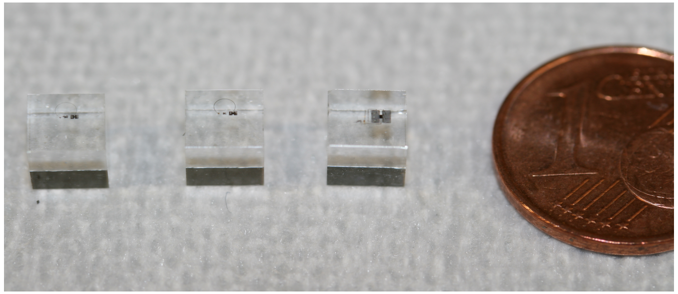
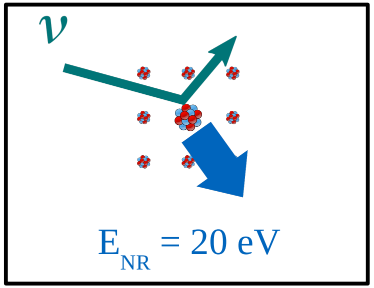
Above-ground operation of 0.5 g Al_2O_3 cryogenic detector prototypes for NUCLEUS



Johannes Rothe,
Technical University Munich

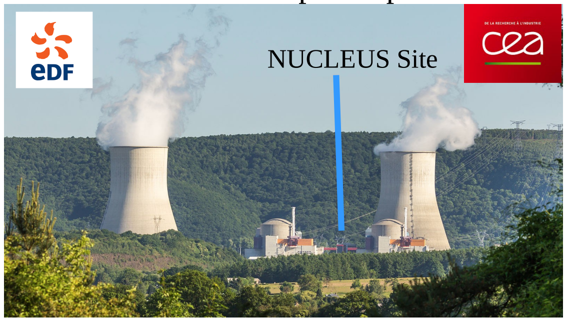
EXCESS workshop, 15-16 June 2021

NUCLEUS overview



- Physics goal: study CEvNS of reactor neutrinos (Chooz, France)

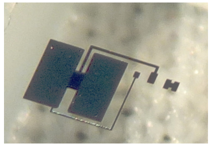
Chooz nuclear power plant



“Very-Near-Site”: 72m & 102m

- Detectors: gram-scale cryogenic calorimeters

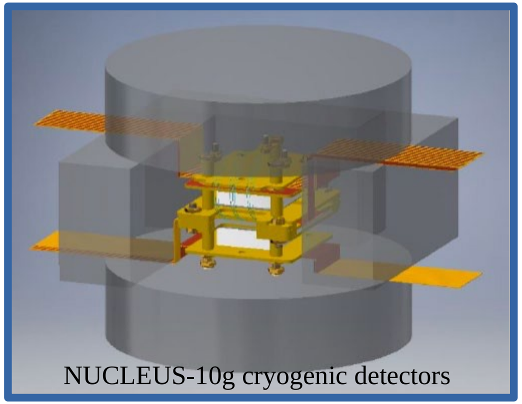
- Sensor technology: tungsten TES + aluminum phonon collectors, ~15mK



developed within CRESST experiment

- Prototype performance: 20 eV nuclear recoil threshold

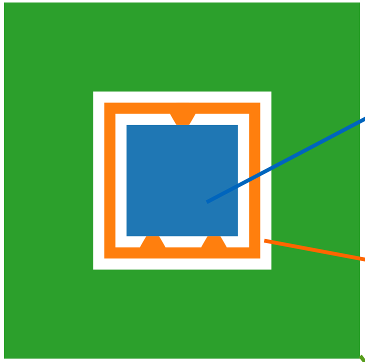
- First physics phase: 2023, 10g target array (Al_2O_3 + $CaWO_4$)



Detector Concept & Prototypes

NUCLEUS detector concept

"Fiducial Volume Cryogenic Detector"



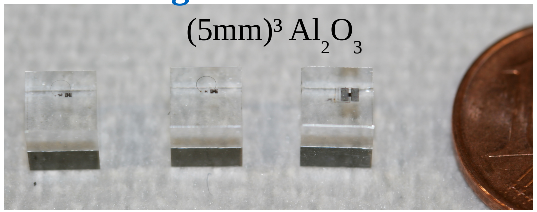
Gram-scale cryogenic calorimeters:
ultra-low energy threshold

Cryogenic inner veto:
instrumented holder & surface veto

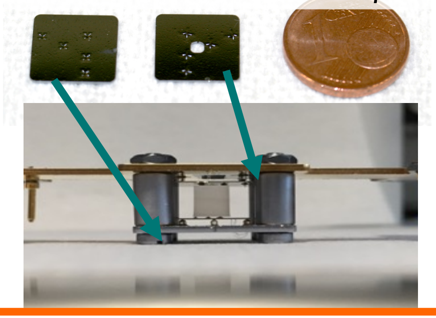
Cryogenic outer veto:
massive anticoincidence veto

NUCLEUS – 1g prototype

Target calorimeters:



Cryogenic inner veto:
flexible silicon wafers: 200µm



Cryogenic outer veto:
(not discussed here)

silicon calorimeters (200g)

Overview of measurements

Run 1	**Feb 2017**	**first NUCLEUS target prototype** (no vetos)
Run 2	Jan 2018	silicon supports, calibration + background
Run 3	Mar 2018	outer veto test
Run 4	Mar 2019	active target + active inner veto

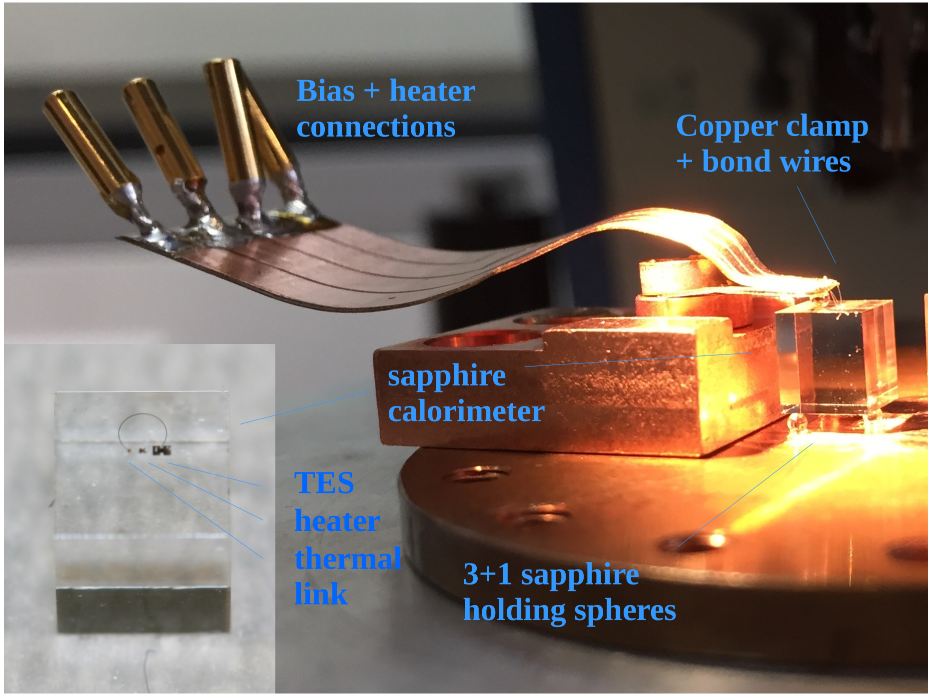
References:

Run1:
Phys Rev D, 96(2):022009, 2017, arxiv:1704.04317,
EPJ C, 77(8):506, 2017, arxiv:1704.04320,
EPJ C, 77(9):637, 2017, arxiv:1707.06749,
data public

Run4:
J Low Temp Phys 199, 433–440 (2020)

all runs: described in
J. Rothe, PhD thesis (2021),
mediatum.ub.tum.de/?id=1576351

Run 1 detector configuration

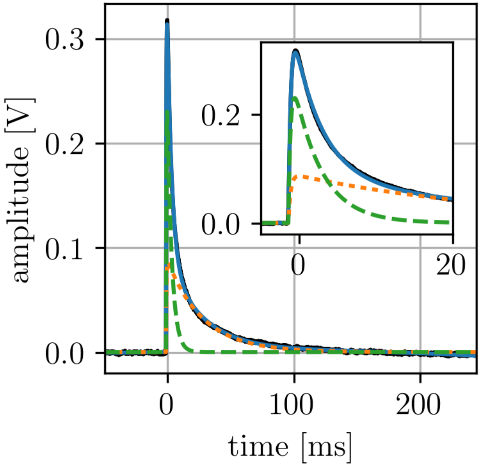


Target detector: (5mm)³ 0.49g Al_2O_3 calorimeter

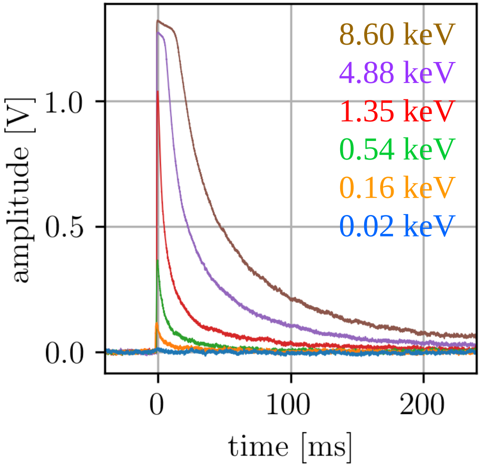
Operation environment: bare crystal operated in dilution refrigerator, above ground (MPP Munich), held by Al_2O_3 spheres, surrounded by copper surfaces

Calibration source: ^{55}Fe (x-rays 5.9/6.5 keV), implanted metal stripe, kapton tape cover, ~0.07 Hz on target

Run 1 analysis procedure



Pulse model:
athermal phonon lifetime:
0.3 ms
TES relaxation time:
3.5 ms
crystal relaxation time:
28.2 ms



Dynamic range:
19.7 eV (threshold)
600 eV (linear range)
12 keV (upper limit of energy reconstruction)

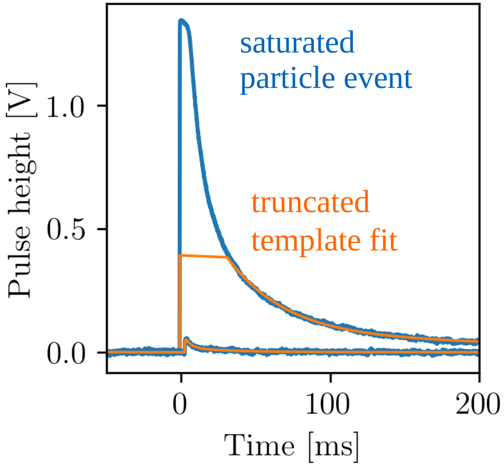
Energy reconstruction:

Truncated template fit (TTF):
- fit only pulse samples below "truncation limit" 0.4V = ~600 eV
- allows energy reconstruction into saturation
- used for calibration at 5.9 keV

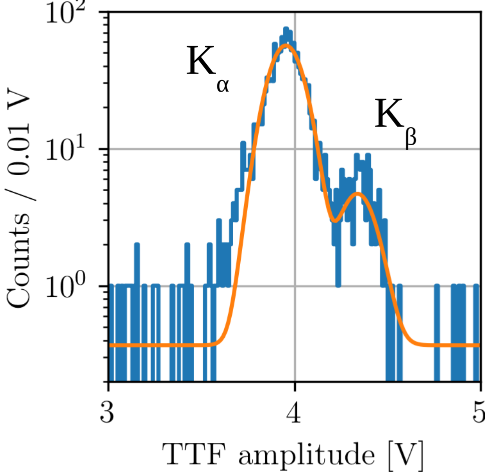
Optimum Filter (OF):
- weights frequency components by S/N ratio
- no treatment of non-linearity

→ used for energy reconstruction up to 600eV

- optimum filter zero-energy resolution: σ_{OF} = 3.84 ± 0.16 eV

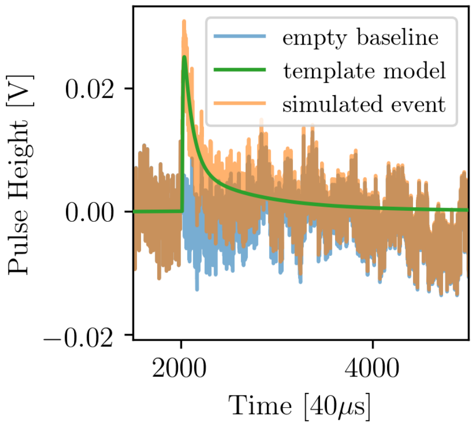


Calibration lines: ^{55}Mn x-rays



plots from: J. Rothe, PhD thesis (2021), mediatum.ub.tum.de/?id=1576351

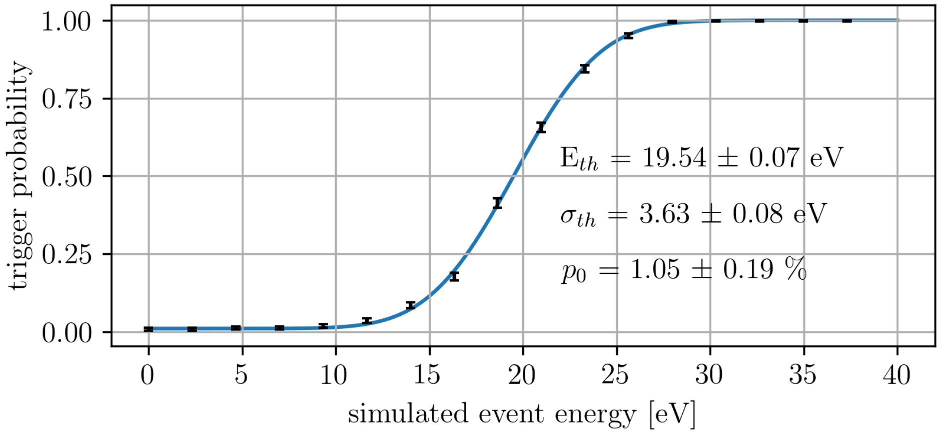
Run 1 spectrum, trigger efficiency

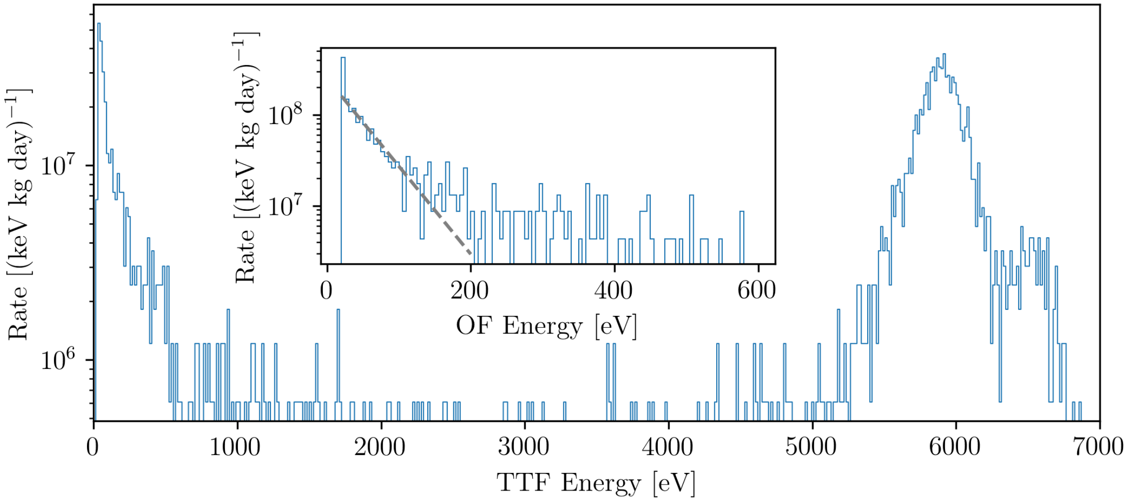


Trigger efficiency simulation:
simulated events from random triggers ("empty baselines")

passed through OF trigger

amplitude scan of simulated events





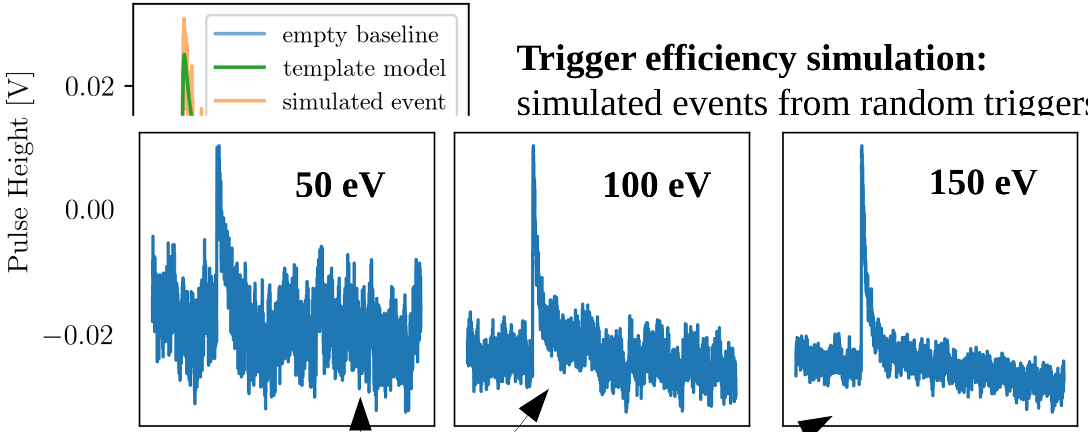
Final event spectra:
ROI: reconstructed with OF (linear range <600 eV)
"high energy" spectrum: < 10 keV, TTF reconstruction

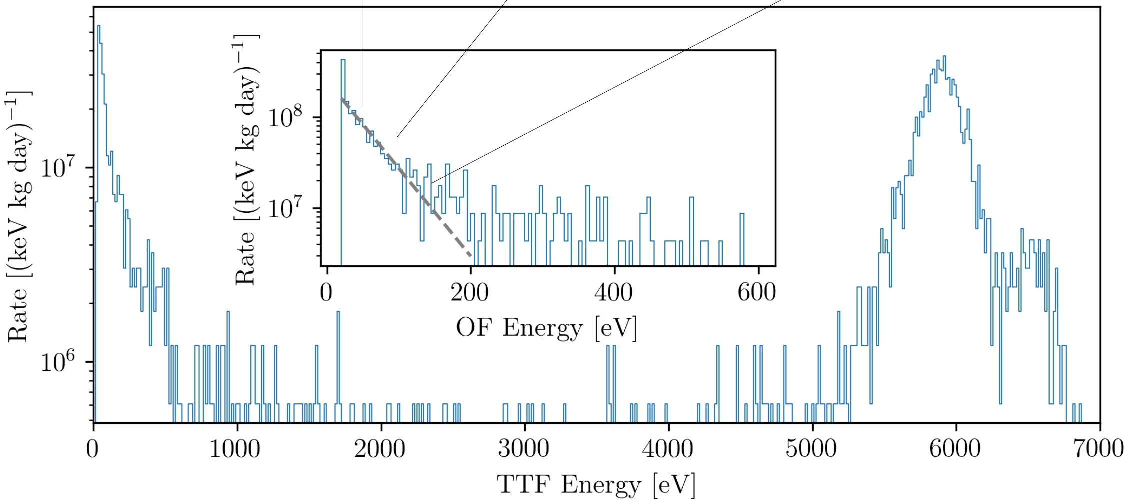
Low energy rise parameters ("guide for the eye")
single exponential: $R/E_0 \cdot \exp(-E/E_0)$
Slope: E_0~45 eV,
Integral rate: R~10^4/g/day, or ~130/kg/s, or ~1/(16s)

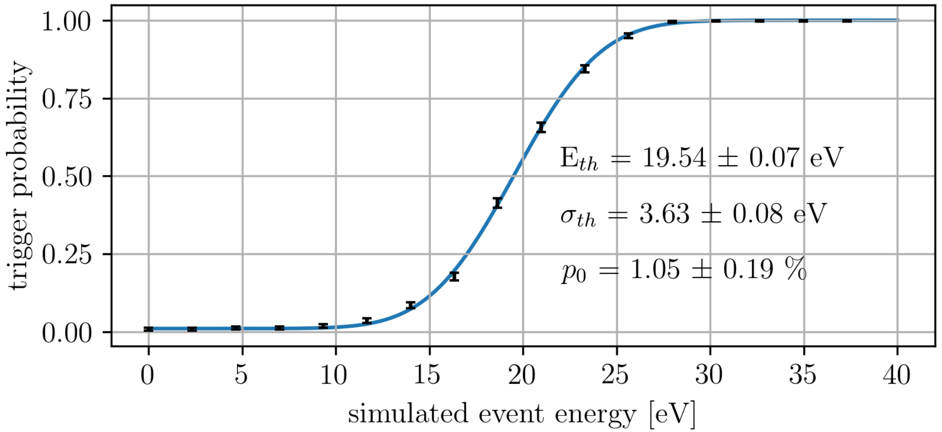
→ dark matter search: **CRESST surface 2017,** EPJ C, 77(9):637, 2017. arxiv:1707.06749

Run 1 spectrum, trigger efficiency

Trigger efficiency simulation:
simulated events from random triggers







Final event spectra:
ROI: reconstructed with OF (linear range <600 eV)
“high energy” spectrum: < 10 keV, TTF reconstruction

Low energy rise parameters (“guide for the eye”)
single exponential: $R/E_0 \cdot \exp(-E/E_0)$

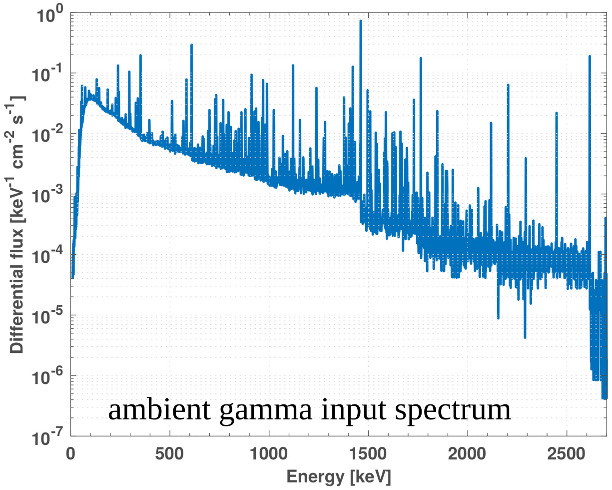
Slope: E_0~45 eV,

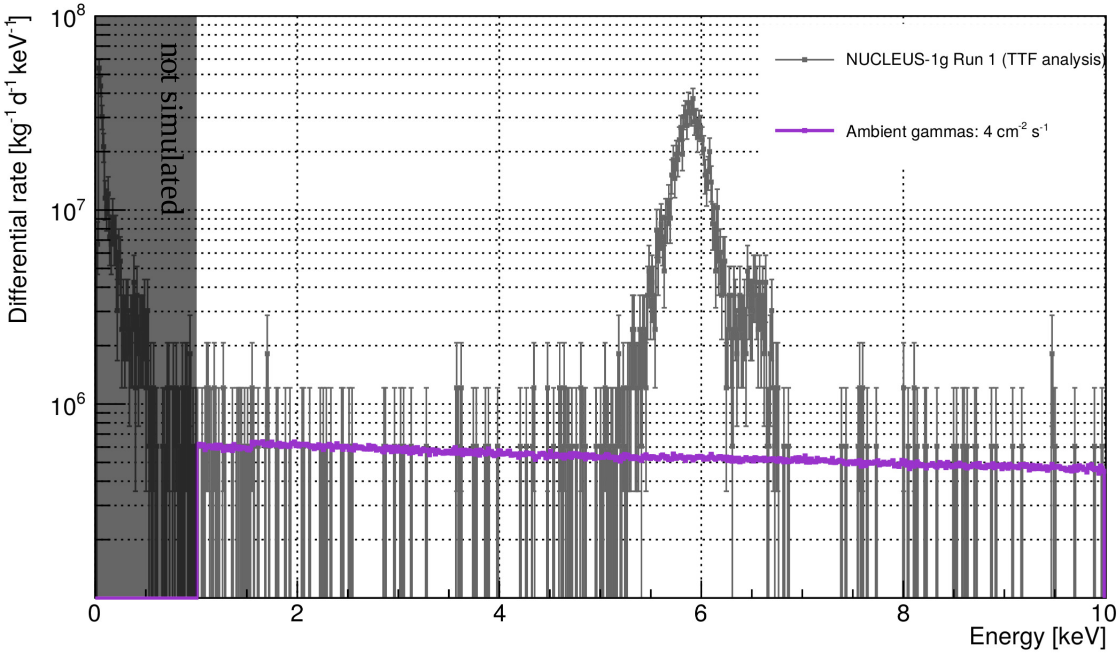
Integral rate: R~10^4/g/day, or ~130/kg/s, or ~1/(16s)

→ dark matter search: **CRESST surface 2017,**
EPJ C, 77(9):637, 2017. arxiv:1707.06749

Run 1, ambient gamma simulation

Geant4 simulation:
simulated geometry: bare crystal only, no holder/cryostat
gamma spectrum: similar to surface measurements
energy range: above 1 keV (below: dependence on setup geometry)
normalisation adjusted to match background rate above and below iron source: 4 γ/cm^2/s





Conclusions:
Obtained ambient gamma flux matches typical values at sea level

absolute fluxes of muons and nucleonic cosmic ray secondaries (n,p) are >100x smaller

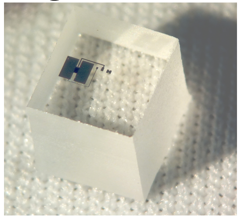
Background above 1 keV most likely dominated by ambient gamma rays

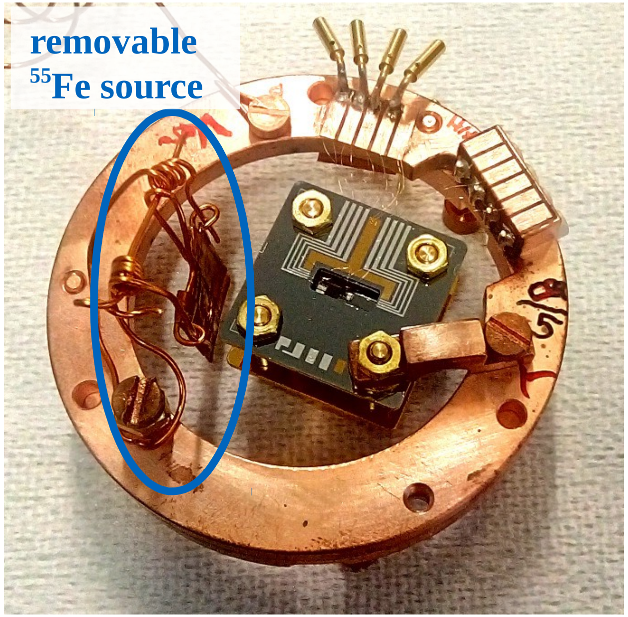
sub-keV background:
more simulation and data needed

Run 2 detector layout

Silicon detector holder

Large-area TES



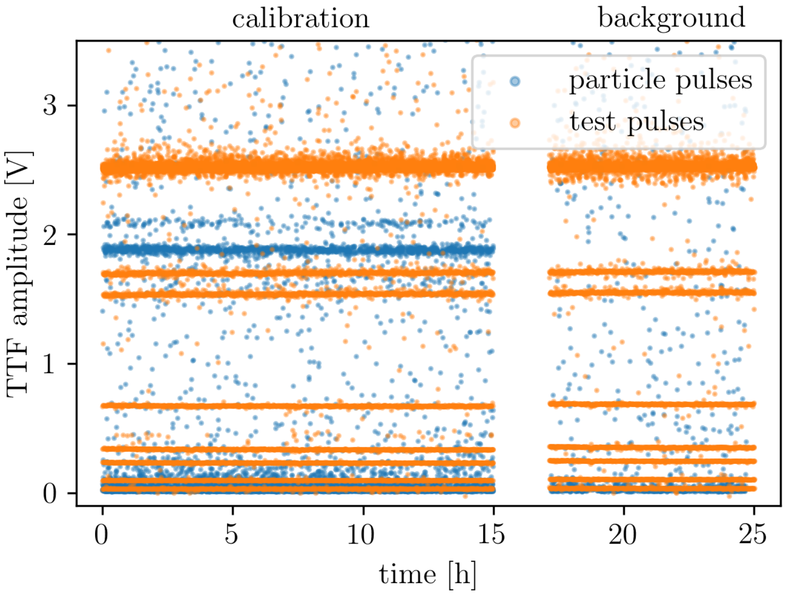


Operation environment: similar cryogenic setup at MPP Munich

New detector holder: silicon structure (covering ~66% of solid angle)
inner veto detectors not instrumented

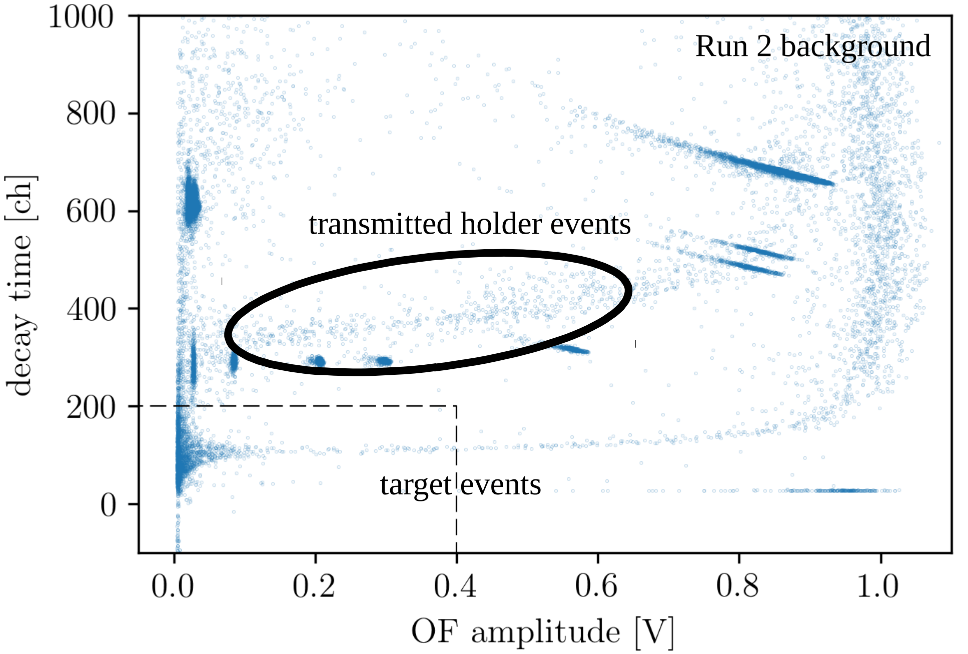
New TES design: zero-energy resolution σ_{OF} = 2.92 ± 0.11 eV

Removable calibration source: pull-string mechanism



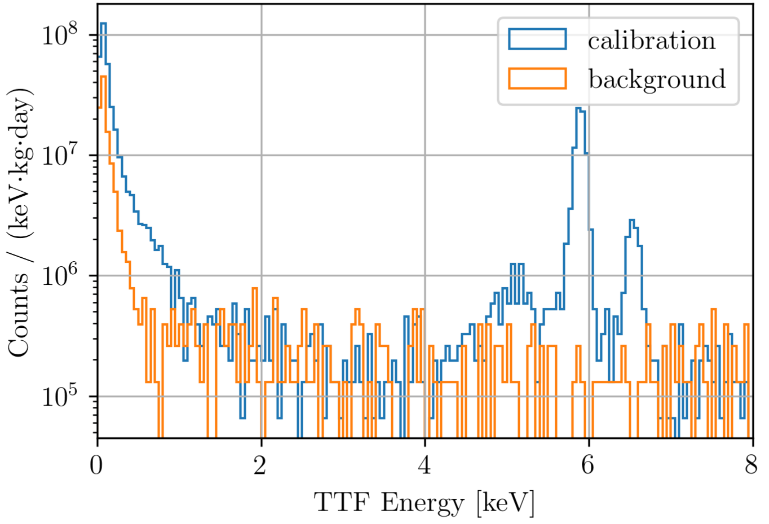
Run 2 calibration & background spectra

New event class: phonon transmission from holder

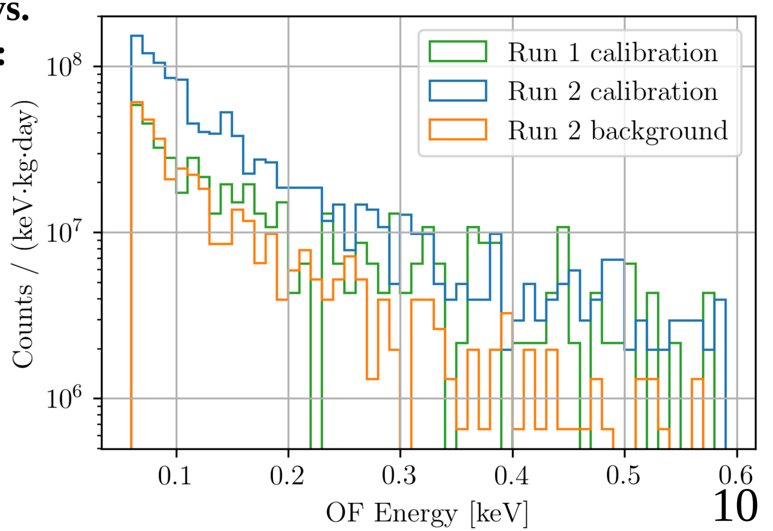


Run 2 calibration vs. background:

same cuts, no simulation of efficiencies



Run 1 calibration vs. Run 2 background:



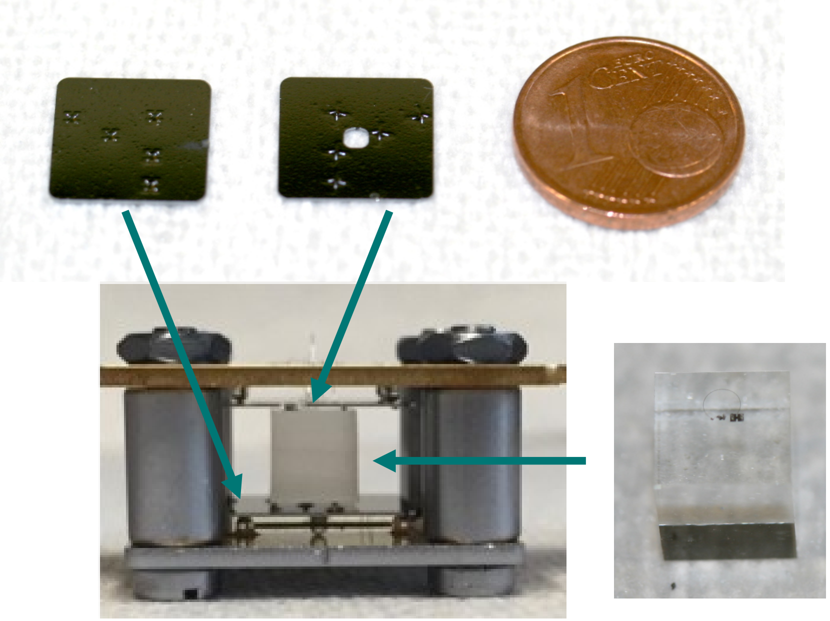
→ Calibration source not responsible for low-energy background
→ Some source configurations do contribute to low-energy events

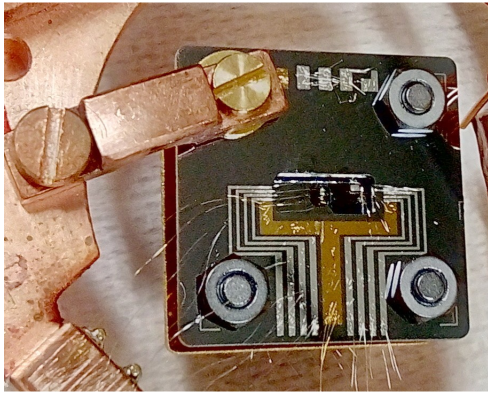
Run 4: target + inner veto

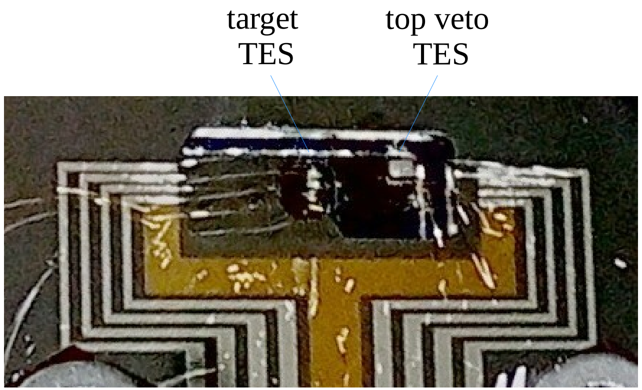
Operation environment: same as Run1
Detector holder: same as Run 2
Operating calorimeters: target, veto top, veto bottom

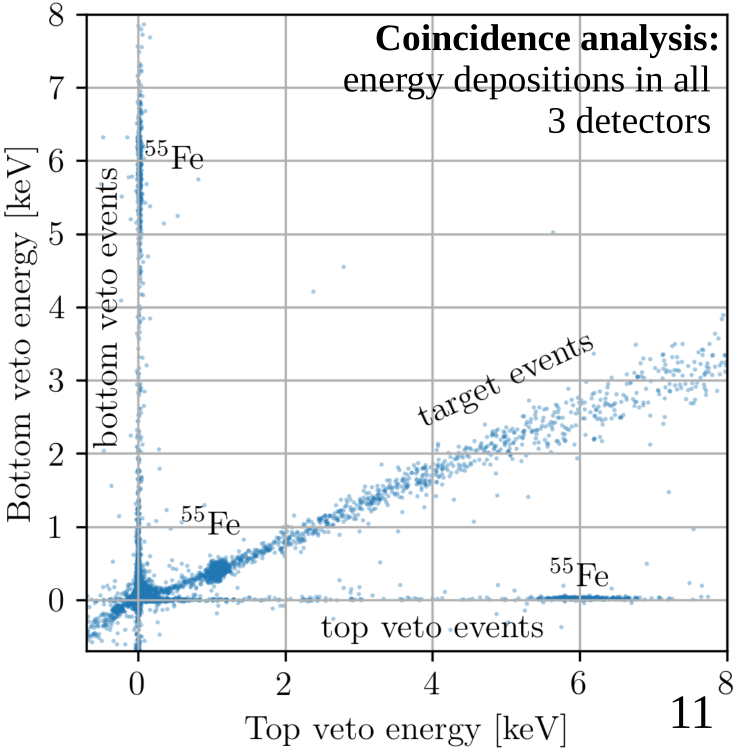
Anticoincidence veto: external low-energy particle and surface background

Zero-energy resolutions:
σ_{OF} = (9.6, 14.7, 8.3) eV
→ 3x threshold < 100 eV





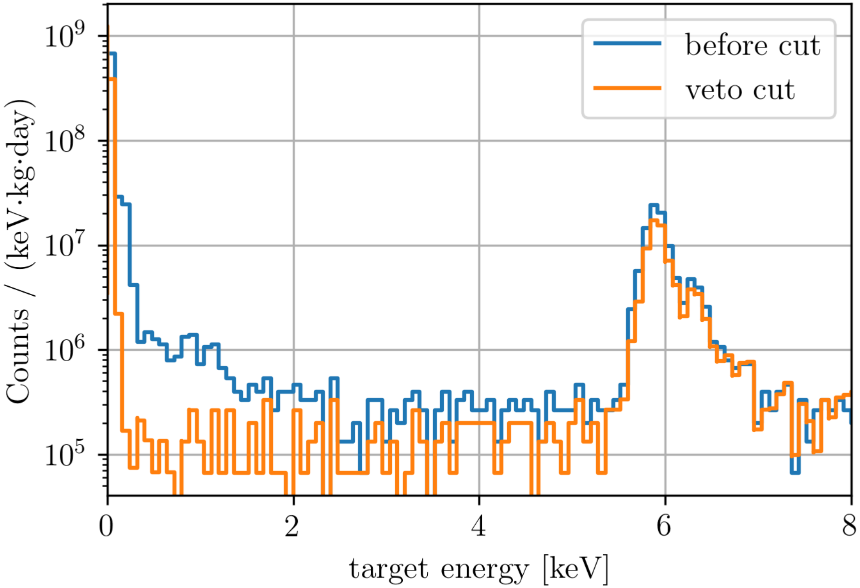


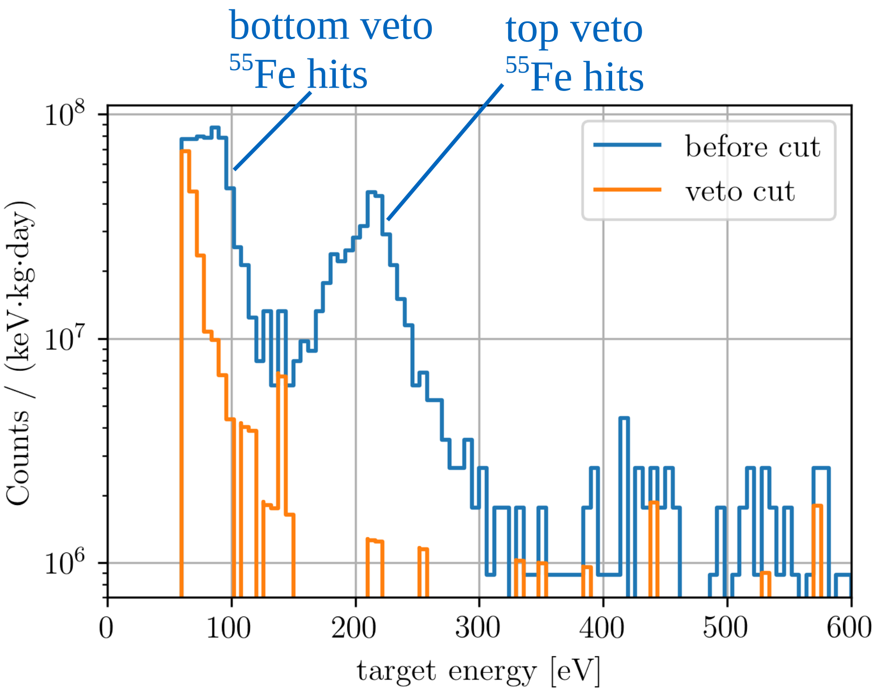


Run 4 spectra, effect of vetos

Anticoincidence-cut effect on sub-keV spectrum:

incl. simulated veto cut efficiency: ~50% @150eV, ~20% @60eV





Inner veto cleans spectrum significantly:
flat from 5 keV down to ~150 eV

Features from ^{55}Fe events in vetos removed
Sharp rise remains below ~100 eV

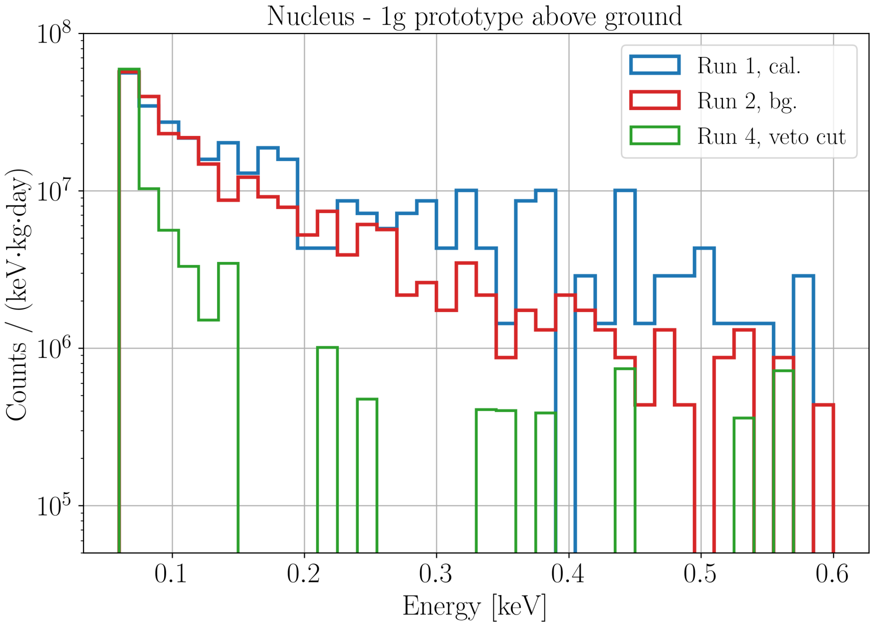
Conclusions

NUCLEUS early prototype measurements, above ground, no shielding

Run 1:
- bulk of keV-scale events explainable by ambient gamma radiati
- sharp rise in event rate below ~250 eV

Run 2: calibration source is not responsible for these events, visible also in background data

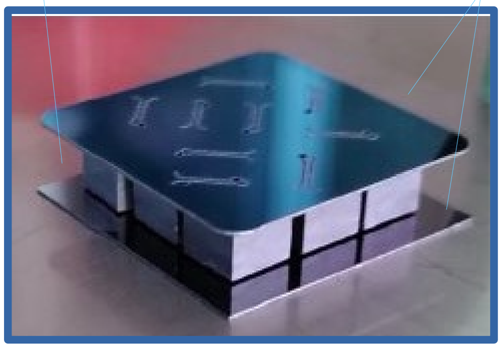
Run 4: active surface veto (partial coverage) appears to push onset below ~150 eV, but does not remove rise towards threshold

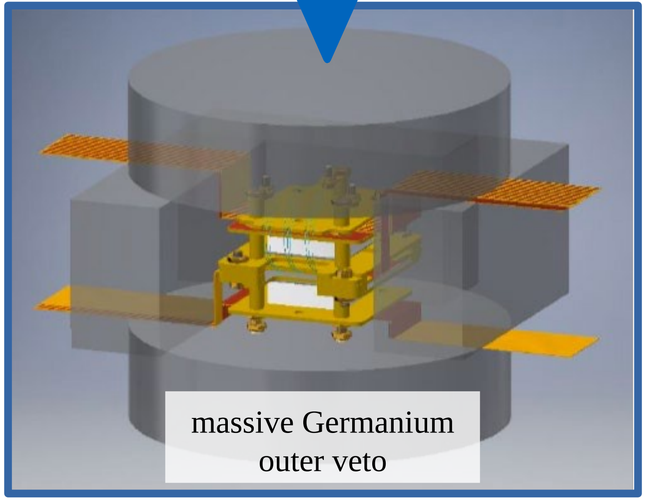


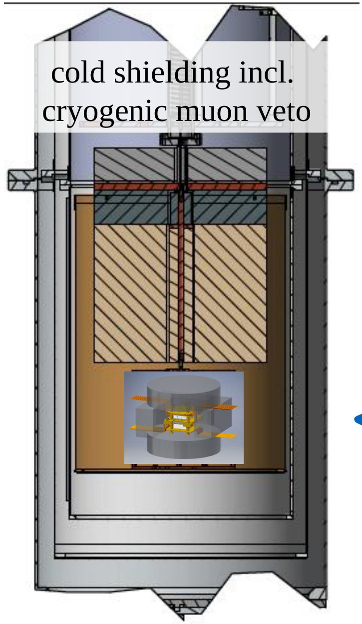
Outlook

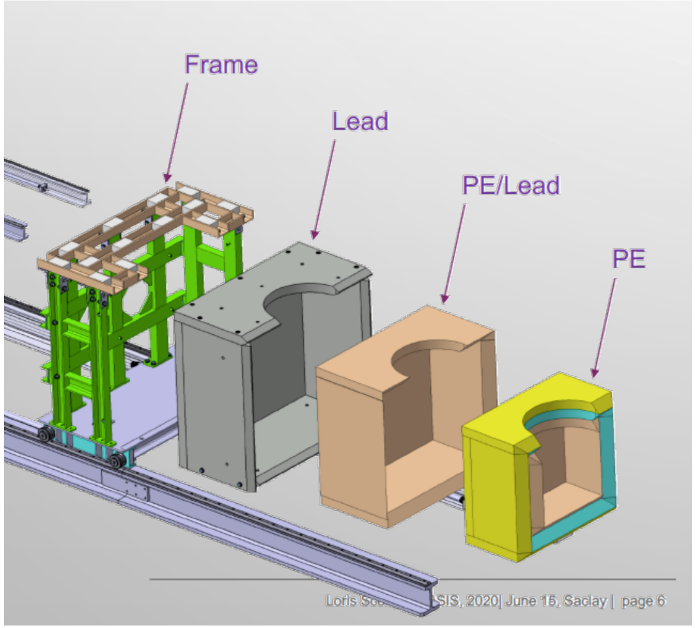
Developments for NUCLEUS-10g
crucial to investigation of low-energy background:

- 4π surface veto (cryogenic inner veto)
- Ge anticoincidence veto (cryogenic outer veto)
- Setup with dedicated Pb+PE shielding
- High-efficiency muon veto
- “blank assembly” in shallow underground lab at TUM
- background simulations for the full setup

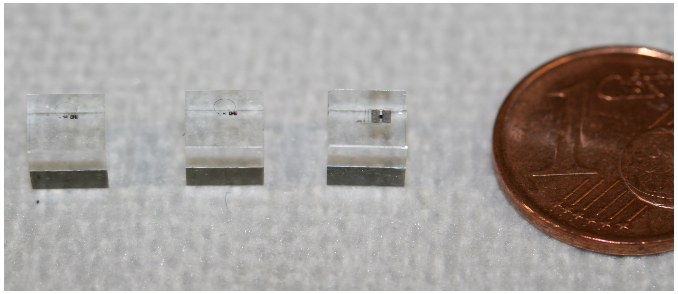








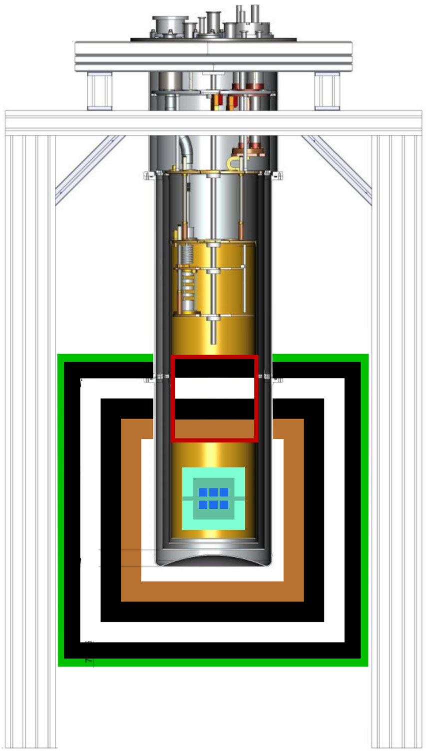
Thank you for your attention!

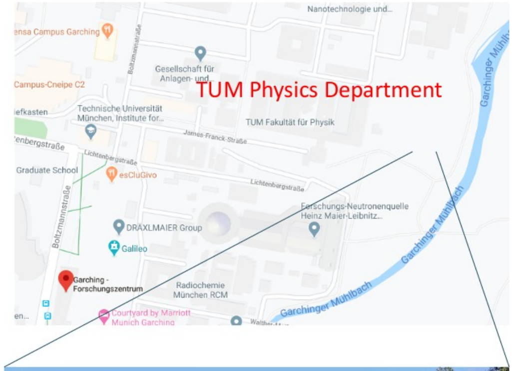


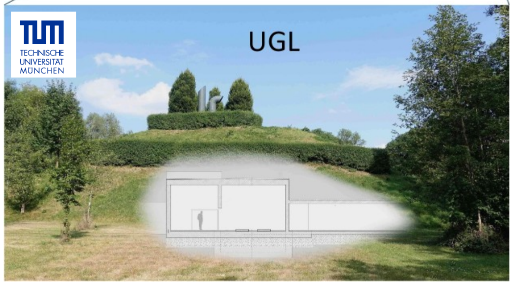
Johannes Rothe,
Technical University Munich

EXCESS workshop, 15-16 June 2021

NUCLEUS Schedule







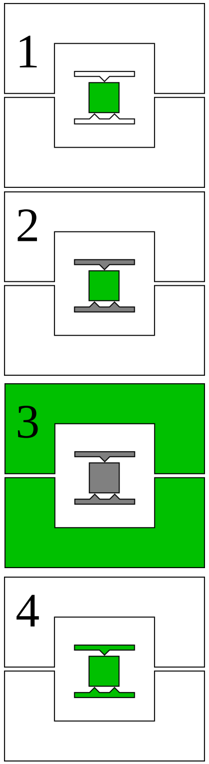
2021: commissioning of individual components

2022: blank assembly of NUCLEUS-10g at TUM UGL shallow underground laboratory

2023: relocation to Chooz (Very-Near-Site) and first physics run

Overview of measurements, prototype components

Components tested:



Run 1	**Feb 2017**	**first NUCLEUS target prototype** (no vetos)
Run 2	Jan 2018	silicon supports, calibration + background
Run 3	Mar 2018	outer veto test
Run 4	Mar 2019	active target + inner veto

→ Arxiv: 1704.04317, 1704.04320, 1707.06749, data public

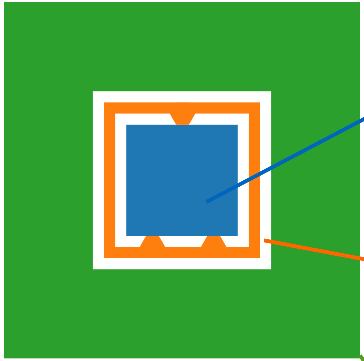
→ J Low Temp Phys 199, 433–440 (2020)

all runs described in J. Rothe, PhD thesis (2021), mediatum.ub.tum.de/?id=1576351

Detector Concept & Prototypes

NUCLEUS detector concept

"Fiducial Volume Cryogenic Detector"



Gram-scale cryogenic calorimeters:
ultra-low energy threshold

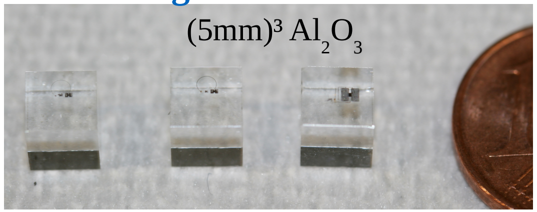
Cryogenic inner veto:
instrumented holder & surface veto

Cryogenic outer veto:
massive anticoincidence veto

NUCLEUS – 1g prototype

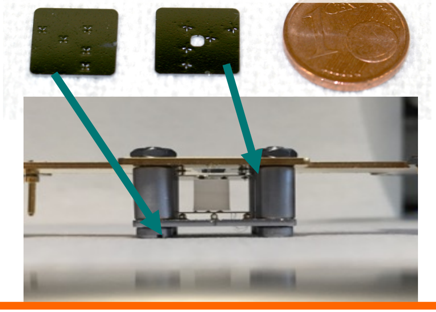
Target calorimeters:

$(5mm)^3$ Al_2O_3



Cryogenic inner veto:

flexible silicon wafers: 200µm



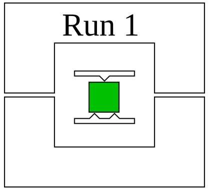
Cryogenic outer veto:
(not discussed here)

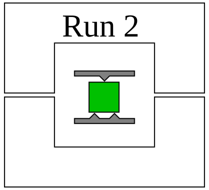
silicon calorimeters (200g)

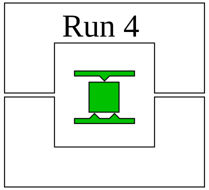
Overview of measurements

Run 1	**Feb 2017**	**first NUCLEUS target prototype** (no vetos)
Run 2	Jan 2018	silicon supports, calibration + background
Run 3	Mar 2018	outer veto test
Run 4	Mar 2019	active target + inner veto

Components tested:







References:

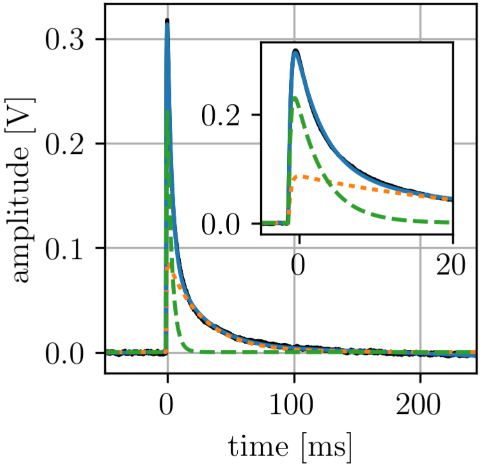
Run1:
arxiv: 1704.04317, 1704.04320, 1707.06749, data public

Run4:
J Low Temp Phys 199, 433–440 (2020)

all runs described in:
J. Rothe, PhD thesis (2021),
mediatum.ub.tum.de/?id=1576351

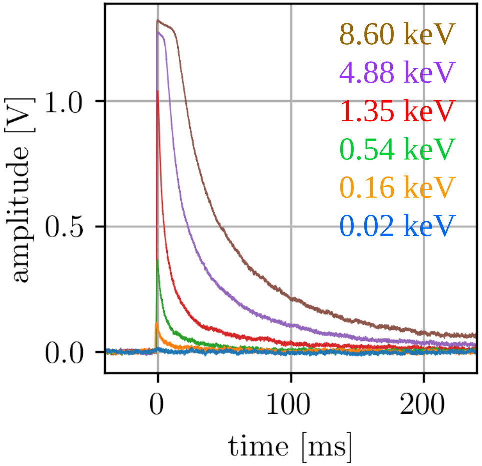
Backup: analysis details

Run 1 analysis steps: pulse shape, NPS



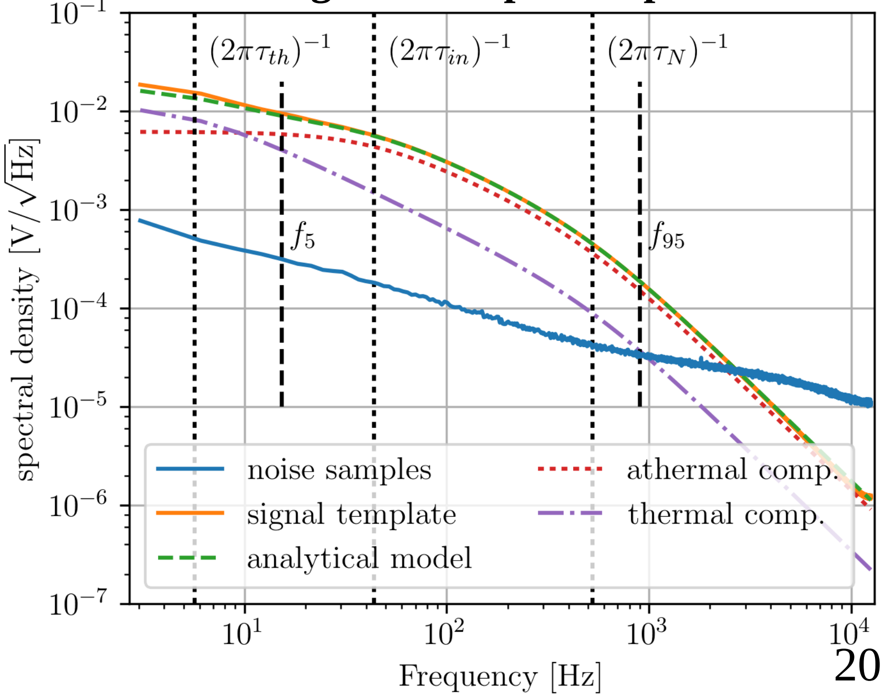
Pulse time-scales:
athermal phonon lifetime: 0.3 ms
TES relaxation time: 3.5 ms
crystal relaxation time: 28.2 ms

plots from: J. Rothe, PhD thesis (2021),
mediatum.ub.tum.de/?id=1576351



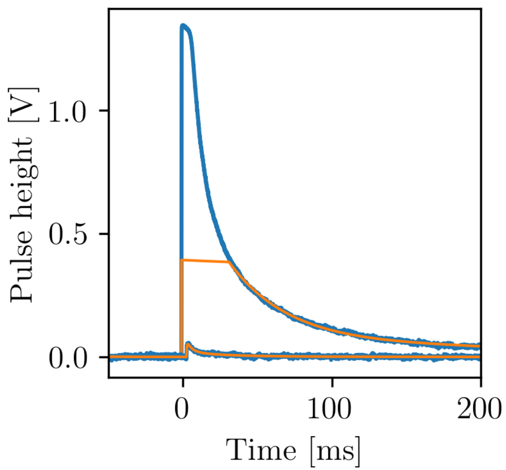
Dynamic range:
19.7 eV (threshold)
600 eV (linear range)
12 keV (upper limit of energy reconstruction)

Signal/noise power spectra:

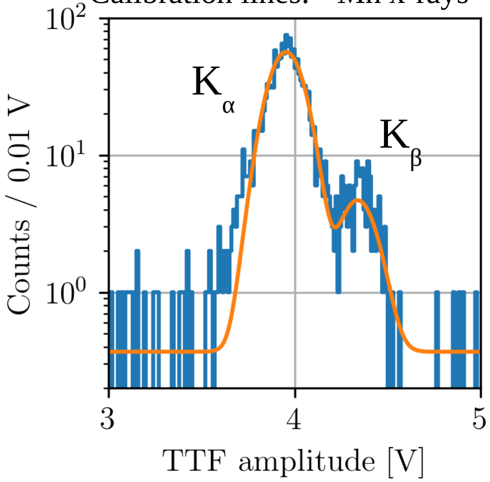


Run 1 analysis steps: energy reconstruction

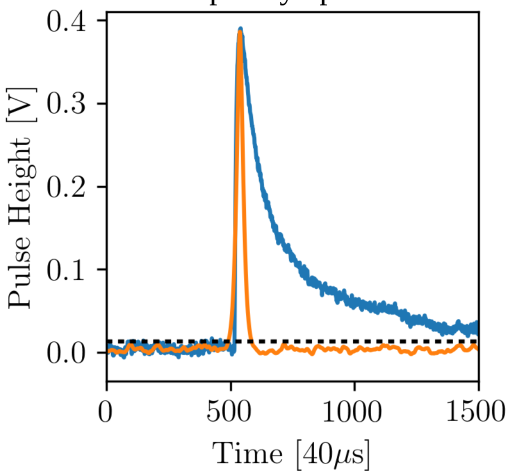
Truncated fit of saturated event:



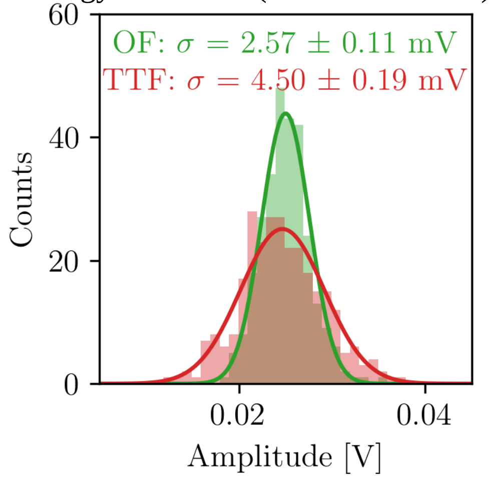
Calibration lines: ^{55}Mn x-rays



Event shaped by optimum filter:



Energy resolution (simulated events):



Truncated template fit (TTF):
fits only pulse samples below “truncation limit” (600 eV)
allows energy reconstruction well into saturated region
used for calibration at 5.9 keV

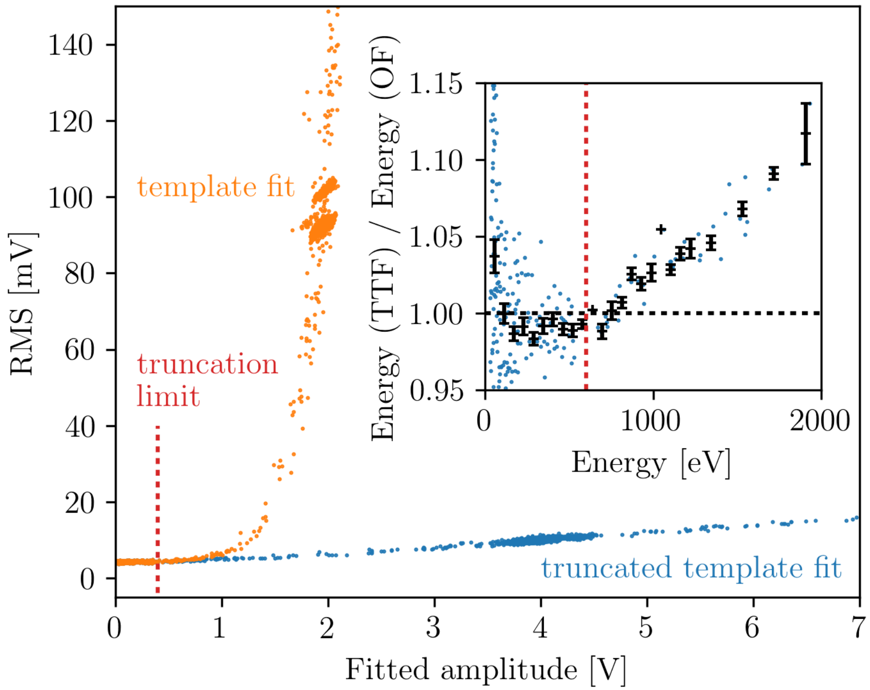
Optimum Filter (OF):
matched filter weights frequency components by S/N ratio
best energy resolution
no treatment of non-linearity
used for energy reconstruction in the Region Of Interest (ROI) up to 600eV

→ optimum filter zero-energy resolution:

σ_{OF} = 3.84 ± 0.16 eV

Run 1 analysis steps: energy reconstruction

Cross-check of energy reconstruction methods:



Truncated template fit (TTF):
fits only pulse samples below “truncation limit” (600 eV)
allows energy reconstruction well into saturated region
used for calibration at 5.9 keV

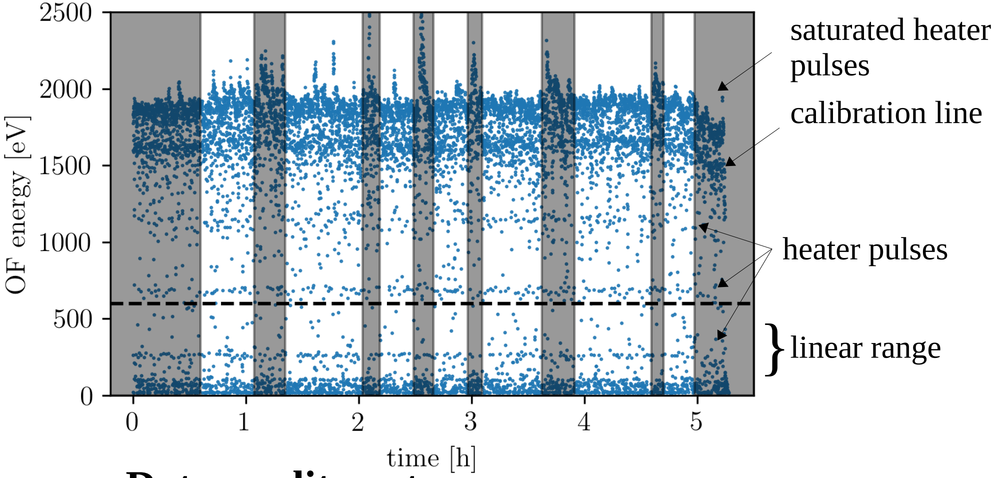
Optimum Filter (OF):
matched filter weights frequency components by S/N ratio
best energy resolution
no treatment of non-linearity
used for energy reconstruction in the Region Of Interest (ROI)

→ optimum filter zero-energy resolution:

$\sigma_{OF} = 3.84 \pm 0.16$ eV

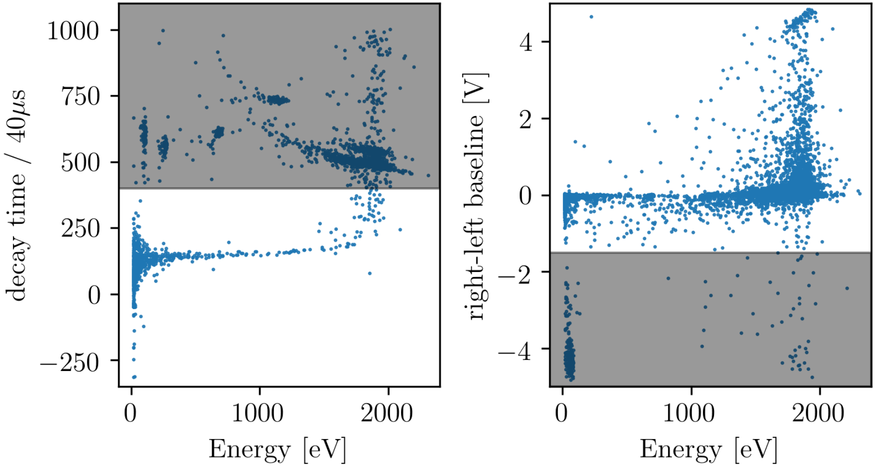
Run 1 analysis steps: data quality cuts

Stability cut:



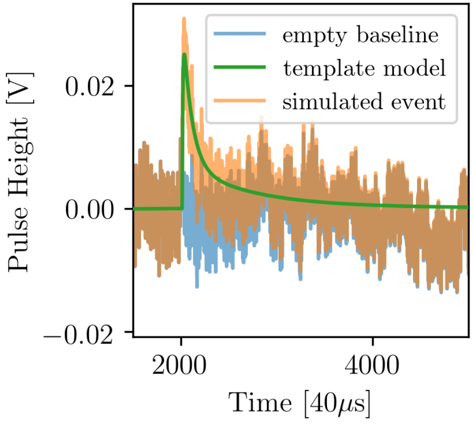
- Detector is actively held at its operating temperature (resistive heater and feedback loop)
- Periods of unstable detector temperature are identified by saturation height and removed
- Live time reduction: 5.31 h → 3.26 h

Data quality cuts:



- Cut on decay time removes heater pulses and misreconstructed saturated pulses
- Cut on “right-left baseline difference” removes artifacts (SQUID resets and pile-up)
- Loose quality cuts do not affect particle events, removed events are counted as dead time
- Live time reduction: 3.26 h → 2.27 h
- Final exposure (ROI): 0.046 g day

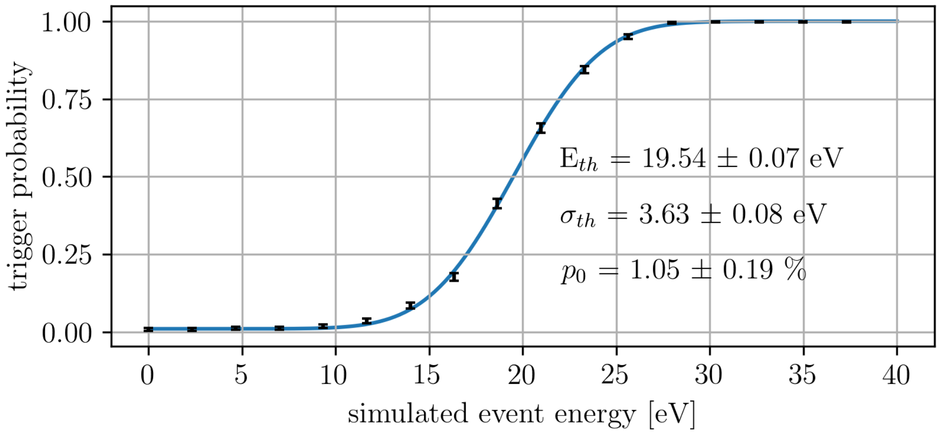
Run 1 spectrum, efficiency, data products

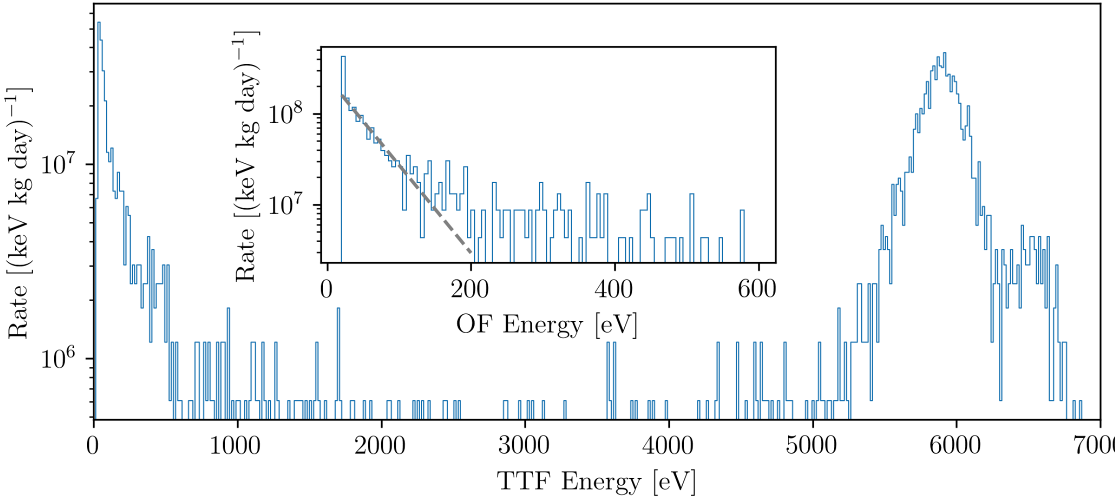


Trigger efficiency simulation:
simulated events from random triggers ("empty baselines")

passed through OF trigger

amplitude scan of simulated events





Final event spectra:
ROI: reconstructed with OF (linear range <600 eV)

"high energy" spectrum: < 10 keV, TTF reconstruction

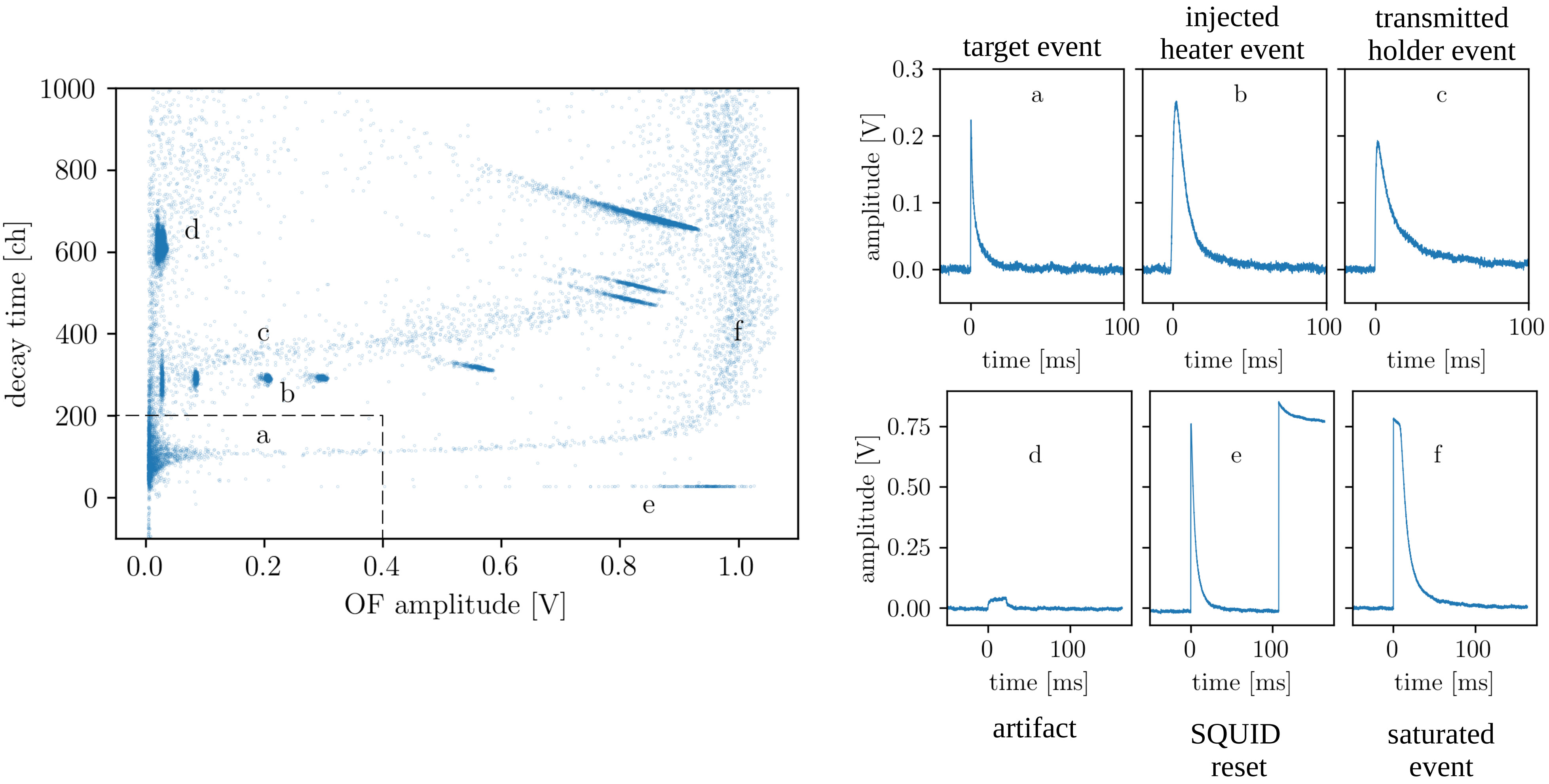
Low energy rise parameters ("guide for the eye")
single exponential: $R/E_0 \cdot \exp(-E/E_0)$

Slope: E_0~45 eV,

Integral rate: R~10^7/kg/day, or ~130/kg/s, or ~1/(16s)

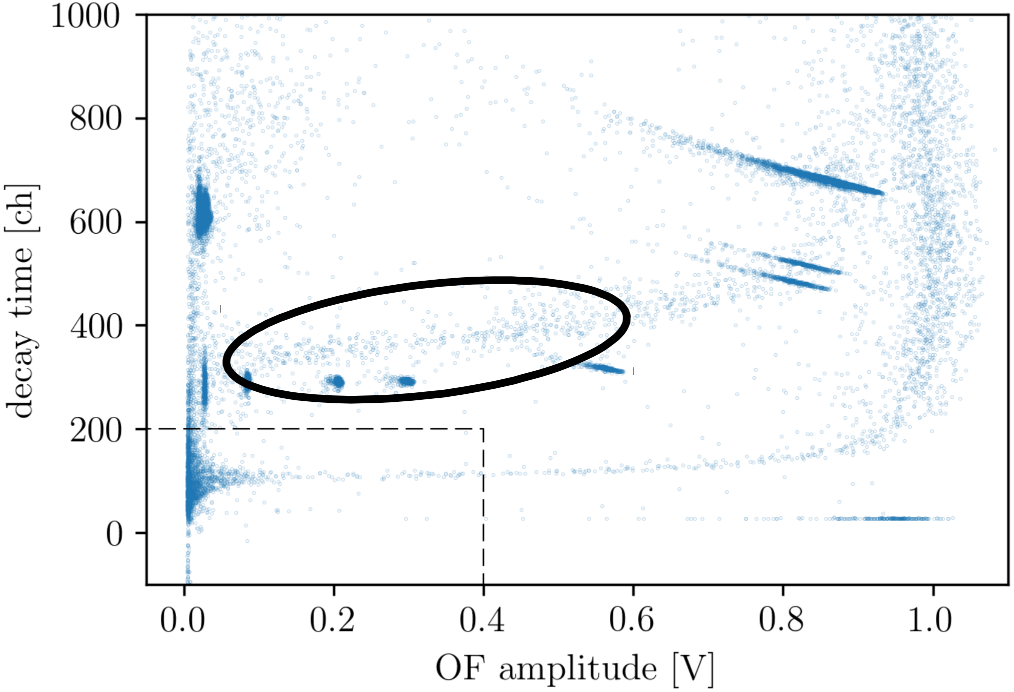
→ dark matter search: **CRESST surface 2017,**
EPJ C, 77(9):637, 2017. arxiv:1707.06749

Run 2 event classes

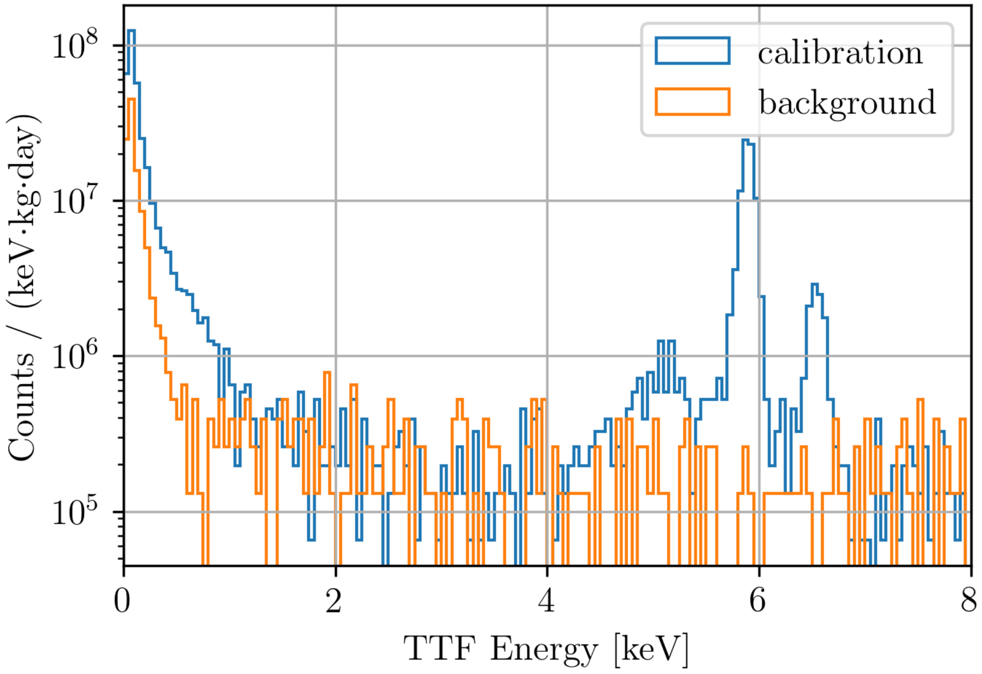


Run 2 calibration & background spectra

New event class (separated in decay time parameter):
phonon transmission from holder

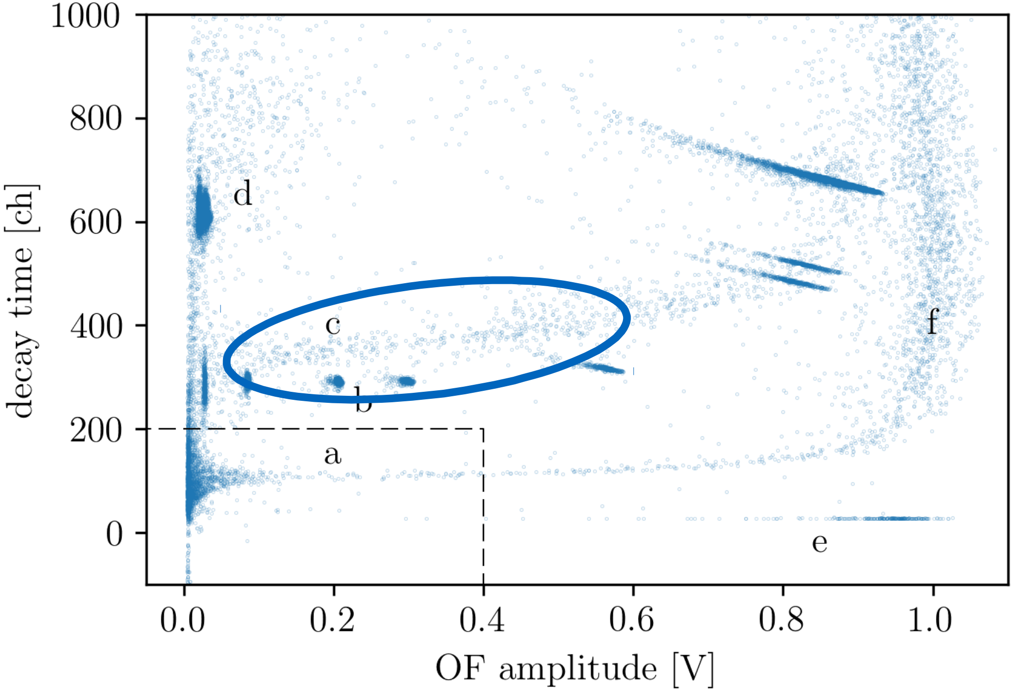


Run2 calibration vs. background:
(without simulation of cut efficiencies)
→ ^{55}Fe contributes to sub-keV background

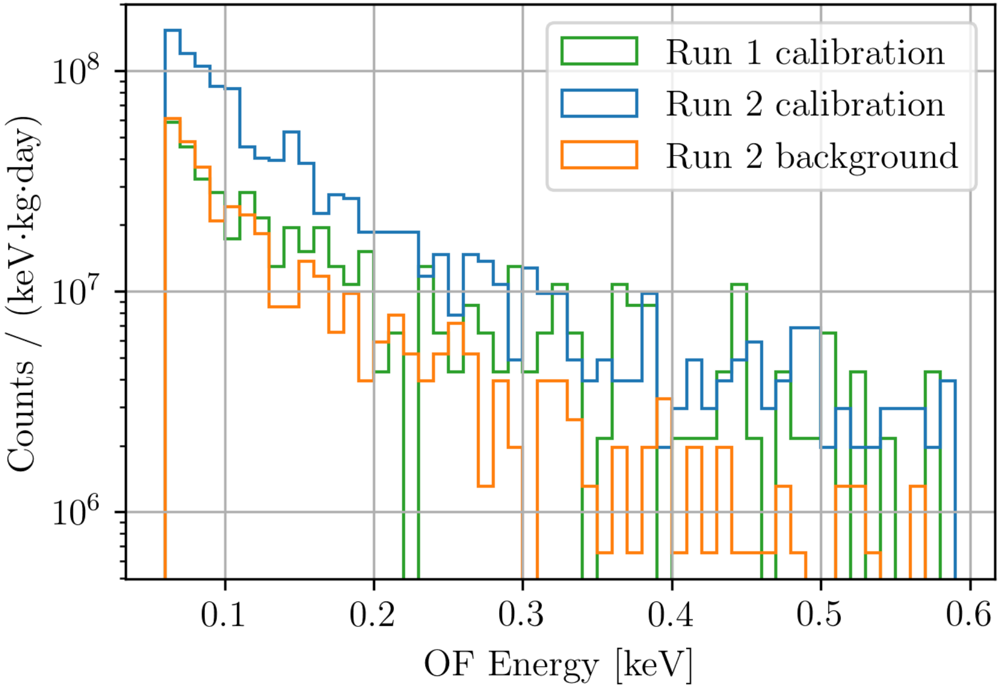


Run 2 calibration & background spectra

New event class (separated in decay time parameter): phonon transmission from holder



Run1 cal. vs Run2 background: comparable sub-keV event rate

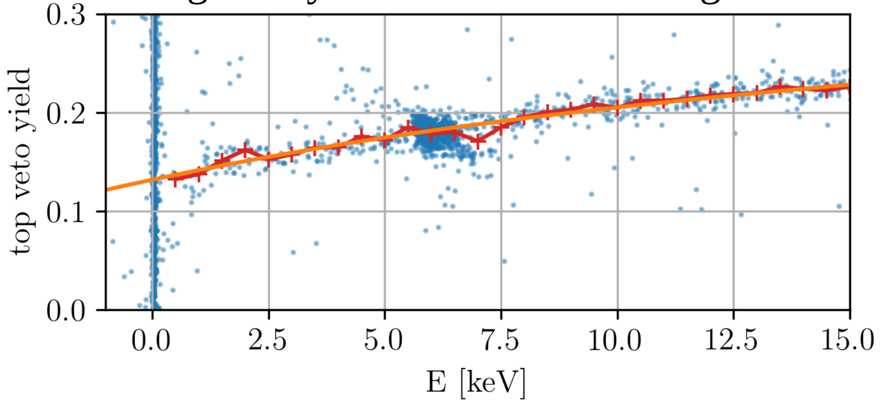


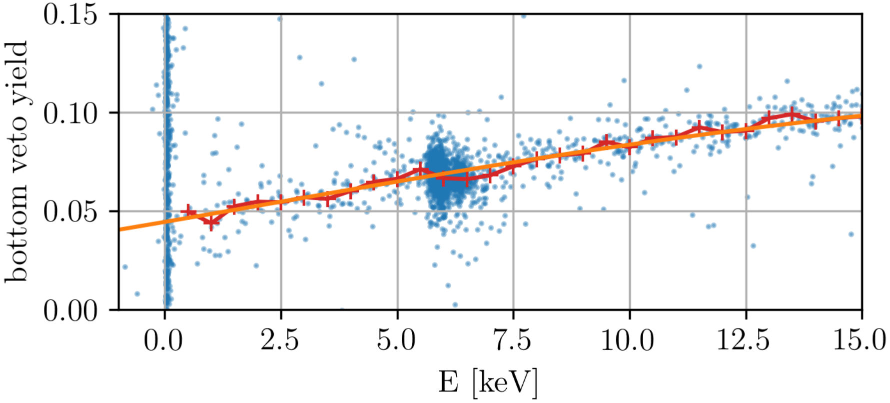
→ Calibration source not responsible for low-energy background
→ Some source configurations do contribute to low-energy events

Run 4, veto anticoincidence cut

Anticoincidence-cut with phonon transmission:
"veto yield" = veto amplitude / target amplitude

fitting veto-yield distribution of target events





Determination of veto cut efficiency:
Simulated 3-channel events according to distribution
Cut survival probability evaluated on simulated events