New limit on the effective neutrino mass by KATRIN

CEA/DRF/Irfu/DPhP Seminar, Saclay, 07/06/2021

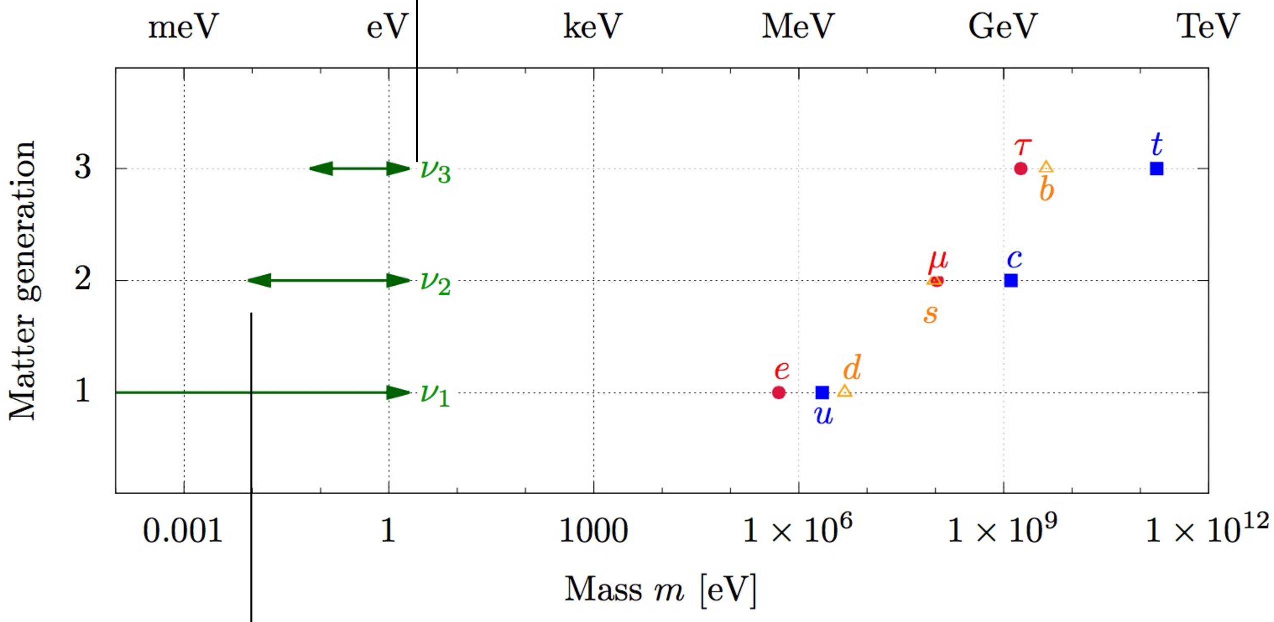
Thierry Lasserre

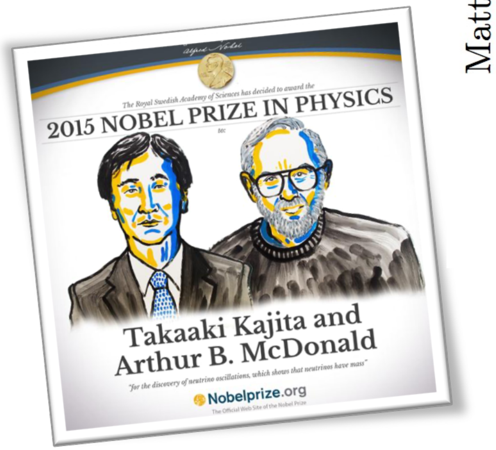
On behalf the KATRIN collaboration

Physics Case

Neutrino mass

Upper bound
from laboratory measurements
& cosmology





Lower bound
from oscillation experiments

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Neutrino mass

Cosmology

Rely on cosmological model
potential: m_ν = 10-50 meV
e.g. Planck + LSS + BAO ...

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

Search for 0νßß

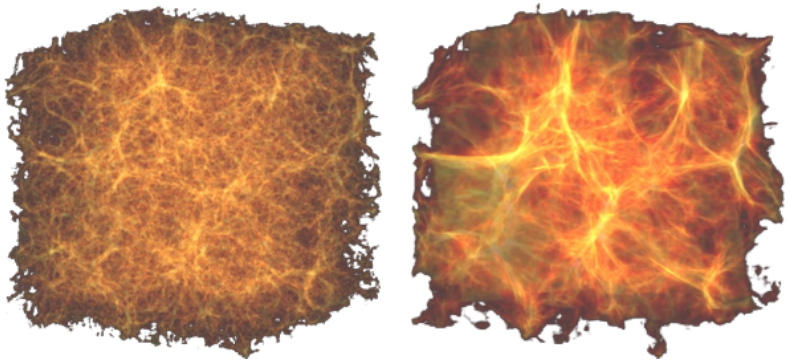
Laboratory-based
potential: $m_{\beta\beta}$ = 15-50 meV
e.g. LEGEND, Cupid

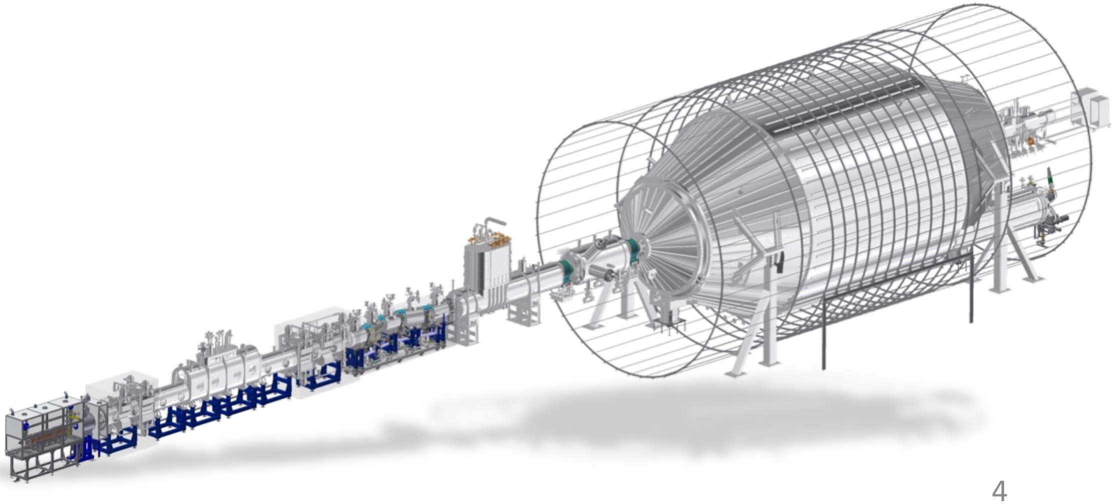
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

Kinematics of ß-decay

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

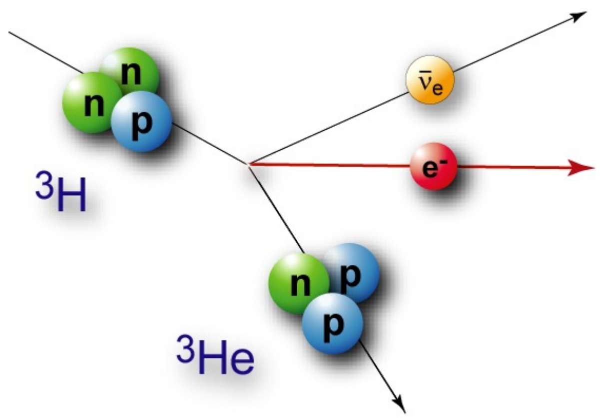
$$m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$



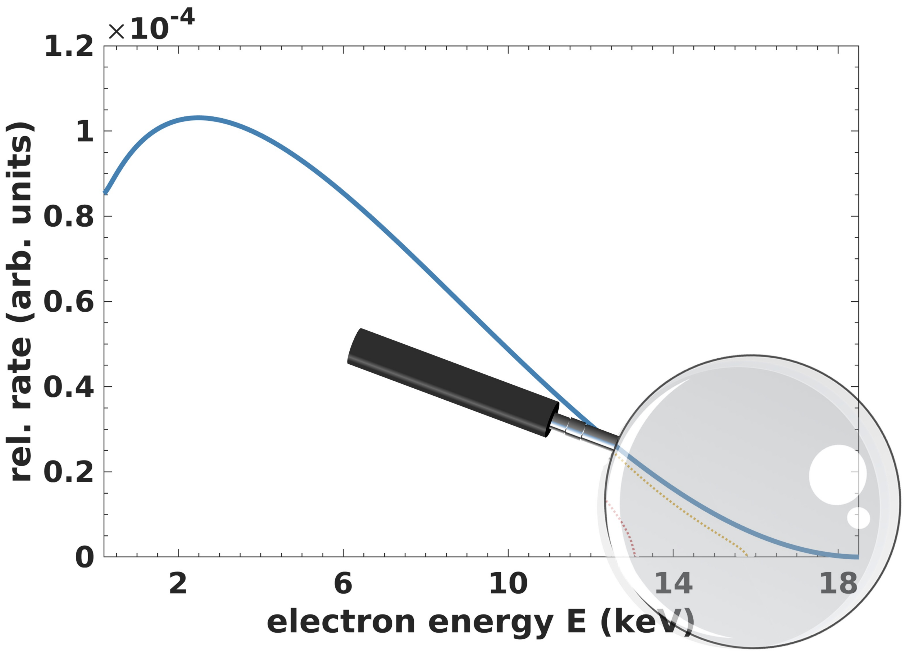


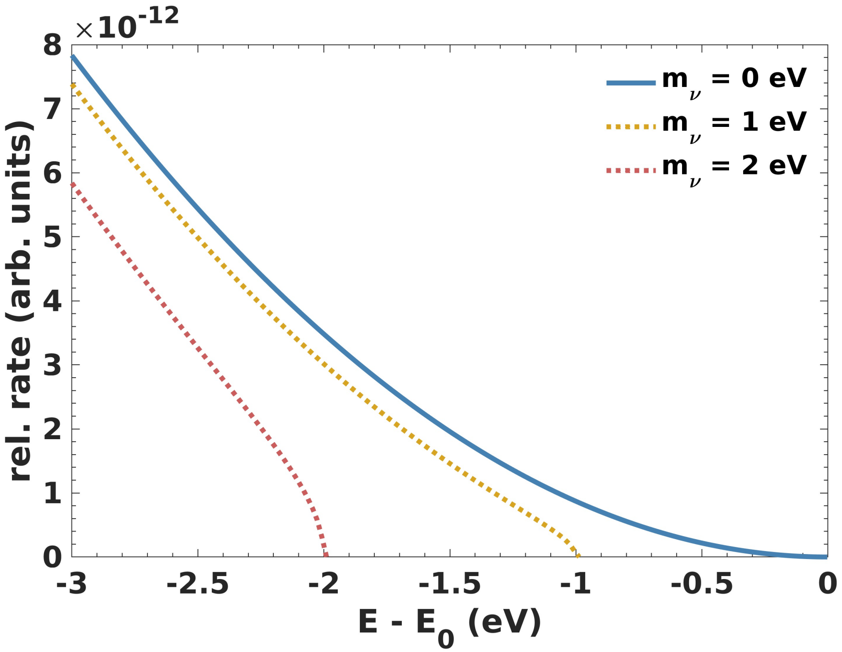
Kinematic Measurement Concept

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



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

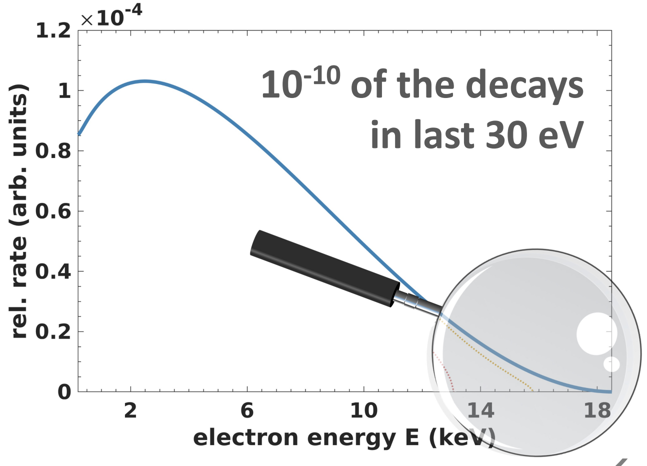




Generic Experimental Challenges

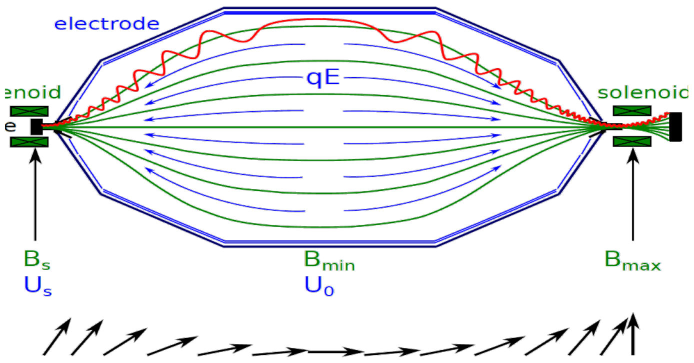
Intense ultra-stable tritium source

- design value: 100 GBq



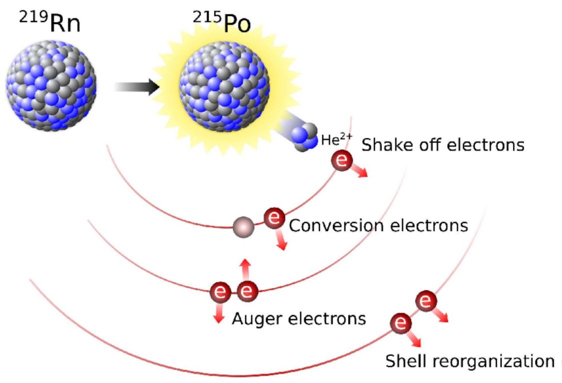
High Energy Resolution

- design value : 1 eV

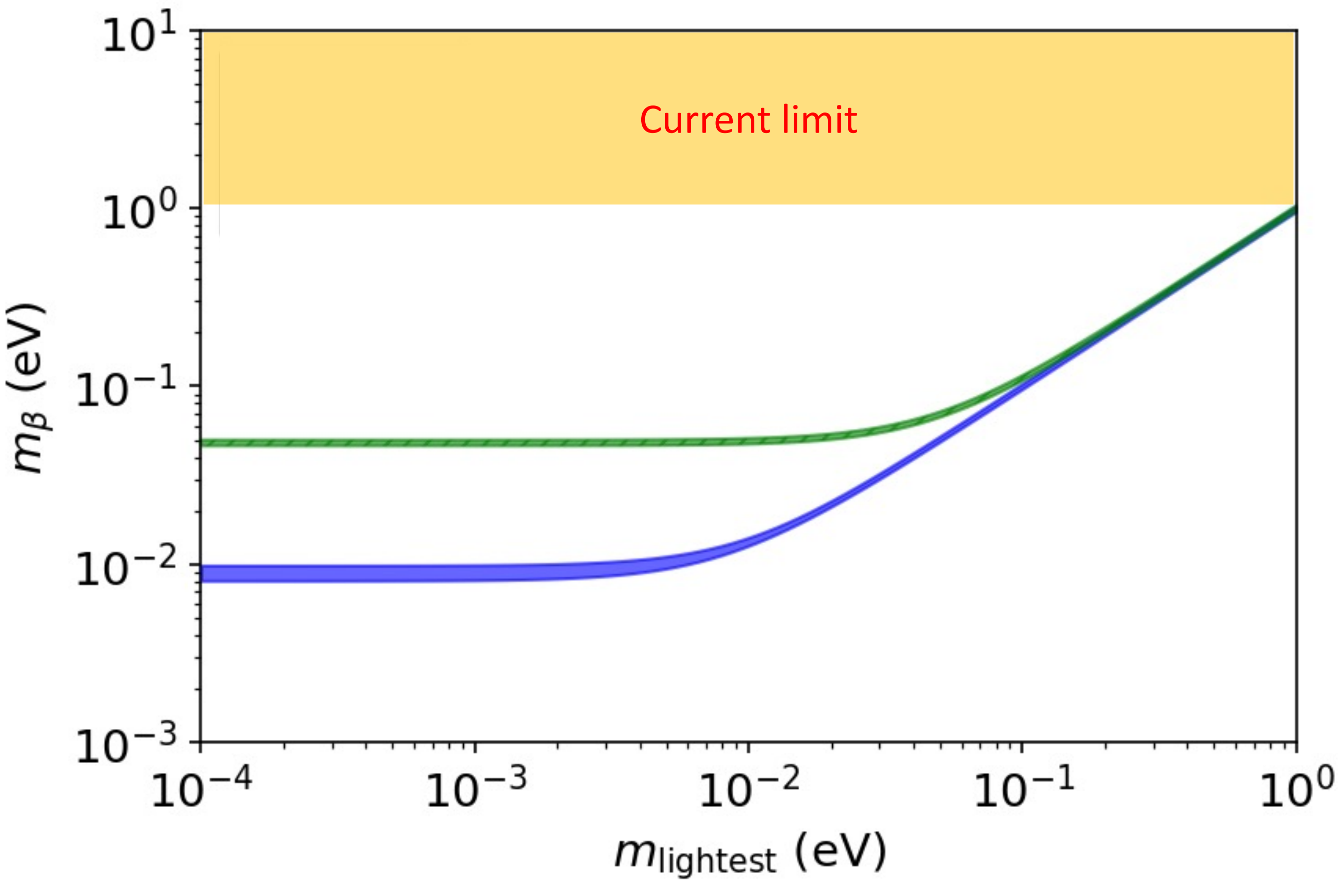


Low electron Background

- design value : 0.01 cps



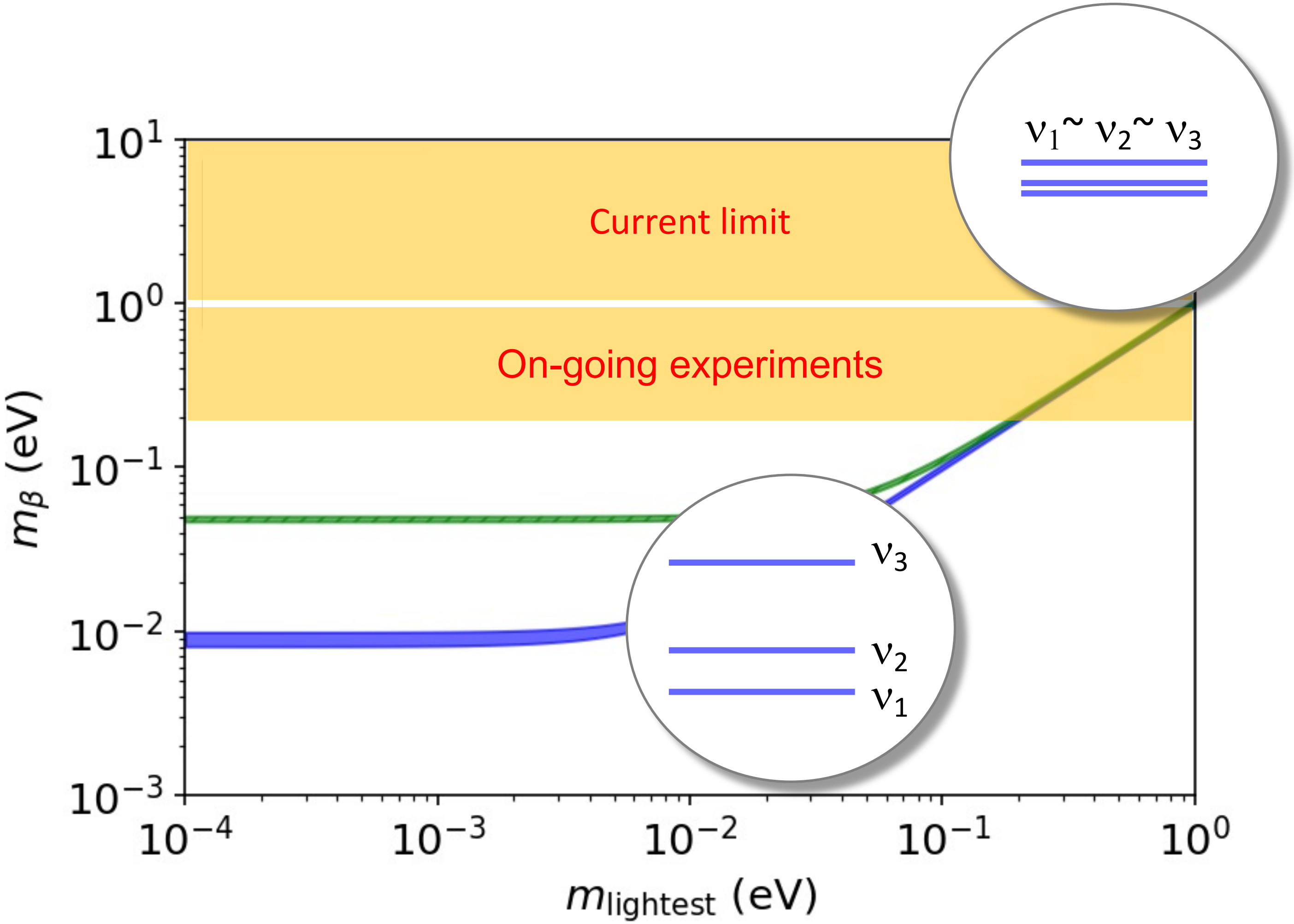
Where do we stand?



- Current best limit:
  $m_\nu < 1.1$ eV (90% CL)
  1st KATRIN data release
  PRL 123 (2019)

➢ New limit in a few slides ☺

Where do we stand?



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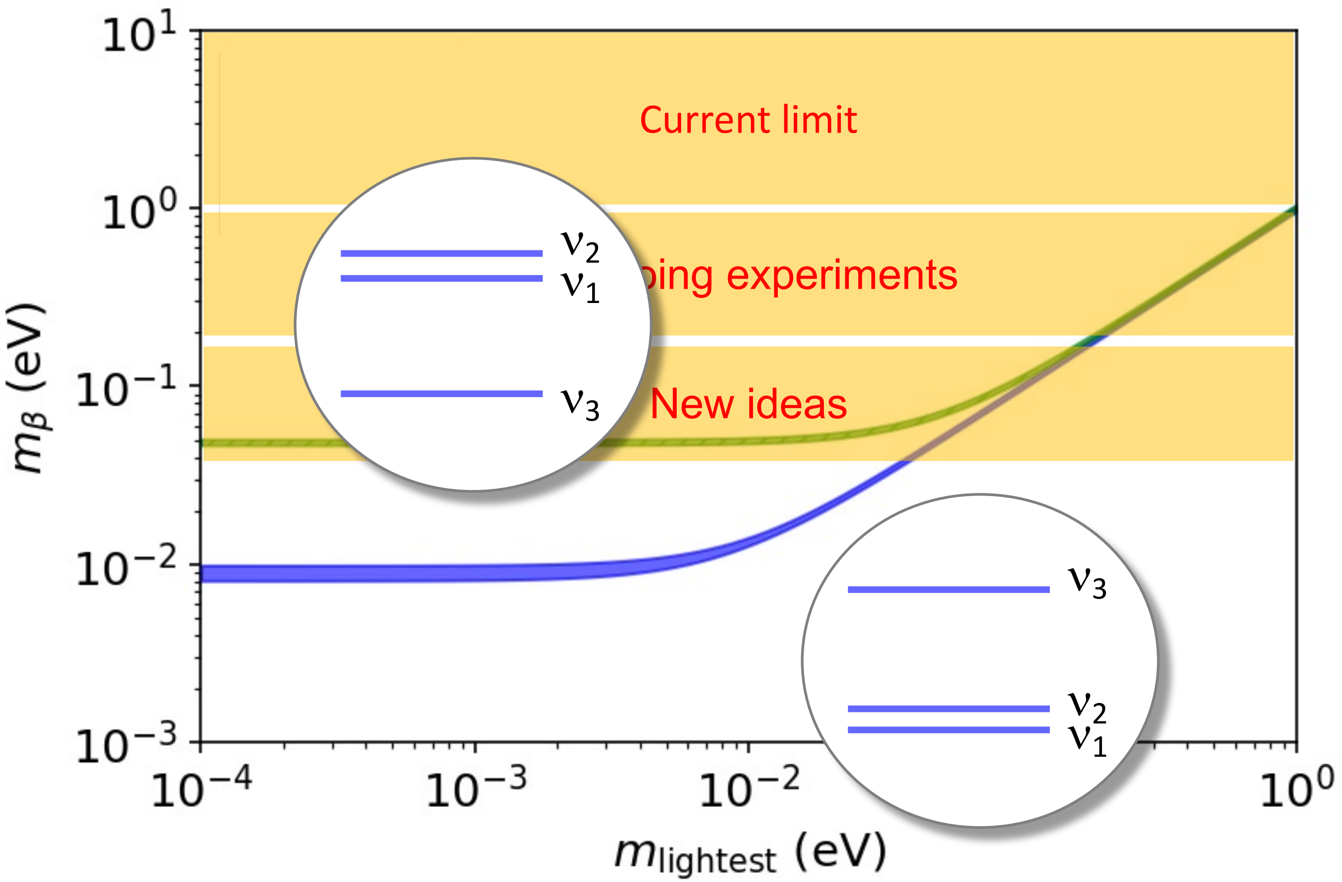
- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario

Where do we stand?



- Current best limit:
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  1st KATRIN data release
  PRL 123 (2019)
- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario
- Future:
  Resolve **normal** vs **inverted** neutrino mass ordering

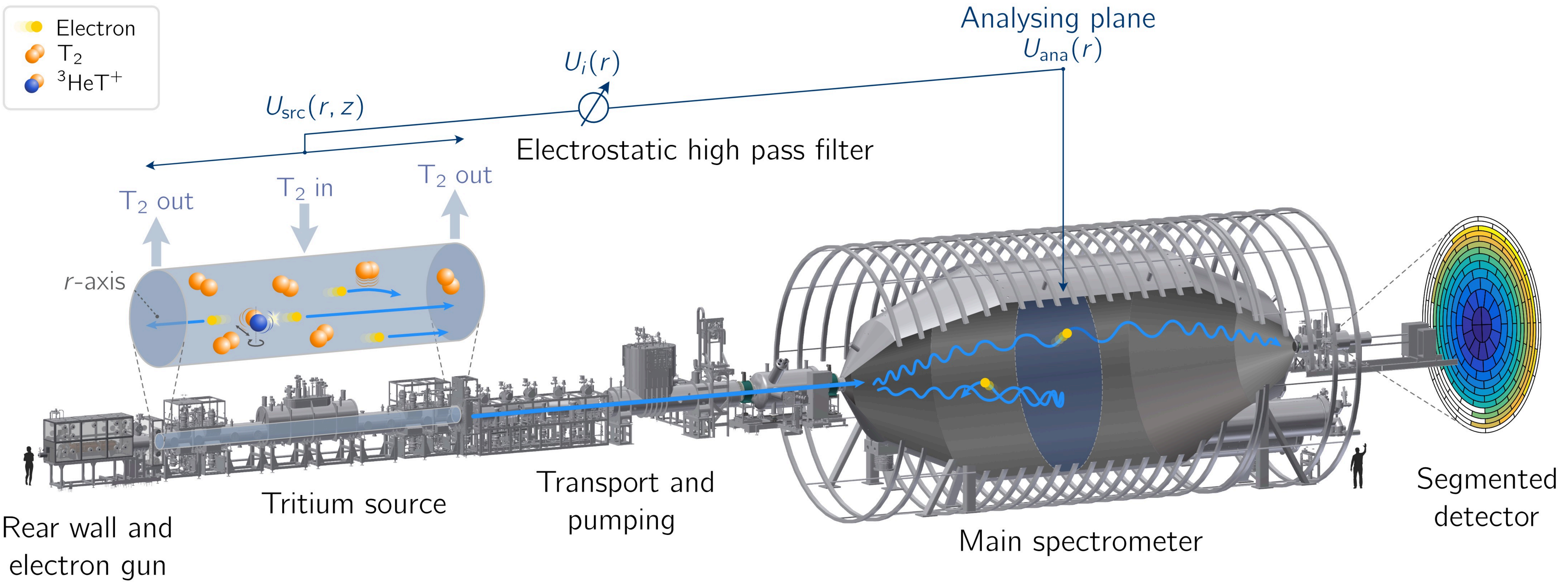
KATRIN


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 Overview

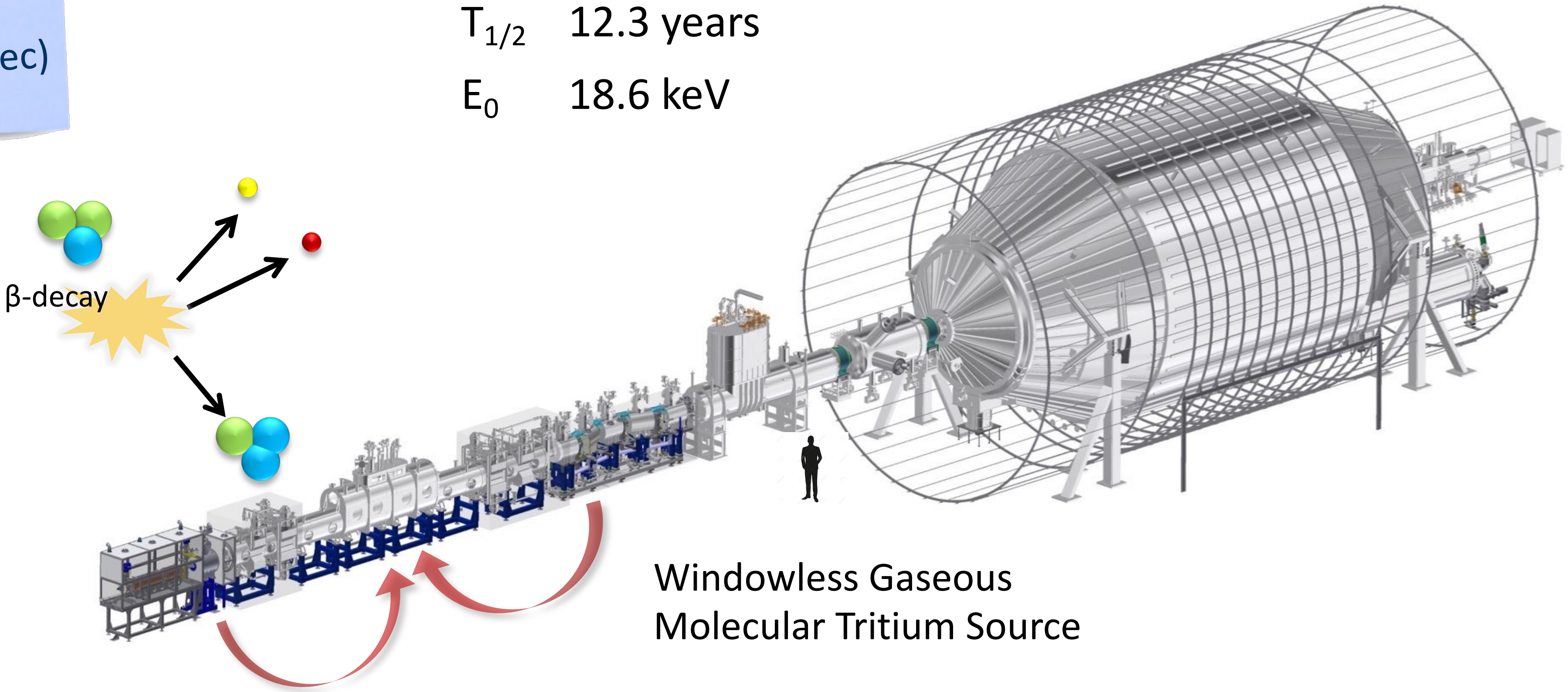


KATRIN Working Principle

high stability
and luminosity

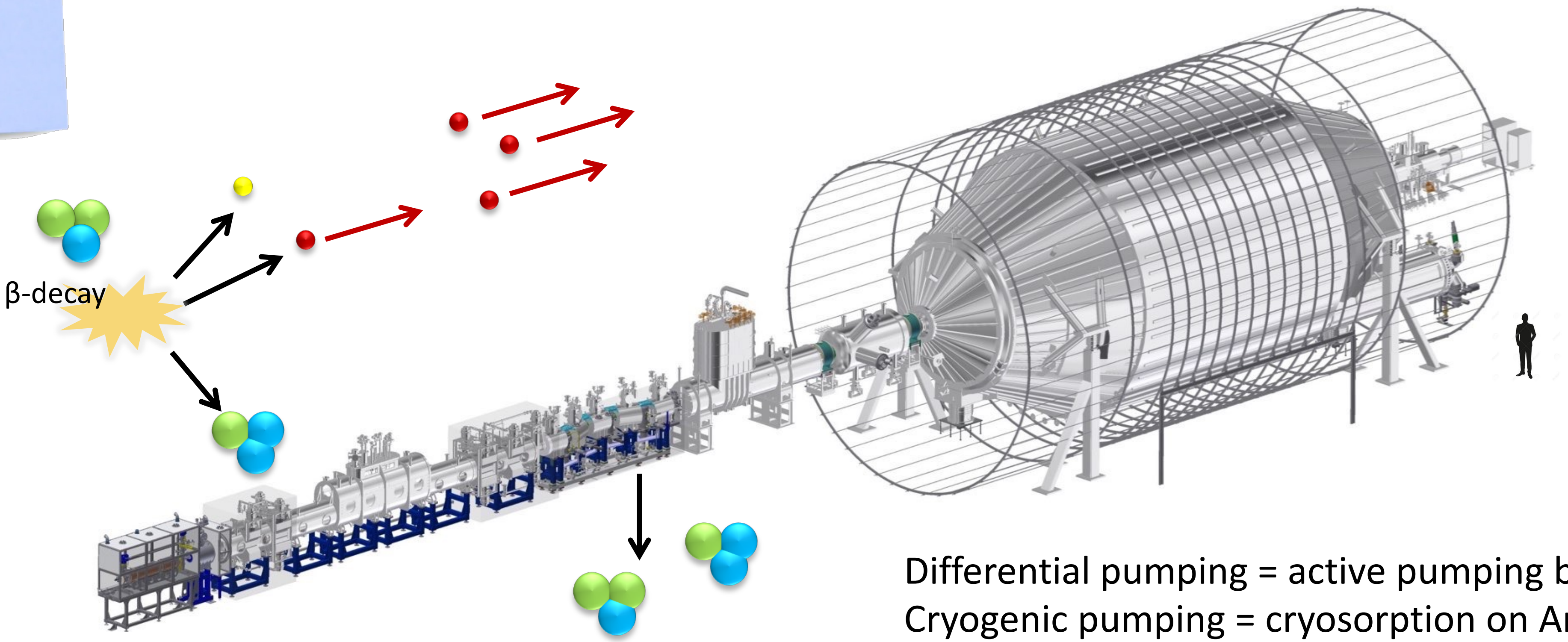
(10^{11} decays/sec)

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



KATRIN Working Principle

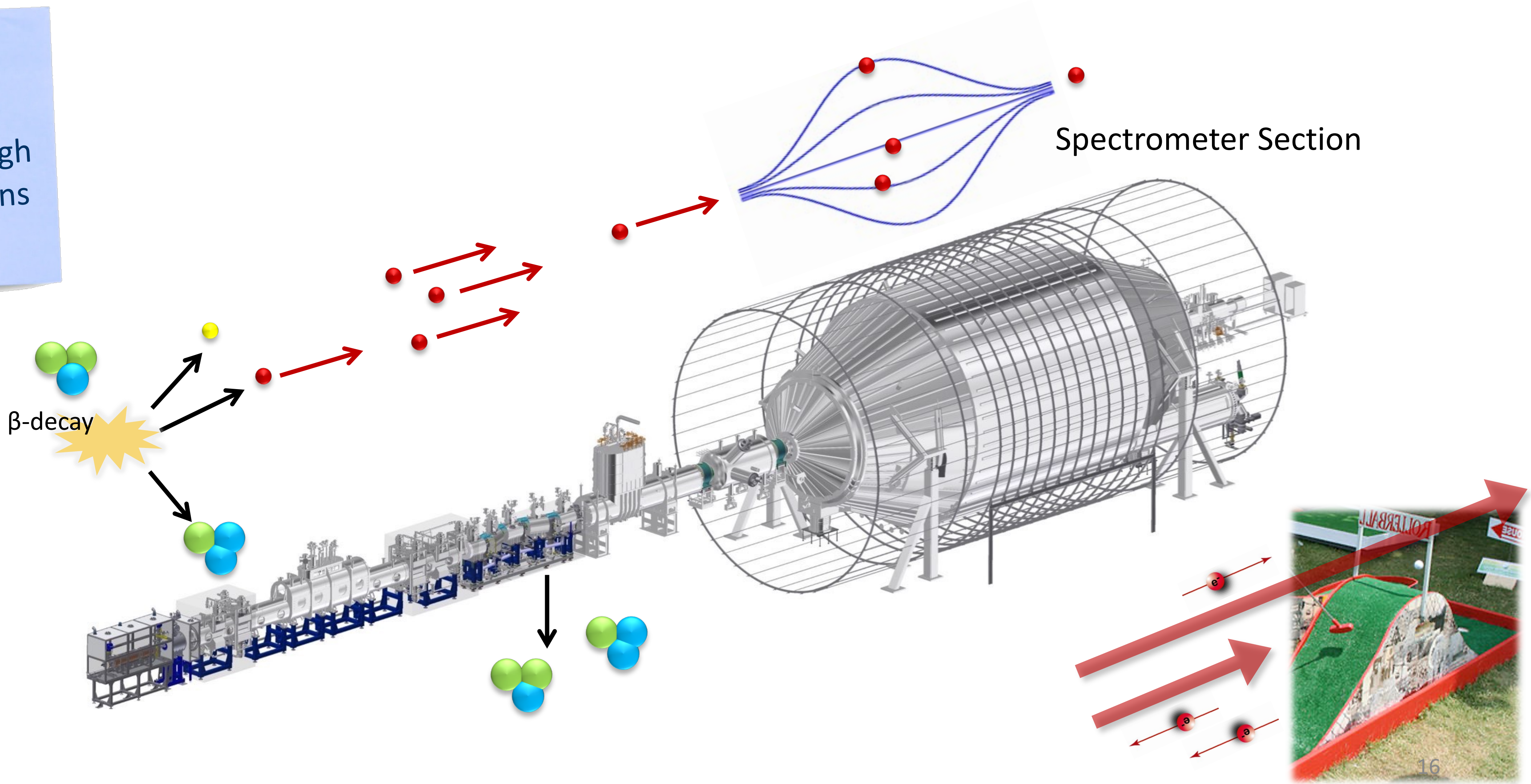
Tritium flow reduction by 14 orders of magnitude



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

KATRIN Working Principle

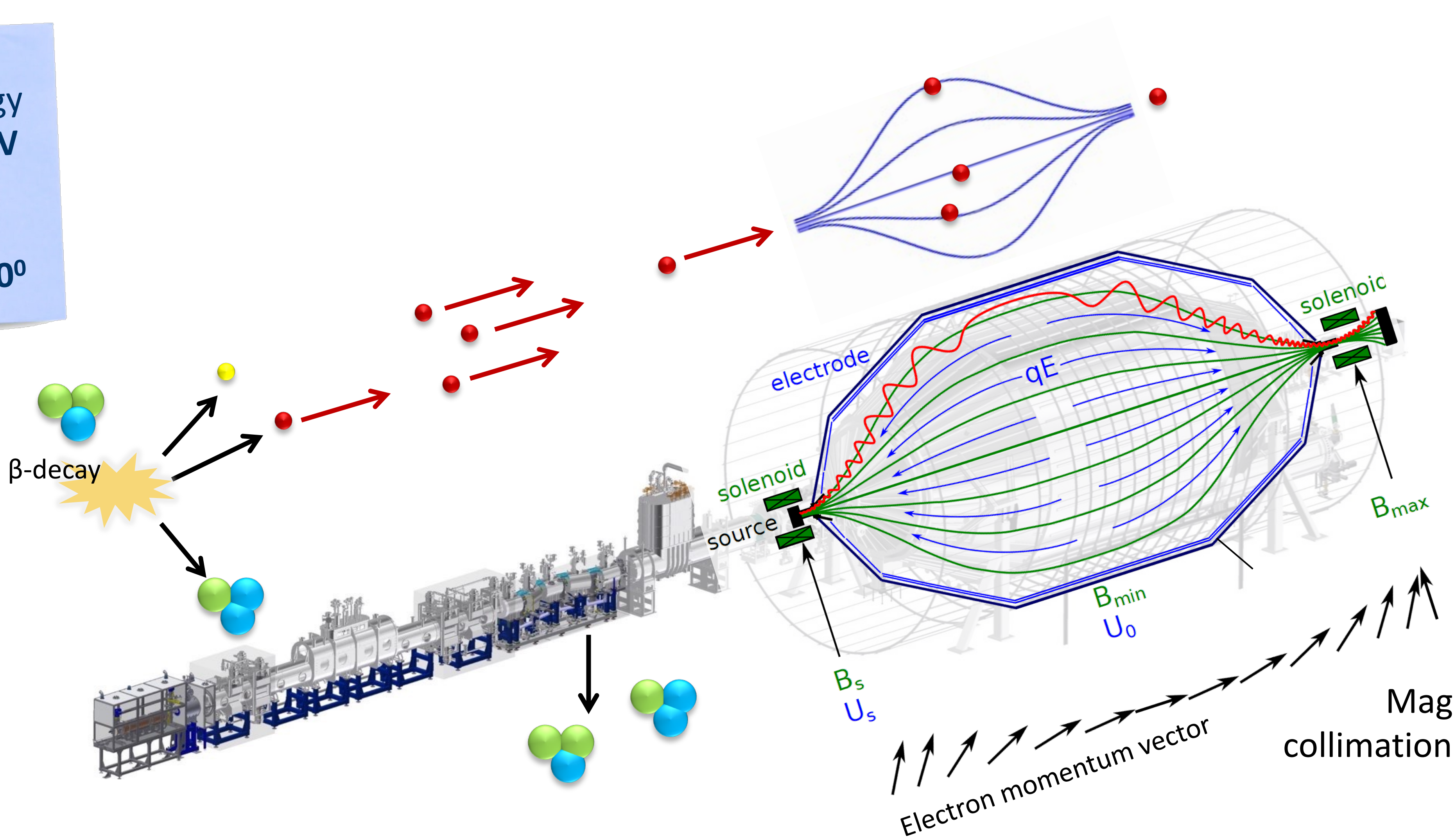
Electrostatic filter selects high energy electrons



KATRIN Working Principle

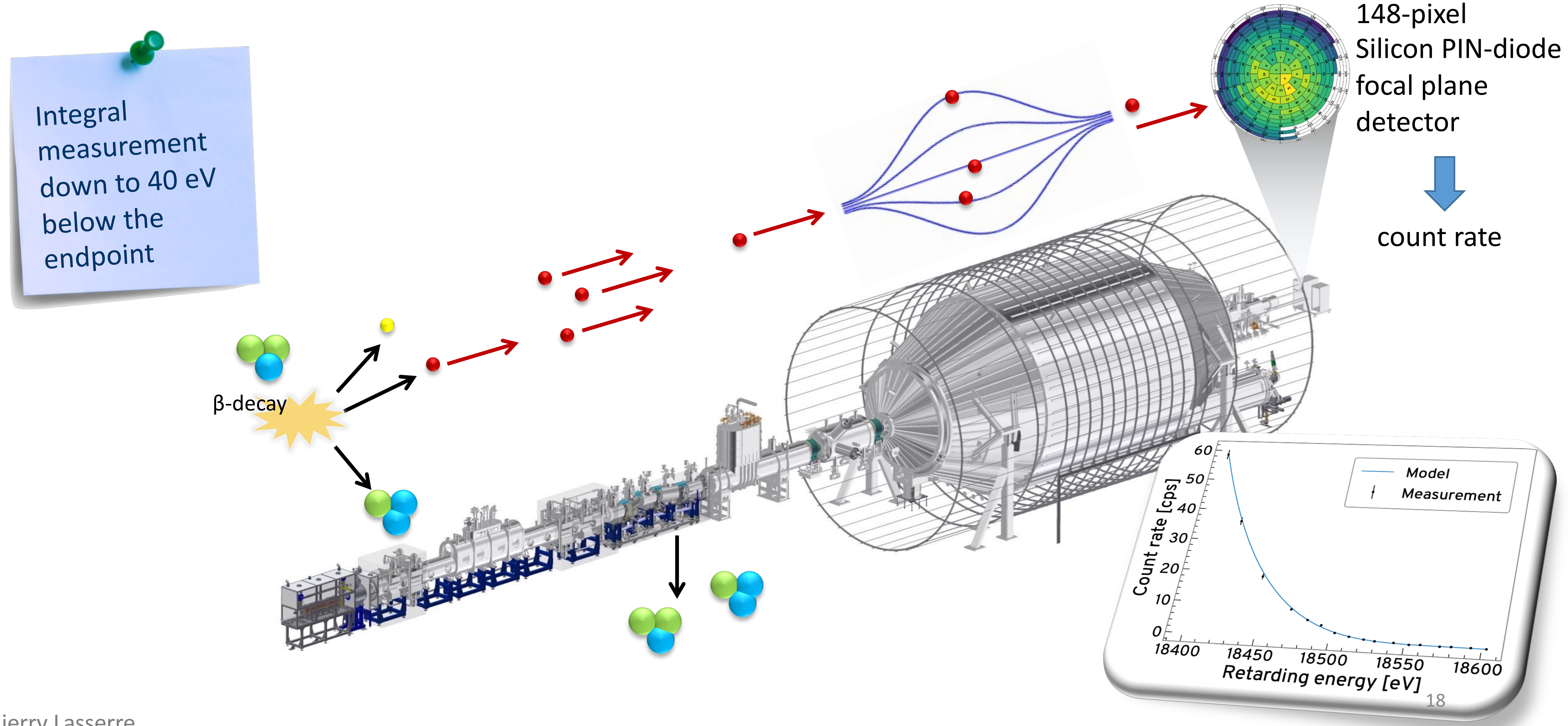
excellent energy resolution: **3 eV**

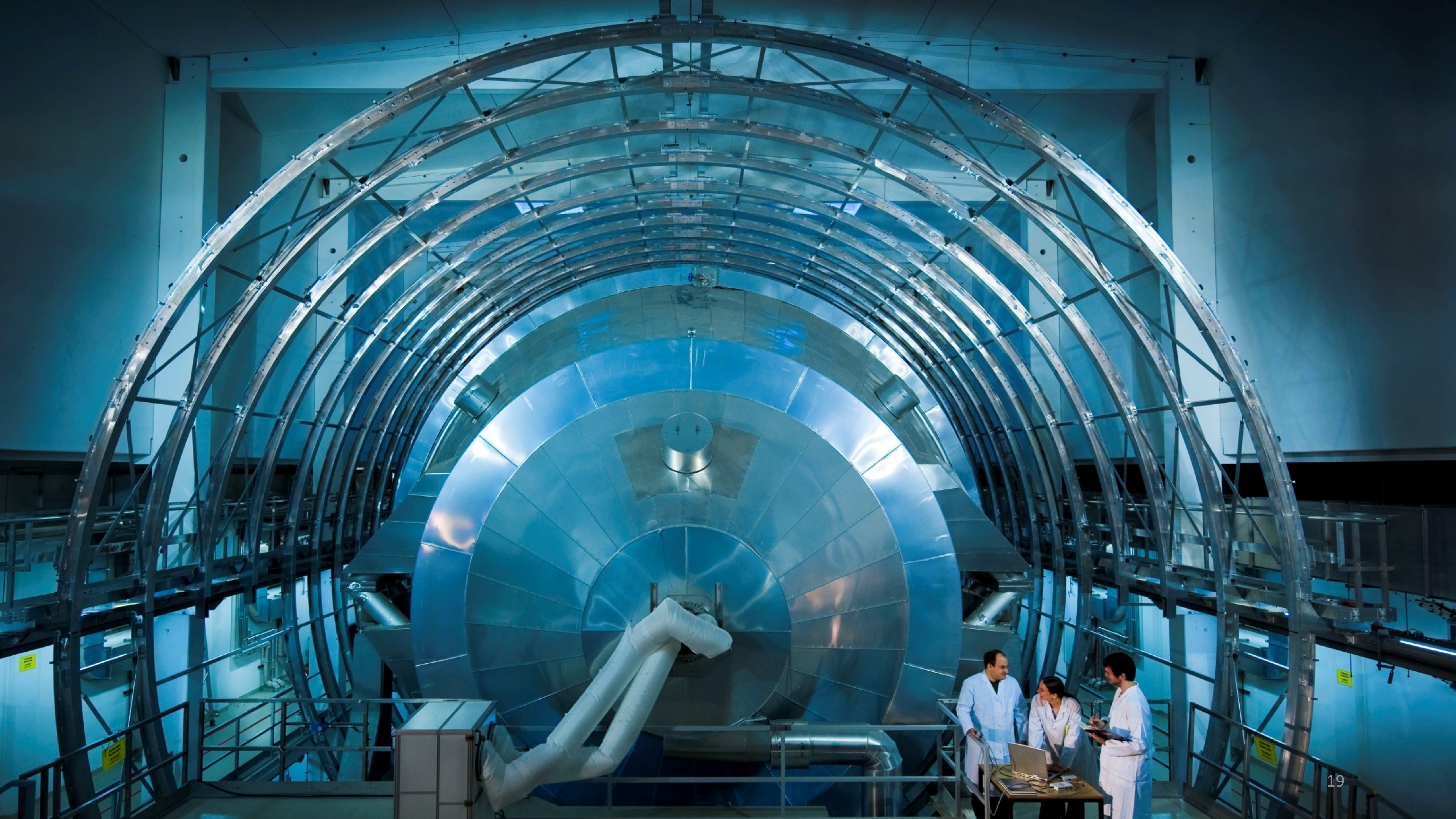
large angle acceptance: **50⁰**



Magnetic adiabatic collimation + electrostatic filter (MAC-E)

KATRIN Working Principle





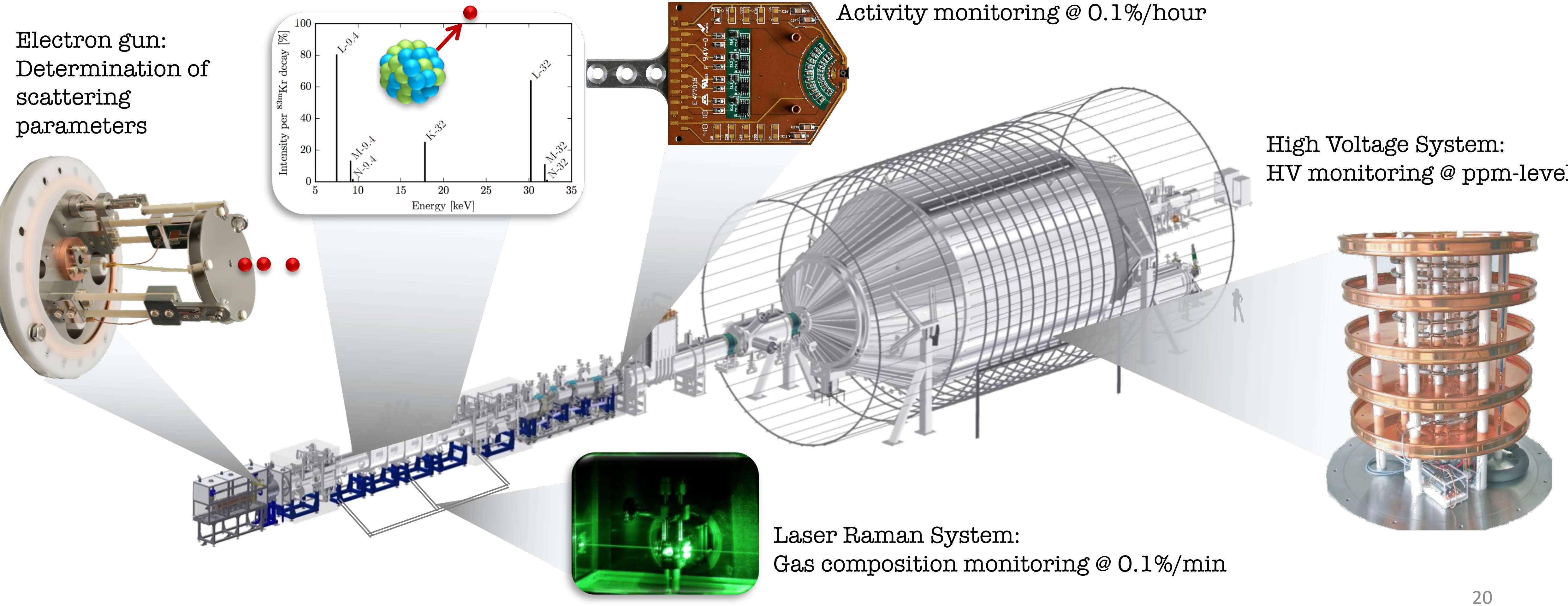
KATRIN Monitoring devices

Gaseous krypton source:
EM field calibration

Electron gun:
Determination of scattering parameters

Forward Beam Monitor:
Activity monitoring @ 0.1%/hour

High Voltage System:
HV monitoring @ ppm-level



Laser Raman System:
Gas composition monitoring @ 0.1%/min

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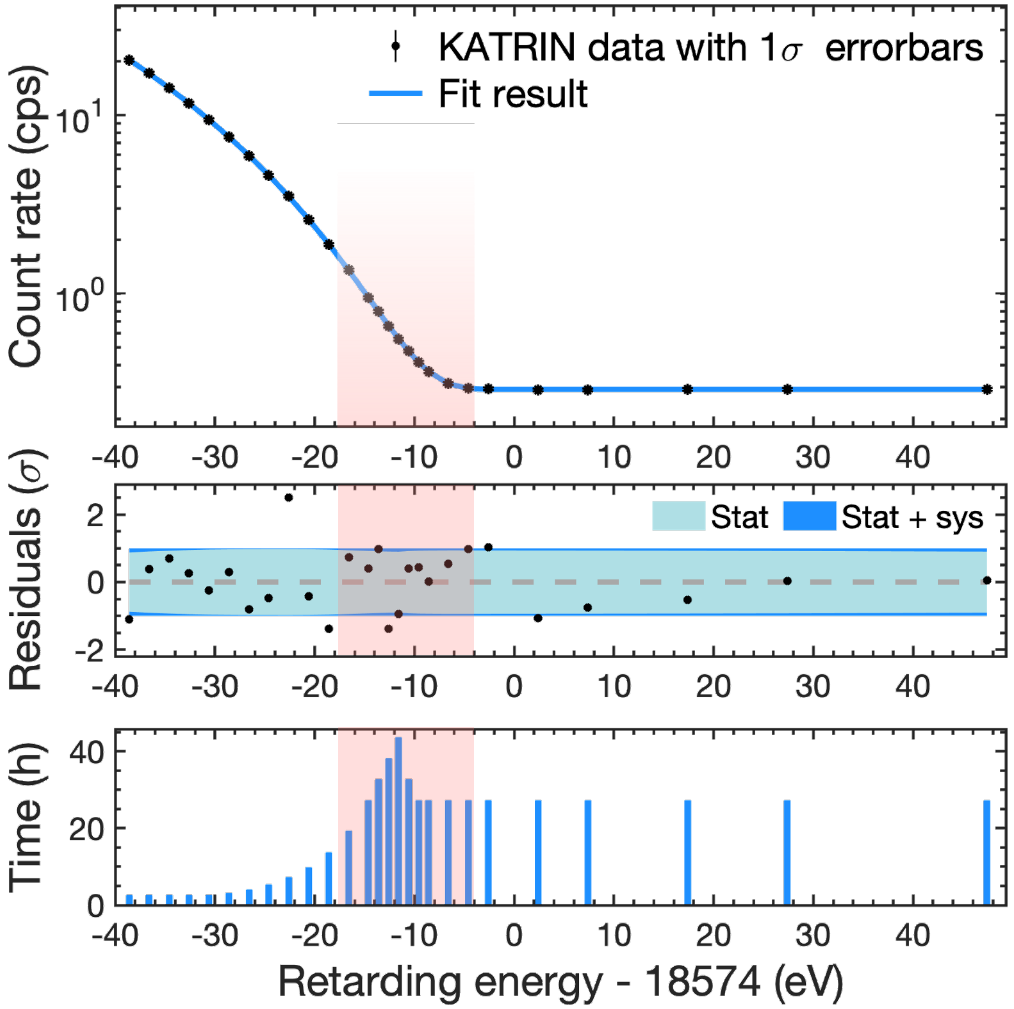
Recap: first KATRIN neutrino mass result



- Four-week campaign at reduced source strength ("burn-in phase" in 2019)
- 9 days of nominal KATRIN only
- Improvement over prev. experiments:

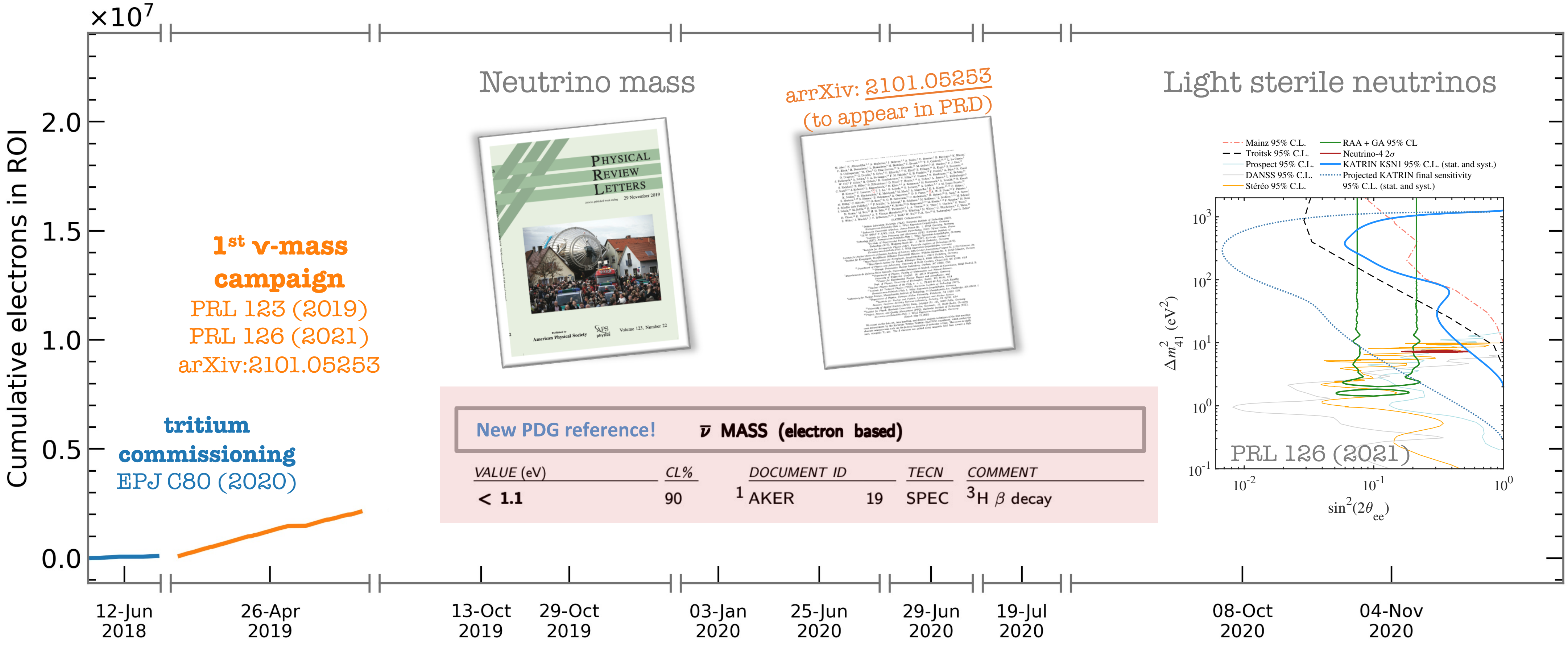
  σ_{stat} = 0.97 eV^2 ➜ factor 2 / Mainz&Troistk

  σ_{syst} = 0.32 eV^2 ➜ factor 6 / Mainz&Troistk
- Best-fit value:

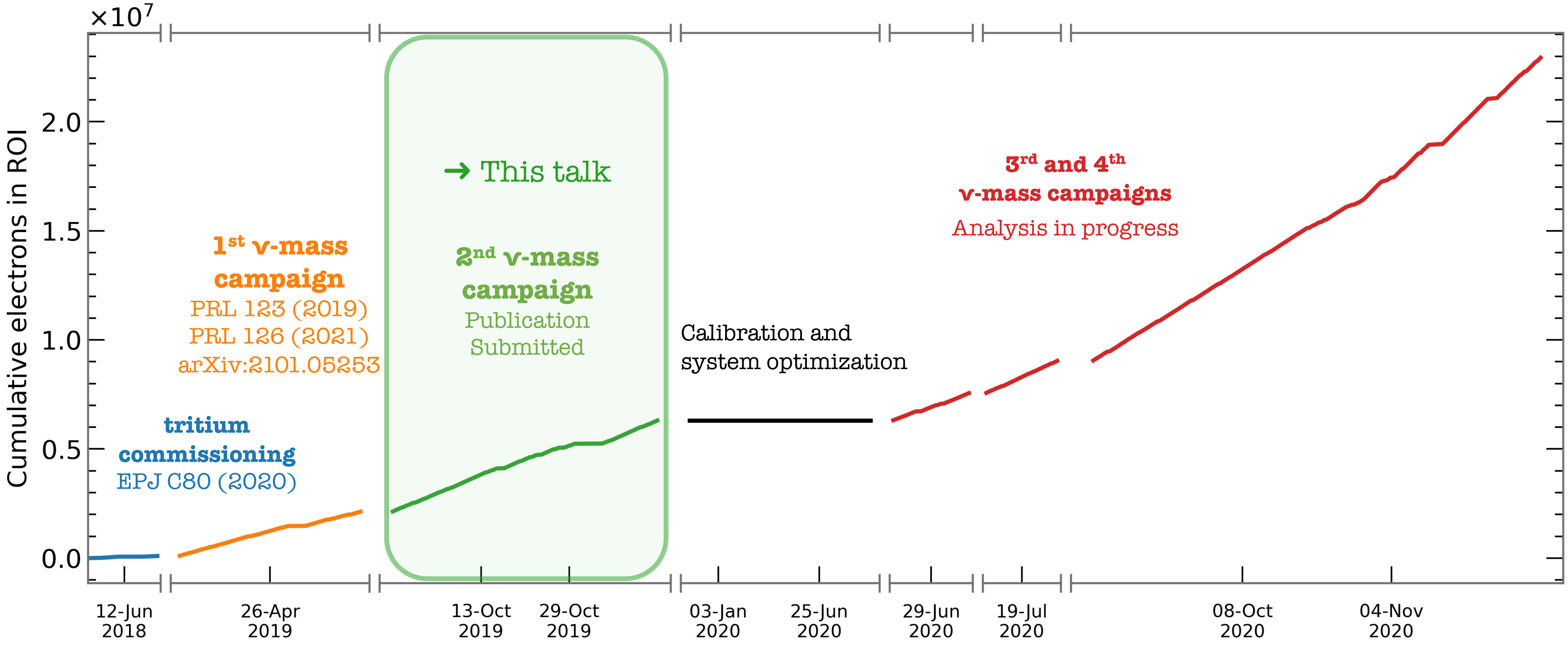
$$\mathbf{m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right) eV^2}$$

- Upper limit: m_n < 1.1 eV (90% C.L.)

KATRIN First Neutrino Mass Result (2019)



New Data Release (2021)



Second Neutrino Mass Campaign

( = systematic uncertainty)

KATRIN neutrino mass campaign #2 (KNM-2)

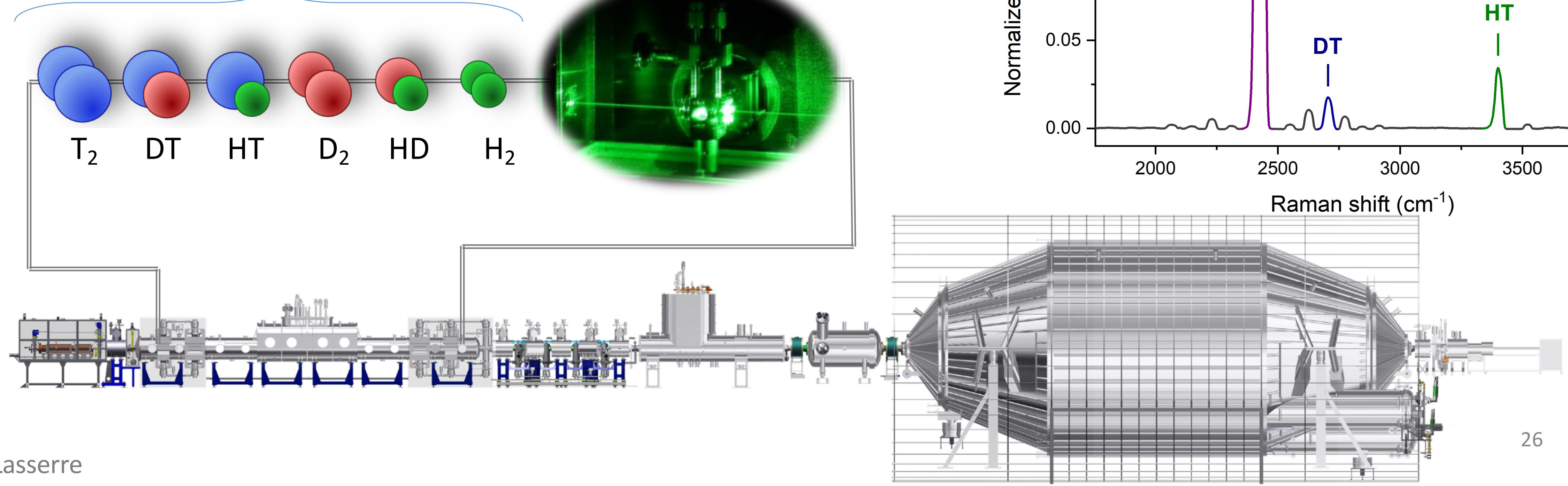
- First ever high-activity tritium operation of KATRIN
- 27.9.2019 - 14.11.2019: **743.7 h (31 days)**
- high-quality data collected **4.3 million electrons**

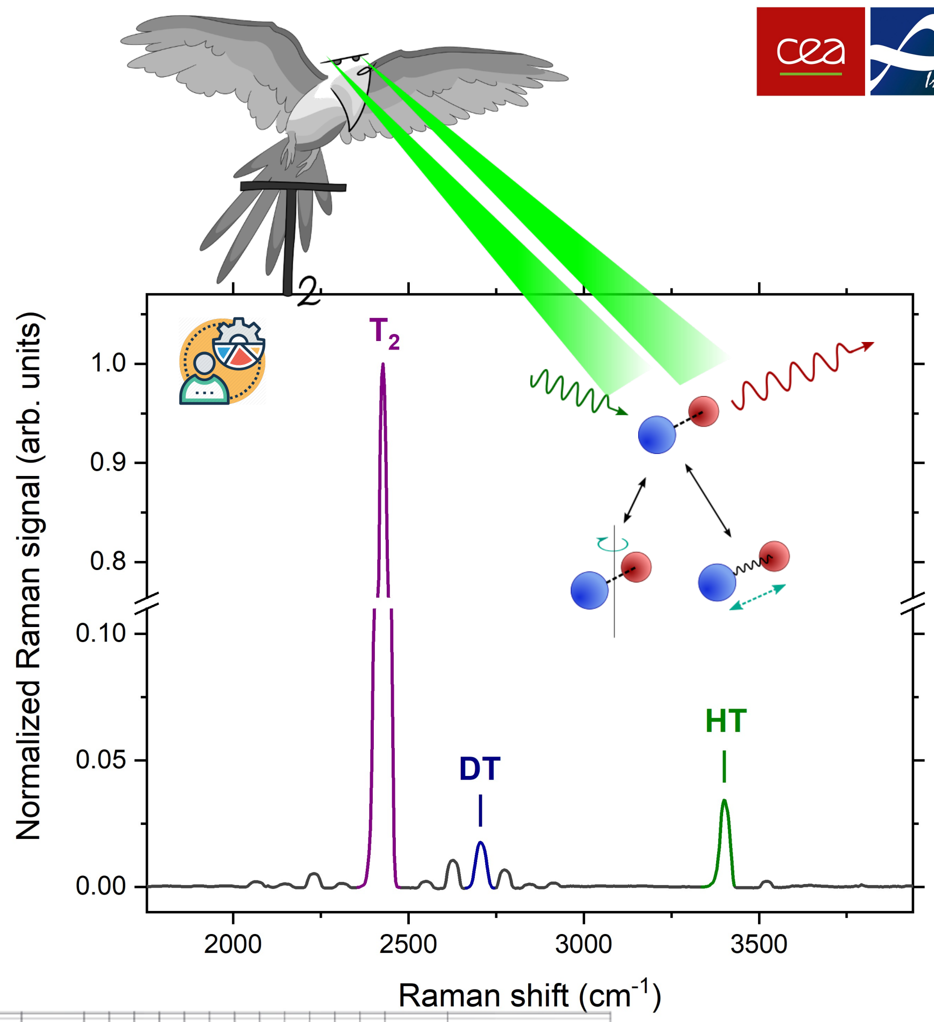
✓ **Second neutrino mass result**

Source composition

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

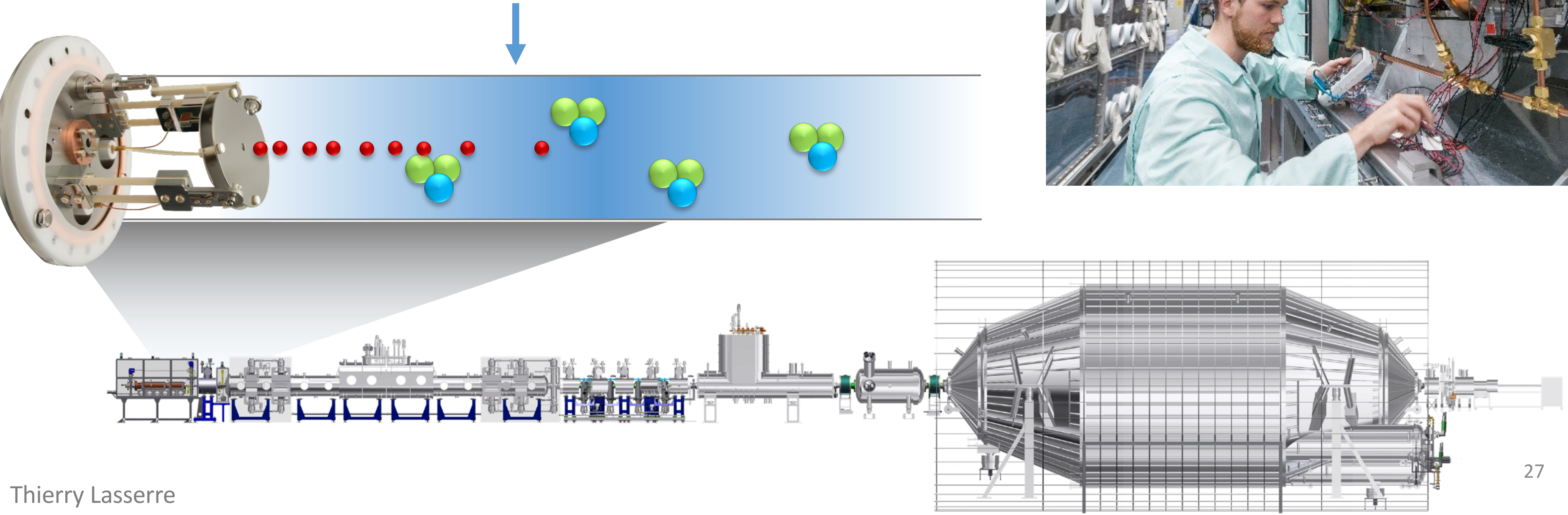
Slightly different energy spectra





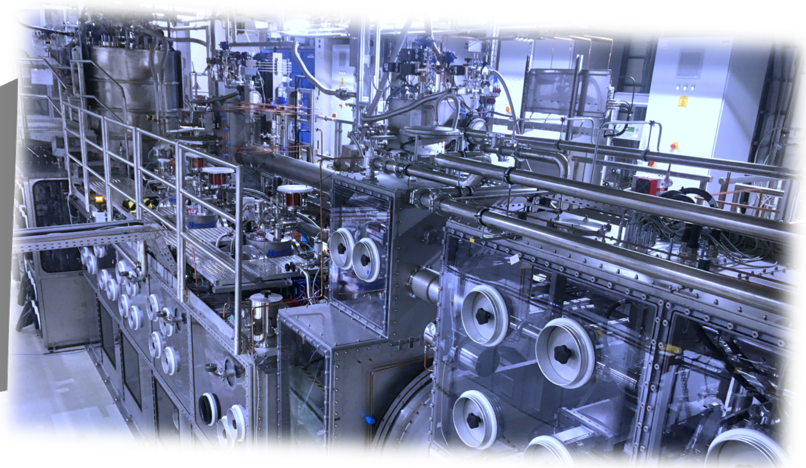
Source density

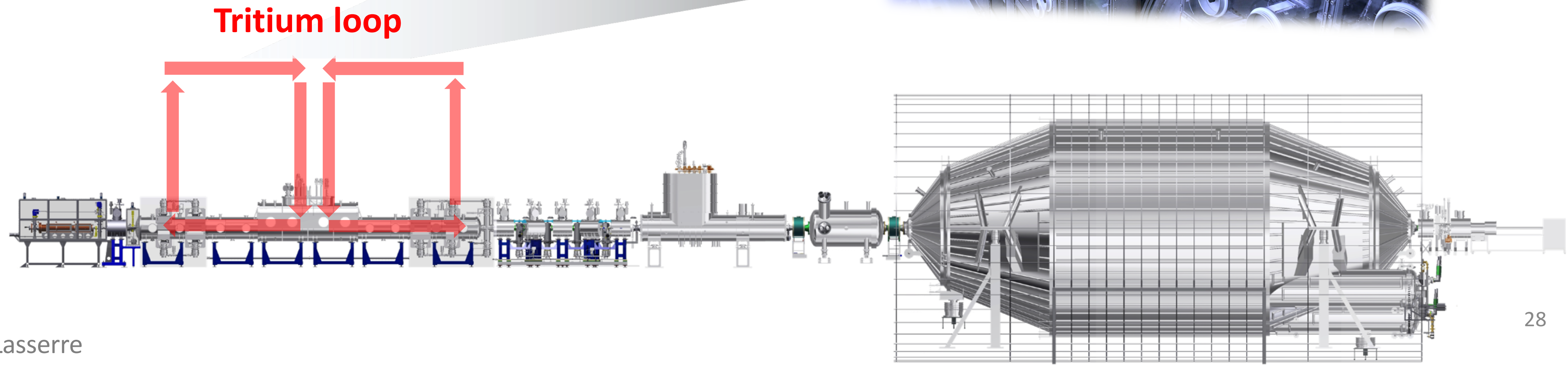
- **High-intensity electron gun**
- Column density 0.84 x 1.1×10^{21} molecules/m^{-2}
- (0.1)%-ish stability of density observed
- Characterized with electron gun



Tritium operation summary

- tritium gas density: **84% of nominal**
- high isotopic tritium purity: **98.7%**
- high source activity: **$9.5 \cdot 10^{10}$ Bq**





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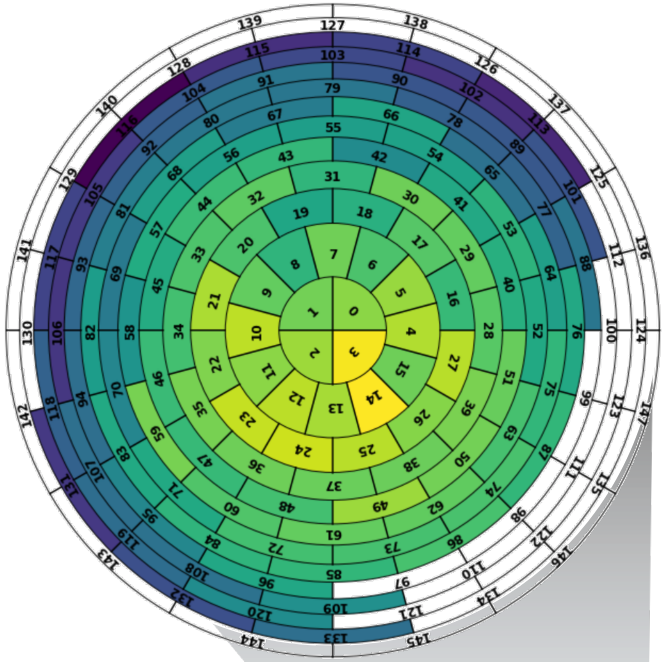
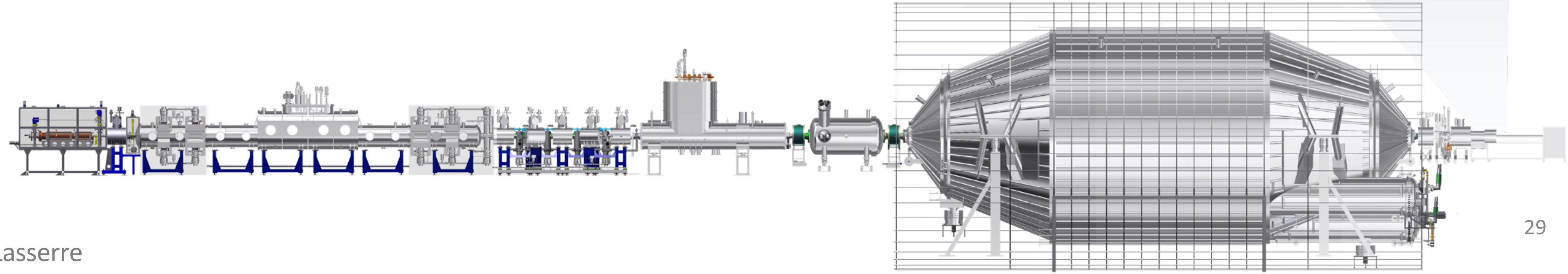
Focal plane detector

- 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





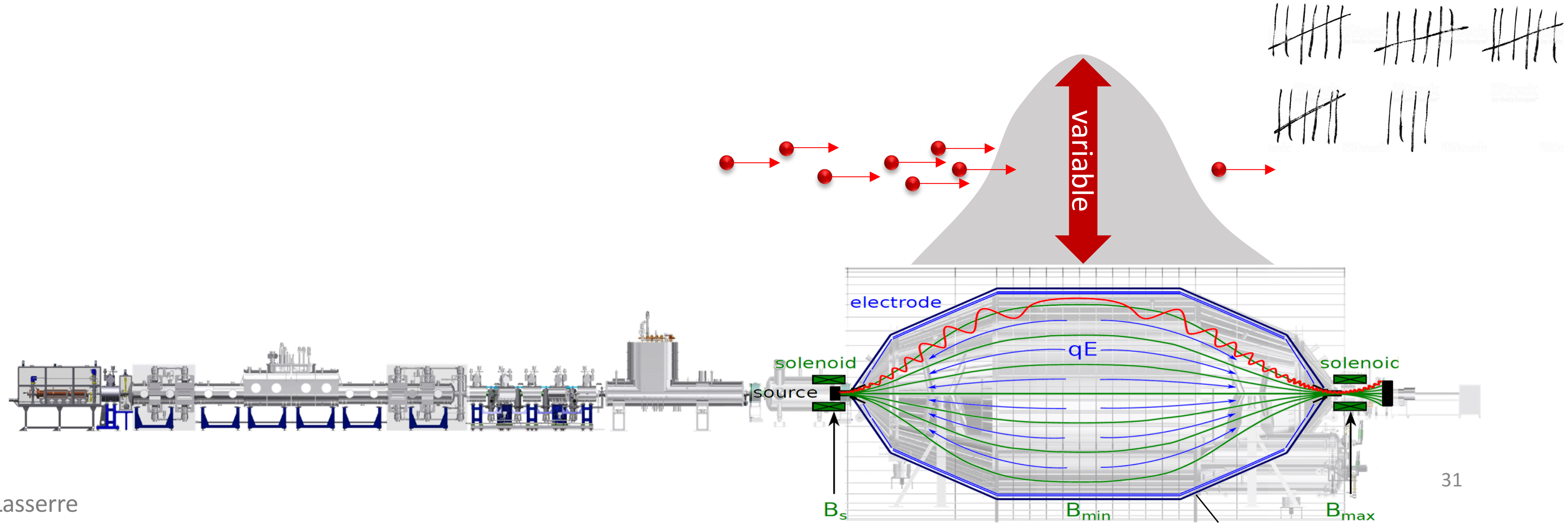
Comparison with first campaign

	1st campaign PRL 123 (2019)	2nd campaign This talk
Campaign date	April-May 2019	Sept-Nov 2019
Total scan time	522 h (274 scans)	744 h (361 scans)
Background	290 mcps	220 mcps
Source activity	25 GBq	98 GBq
Tritium purity	97.6%	98.7%
Electrons in RoI	2 Mio	4.3 Mio

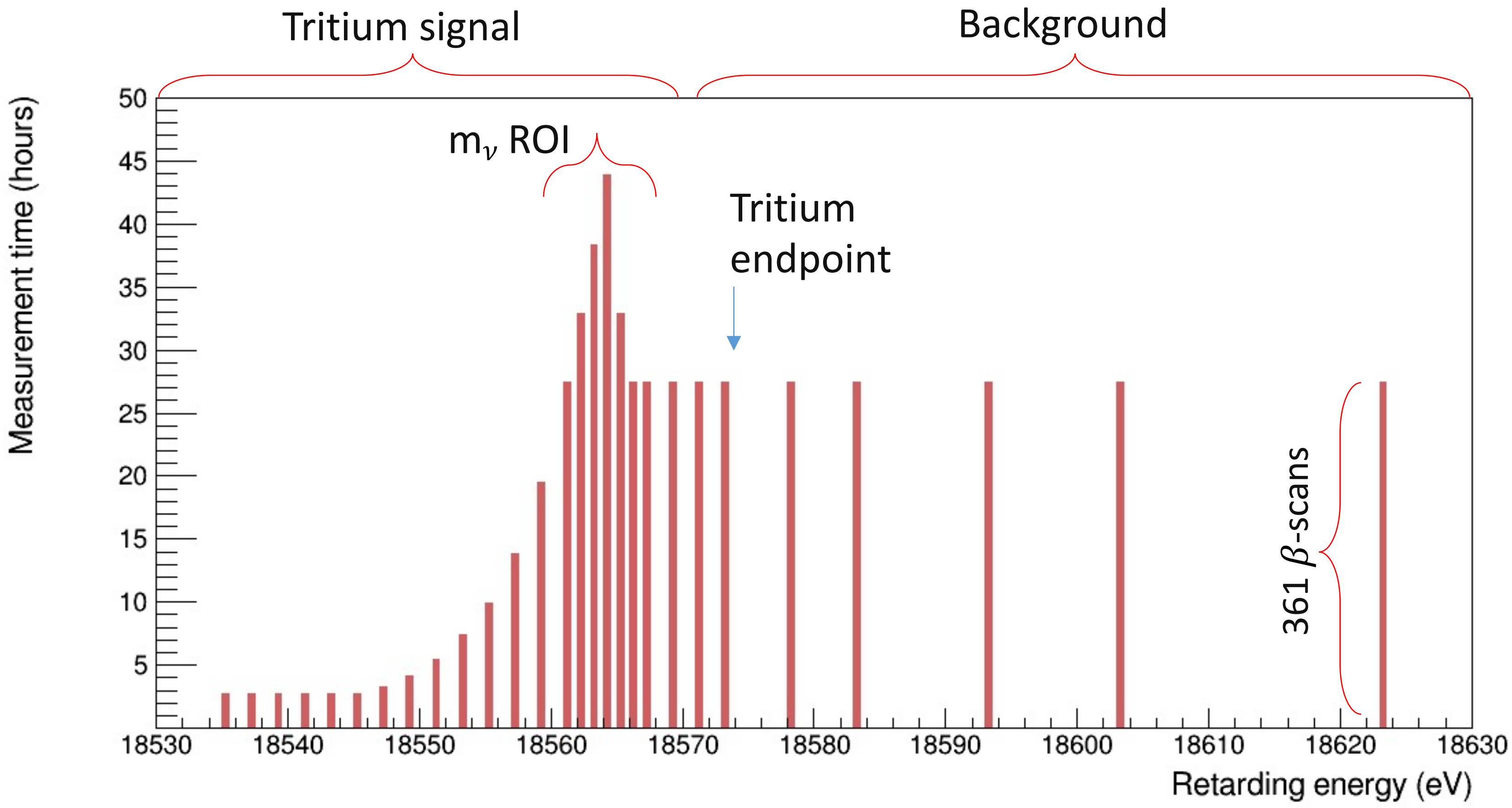
Background: reduction -25% →
Source activity: nominal activity →
Tritium purity: raised purity →
Electrons in RoI: stats doubled →

Scanning Strategy

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



Measurement time distribution



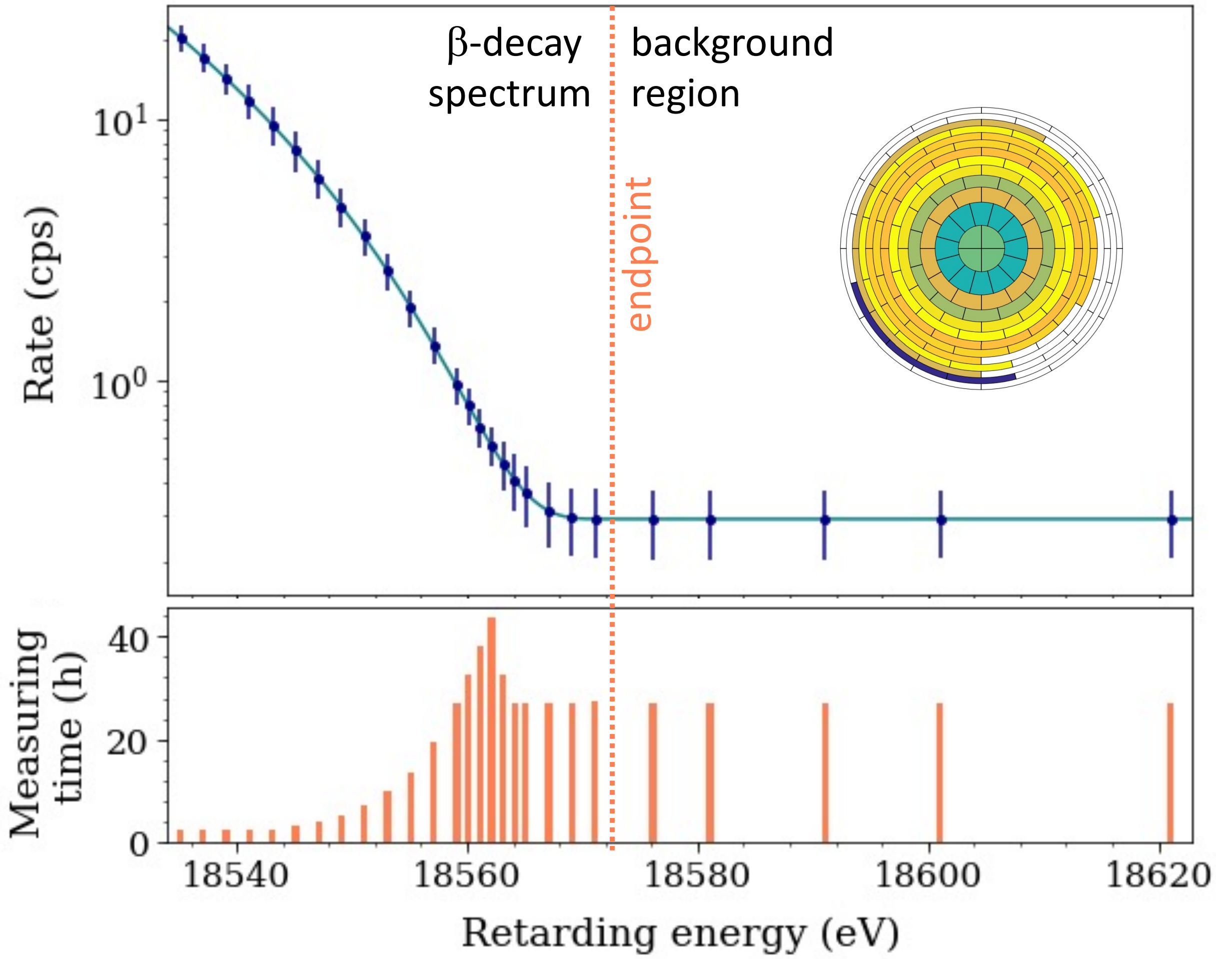
-40 eV
below endpoint

Data taking and combination

- Measurement time: **30 days**
- Measurement interval: **E_0 – 40 eV , E_0 + 135 eV**
- Scanning time: **2 hours**
- Number of β-scans: **361**

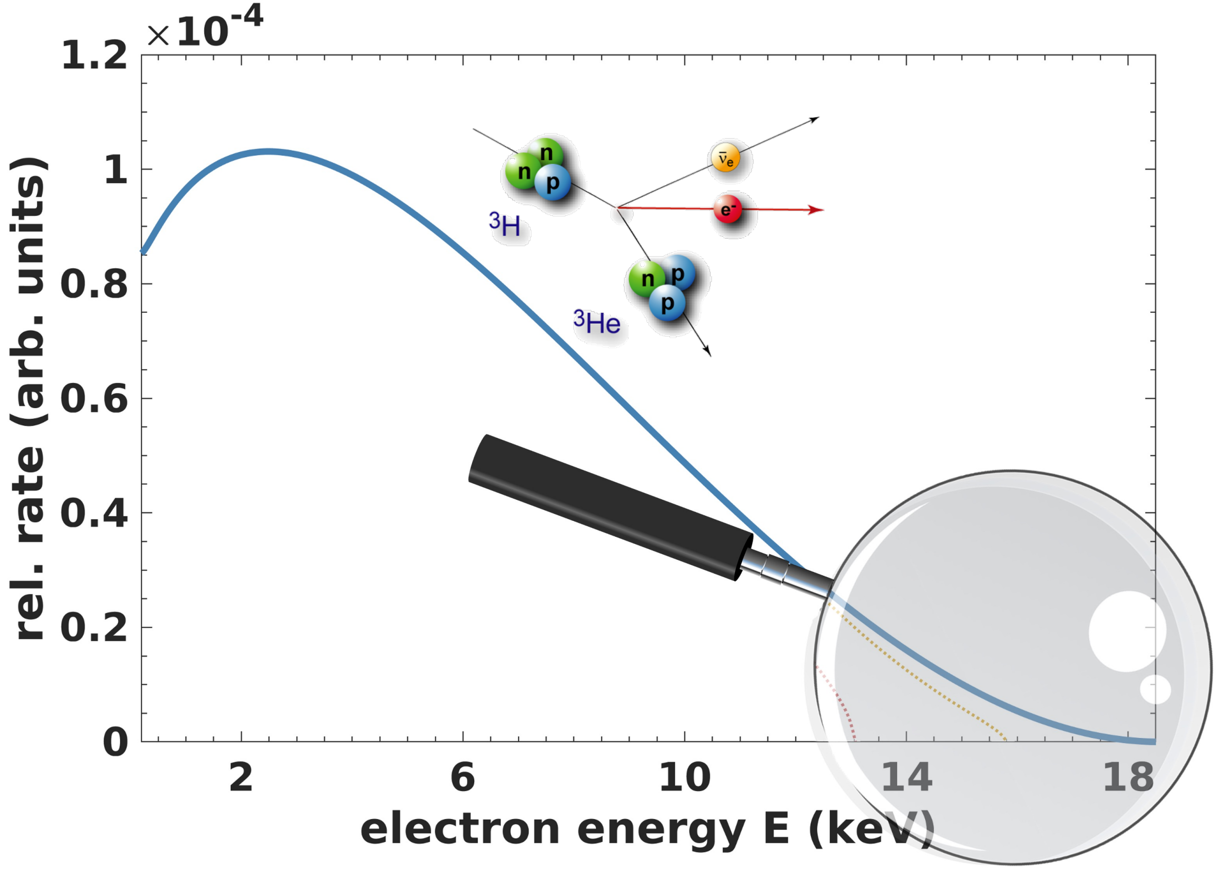
- Scans are combined to high-stat. spectrum

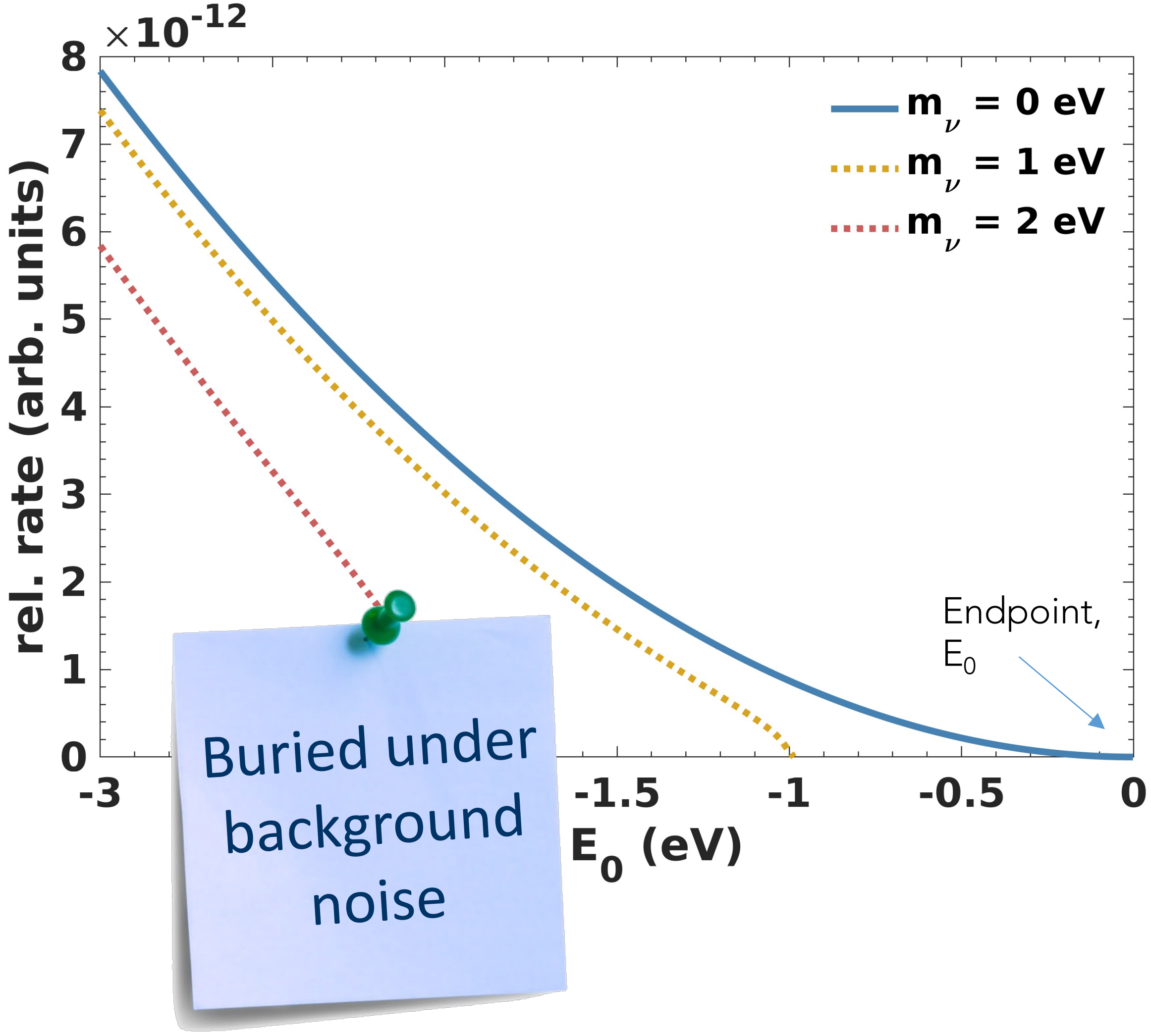
- Individual spectra
  - for each detector pixel
  - pixels can be gathered in 4 or 12 rings



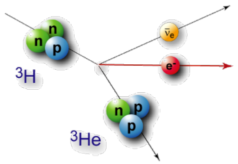
Neutrino Mass Imprint

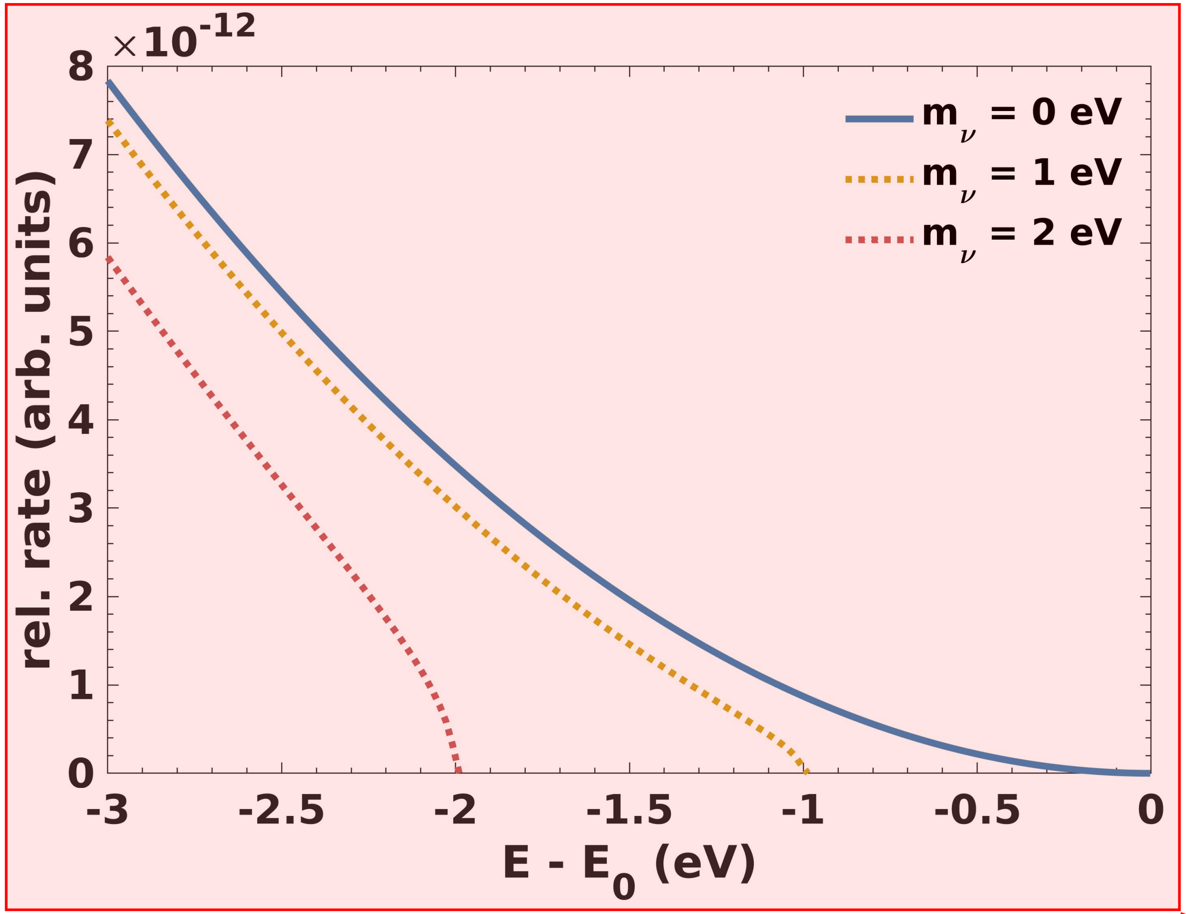
Misleading Display of m_ν Imprint

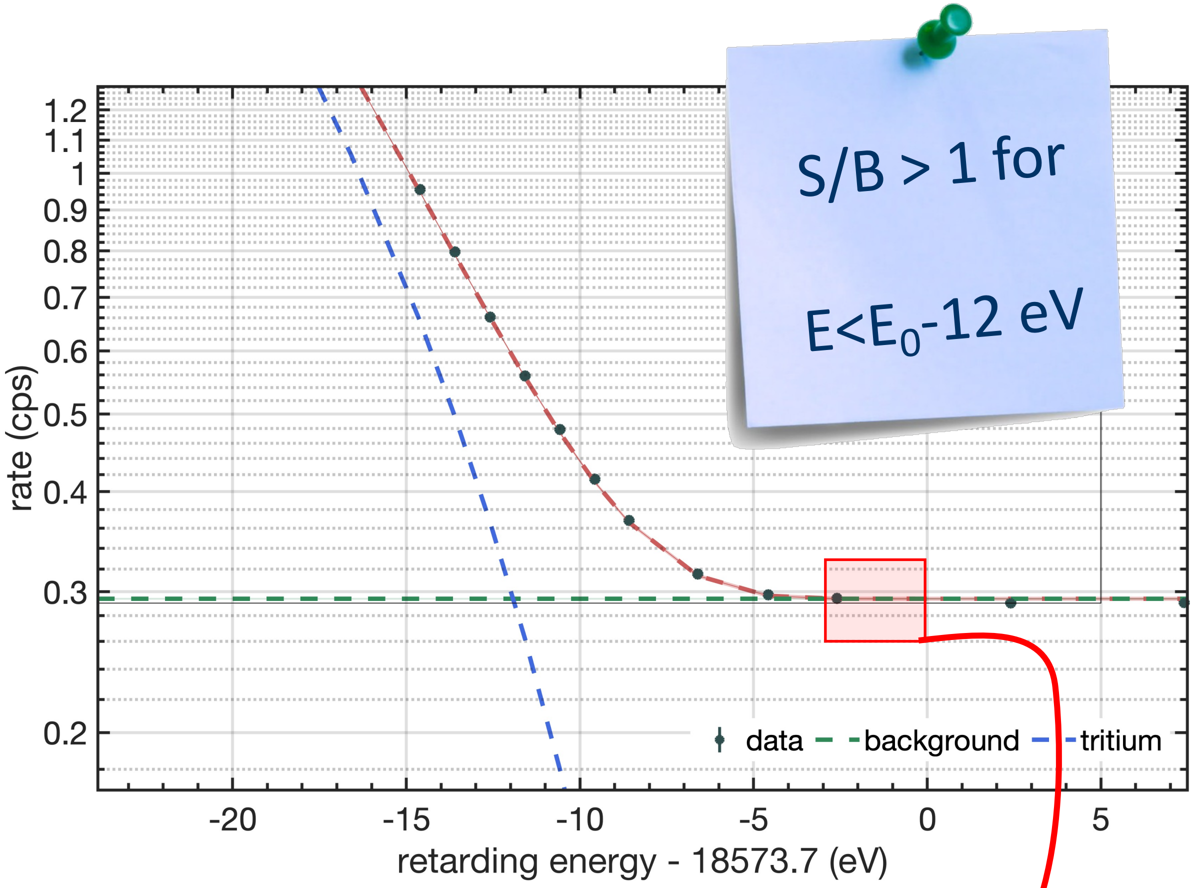




KATRIN Neutrino Mass Imprint







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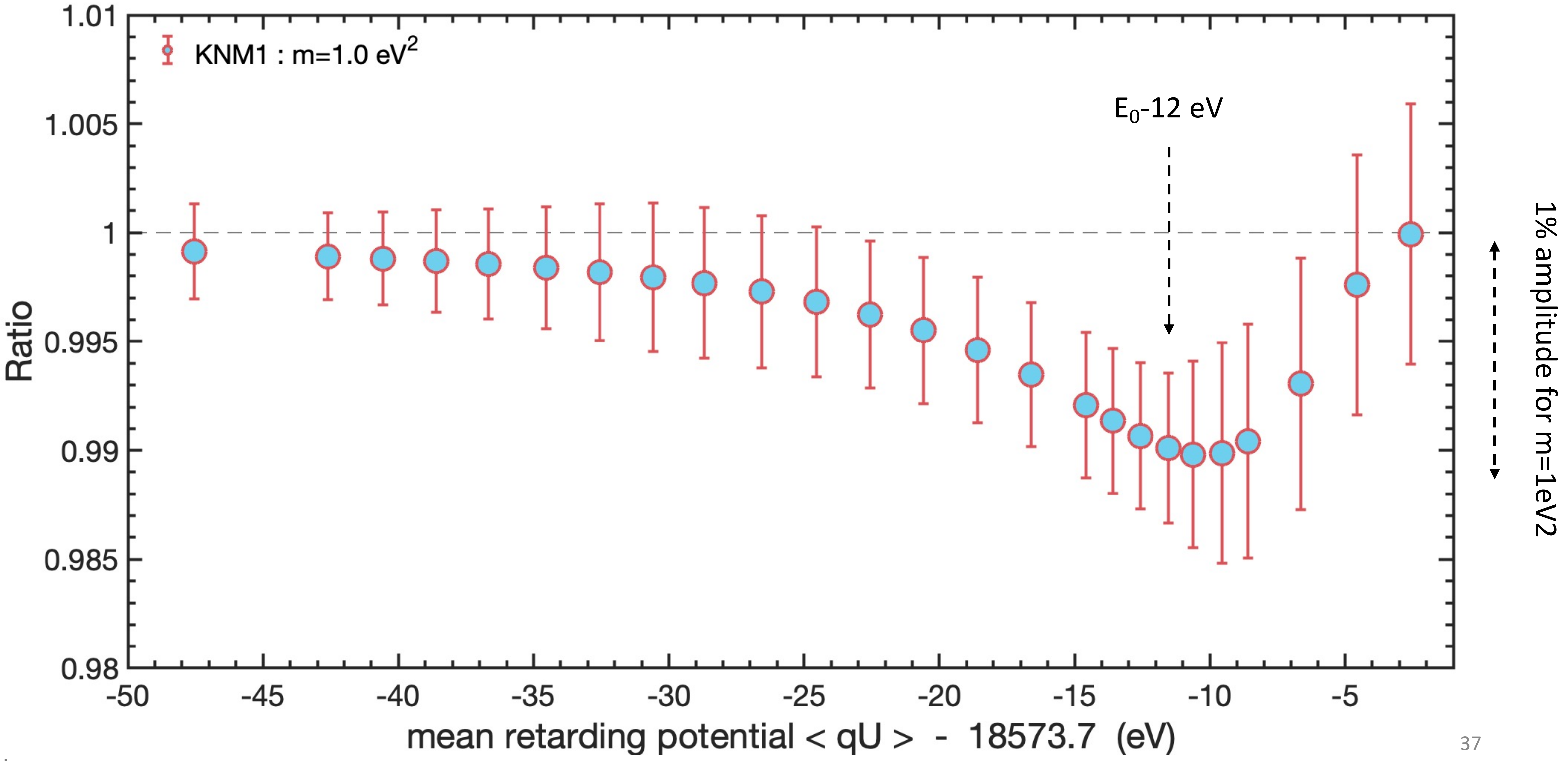
Expected Signal for $m=1eV^2$ (KNM1, here)



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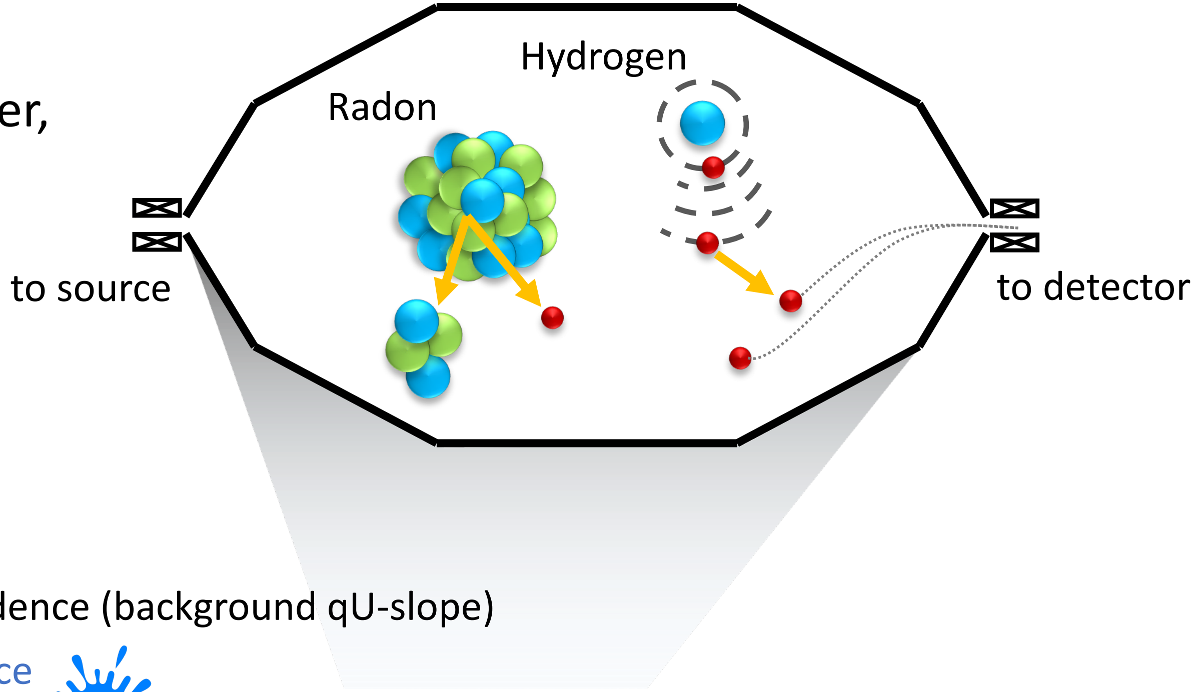
Background

Background characterization

- **Low energy electrons produced & 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
- 3 concerns:
  - Precise determination of background rate
  - Check / limit background retarding-potential dependence (background qU-slope)
  - Check / limit background sub-scan length dependence NEW!



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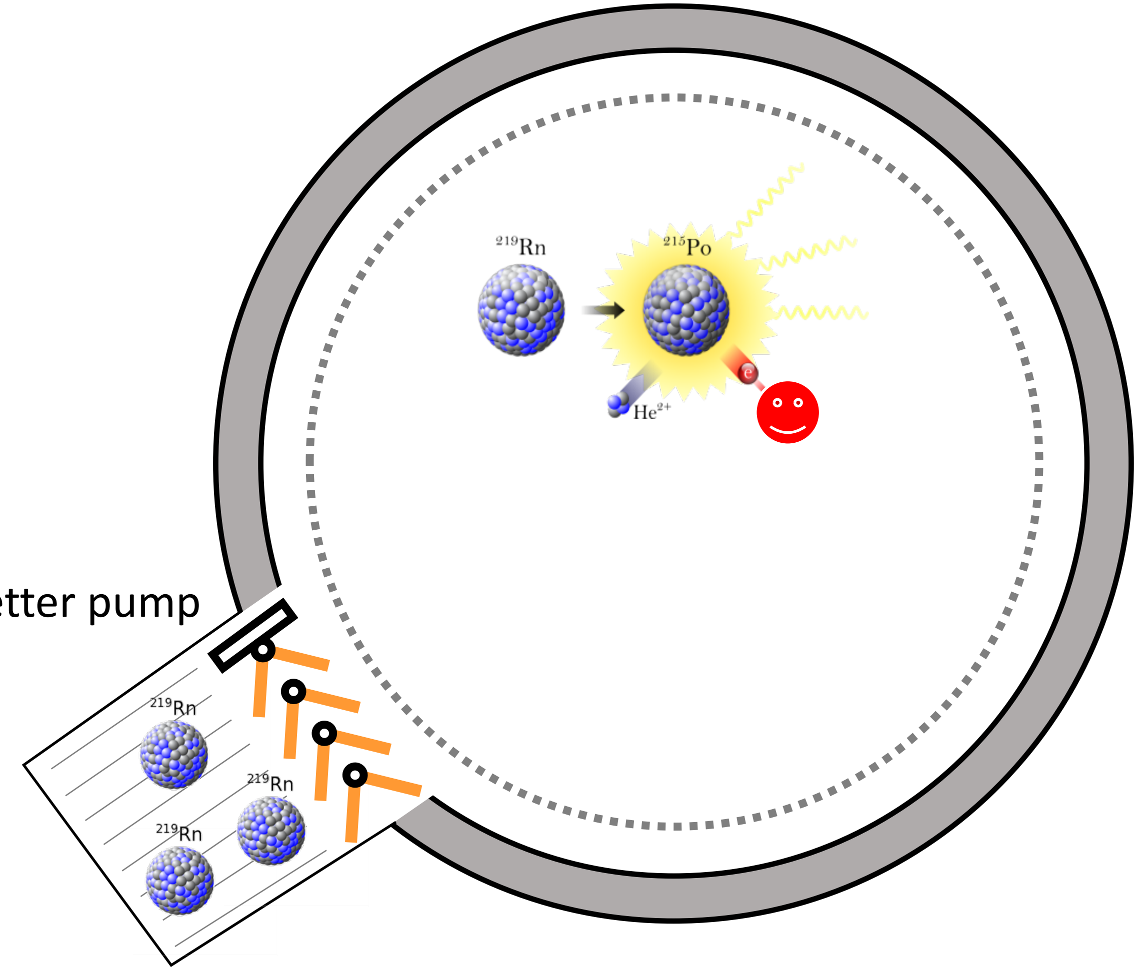
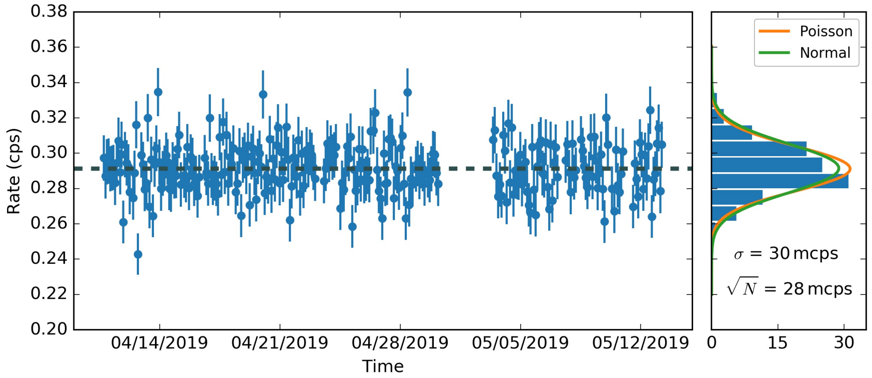
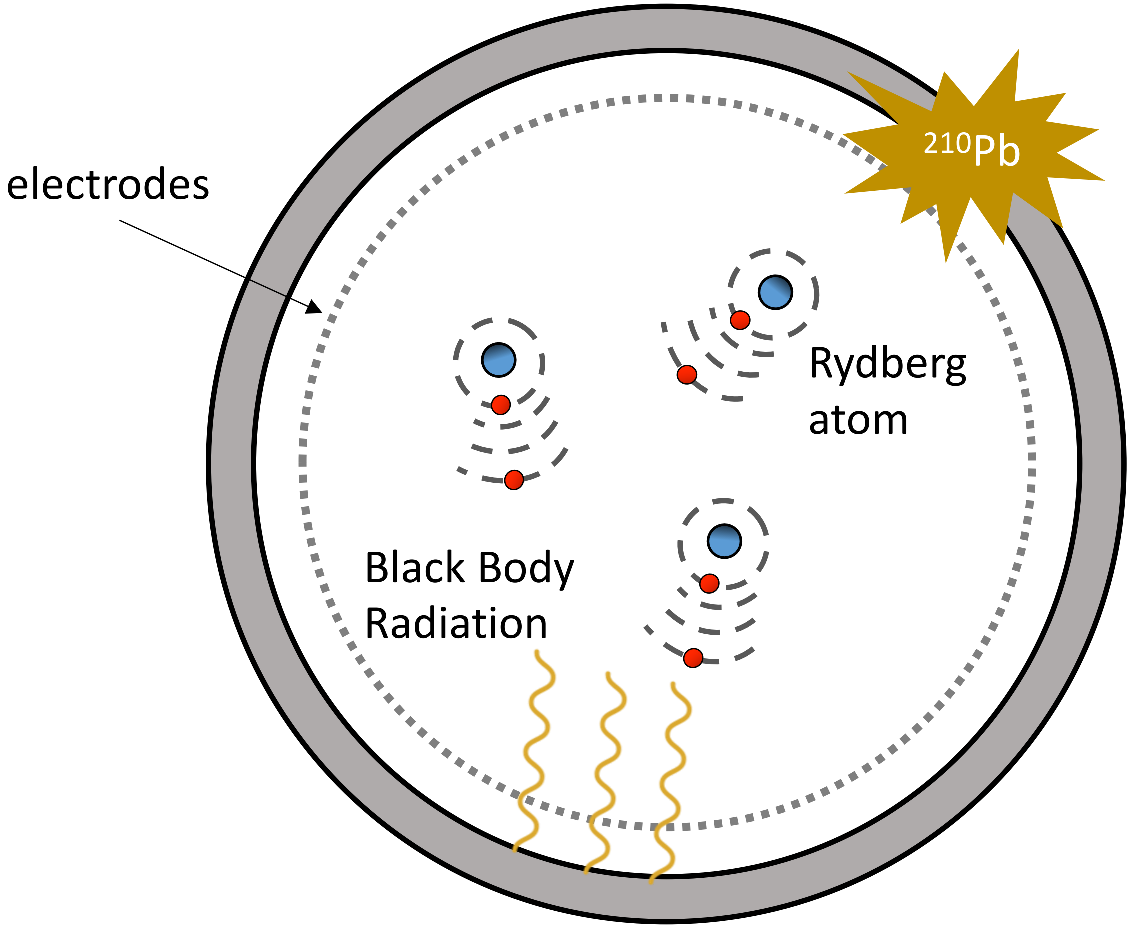
Radon-induced backgrounds



- 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
- 10% Non-Poissonian rate over-dispersion



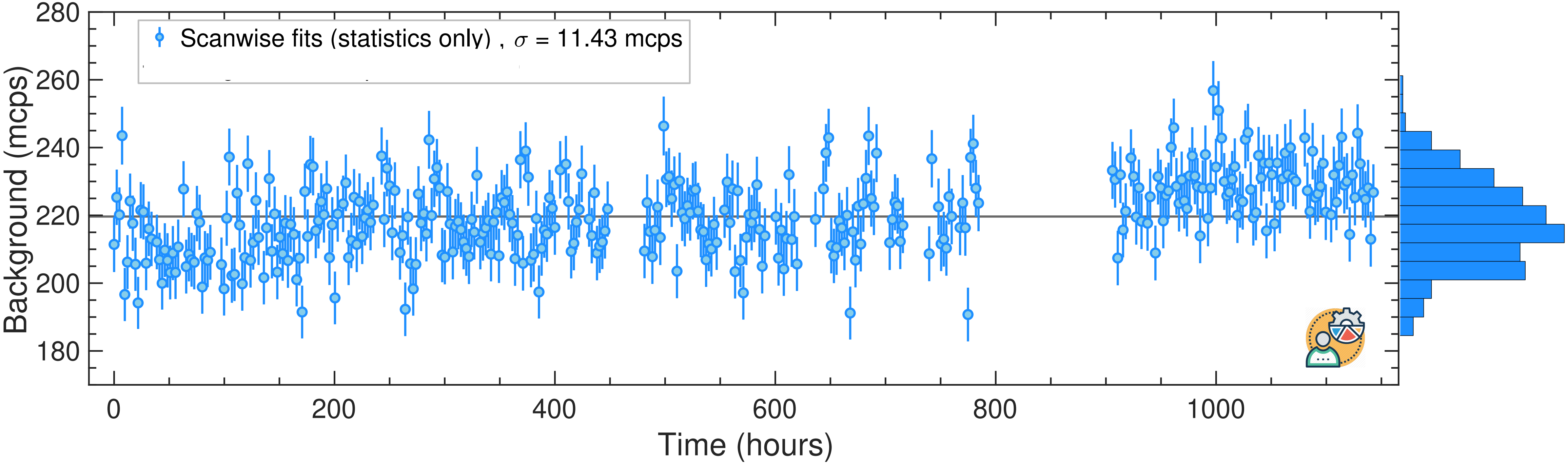
Neutral Excited Atoms



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

Background Rate over 371 scans

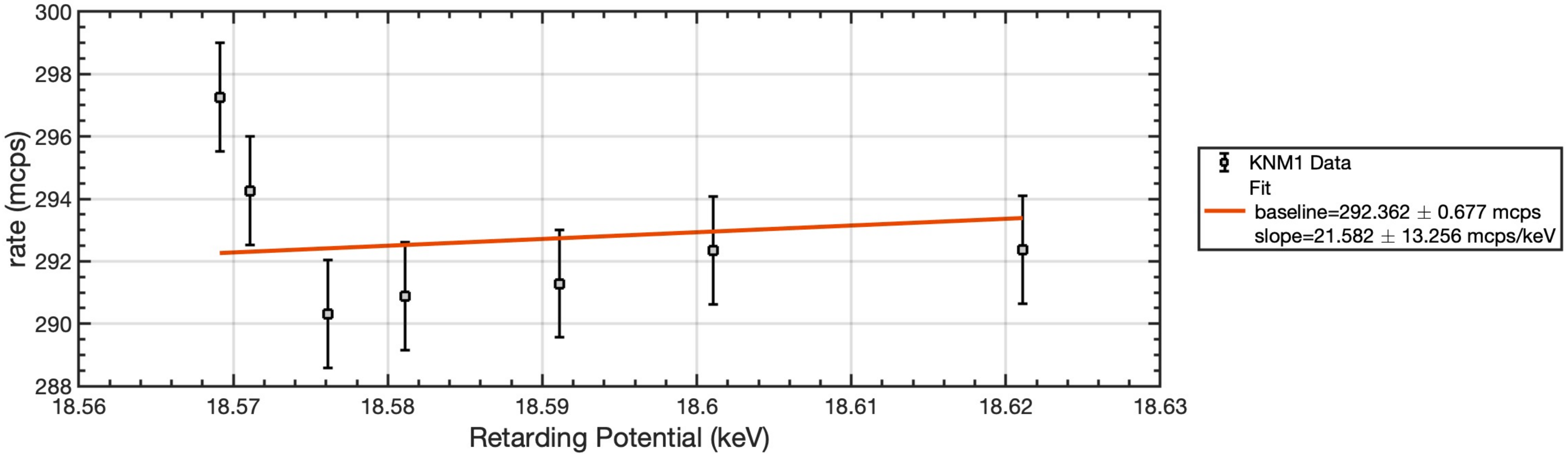
- All detector pixels combined – background reduced by 25% w.r.t. first campaign

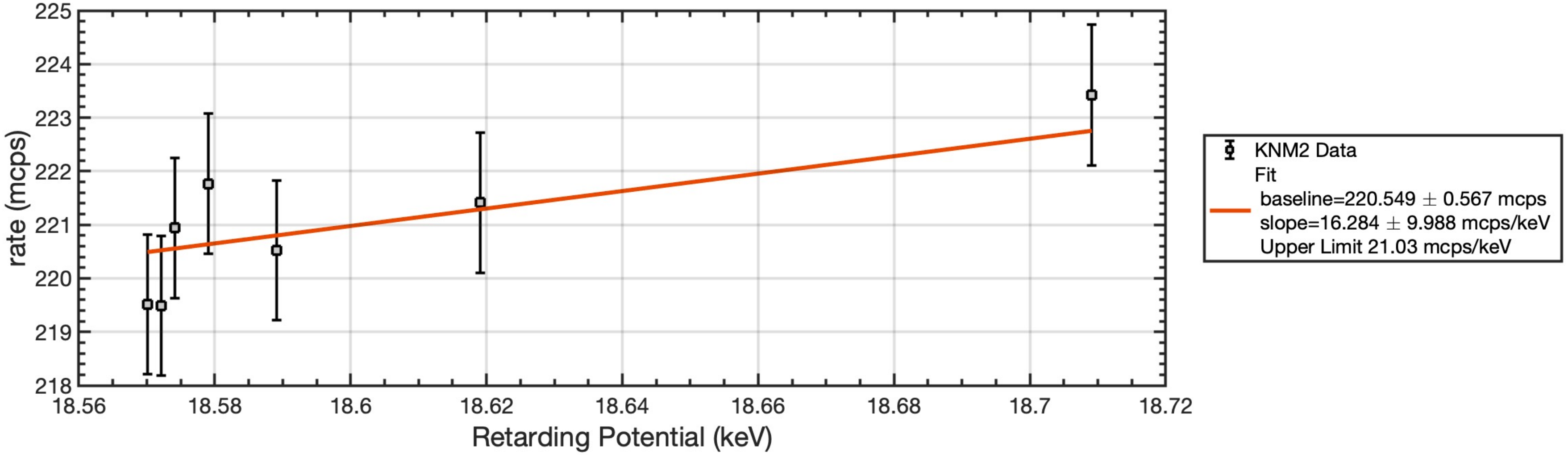


0.220 cps / 117 pixels → Design value = 0.008 cps (x 30)
(a serious challenge for the ultimate sensitivity)

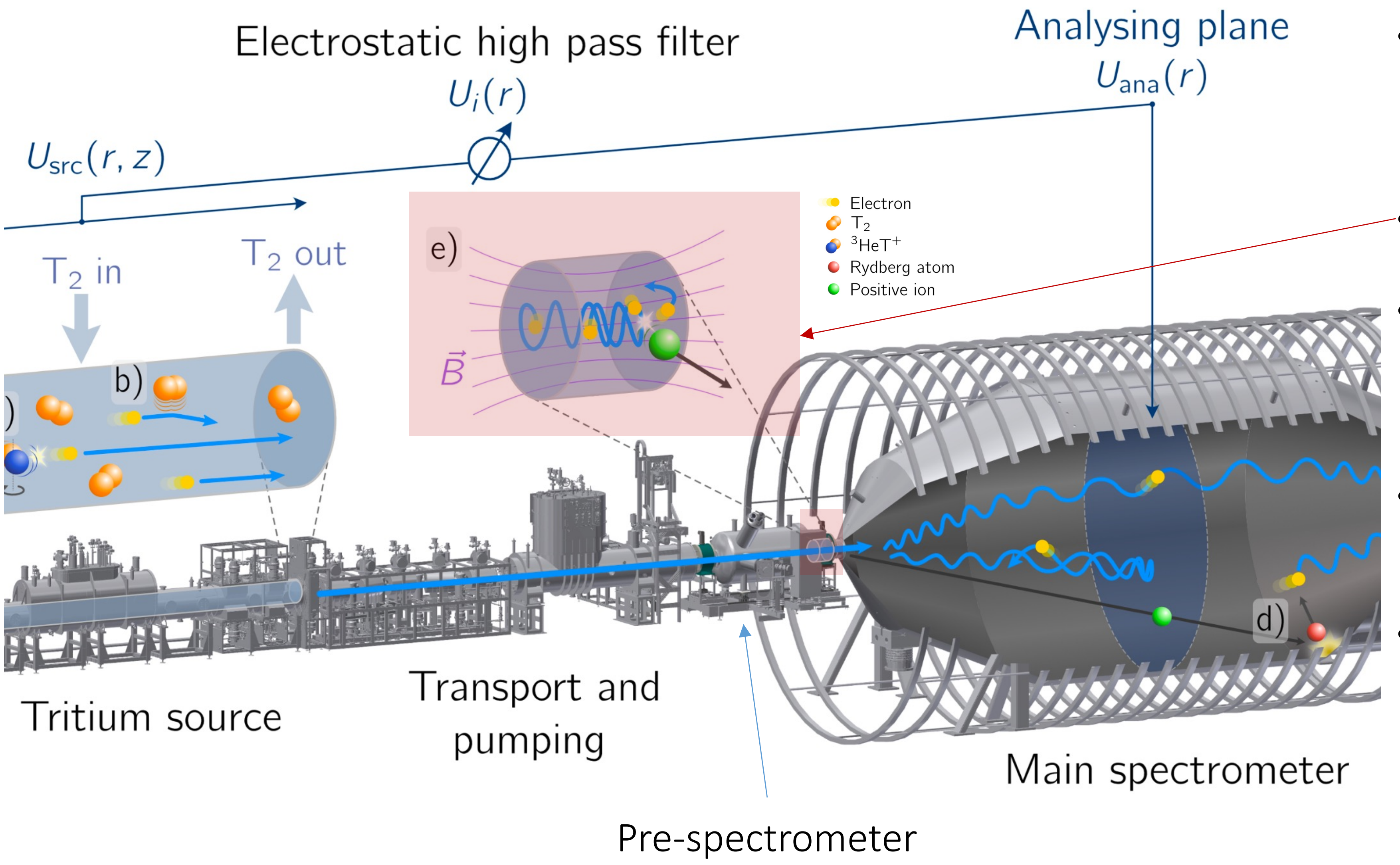
Background qU-dependence 371 scans

- Slight qU-dependence of background can't be excluded
- Assume qU-flat background
- Include possible qU-dependence as systematic error





Penning-trap induced Background

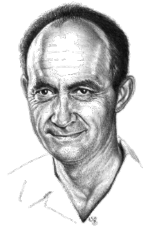


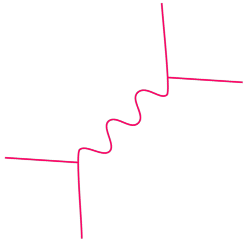
- Both pre- and main spectrometers, operated at high voltage
- create a Penning trap
- Stored electrons create ions$^+$, which can escape the trap into the main spectrometer → background
- Trap emptied with an e$^-$-catcher system after each sub-scan
- Can induce background dependency with sub-scan length

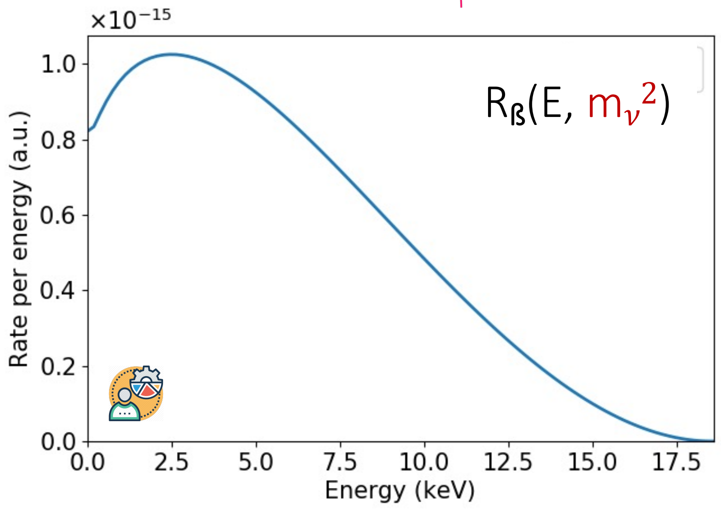
Tritium Signal Modeling

Integral spectrum modeling

tritium β-decay theory



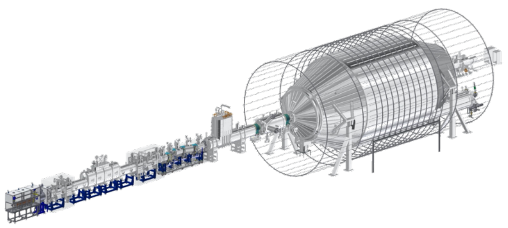


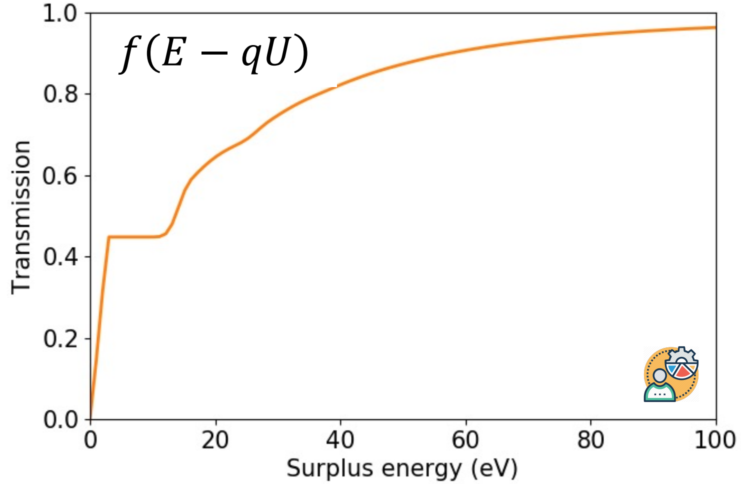


$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C \cdot p_e E_e \cdot \sqrt{(E_e - E_0)^2 - m_{\nu_i}^2} \cdot (E_e - E_0) \cdot F(E_e, Z)$$

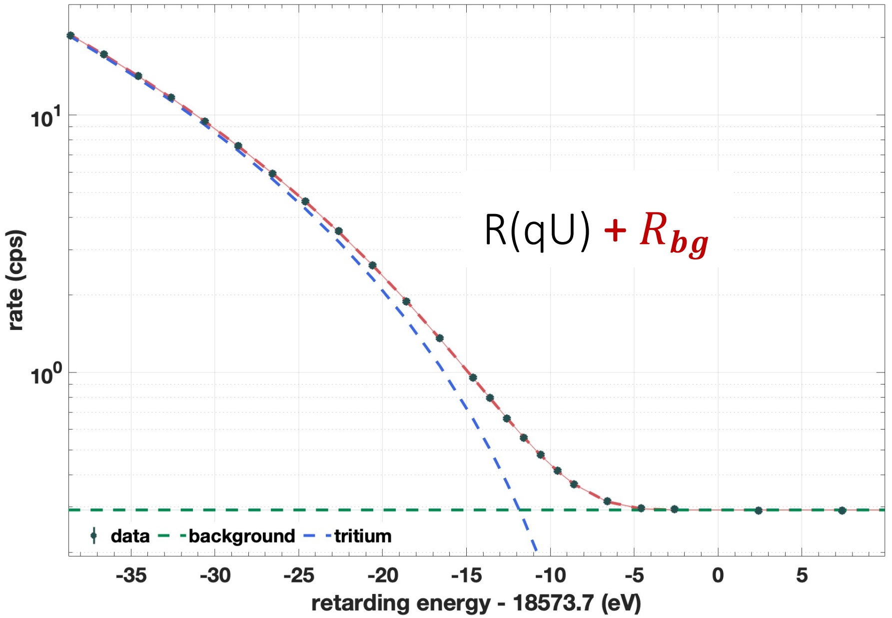
$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_{ß}(E, m_\nu^2) \cdot f(E - qU)\, dE + R_{bg}$$

experimental setup



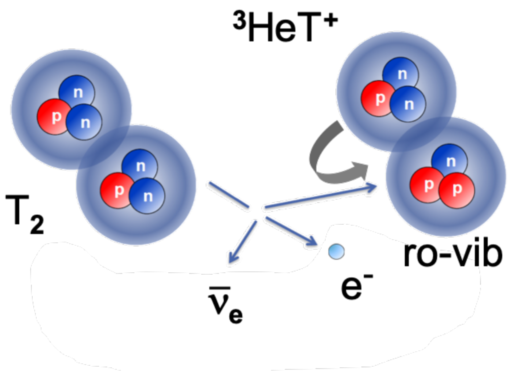


integral β-spectrum



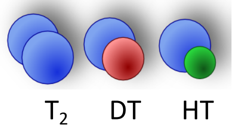
← R_{bg}

Molecular Final States

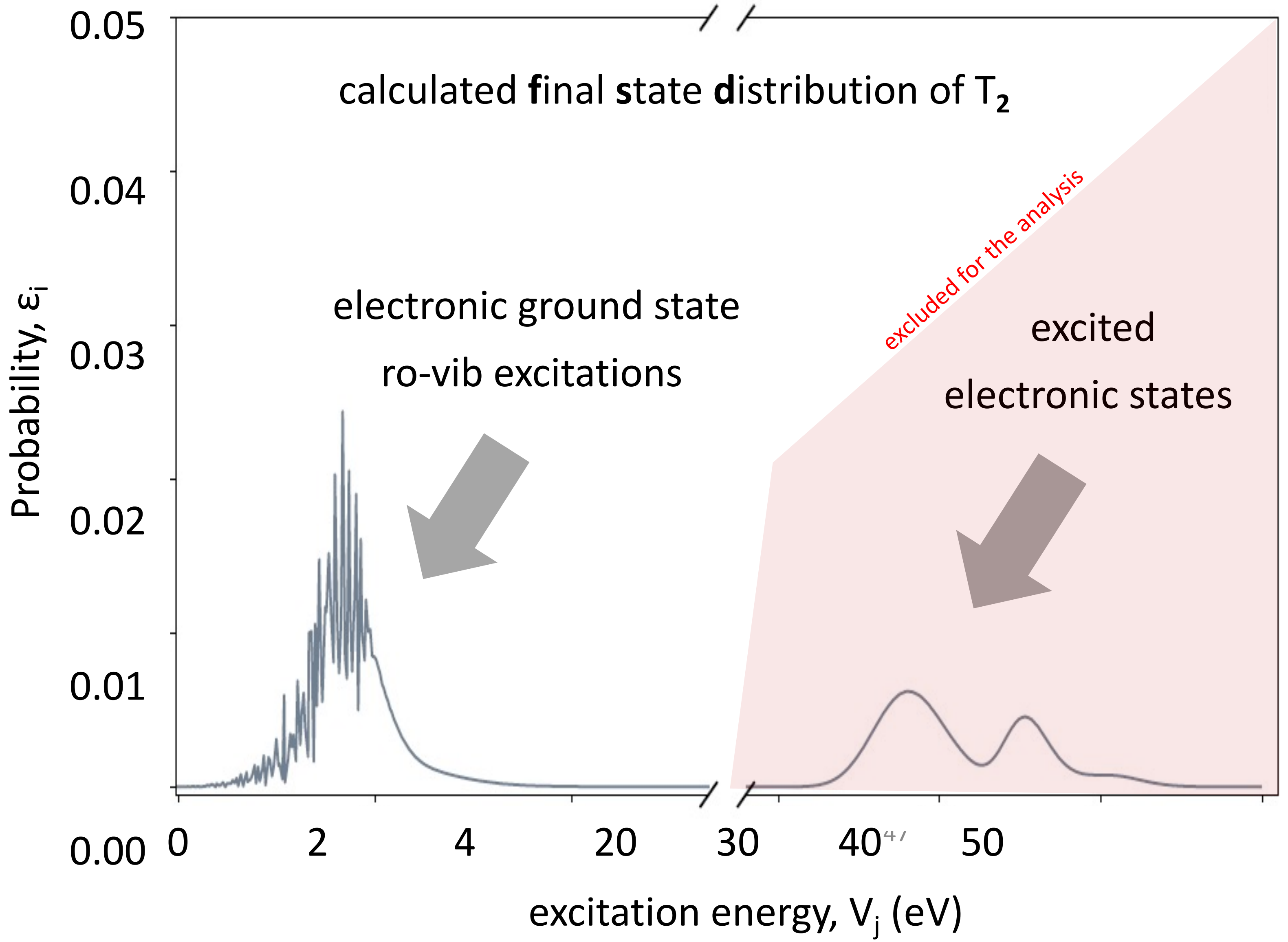


- Modification of the beta decay spectrum shape near the endpoint

- Specific calculation for each isotopolgue



→ Some model dependency in m_ν determination



Tritium Beta Decay calculation

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

fit parameter

fit parameter

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

fit parameter

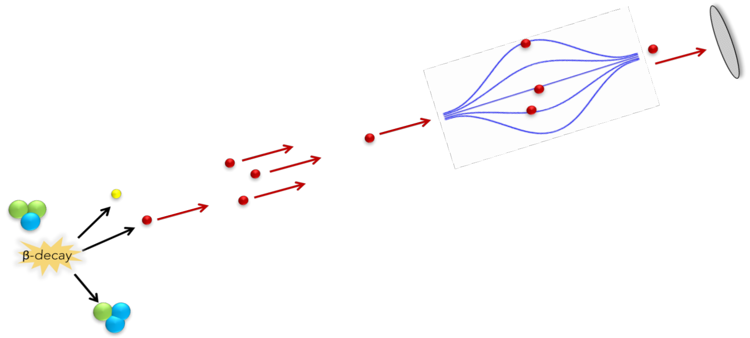
Fermi spectra summed over all rob-vib molecular final states

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

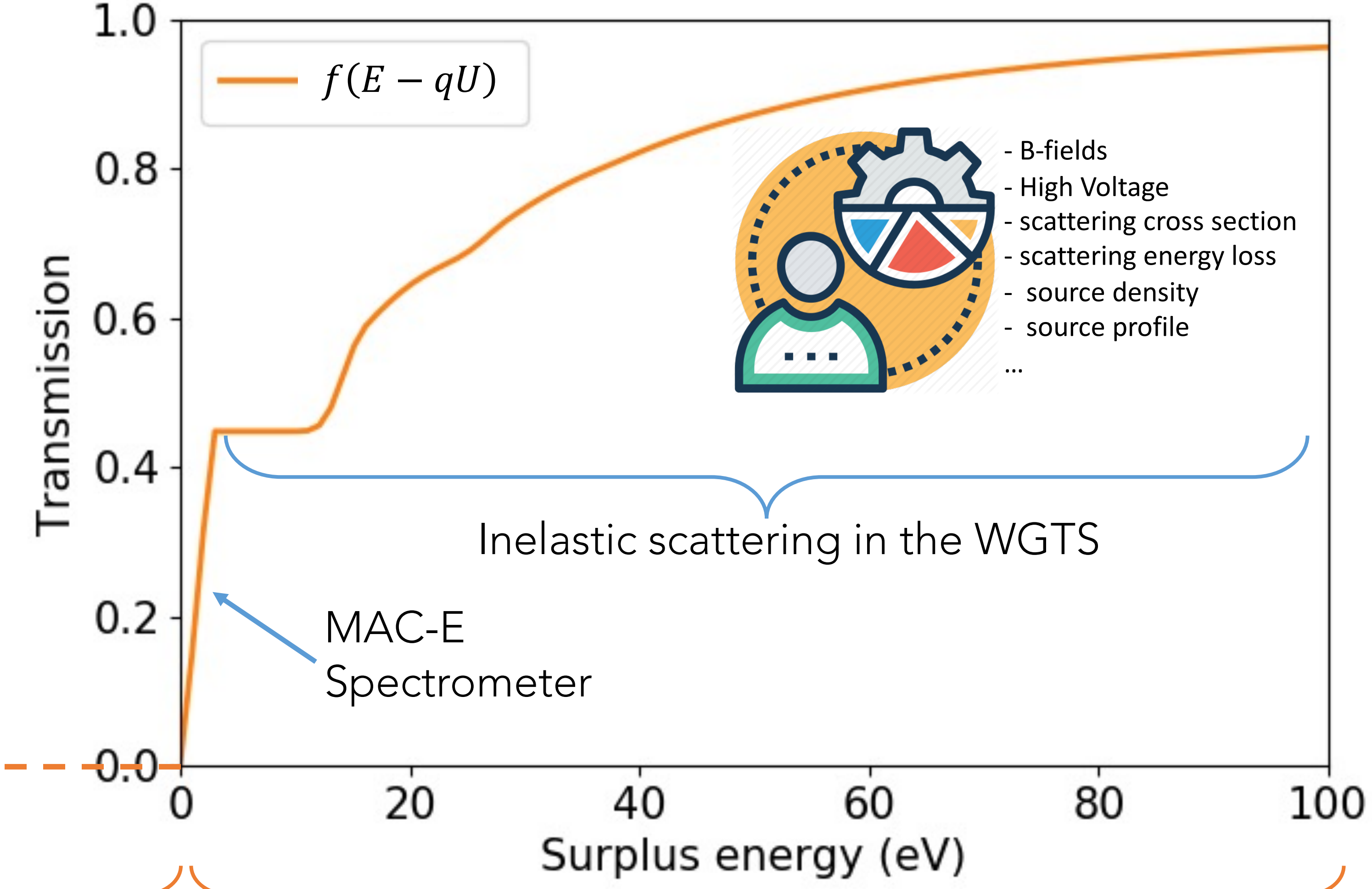
Molecular energy levels

fit parameter

Electron Transmission Model $f_{\mathrm{calc}}(E - \langle qU \rangle)$



1 response for each pixel (117) & beta-scan (361)



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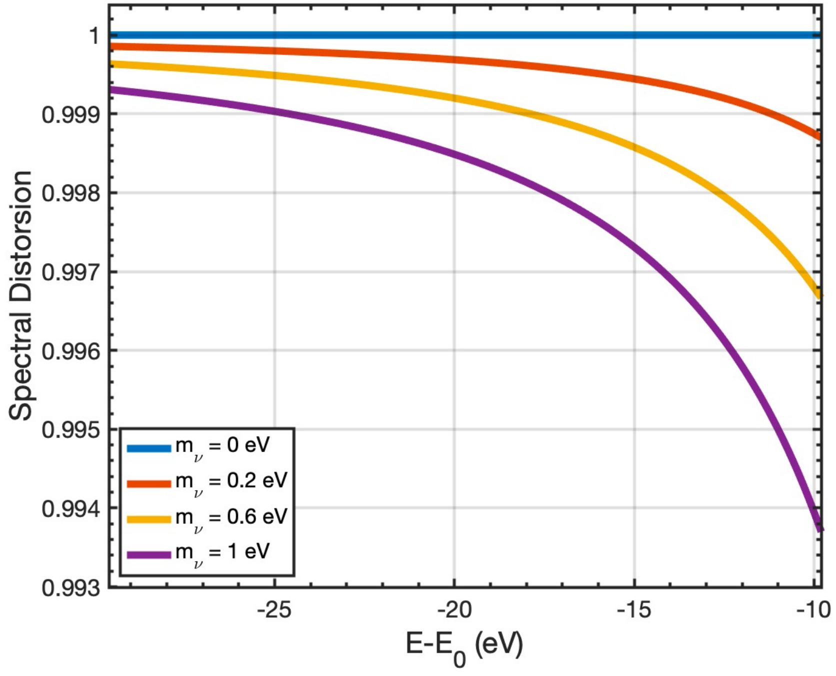
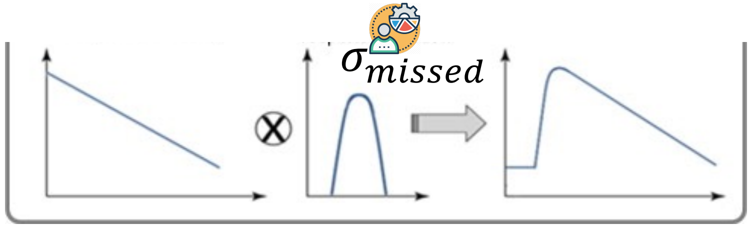
Impact of any mis-modeling?

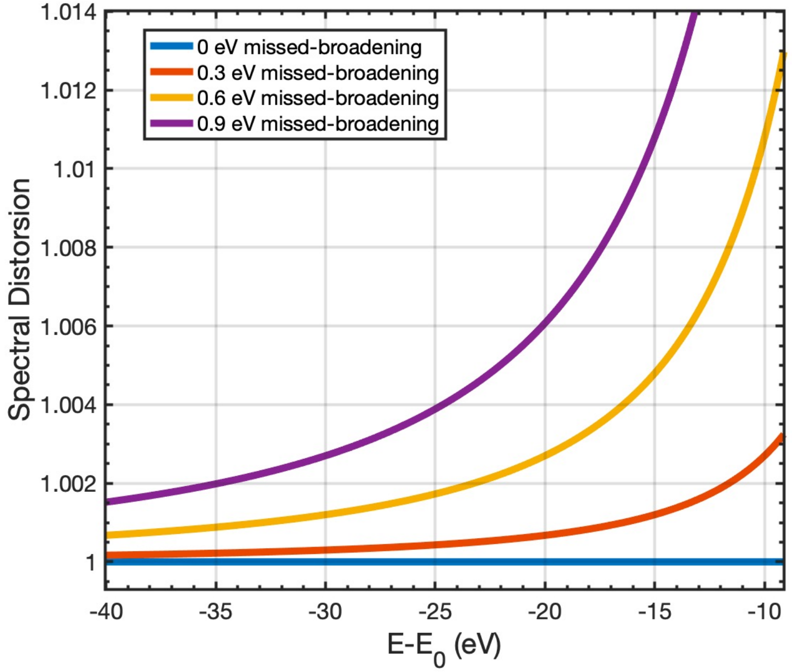
Expected neutrino mass signature
(lower counts near endpoint)



Missed systematics:
spectrum convoluted with gaussian



Increase counts near the endpoint

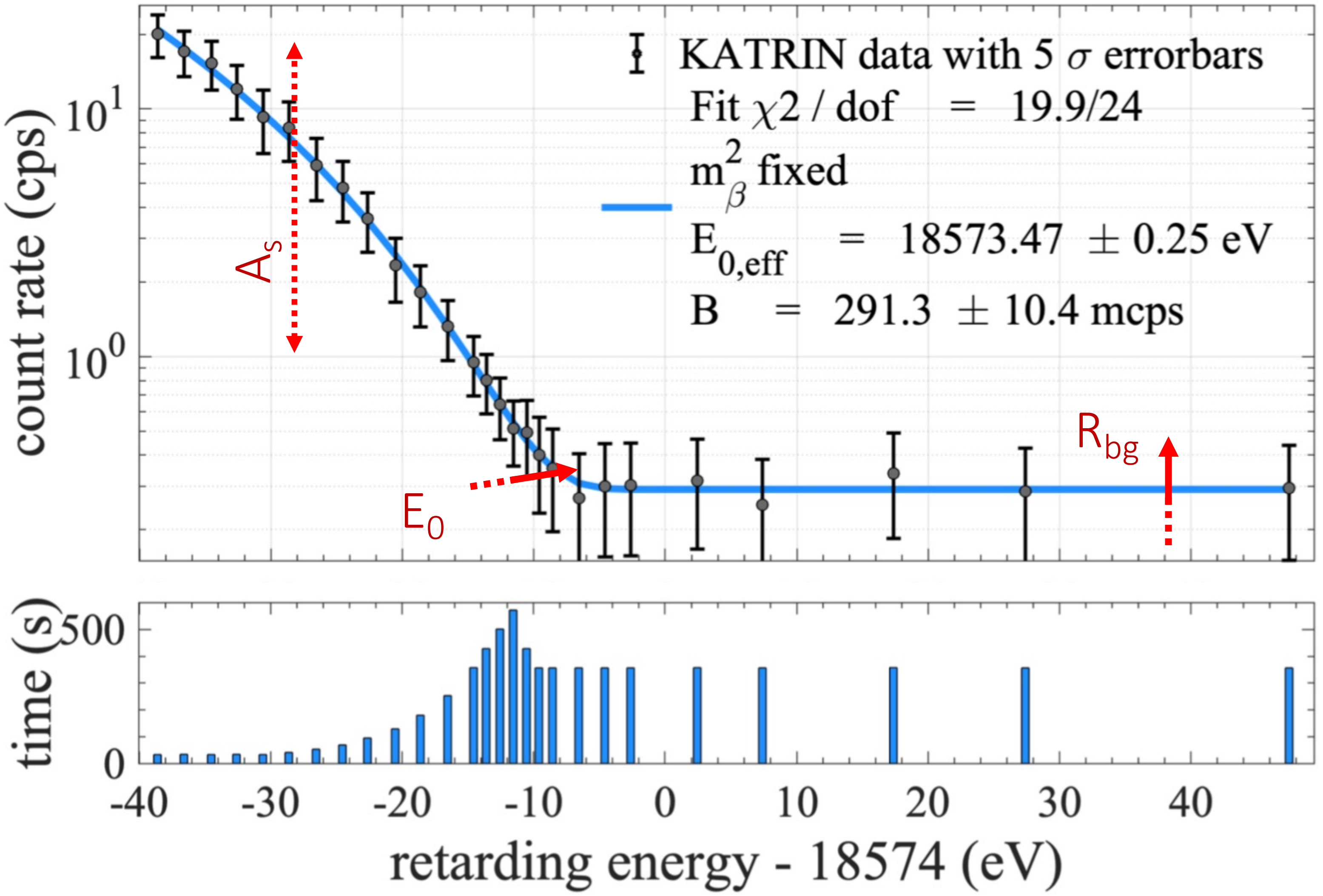


Mimick a 'negative' m_ν^2

Thierry Lasserre

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

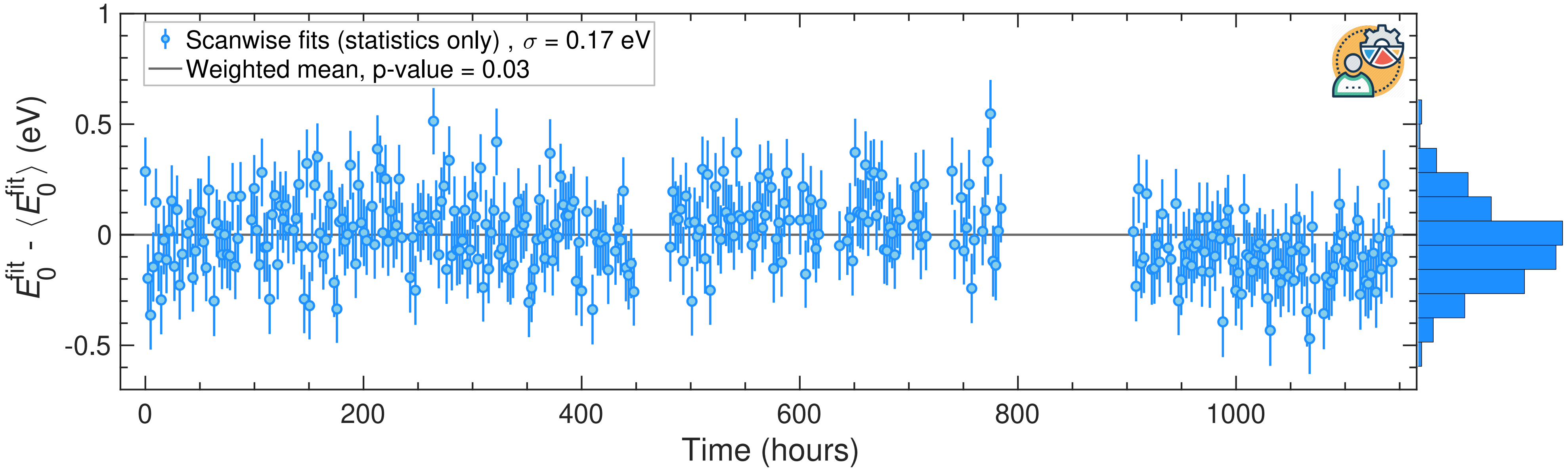
Fit of a single 2-h beta-scan



- A single 2h β-scan
- m_ν fixed to 0
- 3 parameter fit
  - Tritium Activity, A_s
  - Endpoint, E_0
  - Background, R_{bg}
- High level reproducibility

Endpoint Stability over 361 scans

- All detector pixels combined
- Stability of fitted endpoint in time divided in three periods

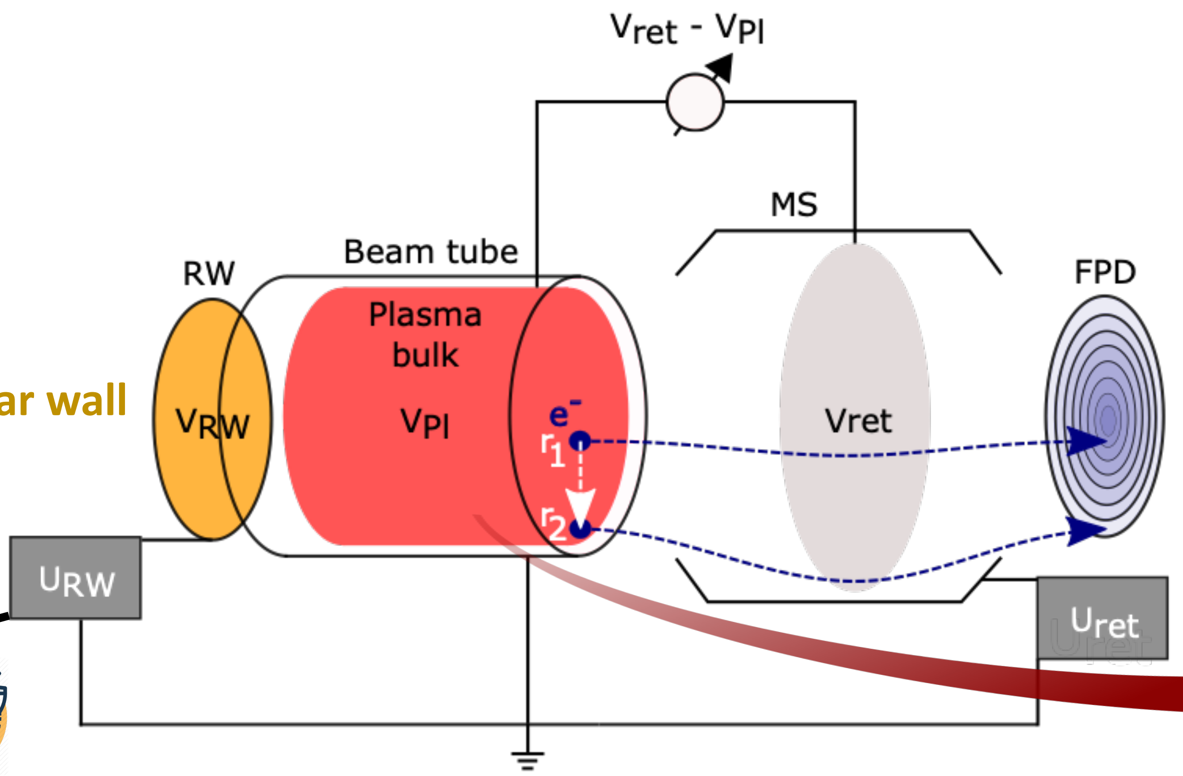


	Rear wall 1 (171 runs)	Rear wall 2 (97 runs)	Rear wall 3 (93 runs)	Average (361 runs)
$\langle E_0 \rangle$ (eV)	18573.68	18573.75	18573.58	18573.67
σ (eV)	0.17	0.15	0.14	0.17

Source Electrical Potential

- Filtering energy = $qU_{spectrometer}$ (V_{ret}) – **qU_{source}** (V_{pi}) → both have to be under control
- Gold-plated rear wall provides the reference potential, qU_{source}
- Absolute **qU_{source}** does not affect the spectral shape of the measured spectrum
- **qU_{source}** shift is absorbed by the effective endpoint (free fit parameter)

Gold-plated rear wall



Low density radioactive magnetized plasma at 30K

1 original setting & 2 resetting during the 2nd campaign included in analysis

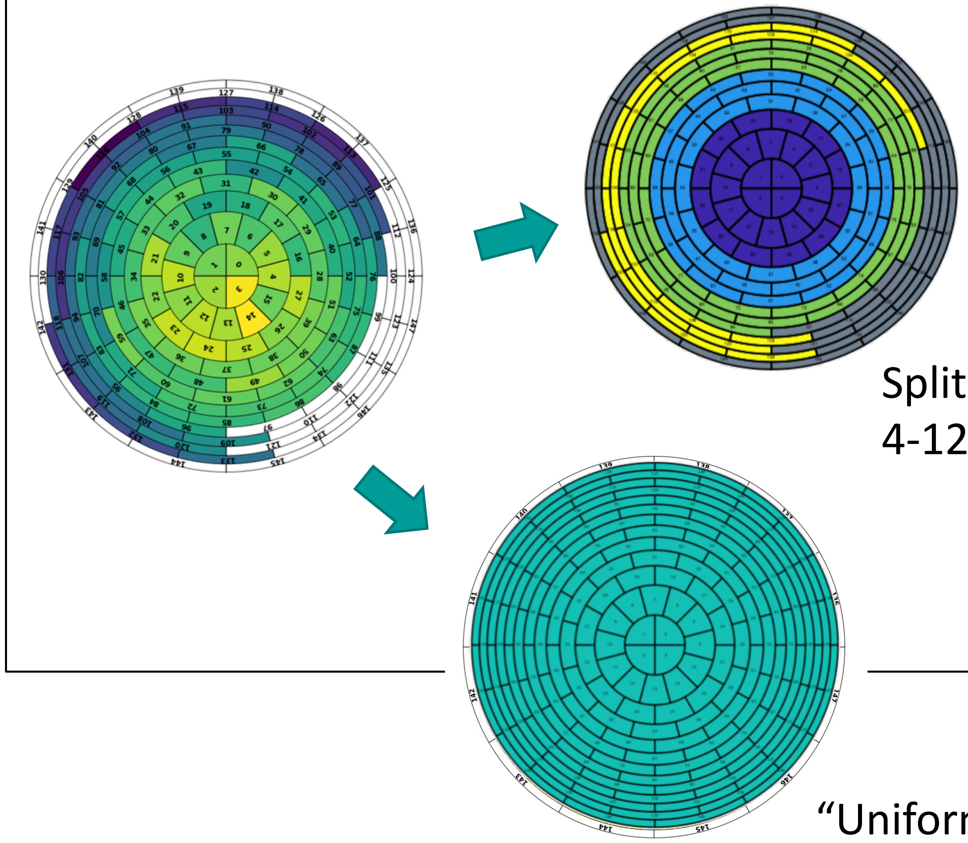
Combination of
361 Scans + 117 Pixels

Data combination

Pixel combination

- Counts in pixels of one FPD ring are added

➢ 1 or 4-12 spectra for each scan

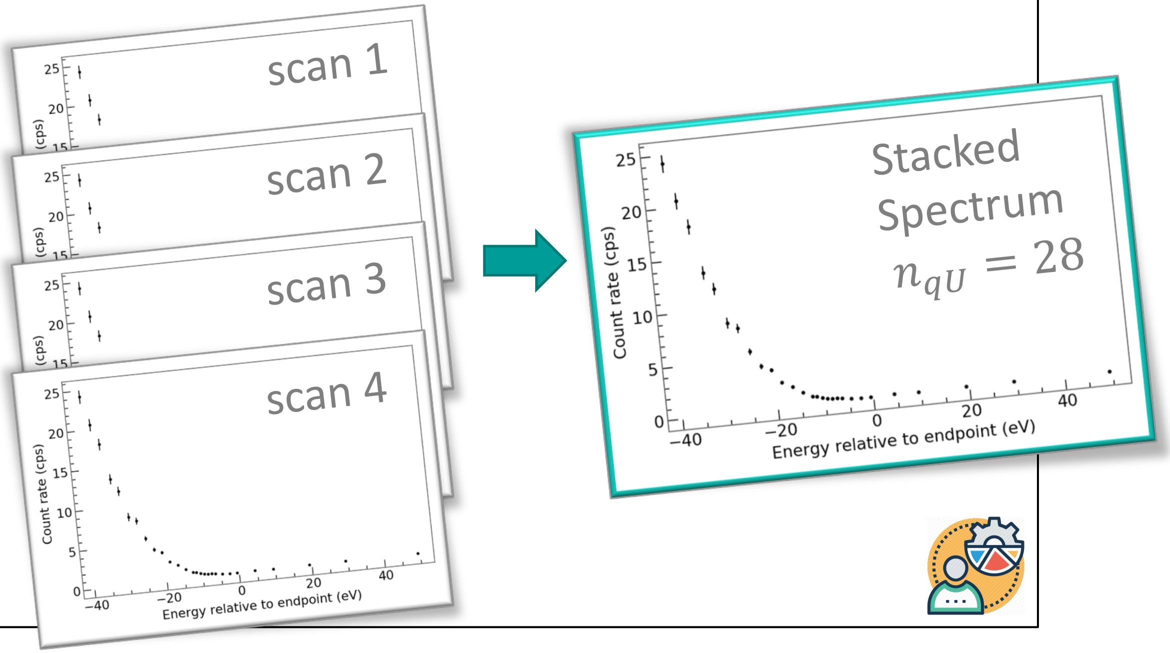


Split into 4-12 rings

Scan combination

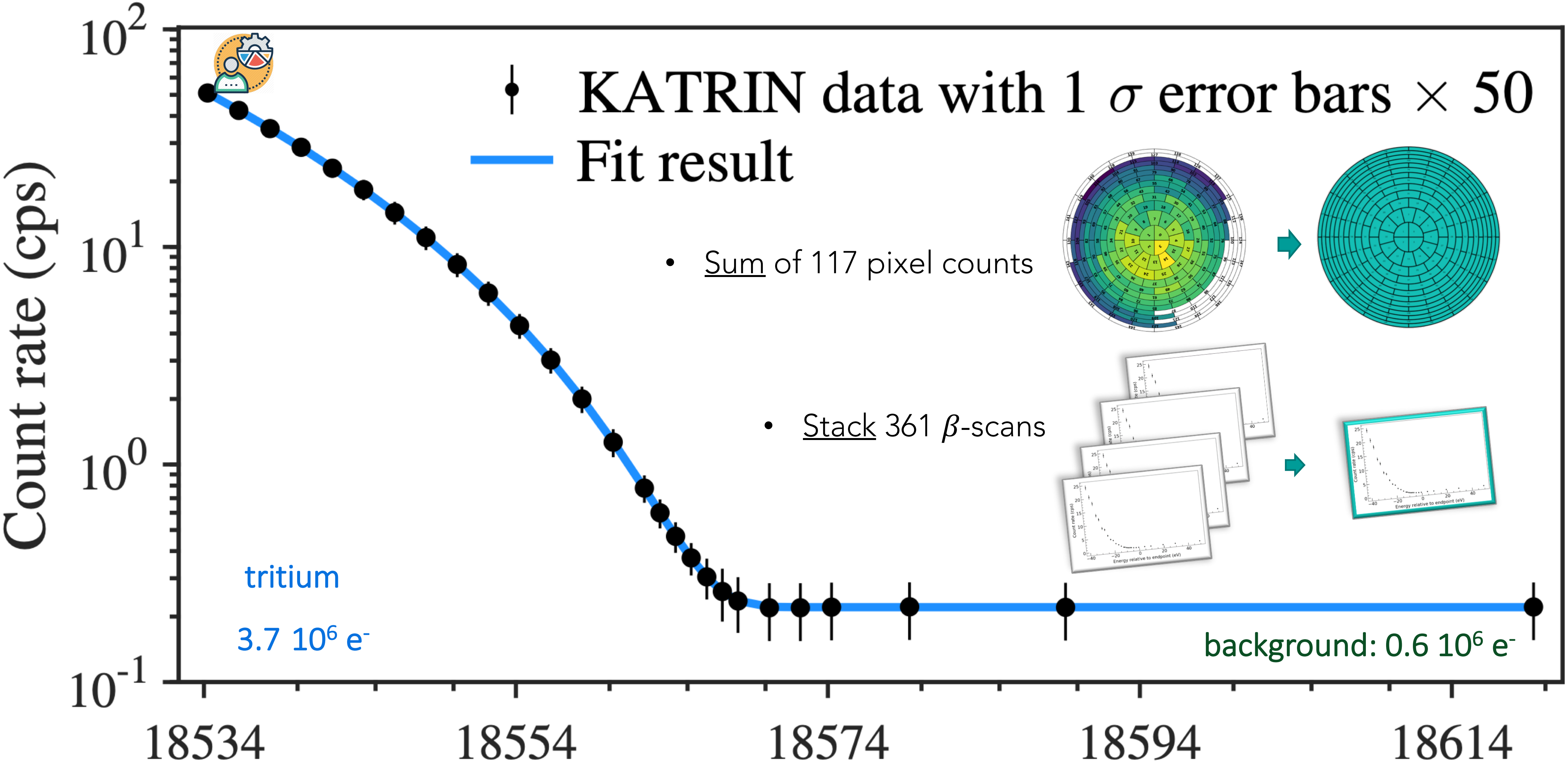
- Counts at the same U_{ret} are added (stacking)

➢ 1 single spectrum from all scans



"Uniform" or Full-stack – all pixels gathered into a super-pixel

Full Stack: combination of 42237 spectra



- Sum of 117 pixel counts
- Stack 361 β-scans

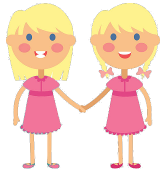
Inferring the Neutrino Mass

Bias-free analysis

Freeze analysis on fake data
- Generate MC-copy of each scan

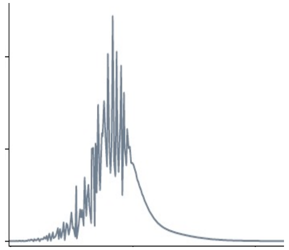
m_ν^2 true data

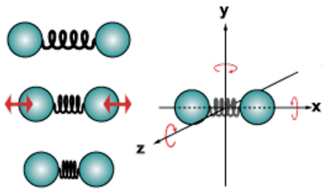
m_ν^2 MC copy



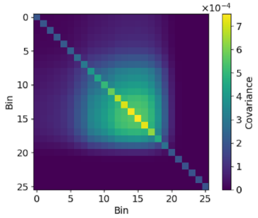
m_ν^2

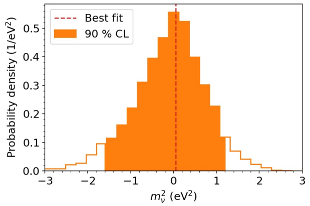
Blinded model
- Modified molecular final state dist.





Independent analysis strategies
- Cov. matrix, MC prop, Pull-terms, Bayes

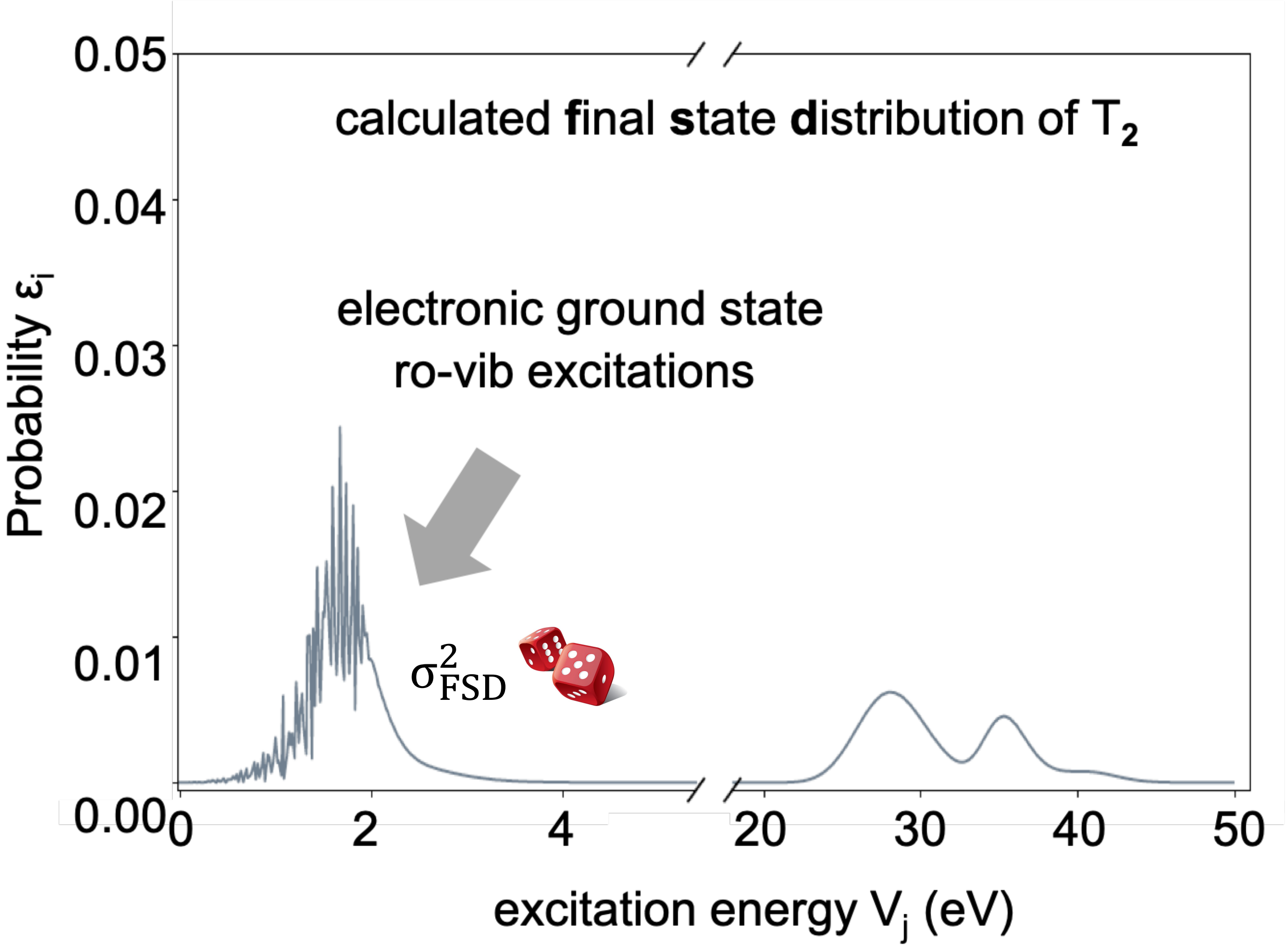




This talk

Blinded Model

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



- Modified FSD distribution used before unblinding
- $\sigma^2_{FSD} \rightarrow \sigma^2_{FSD} + \delta\sigma^2_{FS}$

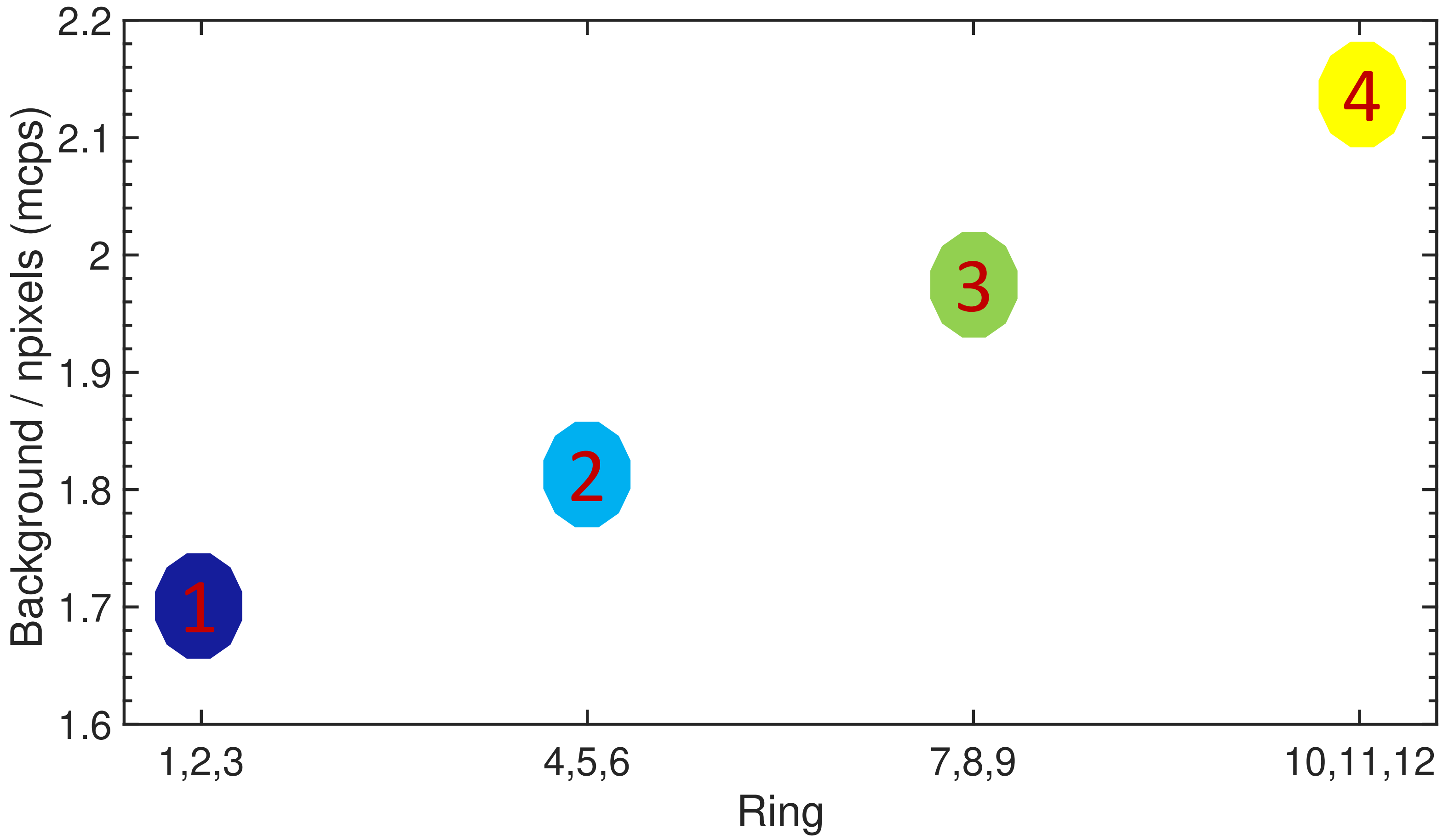
- Hides the fitted neutrino mass only
- Don't affect endpoint value

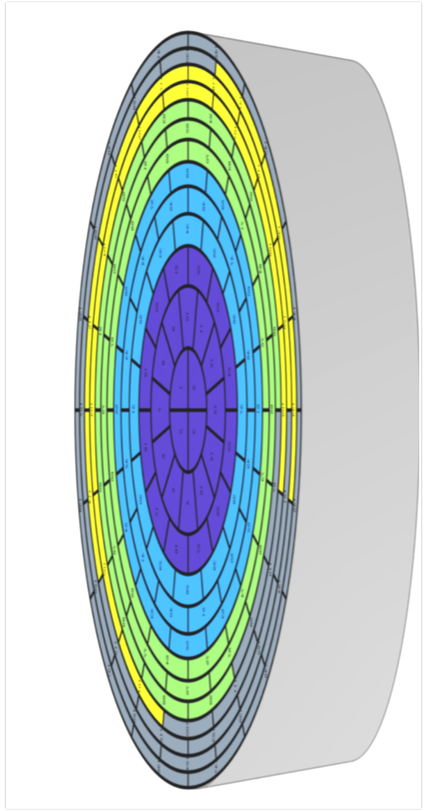
Saclay-MPP’s analysis

Accounting for radial Bkg / qU_{source} dependence

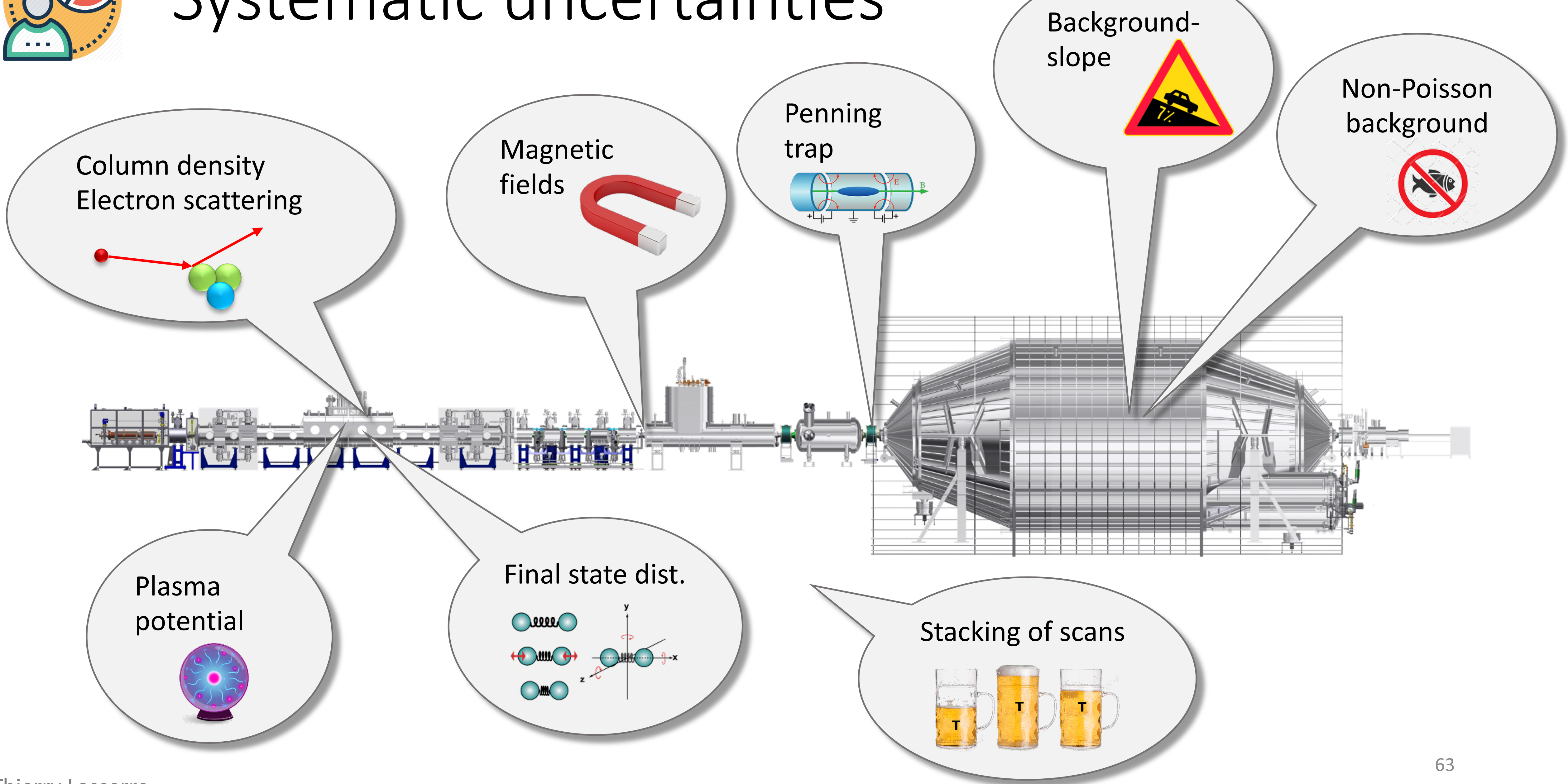
- Background rate is radial dependent
- Radial variation of the source electric potential

} Absorbed by the ring-wise analysis

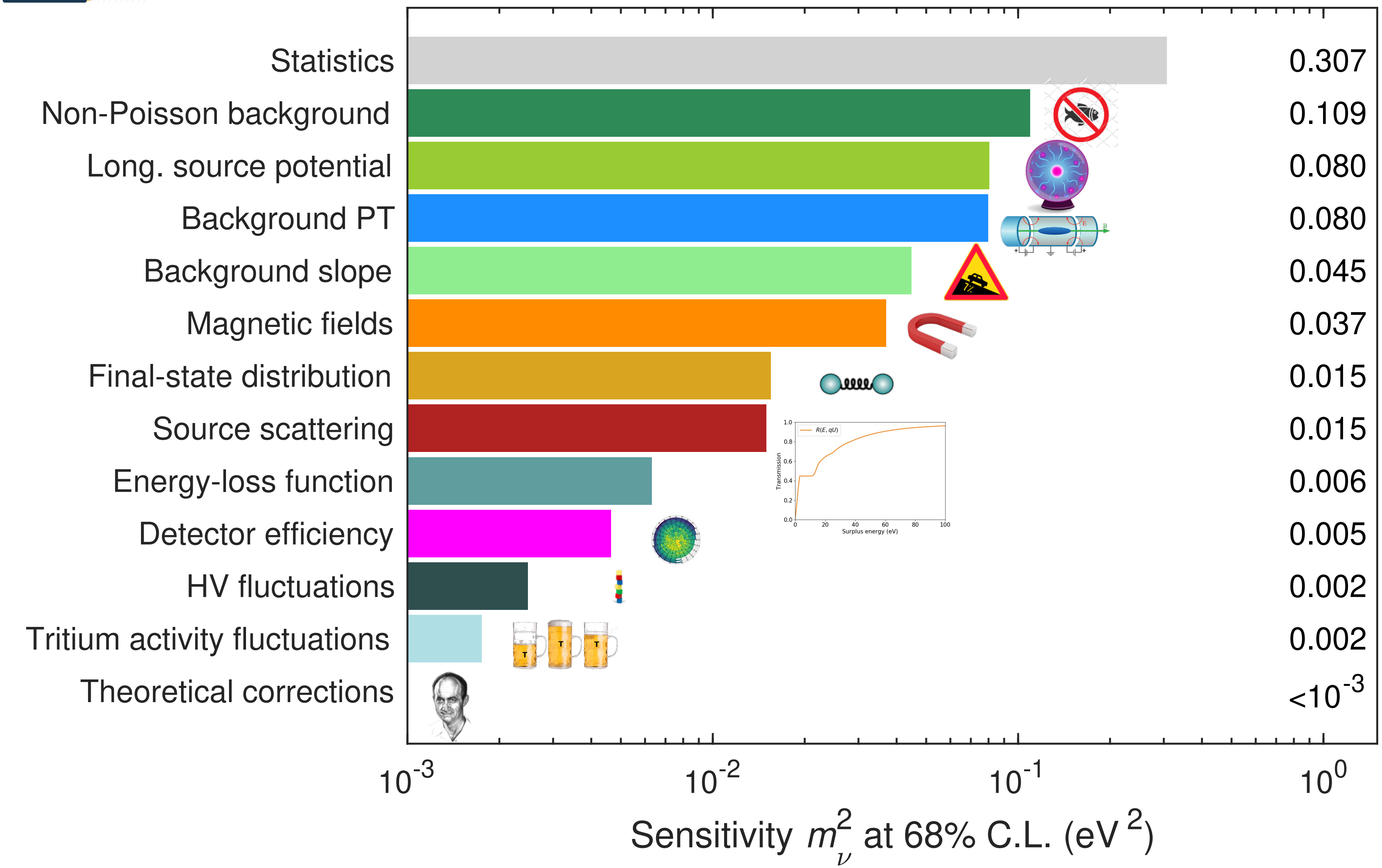




Systematic uncertainties



Budget of uncertainties (MC, 4 rings)

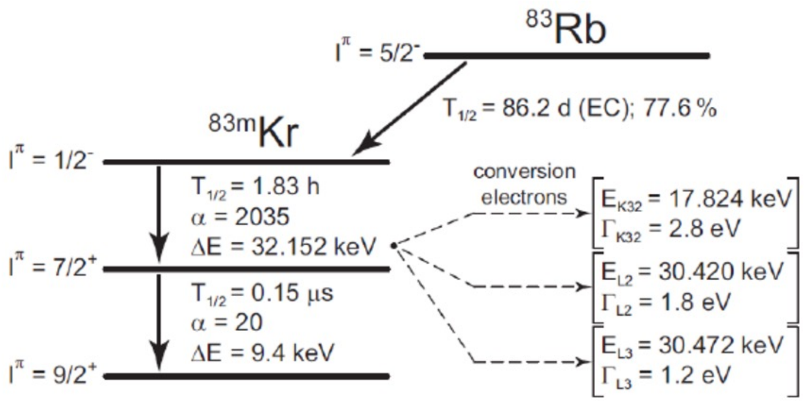


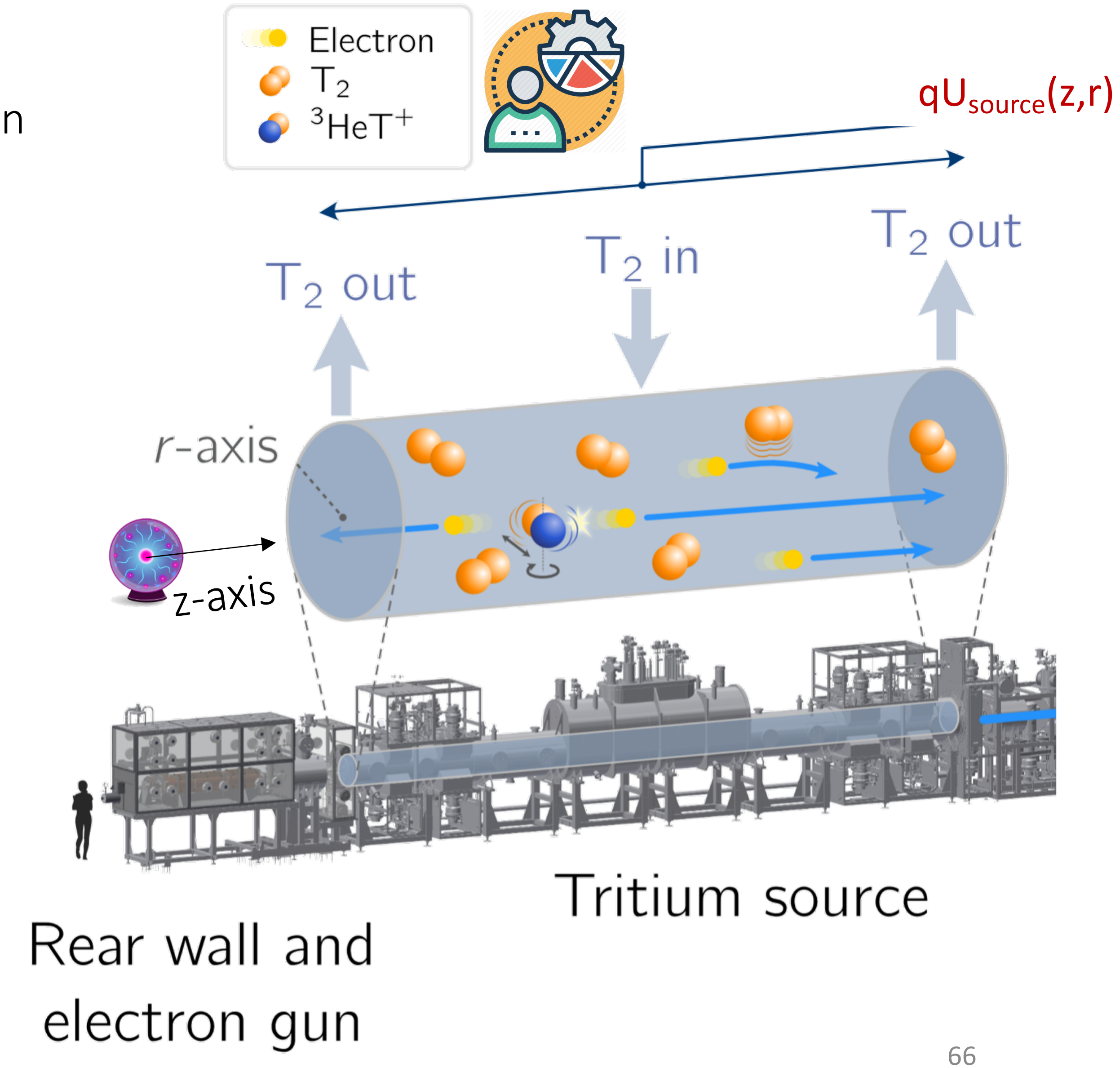
→ Statistics dominated

Plasma Systematics

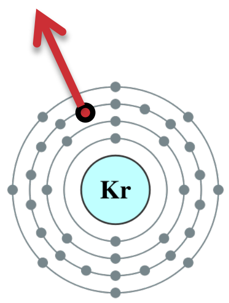
Plasma induced qU_{source} Broadening

- Longitudinal (z) variations of the source potential can lead to spectral distortions
- Parameterised by a Gaussian broadening σ_P
- Assessed with the help of co-circulating ^{83m}Kr gas in the source
- Mono-energetic conversion electron lines



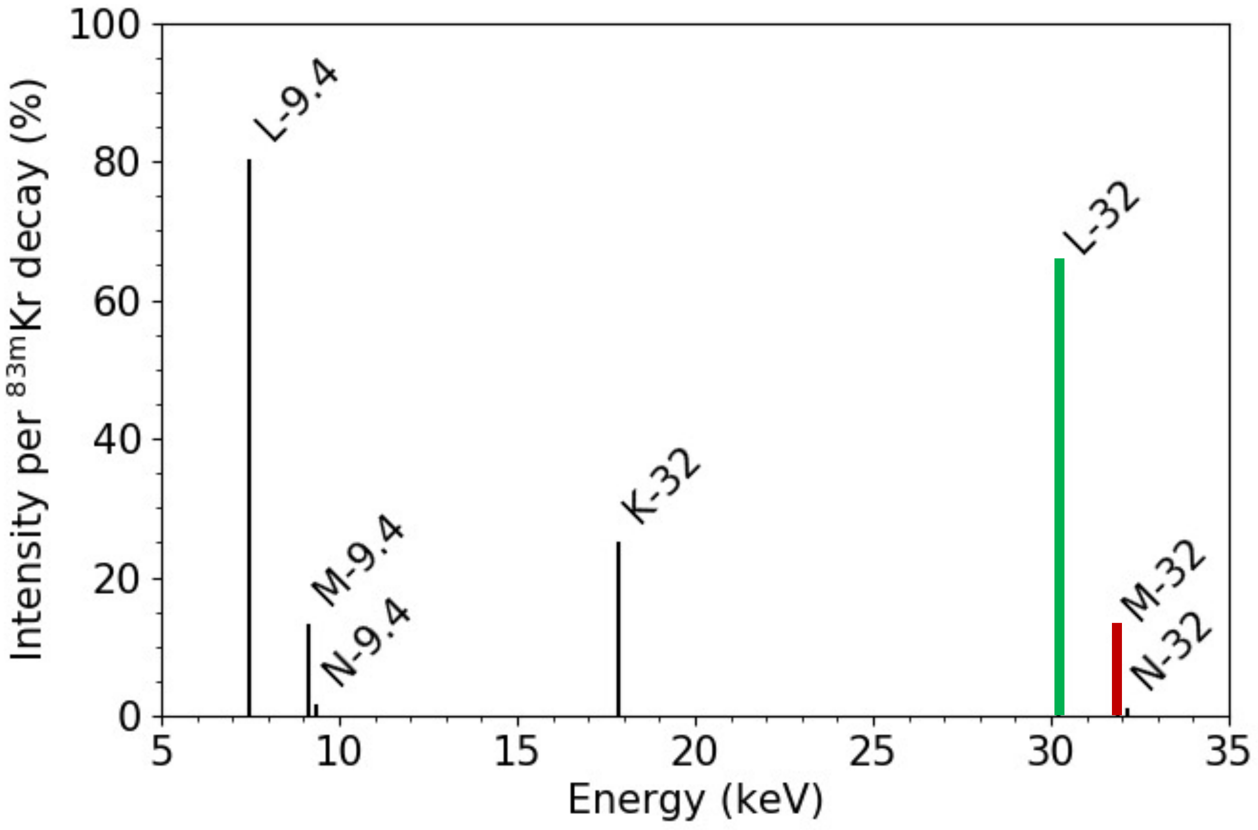


Krypton Signal: monoenergetic electrons

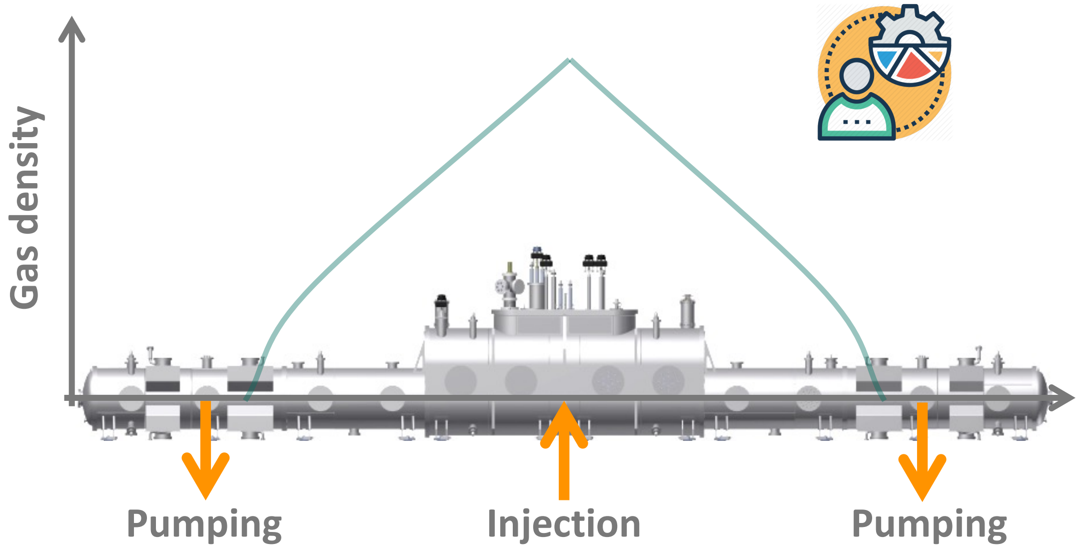


- L-32-line
  - High intensity
  - Natural line width is not known precisely

- N-32-lines (doublet)
  - Low intensity
  - Natural line width is negligible compared to σ_P

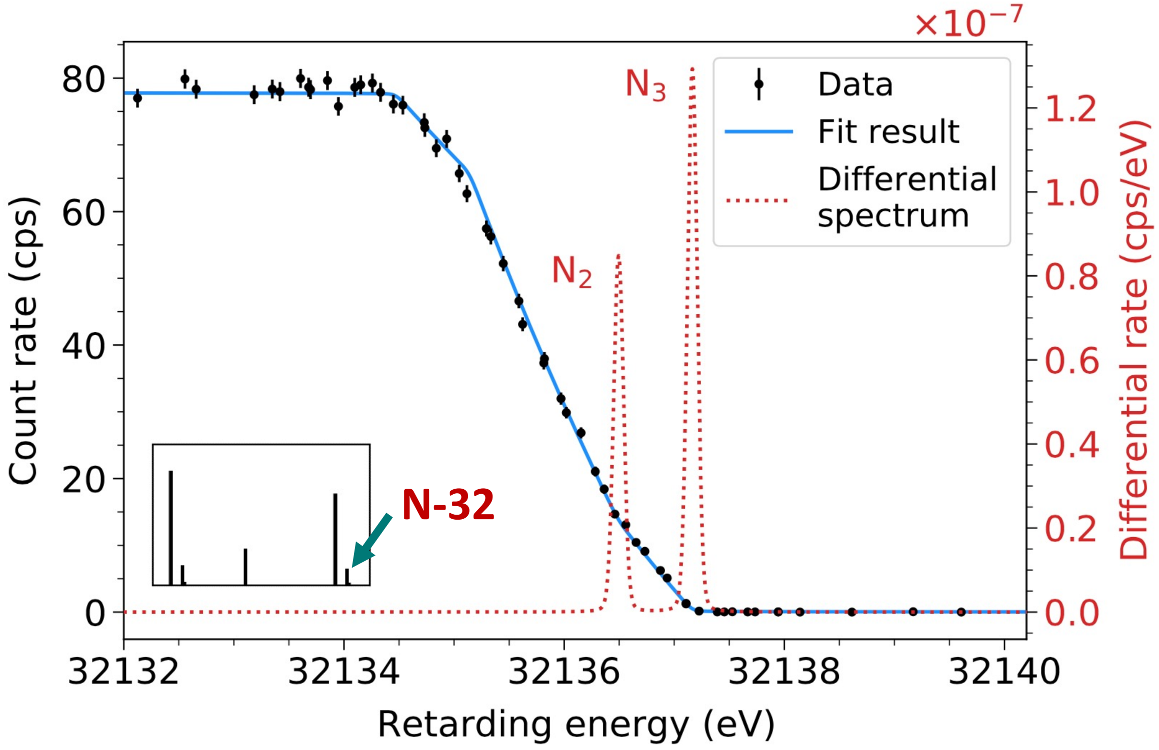


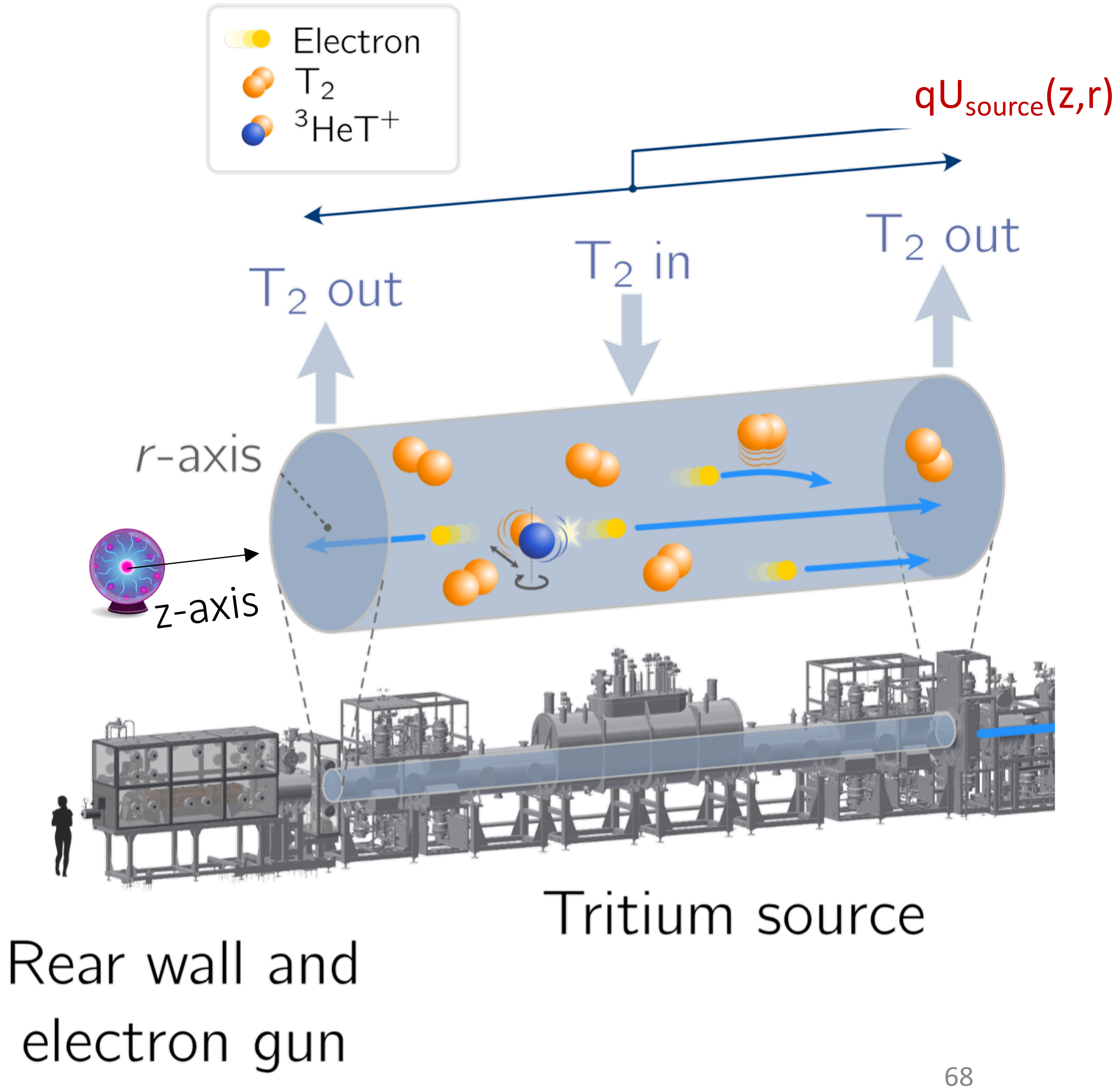
Co-circulation of tritium and ^{83m}Kr at 80 K @ 40% density



Plasma induced qU_{source} Broadening

- Fit of the N-23 doublet model → σ_P





- No significant qU_{source} broadening σ_P
- σ_P value limited by source activity & extrapolation to real tritium scan parameters

Neutrino Mass Spectral Fit

Spectral Fit Method (Saclay-MPP)

- Standard chi-square minimization

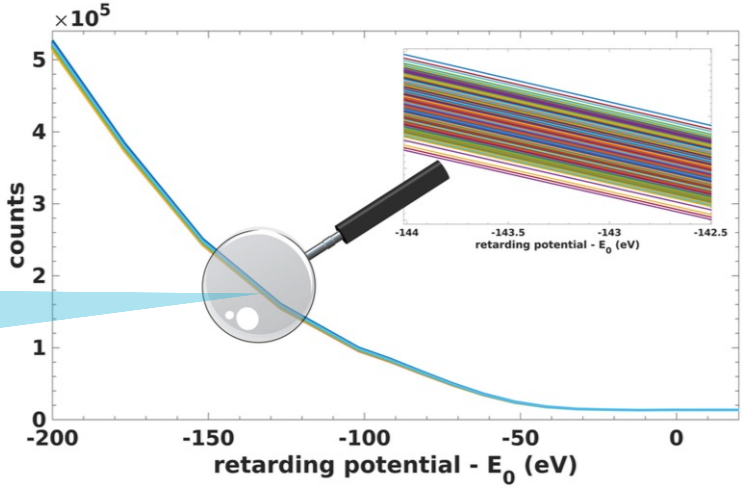
$$\chi^2 = \left(\vec{R}_{\rm data}(q\vec{U},\vec{r}) - \vec{R}(q\vec{U},\vec{r}|\vec{\Theta},\vec{\eta})\right)^T C^{-1} \left(\vec{R}_{\rm data}(q\vec{U},\vec{r}) - \vec{R}(q\vec{U},\vec{r}|\vec{\Theta},\vec{\eta})\right)$$

$\mathrm{m}_\nu^2, \mathrm{E}_0, \mathrm{B}, \mathrm{A}$

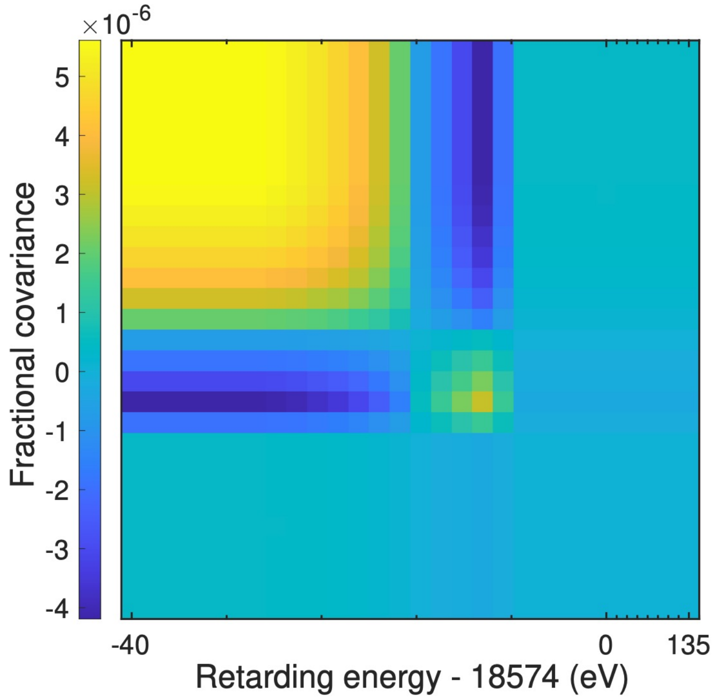
B-fields, ρd, plasma, etc.

- 13 free parameters: m_ν^2 + 4 rings x (E_0, B, A)

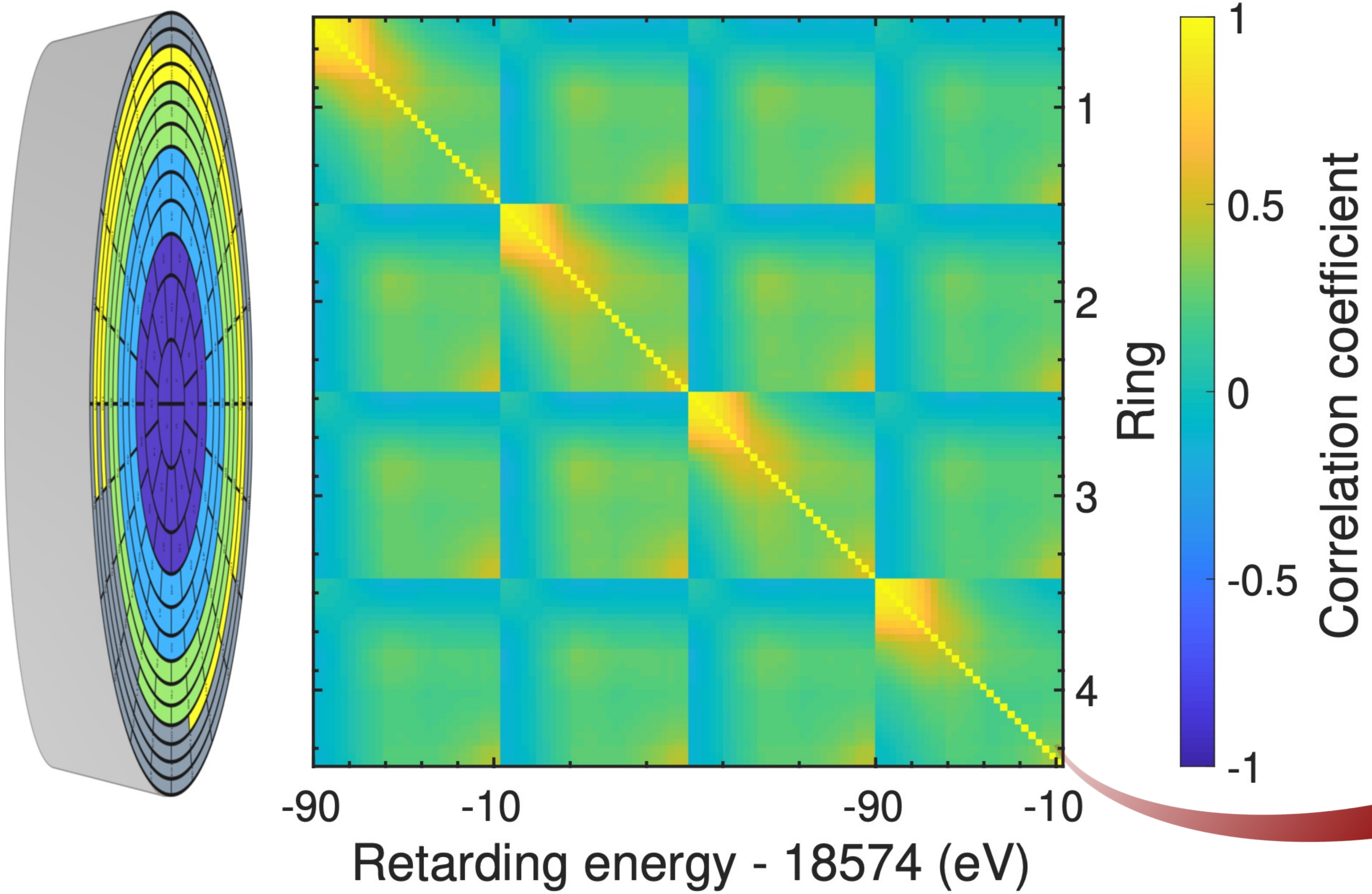
- Uncertainty propagation with covariance matrices



Compute 10^4 spectra with different systematic configurations

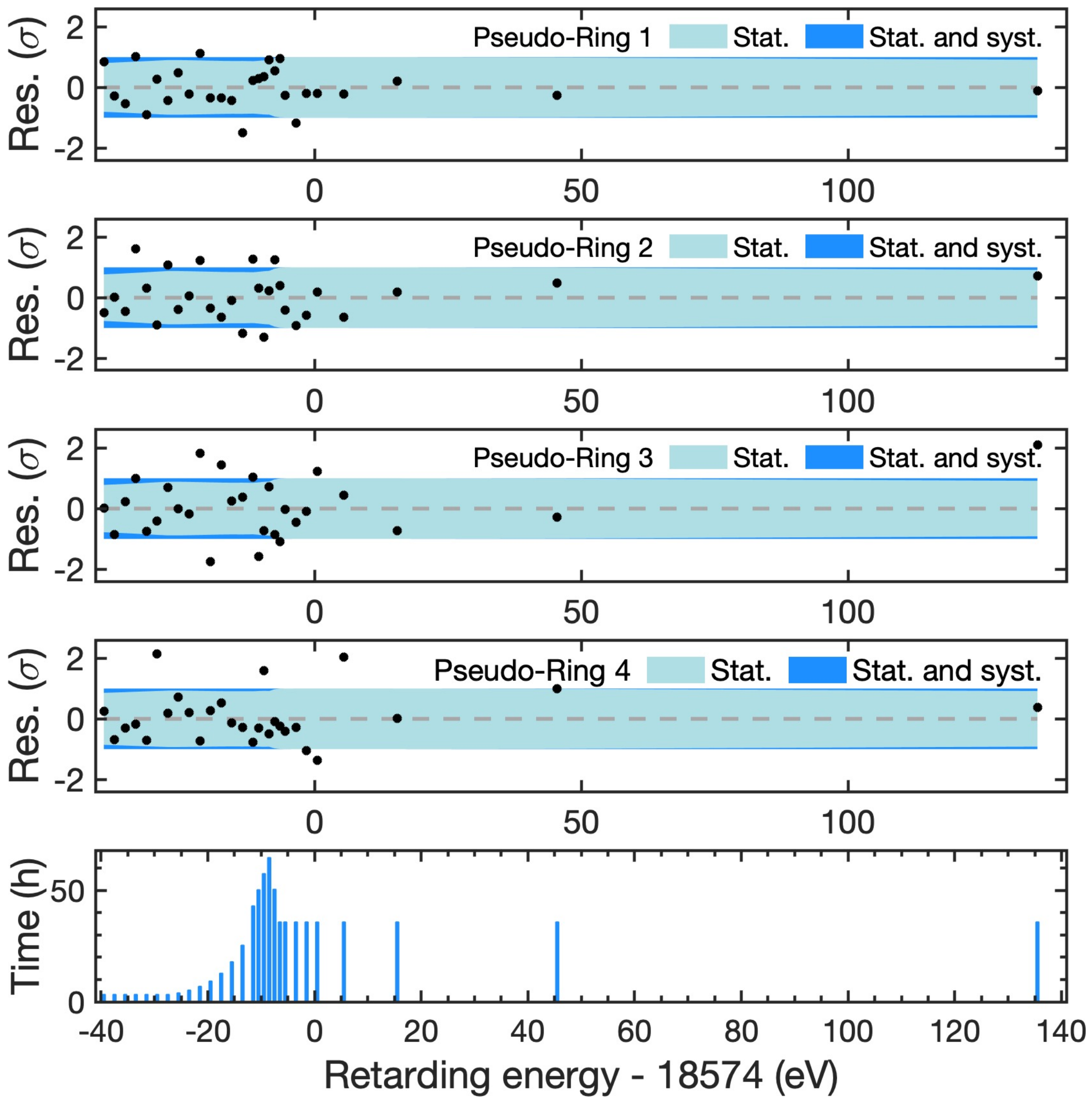


Spectral Fit Method (Saclay-MPP)



- Covariance matrices, response functions, etc. calculated once
- Final fit can be performed on a laptop (MATLAB)
- 15 kWh
- Eq. to a 50 km drive (500g CO_2 / kWh)

Data: Split pixels in 4 rings - MultiRing-fit



- Stack pixel-wise spectra into 4 pseudo-rings + all 361 scans

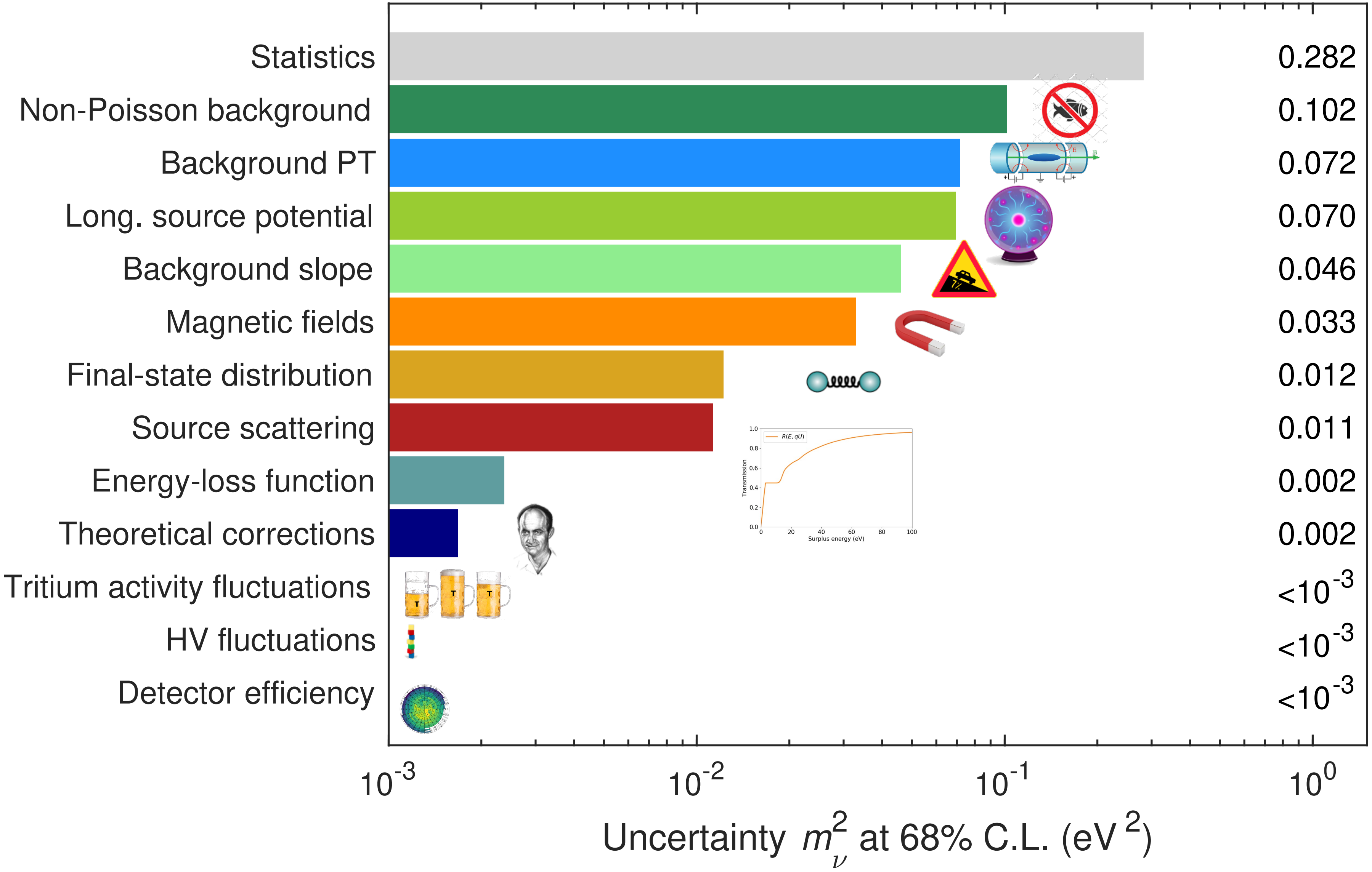
Stat. only

- $m_\nu^2 = 0.29 \pm 0.28\ (^{+0.28}_{-0.28})\ \mathrm{eV}^2$
- $E_0^{\mathrm{fit}} = 18573.74\ \pm 0.03\ \mathrm{eV}$
- $\chi^2_{\mathrm{min}} = 96.6\ (99\ \mathrm{dof})\ \ , p = 0.55$

Total

- $m_\nu^2 = 0.26 \pm 0.32\ (^{+0.32}_{-0.32})\ \mathrm{eV}^2$
- $E_0^{\mathrm{fit}} = 18573.74\ \pm 0.03\ \mathrm{eV}$
- $\chi^2_{\mathrm{min}} = 87.3\ (99\ \mathrm{dof})\ \ , p = 0.80$

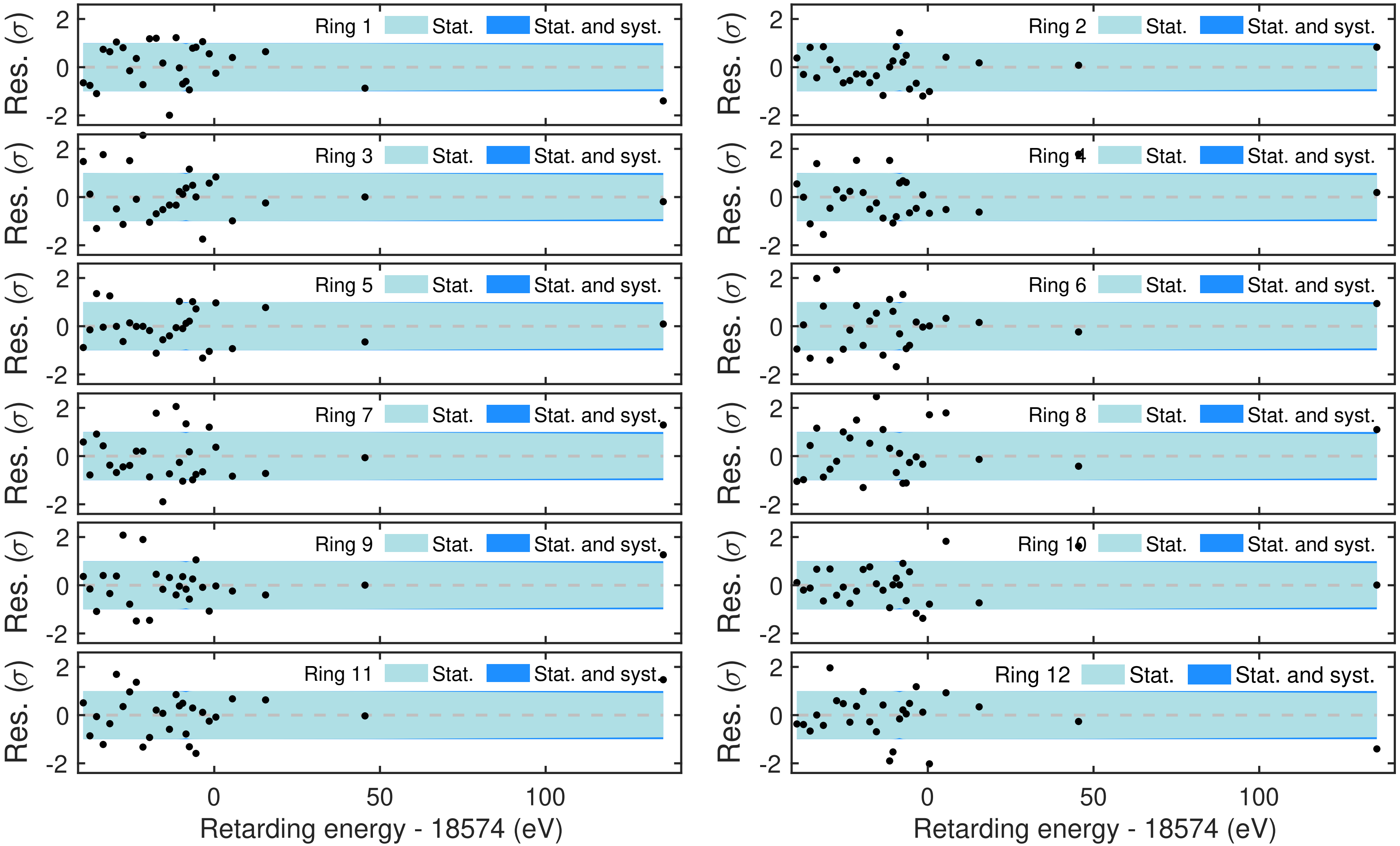
Budget of uncertainties (Data, 4 rings)



1σ m_ν^2
(68.3% C.L.)

stat	0.28 eV^2
sys	0.15 eV^2
total	0.32 eV^2

Data: Split pixels in 12 rings - MultiRing-fit



- Stack pixel-wise spectra into 12 rings

Stat. only

- $m_\nu^2 = 0.28 \pm 0.28$ $(^{+0.28}_{-0.28})$ eV^2
- $\chi^2_{\min} = 310.1$ (299 dof) , $p = 0.32$

Total

- $m_\nu^2 = 0.26 \pm 0.32$ $(^{+0.32}_{-0.32})$ eV^2
- $\chi^2_{\min} = 279.6$ (299 dof) , $p = 0.78$

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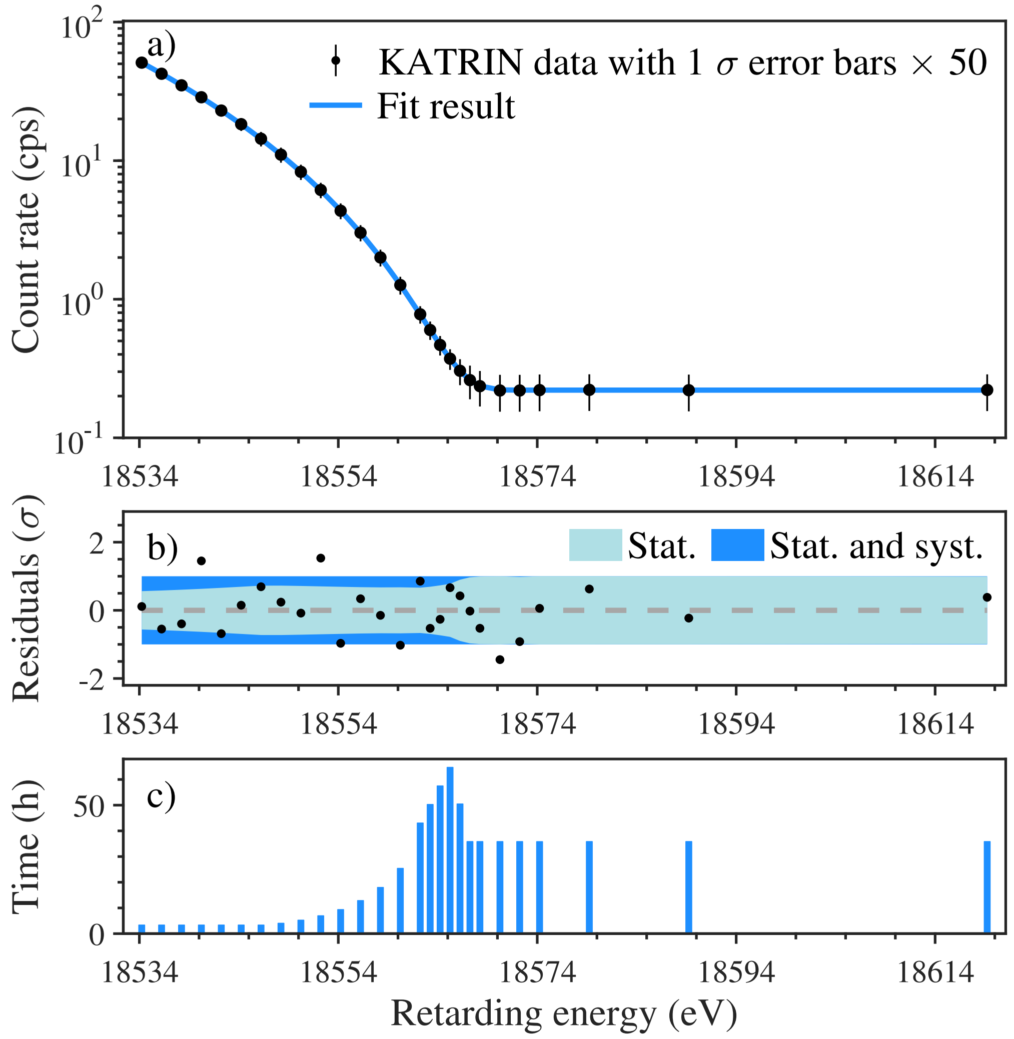
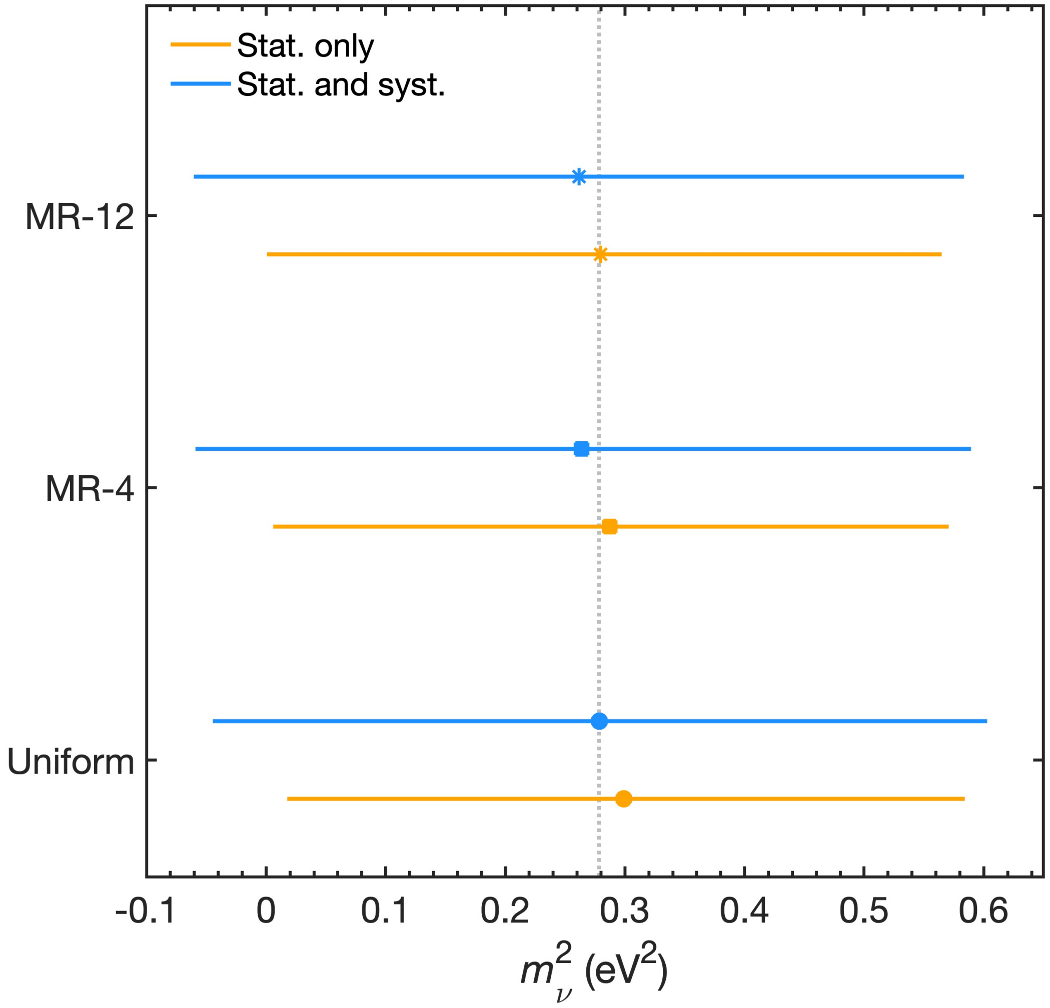
Data: Gather all pixels – Uniform-fit



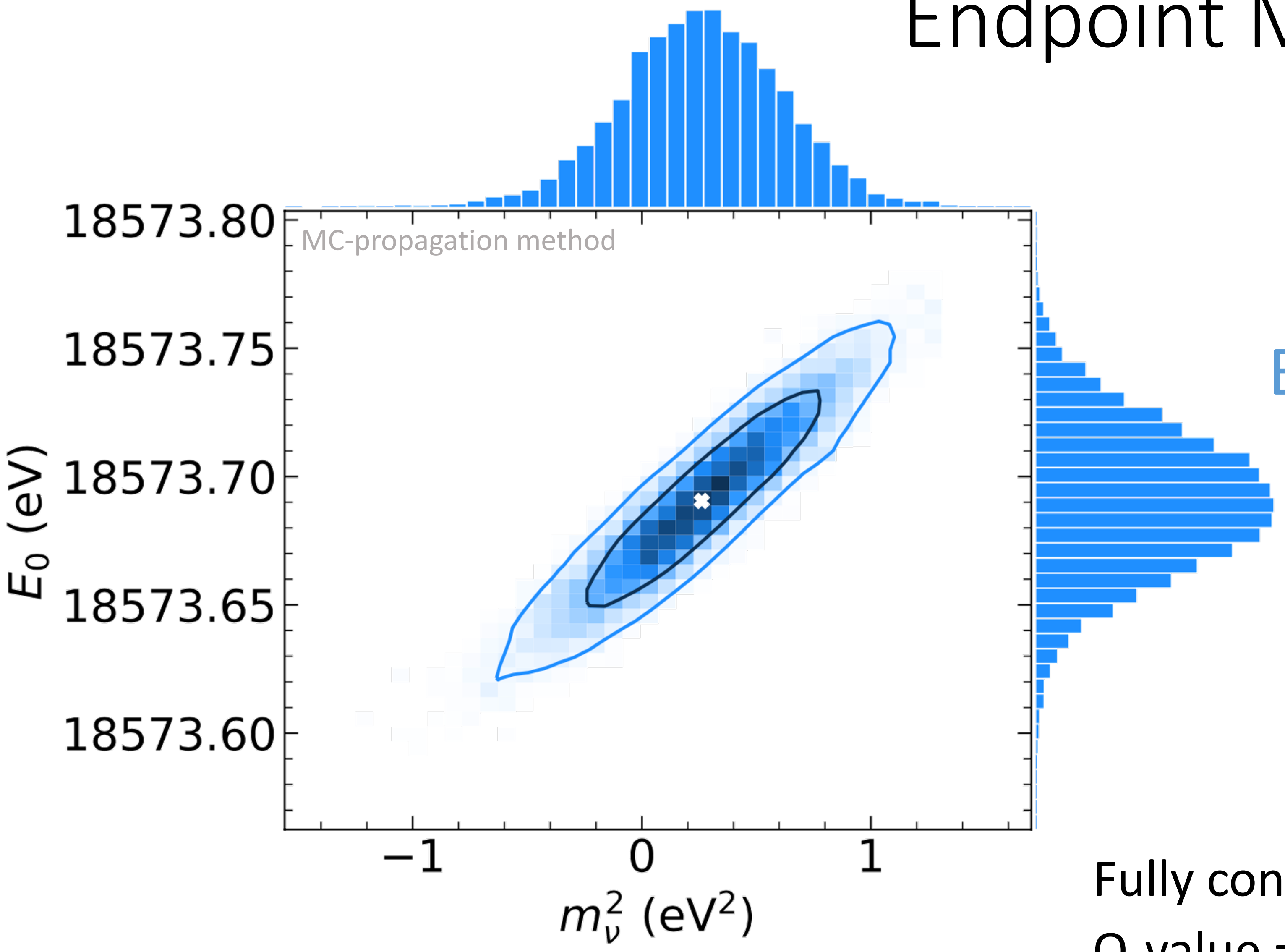
- Stack 117 pixels + all 361 scans
- Stat. Only
  - $m_\nu^2 = 0.30 \pm 0.28\ (^{+0.28}_{-0.28})\ \text{eV}^2$
  - $\chi^2_{\text{min}} = 30.4$ (24 dof) , $p = 0.17$
- Total (with covariance matrix)
  - $m_\nu^2 = 0.28 \pm 0.32\ (^{+0.32}_{-0.32})\ \text{eV}^2$
  - $\chi^2_{\text{min}} = 27.5$ (24 dof) , $p = 0.28$

Comparison pixel combination strategies

- FPD pixel combination strategies:
- **All results are consistent**
- **Uniform:** Stack all pixels
  - ➢ Fast and robust
  - ➢ Allows for many additional studies
- **MR-4**: Stack pixels to 4 pseudo-rings
  - ➢ Our baseline result
- **MR-12:** Stack pixels into "normal" 12 rings
  - ➢ Cross-check for higher granularity radial dependence



Endpoint Measurement



Maximum electron energy in tritium decay

$E_0 = (18573.69 \pm 0.03)$ eV

⇨ Q-value = (18575.2 ± 0.6) eV

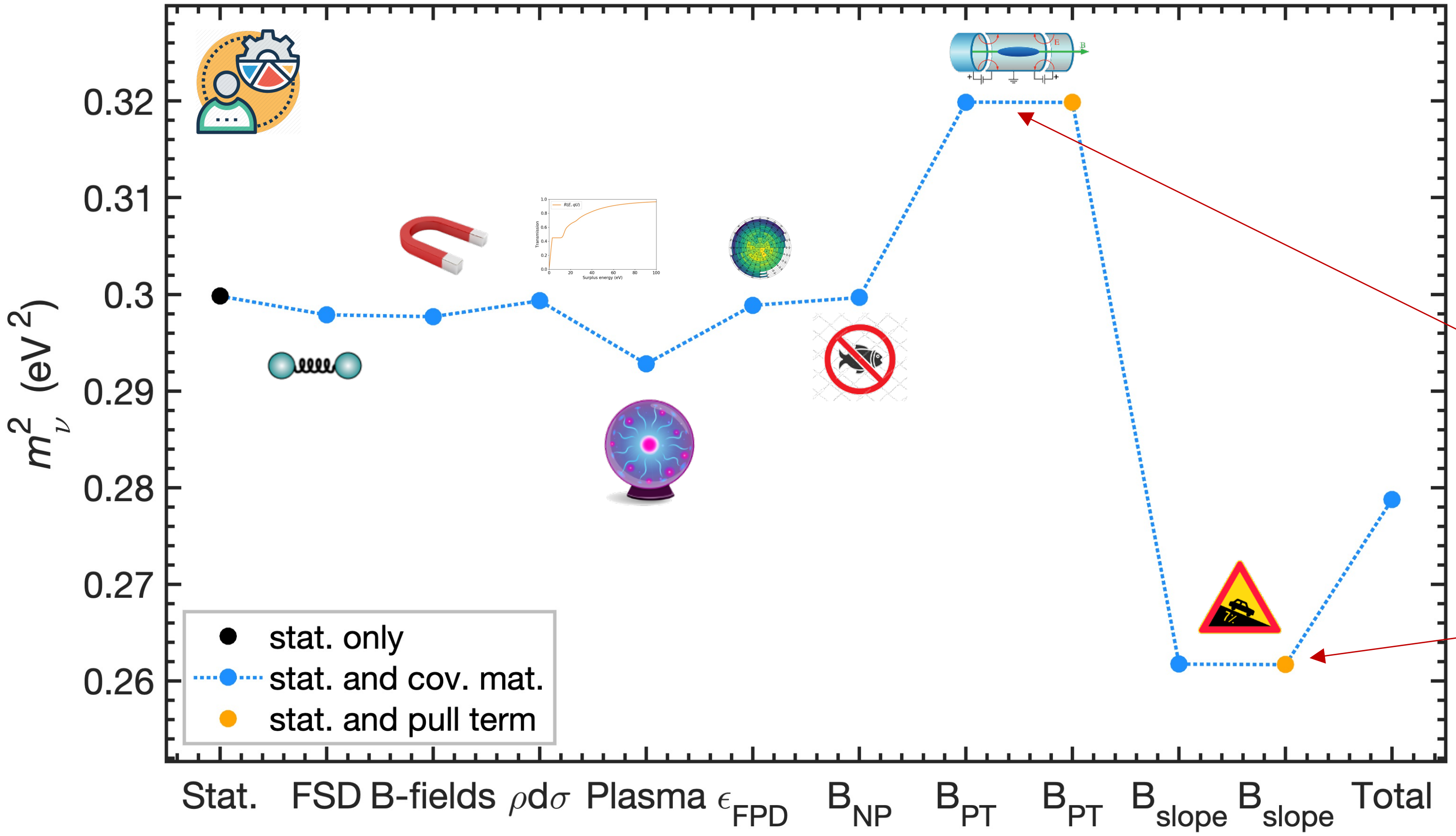
Mass ^3H – Mass ^3He

Fully consistent with the prediction:

Q-value = (18575.72 ± 0.07) eV

Check of the global energy scale

Impact of systematics on central value

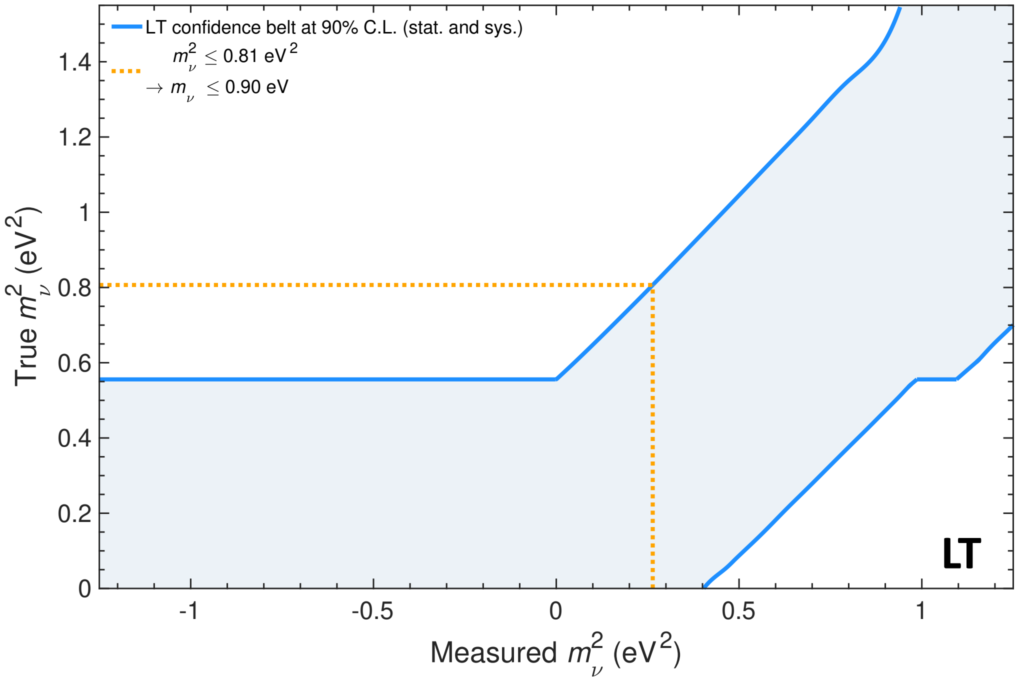


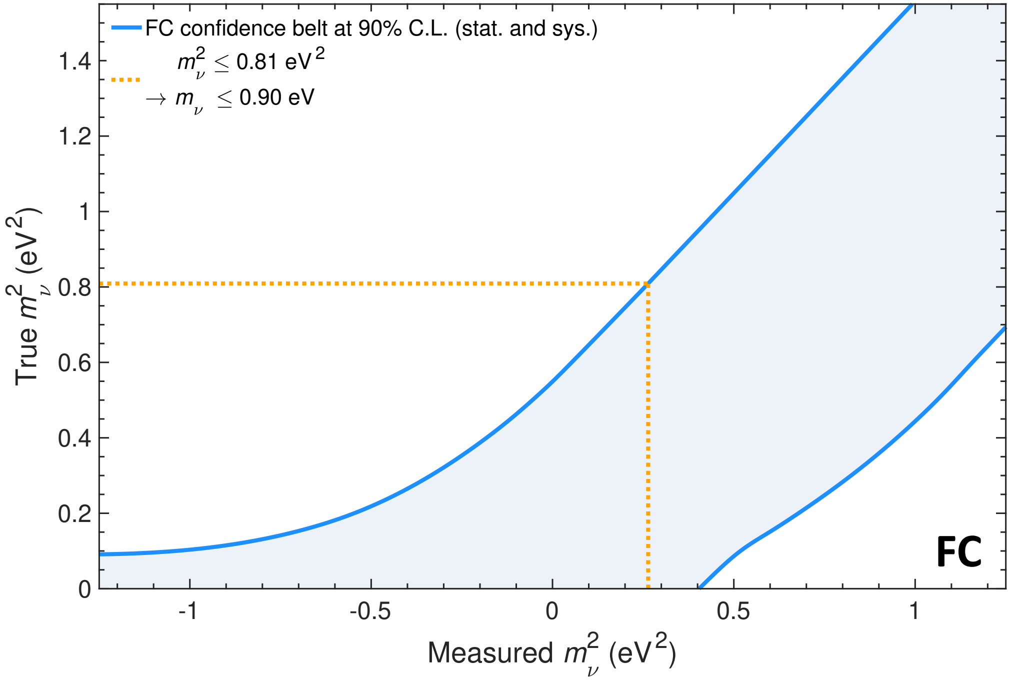
- Stat+1 statistical test
  Fit with stat. and 1 syst. uncertainty
- Stacked Uniform fit
- B_{PT} - Penning-trap background

  positive m^2 shift
- B_{Slope} - qU-background dependence

  negative m^2 shift

New KATRIN limit





Lokhov and Tkachov (LT)

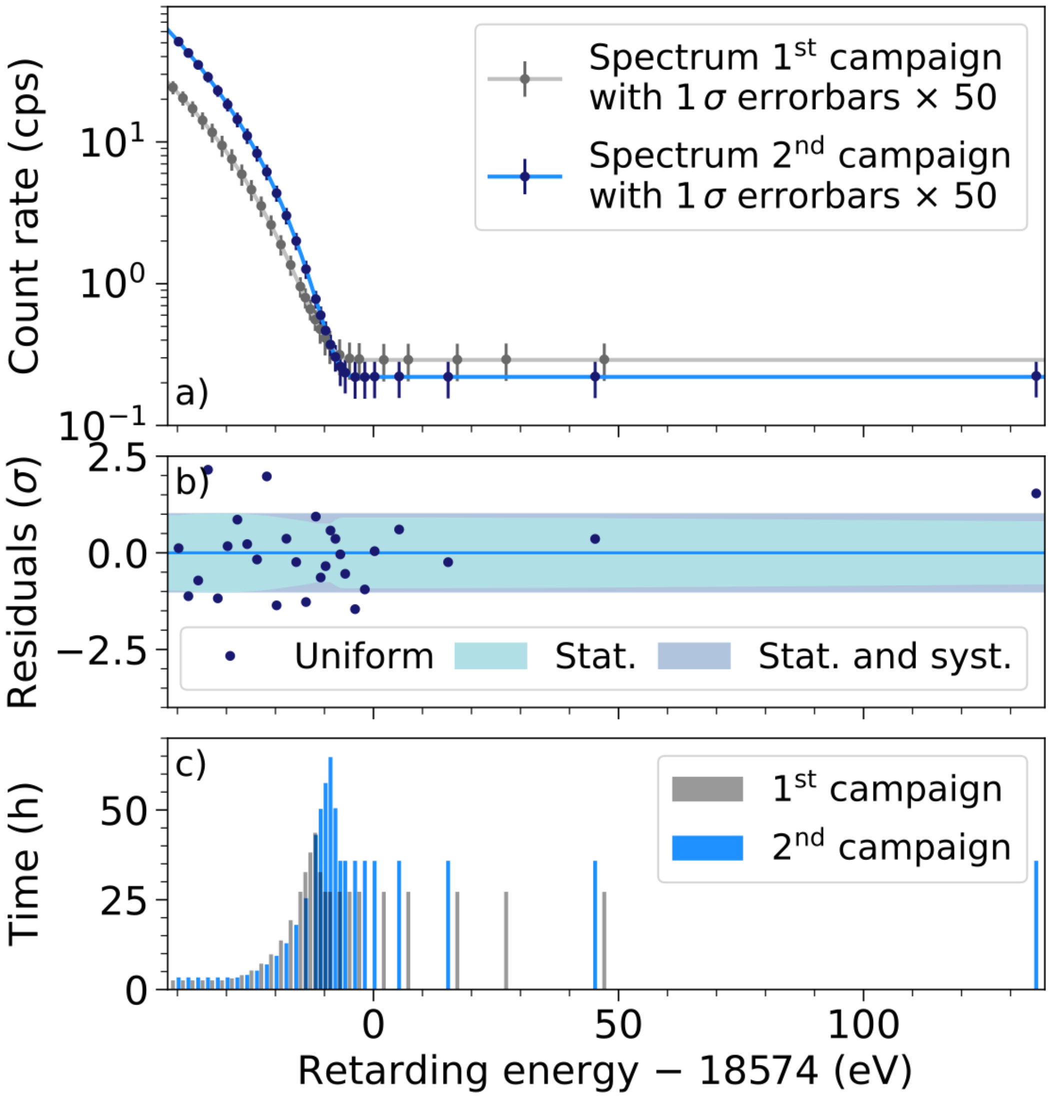
- **m_ν < 0.9 eV at 90% CL**
- Sensitivity: $m_\nu < 0.74$ eV at 90% C.L.

Feldman and Cousins (FC)

- m_ν < 0.9 eV (90% CL)
- Identical to LT

Combination of the first two neutrino mass campaigns

Combination of KNM1 & KNM2



KNM1: 1st campaign:

- total statistics: 2 million events
- background 290 mcps
- best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.0}\right)$eV² (stat. dom.)

KNM2: 2nd campaign:

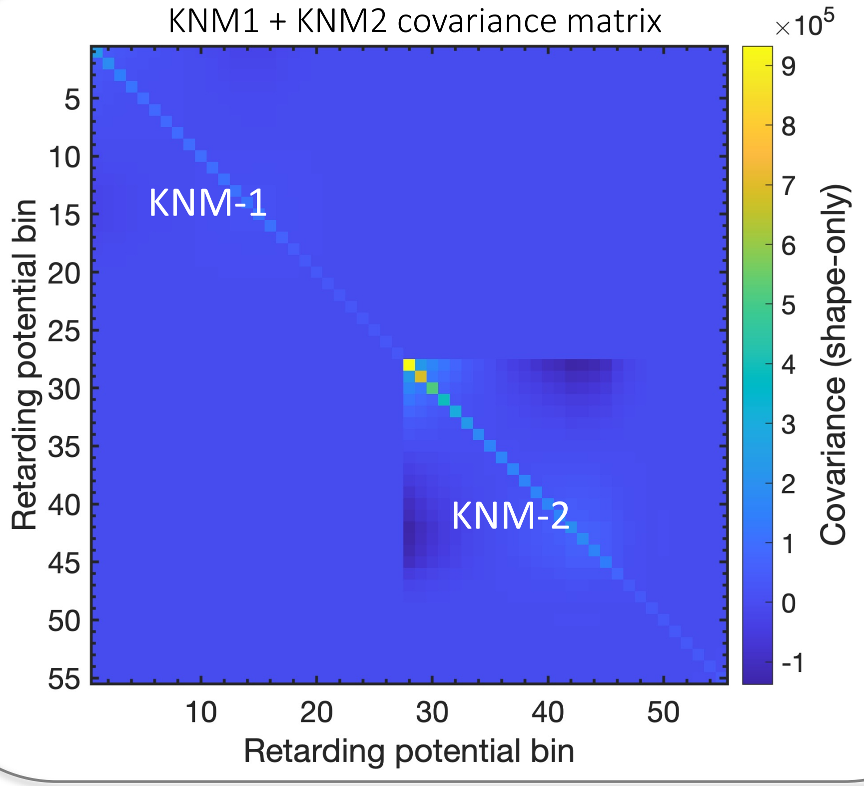
- total statistics: 4.3 million events
- background 220 mcps
- best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$eV² (stat. dom.)

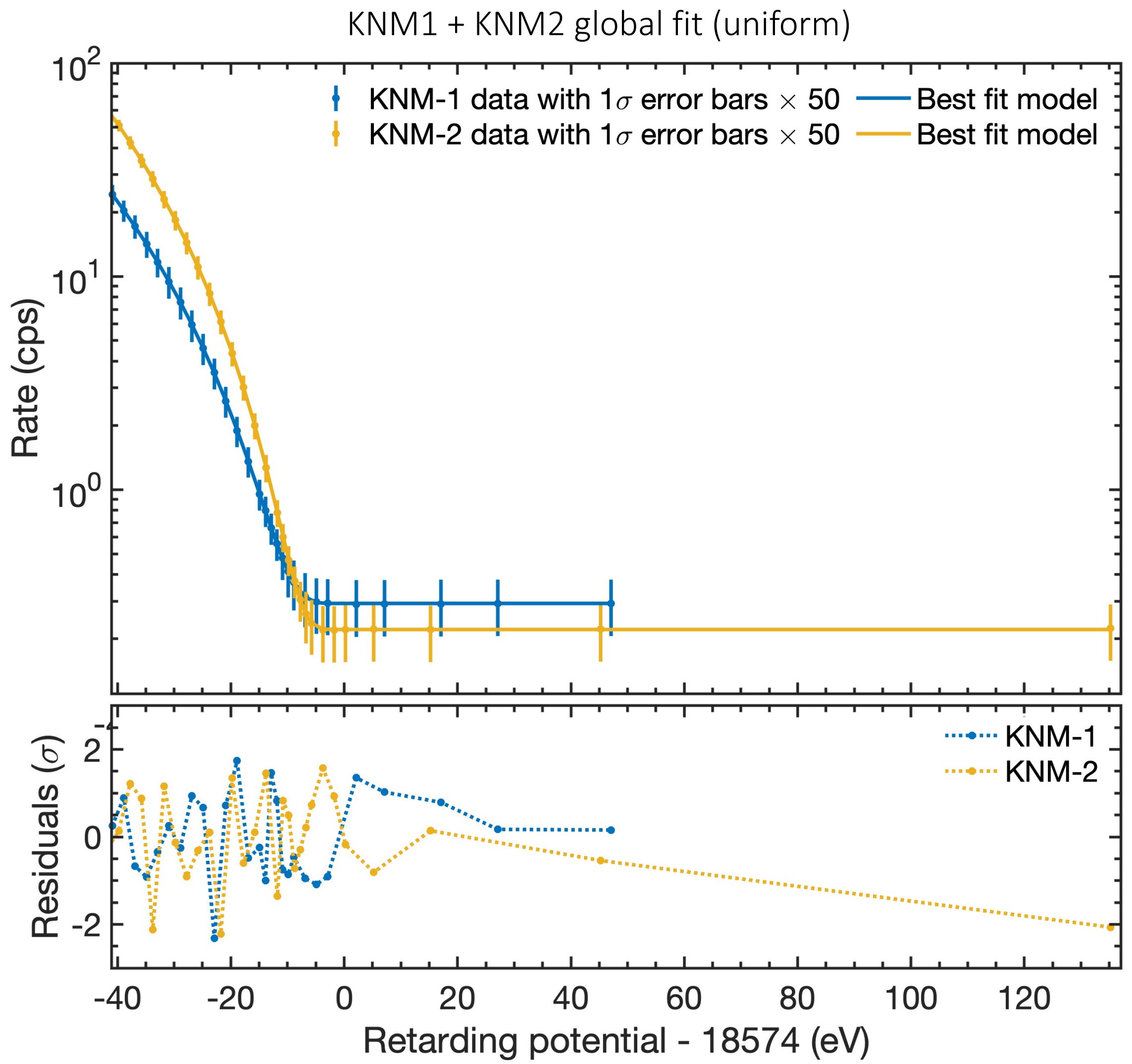
- Both KNM1 and KNM2 are statistics dominated

→Treat them as independent data sets

KNM1 + KNM2 Common-Fit

- Do combined fit by minimizing $\chi^2_{\text{common}}\left(m_\nu^2, E_0^1, E_0^2, N_{sig}^1, N_{sig}^2, B^1, B^2 \middle| \text{KNM1 \& KNM2 data}\right)$





Result: $m_\nu^2 = 0.1^{+0.3}_{-0.3}\ eV^2$ → Limit: $m_\nu < 0.8$ eV (90% CL)

KATRIN in the light of previous results and prospects

Conclusion

KATRIN 2021: first direct neutrino-mass experiment to reach sub-eV sensitivity and limit

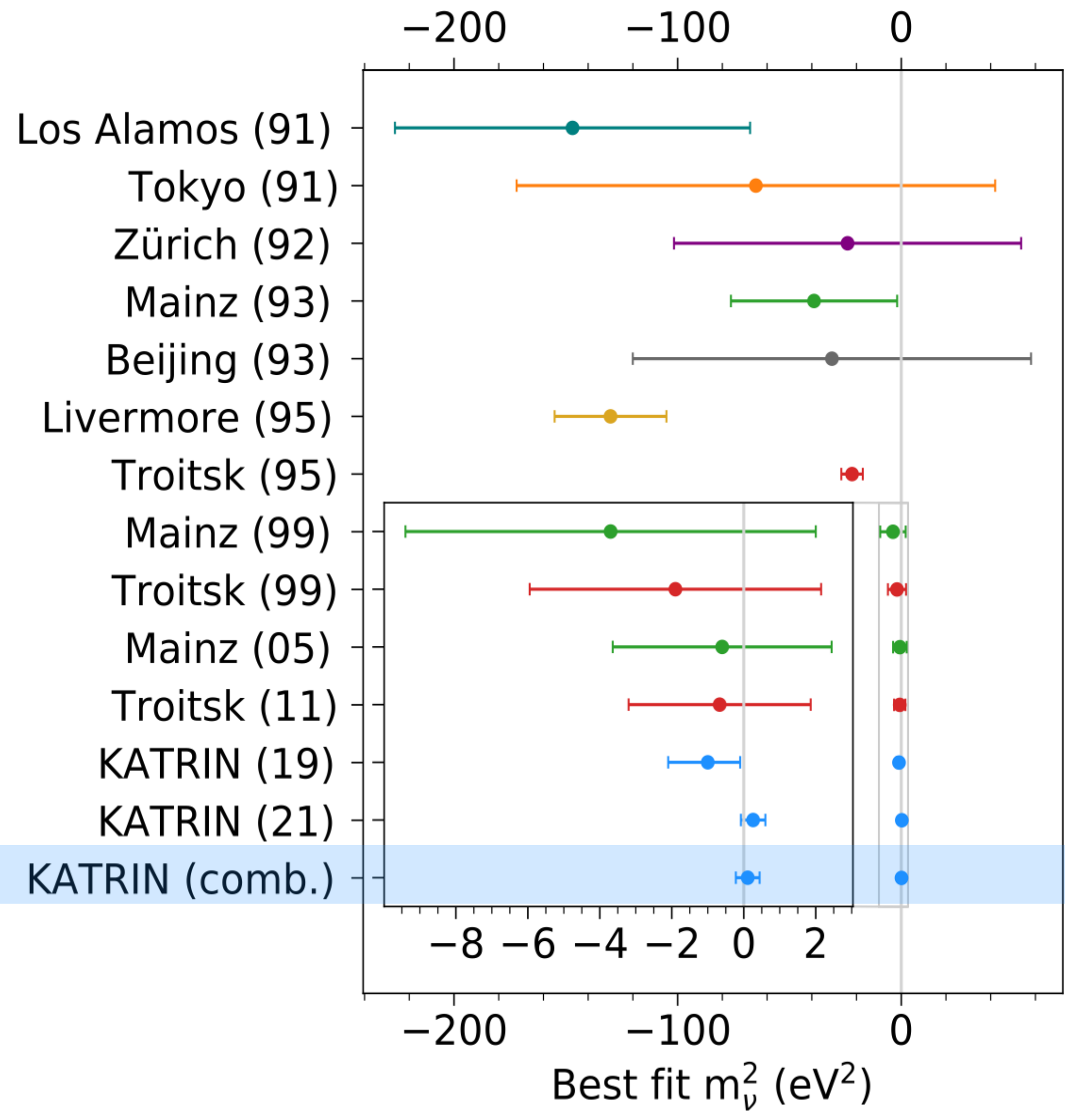
- 1st and 2nd campaign combined result:

$$m_\nu^2 = (0.1^{+0.3}_{-0.3})\,\mathrm{eV}^2$$

- 1st and 2nd campaign combined limit:

$$m_\nu < 0.8 \text{ eV (90\% CL)}$$

- **publication:** https://arxiv.org/abs/2105.08533

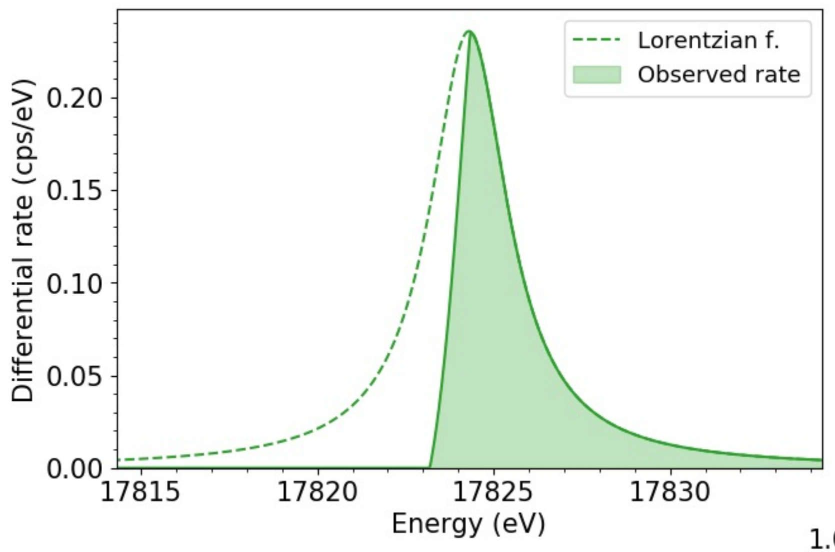


Future:

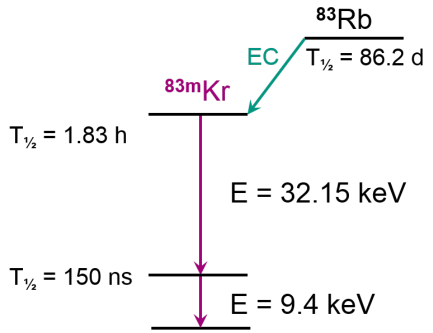
- Reduced background and systematics
- 1000 days of data: 50 x more statistics
- Final goal: $m_\nu < 0.2 - 0.3$ eV (90% CL)

Thanks for your attention

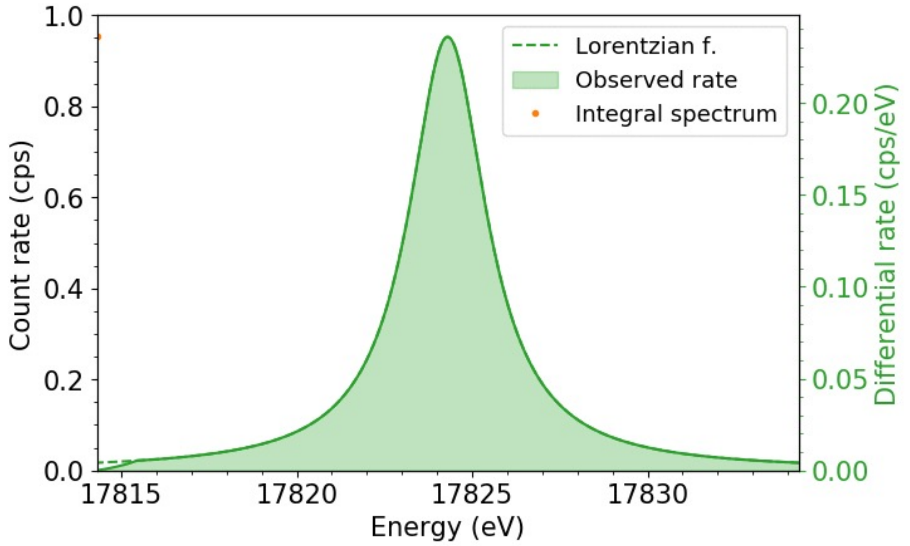
Response to quasi-monoenergic electrons

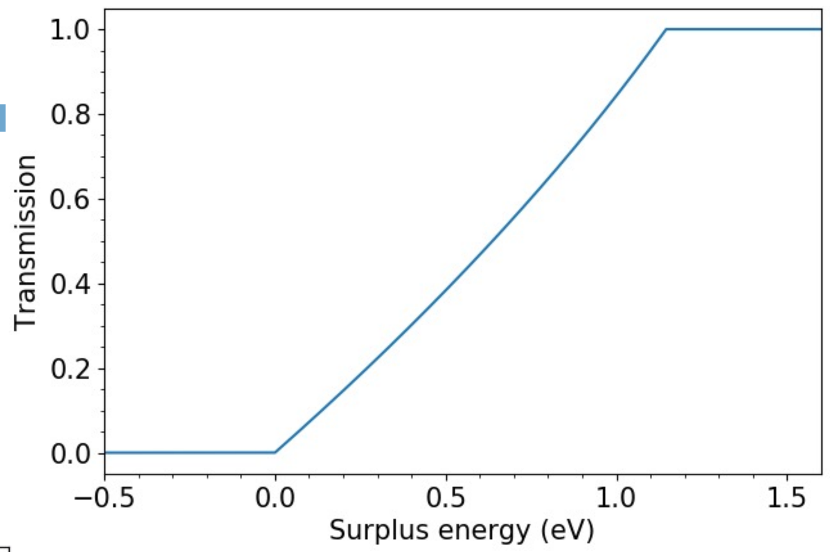


Natural line width of krypton



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





Spectrometer resolution