New limit on the effective neutrino mass by KATRIN

INR Neutrino Meeting, 11/06/2021

Thierry Lasserre (CEA/DRF/Irfu/DPhP)

On behalf the KATRIN collaboration

Neutrino mass

Cosmology

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

Search for 0νßß

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

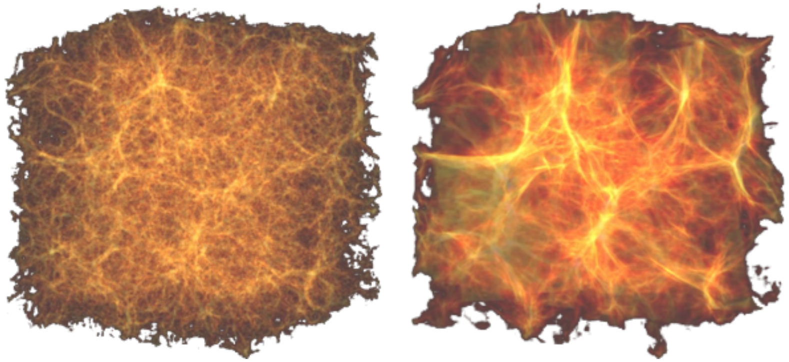
Kinematics of ß-decay

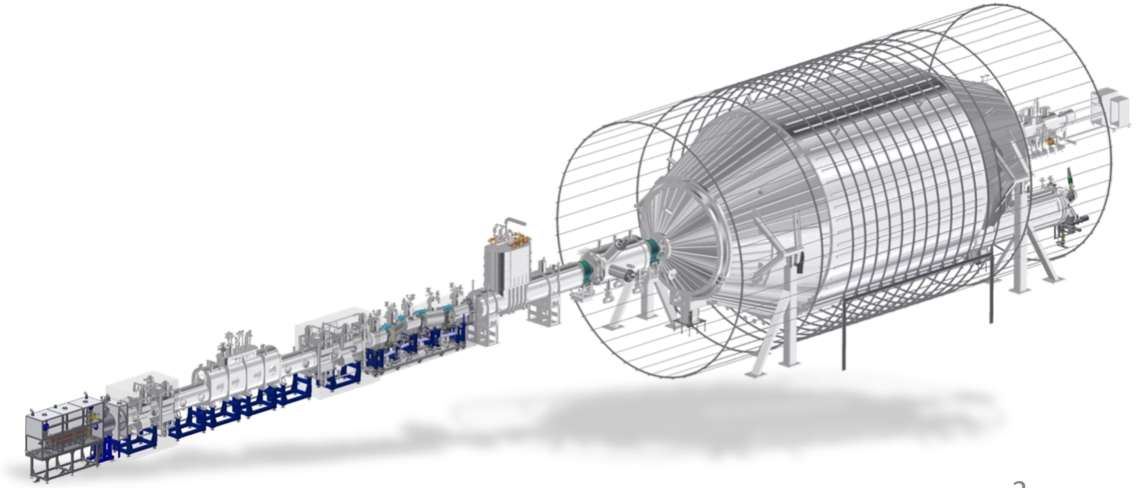
Laboratory-based
potential: m_β = 50 - 200 meV
e.g. KATRIN

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

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

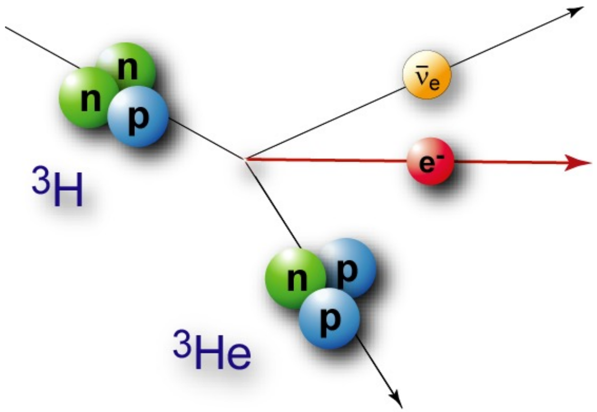
$$m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$



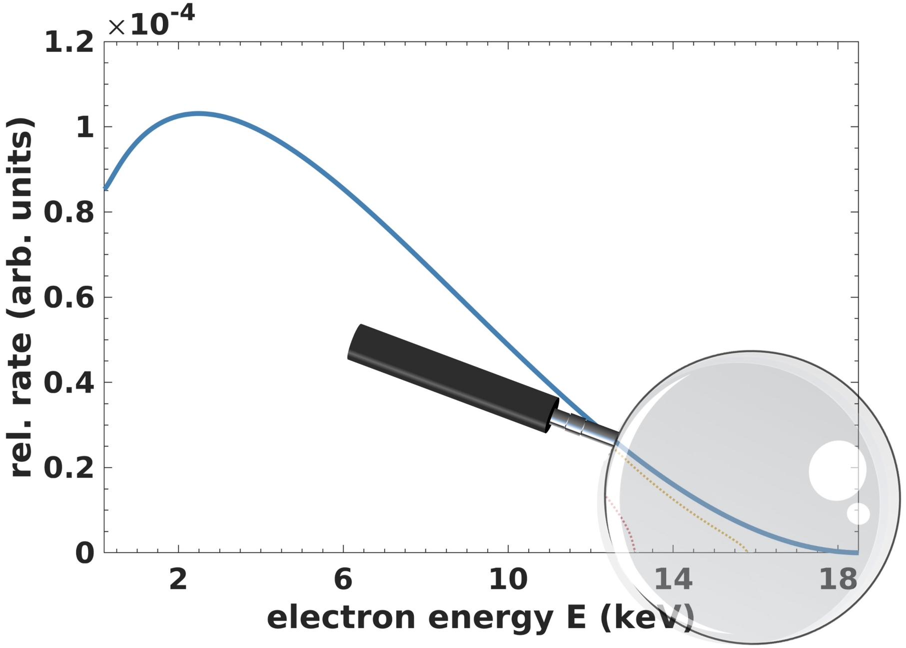


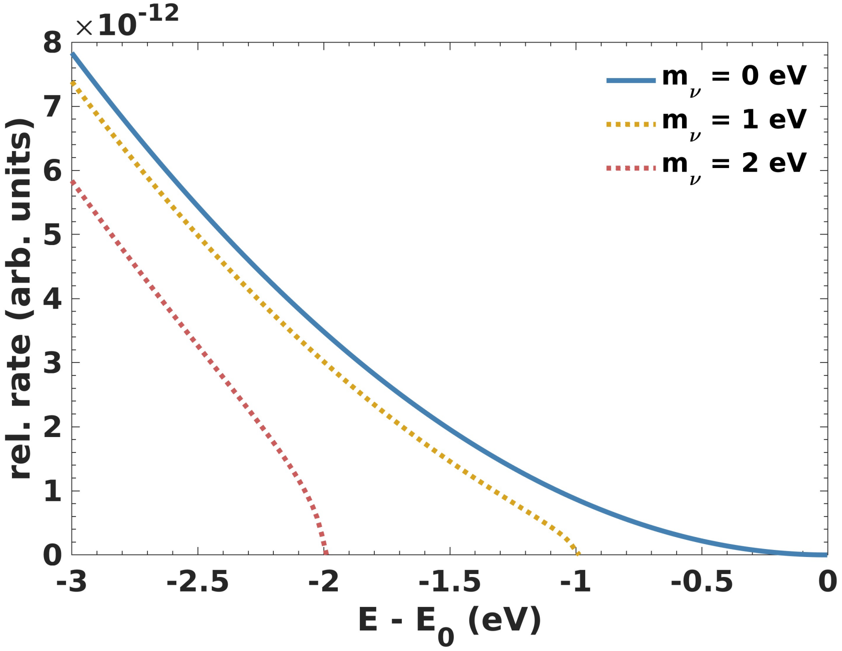
Kinematic Measurement Concept

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

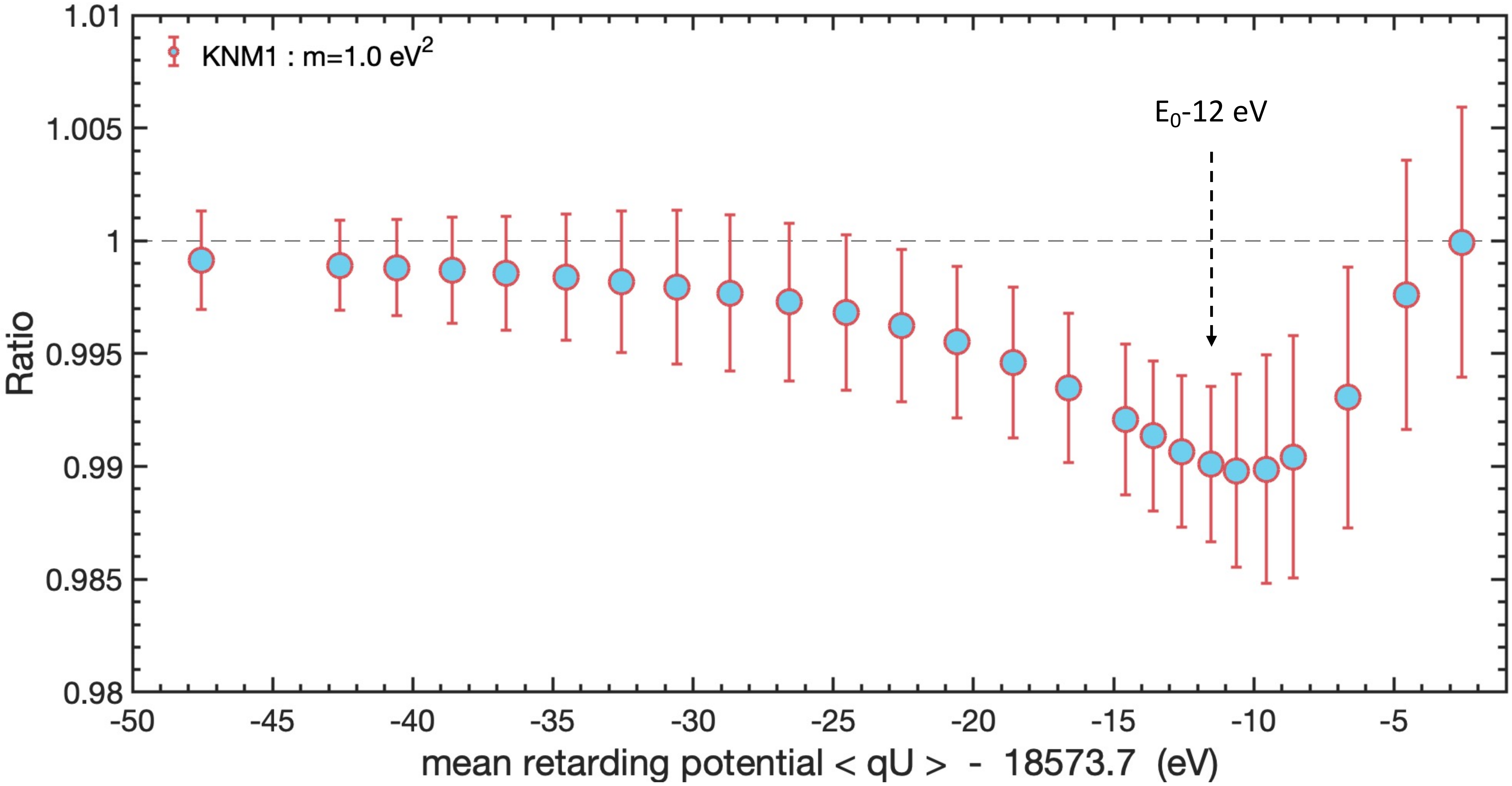


$$m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$$





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



1% amplitude for m=1eV2

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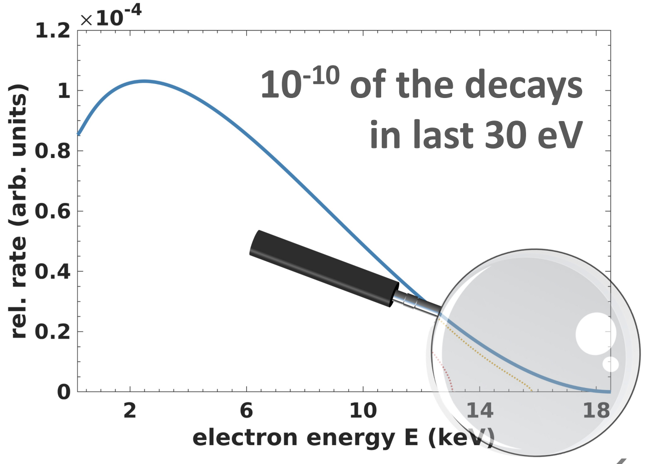
Generic Experimental Challenges

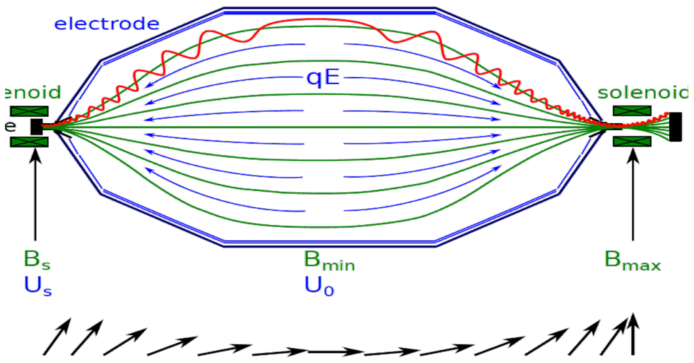
Intense ultra-stable tritium source

- design value: 100 GBq



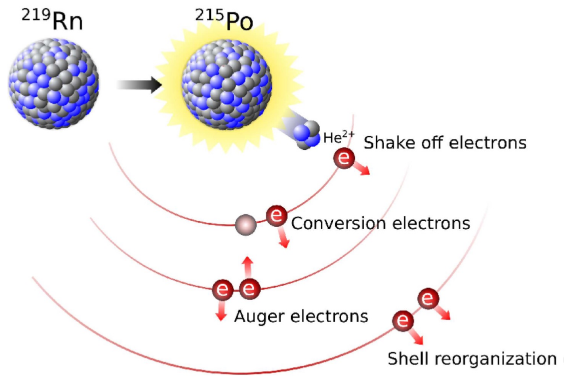
High Energy Resolution

- design value : 1 eV



Low electron Background

- design value : 0.01 cps



Karlsruhe
Tritium
Neutrino
Experiment

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

KIT Karlsruher Institut für Technologie

Max-Planck-Institut für Kernphysik Heidelberg

University of Washington

Case Western Reserve University Est. 1826 think beyond the possible

Westfälische Wilhelms-Universität Münster

Massachusetts Institute of Technology

The University of North Carolina at Chapel Hill

The Czech Academy of Sciences

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

cea

Carnegie Mellon University

Universidad Complutense Madrid

Russian Academy of Sciences

Johannes Gutenberg Universität Mainz

Technische Universität München

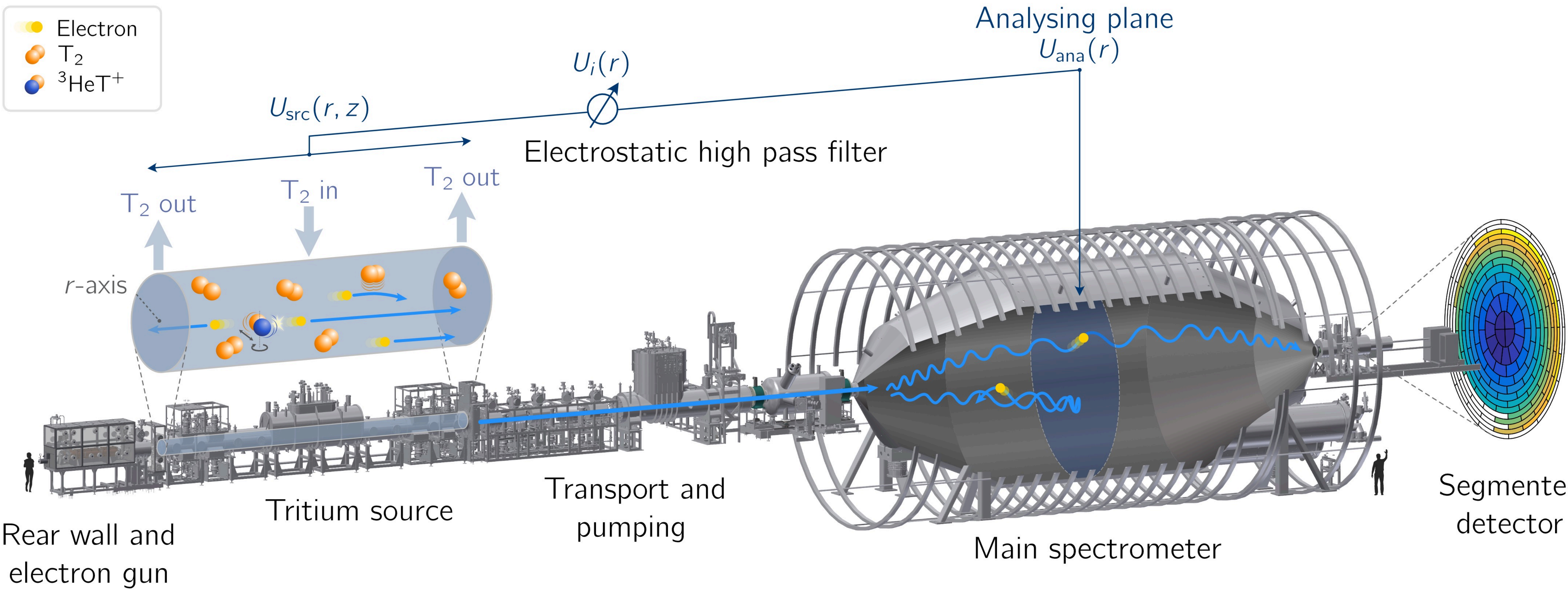
universitätbonn

Hochschule Fulda University of Applied Sciences

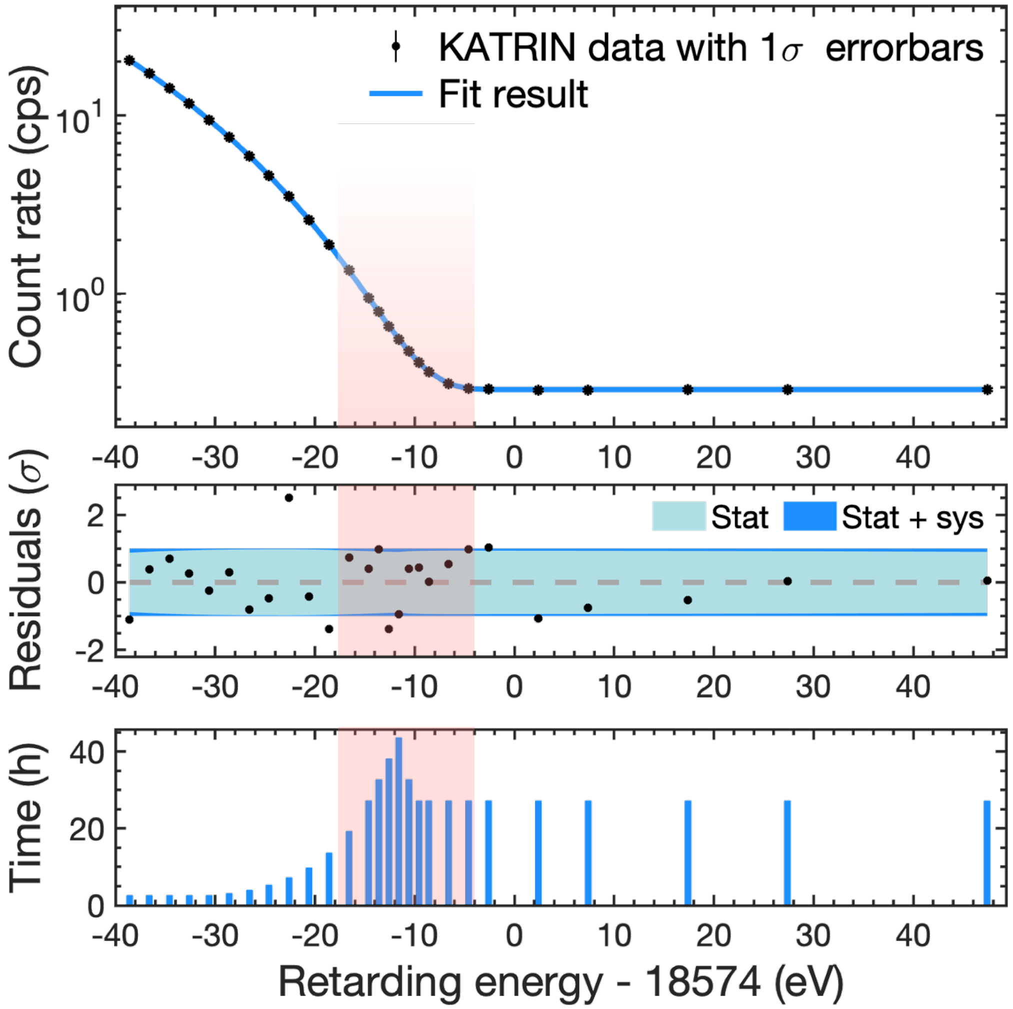
Bergische Universität Wuppertal

Berkeley Lab

KATRIN Overview



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:

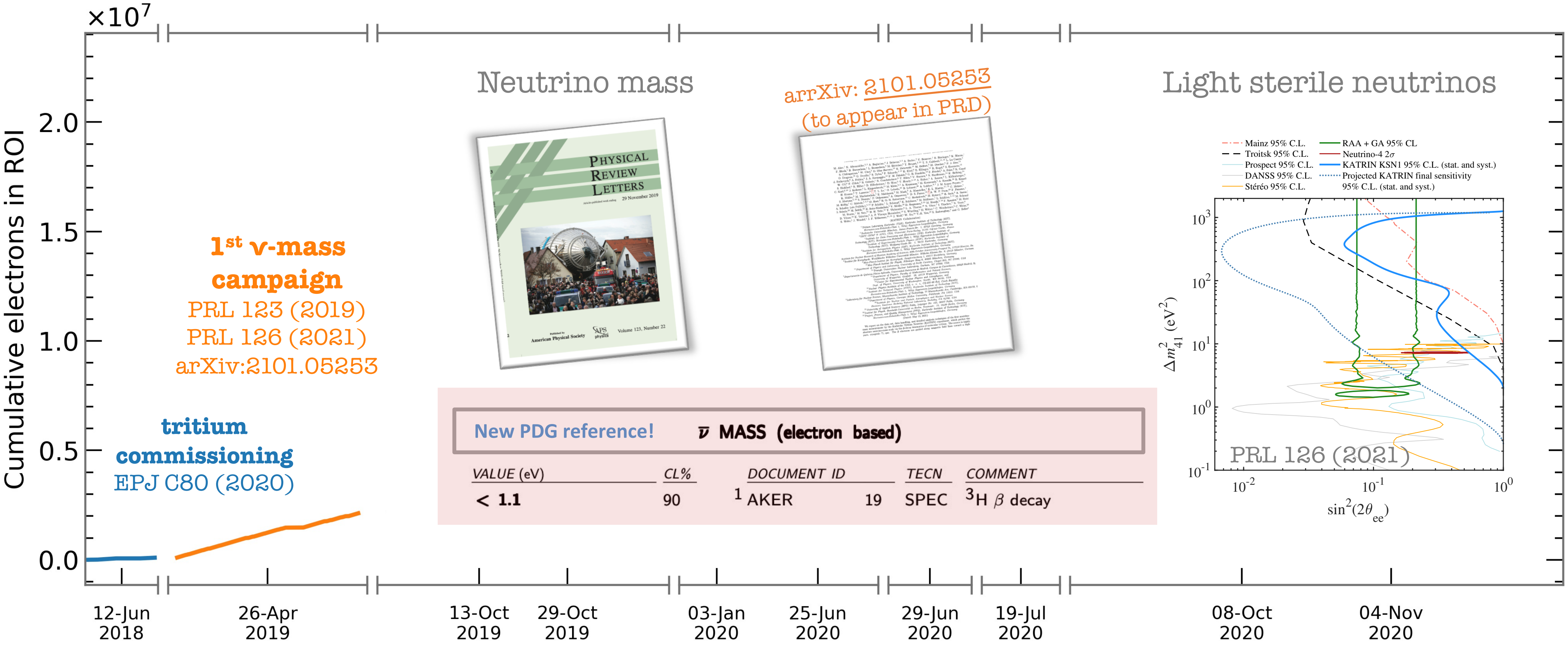
  σ_{stat} = 0.97 eV^2 → factor 2 / Mainz&Troistk

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

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

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

KATRIN First Neutrino Mass Result (2019)



tritium commissioning
EPJ C80 (2020)

1st ν-mass campaign
PRL 123 (2019)
PRL 126 (2021)
arXiv:2101.05253

Neutrino mass

arrXiv: 2101.05253
(to appear in PRD)

Light sterile neutrinos

PRL 126 (2021)

New PDG reference! **$\bar{\nu}$ MASS (electron based)**

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 1.1	90	[1] AKER	19	SPEC	^{3}H β decay

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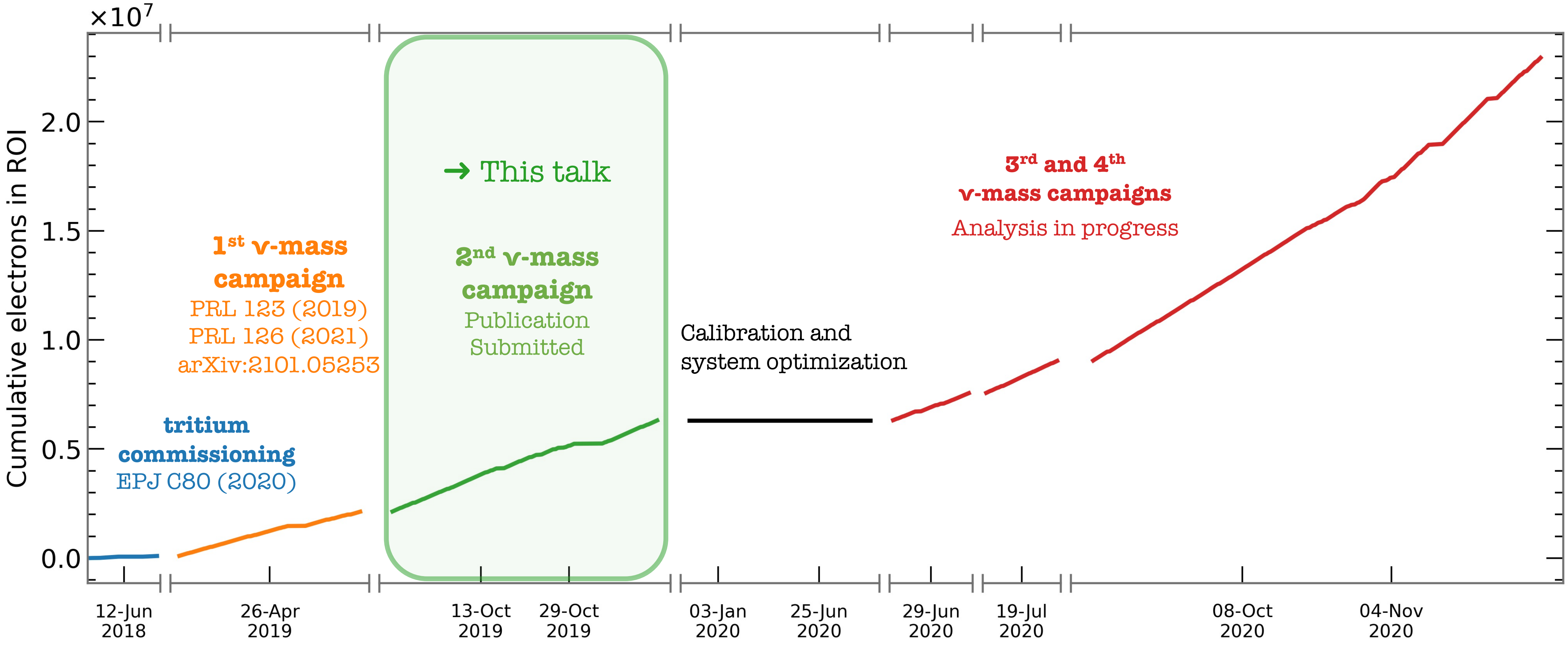
New Data Release (2021)



tritium commissioning
EPJ C80 (2020)

1st ν-mass campaign
PRL 123 (2019)
PRL 126 (2021)
arXiv:2101.05253

→ This talk

2nd ν-mass campaign
Publication Submitted

Calibration and system optimization

3rd and 4th ν-mass campaigns
Analysis in progress

Second Neutrino Mass Campaign

( = systematic uncertainty)

Comparison with first campaign

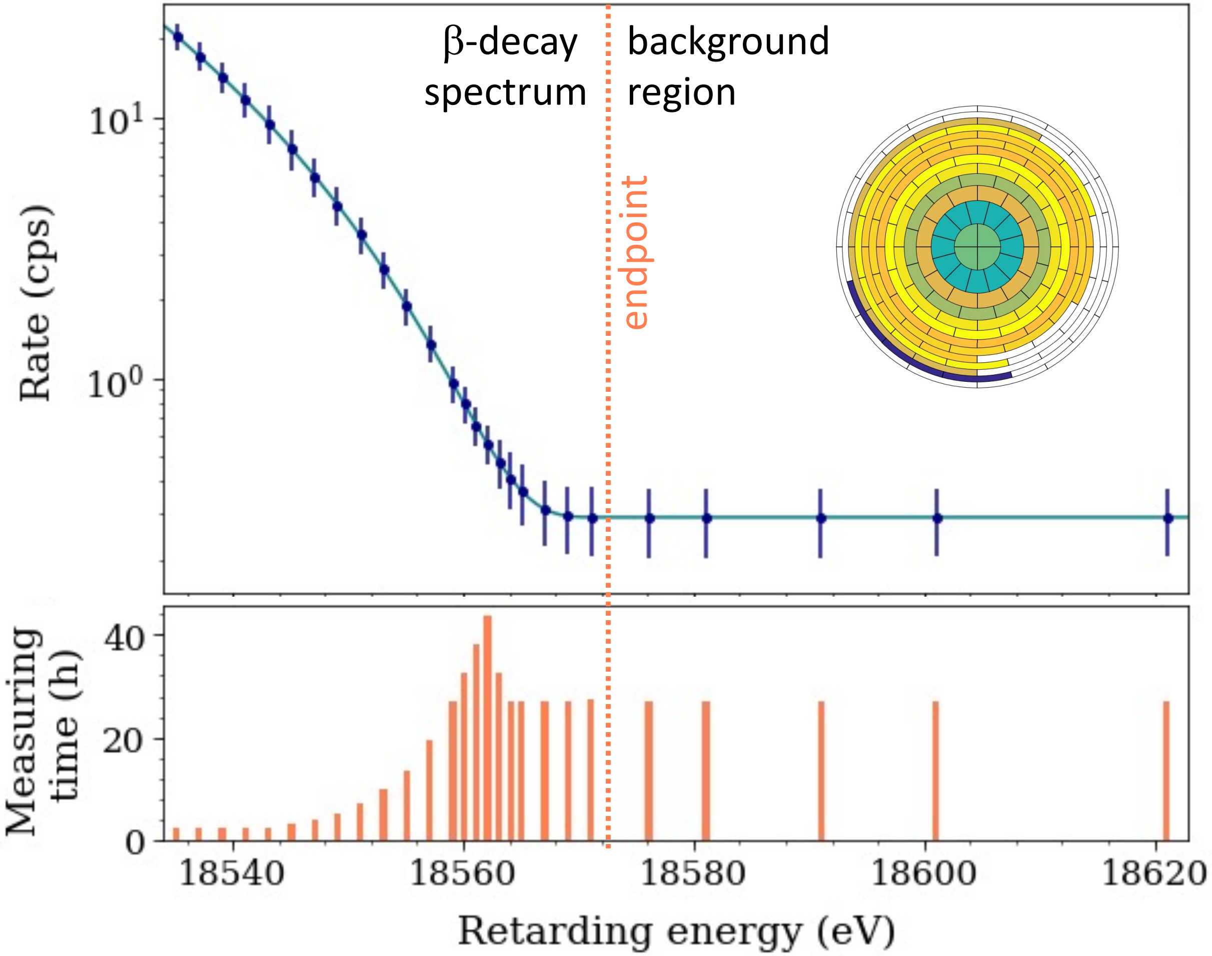
	1st campaign PRL 123 (2019)		2nd campaign This talk
Campaign date	April-May 2019		Sept-Nov 2019
Total scan time	522 h (274 scans)		744 h (361 scans)
Background	290 mcps	reduction -25% →	220 mcps
Source activity	25 GBq	nominal activity →	98 GBq
Tritium purity	97.6%	raised purity →	98.7%
Electrons in RoI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

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

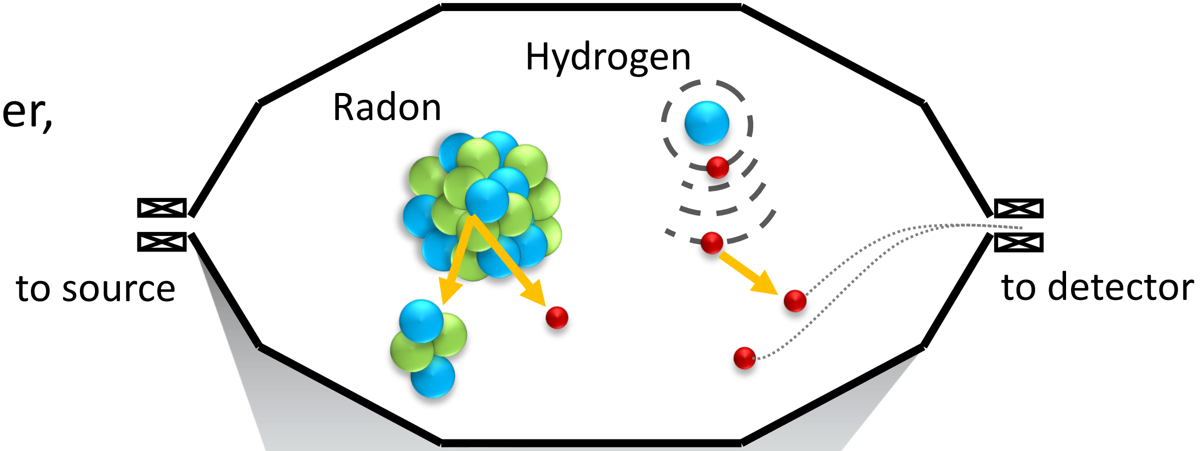


Background characterization

- **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

☹

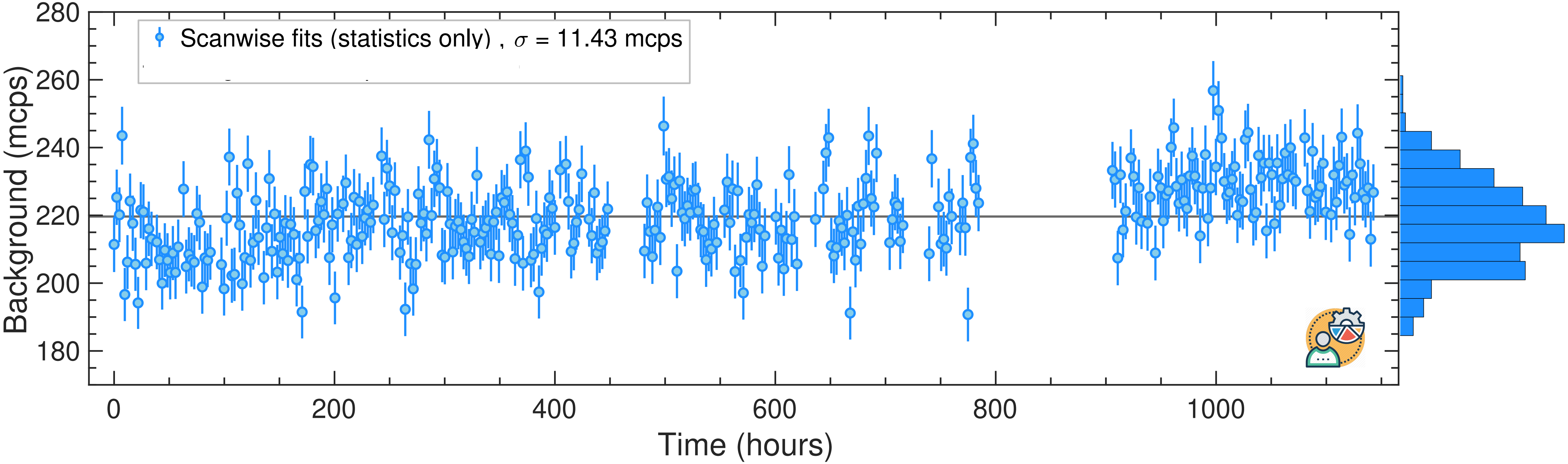


- 3 concerns:
  - Precise determination of background rate
  - Check / limit background retarding-potential dependence (background qU-slope)
  - Check / limit background sub-scan length dependence

NEW!

Background Rate over 371 scans

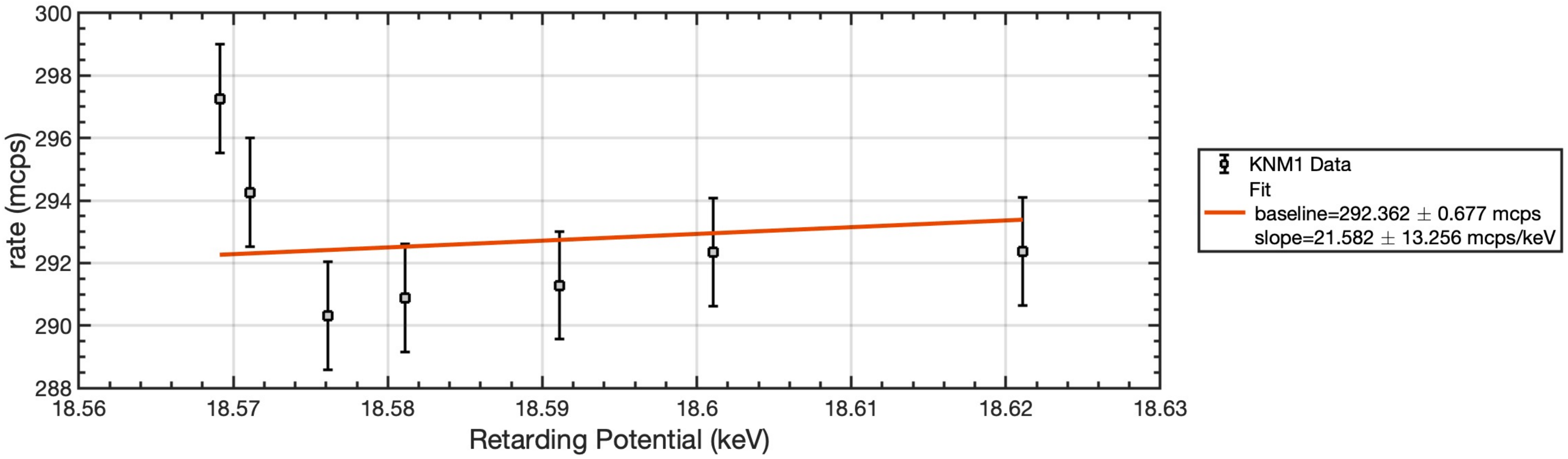
- All detector pixels combined – background reduced by 25% w.r.t. first campaign



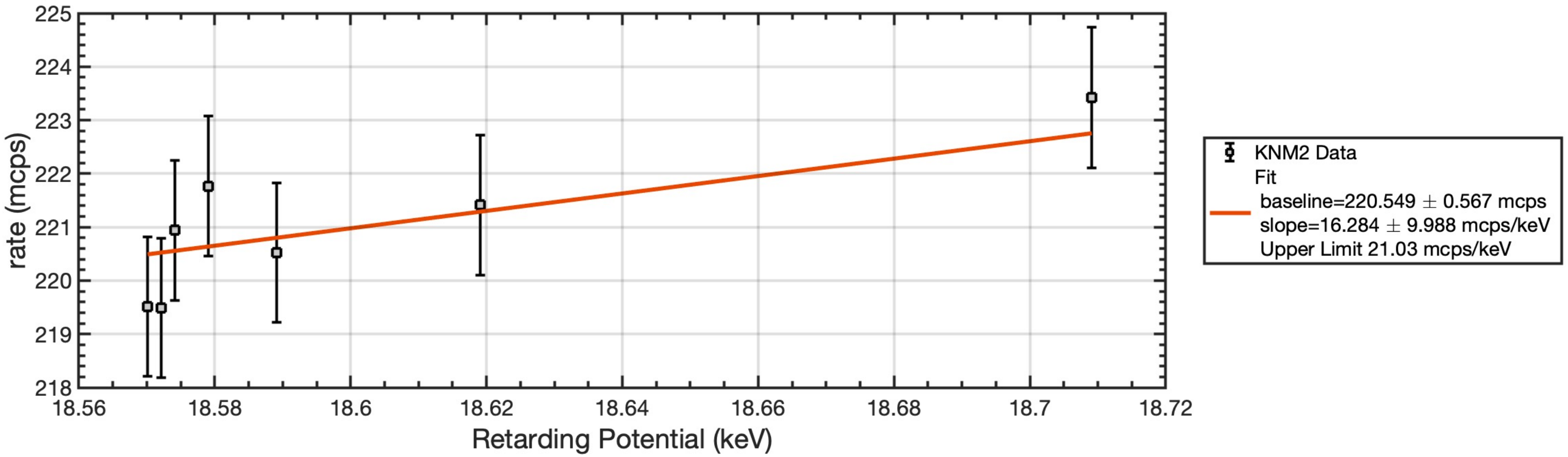
0.220 cps / 117 pixels → Design value = 0.008 cps (x 30)
(a serious challenge for the ultimate sensitivity)

Background qU-dependence 371 scans

- Slight qU-dependence of background can’t be excluded

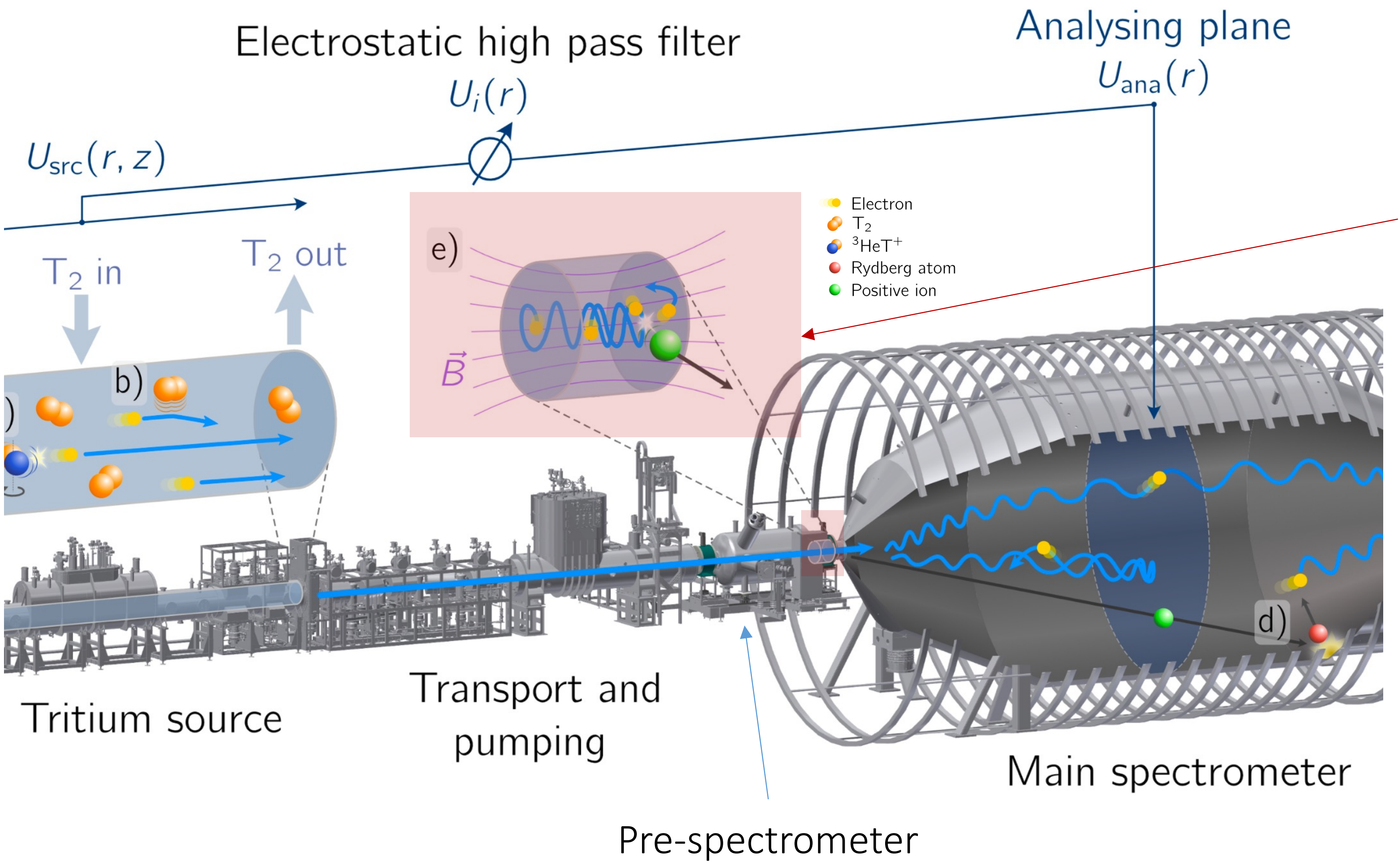


- Assume qU-flat background



- Include possible qU-dependence as systematic error

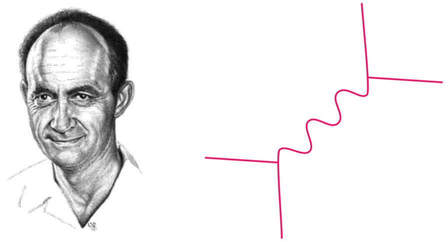
Penning-trap induced Background

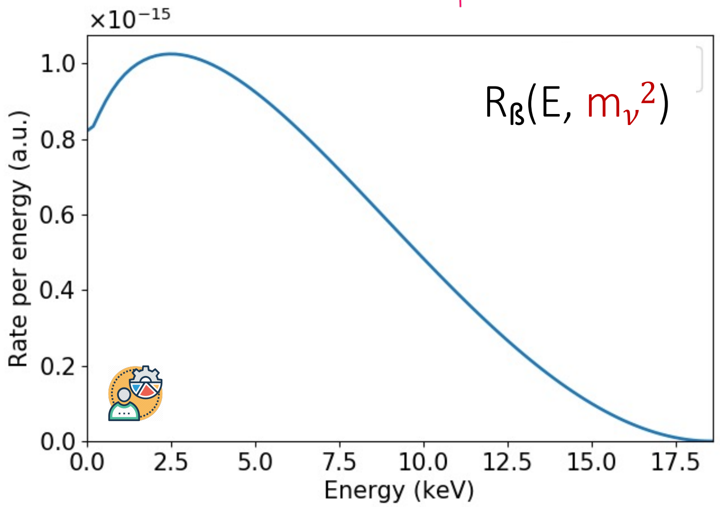


- Both pre- and main spectrometers, operated at high voltage
- create a Penning trap
- Stored electrons create ions$^+$, which can escape the trap into the main spectrometer → background
- Trap emptied with an e$^-$-catcher system after each sub-scan
- Can induce background dependency with sub-scan length

Integral spectrum modeling

tritium β-decay theory

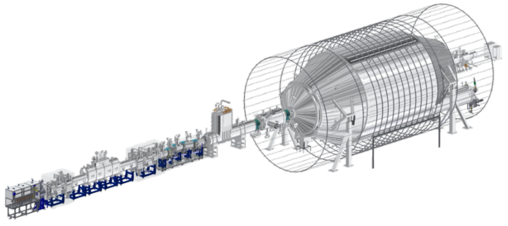


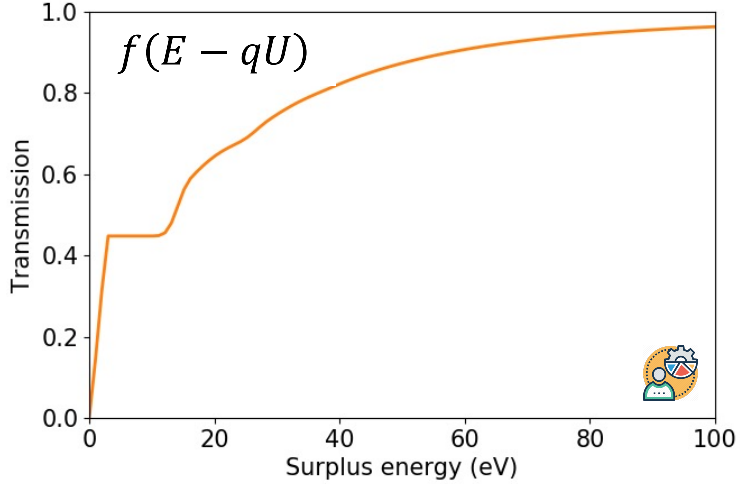


$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C\cdot p_e E_e\cdot\sqrt{(E_e-E_0)^2-m_{\nu_i}^2}\cdot(E_e-E_0)\cdot F(E_e,Z)$$

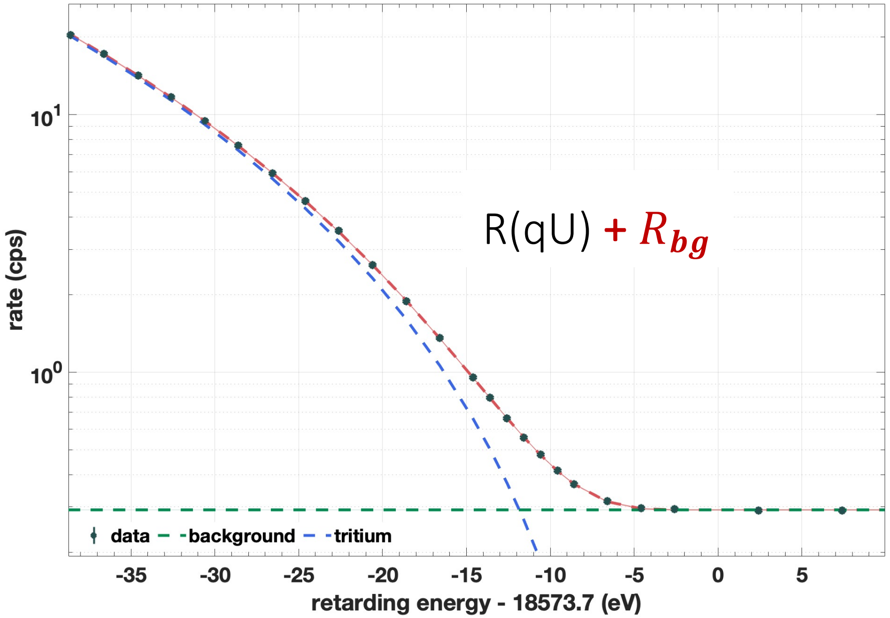
$$R(qU) = A_s \cdot N_T \int_{qU}^{\boxed{E_0}} R_ß(E, m_\nu^2) \cdot f(E-qU)\,dE + R_{bg}$$

experimental setup





integral β-spectrum



← R_{bg}

Tritium Beta Decay calculation

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

fit parameter

fit parameter

Fermi spectra summed over all rob-vib molecular final states

$$R_{\beta}(E) = \frac{G_{\mathrm{F}}^2 \cdot \cos^2\Theta_{\mathrm{C}}}{2\pi^3} \cdot |M_{\mathrm{nucl}}^2| \cdot F(E, Z')$$

$$\cdot (E + m_{\mathrm{e}}) \cdot \sqrt{(E + m_{\mathrm{e}})^2 - m_{\mathrm{e}}{}^2}$$

$$\cdot \sum_{\mathrm{j}} \zeta_j \cdot \varepsilon_j \cdot \sqrt{\varepsilon_j^2 - \boxed{m_{\nu}^2}} \cdot \Theta(\varepsilon_j - m_{\nu})$$

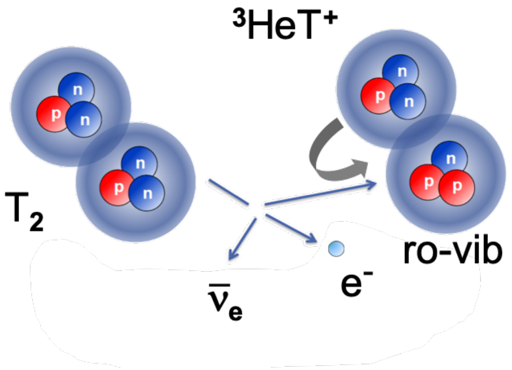
fit parameter

$$\varepsilon_j = \boxed{E_0} - E - V_j$$

Molecular energy levels

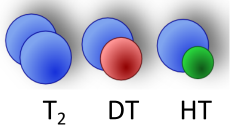
fit parameter

Molecular Final States

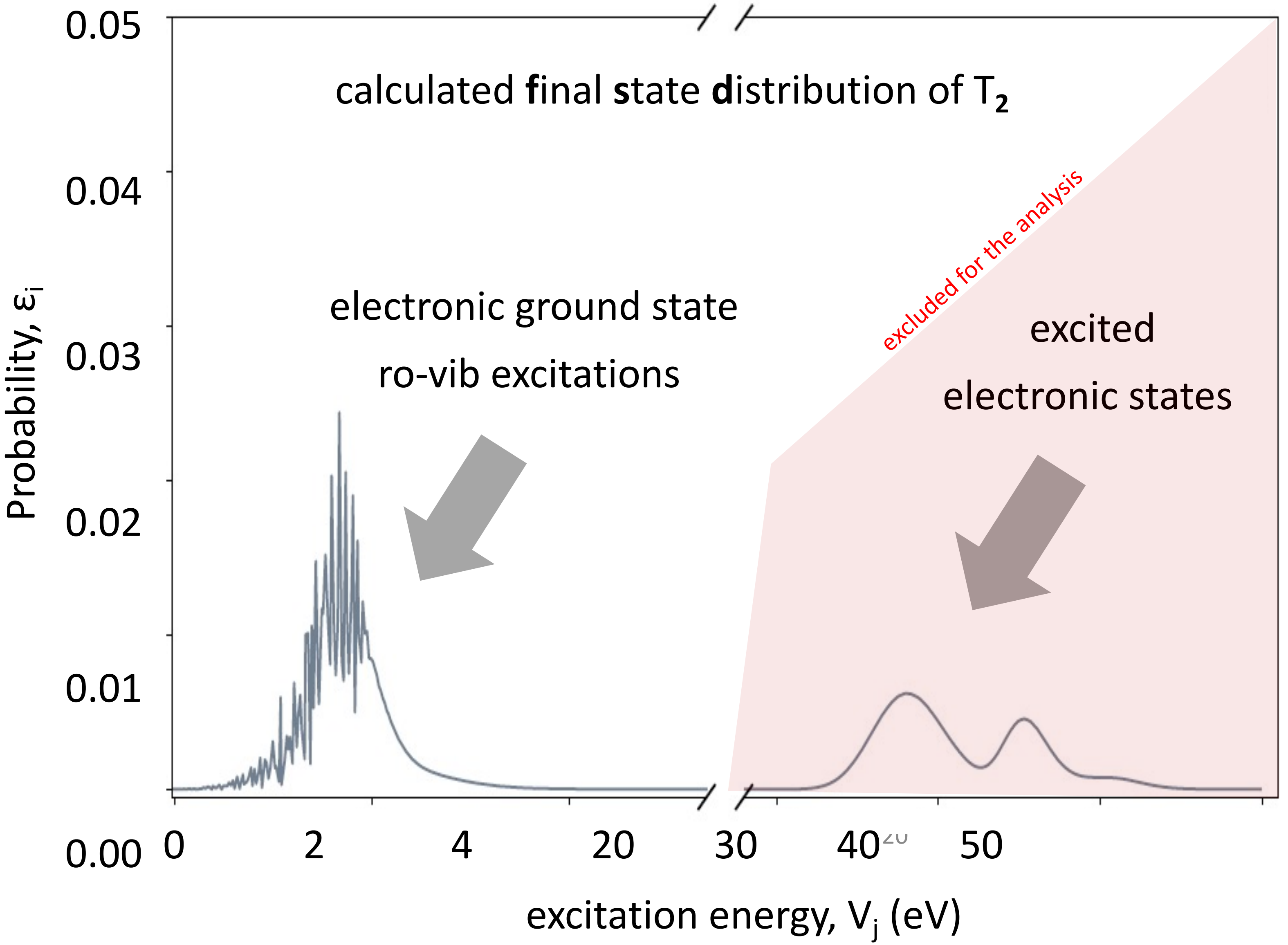


- Modification of the beta decay spectrum shape near the endpoint

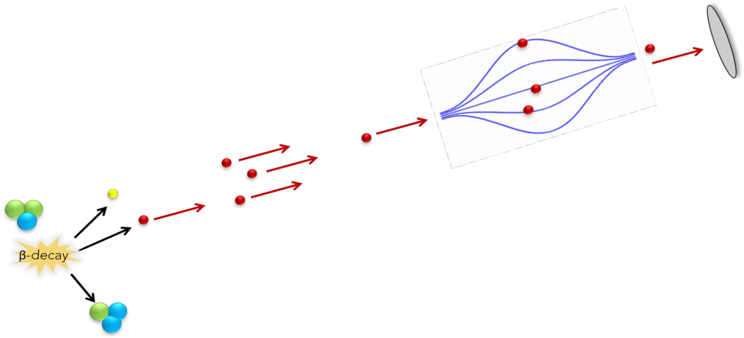
- Specific calculation for each isotopolgue



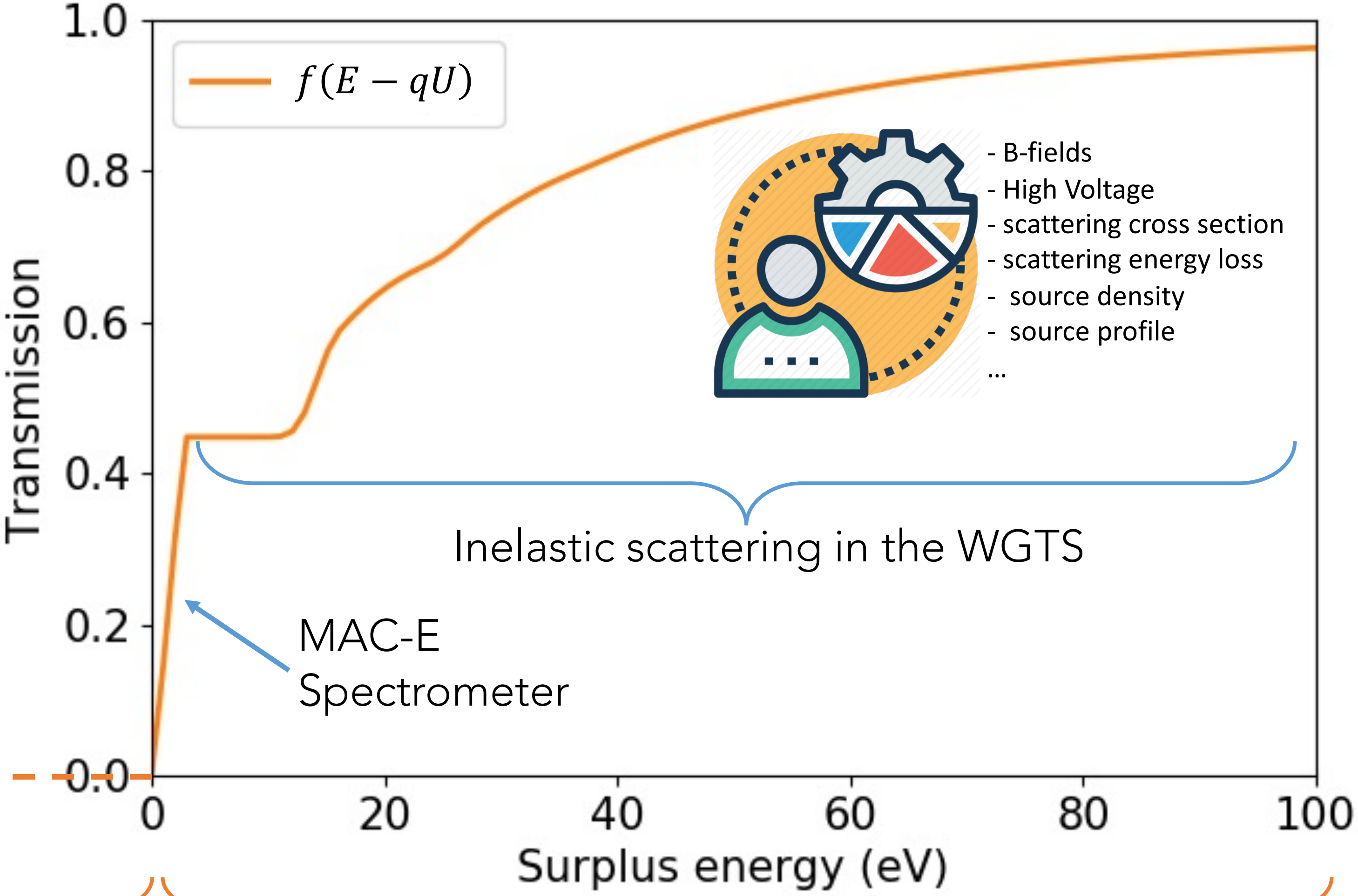
→ Some model dependency in m_ν determination



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



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



- B-fields
- High Voltage
- scattering cross section
- scattering energy loss
- source density
- source profile

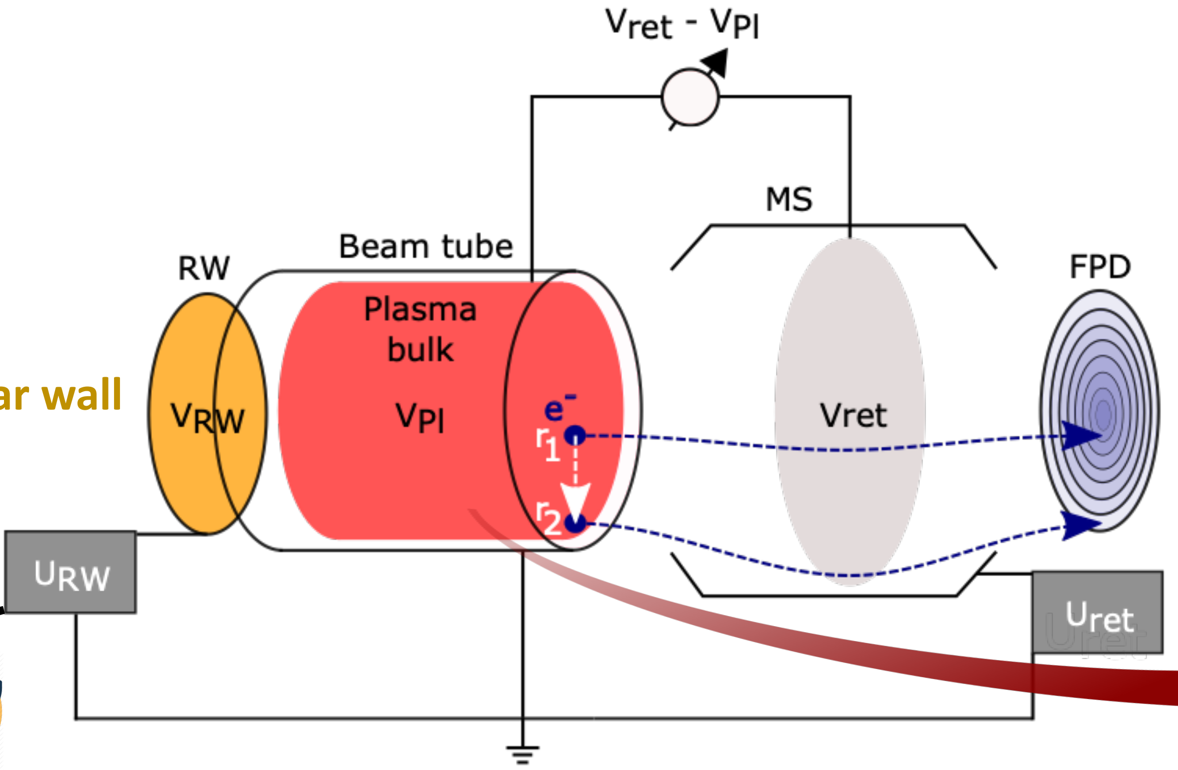
…

e⁻ not transmitted

e⁻ can be transmitted

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

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

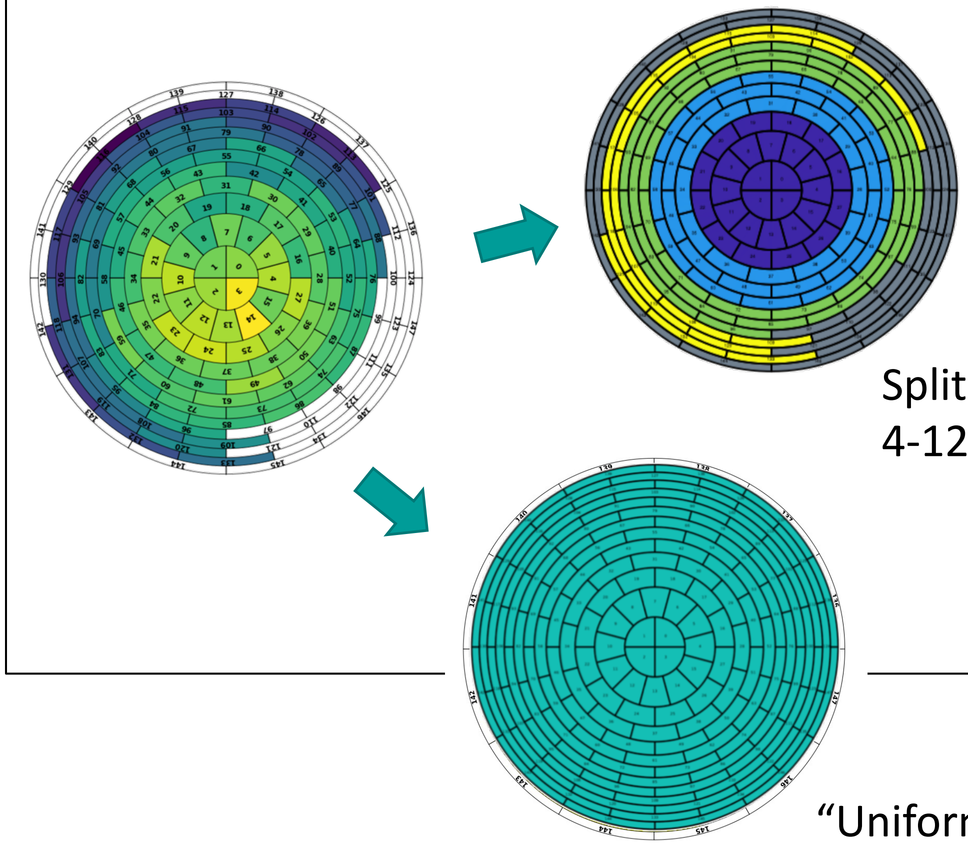
Low density radioactive magnetized plasma at 30K

Data combination

Pixel combination

- Counts in pixels of one FPD ring are added

➢ 1 *or* 4-12 spectra for each scan



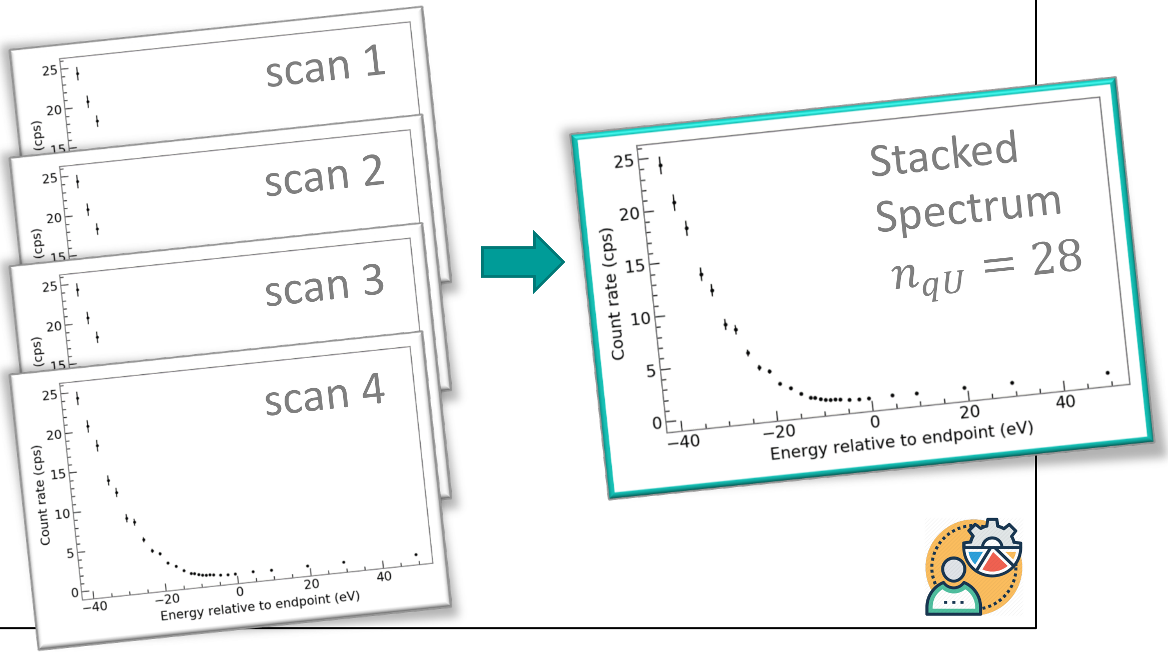
Split into
4-12 rings

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

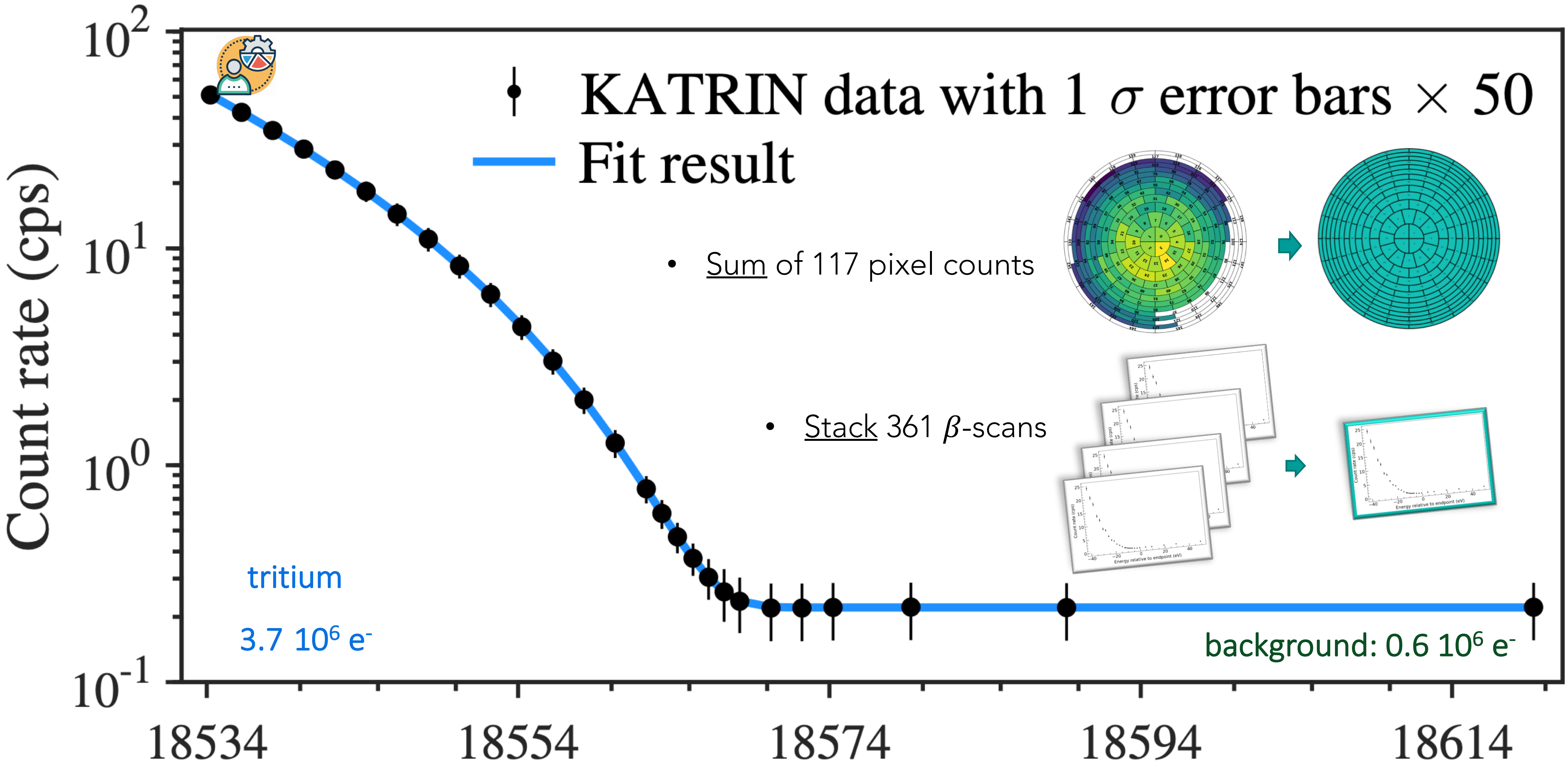
Scan combination

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

➢ 1 single spectrum from all scans



Full Stack: combination of 42237 spectra



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

Bias-free analysis

Freeze analysis on fake data

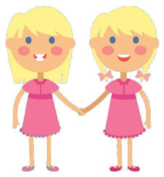
- Generate MC-copy of each scan

m_ν^2

true data

m_ν^2

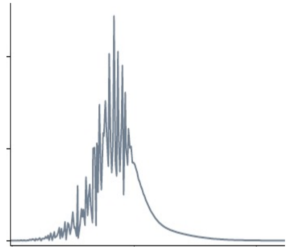
MC copy

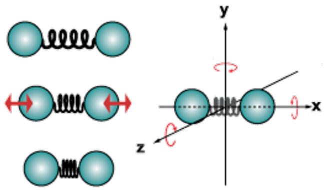


m_ν^2

Blinded model

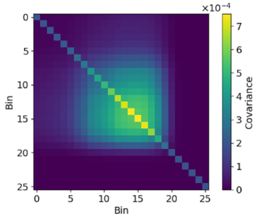
- Modified molecular final state dist.

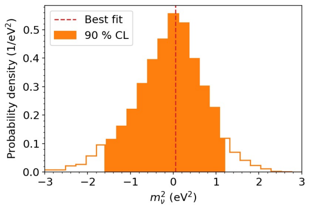




Independent analysis strategies

- Cov. matrix, MC prop, Pull-terms, Bayes



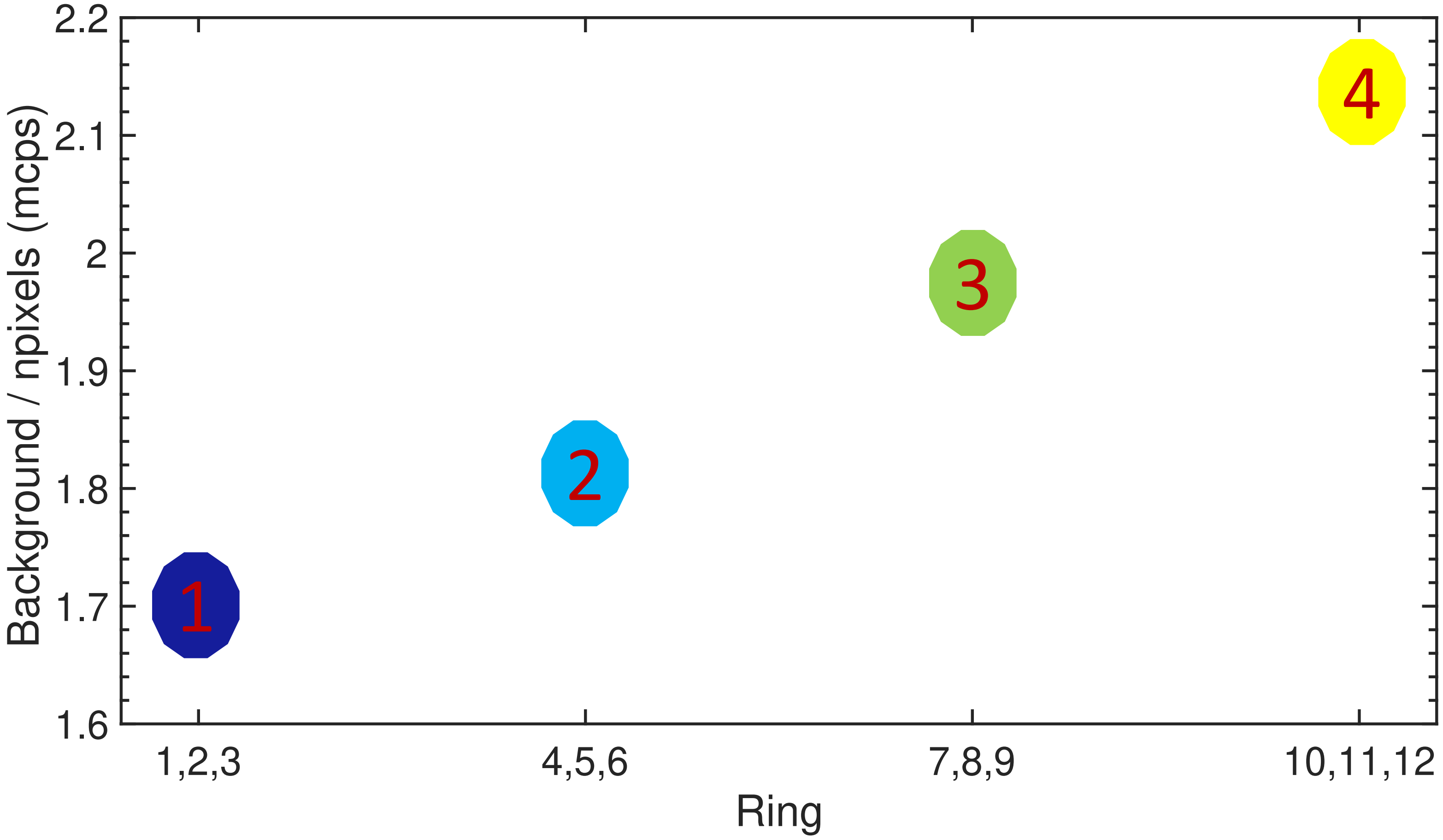


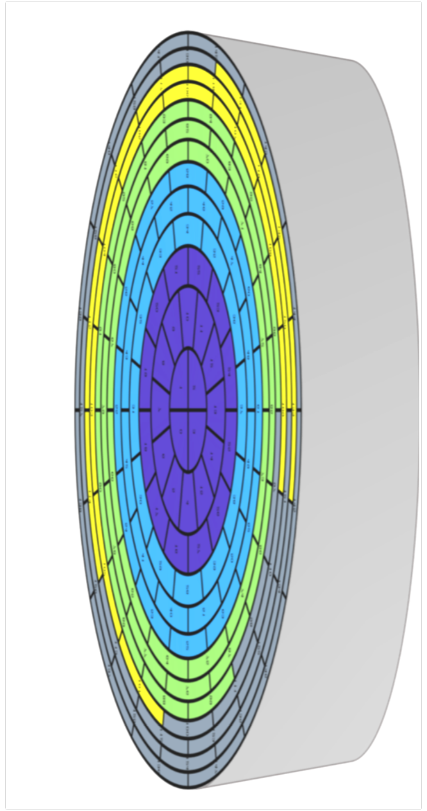
This talk – other analyses can be seen at: https://arxiv.org/abs/2105.08533

Accounting for radial Bkg / qU_{source} dependence

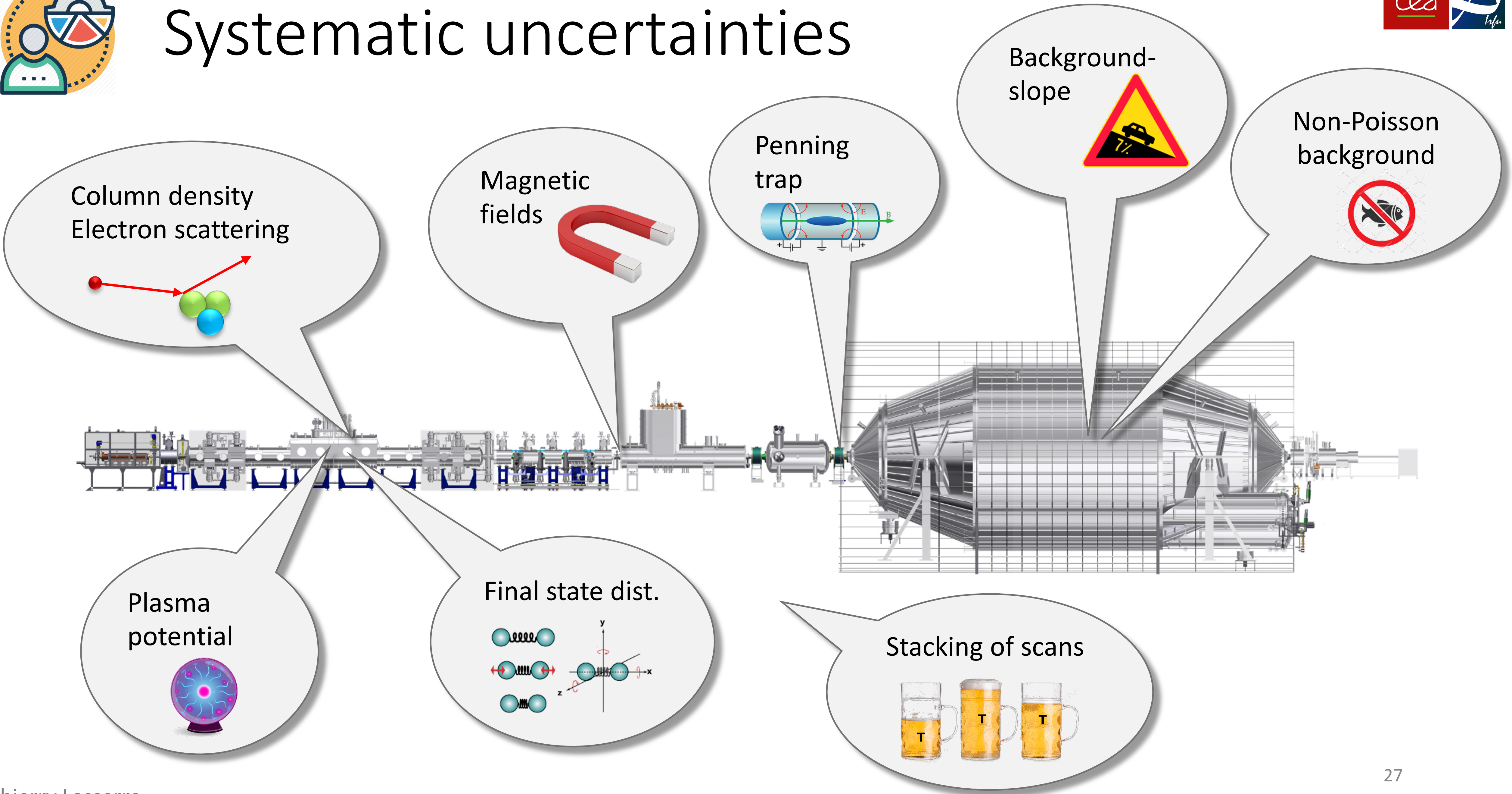
- Background rate is radial dependent
- Radial variation of the source electric potential

} Absorbed by the ring-wise analysis





Systematic uncertainties



Column density

Electron scattering

Magnetic fields

Penning trap

Background-slope

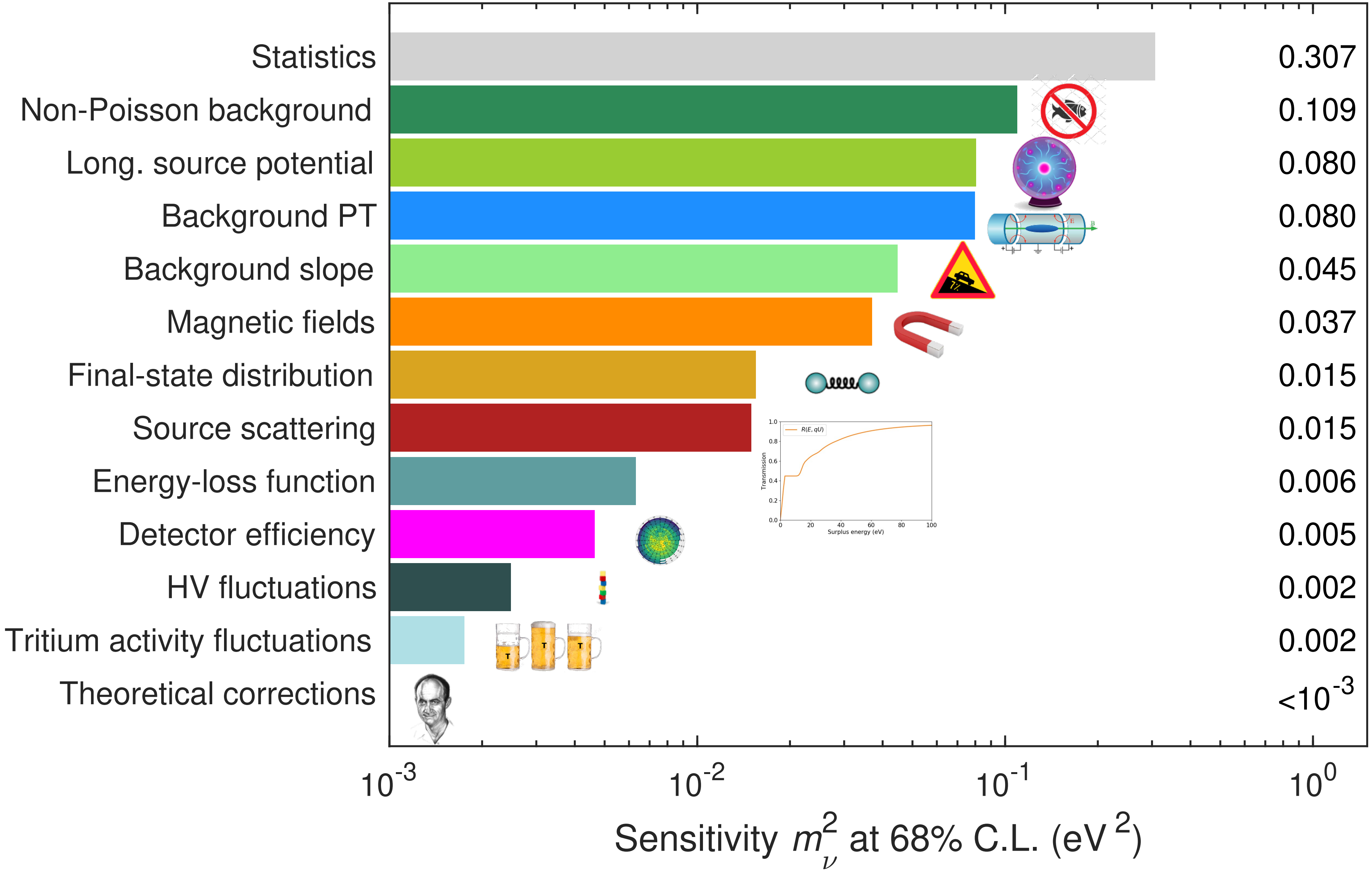
Non-Poisson background

Plasma potential

Final state dist.

Stacking of scans

Budget of uncertainties (MC, 4 rings)



→ Statistics dominated

Spectral Fit Method (Saclay-MPP)

- Standard chi-square minimization

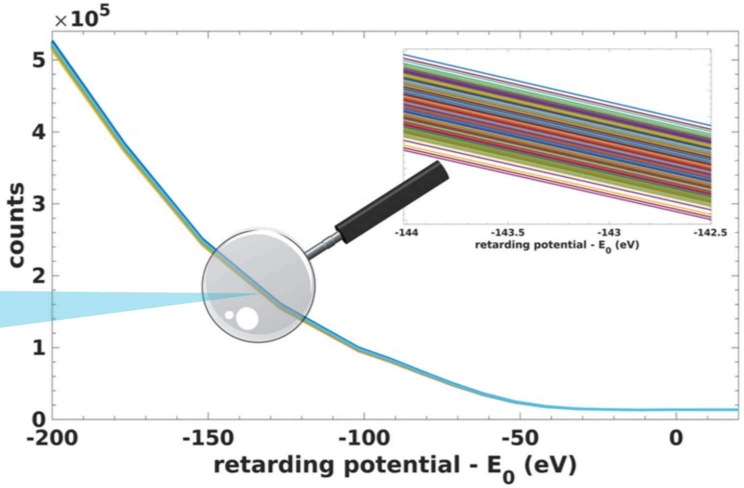
$\mathrm{m}_\nu^2, \mathrm{E}_0, \mathrm{B}, \mathrm{A}$

B-fields,
ρd, plasma,
etc.

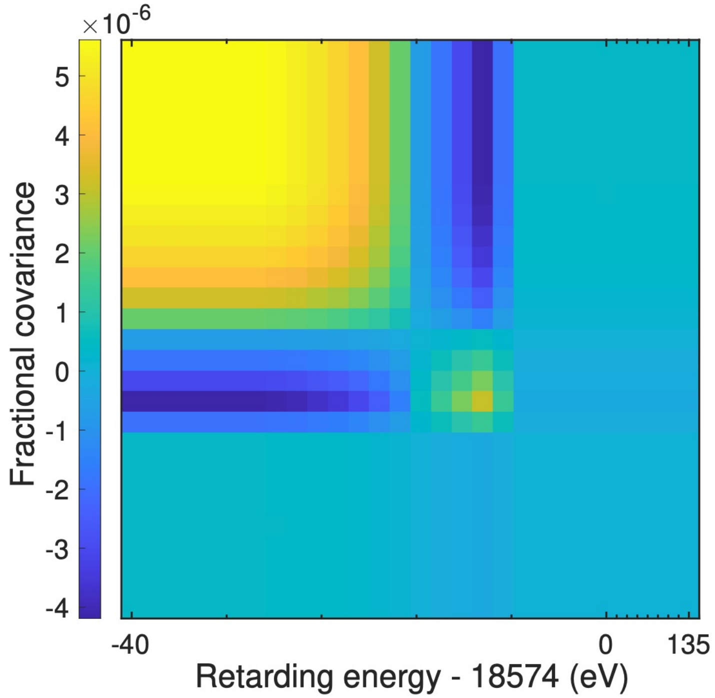
$$\chi^2 = \left(\vec{R}_{\text{data}}(q\vec{U},\vec{r}) - \vec{R}(q\vec{U},\vec{r}|\vec{\Theta},\vec{\eta})\right)^T C^{-1} \left(\vec{R}_{\text{data}}(q\vec{U},\vec{r}) - \vec{R}(q\vec{U},\vec{r}|\vec{\Theta},\vec{\eta})\right)$$

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

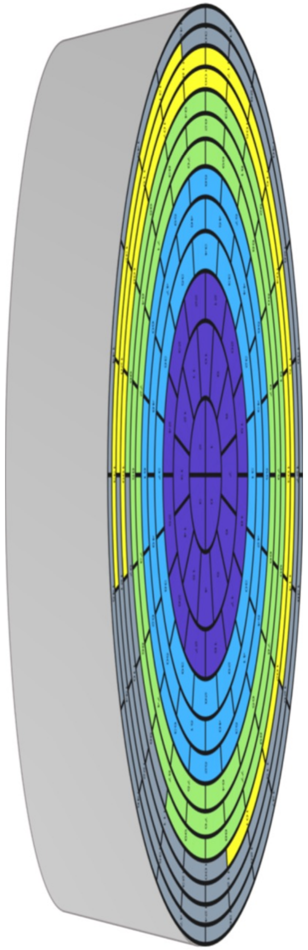
- Uncertainty propagation with covariance matrices

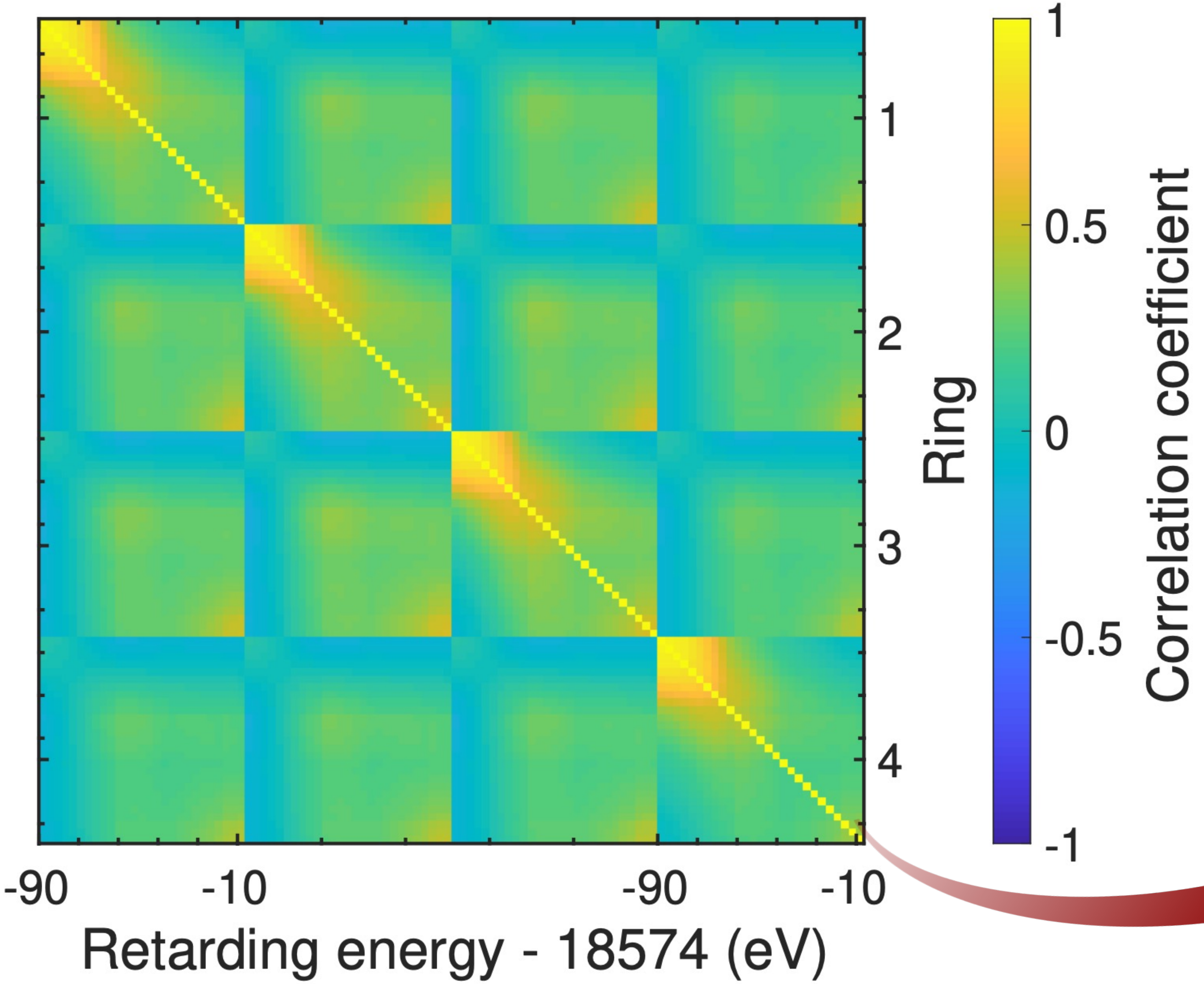


Compute 10^4 spectra with different systematic configurations



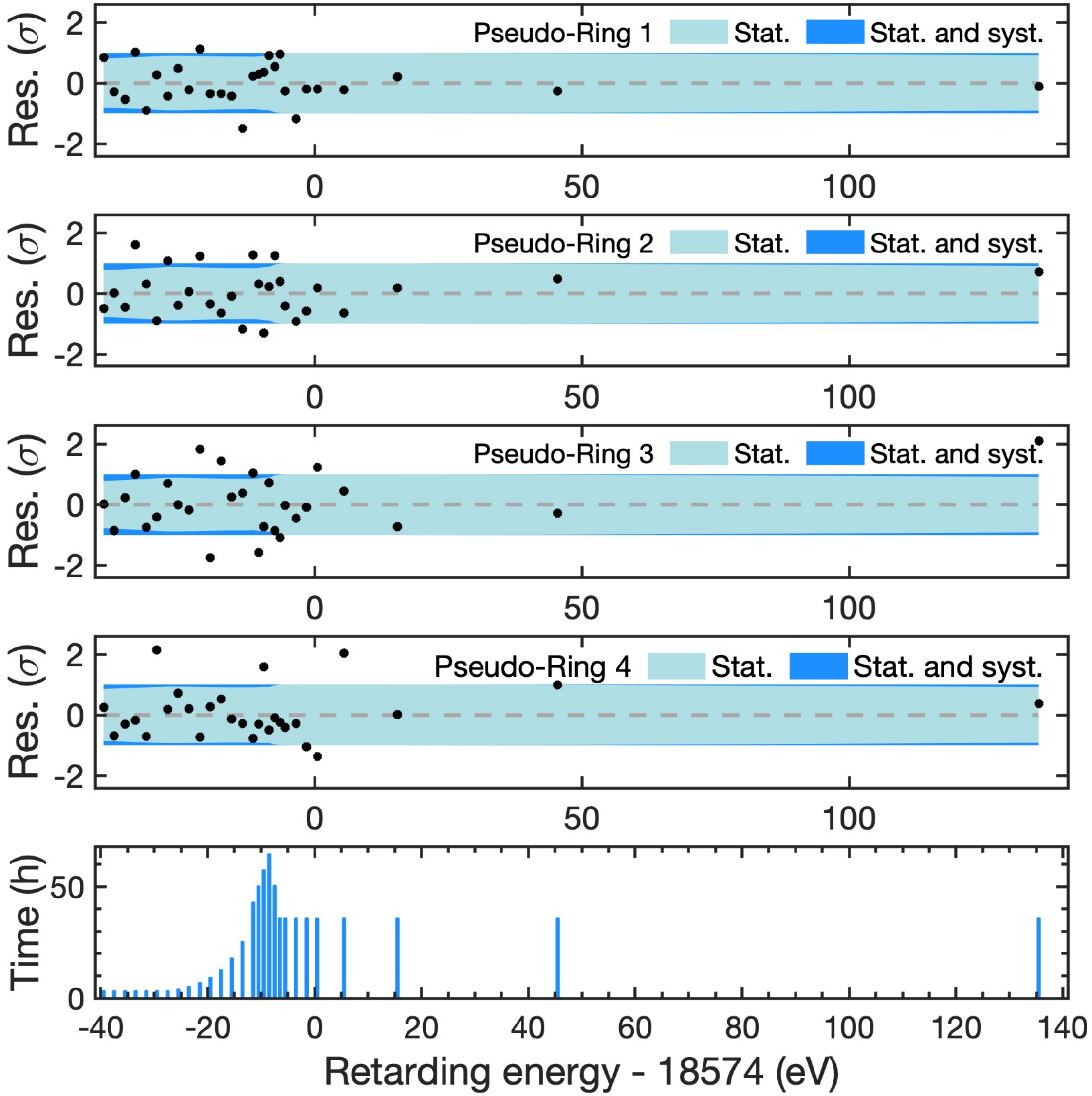
Spectral Fit Method (Saclay-MPP)





- 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

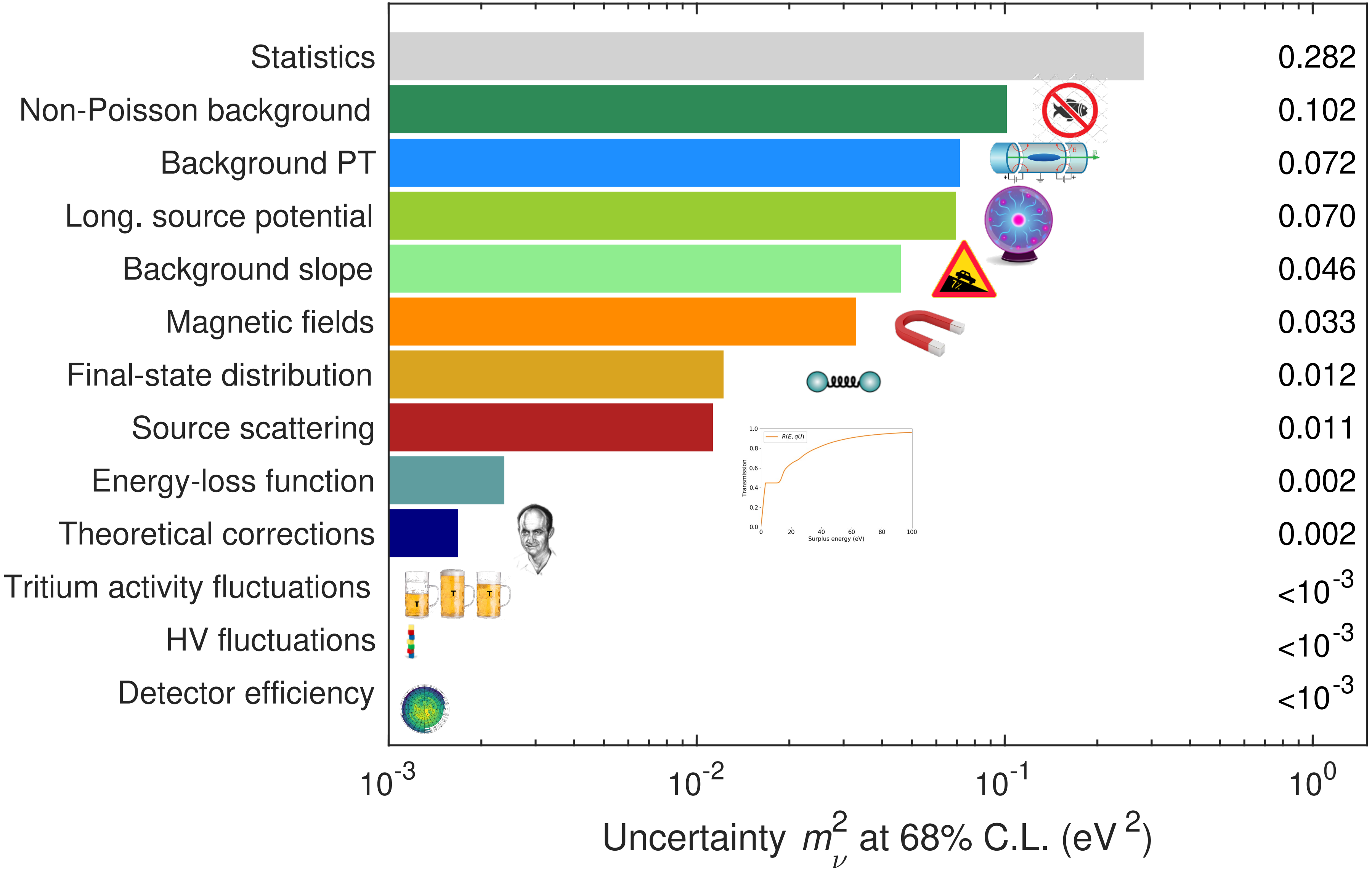
Stat. only

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

Total

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

Budget of uncertainties (Data, 4 rings)

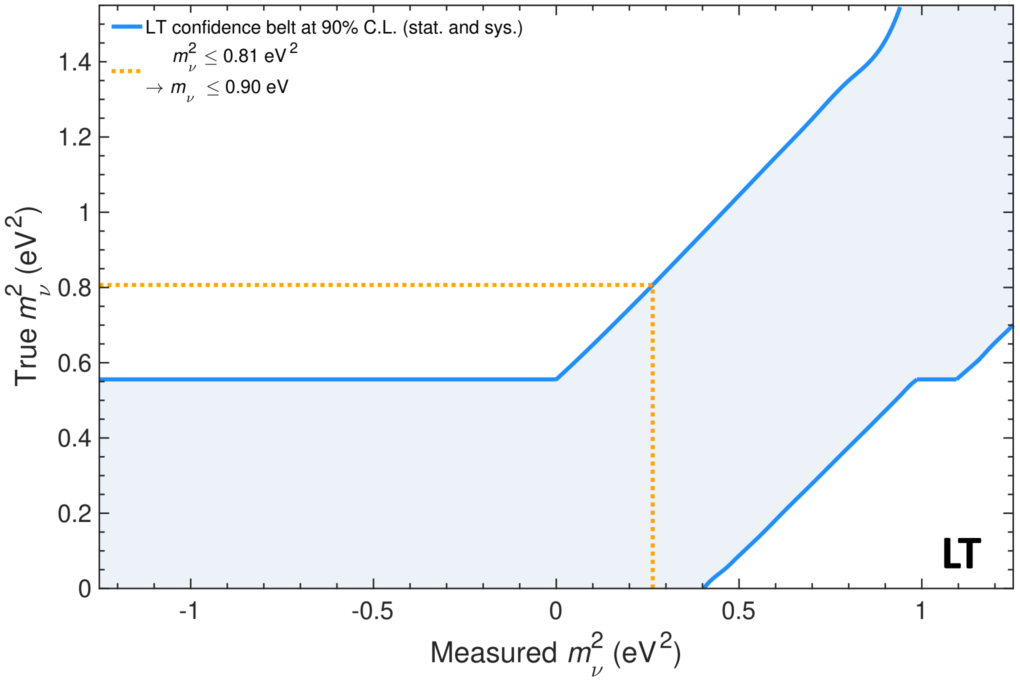


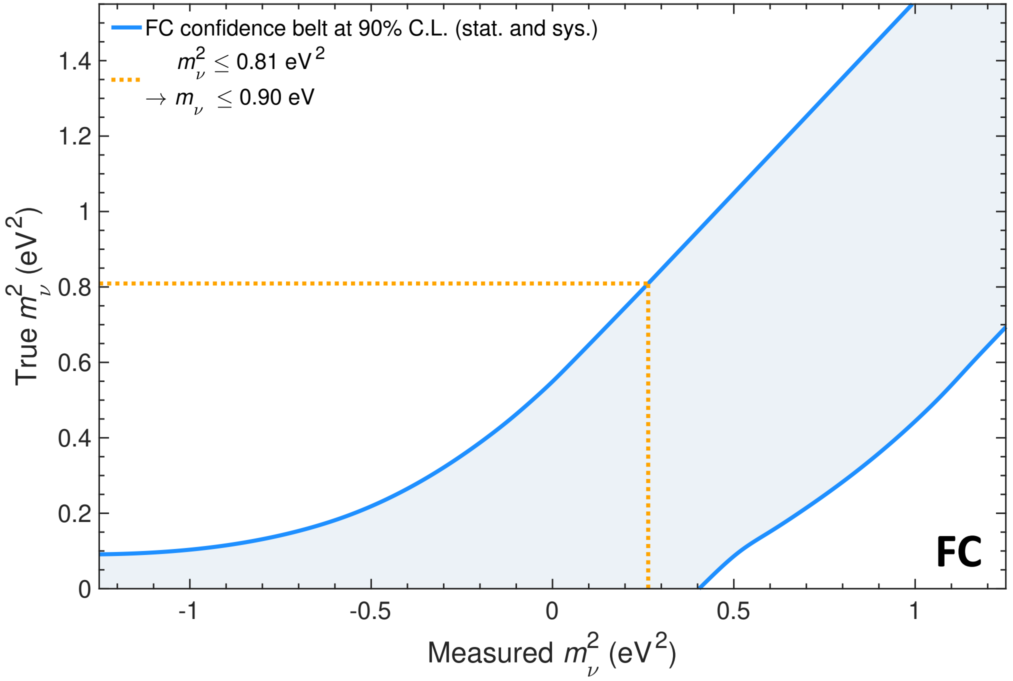
$1\sigma\ \mathrm{m}_\nu^2$

(68.3% C.L.)

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

New KATRIN limit





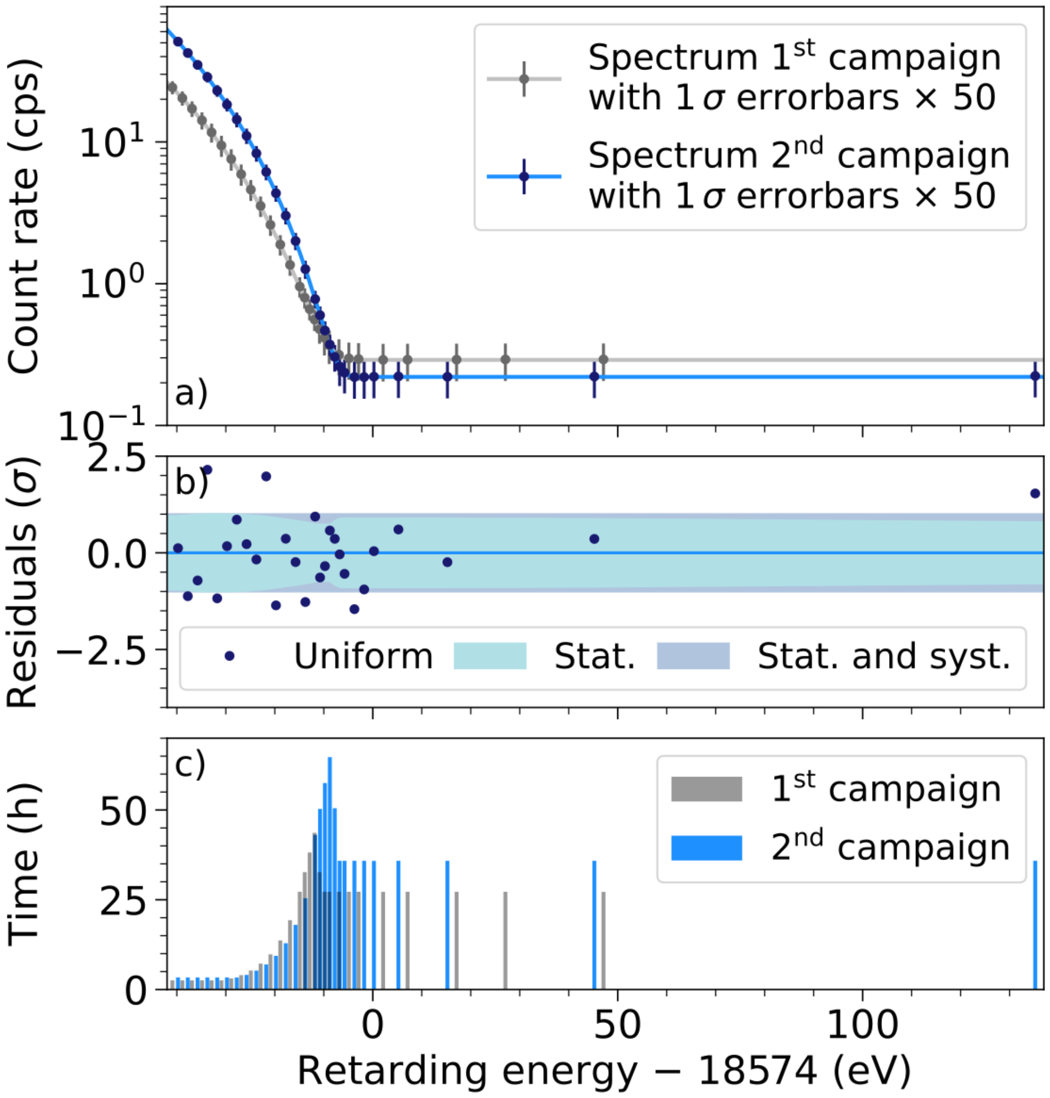
Lokhov and Tkachov (LT)

- **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 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:

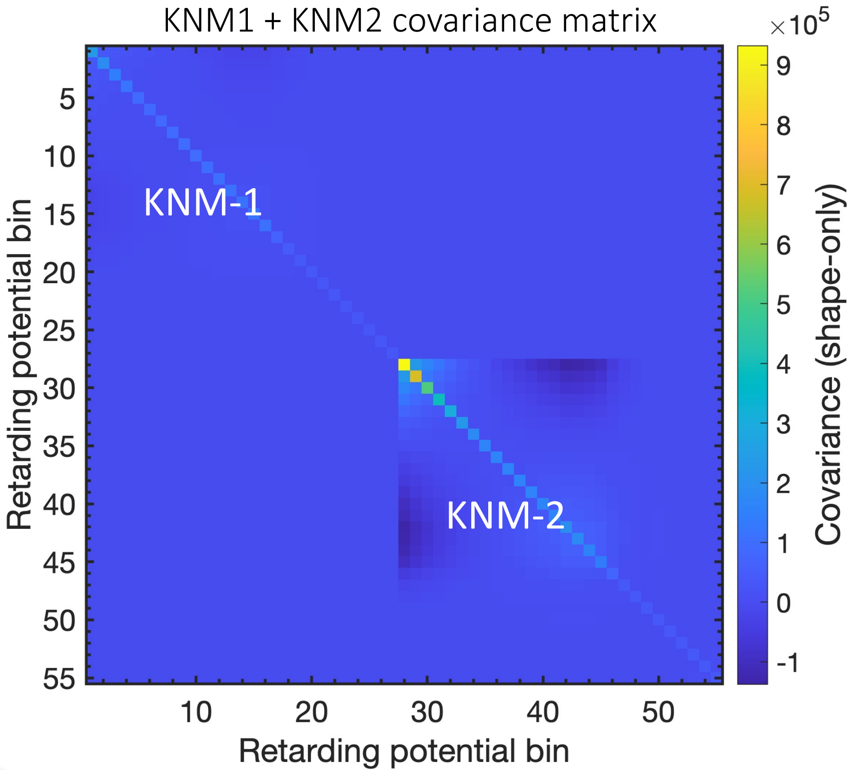
- total statistics: 4.3 million events
- background 220 mcps
- best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$eV² (stat. dom.)

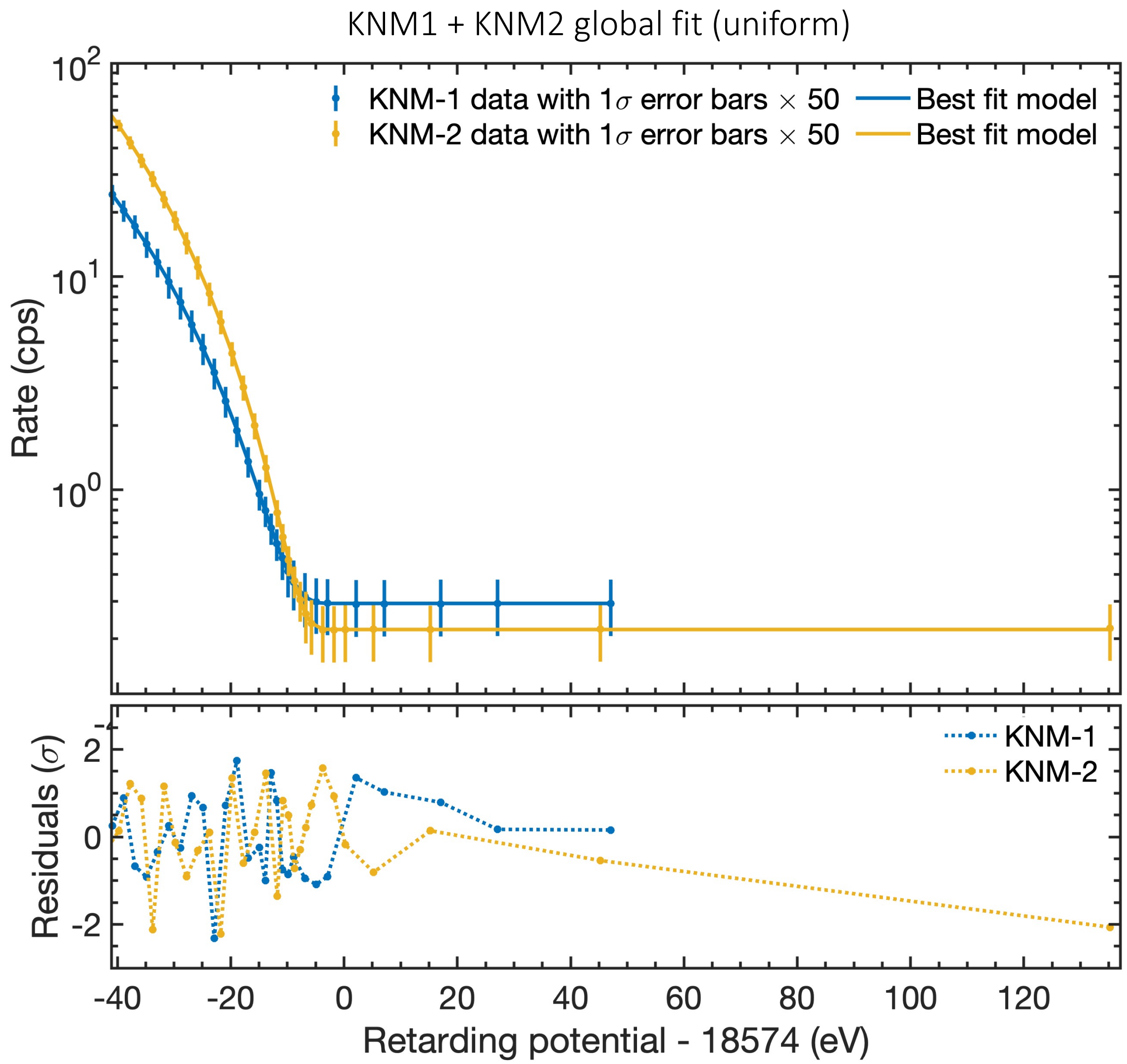
- Both KNM1 and KNM2 are statistics dominated

→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)

Conclusion

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

- 1st and 2nd campaign combined result:

$$m_\nu^2 = \left(0.1^{+0.3}_{-0.3}\right)\text{eV}^2$$

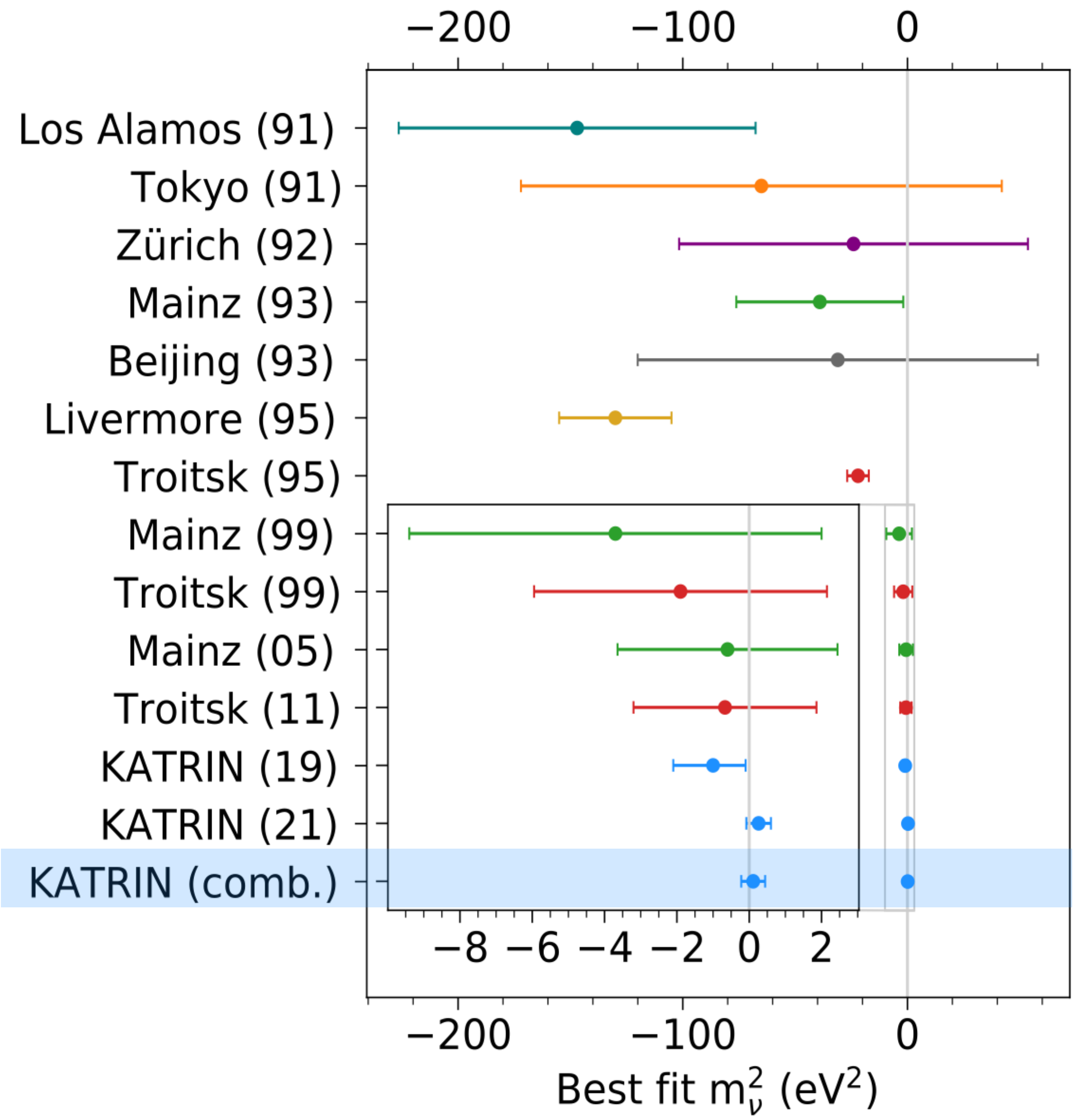
- 1st and 2nd campaign combined limit:

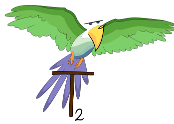
$$m_\nu < 0.8 \text{ eV (90\% CL)}$$

- **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)





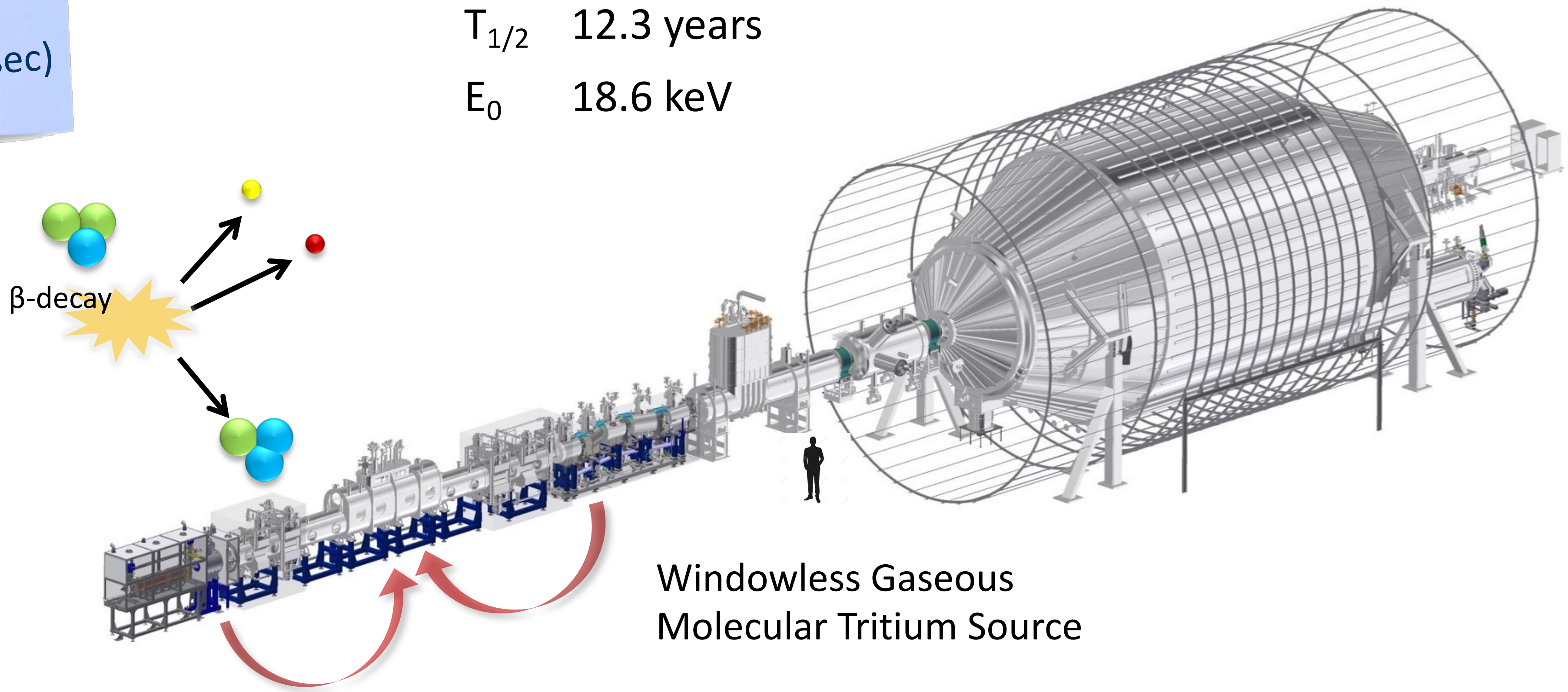
Thanks for your attention

KATRIN Working Principle

high stability
and luminosity

(10^{11} decays/sec)

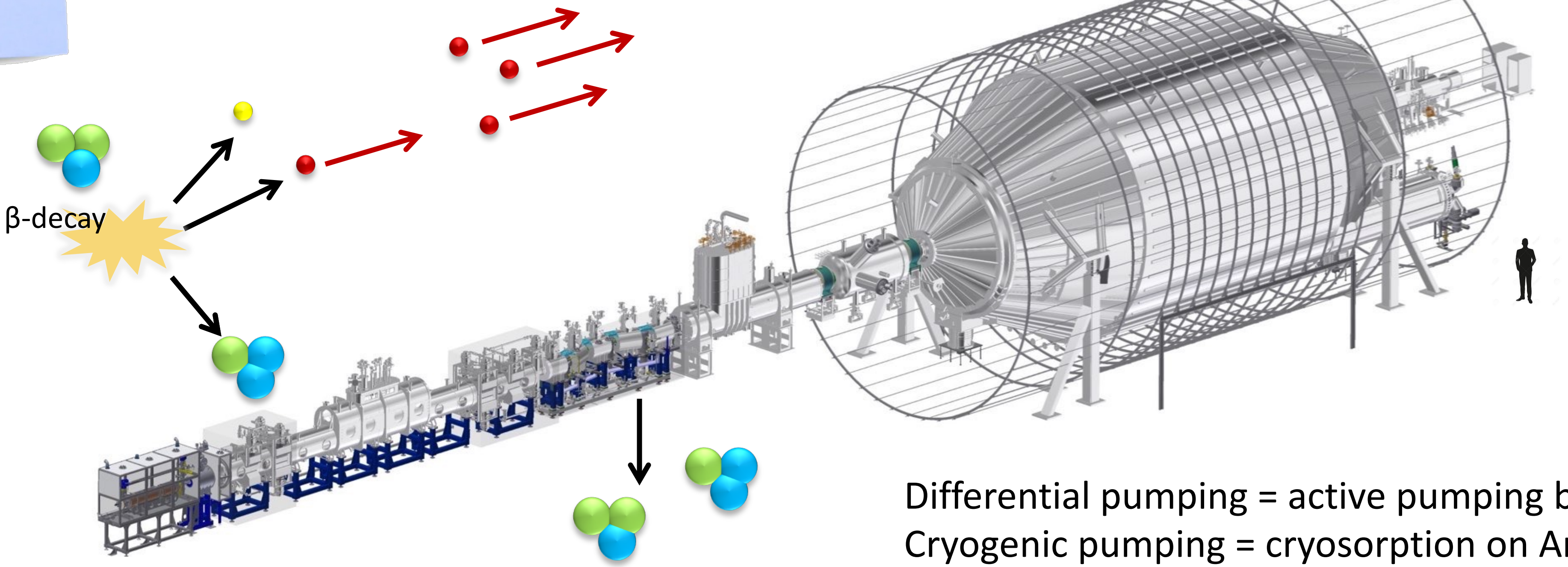
	^{3}H
	super-allowed β-decay
$T_{1/2}$	12.3 years
E_0	18.6 keV



Windowless Gaseous
Molecular Tritium Source

KATRIN Working Principle

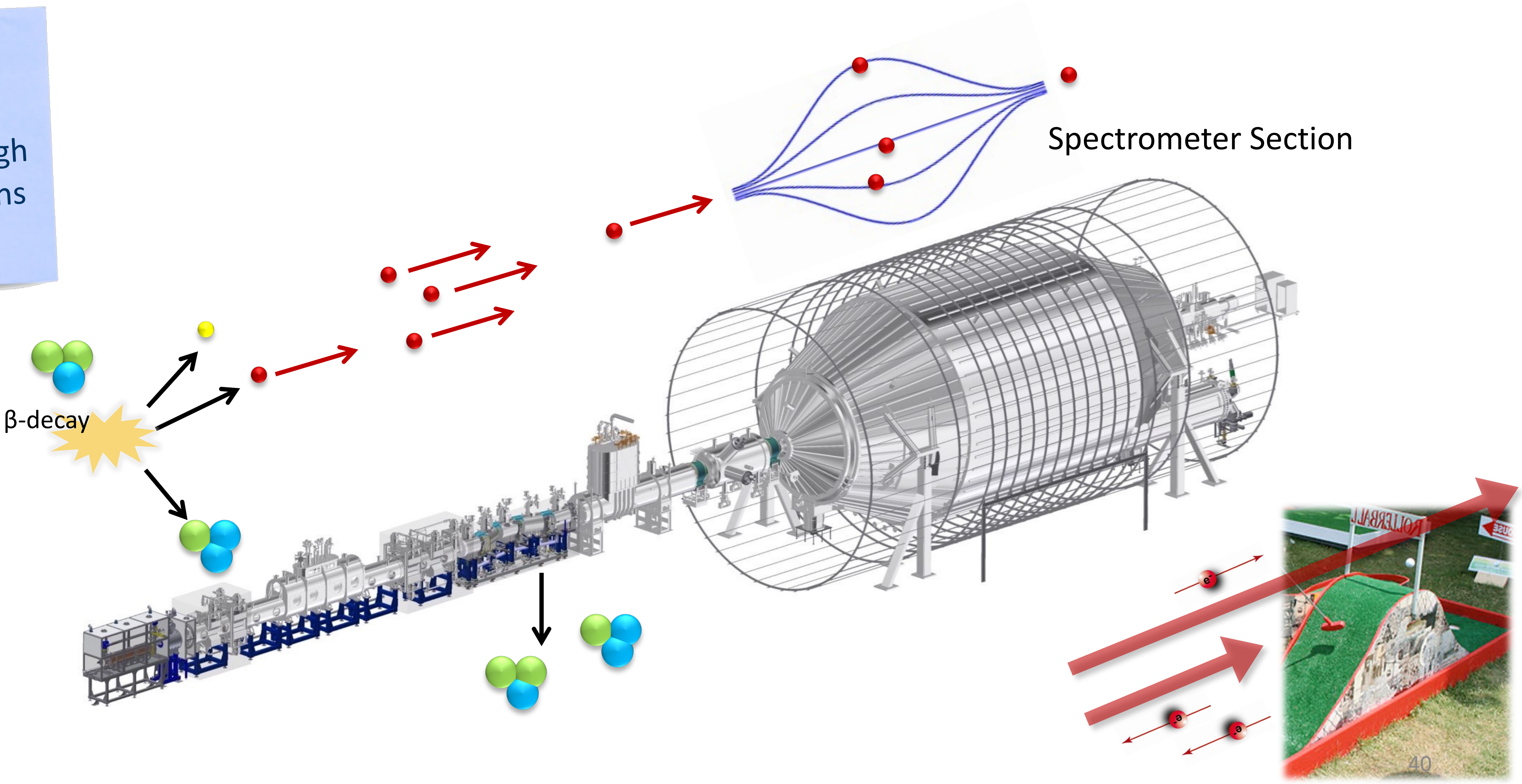
Tritium flow reduction by 14 orders of magnitude



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

KATRIN Working Principle

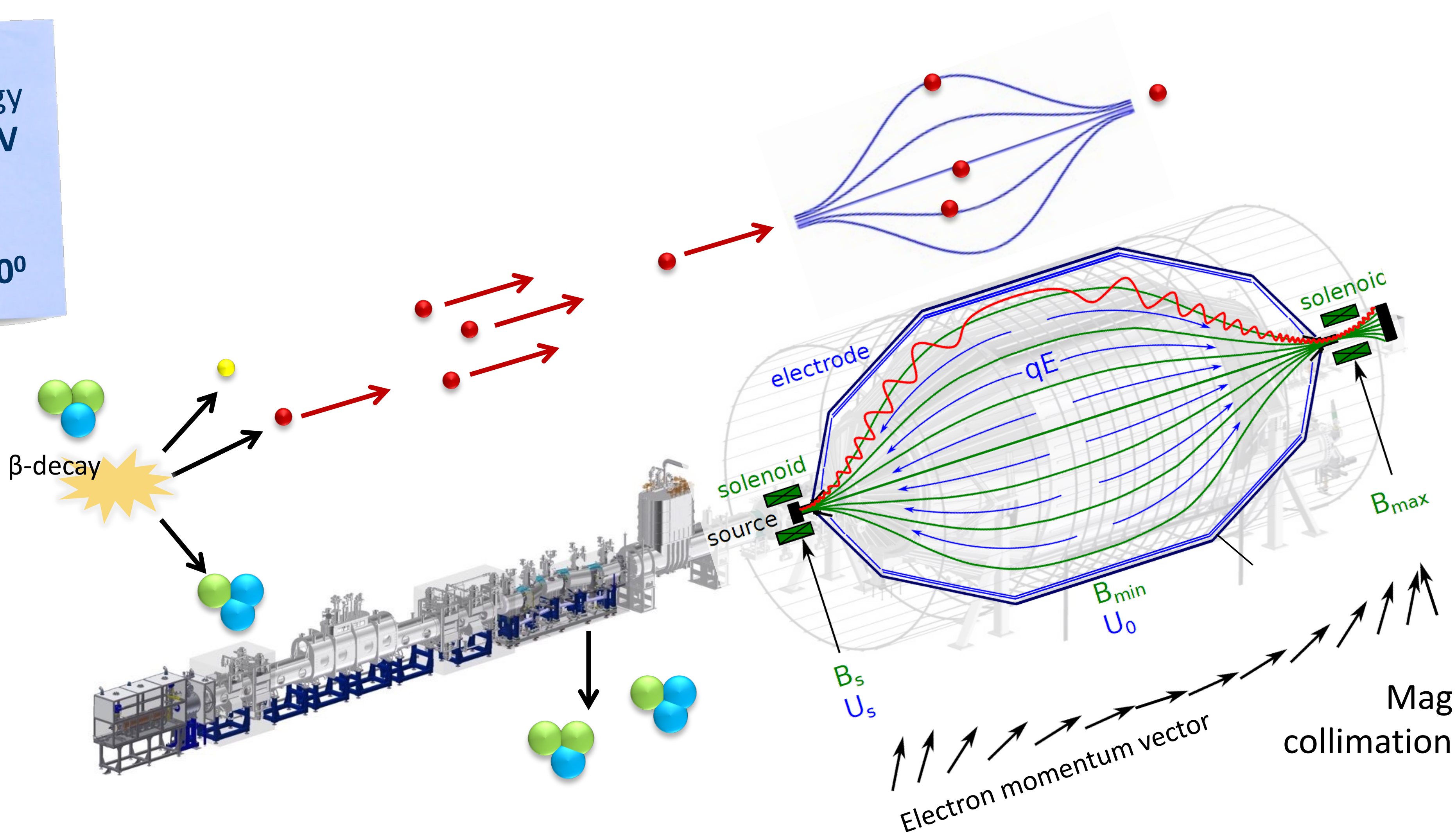
Electrostatic filter selects high energy electrons



KATRIN Working Principle

excellent energy resolution: **3 eV**

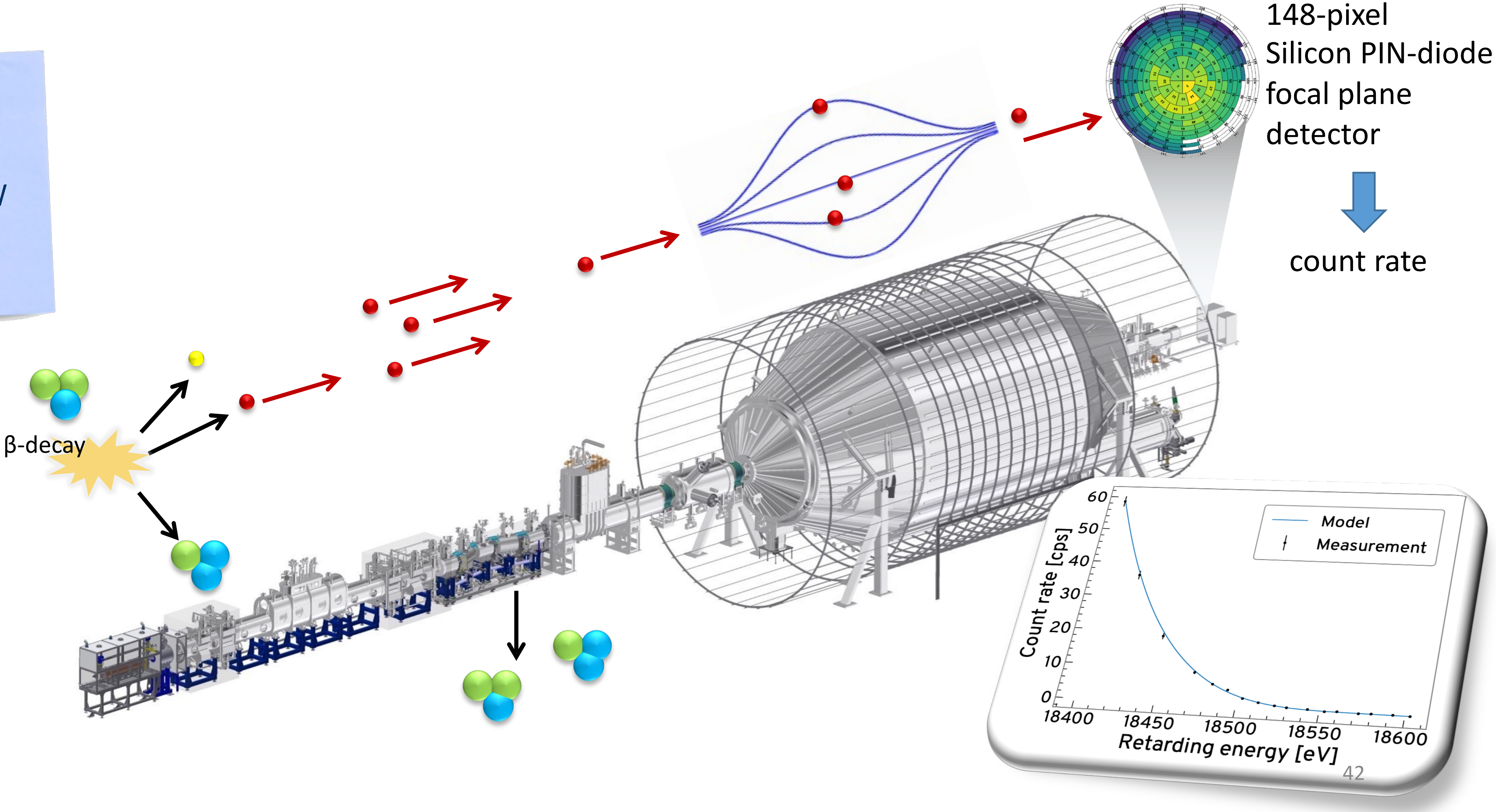
large angle acceptance: **50^0**



Magnetic adiabatic collimation + electrostatic filter (MAC-E)

KATRIN Working Principle

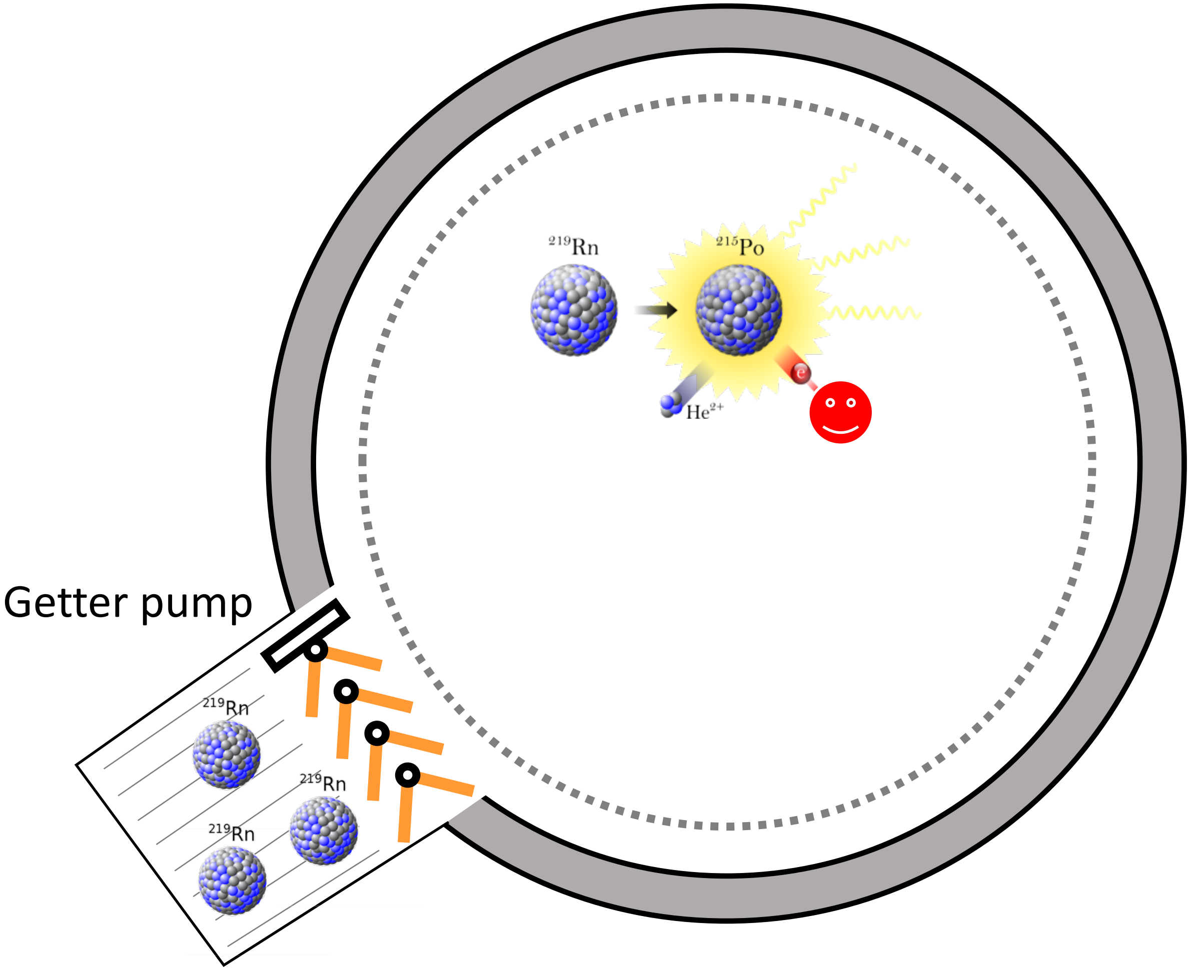
Integral measurement down to 40 eV below the endpoint



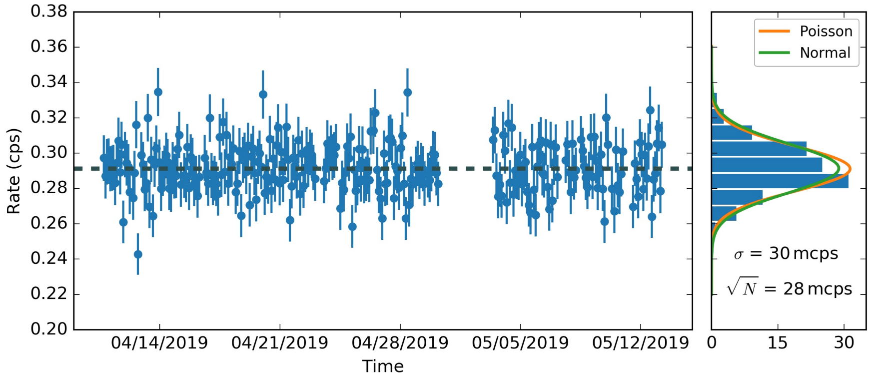
148-pixel Silicon PIN-diode focal plane detector

count rate

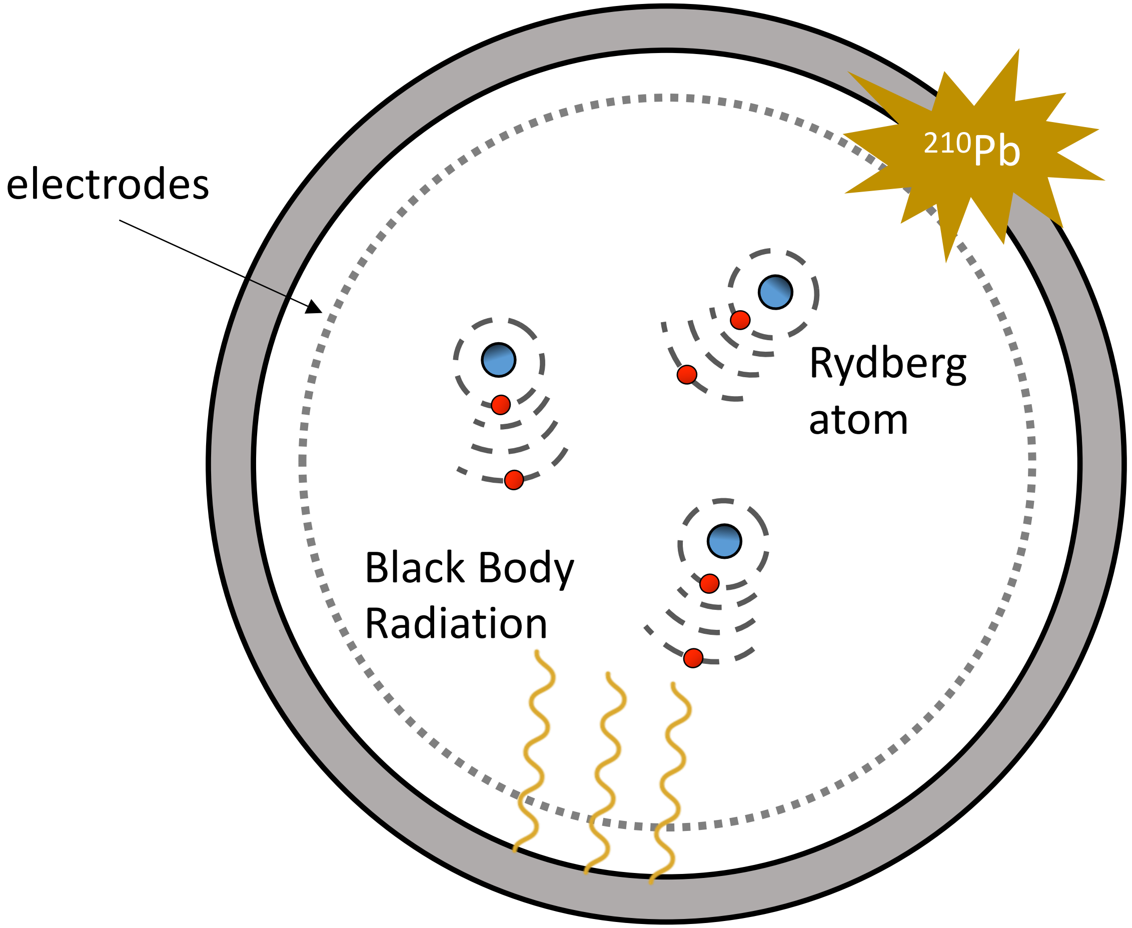
Radon-induced backgrounds



- 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

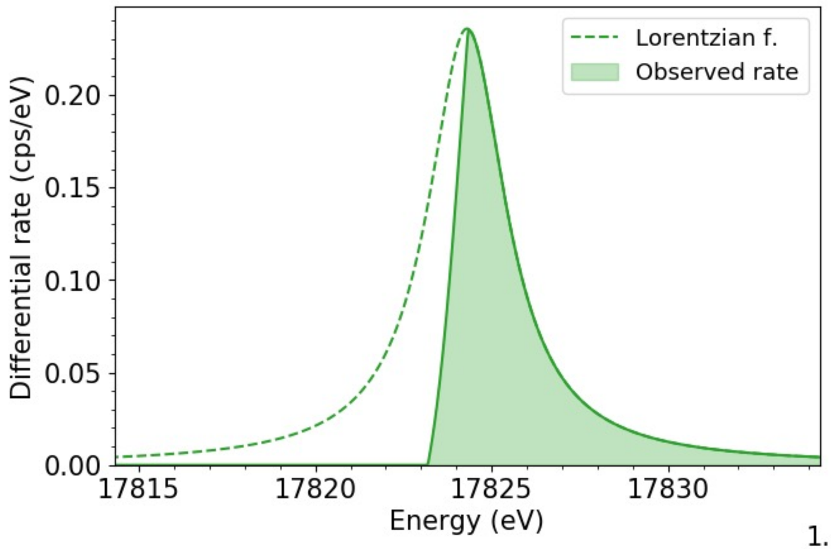


Neutral Excited Atoms

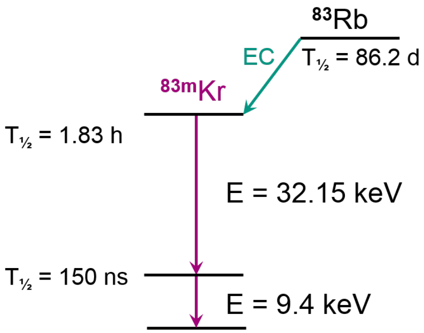


- Radon exposition during construction → ^{210}Pb surface contamination
- Rydberg atoms sputtered off from the spectrometer surfaces by ^{210}Pb α-decays
- Ionisation by thermal radiation
- Low energy e^- emission inside spectrometer
- Scale as the spectrometer volume… ☹

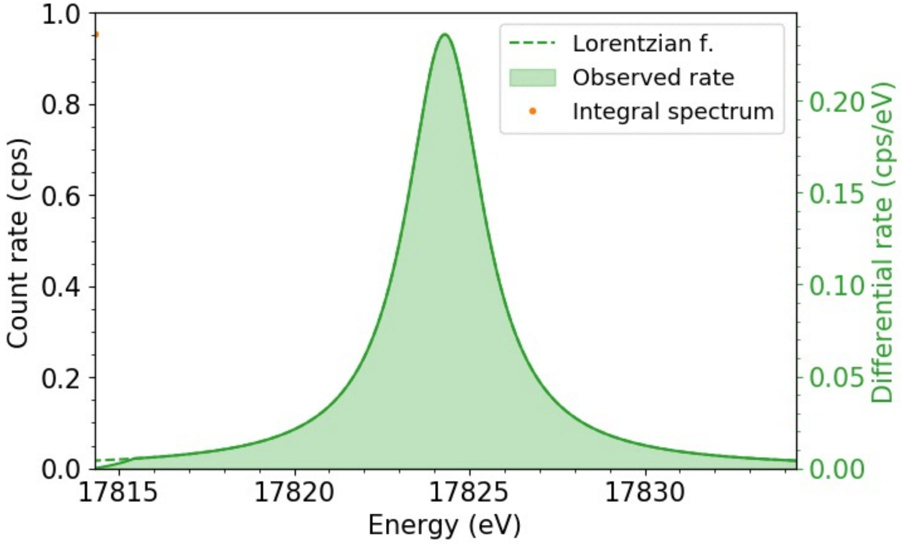
Response to quasi-monoenergic electrons

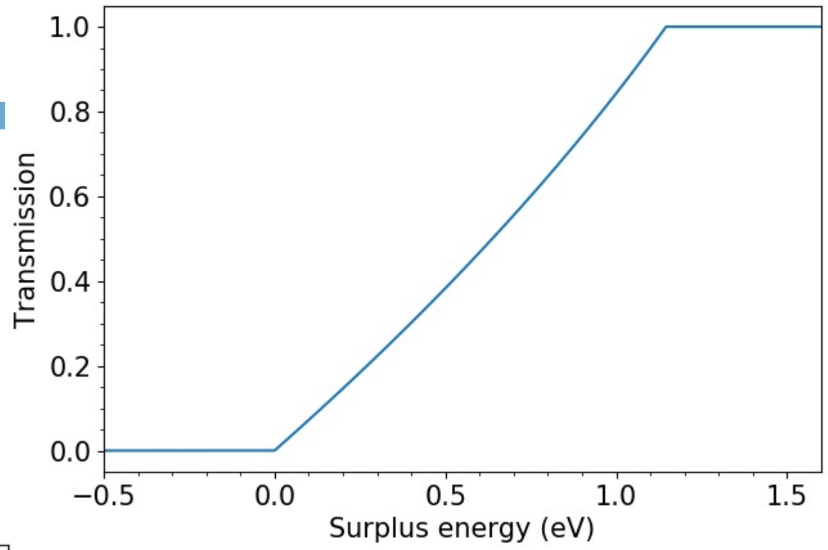


Natural line width of krypton



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

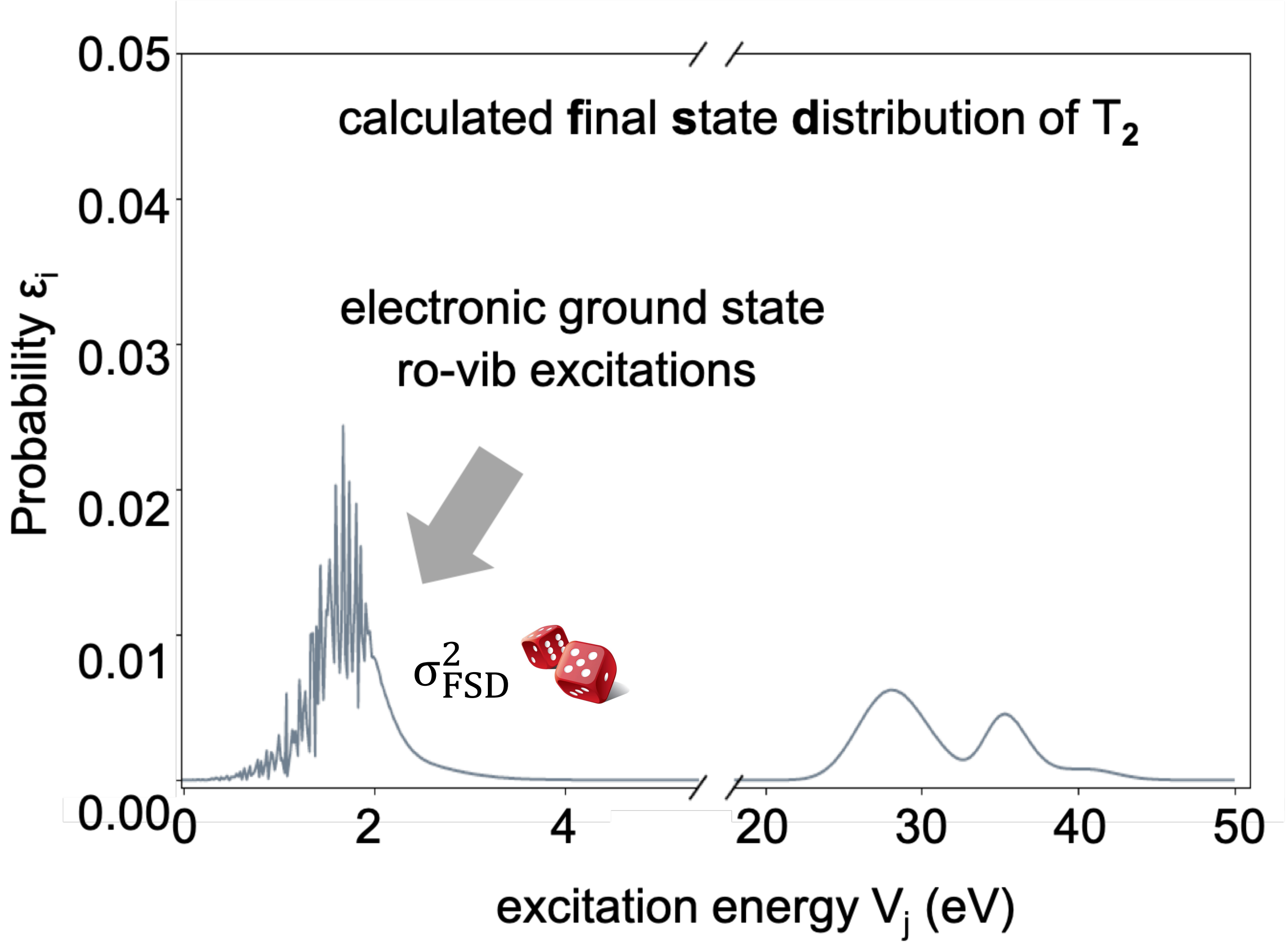




Spectrometer resolution

Blinded Model

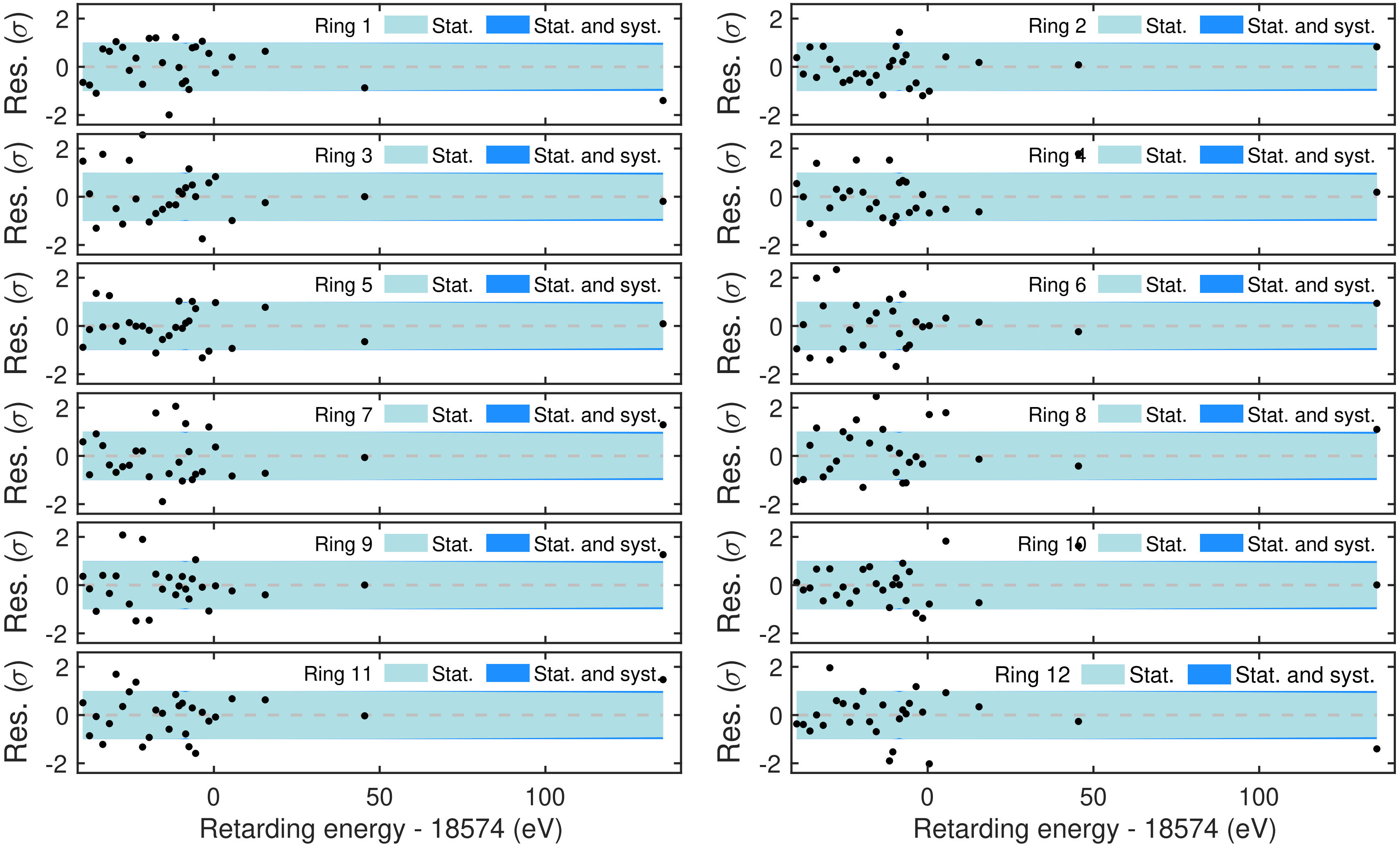
$$R(qU, E_0, m_\nu^2) \propto (qU - E_0)^3 - \overbrace{(\, m_\nu^2 - 2\,\delta\sigma_{FSD}^2)}^{m^2_{\nu,\,effective}}\,(qU - E_0)$$



- 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

Data: Split pixels in 12 rings - MultiRing-fit



- Stack pixel-wise spectra into 12 rings

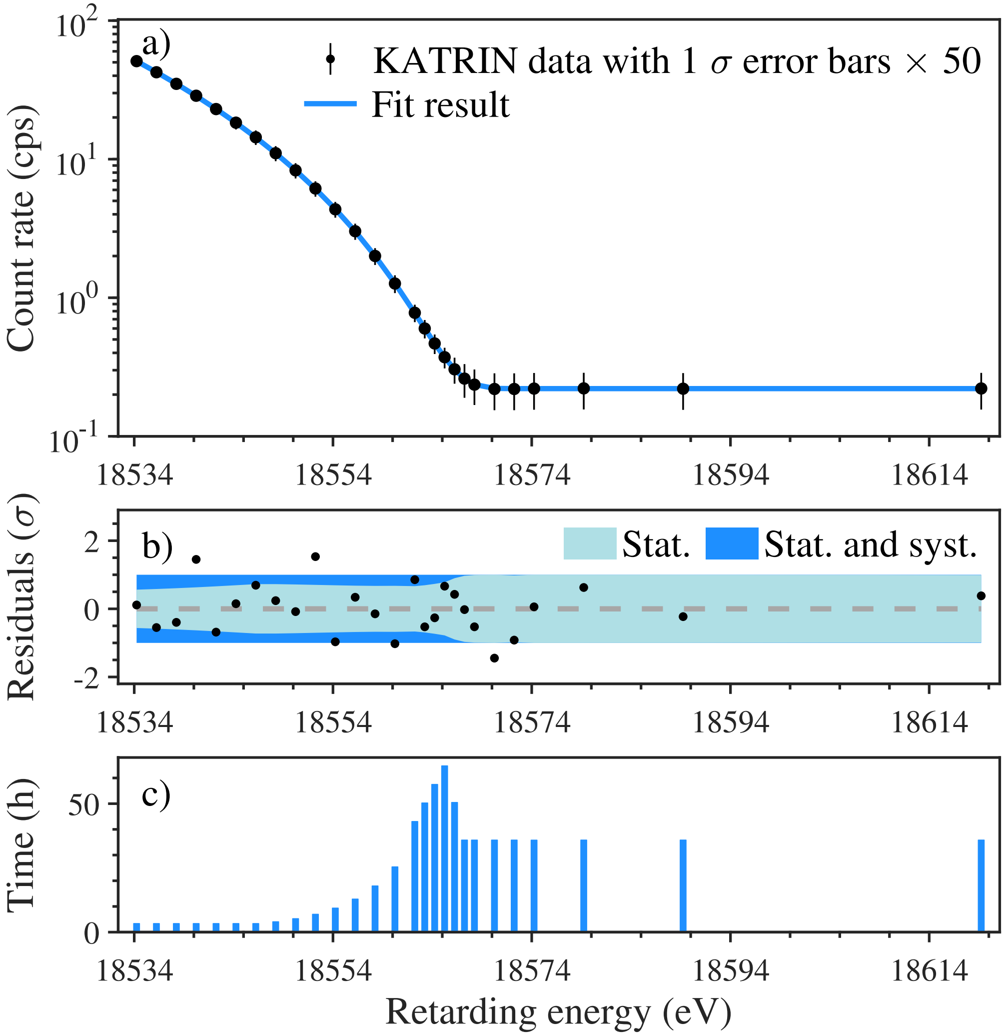
Stat. only

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

Total

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

Data: Gather all pixels – Uniform-fit



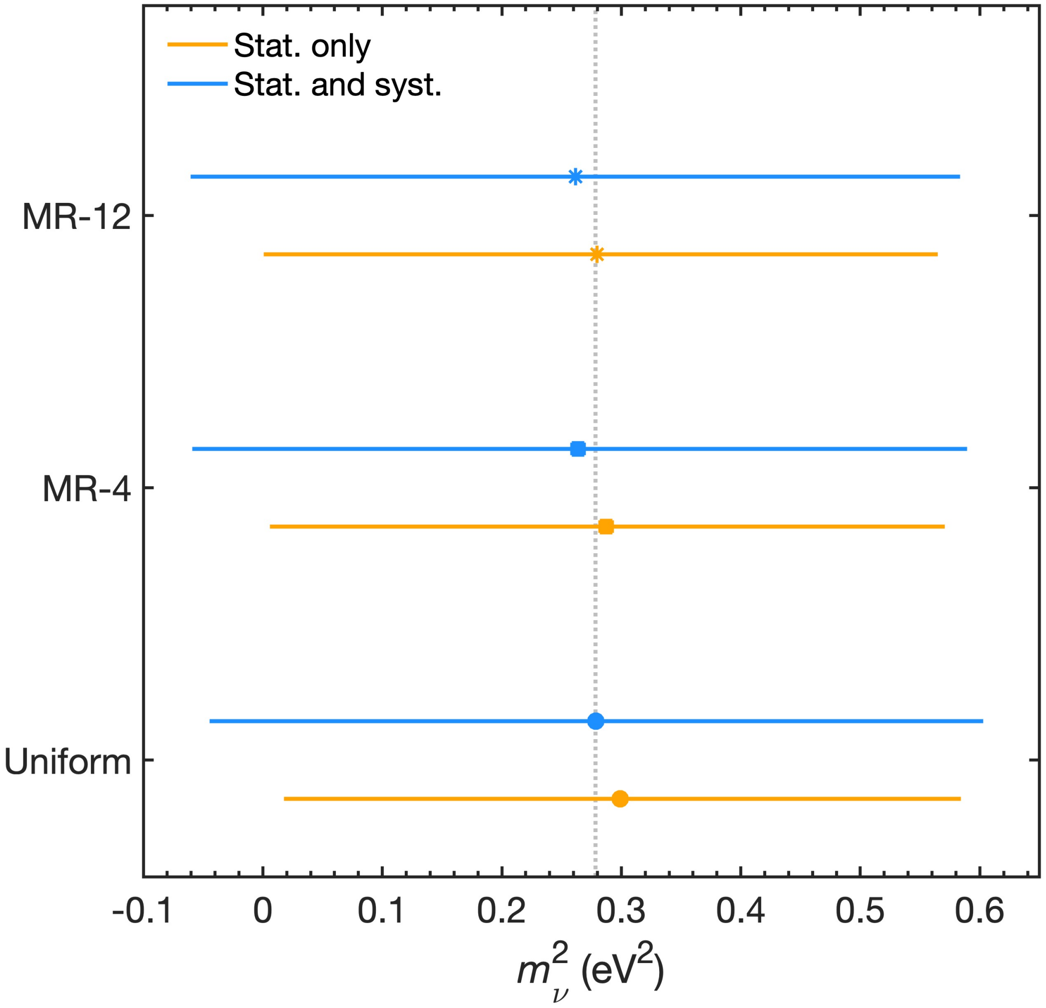
- Stack 117 pixels + all 361 scans

- Stat. Only
  - $m_\nu^2 = 0.30 \pm 0.28\ (^{+0.28}_{-0.28})\ \text{eV}^2$
  - $\chi^2_{\text{min}} = 30.4\ (24\ \text{dof})\ , p = 0.17$

- Total (with covariance matrix)
  - $m_\nu^2 = 0.28 \pm 0.32\ (^{+0.32}_{-0.32})\ \text{eV}^2$
  - $\chi^2_{\text{min}} = 27.5\ (24\ \text{dof})\ ,\ p = 0.28$

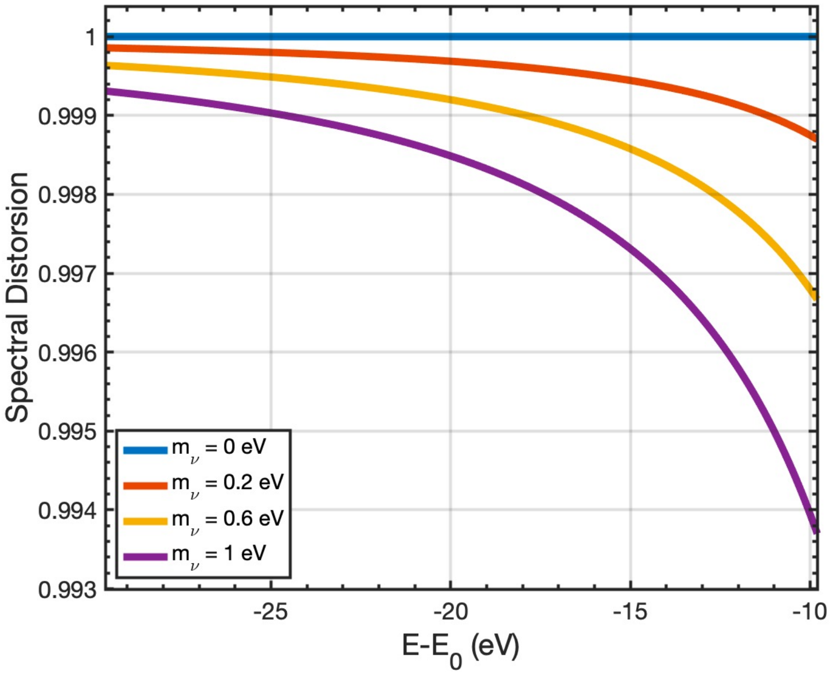
Comparison pixel combination strategies

- 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

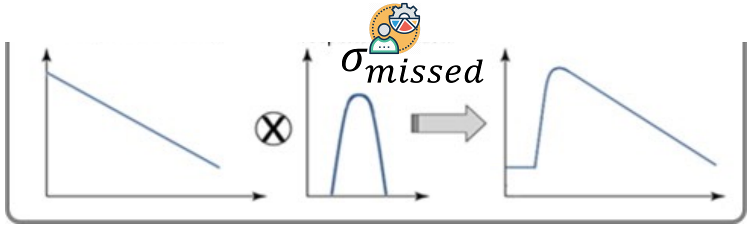


Impact of any mis-modeling?

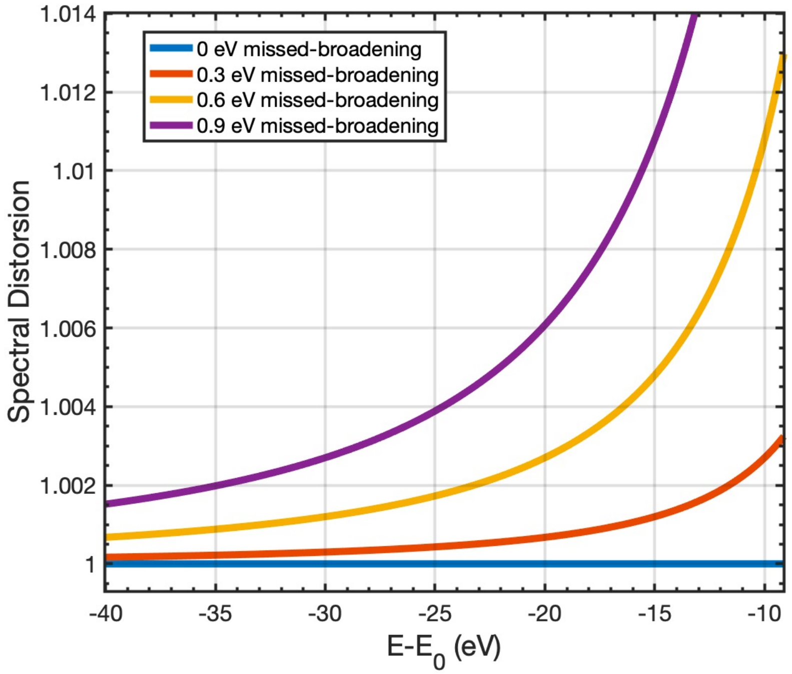
Expected neutrino mass signature
(lower counts near endpoint)



Missed systematics:
spectrum convoluted with gaussian



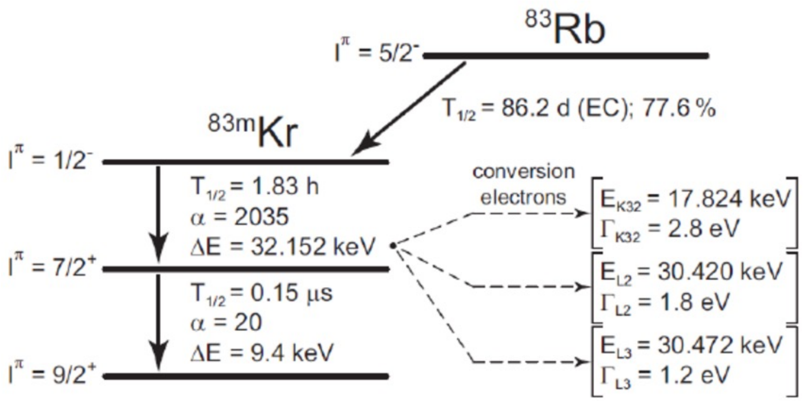
Increase counts near the endpoint

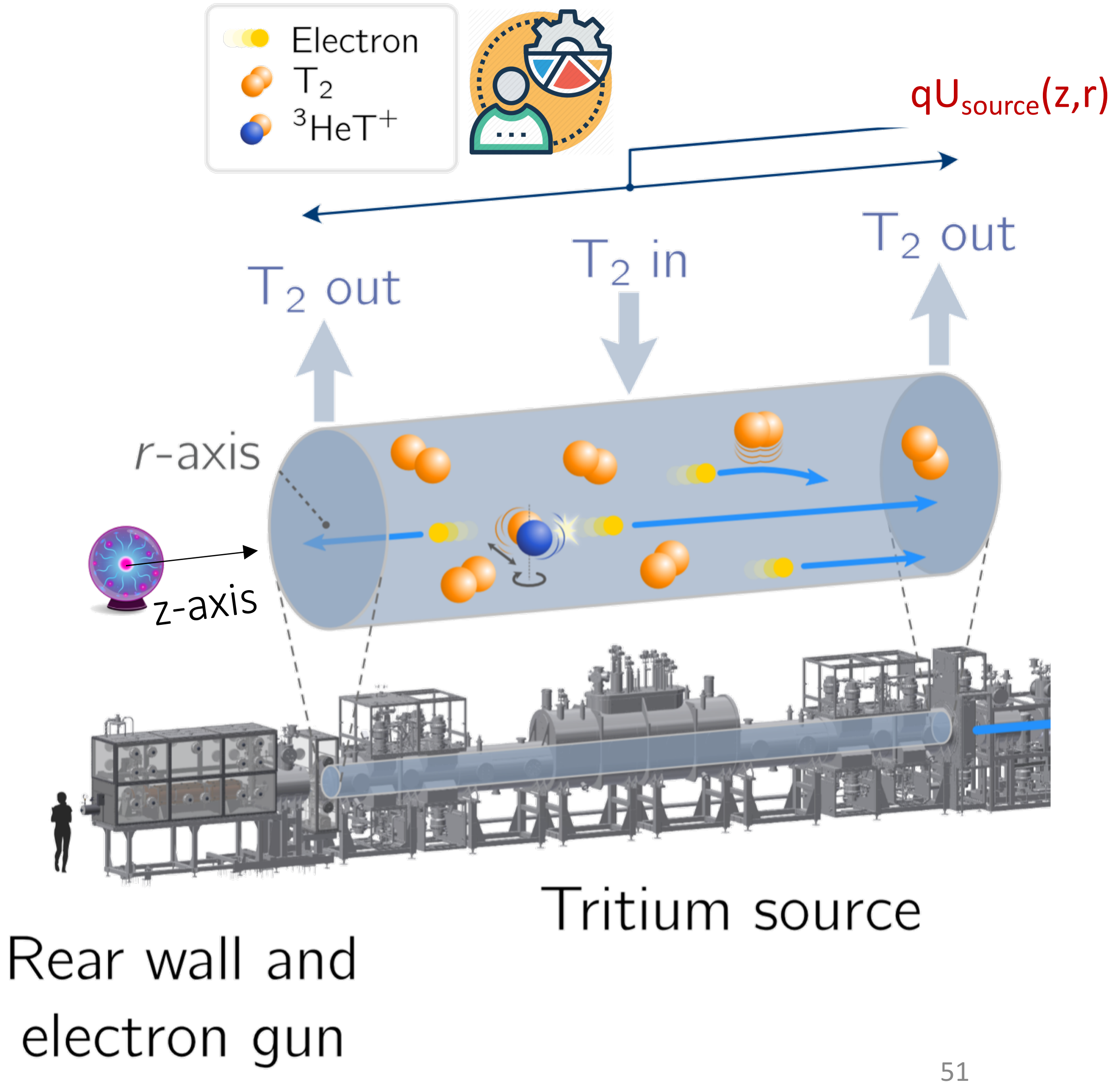


Mimick a ‘negative’ m_ν^2

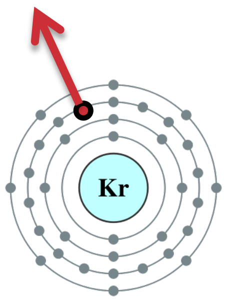
Plasma induced qU_{source} Broadening

- 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



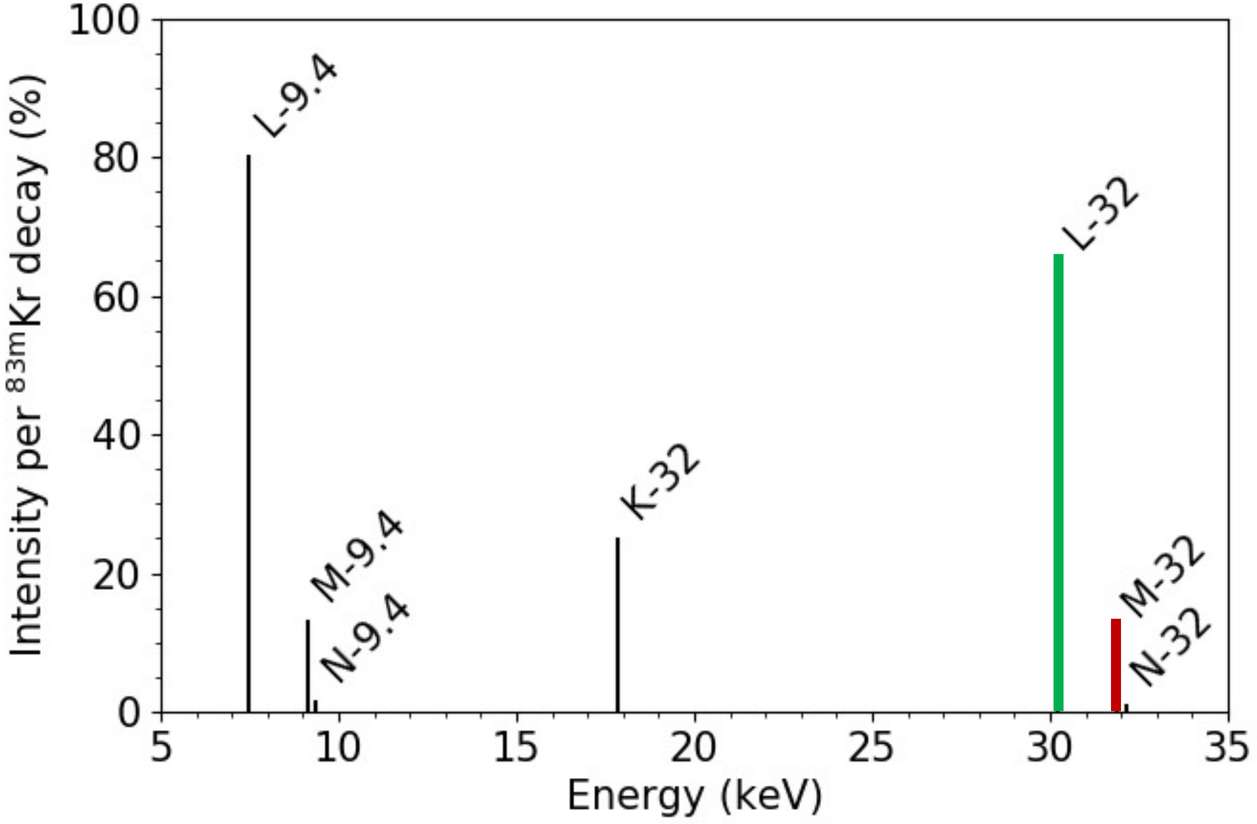


Krypton Signal: monoenergetic electrons

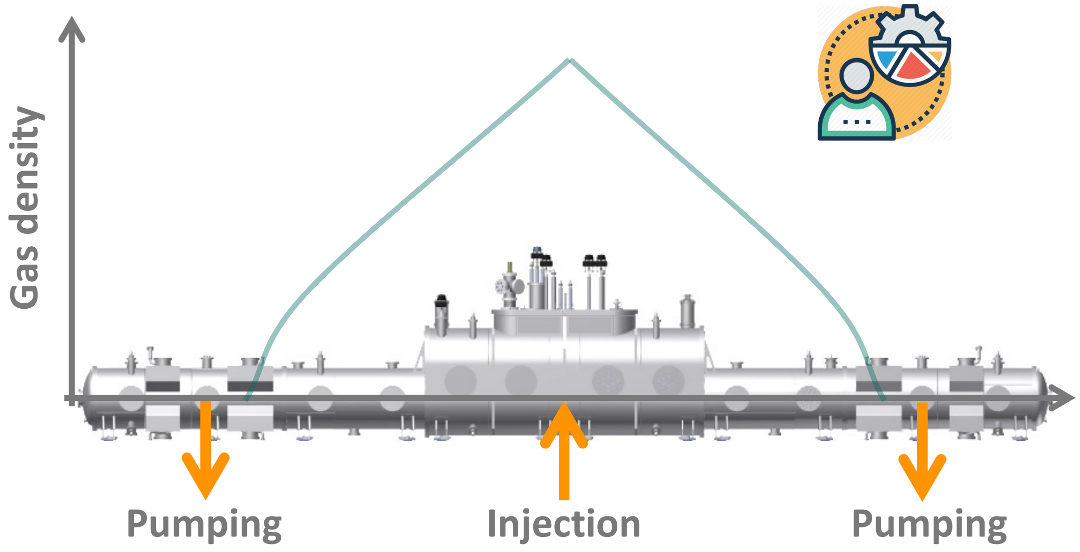


- L-32-line
  - High intensity
  - Natural line width is not known precisely

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

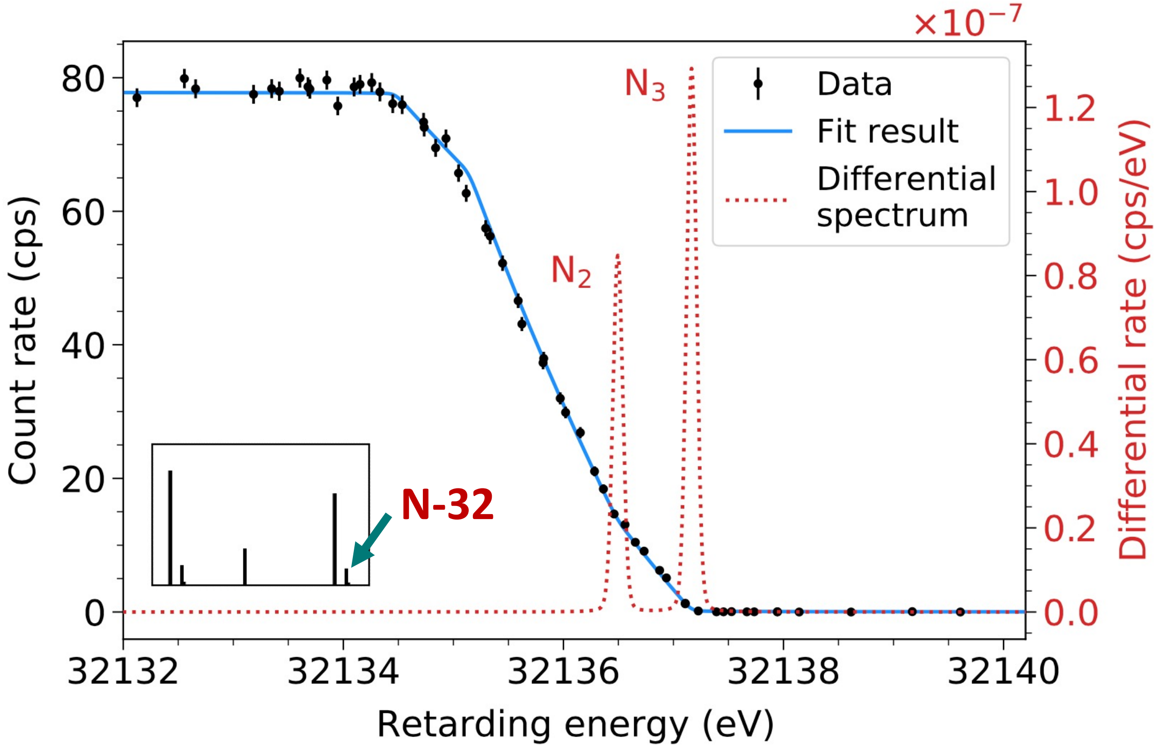


Co-circulation of tritium and ^{83m}Kr at 80 K @ 40% density

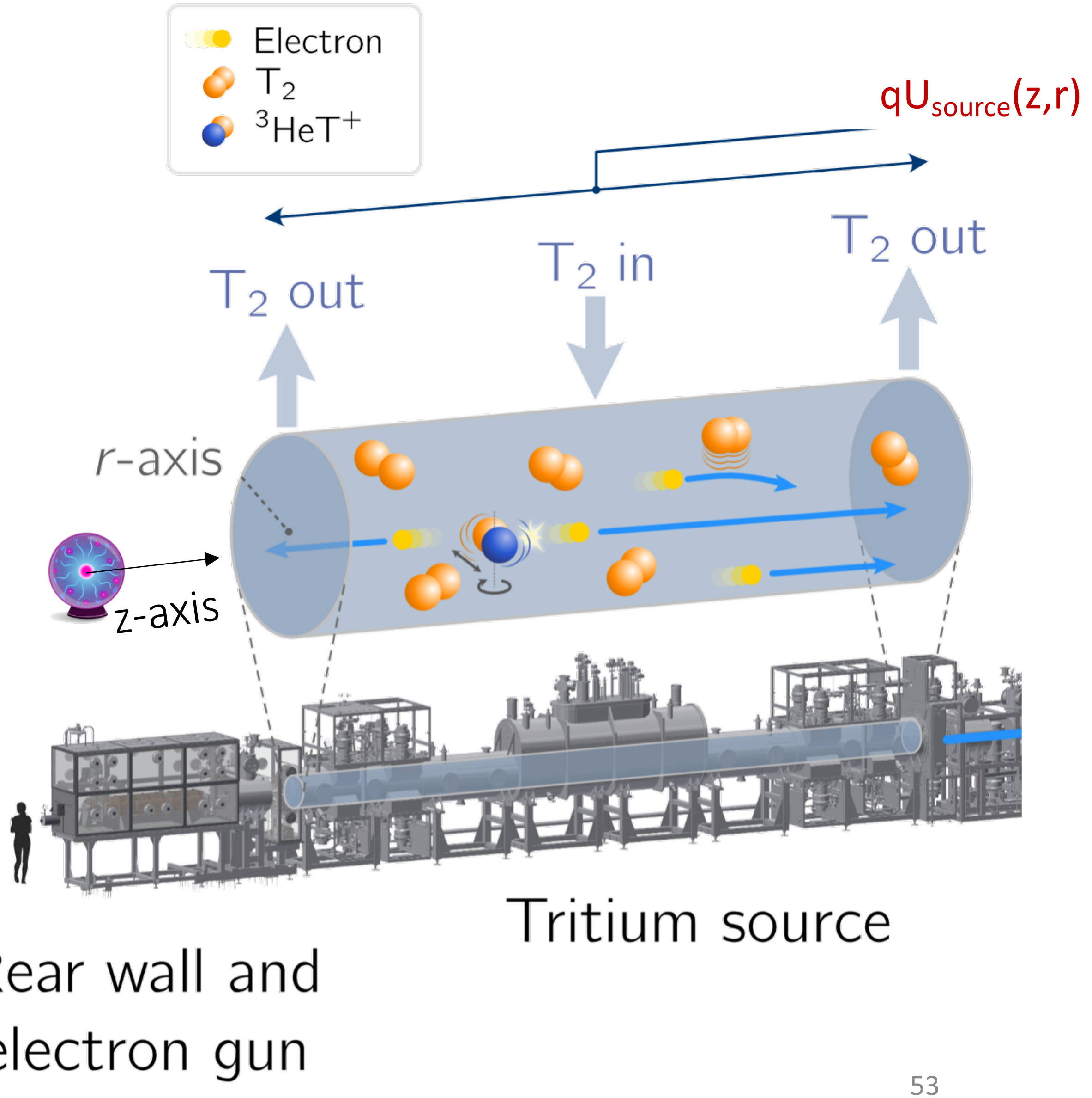


Plasma induced qU_{source} Broadening

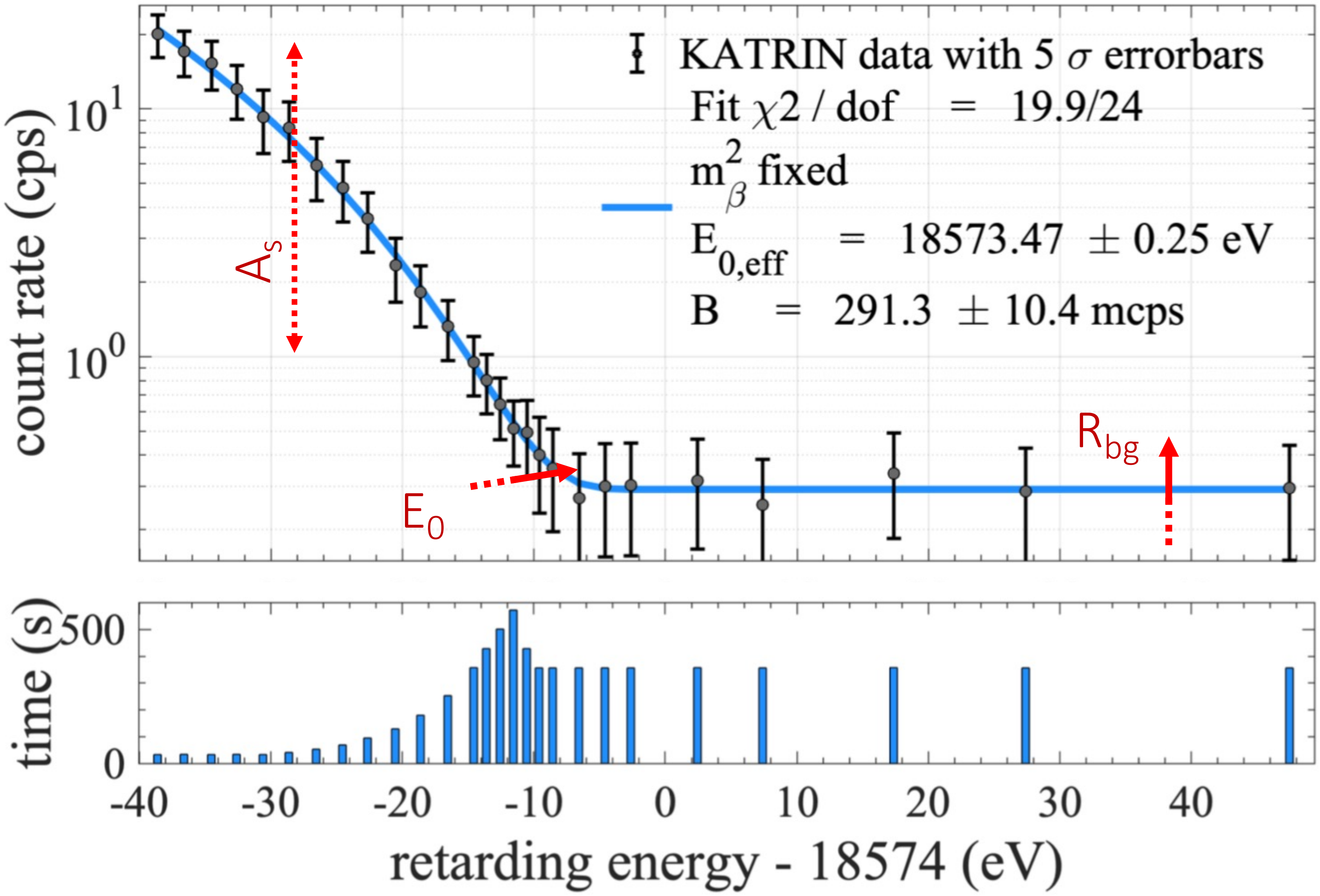
- Fit of the N-23 doublet model → σ_P



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

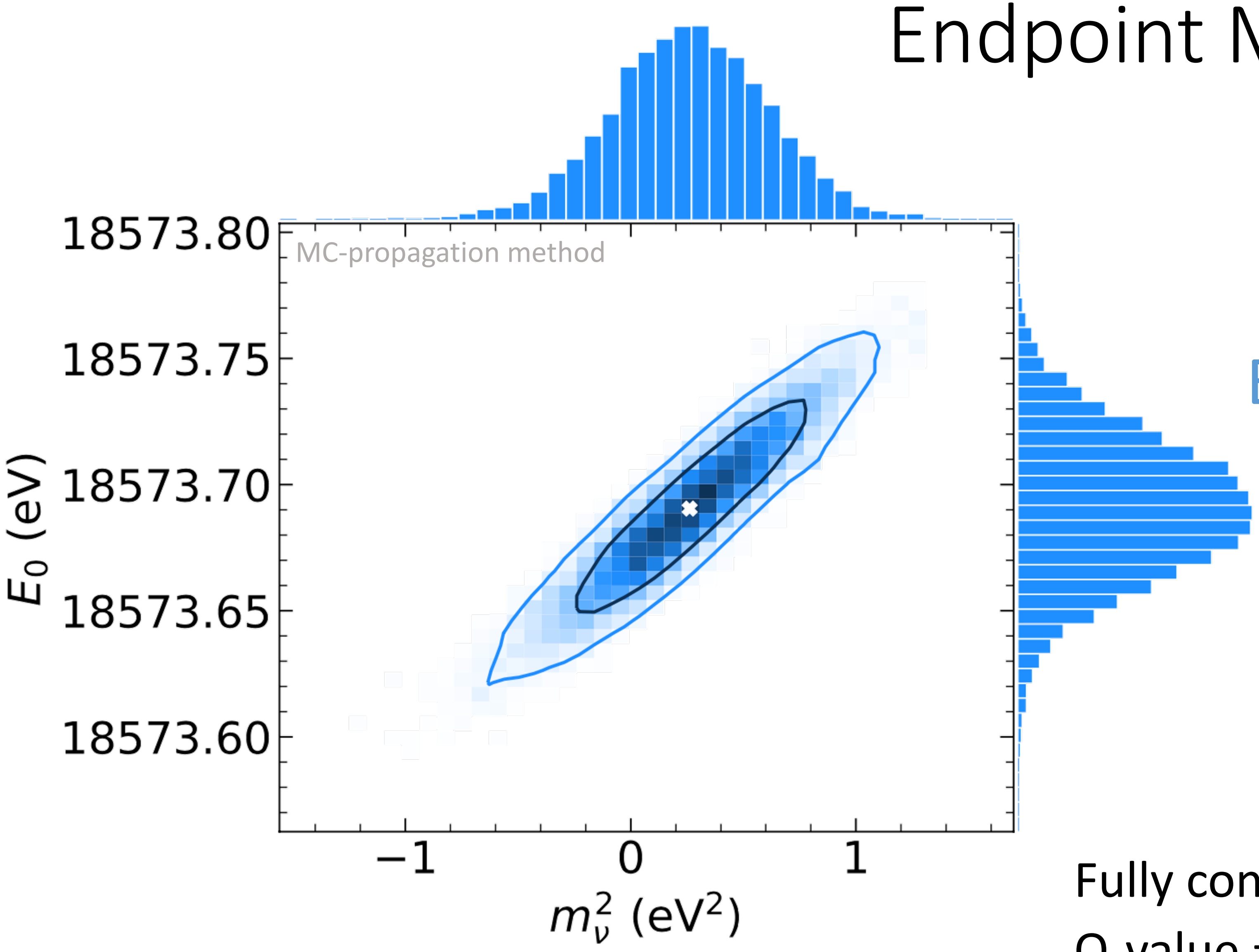


Fit of a single 2-h beta-scan



- 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 level reproducibility

Endpoint Measurement



Maximum electron energy in tritium decay

$E_0 = (18573.69 \pm 0.03)$ eV

⇨ Q-value = (18575.2 ± 0.6) eV

Mass ^{3}H – Mass ^{3}He

Fully consistent with the prediction:

Q-value = (18575.72 ± 0.07) eV

Check of the global energy scale