CRESST – Dark Matter from an Experimental Point of View

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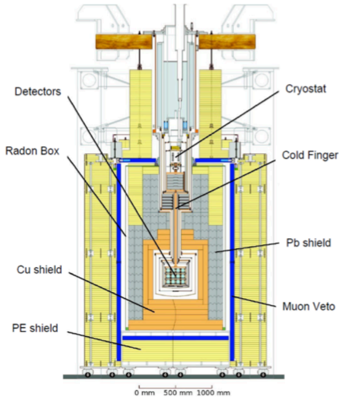
MPI München
MIAPP Garching,
25.2.2015

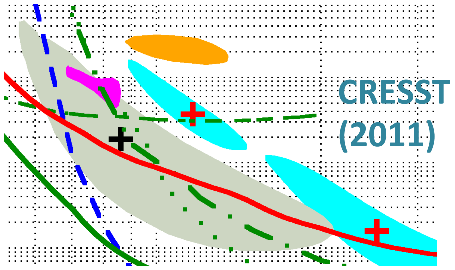
ÖAW
Austrian Academy
of Sciences

UNIVERSITY OF
OXFORD

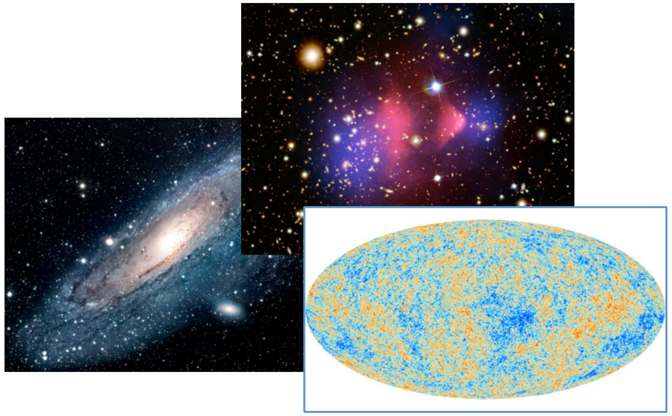
Outline

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





Dark Matter

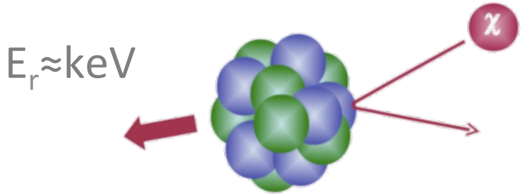


Dark Matter exists in the Universe!

WIMPs

Weakly Interacting Massive Particles

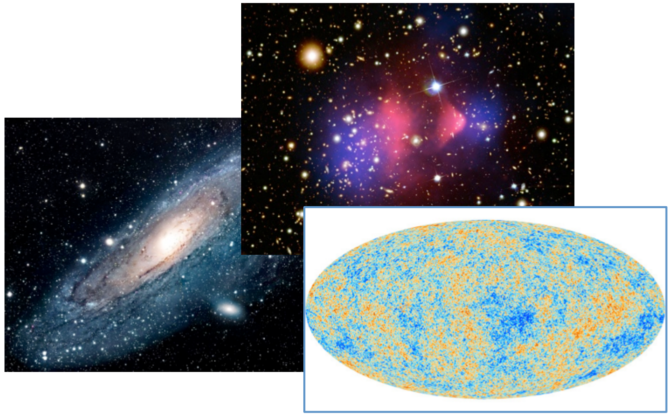
Particles are a well-motivated interpretation



Elastic WIMP-nucleus scattering

Direct detection with Earth-bound experiments

Dark Matter



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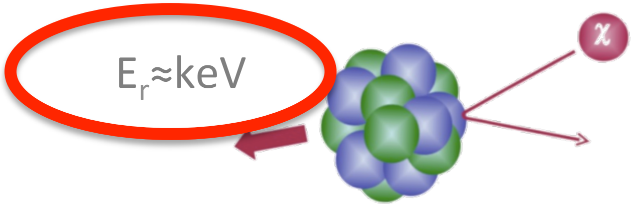
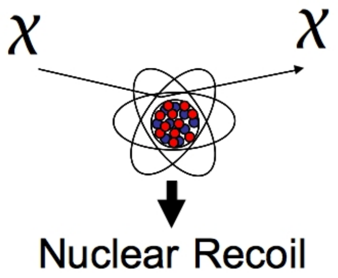


Elastic WIMP-nucleus scattering

Direct detection with Earth-bound experiments

challenging!

How does a possible WIMP signal look like??



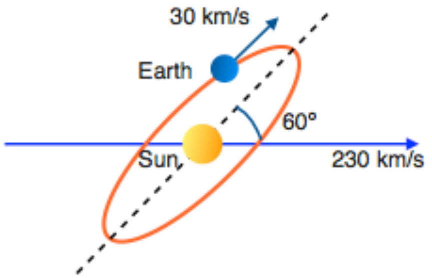
- WIMP interactions via elastic scattering
  - Nuclear recoils (few keV)
  - Single scatters
  - Uniformly distributed in detector

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

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

Ar I Si Ge Ca O Xe W Na

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



WIMP Signals in Dark Matter Detectors

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

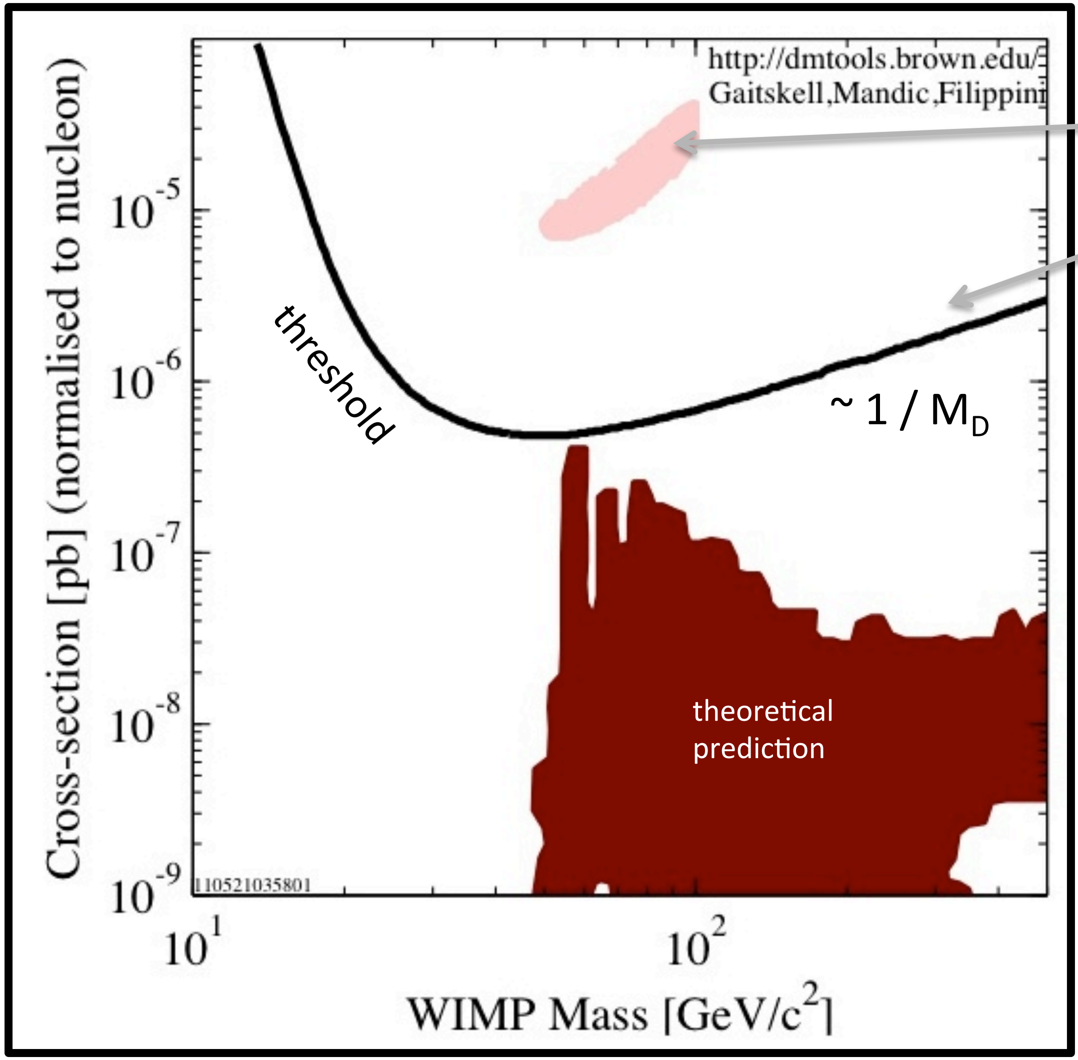
R	measured rate in detector
N	number of target nuclei
E_R	recoil energy of target nucleus
M_D	mass of WIMP
ρ_D	WIMP density @Earth
F^2	nuclear form factor
σ_χ	WIMP nucleus cross section

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

Usual (very basic) assumption:
- Coherent scattering
- Scattering amplitudes add up in phase

➢ $\sigma_\chi \sim A^2$

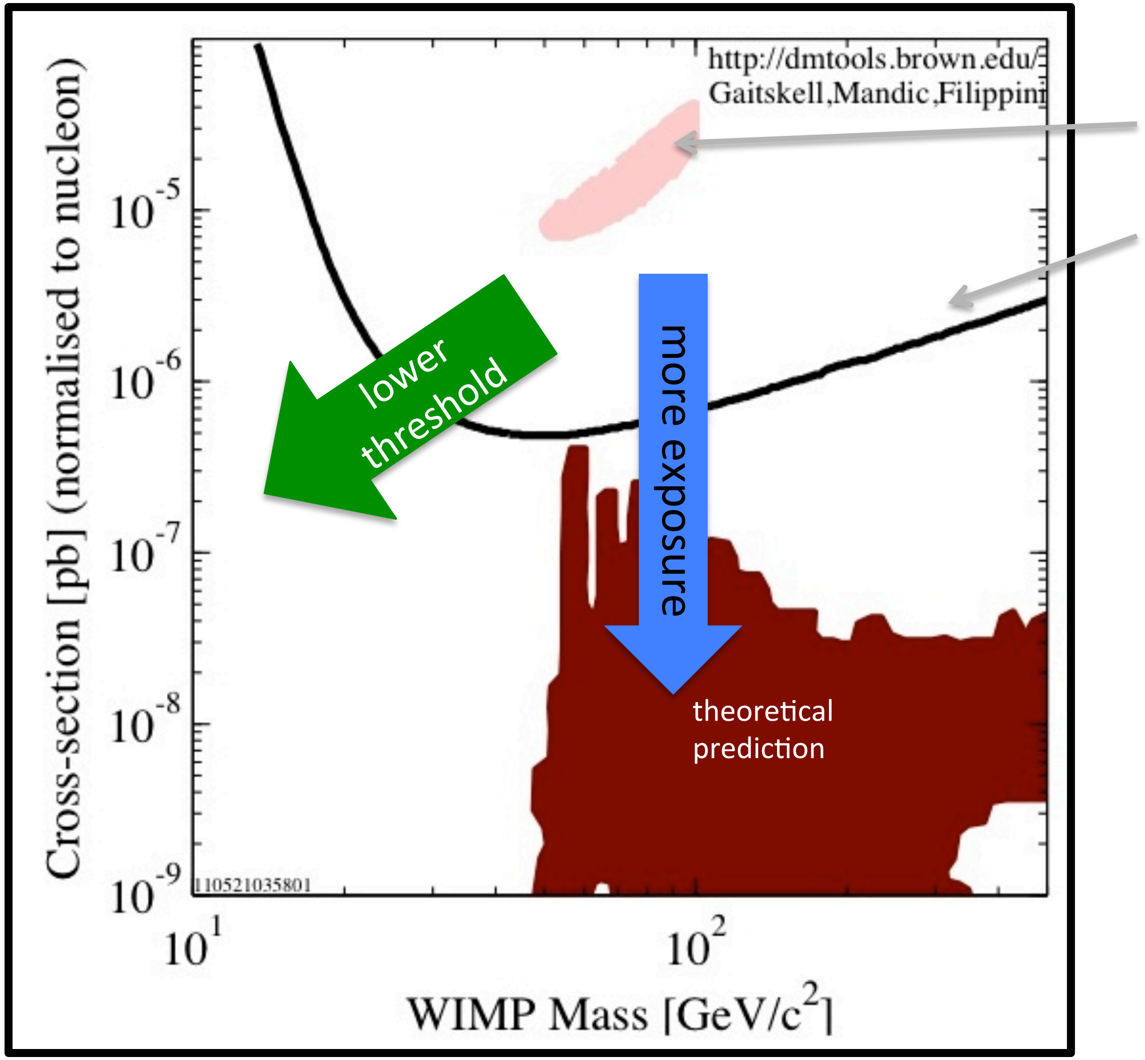
Exclusion Plot – Comparison of Results



Signal claim

Exclusion limit

Exclusion Plot – Comparison of Results



Signal claim

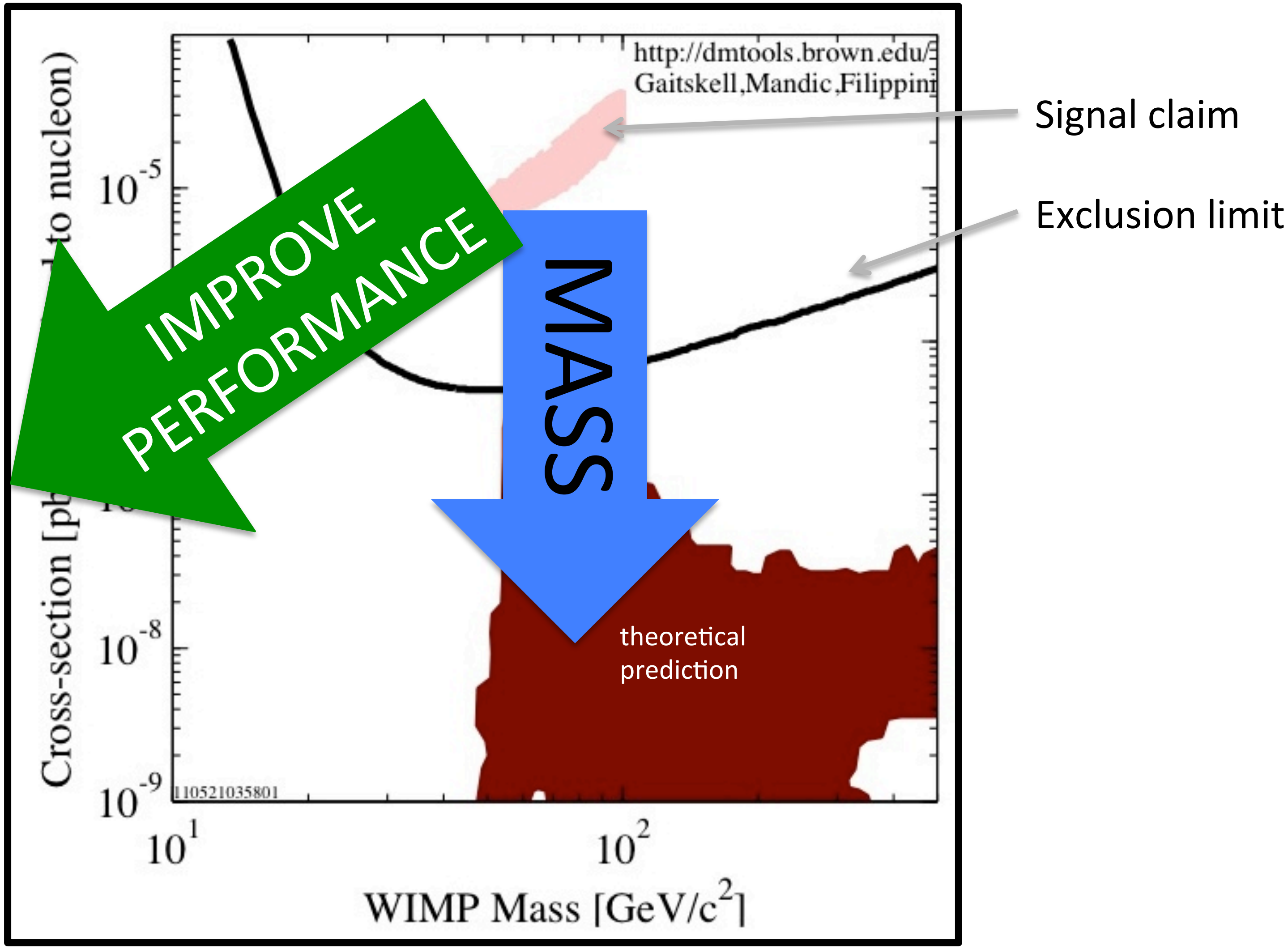
Exclusion limit

lower threshold

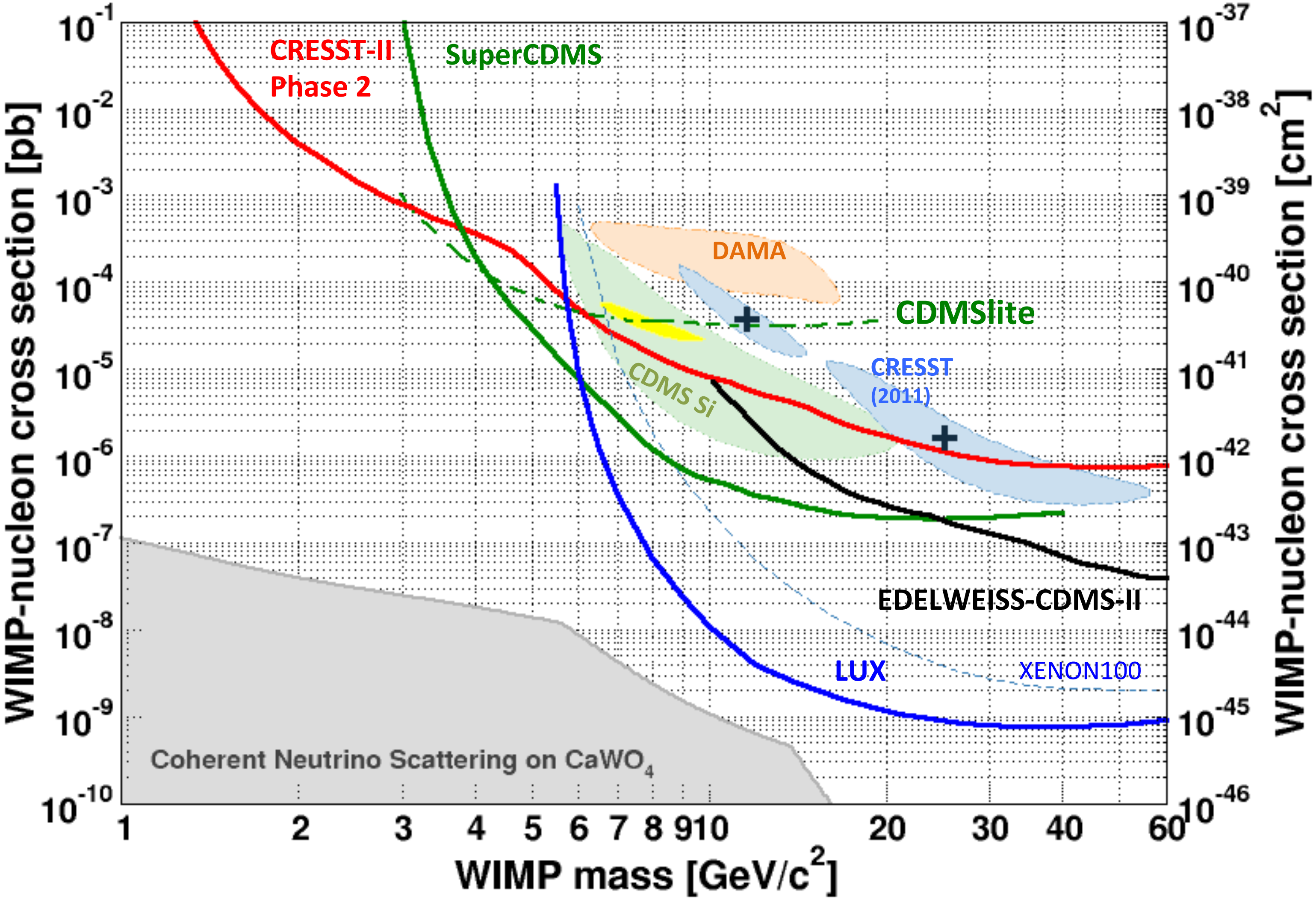
more exposure

theoretical prediction

Exclusion Plot – Comparison of Results



Current Status of Direct Dark Matter Searches



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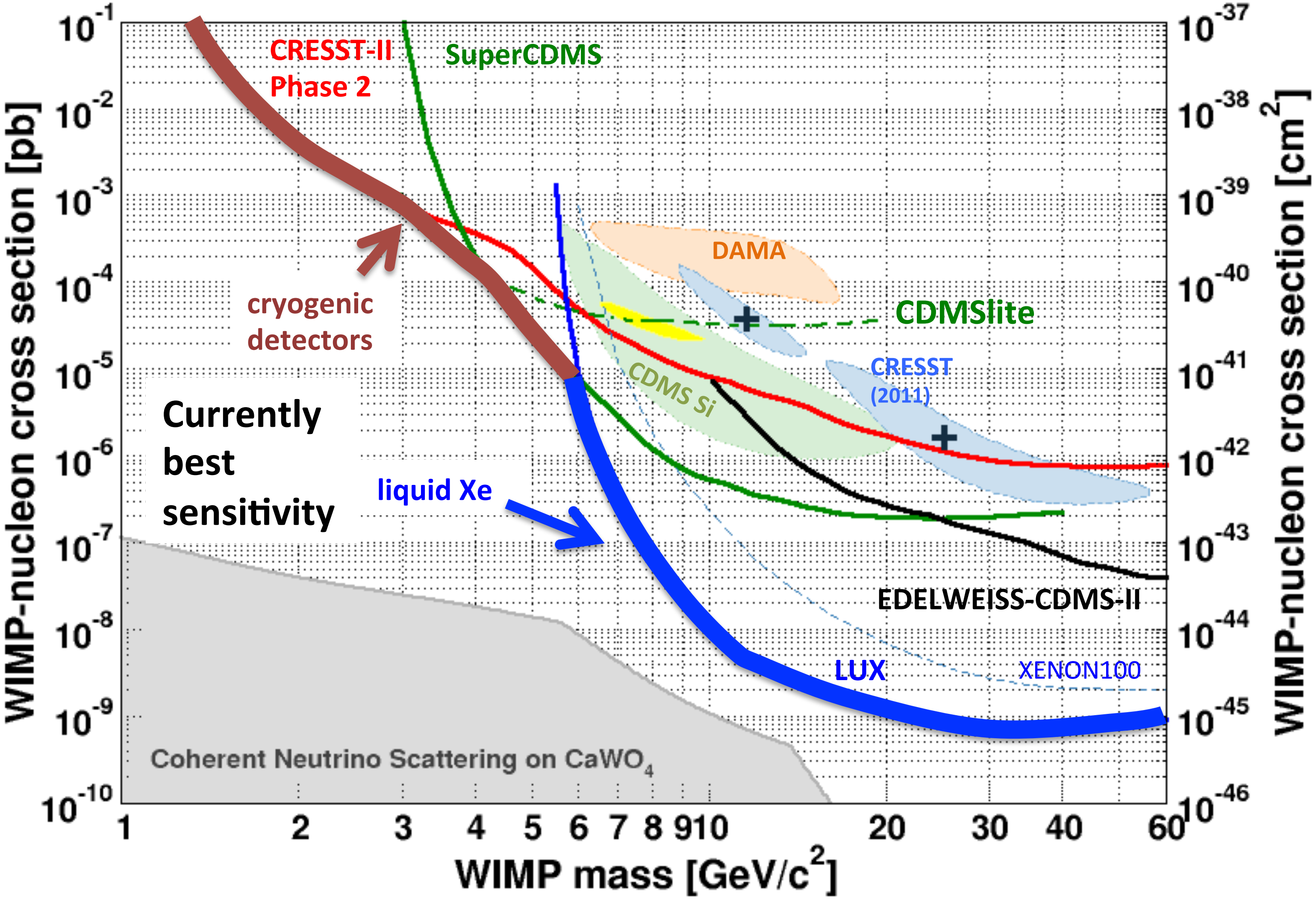


cryogenic detectors

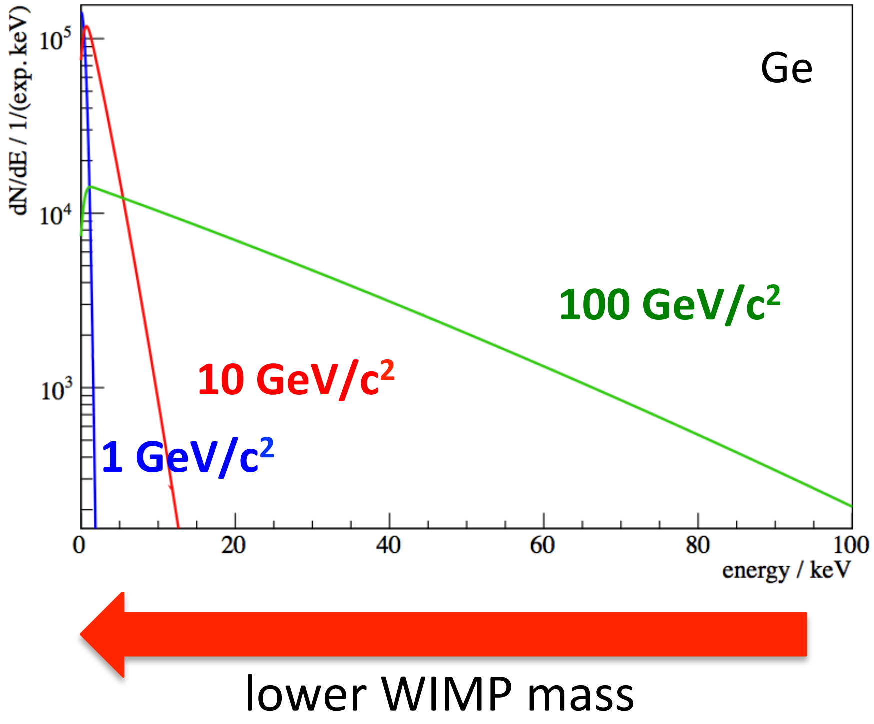
Currently best sensitivity

liquid Xe

Potential of Cryogenic Detectors

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

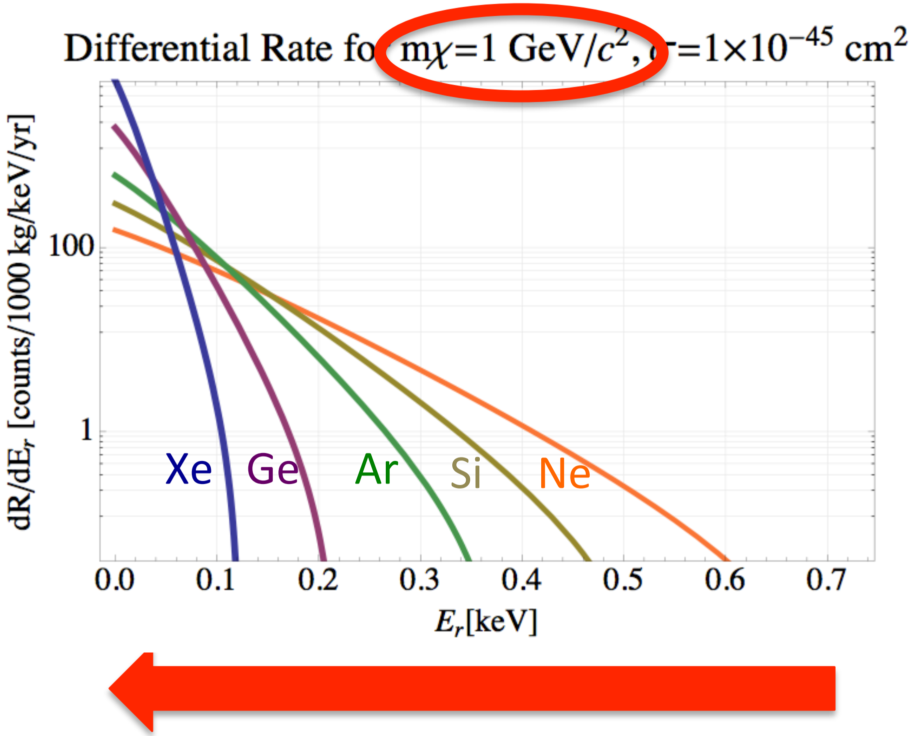
- **Low energy threshold**



Potential of Cryogenic Detectors

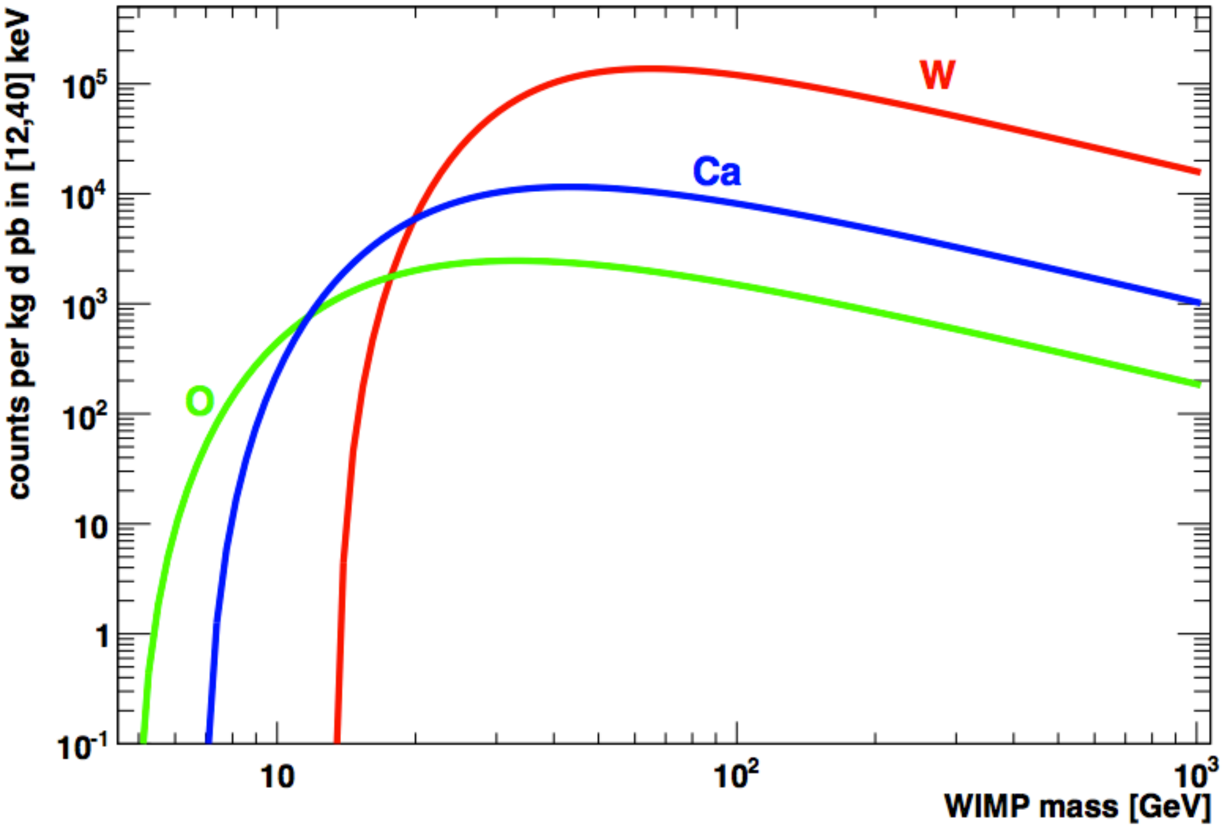
*Why are cryogenic detectors particularly sensitive to **low-mass WIMPs** ?*

- Low energy threshold
- **Light elements**



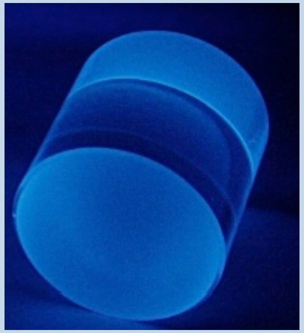
mass of target nucleus

CRESST – Multi-Element Target



Example:

$CaWO_4$ target



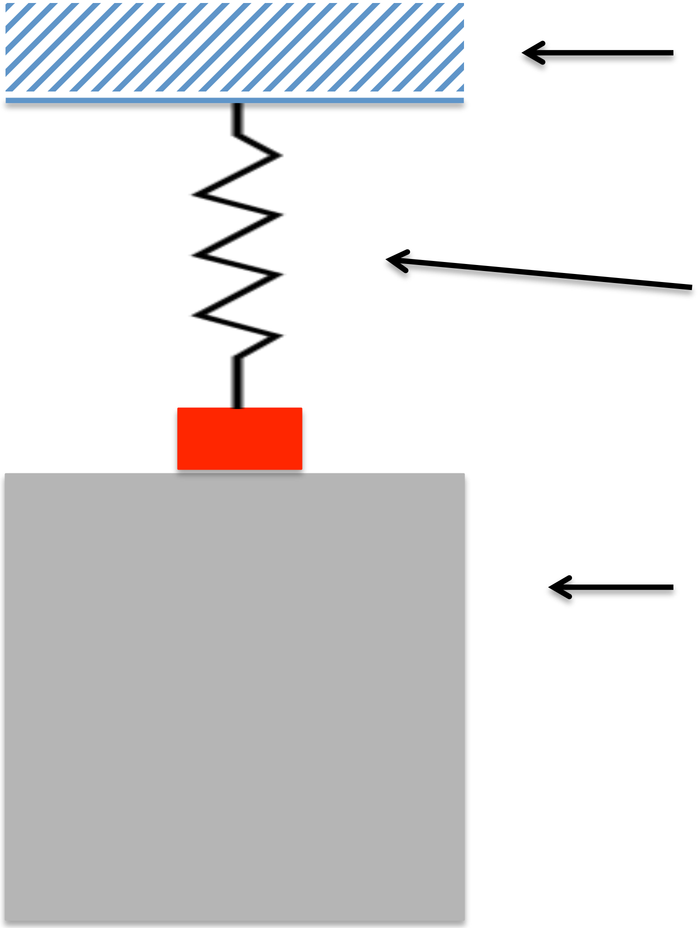
Threshold: 12keV

Cross-section: 1pb

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

Principle of Cryogenic Detectors

Cryogenic Detector



heat bath (T≈10mK)

temperature $\mathbf{T_0}$

weak thermal link

conductance **G**

thermometer

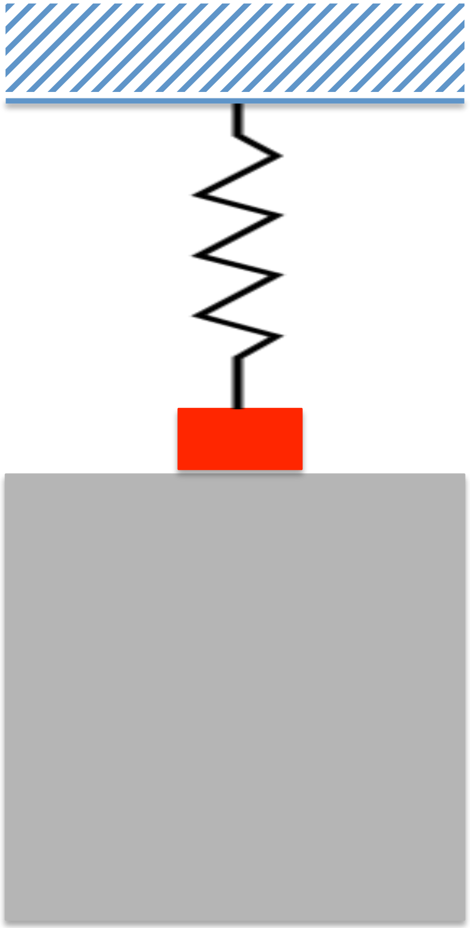
+

absorber material

heat capacity **C**

temperature **T**

Cryogenic Detector

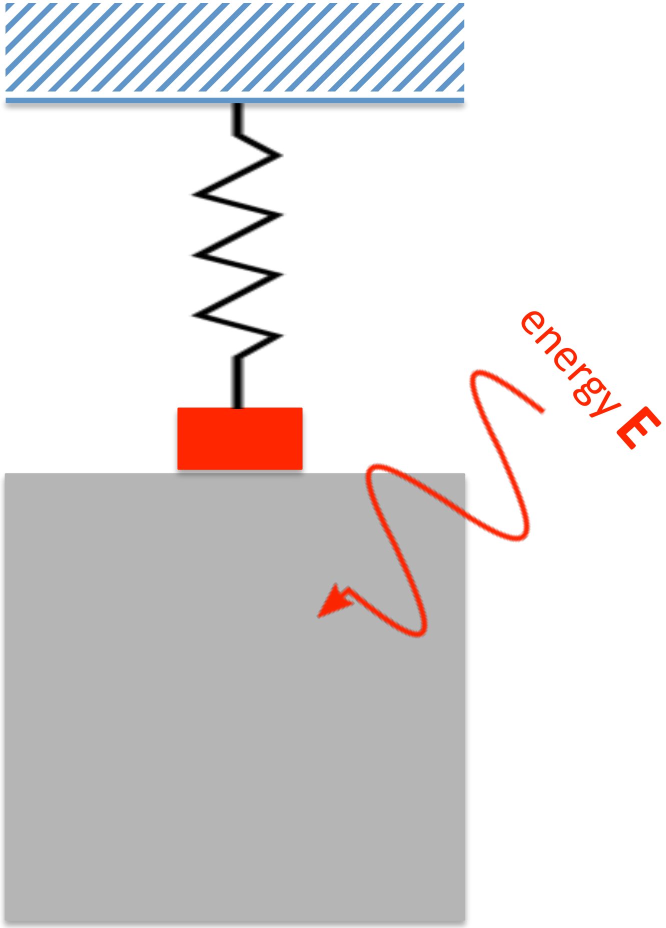


Irreducible thermal fluctuations:

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

Need:
- Low temperature
- Low heat capacity

Cryogenic Detector



Irreducible thermal fluctuations:

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

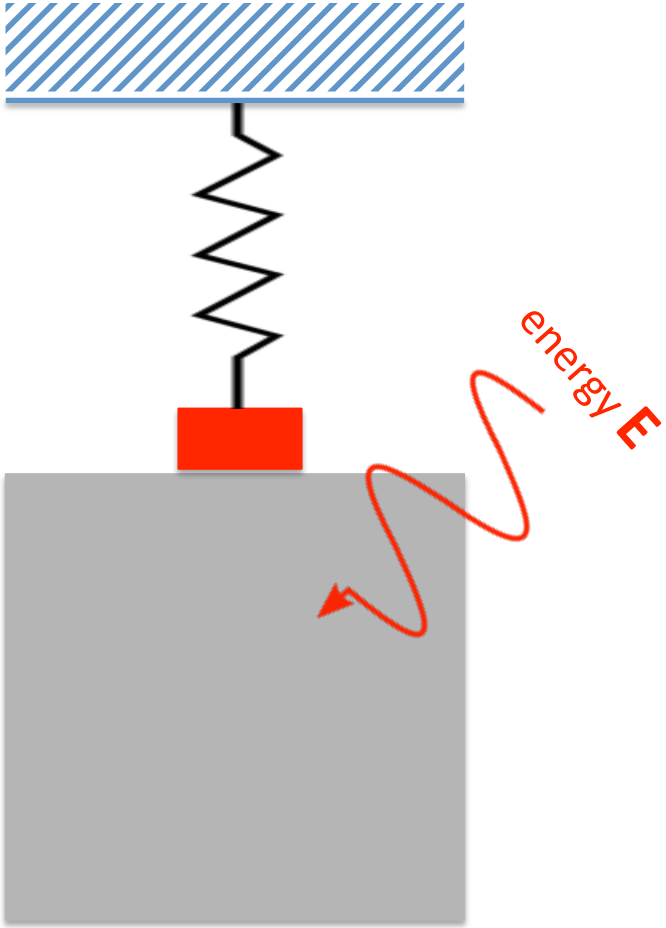
Need:

- Low temperature
- Low heat capacity

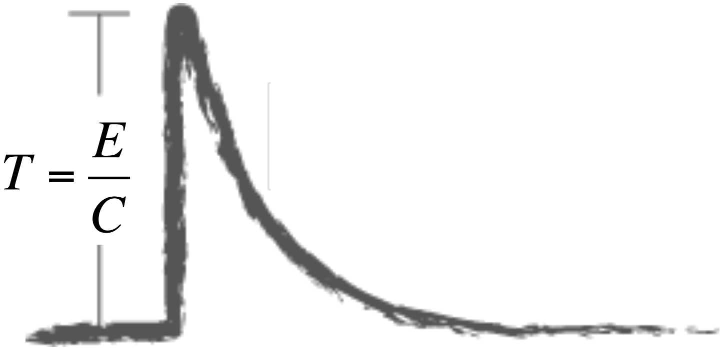
Operation at mK:

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

Cryogenic Detector

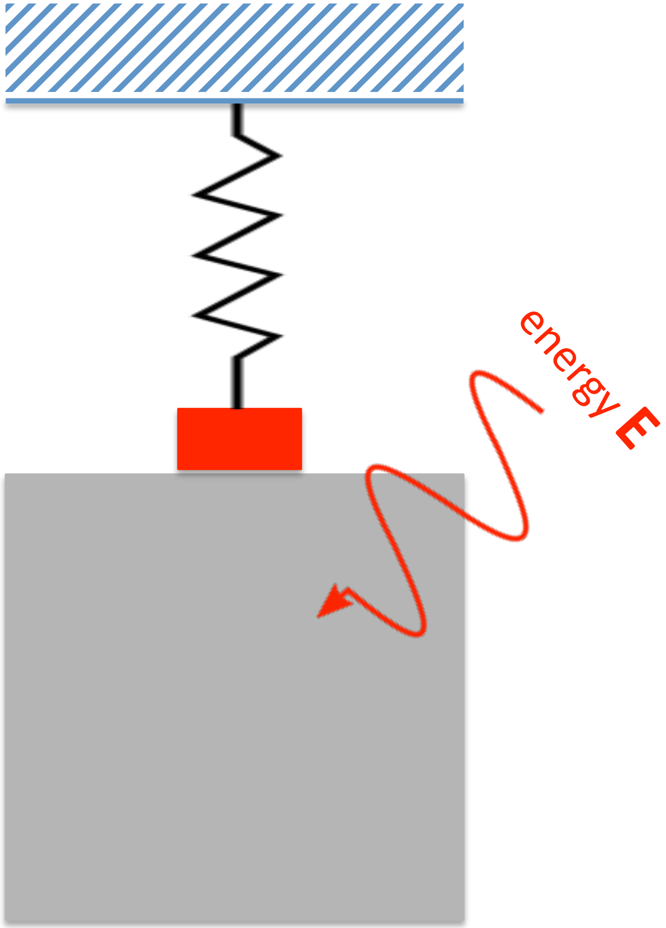


Thermometer response:



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

Cryogenic Detector



Thermometer response:

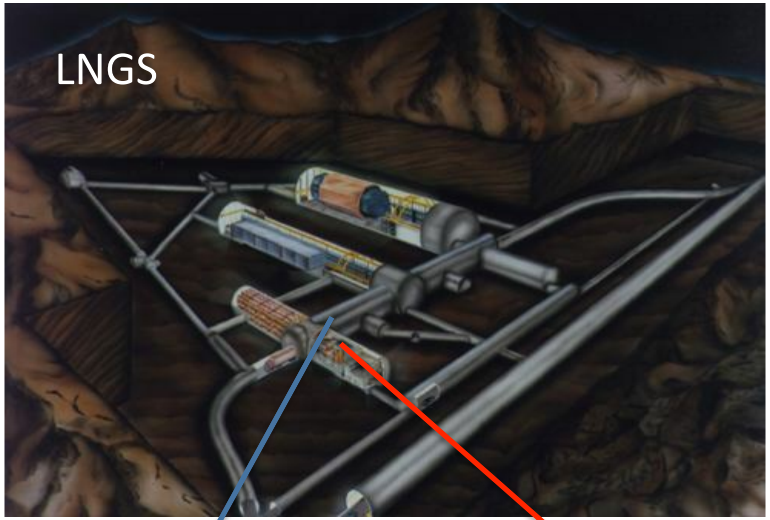
$$\Delta T = \frac{E}{C}$$

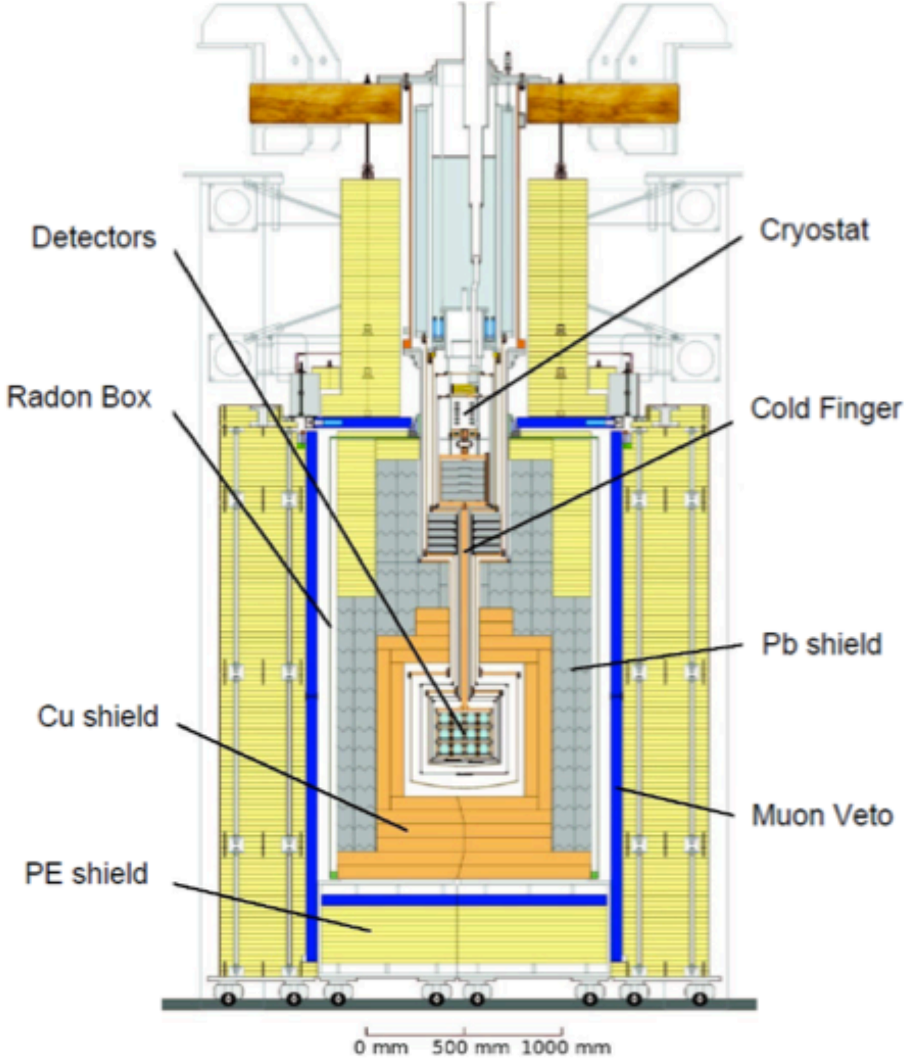
Calorimeter
Direct measurement of total deposited energy!

The CRESST Experiment

The CRESST Experiment

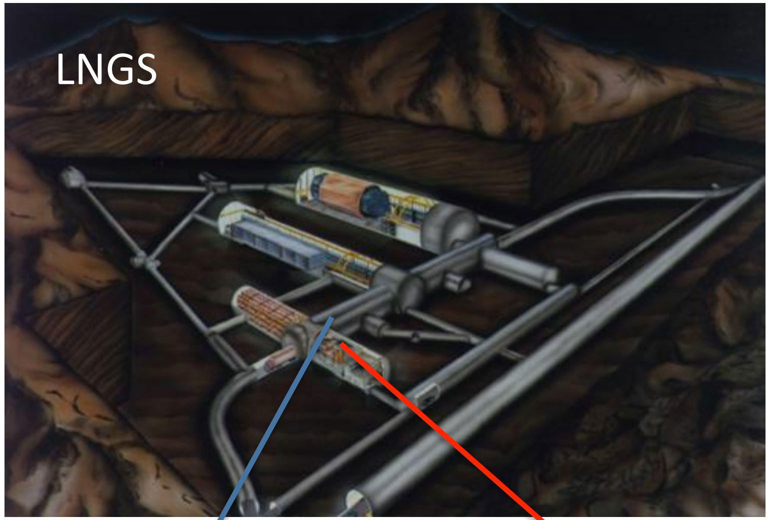
Cryogenic Rare Event Search with Superconducting Thermometers





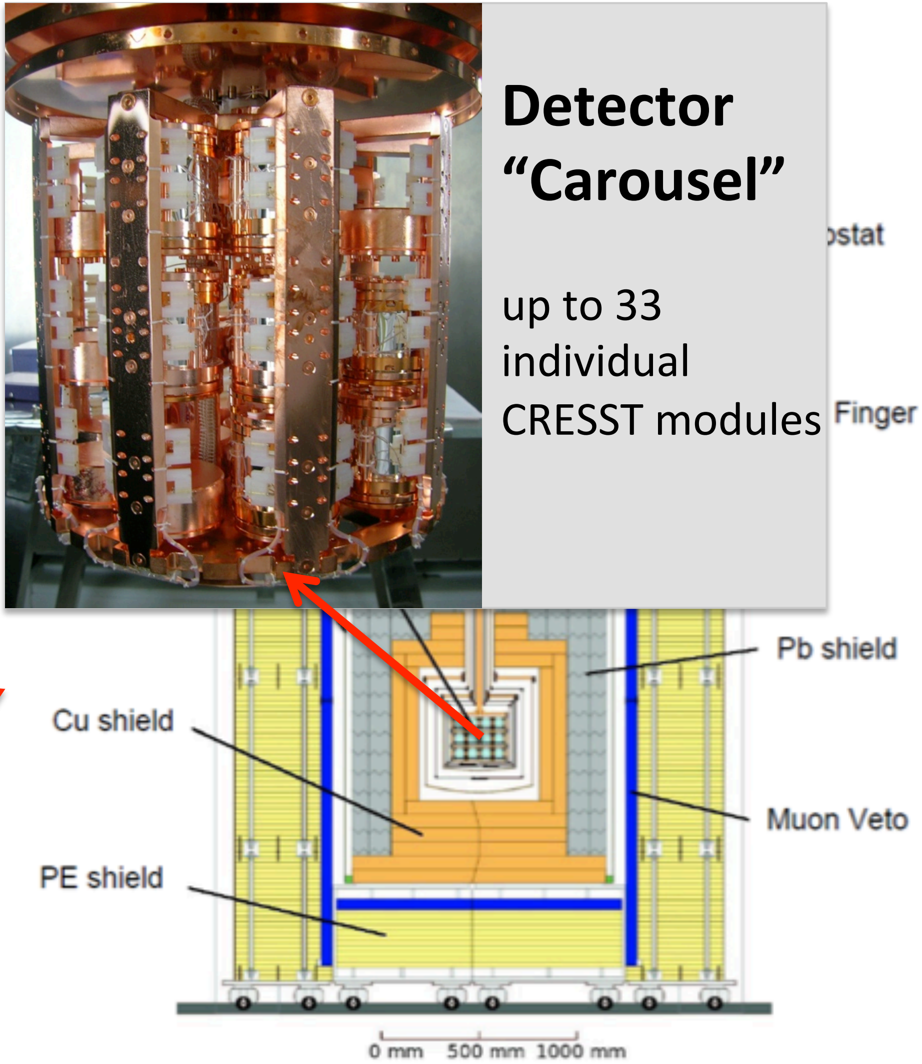
The CRESST Experiment

Cryogenic Rare Event Search with Superconducting Thermometers




CRESST-Testcryostat
truck tunnel

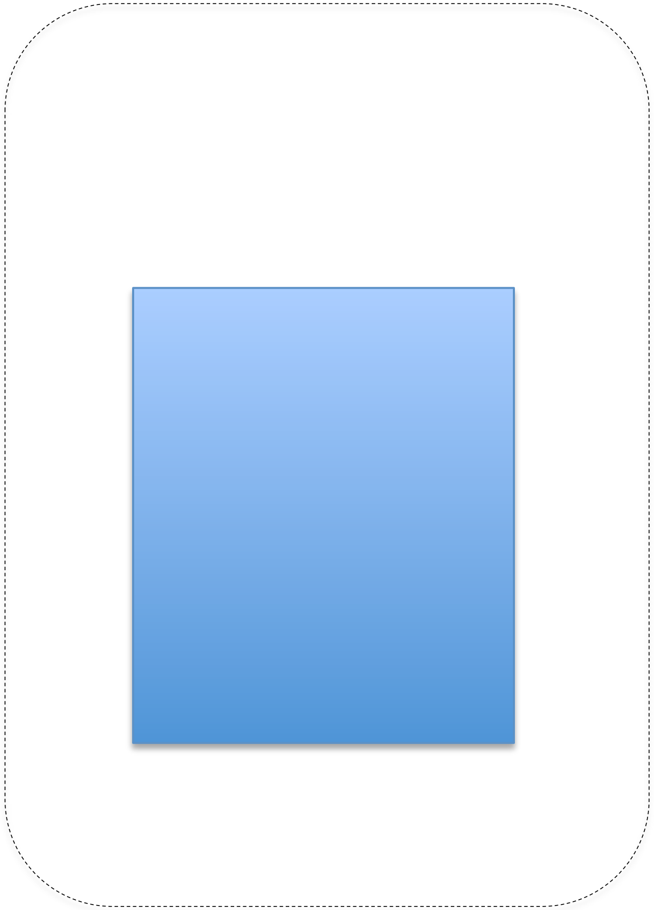

CRESST
sala A


Detector “Carousel”

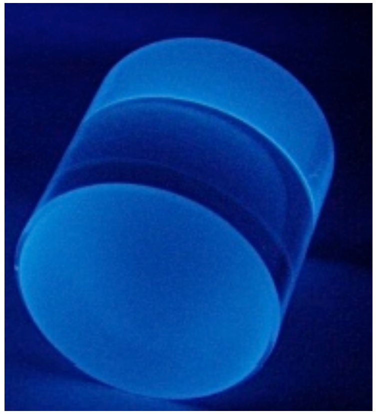
up to 33 individual CRESST modules

The CRESST-II Detector Module

The CRESST-II Detector Module



$CaWO_4$ Target Crystal

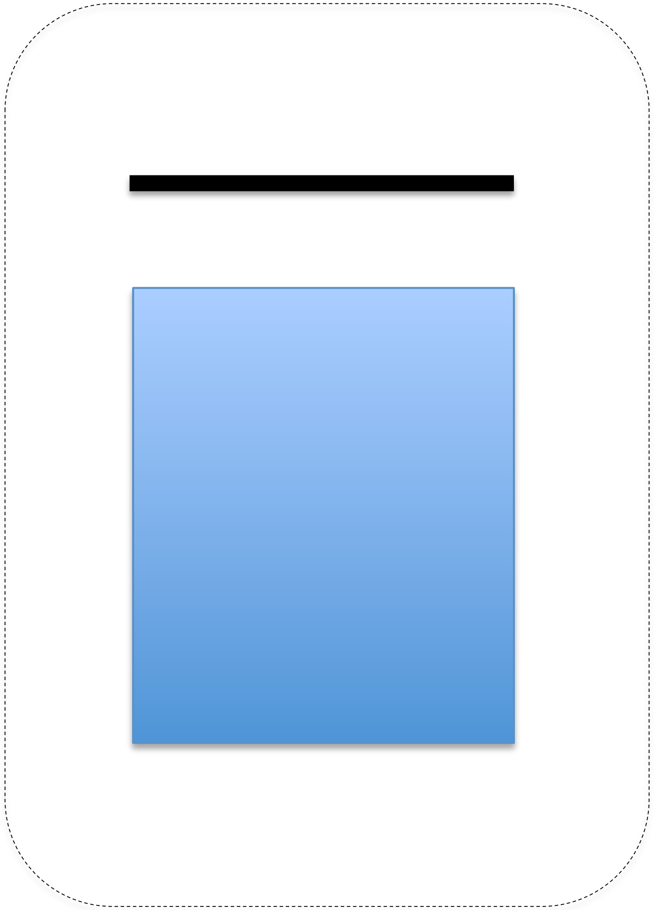


- scintillating
- multi-element target
- mass: 250 – 350 g

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

In-house production and processing at our institutes

The CRESST-II Detector Module

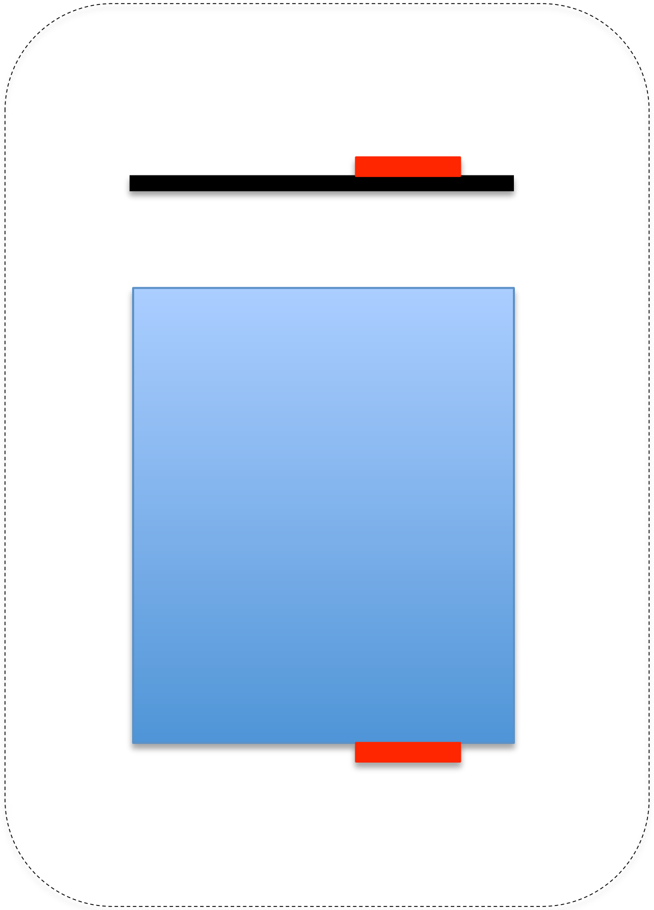


Light Absorber

for scintillation-light detection

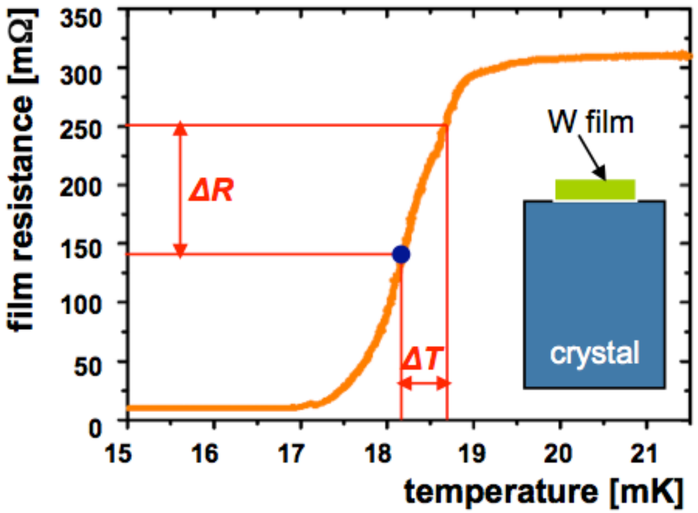
- silicon-on-sapphire disc
- diameter: 40mm
- thickness: 500µm

The CRESST-II Detector Module



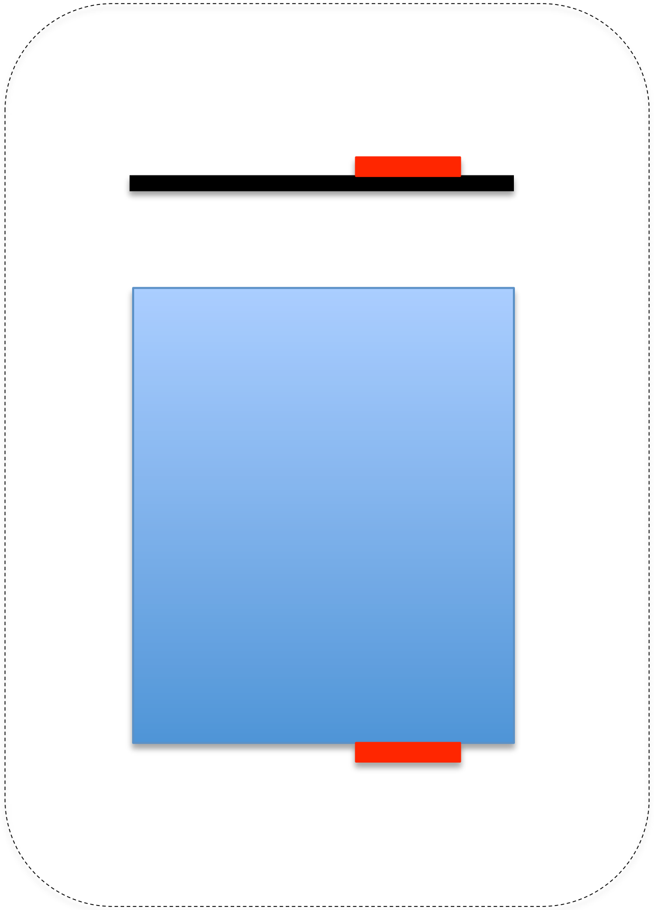
Transition-Edge-Sensors

→ 2 independent calorimeters



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

The CRESST-II Detector Module



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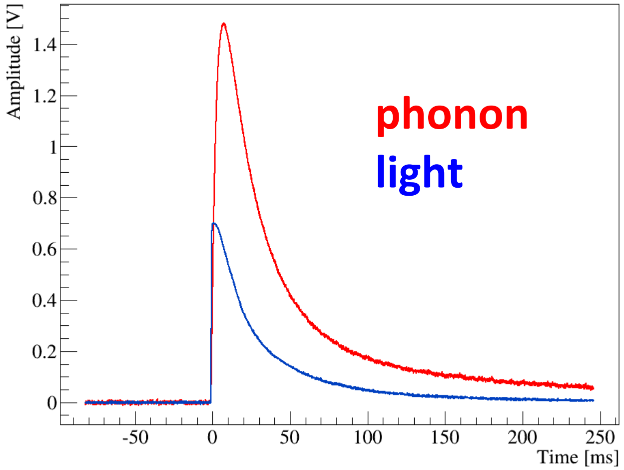


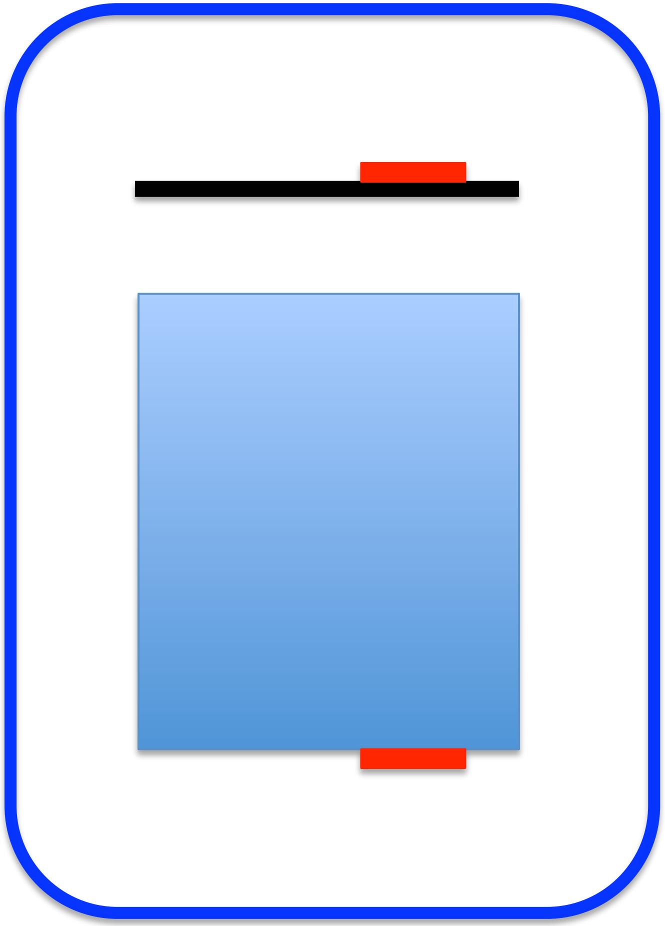
Phonon detector ($CaWO_4$)

- 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

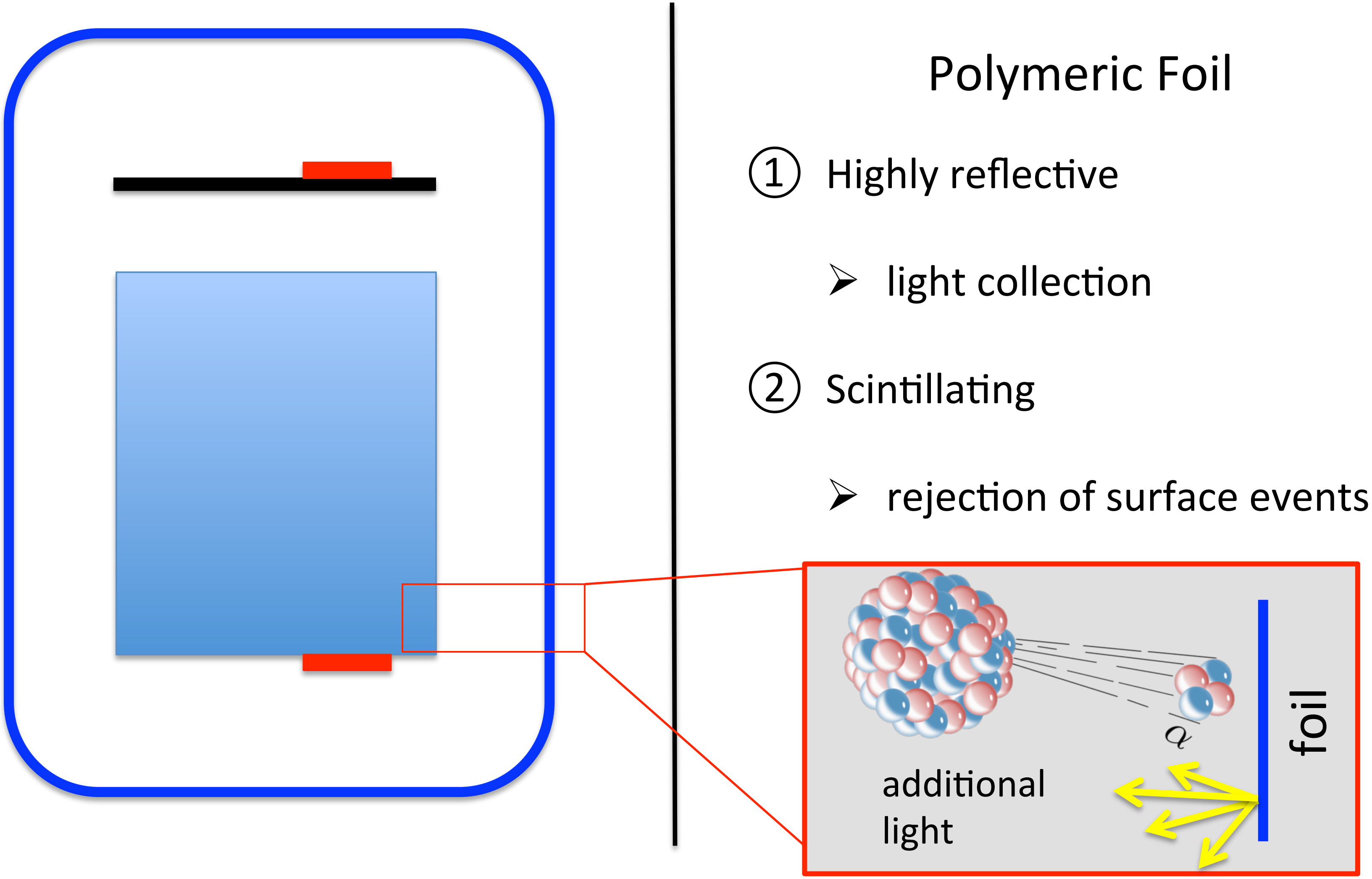
① Highly reflective

  - ➢ light collection

② Scintillating

  - ➢ rejection of surface events

The CRESST-II Detector Module



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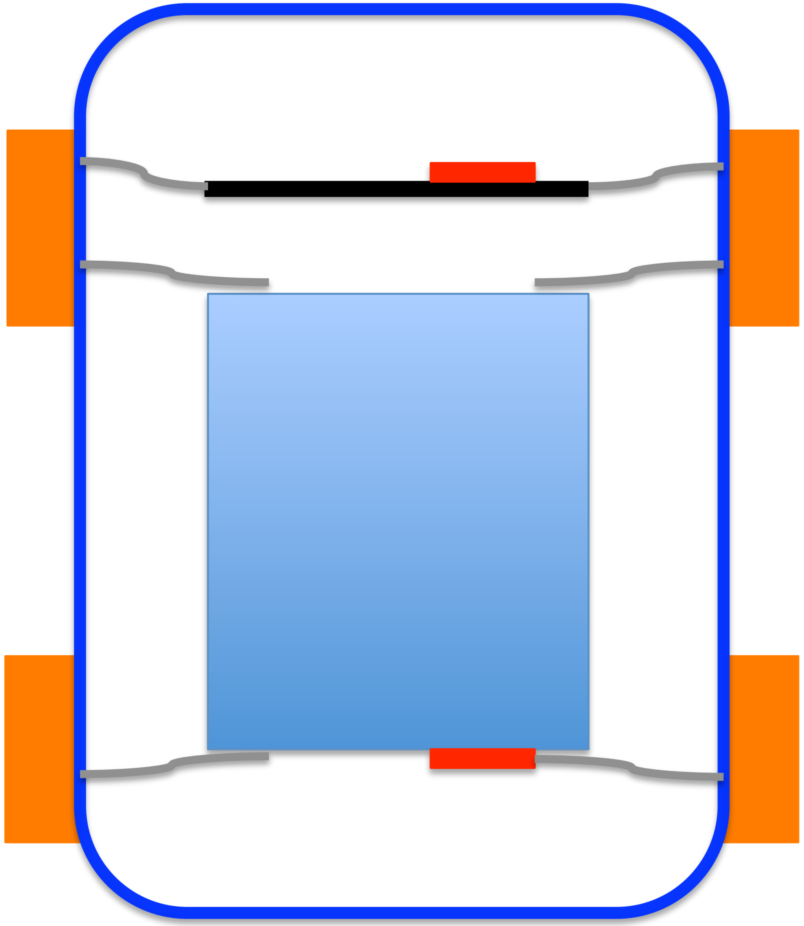
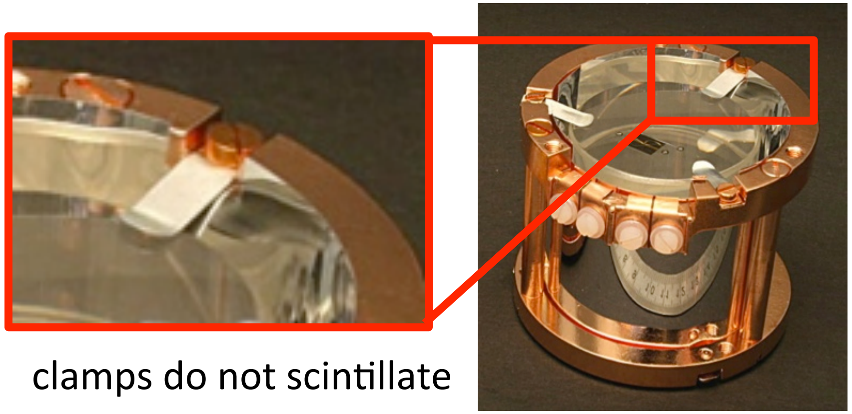


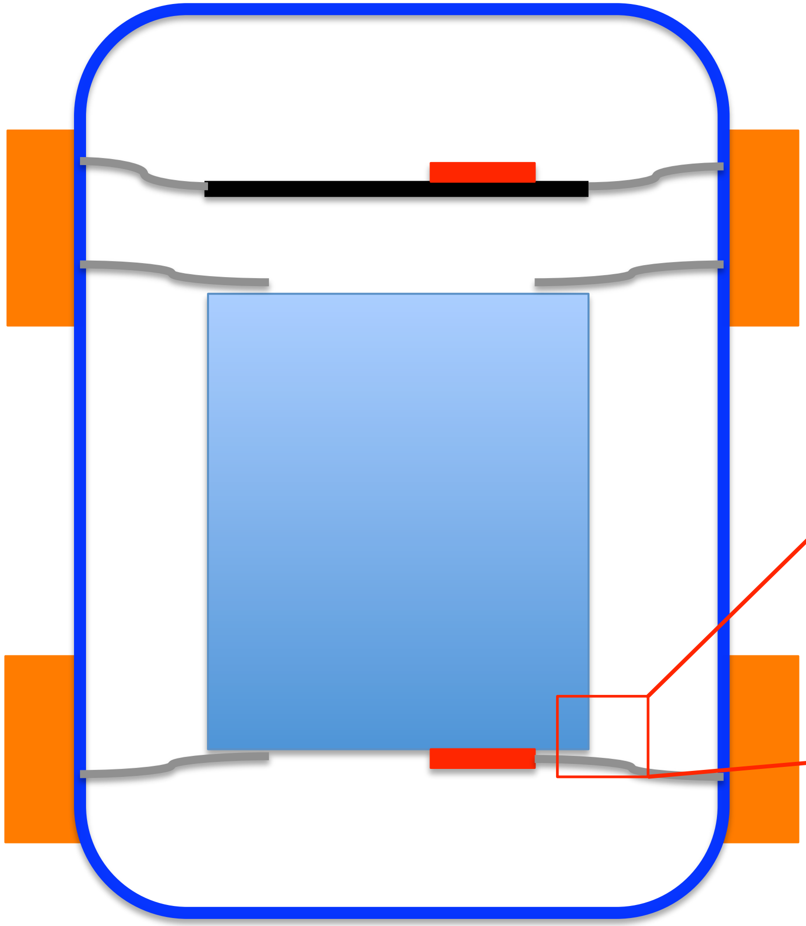
Support Structure

- radio-pure copper
- flexible bronze clamps



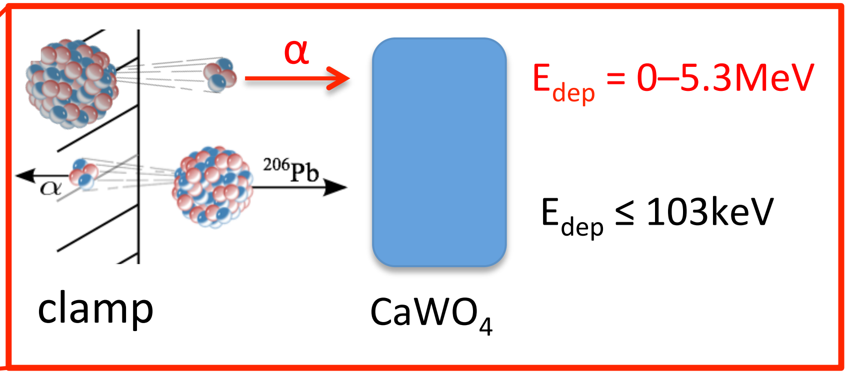
clamps do not scintillate

The CRESST-II Detector Module



Dangerous Surface Backgrounds

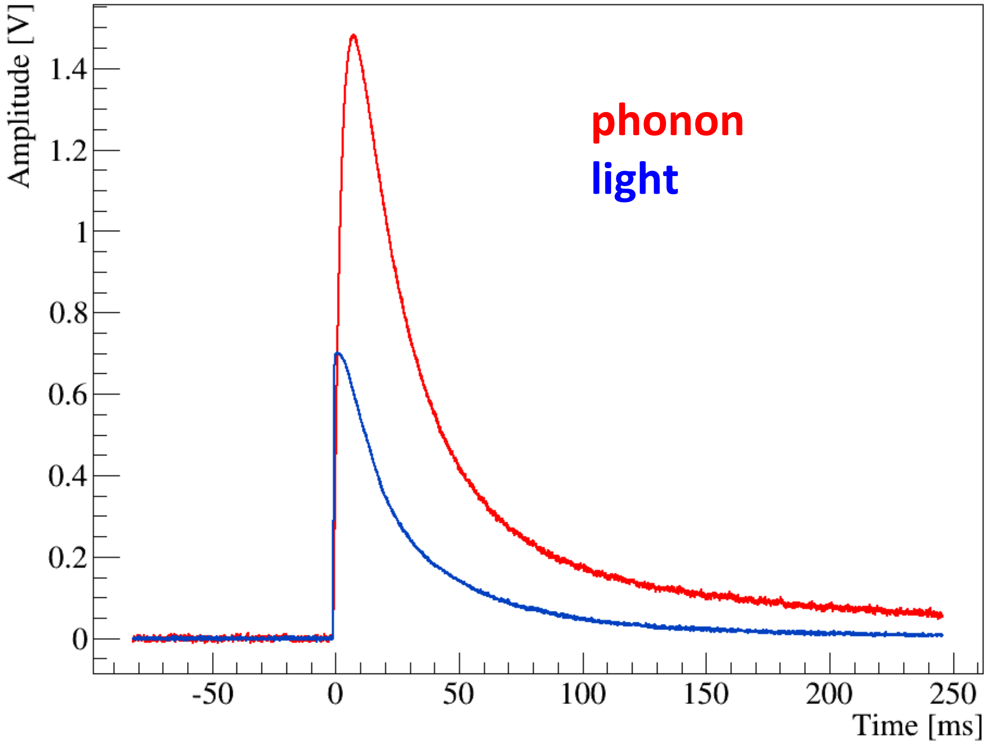
$^{210}Po \rightarrow {}^{206}Pb\ (103keV) + \alpha\ (5.3MeV)$



→ Lead/alpha recoils can mimic WIMPs

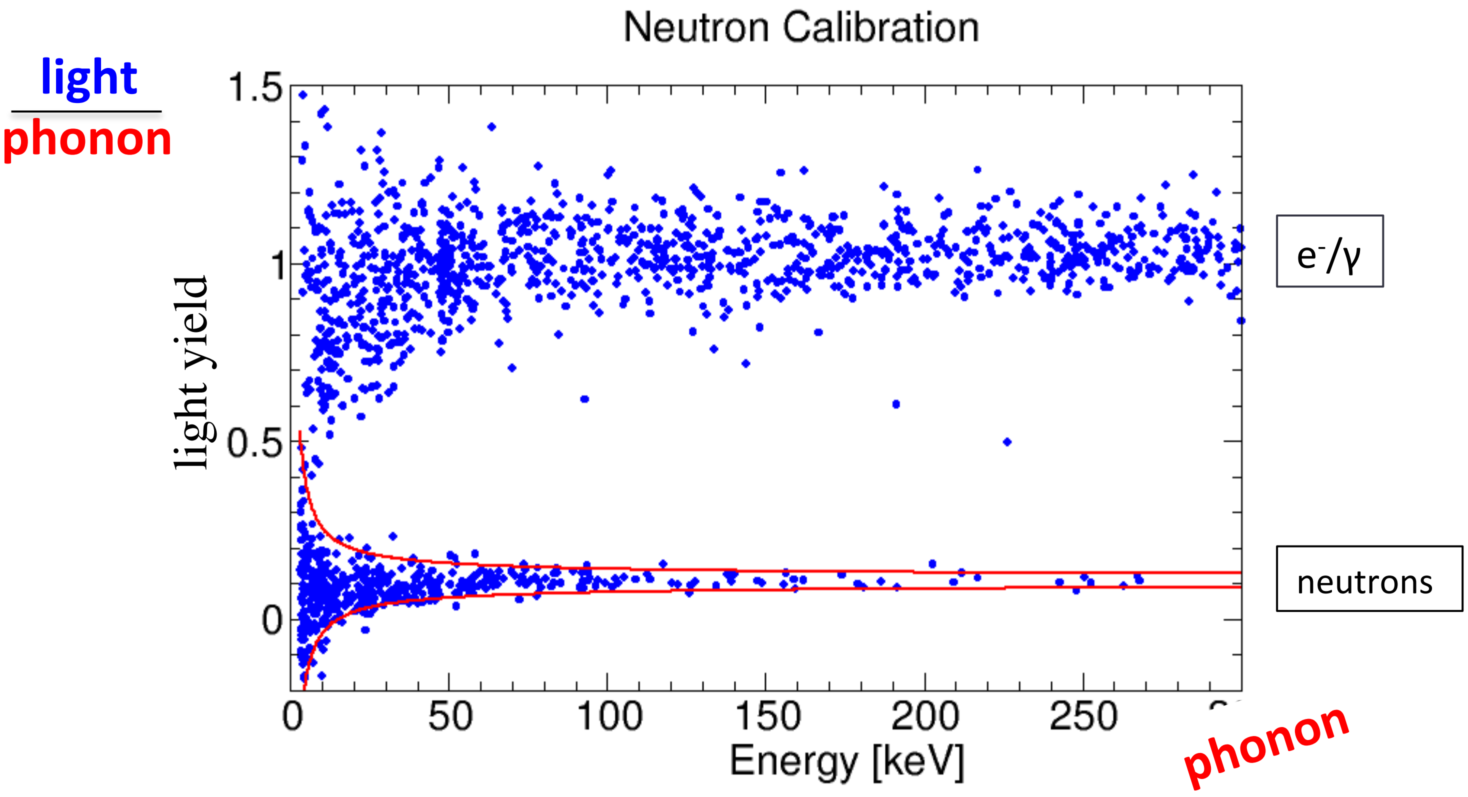
→ Avoid non-scintillating materials!

Phonon-Light Technique



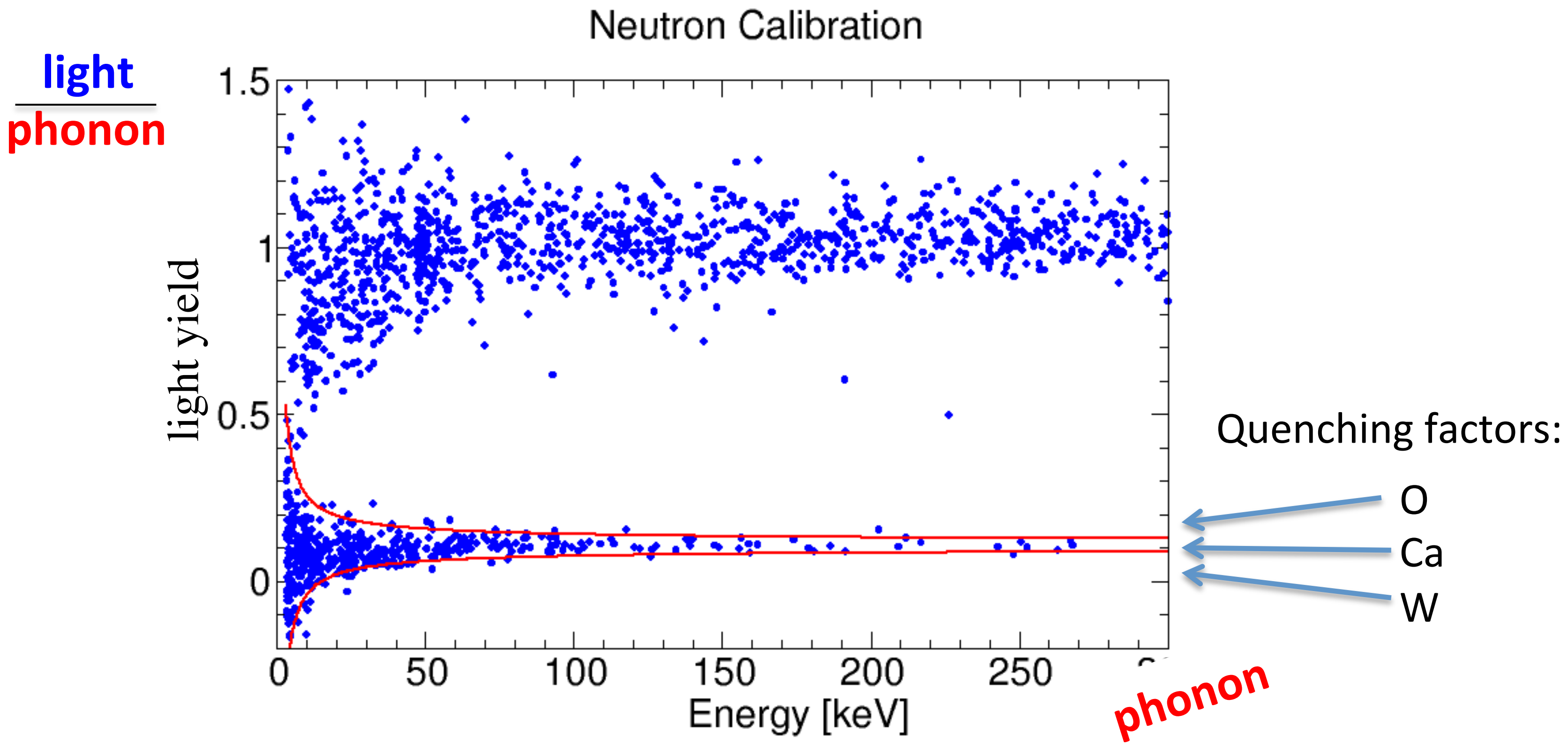
Simultaneous measurement of **phonon** and **light** signal

Phonon-Light Technique



Reduced light output for highly-ionizing particles → Quenching

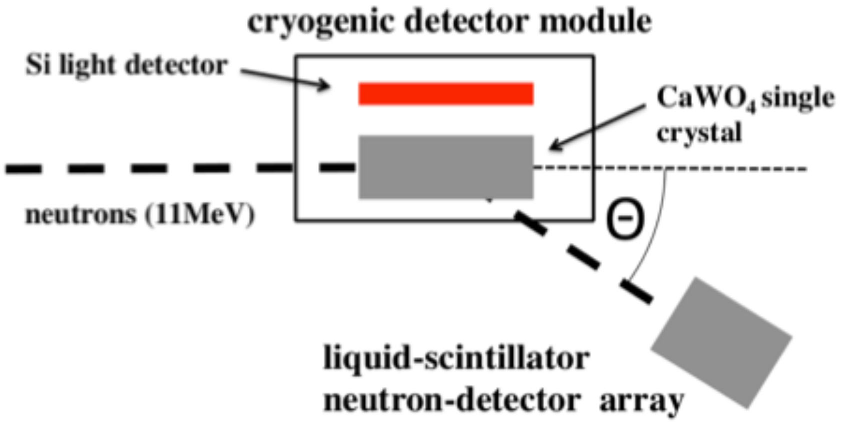
Phonon-Light Technique

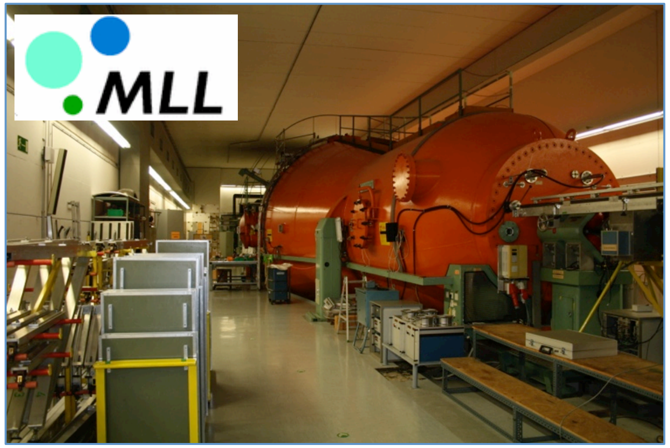


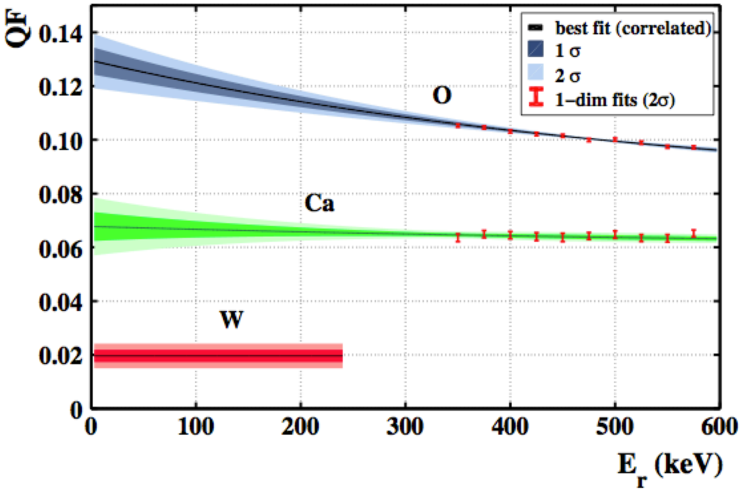
Reduced light output for highly-ionizing particles → Quenching

Quenching Factor Measurements

Neutron-Scattering Facility at MLL Accelerator



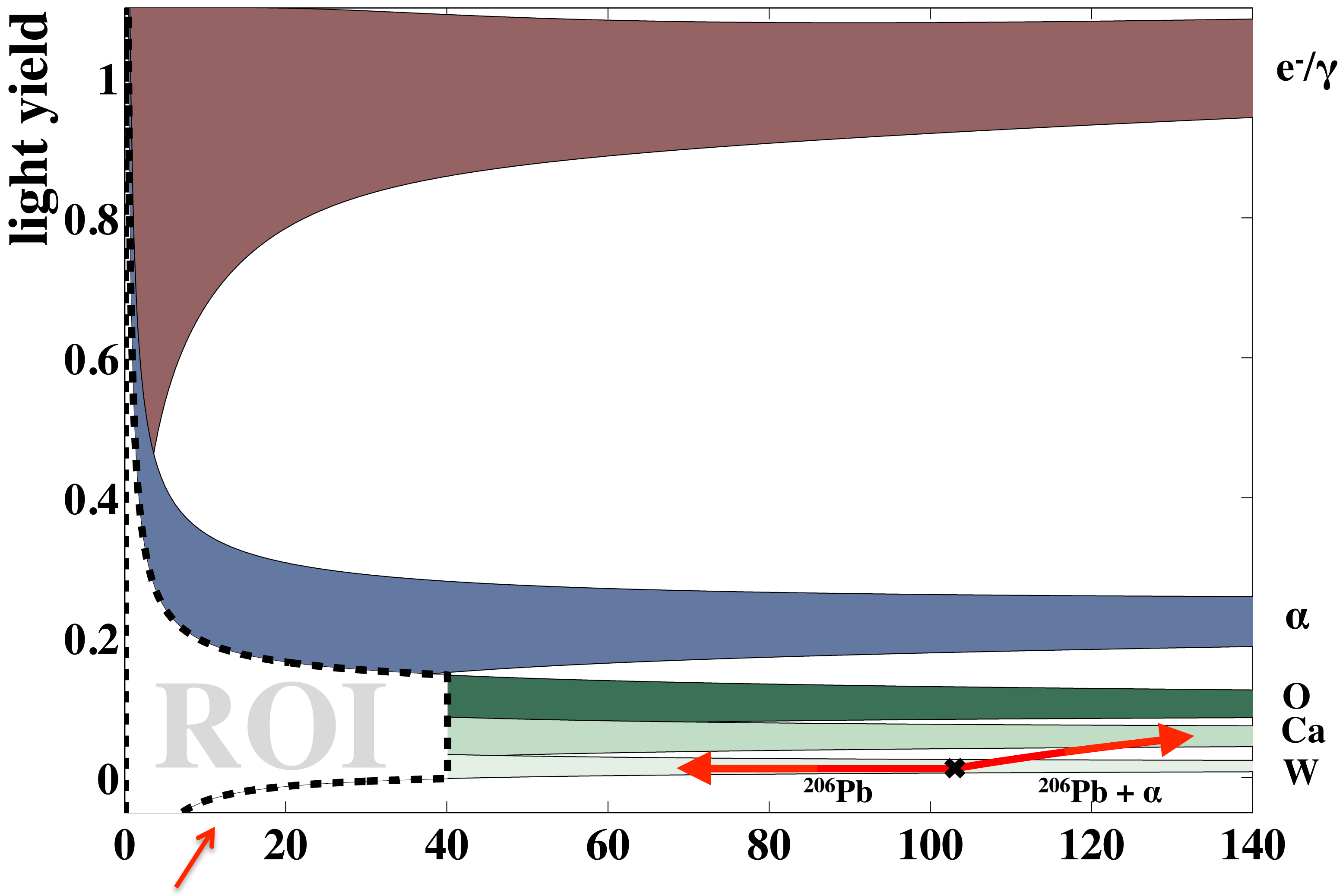




- Precise measurement of QF of O, Ca and W at mK temperatures
- For CRESST detectors in ROI:
  QF_O = (11.2 ± 0.5)%
  QF_{Ca} = (5.94 ± 0.49)%
  QF_W = (1.72 ± 0.21)%

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

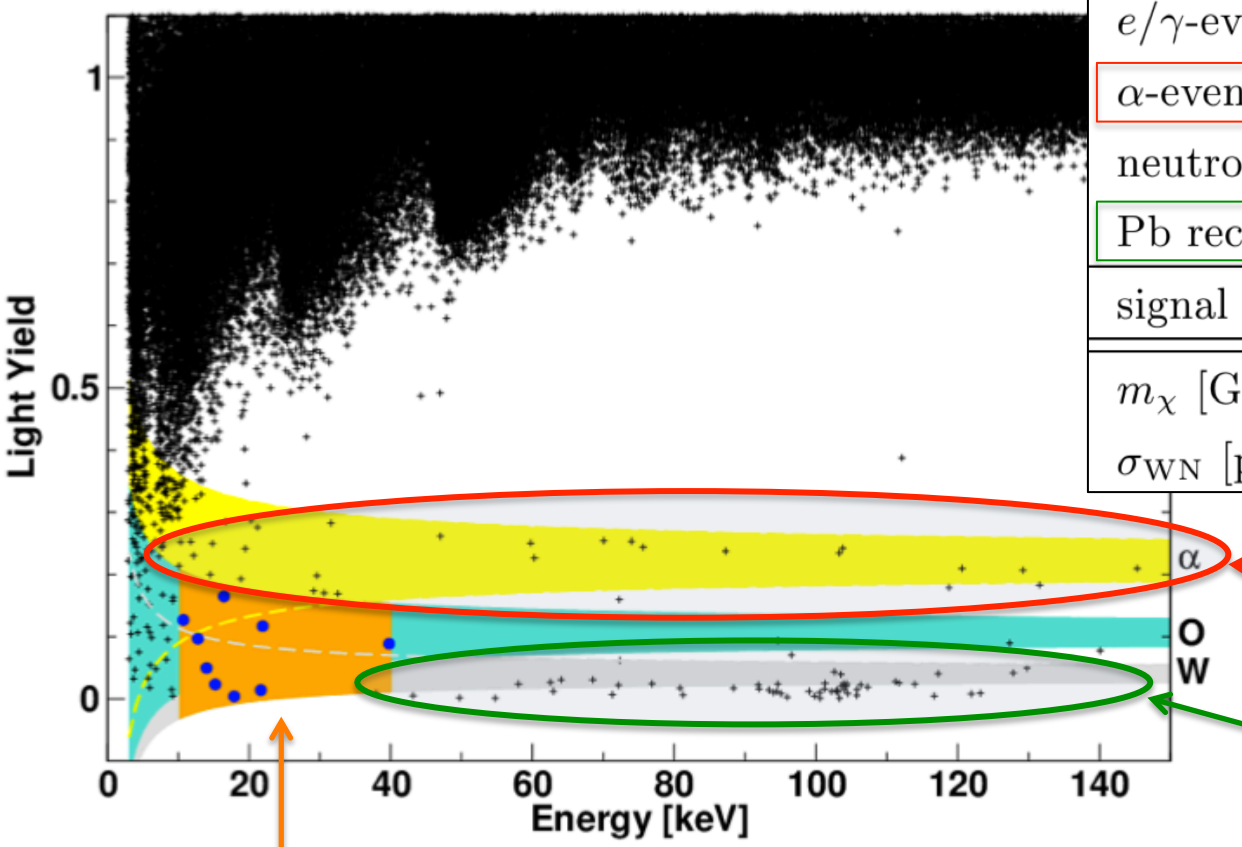
Signal and Backgrounds



Region of interest for Dark Matter Search

Results of the Last 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]	$3.7 \cdot 10^{-5}$



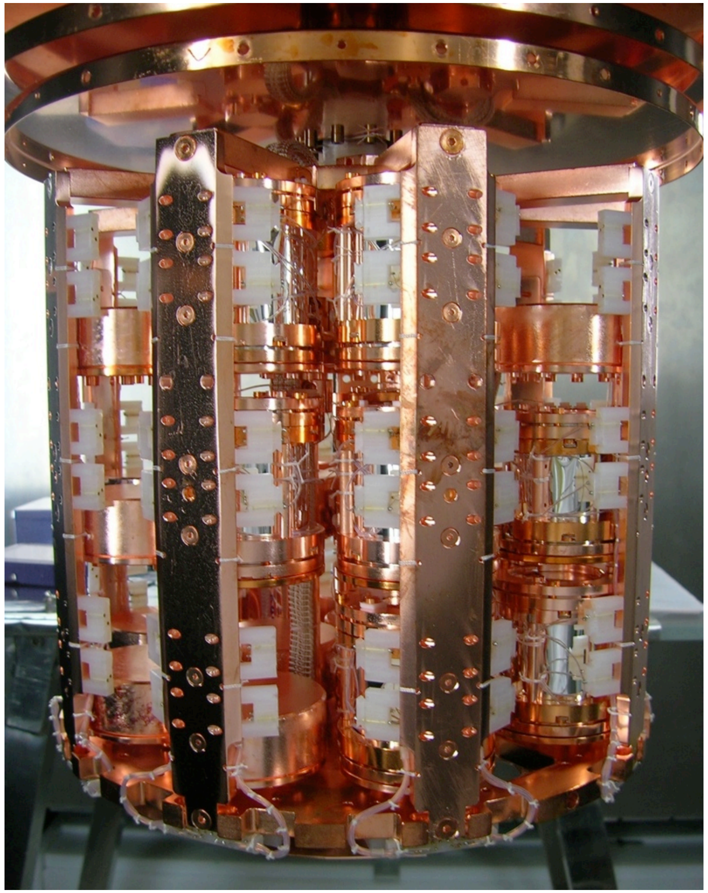
degraded alphas

Pb recoils

ROI 15-40keV

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

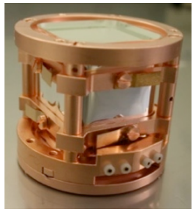
New Run – CRESST-II Upgrade



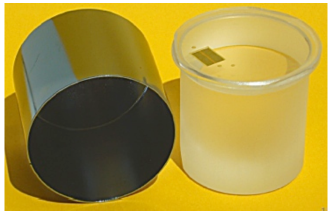
- Data-taking since July 2013
- 18 modules mounted (~ 5kg)
  → 17 of 18 are fully operational

✓ **11 x conventional design (improved)**
  - Use of radiopure clamps
  - Radon prevention

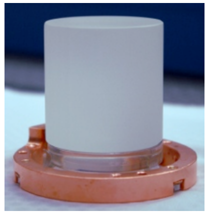
✓ **6 x fully-scintillating new designs**



$CaWO_4$ sticks

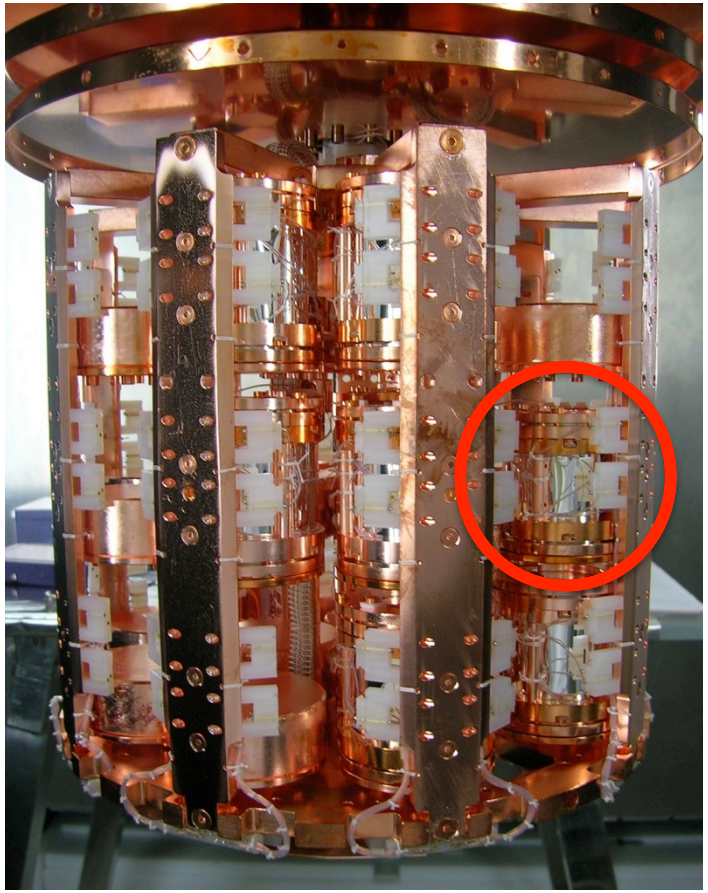


beaker



K-14

New Run – CRESST-II Upgrade



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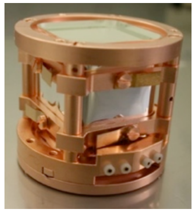
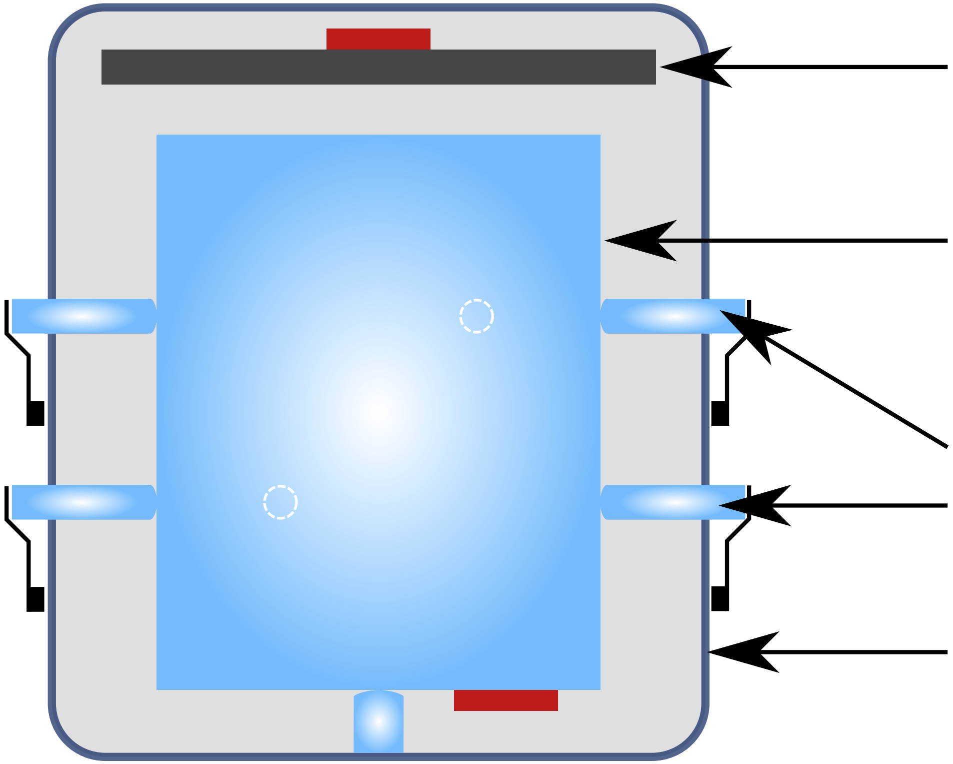


$CaWO_4$ sticks

this talk:
focus on one detector module (TUM-40)
mass: 250g
exposure: 29 kg-days

Fully-Scintillating Design



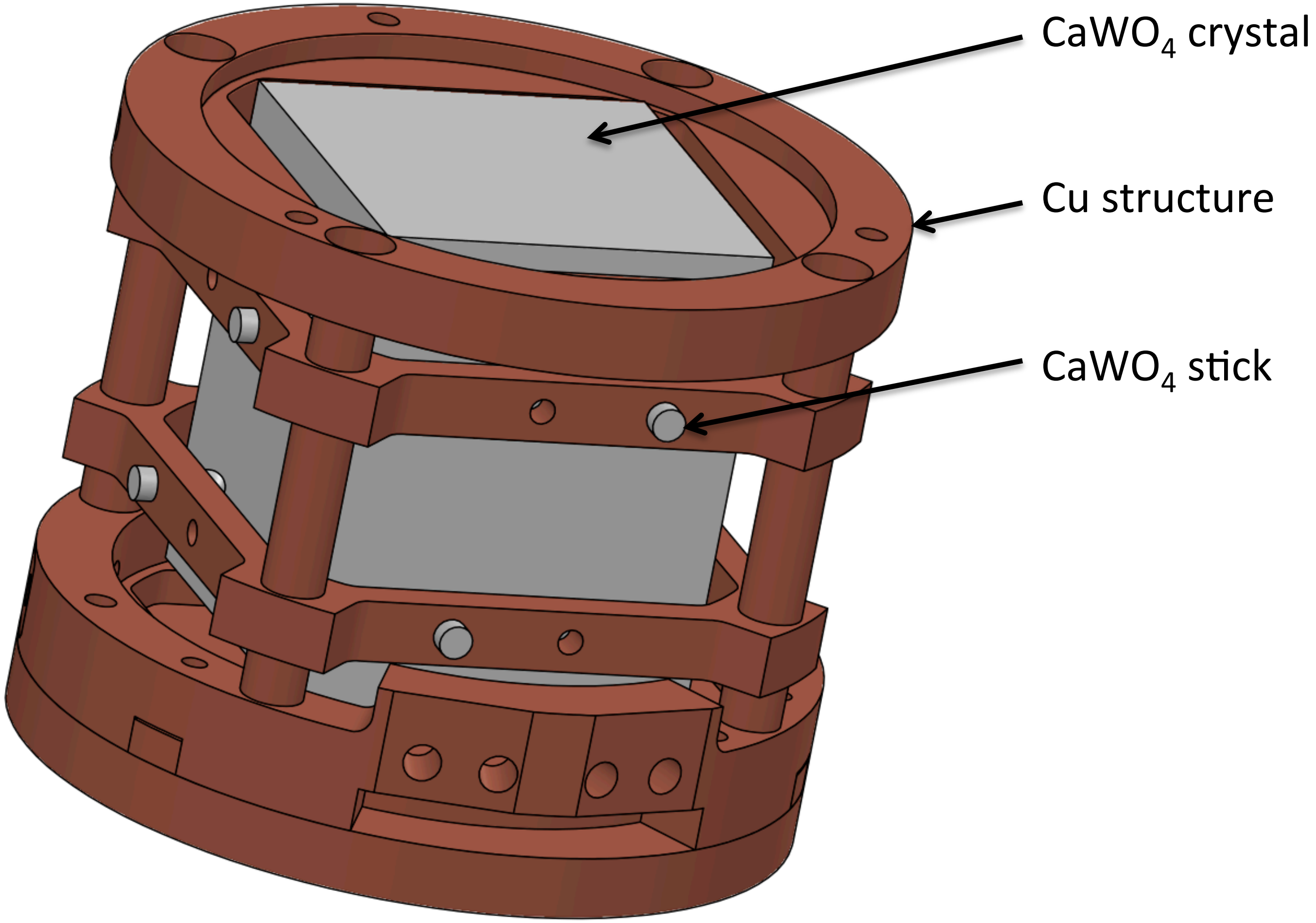
light detector (with TES)

block-shaped target crystal

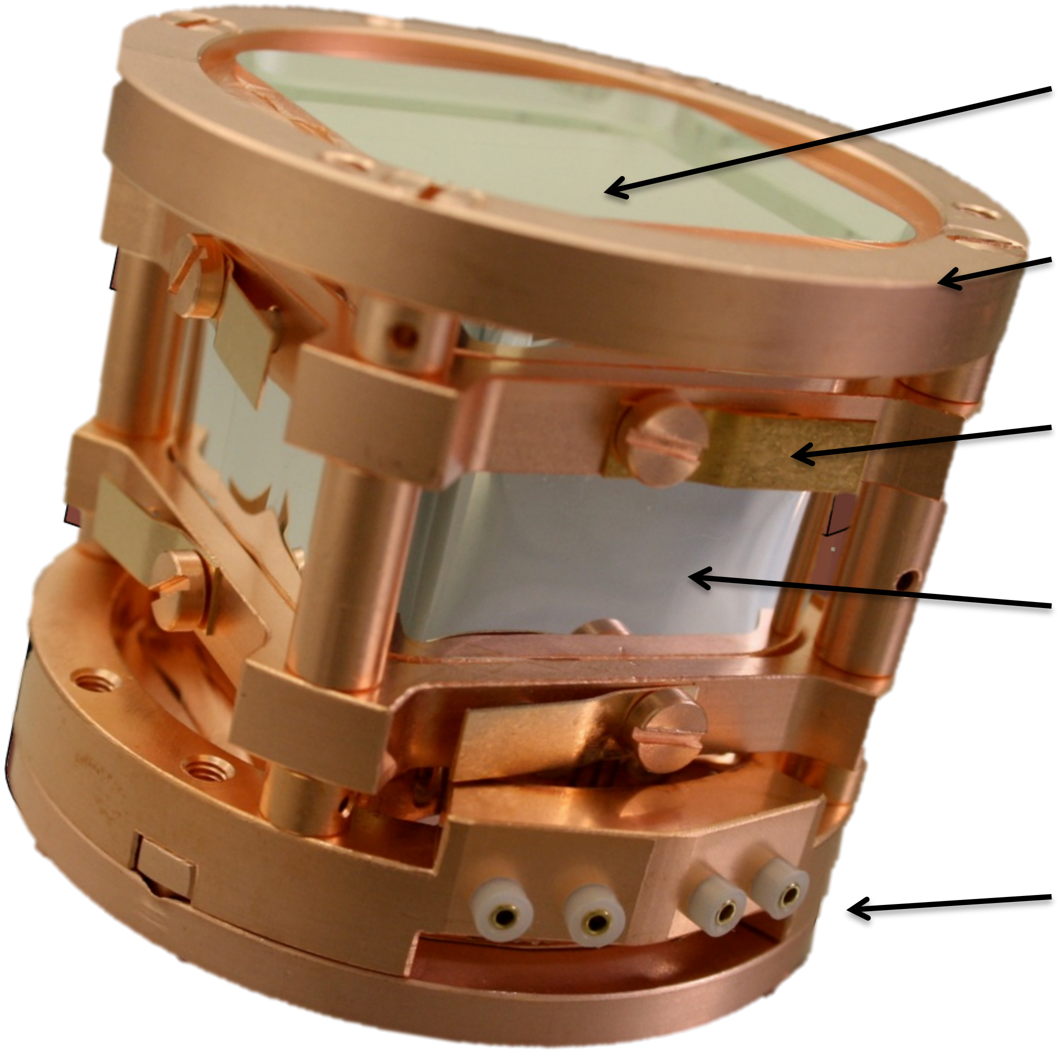
$CaWO_4$ sticks
(with holding clamps)

reflective and
scintillating housing

Stick-Based Detector Holder



Stick-Based Detector Holder



$CaWO_4$ crystal

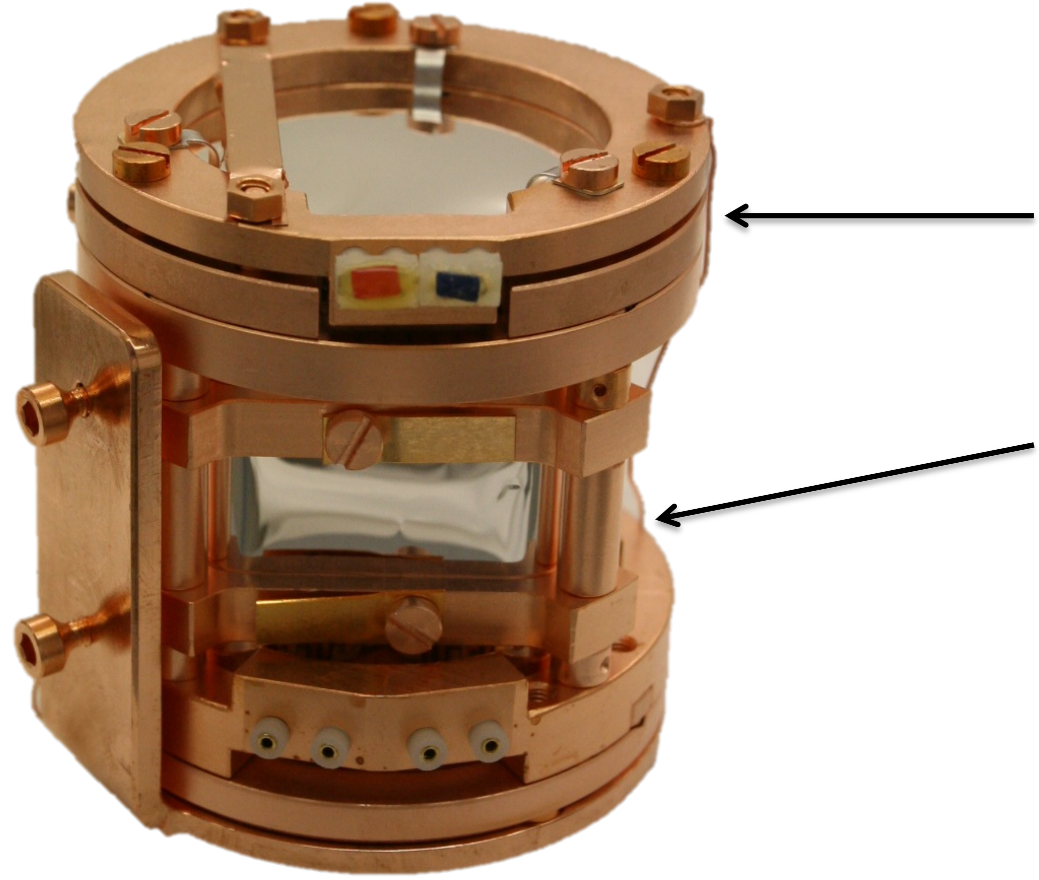
Cu structure

bronze clamp

scintillating/reflective foil

connectors for TES

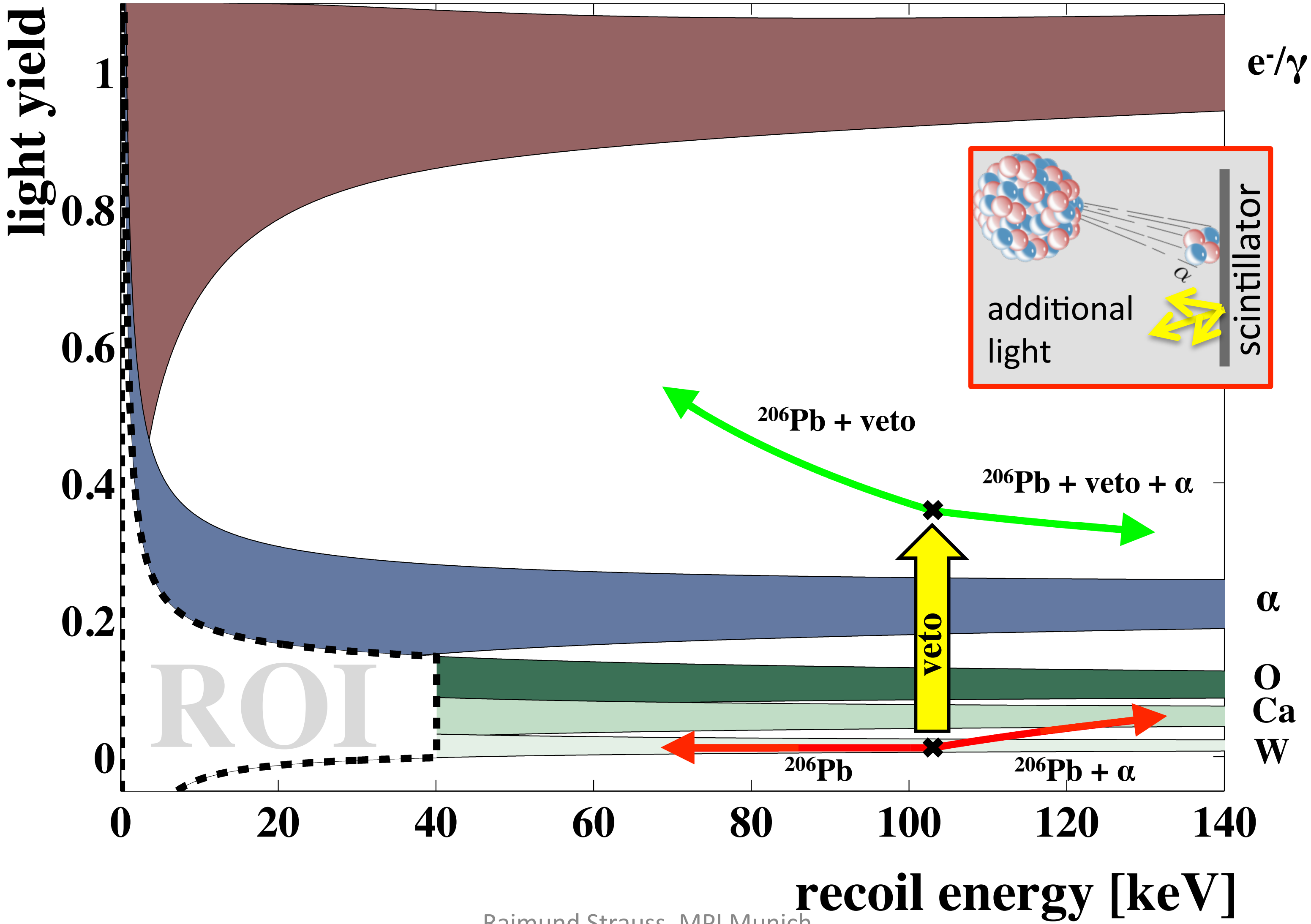
Stick-Based Detector Holder



Light detector „Michael“

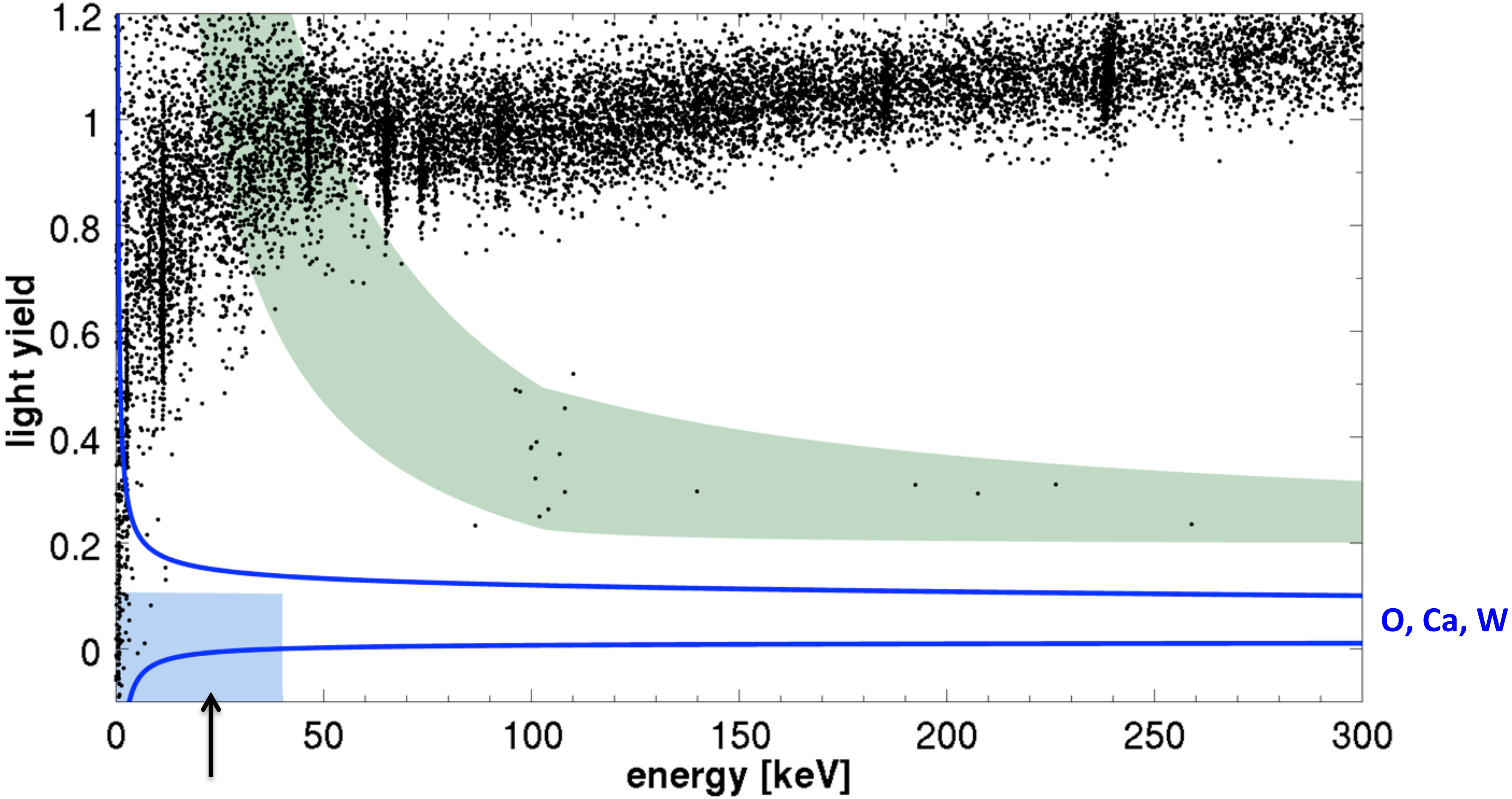
Phonon detector: TUM-40

Efficient Veto of Surface Backgrounds



TUM-40: Surface Backgrounds

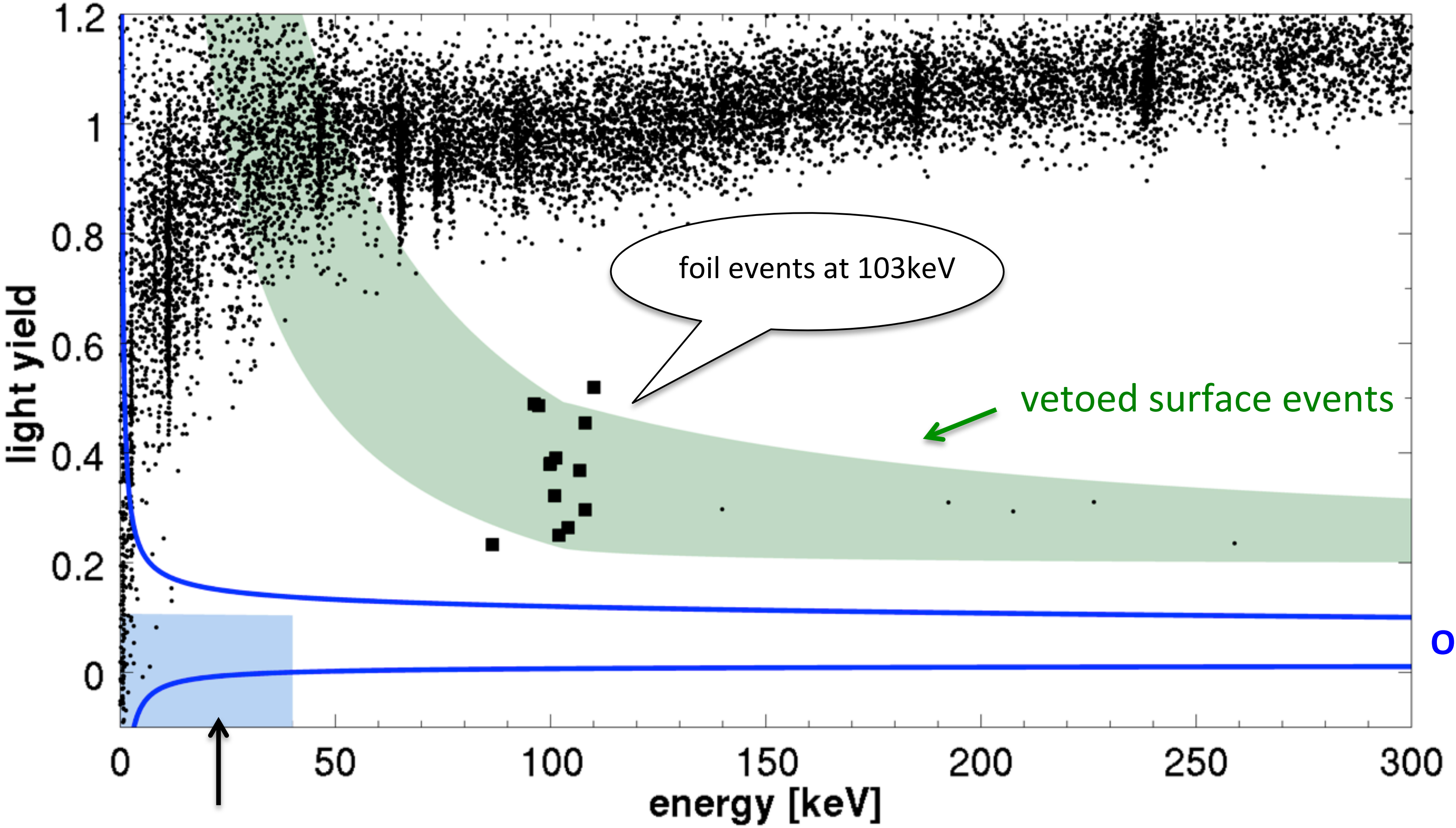
exposure: 29 kg-days



acceptance region

TUM-40: Surface Backgrounds

exposure: 29 kg-days



foil events at 103keV

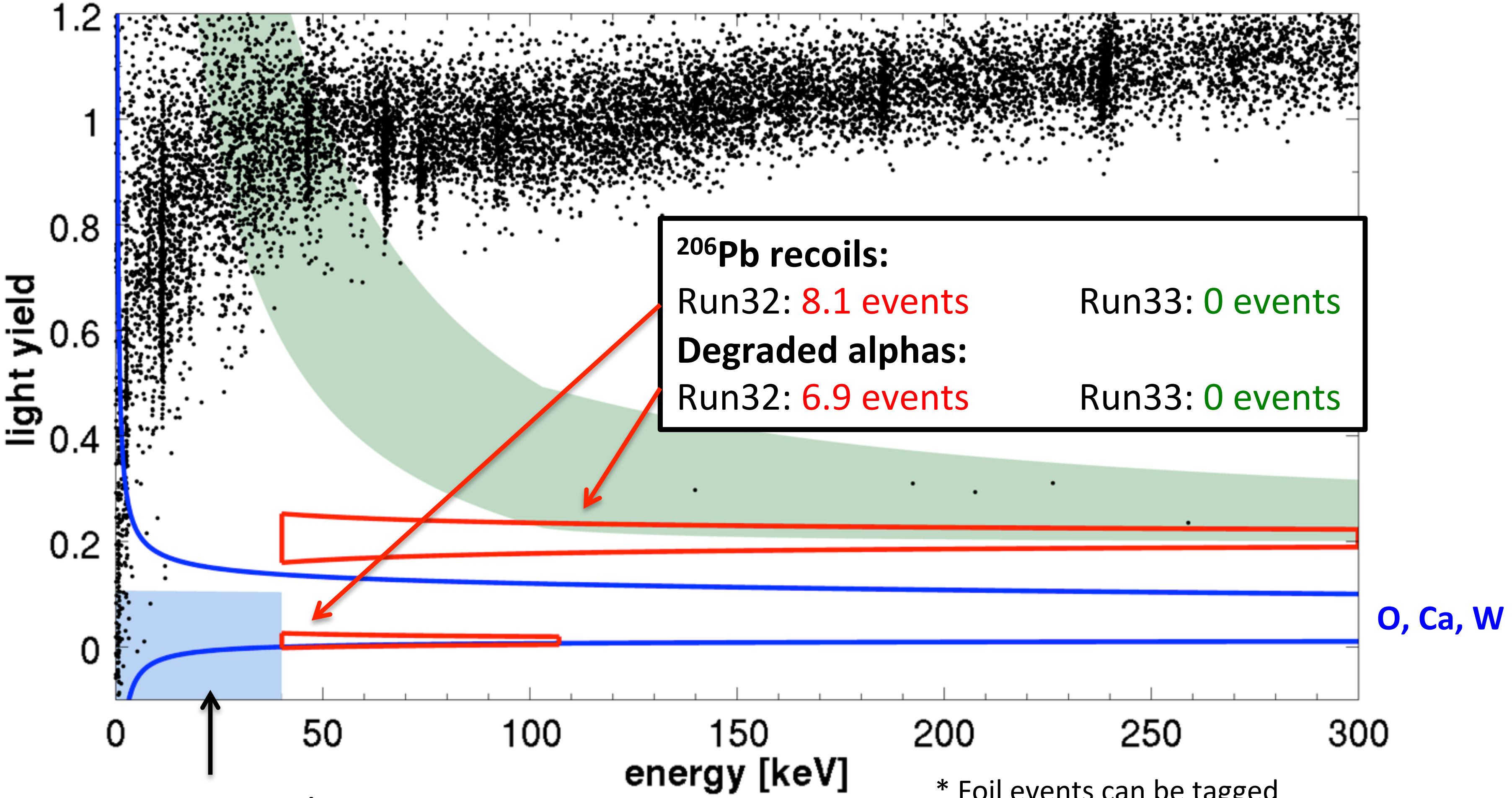
vetoed surface events

O, Ca, W

acceptance region

TUM-40: Surface Backgrounds

exposure: 29 kg-days



^{206}Pb recoils:

Run32: 8.1 events Run33: 0 events

Degraded alphas:

Run32: 6.9 events Run33: 0 events

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:

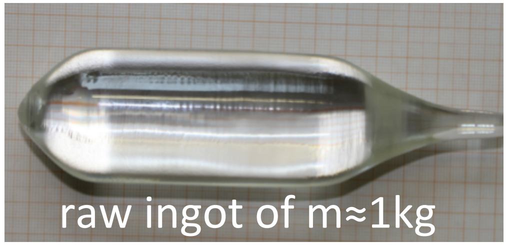
- All production steps under control
- Machining of crystals in-house

Goals :

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

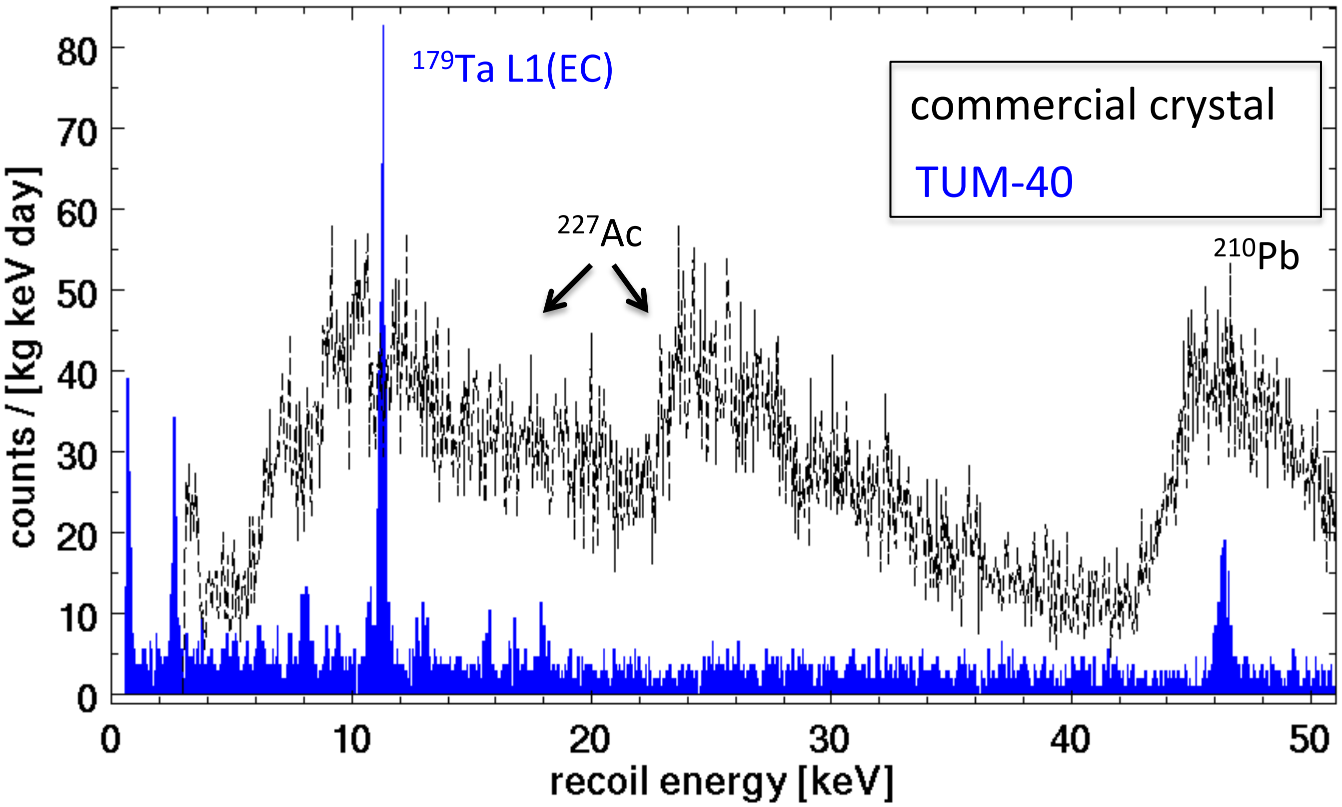
Major achievements:

- 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]

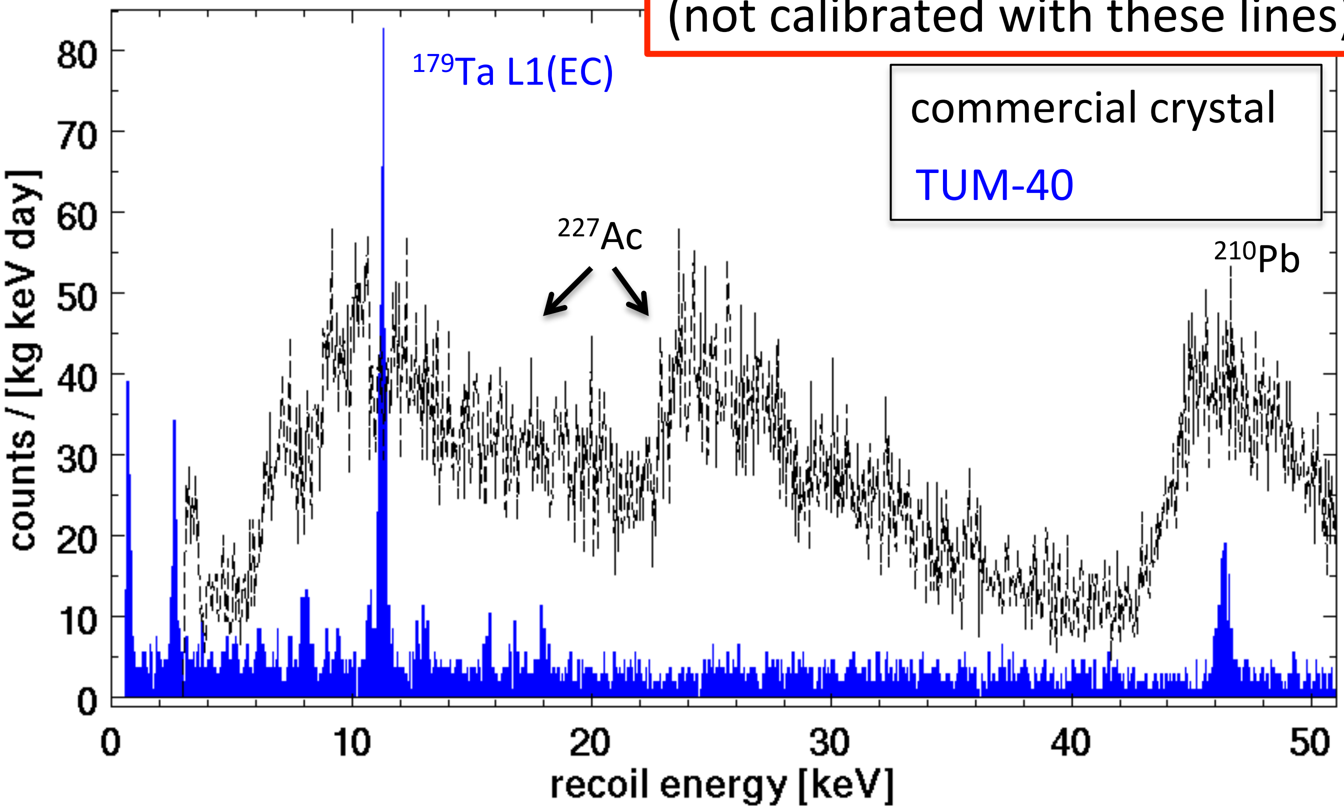
Gamma-lines from **cosmogenic activation**

Excellent resolution:

$\sigma \approx 100$eV

TUM-40: Radiopurity

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



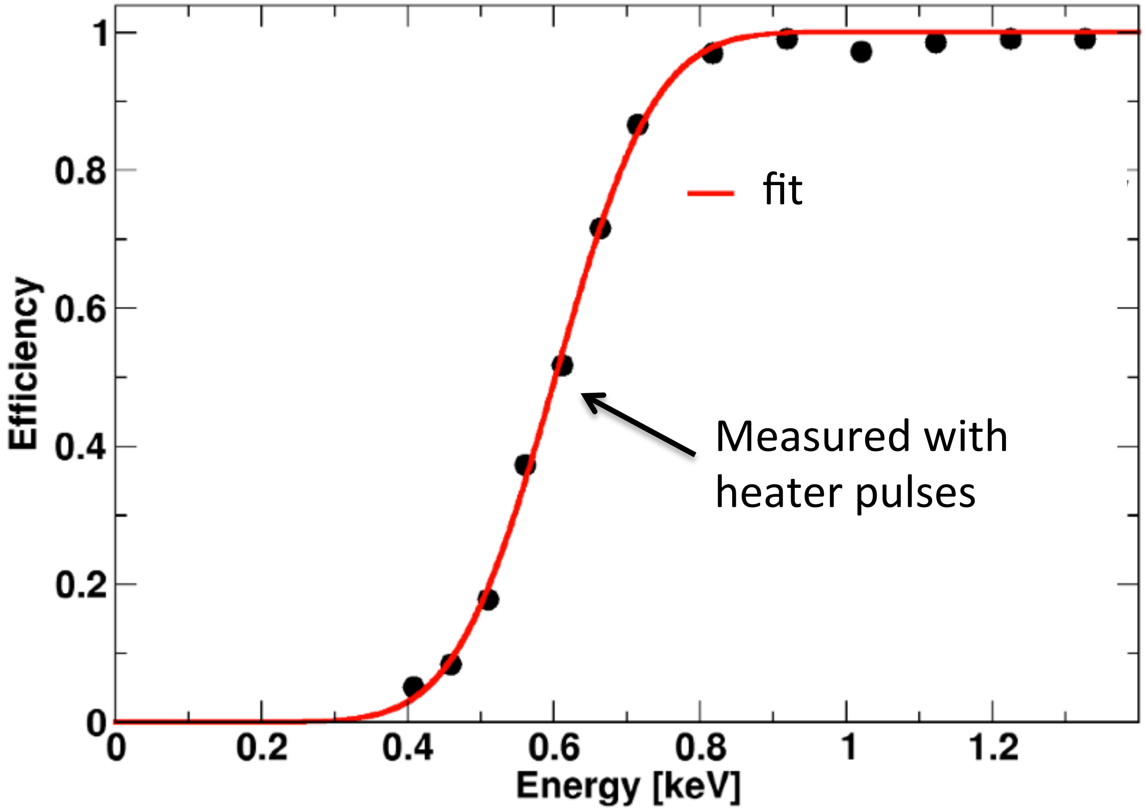
ge rate:
~3.5 counts / [kg keV day]

Gamma-lines from **cosmogenic activation**

Excellent resolution:

$\sigma \approx 100\text{eV}$

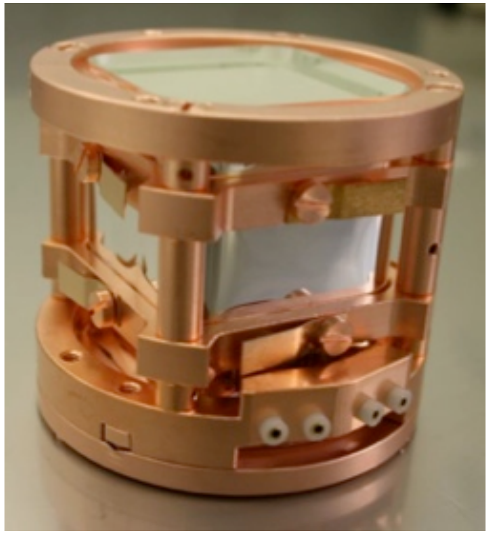
TUM-40: Trigger Threshold



- Extremely low trigger threshold of **E_{th} ≈ 603eV**
- Resolution of σ ≈ **107eV** in agreement with resolution of gamma lines

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

TUM-40: Performance

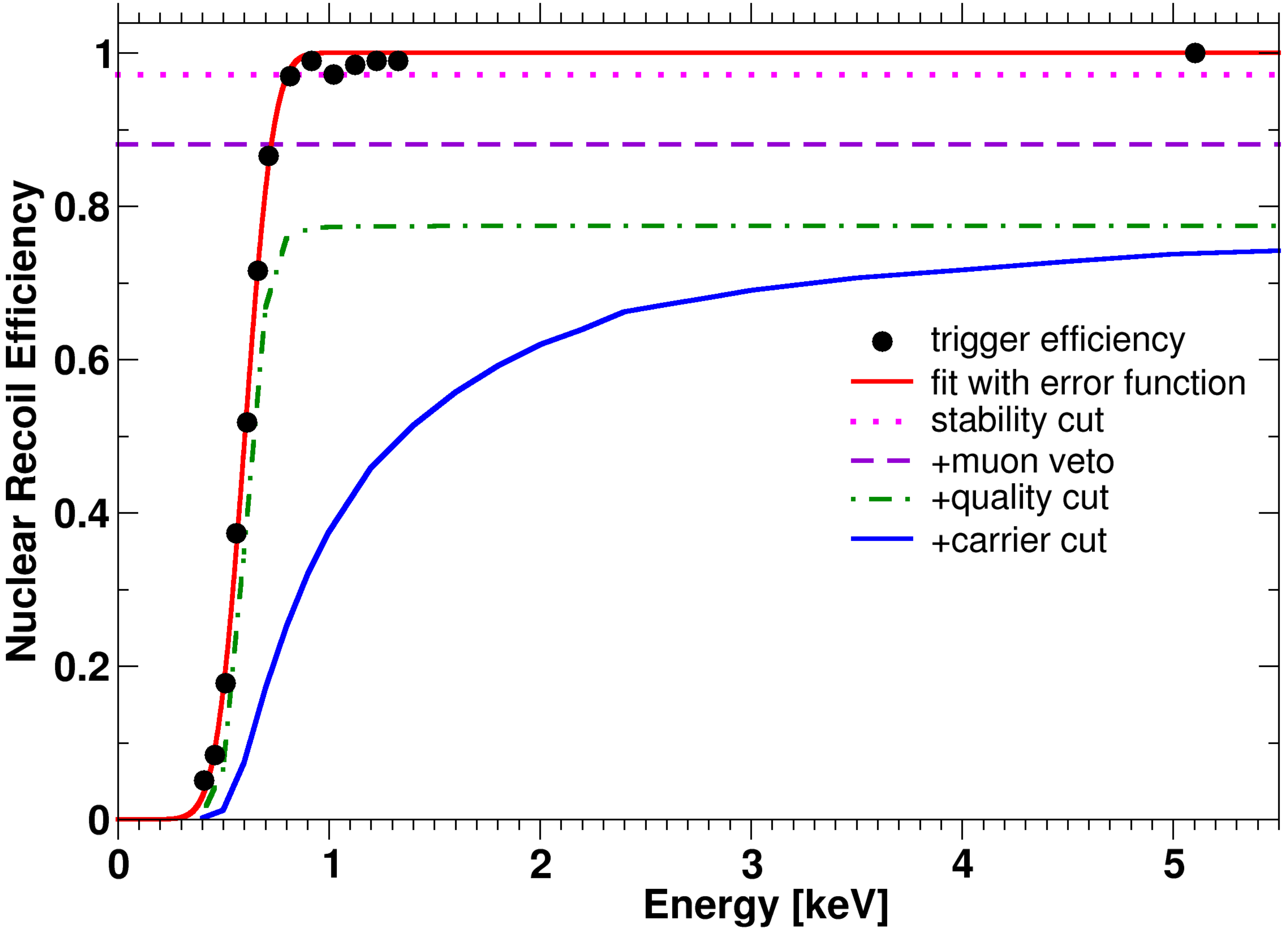


- **No surface backgrounds**
- **Best radiopurity** (≈ 3.5 / [kg keV day])
- **Low trigger threshold** (≈ 0.60 keV)
- **High resolution** ($\sigma \approx$ 100 eV)

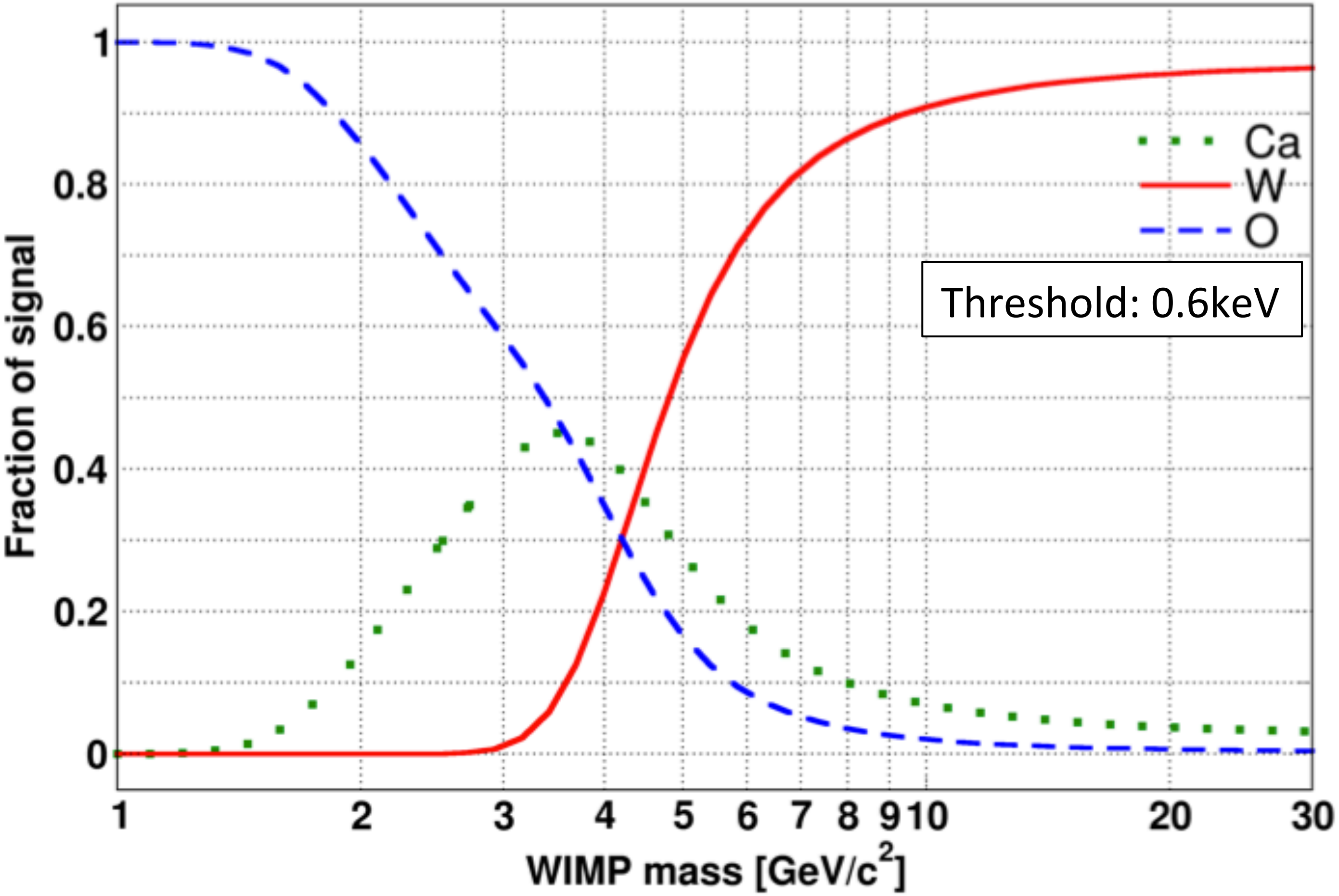
→**Low-threshold** Dark Matter analysis possible

→Use non-blinded dataset of 29kg-days

TUM-40: Acceptance at Lowest Energies

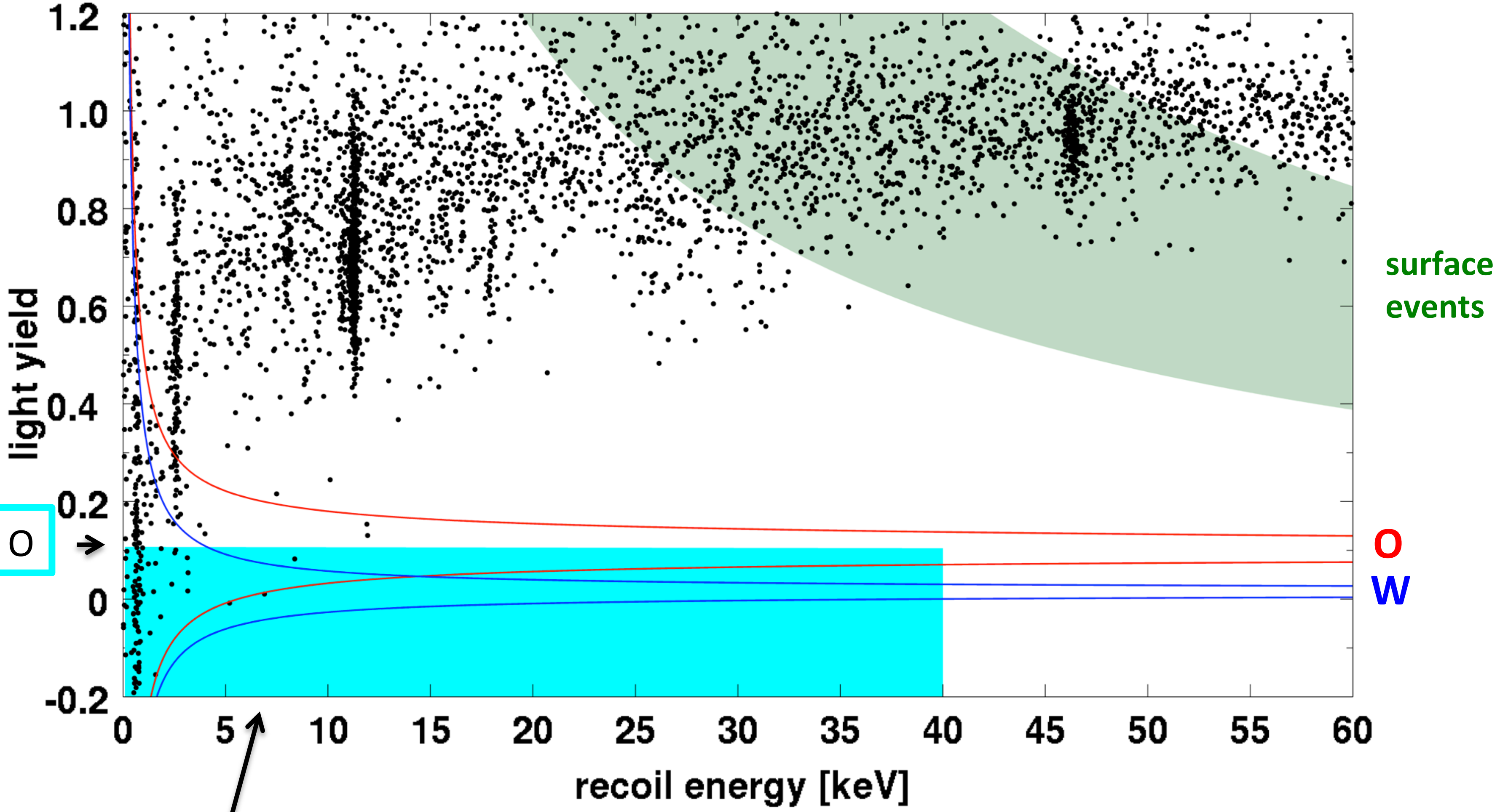


Fraction of WIMP Scatters on O, Ca and W



Threshold: 0.6keV

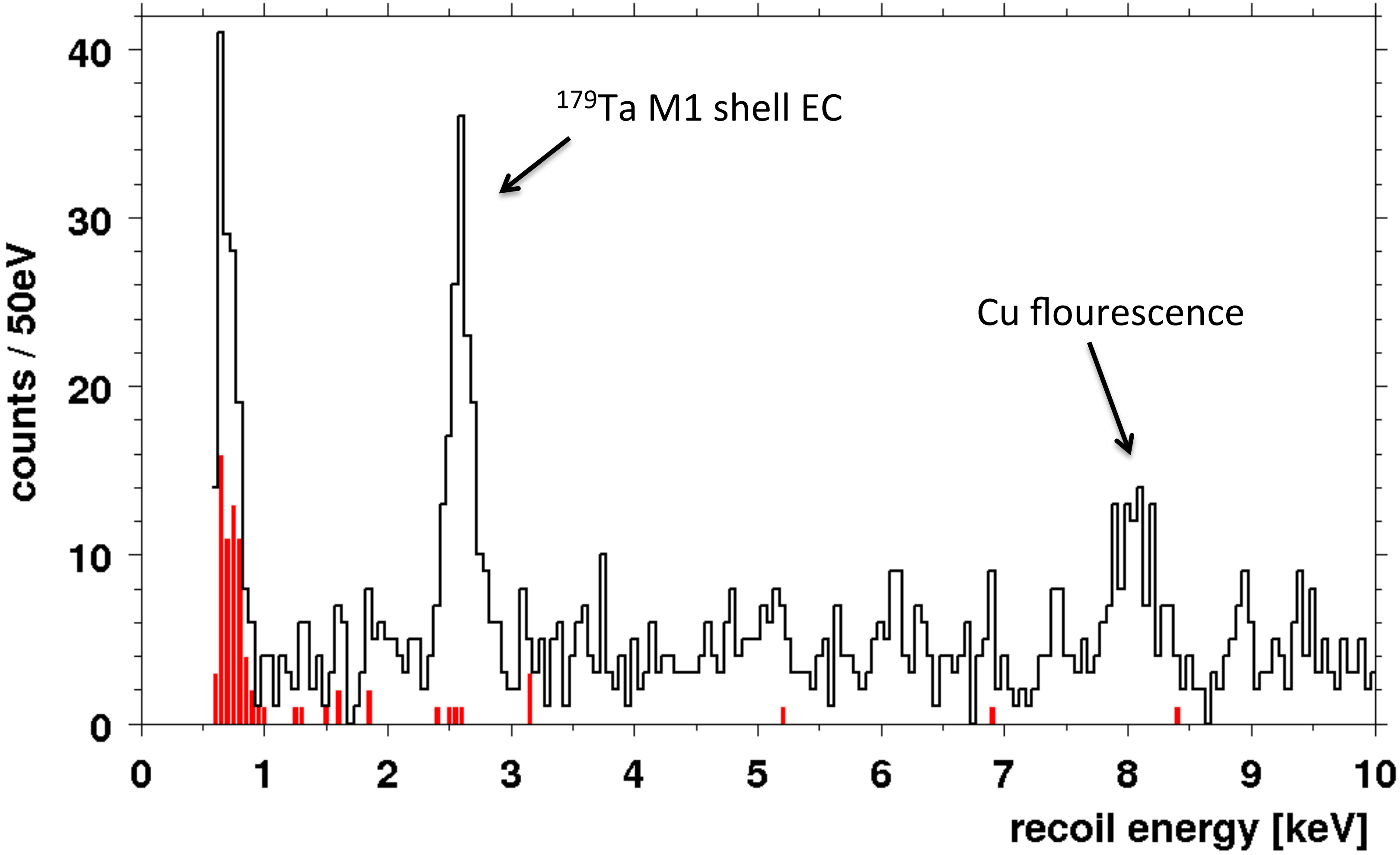
WIMP-Acceptance Region



50% O

acceptance region (E_r = 0.6 - 40keV)

Events in Acceptance Region



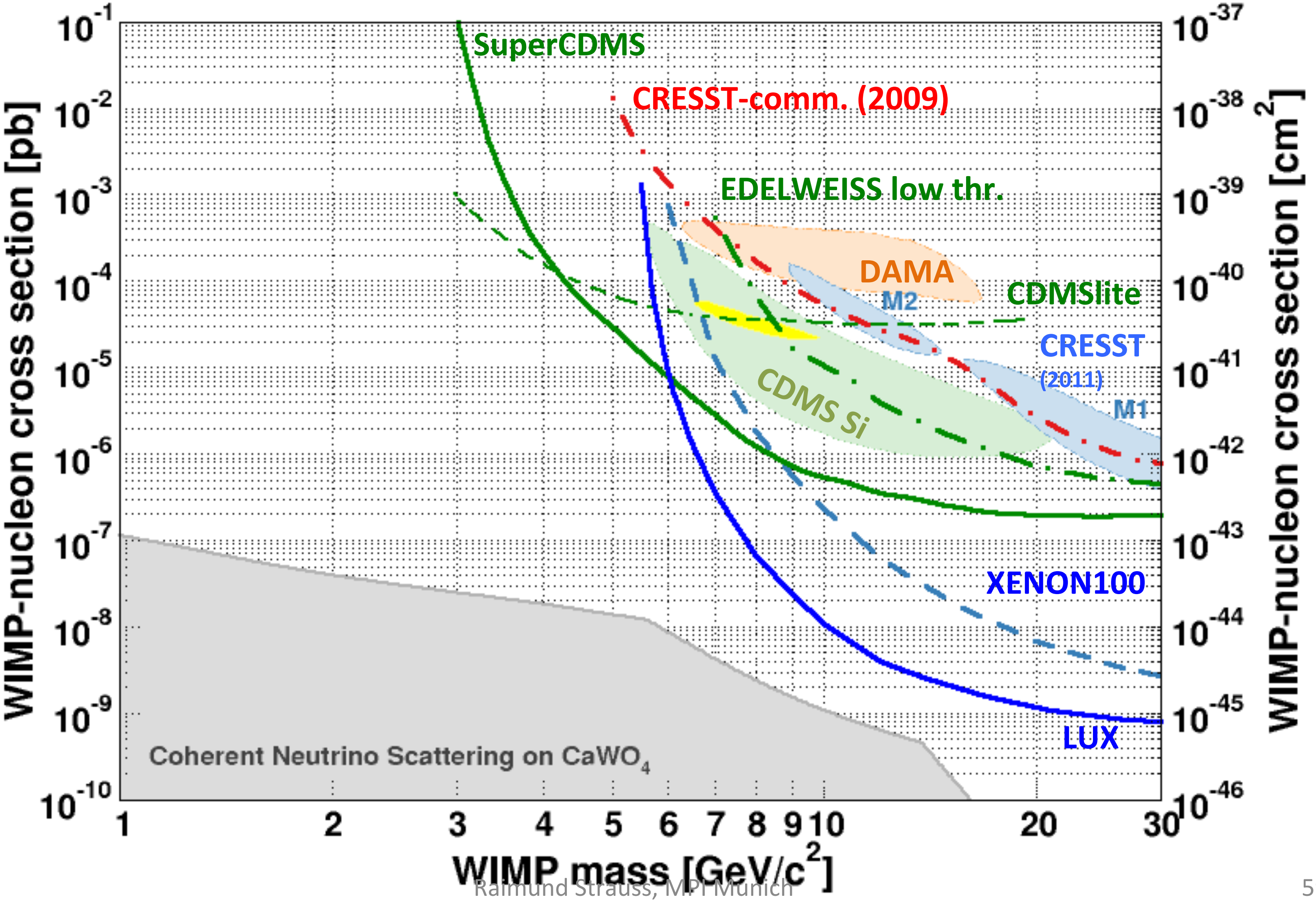
All 79 events accepted are conservatively considered as WIMP scatters!

Analysis Details

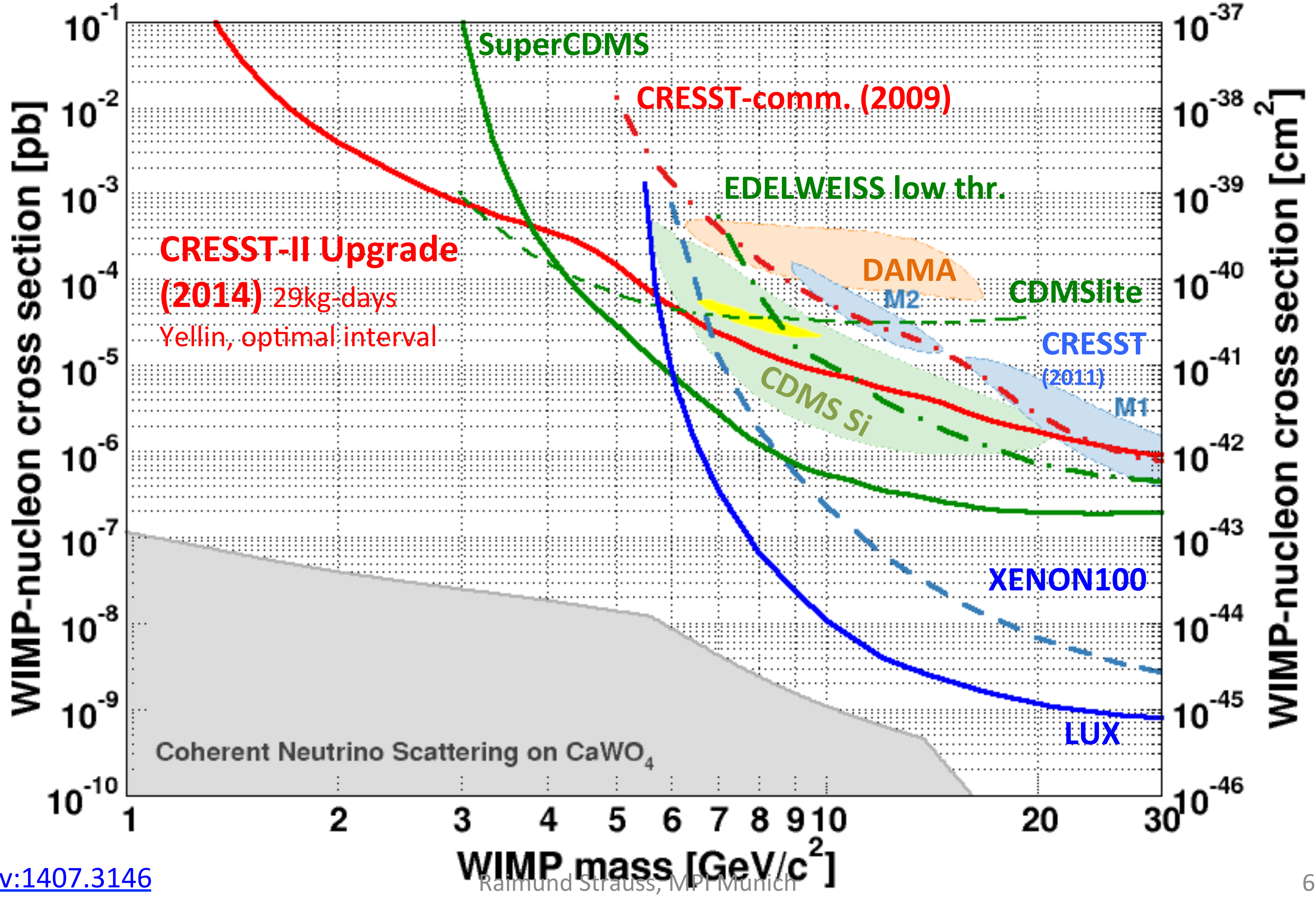
- 3 independent analysis chains (from raw data to final results)
- 3 different software environments

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

Present WIMP Landscape

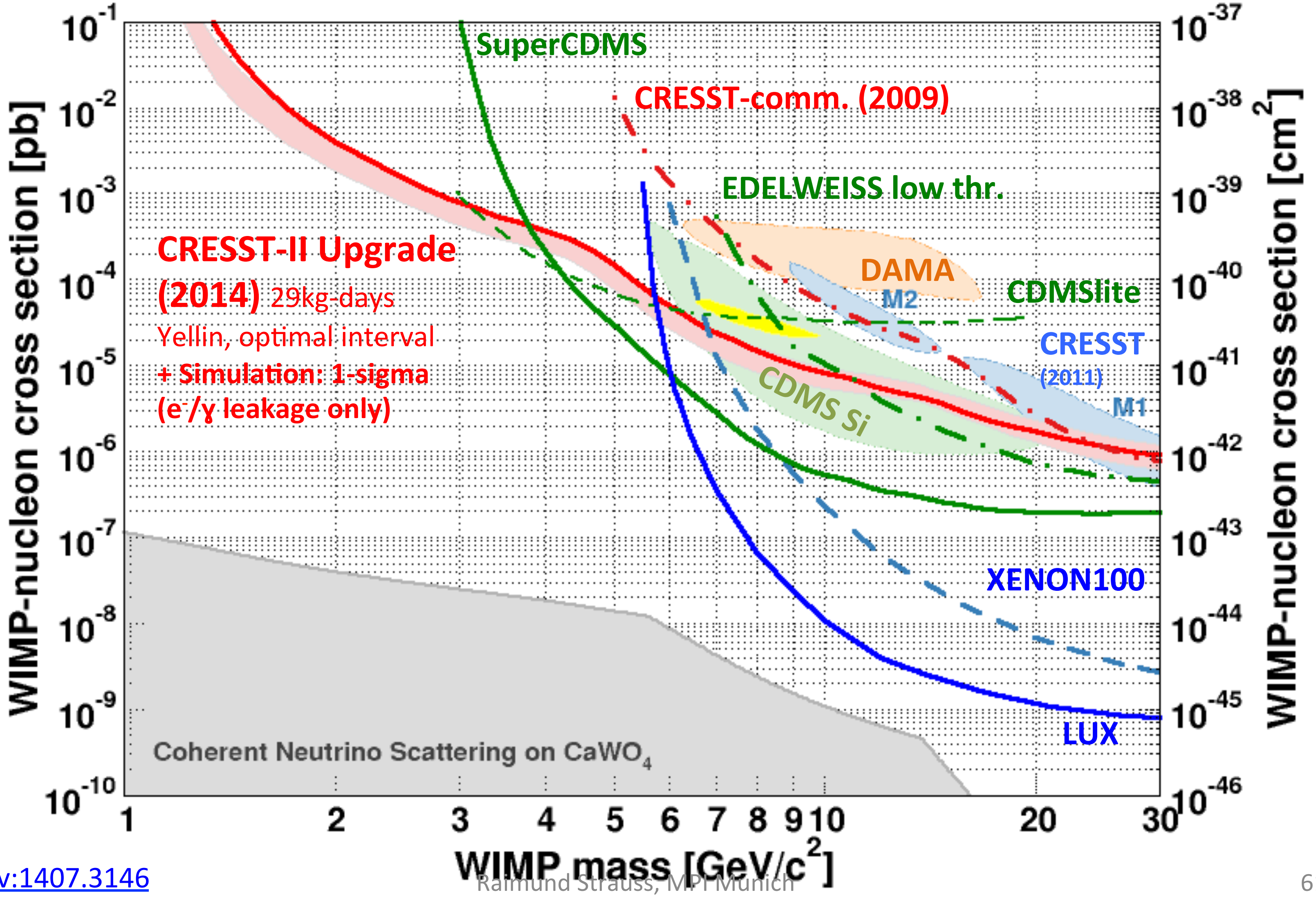


Results from 29kg-days of TUM-40



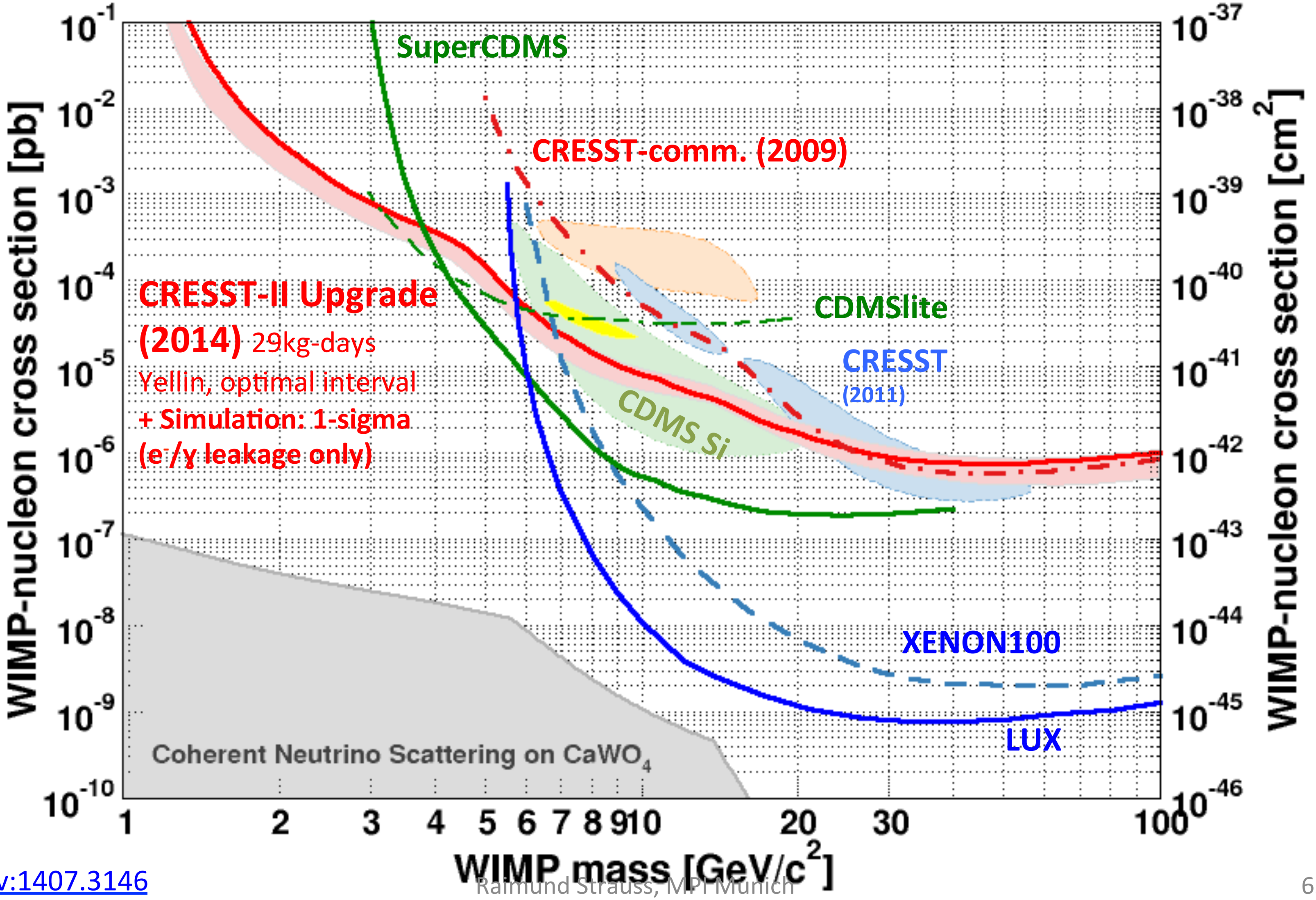
arXiv:1407.3146

Data vs. Simulation



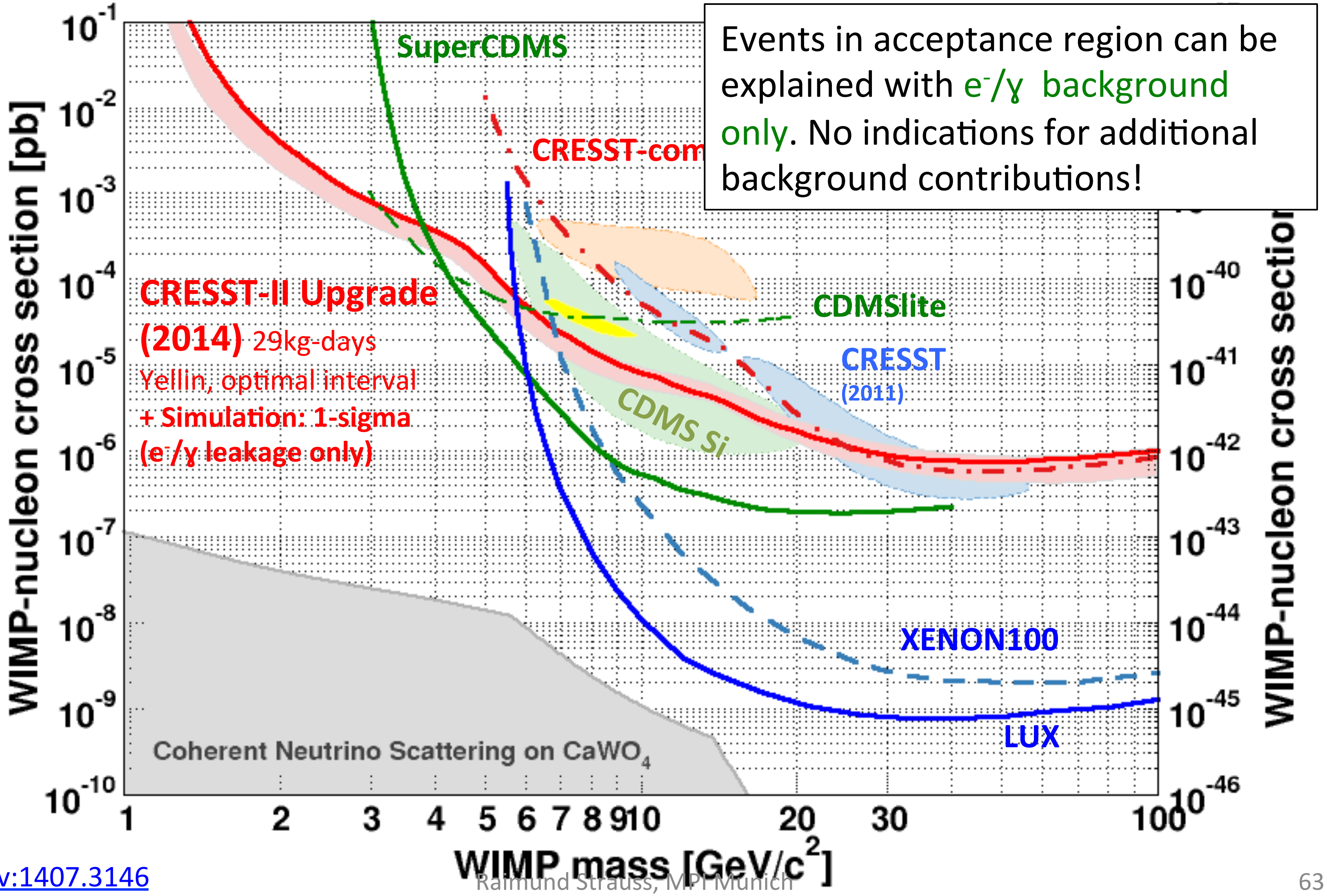
arXiv:1407.3146

Data vs. Simulation



arXiv:1407.3146

Data vs. Simulation



Events in acceptance region can be explained with e^-/ɣ background only. No indications for additional background contributions!

arXiv:1407.3146

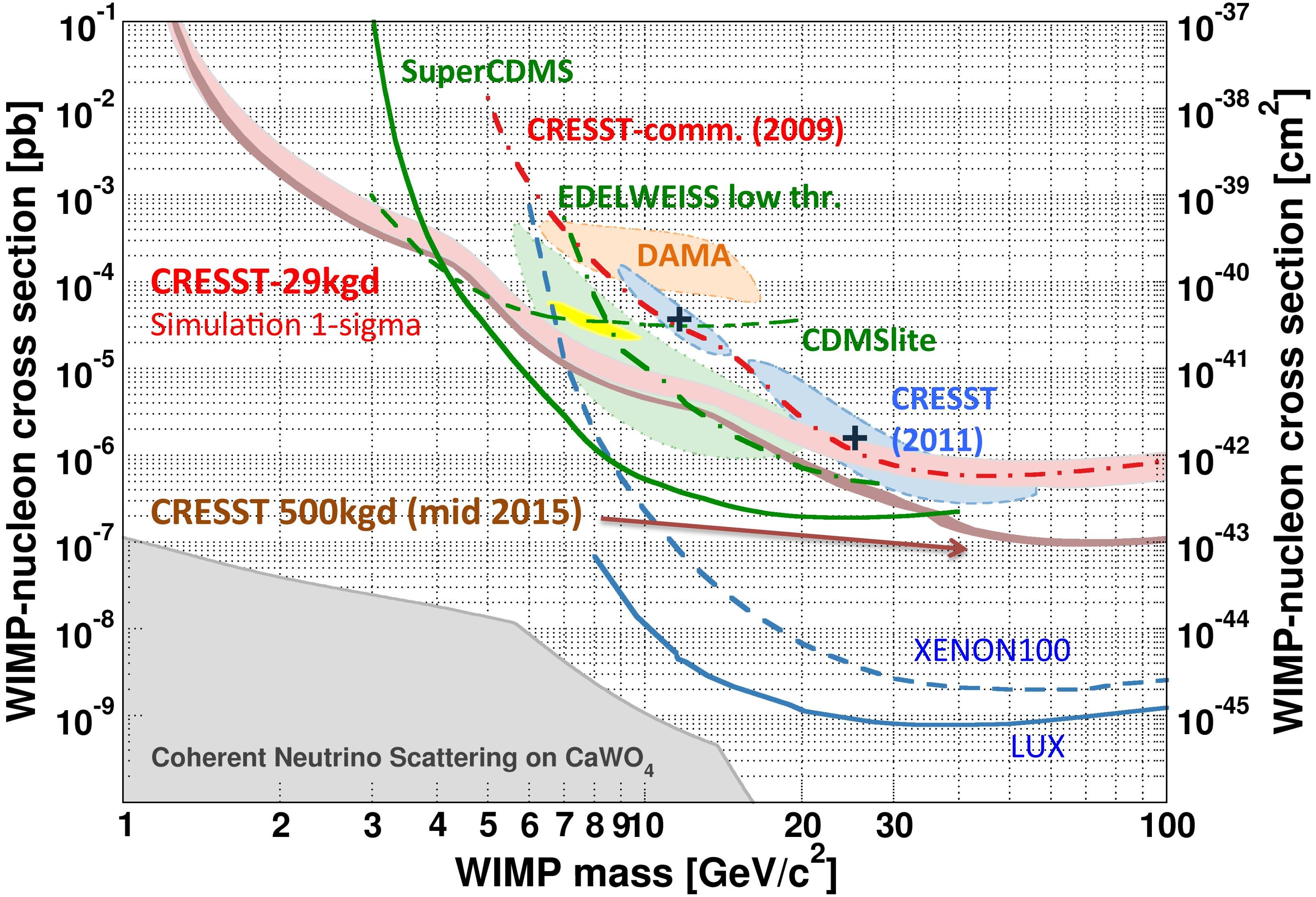
Present Run - Analysis Strategy

Non-blinded data set (115 live days) defines:

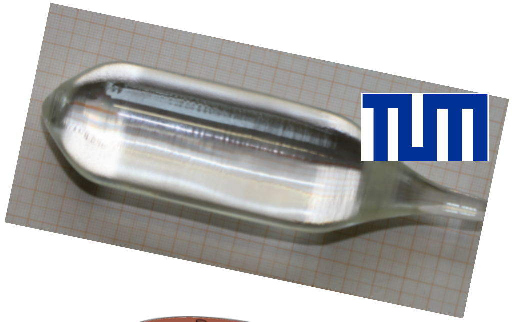
- all data quality cuts
- trigger efficiencies
- selection of detectors

Since Jan 2014 – **blinded data**

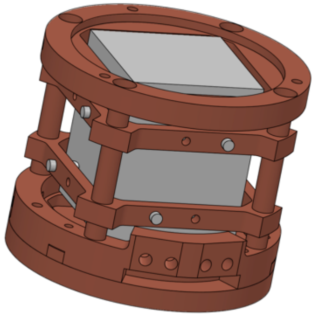
Projection for Current Run



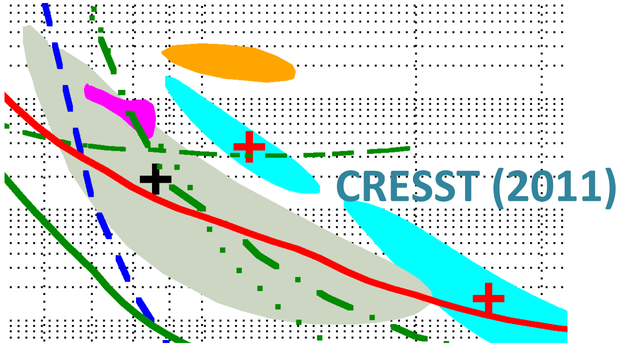
Summary of New Results



- Significant improvement in radiopurity of $CaWO_4$ crystals (3.5 counts/[keV kg day])

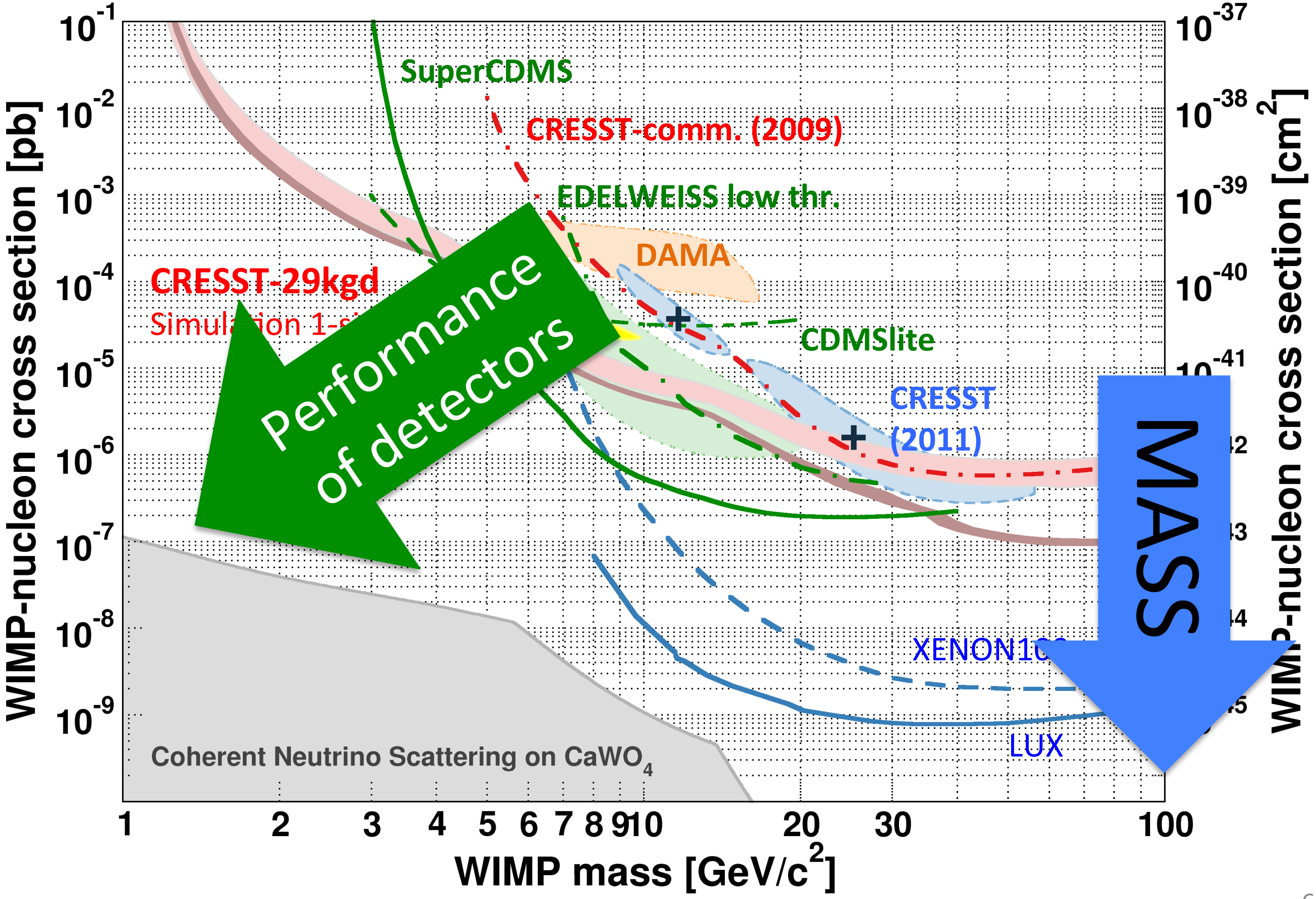


- Efficient rejection of surface backgrounds with fully-scintillating detector design



- CRESST low-mass WIMP solution (M2) completely ruled out
- New WIMP parameter space explored (<3GeV/c^2) with one single $CaWO_4$ detector

Future Strategy



Raimund Strauss, MPI Munich

CRESST-III: Low-Mass WIMP Search

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

Status quo (TUM40)

m = 250g
V = 32x32x40 mm^3

Phonon threshold: $E_{th} \approx 0.4$ keV

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

CRESST-III: Low-Mass WIMP Search

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

Status quo (TUM40)

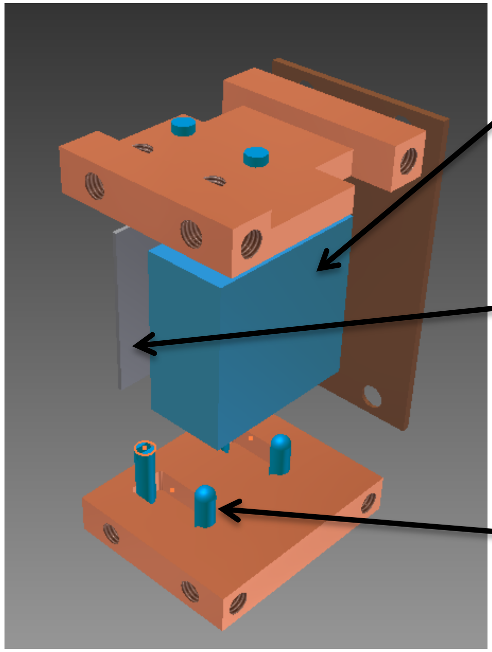
m = 250g
V = 32x32x40 mm^3

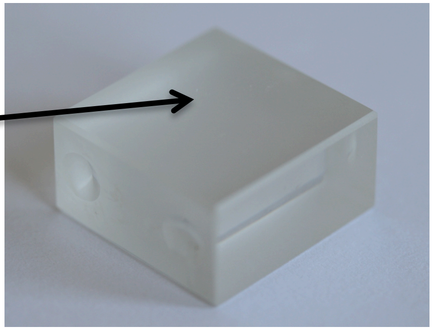
m=24g

Phonon threshold:	$E_{th} \approx 0.4$ keV	improvement by a factor of 5
Light-detector res.:	$\sigma \approx 5$ eV	improvement by a factor of 2

NO improvements assumed concerning radiopurity and optical quality of crystals!

CRESST-III Phase 1 - Prototype

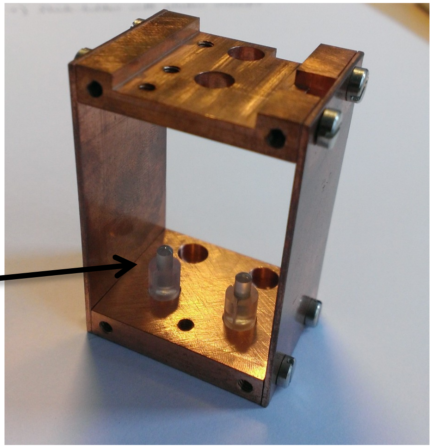




24g block-shaped $CaWO_4$ crystal ($10x20x20mm^3$)

Si light detector ($20x20mm^2$) + 2^{nd} light detector

$CaWO_4$ sticks

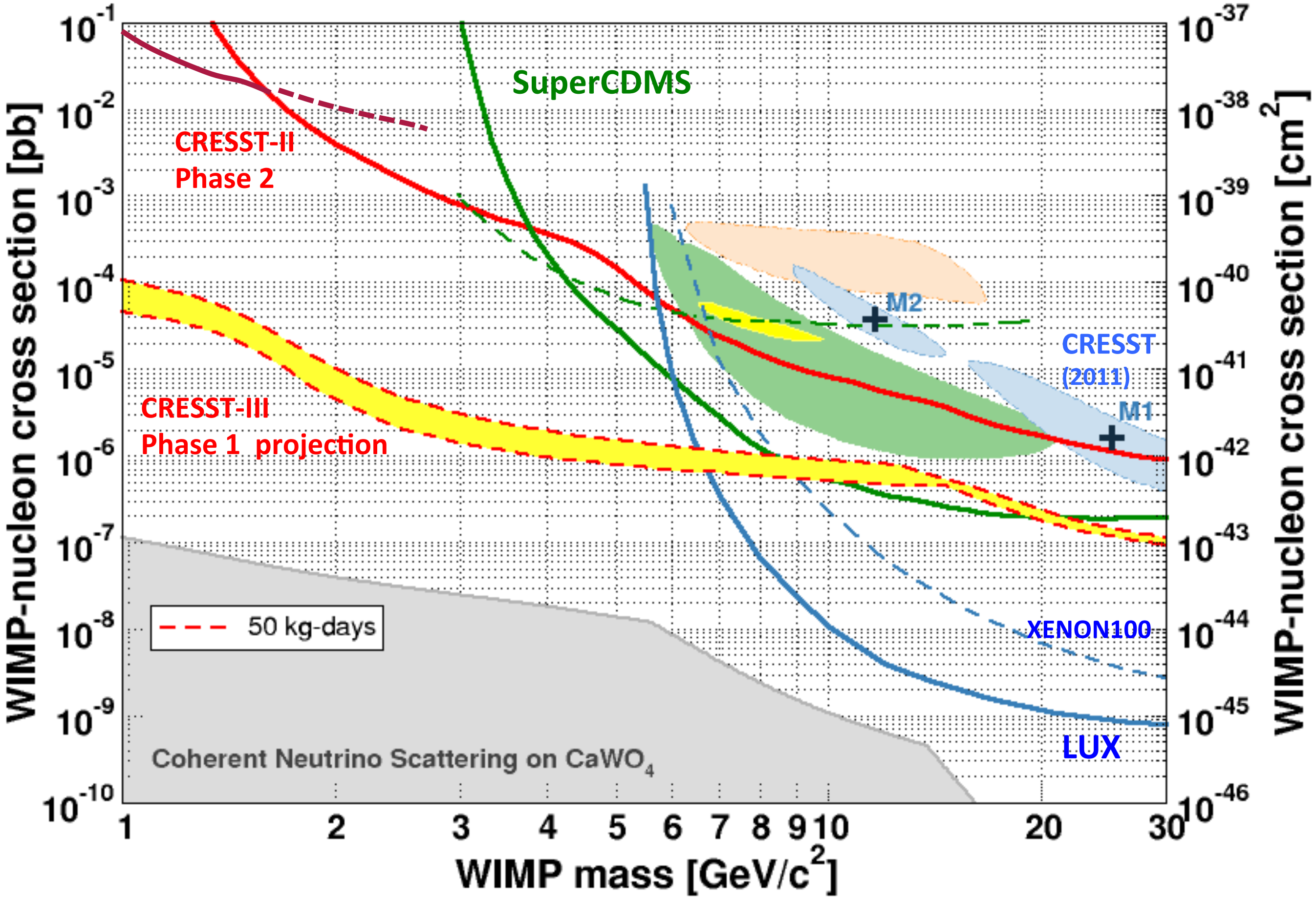


Very recently: **Threshold of 100eV** reached with prototype detector! ✓

CRESST-III Phase 1

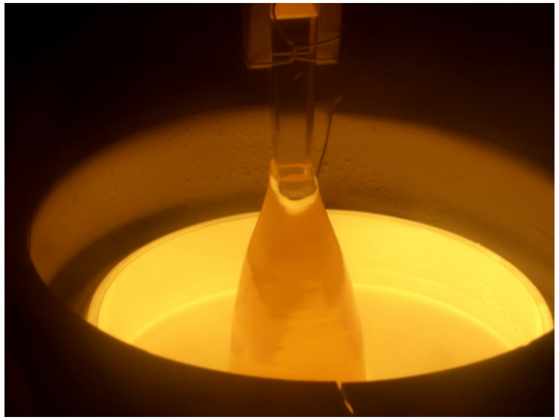
Assumptions:

- $24g\ CaWO_4$ crystal
- $E_{th} = 0.10$ keV
- Light detector improved by factor 2 (due to smaller volume)
- 2x more detected light: due to thin crystal



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

CRESST-III Phase 2



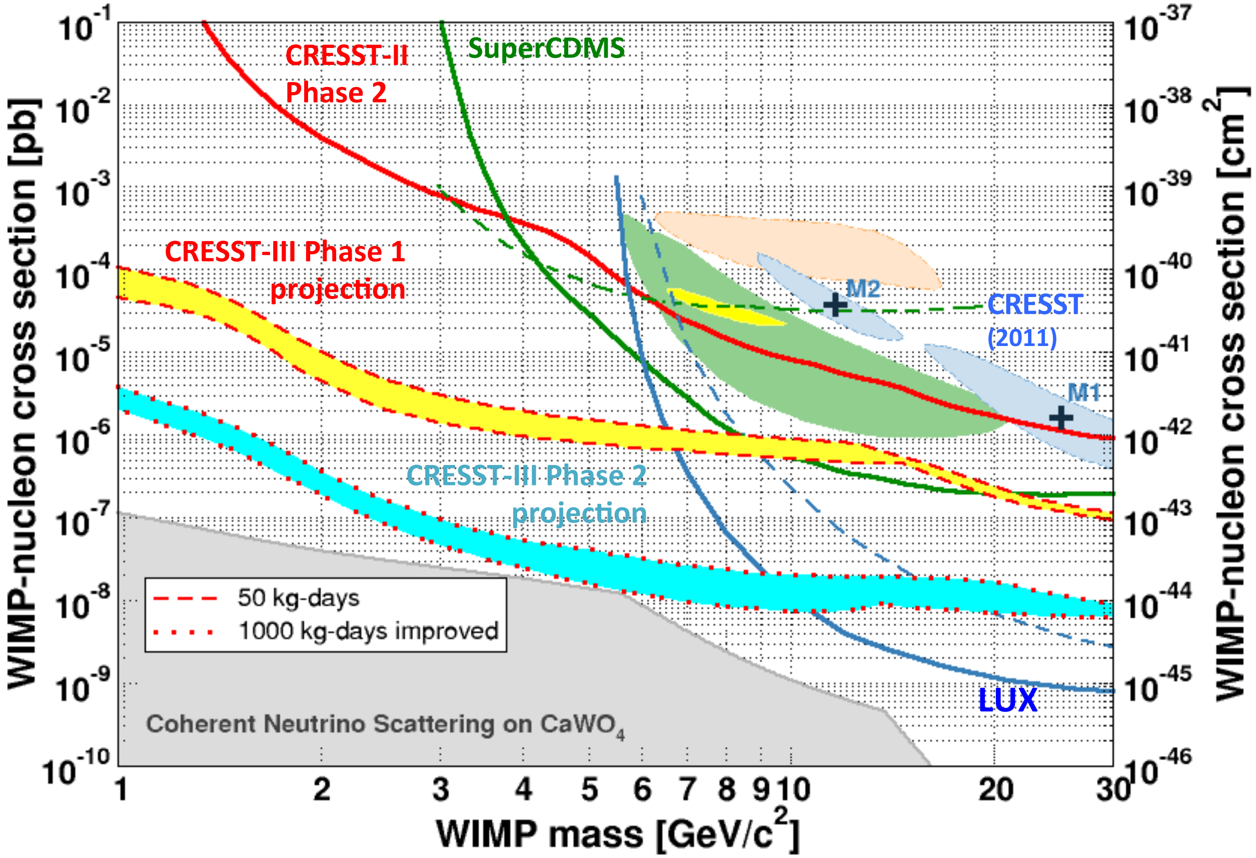
Reduce intrinsic background level of crystals!

- 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

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)

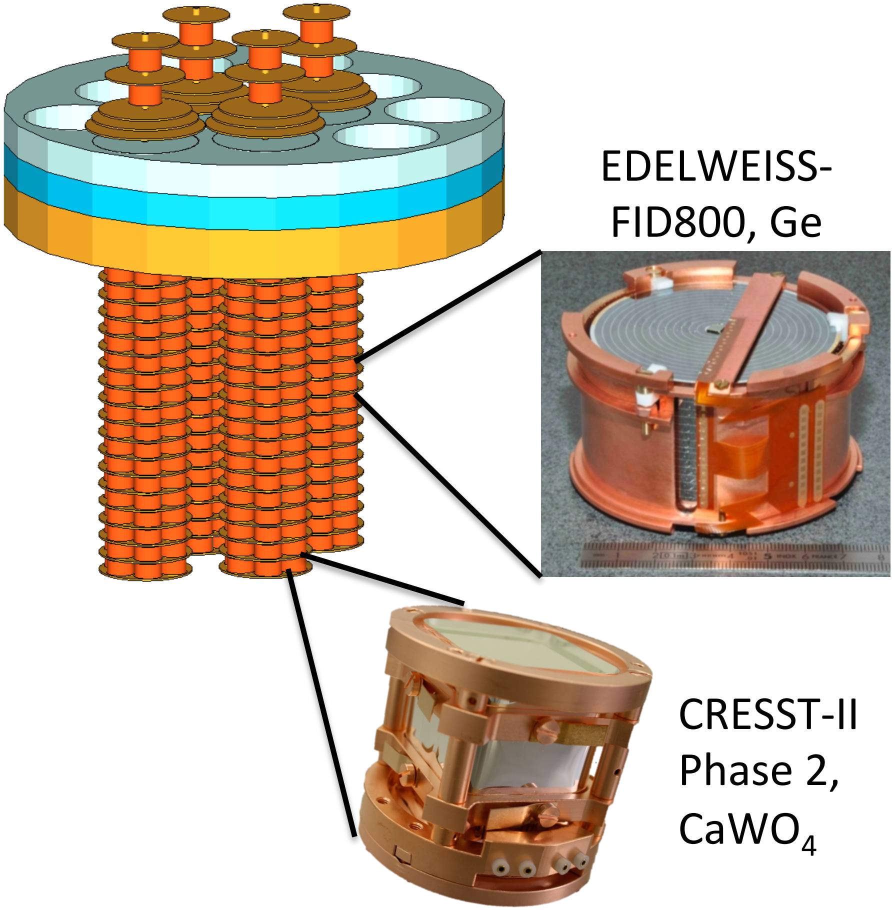
Future European Cryogenic Dark Matter Experiment - EURECA

Project based on CRESST & EDELWEISS technologies

- Conceptual design report 2014

  G. Angloher et al., Physics of the Dark Universe **3** (2014) 41–74

- modular towers in cryostat
- Water shield around cryostat
- ➢ **Phase 1:**
  - six 800g Ge or twelve 300g $CaWO_4$ per tower level
  - Option: 1.6kg Ge and 1kg $CaWO_4$ detectors
- ➢ **Phase 2:** up to 1ton of target mass



EURECA & SuperCDMS

Based on earlier collaborative work between EDELWEISS and CDMS-II

- ➢ Common analysis of Ge detectors Phys. Rev. D 84, 011102(R) (2011)

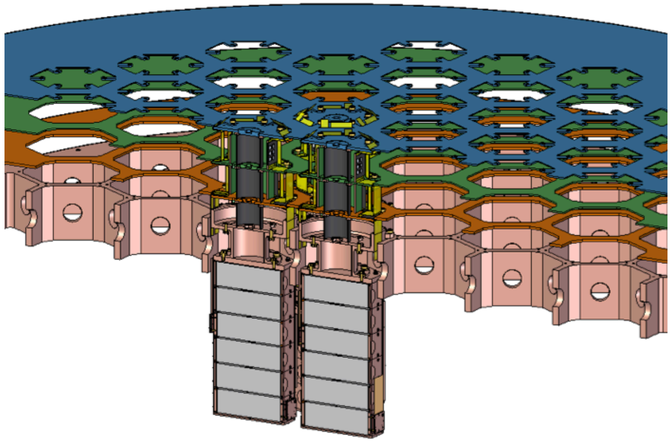
Status SuperCDMS:

Supported experiment after G2-downselection

- Funding for large cryostat (up to 400kg of target mass)
- Funding of 50kg Ge detectors

Expected EURECA contribution:

- Detectors (Ge + $CaWO_4$)
- Cryogenics
- towers & readout
- optimisation of shielding

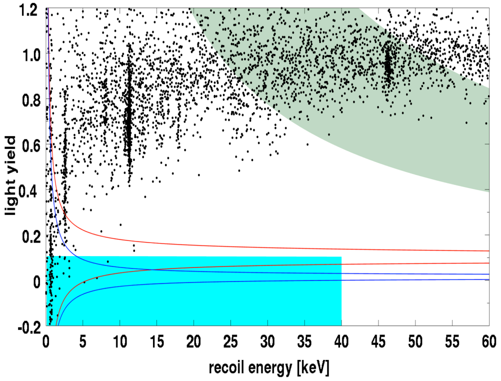


Close contact between EDELWEISS, CRESST and SuperCDMS collaborations!

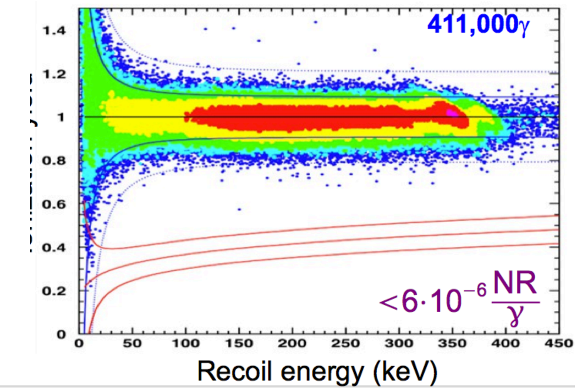
Summary

Standard (high-mass) WIMPs with cryogenic detectors

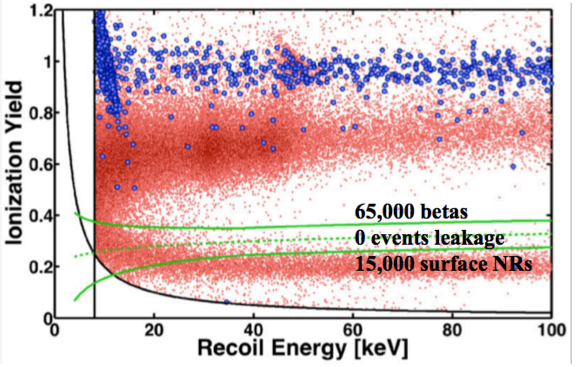
CRESST-II



EDELWEISS-III



SuperCDMS



- background-free technology (above ~15keV)
- ton scale feasible with state-of-the-art detectors

Summary

- CRESST technology has high potential for **low-mass WIMP search**
  - ✓ Lowest thresholds in the field: <=100eV
  - ✓ Background discrimination down to low energies
  - ✓ 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 – starting end of 2015!