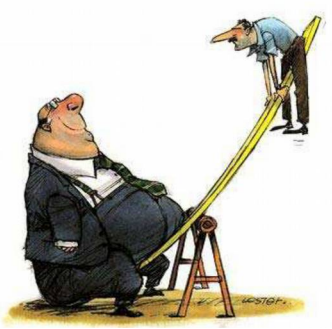
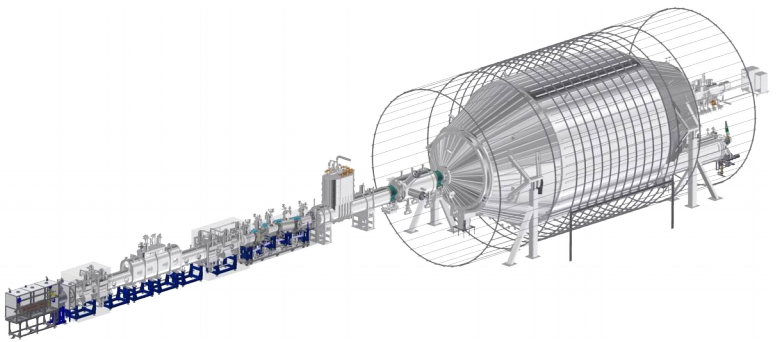


Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

KATRIN : from Neutrino Mass to Dark Matter



T. Houdy, S. Mertens

MPP Review – 15th of Dec 2020

Local Group

Scientists

- Susanne Mertens (PI)
- Thierry Lasserre
- Thibaut Houdy
- Martin Slezak
- Michael Willers (Humboldt fellow)

Institute support

- Diana Werner
- David Fink
- Alexander Sedlak

PhD

- Korbinian Urban
- Christoph Köhler
- Christian Karl
- Lisa Schlüter
- Daniel Siegmann
- Matthias Meyer
- Frank Edzards
- Anna Schaller
- Tim Brunst

Master

- Jacov Kholodkov
- Fabian Kellerer
- Johannes Wickles
- Vikas Gupta
- Alessandro Schwemmer
- Matthias Weidenthaler
- Florian Henkes
- David Casado Moran

Interns

- Aude Glaenzer
- Paul Ripoche
- Nathan Le Guennic
- Joel Dai
- Aidan Wright
- Tiziano Bevilacqua
- Gulden Othman
- Julieta Gruszko
- Alexey Lokhov

Bachelor

- Daniela Spreng
- Christina Bruch
- Christian Forstner
- Xavier Pawlowski

Thanks to all of them as well as to each department and all the administrations services for the support in this complicated year.

Local Group

Scie

Susanne
Thierry La
Thibaut H
Martin Sl
Michael W
(Humbold

Institu

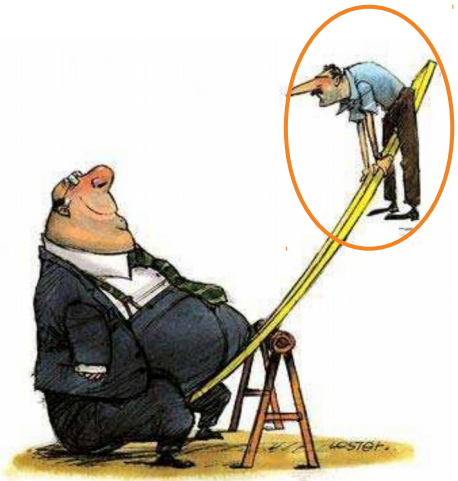
Diana W
David Fir
Alexande

Thanks to all of them as well as to each department and all the administrations services for the support in this complicated year.

Christina Bruch
Christian Forstner
Xavier Pawlowski

Questions

What is the mass of the neutrino ?



What is dark matter ?

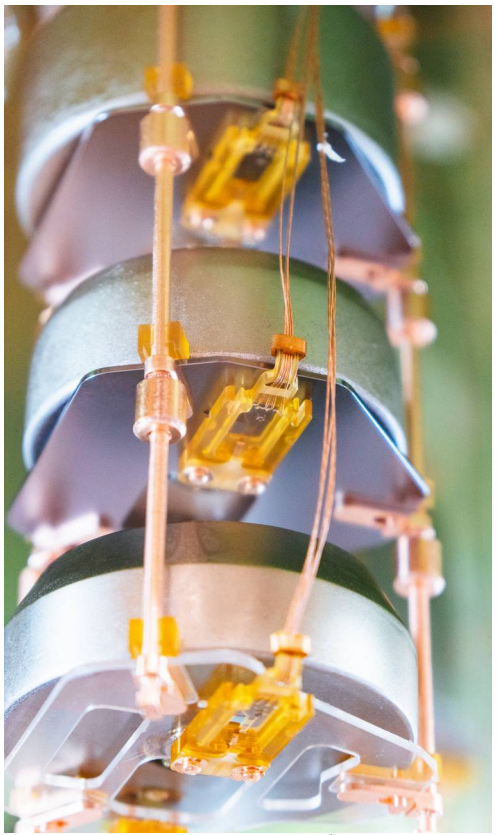
Do sterile neutrinos exist ?

Determining m_ν from 0nßß : LEGEND

Unprecedented discovery potential for neutrino mass and nature

- LEGEND-200 : Integration of low mass front-end electronics
- LEGEND-1000 : Development of a low background ASIC-based read-out
  F. Edzards *et al* 2020 *JINST* 15 P09022
- Ge-detector caracterization in Galatea (thanks to **Iris Abt**)

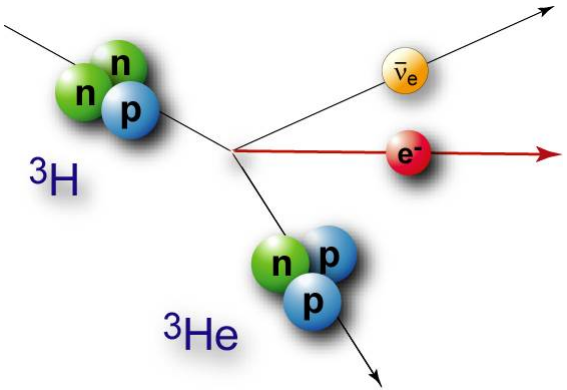
M. Willers, F. Edzards



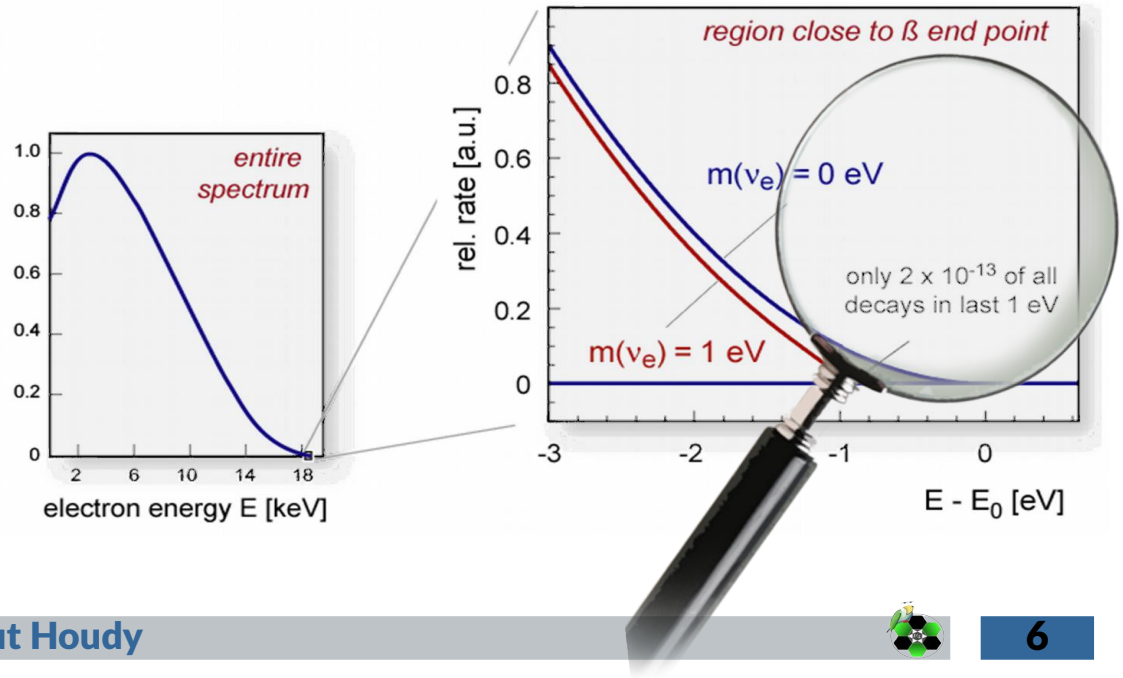
LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Determining m_ν from ß-decay: 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

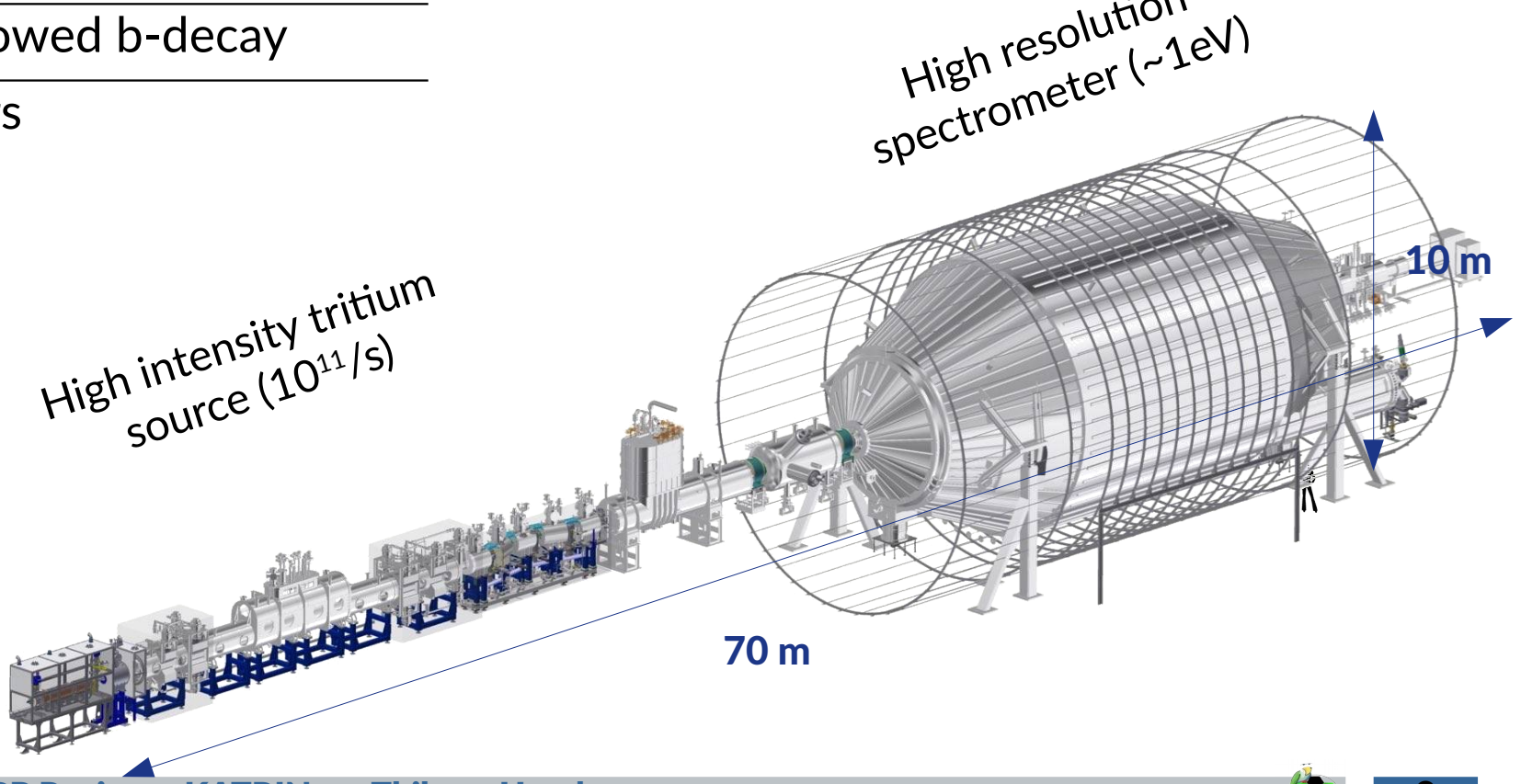


KArlsruhe TRItium Neutrino Experiment : KATRIN

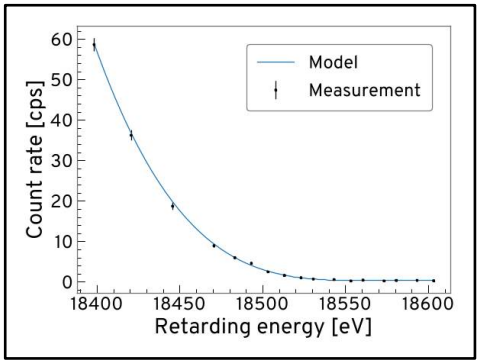
- Experimental site : Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Design sensitivity: 0.2 eV (90% CL)

KATRIN Working Principle

	^{3}H
	super-allowed b-decay
$T_{1/2}$	12.3 years
E_0	18.6 keV

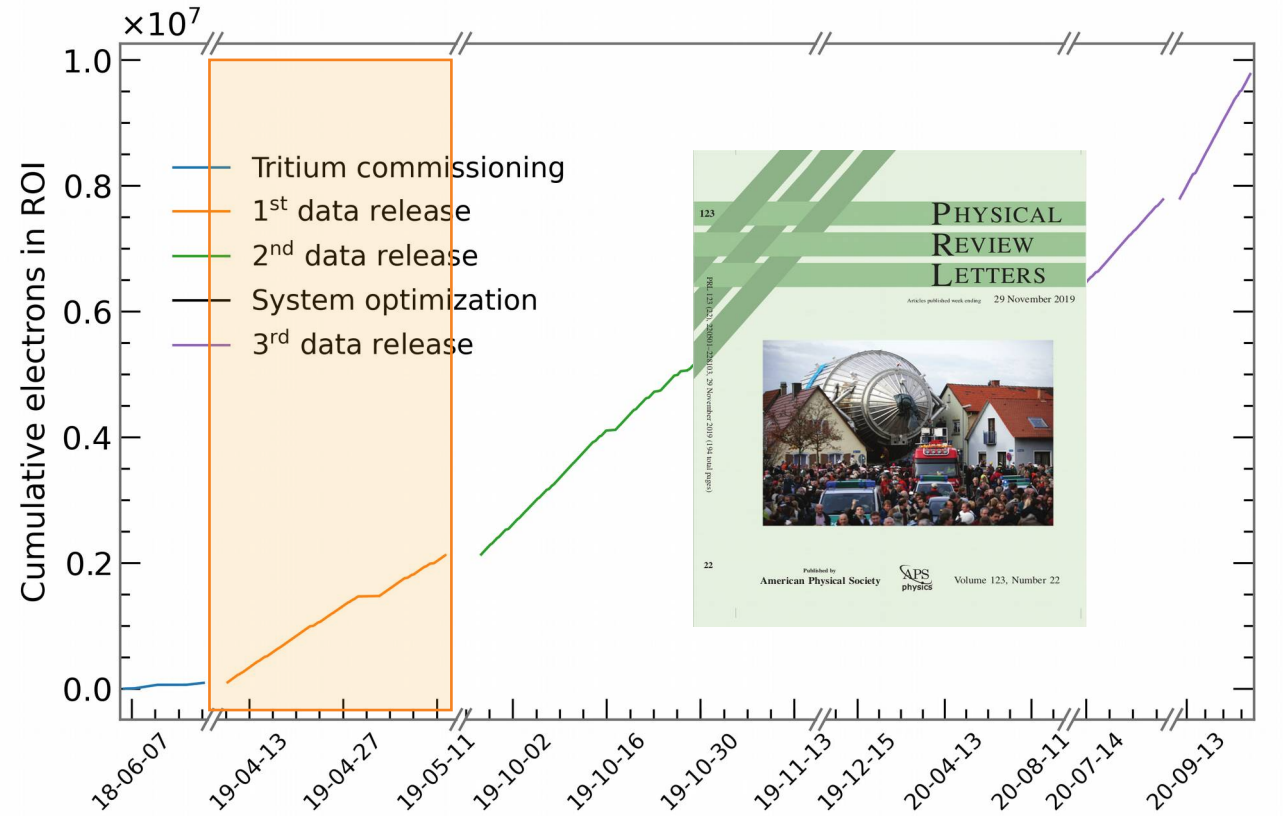


KATRIN Working Principle

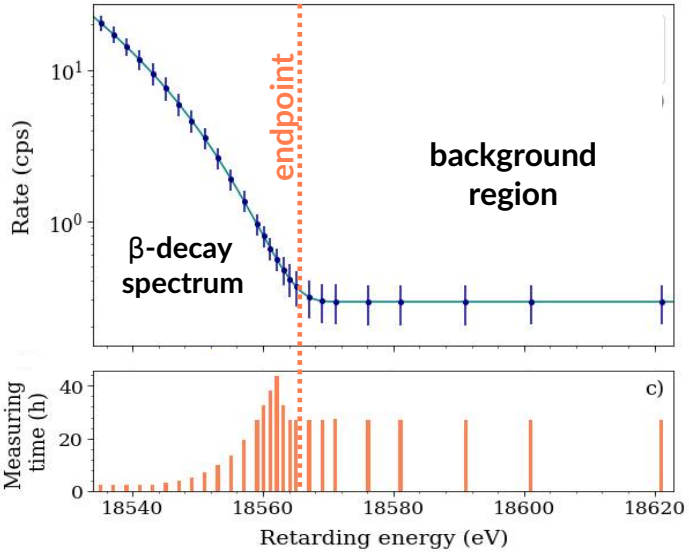


β-decay

1st neutrino mass campaign



- Measurement time: 22 days
- Gas density: 22%
- Isotopic purity: 97.5% tritium
- Source activity: $2.45 \cdot 10^{10}$ Bq
- Total statistics: $2 \cdot 10^{6}$ e's



- *Improved Upper Limit on the Neutrino Mass from a Direct Kinematic Method by KATRIN*, KATRIN Collaboration, **Phys. Rev. Lett. 123, 221802 (2019)**
- *First operation of the KATRIN experiment with tritium.* **Eur. Phys. J. C 80, 264 (2020)**

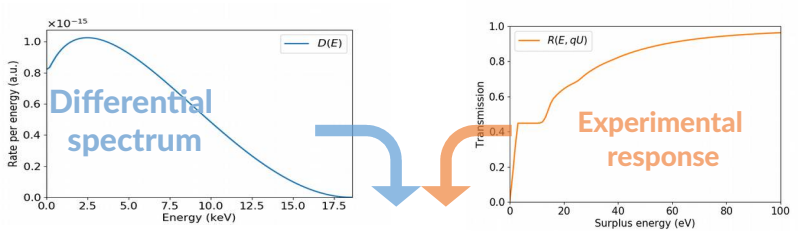
Fitrium : KATRIN Analysis software

- Main KATRIN analysis approach

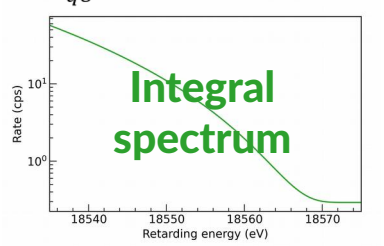
Developed at MPP !

M.Slezak, A.Polithy, C.Karl,
C.Köhler, V.Gupta,
A.Schwemmer, L.Schlüter, T.Lasserre,

Fast and precise model prediction

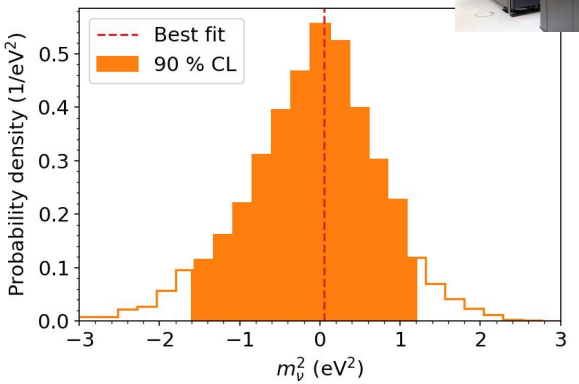


$$\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{\boldsymbol{E_0}} D\left(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}\right) \cdot R(qU, E)\, dE + \boldsymbol{B}$$



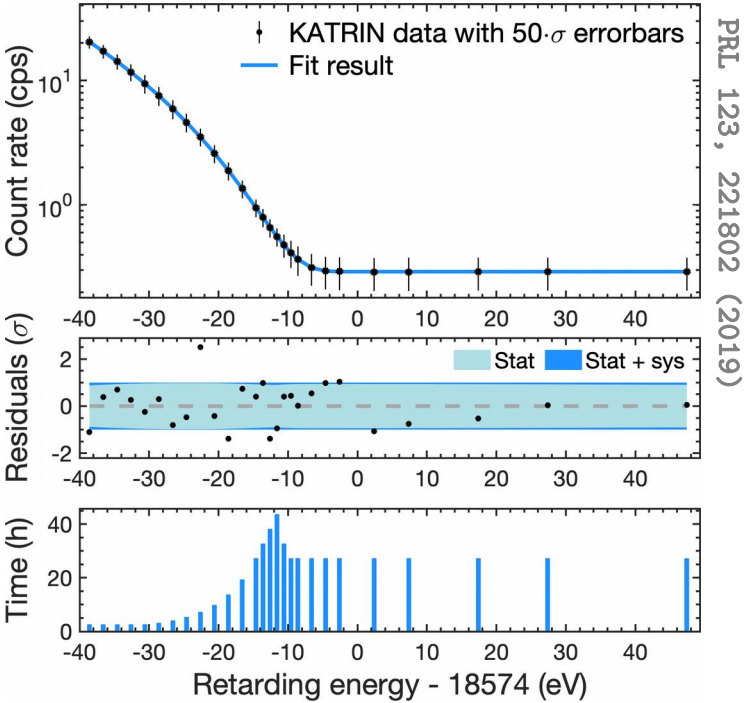
Fitrium

Monte Carlo propagation of systematics

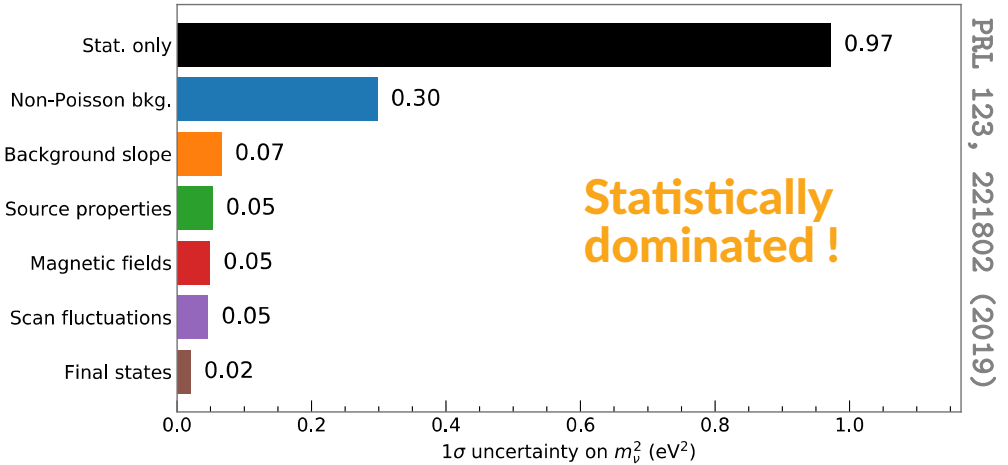


In future : Support granted from ODSL for fast model calculation with neural networks!

1st neutrino mass campaign



PRL 123, 221802 (2019)



PRL 123, 221802 (2019)

Statistically dominated !

- Best fit value : $m_\nu^2 = (-1.0\ ^{+\ 0.9}_{-\ 1.1})\ \mathrm{eV}^2$
- Limit :

BAT :

$$m_\nu < 1.1\ \mathrm{eV}\ (90\%\ \mathrm{CL})$$

$$m_\nu < 0.9\ \mathrm{eV}\ (90\%\ \mathrm{CL})$$

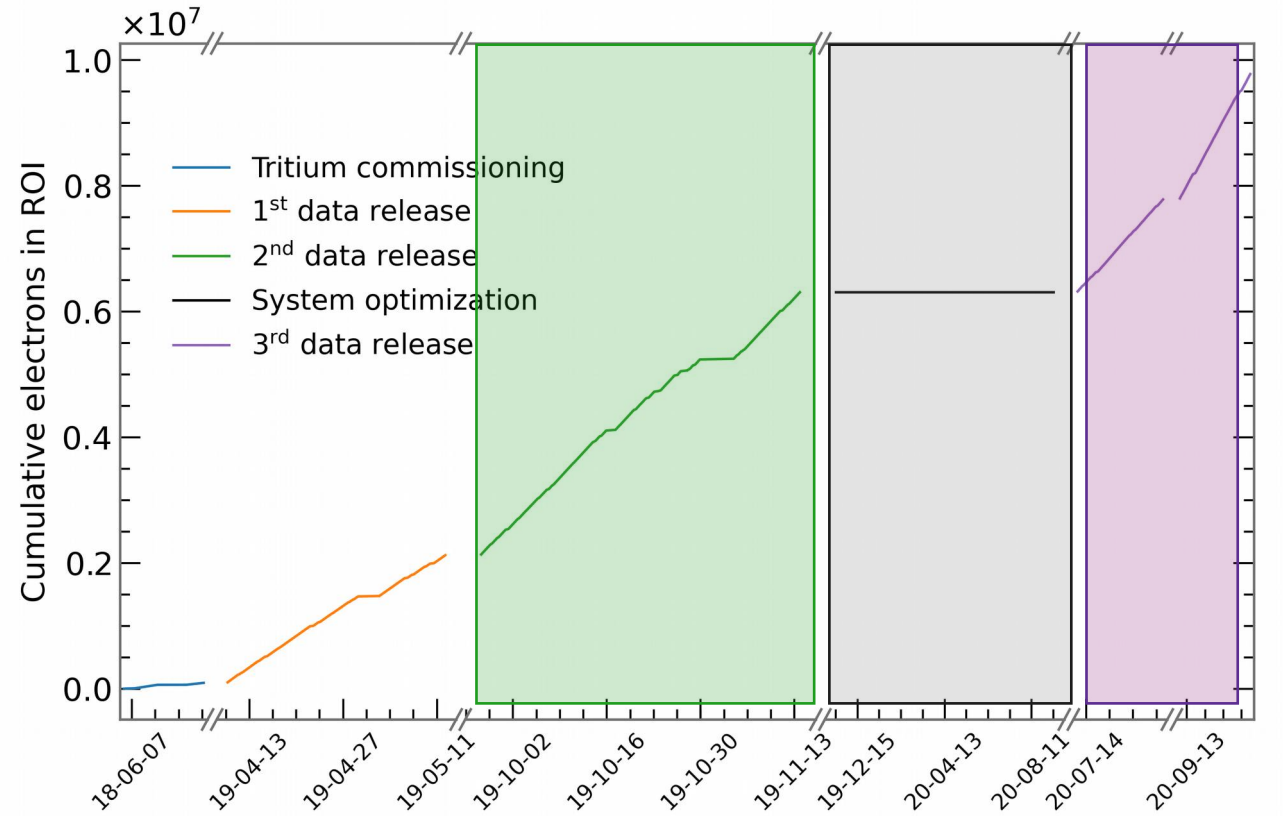
Neutrino Properties

PDG !

See the note on "Neutrino properties listings" in the Particle
Mass $m <$ 1.1 eV, CL = 90% (tritium decay)

T.Lasserre, M.Slezak, C.Karl, L.Schlüter

Next neutrino mass campaigns



M.Slezak, V.Gupta
A.Schaller, A.Schwemmer

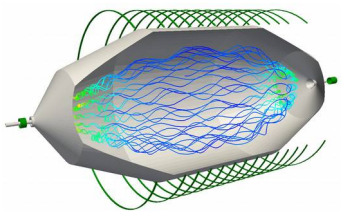
Gas density : 84 %
M_n-sensitivity : 0.7 eV (90% CL)
Data unblinding : Jan 12th

Plasma investigations

M.Slezak et al. **J. Phys. G 47 065002 (2020)**

Improve background configuration

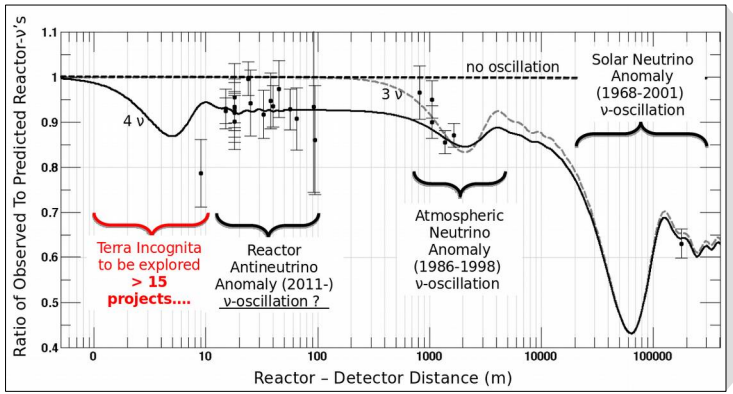
F. Fränkle, A.Schaller et al., **arxiv :2011.05107v1**



Data taking since Summer 2020 :

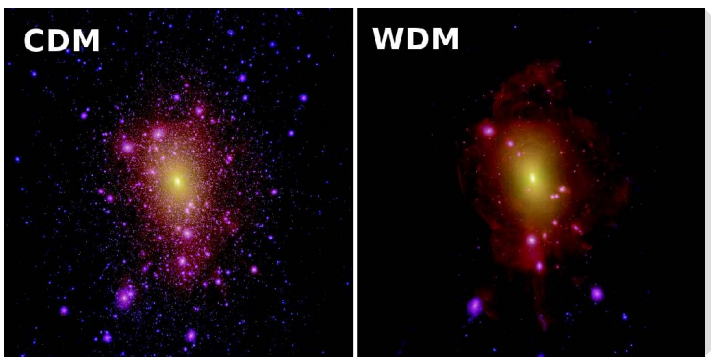
→ 1000 days ↔ < 0.3 eV (90 % CL)

Is there a sterile neutrino ?



S.Böser, et al. (incl. S. Mertens), **PPNP 111 103736** (2020)

eV-scale:
Resolve anomalies in ν-oscillation experiments

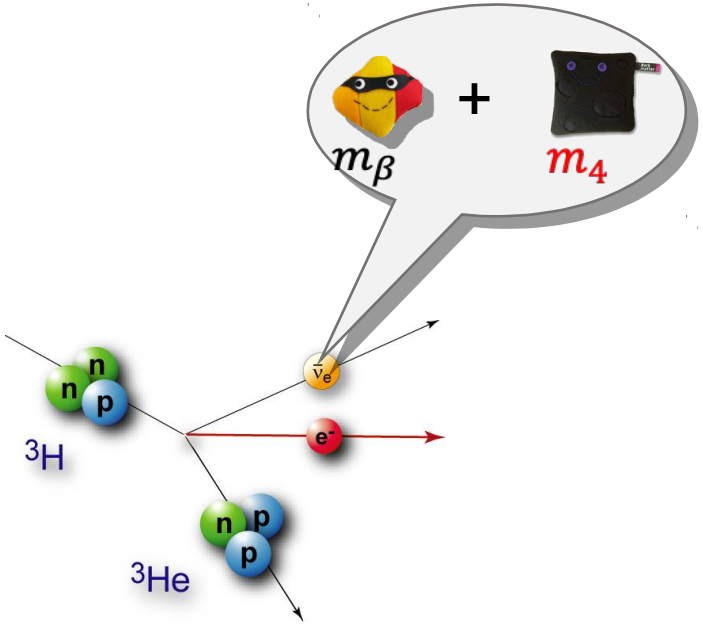


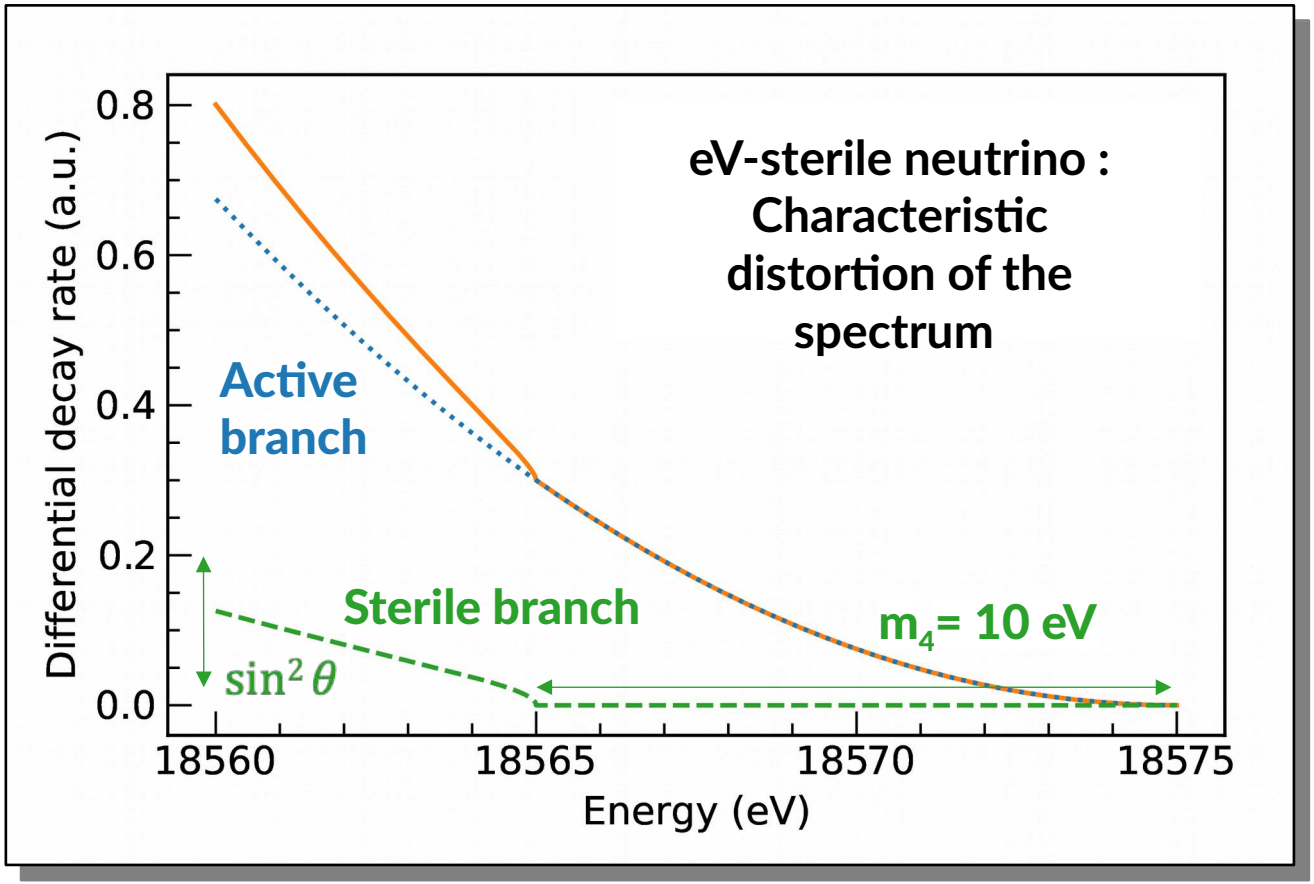
A. Boyarsky, et al. (S. Mertens) **PPNP, 104 1-45**, (2019)

keV-scale:
Dark Matter candidate

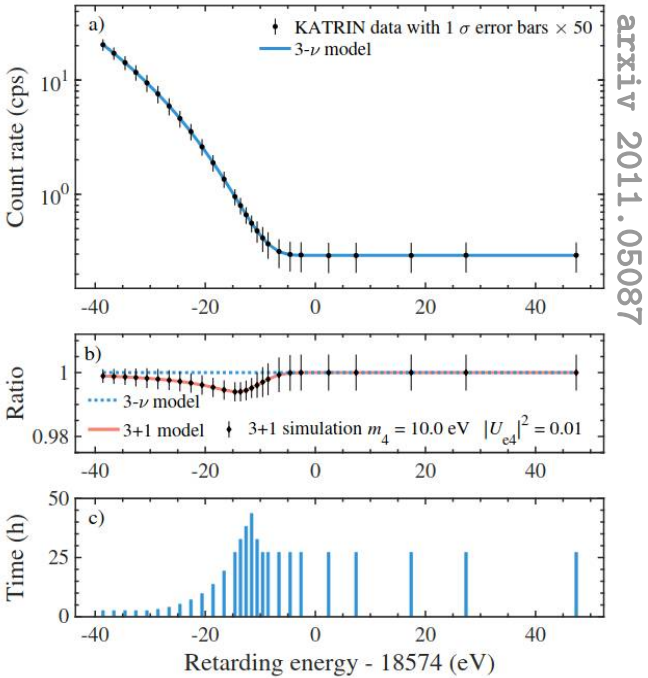
2.4 MeV, 2/3, u, up	1.27 GeV, 2/3, c, charm	171.2 GeV, 2/3, t, top
4.8 MeV, -1/3, d, down	104 MeV, -1/3, s, strange	4.2 GeV, -1/3, b, bottom
< 1 eV, 0, ν_e	~eV ?, N_1, sterile neutrino	
< 1 eV, 0, ν_μ	~keV ?, N_2, sterile neutrino	
< 1 eV, 0, ν_τ	~GeV ?, N_3, sterile neutrino	
0.511 MeV, -1, e, electron	105.7 MeV, -1, μ, muon	1.777 GeV, -1, τ, tau

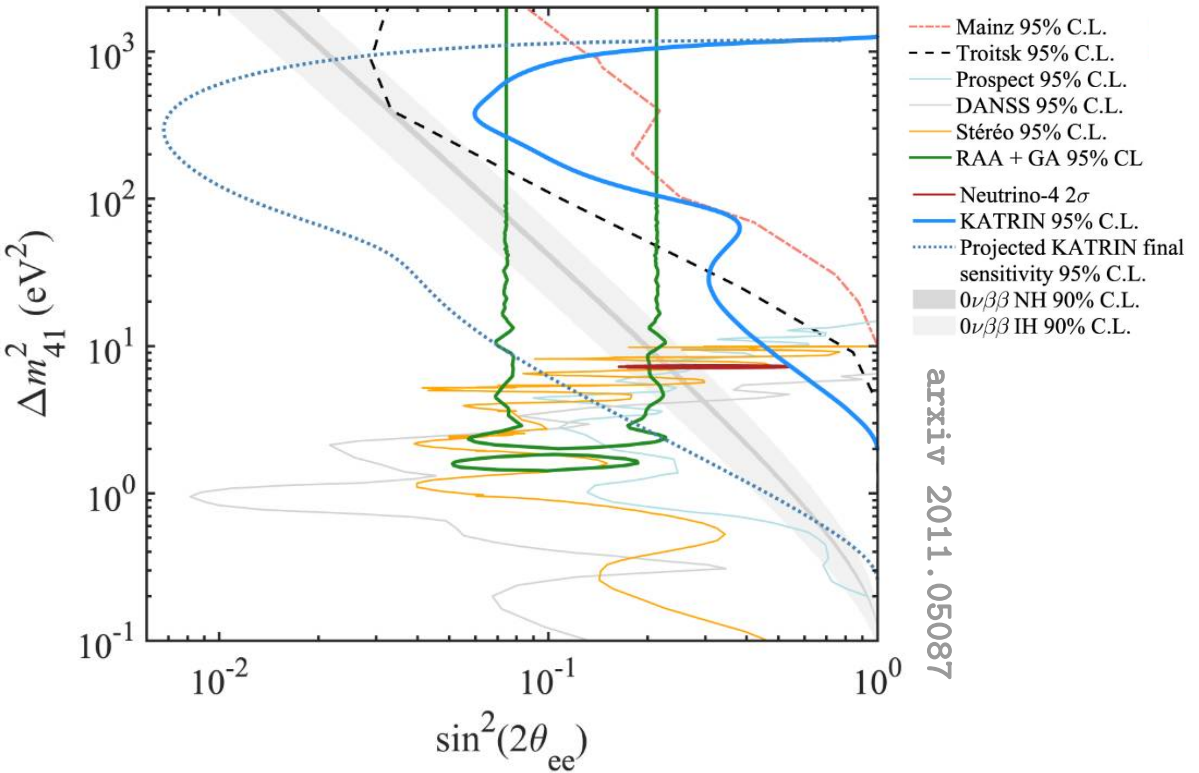
eV-sterile signature in β-decay





Sterile hunt with KATRIN

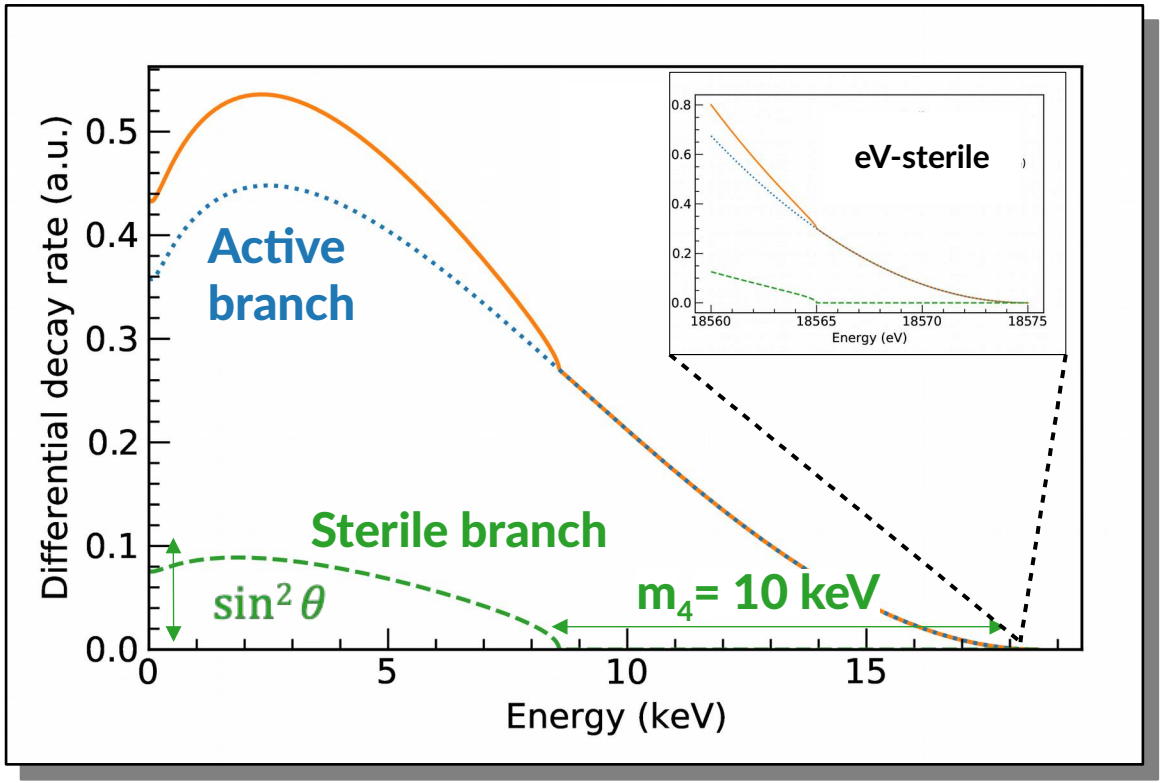




C. Köhler, T.Lasserre, M.Slezak, L.Schlüter

- Unique large window at high mass
- Complementary with Reactor experiments
- Will exclude most of the favored phase-space in the next years

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 3×10^8 Hz)

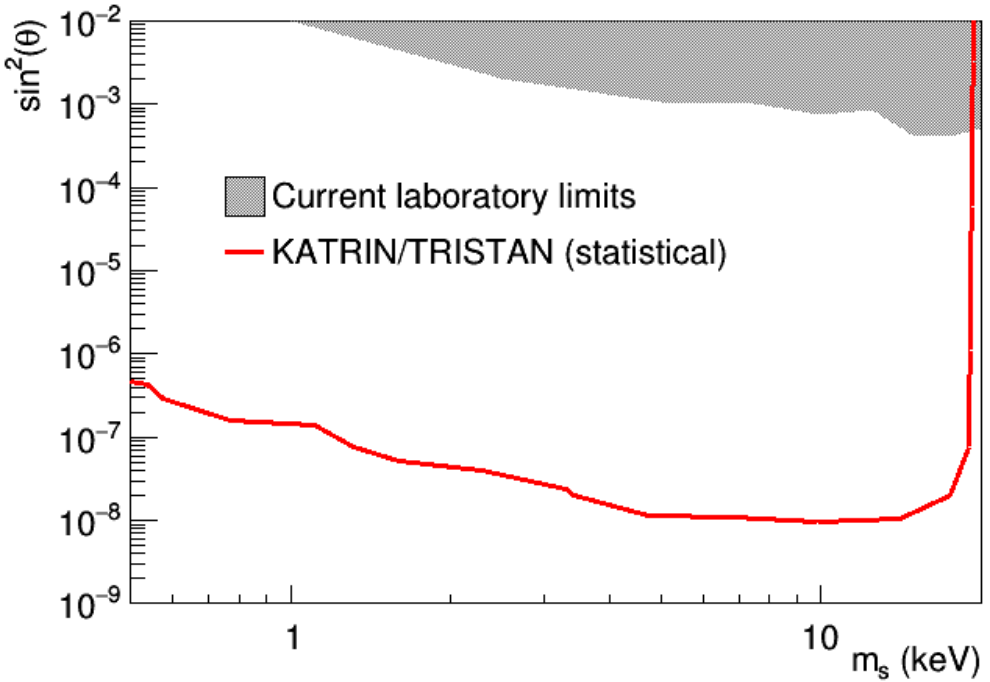
→ Integral and differential phases (detector with **good resolution**)

→ Highly **pixelised**

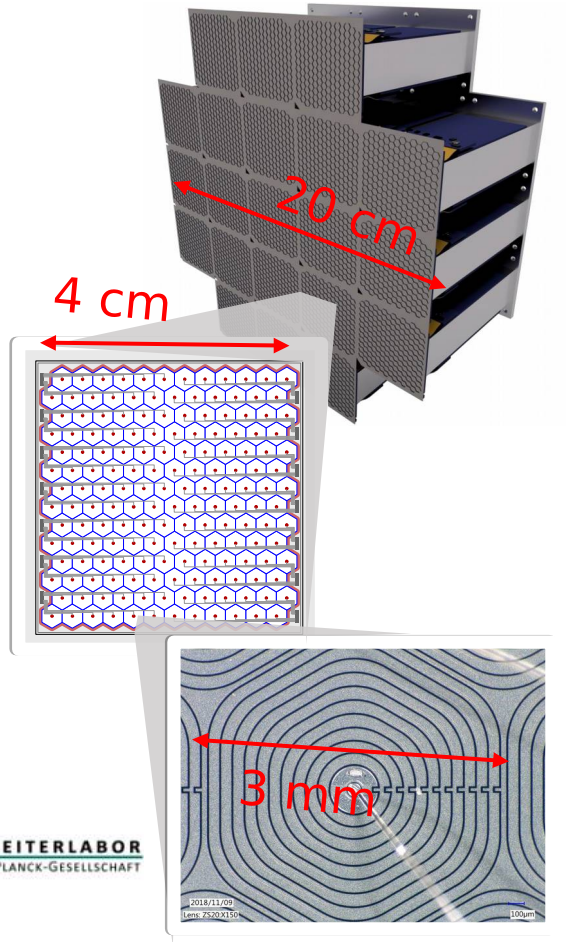
→ **new detector is needed : the TRISTAN project**

TRISTAN Project

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

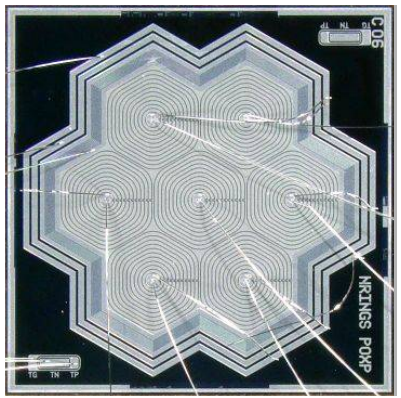


J.Phys. G46 (2019) no.6, 065203



MPG HLL HALBLEITERLABOR DER MAX-PLANCK-GESELLSCHAFT

Staged approach

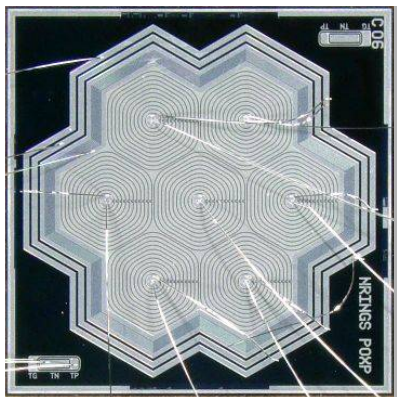


TRISTAN prototype
- 7-pixel
  with external CMOS

TRISTAN module
- 166-pixels
  with integrated JFET

Full TRISTAN detector
- 21 x modules
  → 3500 pixels

Staged approach



TRISTAN prototype
- 7-pixel
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TRISTAN module
- 166-pixels
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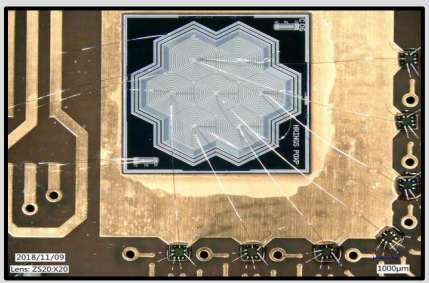
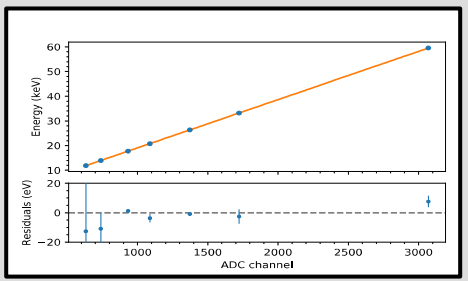
Full TRISTAN detector
- 21 x modules
  → 3500 pixels

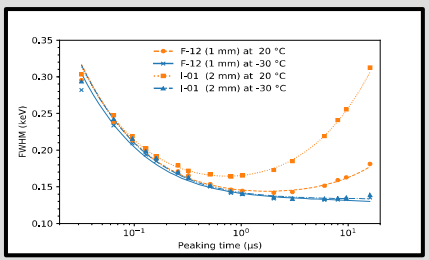
Prototype results

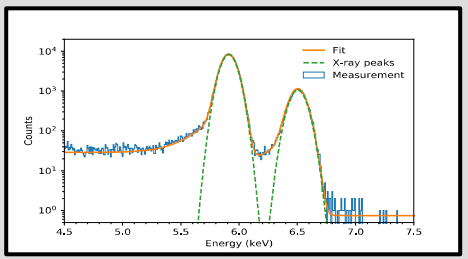
Photon response

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





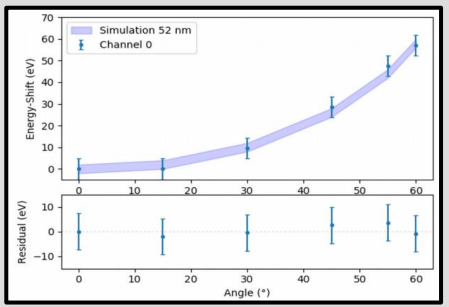


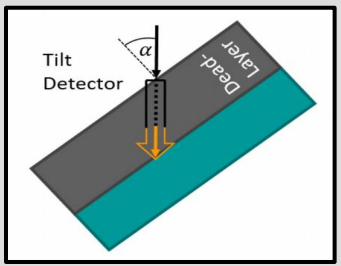


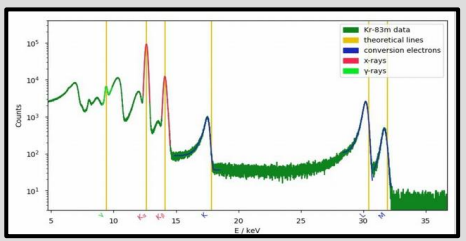
→ Mertens et al, J. Phys. G46 (2019)

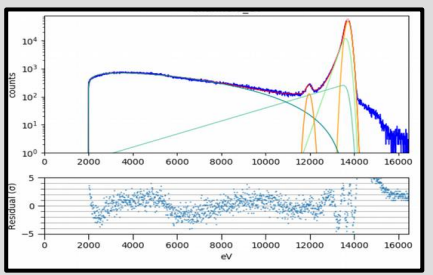
Electron response

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





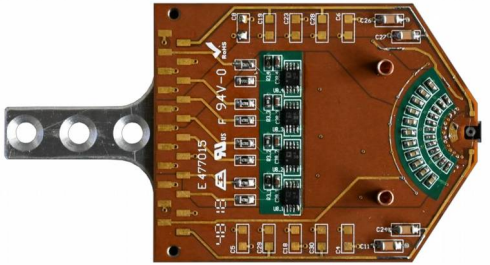




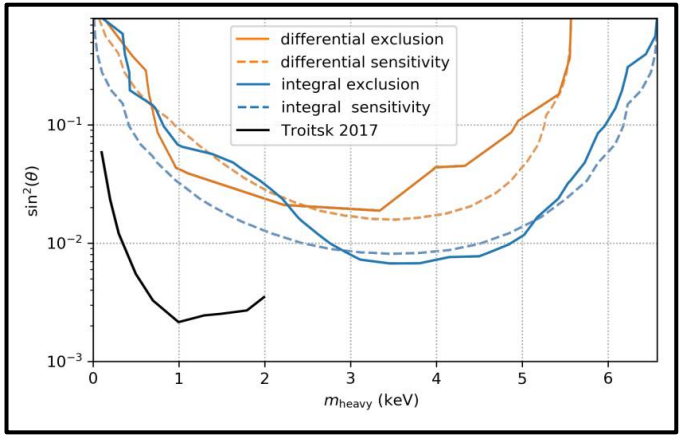
→ Paper accepted by J. Phys. G (2020)

Prototype applications

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

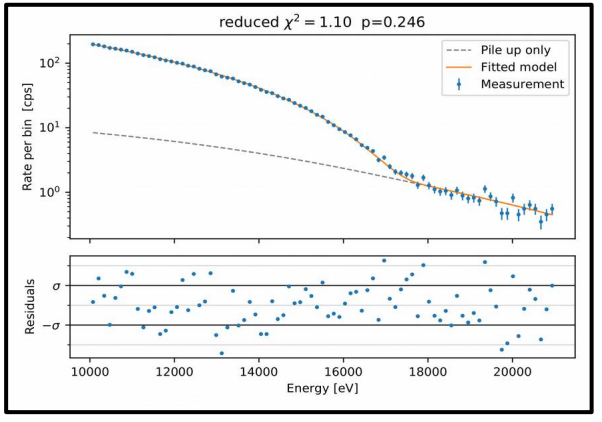


2019-2020 :
TRISTAN 7-pixels prototype implemented in KATRIN as **Forward Beam Monitor**.
Monitoring since KNM2

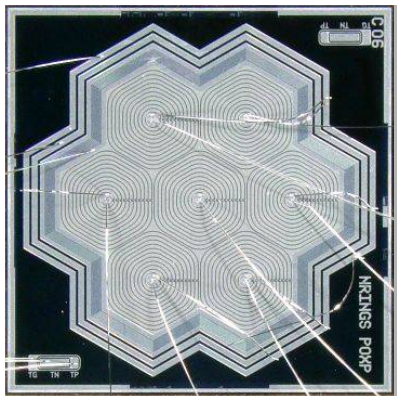


JINST14 P11013 (2019)

T.Brunst K.Urban



Staged approach

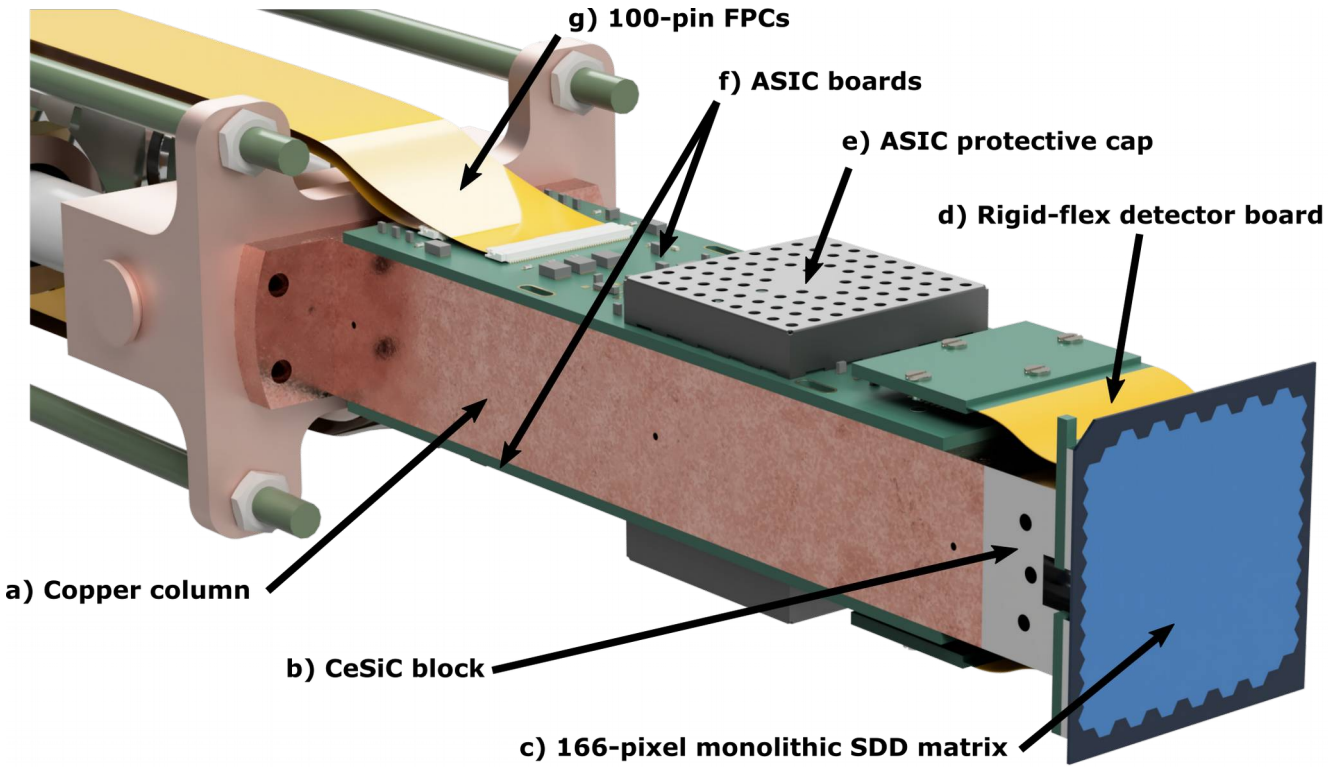


TRISTAN prototype
- 7-pixel
  with external CMOS

TRISTAN module
- 166-pixels
  with integrated JFET

Full TRISTAN detector
- 21 x modules
  → 3500 pixels

Design of the TRISTAN Module

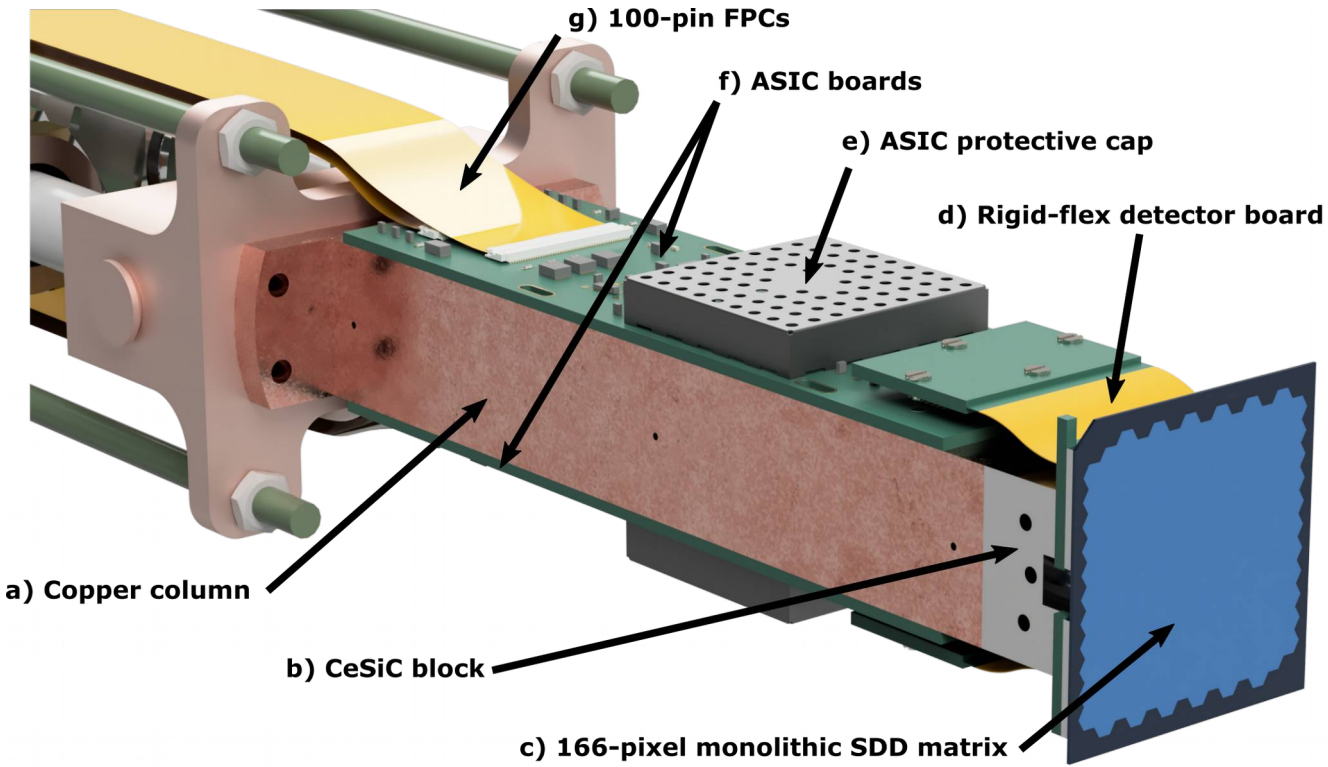


Operating 166-pix SDD, 10^{-8} mbar, -80°C, intense B, low noise (<300 eV res.)

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

Design@MPP

Design of the TRISTAN Module



Assembly of a first dummy module **@MPP**

TRISTAN Module

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

Kerberos, TRISTAN ded. peak sensing ADC

Cooling liquid circulation

Mechanical structure**@MPP**

A.Sedlak + workshop

Planar Design 47-pixels SDD with nFET

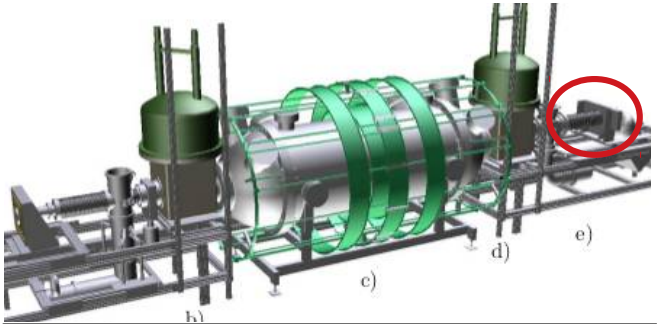
48-ch bias board

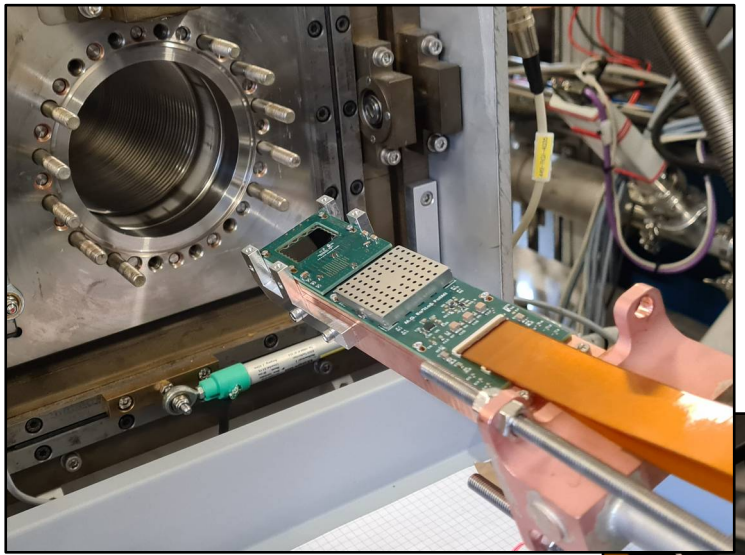
400 pins micro-D CF100 flange

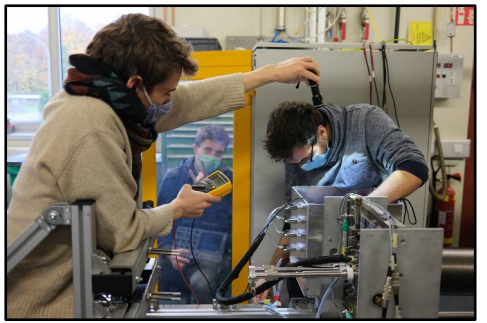
Feedthrough**@MPP**

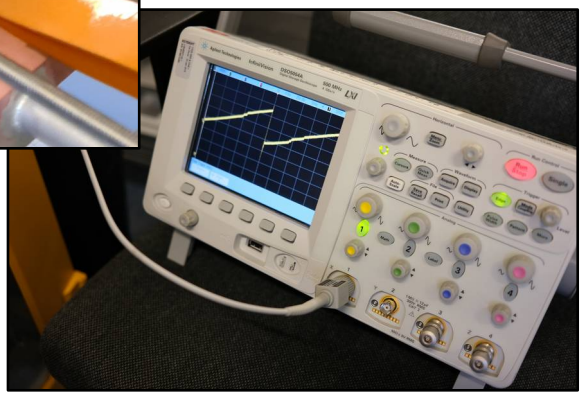
S.Horn, D.Fink

TRISTAN Prototype Integration@KIT







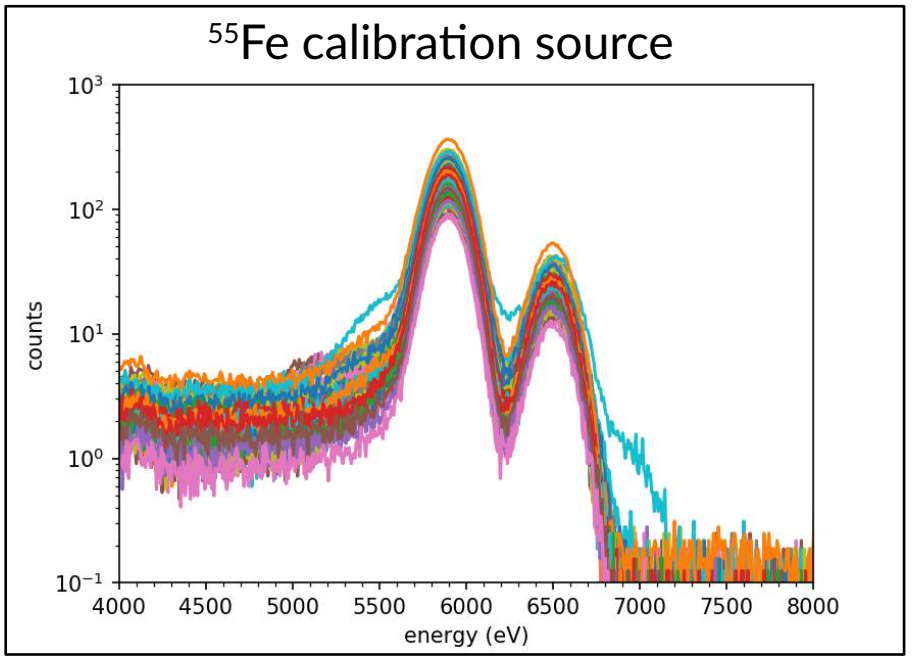


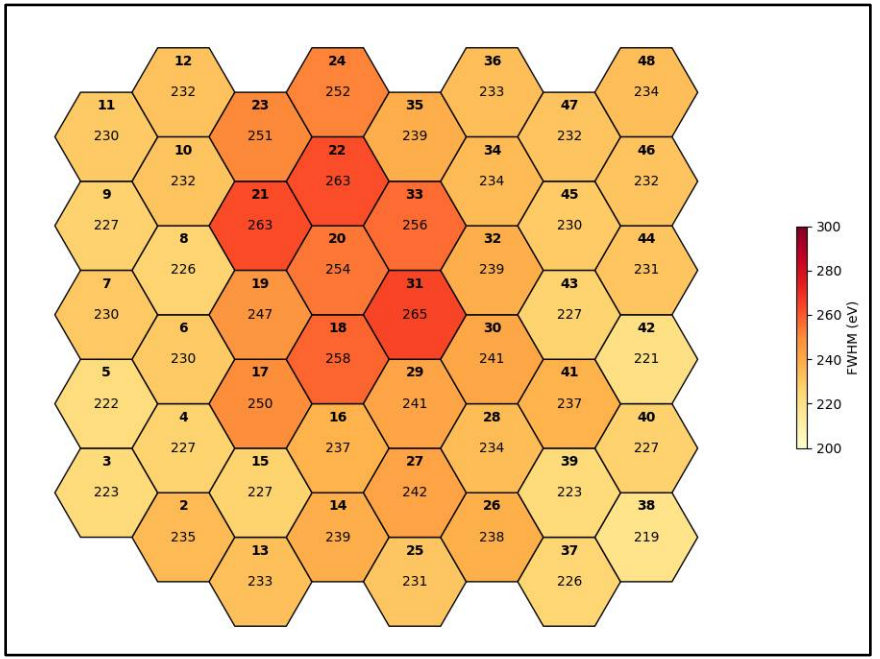
Test in real conditions
- Ultra High Vacuum
- Magnetic Fields
- Cooling system

T.Houdy, D.Siegmann, K.Urban

1st operation of a 47-pix TRISTAN inside MoS KATRIN on Nov 2020

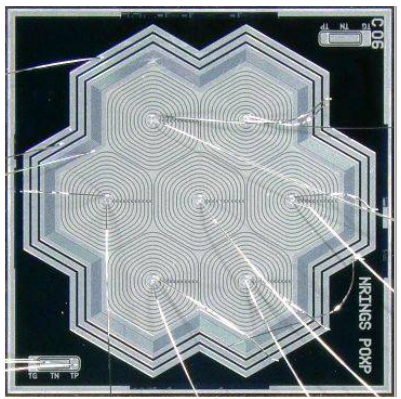
TRISTAN Prototype Integration





- Very good first results → FWHM@6keV < 270 eV, good homogeneity
- Tests on-going (increasing magnetic field, cooling, improving the DAQ, etc)
- Early 2021 → replacing planar by 3D design

Staged approach

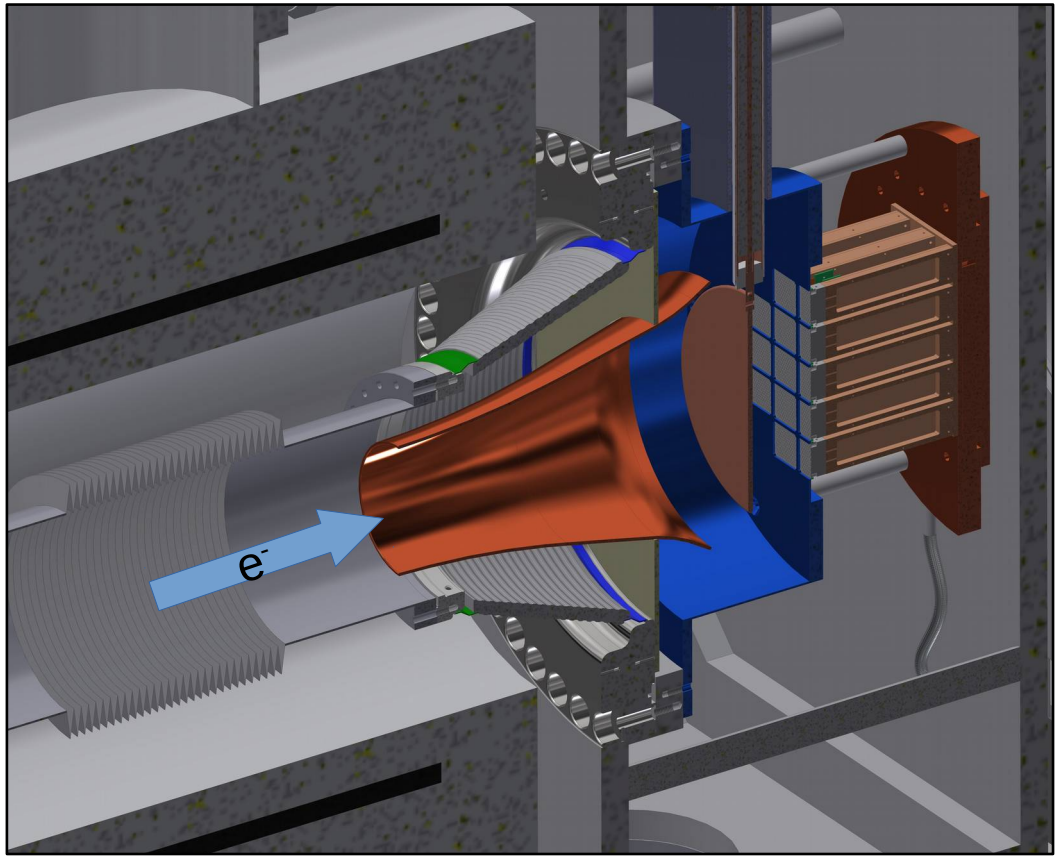


TRISTAN prototype
- 7-pixel
  with external CMOS

TRISTAN module
- 166-pixels
  with integrated JFET

Full TRISTAN detector
- 21 x modules
  → 3500 pixels

TRISTAN Final Detector

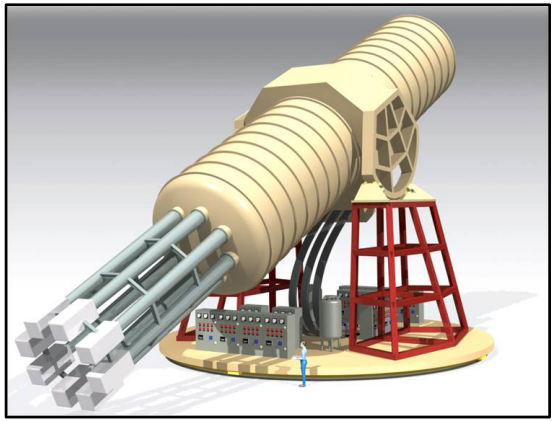


Next milestones :

- **New DAQ** system
  `J.Kholodkov, K.Urban`
- **Full model** of the tritium spectrum
- First physics runs with **9 modules** in the KATRIN beamline (~ 2022)

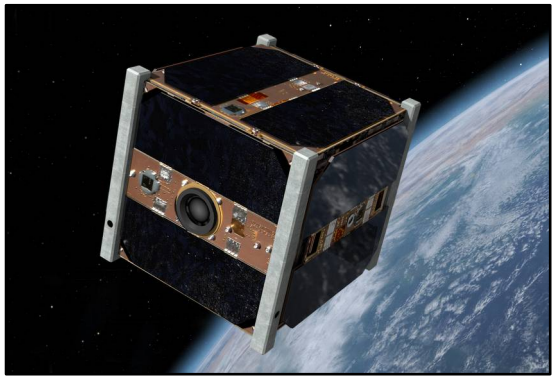
Supported by ERC Grant

Technology transfer & spin offs



TRISTAN as X-ray detector in the solar axion experiment **IAXO**

T.Houdy, D.Casado Moran



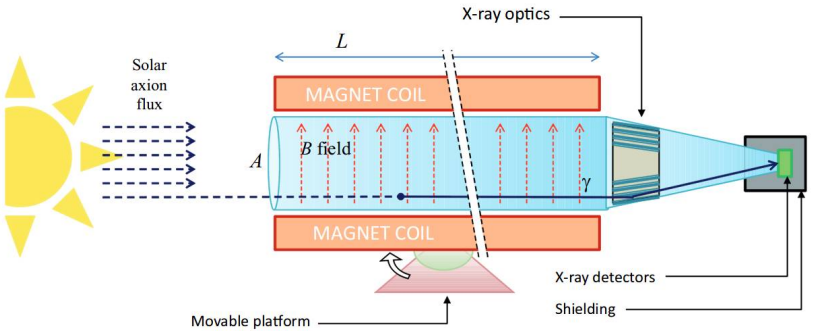
TRISTAN in a CubeSat space mission as Compton telescope **COMPOL**

Collaboration with CEA and ORIGINS Laboratory for rapid space missions (LRSM)

M.Meyers, M.Willers

TRISTAN for IAXO

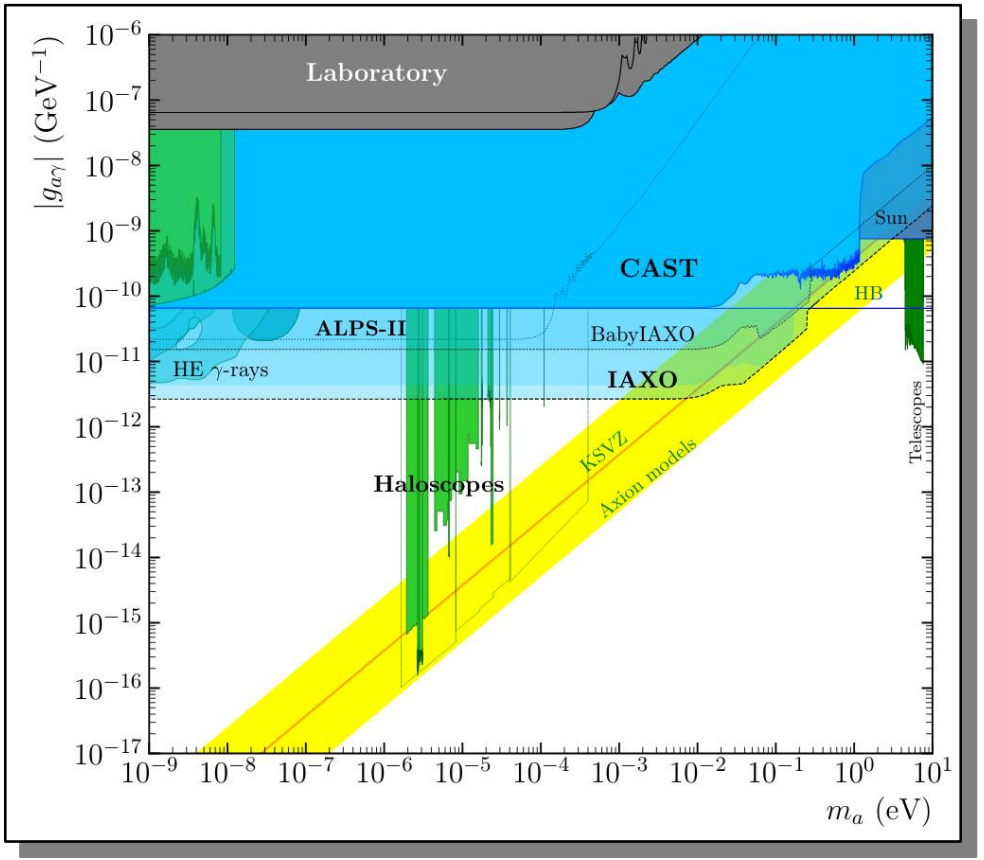
Solar axion search with Helioscope :
International Axions Observatory (IAXO)



Conceptual Design of BabyIAXO, the intermediate stage towards the International Axion Observatory

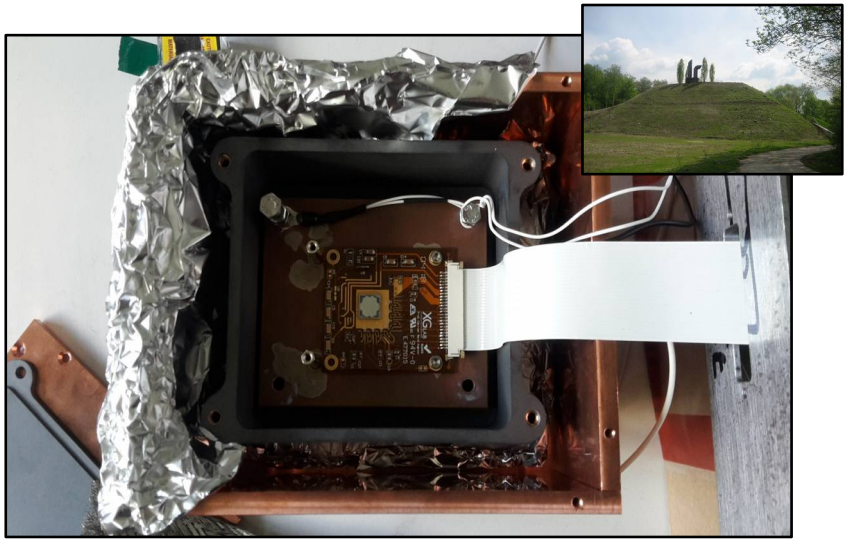
IAXO collaboration

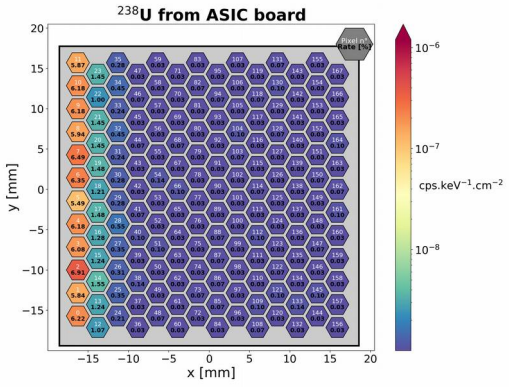
Submitted to JHEP
arxiv ; 2010.12076



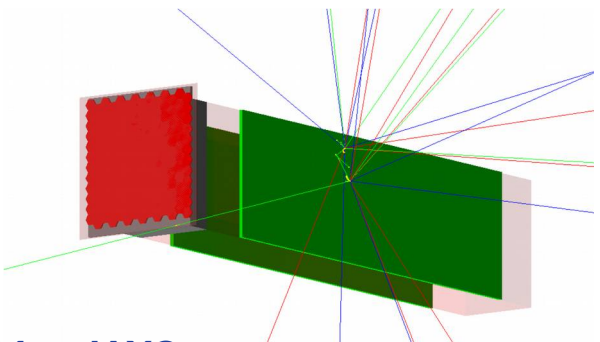
TRISTAN Module for IAXO ?

- Good **resolution** (139 eV @ 5.9 keV)
- **Low threshold** (<1 keV)
- **Linearity** from 1 to 50 keV
- **Which level is the background ?**





Geant-4 MC with Module



Background measurement

- Design specific shield -Supported by ORIGIN Seed money
- Set-up in the UGL
- Background reached : $<10^{-4}$ cnt/keV/s/cm^2

Module electronics → Meet IAXO specifications (in simulation)

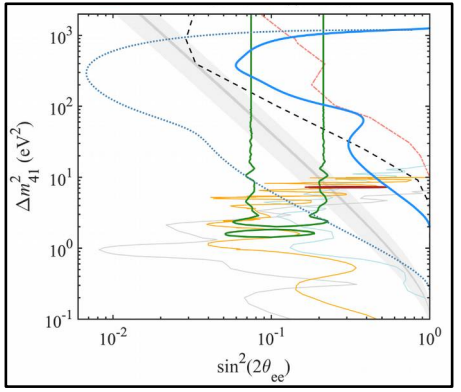
T.Houdy, M.Willers

Conclusion

LEGEND :

unprecedented discovery potential for neutrino mass and nature.

→ **Front-end electronics for LEGEND-200 and LEGEND-1000**



KATRIN:

direct neutrino mass measurement with sub-eV sensitivity

→ World-leading limit: m_ν < 1.1 eV (90% C.L.) and 1st ev-sterile exclusion

→ **Main analysis software (mass, sterile programs, other new physics)**

→ **Inputs to systematics and background**

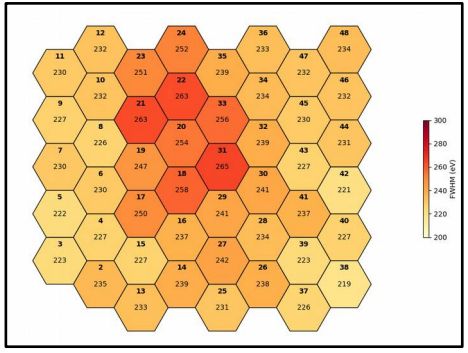
KATRIN with TRISTAN :

promising potential to search for keV-scale sterile neutrinos

→ **Lead institution : MPP**

→ **Design and assembly of the first TRISTAN Module**

→ **Successful integration in KATRIN MAC-E filter**



Spin offs :

Compol, BabyIAXO

Thank you all