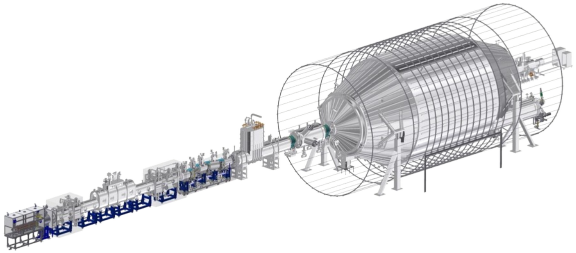


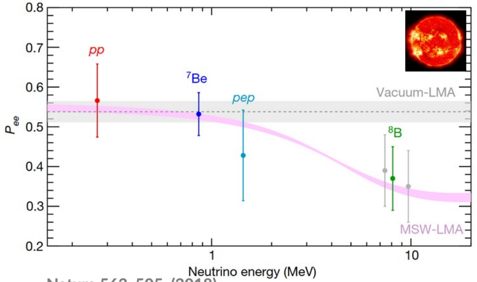
KATRIN : from neutrino mass to dark matter

LAPP Annecy

Thibaut Houdy

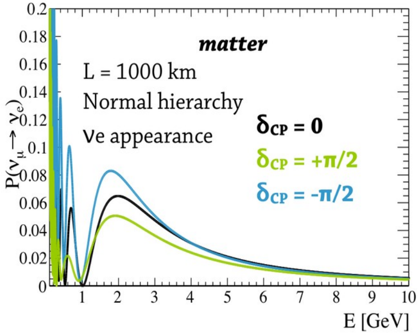
12th of June, 2023

Qui suis-je?



Nature 562, 505, (2018)

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



Doctorat, APC/CEA-Irfu, U. Paris-Diderot (2014 – 2017)

- Etude des **neutrinos solaires (^{8}B) et stériles (eV) dans Borexino**

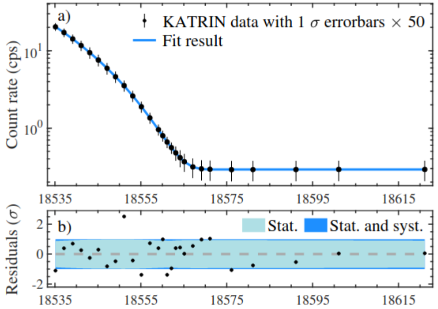
Postdoctorat, Max-Planck Physique, Munich, (2018 - 2021)

- Rejoins **KATRIN (masse du neutrino)**
- Recherche de **neutrinos stériles au keV** avec **KATRIN**

Maitre de conférence, l'U. Paris-Saclay, IJCLab (2021 -)

- Cours en Electromagnétisme, Instrumentations et Nucléaire & Particules. Responsable de la plateforme E_2PN
- Rejoins DUNE (**hiérarchie de masse, phase CP**, unitarité de la matrice PMNS)

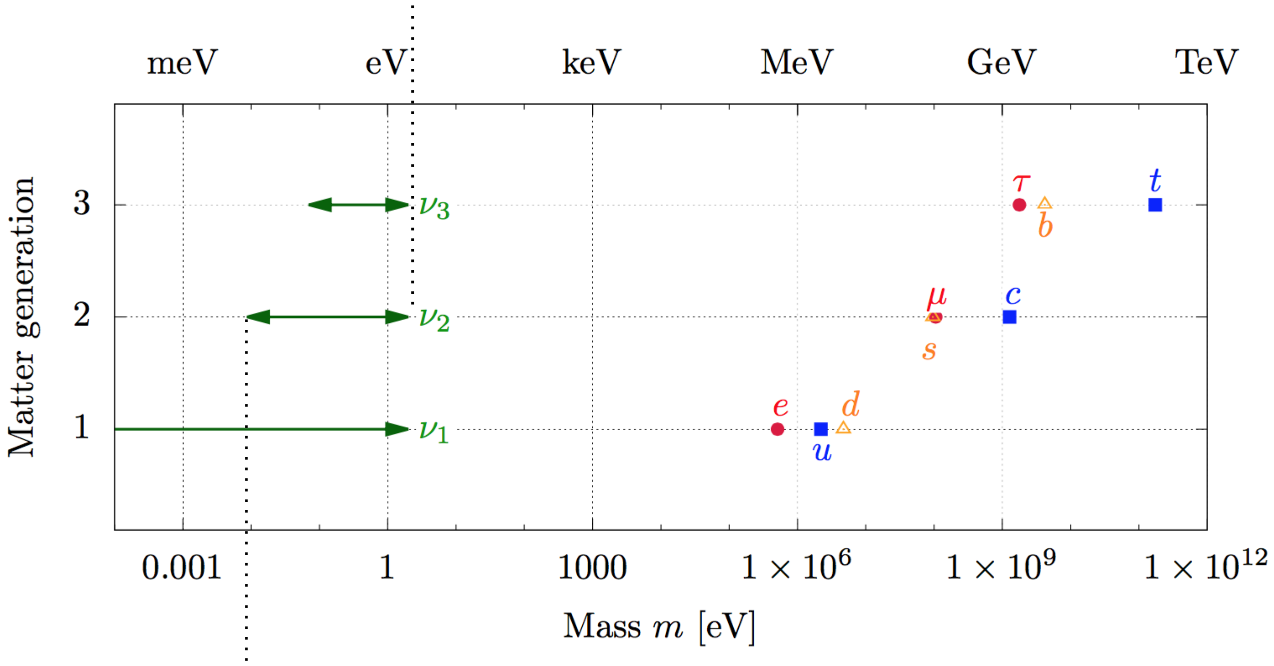
This talk is NOT made in the name of the KATRIN collaboration ;)



Neutrino mass status

Upper bound
from laboratory measurements

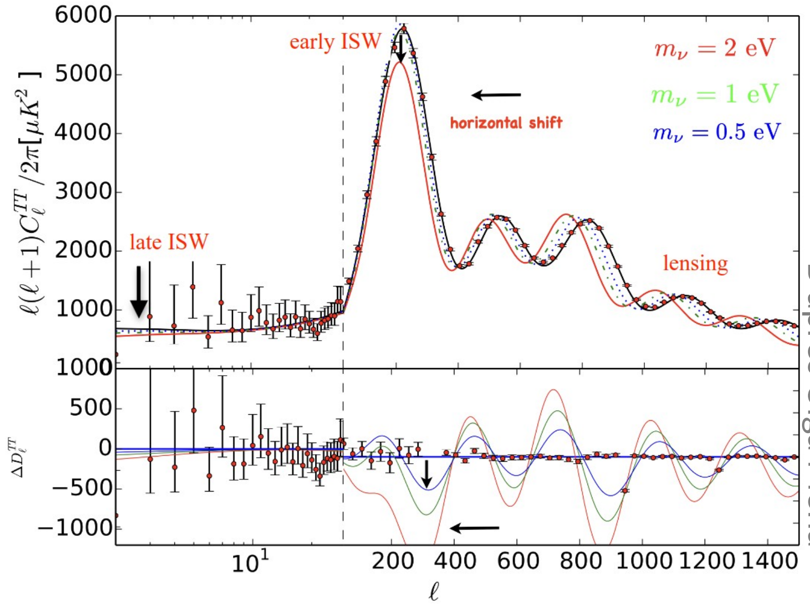
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.515^{+0.028}_{-0.028}$



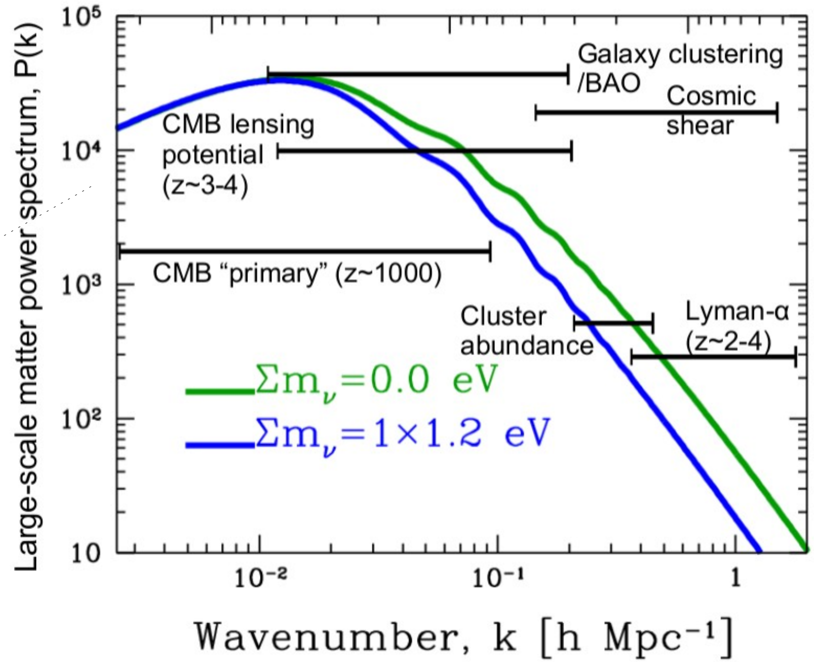
Lower bound
from oscillation experiments

Neutrino mass measurements

- **Cosmology**
  model dependent
  $\Sigma m_\nu < 120$ meV
  Ex : Planck, eBOSS



D'après Olga Mena

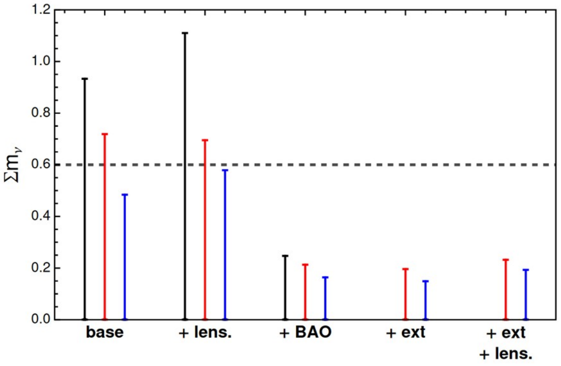


D'après **Neutrino Cosmology**, Y.Y. Wong

- Massive neutrinos wash out small scale structure formation after non-relativistic transition
- Measurement of the CMB lensing → more massive, less structure, less sensing

Neutrino mass measurements

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

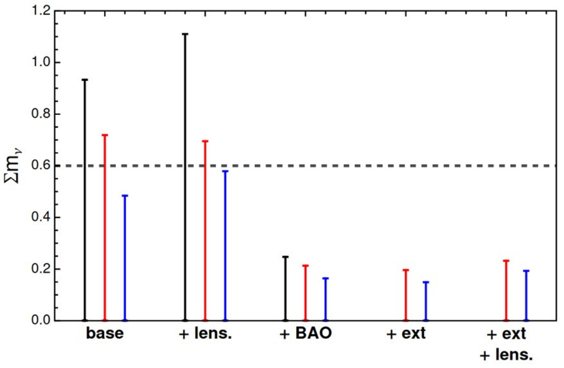


M.Lattanzi 2016 JP,Conf..Ser.718 032008

Neutrino mass measurements

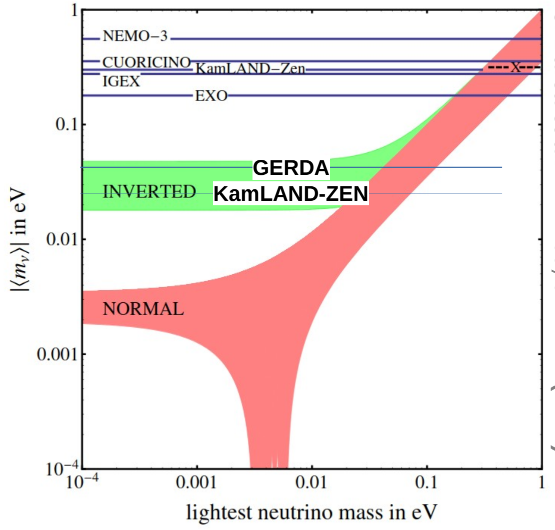
- **Cosmology**
  model dependent
  Σm_ν < 120 meV
  Ex : Planck, eBOSS

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



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

Neutrino mass measurements



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

- **0νββ**
  laboratory based
  $m_{\beta\beta}$ < 100 meV
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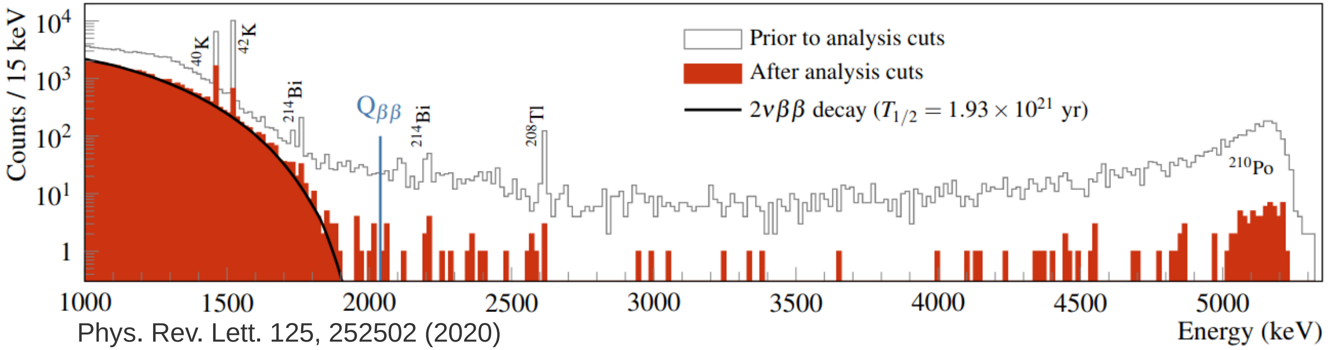


Phys. Rev. Lett. 125, 252502 (2020)

Exclusion from measurement

$$({}^{0\nu}T_{1/2})^{-1} \propto |M^{0\nu}|^2 m_{\beta\beta}^2$$

Matrix element not easily derived

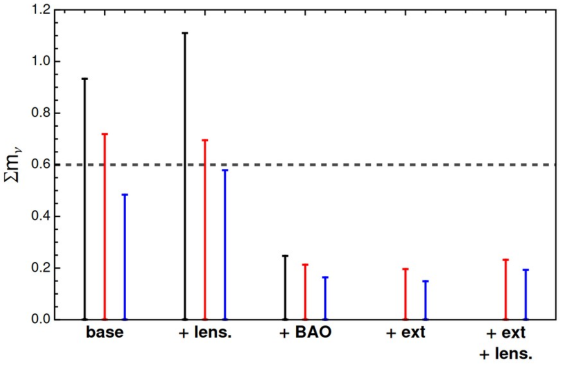
$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

BUT :
- only true if Majorana neutrino
- Depending on an unknown Majorana phase

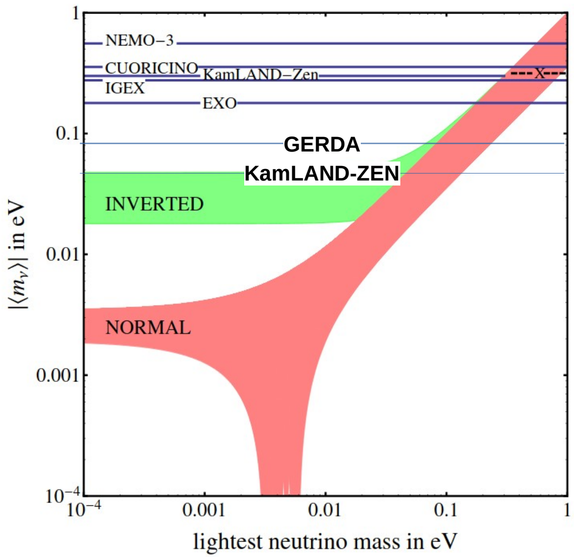
Neutrino mass measurements

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

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



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



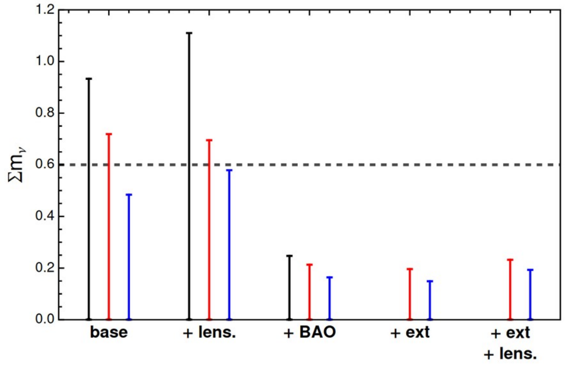
J. Barea et al. PRL 109, 042501 - (2012)

Neutrino mass measurements

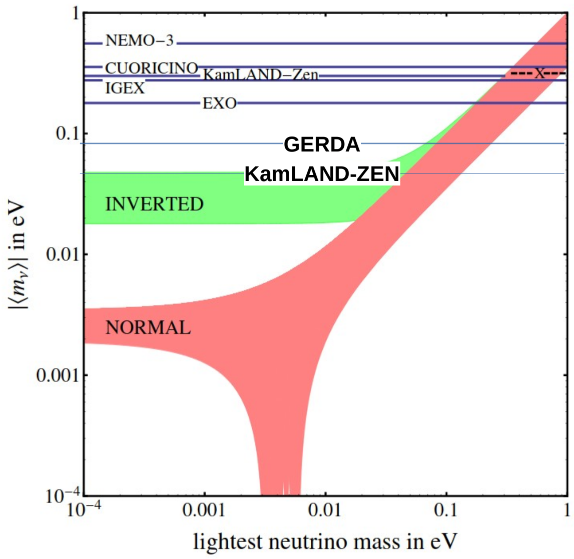
- **Cosmology**
  model dependent
  Σm_ν < 120 meV
  Ex : Planck, eBOSS

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

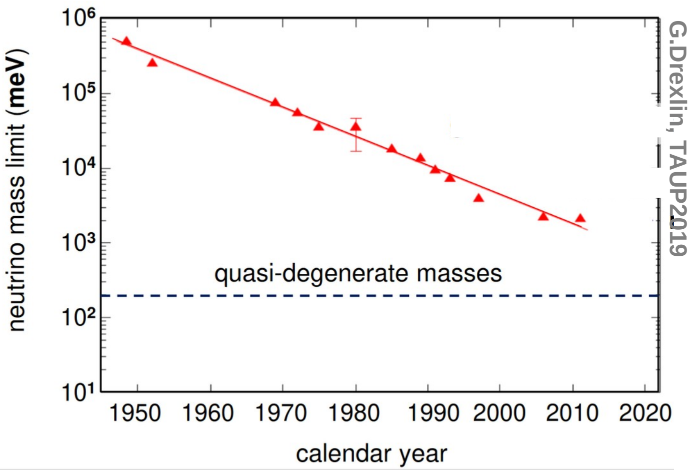
- **Kinematics of β-decay**
  laboratory based
  $m_{\nu e}$=50-200 meV
  Ex : ECHO, KATRIN, Project8



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

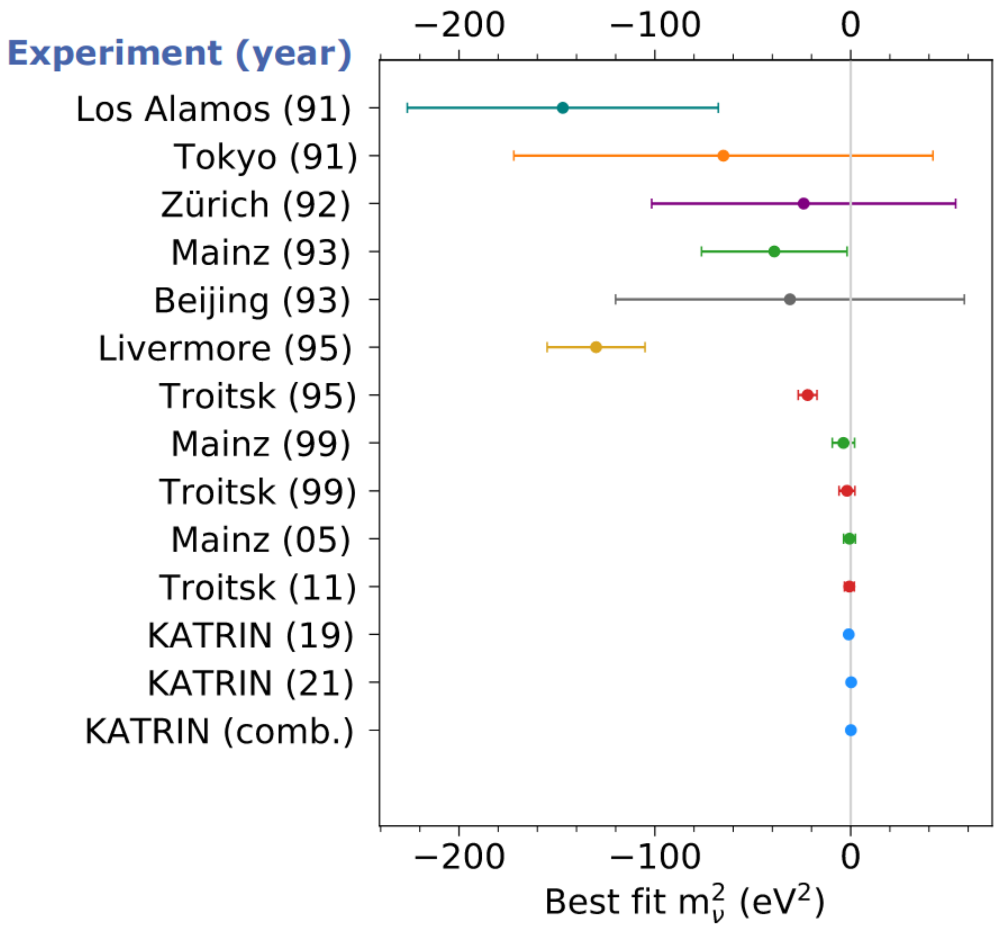


J. Barea et al. PRL 109, 042501 - (2012)

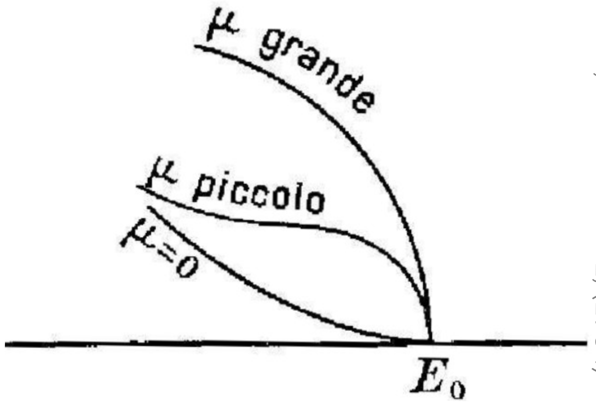


G.Drexlin, TAUP2019

Determining m_ν from ß-decay

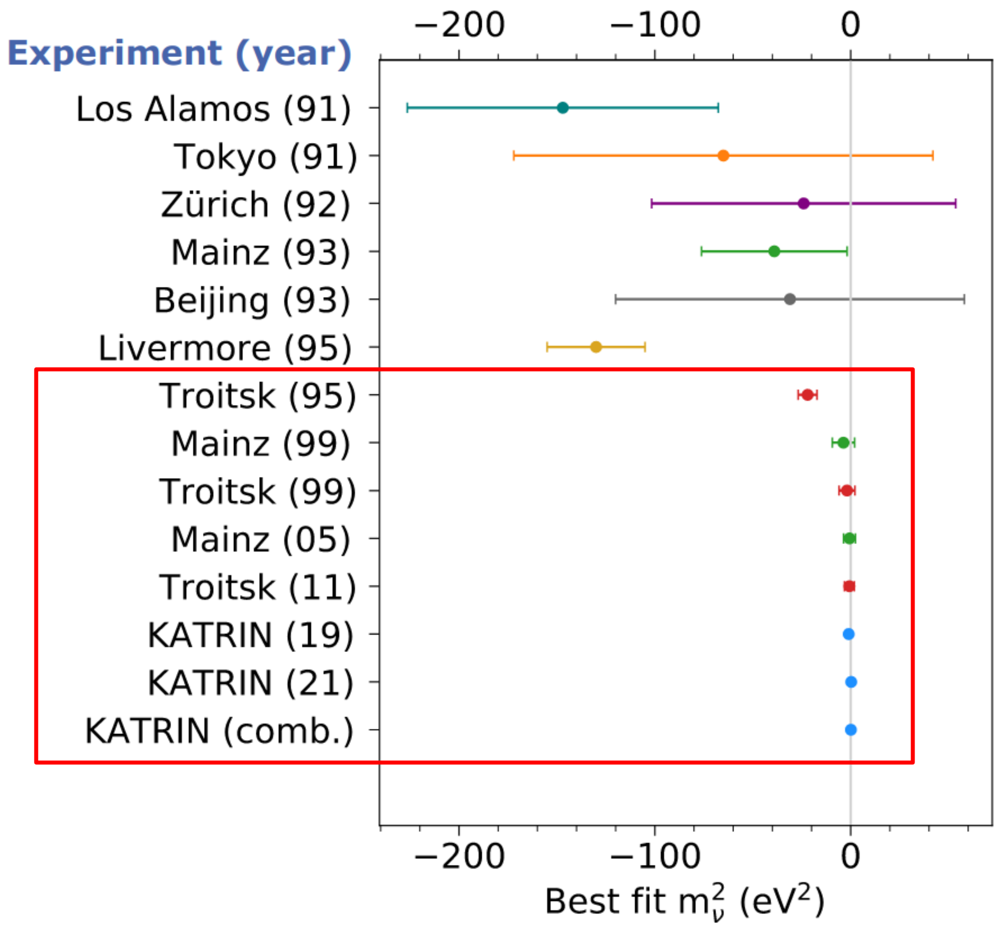


K. Valerius, KIT, DPG Dortmund (2021)

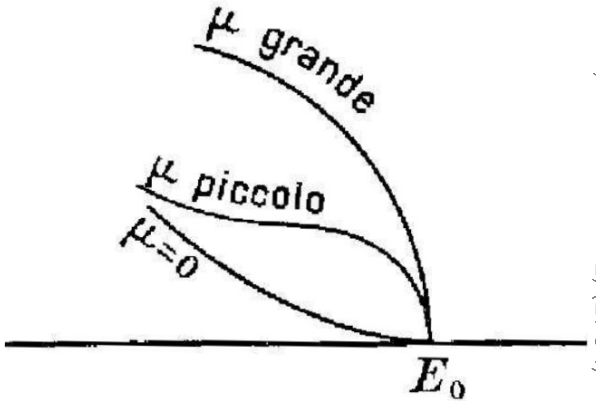


Fermi, Nuovo Cim. 11, (1934)

Determining m_ν from ß-decay



K. Valerius, KIT, DPG Dortmund (2021)



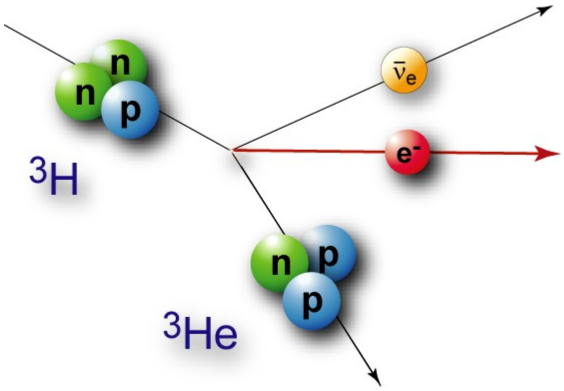
Fermi, Nuovo Cim. 11, (1934)

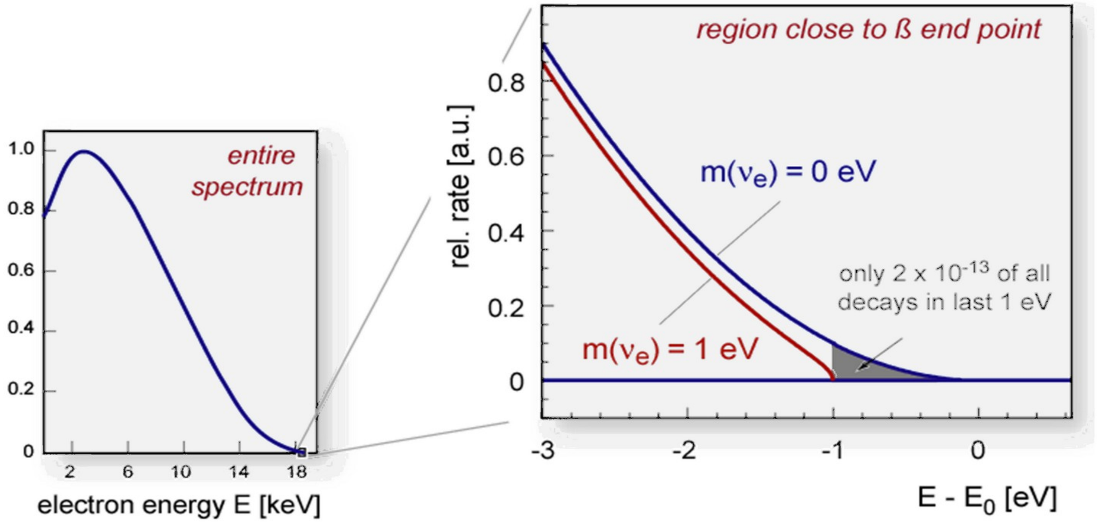
- **Troitsk**
- **Mainz**
- **KATRIN**

→ MAC-E filters with tritium source

Determining m_ν from ß-decay: KATRIN

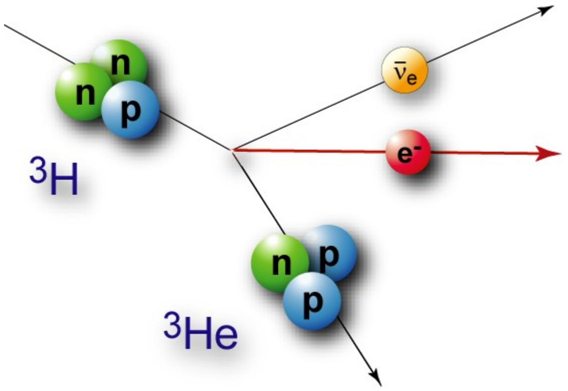
General Idea



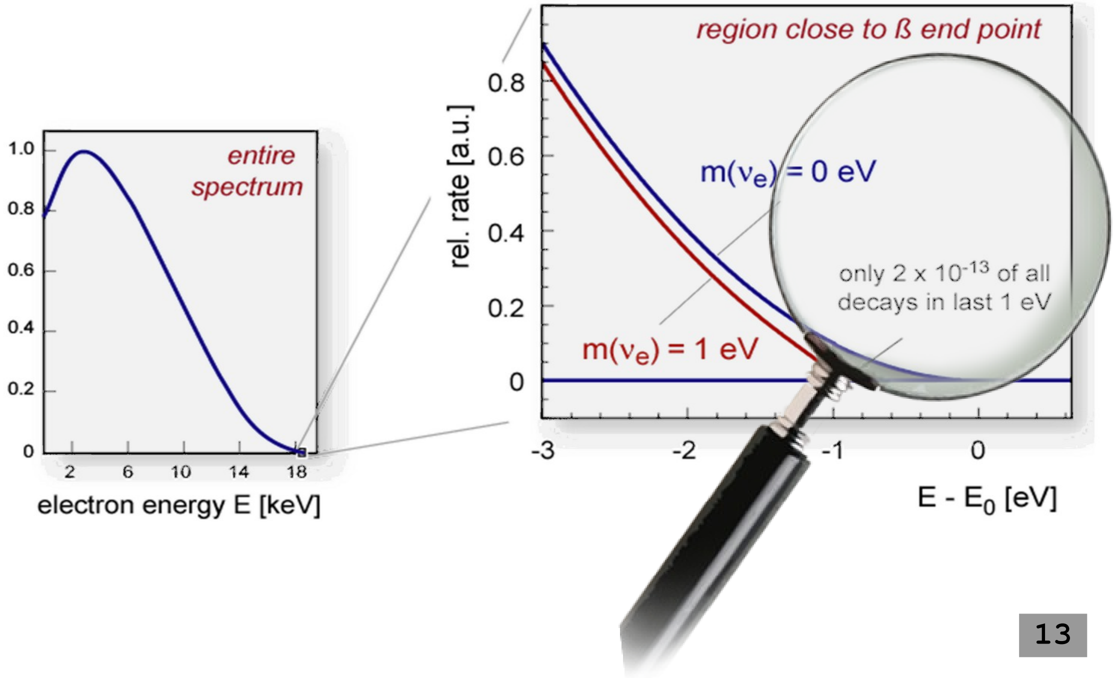


Determining m_ν from ß-decay: KATRIN

General Idea



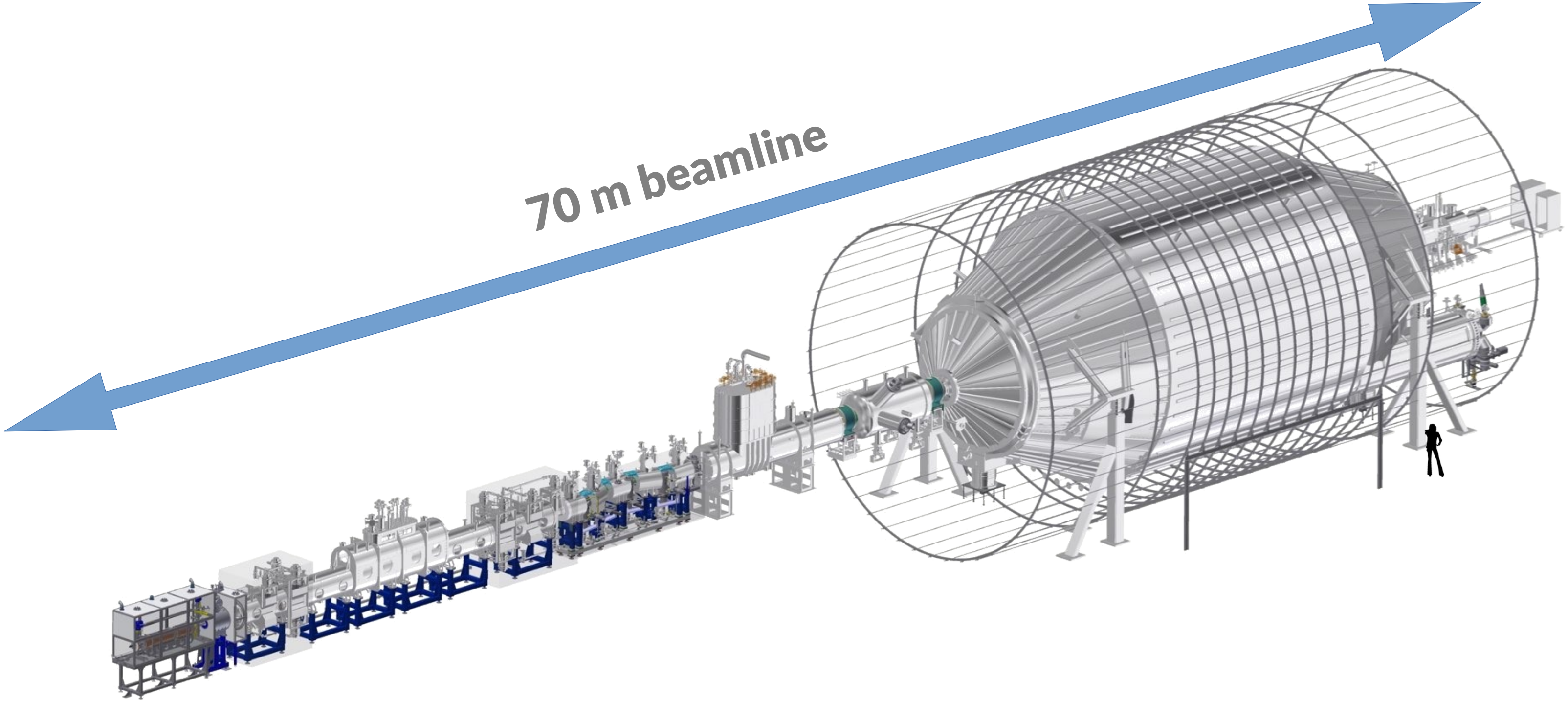
- Ultra-strong β-source 10¹¹ decays/s
- Low background level < 0.1 cps
- Excellent energy resolution ~ 1 eV
- Precise understanding of spectrum



KArlsruhe TRItium Neutrino Experiment : KATRIN

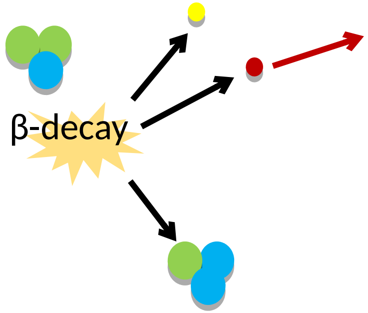
- Experimental site : Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Design sensitivity: 0.2 eV (90% CL)

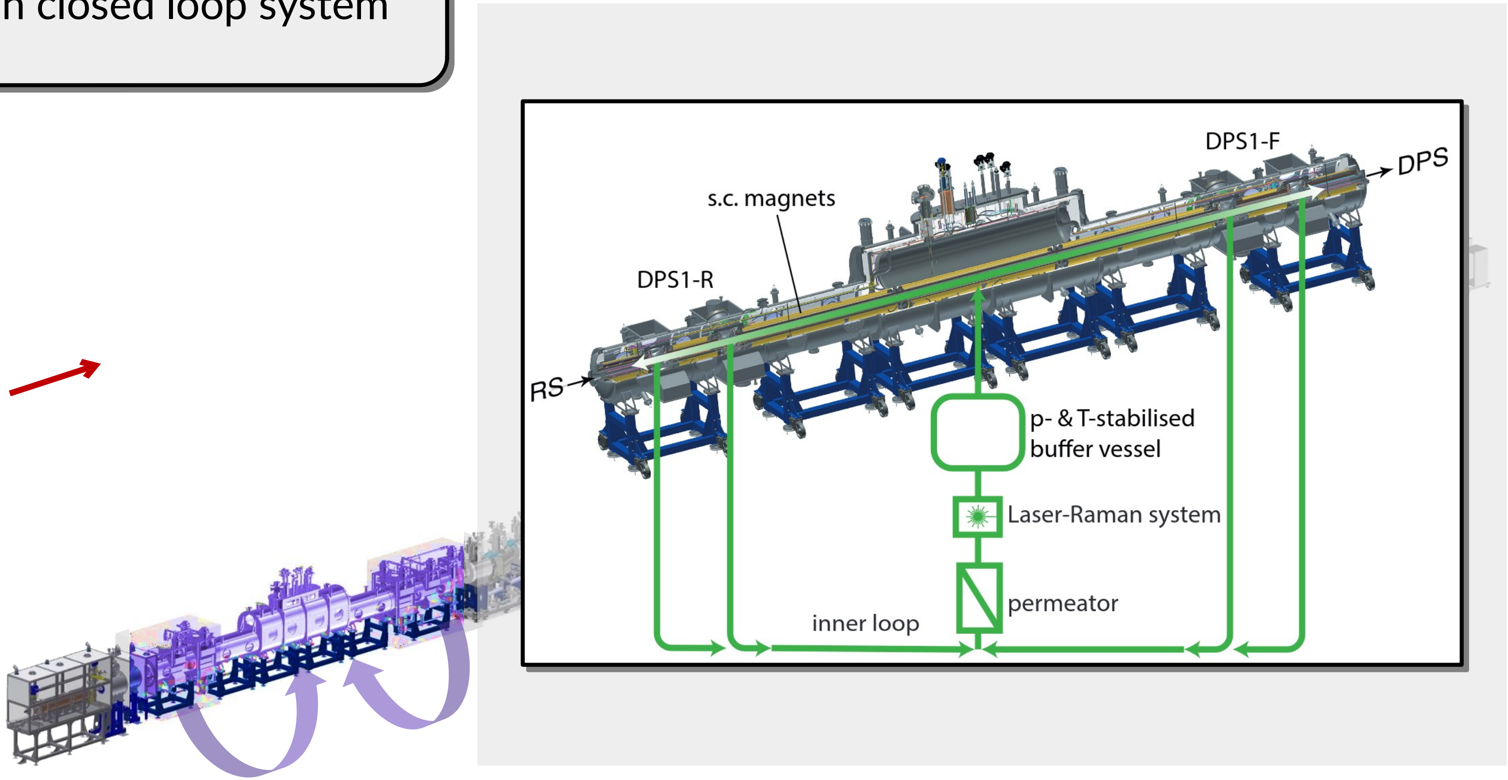
KATRIN Working Principle



KATRIN Working Principle

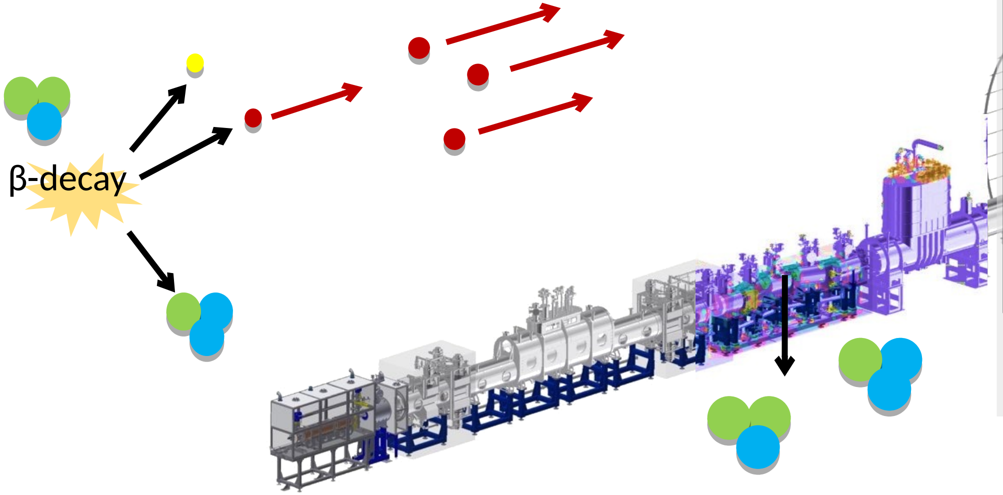
Windowless gaseous tritium source
- molecular tritium in closed loop system
- 10^{11} decays/s

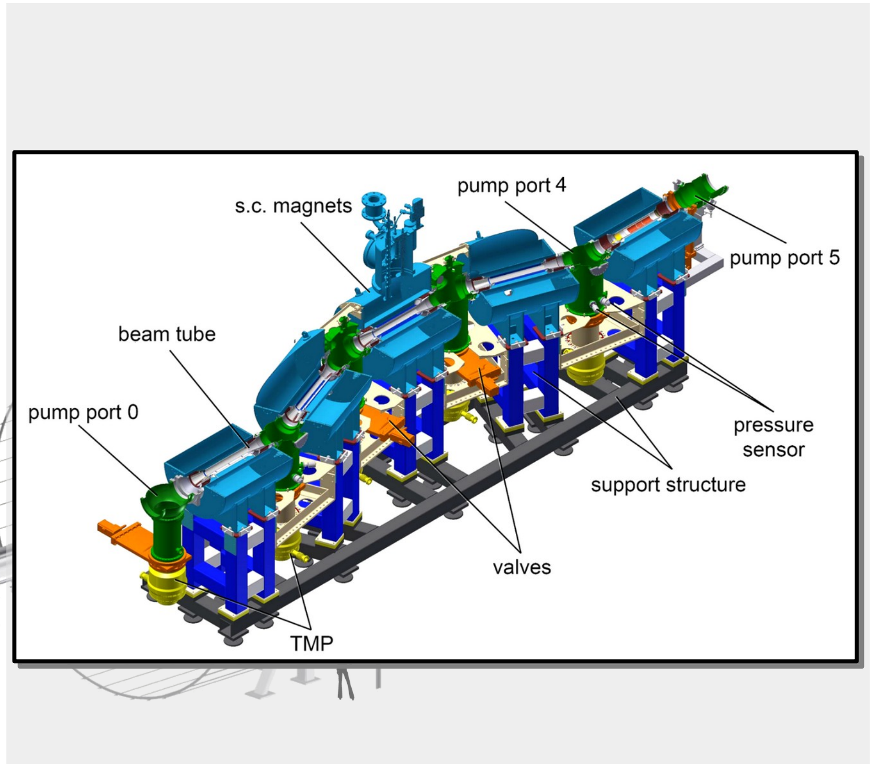




KATRIN Working Principle

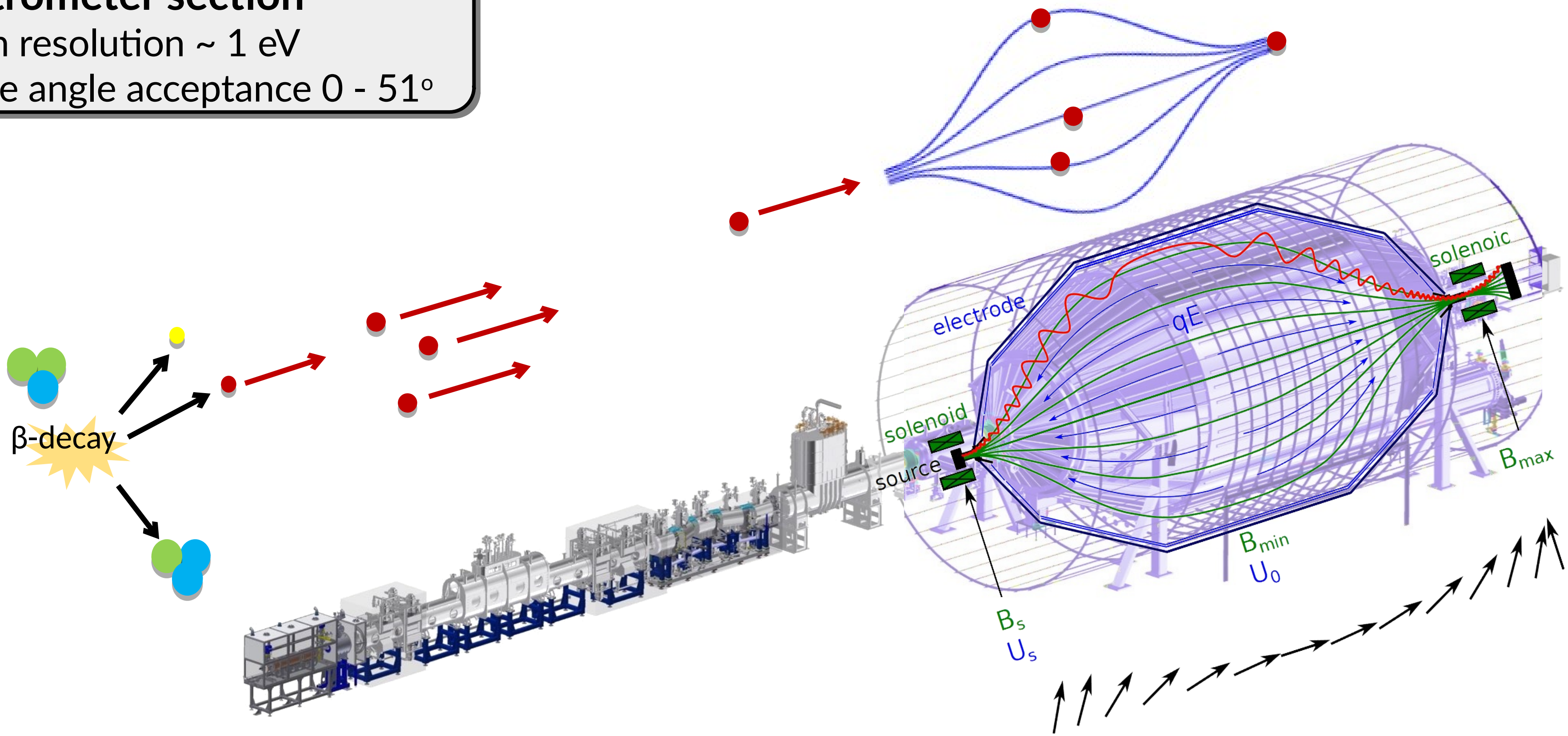
Transport section
- magnetic guidance of electrons (@ 4 T)
- tritium flow reduction by > 10^{14} + tritium ion removal





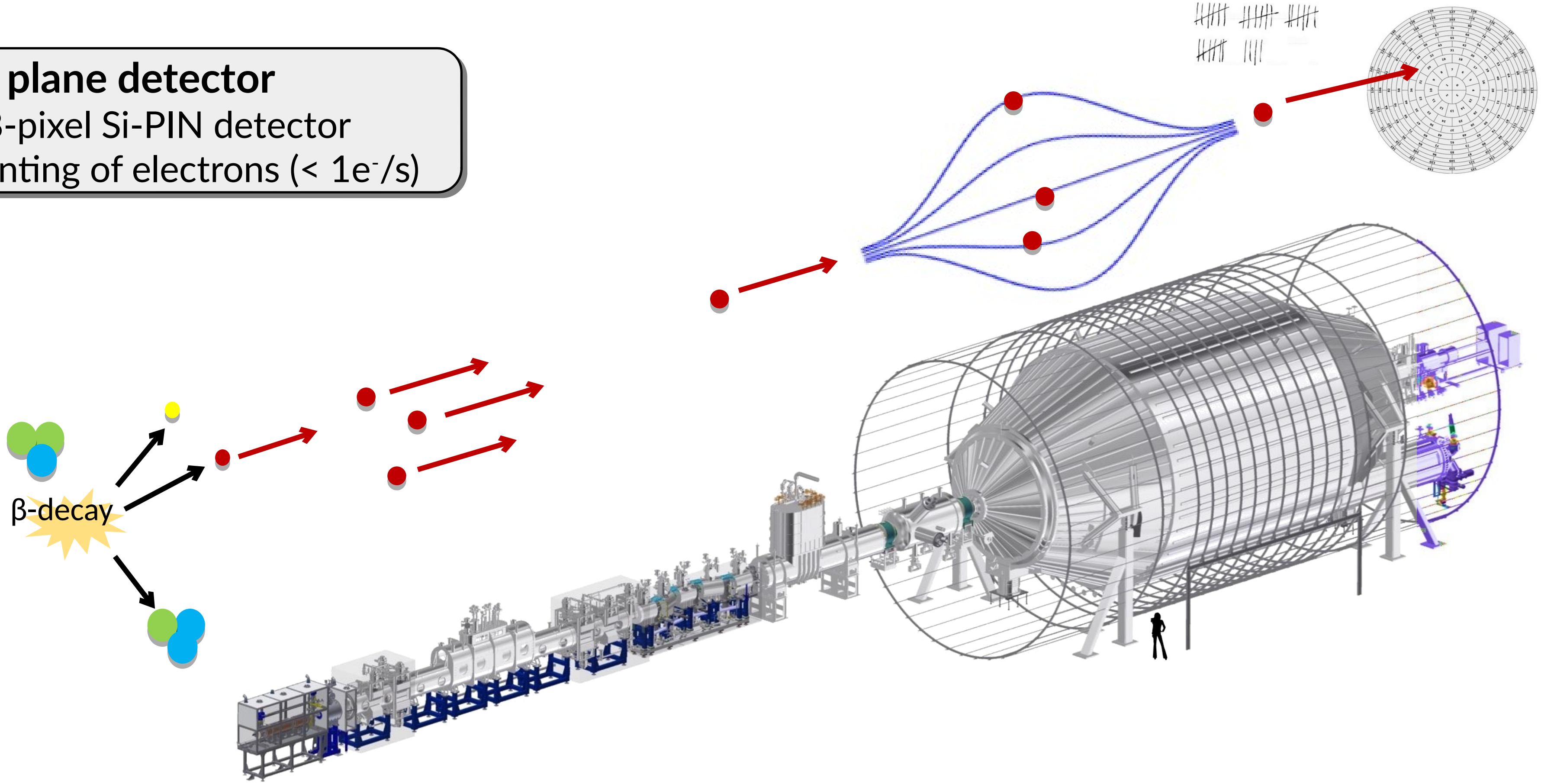
KATRIN Working Principle

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

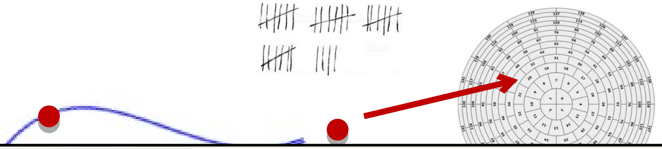


KATRIN Working Principle

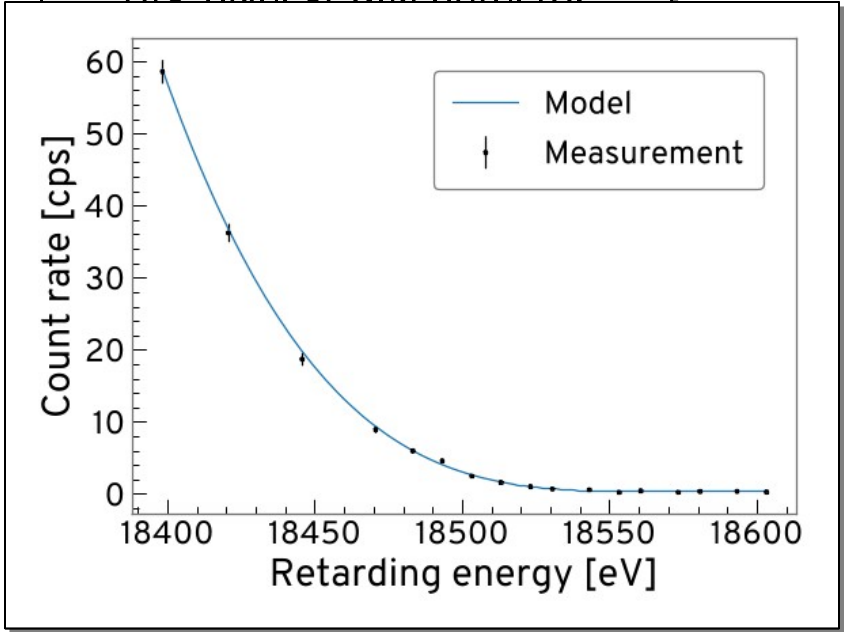
Focal plane detector
- 148-pixel Si-PIN detector
- counting of electrons (< 1e$^-$/s)

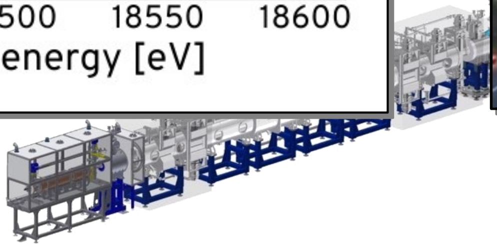


KATRIN Working Principle

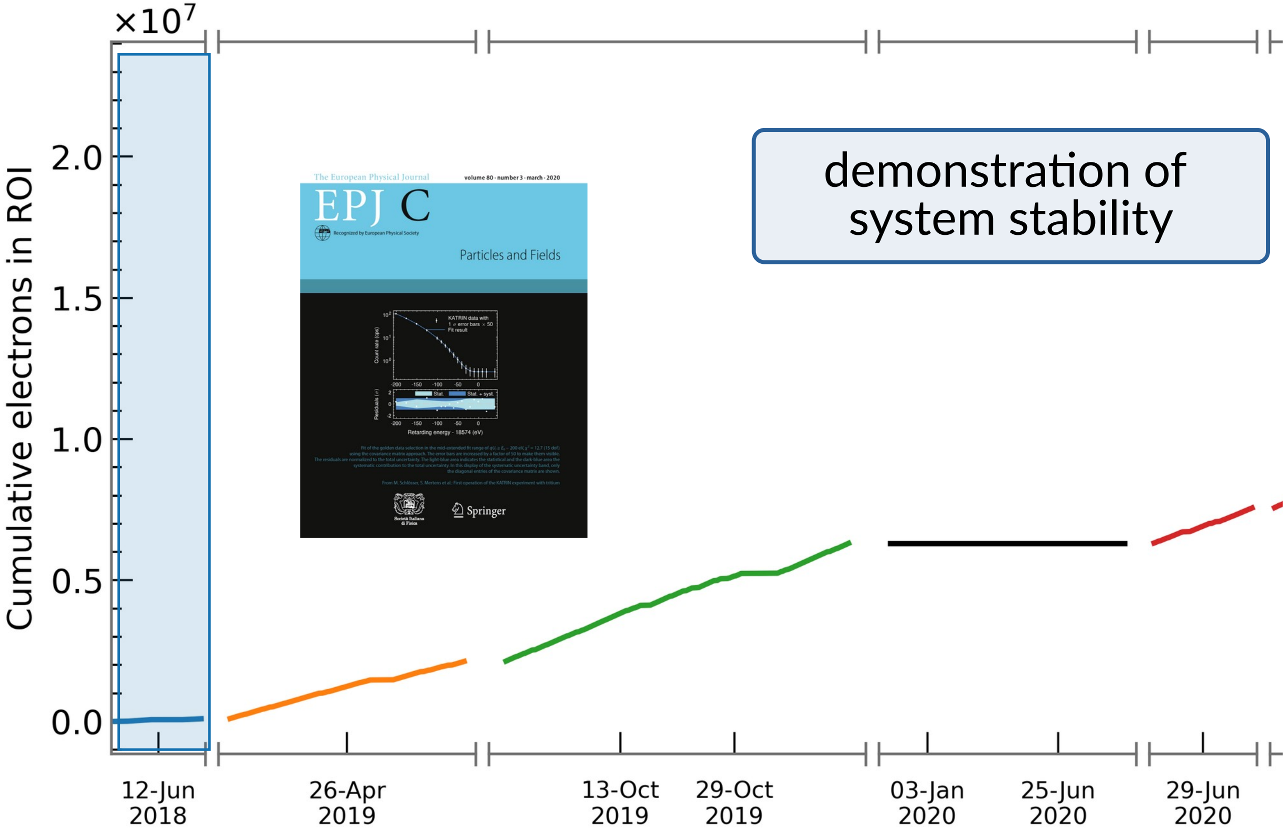


Focal plane detector
- 148-pixel Si-PIN detector

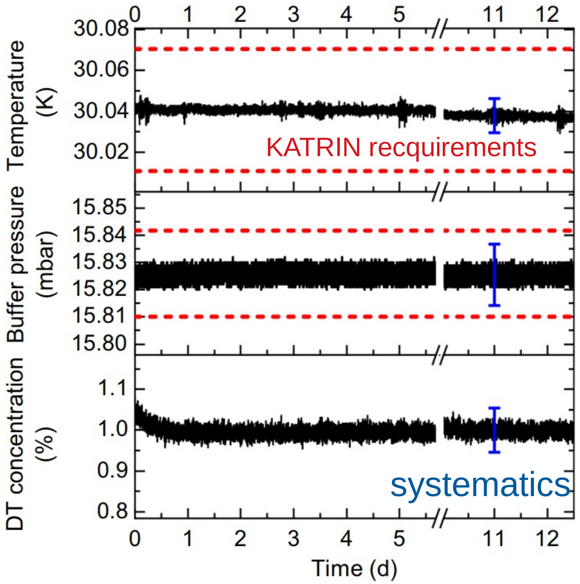




First tritium campaign

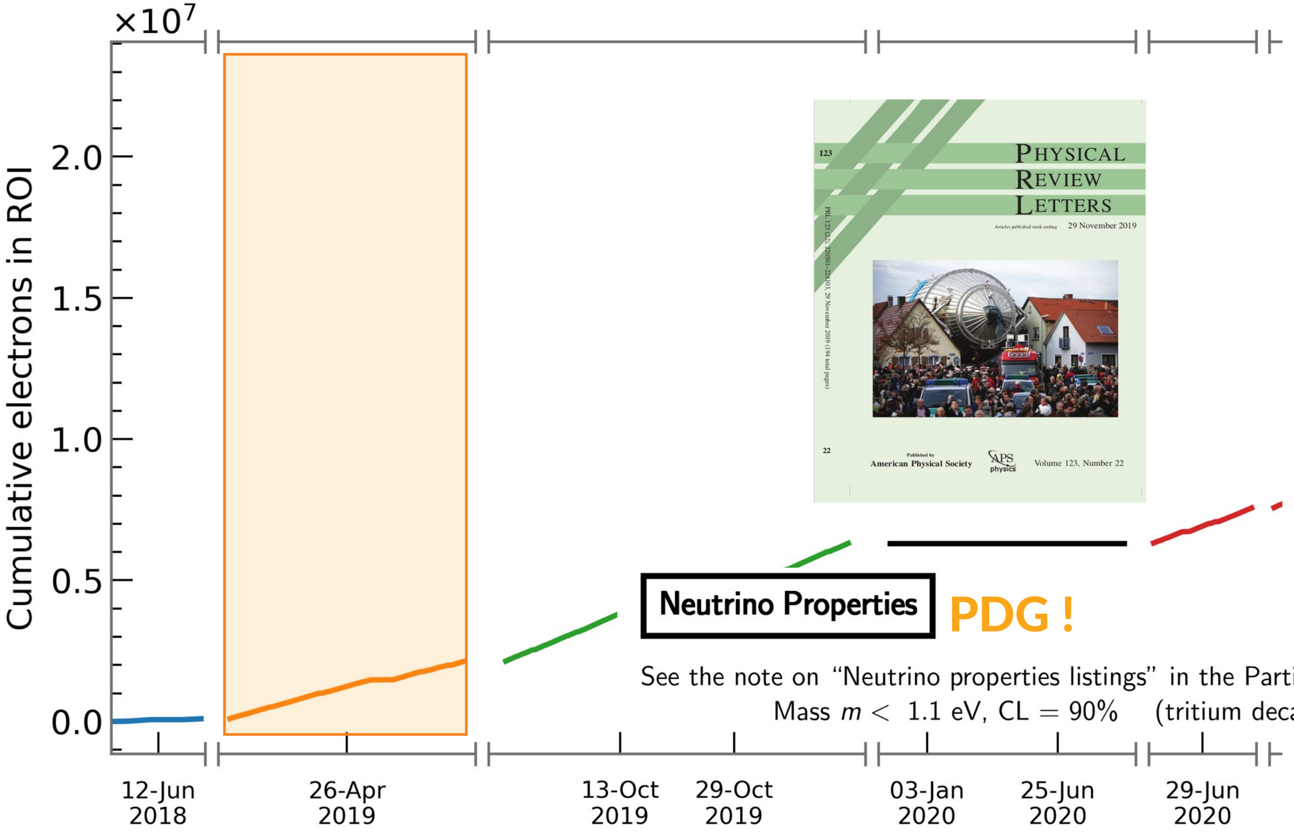


demonstration of system stability



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

1st neutrino mass campaign

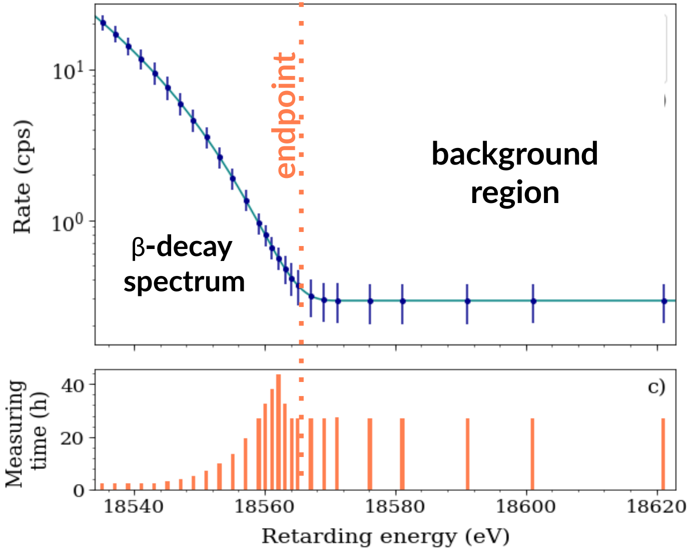


Neutrino Properties PDG !

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

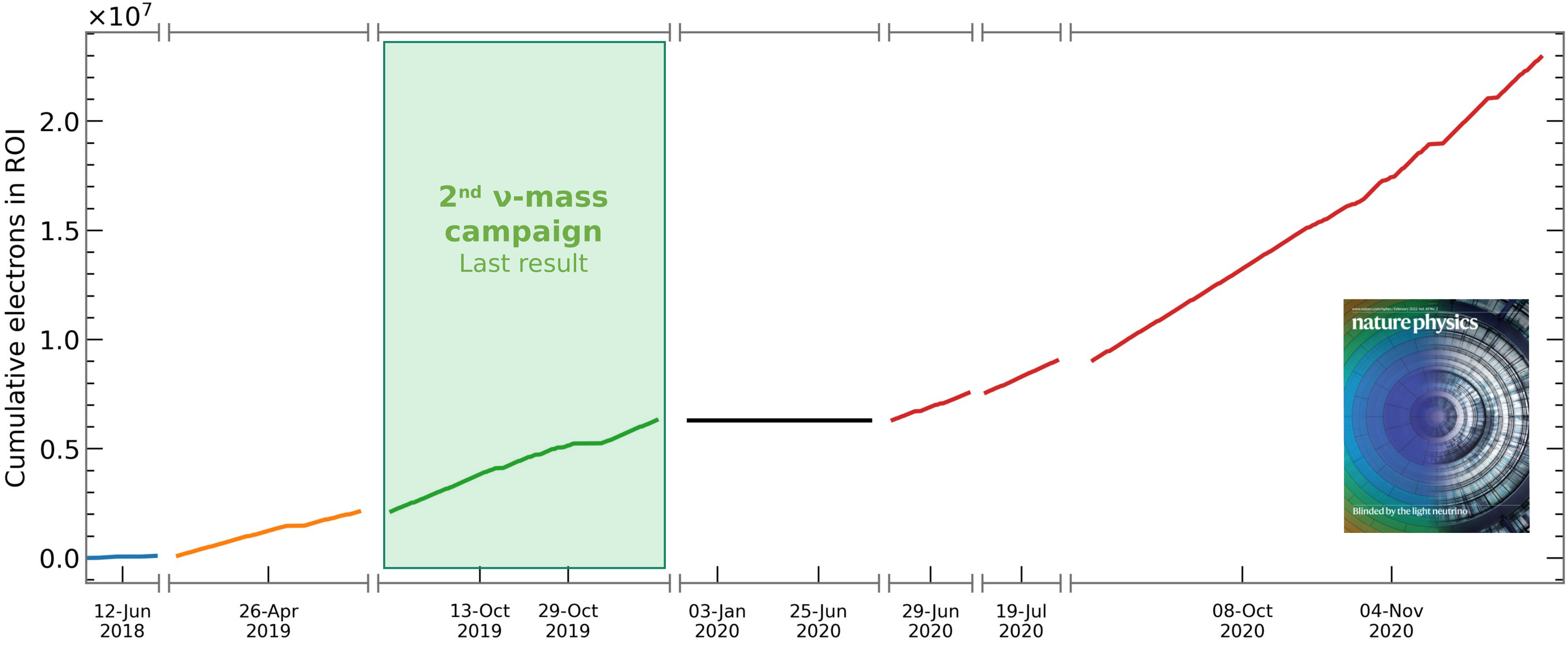
Mass $m <$ 1.1 eV, CL = 90% (tritium decay)

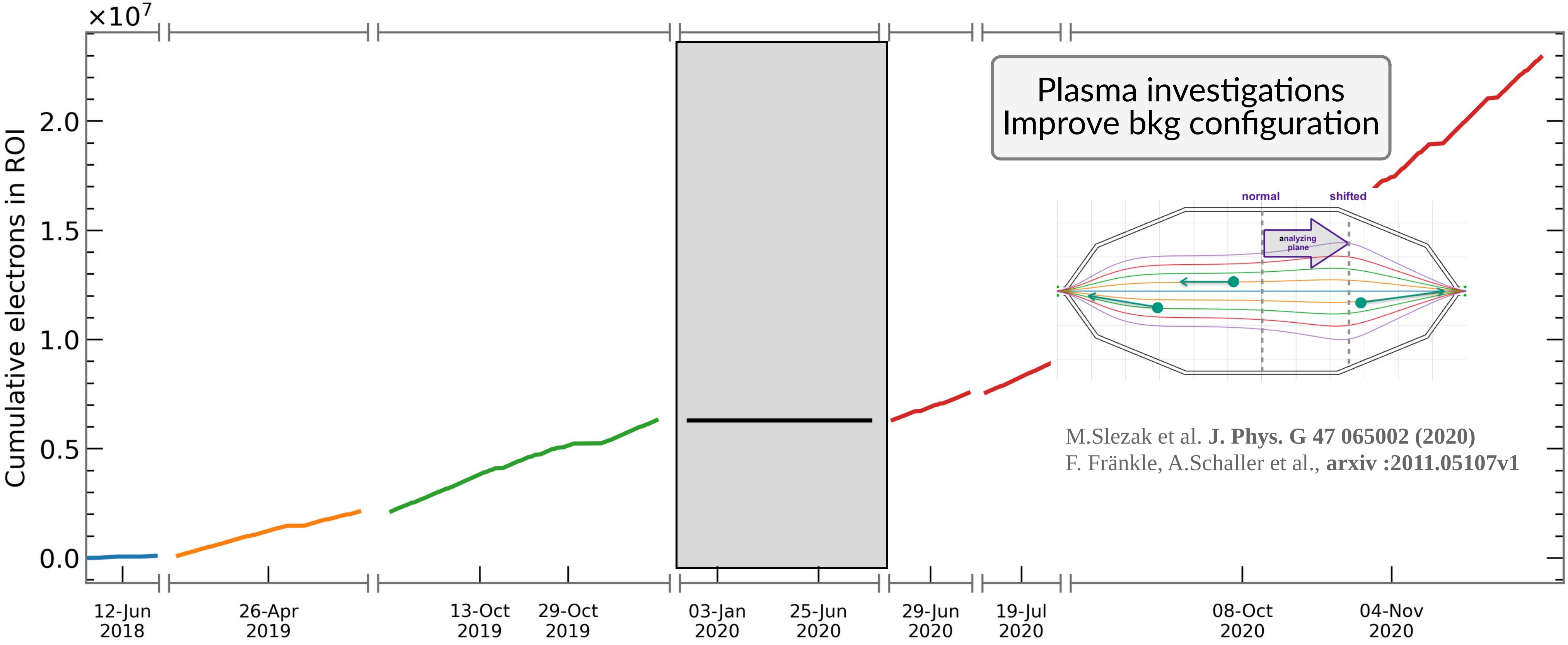
- Measurement time: 22 days
- Gas density: 22%
- Isotopic purity: 97.5% tritium
- Source activity: $2.45 \cdot 10^{10}$ Bq
- Total statistics: $2 \cdot 10^6$ e's



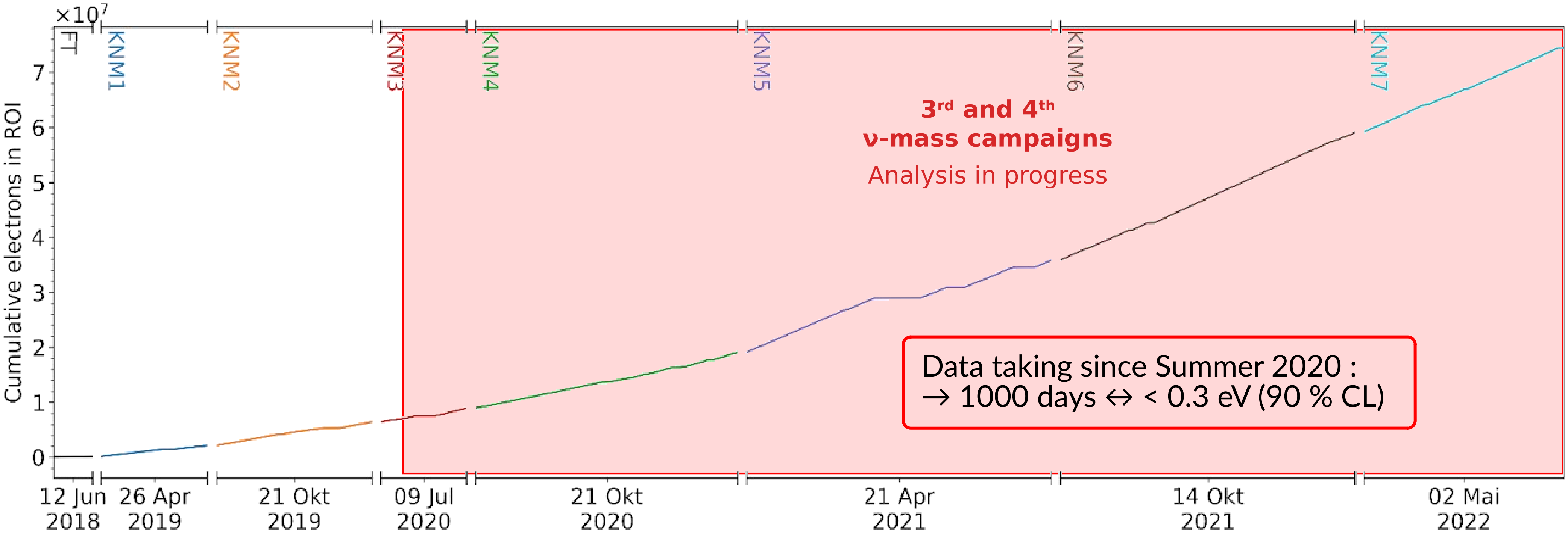
- *Improved Upper Limit on the Neutrino Mass from a Direct Kinematic Method by KATRIN*, KATRIN Collaboration, **Phys. Rev. Lett. 123, 221802 (2019)**

2nd neutrino mass campaign

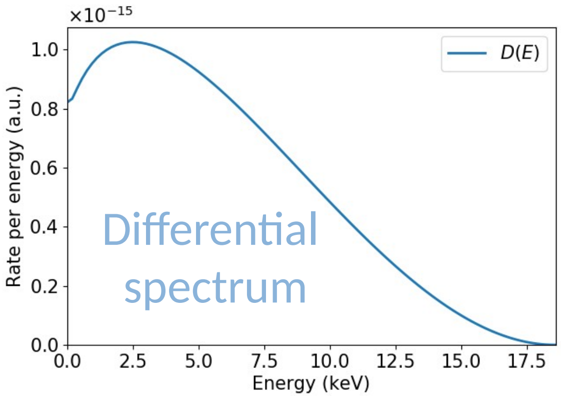


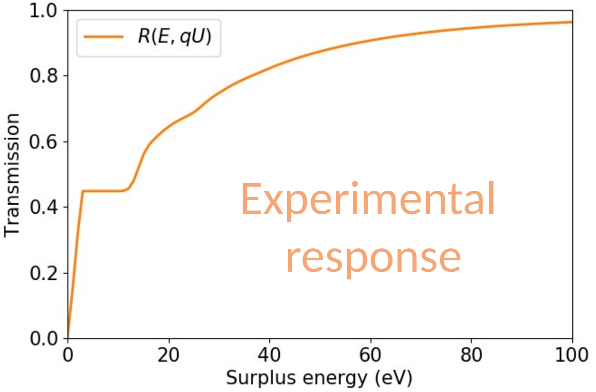

×10^7
Cumulative electrons in ROI
2.0
1.5
1.0
0.5
0.0
12-Jun 2018
26-Apr 2019
13-Oct 2019
29-Oct 2019
03-Jan 2020
25-Jun 2020
29-Jun 2020
19-Jul 2020
08-Oct 2020
04-Nov 2020
normal
shifted
analyzing plane
Plasma investigations
Improve bkg configuration
M.Slezak et al. J. Phys. G 47 065002 (2020)
F. Fränkle, A.Schaller et al., arxiv :2011.05107v1

Cruising mode



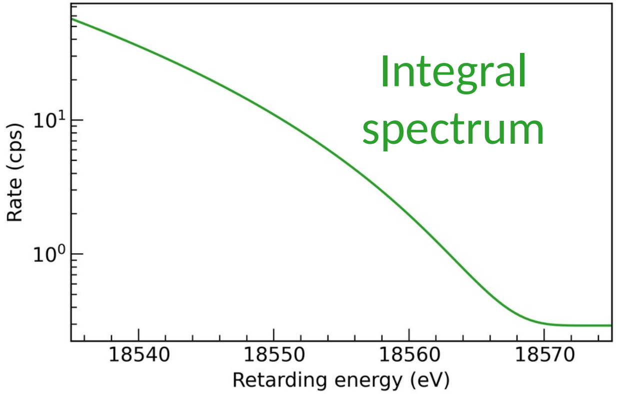
Model





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

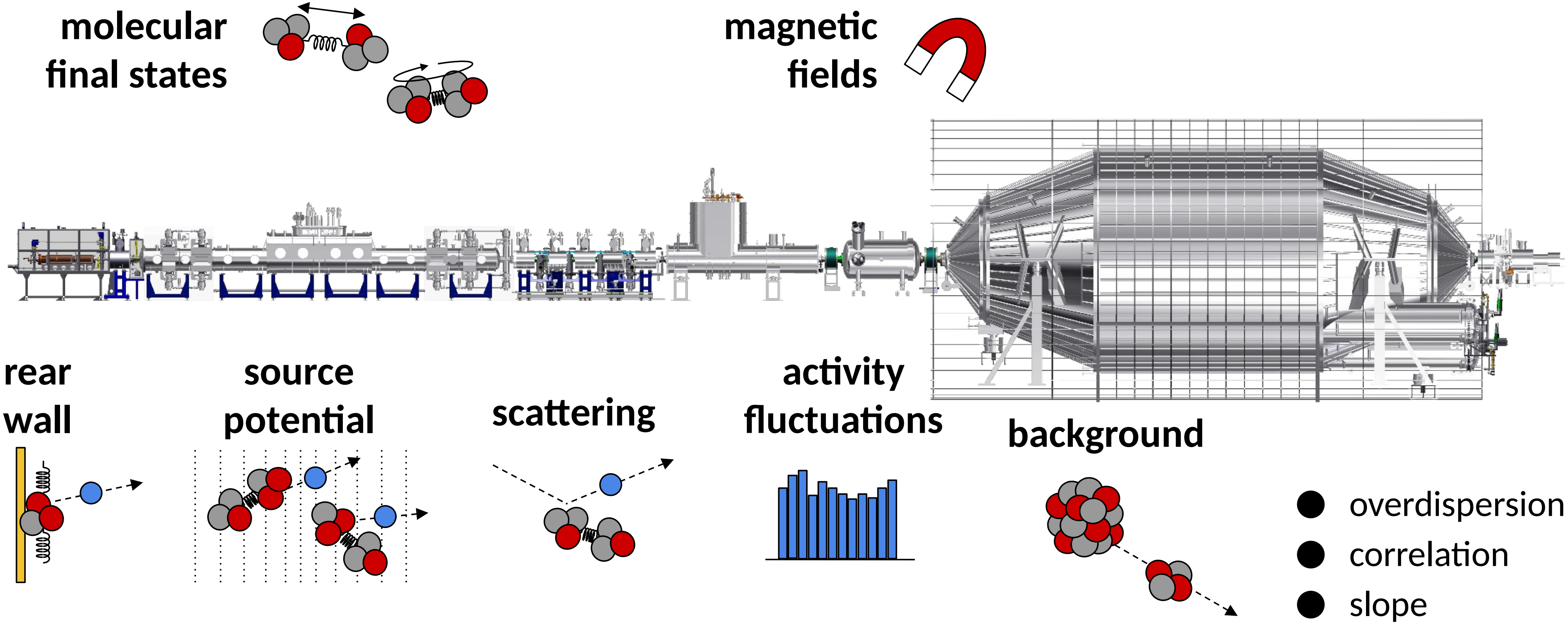
- Fermi theory
- Molecular final states
- Doppler broadening
- Radiative corrections
- ...



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

Analysis methods for the first KATRIN neutrino-mass measurement Phys. Rev. D 104, 012005 (2021)

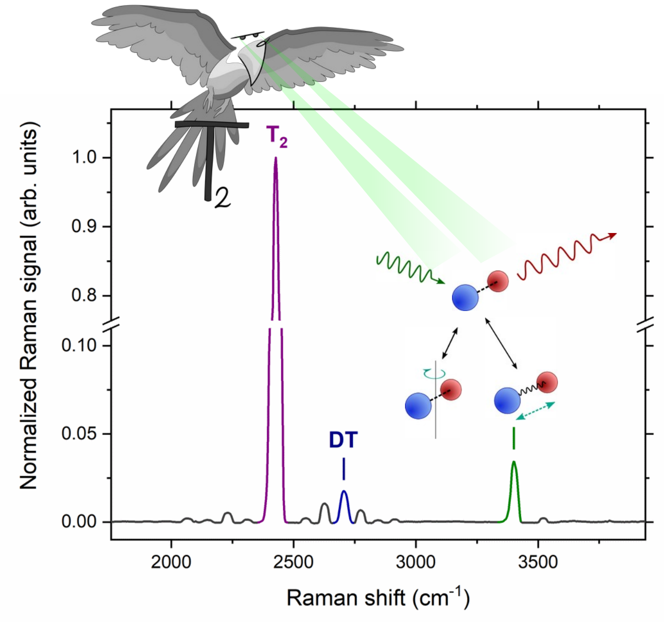
Systematic uncertainties



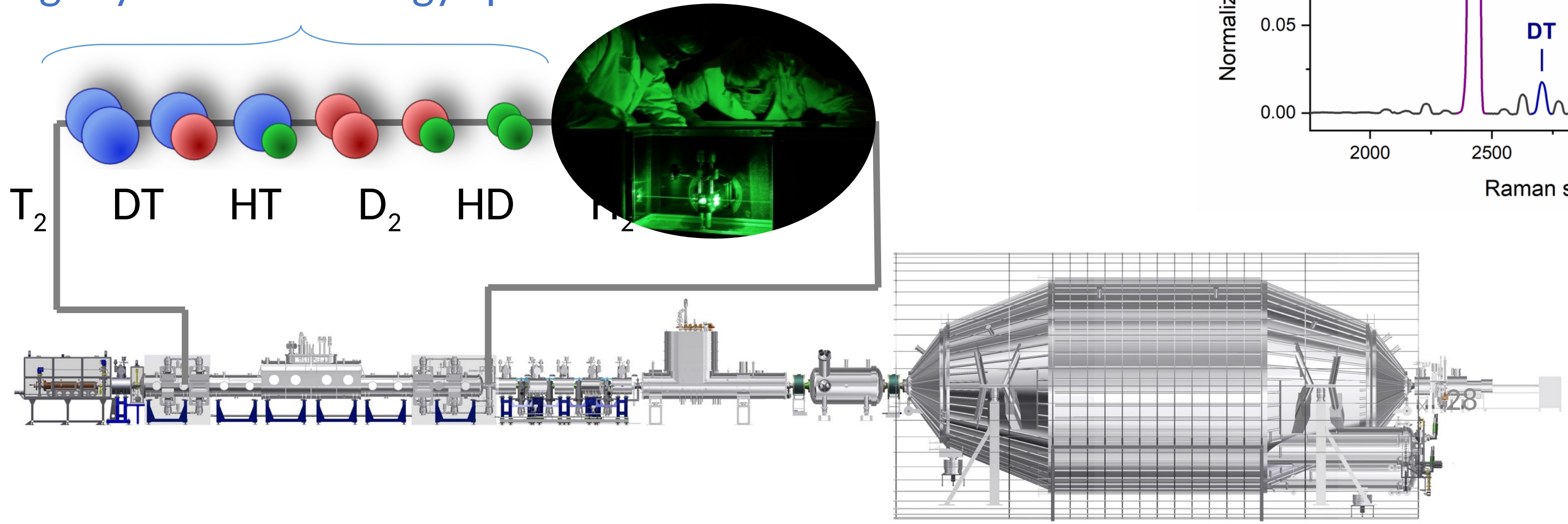
D'après Thierry Lasserre - EDSU 2022

Source composition

- **Laser Raman IR Spectroscopy**
- High purity and stability established (98.7 %)



Slightly different energy spectra

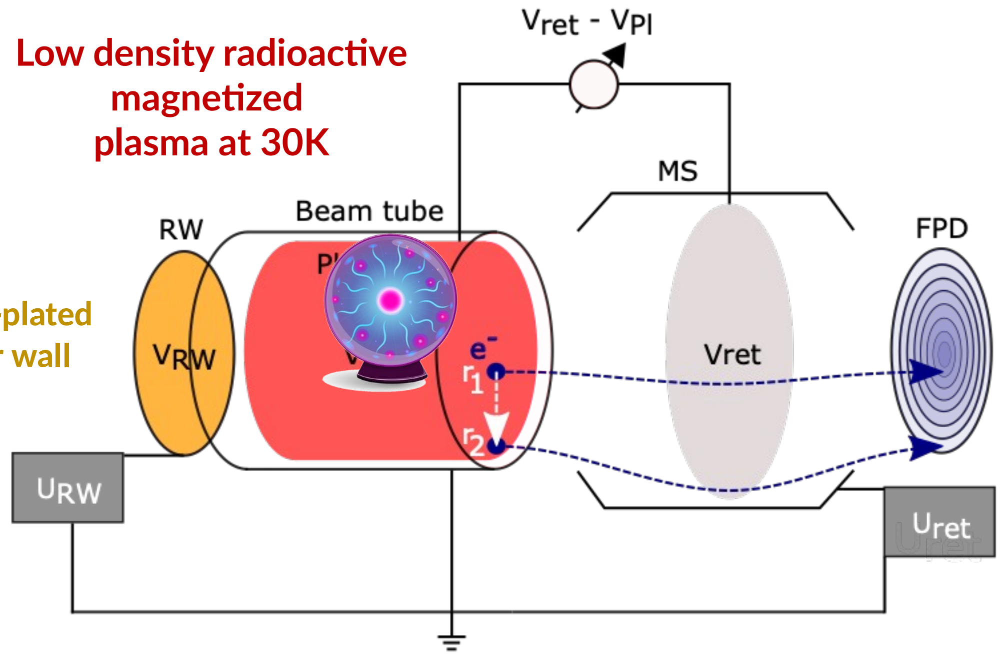


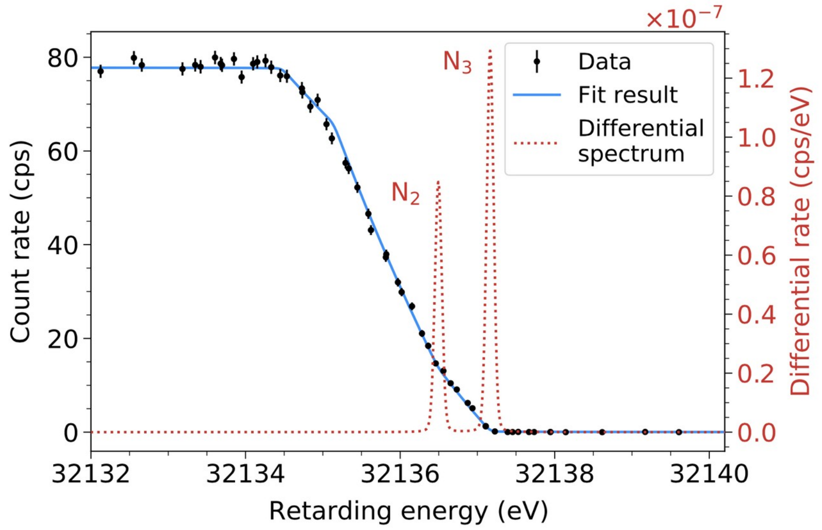
Source potential

- Spectroscopy through E threshold → $qU_{spectrometer}$ (V_{ret}) – **qU_{source}** (V_{pi})
- Absolute value does not affect the shape (endpoint free fit parameter)
- Calibration using gazeous ^{83m}Kr injected in the source, Ring-wise analysis for r-dependancy

Low density radioactive magnetized plasma at 30K

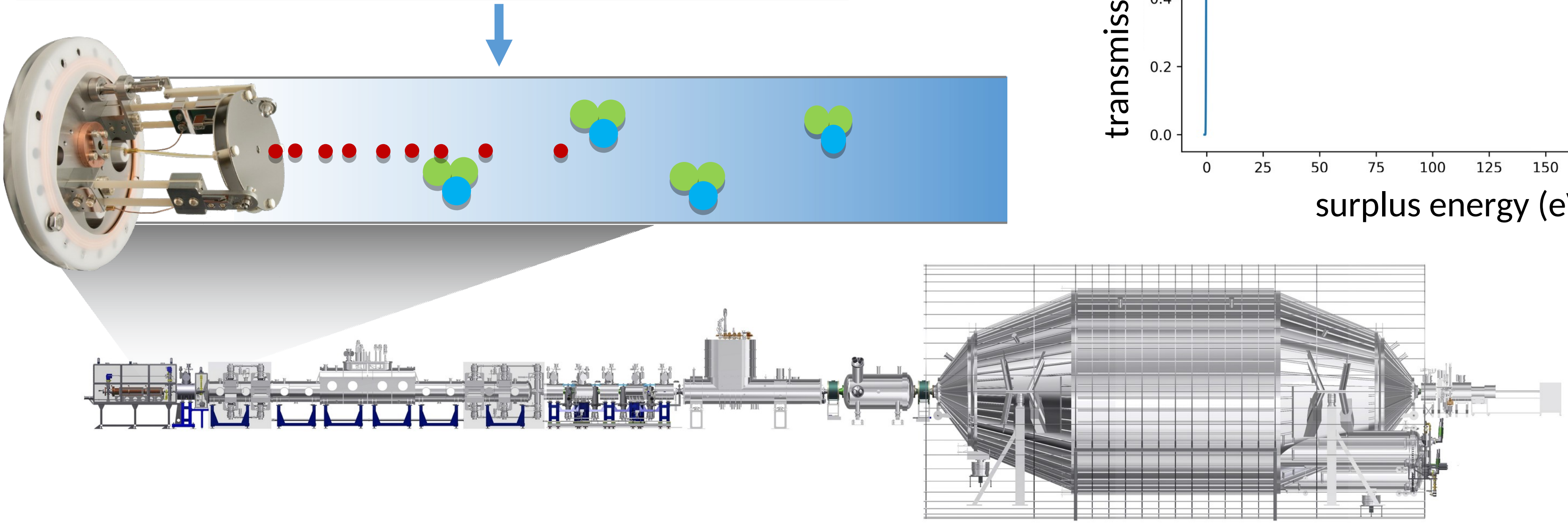
Gold-plated rear wall

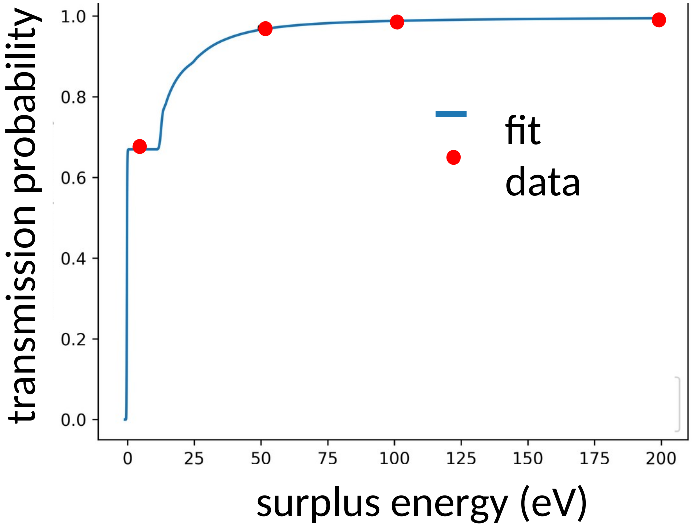




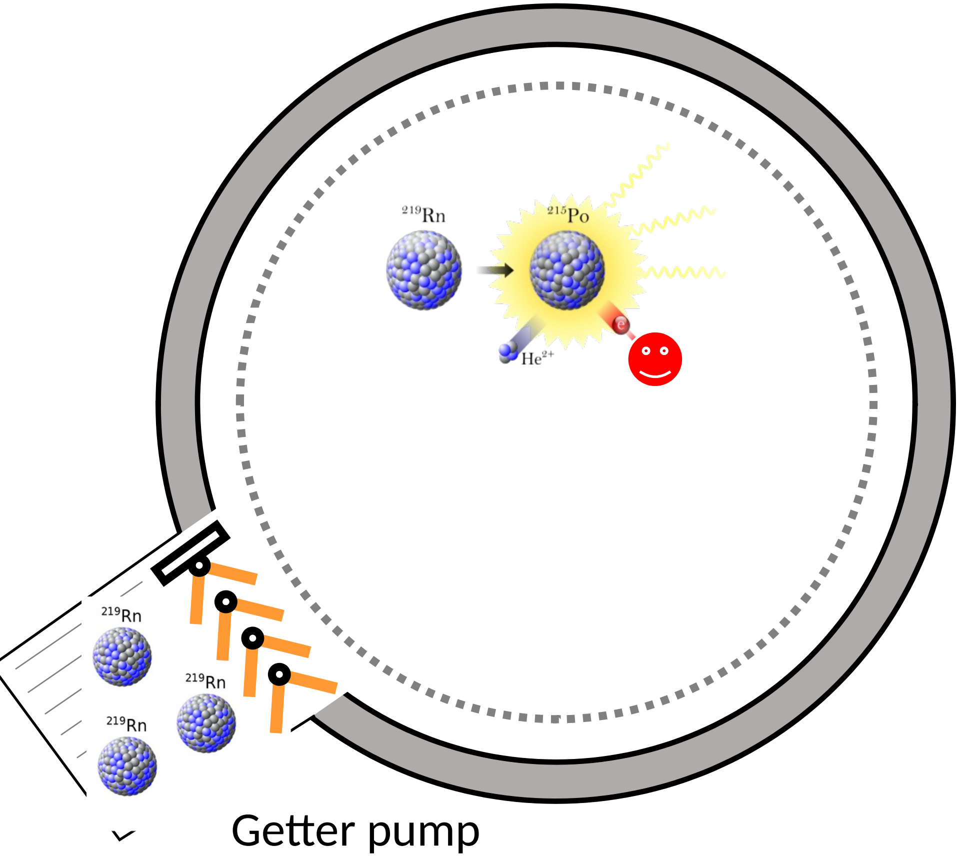
Source density

- **High-intensity electron gun**
- Column density 0.84 x 1.1 × 10^{21} molecules/m^{-2}
- (0.1)%-ish stability of density observed
- Characterized with electron gun



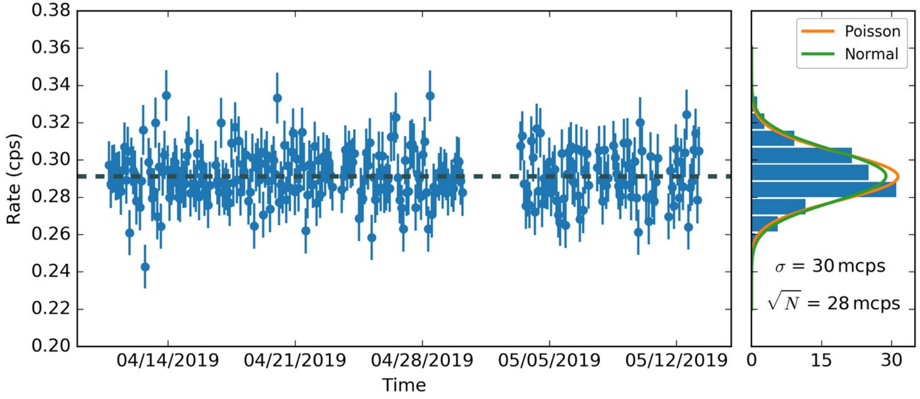


Radon-induced backgrounds

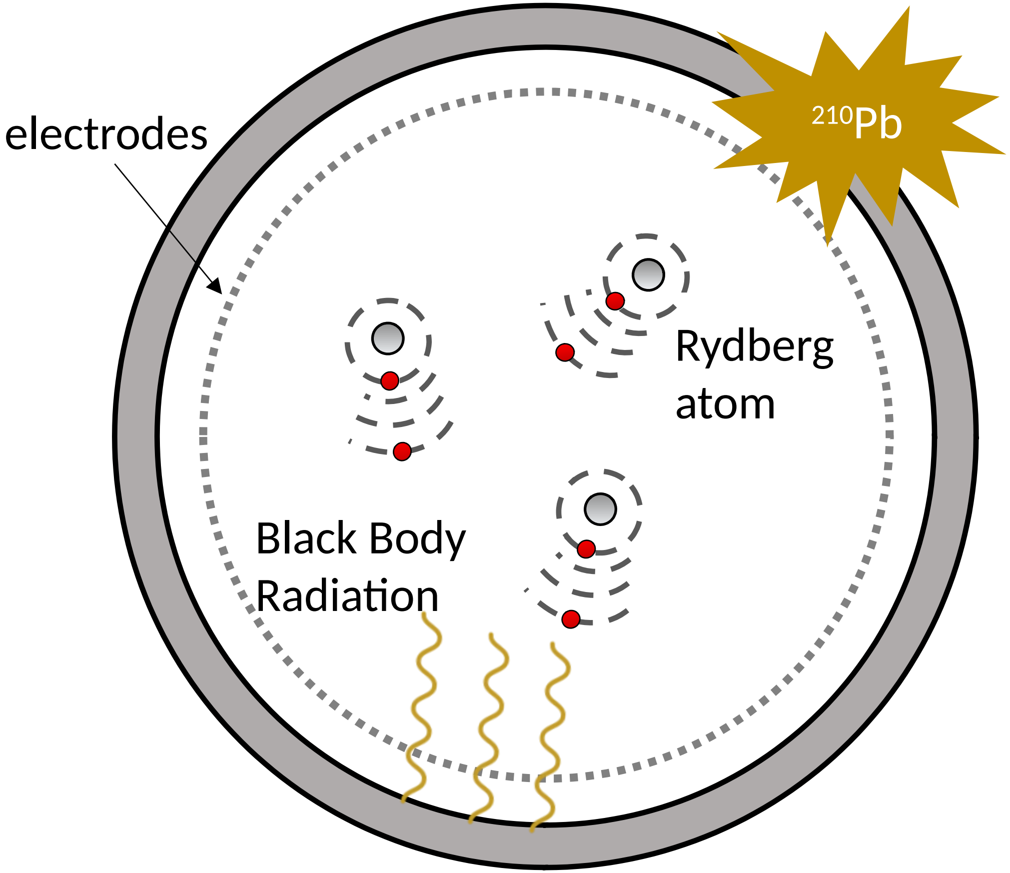


Getter pump

- NEG pumps radon emanation
- α−decays of single ^{219}Rn atoms (3.96 s)
- Low energy e$^-$ emission inside spectrometer
- Effective reduction via nitrogen-cooled baffle system
- 10% Non-Poissonian rate over-dispersion

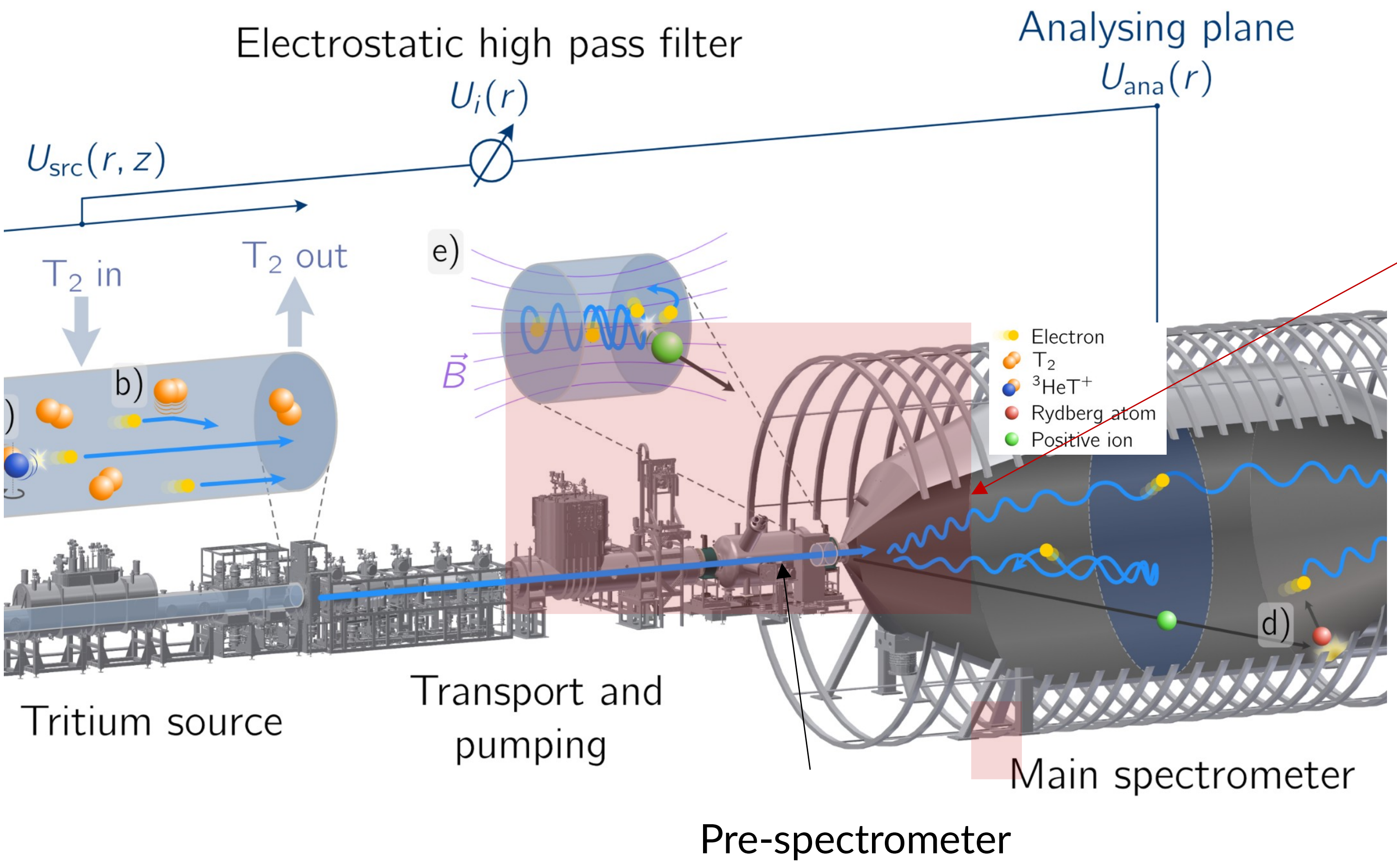


Neutral Excited Atoms



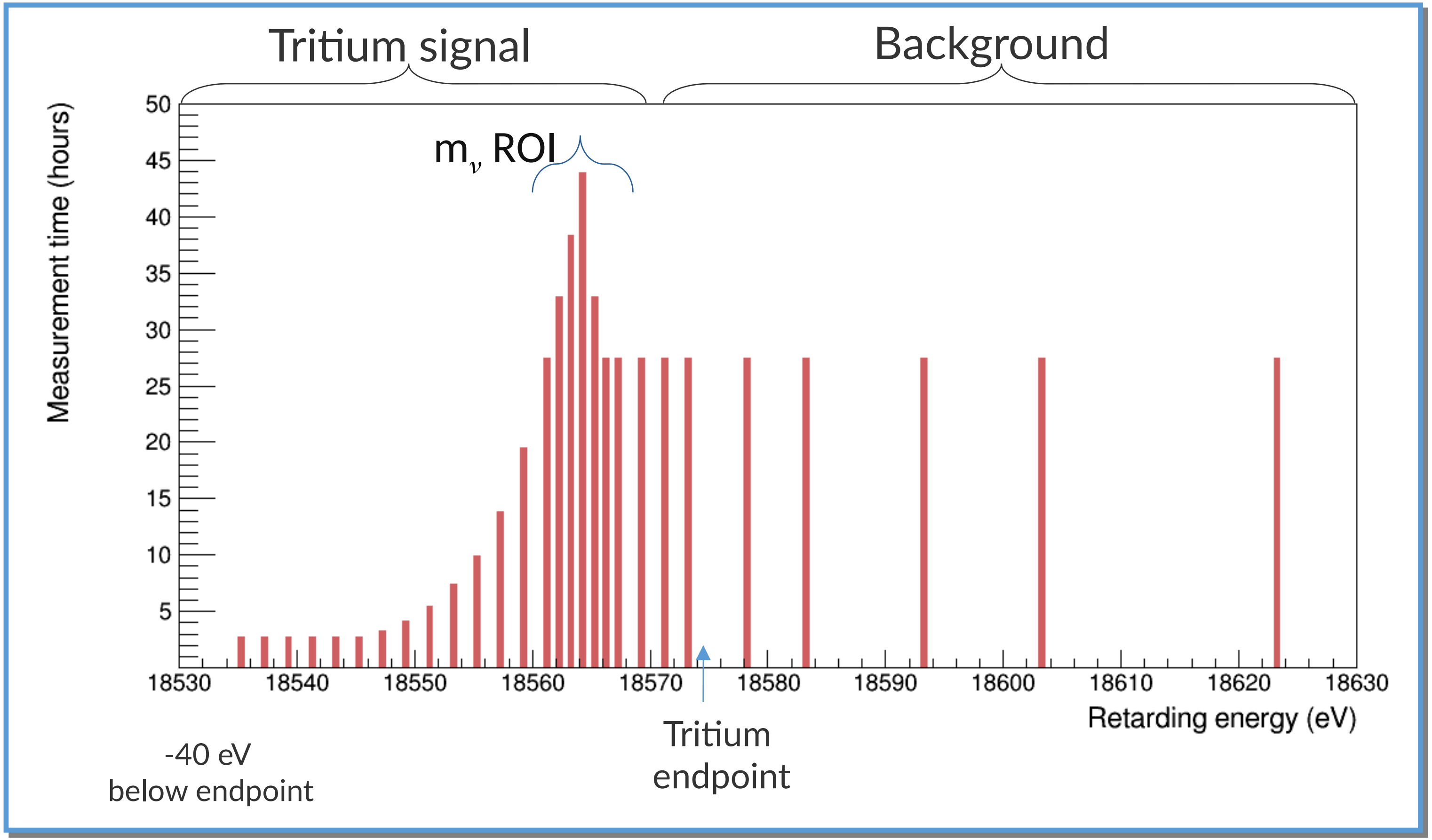
- Radon exposition during construction
  → ^{210}Pb surface contamination
- Rydberg atoms sputtered off from the spectrometer surfaces by ^{210}Pb α-decays
- Ionisation by thermal radiation
- Low energy e^- emission inside spectrometer
- Scale as the spectrometer volume…

Penning-trap induced Background



- Both pre- and main spectrometers, operated at high voltage
- create a Penning trap
- Stored electrons create ions$^+$, which can escape the trap into the main spectrometer → background
- Trap emptied with an e^--catcher system after each sub-scan
- Can induce background dependency with sub-scan length

Scanning strategy

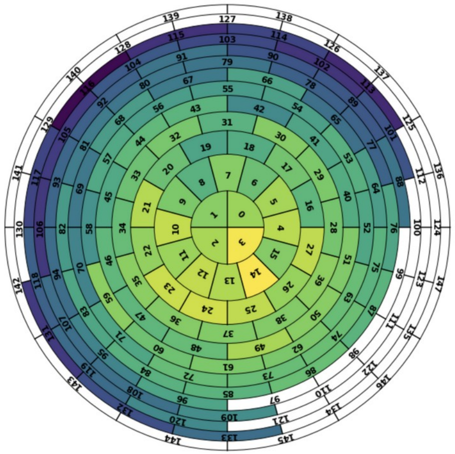


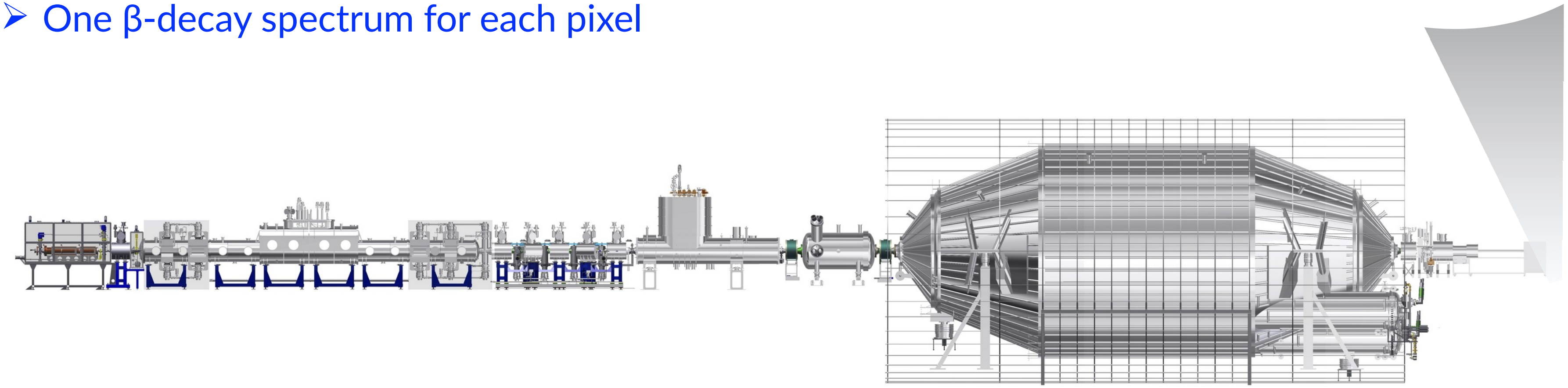
X 361 β-scans

Focal plane detector

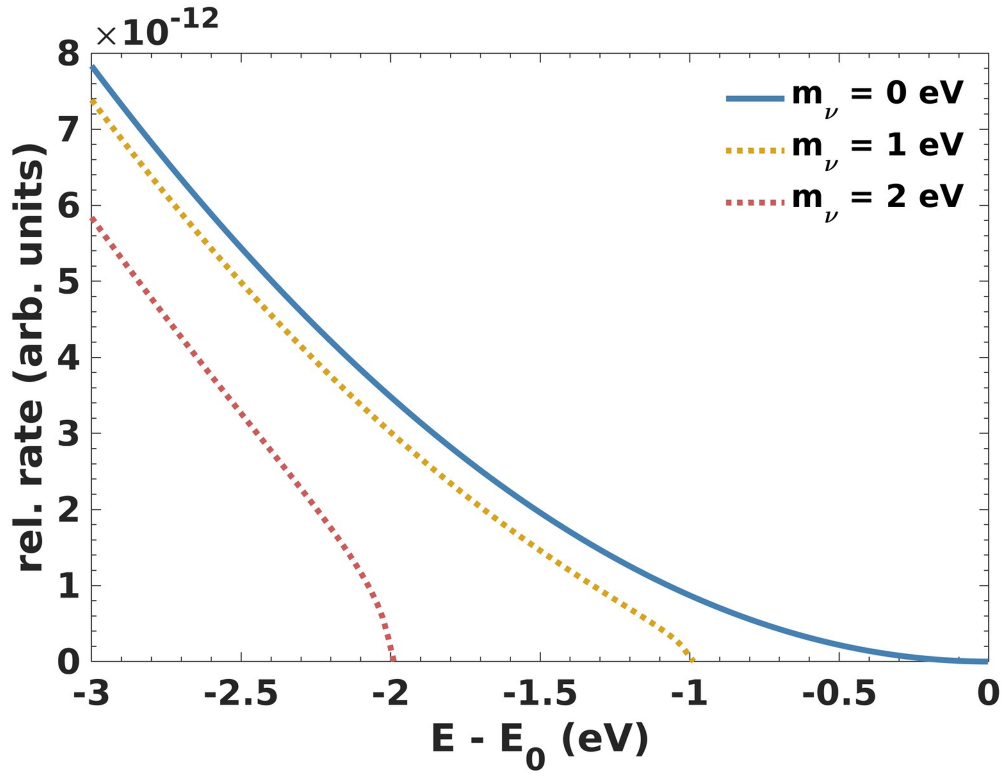
- multi-pixel silicon array
- 117/148 (79%) of all pixels used
- detection efficiency of 90%
- negligible retarding-potential dependence of efficiency
- negligible intrinsic background (~ 1mcps)

➢ One β-decay spectrum for each pixel



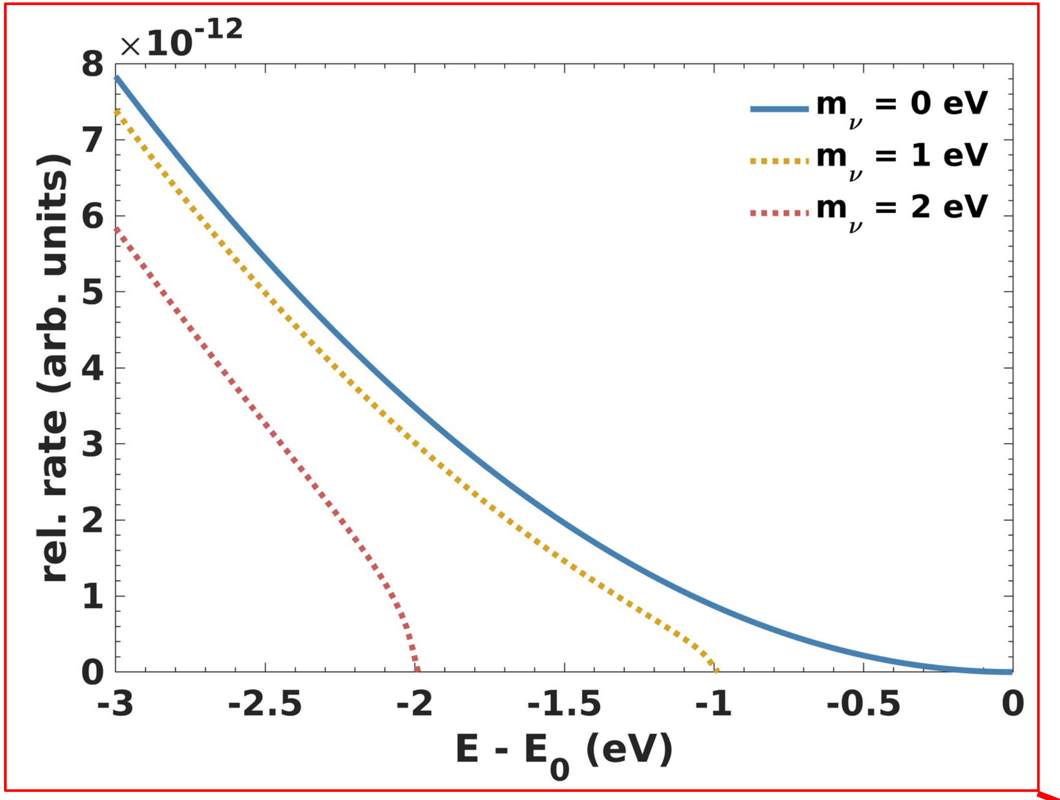


Fitting the mass imprint



Courtesy of Thierry Lasserre

Fitting the mass imprint



Courtesy of Thierry Lasserre

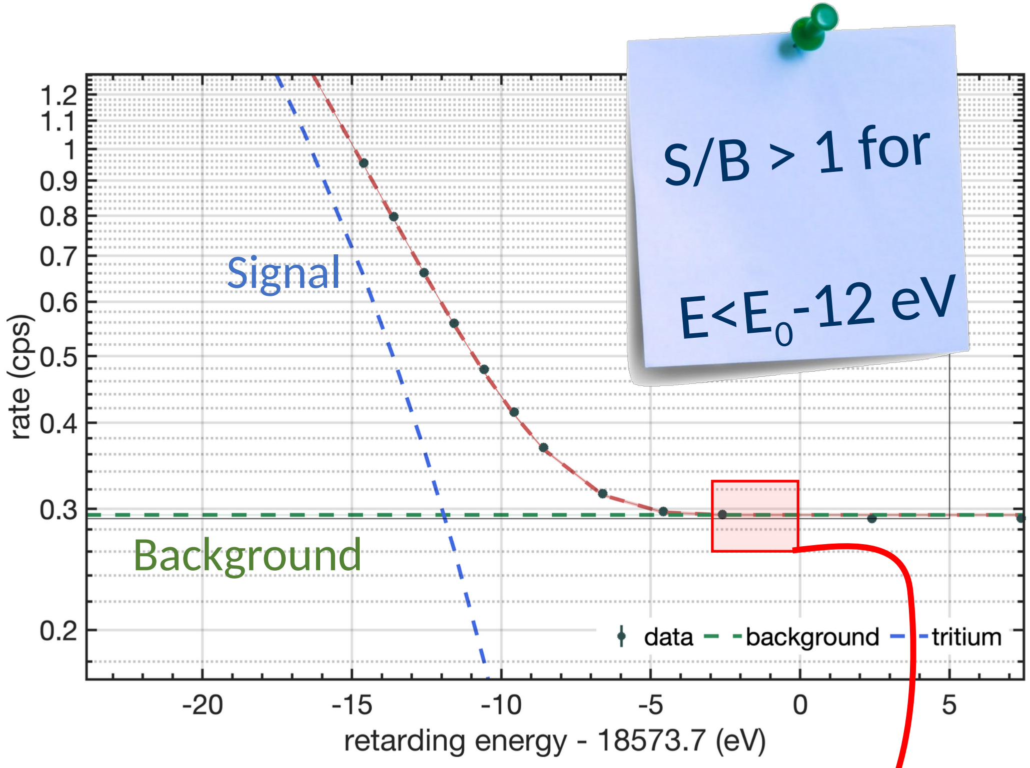
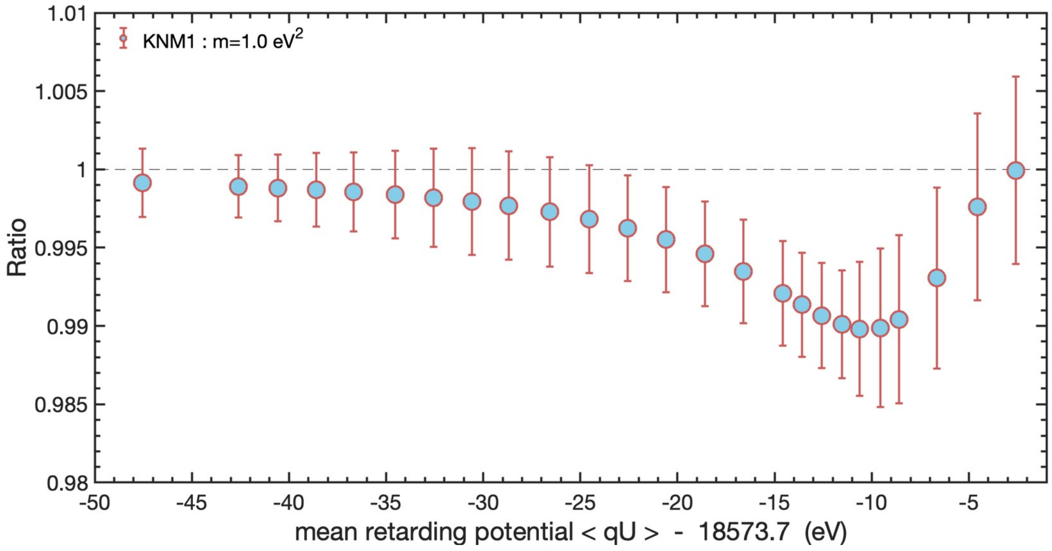


Illustration using 1st neutrino mass campaign

Fitting the mass imprint



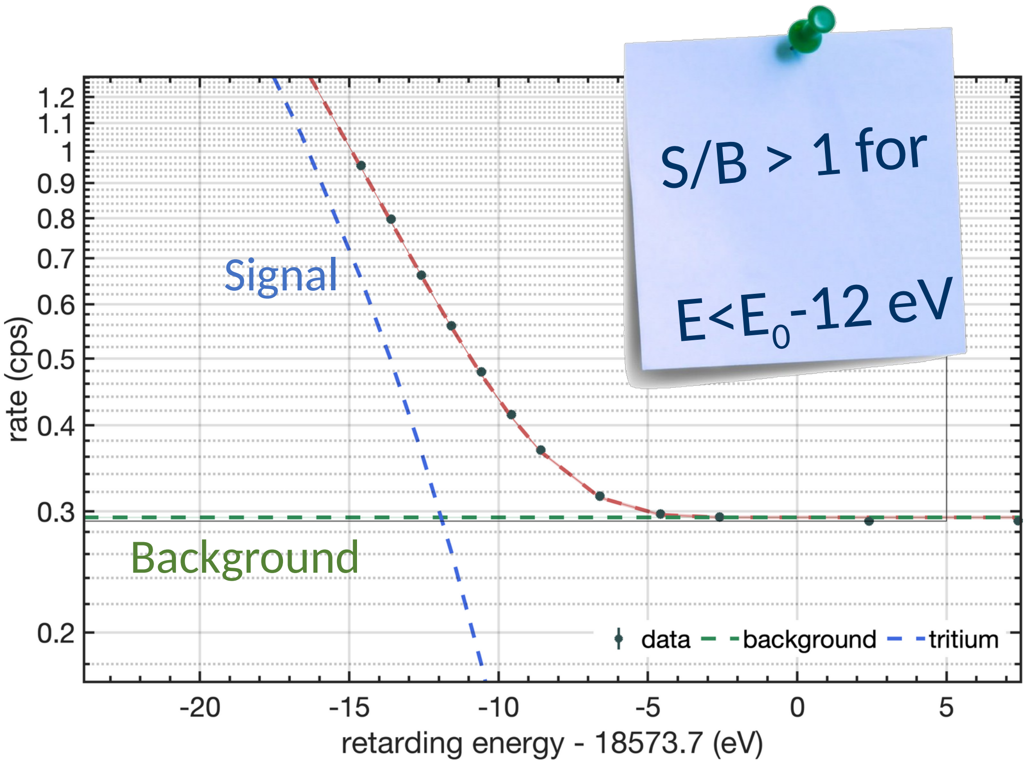


Illustration using 1st neutrino mass campaign

Courtesy of Thierry Lasserre

Fitting the mass imprint

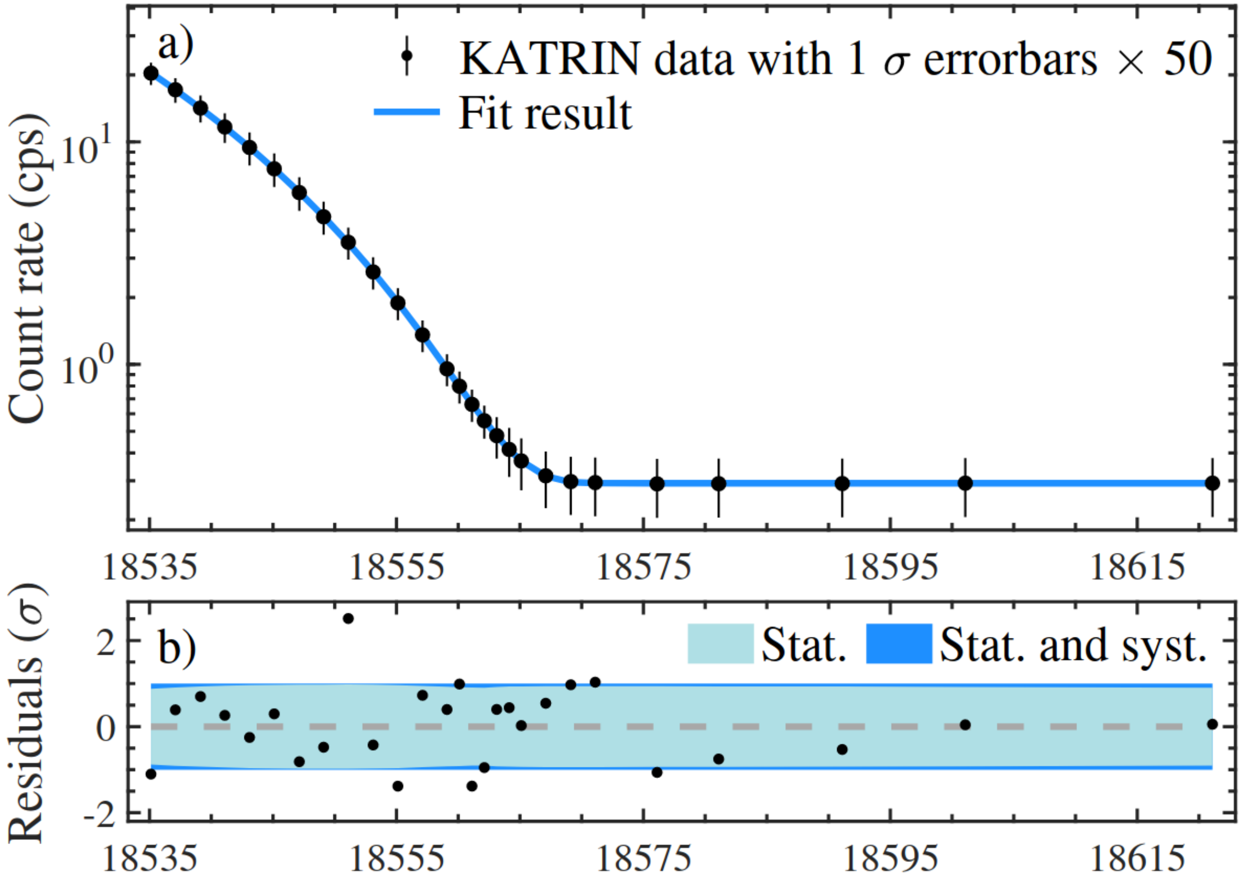
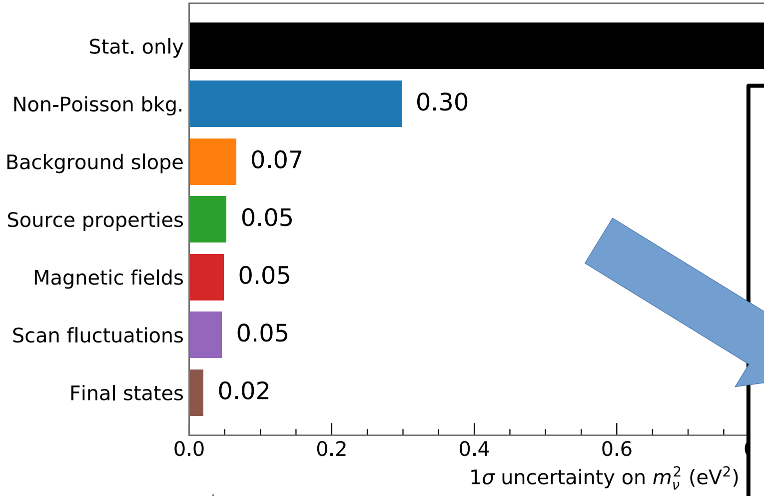


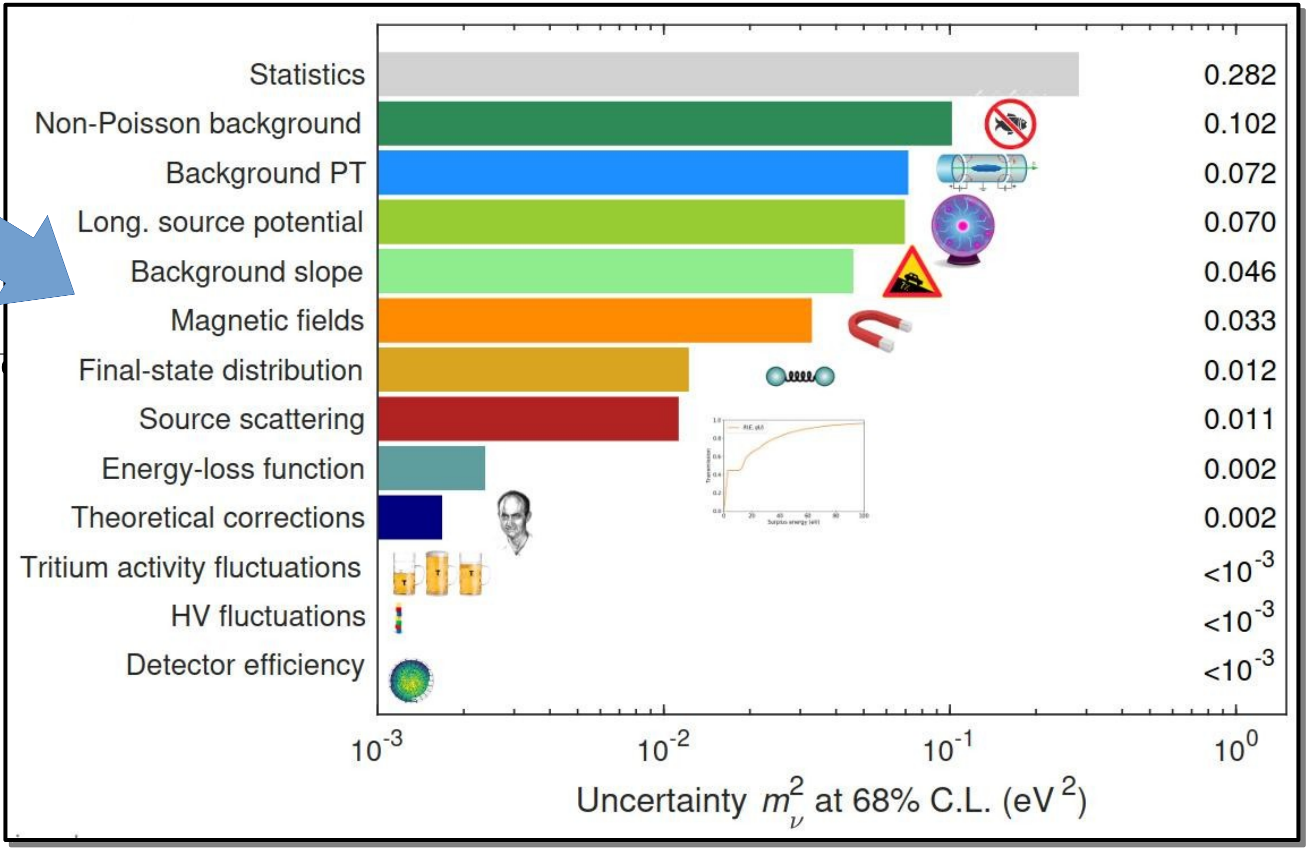
Illustration using 1st neutrino mass campaign

Systematics

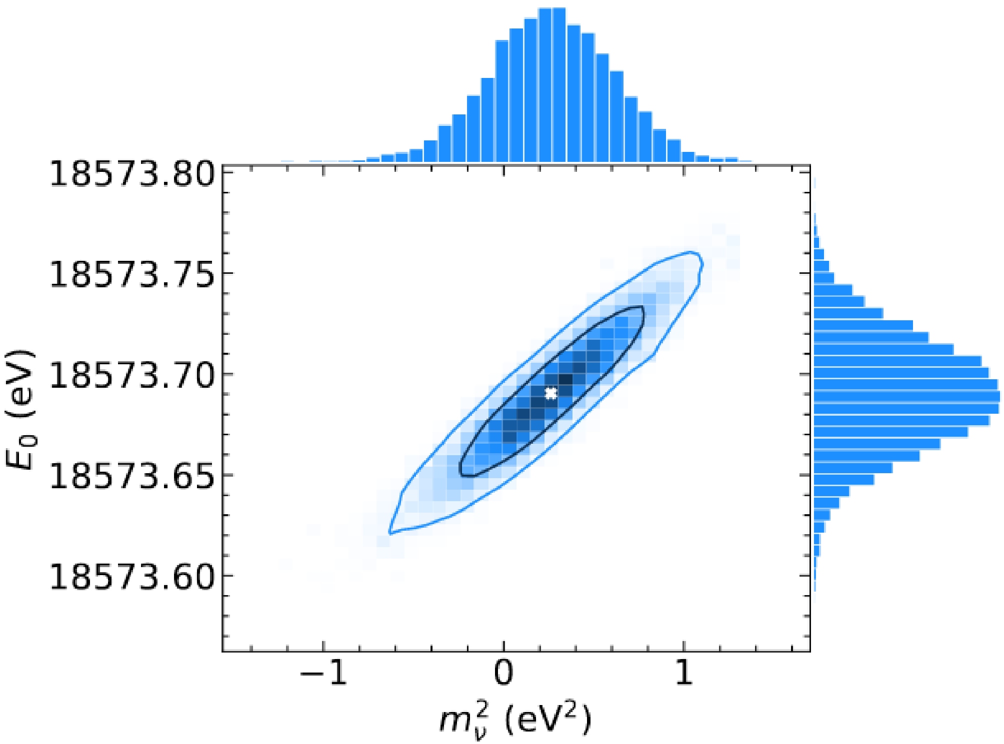


1st neutrino mass campaign

2nd neutrino mass campaign



Neutrino mass results

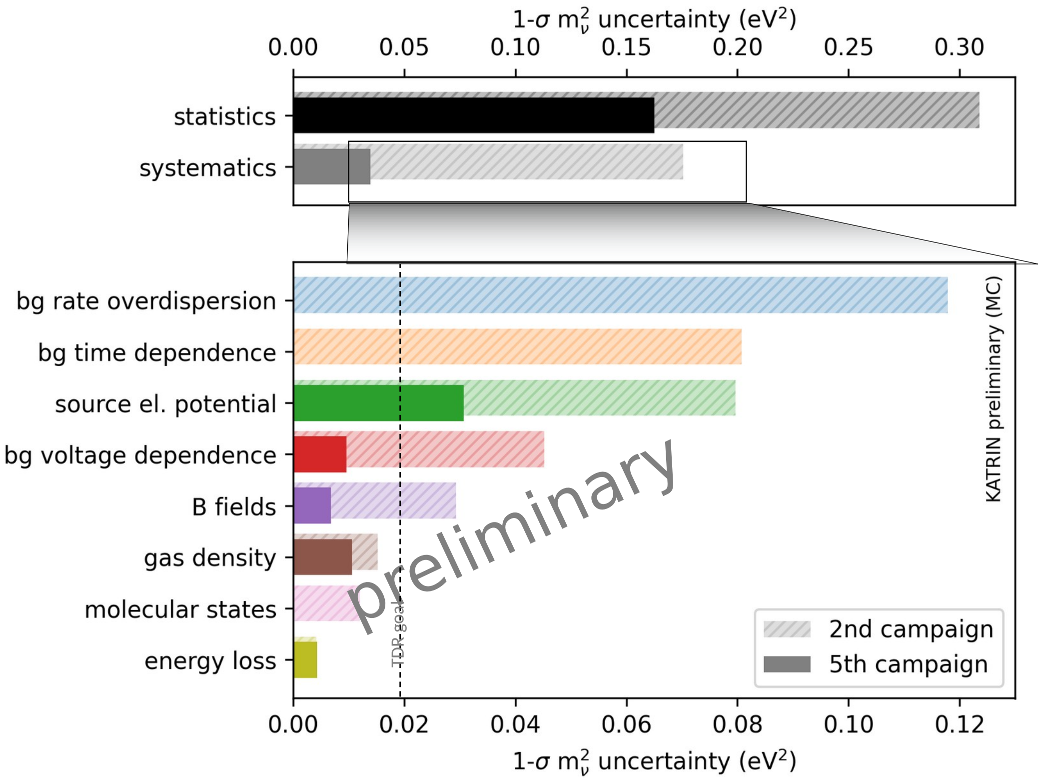


Gas density : 84 %
Sensitivity : $m_\nu < 0.7$ eV (90% CL)
Electrons in ROI : $4.2 \cdot 10^6$
Scan time : 31 days

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

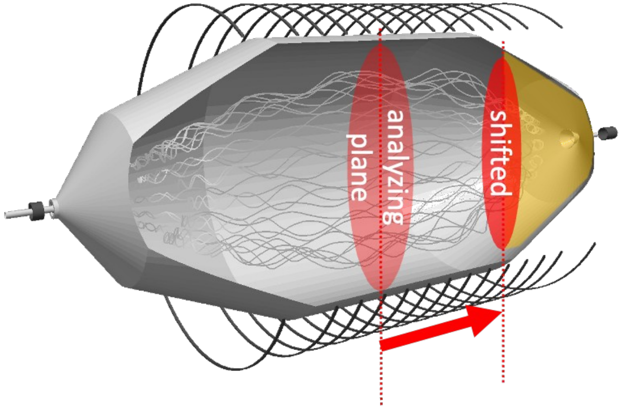
Results:
$m_\nu^2 = 0.26 \pm 0.35$ eV^2
$m_\nu < 0.9$ eV (90% CL)

Recent achievements



Major improvements:

✓ background reduction (2) via new EM field layout A. Lokhov et al, EPJC 82, 258 (2022)



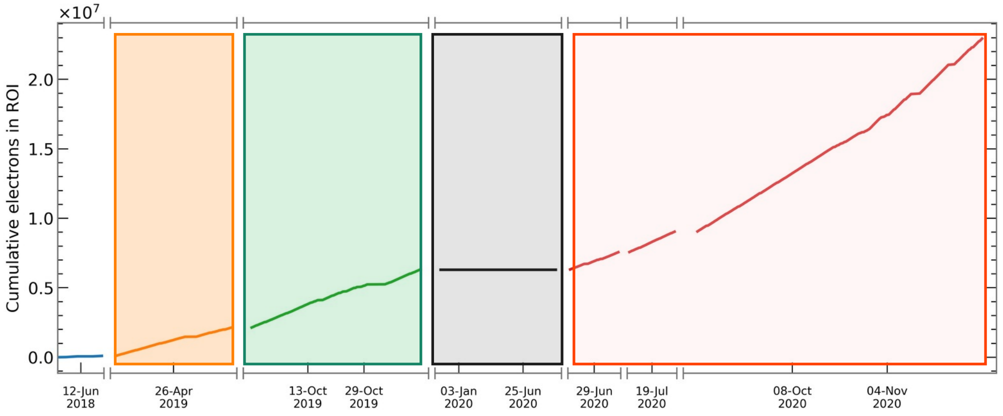
✓ KNM 1 2 + 3 4 5 (2019 – 2022 data)

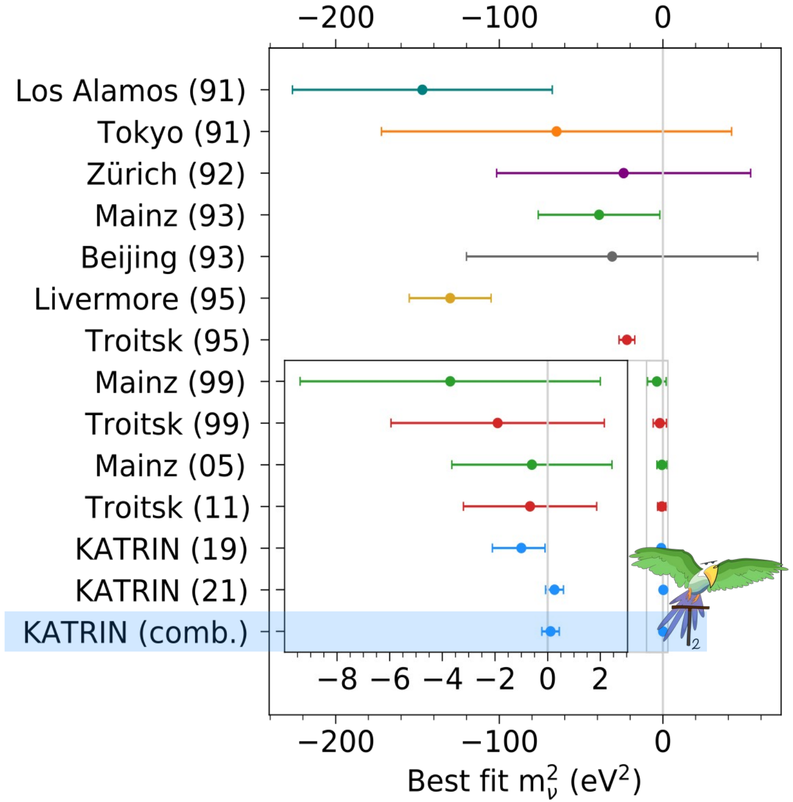
- ✓ 30 millions of electrons in ROI
- ✓ <0.5 eV sensitivity
- ✓ **Next results in summer 2023**

D'après Thierry Lasserre - Moriond EW 2023

Conclusion

Neutrino mass with KATRIN





1st and 2nd campaign combined limit:

m_ν < 0.8 eV (90% CL)

In Nature Physics 18, 160–166 (2022)

Future:

- Reduced background and systematics
- **New results coming soon (stats x6)!** Stay tune for a follow up!

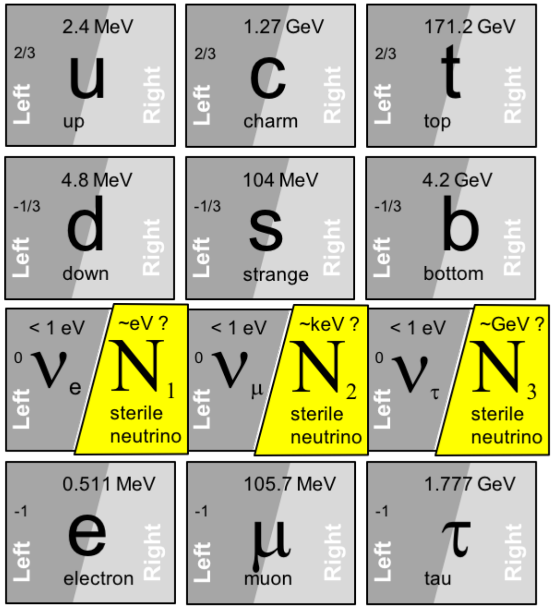
How to generate mass from the SM ?

- 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

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

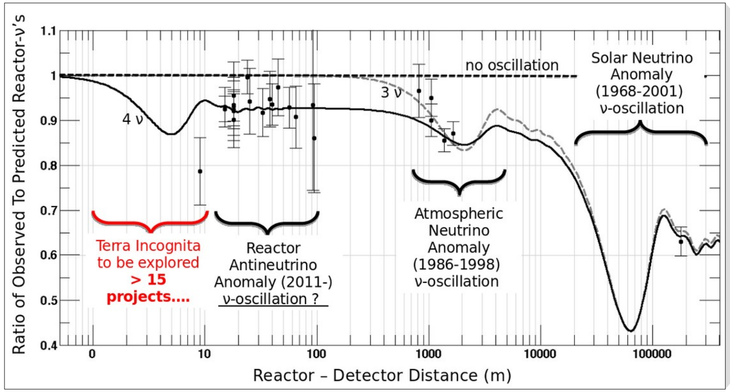
Dirac
mass term

Majorana
mass term

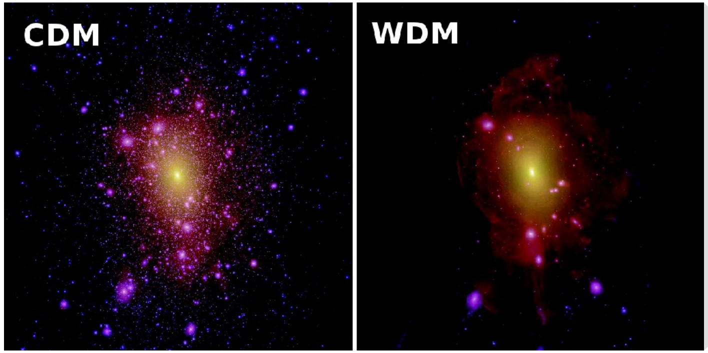


RH neutrinos → Sterile neutrinos

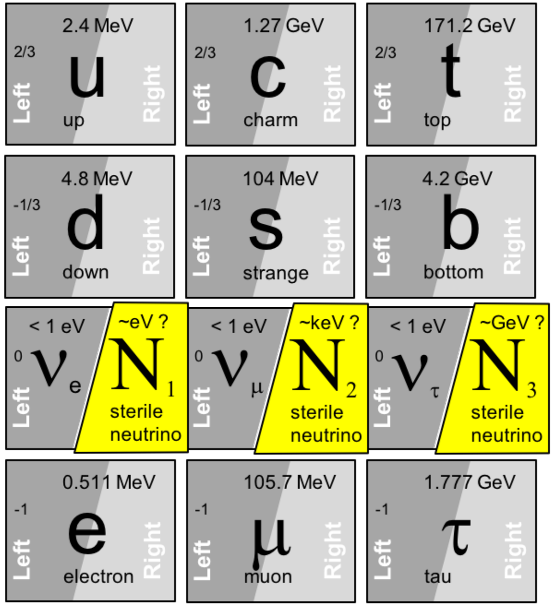
Is there a sterile neutrino ?



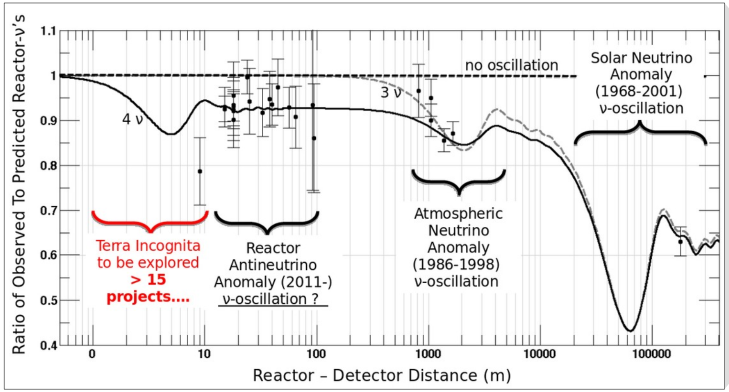
eV-scale:
Resolve anomalies in oscillation experiments



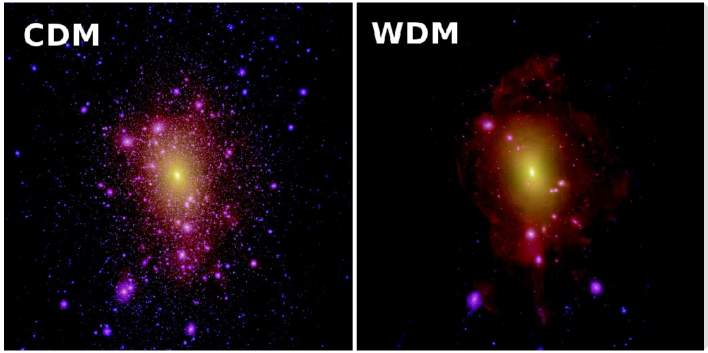
keV-scale:
Dark Matter candidate



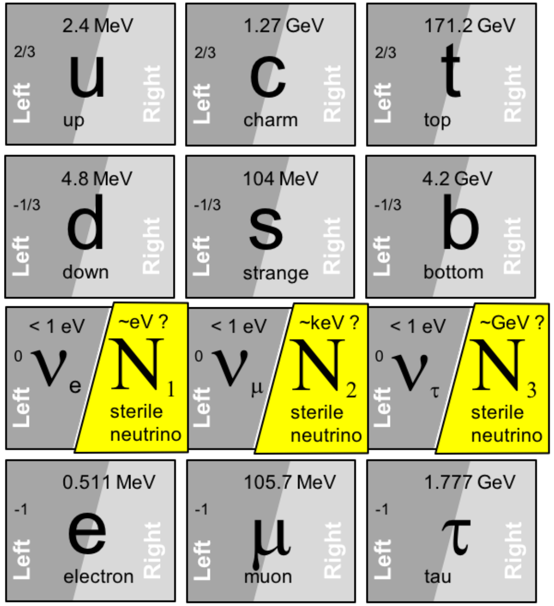
Is there a sterile neutrino ?



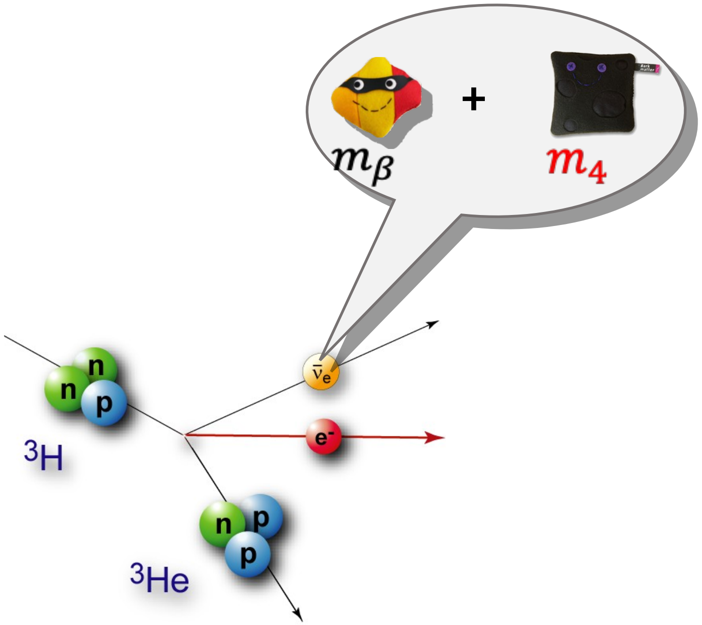
eV-scale:
Resolve anomalies in oscillation experiments

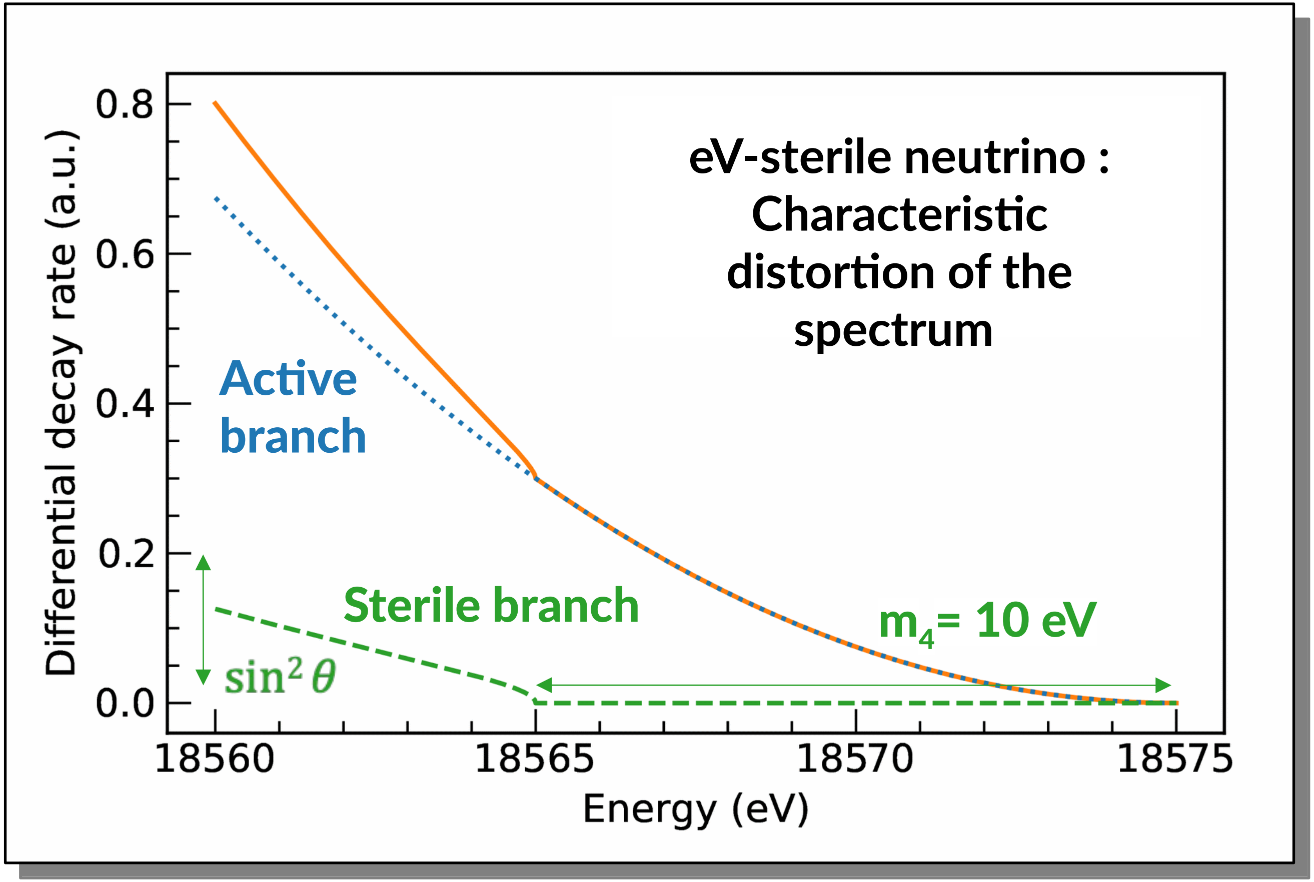


keV-scale:
Dark Matter candidate

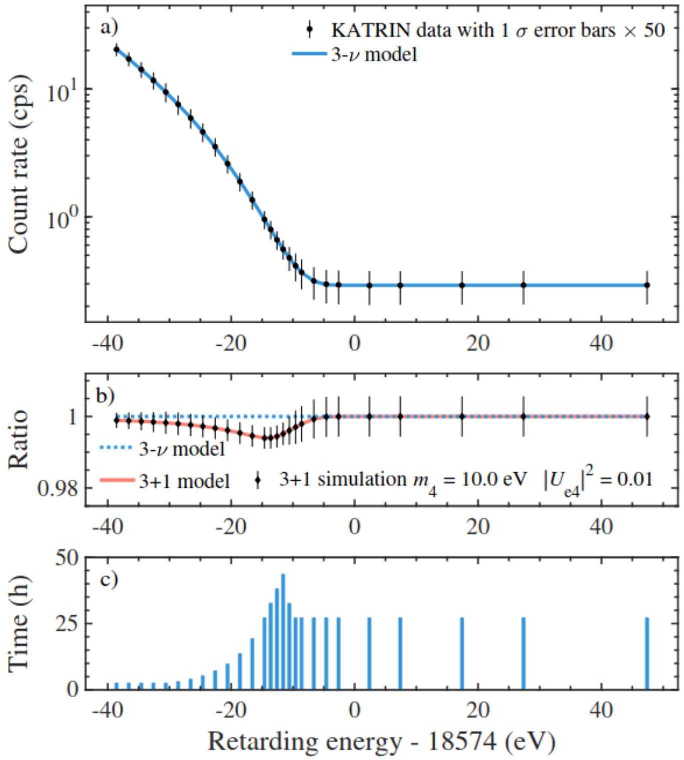


eV-sterile signature in β-decay

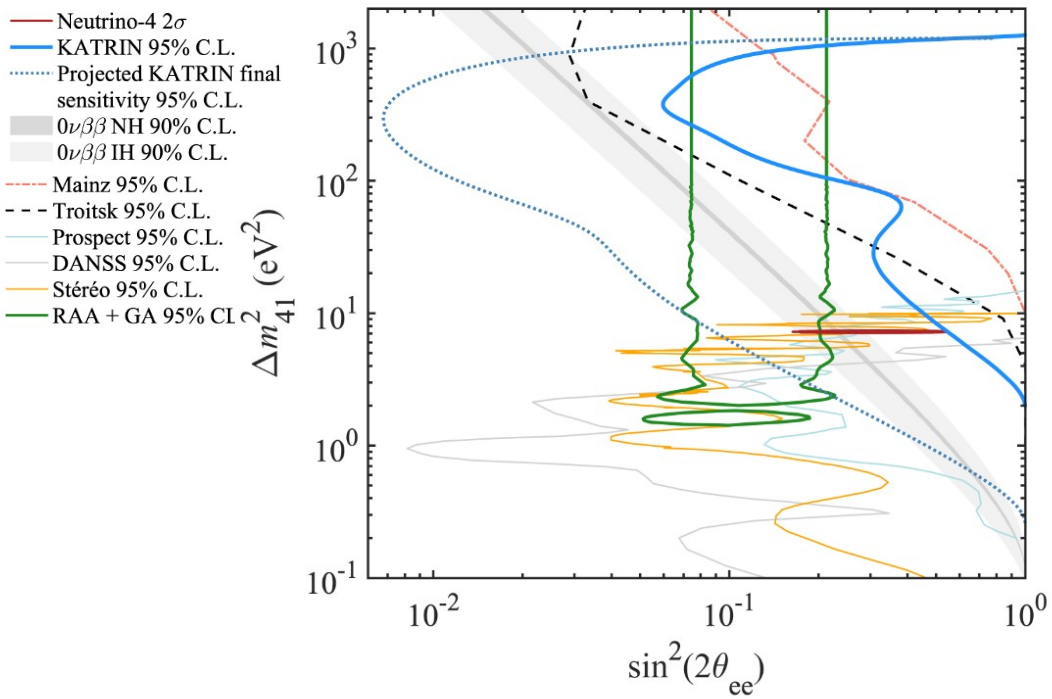




Sterile hunt with KATRIN



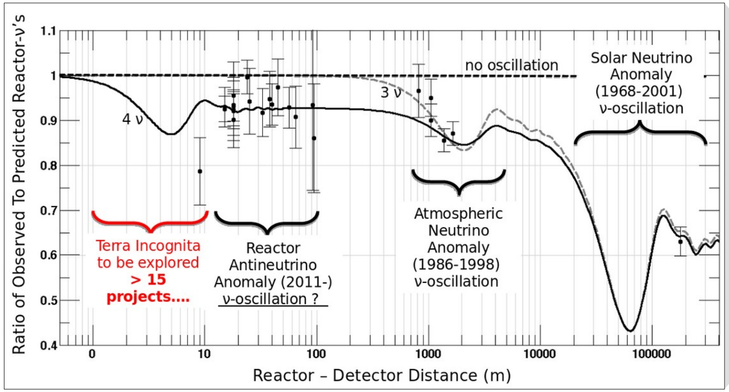
PRL 126, 091803



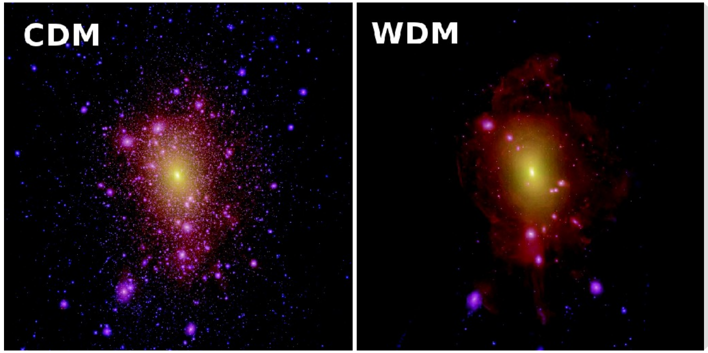
PRL 126, 091803

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

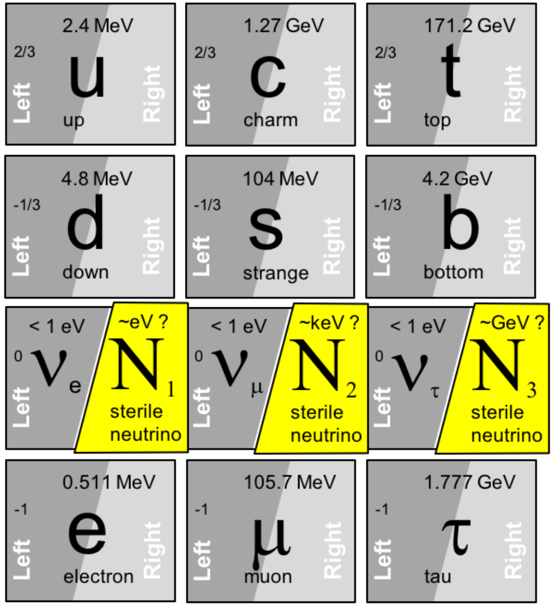
Is there a sterile neutrino ?



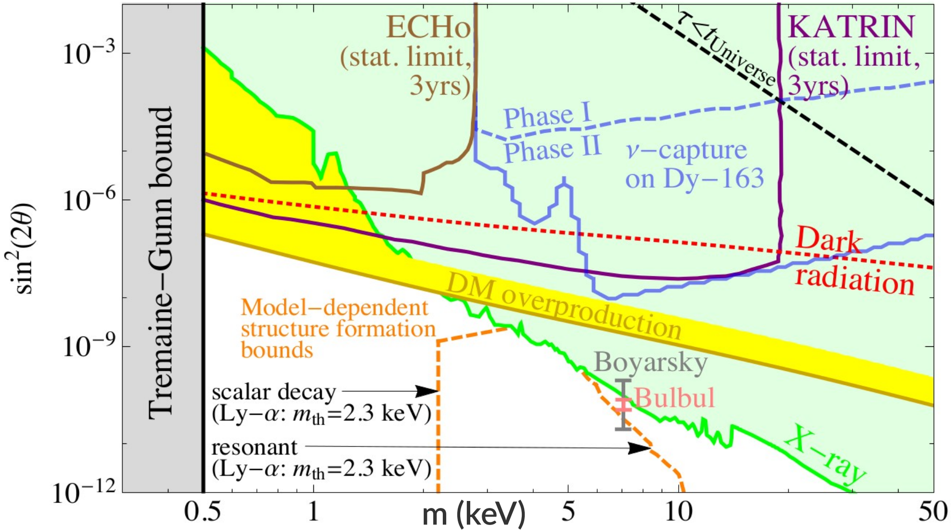
eV-scale:
Resolve anomalies in oscillation experiments

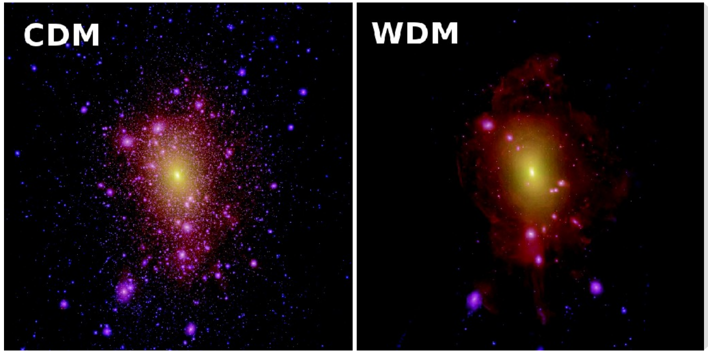


keV-scale:
Dark Matter candidate

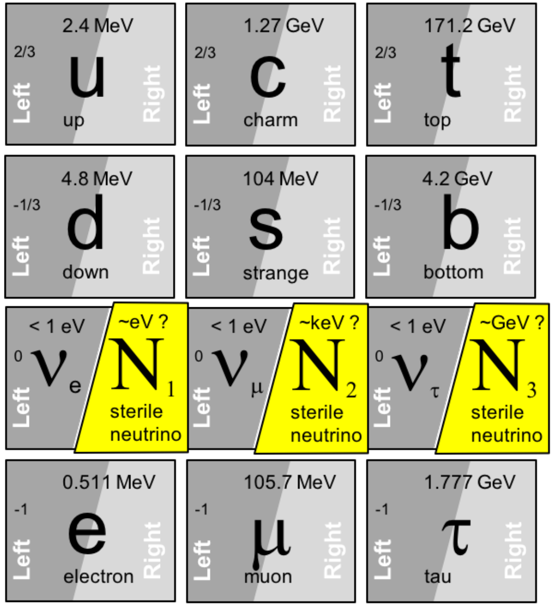


Is there a sterile neutrino ?

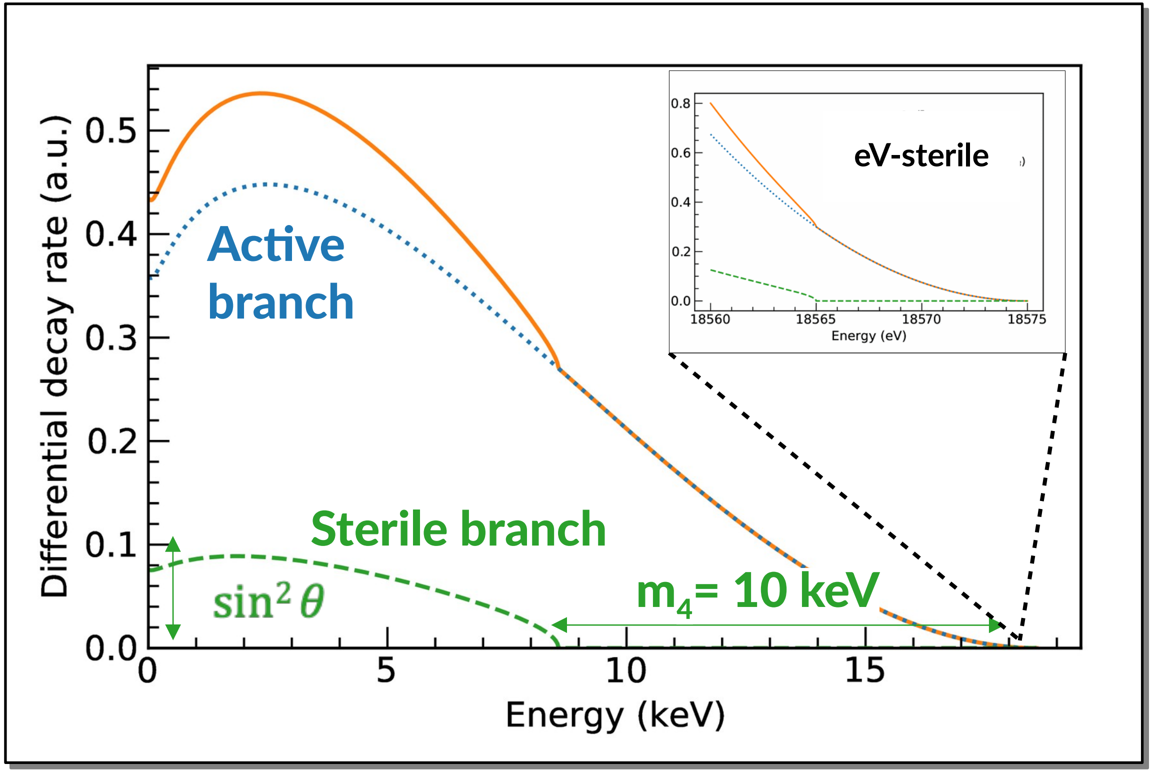




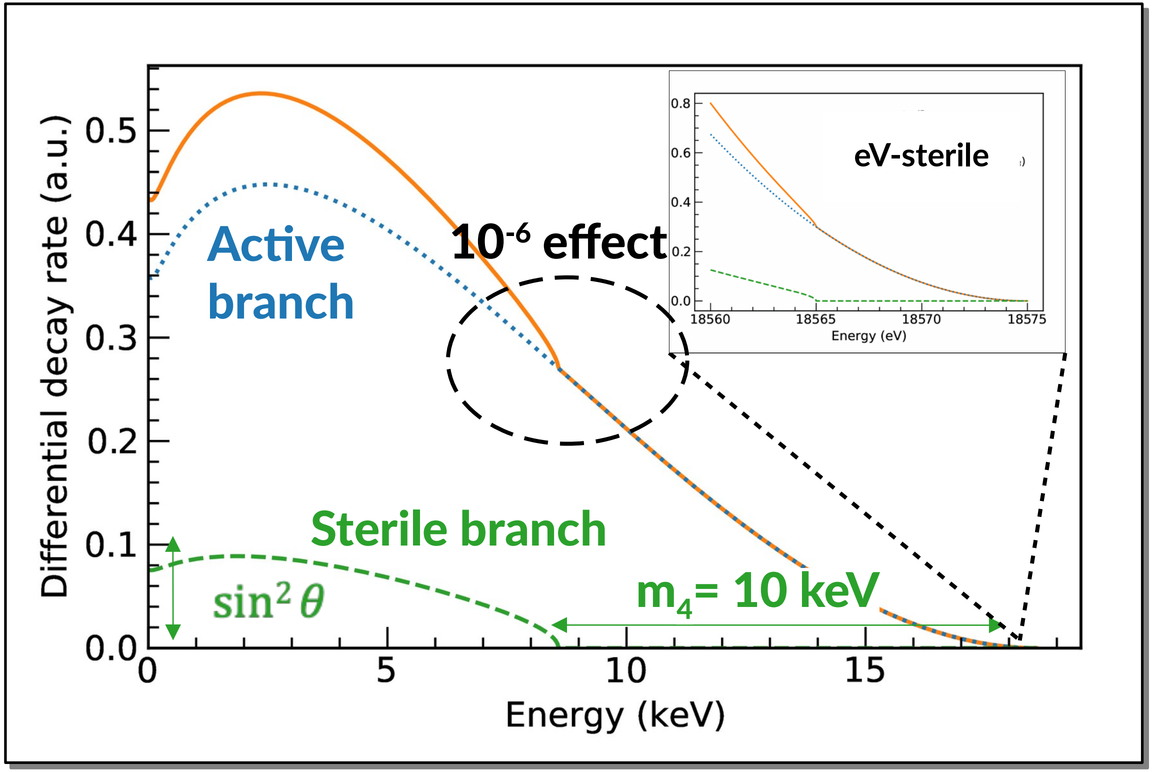
keV-scale:
Dark Matter candidate



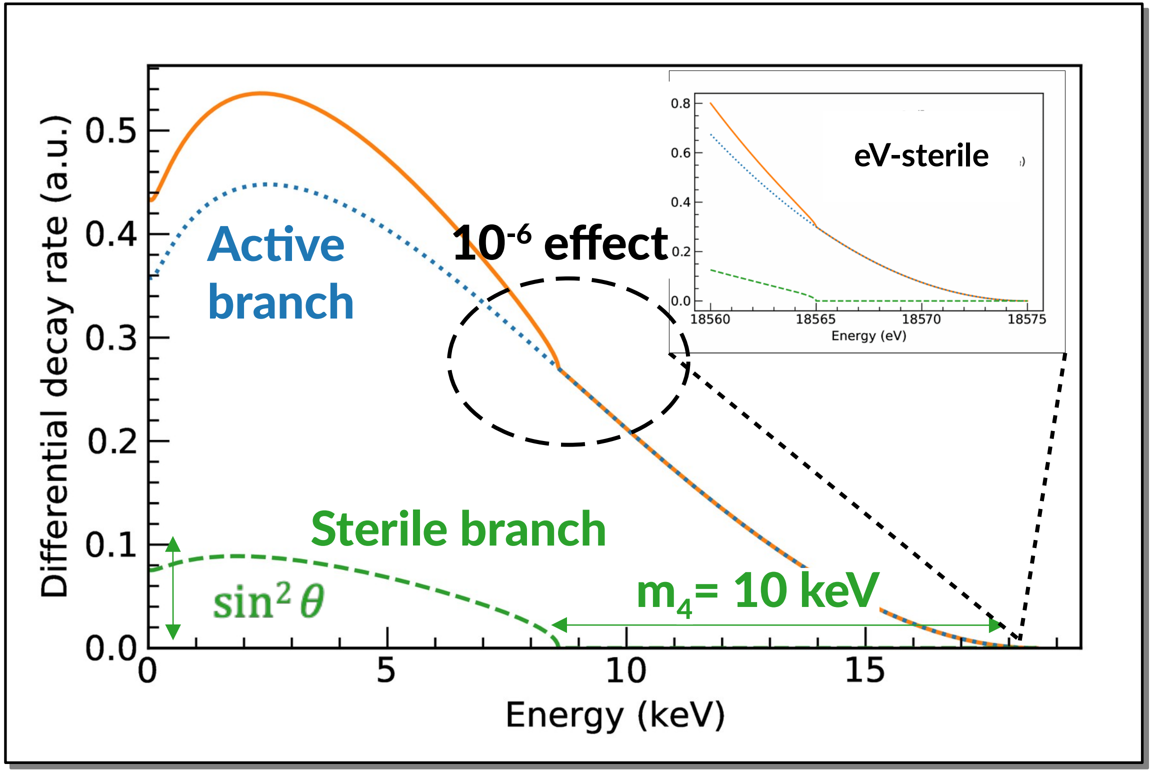
keV-sterile signature in β-decay



keV-sterile signature in β-decay



keV-sterile signature in β-decay



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

→ Dramatic **increase of the count rate** (up to 3×10^8 Hz)

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

→ Highly **pixelised**

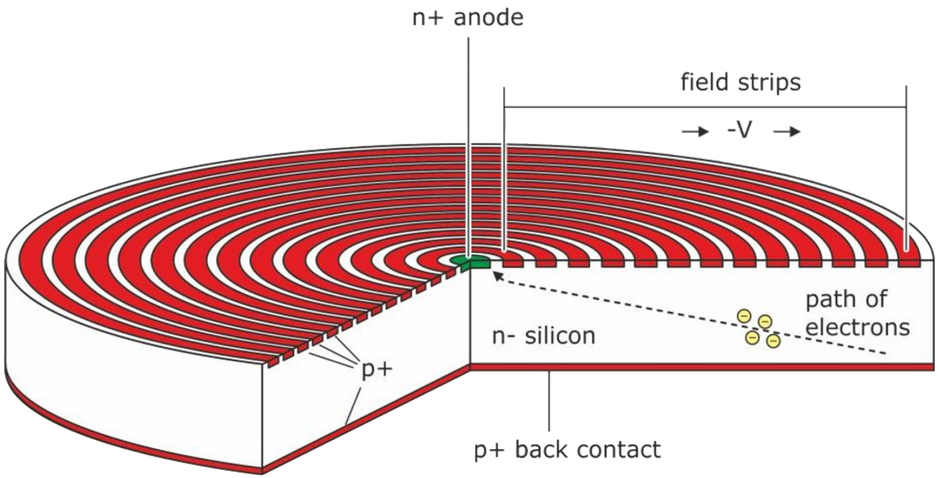
→ new detector is needed : the TRISTAN project

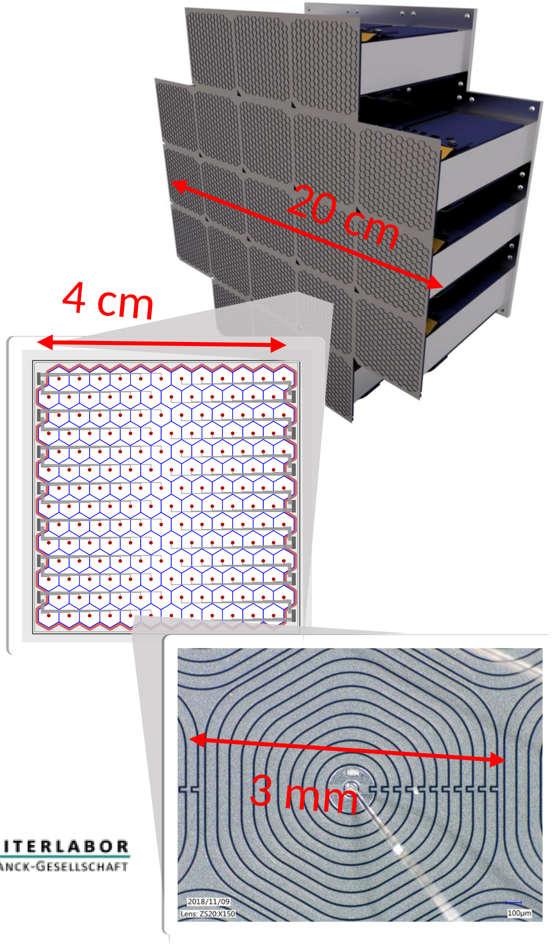
PI : S. Mertens

TRISTAN Project

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

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

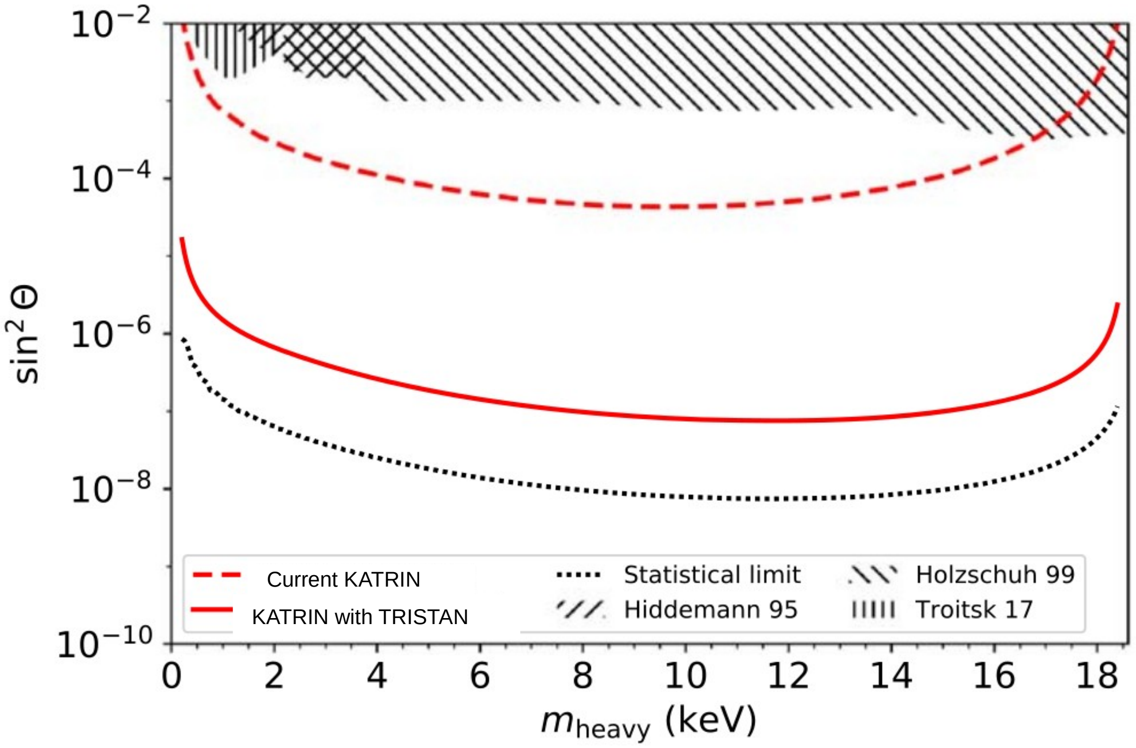




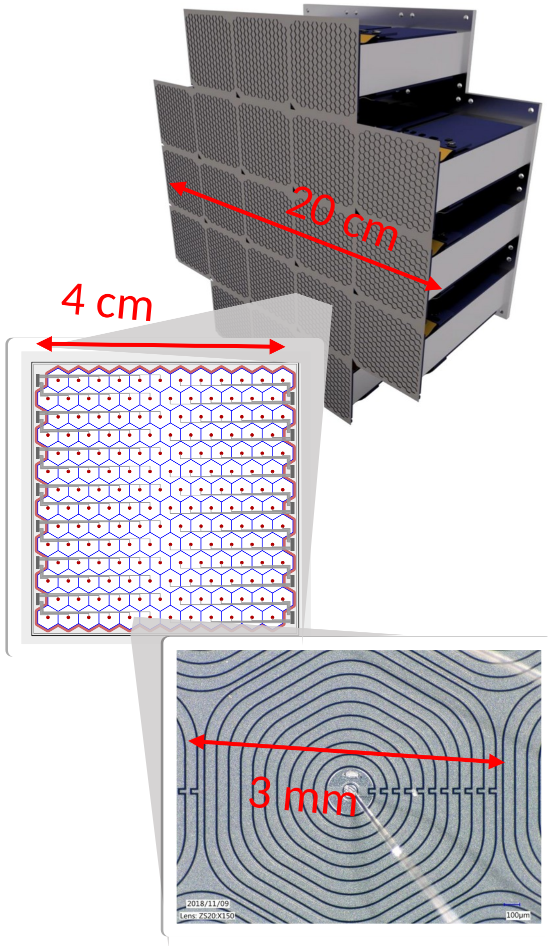
HALBLEITERLABOR DER MAX-PLANCK-GESELLSCHAFT

TRISTAN Project

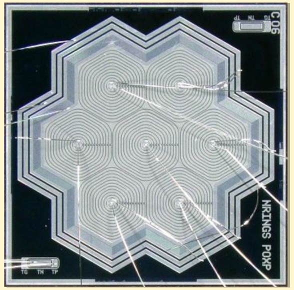
TRISTAN : Development of a large area SDD array and read-out system to look for keV-sterile neutrino with the KATRIN experiment



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

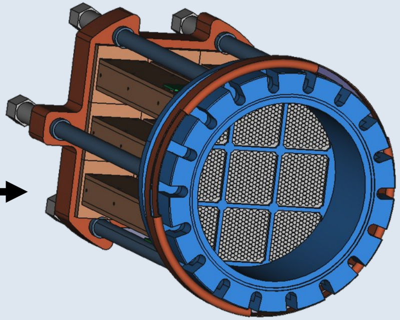


Staged approach

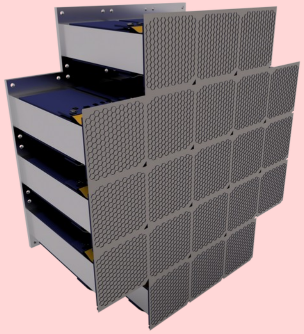


x24

x9



x2.5



Prototypes

Module

Present

Phase 1

Phase 2

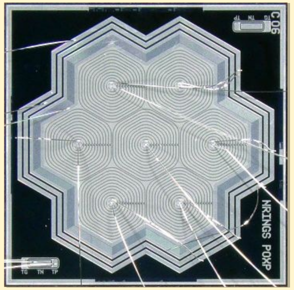
TRISTAN prototype
- 7-pixels with external CMOS

TRISTAN module
- 166-pixels with integrated JFET

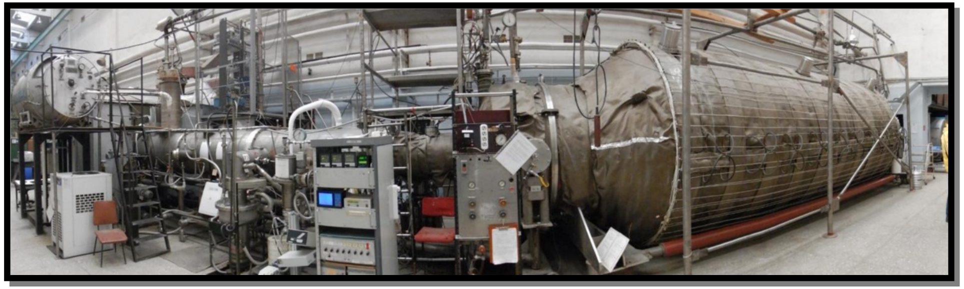
Mini-TRISTAN
- 9 x modules → 1500 pixels

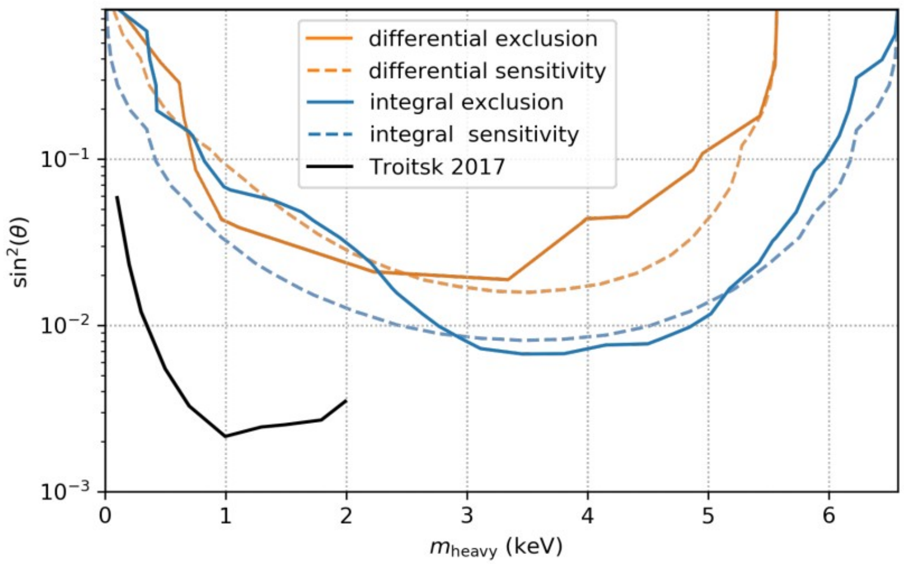
Full TRISTAN
- 21 x modules → 3500 pixels

Staged approach



Prototypes



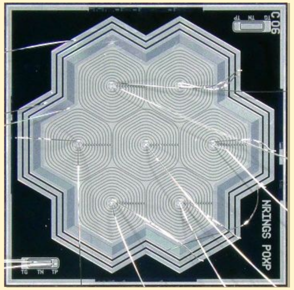


JINST14 P11013 (2019)

TRISTAN prototype

- 7-pixels with external CMOS

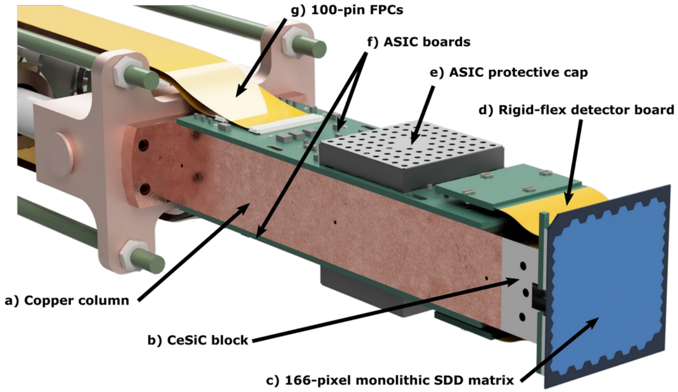
Staged approach



Prototypes

x24

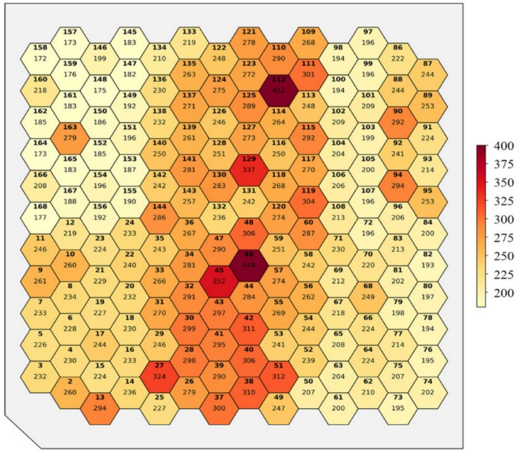
Module



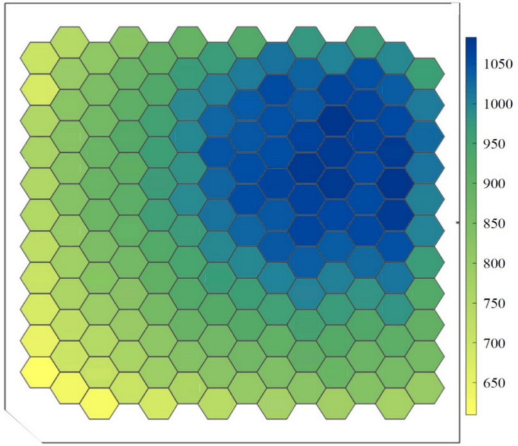
TRISTAN module

- 166-pixels with integrated JFET

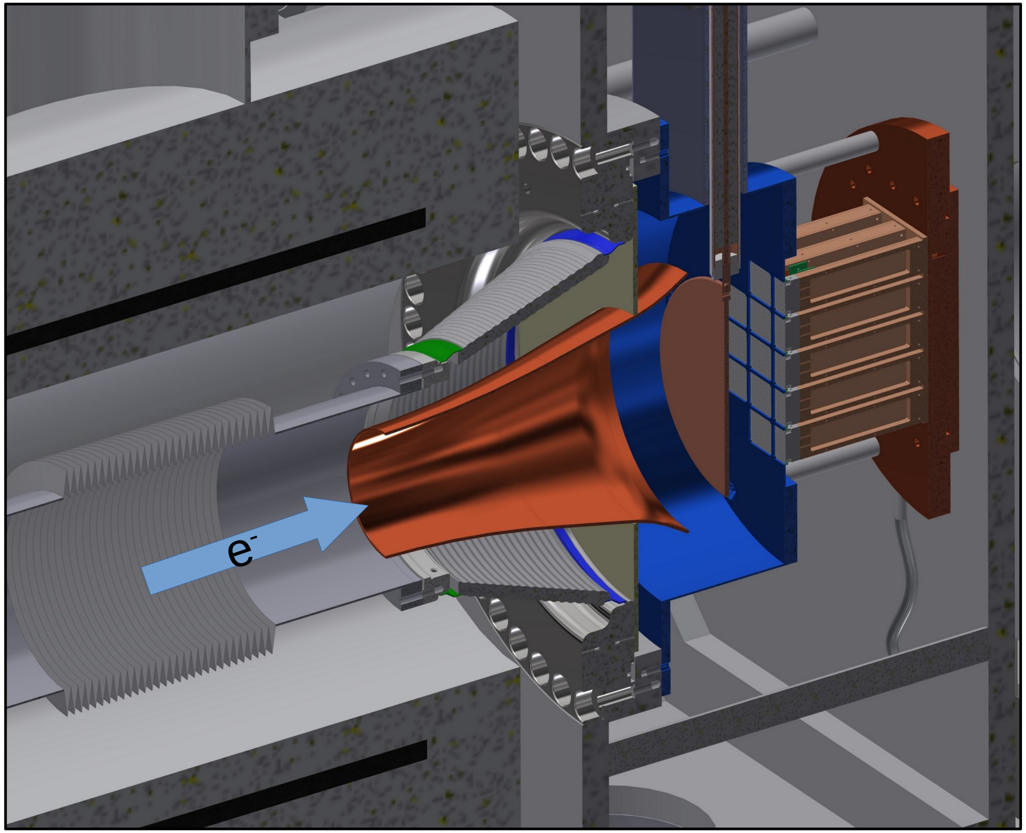
(a) Energy Resolution [eV FWHM]

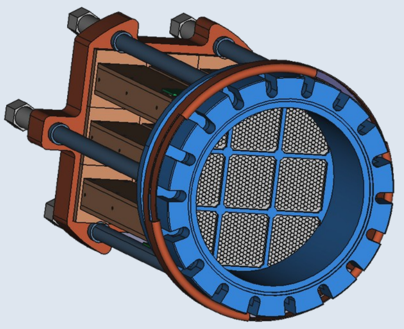


(b) Count Rate [cps]



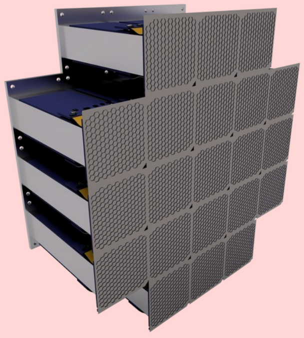
Staged approach





Phase 1

x2.5

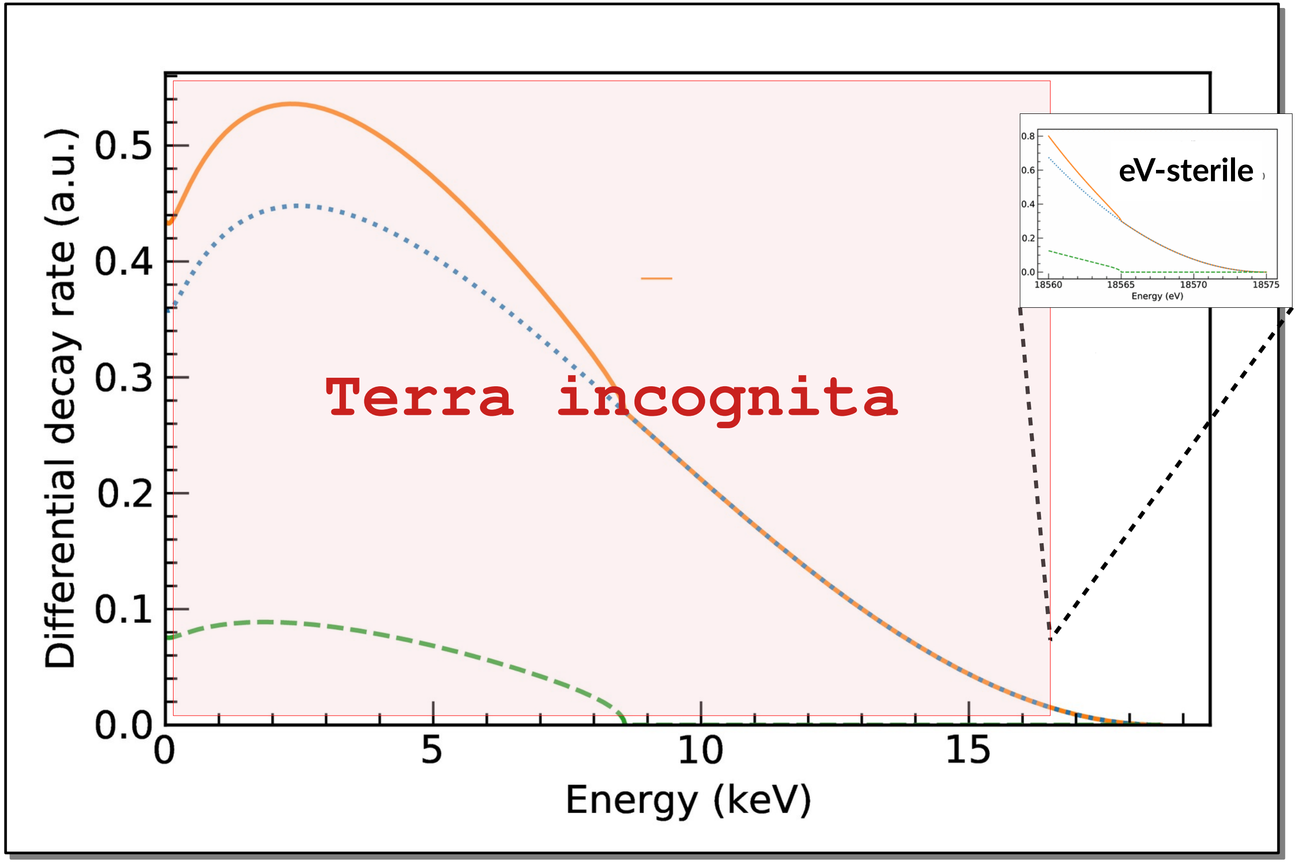


Phase 2

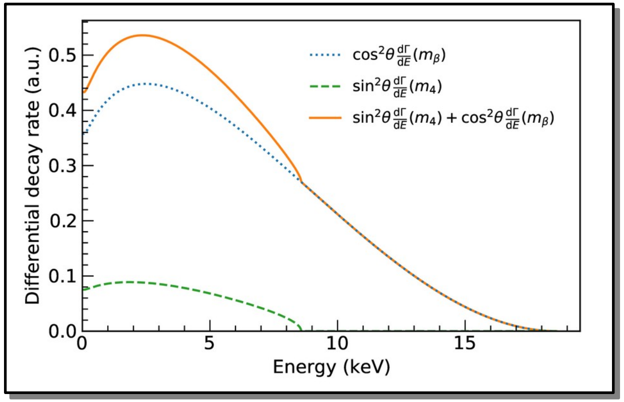
Mini-TRISTAN
- 9 x modules
  → 1500 pixels

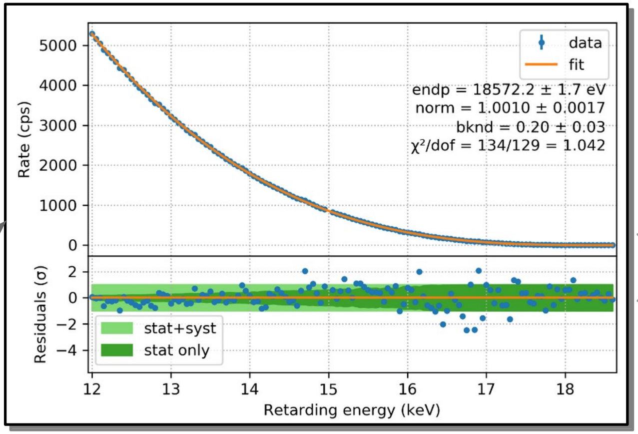
Full TRISTAN
- 21 x modules
  → 3500 pixels

Deep Tritium Model

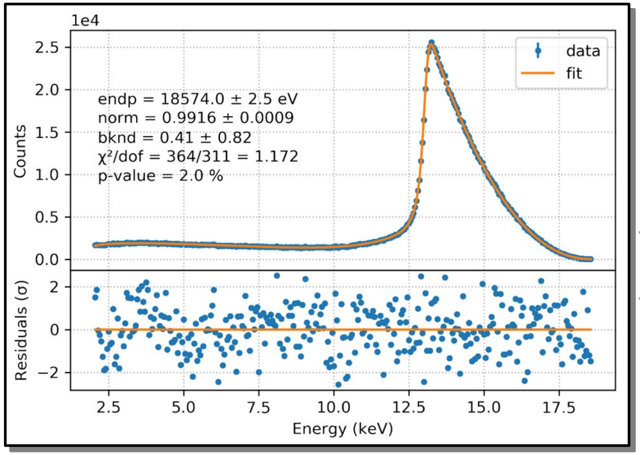


Deep Tritium Model

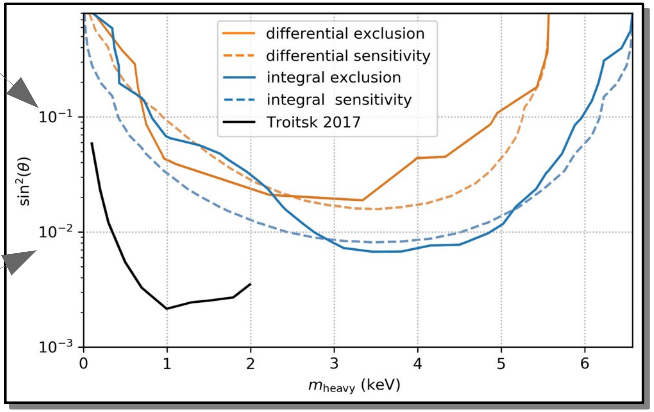




JINST 14 P11013 (2019)



JINST 14 P11013 (2019)



Deep Tritium Model : effects to consider

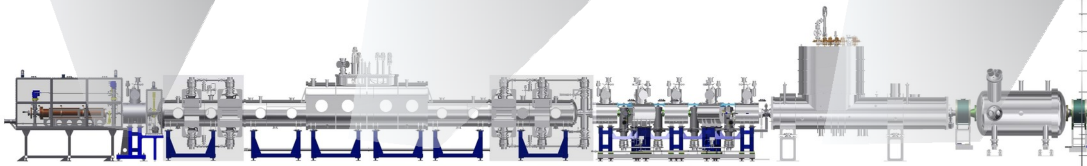
Effect can be different for differential and integral mode

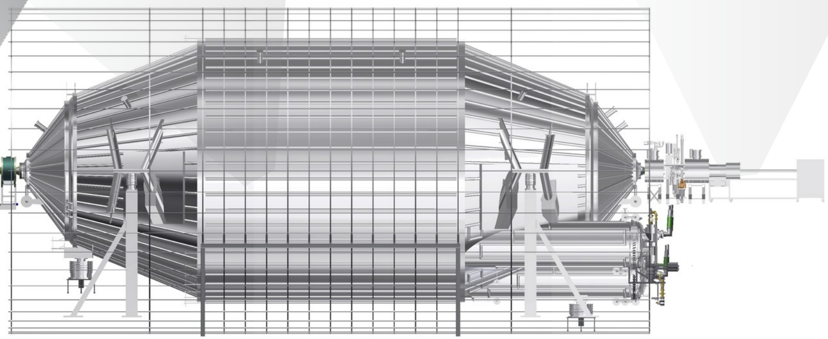
Rear-Wall
- Back-scattering
- Auger electron emission
- Residual beta-activity

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

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

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

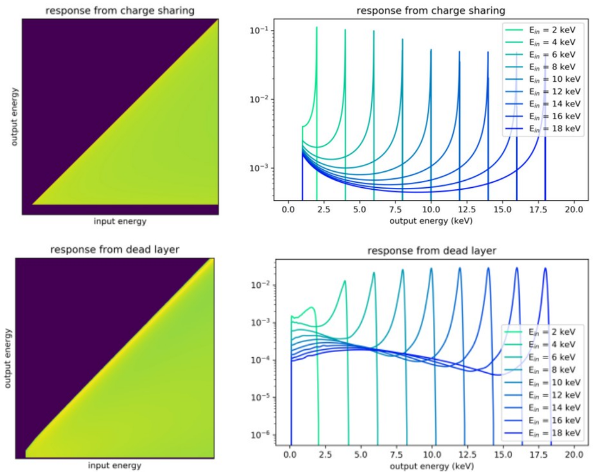




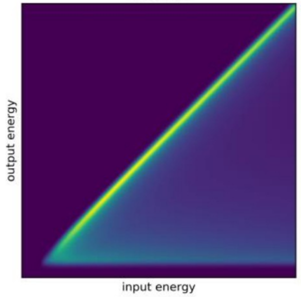
- all these effects have been estimated individually
- Global model on construction

Deep Tritium Model

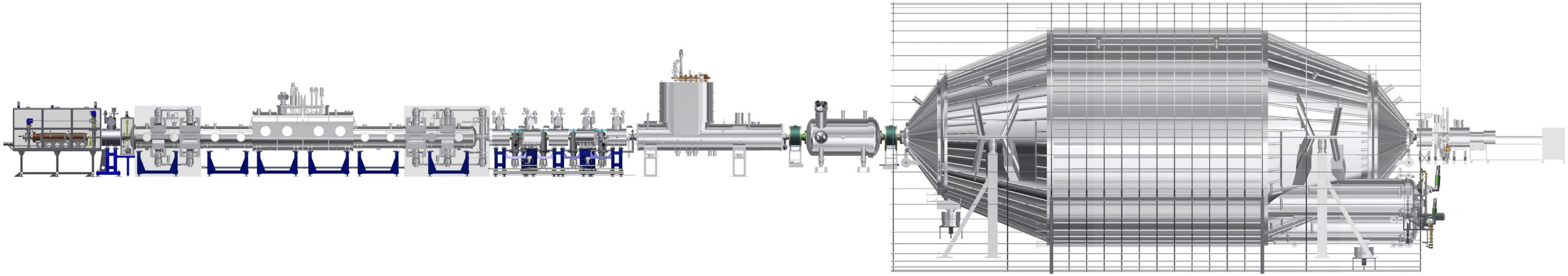
Each physical effect described with a response matrix



Combined responses

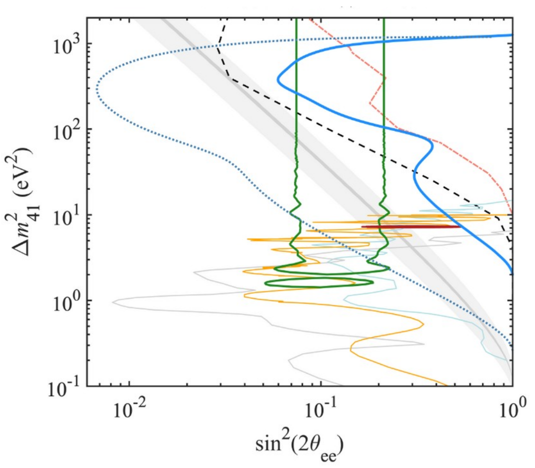


Convolution to the initial spectrum



Conclusion

Sterile neutrinos with KATRIN



KATRIN has now presented a first study on eV sterile neutrinos

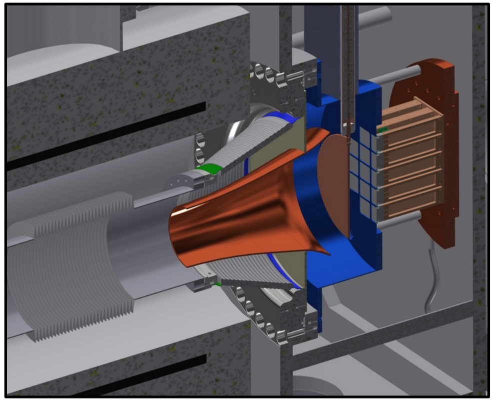
KATRIN with TRISTAN :

- 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

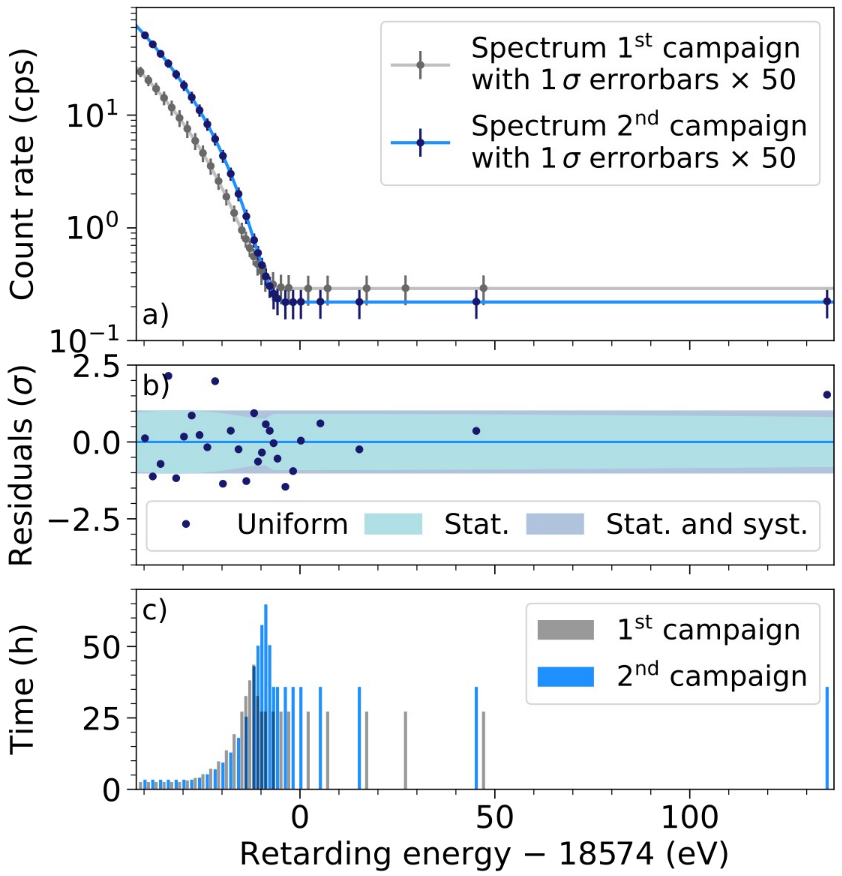
- A complete **deep tritium model** is being built. New sensitivity studies will be done to reduce systematics

- The TRISTAN technology is also being studied to join solar axion search with the IAXO project



Thank you!

Combination of KNM1 & KNM2



KNM1: 1st campaign:

- total statistics: 2 million electrons
- background 290 mcps
- best fit: **$1.0^{+0.9}_{-1.1}$ eV²** **(stat. Dom.)**

m_ν < 1,1 eV (90% CL)

KNM2: 2nd campaign:

- total statistics: 4.3 million electrons
- background 220 mcps
- best fit: **0.26± 0.34 eV² (stat. dom.)**

m_ν < 0.9 eV (90% CL)

- Both KNM1 and KNM2 are statistically domin.
  → Treat them as independent data sets

m_ν < 0.8 eV (90% CL)