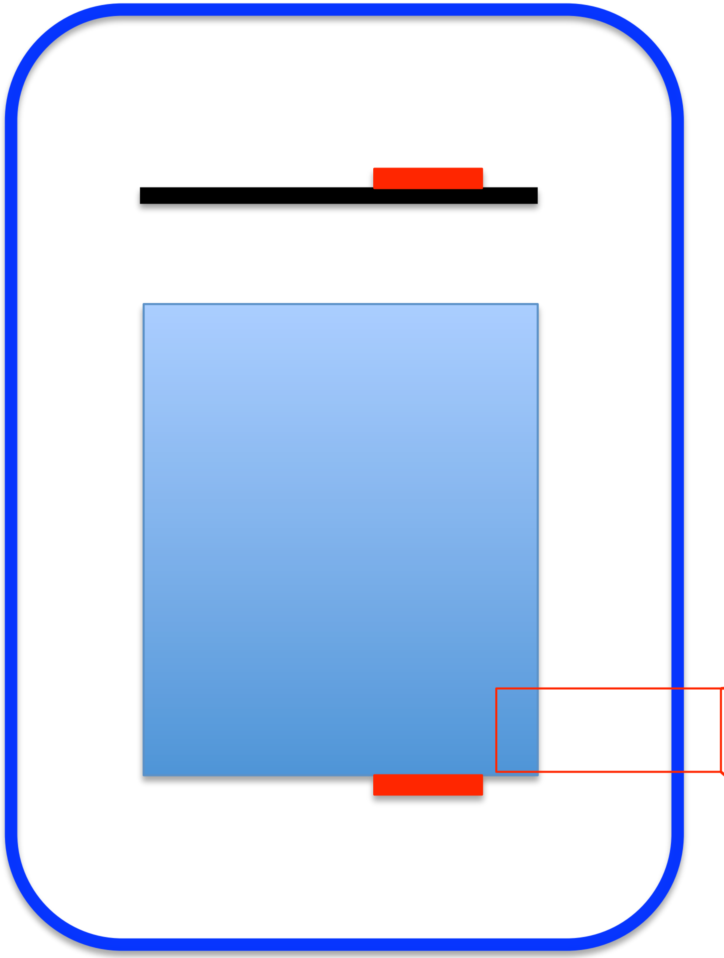
① Highly reflective

- ➢ light collection

② Scintillating

- ➢ rejection of surface events

The CRESST-II Detector Module



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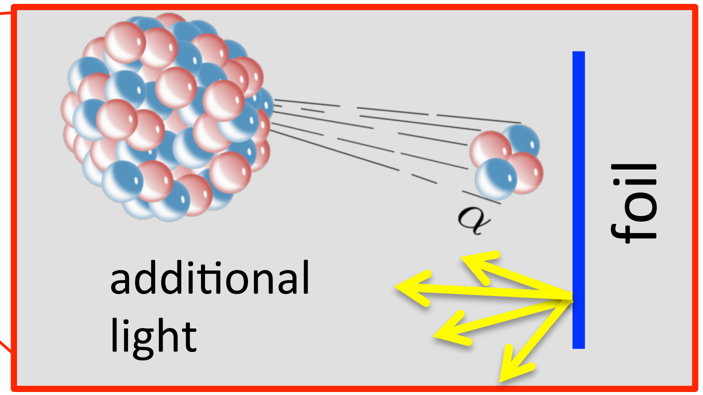

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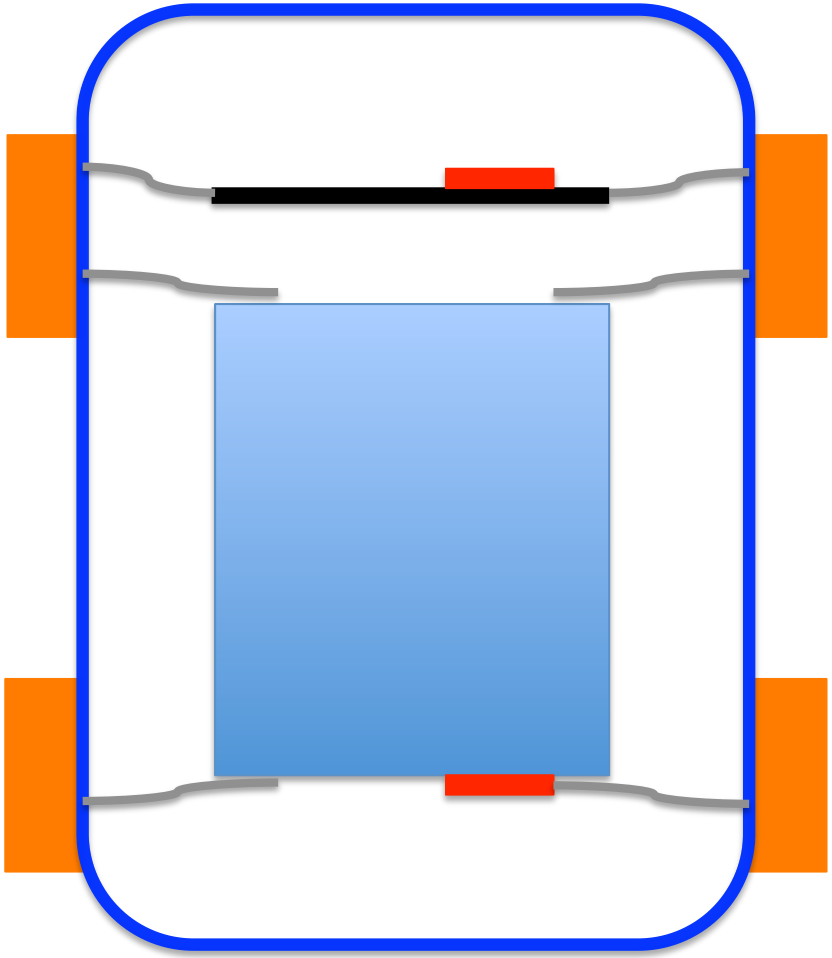
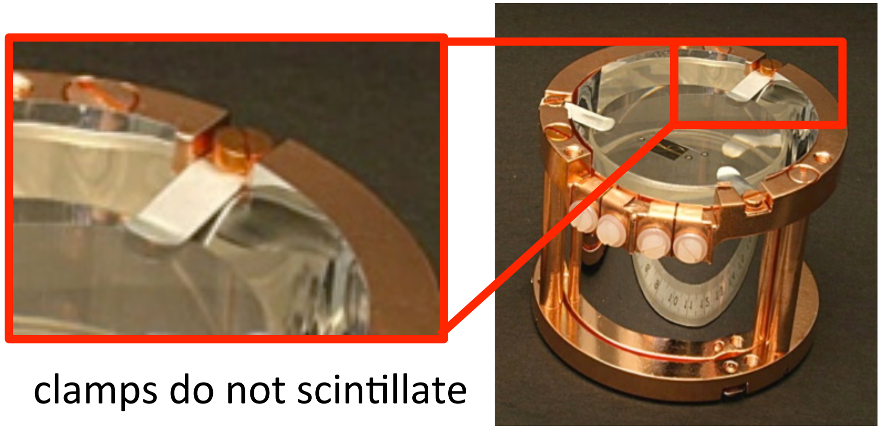


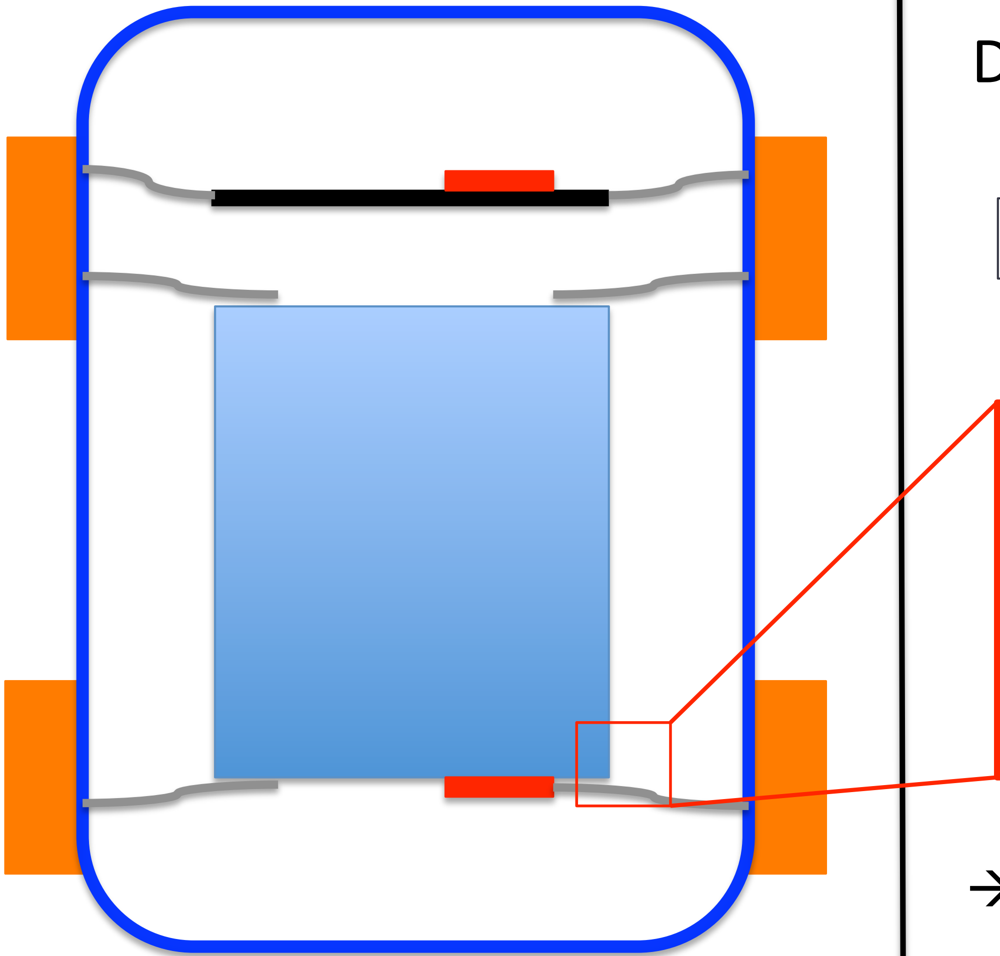
Support Structure

- radio-pure copper
- flexible bronze clamps



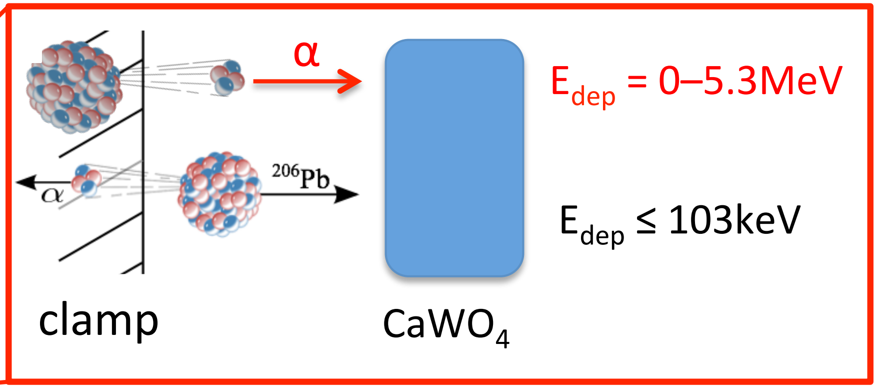
clamps do not scintillate

The CRESST-II Detector Module



Dangerous Surface Backgrounds

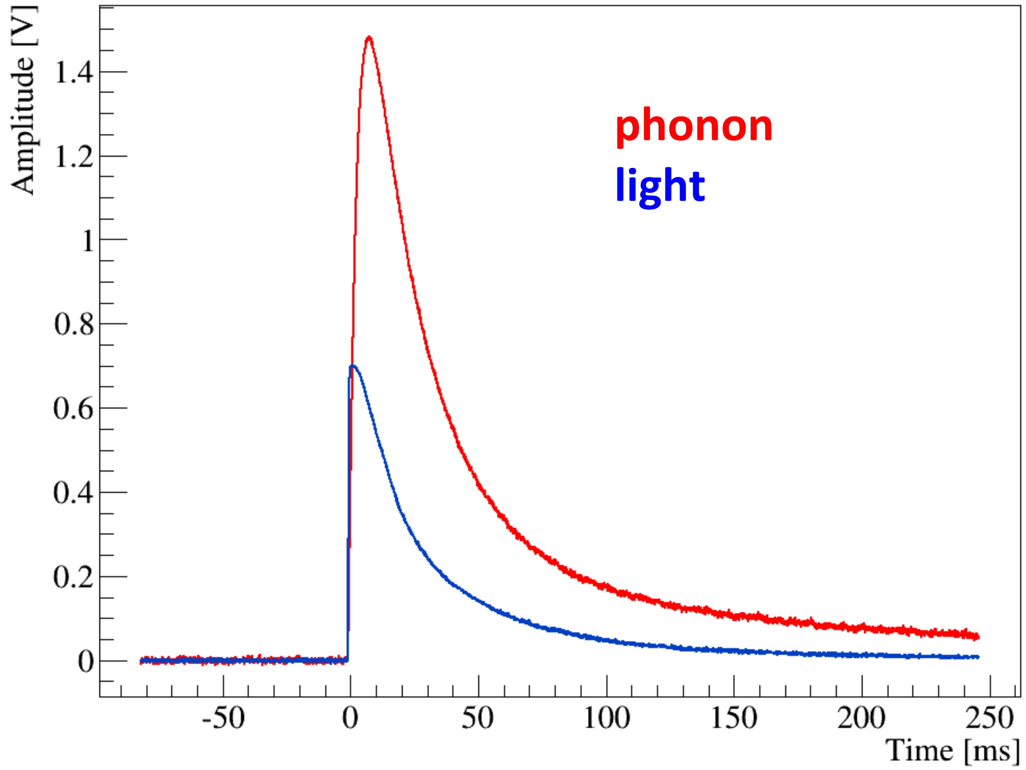
$^{210}Po \rightarrow {}^{206}Pb$ (103keV) + α (5.3MeV)



→ Lead/alpha recoils can mimic WIMPs

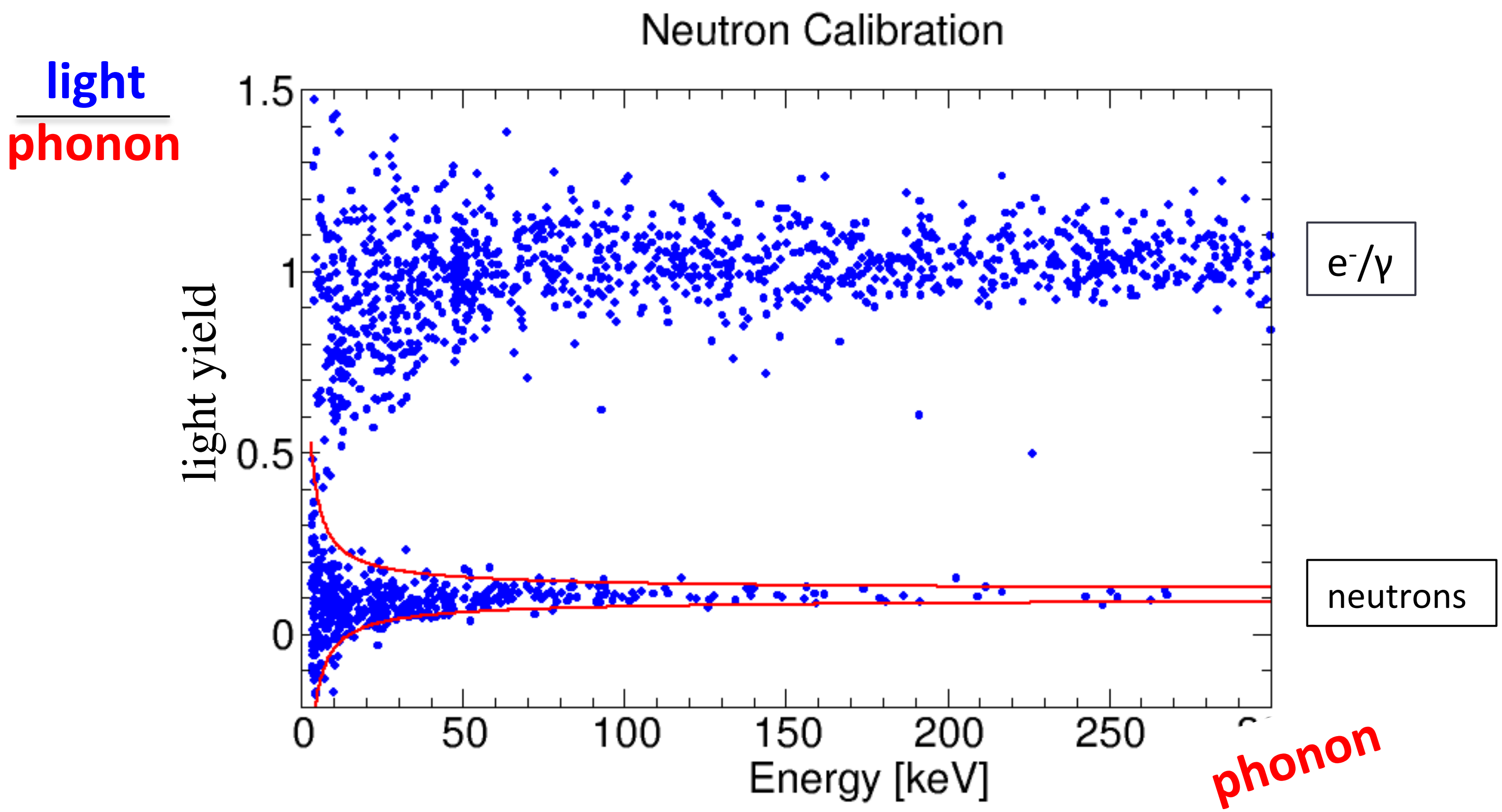
→ Avoid non-scintillating materials!

Phonon-Light Technique



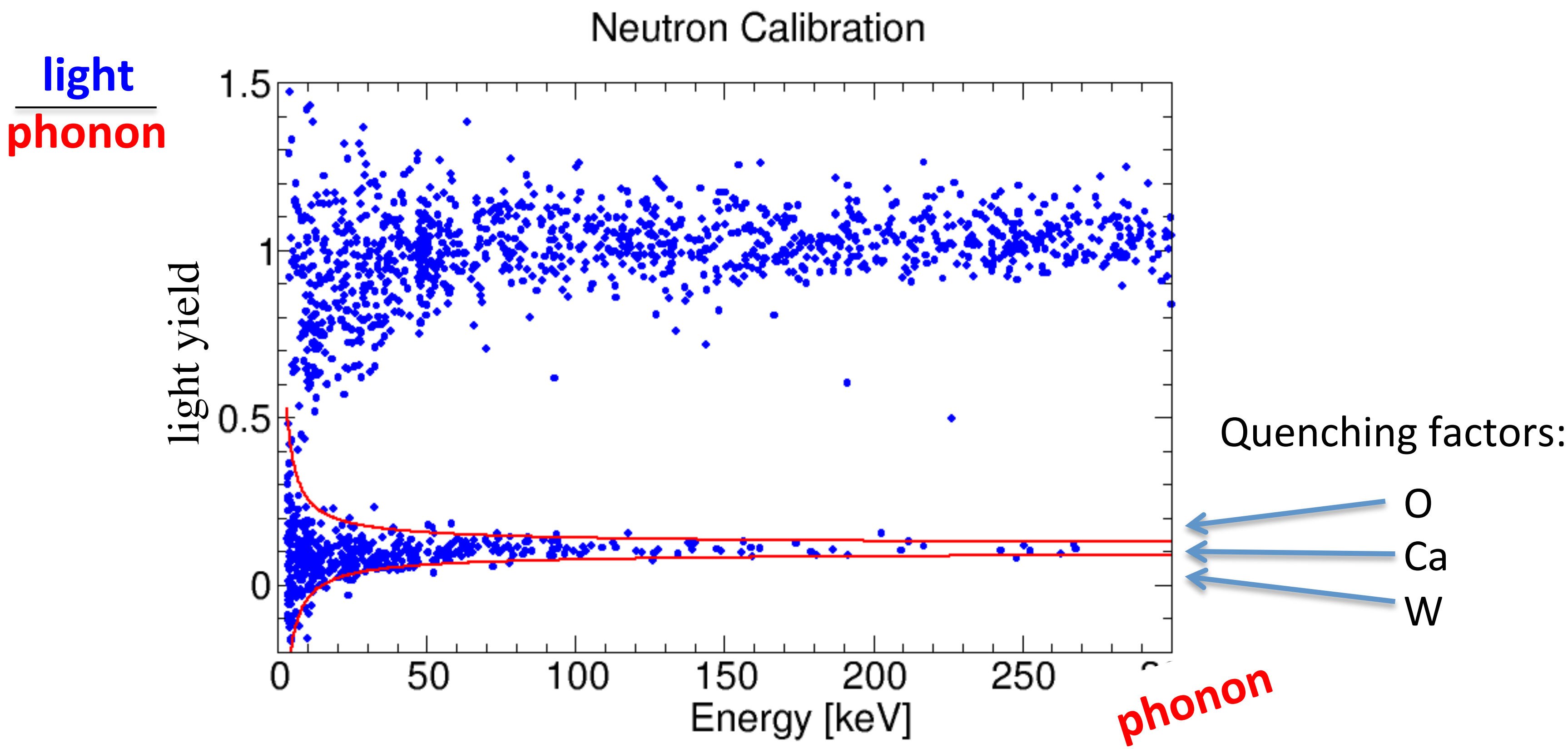
Simultaneous measurement of **phonon** and **light** signal

Phonon-Light Technique



Reduced light output for highly-ionizing particles → Quenching

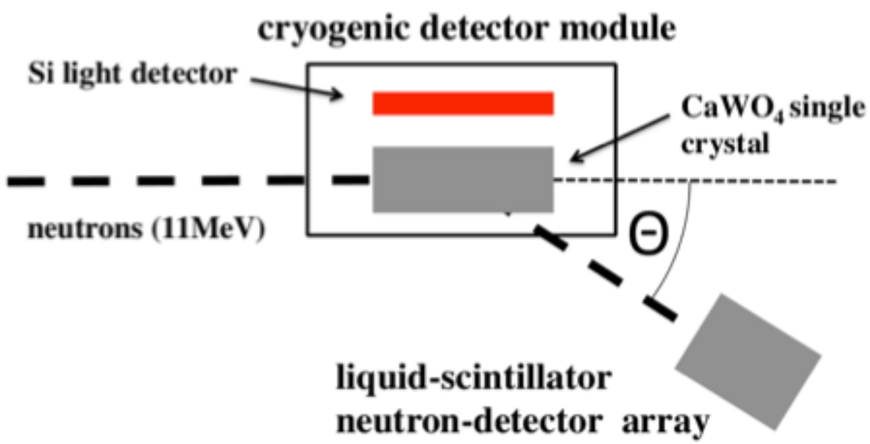
Phonon-Light Technique

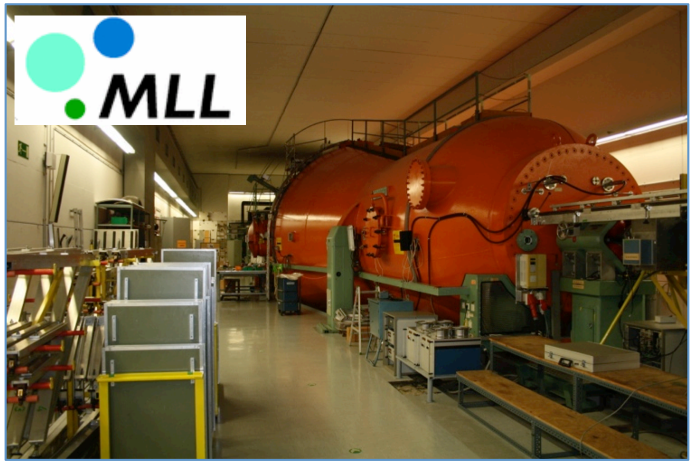


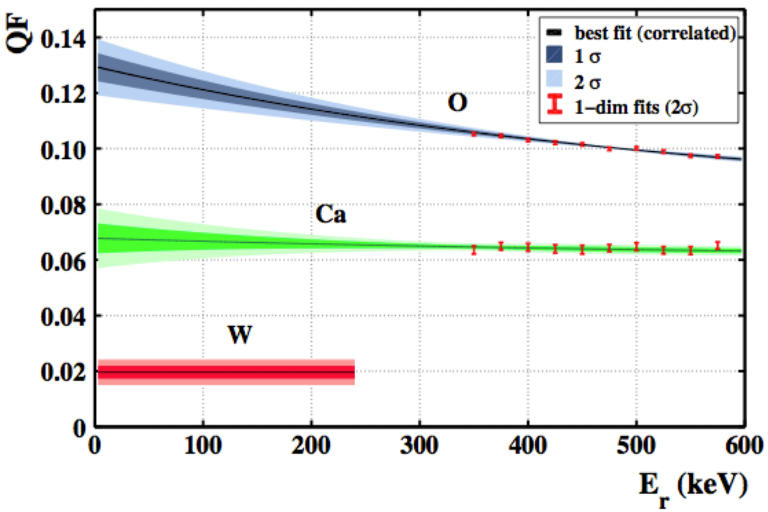
Reduced light output for highly-ionizing particles → Quenching

Quenching Factor Measurements

Neutron-Scattering Facility at MLL Accelerator



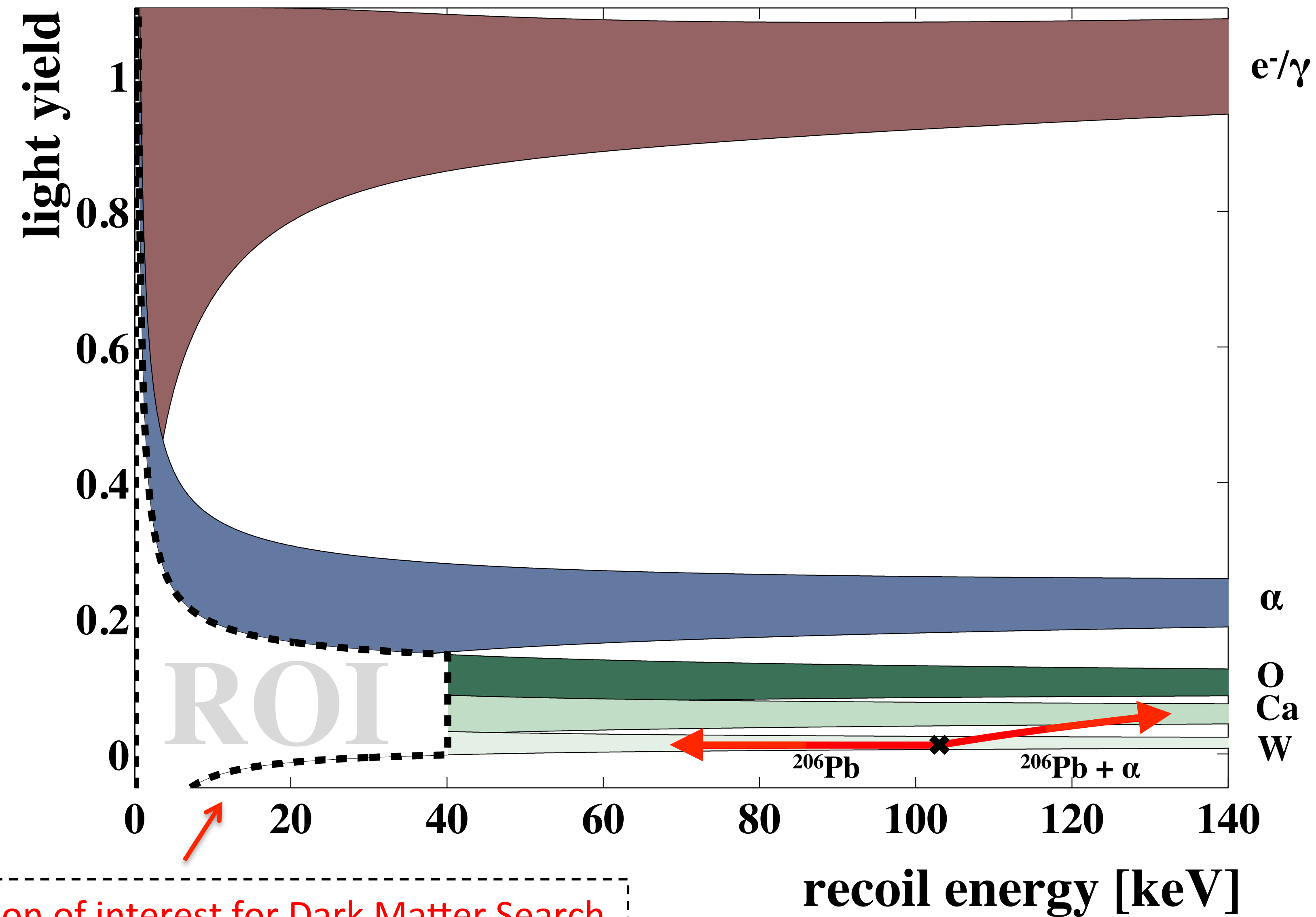




- Precise measurement of QF of O, Ca and W at mK temperatures
- For CRESST detectors in ROI:
  $QF_O = (11.2 \pm 0.5)\%$
  $QF_{Ca} = (5.94 \pm 0.49)\%$
  $QF_W = (1.72 \pm 0.21)\%$

R. Strauss et al., EPJ-C , **arXiv:1401.3332**

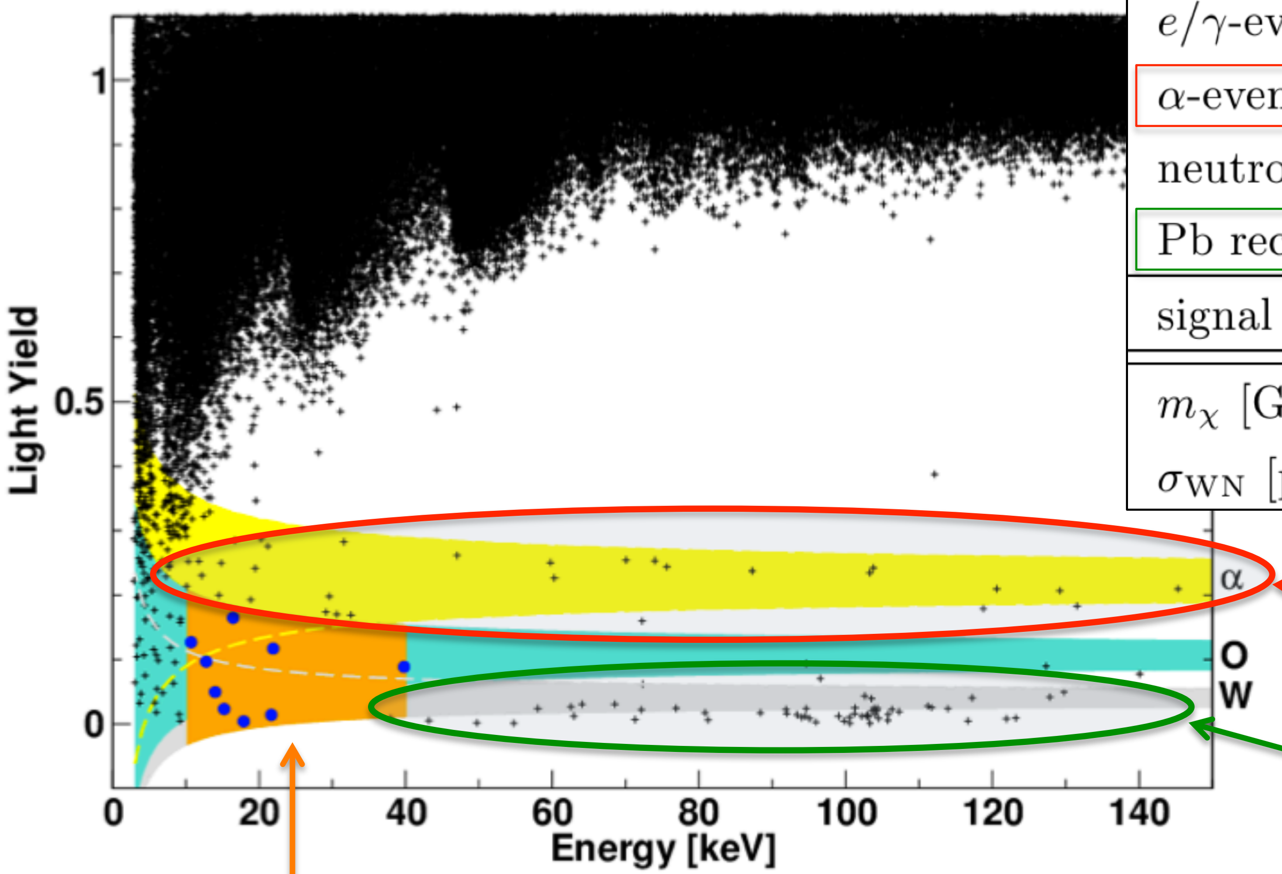
Signal and Backgrounds



Region of interest for Dark Matter Search

Results of the Previous Run – Run32

	M2
e/γ-events	8.00 ± 0.05
α-events	$11.2\,^{+2.5}_{-2.3}$
neutron events	$9.7\,^{+6.1}_{-5.1}$
Pb recoils	$18.7\,^{+4.9}_{-4.7}$
signal events	$24.2\,^{+8.1}_{-7.2}$
m_χ [GeV]	11.6
σ_{WN} [pb]	$3.7 \cdot 10^{-5}$



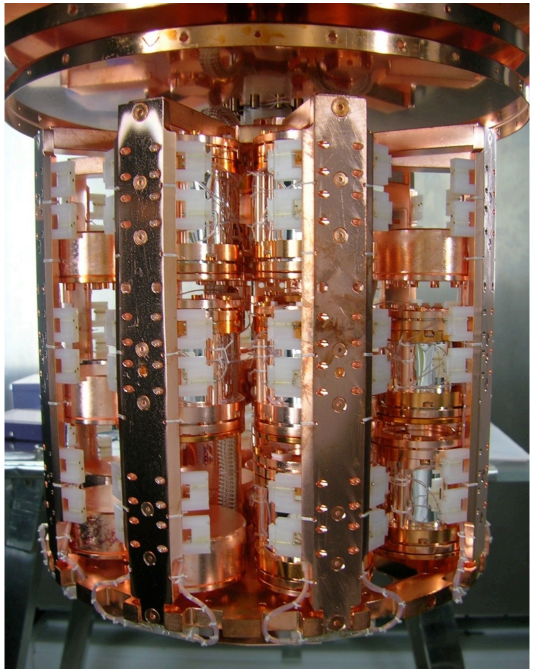
G. Angloher et al., Eur. Phys. J. C, 72, 4 (2012)

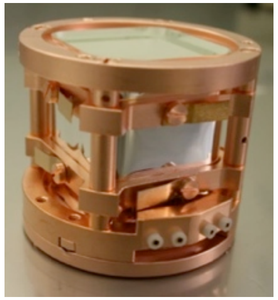
STATE-OF-THE-ART

CRESST II

Recently Finished – CRESST-II Phase 2

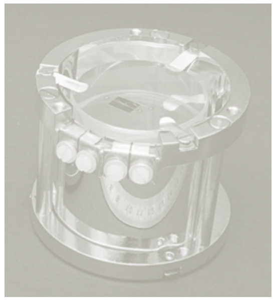
Data-taking from July 2013 to August 2015





2014 Results: "TUM-40"

- Efficient surface-event rejection
- Best intrinsic background level
- Best *overall* performance



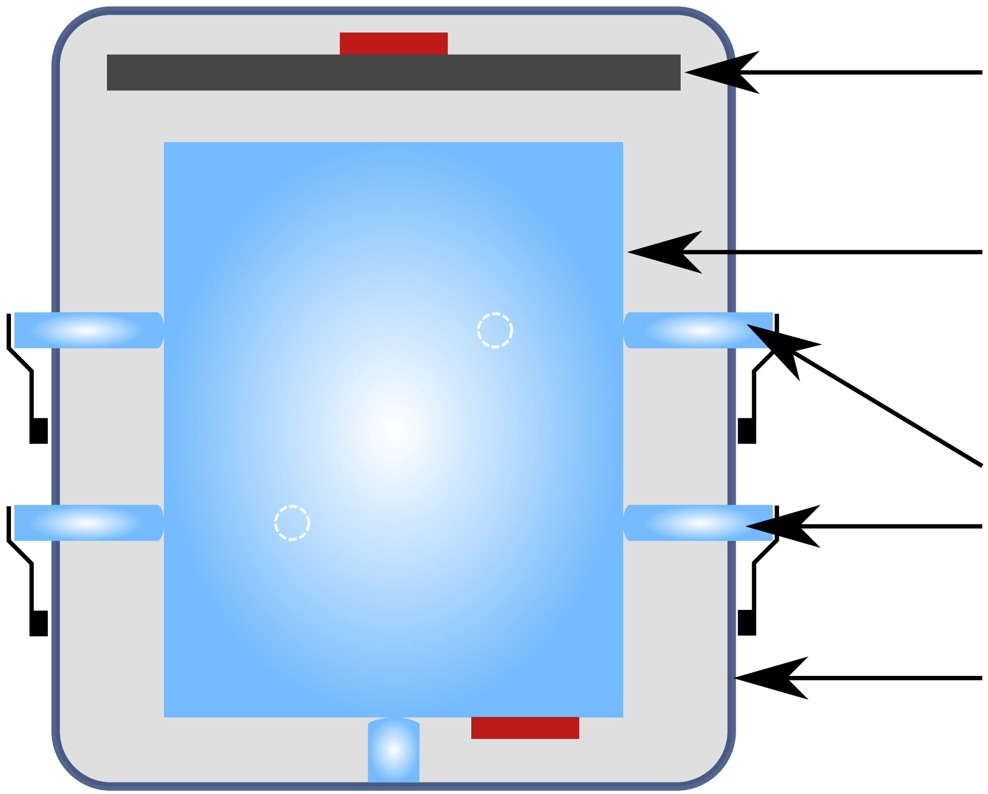
2015 Results: "Lise"

- Incomplete surface rejection
- Lowest threshold
- Factor ~2 higher background

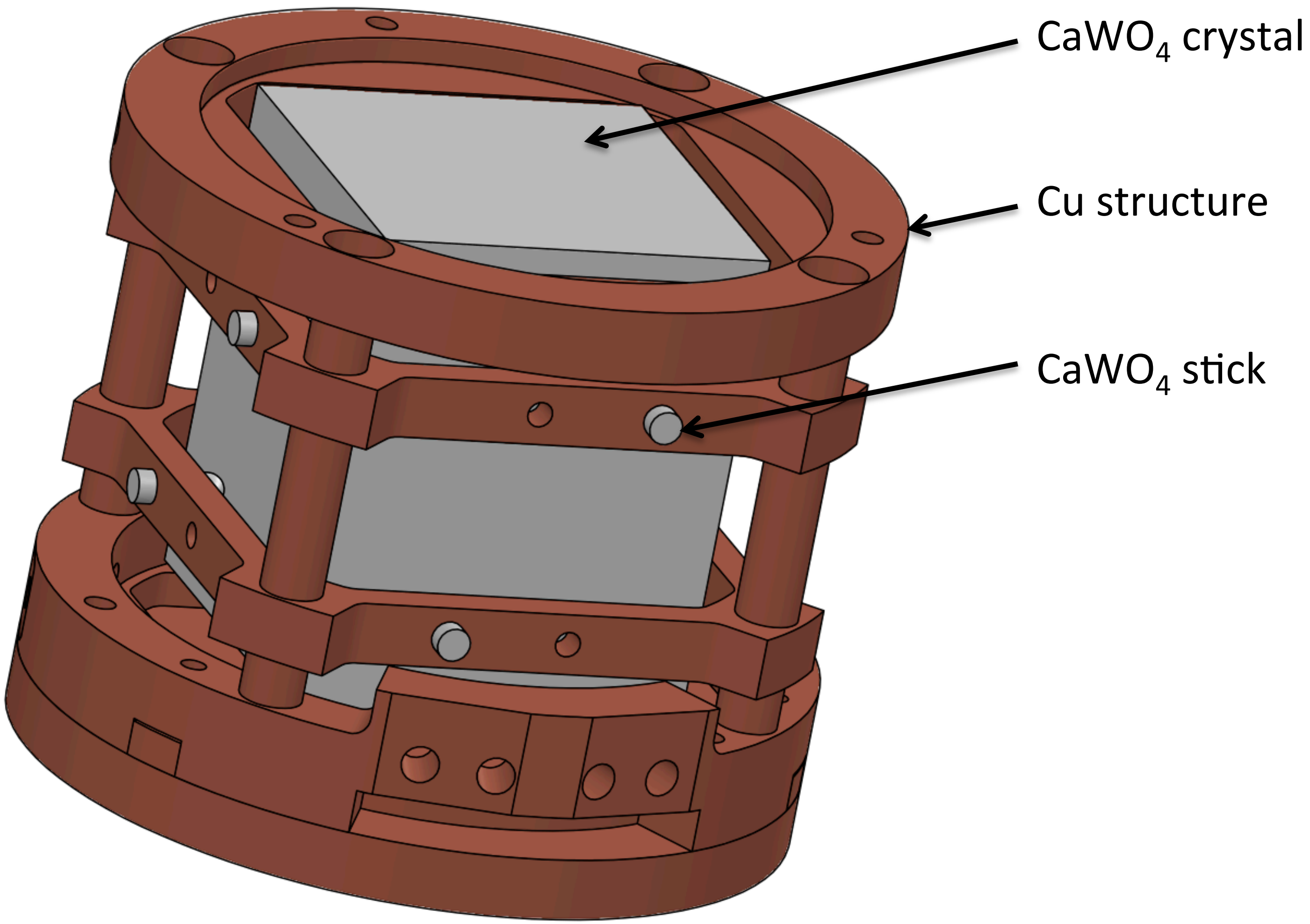
Final Data: Total exposure

- About 500 kg-days acquired
- Data release end of 2015

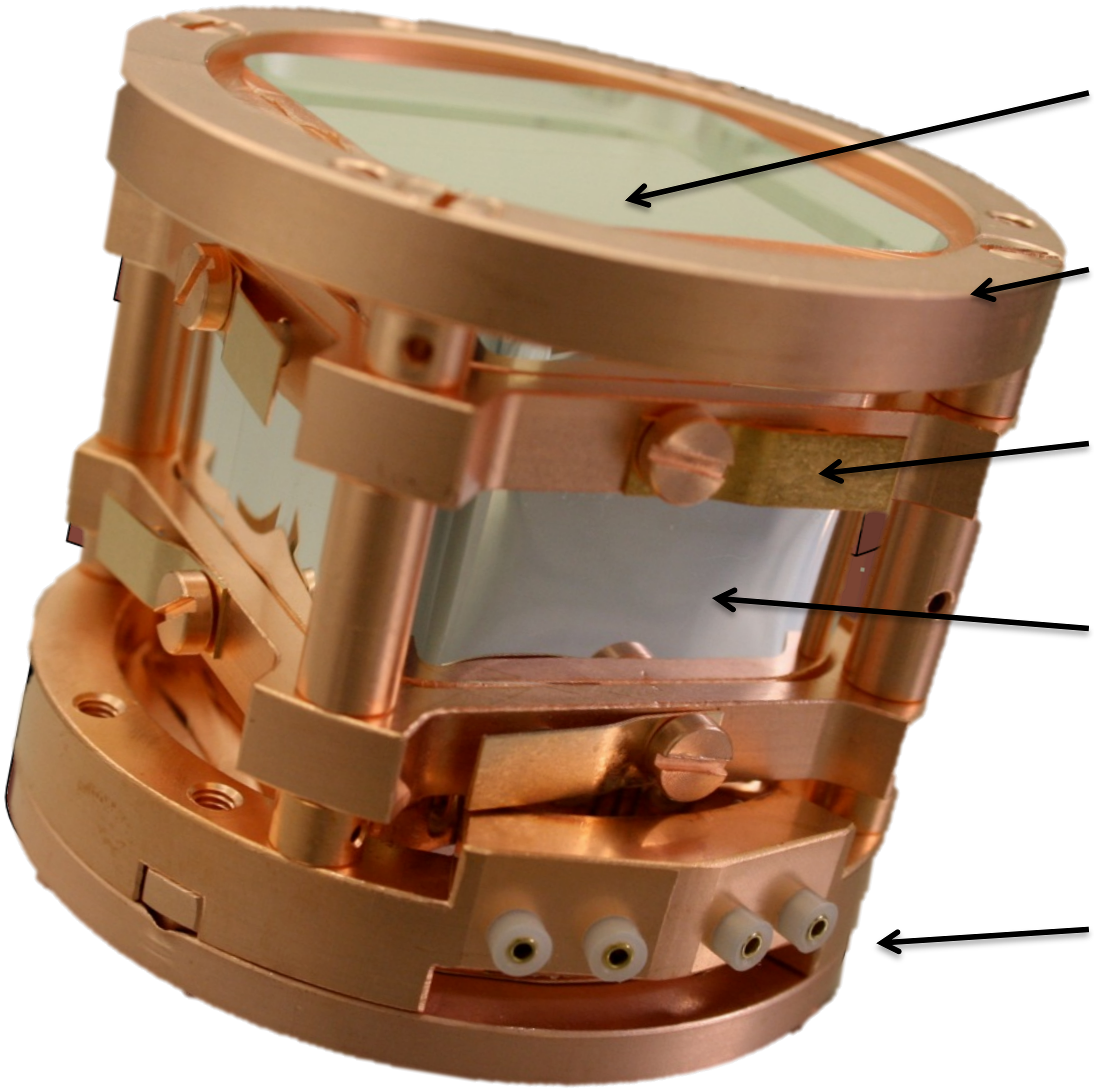
Fully-Scintillating Design



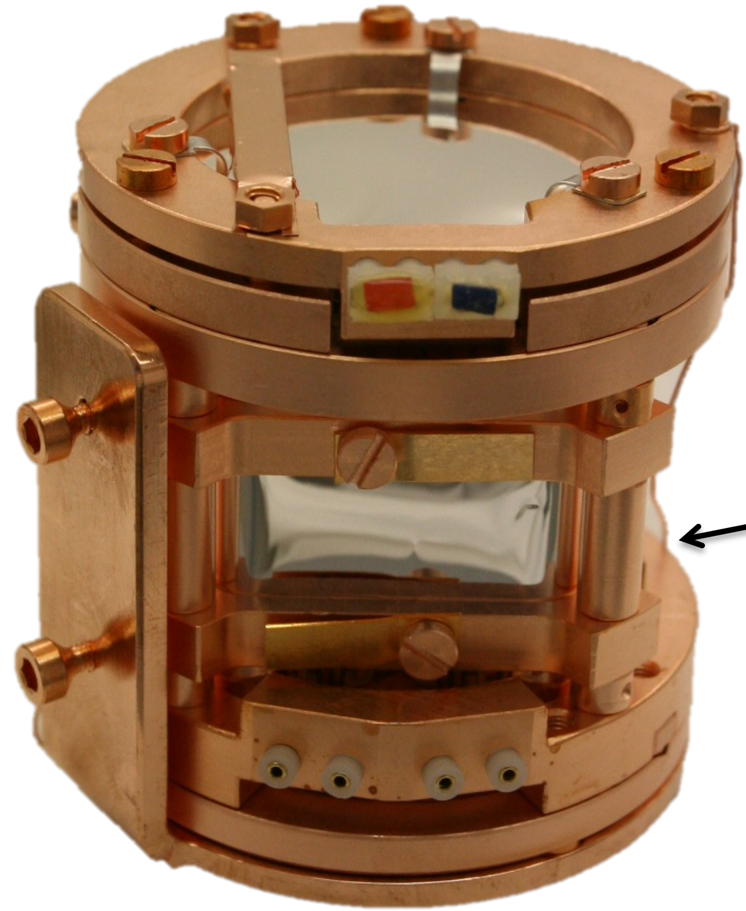
Stick-Based Detector Holder



Stick-Based Detector Holder



Stick-Based Detector Holder

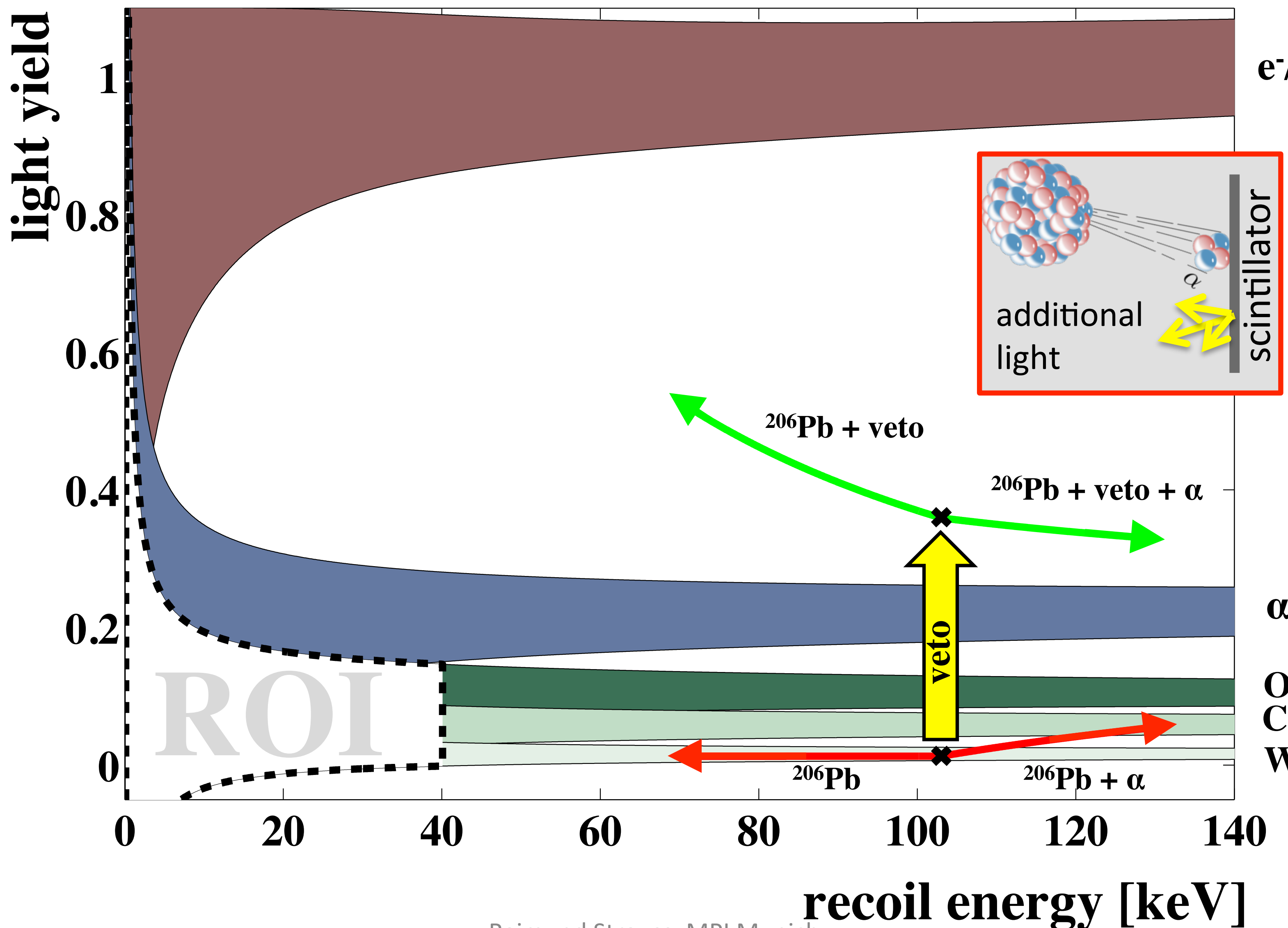


Light detector „Michael“

Phonon detector: TUM-40

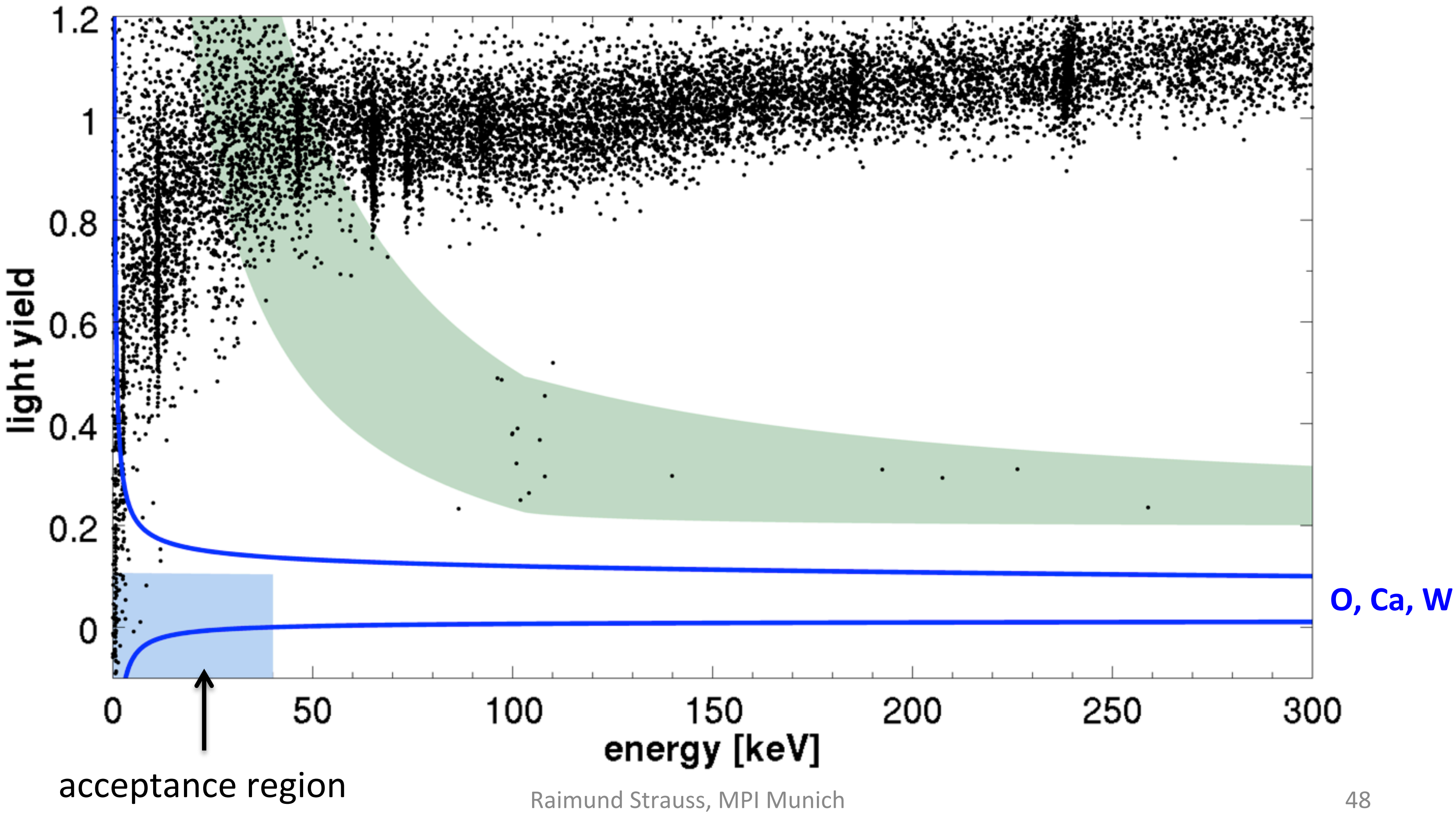
R. Strauss et al. arxiv:1410.1753 EPJ-C (2015)

Efficient Veto of Surface Backgrounds

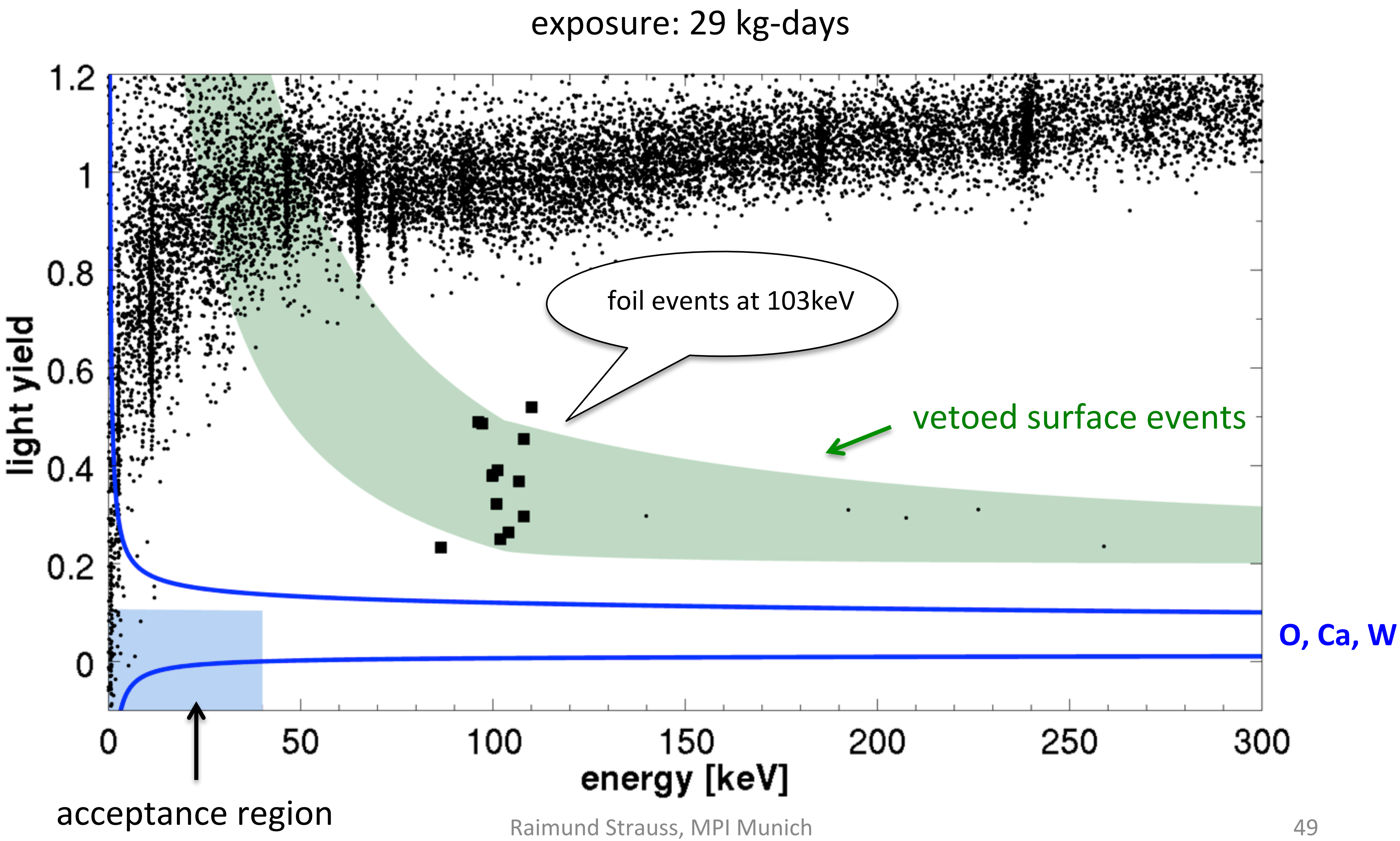


TUM-40: Surface Backgrounds

exposure: 29 kg-days

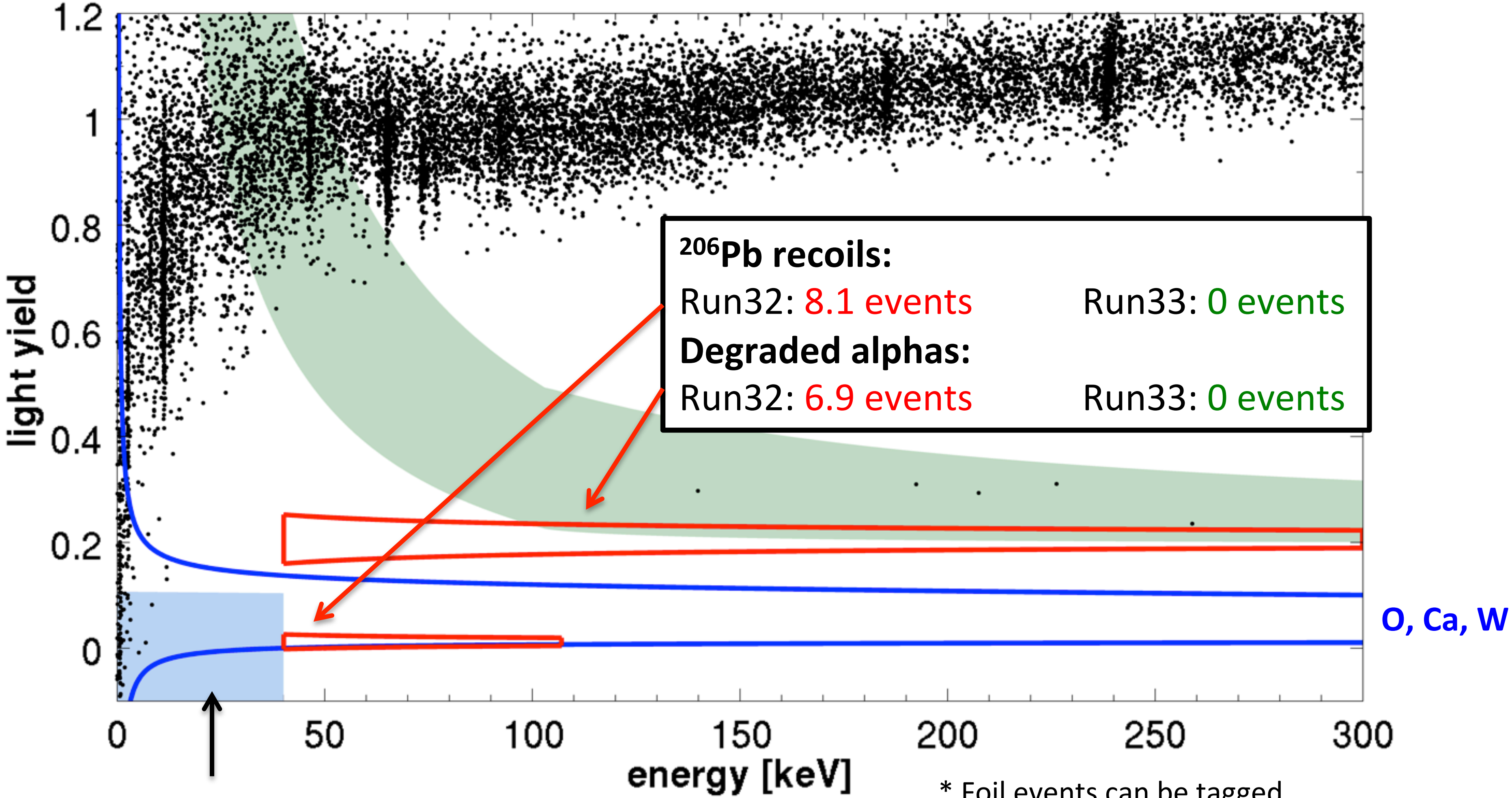


TUM-40: Surface Backgrounds



TUM-40: Surface Backgrounds

exposure: 29 kg-days



acceptance region

* Foil events can be tagged by a different pulse shape

$CaWO_4$ Crystal Production at TU Munich

Furnace for **Czochralski process**

Dedicated machine for CRESST:

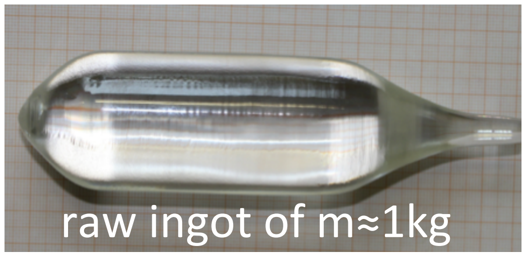
- All production steps under control
- Machining of crystals in-house

Goals :

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

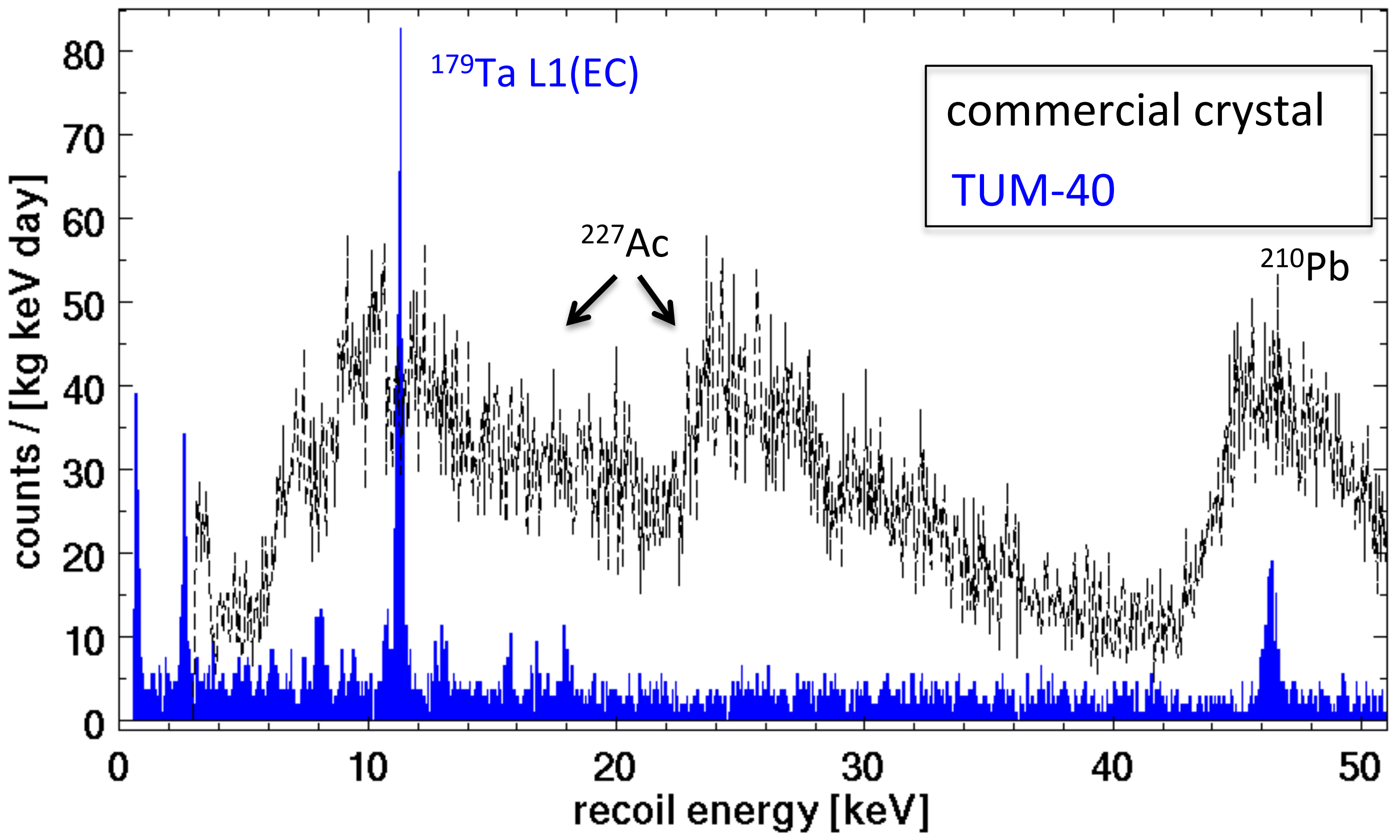
Major achievements:

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



A. Erb and J.-C. Lanfranchi, *CrystEngComm*, 2013,**15**, 2301-2304
M. von Sivers, Opt. Mat. 34, 11 (2012) 1843-1848, arXiv:1206.1588

TUM-40: Radiopurity



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

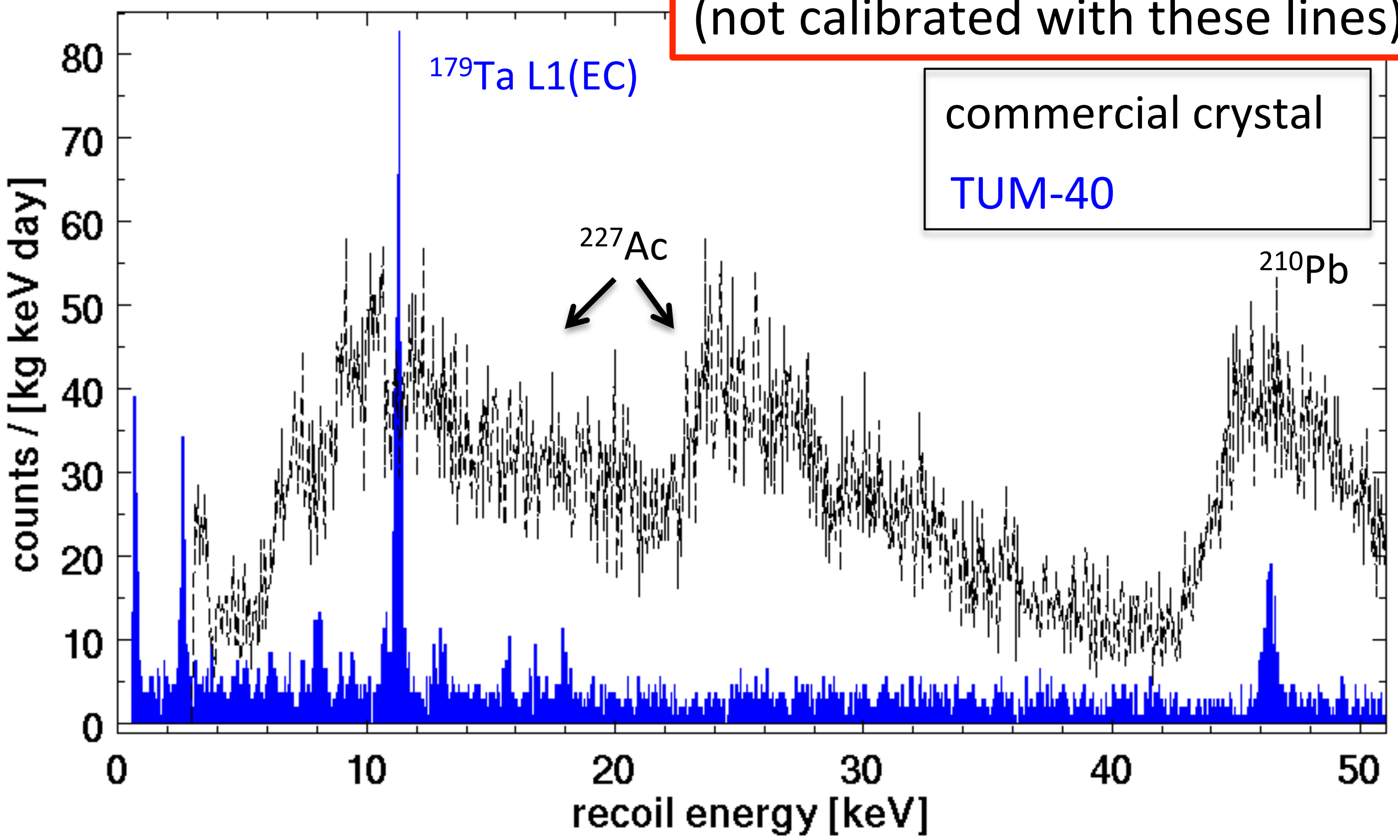
Gamma-lines from **cosmogenic activation**

Excellent resolution:
$\sigma \approx 100\text{eV}$

See: CRESST collab. G. Angloher et al. arXiv:1407.3146, EPJ-C (2014) 74
CRESST collab. *R. Strauss et al. arxiv:1410.4188, JCAP 06(2015)030*

TUM-40: Radiopurity

All gamma lines agree within < 5eV
with tabulated values !!
(not calibrated with these lines)



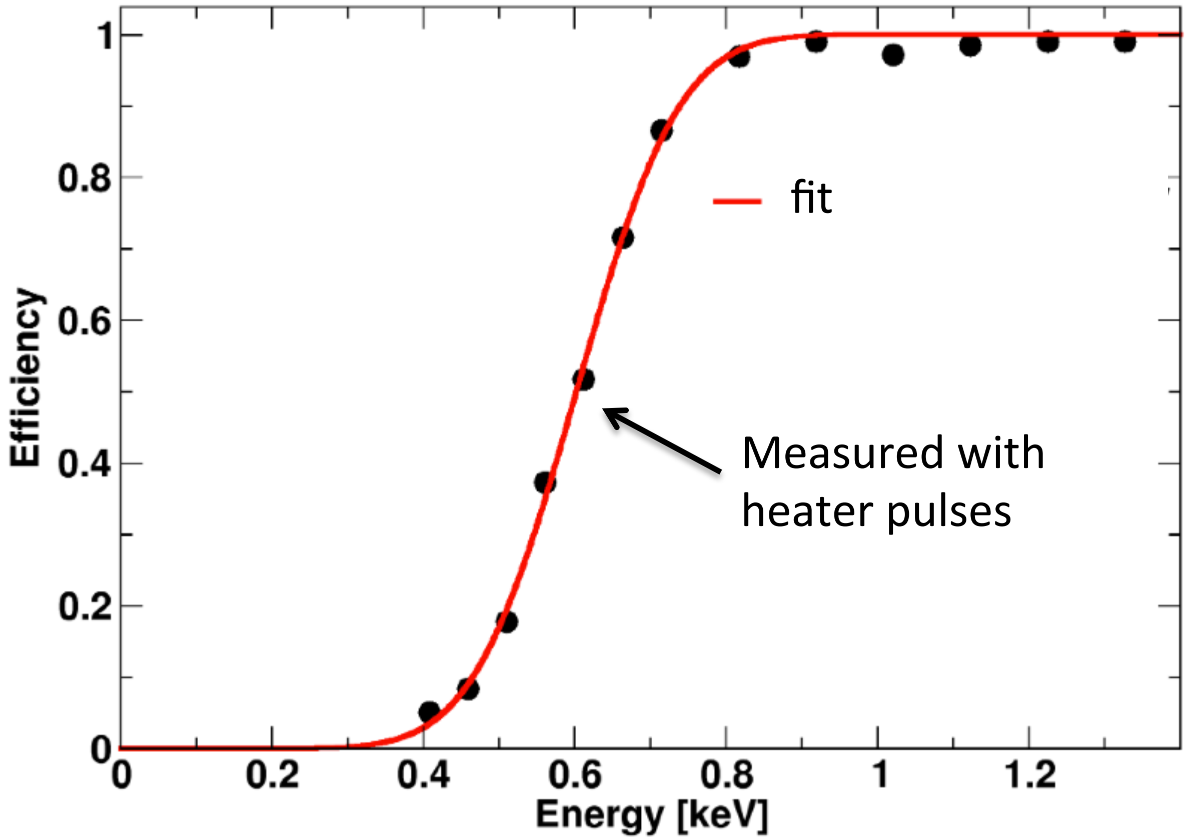
ge rate:
~3.5 counts / [kg keV day]

Gamma-lines from **cosmogenic activation**

Excellent resolution:
$\sigma \approx 100$eV

See: CRESST collab. G. Angloher et al. arXiv:1407.3146, EPJ-C (2014) 74
CRESST collab. *R. Strauss et al. arxiv:1410.4188, JCAP 06(2015)030*

TUM-40: Trigger Threshold

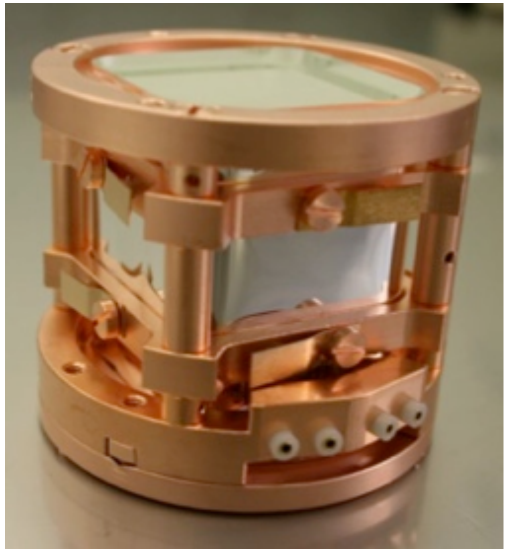


- Low trigger threshold of $\mathbf{E_{th} \approx 603eV}$
- Resolution of σ **≈ 107eV** in agreement with resolution of gamma lines

- Nuclear-recoil energy **precisely known**!

TUM-40: Performance

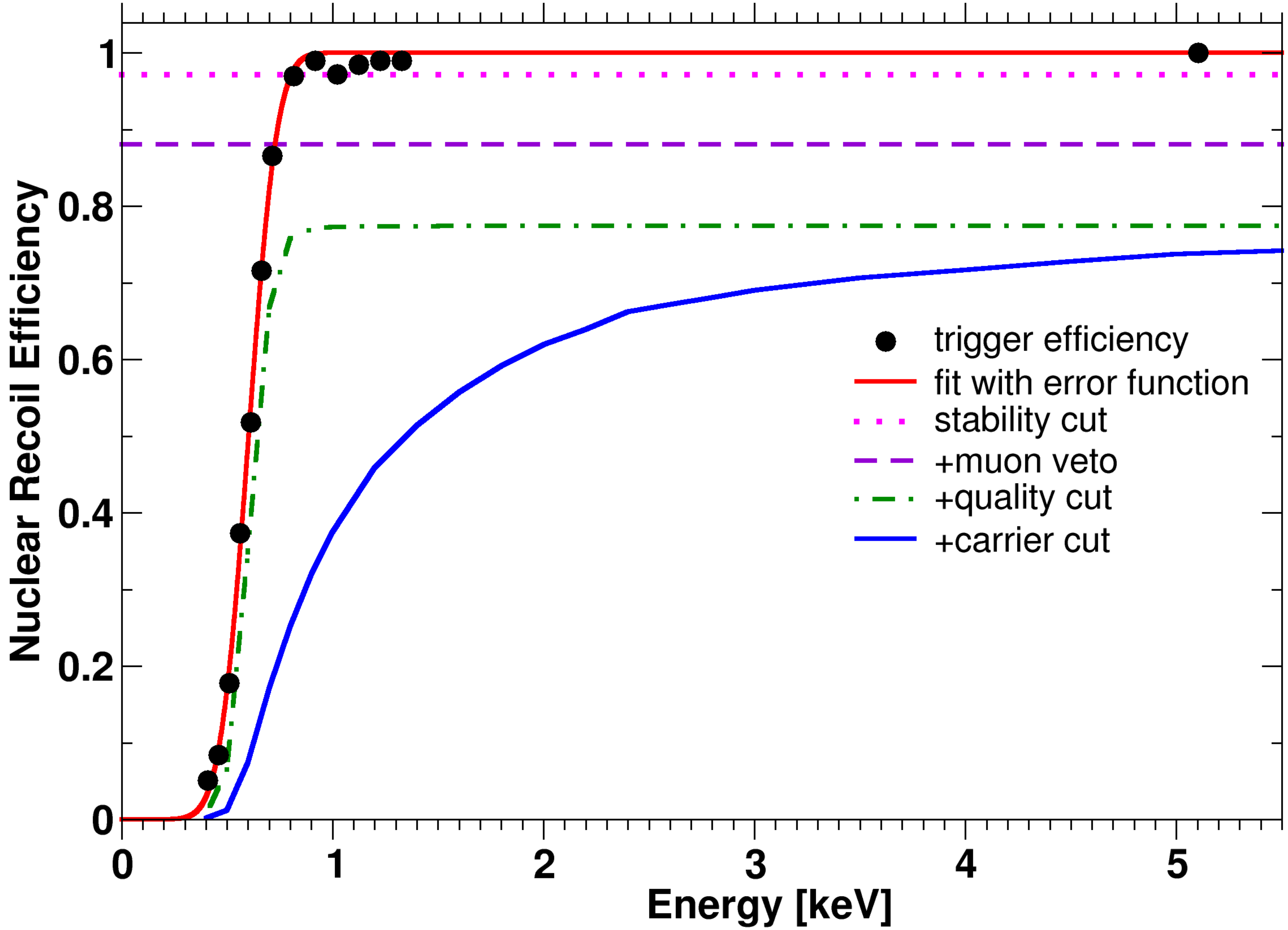
- **No surface backgrounds**
- **Best radiopurity** (≈ 3.5 / [kg keV day])
- **Low trigger threshold** (≈ 0.60 keV)
- **High resolution** (σ ≈ 100 eV)



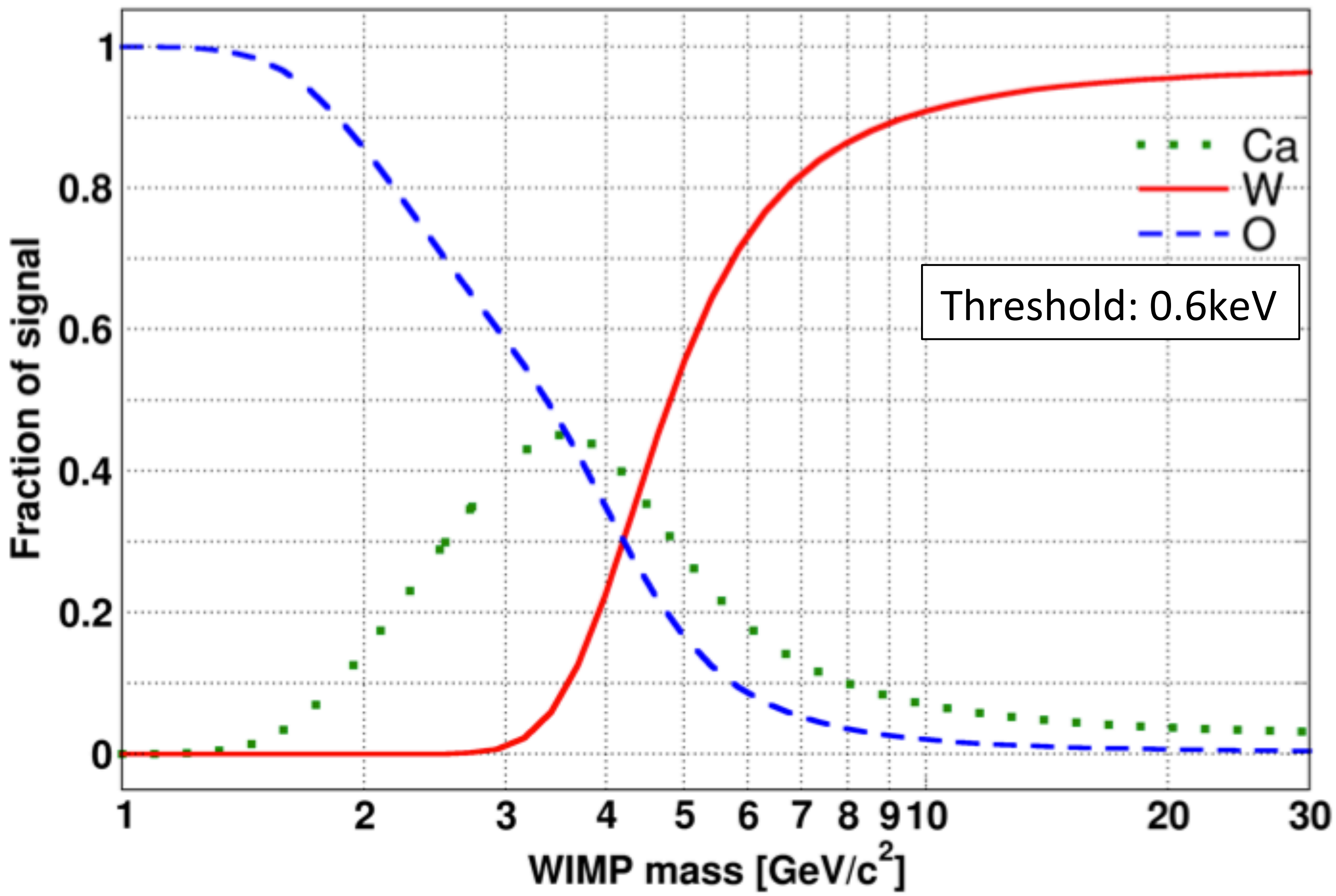
→**Low-threshold** Dark Matter analysis possible

→Use non-blinded dataset of 29kg-days

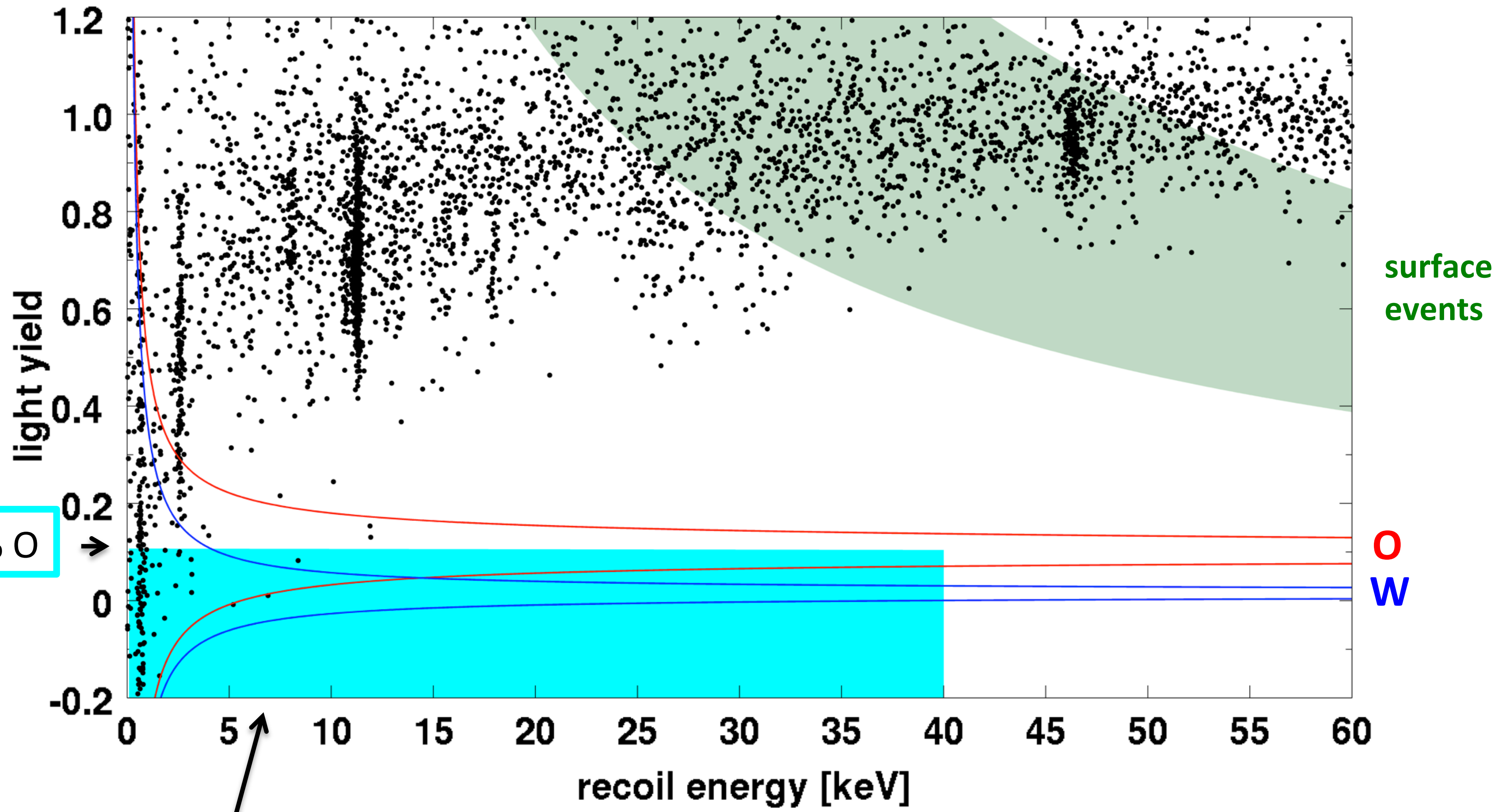
TUM-40: Acceptance at Lowest Energies



Fraction of WIMP Scatters on O, Ca and W



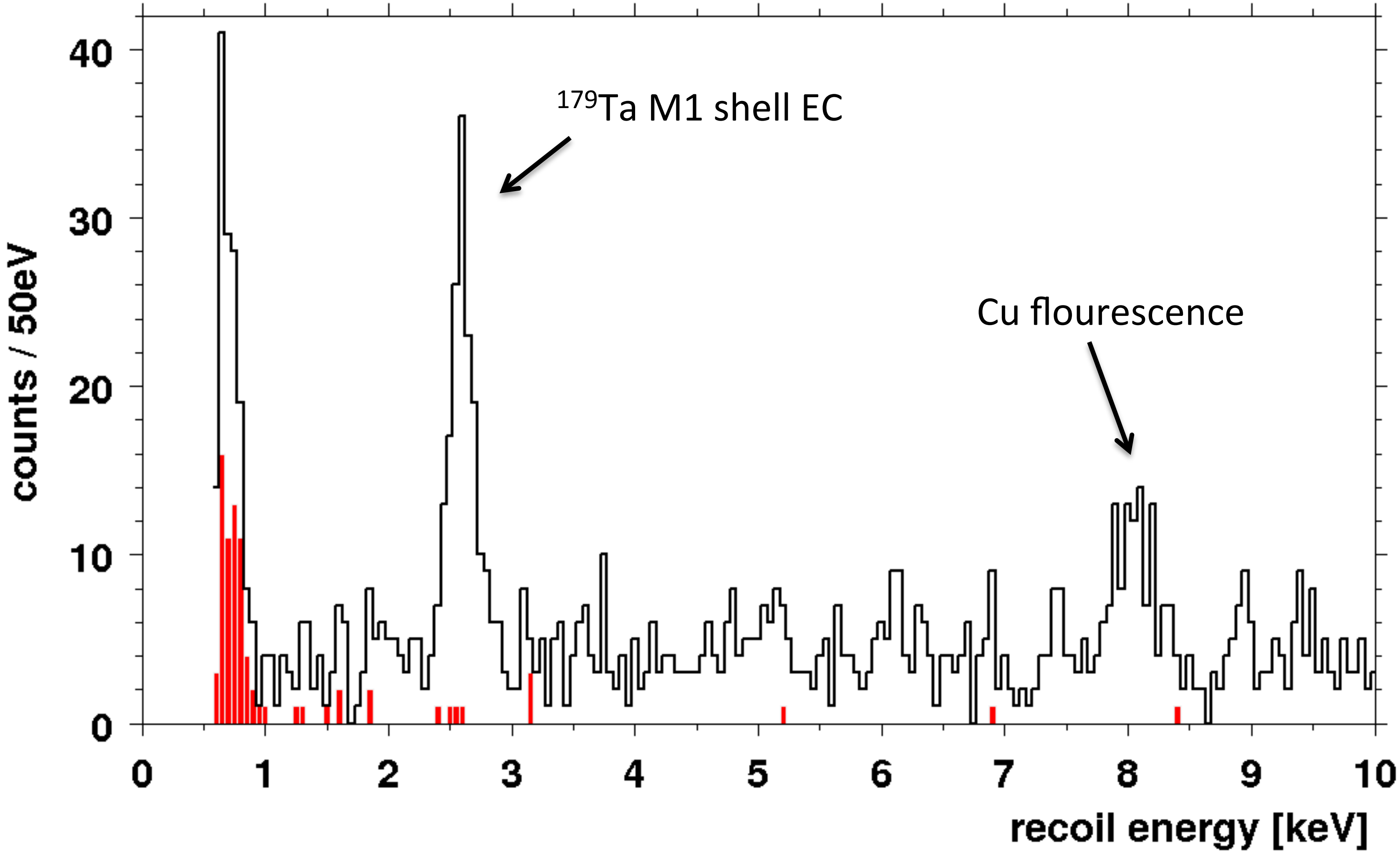
WIMP-Acceptance Region



50% O

acceptance region (E_r = 0.6 - 40keV)

Events in Acceptance Region



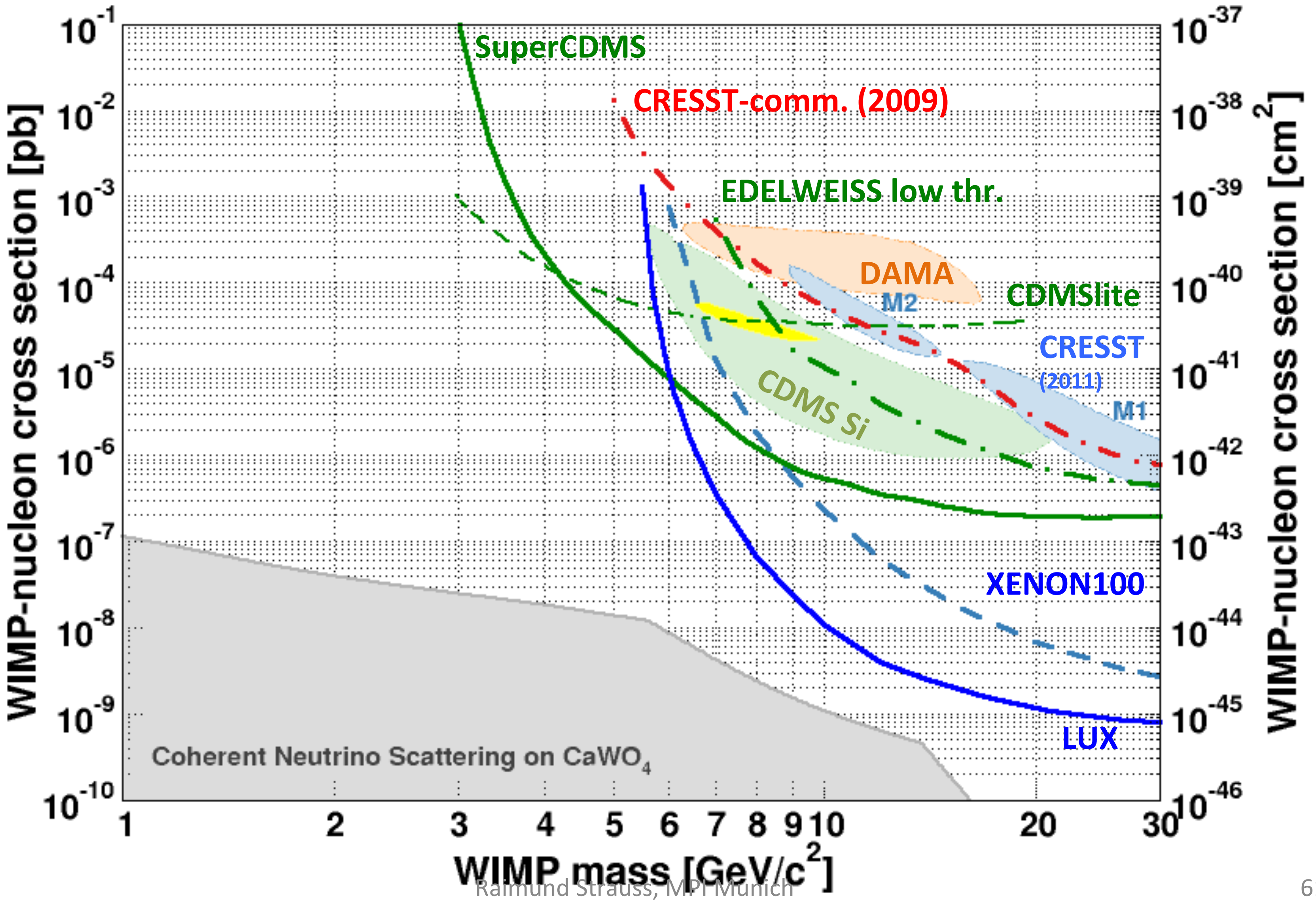
All 79 events accepted are conservatively considered as WIMP scatters!

Analysis Details

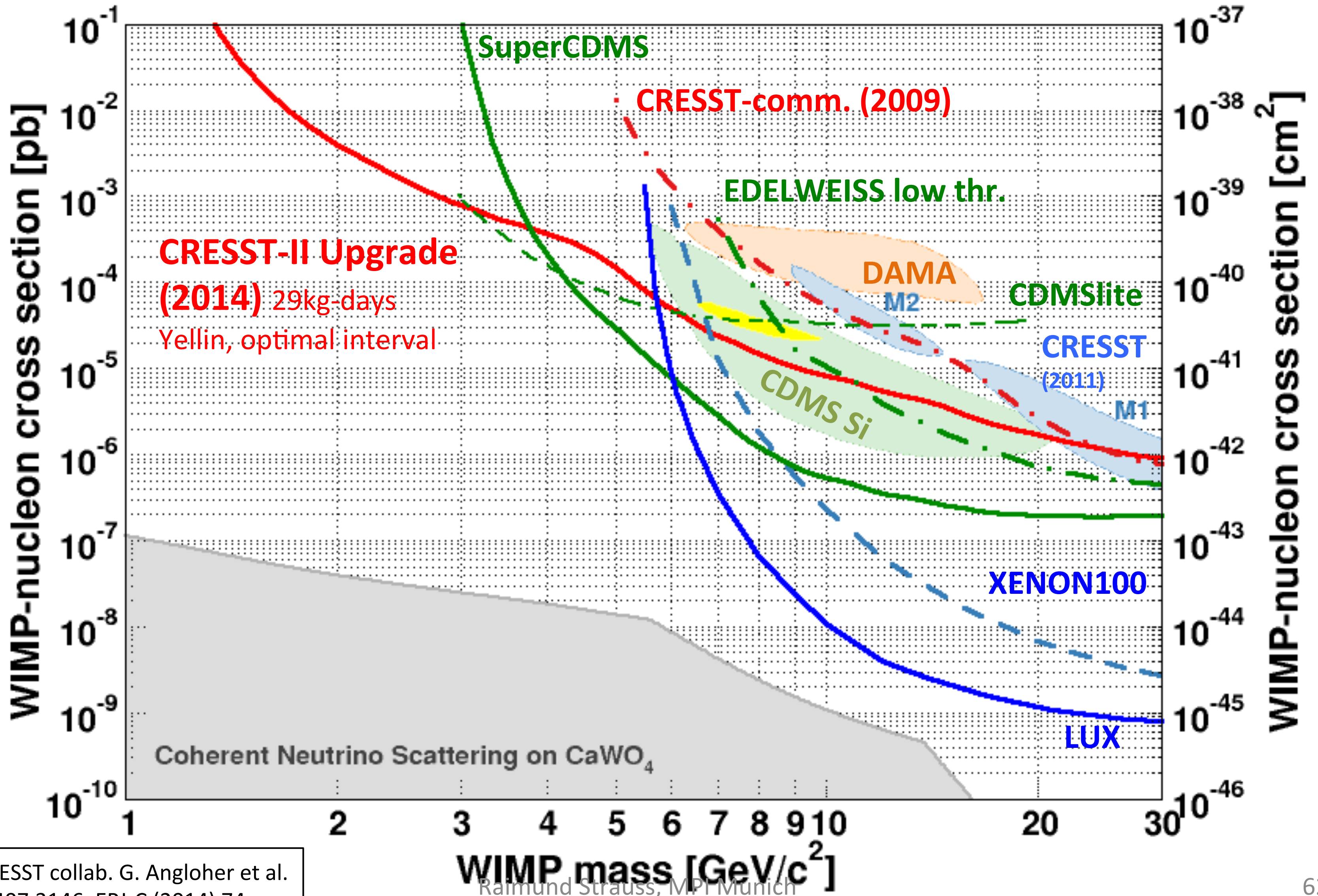
- 3 independent analysis chains (from raw data to final results)
- 3 different software environments

- All events conservatively treated as WIMP scatters
- Yellin optimal-interval method used to derive an upper limit

2014 WIMP Landscape



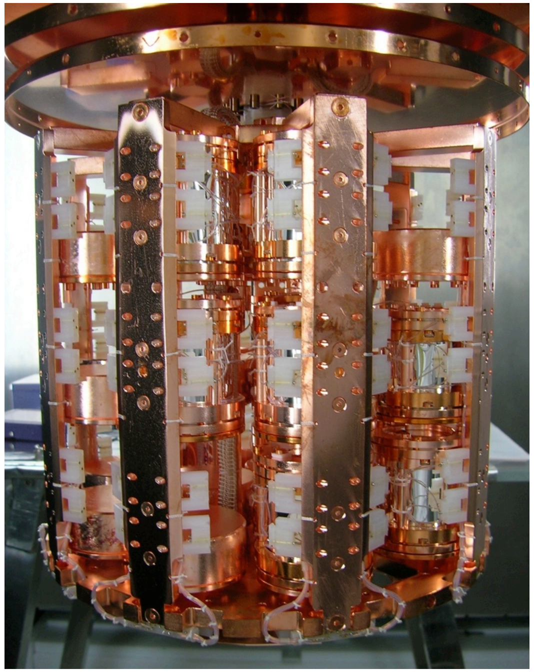
Status 2014: Results from TUM-40

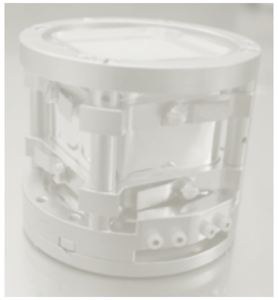


See: CRESST collab. G. Angloher et al. arXiv:1407.3146, EPJ-C (2014) 74

Recently Finished – CRESST-II Phase 2

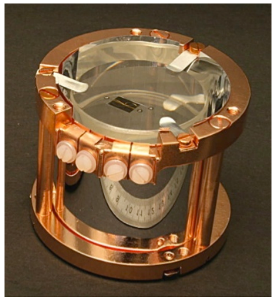
Data-taking from July 2013 to August 2015





2014 Results: "TUM-40"

- Efficient surface-event rejection
- Best intrinsic background level
- Best *overall* performance



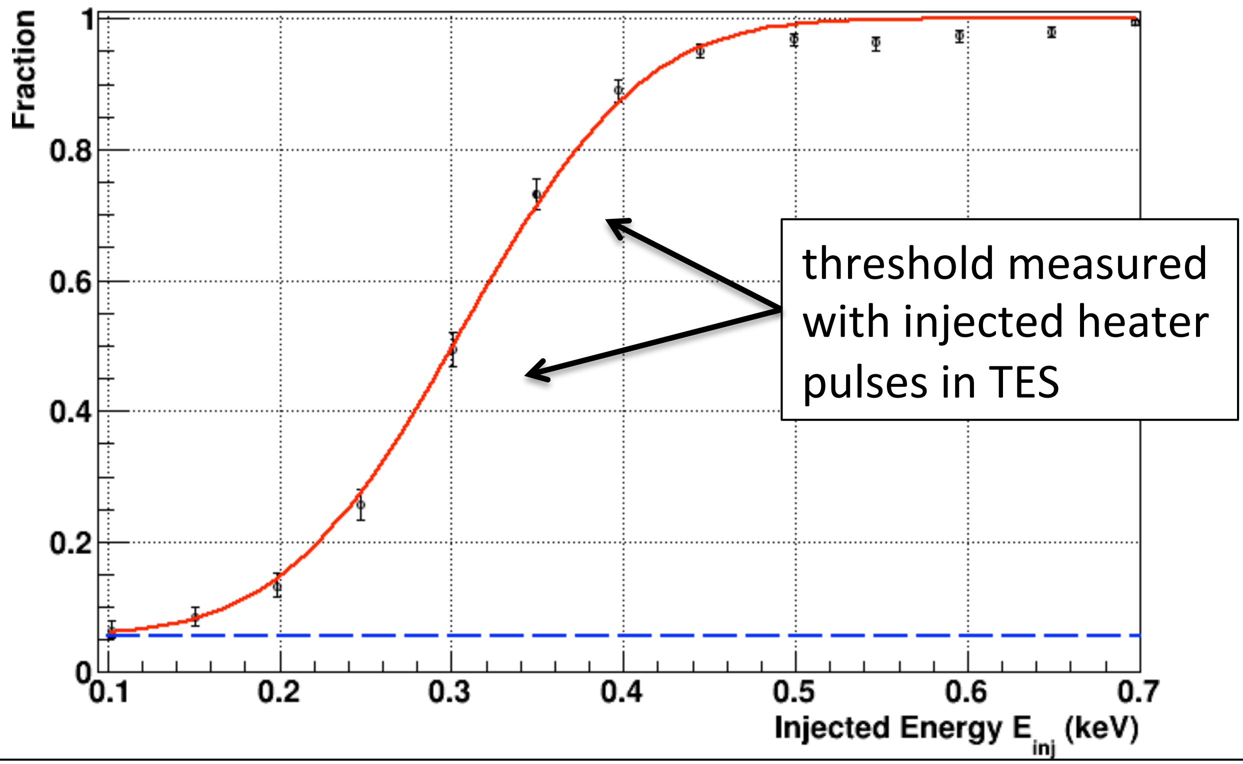
2015 Results: "Lise"

- Incomplete surface rejection
- Lowest threshold
- Factor ~2 higher background

Final Data: Total exposure

- About 500 kg-days acquired
- Data release end of 2015

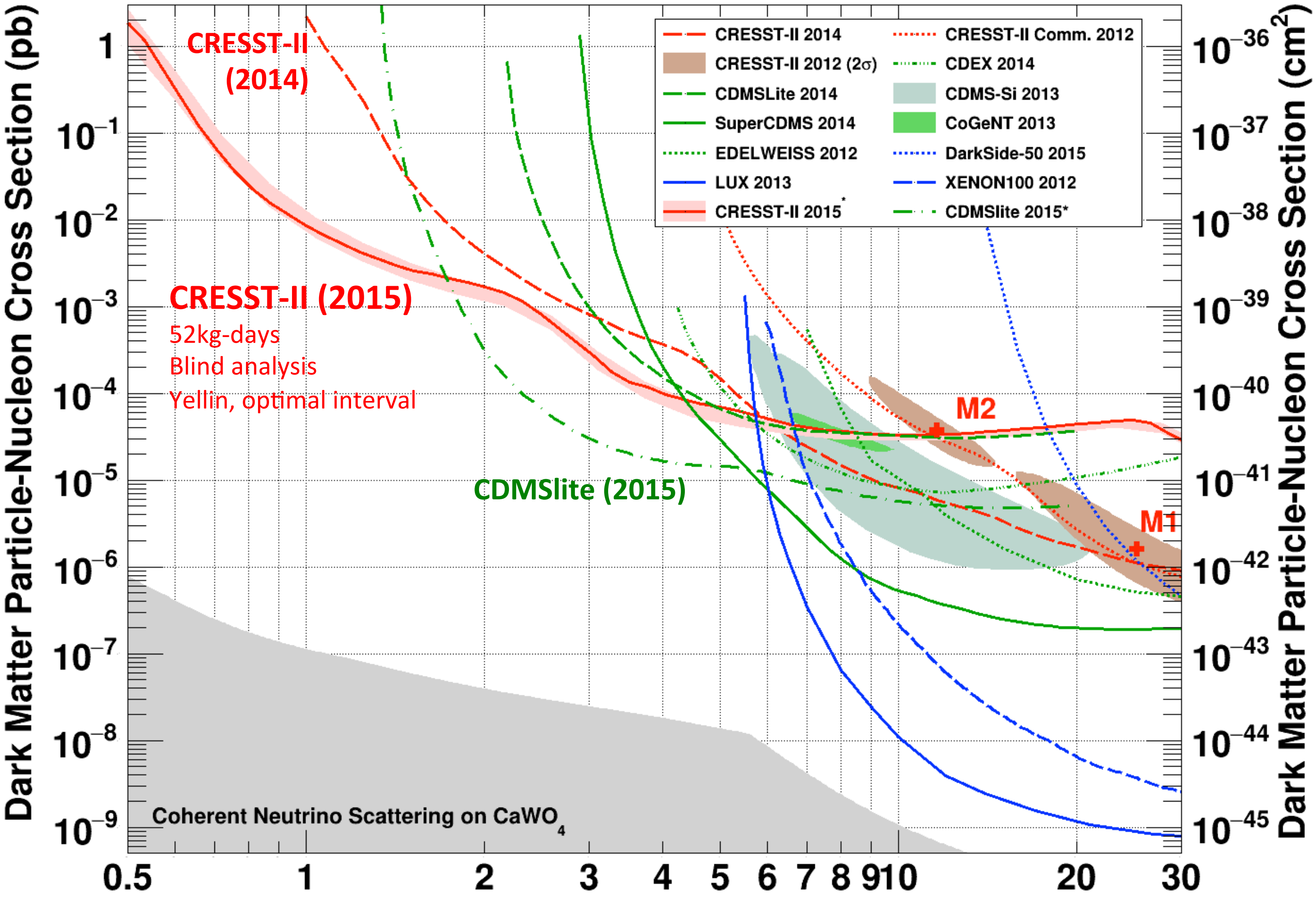
“Lise”: Trigger Threshold



Lowest trigger threshold among all Dark Matter searches!

Direct measurement of nuclear-recoil energy with calorimetric detector!

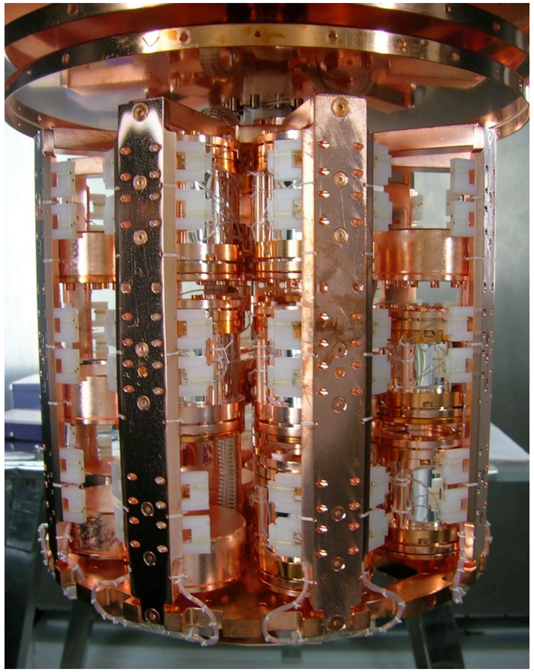
“Lise”: Results 2015

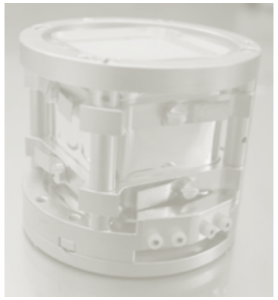


See: CRESST collab. G. Angloher et al. arXiv1509.01515

Recently Finished – CRESST-II Phase 2

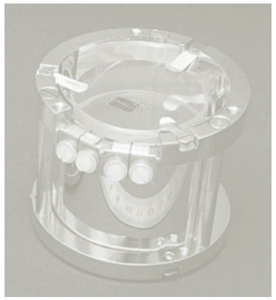
Data-taking from July 2013 to August 2015





2014 Results: "TUM-40"

- Efficient surface-event rejection
- Best intrinsic background level
- Best *overall* performance



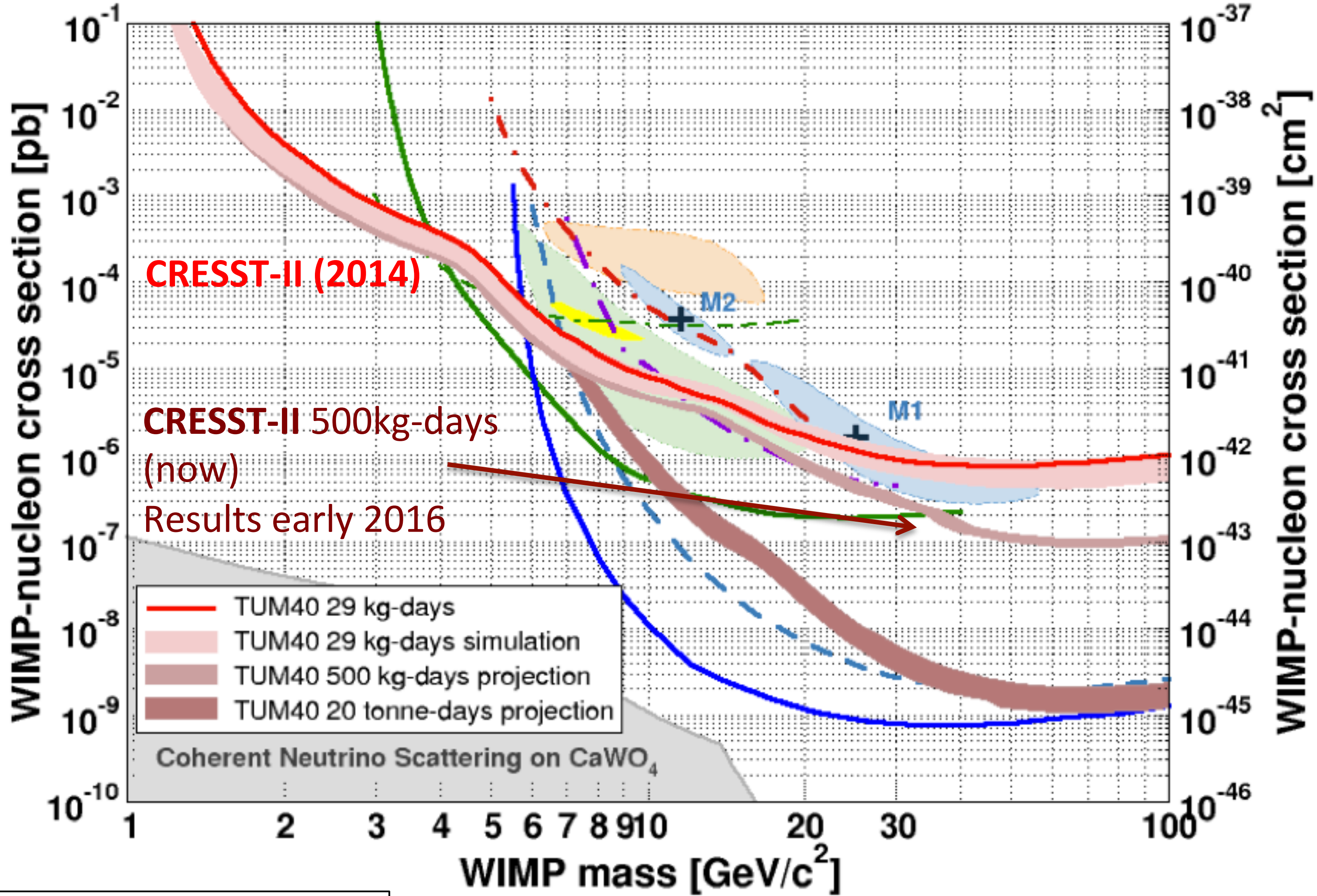
2015 Results: "Lise"

- No surface rejection
- Lowest threshold
- Factor ~2 more higher background

Final Data: Total exposure

- About 500 kg-days acquired
- Data release 2016

Final Data Release: Projections

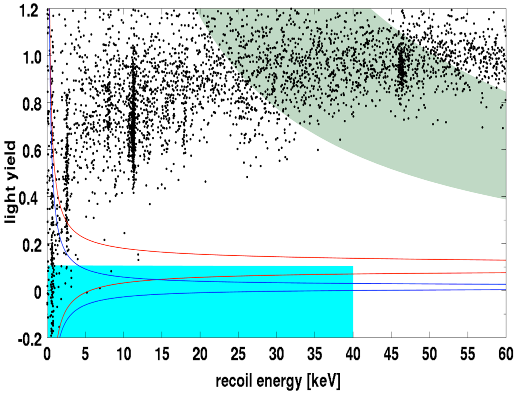


G. Angloher et al. arXiv:1503.08065

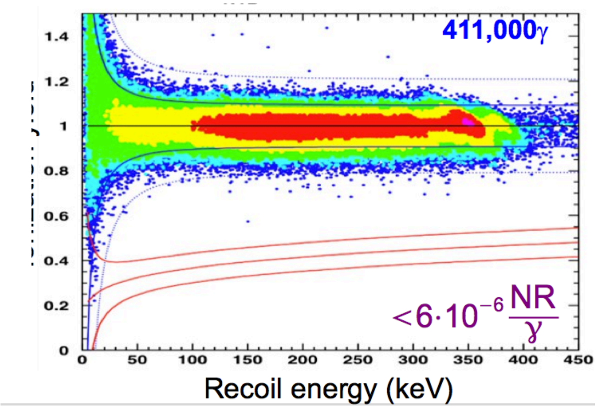
A Remark...

Search for standard (high-mass) WIMPs:

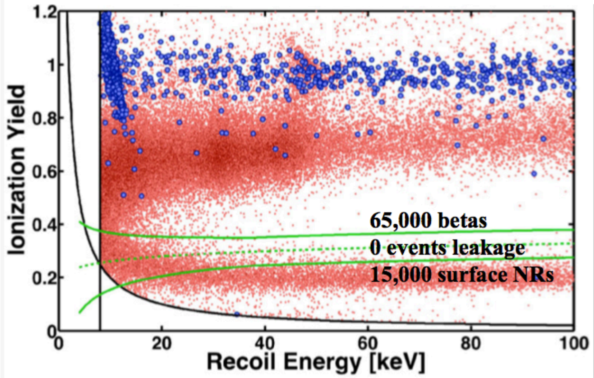
CRESST-II



EDELWEISS-III

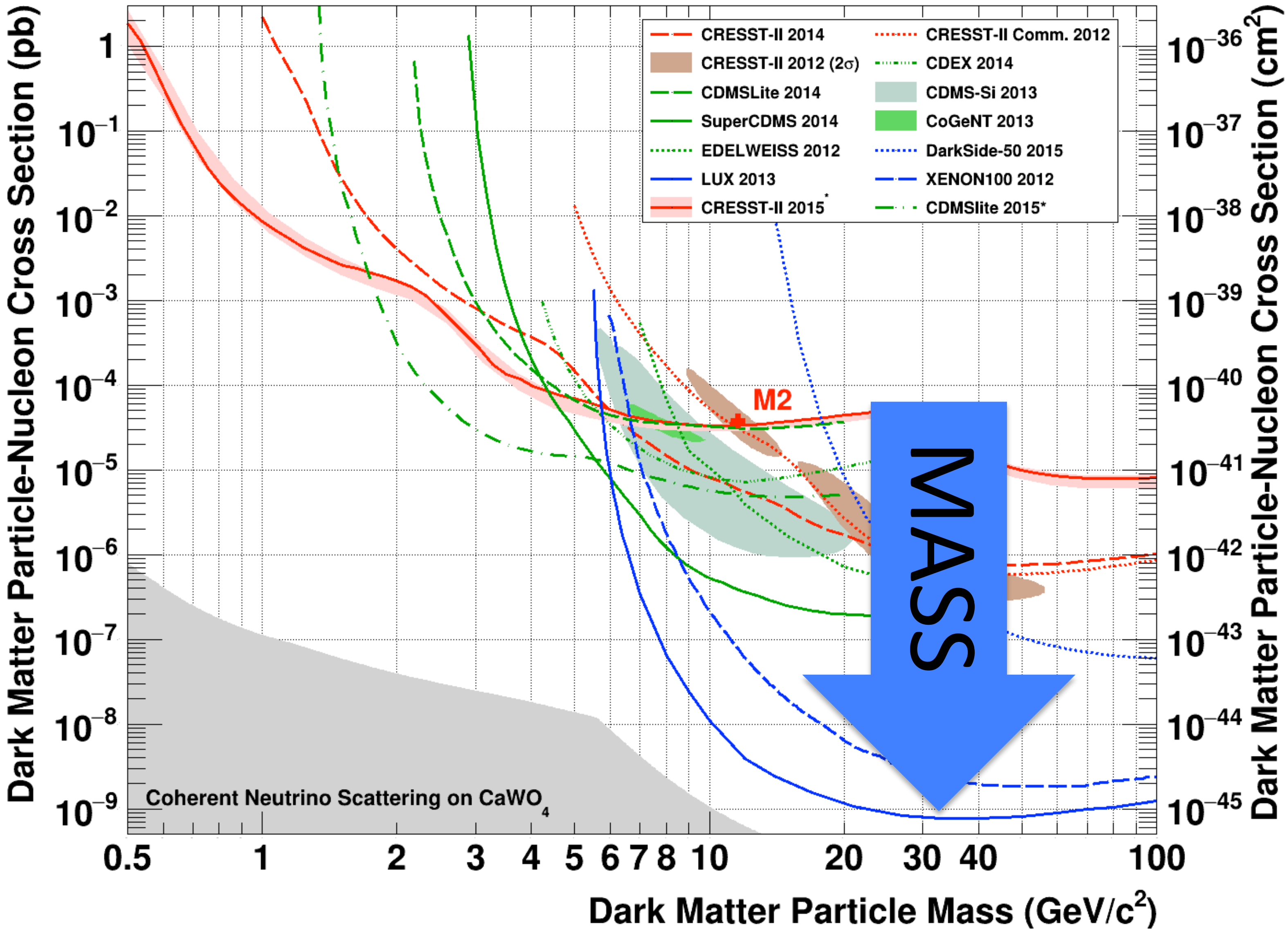


SuperCDMS

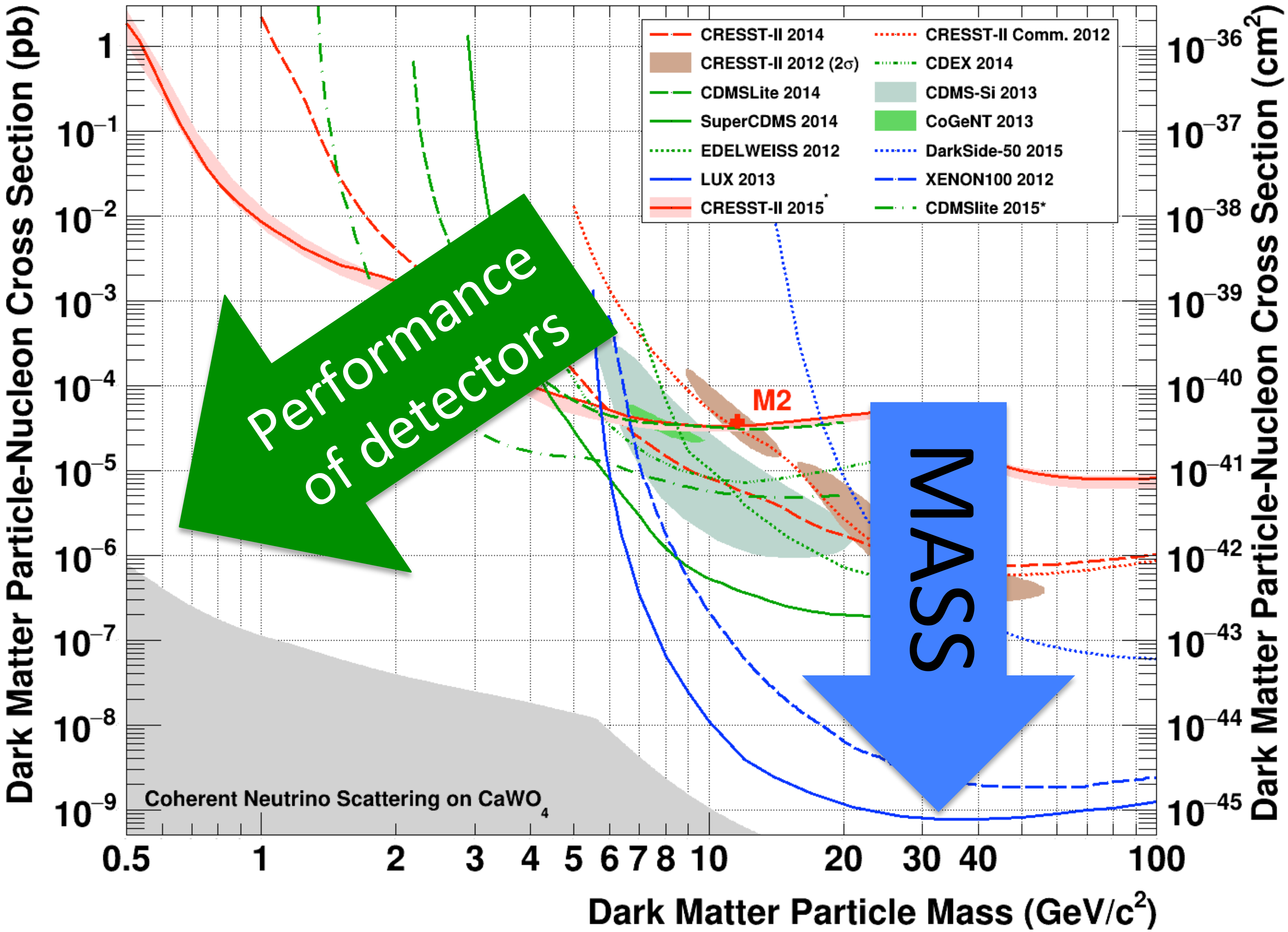


- background-free technology (above ~15keV)
- Ton scale feasible

Future of Dark Matter Searches



Future of Dark Matter Searches



NEAR FUTURE

CRESST III

CRESST-III: Low-Mass Dark Matter Search

Straight-forward approach for near future: **CRESST-III** Phase 1

Status quo

m = 250g
V = 32x32x40 mm^3

Phonon threshold: $E_{th} \lesssim 500eV$

Light-detector res.: $\sigma \approx 5$ eV

CRESST-III: Low-Mass Dark Matter Search

Straight-forward approach for near future: **CRESST-III** Phase 1

Status quo

m = 250g
V = 32x32x40 mm^3

m=24g

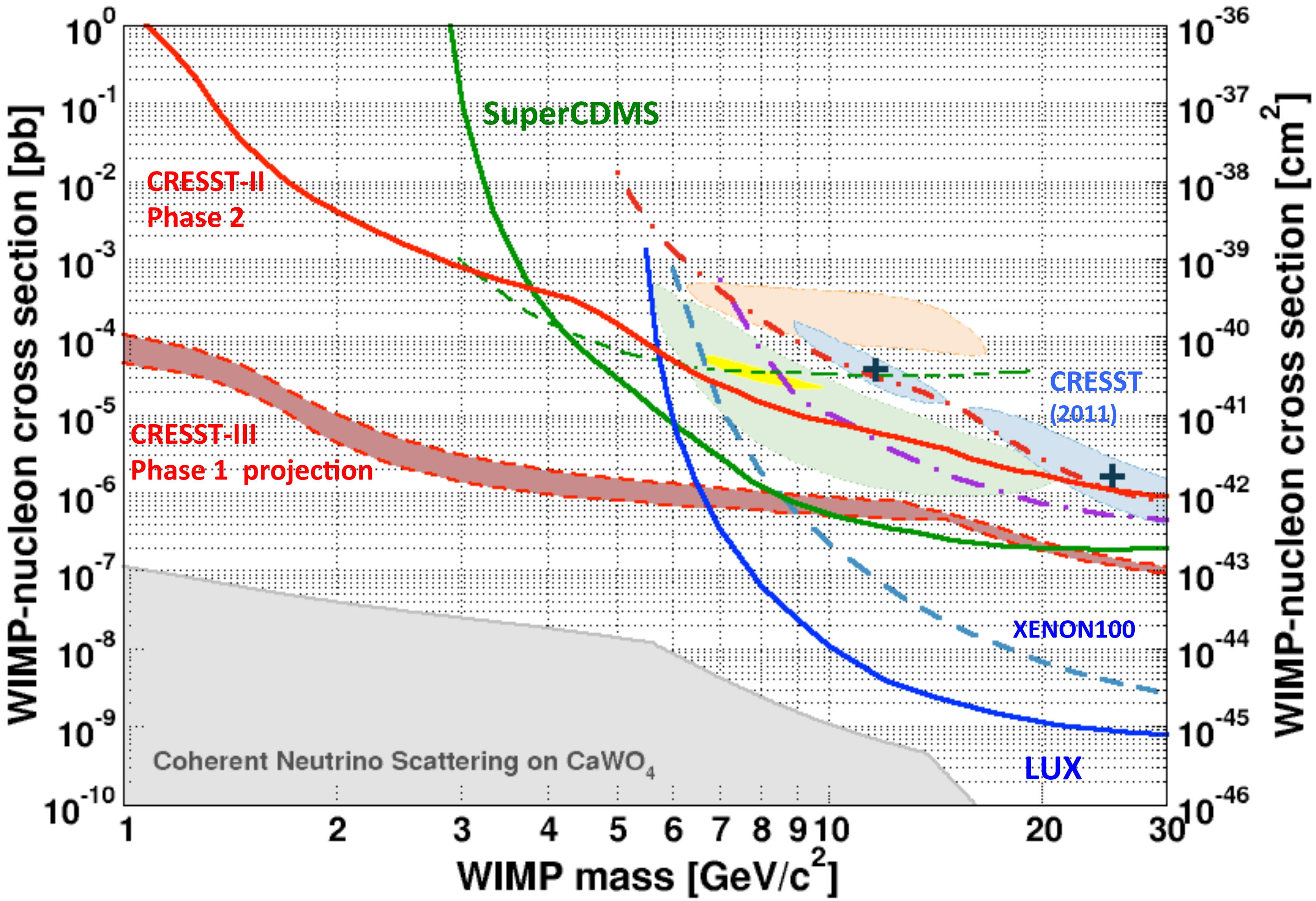
Phonon threshold: $E_{th} \lesssim 500eV$ **improvement by a factor of 5-10**

Light-detector res.: $\sigma \approx 5$ eV **improvement by a factor of 2**

CRESST-III Phase 1

Assumptions:

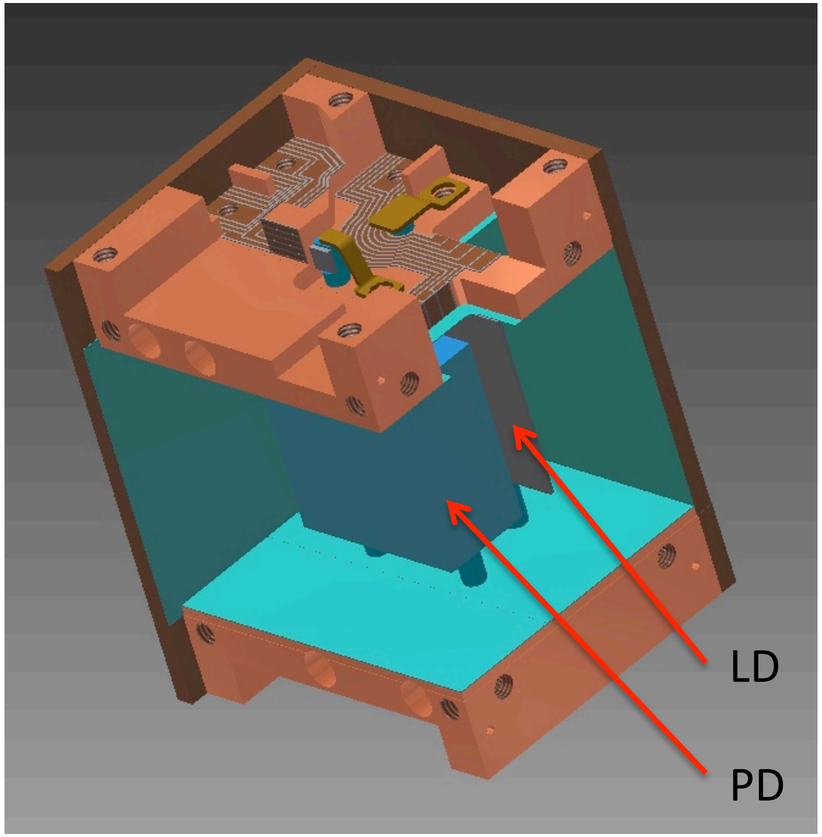
- 24g $CaWO_4$ crystal
- **E_{th} = 100eV**
- Light detector improved by factor 2 (due to smaller volume)
- 2x more detected light: due to thin crystal
- **CRESST-II radiopurity**

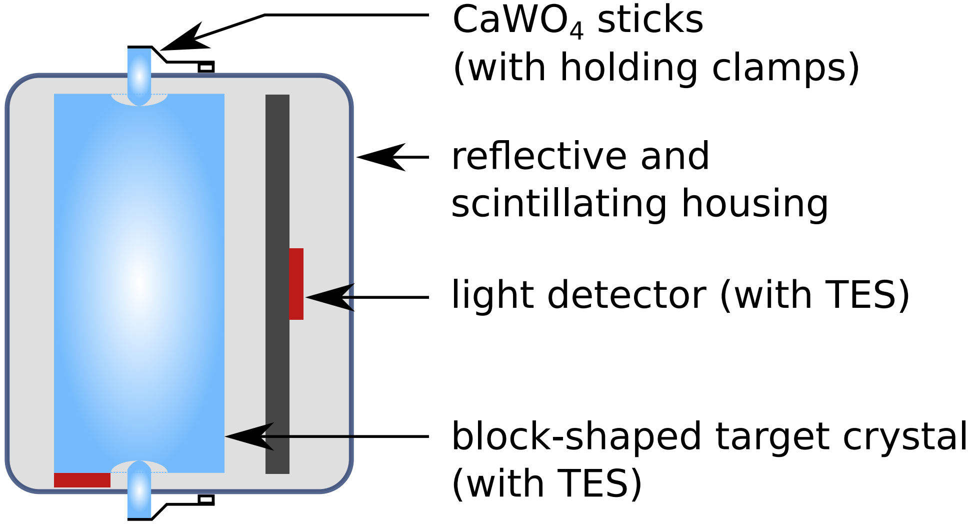


10 x 24g detectors operated for one year ≈ **50 kg-days** (net)

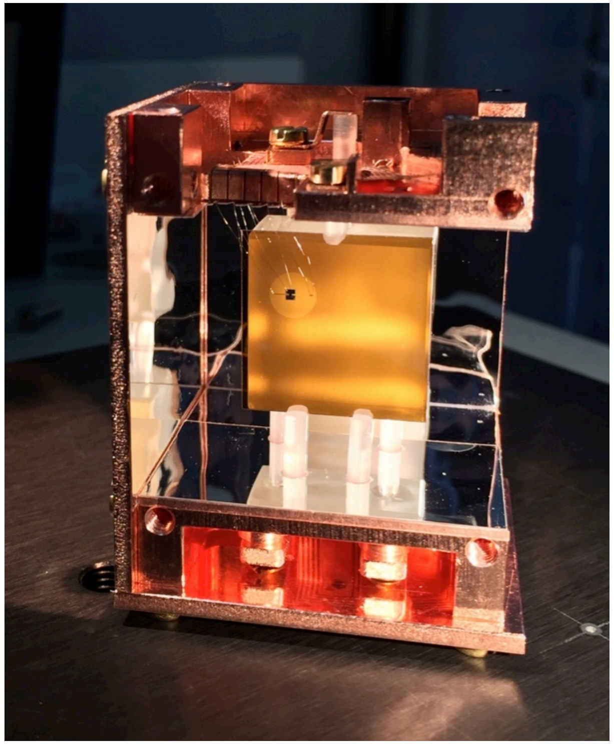
See: CRESST collab. G. Angloher et al. arXiv:1503.08065

CRESST-III Detector Prototype

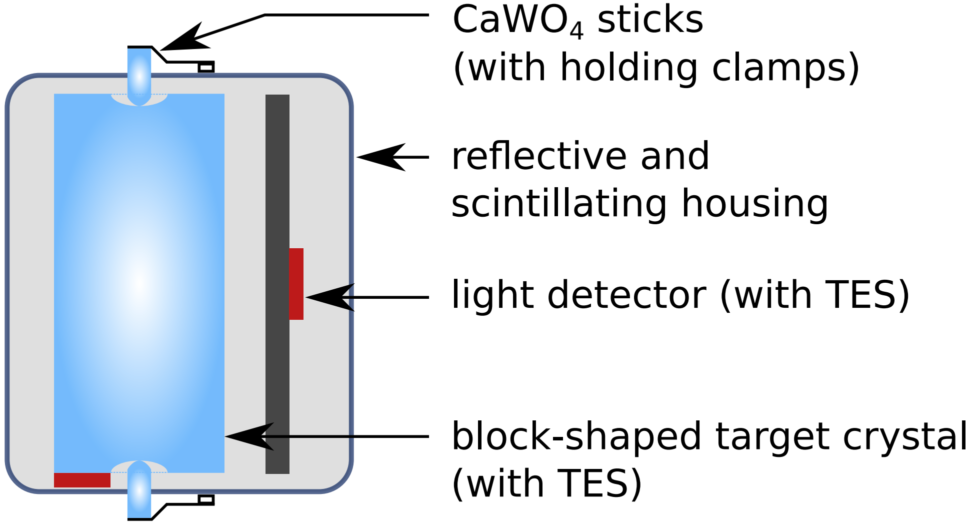




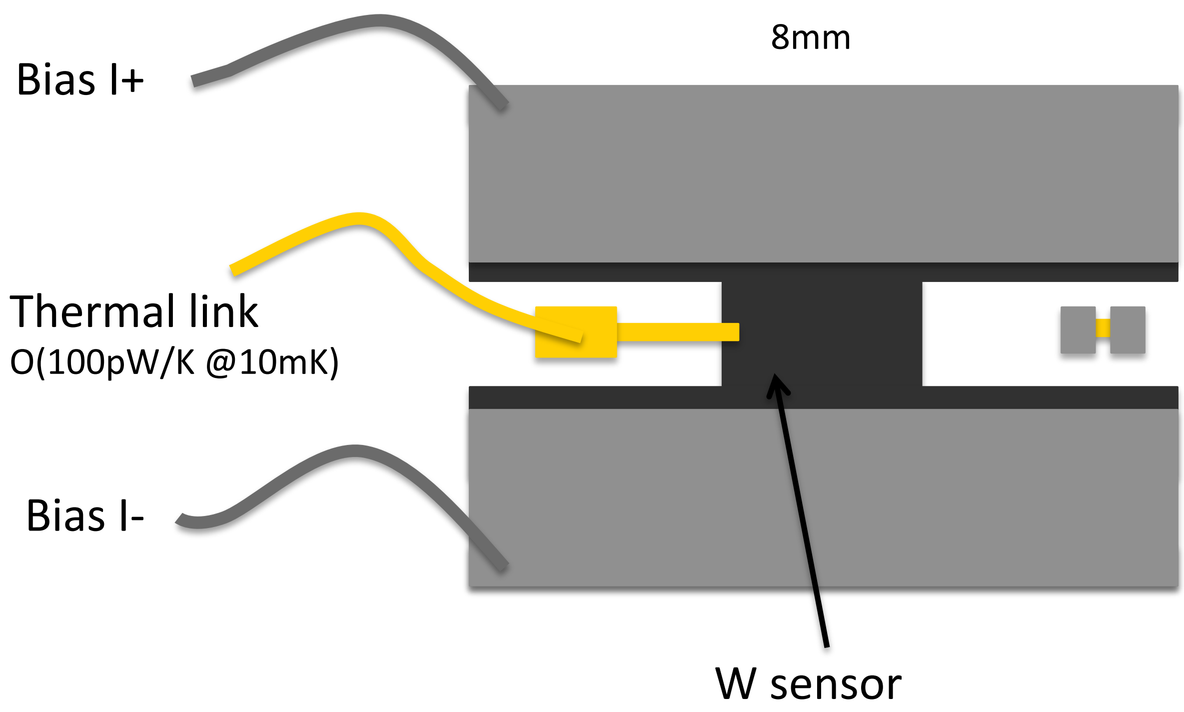
CRESST-III Detector Prototype



First modules ready



TES Design: Crucial for Energy Threshold

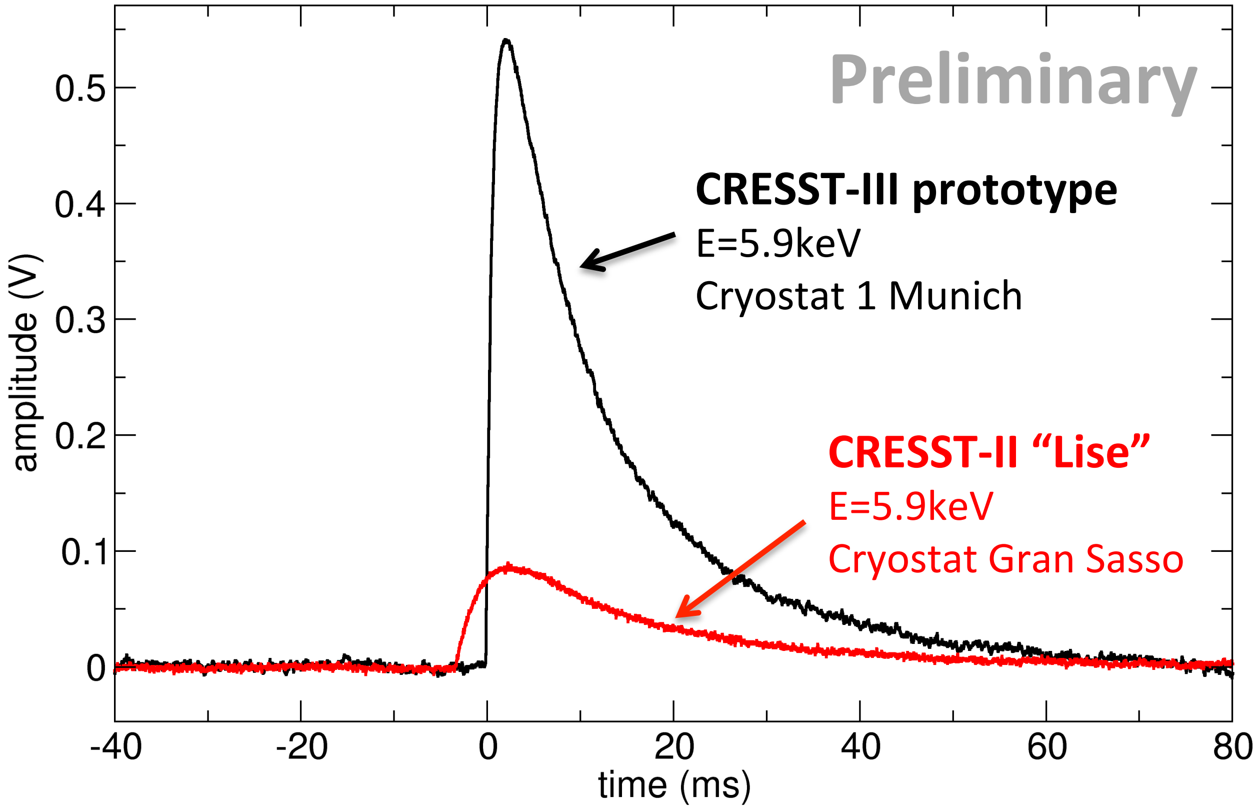


New TES design for 24g crystals:

- **calorimetric** operation
- Similar to CRESST light detector
- W film: 8 times smaller
- weak thermal coupling to bath
- large-area Al phonon collectors

Theoretical improvement: factor **10** in signal/noise

First Results of CRESST-III Detector



<u>Promising results:</u>

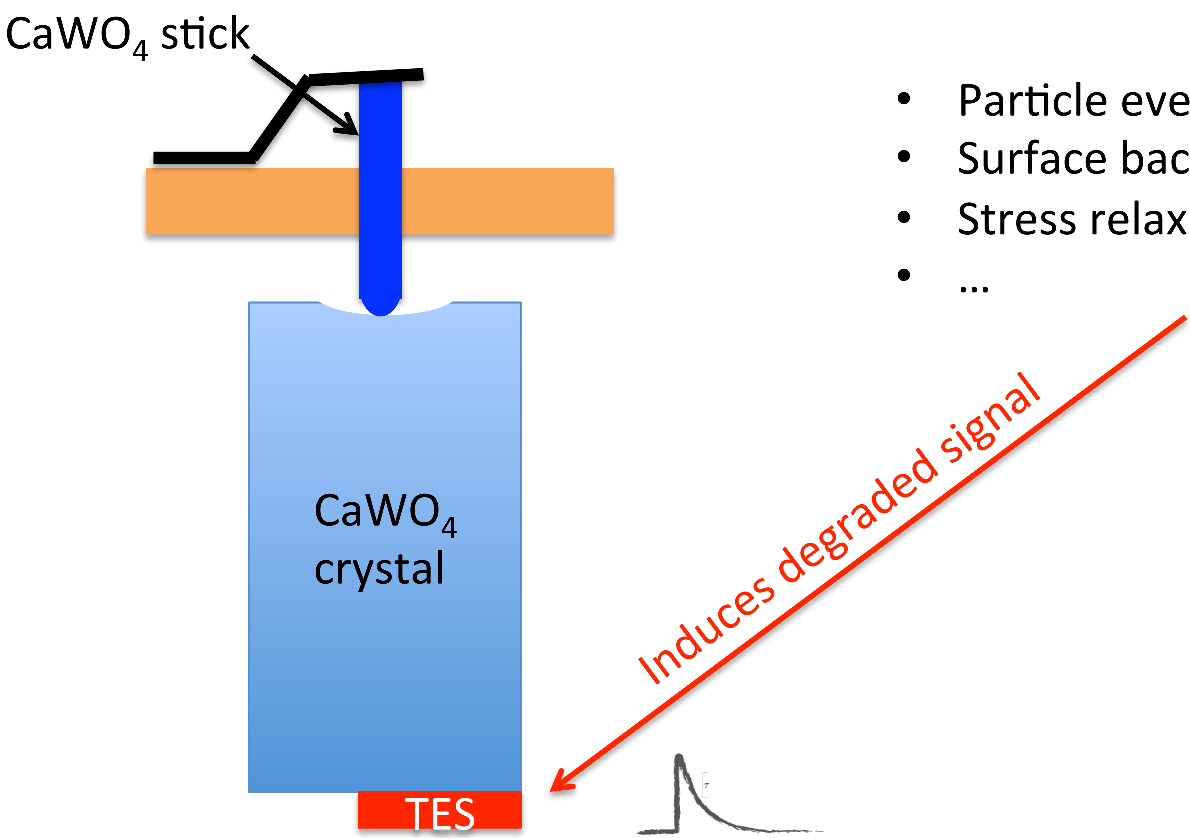
Improvement by **factor 6.2** compared to best CRESST-II detector (E_{th} = 298eV)

→ Baseline noise @GS 1.8-3.0mV RMS

→ **Threshold:** $\mathbf{E_{th}}$**= 45-60eV**

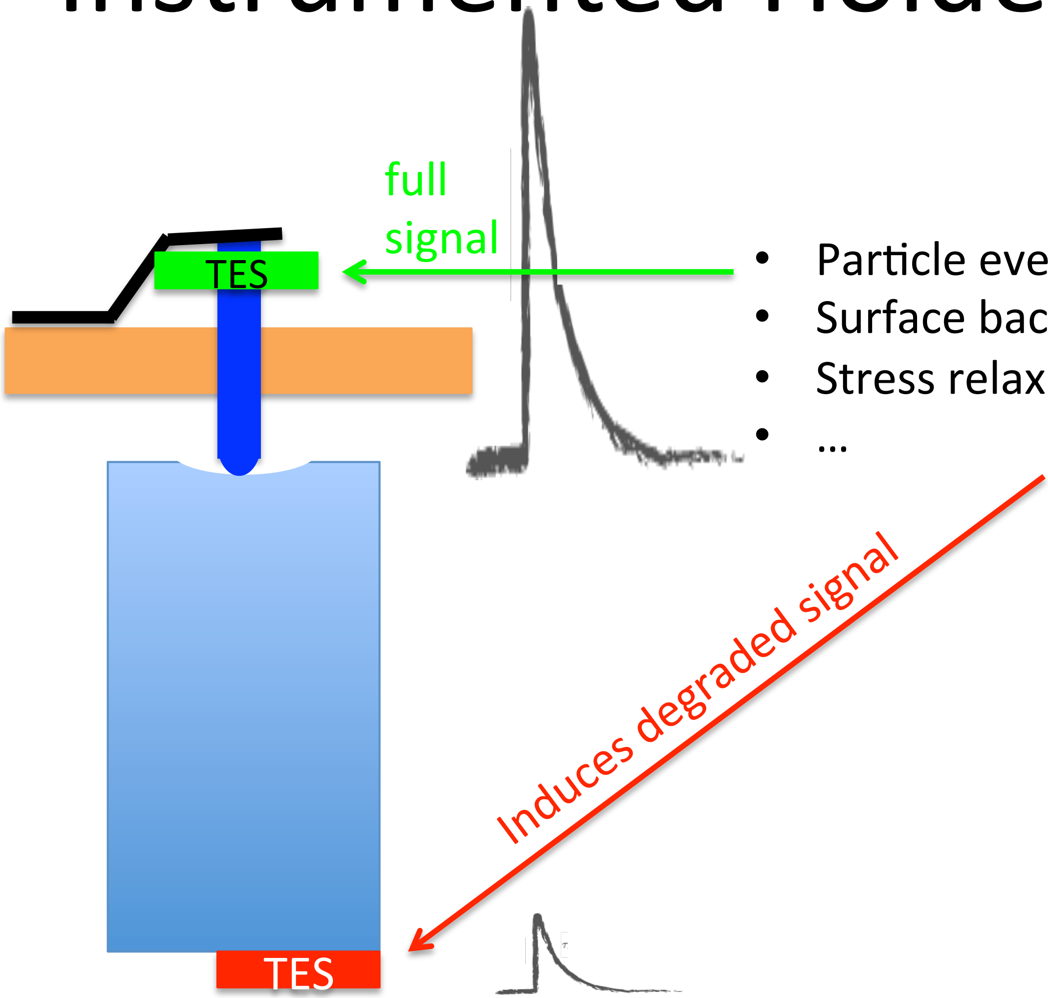
Design goal (E_{th}=100eV) for **CRESST-III** Phase 1 exceeded!

Instrumented Holder - iSticks



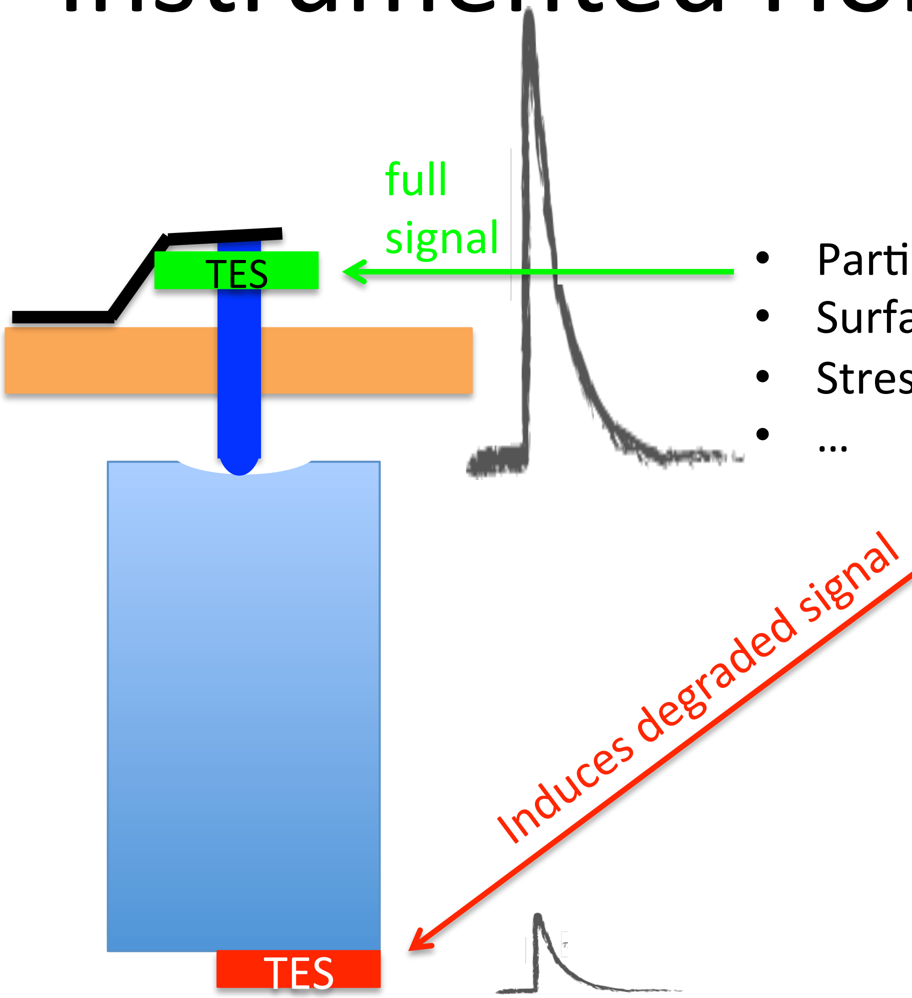
- Particle events in sticks
- Surface backgrounds
- Stress relaxations
- …

Instrumented Holder - iSticks



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

Instrumented Holder - iSticks

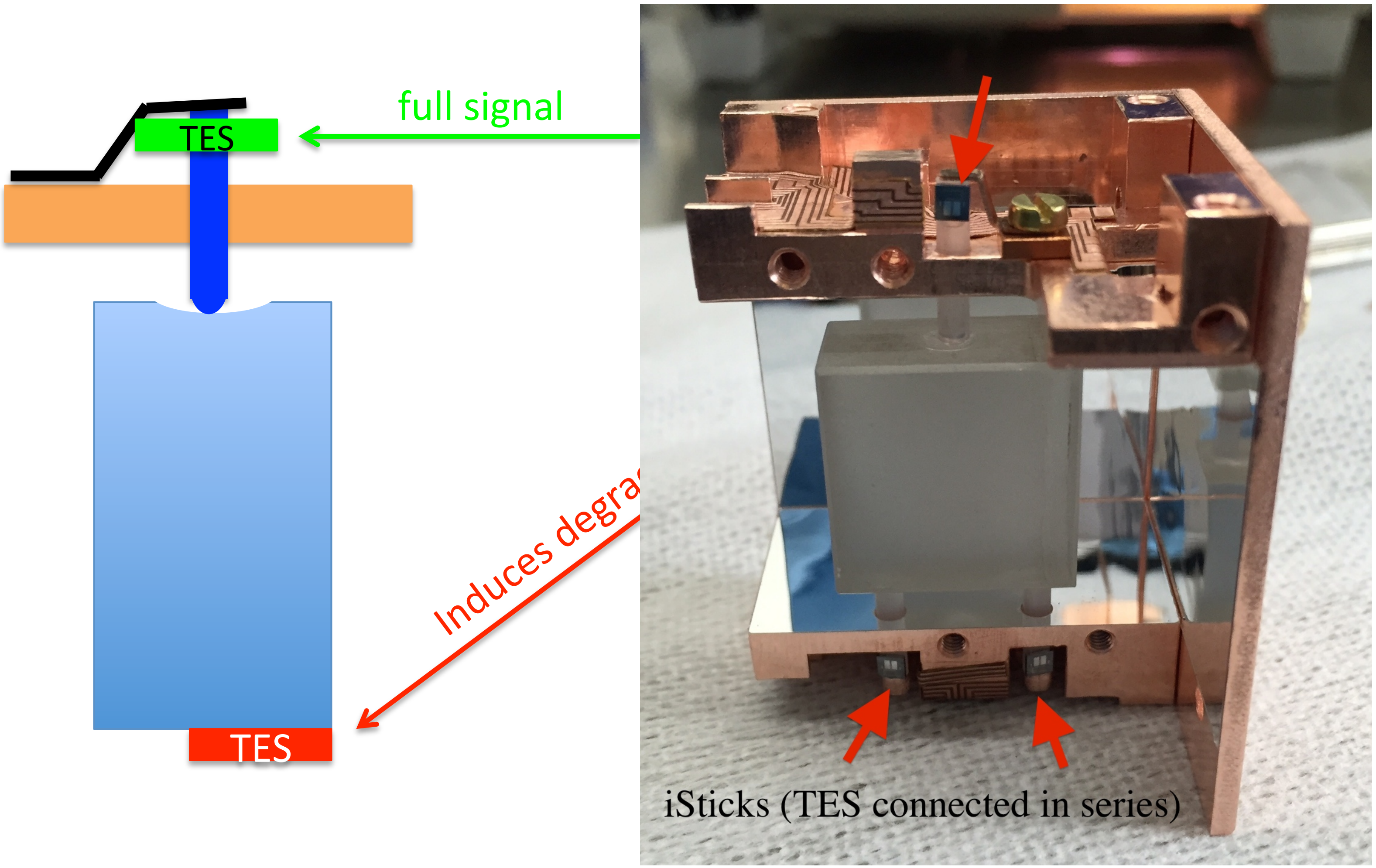


- Particle events in sticks
- Surface backgrounds
- Stress relaxations
- …

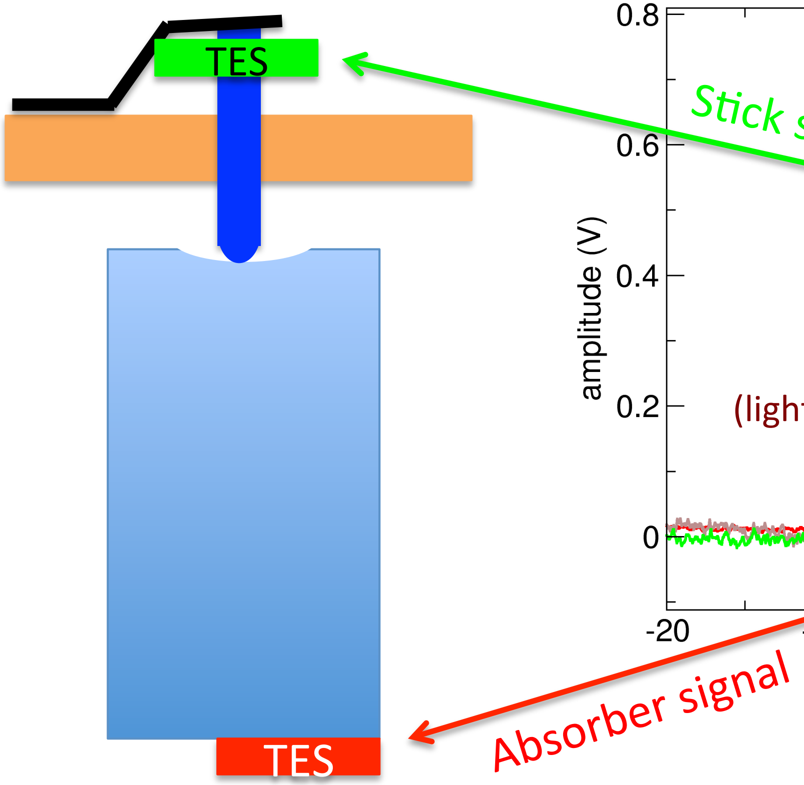
ratio $\frac{\text{stick}}{\text{absorber}}$

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

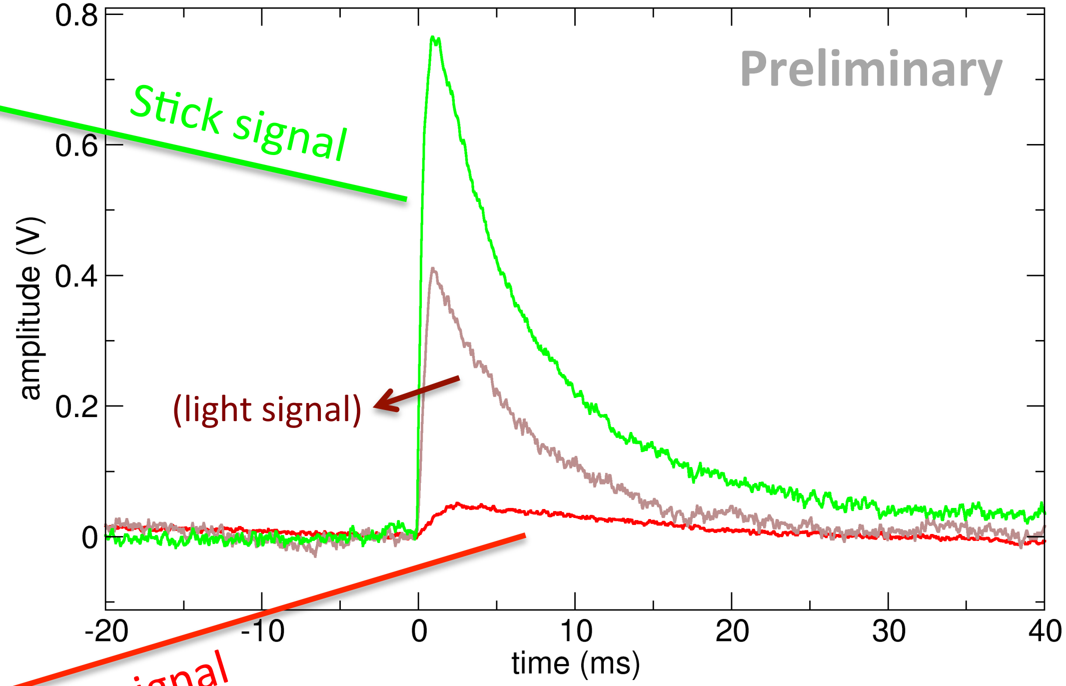
Instrumented Holder - iSticks



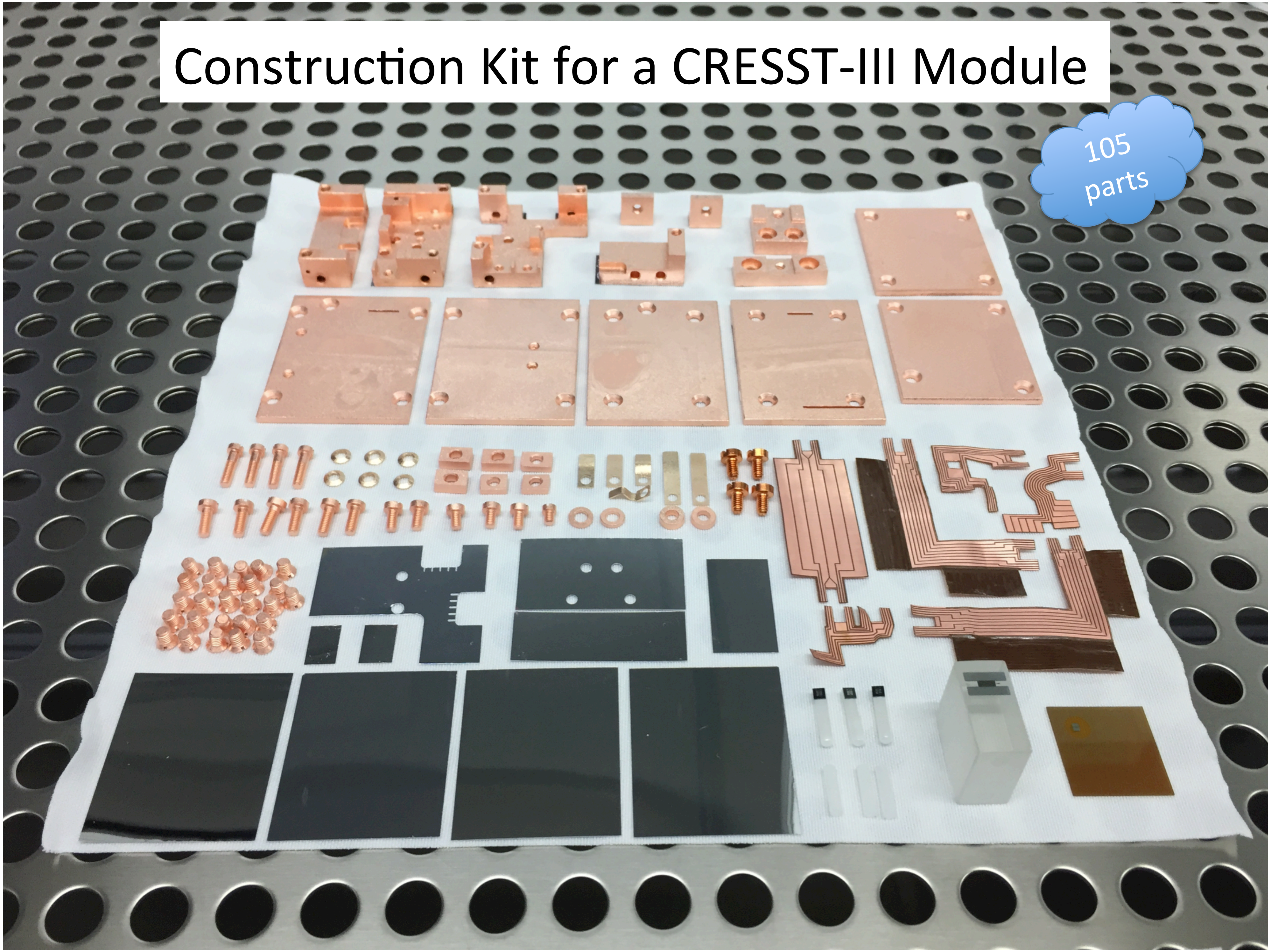
Instrumented Holder - iSticks



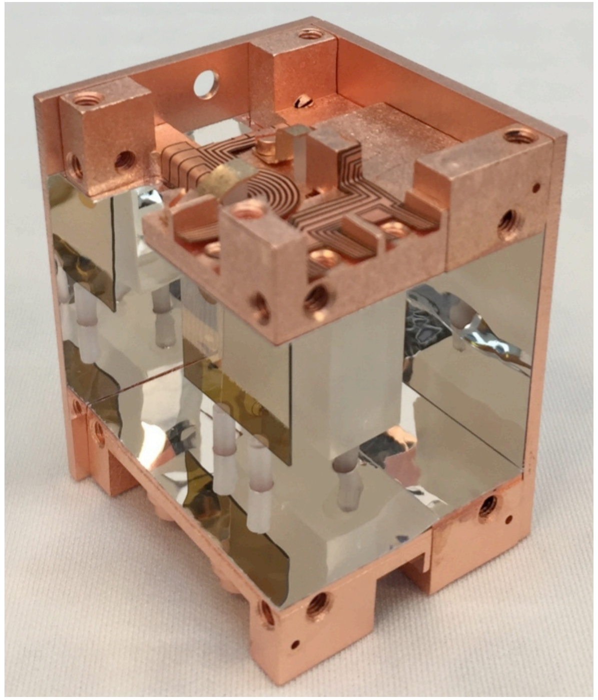
Gamma event of ≈40keV in stick

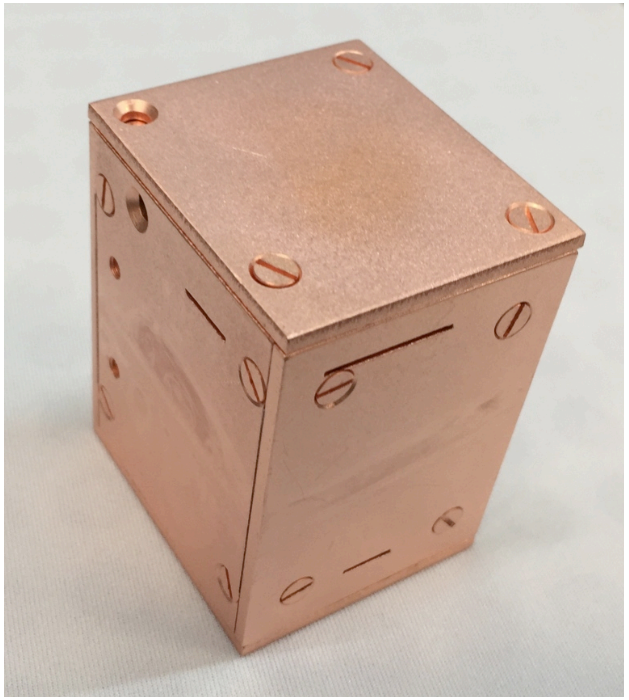


Construction Kit for a CRESST-III Module



Assembly in Progress…

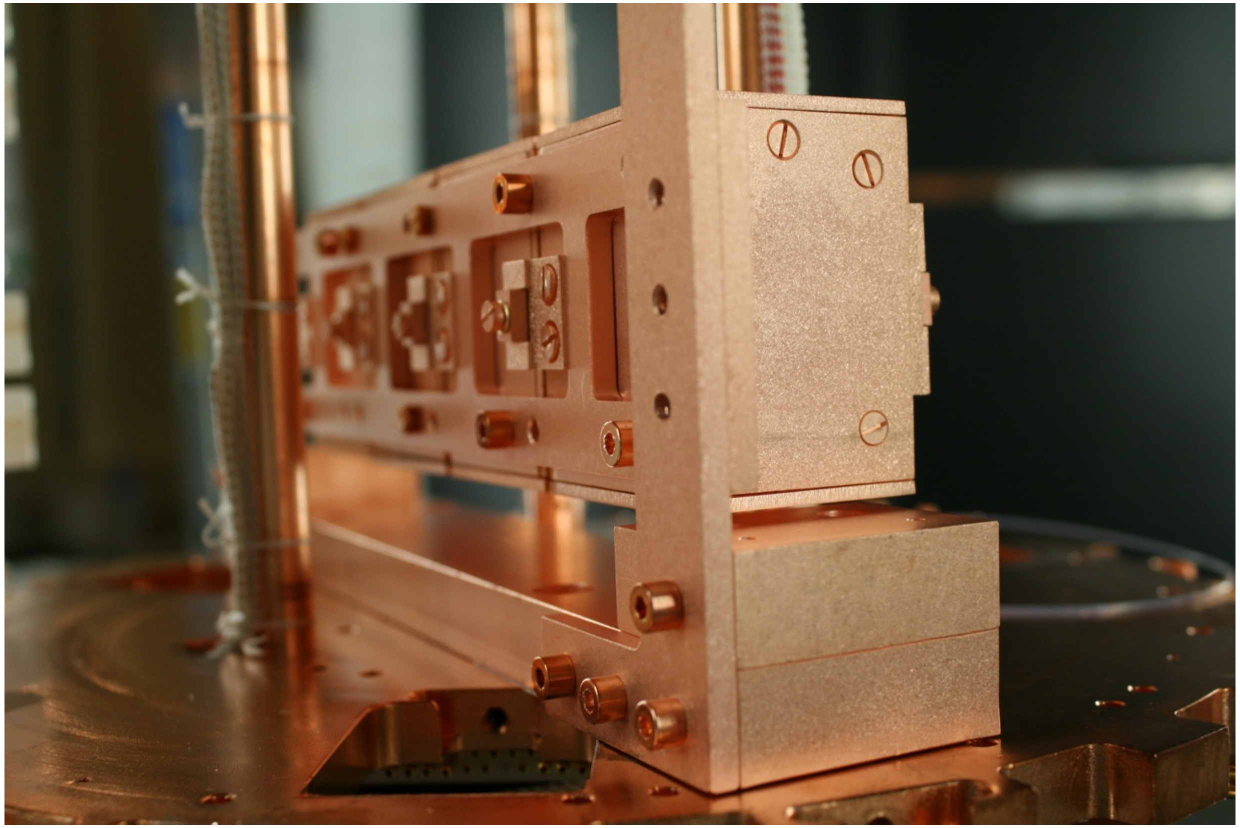




New dedicated cleanroom for CRESST-III at MPI Munich

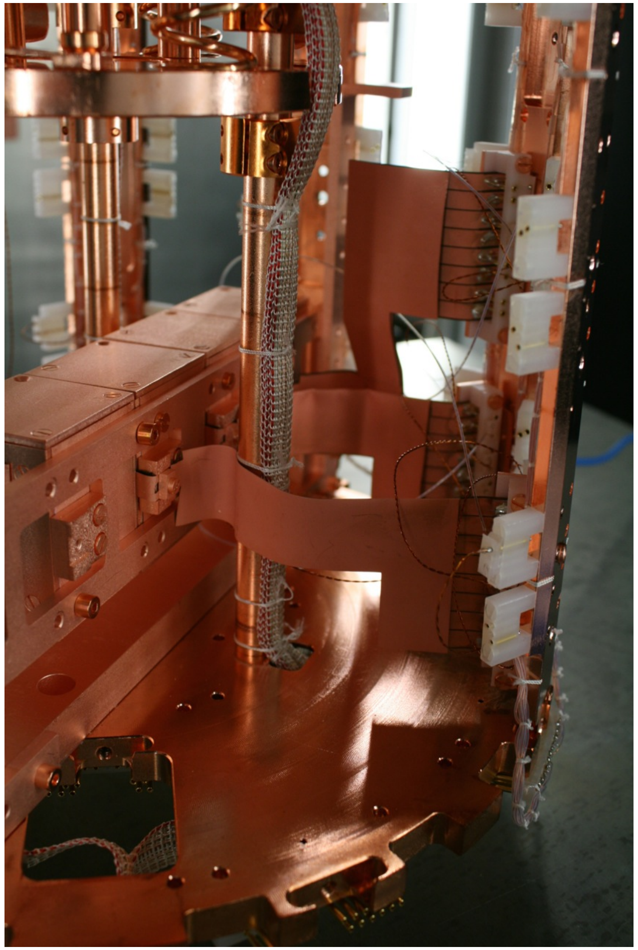
Very recently: first 5 module for CRESST-III phase 1 ready

Mounting at Gran Sasso – First Step Done



4 modules mounted in CRESST cryostat (last week!)

Mounting at Gran Sasso – First Step Done



New cabling scheme successfully tested!

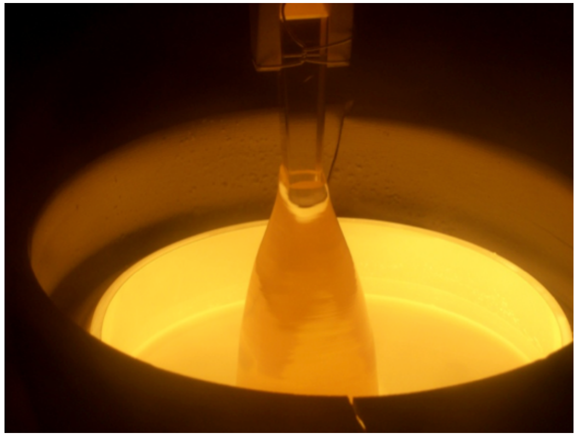
Final mounting: end of February

Start of measurement: mid of March

Future

CRESST-III PHASE 2

CRESST-III Phase 2



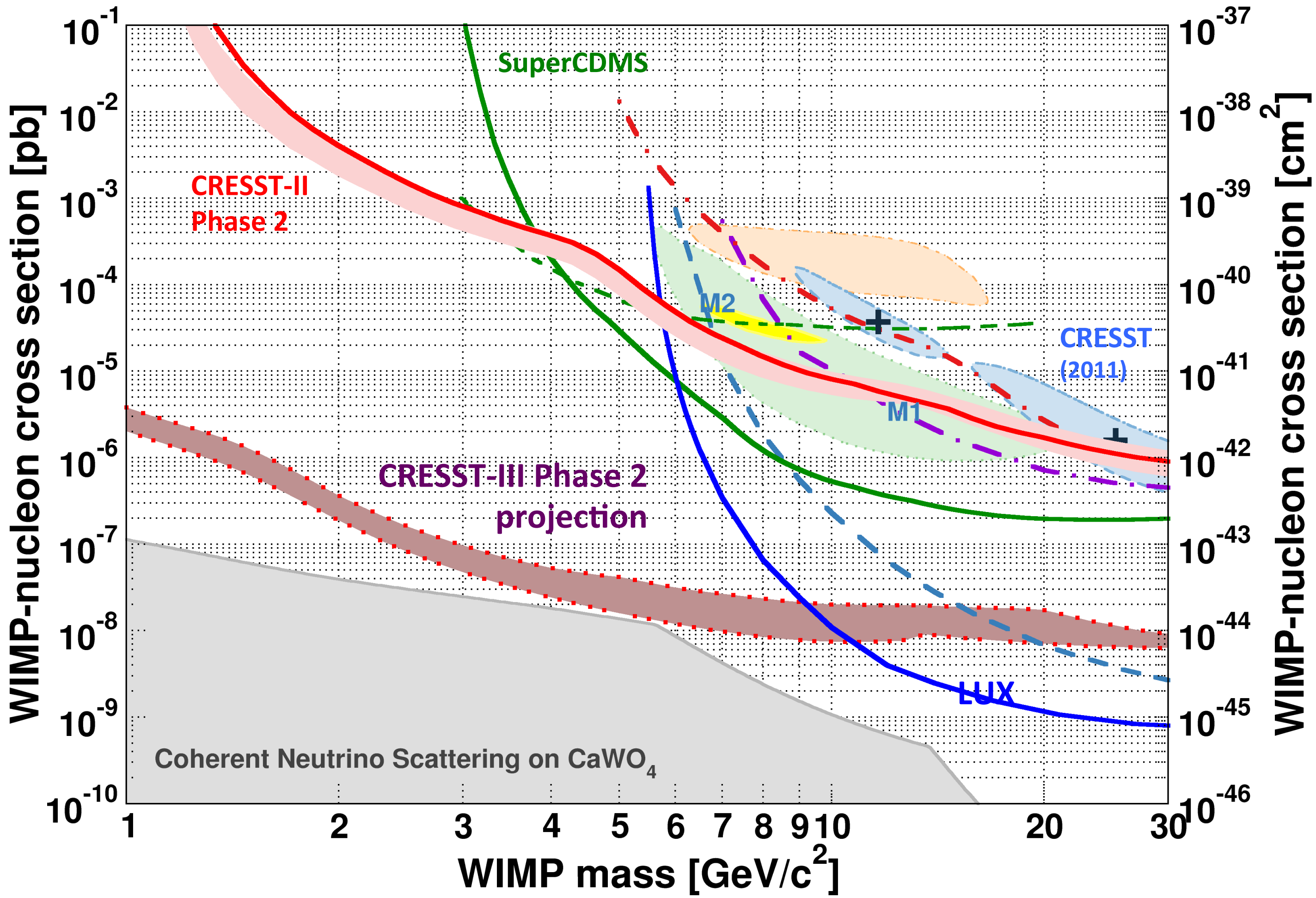
Reduce intrinsic background level of crystals!

- Growth of $CaWO_4$ crystals in-house (TUM)
- All production steps under control
- Improvement by factor 10 already achieved
- Cleaning procedure e.g. by re-crystallization, chemical purification of raw materials

REALISTIC GOAL (in 2 years):

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

CRESST-III Phase 2



100 x 24g detectors of improved quality operated for 2 year ≈ 1000 kg-days (net)

Recent Exciting Progress at TUM

First steps in chemical purification of $CaCO_3$ powder:

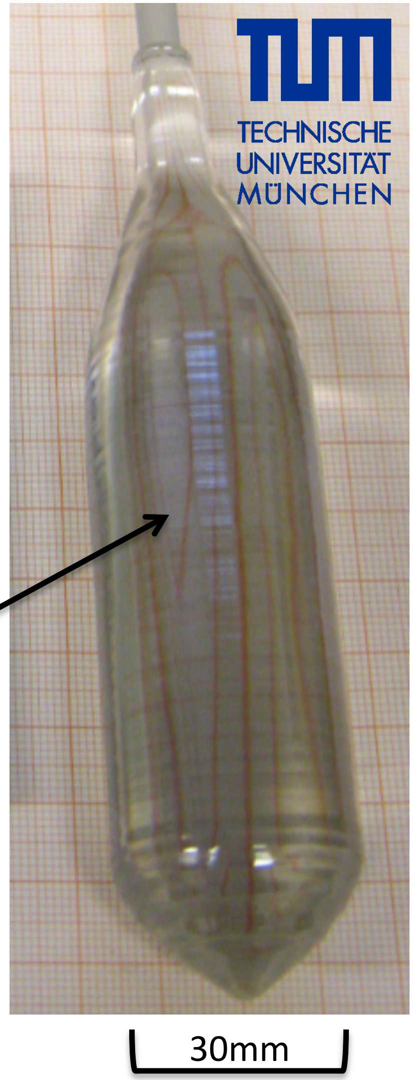
- Measurements indicate purification
  - **Th** contamination decreased by factor 2-7
  - **U** contamination decreased by factor 15-35

- Crystal growth successful

Raw ingot enough for 3-4 CRESST-III detectors

- Two such crystals will be implemented already to CRESST-III phase 1 !!

work by H.H. Trinh Thi, A. Münster, A. Erb



Summary

- CRESST technology proved high potential for **low-mass WIMP search**
  - ✓ Lowest thresholds in the field: 300eV
  - ✓ Nuclear-recoil energy scale precisely known
  - ✓ Background discrimination down to low energies
  - ✓ Efficient rejection of surface backgrounds
  - ✓ Multi-element target

- **CRESST-II** probed new region of parameter space for WIMP masses below 3GeV/c^2

- **CRESST-III** has unique potential to explore low-mass WIMP region
  - ✓ Threshold of <=100eV reached with prototype detector
  - ✓ iStick technology to reject holder-related events
  - ✓ First crystals of improved quality already in phase 1

Start: March 2016