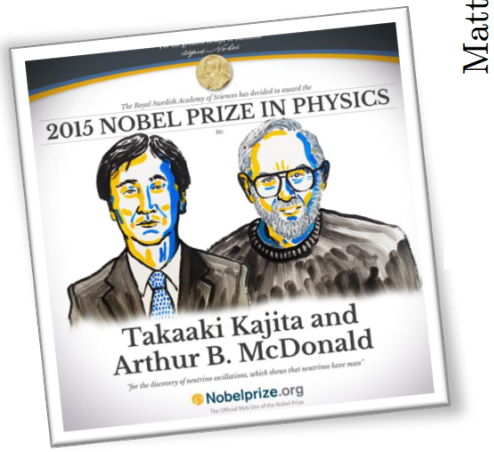
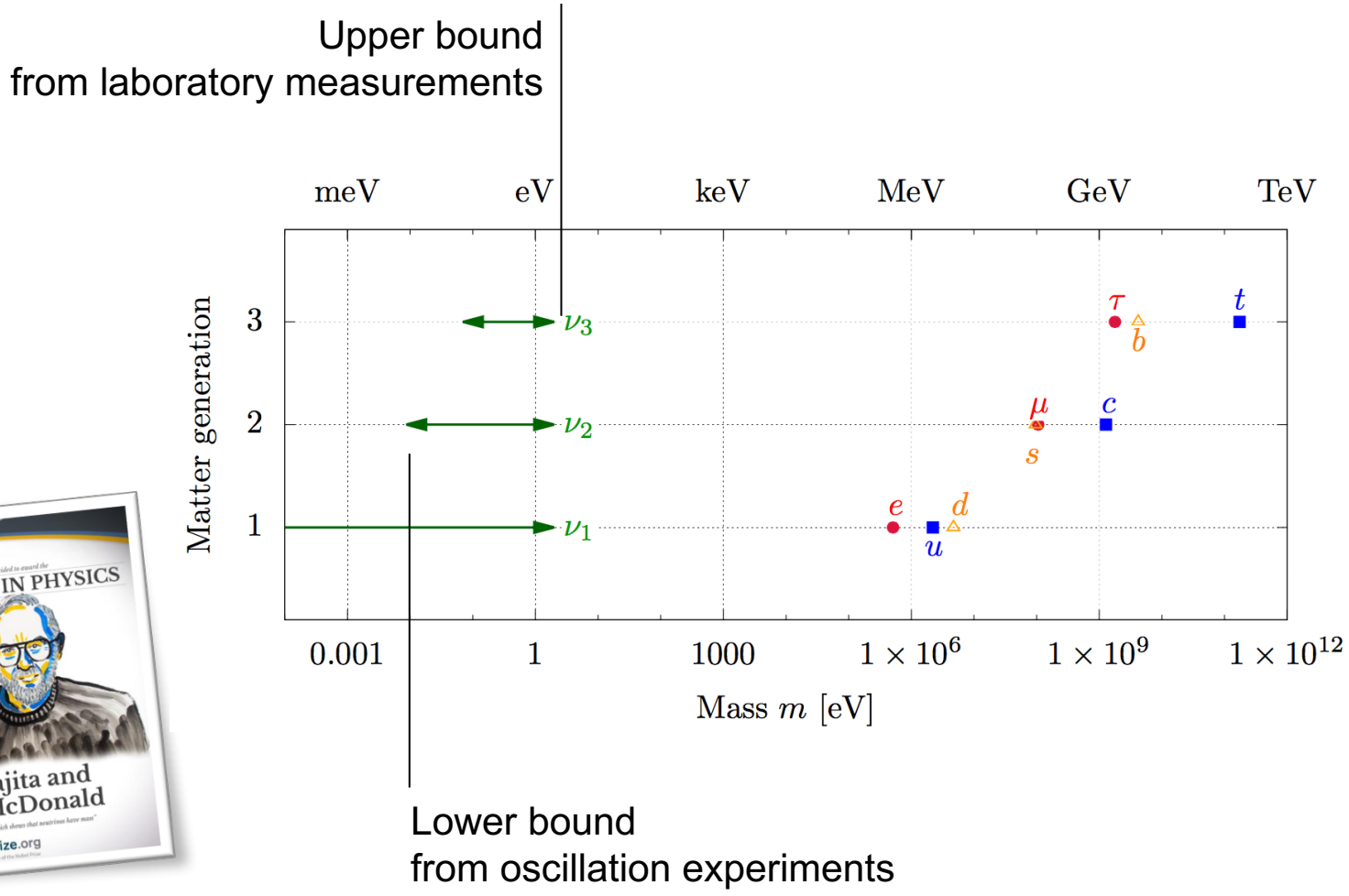
First results from the KATRIN experiment

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

Neutrino mass





Neutrino mass

Cosmology

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

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

Search for 0νßß

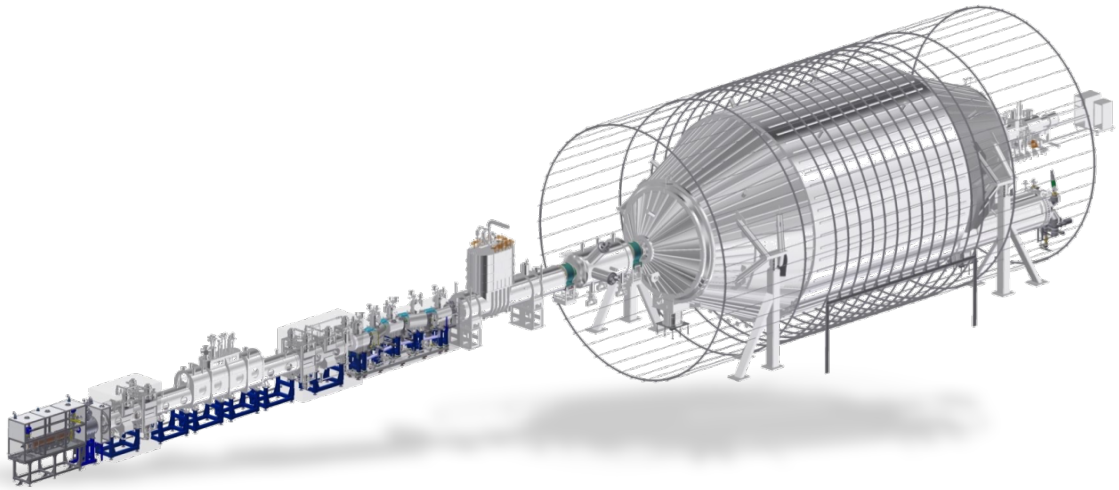
Laboratory-based
potential: $m_{ßß}$ = 15-50 meV
e.g. LEGEND

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

Kinematics of ß-decay

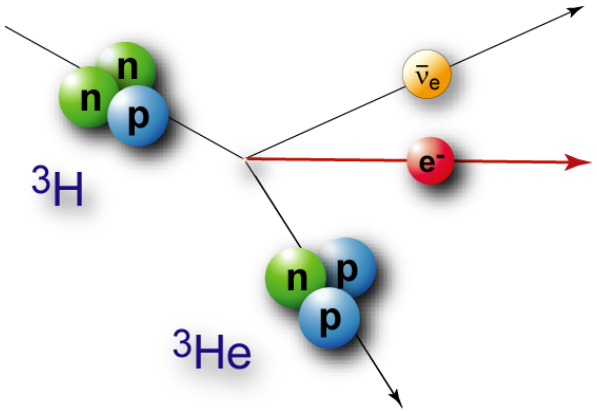
Laboratory-based
potential: m_β = 50 - 200 meV
e.g. KATRIN

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

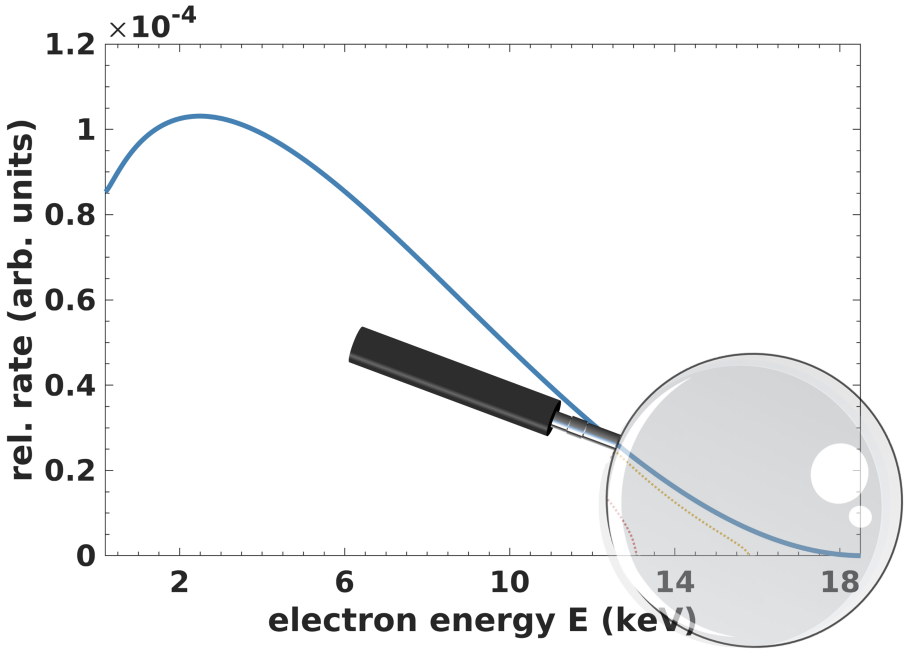


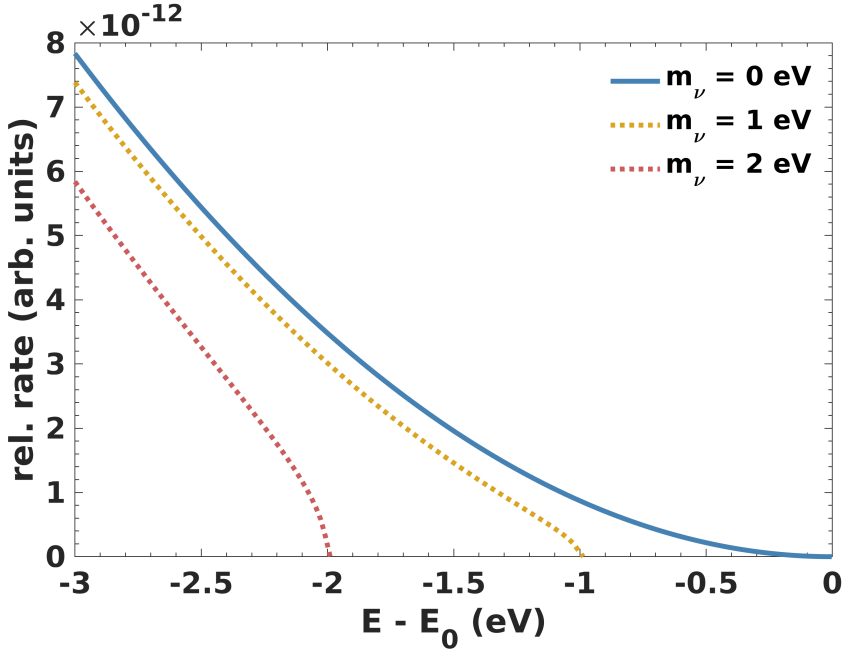
The basic idea

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

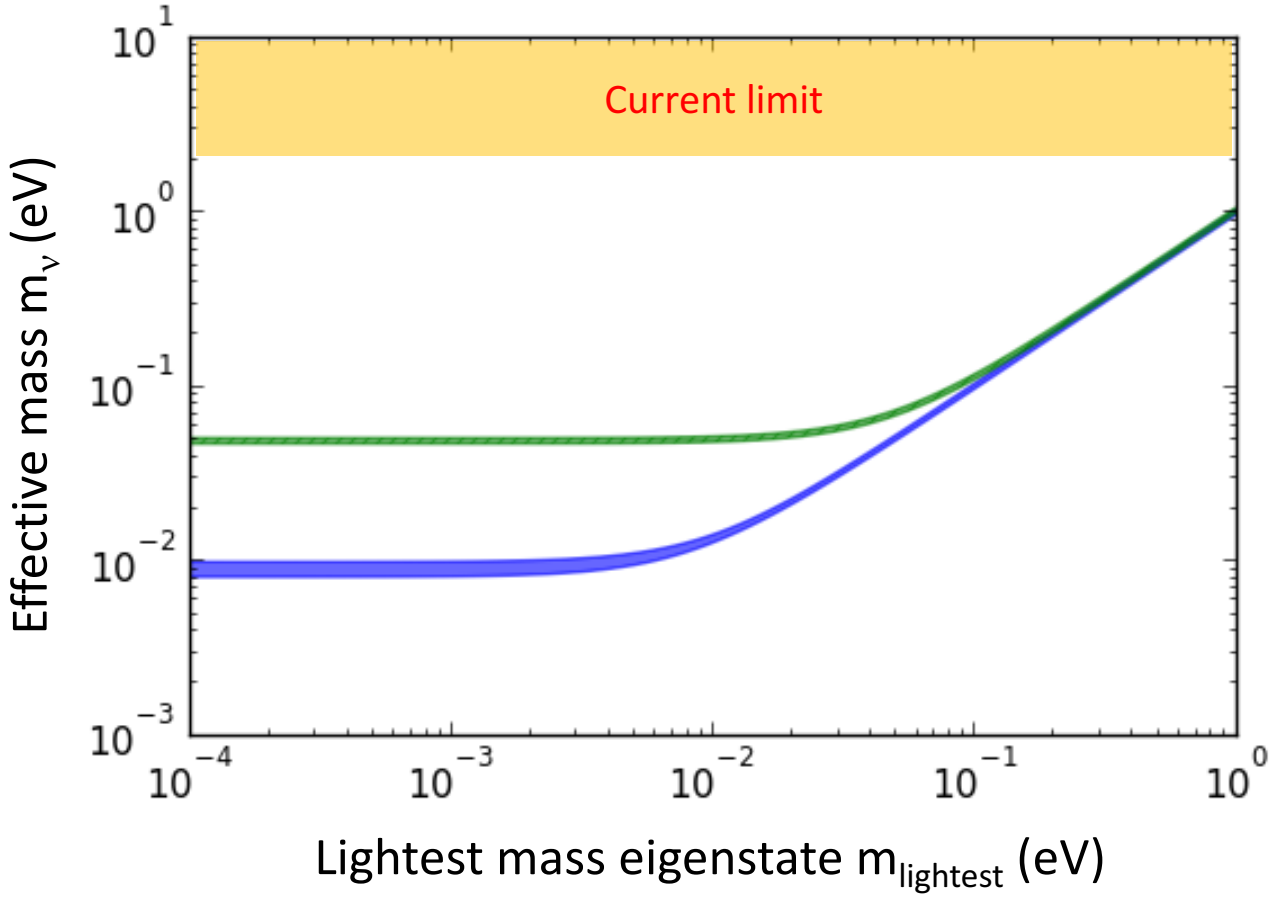


$$m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$



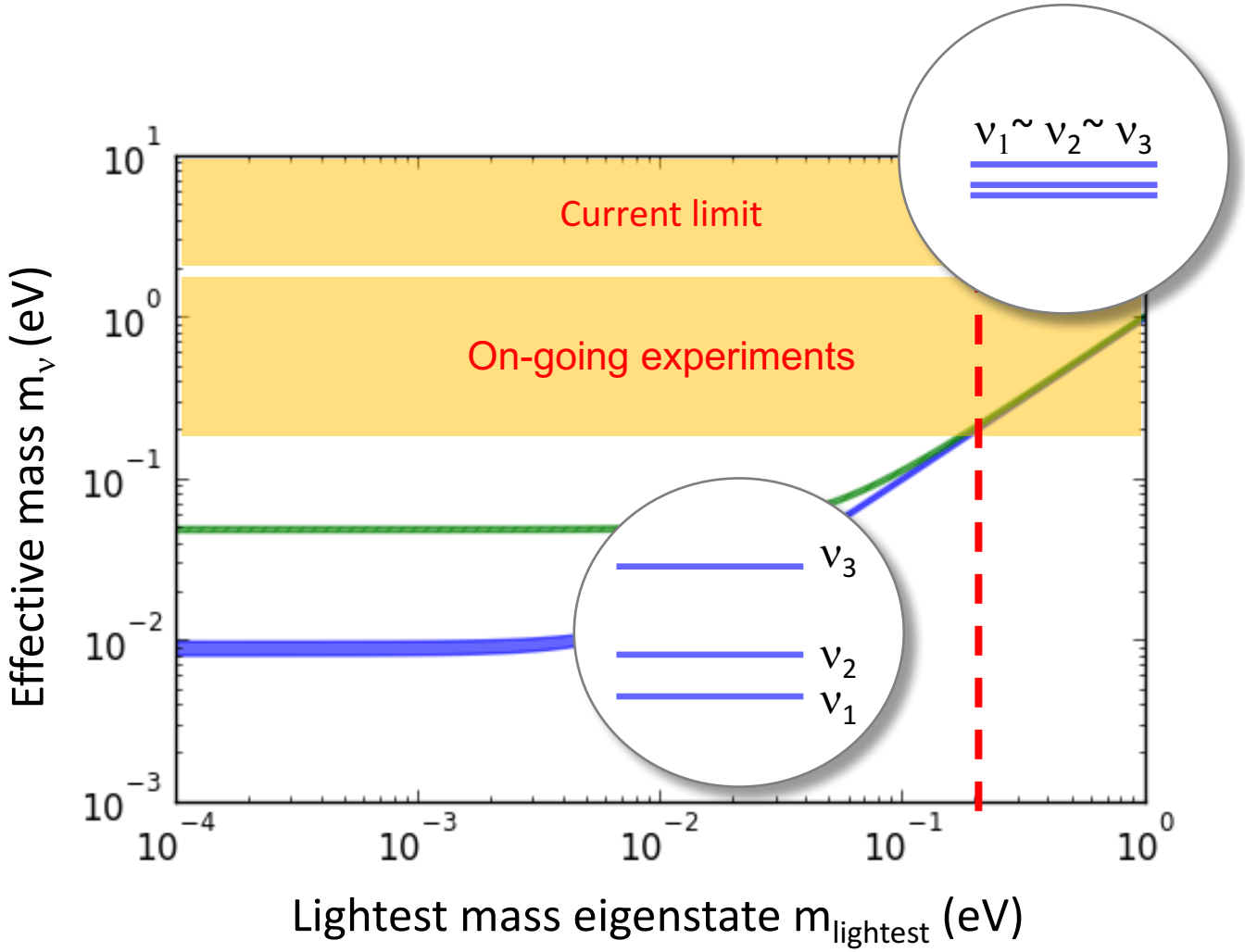


Where do we stand?



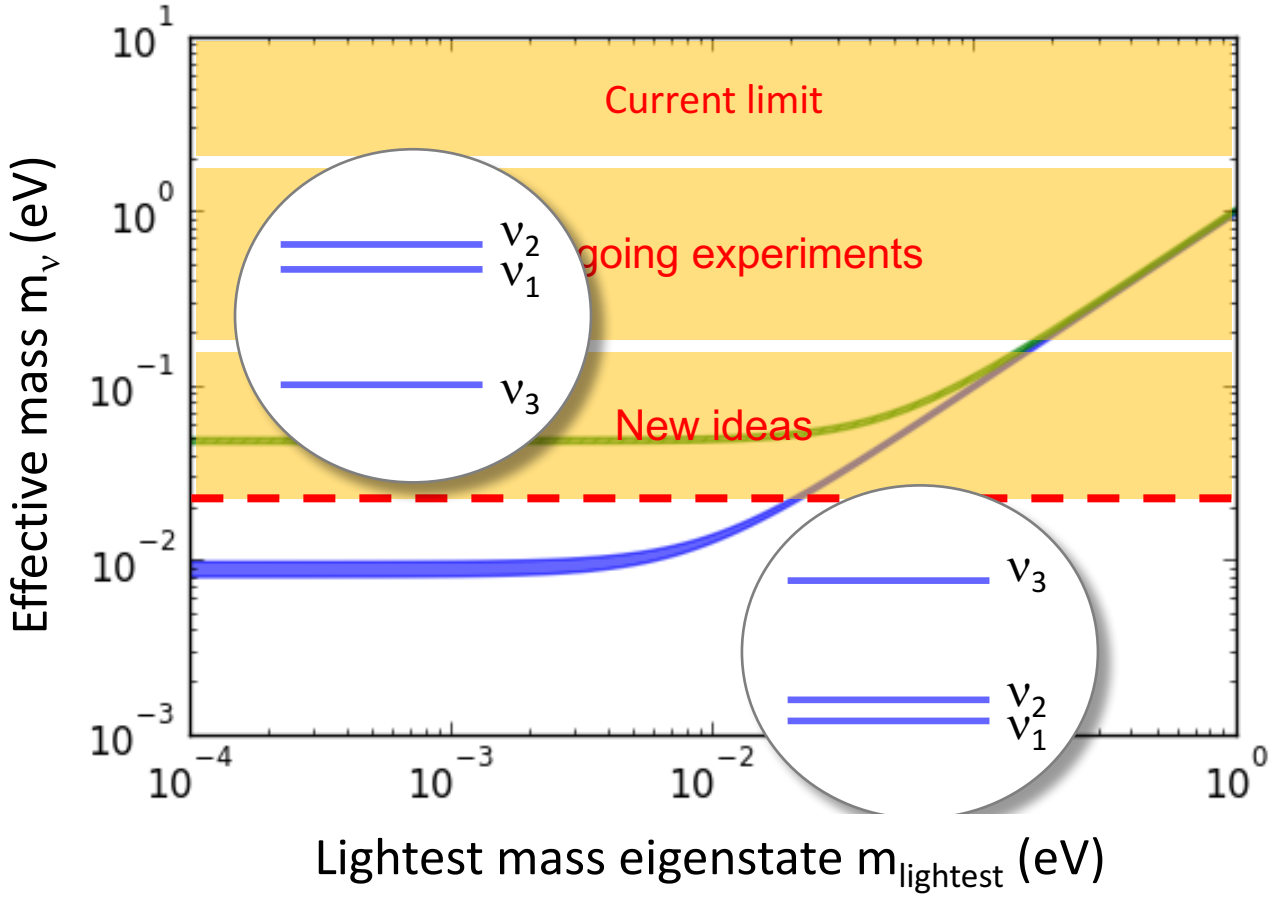
- Current limit:
  Mainz and Troitsk Experiment
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)

Where do we stand?



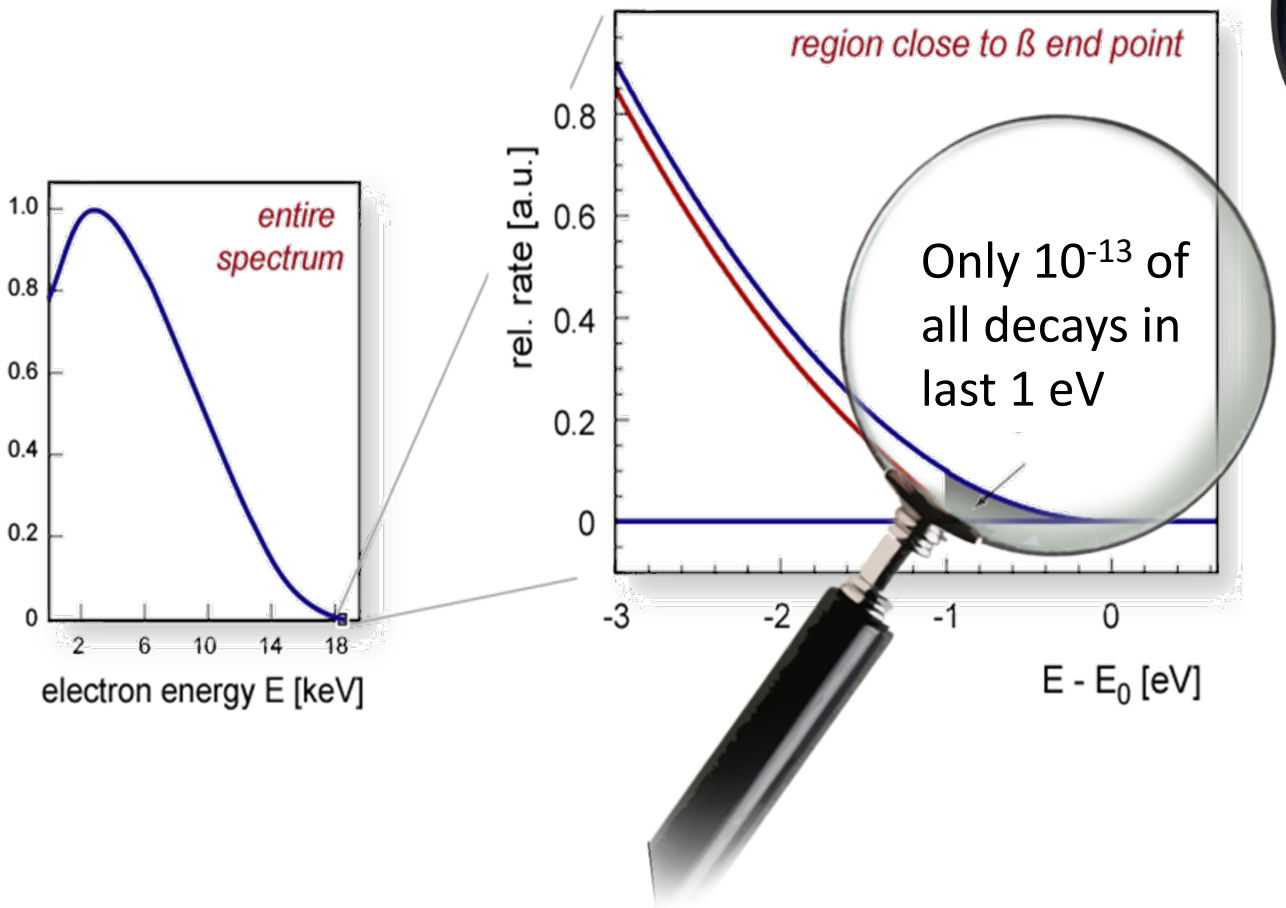
- Current limit:
  Mainz and Troitsk Experiment
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario

Where do we stand?



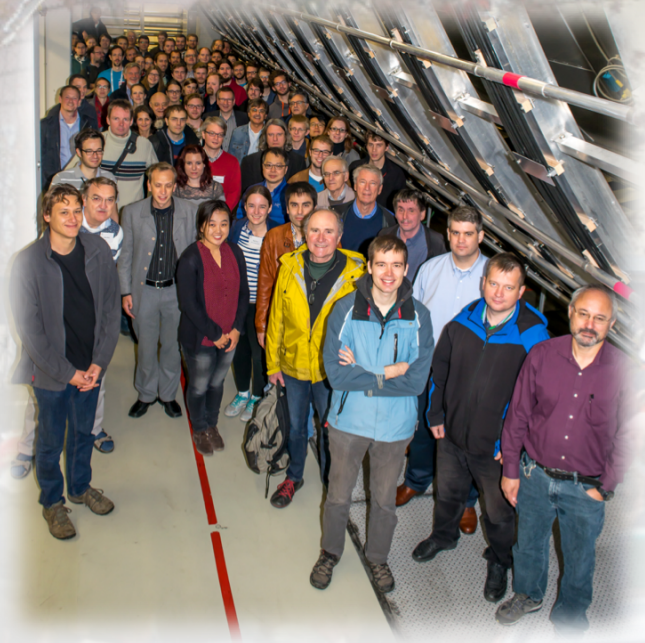
- Current limit:
  Mainz and Troitsk Experiment
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario
- New ideas:
  Resolve **normal** vs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

The challenge




Karlsruhe
Tritium
Neutrino
Experiment

Karlsruhe Tritium Neutrino Experiment

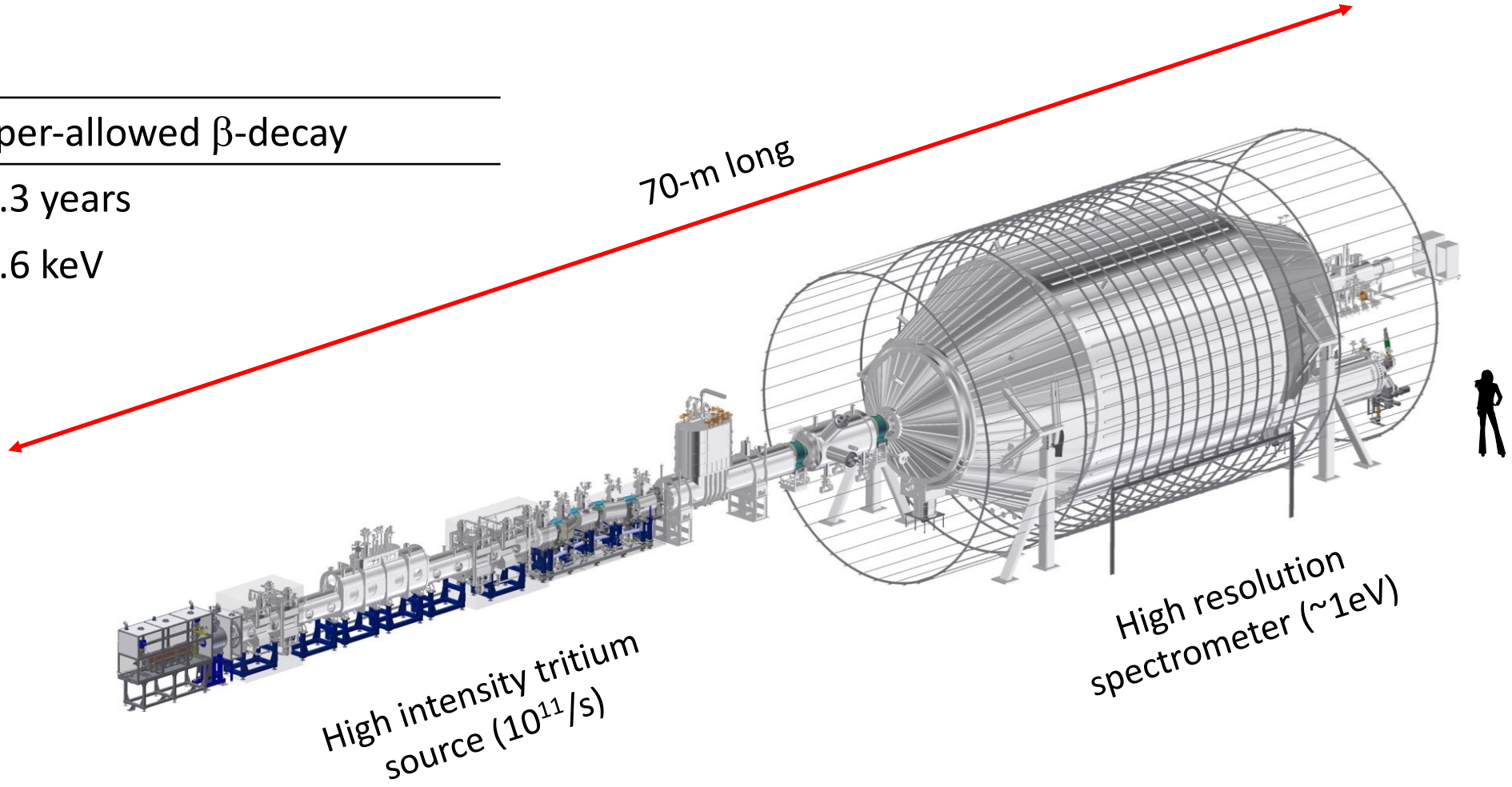


- Experimental site: Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Sensitivity m_ν = 0.2 eV (90% CL) after 3 net-years

Karlsruher Institut für Technologie
Max-Planck-Institut für Kernphysik Heidelberg
University of Washington
Case Western Reserve University
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
cea
Carnegie Mellon University
Universidad Complutense Madrid
Russian Academy of Sciences
Johannes Gutenberg Universität Mainz
universitätbonn
Hochschule Fulda University of Applied Sciences
Bergische Universität Wuppertal
Technische Universität München
Berkeley Lab

KATRIN Working Principle

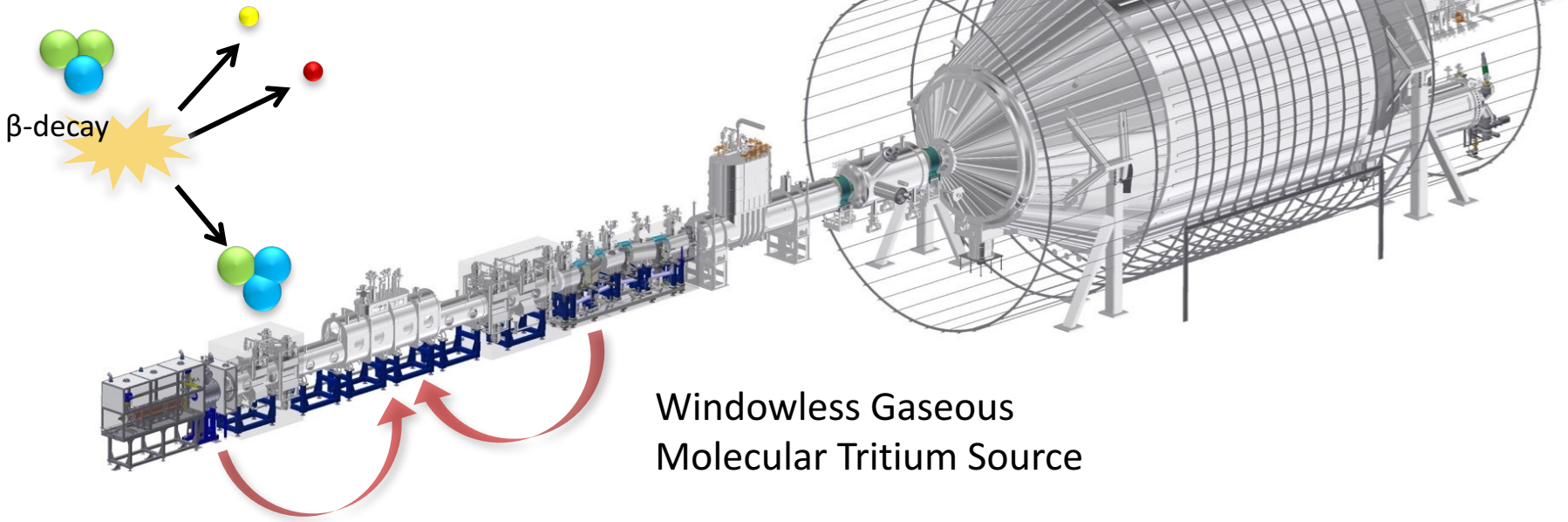
	^{3}H
	super-allowed β-decay
$T_{1/2}$	12.3 years
E_0	18.6 keV



KATRIN Working Principle

high stability
and luminosity

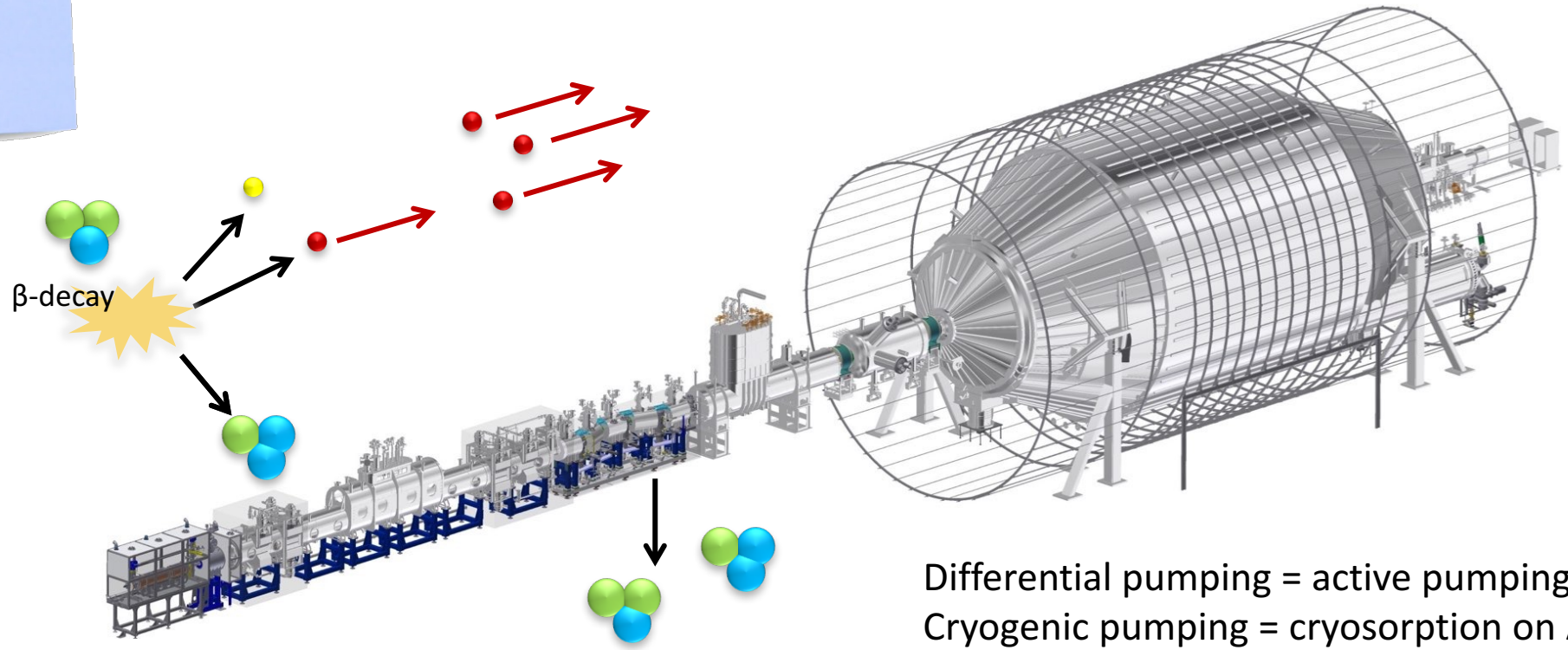
(10^{11} decays/sec)



Windowless Gaseous
Molecular Tritium Source

KATRIN Working Principle

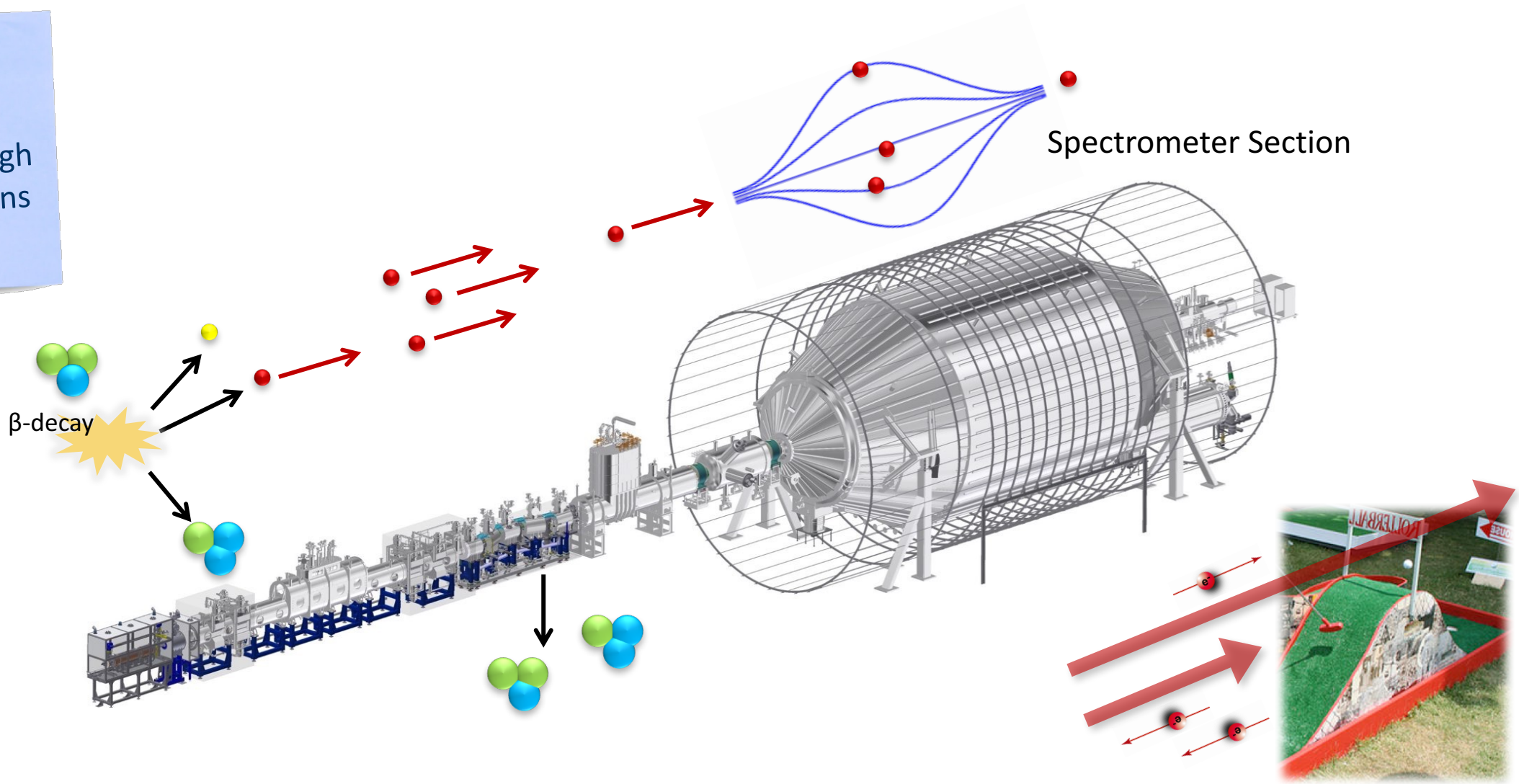
Tritium flow reduction by 14 orders of magnitude



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

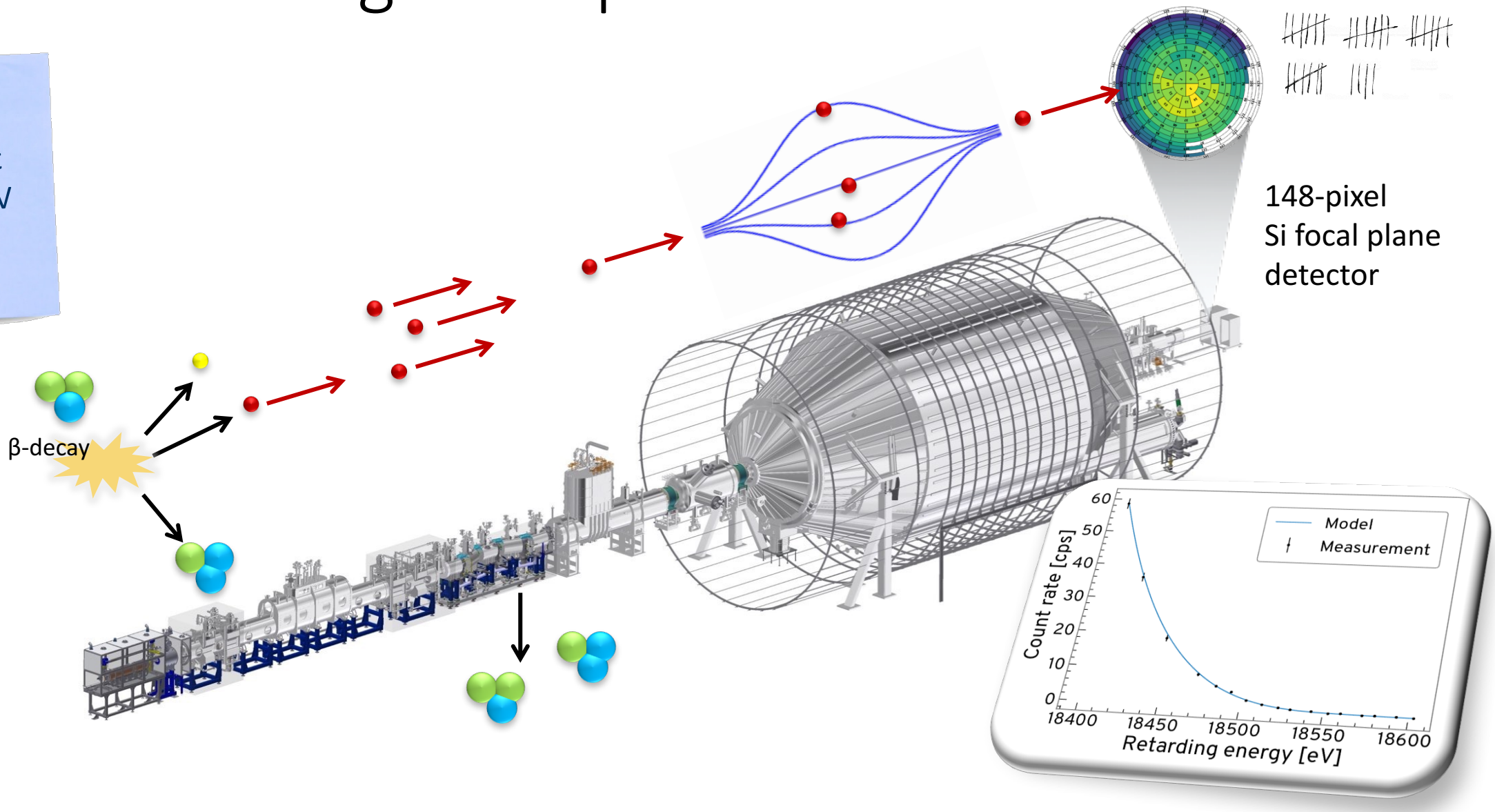
KATRIN Working Principle

Electrostatic filter selects high energy electrons



KATRIN Working Principle

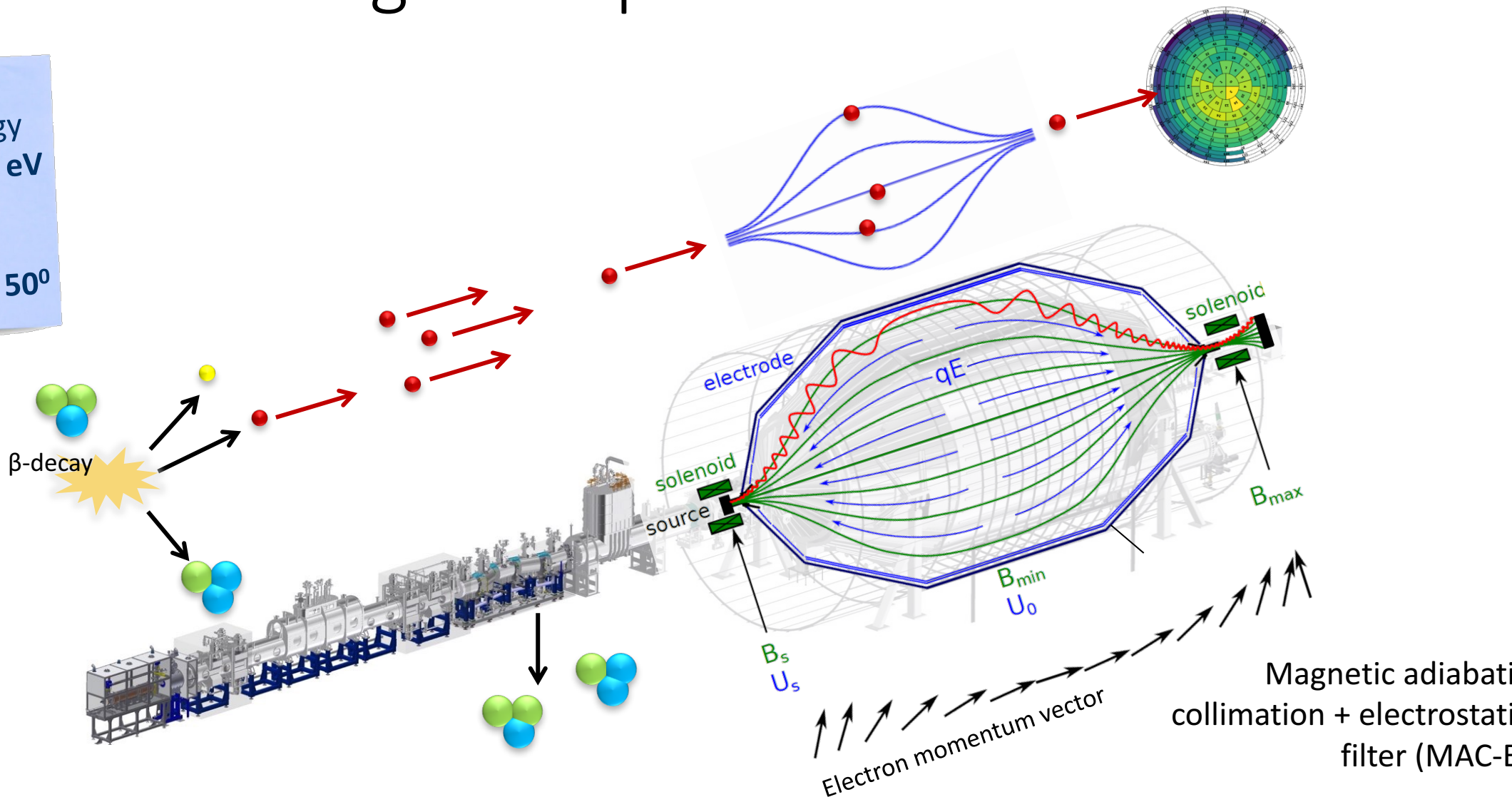
Integral measurement down to 40 eV below the endpoint

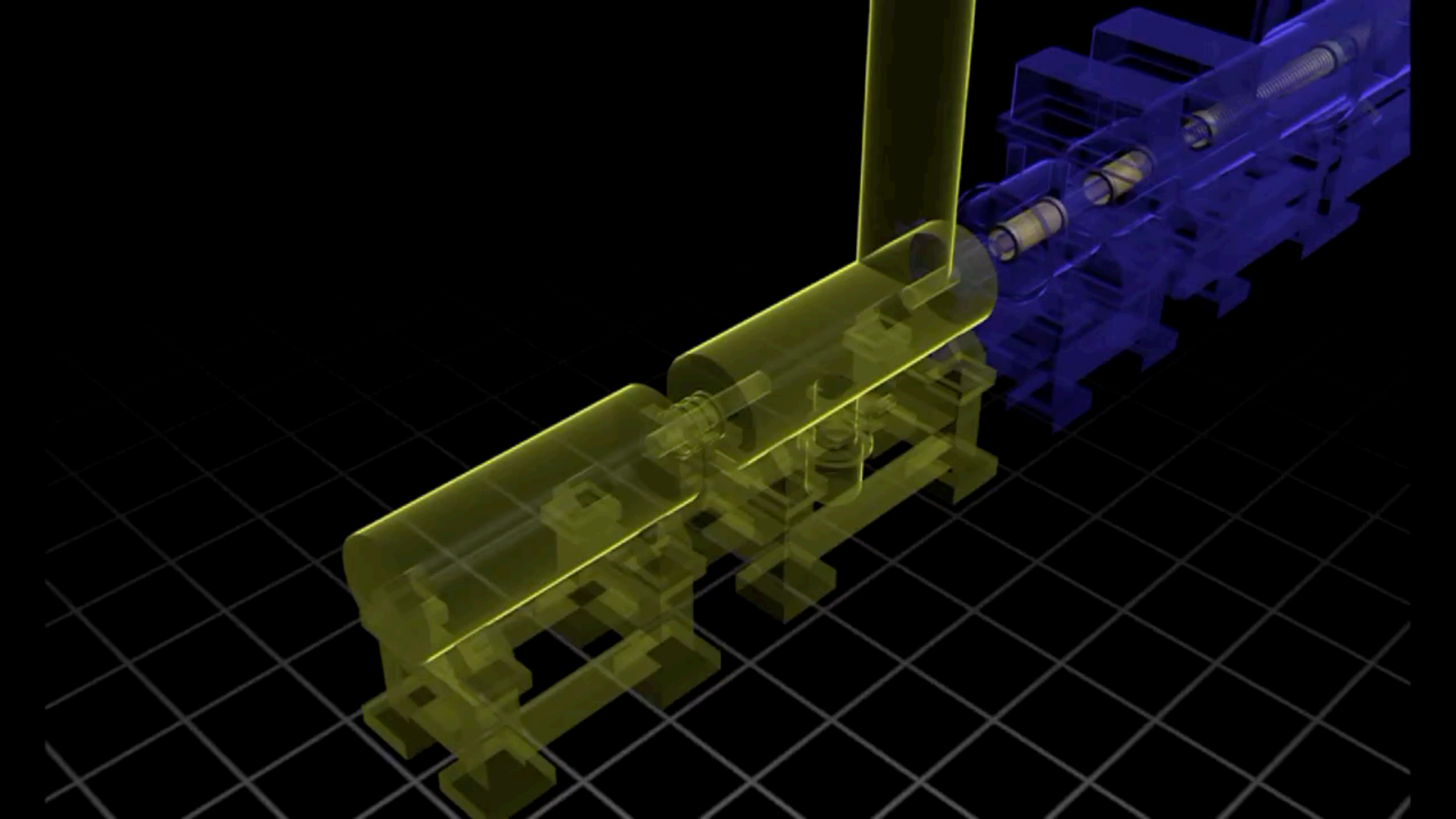


KATRIN Working Principle

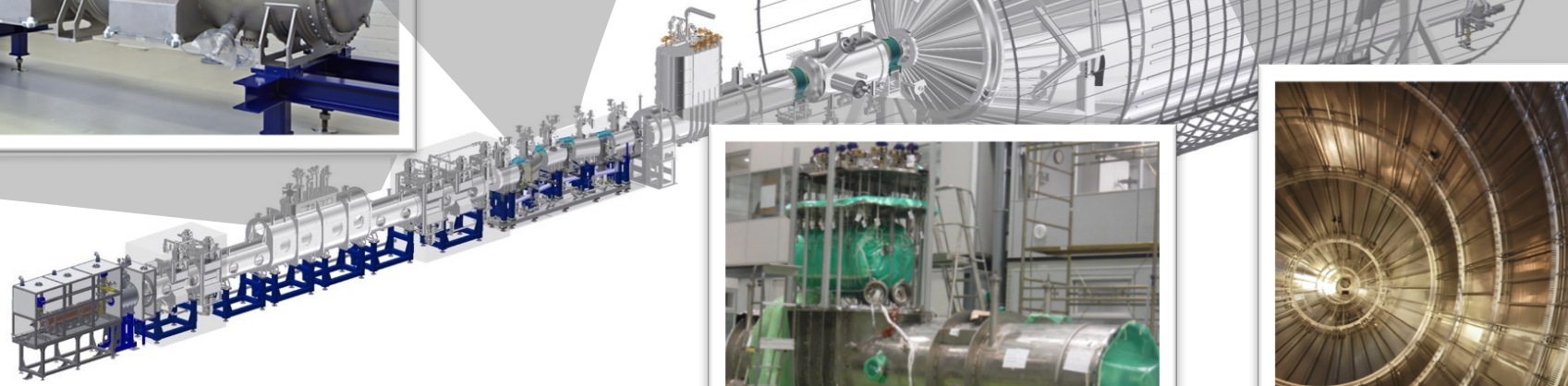
excellent energy resolution: **~ 1 eV**

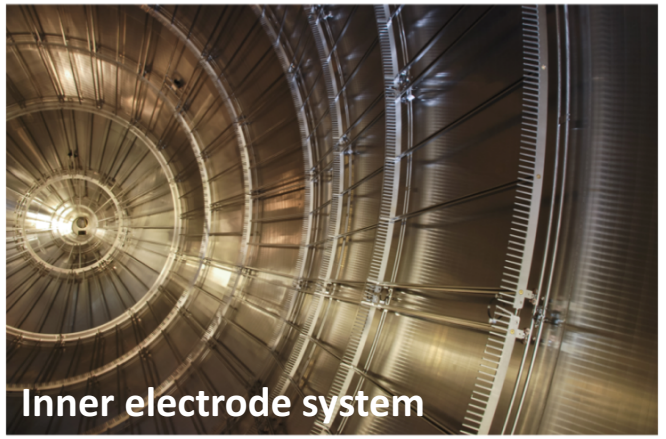
large angle acceptance: **~ 50⁰**





KATRIN (in real)





JINST 11 P04011 (2016)
JINST 13 P04020 (2018)

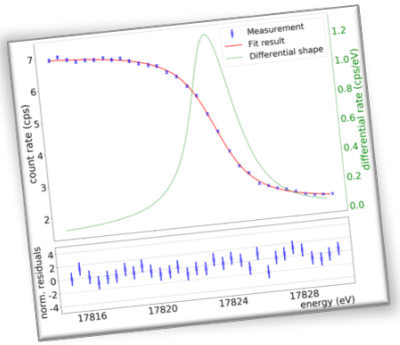
18-years of KATRIN history

Letter of Intent

2001

Main spectrometer

2006



Krypton calibration

2016 2017

First neutrino mass

2019

Design Report

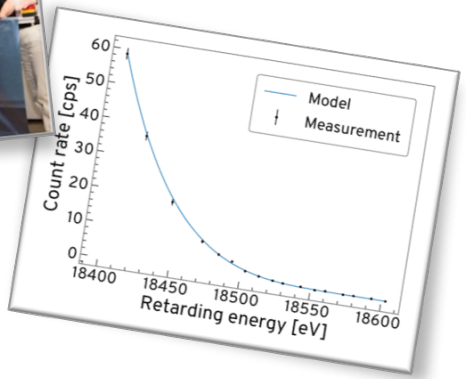
2004

KATRIN Design Report 2004

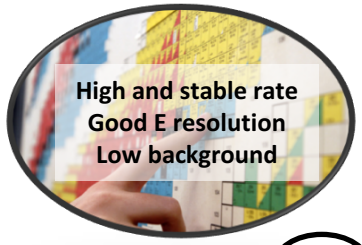
First light

2018

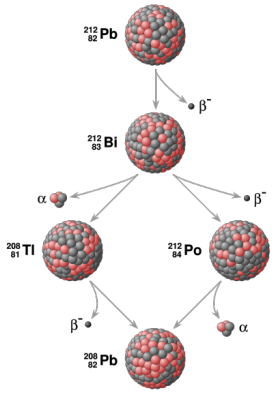
First tritium

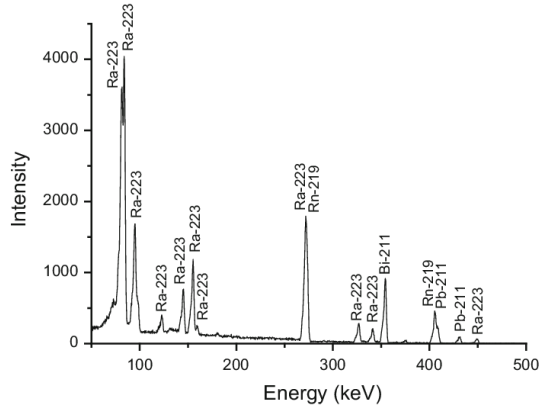


Test of Unique Properties of KATRIN

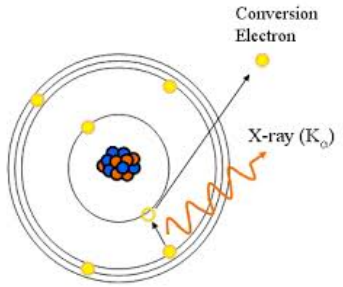


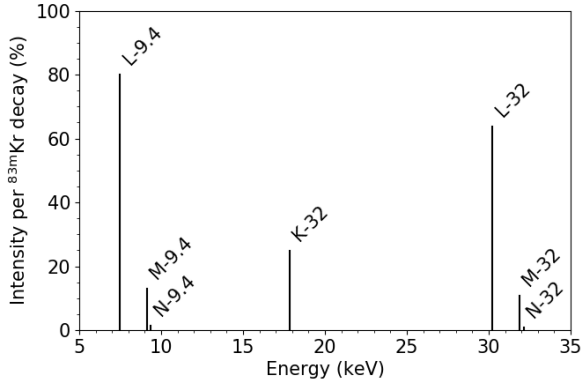
Low Background



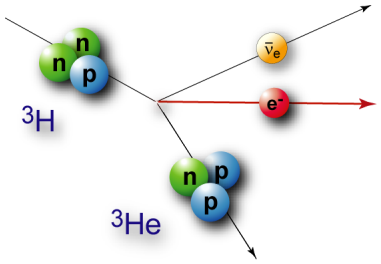


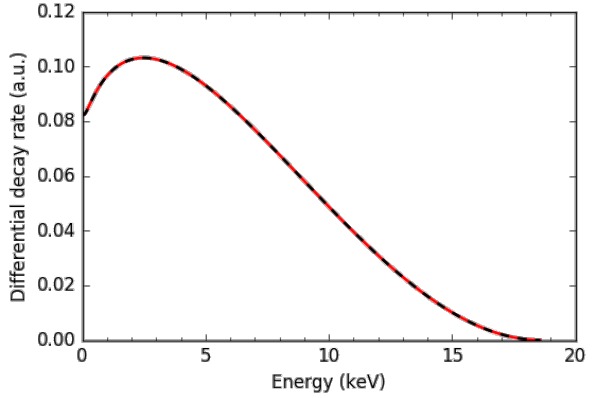
high-resolution MAC-E filter





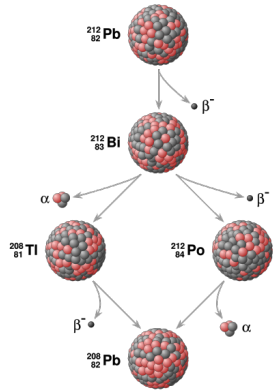
ultra-stable tritium source

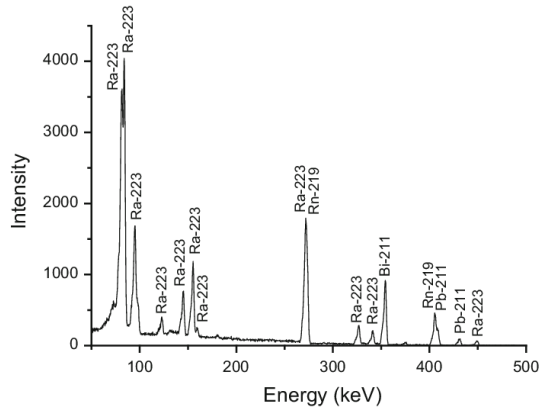




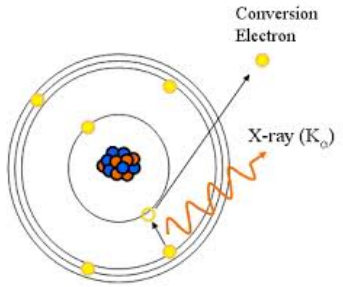
Test of Unique Properties of KATRIN

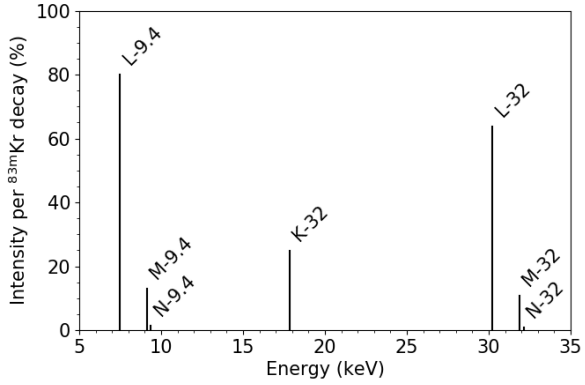
Low Background



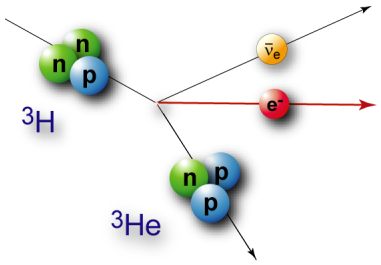


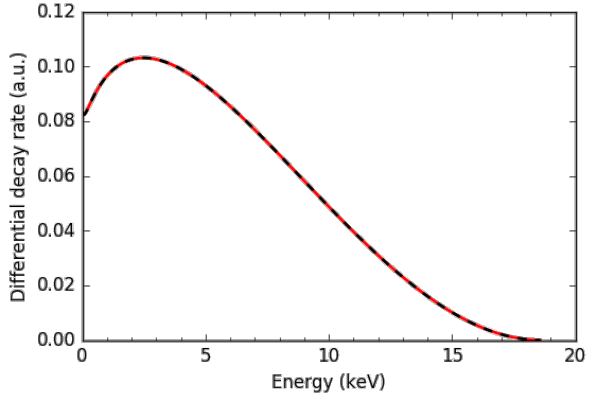
high-resolution MAC-E filter





ultra-stable tritium source

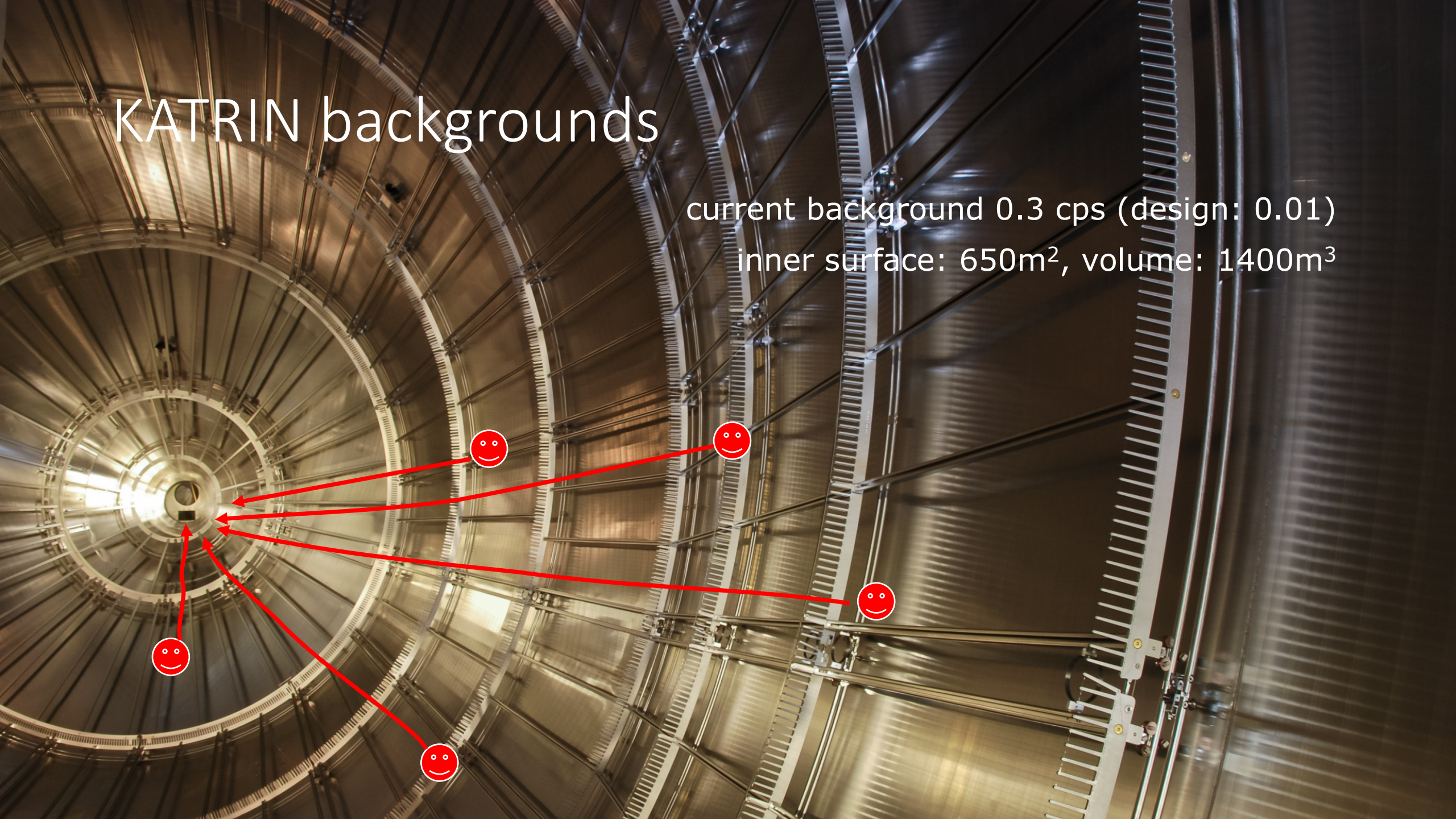




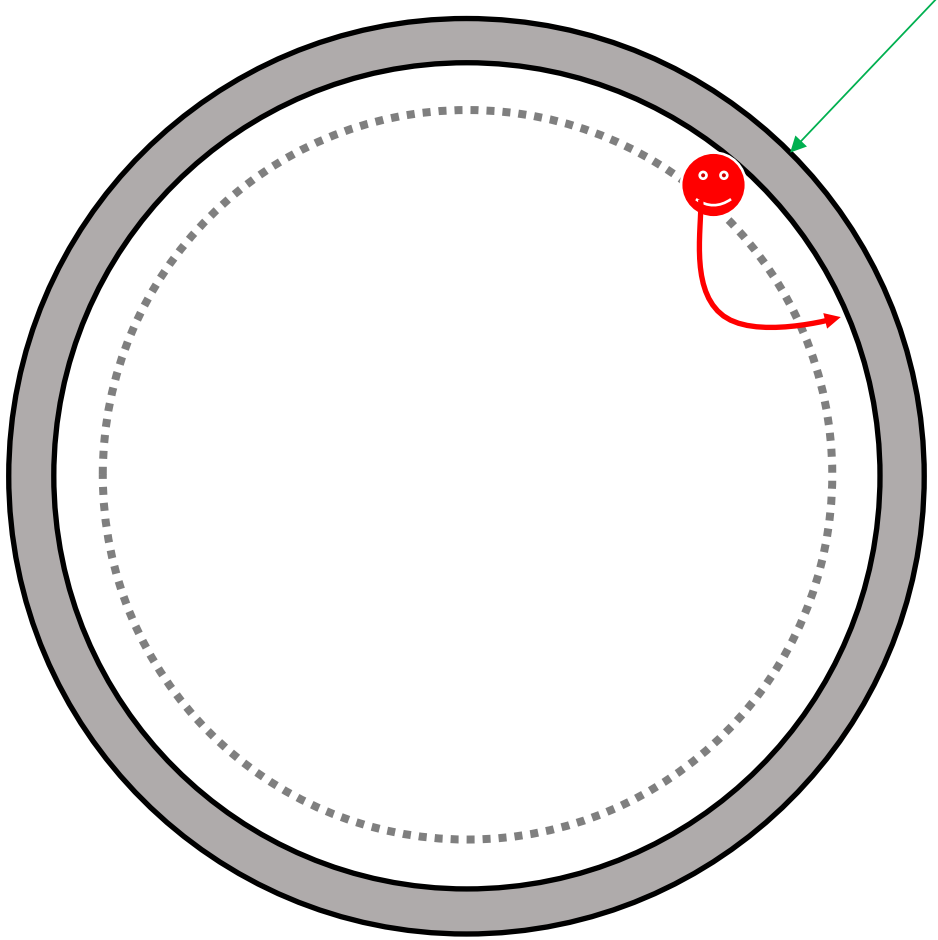
KATRIN backgrounds

current background 0.3 cps (design: 0.01)

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

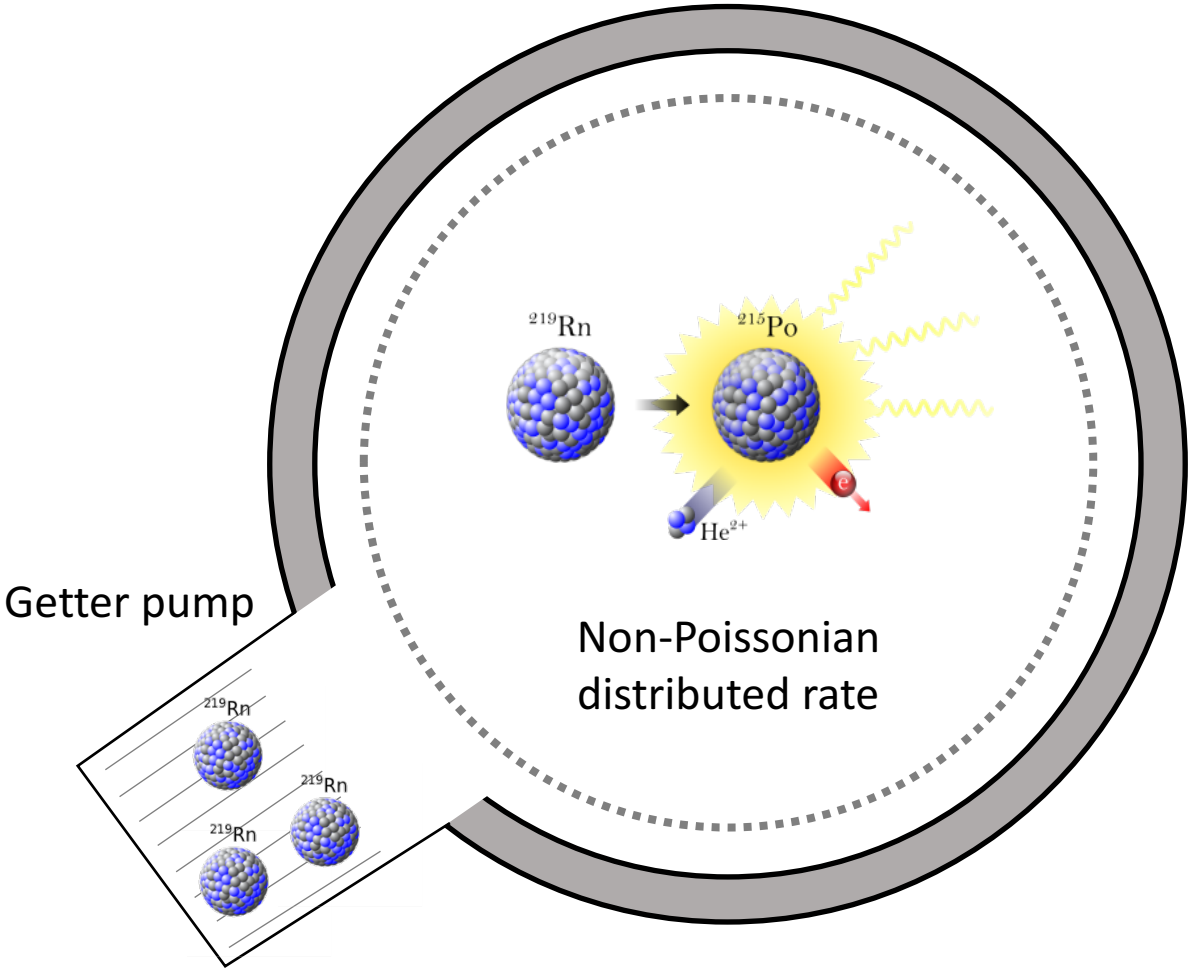


KATRIN backgrounds

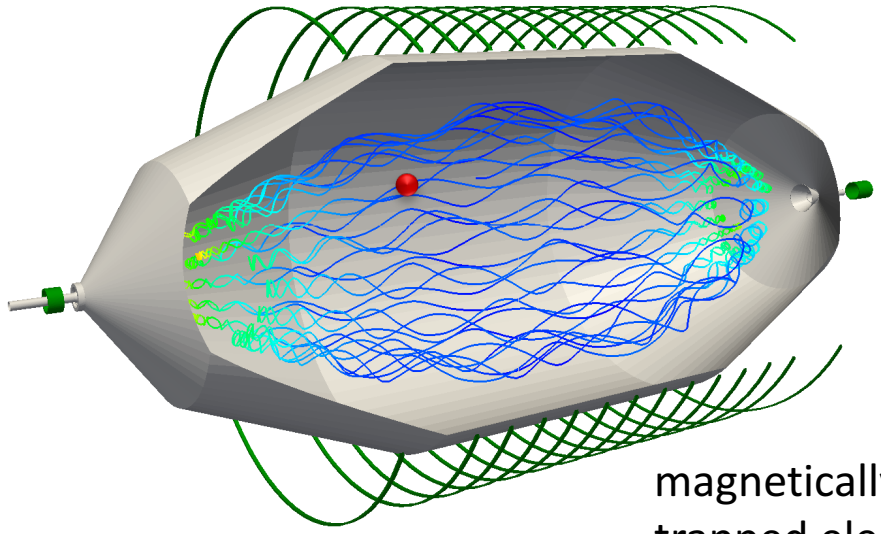


- ✓ Effective electric and magnetic shielding against charged particles from the surface
  KATRIN Collab, JINST 13 T10004 (2018)

KATRIN backgrounds

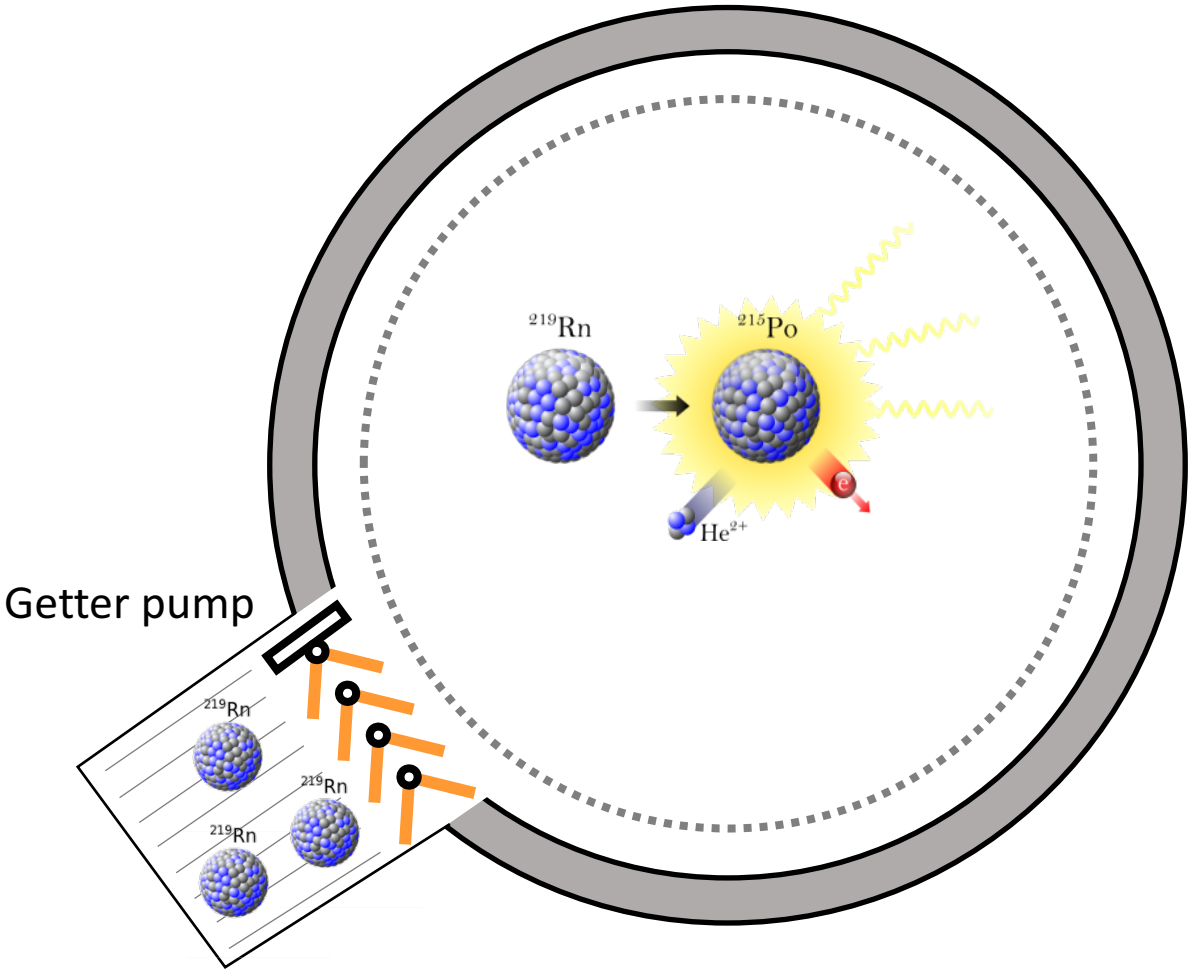


- ✓ Effective electric and magnetic shielding against charged particles from the surface
  KATRIN Collab, JINST 13 T10004 (2018)
- Radon-induced background
  S. M. et al, Astropart. Phys. 41 (2013), 52–62
  S. M. et al, JINST 7 (2012) P08025

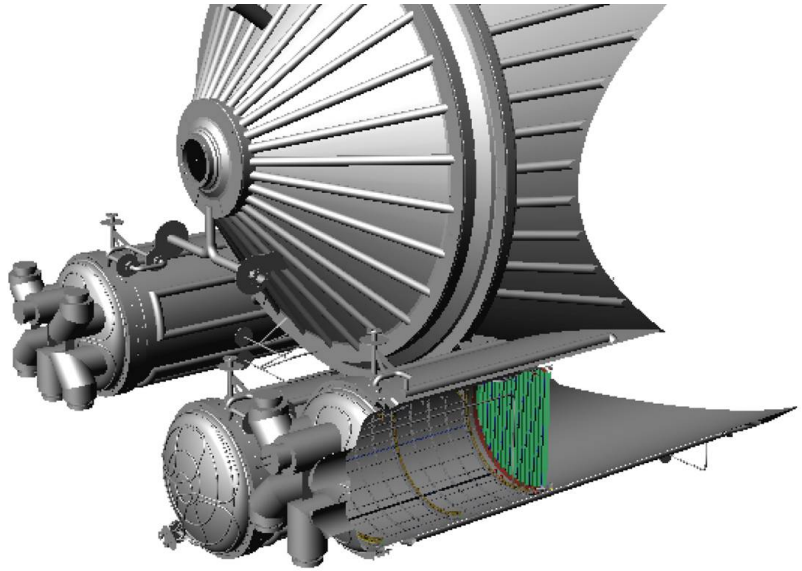


magnetically
trapped electron

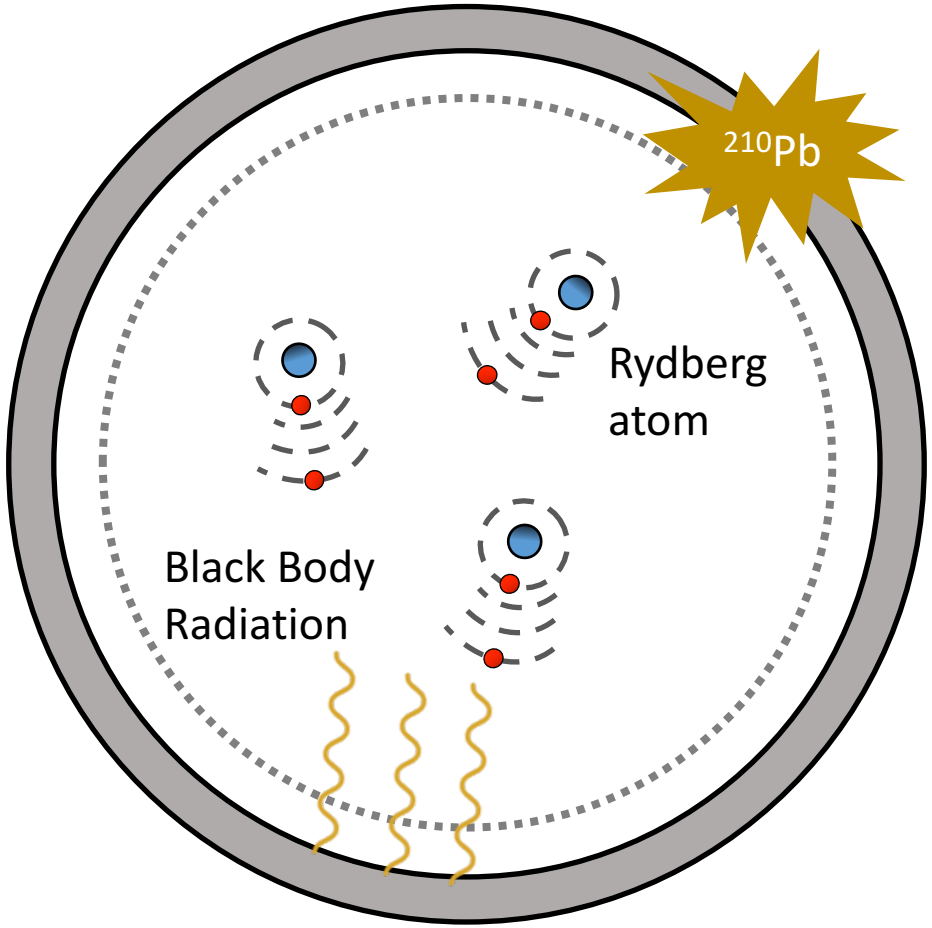
KATRIN backgrounds



- ✓ 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

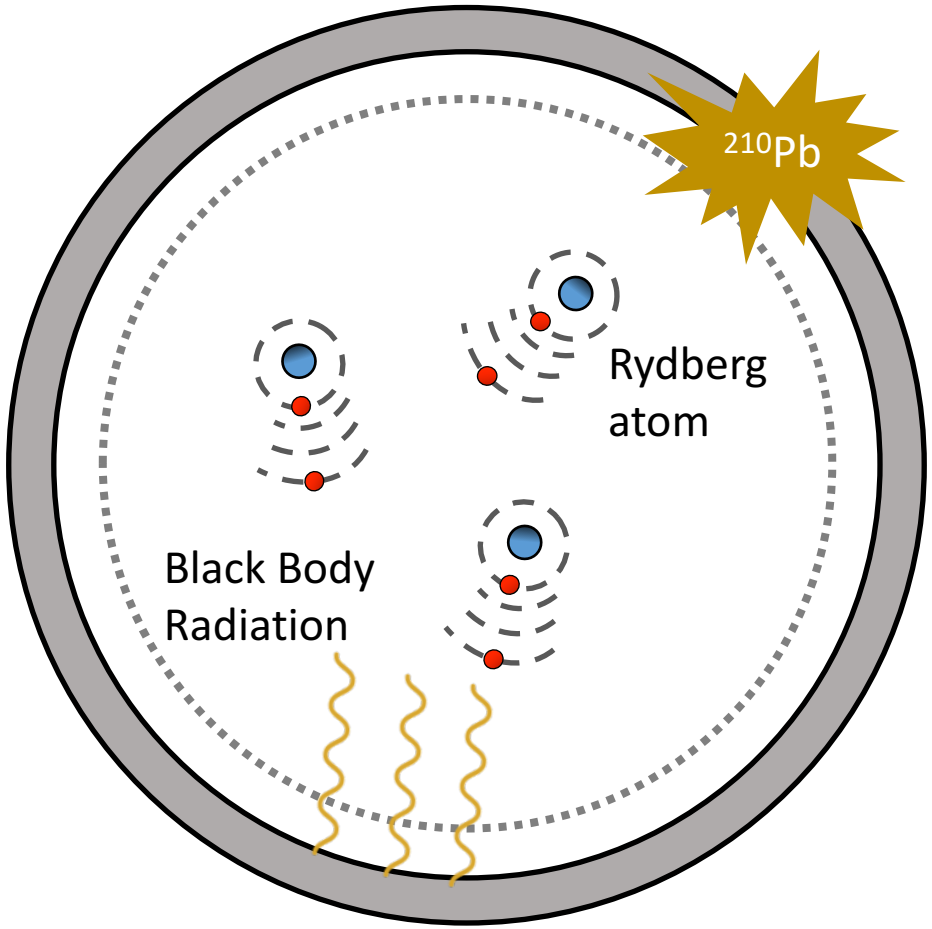


KATRIN backgrounds

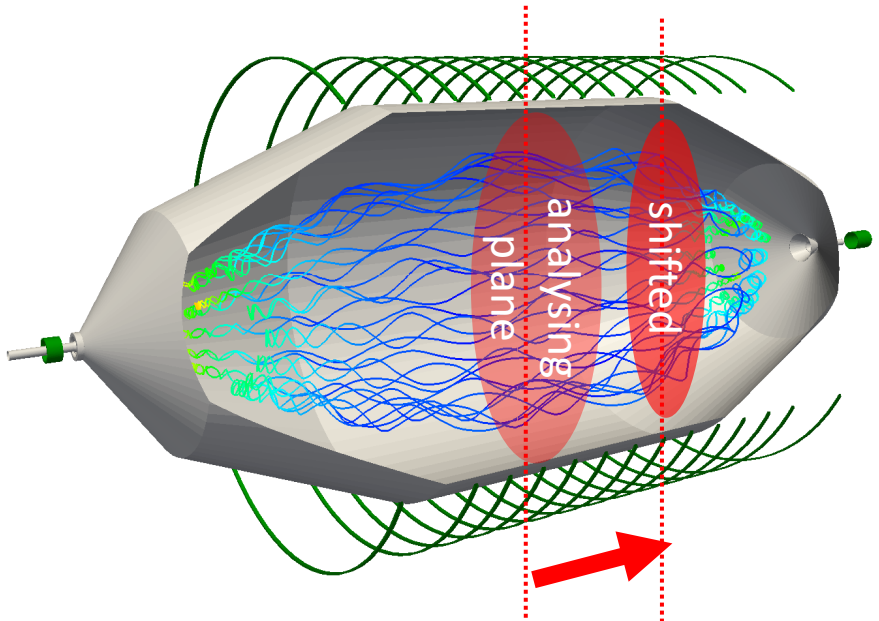


- ✓ Effective electric and magnetic shielding against charged particles from the surface
  KATRIN Collab, JINST 13 T10004 (2018)
- ✓ Effective reduction of radon-induced background via nitrogen-cooled baffle system
  S. Goerhardt, et al., JINST 13 (2018) no.10, T10004
- Highly excited hydrogen atoms

KATRIN backgrounds

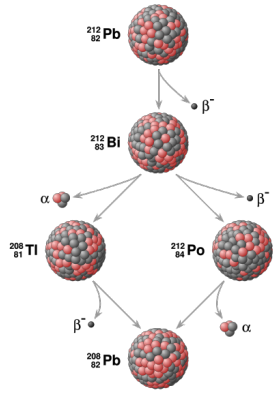


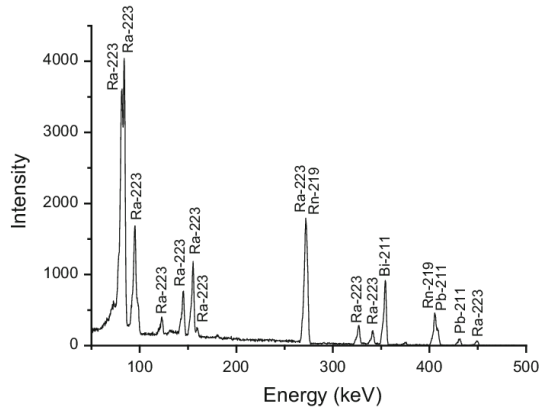
- ✓ Effective electric and magnetic shielding against charged particles from the surface
  KATRIN Collab, JINST 13 T10004 (2018)
- ✓ Effective reduction of radon-induced background via nitrogen-cooled baffle system
  S. Goerhardt, et al., JINST 13 (2018) no.10, T10004
- ✓ Effective mitigation by shifting analyzing plane



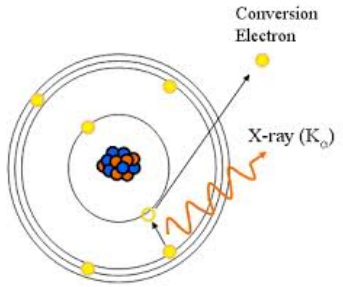
Test of Unique Properties of KATRIN

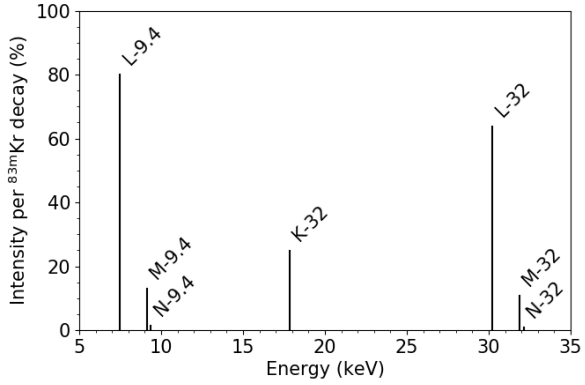
Low Background



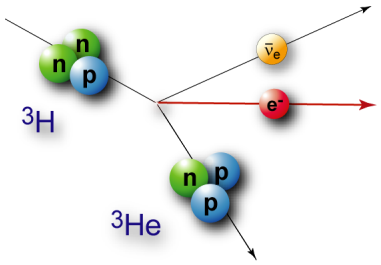


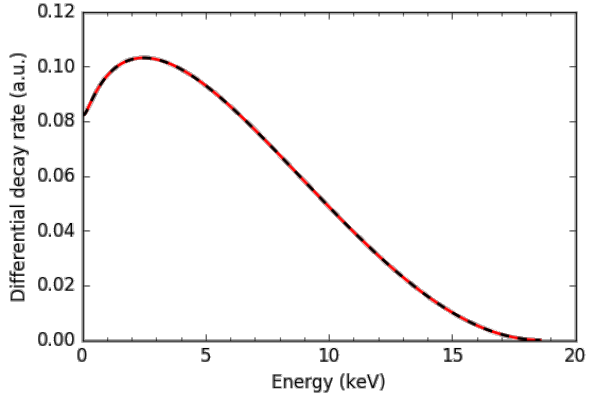
high-resolution MAC-E filter



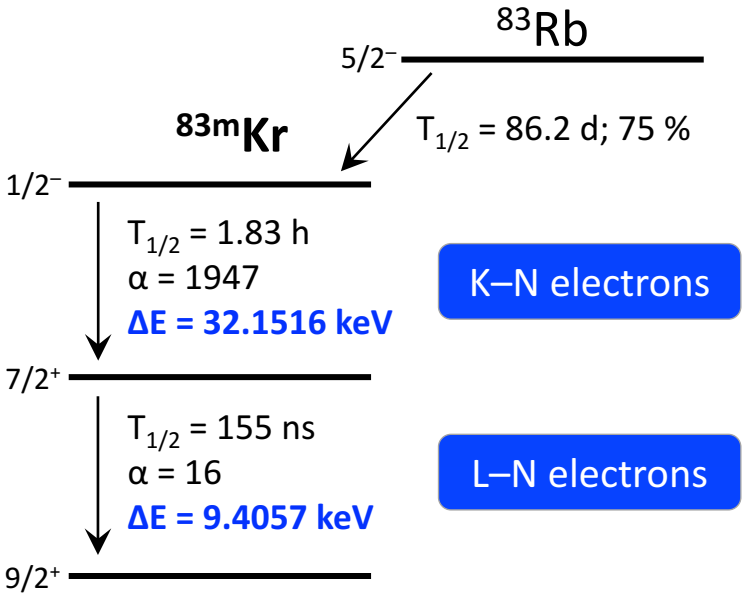


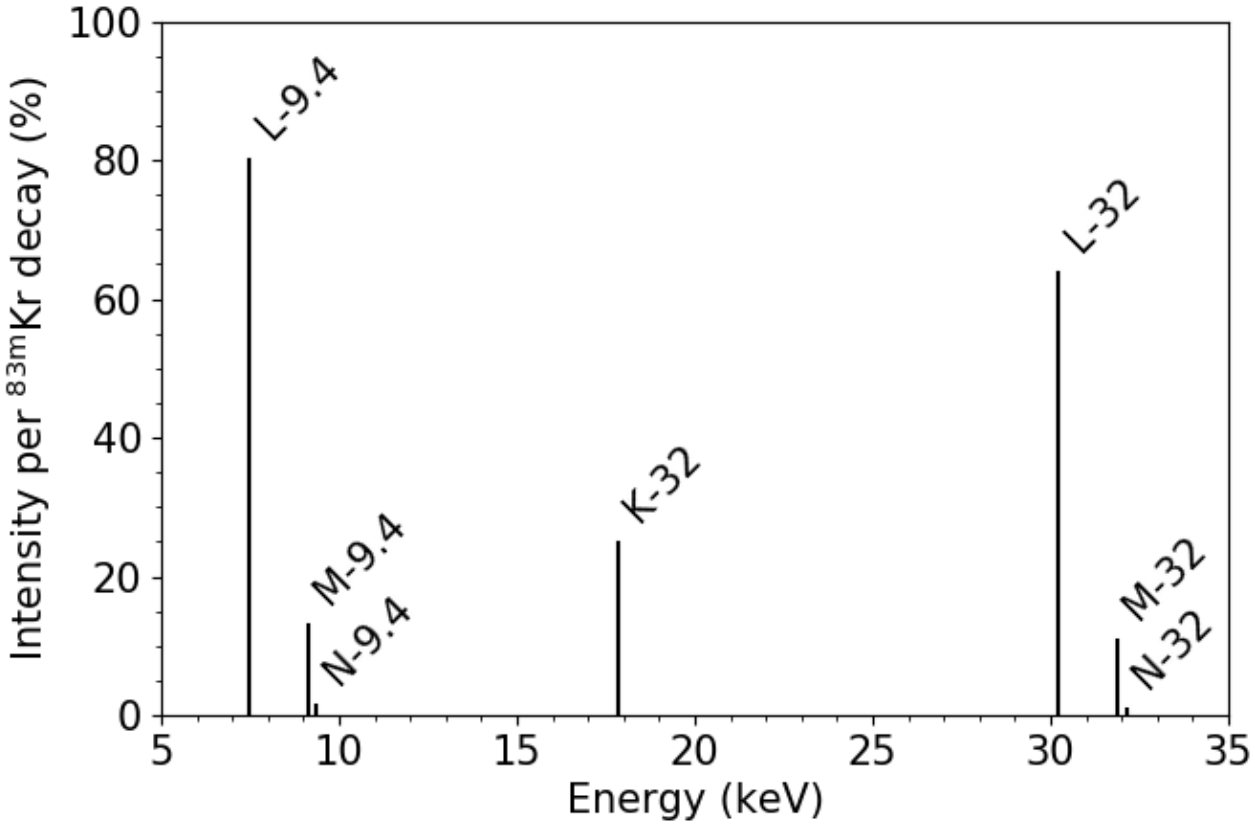
ultra-stable tritium source



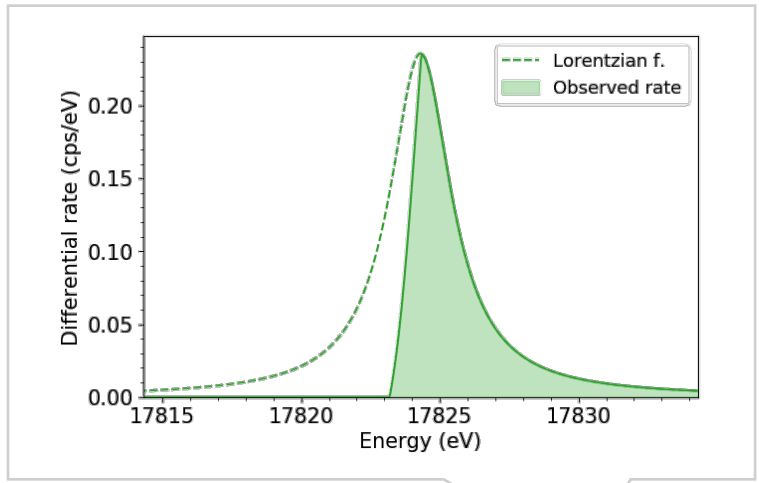


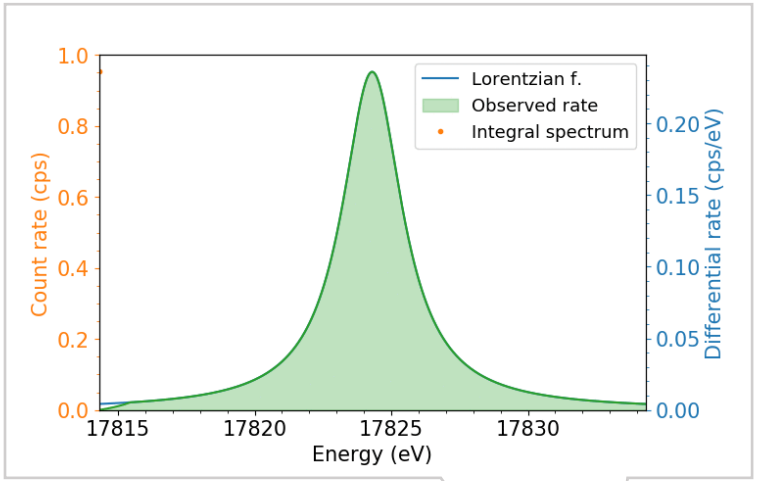
Krypton calibration source

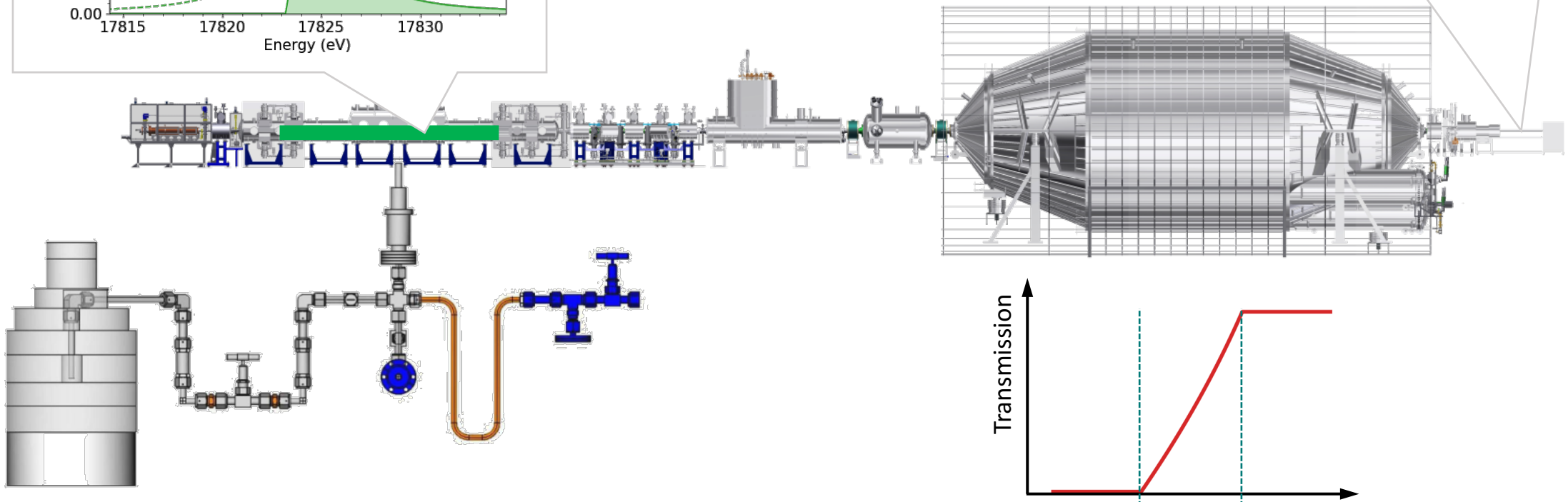




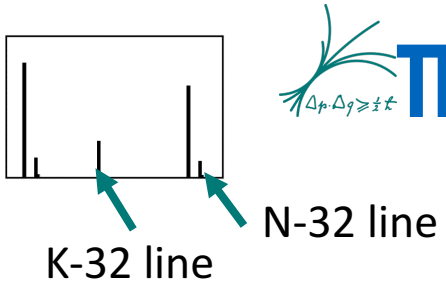
Krypton campaign (2017)



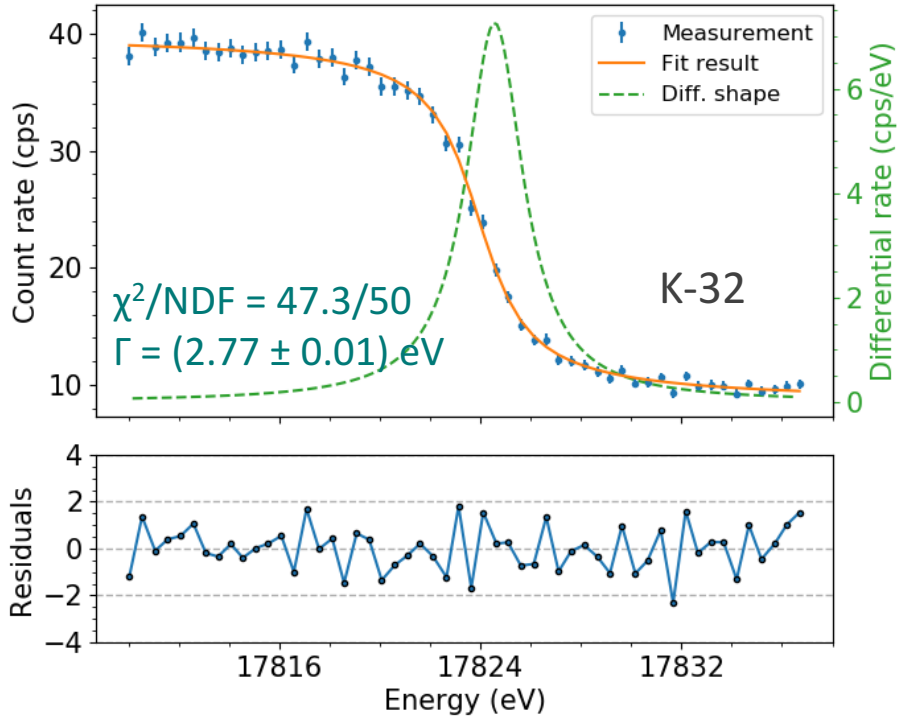


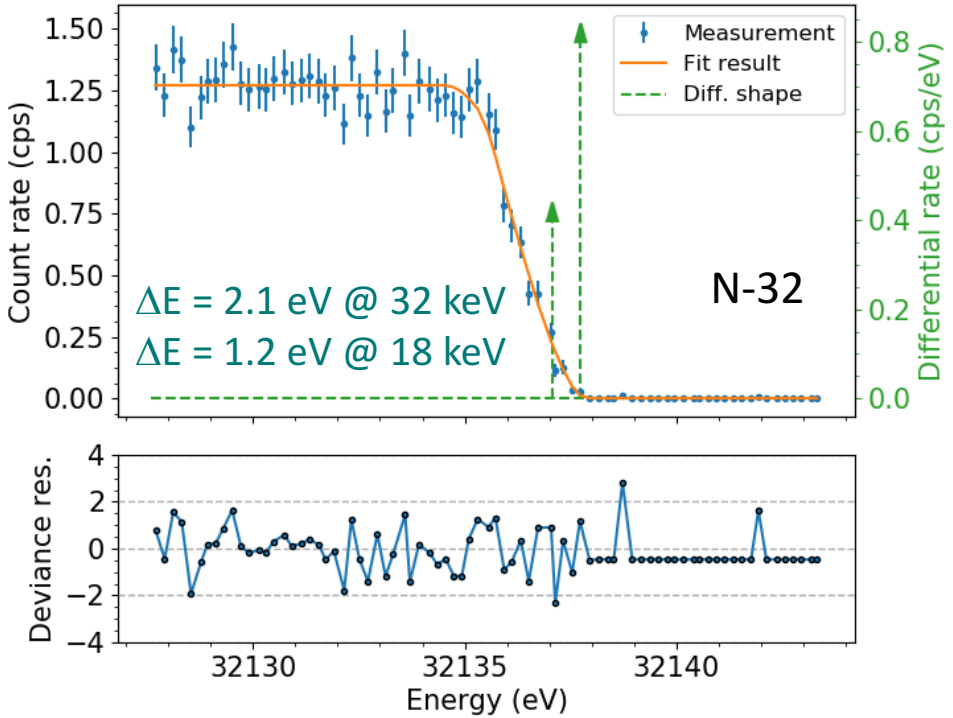


Krypton Results



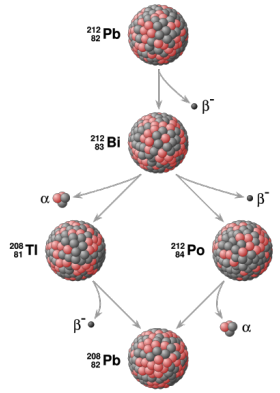
- ✓ Spectrometer resolution of ~1 eV @ 18 keV *(JINST 13 (2018) P04018, arXiv:1903.06452)*
- ✓ HV calibration on the ppm level *(EPJ C **78** 368 (2018))*

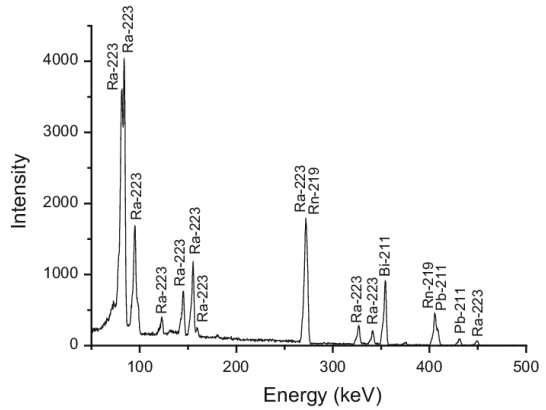




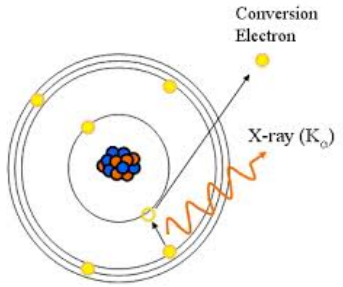
Test of Unique Properties of KATRIN

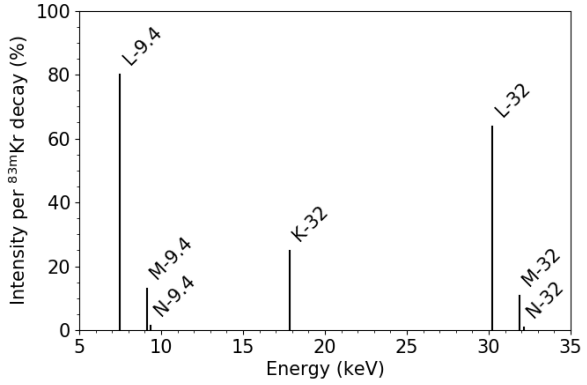
Low Background



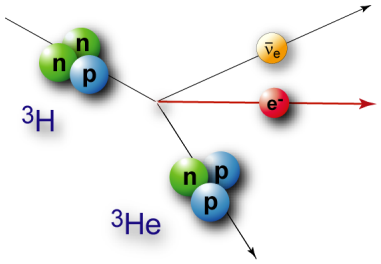


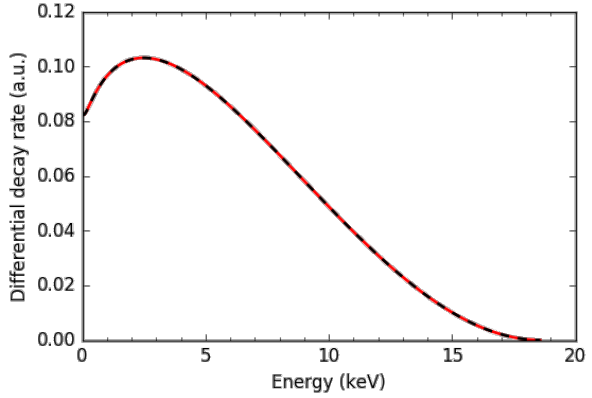
high-resolution MAC-E filter





ultra-stable tritium source





First tritium campaign (2018)

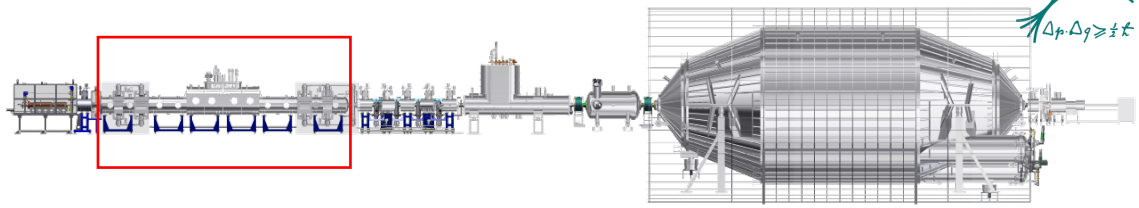
- Commissioning of system with tritium (1% of nominal activity = ~500 MBq!)
- 14 days of operation (without interruption)

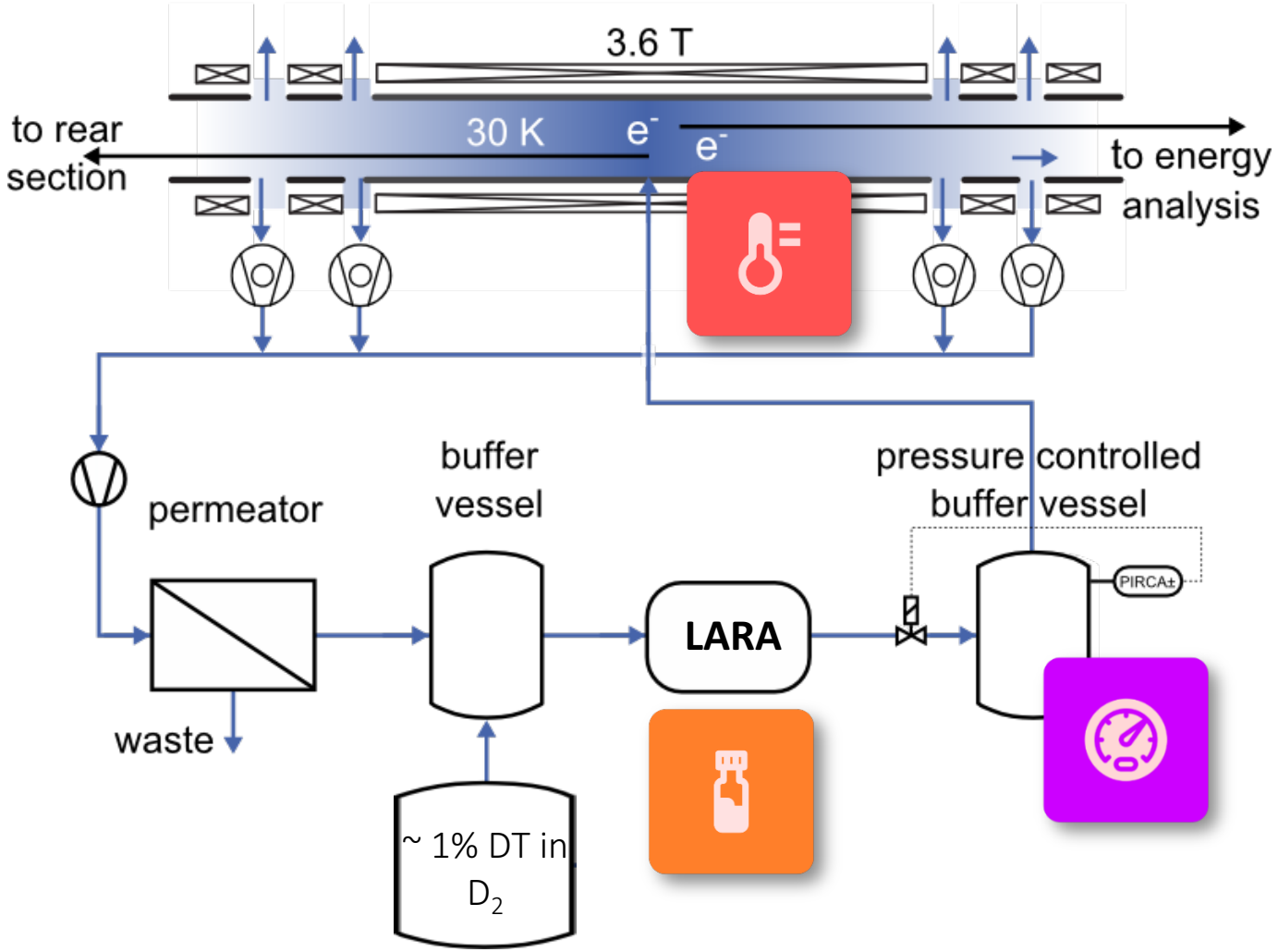
✓ Demonstrate global system stability

[arXiv:1909.06069]

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

Tritium loop system

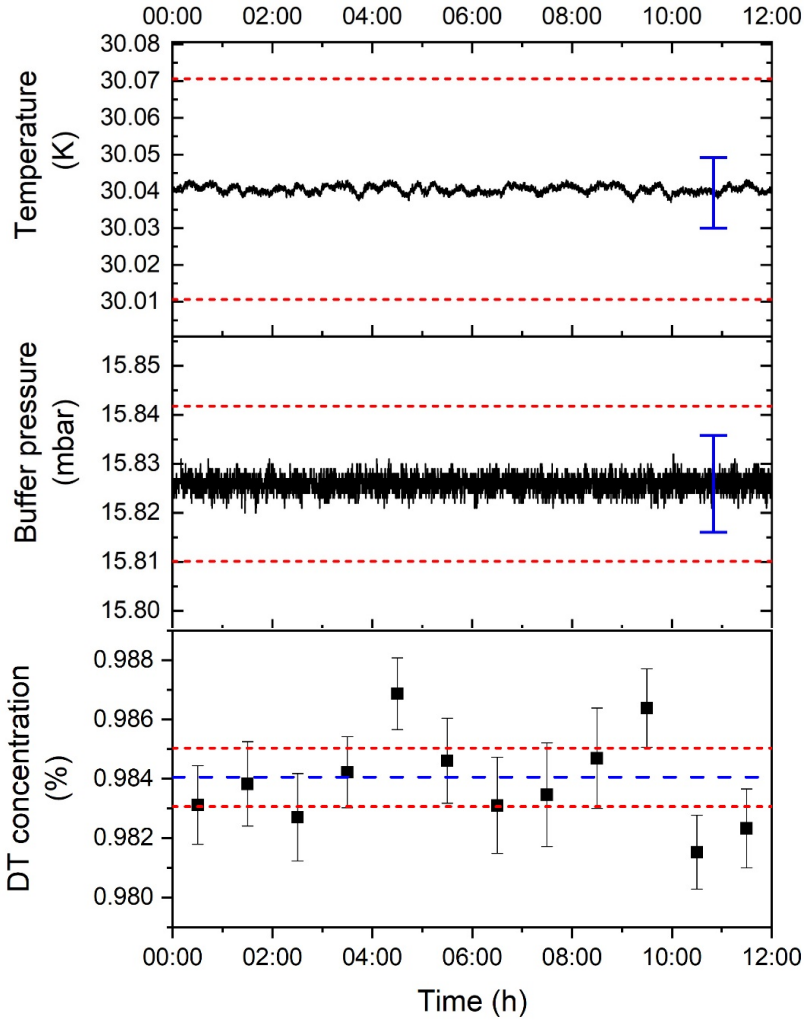




Relevant control parameters:

- Temperature
- Pressure
- Isotopic composition

Stability of source parameters

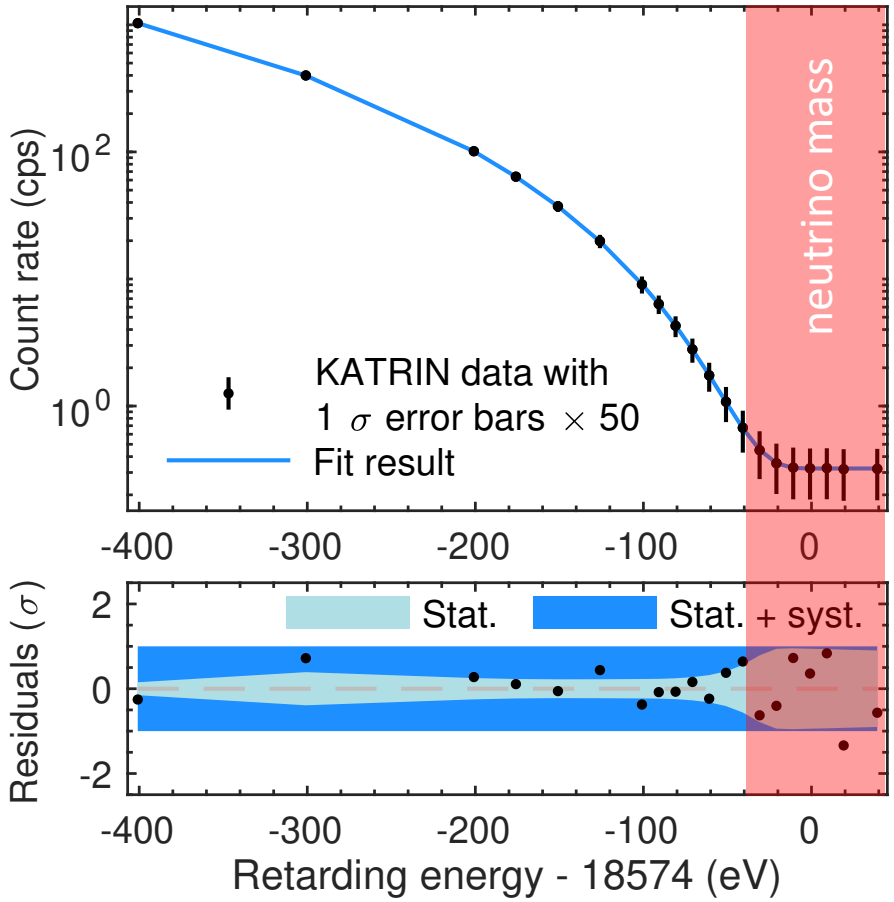


Blue arrow:
systematic uncertainty

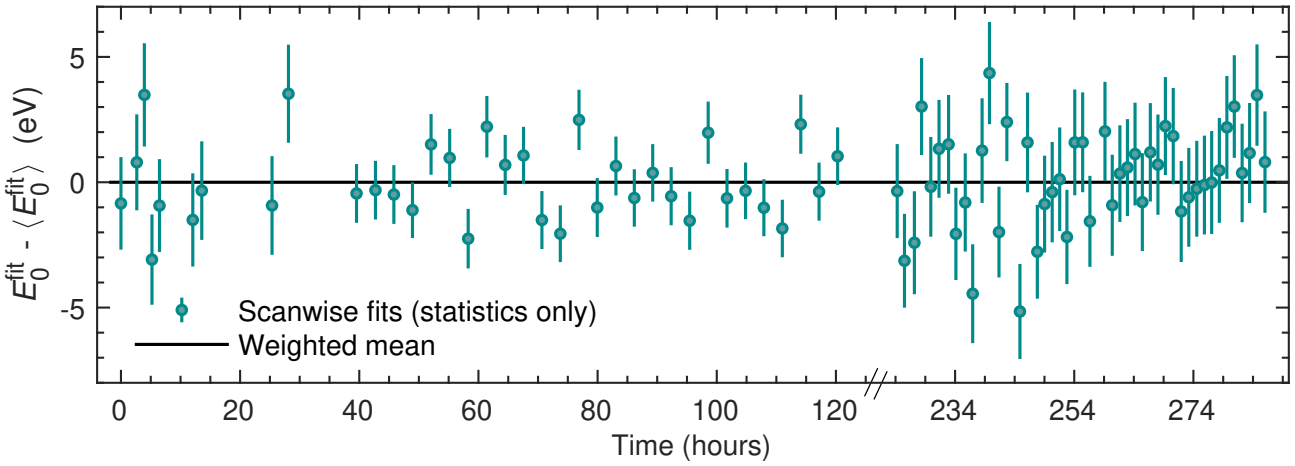
Red dashed line:
± 0.1 % reference

✓ 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



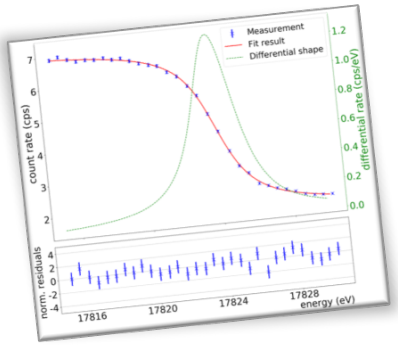
18-years of KATRIN history

Letter of Intent

2001

Main spectrometer

2004



Krypton calibration

2006

First neutrino mass

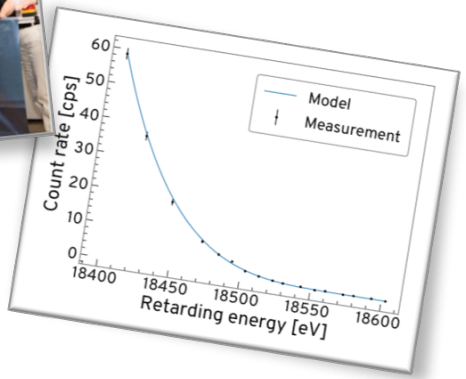
2016 2017 2018 2019

Design Report

KATRIN Design Report 2004

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 ☺**

submitted to PRL: arXiv:1909.06048

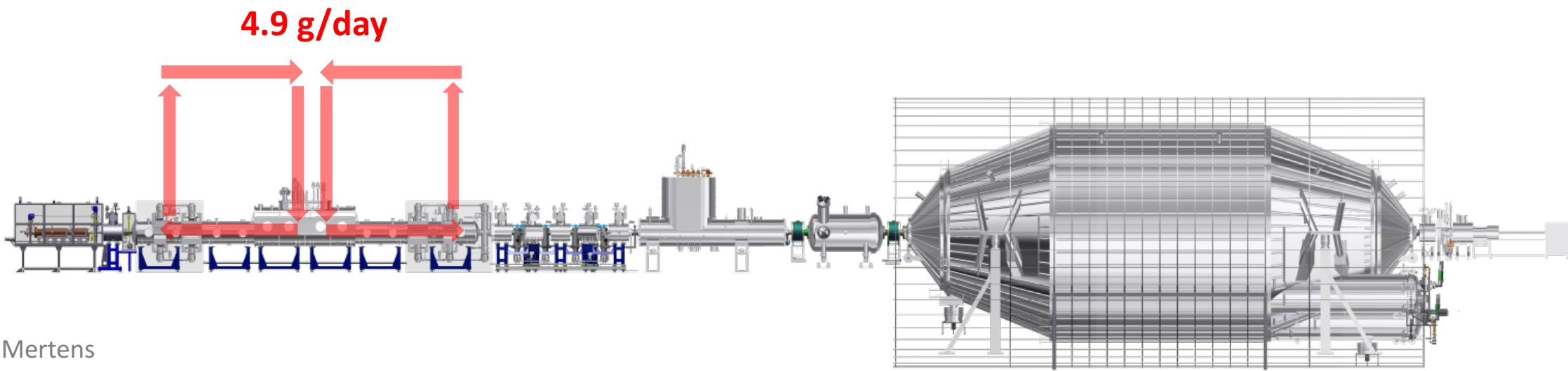
KATRIN neutrino mass campaign #1 (KNM-1)

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

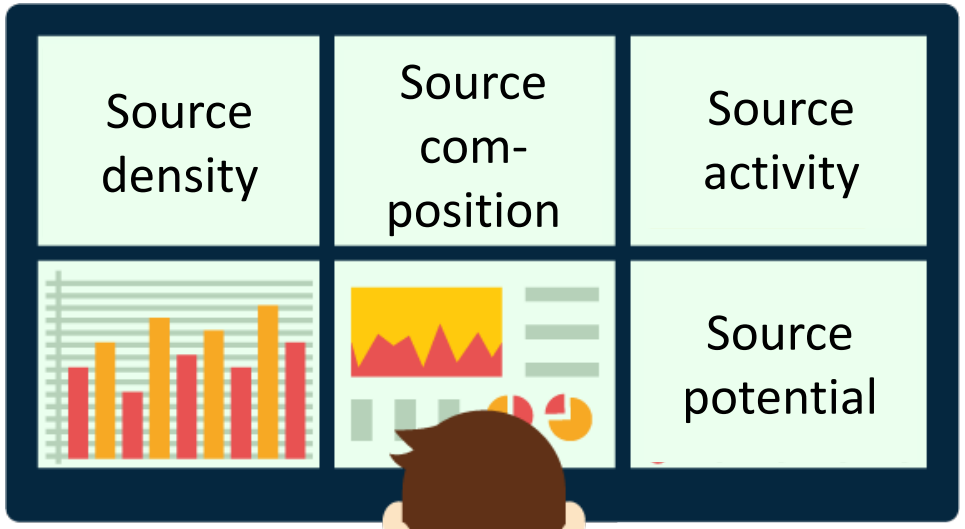
✓ **First neutrino mass result ☺**

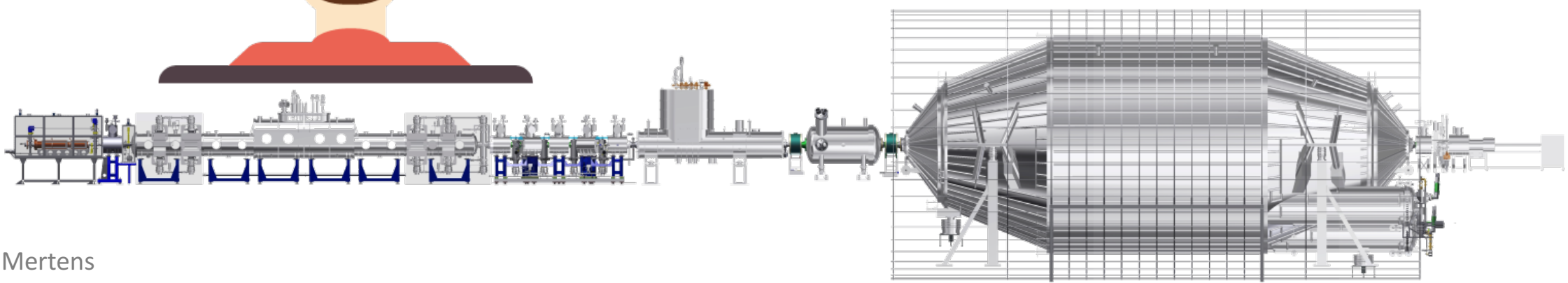
High activity tritium operation

- 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)**



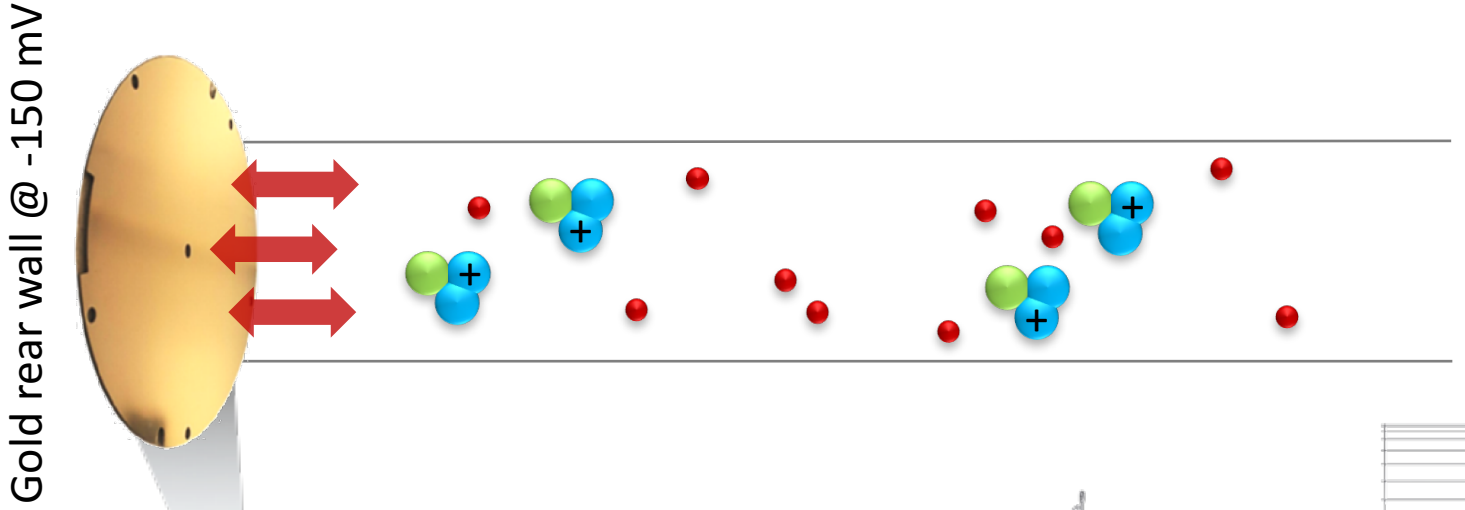
Monitoring and characterization of source

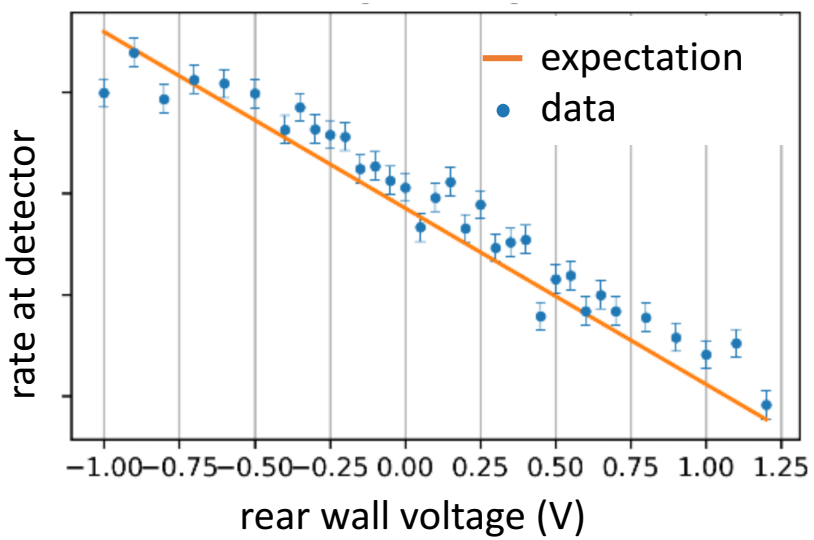


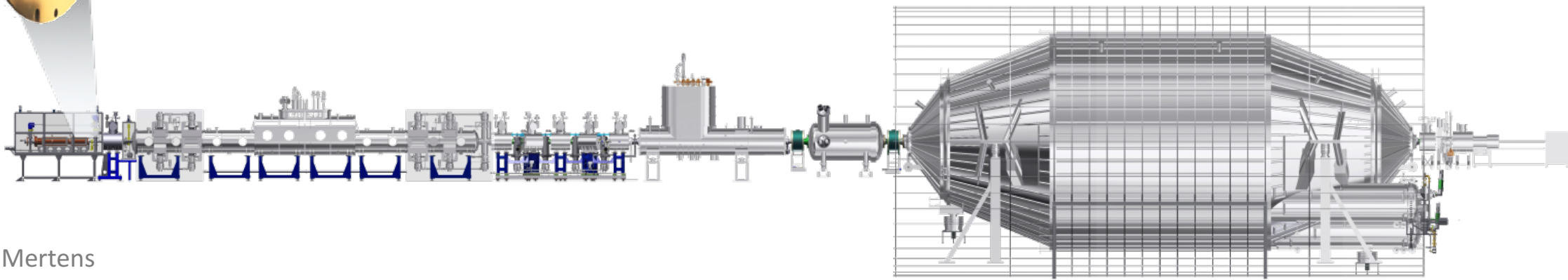


Source potential

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

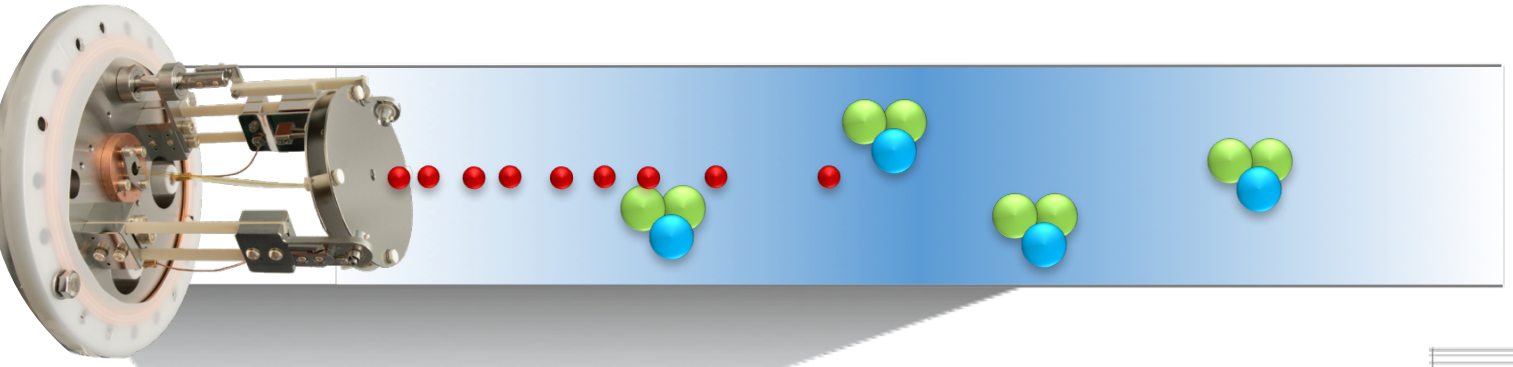


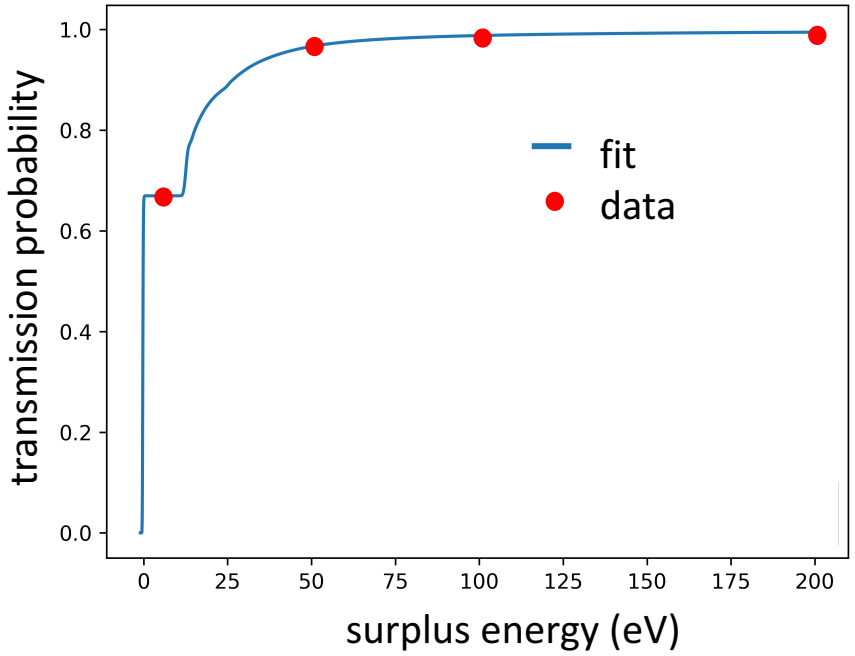


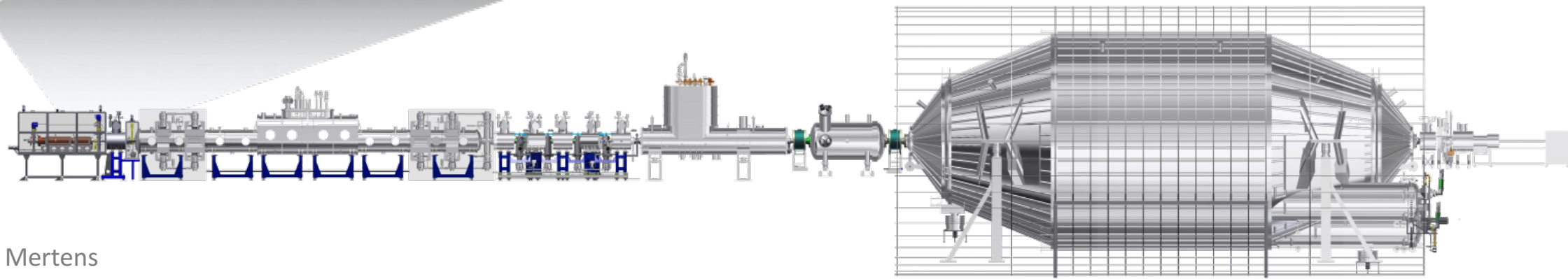


Source density

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

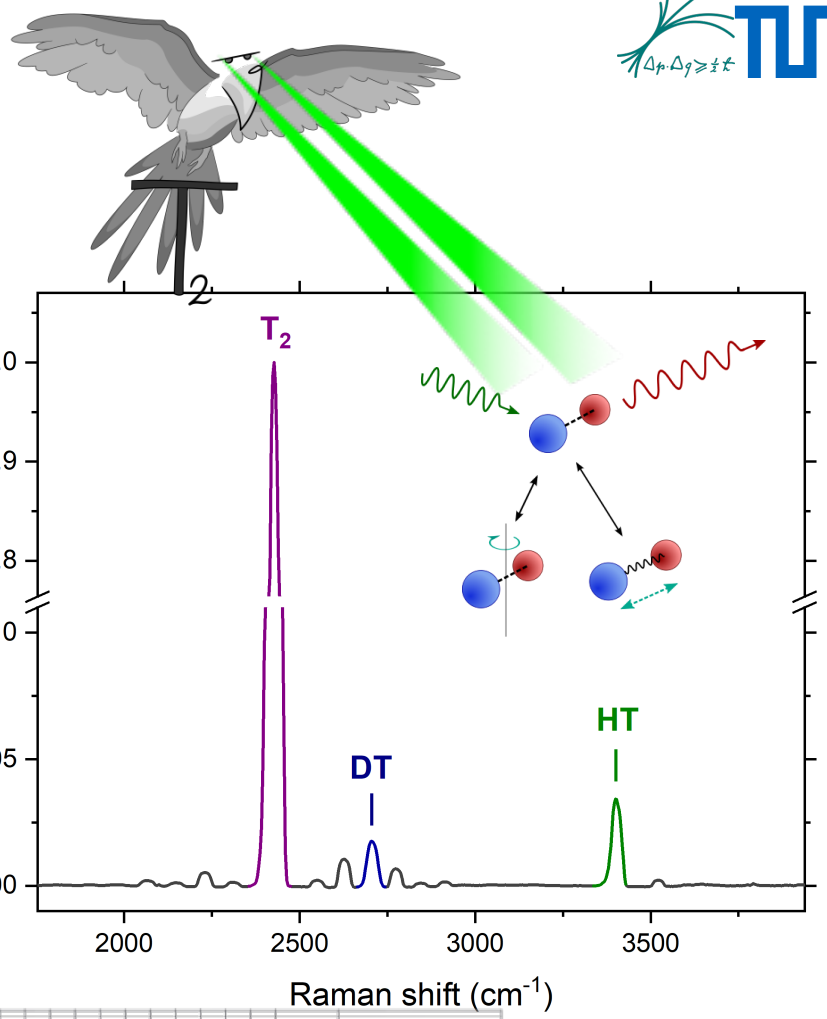


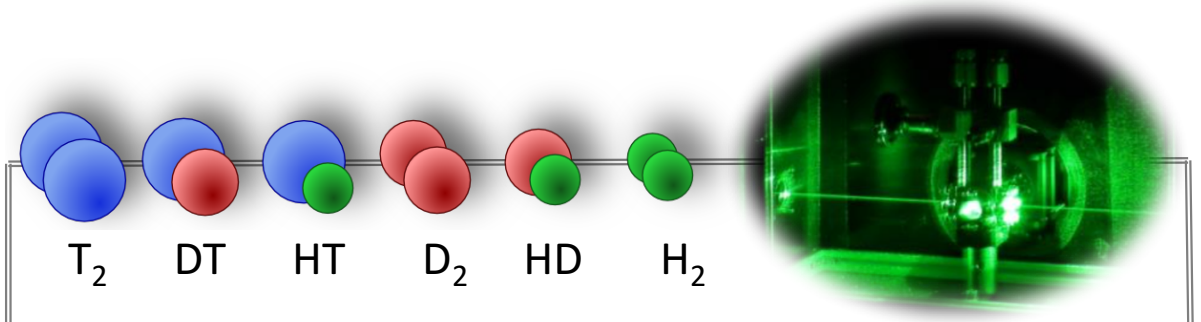


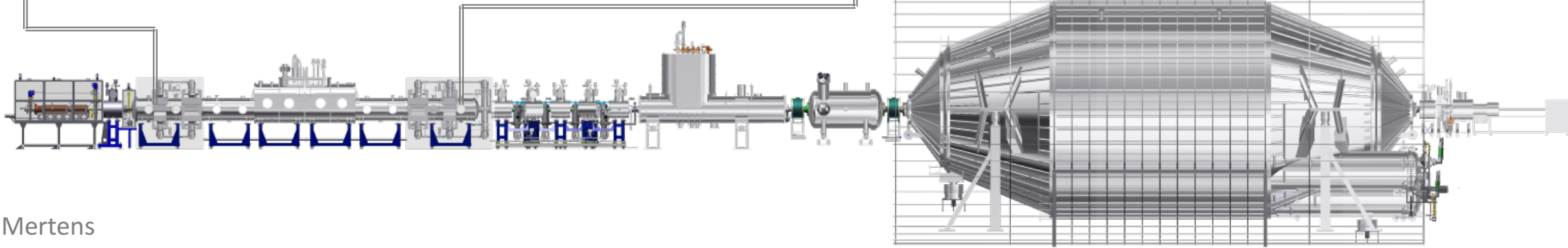


Source composition

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



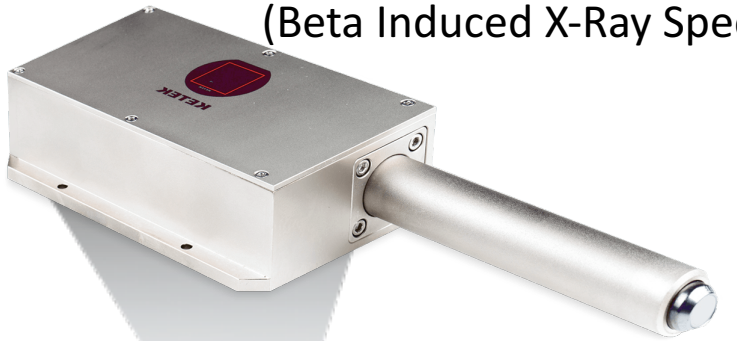




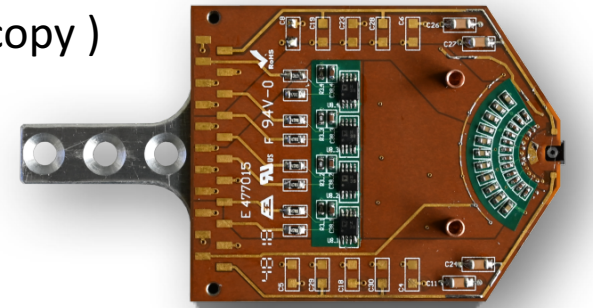
Source activity

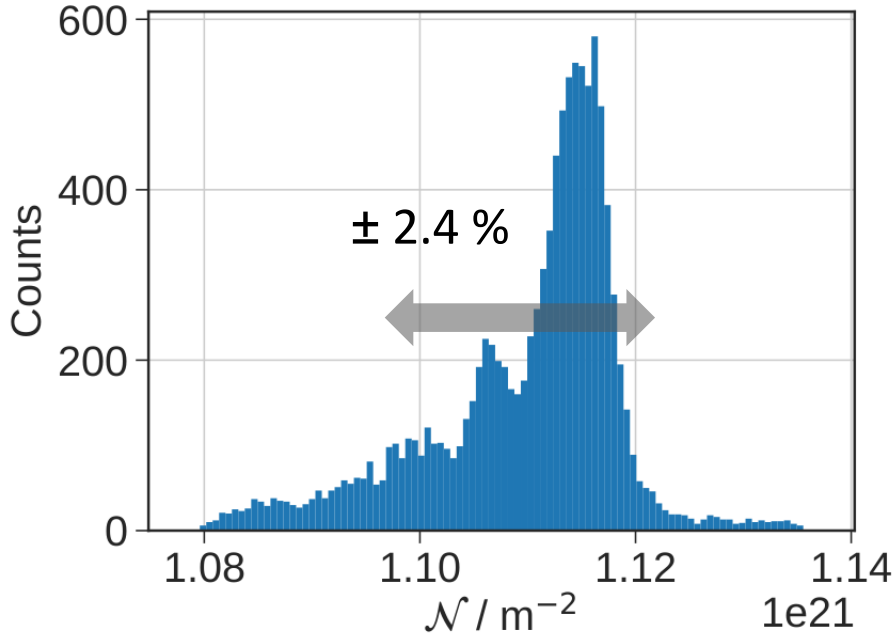
- **Forward beam monitor, BIXS System, multiple Sensors**
- Stability at the 2% level achieved

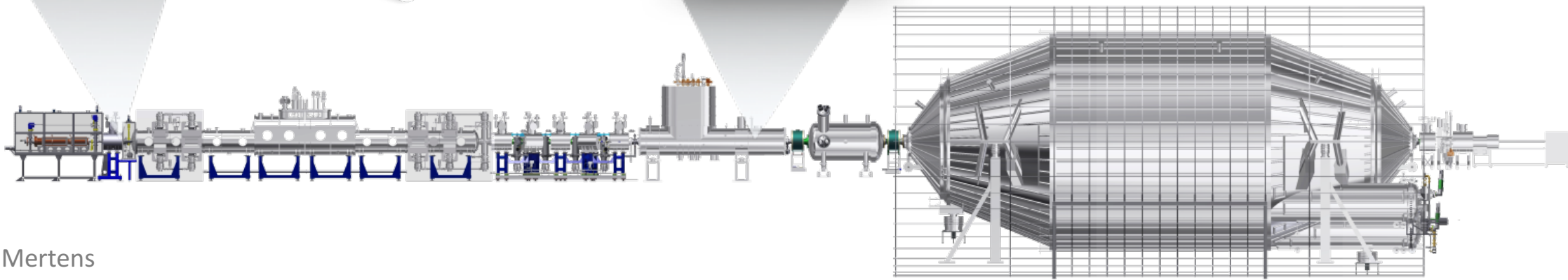
BIXS
(Beta Induced X-Ray Spectroscopy)



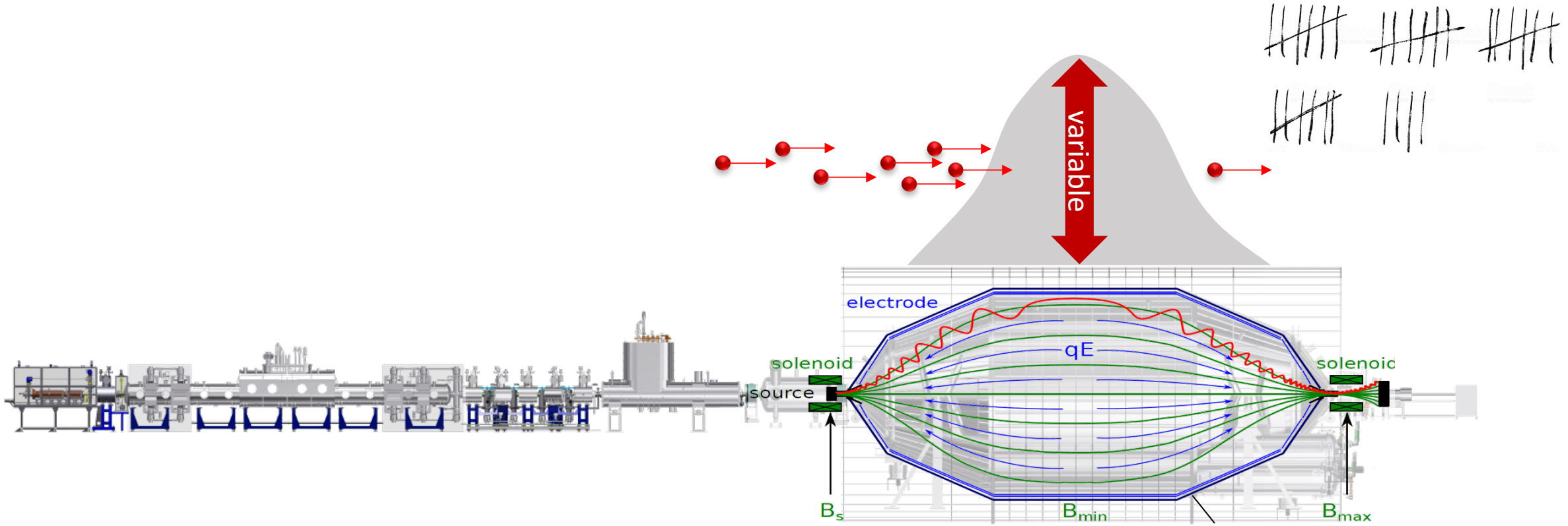
FBM







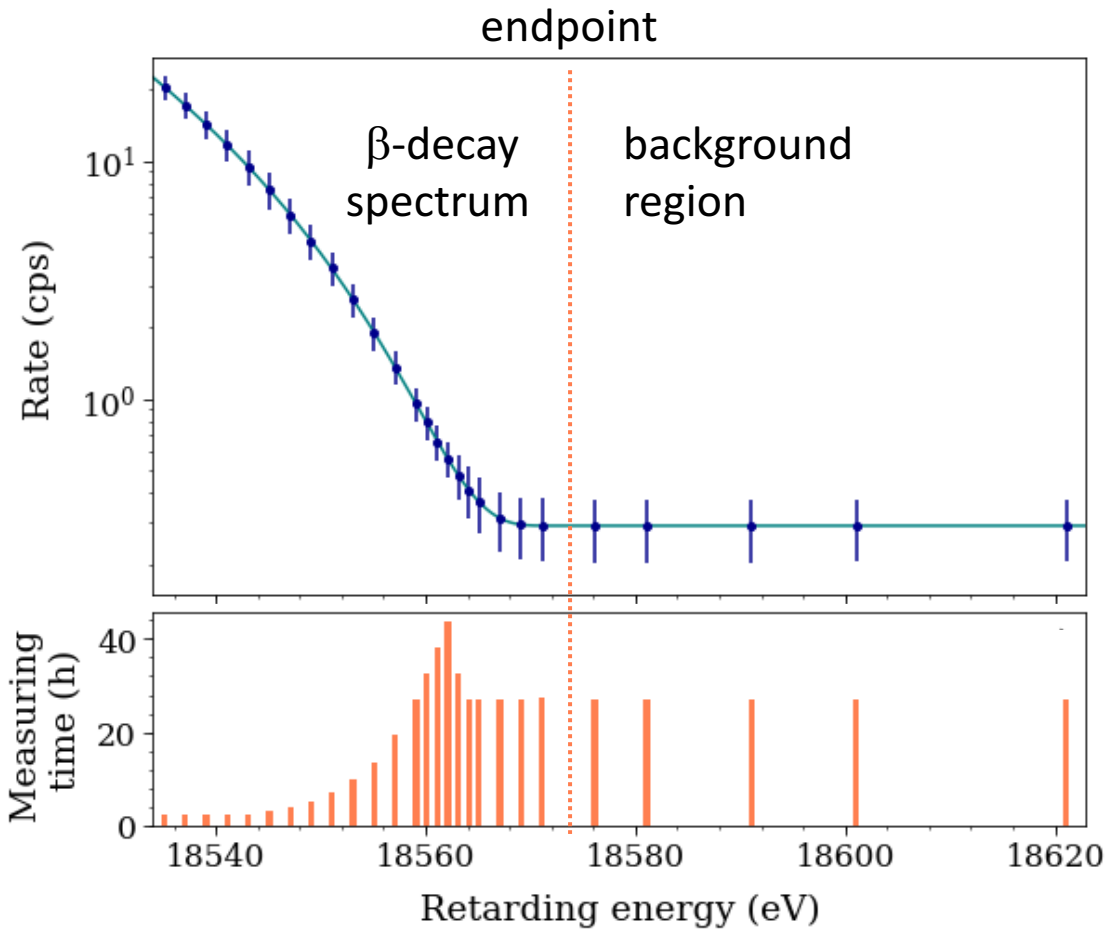
How to obtain the tritium spectrum?



Scanning Strategy

- 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**

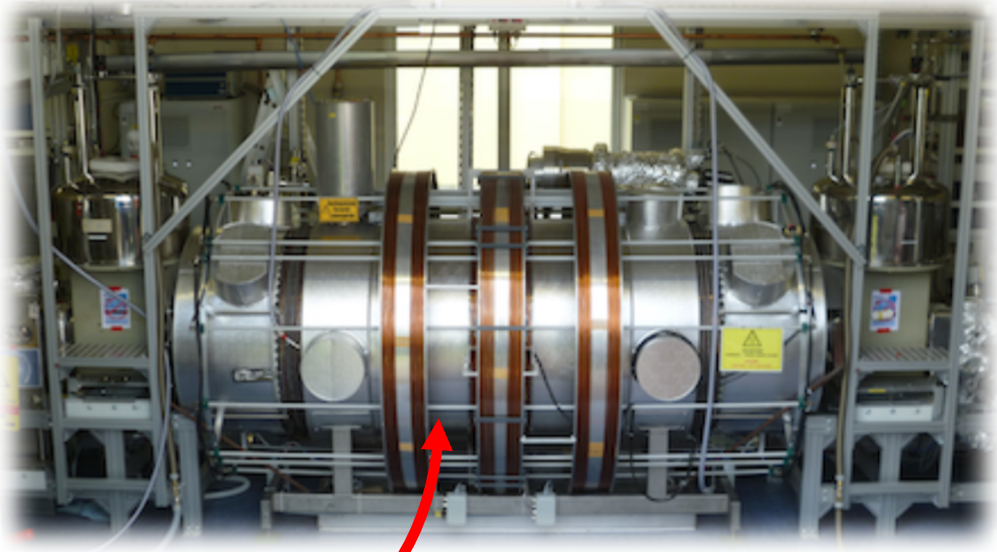
➢ **One β-decay spectrum for each scan**



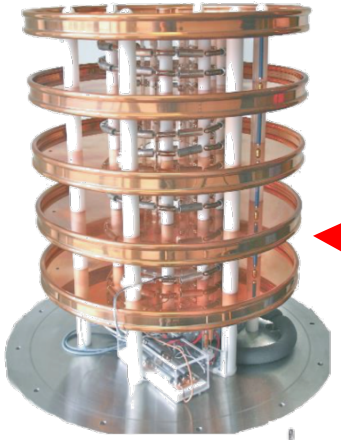
High voltage stability

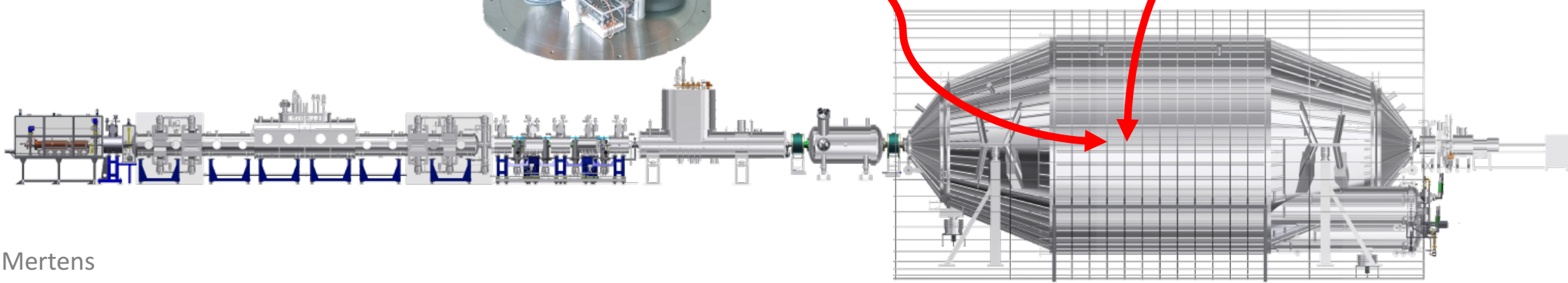
- Short term (seconds) HV stability: < 20 mV
- Long-term (days) HV stability: < 20 mV/day

Monitor Spectrometer



High Voltage Divider

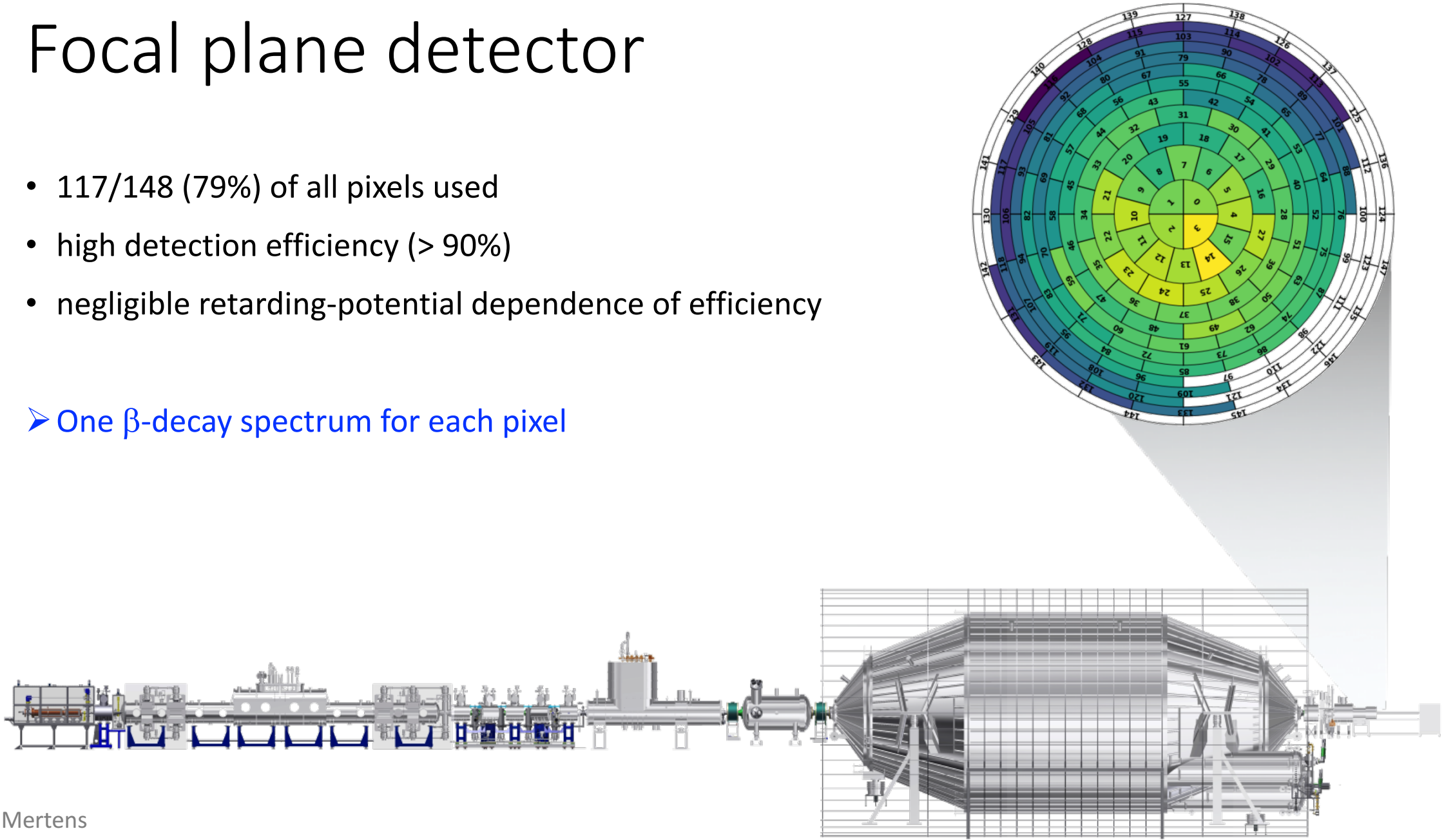




Focal plane detector

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

➢ One β-decay spectrum for each pixel



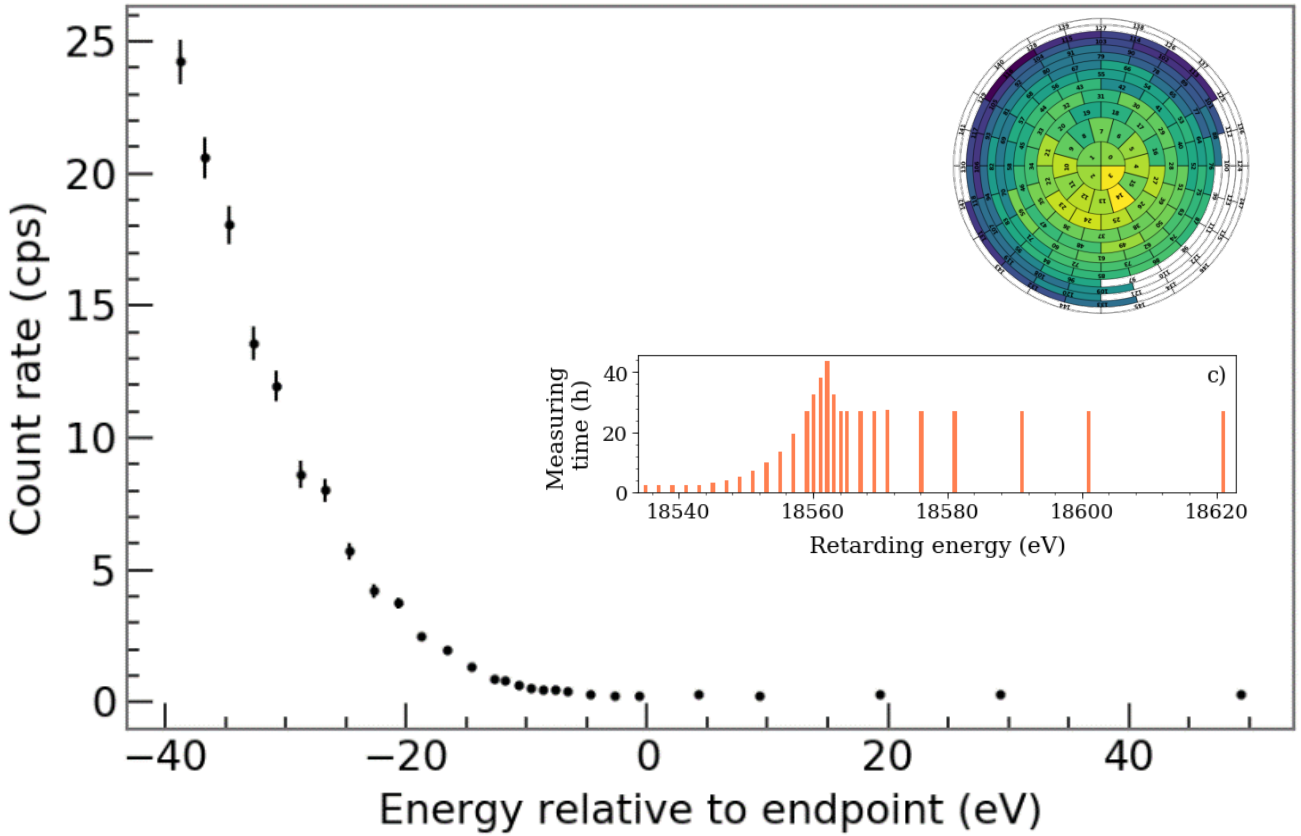
… and finally: the tritium spectrum

32058 β-decay spectra

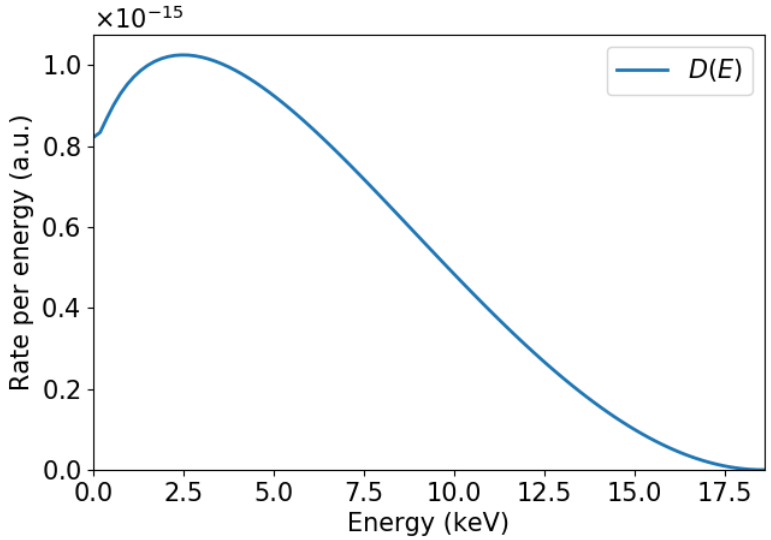
- for each detector pixel
- for each scan

Task of "fitting" teams

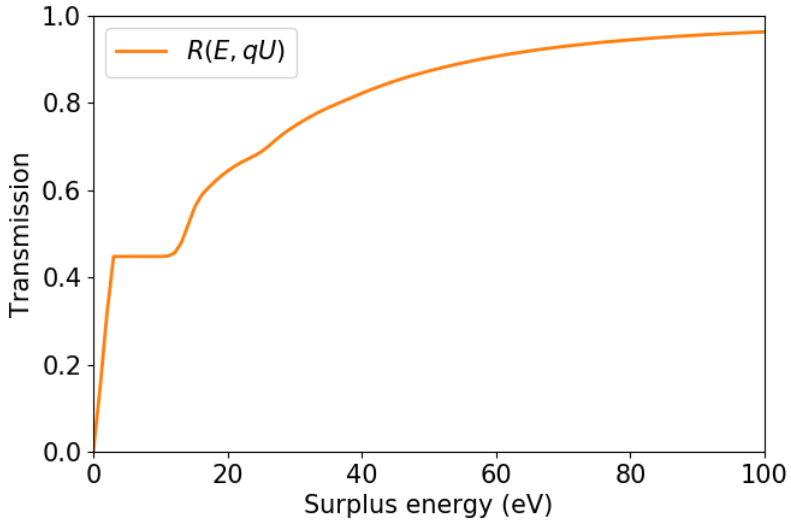
- combine spectra in a smart way
- infer physics parameters

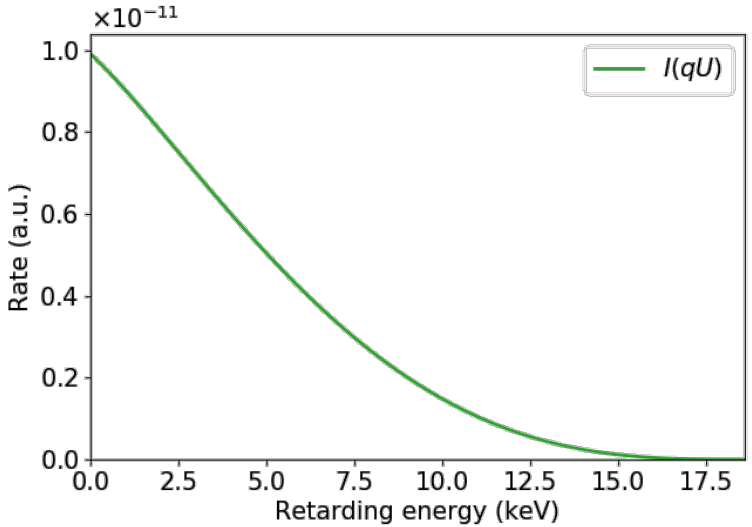


Tritium spectrum calculation



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

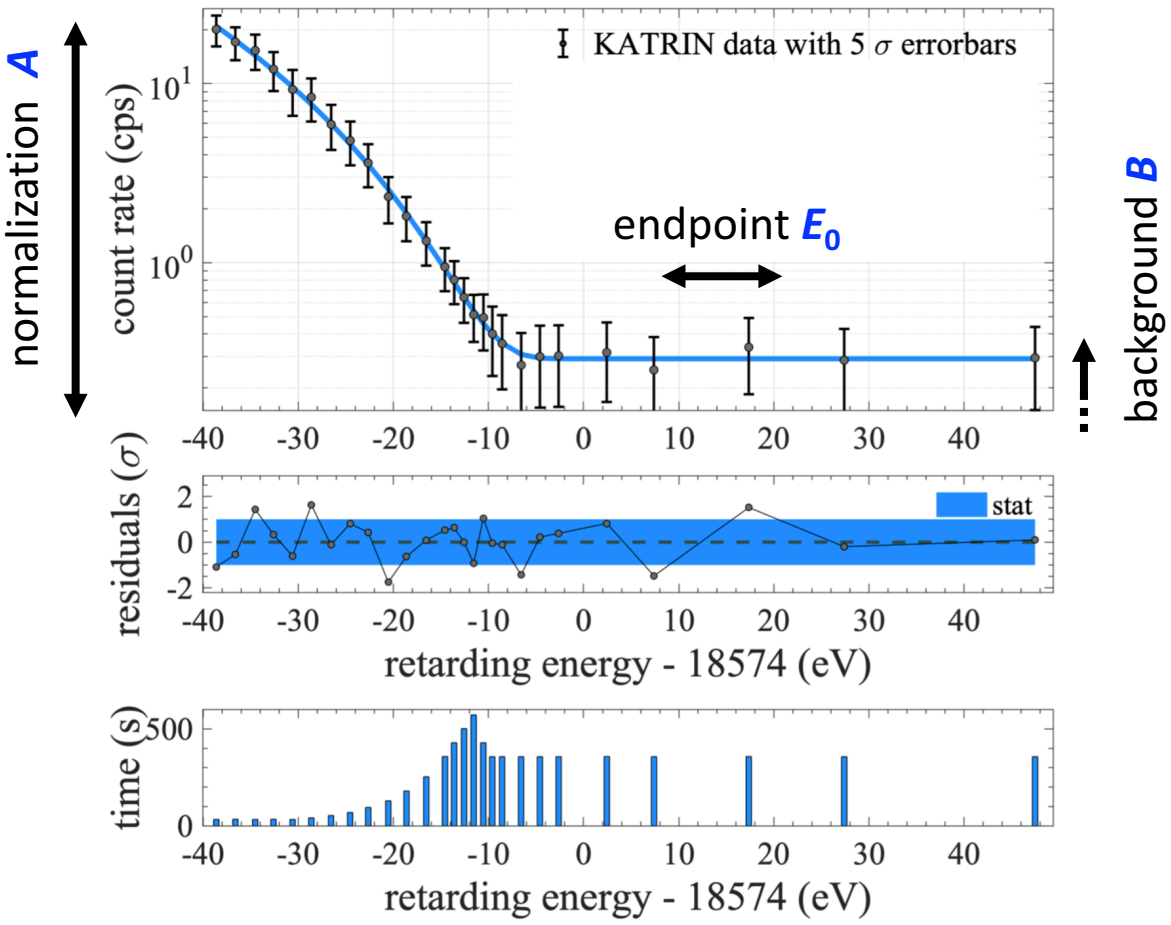




- Fermi theory
- Decay to molecular final states
- Doppler broadening

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

Fit of a single 2-h beta-scan

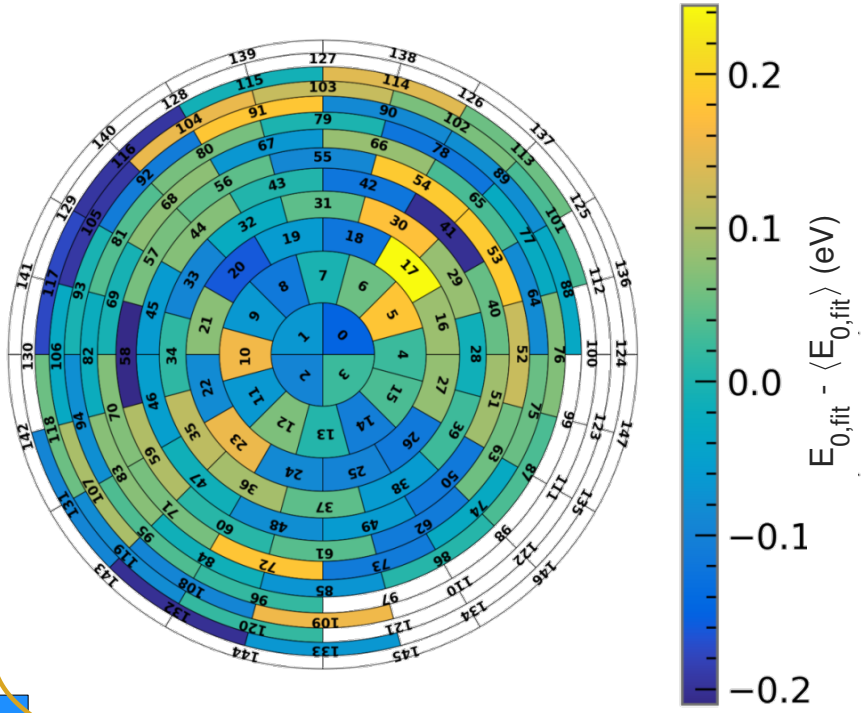


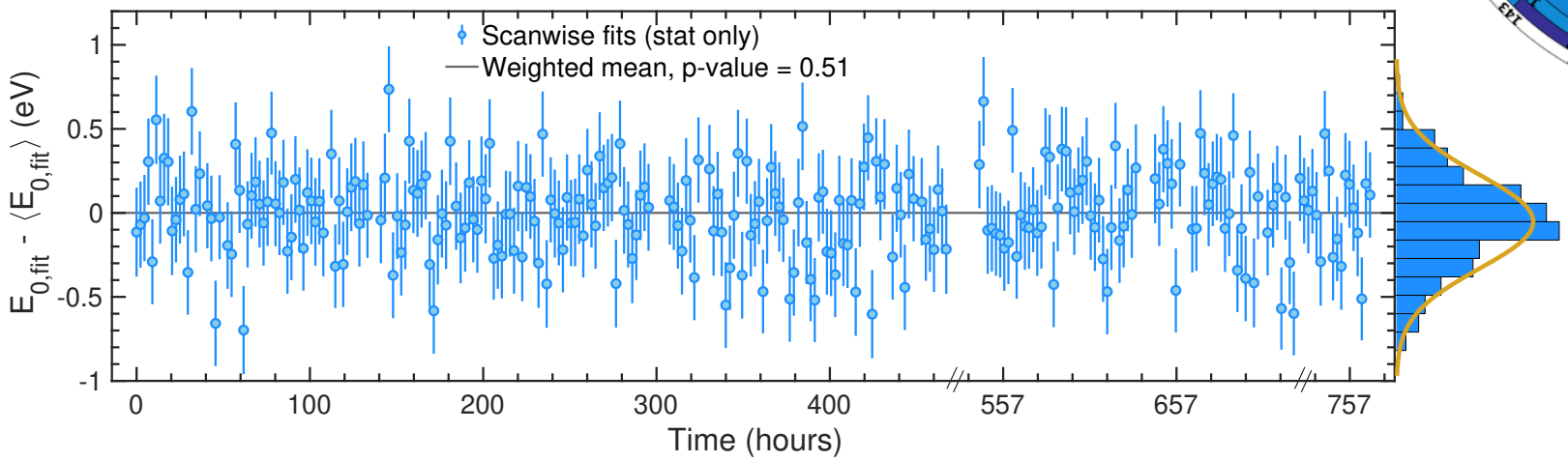
$$\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{\boldsymbol{E_0}} D\left(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}\right) \cdot R(qU, E)\, dE + \boldsymbol{B}$$

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

Stability of fitted endpoint

- ✓ Stable from scan to scan
- ✓ Homogeneous of detector pixels

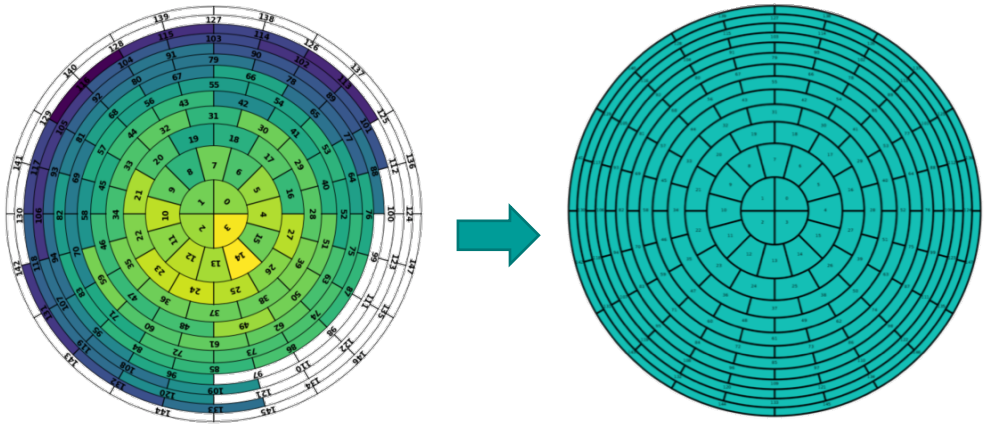




Data combination

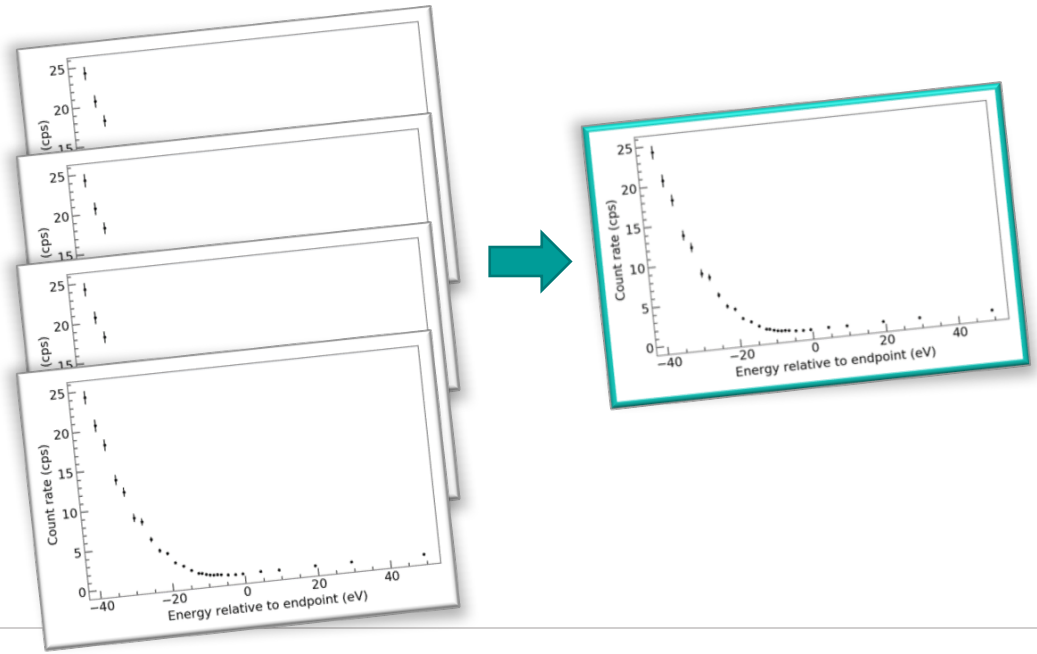
Pixel combination

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



Scan combination

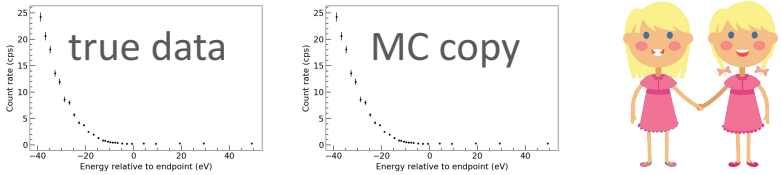
- sum the counts of all sub-scans
- use average HV ($\sigma_{HV} < 34$ mV) + slow control



3-fold bias free analysis

Freeze analysis on fake data

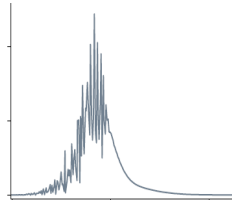
- Generate MC-copy of each scan
- Use slow control data as input

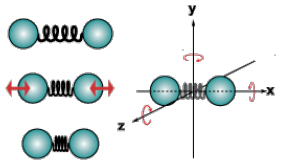


m_ν^2

Blinded model

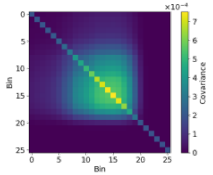
- Modified molecular final state dist.
- Affects only neutrino mass

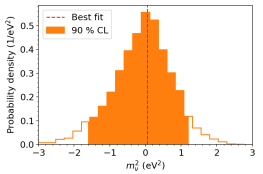




Two independent analysis strategies

- Covariance matrix
- Monte Carlo propagation

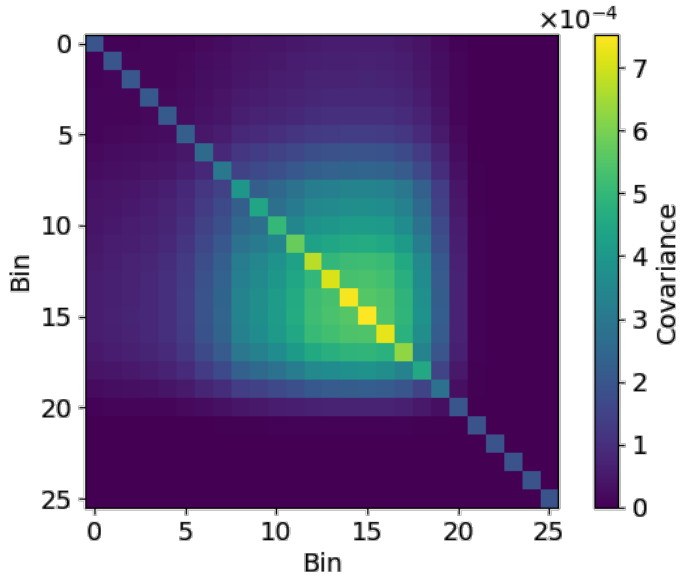




Two independent analysis approaches

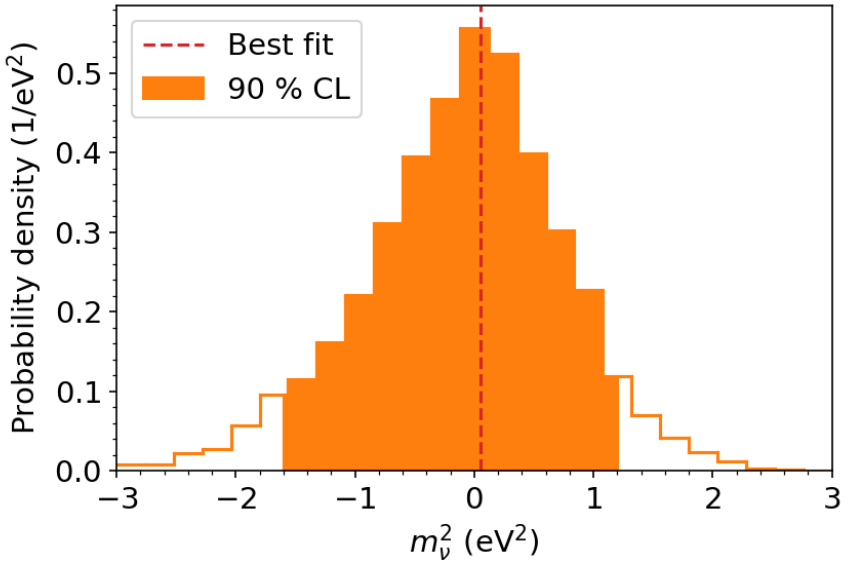
Covariance matrix

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

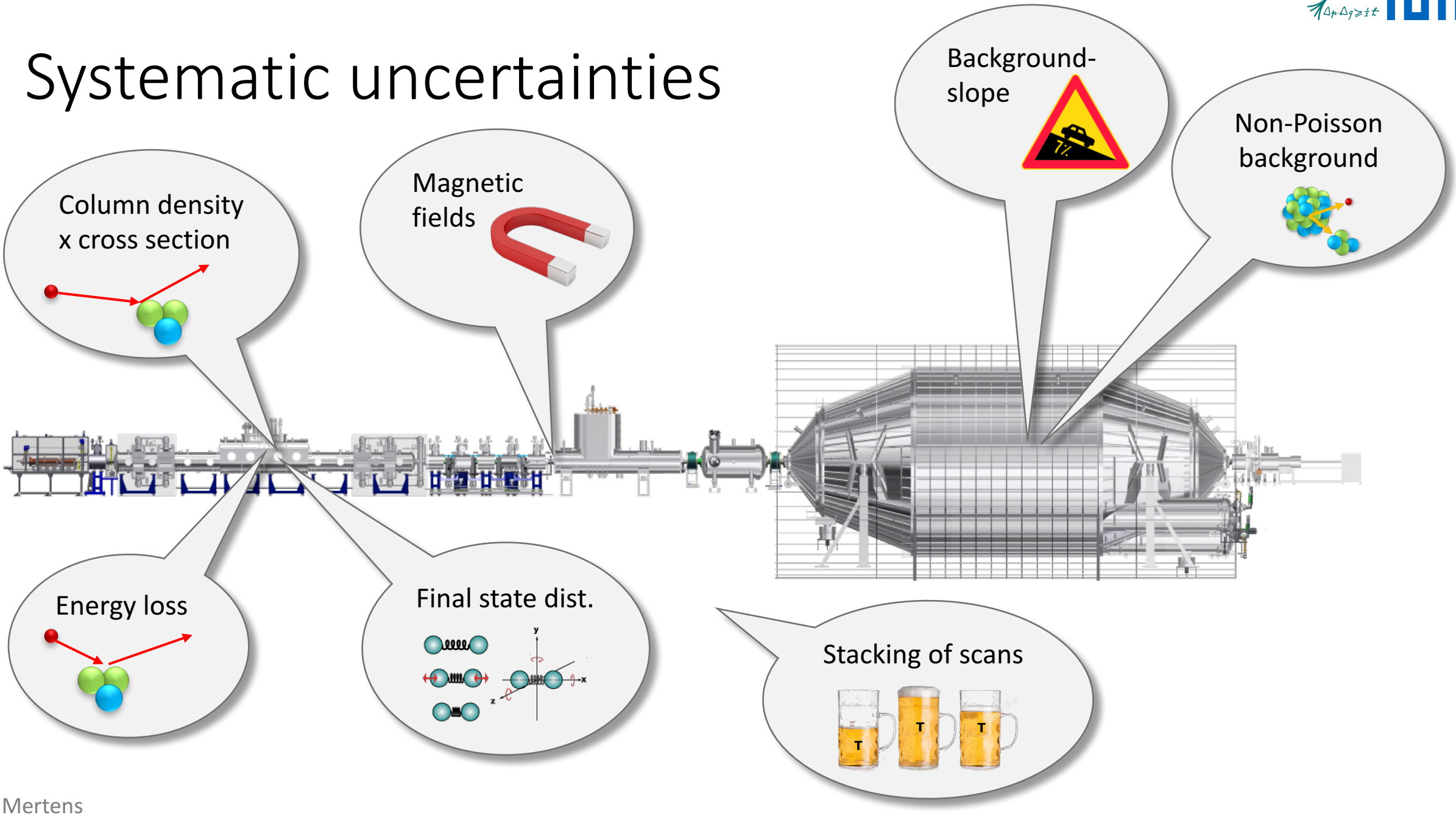


MC propagation

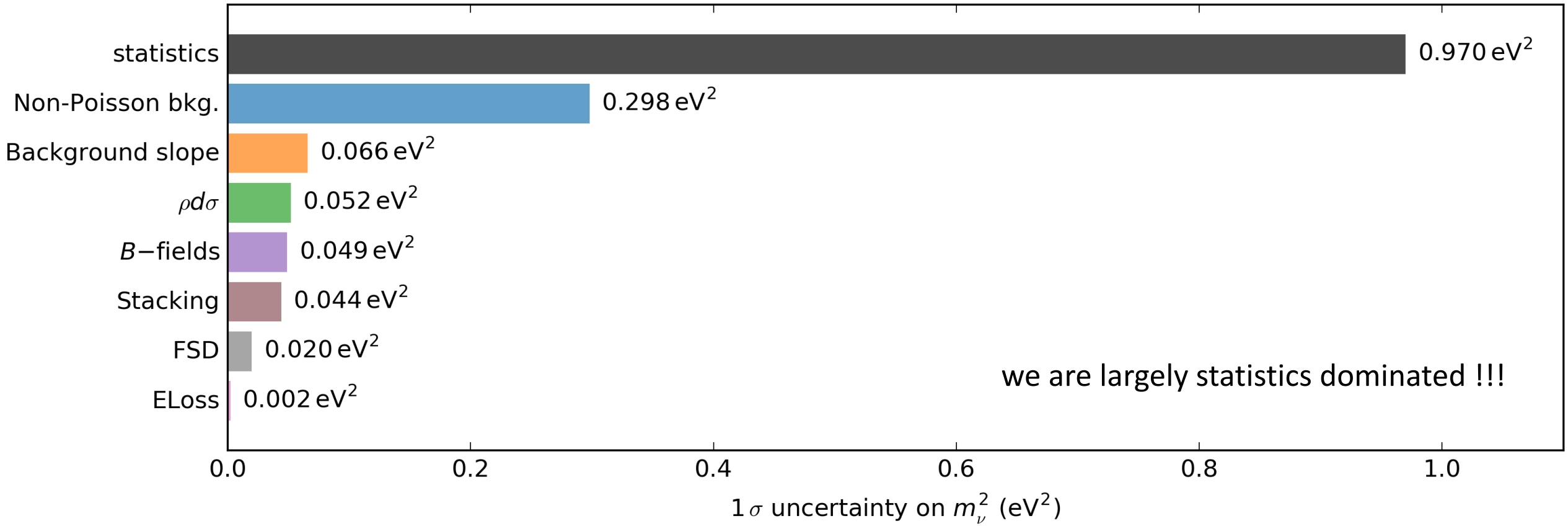
- $-2 \log \mathcal{L} = 2 \sum_i [m_i - d_i + d_i \log(d_i/m_i)]$
- Systematics: **Fit** performed 10^5 times



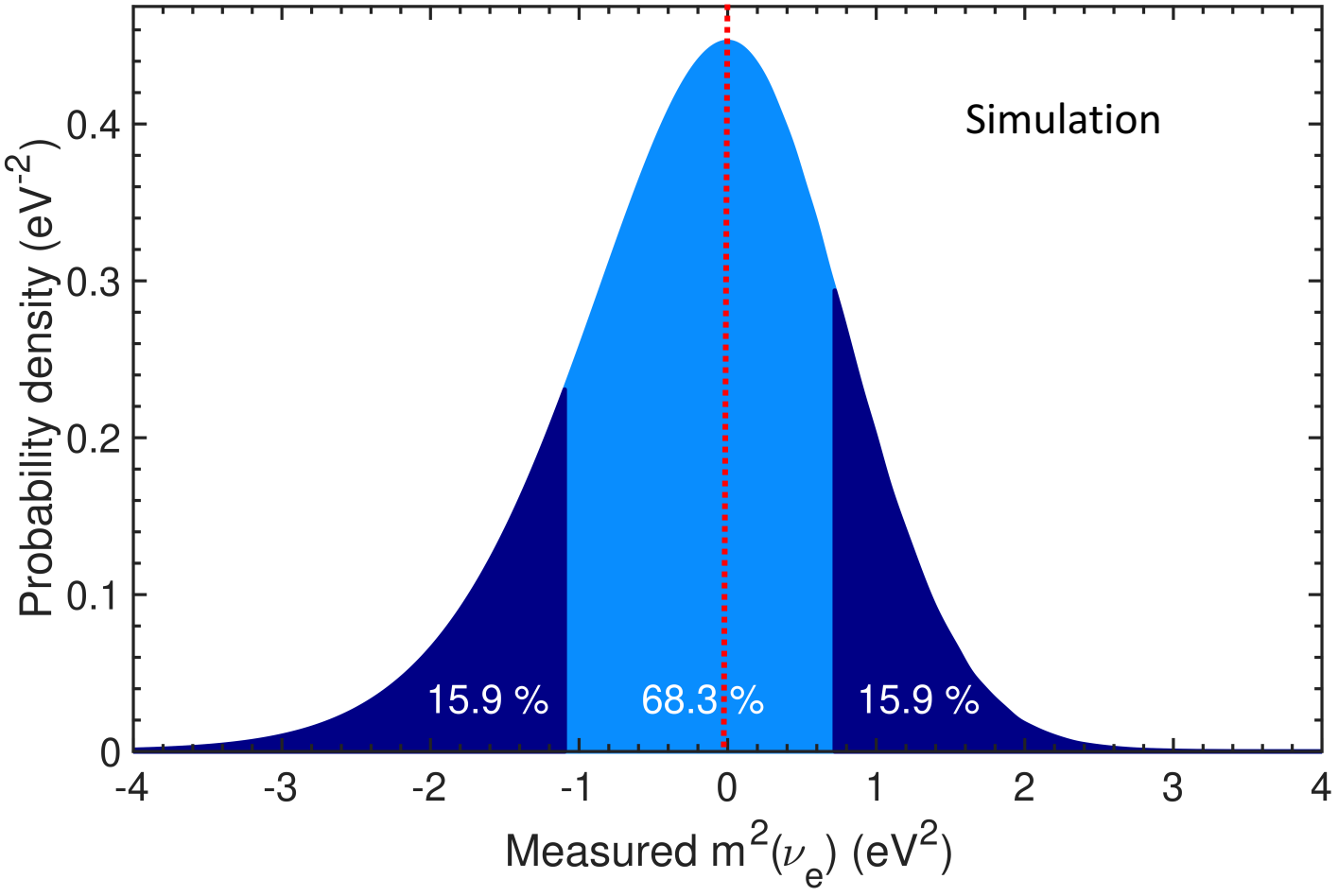
Systematic uncertainties



Budget of uncertainties

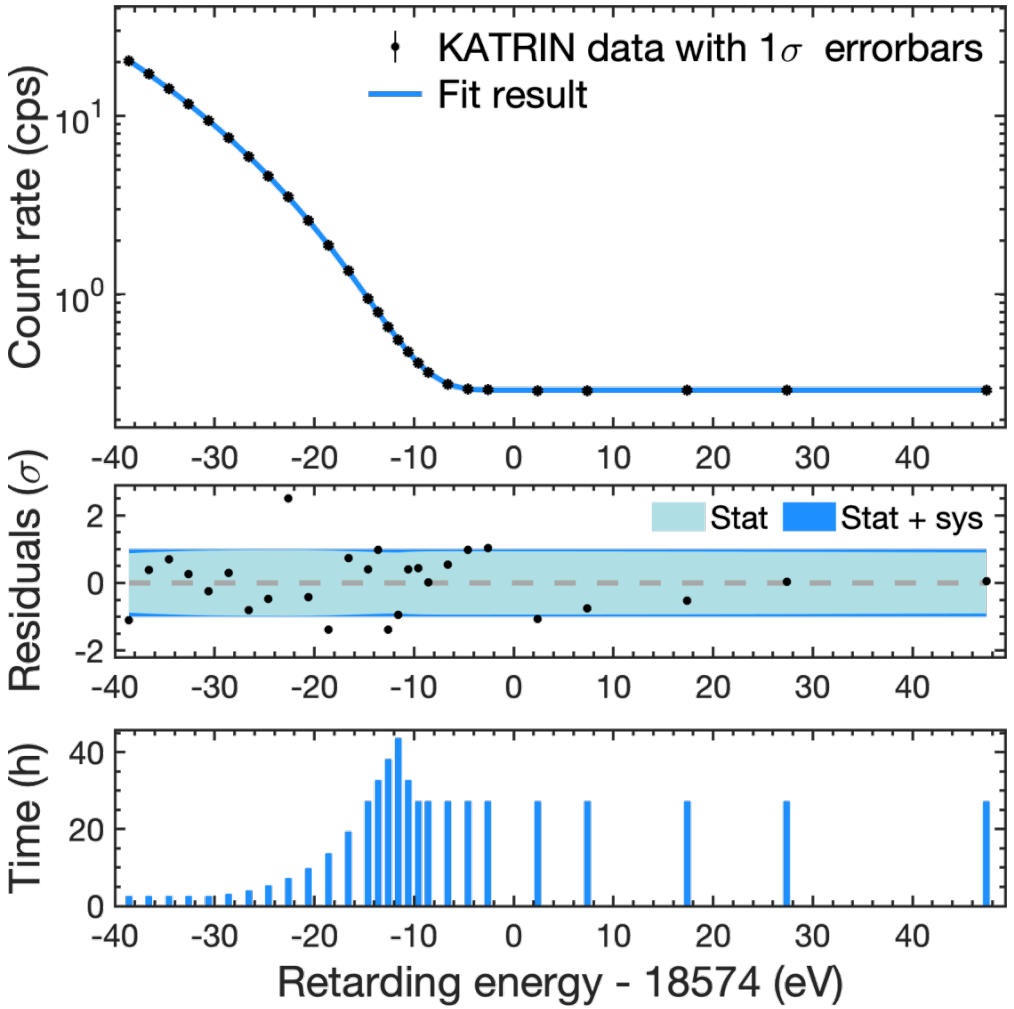


What do we expect to measure?



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

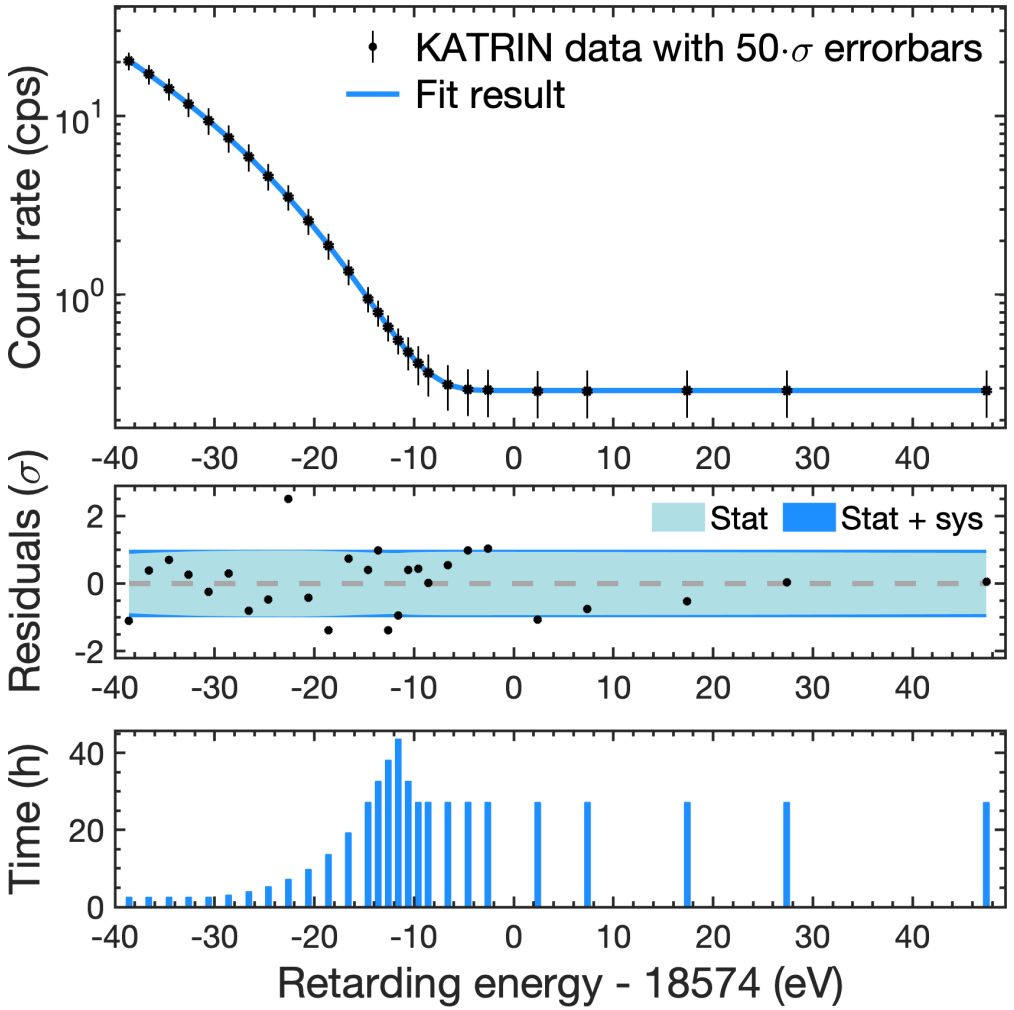
Final fit result (neutrino mass)



- 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)



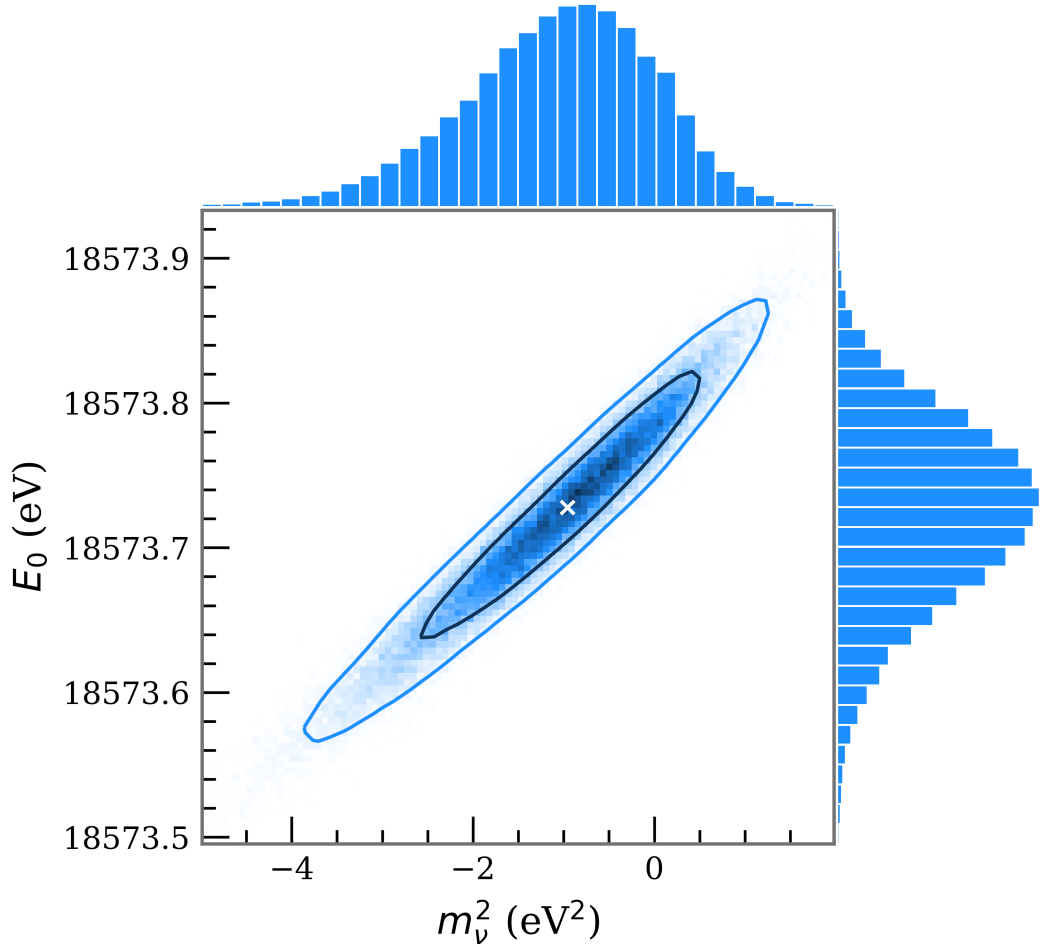
- 2 million events
- 4 free parameters:
  background, signal normalization, E_0, m_ν^2
- excellent goodness-of-fit:
  p-value = 0.56
- Neutrino mass best fit

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

- very clean data set !

Final fit result (endpoint)

$$E_0^{fit} = E_0 + \phi_{src} - \phi_{spec}$$

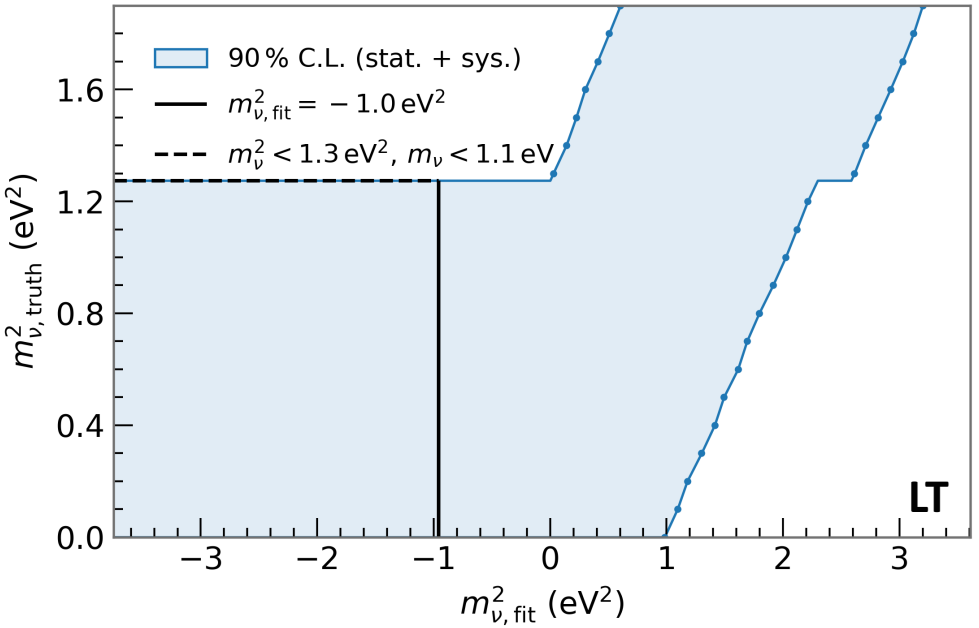


- fitted E_0 = (18573.7 ± 0.1) eV
- Q-value (KATRIN): (18575.2 ± 0.5) eV
- Q-value (literature): (18575.72 ± 0.07) eV

✓ excellent agreement

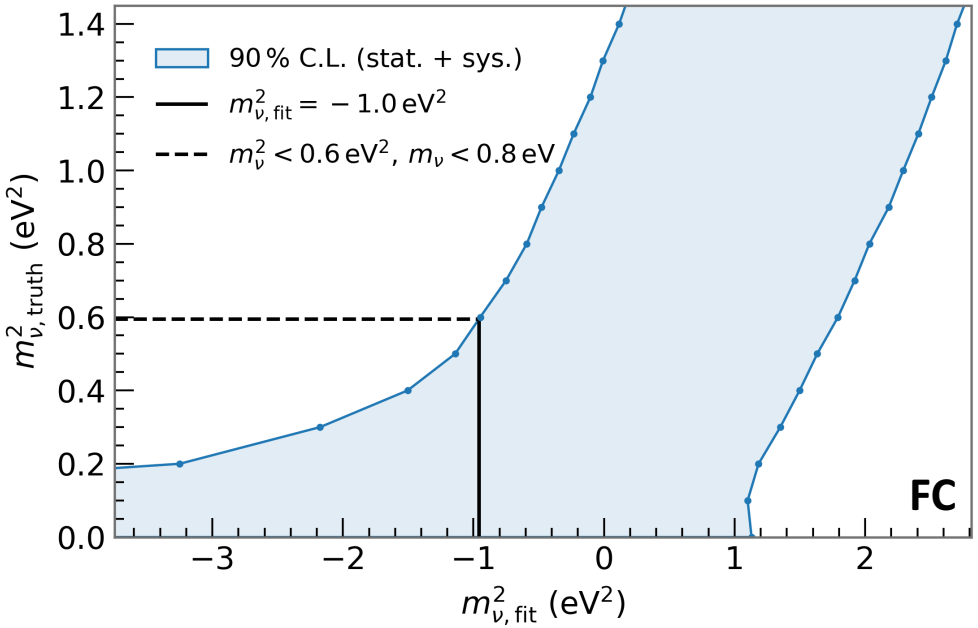
✓ confidence in overall energy scale ☺

New KATRIN limit



Lokhov and Tkachov (LT)

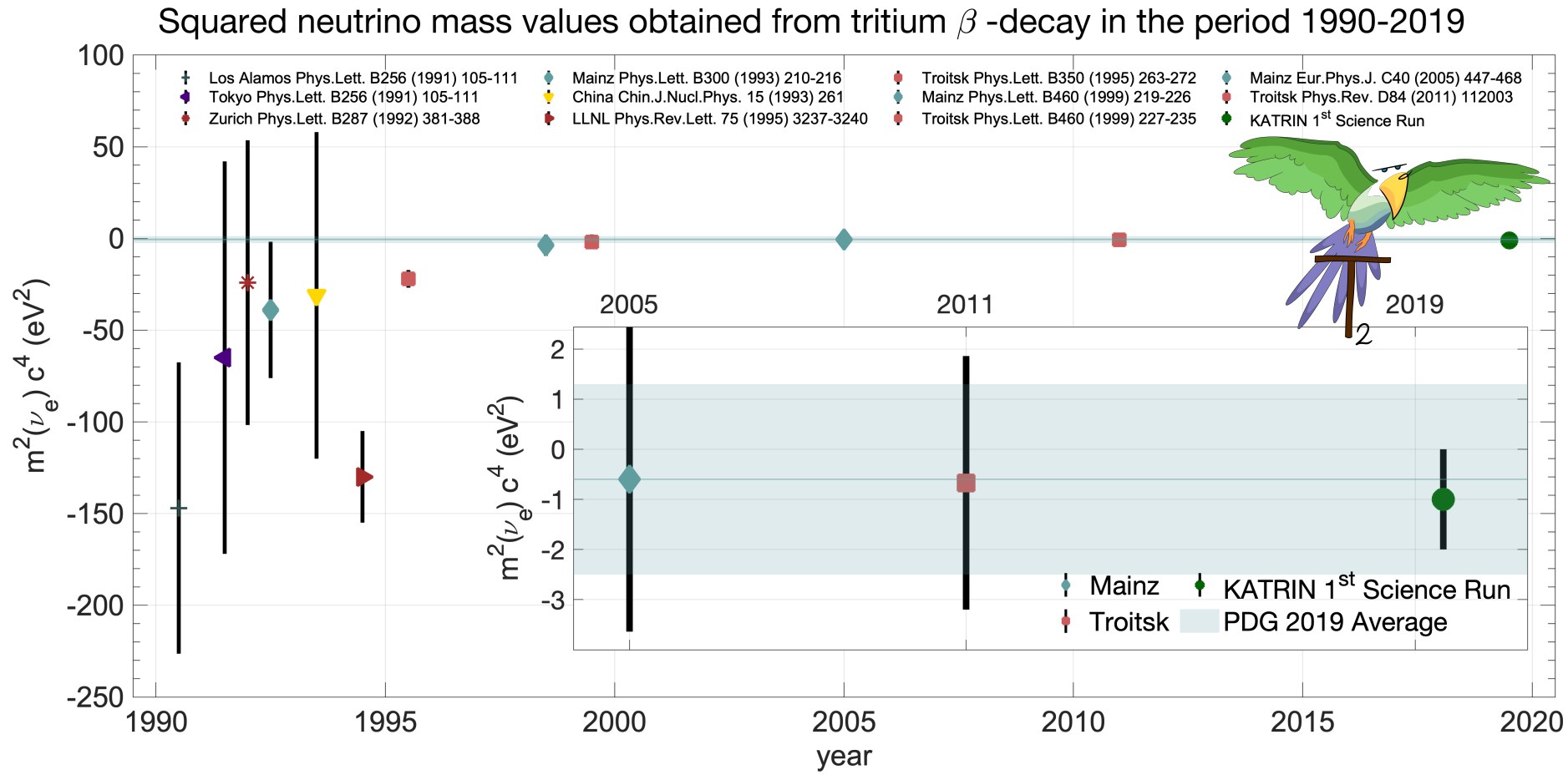
- **m_ν < 1.1 eV (90% CL) = sensitivity**
- official KATRIN limit



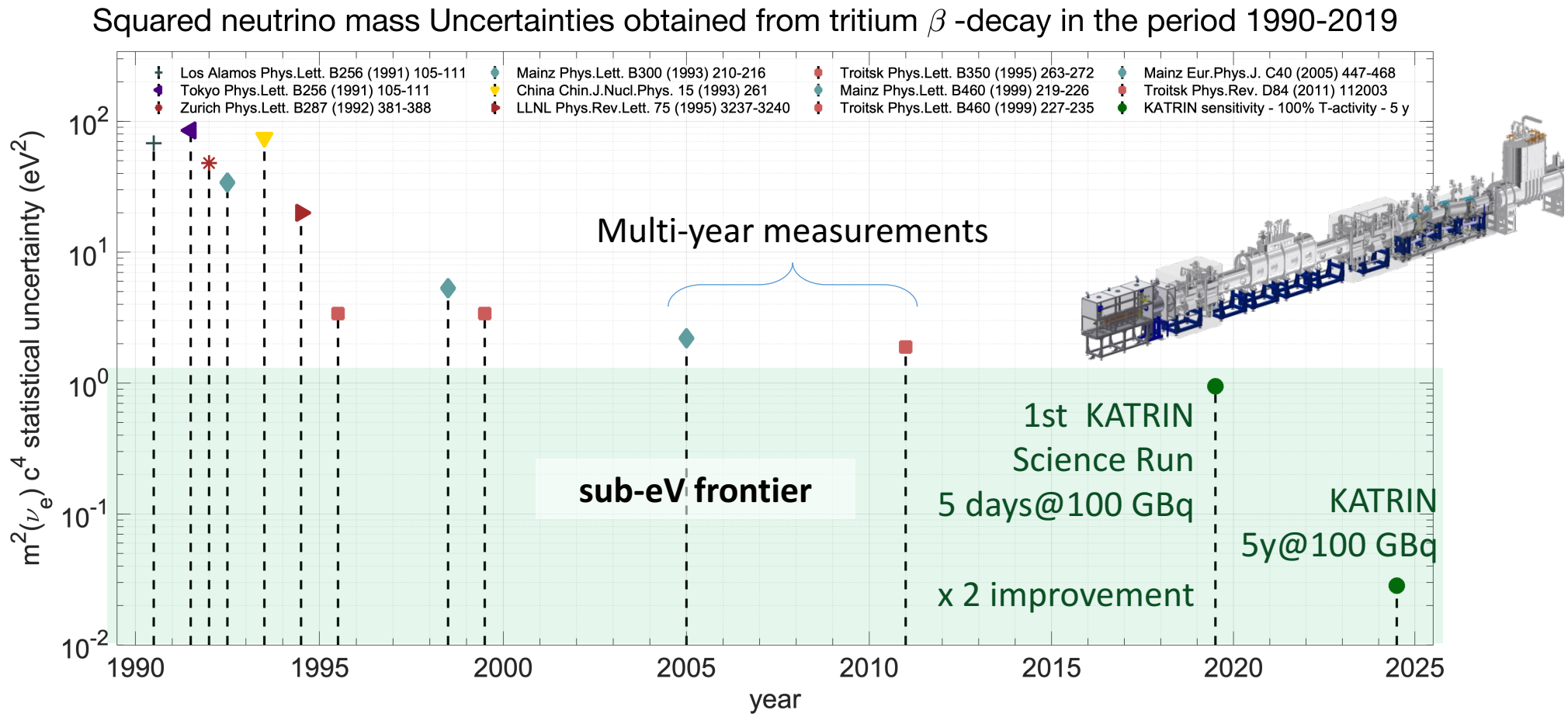
Feldman and Cousins (FC)

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

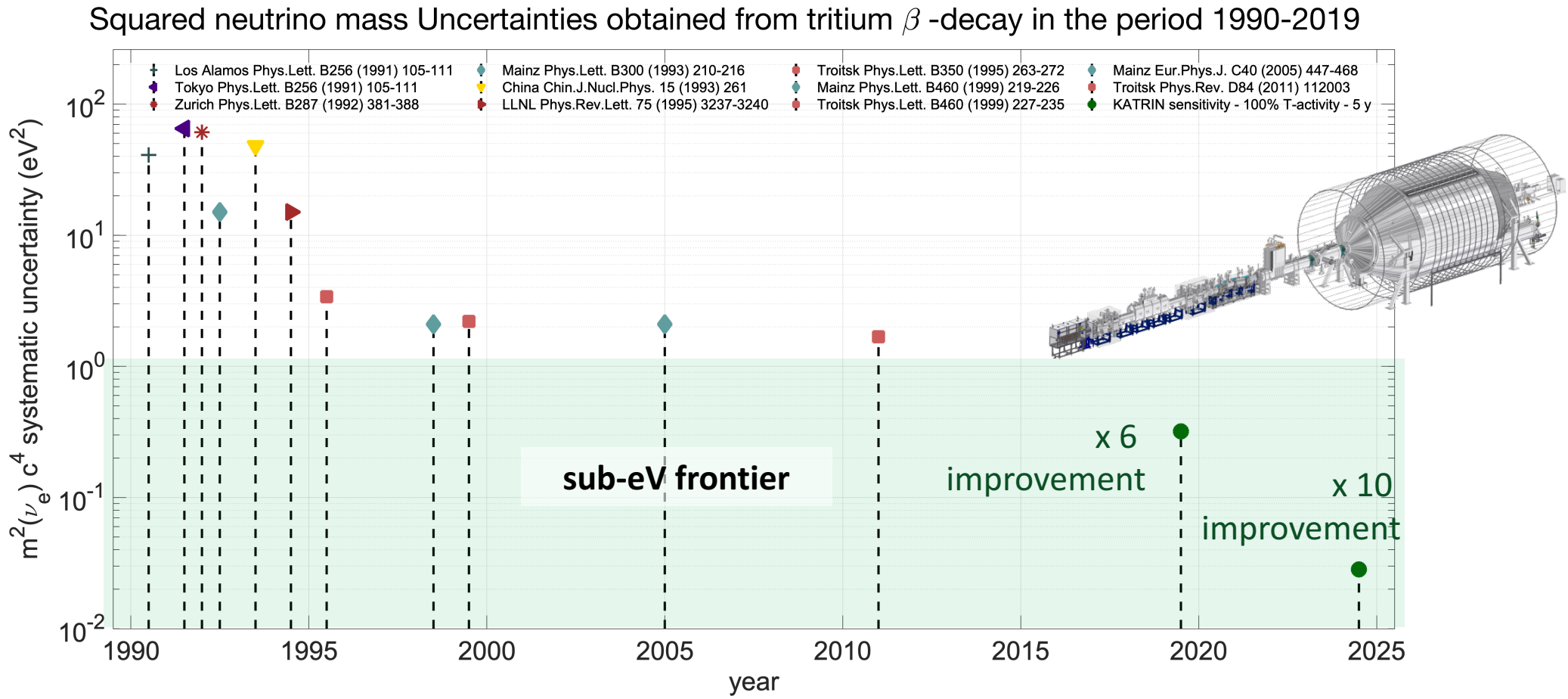
Historical context



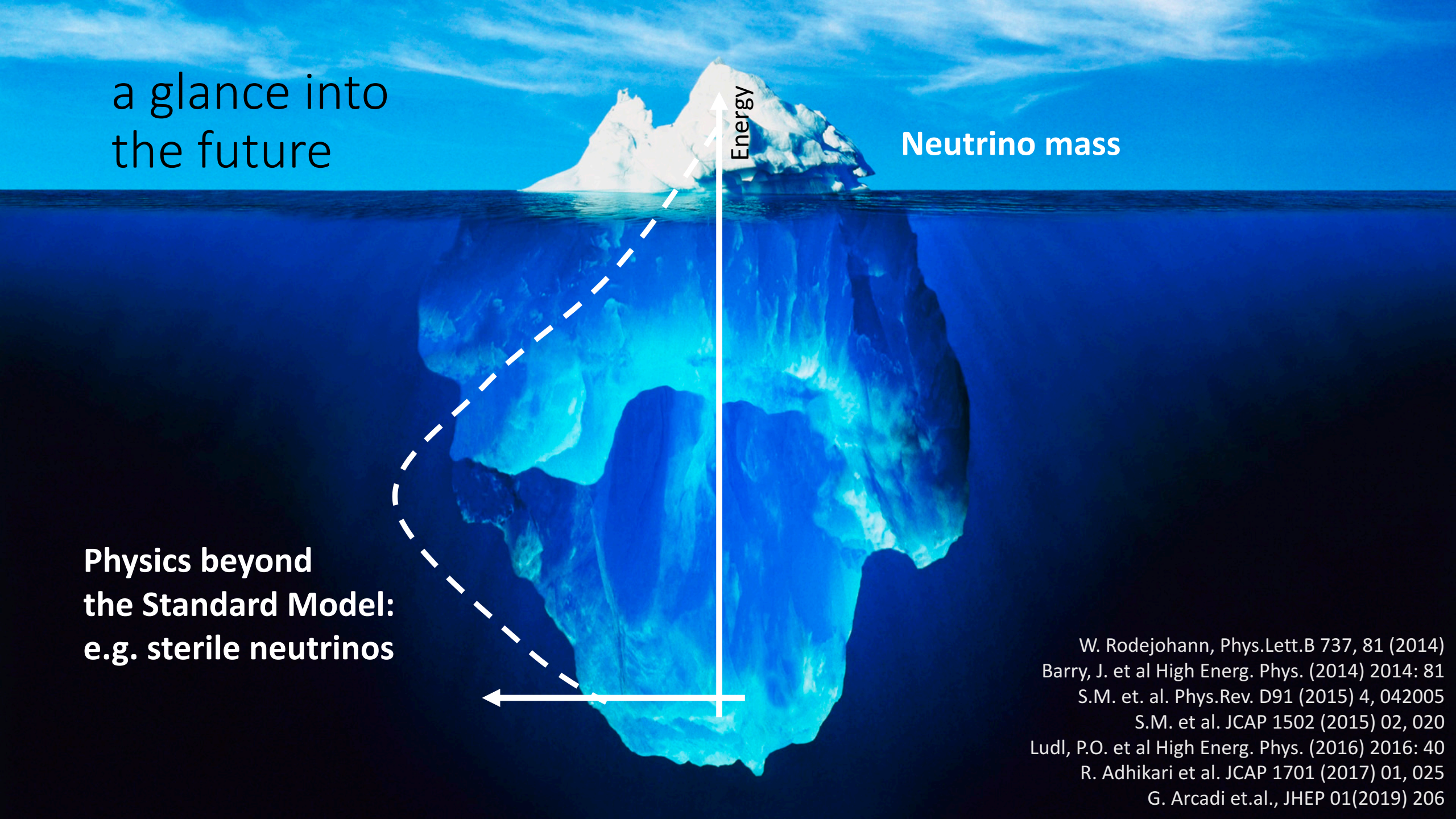
Improvements in statistics



Improvements in systematics

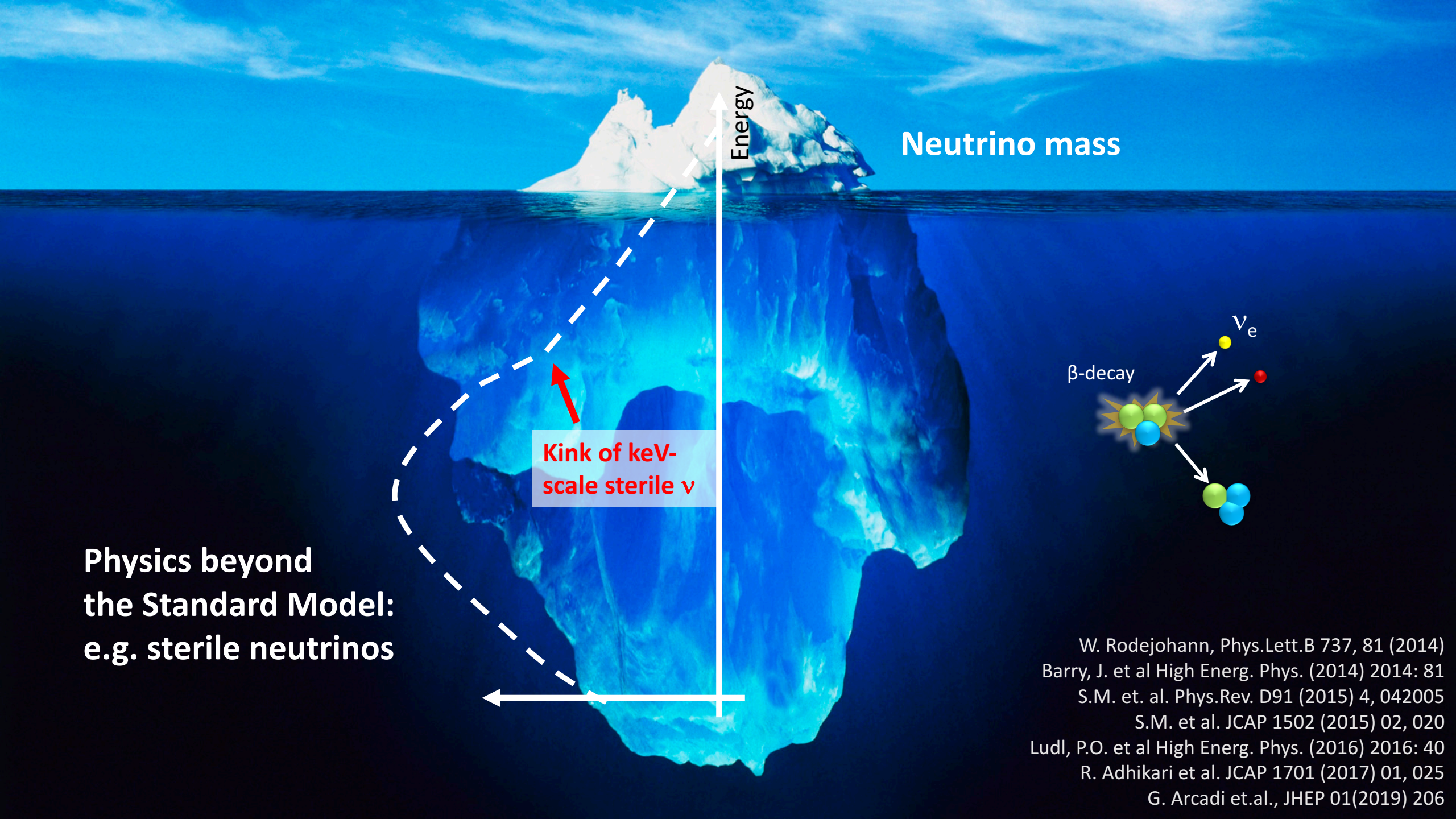


a glance into the future



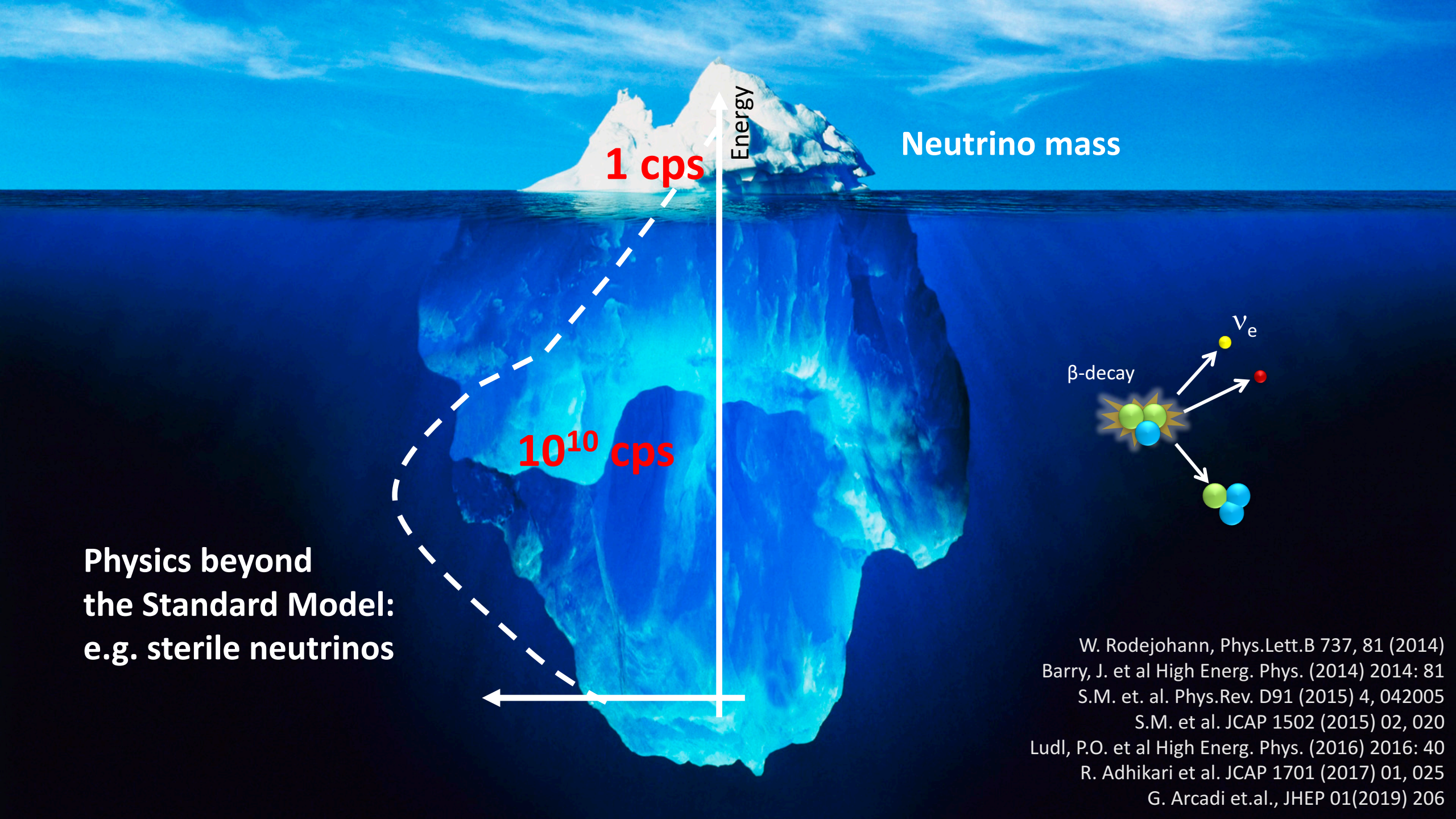
Physics beyond the Standard Model: e.g. sterile neutrinos

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



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

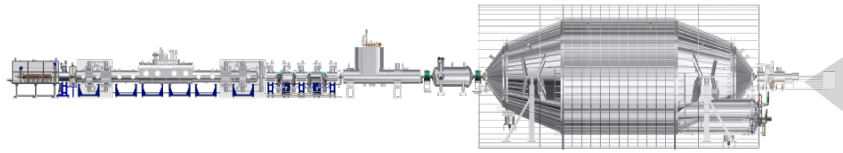
W. Rodejohann, Phys.Lett.B 737, 81 (2014)
Barry, J. et al High Energ. Phys. (2014) 2014: 81
S.M. et. al. Phys.Rev. D91 (2015) 4, 042005
S.M. et al. JCAP 1502 (2015) 02, 020
Ludl, P.O. et al High Energ. Phys. (2016) 2016: 40
R. Adhikari et al. JCAP 1701 (2017) 01, 025
G. Arcadi et.al., JHEP 01(2019) 206

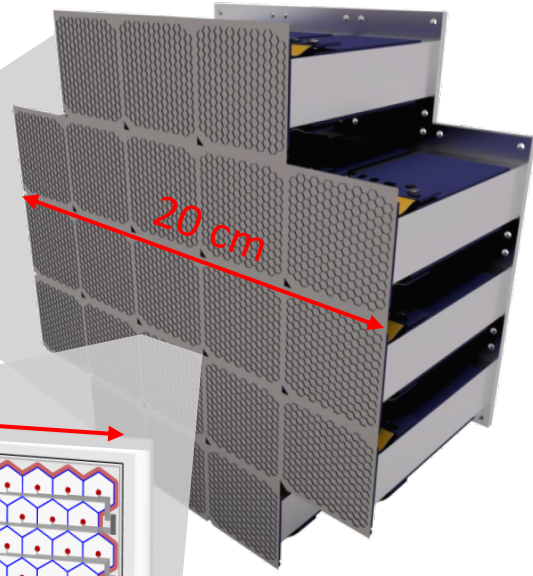


Physics beyond the Standard Model: e.g. sterile neutrinos

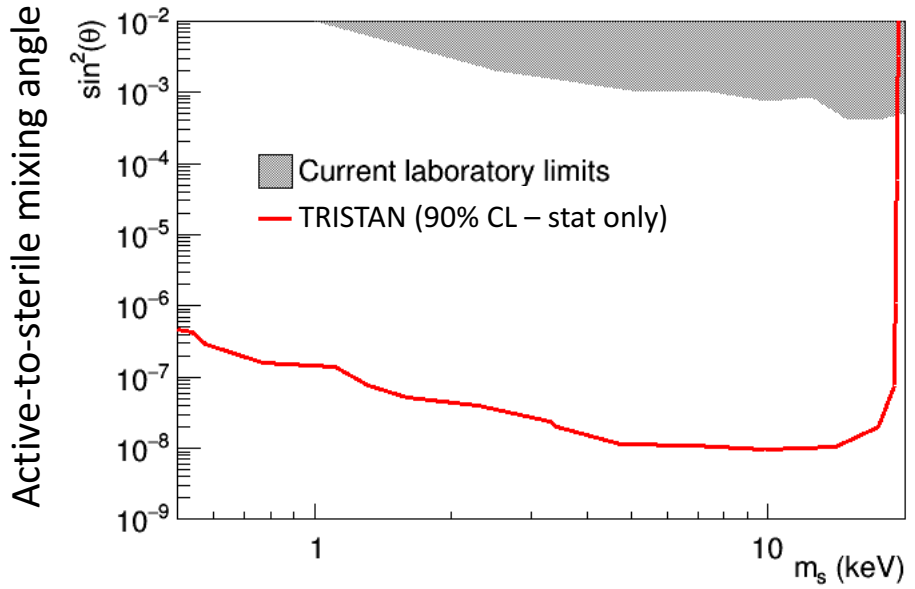
W. Rodejohann, Phys.Lett.B 737, 81 (2014)
Barry, J. et al High Energ. Phys. (2014) 2014: 81
S.M. et. al. Phys.Rev. D91 (2015) 4, 042005
S.M. et al. JCAP 1502 (2015) 02, 020
Ludl, P.O. et al High Energ. Phys. (2016) 2016: 40
R. Adhikari et al. JCAP 1701 (2017) 01, 025
G. Arcadi et.al., JHEP 01(2019) 206

TRISTAN Project

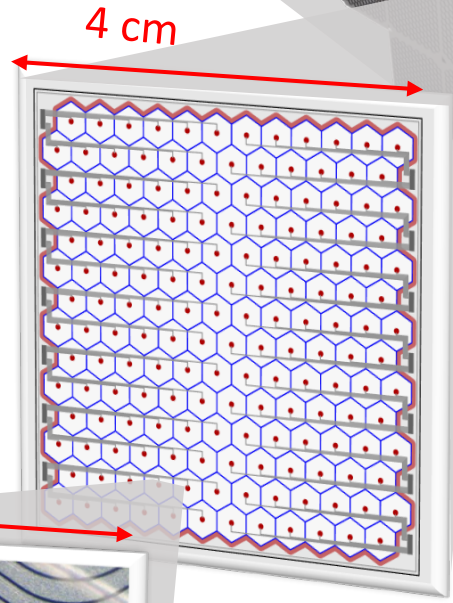




- 3500-pixel Silicon Drift Detector (SDD) focal plane array
- Significant improvement of laboratory limits on keV-scale sterile neutrinos expected

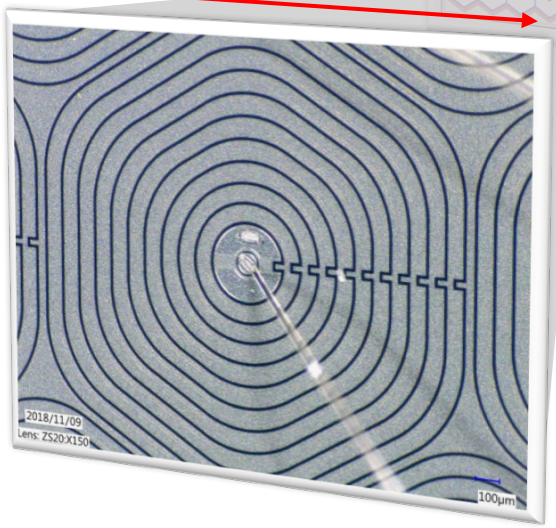


Sterile neutrino mass (keV)



Full detector

Detector Module

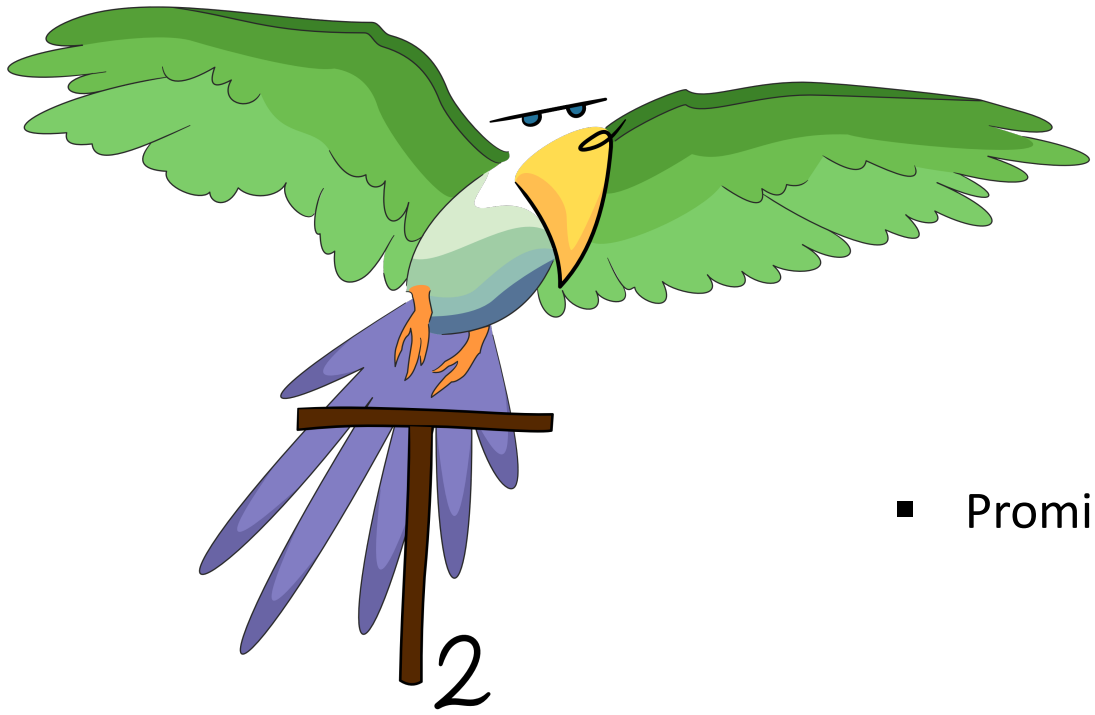


Detector pixel

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]

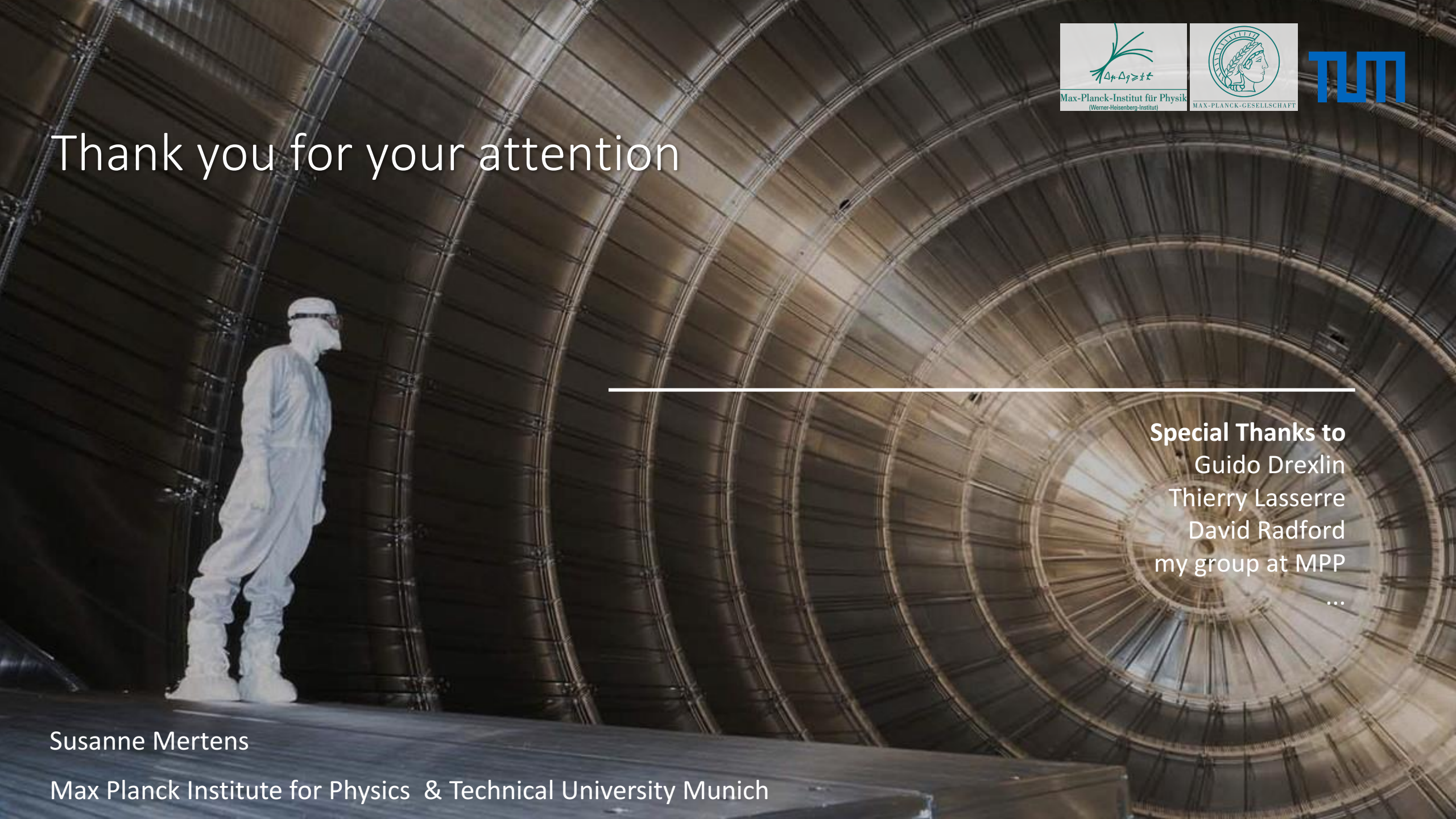
Conclusion

- New World Best Direct Neutrino Mass Measurement: $m_\nu < 1.1$ eV (90% C.L.)



- 2nd measurement campaign starts tomorrow
- Background improvement experimentally verified
- Final sensitivity of 0.2 eV reached after 5-years
- 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