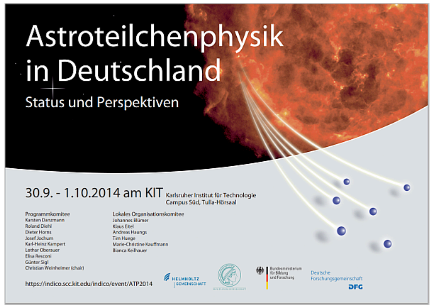
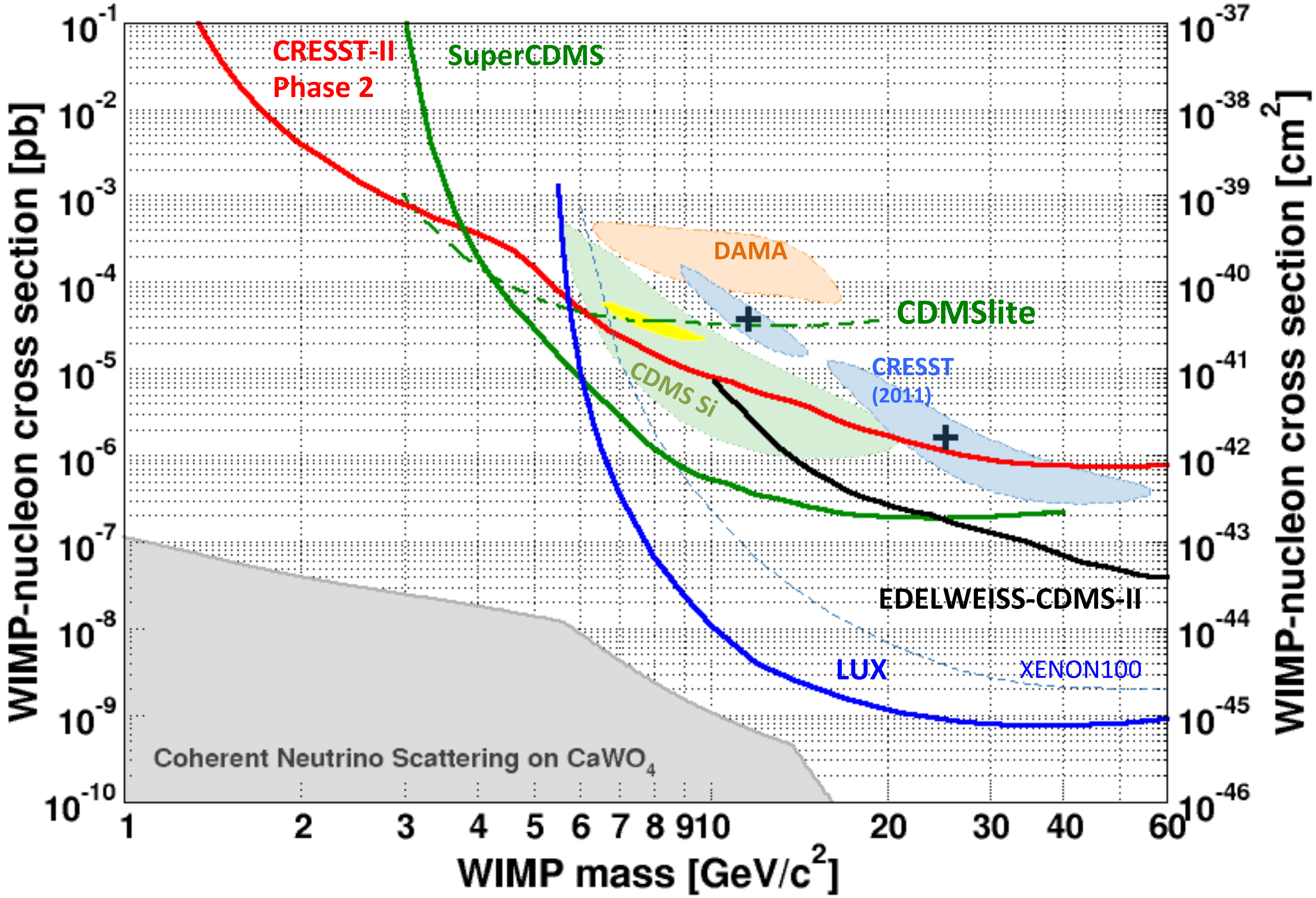
Suche nach Dunkler Materie mit Kryo-Bolometern

Raimund Strauss
MPP München

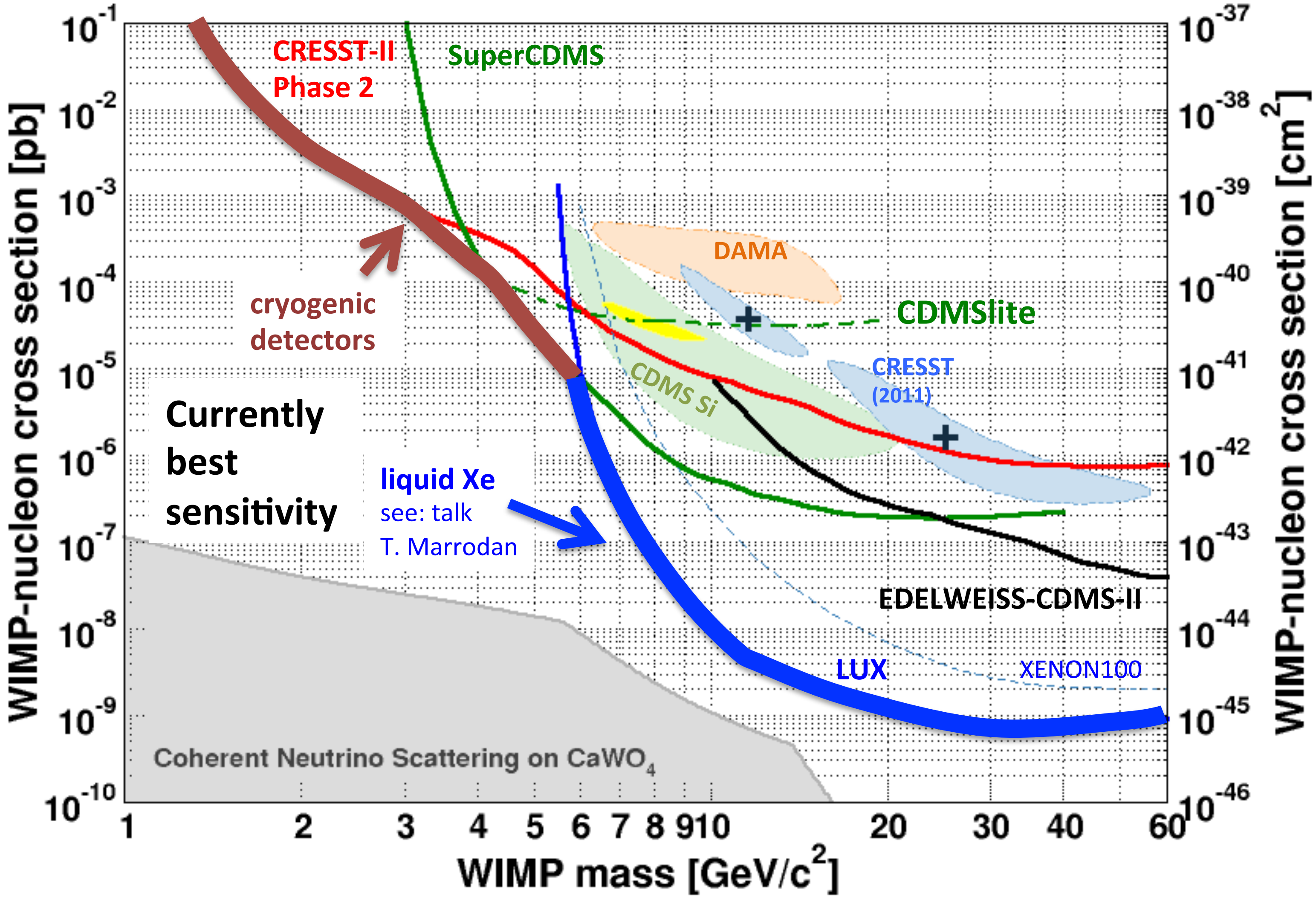
Astroteilchenphysik in Deutschland,
Karlsruhe,
01.10.2014



Current Status of Direct Dark Matter Searches



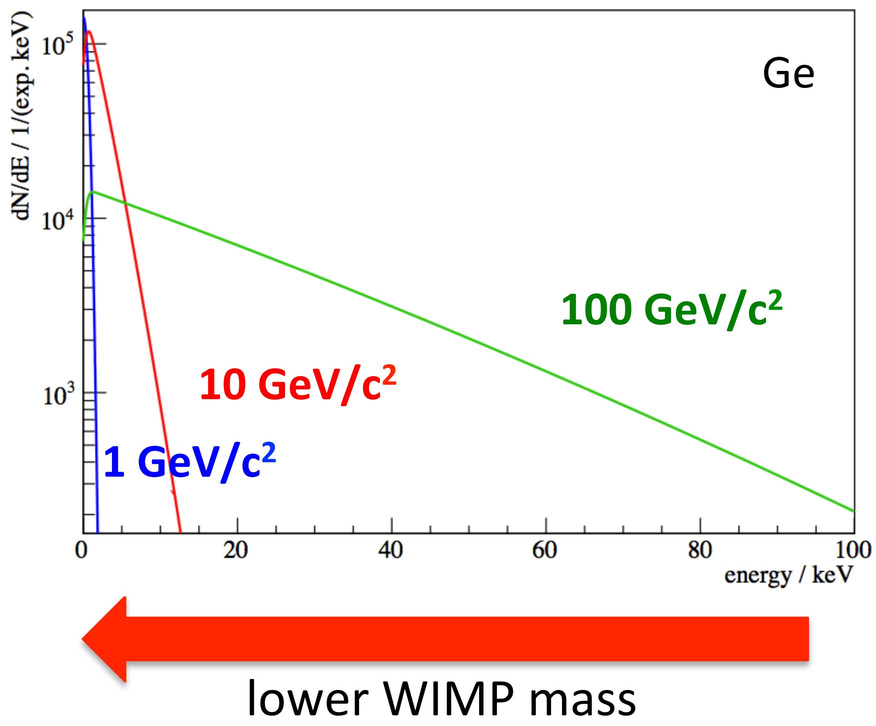
Current Status of Direct Dark Matter Searches



Potential of Cryogenic Detectors

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

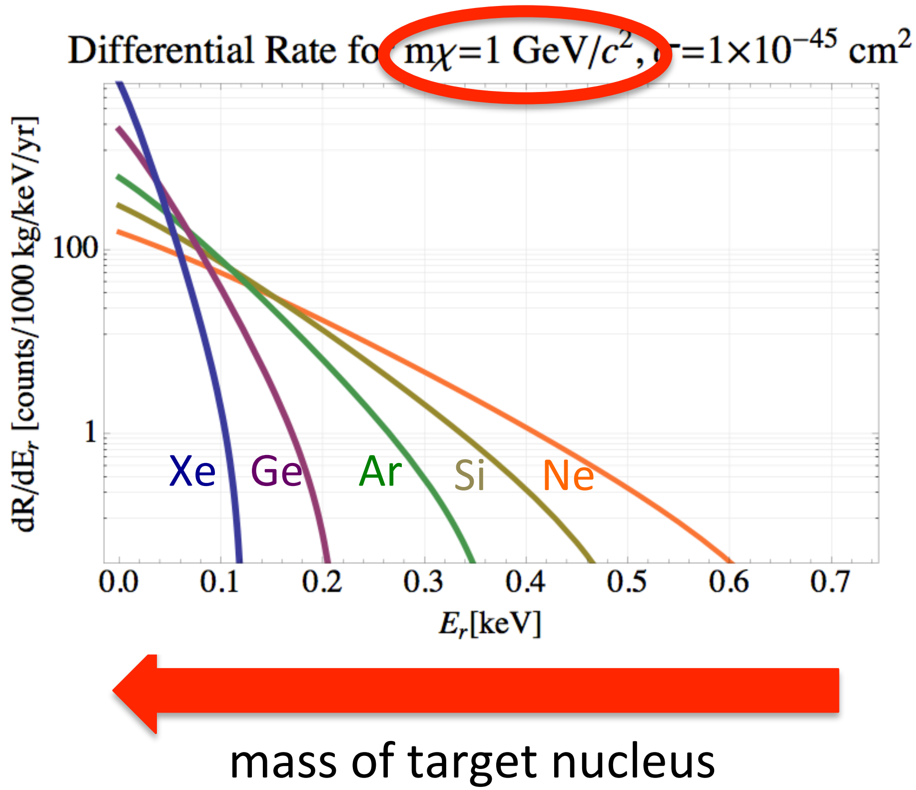
- **Low energy threshold**



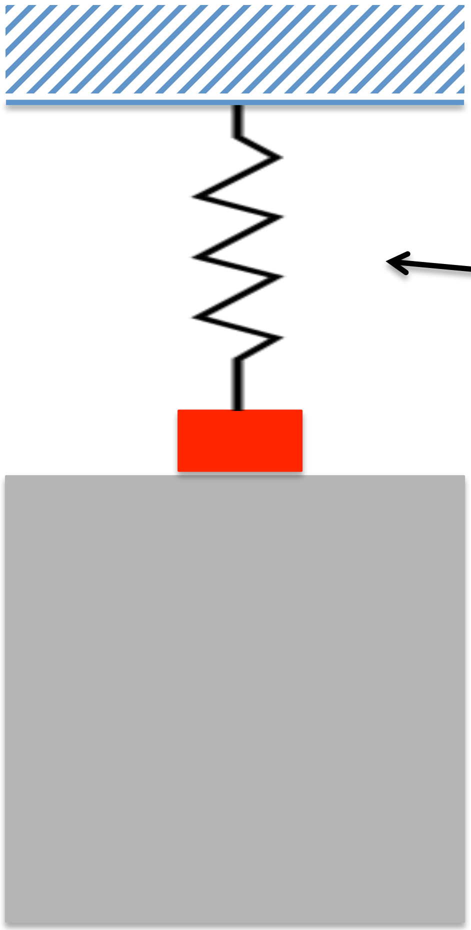
Potential of Cryogenic Detectors

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

- Low energy threshold
- **Light elements**



Cryogenic Detector



heat bath (T≈10mK)

temperature T_0

weak thermal link

conductance **G**

thermometer

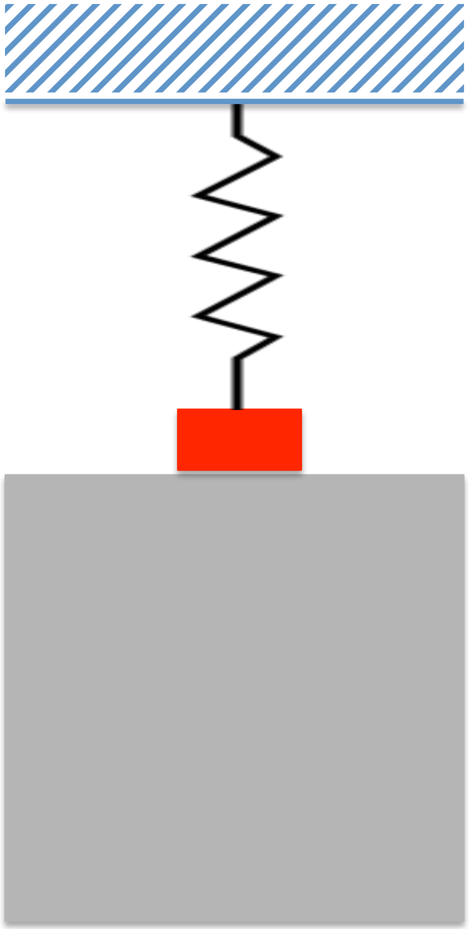
+

absorber material

heat capacity **C**

temperature **T**

Cryogenic Detector



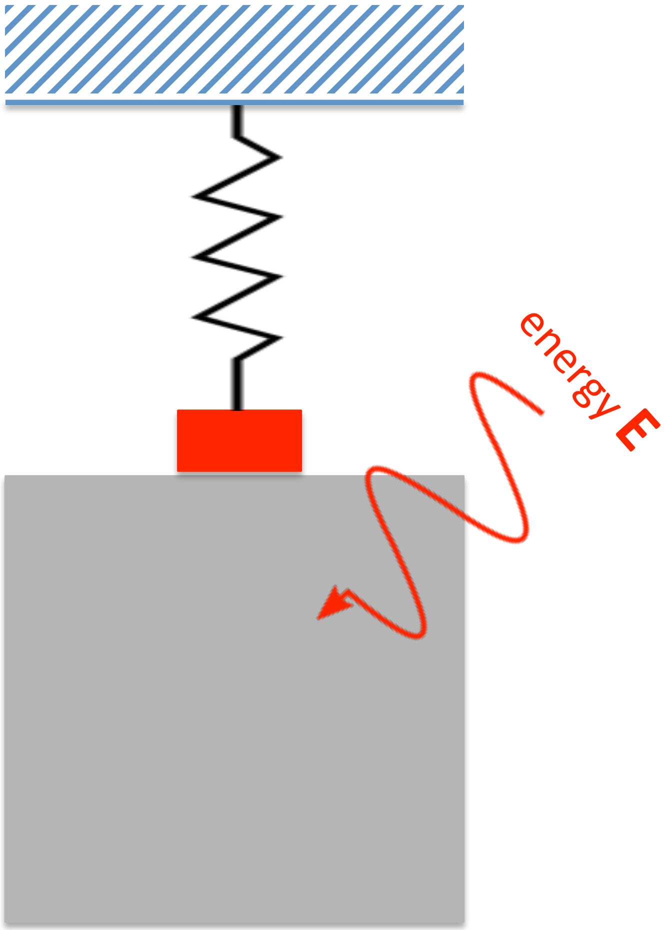
Irreducible thermal fluctuations:

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

Need:

- Low temperature
- Low heat capacity

Cryogenic Detector



Irreducible thermal fluctuations:

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

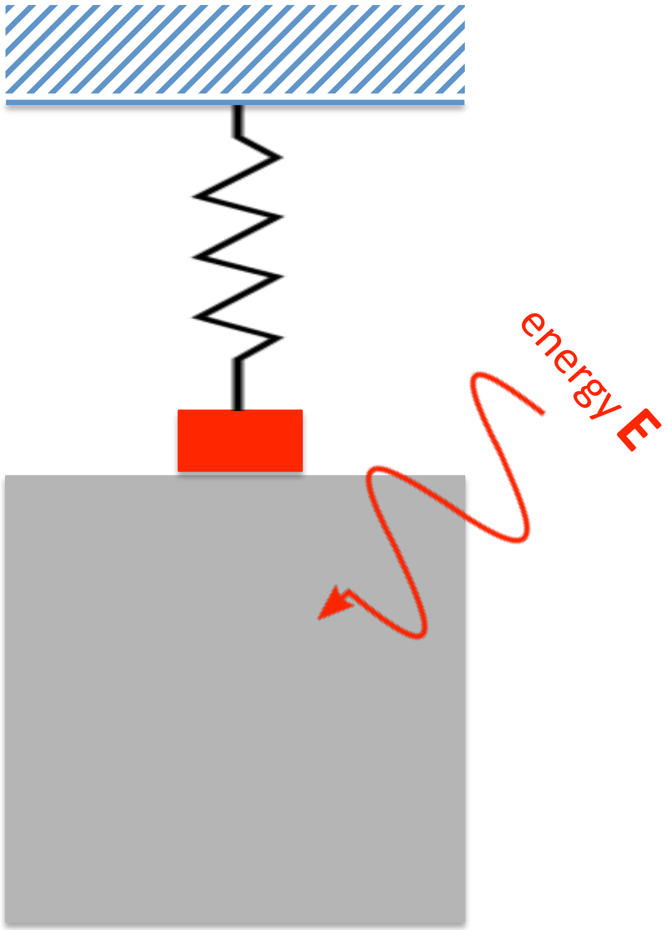
Need:

- Low temperature
- Low heat capacity

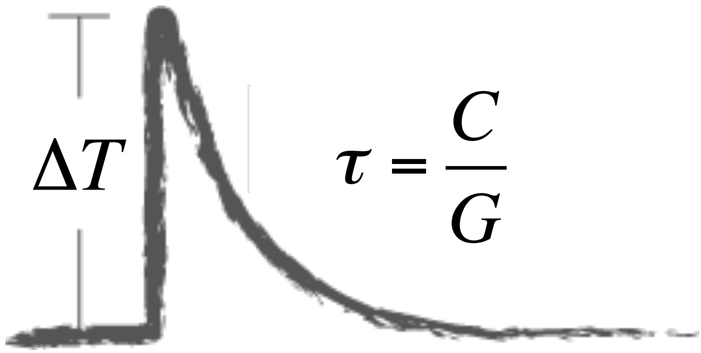
Operation at mK:

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

Cryogenic Detector

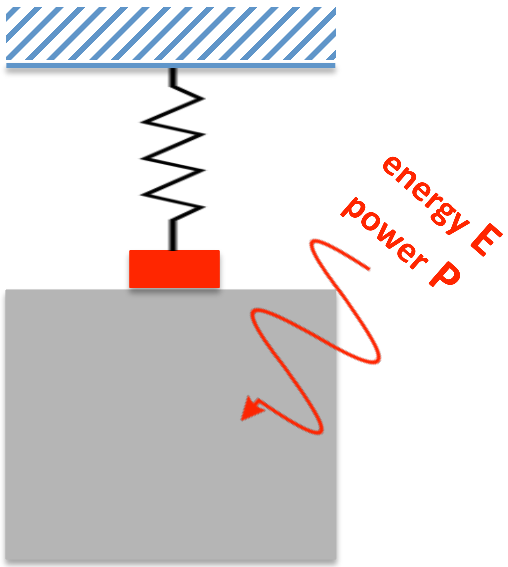


Thermometer response:



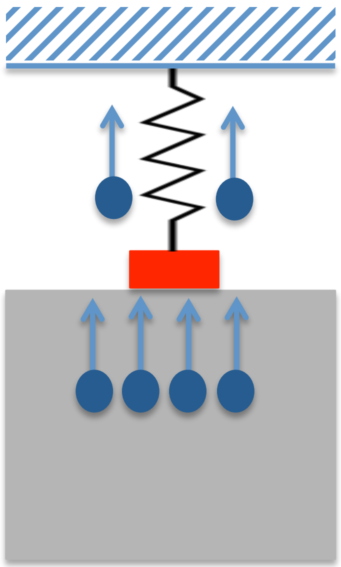
Calorimeter or Bolometer ?

"Calorimetric mode"

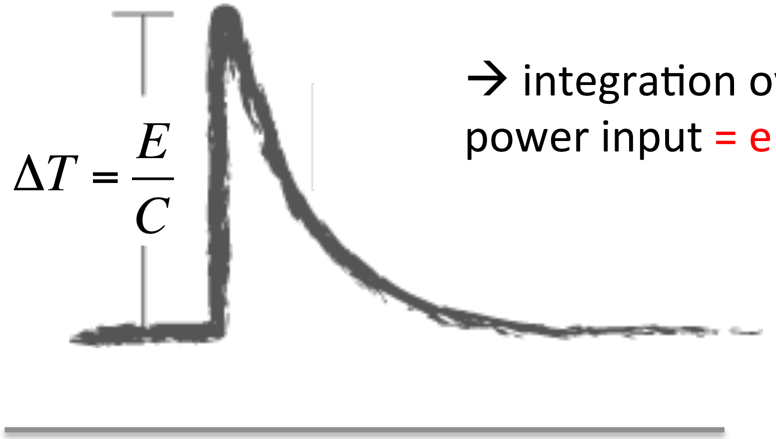


Calorimeter or Bolometer ?

"Calorimetric mode"



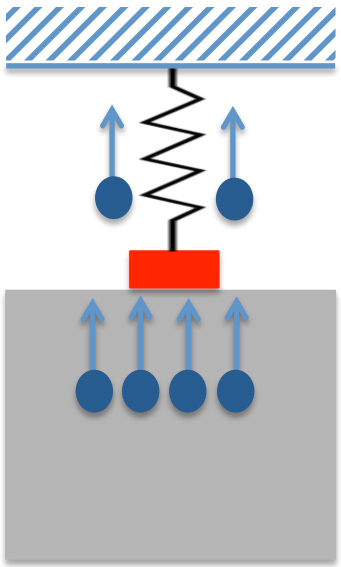
"phonons flow into the thermometer more quickly than out of it !"



→ integration over power input = energy

Calorimeter or Bolometer ?

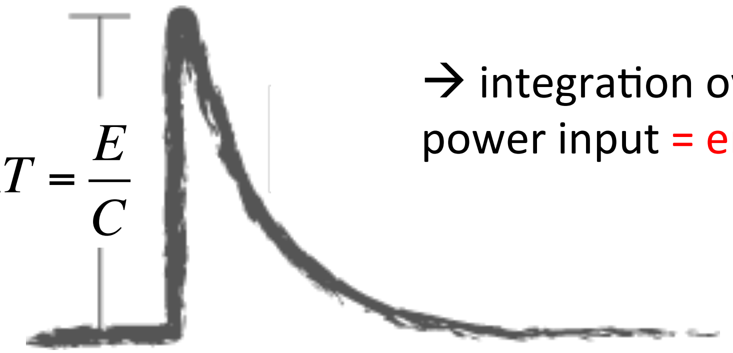
“Calorimetric mode”



phonons

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

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

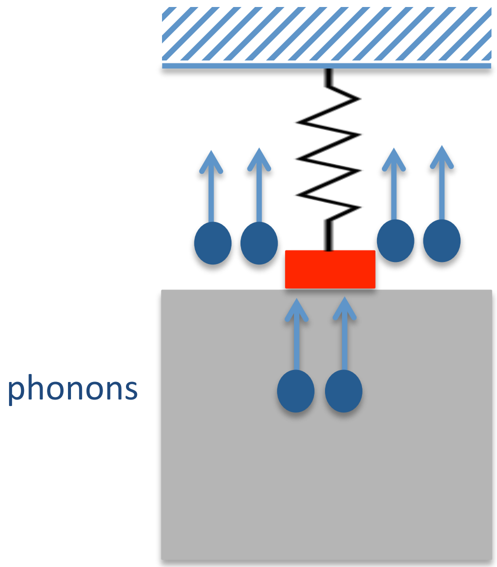


→ integration over power input = energy

← measure filling level

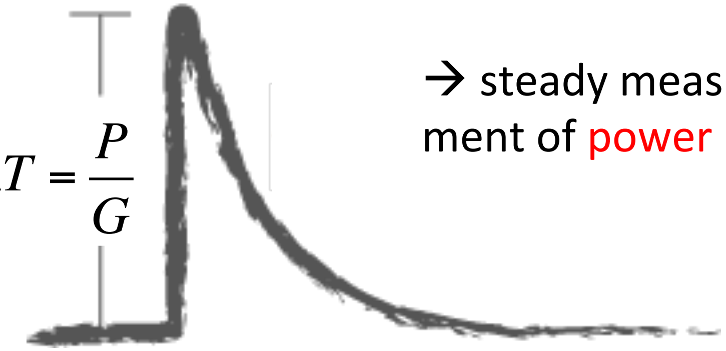
Calorimeter or Bolometer ?

“Bolometric mode”



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

$$\Delta T = \frac{P}{G}$$

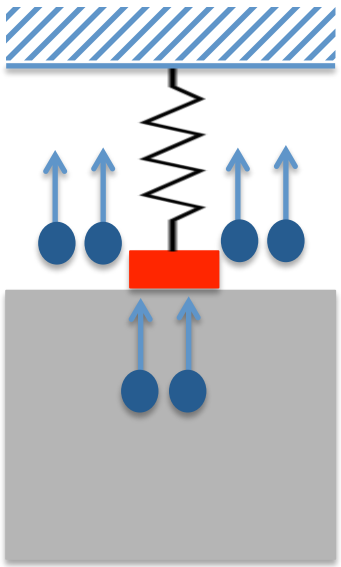


→ steady measure-ment of power input

measure flux

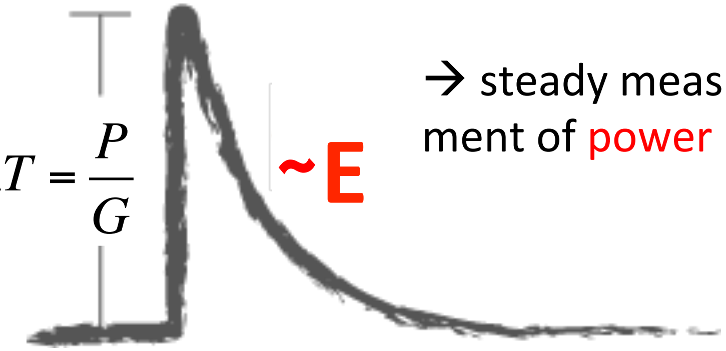
Calorimeter or Bolometer ?

“Bolometric mode”



phonons

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



$$\Delta T = \frac{P}{G}$$

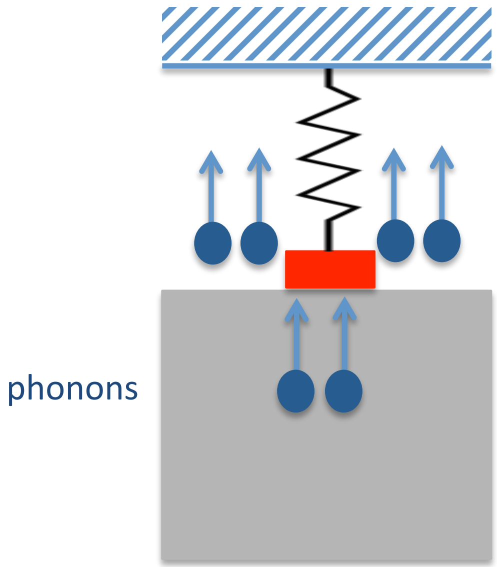
~E

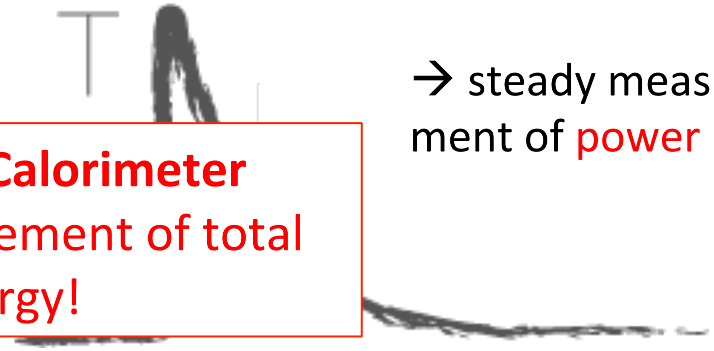
→ steady measurement of power input

measure flux

Calorimeter or Bolometer ?

“Bolometric mode”





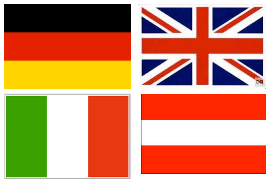
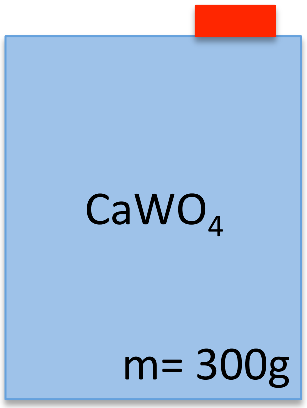
Bolometer & Calorimeter
Direct measurement of total deposited energy!

→ steady measure-ment of power input

measure flux

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

Cryogenic Dark Matter Experiments

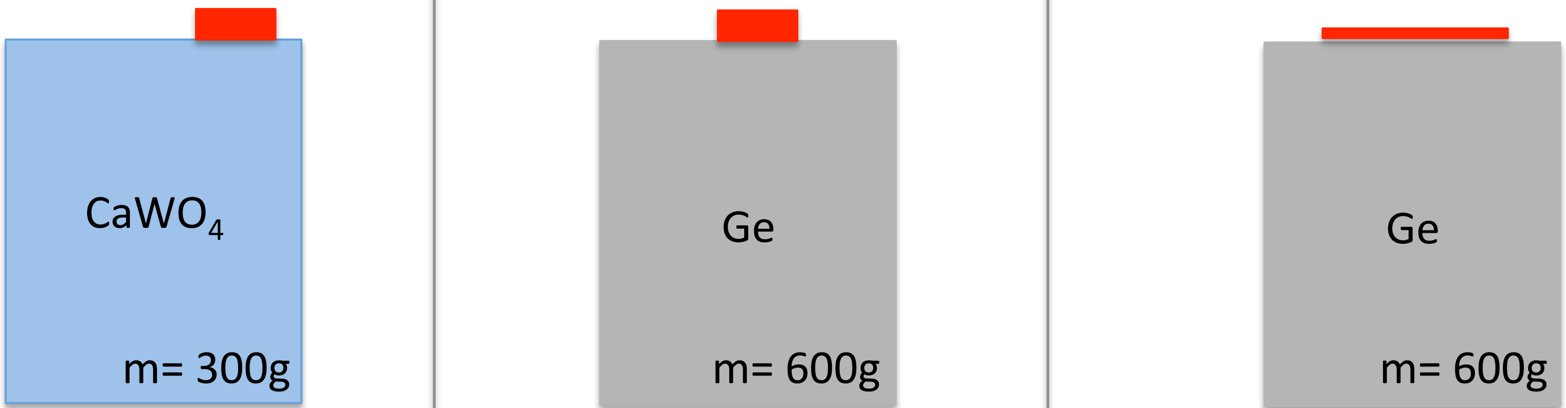
CRESST	EDELWEISS	SuperCDMS
Gran Sasso 		
		

Cryogenic Dark Matter Experiments

CRESST	EDELWEISS	SuperCDMS
Gran Sasso	LSM Modane	
$CaWO_4$ m= 300g	Ge m= 600g	

Cryogenic Dark Matter Experiments

CRESST	EDELWEISS	SuperCDMS
Gran Sasso	LSM Modane	Soudan, SNOLAB



Cr ts

CR MS

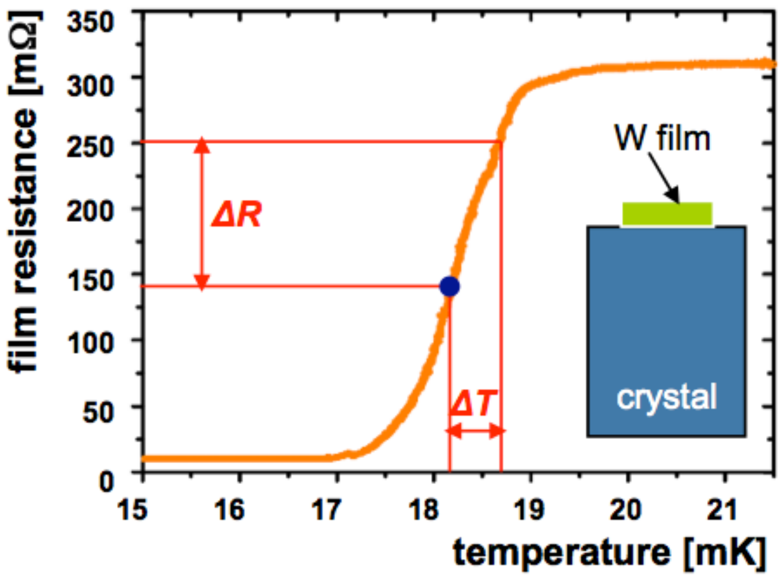
Gran Sasso

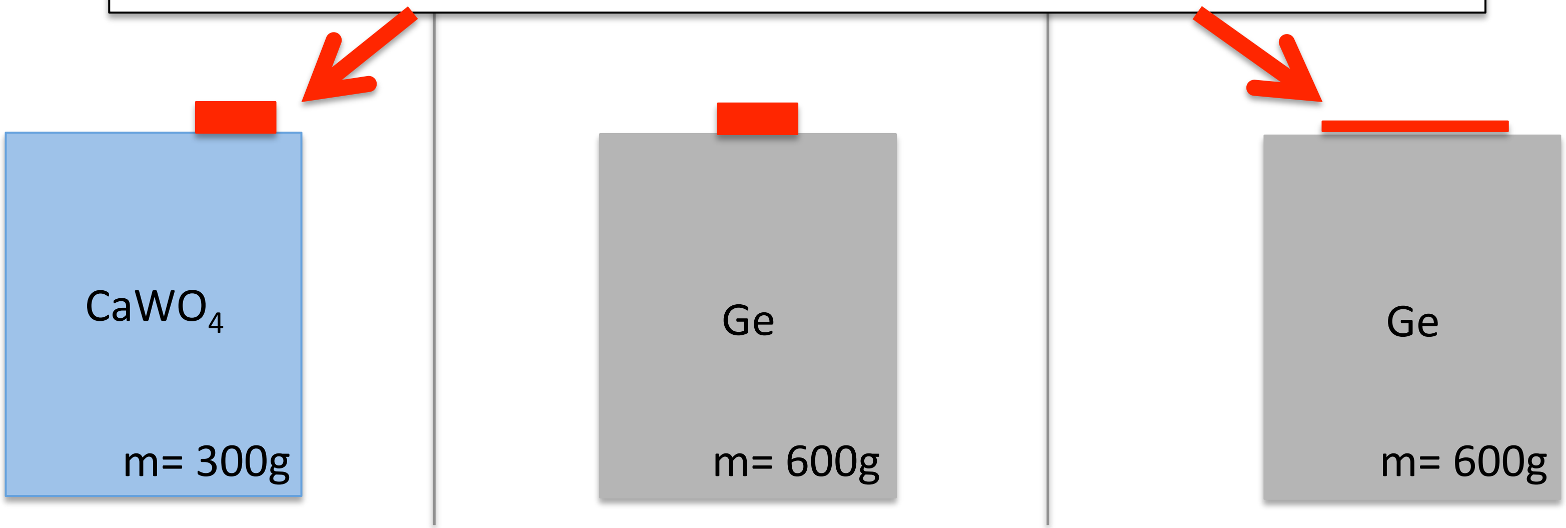
SNOLAB

Transition-edge sensor (TES)

Superconducting metal films (tungsten)

Read-out by SQUID system





Cr ... ts

CR ... MS

Gran Sasso

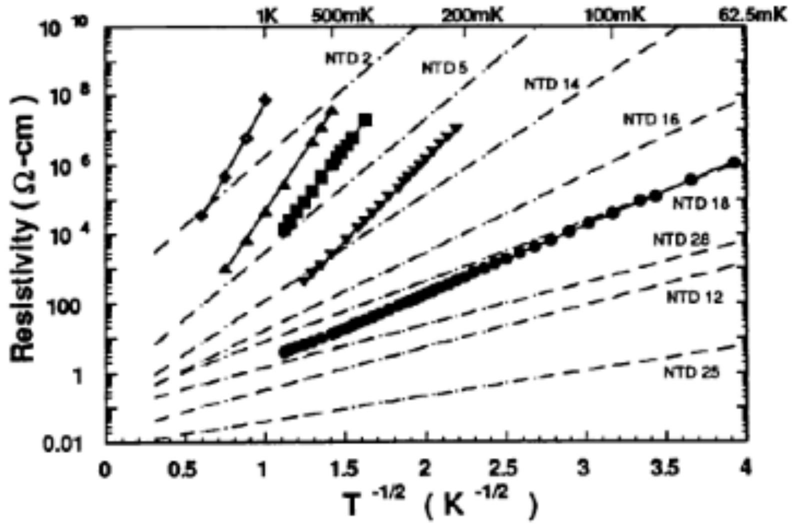
SNOLAB

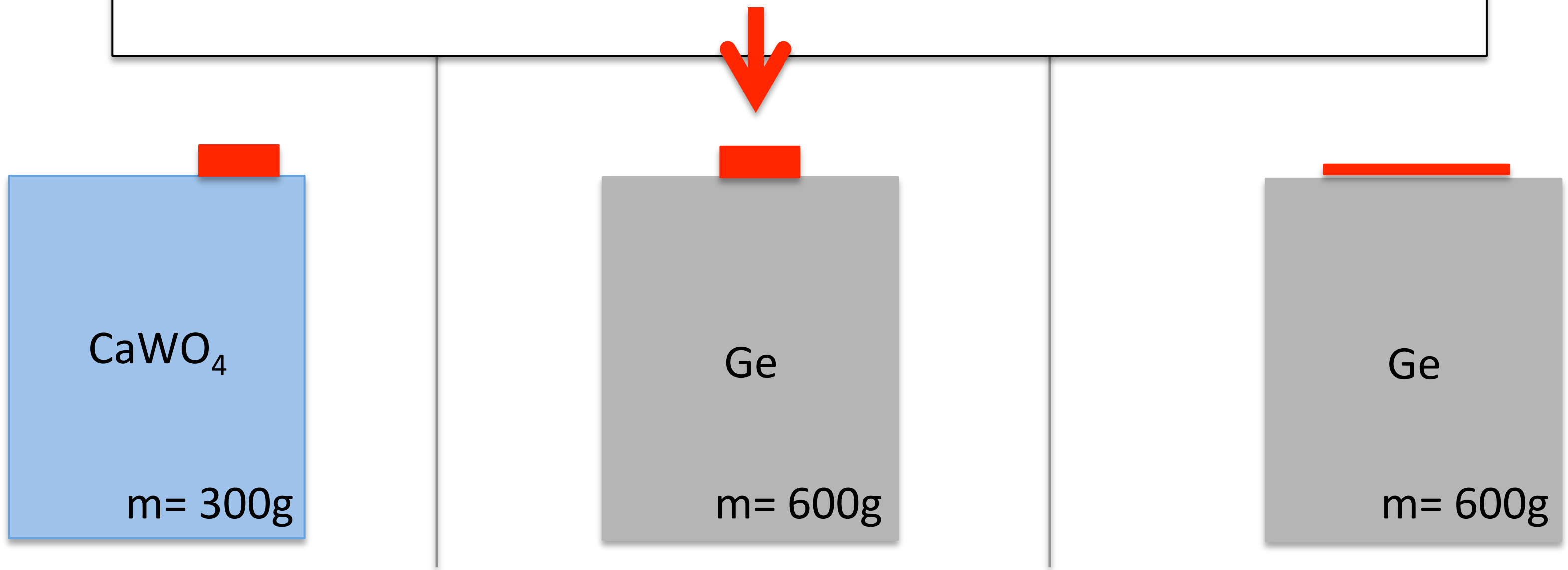
Neutron Transmutation Doped Thermistors (NTD)

Ge NTDs

Resistance R(T) depends strongly on temperature

Read-out with FETs (future: HEMTs)





Cryogenic Dark Matter Experiments

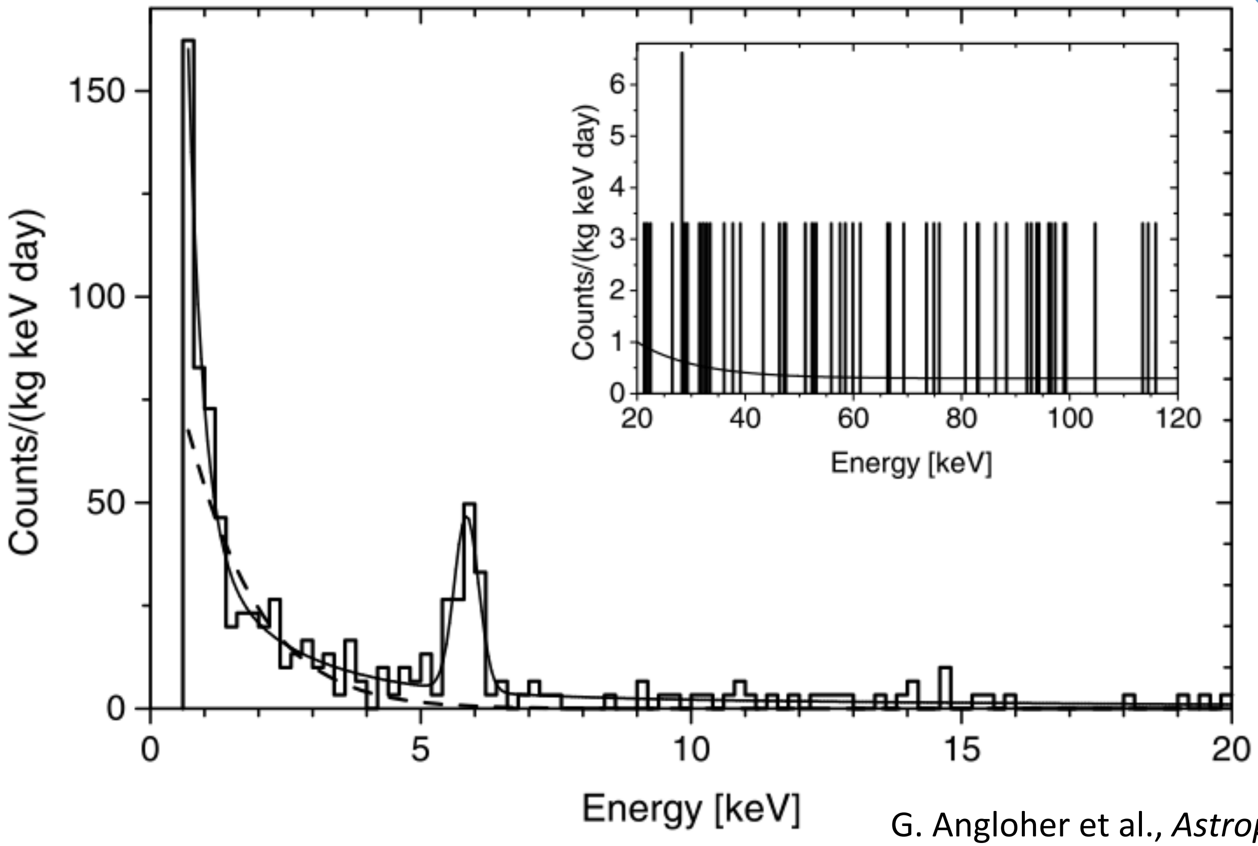
	CRESST	EDELWEISS	SuperCDMS
Threshold:	$E_{th} \approx 0.4$ keV	$E_{th} \approx 3$ keV	$E_{th} \approx 1.5$ keV
Baseline noise:	$\sigma \approx 0.075$ keV	$\sigma \approx 0.5$ keV	$\sigma \approx 0.4$ keV
	transition-edge-sensor	NTD sensor	transition-egde-sensor
	$CaWO_4$	Ge	Ge
	m= 300g	m= 800g	m= 600g

First Generation Experiments

Year 2002

CRESST-I Al_2O_3 - exposure 36 kg-h

Use only phonon channel (1-channel readout)!



G. Angloher et al., *Astroparticle Physics 18 (2002) 43-55.*

First Generation Experiments

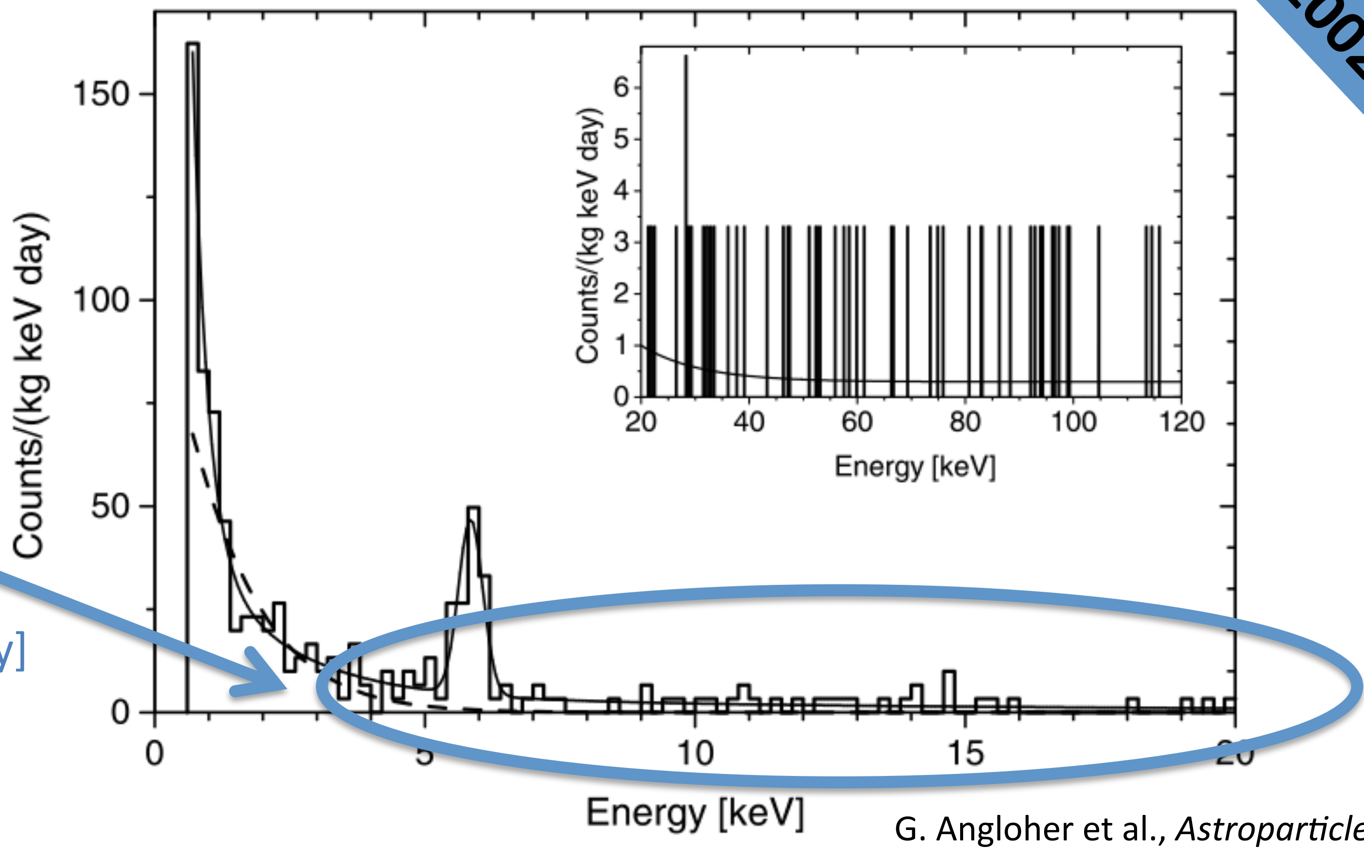
CRESST-I Al_2O_3 - exposure 36 kg-h

Year 2002

Use only phonon channel!

Unavoidable gamma/beta radioactive backgrounds

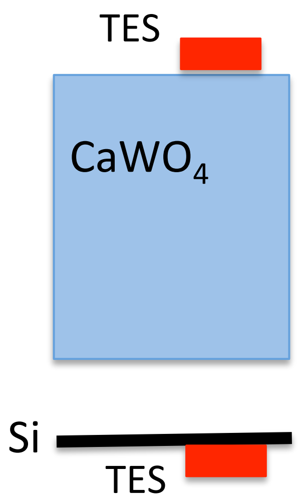
Of order:
1 count / [kg keV day]



G. Angloher et al., *Astroparticle Physics 18 (2002) 43-55.*

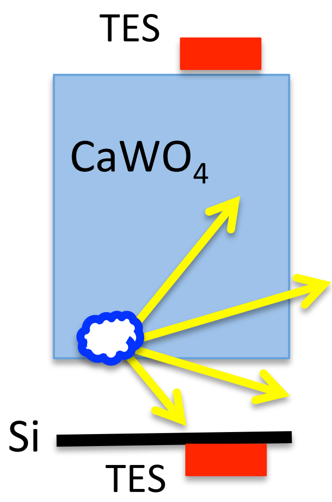
Active Background Discrimination

CRESST	EDELWEISS	SuperCDMS
Light - Phonon	Charge - Phonon	



Active Background Discrimination

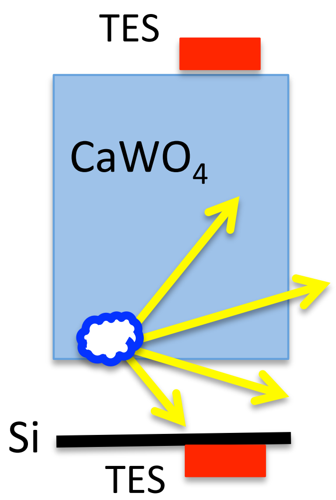
CRESST	EDELWEISS	SuperCDMS
Light - Phonon	Charge - Phonon	



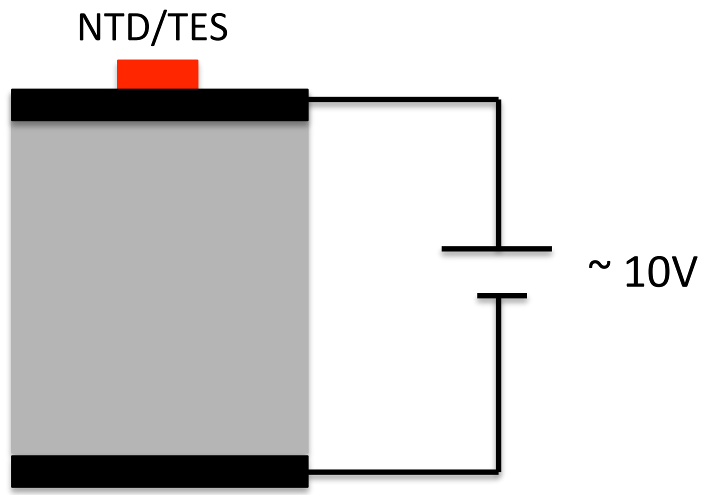
O(5%) of total energy deposition converted to scintillation light

Active Background Discrimination

CRESST	EDELWEISS	SuperCDMS
Light - Phonon	Charge - Phonon	



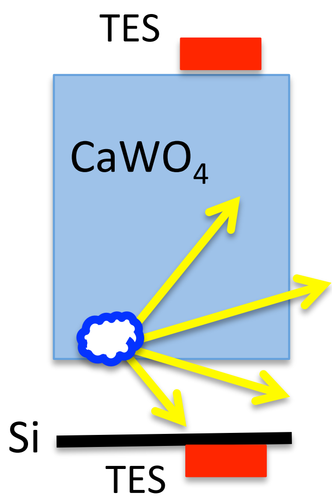
O(5%) of total energy deposition converted to scintillation light



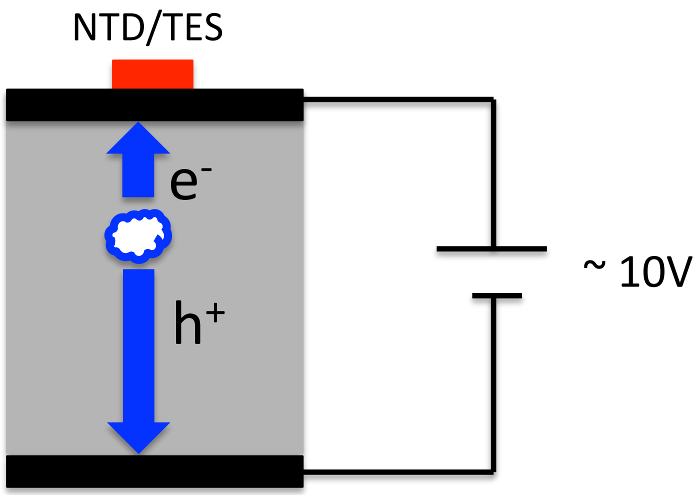
O(25%) of total energy deposition converted to ionisation

Active Background Discrimination

CRESST	EDELWEISS	SuperCDMS
Light - Phonon	Charge - Phonon	



O(5%) of total energy deposition converted to scintillation light



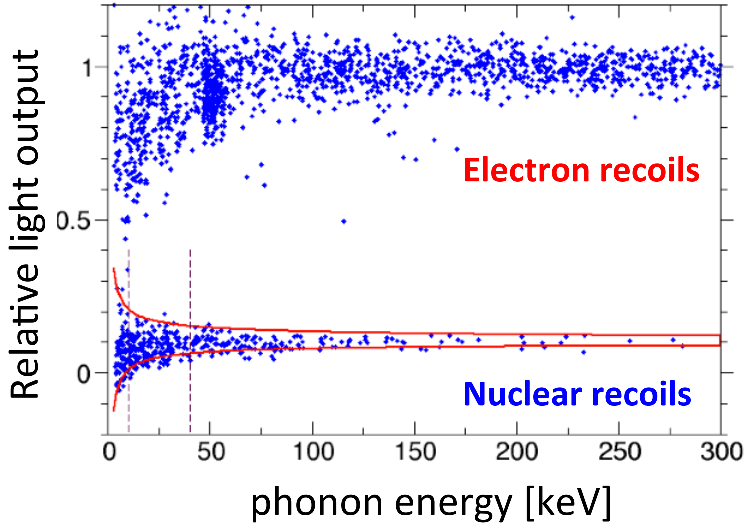
O(25%) of total energy deposition converted to ionisation

Active Background Discrimination

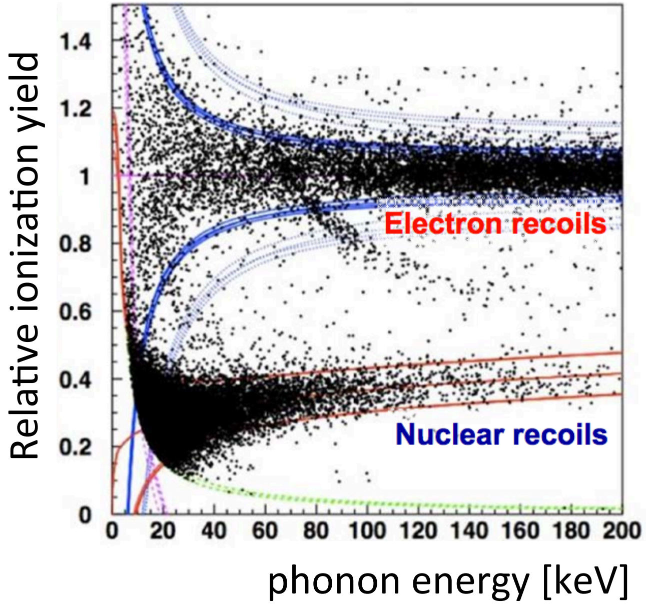
Year 2005

Neutron calibration data

CRESST (Light-Phonon)



EDELWEISS (Charge-Phonon)



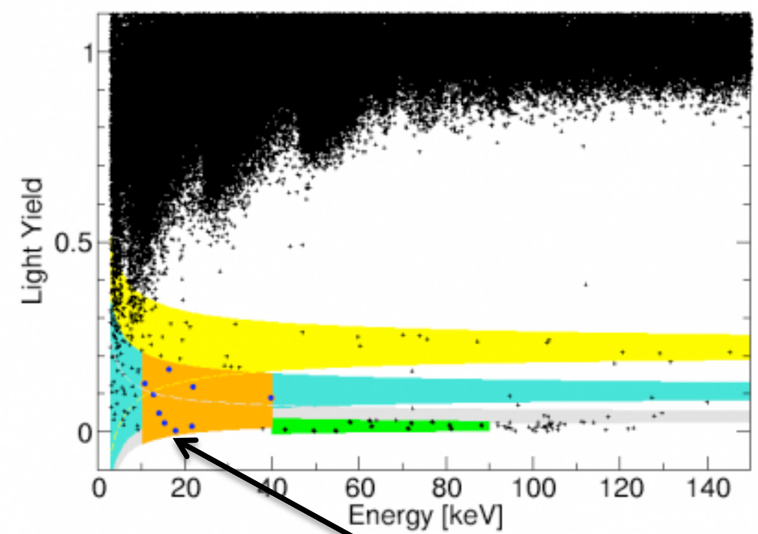
O(5%) of total energy deposition converted to scintillation light

O(25%) of total energy deposition converted to ionisation

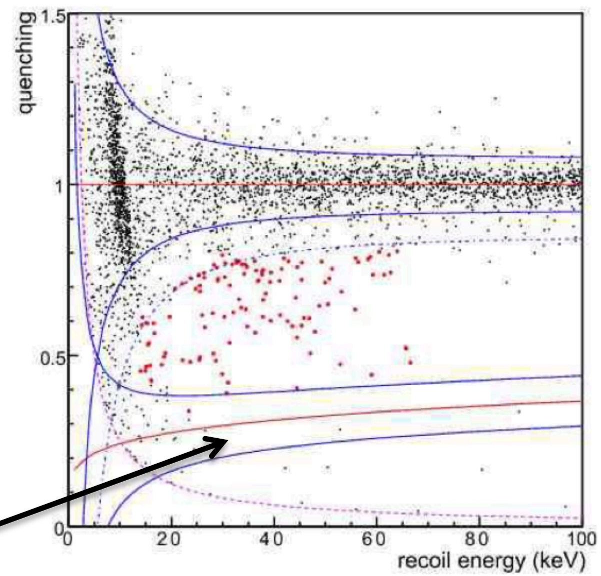
Surface Backgrounds

Year 2008-

CRESST-II



EDELWEISS



WIMP-acceptance region

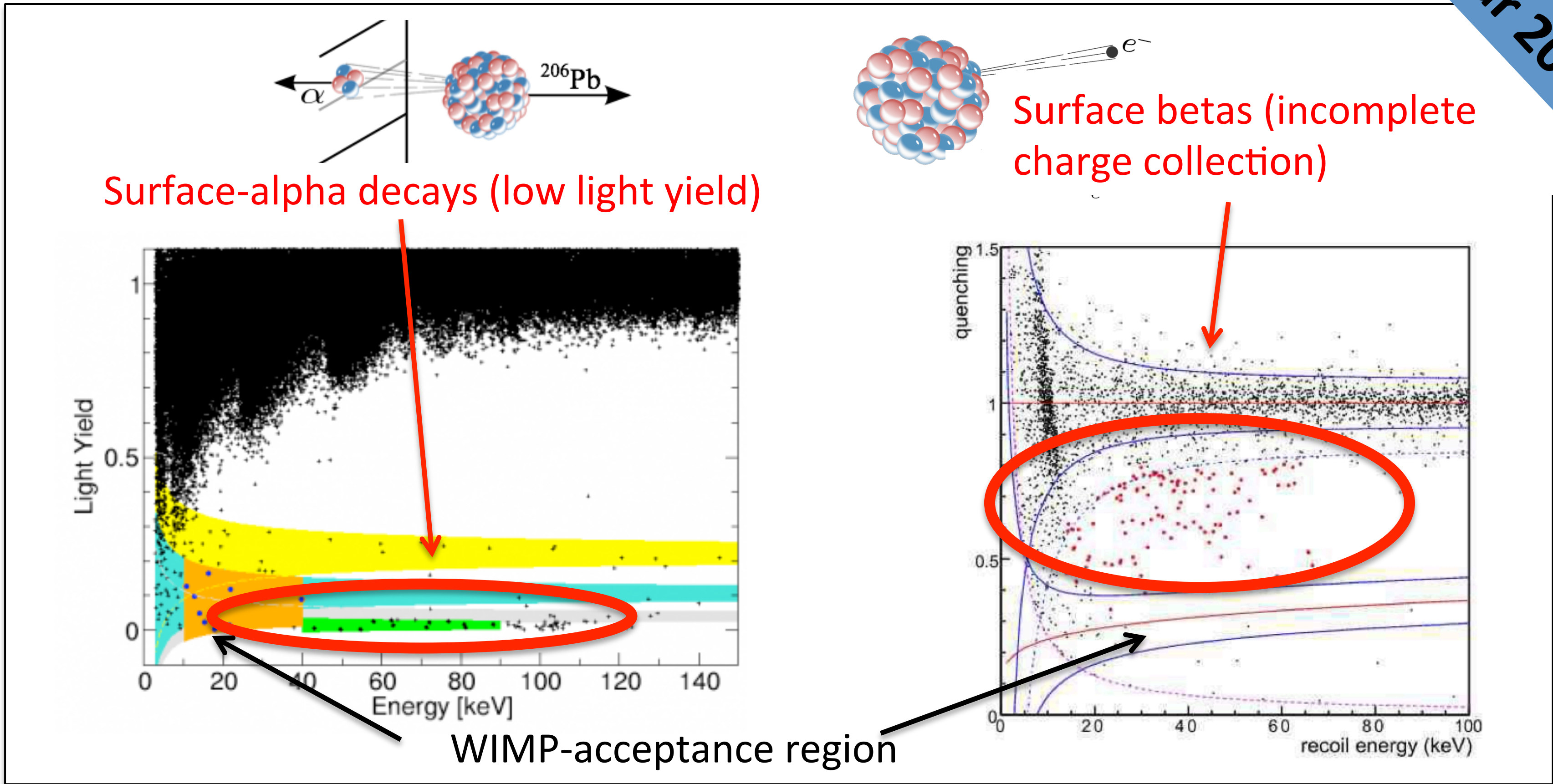
TES

O(5%) of total energy deposition converted to scintillation light

O(25%) of total energy deposition converted to ionisation

Surface Backgrounds

Year 2008-



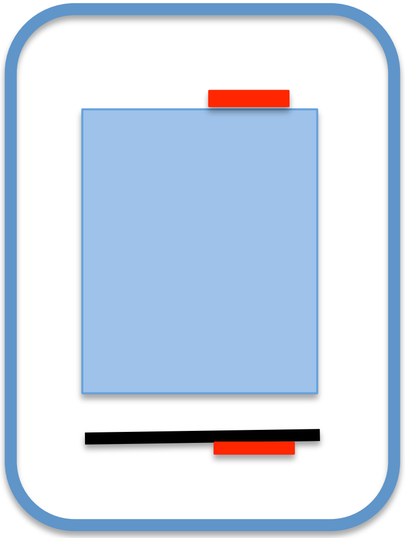
TES

O(5%) of total energy deposition converted to scintillation light

O(25%) of total energy deposition converted to ionisation

Active Surface-Event Discrimination

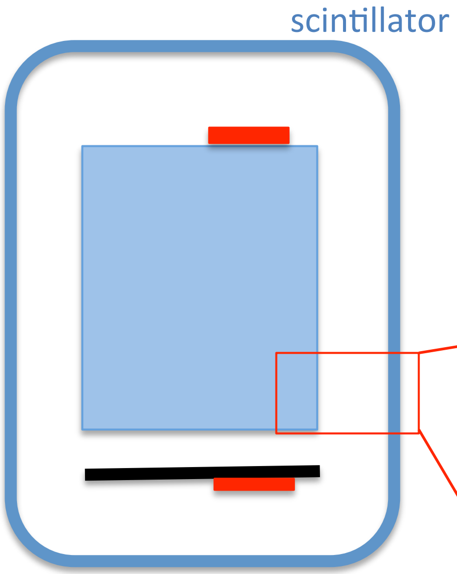
CRESST	EDELWEISS	SuperCDMS
Scintillating housing	Veto electrodes	



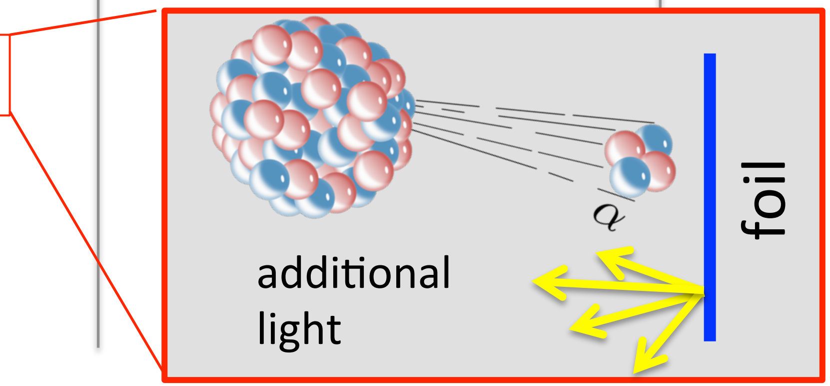
Rejection of surface-alpha backgrounds

Active Surface-Event Discrimination

CRESST	EDELWEISS	SuperCDMS
Scintillating housing	Veto electrodes	



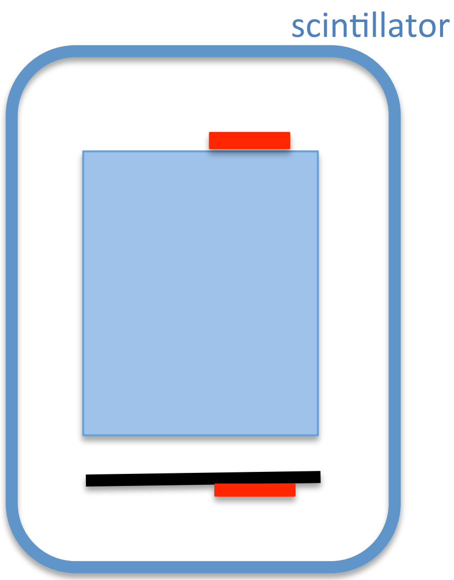
Rejection of surface-alpha backgrounds



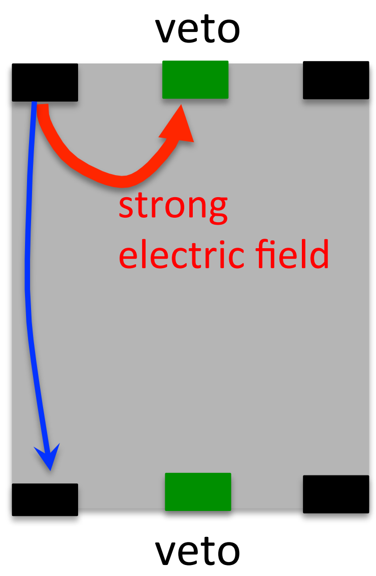
Raimund Strauss, MPI Munich

Active Surface-Event Discrimination

CRESST	EDELWEISS	SuperCDMS
Scintillating housing	Veto electrodes	

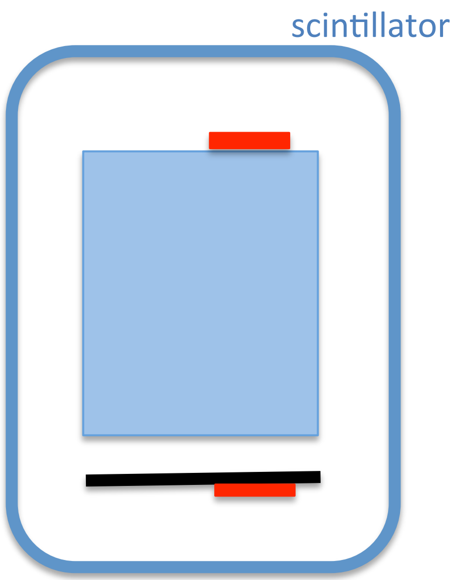


Rejection of surface-alpha backgrounds

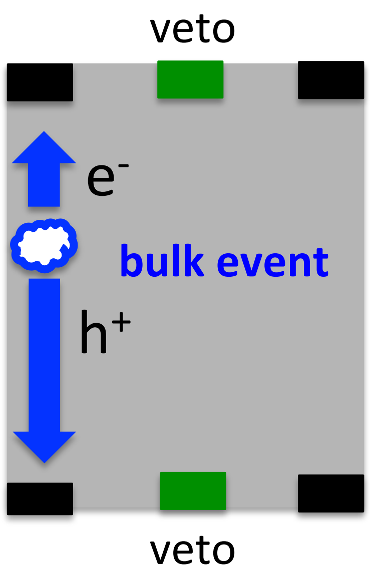


Active Surface-Event Discrimination

CRESST	EDELWEISS	SuperCDMS
Scintillating housing	Veto electrodes	

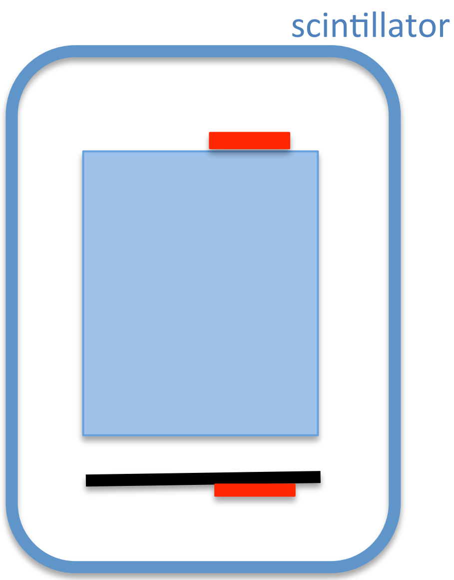


Rejection of surface-alpha backgrounds

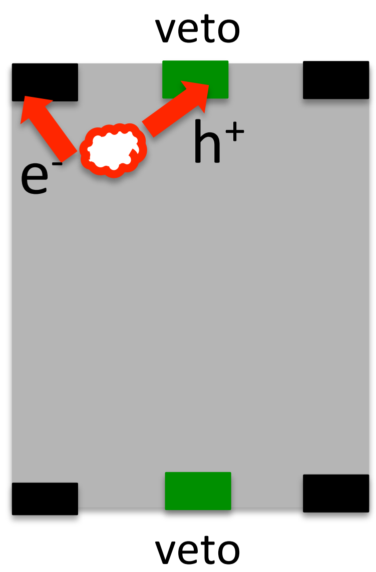


Active Surface-Event Discrimination

CRESST	EDELWEISS	SuperCDMS
Scintillating housing	Veto electrodes	



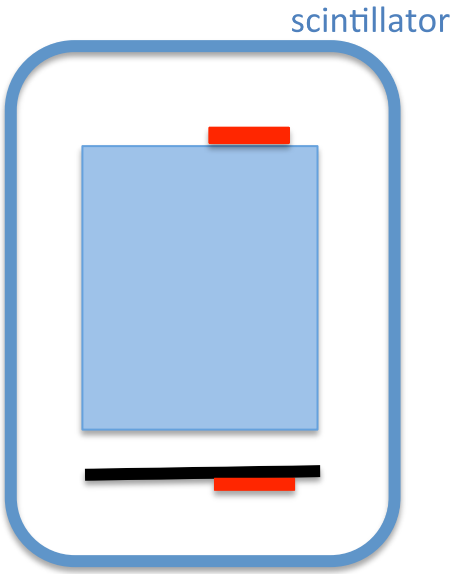
Rejection of surface-alpha backgrounds



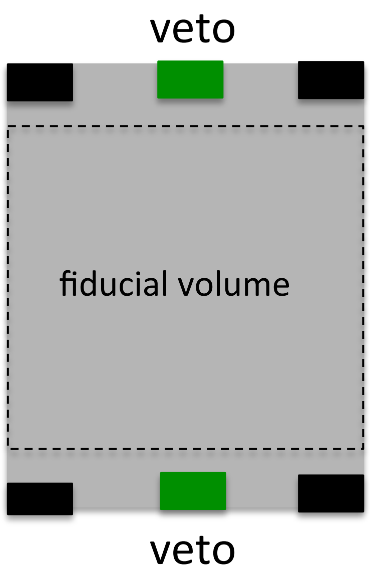
Rejection of surface layer

Active Surface-Event Discrimination

CRESST	EDELWEISS	SuperCDMS
Scintillating housing	Veto electrodes	



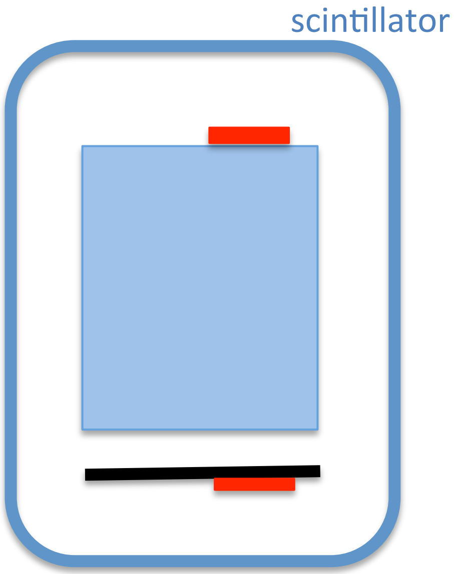
Rejection of surface-alpha backgrounds



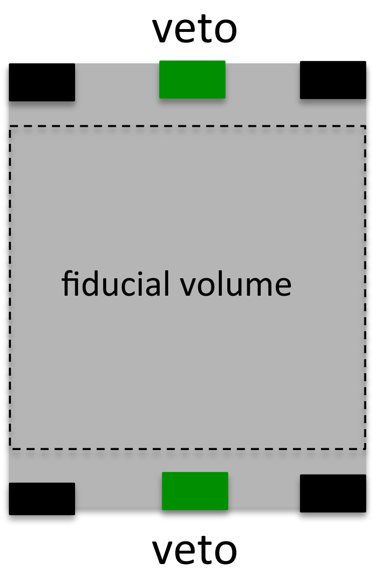
Rejection of surface layer

Active Surface-Event Discrimination

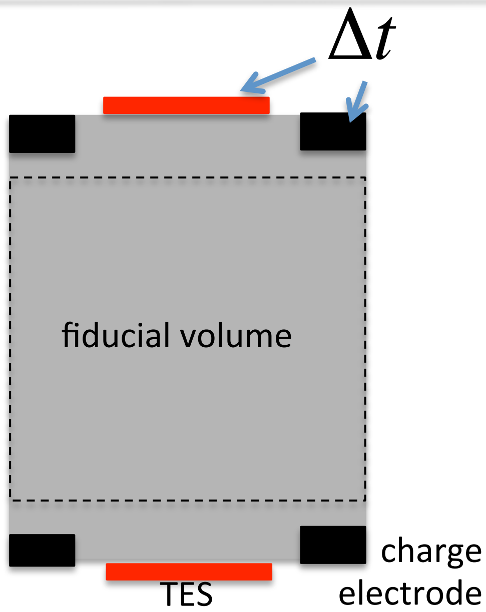
CRESST	EDELWEISS	SuperCDMS
Scintillating housing	Veto electrodes	Timing (Charge-Phonon)



Rejection of surface-alpha backgrounds



Rejection of surface layer

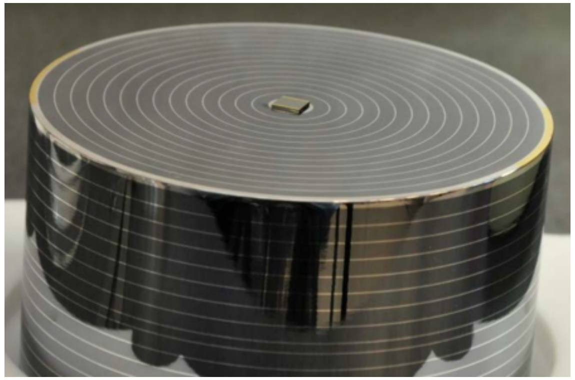


Rejection of surface layer

Direct Dark Matter Experiments

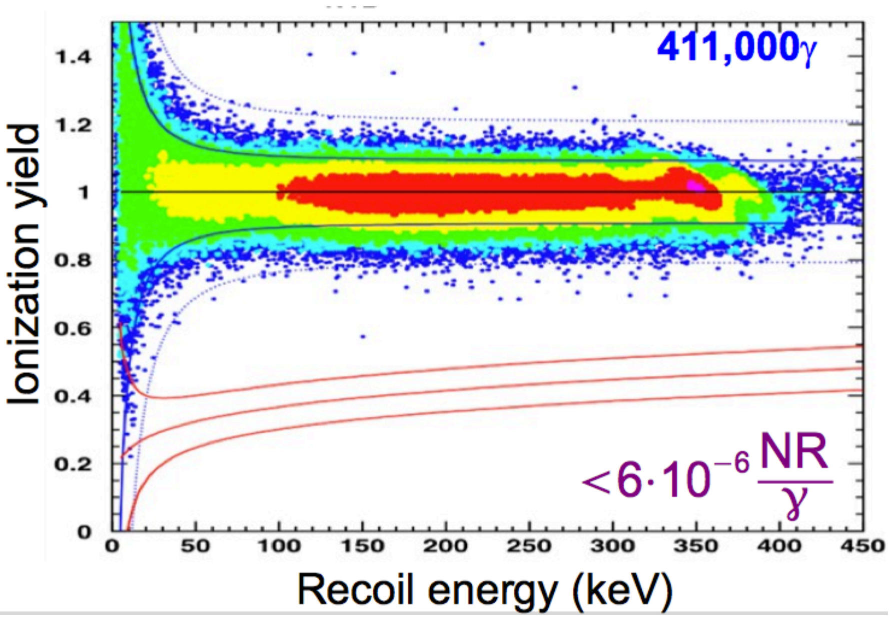
CURRENT STATUS

EDELWEISS - III



Ge-FID800 (Fully **I**nter-digitized **D**etectors**)**

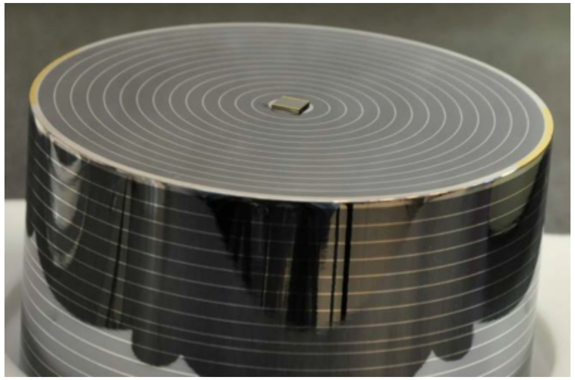
- m=800g
- High fiducial volume (75%)
- highly-improved charge read-out
- 2 NTD sensors for phonon measurement



Excellent rejection of gamma events

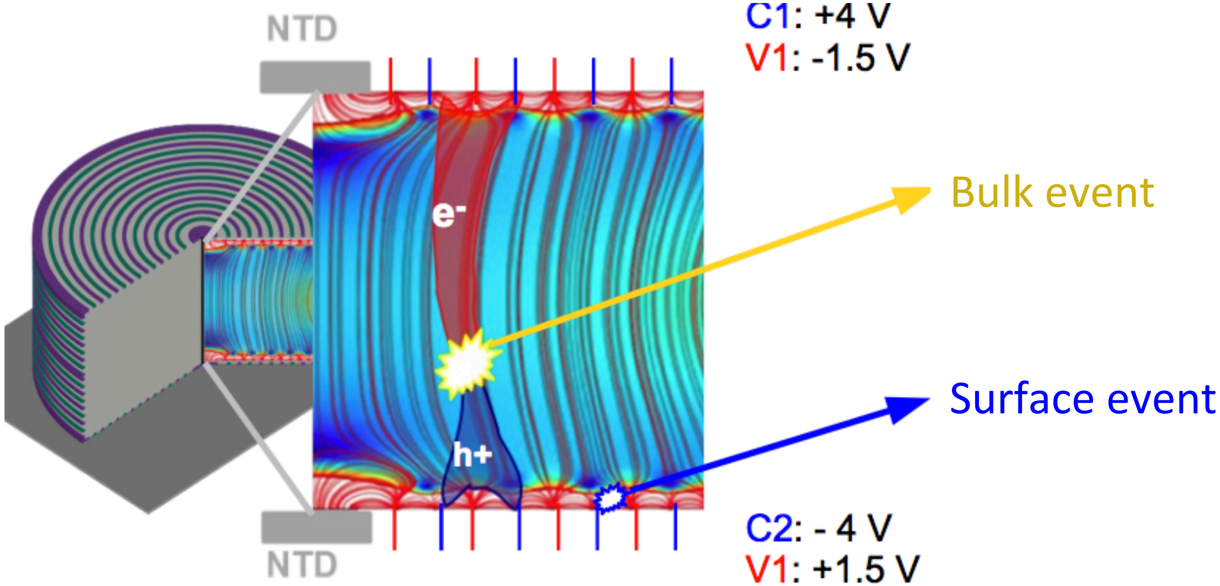
Improvement by a factor of 5

EDELWEISS - III

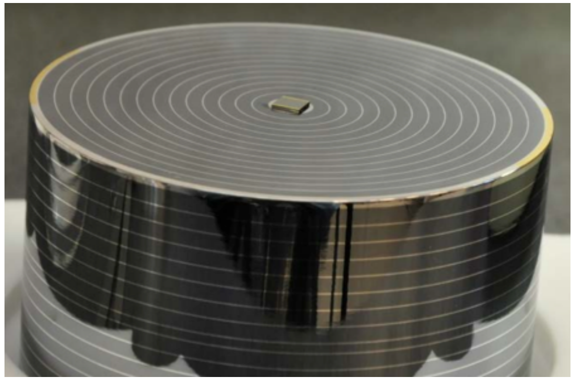


Ge-FID800 (Fully Inter-digitized Detectors)

- m=800g
- High fiducial volume (75%)
- highly-improved charge read-out
- 2 NTD sensors for phonon measurement

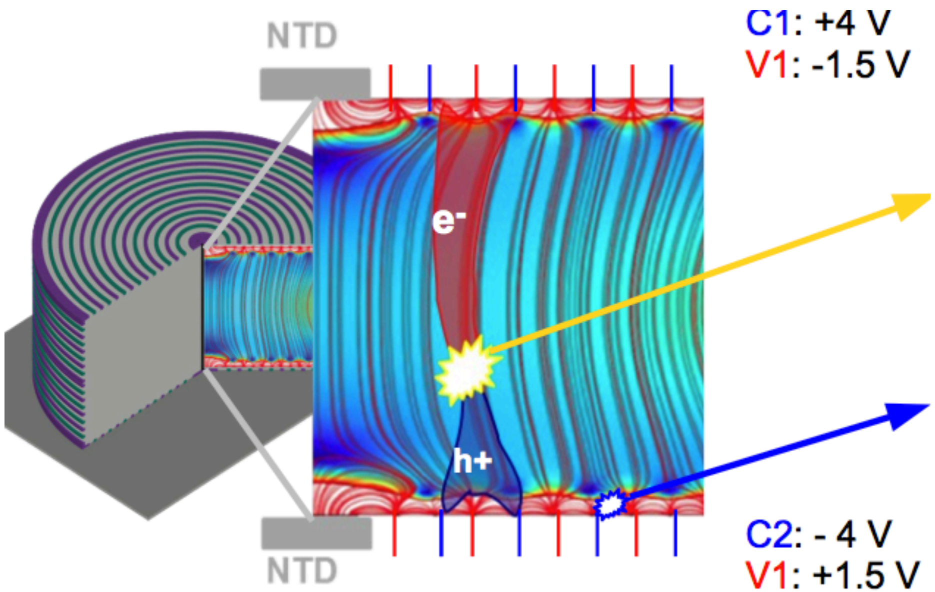


EDELWEISS - III



Ge-FID800 (Fully **I**nter-digitized **D**etectors**)**

- m=800g
- High fiducial volume (75%)
- highly-improved charge read-out
- 2 NTD sensors for phonon measurement

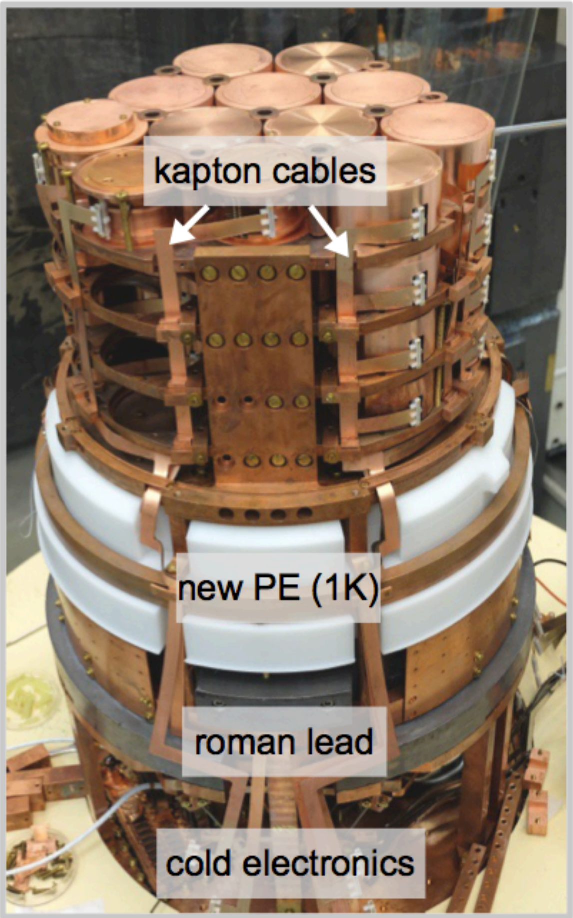


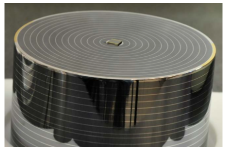
Excellent discrimination of surface-beta events

misidentified events:
$< 4 \times 10^{-5}$ events / [kg day]

Improvement by factor of 1.5

EDELWEISS - III



36 x  = 27kg target mass

Highly-improved setup:

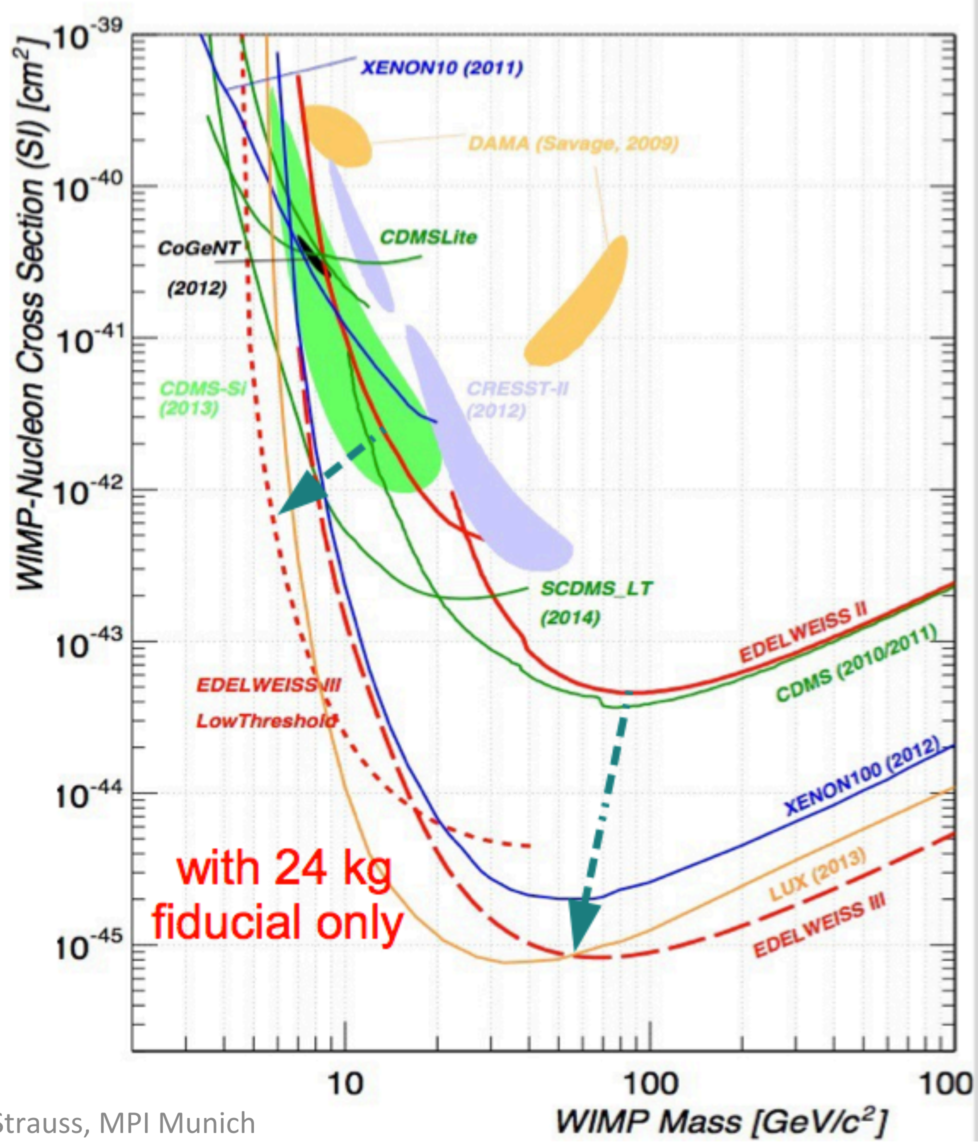
- Cryogenics
- Electronics
- Background suppression

background [20,200] keV	EDELWEISS-III [evts/kg/day]	improvement
Gamma	14 - 44	÷ 2 to 6
Ambient n's	$(0.8\text{-}\ 1.9)\times10^{-4}$	÷ ~100
μ-induced n's	$< 2\times10^{-4}$	÷ 10

EDELWEISS - III

Current status:

- 36 FID800 installed (24 are read-out)
- Data-taking since 2 months
- First data release planned for spring 2015



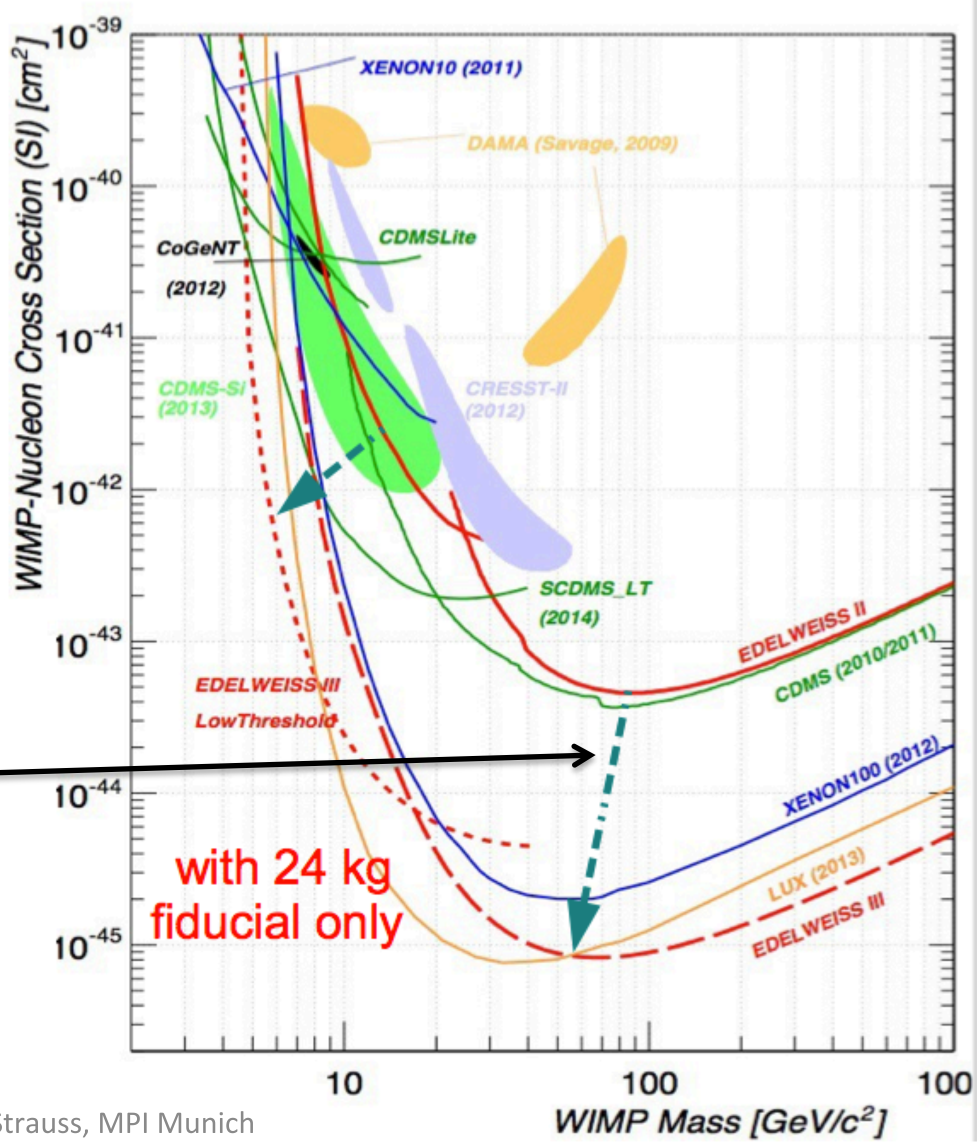
EDELWEISS - III

Current status:

- 36 FID800 installed (24 are read-out)
- Data-taking since 2 months
- First data release planned for spring 2015

Projected sensitivity:

- Standard WIMPs (12.000kg-days) after 500 days, background-free above 15keV



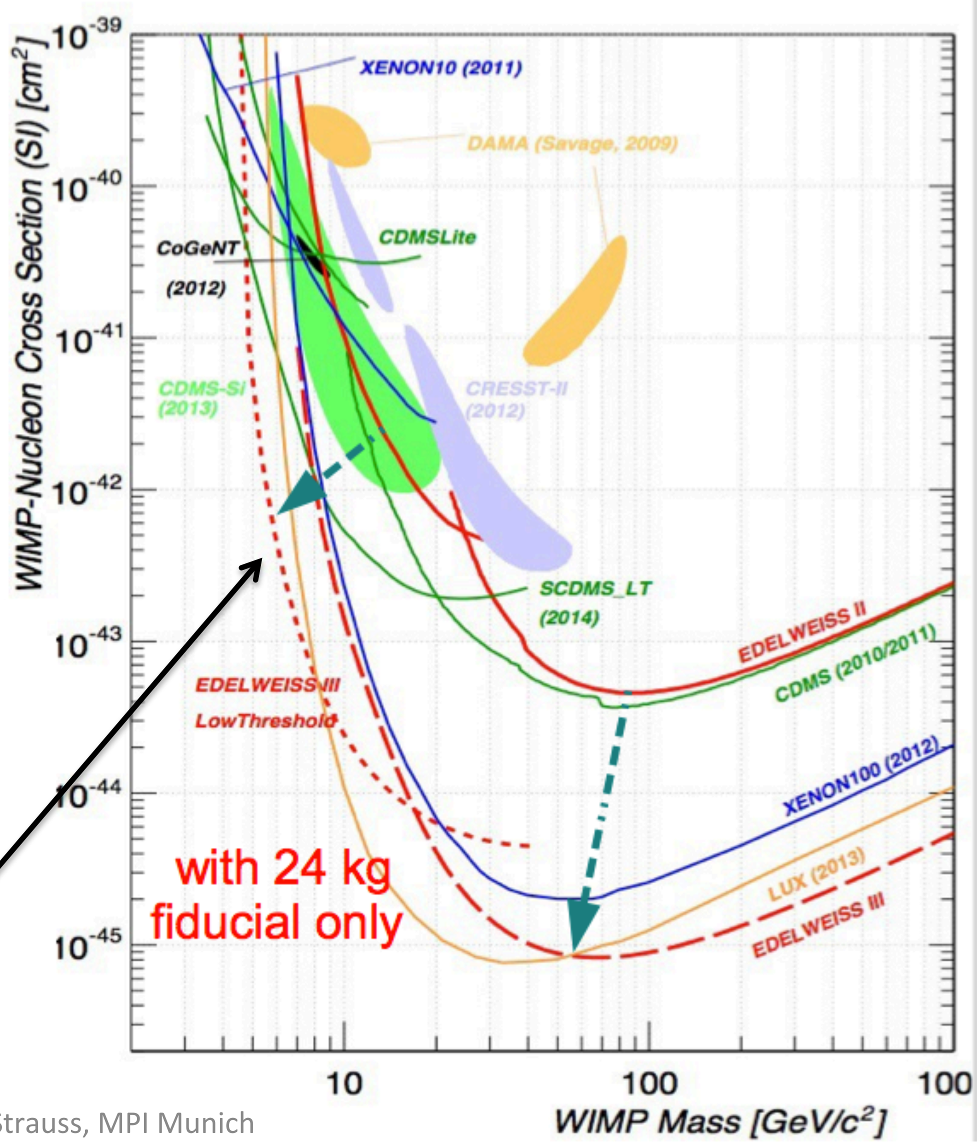
EDELWEISS - III

Current status:

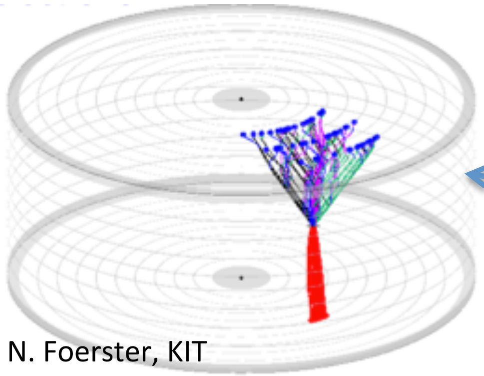
- 36 FID800 installed (24 are read-out)
- Data-taking since 2 months
- First data release planned for spring 2015

Projected sensitivity:

- Standard WIMPs (12.000kg-days) after 500 days, background-free above 15keV
- Low-mass WIMPs (4 detectors) highly improved resolution



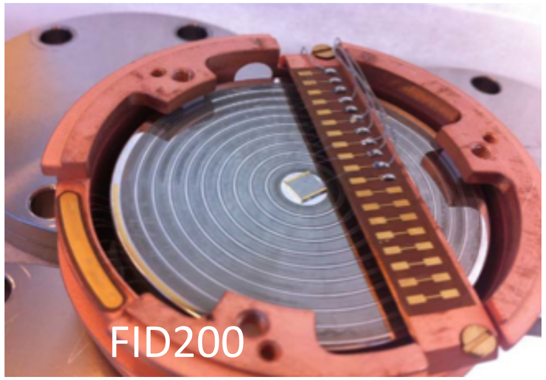
R&D for EDELWEISS



Studies on charge migration in FID detectors

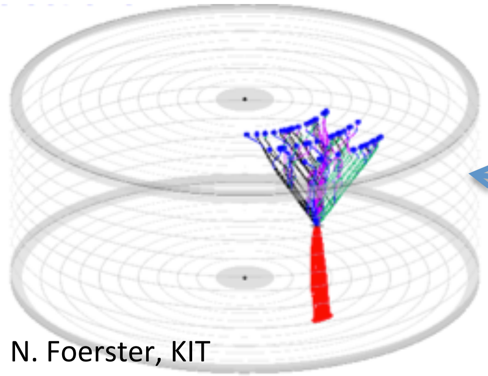
Simulations

R&D detector



R&D for EDELWEISS

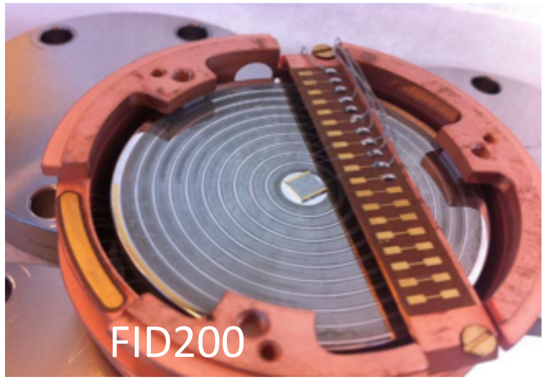
Karlsruher Institut für Technologie



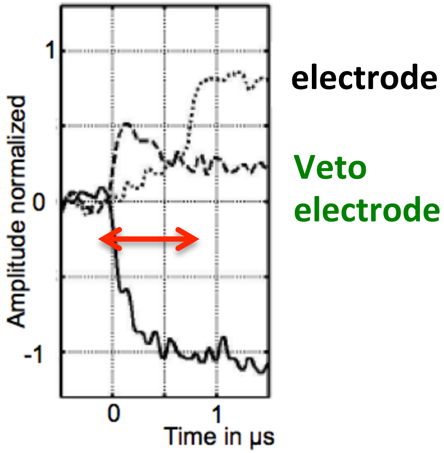
Studies on charge migration in FID detectors

Simulations

R&D detector

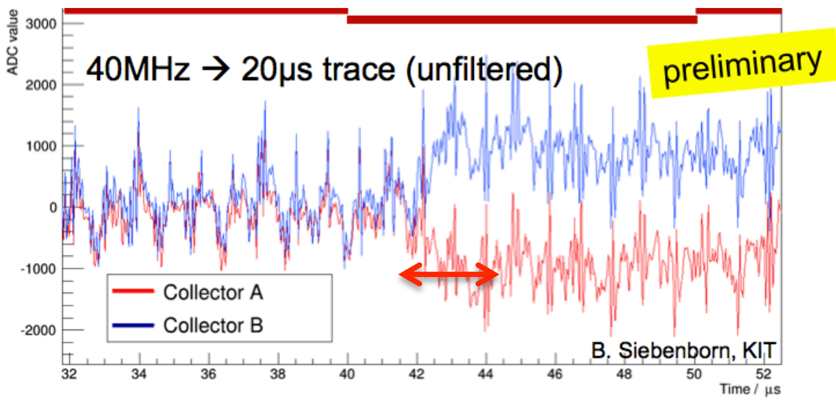


Goal: time-resolved ionisation signals

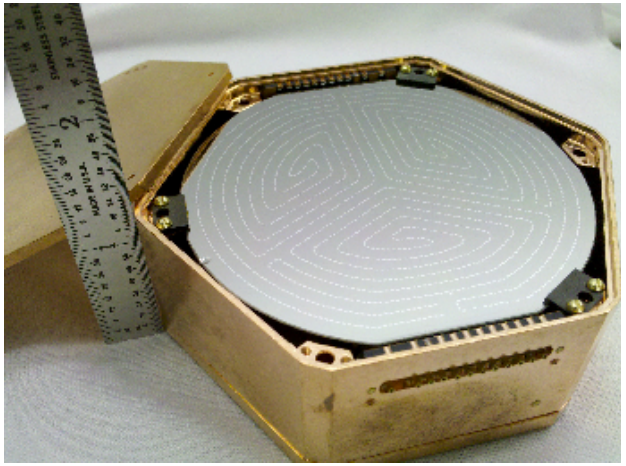


Broniatowski et al. PLB681(2009)

First results



SuperCDMS

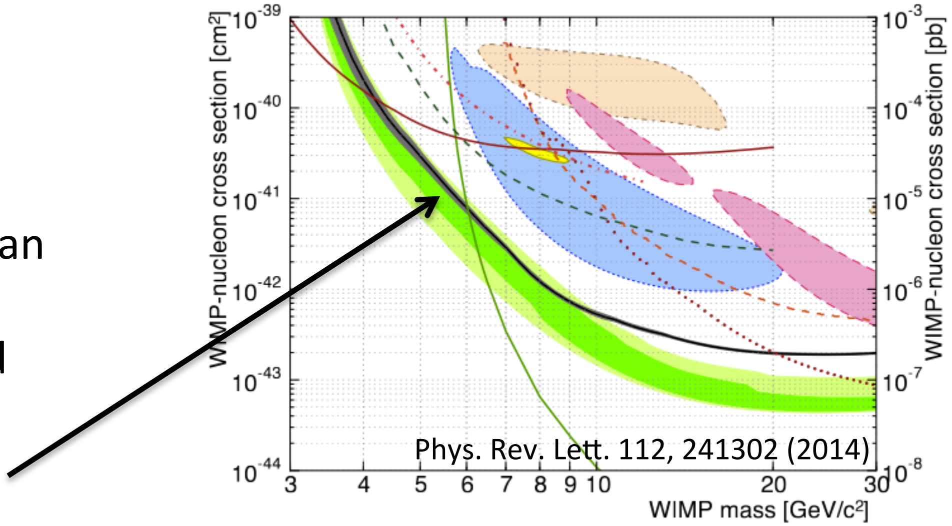


iZIP detectors (600g Ge)

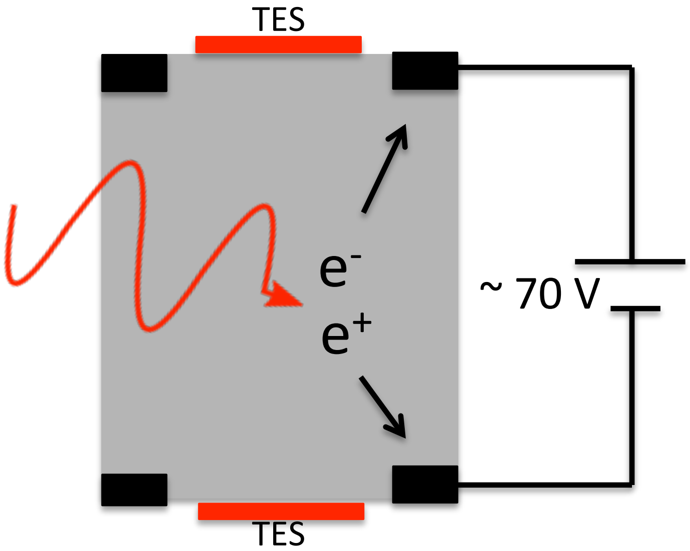
i → interleaved electrodes
Z → Z-sensitive
I → ionisation (4 channels each)
P → phonon (8 channels each)

First data release in spring 2014

- 15 detectors in operation at Soudan
- 577kg-days of exposure
- Improved rejection of gamma and surface events
- Probed new parameter below 6 GeV/c^2



SuperCDMS – Voltage Assisted Detectors



High voltage applied on electrodes

→ Drifting of electrons and holes

→ Amplification of phonon signal (Neganov-Luke effect)

Use phonons to read charge!

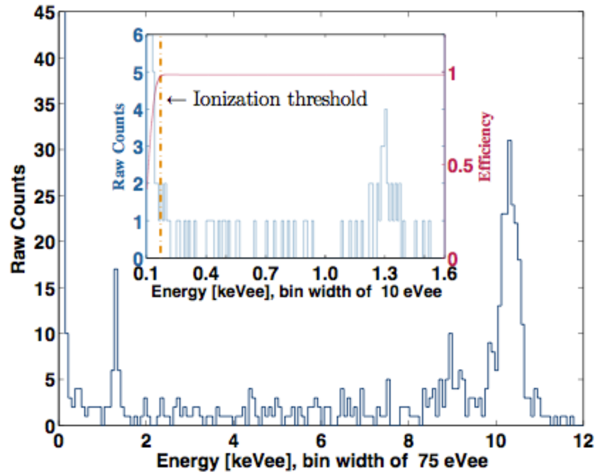
+ Excellent threshold: 170 eV_{ee} (for electron recoils)

– Loss of background discrimination (only 1 channel experiment)

SuperCDMS – Voltage Assisted Detectors

Ionization quenching for nuclear recoils by a factor of k=0.1-0.2

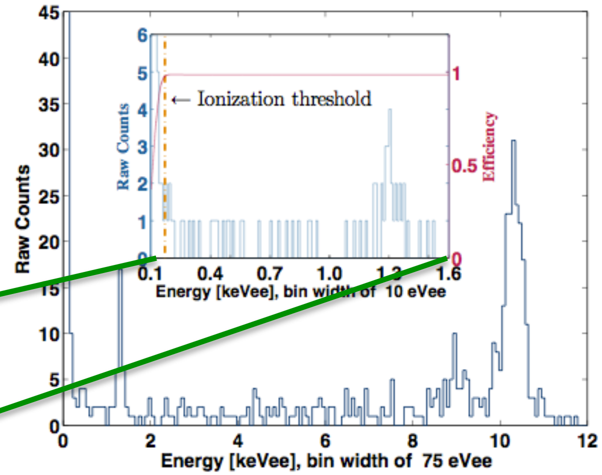
– Energy scale must be scaled (→uncertainty)
+ Dilution of background

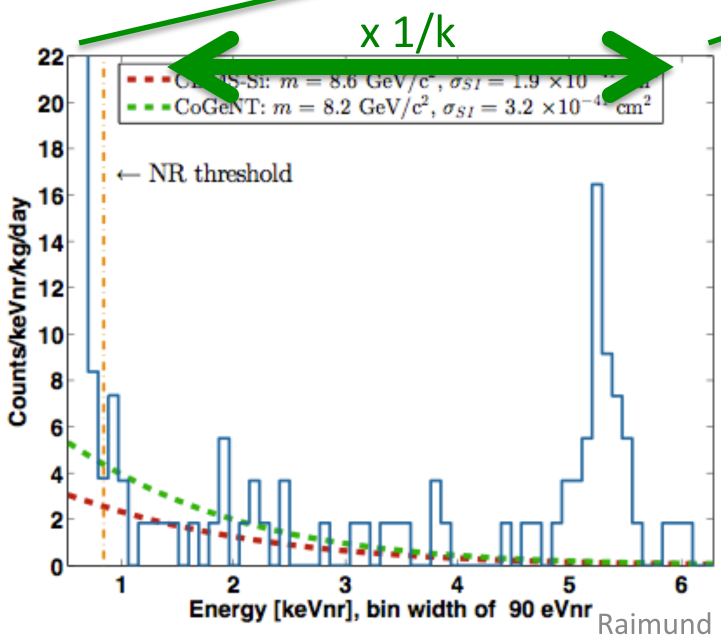


SuperCDMS – Voltage Assisted Detectors

Ionization quenching for nuclear recoils by a factor of k=0.1-0.2

– Energy scale must be scaled (→uncertainty)
+ Dilution of background

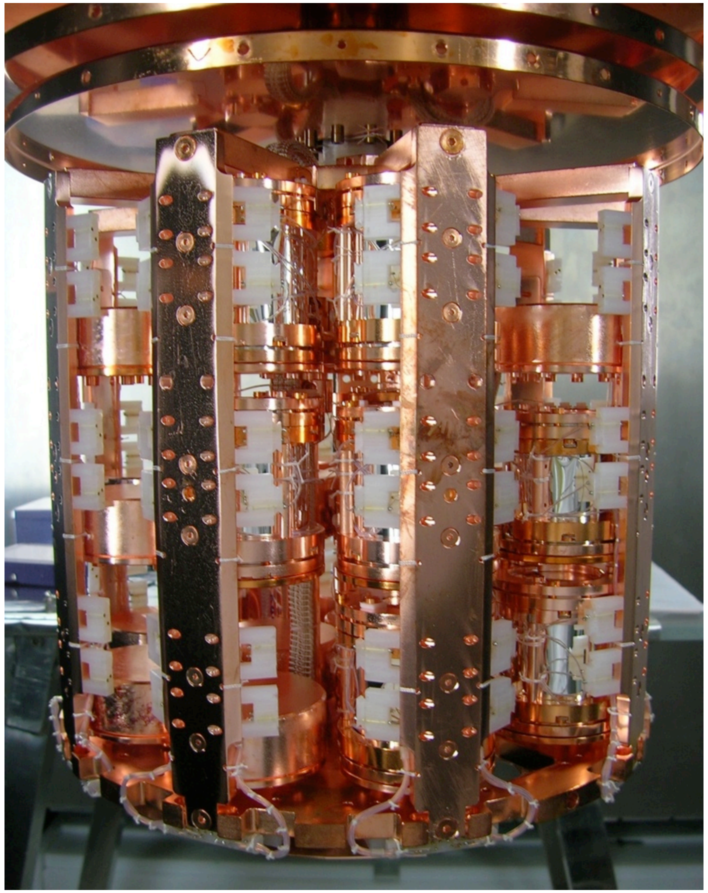




Threshold for nuclear recoils: 840 eV_{nr}

- High sensitivity for low-mass WIMPs
  PRL 112, 041302 (2014)
- Part of low-mass WIMP strategy of SuperCDMS

CRESST-II Phase 2



Data-taking since July 2013

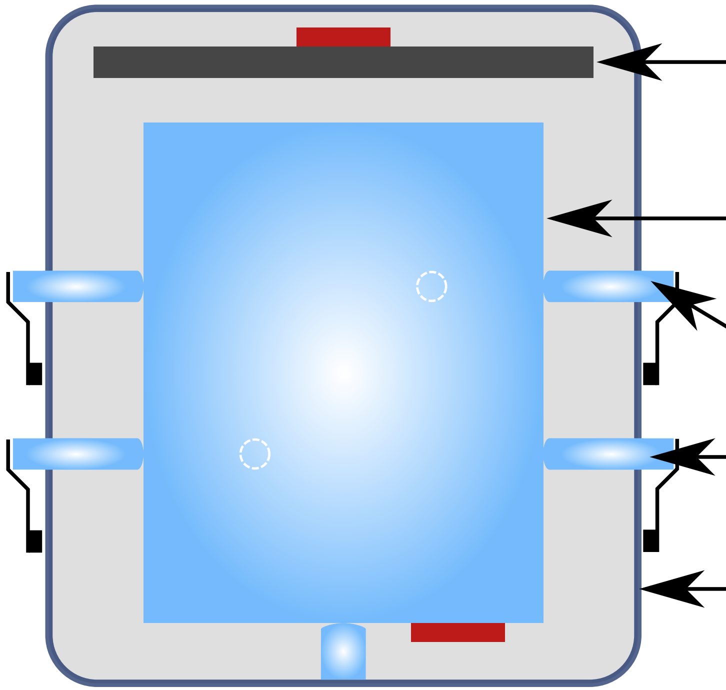
- 18 modules mounted (~ 5kg)

Release of first data on low-mass WIMPs in July 2014

- 29 kg-days of exposure with a single detector module (TUM40)
- Novel detector design employed

CRESST-II Phase 2

Novel fully-scintillating detector design



→ Highly-efficient rejection of surface-alpha backgrounds!

CRESST-II Phase 2

$CaWO_4$ crystal growth at TU Munich

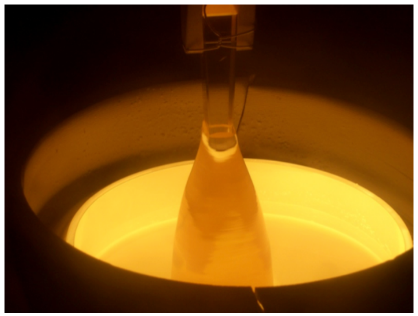
A. Erb and J.-C. Lanfranchi, *CrystEngComm*, 2013,**15**, 2301-2304
M. von Sivers, Opt. Mat. 34, 11 (2012) 1843-1848, arXiv:1206.1588

Goals :

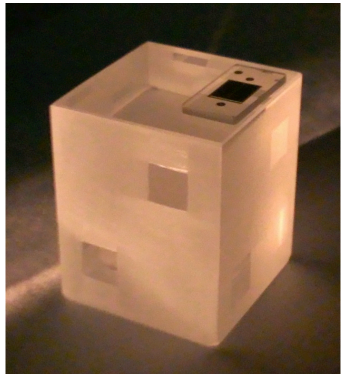
- Increase radiopurity
- Increase light output
- Ensure supply (for ton scale)

Major achievements:

- Reproducible growth of CRESST-size crystals
- Unprecedented intrinsic radiopurity

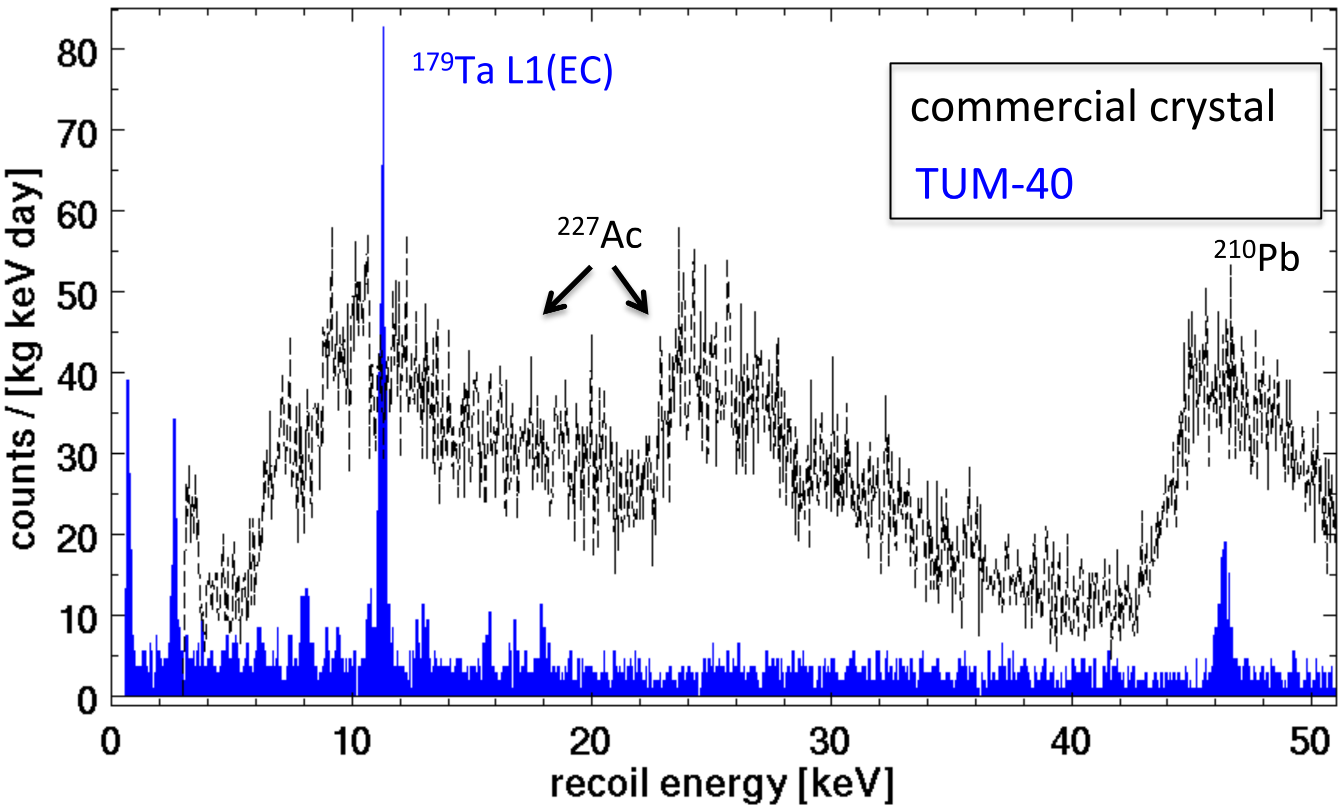


TUM-40
m=250g



CRESST-II Phase 2

Total event rate of TUM40



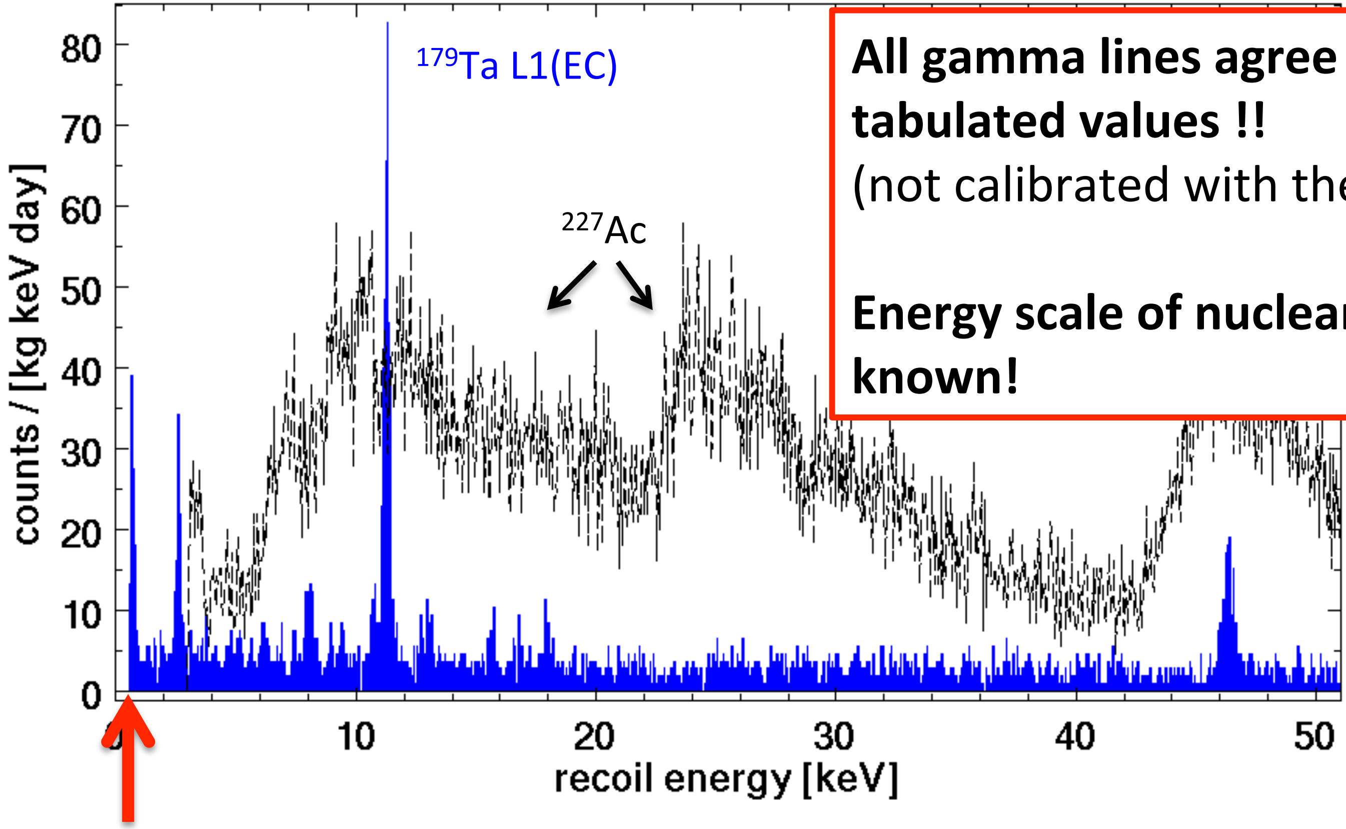
Unprecedented background rate:
~3.5 counts / [kg keV day]

Gamma-lines from **cosmogenic activation**

Excellent resolution:
$\sigma \approx$90 eV (@2.6keV)

CRESST-II Phase 2

Total event rate of TUM40



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

Energy scale of nuclear recoils precisely known!

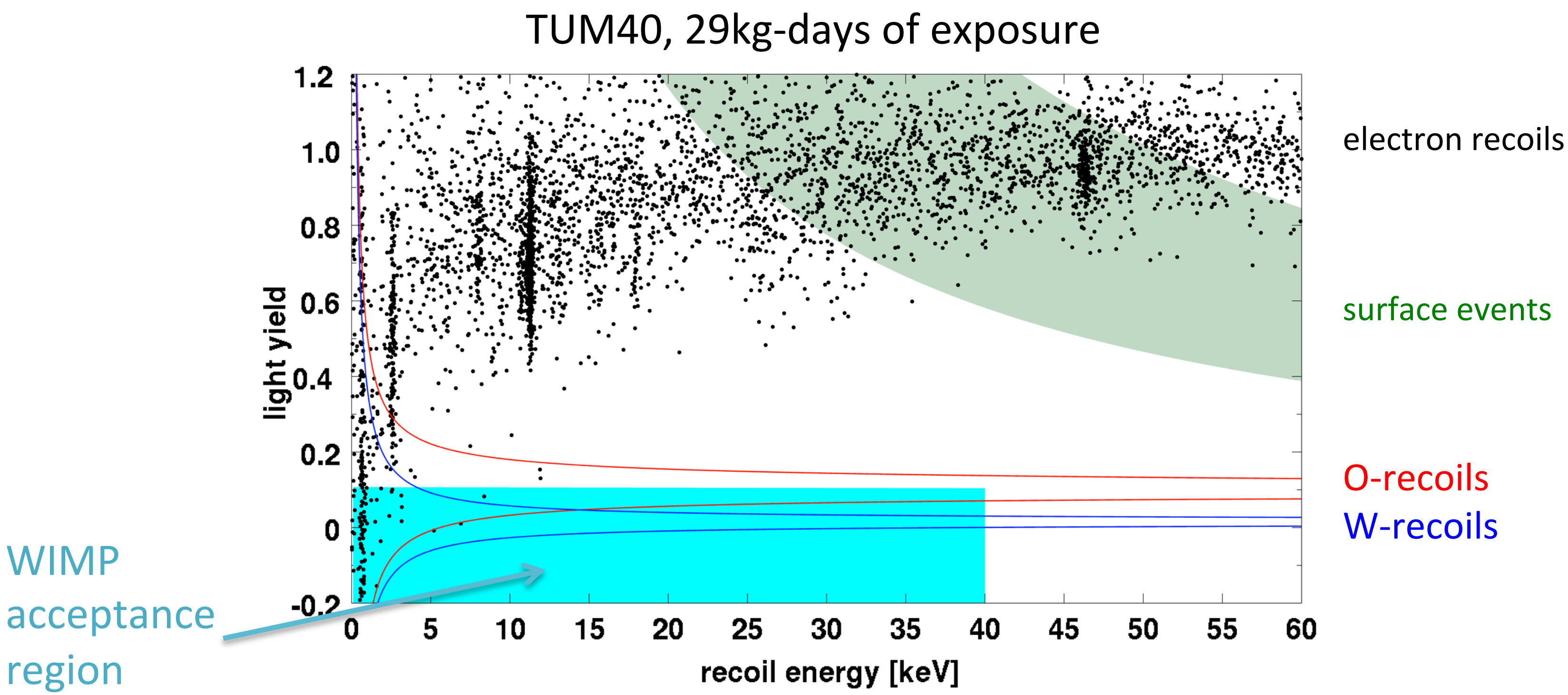
activation

Excellent resolution:

$\sigma \approx 90$ eV (@2.6keV)

Threshold: 0.6 keV (50 %)

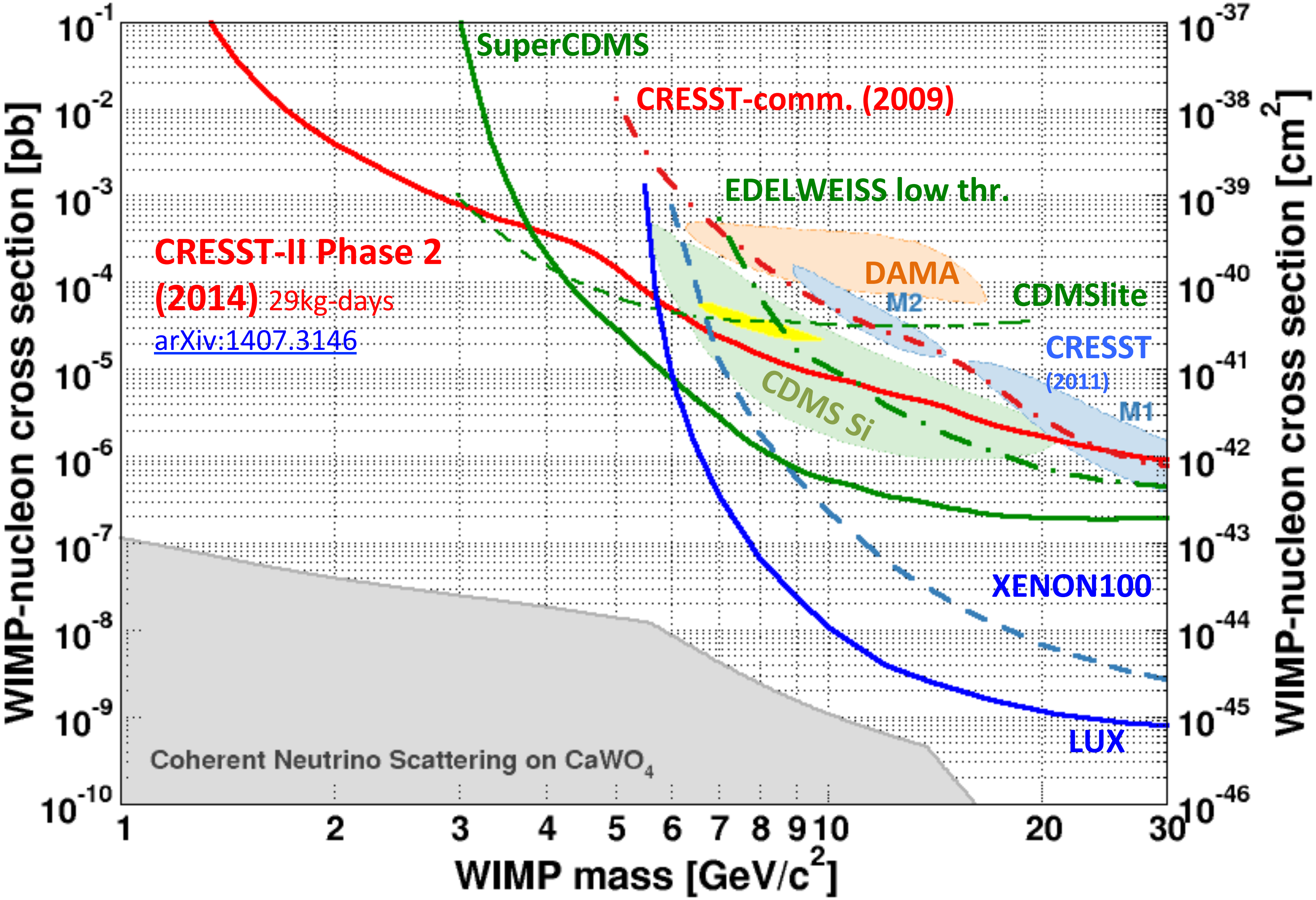
CRESST-II Phase 2



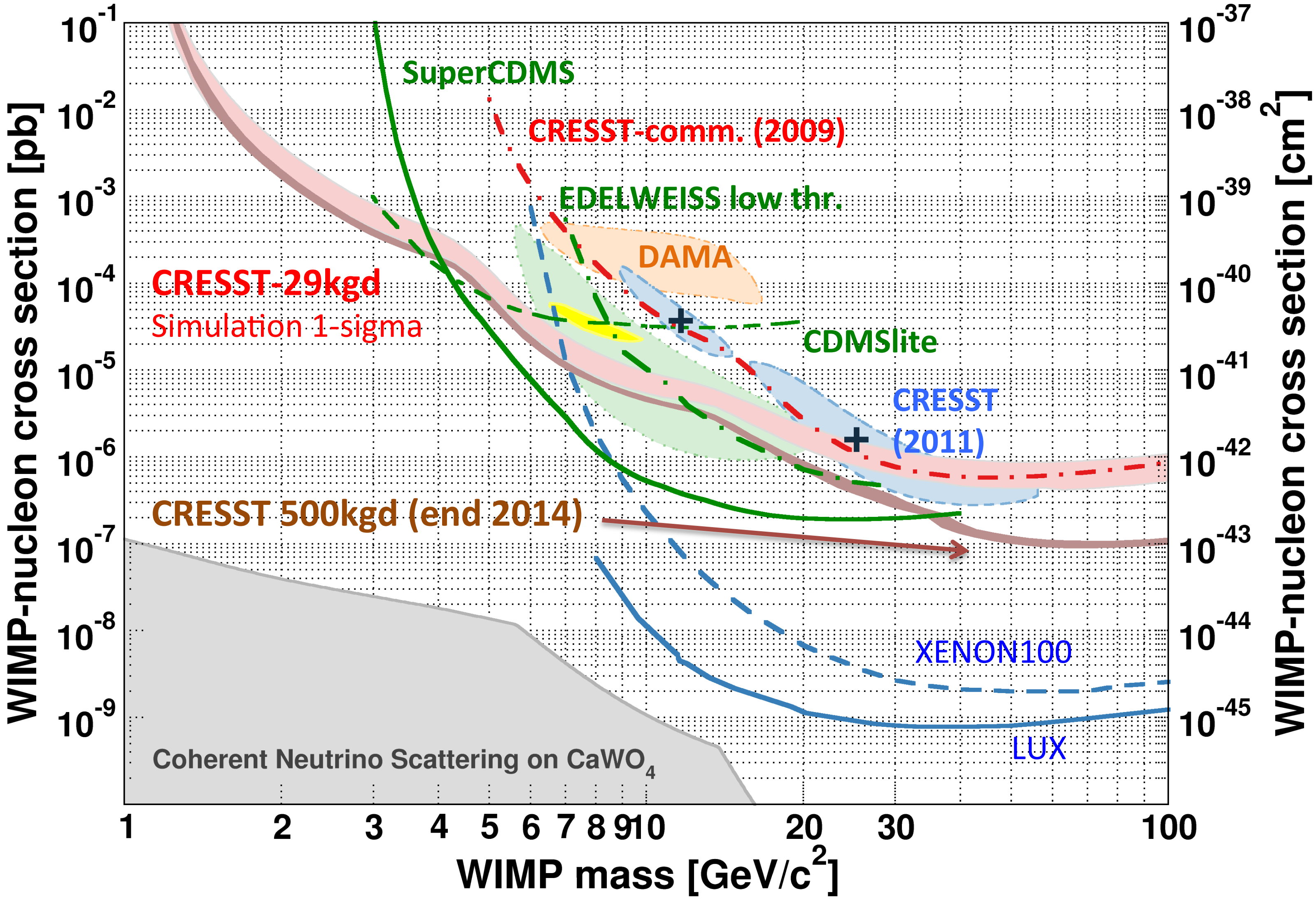
Phonon and Light channels fully-exploitable down to lowest energies!

→ Dilution of background

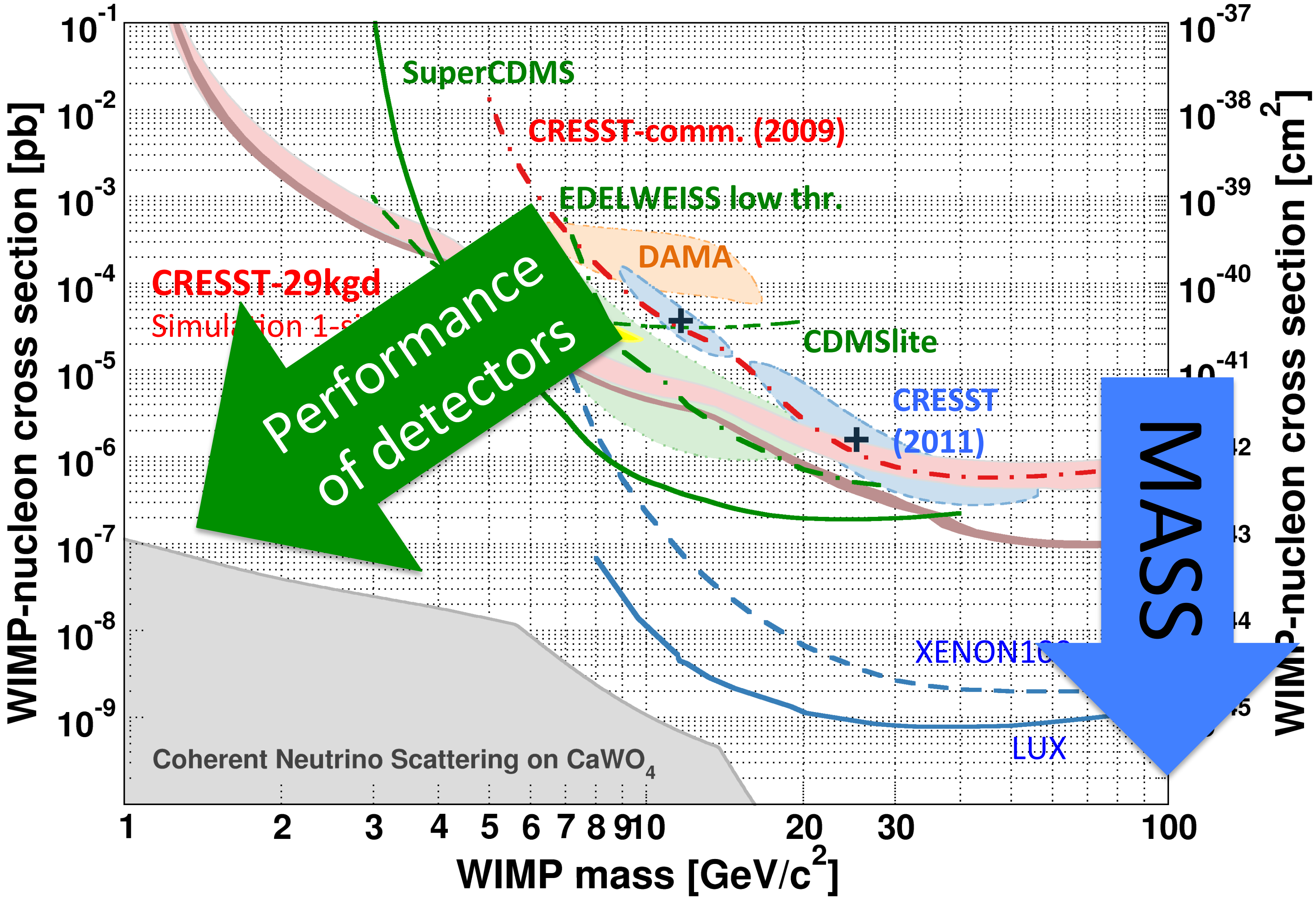
Results from 29kg-days of CRESST-II Phase 2



Projection for Final Exposure of CRESST-II Phase 2



Projection for Final Exposure of CRESST-II Phase 2



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

Scale down size by factor 10

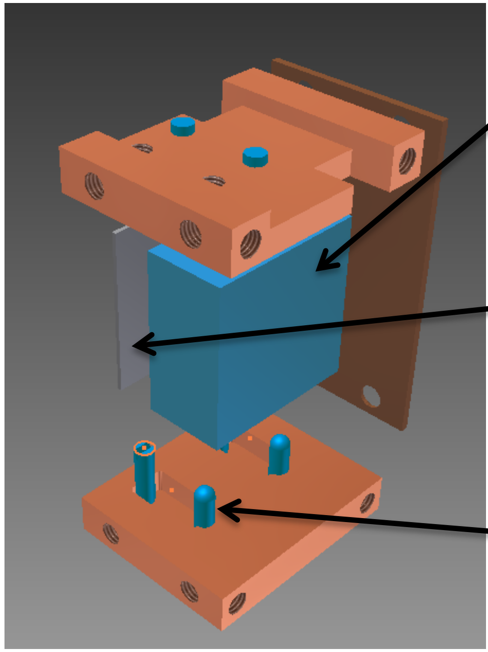
m=24g

+ use 2 light detectors

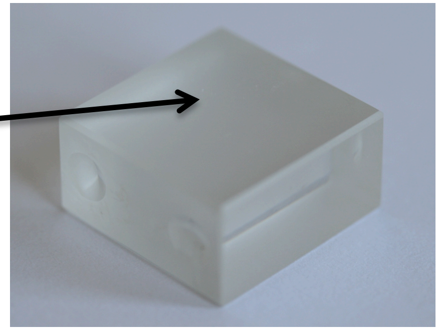
Phonon threshold:	$E_{th} \approx 0.4$ keV	**improvement by a factor of 5**
Light-detector res.:	$\sigma \approx 5$ eV	**improvement by a factor of 2**

NO improvements assumed concerning radiopurity and optical quality of crystals!

CRESST-III Phase 1 - Prototype

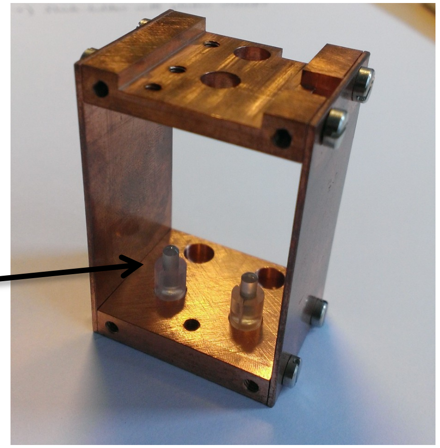


24g block-shaped $CaWO_4$ crystal ($10x20x20mm^3$)



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

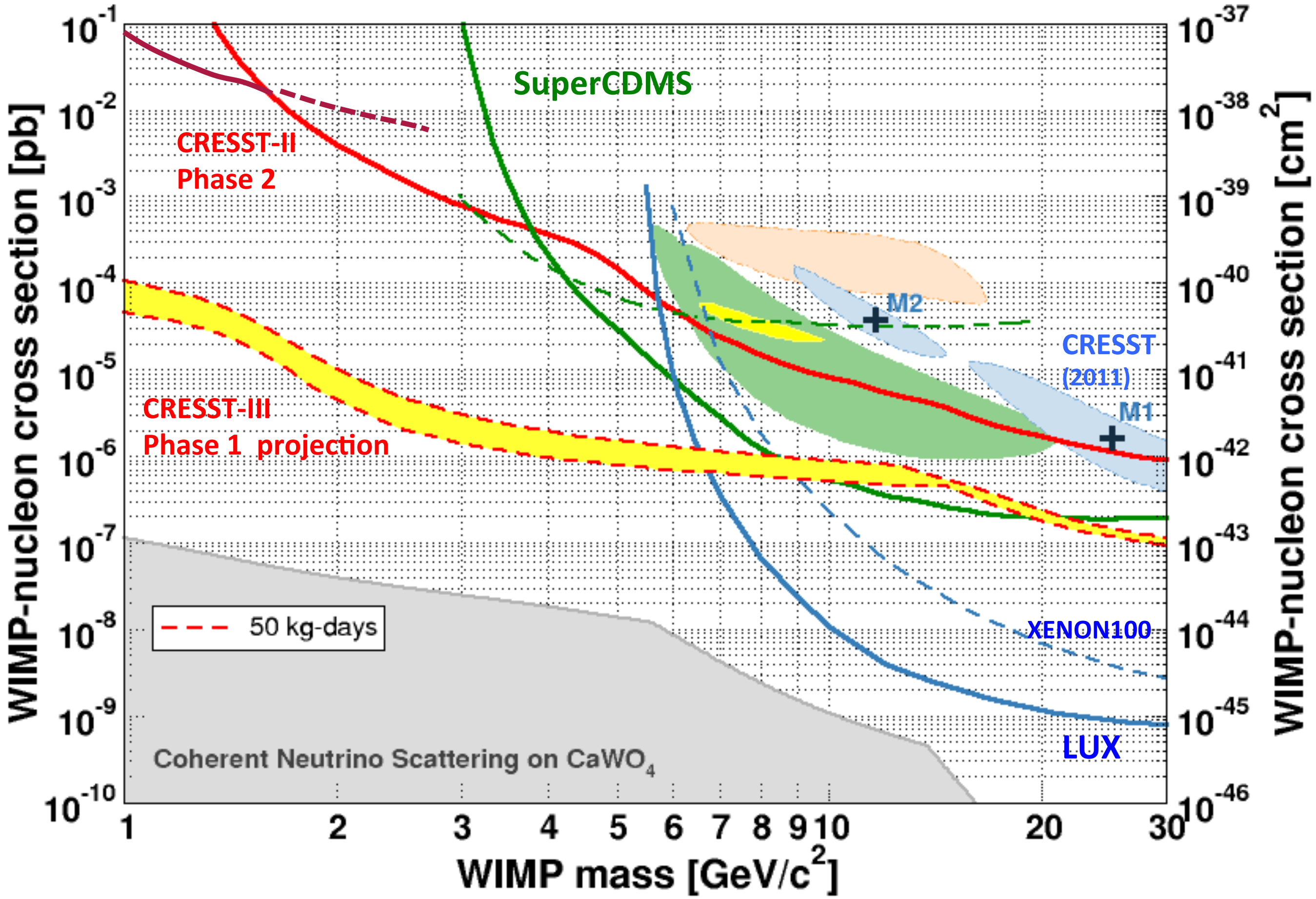
$CaWO_4$ sticks



CRESST-III Phase 1

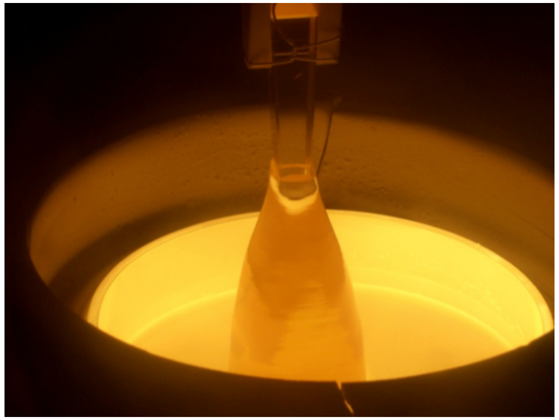
Assumptions:

- 24g $CaWO_4$ crystal
- E_{th} = 0.10 keV
- Light detector improved by factor 2 (due to smaller volume)
- 3x more detected light: due to thin crystal + 2nd light detector



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

CRESST-III Phase 2



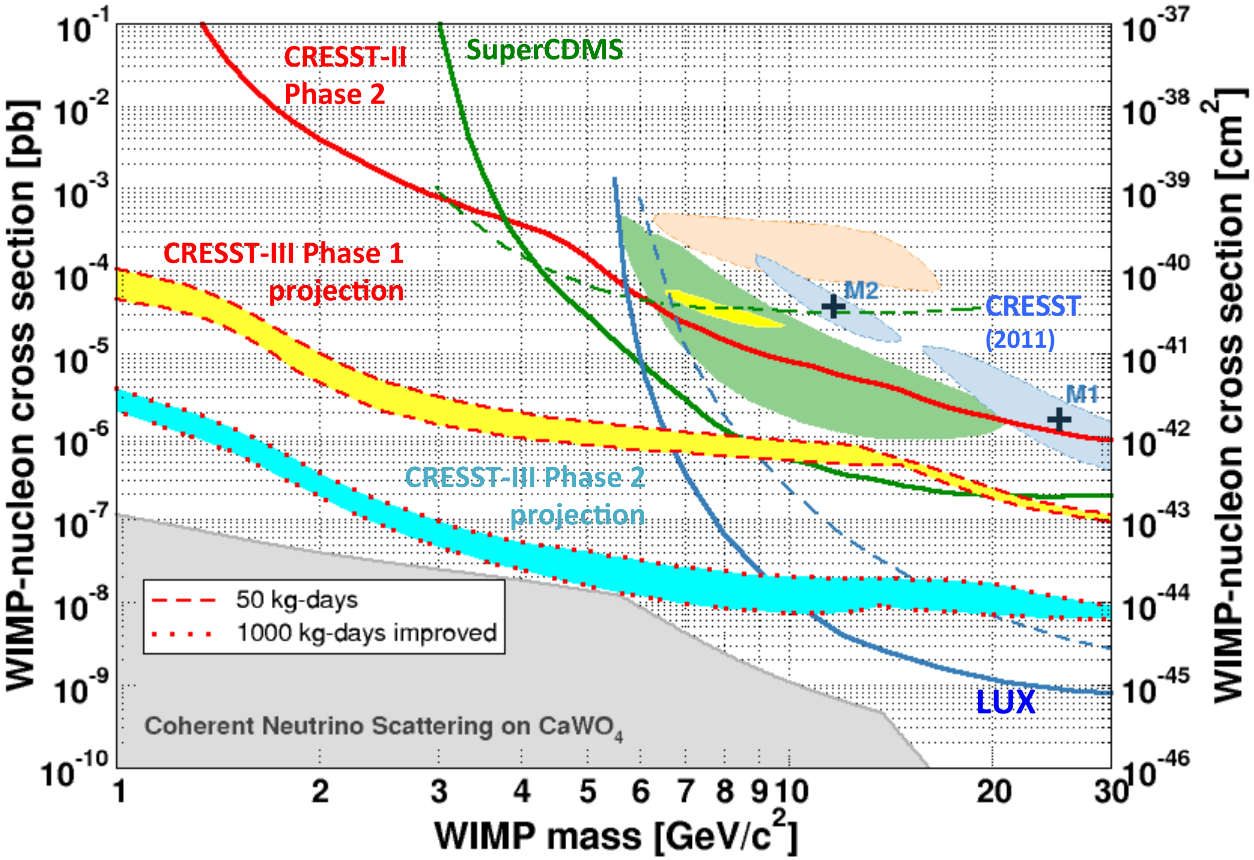
Reduce intrinsic background level of crystals!

- 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

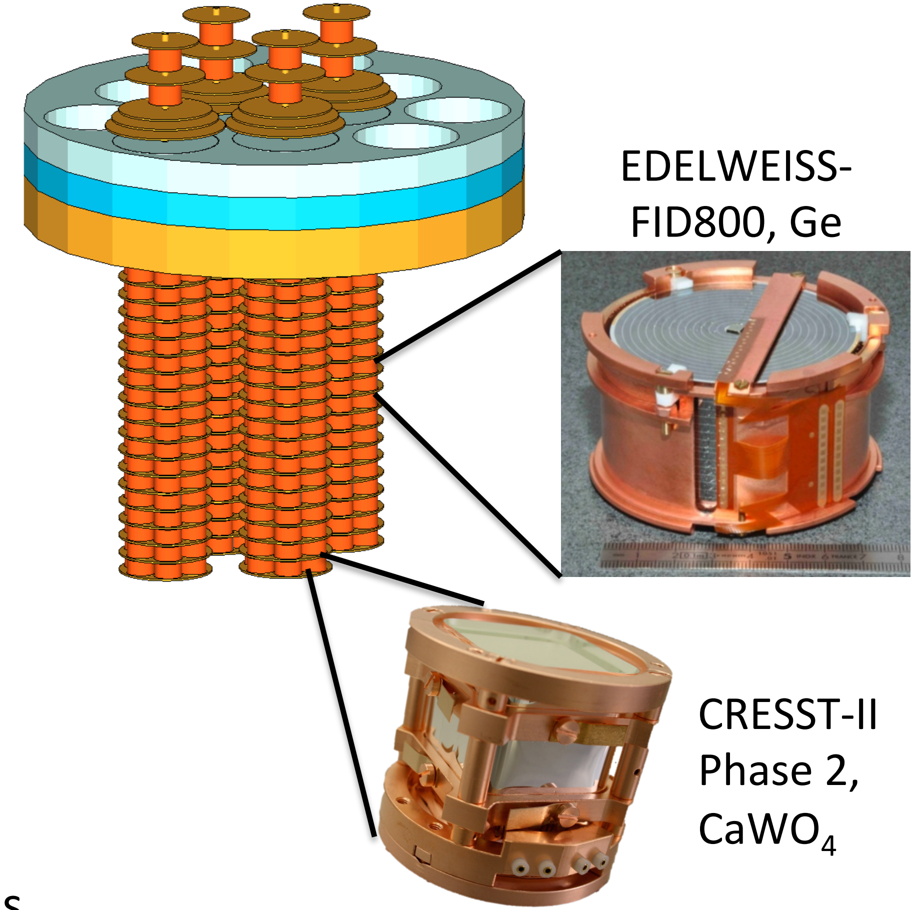
Project based on CRESST & EDELWEISS technologies

- 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

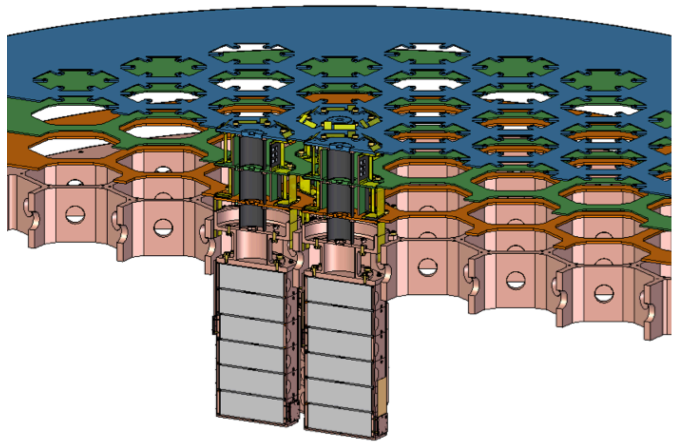
➢ **Phase 2:** up to 1ton of target mass



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

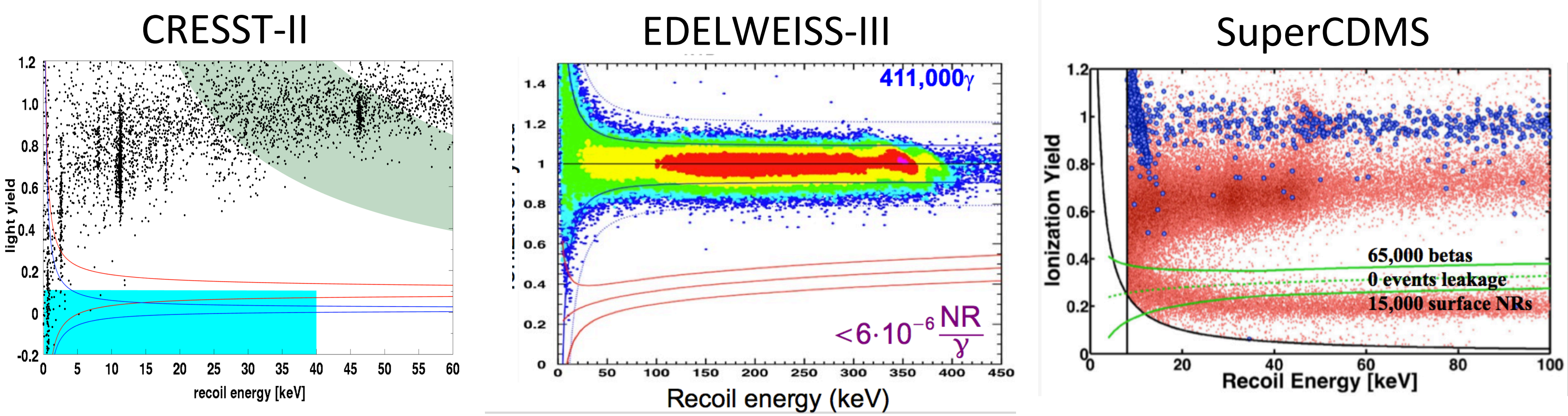
Expected EURECA contribution:

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

Close contact between EDELWEISS, CRESST and SuperCDMS collaborations!

Summary

Standard (high-mass) WIMPs



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

Summary

High potential for low-mass WIMP search

SuperCDMS (+EDELWEISS)

- Application of Neganov-Luke voltage
- Low threshold
- Dilution of backgrounds

CRESST

- Lowest thresholds
- Phonon-light technique
- Multi-element target