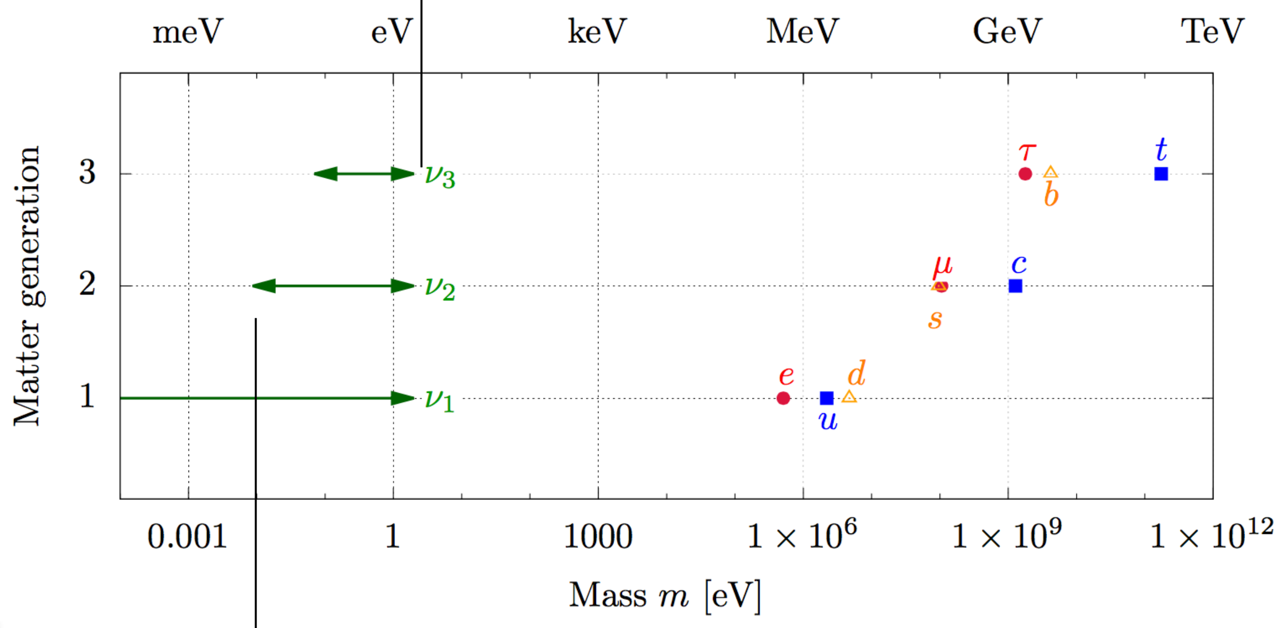
First results from the KATRIN experiment

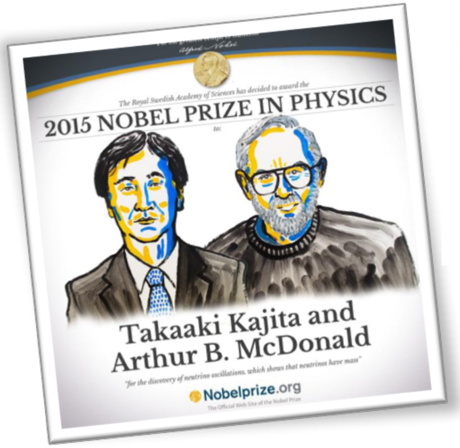
Susanne Mertens
Max Planck Institute for Physics & Technical University Munich
Erice, September 2019

Neutrino mass

Upper bound
from laboratory measurements



Lower bound
from oscillation experiments



Neutrino mass

Cosmology

model-dependent
potential: m_ν = 15-50 meV
e.g. Planck

$$m_{cosmo} = \sum_i m_i$$

Search for 0νßß

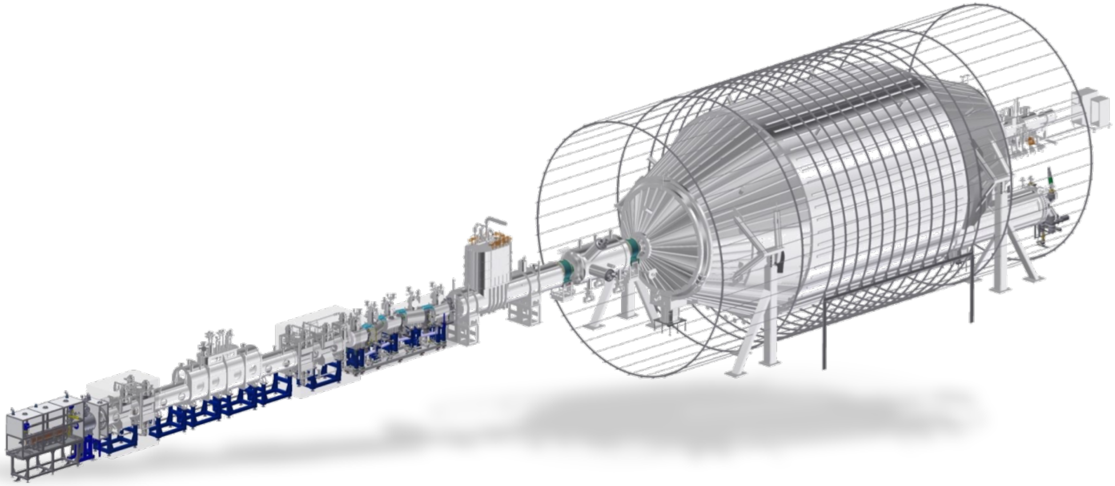
Laboratory-based
potential: $m_{ßß}$ = 15-50 meV
e.g. LEGEND

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

Kinematics of ß-decay

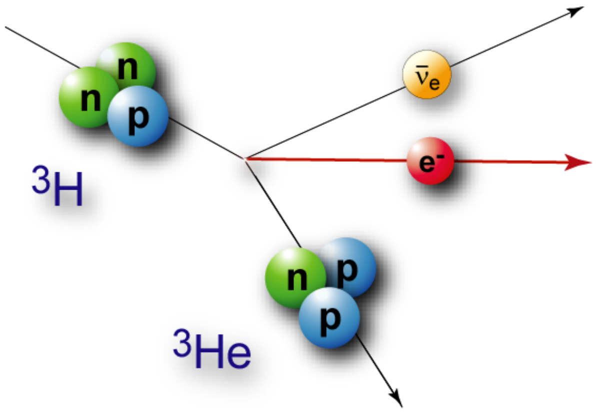
Laboratory-based
potential: m_β = 50 - 200 meV
e.g. KATRIN

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

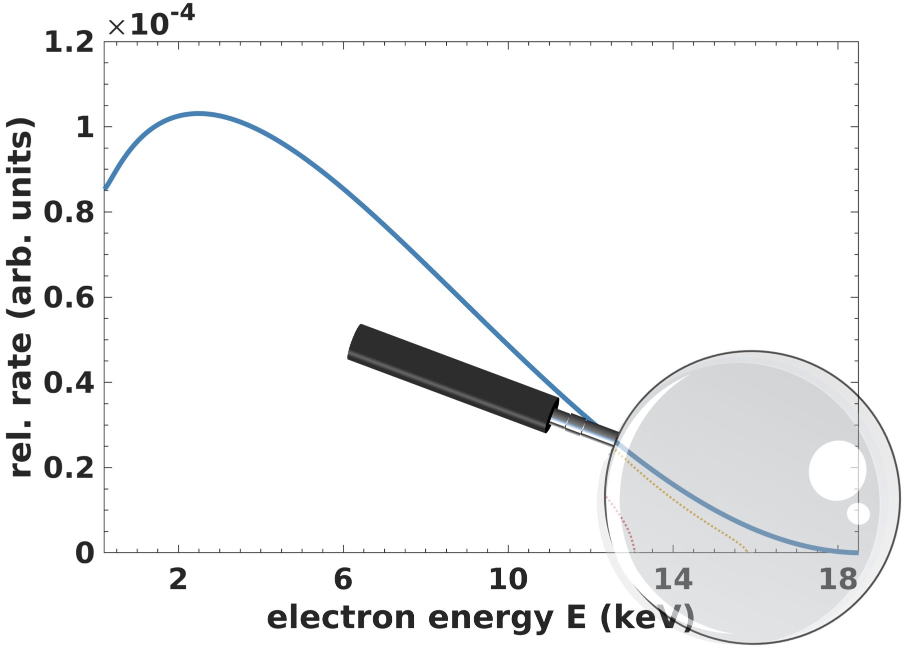


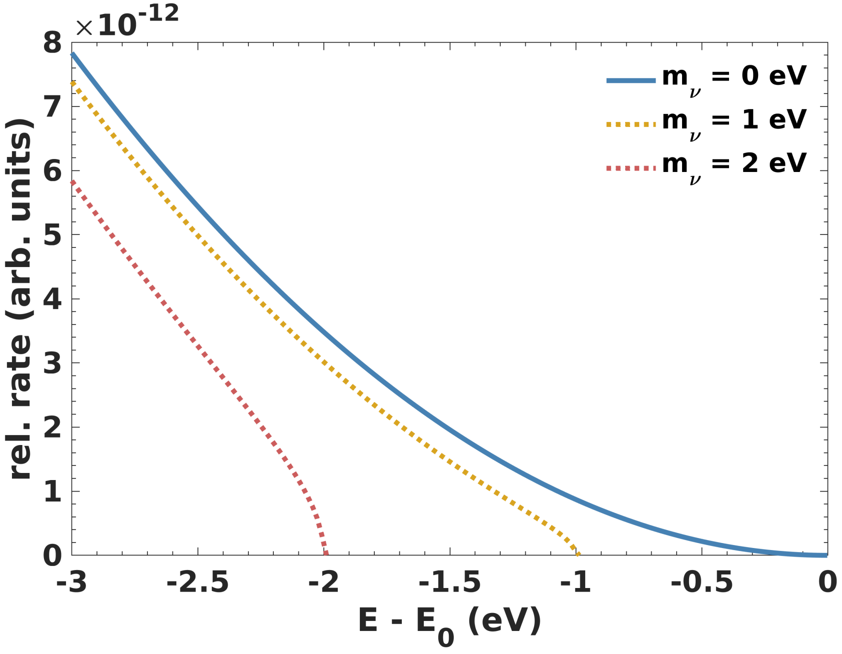
The basic idea

- Kinematic determination of the neutrino mass
- Non-zero neutrino mass reduces the endpoint and distorts the spectrum

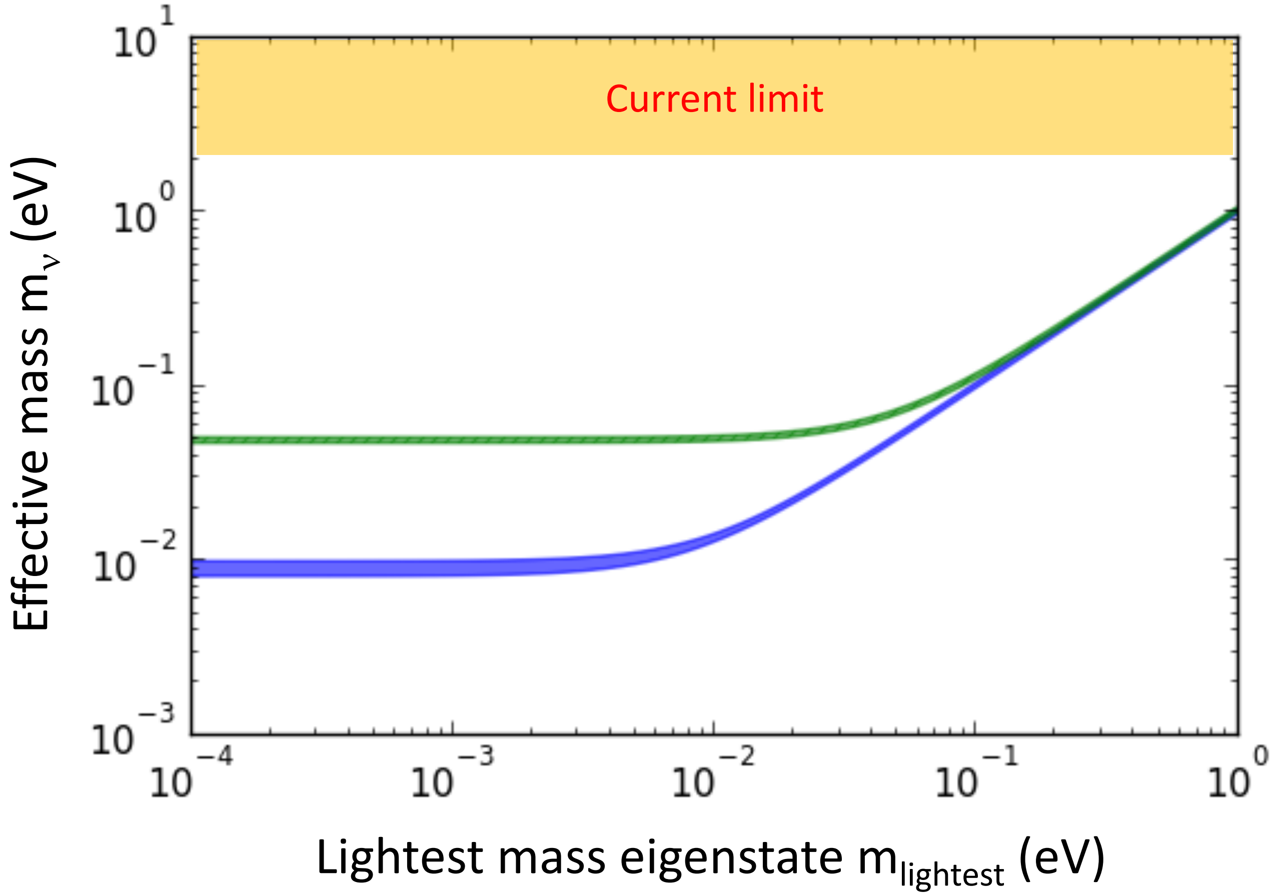


$$m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$



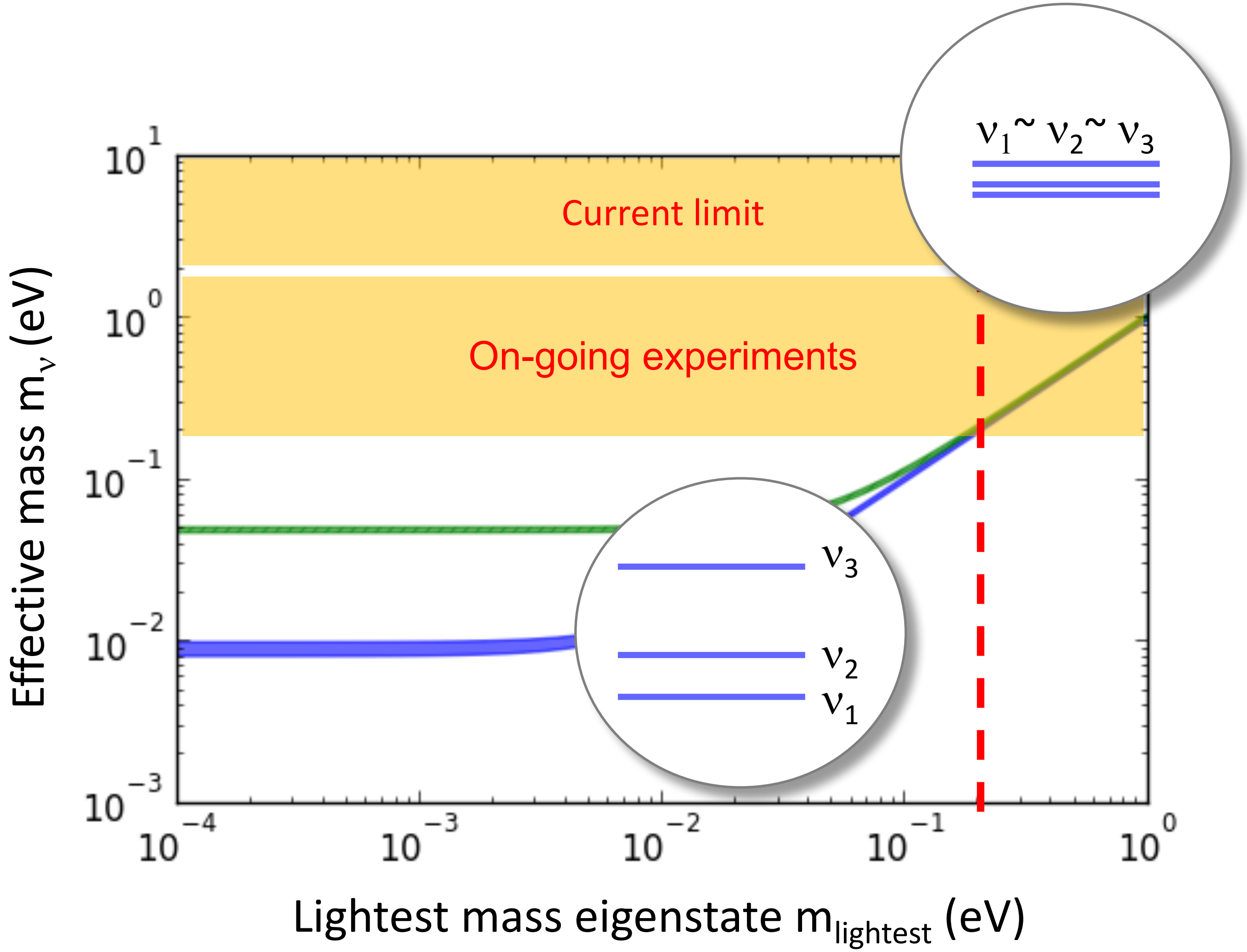


Where do we stand?



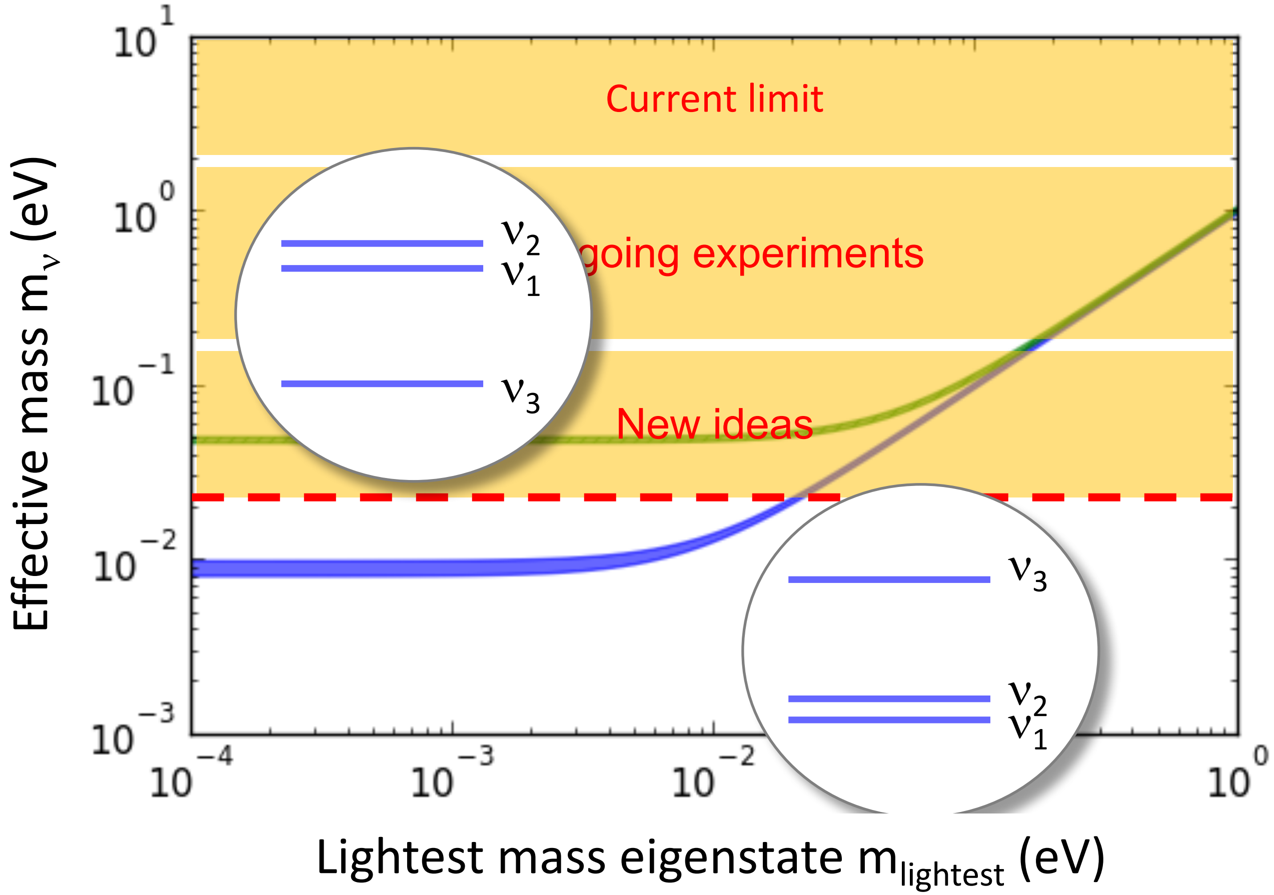
- Current limit:
  Mainz and Troitsk Experiment
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)

Where do we stand?



- Current limit:
  Mainz and Troitsk Experiment
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario

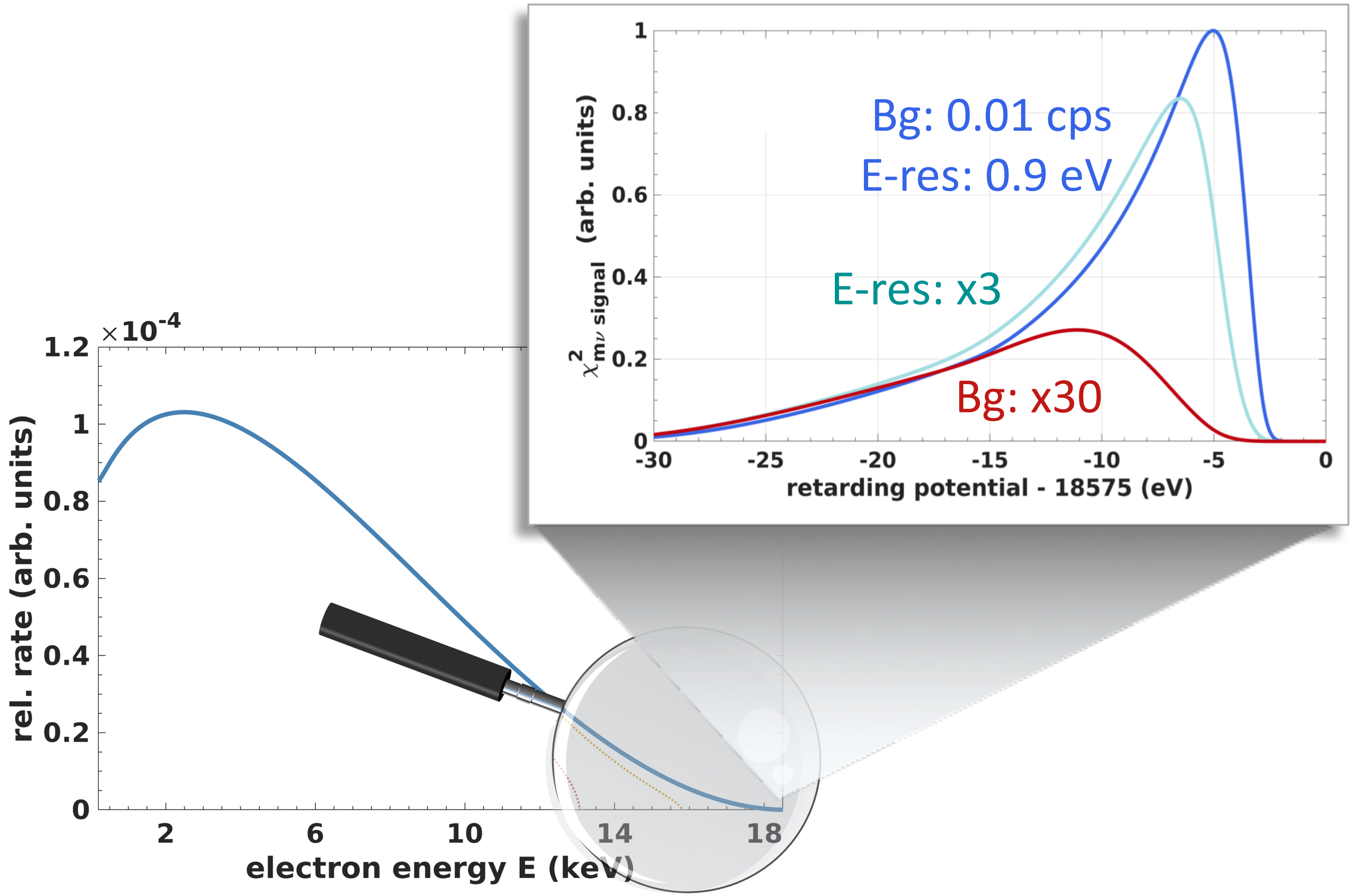
Where do we stand?



- Current limit:
  Mainz and Troitsk Experiment
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario
- New ideas:
  Resolve **normal** vs **inverted** neutrino mass hierarchy

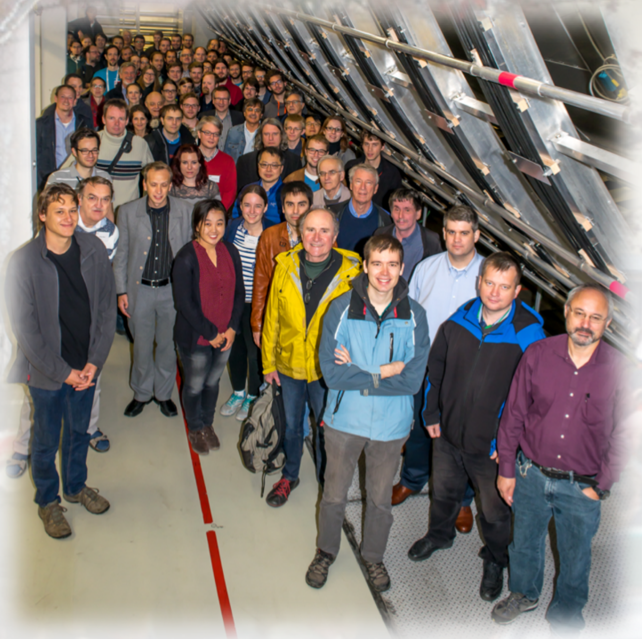
The challenge

Only 10^{-10} in last 30 eV




Karlsruhe
Tritium
Neutrino
Experiment

Karlsruhe Tritium Neutrino Experiment



- Experimental site: Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Sensitivity m_ν = 0.2 eV (90% CL) after 3 net-years

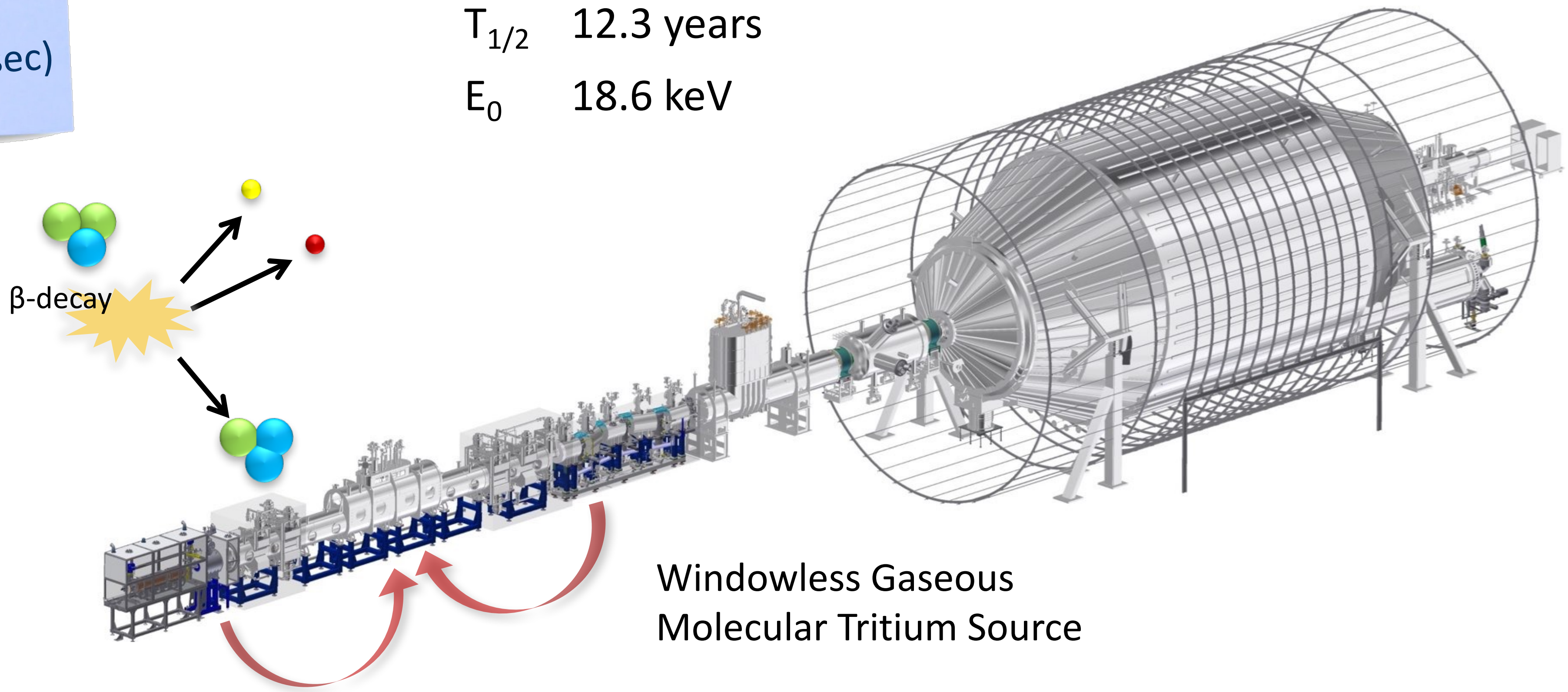
KIT Karlsruher Institut für Technologie
Max-Planck-Institut für Kernphysik Heidelberg
University of Washington
Case Western Reserve University EST. 1826 think beyond the possible
Westfälische Wilhelms-Universität Münster
Massachusetts Institute of Technology
The University of North Carolina at Chapel Hill
The Czech Academy of Sciences
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
cea
Carnegie Mellon University Pittsburgh Pennsylvania 1900
Universidad Complutense Madrid
Russian Academy of Sciences
JG|U Johannes Gutenberg Universität Mainz
Technische Universität München
universitätbonn
Hochschule Fulda University of Applied Sciences
Bergische Universität Wuppertal
Berkeley Lab

KATRIN Working Principle

high stability
and luminosity

(10^{11} decays/sec)

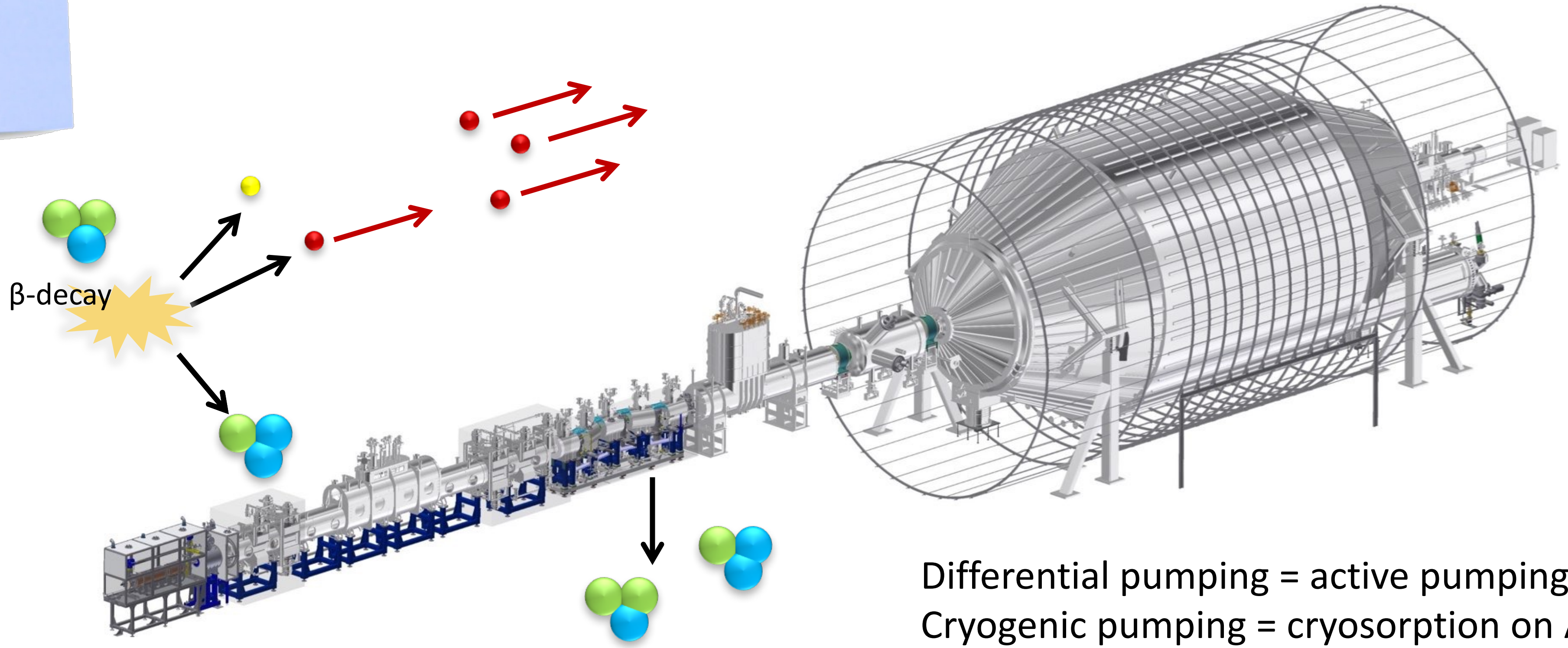
	^3H
	super-allowed β-decay
$T_{1/2}$	12.3 years
E_0	18.6 keV



Windowless Gaseous
Molecular Tritium Source

KATRIN Working Principle

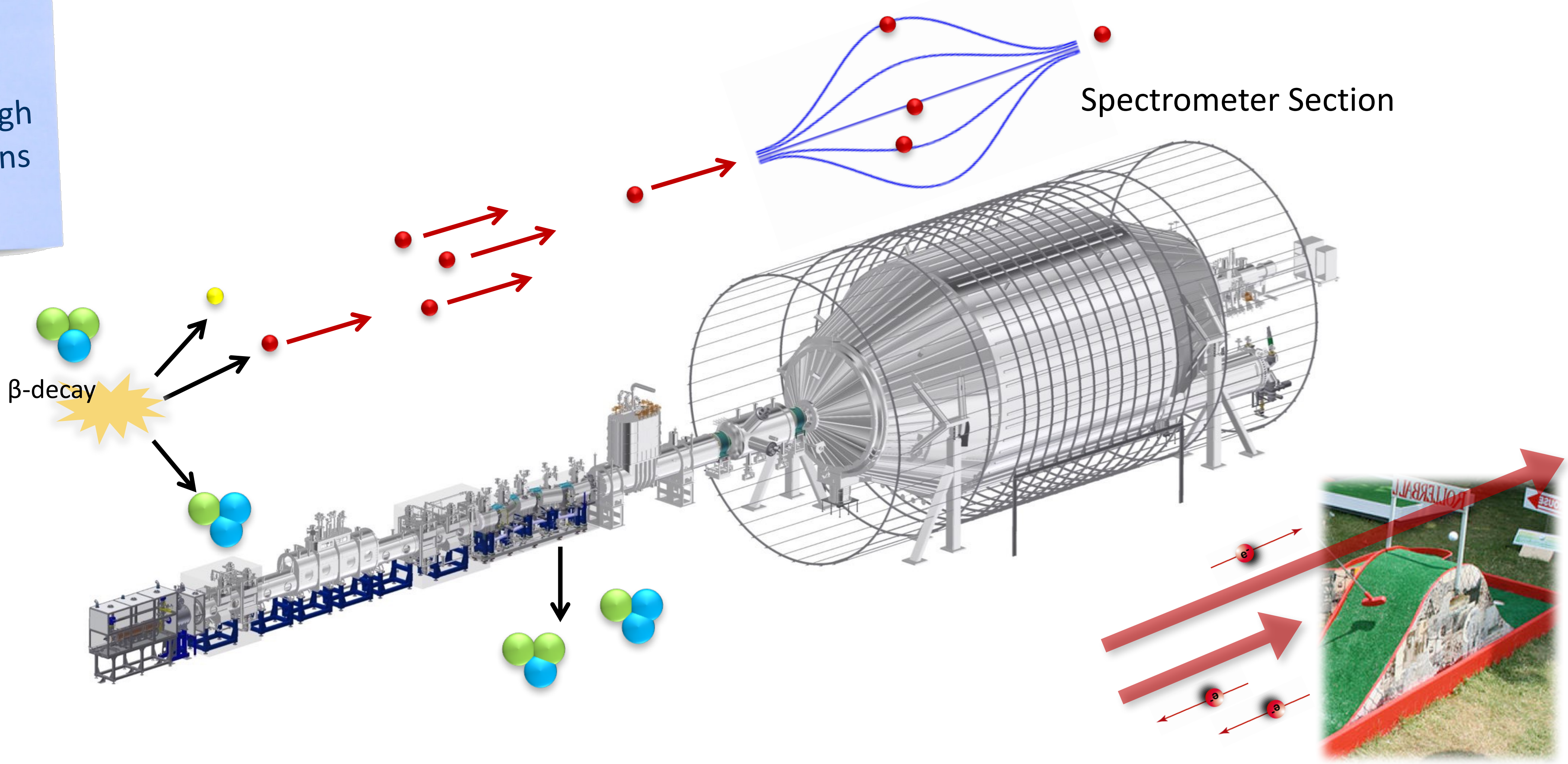
Tritium flow reduction by 14 orders of magnitude



Differential pumping = active pumping by TMPs
Cryogenic pumping = cryosorption on Ar-frost

KATRIN Working Principle

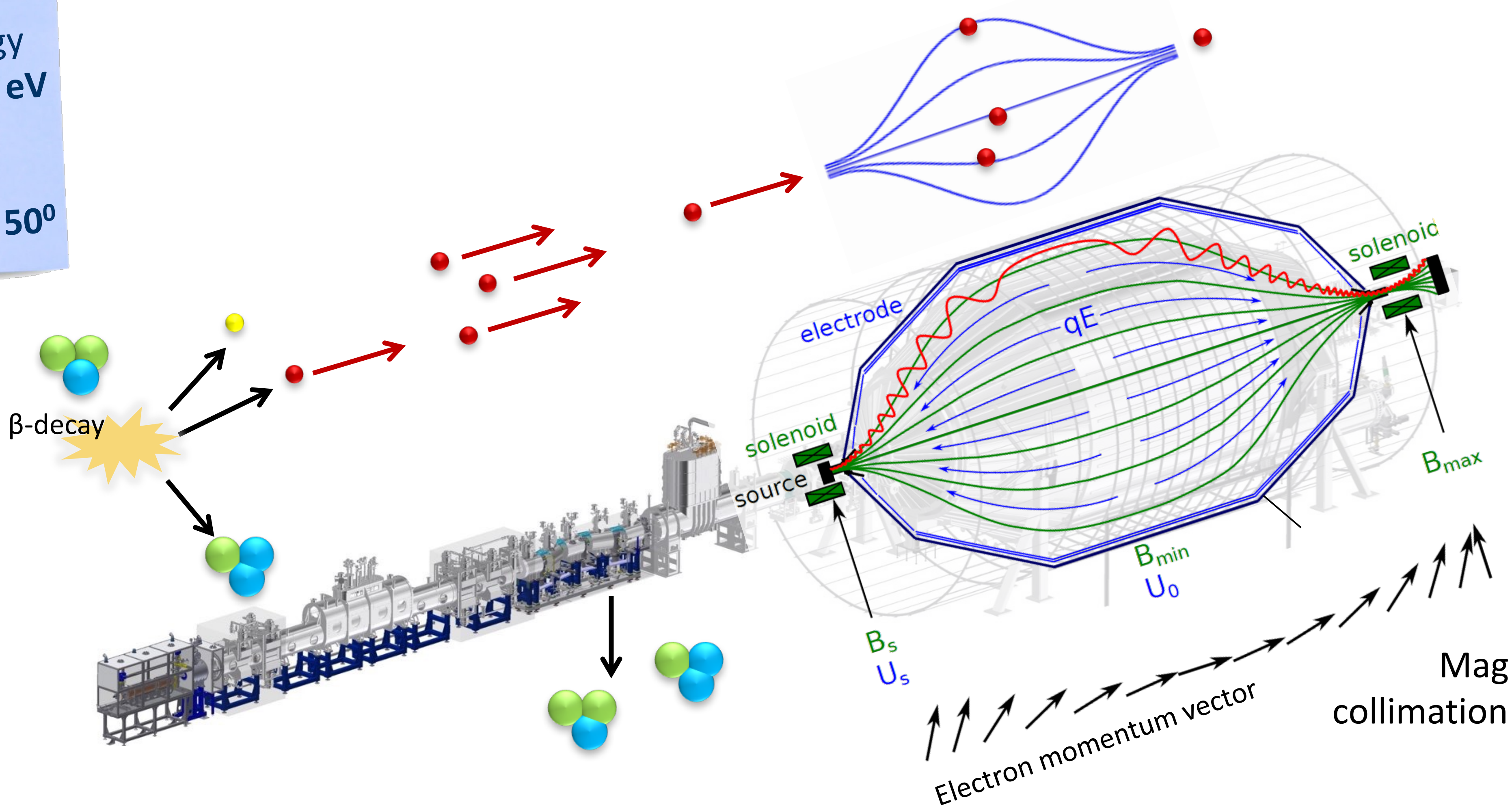
Electrostatic filter selects high energy electrons



KATRIN Working Principle

excellent energy resolution: **~ 1 eV**

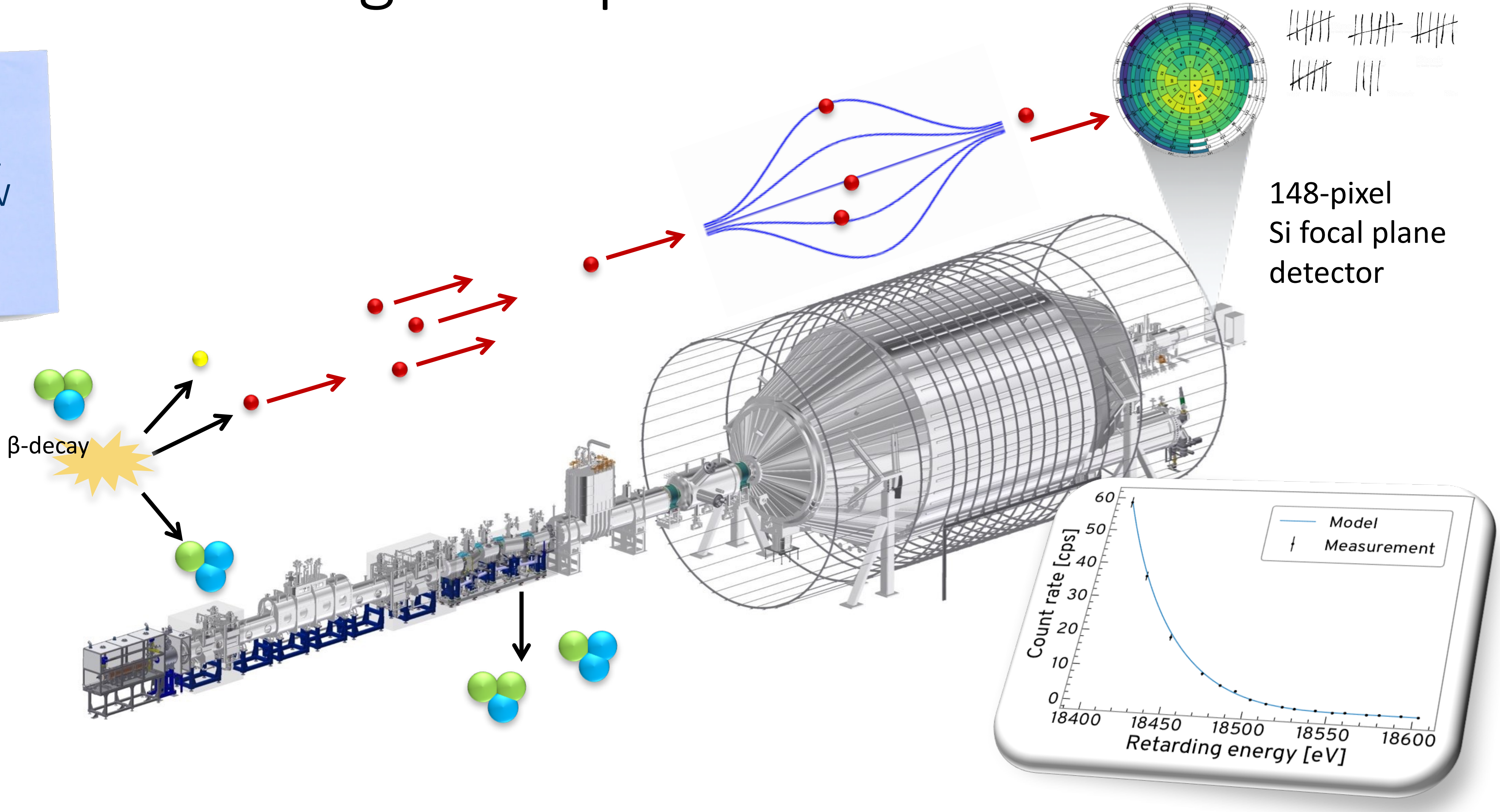
large angle acceptance: **~ 50⁰**

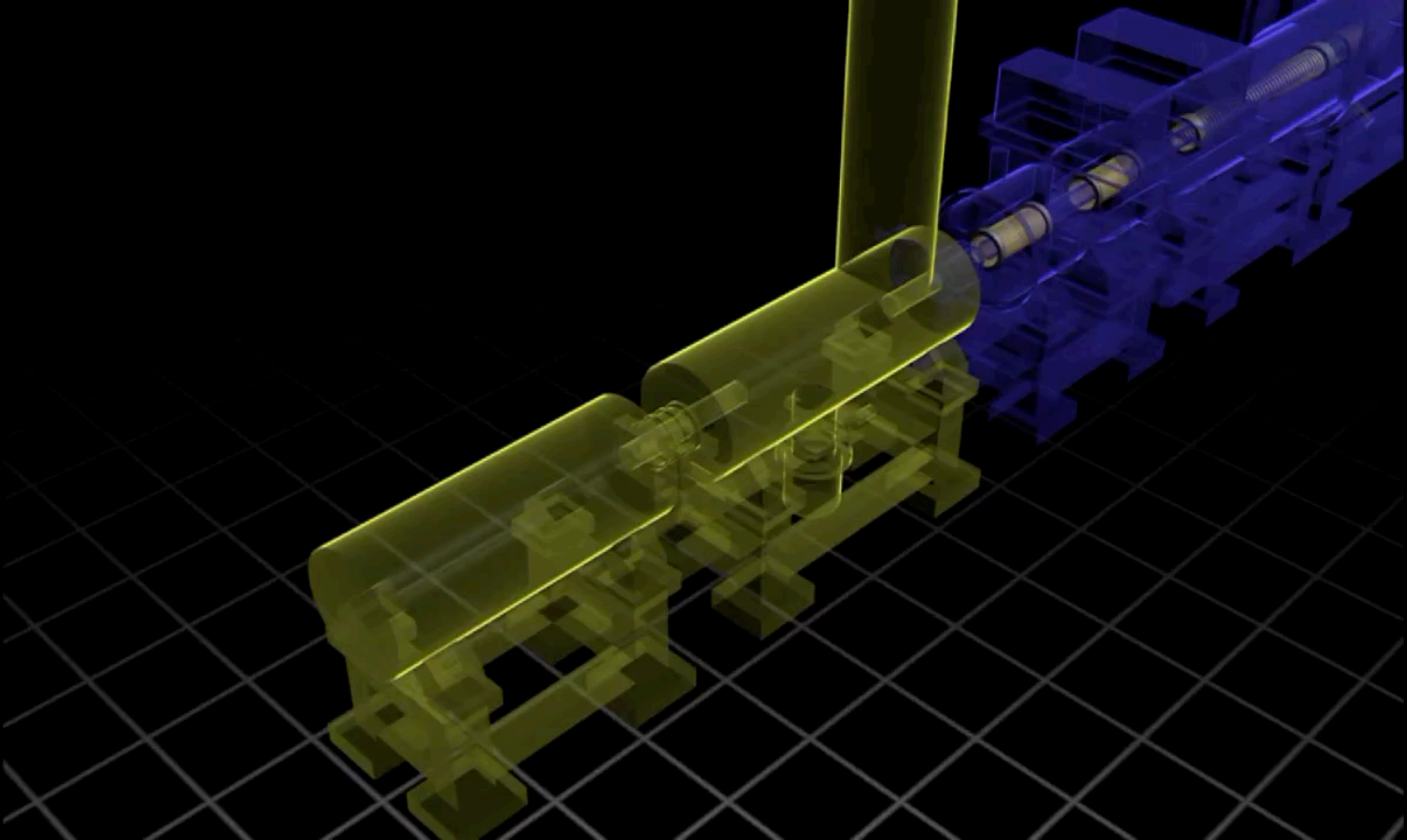


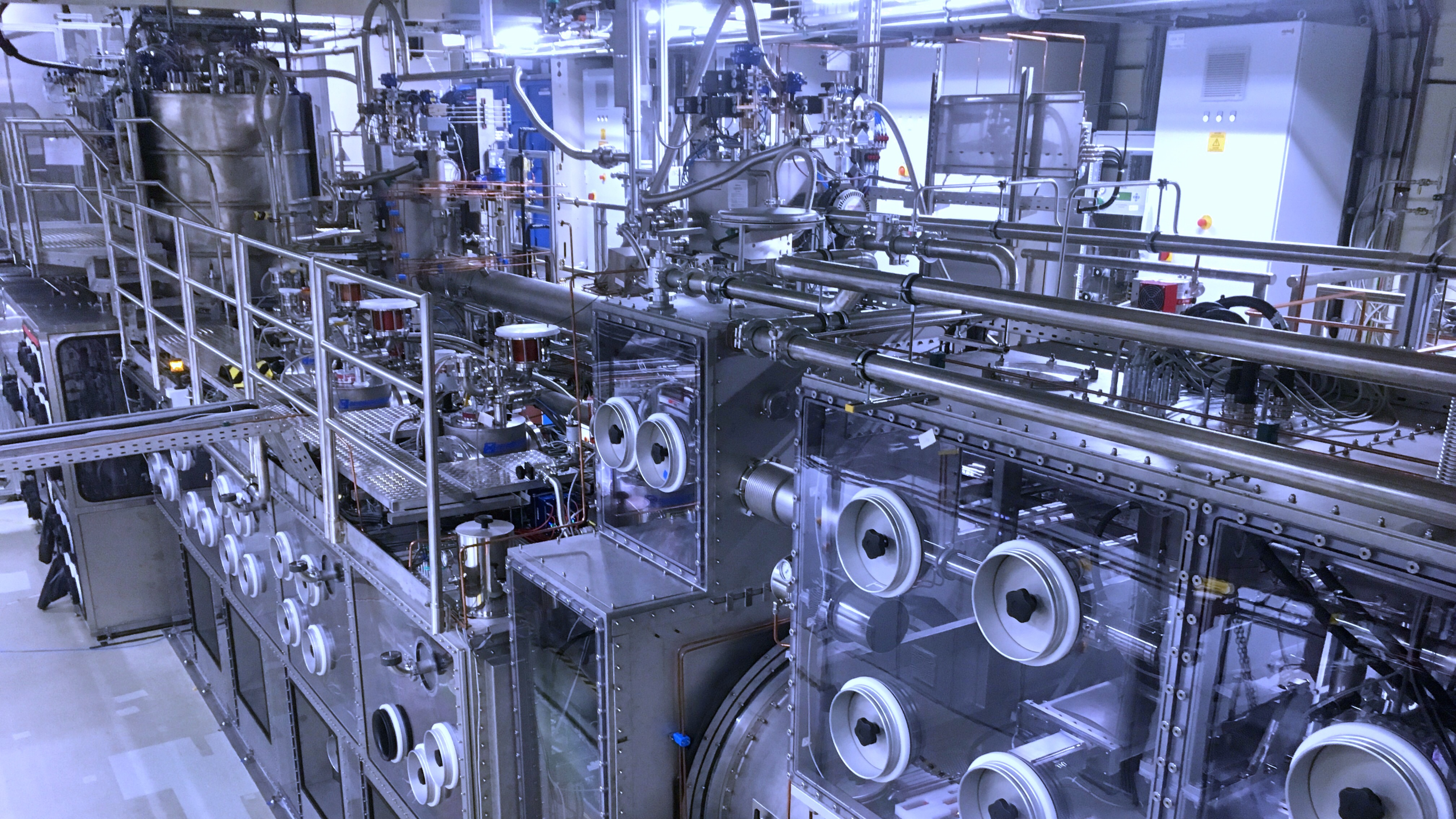
Magnetic adiabatic collimation + electrostatic filter (MAC-E)

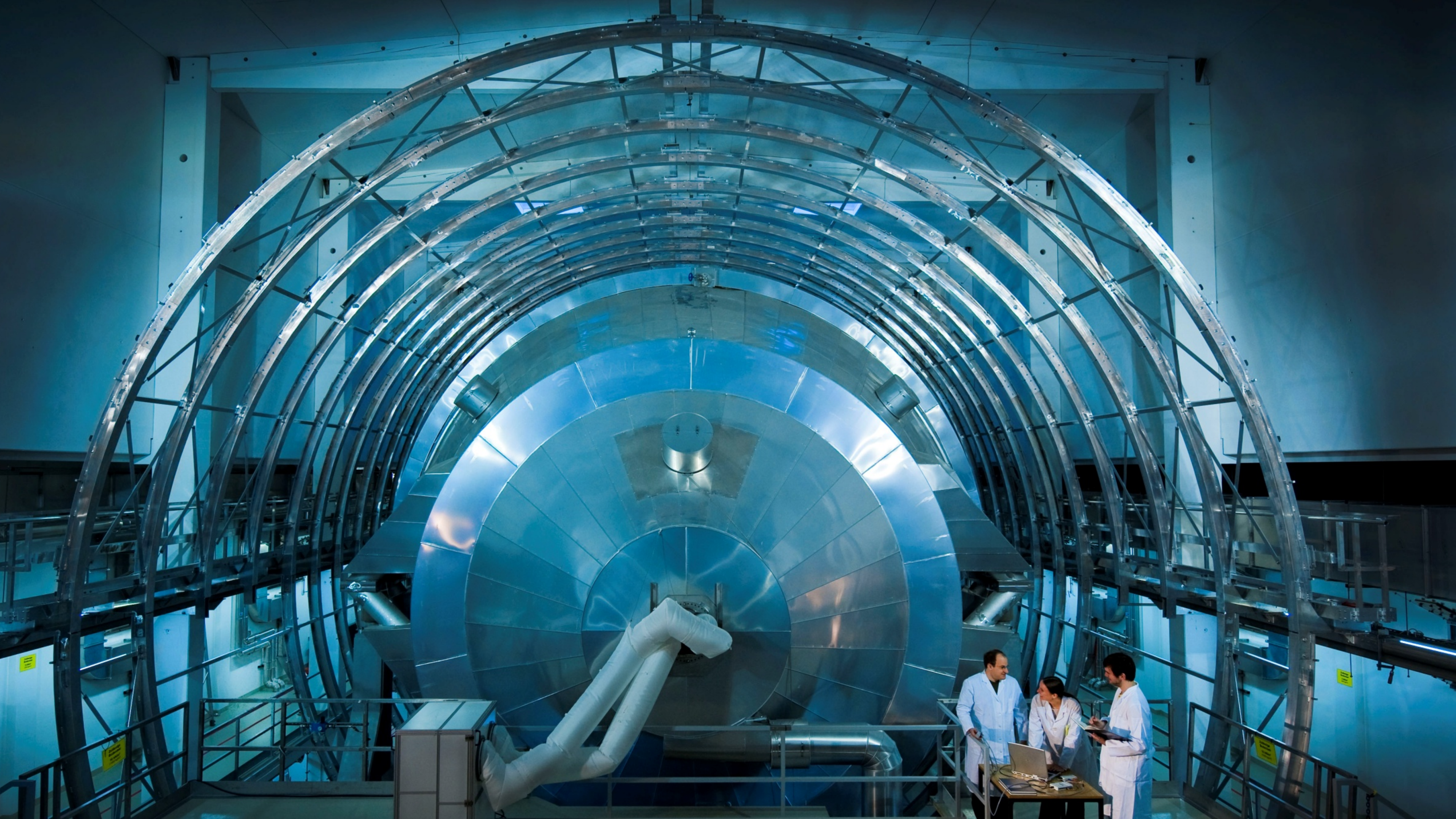
KATRIN Working Principle

Integral measurement down to 40 eV below the endpoint









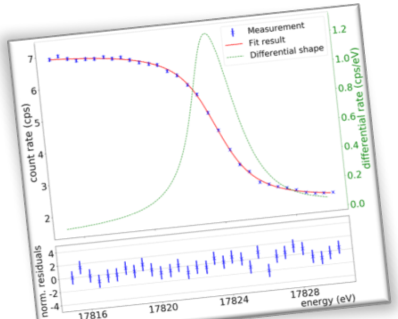
18-years of KATRIN history

Letter of Intent

2001

Main spectrometer

2006



Krypton calibration

2017

First neutrino mass

2019

2004

Design Report


Report NPI ASCR Řež, EXP-01/2005
FZKA Scientific Report 7090
MS-KP-0501

KATRIN Design Report 2004

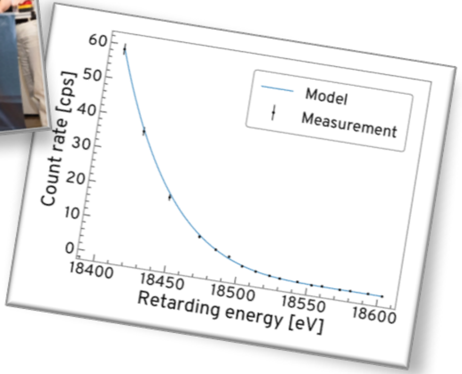
The KATRIN Collaboration

2016

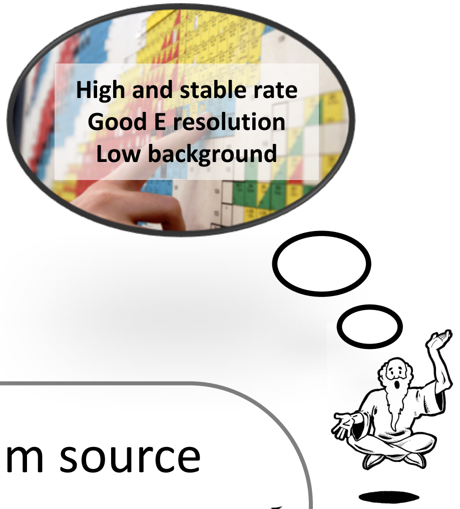
First light

2018

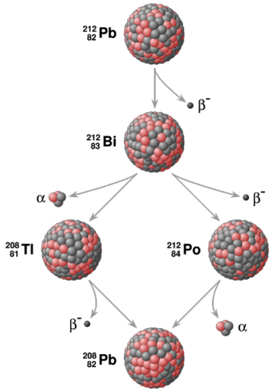
First tritium

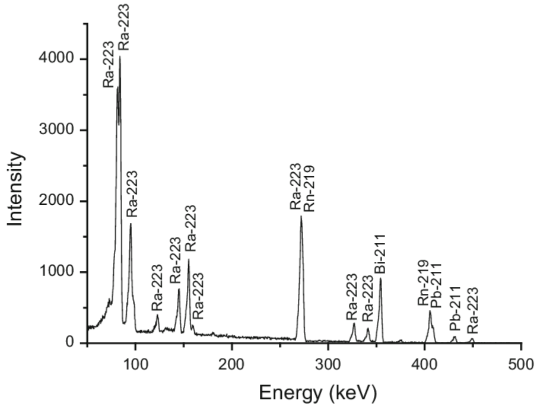


Test of Unique Properties of KATRIN

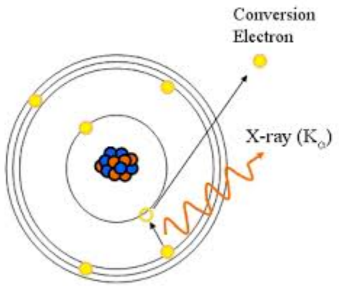


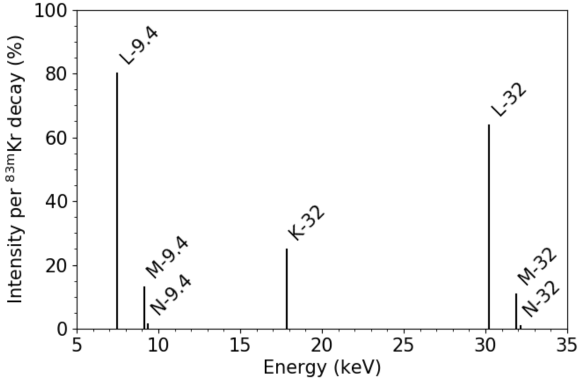
Low Background



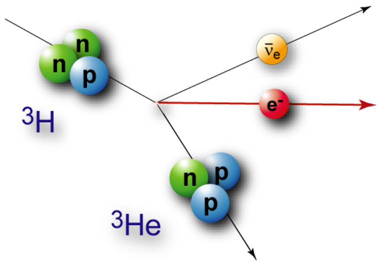


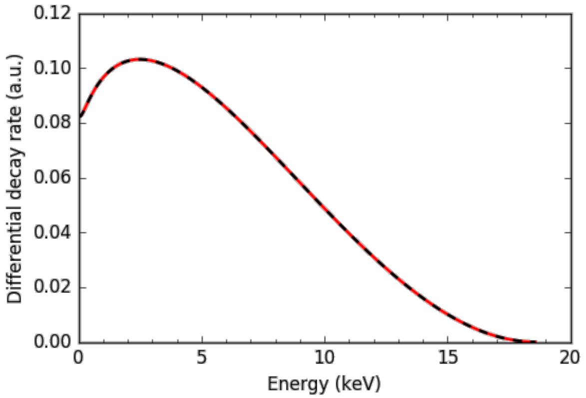
high-resolution MAC-E filter





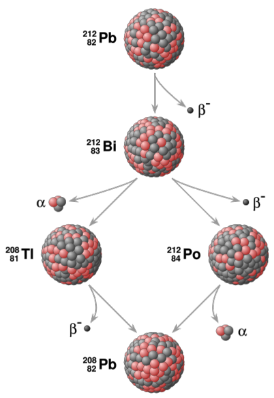
ultra-stable tritium source

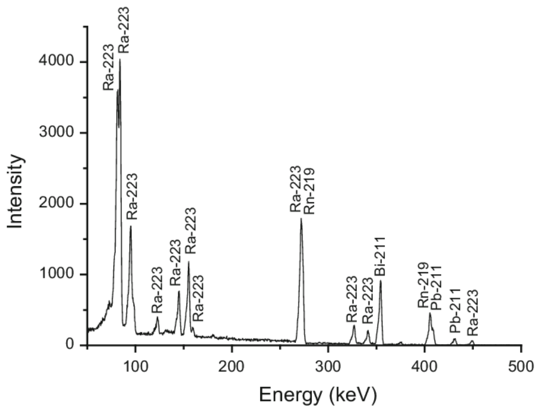




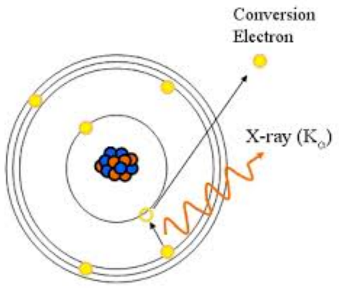
Test of Unique Properties of KATRIN

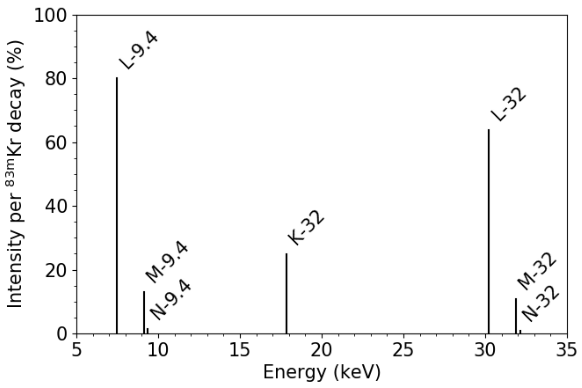
Low Background



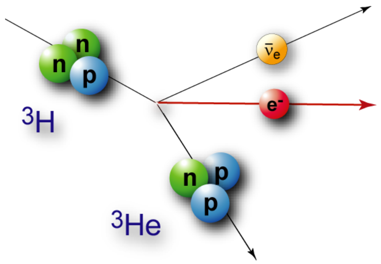


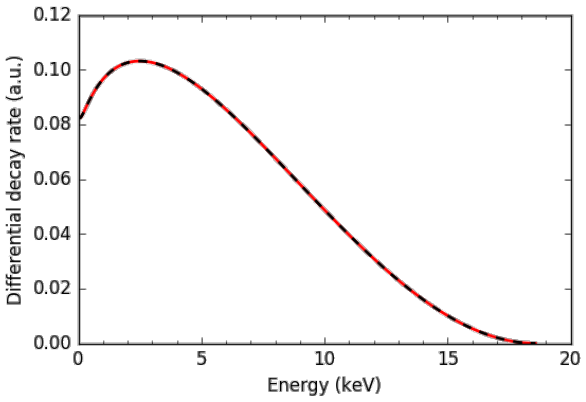
high-resolution MAC-E filter





ultra-stable tritium source

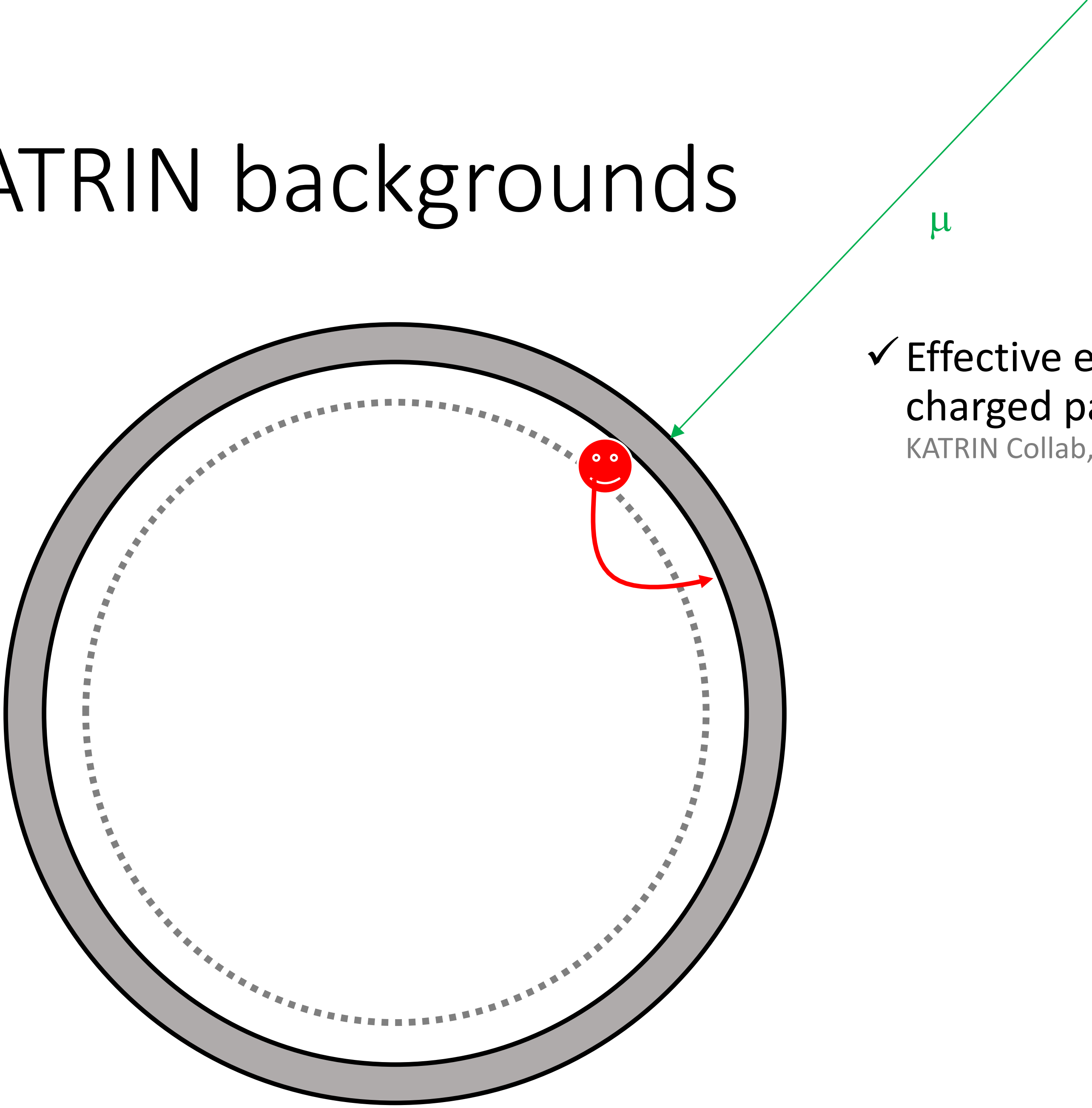




KATRIN backgrounds

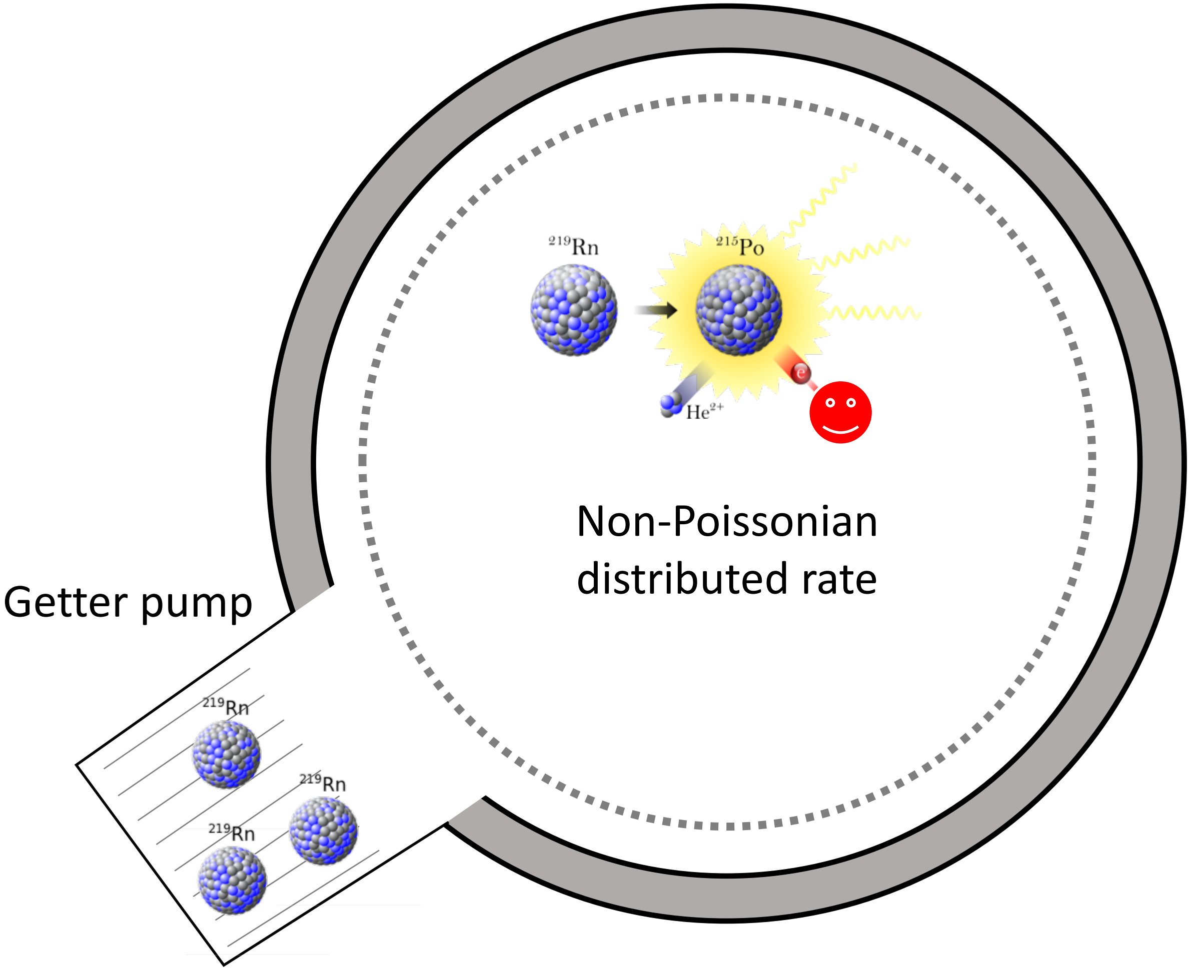
inner surface: 650m^2, volume: 1400m^3

KATRIN backgrounds



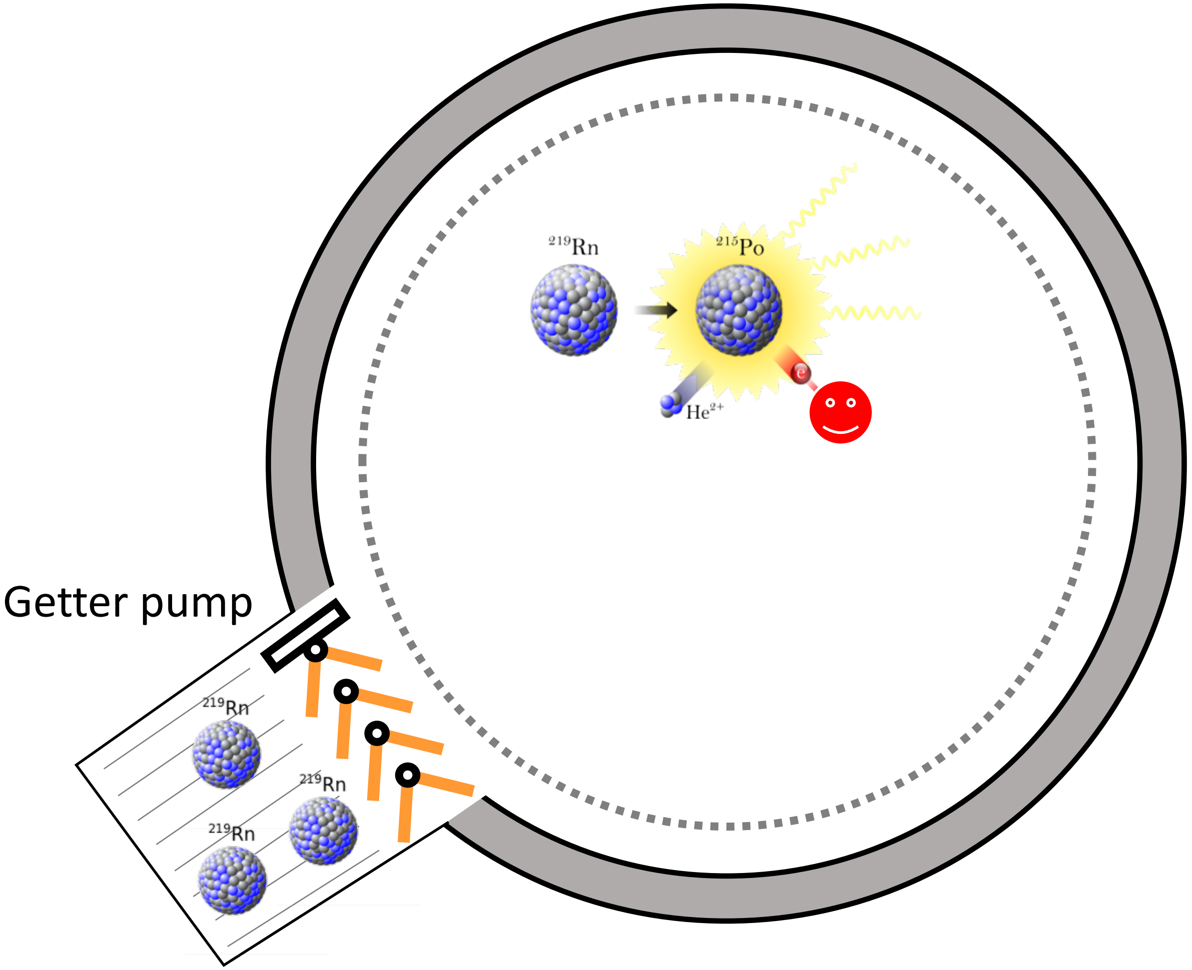
✓ Effective electric and magnetic shielding against charged particles from the surface
KATRIN Collab, JINST 13 T10004 (2018)

KATRIN backgrounds

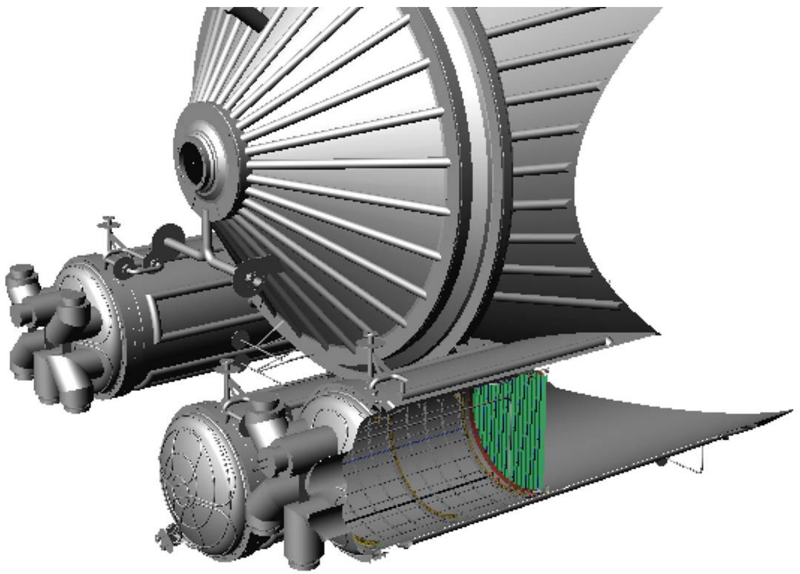


✓ Effective electric and magnetic shielding against charged particles from the surface
KATRIN Collab, JINST 13 T10004 (2018)

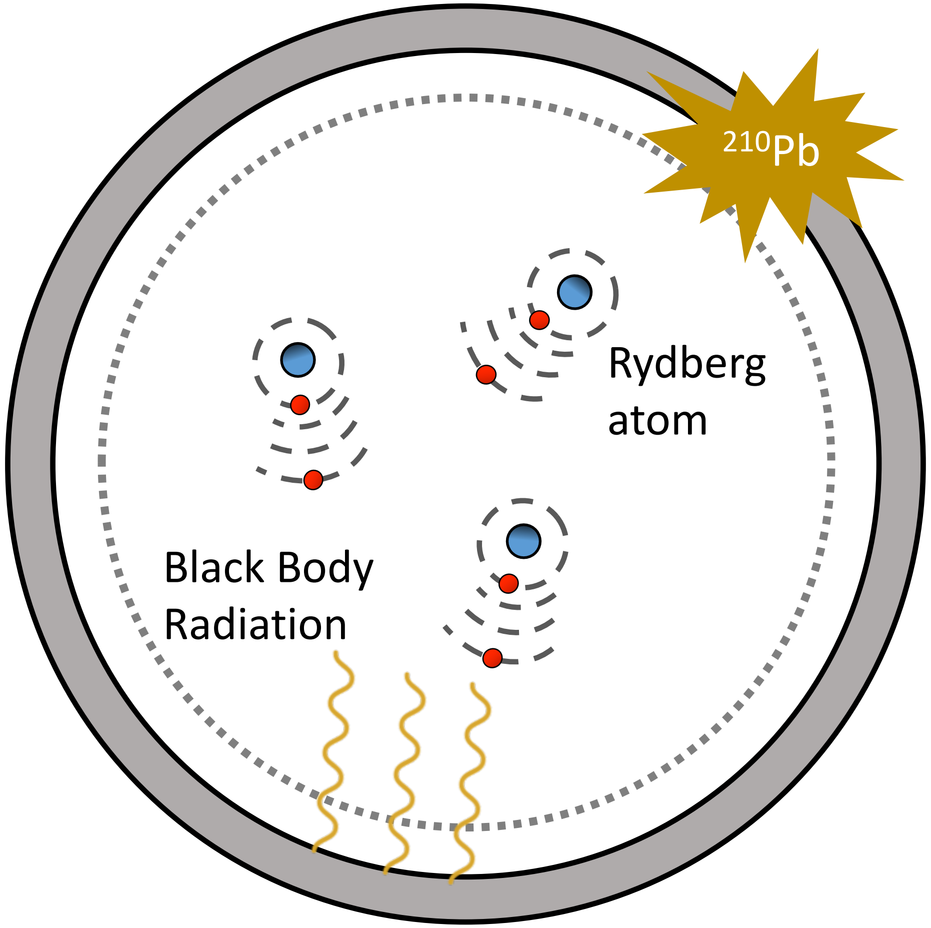
KATRIN backgrounds



- ✓ Effective electric and magnetic shielding against charged particles from the surface
  KATRIN Collab, JINST 13 T10004 (2018)
- ✓ Effective reduction of radon-induced background via nitrogen-cooled baffle system
  S. Goerhardt, et al., JINST 13 (2018) no.10, T10004
  S. M. et al, Astropart. Phys. 41 (2013), 52–62
  S. M. et al, JINST 7 (2012) P08025



KATRIN backgrounds

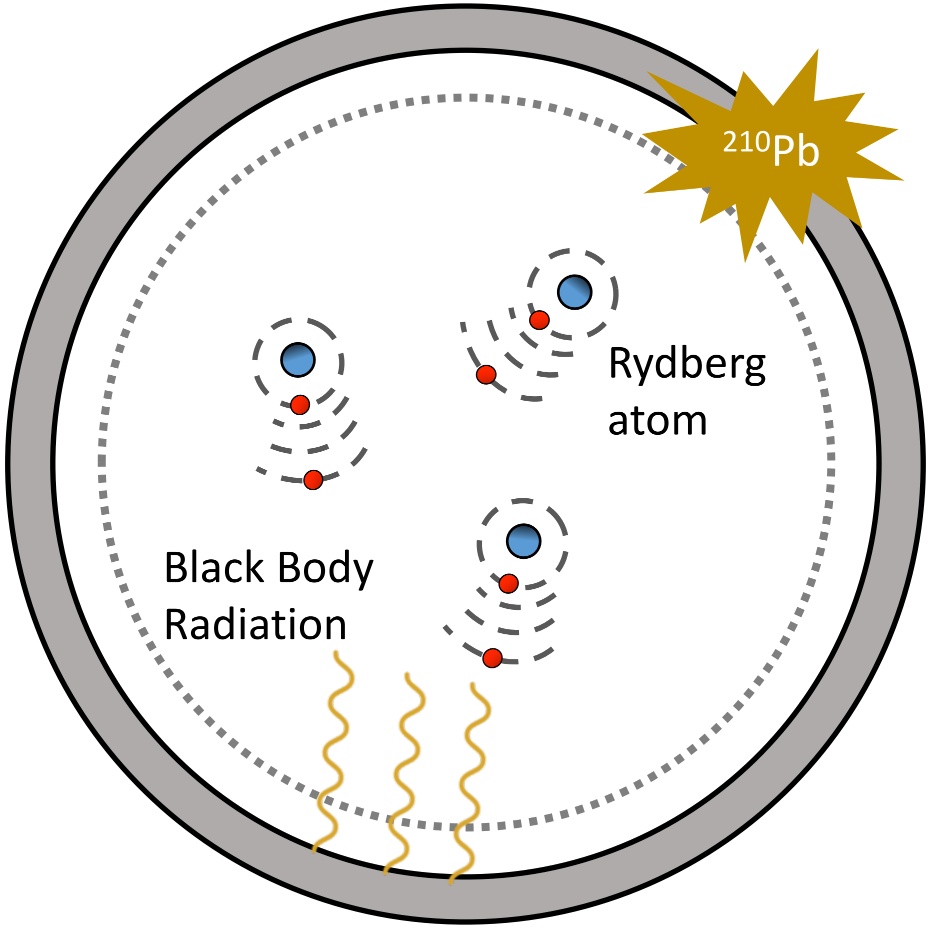


✓ Effective electric and magnetic shielding against charged particles from the surface
KATRIN Collab, JINST 13 T10004 (2018)

✓ Effective reduction of radon-induced background via nitrogen-cooled baffle system
S. Goerhardt, et al., JINST 13 (2018) no.10, T10004
S. M. et al, Astropart. Phys. 41 (2013), 52–62
S. M. et al, JINST 7 (2012) P08025

✓ Remaining background: Rydberg atoms

KATRIN backgrounds



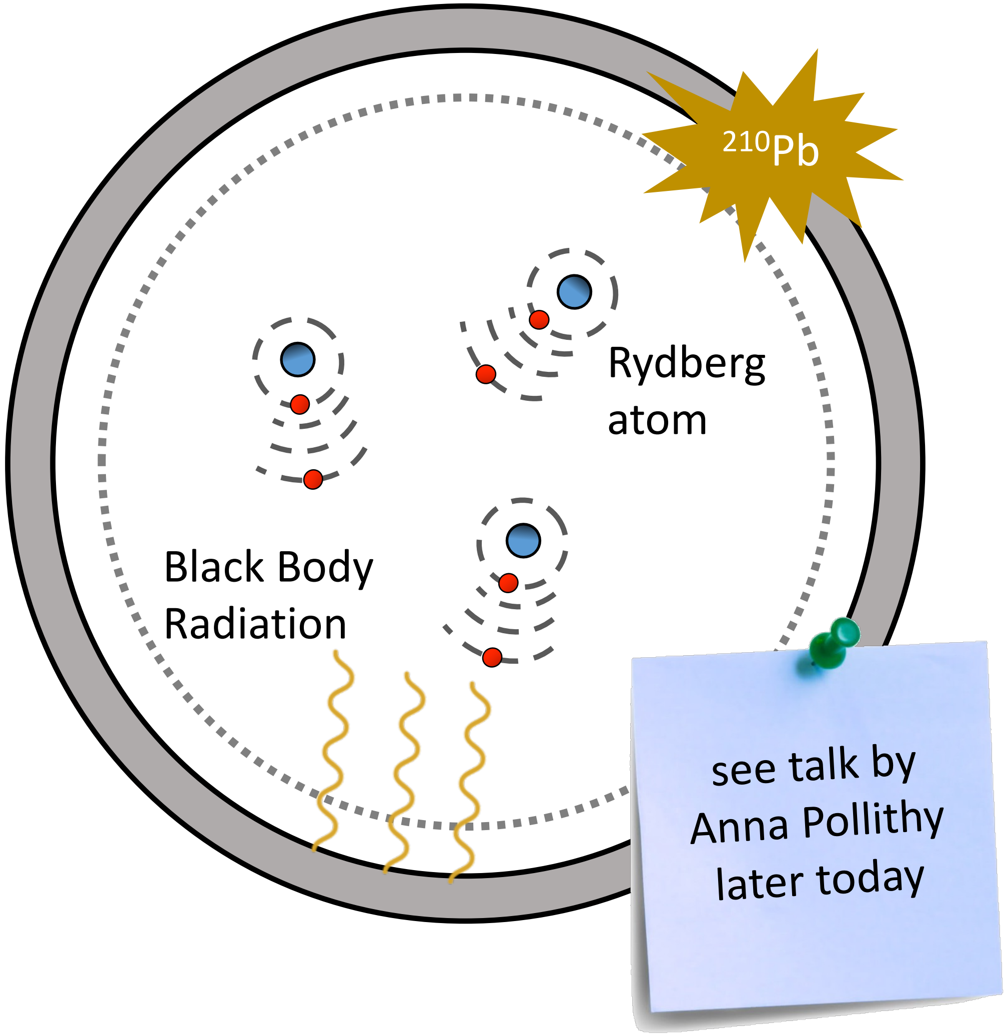
✓ Effective electric and magnetic shielding against charged particles from the surface
KATRIN Collab, JINST 13 T10004 (2018)

✓ Effective reduction of radon-induced background via nitrogen-cooled baffle system
S. Goerhardt, et al., JINST 13 (2018) no.10, T10004
S. M. et al, Astropart. Phys. 41 (2013), 52–62
S. M. et al, JINST 7 (2012) P08025

✓ Remaining background: Rydberg atoms

- current: 0.36 cps (design: 0.01 cps)
- background reduction verified:
  - ✓ by renewing efficiency of baffles
  - ✓ by reducing fiducial volume of fluxtube

KATRIN backgrounds

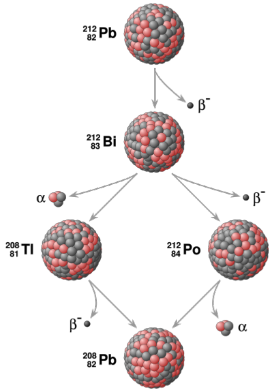


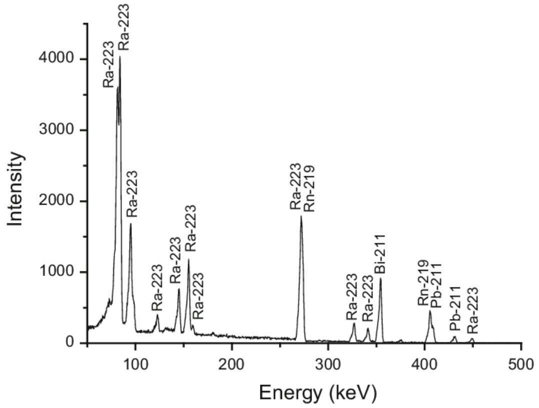
- ✓ Effective electric and magnetic shielding against charged particles from the surface
  KATRIN Collab, JINST 13 T10004 (2018)
- ✓ Effective reduction of radon-induced background via nitrogen-cooled baffle system
  S. Goerhardt, et al., JINST 13 (2018) no.10, T10004
  S. M. et al, Astropart. Phys. 41 (2013), 52–62
  S. M. et al, JINST 7 (2012) P08025
- ✓ Remaining background: Rydberg atoms

- current: 0.36 cps (design: 0.01 cps)
- background reduction verified:
  - ✓ by renewing efficiency of baffles
  - ✓ by reducing fiducial volume of fluxtube

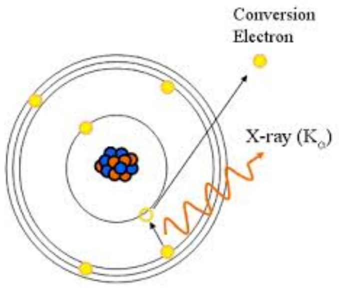
Test of Unique Properties of KATRIN

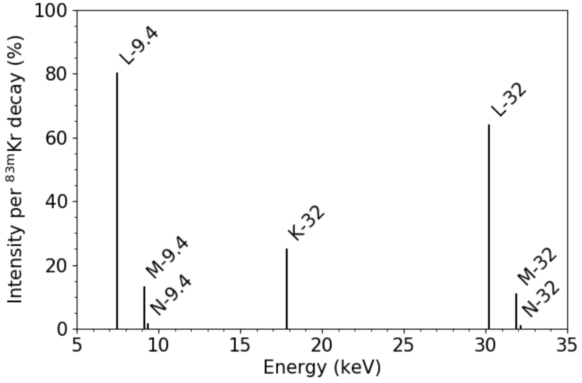
Low Background



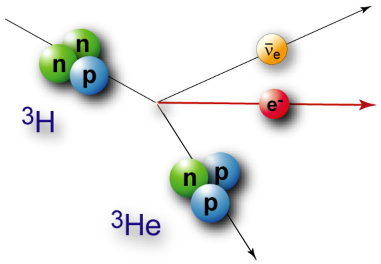


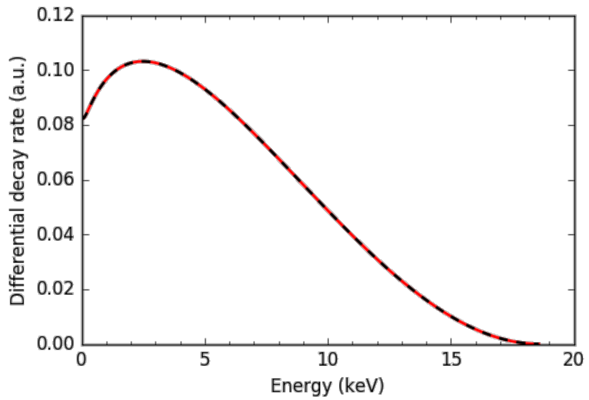
high-resolution MAC-E filter



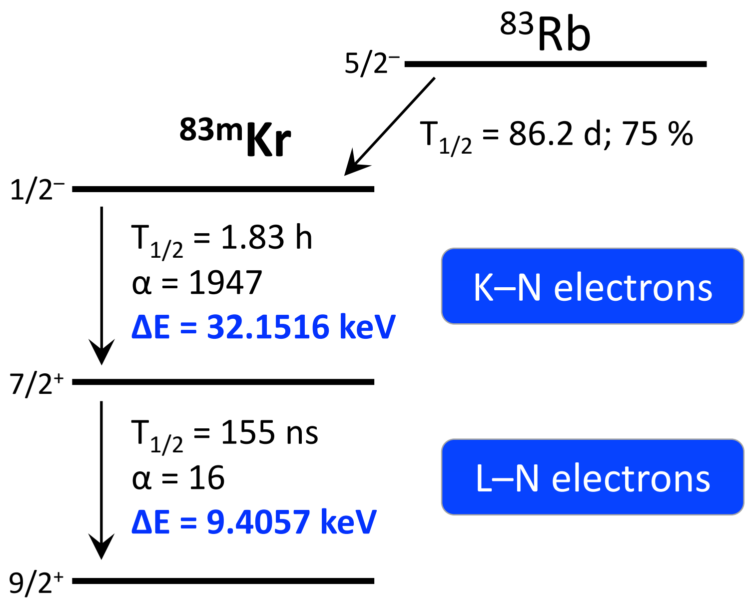


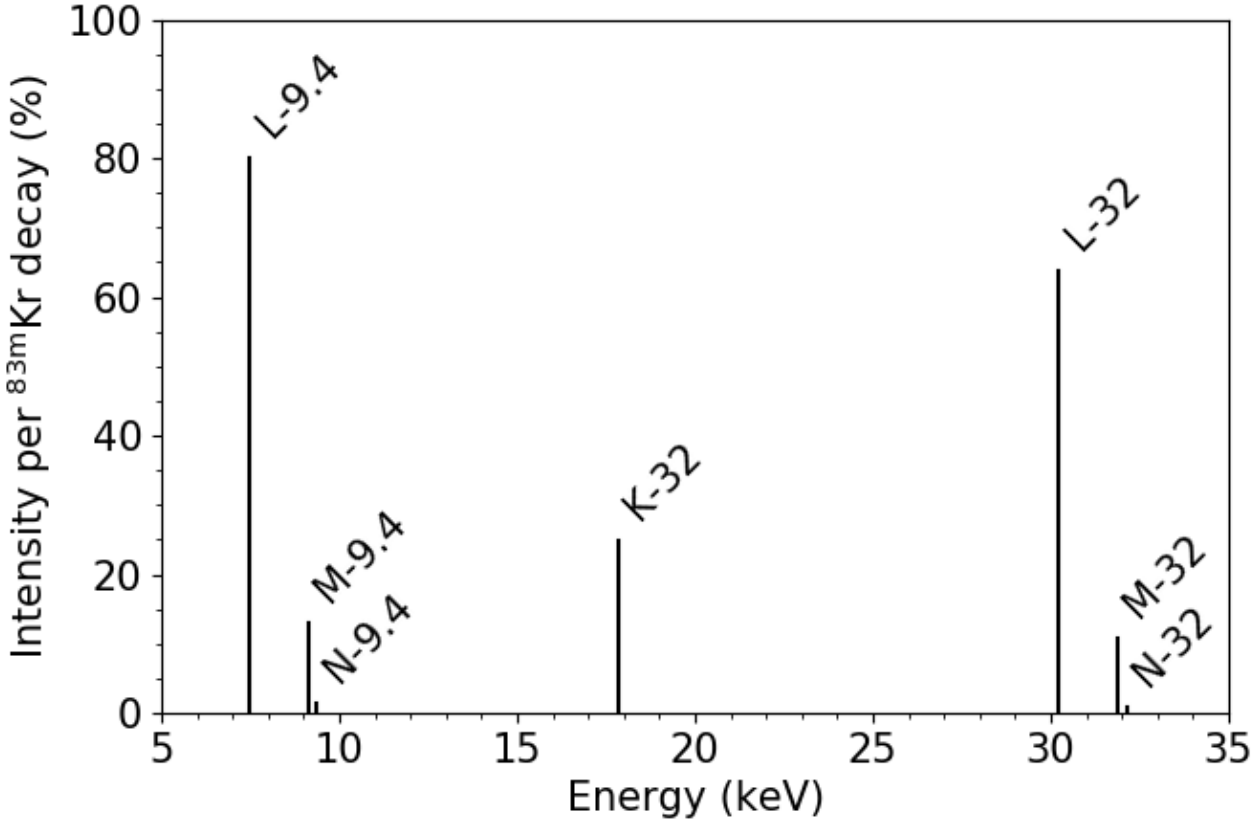
ultra-stable tritium source



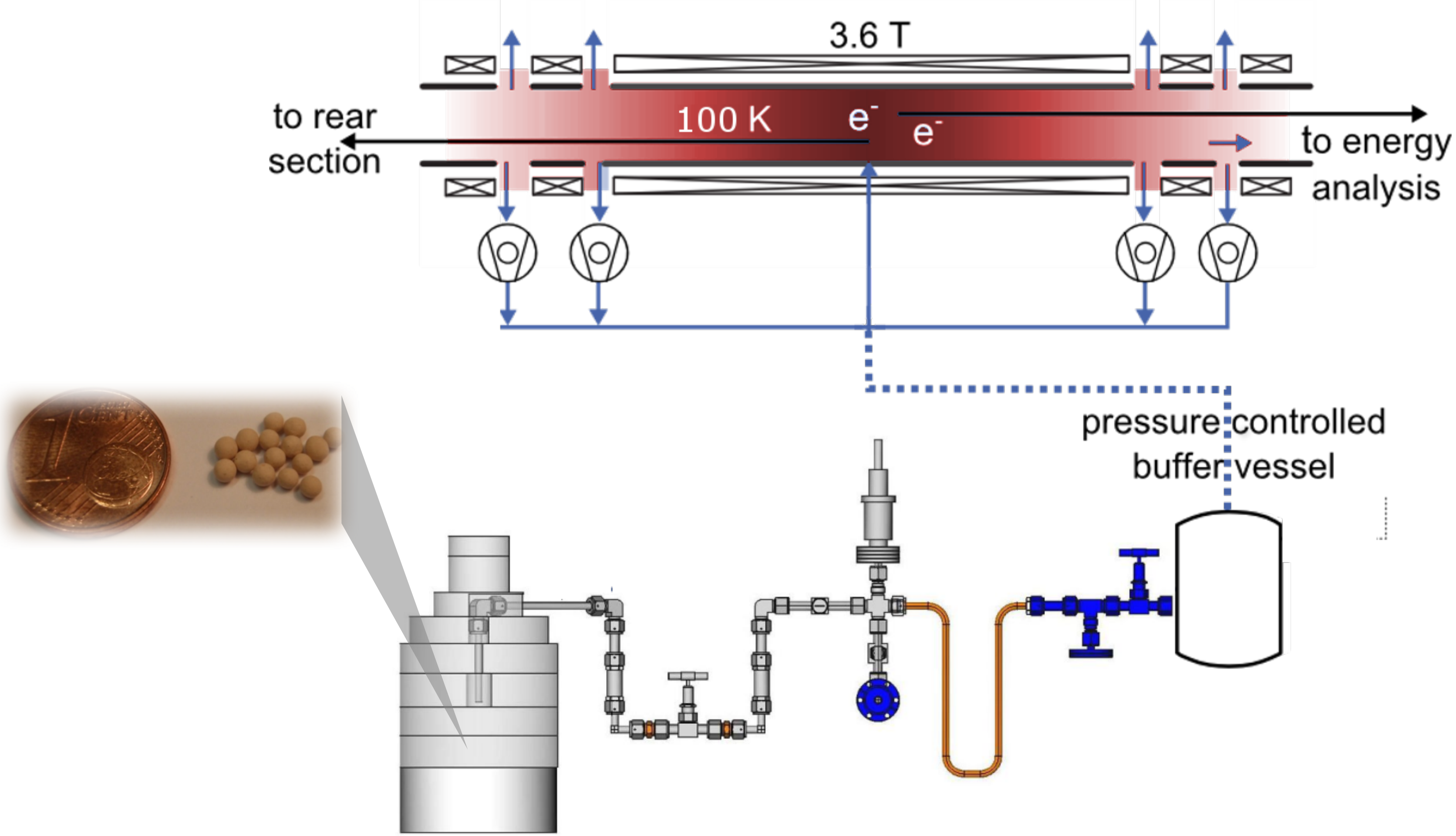


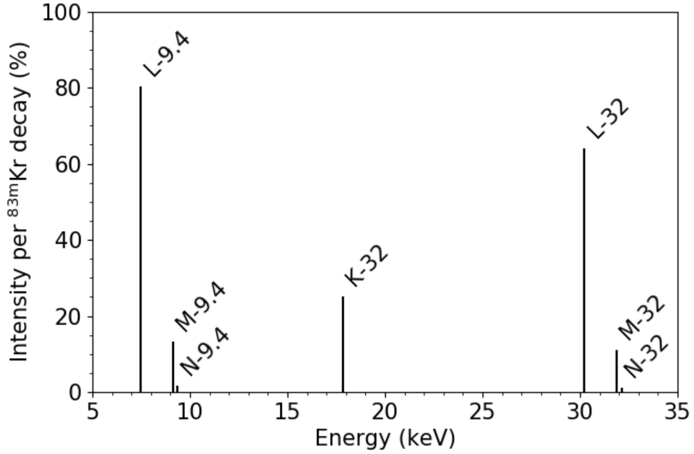
Krypton campaign (2017)



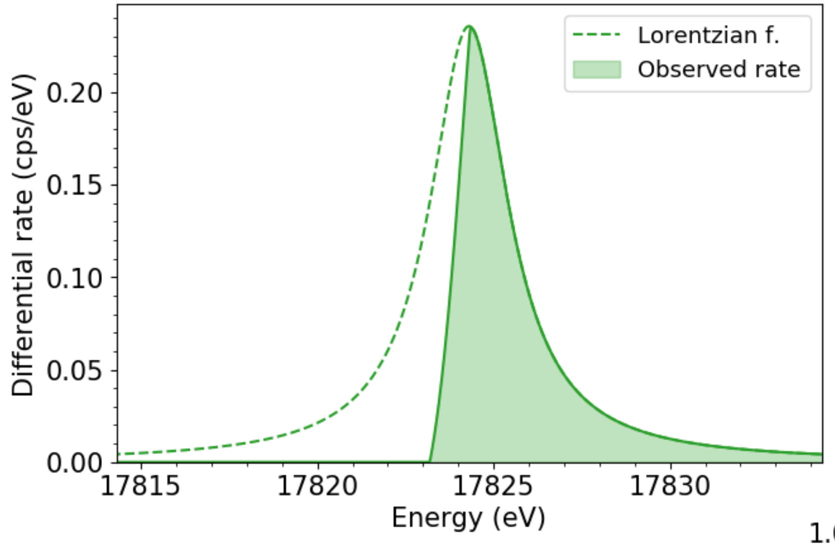


Krypton calibration



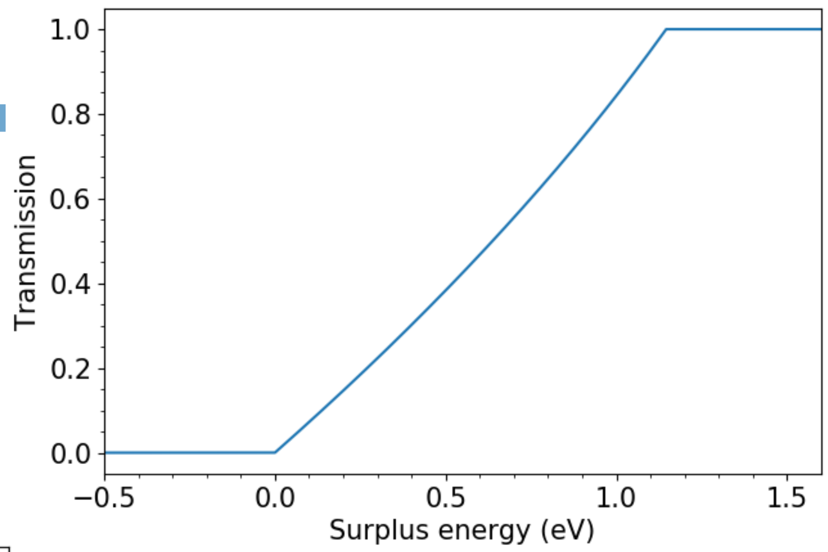


Krypton Model

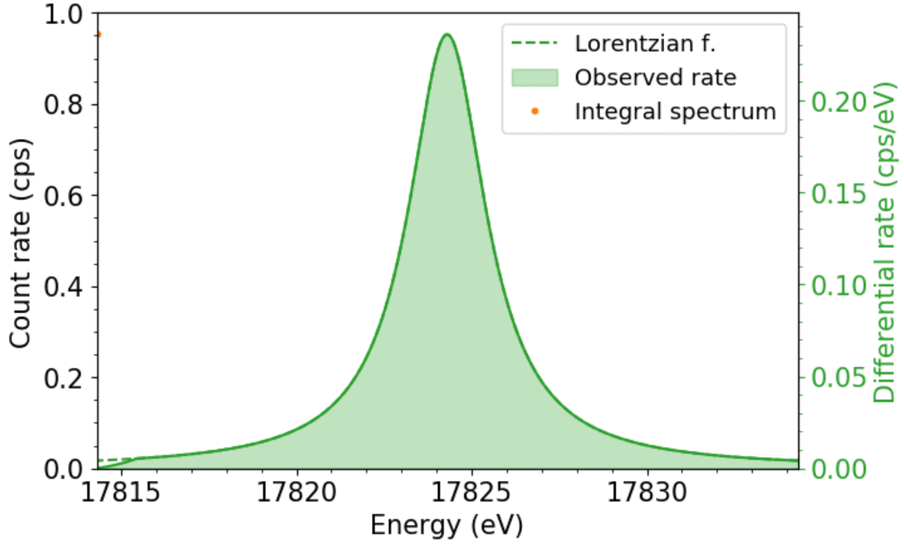


Natural line width of krypton

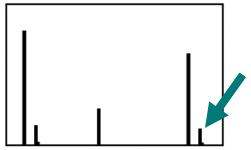
$$I(qU) = \int_{qU}^{E_0} D(E)T(E,qU)dE$$



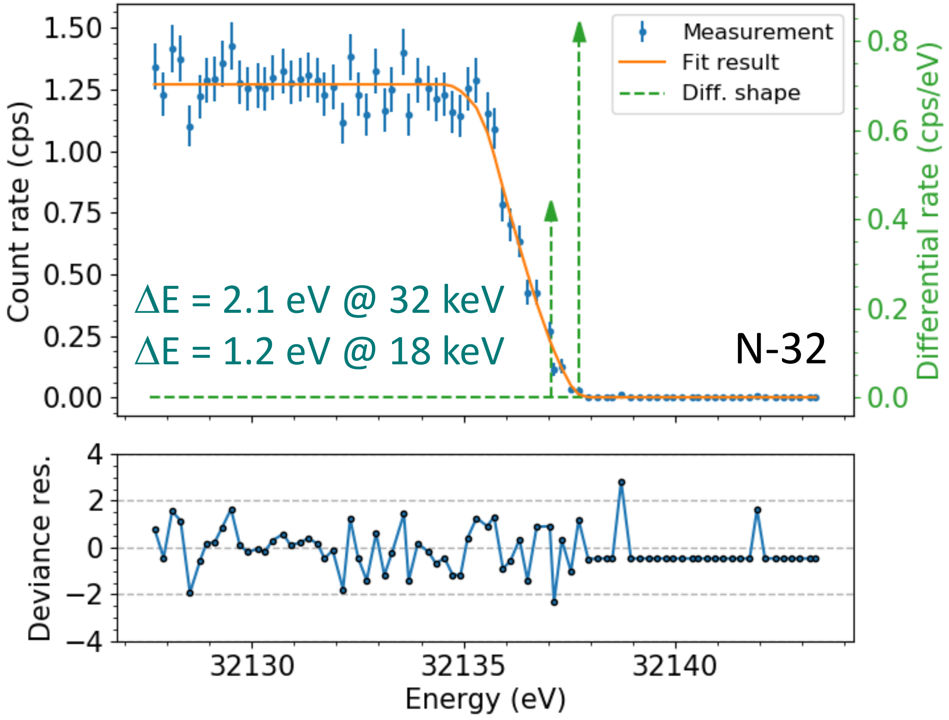
Spectrometer resolution

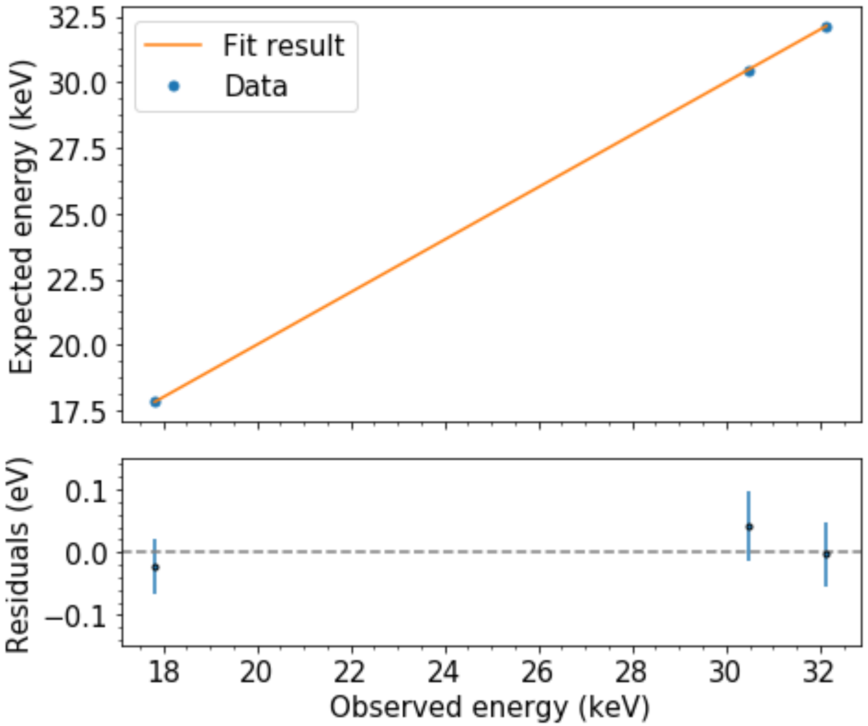


Krypton Results



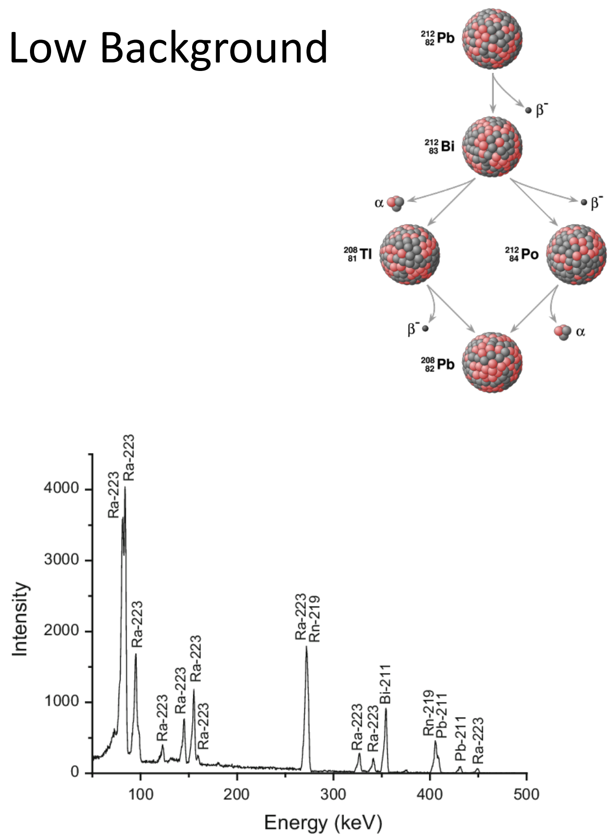
- ✓ Spectrometer resolution of ~1 eV @ 18 keV *(JINST 13 (2018) P04018, arXiv:1903.066452)*
- ✓ HV calibration on the ppm level *(EPJ C **78** 368 (2018))*



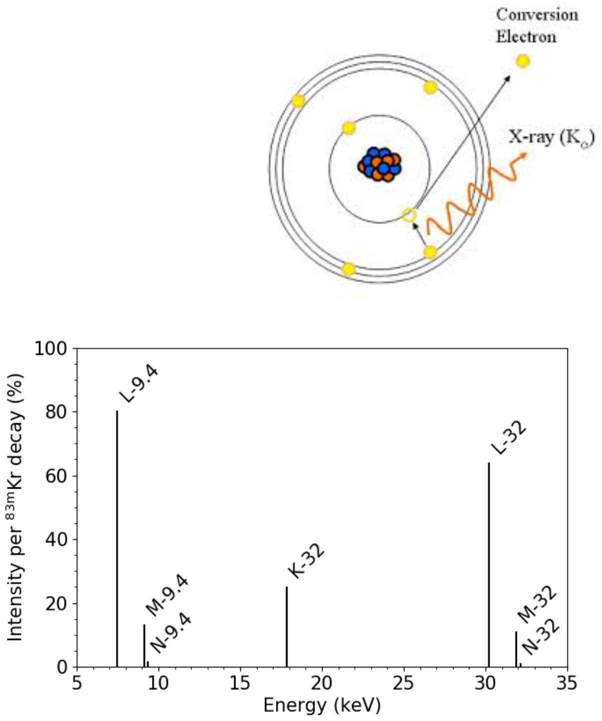


Test of Unique Properties of KATRIN

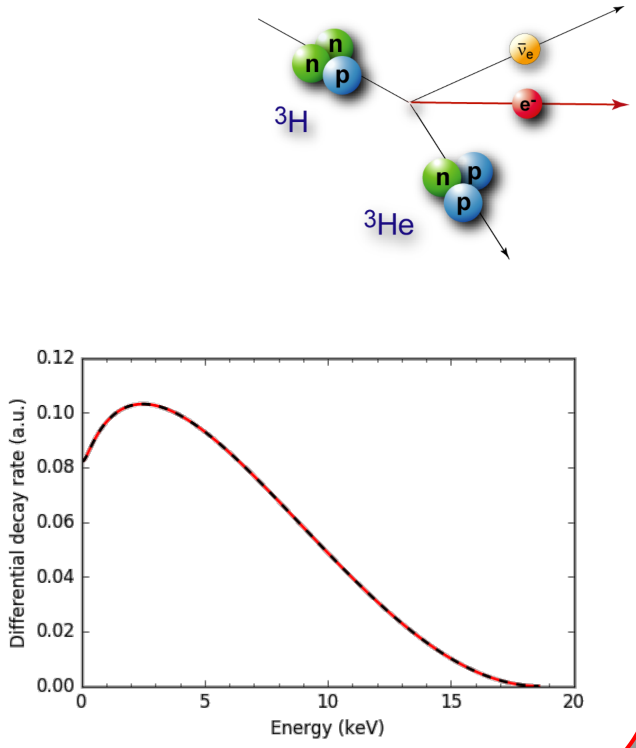
Low Background



high-resolution MAC-E filter



ultra-stable tritium source



First tritium campaign (2018)

- Commissioning of system with tritium (1% of nominal activity = ~500 MBq!)
- 14 days of operation (without interruption)

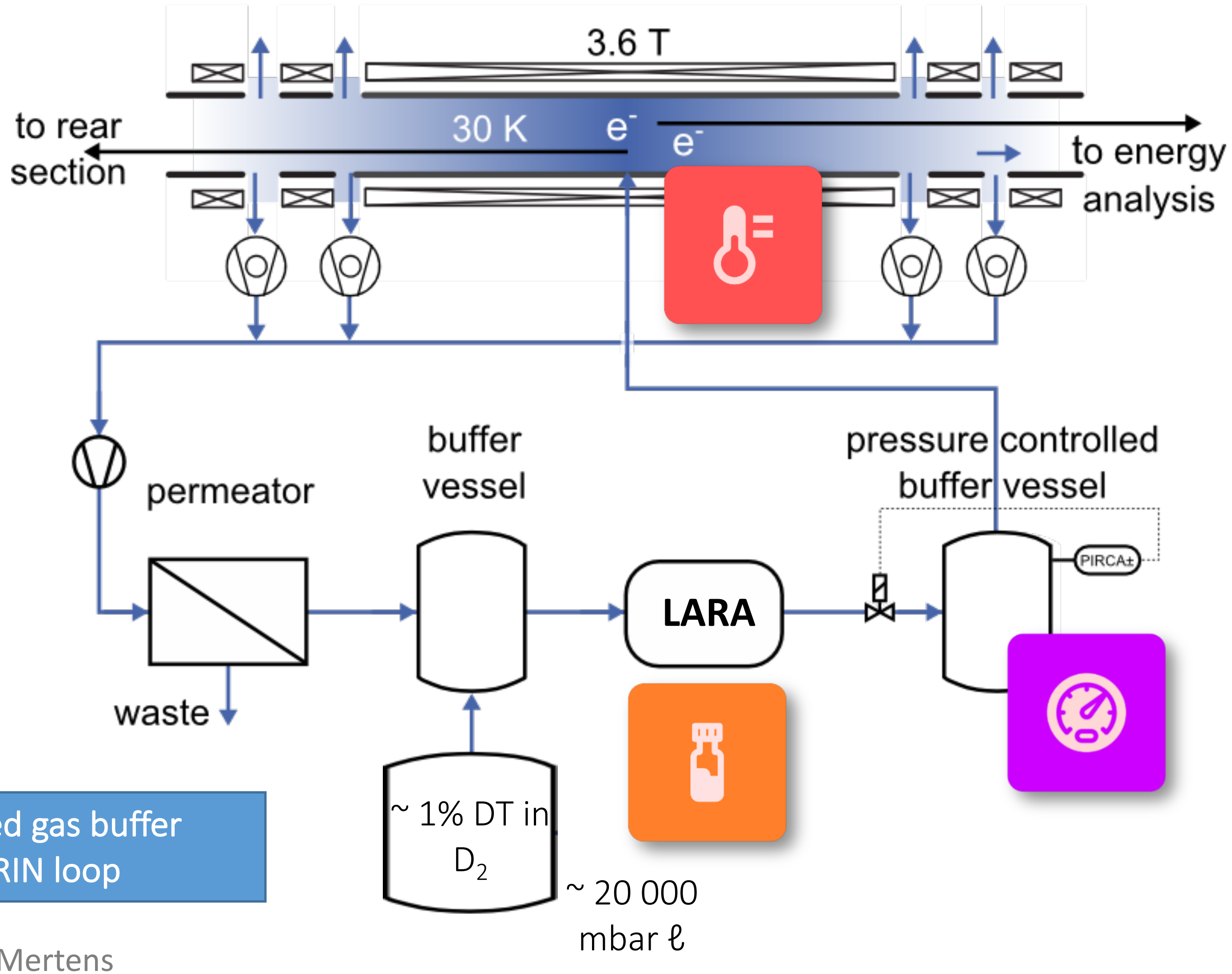
✓ Demonstrate global system stability

✓ Test analysis strategies

[arXiv:1909.06069]

First tritium injection:
Friday 18 May
7:48 am UTC

Tritium loop system

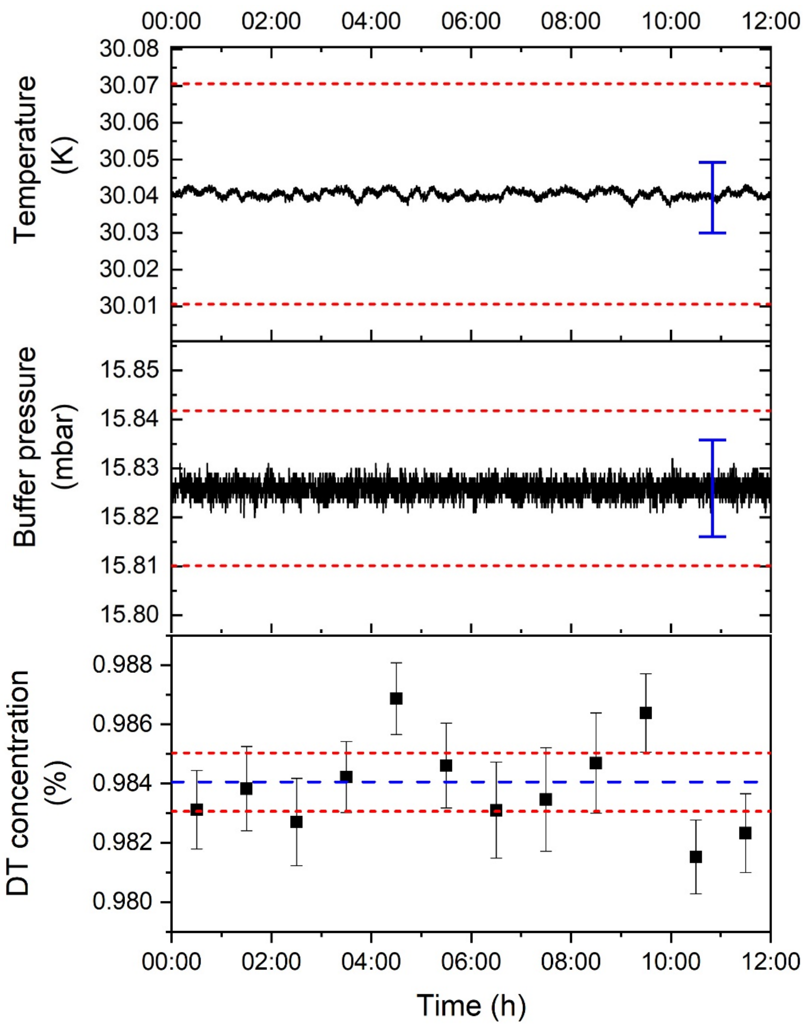


Prefilled gas buffer in KATRIN loop

Relevant control parameters:

- Temperature
- Pressure
- Isotopic composition

Stability of source parameters

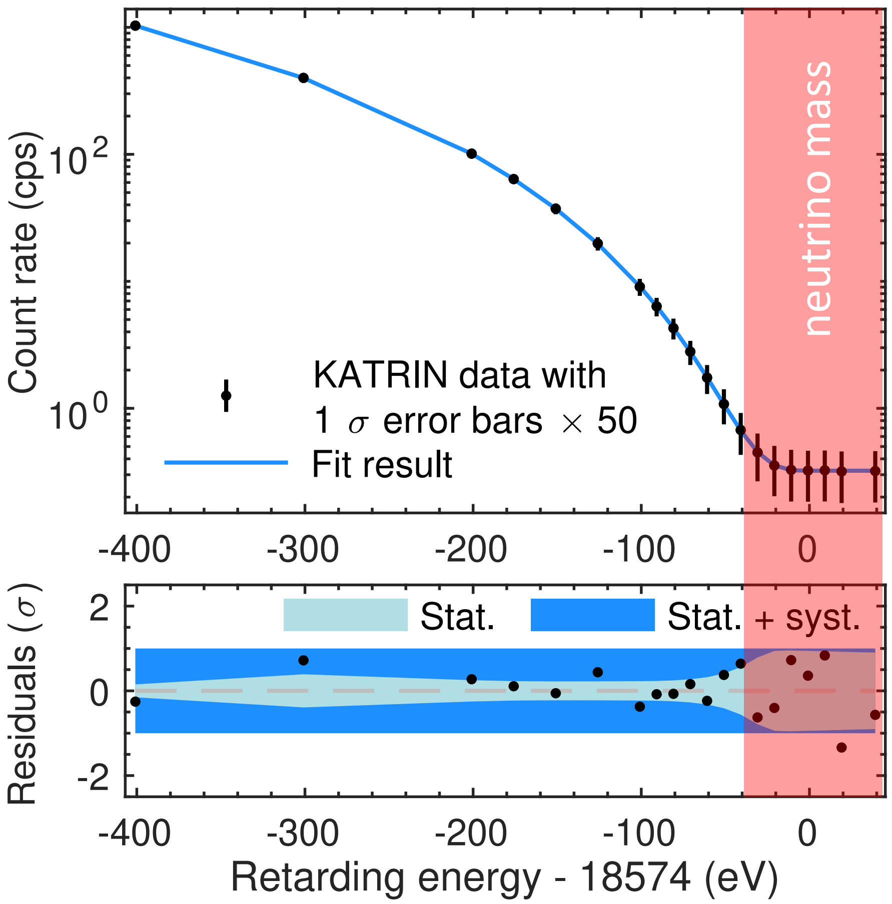


Blue arrow:
systematic uncertainty

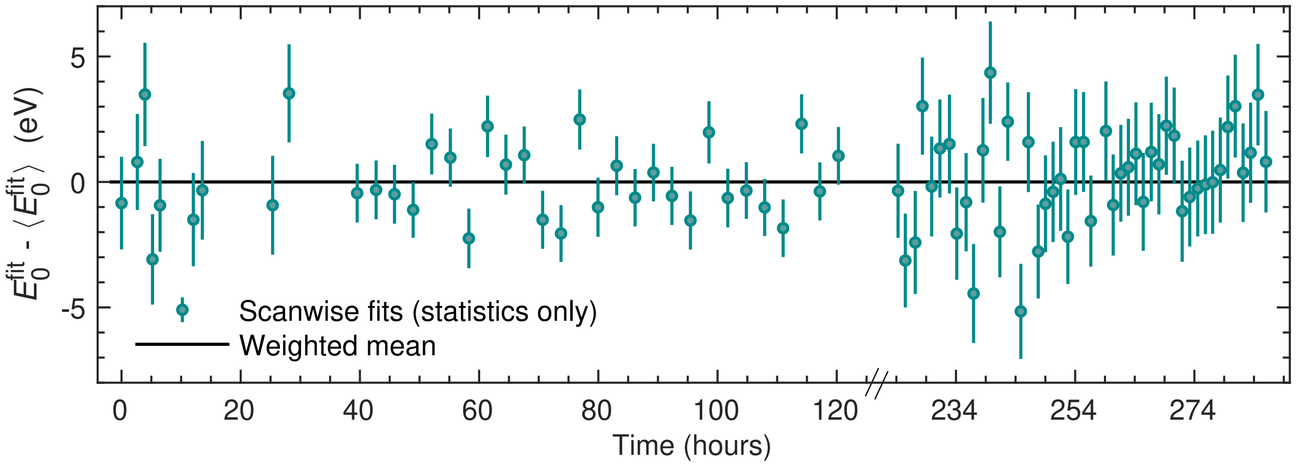
Red dashed line:
± 0.1 % reference

✓ Source parameters are stable and within the specifications

First tritium spectra



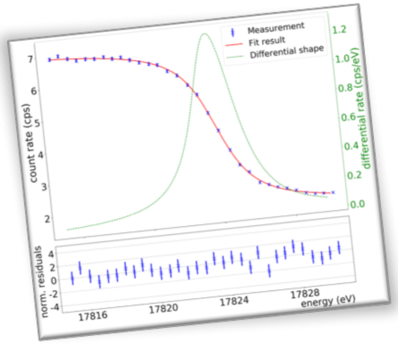
- ✓ Excellent agreement of model with data over wide energy range
- ✓ Stability of fitted endpoint over 12 days



18-years of KATRIN history

Letter of Intent

Main spectrometer



Krypton calibration

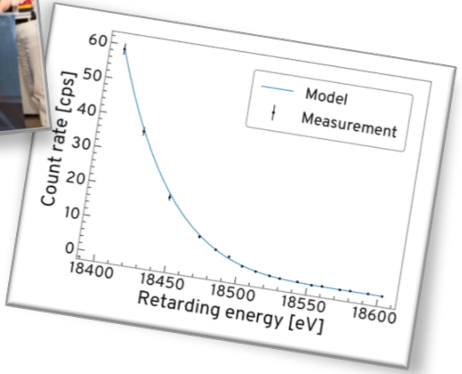
First neutrino mass

2001 2004 2006 2016 2017 2018 2019

Design Report

First light

First tritium



KATRIN neutrino mass campaign #1 (KNM-1)

- First ever high-activity tritium operation of KATRIN
- April 10 – May 13 2019: **780 h (~4 weeks)**
- high-quality data collected **2 million electrons**

✓ **First neutrino mass result ☺**

KATRIN neutrino mass campaign #1 (KNM-1)

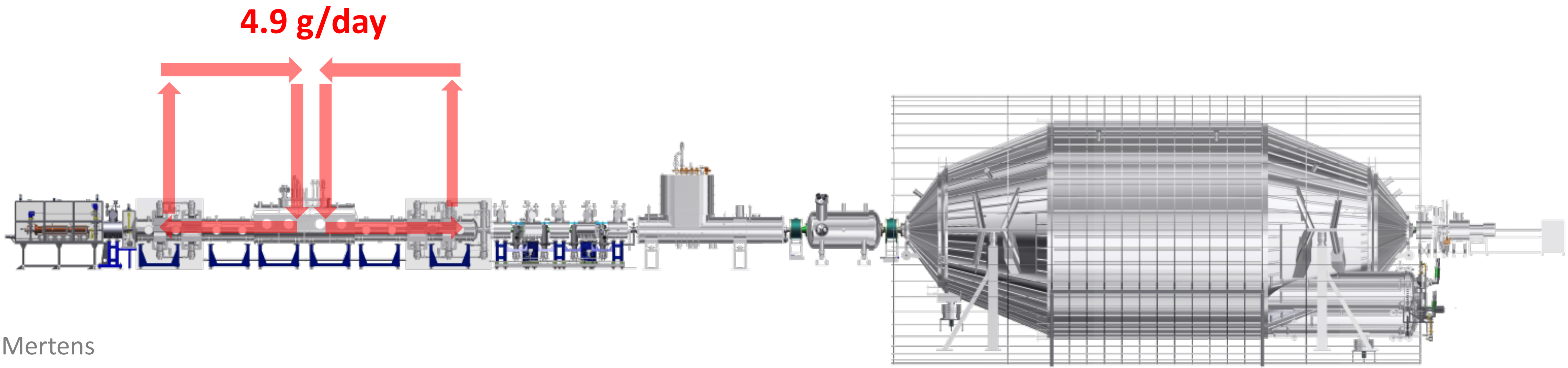
- First ever high-activity tritium operation of KATRIN
- April 10 – May 13 2019: **780 h (~4 weeks)**
- high-quality data collected **2 million electrons**

✓ **First neutrino mass result ☺**

What does it take to acquire high-quality data

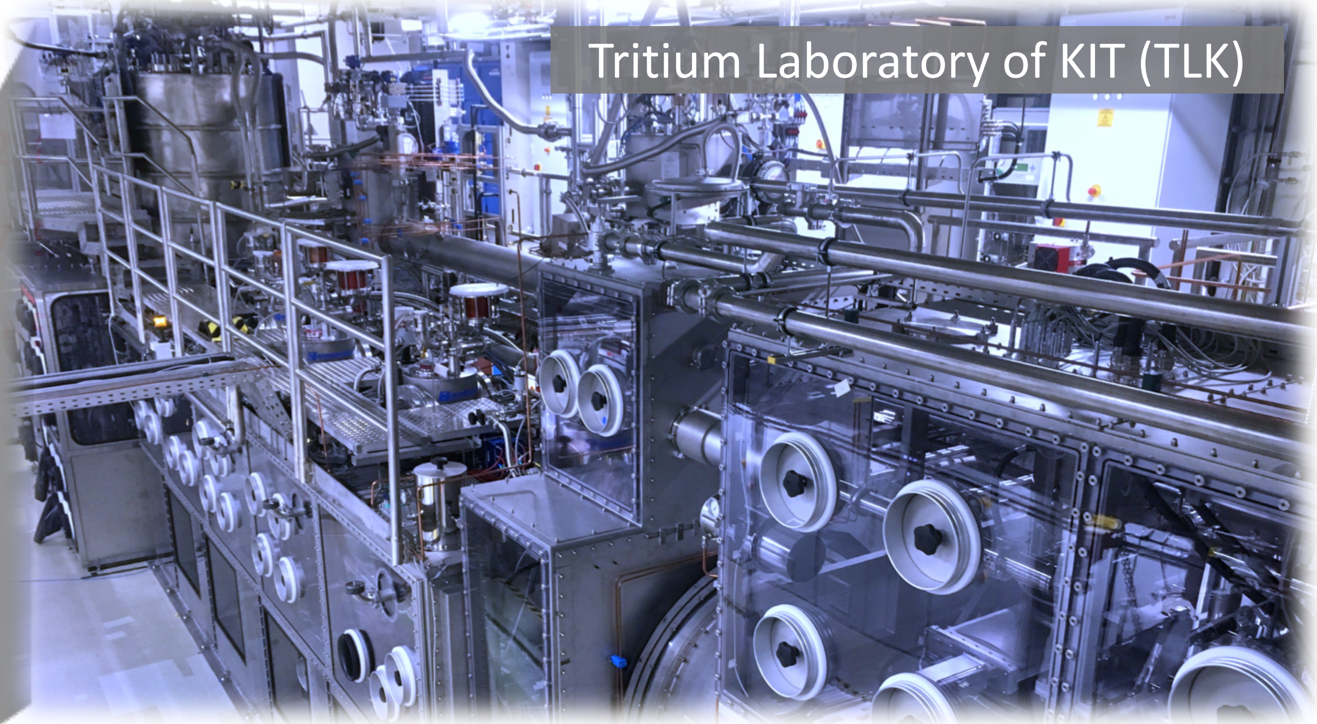
Tritium operation of KATRIN

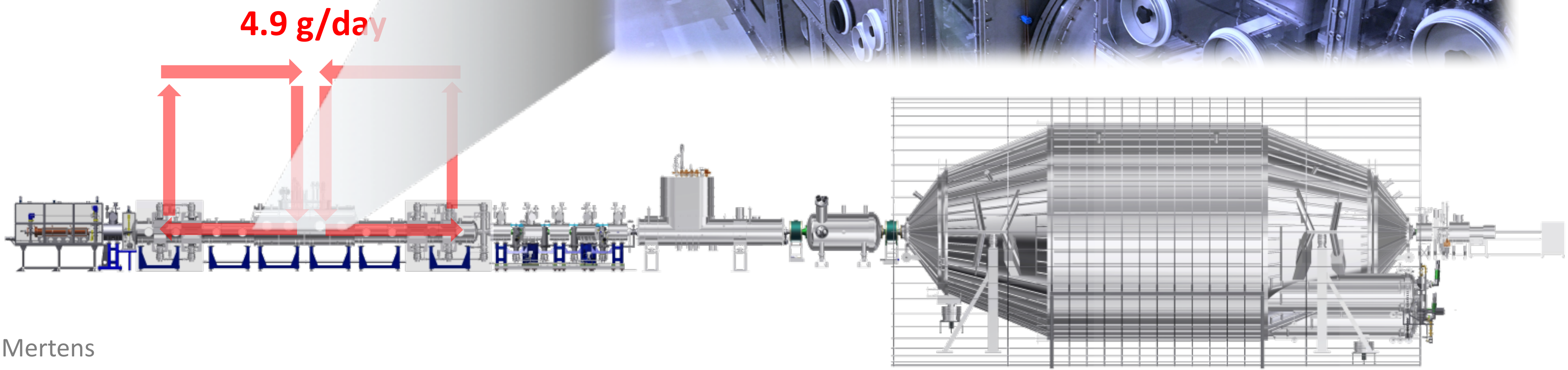
- tritium gas density: **22% of nominal (burn-in period)**
- high isotopic tritium purity: **97.5%**
- high source activity: **$2.45 \cdot 10^{10}$ Bq (24.5 GBq)**



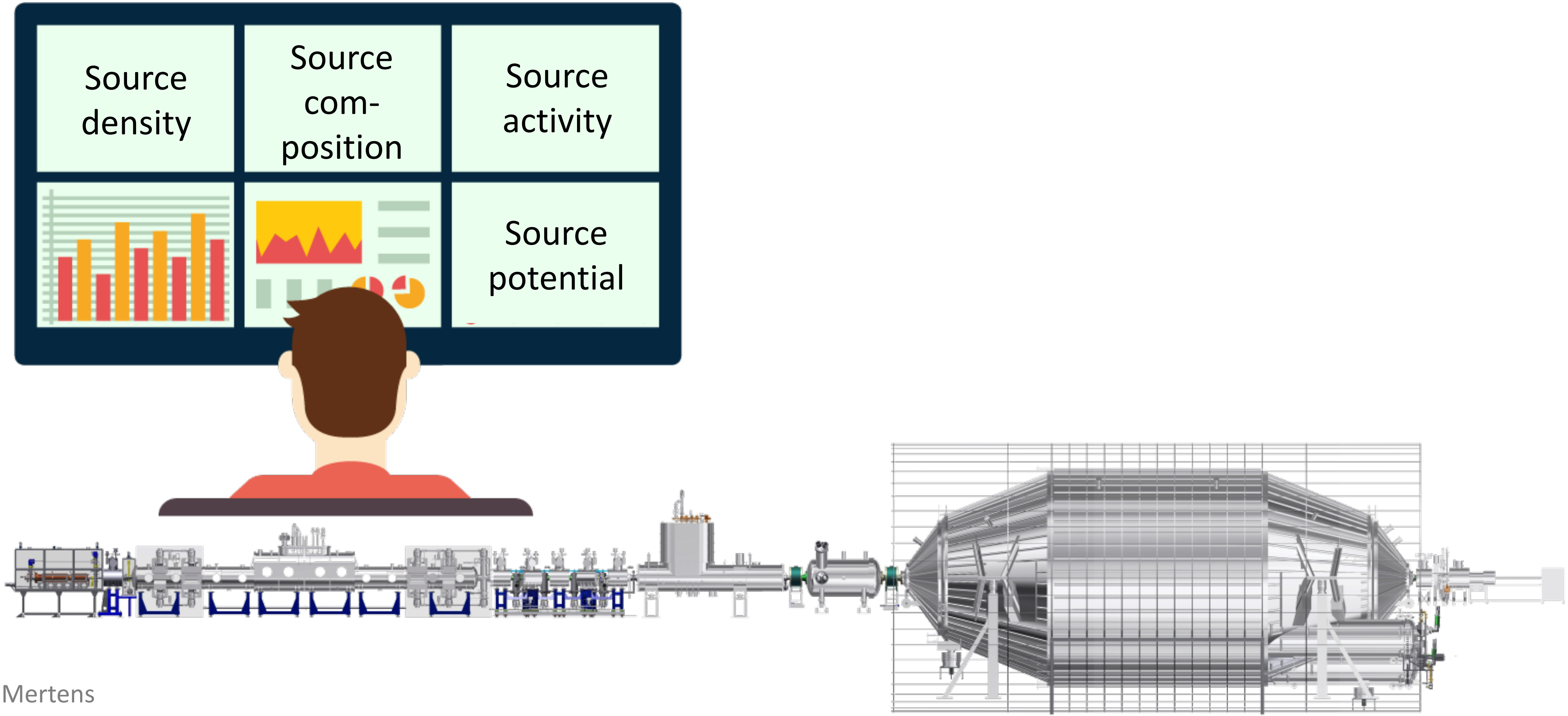
Tritium operation of KATRIN

- tritium gas density:
- high isotopic tritium purity:
- high source activity:



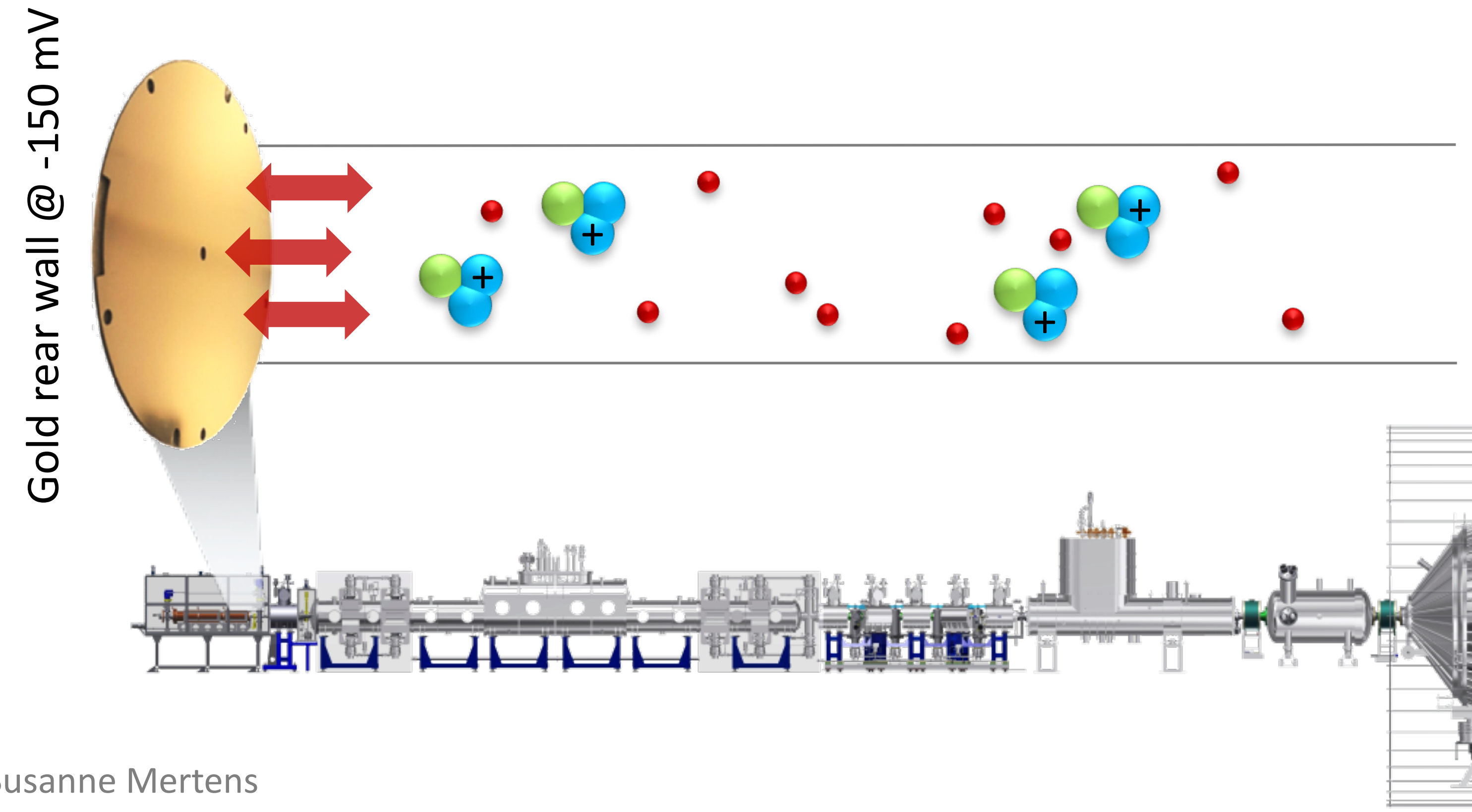


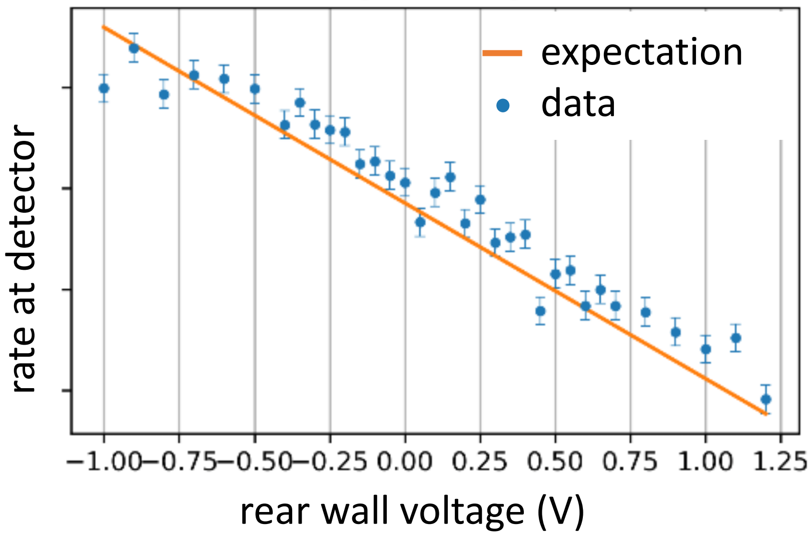
Monitoring and characterization of source



Source Potential

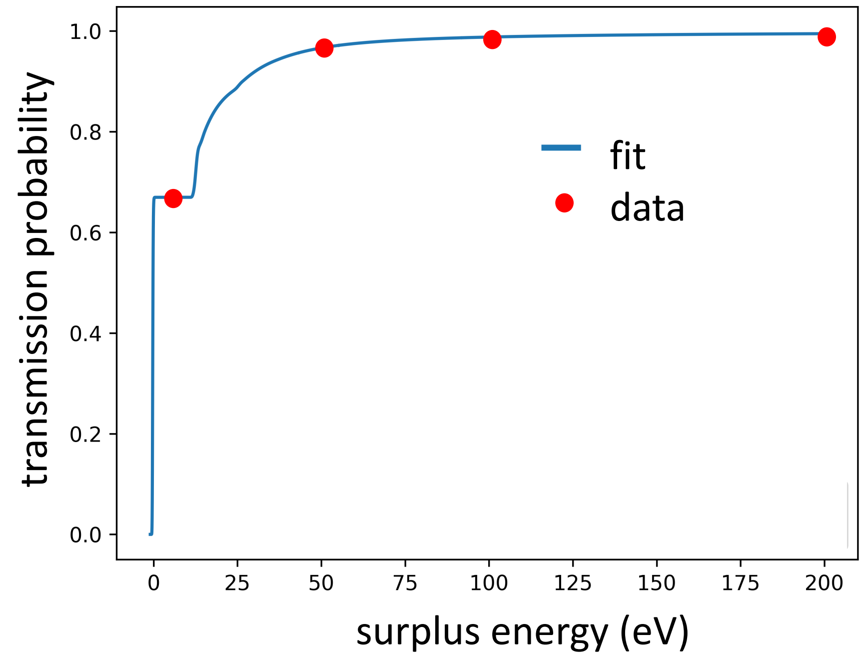
- **Gold-plated rear wall**
- Optimization of homogeneity and coupling of plasma potential

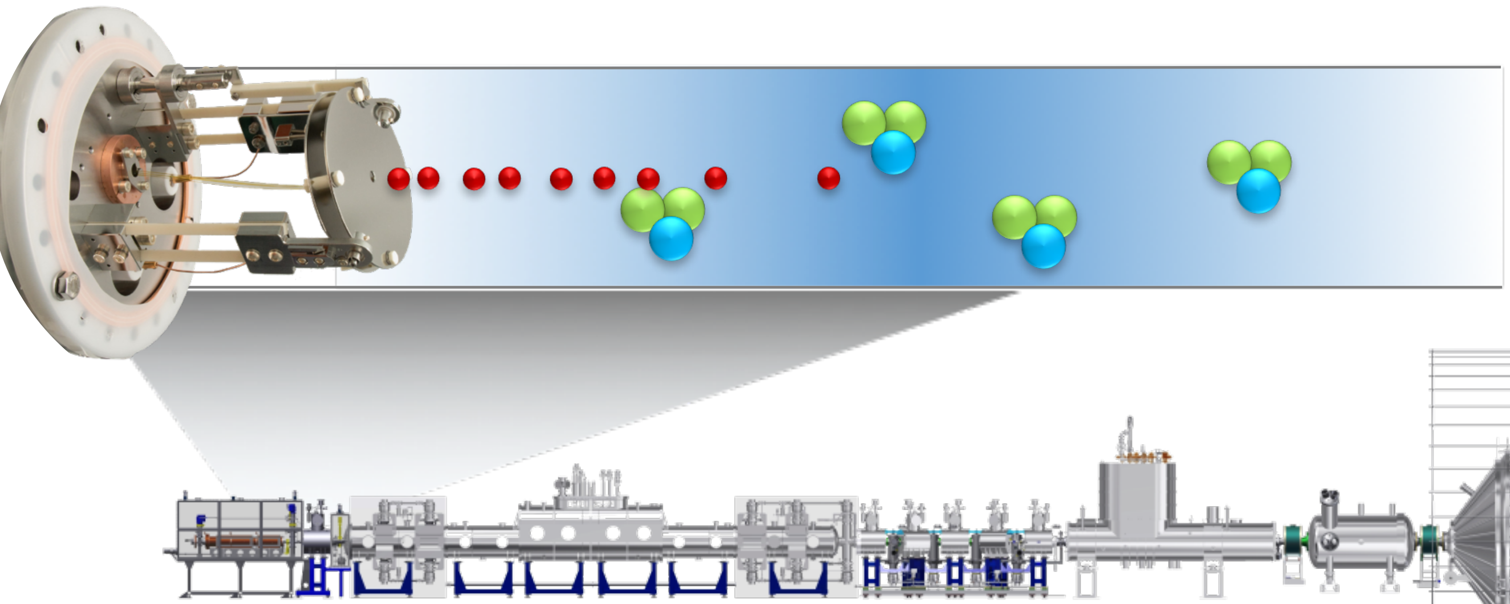


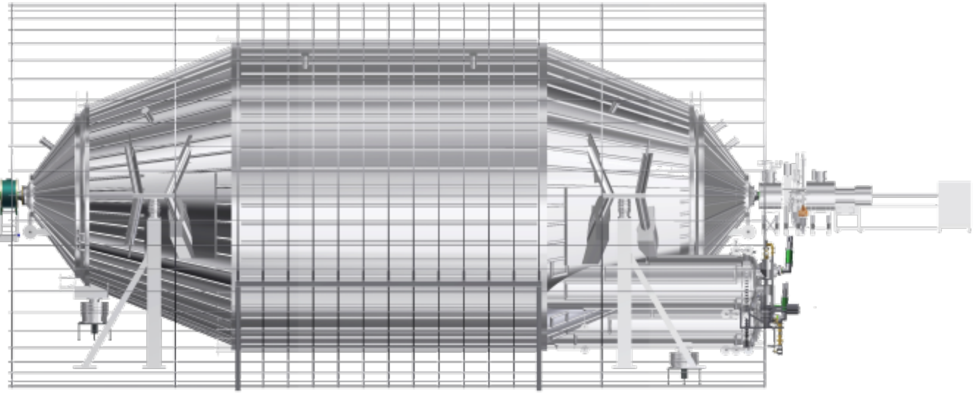


Source density

- **High-intensity electron gun**
- Gas density $1.1 \times 10^{21}\ m^{-2}$ (precision of < 1 %)



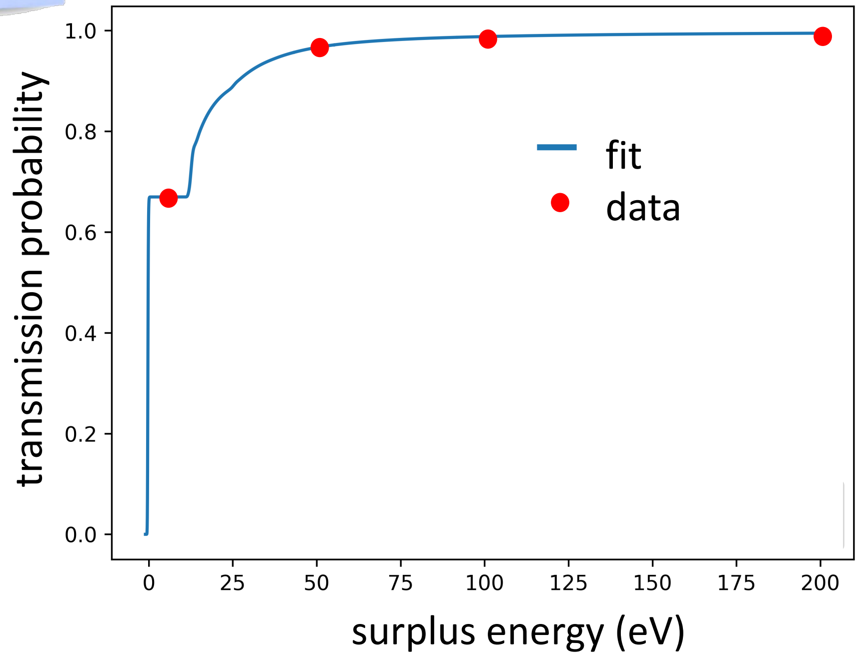


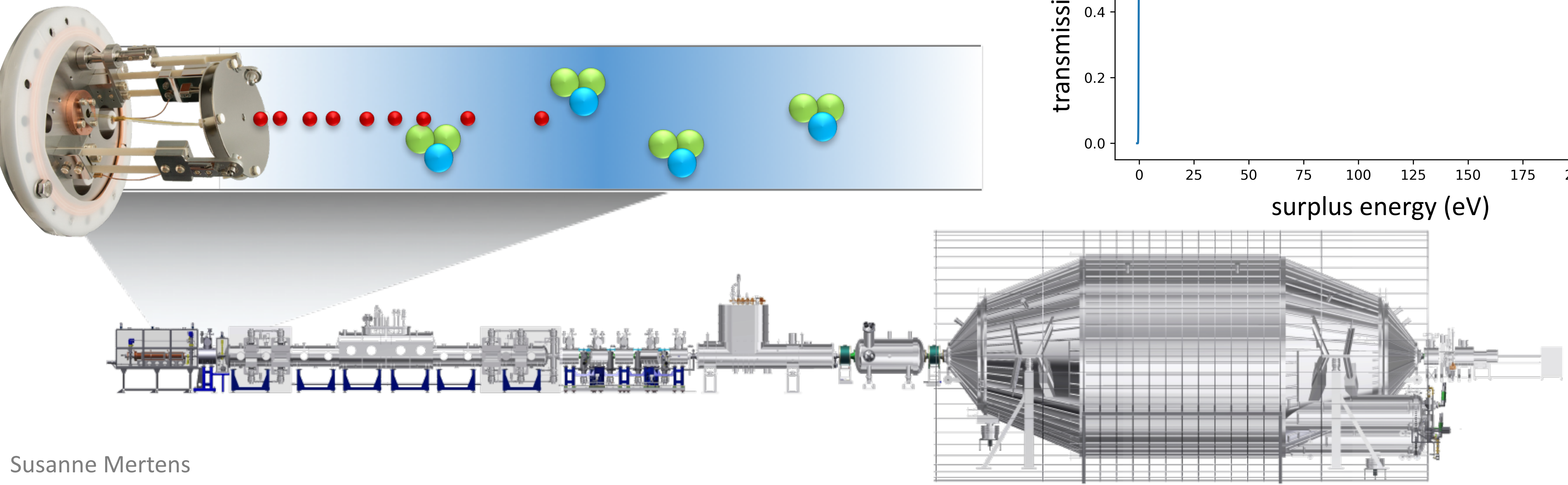


Source density

- **High-intensity electron gun**
- Gas density $1.1 \times 10^{21}\ m^{-2}$ (precision of < 1 %)

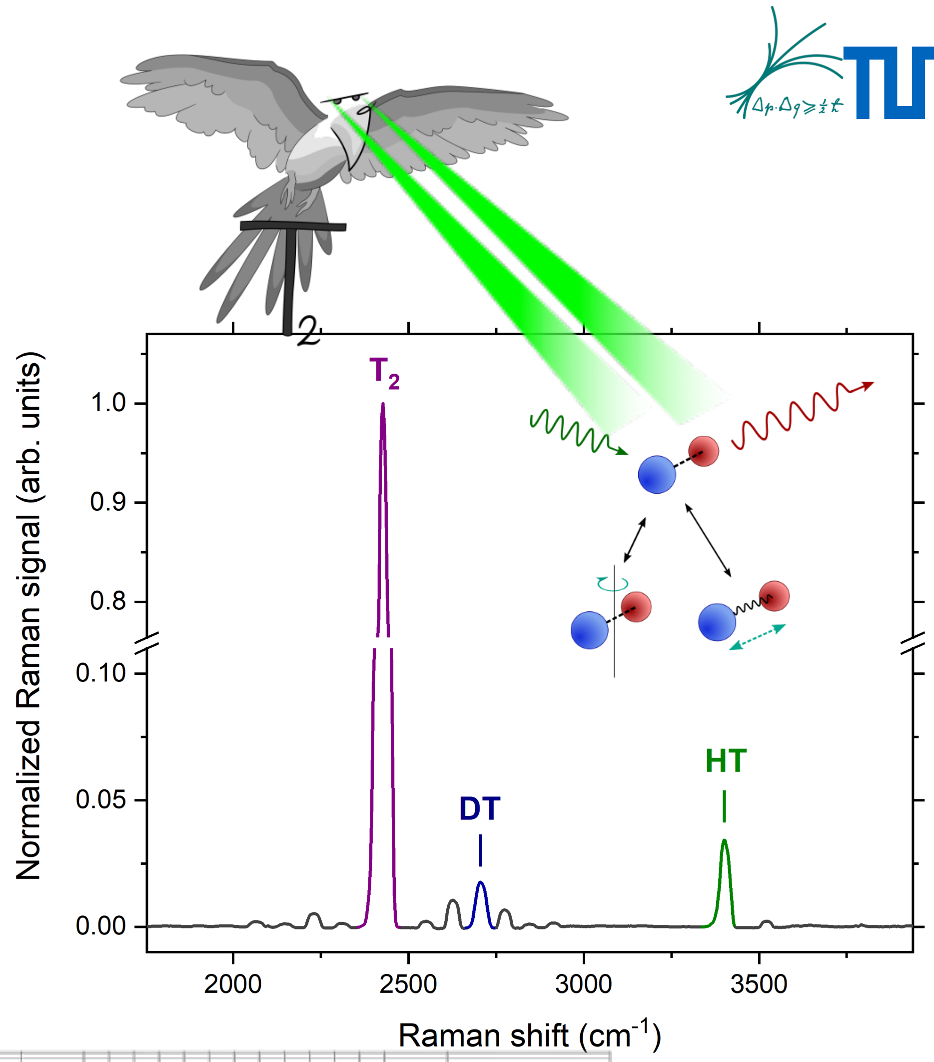
see talk by Christiph Köhler later today

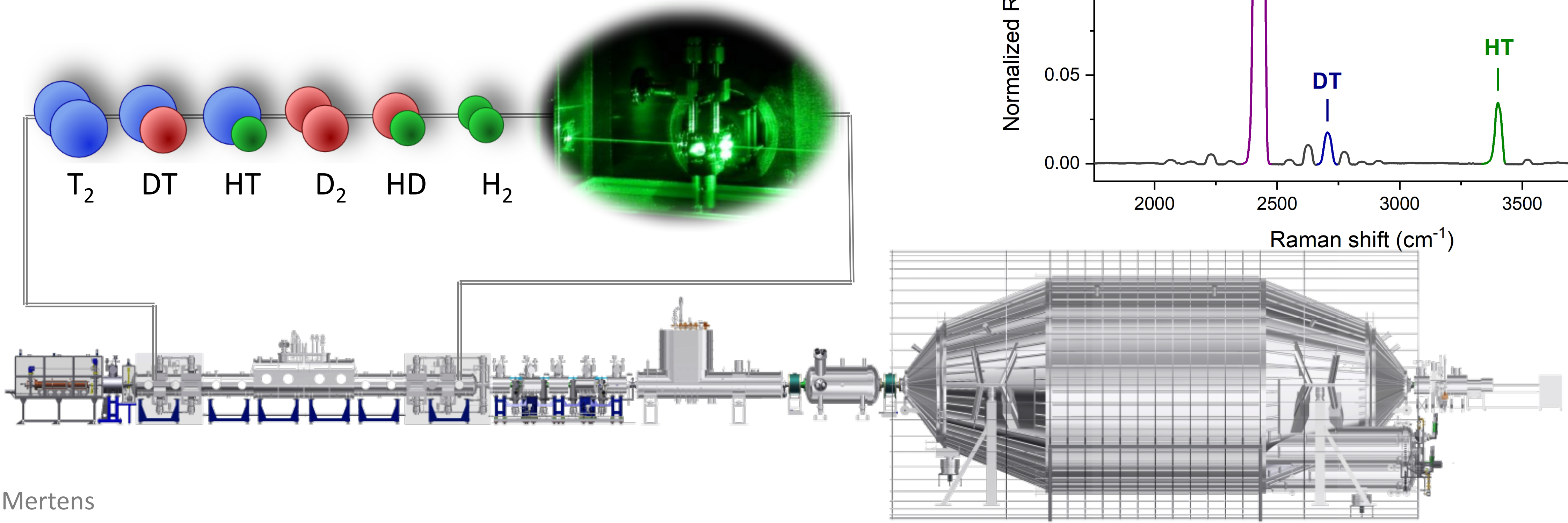




Source composition

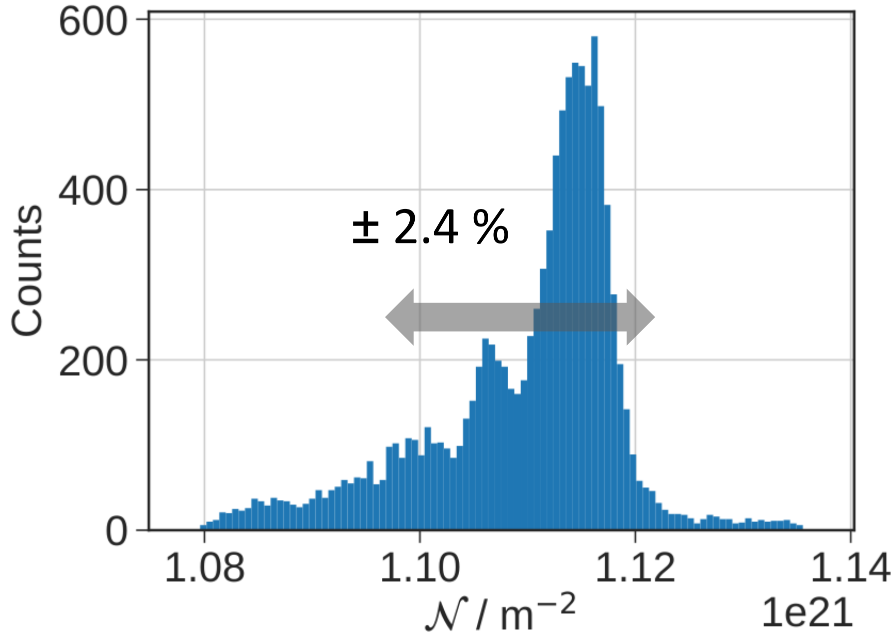
- **Laser Raman system**
- High purity and stability established (97.5 %)



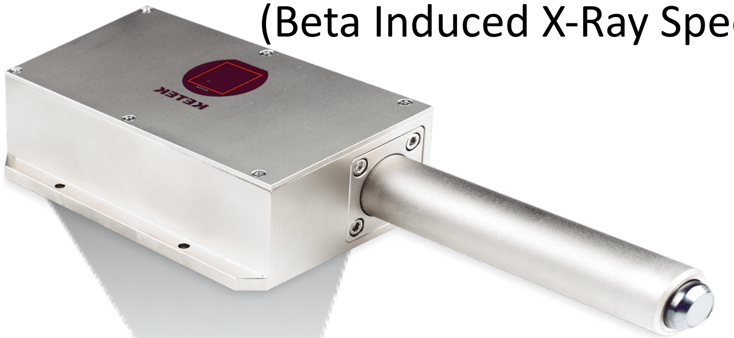


Source activity

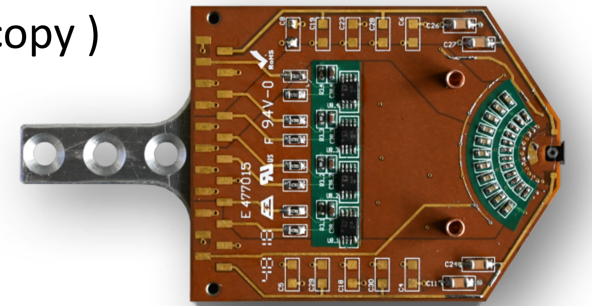
- **Forward beam monitor, BIXS System, multiple Sensors**
- Stability at the 2% level achieved

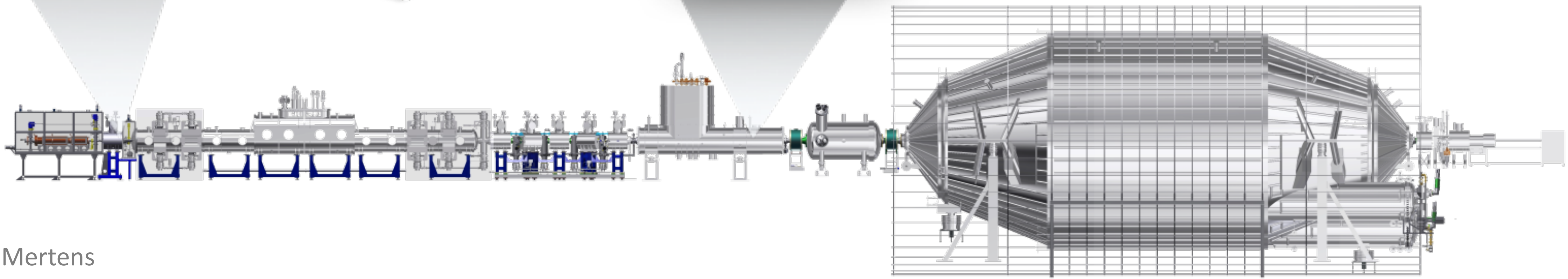


BIXS
(Beta Induced X-Ray Spectroscopy)



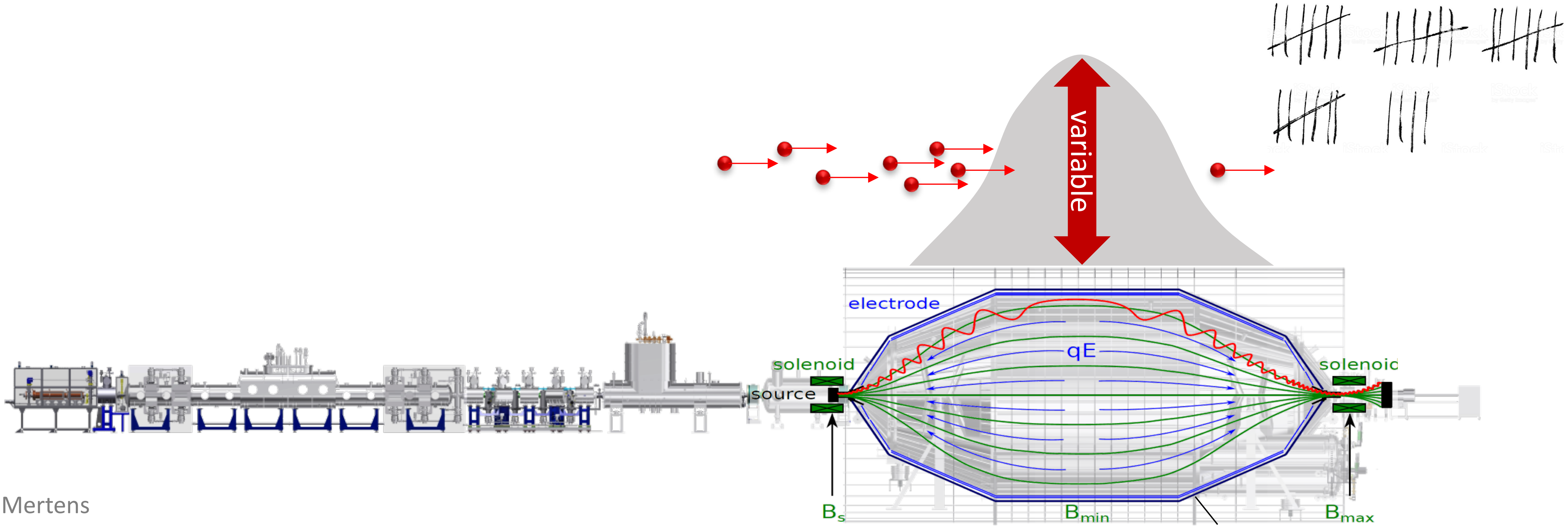
FBM





Scanning Strategy

- Idea: count electron as a function of retarding potential
- **… but at which retarding potentials and how long at each potential?**



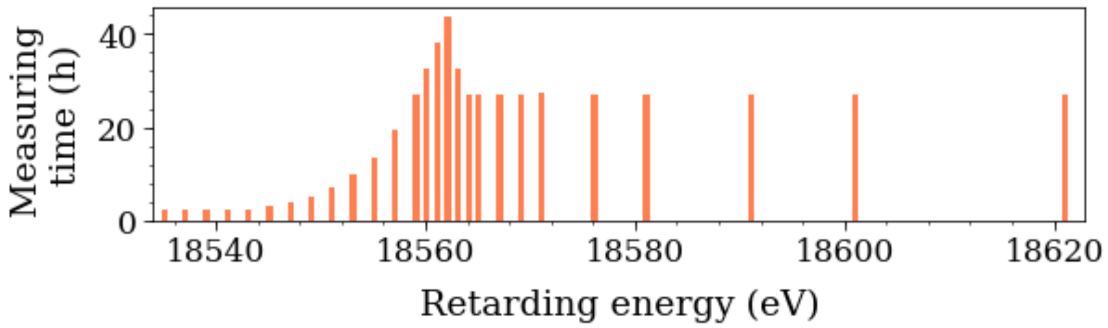
Susanne Mertens

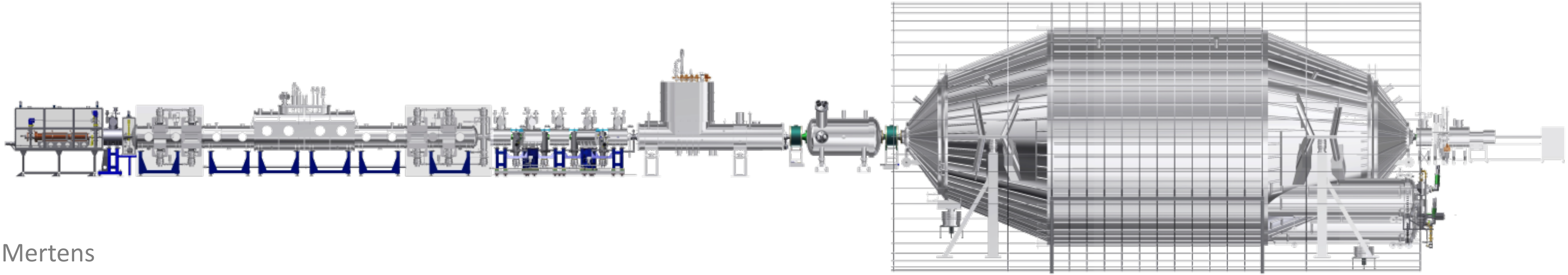
Scanning Strategy

Optimized to maximize ν-mass sensitivity

- interval: E_0 – 40 eV , E_0 + 50 eV
- # HV set points: 27
- scanning time: 2 hours
- Number of scans: 274
- Sequence of scans: alternating up/down

Measurement time distribution



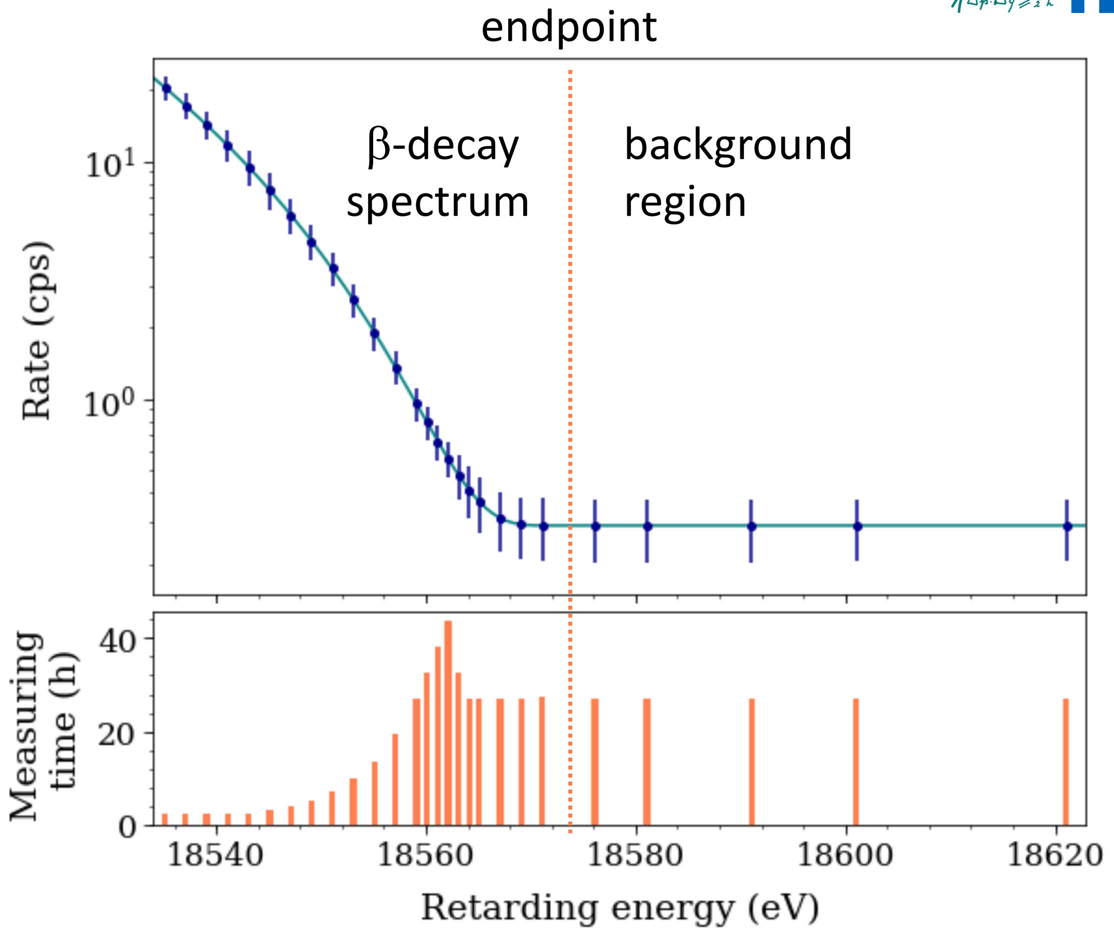


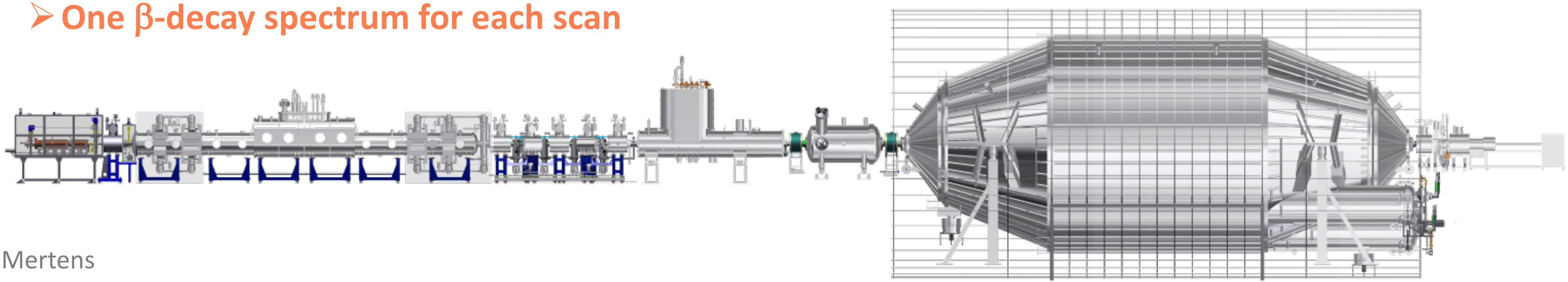
Scanning Strategy

Optimized to maximize ν-mass sensitivity

- interval: **E_0 – 40 eV , E_0 + 50 eV**
- # HV set points: **27**
- scanning time: **2 hours**
- Number of scans: **274**
- Sequence of scans: **alternating up/down**

➢ **One β-decay spectrum for each scan**

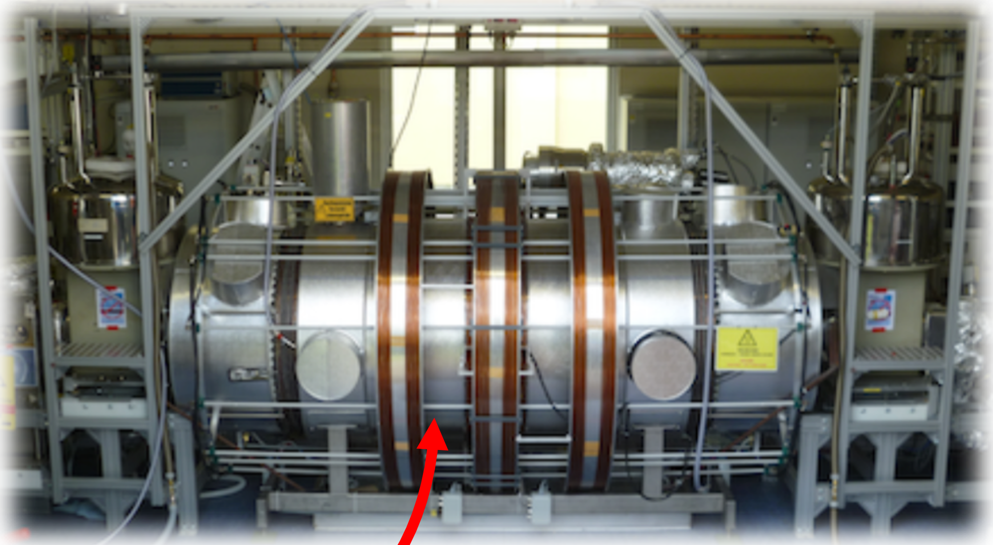




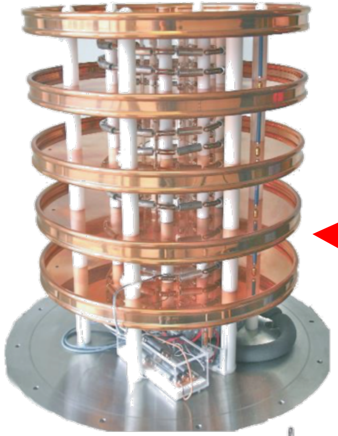
High voltage stability

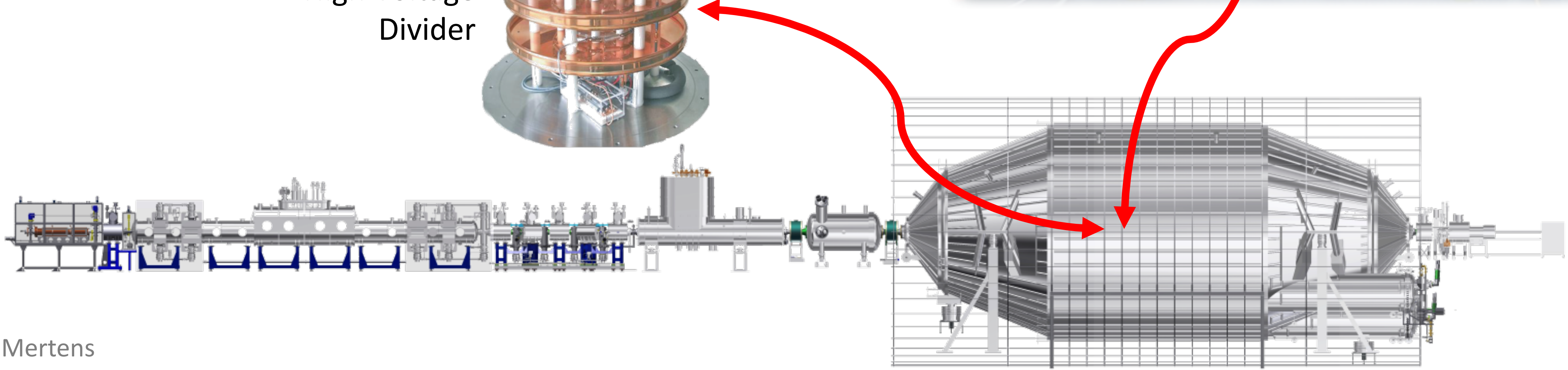
- Short term (seconds) HV stability: < 20 mV
- Long-term (days) HV stability: < 20 mV/day

Monitor Spectrometer



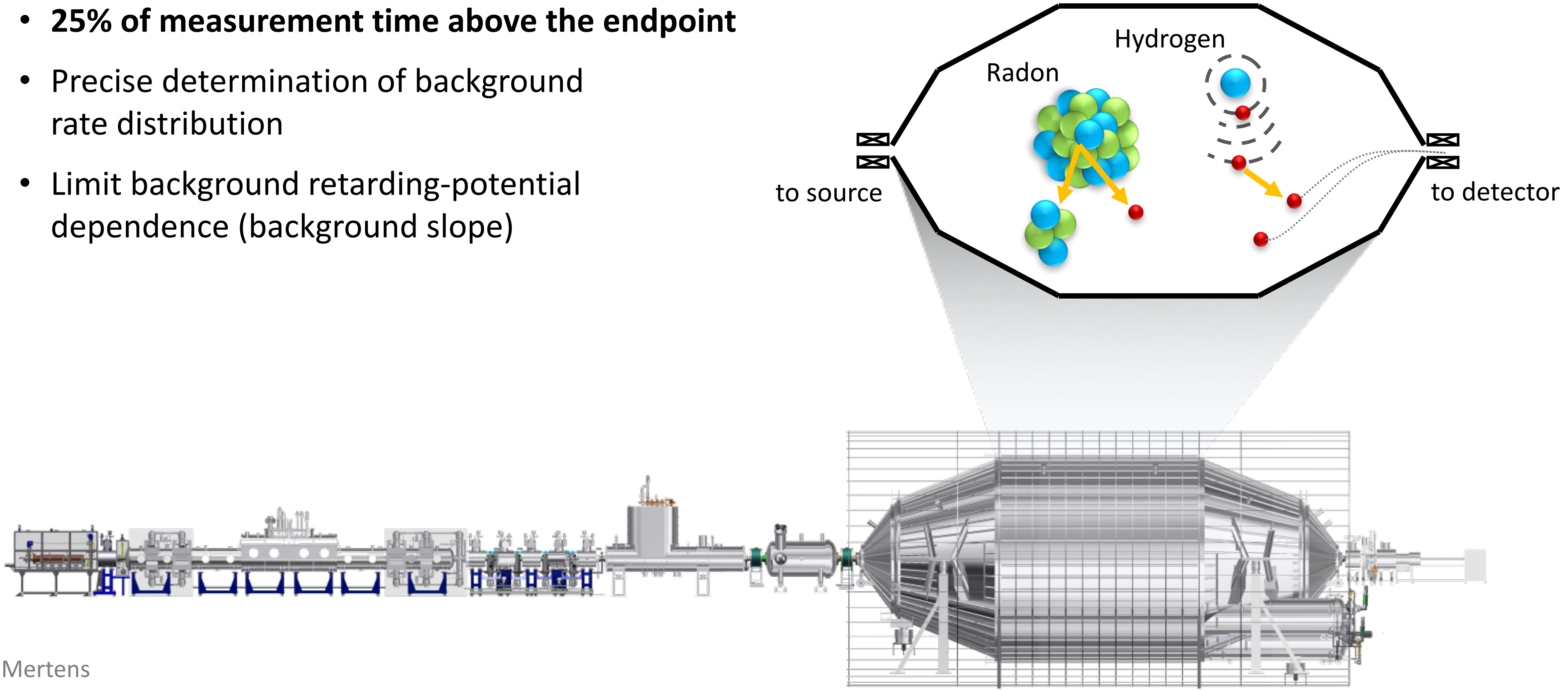
High Voltage Divider



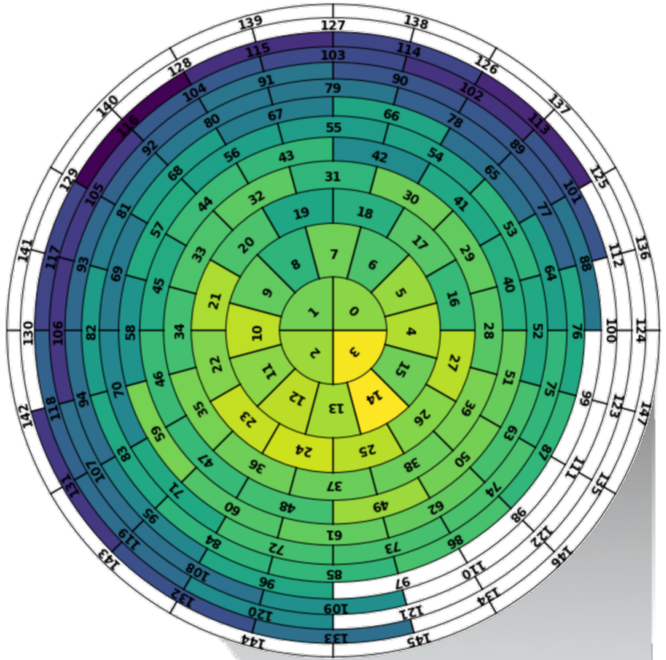


Background characterization

- **25% of measurement time above the endpoint**
- Precise determination of background rate distribution
- Limit background retarding-potential dependence (background slope)

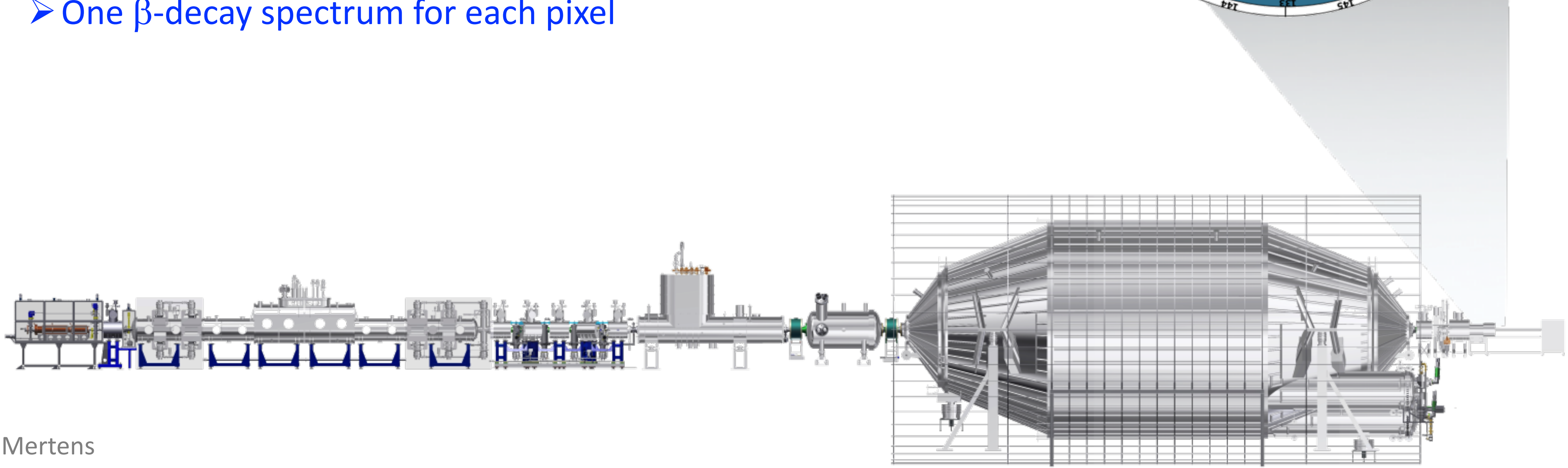


Focal plane detector



- 117/148 (79%) of all pixels used
- high detection efficiency (> 90%)
- negligible retarding-potential dependence of efficiency

➢ One β-decay spectrum for each pixel



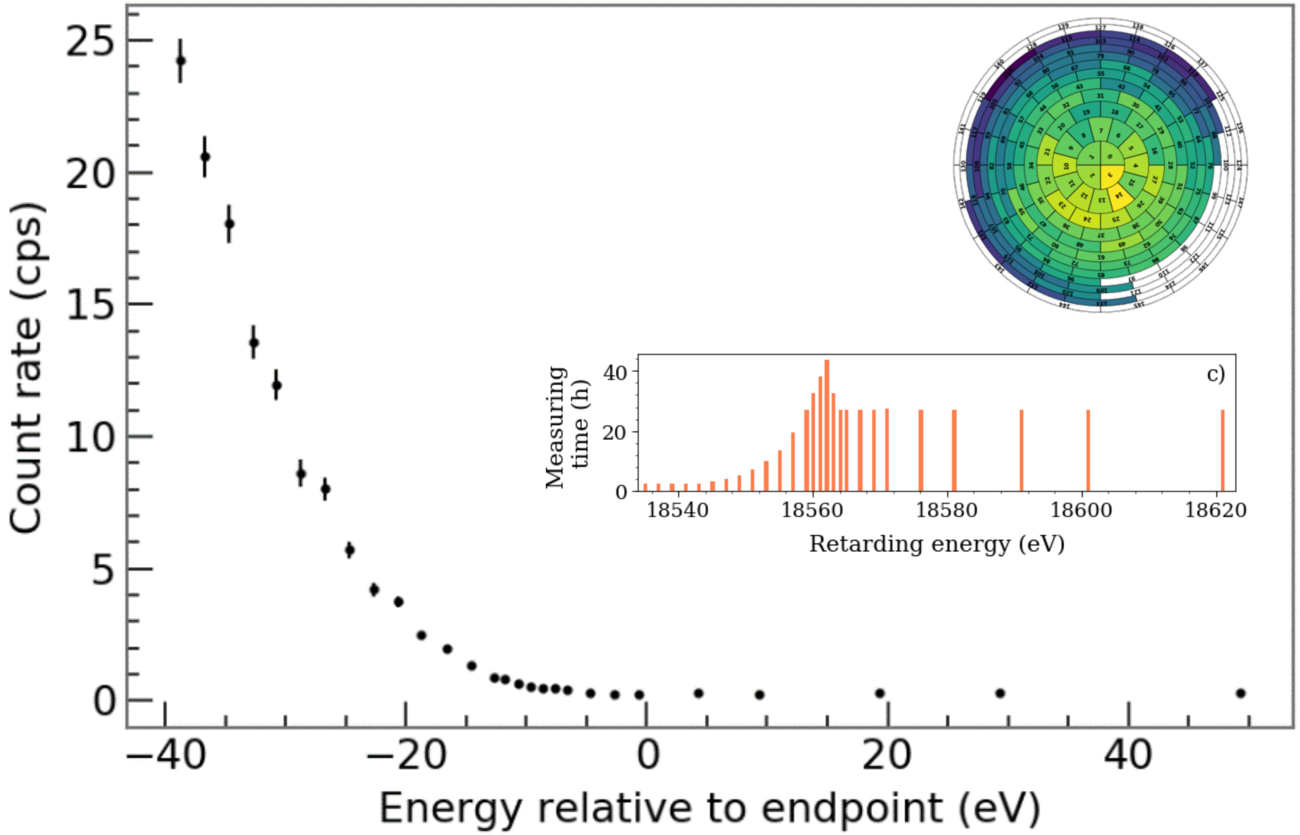
… and finally: the tritium spectrum

32058 β-decay spectra

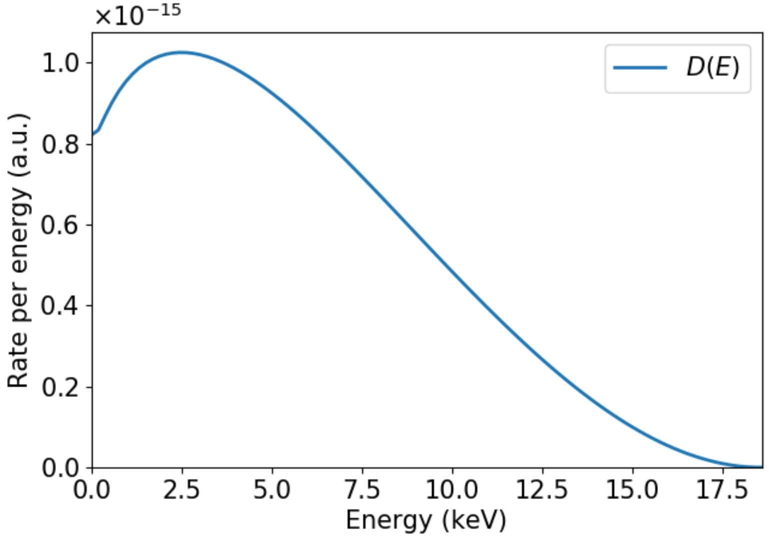
- for each detector pixel
- for each scan

Task of “fitting” teams

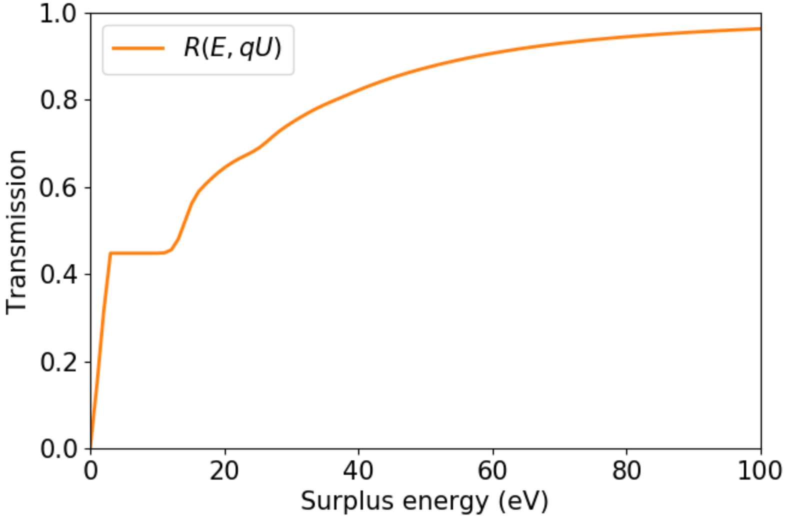
- combine spectra in a smart way
- infer physics parameters

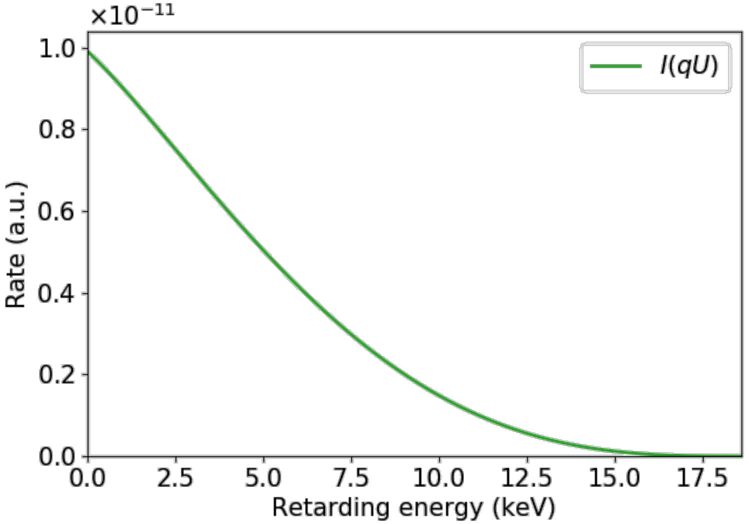


Tritium spectrum calculation



$$I(qU) = \int_{qU}^{E_0} D(E)R(E, qU)dE$$

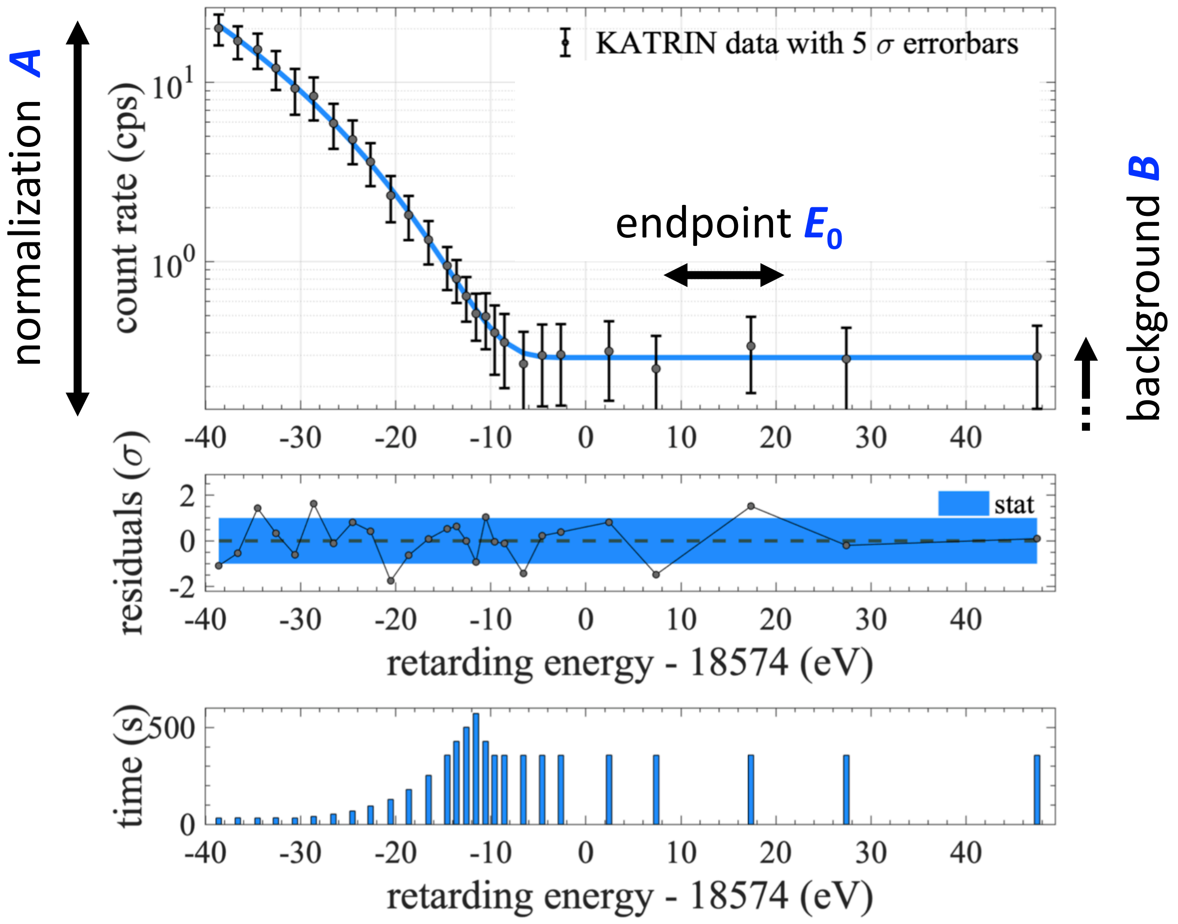




- Fermi theory
- Decay to molecular final states
- Doppler broadening

- Scattering in the source
- MAC-E filter transmission
- Synchrotron radiation

Fit of a single 2-h beta-scan

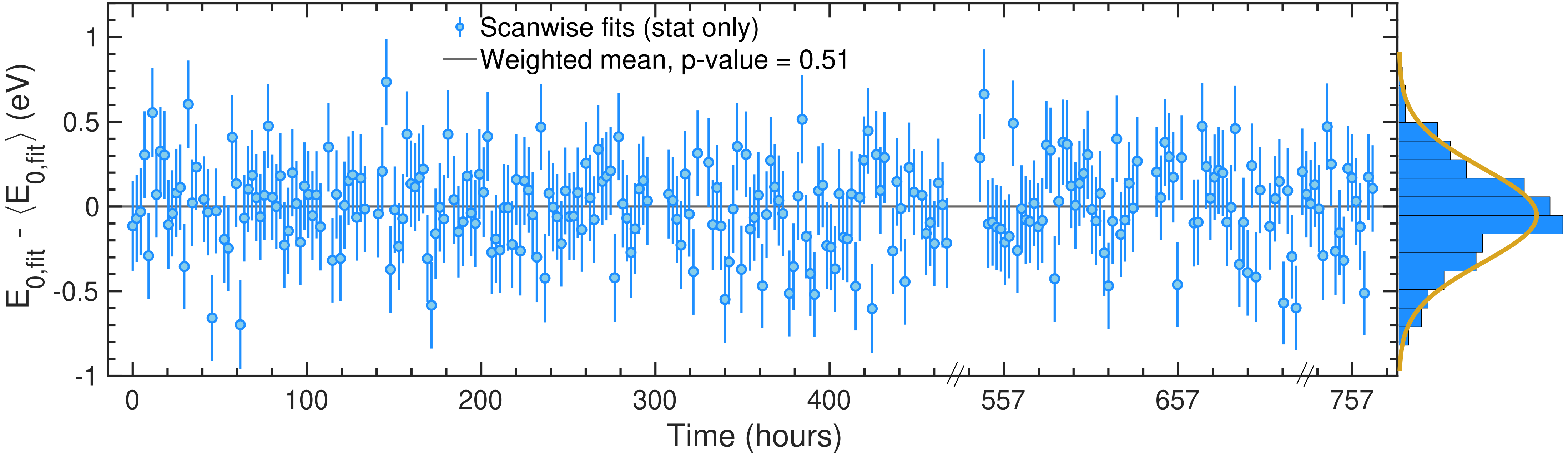


$$\Gamma(qU) \propto A \cdot \int_{qU}^{E_0} D(E; m_\nu^2, E_0) \cdot R(qU, E)\, dE + B$$

- 3 parameter fit – stat. only
- neutrino mass fixed to zero
- Check for stability of fits before combining data

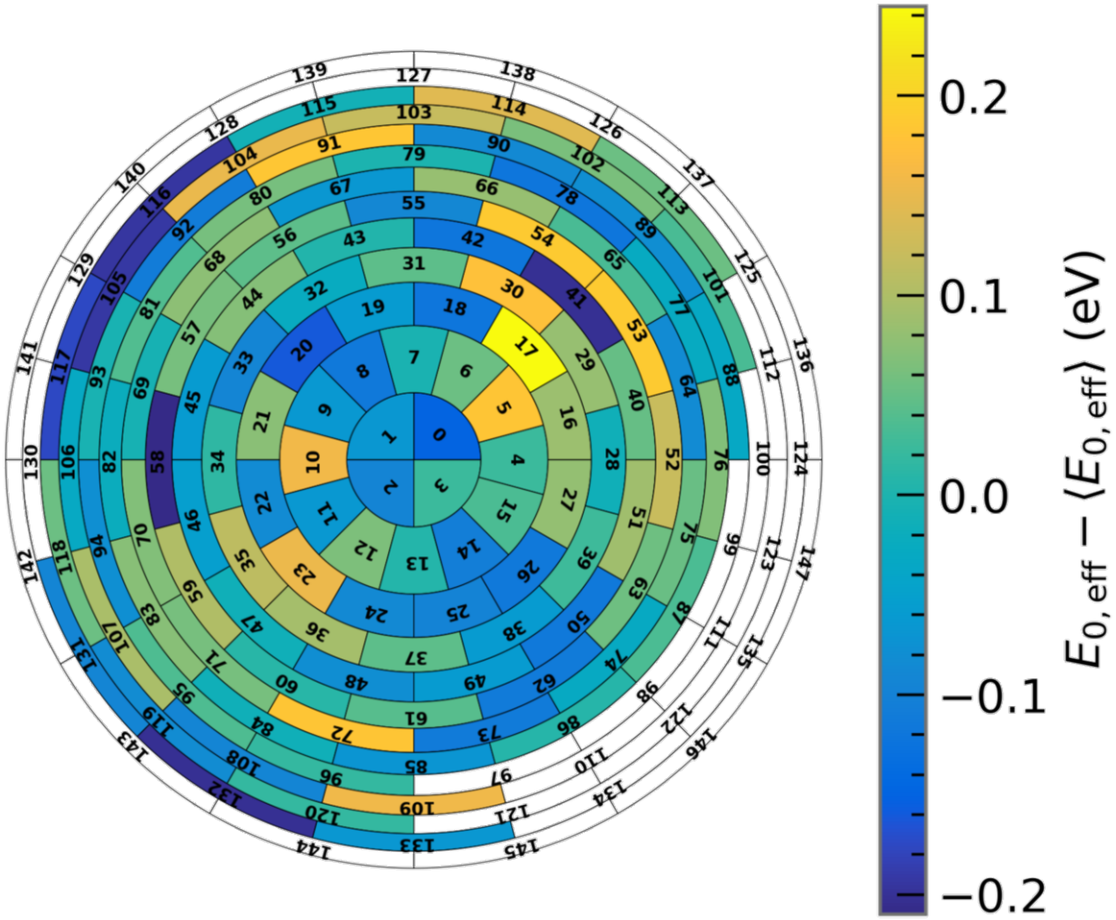
Stability over 274 scans

- All detector pixels combined
- Stability of fitted endpoint in time



Stability over 117 pixels

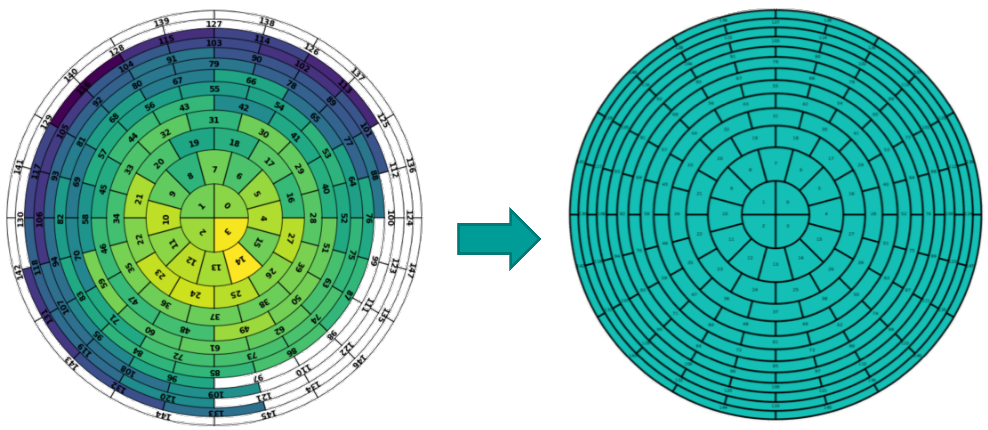
- All scans combined
- Spatial homogeneity over detector wafer



Data combination

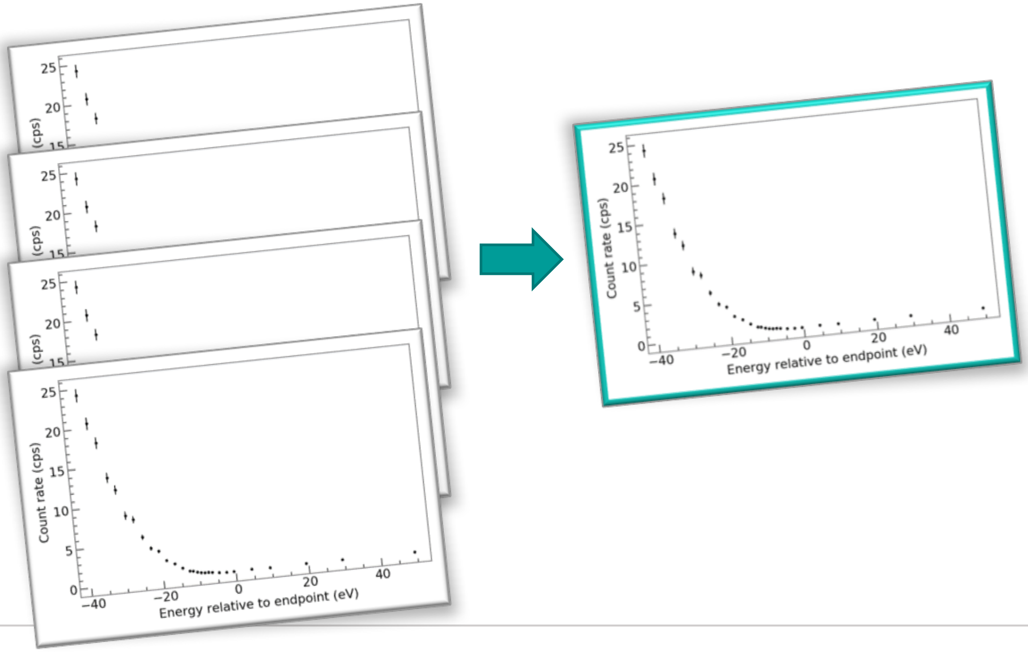
Pixel combination

- sum the counts of all pixels
- use average response function



Scan combination

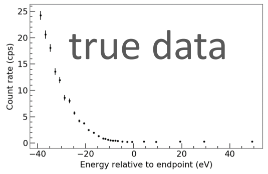
- sum the counts of all sub-scans
- use average HV ($\sigma_{HV} < 34\ \mathrm{mV}$) + slow control

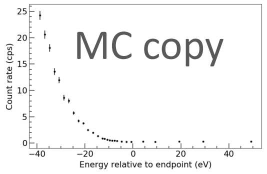


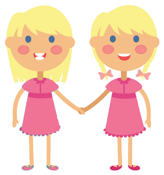
3-fold bias free analysis

Freeze analysis on fake data

- Generate MC-copy of each scan
- Use slow control data as input

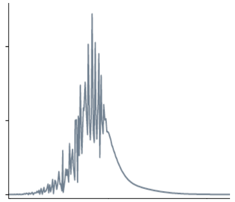


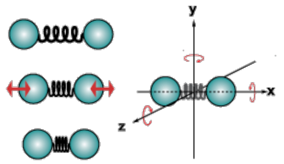




Blinded model

- Modified molecular final state dist.
- Affects only neutrino mass

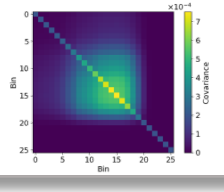


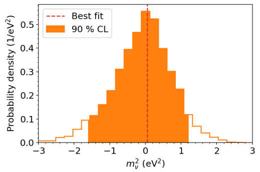


m_ν^2

Two independent analysis strategies

- Covariance matrix
- Monte Carlo propagation

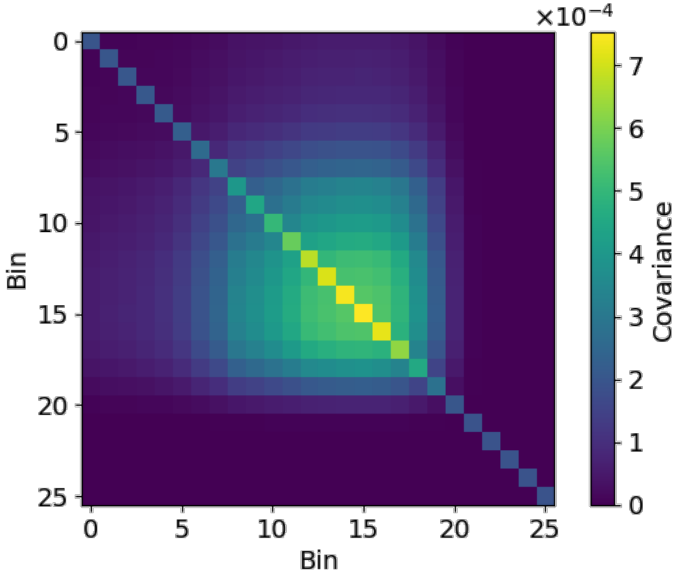




Two independent analysis approaches

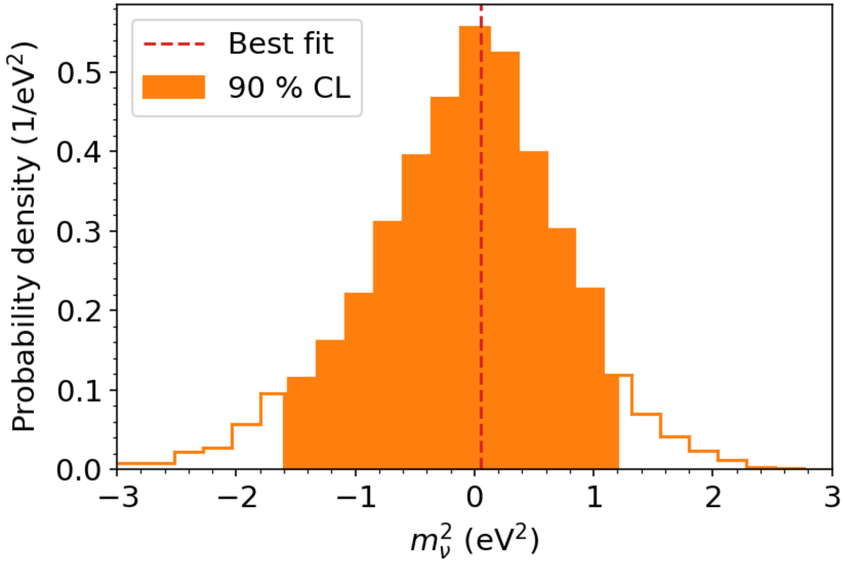
Covariance matrix

- $\chi^2 = (\vec{m} - \vec{d})^T V_{tot}^{-1} (\vec{m} - \vec{d})$
- Systematic: Spectrum computed 10^5 times

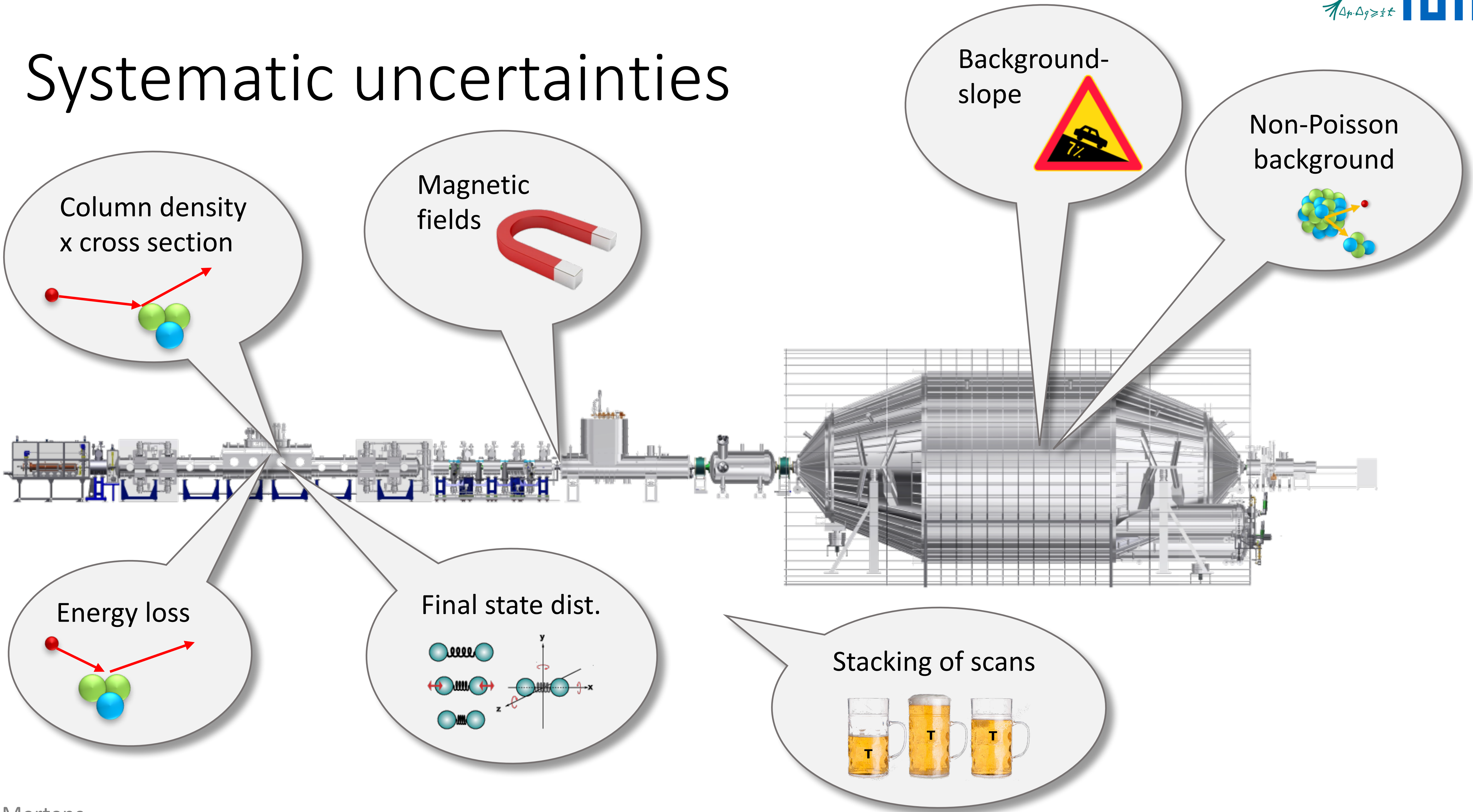


MC propagation

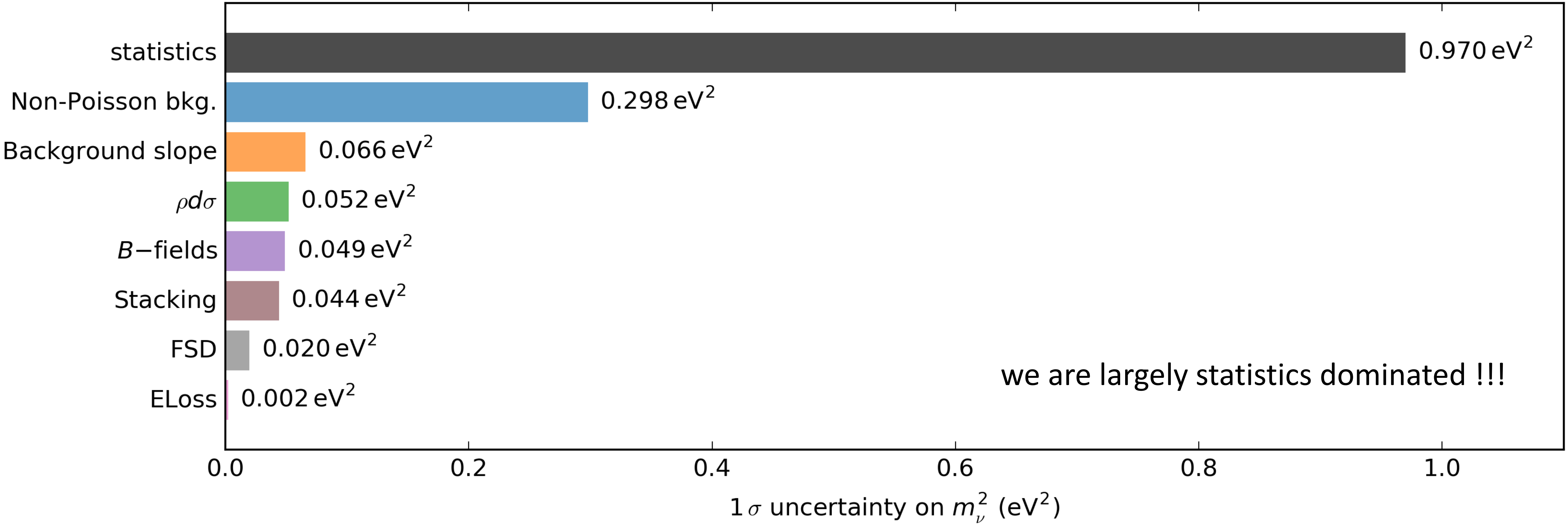
- $-2 \log \mathcal{L} = 2 \sum_i [m_i - d_i + d_i \log(d_i/m_i)]$
- Systematics: Fit performed 10^5 times



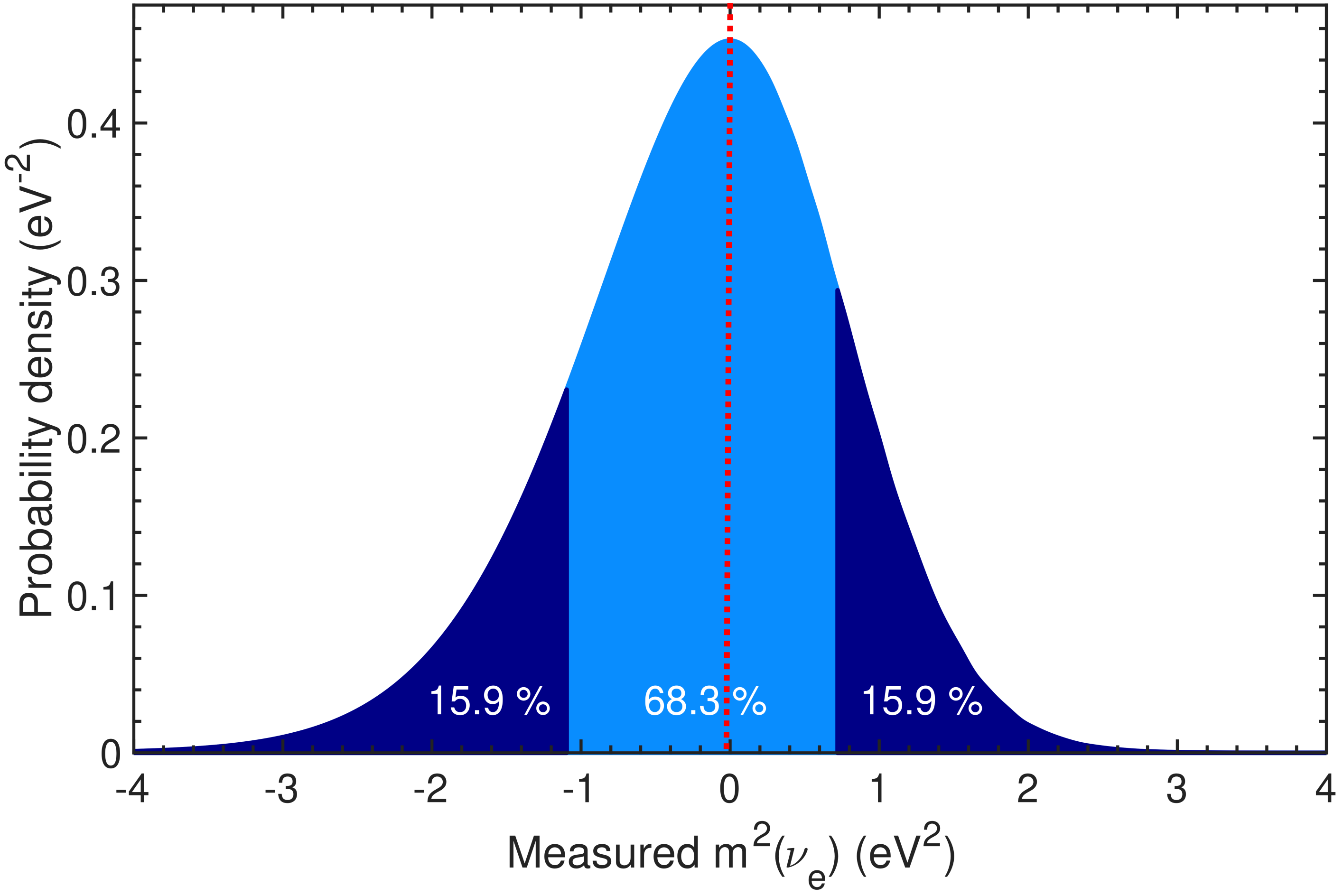
Systematic uncertainties



Budget of uncertainties

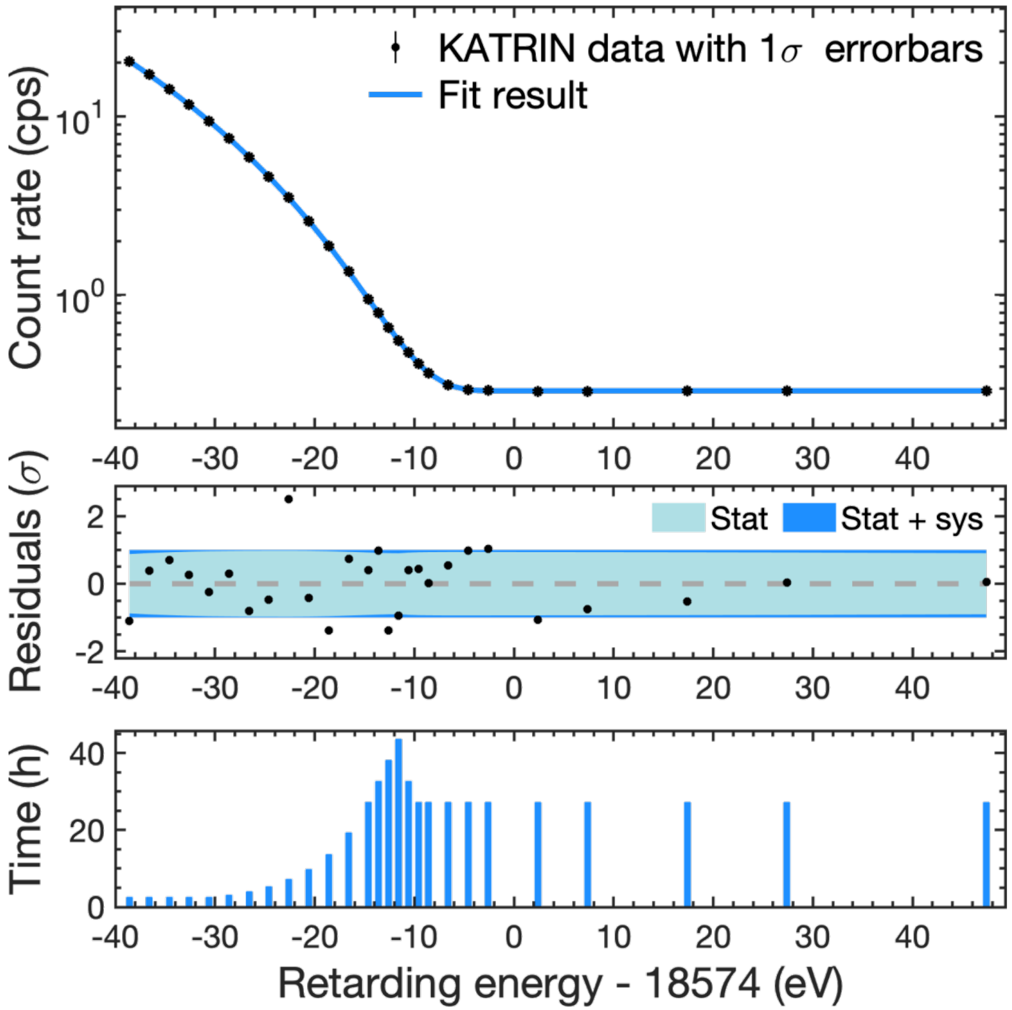


What do we expect to measure?



- If the neutrino mass was zero…
- 68% probability:
  m_ν^2 in $[-1; +1]$eV²
- 95% probability:
  m_ν^2 in $[-2; +2]$eV²

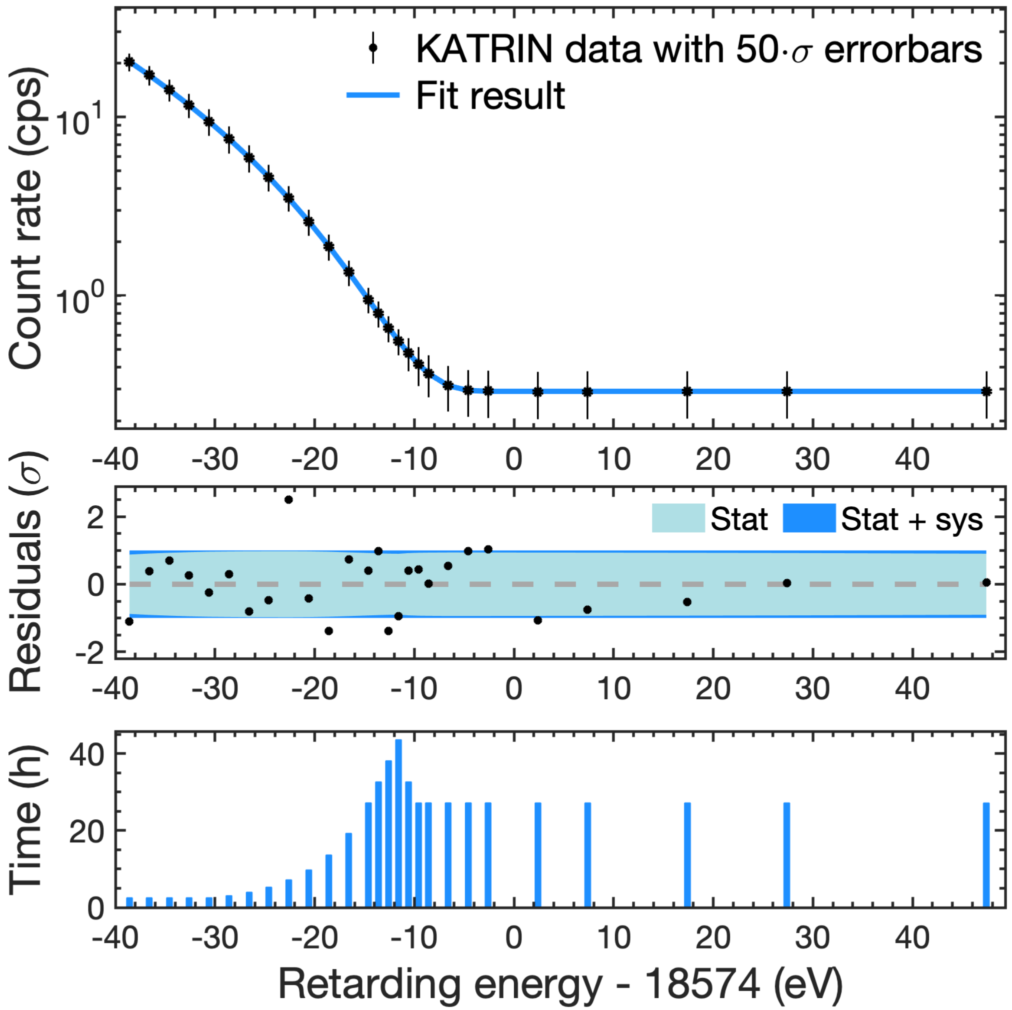
Final fit result (neutrino mass)



- 2 million events
- 4 free parameters:
  background, signal normalization, E_0, m_ν^2
- excellent goodness-of-fit:
  p-value = 0.56
- Neutrino mass best fit

$$m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)\mathrm{eV}^2$$

Final fit result (neutrino mass)

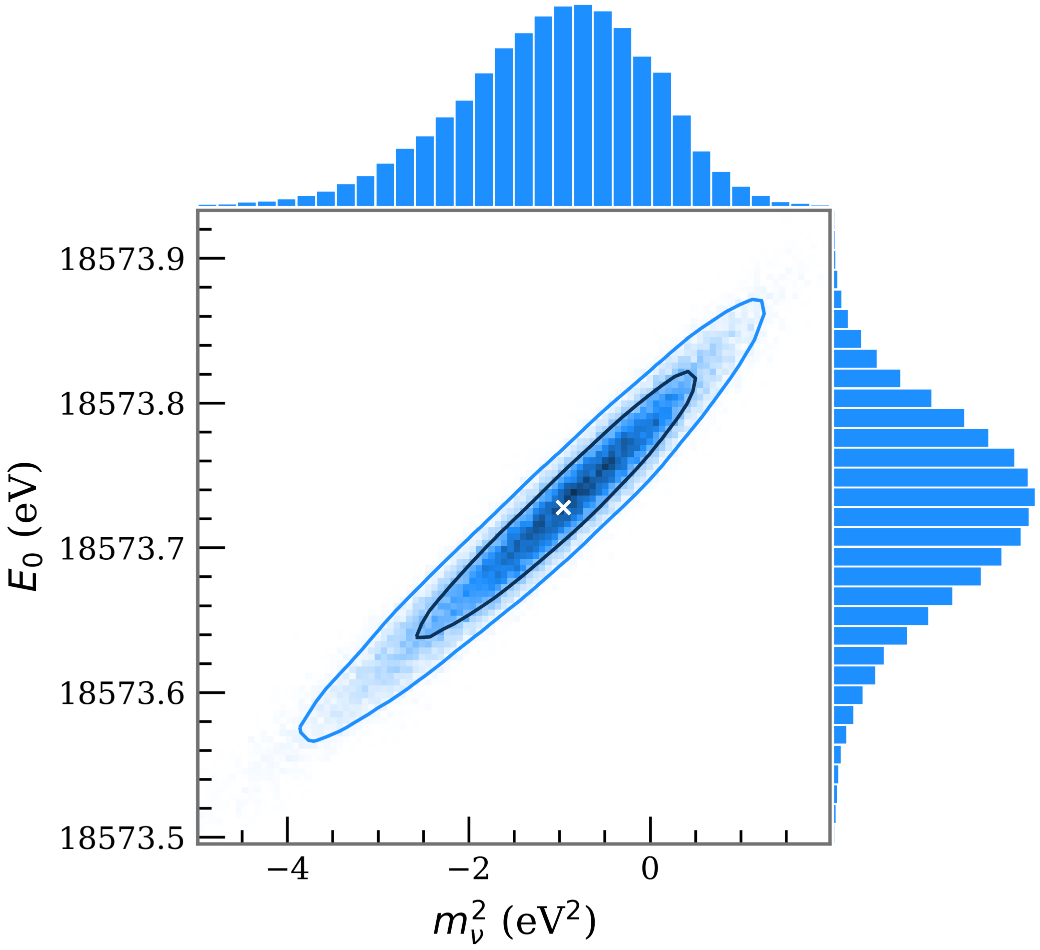


- 2 million events
- 4 free parameters: background, signal normalization, E_0, m_ν^2
- excellent goodness-of-fit: p-value = 0.56
- Neutrino mass best fit

$$m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)\text{eV}^2$$

- very clean data set !

Final fit result (endpoint)



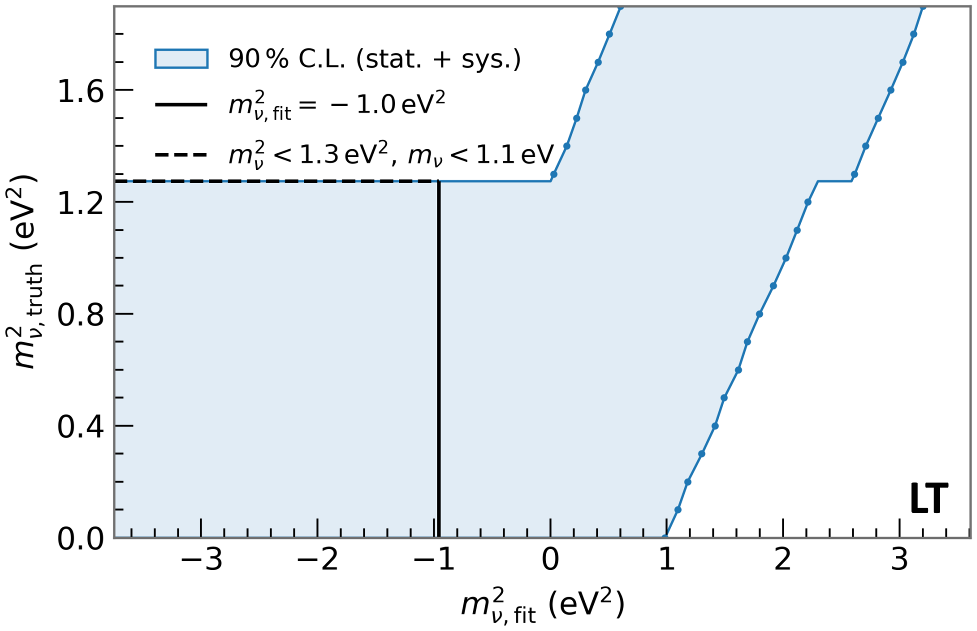
$$E_0^{fit} = E_0 + \phi_{source} - \phi_{WF,MS}$$

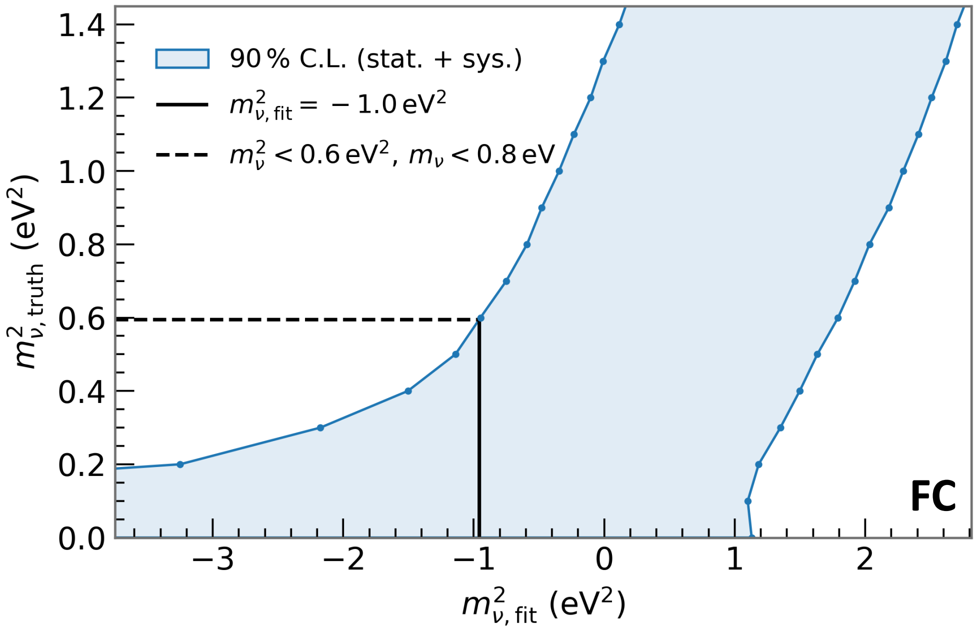
- fitted E_0 = (18573.7 ± 0.1) eV
- Q-value (KATRIN): (18575.2 ± 0.5) eV
- Q-value (literature): (18575.72 ± 0.07) eV

✓ excellent agreement

✓ confidence in overall energy scale ☺

New KATRIN limit





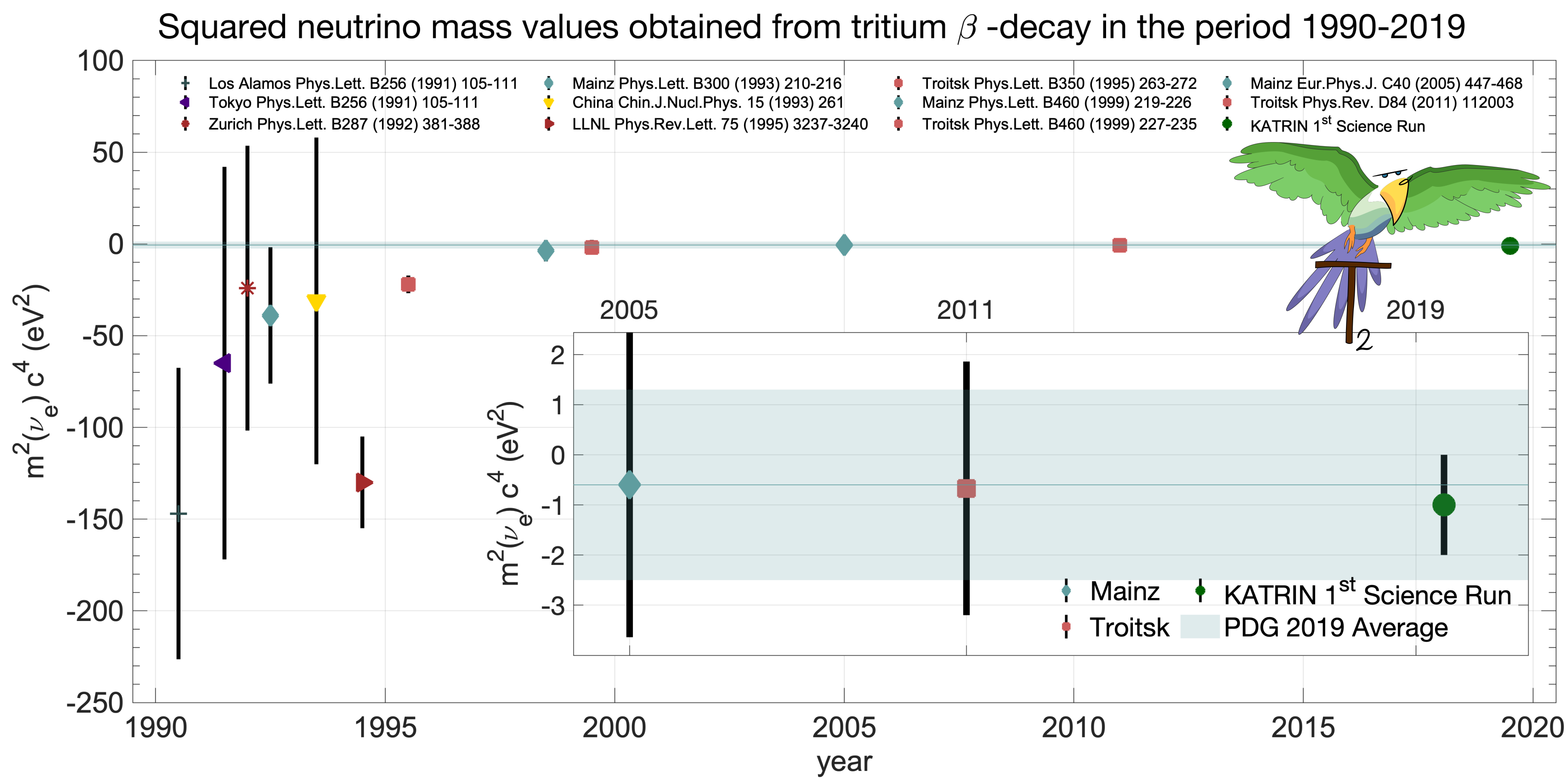
Lokhov and Tkachov (LT)

- **m_ν < 1.1 eV (90% CL) = sensitivity**
- official KATRIN limit

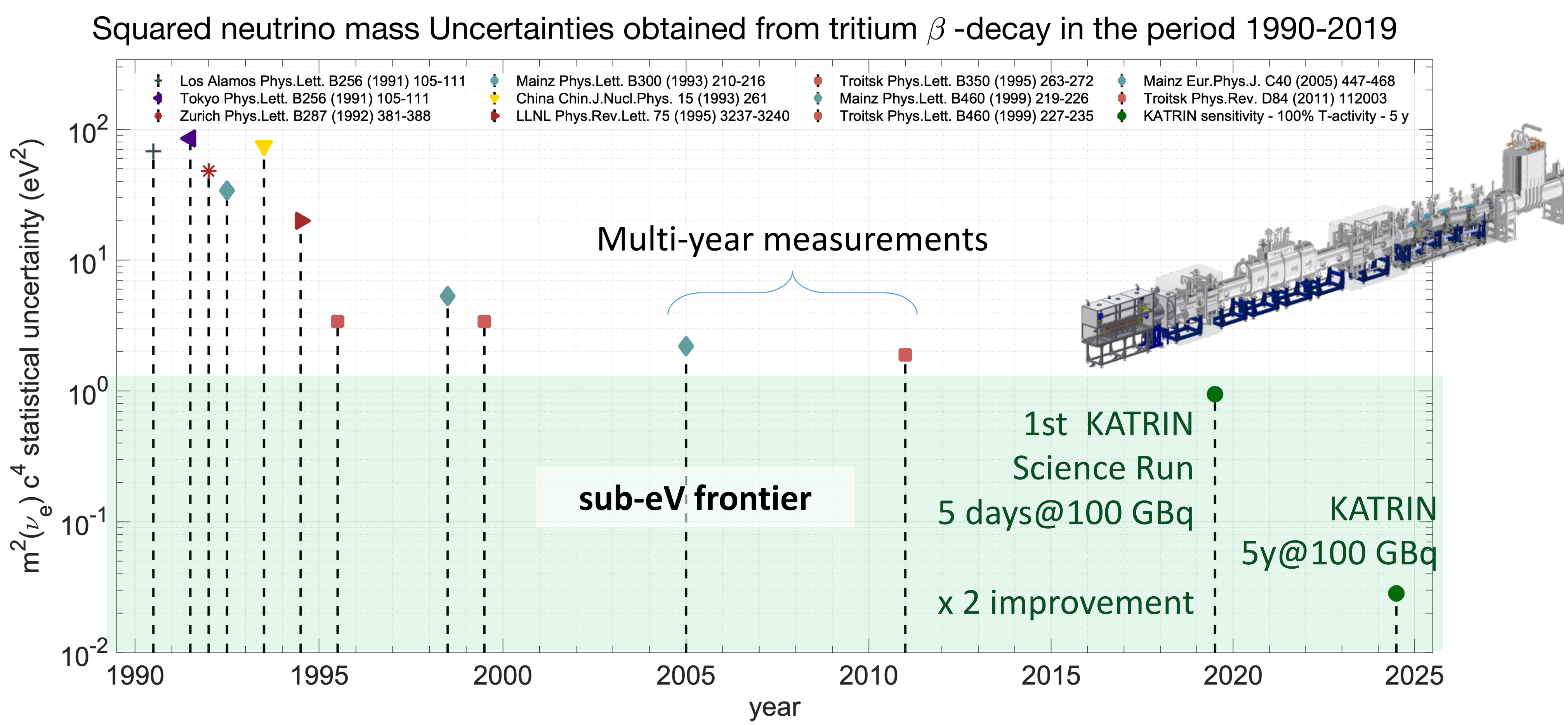
Feldman and Cousins (FC)

- m_ν < 0.8 eV (90% CL)
- m_ν < 0.9 eV (95% CL)

Historical context

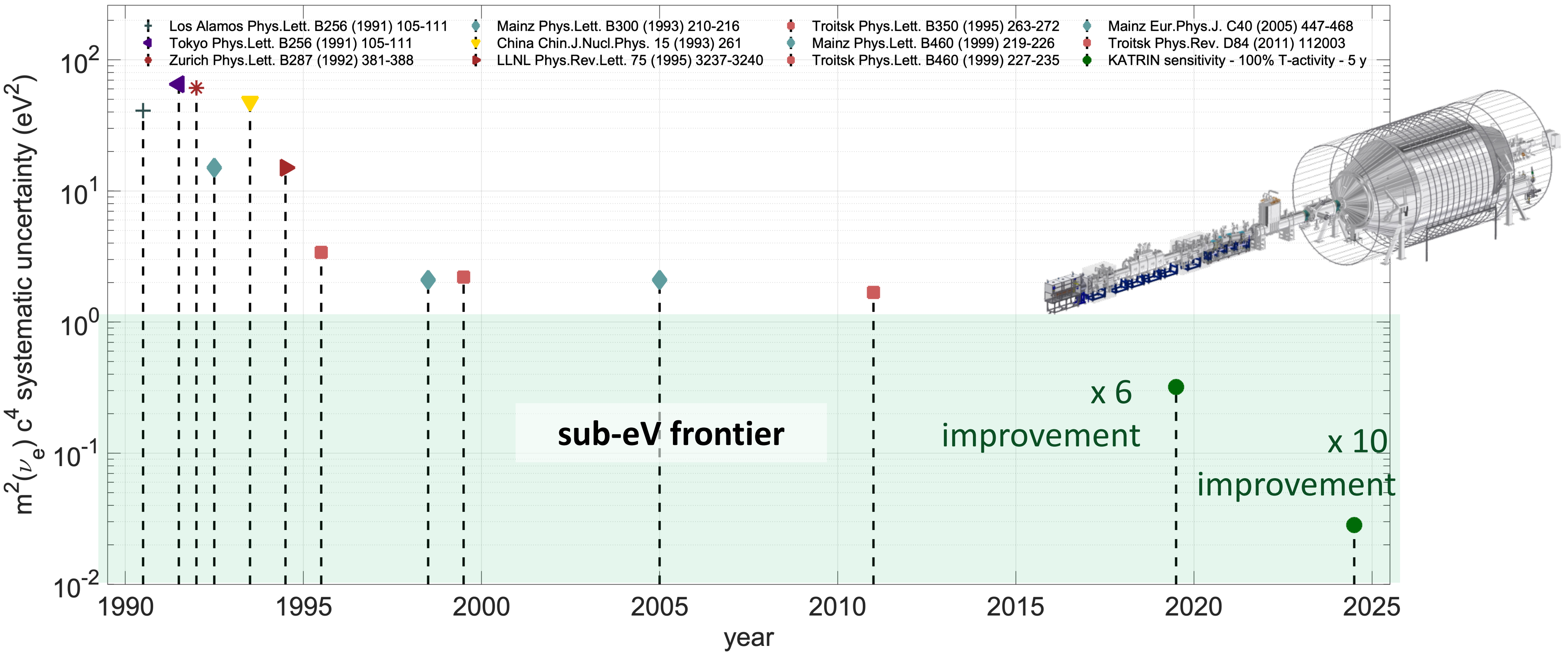


Improvements in statistics



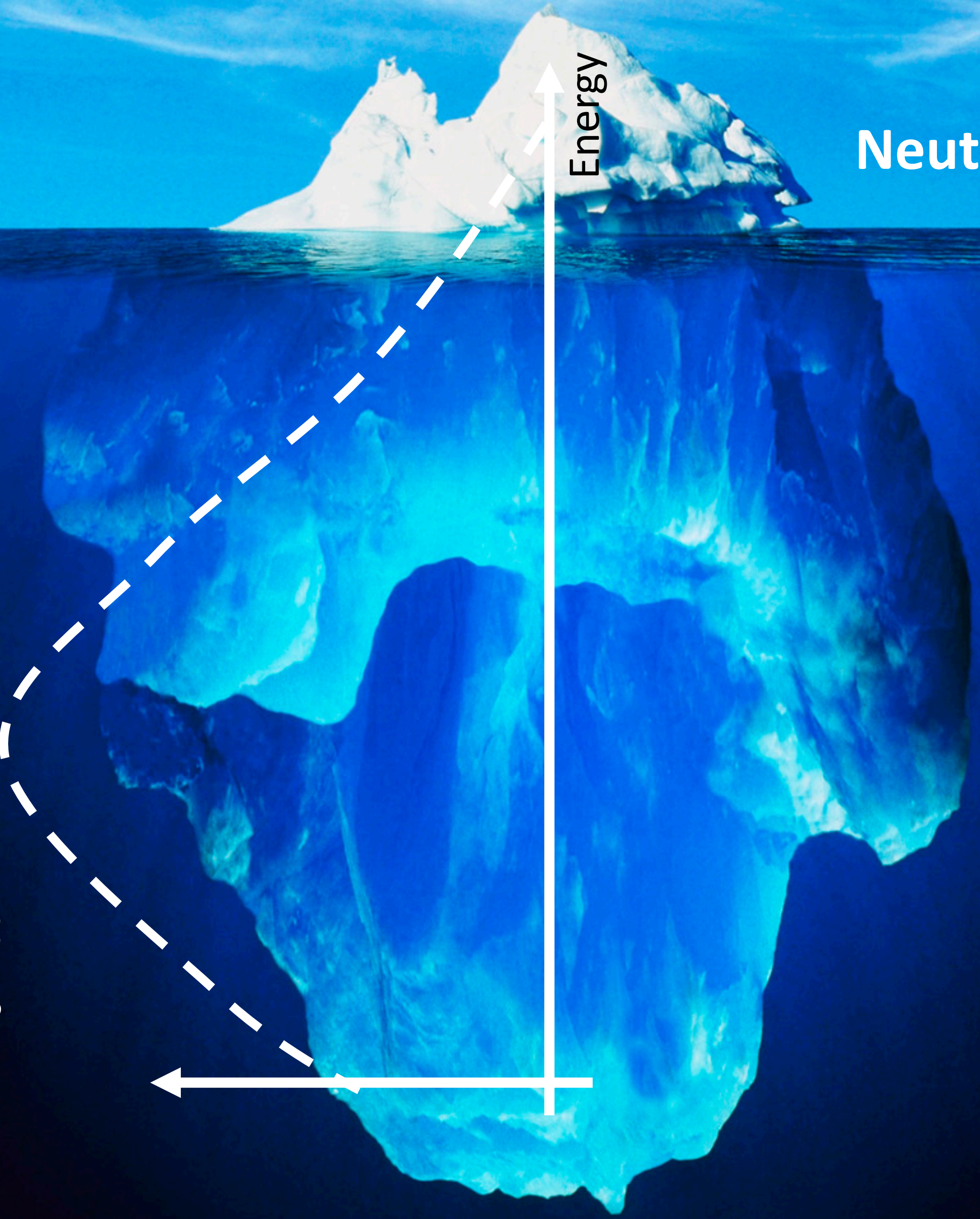
Improvements in systematics

Squared neutrino mass Uncertainties obtained from tritium β -decay in the period 1990-2019



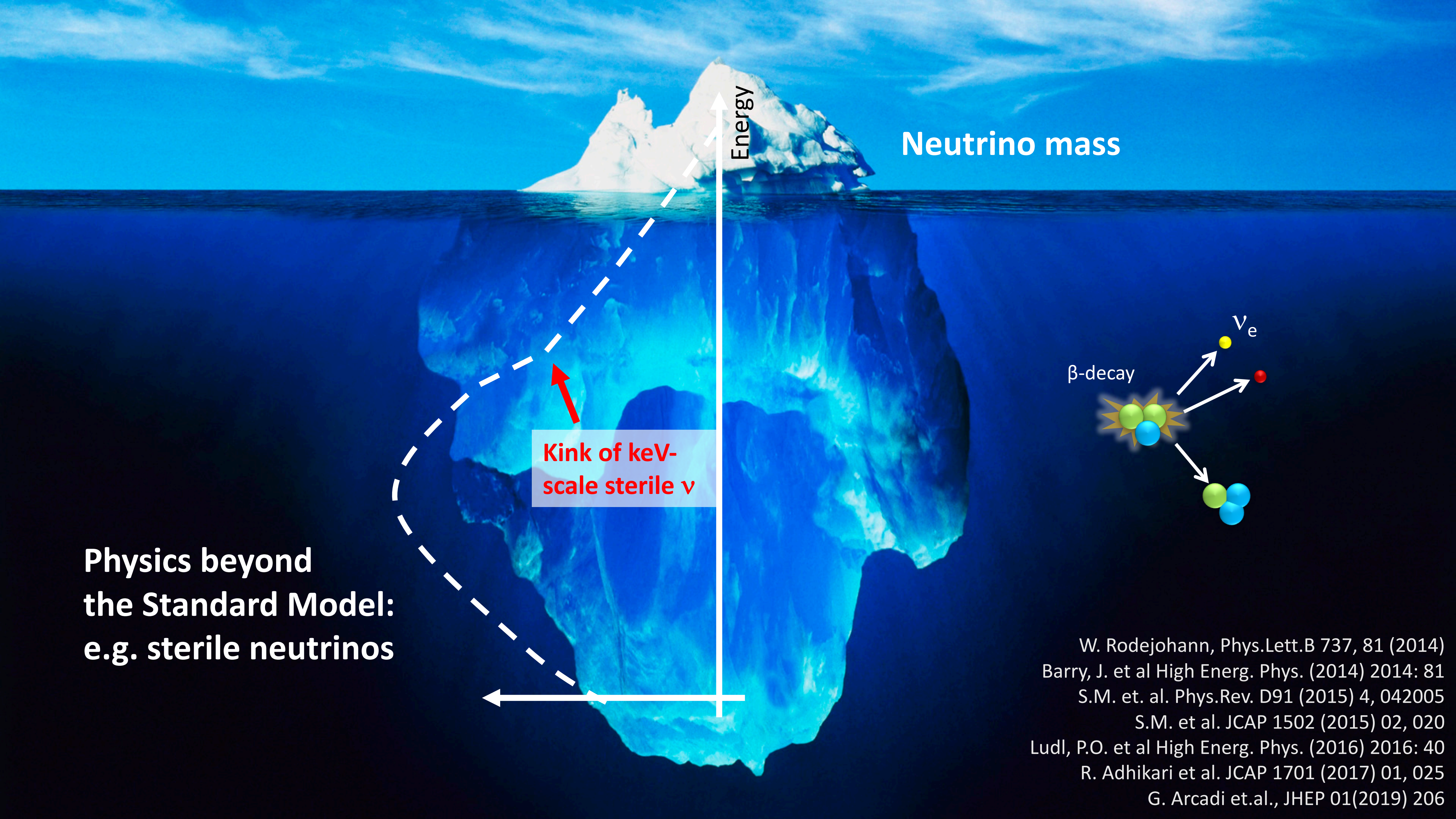
a glance into the future

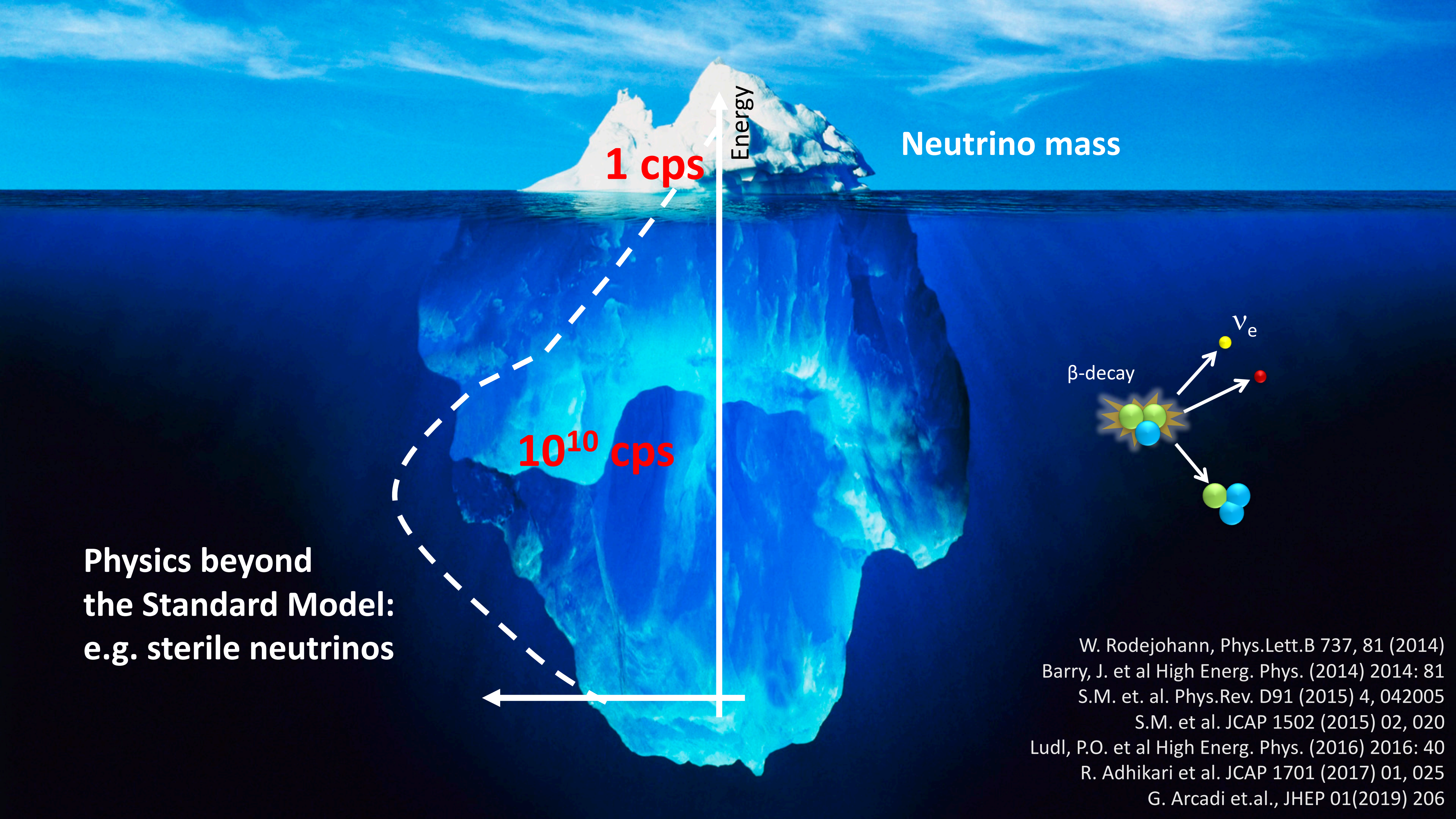
Neutrino mass



Physics beyond the Standard Model: e.g. sterile neutrinos

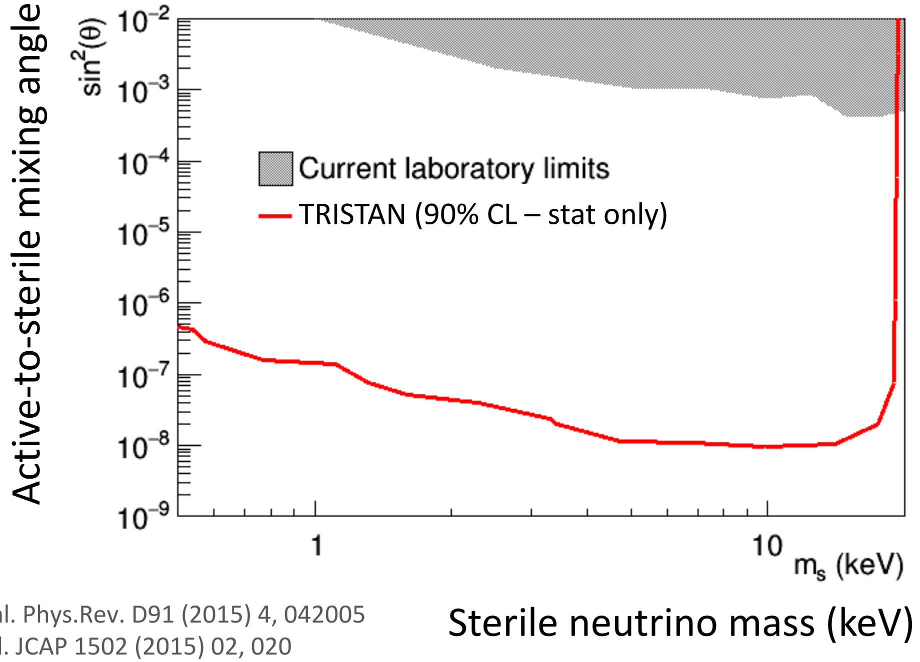
W. Rodejohann, Phys.Lett.B 737, 81 (2014)
Barry, J. et al High Energ. Phys. (2014) 2014: 81
S.M. et. al. Phys.Rev. D91 (2015) 4, 042005
S.M. et al. JCAP 1502 (2015) 02, 020
Ludl, P.O. et al High Energ. Phys. (2016) 2016: 40
R. Adhikari et al. JCAP 1701 (2017) 01, 025
G. Arcadi et.al., JHEP 01(2019) 206

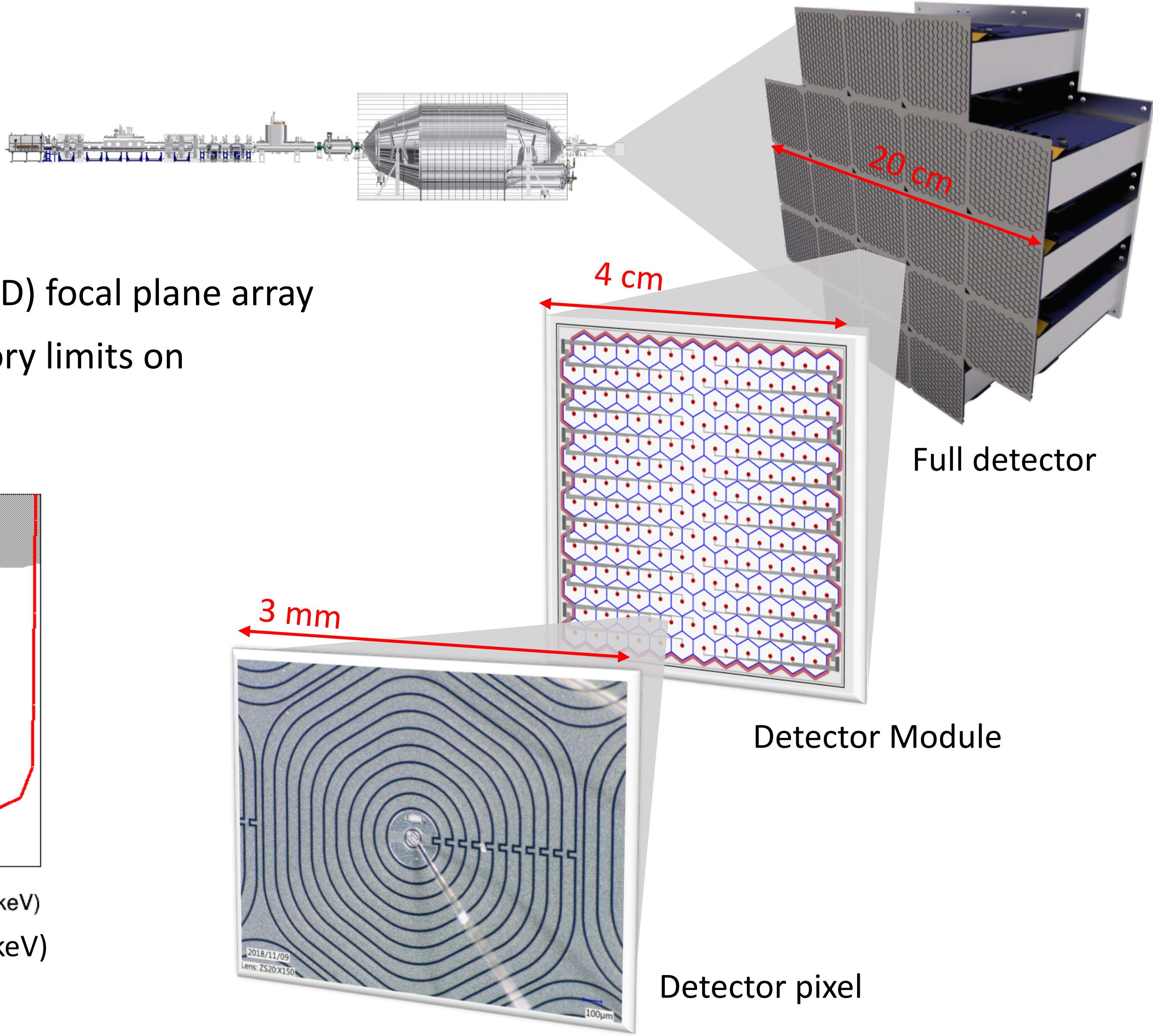

Neutrino mass
Energy
Kink of keV-scale sterile ν
Physics beyond the Standard Model: e.g. sterile neutrinos
β-decay
ν_e
W. Rodejohann, Phys.Lett.B 737, 81 (2014)
Barry, J. et al High Energ. Phys. (2014) 2014: 81
S.M. et. al. Phys.Rev. D91 (2015) 4, 042005
S.M. et al. JCAP 1502 (2015) 02, 020
Ludl, P.O. et al High Energ. Phys. (2016) 2016: 40
R. Adhikari et al. JCAP 1701 (2017) 01, 025
G. Arcadi et.al., JHEP 01(2019) 206


Neutrino mass
Energy
1 cps
10^{10} cps
Physics beyond
the Standard Model:
e.g. sterile neutrinos
β-decay
ν_e
W. Rodejohann, Phys.Lett.B 737, 81 (2014)
Barry, J. et al High Energ. Phys. (2014) 2014: 81
S.M. et. al. Phys.Rev. D91 (2015) 4, 042005
S.M. et al. JCAP 1502 (2015) 02, 020
Ludl, P.O. et al High Energ. Phys. (2016) 2016: 40
R. Adhikari et al. JCAP 1701 (2017) 01, 025
G. Arcadi et.al., JHEP 01(2019) 206

TRISTAN Project

- 3500-pixel Silicon Drift Detector (SDD) focal plane array
- Significant improvement of laboratory limits on keV-scale sterile neutrinos expected

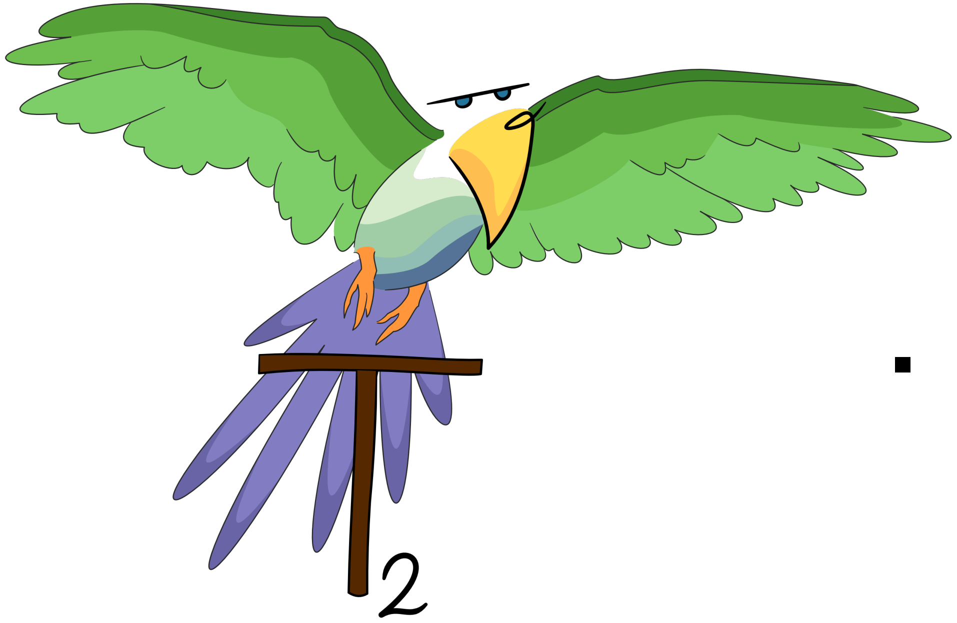




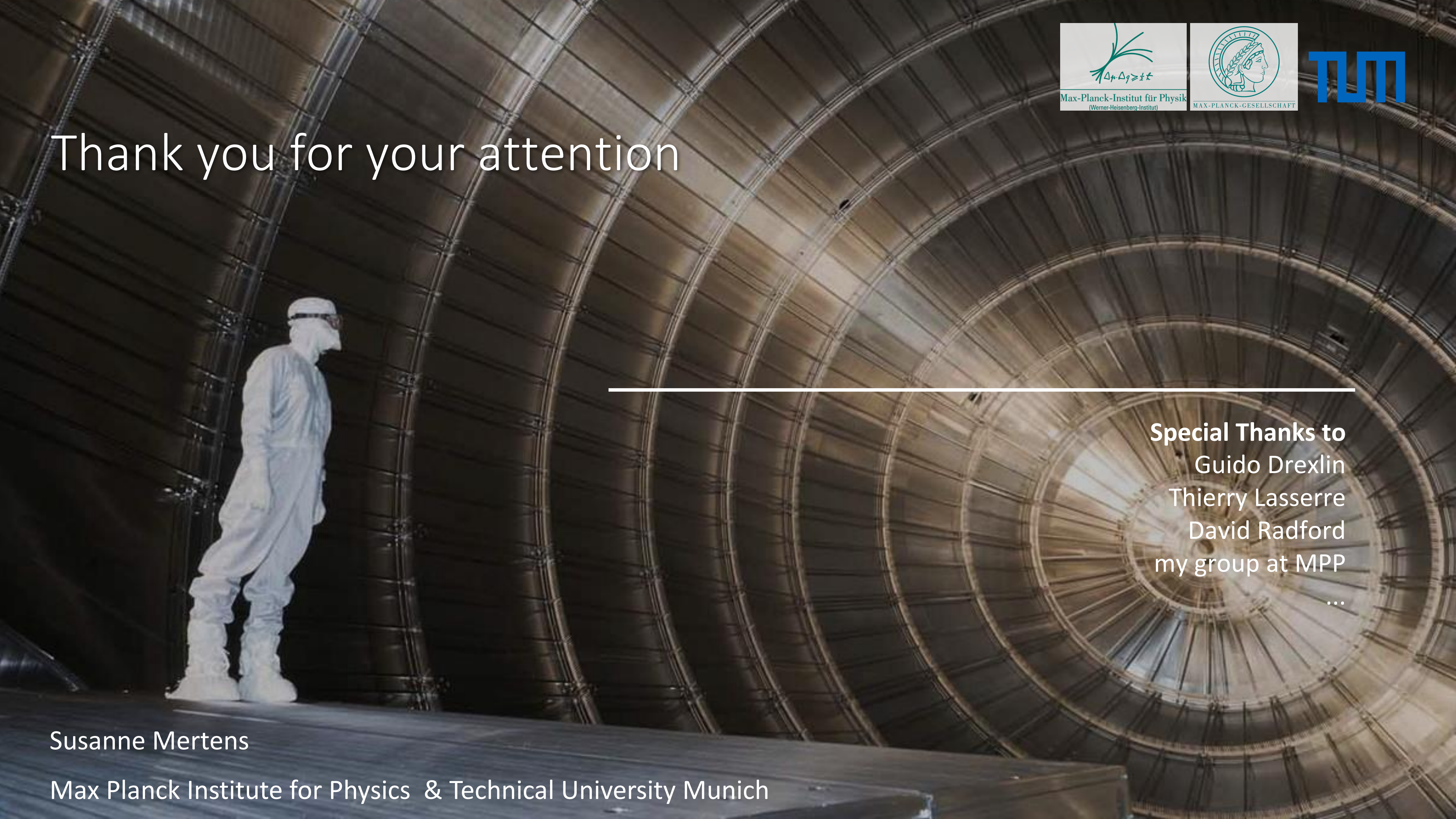
Mertens et. al. Phys.Rev. D91 (2015) 4, 042005
Mertens et al. JCAP 1502 (2015) 02, 020
K. Dolde, S.M., D. Radford et. al. NIM-A 848 (2017)
Mertens, J. Phys. G46 (2019)
T. Brunst et al, arXiv:1801.08182 [physics.ins-det]

Conclusion

- High-quality data collected over 780 hours @25 GBq = 5 days of nominal KATRIN @100GBq
- World Best Direct Neutrino Mass Measurement: m_ν < 1.1 eV (90% C.L.)
- more information: http://arxiv.org/abs/1909.06048



- Background improvement experimentally verified
- Promising perspectives to search for eV to keV sterile neutrinos



Thank you for your attention

Special Thanks to
Guido Drexlin
Thierry Lasserre
David Radford
my group at MPP
…

Susanne Mertens

Max Planck Institute for Physics & Technical University Munich