Title: Results from the Latest Run of the CRESST-II Dark Matter Search

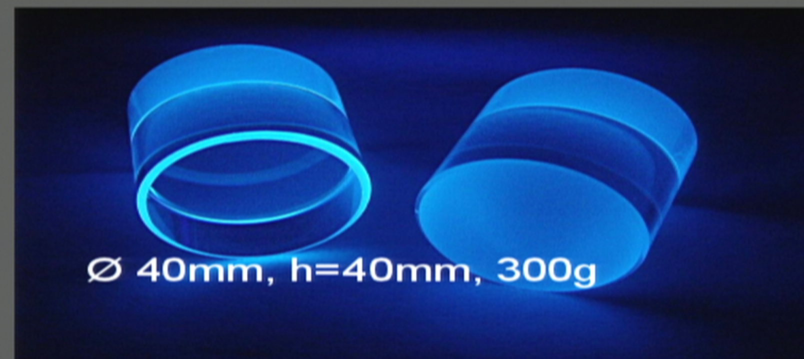
Date: Feb 14, 2012 01:00 PM

URL: http://pirsa.org/12020081

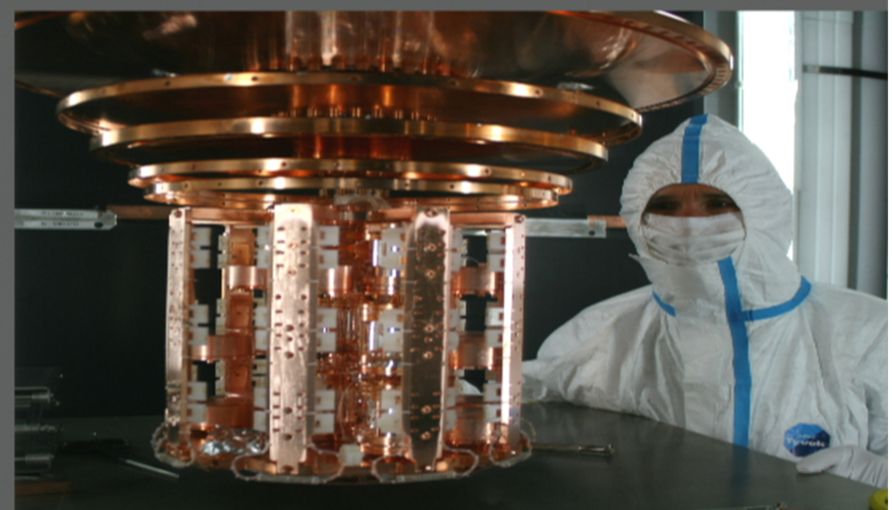
Abstract:

Results from the latest run of the CRESST Dark Matter Search

Collaboration
MPI für Physik, Oxford University,
TU München, Universität Tübingen
Laboratori Nazionali del Gran Sasso



- Cryogenic Dark Matter search
- Located in hall A of LNGS
- Scintillating $CaWO_4$ target crystals
- Up to 33 crystals in modular Structure (10 kg target mass)



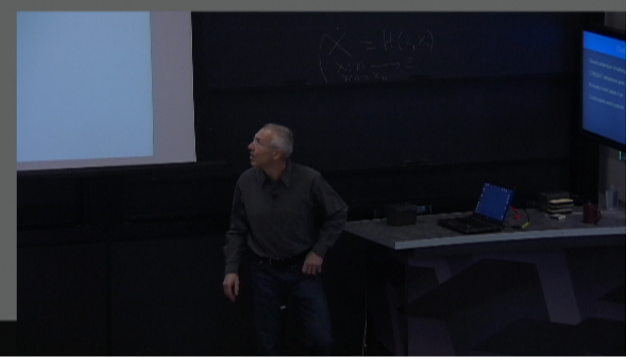
Outline

Direct detection challenge

CRESST detectors and setup

Results from latest run

Conclusion and outlook

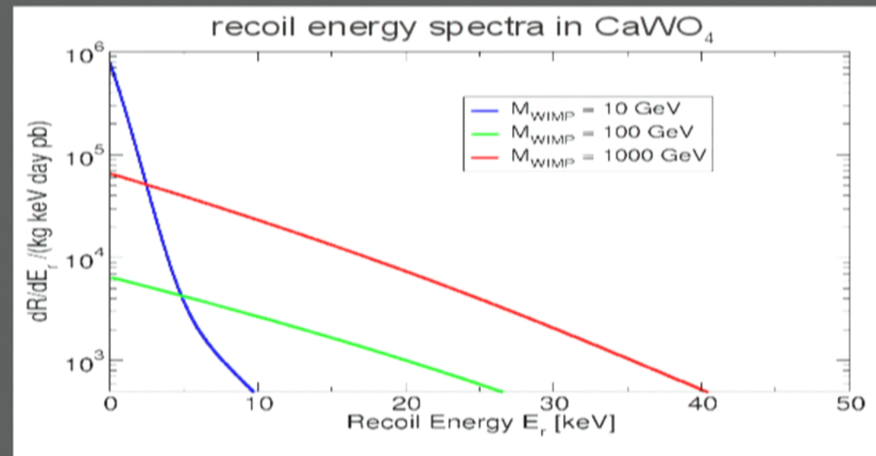


WIMP direct detection challenge

Detection via elastic scattering off target nuclei

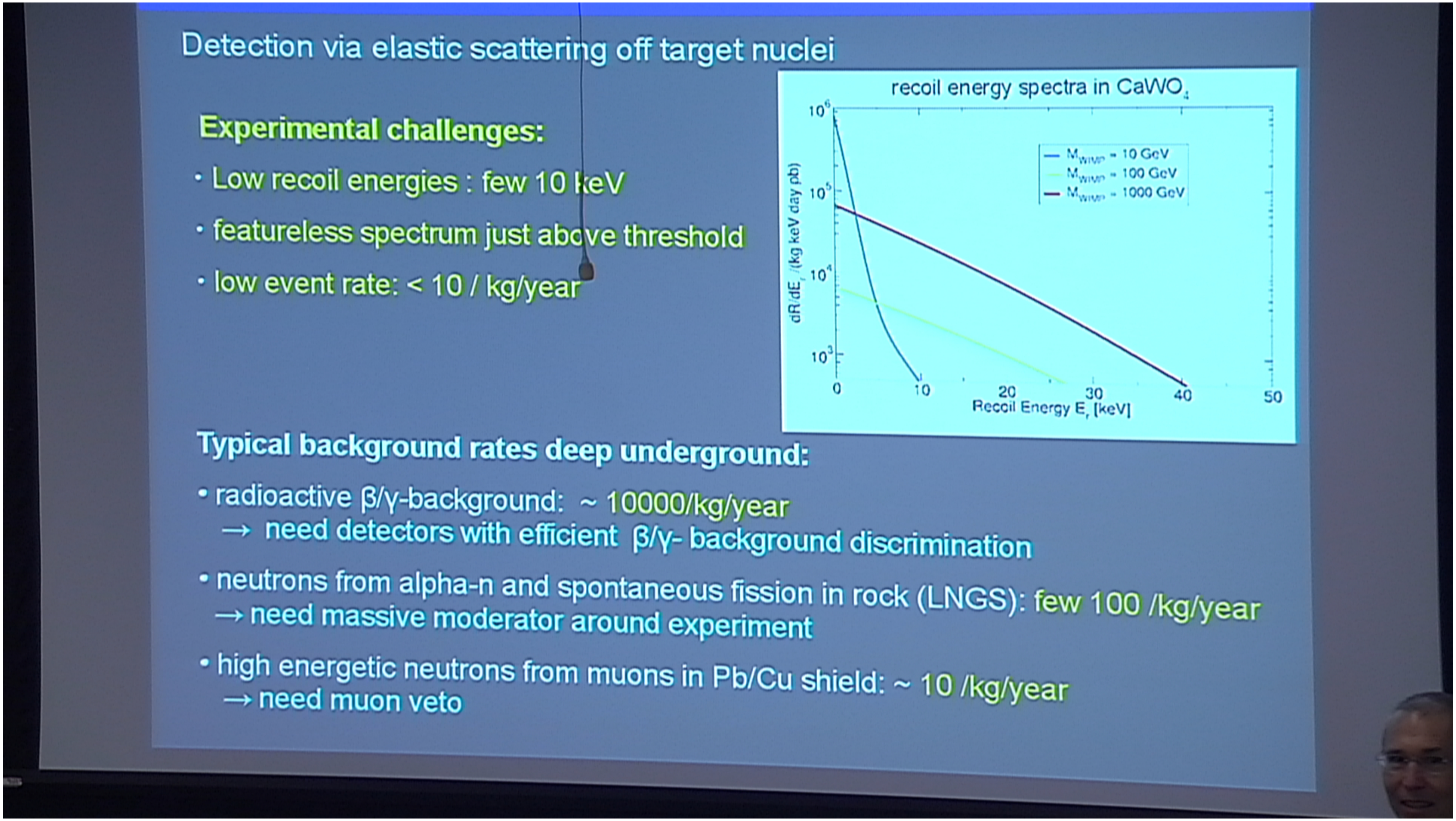
Experimental challenges:

- Low recoil energies : few 10 keV
- featureless spectrum just above threshold
- low event rate: < 10 / kg/year



Typical background rates deep underground:

- radioactive β/γ-background: ~ 10000/kg/year
  → need detectors with efficient β/γ- background discrimination
- neutrons from alpha-n and spontaneous fission in rock (LNGS): few 100 /kg/year
  → need massive moderator around experiment
- high energetic neutrons from muons in Pb/Cu shield: ~ 10 /kg/year
  → need muon veto


Detection via elastic scattering off target nuclei
Experimental challenges:
• Low recoil energies : few 10 keV
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recoil energy spectra in CaWO4
M_WIMP = 10 GeV
M_WIMP = 100 GeV
M_WIMP = 1000 GeV
dR/dE_r /(kg keV day pb)
Recoil Energy E_r [keV]
10^6
10^5
10^4
10^3
0
10
20
30
40
50
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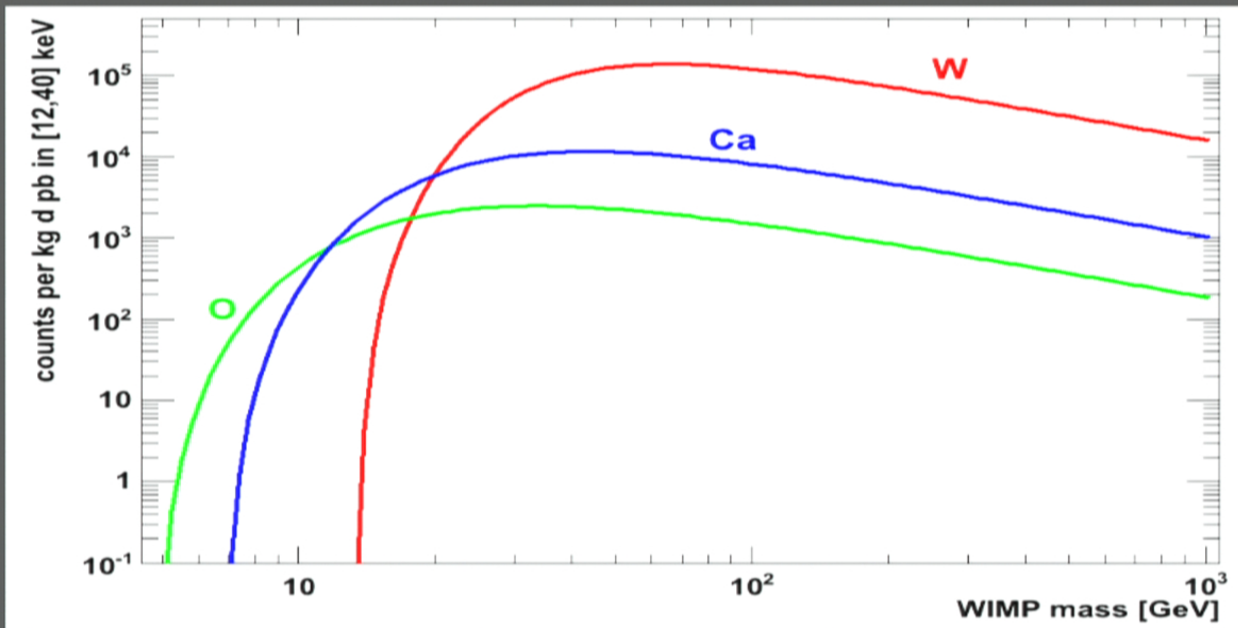
Type of recoil nucleus seen in $CaWO_4$



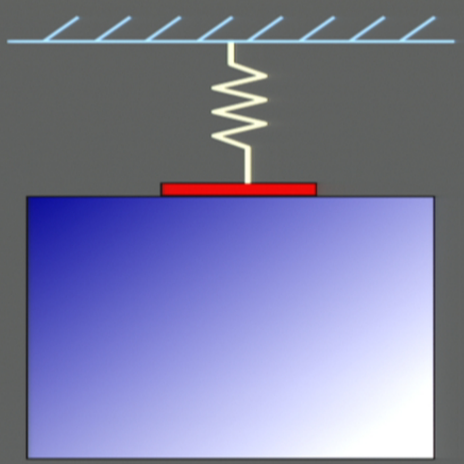
assuming $\sigma \propto A^2$

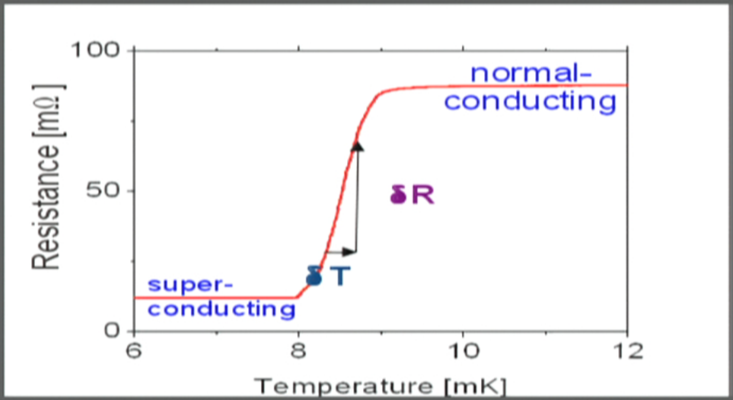
sensitive range:
12 to 40 keV

- For small WIMP masses <10 GeV only oxygen recoils above threshold
- Calcium important around 10 GeV
- Tungsten dominates at large WIMP masses due to $\sigma \propto A^2$

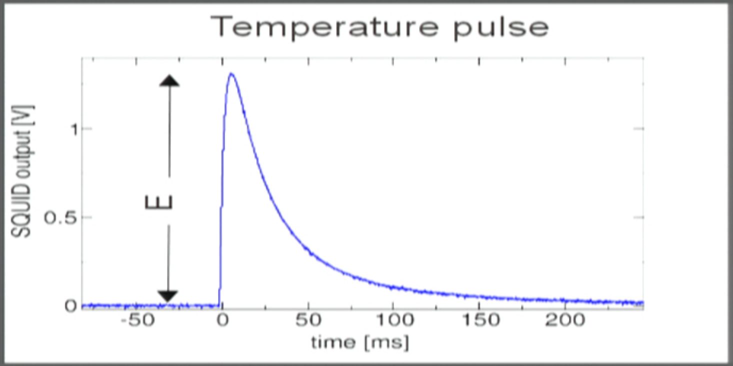
→ Consider all 3 nuclei in analysis to cover largest possible range of WIMP masses

CRESST type cryogenic Detectors





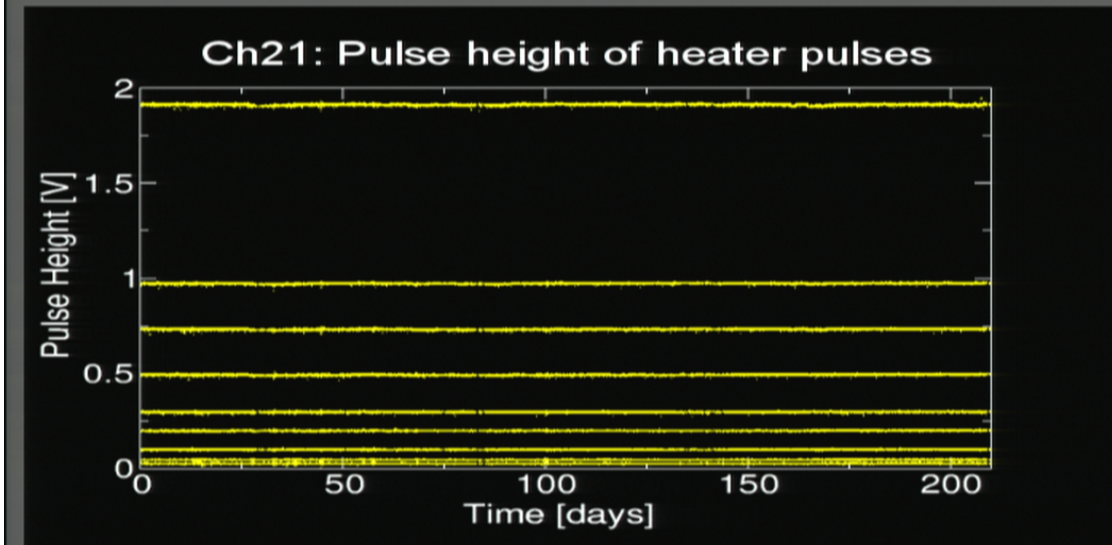
SQUID based read out
Operating temperature: 10 to 20 mK
Width of transition: ~1mK, keV signals: ~ μK
Longterm stability: ~ μK

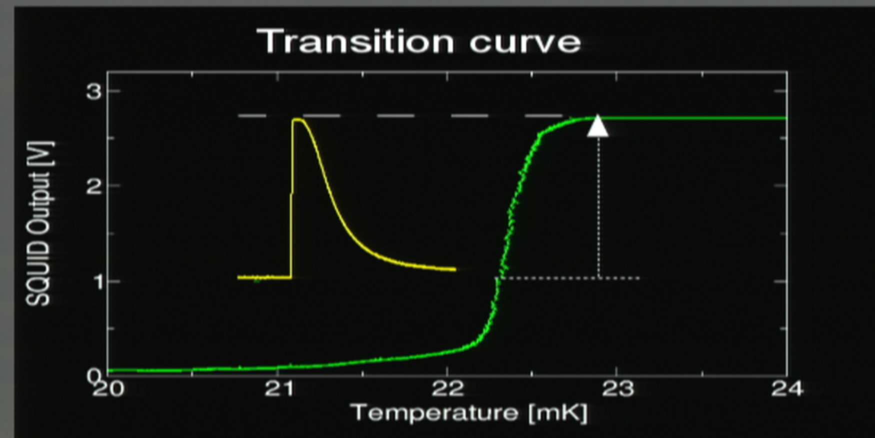


Advantages of technique:

- Precise calorimetric measurement of deposited energy
- Low energy threshold and excellent energy resolution
- Different materials

Stability of Energy Response



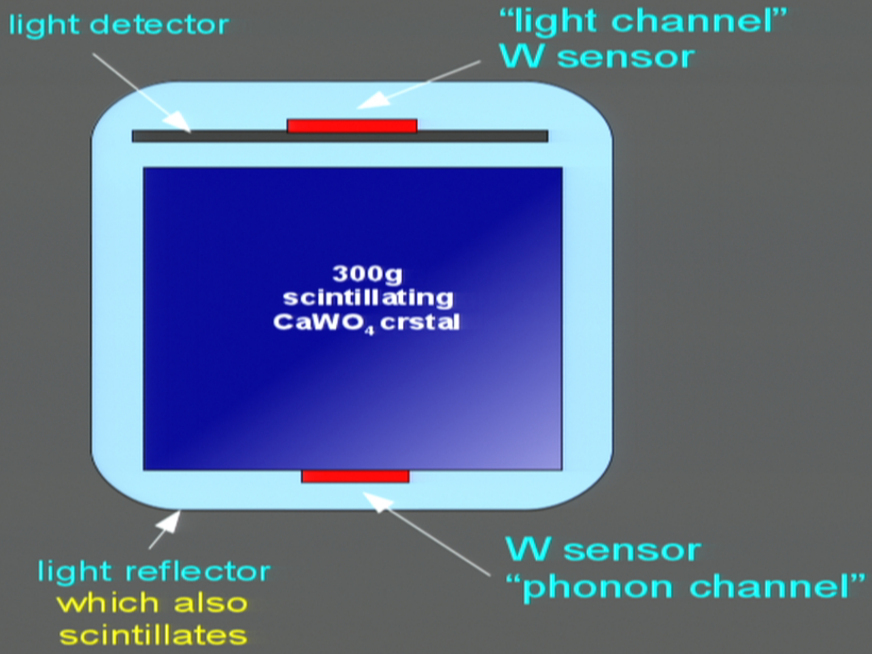


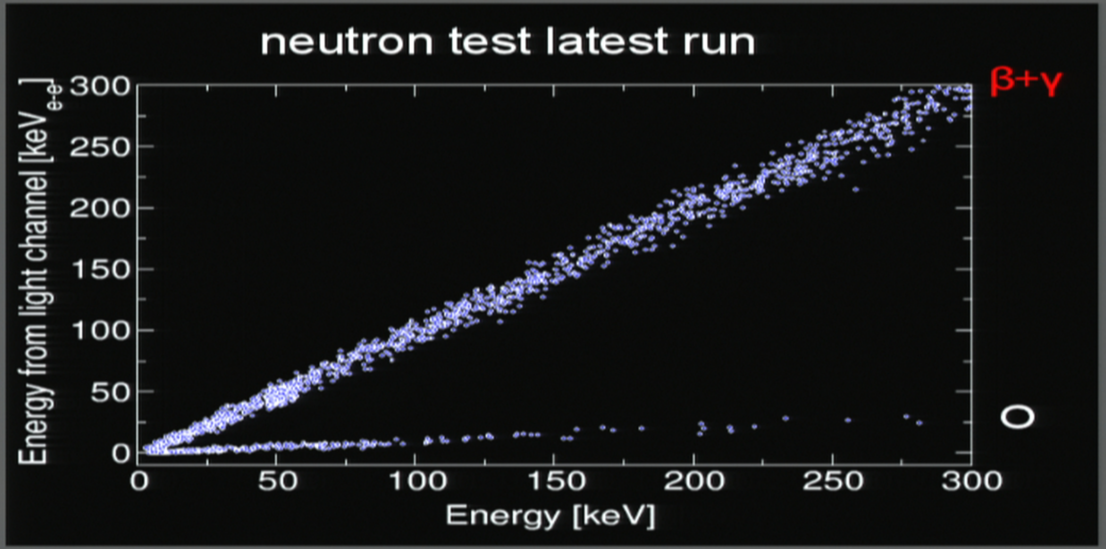
Operating temperature controlled with large heater pulses

Calibration continuously monitored with heater pulses

100% trigger efficiency close to threshold confirmed with lowest energy heater pulses

CRESST-II Detectors





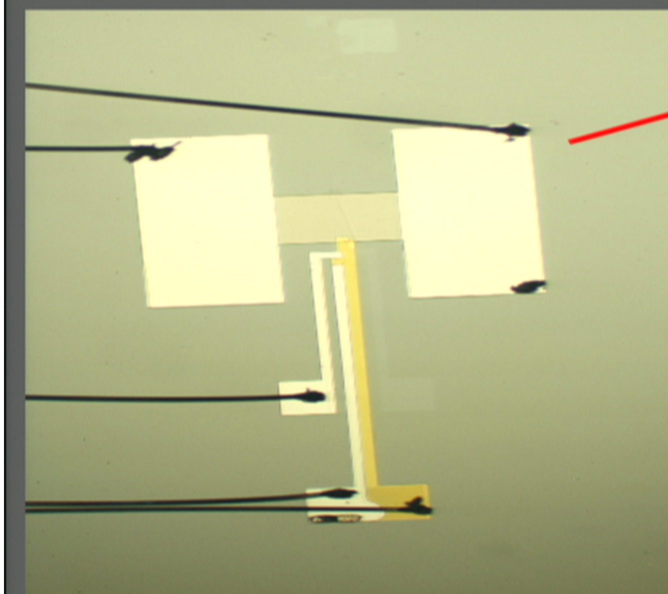
→ phonon channel provides precise measurement of deposited energy

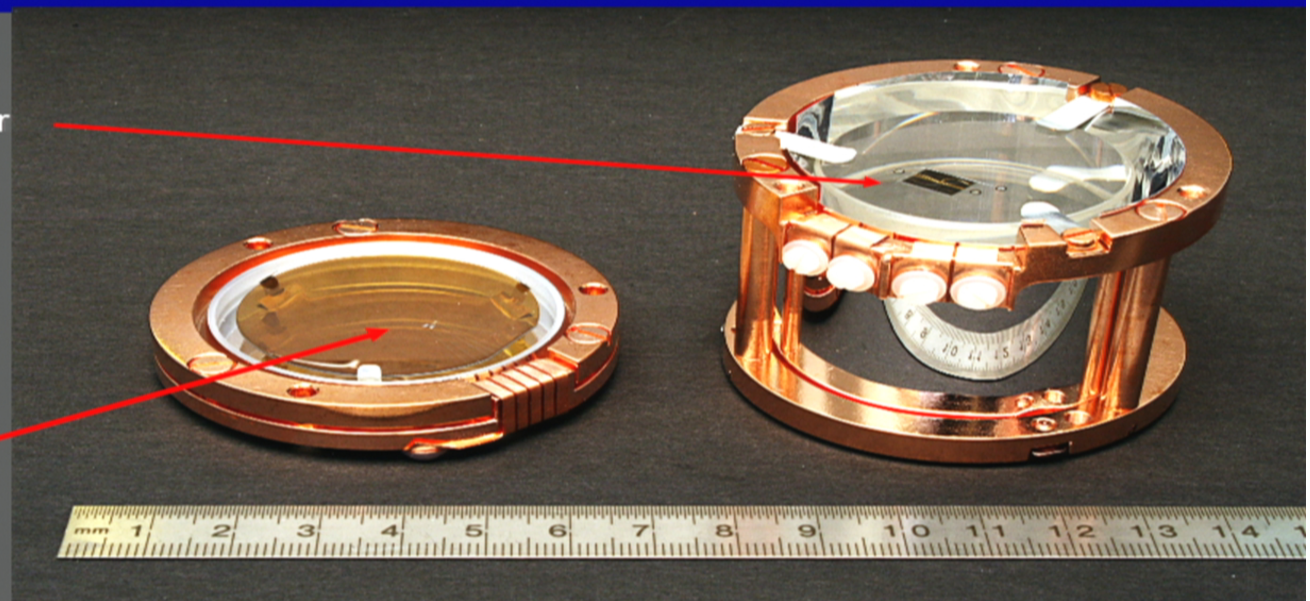
→ Light channel distinguishes interaction type

→ Types of recoiling nuclei distinguished by different slopes in light energy plane

300 g Detector Module

The phonon detector:
300 g cylindrical $CaWO_4$ crystal,
evaporated tungsten thermometer
with attached heater.





The light detector:
Ø=40 mm silicon on sapphire wafer.
Tungsten thermometer with attached
aluminum phonon collectors and thermal link.
Part of thermal link used as heater

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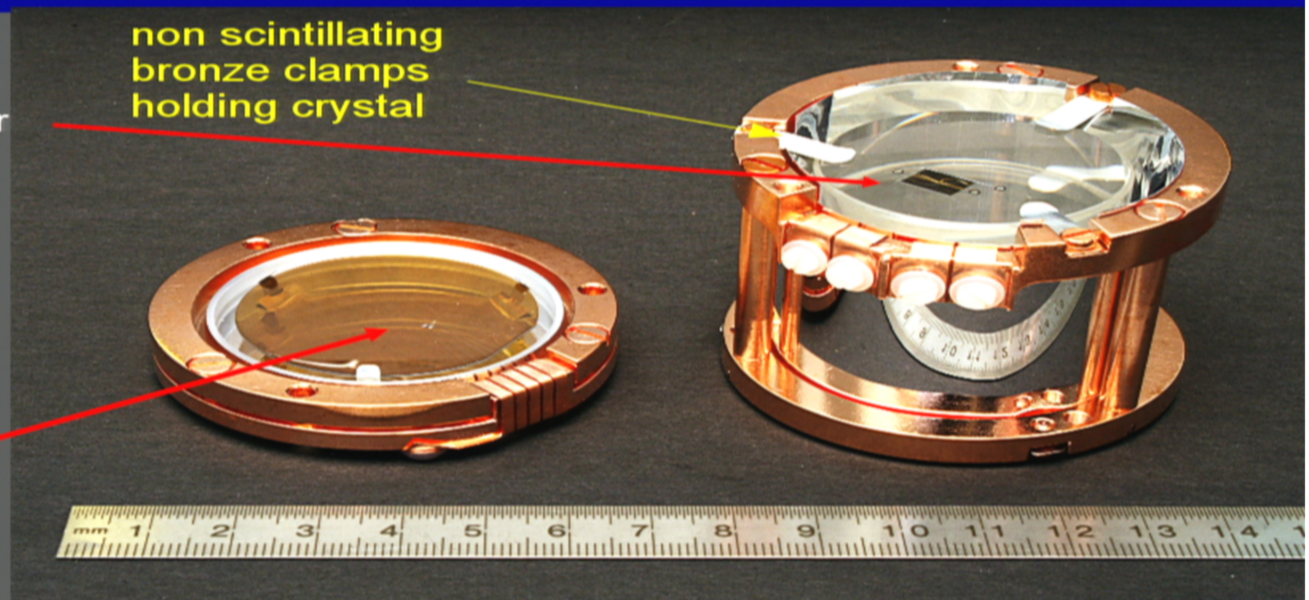

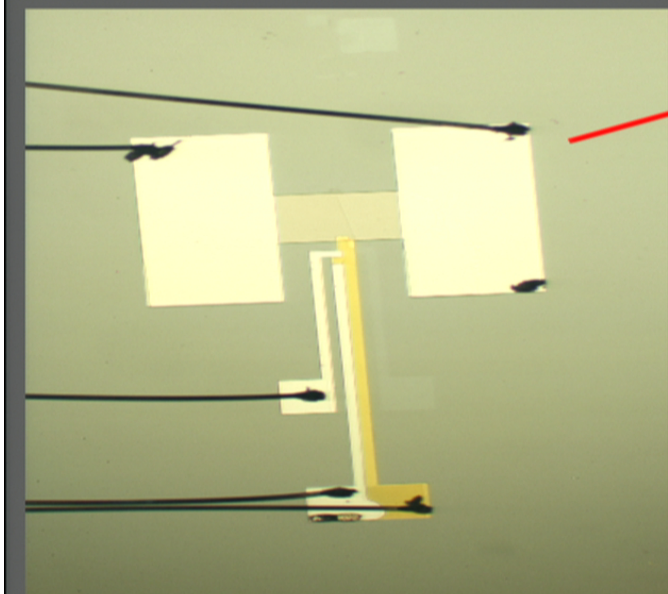

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Rejection of ^{206}Pb recoil background

^{210}Pb is first long lived isotope in chain after ^{222}Ra

^{210}Pb 22.3 y

β^- ↓

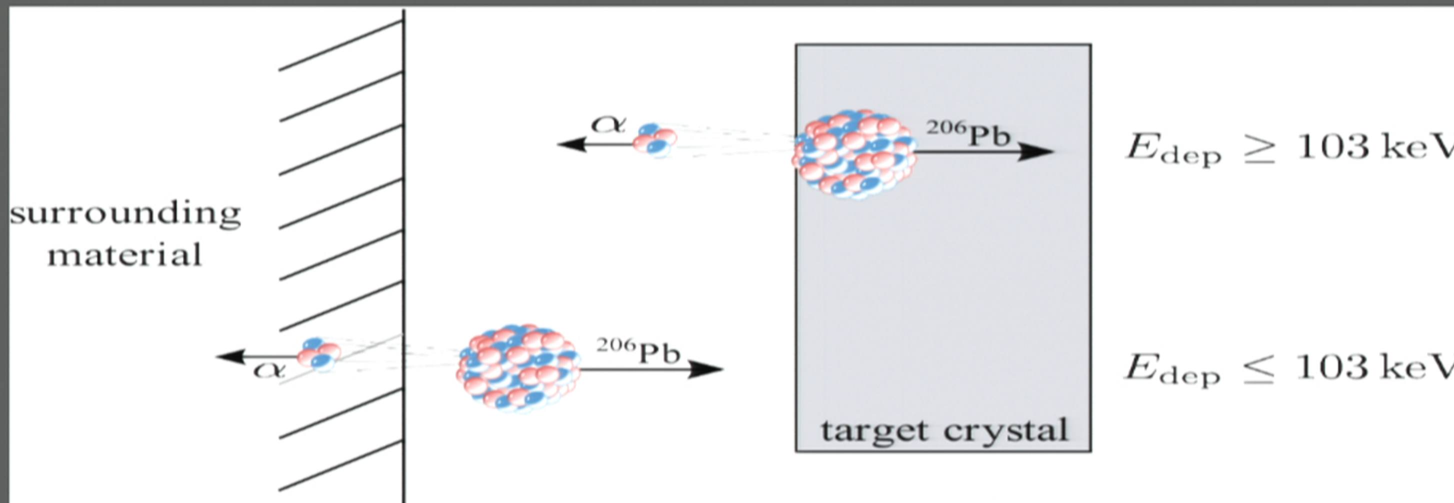
^{210}Bi

β^- ↓

^{210}Po 138 d

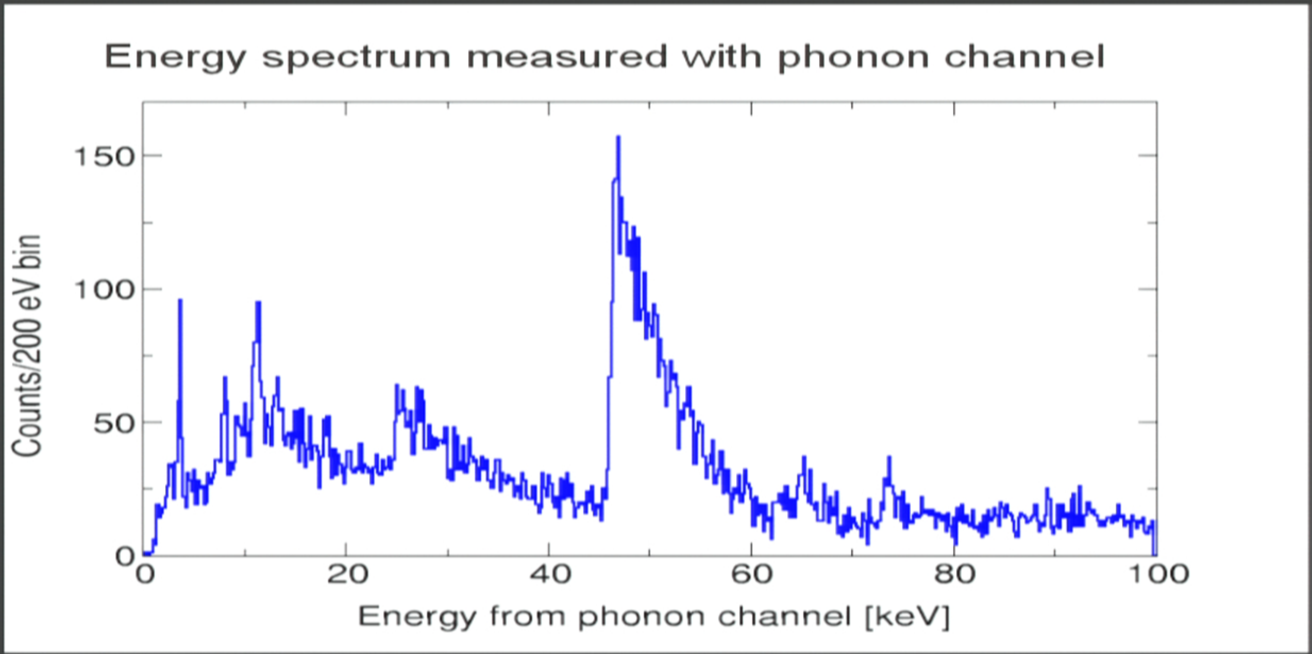
α ↓ 5.3 MeV

^{206}Pb



- ^{210}Pb on surfaces of crystal and surrounding material
- ^{206}Pb recoils with E<100 keV from surface of surrounding
- ^{206}Pb and W recoils have similar low light yield
- **Extra light from alpha in completely scintillating housing allows to veto ^{206}Pb recoils (exception: clamps)**

Detector performance at low energies



^{41}Ca 3.61 keV
found @3.6 keV

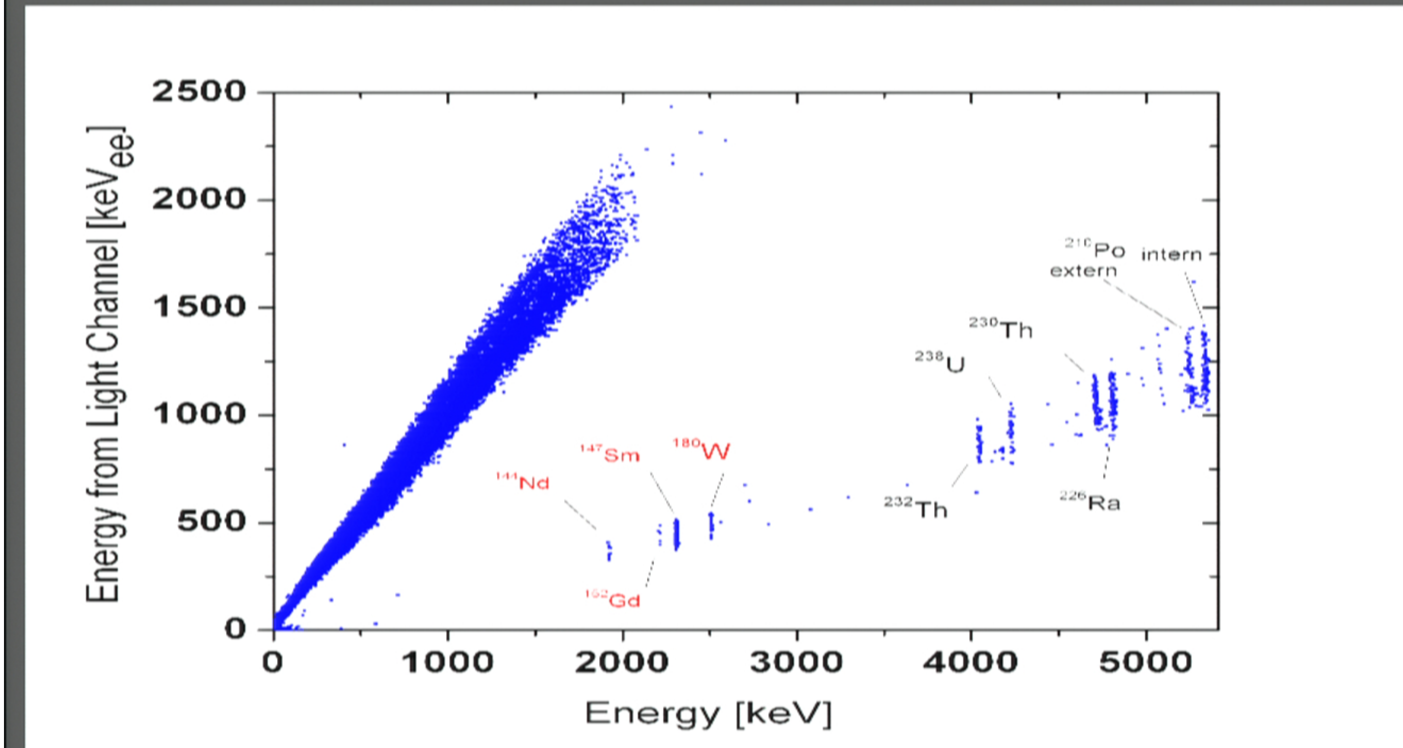
Cu K_α 8.1 keV
found @8.2 keV

^{210}Pb 46.5 keV
found @ 46.5 keV

^{227}Ac structures at
9.3 keV and 24.5 keV

- Precise energy calibration
- Lines down to 3.6 keV identified with excellent energy resolution of 300 eV (FWHM).

Detector Performance in wide energy range



- Good energy resolution in in wide energy range
- Identification of alpha peaks from emitters inside crystal

Same light of external and internal ^{210}Po peaks demonstrates absence of surface degradation

CRESST setup at LNGS

Shielding

Neutron shield 45 cm PE

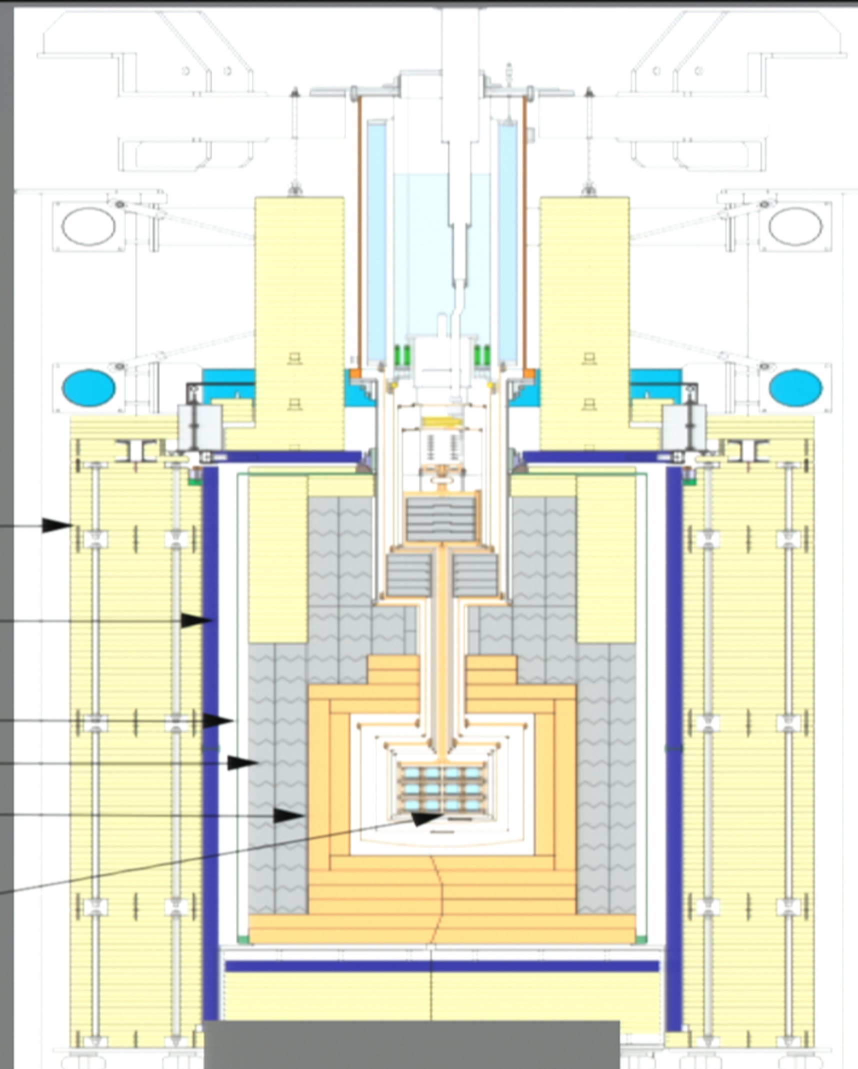
Muon veto

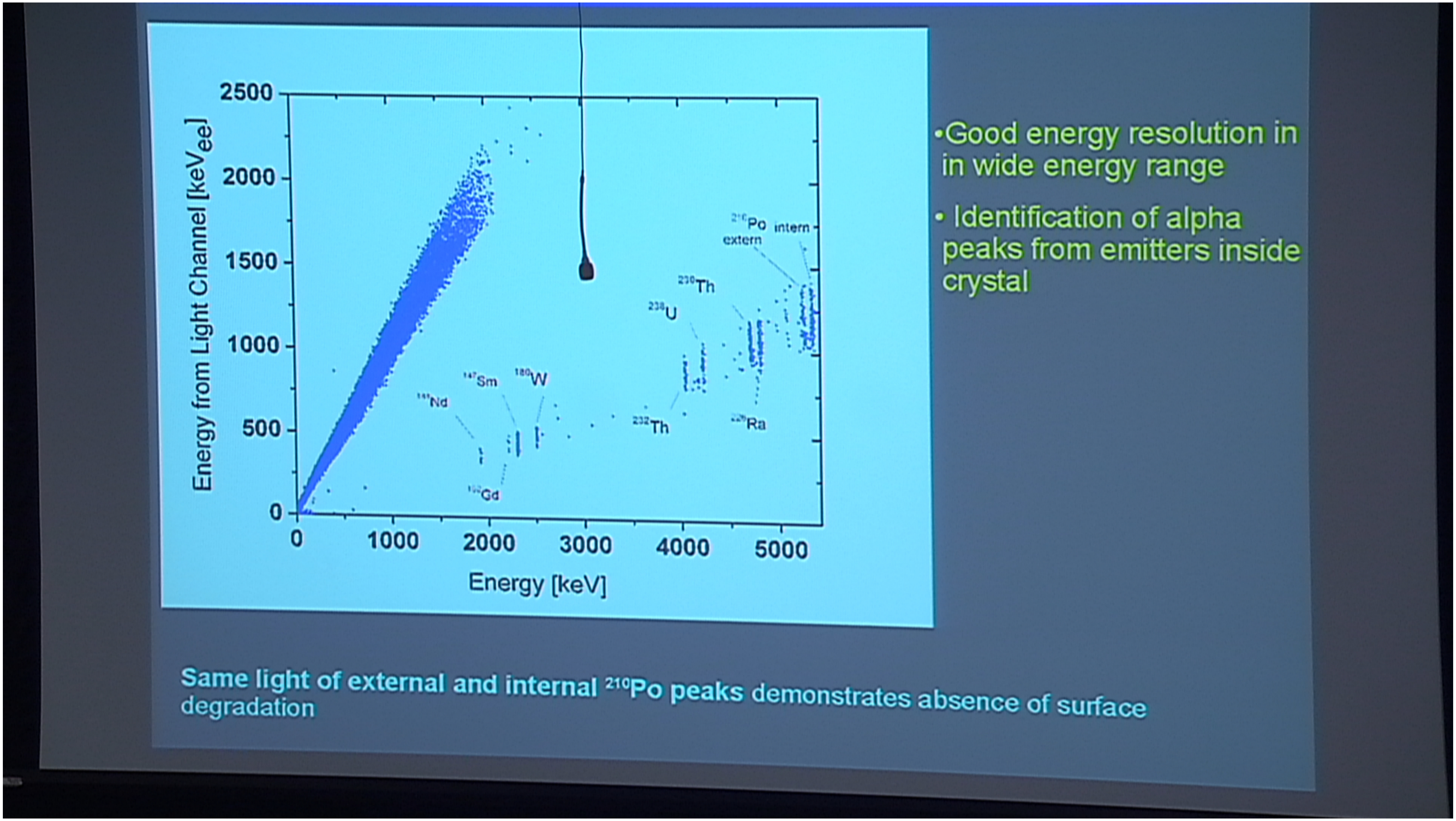
Radon box

20cm Pb

14 cm Cu

Detectors




Energy from Light Channel [keVee]
Energy [keV]
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
Sm
W
Nd
Gd
Th
U
Th
Ra
Po
intern
extern
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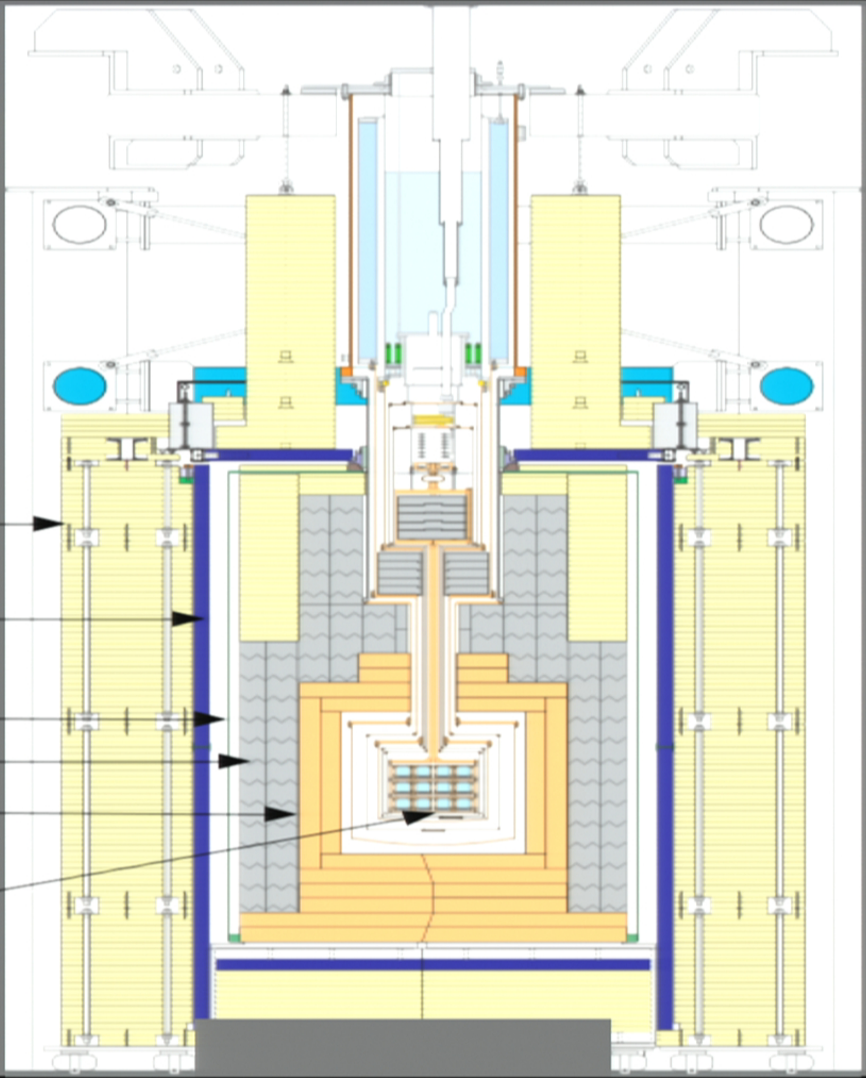


The latest CRESST run

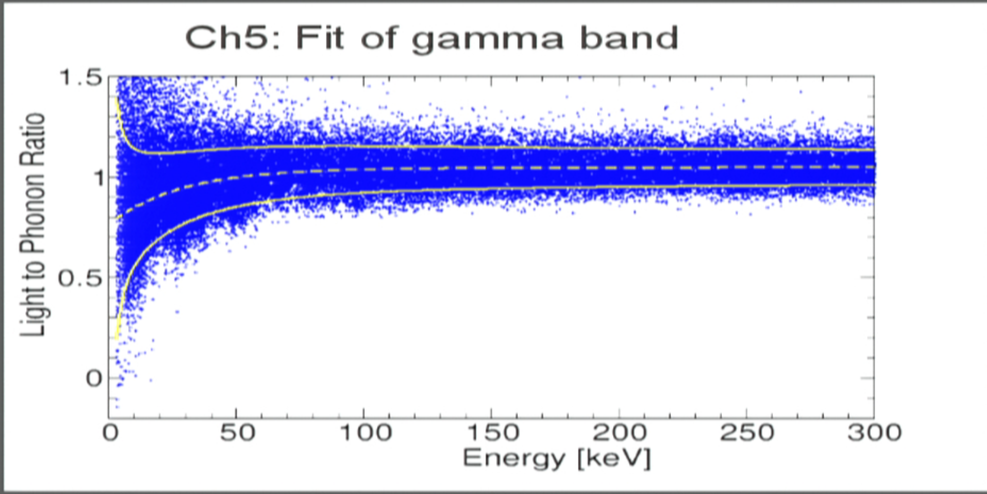
From June 2009 to April 2011

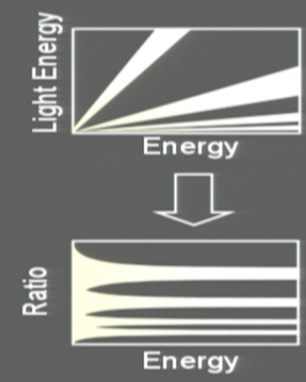
- Gamma calibrations with ^{57}Co and ^{232}Th sources
- Neutron tests

- 18 modules installed
  - → 10 complete modules operated (9 $CaWO_4$+1 $ZnWO_4$)
  - → 8 $CaWO_4$ modules used for analysis
  - → 10 complete modules + 7 individual detectors used for tagging coincidences

- Net exposure after cuts: 730 kg days

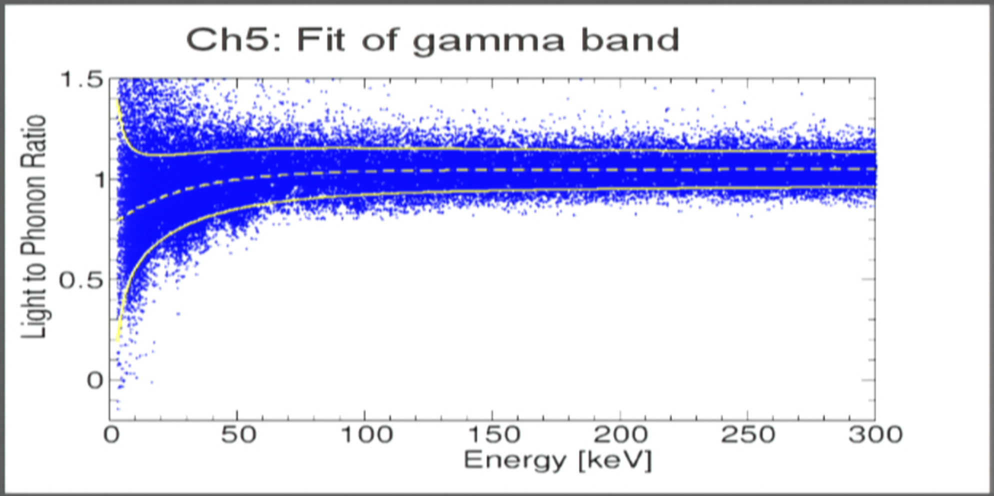
Definition of recoil acceptance regions

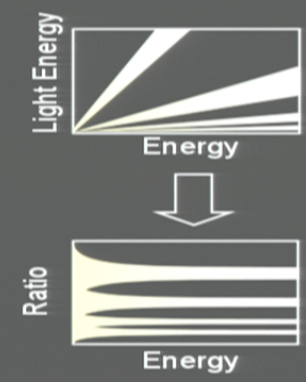




- Width of nuclear recoil bands mostly given by energy resolution of light detector
- Center of gamma band and resolution of light detector as a function of detected light energy extracted by a fit of gamma band
- Light detector resolution at quenched light energy then yields nuclear recoil acceptance band

Definition of recoil acceptance regions





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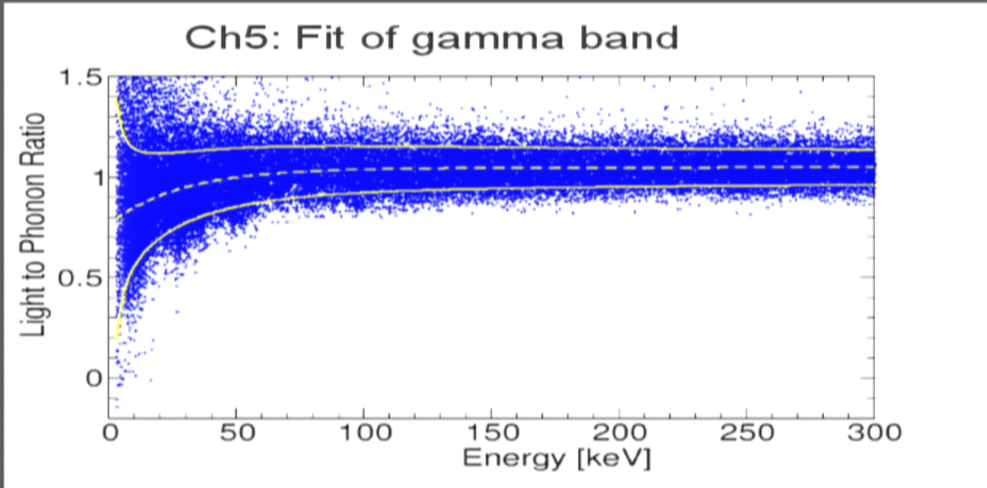

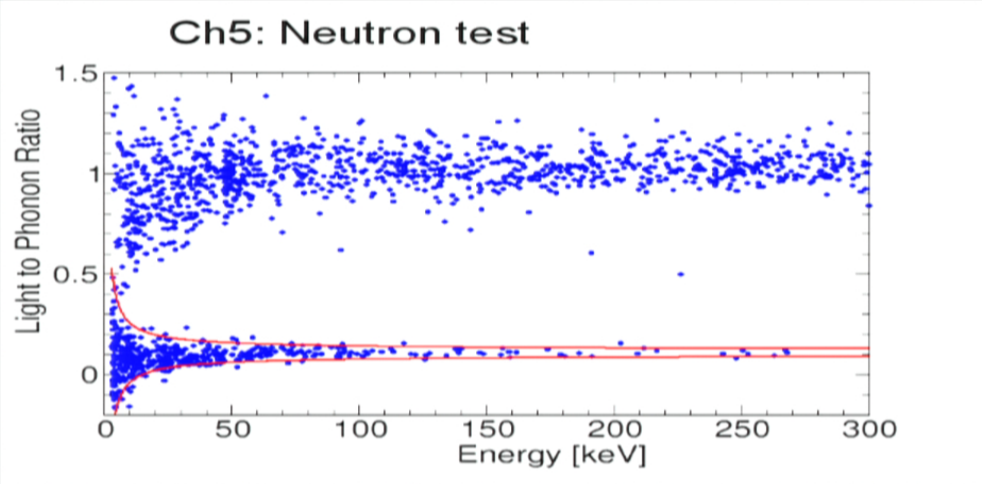

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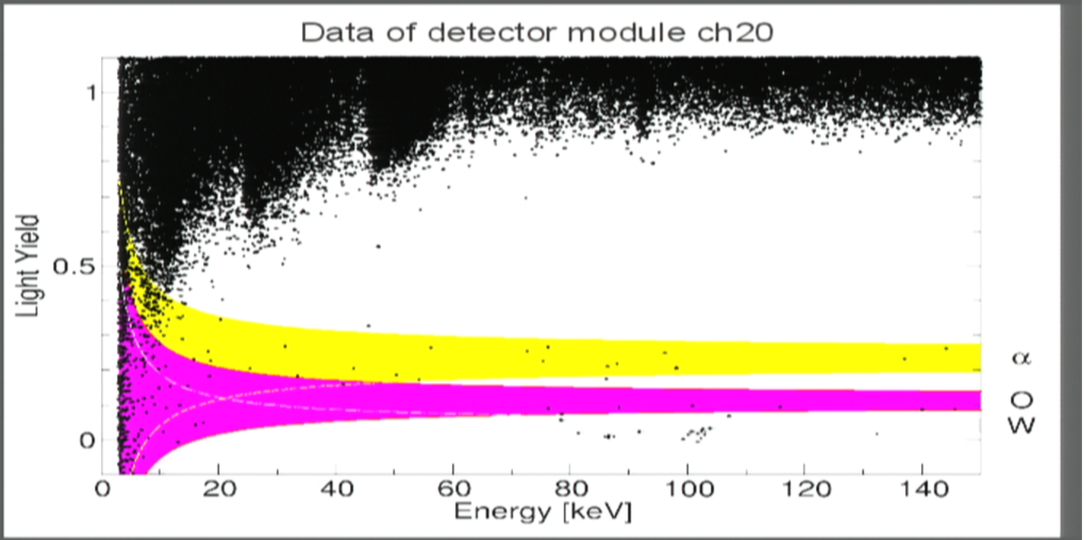
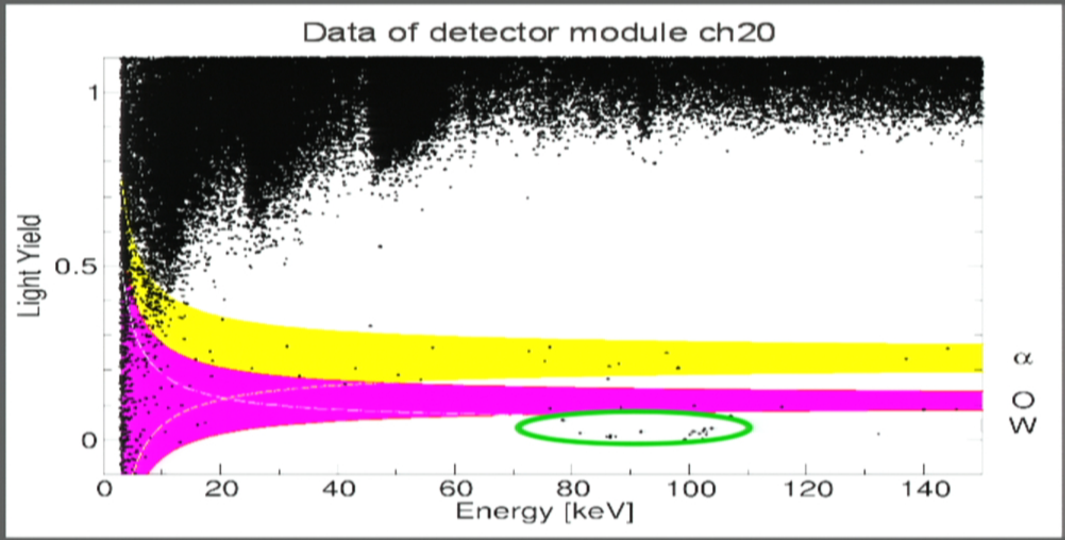
Observed Events

- highly populated e/γ-band



Observed Events

- highly populated e/γ-band
- low energy α-events from α-contamination in clamps
- ^{206}Pb nuclei from ^{210}Po α-decays on non scintillating surface of clamps



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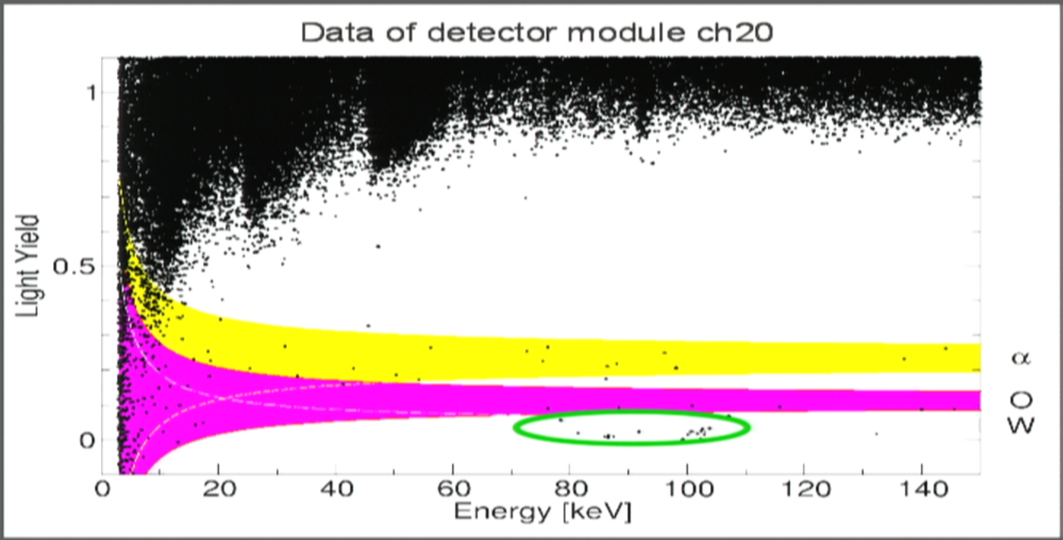

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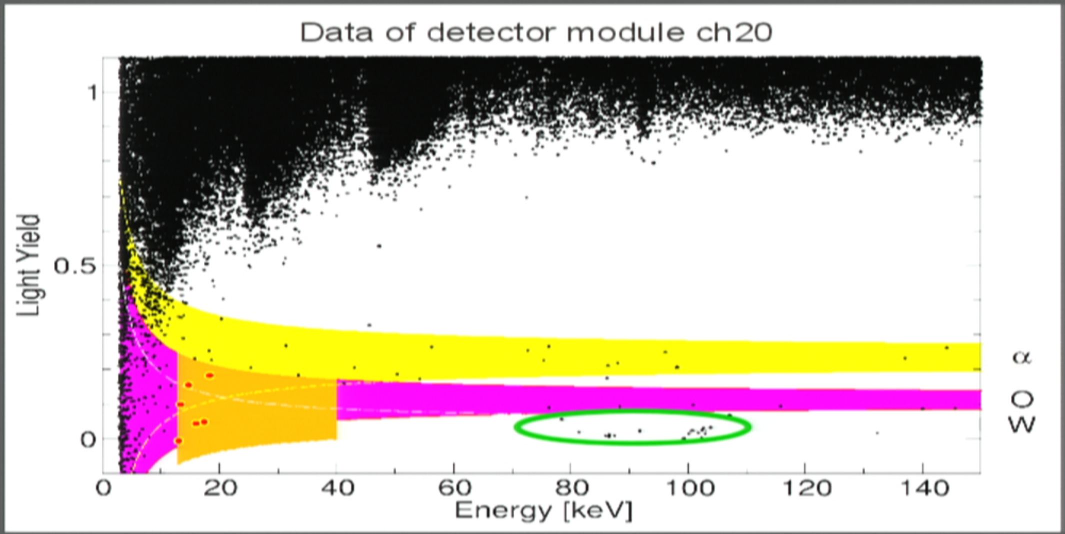


Acceptance region:

- O, Ca and W bands
- E_{max}=40 keV, E_{min}: e/γ leakage = 1 event per module in whole data set (module specific)

67 accepted events in 730 kg days

Events in Acceptance Region

Backgrounds

- Leakage from e/γ-band at low energies
- α-events from degraded alphas
- Neutron background
- ^{206}Pb recoils from α-decays of ^{210}Po on surfaces of clamps

WIMP signal

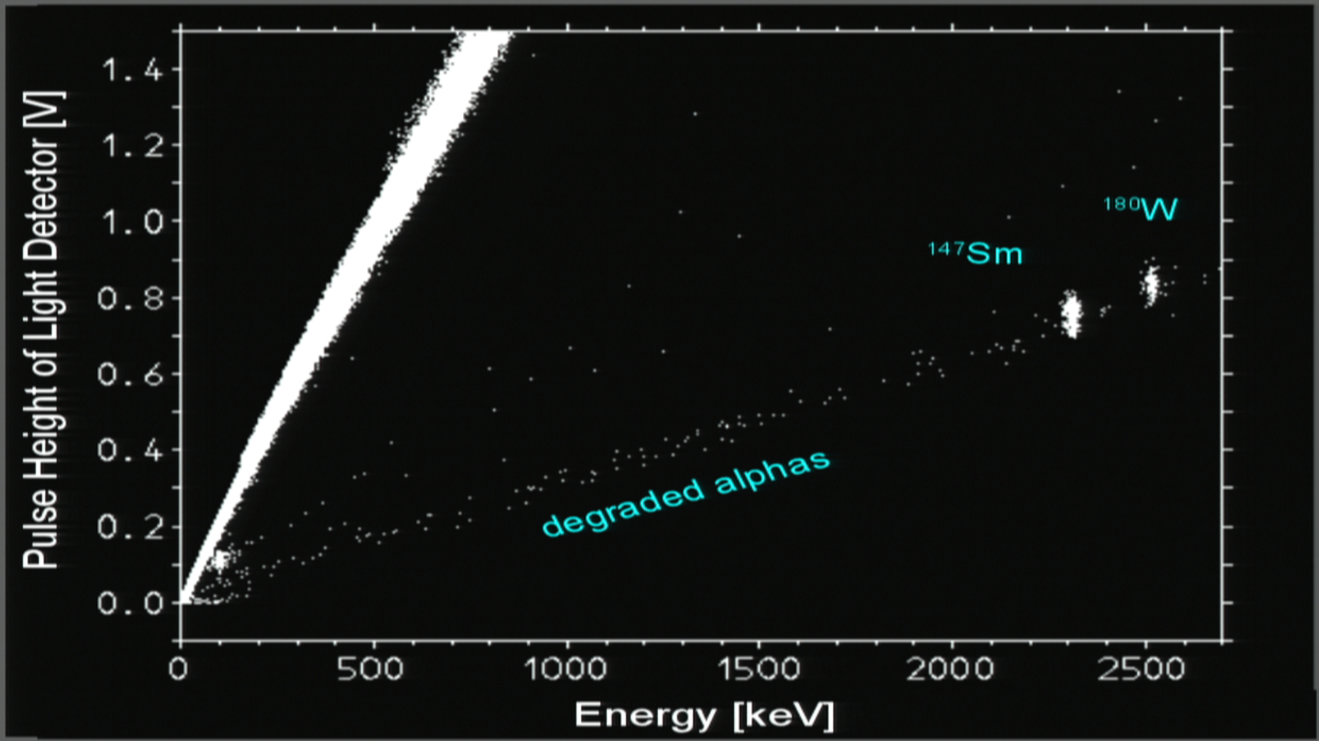
Aim: Estimate these backgrounds and determine room for possible WIMP signal via likelihood analysis

In this talk: Qualitative background estimate to illustrate the principle

Likelihood analysis:

- Considers full information of events in energy light plane
- Accounts for a possible WIMP contribution
- Takes into account uncertainties of all relevant parameters
- Includes information from measurements in reference regions (alpha, Pb, multiplicities)

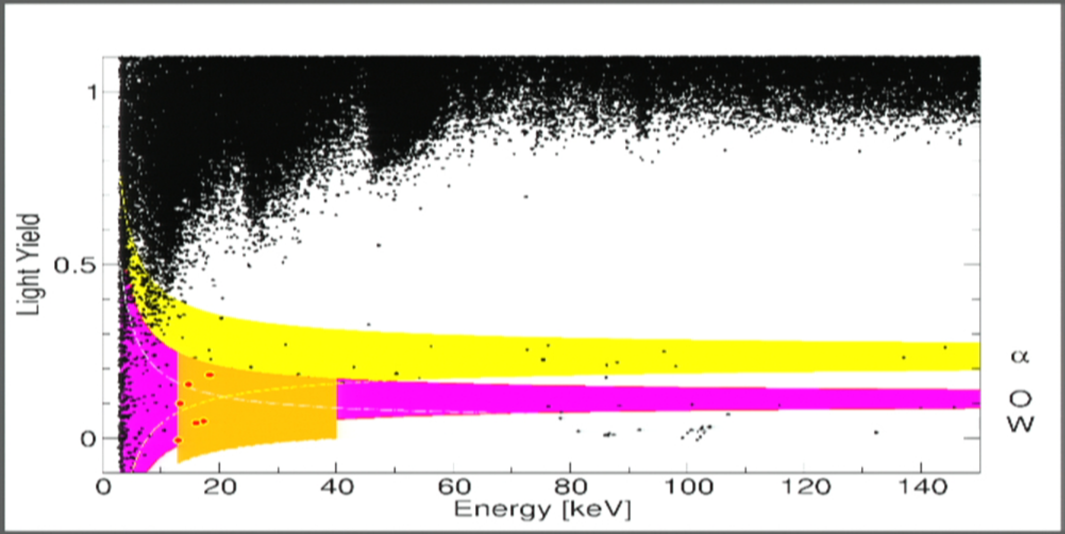
Alpha Background



- Discrete alpha lines from alpha emitters in crystal
- Degraded alphas with continuous energy distribution down to lowest energies from ^{210}Pb contamination in material of clamps holding the crystal

Estimation of Alpha Background

- α-band and acceptance region partially overlap
- dN_{α}/dE flat within statistics



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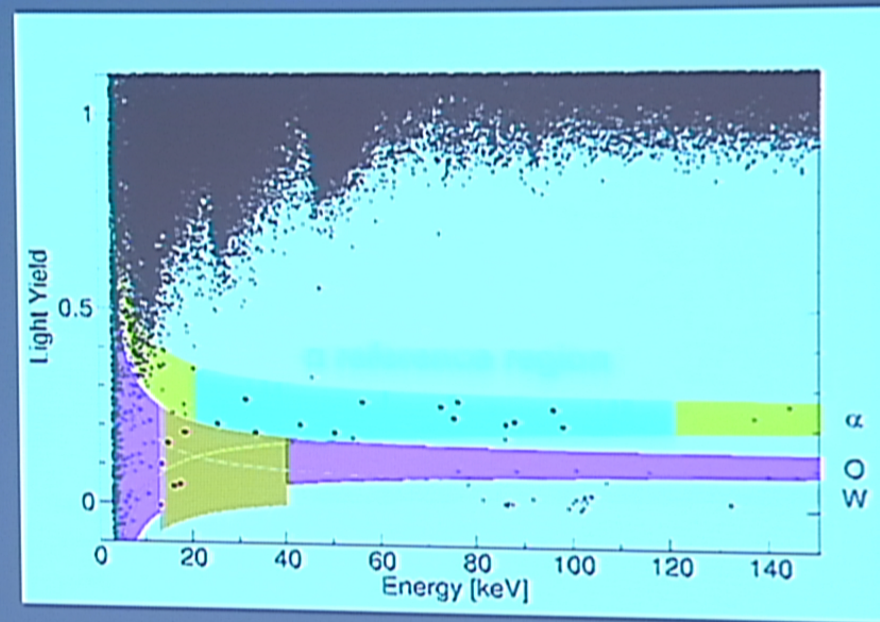
- define overlap free reference region to determine dN_α/dE



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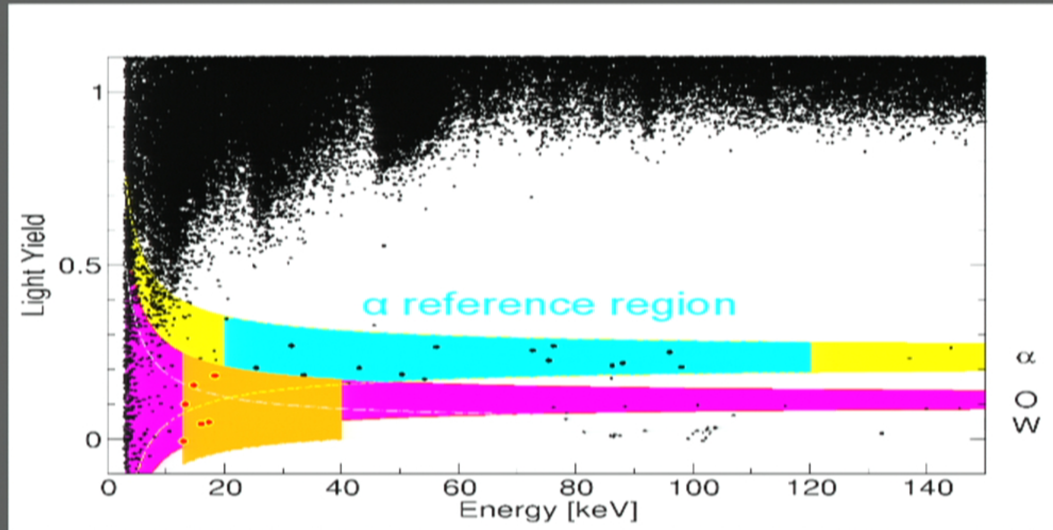
module	counts in ref. region	expected acc. region
Ch05	17	1.6
Ch20	14	1.5
Ch29	14	1.2
Ch33	8	0.9
Ch43	8	0.6
Ch45	5	0.8
Ch47	9	1.2
Ch51	18	1.4
Total	**93**	**9.2**

- simple estimate: → 9.2 events



- Likelihood analysis:
  - allow for linear energy dependence of dN_α/dE
  - result very similar to simple estimate

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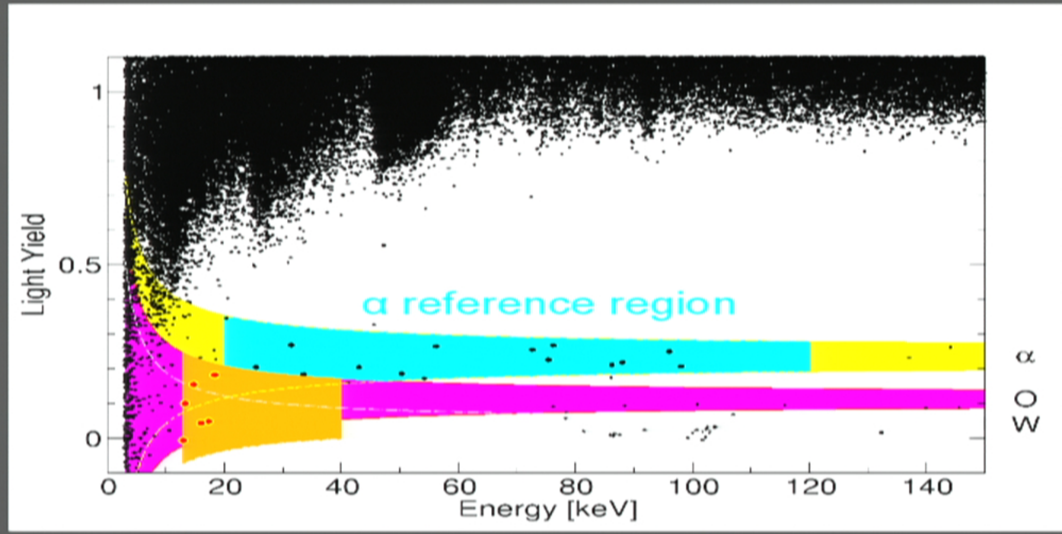

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Estimation of Neutron Background

- neutrons produce mainly oxygen recoils, very much like light WIMPs
- neutrons may cause coincidences in several detectors

In data set:
3 coincident events in acceptance region: 2 with multiplicity 3 and 1 with multiplicity 5

Idea for estimation of neutron singles:
Calibrate ratio of single / coincident of neutron induced recoils with neutron source in separate measurement and estimate neutron singles from the observed coincidences of the 3 events in data set

Two types of neutron background

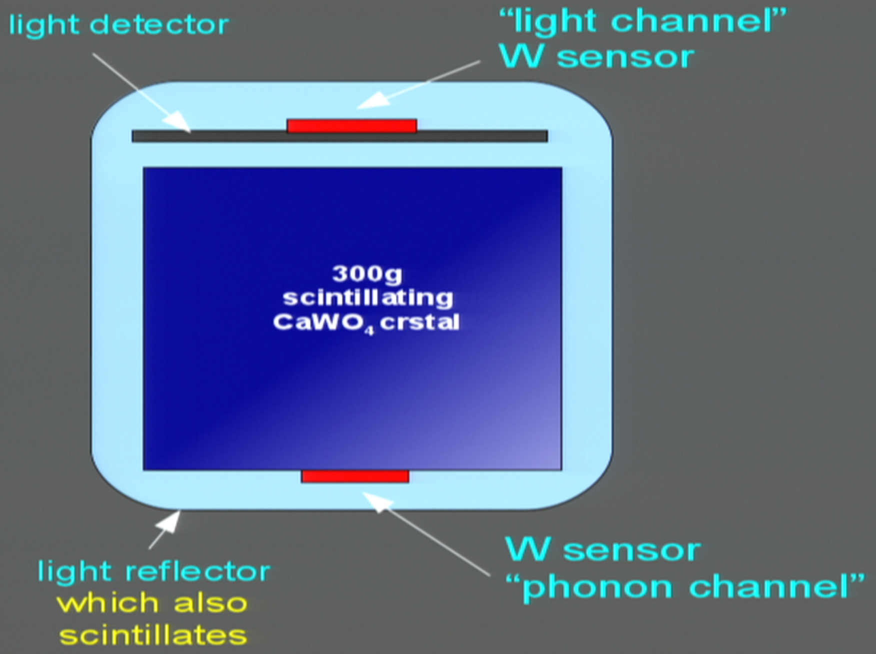
neutrons from radioactive processes inside neutron shielding:
spontaneous fission Pb/Cu shield
(α,n) reactions in Cu shield

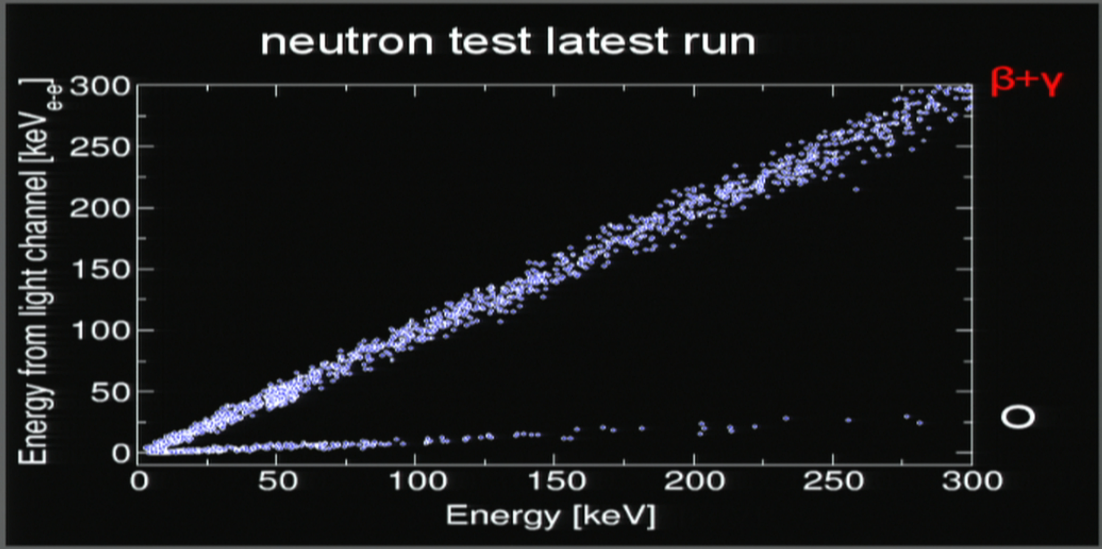
muon induced neutrons:
- in Pb/Cu shielding (missed by veto)
- neutrons from muon interactions in rock

can be studied with neutron source

can be studied with muon coincident events

CRESST-II Detectors





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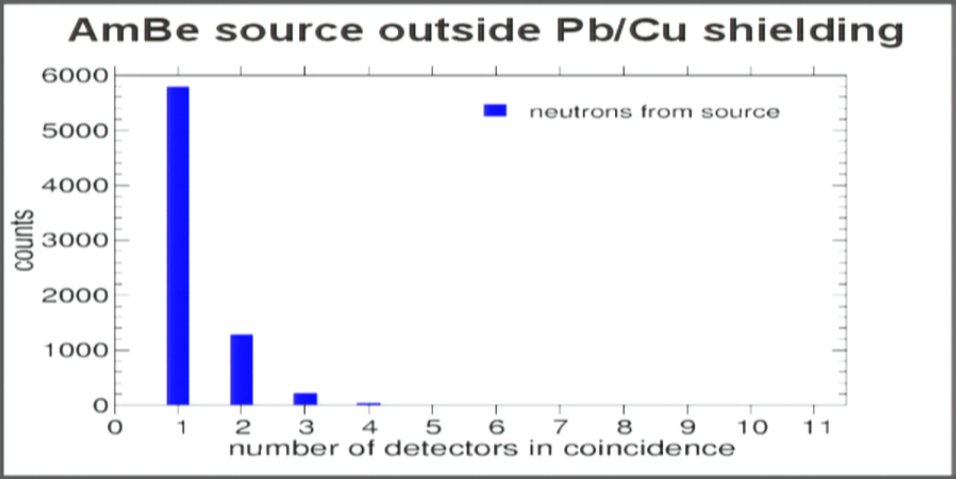
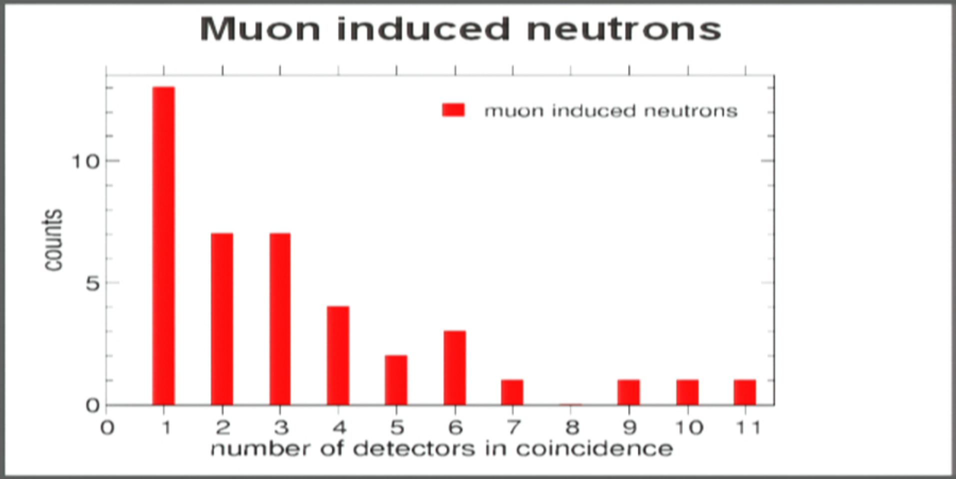
Multiplicity of Neutron Induced Events





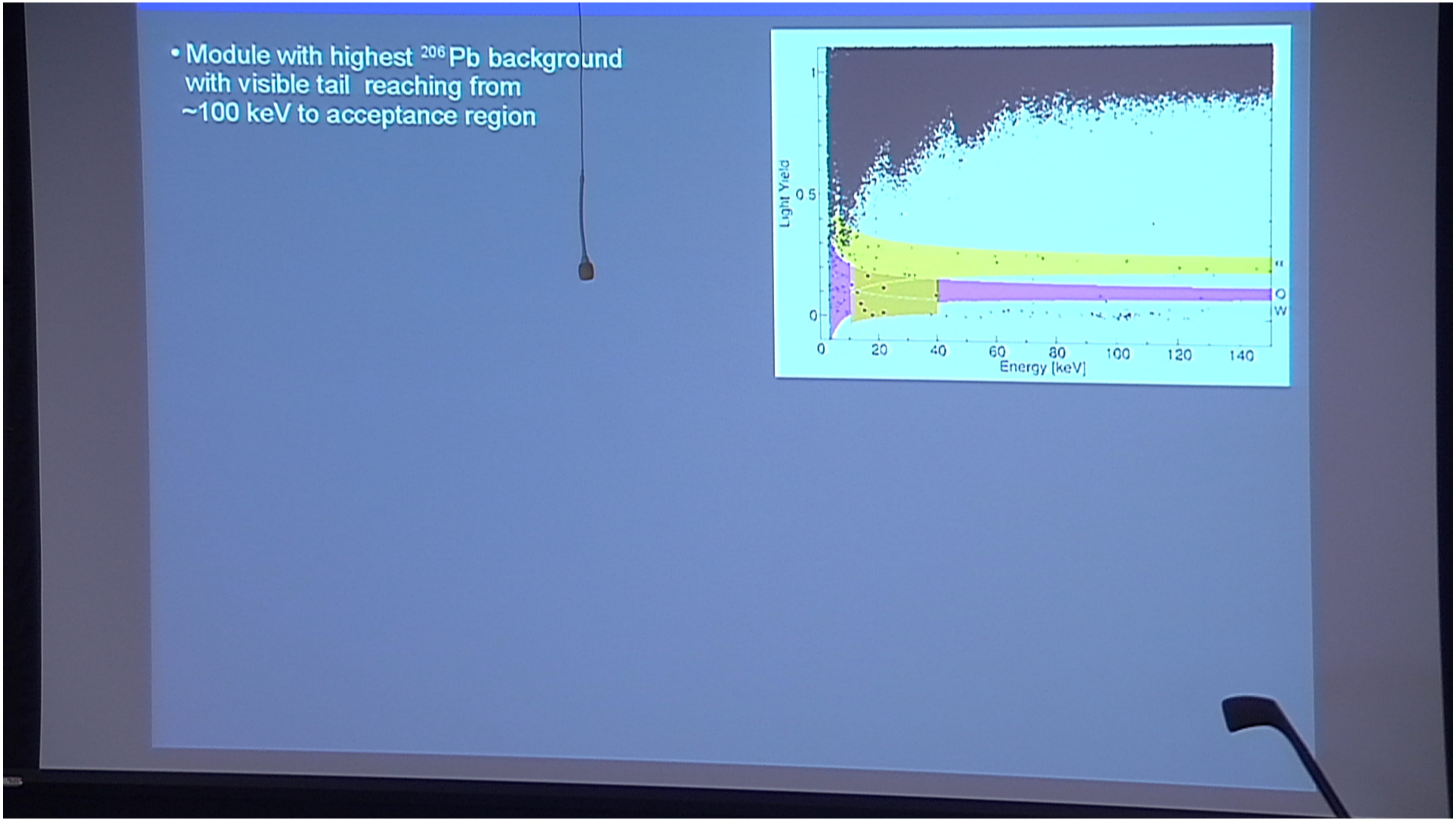
- simple estimate (limiting cases):
  single/coincident ~ 3.8
  single/coincident ~ 0.5

~11.4 single events expected

~1.5 single events expected

- Measured recoil energy spectra of both sources agree within statistics

Likelihood analysis:
- accounts for both types of sources
- uses multiplicities and of events in data to constrain contribution of the two processes
- includes spectral and yield information of neutron events (same for both types)
- final result is between limiting cases of simple estimate

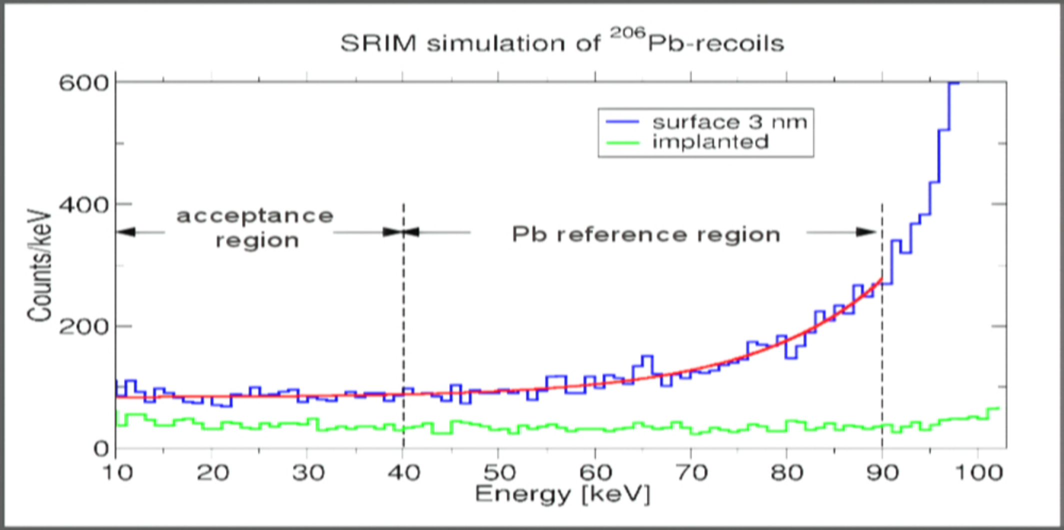

• Module with highest 206 Pb background with visible tail reaching from ~100 keV to acceptance region
Light Yield
1
0.5
0
0
20
40
60
80
100
120
140
Energy [keV]
O
W

SRIM simulation of ^{206}Pb energy spectrum

Simulation to check validity of extrapolation

Depth distributions of ^{210}Po nuclei:

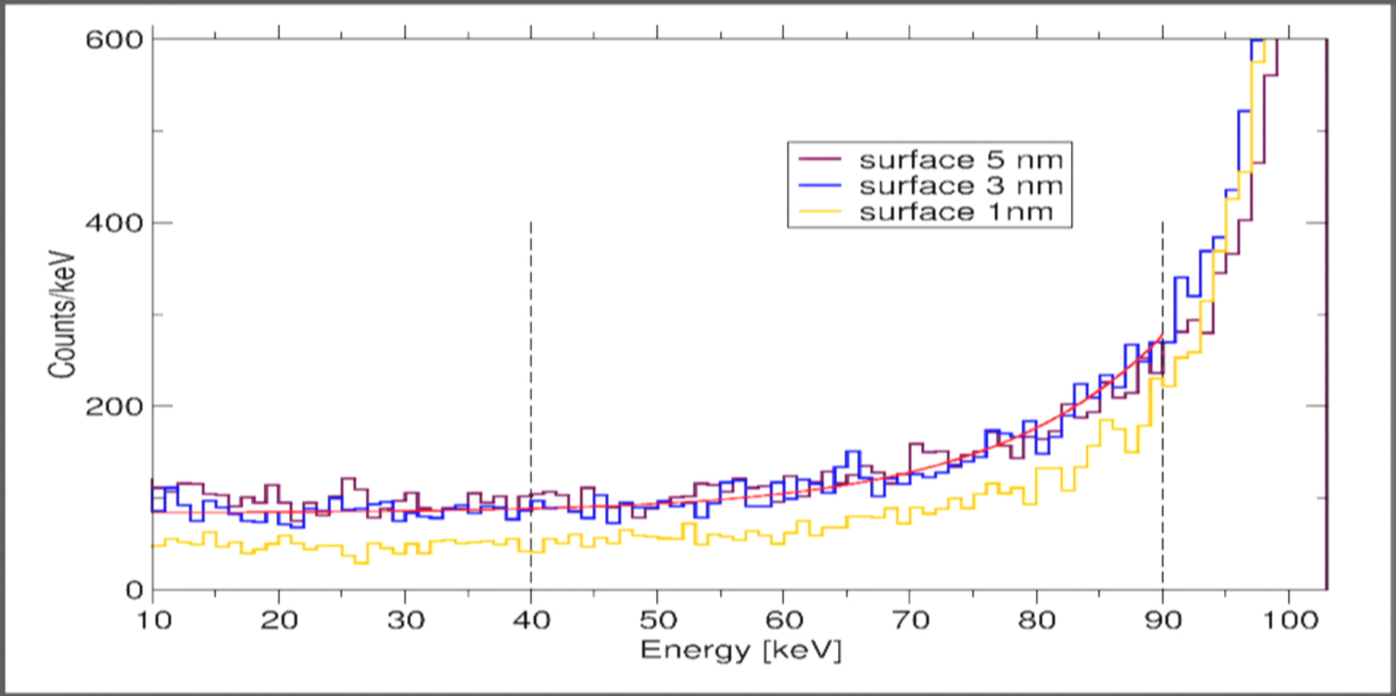
- 3 nm thick surface layer
- implantation of ^{210}Po via α-decays



- Simulated spectra are not rising in acceptance region
- surface distribution resembles data

- Fit of model in energy range of reference region
- **Extrapolation of fit in acceptance region describes simulated data very well and justifies extrapolation for background estimate**

SRIM simulation of energies of ^{206}Pb atoms escaping from ^{210}Po surface layers



- Shape of tail similar for different thicknesses of the ^{210}Po layer on surface of clamps

Likelihood Analysis - Basic Ingredients

- density function for each expected source of events in energy-yield plane, may depend on set of fit parameters p_x

$$\rho_x^d(E, y \mid \mathbf{p}_x) = \frac{dN_x}{dE}(E) \times \mathbf{Gaussian}\,(y \mid QF_x, resolution)$$

- Expected event distribution in each detector described by

$$\rho^d(E, y \mid \mathbf{p}) = \rho_\gamma^d + \rho_\alpha^d + \rho_n^d + \rho_{Pb}^d + \rho_{WIMPs}^d$$

- Number of events expected in acceptance region of all detectors

$$N(\mathbf{p}) = \sum_d \iint_{acc-region} \rho_x^d(E, y \mid \mathbf{p})\, dE\, dy$$

- extended likelihood formalism gives likelihood function for events in acc. region

$$L_{acc}(\mathbf{p}) = \left[\prod_d \prod_i \rho^d(E_i, y_i \mid \mathbf{p}) \right] \mathbf{exp}(-N(\mathbf{p}))$$

Inner product runs over events in acceptance region of respective detector, the outer one over detectors. Exponential accounts for normalization. No binning required.

Likelihood Analysis - Basic Ingredients

- Independent reference measurements included in fit to further constrain parameters. Reference measurements provide additional factors for likelihood

$$L_{total}(\mathbf{p}) = L_{acc}(\mathbf{p}) \times L_{ref1}(\mathbf{p}) \times L_{ref2}(\mathbf{p}) \times \cdots$$

- Maximizing L_{total} gives most likely parameters for signal and backgrounds

- Likelihood ratio test to estimate significance of a signal

$$\Lambda = \frac{L(\sigma_{WN}=0, \tilde{\mathbf{p}})}{L(\hat{\sigma}_{WN}, \hat{\mathbf{p}})}$$

Λ is measure of how signal like observation is

- Significance for rejecting background only hypothesis:

$$q = -2\ln(\Lambda)$$

Wilk's theorem: if σ=0 is true, q follows a χ^2-distribution.

Significance $S = \sqrt{q}$

Strictly valid for large statistics. Validity confirmed in our case with Monte Carlo

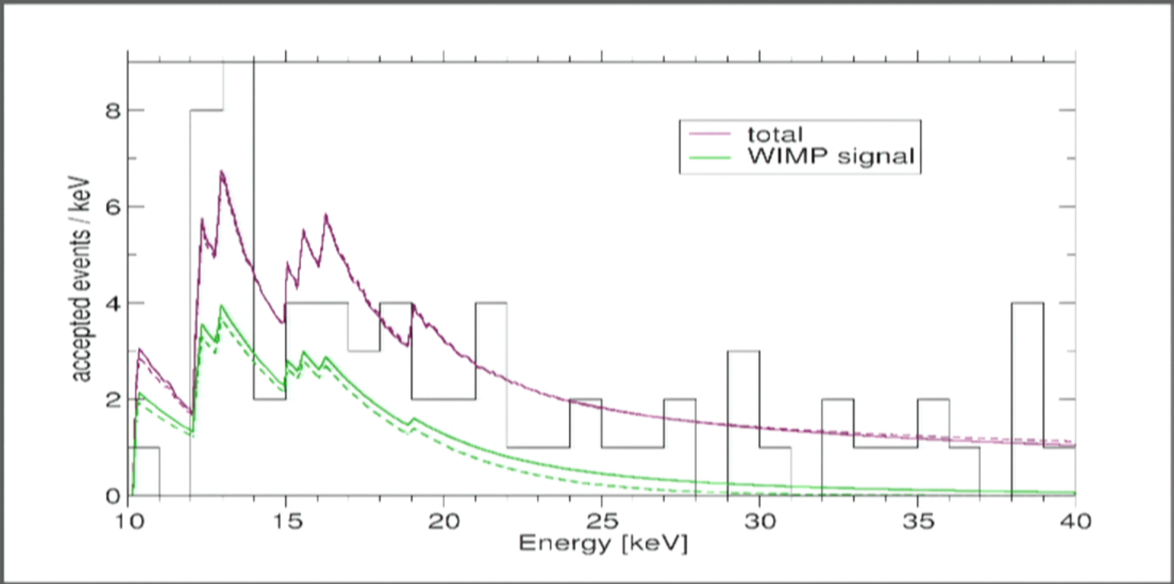
Results from Likelihood Fit

	M1	M2
e/γ-events	8.00 ± 0.05	8.00 ± 0.05
α-events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$

Total likelihood has two maxima

- M1 is global maximum
- M2 only slightly disfavored

Fit Results: Energy Spectrum

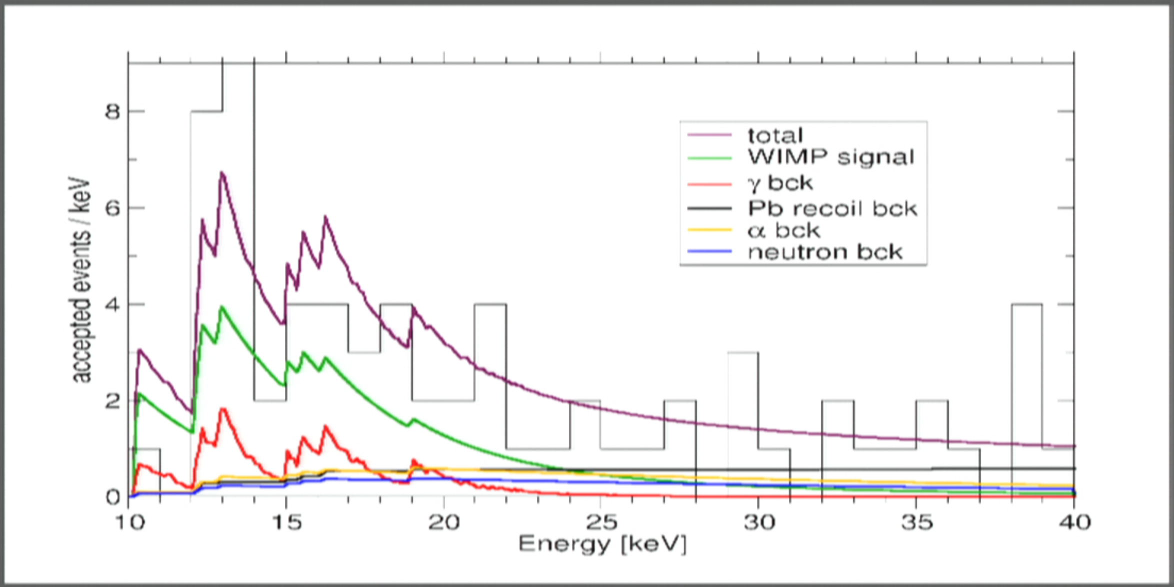


Full curves for M1
dashed curves for M2

→ total energy spectra (signal+background) indistinguishable for M1 and M2
→ WIMP spectra very similar for M1 and M2

Composition of WIMP spectra:
M1 (m_χ ~25.3 GeV) W: 69%, Ca: 25%, O: 7%
M2 (m_χ ~11.6 GeV) O: 52%, Ca: 48%

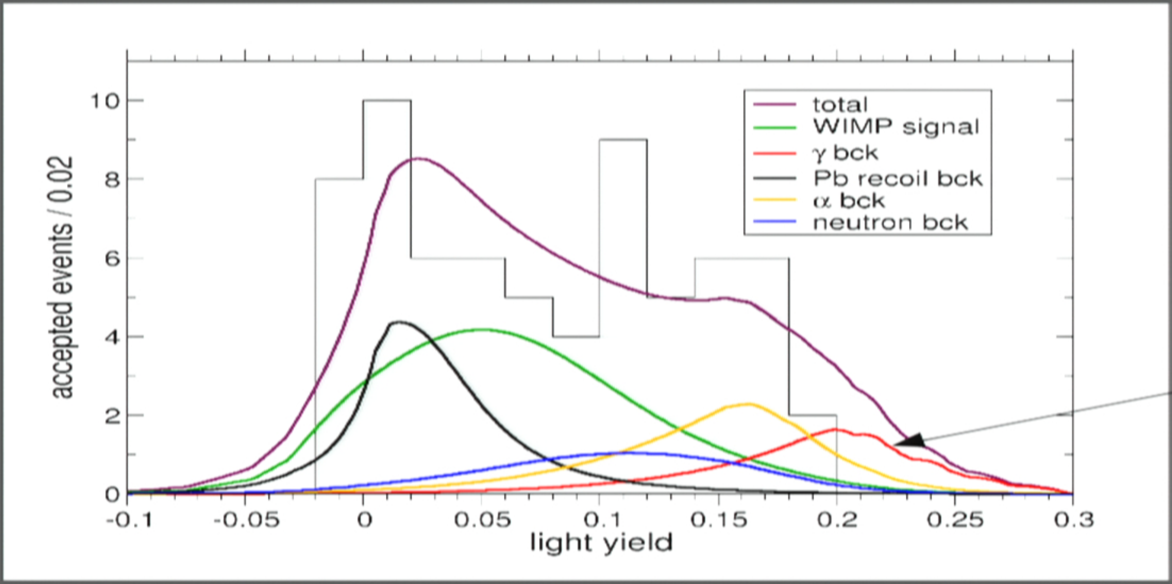
Fit Results: Energy Spectrum



Only M1 shown with fitted signal and all backgrounds

- Shape of α, neutron and Pb backgrounds differs from WIMP signal and do not rise towards low energies. Can not explain observation
- Only gamma leakage and WIMP signal rises significantly towards low energies

Fit Results: yield projection of accepted events



Full curves for M1
dashed curves for M2

gamma leakage

- gamma leakage largest at high yields
- Measured yield spectrum incompatible with significantly larger gamma leakage

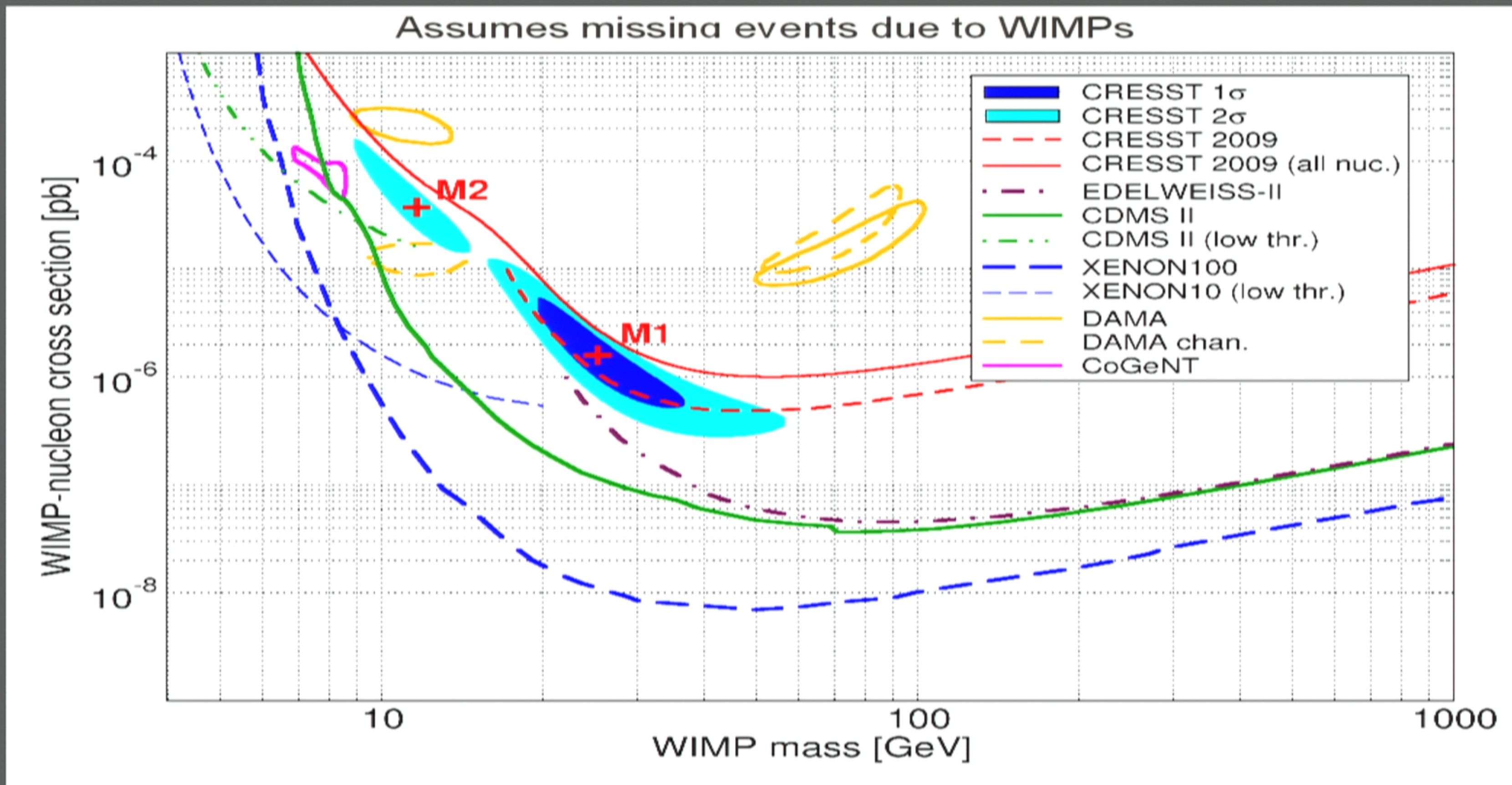
Significance of Signal

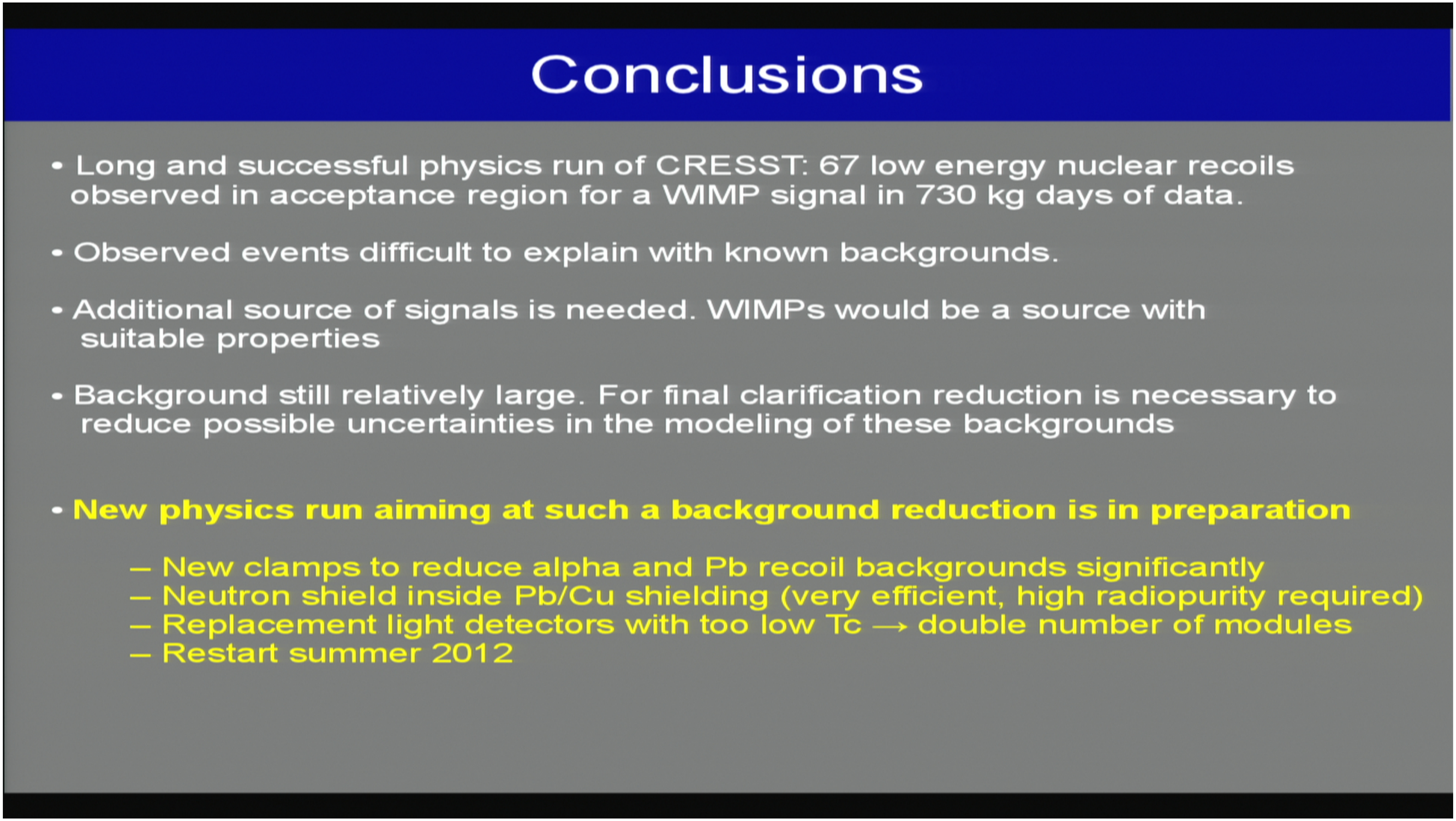
- Use likelihood ratio test to obtain a statistical measure if something else than the considered backgrounds is needed to explain the observation
- Significance that signal is not produced by statistical background fluctuation:

  4.7 σ for M1
  4.2 σ for M2

- Considered background sources alone are not sufficient to explain data at high statistical significance
- Additional source of events is needed and WIMP would be such a source with suitable properties
- Background contributions still relatively large. For ultimate clarification reduction is necessary to reduce possible uncertainties in modeling of these backgrounds.

WIMP parameter space




Conclusions
• Long and successful physics run of CRESST: 67 low energy nuclear recoils observed in acceptance region for a WIMP signal in 730 kg days of data.
• Observed events difficult to explain with known backgrounds.
• Additional source of signals is needed. WIMPs would be a source with suitable properties
• Background still relatively large. For final clarification reduction is necessary to reduce possible uncertainties in the modeling of these backgrounds
• New physics run aiming at such a background reduction is in preparation
– New clamps to reduce alpha and Pb recoil backgrounds significantly
– Neutron shield inside Pb/Cu shielding (very efficient, high radiopurity required)
– Replacement light detectors with too low Tc → double number of modules
– Restart summer 2012