CRESST-II results on low-mass dark matter particles

Lake Louise Winter Institute
February 10, 2016

Florian Reindl
Max-Planck-Institute for Physics Munich

for the CRESST Collaboration

The CRESST Collaboration

HEPHY
Institut für Hochenergiephysik

INFN
Laboratori Nazionali del Gran Sasso

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

TUM
TECHNISCHE UNIVERSITÄT MÜNCHEN

UNIVERSITY OF OXFORD

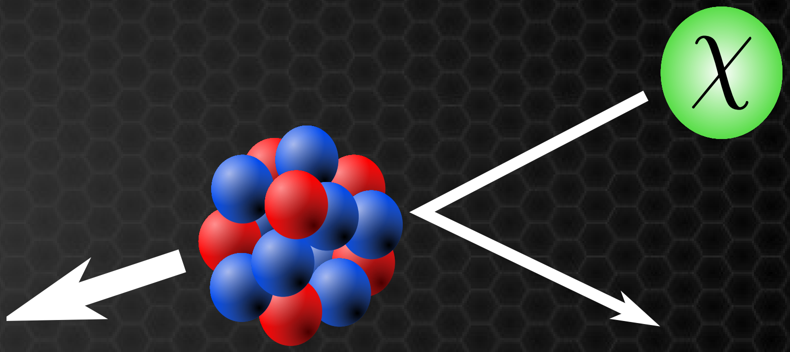
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Laboratori Nazionali del Gran Sasso

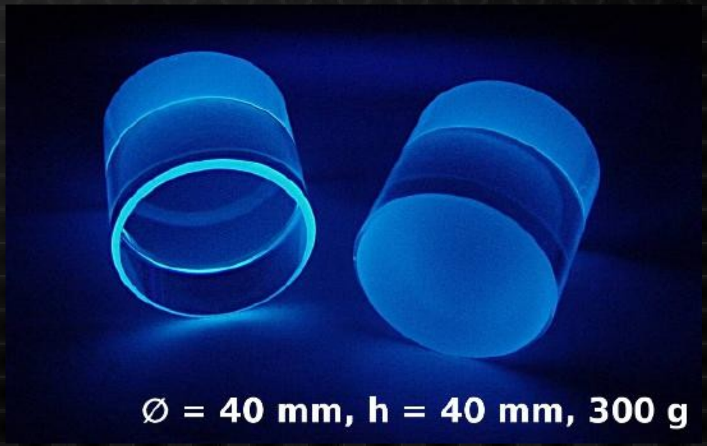
3600 m.w.e.

The Cryogenic Rare Event Search with Superconducting Thermometers

aims to detect elastic dark matter particle-nucleus scattering



uses scintillating $CaWO_4$ crystals as target



Detector Module

Particle interaction in the crystal

Phonon signal
deposited energy

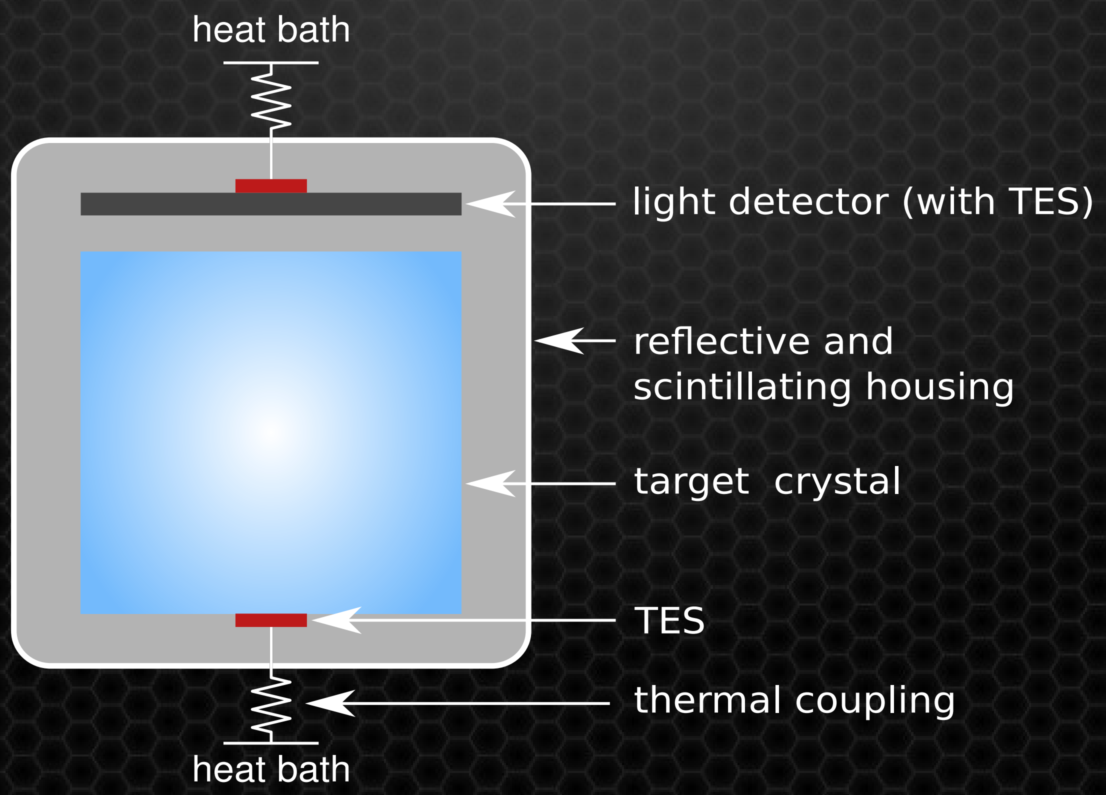
Scintillation light
particle discrimination

Detector Module

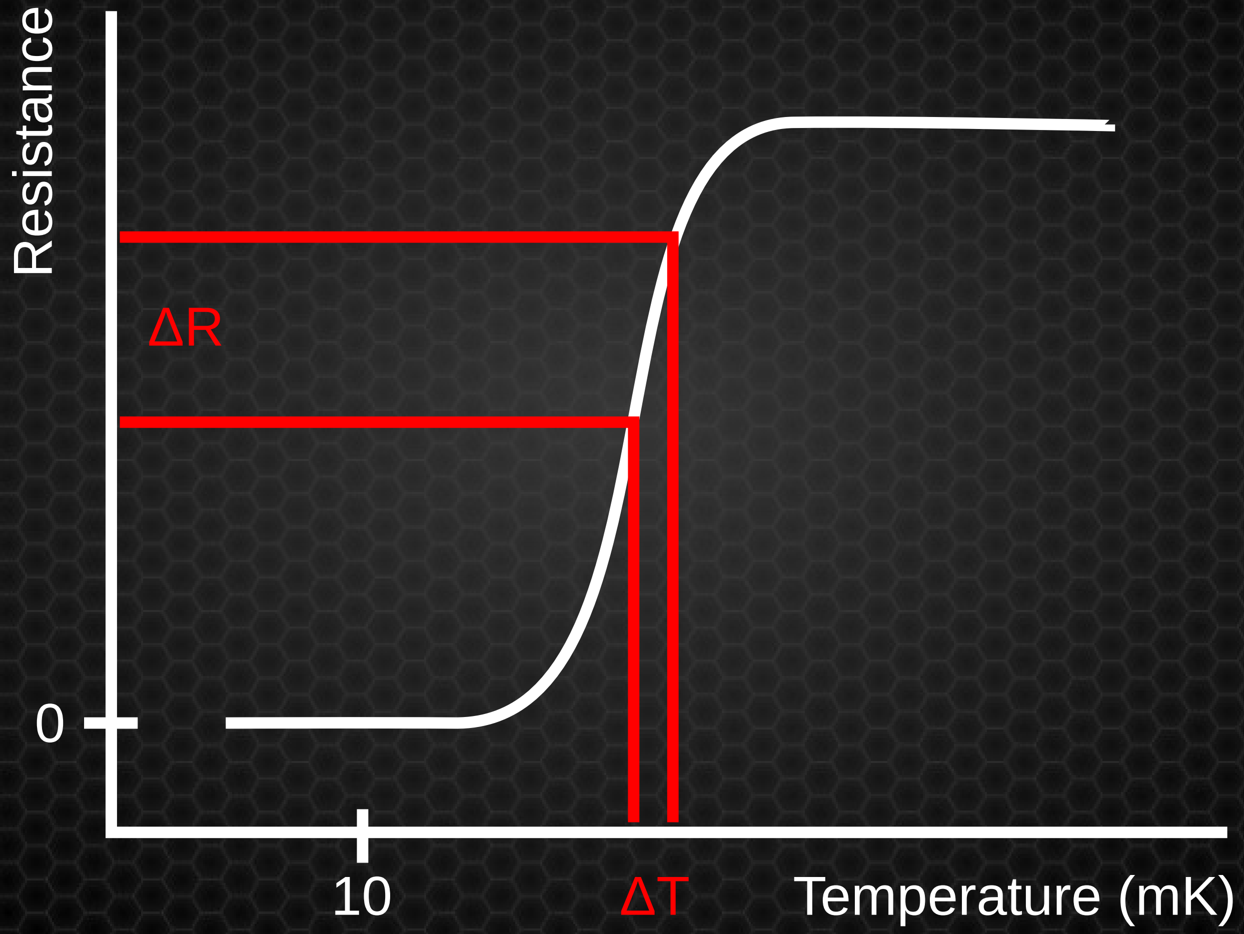
Particle interaction in the crystal

Phonon signal
deposited energy

Scintillation light
particle discrimination

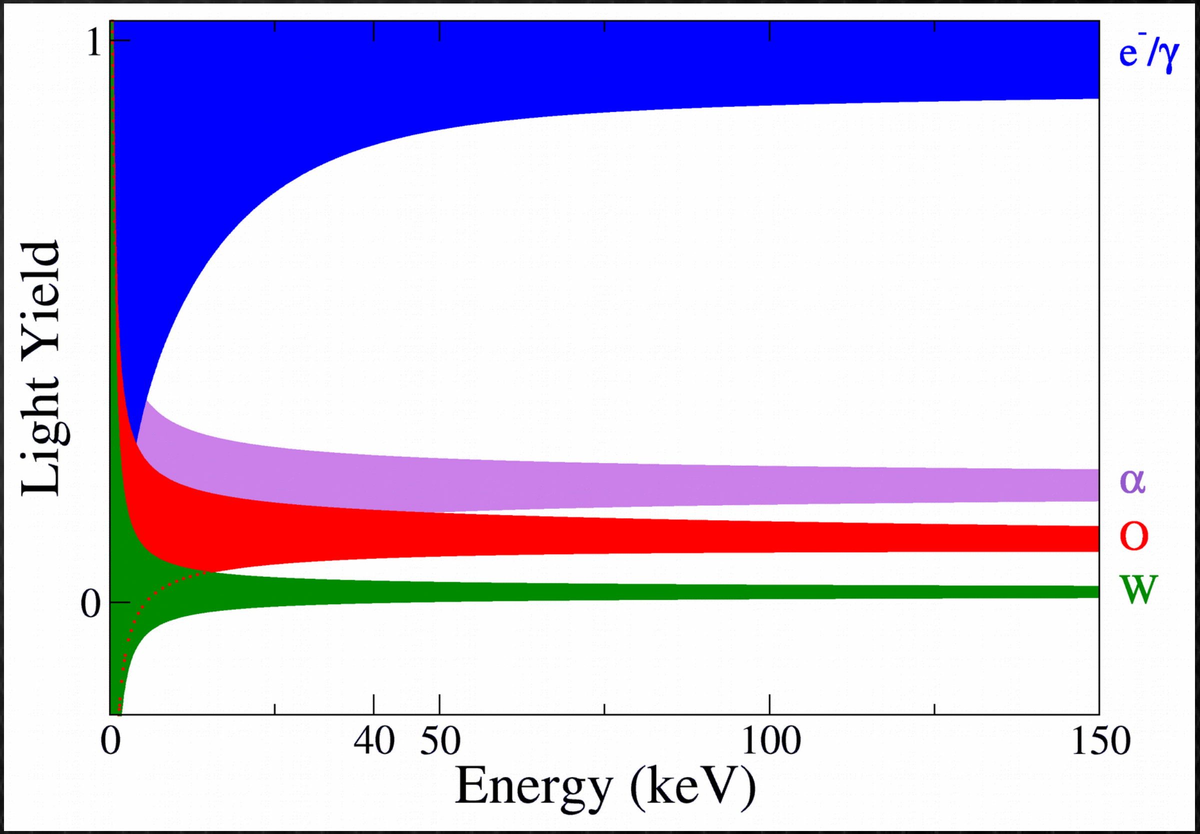


Transition Edge Sensor



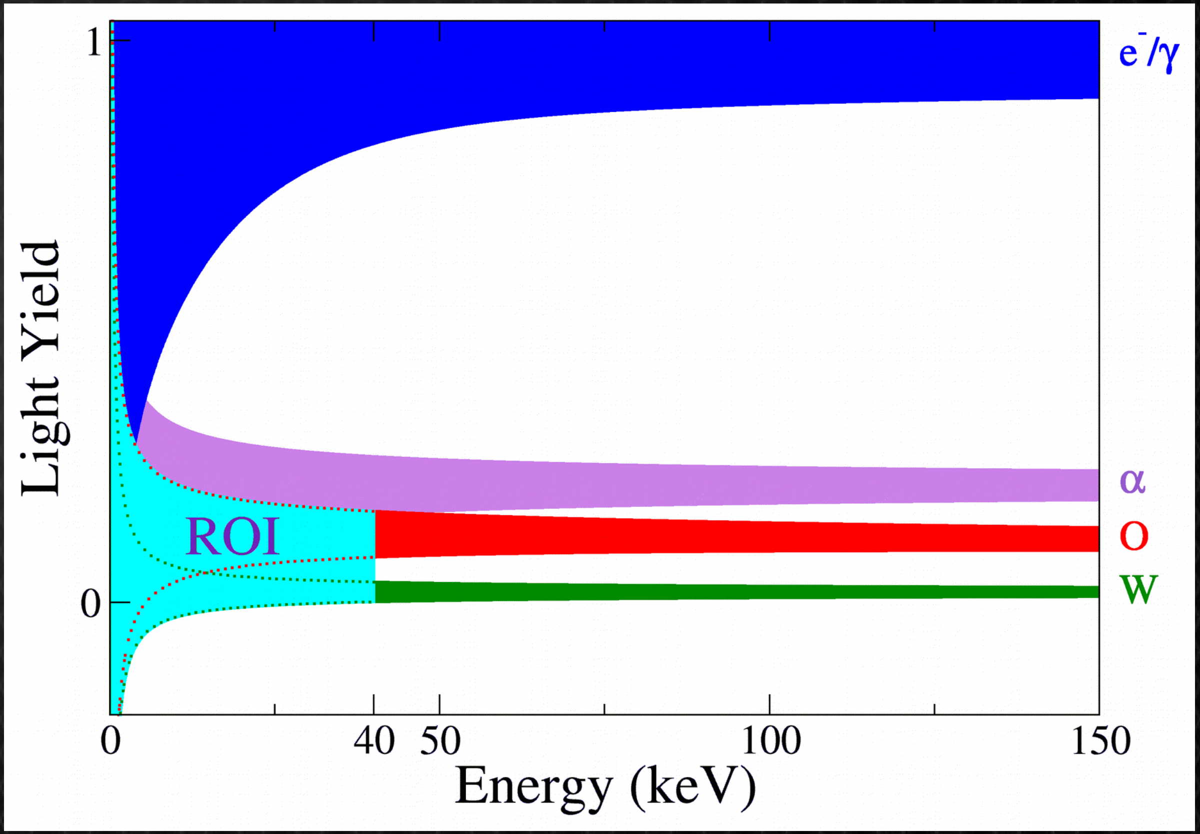
Event Discrimination

$$\text{light yield} = \frac{\text{light signal}}{\text{phonon signal}}$$



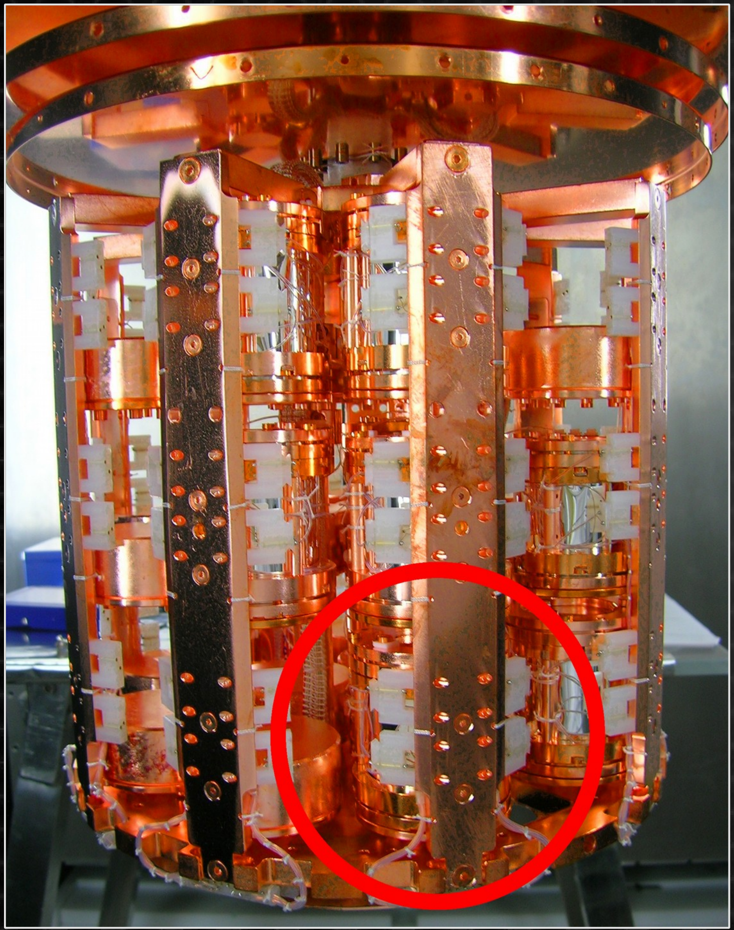
Event Discrimination

$$\text{light yield} = \frac{\text{light signal}}{\text{phonon signal}}$$



ROI: Region of interest for dark matter search

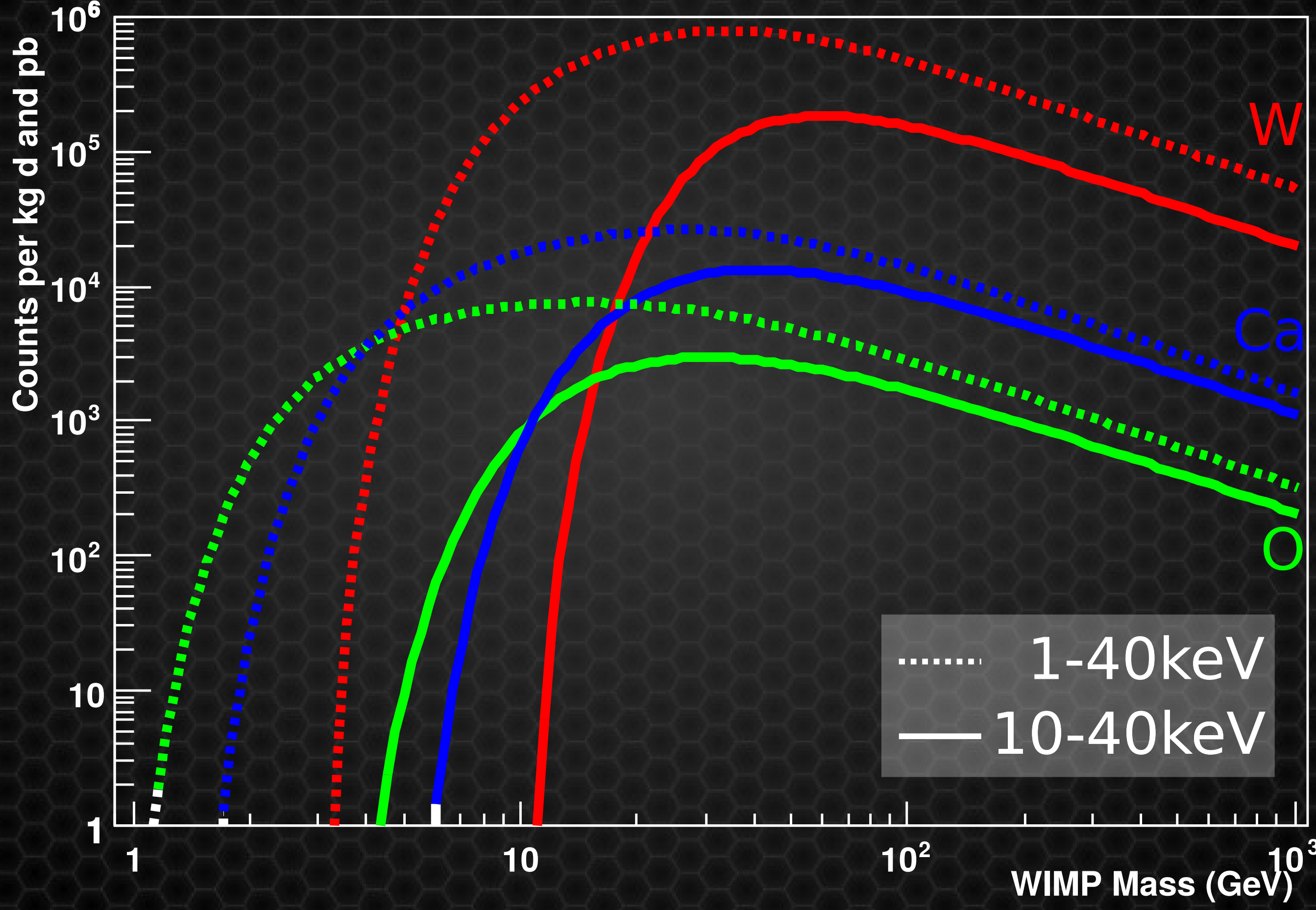
CRESST-II: Current Phase 2



- Data taking from July 2013
  to August 2015
- Result discussed today
  - Single module Lise
  - 52 kg days of exposure
  - Blind analysis

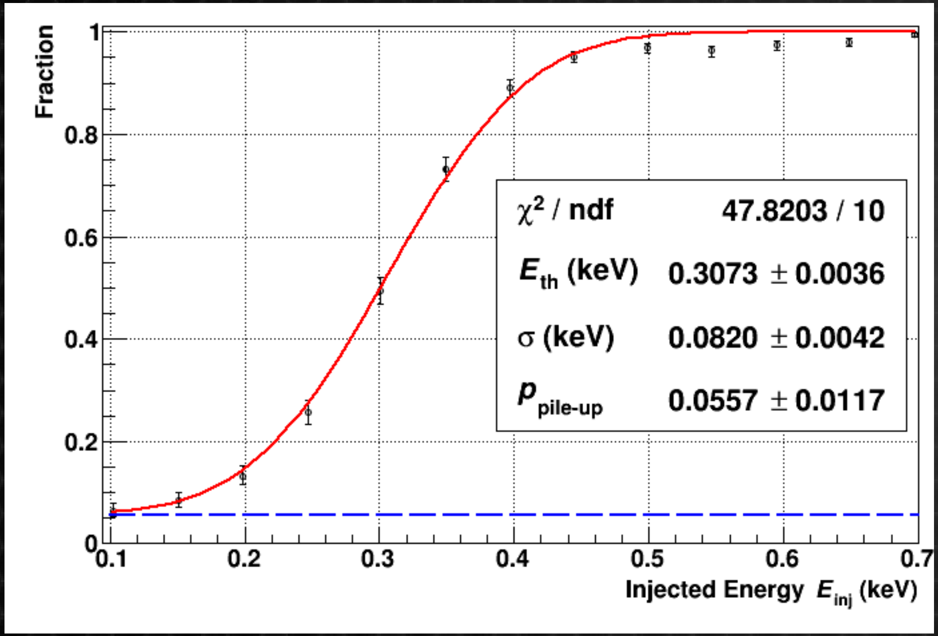
Eur. Phys. J. C 76 (2016)

Low Threshold Analysis - Motivation



Lise – Trigger and Cut Acceptance

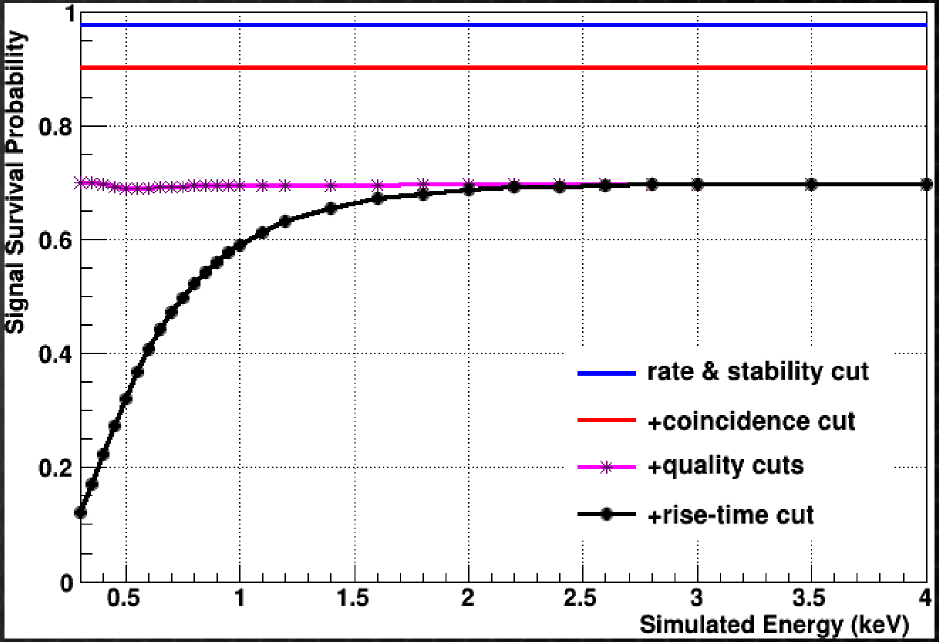
Trigger



Precisely measured with pulses injected to the heater

Nuclear recoil threshold: 307eV

Signal Survival Probability



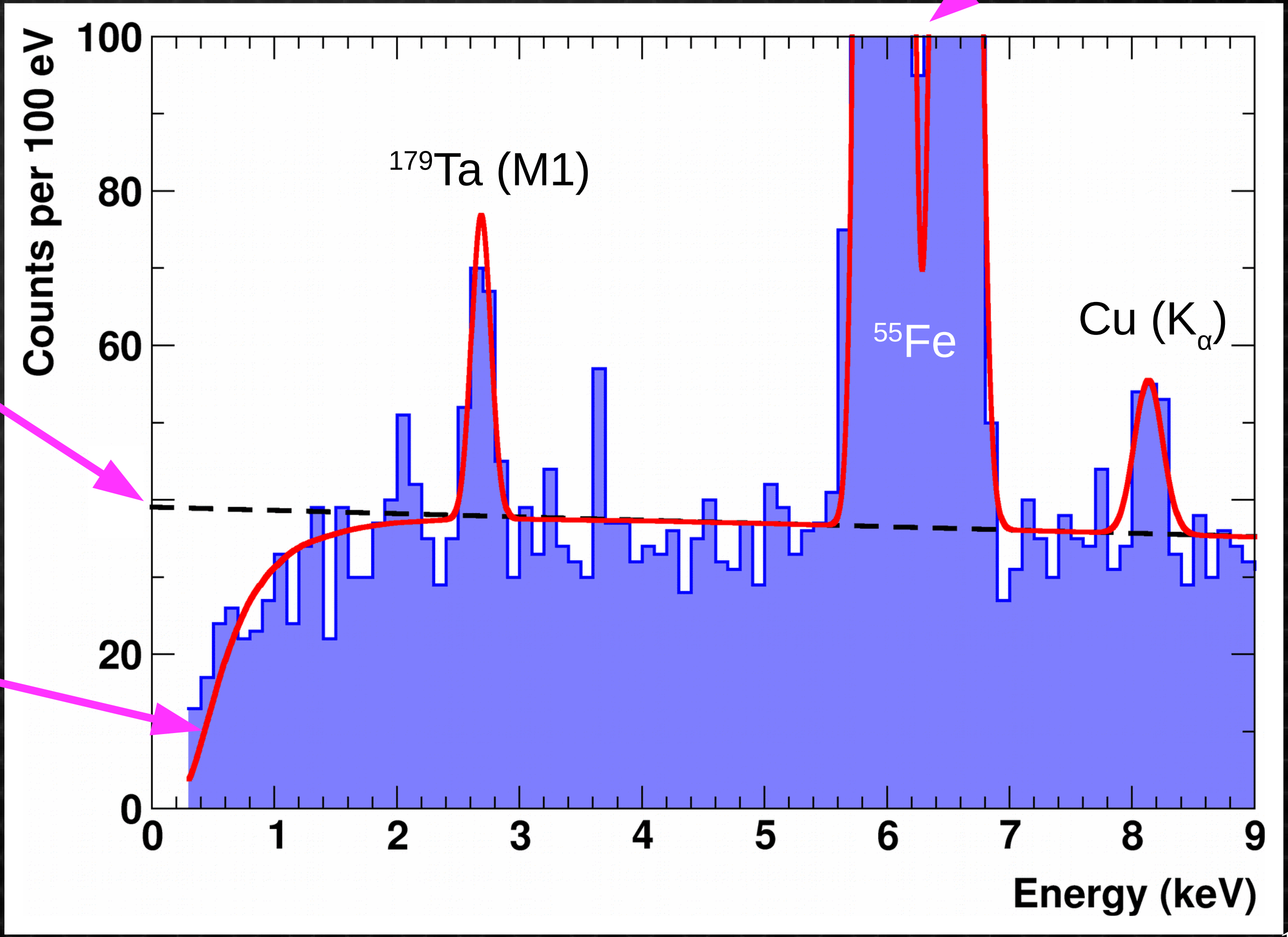
Acceptance down to threshold energy

12% @ 0.3keV 70% @2keV

Overall Background

External ^{55}Fe source

Flat background down to threshold!



Linear decrease

Data-driven back-ground model

~8.5 counts per (kg keV day)

Overall Background

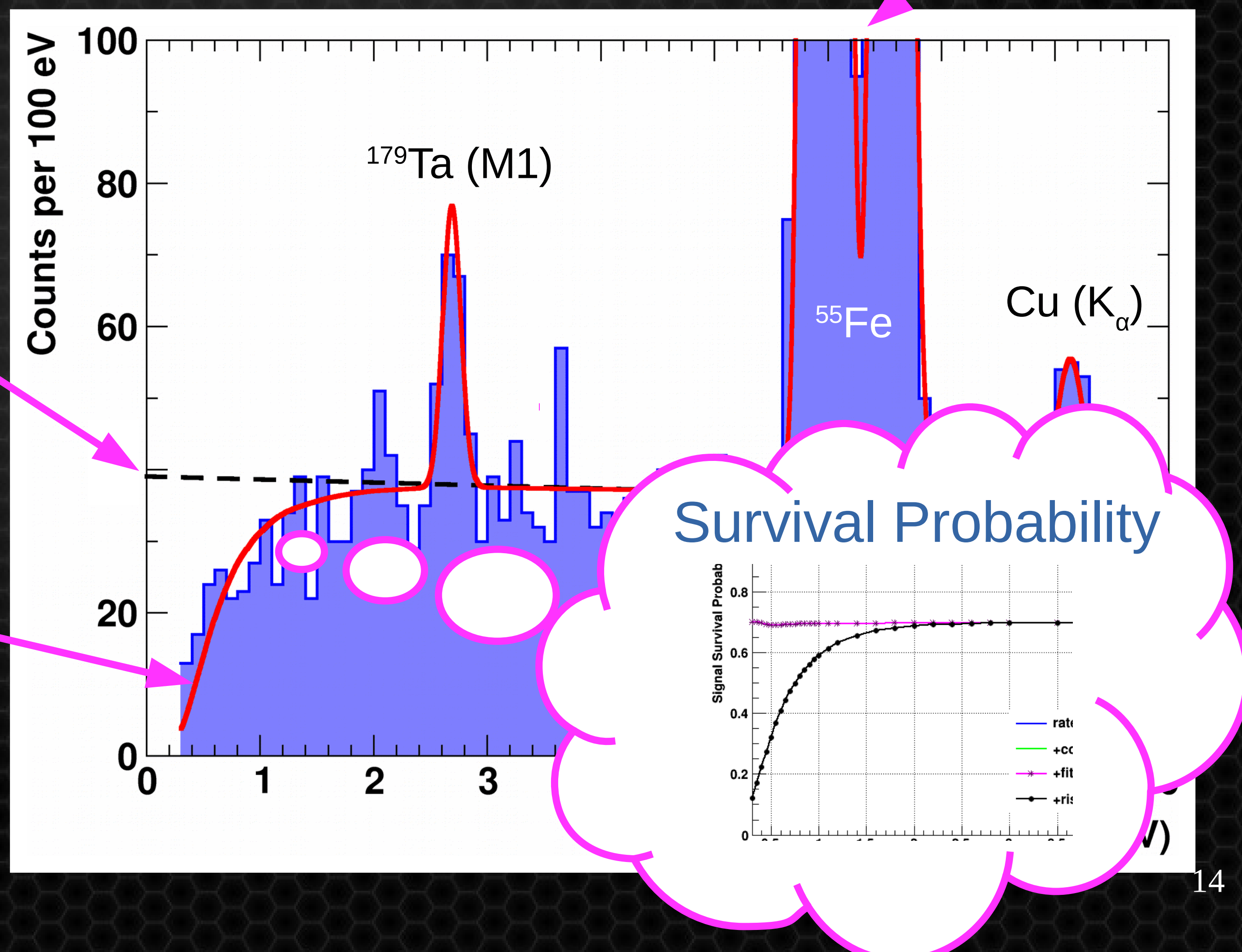
External ^{55}Fe source

Flat background down to threshold!

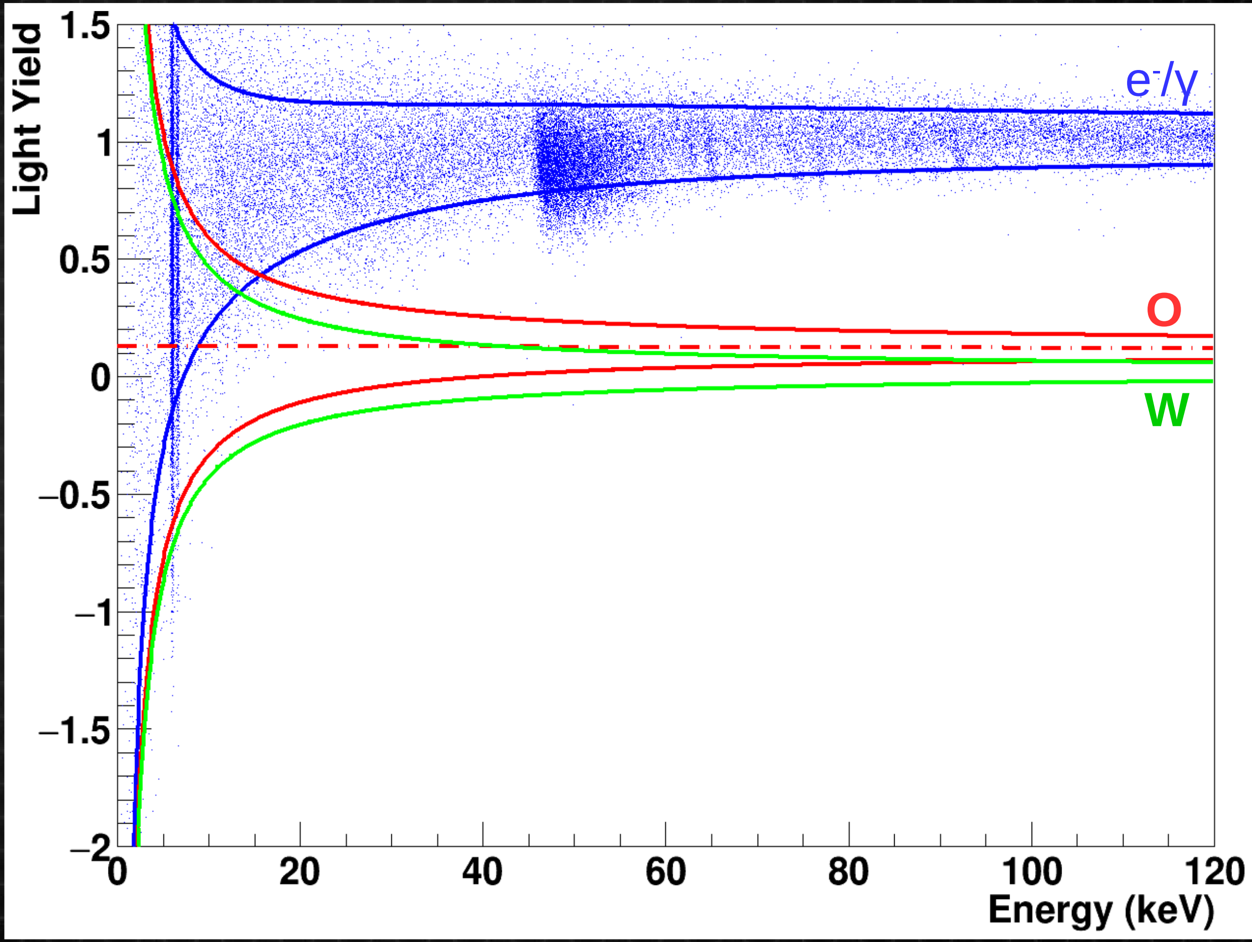
Linear decrease

Data-driven back-ground model

~8.5 counts per (kg keV day)



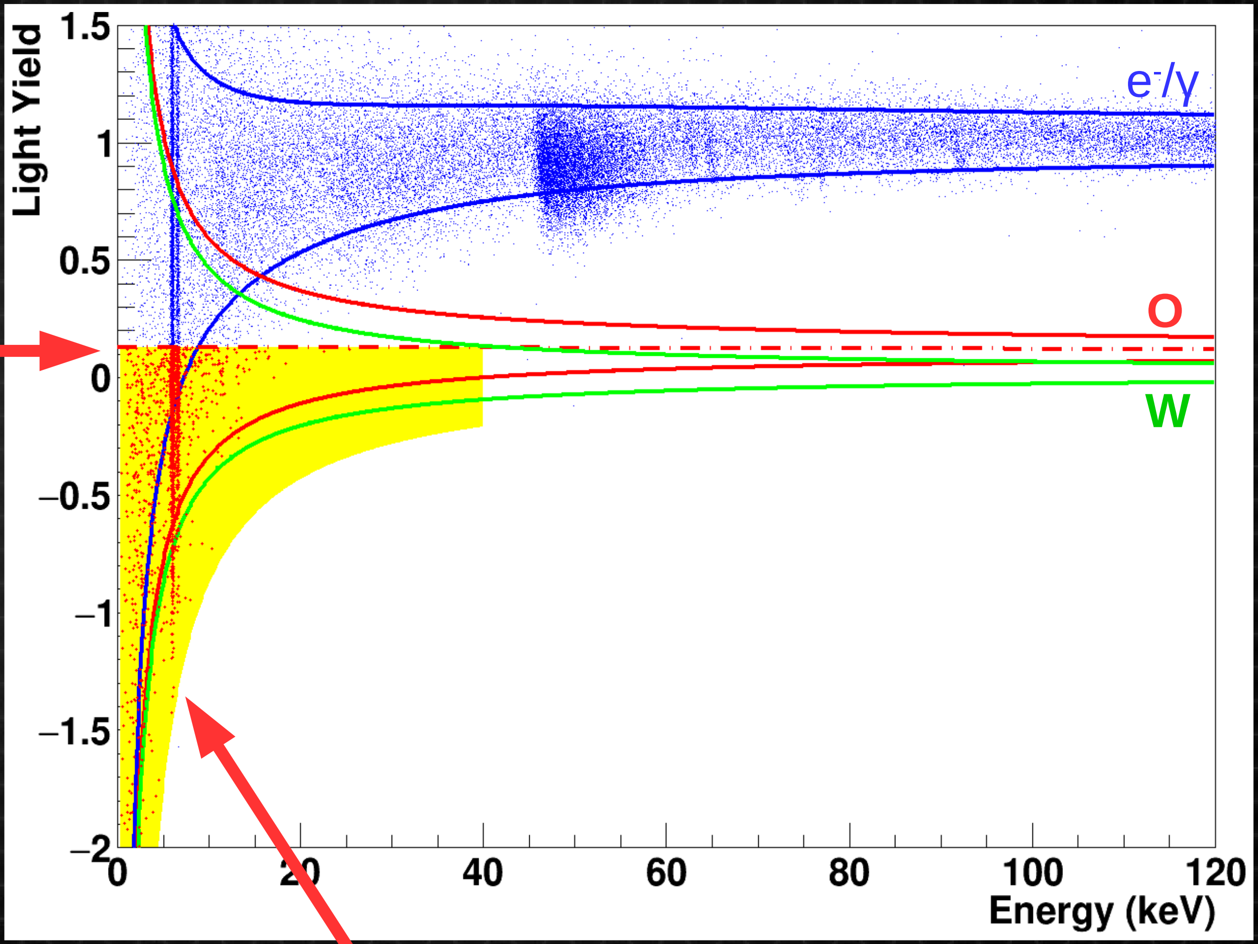
Data



Light Yield
1.5
1
0.5
0
−0.5
−1
−1.5
−2
0
20
40
60
80
100
120
Energy (keV)
e⁻/γ
O
W

Acceptance Region

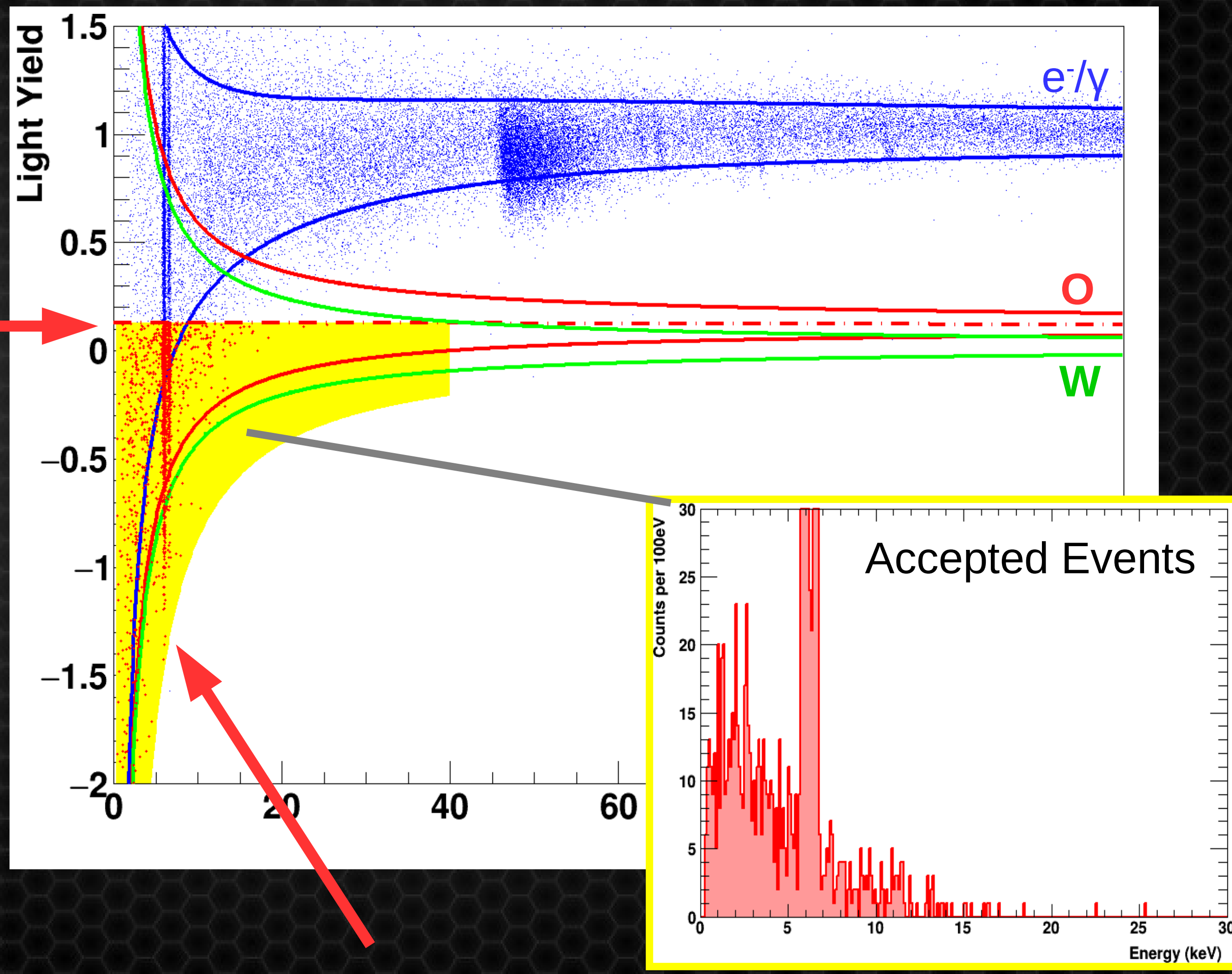
50% of oxygen recoils below



99.5% of tungsten recoils above

Acceptance Region

50% of oxygen recoils below



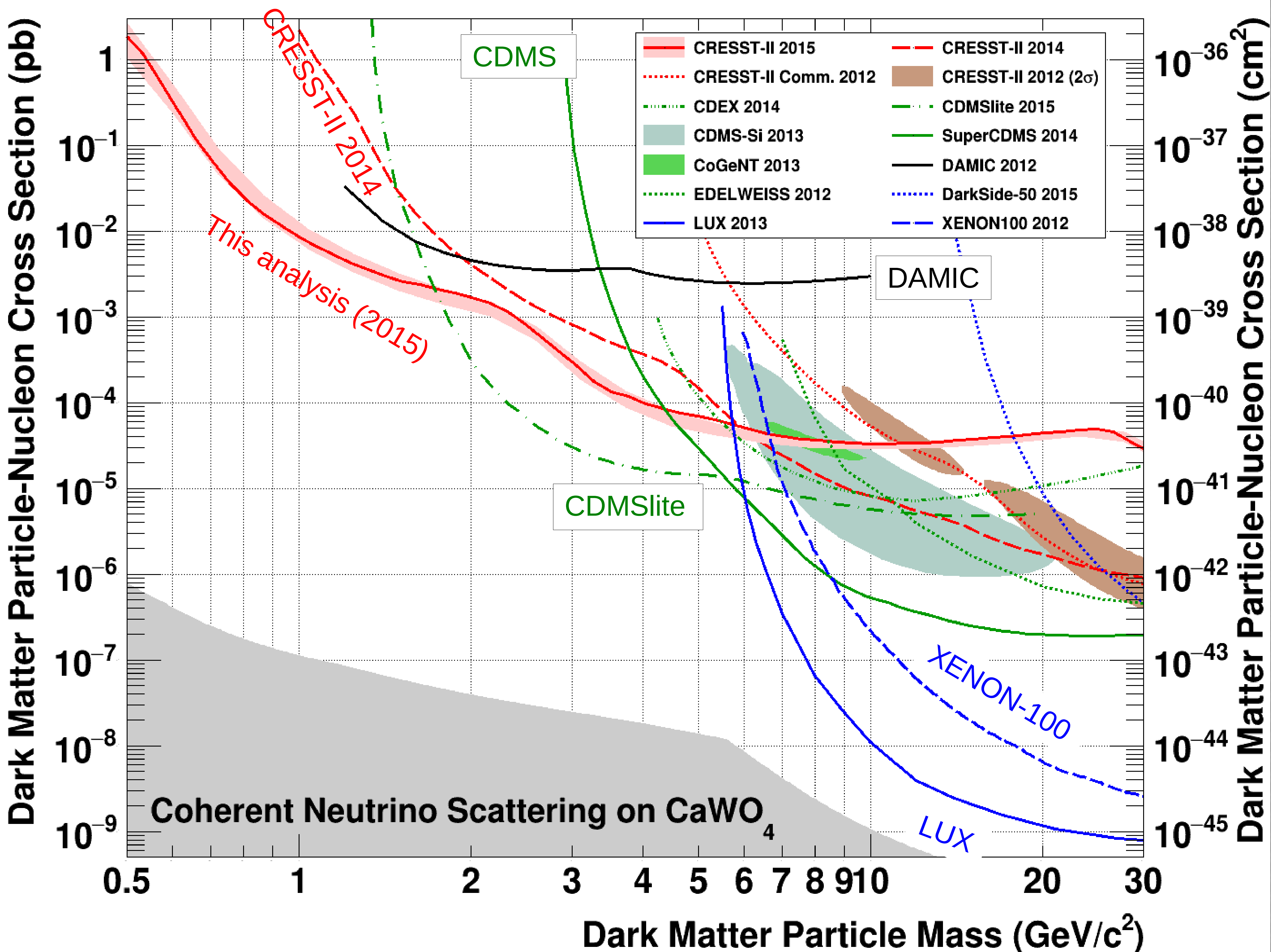
99.5% of tungsten recoils above

Expected energy spectrum

Energy spectrum of accepted events

Yellin optimum interval (one-dimensional)

Result



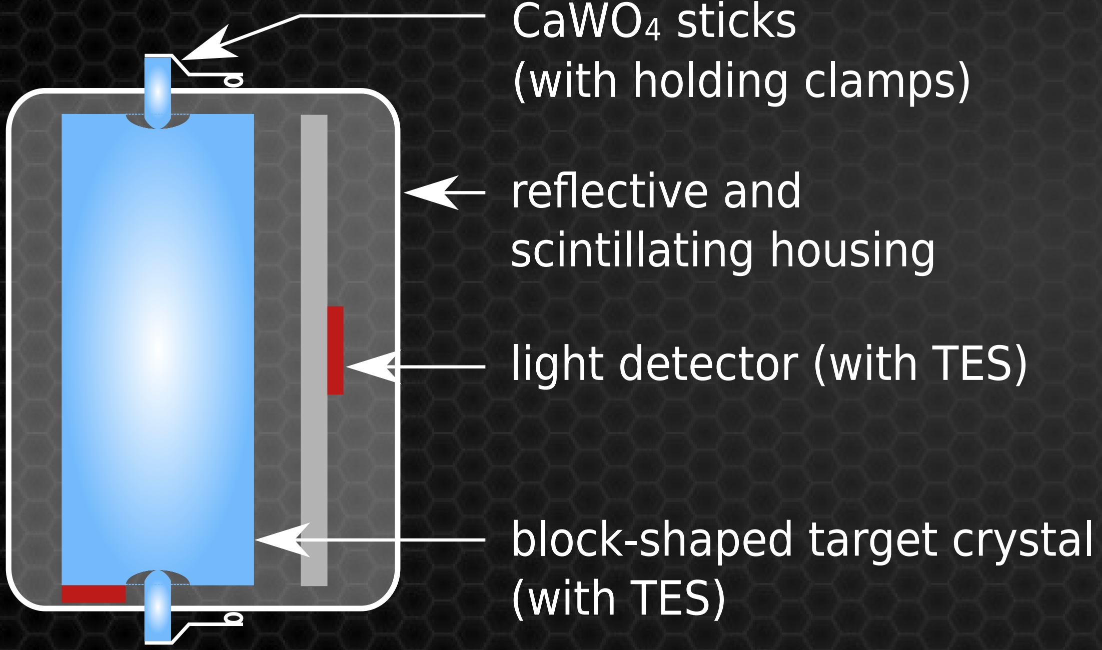
CRESST-II 2015
CRESST-II 2014
CRESST-II Comm. 2012
CRESST-II 2012 (2σ)
CDEX 2014
CDMSlite 2015
CDMS-Si 2013
SuperCDMS 2014
CoGeNT 2013
DAMIC 2012
EDELWEISS 2012
DarkSide-50 2015
LUX 2013
XENON100 2012
CDMS
CRESST-II 2014
This analysis (2015)
DAMIC
CDMSlite
XENON-100
LUX
Coherent Neutrino Scattering on CaWO4
Dark Matter Particle-Nucleon Cross Section (pb)
Dark Matter Particle-Nucleon Cross Section (cm²)
Dark Matter Particle Mass (GeV/c²)

Conclusions

- Blind analysis of detector with lowest threshold (307eV) operated in phase 2
- World-leading below 1.7GeV/c^2
- Exploring new parameter space down to 0.5GeV/c^2

Hunting light dark matter requires a low threshold!

New Modules for CRESST-III



Design goal:

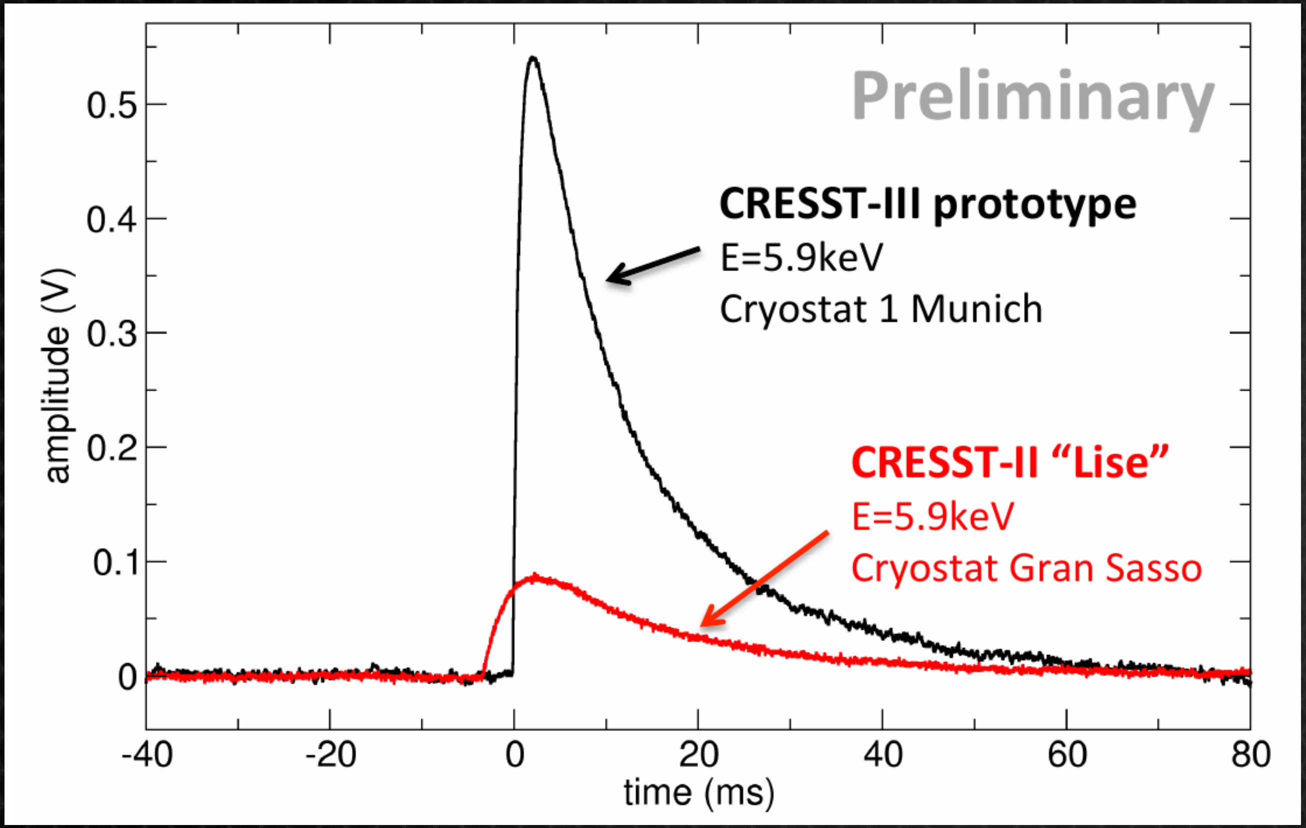
Threshold of 100eV

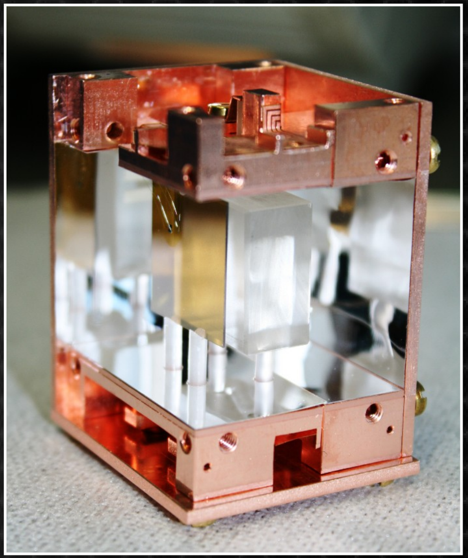
How?

smaller crystals of available quality

250g → 24g

Prototype Measurement



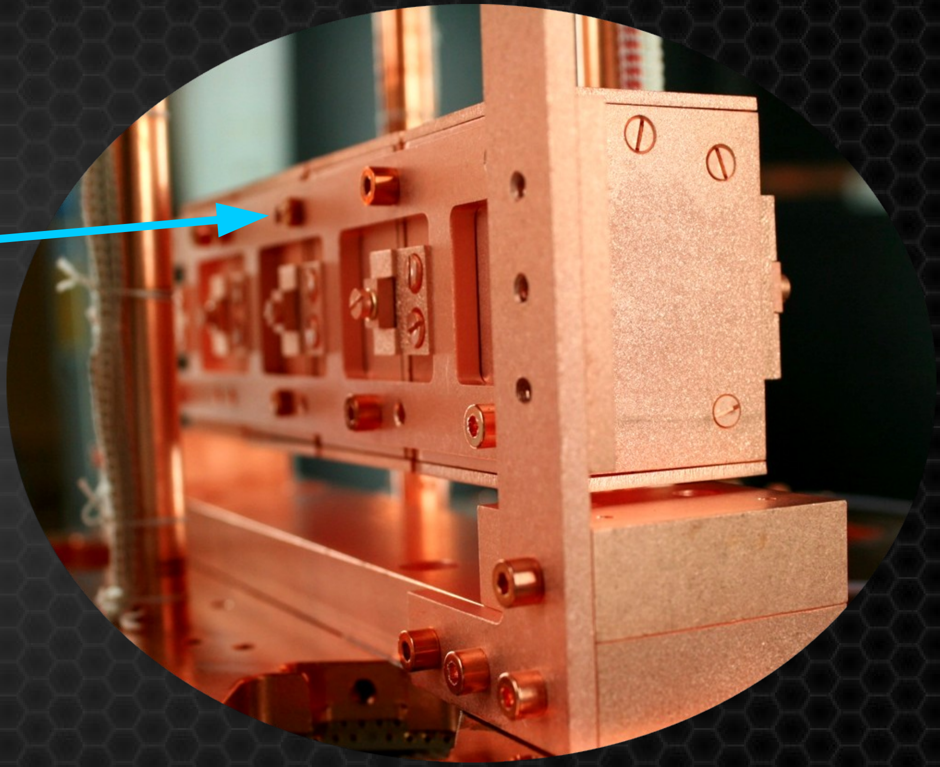


Signal/Noise improved by a factor of ~6
→ Threshold of ~50eV

Design goal (100eV) exceeded

On the Road to CRESST-III

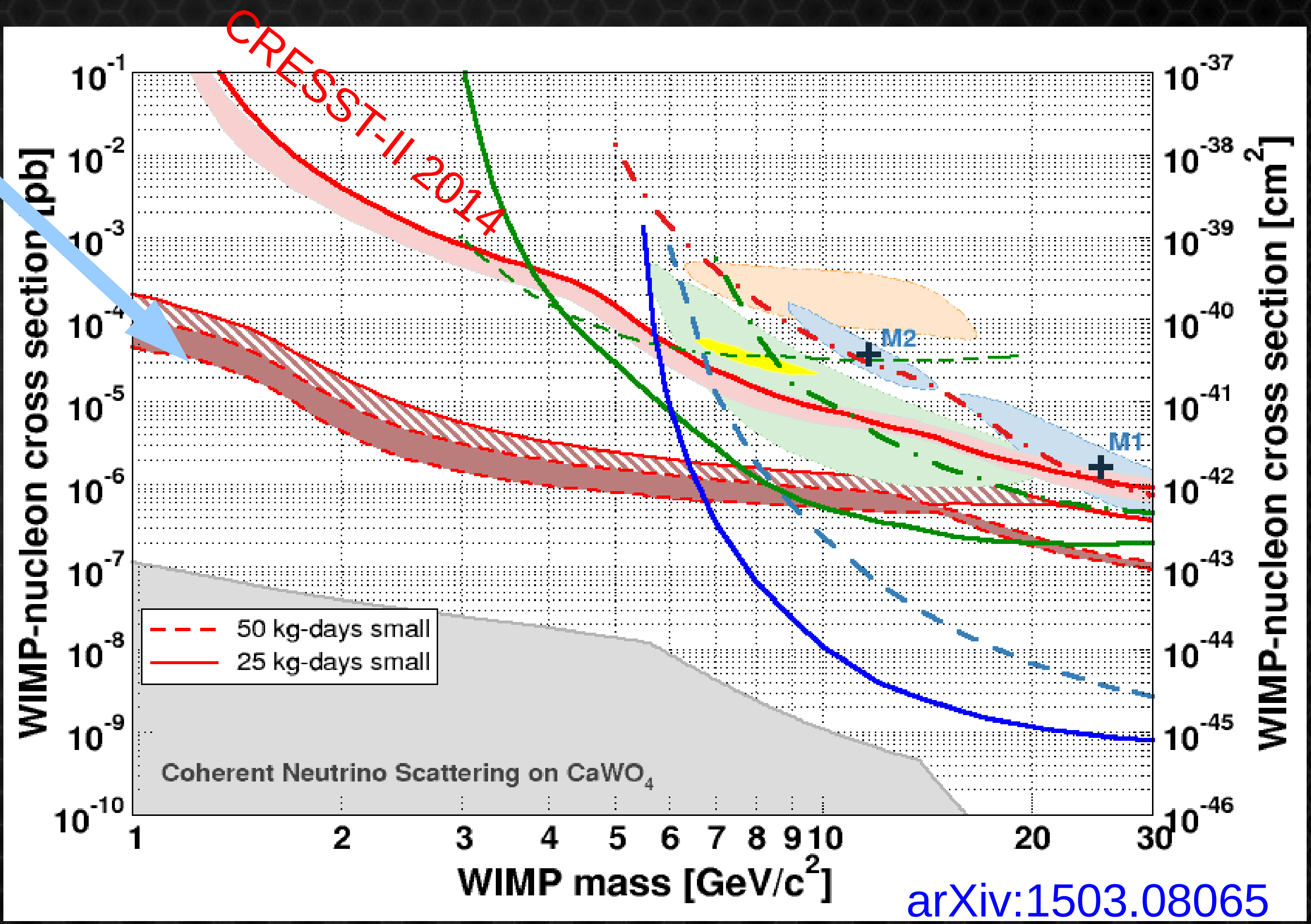
- Prototype(s) successfully tested
- First four modules mounted in cryostat last week (Feb. 02-04)



Cool-down: March 2016

Projection for CRESST-III Phase 1&2

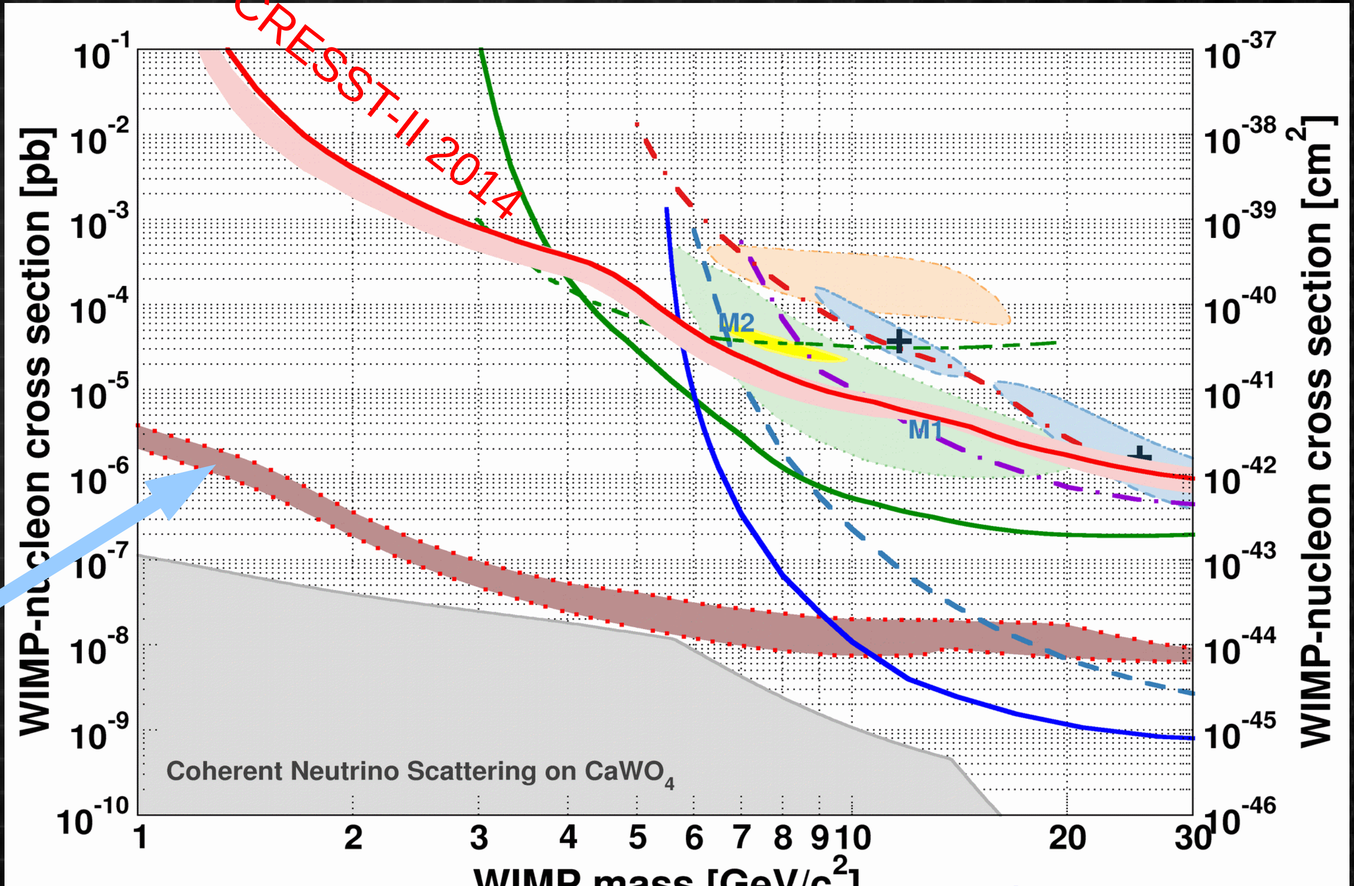
Phase 1
- 50kg days: 10 modules, 1 year



arXiv:1503.08065

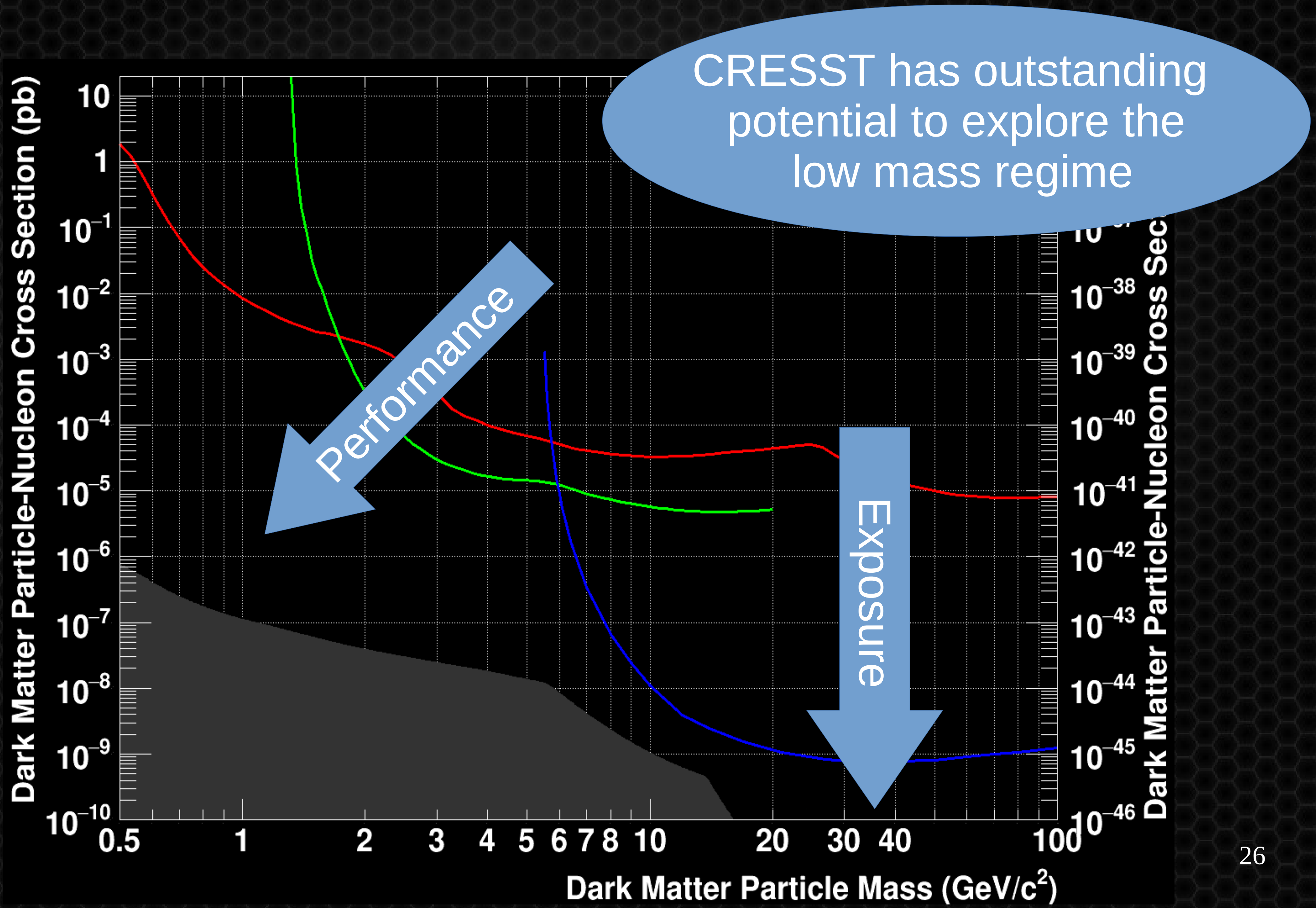
Projection for CRESST-III Phase 1&2

Phase 2
- 1 tonne days: 100 modules, 2 years
- background improved by ~100



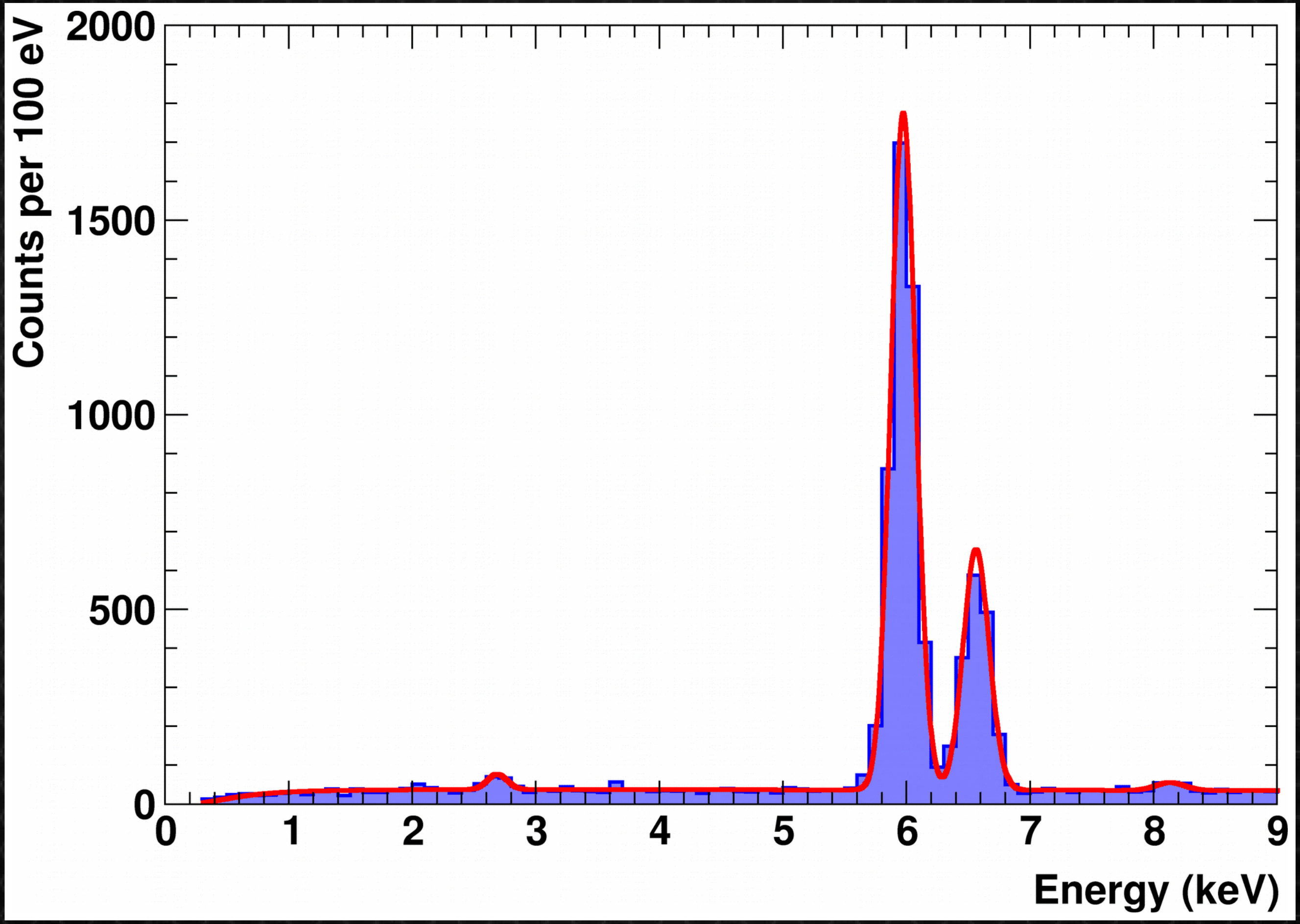
arXiv:1503.08065

Final Statement



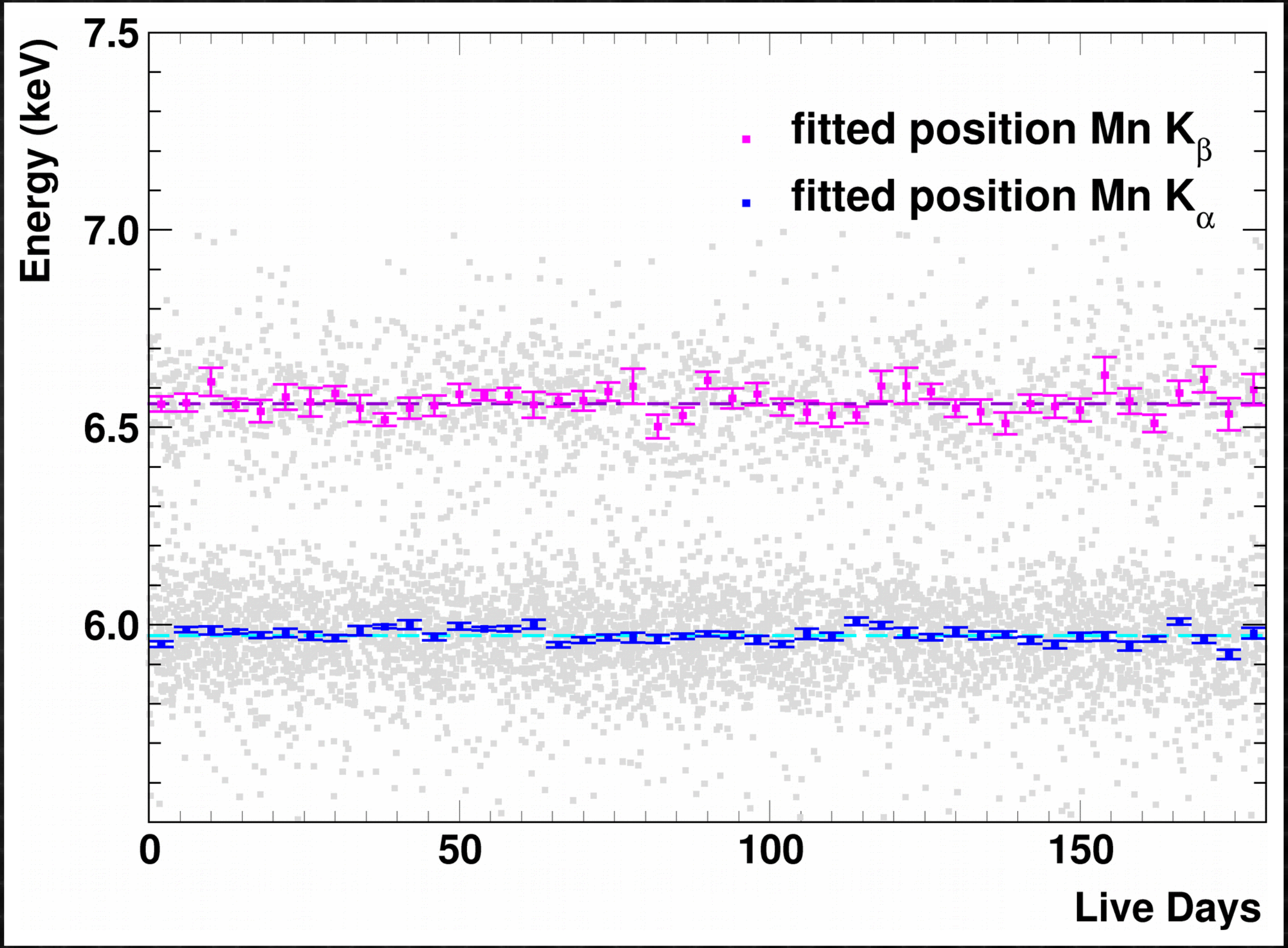
BACKUP

Overall Background – Zoom Out

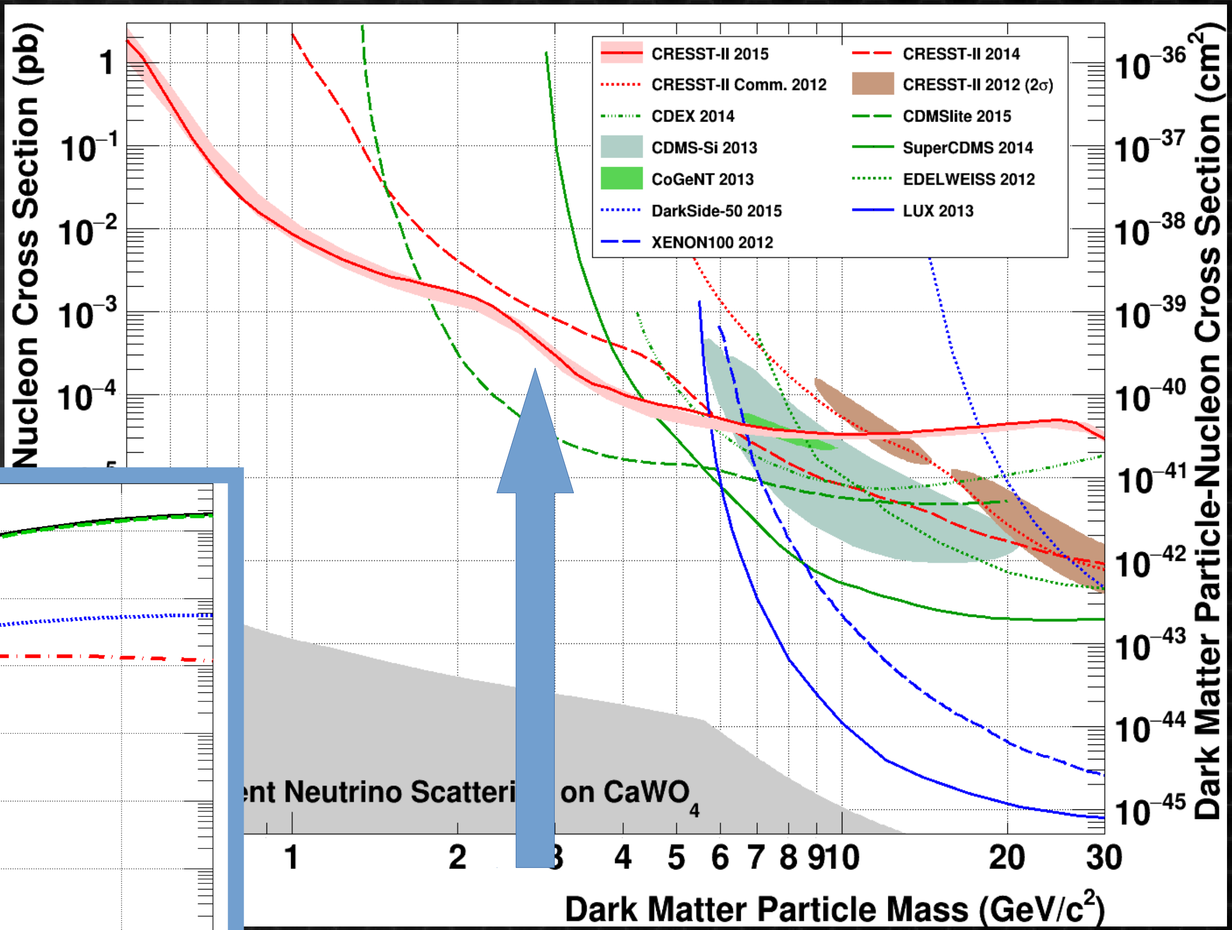


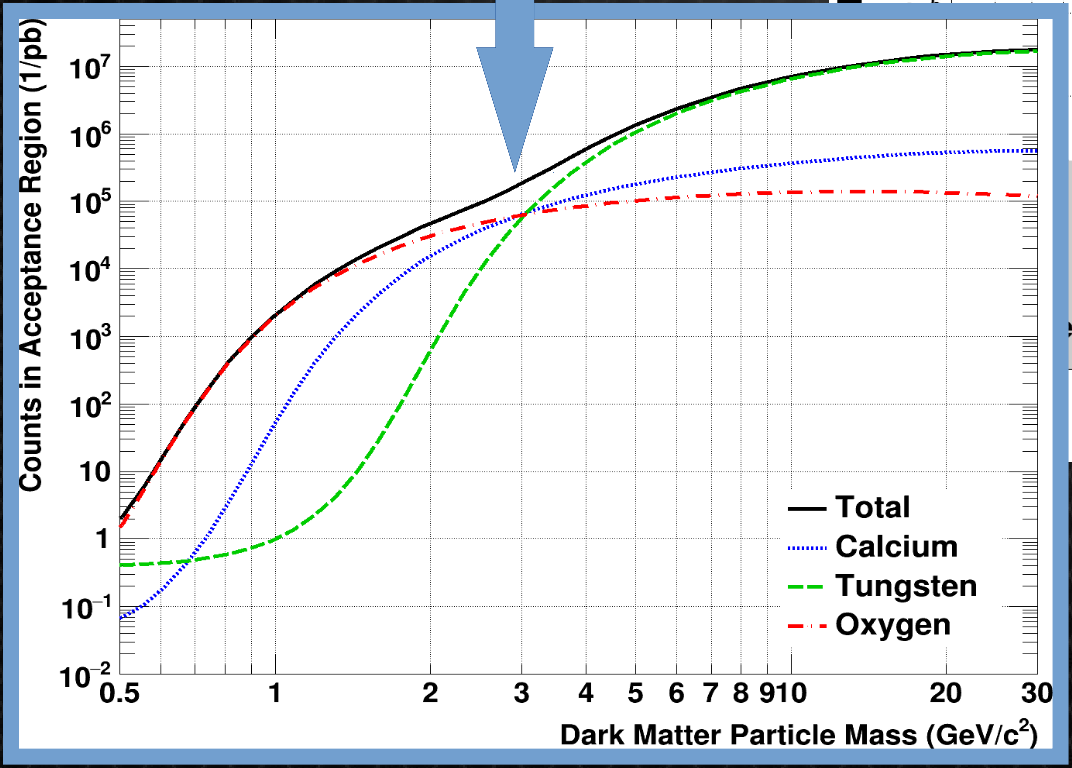
Detector: Long-term Stability

Detector operating stably throughout entire data taking



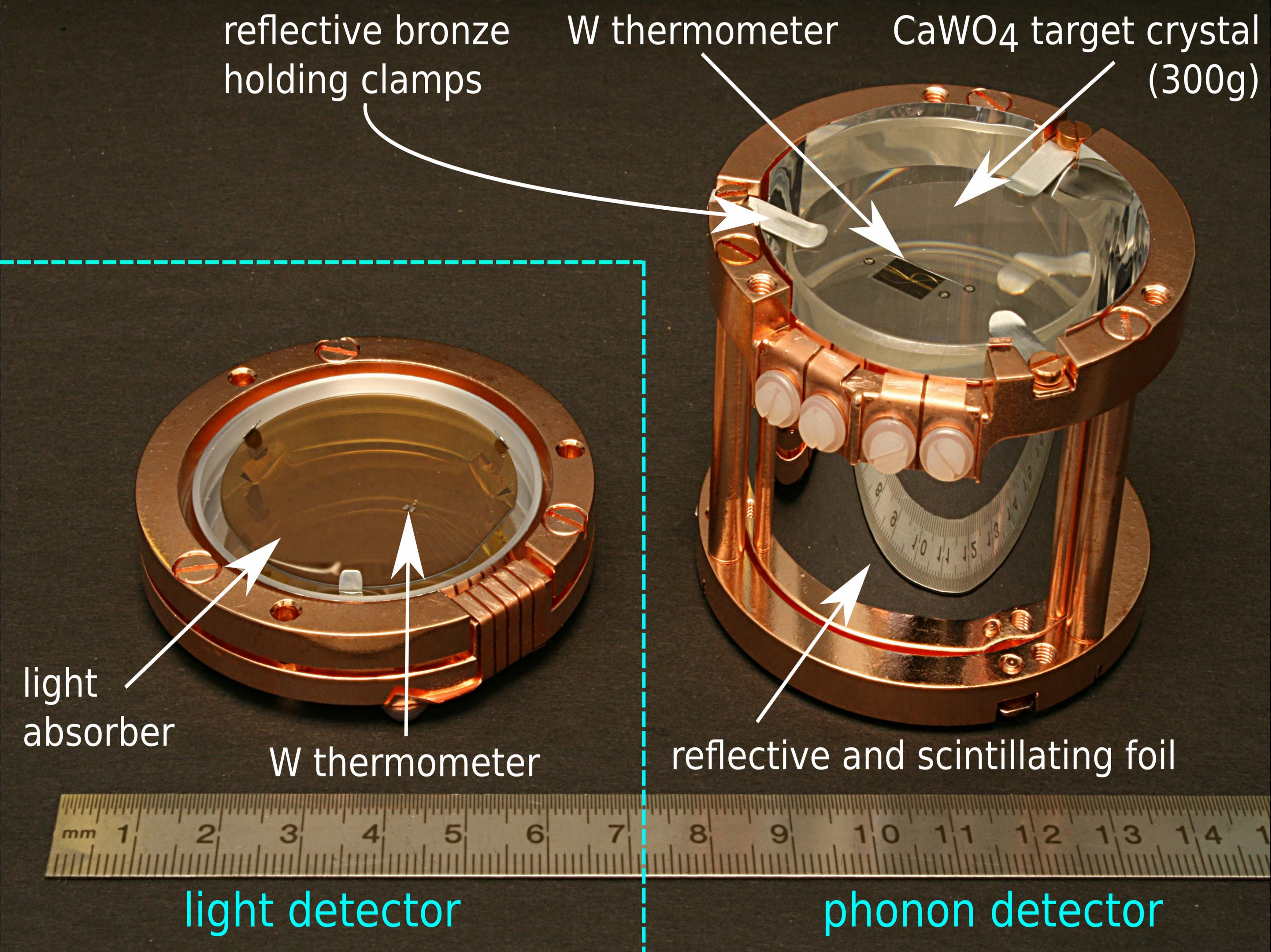
Multi-Element Target





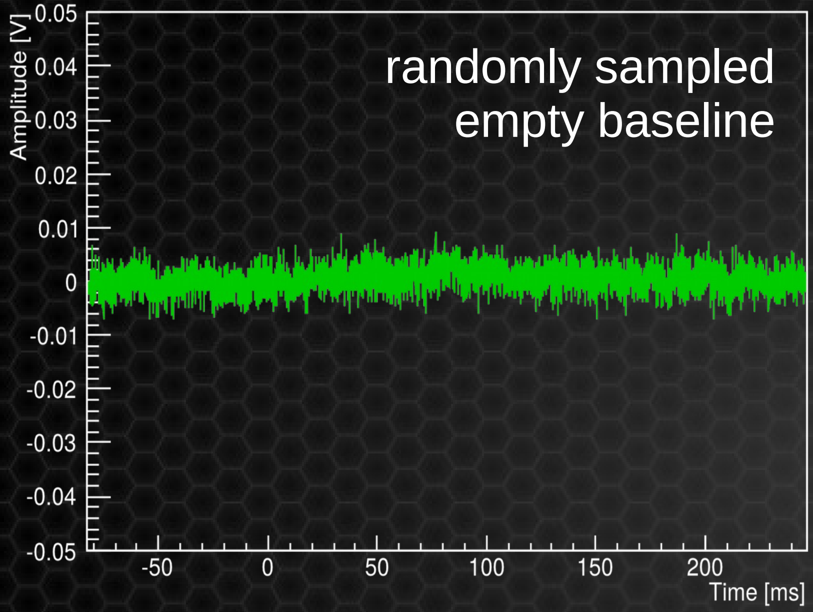
above 3Gev/c²: W dominates

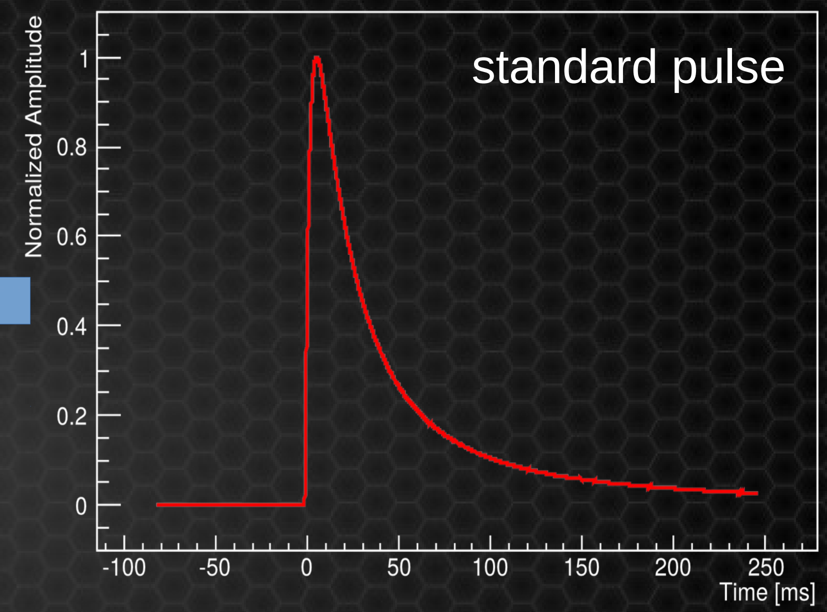
below 3Gev/c²: O dominates

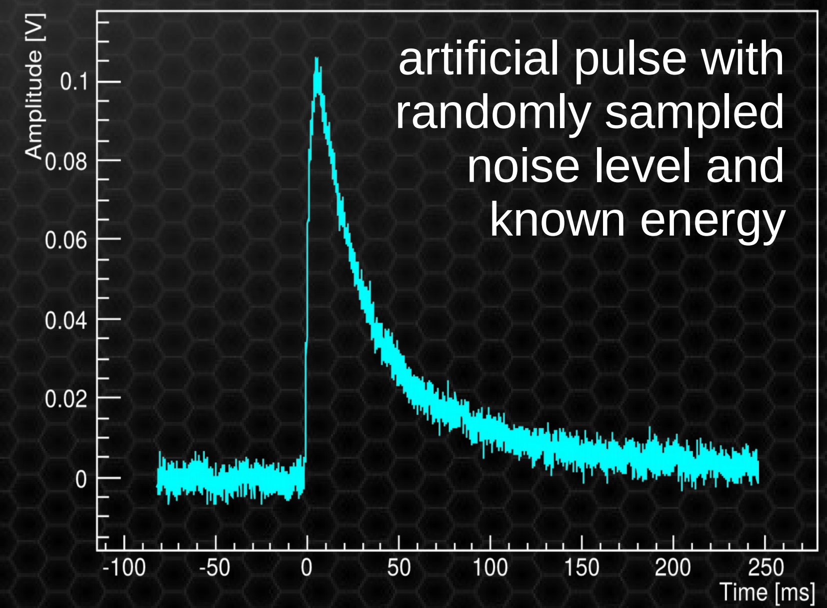


reflective bronze holding clamps
W thermometer
$CaWO_4$ target crystal (300g)
light absorber
W thermometer
reflective and scintillating foil
light detector
phonon detector

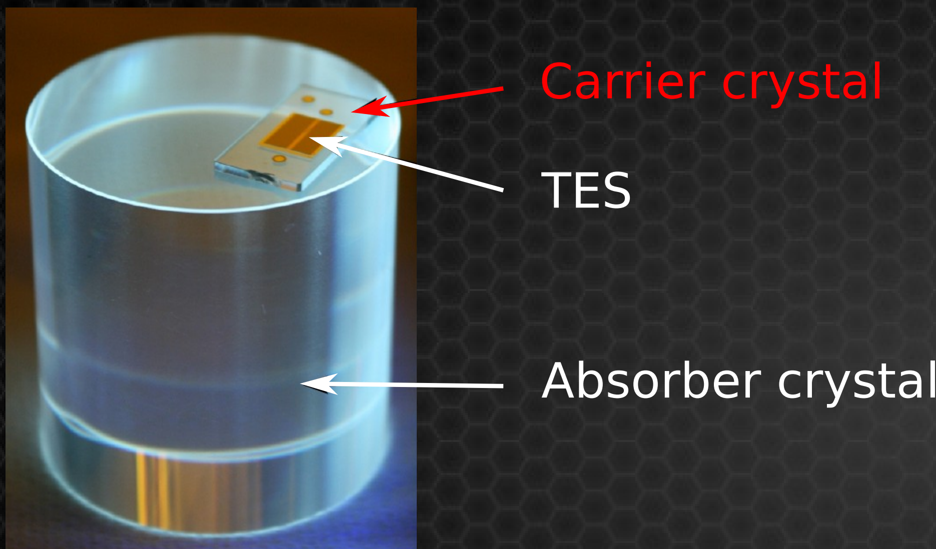
Signal Survival Probability
Determination

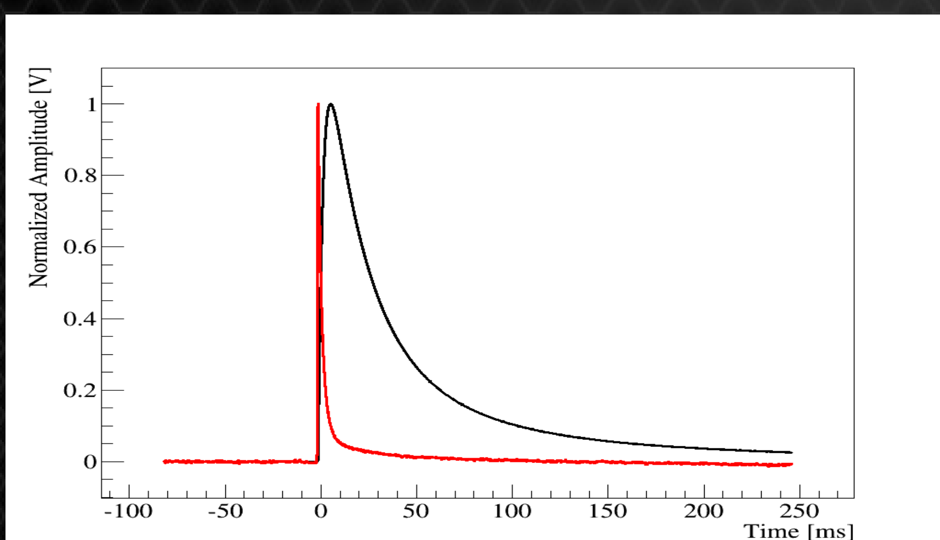






TES-Carrier (Composite Design)

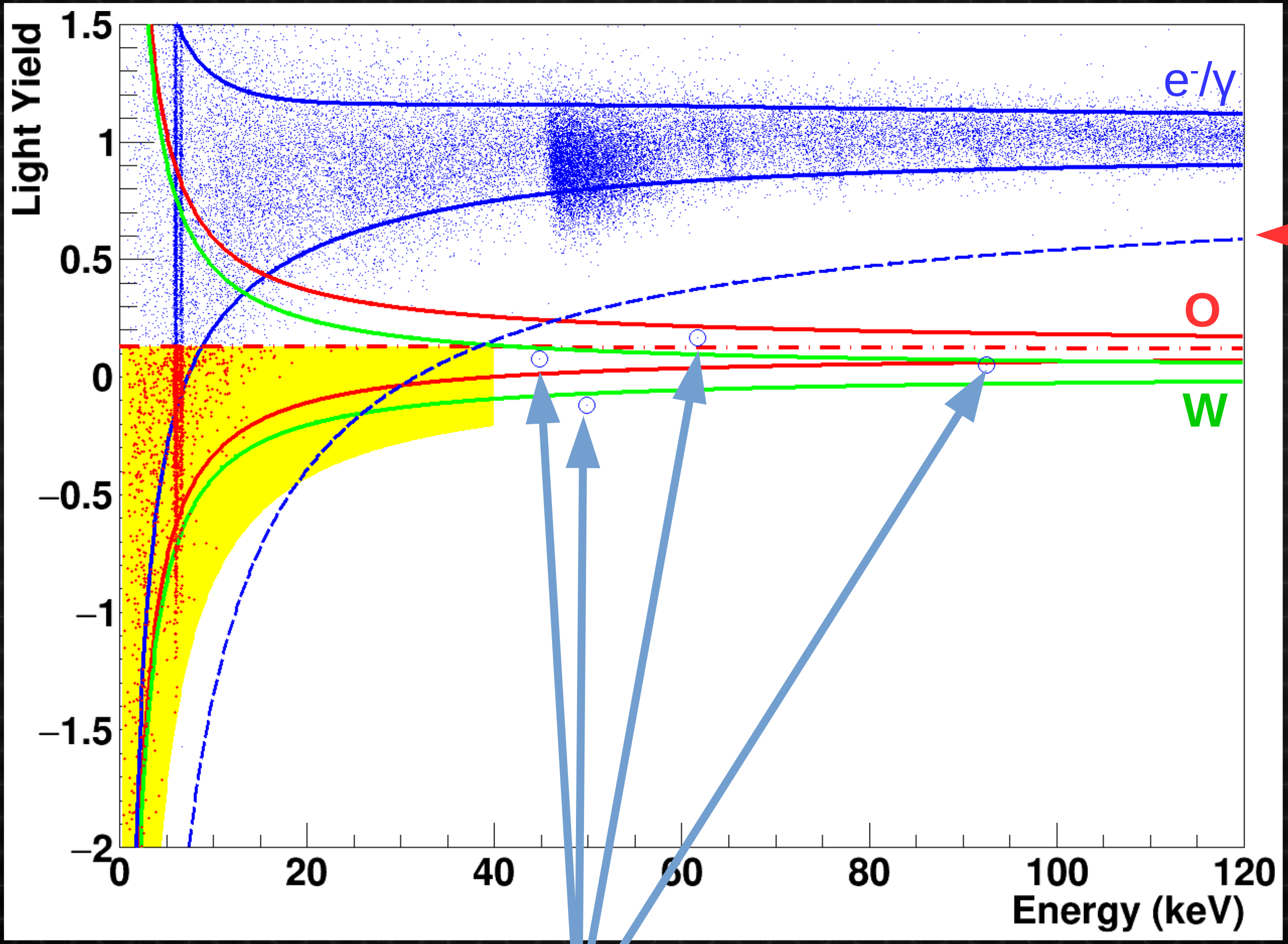




- Discrimination of events in carrier via pulse shape
- Challenging when approaching low energies

➔ CRESST-III: directly evaporate TES onto absorber

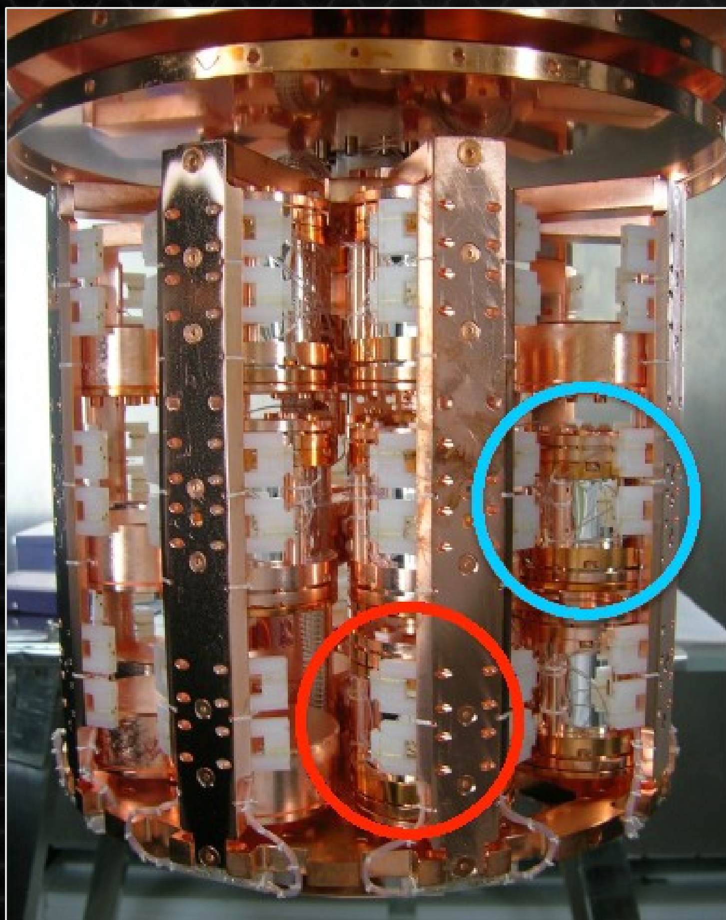
Presence of Recoil Backgrounds



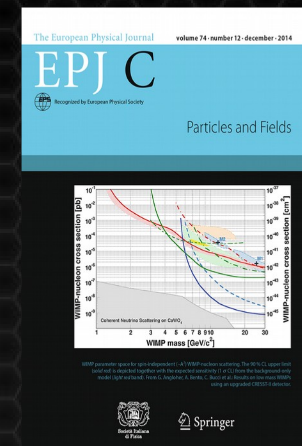
5σ

Statistically incompatible
with leakage from e-/γ-band

CRESST-II: Current Phase 2



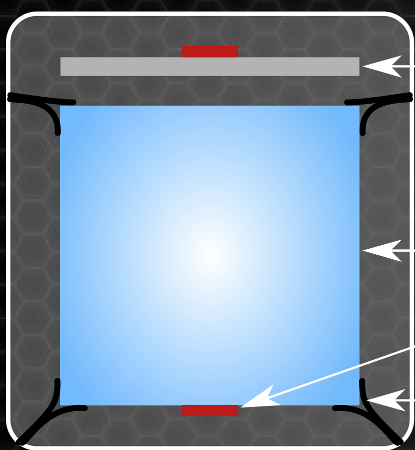
- Result published in 2014:
  - Single module TUM40
  - 29 kg days of exposure
  - Nonblinded 2013 dataset



- Result discussed today
  - Single module Lise
  - 52 kg days of exposure
  - Blind analysis

Detector Designs

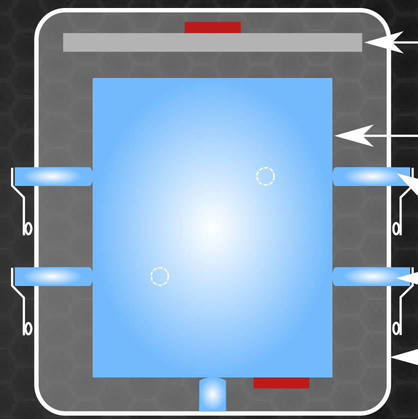
Conventional — 2015 - Lise



- ~~Veto for recoil backgrounds~~
- Background level:

  ~8.5 counts / (keV kg day)
- 307eV threshold
- 62eV resolution

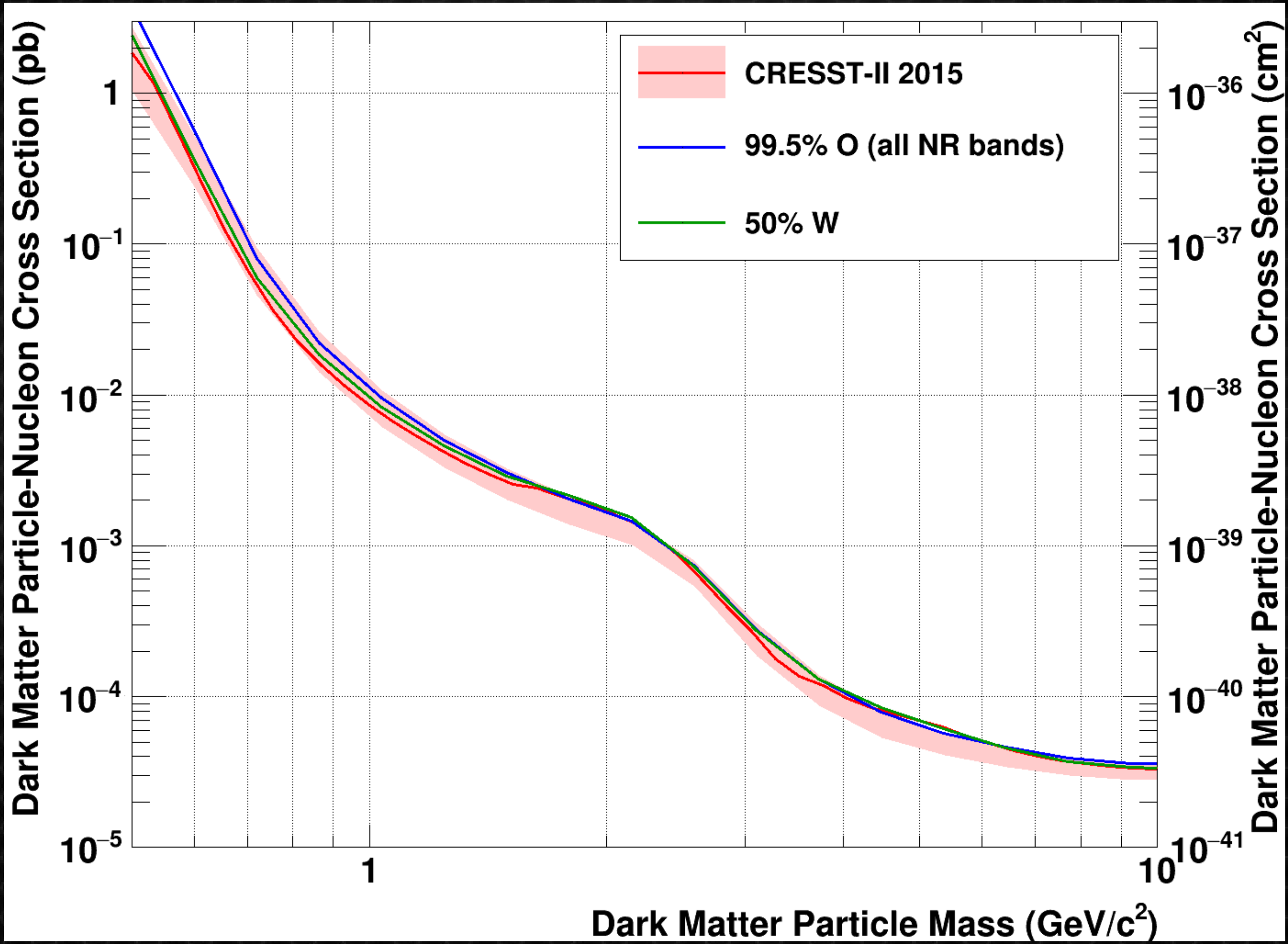
Stick — 2014 - TUM40



- Veto for recoil backgrounds
- Background level:

  ~3.5 counts / (keV kg day)
- 603eV threshold
- 100eV resolution

Choice of Acceptance Region



Differential Interaction Rate

counts per kg, day and keV recoil energy

galactic escape velocity

velocity distribution

WIMP-nucleon cross section

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_N m_\chi} \cdot \int_{v_{\min}}^{v_{\text{esc}}} d^3\nu \, f(\vec{\nu})\nu \, \frac{d\sigma(\vec{v}, E_R)}{dE_r}$$

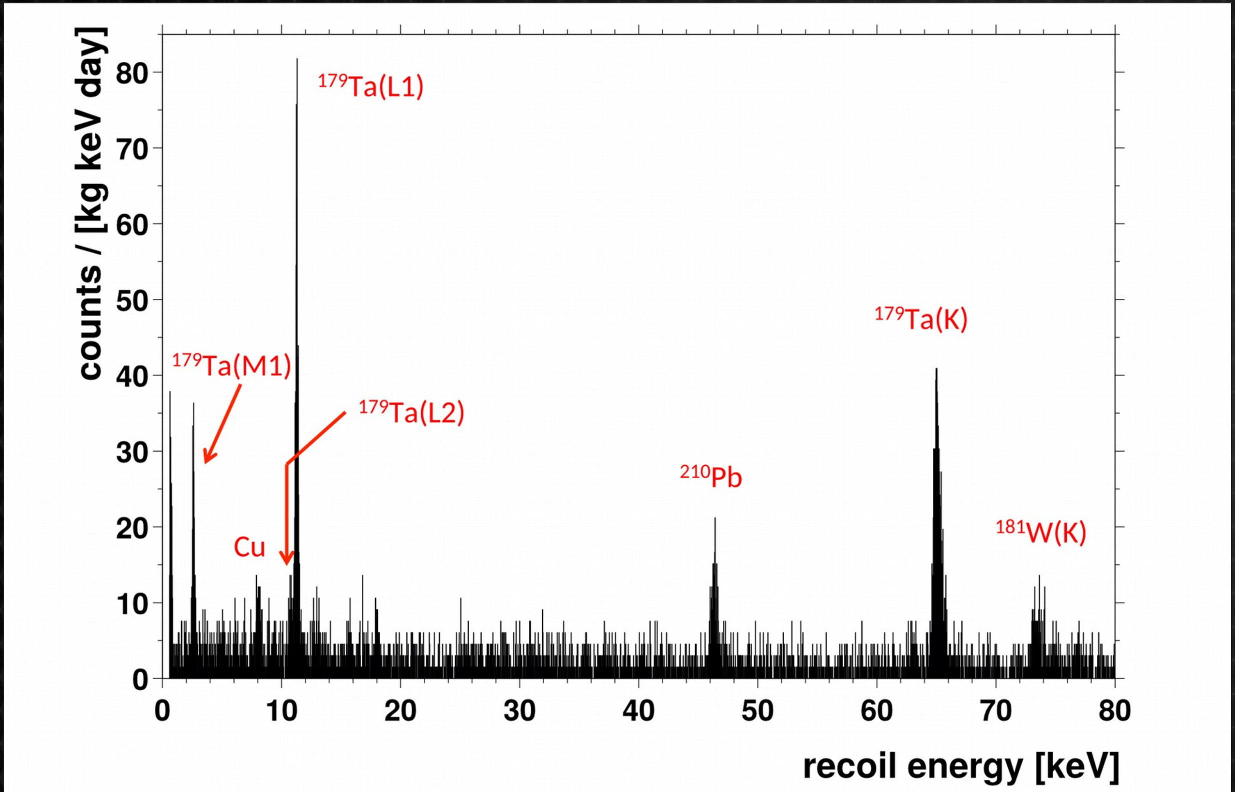
minimal velocity to produce a recoil of energy E_R

~ A^2

~ form factor

$$v_{\min} = \sqrt{m_N E_{\mathrm{R}} / 2\mu_N^2}$$

TUM 40 - Energy Spectrum

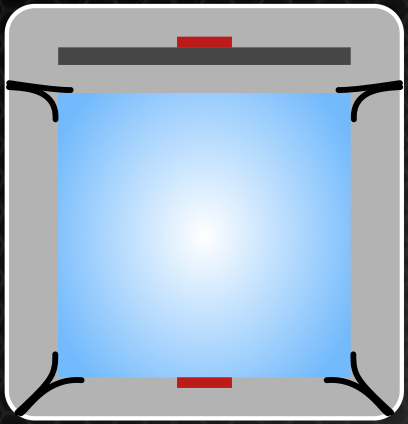


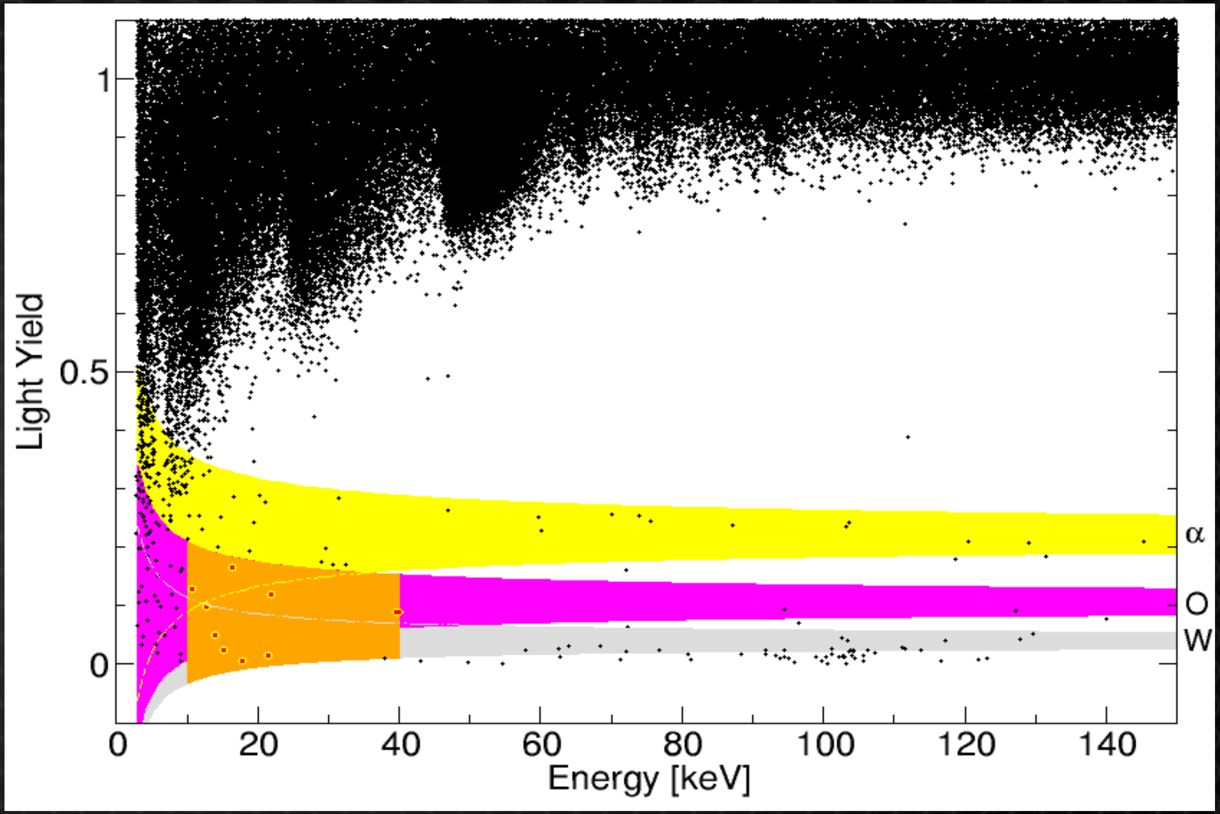
gamma lines caused by cosmogenic activation

energy resolution: σ<100eV

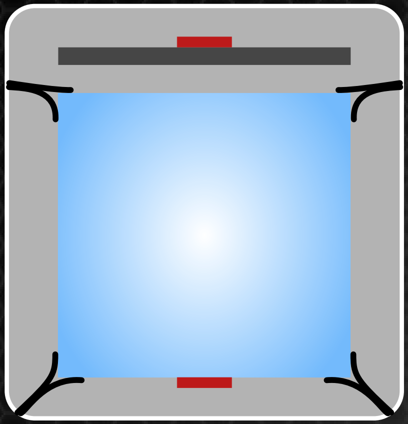
all lines within 5eV to tabulated values

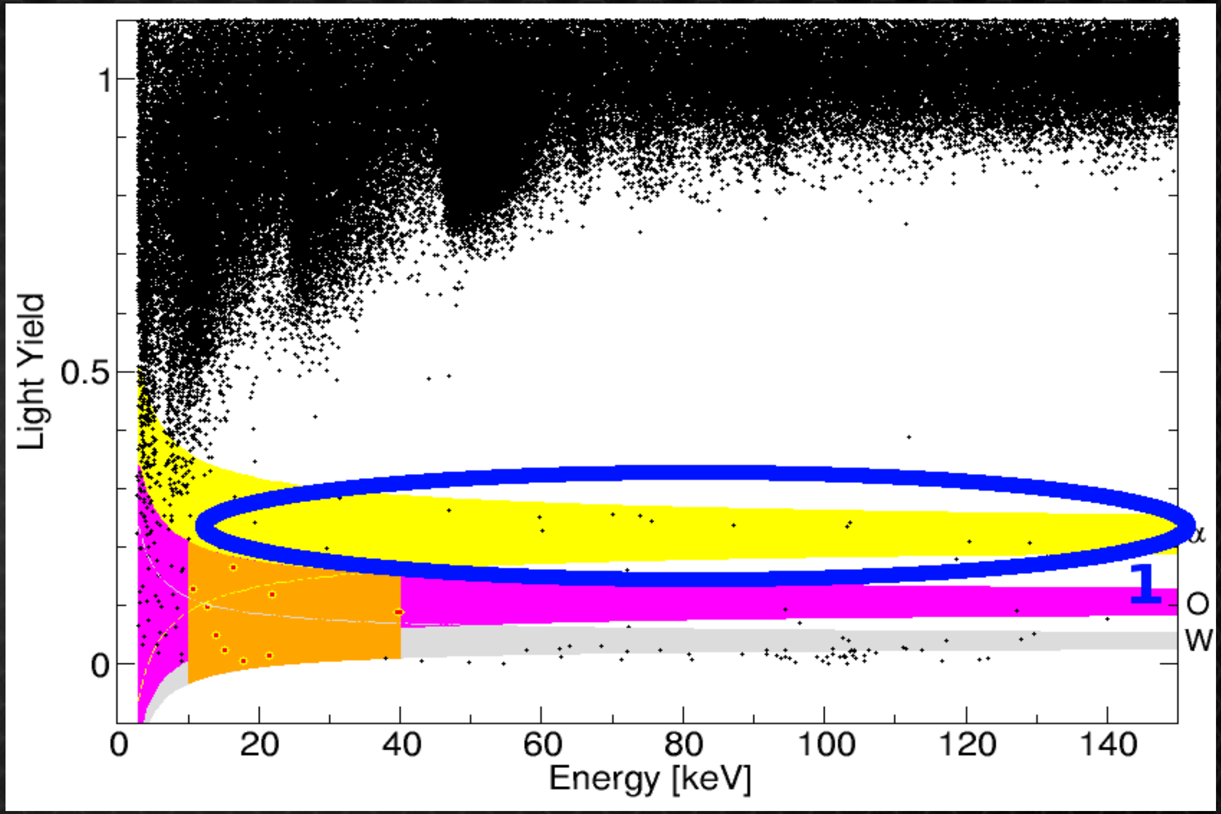
$$^{210}\mathrm{Po} \rightarrow {}^{206}\mathrm{Pb}\left(103\,\mathrm{keV}\right) + \alpha\left(5.3\,\mathrm{MeV}\right)$$





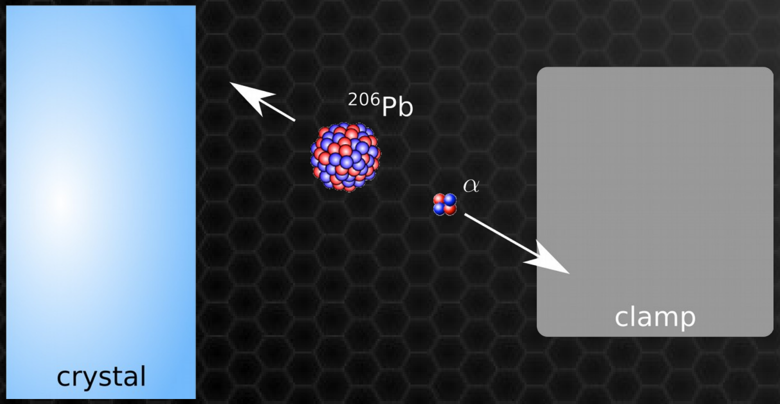
$$^{210}Po \rightarrow {}^{206}Pb\left(103\,keV\right) + \alpha\left(5.3\,MeV\right)$$

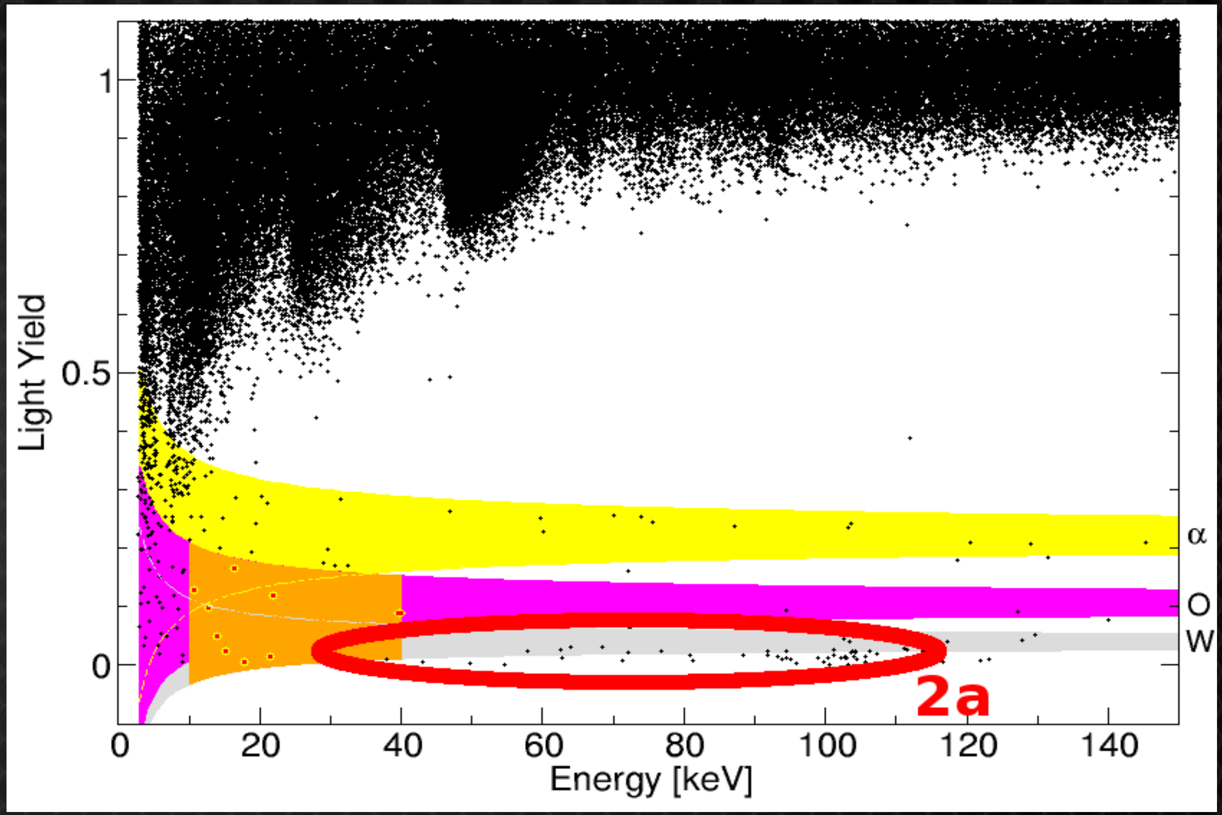




1. decay inside clamp material

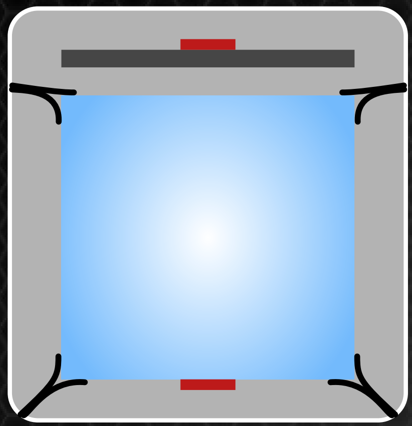
$$^{210}Po \rightarrow {}^{206}Pb\left(103\,keV\right) + \alpha\left(5.3\,MeV\right)$$

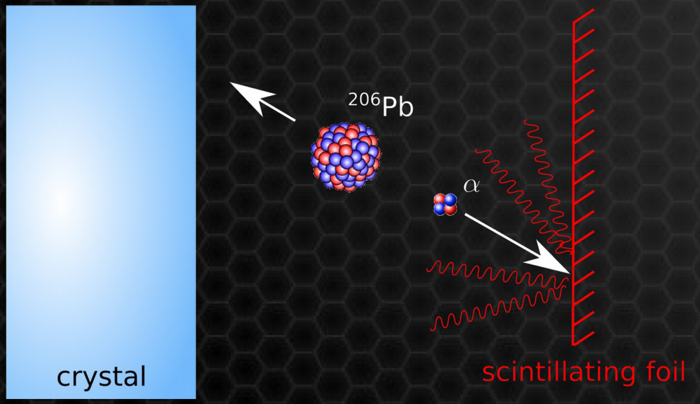


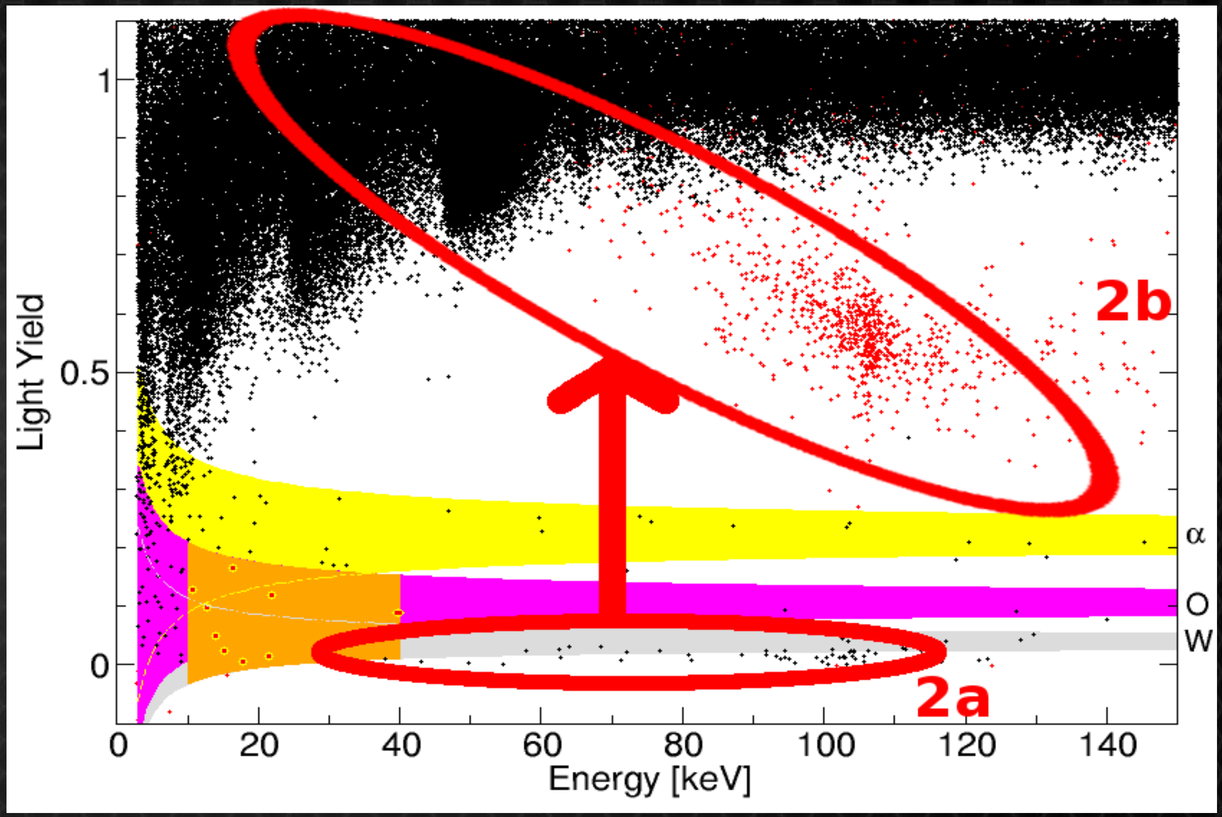


1. decay inside clamp material
2. decay on or slightly below surface of the clamp
   a) α hitting clamp → no scintillation light

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

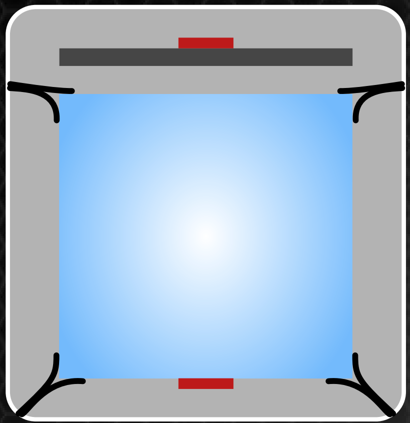


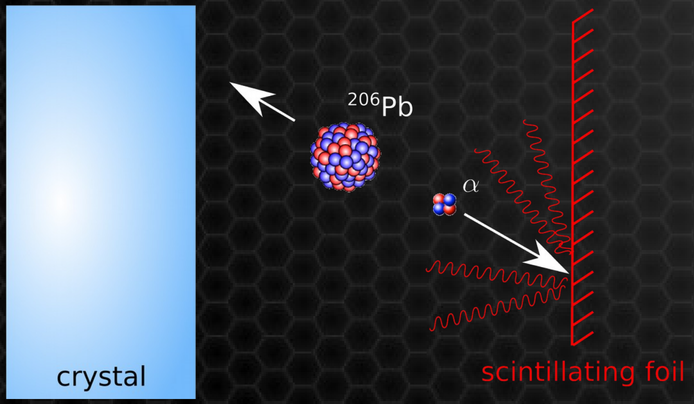


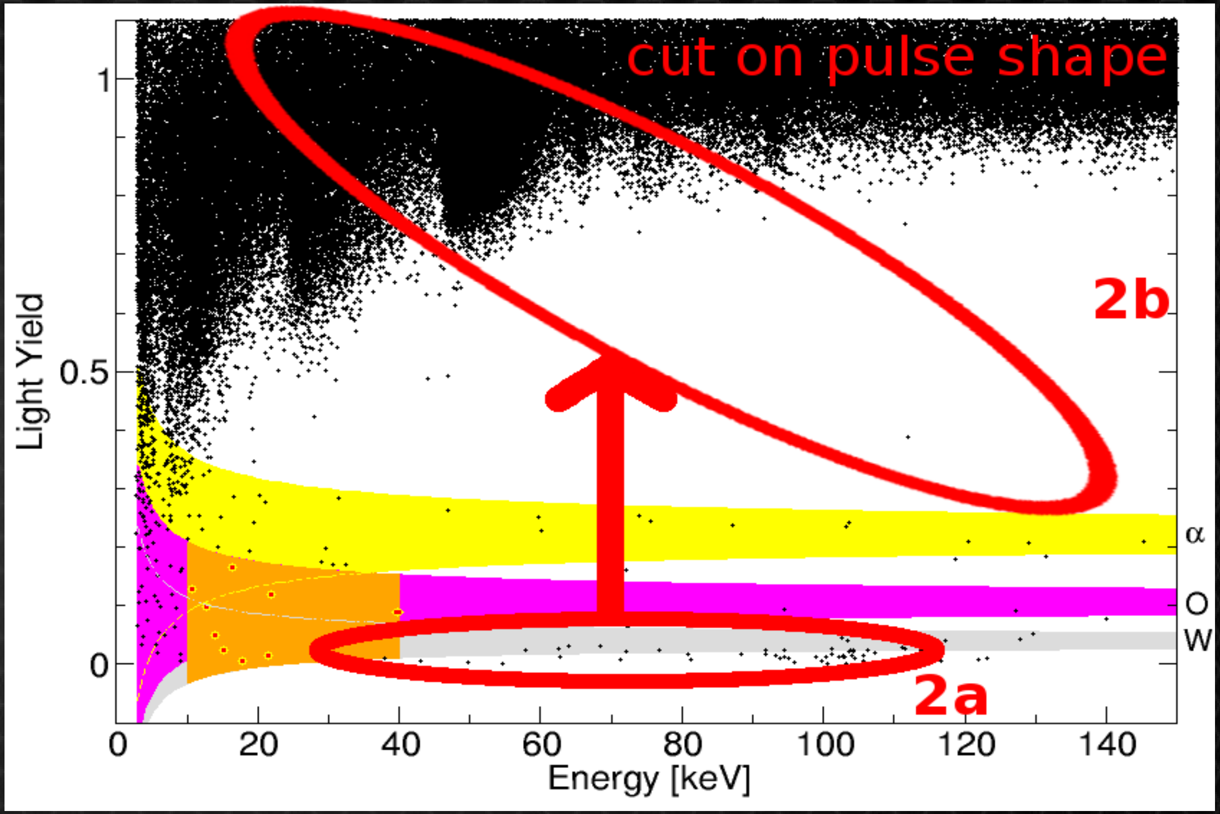


1. decay inside clamp material
2. decay on or slightly below surface of the clamp
   a) α hitting clamp → no scintillation light
   b) α hitting foil → additional scintillation light (with different pulse shape)

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







1. decay inside clamp material
2. decay on or slightly below surface of the clamp
   a) α hitting clamp → no scintillation light
   b) α hitting foil → additional scintillation light (with different pulse shape)

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

How to get rid of above background?

passive

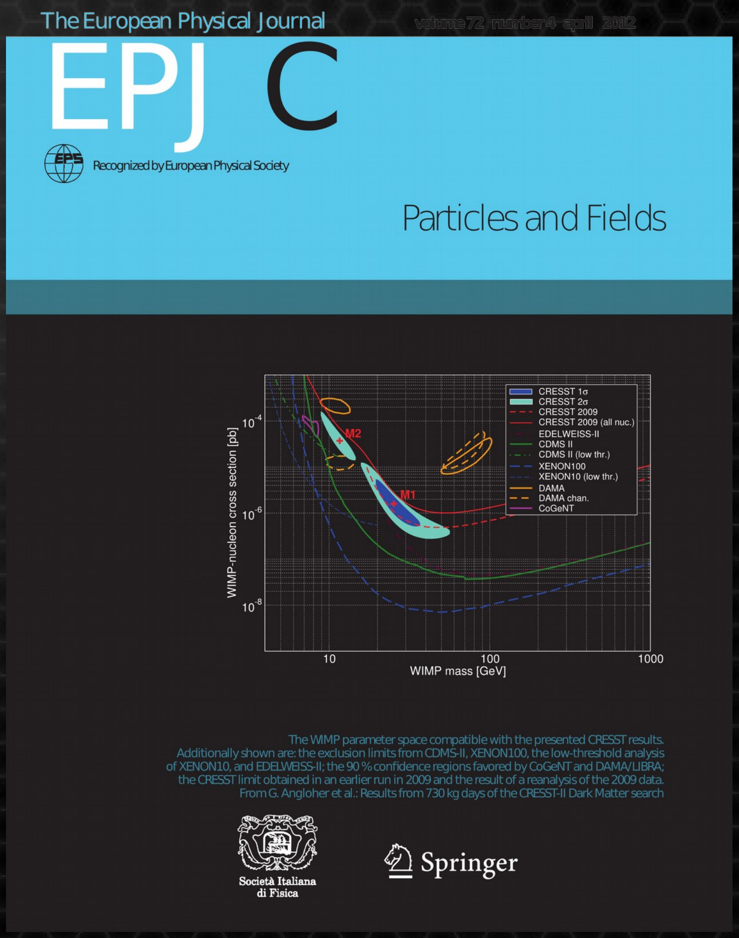
Radon prevention
even cleaner clamp material

active

only active surfaces facing the crystal

CRESST-II Phase 1

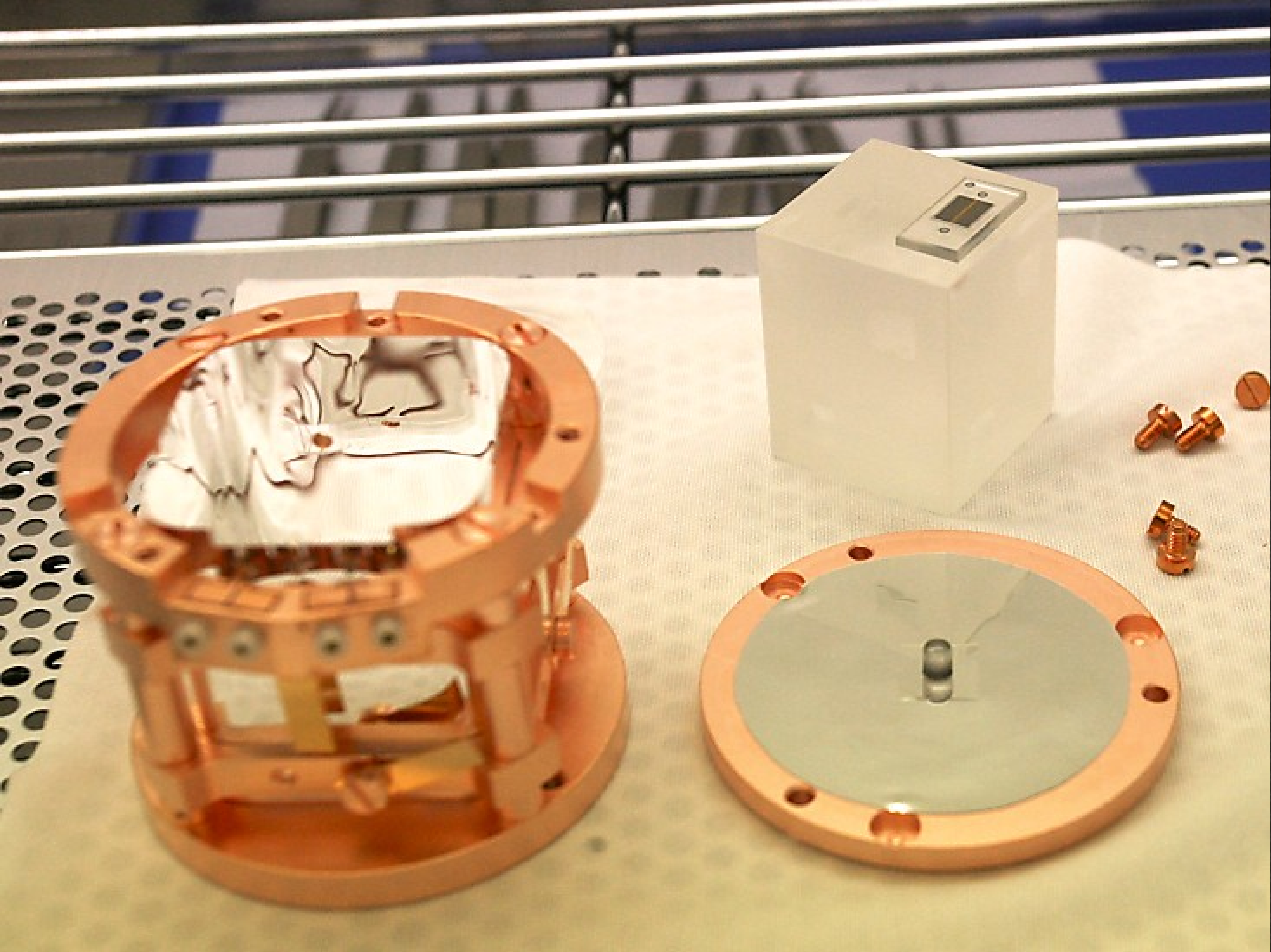
- extensive physics run from 2009 to 2011
- 8 $CaWO_4$ modules used for DM analysis
- 67 events in WIMP search regions



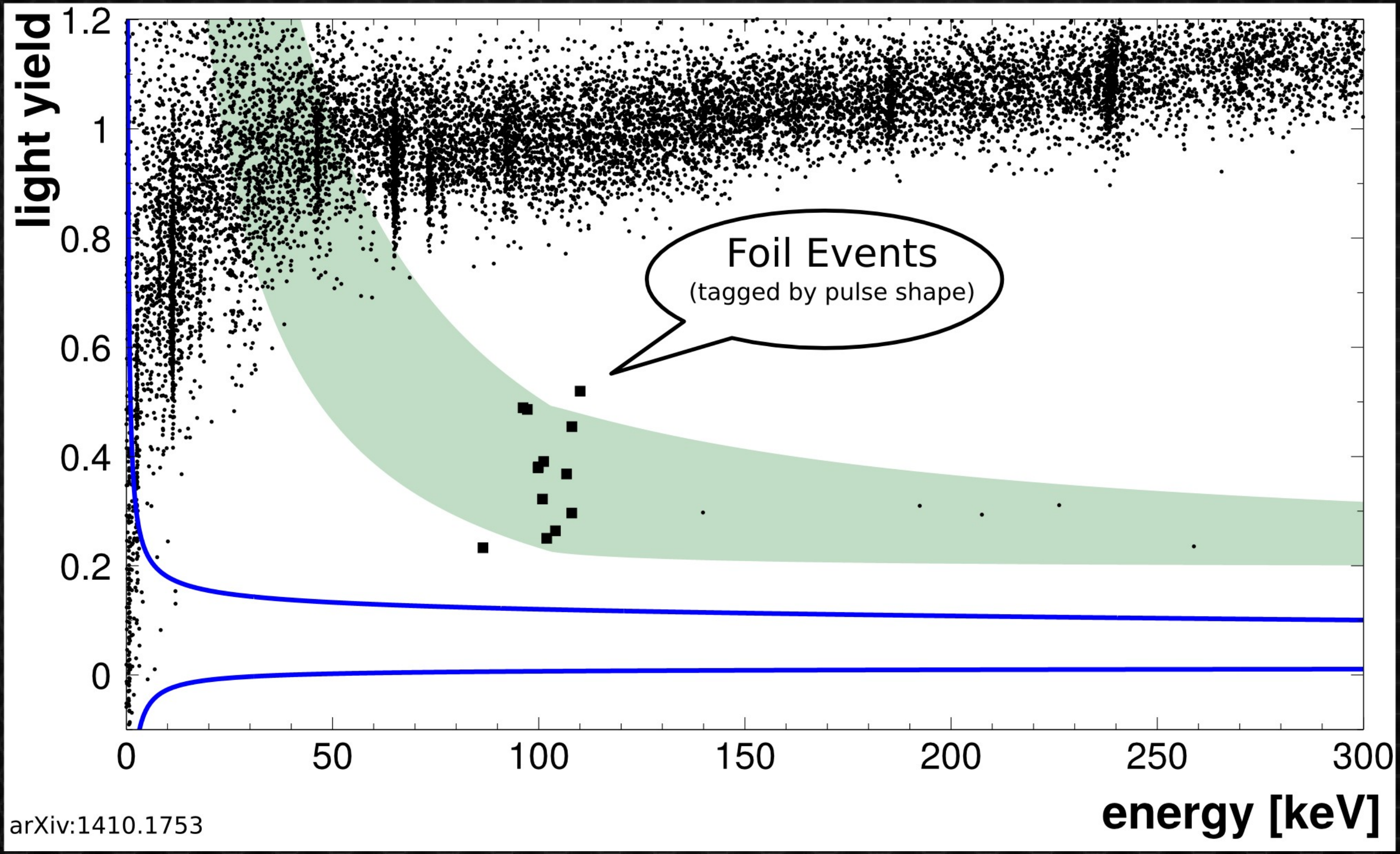
Phase 1 - Maximum Likelihood Analysis

	M1	M2
e^-/γ-events	8.00	8.00
α-events	11.5	11.2
neutrons	7.5	9.7
Pb recoils	15.0	18.7
signal events	29.4	24.2
m_{WIMP} (GeV)	25.3	11.6
statistical significance	4.7 σ	4.2 σ

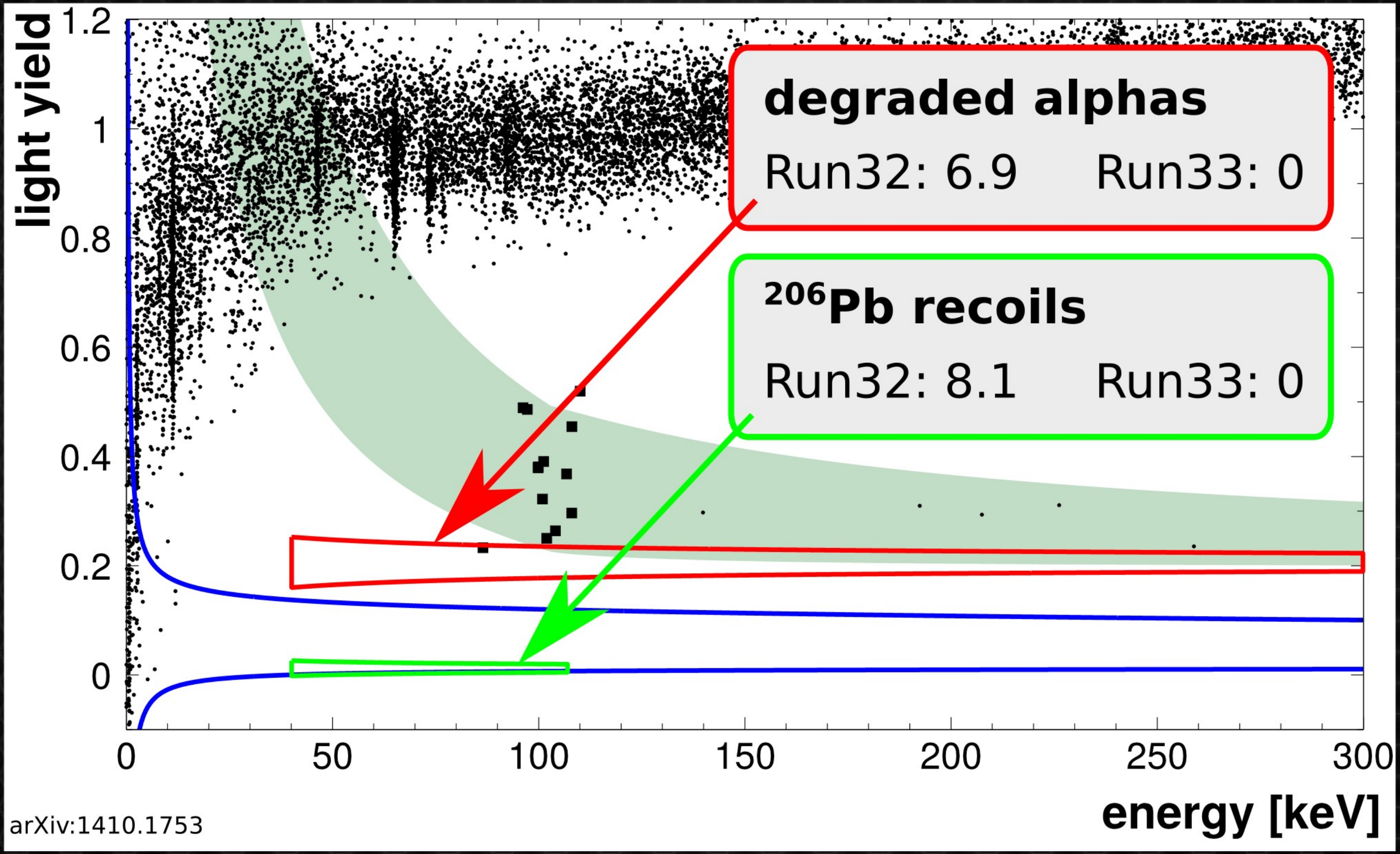
- excess above known background
- WIMPs would fit
- lower background level mandatory for clarification



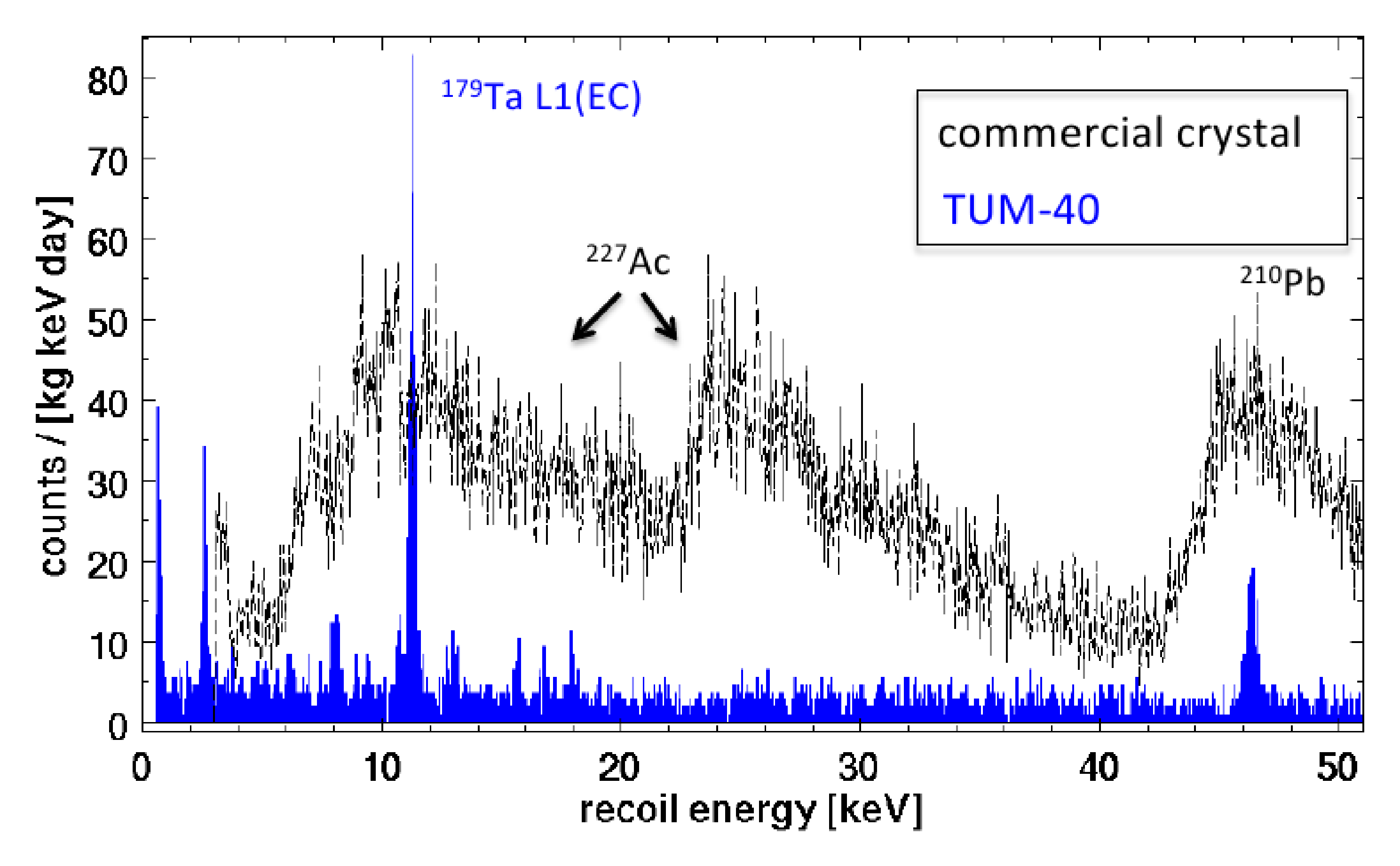
TUM40 - Veto of Surface Backgrounds



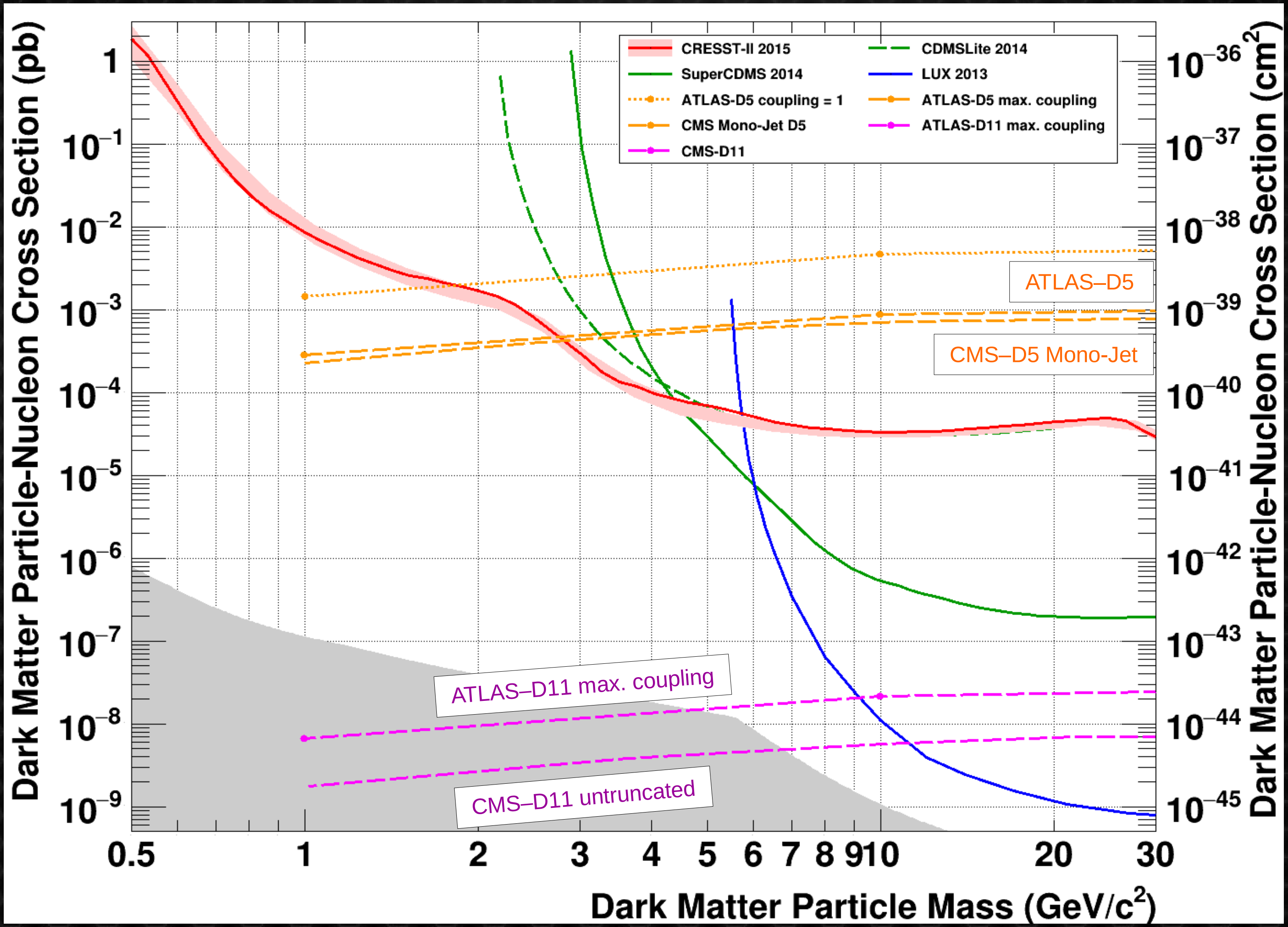
TUM40 - Veto of Surface Backgrounds



TUM40 - Radiopurity

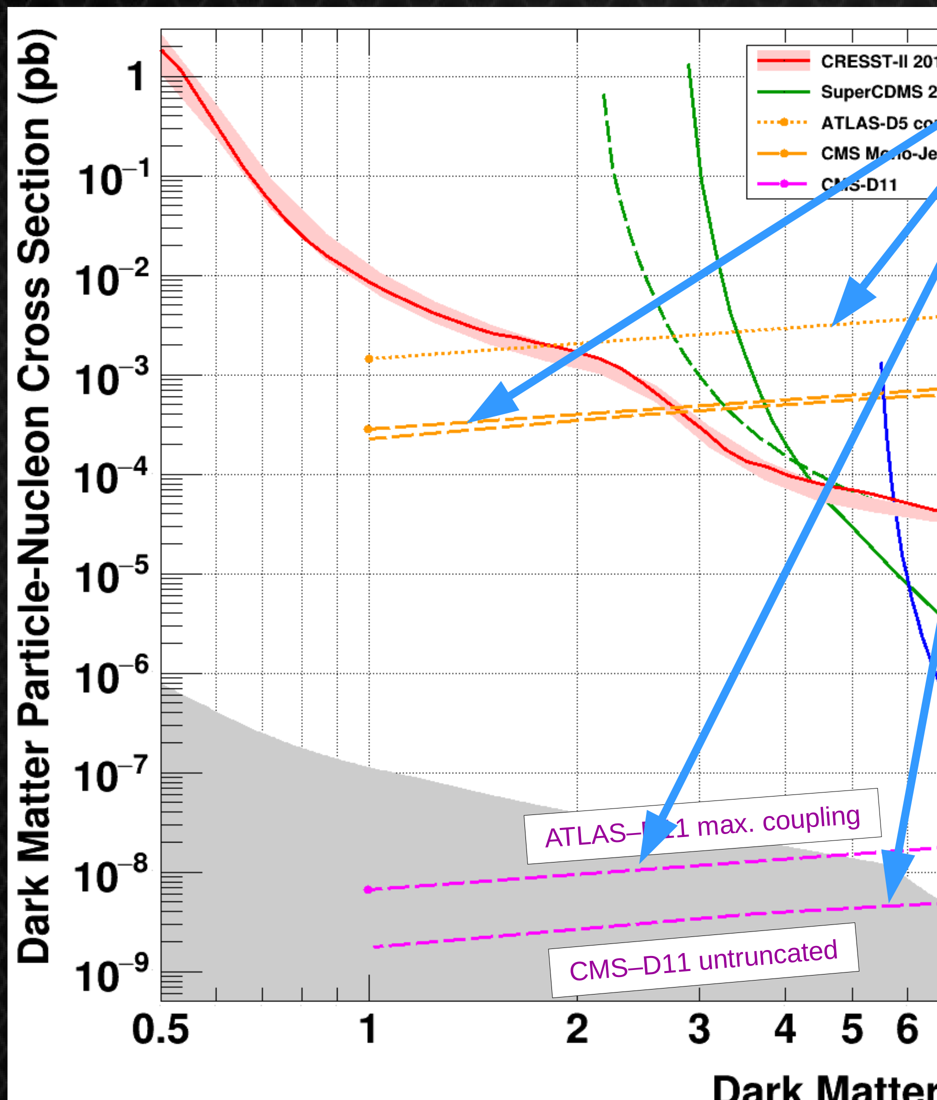


Direct Detection ↔ LHC

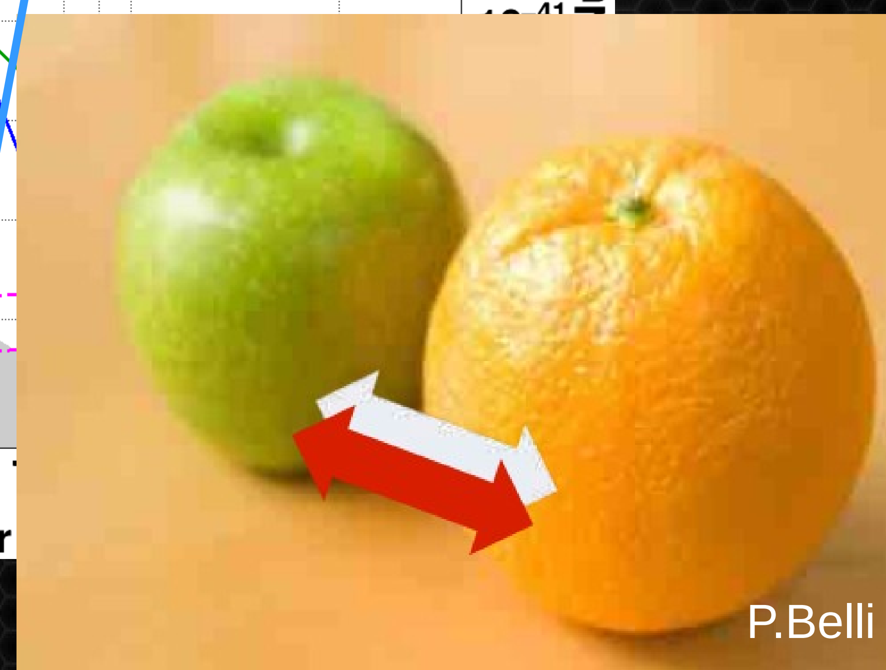


LHC limits from;
EPJ. C (2015) 75:299
CMS-PAS-EXO-12-054
(and references therein)

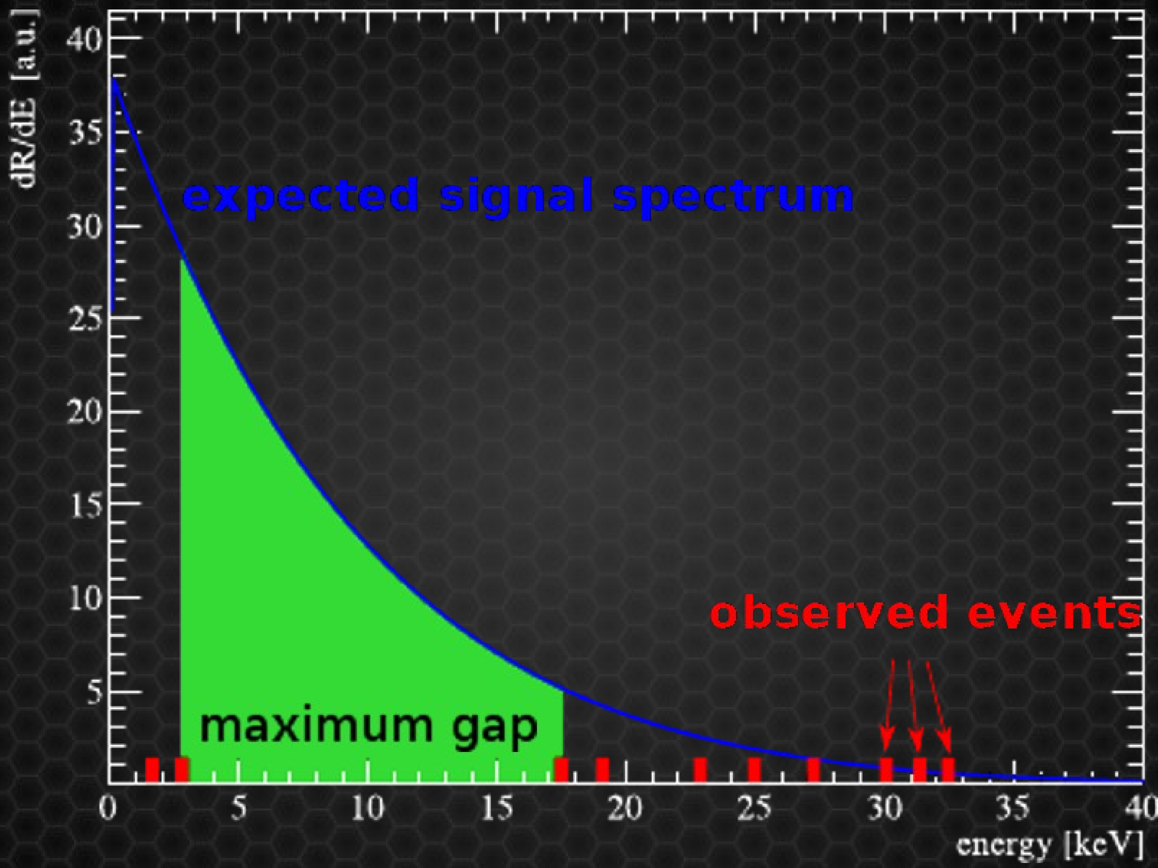
Direct Detection ↔ LHC



Strongly model-dependent

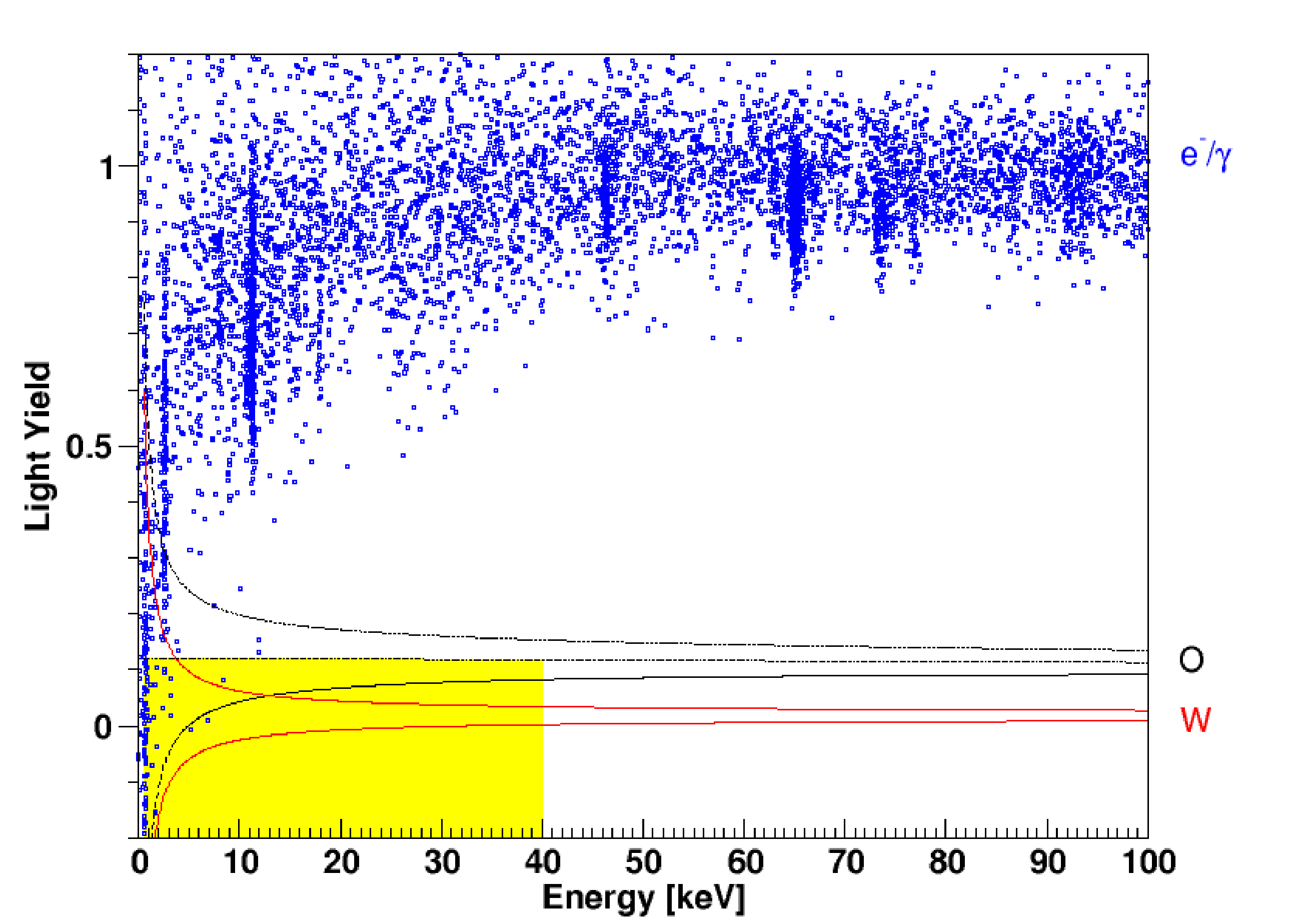


Yellin Maximum Gap



- Maximum Gap: Search for gap without event (N_{events} = 0)
- Optimum Interval: Search for largest interval with N_{events} = 1,2,3...

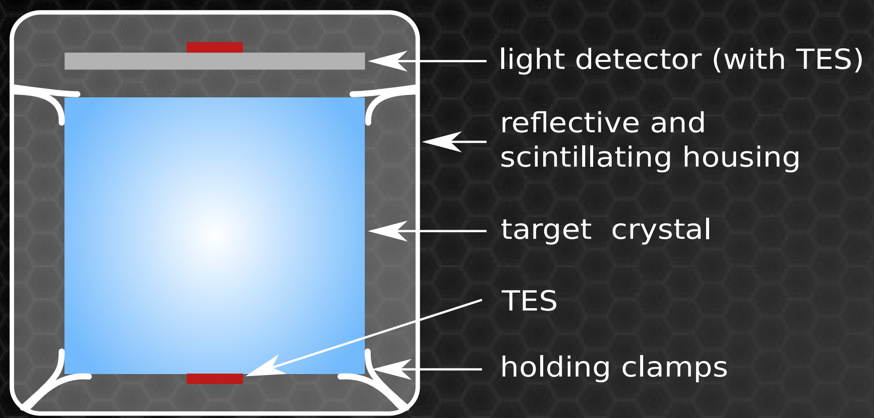
TUM40 - Acceptance Region



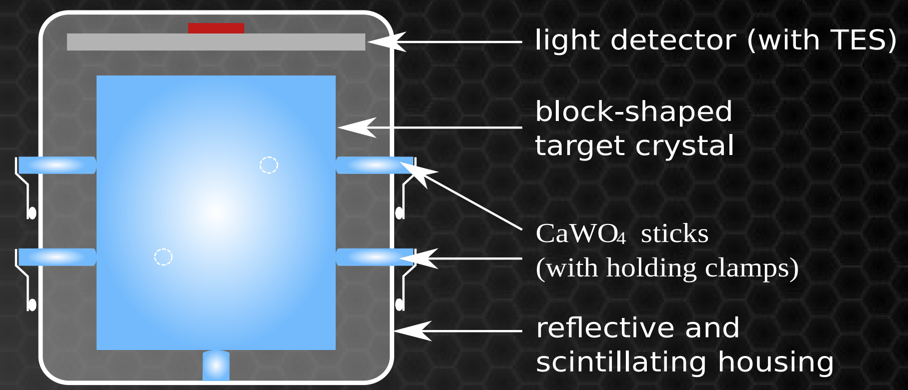
middle of oxygen band and below:
leakage of gamma band ↔ including all nuclear recoil bands

CRESST-II Detector Designs

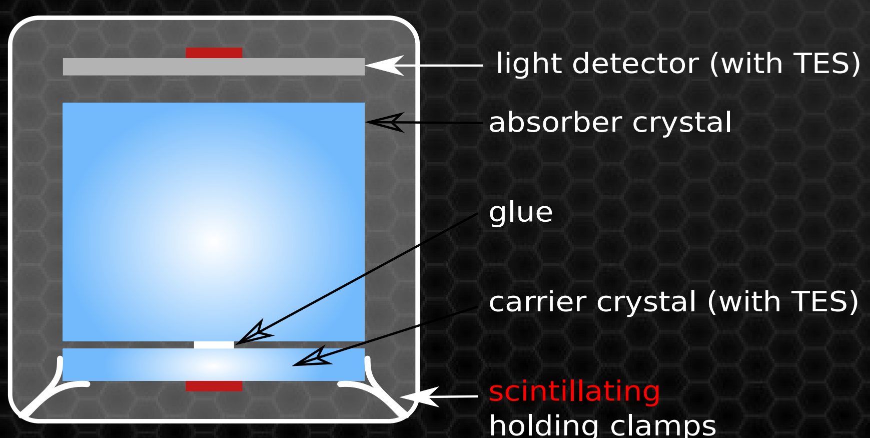
Conventional Design



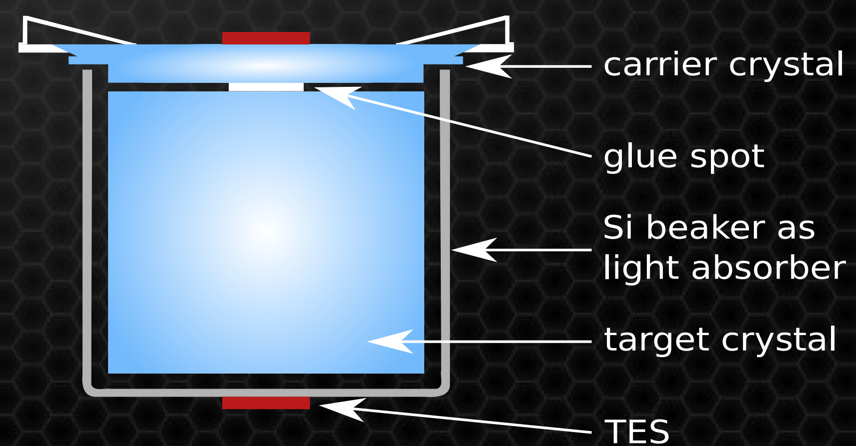
Stick/Raimund-Design



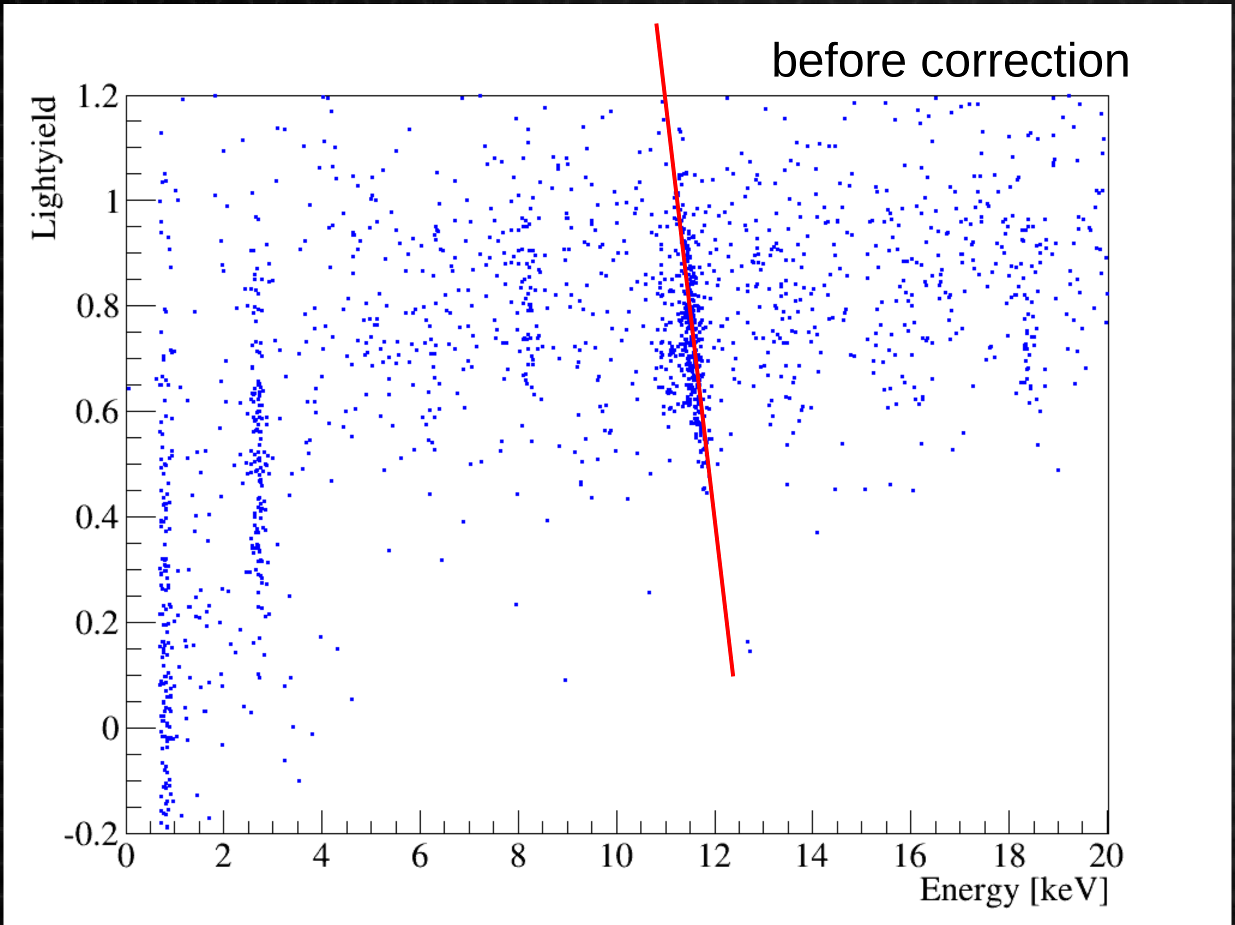
K14 Design



Beaker/Gode-Design



Event-type Independent Total Energy

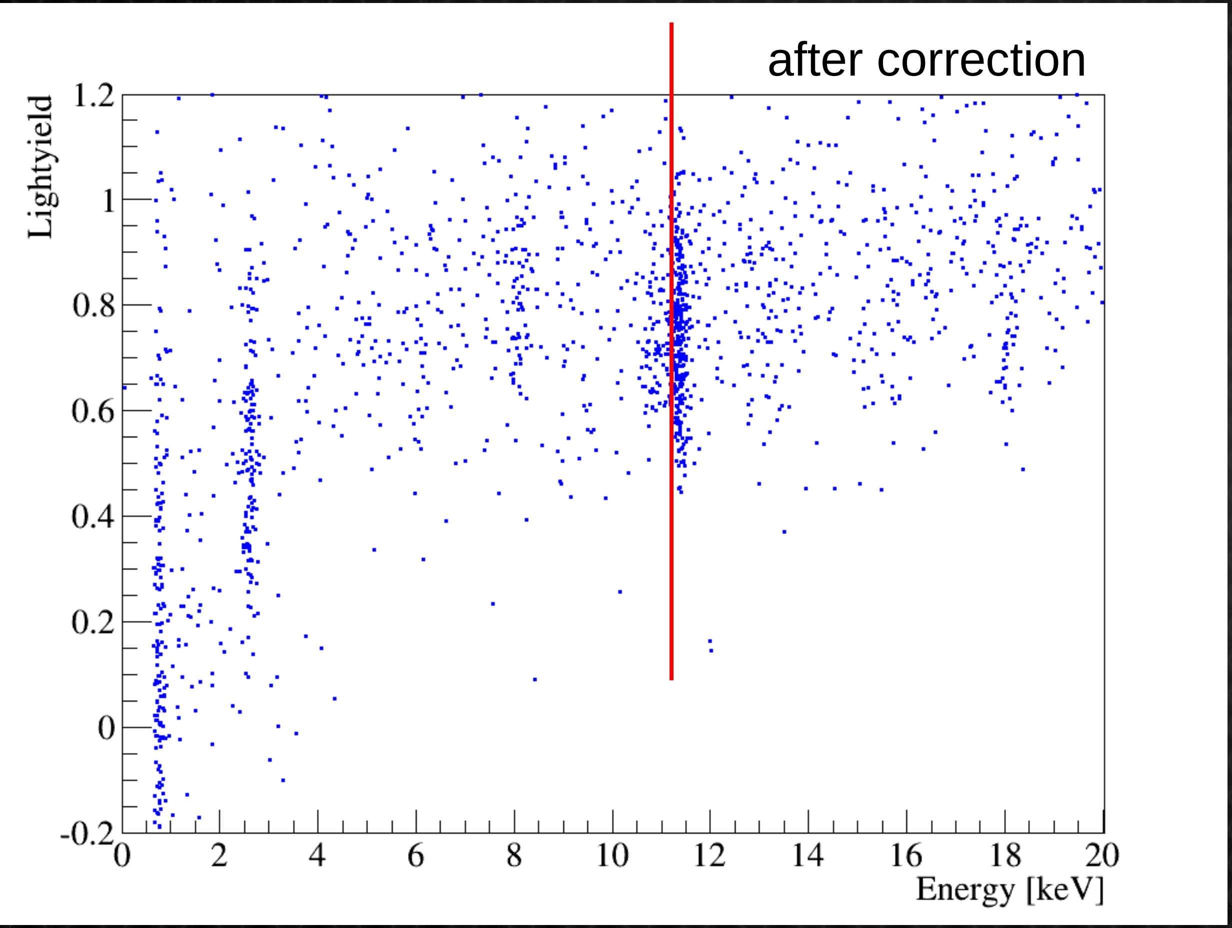


- Energy is shared between phonon and light channel, quantified by the scintillation efficiency η
- The calibration is done for 122keV gamma's (η_{TUM40}=6.6%)

- for LY=1: no correction
- for LY=0: 6.6% correction

$$E = \eta E_l + (1-\eta) E_p = [1-\eta(1-LY)] E_p$$

Event-type Independent Total Energy



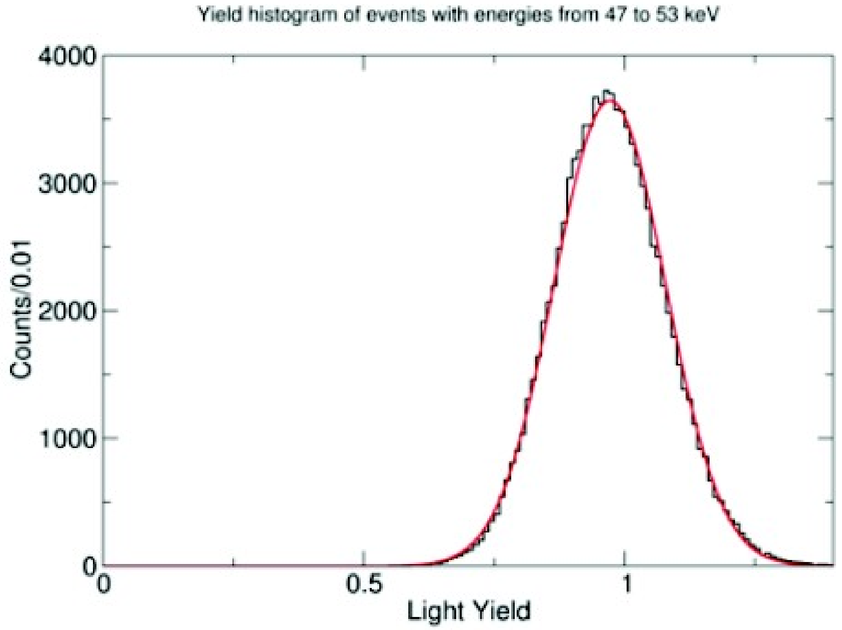
- Energy is shared between phonon and light channel, quantified by the scintillation efficiency η
- The calibration is done for 122keV gamma's (η_{TUM40}=6.6%)

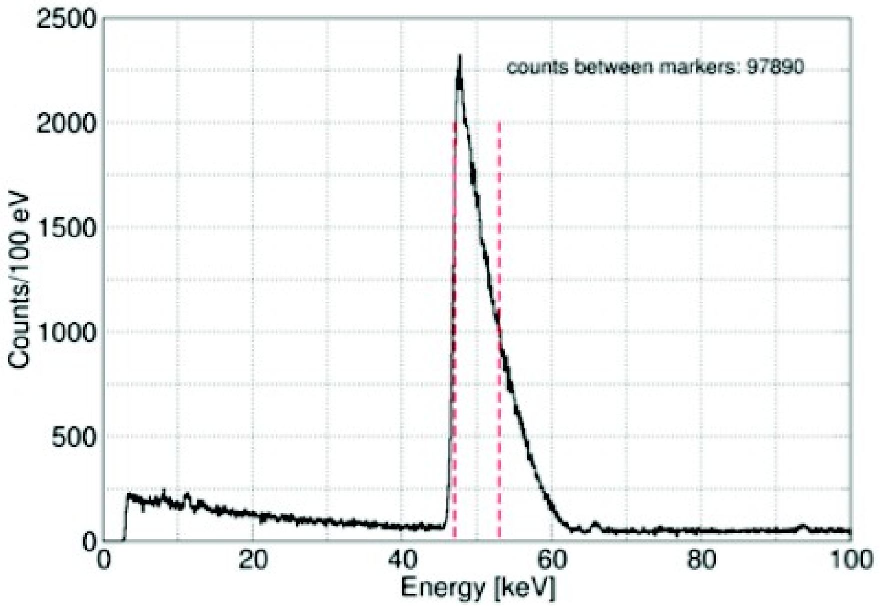
- for LY=1: no correction
- for LY=0: 6.6% correction

- correction straightens gamma lines
- corrections yield correct Q-value for internal alpha decays

$$E = \eta E_l + (1-\eta) E_p = [1 - \eta(1 - LY)] E_p$$

Gaussianity of Recoil Bands





- perfect Gaussian behaviour
- 10^5 events in peak – only 1 outlier (probably alpha event)

less than 1 leakage event expected out of 10^5 events !

Slide by: R. Strauss

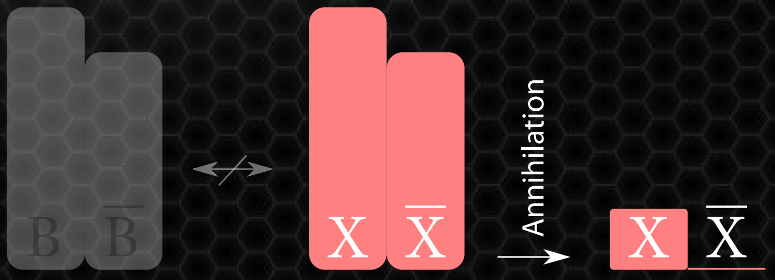
Motivation for low-mass dark matter

WIMP "Miracle"

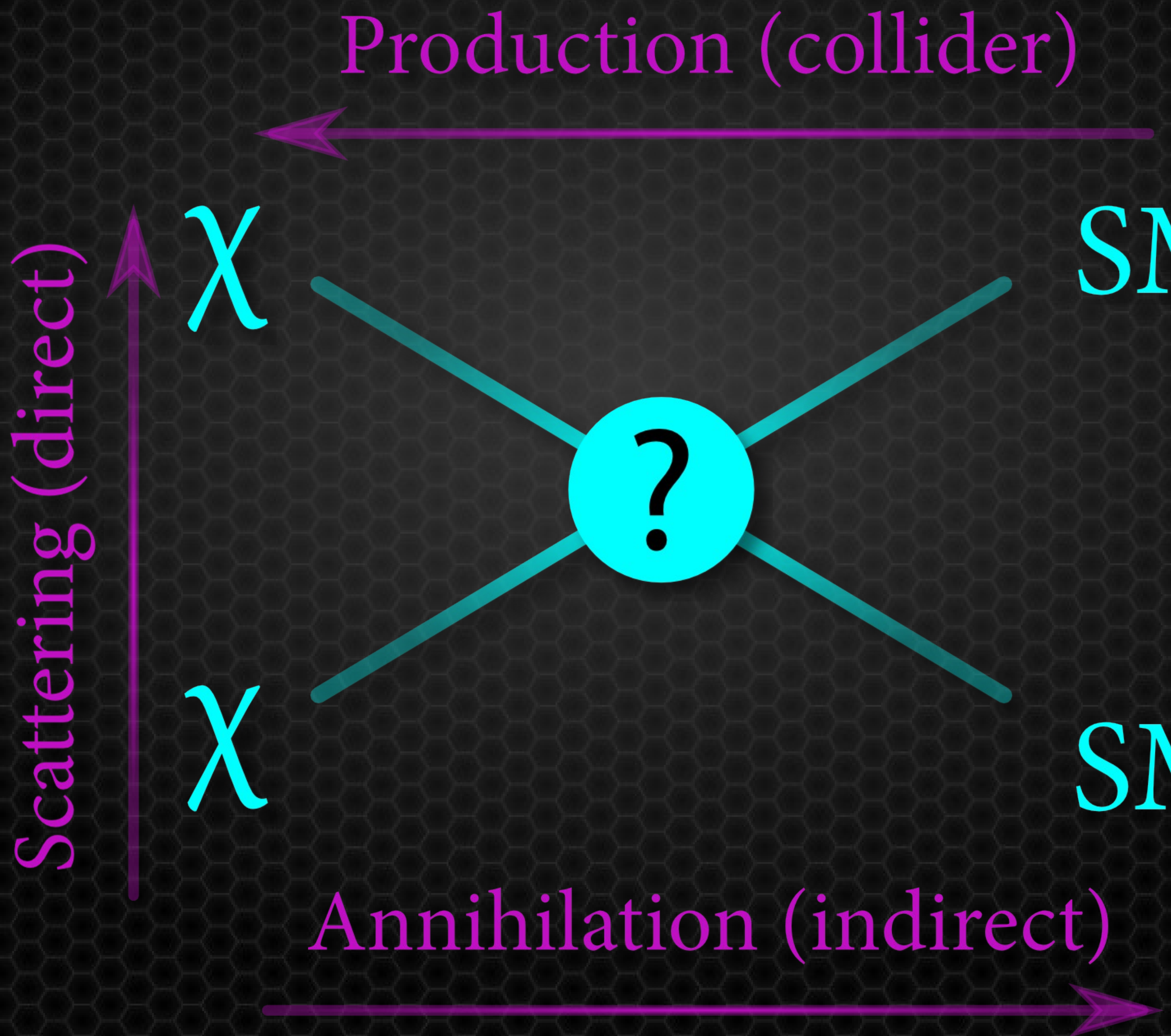
- Thermally produced in early Universe
- Weak scale yields correct relic density
- 10GeV/c^2 ~ 1TeV/c^2

Asymmetric Dark Matter

- $\Omega_{DM}/\Omega_B \sim 5$: Why?
- Link asymmetries for baryons and DM in early Universe
- 0.1GeV/c^2 ~10GeV/c^2



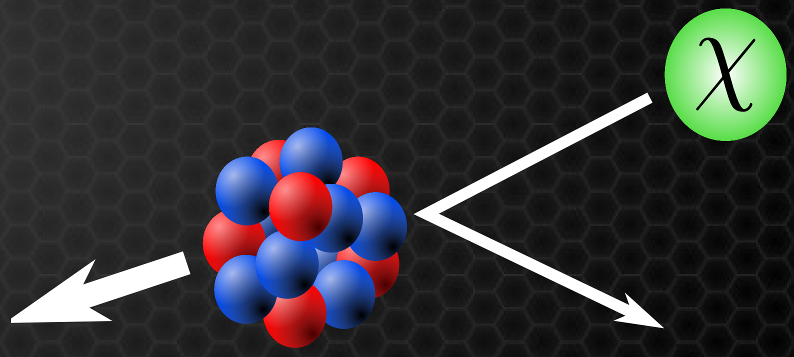
Detection Channels



Direct Dark Matter Detection

Most common scenario: dark matter particle scatter

- off nuclei
- elastically
- coherently: ~A^2
- (spin-independent)



Detection Techniques