Deciphering neutrinos and searching for dark matter

- Susanne Mertens
- Technical University Munich

- MPP Symposium 2022

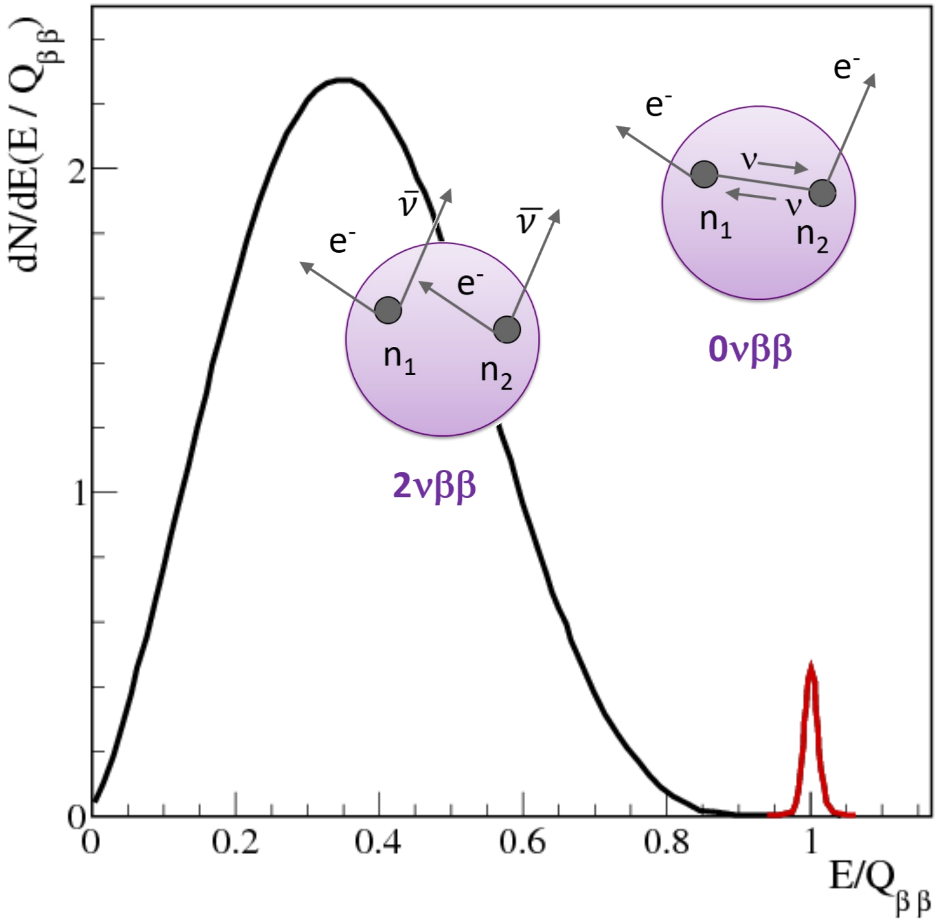
Open questions

Are neutrinos their own antiparticle ?

What is the mass of neutrinos ?

What is the nature of dark matter ?

General idea

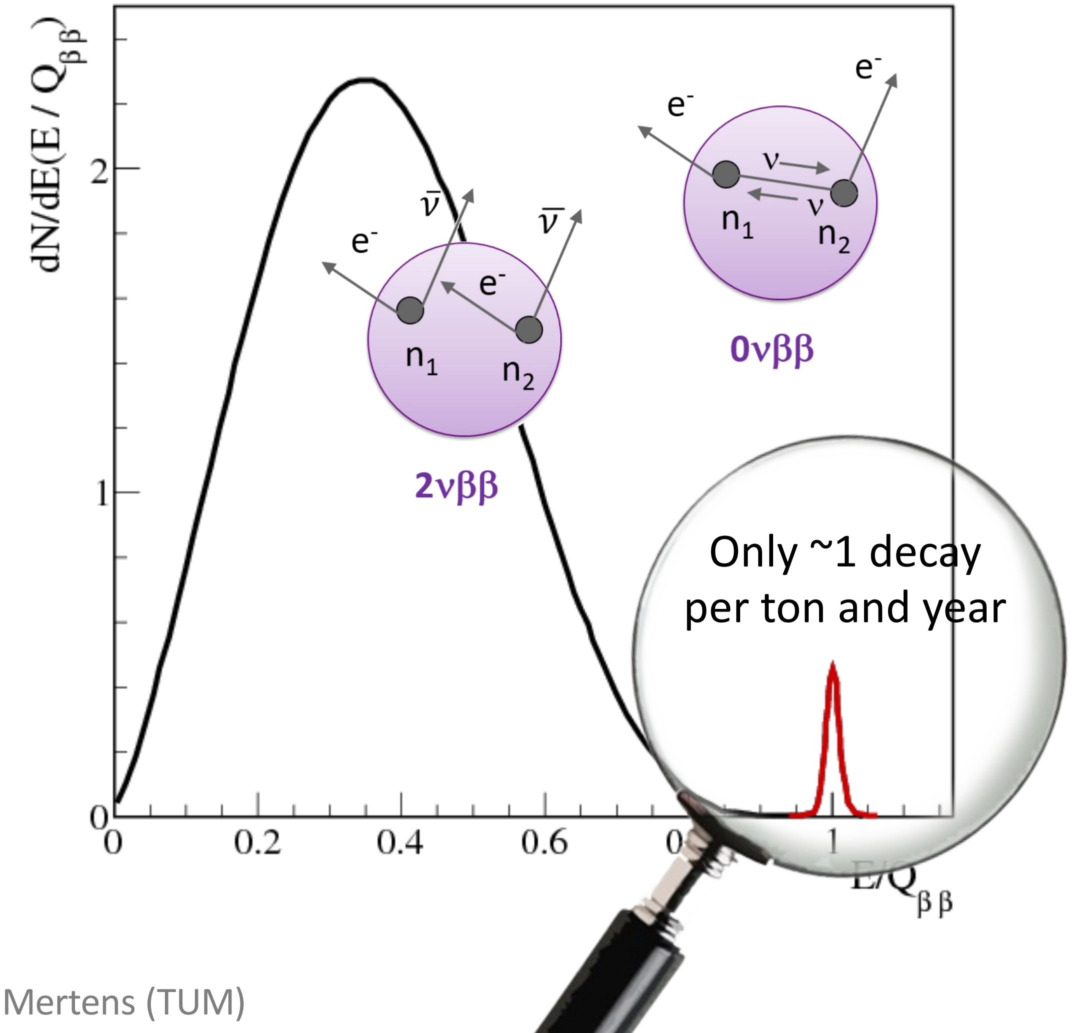


Discovery of 0νββ:

- Shed light on matter-antimatter asymmetry
- Prove that neutrinos are Majorana particles and that Lepton number is violated
- Half life reveals neutrino mass:

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

The challenge



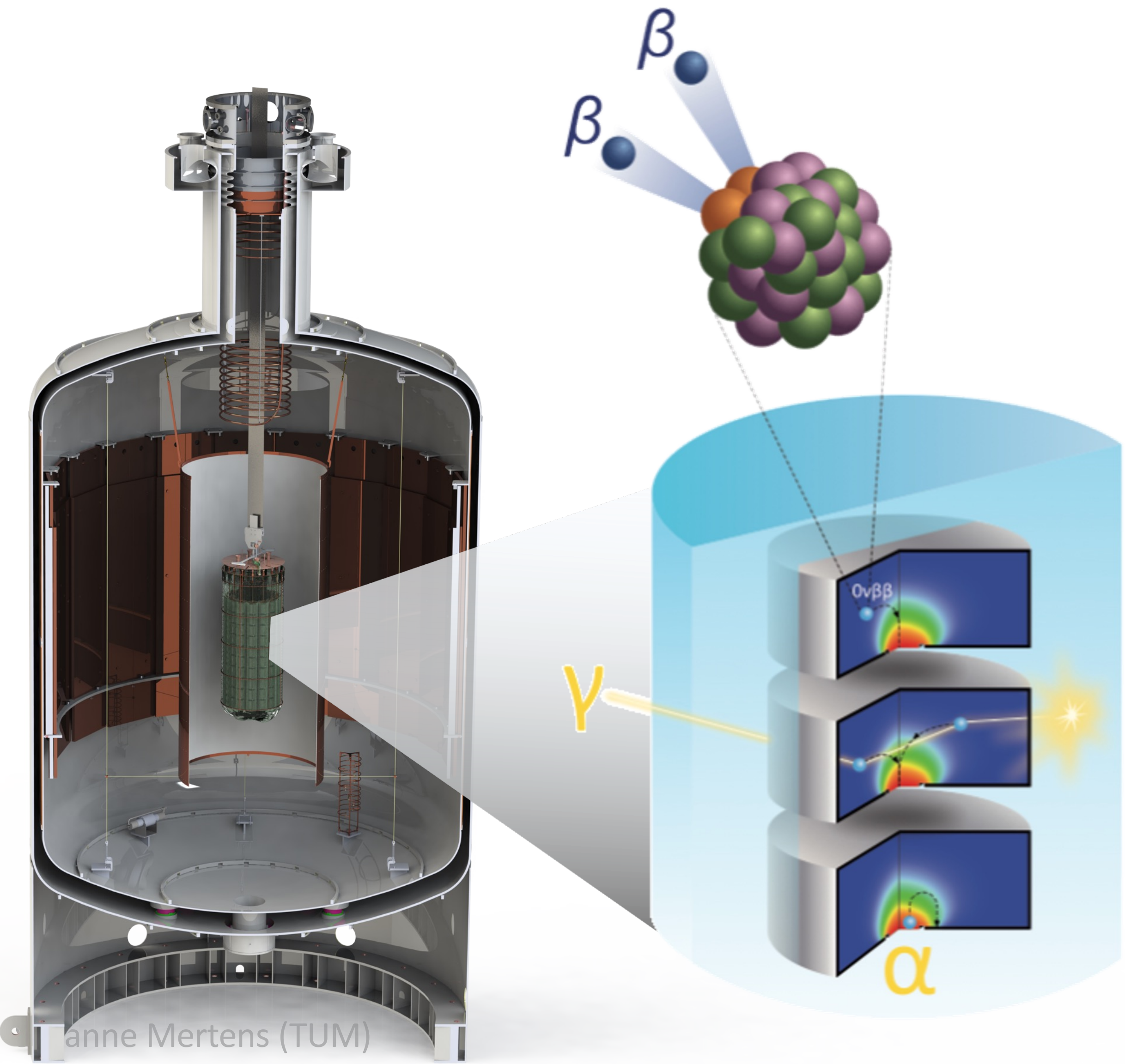
Key requirements:

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

LEGEND experiment

- Successor of GERDA and MAJORANA
- Experimental site (1st stage): Laboratori Nazionali del Gran Sasso (LNGS)
- International Collaboration (250 members)
- Sensitivity: **$T_{1/2}$ (3σ DS) > 10^{28} yrs and $m_{\beta\beta}$ < 10 - 17 meV**

LEGEND working principle

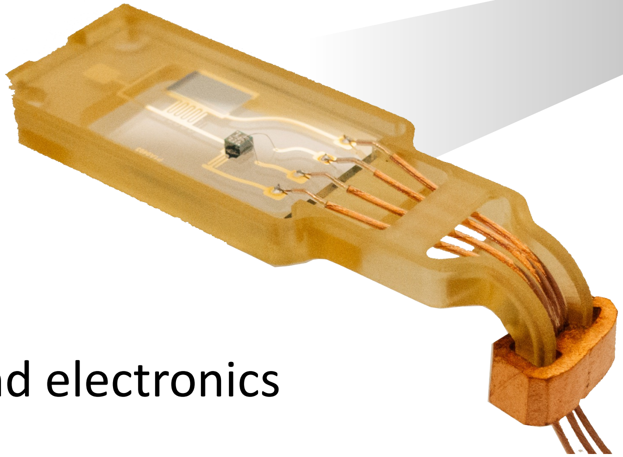


- **Search for 0νββ in ^{76}Ge**
- High-purity Ge detectors (enriched to 87% in ^{76}Ge), immersed in liquid argon active shield
- Point contact geometry provides:
  - excellent energy resolution (0.12% FWHM @ $Q_{\beta\beta}$)
  - excellent pulse-shape-discrimination against background
- Staged approach
  - LEGEND-200 (200 kg of Ge detectors)
  - LEGEND-1000 (1-ton of Ge detectors)

LEGEND electronics

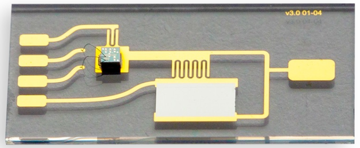
Low noise: amplification **CLOSE** to the detector

Low background: amplification **FAR** from the detector

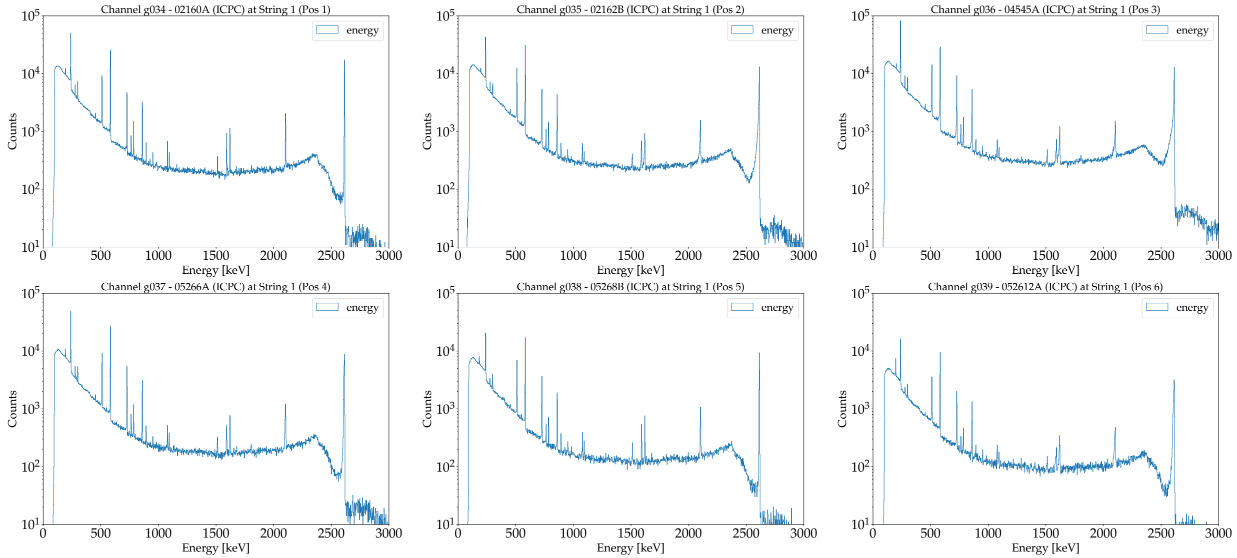


✓ Solution:
Low-mass and high-radiopurity front-end electronics

LEGEND electronics



- LEGEND-200:
  - discrete low-mass front end electronics
  - electronics integration, optimization, characterization
    F. Edzards et al Particles 4 (2021) 4, 489-511
  - highlight: LEGEND-60 kg (27 detectors) operational



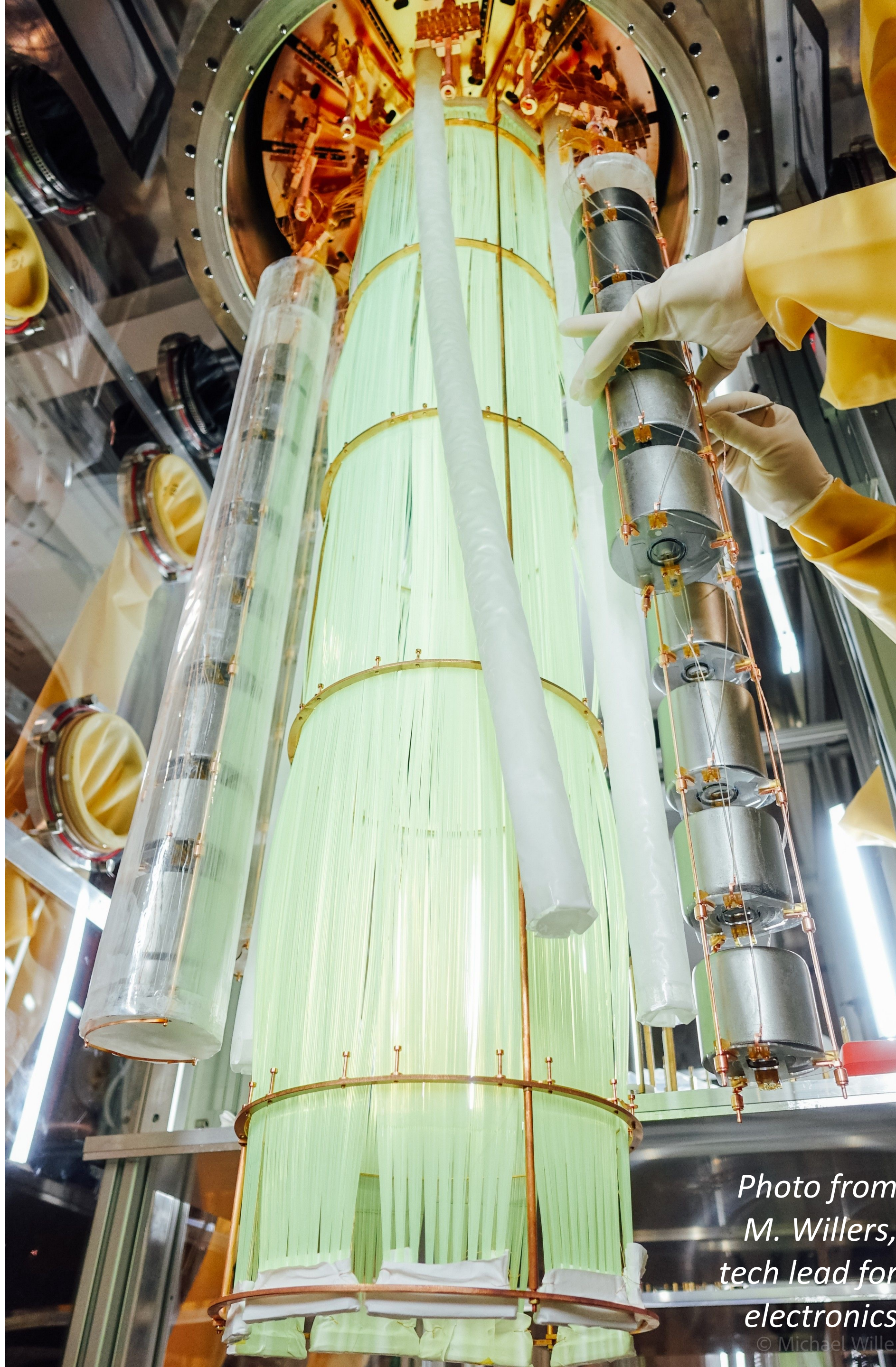
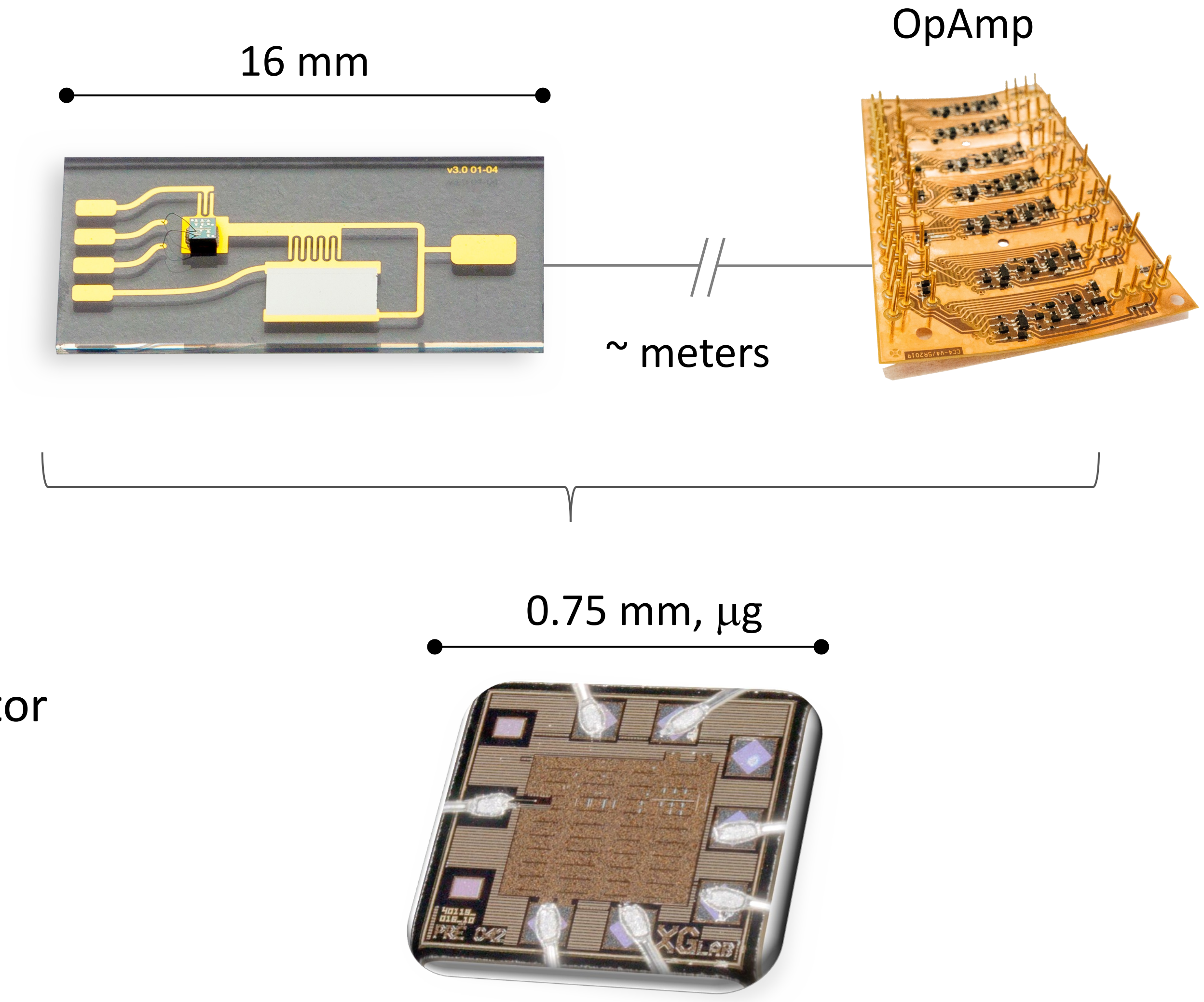


Photo from M. Willers, tech lead for electronics

LEGEND electronics

- LEGEND-200:
  - discrete low-mass front end electronics
  - electronics optimization
    F. Edzards et al Particles 4 (2021) 4, 489-511
  - highlight: LEGEND-60 kg

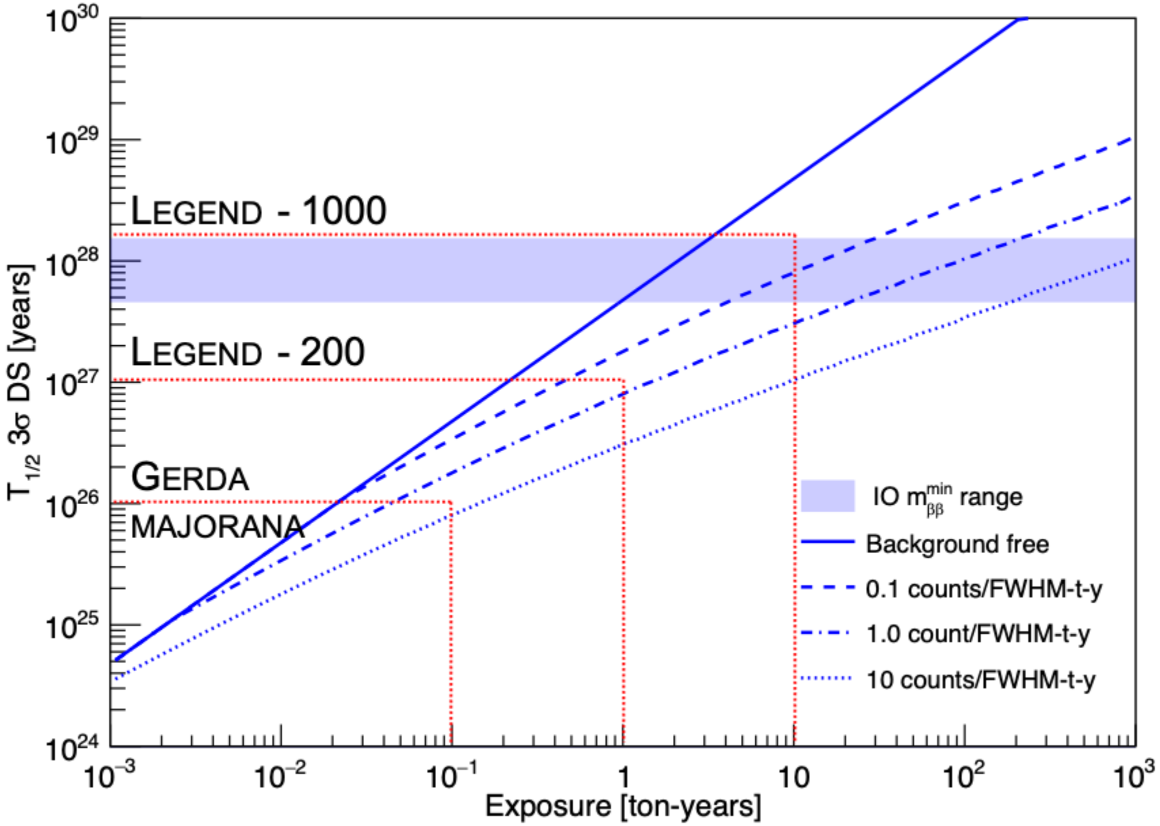
- LEGEND-1000:
  - miniaturized ASIC-based read-out
  - first successful tests with ASIC + Ge-detector
    (resolution, pulse-shape analysis, radiopurity)
    F. Edzards et al 2020 JINST 15 P09022
  - further R&D ongoing



SFB 1258 Neutrinos Dark Matter Messengers

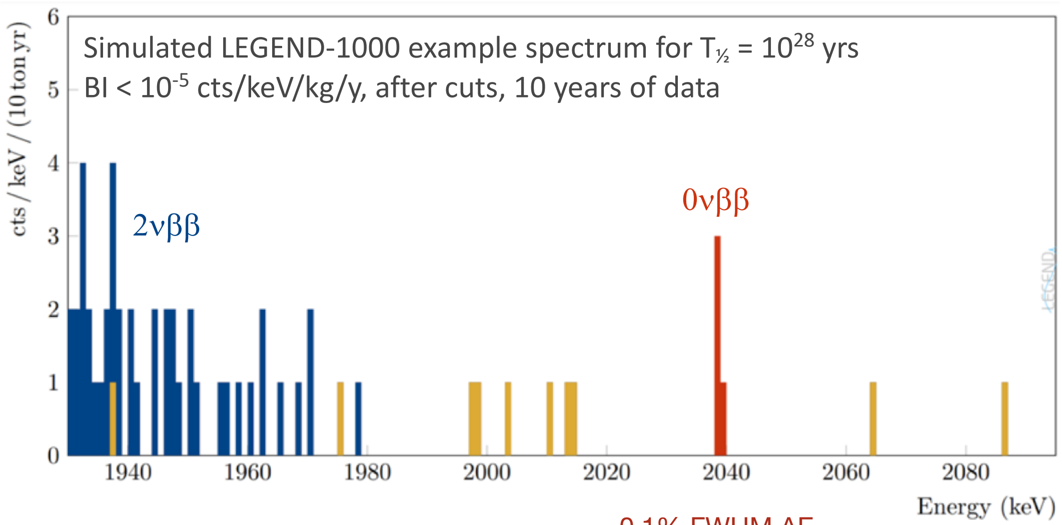
Strong collaboration with B. Majorovits

LEGEND Perspective



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

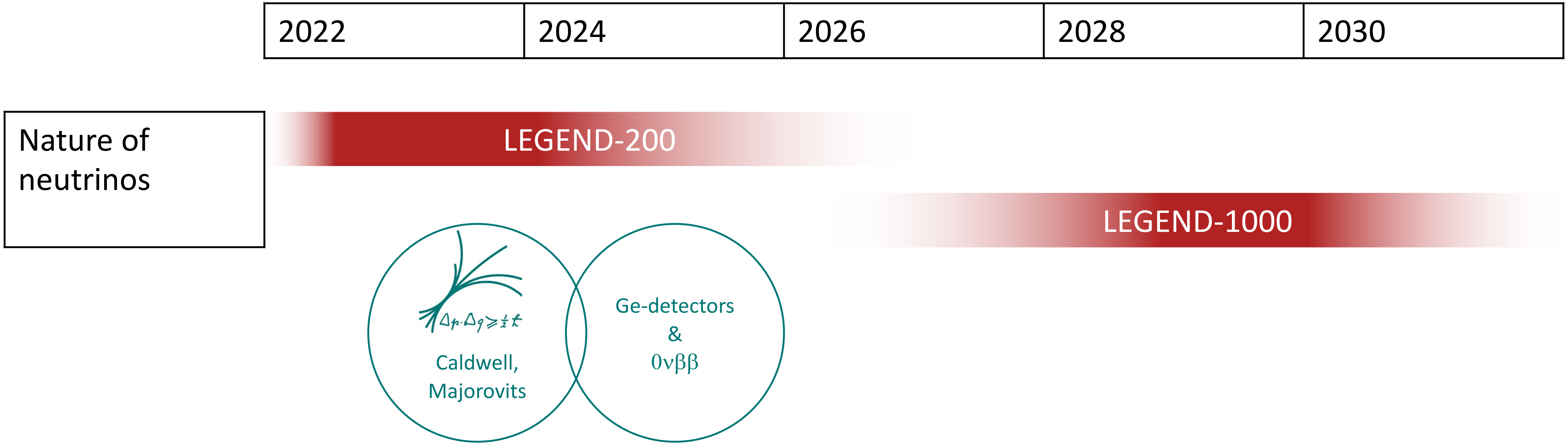
➢ cover inverted mass ordering



0.1% FWHM ΔE

*NME = 3.5 - 6.1

Timeline & Connections



Open questions

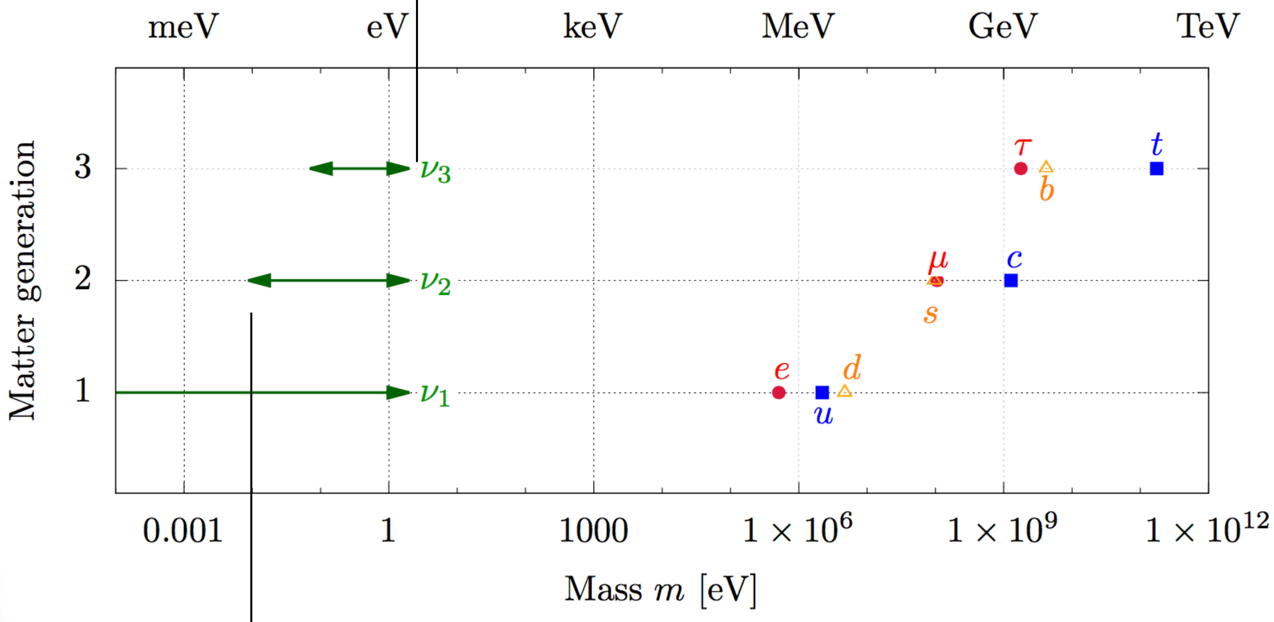
Are neutrinos their own antiparticle ?

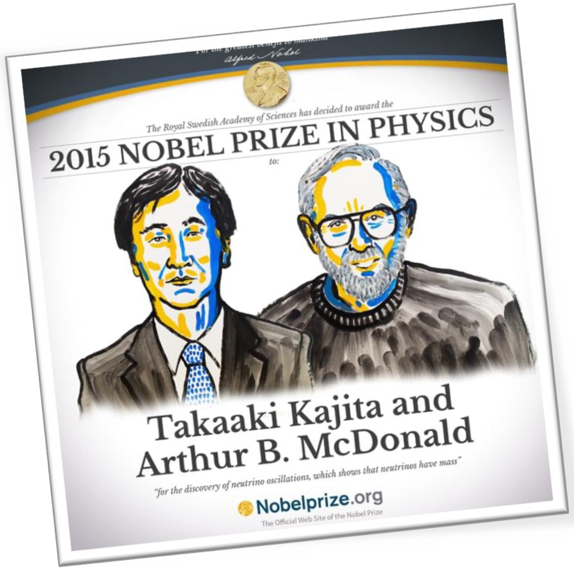
What is the mass of neutrinos ?

What is the nature of dark matter ?

Neutrino mass

Upper bound
from direct measurements



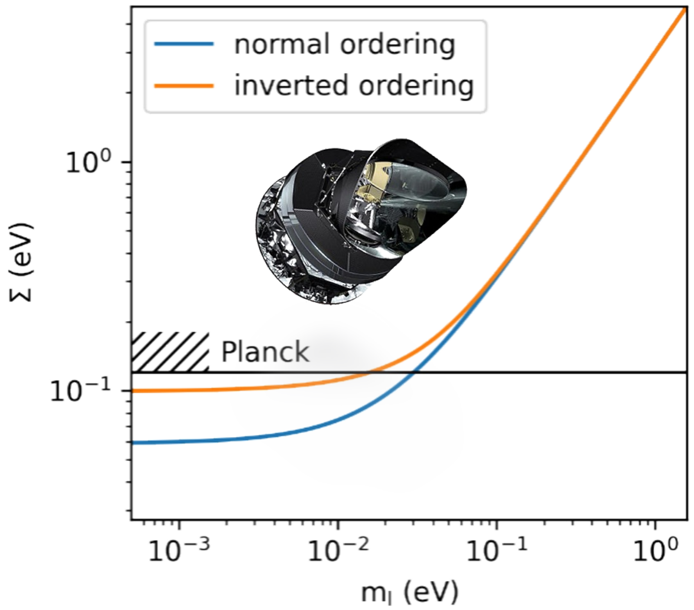


Lower bound
from oscillation experiments

Neutrino mass

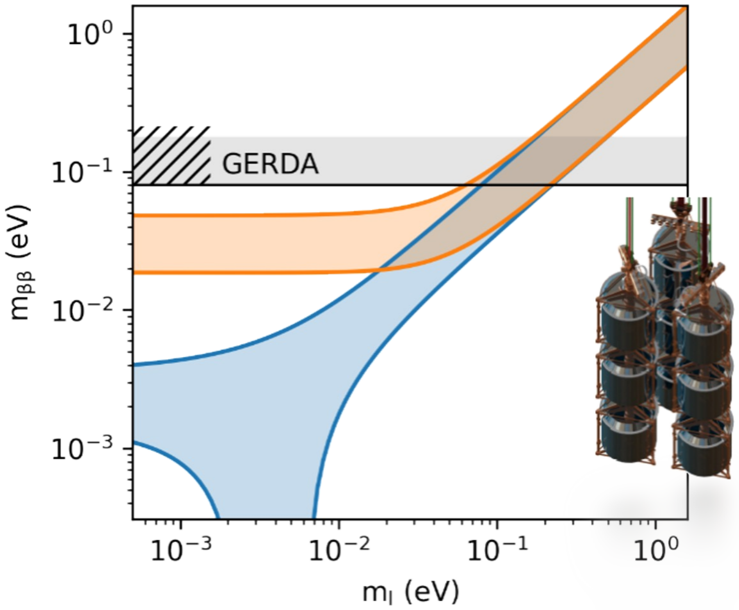
Cosmology

$$\Sigma = \sum_i m_i$$



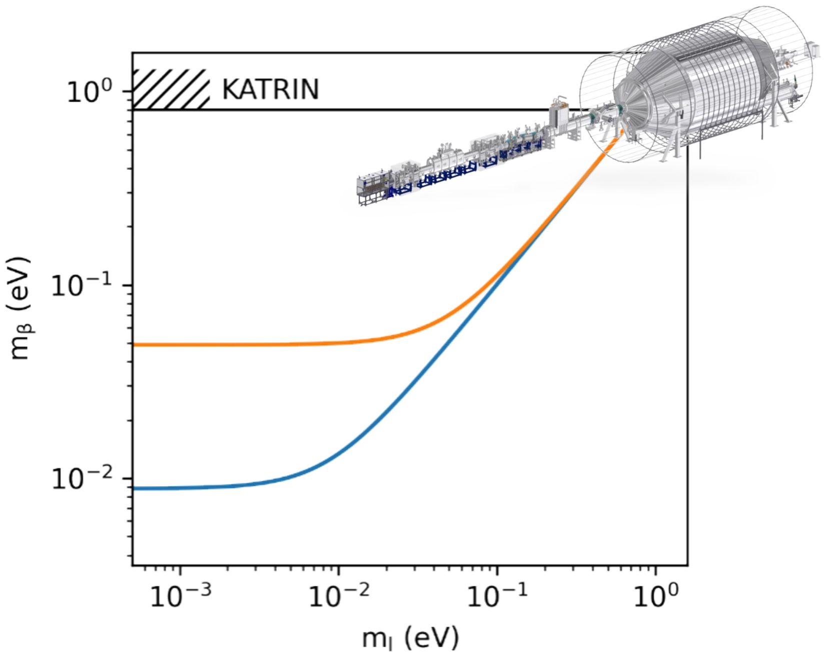
Neutrinoless ßß decay

$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

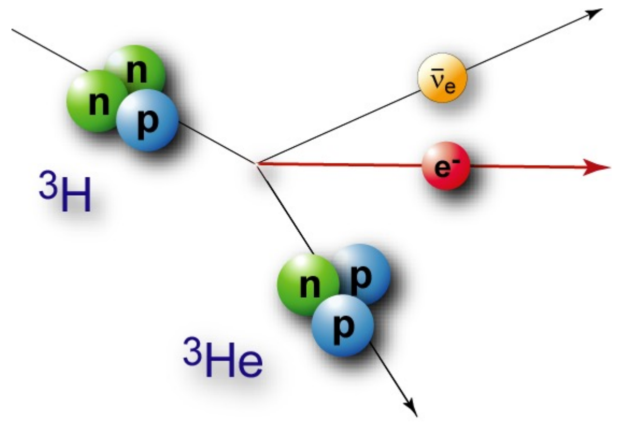


ß-decay kinematics

$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

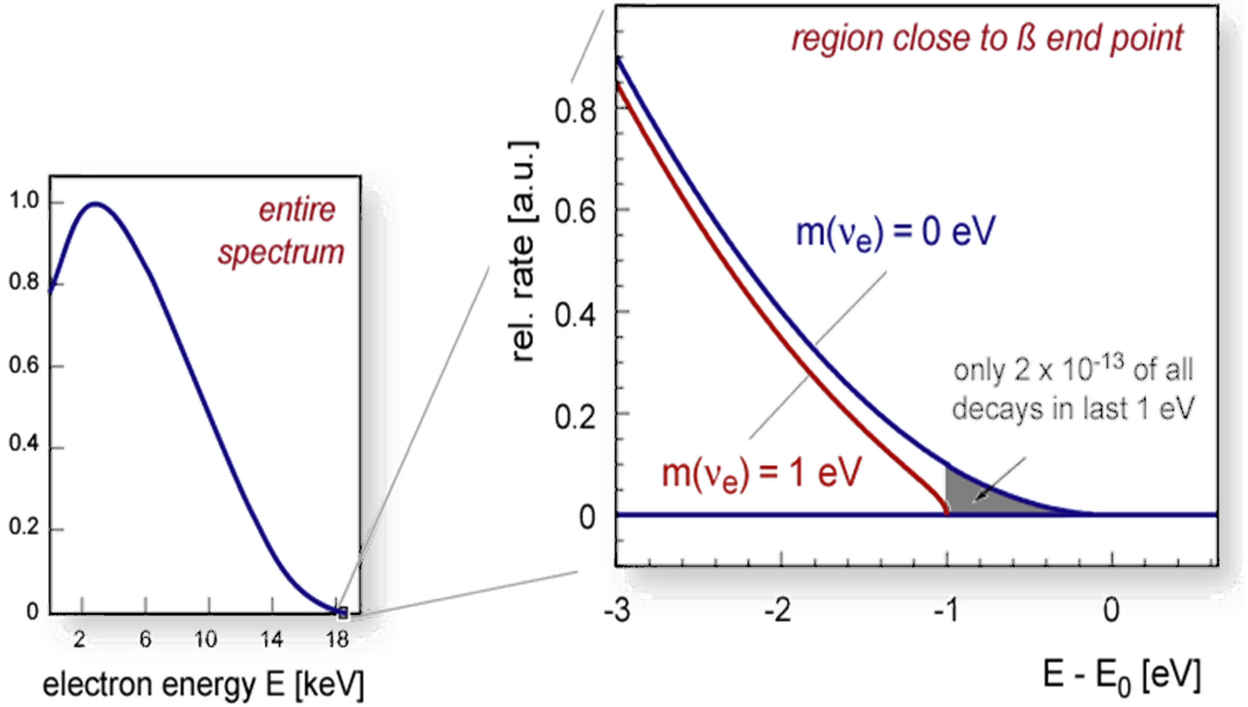


General idea



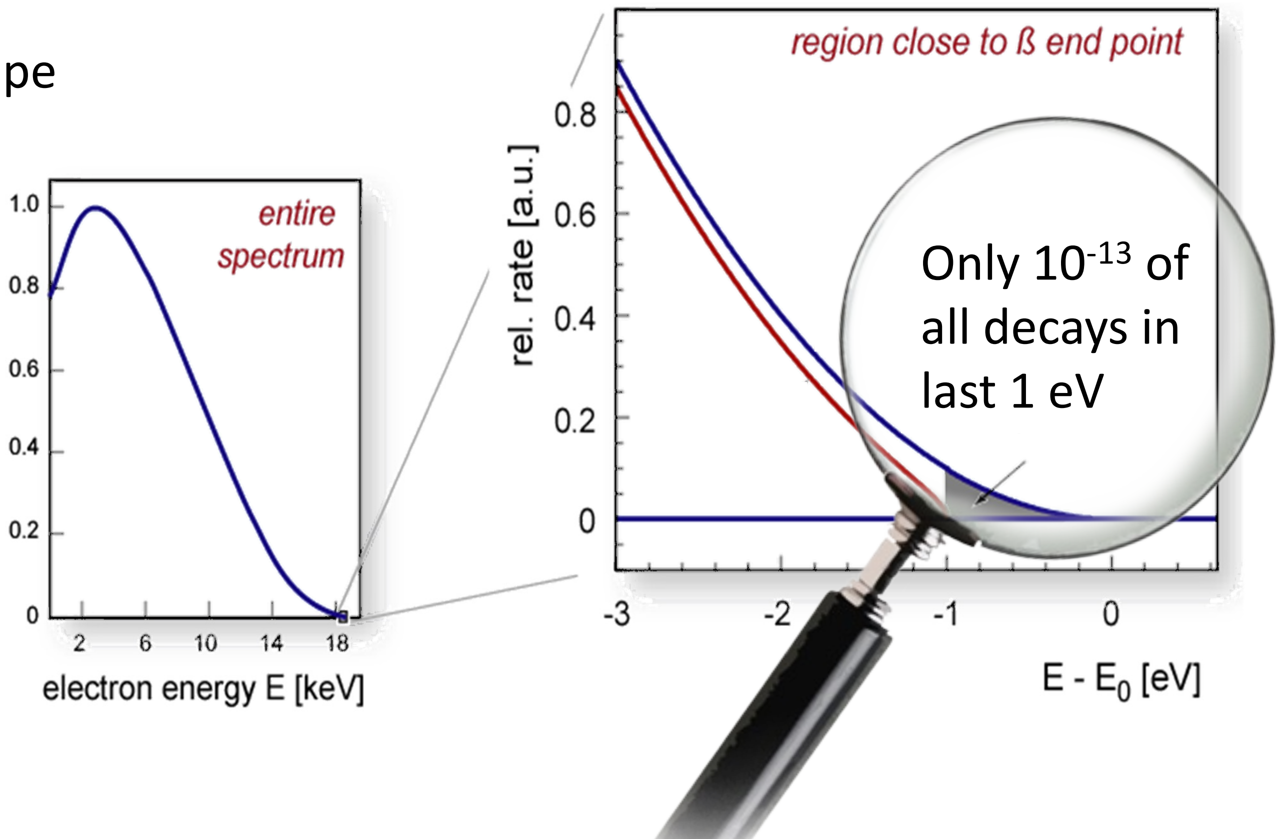
	^{3}H
	super-allowed β-decay
$T_{1/2}$	12.3 years
E_0	18.56 keV

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



The challenge

- Strong tritium source: 10^{11} decays/s
- Low background level: < 0.1 cps
- Excellent energy resolution: ~ 1 eV
- Precise understanding of the spectral shape




Karlsruhe
Tritium
Neutrino
Experiment

KATRIN

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

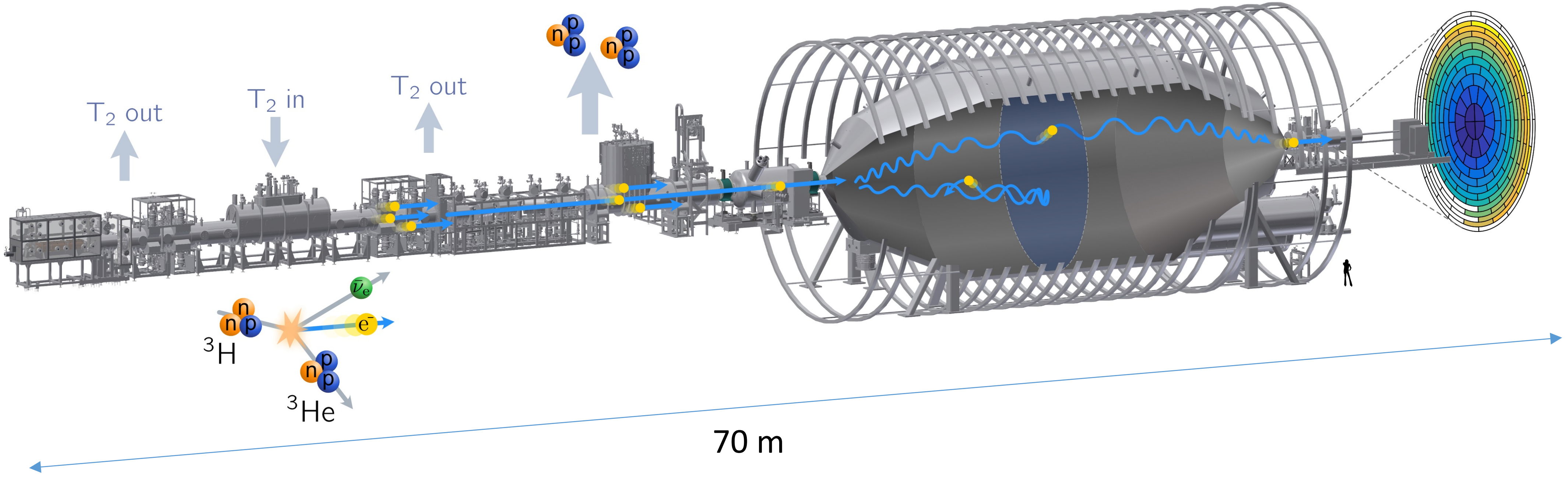
KIT Karlsruher Institut für Technologie
Max-Planck-Institut für Kernphysik Heidelberg
University of Washington
Case Western Reserve University est. 1826 think beyond the possible
Westfälische Wilhelms-Universität Münster
Università degli Studi di Milano Bicocca
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
The University of North Carolina at Chapel Hill
Massachusetts Institute of Technology
The Czech Academy of Sciences
Hochschule Fulda University of Applied Sciences
Carnegie Mellon University
Universidad Complutense Madrid
Politecnico Milano 1863
cea
Johannes Gutenberg Universität Mainz
TUM Technische Universität München
universität bonn
Humboldt-Universität zu Berlin
Bergische Universität Wuppertal
Berkeley Lab
Russian Academy of Sciences

Working Principle

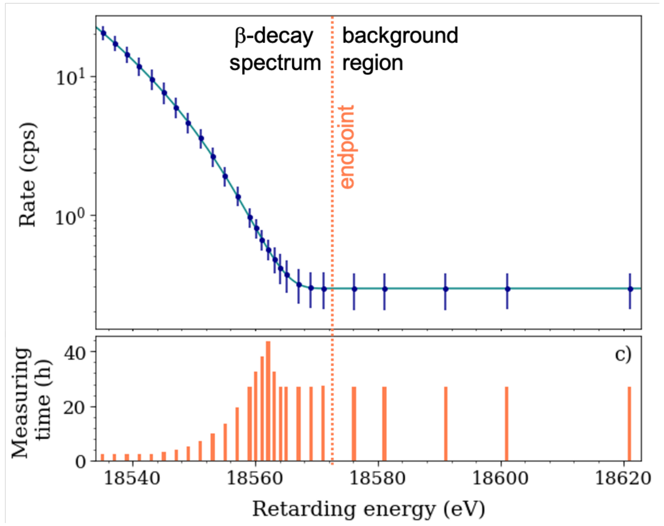
Tritium source
- 100 μg of gaseous T_2
- 10^{11} T_2 decays/s

Spectrometer
- Electrostatic filter
- MAC-E filter principle

Detector
- Counts electrons
- Rate vs potential

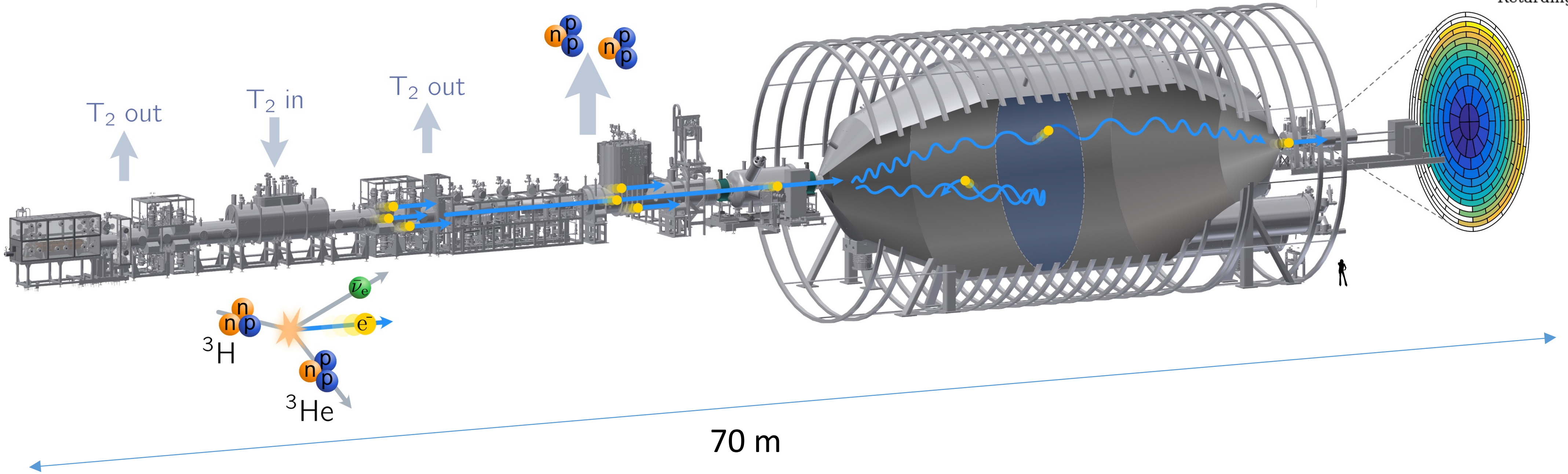


Working Principle



Tritium source
- 100 µg of gaseous T_2
- 10^{11} T_2 decays/s

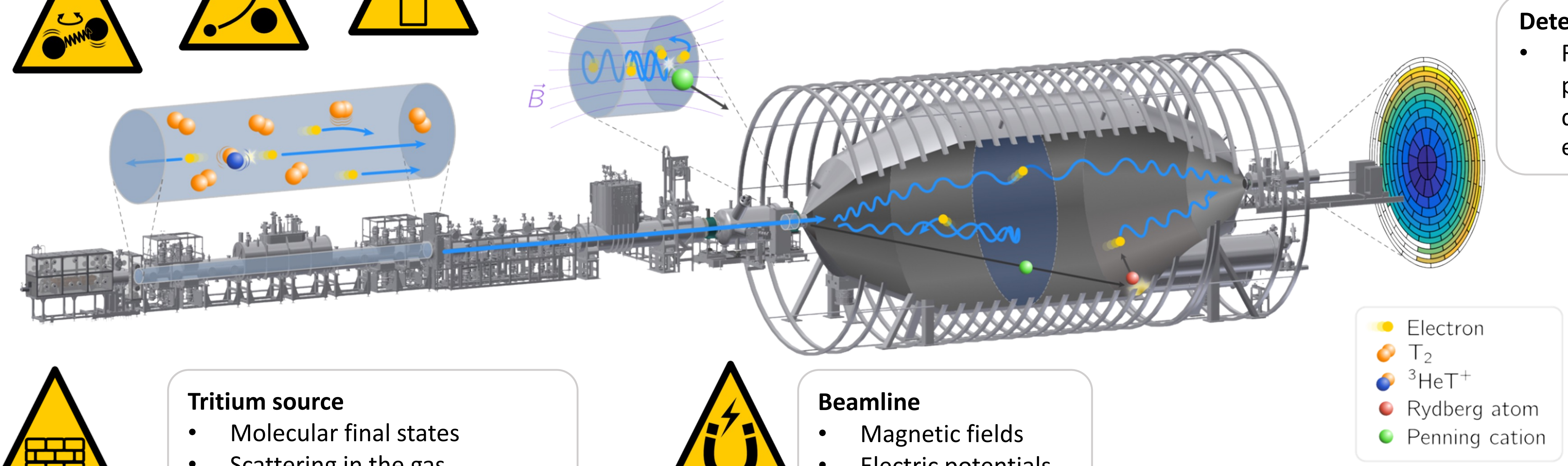
Spectrometer
- Electrostatic filter
- MAC-E filter principle



Working Principle

Background
- Retarding-potential dependence
- Time-dependence

Detector
- Retarding-potential dependent efficiency

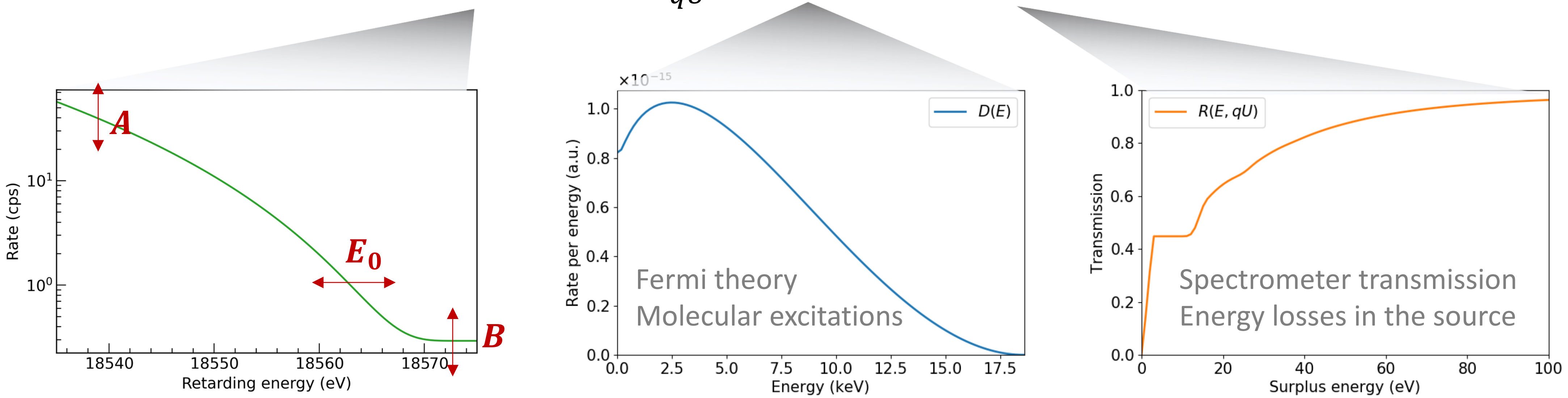


Tritium source
- Molecular final states
- Scattering in the gas

Beamline
- Magnetic fields
- Electric potentials

Data analysis strategy

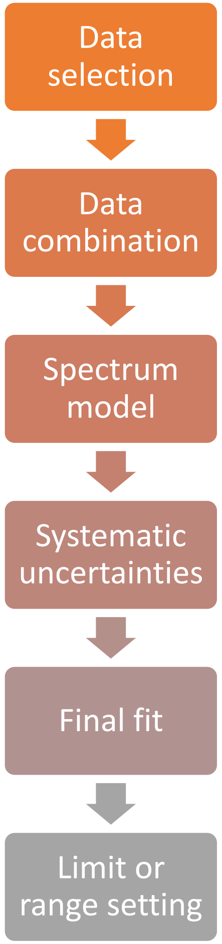
- Fit of theoretical prediction: $\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{E_0} D\left(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}\right) \cdot R(qU, E)\, dE + \boldsymbol{B}$

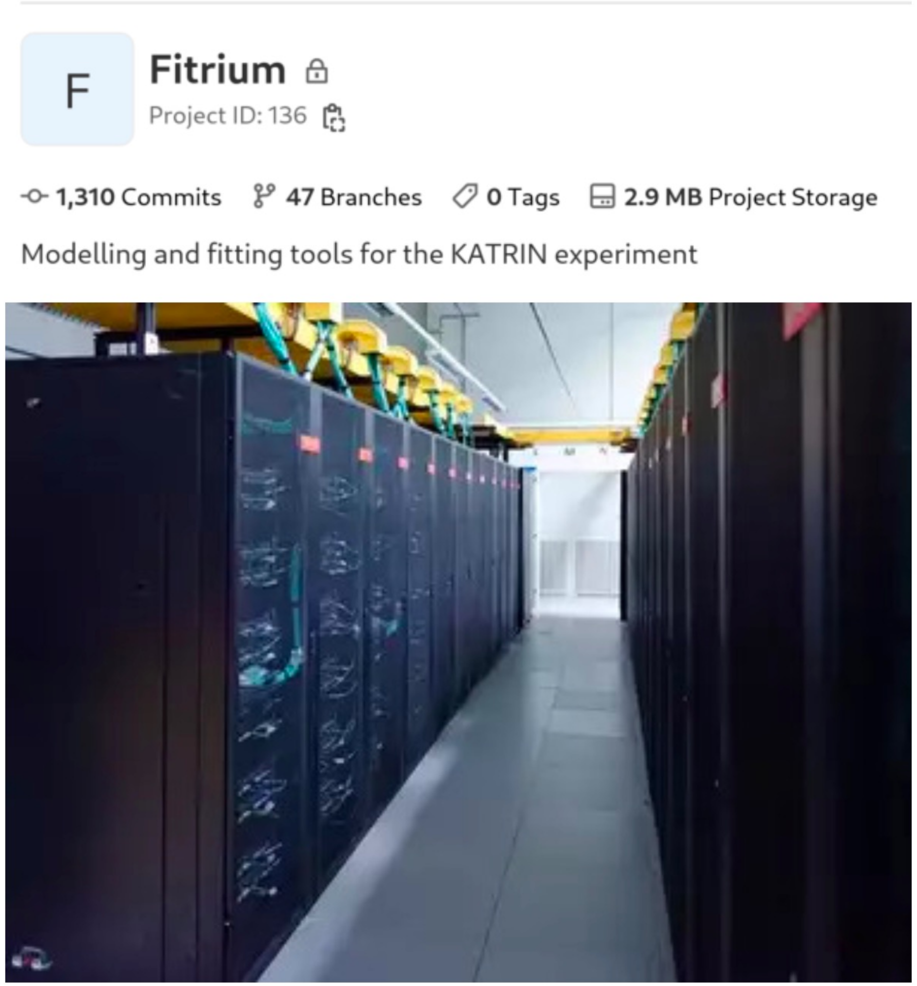


- Free parameters: $\boldsymbol{m_\nu^2}, \boldsymbol{E_0}, \boldsymbol{B}, \boldsymbol{A}$ + $O(20)$ nuisance parameters (constrained via calibrations)
- Blinded analysis: 1. MC twin data, 2. model blinding, 3. independent analysis teams

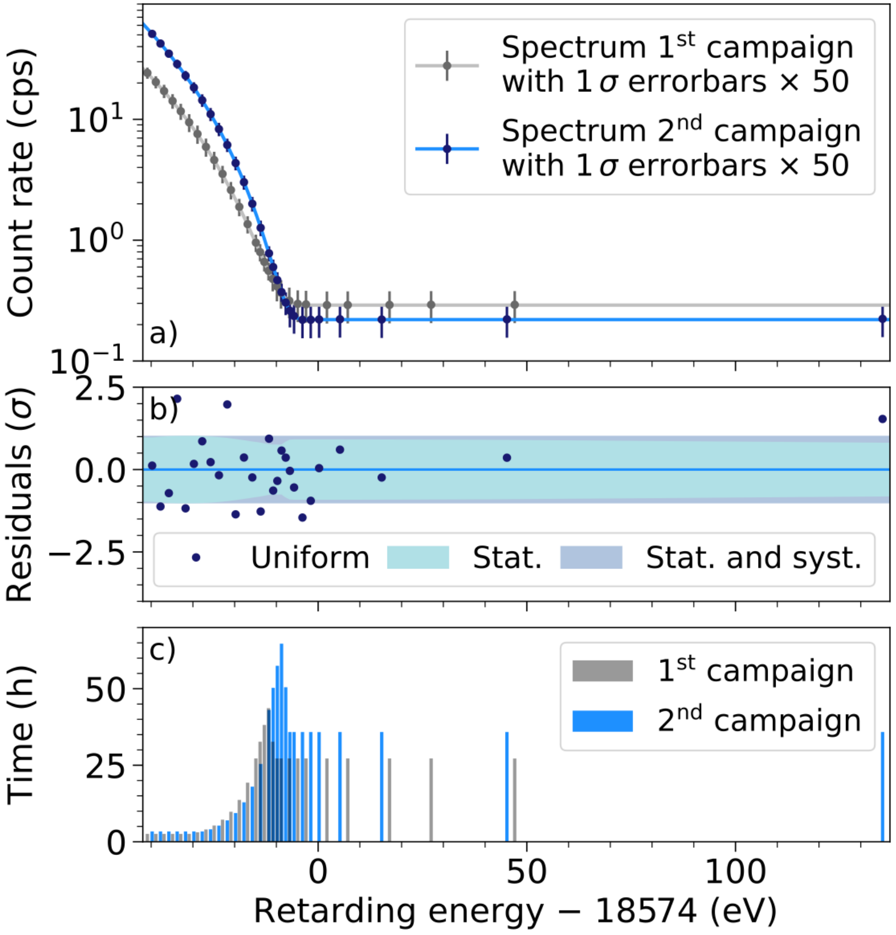
New analysis framework: *Fitrium*

- ✓ Complete analysis chain
- ✓ Official framework used for the neutrino mass analyses
- ✓ Application for calibration analysis
  - ✓ E-gun measurements (gas density)
  - ✓ Gaseous krypton (E&B fields)





Latest results



First campaign:

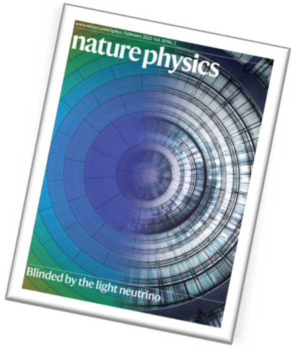
- total statistics: 2 million events
- best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ **eV² (stat. dom.)**

PRL. 123, 221802 (2019)
Phys. Rev. D 104, 012005 (2021) (corresponding author MPP/TUM)

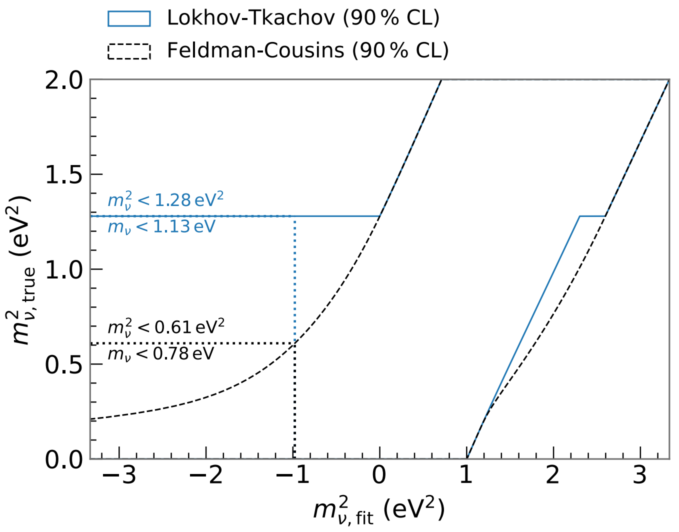
Second campaign:

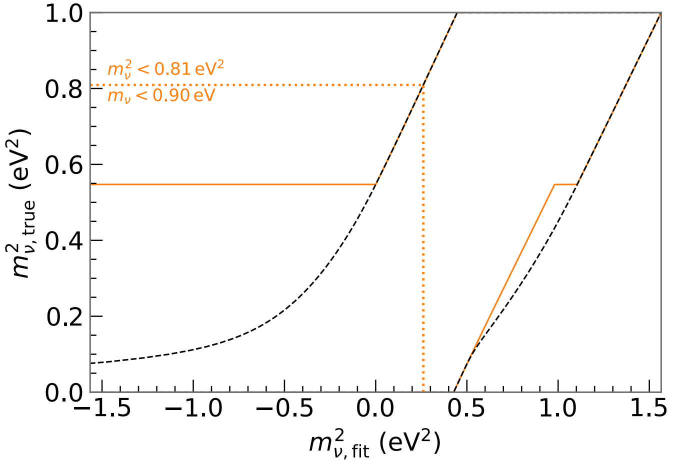
- total statistics: 4 million events
- best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$**eV² (stat. dom.)**

Nat. Phys. ***18,*** *160–166 (2022) (corresponding author S.Mertens)*



Latest results

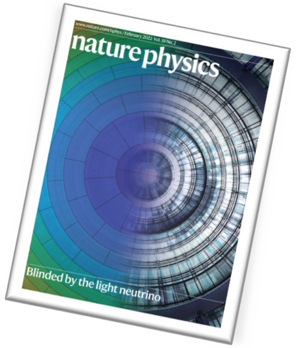




First campaign:

- total statistics: 2 million events
- best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ eV² (stat. dom.)
- limit: $m_\nu < 1.1$ eV (90% CL)

PRL. 123, 221802 (2019)
Phys. Rev. D 104, 012005 (2021) (corresponding author MPP/TUM)



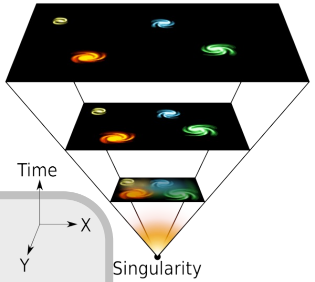
Second campaign:

- total statistics: 4 million events
- best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$eV² (stat. dom.)
- limit: $m_\nu < 0.9$ eV (90% CL)

*Nat. Phys. **18**, 160–166 (2022) (corresponding author S.Mertens)*

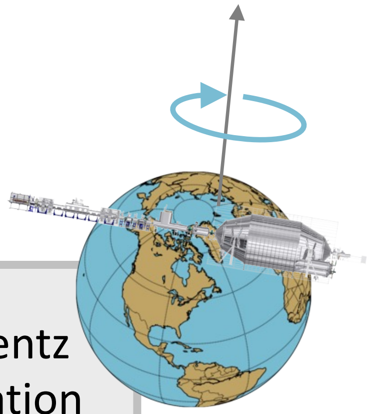
- **Combined result: $m_\nu < 0.8$ eV (90% CL)**

Beyond neutrino mass



Constrain local overdensity of big-bang neutrinos
(peak search)

Search for eV sterile neutrinos
(kink search)



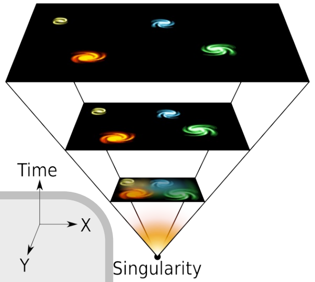
Search for Lorentz invariance violation
(sidereal modulation)

→ Best limit based on terrestrial experiment
Phys. Rev. Lett. **129**, 011806 (2022)
(corresponding author MPP/TUM)

→ Complementary results to oscillation experiments
Phys. Rev. Lett. **126**, 091803 (2021)
(corresponding author MPP/TUM)
Phys. Rev. D **105**, 072004 (2022)
(corresponding author MPP/TUM)

→ First limit on oscillation-free LV parameter
arxiv:2207.06326 (2022)
(corresponding author S. Mertens)

Beyond neutrino mass



Constrain local overdensity of big-bang neutrinos
(peak search)

→ Best limit based on terrestrial experiment
Phys. Rev. Lett. **129**, 011806
(corresponding author MPP/TUM)

A Step Closer to Detecting Ancient Neutrinos

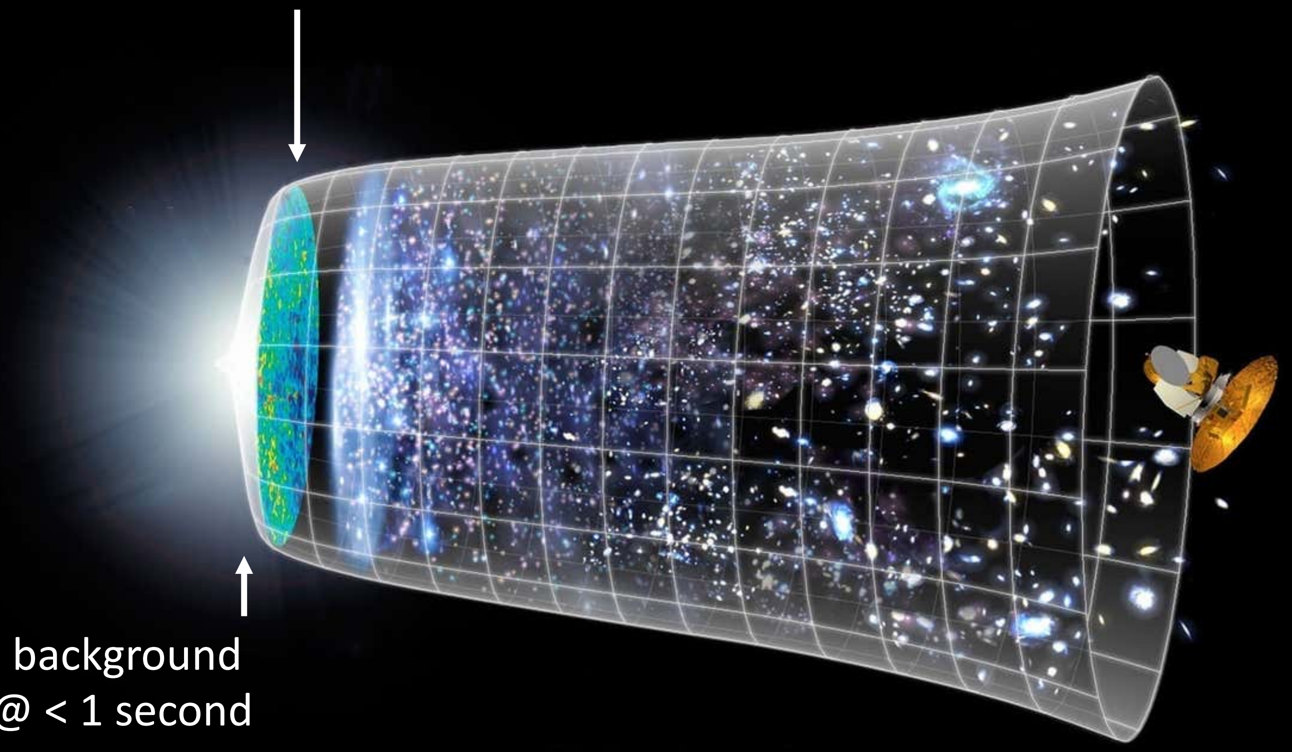
June 29, 2022 • *Physics* 15, s85

Using radioactive tritium, scientists improve laboratory constraints on the overdensity signal of cosmic relic neutrinos by a factor of 100, an advance that should improve the chances of spotting this elusive particle.

Cosmic neutrino background

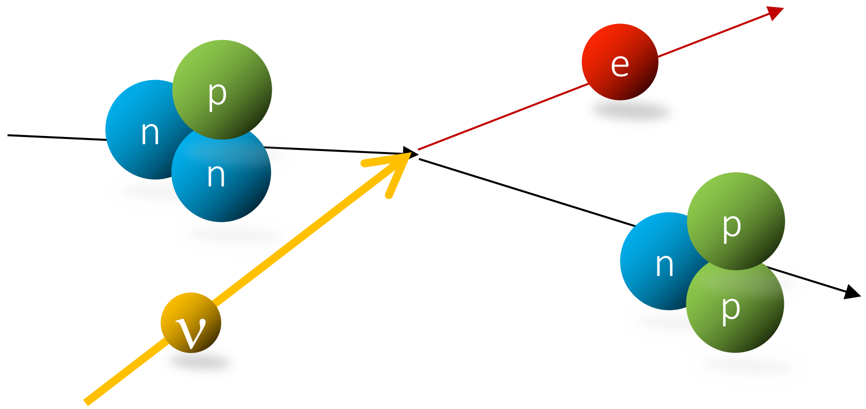
- Neutrinos decouple 1 s after the Big Bang
- About 400 ν's per cm^3 today
- Detection would confirm Big Bang theory

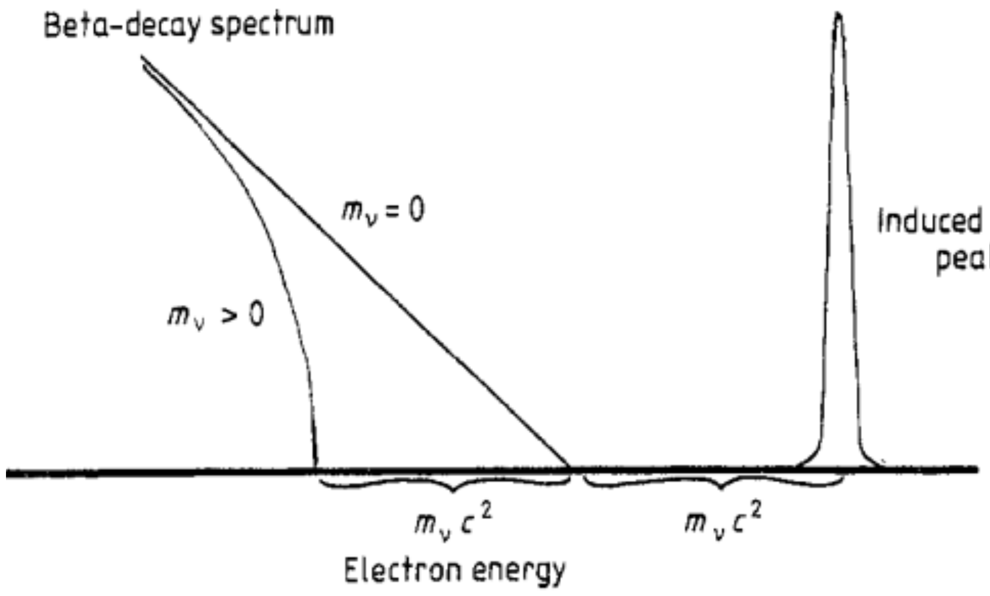
- Challenge: tiny cross-section



Signature of Relic Neutrinos

- Neutrino capture on tritium: no energy threshold
- Electron peak above endpoint
- $^{3}\mathrm{H} + \nu_e \longrightarrow \, ^{3}\mathrm{He} + e$





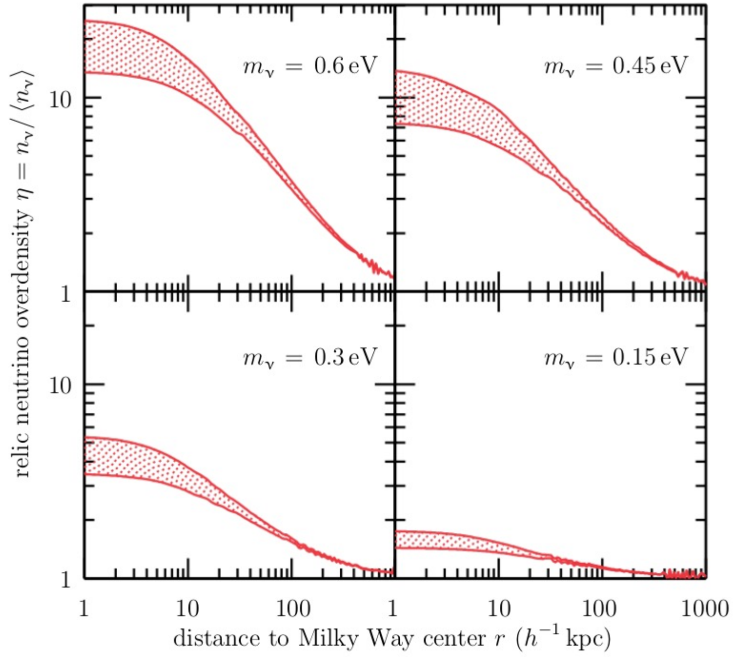
100 g tritium yields 10 ν captures per year

< 1 eV: very good energy resolution

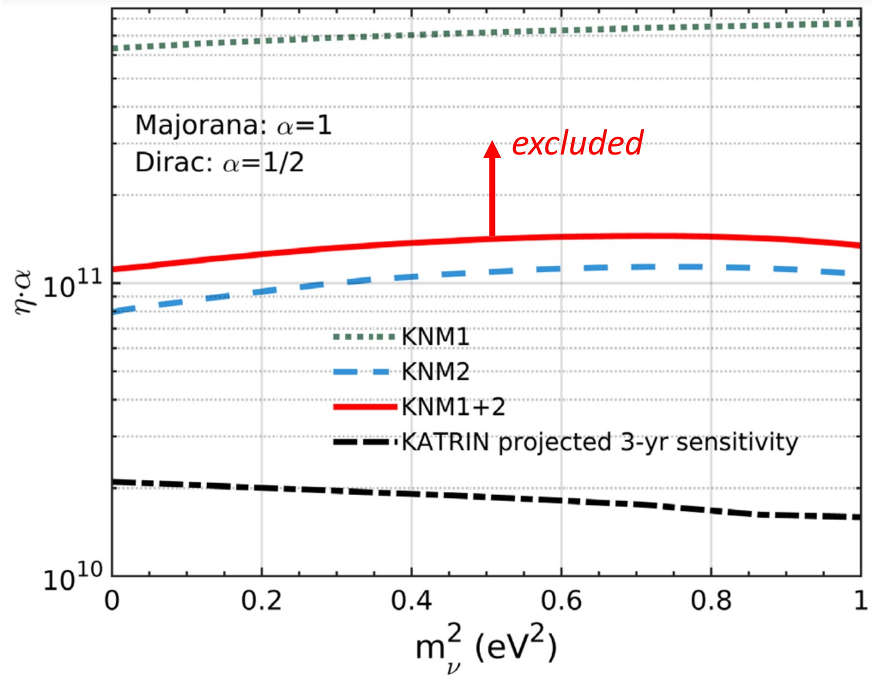
Results of Relic Neutrino Search

- Test for large **overdensity** η of neutrinos in our galaxy (based on **1st** and **2nd** ν-mass campaigns)
- Improved limit by **2 orders of magnitude** wrt previous laboratory limits

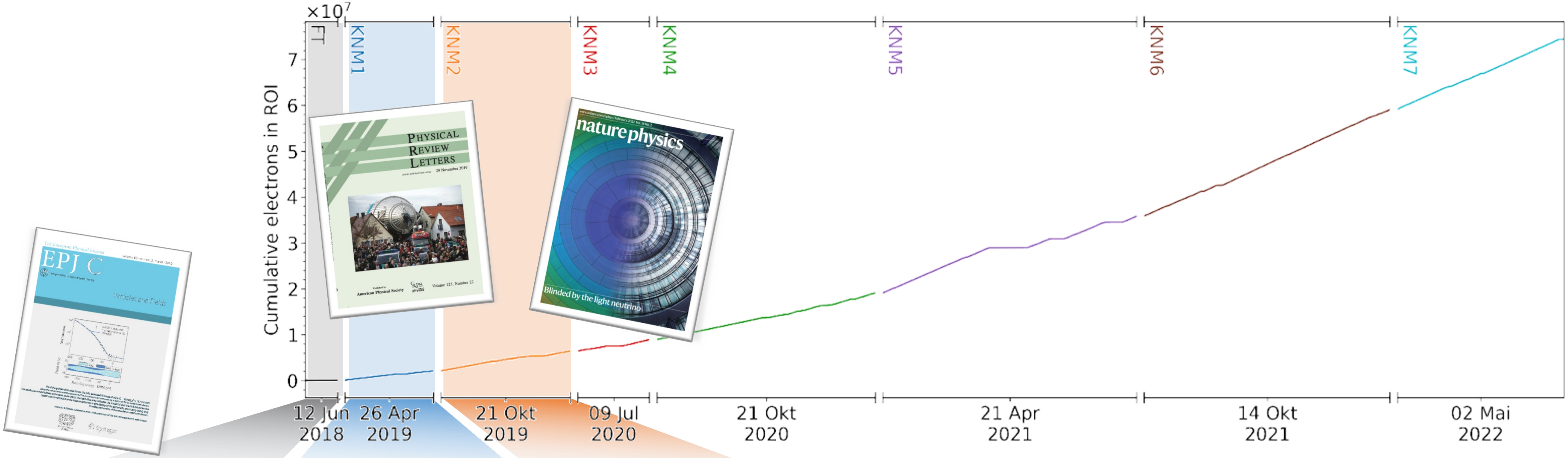
Ringwald, Wong JCAP 0412 (2004) 005



KATRIN Collab. PRL **129**, 011806 (2022)
corresponding author MPP/TUM



KATRIN Data Taking Overview



- Commissioning
- Only 0.5% tritium

EPJ C 80, 264 (2020)

- 1^{st} m_ν campaign
- $m_\nu < 1.1$ eV

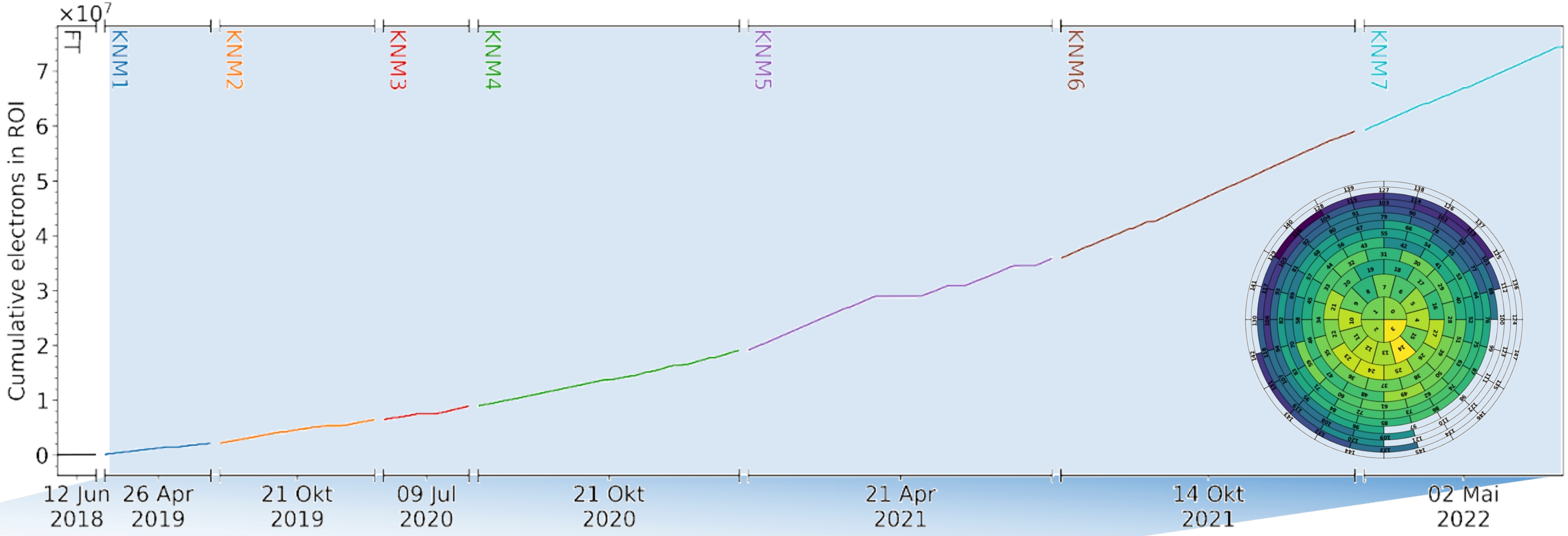
PRL. 123, 221802 (2019)

Phys. Rev. D 104, 012005 (2021)

- 2^{nd} m_ν campaign
- $m_\nu < 0.8$ eV

Nat. Phys. **18,** 160–166 (2022)

KATRIN Data Taking Overview



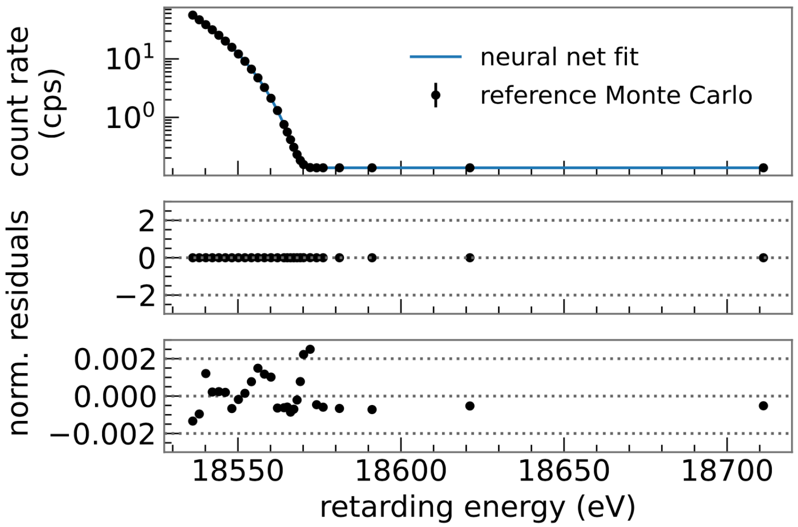
New challenge:

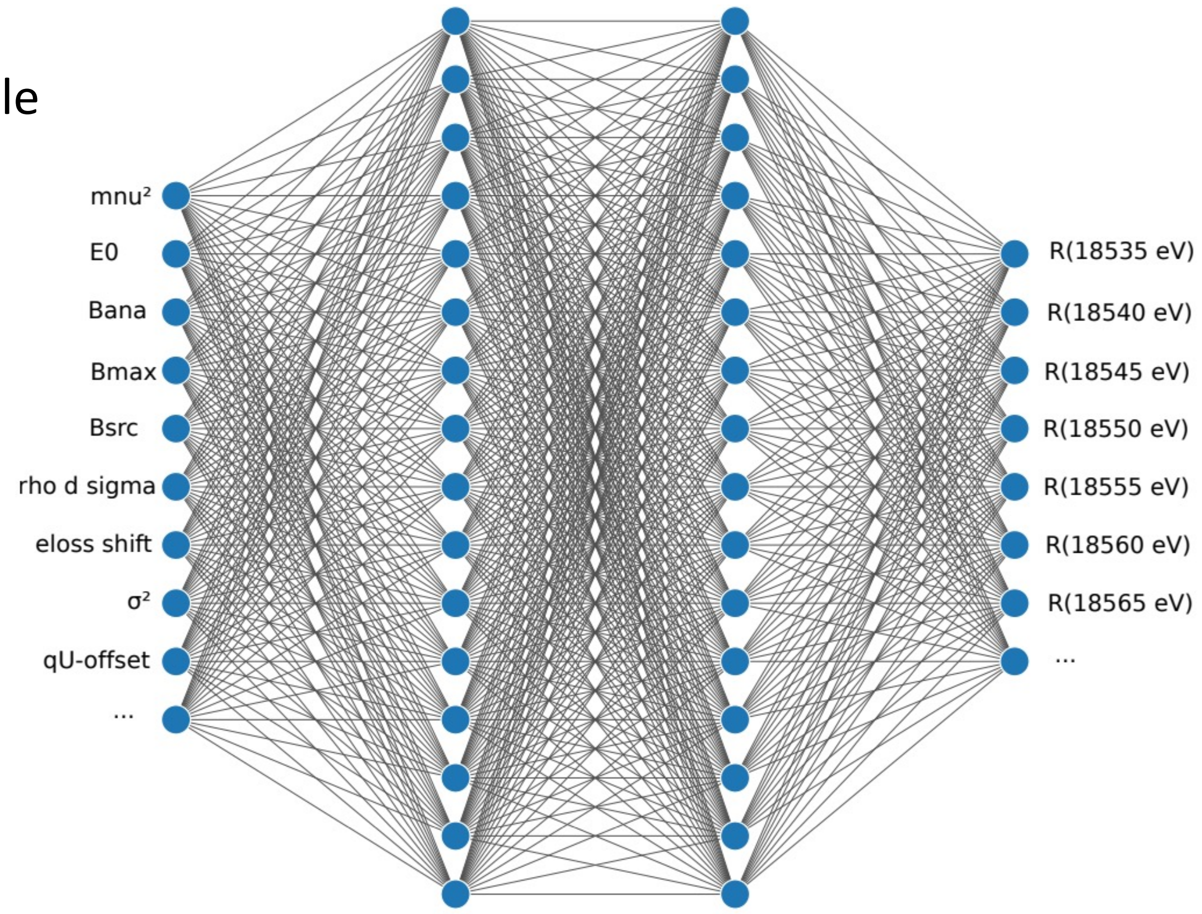
- Combined fit of multiple-campaigns at different experimental conditions
- > 1000 data points and > 100 nuisance parameters
- Fit with analytical model becomes unpractical

Novel analysis with Machine Learning

- neural network = "smart" interpolator
- **negligible uncertainty and bias** on m_ν^2 achievable
- **speed improvement** by 3 orders of magnitudes

Karl, Eller, Mertens, EPJ C 82 (2022) 5, 439





Historical context and outlook

1st and 2nd campaign combined limit:

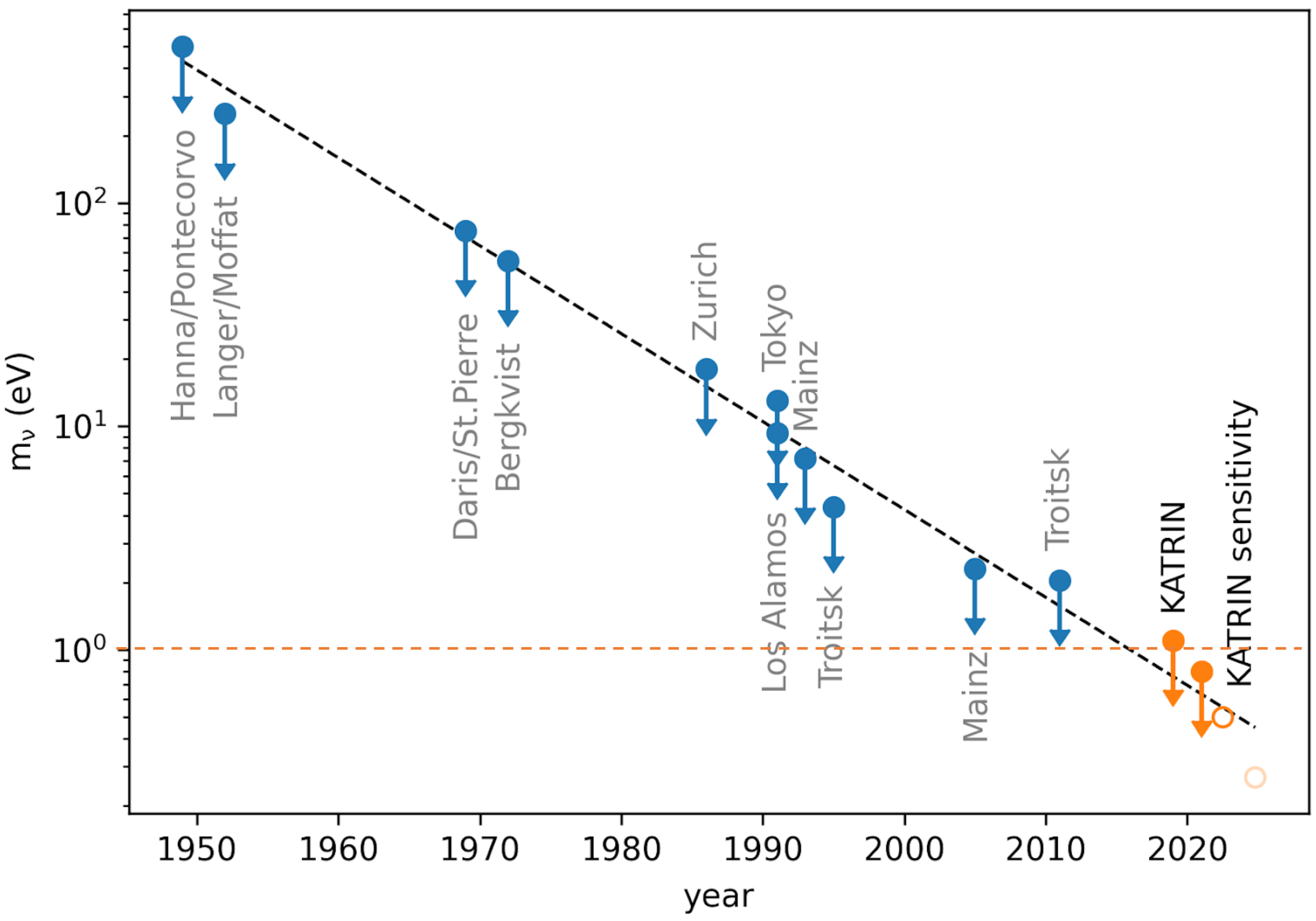
- $m_\nu < 0.8$ eV (90% CL)
- first direct neutrino-mass experiment to reach sub-eV sensitivity and limit

First five campaigns

- Analysis performed with NN
- Sensitivity of $m_\nu < 0.5$ eV (90% CL)
- Unblinding in < 2 weeks in Munich

Final sensitivity

- $m_\nu < 0.2 - 0.3$ eV (90% CL)



Historical context and outlook

1st and 2nd campaign combined limit:

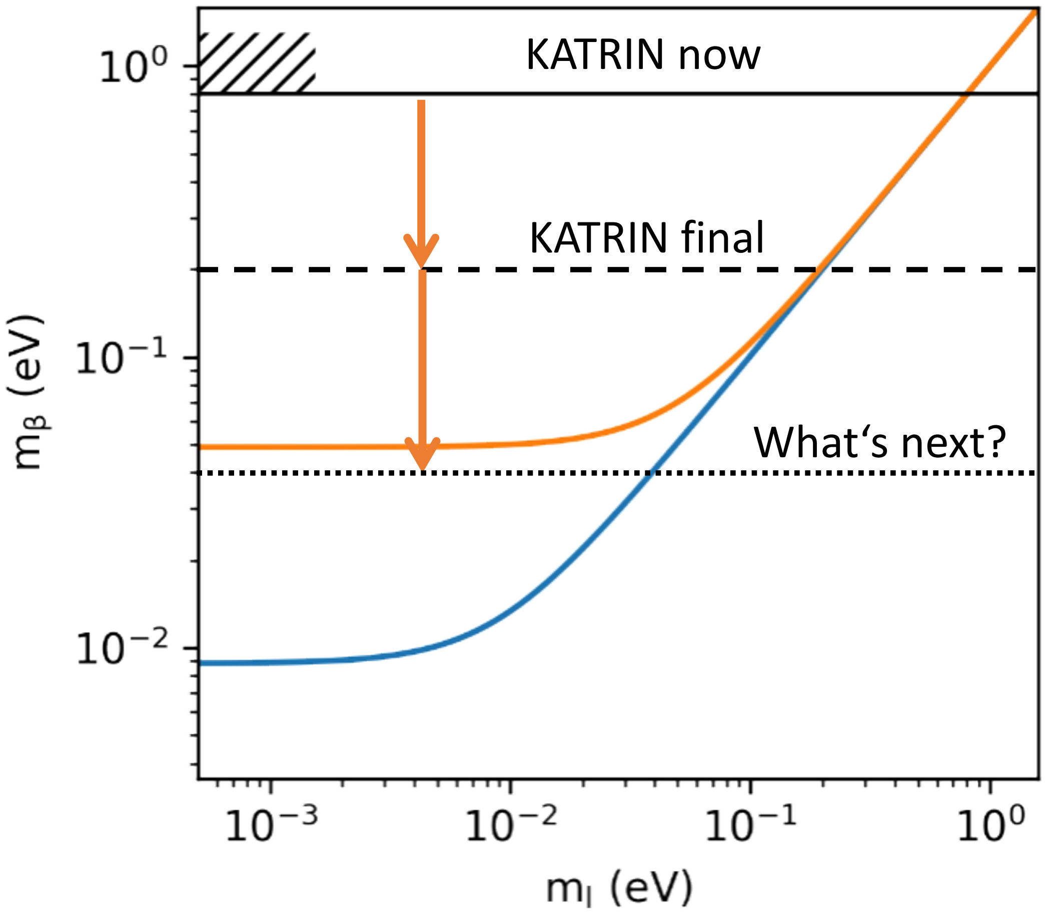
- $m_\nu < 0.8$ eV (90% CL)
- first direct neutrino-mass experiment to reach sub-eV sensitivity and limit

First five campaigns

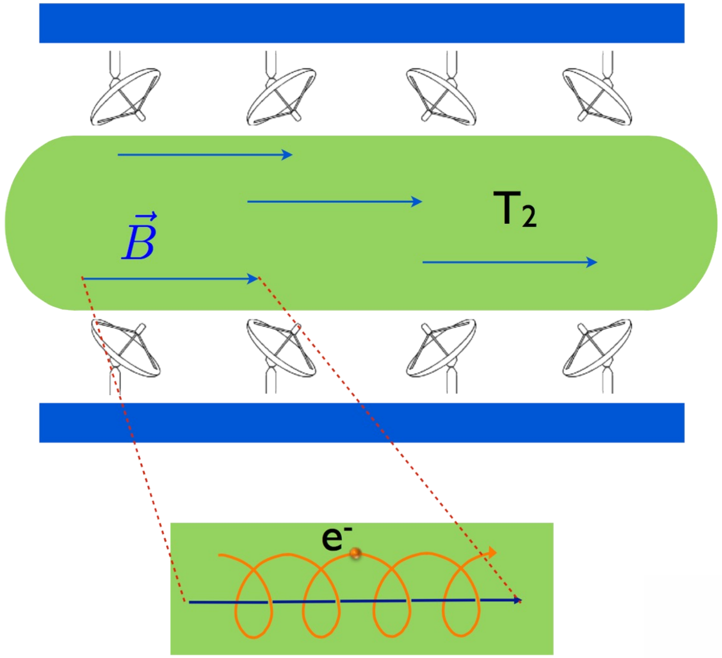
- Analysis performed with NN
- Sensitivity of $m_\nu < 0.5$ eV (90% CL)
- Unblinding in < 2 weeks in Munich

Final sensitivity

- $m_\nu < 0.2 - 0.3$ eV (90% CL)



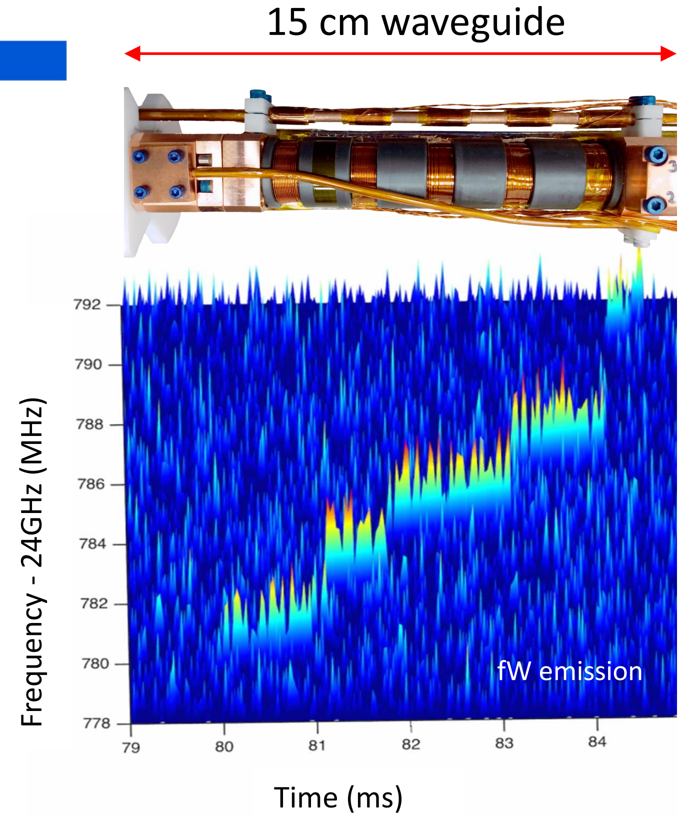
Beyond KATRIN



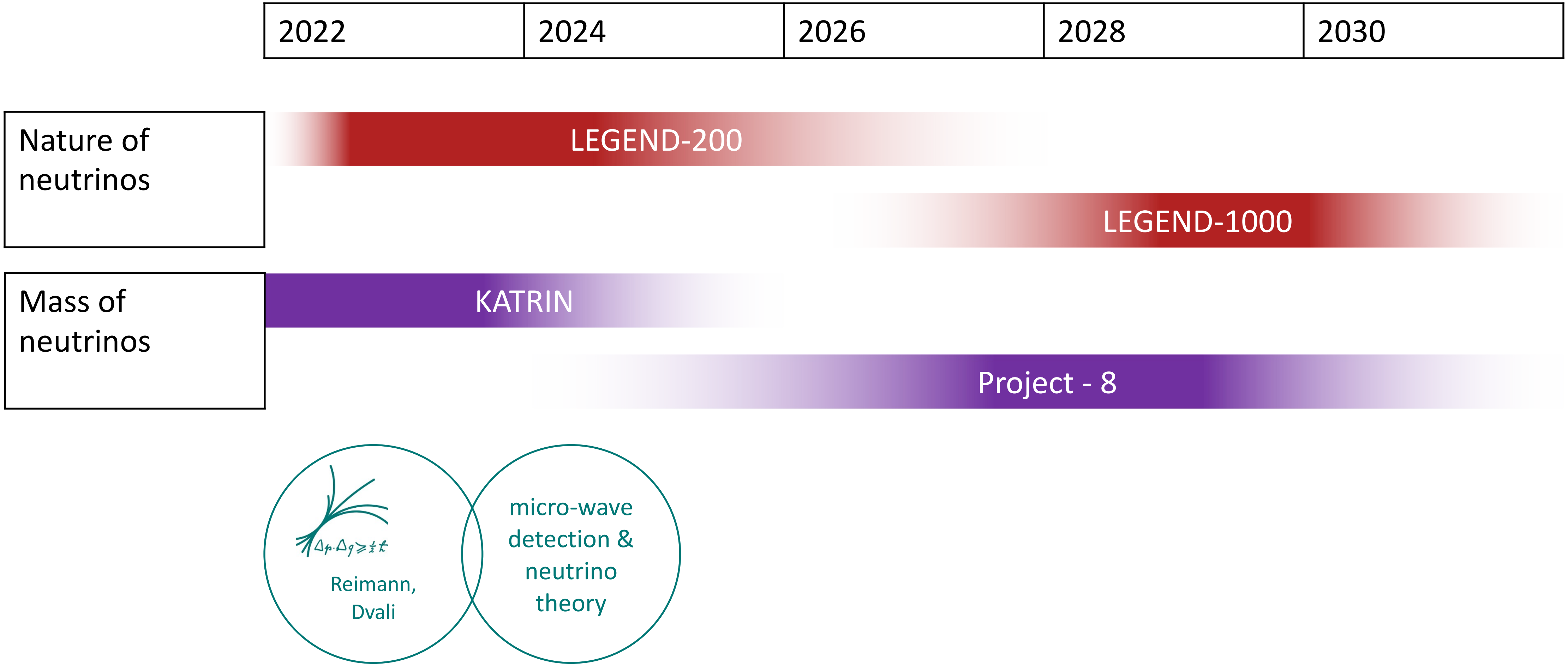
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$$

- Cyclotron Emission Radiation Spectroscopy (CRES)
  - ✓ eV-scale differential measurement
  - ✓ „source = detector“ concept
- CRES technology demonstrated by Project-8 experiment
  Phys. Rev. Lett. 114, 1162501 (2015)
  J. Phys. G44 (2017) no.5, 054004
- Ultimate goal: 40 meV sensitivity
  Phys. Rev. C 103, No.6. (2021)

- Potentially strong contribution from MPP through microwave-detection expertise (MadMax)



Timeline & Connections



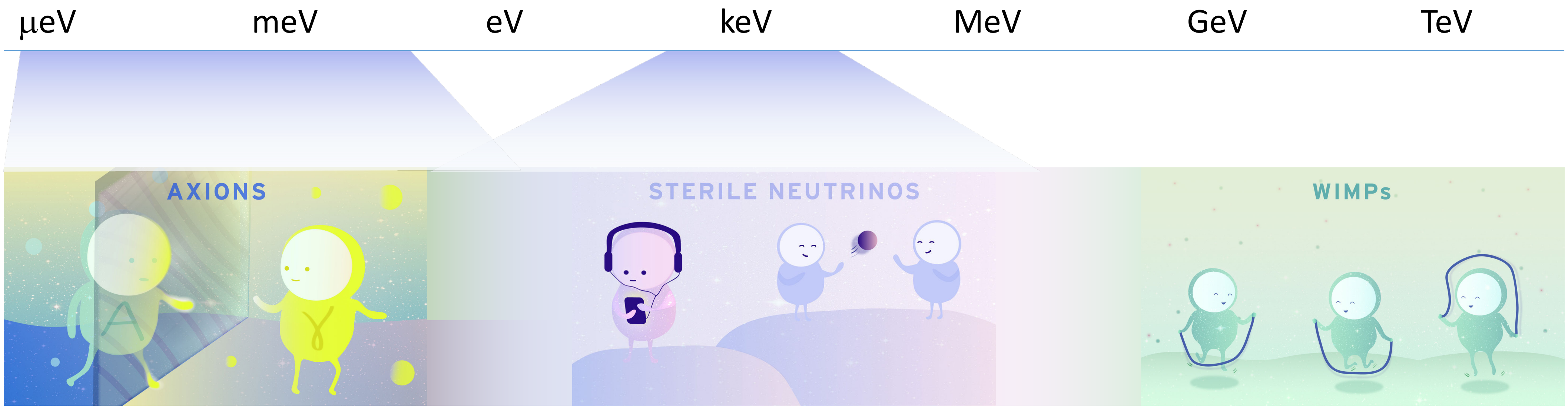
Open questions

Are neutrinos their own antiparticle ?

What is the mass of neutrinos ?

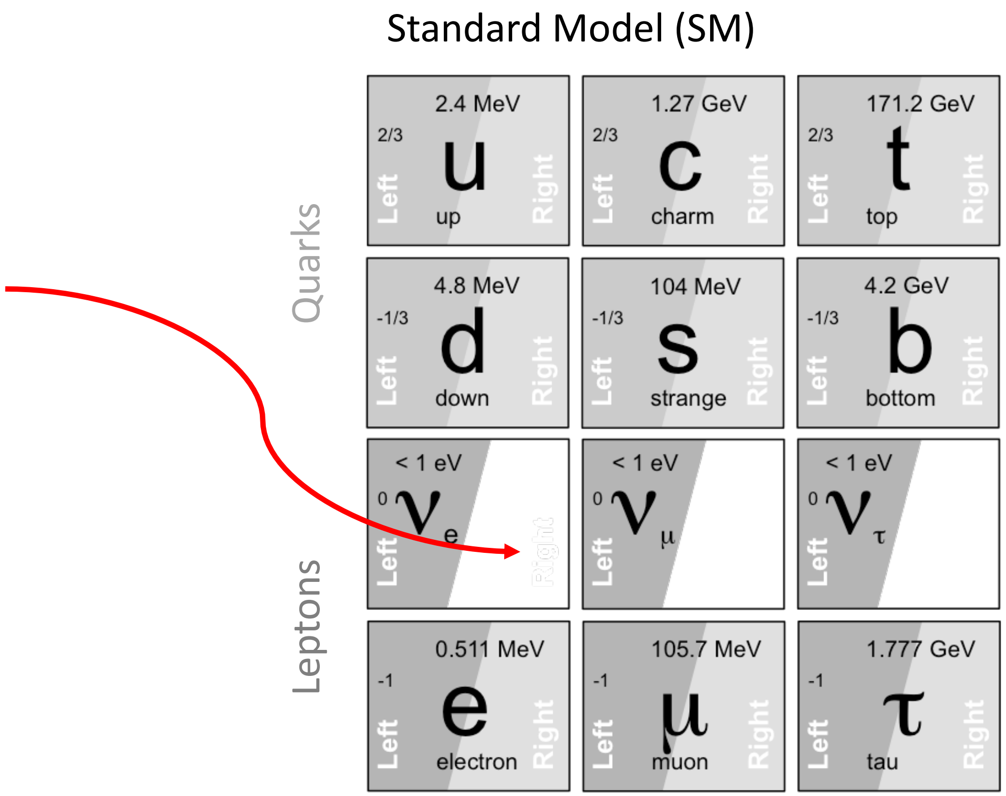
What is the nature of dark matter ?

Dark Matter Candidates



Sterile Neutrinos

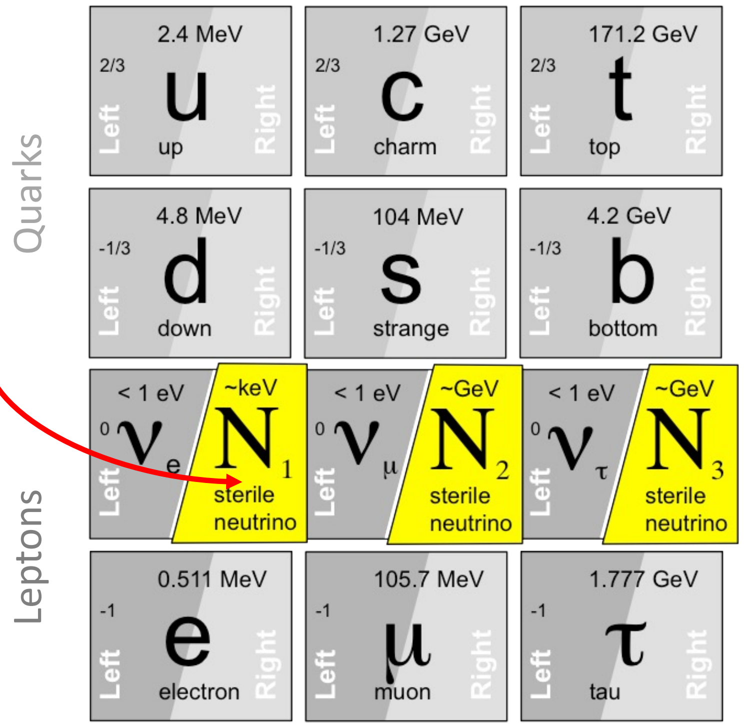
No right-handed neutrino in the SM



Sterile Neutrinos

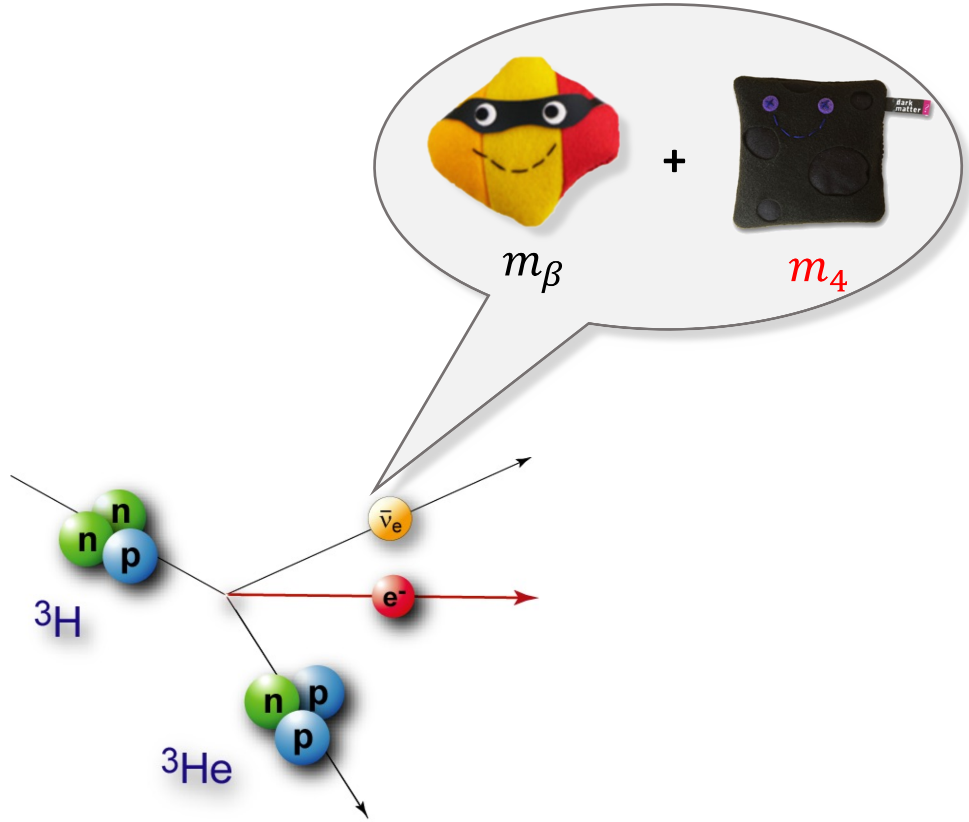
Minimal Neutrino Standard Model

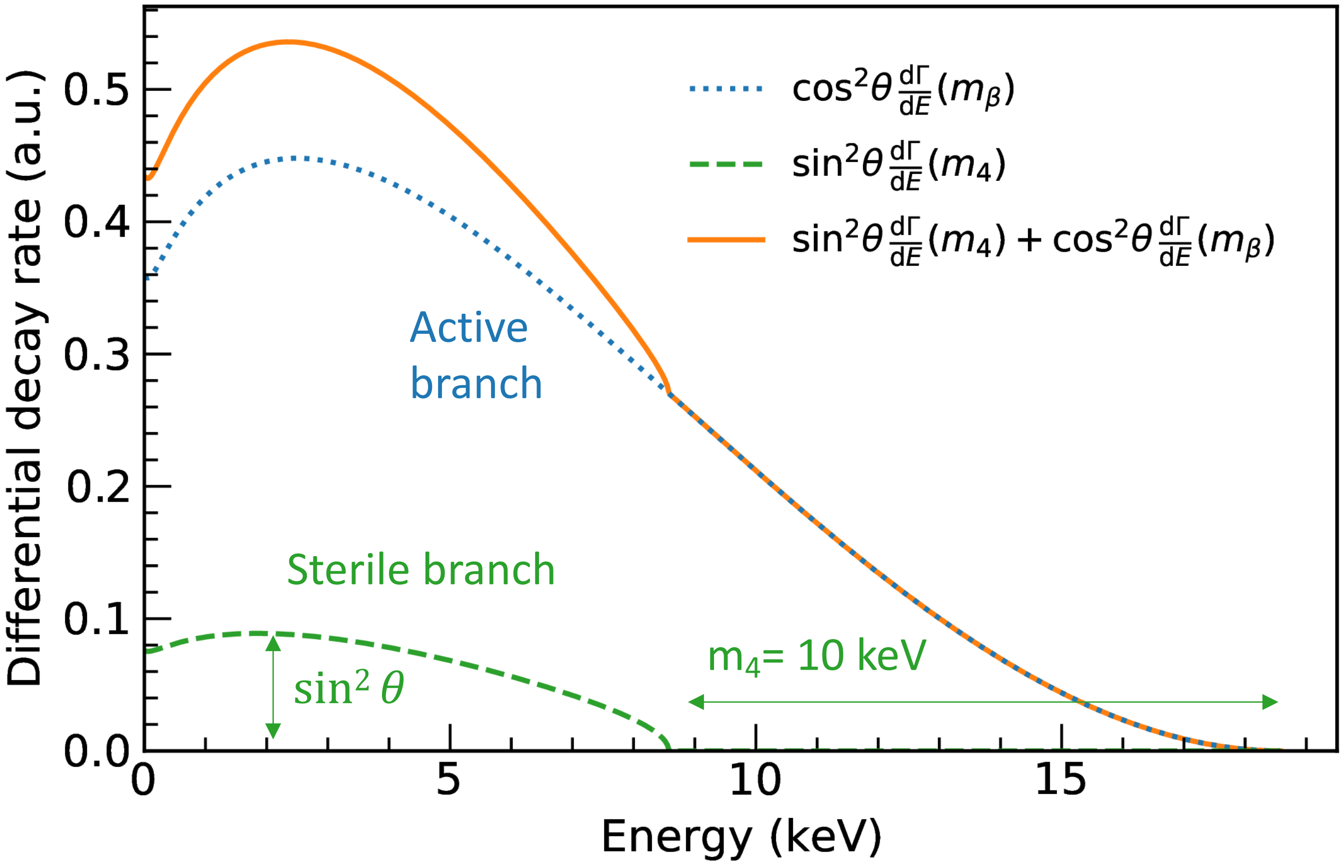
Sterile neutrinos in the keV mass range are dark matter candidates



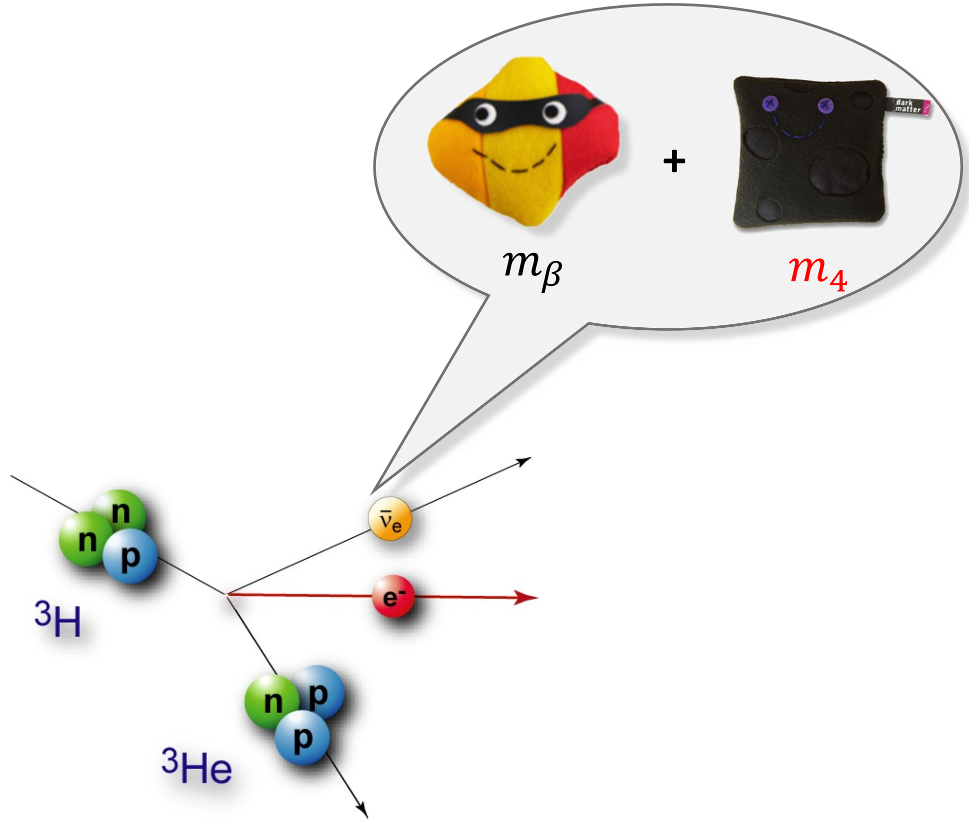
L. Canetti, M. Drewes, and M. Shaposhnikov, PRL **110** 061801 (2013)

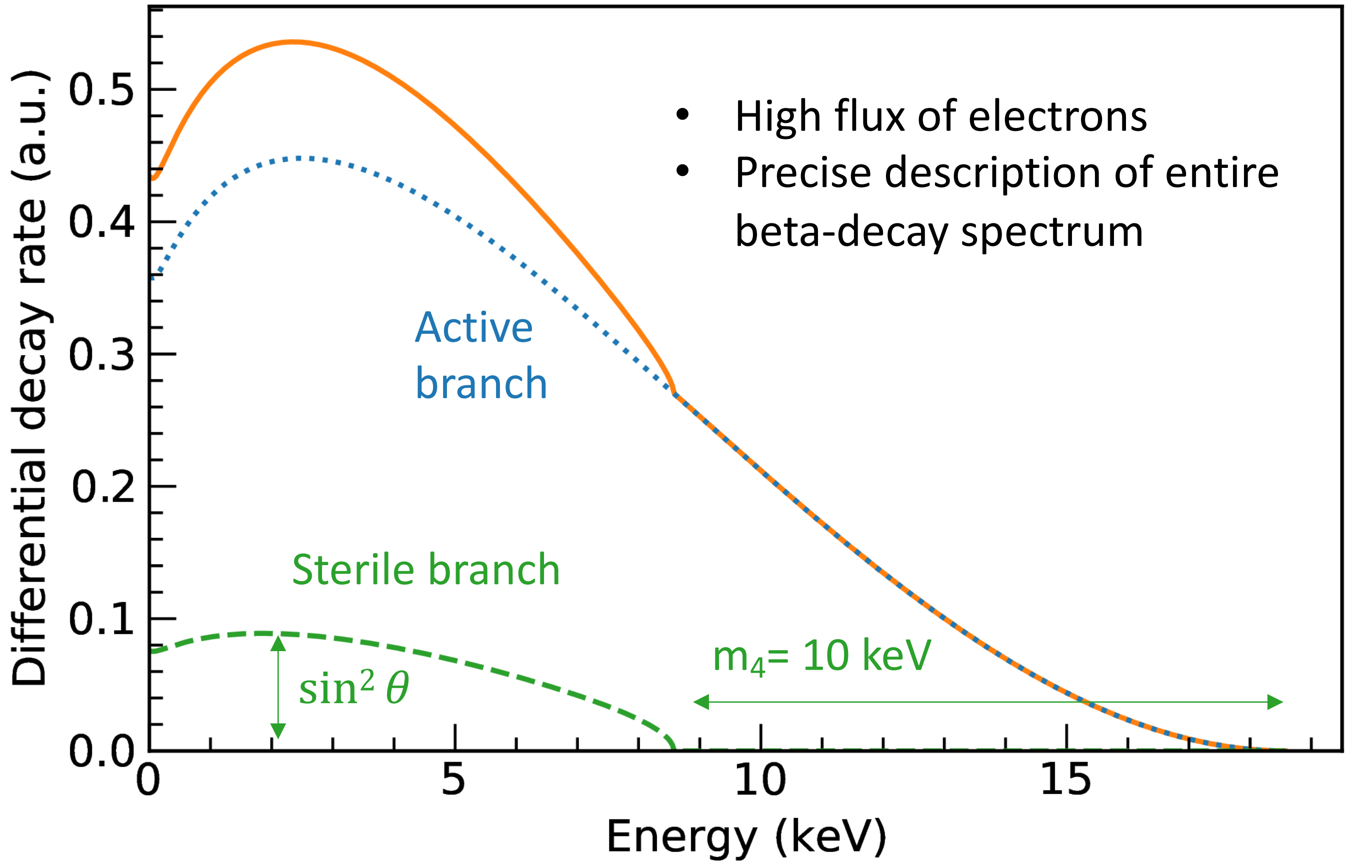
Signature in beta decays





The challenge



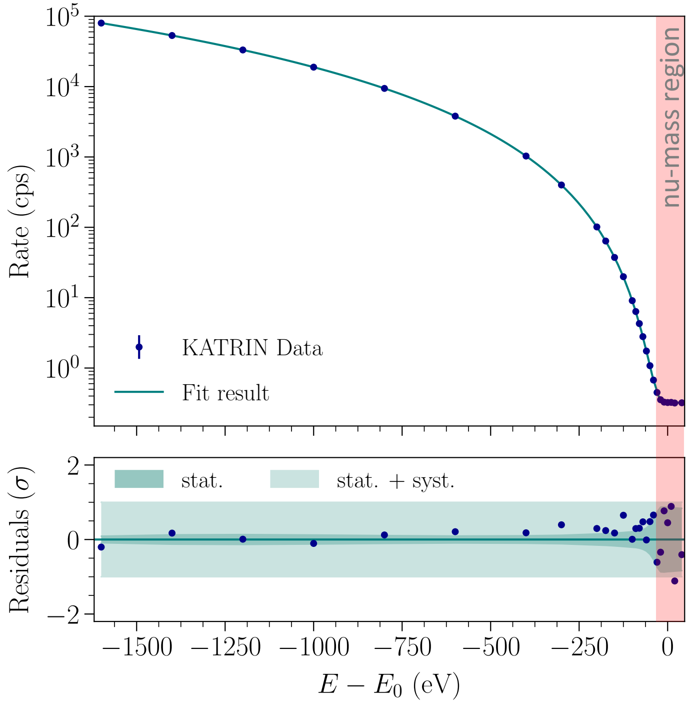


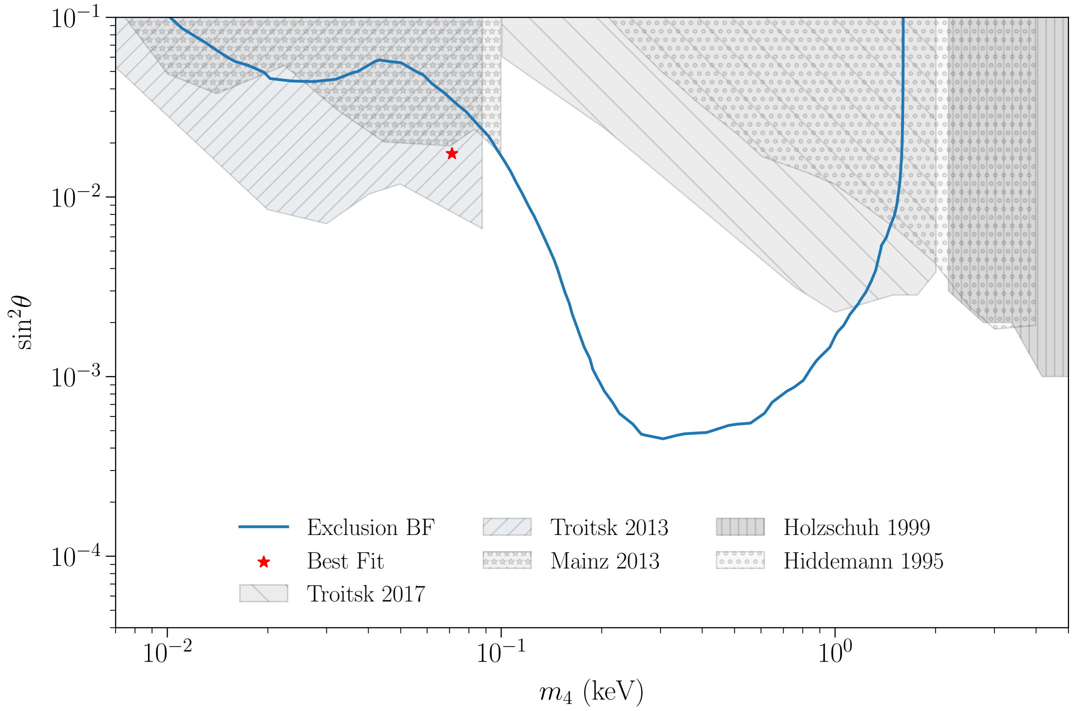
A first deep look

Low-activity (0.5% of nominal) KATRIN run, down to 1.6 keV below E_0 with (10^9 electrons)

✓ excellent agreement of model and data (p-value = 0.6)

✓ improved sensitivity to $\sin^2\theta < 10^{-3}$ @ $m_4 = 0.4$ keV (arxiv 2207.06337, corresponding author S. Mertens)



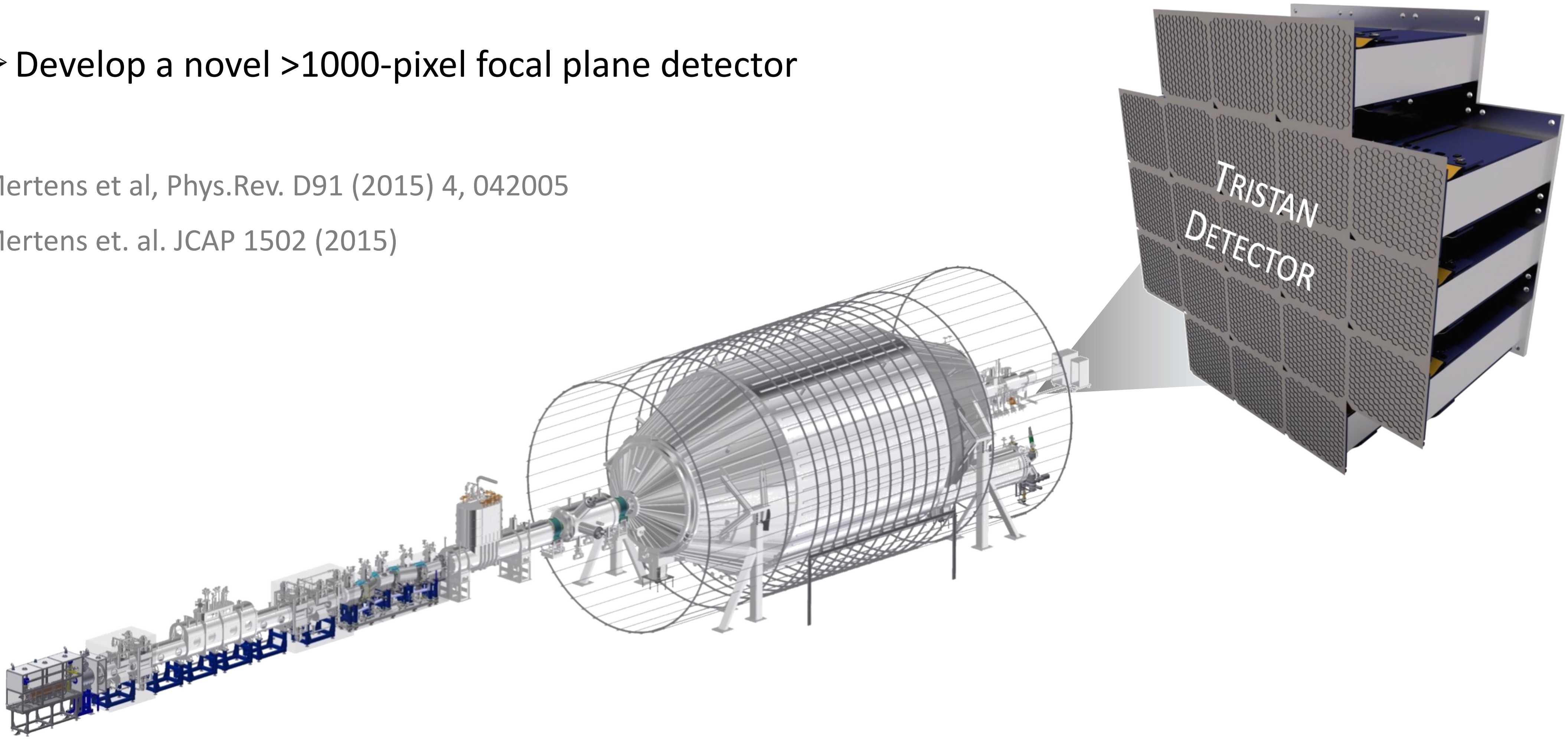


Full spectrum measurement

- ➢ Develop a novel >1000-pixel focal plane detector

Mertens et al, Phys.Rev. D91 (2015) 4, 042005

Mertens et. al. JCAP 1502 (2015)



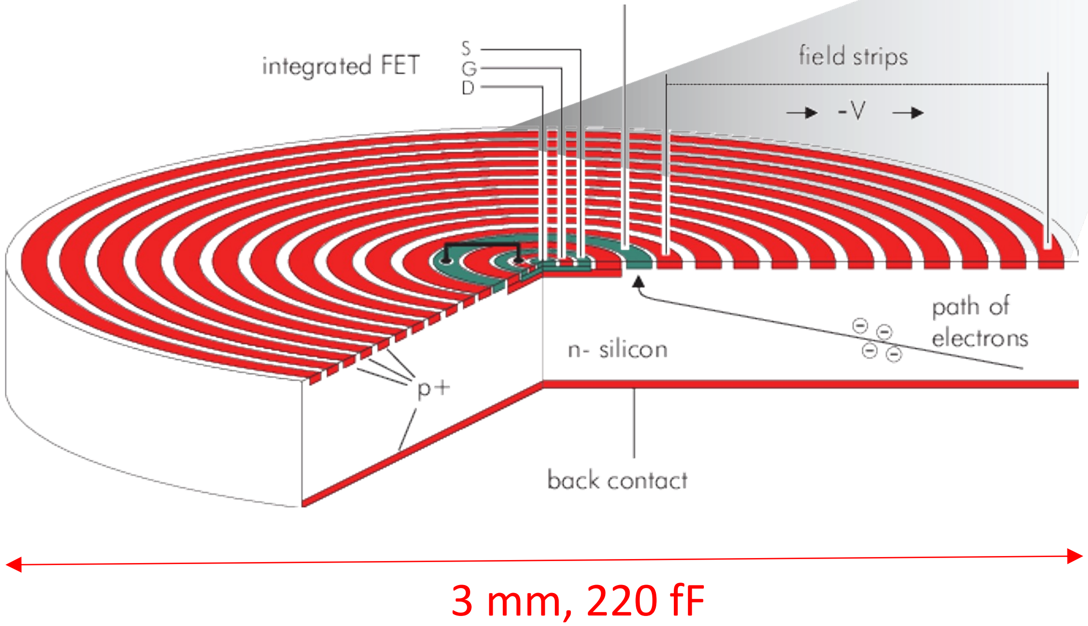
TRISTAN Detector

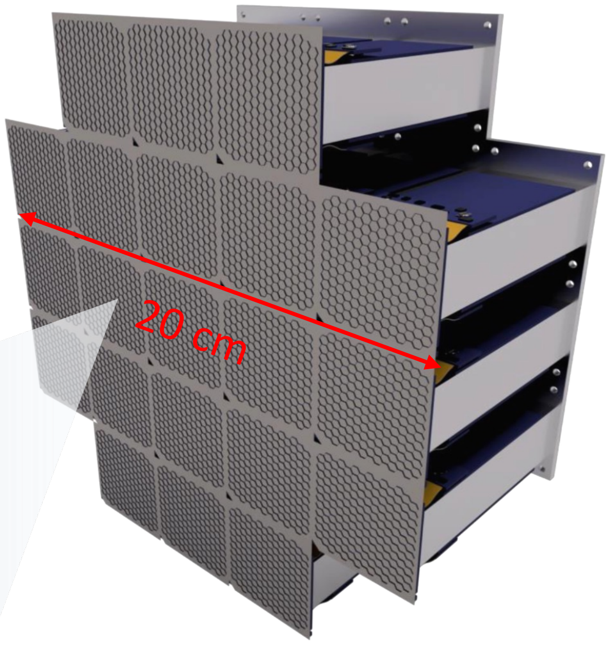
Silicon drift detector (SDD) with > 1000 pixels

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

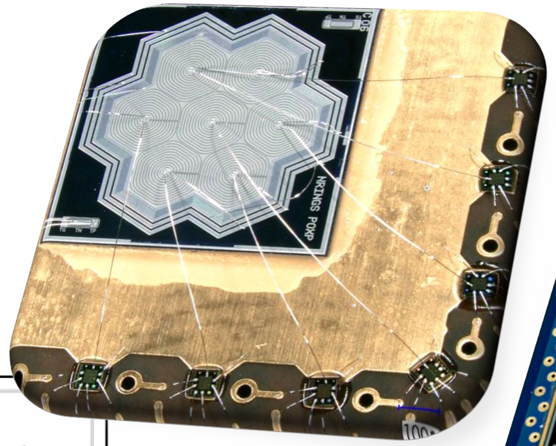
✓ Excellent energy resolution (300 eV @ 20 keV) → diff. measurement

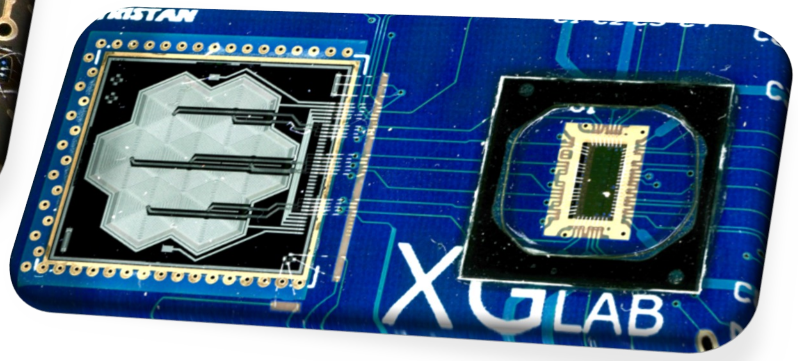
✓ Integrated read-out → focal plane design



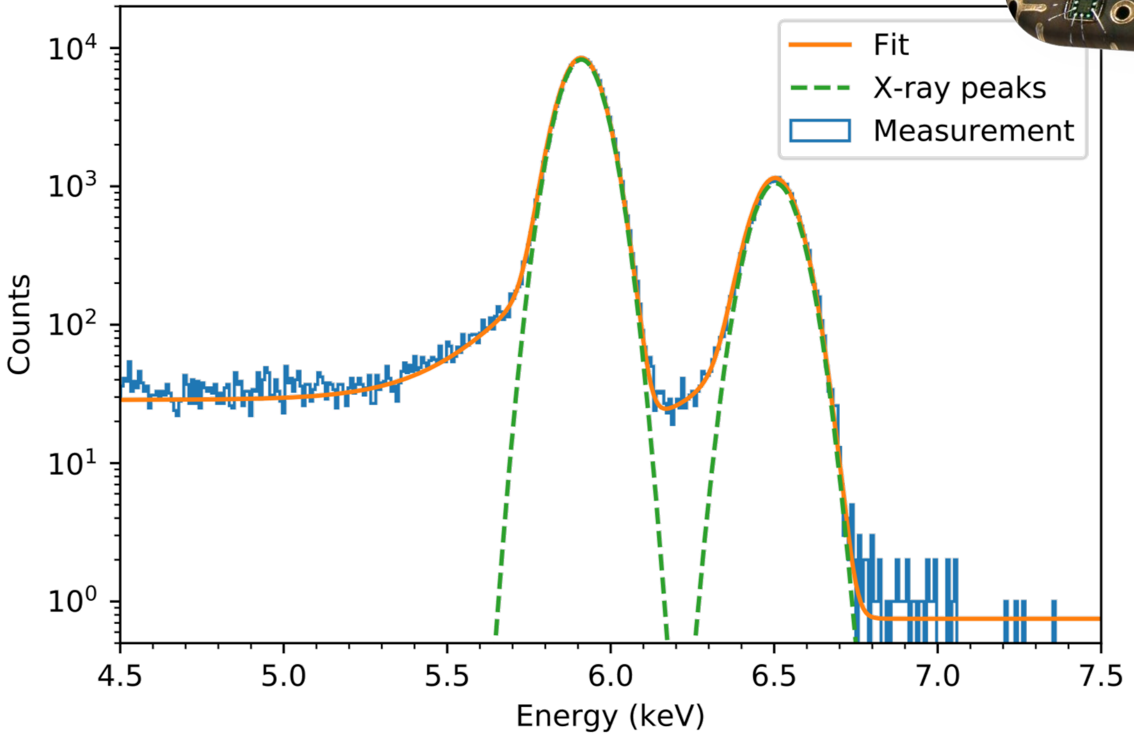


TRISTAN Detector





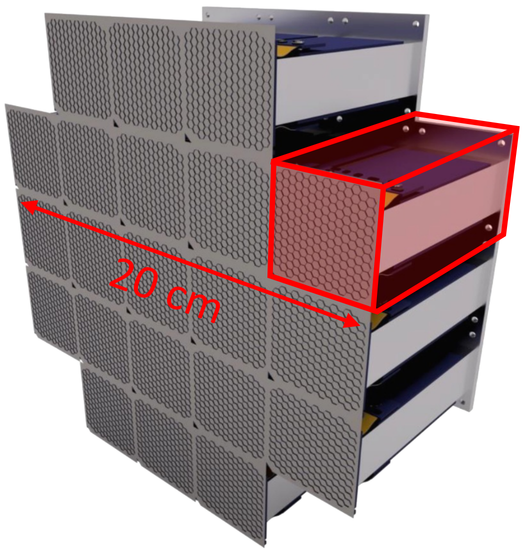
130 eV (FWHM) @ 6 keV @ 1 μs shaping

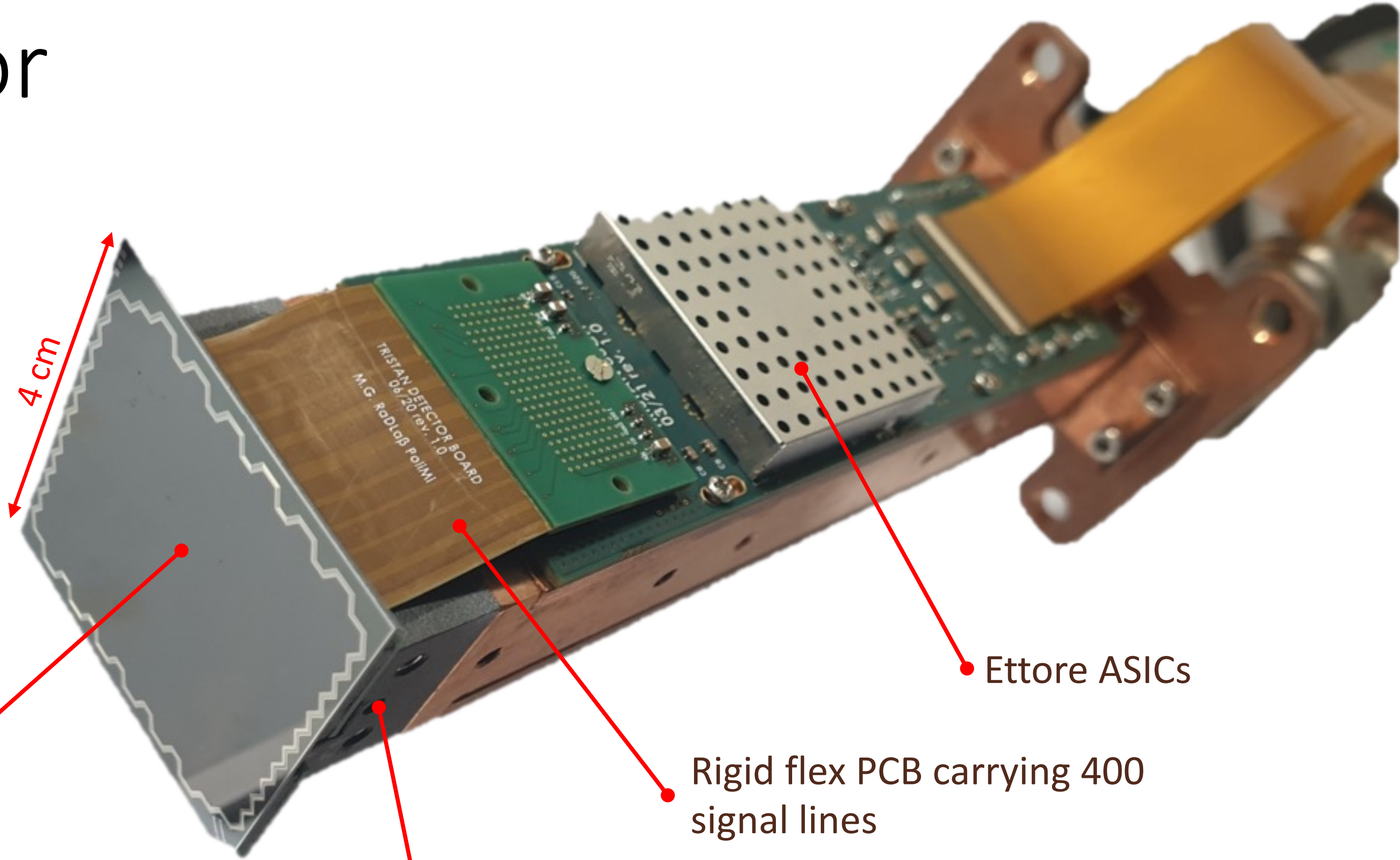


- ✓ Multiple iterations and optimizations
- ✓ Detailed characterization with x-rays and electrons
- ✓ Excellent performance (resolution, noise, linearity)

S. Mertens et al, J. Phys. G46 (2019)
S. Mertens et al, J. Phys. G48 (2020)
M. Gugiatti et al, NIM-A 979 (2020)
M. Biassoni et al, Eur. Phys. J. Plus 136, 125 (2021)
P. King et al JINST 16 T07007 (2021)

TRISTAN Detector





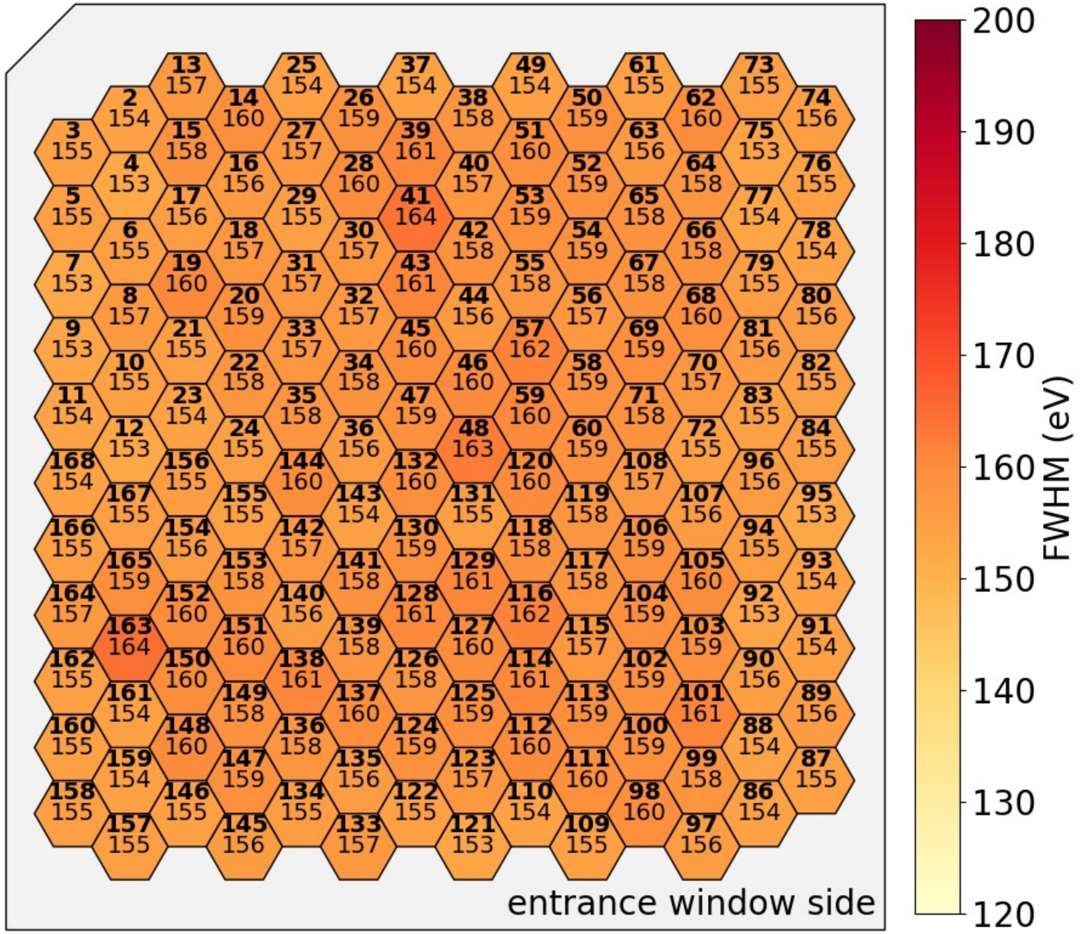
166-pixel SDD with integrated JFET

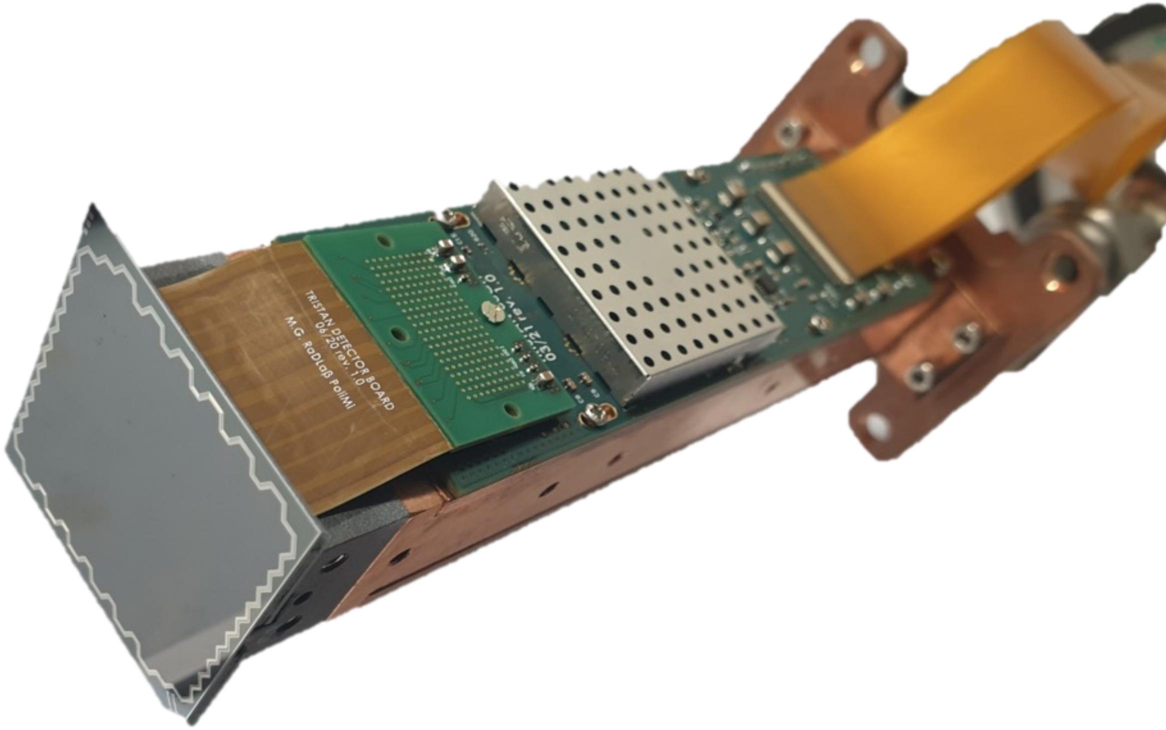
Silicon carbide (CeSic) cooling link on copper cooling block

Rigid flex PCB carrying 400 signal lines

Ettore ASICs

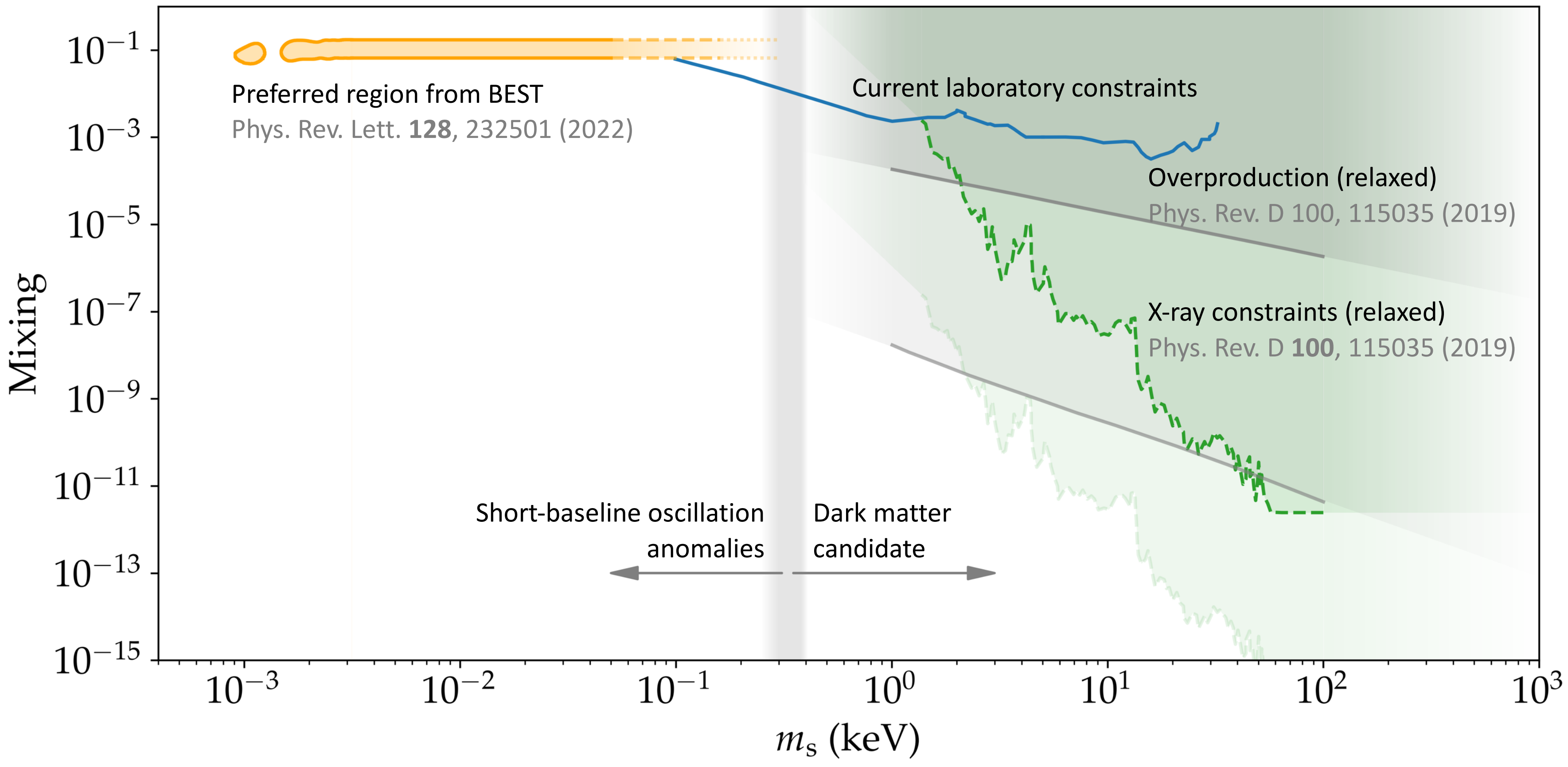
TRISTAN Detector



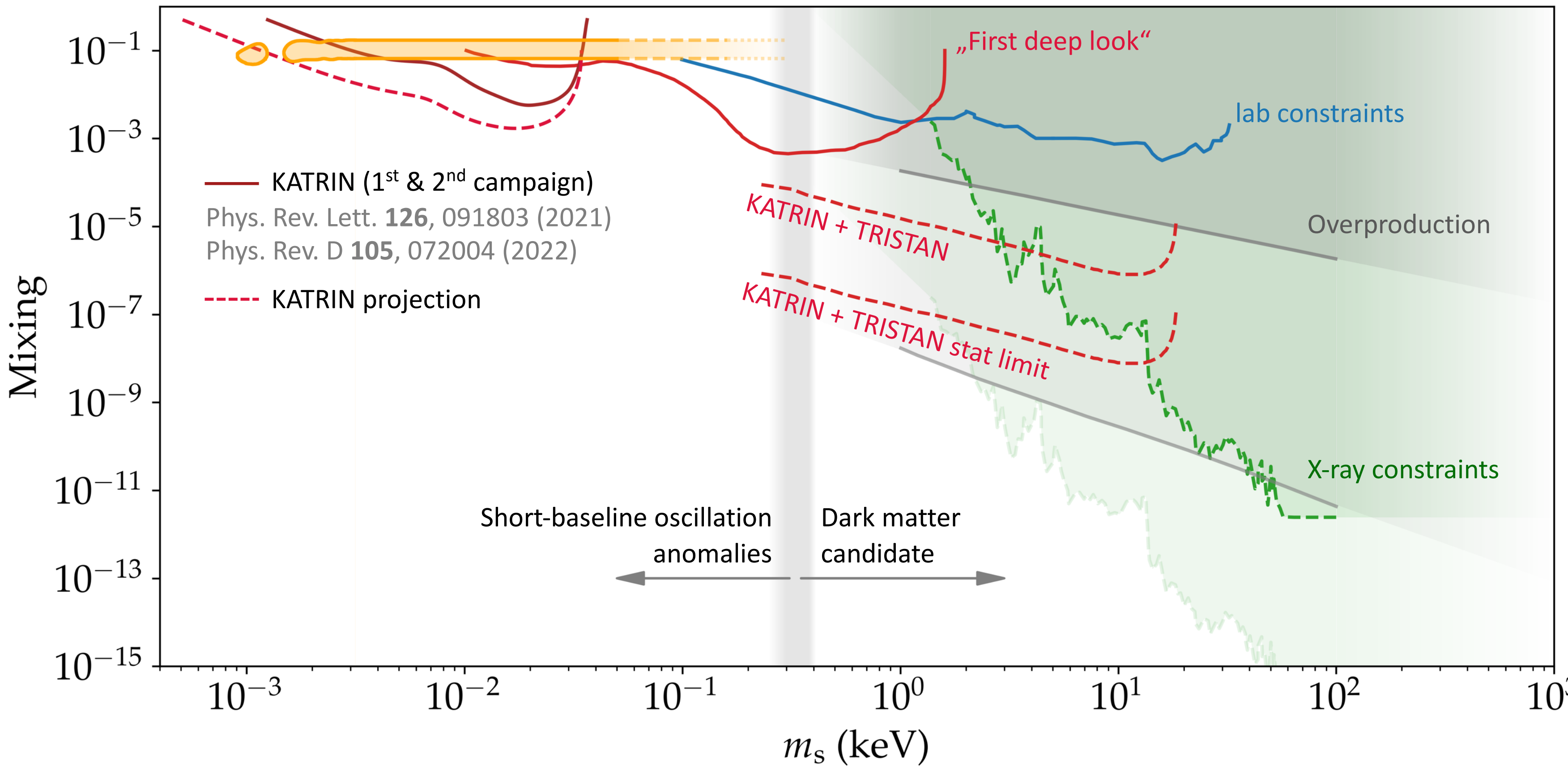


- ✓ Largest monolithic SDD ever operated ☺
- ✓ All pixels working
- ✓ Average resolution of 160 eV (FWHM) at 6 keV
- ✓ Homogeneous performance
- ✓ Integration in KATRIN
  1 module (2022), 9 modules (2024/2025)

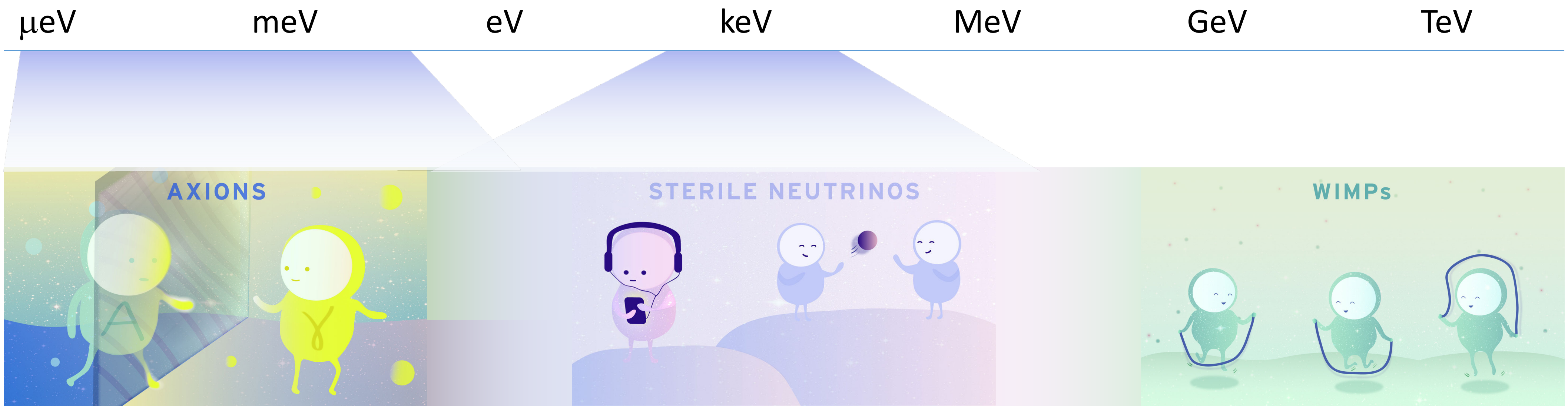
KATRIN/TRISTAN sensitivity to steriles



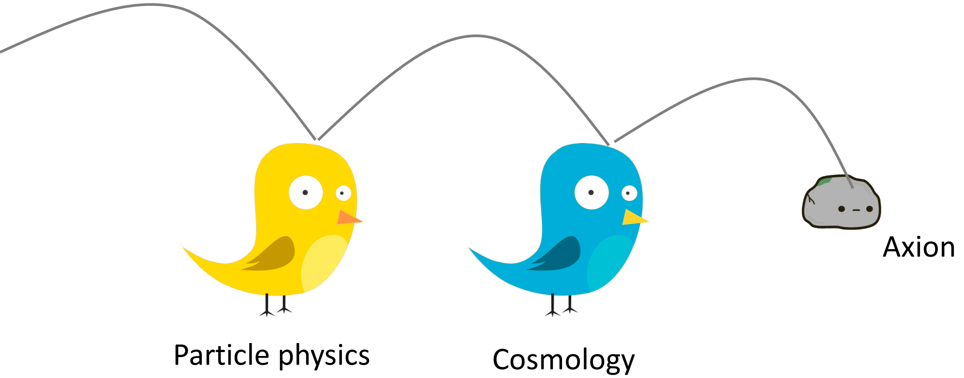
KATRIN+TRISTAN sensitivity to steriles



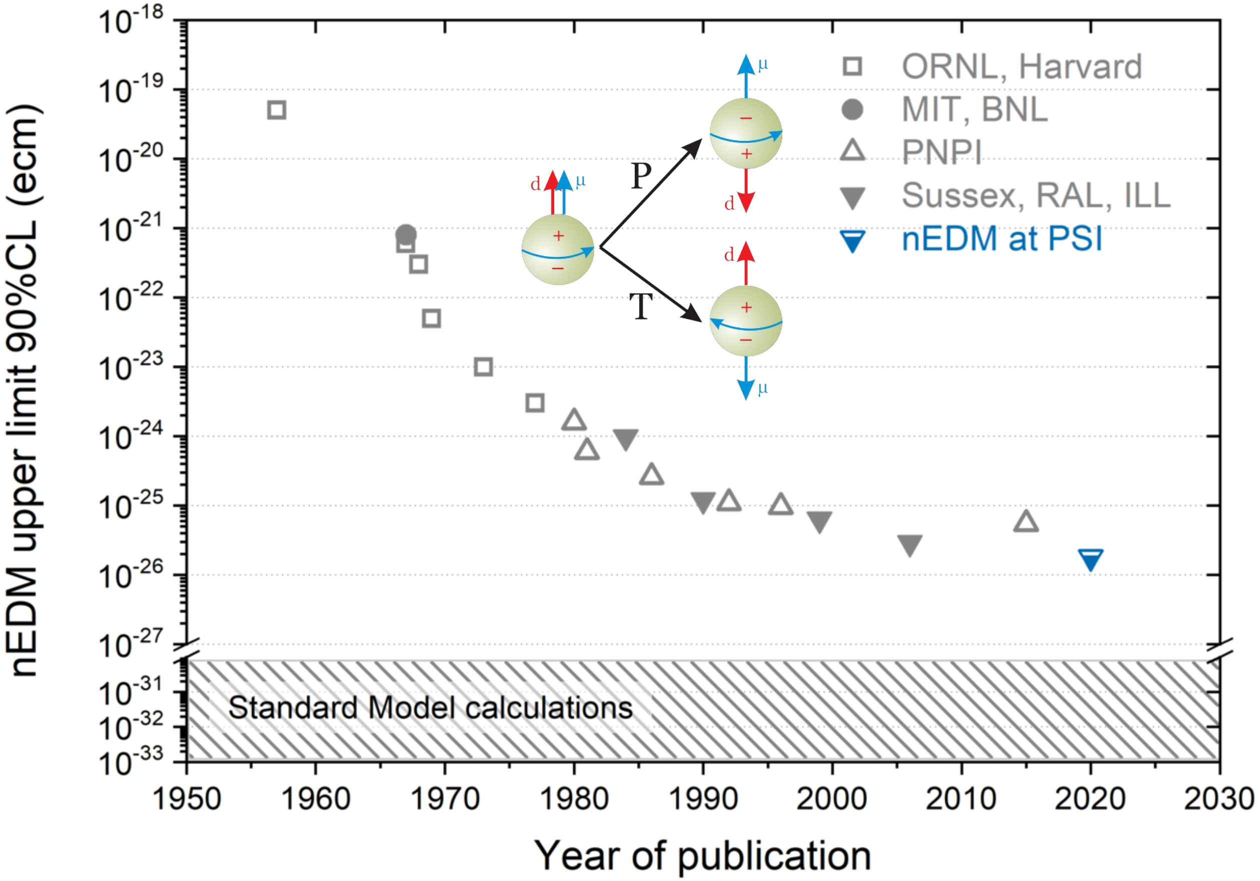
Dark Matter Candidates



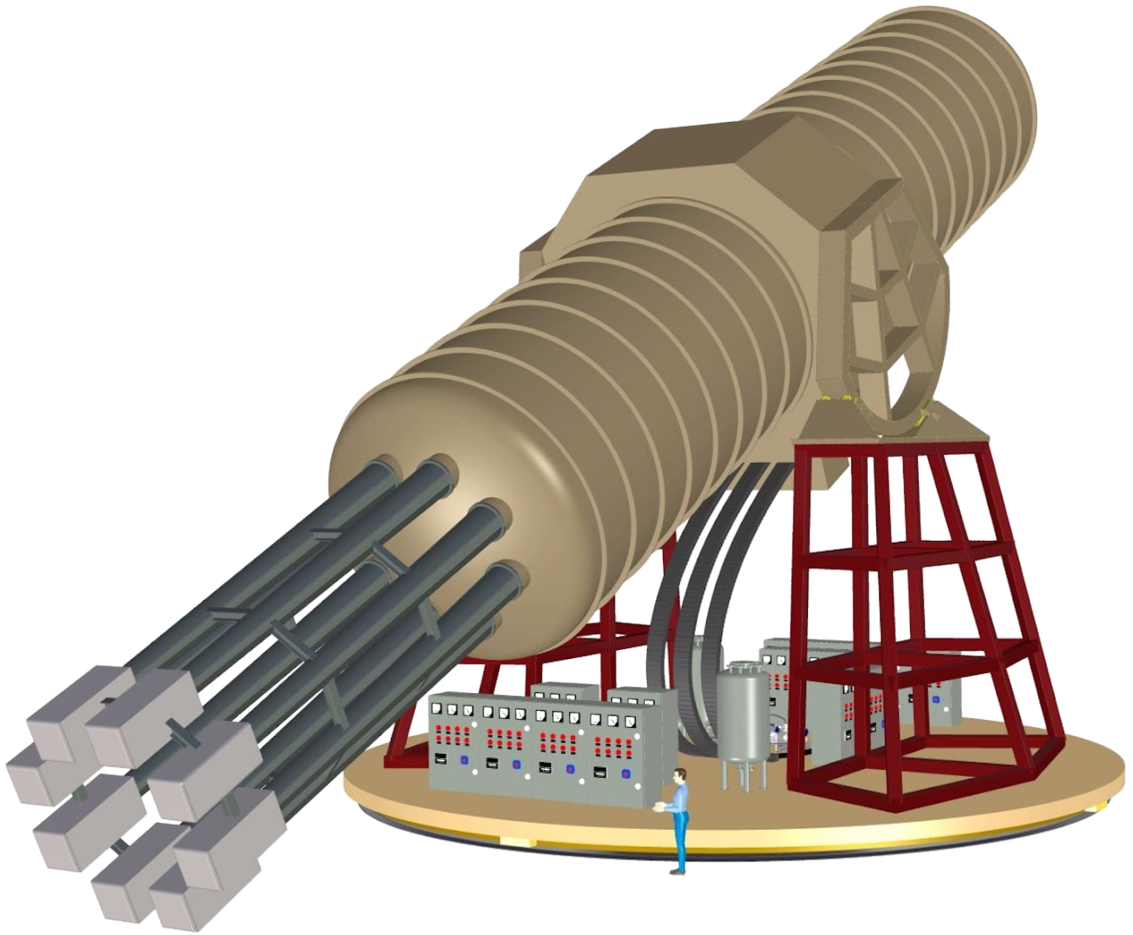
Axions

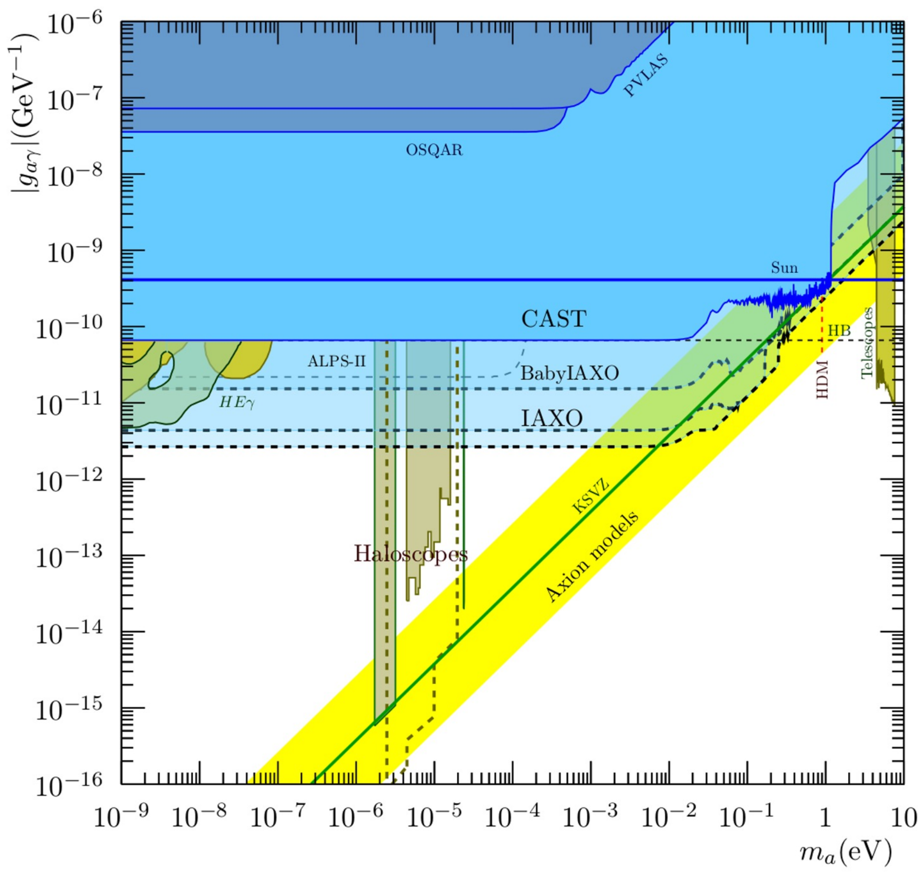


- ✓ Solution to the strong CP problem
  $\theta_{QCD}\,\tilde{G}^{\mu\nu}G_{\mu\nu}$
- ✓ Promising dark matter candidate

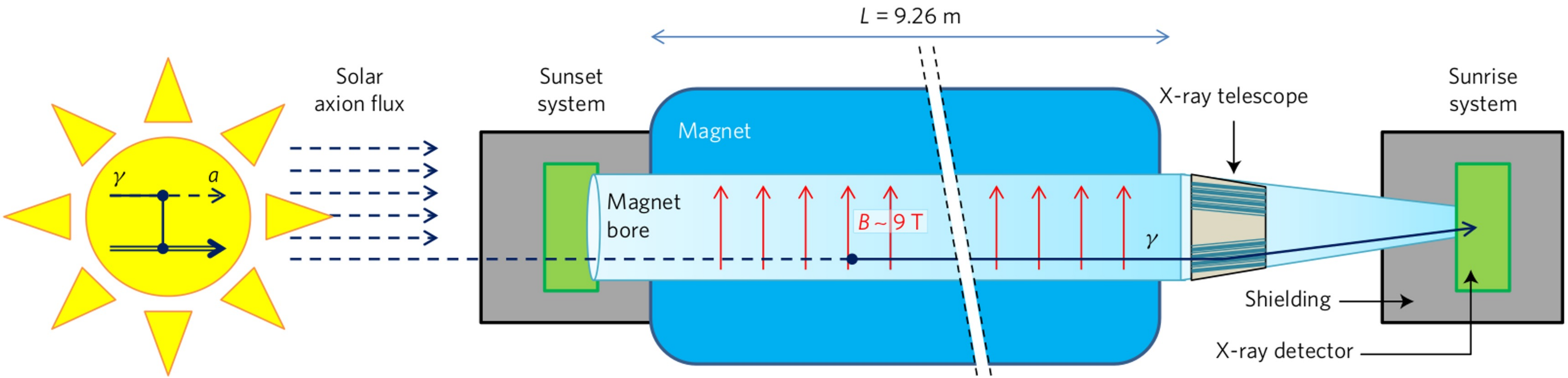


IAXO next-generation solar axion search

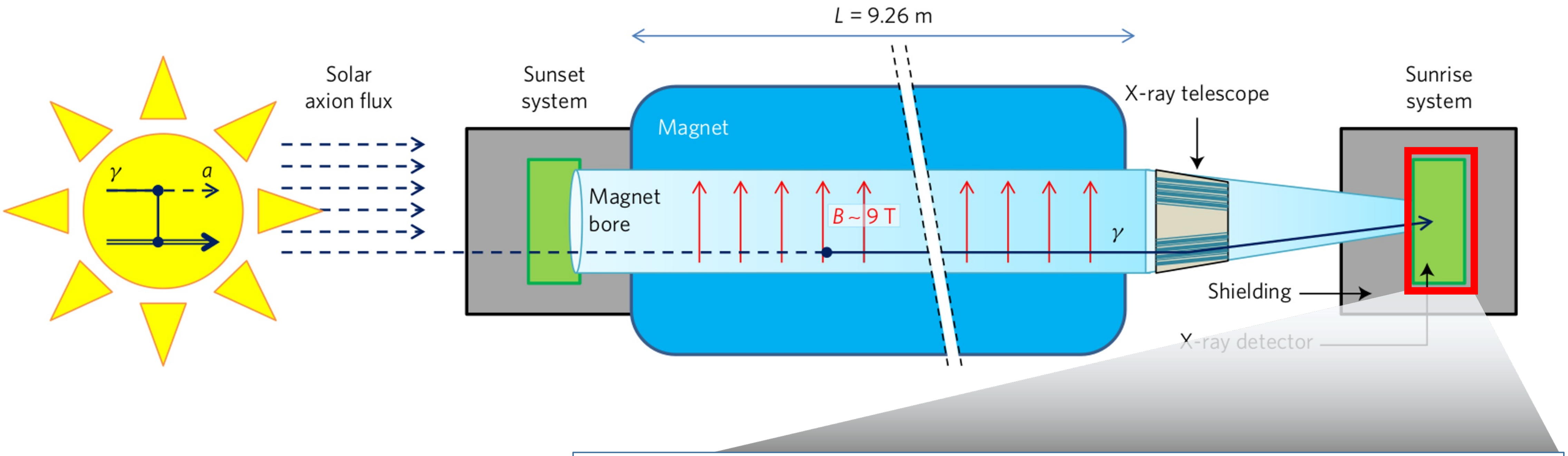




IAXO: working principle



IAXO: the challenge



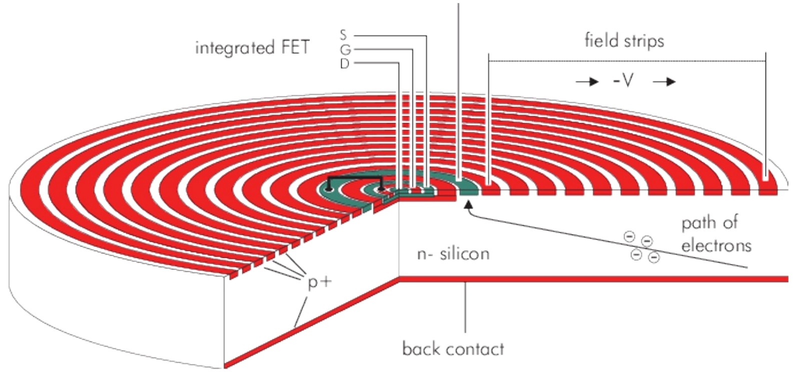
- Ultra-low background x-ray detector: **< 10^{-7} cts/keV/cm^2/s**
- Comparable to deep-underground detectors (e.g. CRESST)
- Never achieved at shallow depth

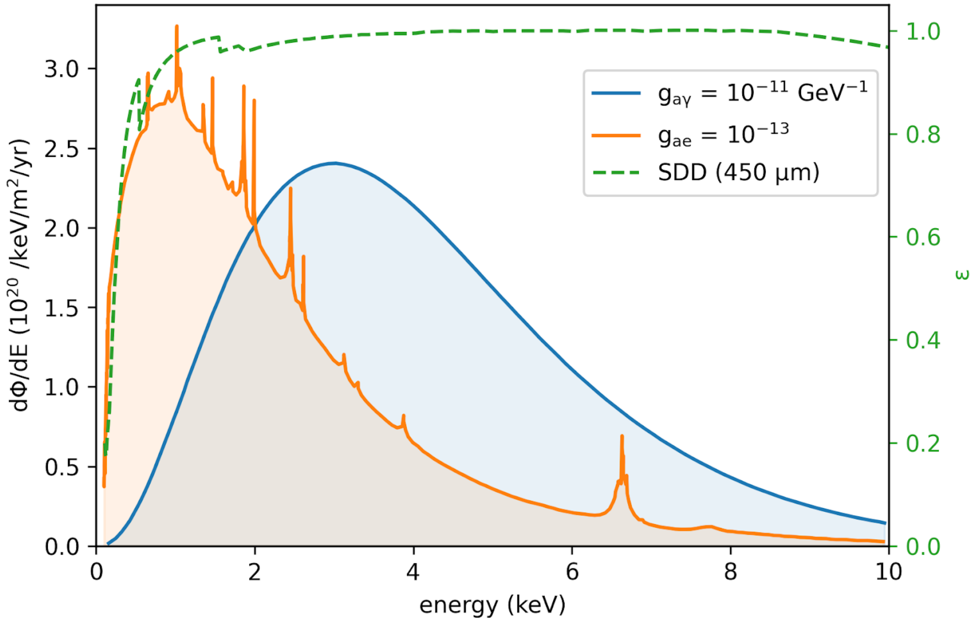
Our idea: low background SDD system

- ✓ Designed for x-ray detection
- ✓ Almost 100% efficiency in interesting energy region
- ✓ Excellent energy resolution (150 eV @ 1 – 10 keV)
- ✓ Low energy threshold (0.5 eV)
- ✓ No/little cooling, flexible footprint and pixel number

- ➢ **technical implementation feasible**
- ➢ **improve the physics case of IAXO**

- ○ **Can we reach the background goal ?**

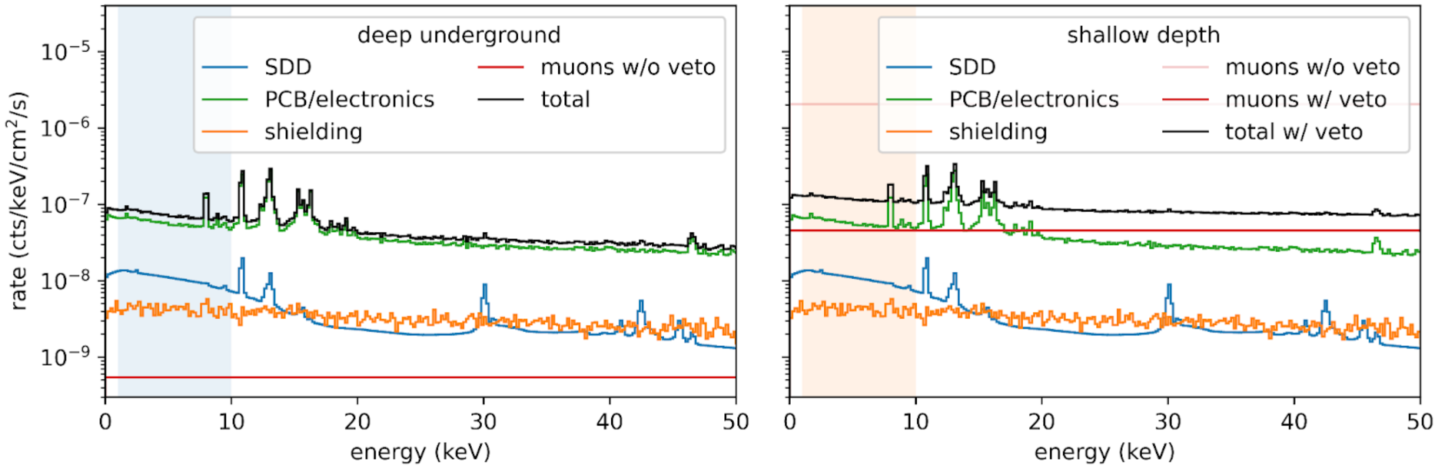


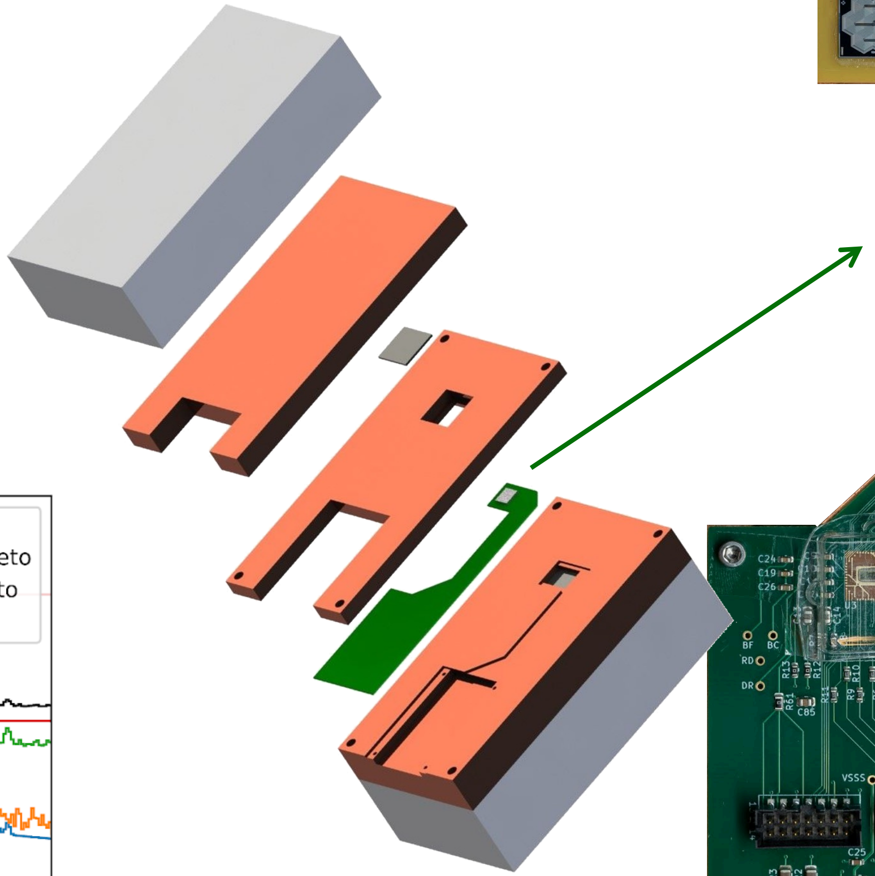


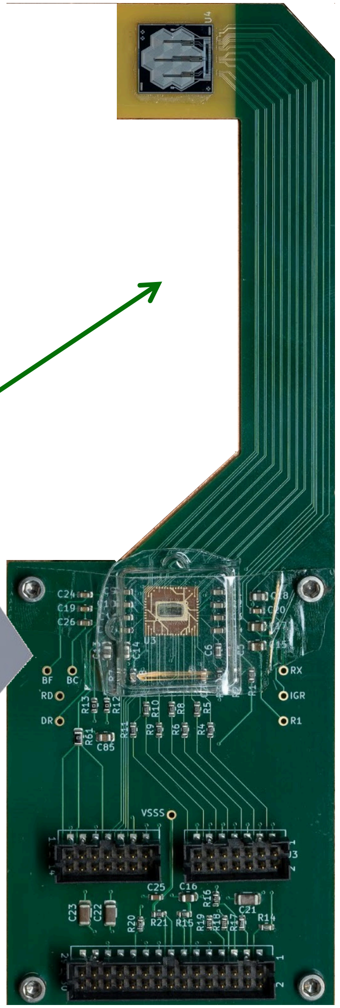
Background Demonstrator

- ✓ Design complete, assembly ongoing
- ✓ Operation at CanFranc underground laboratory and TUM shallow underground laboratory from September
- ✓ Very promising background projections

GEANT-4-based background projections



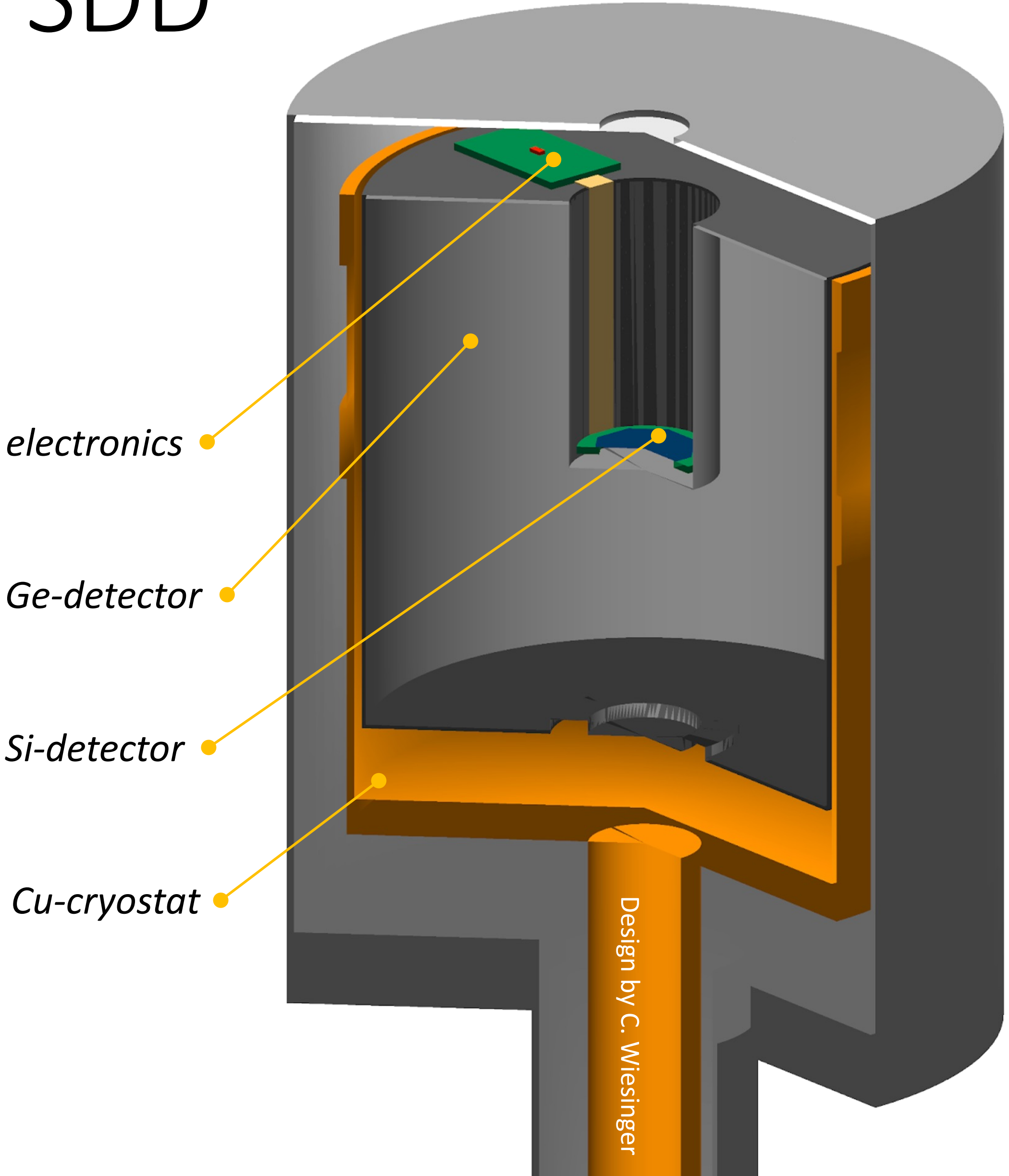




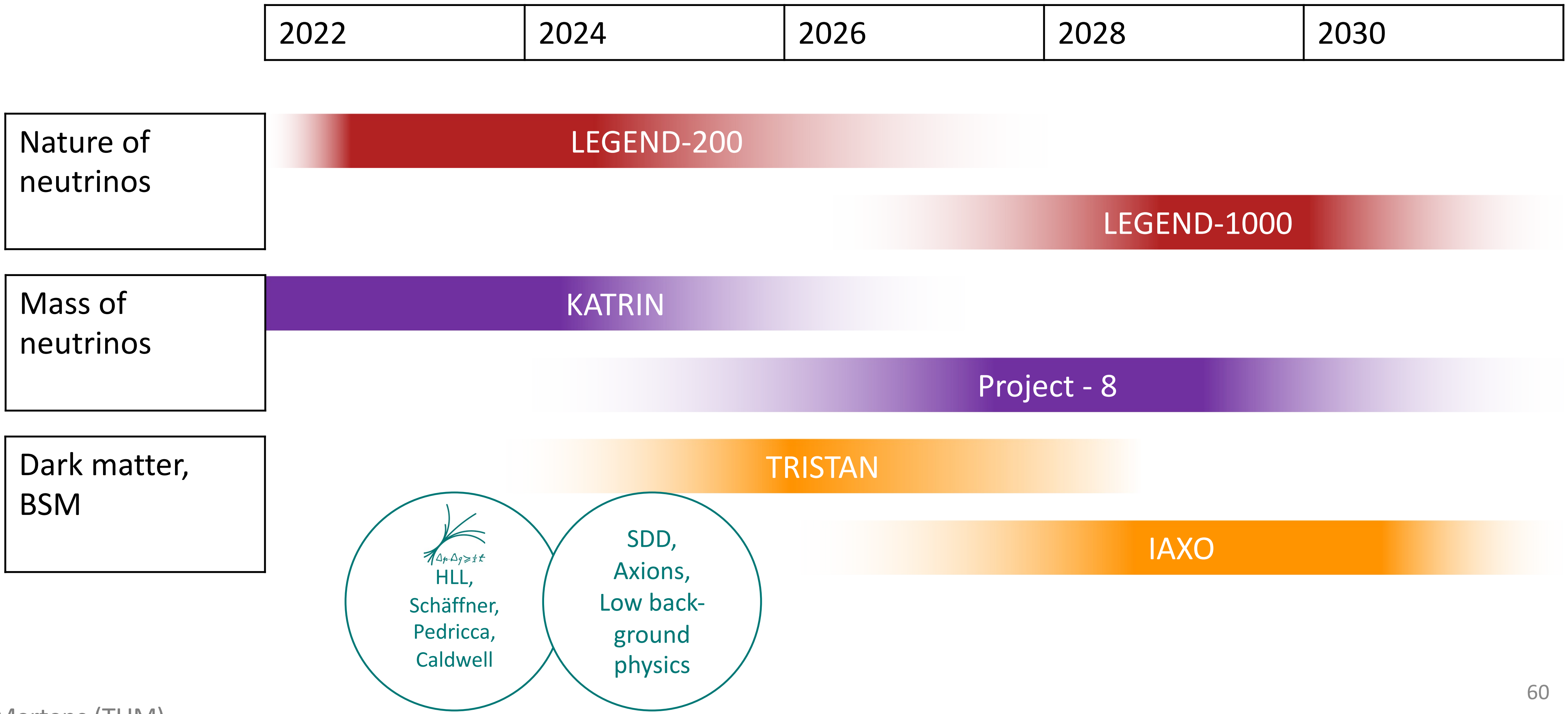
Ultimate low background SDD

- **Novel Active shield idel**
  - use deep-well Ge-detector as active shield for SDD system
  - combine expertise from TRISTAN and LEGEND
- **Passive shield**: dedicated for shallow-depth
  - scintillator plates
  - neutron shield: Pb/borated PE
- Projected bg-index: **10^{-9} cts/keV/cm^2/s**

Strong synergies with
K. Schäffner (Cosinus) and F. Pedricca (CRESST)



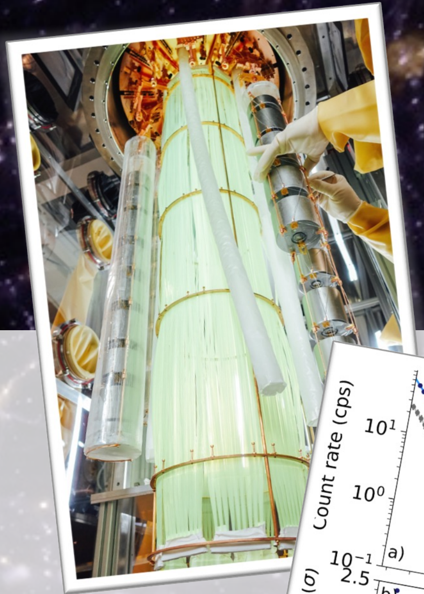
Timeline & Connections

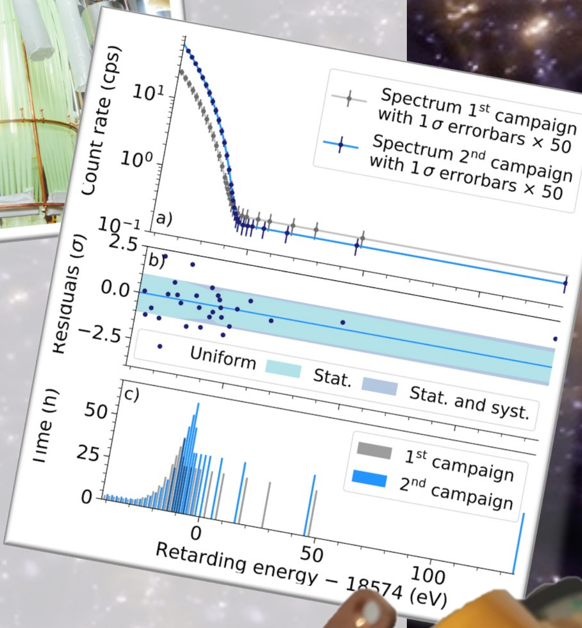


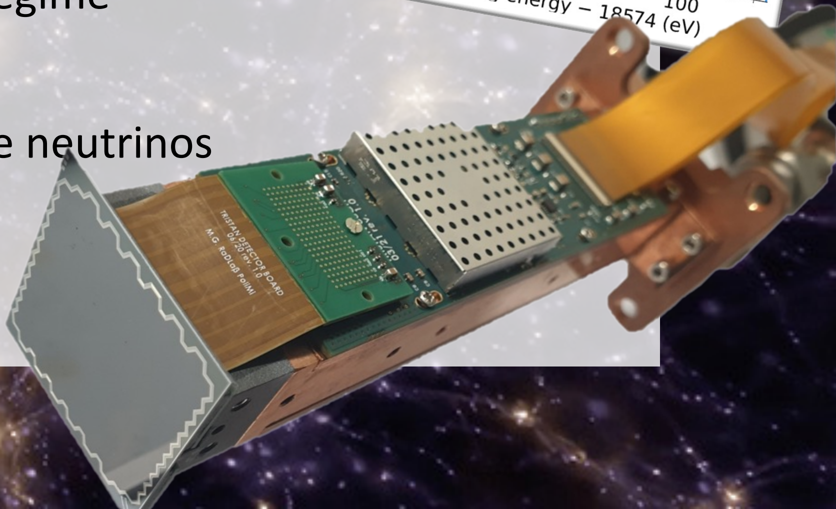
Conclusion

- Many exciting open questions ahead of us
- Search for $0\nu\beta\beta$
  - first detector strings of LEGEND-200 are operational,
  - promising R&D for ASIC-based read-out to reach ultimate discovery potential
- Direct measurement of the neutrino mass
  - first sub-eV kinematical limit on the neutrino mass with KATRIN
  - leading limits on relic neutrinos, eV-sterile neutrinos, Lorentz invariance violation
  - new concepts (a-la Project-8) to probe the hierarchical neutrino mass regime
- Dark matter search
  - finalized TRISTAN detector module: upgrade KATRIN to search for sterile neutrinos
  - new low-background SDD-detector for a solar axion search with IAXO

✓ Promising potential for discoveries in the coming years







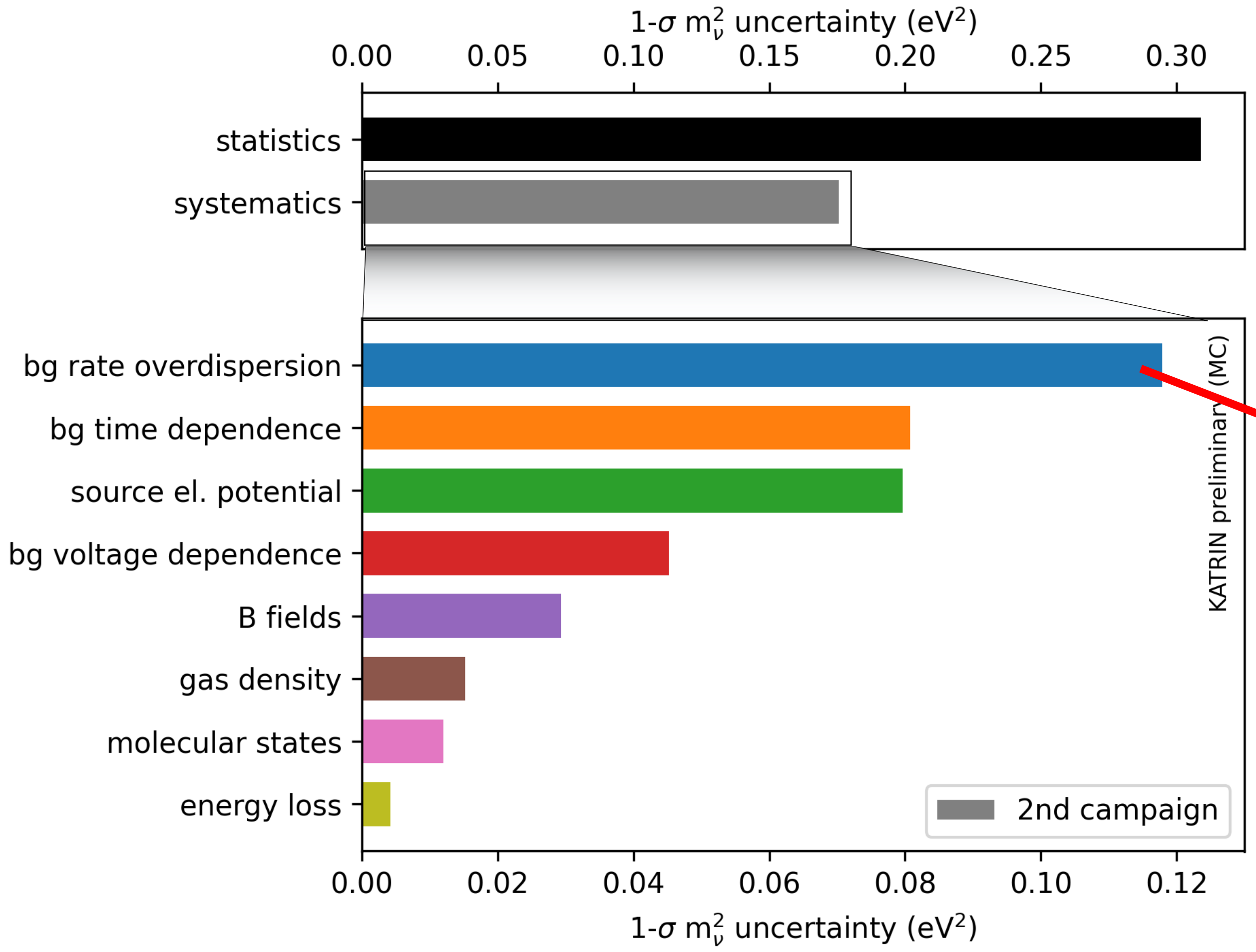
Thank you for your attention

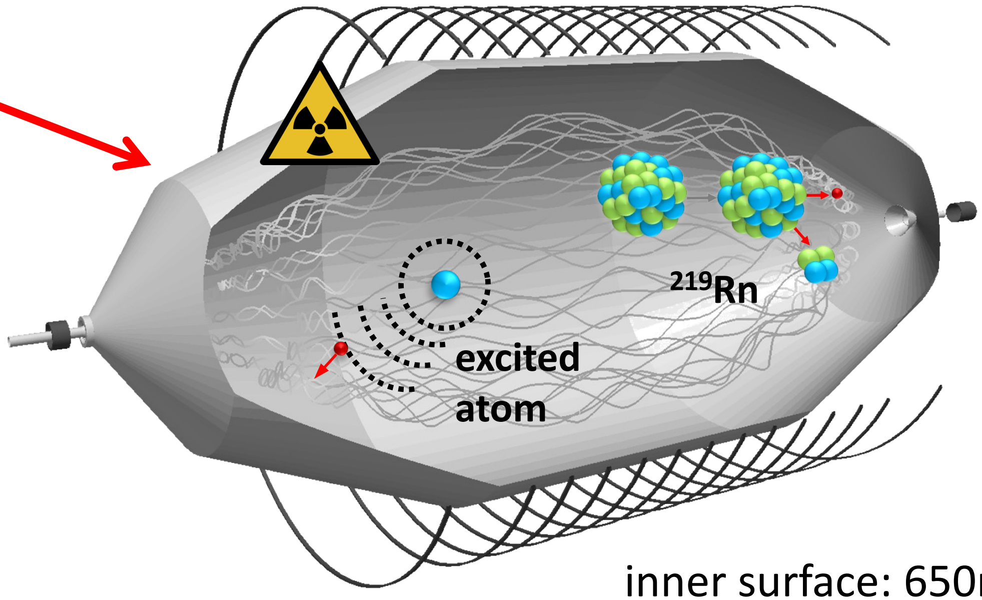
Susanne Mertens

Technical University Munich & Max Planck Institute for Physics

Backup slides

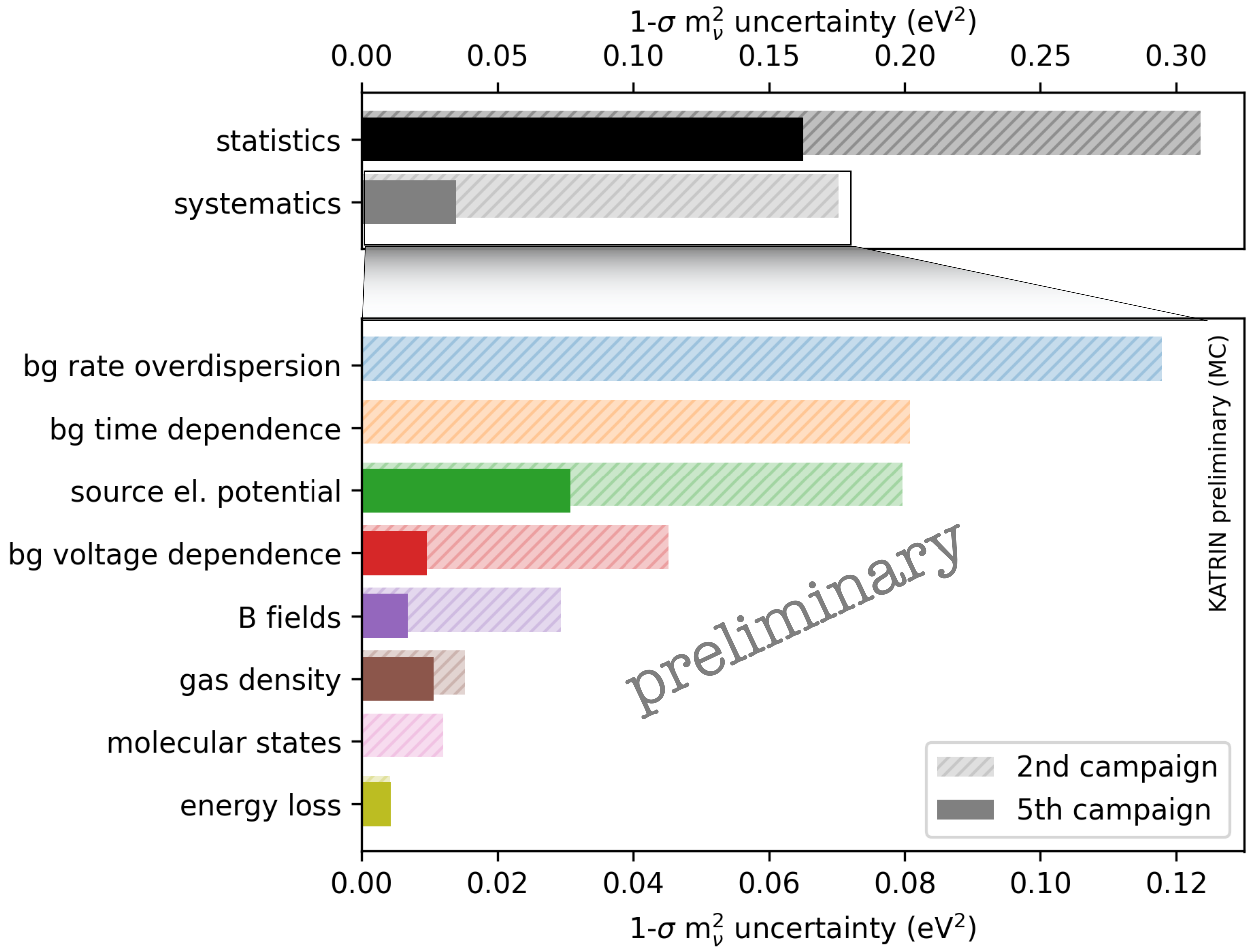
Uncertainty budget in second campaign





inner surface: 650m^2
volume: 1400m^3

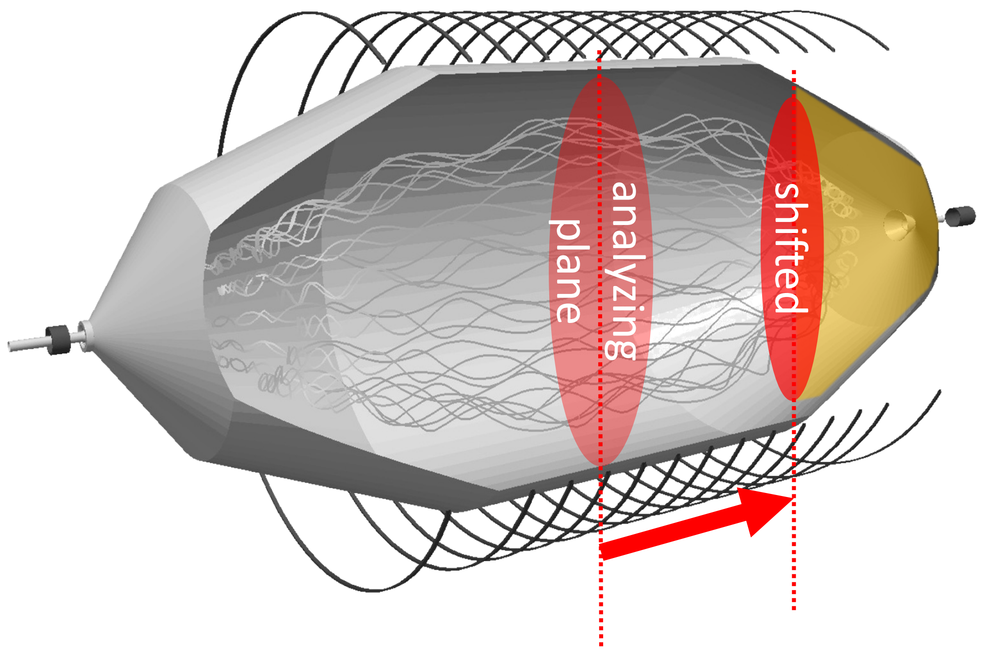
Sneak preview



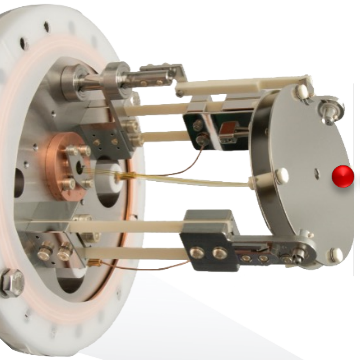
Major improvement:

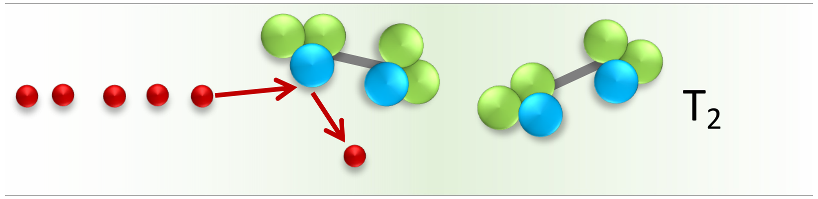
- Background reduction (÷2) via new EM field layout

Lokhov et al arXiv:2201.11743 (2022)

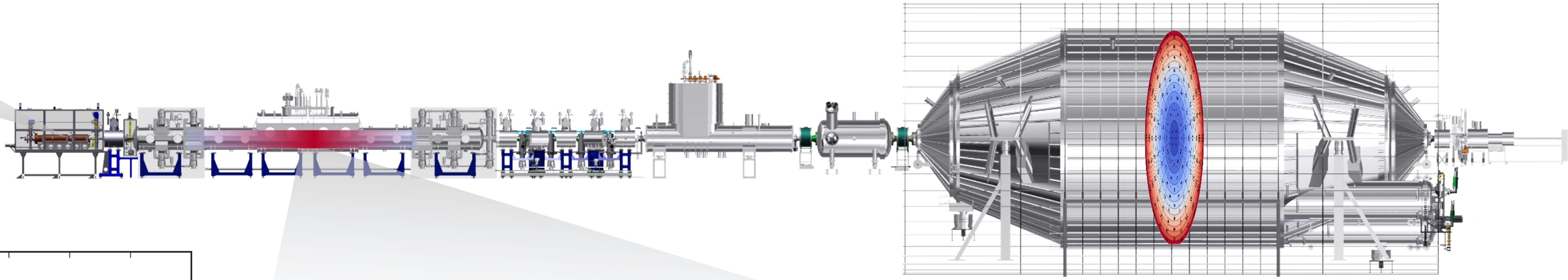


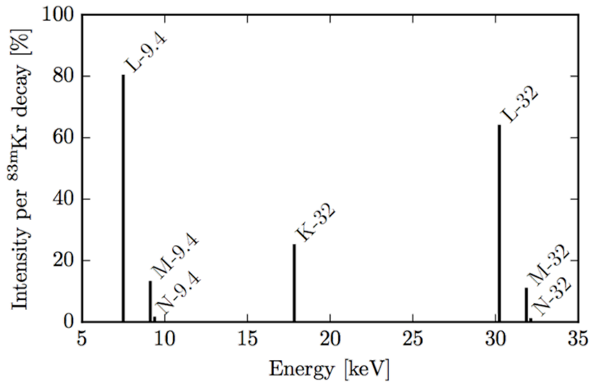
Calibration: e-gun, ^{83m}Kr

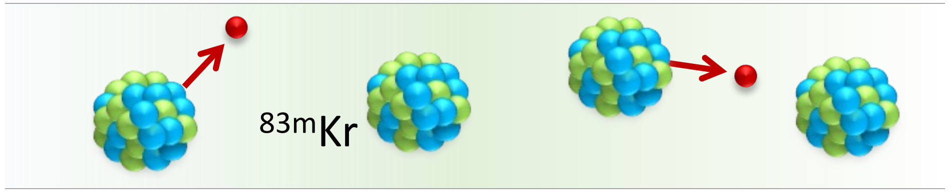




✓ Measurement of gas density and energy losses



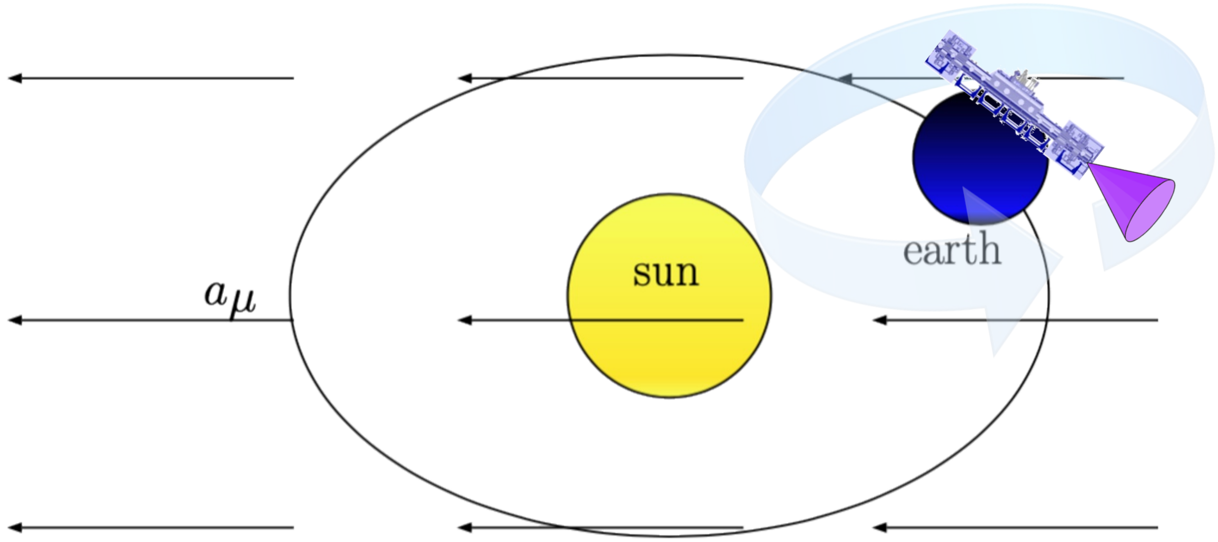




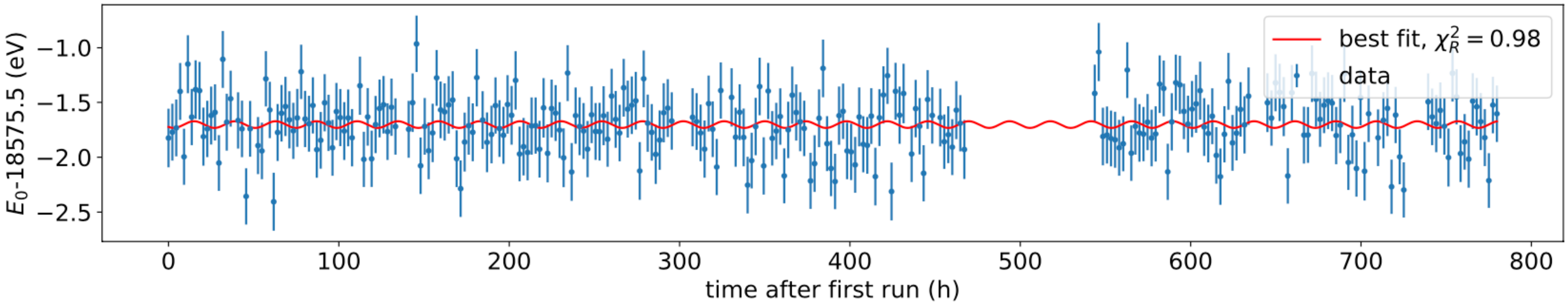
✓ Measurement of E/M fields var. in the source and spectrometer

Lorentz Violation

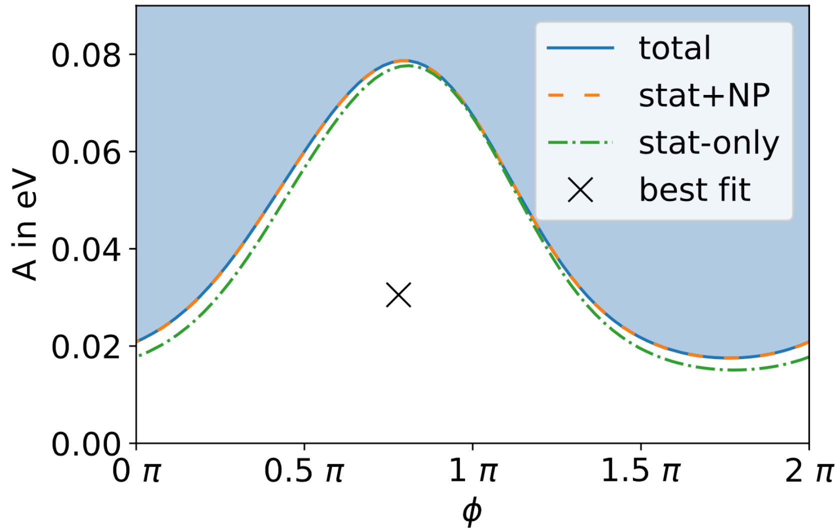
- LV parametrized with a_μ (vector field)
- KATRIN acceptance angle introduces a preferred "direction"
- As the earth is rotating, the relative direction of KATRIN to the LV-violating vector changes
- Signature: oscillation of tritium endpoint with sidereal frequency (23h 56 min)



Lorentz Violation

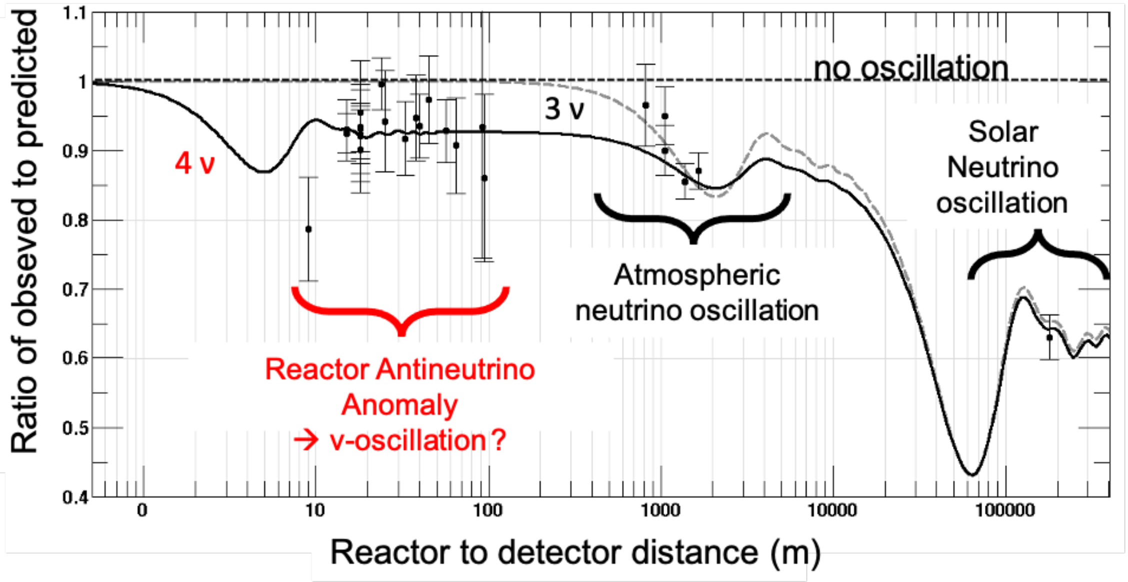


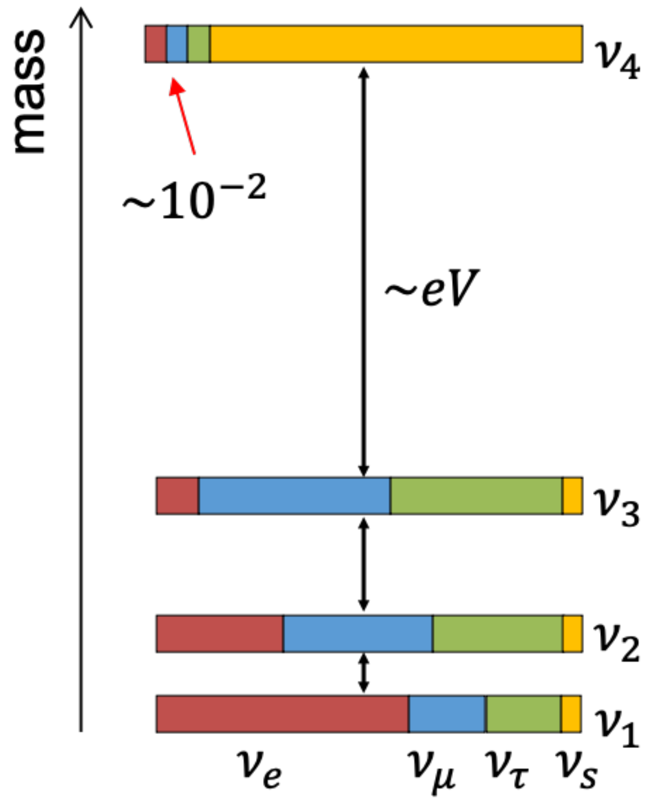
- Search for oscillation in **first** nu-mass data
- No significant oscillation found
- First limit on $\left|\left(a_{of}^{(3)}\right)_{11}\right| < 3 \cdot 10^{-6}$ GeV
- arxiv:2207.06326 (2022), corresponding author S. Mertens



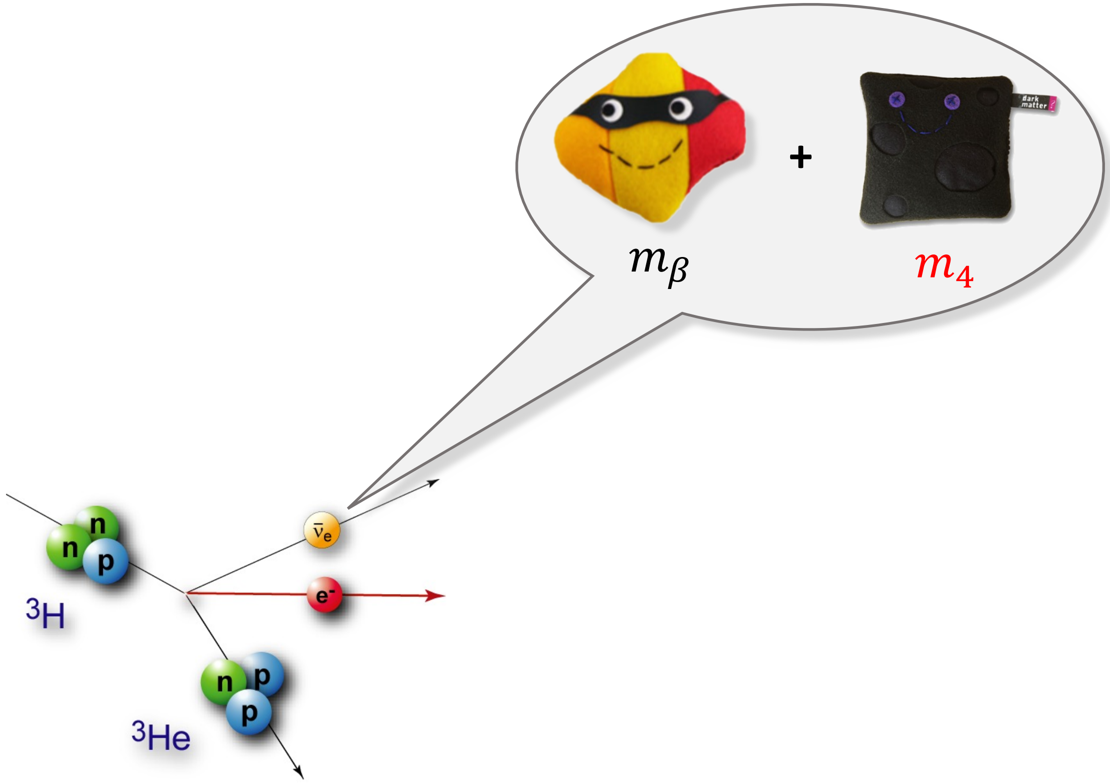
eV-scale Sterile Neutrinos

- Sterile neutrinos are a natural extension of the SM
- eV-scale motivated by anomalies in ν–oscillation experiments

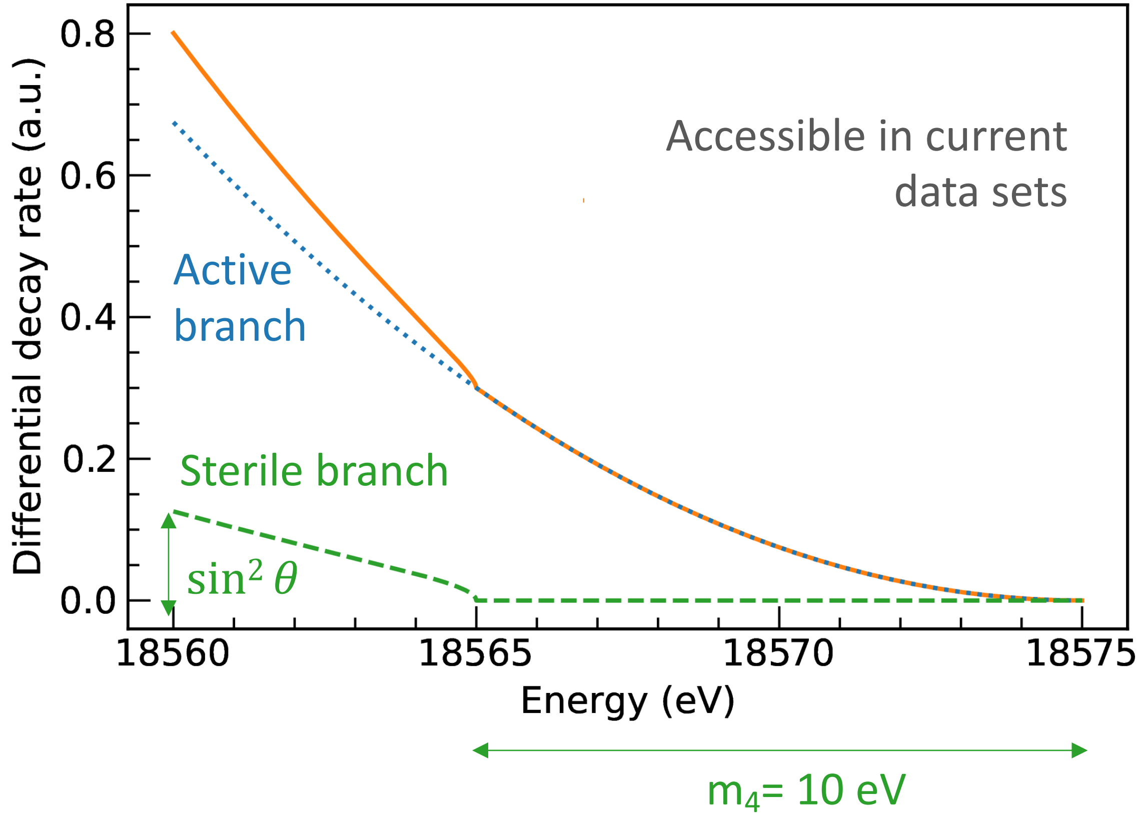




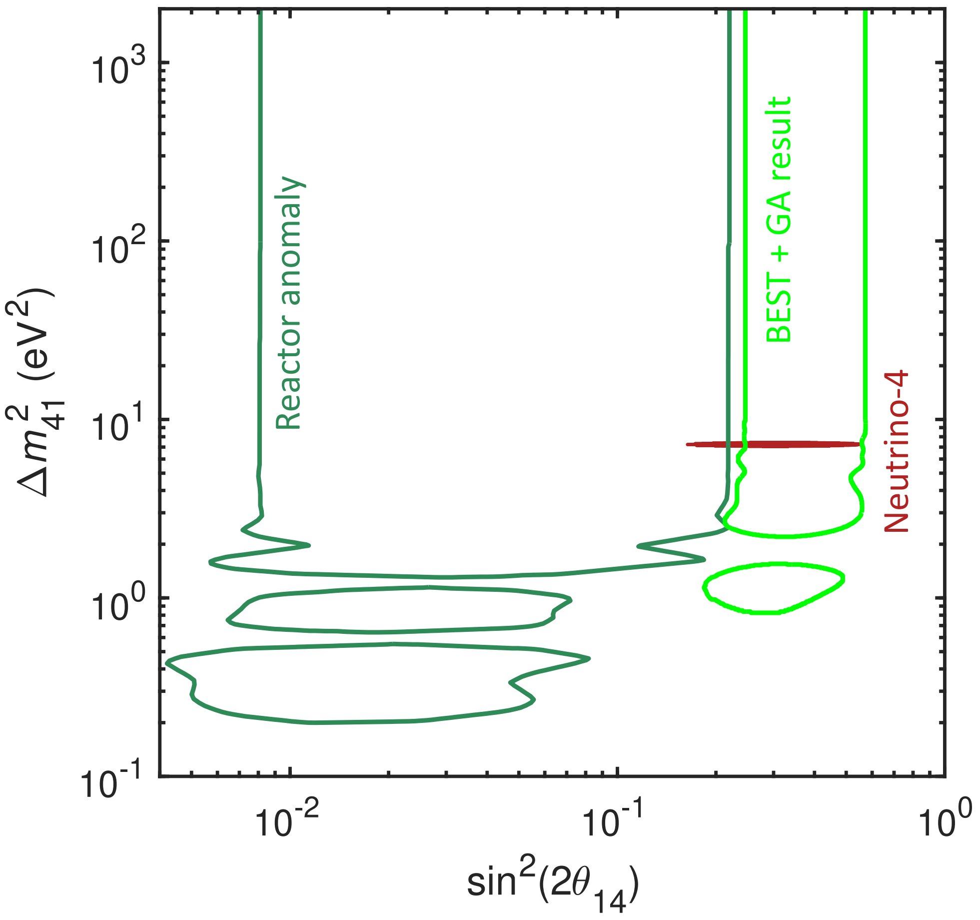
Signature in beta decays



eV-scale sterile neutrino



Sterile neutrino search in KATRIN

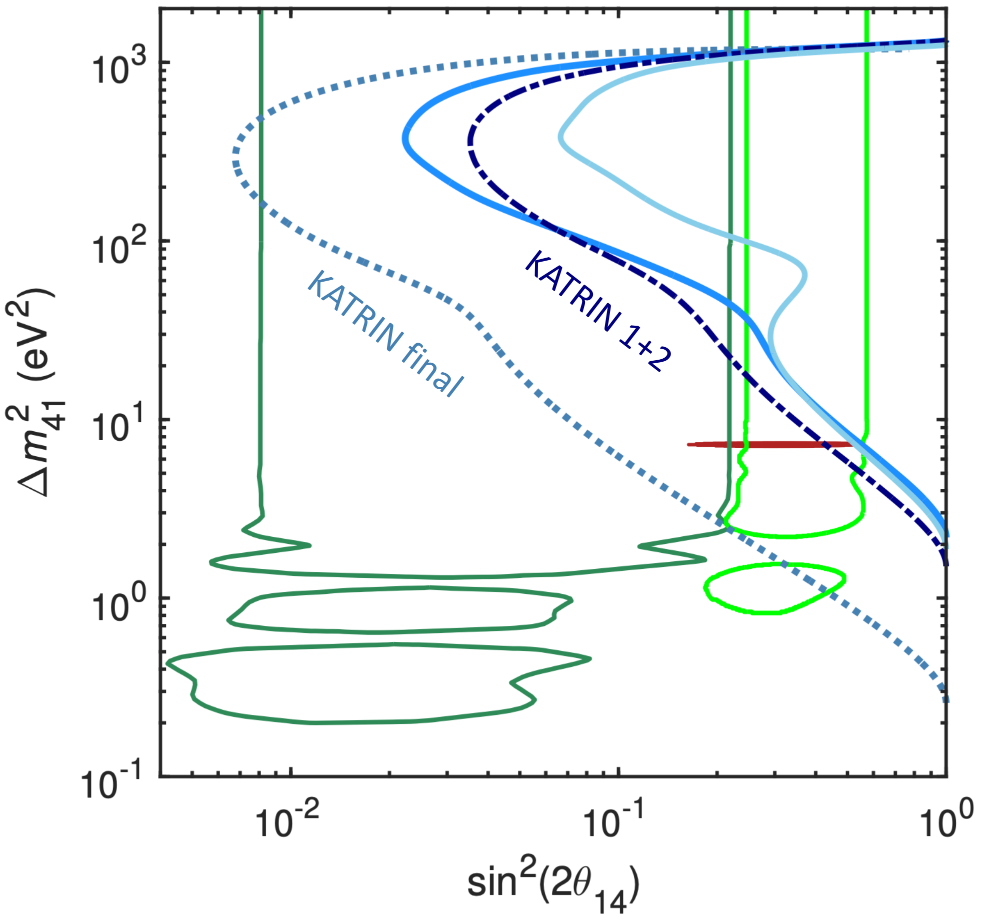


G. Mention et al Phys. Rev. D **83**, 073006 (2011)

A. P. Serebrov et al., Pisma Zh. Eksp. Teor. Fiz. 109, 209 (2019)

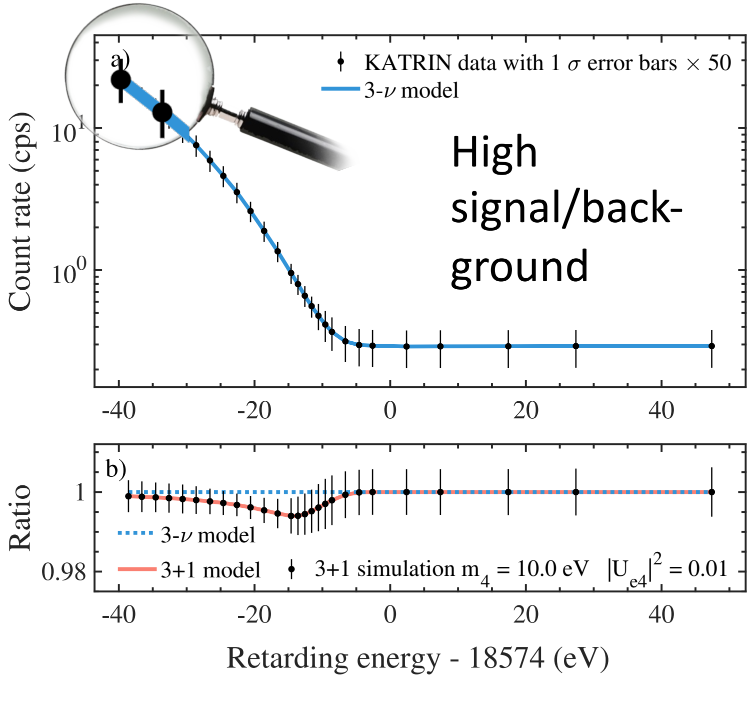
V. V. Barinov et al. (BEST), arXiv:2109.11482 (2021)

Sterile neutrino search in KATRIN

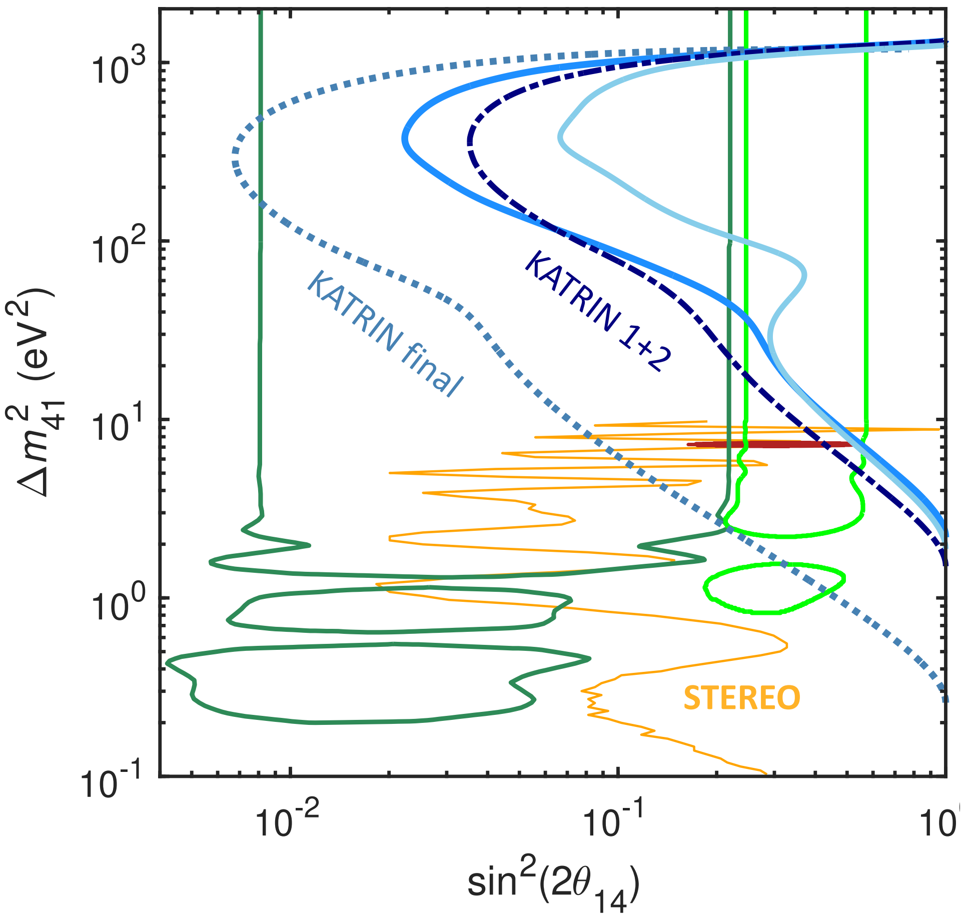


✓ Start probing interesting parameters space

Phys. Rev. Lett. **126**, 091803 (2021), SFB corresp. author
Phys. Rev. D **105**, 072004 (2022), SFB corresp. author



Sterile neutrino search in KATRIN



- ✓ Start probing interesting parameters space

Phys. Rev. Lett. **126**, 091803 (2021), SFB corresp. author
Phys. Rev. D **105**, 072004 (2022), SFB corresp. Author

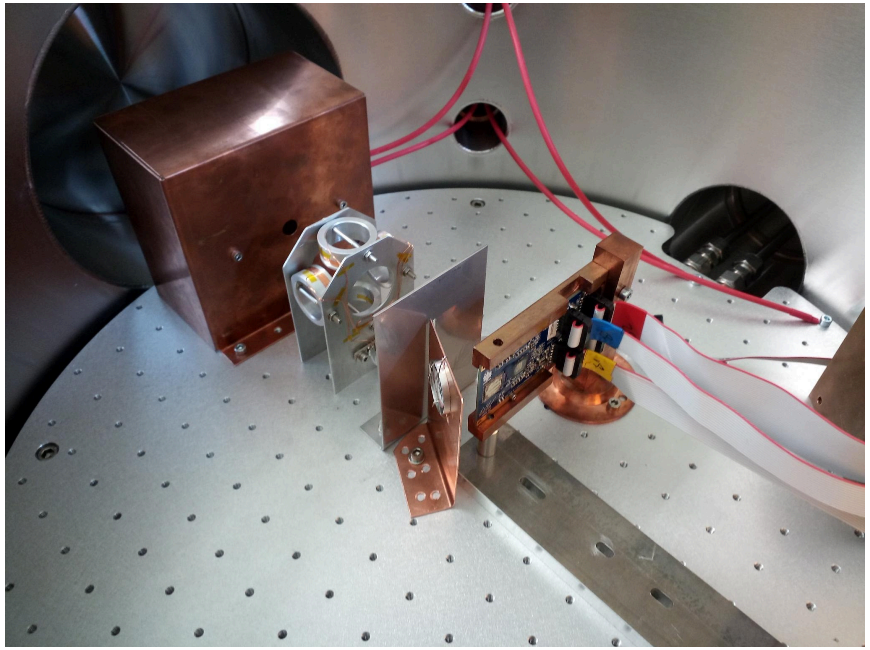
- ✓ Complementary probe to oscillation-based experiments

DANSS, arXiv:1911.10140 (2019)
STEREO, Phys. Rev. D 102, 052002 (2020)
PROSPECT, Phys. Rev. D 103, 032001 (2021)

TRISTAN Detector characterization

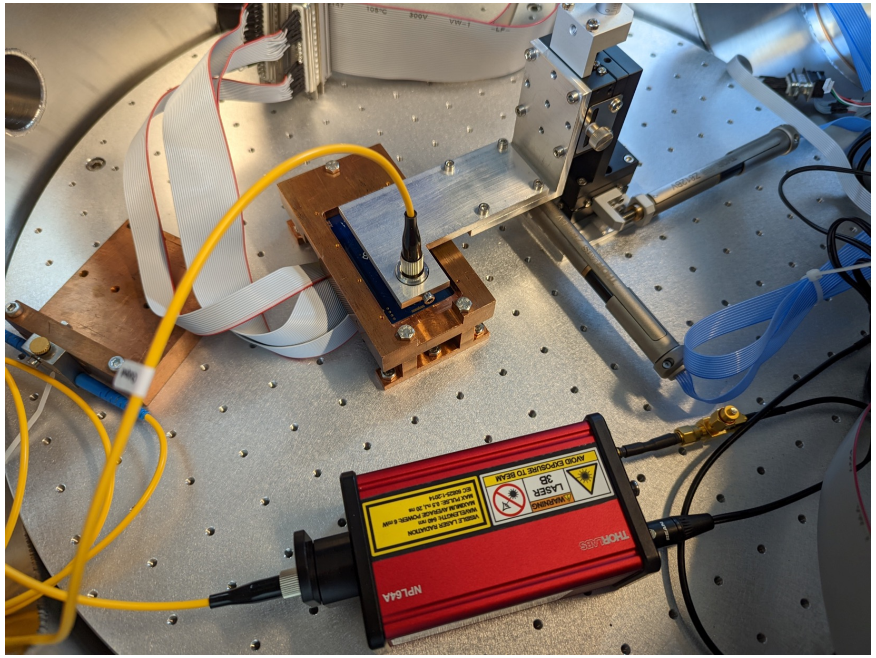
Custom-developed electron-gun:

- Measuremet of dead-layer, backscattering, charge-sharing

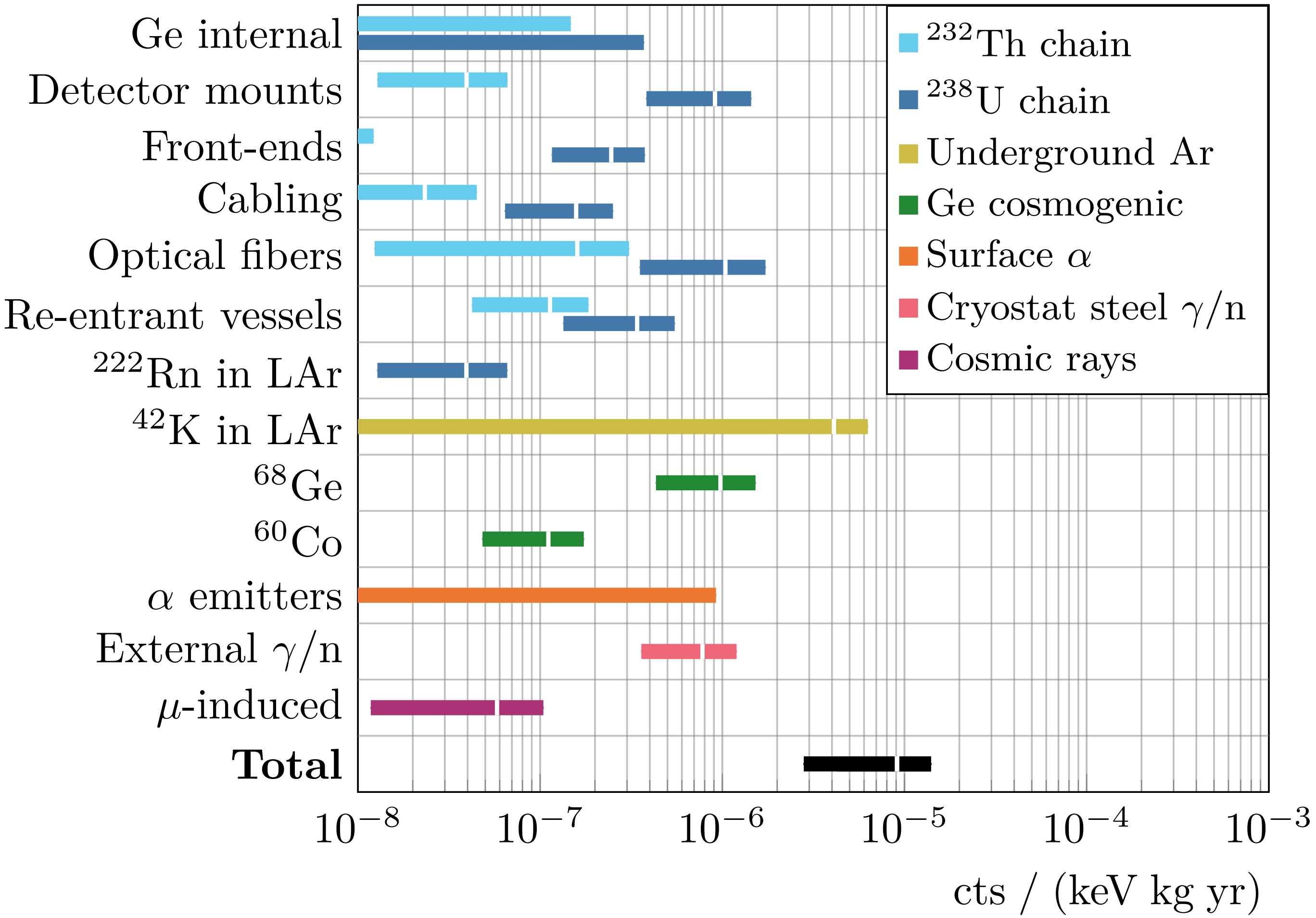


Custom-developed laser calibration source

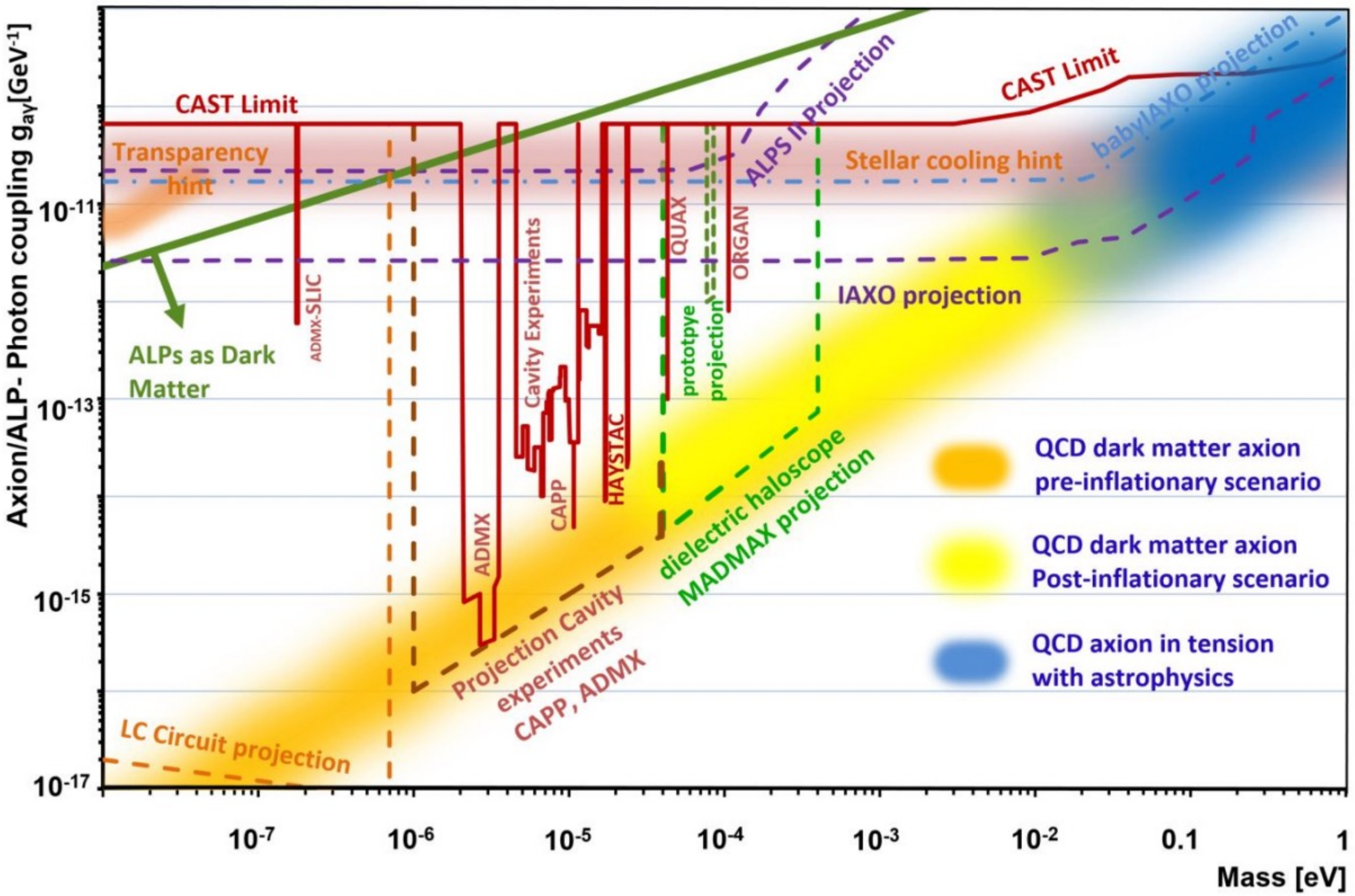
- Measurement of charge drift times



LEGEND background projection



IAXO perspective



KATRIN+TRISTAN sensitivity to steriles