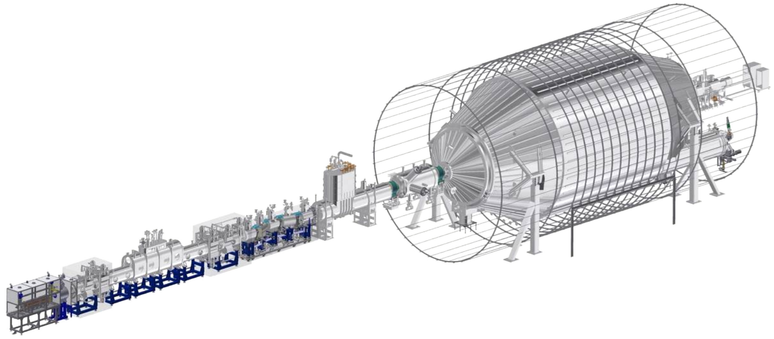
Technical University of Munich

MAX-PLANCK-INSTITUT FÜR PHYSIK



Search for keV sterile neutrinos

16th PATRAS Workshop

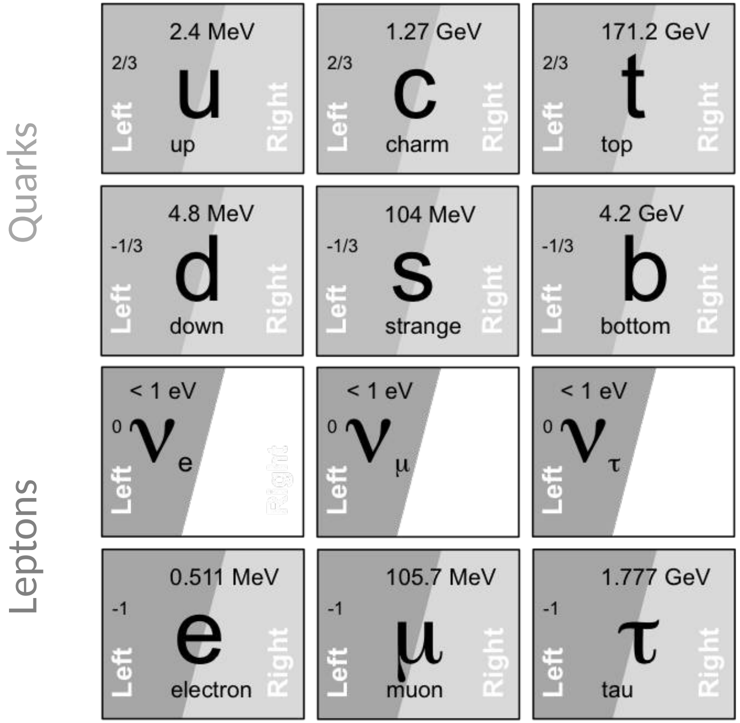
Thibaut Houdy, Susanne Mertens

18th of June, 2021

What are neutrinos?

Neutrinos oscillate → they are massive

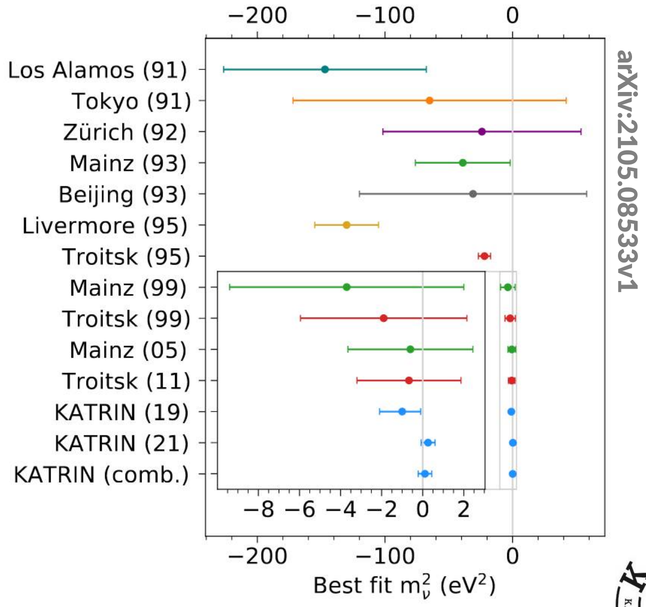
Standard Model (SM)



What are neutrinos?

Neutrinos oscillate → they are massive

What is their mass?

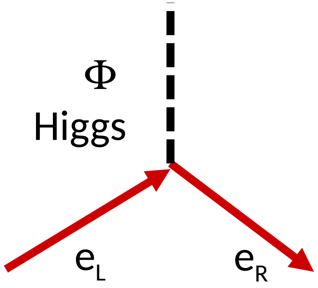


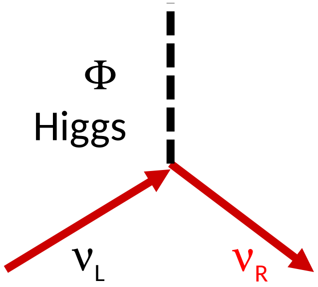
$$m_\nu < 0.9\,\mathrm{eV} \text{ at } 90\,\% \text{ CL}$$

What are neutrinos?

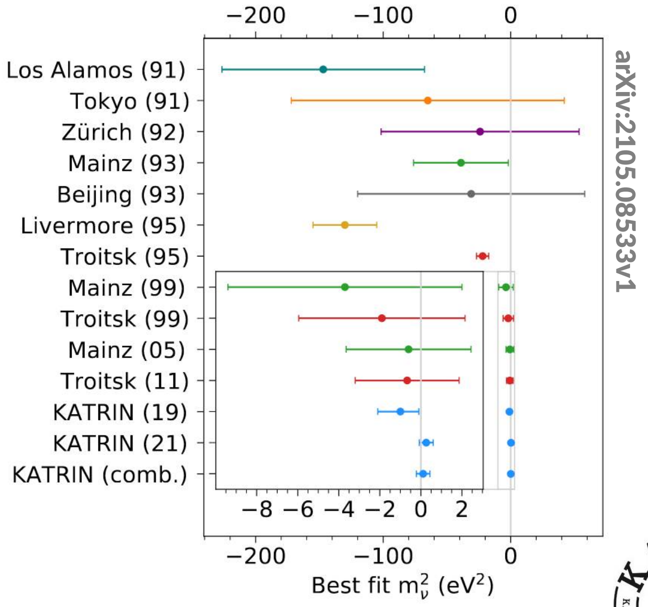
Neutrinos oscillate → they are massive

How is it generated?





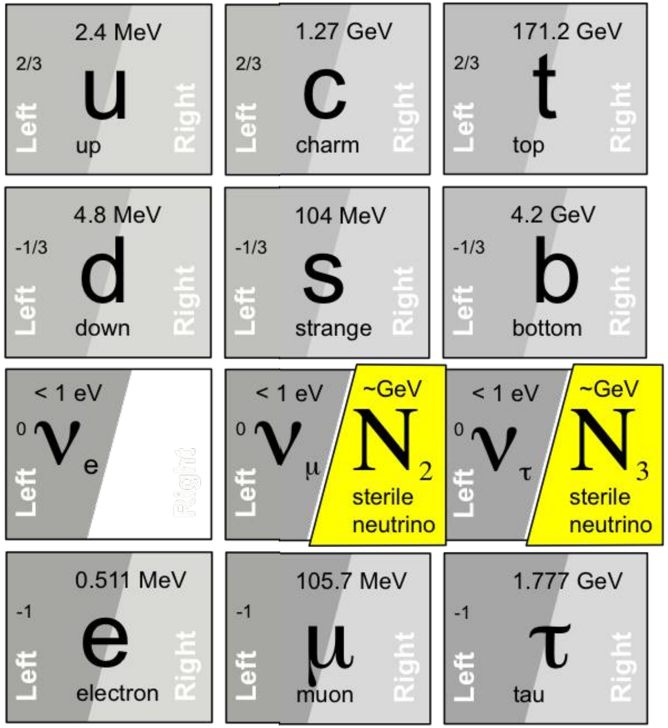
What is their mass?



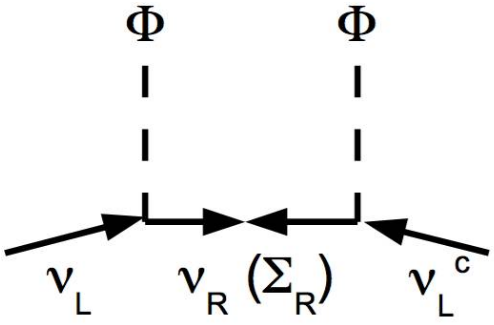
$$m_\nu < 0.9\,\mathrm{eV} \text{ at } 90\,\%\ \mathrm{CL}$$

What are neutrinos?

Neutrinos oscillate → they are massive
Mass generation → existence of a sterile neutrino? (ex: See-Saw mechanism)

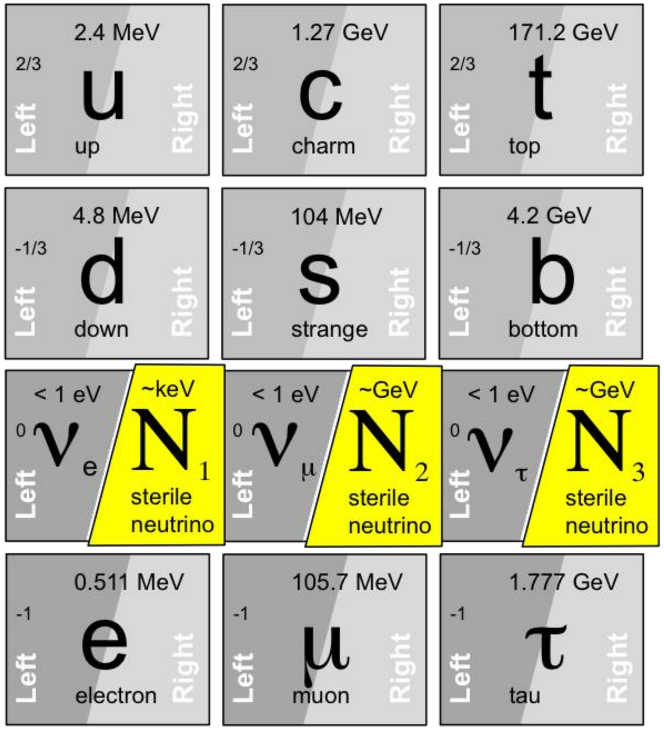


L. Canetti,et al. PRL 110 061801 (2013)



What are neutrinos?

Neutrinos oscillate → they are massive
Mass generation → existence of a sterile neutrino? (ex: See-Saw mechanism)
Simple extension of the standard model (ex: νMSM[1])



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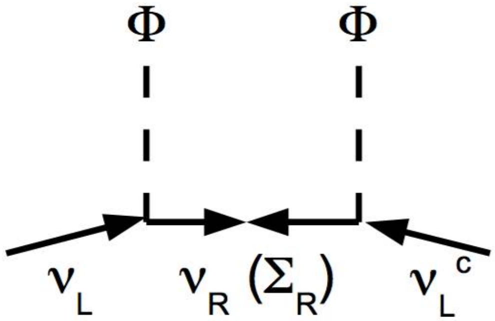
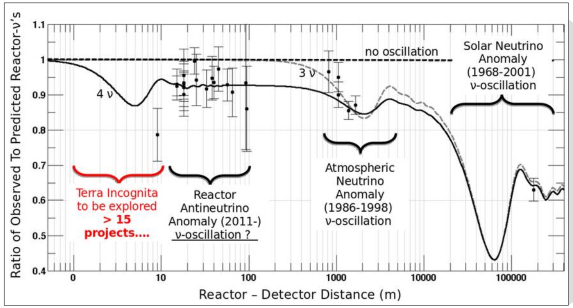
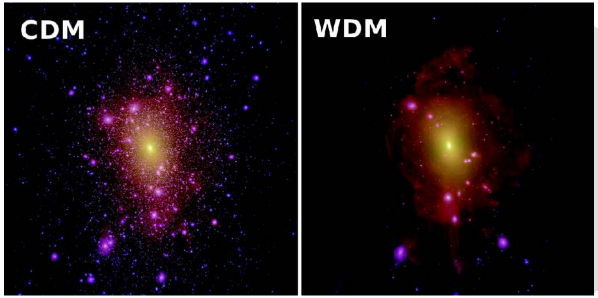


1. T. Asaka, S. Blanchet and M. Shaposhnikov The nuMSM, dark matter and neutrino masses, Phys. Lett. B631:151-156 (2005)

Is there a sterile neutrino ?

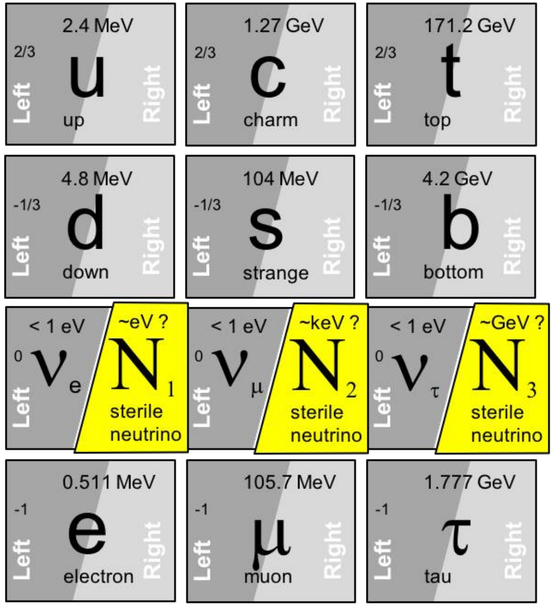


eV-scale:
Resolve anomalies in oscillation experiments



keV-scale:
Dark Matter candidate

GeV-scale:
See-saw candidate



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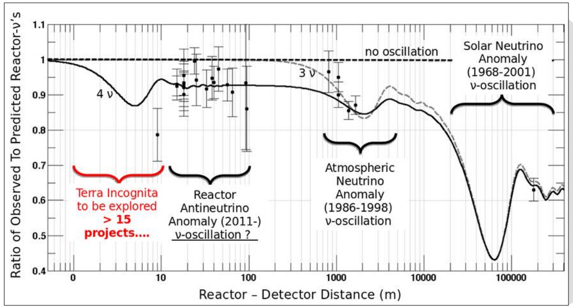

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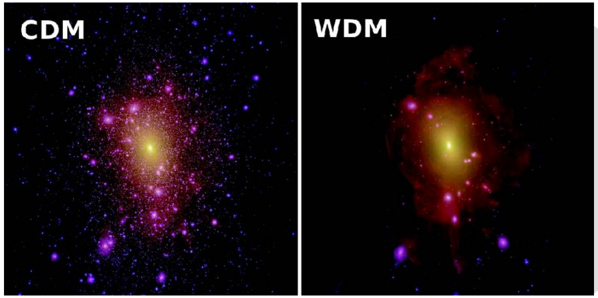
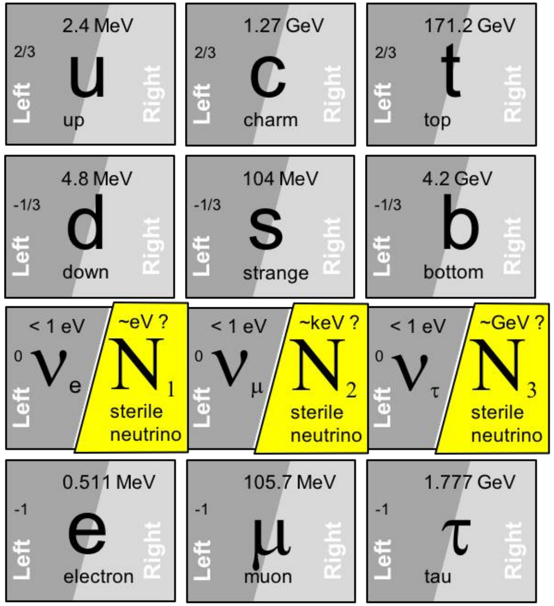


keV-scale:
Dark Matter candidate

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

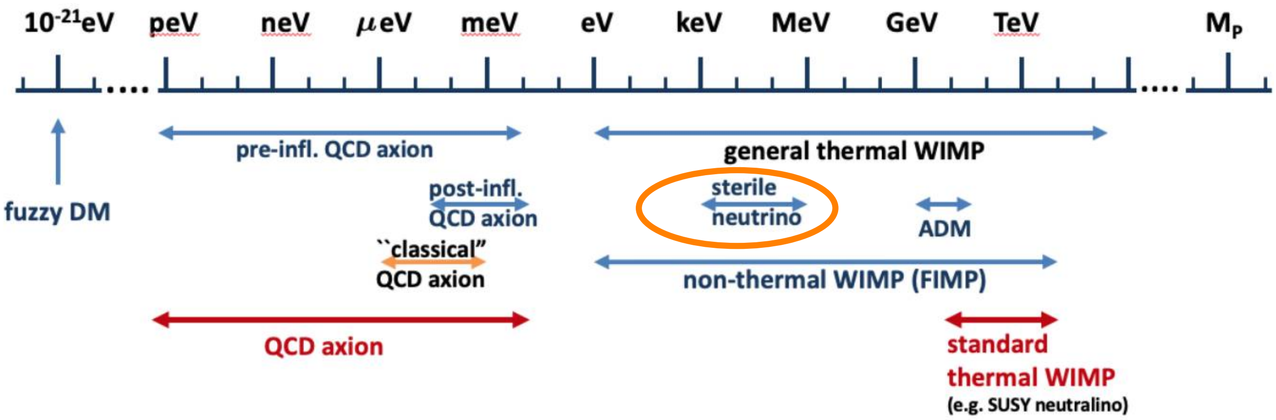
R. Adhikari et al JCAP01(2017)025

A White Paper on keV sterile neutrino Dark Matter



keV-sterile neutrinos as Dark Matter

https://arxiv.org/abs/2104.07634



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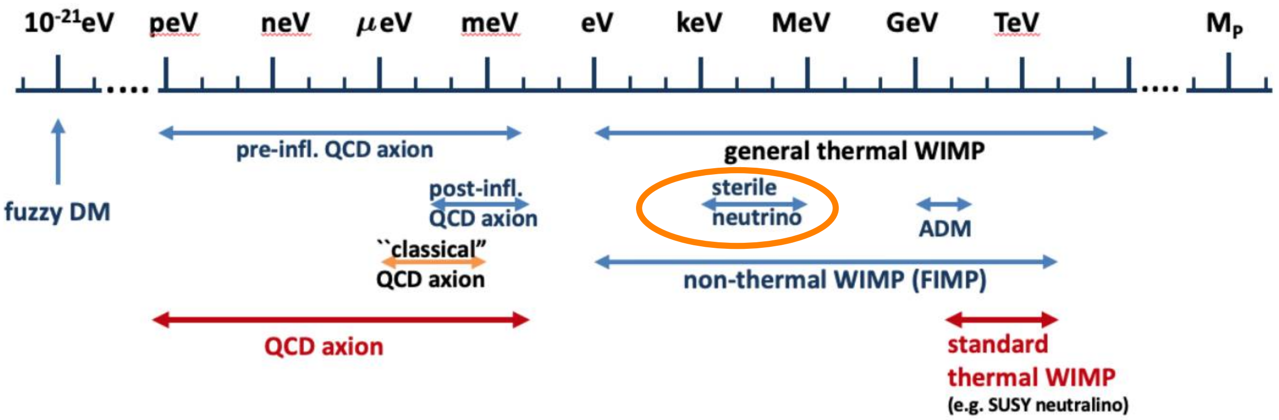
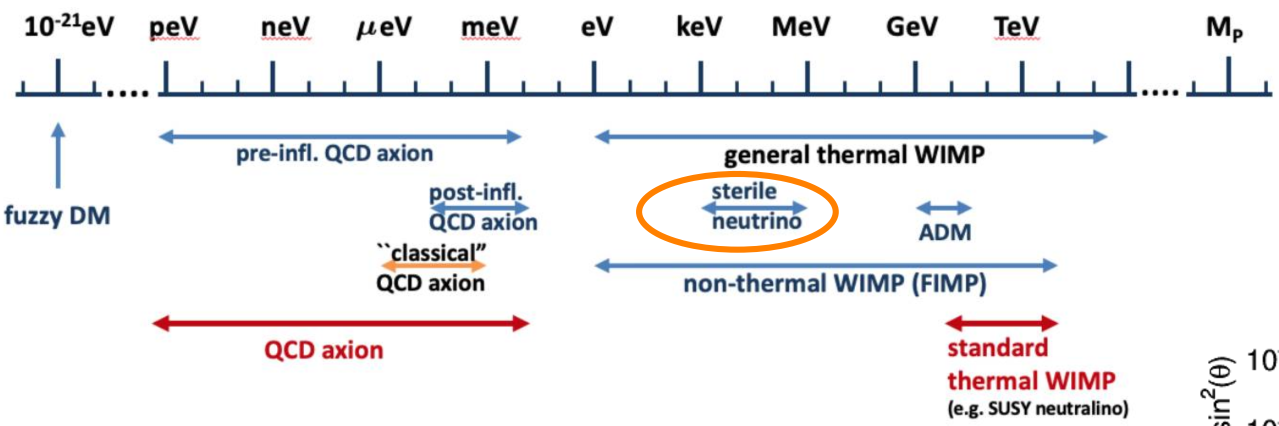


Production mechanisms:

- Thermal production
- Oscillation from active ν via scattering (Dodelson-Widrow)
- Enhancement via leptonnumber (Shi-Fuller)
- Decay of heavy scalar
- and many others...

keV-sterile neutrinos as Dark Matter



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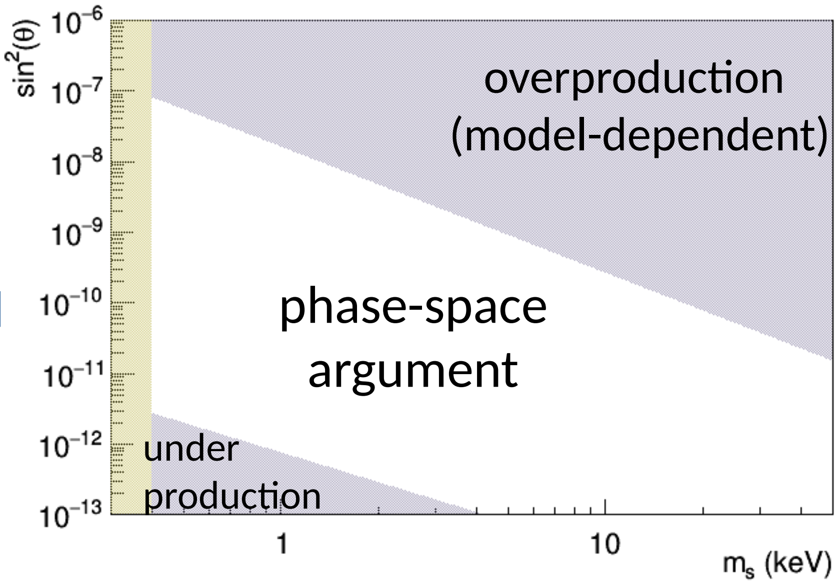
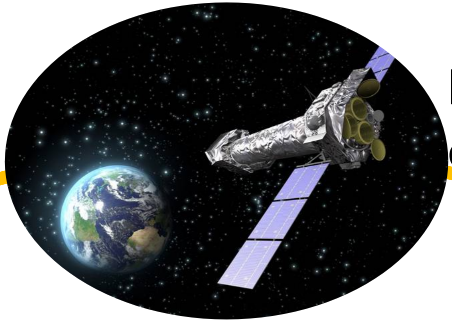
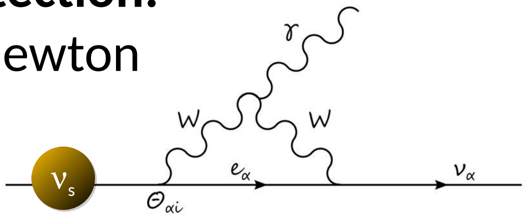
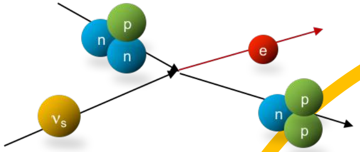


Experimental searches

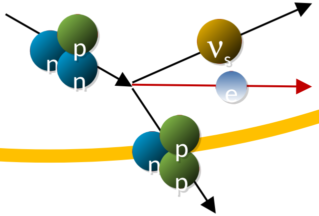


Indirect Detection:
e.g. XMM Newton



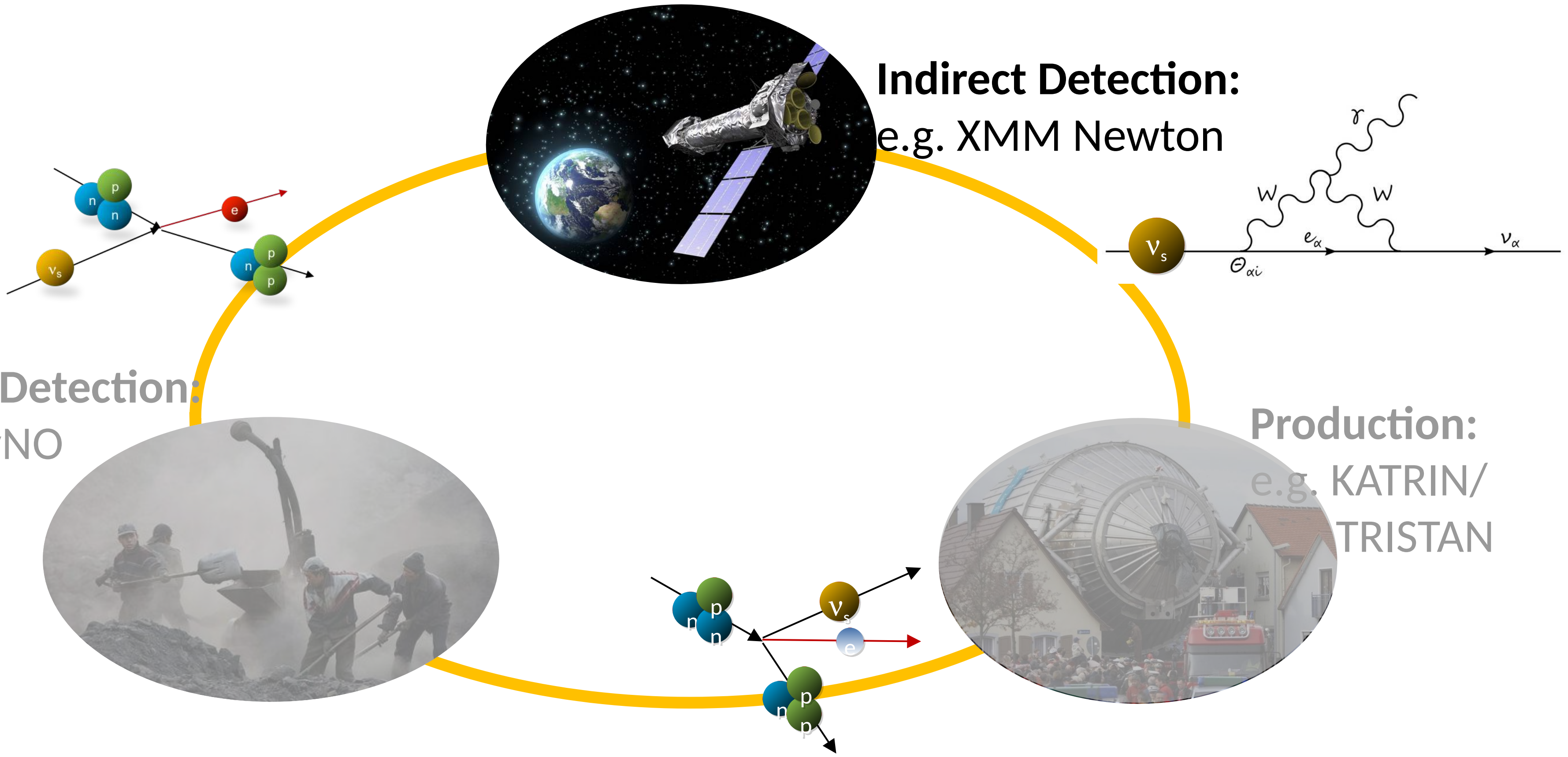


Direct Detection:
e.g. DyNO



Production:
e.g. KATRIN/
TRISTAN

Experimental searches



Indirect searches

- **Structure formations**

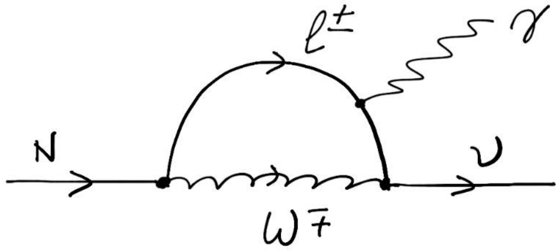
- **Radiative decay**

Looking for keV x-ray signals emitted in high density DM locations via radiactive decay of sterile neutrino

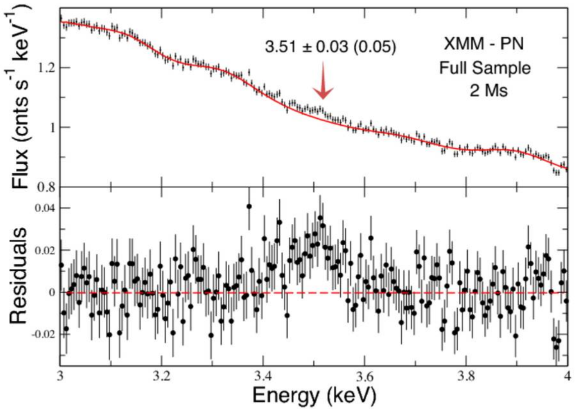
→ signal at 3.5 keV observed by stacking galaxy clusters (XMM-Newton, Suzaku, Chandra), in Andromeda and Milky Way

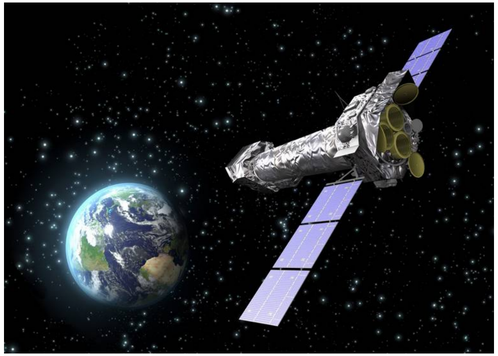
Some results are contradictory (Hitomi)

Atomic transition is still discussed



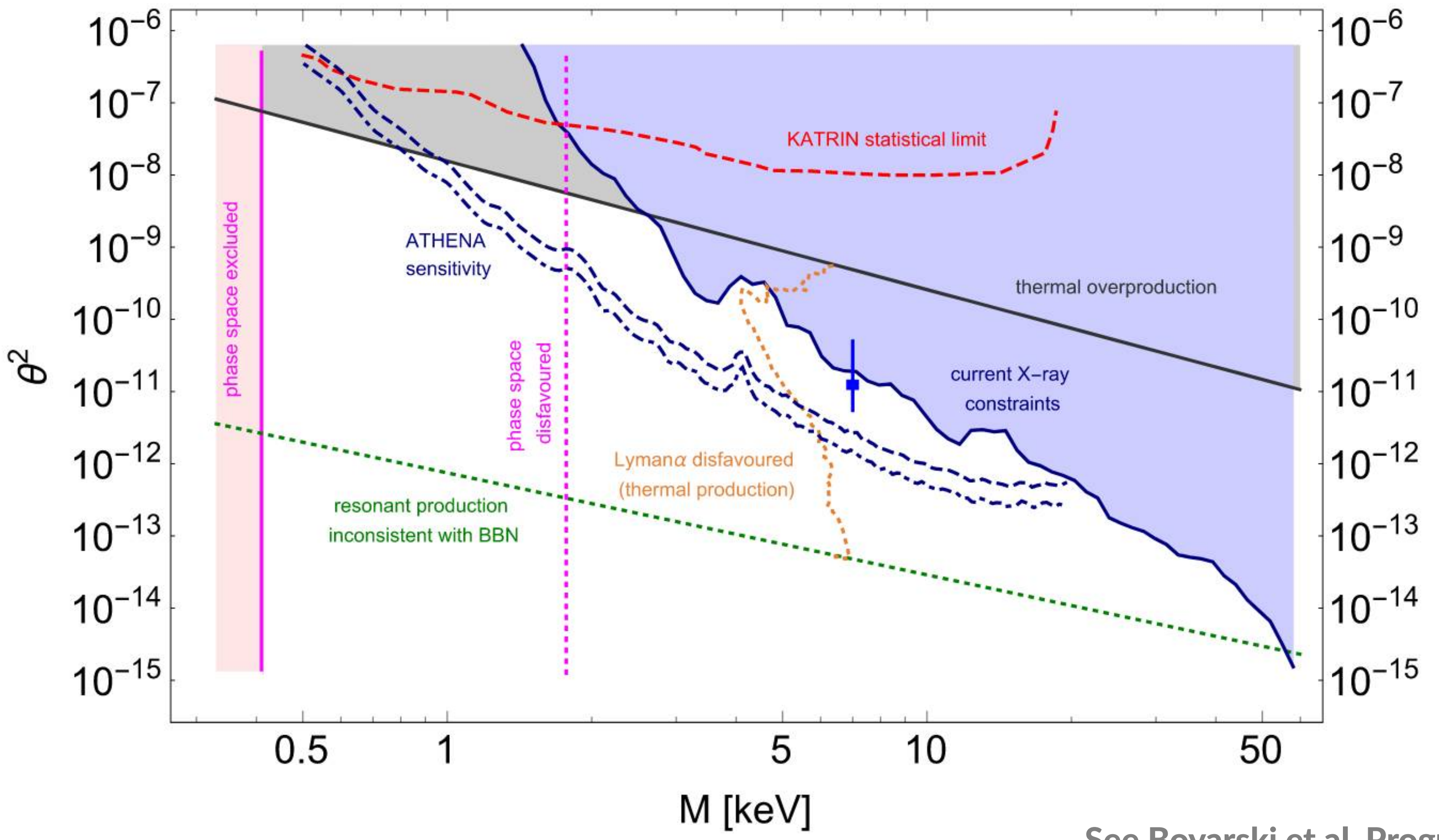
Radiative decay of sterile neutrino





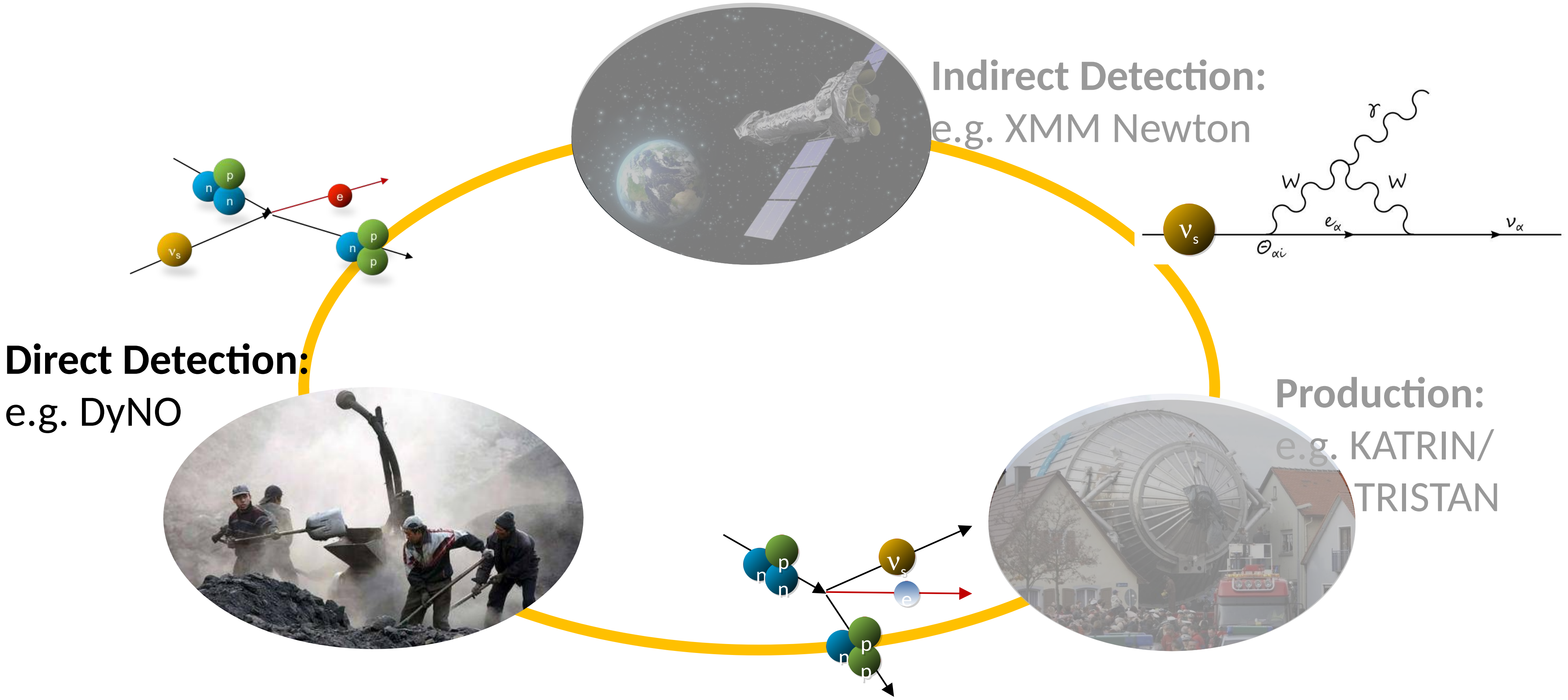
Bulbulet al1402.2301, Boyarskyet al1402.4119
Dessert et al, Science 367 (2020)

keV-sterile neutrinos as Dark Matter



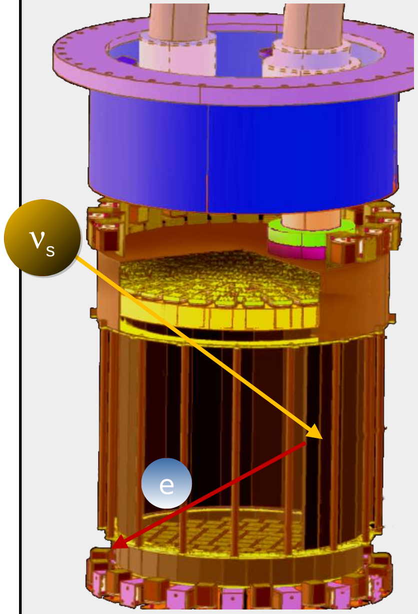
See Boyarski et al, Progress in Particle and Nuclear Physics 104, 1-45 (2019)

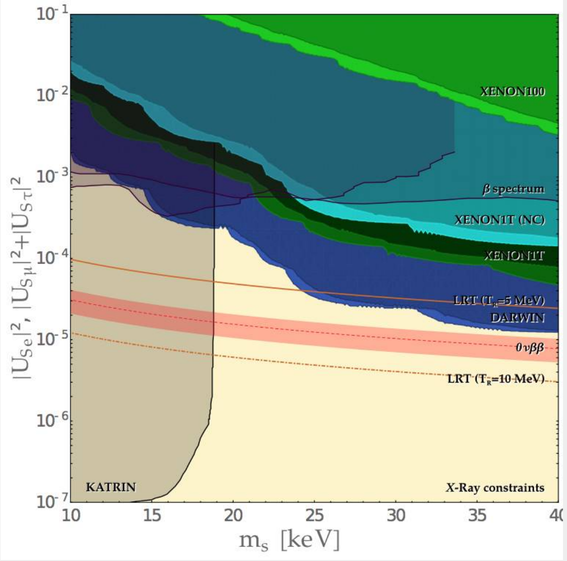
Experimental searches



Direct detection

- **Electronic recoil in massive DM exp.**

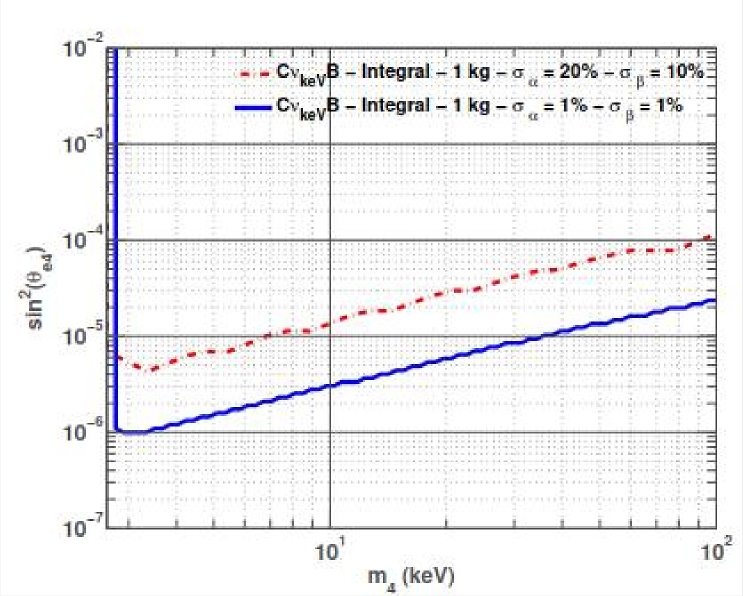




XENON1T, XENONNT, DARWIN

Miguel D. Campos, Werner Rodejohann: Phys. Rev. D 94, 095010 (2016)

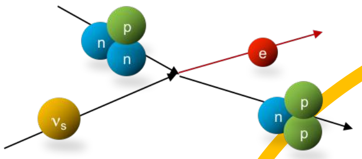
- **Neutrino capture on stable isotope**

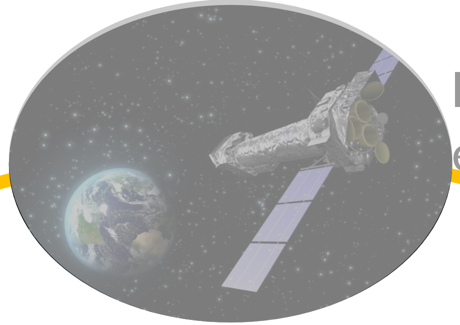


arXiv:1609.04671v2

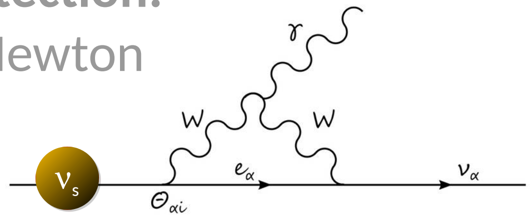
Dyno:
Neutrino capture on ^{163}Dy to produce ^{163}Ho. Extraction and measure of Ho/Do

Experimental searches

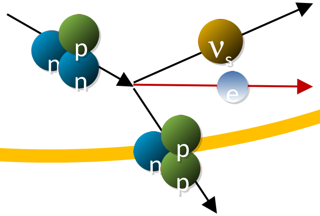




Indirect Detection:
e.g. XMM Newton

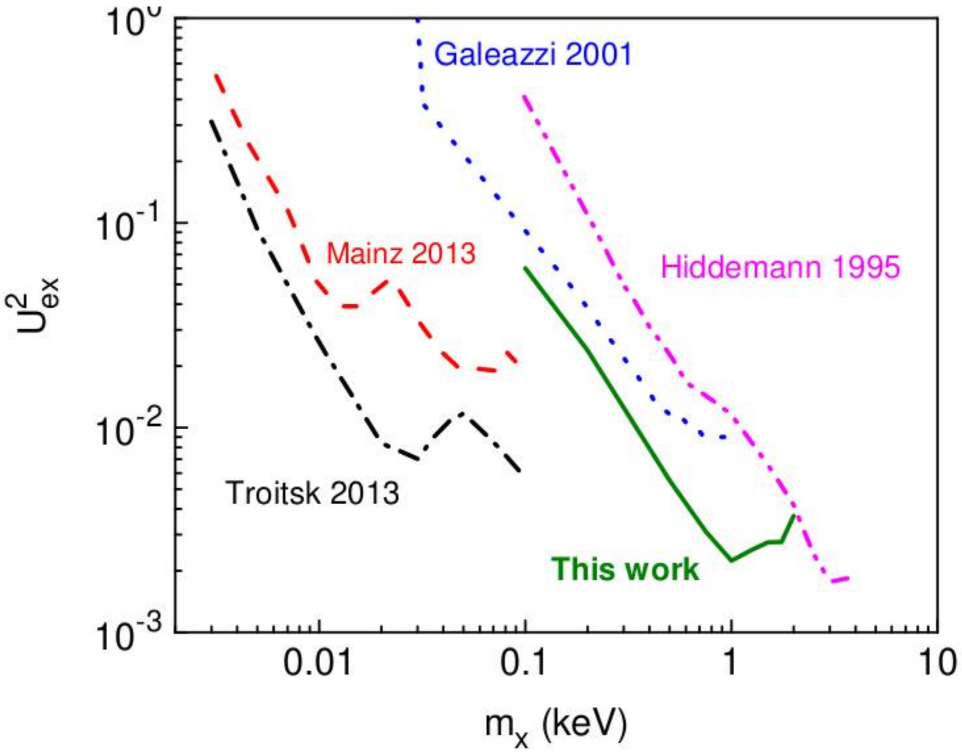


Direct Detection:
e.g. DyNO

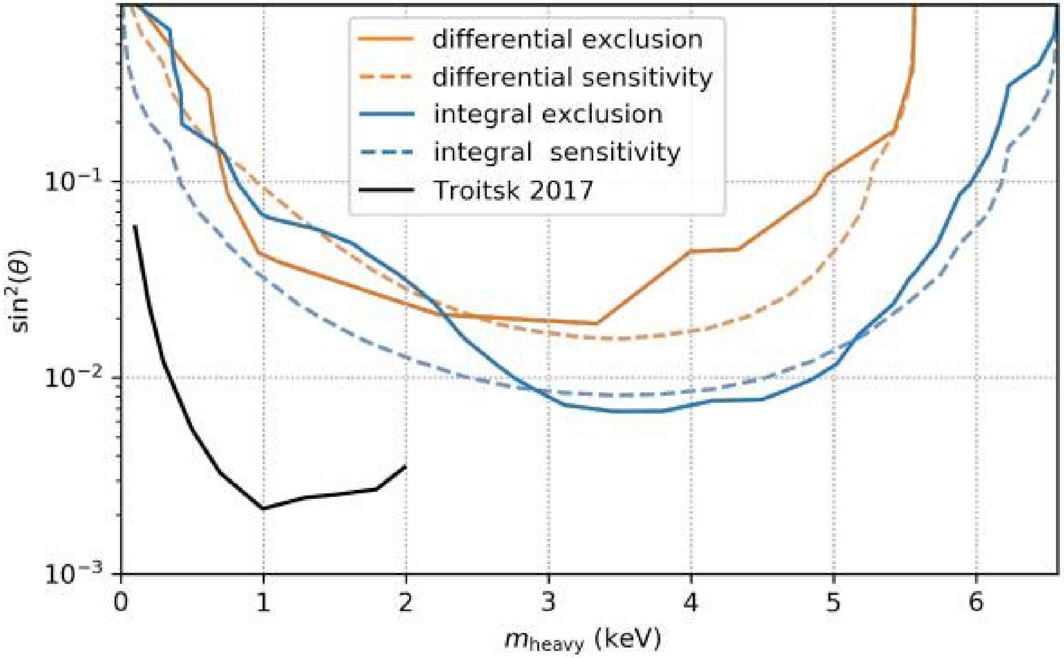


Production:
e.g. KATRIN/
TRISTAN

Production



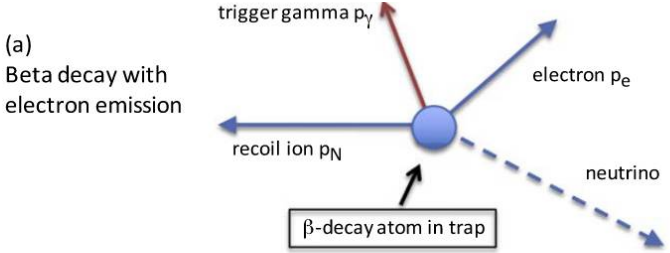
Abdurashitov, J.N., Belesev, A.I., Chernov, V.G. et al. Jetp Lett. 105, 753–757 (2017)



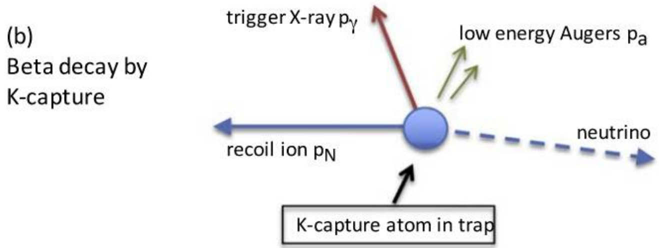
Brunst T., Houdy T. et al. JINST14 P11013 (2019)

Total Energy–Momentum reconstruction

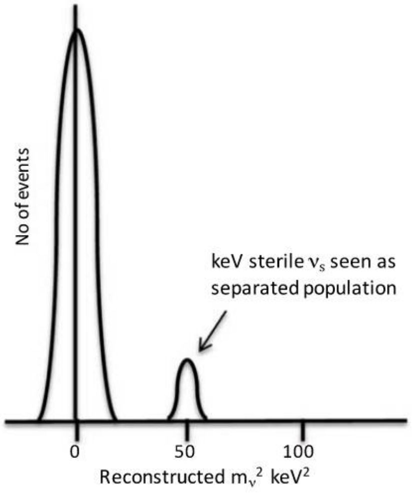
HUNTER

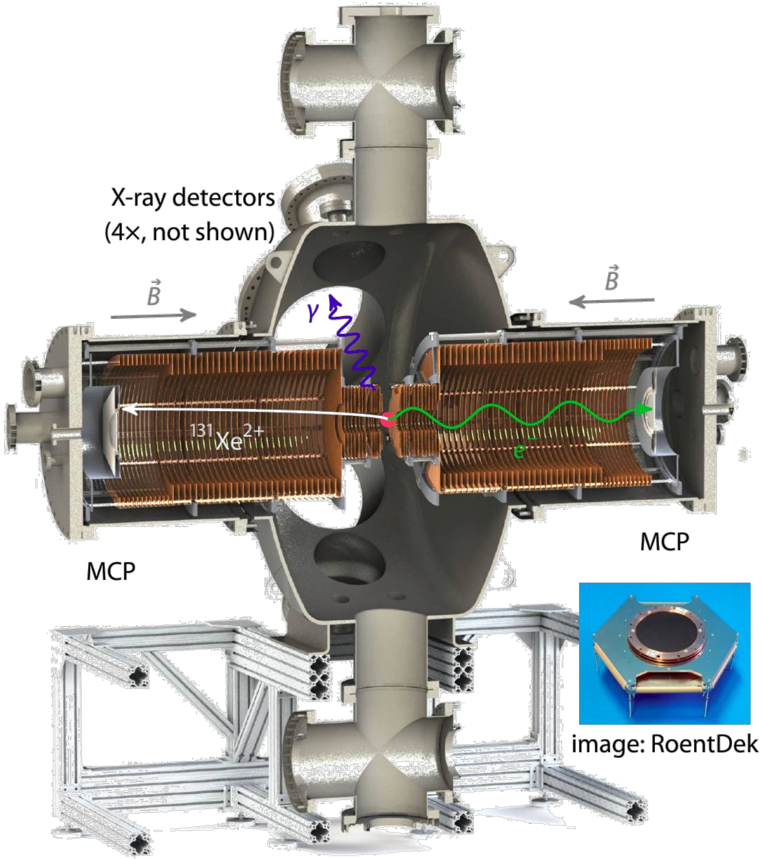


$$m_\nu^2 = [Q - E_e - E_\gamma - E_N]^2 - [\mathbf{p_\gamma + p_e + p_N}]^2$$



$$m_\nu^2 = [Q - E_a - E_\gamma - E_N]^2 - [\mathbf{p_\gamma + p_a + p_N}]^2$$





Possible source: atoms in a Magneto-Optical Trap (e.g. ^{203}Hg, ^{131}Cs, ^{7}Be)
Possible detector: Cold Target Recoil Ion Momentum Spectroscopy, COLTRIMS

Peter F Smith 2019 New J. Phys.21 053022

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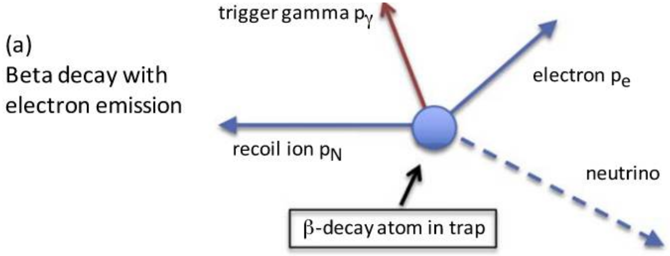

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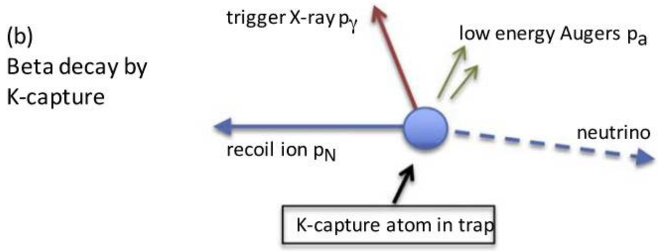

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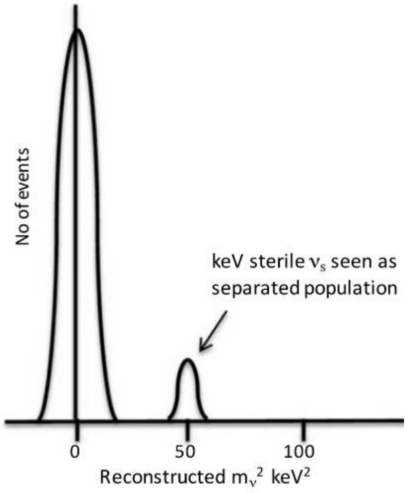

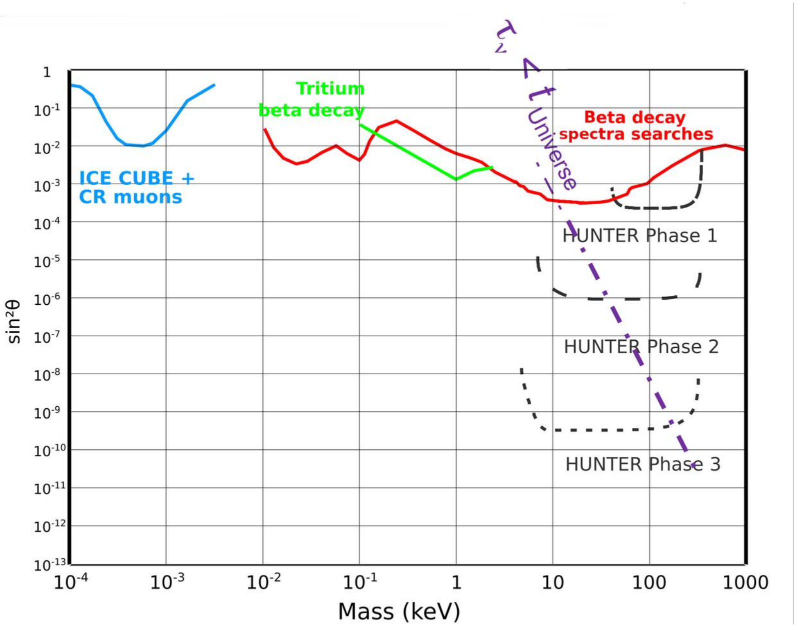

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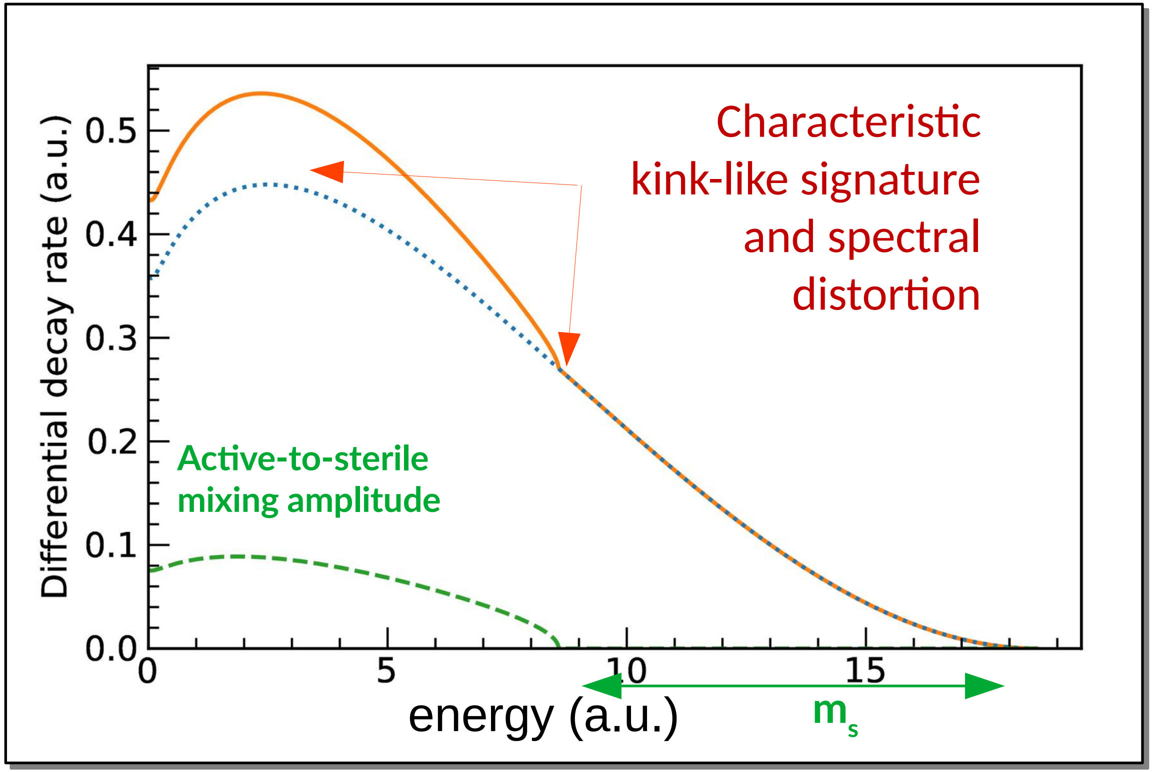
Peter F Smith 2019 New J. Phys.21 053022

Studying ß-decay

Existence of a new mass eigenstate distorts the shape of the ß-decay

$$\frac{d\Gamma}{dE}=\cos 2\theta\frac{d\Gamma}{dE}(m_\beta)+\sin 2\theta\frac{d\Gamma}{dE}(m_s)$$



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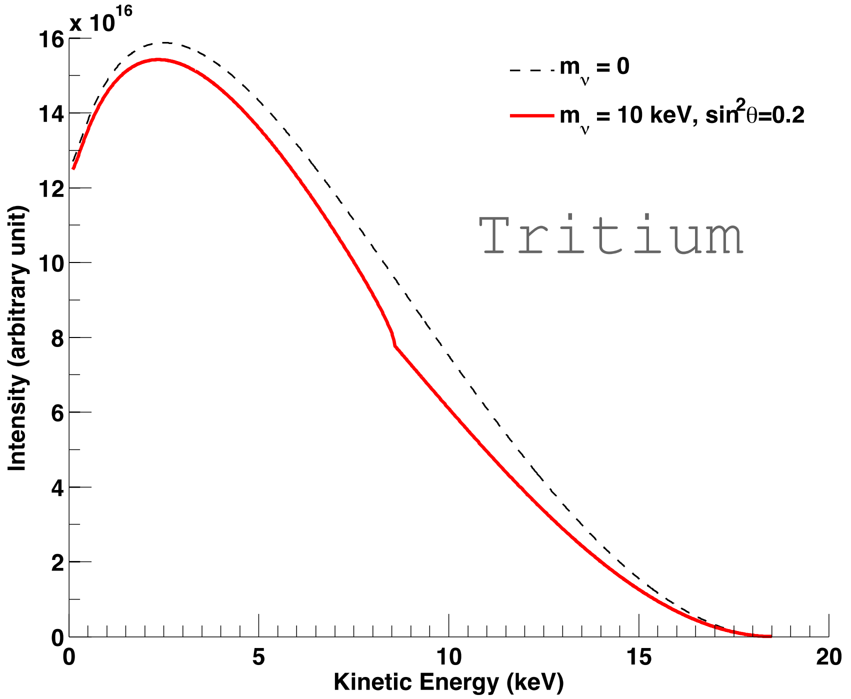
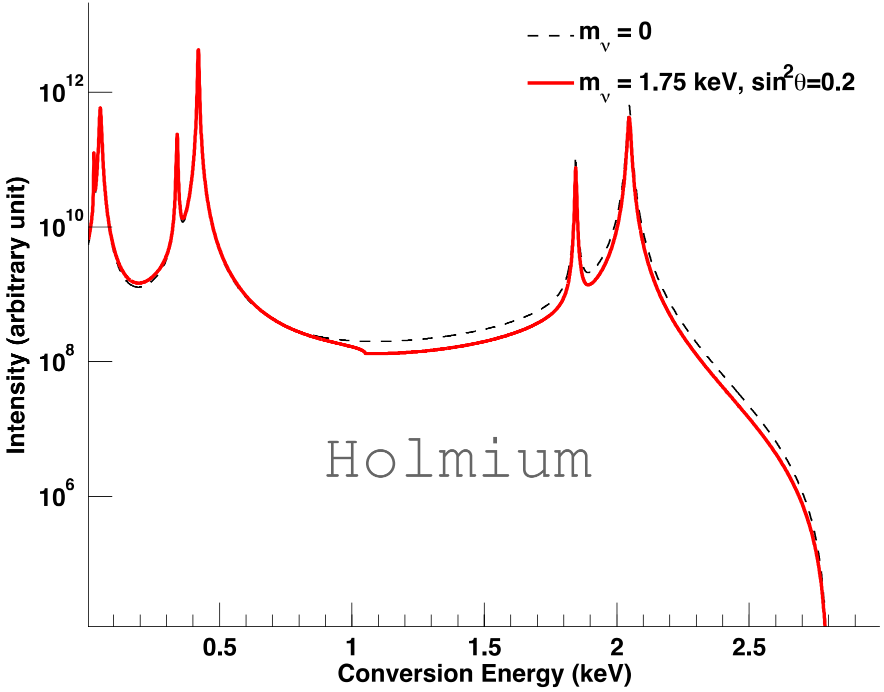


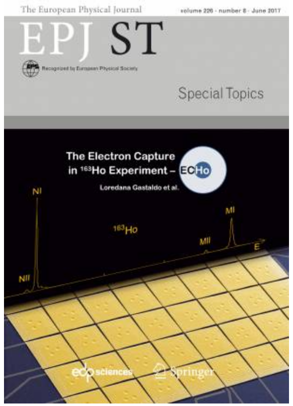


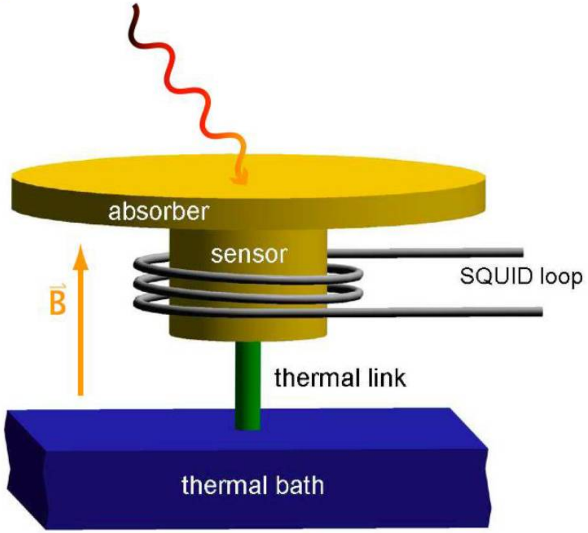
Different mass sensitivities, complexity of modelling, experimental challenges

Studying ß-decay

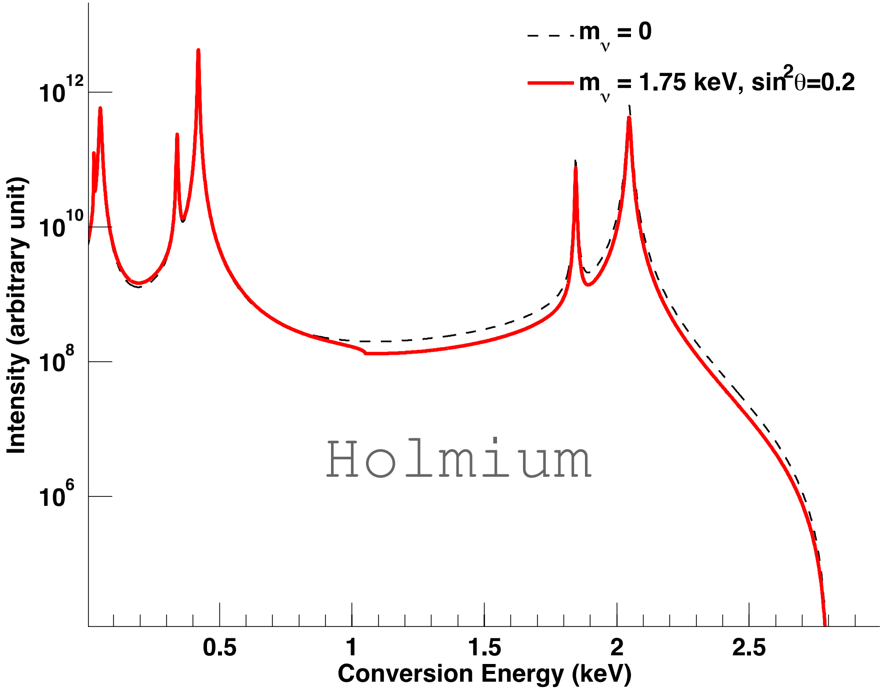
$^{163}Ho \rightarrow {}^{163}Dy^* + \nu_e$

- Metallic Magnetic Calorimeter with SQUID multiplexing read-out
- 5 eV FWHM resolution
- 4 pixels with 0.18 Bq





C.Velte et al. Eur. Phys. J. C (2019) 79:1026



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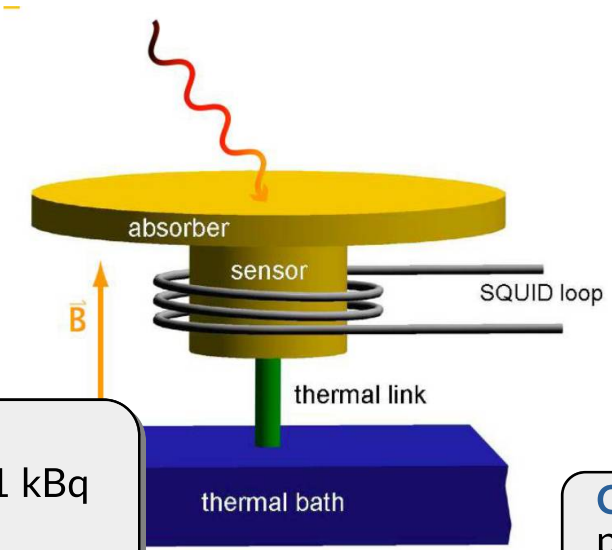
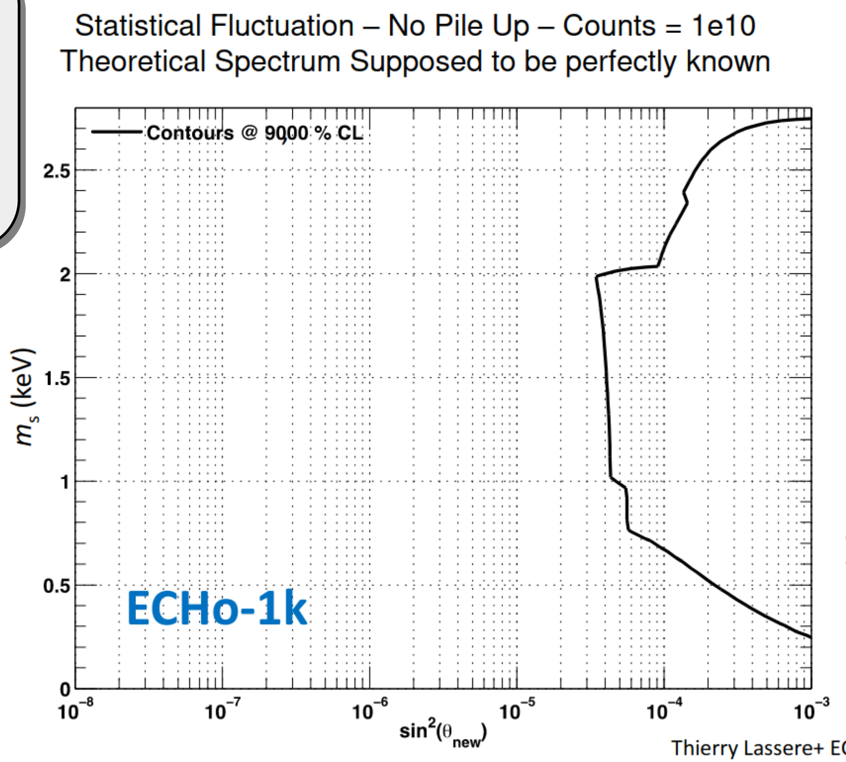




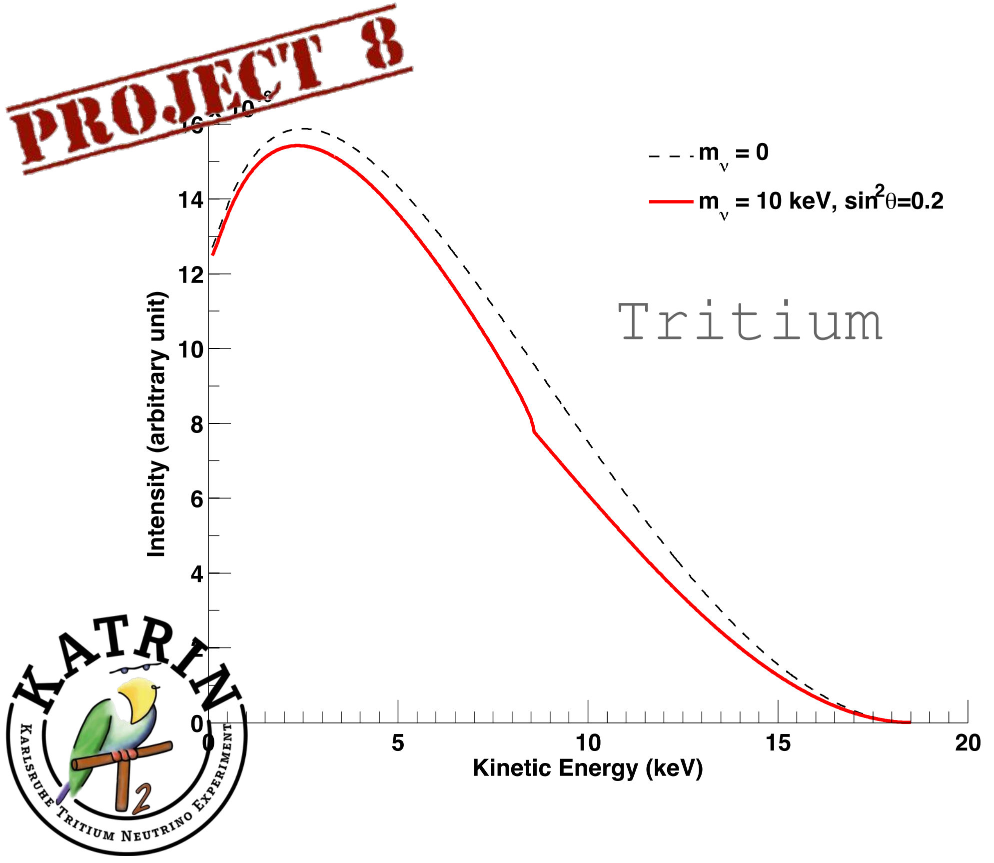
Clemens Hassel, The Status of the ECHo experiment for investigation of keV sterile neutrinos, International School for Astrophysics, 2015

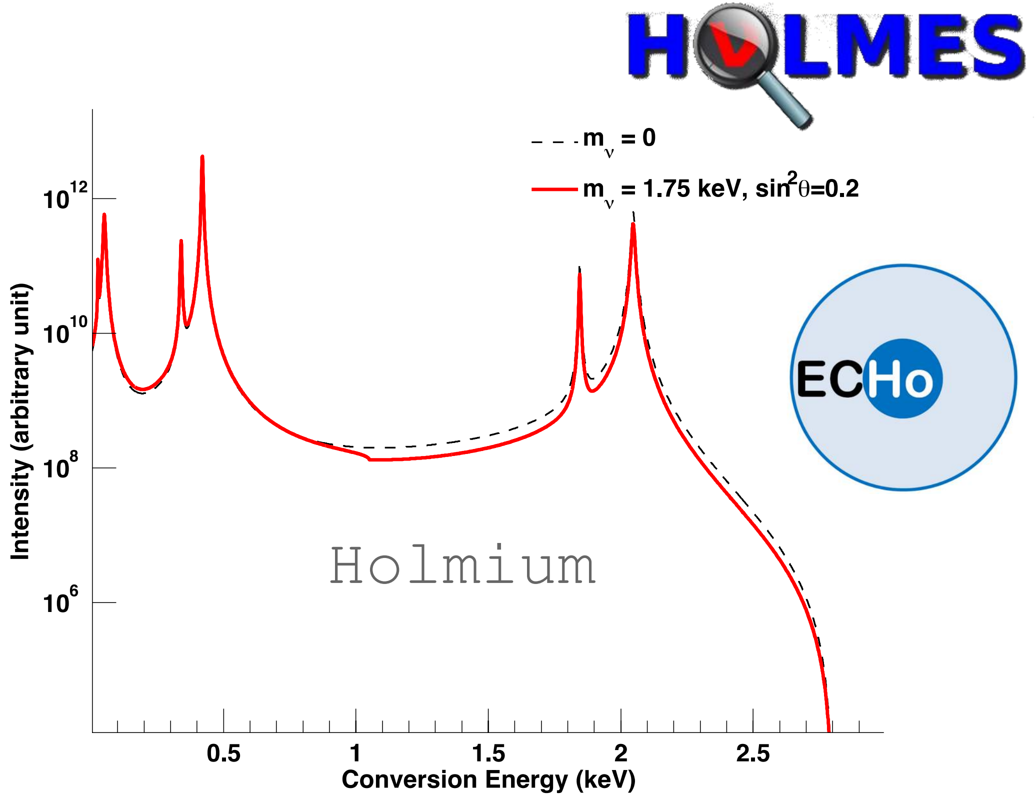
Thierry Lassere+ ECHo, in progress

Target of ECHo-1k
→ Total activity of 1 kBq
→ 1 eV resolution
→ 10 eV sensitivity on m_ν

Challenges:
pile-up, multiplexing, statistics, background, theoretical description of the spectrum

Studying ß-decay



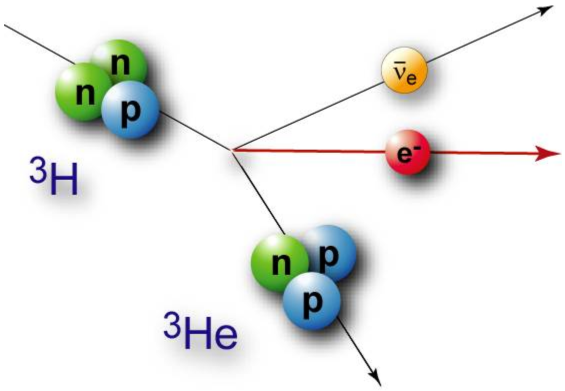


KArlsruhe TRItium Neutrino Experiment : KATRIN

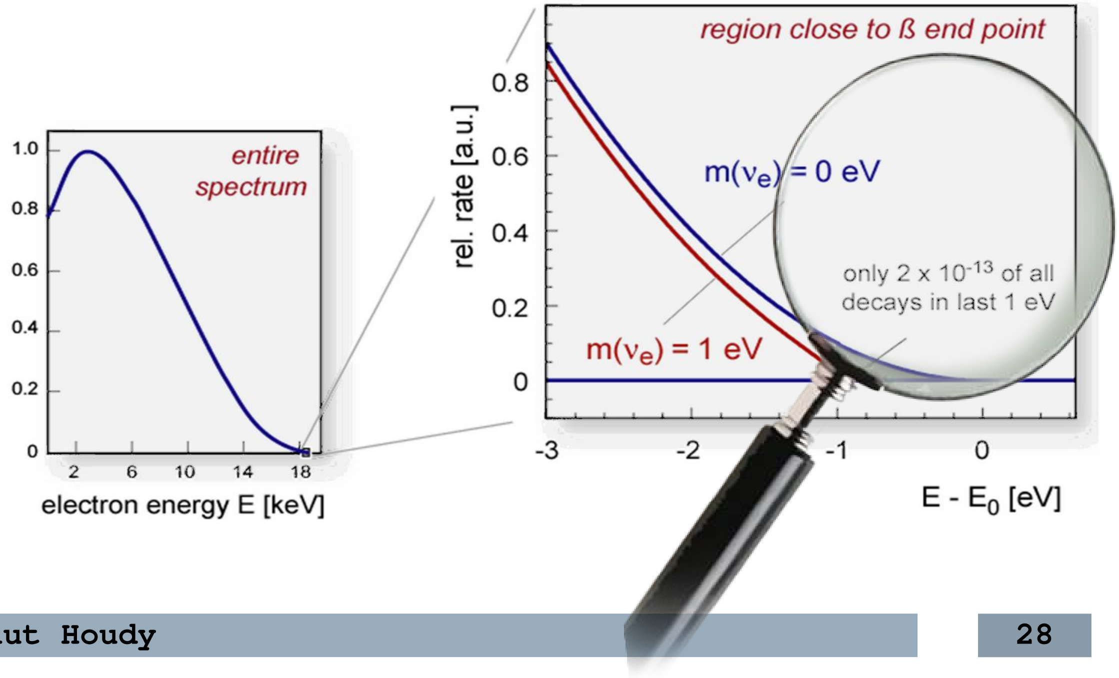
- Experimental site : Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Design sensitivity: 0.2 eV (90% CL)

KATRIN

General Idea

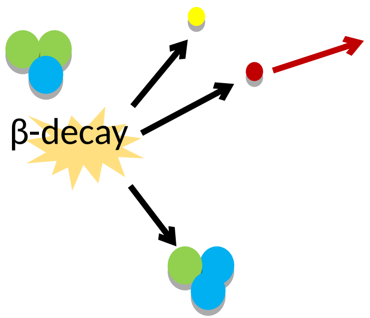


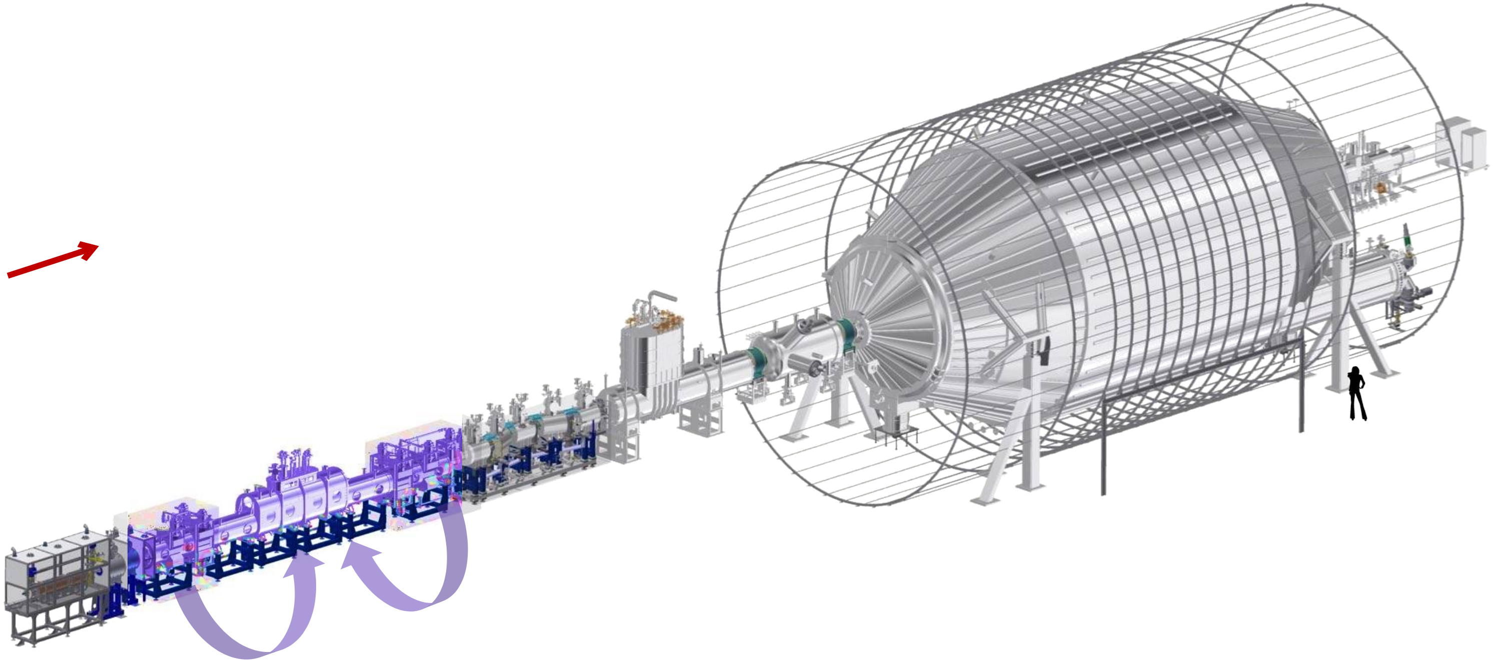
- Ultra-strong β-source 10^{11} decays/s
- Low background level < 0.1 cps
- Excellent energy resolution ~ 1 eV
- Precise understanding of spectrum



KATRIN Working Principle

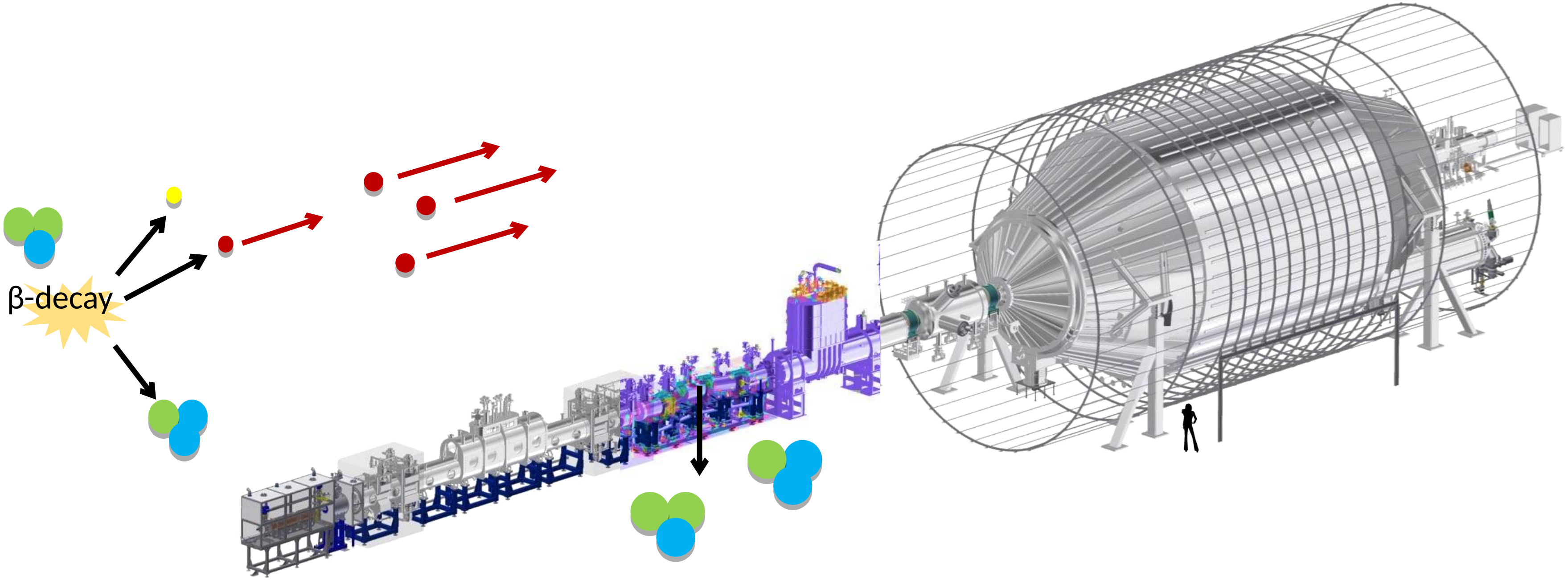
Windowless gaseous tritium source
- molecular tritium in closed loop system
- 10^{11} decays/s





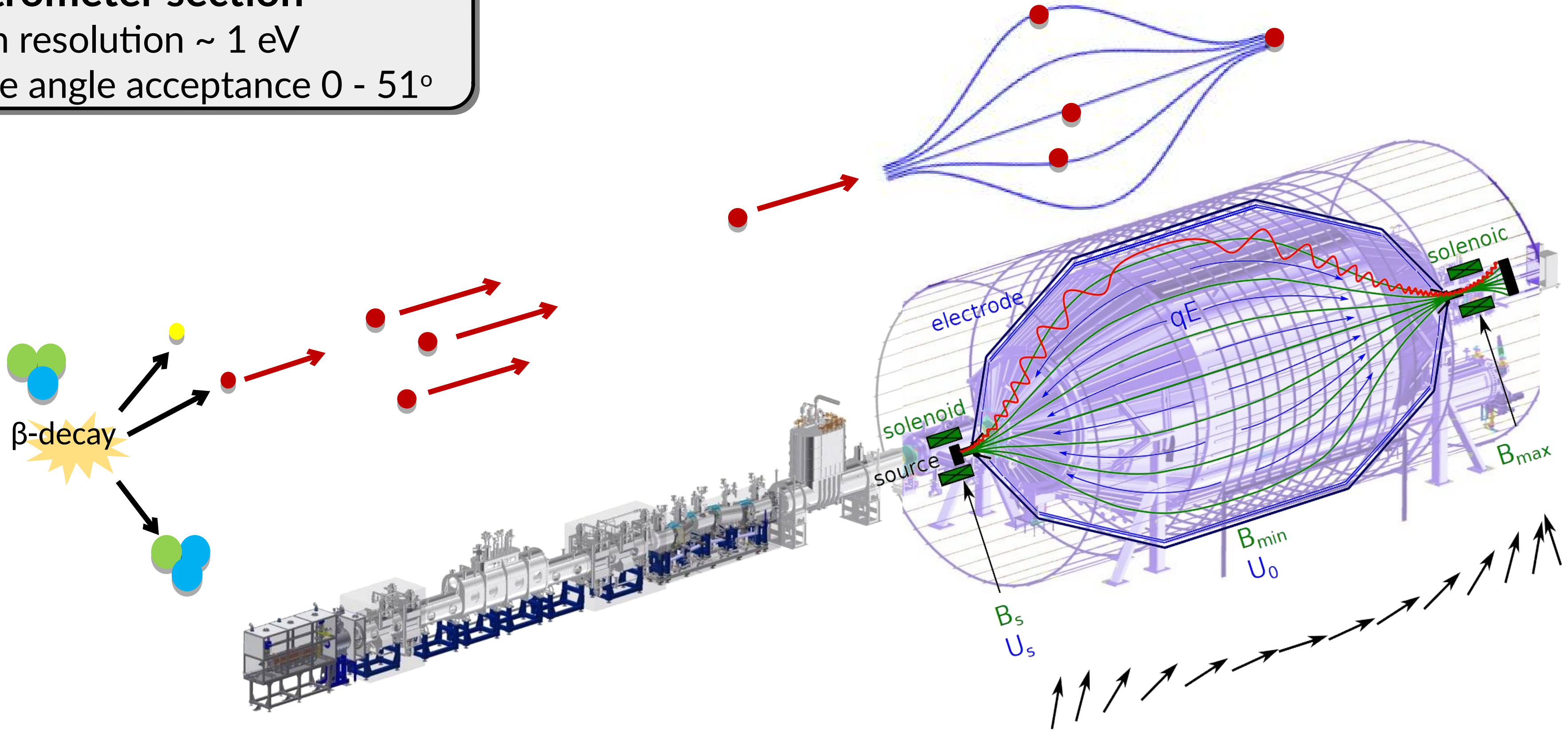
KATRIN Working Principle

Transport section
- magnetic guidance of electrons (@ 4 T)
- tritium flow reduction by > 10^{14} + tritium ion removal



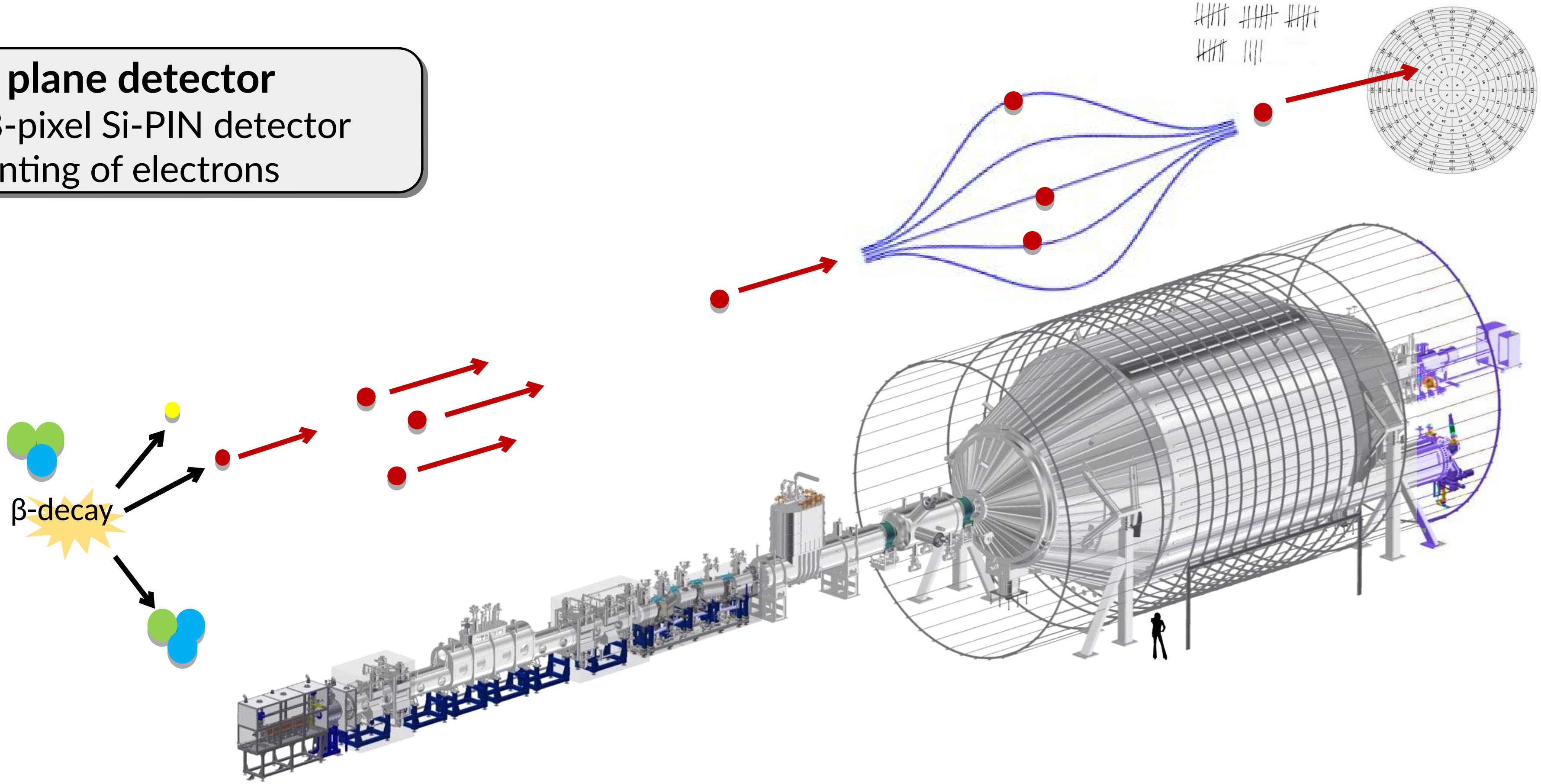
KATRIN Working Principle

Spectrometer section
- high resolution ~ 1 eV
- large angle acceptance 0 - 51°

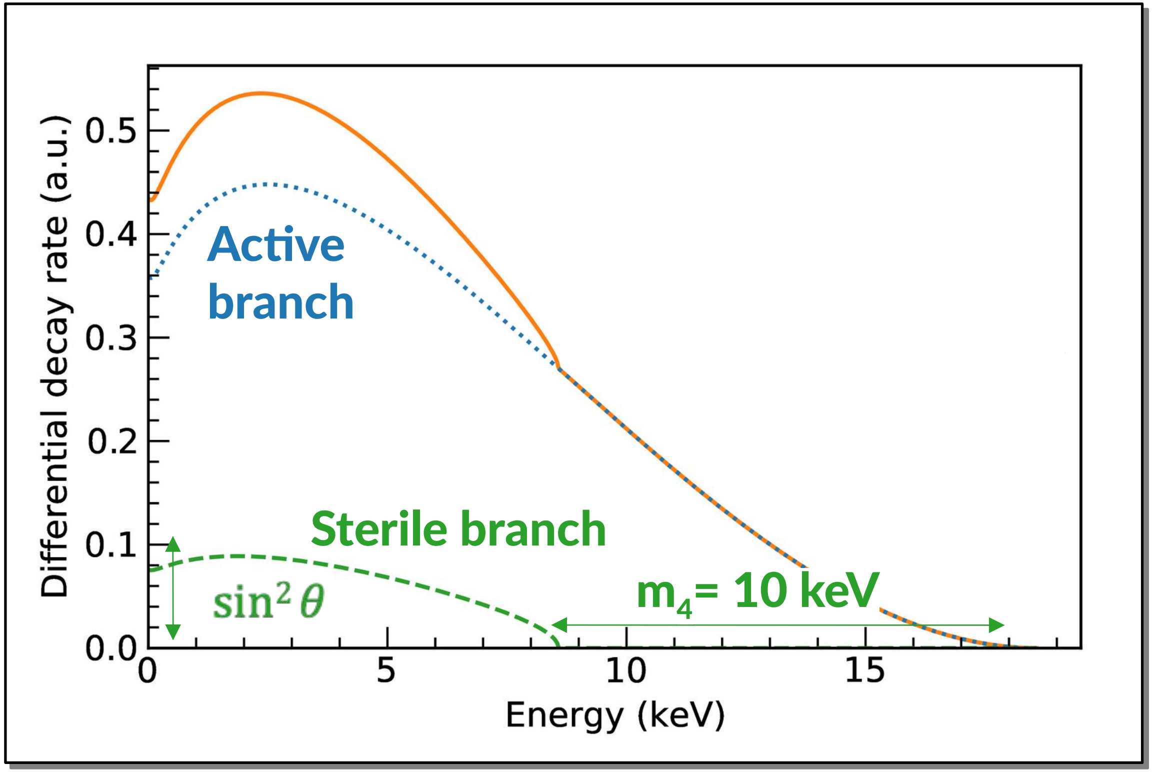


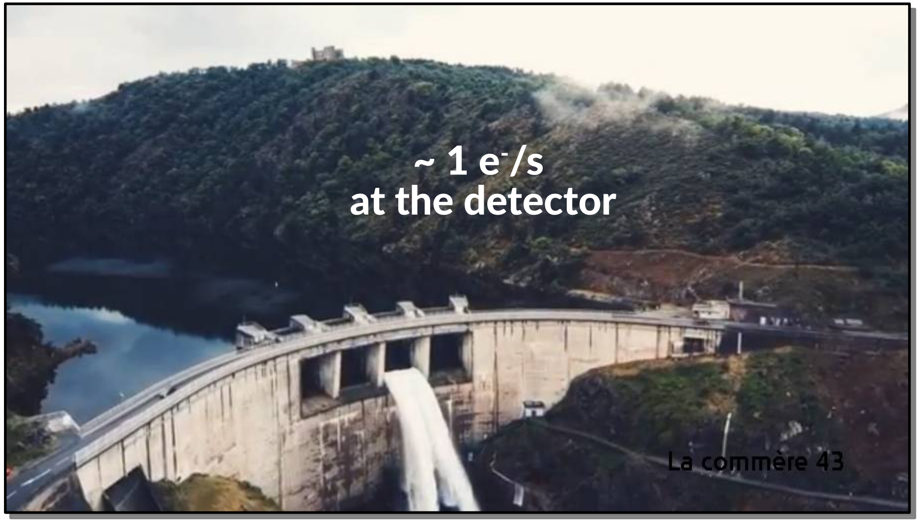
KATRIN Working Principle

Focal plane detector
- 148-pixel Si-PIN detector
- counting of electrons

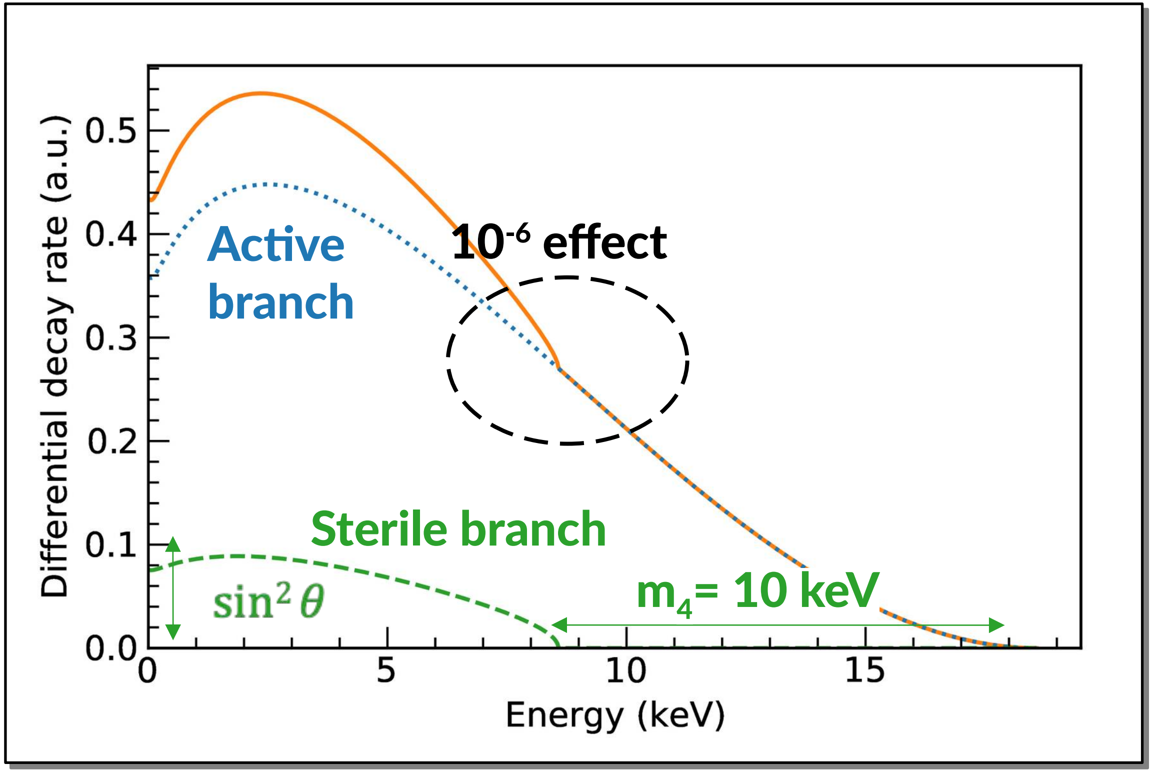


keV-sterile signature in β-decay

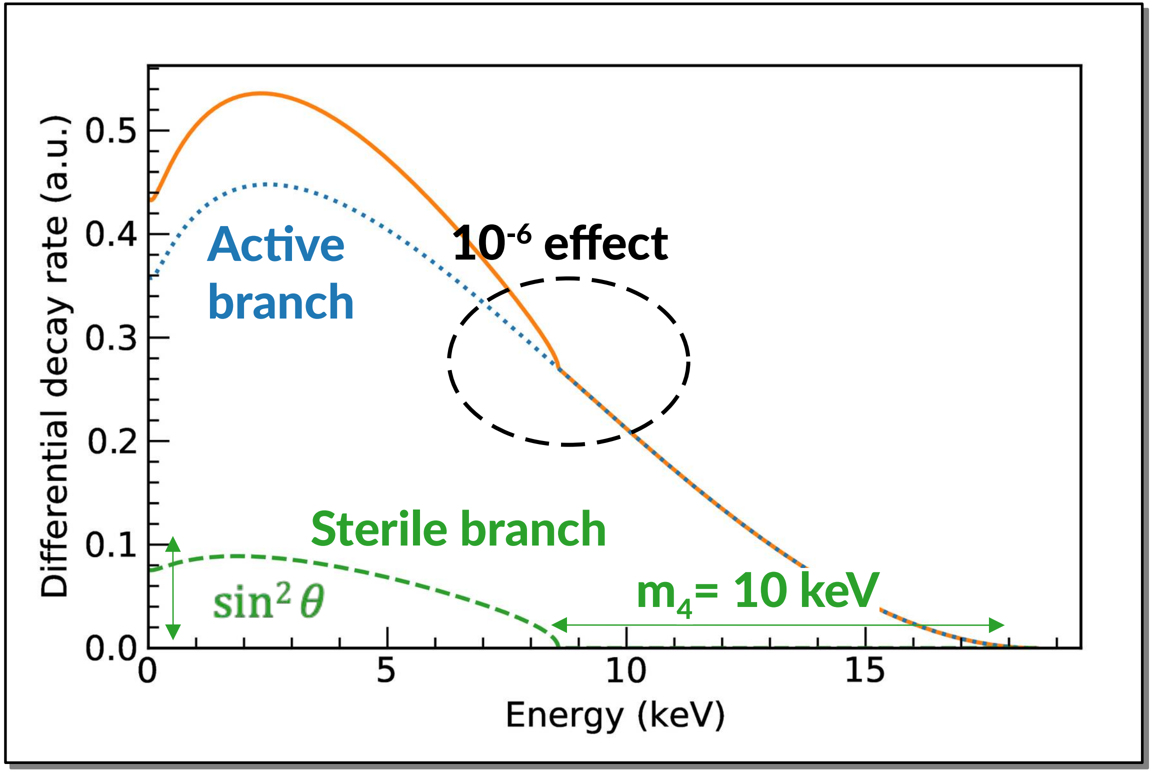




keV-sterile signature in β-decay



keV-sterile signature in β-decay



Stringent limit from **astrophysical** and **cosmological** observations ($\sin^2(\theta)<10^{-7}$) :

→ Dramatic **increase of the count rate** (up to $3\text{x}10^8$ Hz)

→ Integral and differential phases (detector with **good resolution**)

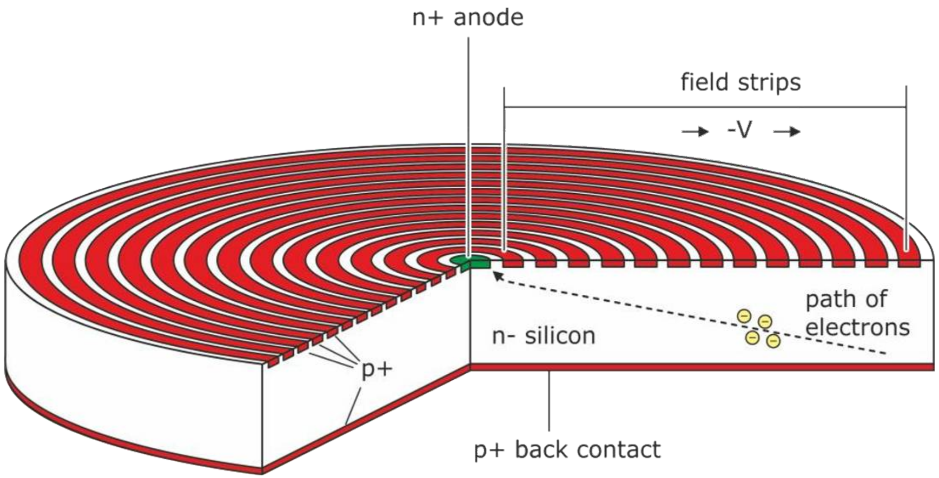
→ Highly **pixelised**

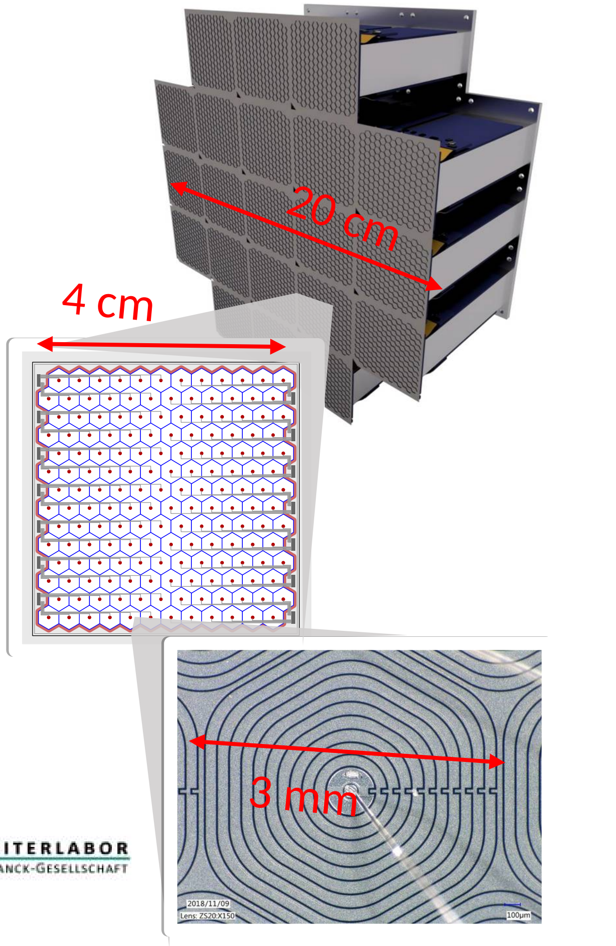
→ new detector is needed : the TRISTAN project

TRISTAN Project

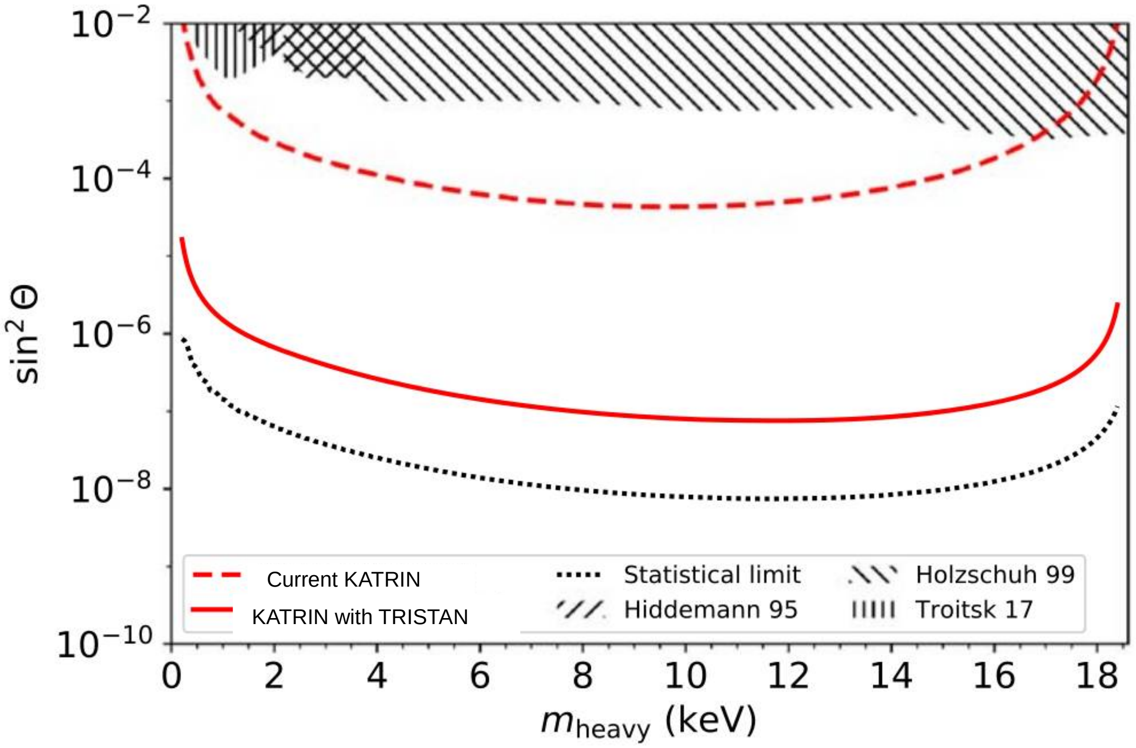
Capability of handling high rates (> 3 x 10^8 cps)
+ Excellent energy resolution (300 eV @ 20 keV)

- Silicon Drift Detector (SDD) Technology
- Novelty: large number of pixels (about 3500)
- Novelty: application to high-precision β-spectroscopy

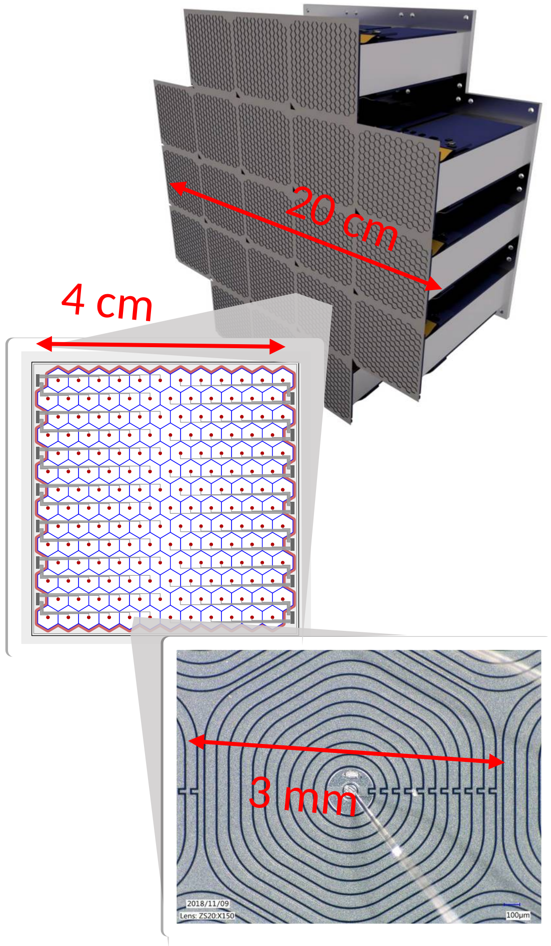




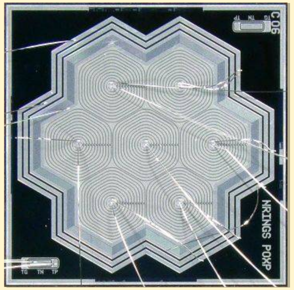
TRISTAN : Development of a large area SDD array and read-out system to look for keV-sterile neutrino with the KATRIN experiment



J.Phys. G46 (2019) no.6, 065203



Staged approach

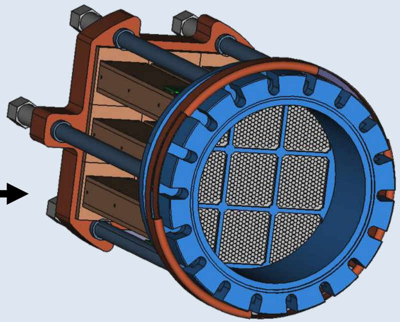


Prototypes

x24

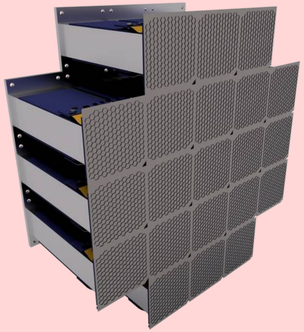
Module

x9



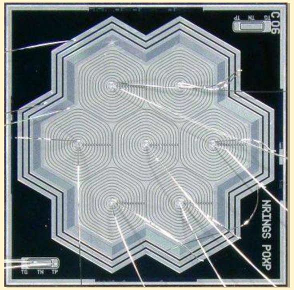
Phase 1

x2.5



Phase 2

Staged approach

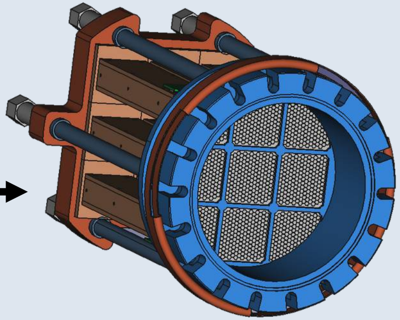


Prototypes

x24

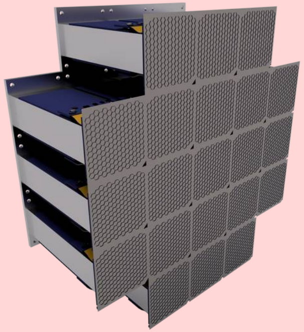
Module

x9



Phase 1

x2.5



Phase 2

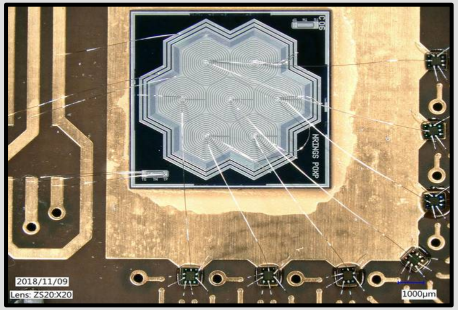
TRISTAN prototype

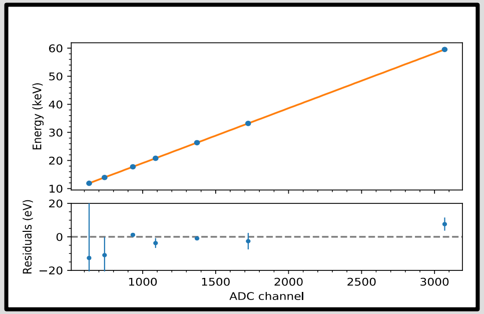
- 7-pixels with external CMOS

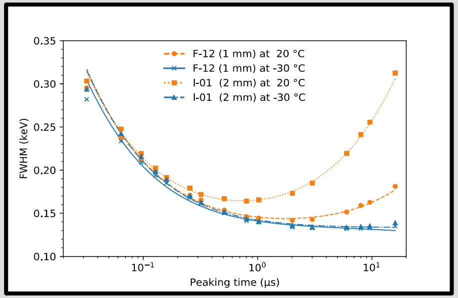
Prototype results

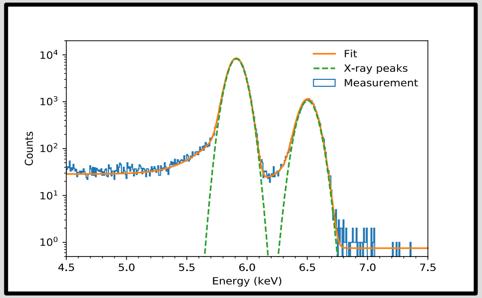
Photon response

- 130 eV (FWHM) at 6 keV
- <150 eV (FWHM) for <1 us shaping time
- 0.1 % linearity over 60 keV range









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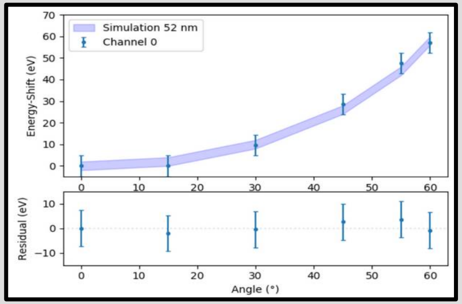
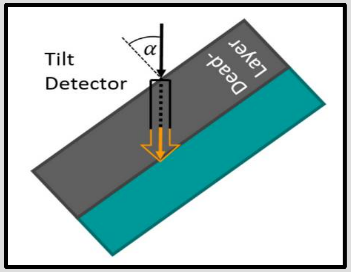
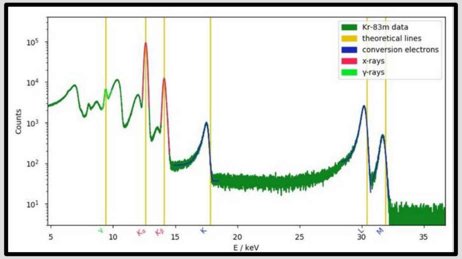
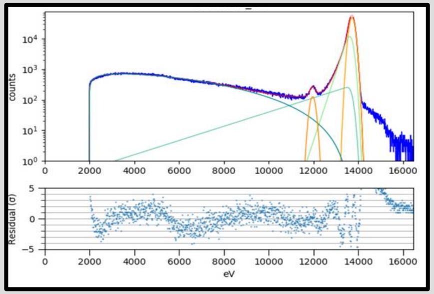
Electron response

- Semi empirical model in construction
- Dead-layer measurements using e-gun (tilting the detector) and ^{241}Am sources





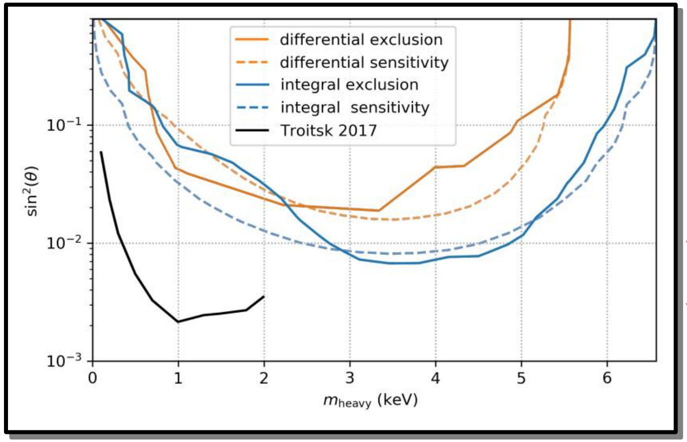




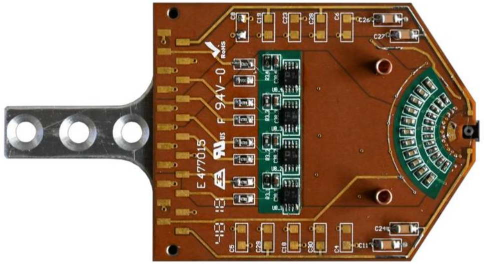
J. Phys. G: 48 015008 (2021)

Prototype applications

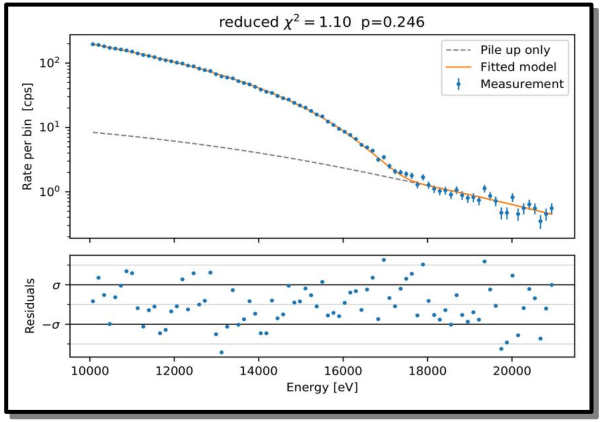
2017-2019 :
TRISTAN 7-pixels prototype implemented in **Troitsk** nu mass spectrometer → differential and integral measurements



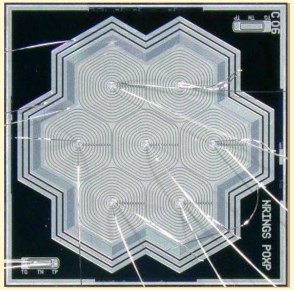
JINST14 P11013 (2019)



2019-2020 :
TRISTAN 7-pixels prototype implemented in KATRIN as **Forward Beam Monitor**.
Monitoring since KNM2



Staged approach

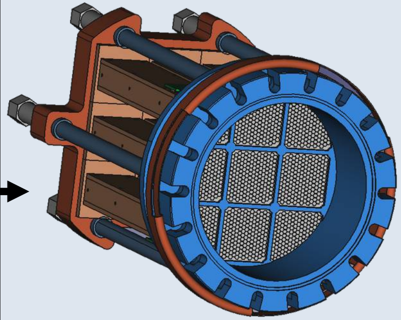


Prototypes

→ x24

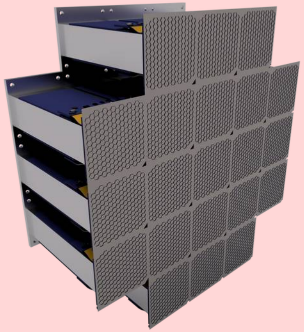
Module

→ x9



Phase 1

→ x2.5

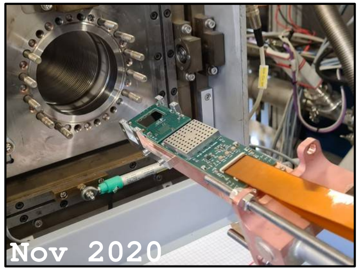


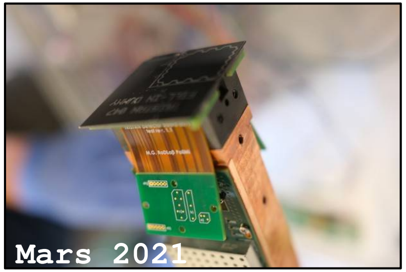
Phase 2

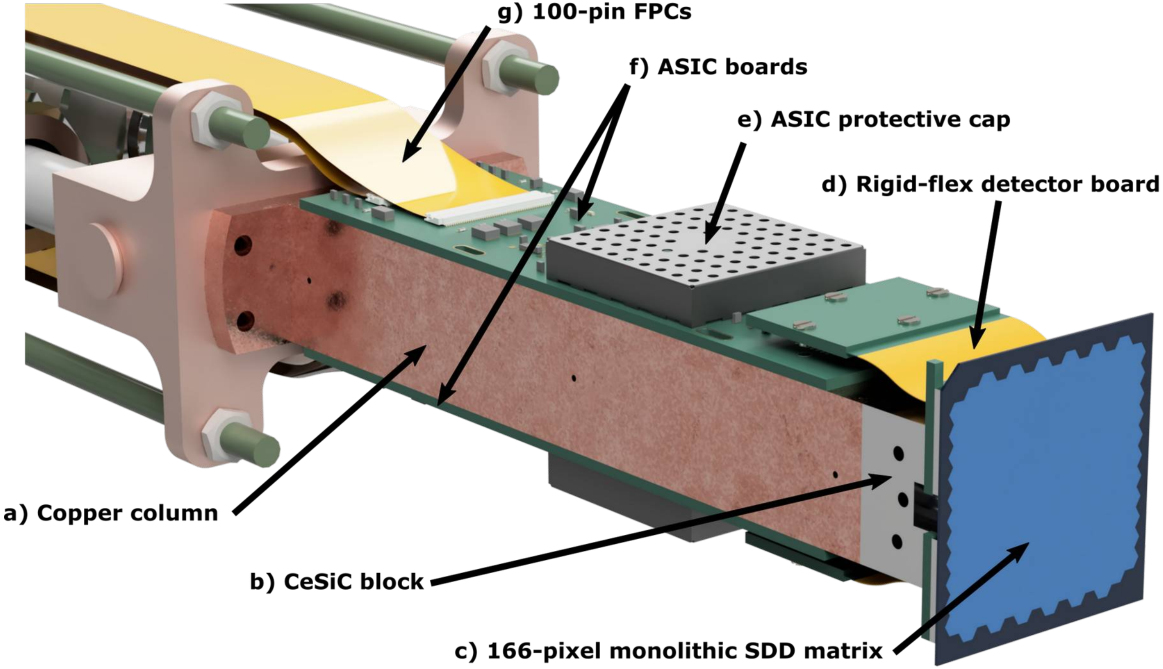
TRISTAN module

- 166-pixels with integrated JFET

Design of the TRISTAN Module







Operating 166-pix SDD in UHV (10^{-8} mbar), cool (-80°C), intense B field (~1 T), low noise (<300 eV FWHM)

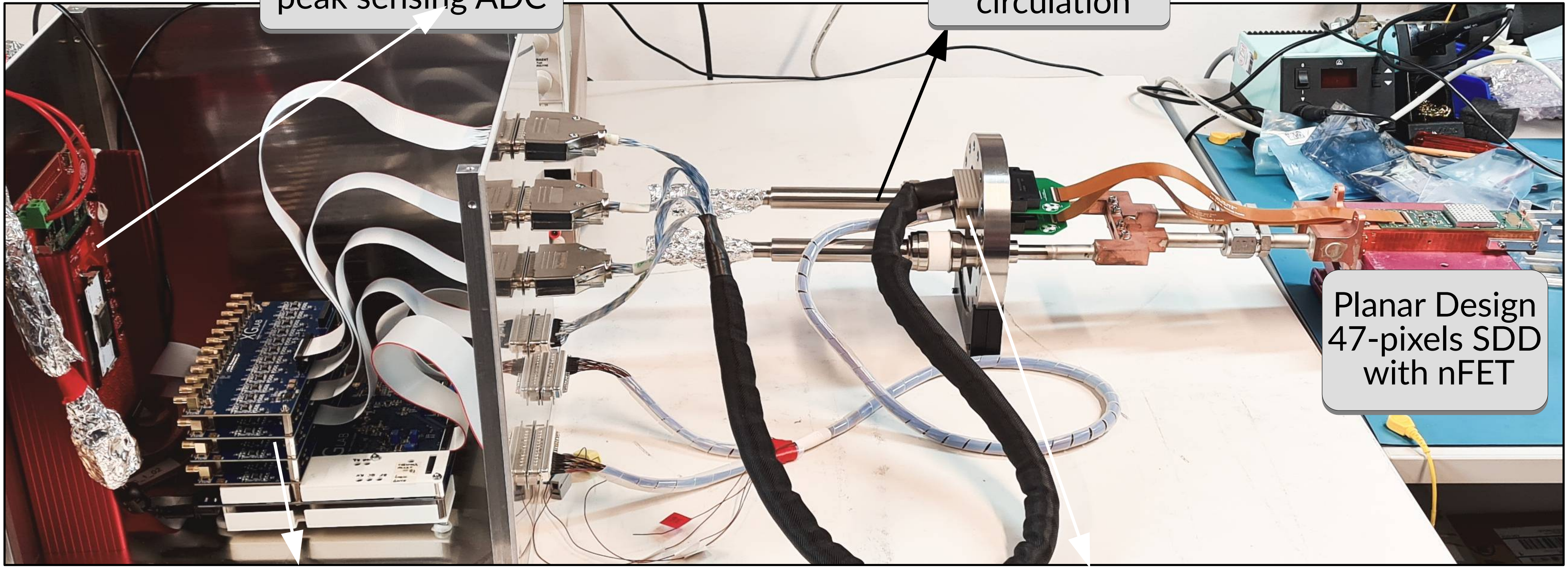
- Large SDD matrix with integrated FET
- CeSiC : carbon-fiber reinforced silicon carbide
- Rigid-flex with high density
- Dedicated ASIC
- 1-m long Kapton flex cable

TRISTAN Module

1st operation of a 47-pix TRISTAN SDD on Oct 2020

Kerberos, TRISTAN peak sensing ADC

Cooling liquid circulation

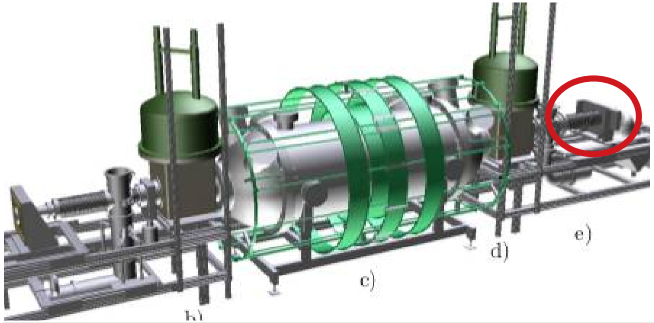


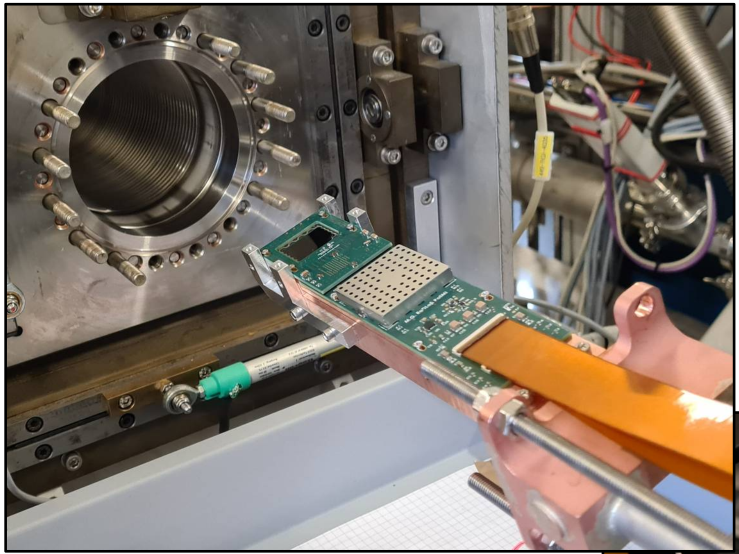
Planar Design 47-pixels SDD with nFET

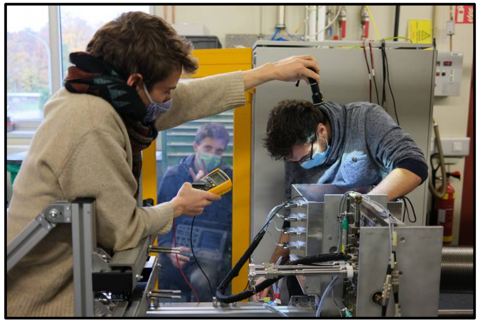
48-ch bias board

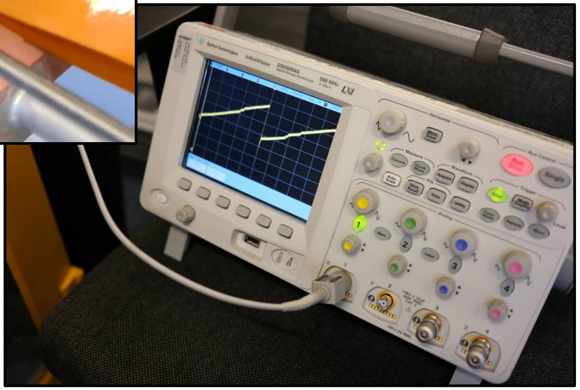
400 pins micro-D CF100 flange

TRISTAN Module Integration





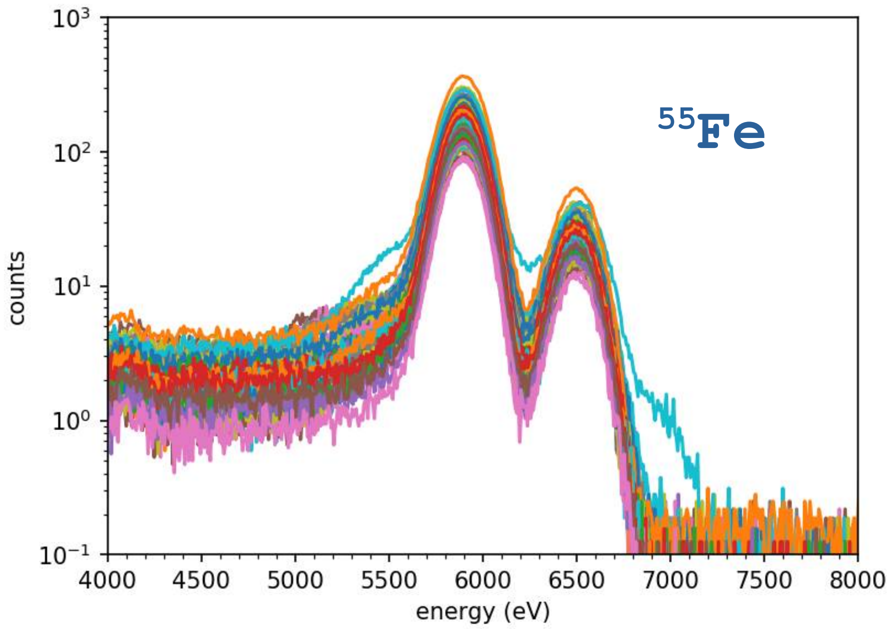


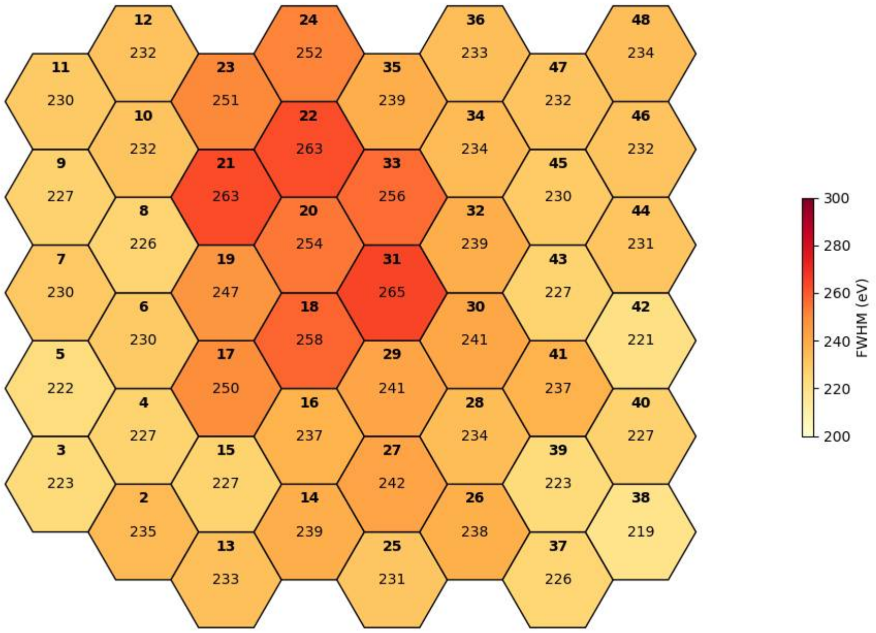


Test in **realistic conditions**
- Ultra High Vacuum
- Magnetic Fields
- Cooling system

Insertion of a 47-pix planar design → test the full chain of acquisition

TRISTAN Module Integration

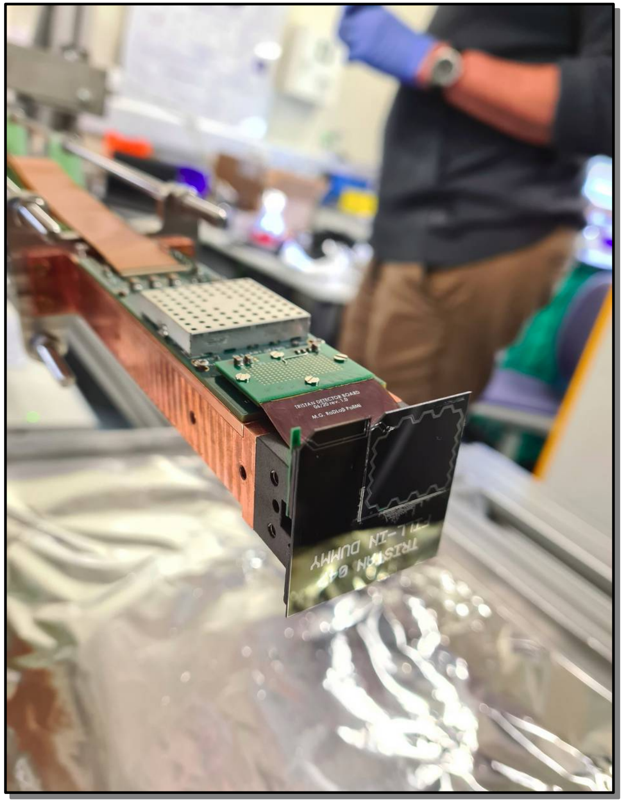


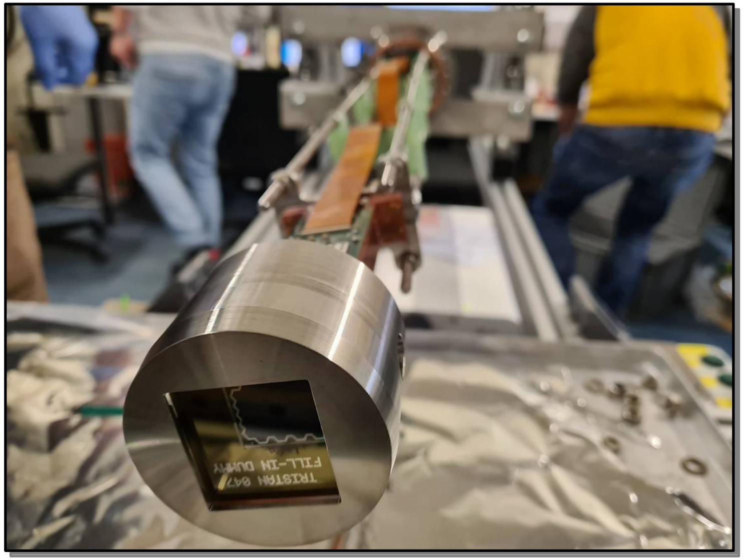


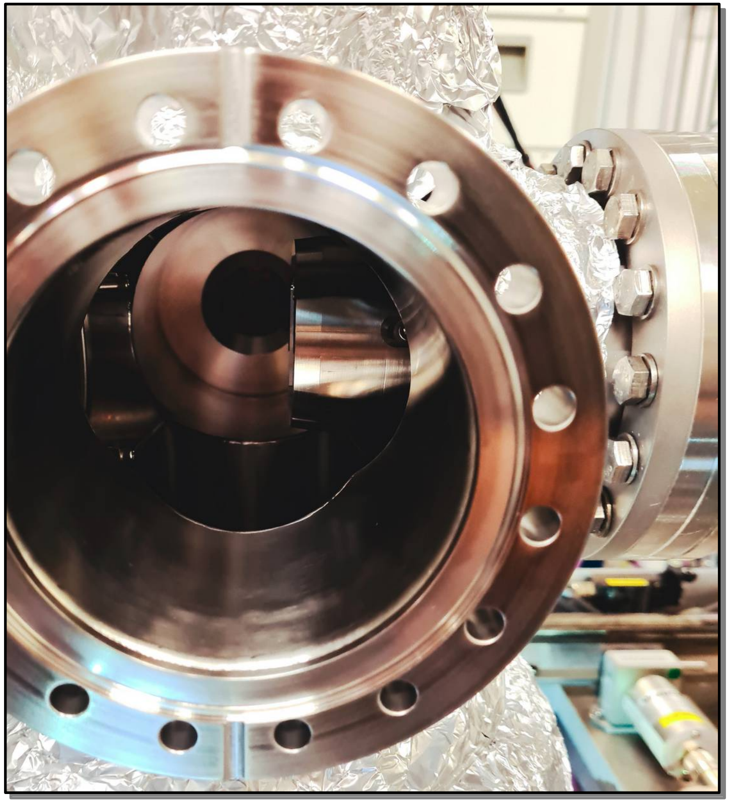
^{55}Fe x-rays

- Test with integrated set-up
- Homogeneous
- Stable

TRISTAN Module Integration





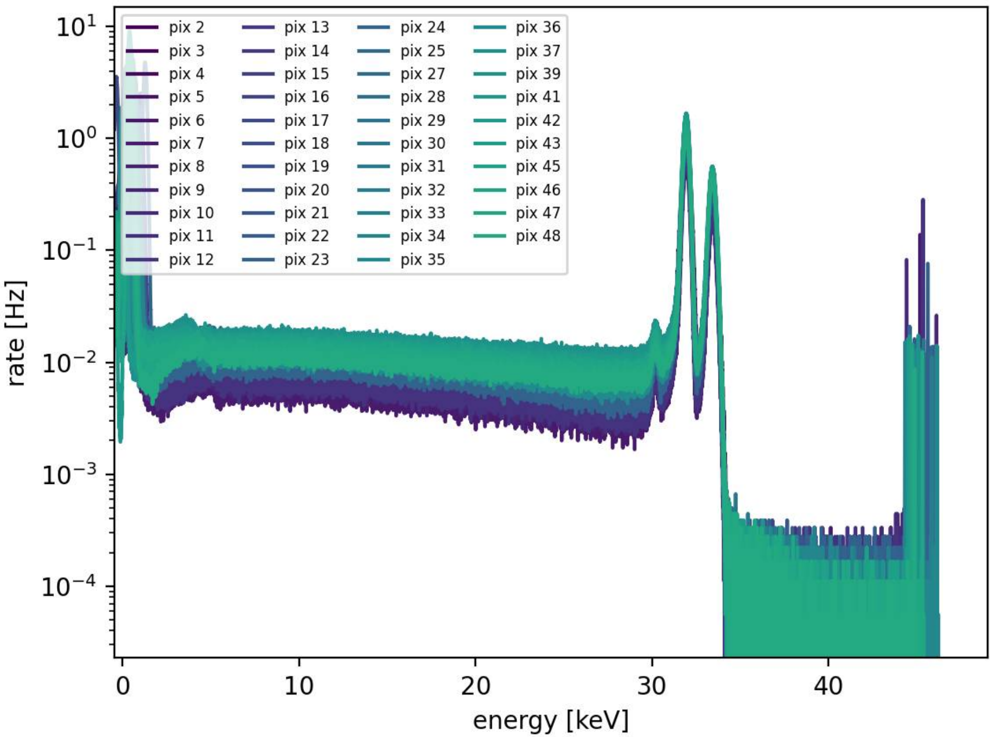


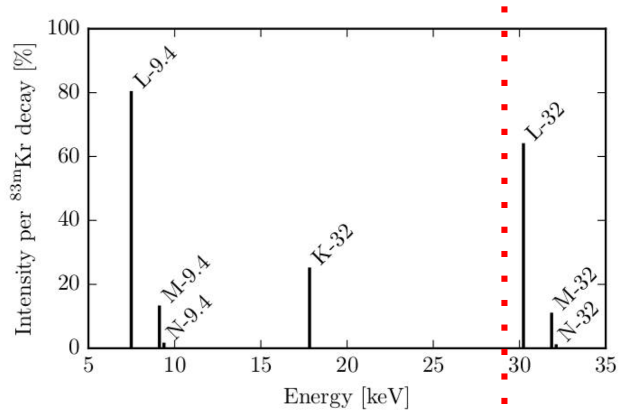
^{83m}Kr electrons from MoS

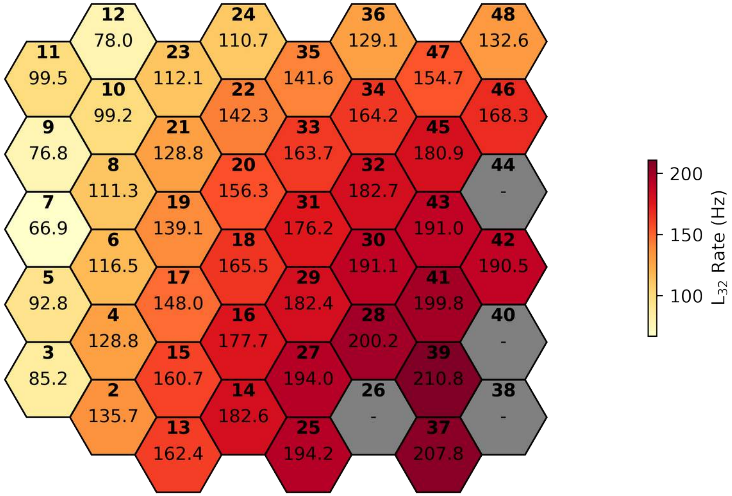
- Monoenergetic
- Vacuum (10^{-8} mbar)
- Operating at -50°C

1st electron light with a 47-pix TRISTAN inside MoS KATRIN on April 2021

TRISTAN Module Integration

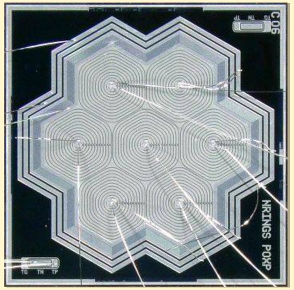






- Studying of the **electron response**
- Analyzing plane HV to 30 kV to focus on L32 line
- Size of the source ~ size of the detector

Staged approach

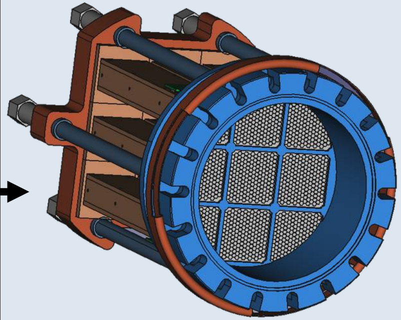


Prototypes

x24

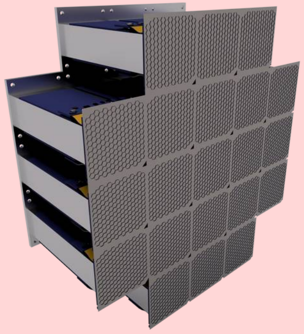
Module

x9



Phase 1

x2.5



Phase 2

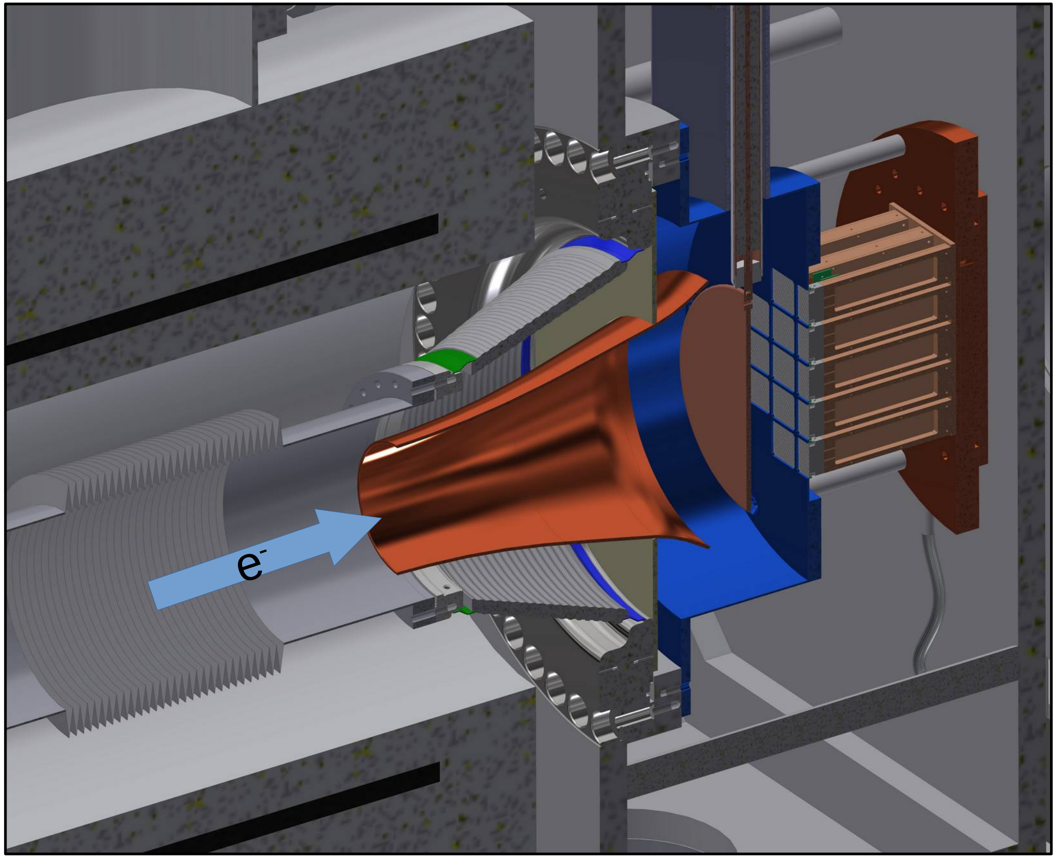
Mini-TRISTAN

- 9 x modules
  → 1500 pixels

Full TRISTAN

- 21 x modules
  → 3500 pixels

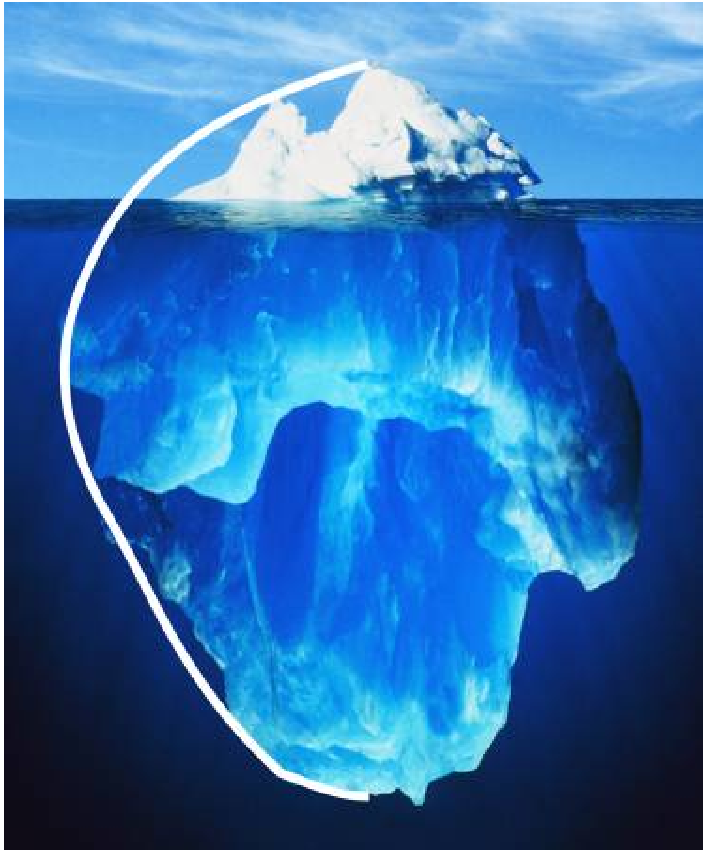
TRISTAN Final Detector

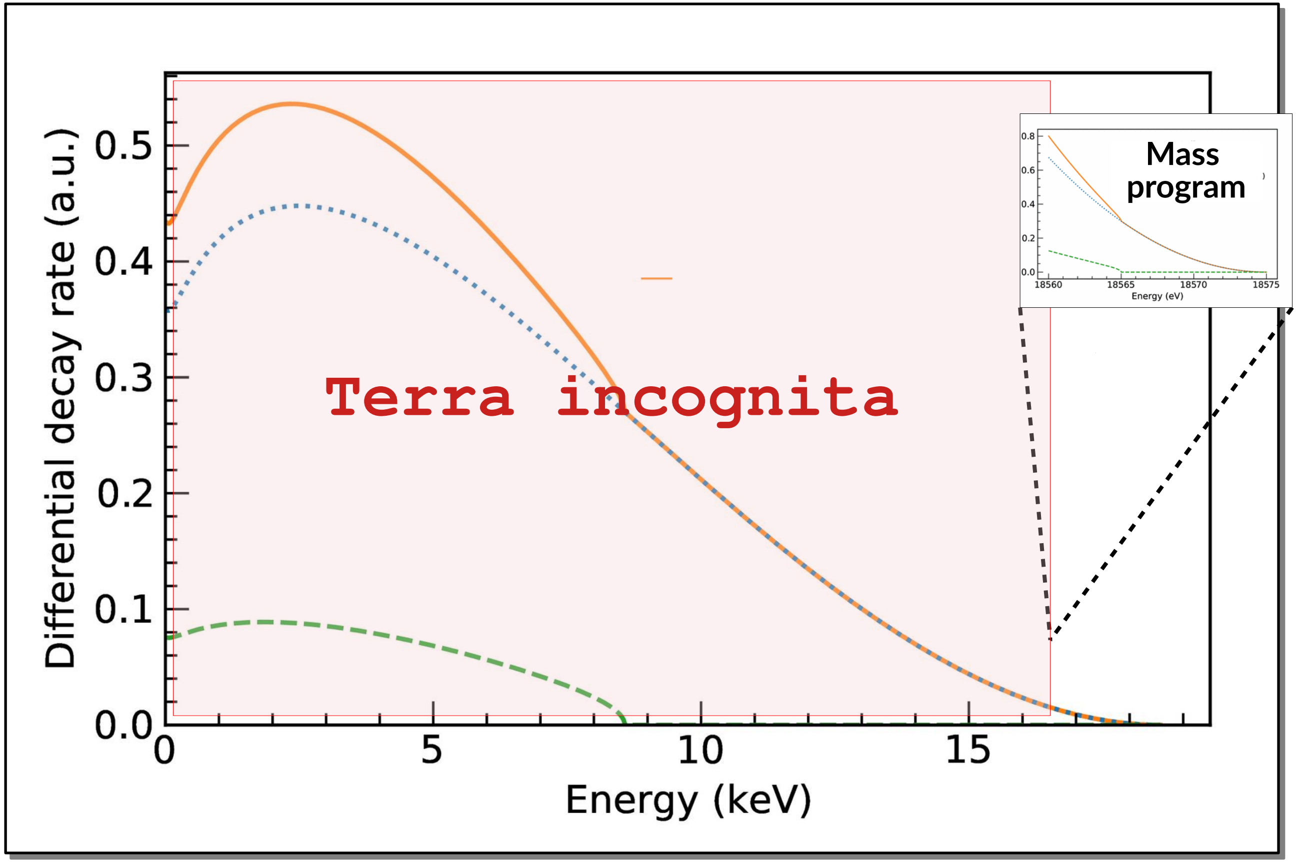


Next milestones :

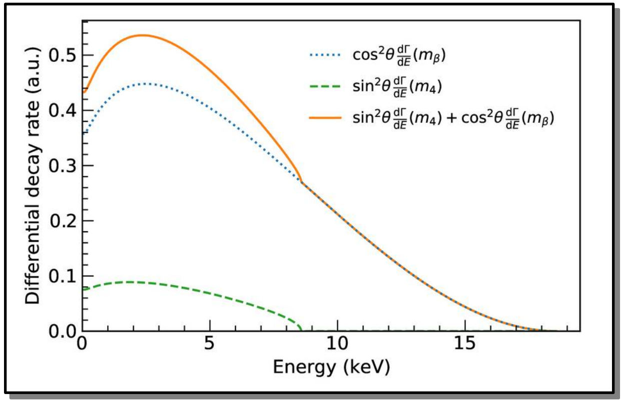
- **New DAQ** system
- **Full model** of the tritium spectrum
- First physics runs with **9 modules** in the KATRIN beamline (~ 2022)

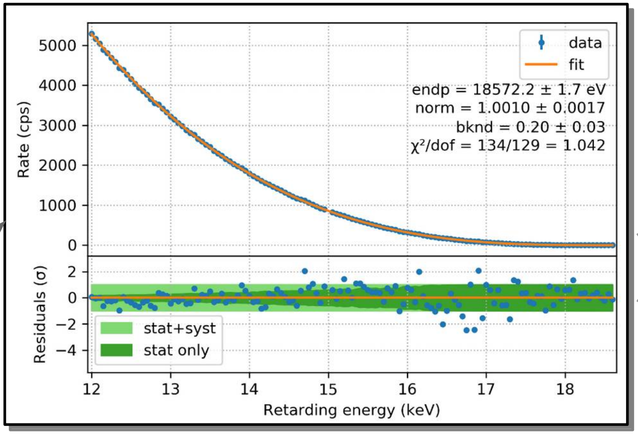
Deep Tritium Model



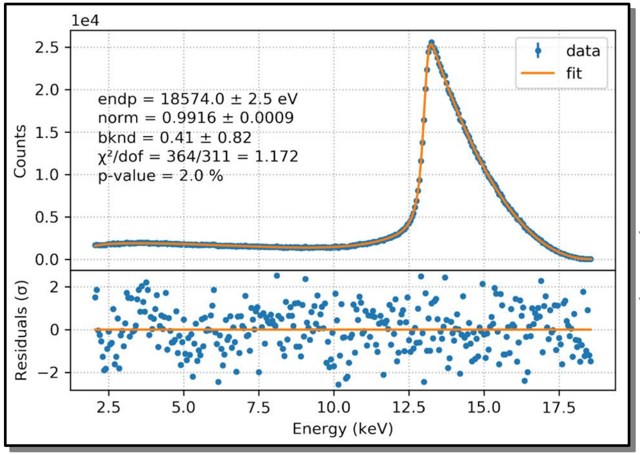


Deep Tritium Model

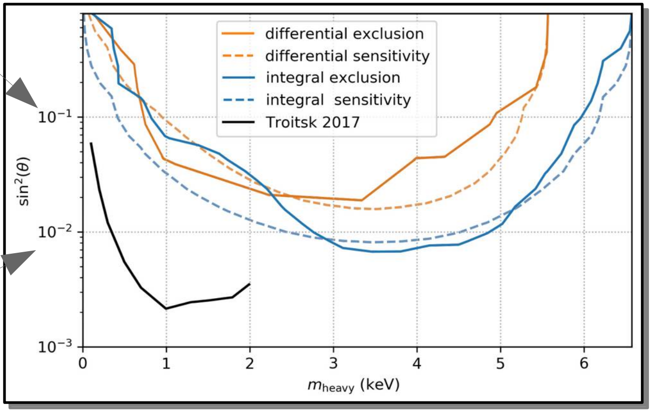




JINST 14 P11013 (2019)



JINST 14 P11013 (2019)



Deep Tritium Model : effects to consider

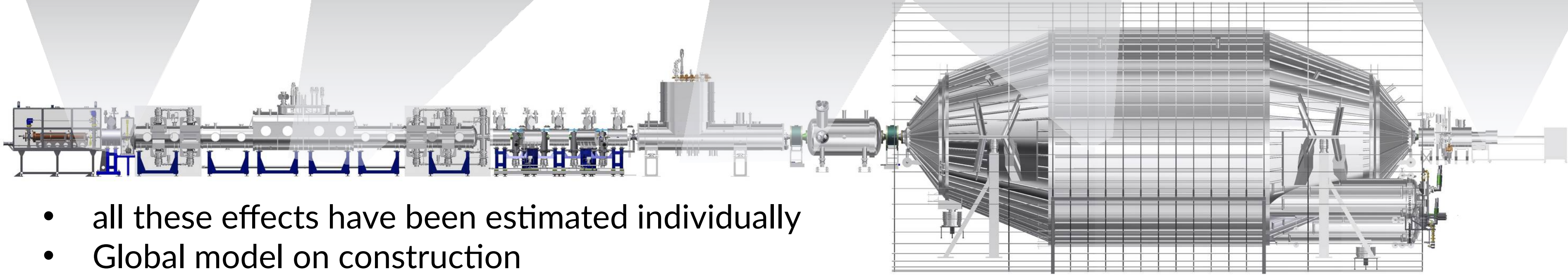
Effect can be different for differential and integral mode

Rear-Wall
- Back-scattering
- Auger electron emission
- Residual beta-activity

Source
- Scattering
- Magnetic traps
- Plasma effects
- Stability
- Gas composition and impurities

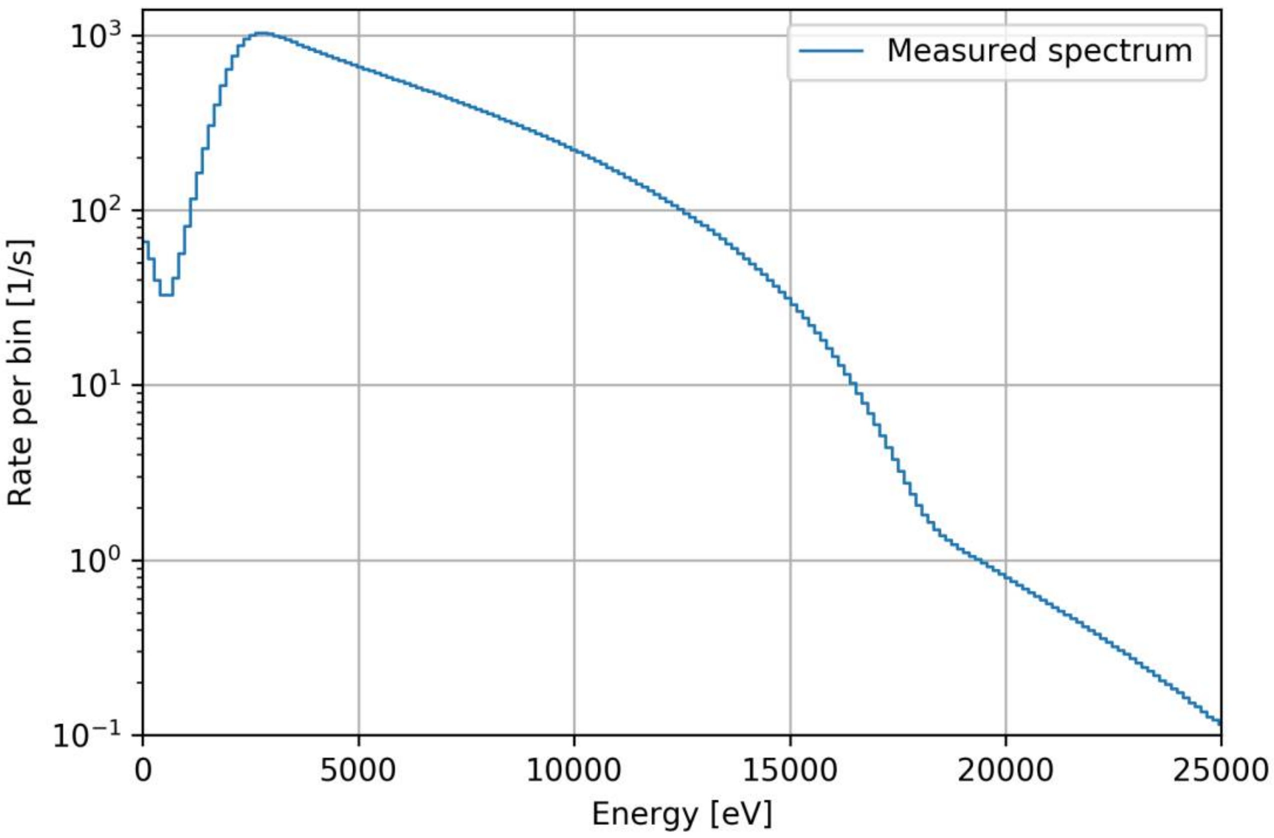
Transport - Spectrometer
- Non-adiabaticity transport
- Synchrotron radiation
- HV stability
- Background
- B-field stab.

Detector
- SDD response
- Read-out resp
- ADC NL
- Post acceleration electrode
- Pile-up, backscattering
- Penning traps
- Stability

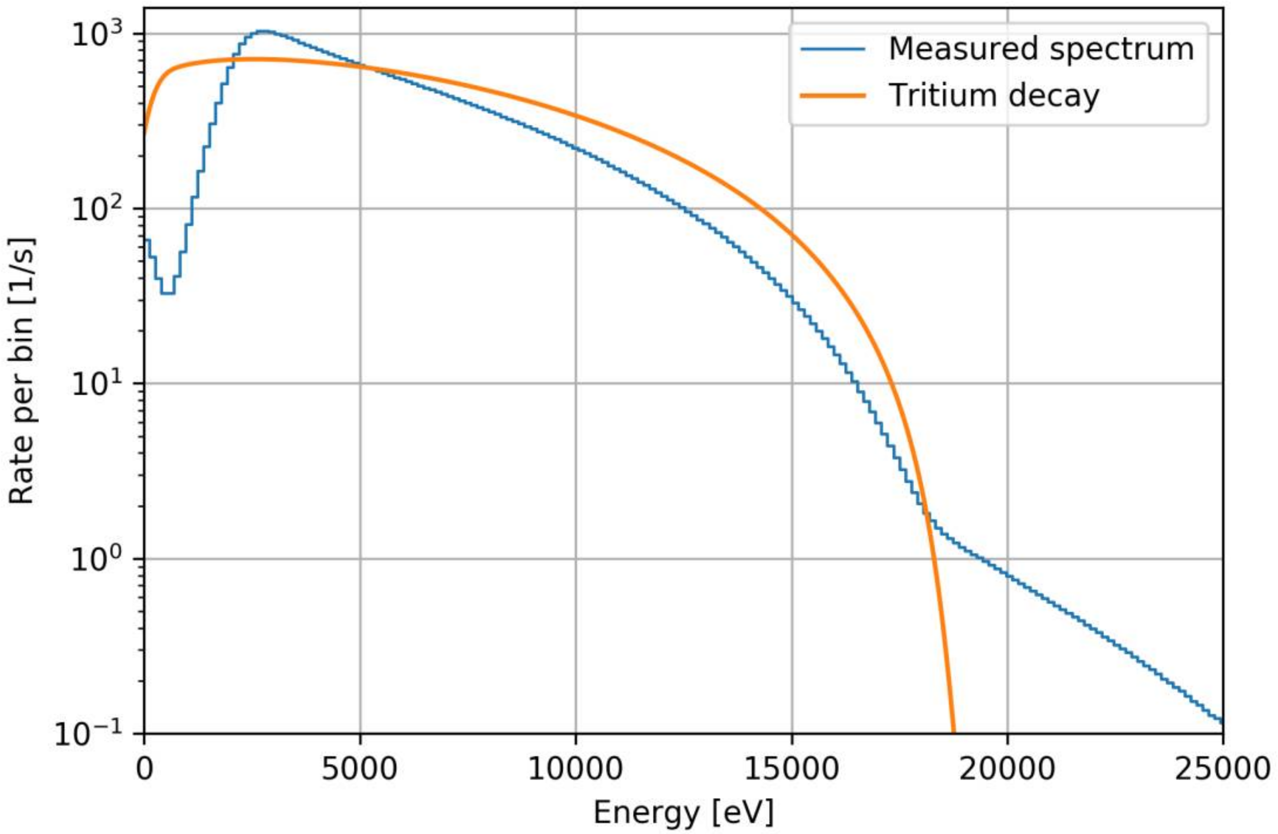


- all these effects have been estimated individually
- Global model on construction

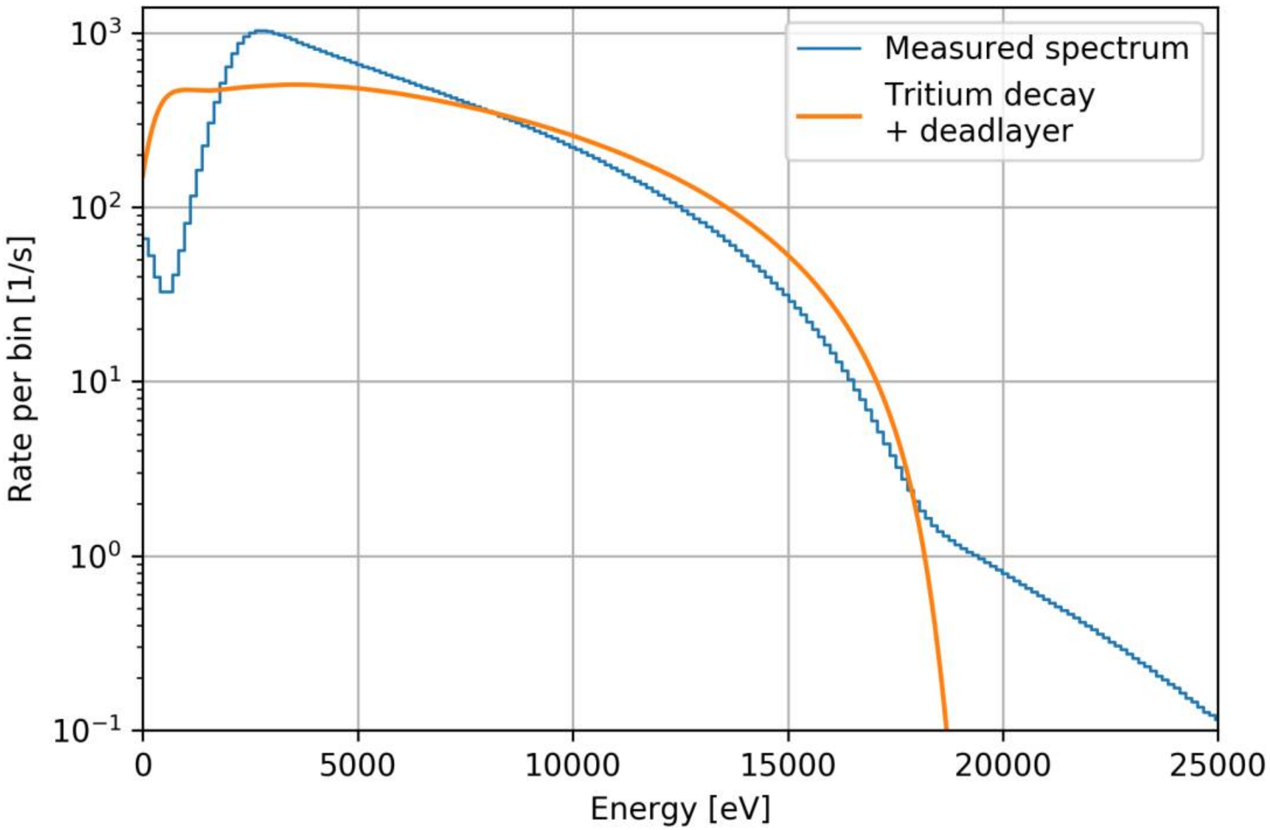
Deep Tritium Model : illustration



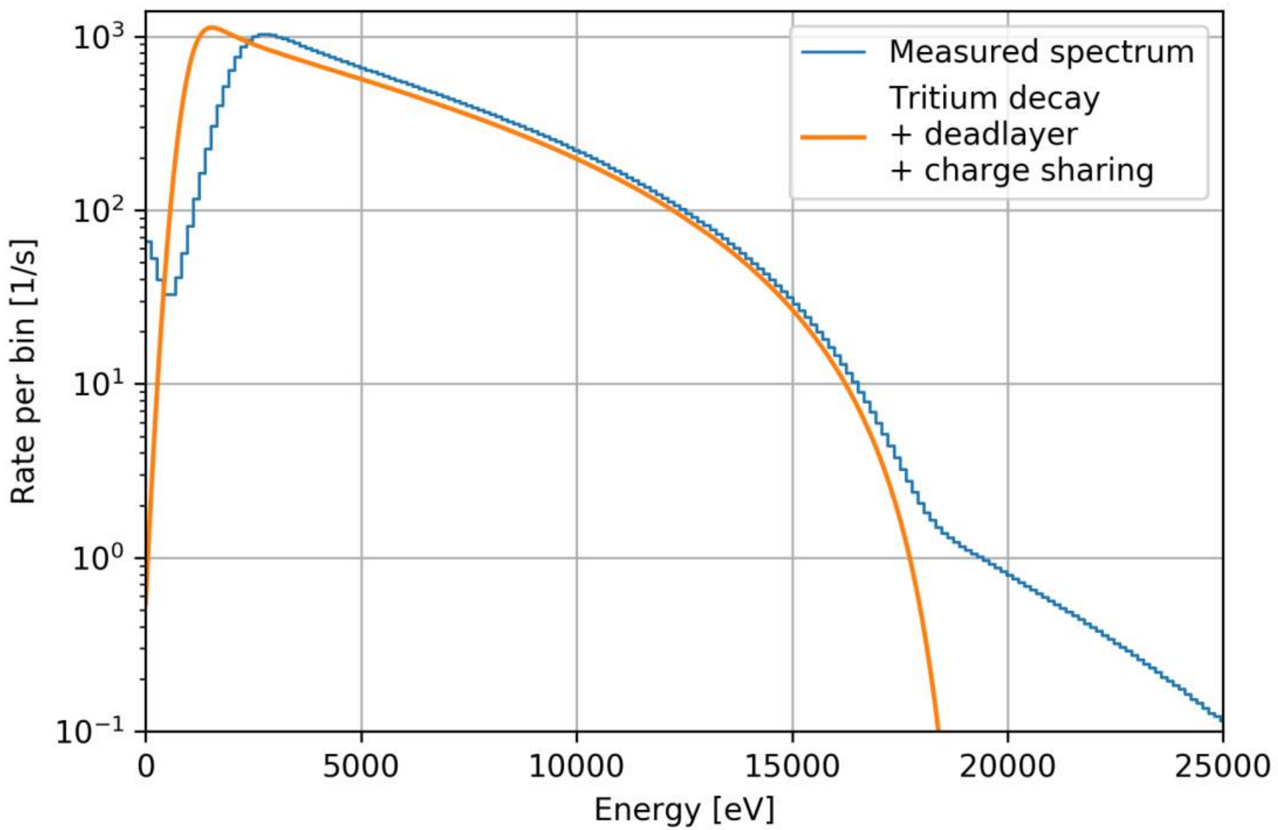
Deep Tritium Model : illustration



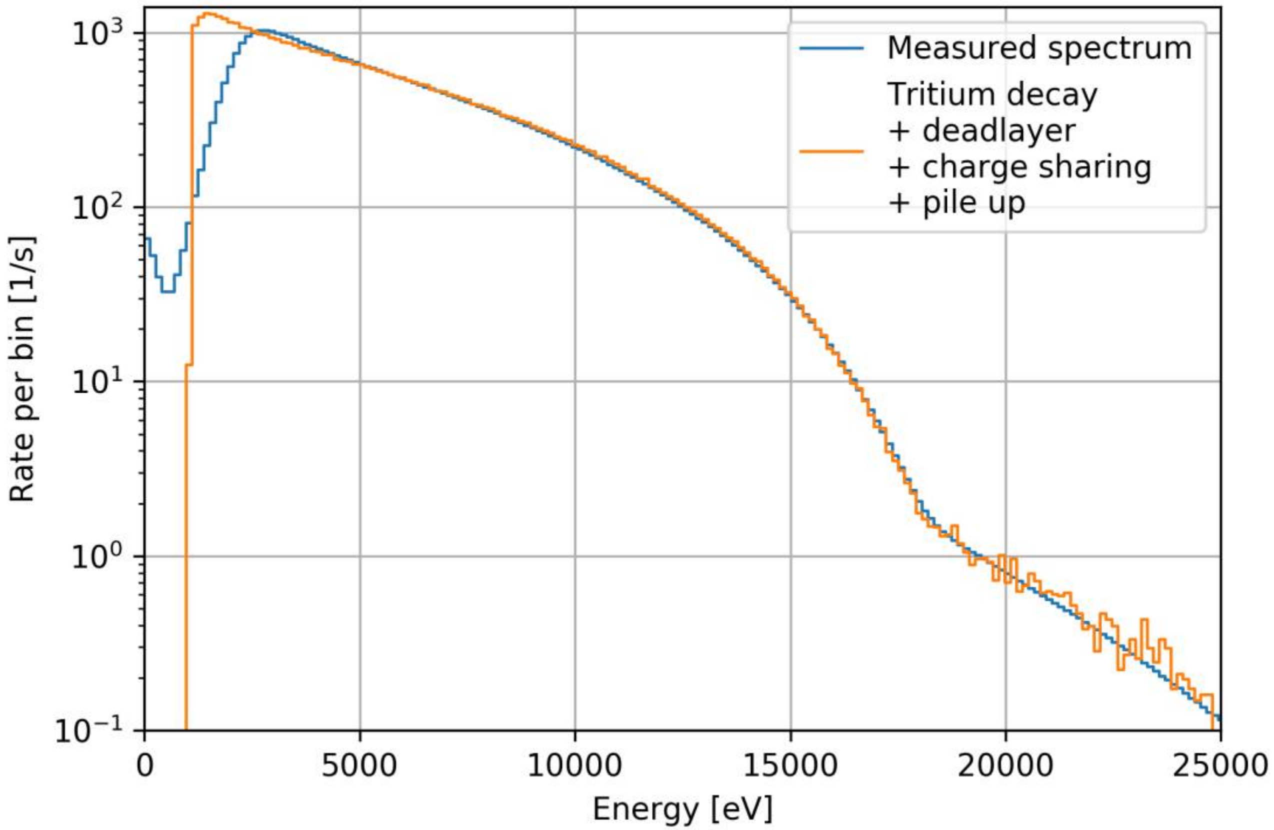
Deep Tritium Model : illustration



Deep Tritium Model : illustration

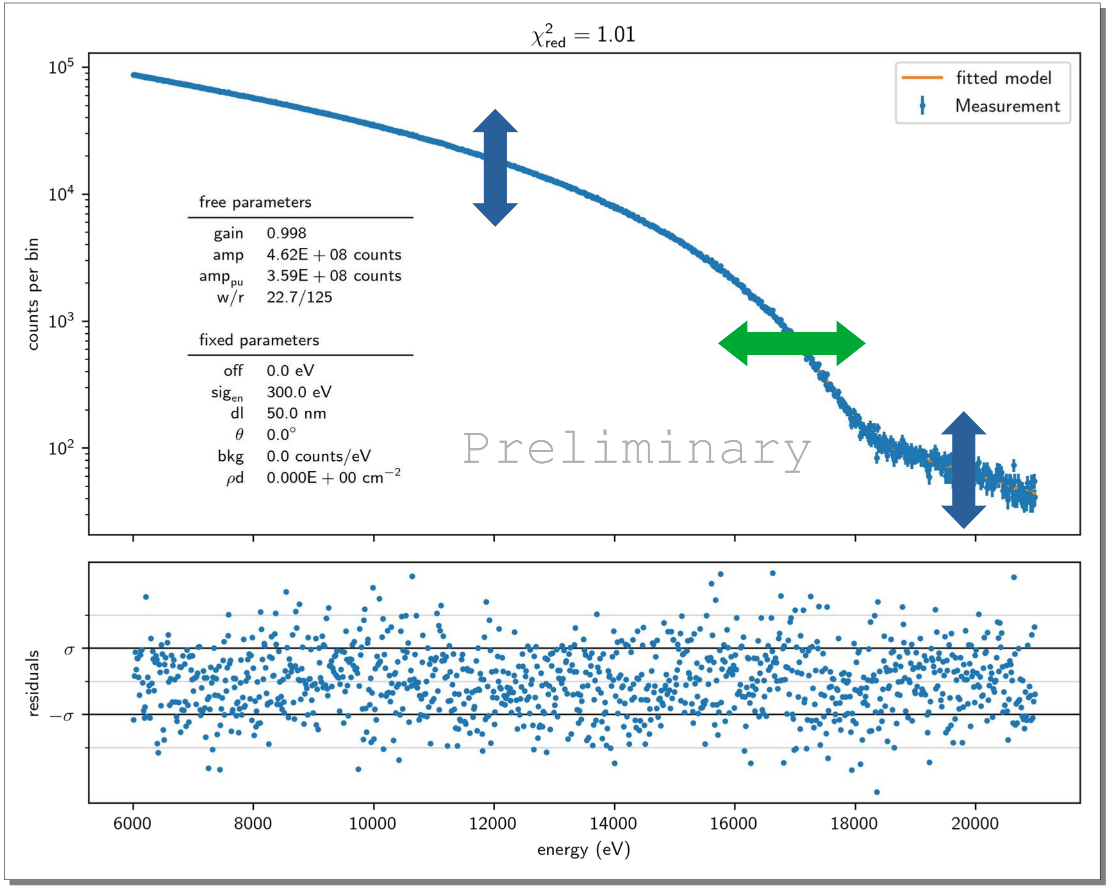


Deep Tritium Model : illustration



Deep Tritium Model : illustration

- Development of a full model for complete sensitivity studies
- **1h of nominal mass campaign**
- Total countrate: 16079 cps
- Countrate in ROI: 7496 cps
- Counts : 2.3 10^6 electrons

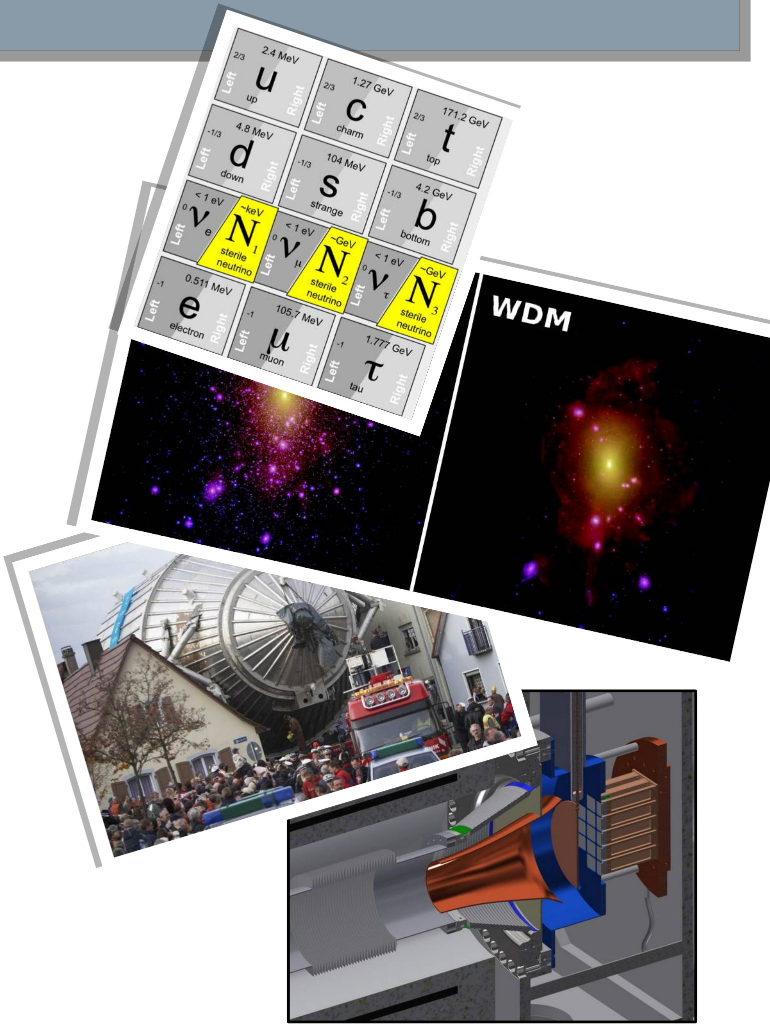


Conclusion

- Sterile neutrinos are a natural extension of the SM
- keV-sterile neutrinos are a viable dark matter candidate
- New ideas are being explored to search to search these particles. Exciting new measurements are coming!

KATRIN now **holds the best direct limit** on the neutrino mass

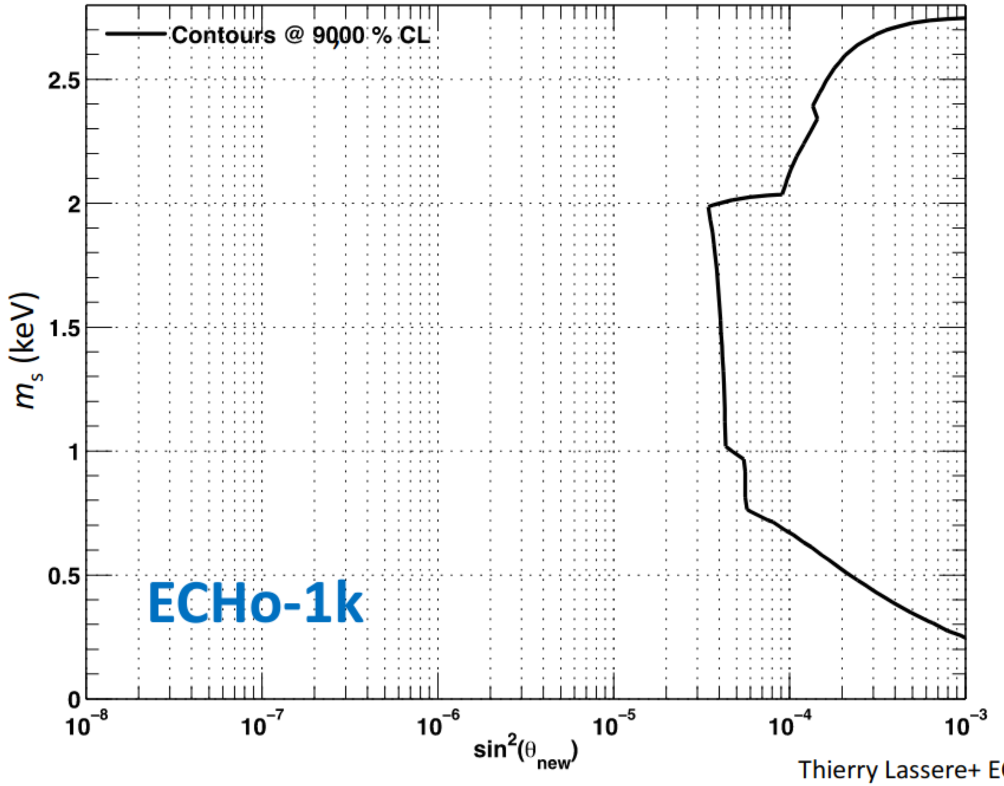
TRISTAN is getting ready to allow KATRIN to **search for keV-sterile neutrinos**



Thank you all

ECHO

Statistical Fluctuation – No Pile Up – Counts = 1e10
Theoretical Spectrum Supposed to be perfectly known



Thierry Lassere+ ECHo, in progress