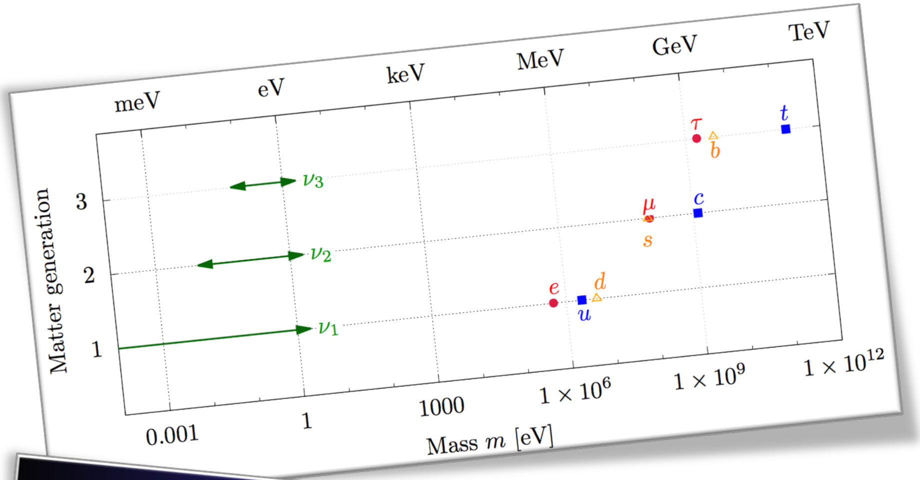
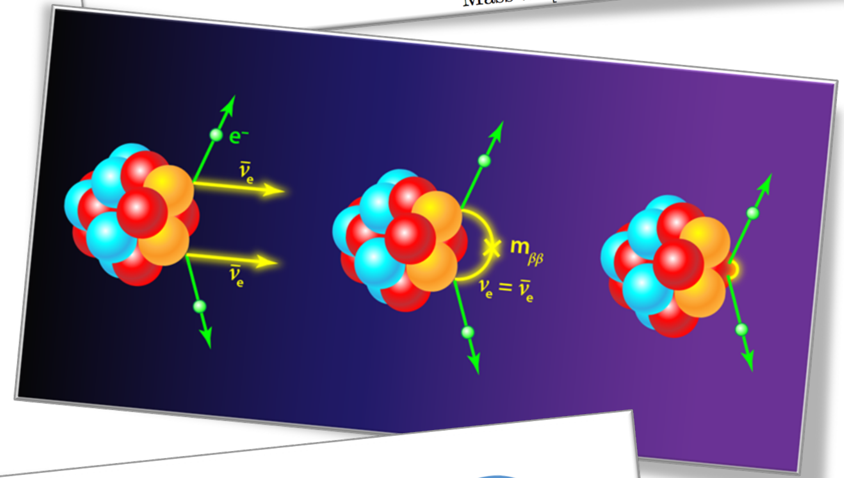
KATRIN, TRISTAN, and beyond

Susanne Mertens
Max Planck Institute for Physics & Technical University Munich

Neutrinos

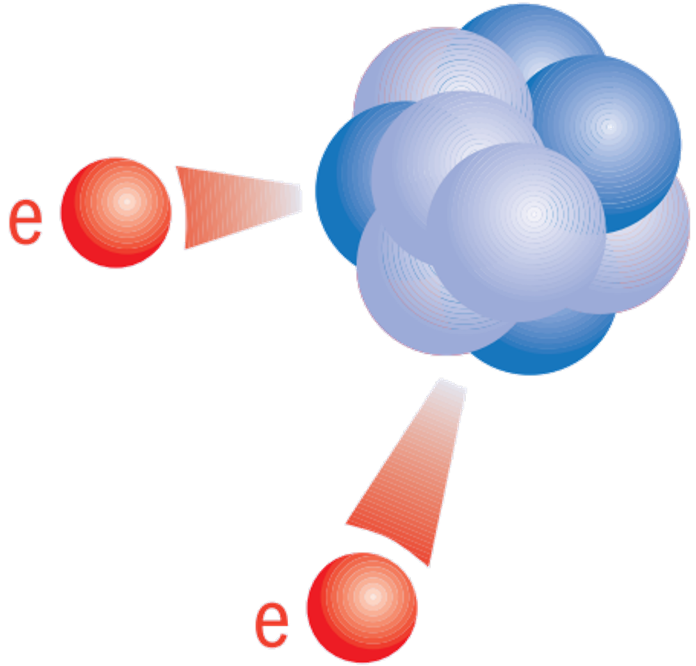
- What is their mass and its origin?
- Is the neutrino its own antiparticle?
- Are there more than just three neutrinos?



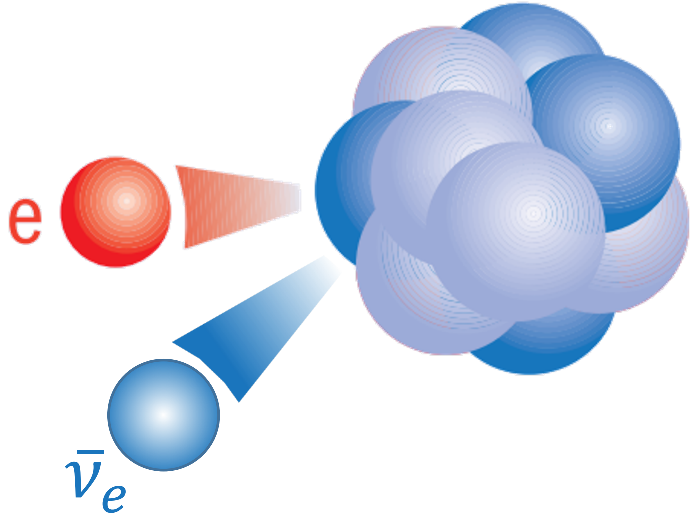


Unique probe: Beta Decay

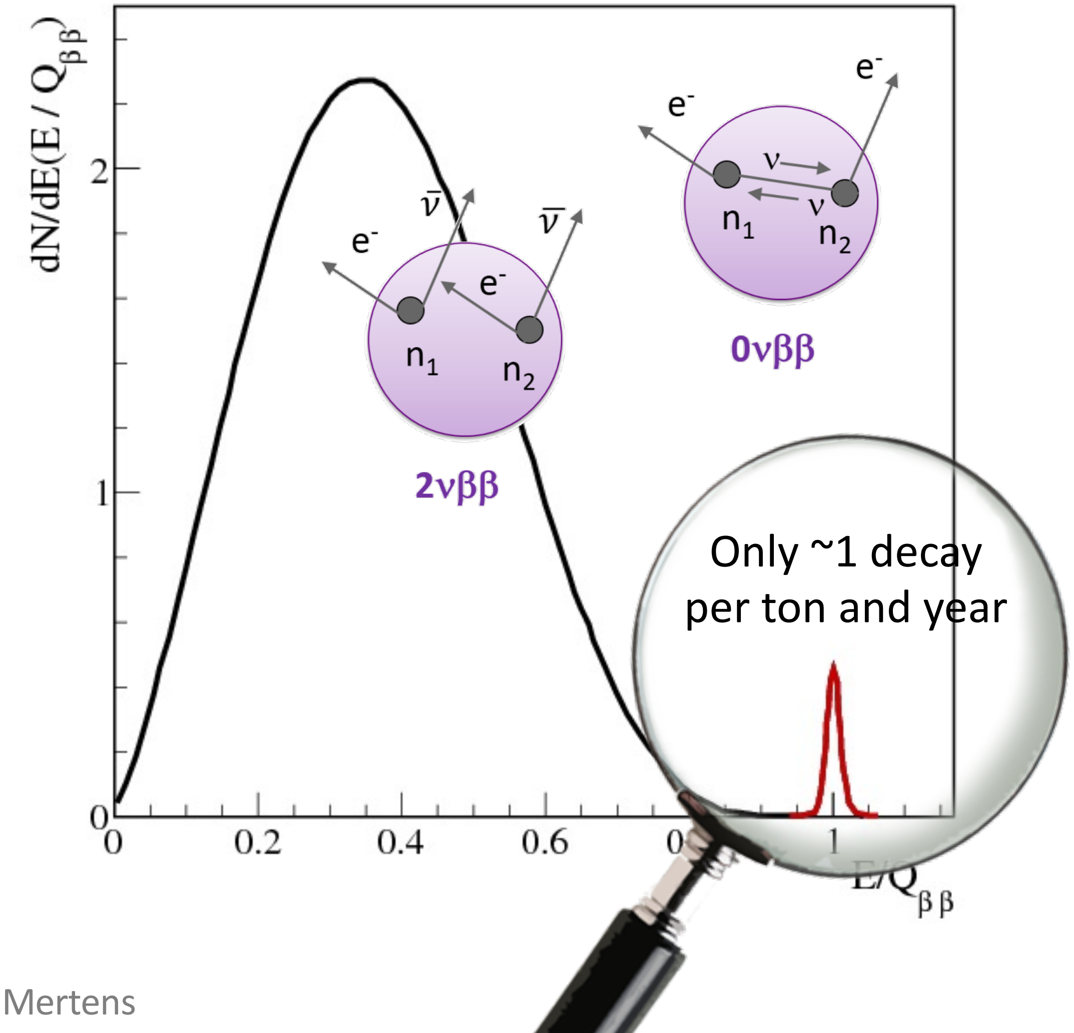
Double beta decay



Single beta decay



General idea



Discovery of 0νββ:

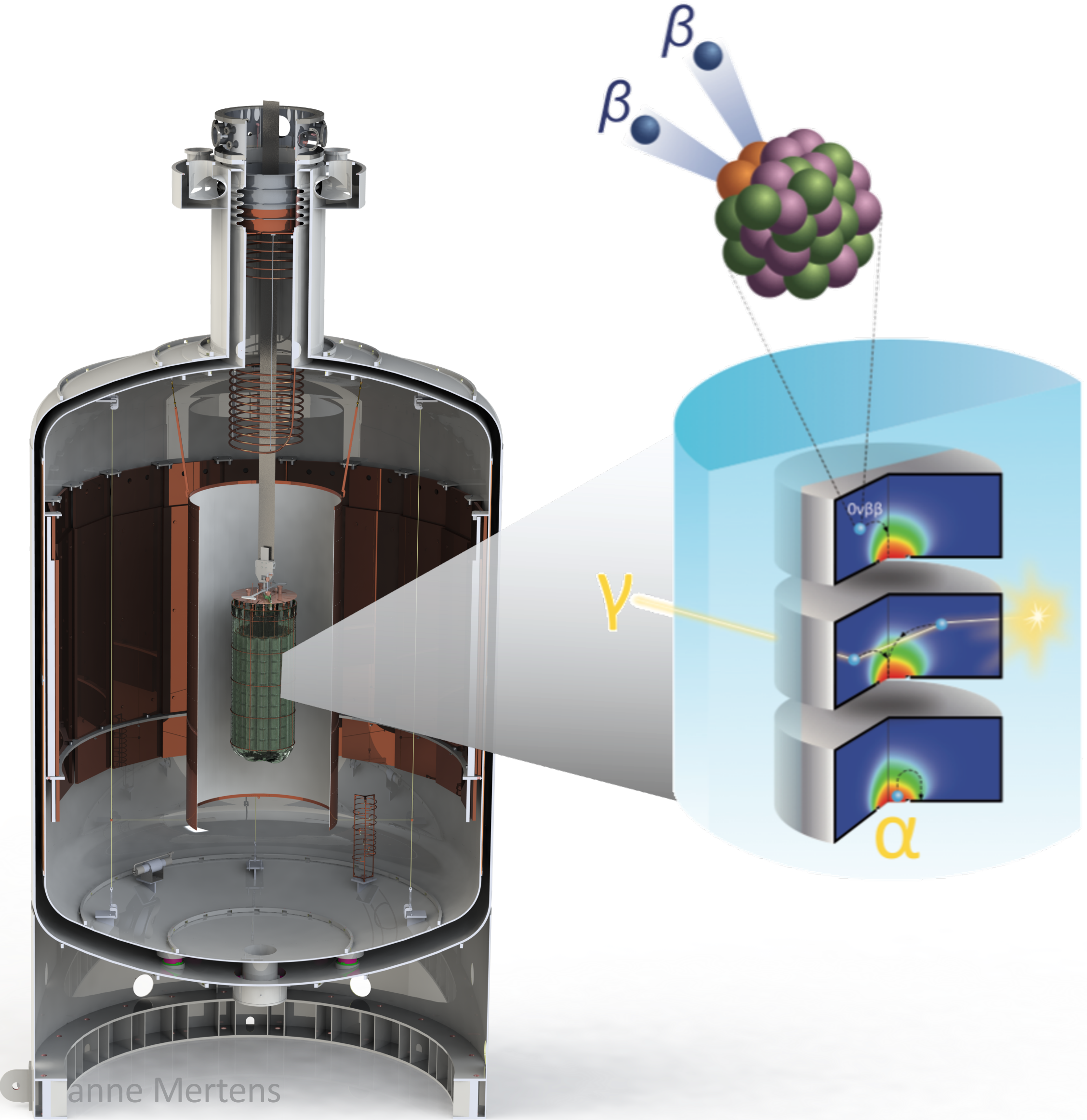
- Shed light on matter-antimatter asymmetry
- Half life reveals neutrino mass

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q,Z) \cdot |M^{0\nu}|^2 \cdot \boldsymbol{m_{\beta\beta}^2}$$

Key requirements:

- Large exposure (tonne-scale)
- Excellent energy resolution (~ 1% @ $Q_{\beta\beta}$)
- Low background (< 1 cts/year/t/ROI)

LEGEND Experiment



- **Search for $0\nu\beta\beta$ in ^{76}Ge**
- Staged approach
  - LEGEND-200 (200 kg of Ge detectors)
  - LEGEND-1000 (1-ton of Ge detectors)

- $T_{1/2}$ (3σ DS) > 10^{28} yr
- $m_{\beta\beta}$ < 10 - 17 meV (inverted ordering)

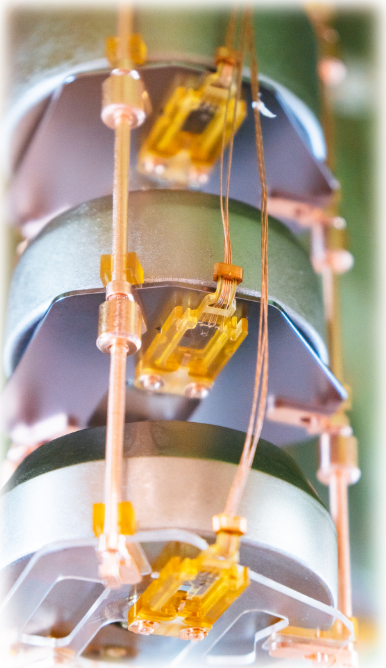
- More by Iris tomorrow

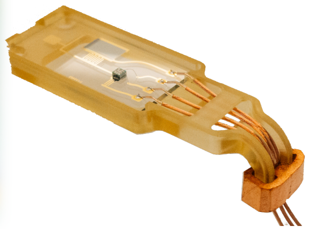
Our contributions

M. Willers (PD)
F. Edzards (PD)
F. Henkes (MSc)

- Electronics integration for LEGEND-200

M. Willers, tech lead for electronis

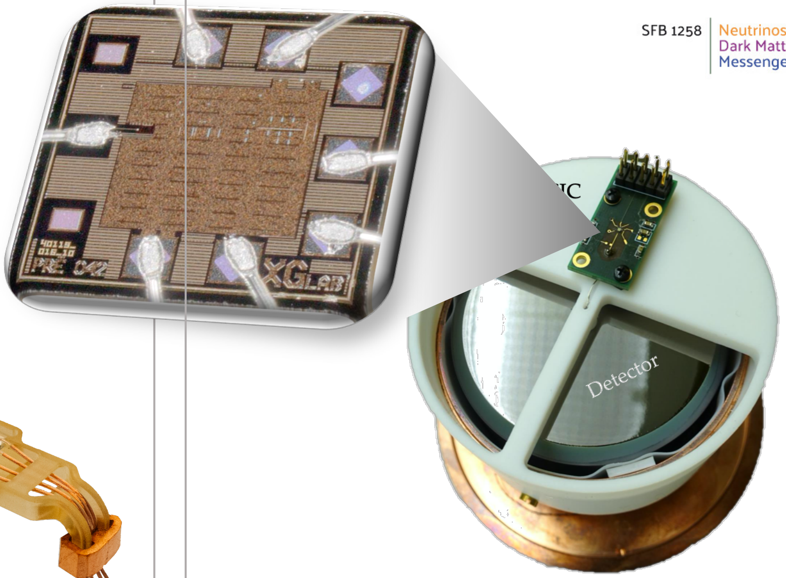




- Development of ASIC-based read-out for LEGEND-1000

F. Edzards *et al* 2020 *JINST* **15** P09022

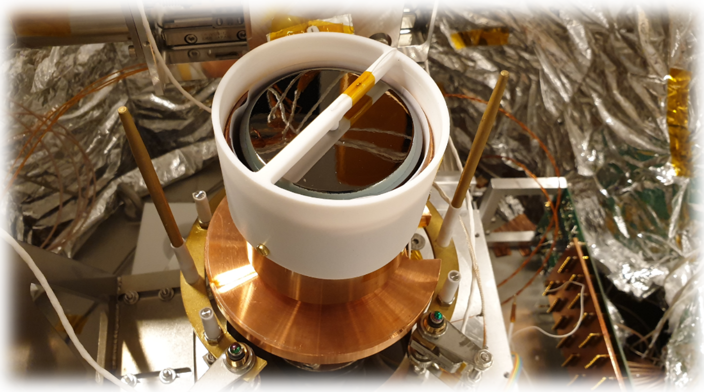
SFB 1258 Neutrinos Dark Matter Messengers



- Surface background characterization

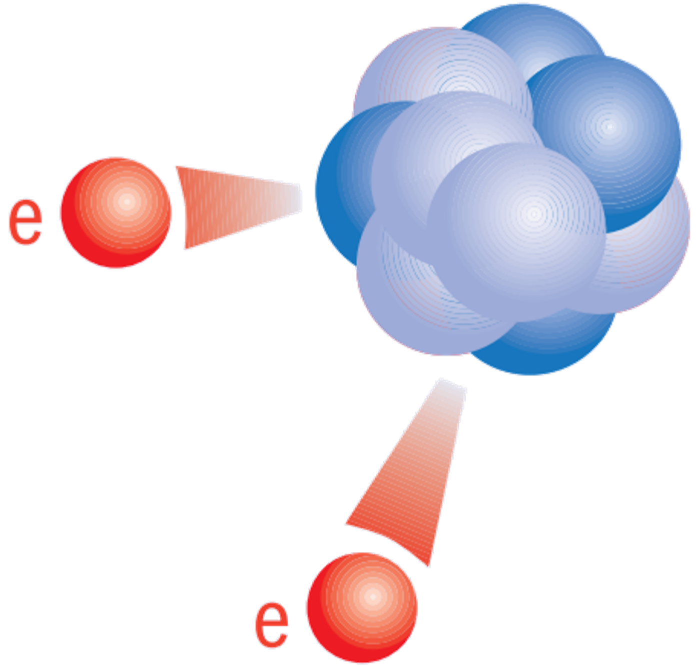
F. Edzards, L. Hauertmann, et al Particles 4 (2021) 4, 489-511

Thanks to Iris group

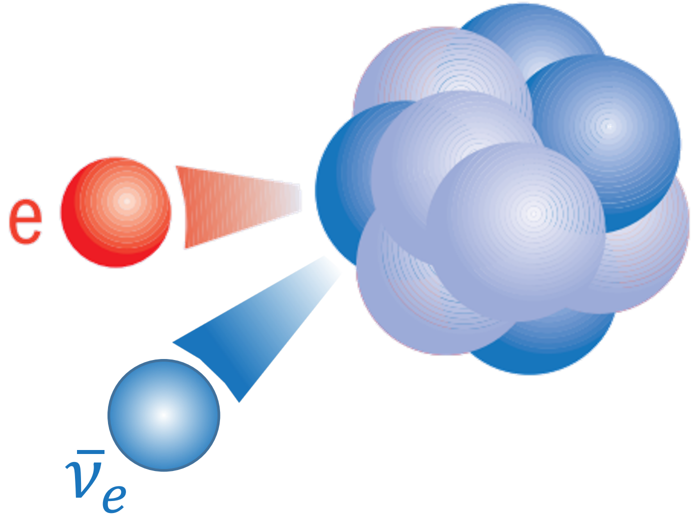


Unique probe: Beta Decay

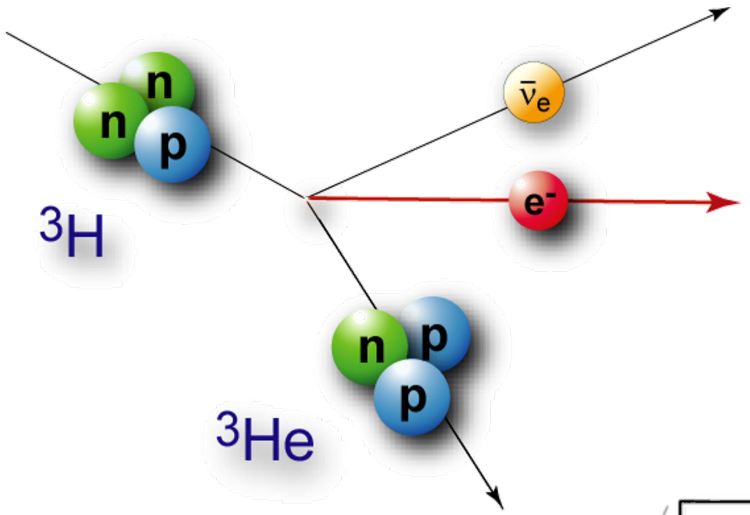
Double beta decay



Single beta decay



General idea

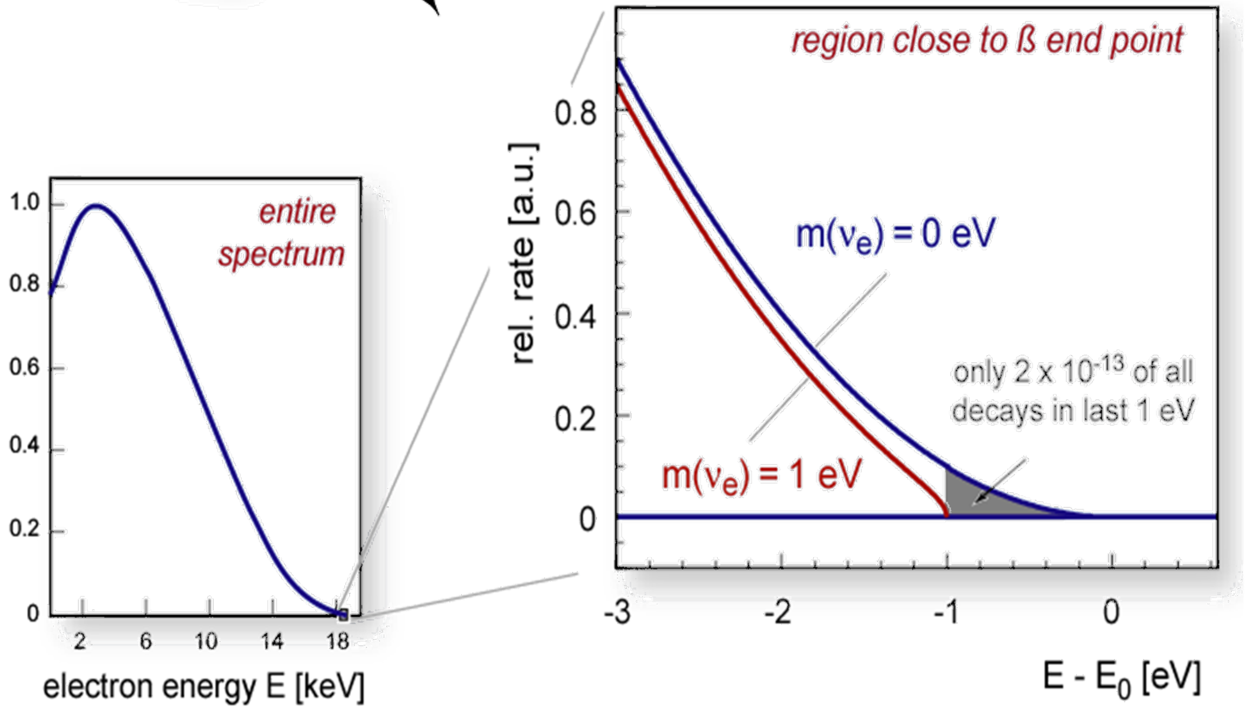


Direct neutrino mass measurement

- Independent of neutrino nature
- Independent of cosmology

Key requirements:

- Strong tritium source (10^{11} decays/s)
- Excellent energy resolution (~ 1 eV)
- Low background (< 100 mcps)

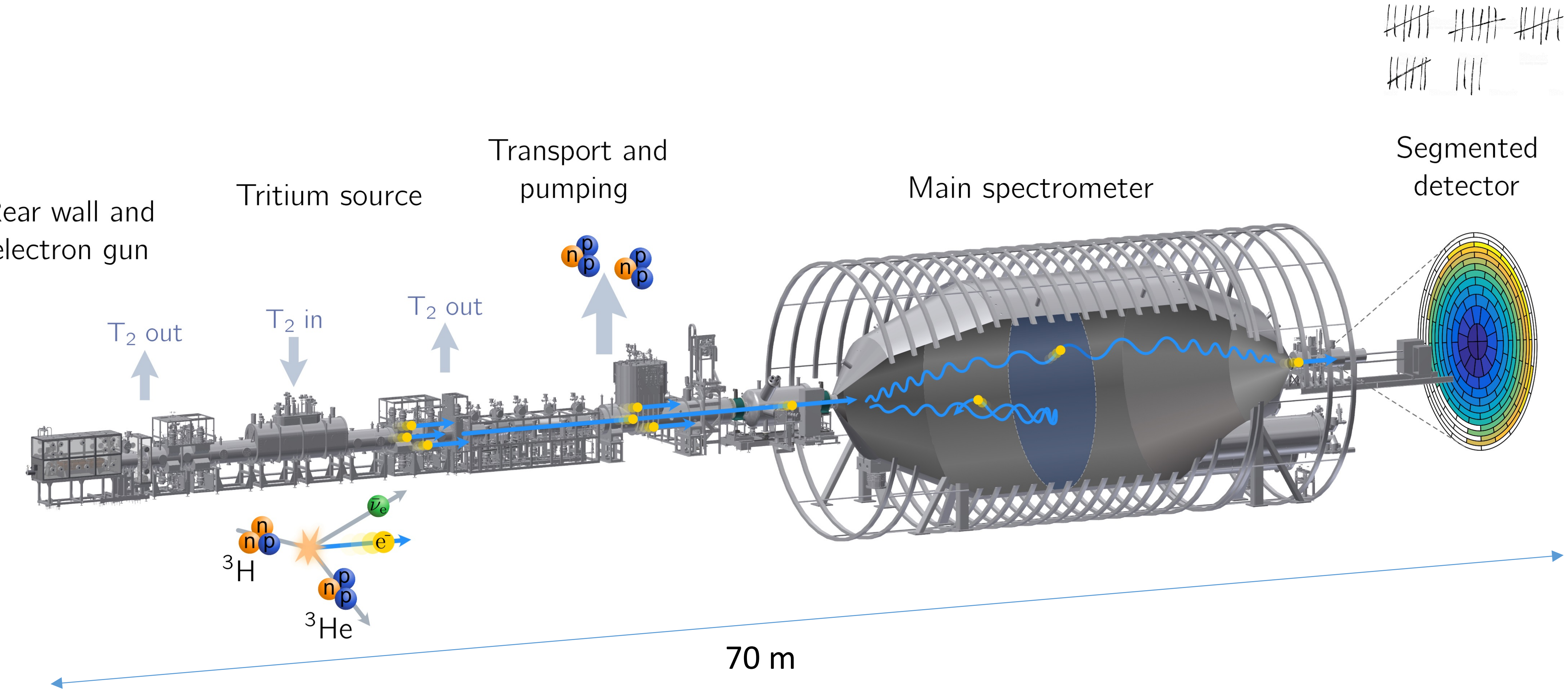



Karlsruhe
Tritium
Neutrino
Experiment

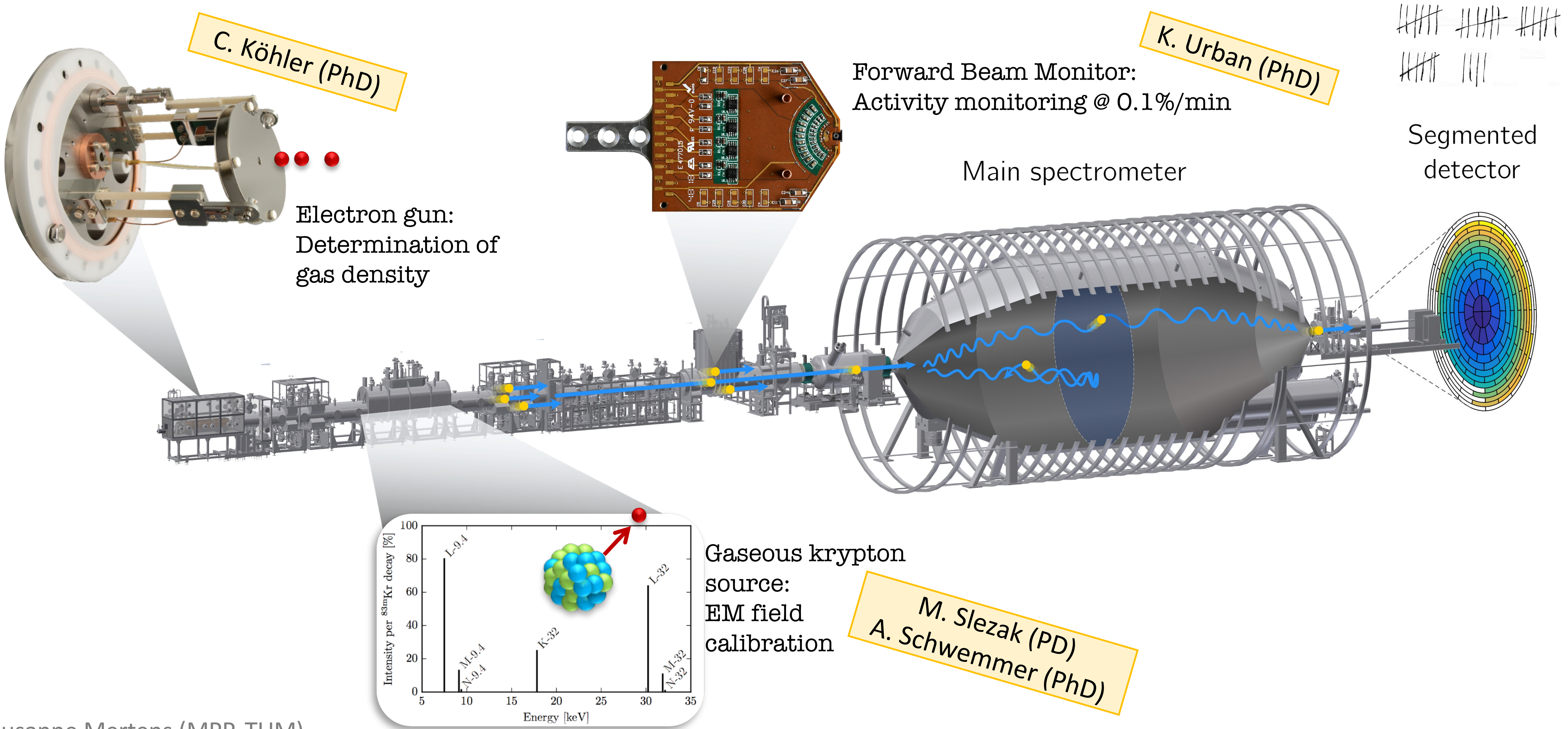
KATRIN

- **Experimental site: Karlsruhe Institute of Technology (KIT)**
- **International Collaboration (150 members)**
- **Design sensitivity: 0.2 eV (90% CL)**
  (1000 days of measurement time)

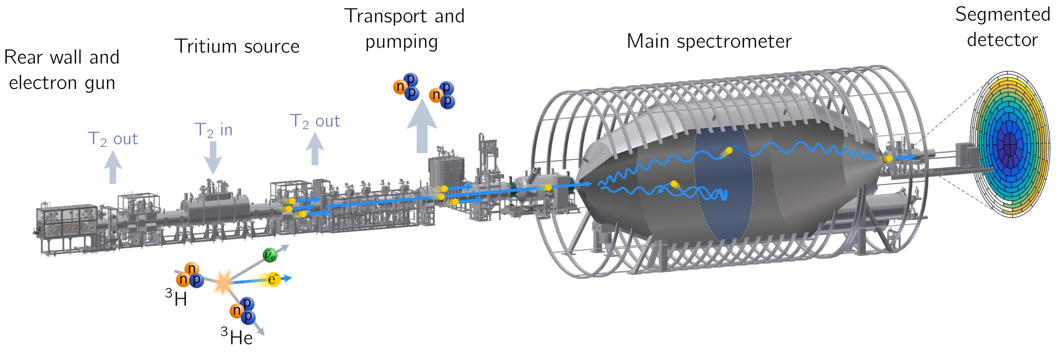
KATRIN Working Principle



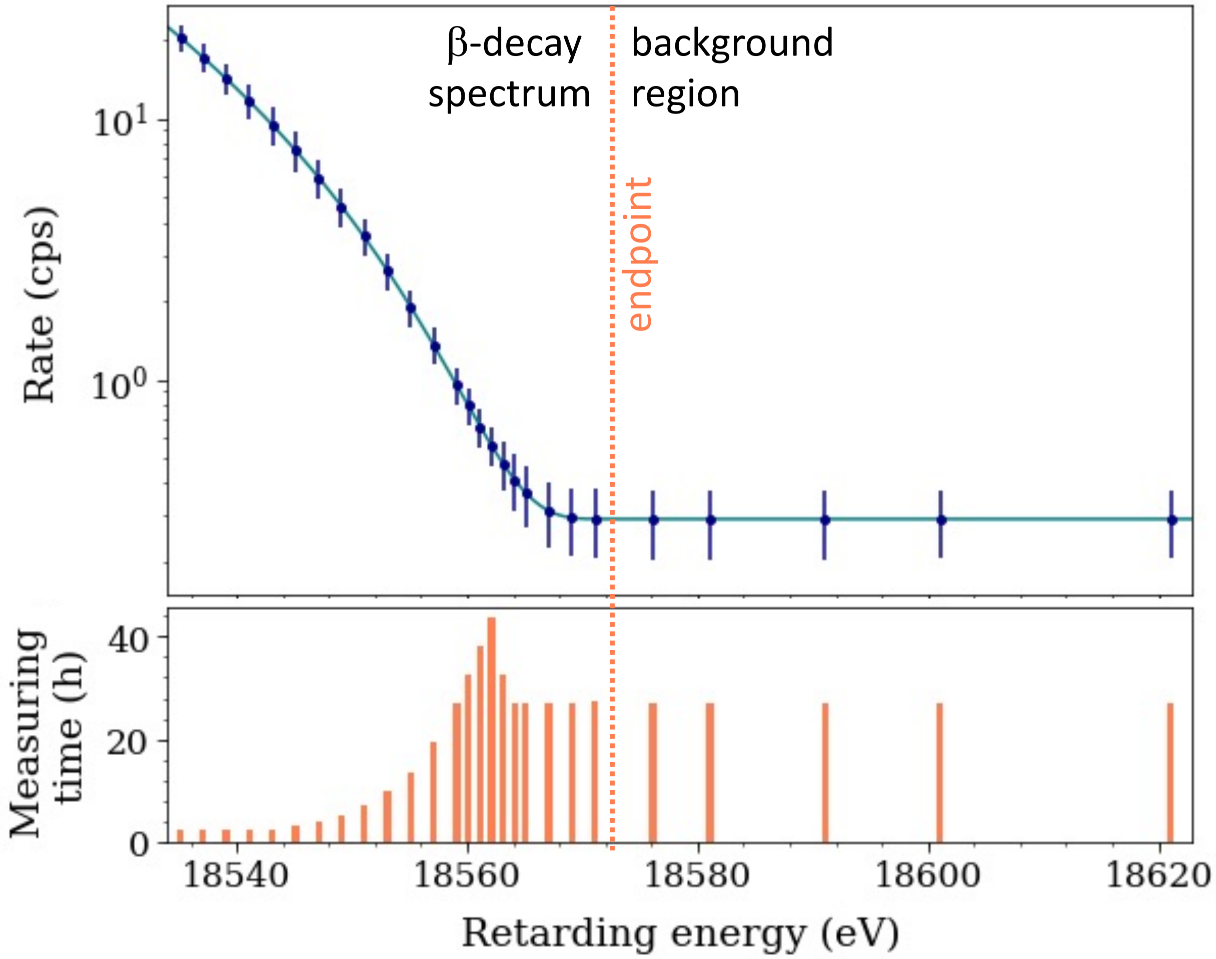
KATRIN Working Principle



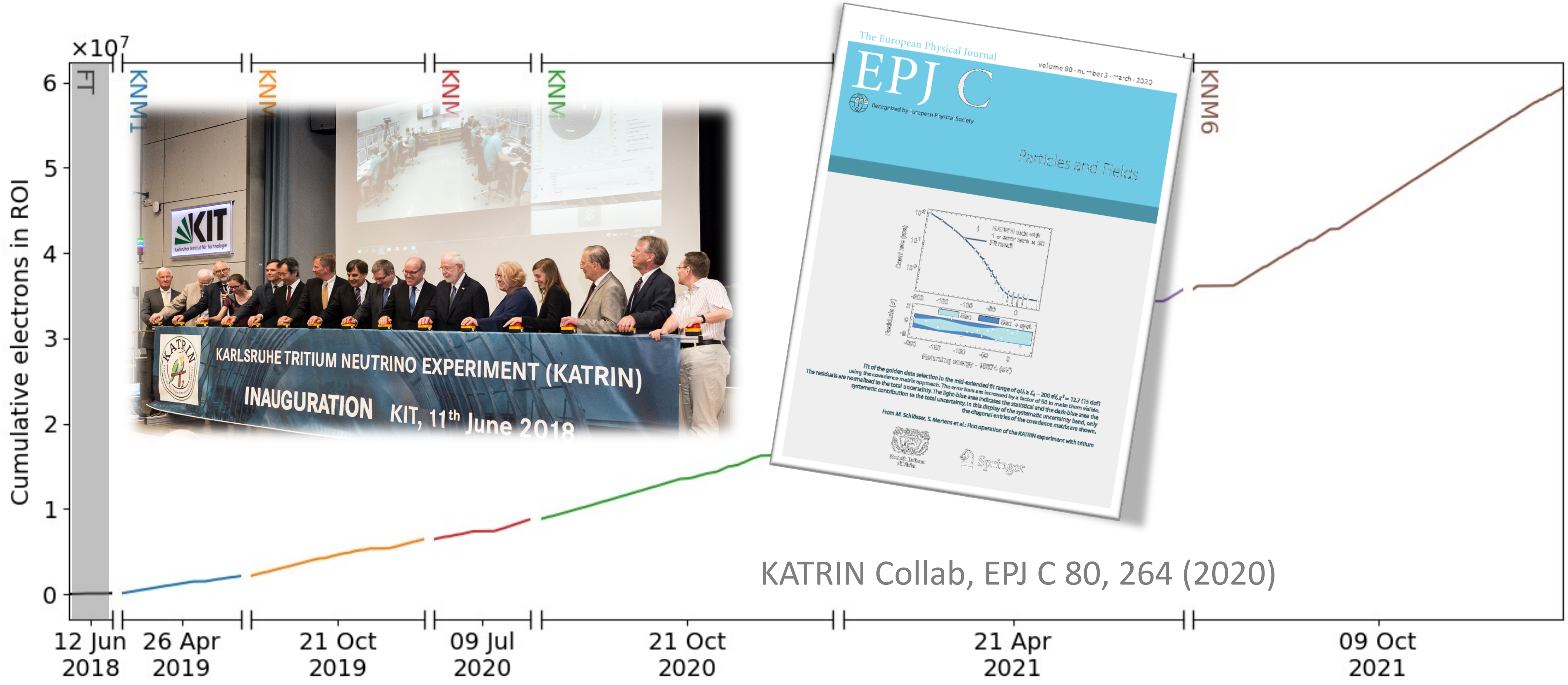
KATRIN Working Principle



- Scan interval: **E_0 – 40 eV , E_0 + 135 eV**
- Scan time: **2 hours**
- Hundreds of scan per campaign
- **Infer ν-mass from spectral fit**

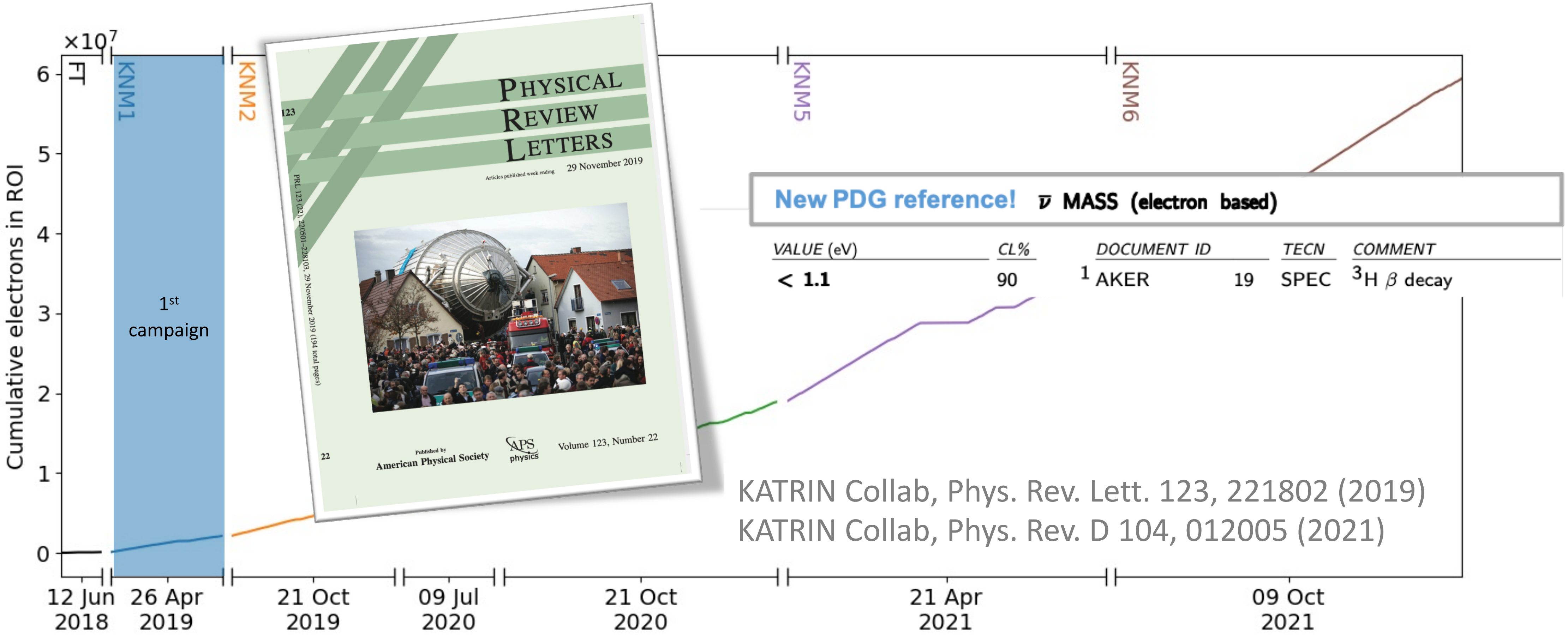


KATRIN Data Taking Overview



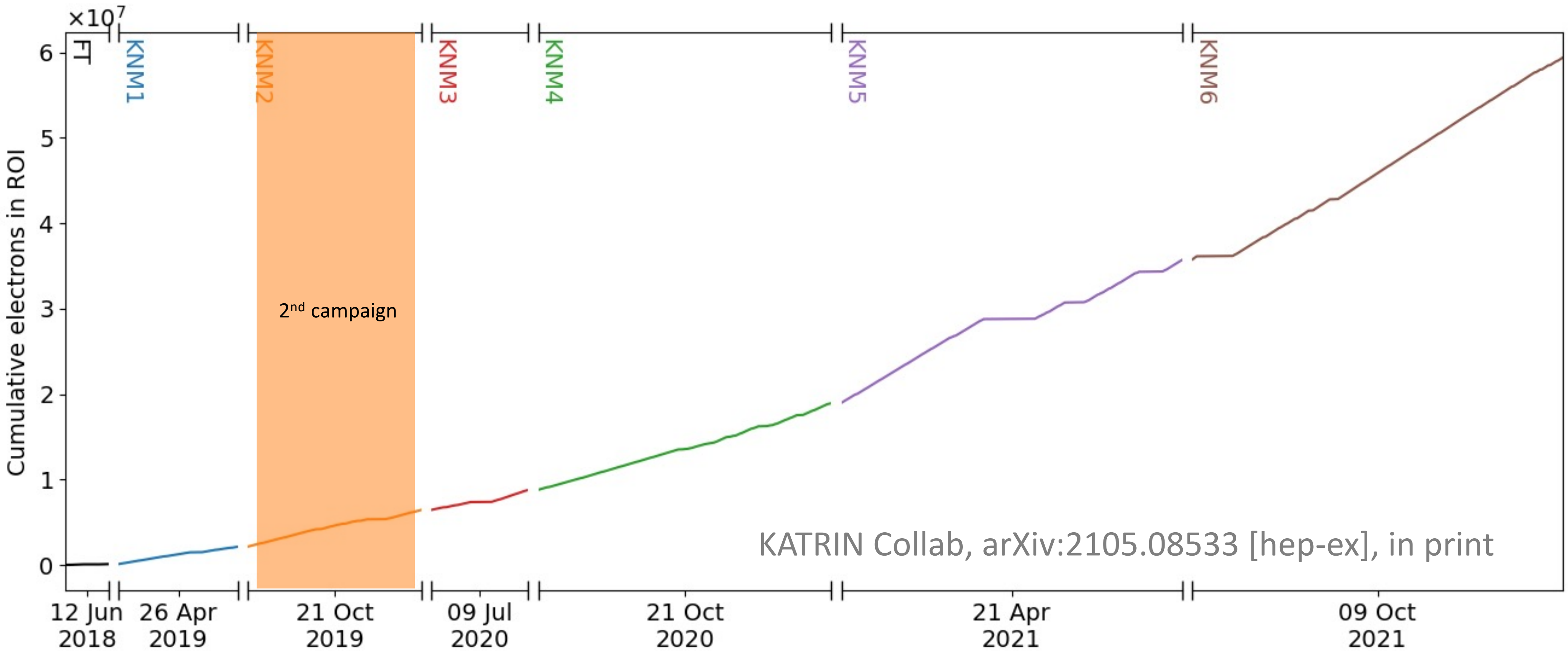
KATRIN Collab, EPJ C 80, 264 (2020)

KATRIN Data Taking Overview



KATRIN Collab, Phys. Rev. Lett. 123, 221802 (2019)
KATRIN Collab, Phys. Rev. D 104, 012005 (2021)

KATRIN Data Taking Overview



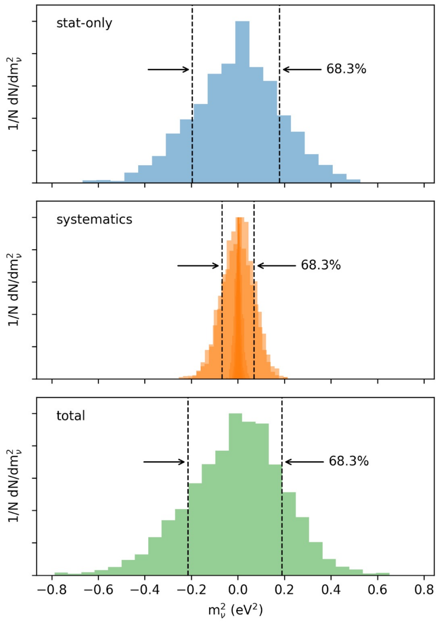
MPP analysis team

C. Wiesinger (PD)
Schwemmer (PhD)
C. Karl (PhD)
C. Köhler (PhD)
L. Schlüter (PhD)
M. Weidenthaler (MSc)
F. Kellerer (MSc)
X. Stribl (MSc)
T. Lasserre (staff)

MC propagation technique

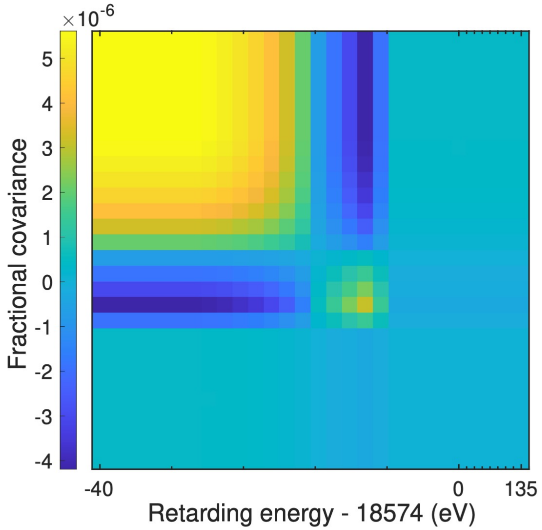
- Systematics propagated by 10^5 fits
- Developed by M. Slezak and C. Karl

Thanks to the MPCDF

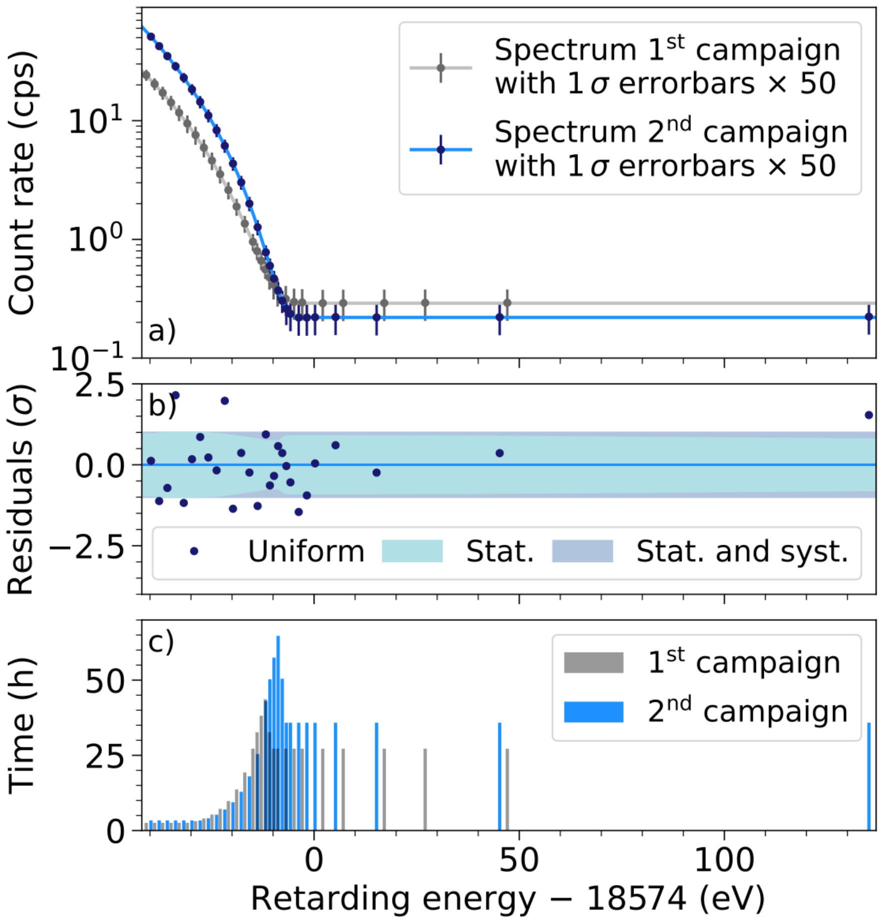


Covariance matrix method

- Systematics propagated via cov-matrix obtained from multiple simulations of the spectrum
- Developed by T. Lasserre and L. Schlüter



Result of 2nd campaign



Main achievements wrt. 1st campaign:

- tritium activity increased by a factor of 4
- background reduced by 25%

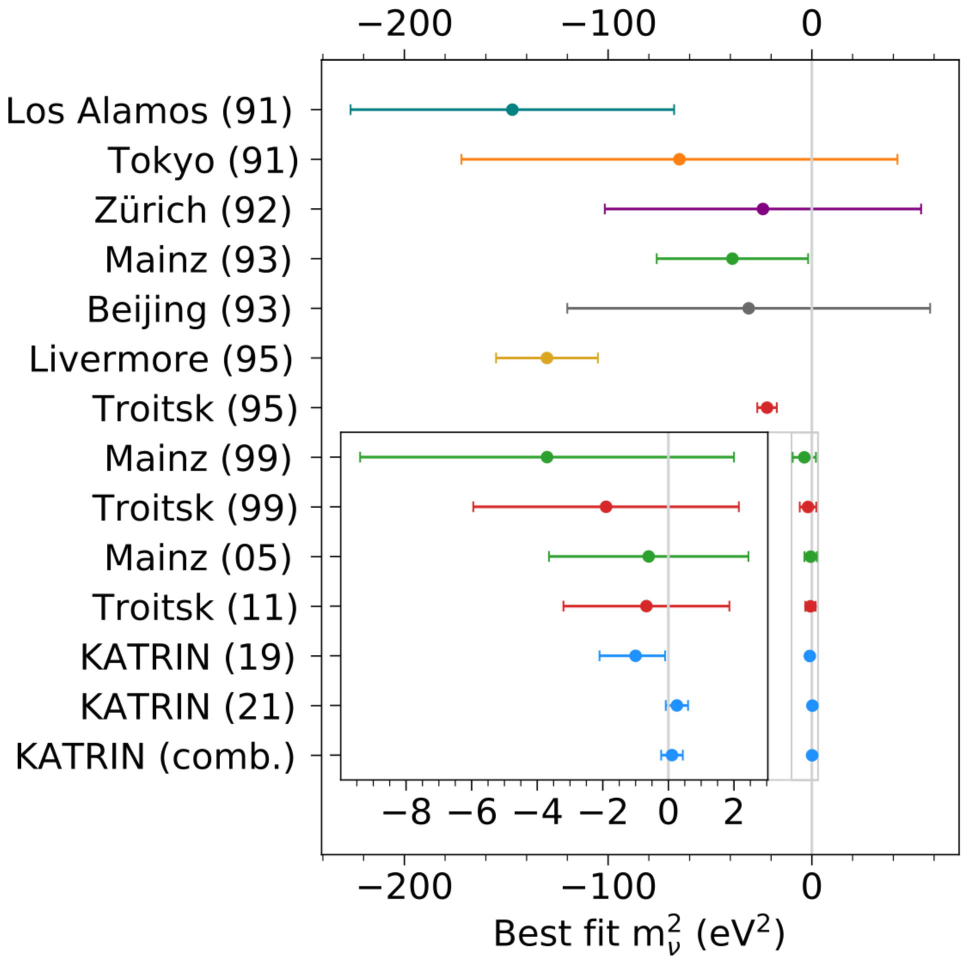
Final result:

- total statistics: 4 million events
- excellent goodness-of-fit: p-value = 0.8

- best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$eV² (stat. dom.)
- new limit: $m_\nu < 0.9$ eV (90% CL)

KATRIN Collab, arXiv:2105.08533 [hep-ex], in print

Historical context



- KATRIN (2021):

  first direct neutrino-mass experiment to reach sub-eV sensitivity and limit

- 1st and 2nd campaign combined result:

  $$m_\nu^2 = \left(0.11^{+0.33}_{-0.33}\right)\text{eV}^2$$

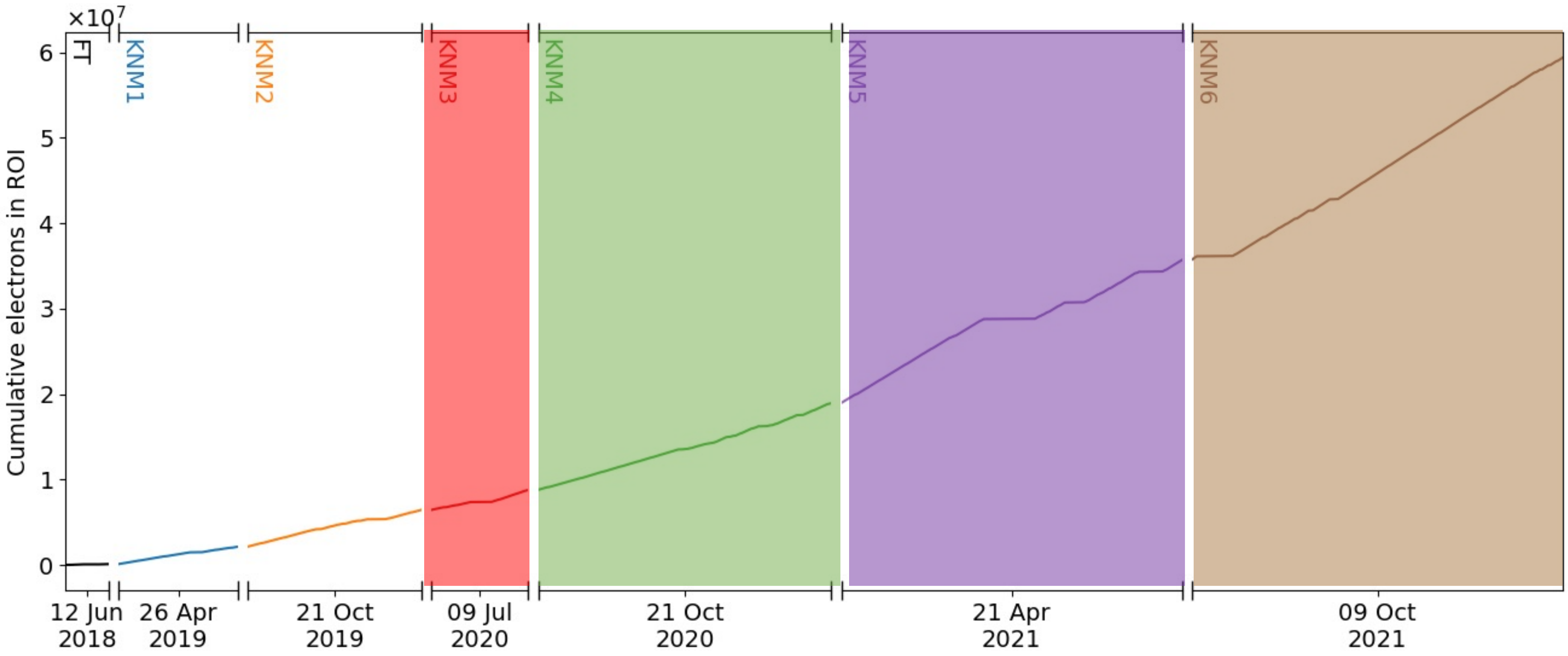
- 1st and 2nd campaign combined limit:

  $$m_\nu < 0.8 \text{ eV (90\% CL)}$$

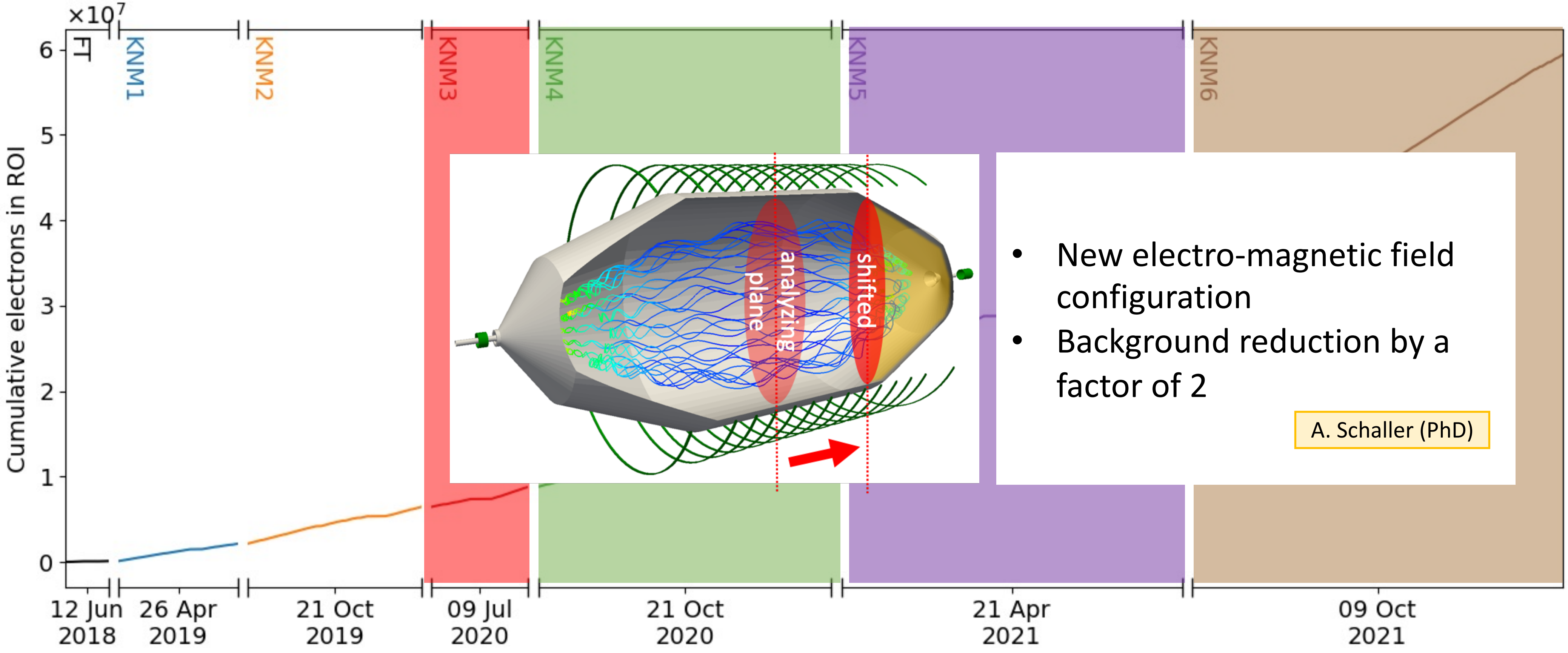
KATRIN Collab, arXiv:2105.08533 [hep-ex], in print

Outlook

+ many more to come



Outlook – reduced background

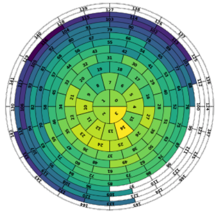


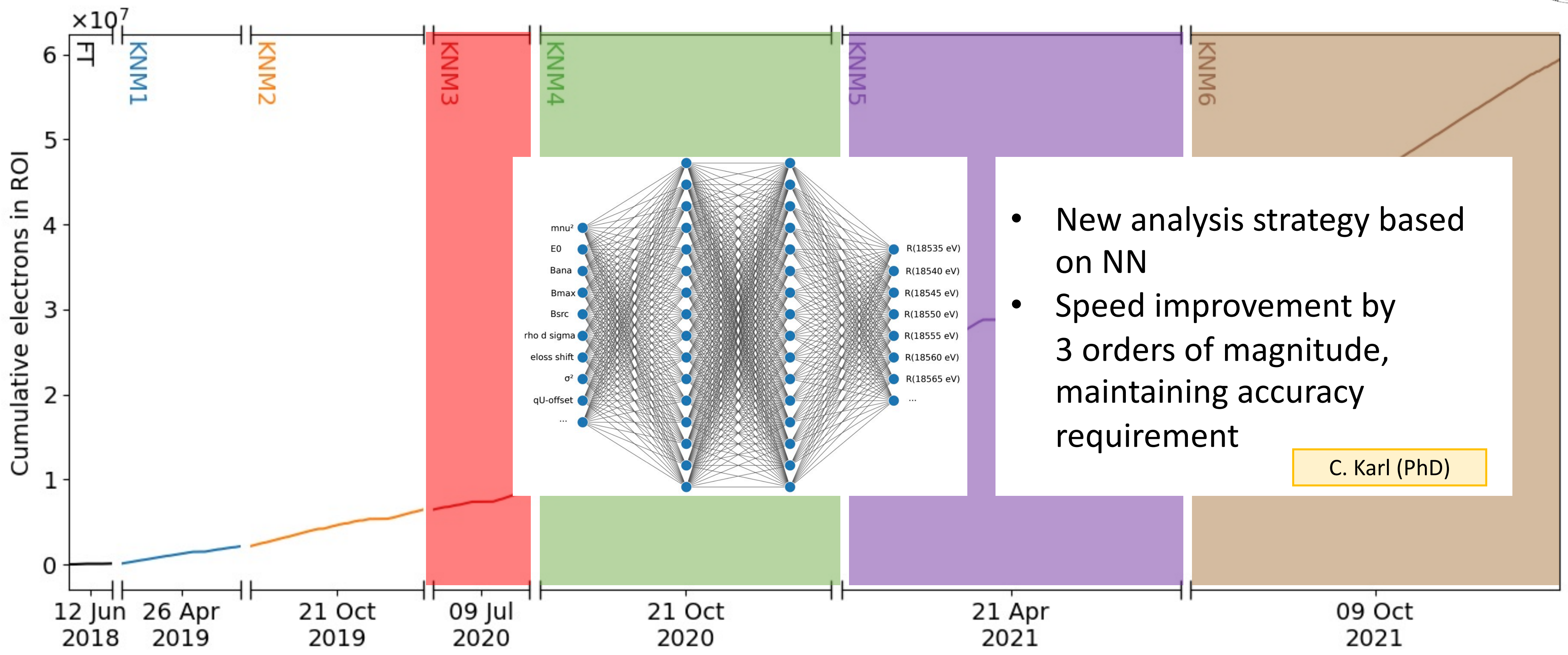
- New electro-magnetic field configuration
- Background reduction by a factor of 2

A. Schaller (PhD)

F. Fränkle, A. Schaller, et al. arXiv:2011.05107

Outlook – new analysis strategy



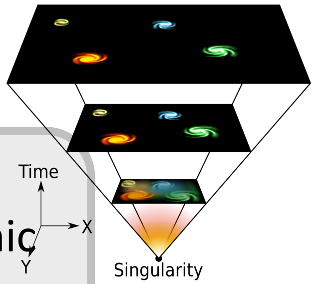


- New analysis strategy based on NN
- Speed improvement by 3 orders of magnitude, maintaining accuracy requirement

C. Karl (PhD)

Thanks to the Origins Data Science Lab

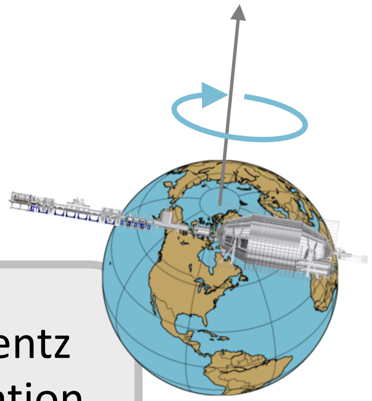
New Physics with KATRIN



Constrain local overdensity of cosmic relic neutrinos
(peak search)

→ Best limit based on terrestrial experiment

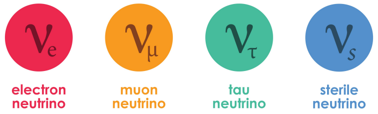
F. Kellerer
T. Lasserre



Search for Lorentz invariance violation
(sidereal modulation)

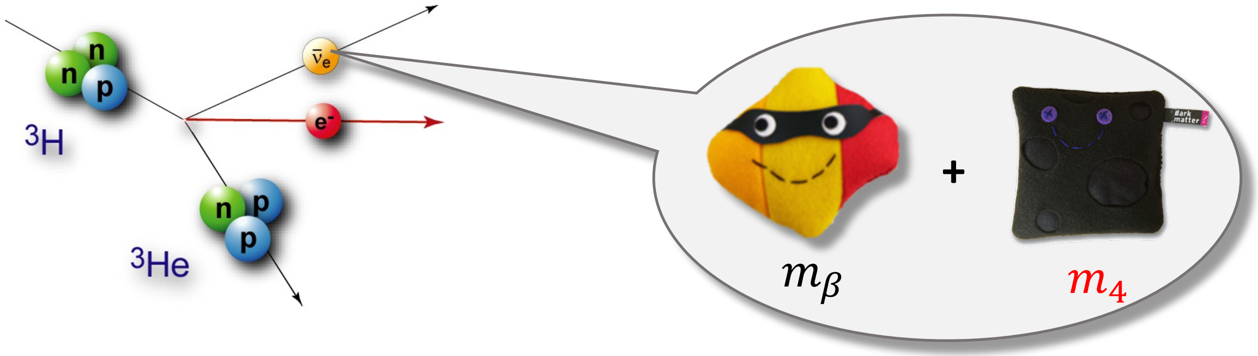
→ First limit on specific LV parameter

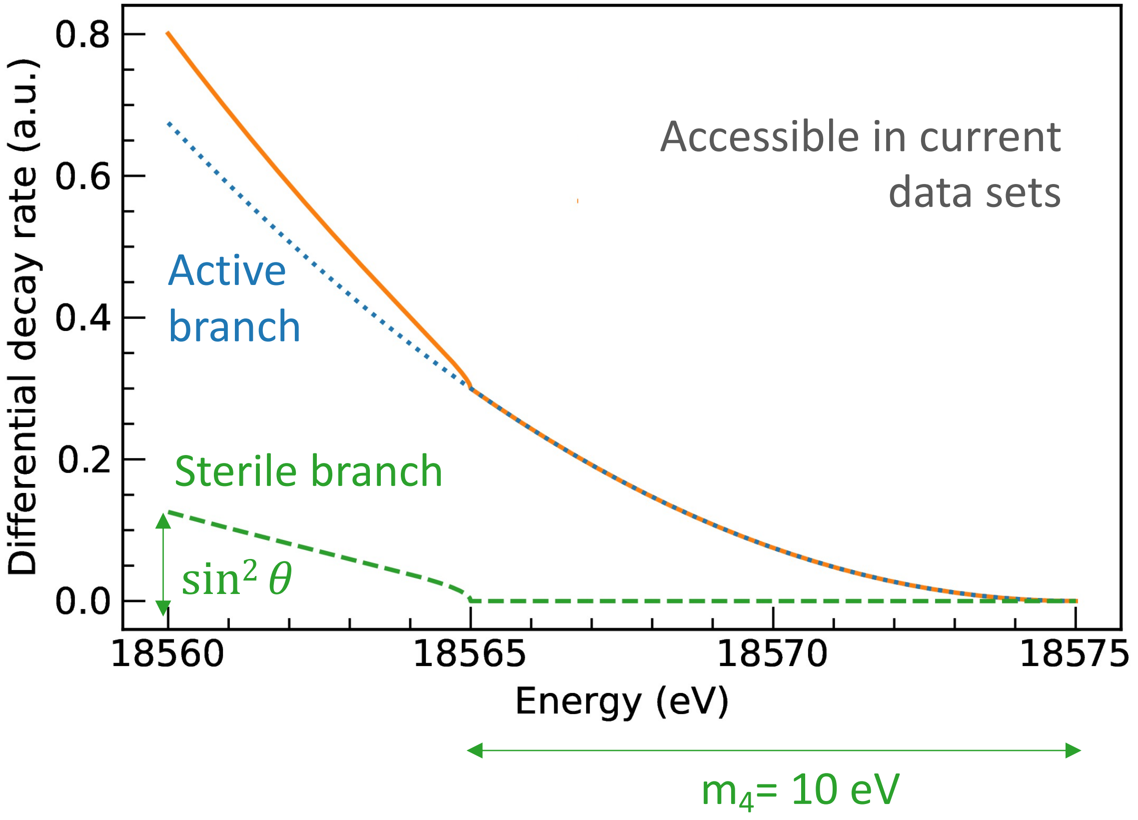
J. Wickles
C. Karl

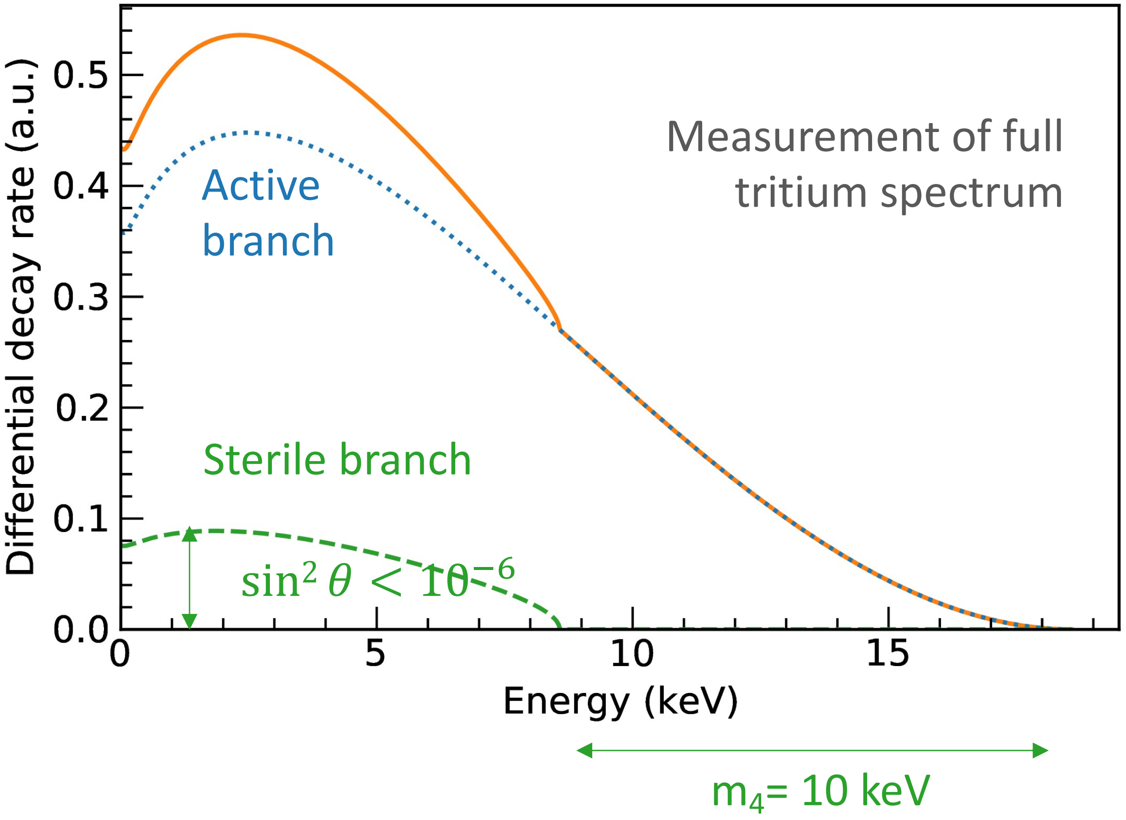


Search for eV-keV sterile neutrinos
(kink search)

Sterile neutrinos

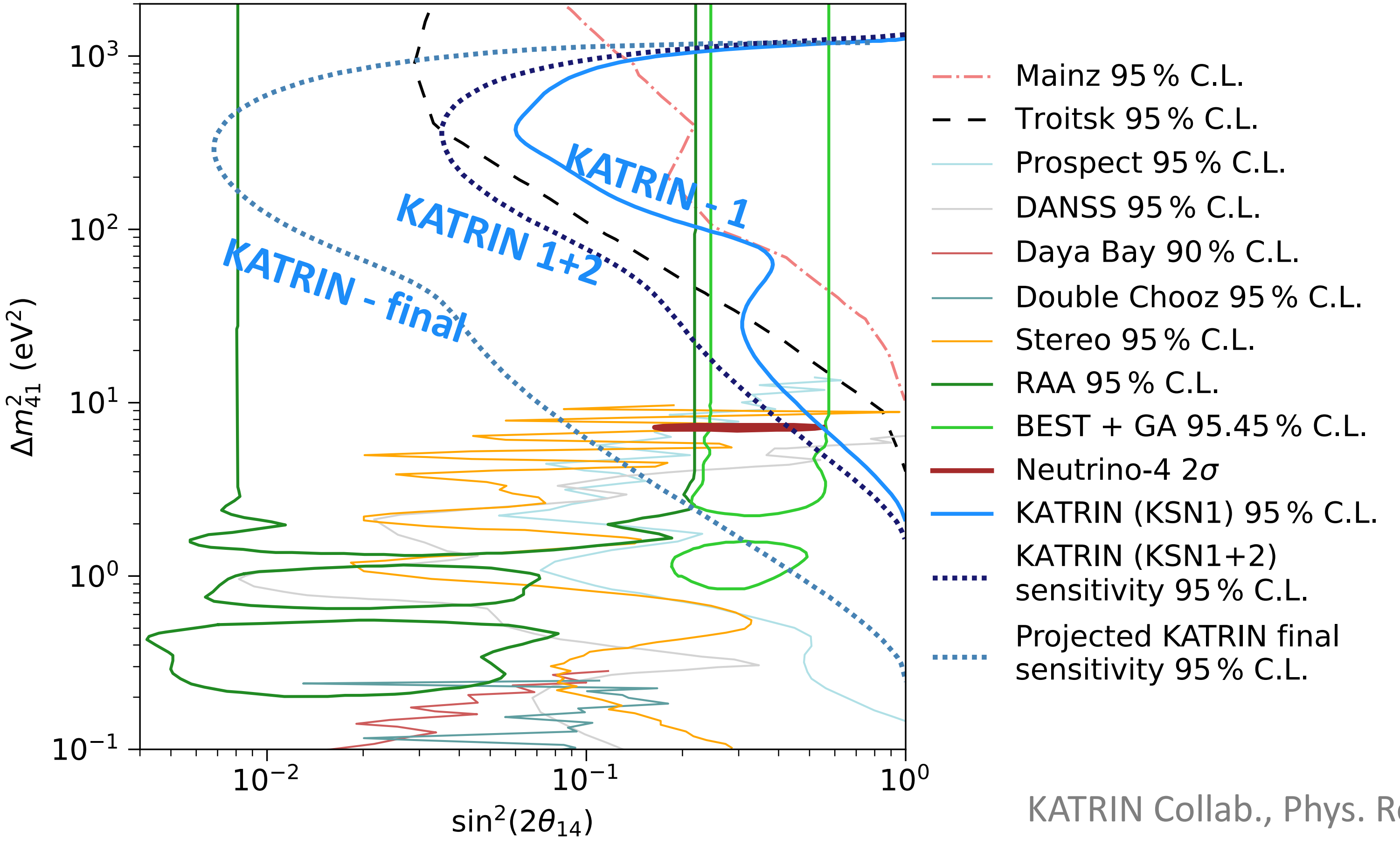






eV-scale sterile neutrino search

T. Lasserre
L. Schlüter
M.Slezak
C. Köhler
X. Stribl



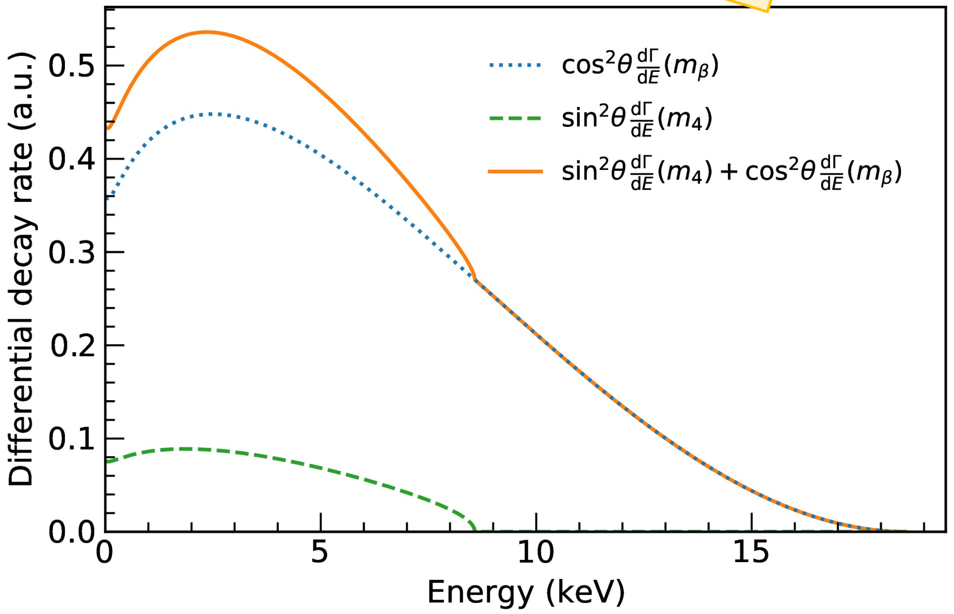
- ✓ Improve MAINZ and TROITSK limit
- ✓ Improve exclusion with respect to DANSS, PROSPECT, and STEREO
- ✓ Test recent interesting results from NEUTRINO-4 and BEST

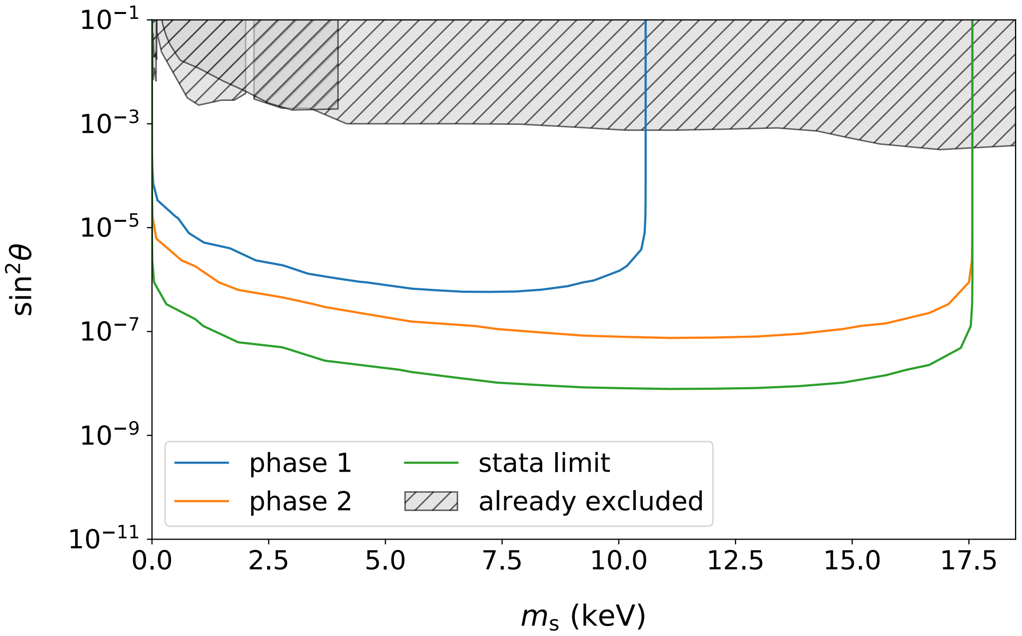
KATRIN Collab., Phys. Rev. Lett. 126, 091803 (2021)

keV-scale sterile neutrinos

- Idea: make use of the KATRIN source to explore full beta spectrum to search for BSM physics
- Challenge: Precise modelling of full tritium spectrum with all experimental effects
  → *work in progress*

A. Onillon



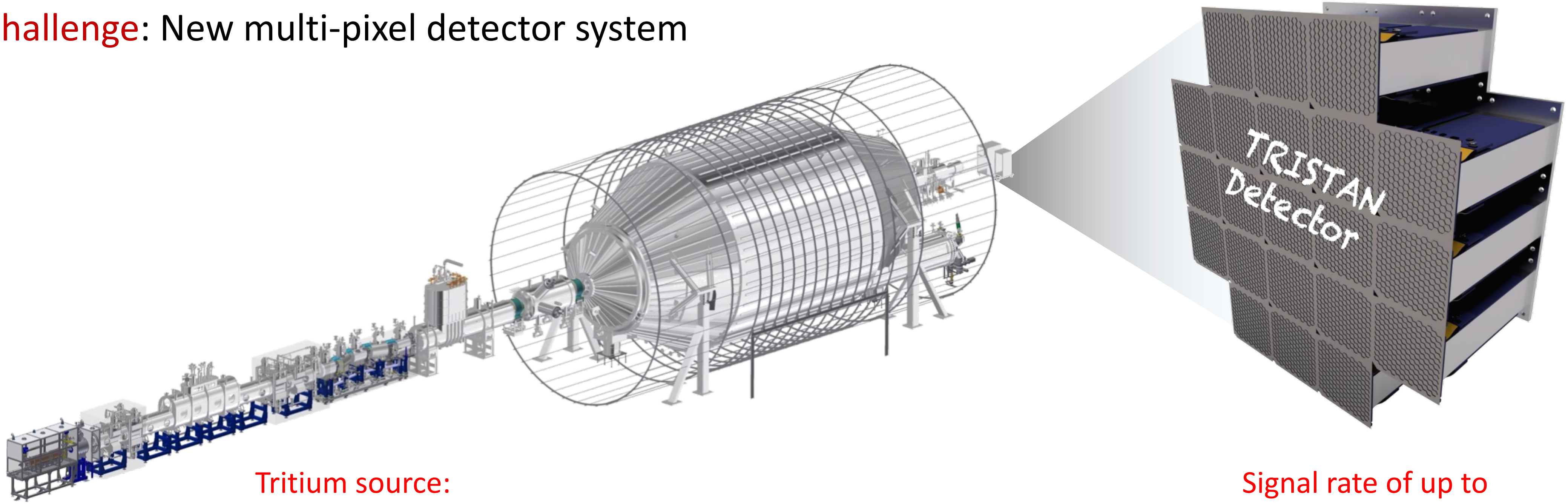


Mertens et al, Phys.Rev. D91 (2015) 4, 042005
Mertens et al, JCAP 1502 (2015) 02, 020

T. Houdy (PD)
F. Edzards (PD)
A. Onillon (PD)
D. Siegmann (PhD)
K. Urban (PhD)
L. Wunderl (MSc)
D. Spreng (MSc)
C. Bruch (MSc)
C. Forstner (MSc)

keV-scale sterile neutrinos

- Idea: make use of the KATRIN source to explore full beta spectrum to search for BSM physics
- Challenge: Precise modelling of full tritium spectrum with experimental effects
- Challenge: New multi-pixel detector system



Tritium source:
10^{11} decays/s

Signal rate of up to
10^{10} electrons/s

Mertens et al, Phys.Rev. D91 (2015) 4, 042005
Mertens et al, JCAP 1502 (2015) 02, 020

TRISTAN detector design

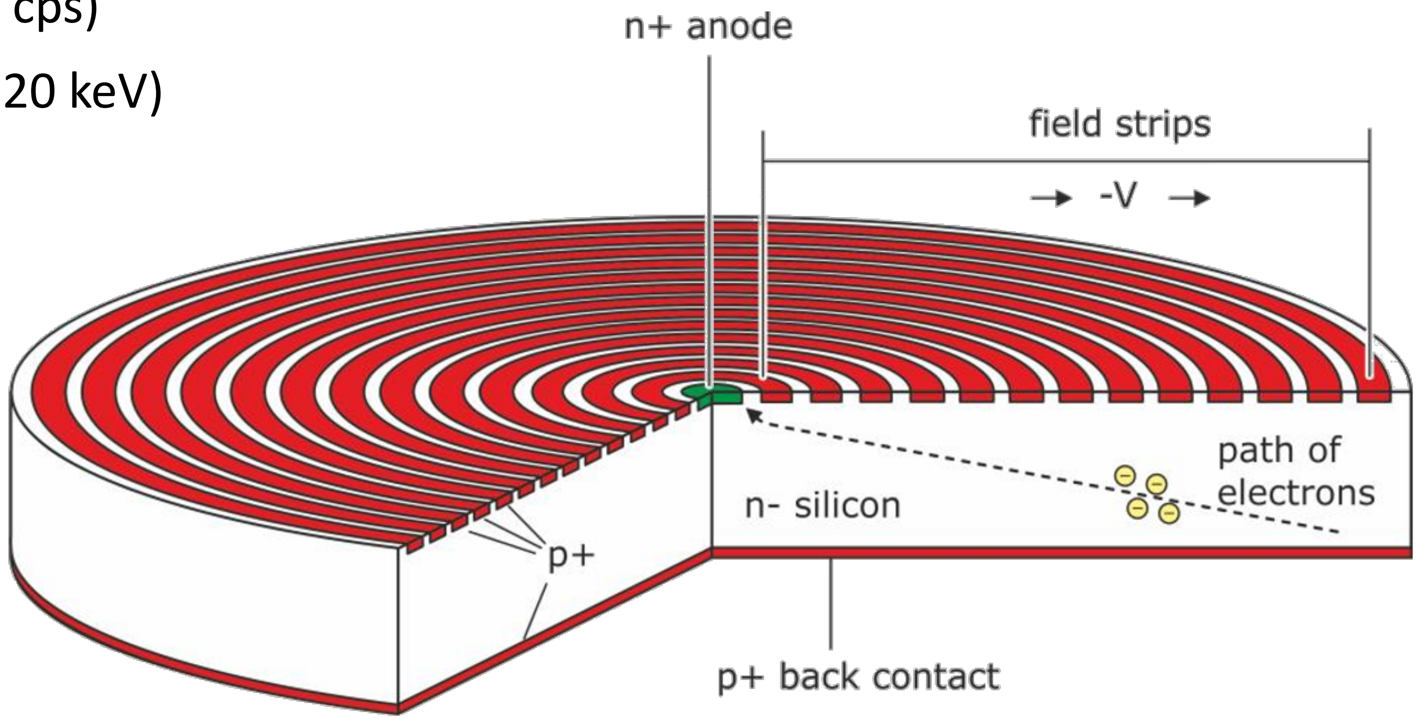
Thanks to the Max Planck Semiconductor Laboratory

Silicon drift detector (SDD) technology

✓ Capability of handling high rates (> 10^8 cps)

✓ Excellent energy resolution (300 eV @ 20 keV)

✓ Large area pixels (3 mm diameter)

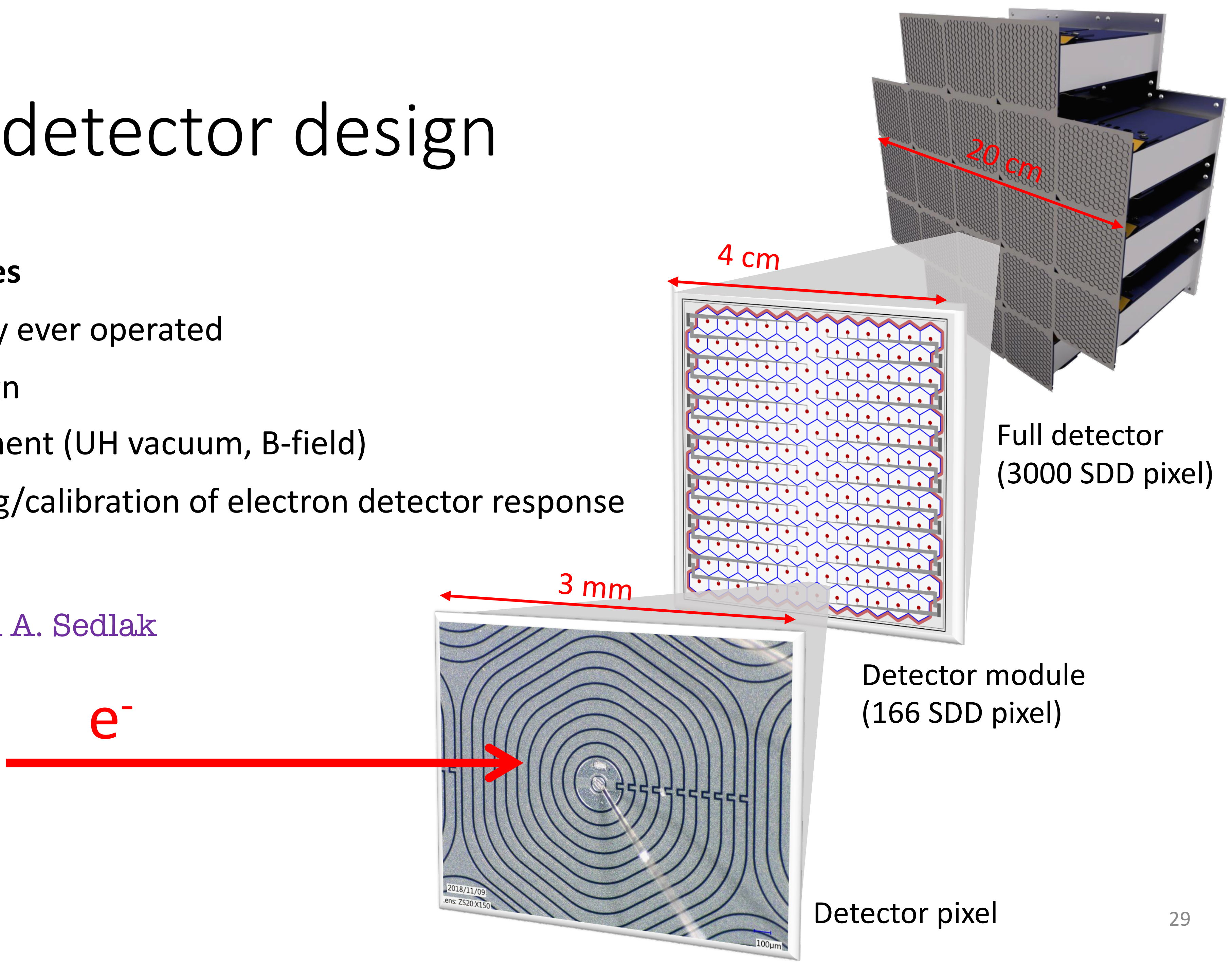


TRISTAN detector design

Technical challenges

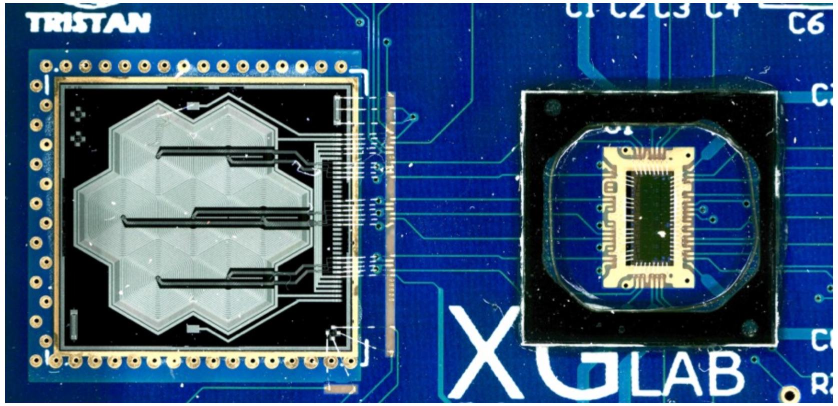
- Largest SDD array ever operated
- Focal plane design
- KATRIN environment (UH vacuum, B-field)
- Precise modelling/calibration of electron detector response

Thanks to D. Fink and A. Sedlak

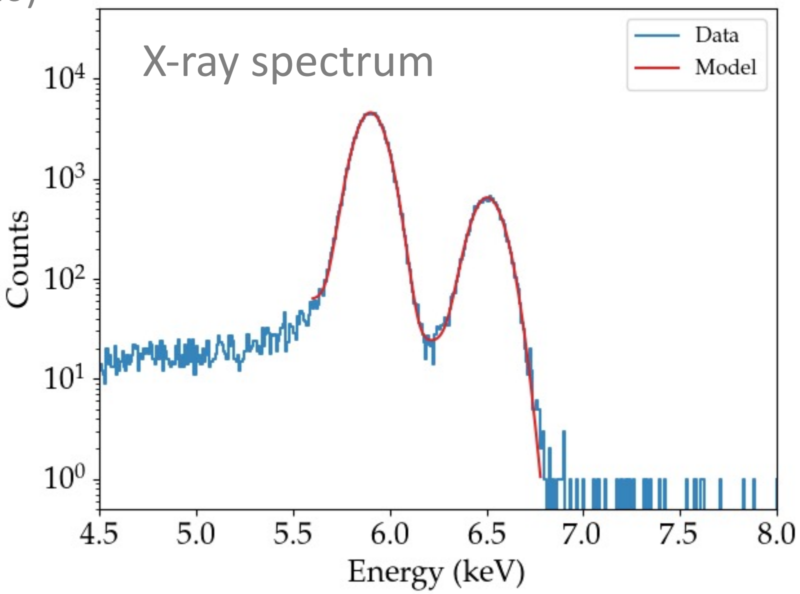


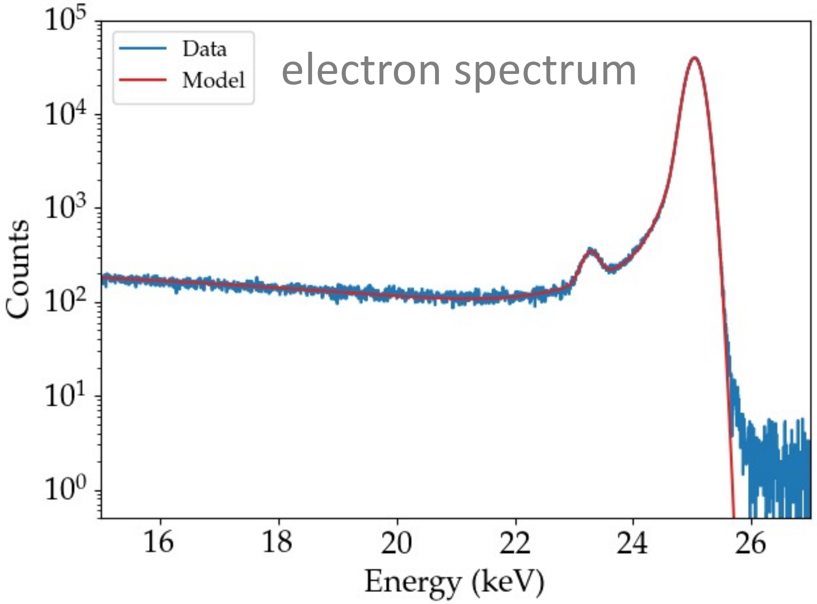
Susanne Mertens (MPP, TUM)

SDD characterization



- ✓ Excellent performance for x-rays
  S. Mertens et al, J. Phys. G46 (2019)
  - ✓ Linearity (0.1%)
  - ✓ Noise (10 e at 1μs shaping time)
  - ✓ Resolution (140 eV @ 6 keV)
- ✓ Detailed characterization with electrons (electron microscope, krypton, e-gun, laser)
  S. Mertens et al, J. Phys. G48 (2020)
  - ✓ Dead-layer
  - ✓ Charge-sharing
  - ✓ Backscattering





Scaling up: 166-pixel module

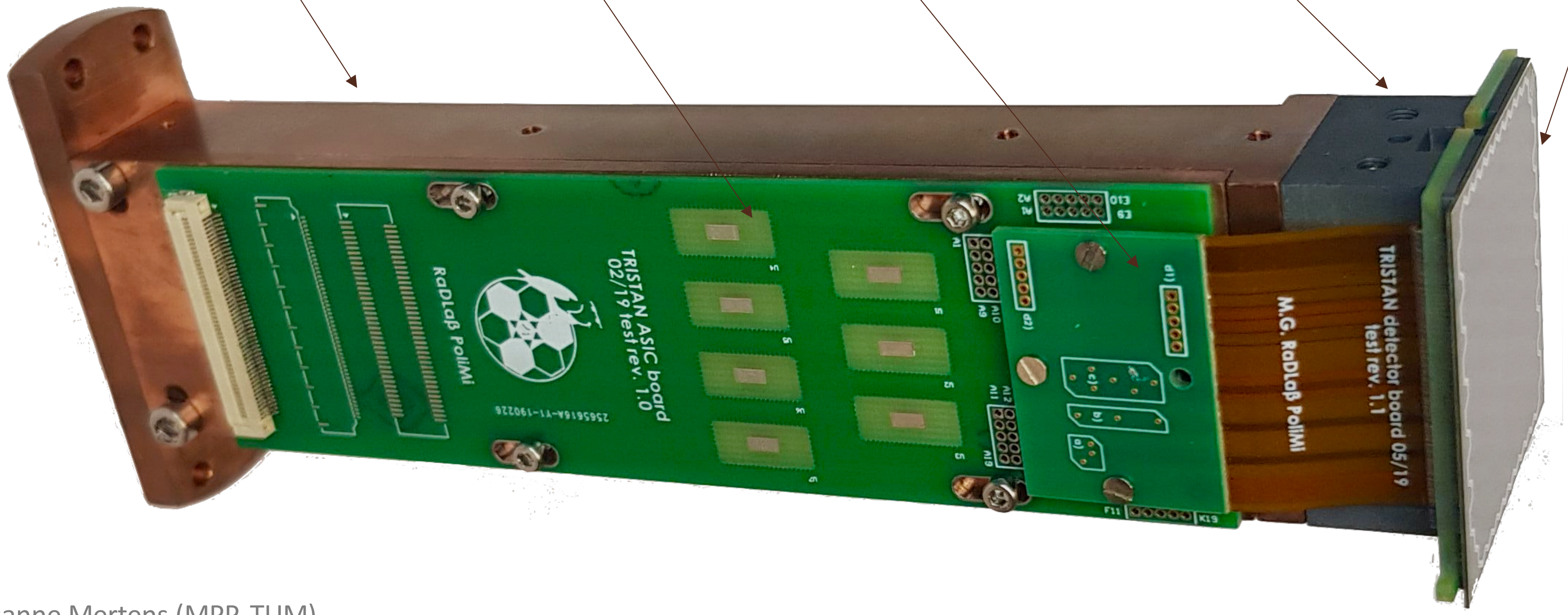
OHC copper cooling and holding structure

Ettore ASICs

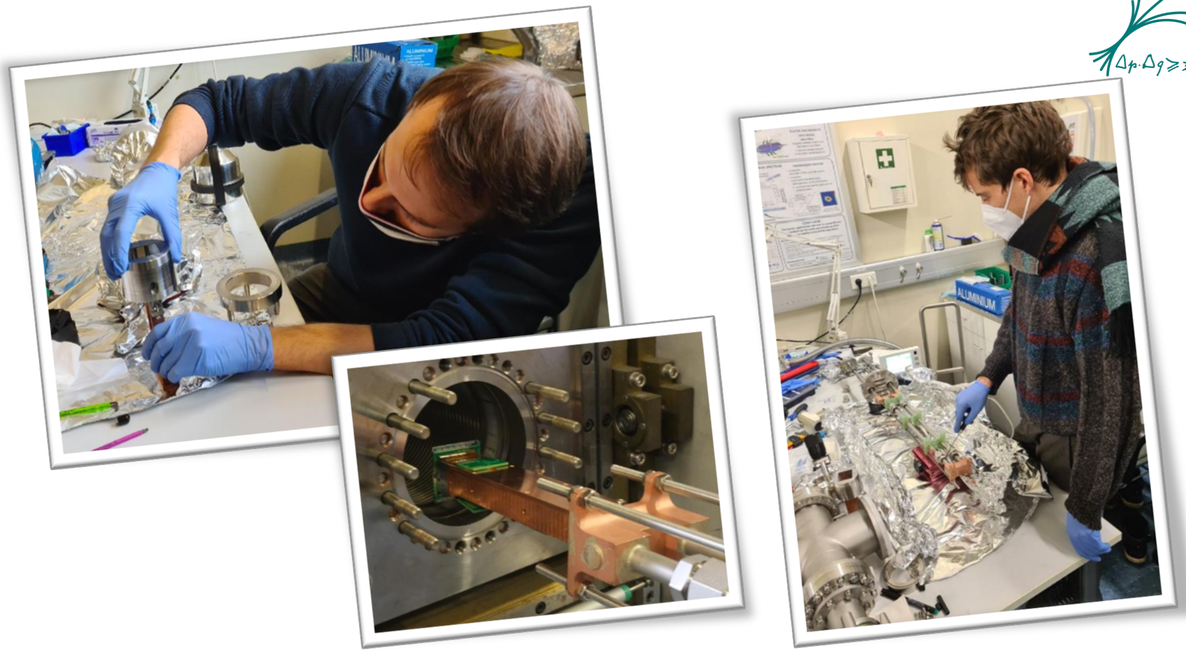
Rigid flex PCB carrying 400 signal lines

Silicon carbide (CeSic) cooling link

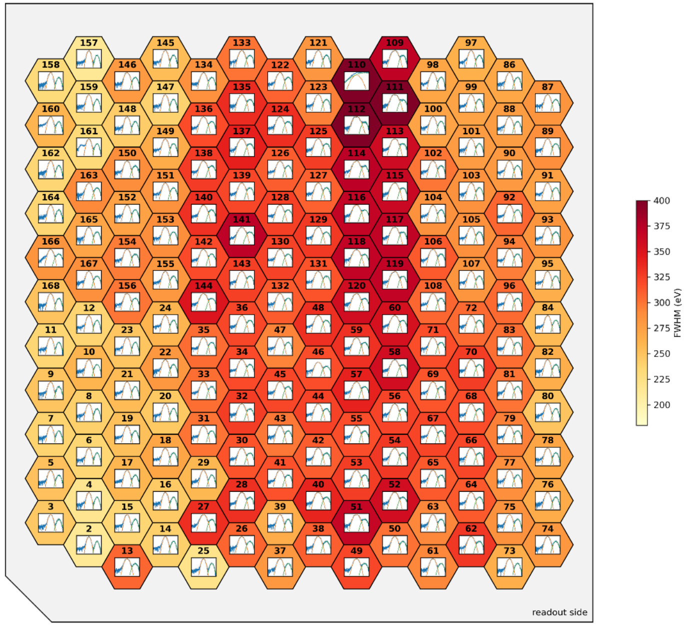
166-pixel SDD with integrated JFET

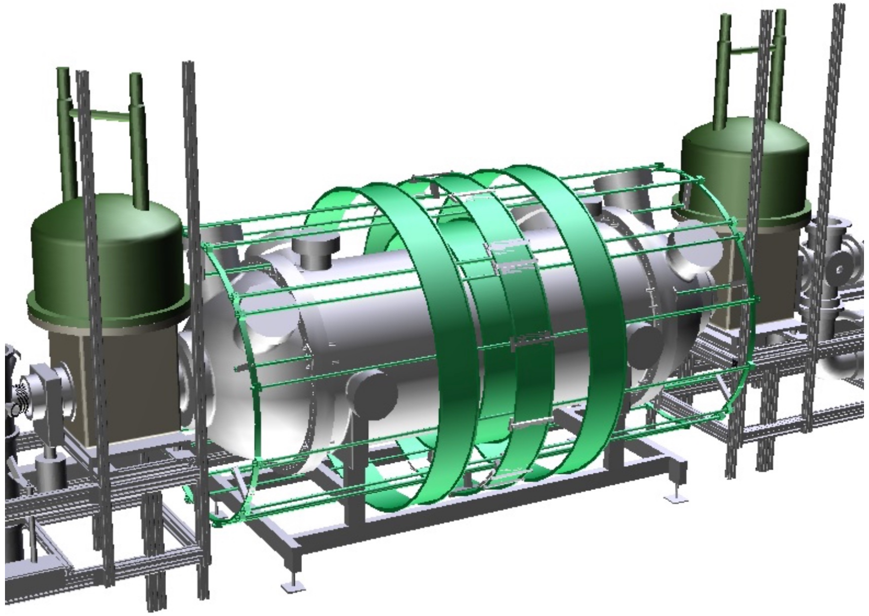


Recent Highlights

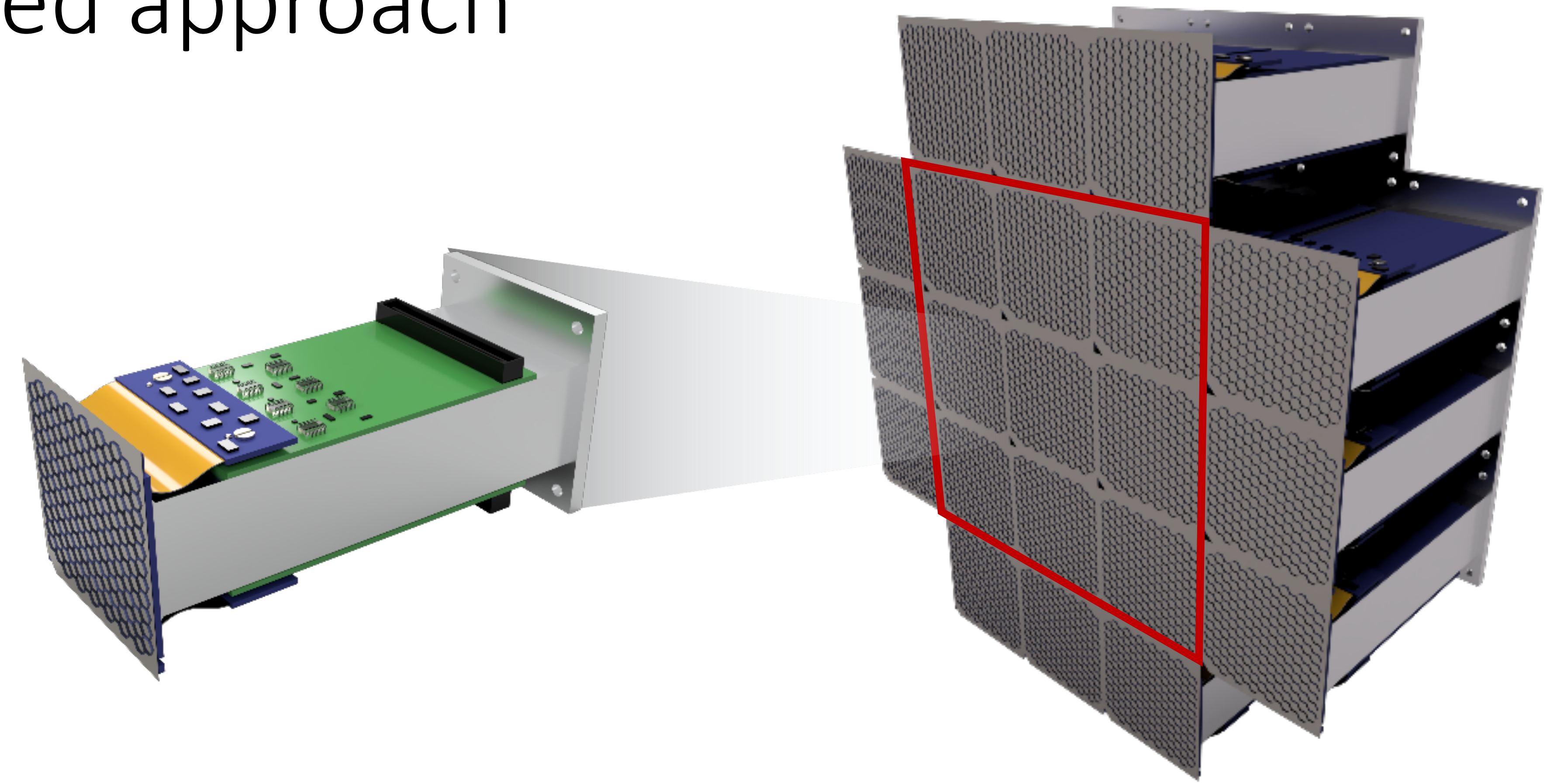


- ✓ Largest SDD array ever operated (planar)
- ✓ Successful operation of 3D module in KATRIN monitor spectrometer (-40° C, 10^{-9} mbar, 0.4 T)





Staged approach

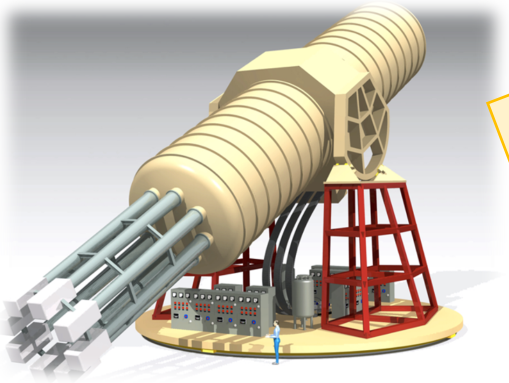


- Integration of 9 modules in KATRIN beamline in 2024
- Option of scaling up to 21 modules

Spin off's: SDDs for…

IAXO: Solar axion experiment

- Member of IAXO since 2021
- Challenge: ultra-low background
  10^{-7} c/s/keV/cm^2 (1 – 10 keV)
- First measurements in UGL and design optimizations ongoing

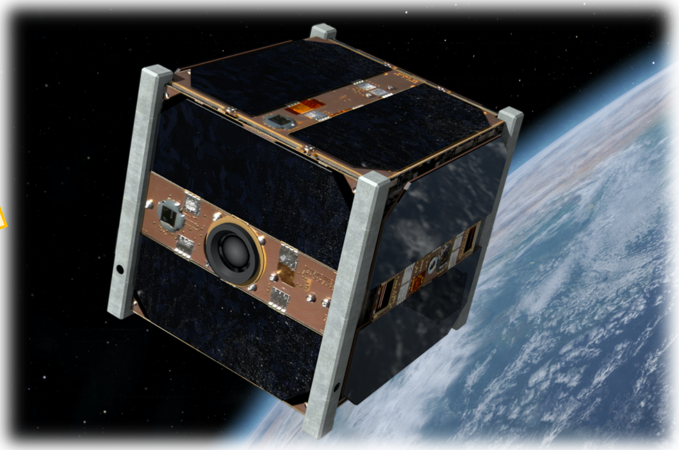


C. Wiesinger (PD)
F. Edzards (PhD)
J. Beteta (BSc)
D. Moran (MSc)

ComPol: compton polarimeter in a Cube-Sat to observe hard x-rays from Cygnus X1

- Part of ORIGINs Laboratory Rapid Space Mission (LRSM)
- Test launch to ISS planned for 2022/2023

M. Meier (PhD)
C. Glas (MSc)
K. Geigenmüller (MSc)
M. Willers (PD)



Posdocs

- Michael Willers
- Frank Edzards
- Anthony Onillon
- Christoph Wiesinger
- Tobias Bode
- Thibaut Houdy
- Martin Slezak

PhD

- Korbinian Urban
- Christoph Köhler
- Christian Karl
- Lisa Schlüter
- Daniel Siegmann
- Matthias Meyer
- A. Schwemmer
- Frank Edzards
- Anna Pollithy
- Tim Brunst

Master

- Florian Henkes
- Cynthia Glas
- Katrin Geigenberger
- Lena Wunderl
- Xaver Stribl
- Matthias Weidenthaler
- David Casado
- Jakov Kholodkov
- Fabian Kellerer
- Johannes Wickles
- Vikas Gupta
- Alessandro Schwemmer
- Manuel Lebert
- Fotis Megas
- Cornelius Schatz
- Madlen Steven
- Pablo Morales
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