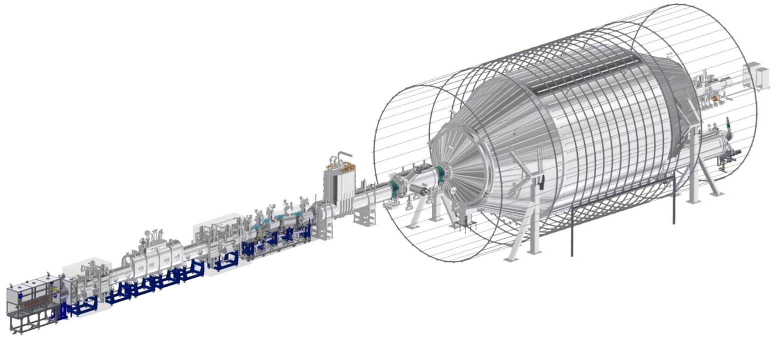
Technical University of Munich

MAX-PLANCK-INSTITUT FÜR PHYSIK



KATRIN: from Neutrino Mass to Dark Matter

Séminaire du PHE, IJCLab

Thibaut Houdy

11th of October, 2021

Who am I?

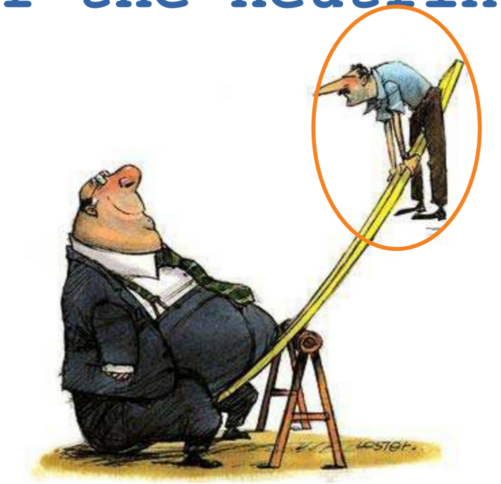
- New comer to the IJCLab as maître de conférence.
- Joining the DUNE experiment and Fabien Cavalier’s team.
- 2014-2017: PhD between APC/CEA about solar and sterile neutrinos with the SOX project and the Borexino experiment.

- 2018-2021: Postdoc in Susanne Mertens’ group in Max Planck Institute for Physics, Munich about KATRIN.
- Mostly working on neutrino/dark matter physics with an experimental taste.
- During my studies on Orsay’s campus: internship @ CSNSM, lecture @ IPNO, Englert’s conference on Higgs @ LAL …
- Looking forward to collaborating with you all!

→ **KATRIN: from Neutrino Mass to Dark Matter**

This talk is about:

What is the mass of the neutrino?

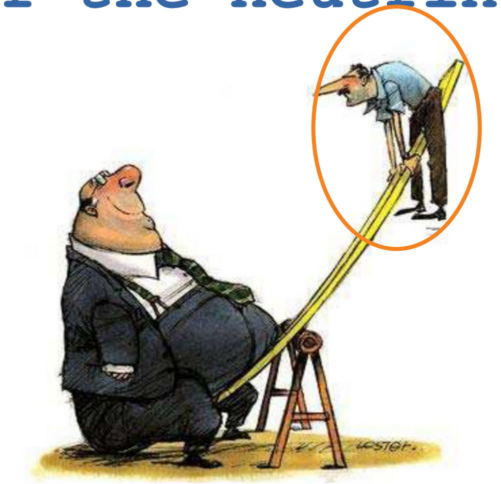


Do sterile neutrinos exist?

What is dark matter?

This talk is about:

What is the mass of the neutrino?



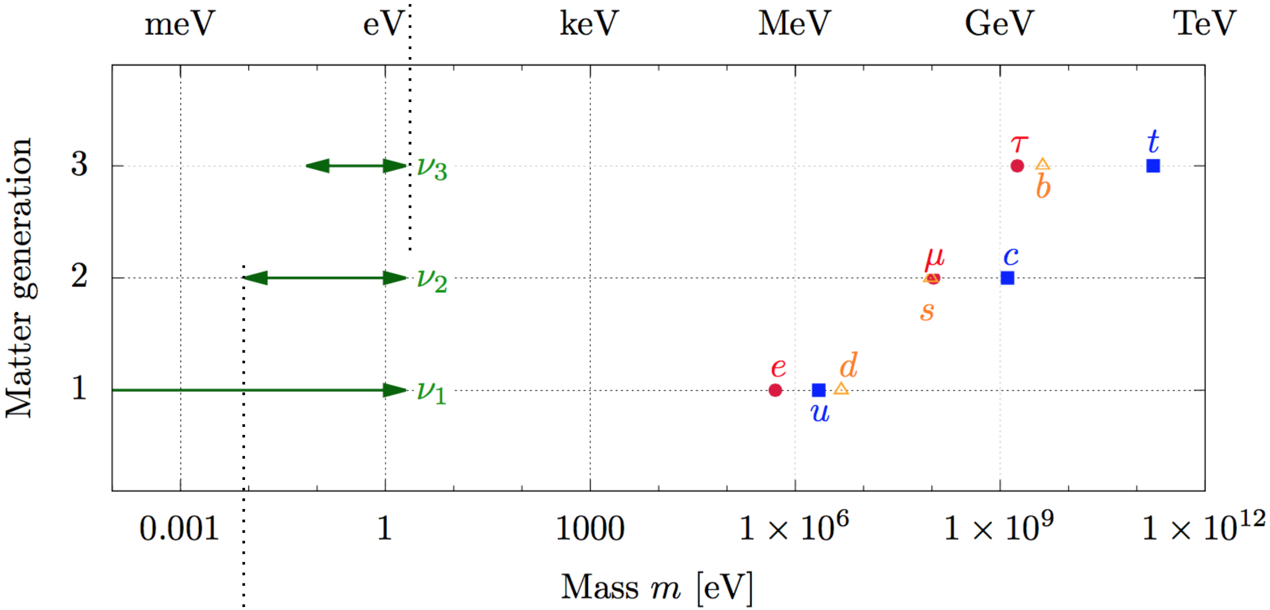
Beyond the Standard Model

What is dark matter?

Do sterile neutrinos exist?

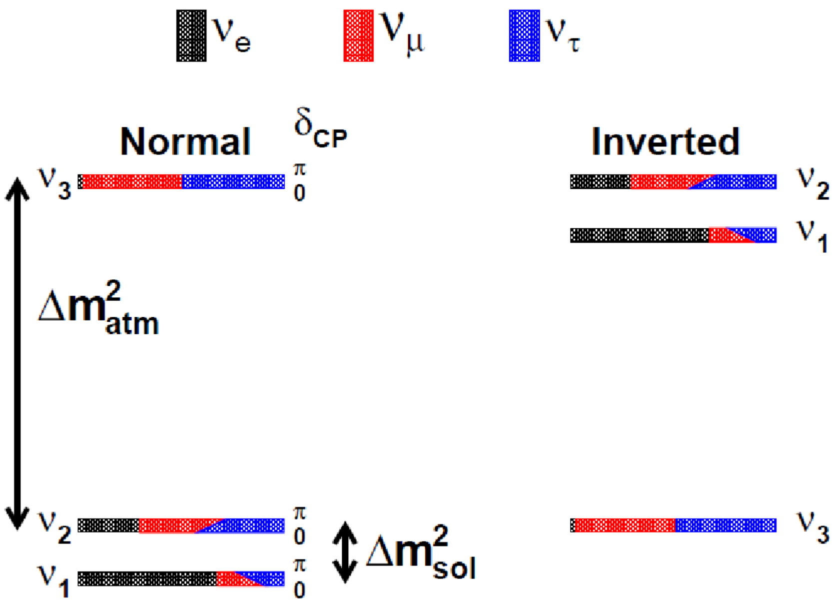
Neutrino mass status

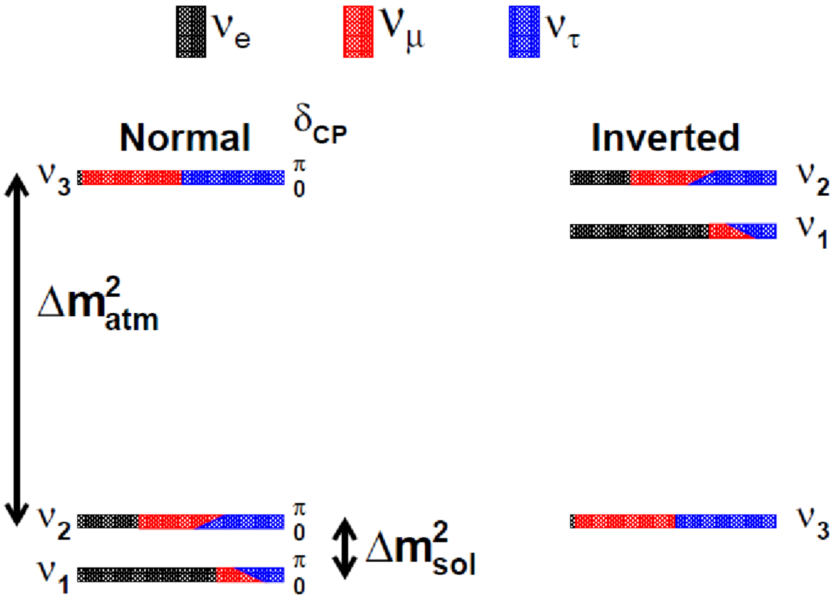
Upper bound
from laboratory measurements

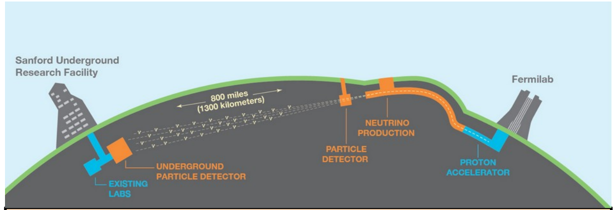


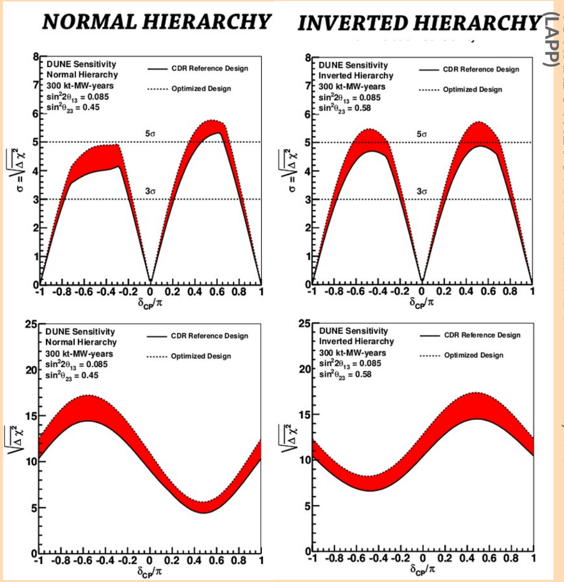
Lower bound
from oscillation experiments

Neutrino mass hierarchy





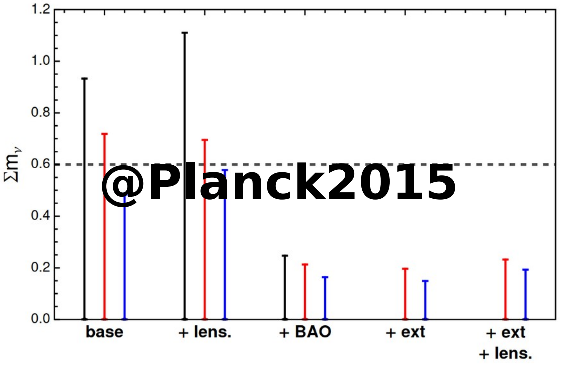




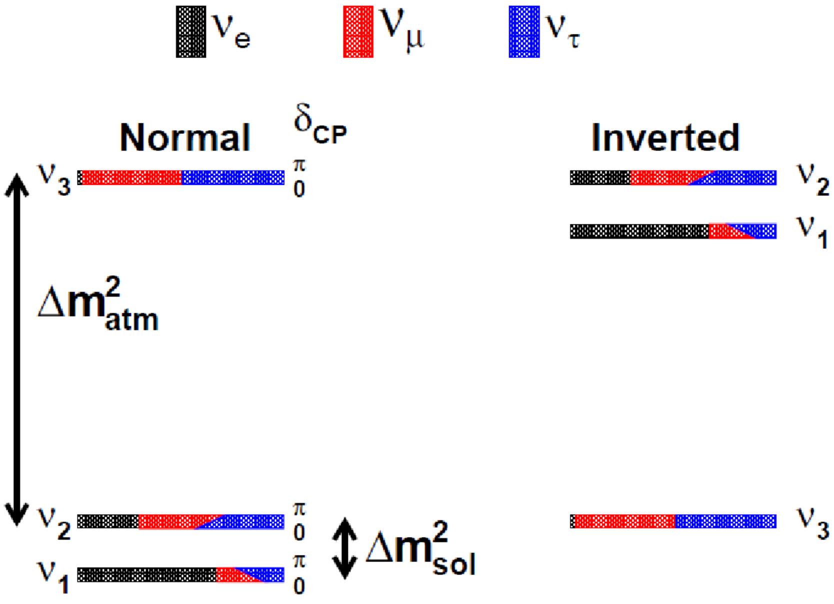
TOWARDS THE FUTURE OF LBN EXPERIMENTS, L.Zambelli (LAPP)

Neutrino mass measurements

- **Cosmology**
  model dependent
  Σm_ν < 120 meV
  Ex : Planck, eBOSS



M.Lattanzi 2016 JP,Conf.Ser.718 032008



Neutrino mass measurements

- **Cosmology**
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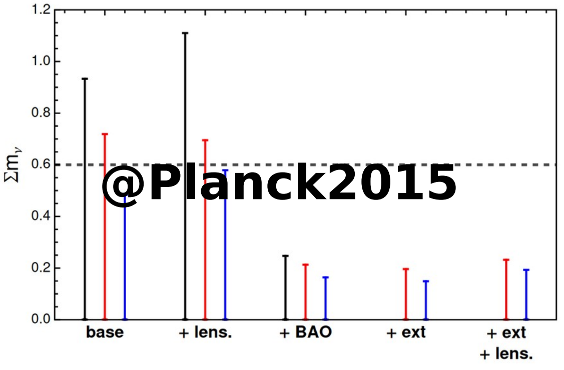
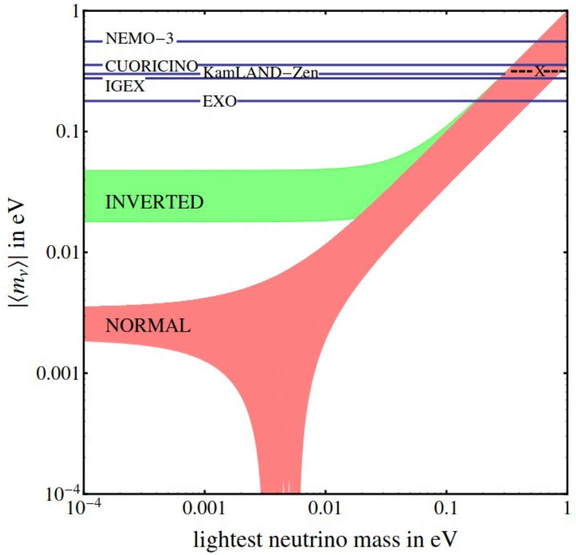
- **0νββ**
  laboratory based
  $m_{\beta\beta}$< 100 meV
  Ex : CUPID, LEGEND, etc



M.Lattanzi 2016 JP.Conf.Ser.718 032008



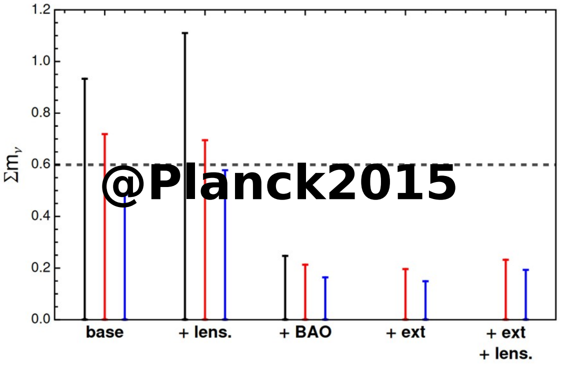
J. Barea et al. PRL 109, 042501 - (2012)

Neutrino mass measurements

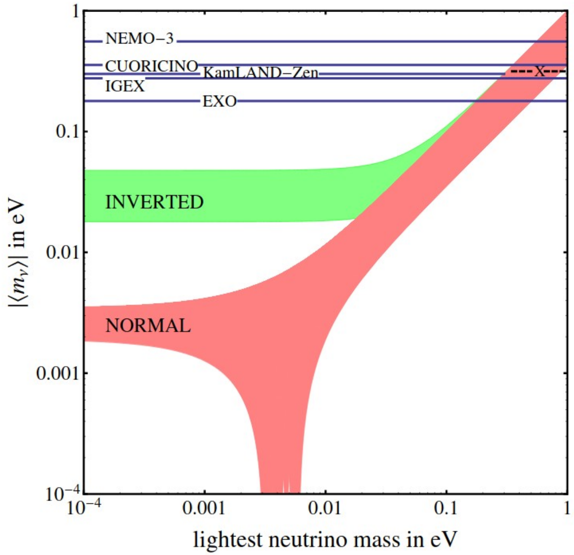
- **Cosmology**
  model dependent
  Σm_ν < 120 meV
  Ex : Planck, eBOSS

- **0νββ**
  laboratory based
  $m_{\beta\beta}$< 100 meV
  Ex : CUPID, LEGEND, etc

- **Kinematics of β-decay**
  laboratory based
  $m_{\nu e}$=50-200 meV
  Ex : ECHO, KATRIN, Project8



M.Lattanzi 2016 JP.Conf.Ser.718 032008



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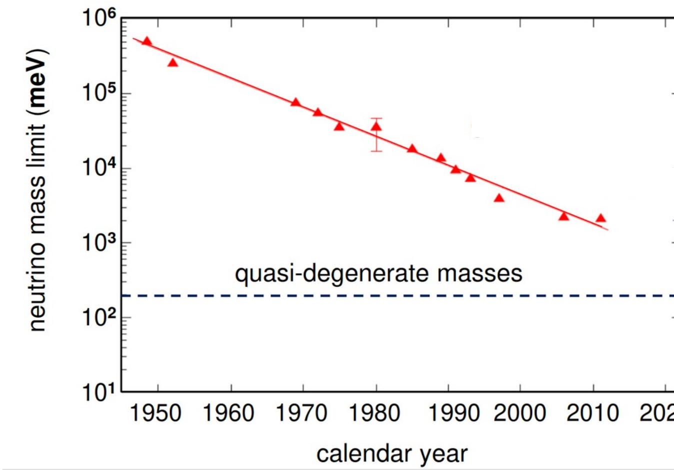
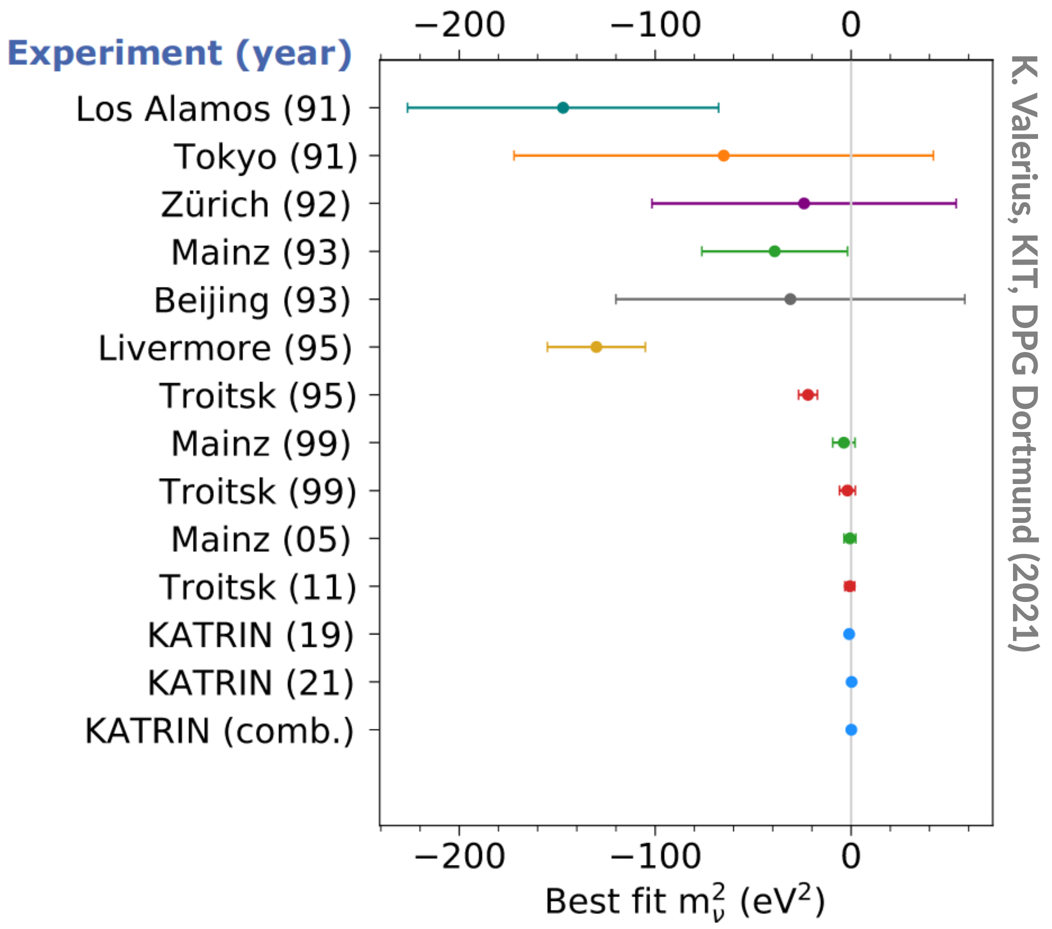
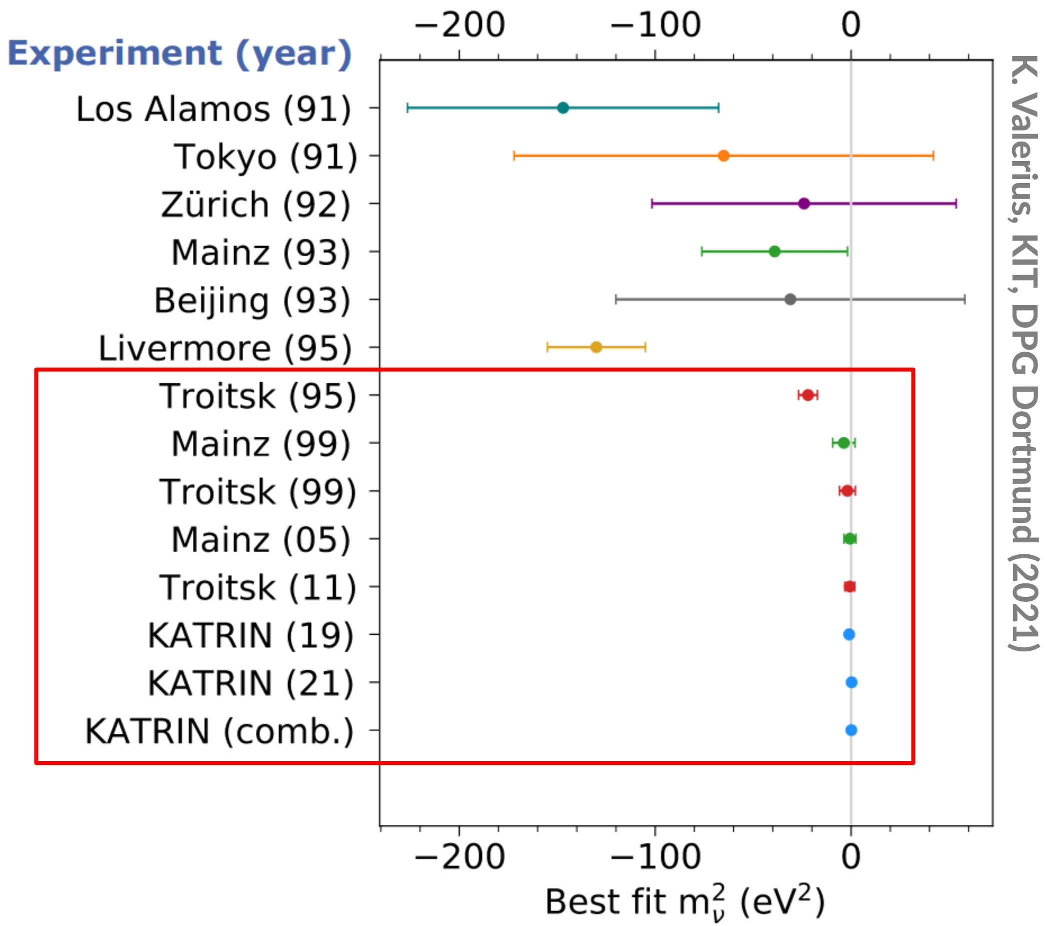


G.Drexlin_TAUP2019

Determining m_ν from ß-decay



Determining m_ν from ß-decay

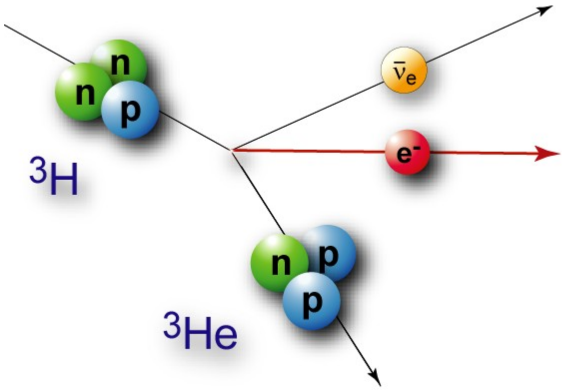


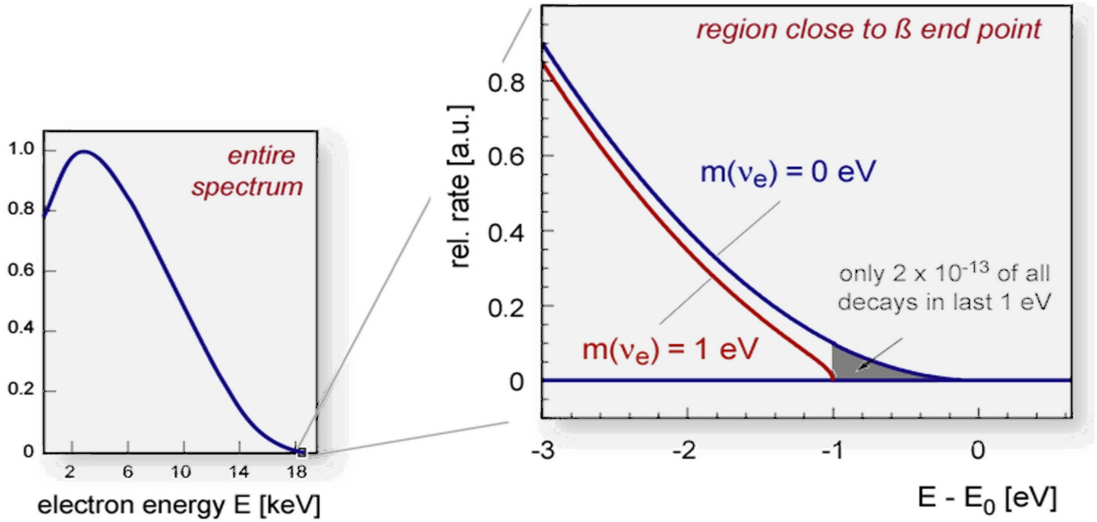
- **Troitsk**
- **Mainz**
- **KATRIN**

→ MAC-E filters with tritium source

Determining m_ν from ß-decay: KATRIN

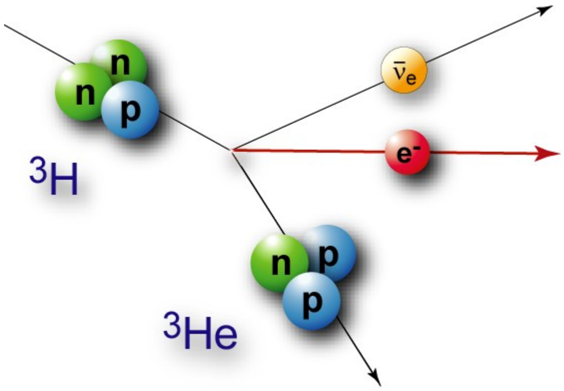
General Idea



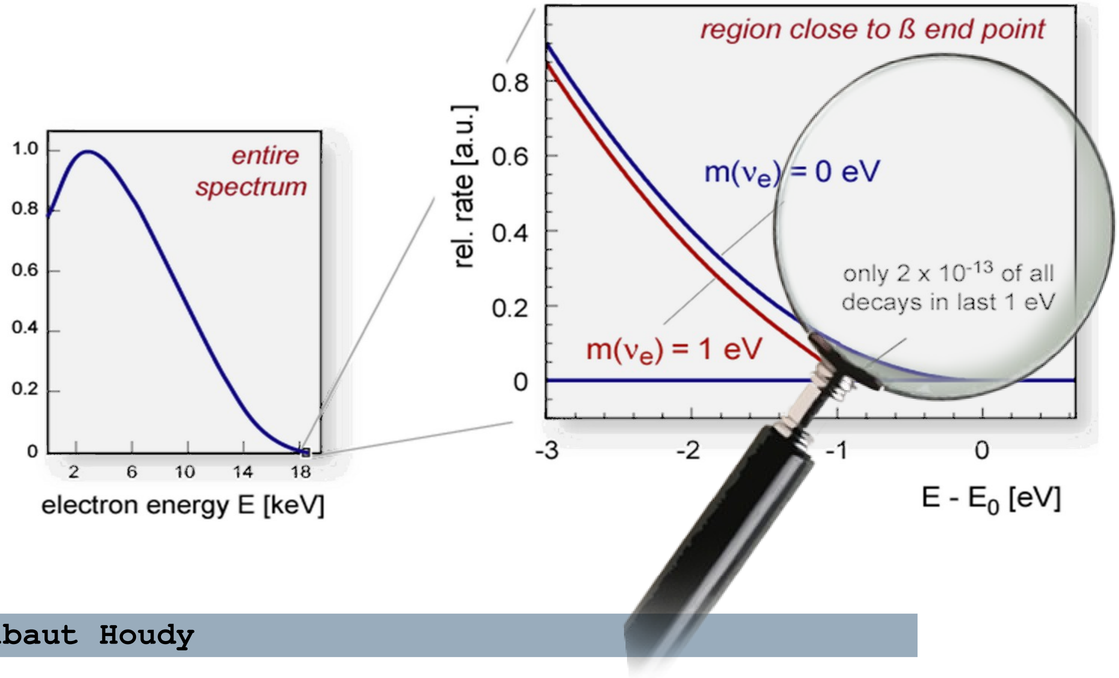


Determining m_ν from ß-decay: KATRIN

General Idea



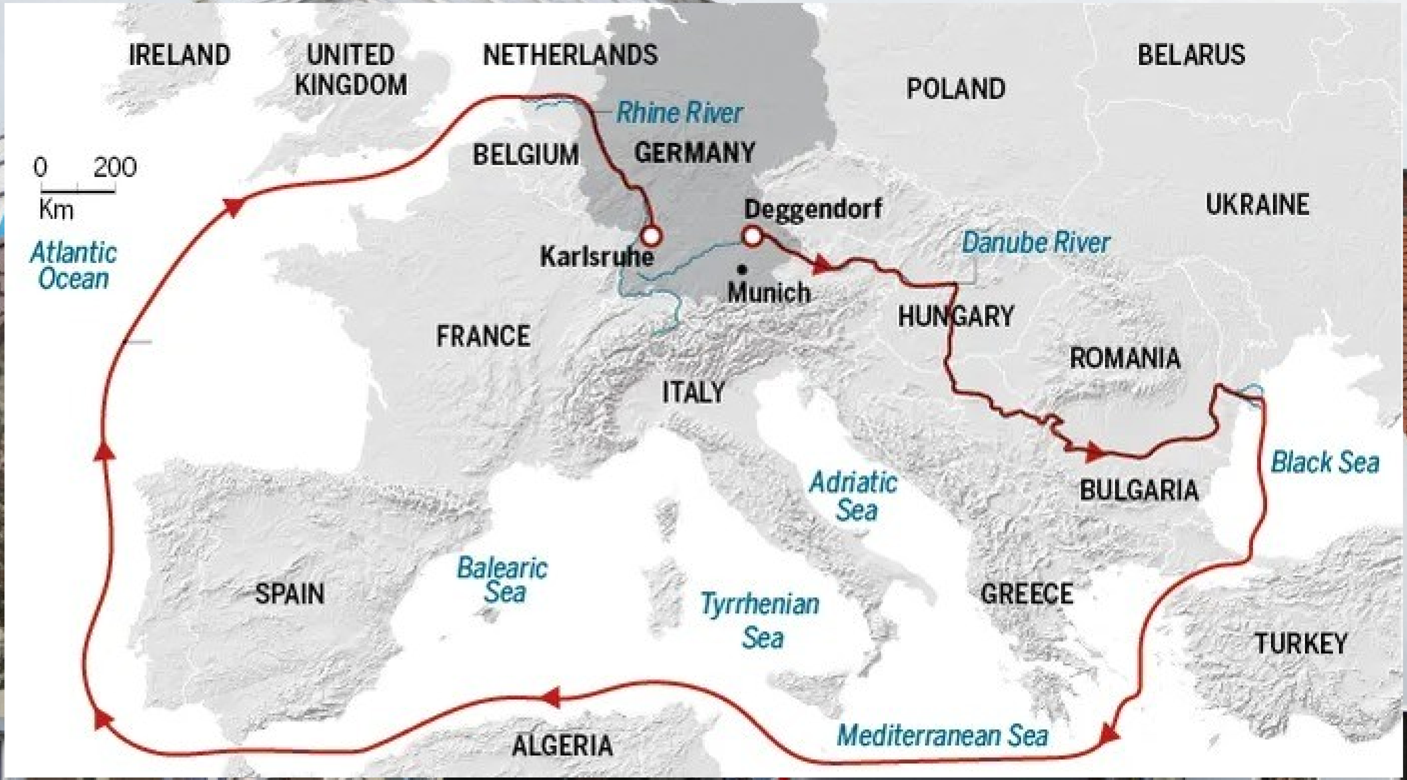
- Ultra-strong β-source 10^{11} decays/s
- Low background level < 0.1 cps
- Excellent energy resolution ~ 1 eV
- Precise understanding of spectrum



KArlsruhe TRItium Neutrino Experiment : KATRIN

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

KArlsruhe TRItium Neutrino Experiment : KATRIN



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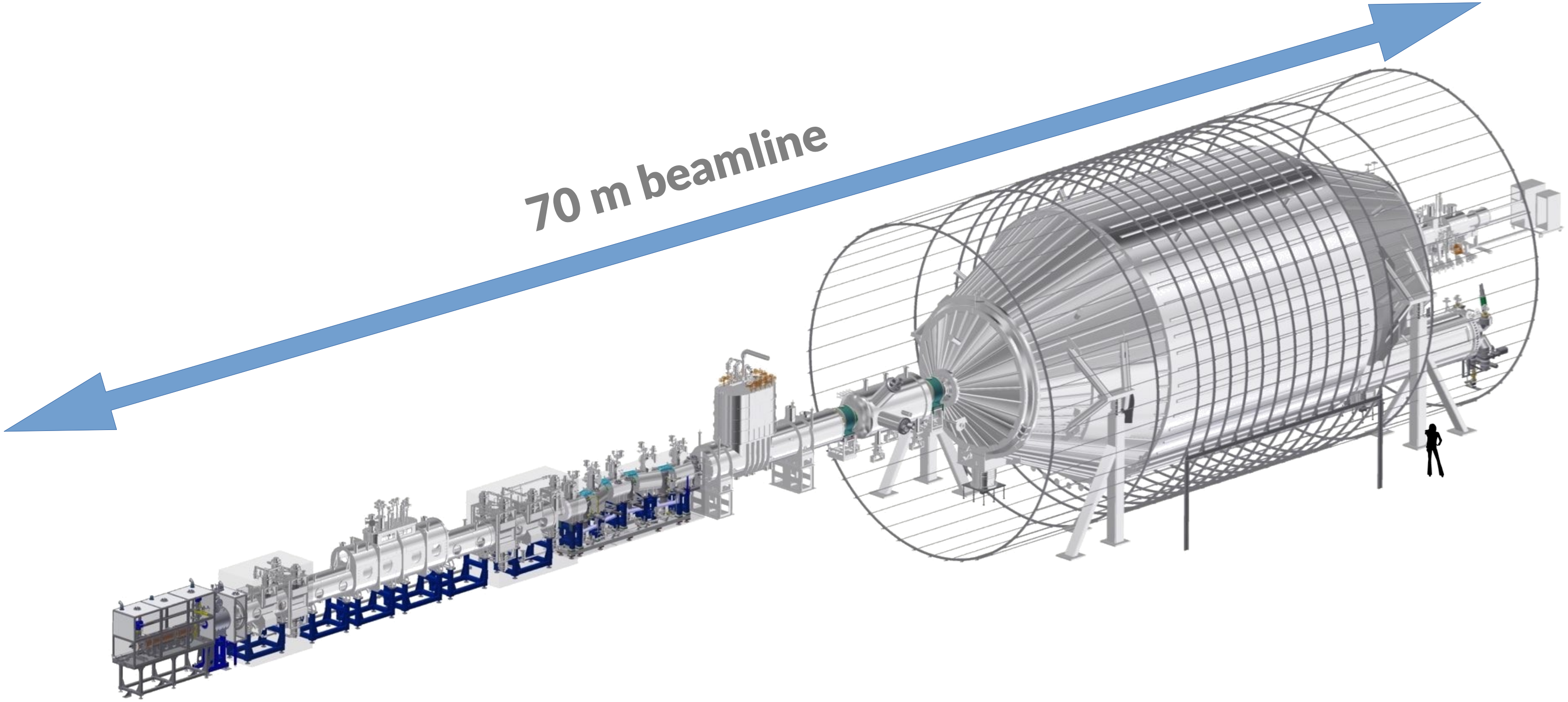
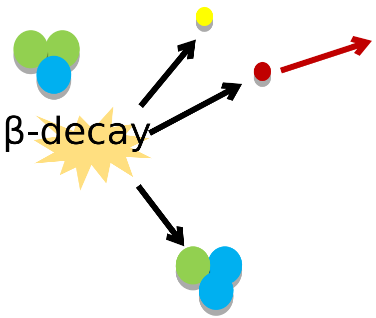
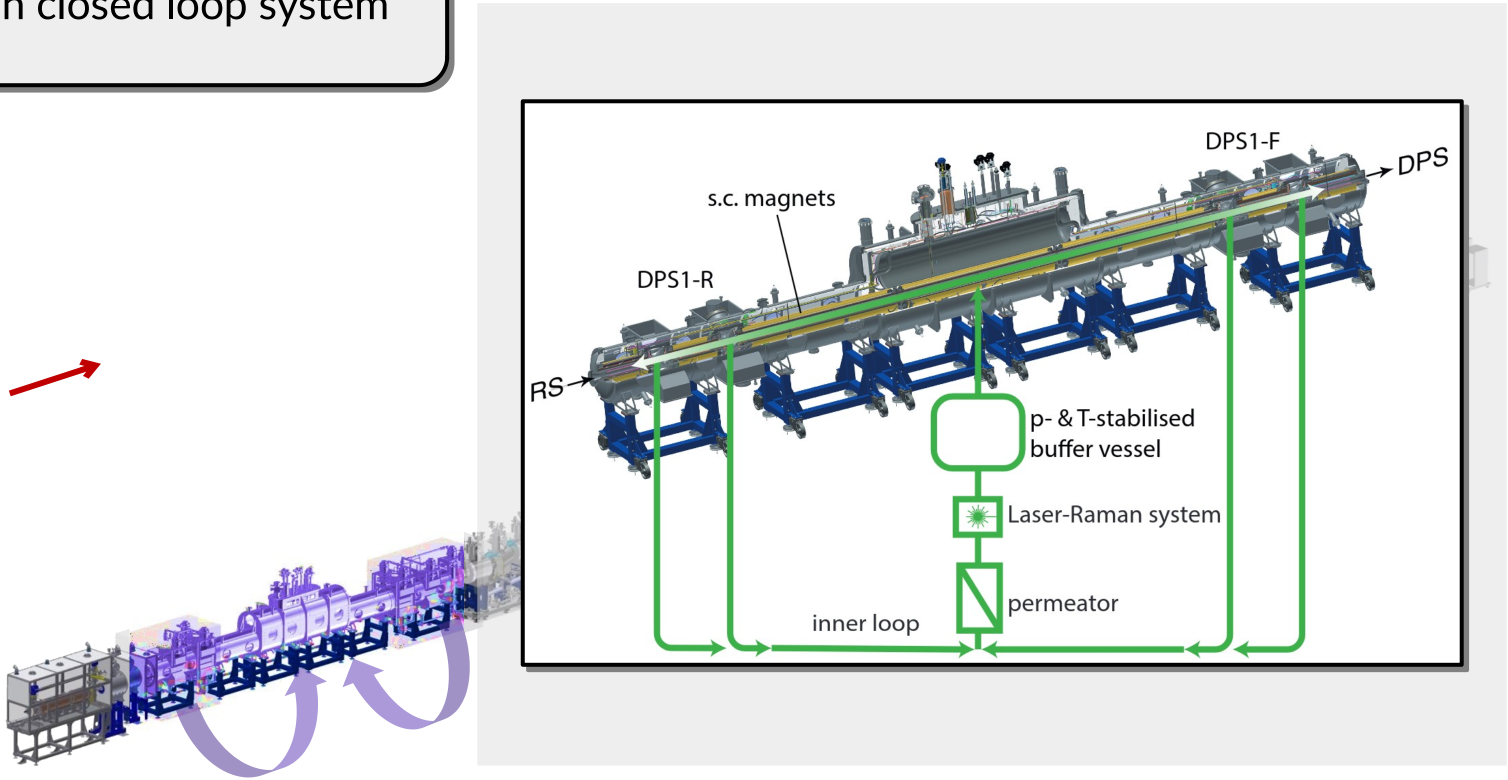
KATRIN Working Principle



KATRIN Working Principle

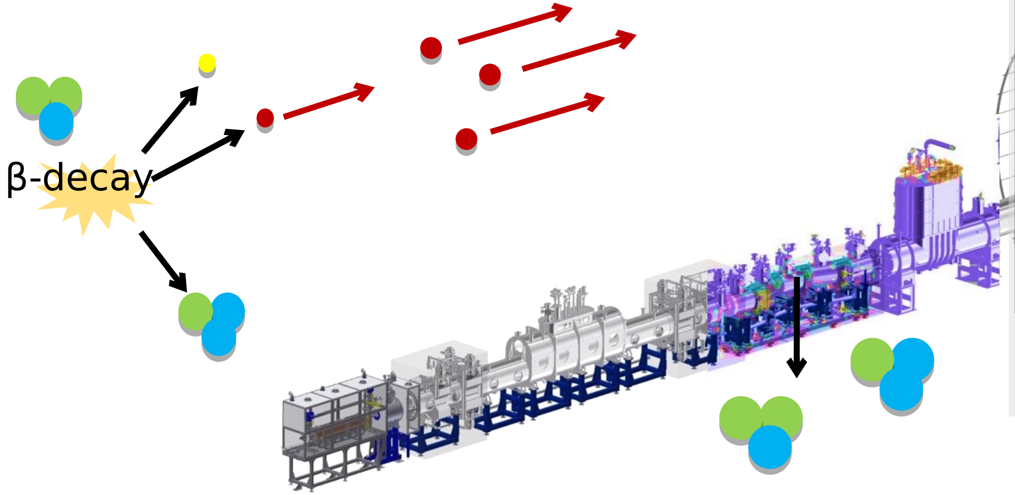
Windowless gaseous tritium source
- molecular tritium in closed loop system
- 10^{11} decays/s

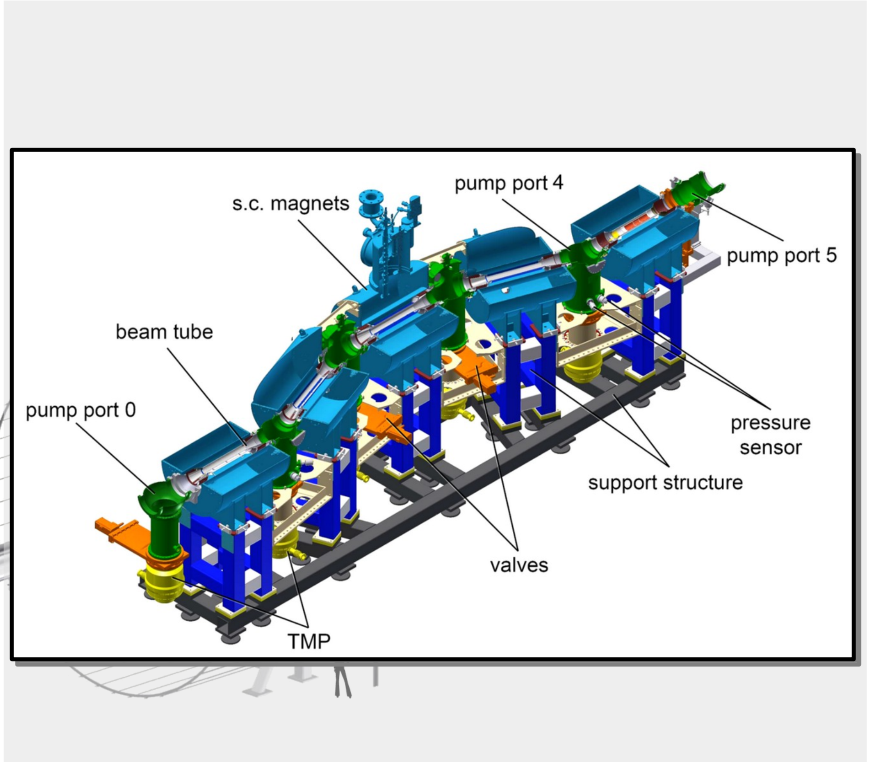




KATRIN Working Principle

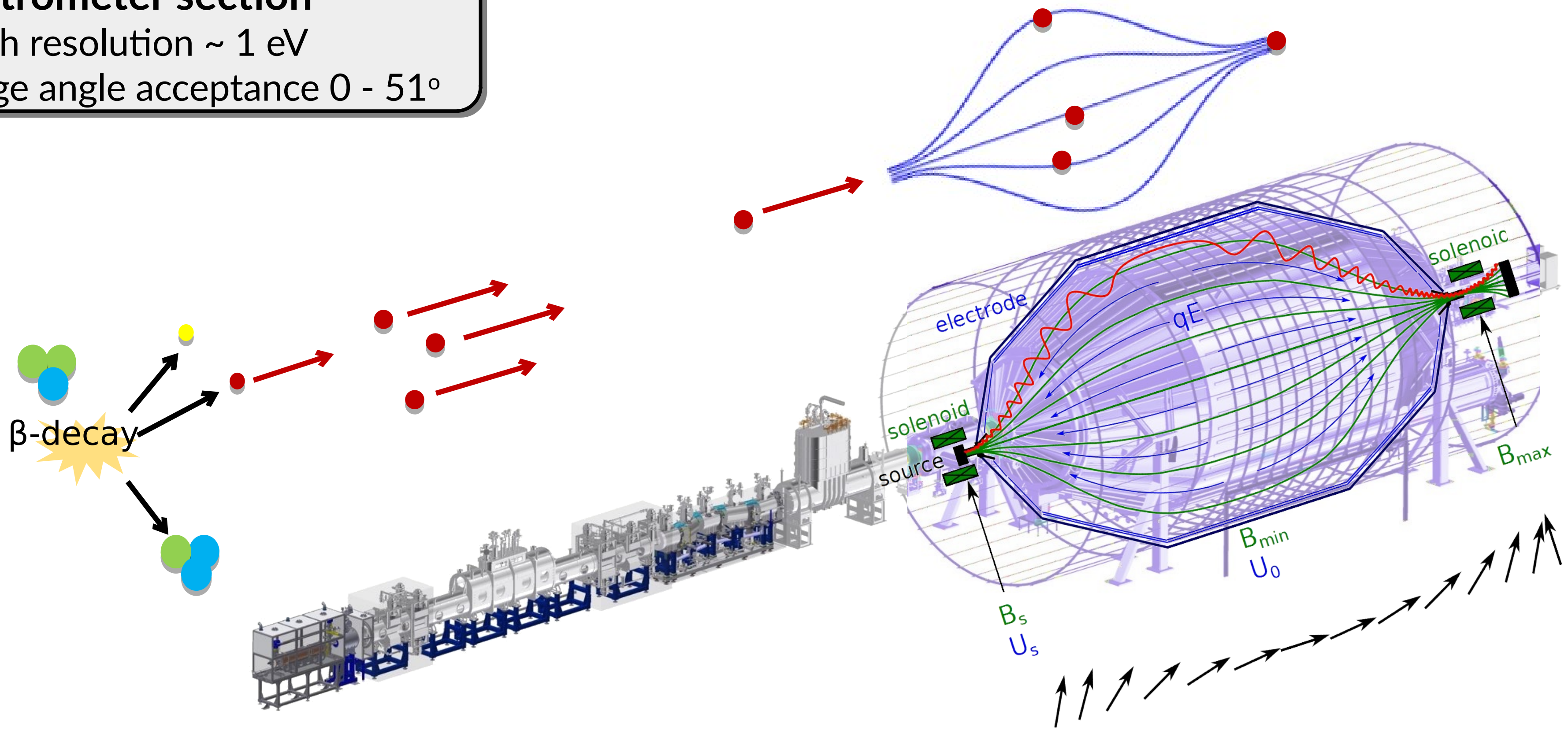
Transport section
- magnetic guidance of electrons (@ 4 T)
- tritium flow reduction by > 10^{14} + tritium ion removal





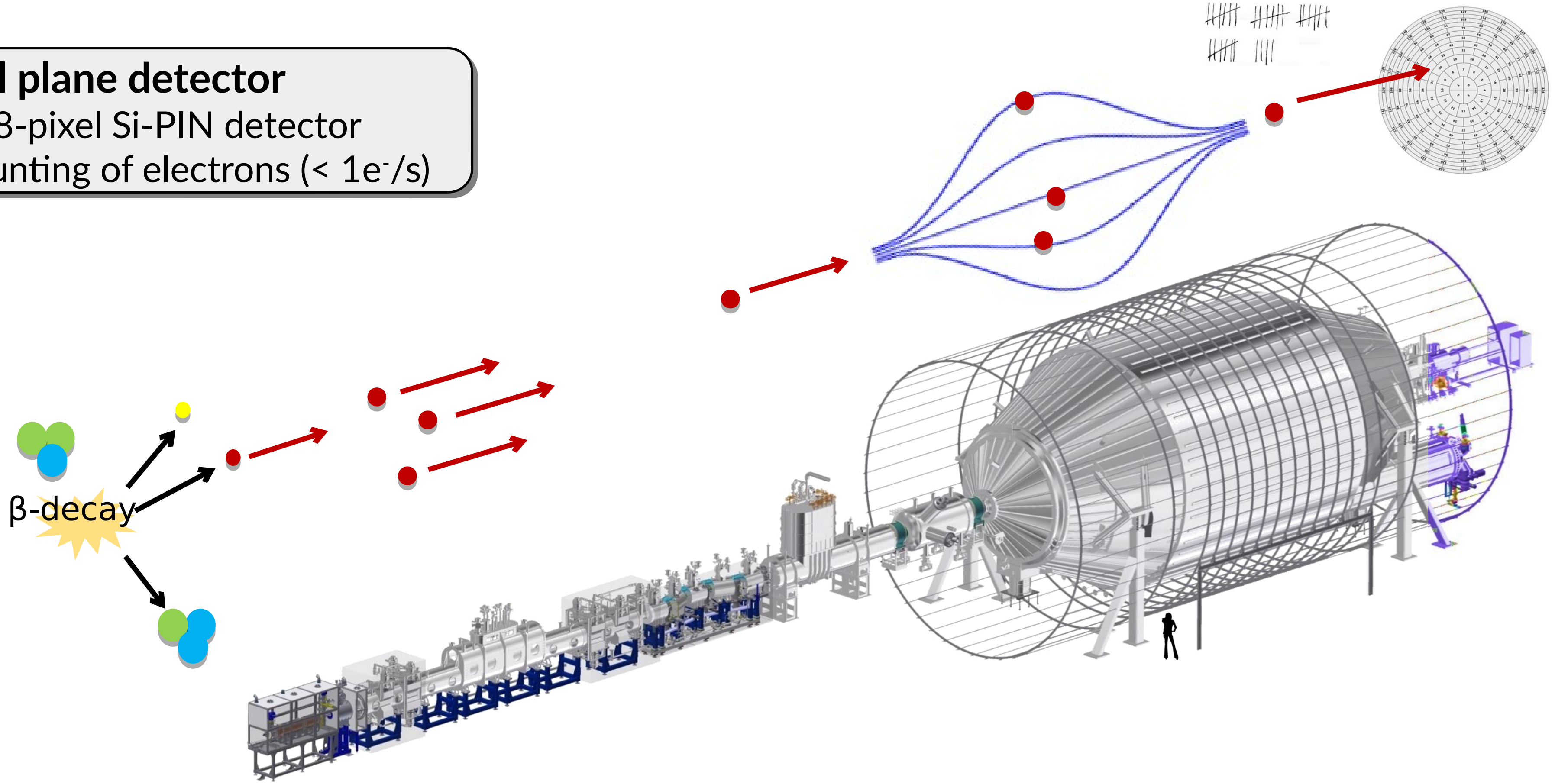
KATRIN Working Principle

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

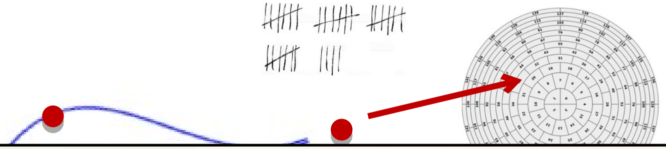


KATRIN Working Principle

Focal plane detector
- 148-pixel Si-PIN detector
- counting of electrons (< 1e⁻/s)

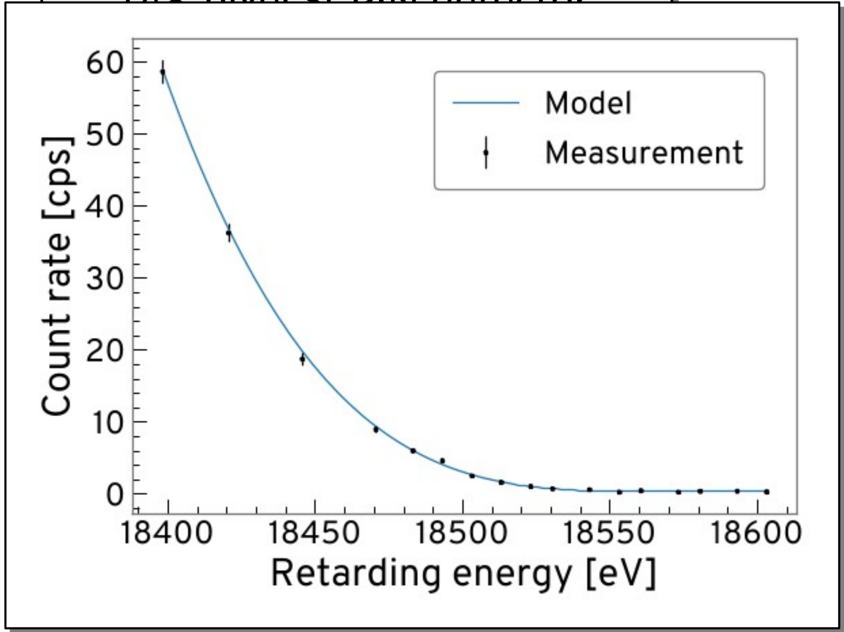


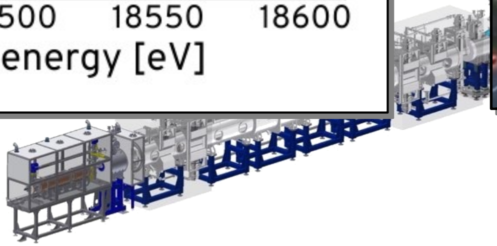
KATRIN Working Principle



Focal plane detector

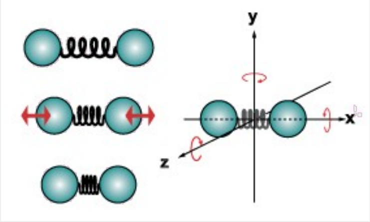
- 148 pixel Si-PIN detector





Systematic uncertainties

Molecular Final States

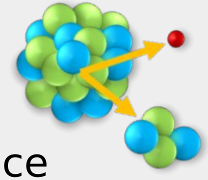


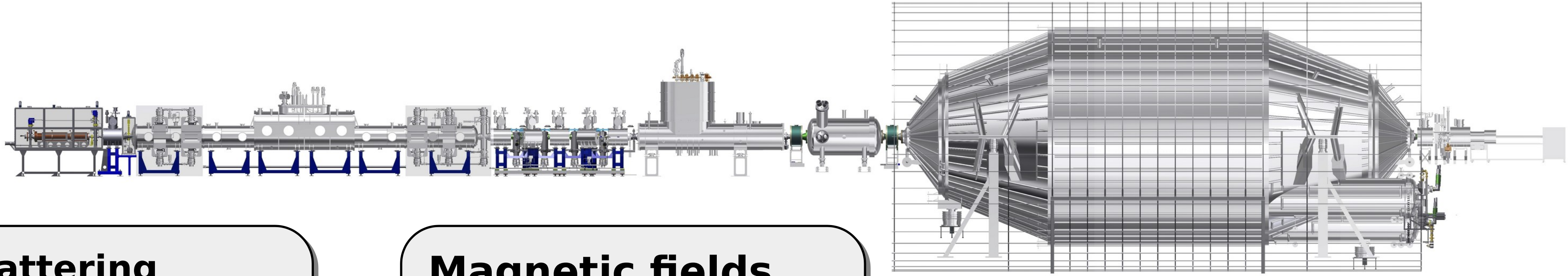
Activity fluctuations

Challenge: < 0.1 %

Background:

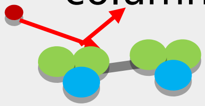
- time correlation
- retarding potential dependence
- Challenge: < 0.1 cps





Scattering

- energy loss
- column density



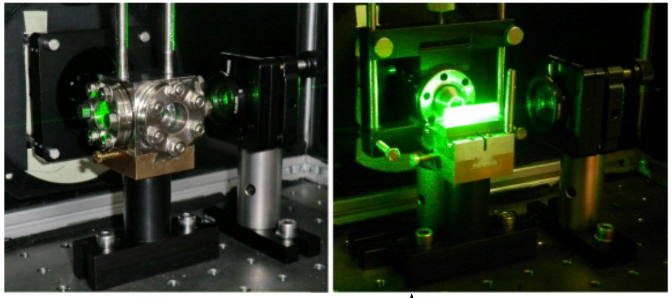
Magnetic fields

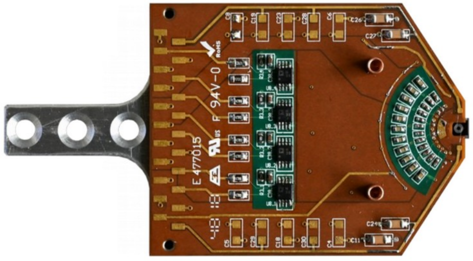
- source
- spectrometer
- detector

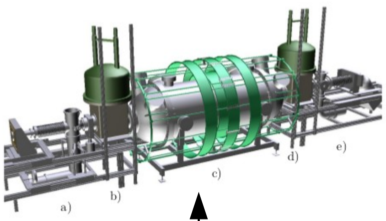
Data combination

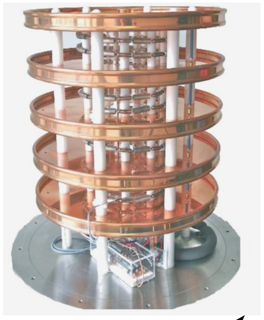
Key Monitoring Devices

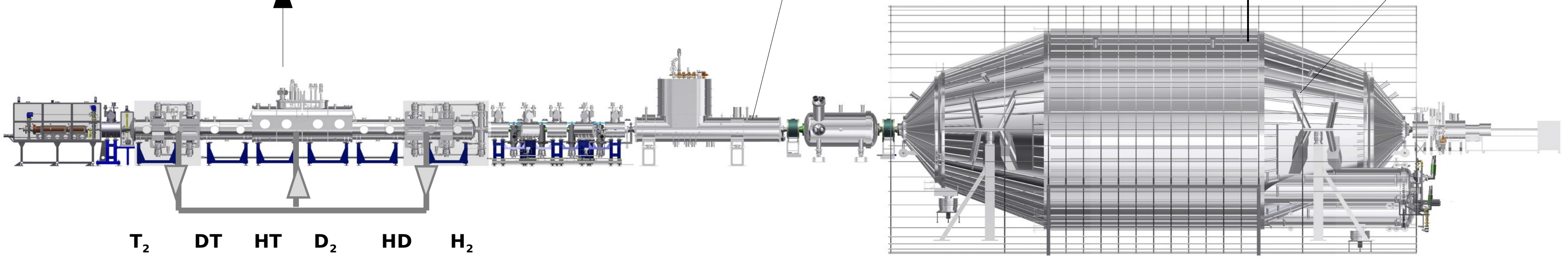
Laser Raman system: monitoring of tritium purity and gas composition at the 0.1% level
Forward beam monitor: monitoring of activity at the 0.1% level
High voltage system: monitoring of high voltage at the ppm level (20 mV)



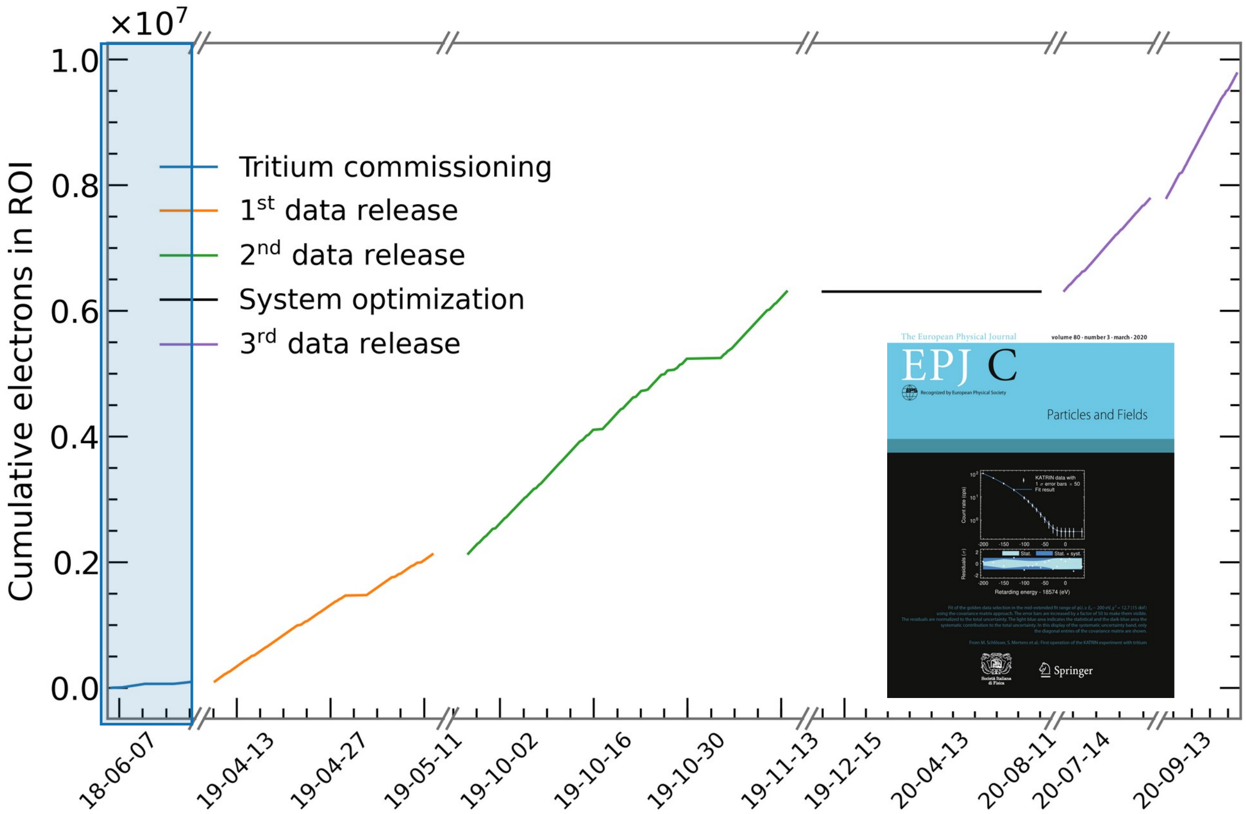




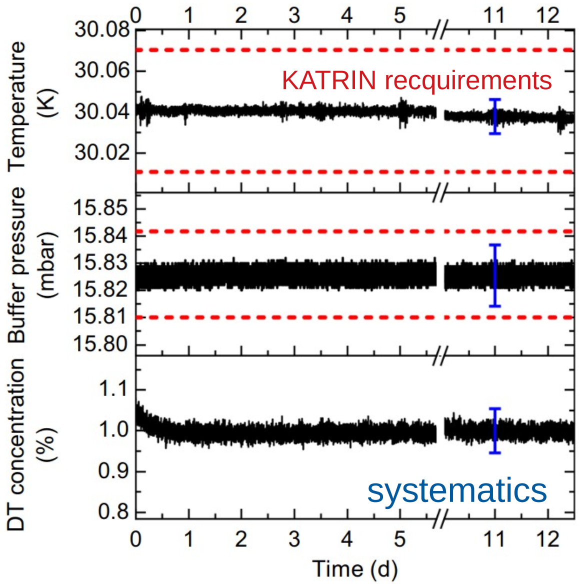




First tritium campaign

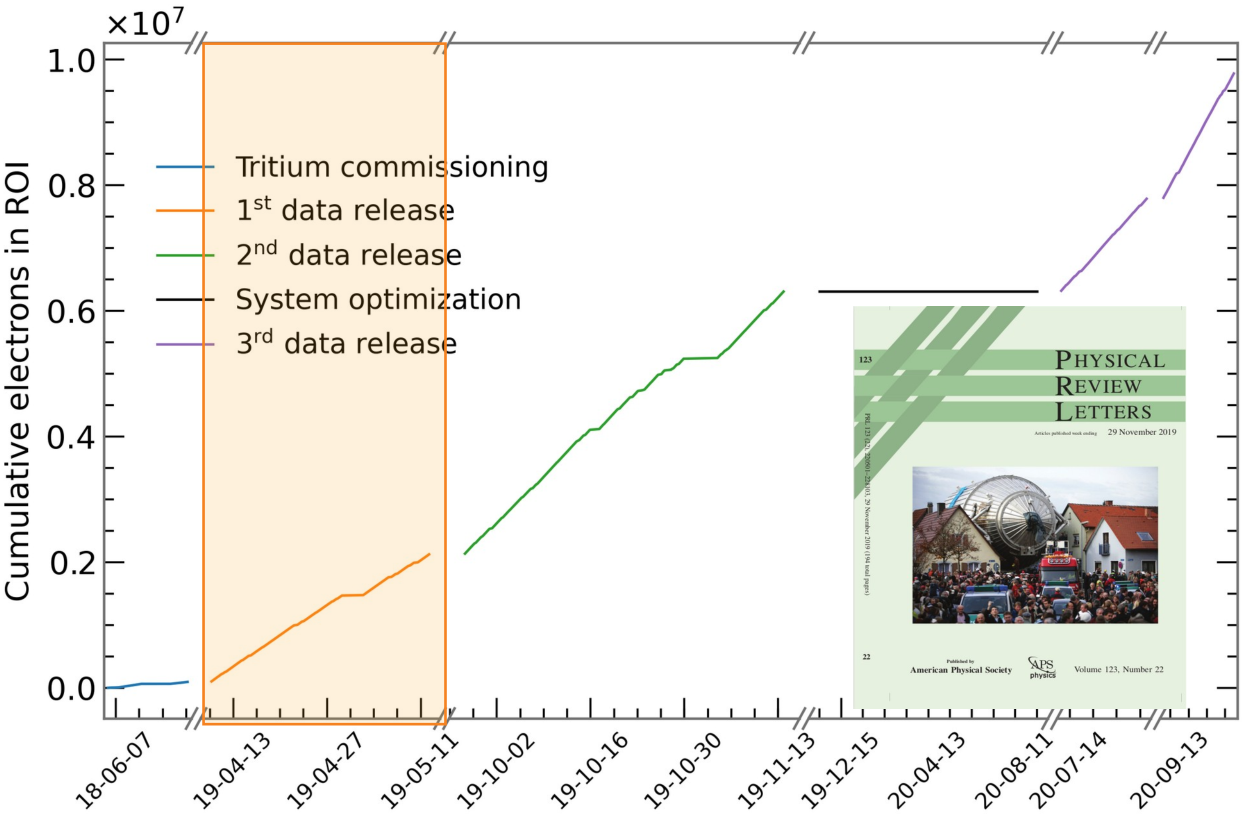


demonstration of system stability

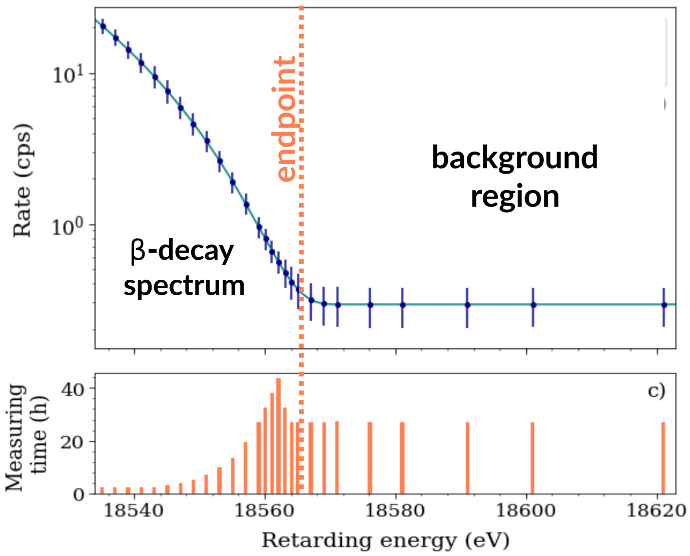


- *First operation of the KATRIN experiment with tritium.* **Eur. Phys. J. C 80, 264 (2020)**

1st neutrino mass campaign

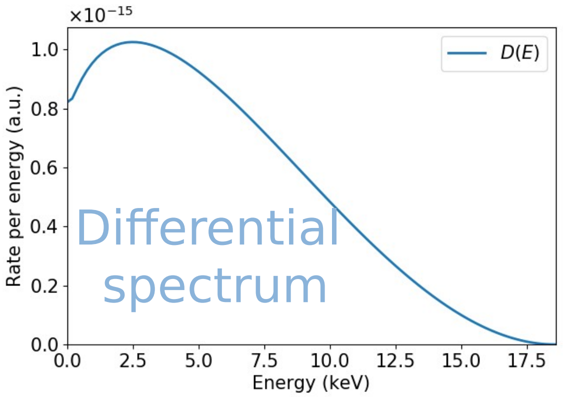


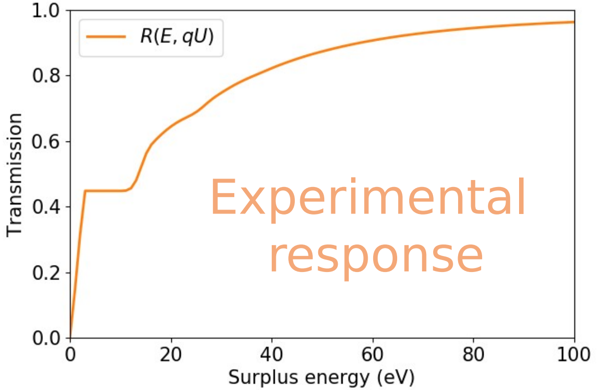
- Measurement time: 22 days
- Gas density: 22%
- Isotopic purity: 97.5% tritium
- Source activity: $2.45 \cdot 10^{10}$ Bq
- Total statistics: $2 \cdot 10^{6}$ e's



- *Improved Upper Limit on the Neutrino Mass from a Direct Kinematic Method by KATRIN*, KATRIN Collaboration, **Phys. Rev. Lett. 123, 221802 (2019)**

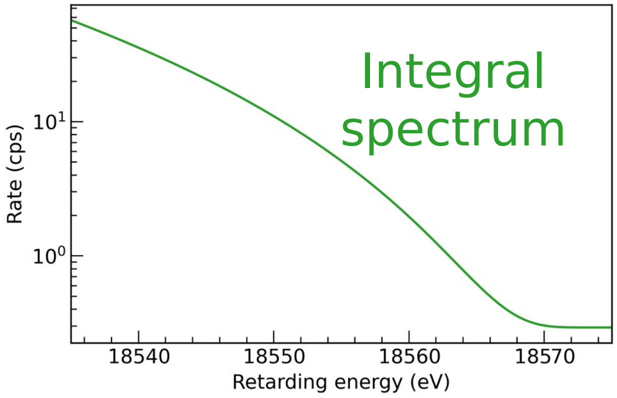
Model





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

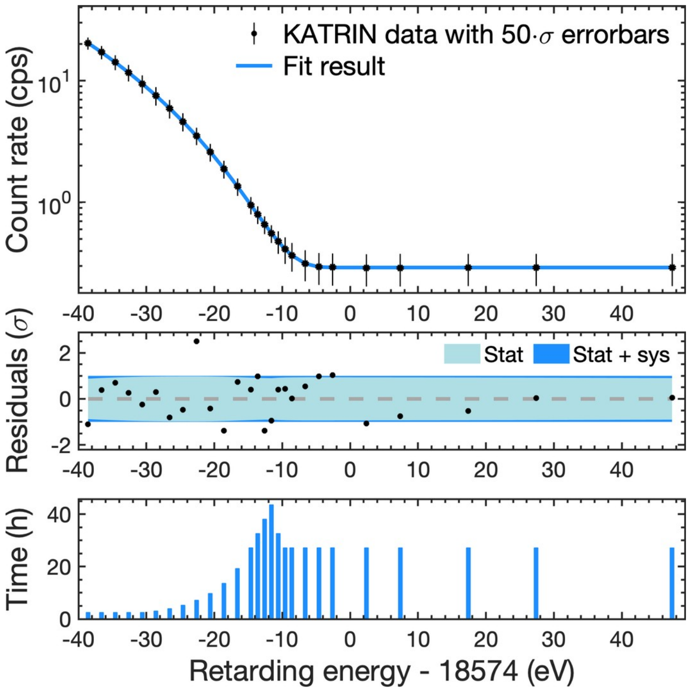
- Fermi theory
- Molecular final states
- Doppler broadening
- Radiative corrections
- …



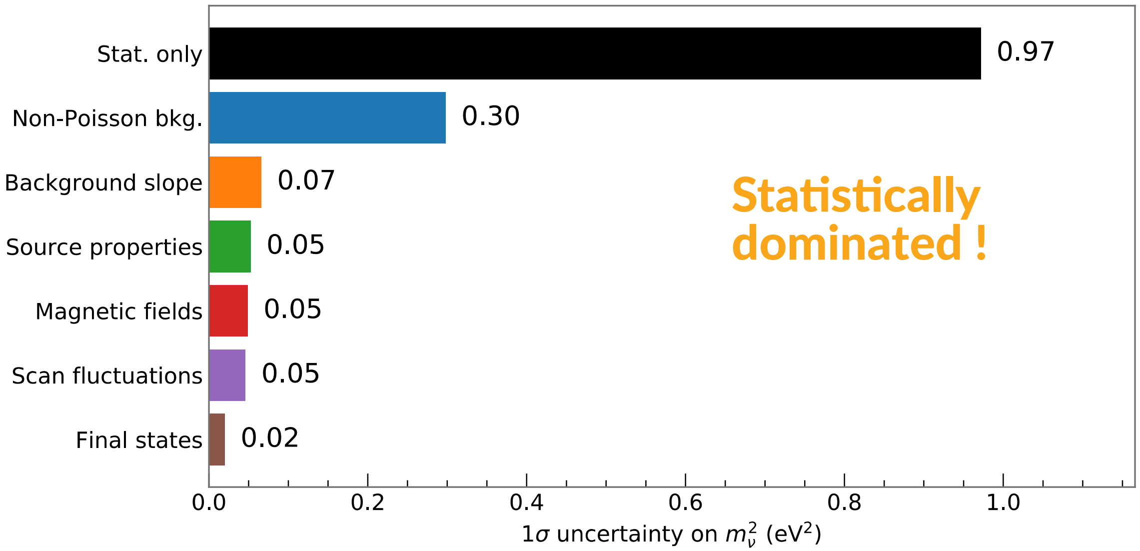
- Spectrometer resolution
- Scattering in the source
- Synchrotron radiation
- …

https://arxiv.org/pdf/2101.05253.pdf

1^{st} neutrino mass campaign



PRL 123, 221802 (2019)



PRL 123, 221802 (2019)

Statistically dominated !

Neutrino Properties **PDG !**

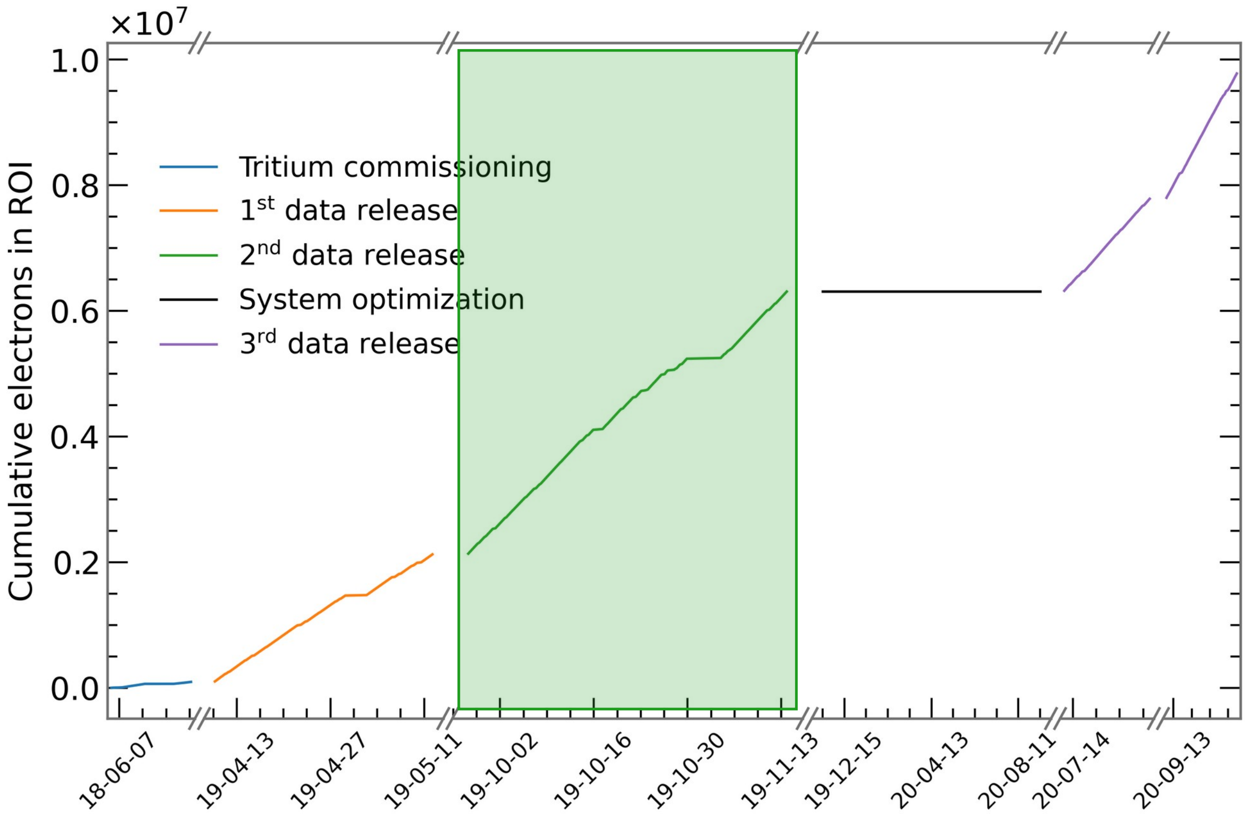
See the note on "Neutrino properties listings" in the Particle

Mass $m <$ 1.1 eV, CL = 90% (tritium decay)

- Best fit value : $m_\nu^2 = (-1.0 \, {}^{+\,0.9}_{-\,1.1})\ \mathrm{eV}^2$
- Limit : $m_\nu < 1.1\ \mathrm{eV}\ (90\%\ \mathrm{CL})$

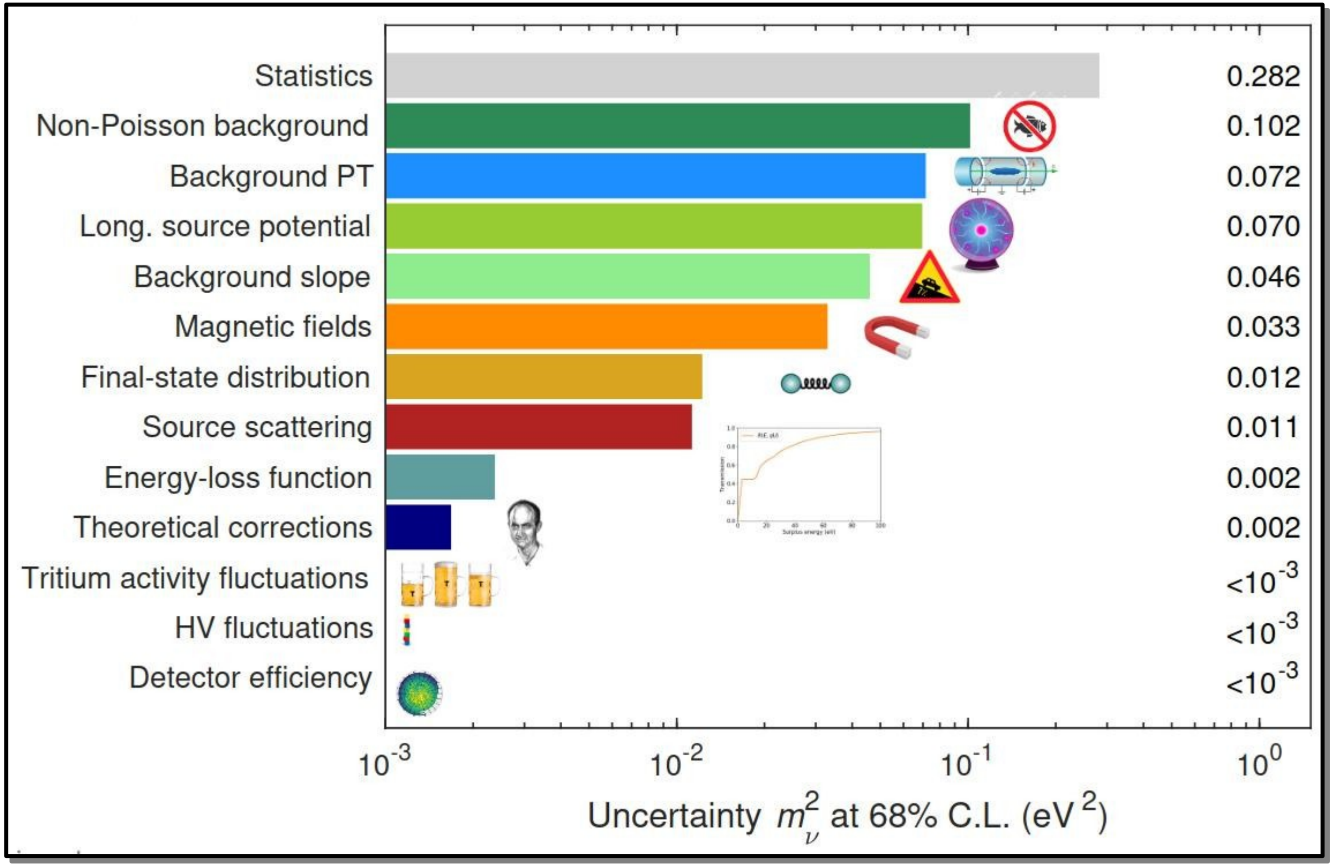
BAT : $m_\nu < 0.9\ \mathrm{eV}\ (90\%\ \mathrm{CL})$

2nd neutrino mass campaign



Gas density : 84 %
Sensitivity : $m_\nu < 0.7$ eV (90% CL)
Electrons in ROI : $4.2 \cdot 10^6$
Scan time : 31 days

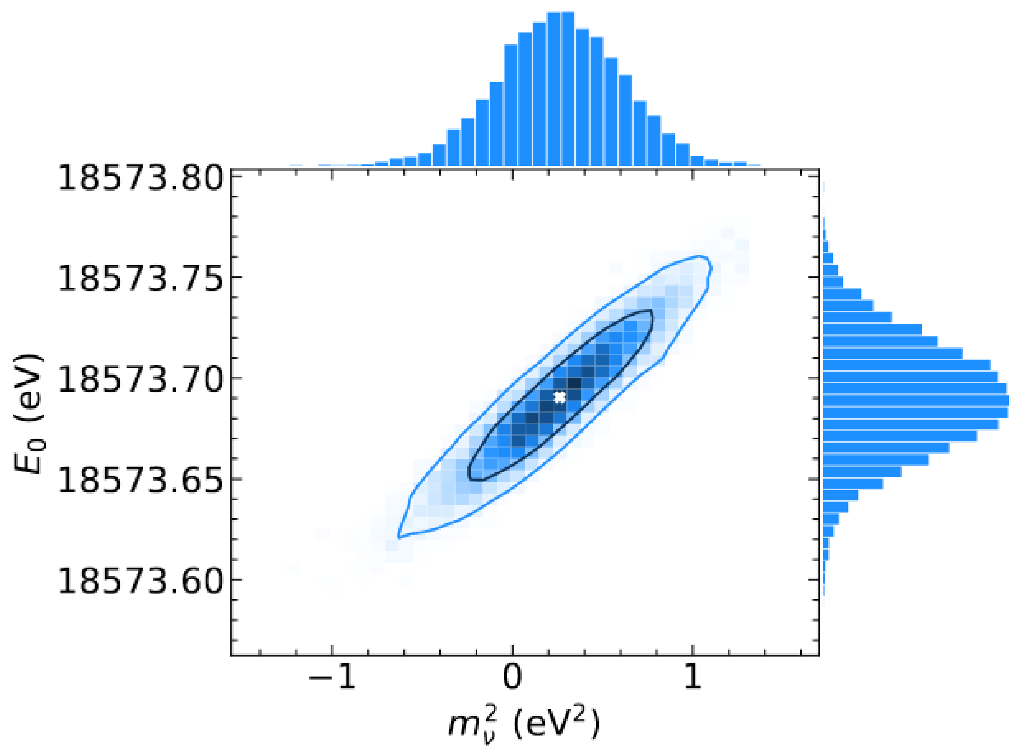
2^{nd} neutrino mass campaign



Gas density : 84 %
Sensitivity : m_ν < 0.7 eV (90% CL)
Electrons in ROI : $4.2 \cdot 10^6$
Scan time : 31 days

$\sigma_{stat} \sim 0.28\ eV^2$
$\sigma_{syst} \sim 0.15\ eV^2$
$\sigma_{tot} \sim 0.35\ eV^2$

2^{nd} neutrino mass campaign

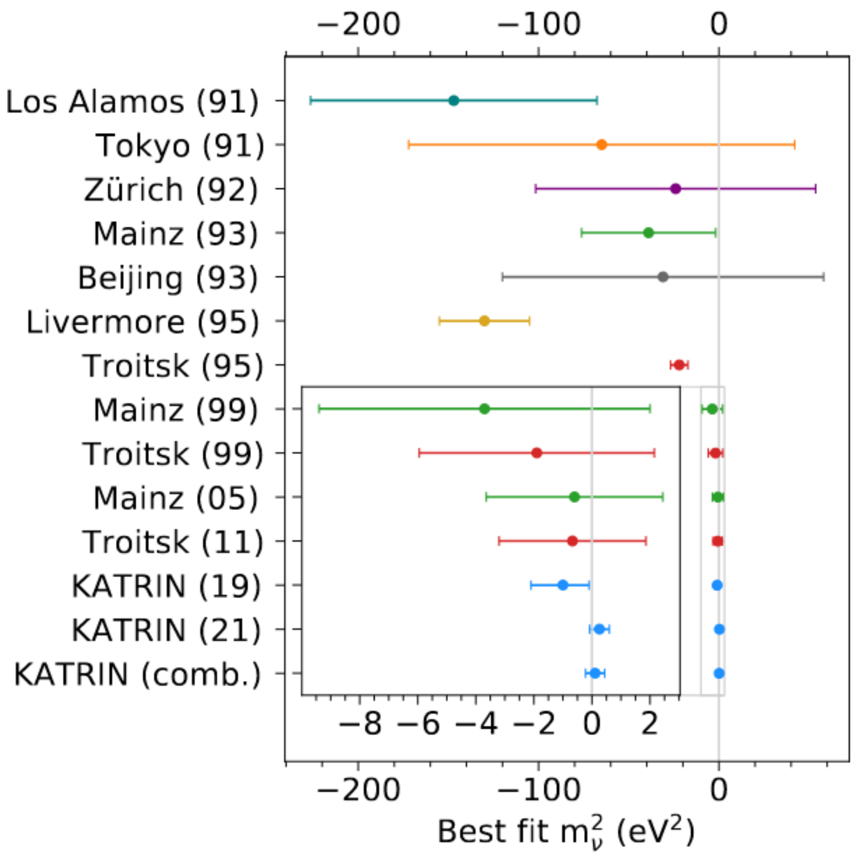


Gas density : 84 %
Sensitivity : m_ν < 0.7 eV (90% CL)
Electrons in ROI : $4.2 \cdot 10^6$
Scan time : 31 days

σ_{stat} ~ 0.28 eV^2
σ_{syst} ~ 0.15 eV^2
σ_{tot} ~ 0.35 eV^2

Results:
$m_\nu^2 = 0.26 \pm 035$ eV^2
m_ν < 0.9 eV (90% CL)

2nd neutrino mass campaign



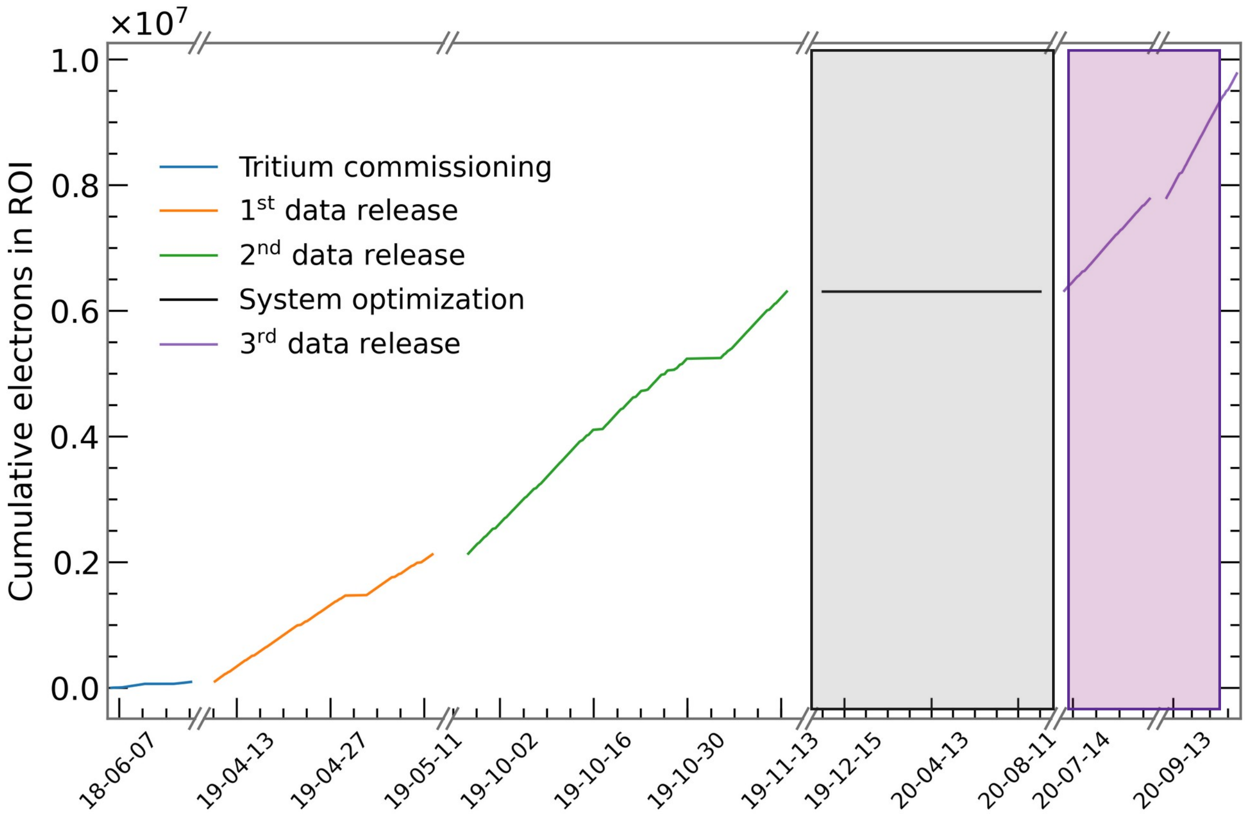
Combining the two campaigns :
m_ν < 0.8 eV (90% CL)

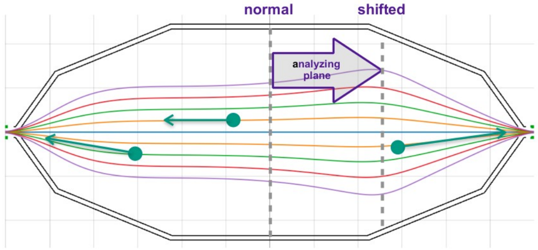
First direct neutrino-mass measurement with sub-eV sensitivity

M. Aker,[1] A. Beglarian,[2] J. Behrens,[3,4] A. Berlev,[5] U. Besserer,[1] B. Bieringer,[6] F. Block,[3] B. Bornschein,[1] Bornschein,[4] M. Böttcher,[6] T. Brunst,[7,8] T. S. Caldwell,[9,10] R. M. D. Carney,[11] L. La Cascio,[3] S. Chilingaryan,[2] W. Choi,[3] K. Debowski,[12] M. Deffert,[3] M. Descher,[3] D. Díaz Barrero,[13] P. J. Doe,[14] O. Dragoun,[15] G. Drexlin,[3]

(submitted arxiv: 2105.08533.pdf)

Next neutrino mass campaigns



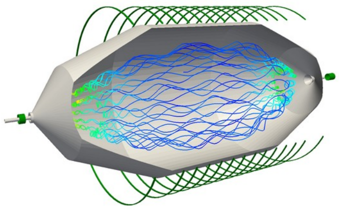


Plasma investigations

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

Improve background configuration

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

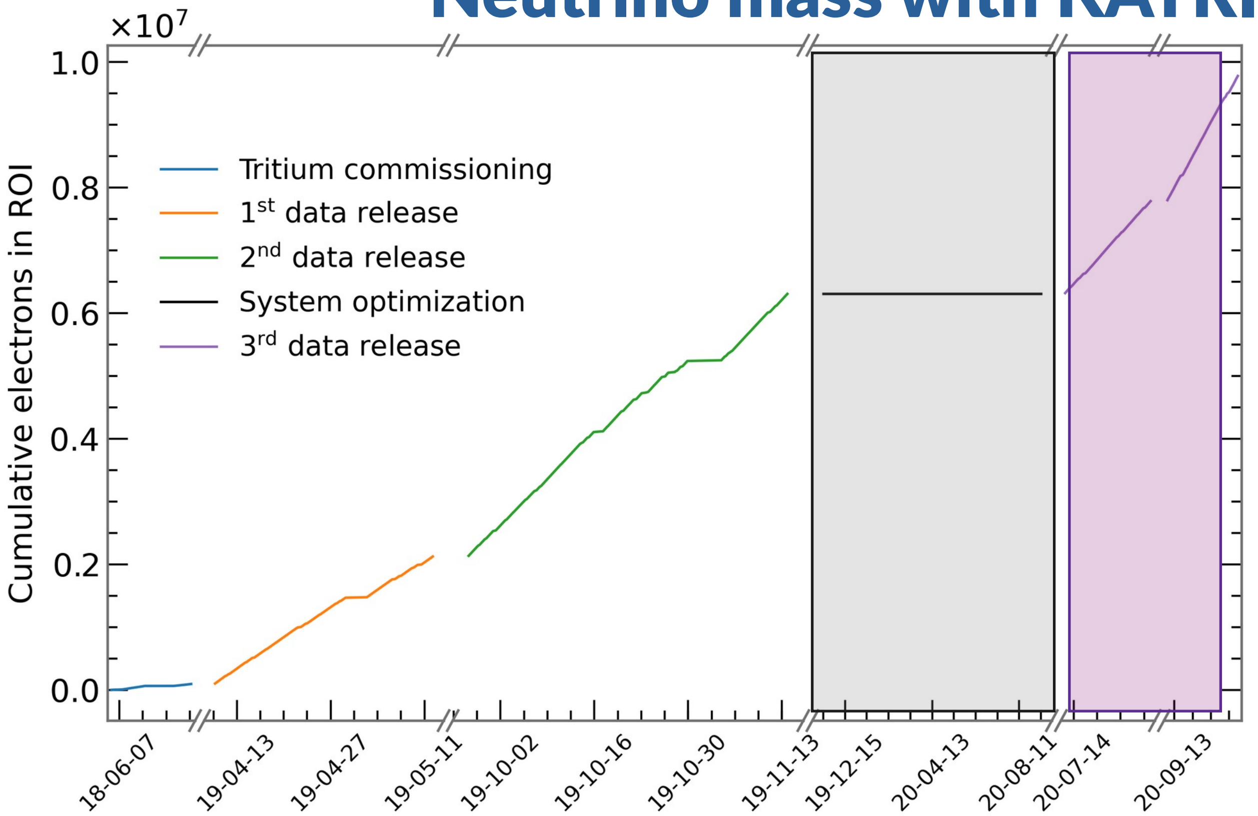


Data taking since Summer 2020 :

→ 1000 days ↔ < 0.3 eV (90 % CL)

Conclusion

Neutrino mass with KATRIN



- 1st tritium campaign :
  → **very good stability**
- 1st mass campaign
  → **best limit on the m_ν** from direct measure (m_ν<1.1 eV)
- 2nd mass campaign
  → **sub-eV regime**

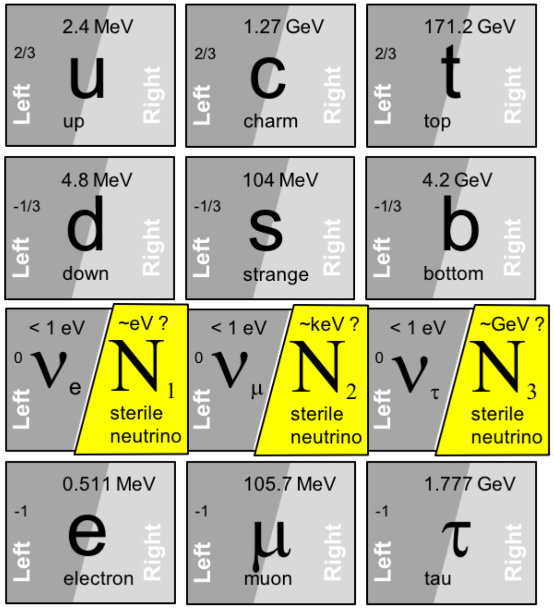
How to generate mass from the SM ?

- In the SM, fermions masses = Yukawa coupling between RH-LH and Higgs field
- No RH neutrinos exist in SM → neutrino massless
- To generate mass : need of RH partners
- A lot of different models – all must extend SM

$$-\mathcal{L}_{M_\nu} = M_{D\,ij}\bar{\nu}_{si}\nu_{Lj} + \frac{1}{2}M_{N\,ij}\bar{\nu}_{si}\nu^c_{sj} + \text{h.c.}$$

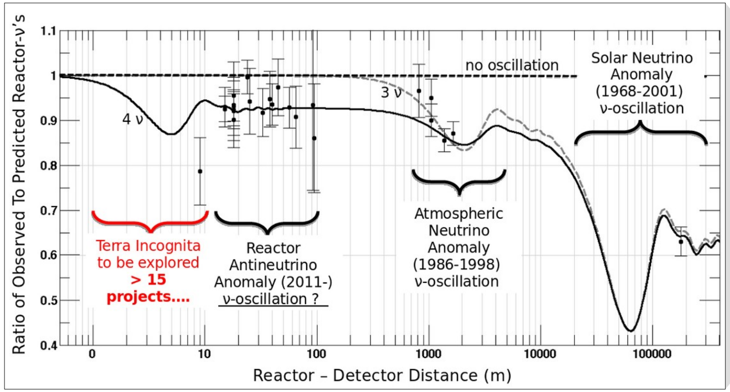
Dirac
mass term

Majorana
mass term

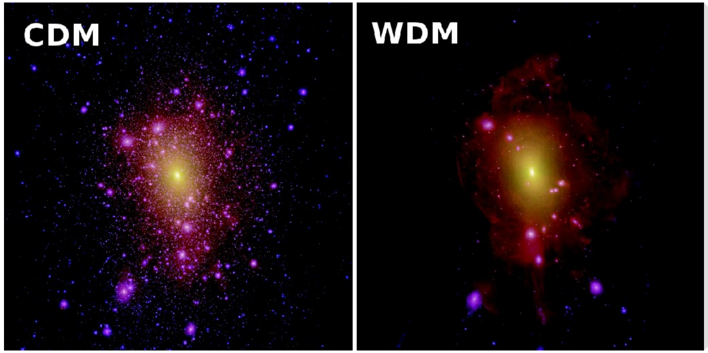


RH neutrinos → Sterile neutrinos

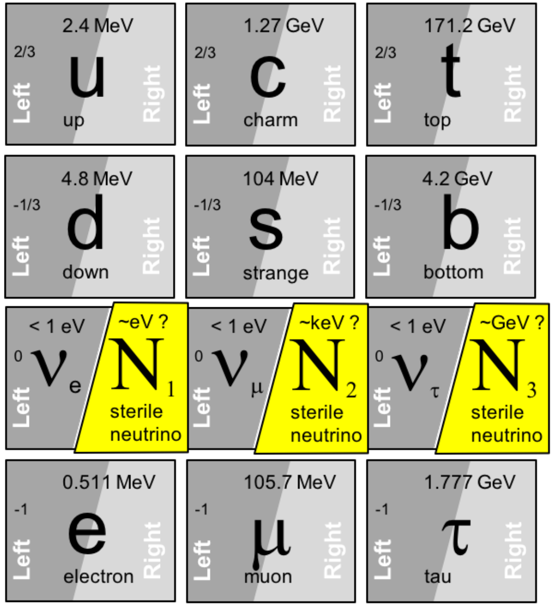
Is there a sterile neutrino ?



eV-scale:
Resolve anomalies in oscillation experiments



keV-scale:
Dark Matter candidate



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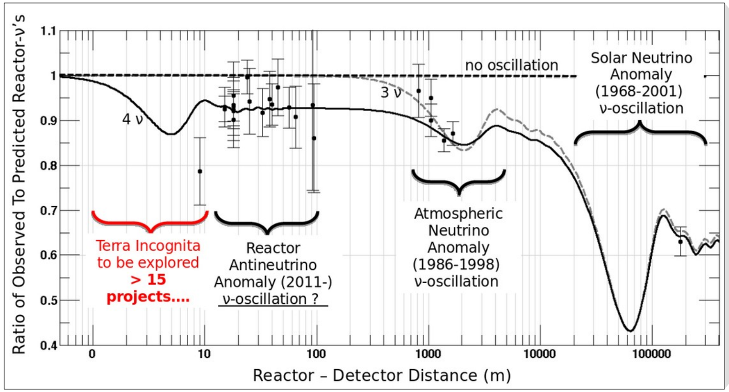

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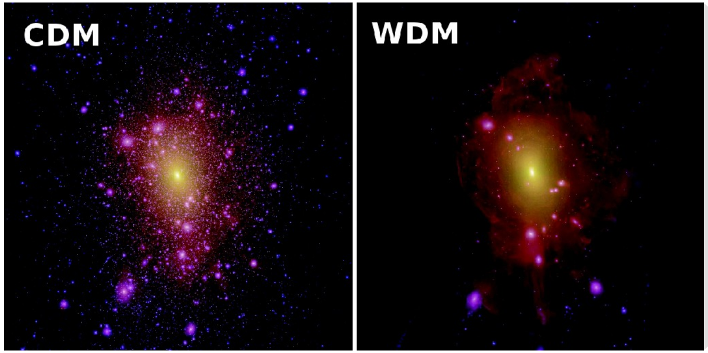

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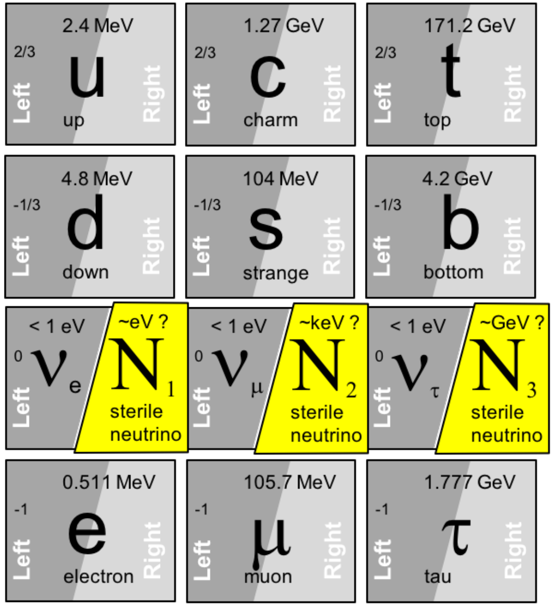
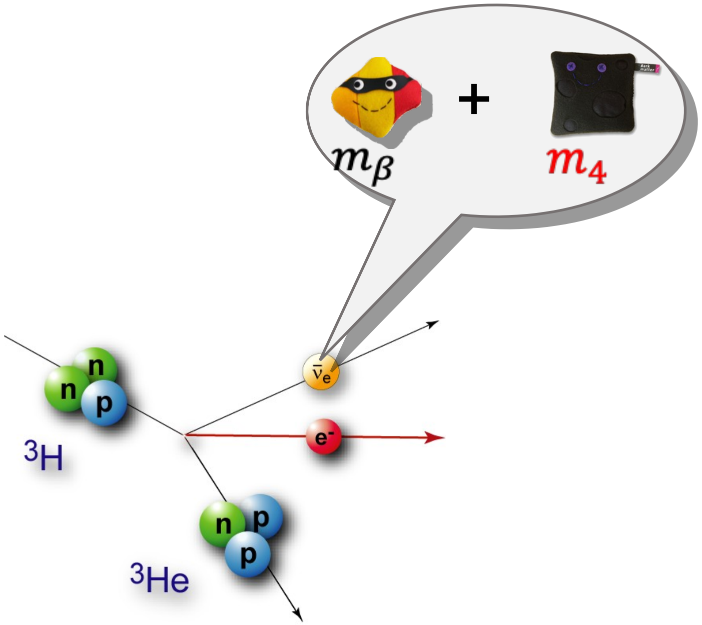
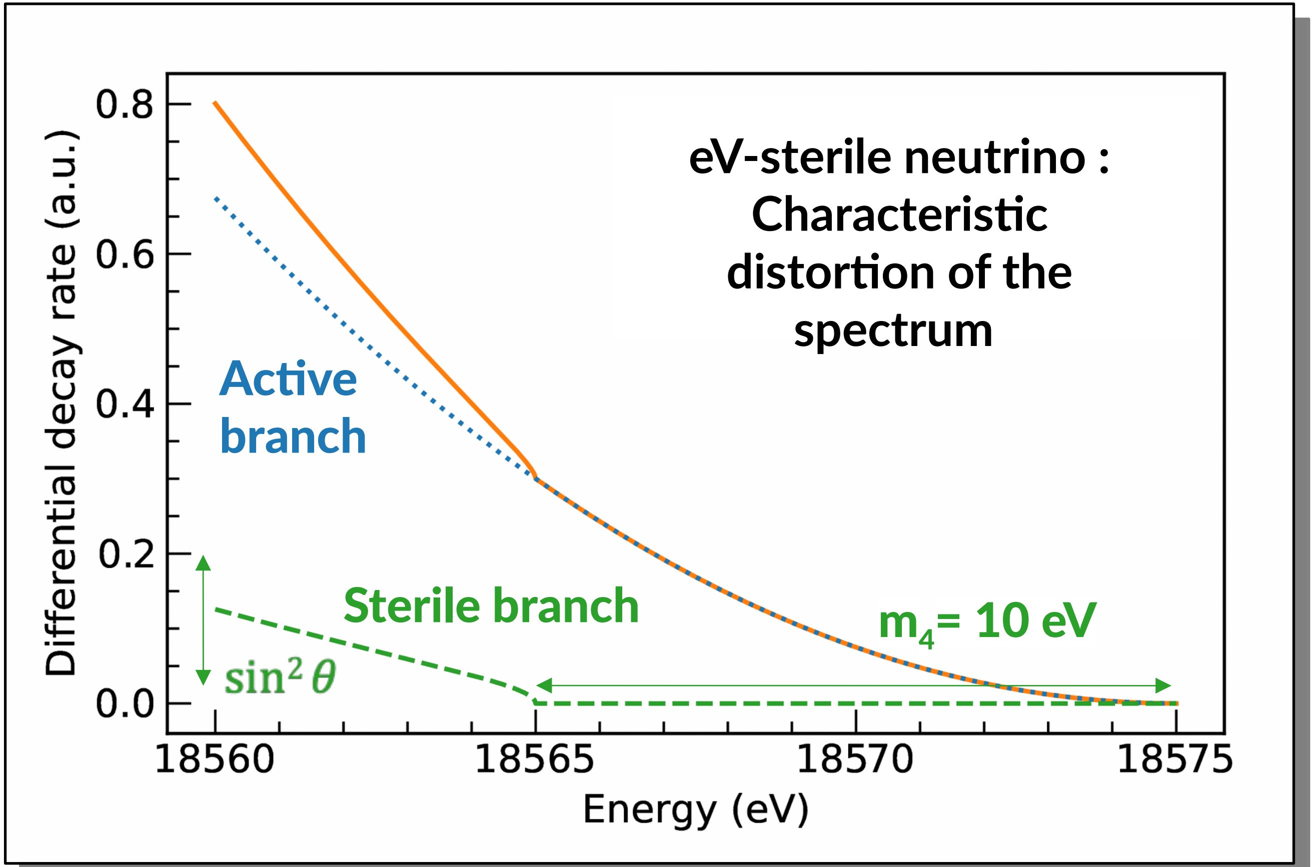
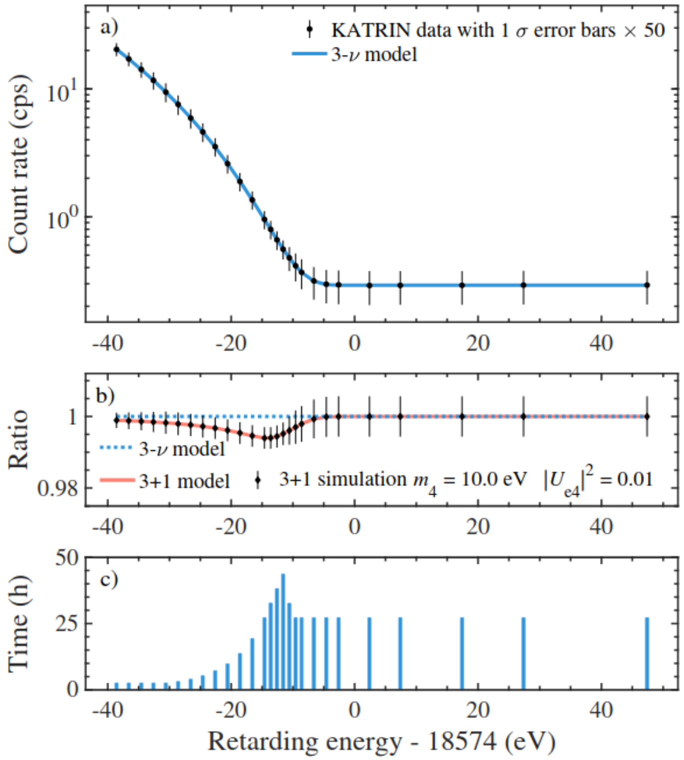


eV-sterile signature in β-decay

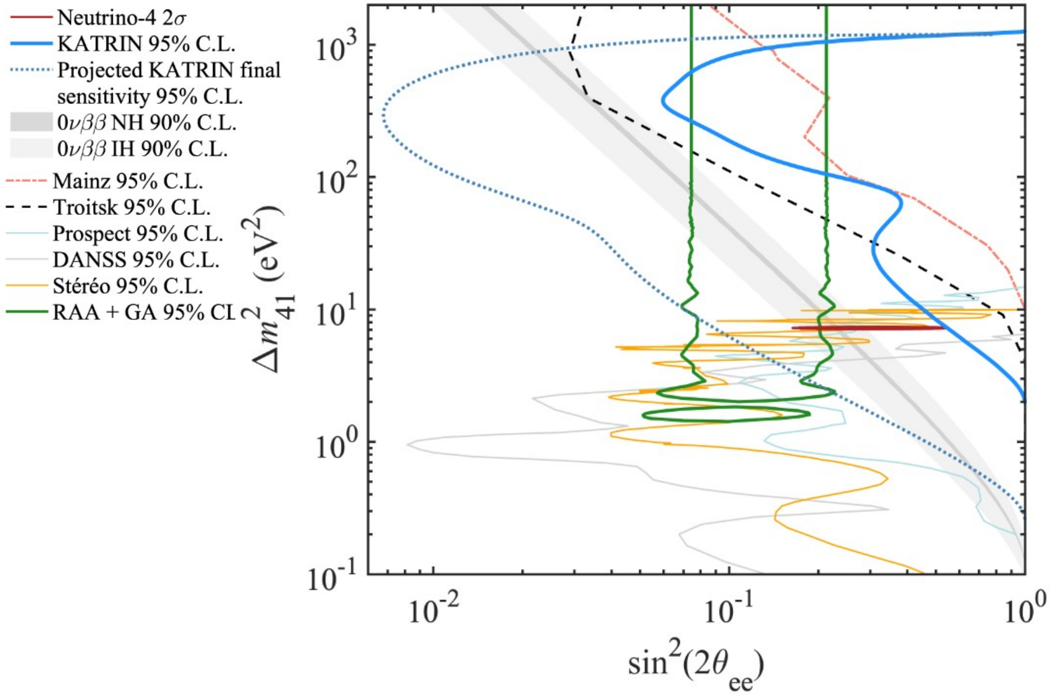




Sterile hunt with KATRIN



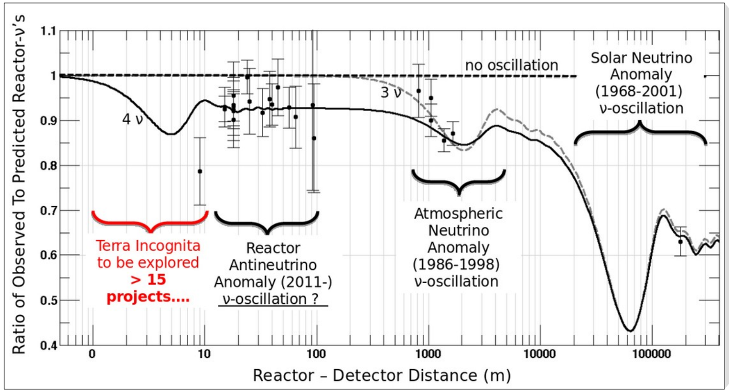
PRL 126, 091803



PRL 126, 091803

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

Is there a sterile neutrino ?



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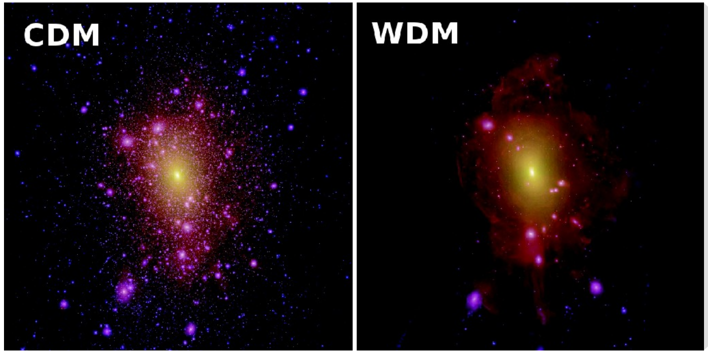
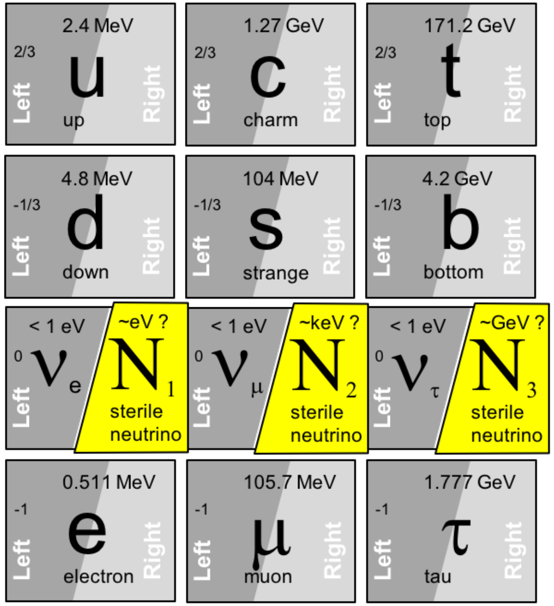
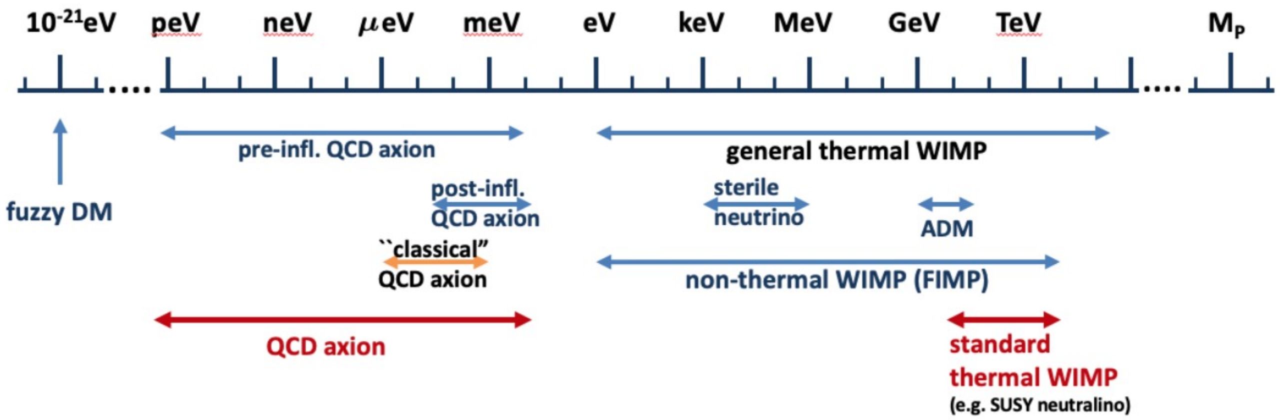
Resolve anomalies in oscillation experiments



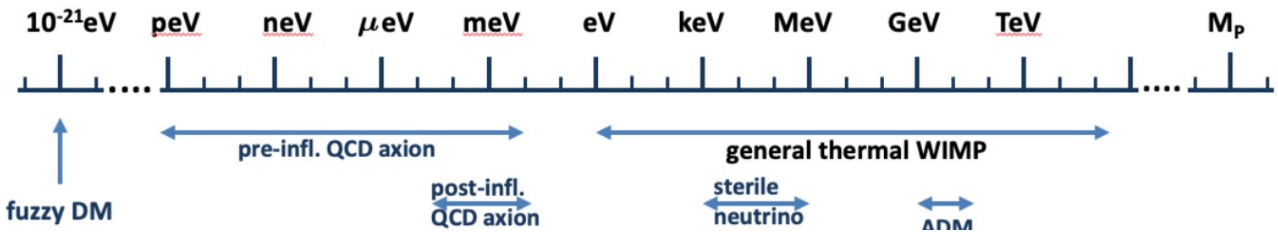
keV-scale:
Dark Matter candidate

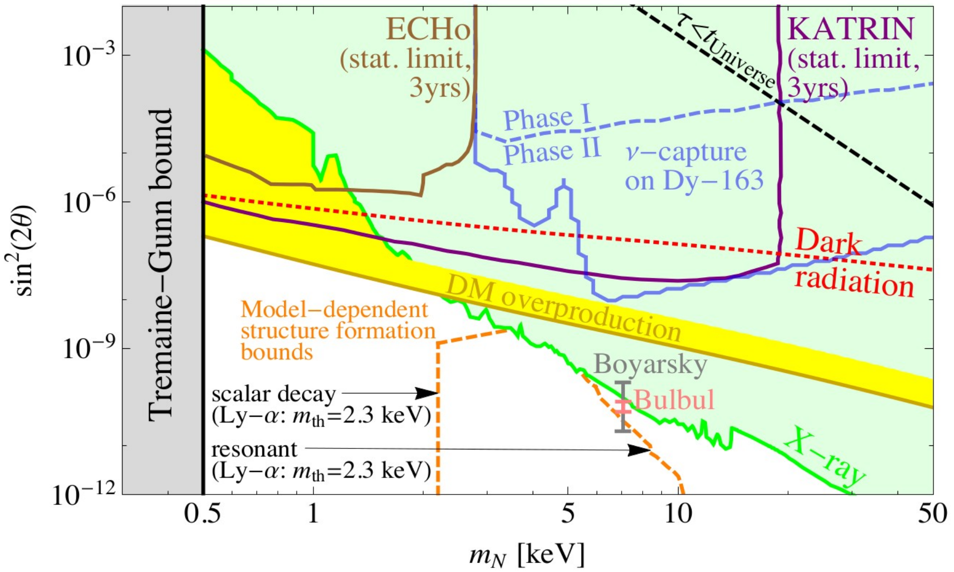


keV-sterile neutrinos as Dark Matter

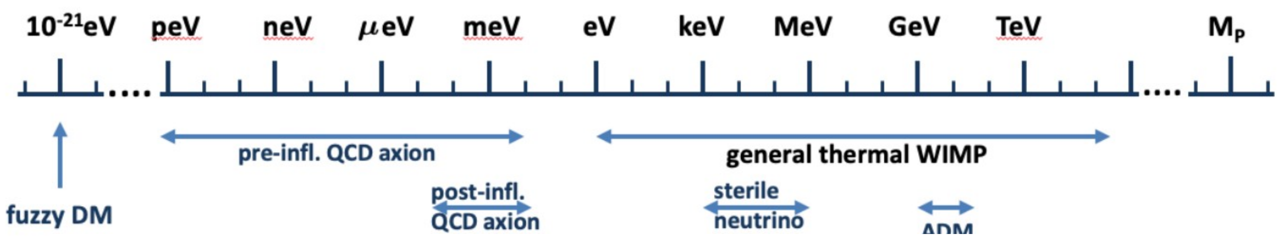


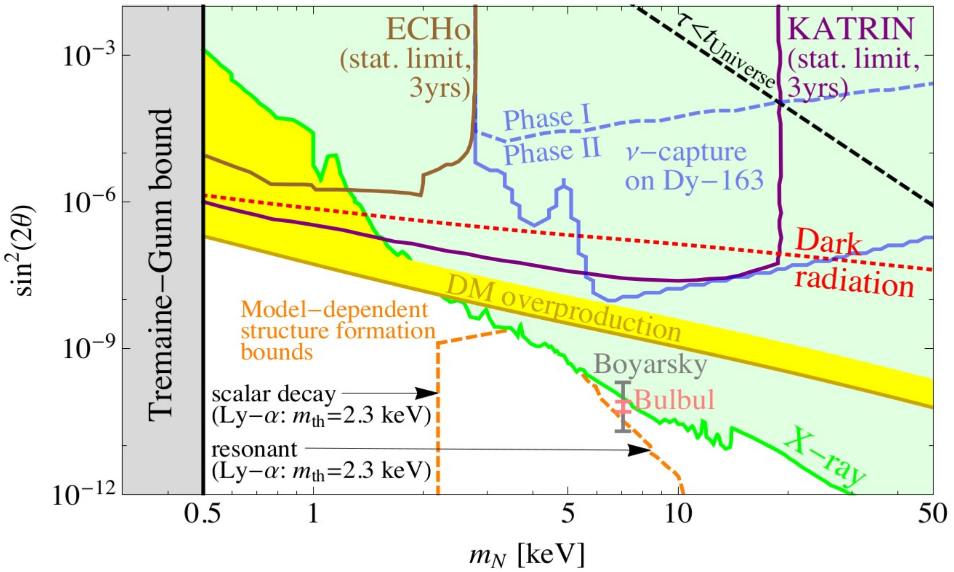
keV-sterile neutrinos as Dark Matter

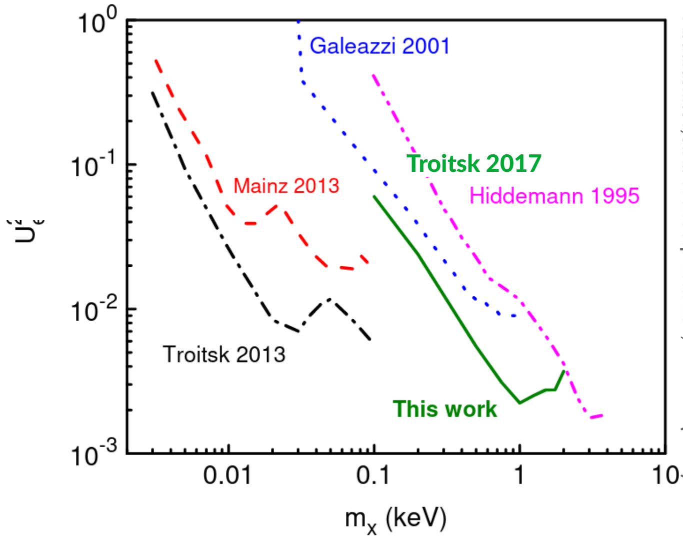




keV-sterile neutrinos as Dark Matter

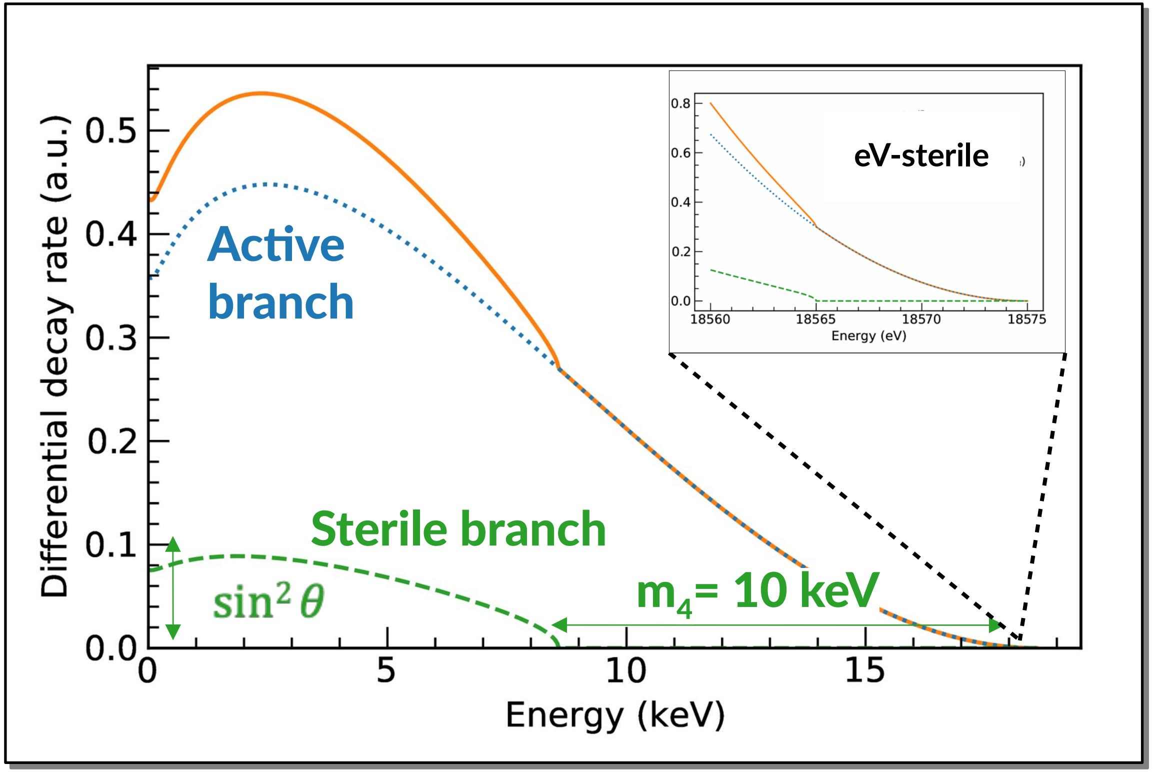




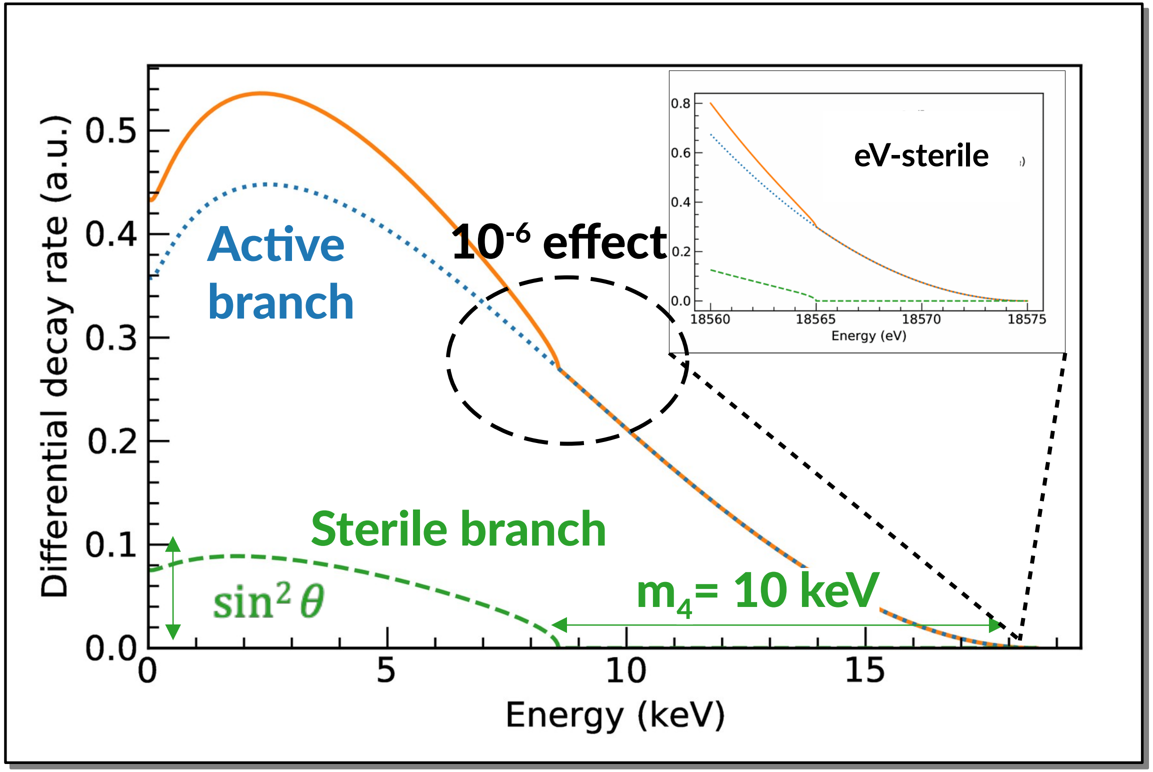


Abdurashitov, J.N. et al. Jetp Lett. 105, 753-757 (2017)

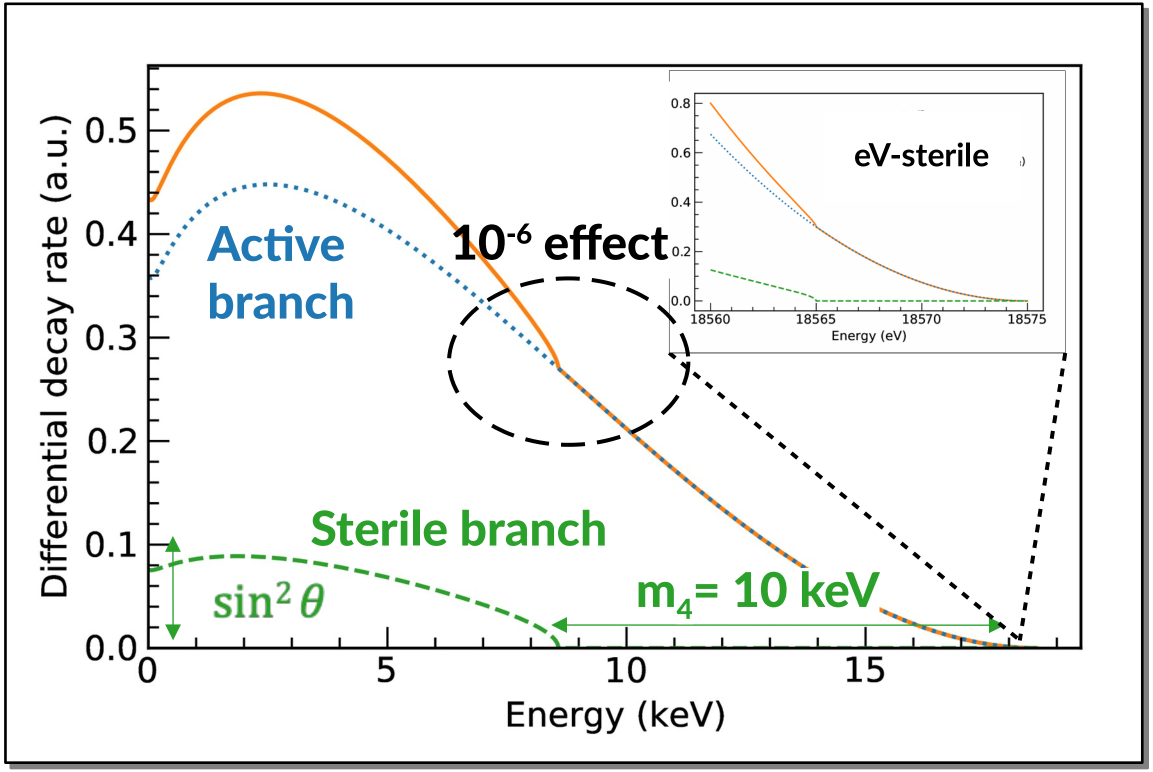
keV-sterile signature in β-decay



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 3x10^8 Hz)

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

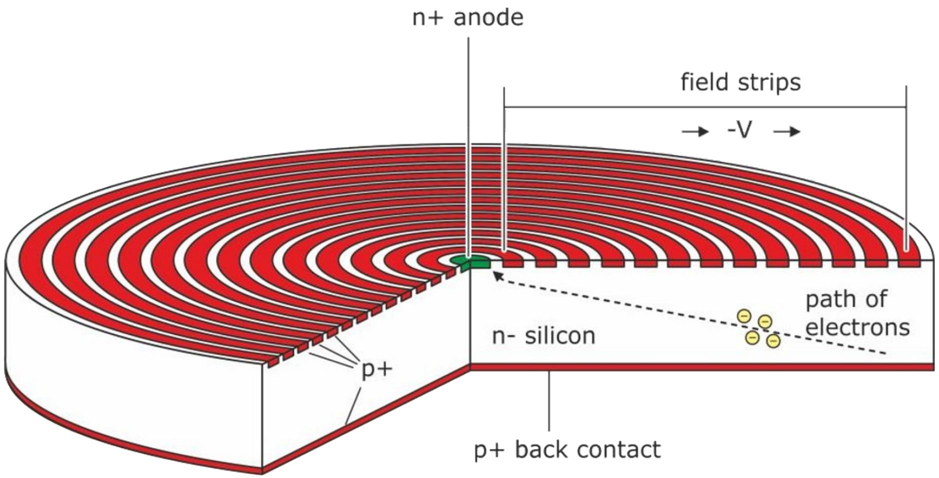
→ Highly **pixelised**

→ new detector is needed : the TRISTAN project

Silicon Drift Detectors

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 Project

Capability of handling high rates (> 3 x 10^8 cps)
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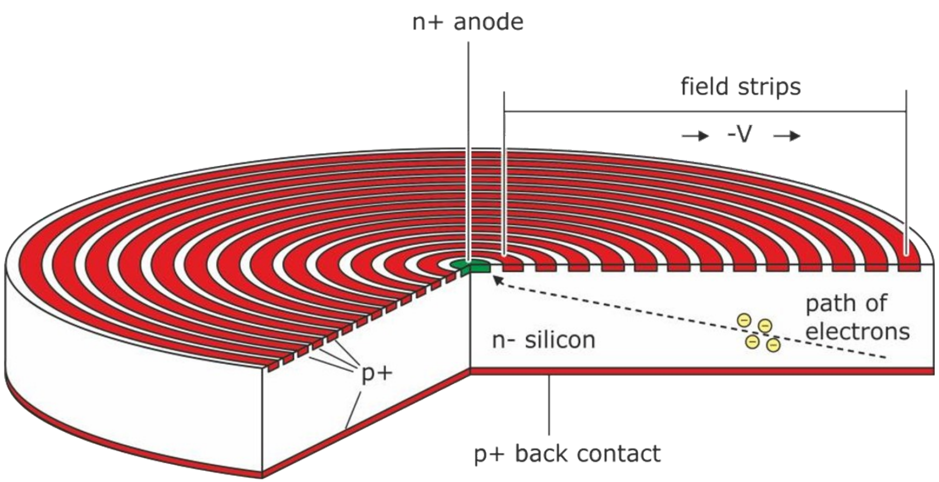
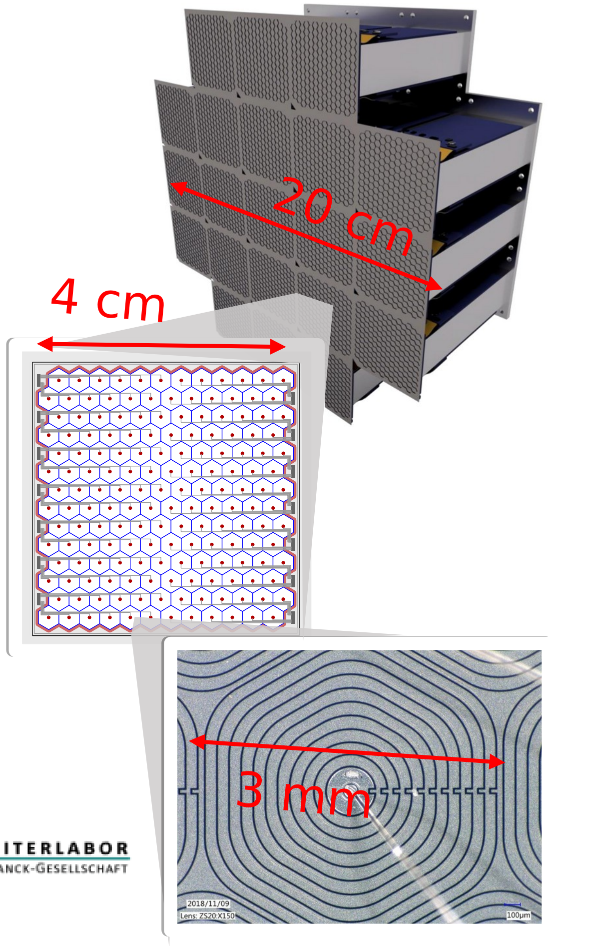
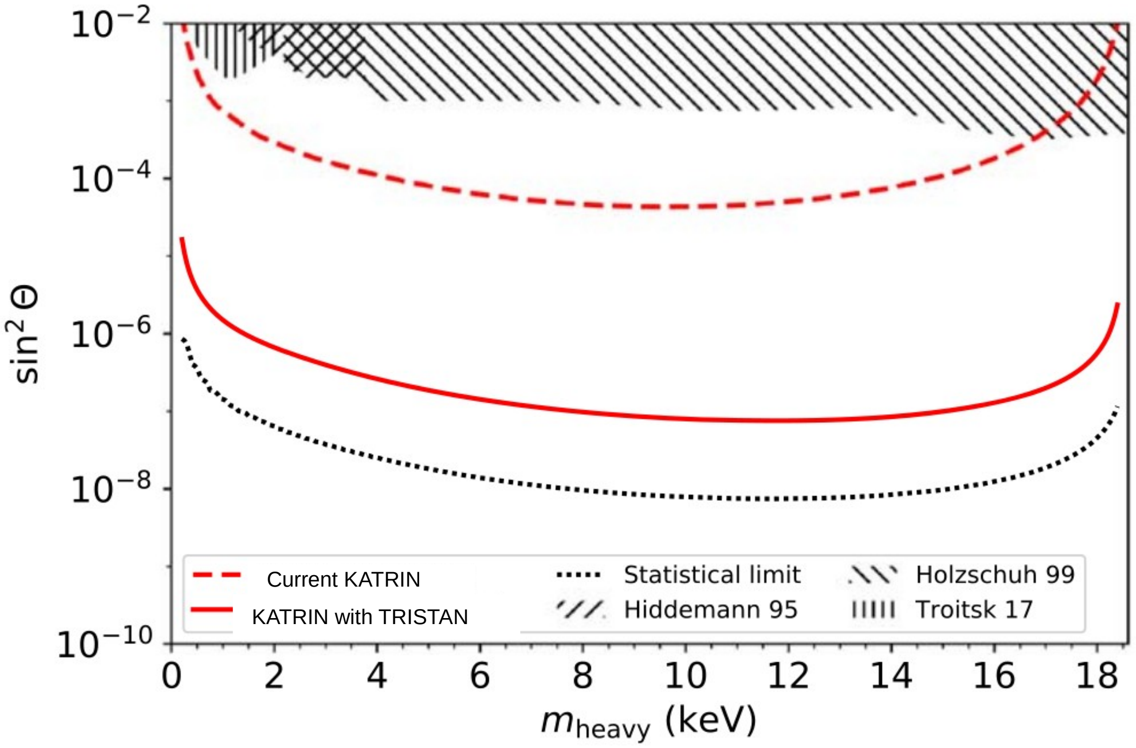




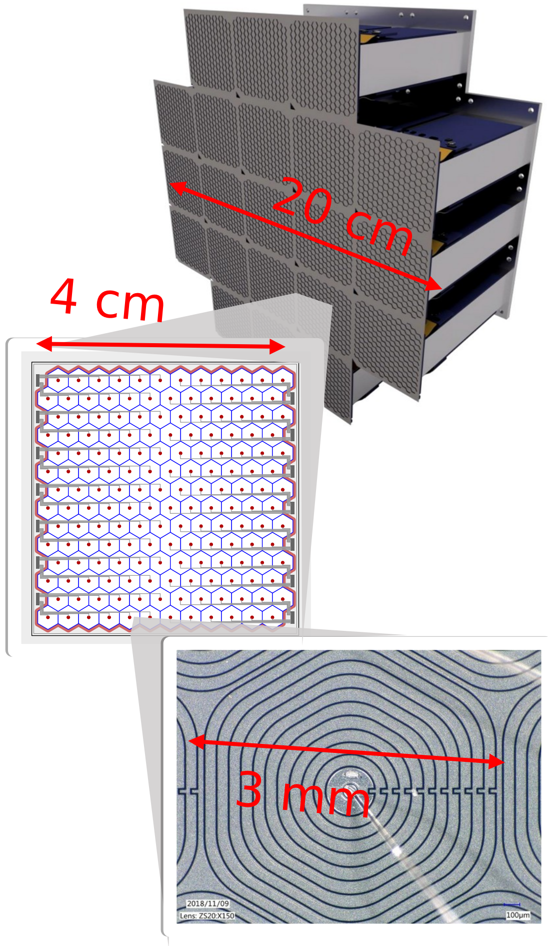
HALBLEITERLABOR DER MAX-PLANCK-GESELLSCHAFT

TRISTAN Project

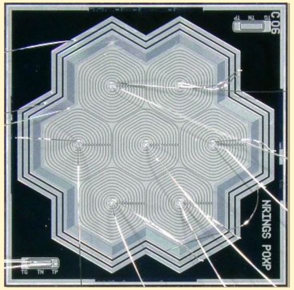
TRISTAN : Development of a large area SDD array and read-out system to look for keV-sterile neutrino with the KATRIN experiment



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



Staged approach

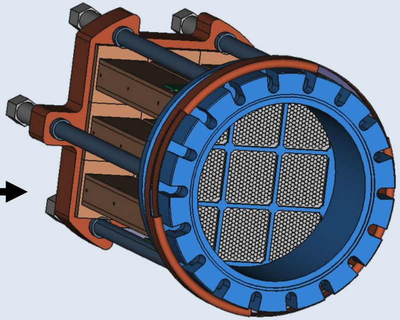


Prototypes

x24

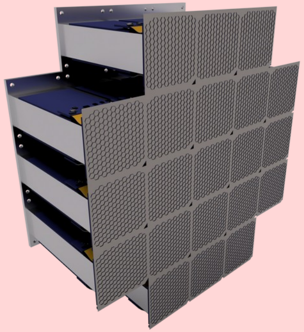
Module

x9



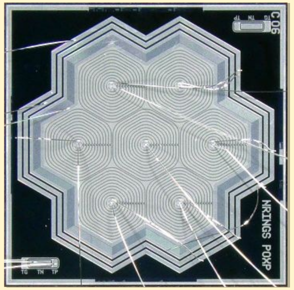
Phase 1

x2.5



Phase 2

Staged approach

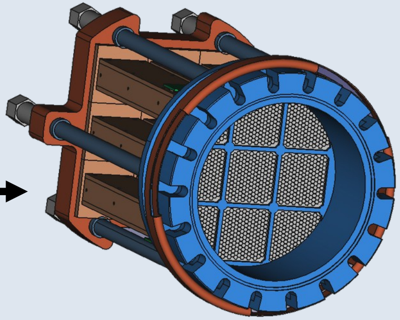


Prototypes

x24

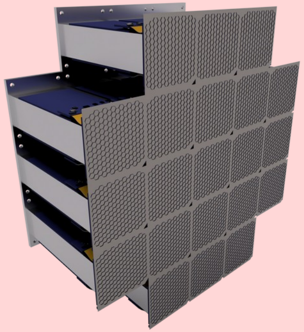
Module

x9



Phase 1

x2.5



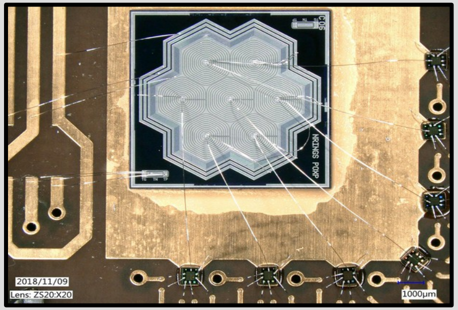
Phase 2

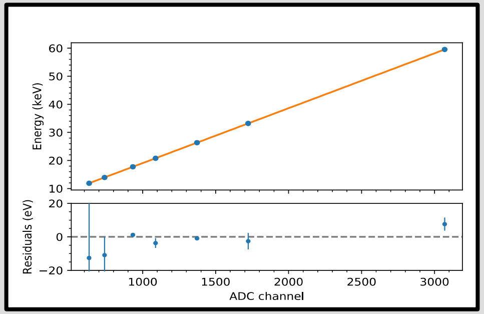
TRISTAN prototype
- 7-pixels with external CMOS

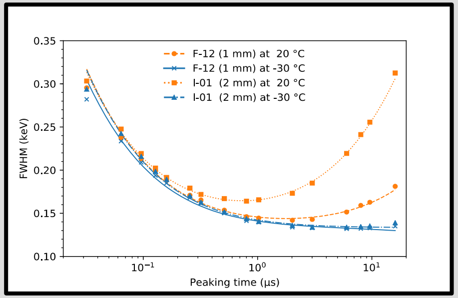
Prototype results

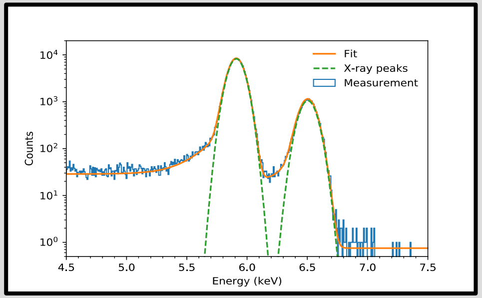
Photon response

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





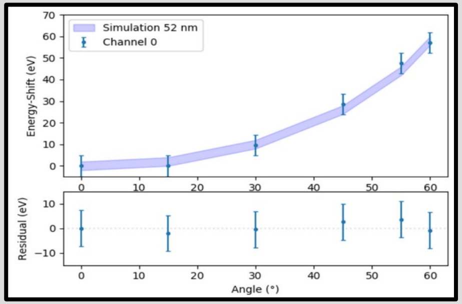


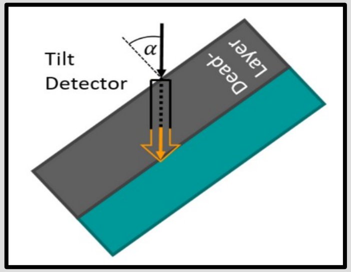


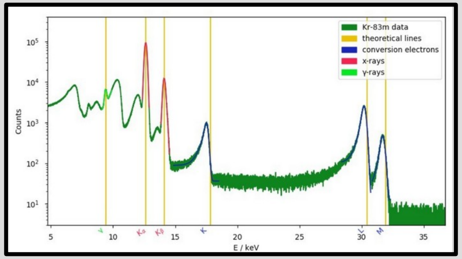
J. Phys. G46 46 065203 (2019)

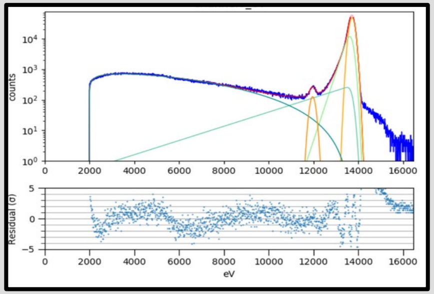
Electron response

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





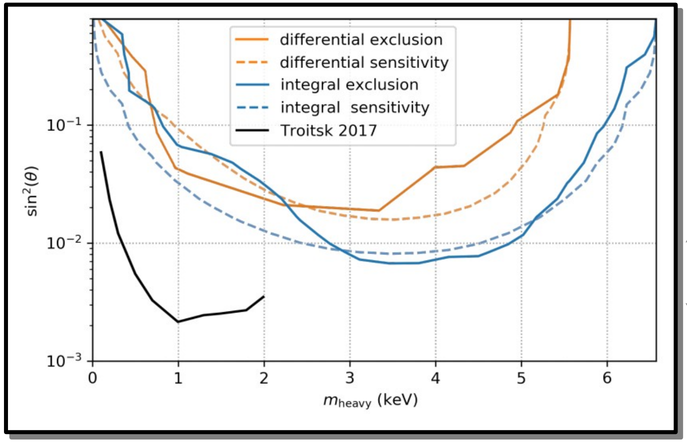




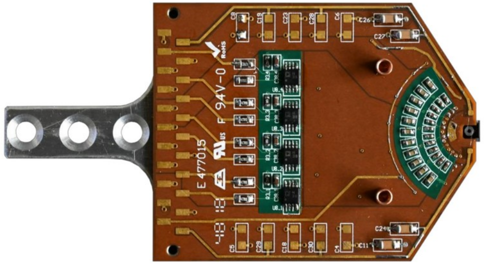
J. Phys. G: 48 015008 (2021)

Prototype applications

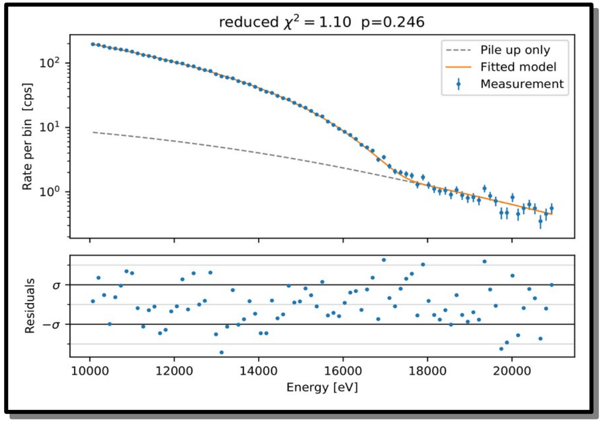
2017-2019 :
TRISTAN 7-pixels prototype implemented in **Troitsk** nu mass spectrometer → differential and integral measurements



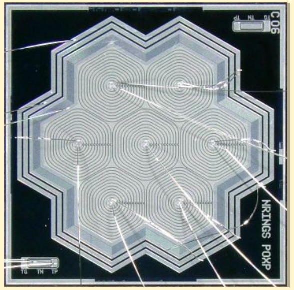
JINST14 P11013 (2019)



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

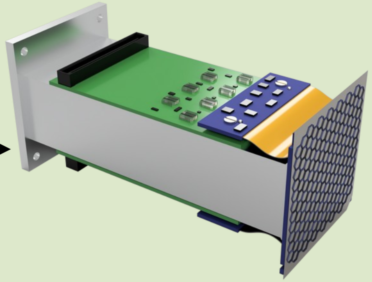


Staged approach



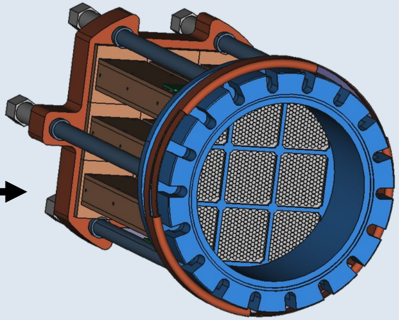
Prototypes

x24



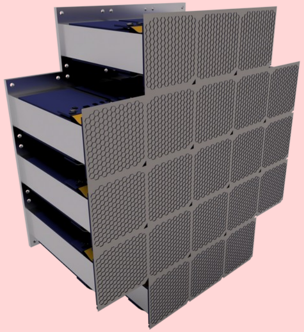
Module

x9



Phase 1

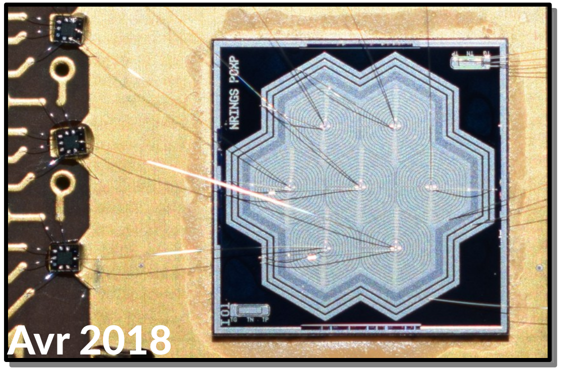
x2.5

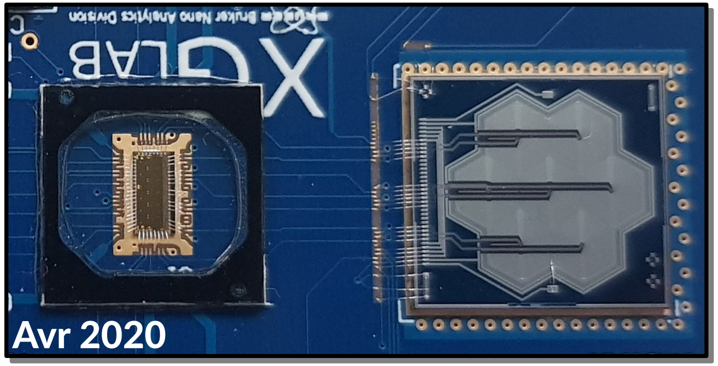


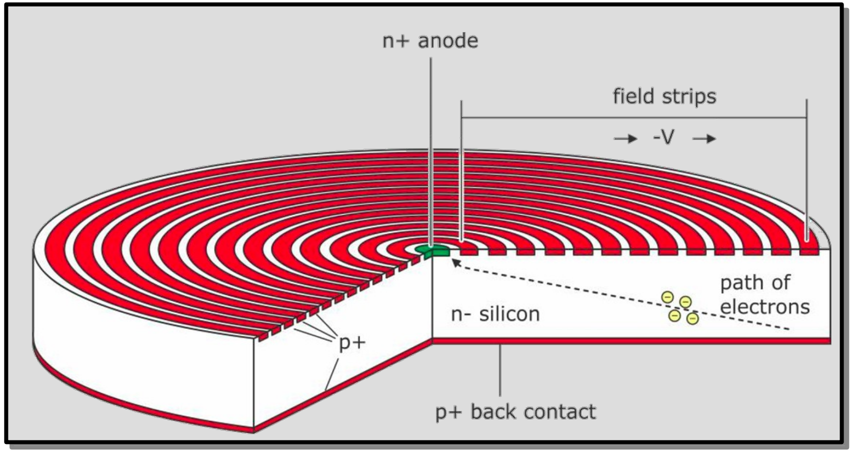
Phase 2

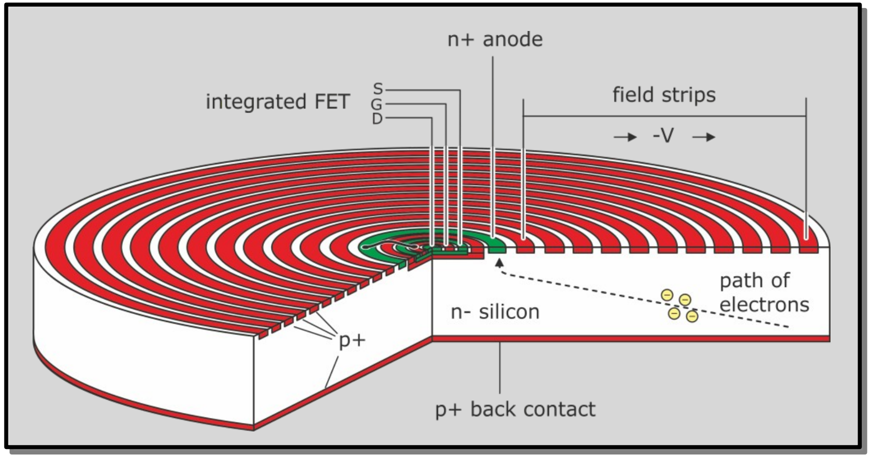
TRISTAN module
- 166-pixels with integrated JFET

Optimized design

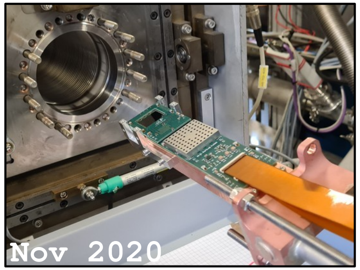


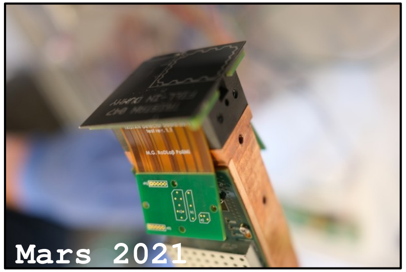


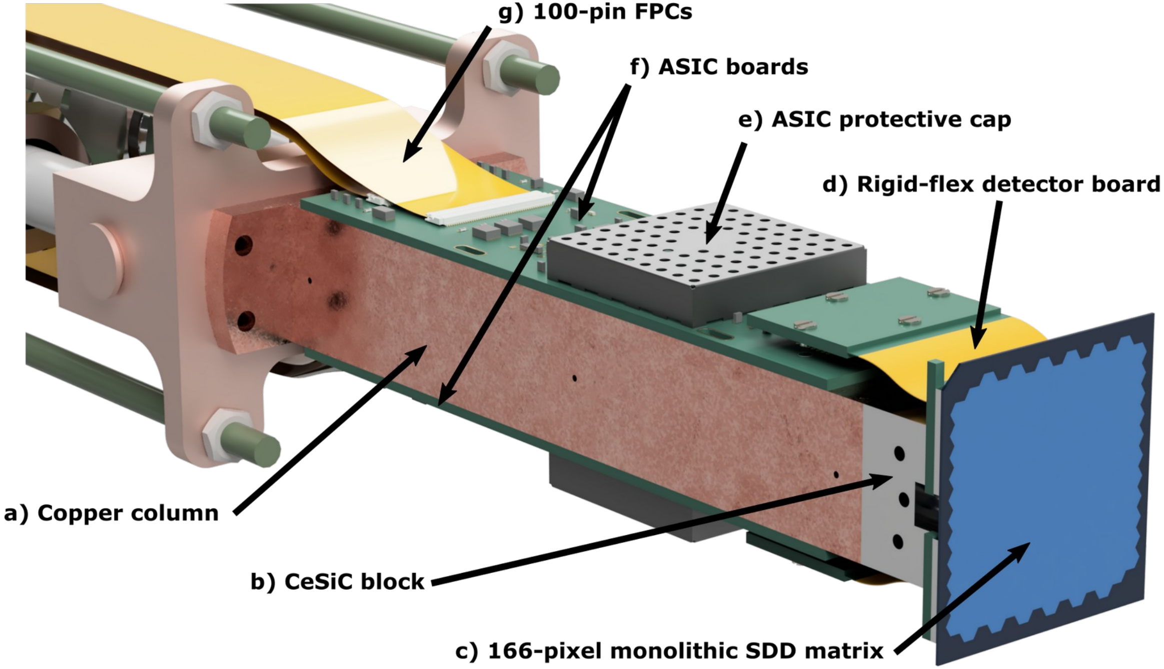




Design of the TRISTAN Module





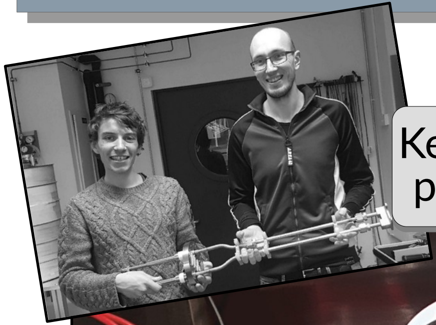


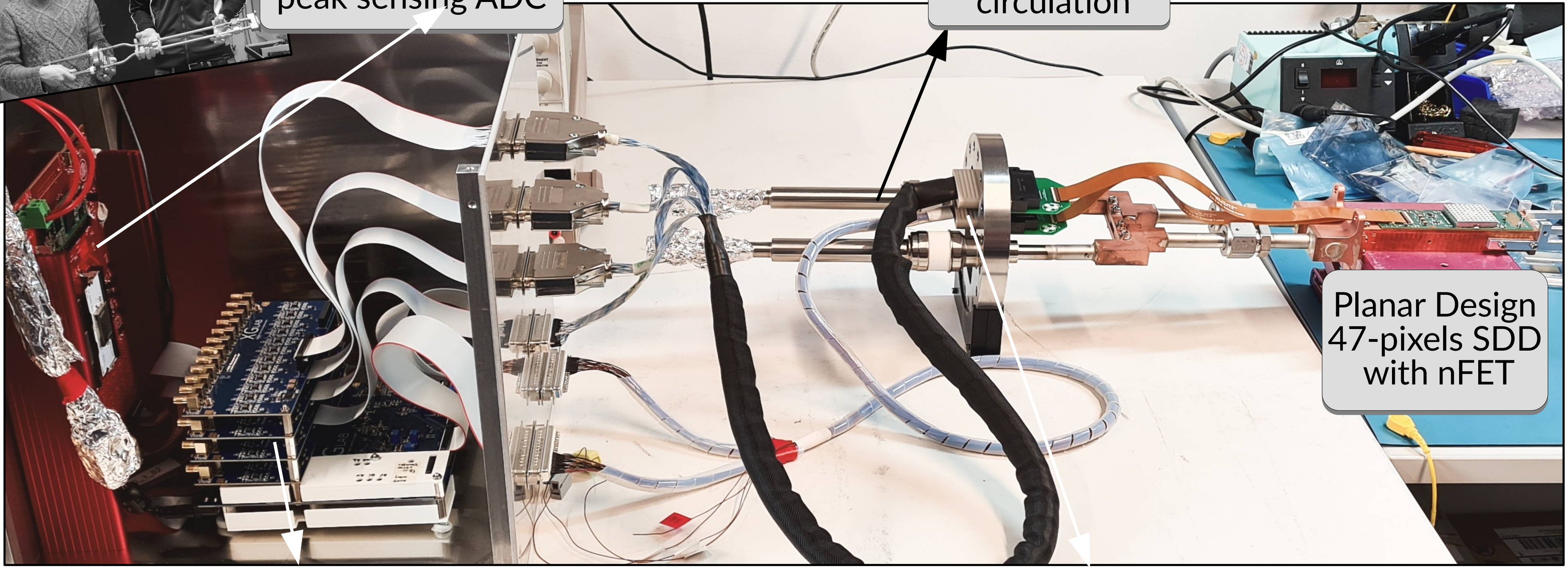
Operating 166-pix SDD in UHV (10^{-8} mbar), cool (-80°C), intense B field (~1 T), low noise (<300 eV FWHM)

- 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

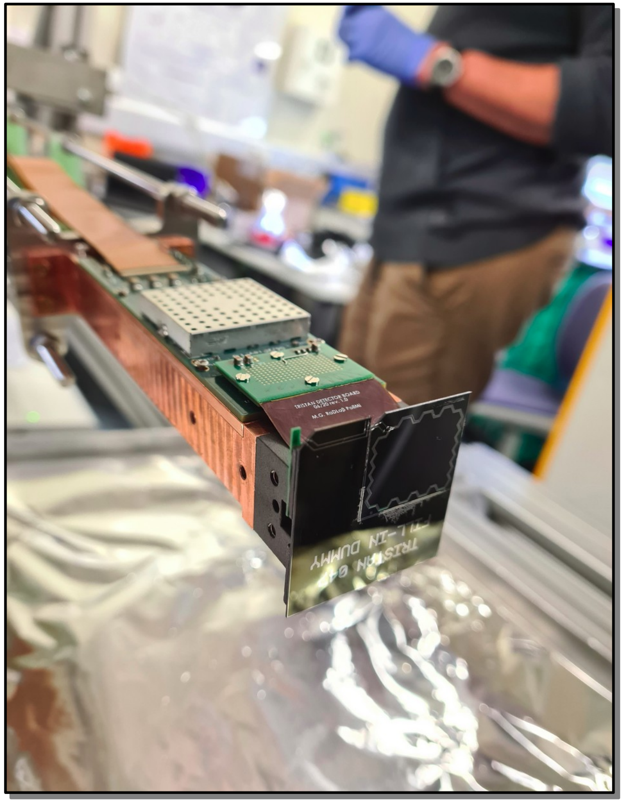
Cooling liquid circulation

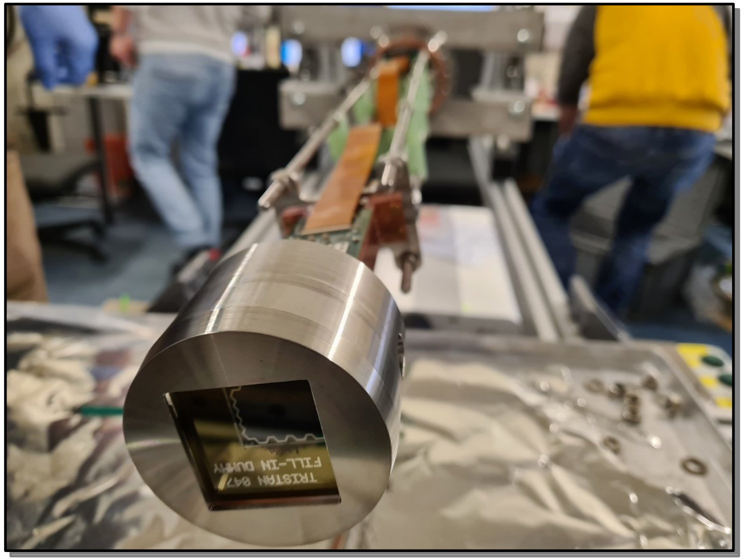
Planar Design 47-pixels SDD with nFET

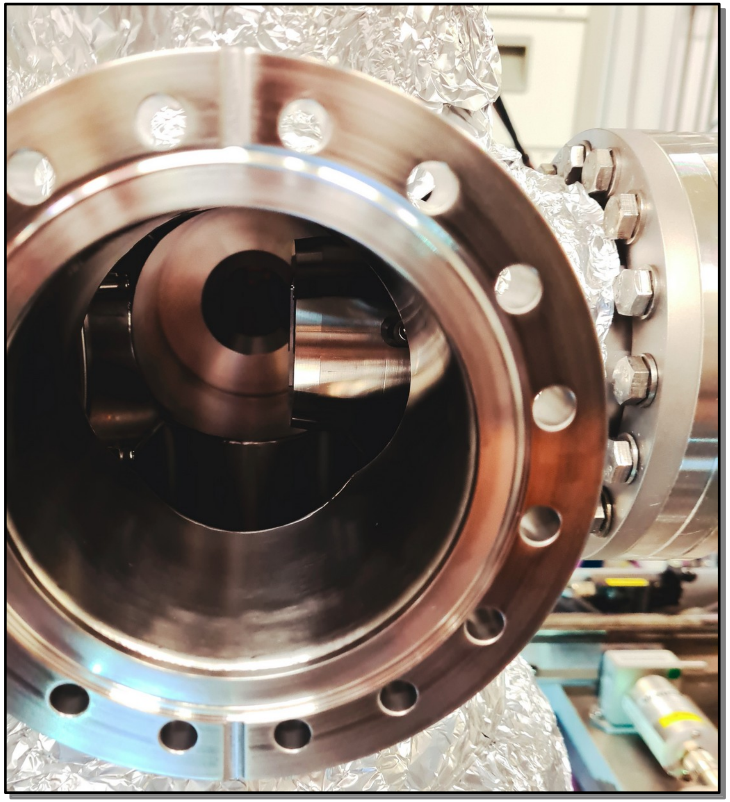
48-ch bias board

400 pins micro-D CF100 flange

TRISTAN Module Integration



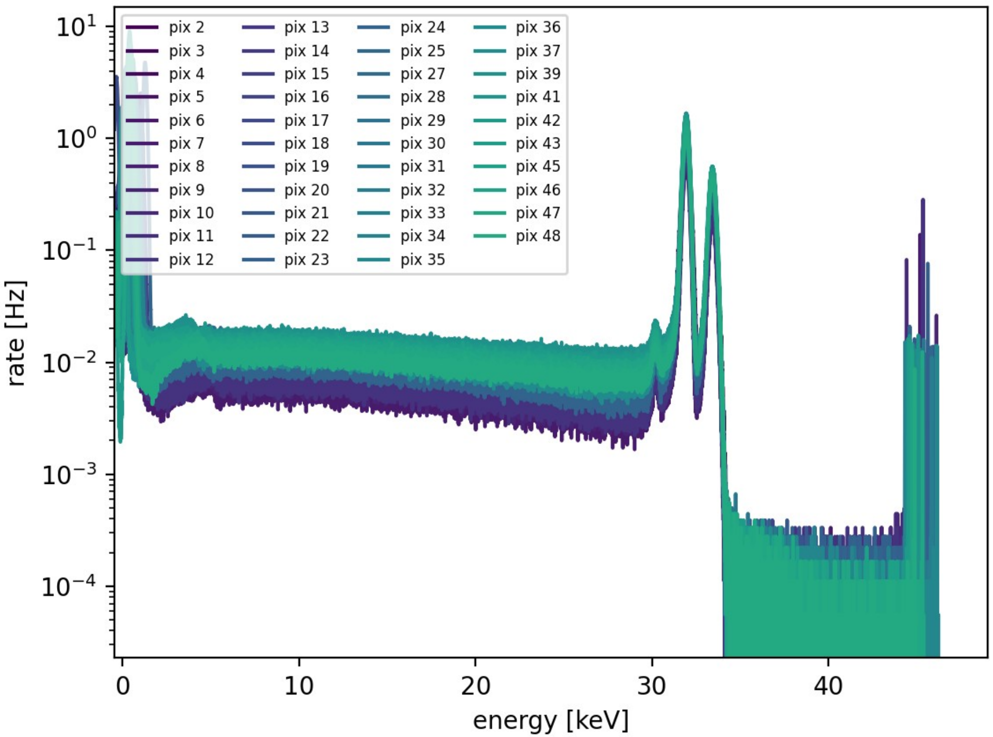


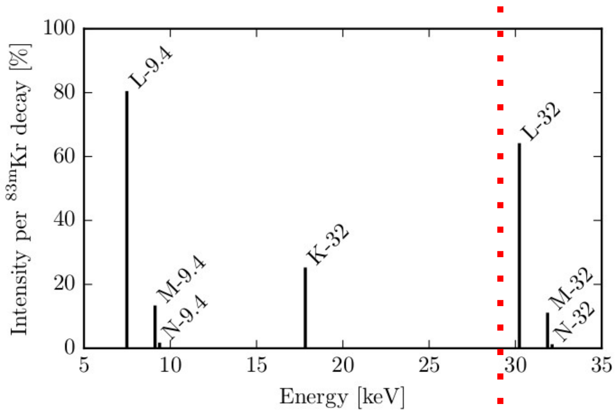


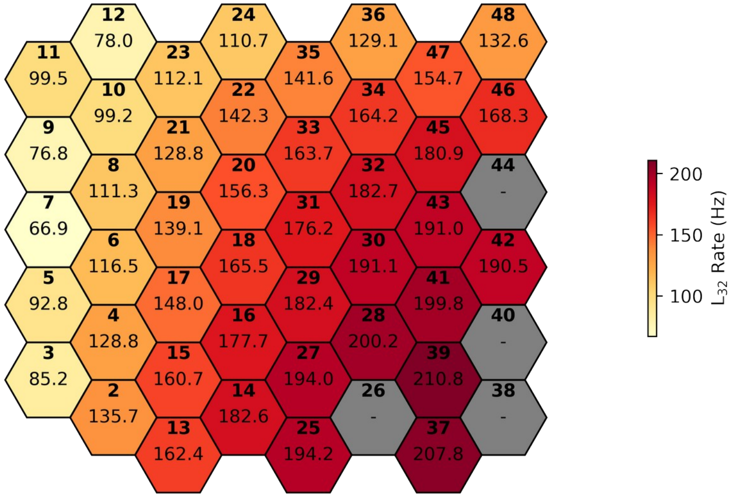
^{83m}Kr electrons from MoS
- Monoenergetic
- Vacuum (10^{-8} mbar)
- Operating at -50°C

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

TRISTAN Module Integration

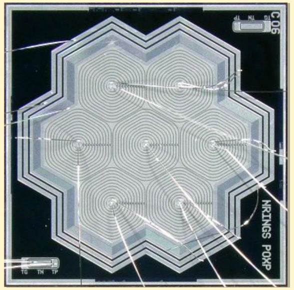






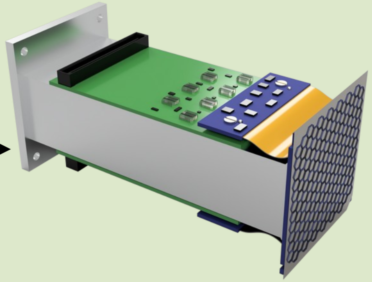
- Studying of the **electron response**
- Analyzing plane HV to 30 kV to focus on L32 line
- Size of the source ~ size of the detector

Staged approach



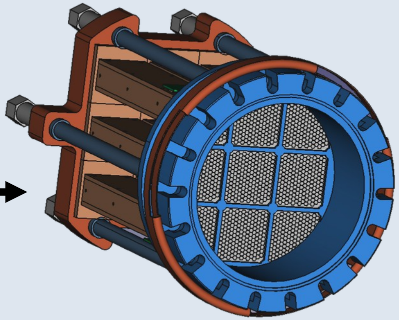
Prototypes

x24



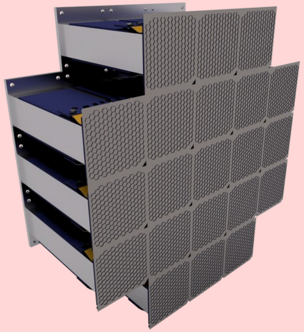
Module

x9



Phase 1

x2.5

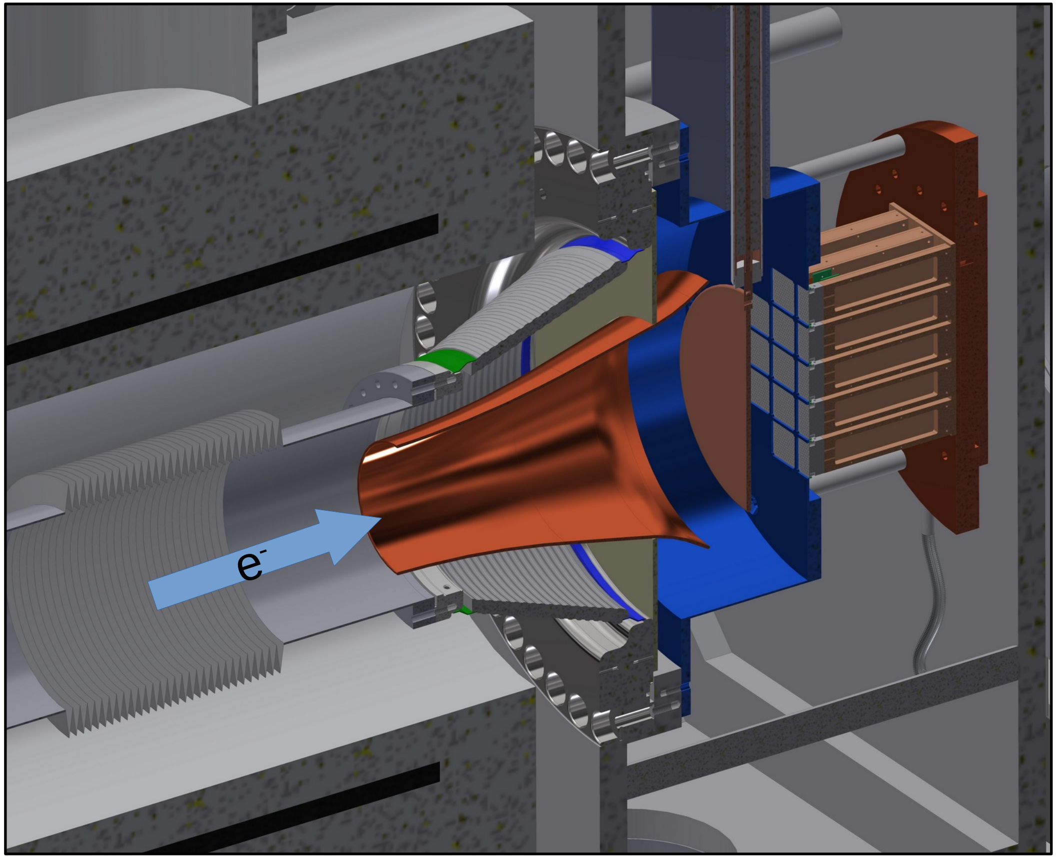


Phase 2

Mini-TRISTAN
- 9 x modules → 1500 pixels

Full TRISTAN
- 21 x modules → 3500 pixels

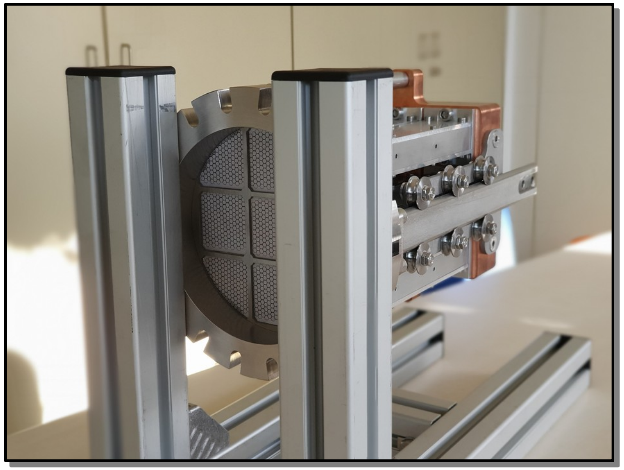
TRISTAN Final Detector

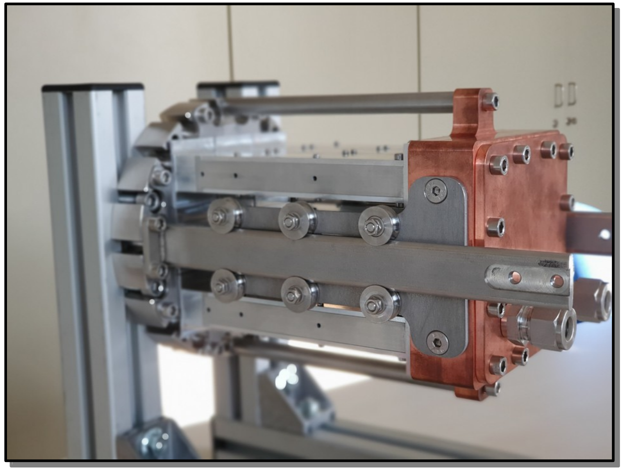


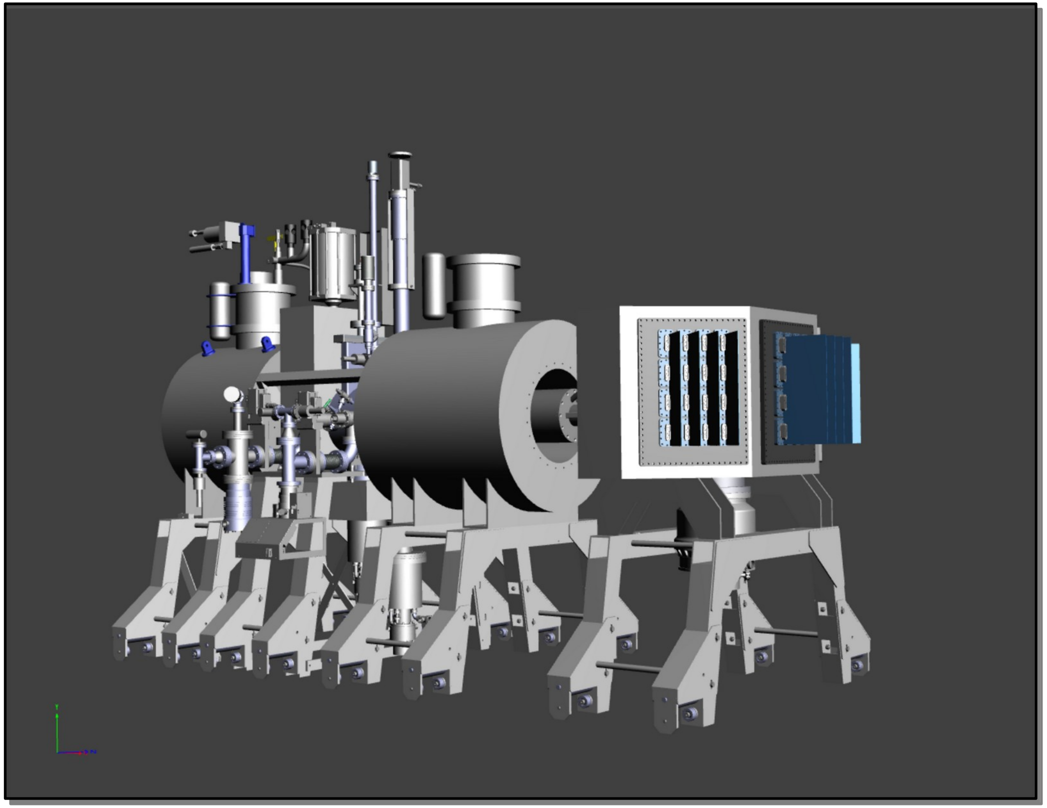
Next milestones :

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

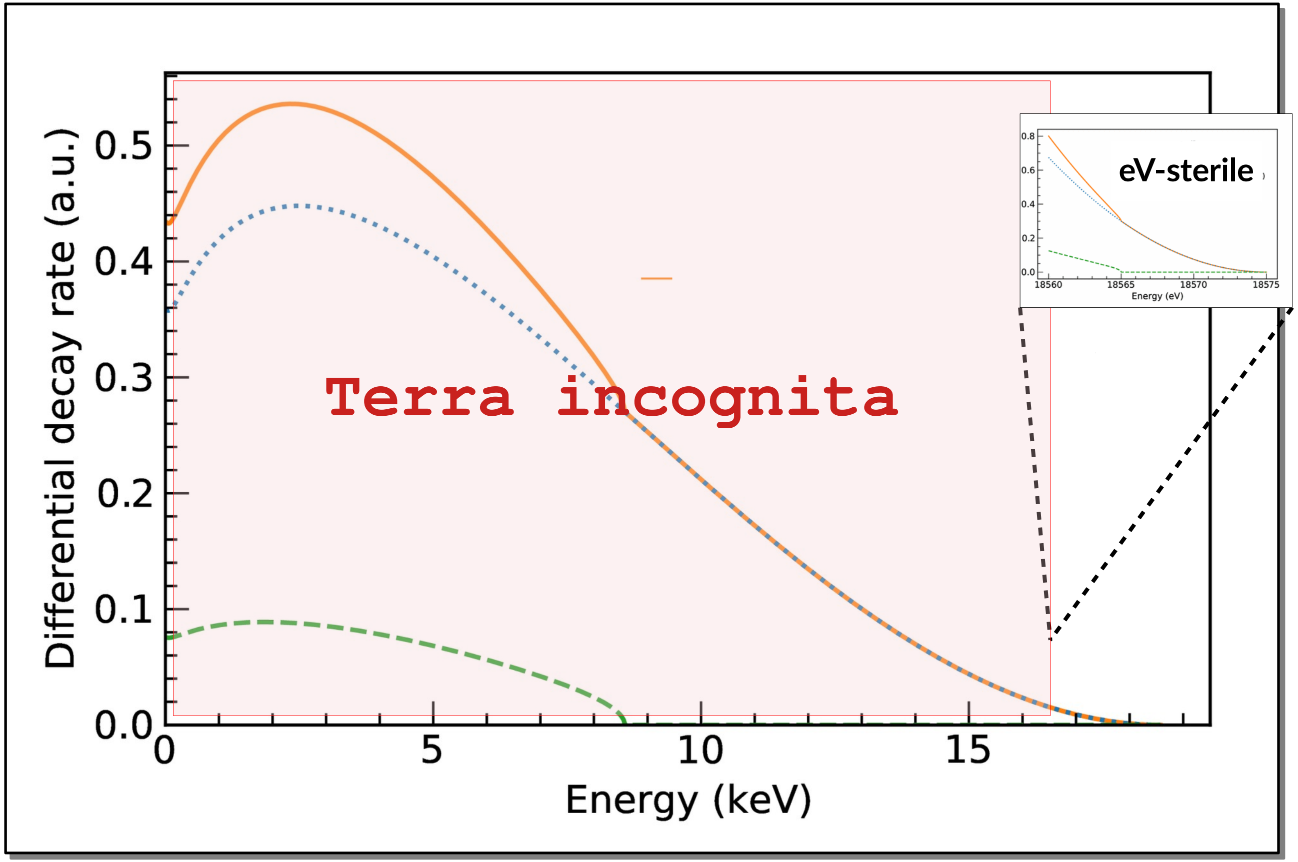
Integration in KATRIN Beam-line



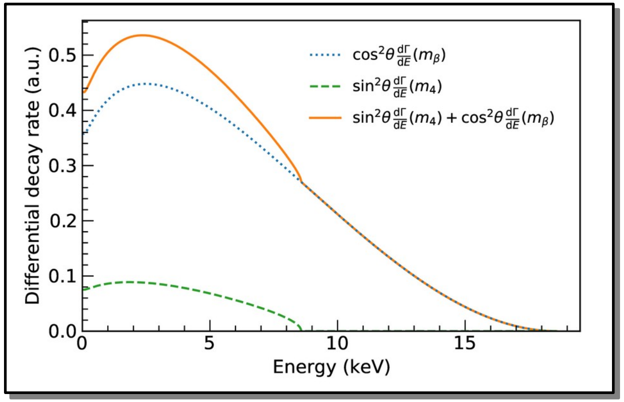


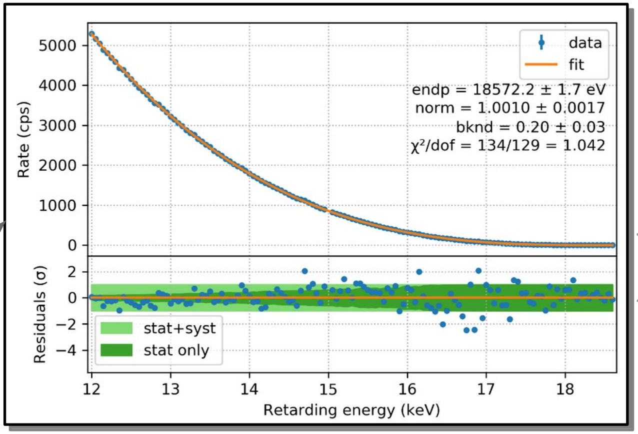


Deep Tritium Model

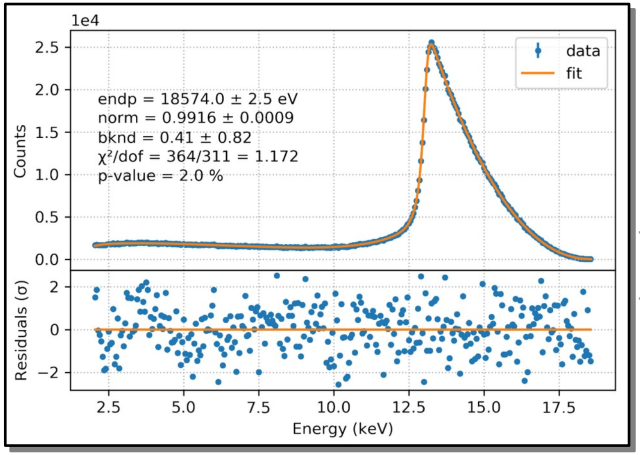


Deep Tritium Model

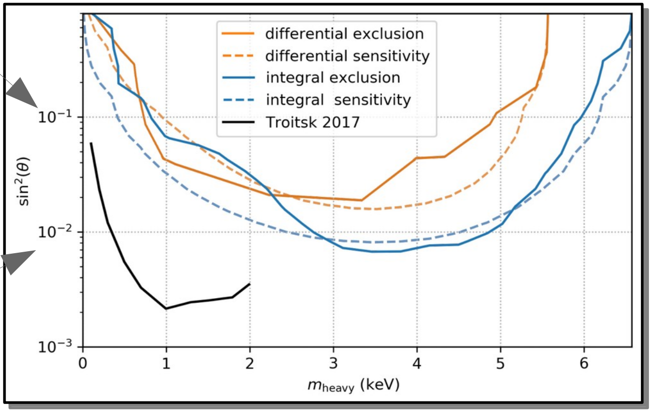




JINST 14 P11013 (2019)

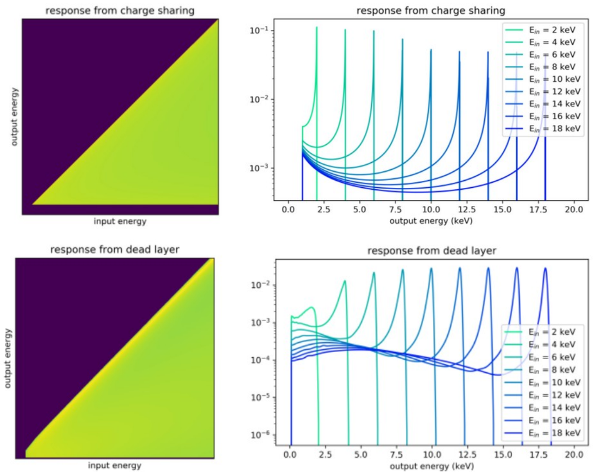


JINST 14 P11013 (2019)

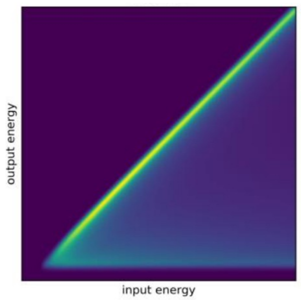


Deep Tritium Model

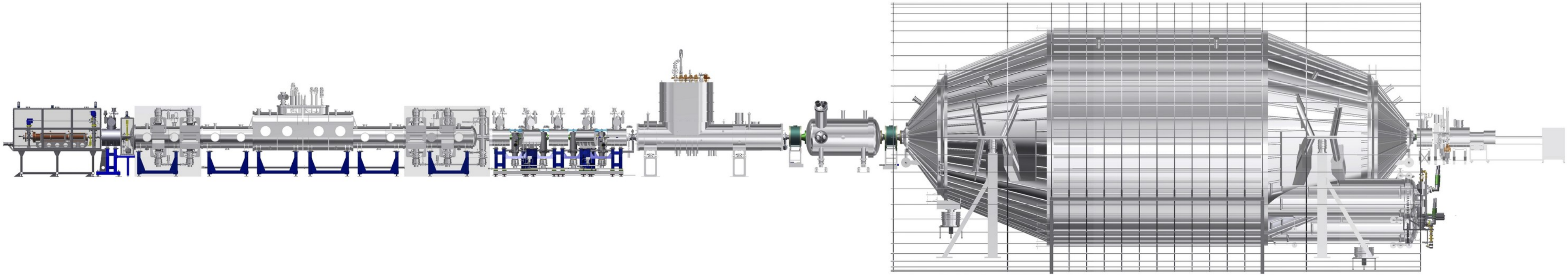
Each physical effect described with a response matrix



Combined responses



Convolution to the initial spectrum



Deep Tritium Model : effects to consider

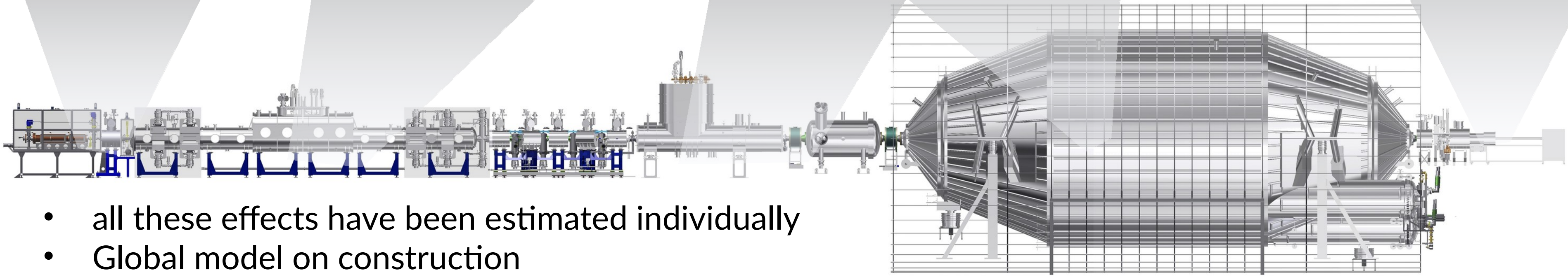
Effect can be different for differential and integral mode

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 : effects to consider

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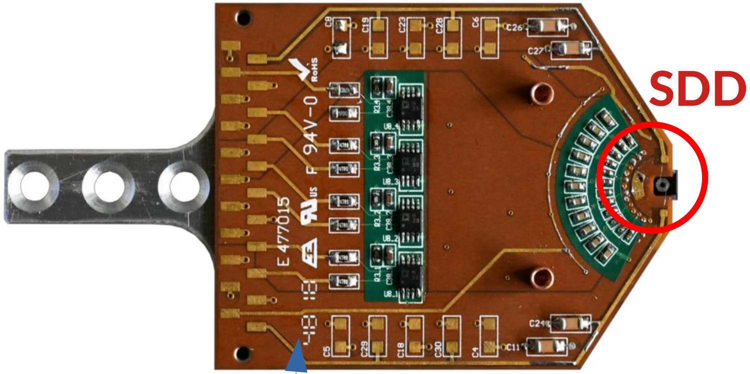

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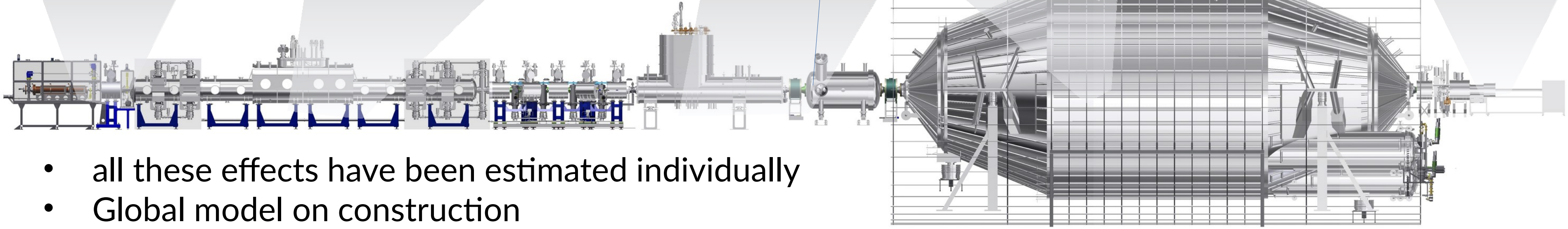
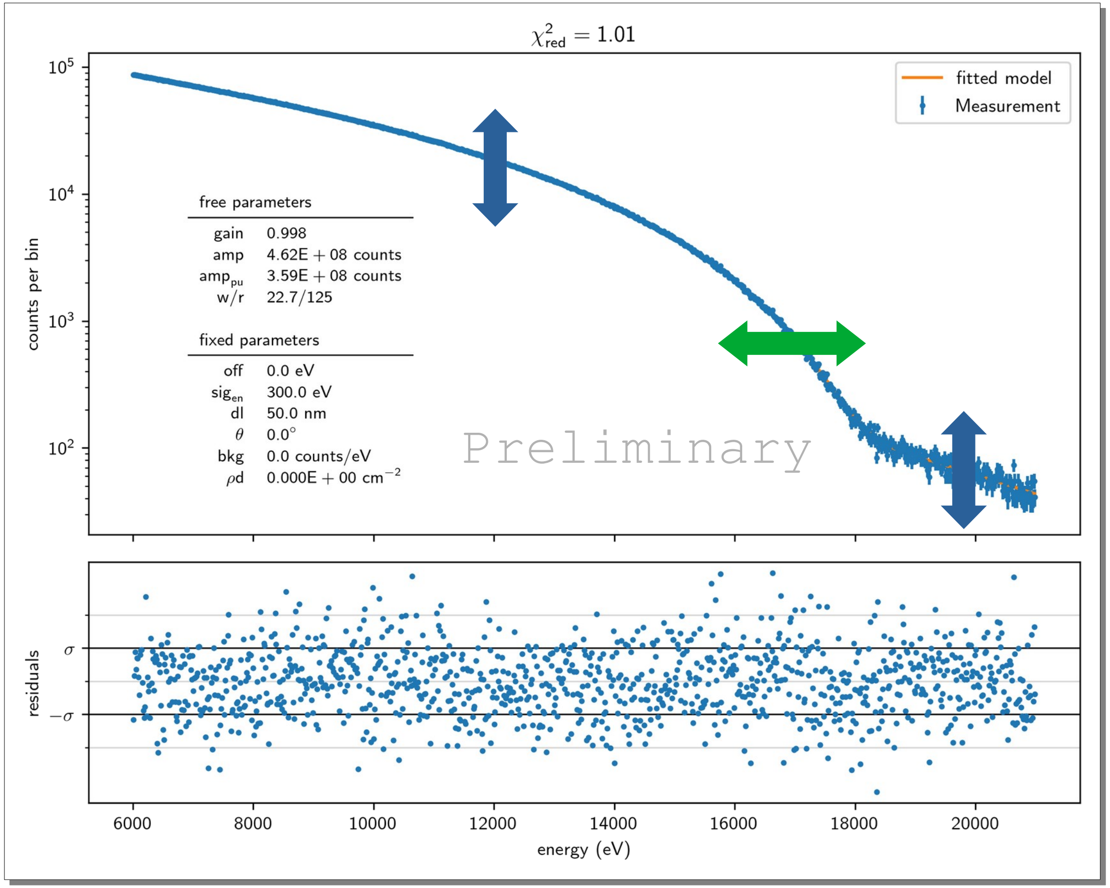


- all these effects have been estimated individually
- Global model on construction

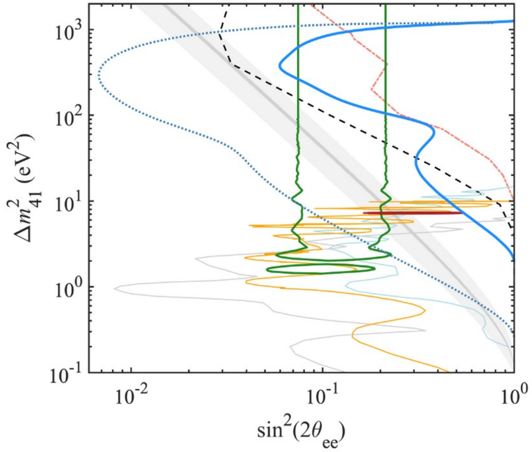
Deep Tritium Model : illustration

- 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

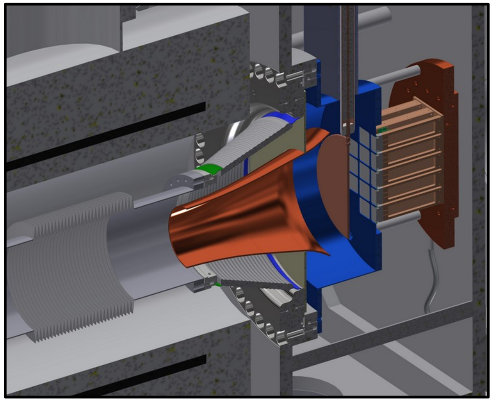
Sterile neutrinos with KATRIN



KATRIN has now presented a first study on eV sterile neutrinos

KATRIN with TRISTAN :

- feasability of the SDD technology for the keV-sterile neutrino search has been demonstrated
    - with photons and electrons
    - with tritium in realistic conditions (Troitsk)



- A **first TRISTAN module** is being commissioned in KATRIN
- First physics run with 9 module expected 2022
- A complete **deep tritium model** is being built. New sensitivity studies will be done to reduce systematics.

Thank you all