The First KATRIN Neutrino Mass Result

CEA/DRF/Irfu/DPhP Seminar, Saclay, 07/10/2019

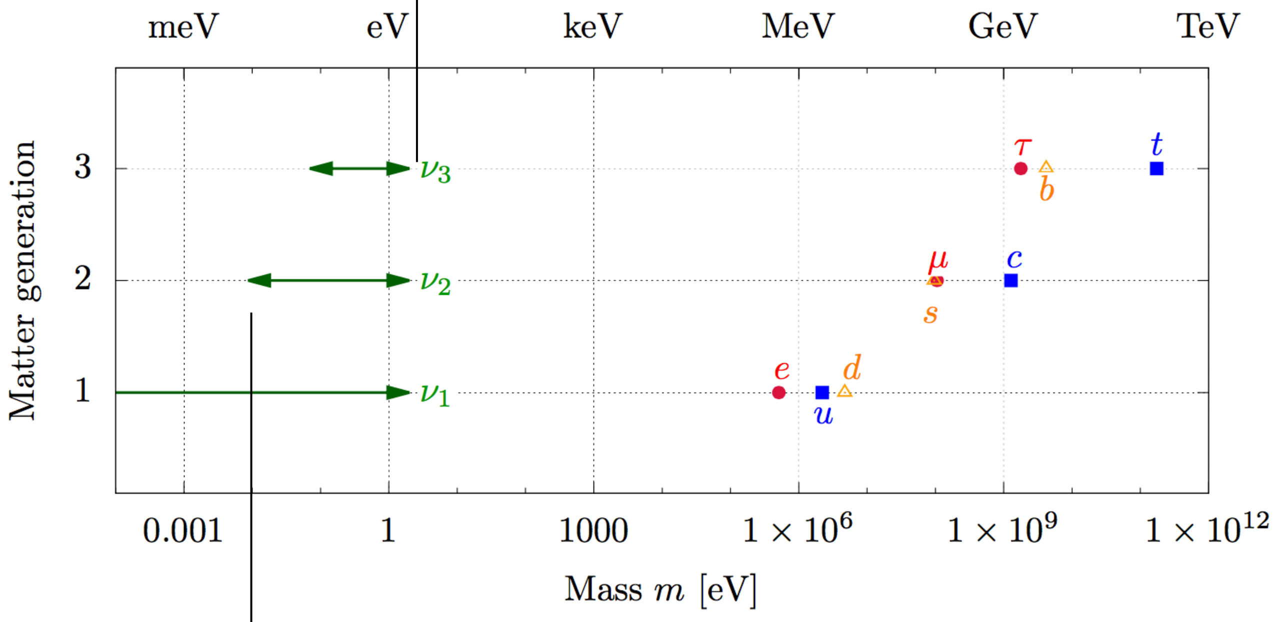
Thierry Lasserre

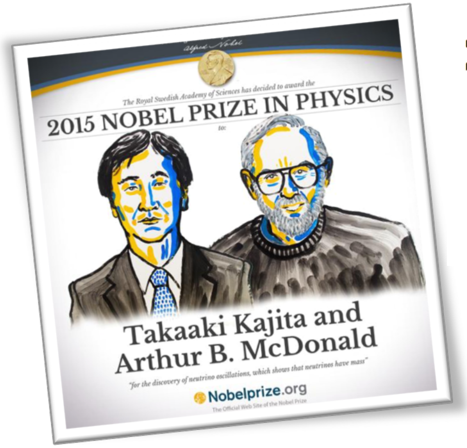
On behalf the KATRIN collaboration

Physics Case

Neutrino mass

Upper bound
from laboratory measurements





Lower bound
from oscillation experiments

Neutrino mass

Cosmology

model-dependent
potential: m_ν = 10-50 meV
e.g. Planck + ...

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

Search for 0νßß

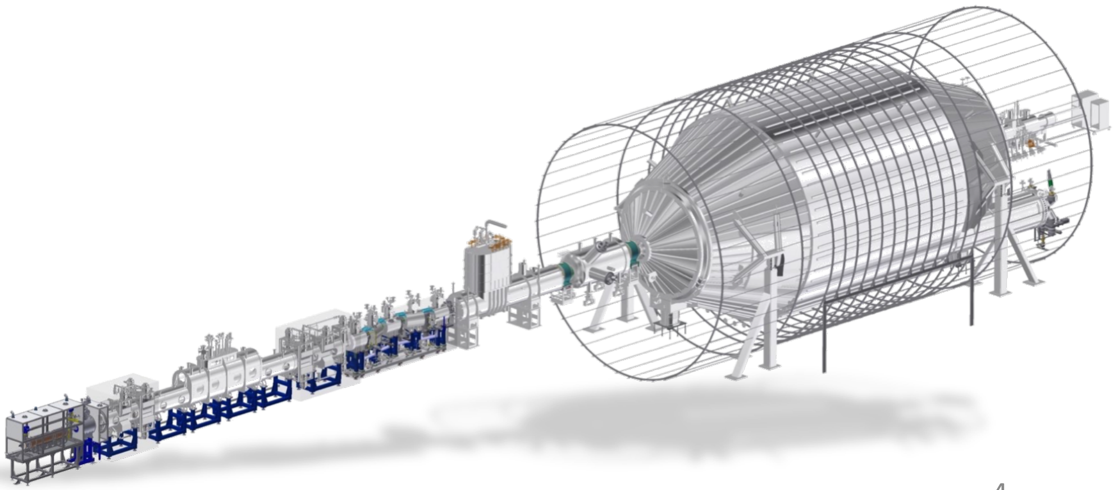
Laboratory-based
potential: $m_{ßß}$ = 15-50 meV
e.g. LEGEND, Cupid

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

Kinematics of ß-decay

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

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



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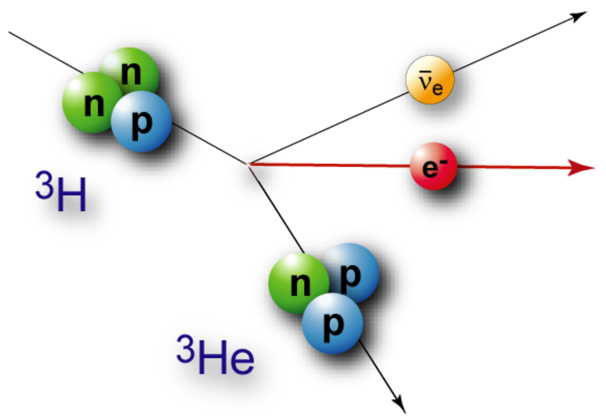
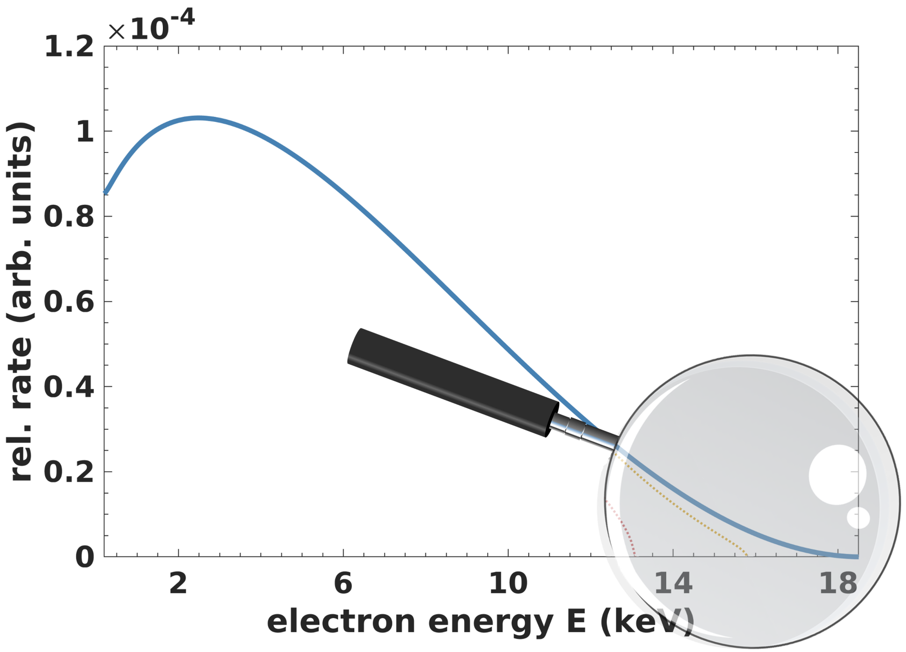
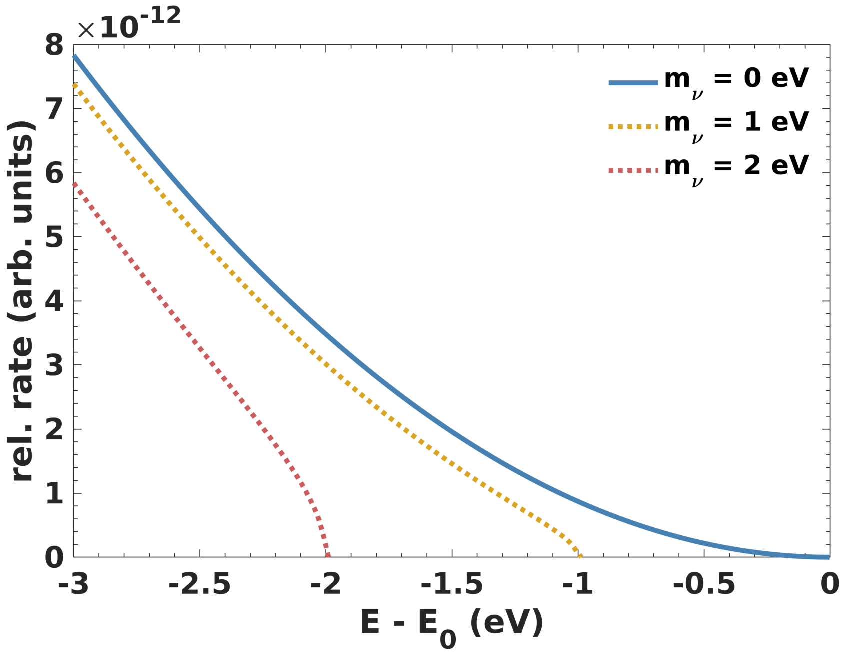
Kinematic Measurement Concept

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



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

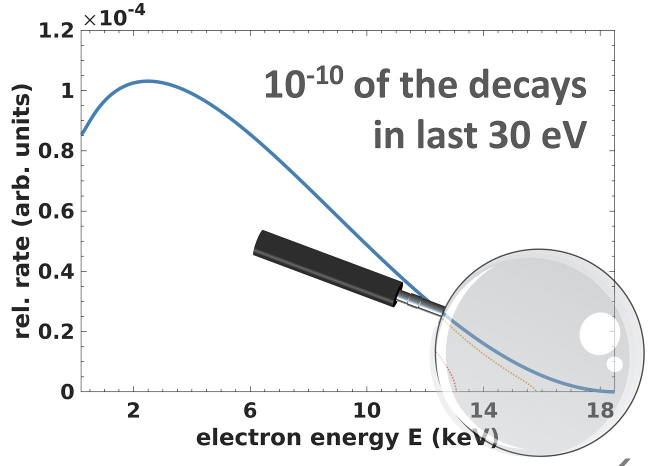




Experimental Challenges

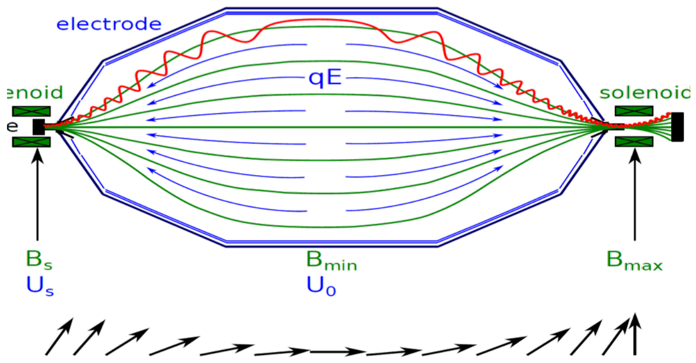
Intense ultra-stable tritium source

- design value: 100 GBq



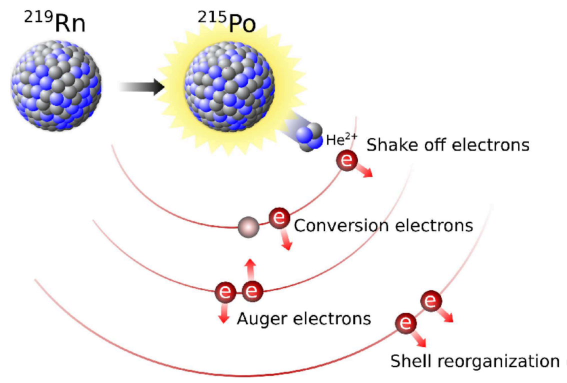
High Energy Resolution

- design value : 1 eV



Low electron Background

- design value : 0.01 cps



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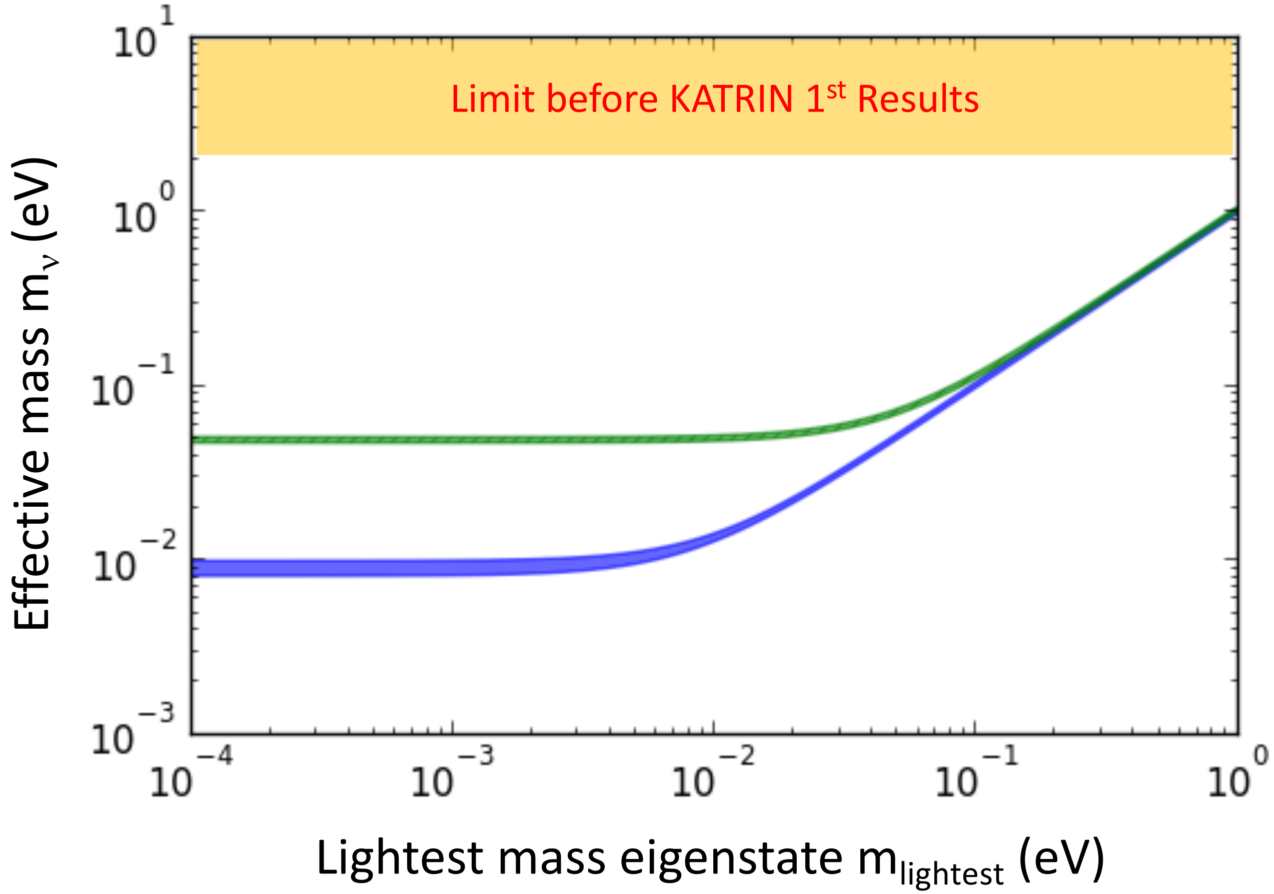
Where do we stand?



- Current limit:
  Mainz and Troitsk Experiments

  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)

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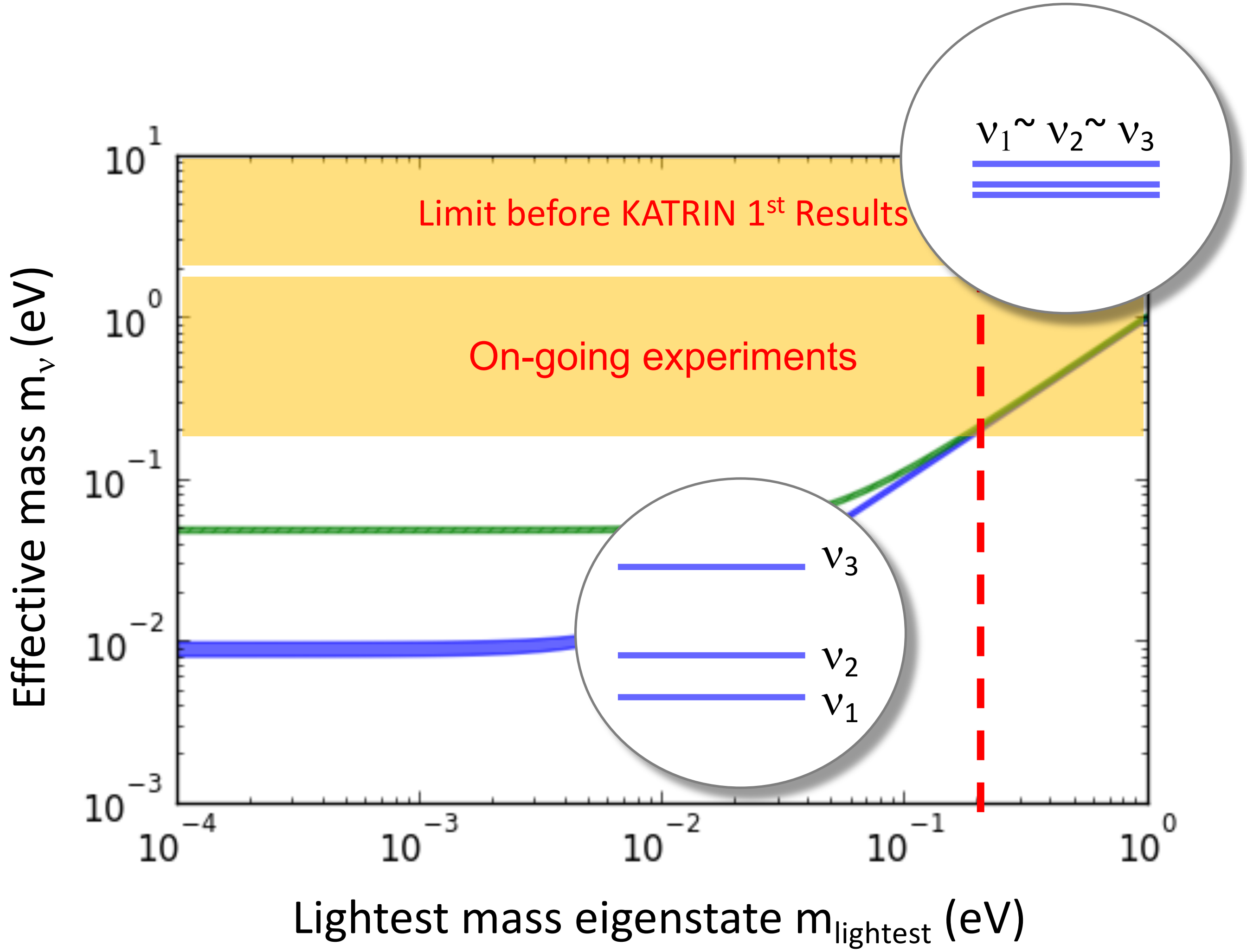

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- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario

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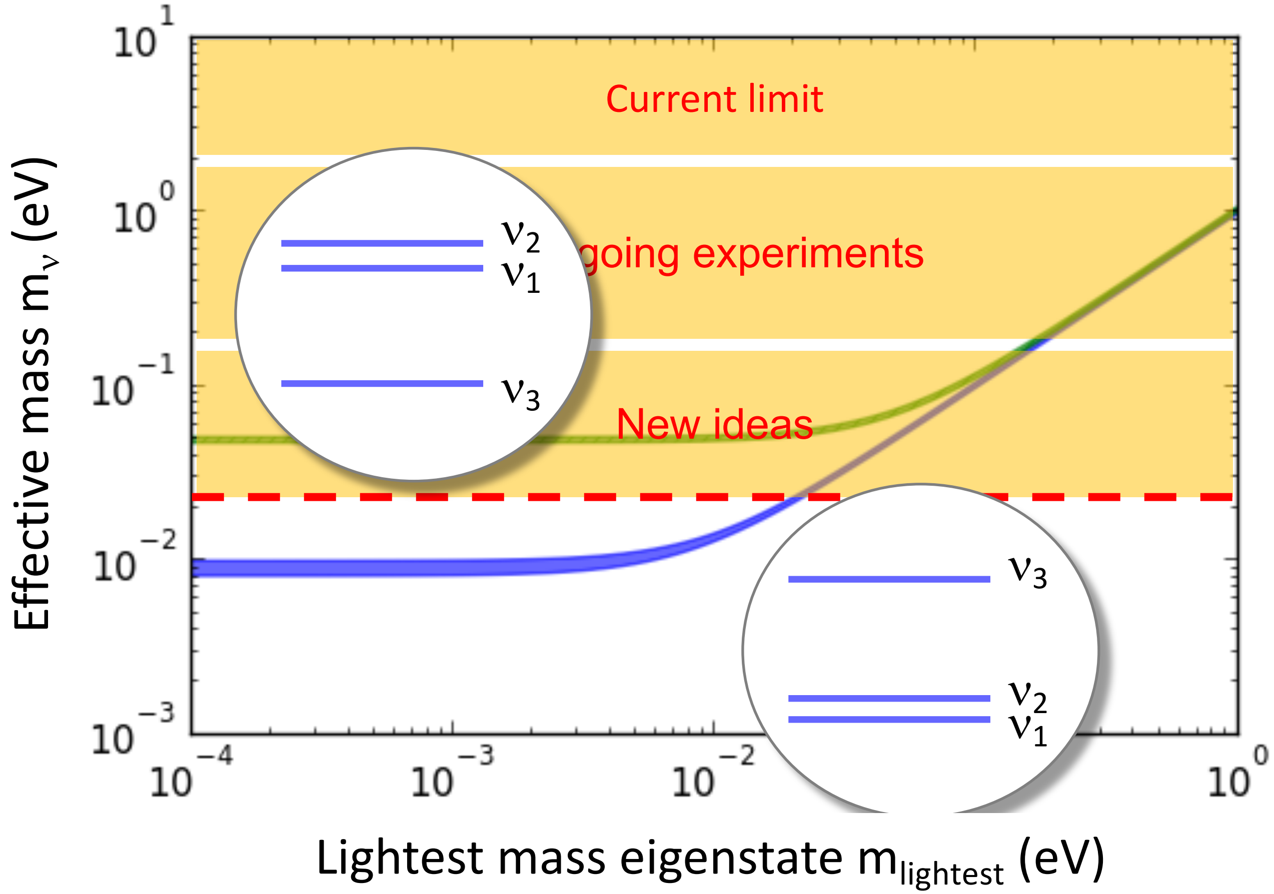

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- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario
- New ideas:
  Resolve **normal** vs **inverted** neutrino mass hierarchy

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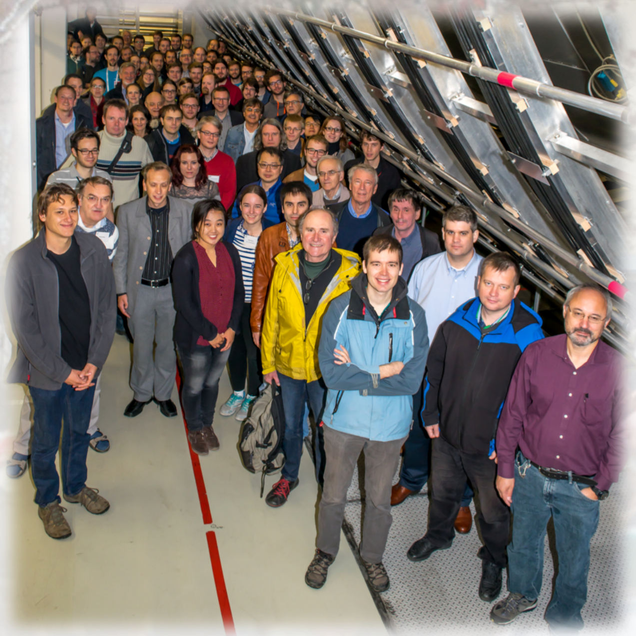
KATRIN

Karlsruhe Tritium Neutrino Experiment

Karlsruhe
Tritium
Neutrino
Experiment



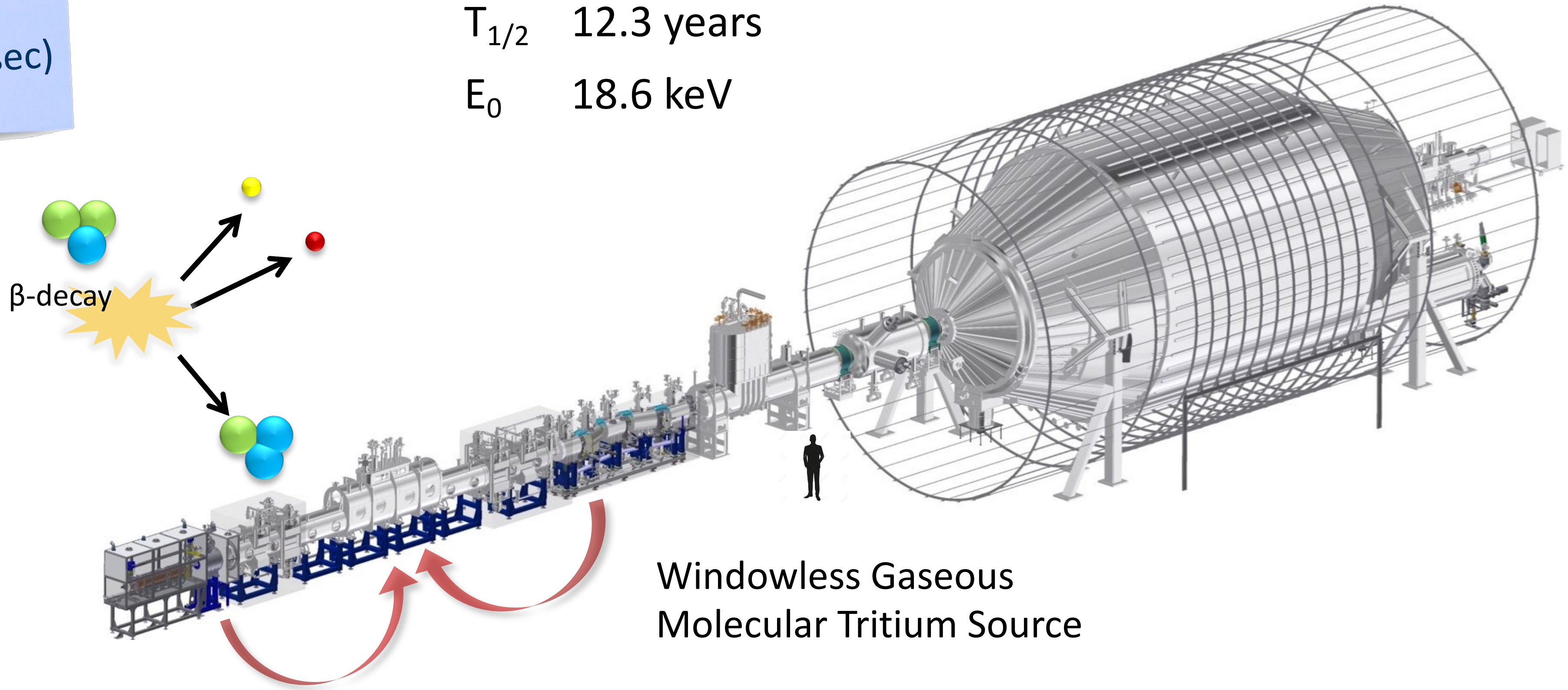
- Experimental site: Karlsruhe Institute of Technology (KIT)
- International Collaboration (150 members)
- Sensitivity m_ν = 0.2 eV (90% CL) after 3 net-years

KATRIN Working Principle

high stability
and luminosity

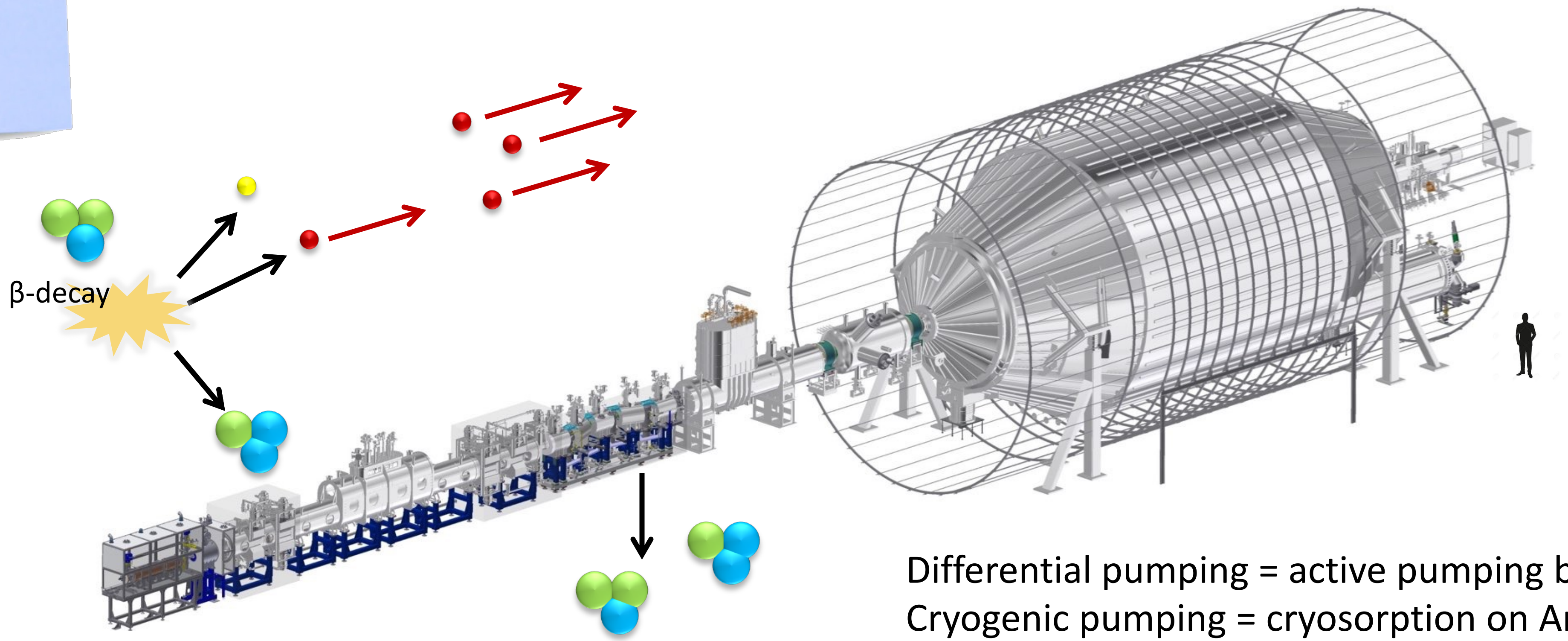
(10^{11} decays/sec)

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

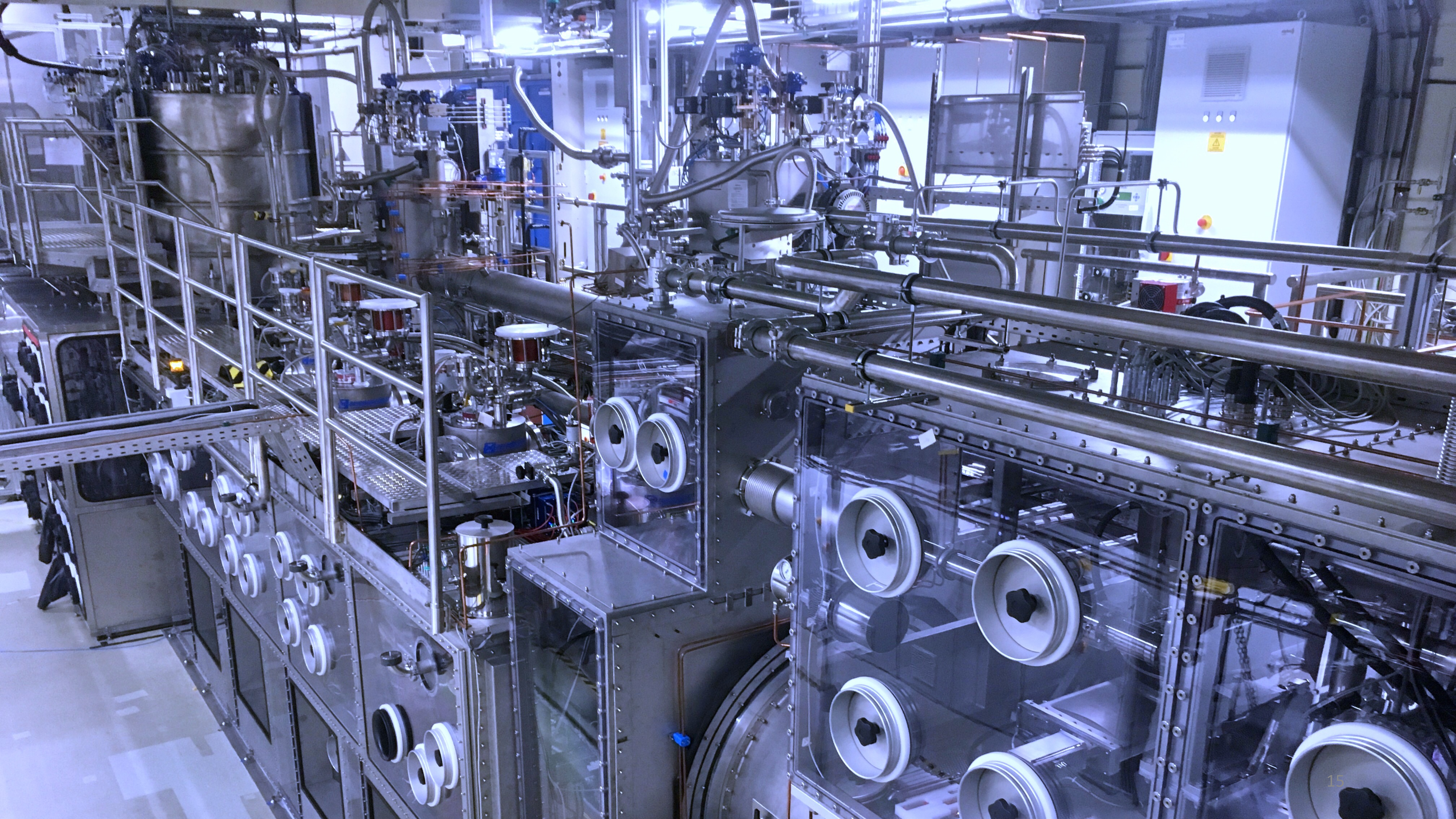


KATRIN Working Principle

Tritium flow reduction by 14 orders of magnitude

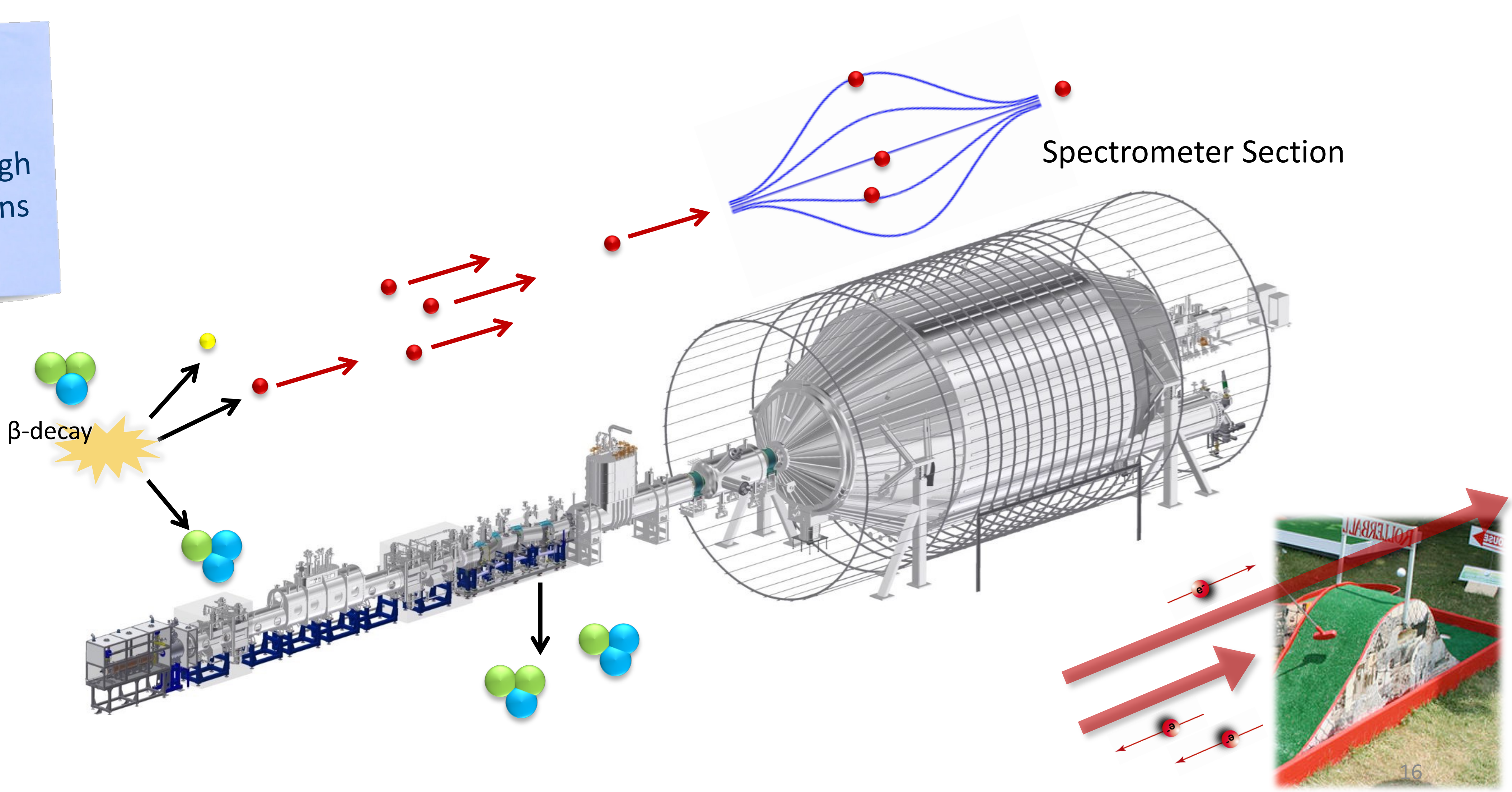


Differential pumping = active pumping by TMPs
Cryogenic pumping = cryosorption on Ar-frost



KATRIN Working Principle

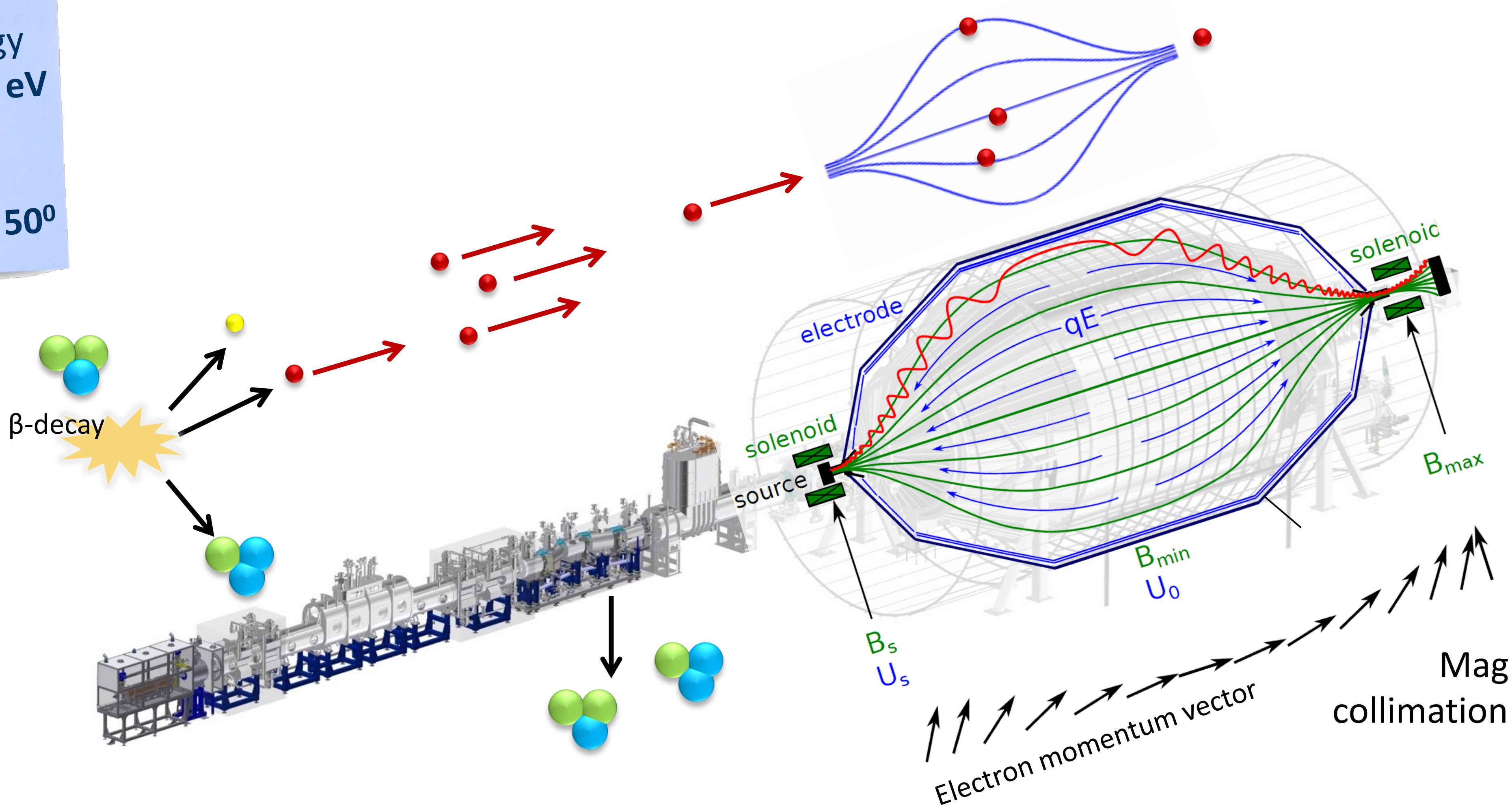
Electrostatic filter selects high energy electrons



KATRIN Working Principle

excellent energy resolution: **~ 3 eV**

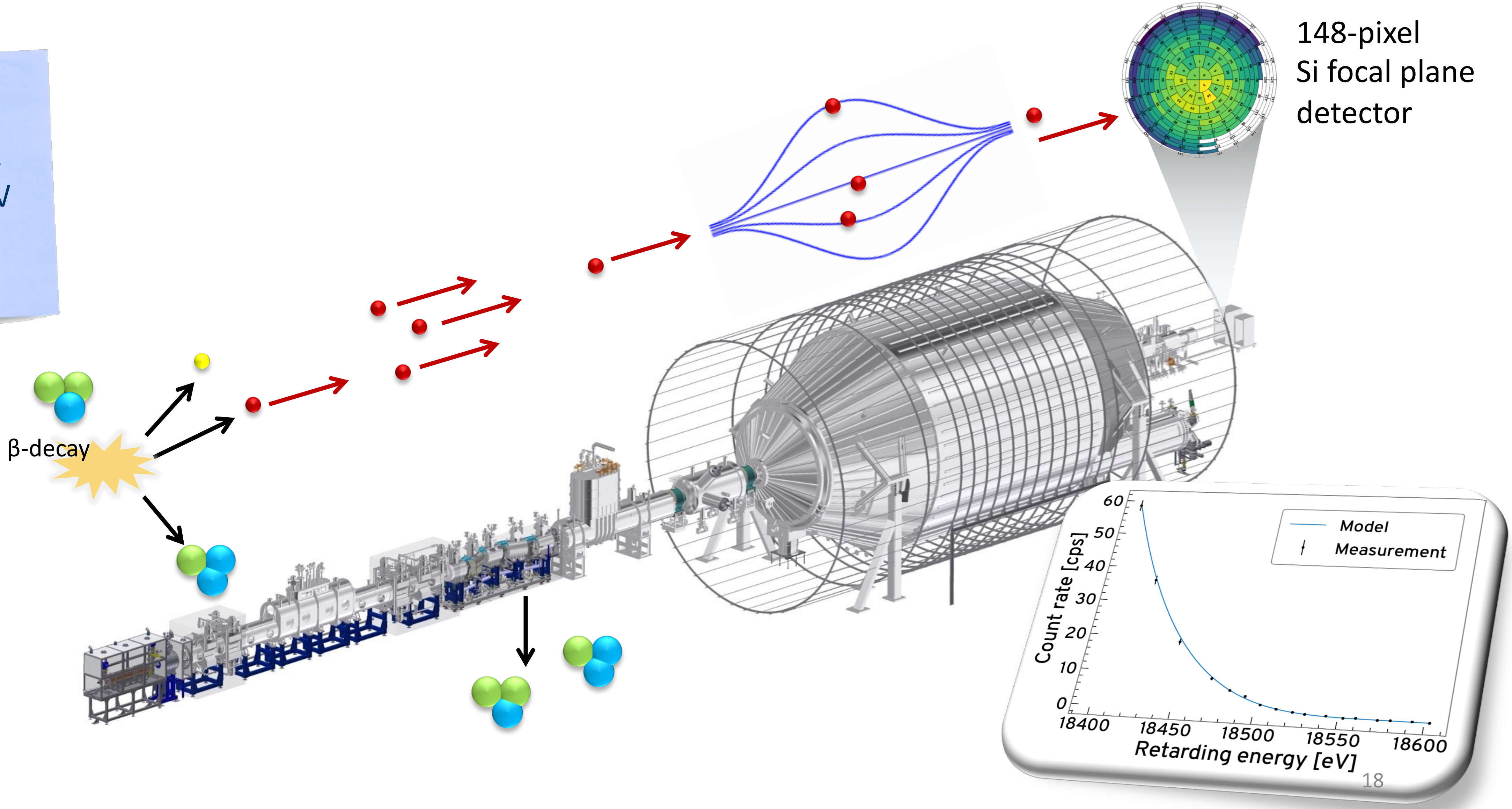
large angle acceptance: **~ 50⁰**



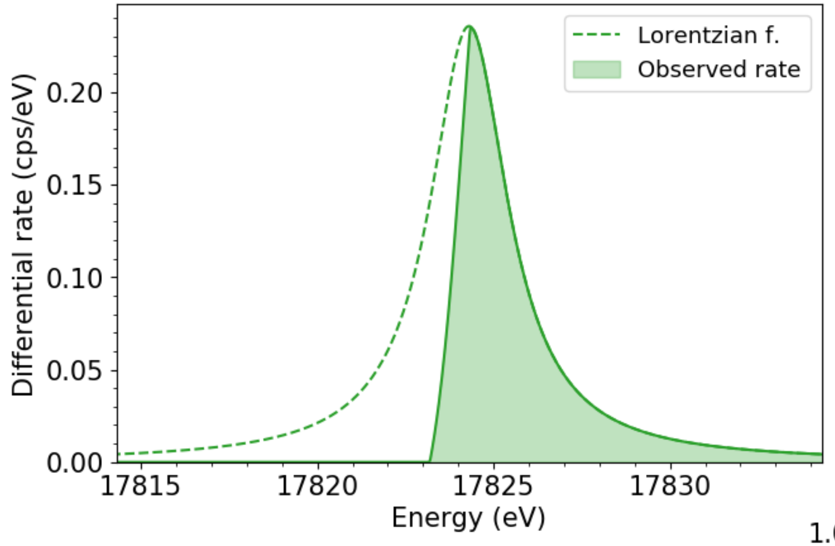
Magnetic adiabatic collimation + electrostatic filter (MAC-E)

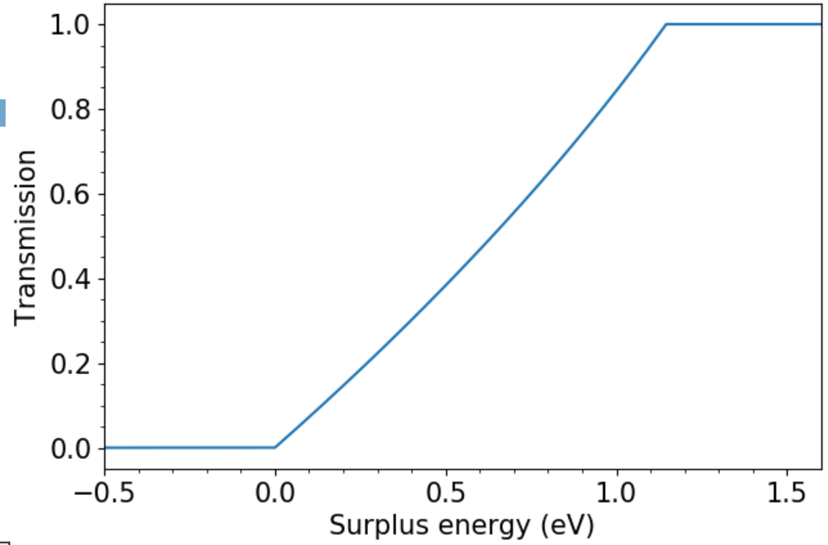
KATRIN Working Principle

Integral measurement down to 40 eV below the endpoint



Response to quasi-monoenergic electrons

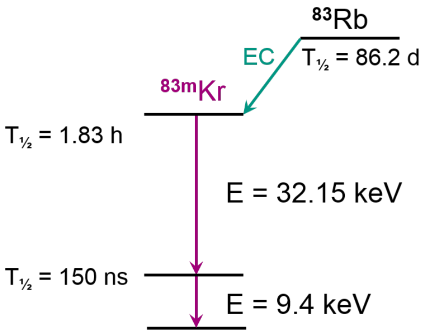


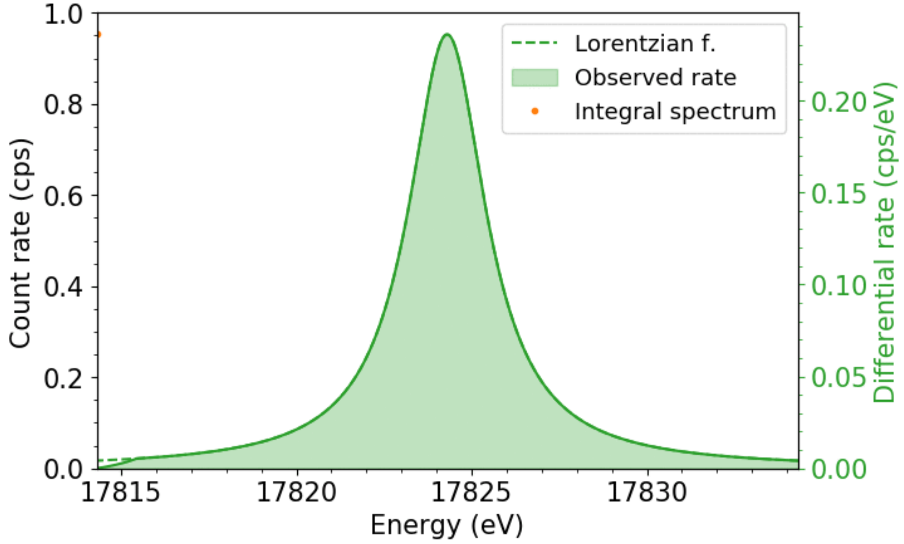


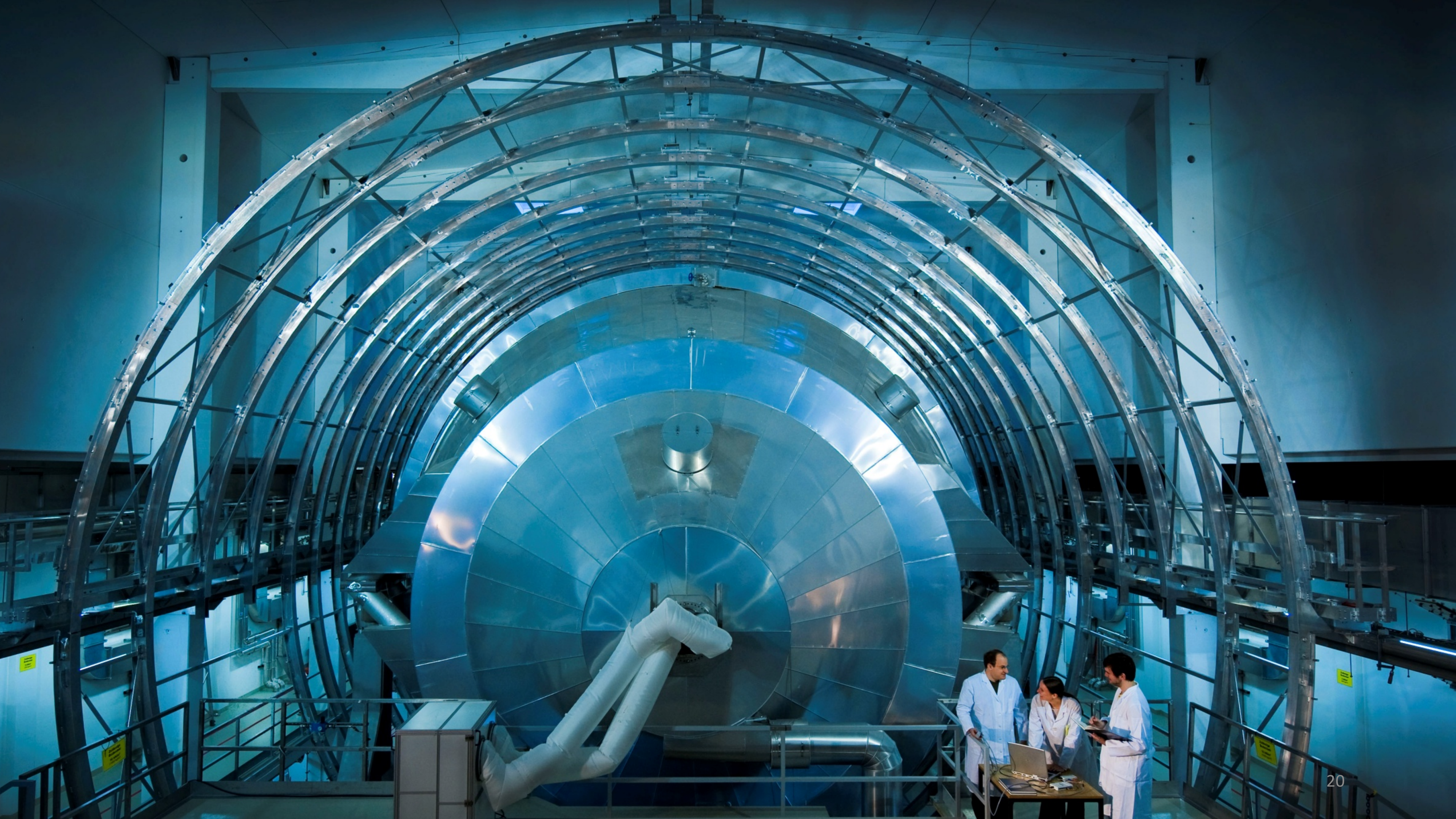
$$I(qU) = \int_{qU}^{E_0} D(E)T(E,qU)dE$$

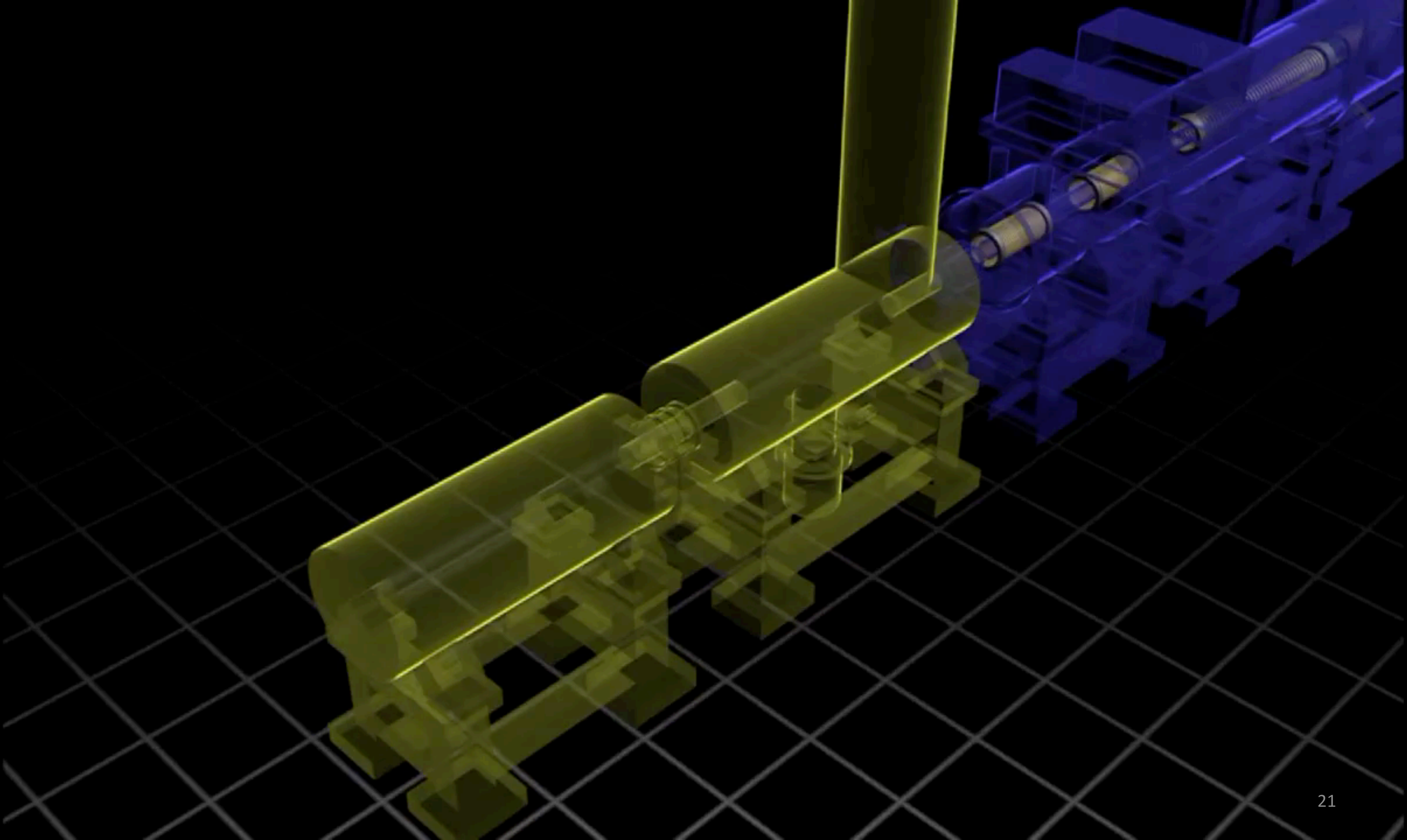
Natural line width of krypton

Spectrometer resolution





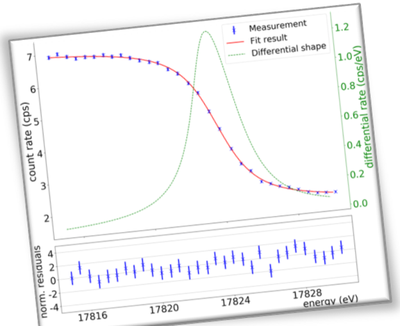




18-years of KATRIN history

Letter of Intent

Main spectrometer

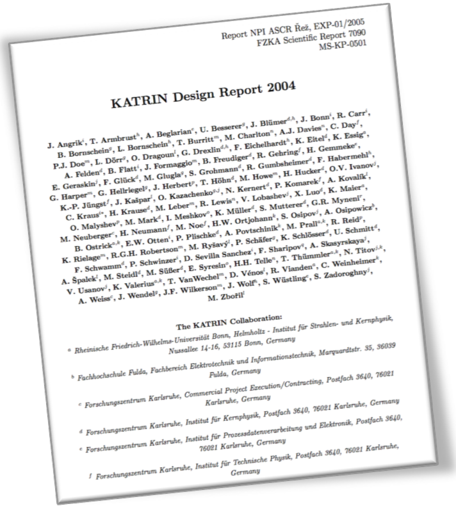


Krypton calibration

First neutrino mass

2001 2004 2006 2016 2017 2018 2019

Design Report



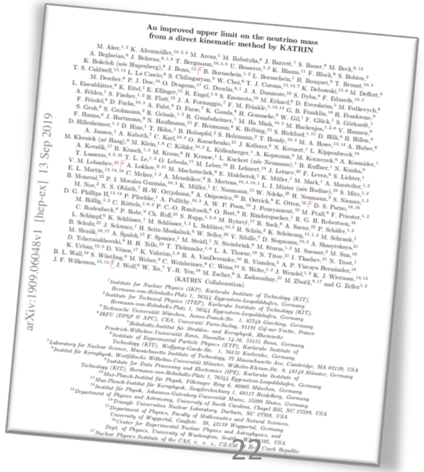
Report NPI ASCR Řež, EXP-01/2005
FZKA Scientific Report 7090
MS-KP-0501

KATRIN Design Report 2004

The KATRIN Collaboration

First light

First tritium



An improved upper limit on the neutrino mass from a direct kinematic method by KATRIN

(KATRIN Collaboration)

arXiv:1909.06048v1 [hep-ex] 13 Sep 2019

First Neutrino Mass Campaign

KATRIN neutrino mass campaign #1 (KNM-1)

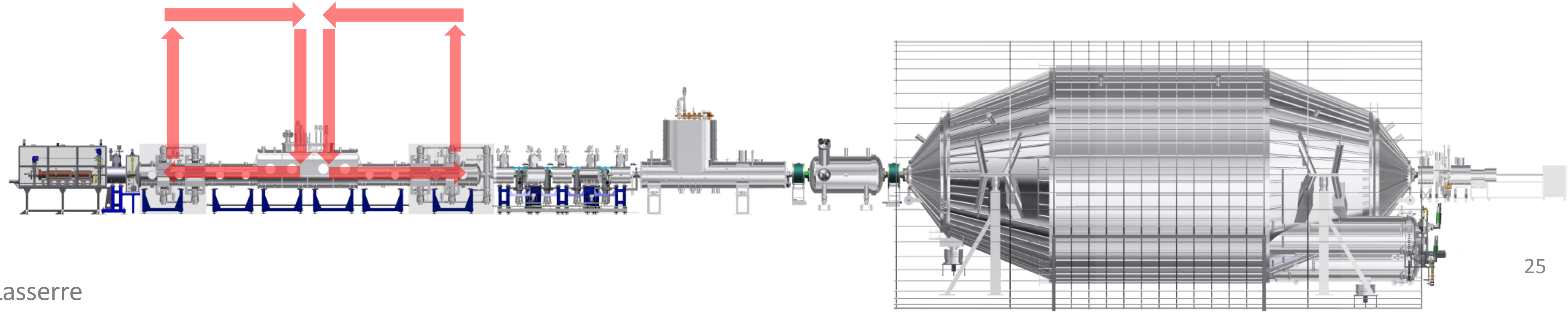
- First ever high-activity tritium operation of KATRIN
- April 10 – May 13 2019: **780 h (4 weeks)**
- high-quality data collected **2 million electrons**

✓ **First neutrino mass result**

Tritium operation of KATRIN

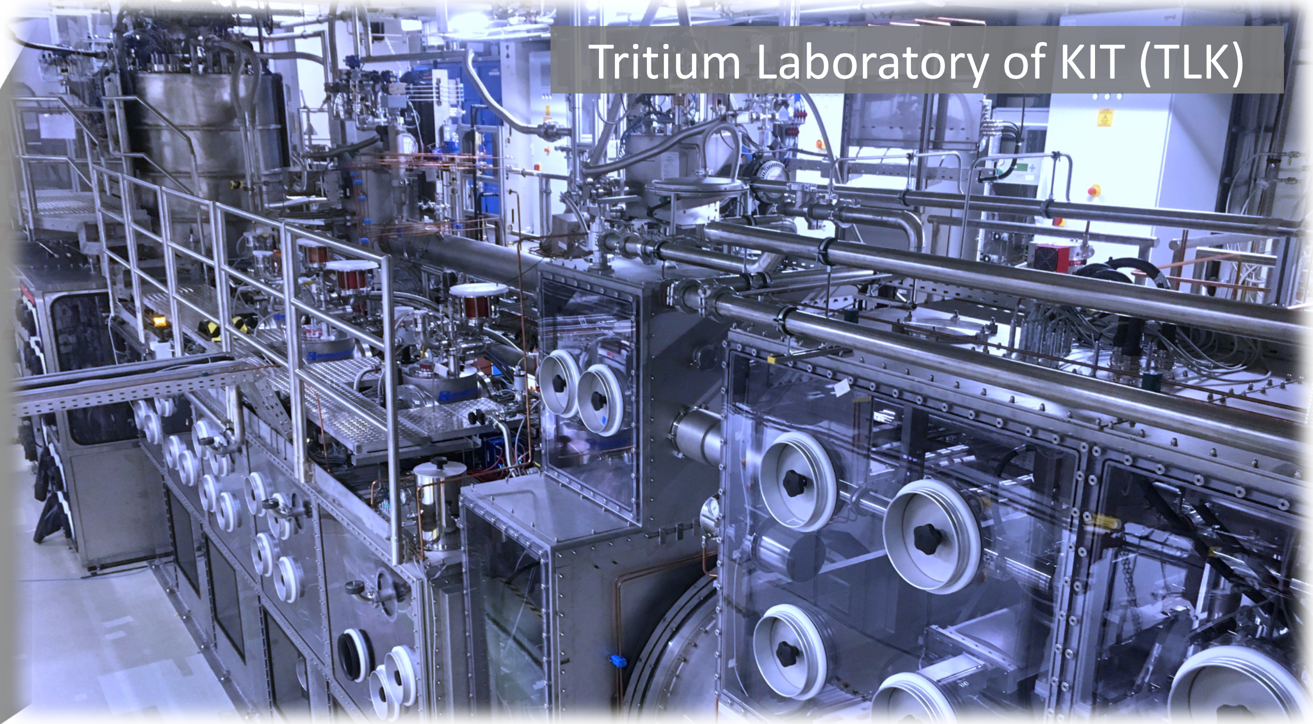
- tritium gas density: **22% of nominal (burn-in period)**
- high isotopic tritium purity: **97.5%**
- high source activity: **$2.45 \cdot 10^{10}$ Bq**

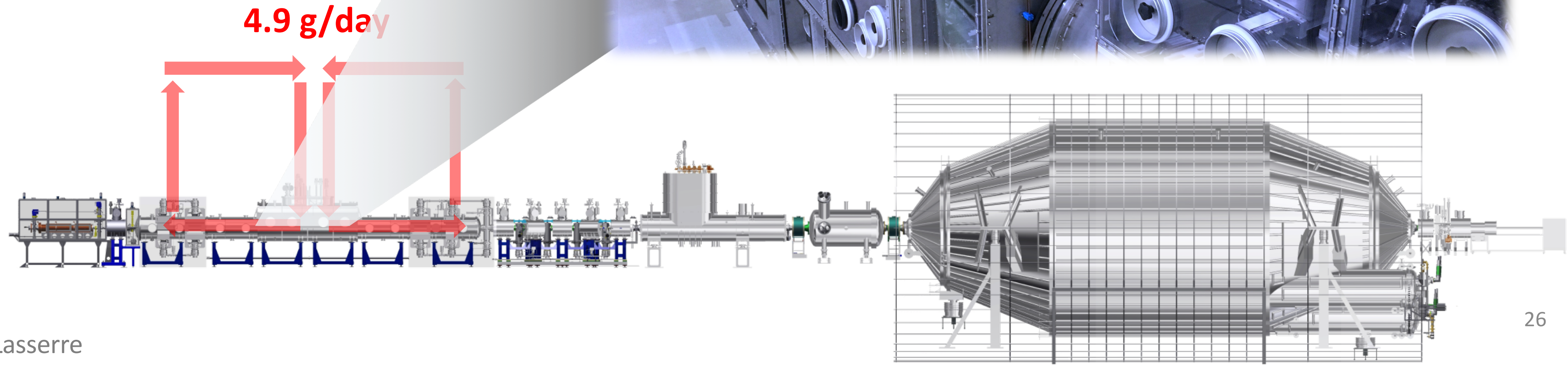
Throughput: 4.9 g/day



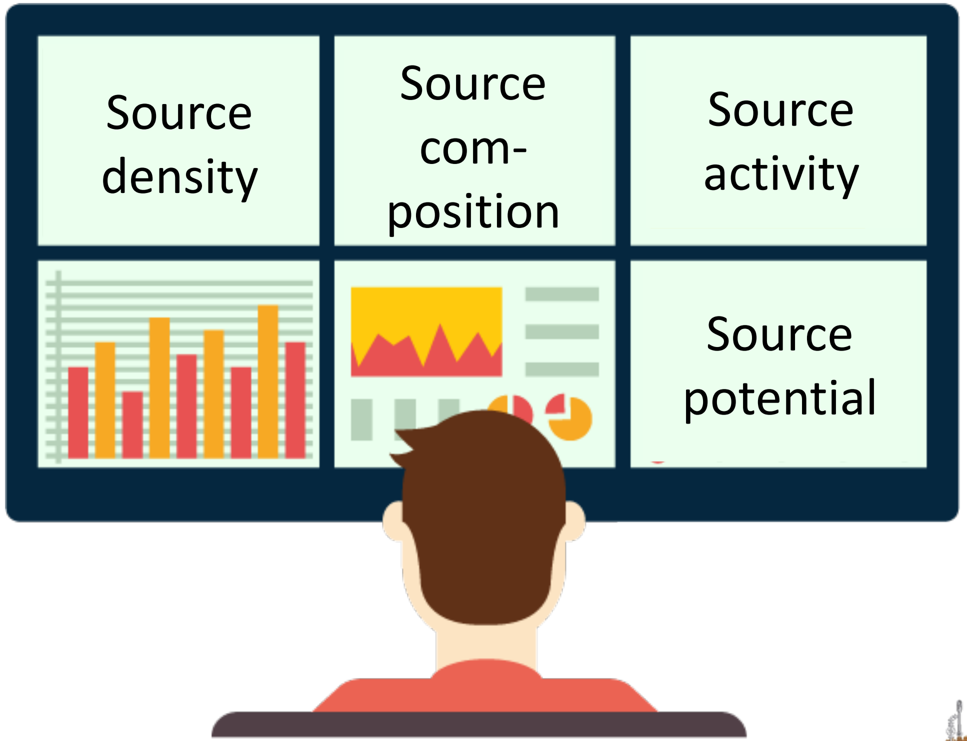
Tritium operation of KATRIN

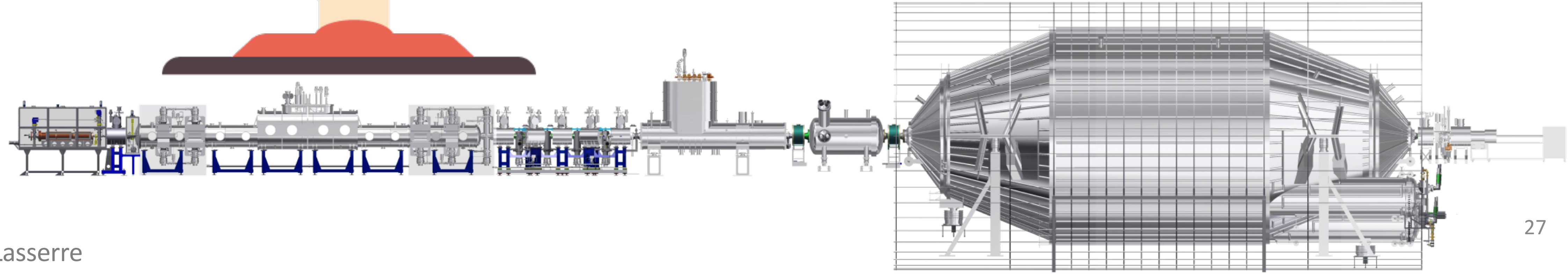
- tritium gas density:
- high isotopic tritium purity:
- high source activity:





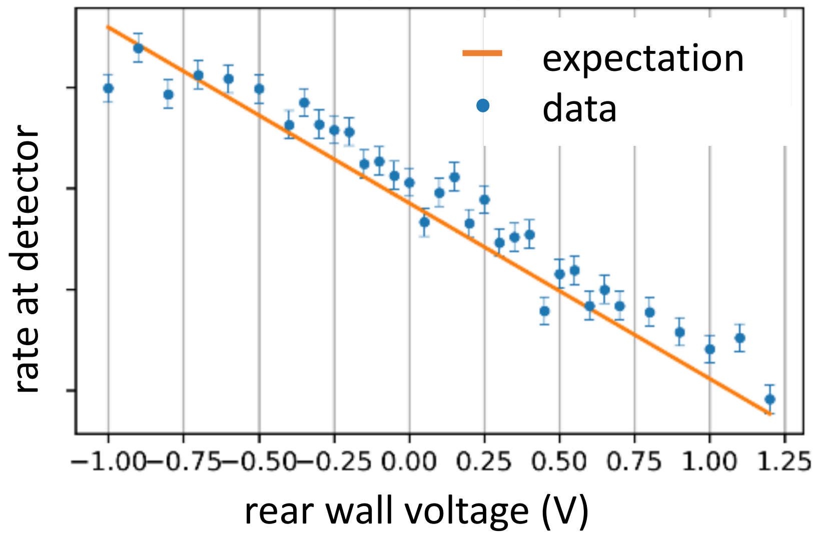
Monitoring and characterization of source

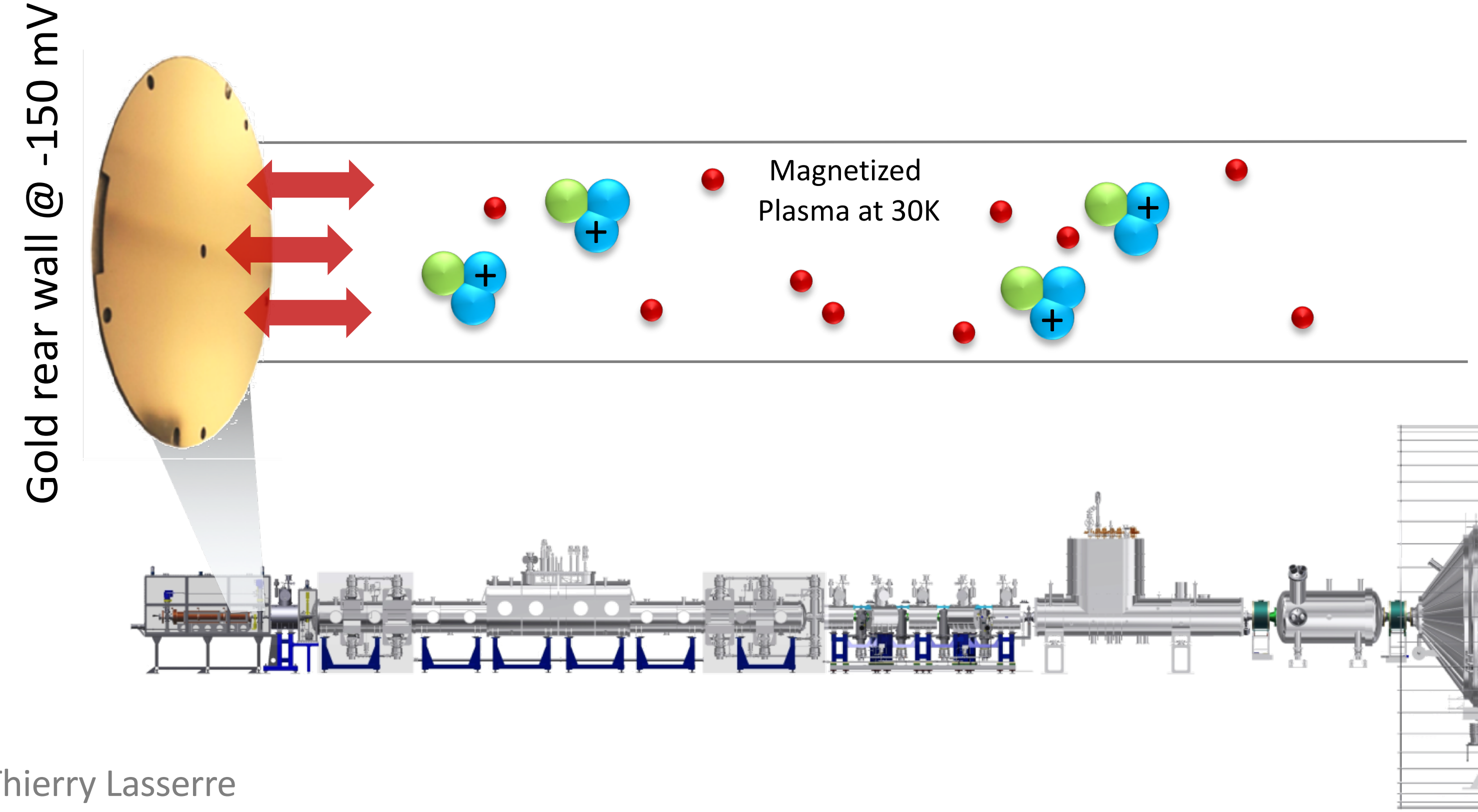




Source Potential

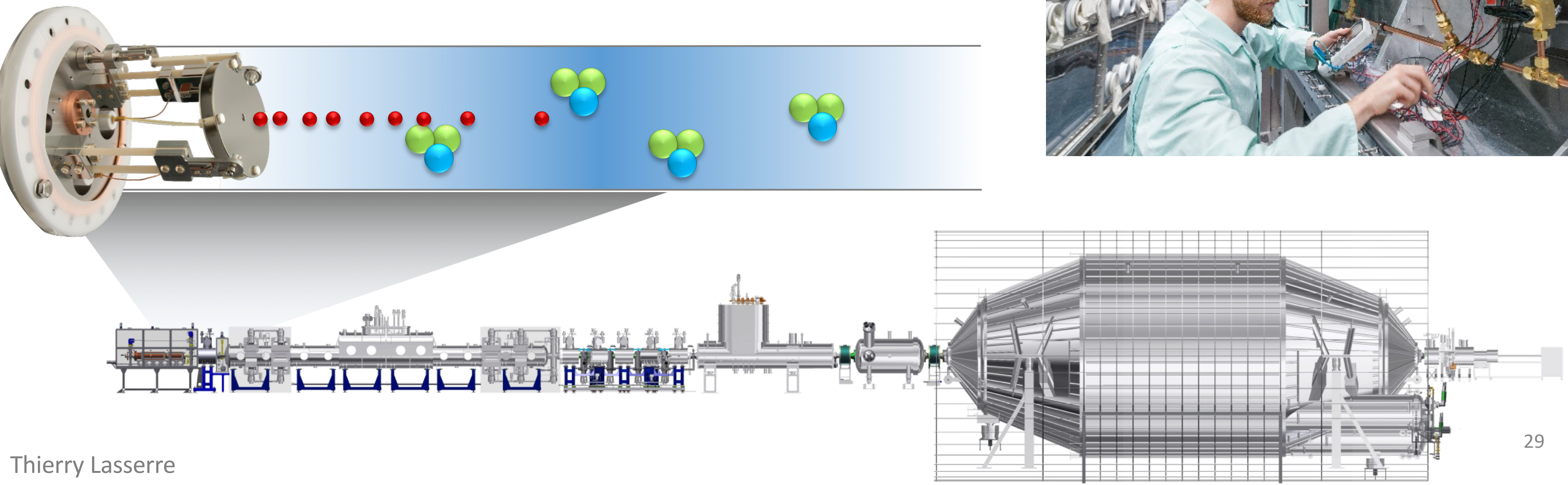
- **Filtering energy = $qU_{spectrometer}$ - qU_{source}**
- **Gold-plated rear wall provides the reference potential, qU_{source}**
- Optimization of homogeneity and coupling of plasma potential



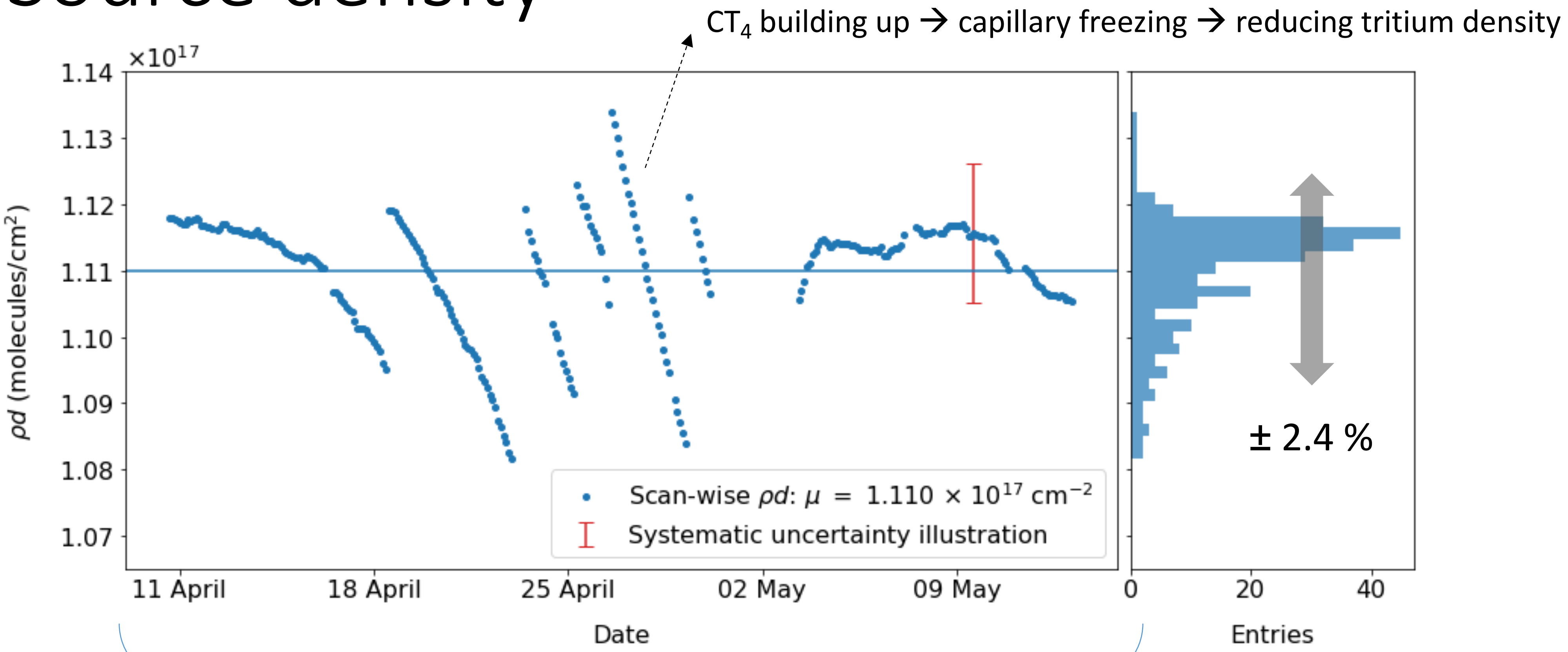


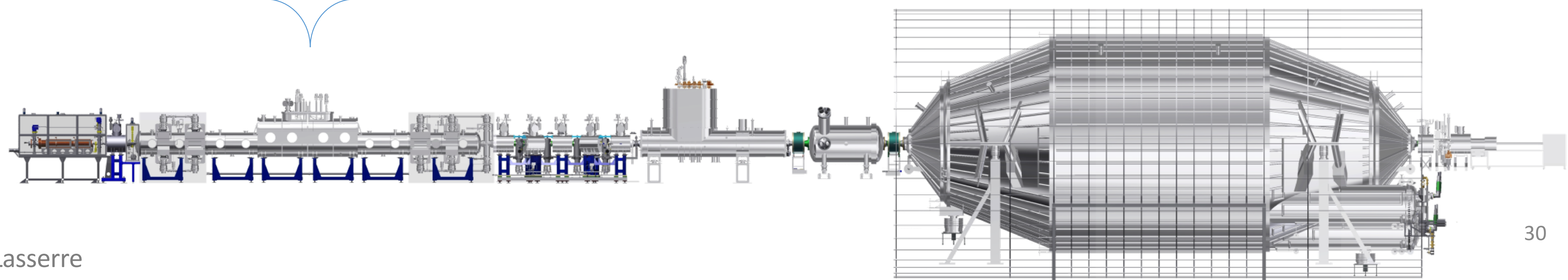
Source density

- **High-intensity electron gun**
- Column density 1.1×10^{21} molecules/m^{-2} (precision < 1 %)
- %-ish drift of density observed



Source density





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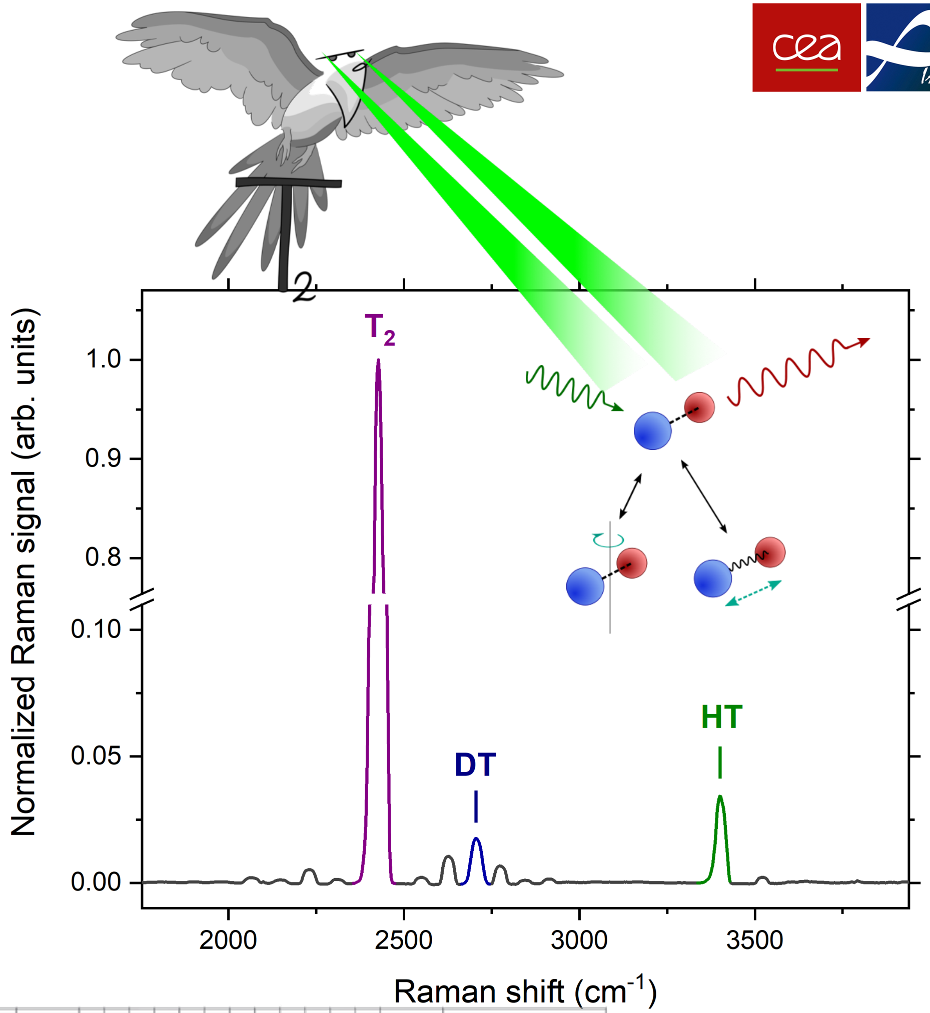
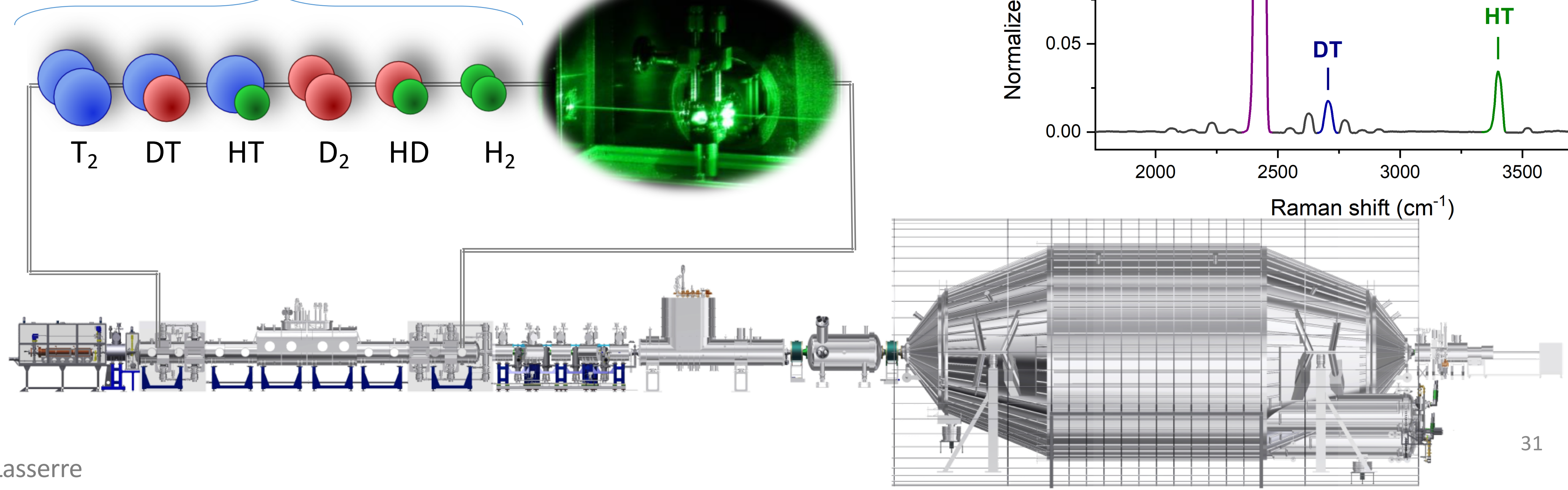
Source composition

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



Slightly different energy spectra



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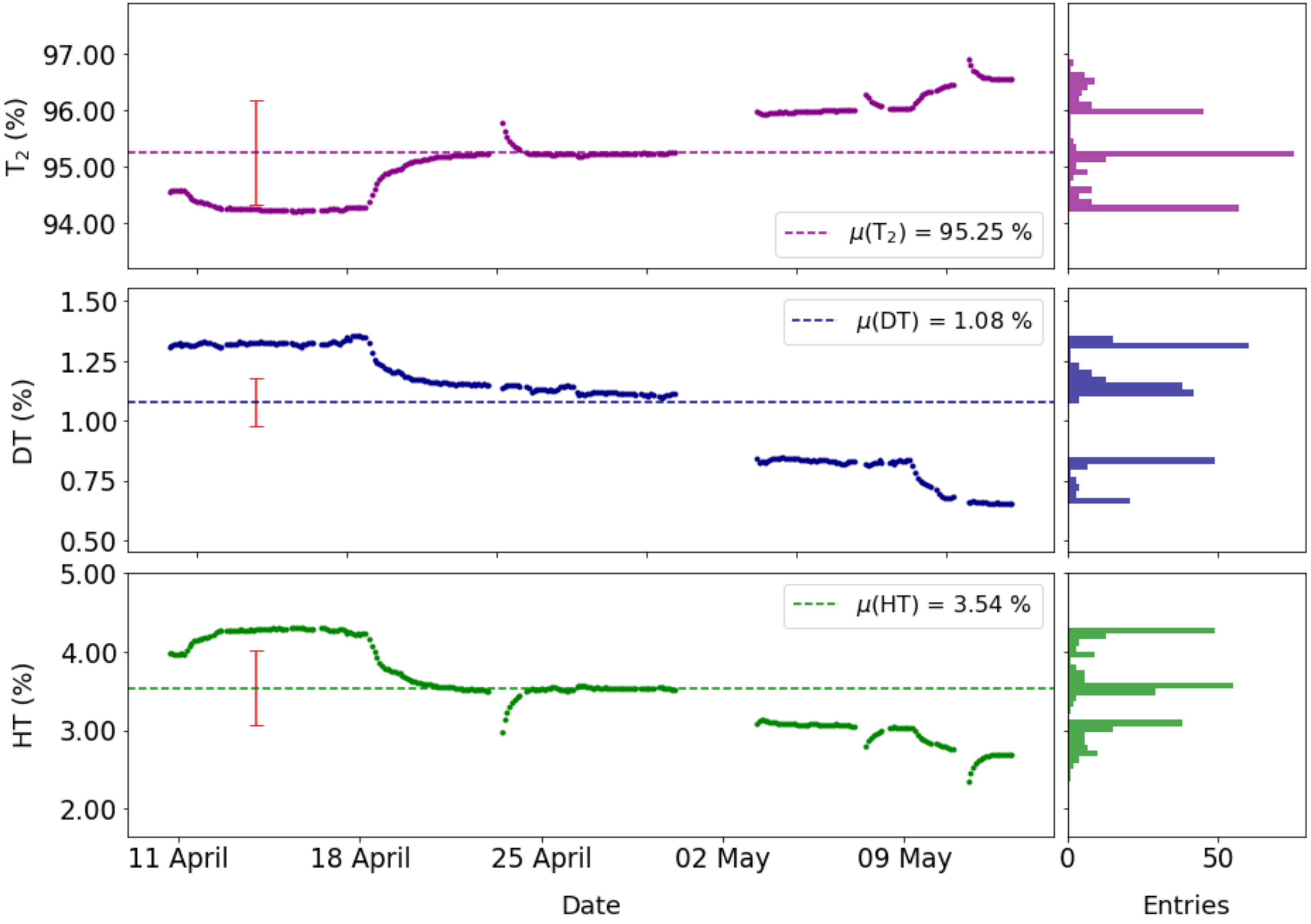
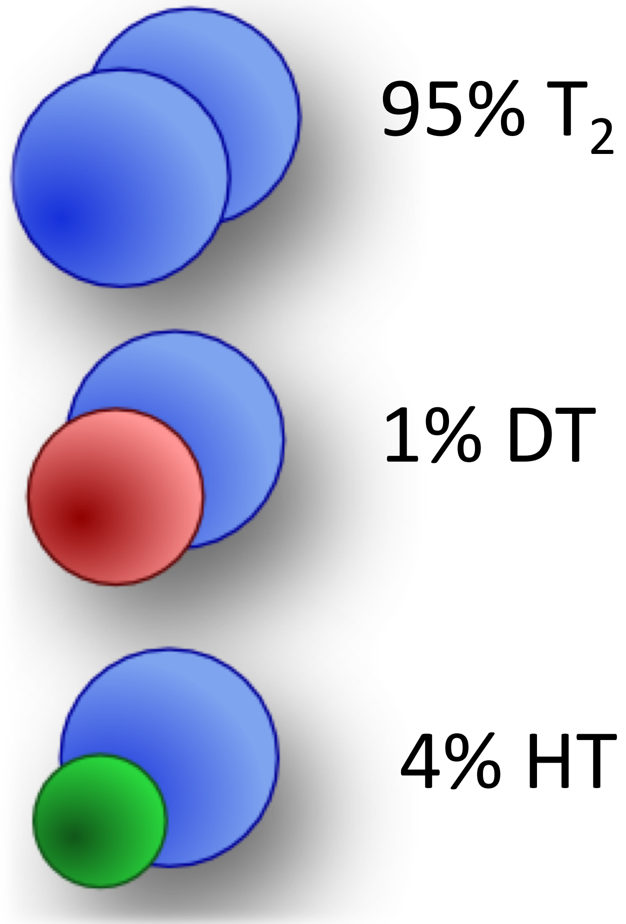
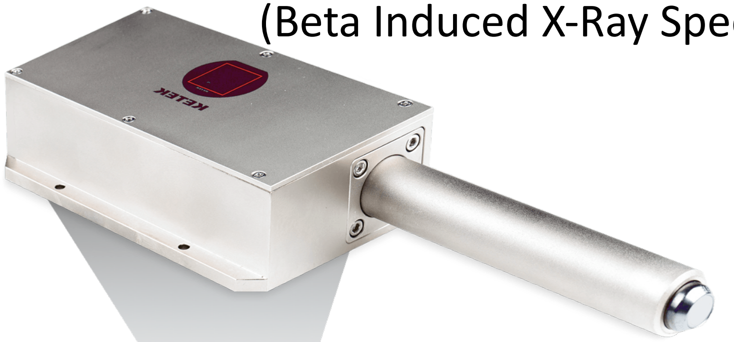




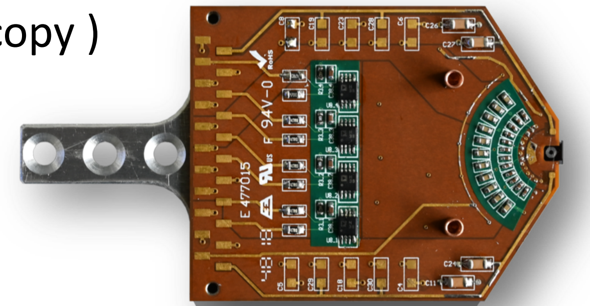
Source activity

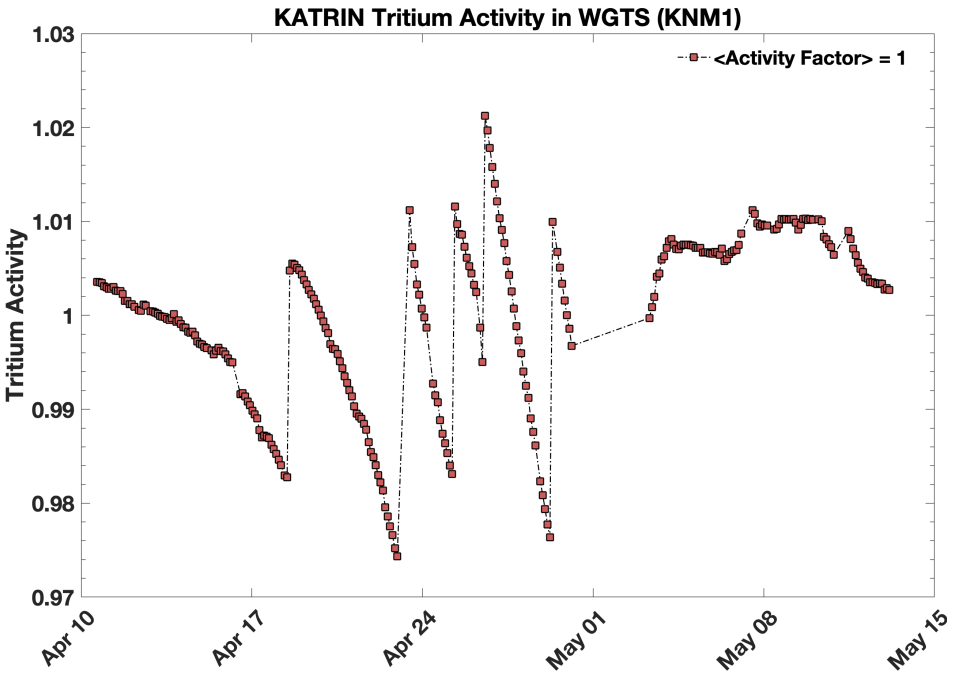
- **Electron monitor (FBM), BIXS detector**
- Stability at the ±2% level achieved

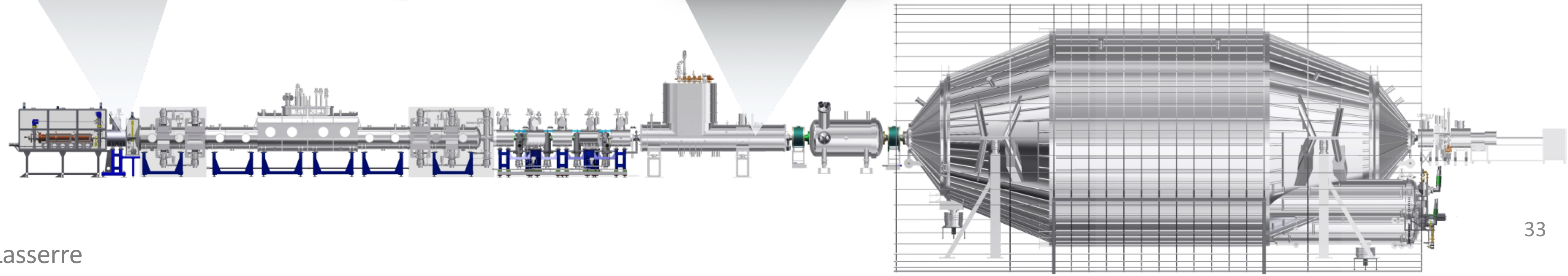
BIXS
(Beta Induced X-Ray Spectroscopy)



FBM

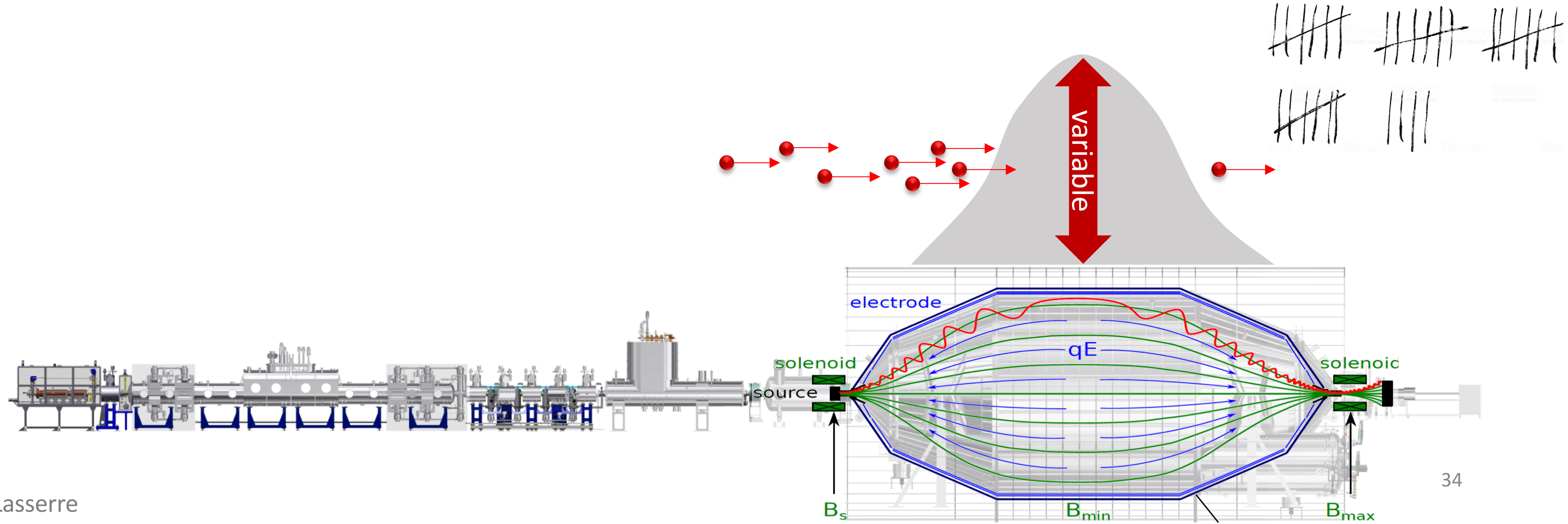






Scanning Strategy

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

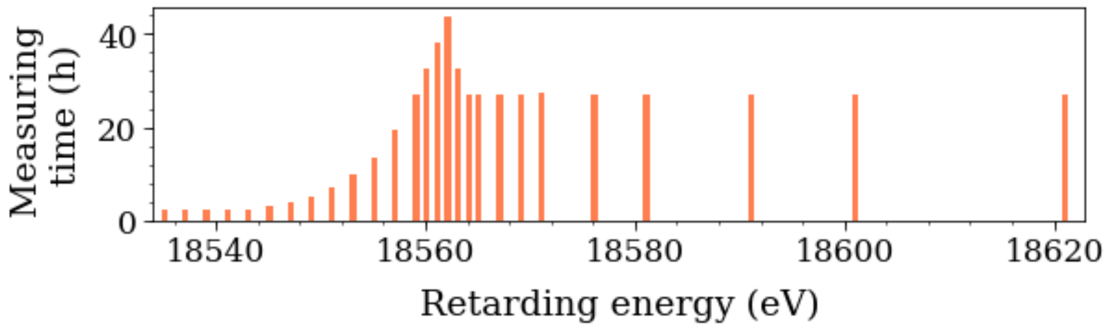


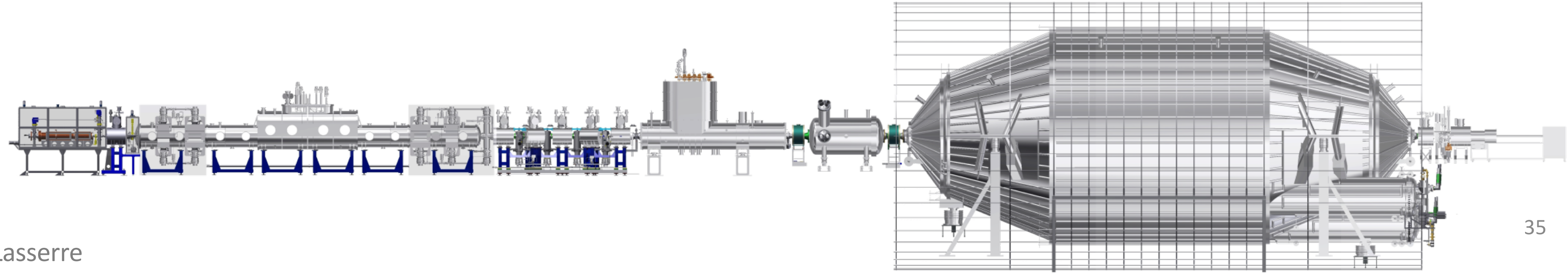
Scanning Strategy

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: **upward/downward potential ramping**

Measurement time distribution





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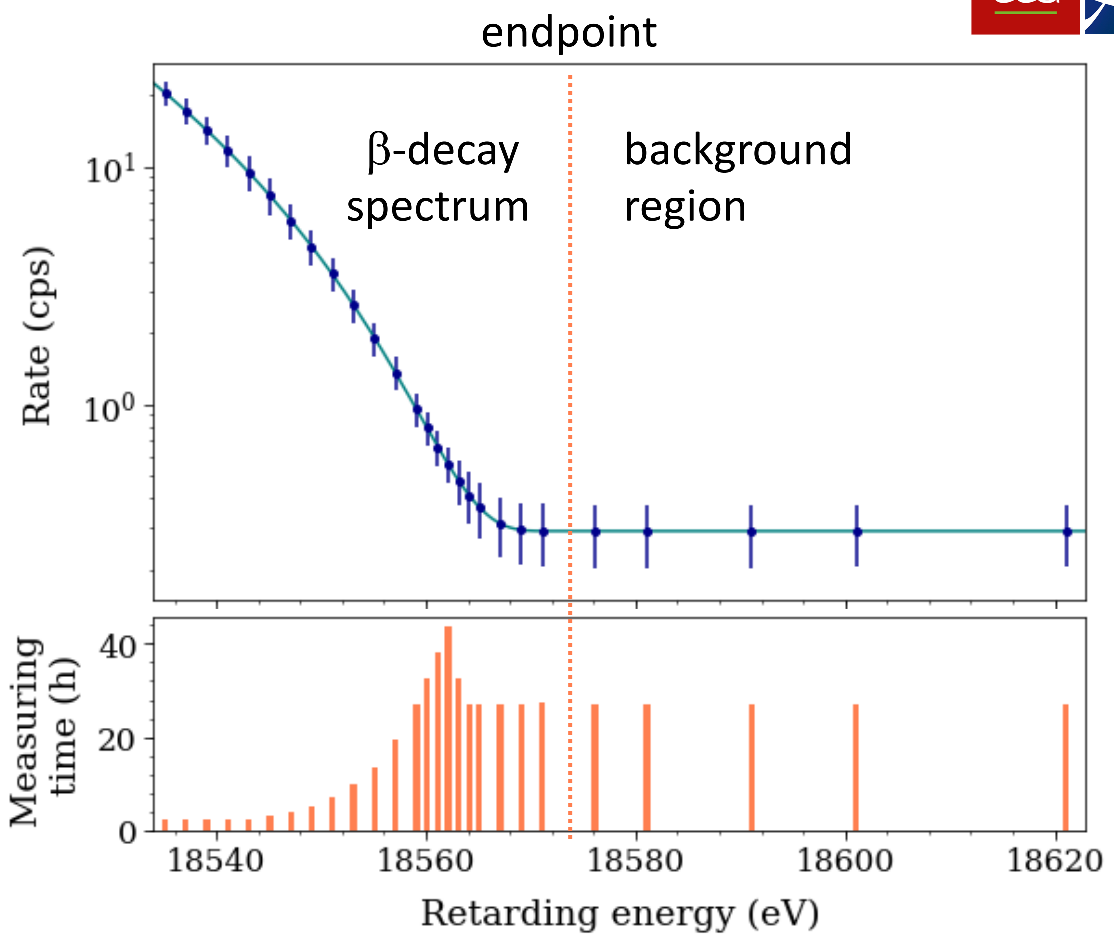
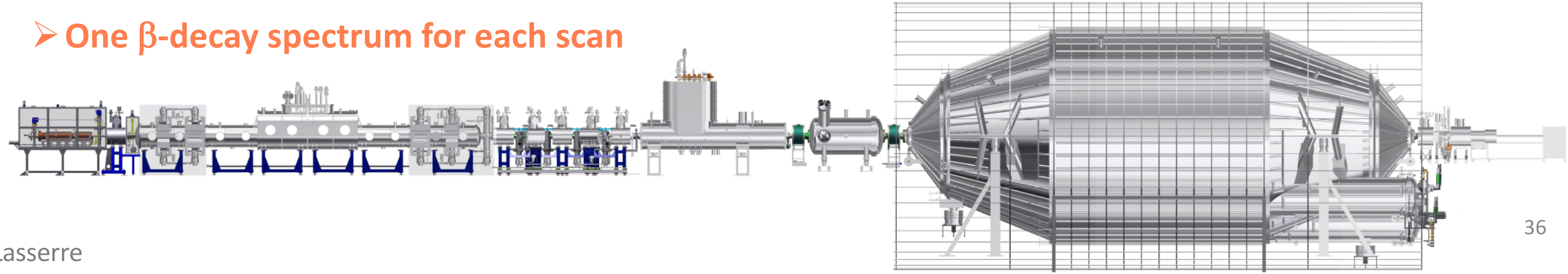
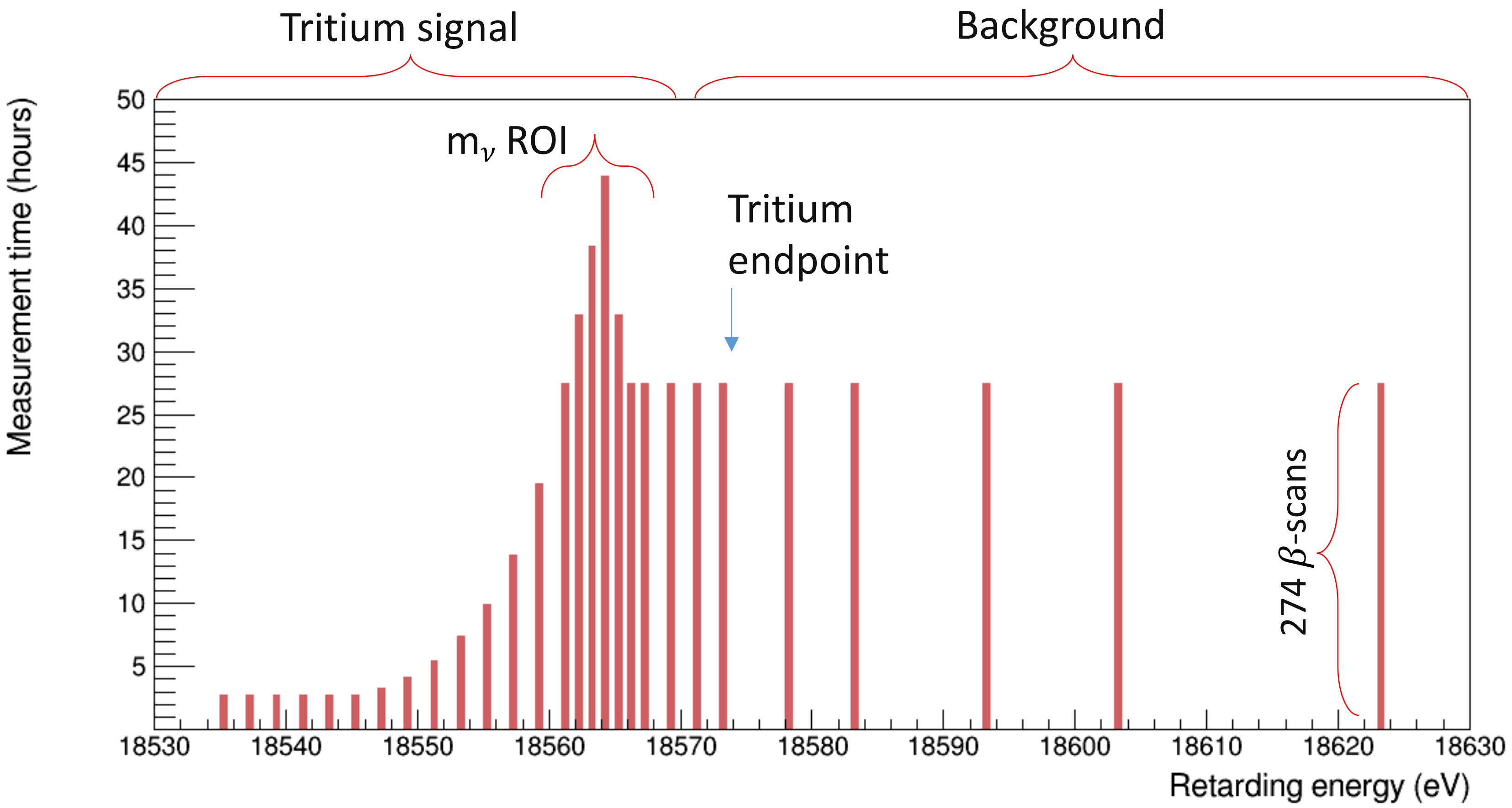


➢ **One β-decay spectrum for each scan**



Summary of the KNM-1 data taking



-40 eV
below endpoint

+50 eV
above endpoint

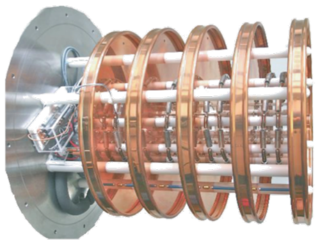
- April 10 2019 – May 13 2019

  Elapsed time: 780 hours

- 274 x 2 hour β-scans

- 27 HV setpoints / β-scan

  - 34 mV HV reproducibility



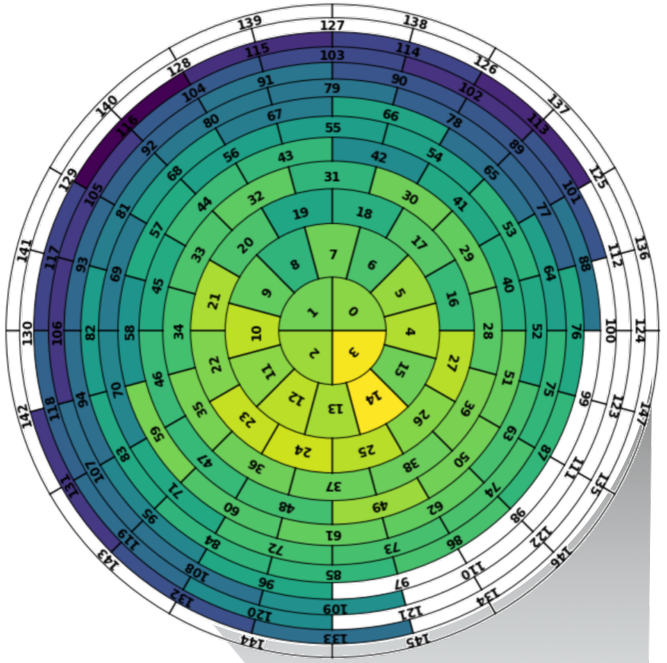
ppm-level
HV divider

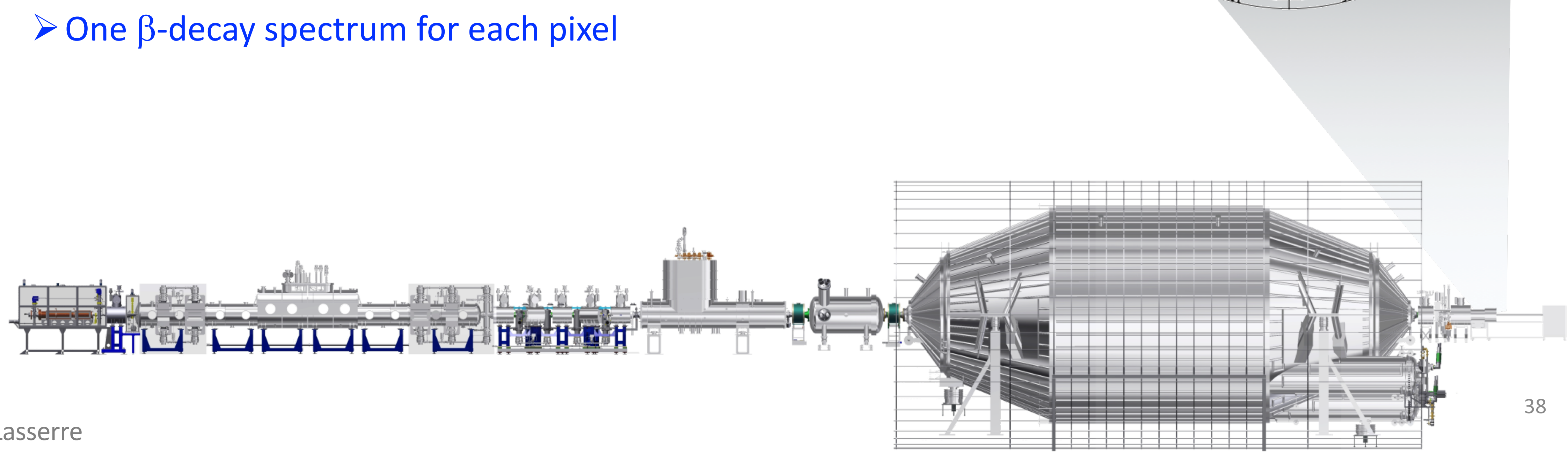
- Effective β-scan time: 522 hours

Focal plane detector

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

➢ One β-decay spectrum for each pixel

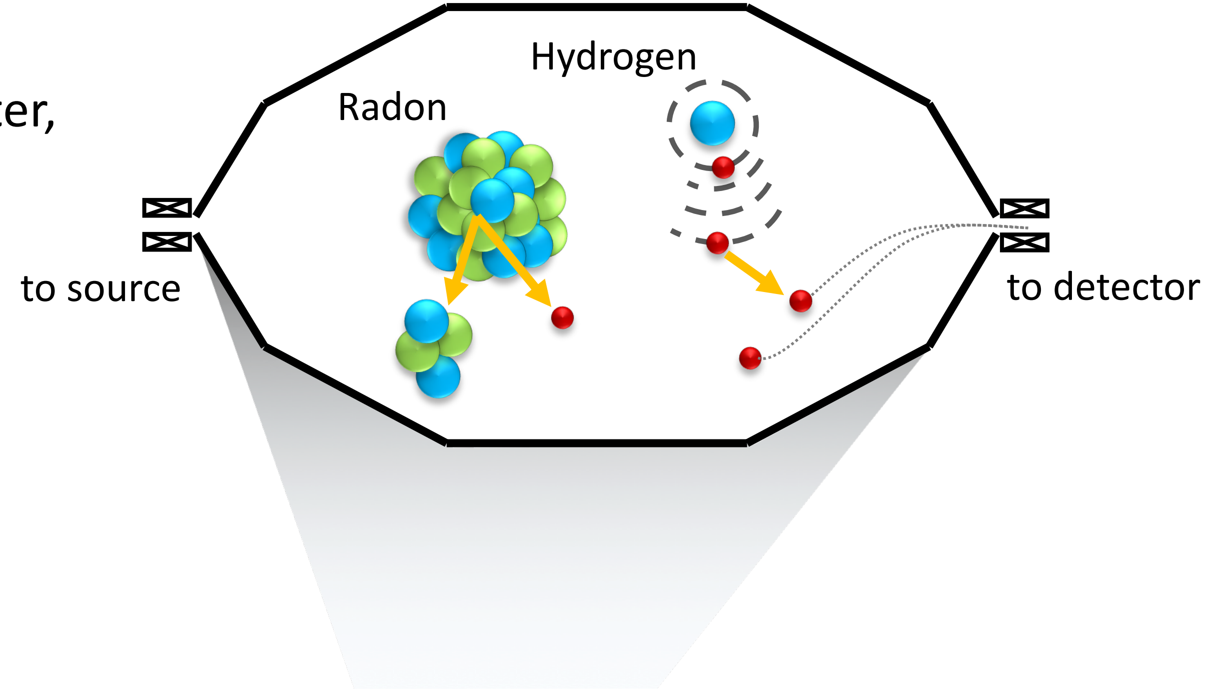




Background

Background characterization

- **low energy electrons trapped in the spectrometer are guided to the focal plane detector**
- 25% of measurement time above the endpoint
- main backgrounds come from the spectrometer, scaling thus with:
  - inner surface: 650m^2
  - volume: 1400m^3
- 2 tasks:
  - Precise determination of background rate distribution
  - Check / limit background retarding-potential dependence (background slope)



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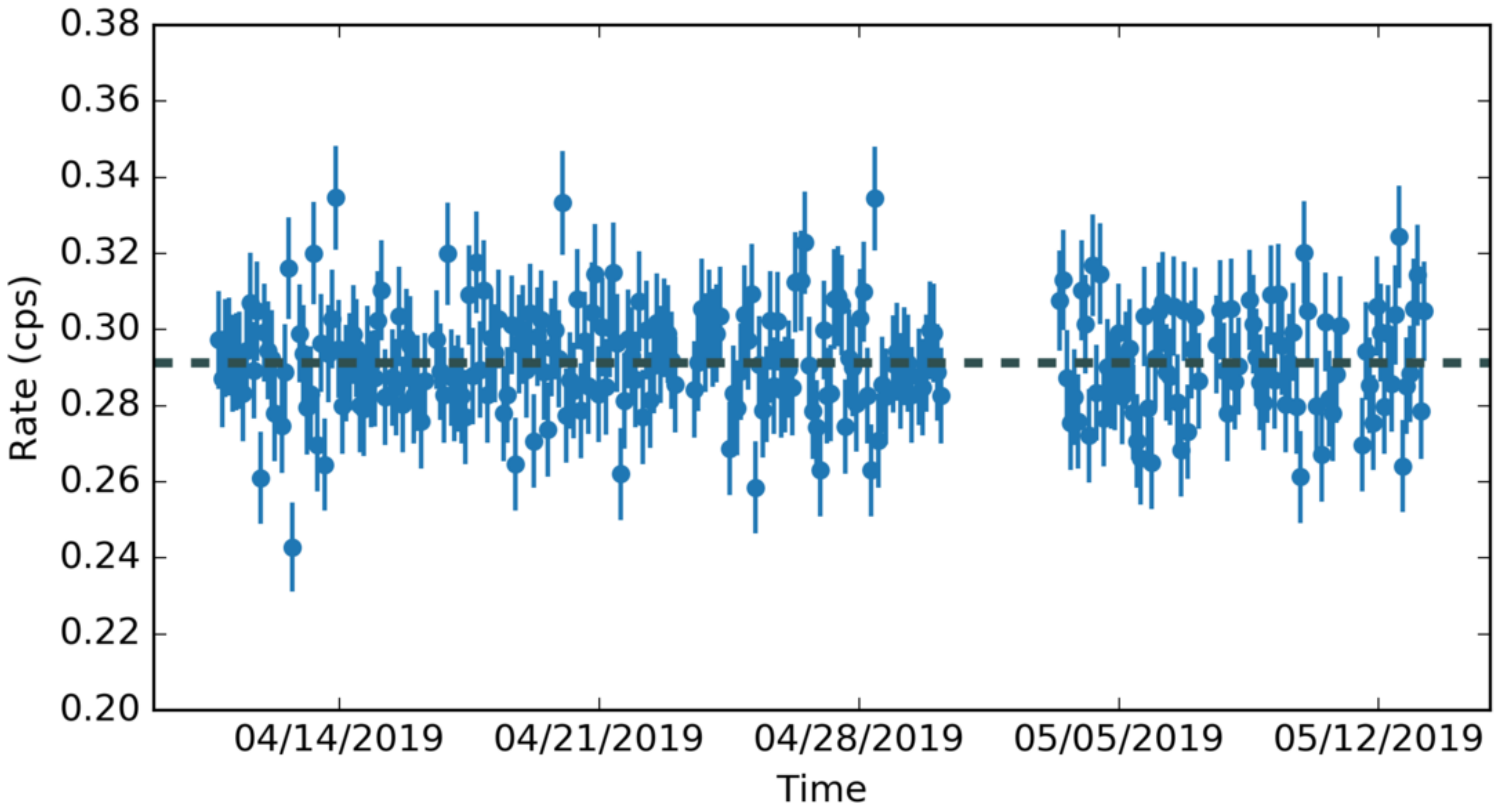
Background Study over 274 scans

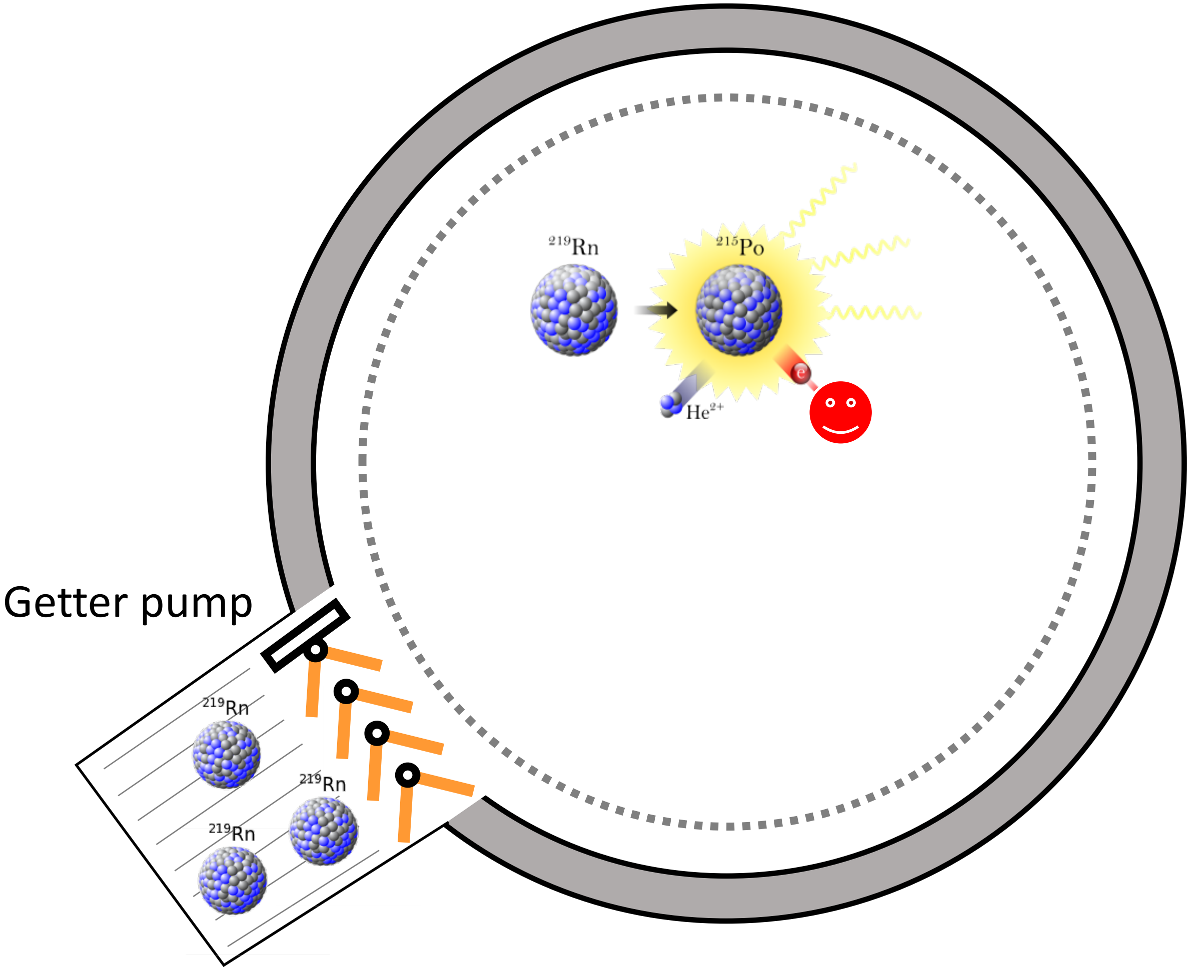
- All detector pixels combined



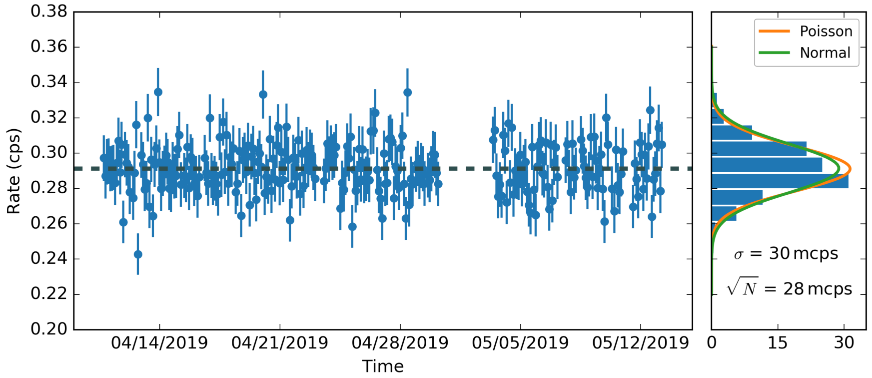
0.29 cps / 117 pixels

Design value = 0.008 cps
(a serious issue for the
ultimate sensitivity)

Radon-induced backgrounds



- 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
- Non-Poisson fluctuations



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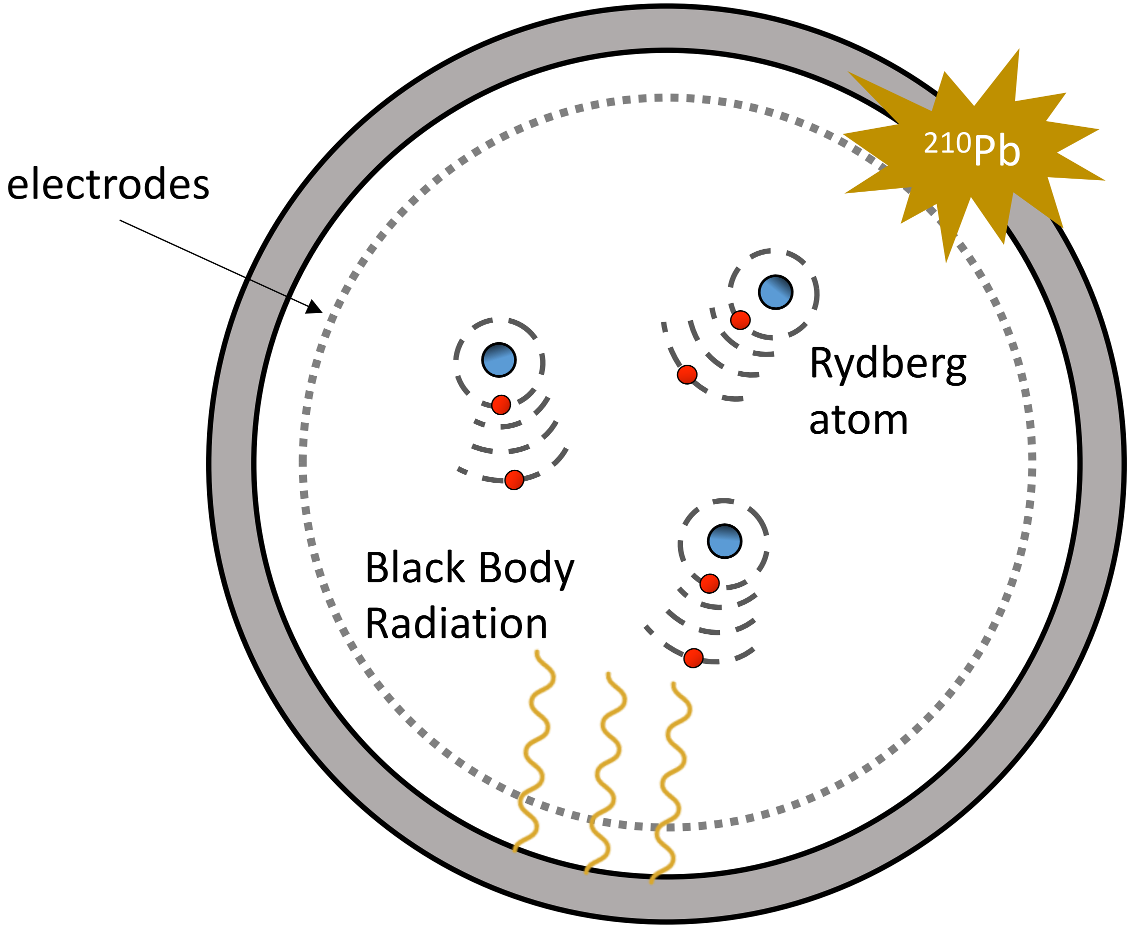
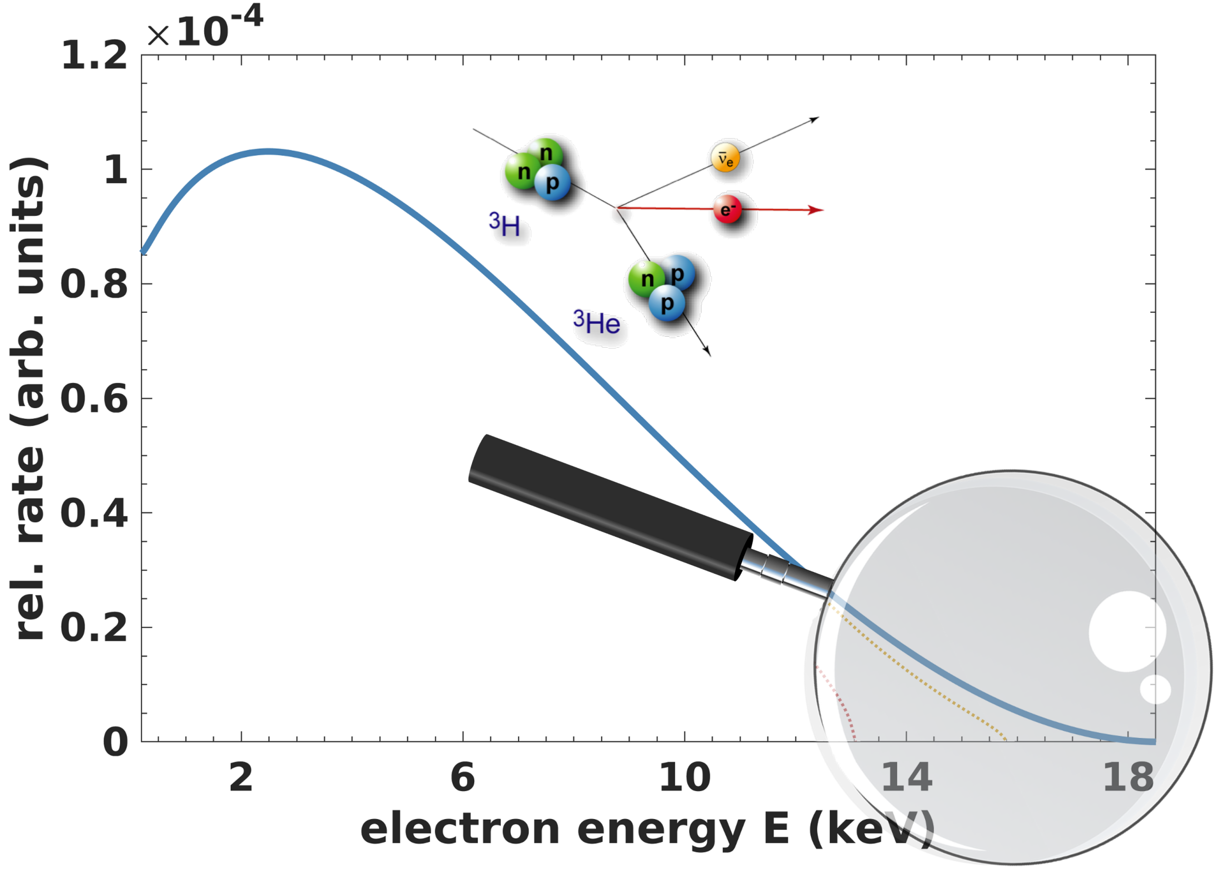
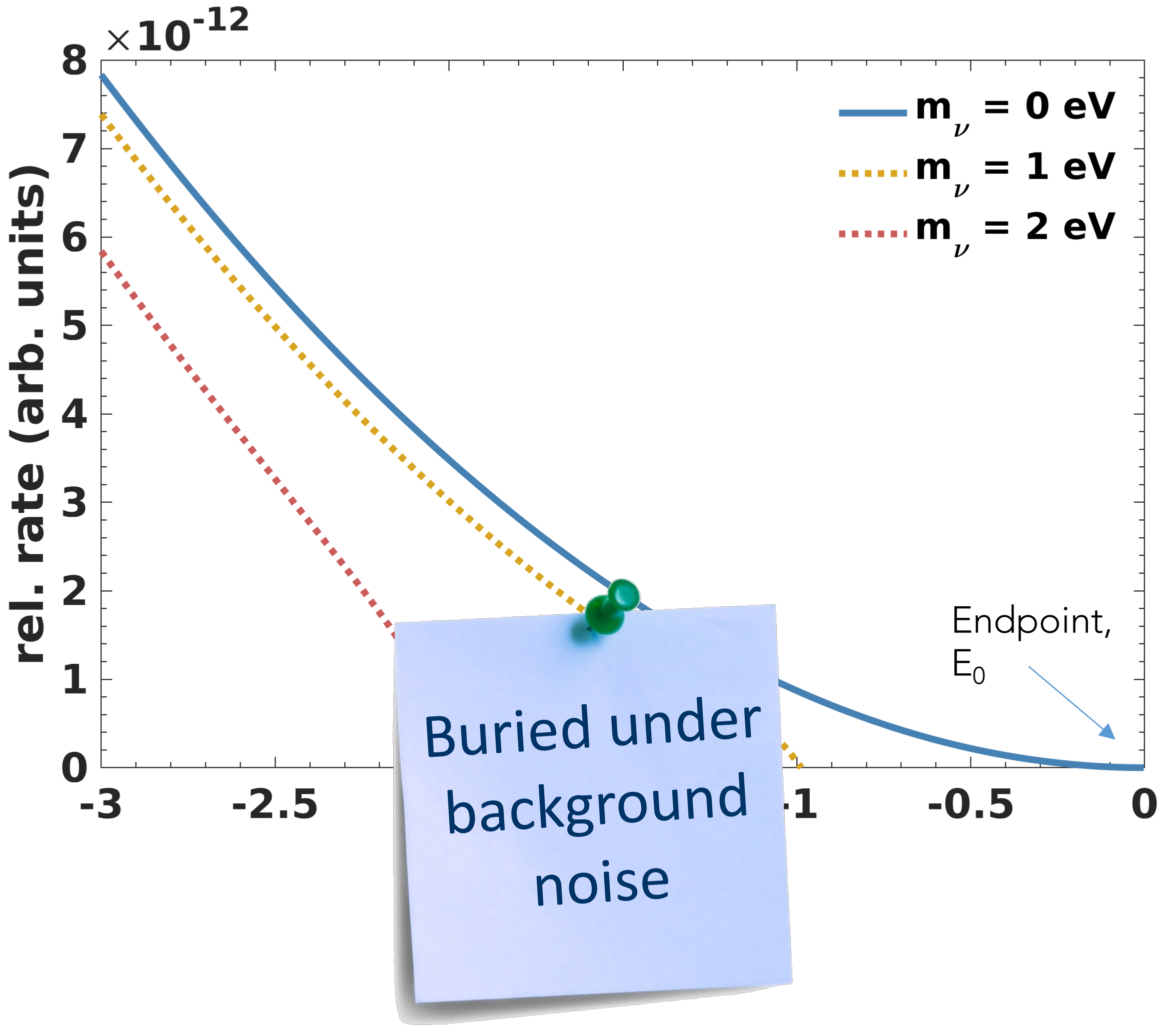
Neutral Excited Atoms



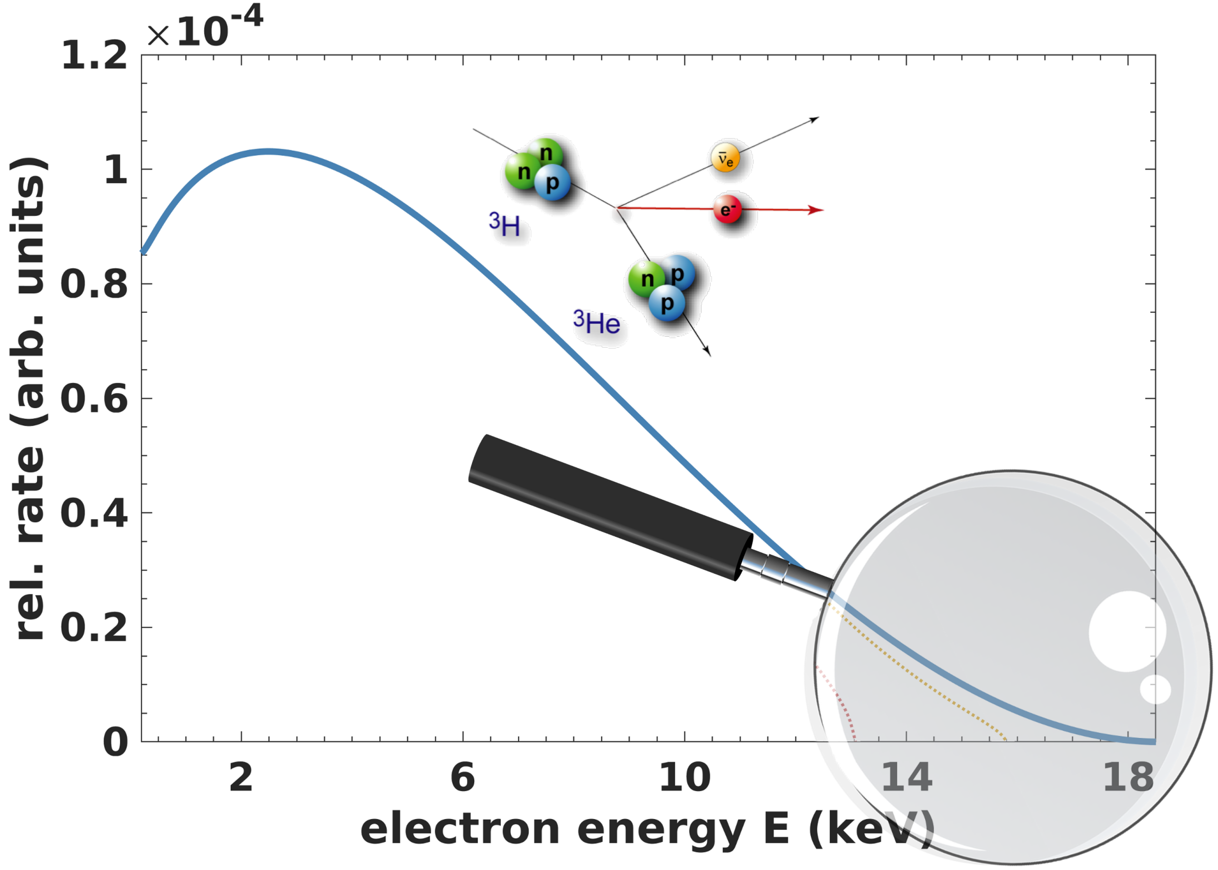
- Radon exposition during construction
  → ^{210}Pb surface contamination
- Rydberg atoms sputtered off from the spectrometer surfaces by ^{210}Pb α-decays
- Ionisation by thermal radiation
- Low energy e^- emission inside spectrometer
- Scale as the spectrometer flux-tube volume…

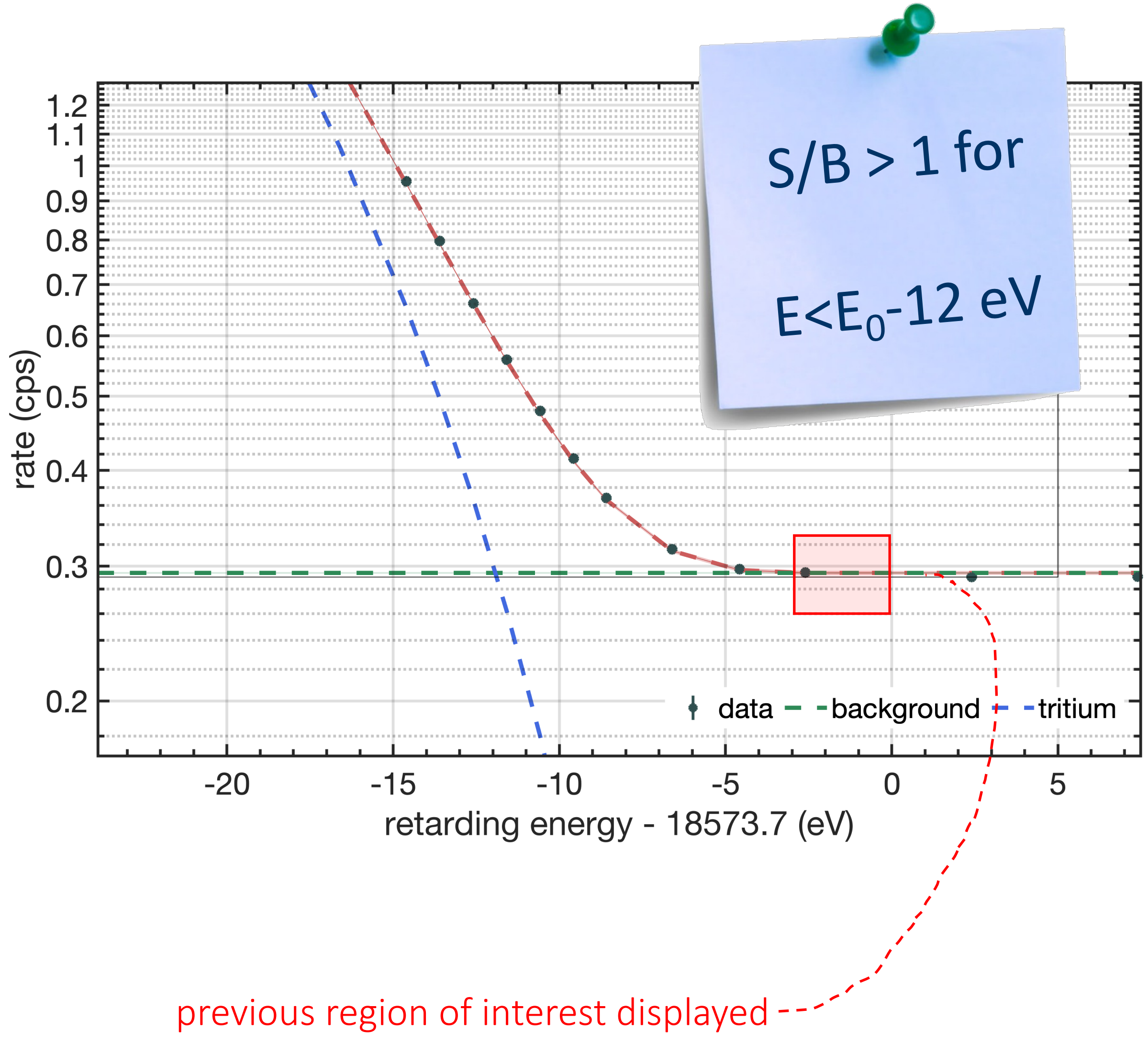
Misleading Display of m_ν Imprint



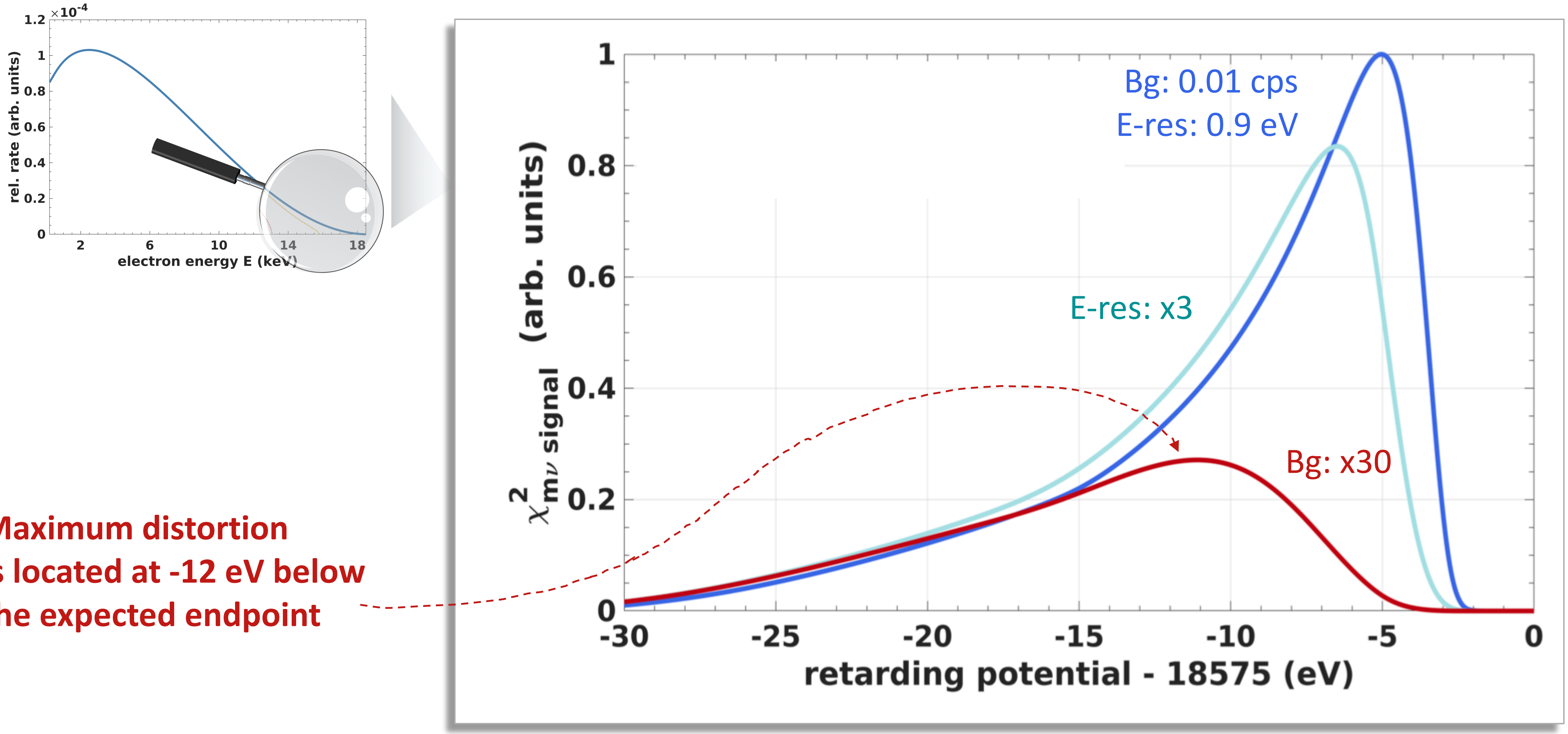


Correct Display of Neutrino Mass





Impact on the sensitivity

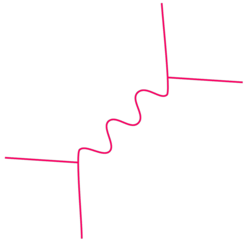


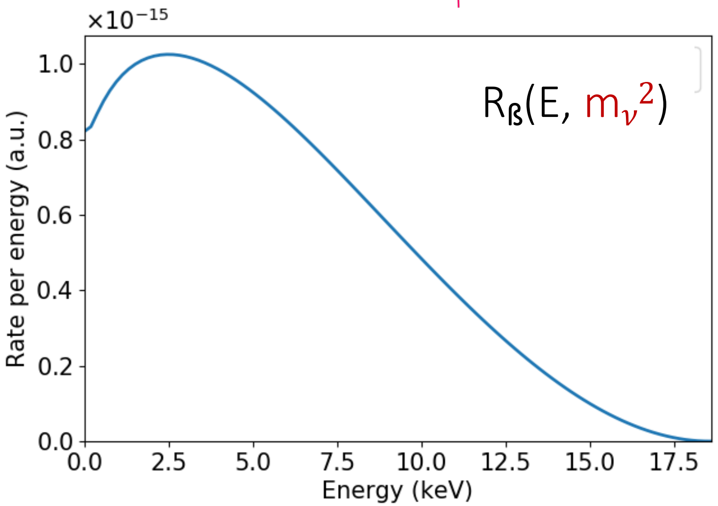
Maximum distortion is located at -12 eV below the expected endpoint

Tritium Signal Modeling

Integral spectrum modeling

tritium β-decay theory

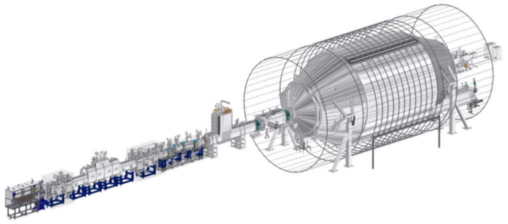


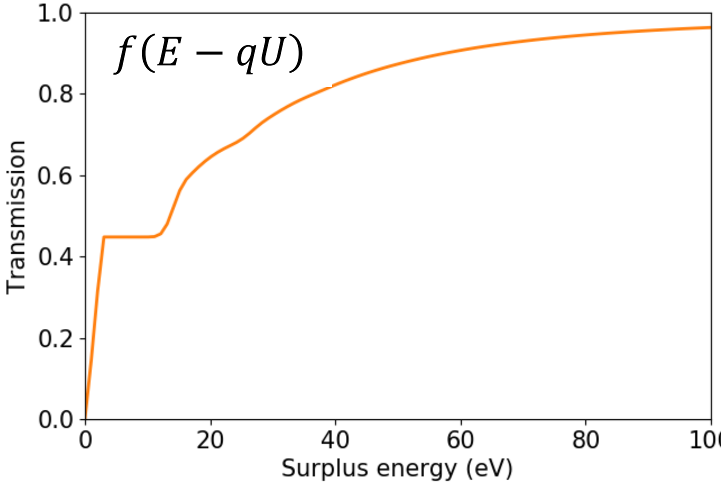


$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C \cdot p_e E_e \cdot \sqrt{(E_e - E_0)^2 - m_{\nu_i}^2} \cdot (E_e - E_0) \cdot F(E_e, Z)$$

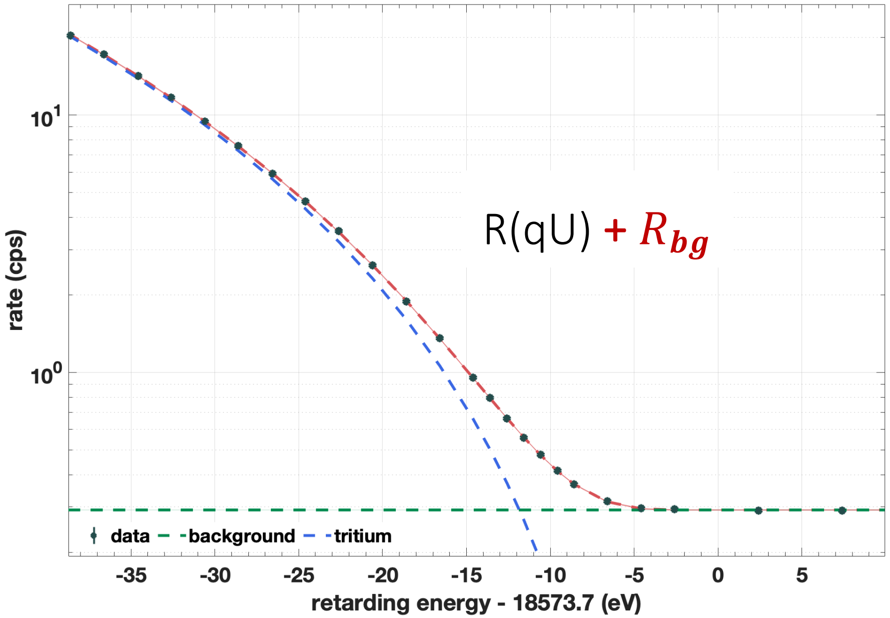
$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_{ß}(E, m_\nu^2) \cdot f(E - qU)\, dE + R_{bg}$$

experimental setup



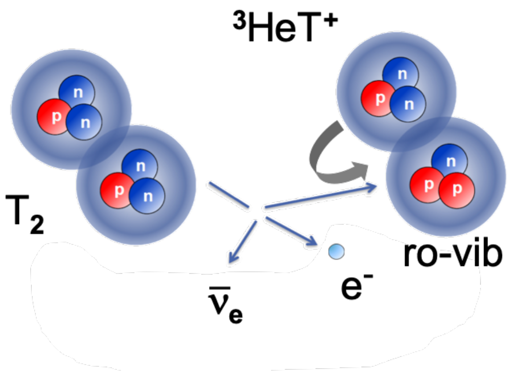


integral β-spectrum



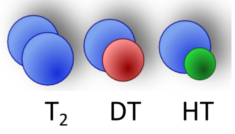
← R_{bg}

Molecular Final States

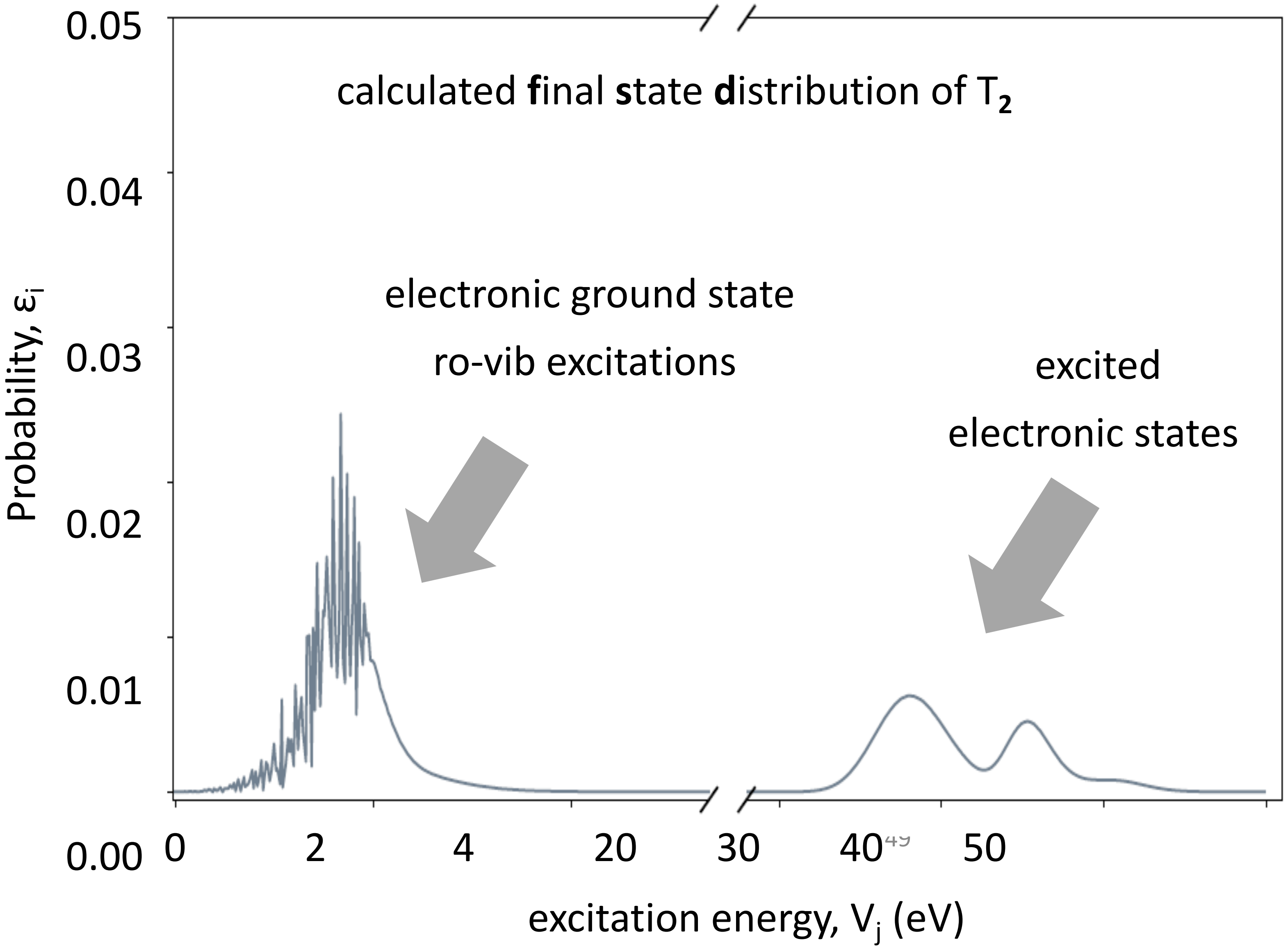


- Modification of the beta decay spectrum shape near the endpoint

- Specific calculation for each isotopolgue



→ Model dependency in m_ν determination!



Tritium Beta Decay calculation

$$R_{\mathrm{calc}}(\langle qU\rangle) = A_{\mathrm{s}} \cdot N_{\mathrm{T}} \int R_{\beta}(E) \cdot f_{\mathrm{calc}}(E - \langle qU\rangle)\, dE + R_{\mathrm{bg}}$$

Fermi spectra summed over all rob-vib molecular final states

$$R_{\beta}(E) = \frac{G_{\mathrm{F}}^2 \cdot \cos^2\Theta_{\mathrm{C}}}{2\pi^3} \cdot |M_{\mathrm{nucl}}^2| \cdot F(E, Z') \cdot (E + m_{\mathrm{e}}) \cdot \sqrt{(E+m_{\mathrm{e}})^2 - {m_{\mathrm{e}}}^2} \cdot \sum_{\mathrm{j}} \zeta_j \cdot \varepsilon_j \cdot \sqrt{\varepsilon_j^2 - m_\nu^2} \cdot \Theta(\varepsilon_j - m_\nu)$$

Fit parameter

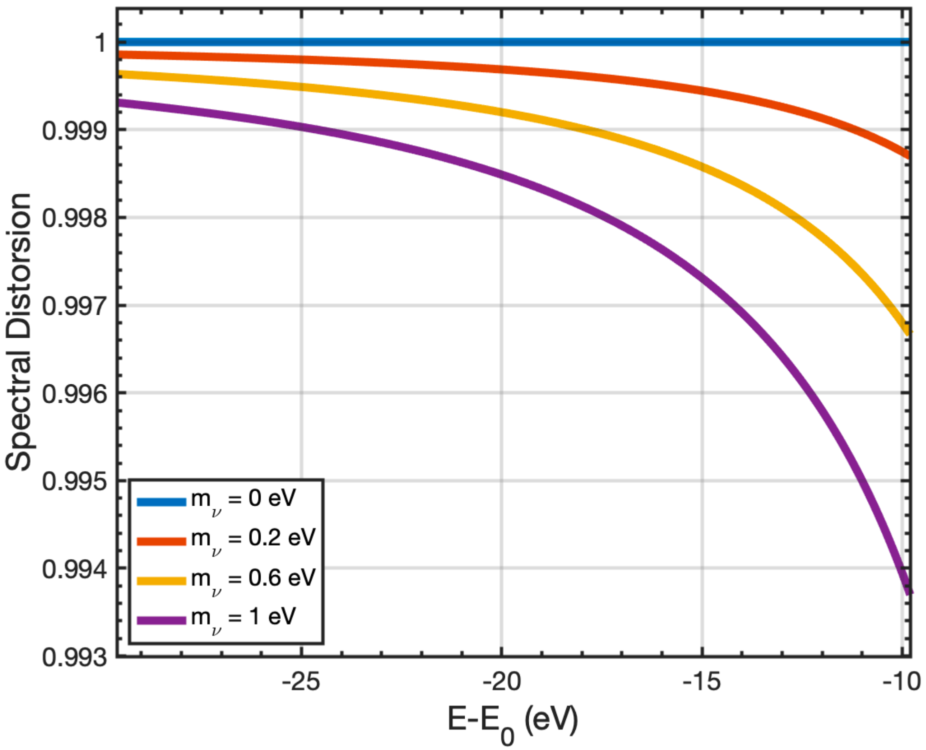
final states

$$\varepsilon_j = E_0 - E - V_j$$

Simplified but helpful view of the signal

$$R(qU, E_0, m_\nu^2) \;\; \propto (qU - E_0)^3 - m_\nu^2 \, (qU - E_0)$$

$$R(qU, E_0, m_\nu^2) / \, R(qU, E_0, 0)$$



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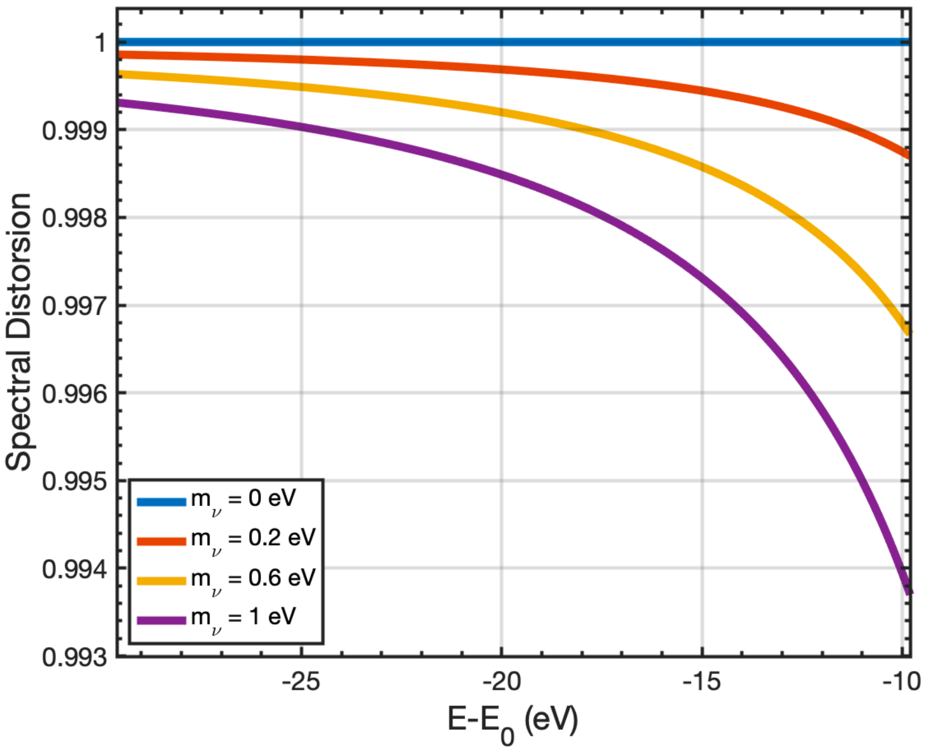
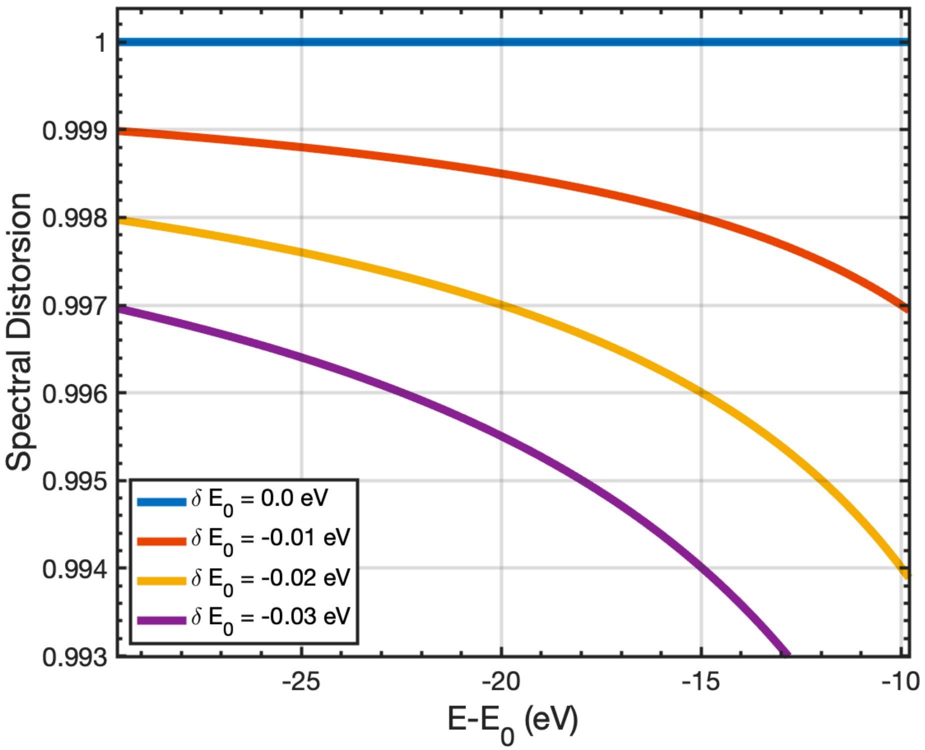
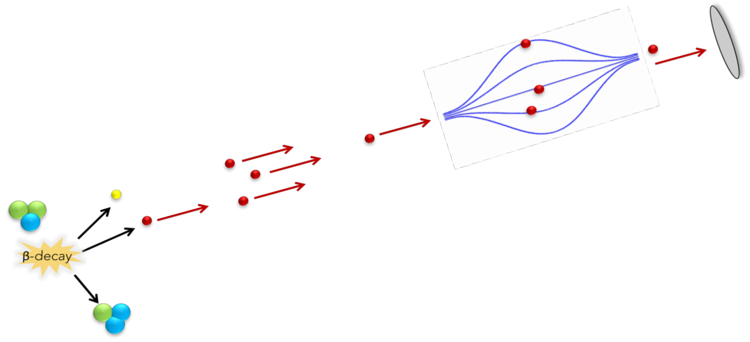


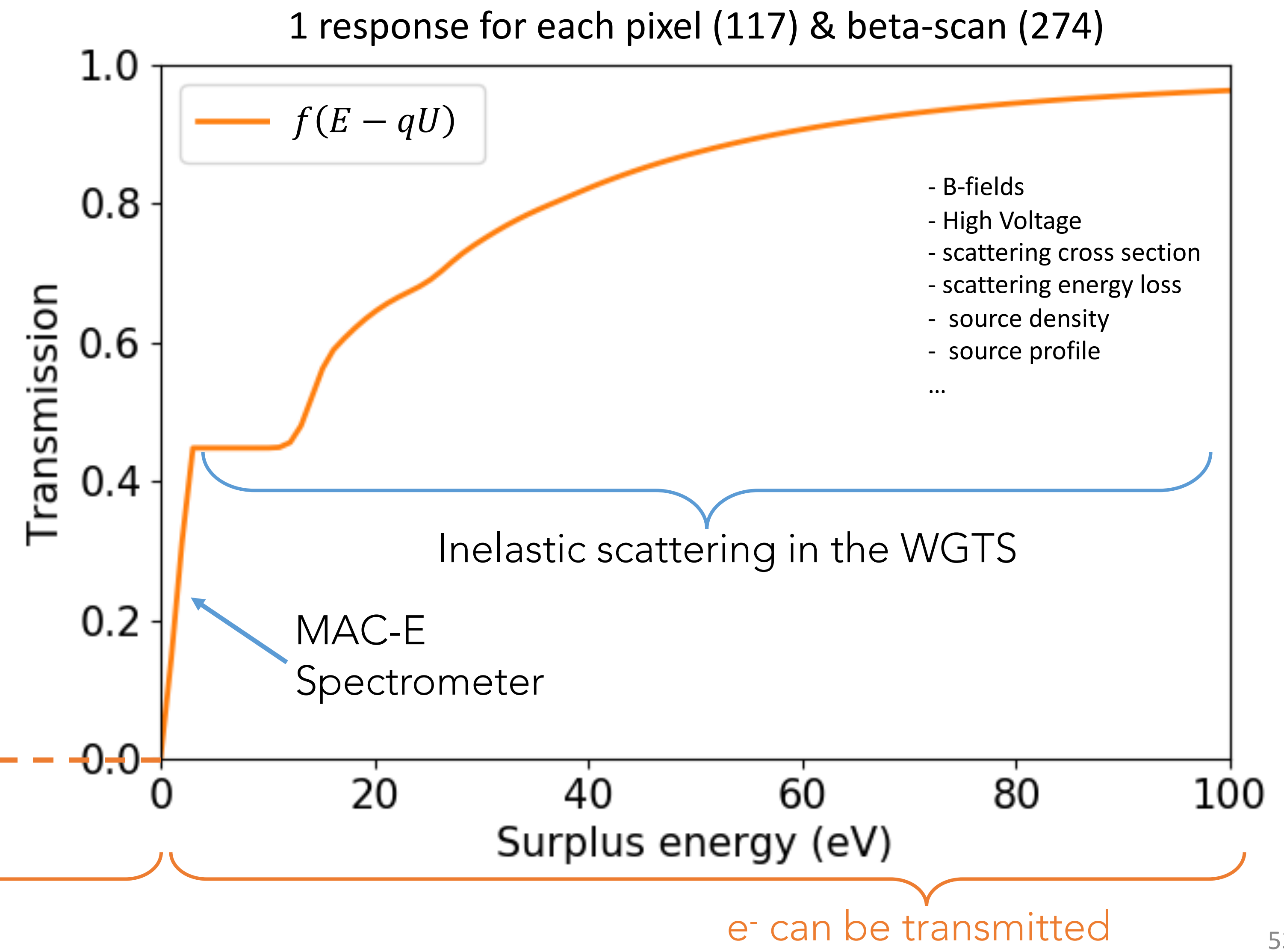
$R(qU, E_0 + \delta E_0, 0) / \, R(qU, E_0, 0)$



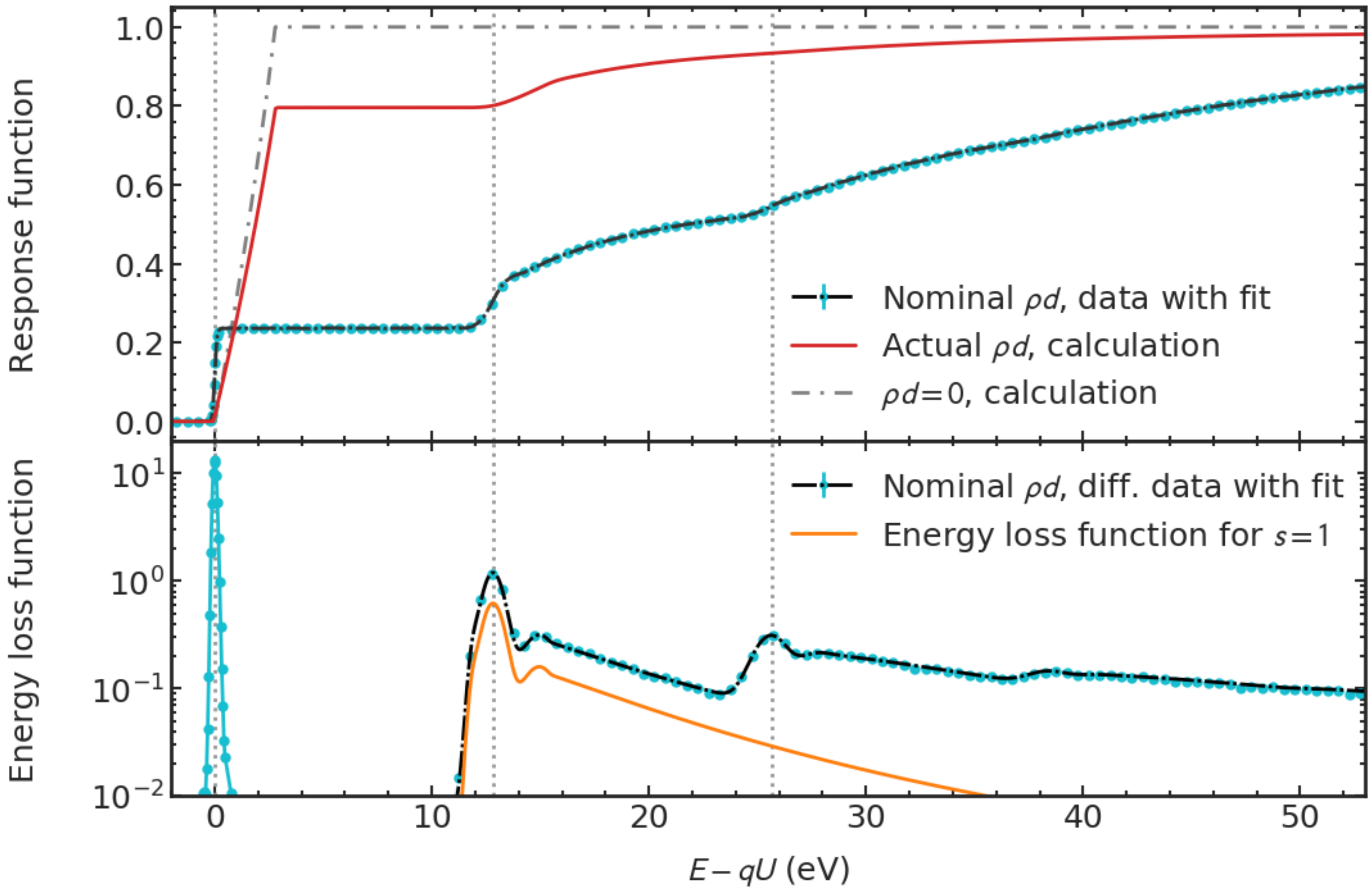
- Sub-percent spectral distortion
- E_0 , m_ν^2 correlation

Electron Transmission Model





Electron Transmission Calibration



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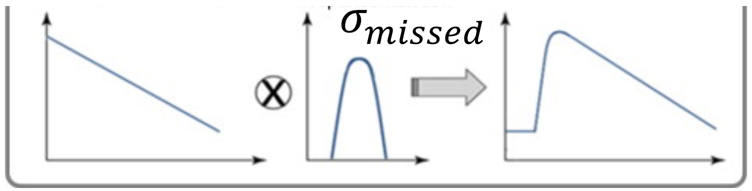
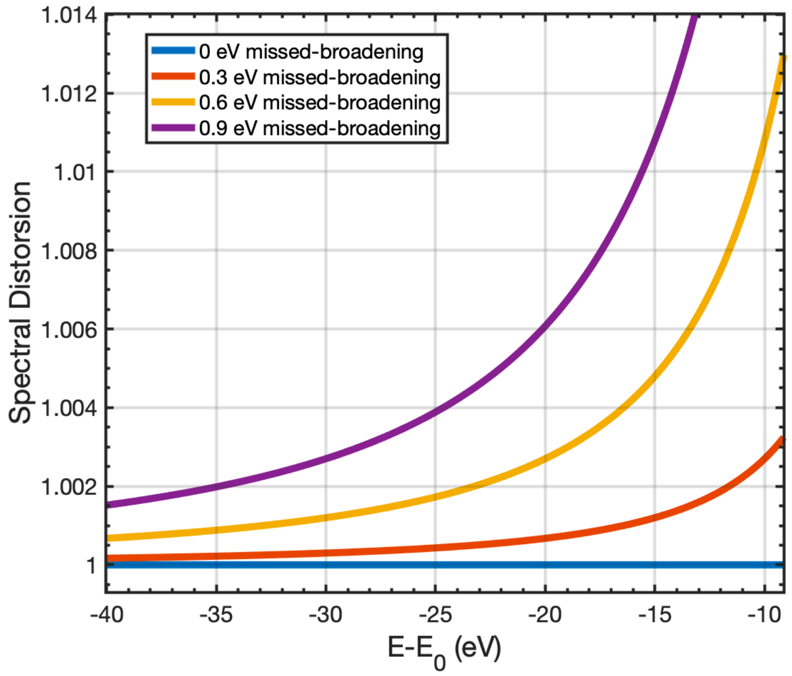
Impact of any mis-modeling?

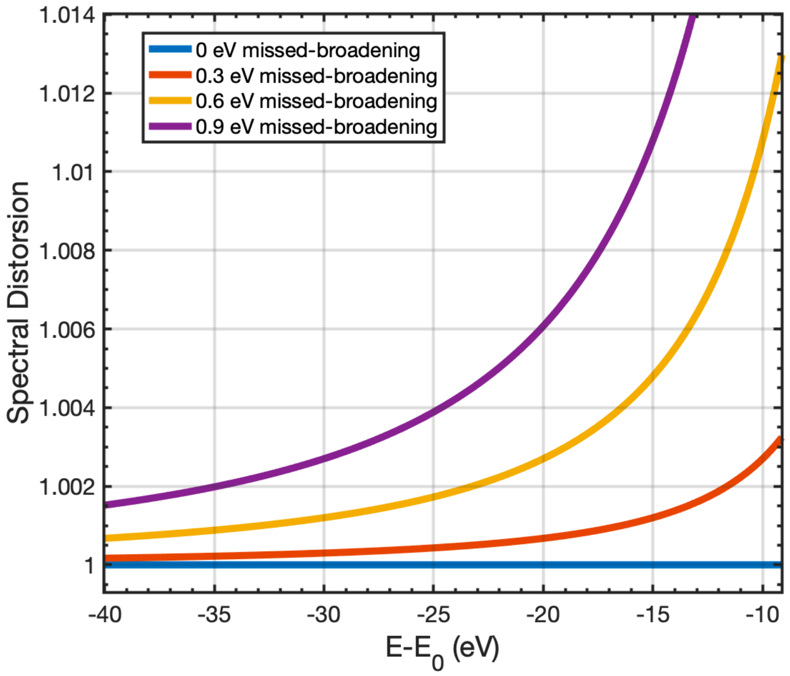
spectrum convoluted with gaussian



- Mimick a 'negative' m_ν^2

$$R(qU, E_0, m_\nu^2) \;\; \propto (qU \; - E_0)^3 + 2\,\sigma_{missed}^2\,(qU \; - E_0)$$

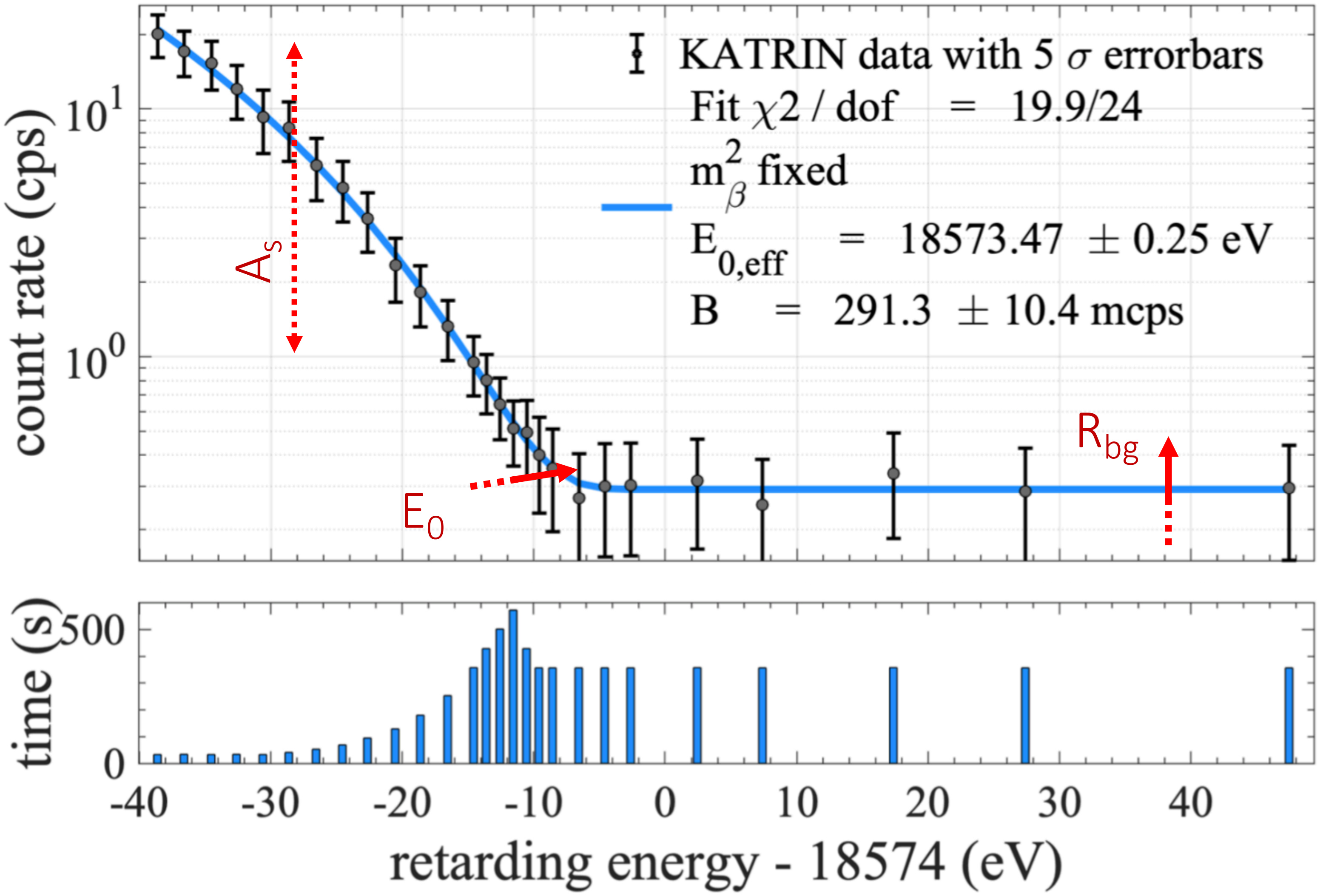




- Sub-percent spectral distortion
- m_ν^2 = -2 σ_{missed}^2

β-scan-wise Analysis (117-Pixel Combined)

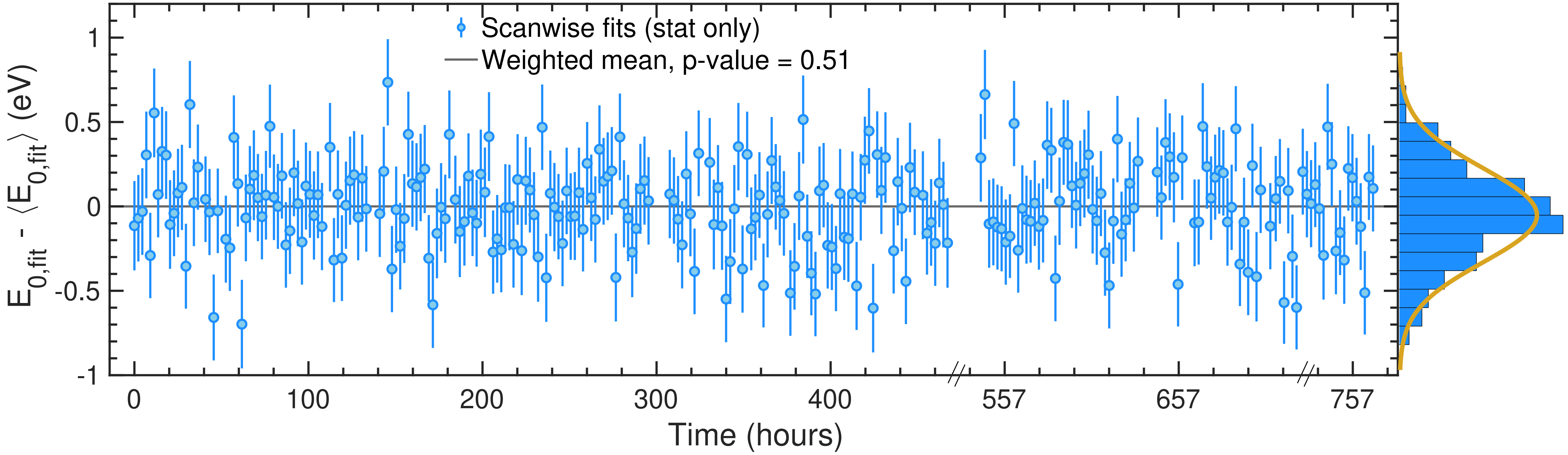
Fit of a single 2-h beta-scan



- A single <u>2h β-scan</u>
- m_ν fixed to 0
- 3 parameter fit
  - Tritium Activity, A_s
  - Endpoint, E_0
  - Background, R_{bg}
- High quality data

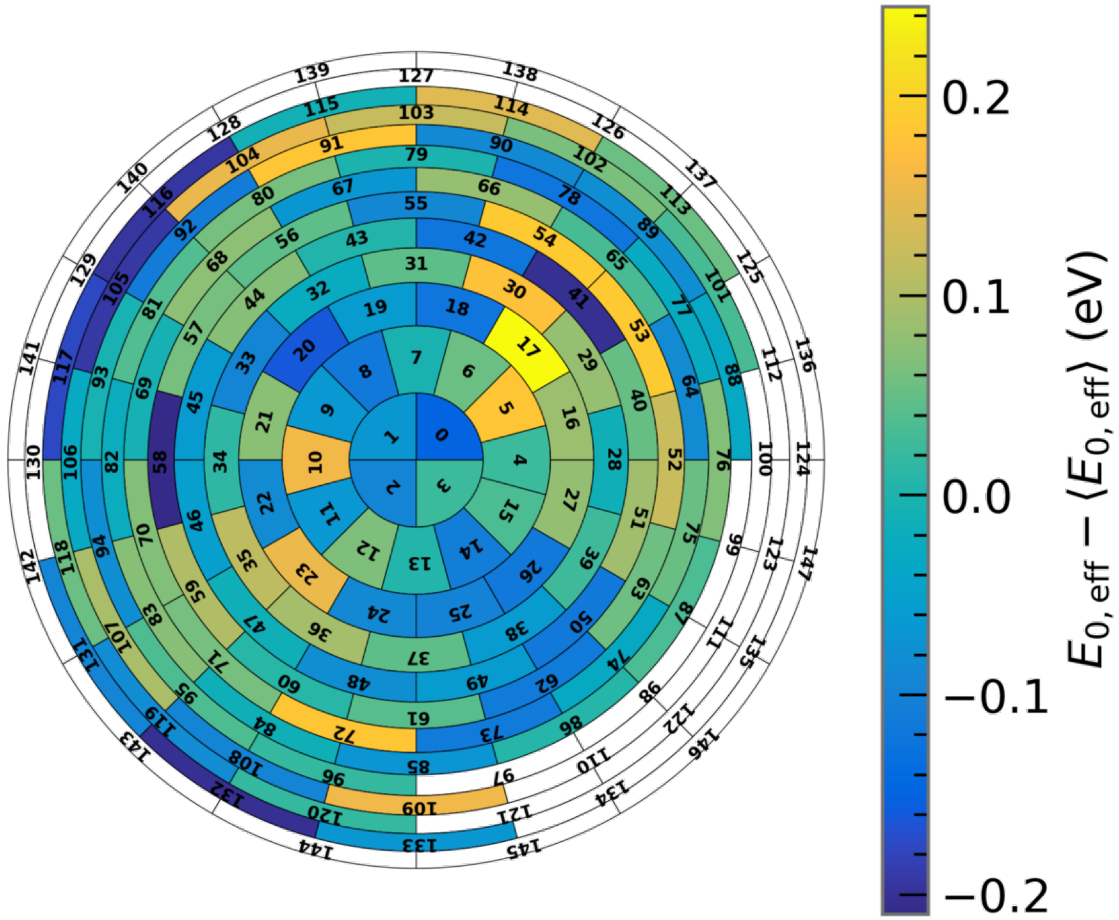
Stability over 274 scans

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



Uniformity over 117 pixels

- All scans combined
- Spatial homogeneity over detector wafer

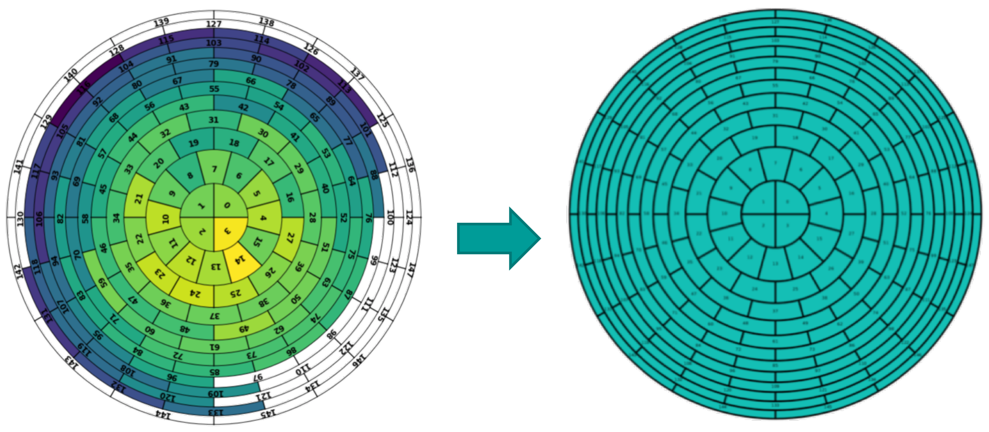


Combination of 274 Scans + 117 Pixels

All Scans + all Pixels combination

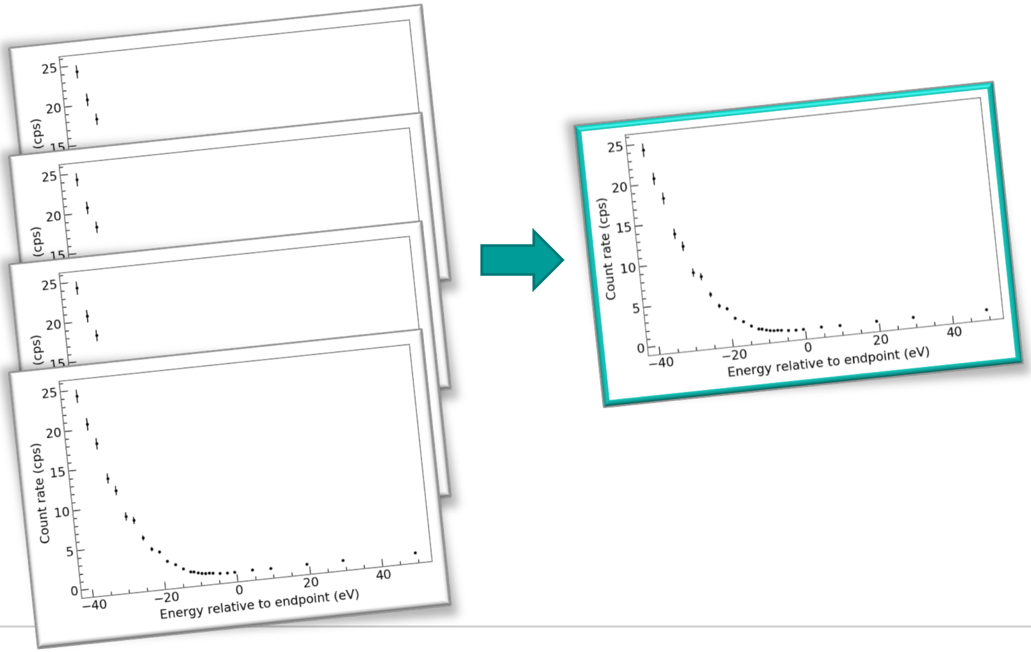
Pixel combination

- sum the counts of all pixels
- <u>use average response function</u>

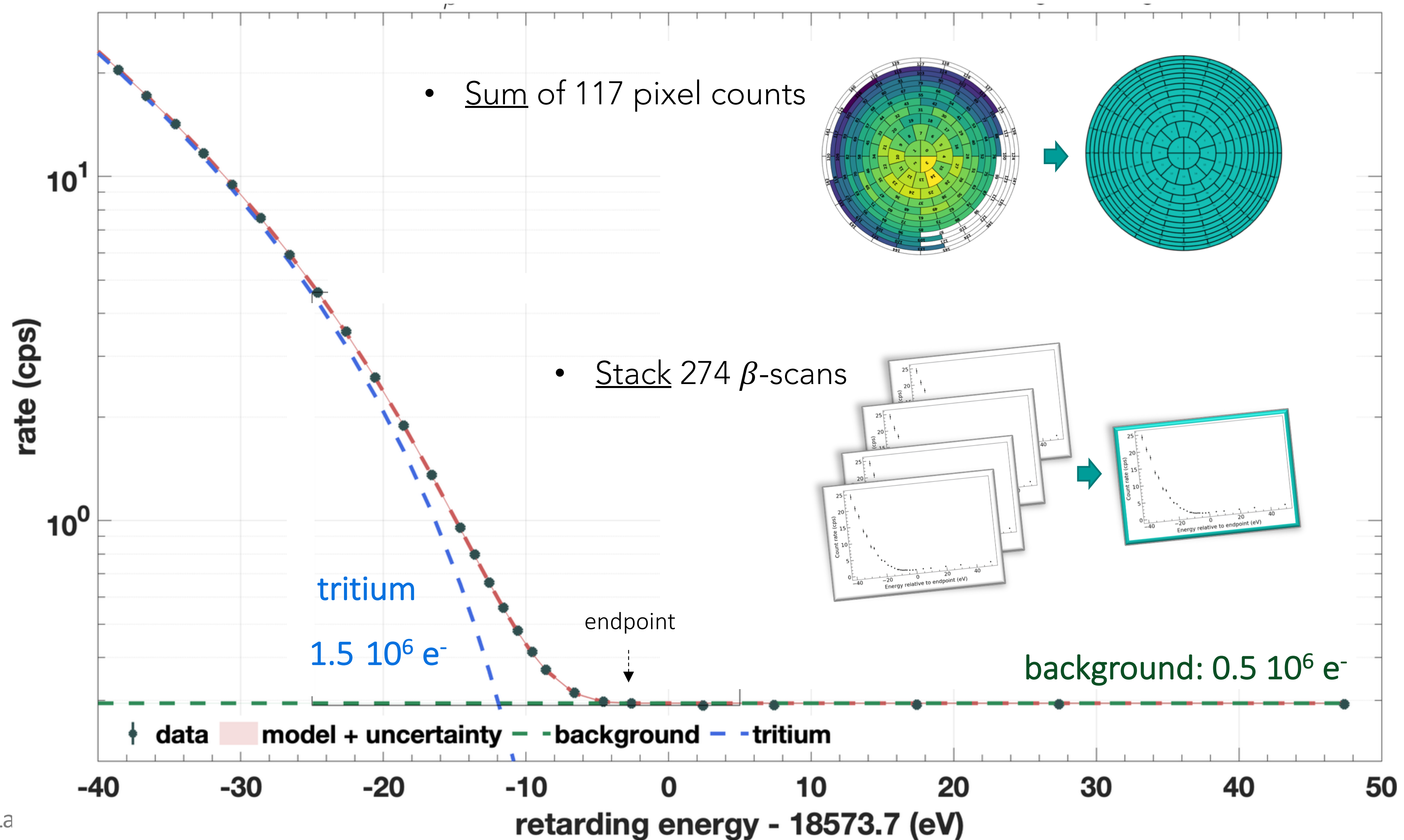


Scan combination

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



… combination of 32058 spectra

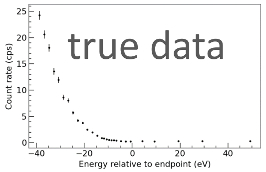


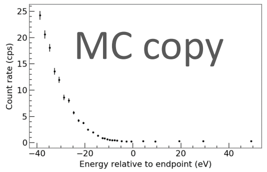
Inferring the Neutrino Mass

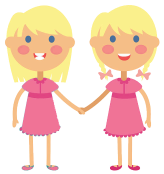
3-fold bias free final fit

Freeze analysis on fake data

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

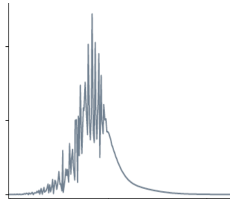


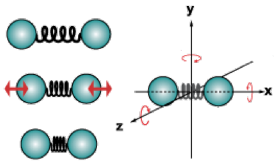




Blinded model

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

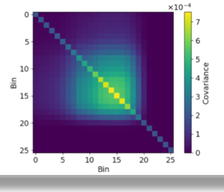


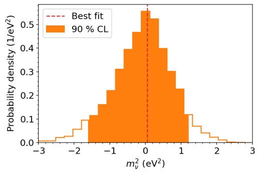


m_ν^2

Two independent analysis strategies

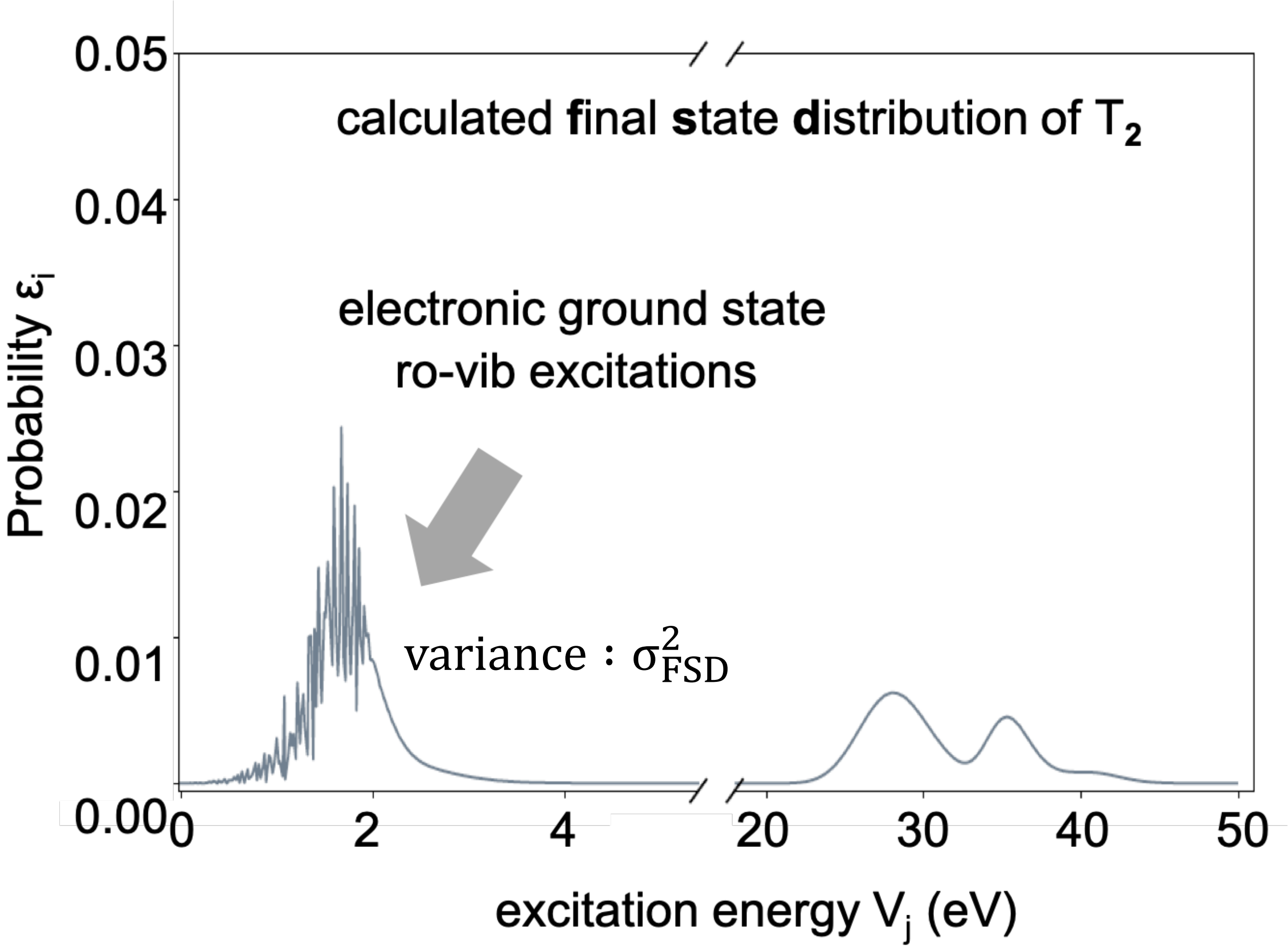
- Covariance matrix
- Monte Carlo propagation





Blinded Model

$$R(qU, E_0, m_\nu^2) \propto (qU - E_0)^3 - \underbrace{(m_\nu^2 - 2\,\delta\sigma_{FSD}^2)}_{m^2_{\nu,\,effective}}(qU - E_0)$$

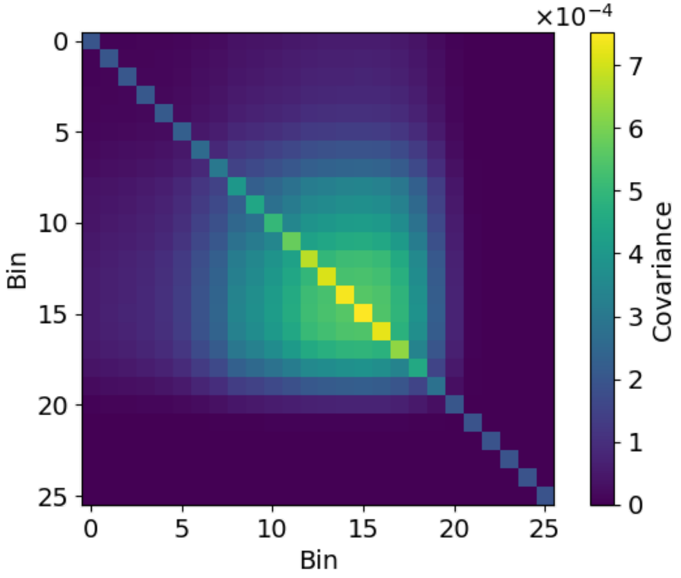


- Modified FSD distribution used before unblinding
- $\sigma_{FSD}^2 \rightarrow \sigma_{FSD}^2 + \delta\sigma_{FSD}^2$
- Hides the fitted neutrino mass only

Two independent analysis approaches

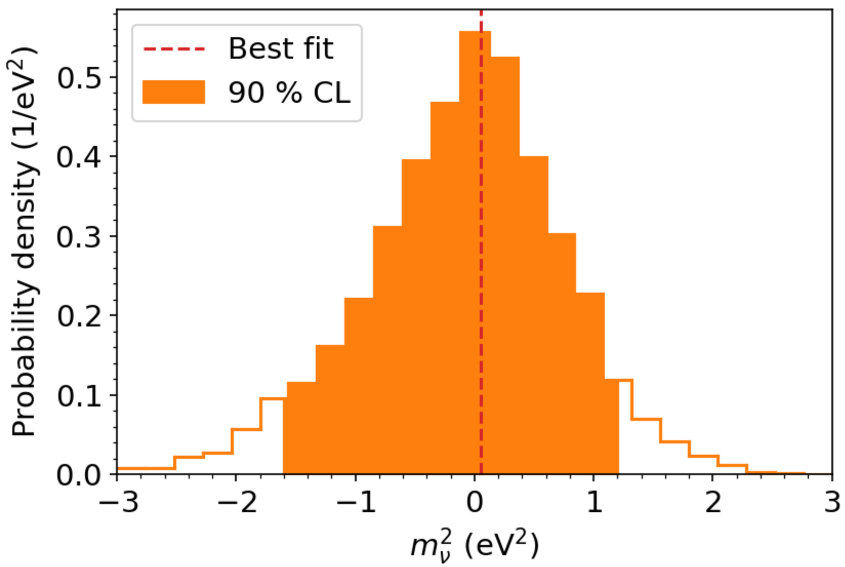
Covariance matrix

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

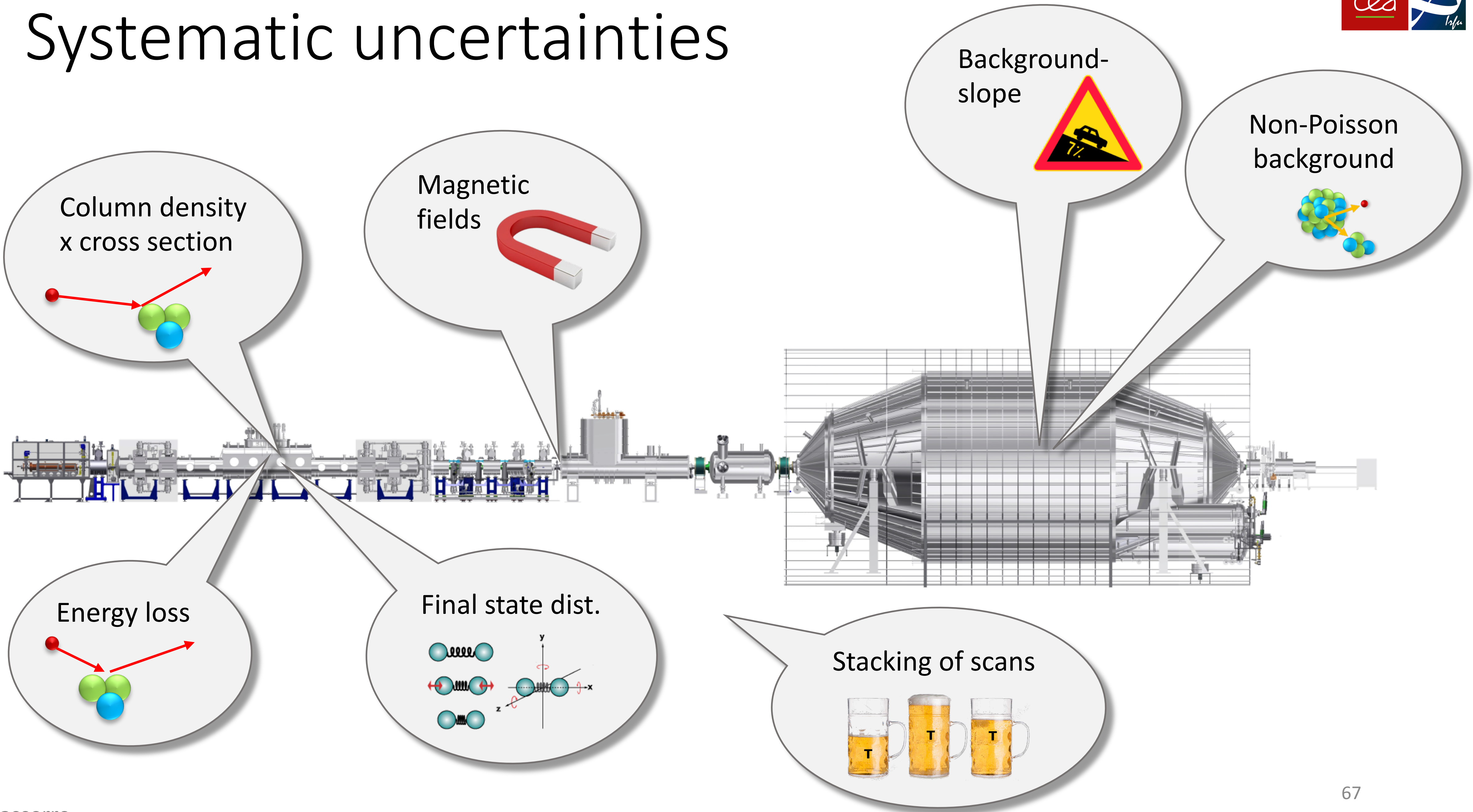


MC propagation

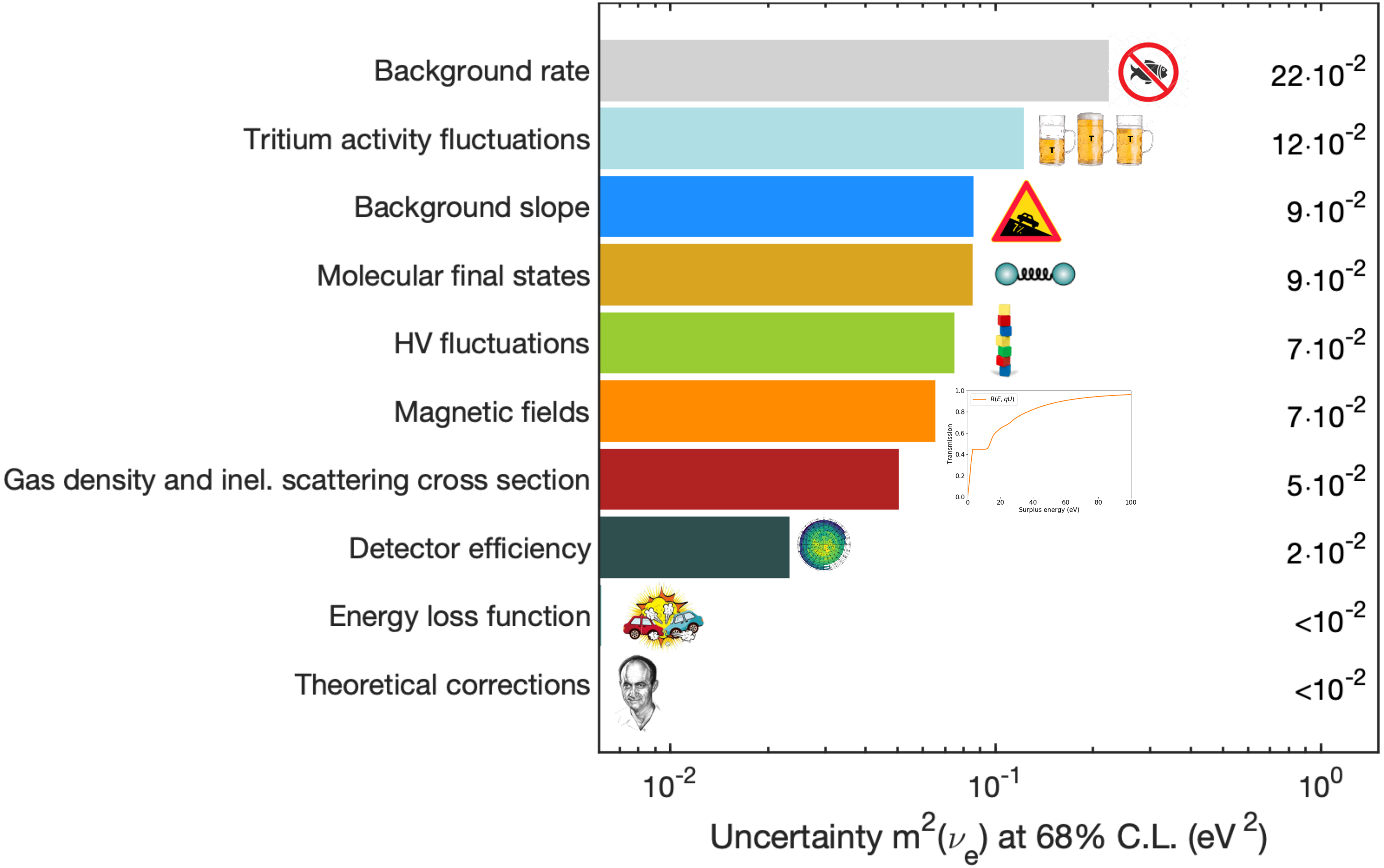
- $-2 \log \mathcal{L} = 2 \sum_i [m_i - d_i + d_i \log(d_i/m_i)]$
- Systematics: Fit performed 10^5 times



Systematic uncertainties



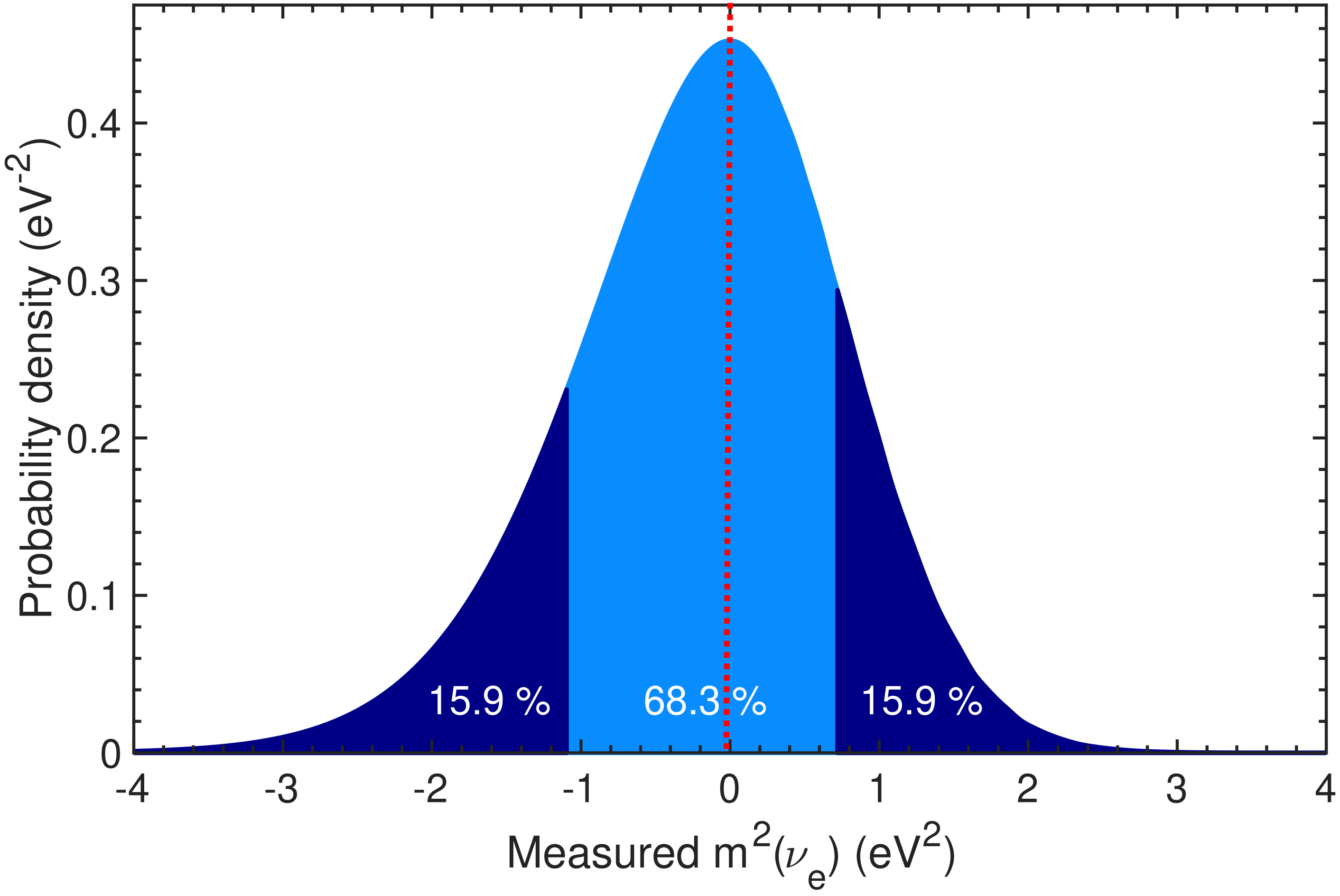
Budget of uncertainties



$1\sigma\ \mathrm{m}_\nu^2$
(68.3% C.L.)

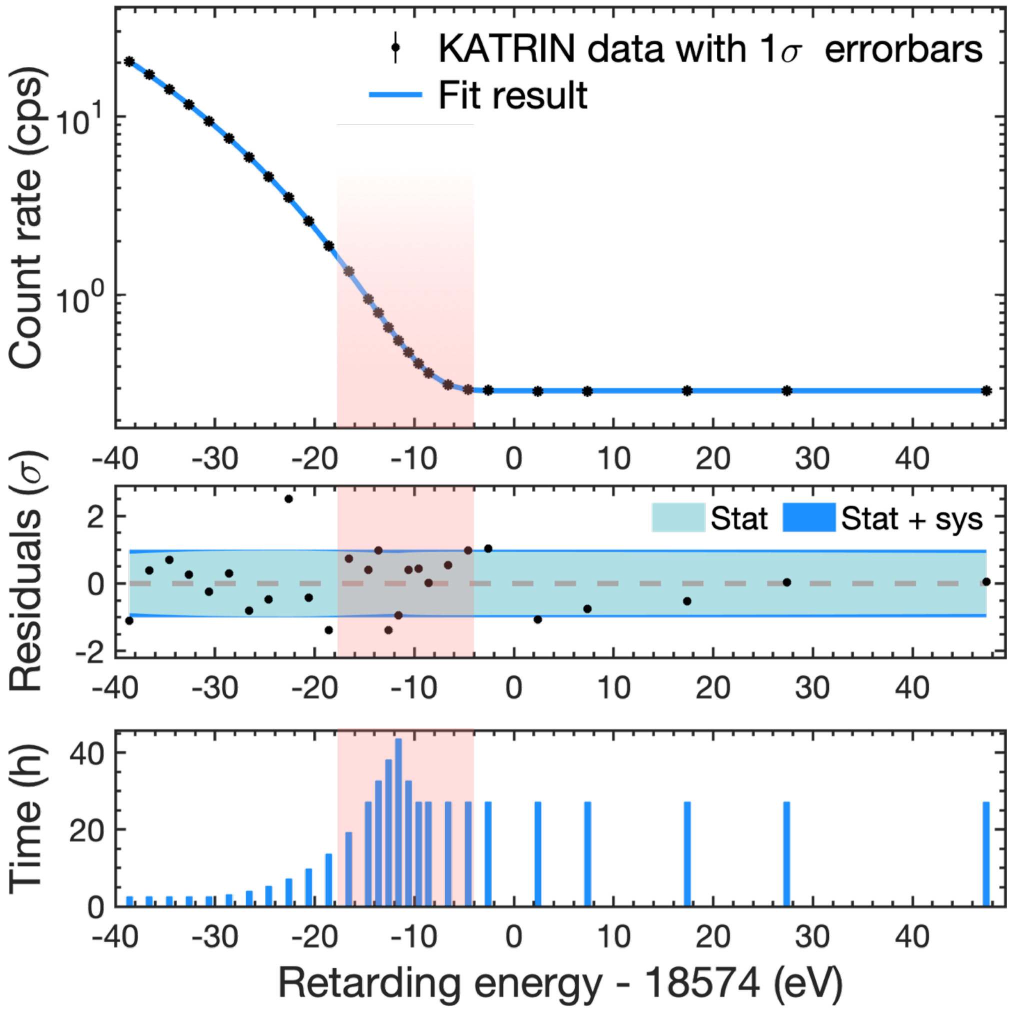
stat	0.75 eV^2
sys	0.25 eV^2
total	0.8 eV^2

What do we expected 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

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

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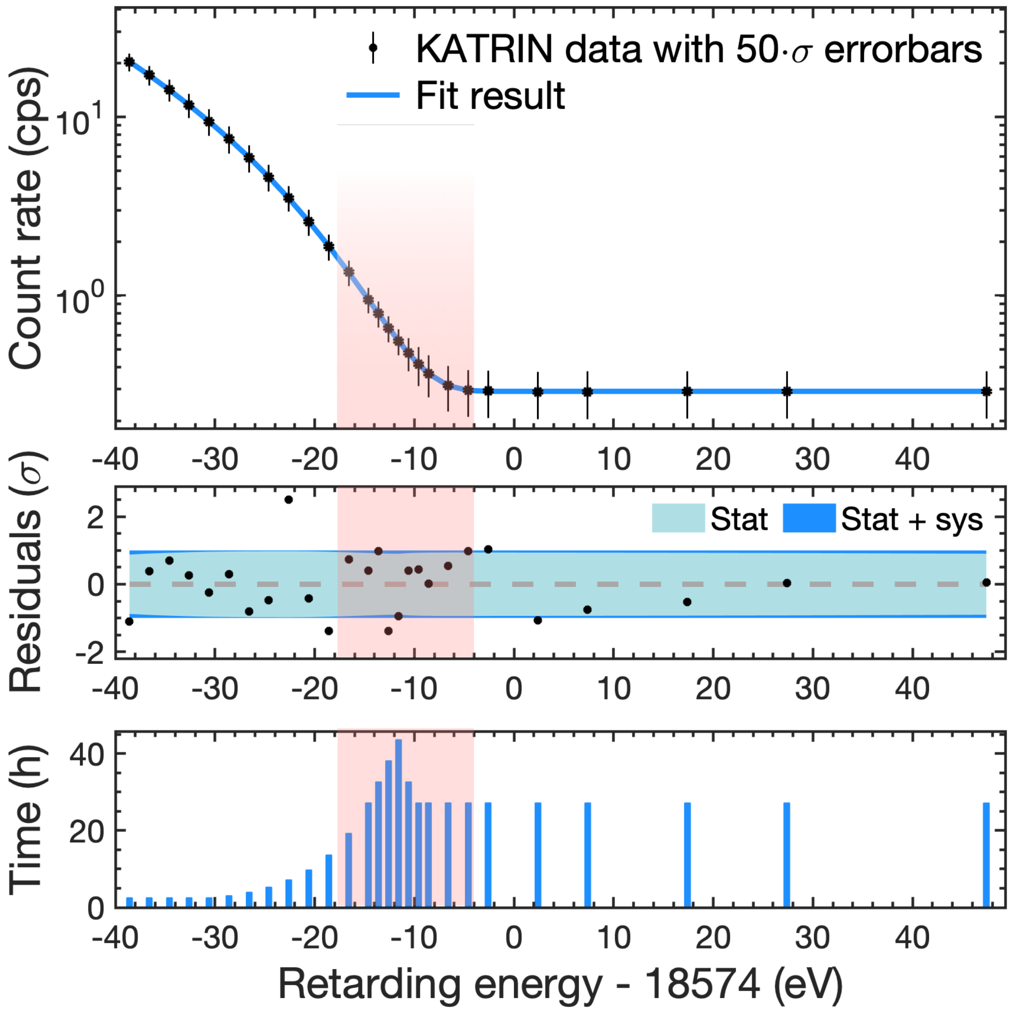
Final fit result (neutrino mass)

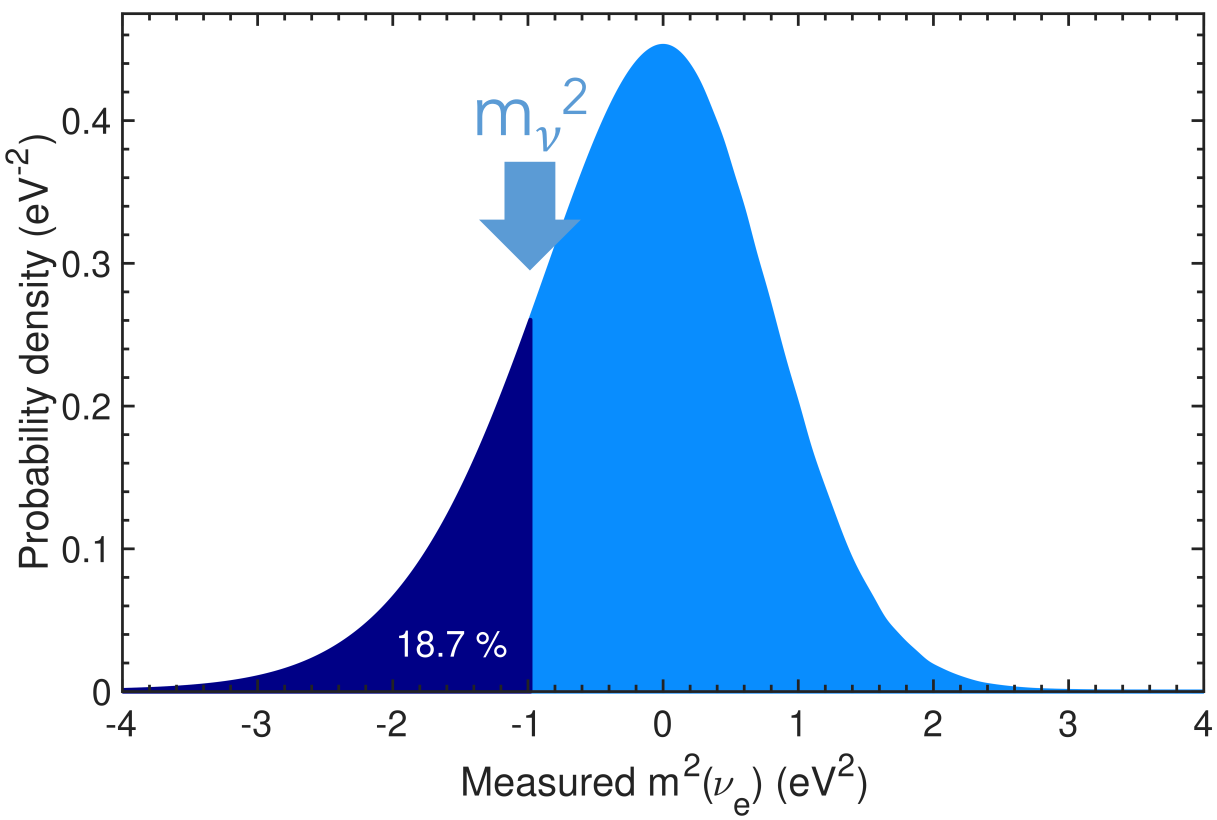


- 2 million events
- 4 free parameters: background, signal normalization, E_0, m_ν^2
- excellent goodness-of-fit: p-value = 0.56
- Neutrino mass best fit

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

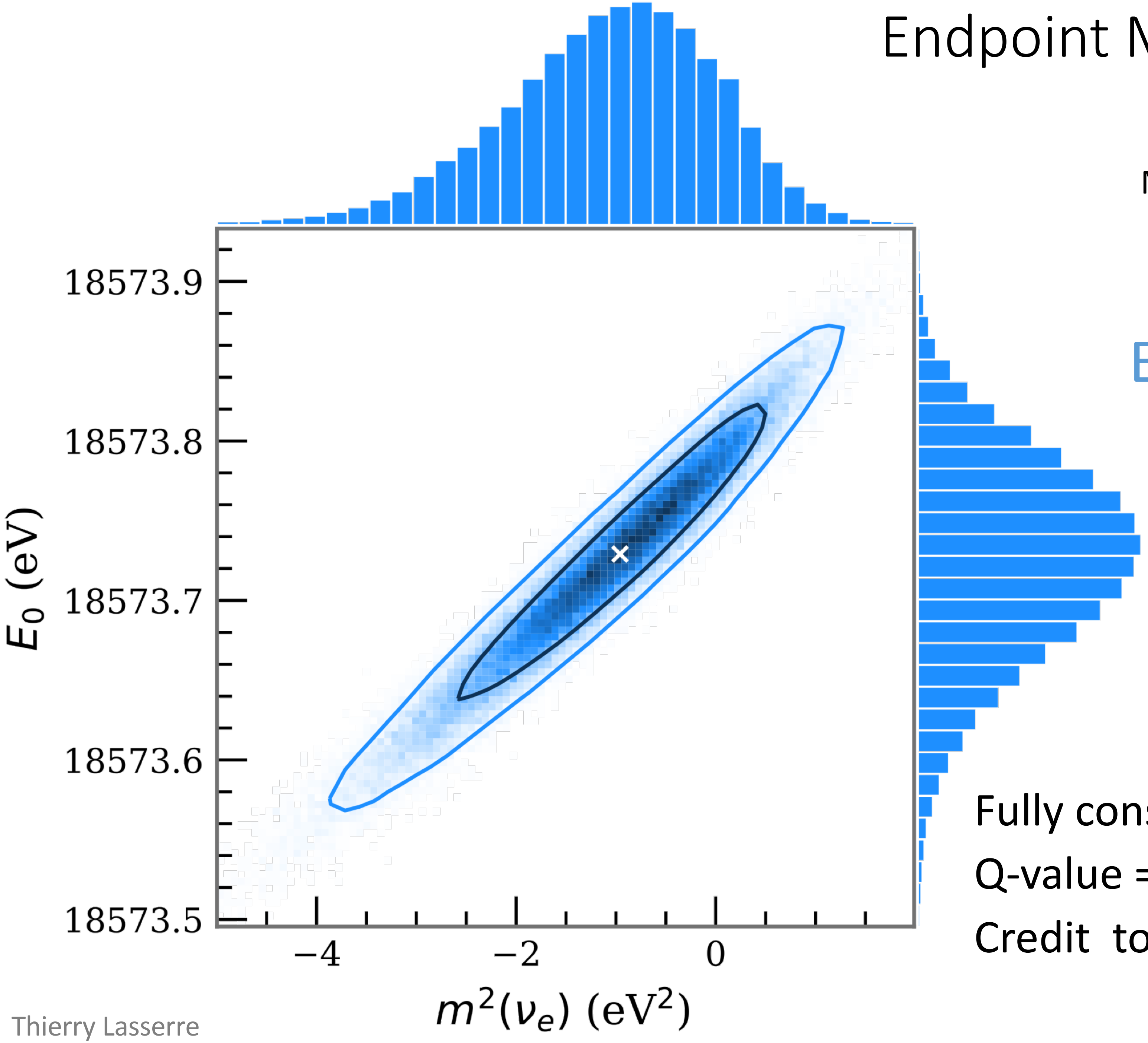
- Uncertainties dominated by statistical fluctuations (0.97 eV^2)

Actual Result Compared to Expectation



- 18.7% probability to find a m_ν^2 value less than 1 eV^2
- Shift interpreted as 1σ statistical fluctuation
- Best-fit m_ν^2 fully consistent with expectations

Endpoint Measurement



Maximum electron energy in tritium decay

E_0 = (18573.7 ± 0.1) eV

⇨ Q-value = (18575.2 ± 0.5) eV

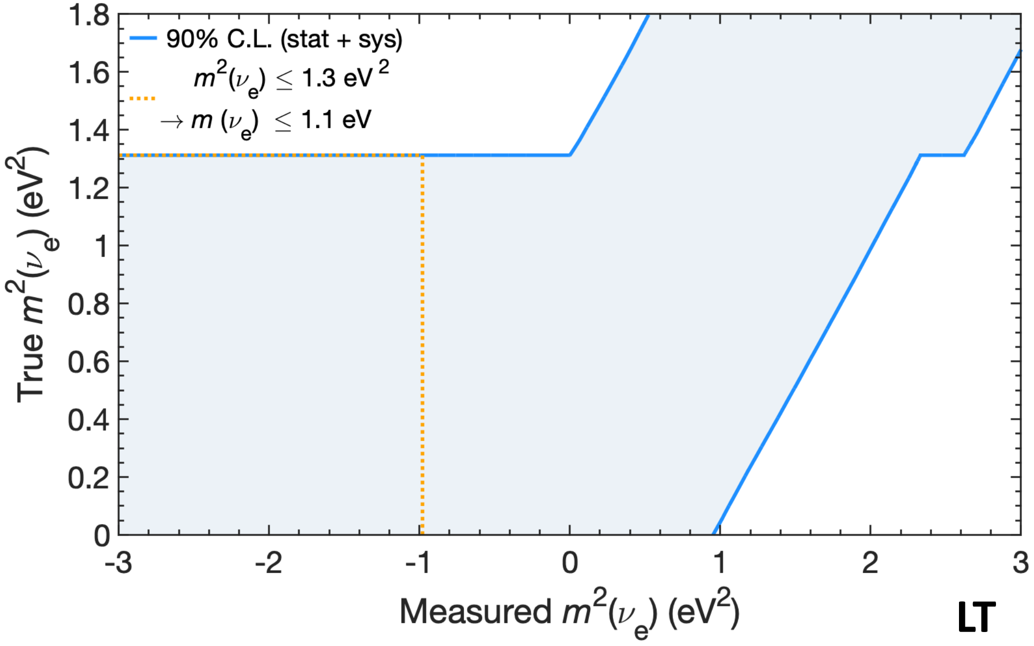
Mass ^3H – Mass ^3He

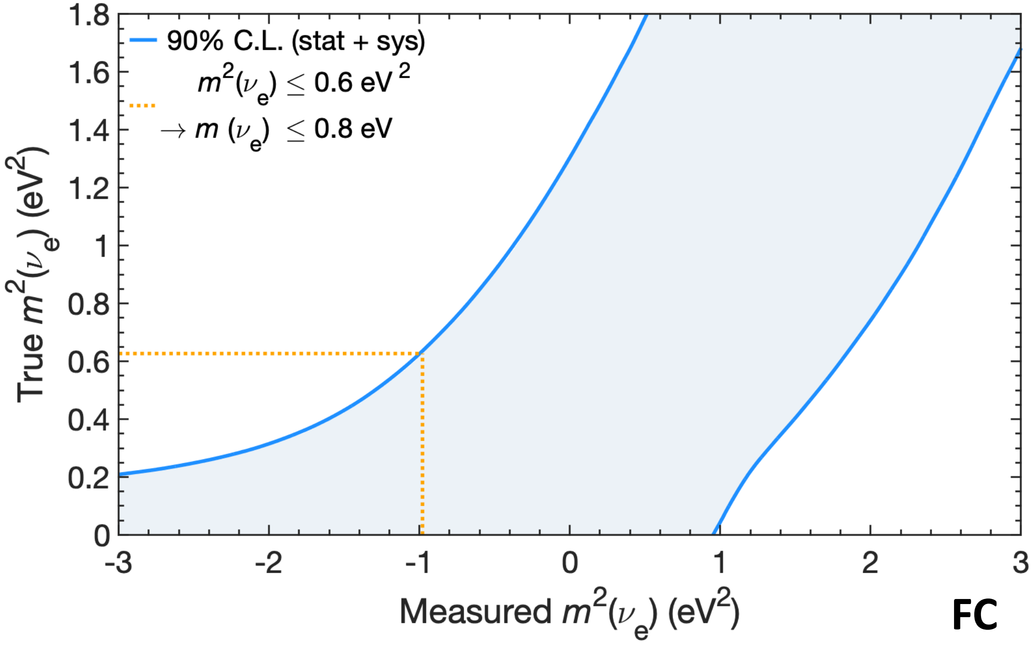
Fully consistent with the prediction:

Q-value = (18575.72 ± 0.07) eV

Credit to the overall energy scale

New KATRIN limit





Lokhov and Tkachov (LT)

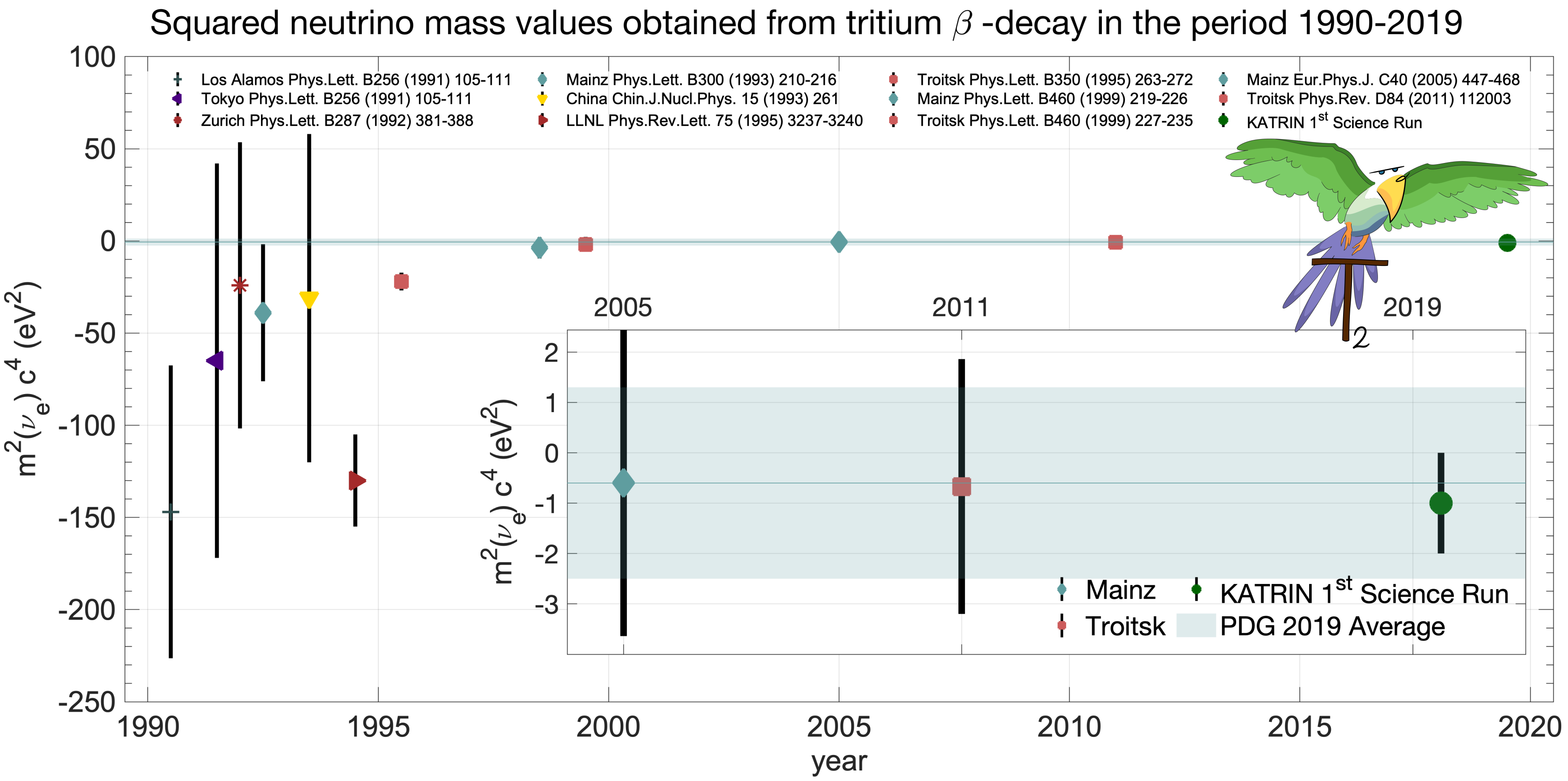
- **m_ν < 1.1 eV (90% CL) = sensitivity**
- official KATRIN limit

Feldman and Cousins (FC)

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

KATRIN in the light of previous results and prospects

Historical context



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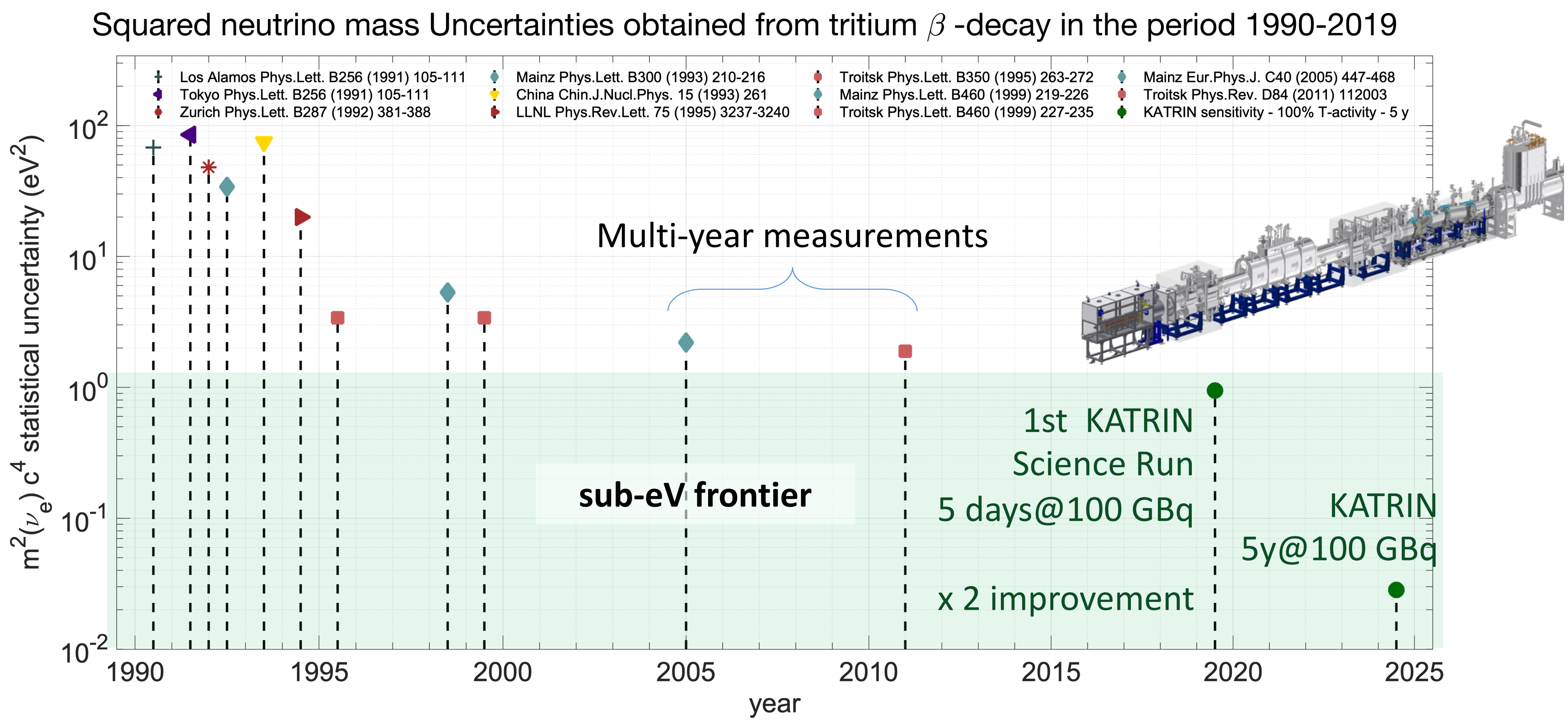
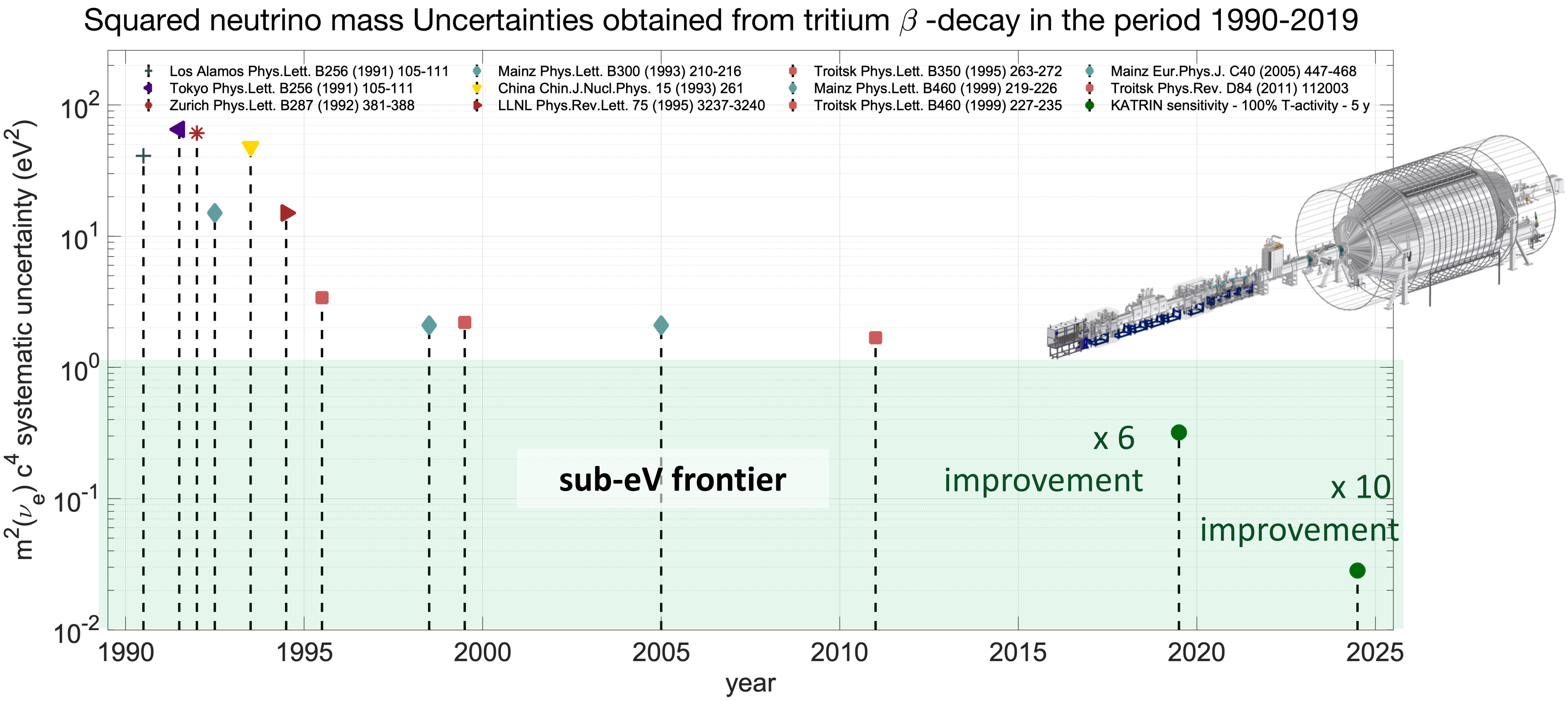
Improvements in statistics



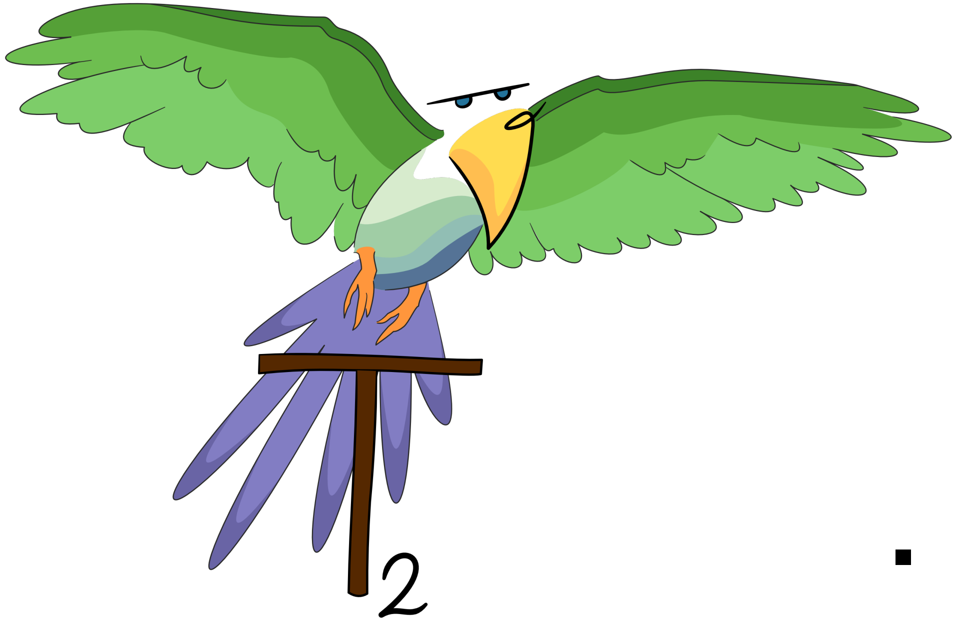
Improvements in systematics



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

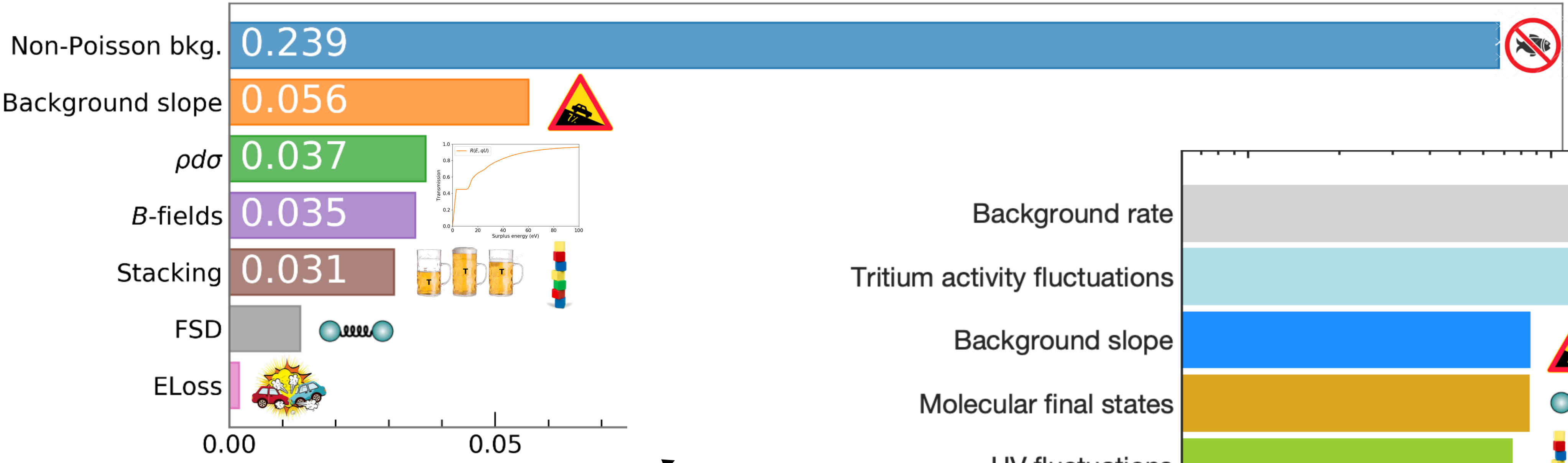
  see also https://arxiv.org/abs/1909.06069



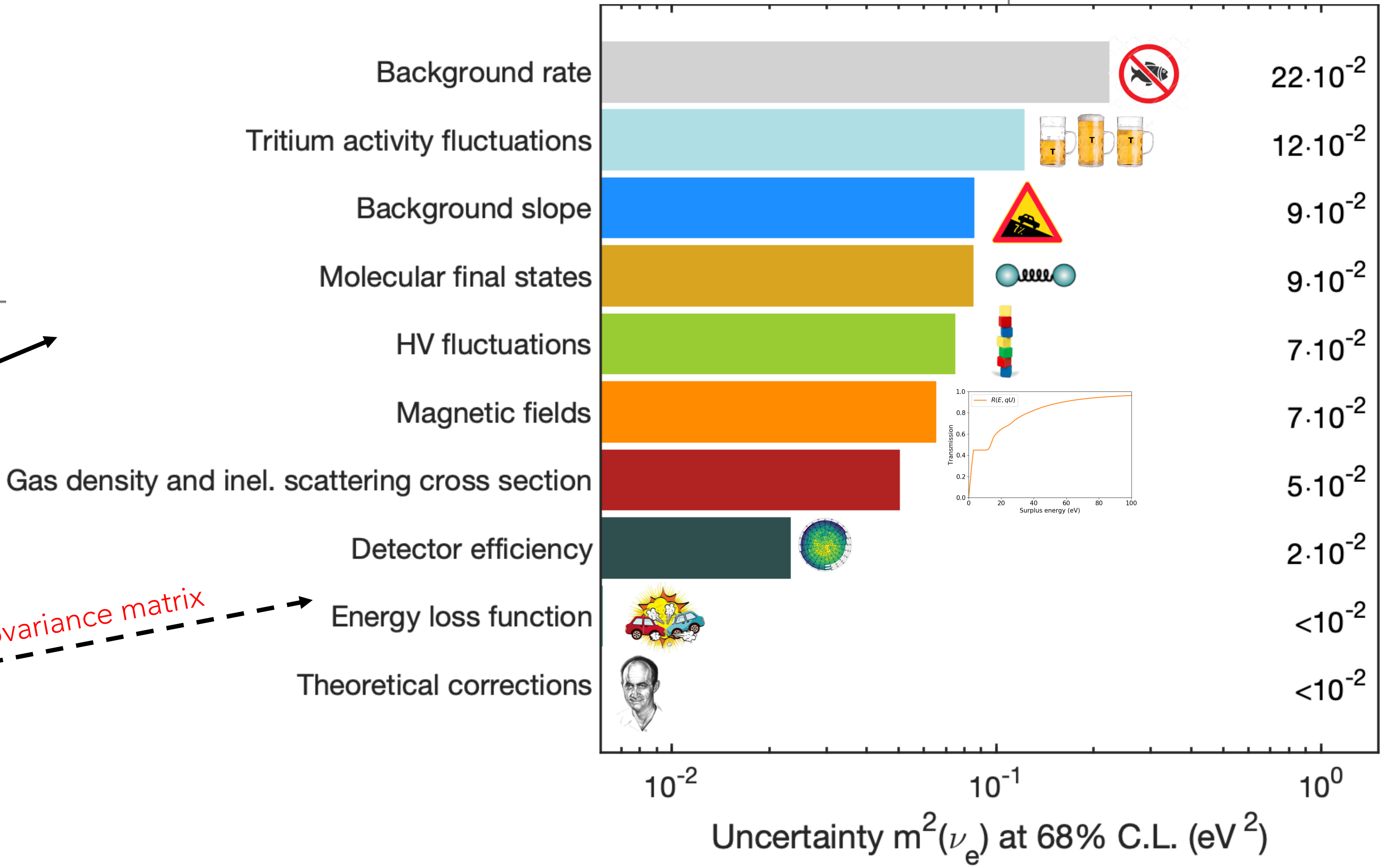
- Background improvement experimentally verified

  …towards the 0.2 eV 5y design goal
- Promising perspectives to search for eV to keV sterile neutrinos

Thanks for your attention



Monte Carlo propagation

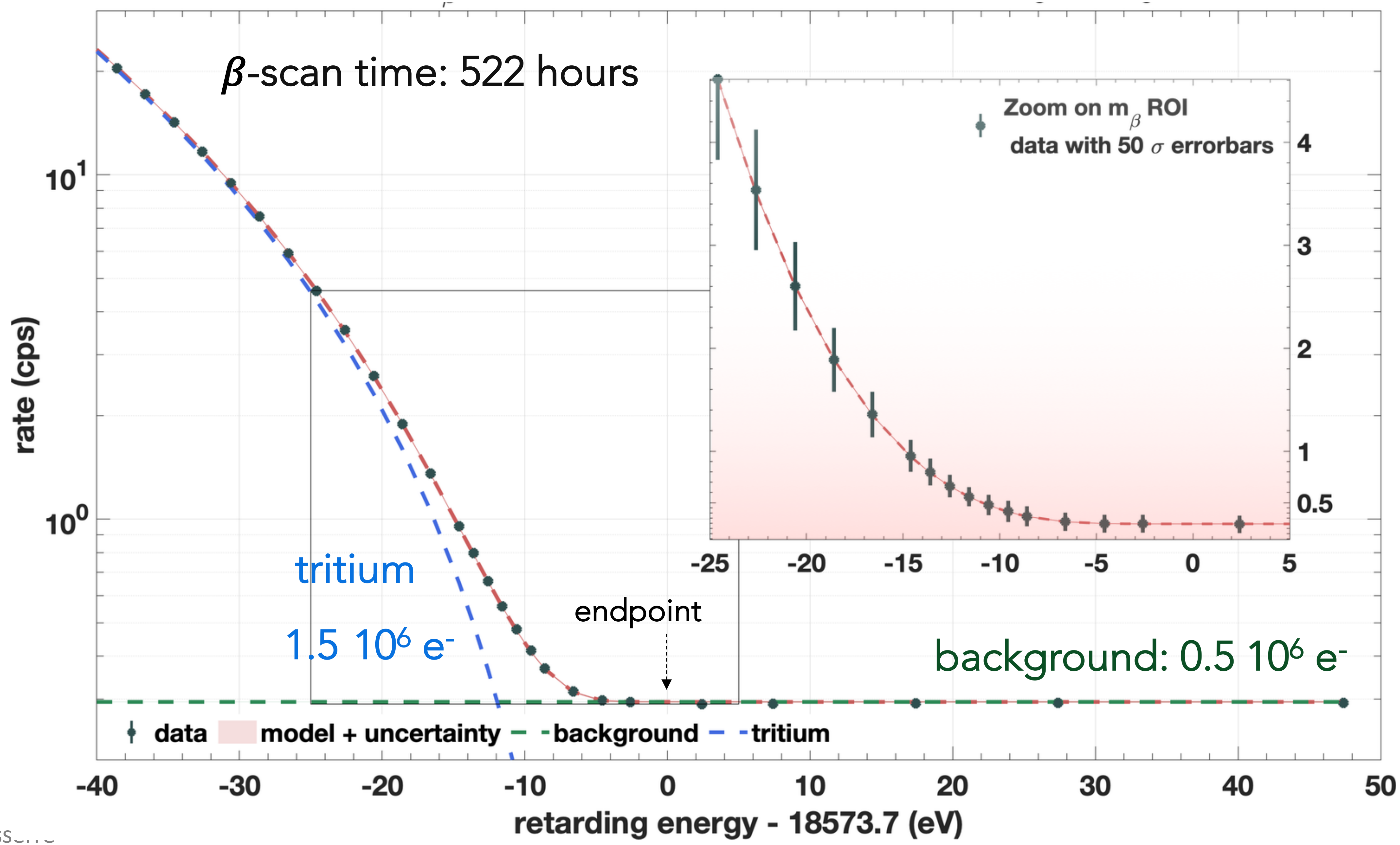


Covariance matrix

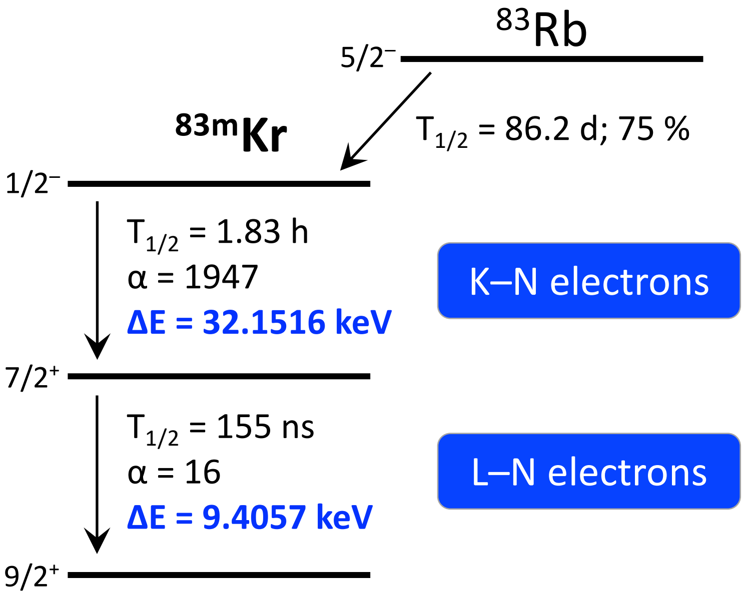
Systematics on m_ν^2
0.3 eV^2 at 68.3% C.L.

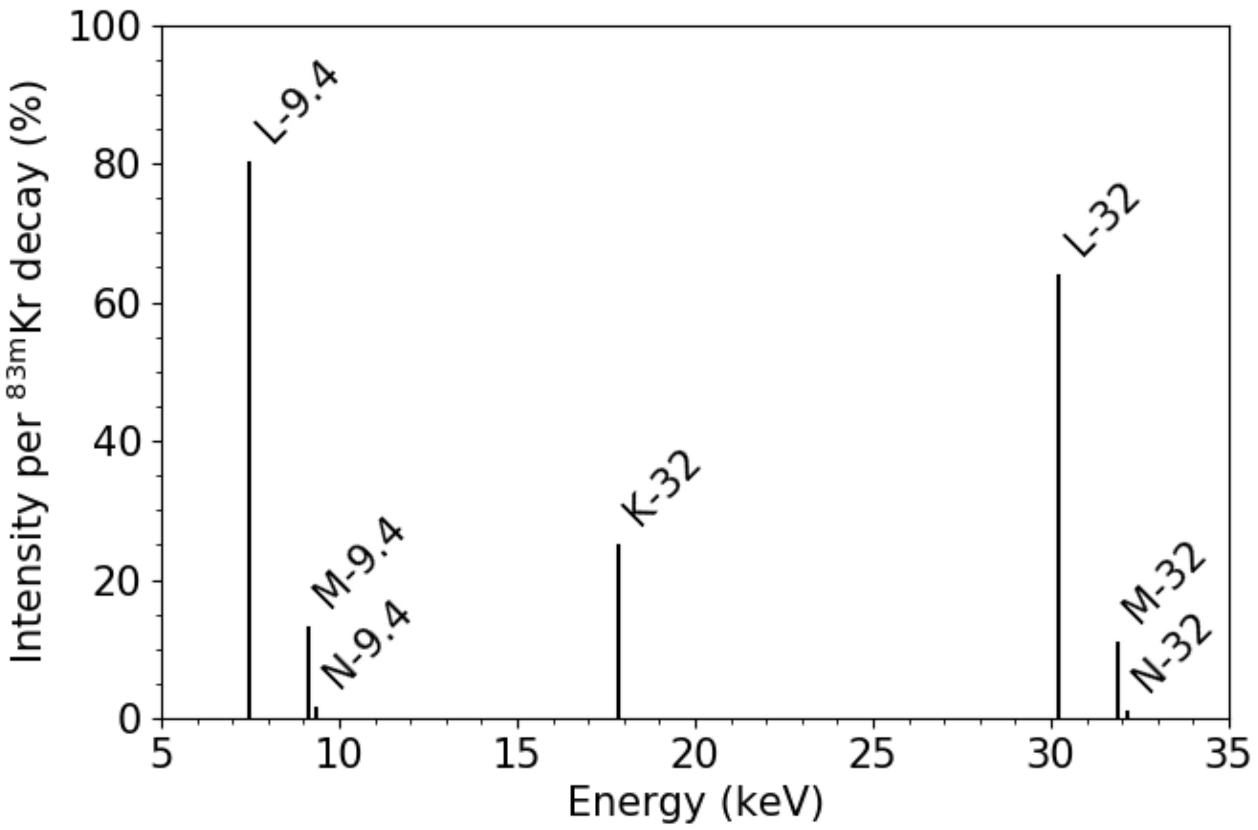
Systematics identified & evaluated independently

Integral tritium ß-decay spectrum: Real Data



Krypton campaign (2017)





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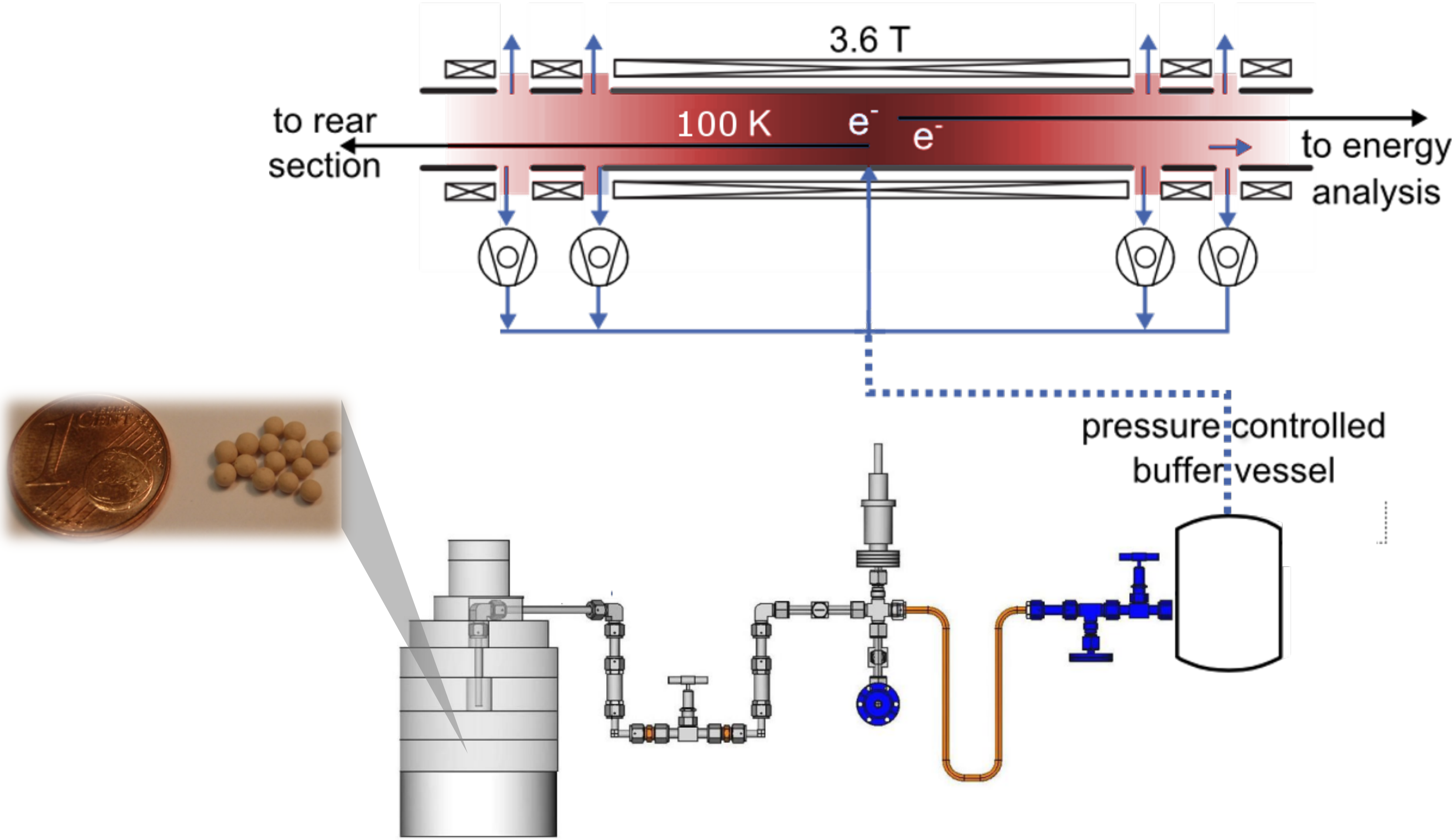
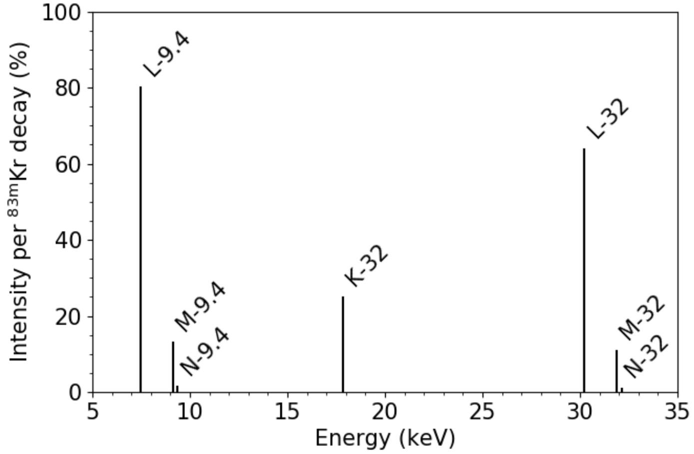
Krypton calibration



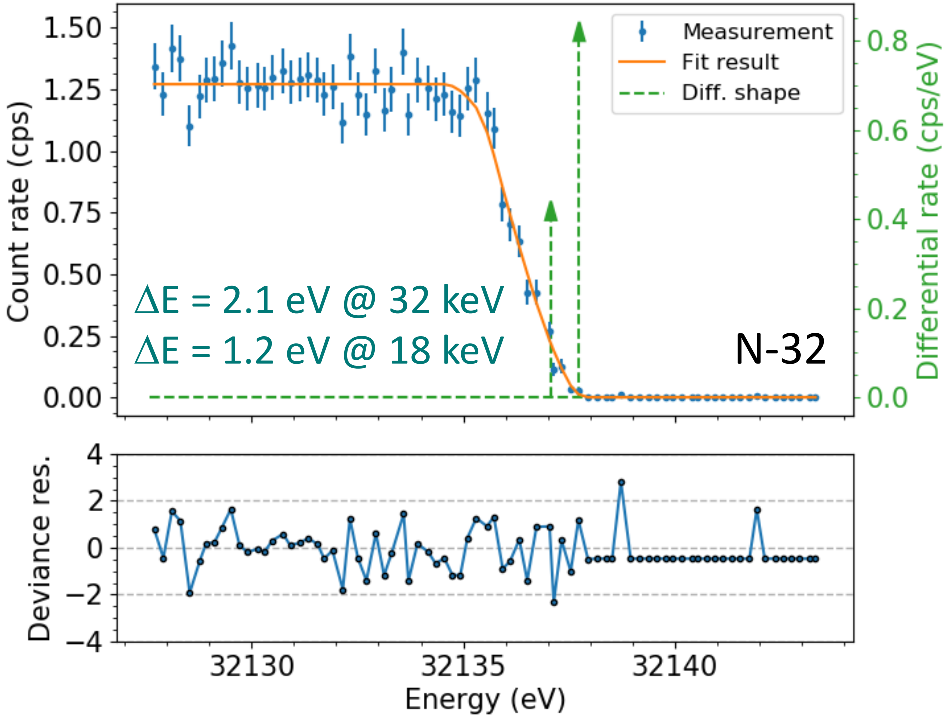


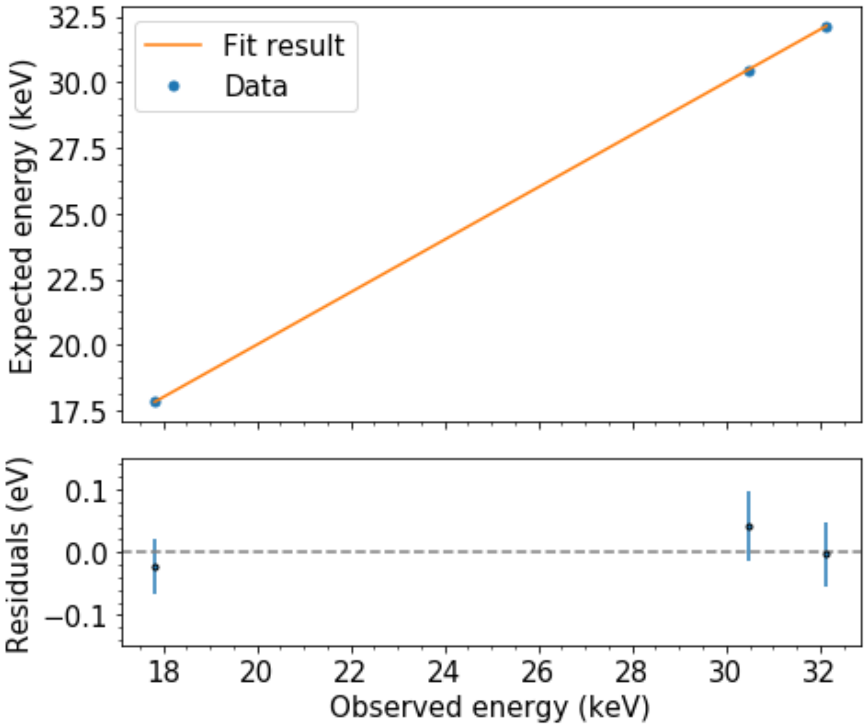
Krypton Results

N-32 line

✓ 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))*





First tritium campaign (2018)

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

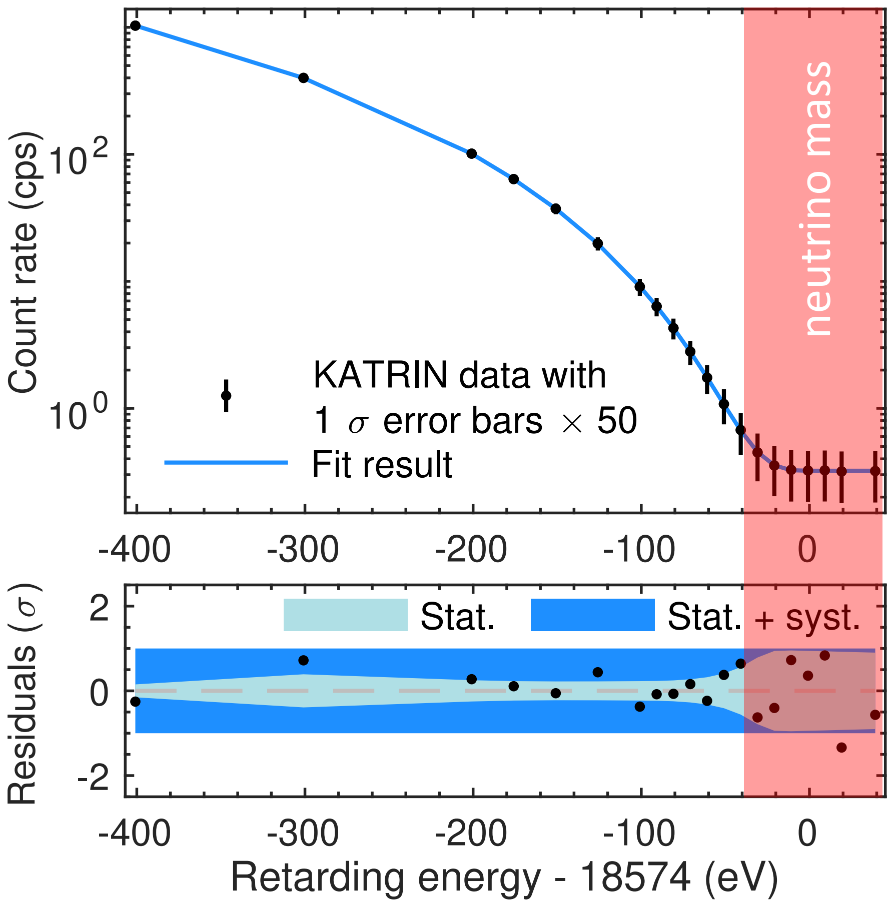
✓ Demonstrate global system stability

✓ Test analysis strategies

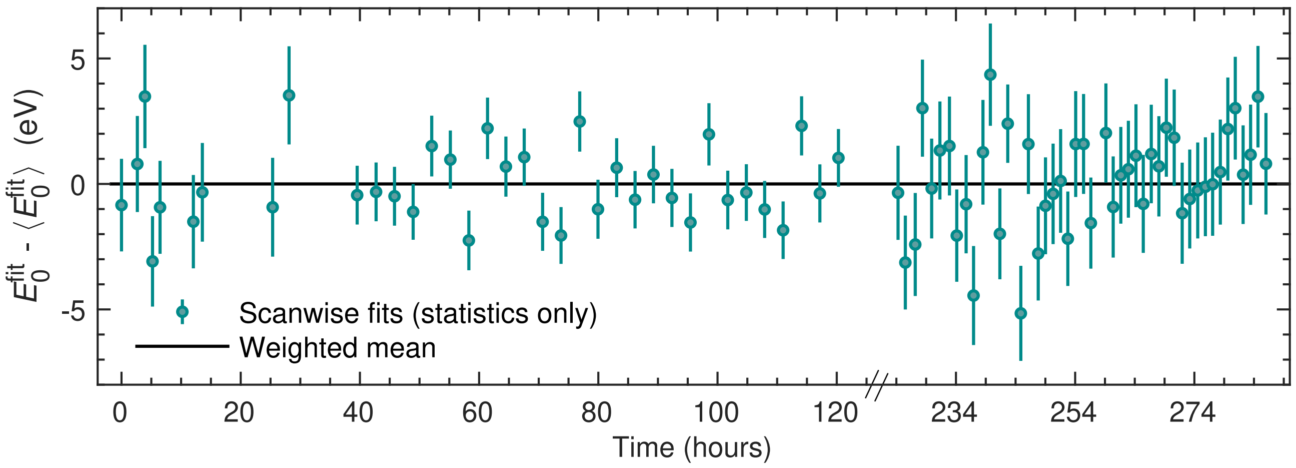
[arXiv:1909.06069]

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

First tritium spectra



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



Thierry Lasserre

TRISTAN Project

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