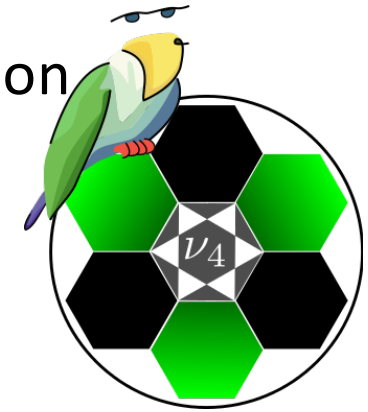
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Development of a novel detector system for the keV sterile neutrino search with KATRIN

Tobias Bode for the KATRIN collaboration

Max Planck Institute for Physics



Introduction

Sterile neutrinos and particle physics

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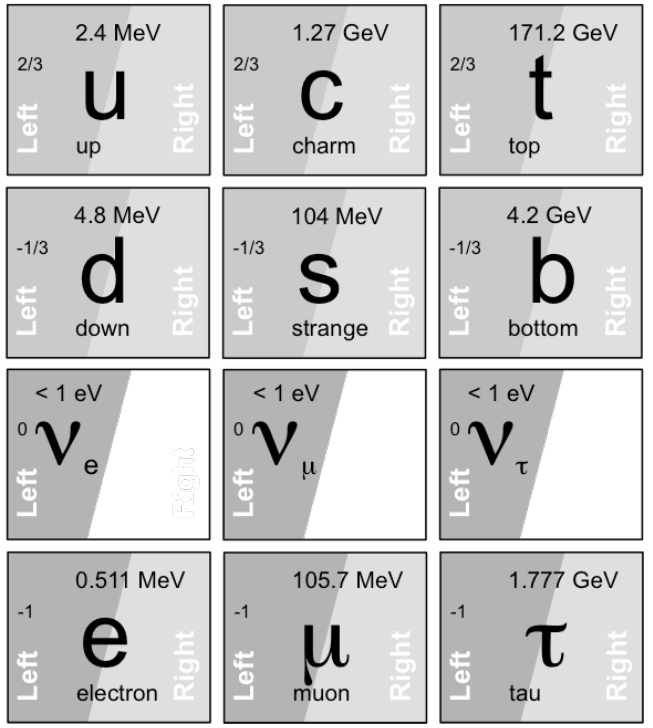
Standard Model (SM)



Sterile neutrinos and particle physics

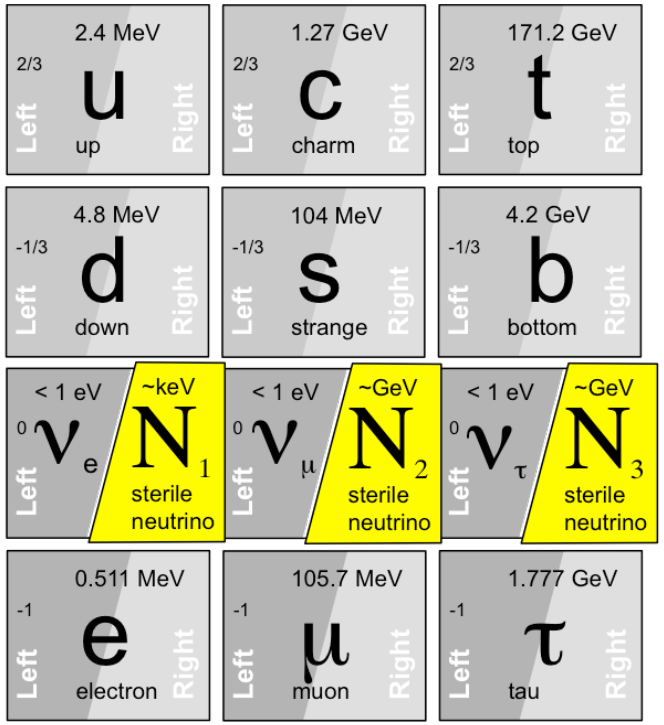
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Introduction of sterile
(right – handed) neutrinos to the Standard Model

- Natural way to explain neutrino mass (Seesaw)
- Allows to explain
  matter – antimatter asymmetry (GeV)
- Provides Dark Matter candidate (keV)

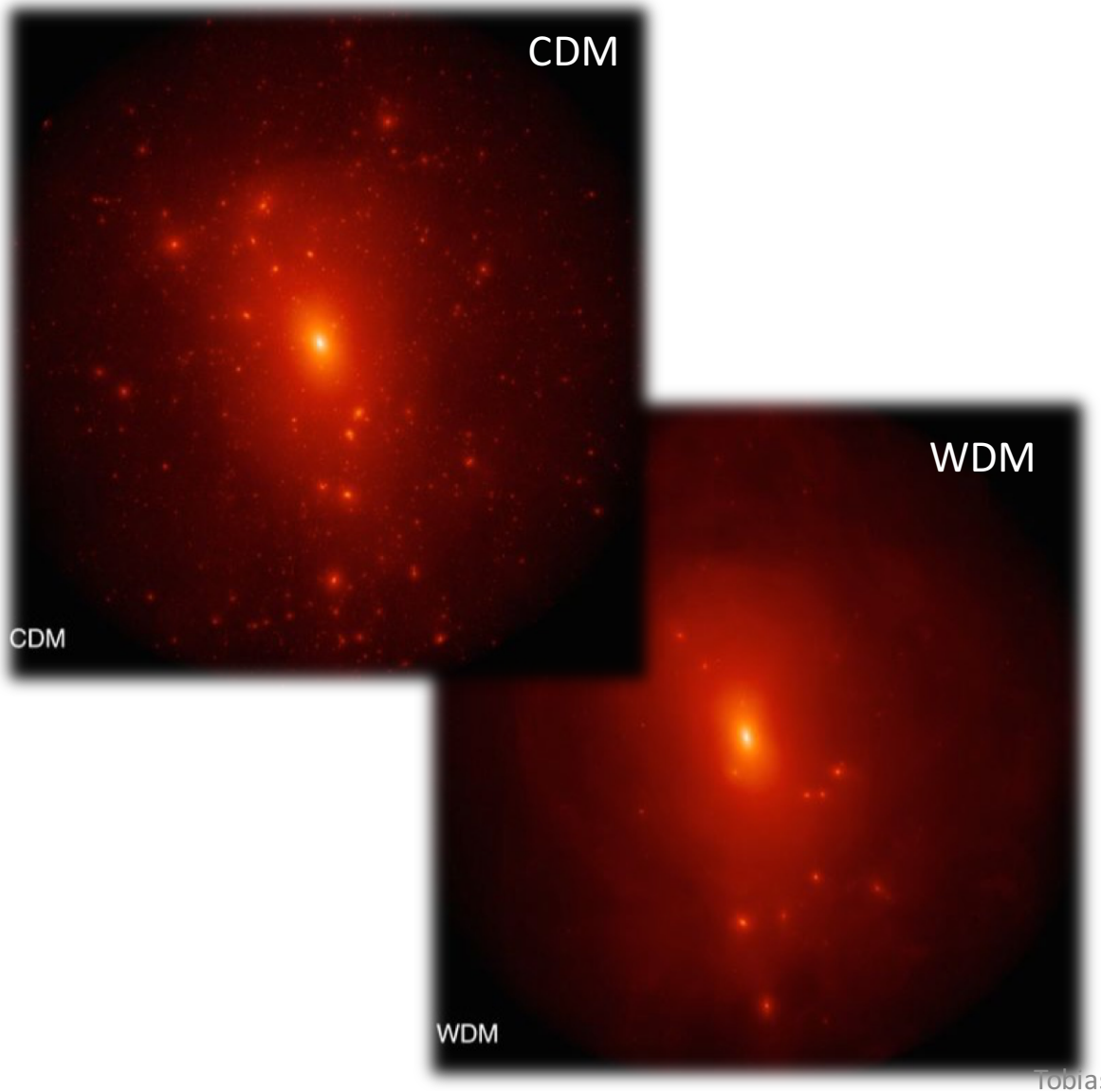
A White Paper on keV Sterile Neutrino Dark Matter (JCAP 1701 (2017) no.01, 025)

nuMSM



L. Canetti, M. Drewes, and
M. Shaposhnikov, PRL **110** 061801
(2013)

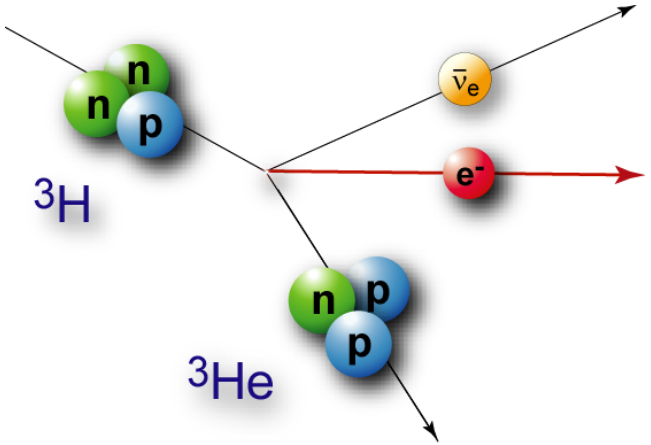
Sterile neutrinos as dark matter?



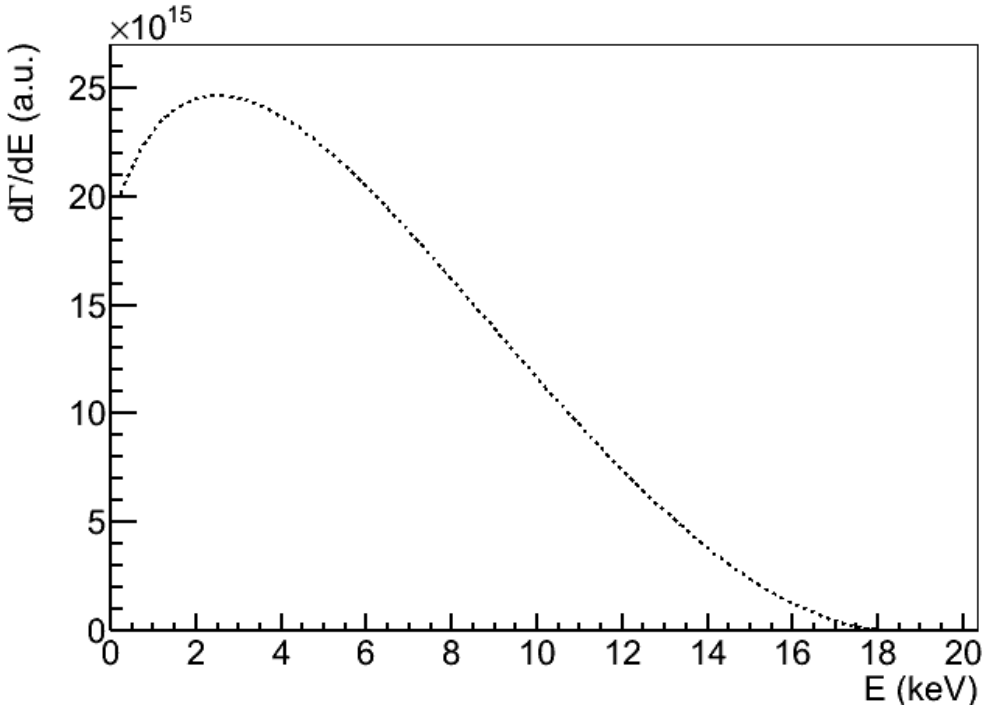
- Sterile neutrinos in the keV mass range are a good candidate for dark matter
- In agreement with cosmological observations
  X. Shi, G. M. Fuller 1999 *PRL* **82**
- May solve Cusp/Core & too-big to-fail problem
- Indirect hint from satellite experiments ? (disputed)
  E. Bulbul *et al.* 2014 *ApJ* **789,** Boyarsky *et al.* 2014 *PRL* **113**

TRISTAN:
Tritium Beta Decay to Search for Sterile Neutrinos

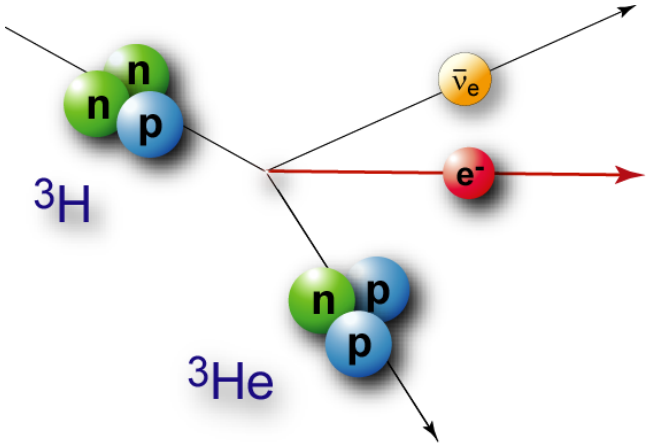
Tritium beta decay



$$\frac{dN}{dE} = R(E) \cdot (E - E_0) \cdot \sqrt{(E - E_0)^2 - m_\nu}$$



Tritium beta decay



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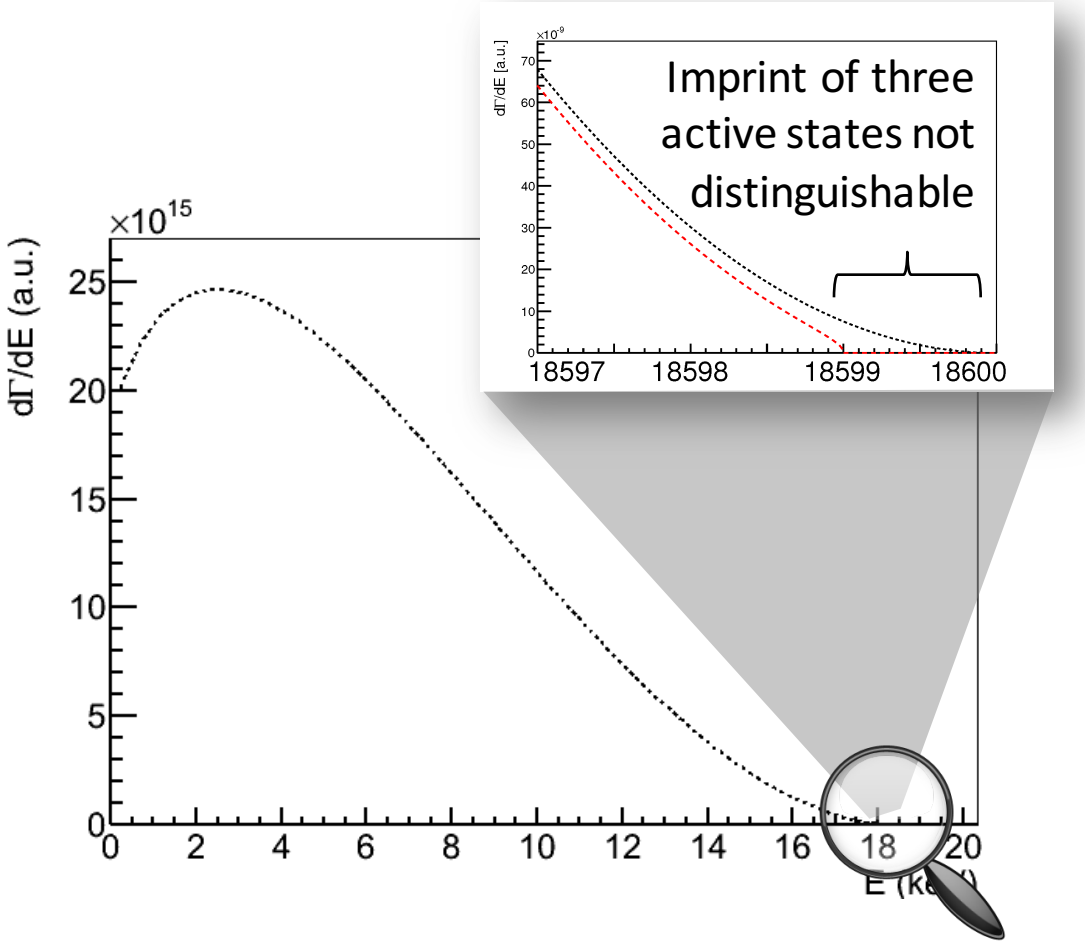
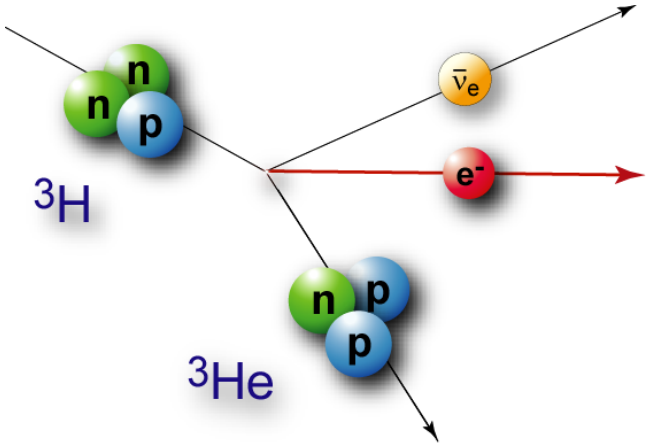


Imprint of sterile ν's on ß-spectrum



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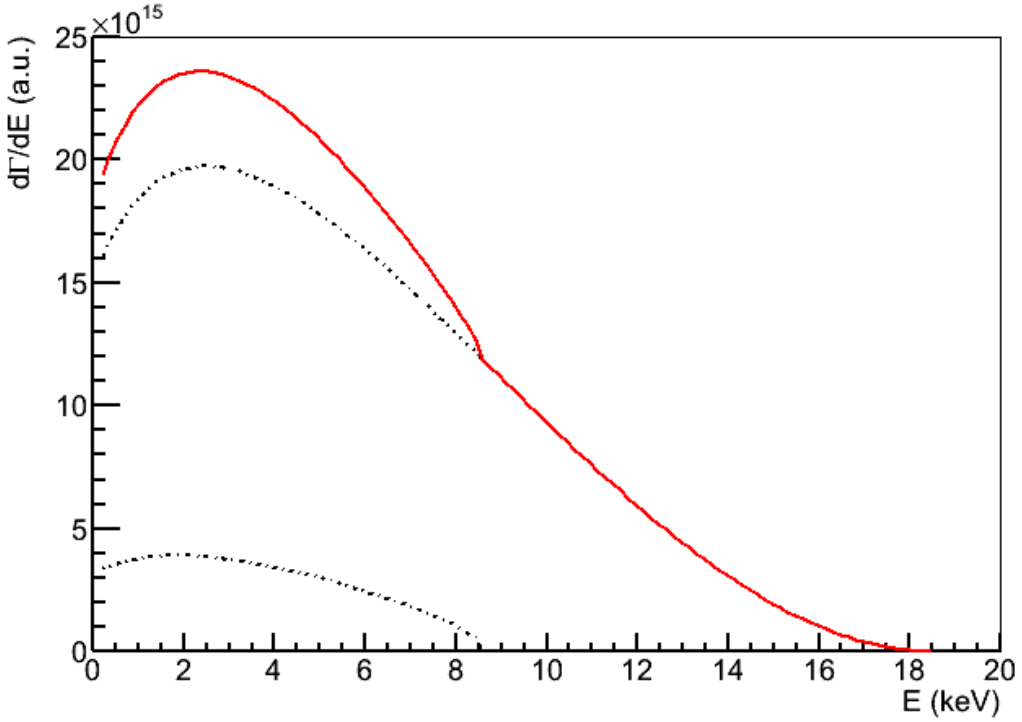

Imprint of sterile ν's on ß-spectrum

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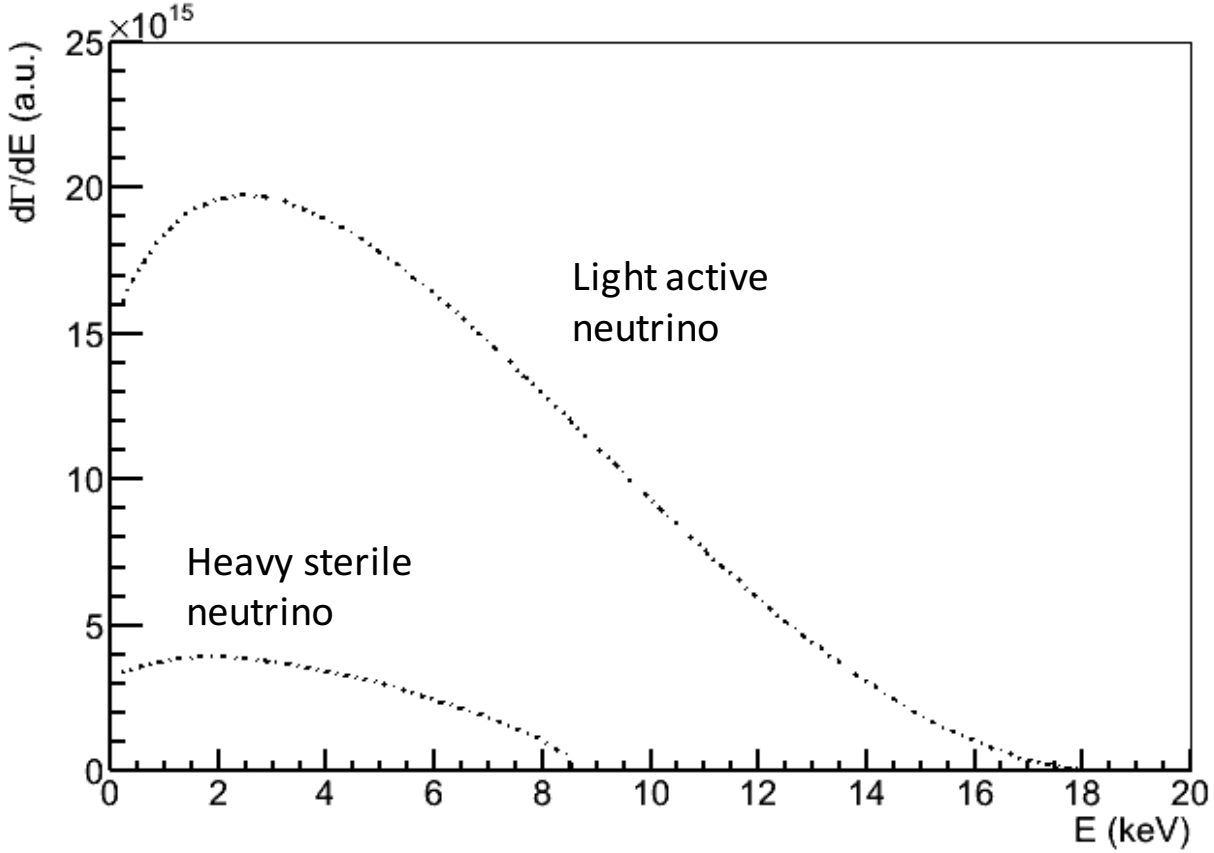
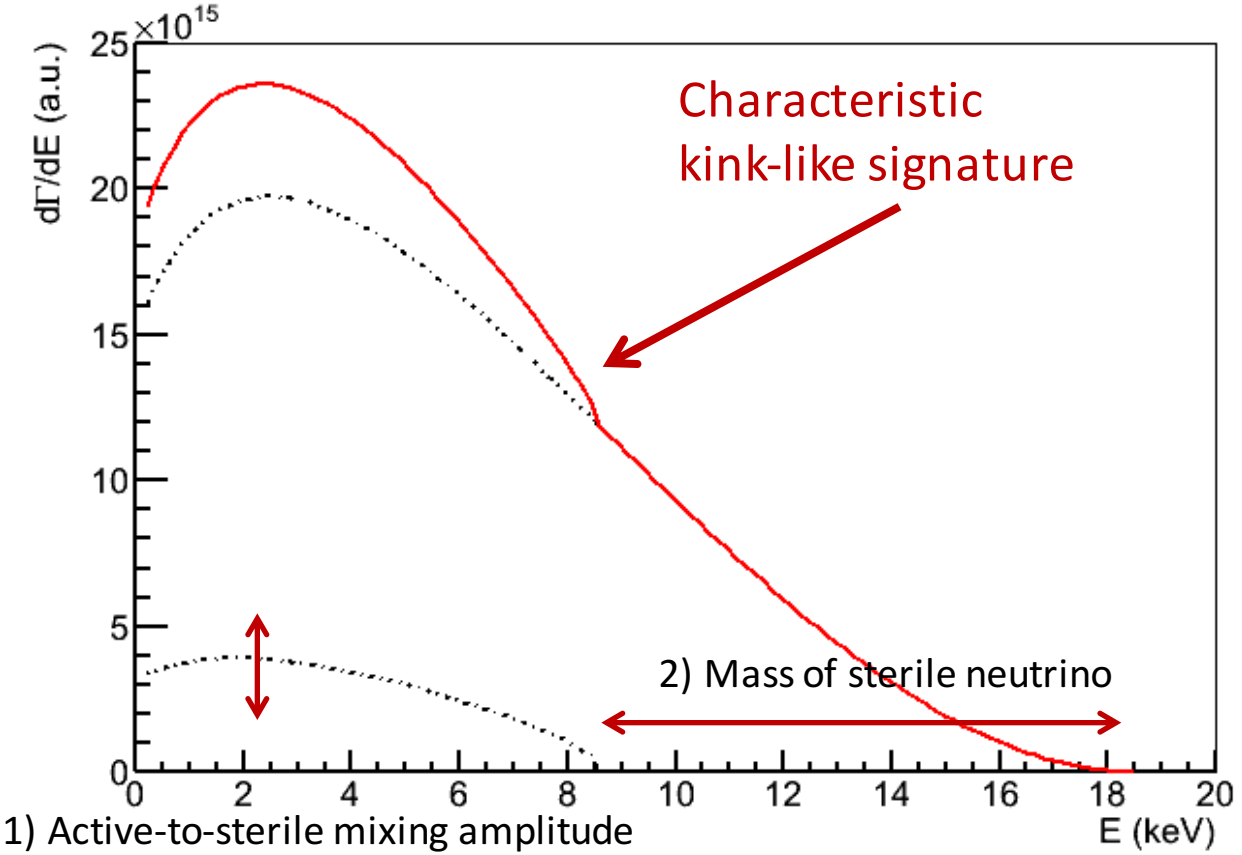
$$\frac{dN}{dE} = \cos^2\theta \frac{dN}{dE}\left(m_{\nu,active}\right) + \sin^2(\theta) \frac{dN}{dE}\left(m_{\nu,s}\right)$$



Imprint of sterile ν's on ß-spectrum

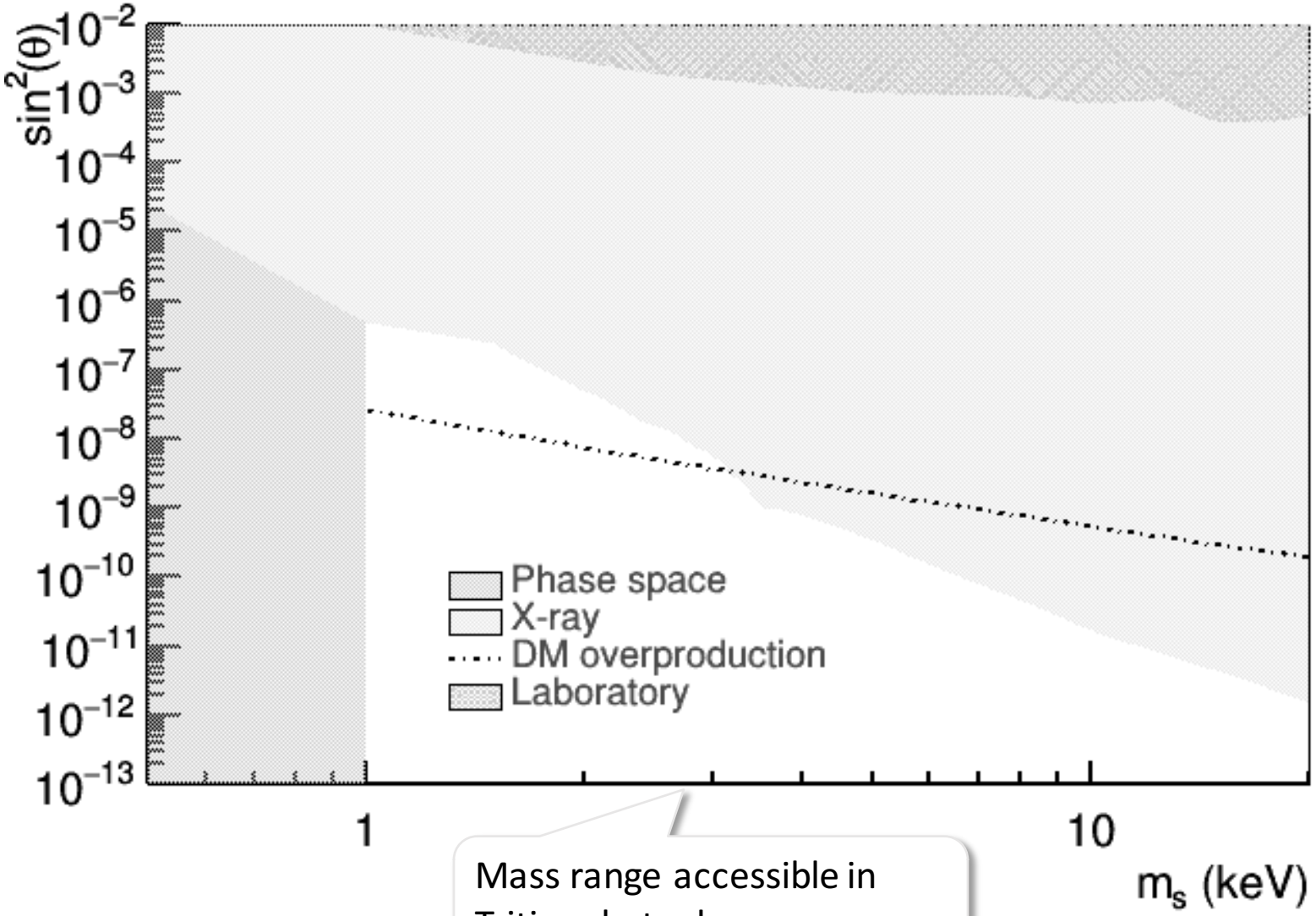
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

$$\frac{dN}{dE} = \cos^2\theta \frac{dN}{dE}(m_{\nu,active}) + \sin^2(\theta)^{1)} \frac{dN}{dE}(m_{\nu,s})^{2)}$$



1) Active-to-sterile mixing amplitude

Existing limits & constraints for keV sterile neutrino



Mass range accessible in Tritium beta decay

TRISTAN Project

TRISTAN project

Requirements for sensitive search:

- High statistics
  - High luminosity tritium source

TRISTAN project

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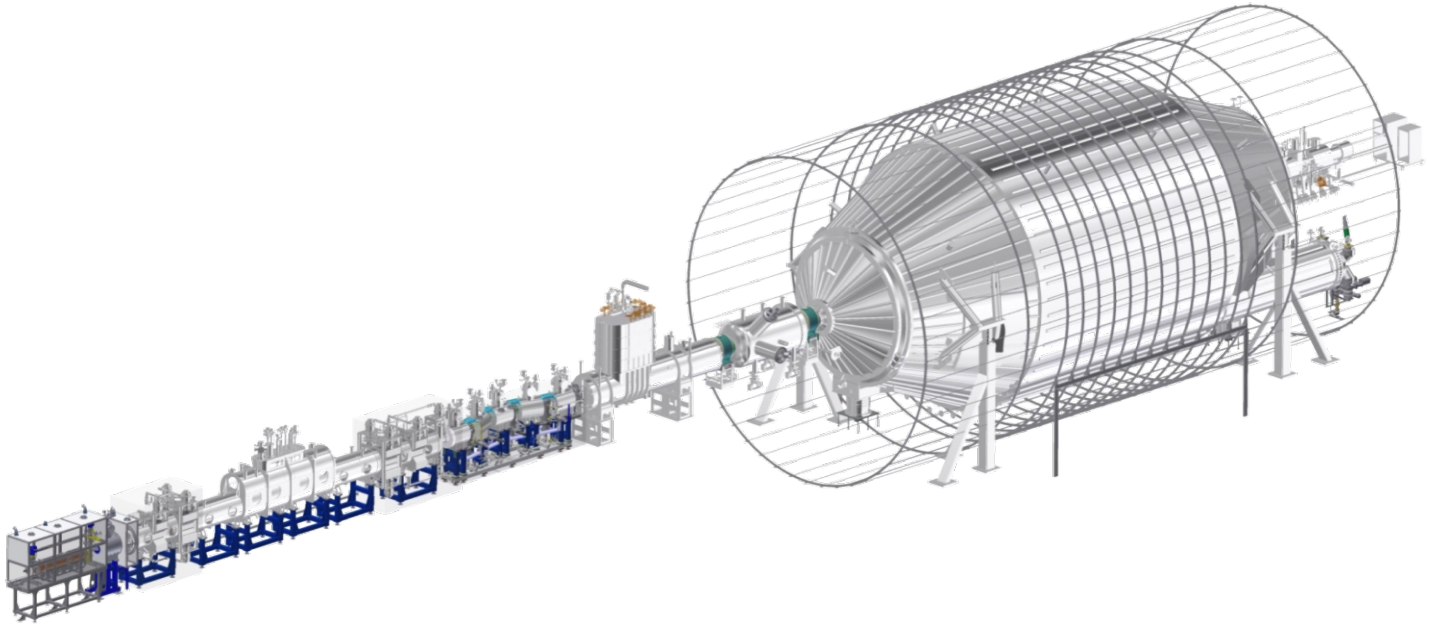
KATRIN experiment

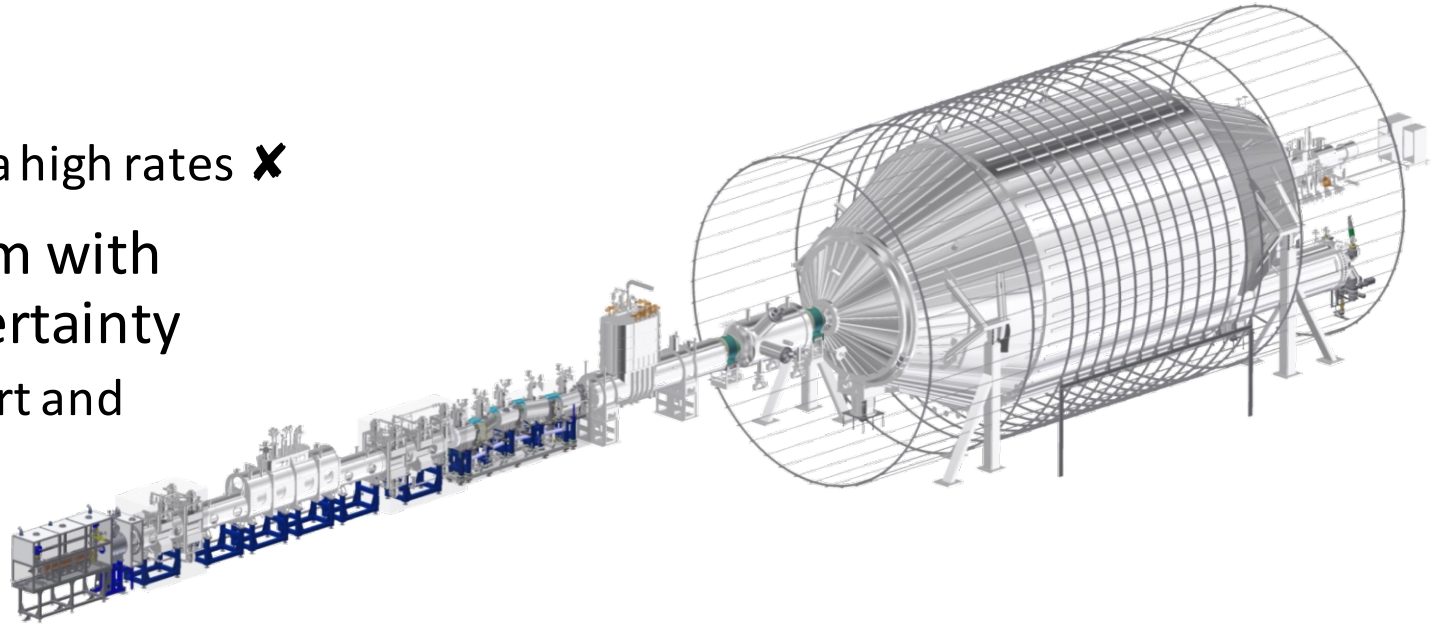


TRISTAN project

Requirements for sensitive search:

- High statistics
  - High luminosity tritium source ✓
  - Detector equipped to handle ultra high rates ✘
- Measurement of entire spectrum with extremely small systematic uncertainty
  - Understanding of source, transport and detection systems

KATRIN experiment



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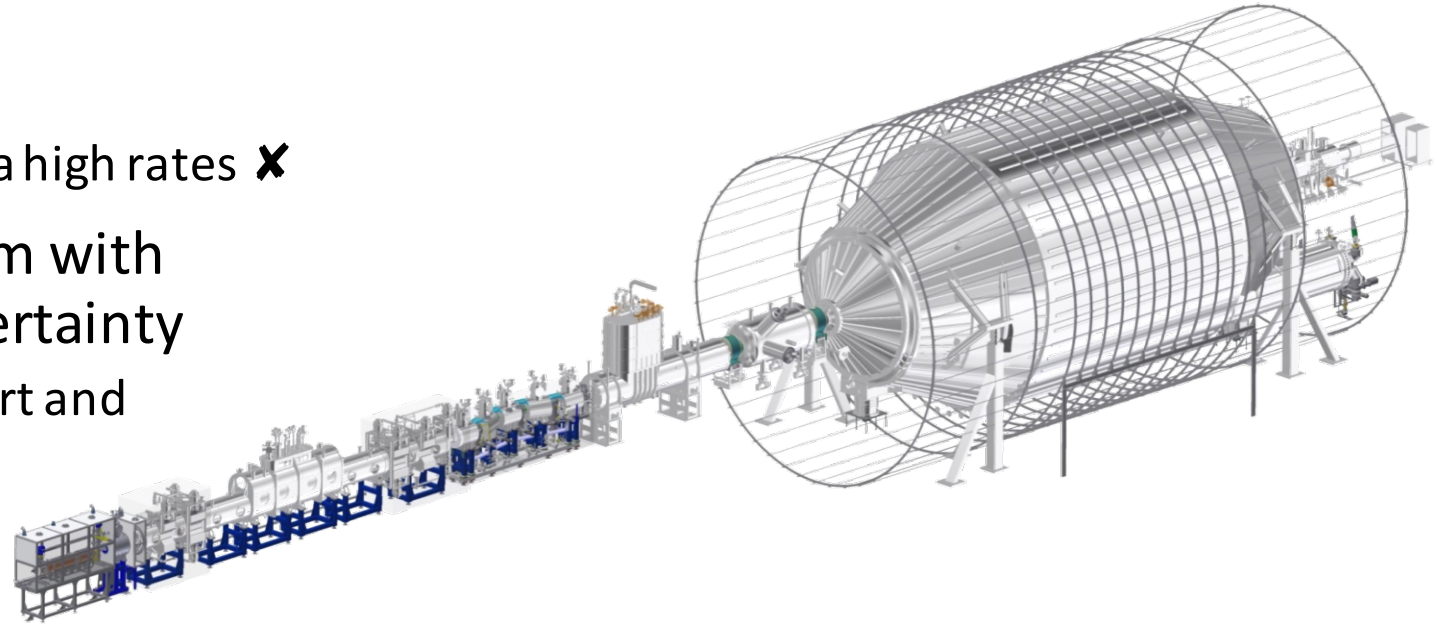
KATRIN experiment



- TRISTAN will proceed in two phases
- Phase-0: Usage of existing KATRIN systems
- Phase-1: New detector system

TRISTAN Phase-0

TRISTAN Phase-0

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

Goal: Improve current laboratory limit by orders of magnitude ($\sin^2\theta \approx 10^{-4}$)

How to use KATRIN – neutrino mass mode

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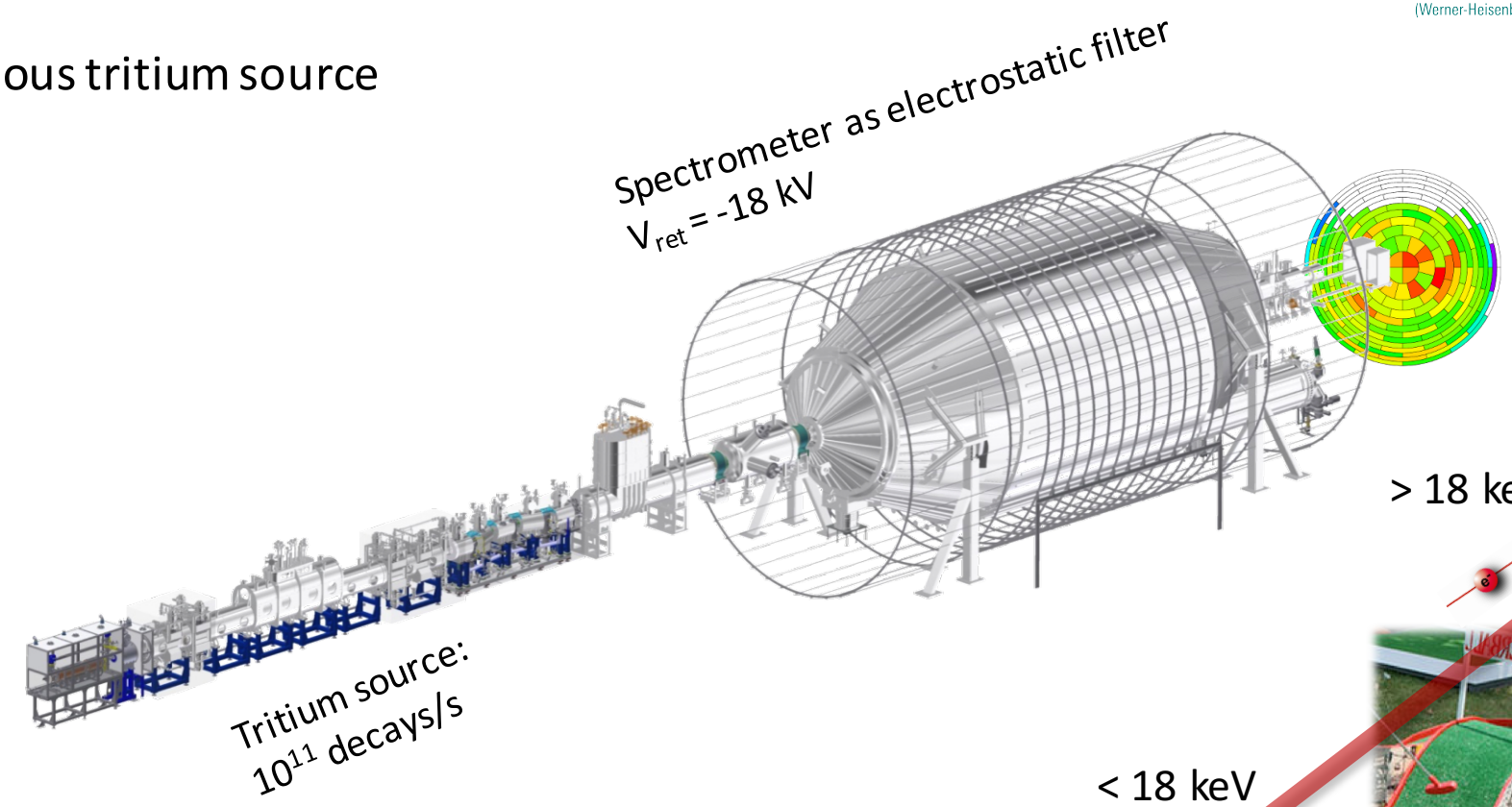
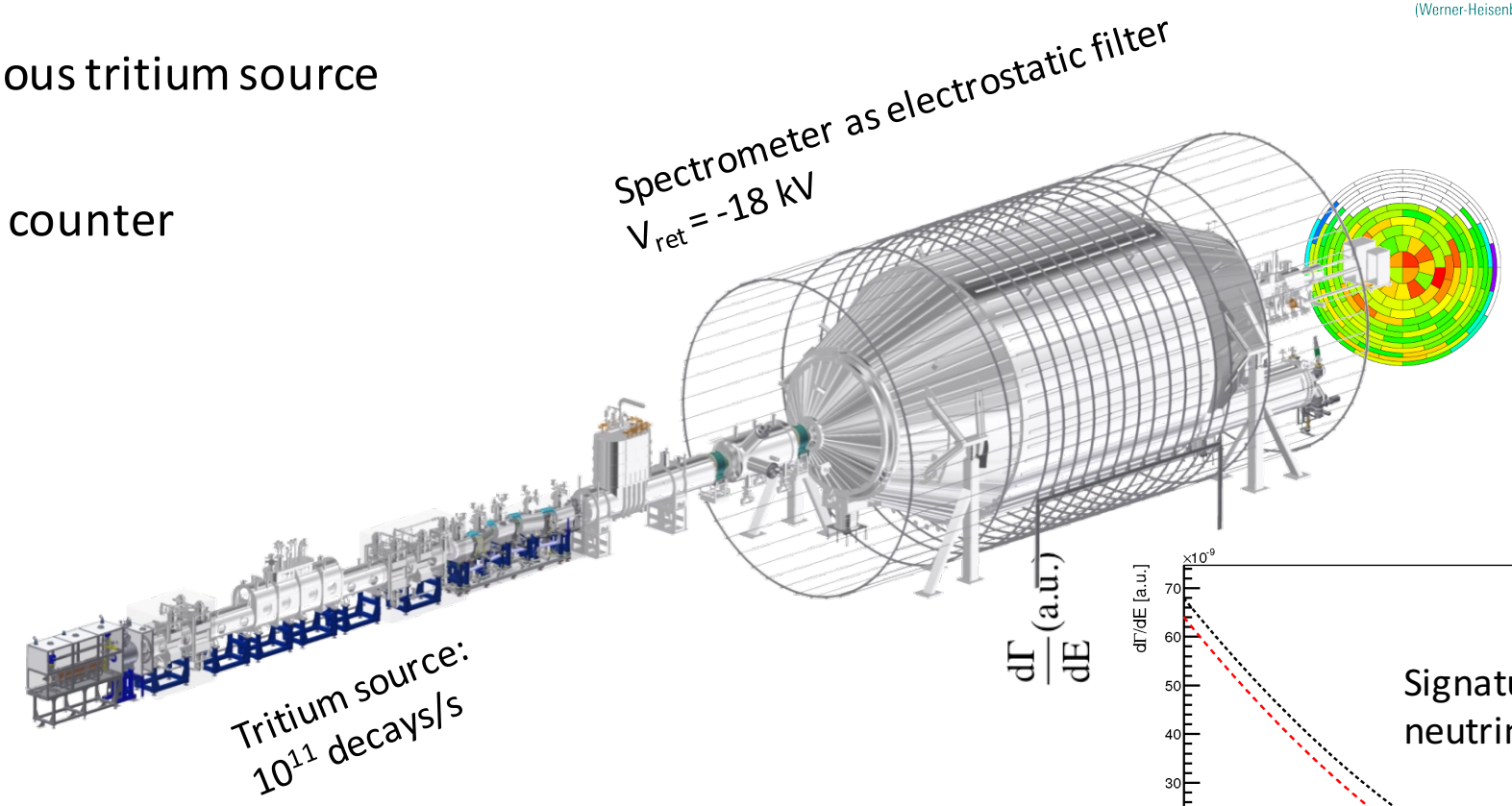
(Werner-Heisenberg-Institut)

- Ultra-luminous tritium source



How to use KATRIN – neutrino mass mode

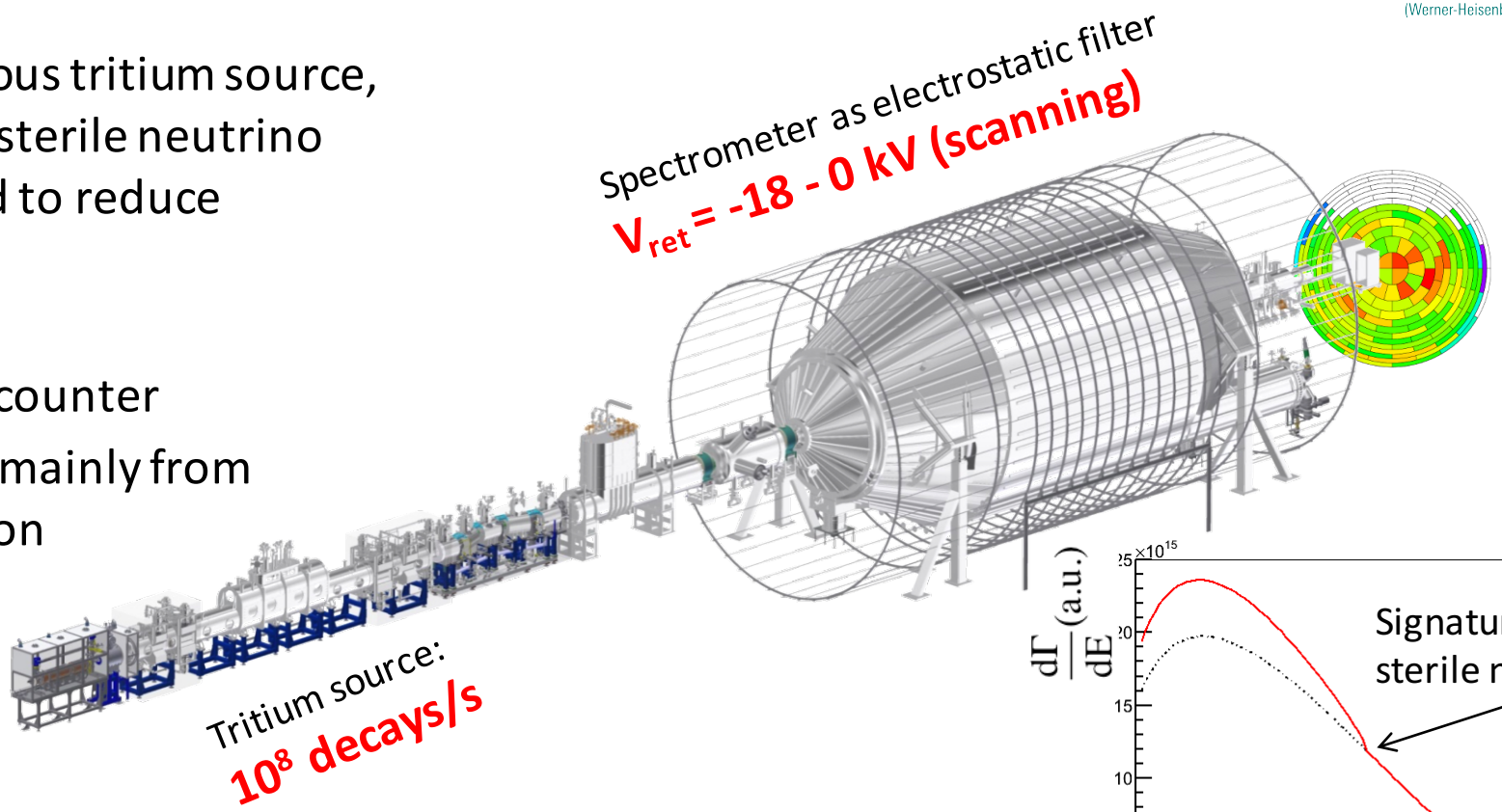
- Ultra-luminous tritium source
- Detector as counter



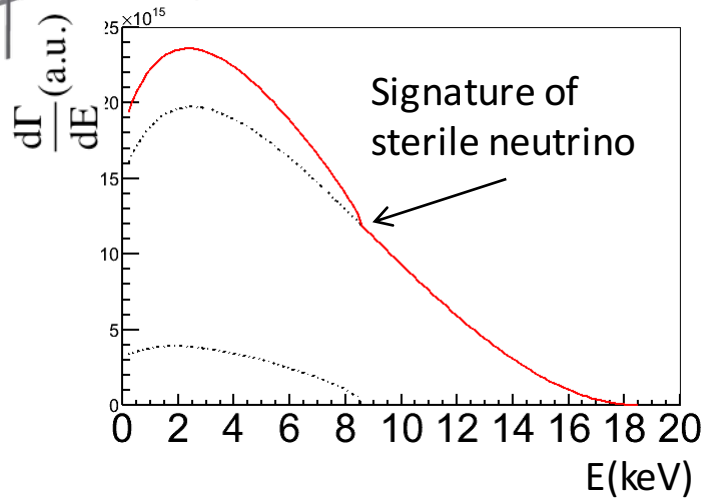
How to use KATRIN – TRISTAN integral mode

- Ultra-luminous tritium source, too high for sterile neutrino search, need to reduce activity

- Detector as counter
- Systematics mainly from source section



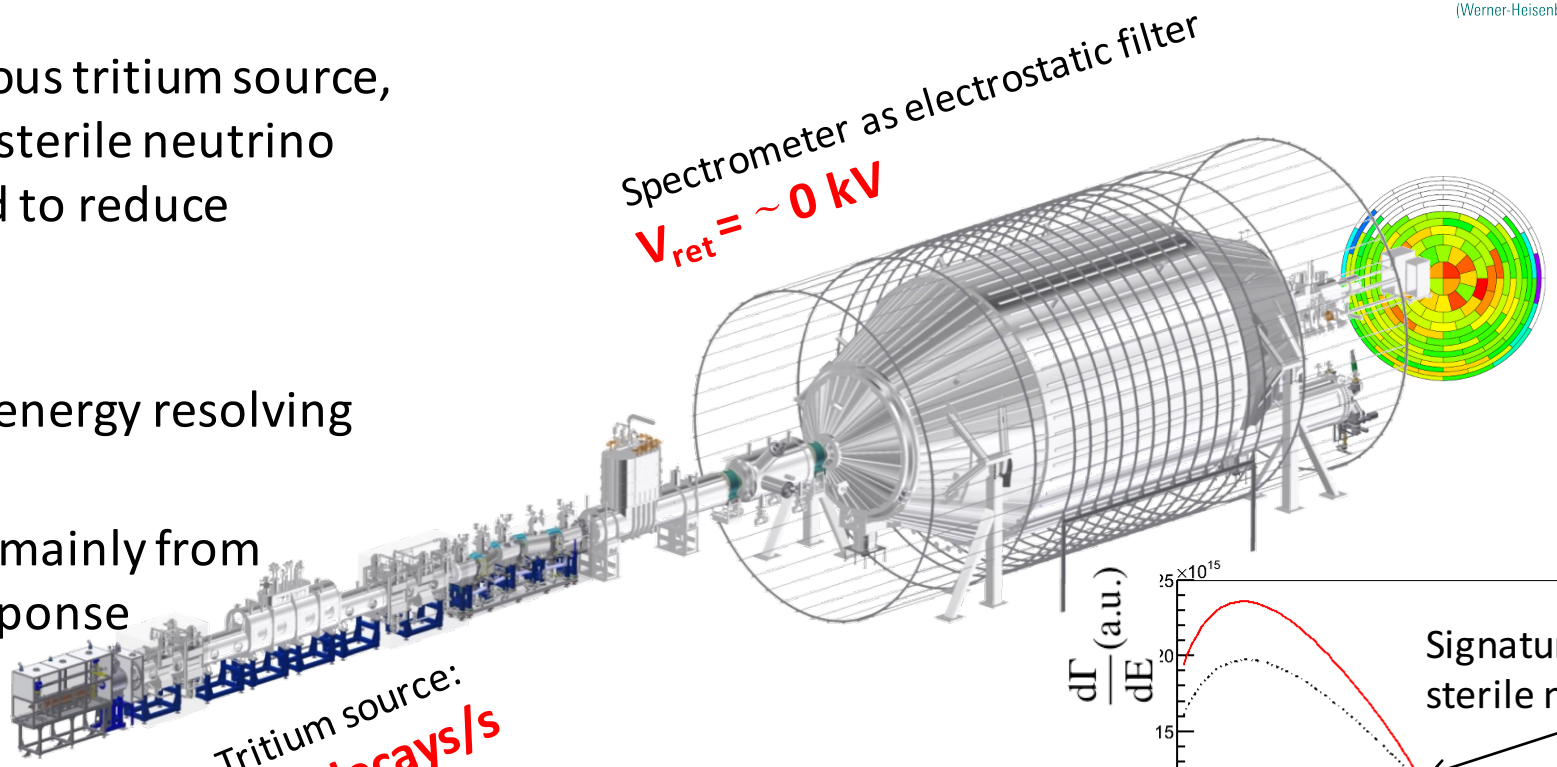
Rate @det: 10^6 cps

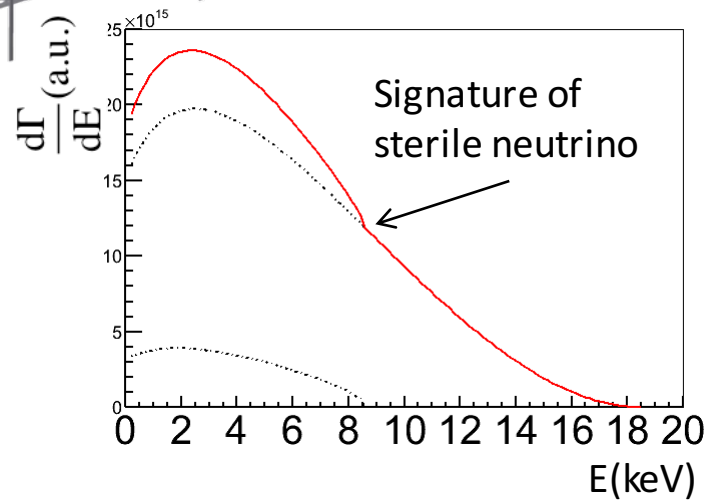


How to use KATRIN – TRISTAN differential mode

- Ultra-luminous tritium source, too high for sterile neutrino search, need to reduce activity

- Detector as energy resolving device
- Systematics mainly from detector response





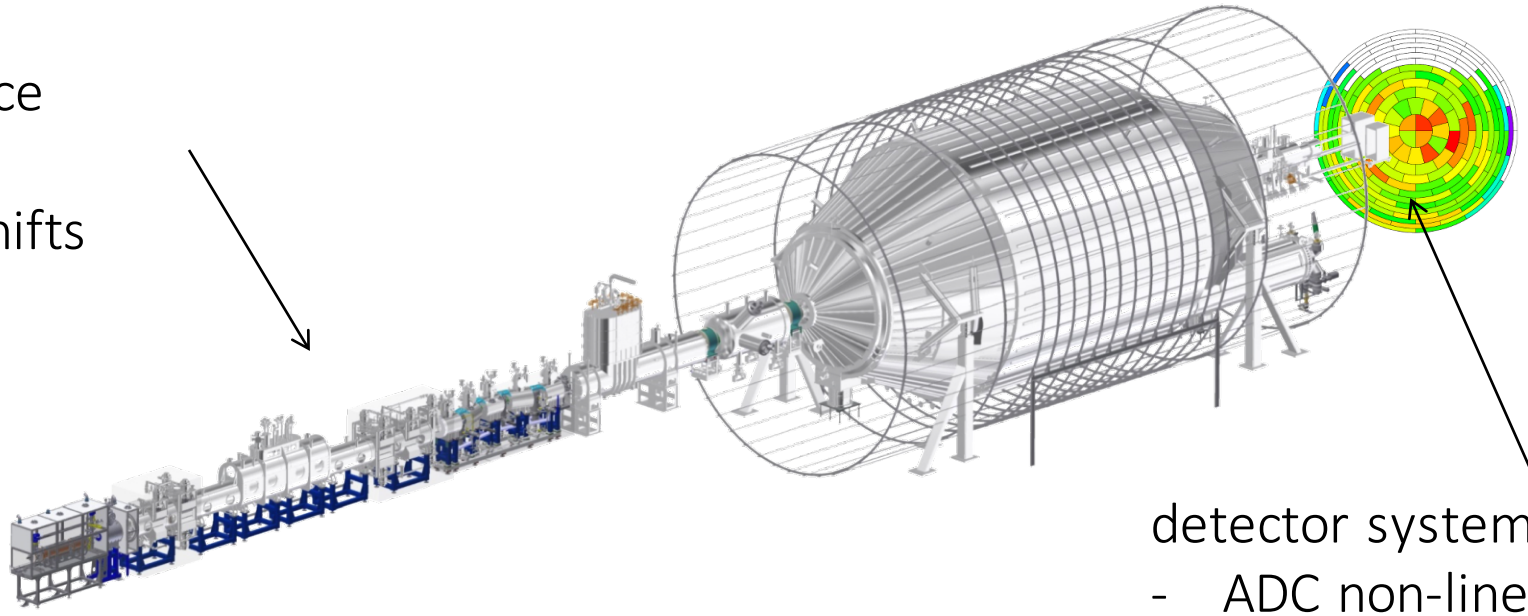
TRISTAN Phase-0

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

Goal: Improve current laboratory limit by orders of magnitude ($\sin^2\theta \approx 10^{-4}$)

Identify, quantify & model systematic effects (non-smooth changes of pure spectrum)

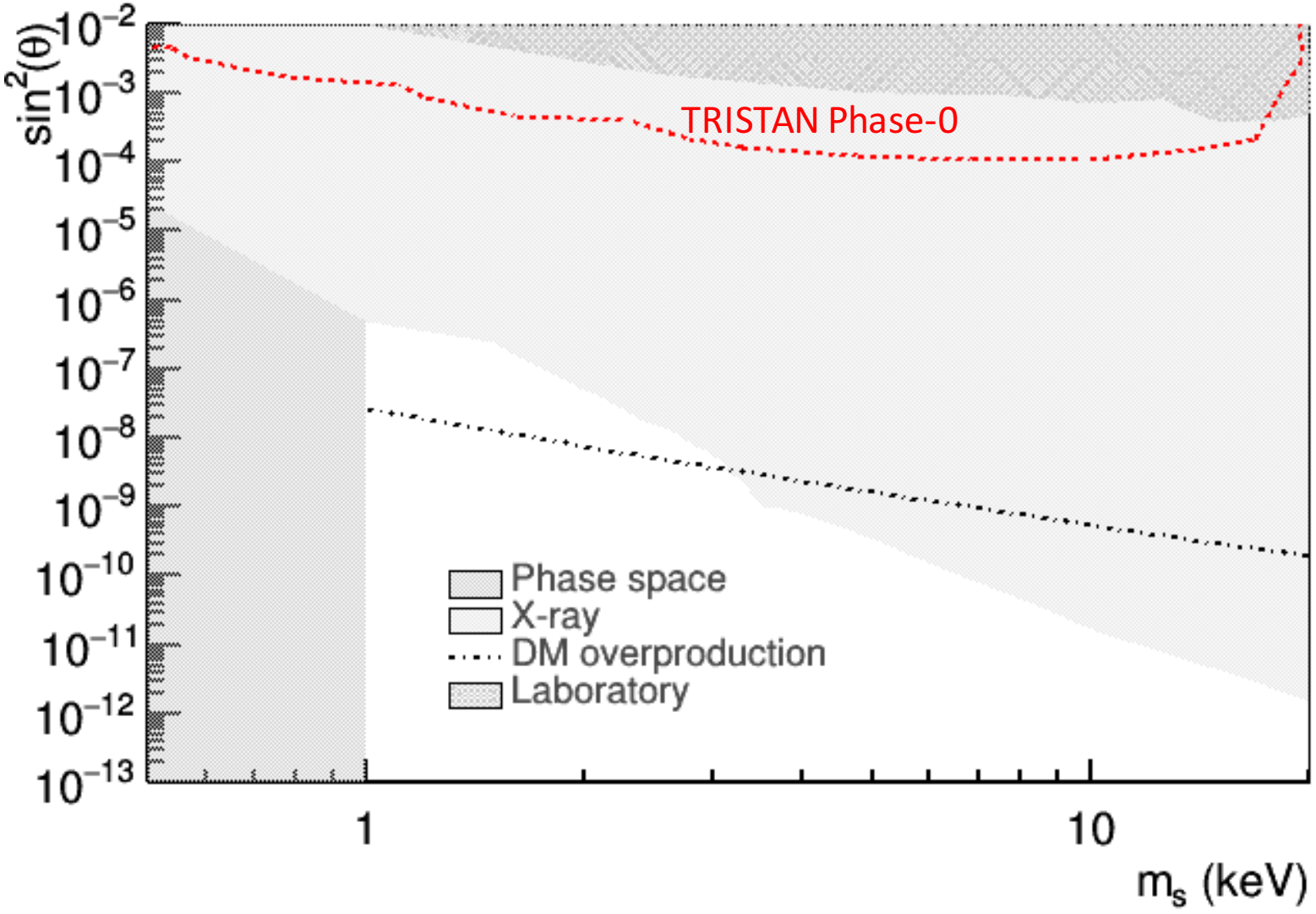
- scattering in the source
- magnetic traps
- source fluctuations/shifts
- …



detector systematics:

- ADC non-linearities (Dolde et al., NIM A, 2017, Vol.848)
- charge sharing
- backscattering
- …

Sensitivity for keV sterile neutrino



- 1 week measurement time, directly before KATRIN starts

TRISTAN Phase-1

TRISTAN Phase-1

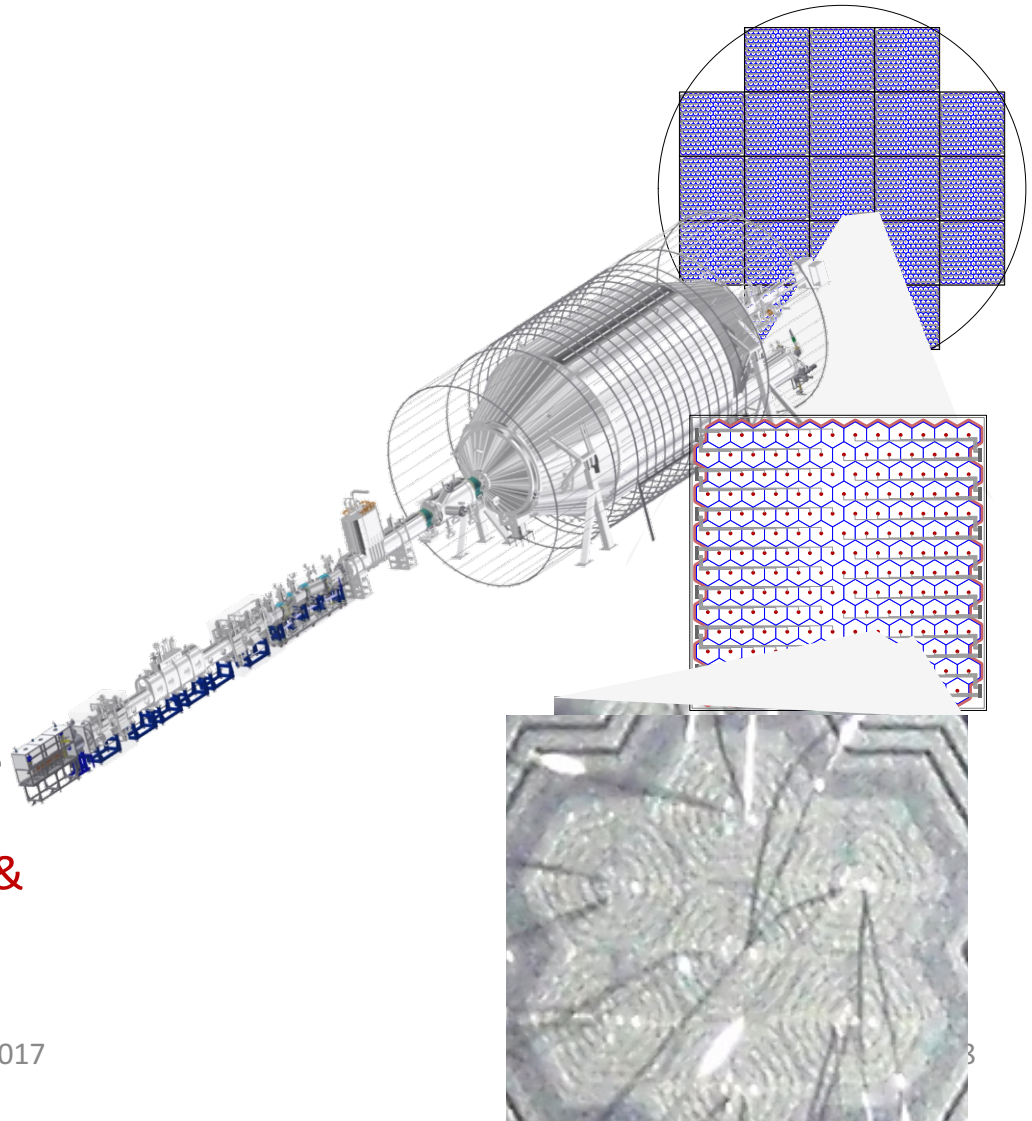
- Goal: Reach astrophysically interesting parameter space ($< \sin^2\theta \approx 10^{-6}$)
- Unprecedented statistics needed (10^{16} signal electrons for 10^{-6} stat. uncertainty) ≈ 10^8 electrons/s for three years!
- Extremely high rate on detector
- Systematic uncertainties on same level!
  - Understanding & modeling of detector response
- New detector & read-out system needed

Detector system requirements

- Capability of handling high rates (≈10^8 cnts/s)
  - ➢ O(4000) pixel
- Excellent energy resolution (≲ 300 eV @ 20keV)

  Low energy threshold (<1 keV)

  Low backscattering probability & impact
  - ➢ Silicon-Drift-Detector (SDD)
  - ➢ Thin entrance window(~10 nm)
- Large pixel size with low noise (cell size ~ 3mm)
  - ➢ Multi-drift-ring design
- Minimize & understand systematics (Pile-up, charge sharing, backscattering)
  - ➢ Waveform digitization, timing info-> high quality ADCs & pulse processing

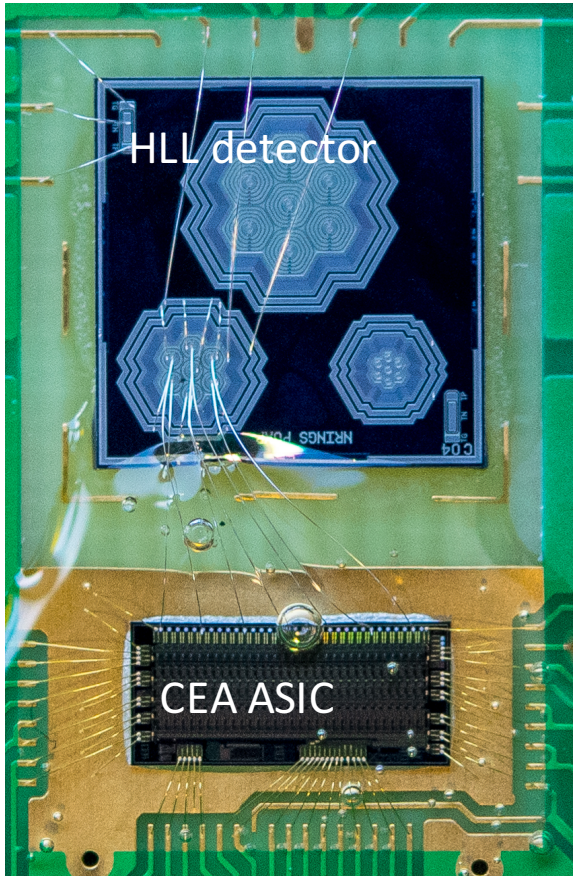


Prototype-0

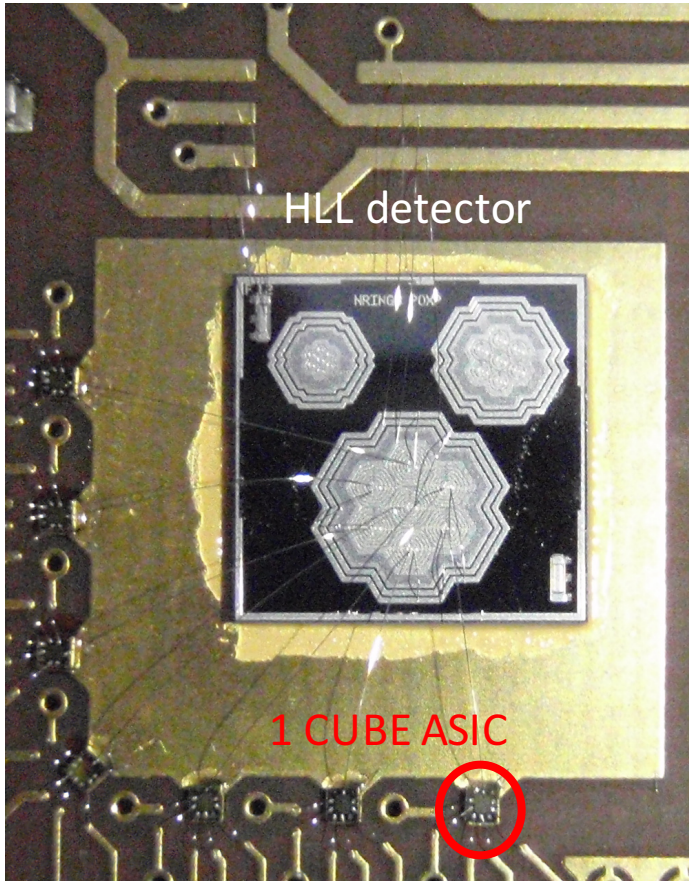
- Silicon-Drift-Detector developed by Semiconductor Lab of MPG (HLL)
- Read-out realized by three different electronic systems

KIT setup

CEA setup



MPP setup



Prototype-0 detector CUBE ASIC

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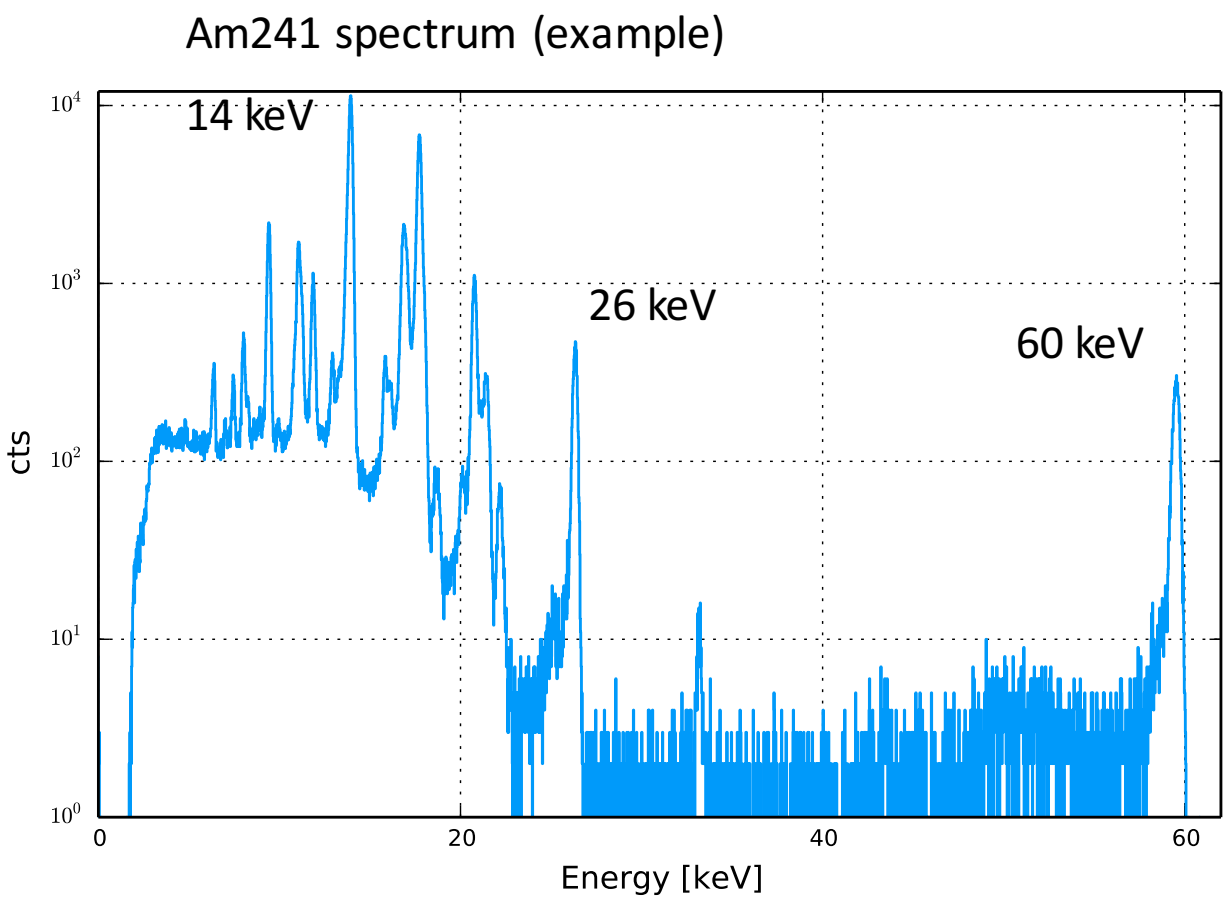
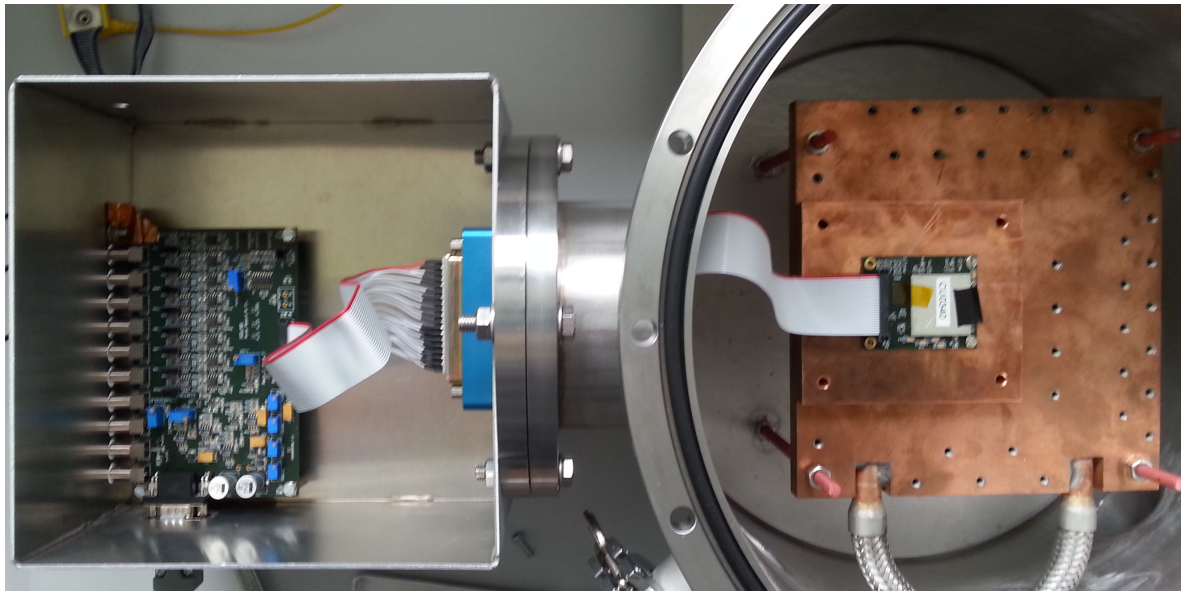
(Werner-Heisenberg-Institut)



- 7 pixel SDD with 1 mm diameter each
- Each pixel connected to on CUBE ASIC
- Read out by DANTE digital pulse processor



Prototype-0 detector CUBE ASIC

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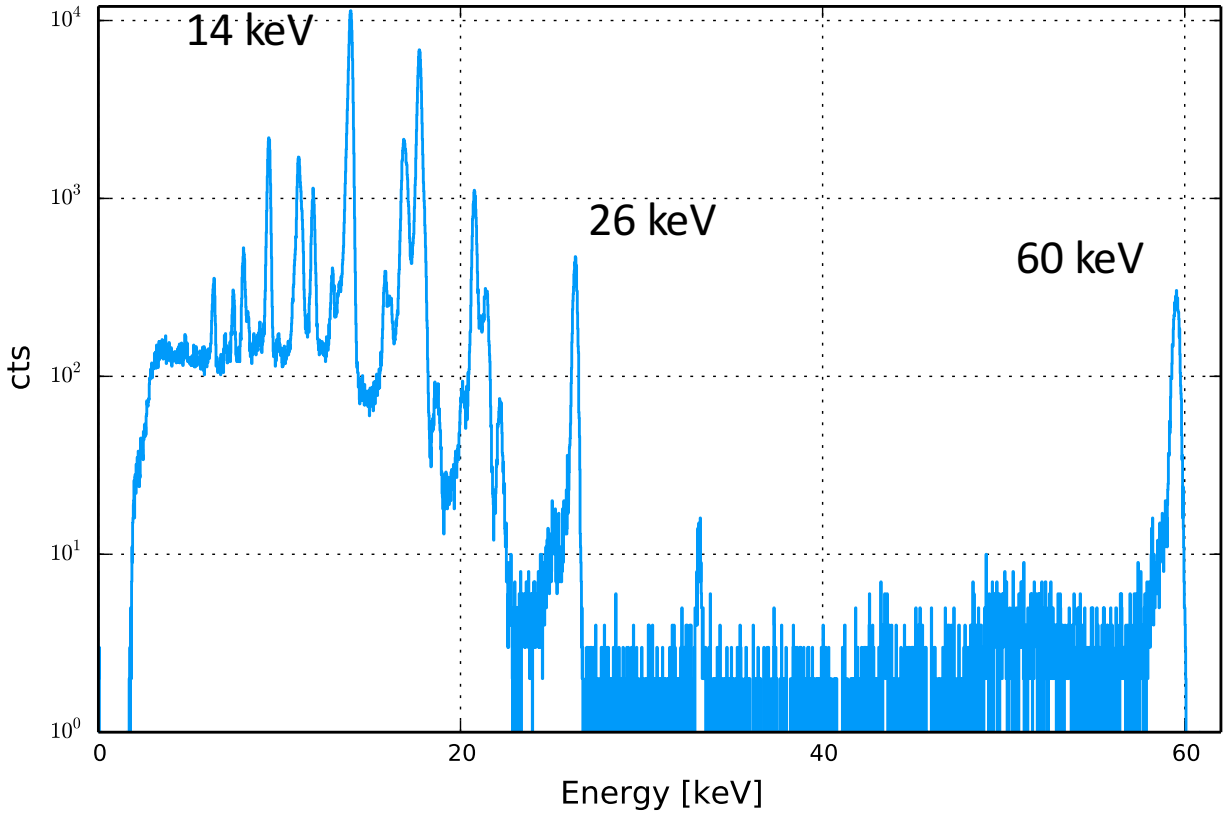
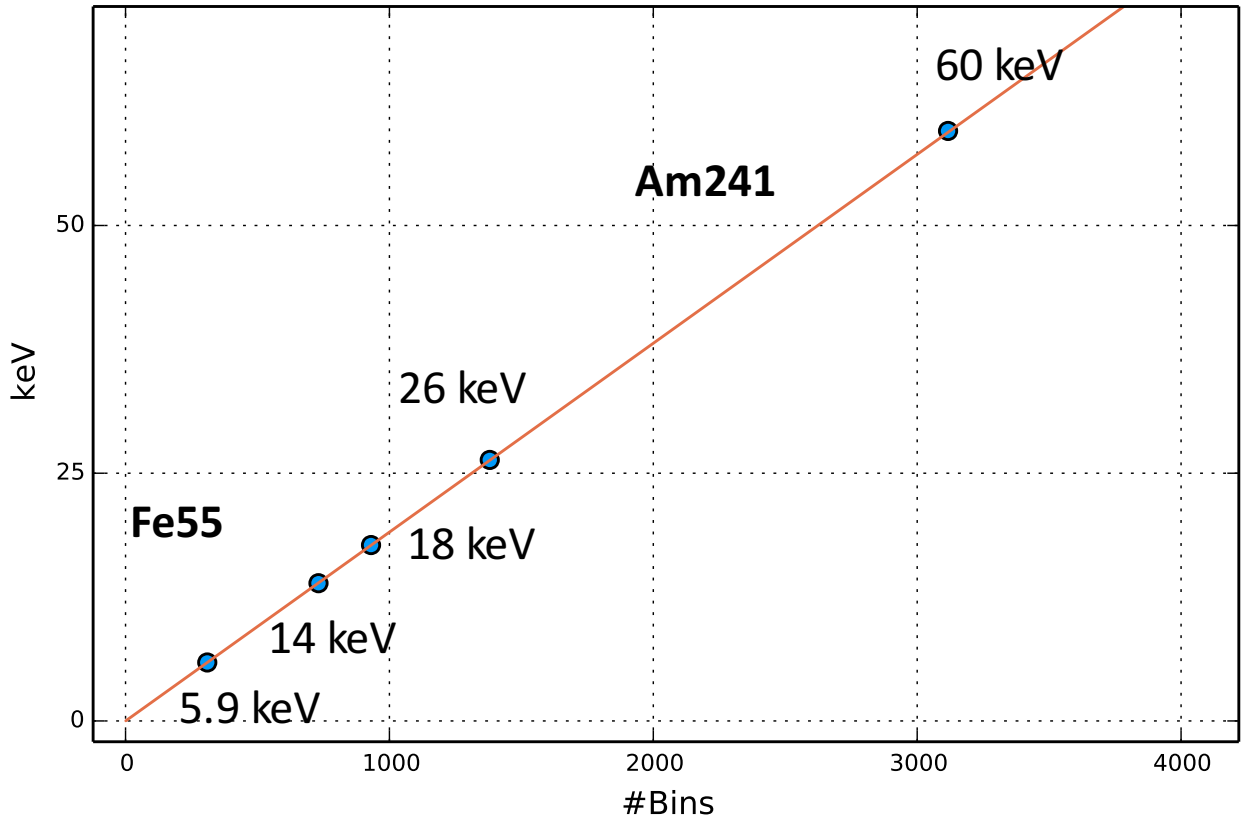
Am241 spectrum (example)



Calibration



Prototype-0 detector CUBE ASIC

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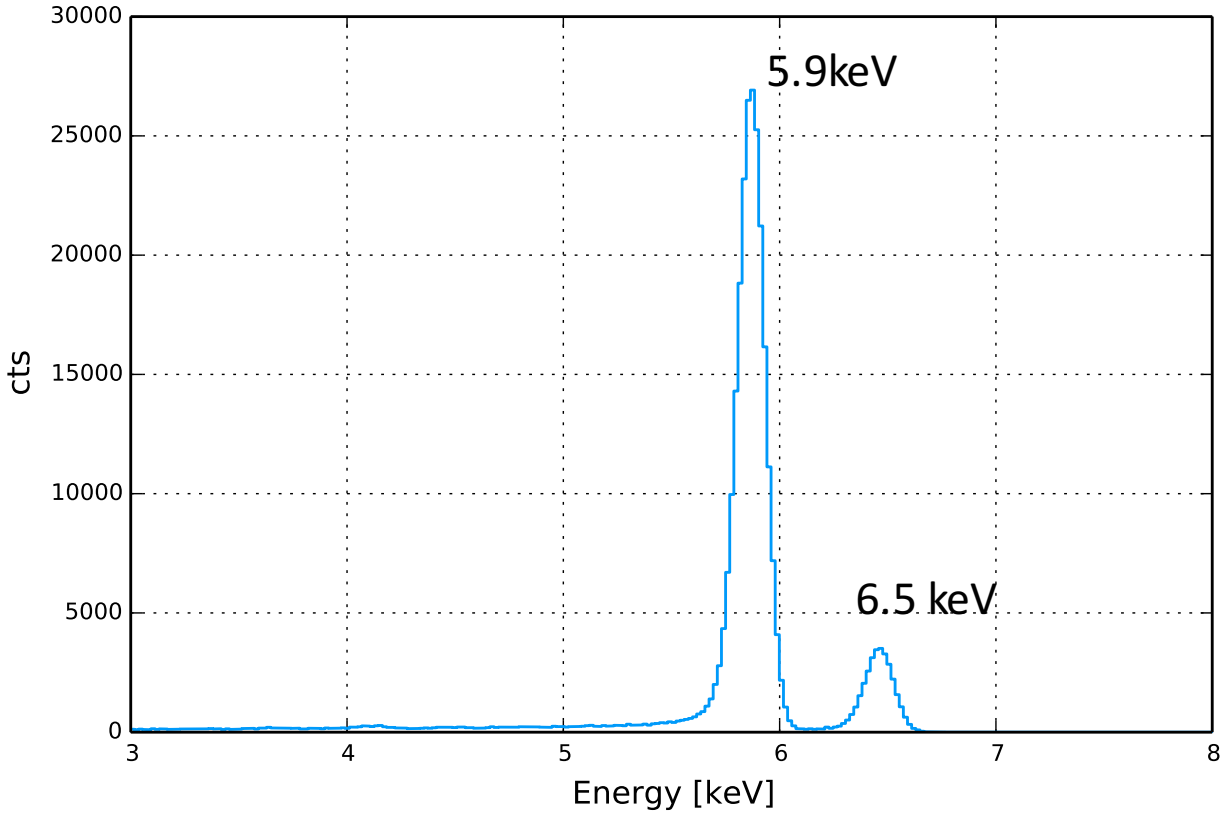
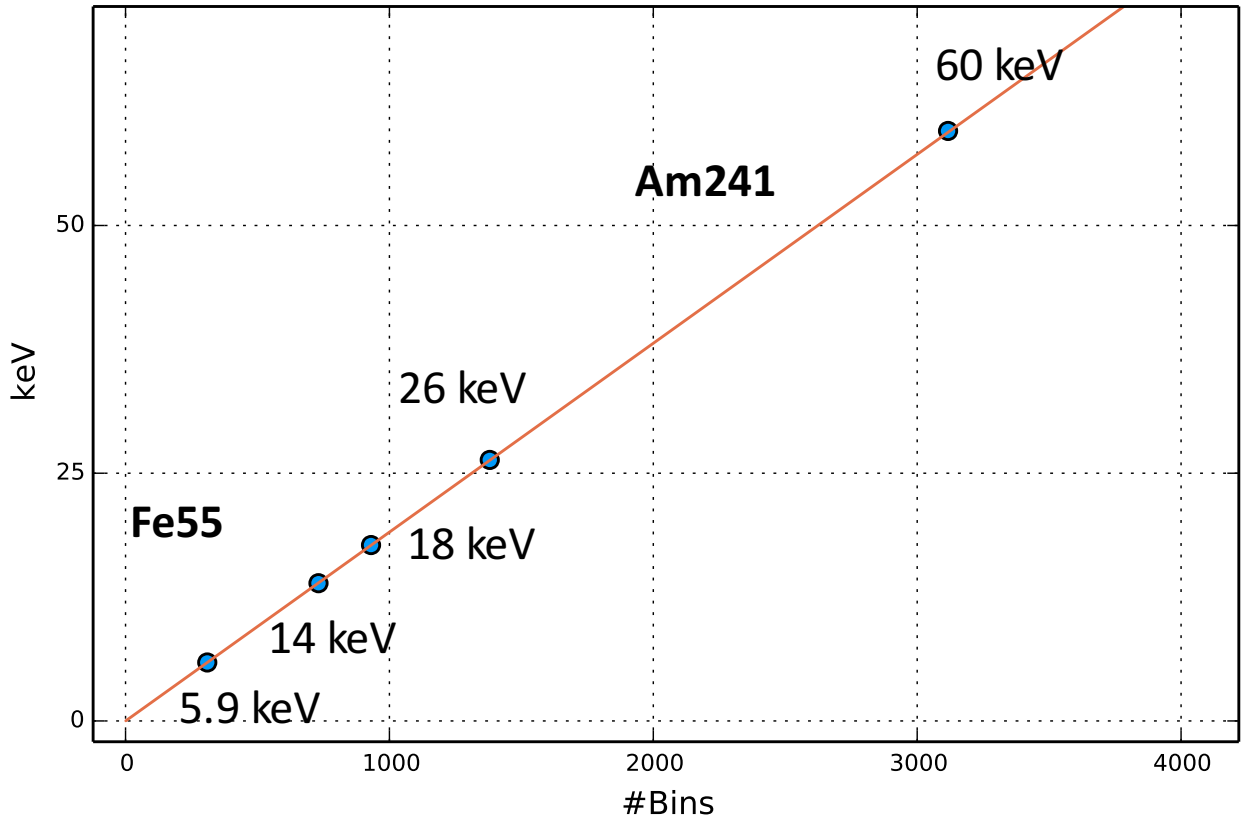
Fe55 spectrum (example)



Calibration



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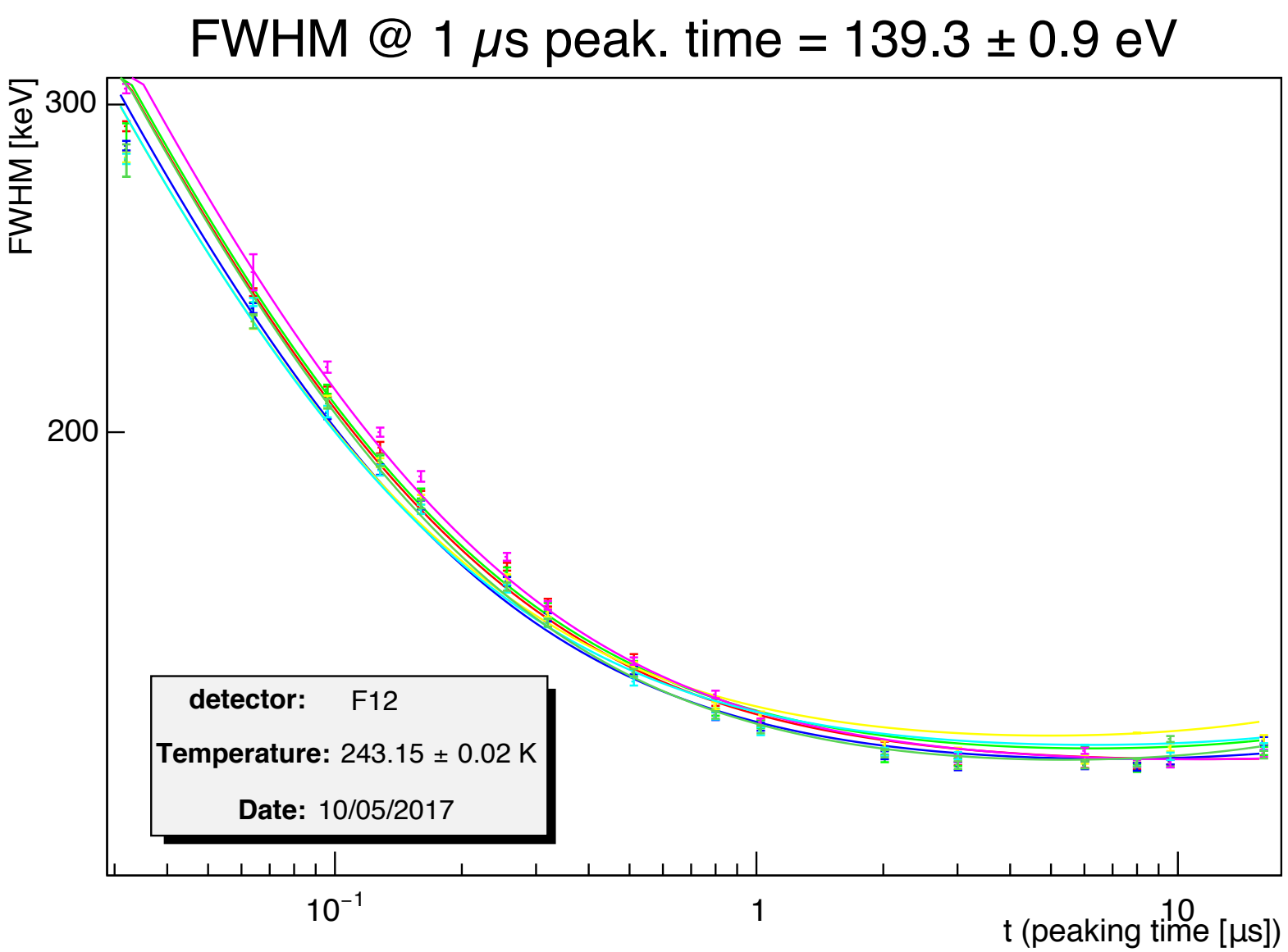


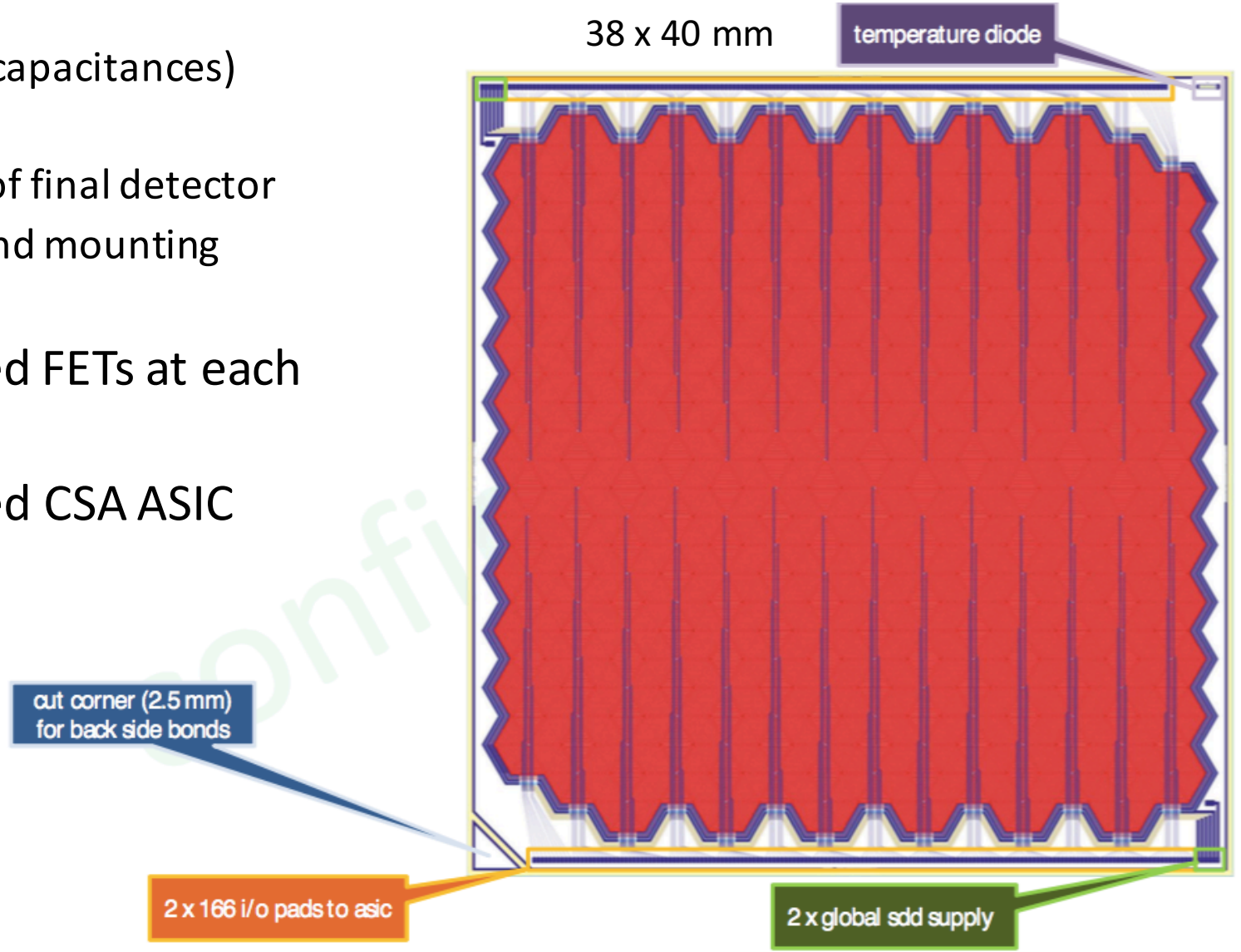
- Noise curve of SDD with CUBE ASIC (MPP setup)
- FWHM (ENC) of 5.9 keV of Fe-55
- SDD@ -30 °C
- Energy resolution requirements met
- Excellent FWHM with sufficiently short peaking times
- Precise measurement at high signal rates possible

Planned measurements Prototype-0

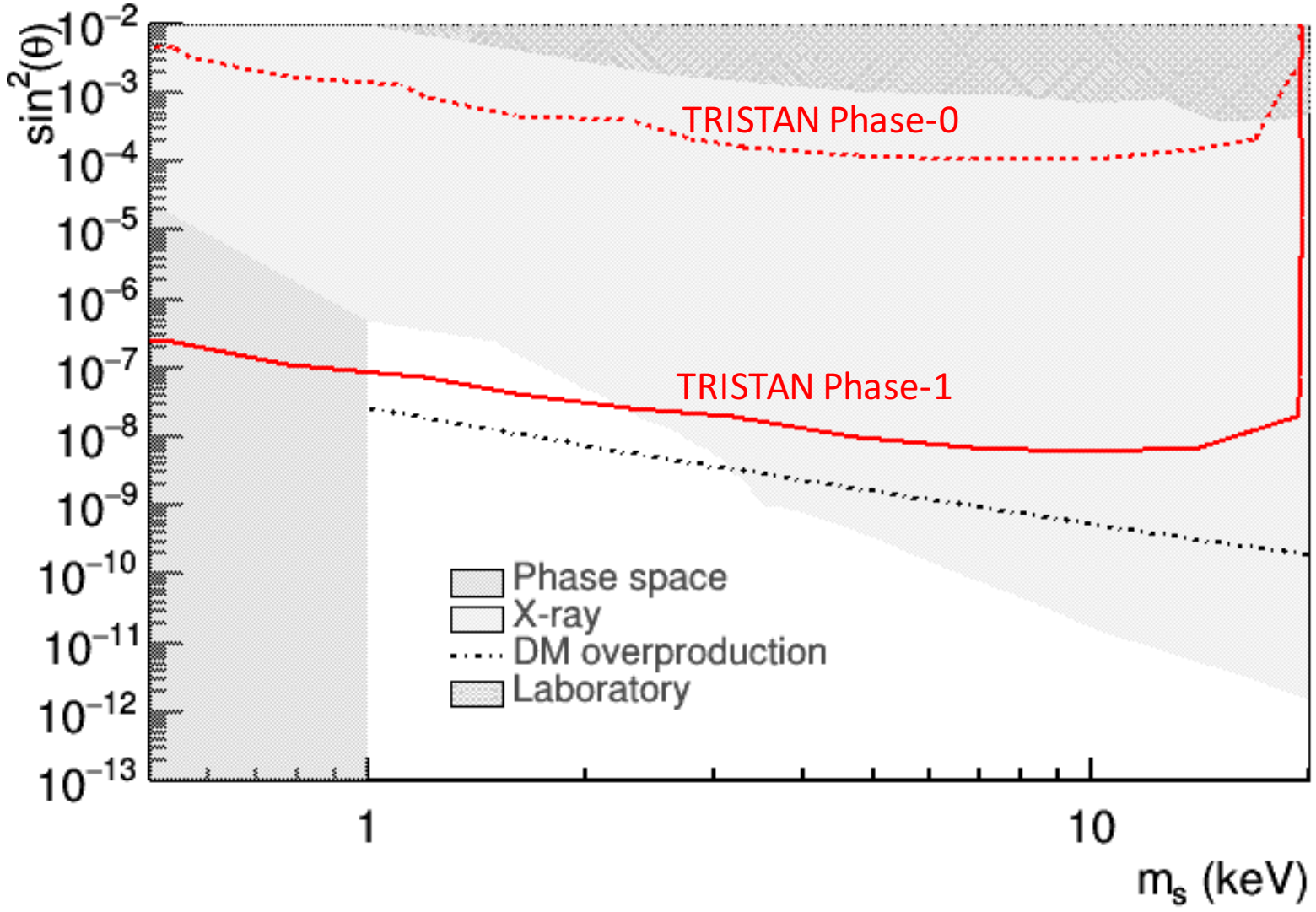
- First test measurements at Troitzk Nu-mass experiment next week (first Tritium!)
- Gaseous Kr-83m with several monoenergetic electrons and x-rays (10 – 30 keV) for direct comparison of them
- Low (3-20keV), monoenergetic e-gun for entrance window thickness determination

Prototype-1 development

- Design considerations:
  - Short signal traces (parasitic capacitances)
  - Small dead area
  - Close to design of one “tile” of final detector
  - Investigate noise, crosstalk and mounting procedure
- 166 pixel SDD with integrated FETs at each anode
- Read-out by custom designed CSA ASIC



Sensitivity for keV sterile neutrino



- 3 years measurement time, after KATRIN finished with neutrino mass measurement

Summary

- keV sterile neutrino are a minimal extension of the Standard Model & an interesting candidate for dark matter
- Tritium beta decay & KATRIN setup well suited for sterile neutrino search

- TRISTAN Phase-0:
  Improve laboratory limits by orders of magnitude with existing KATRIN setup & reduced source activity

- TRISTAN Phase-1:
  Reach limits in the astrophysically interesting range with upgraded KATRIN setup & high source activity

Links

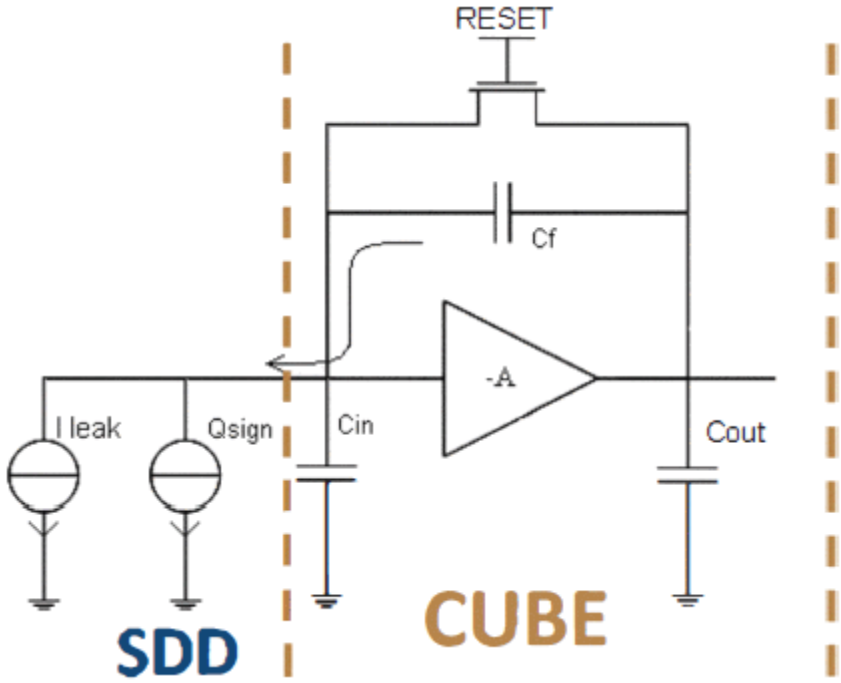
- http://www.katrin.kit.edu/
- https://www.mpp.mpg.de/en/research/astroparticle-physics-and-cosmology/katrin-and-tristan-neutrinos-and-dark-matter/
- keV sterile neutrino white paper: https://arxiv.org/abs/1602.04816

Thank you for your attention!

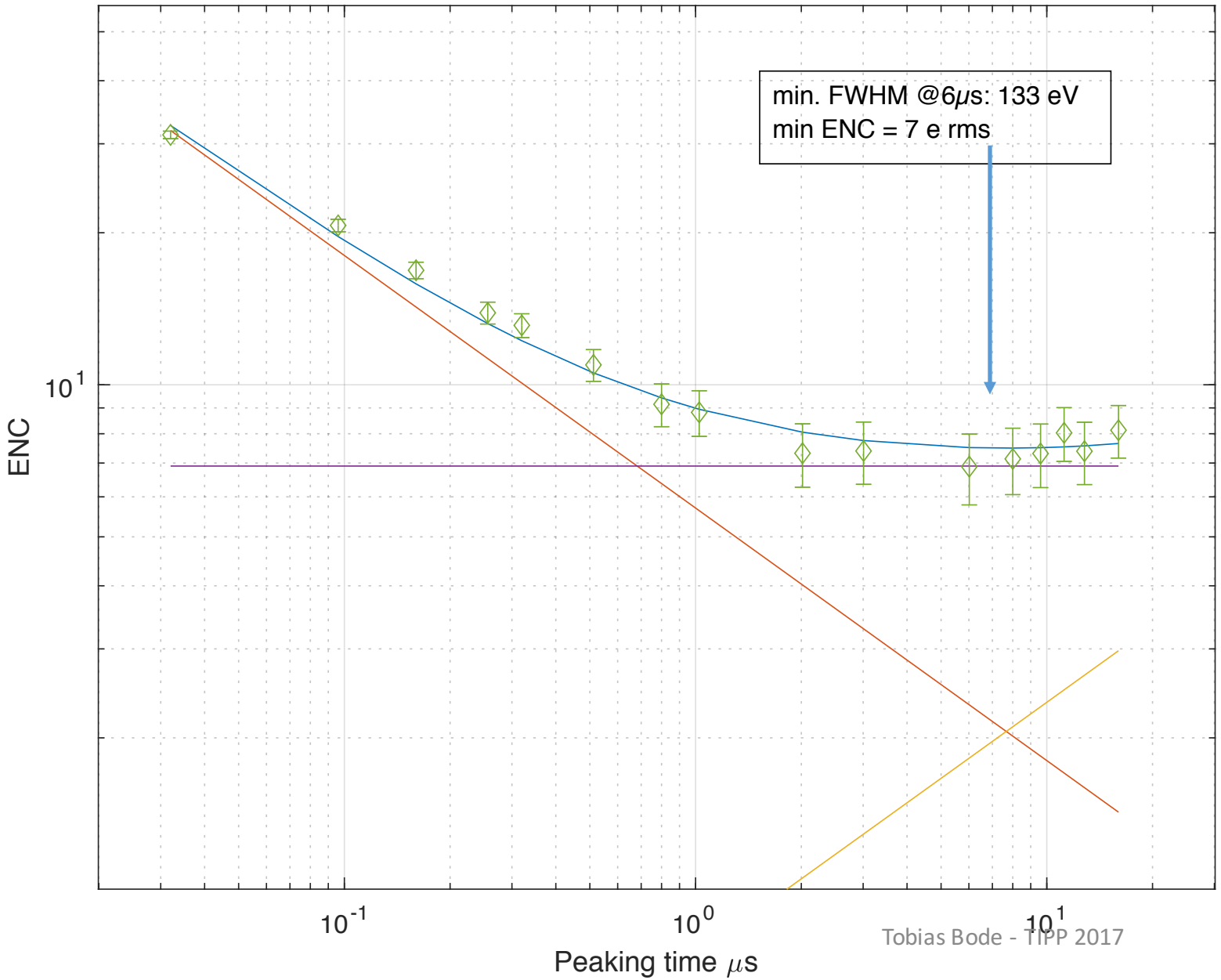
CUBE ASIC by XGLab S.R.L.

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

- monolithic CMOS charge sensitive amplifier (0.75 x 0.75 x 0.25 mm)
- High signal level at output
- Drives “long” connections
- Low series noise
- Power consumption ~6.4 mW
- Pulsed-reset
- Noise: 3.4 ENC (no SDD)
- Works at cryogenic T (~50 K)
- Mcps have been achieved with very good energy resolution



Prototype-0 detector CUBE ASIC



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