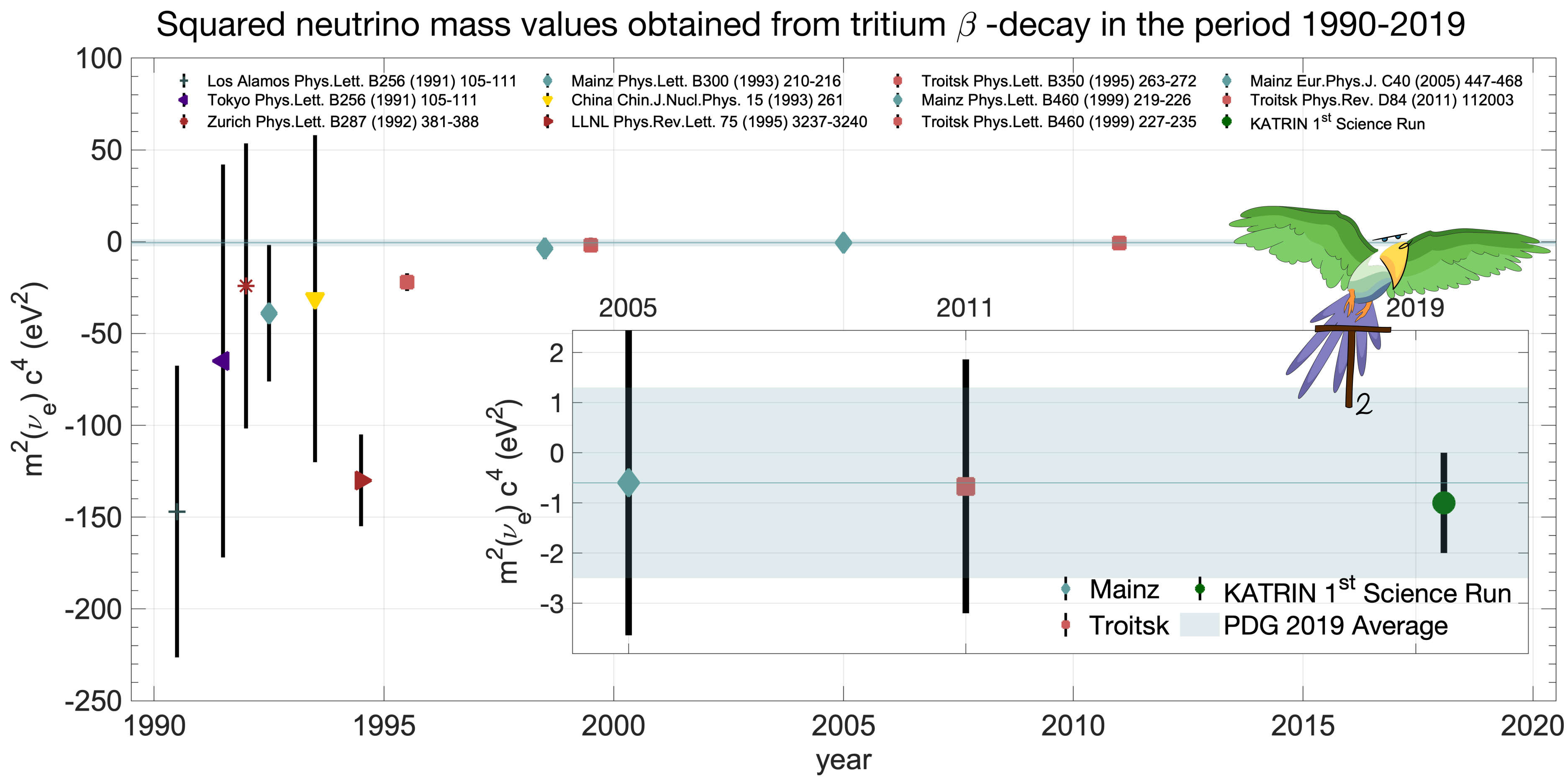
Bound on 3+1 active-sterile neutrino mixing from the first science run of KATRIN

GDR Neutrino, Virtual Meeting, 23/11/2020

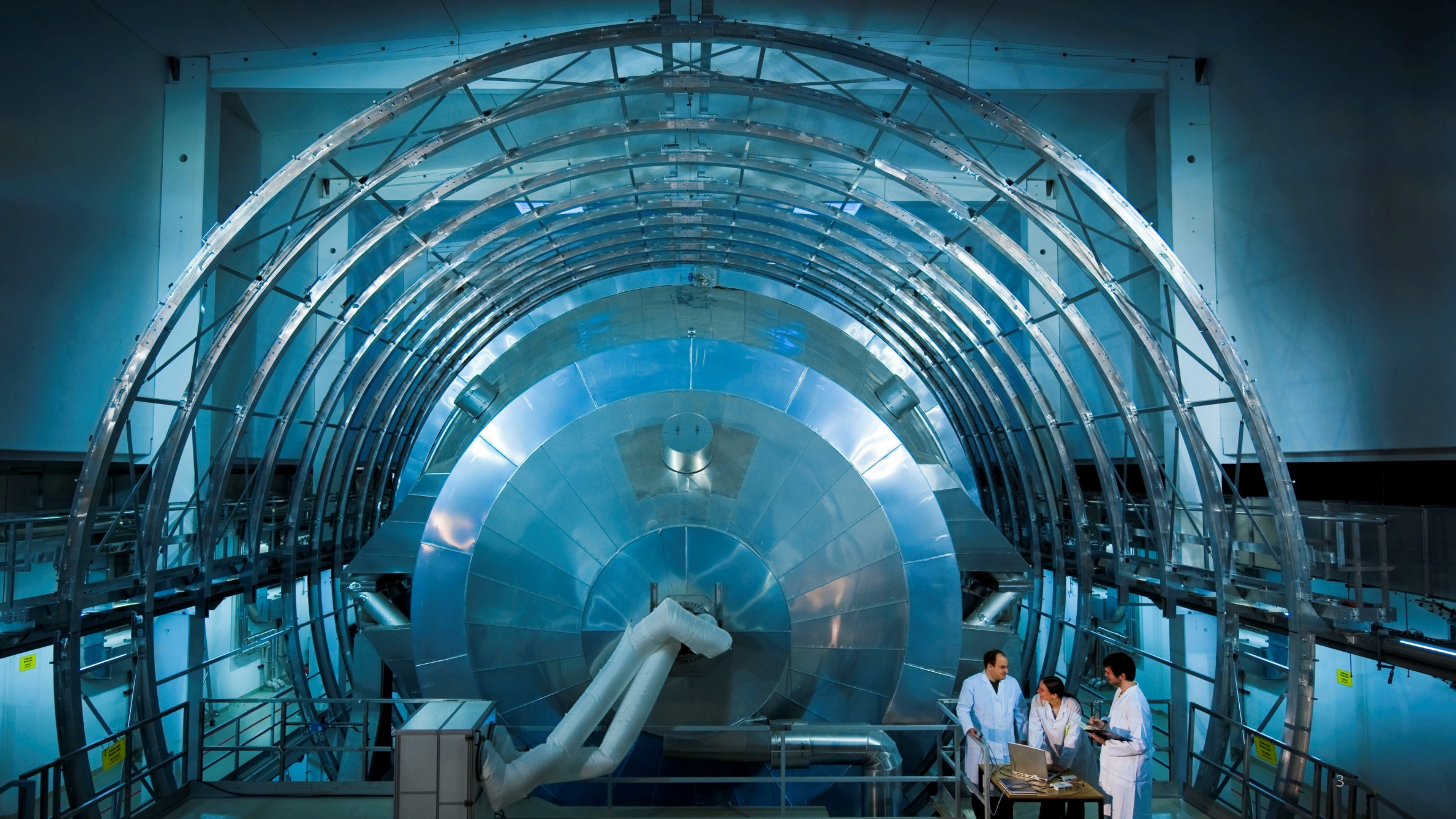
Thierry Lasserre (CEA Irfu & APC Laboratory)

On behalf the KATRIN collaboration

First KATRIN Neutrino Mass Result (2019)



https://indico.in2p3.fr/event/19474/contributions/75239/attachments/55626/73384/KATRIN-KNM1-GDR.pdf

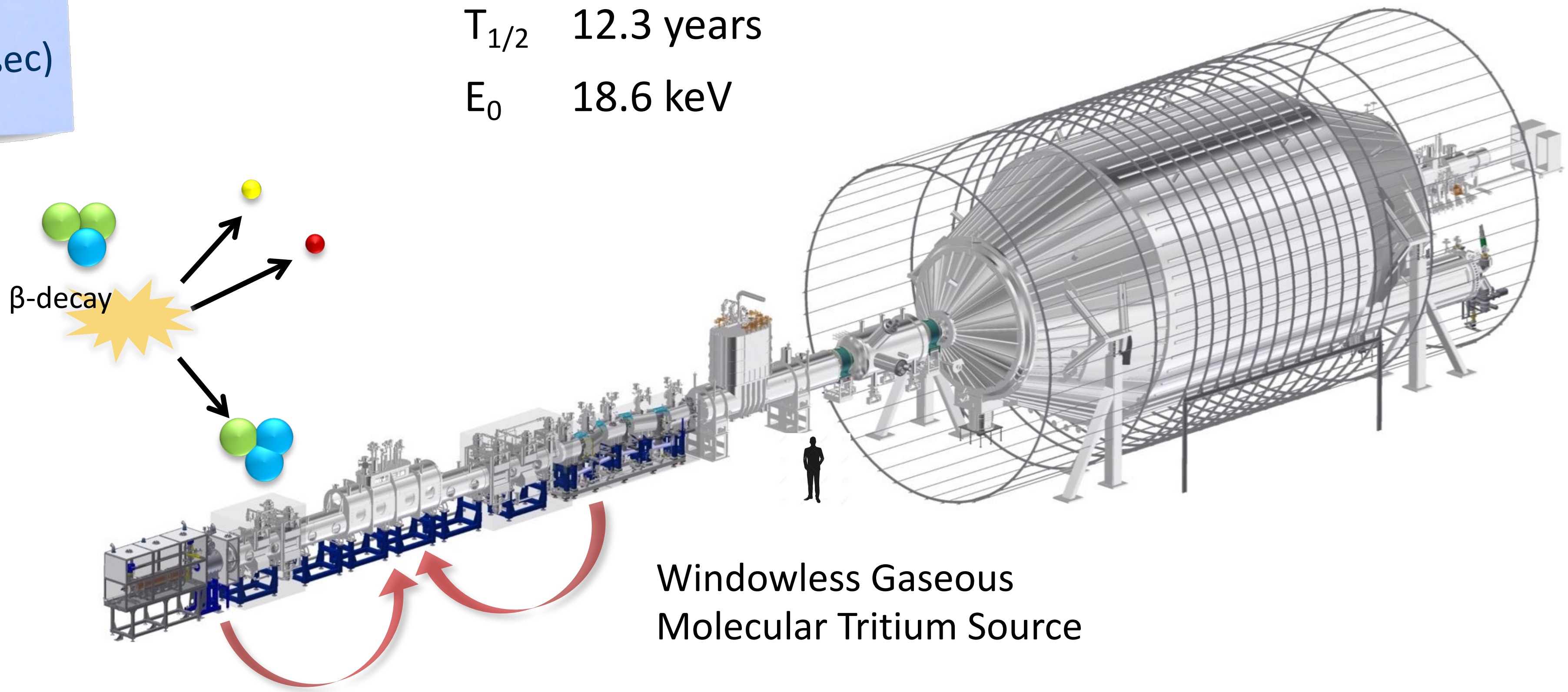


KATRIN Working Principle

high stability
and luminosity

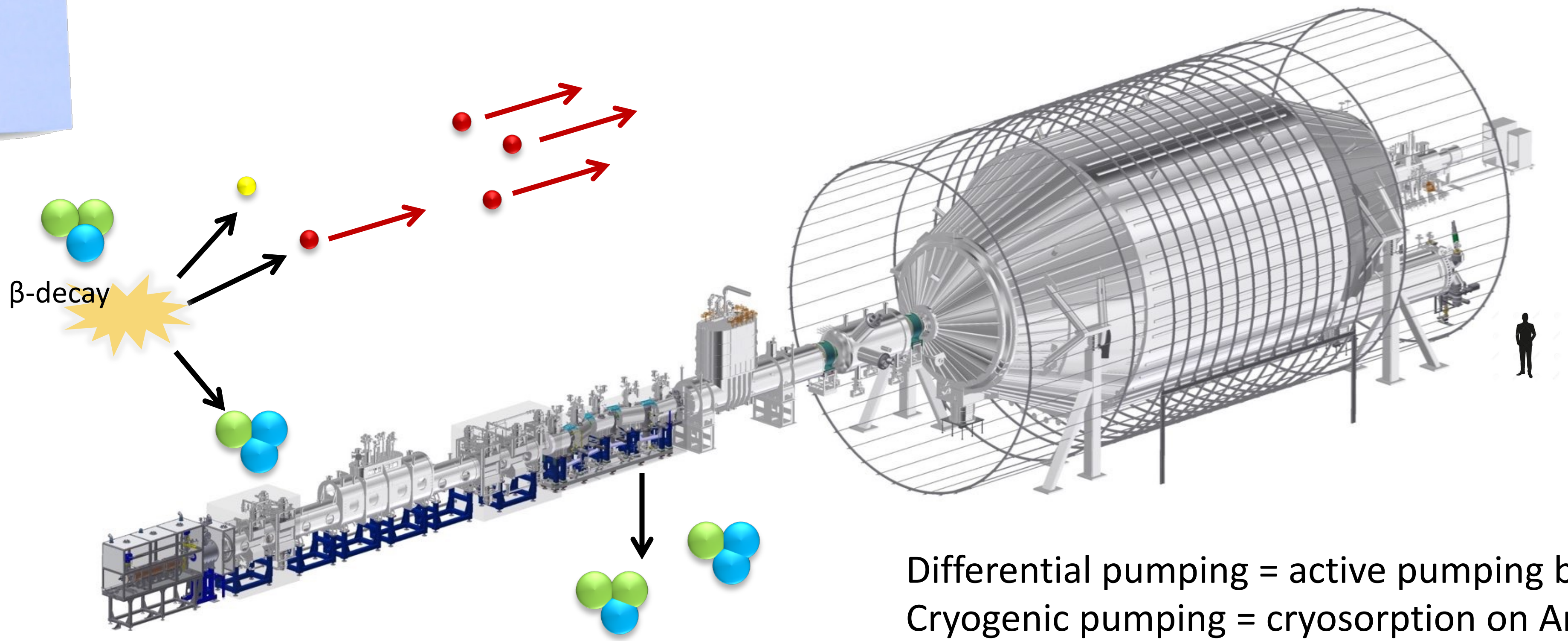
(10^{11} decays/sec)

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



KATRIN Working Principle

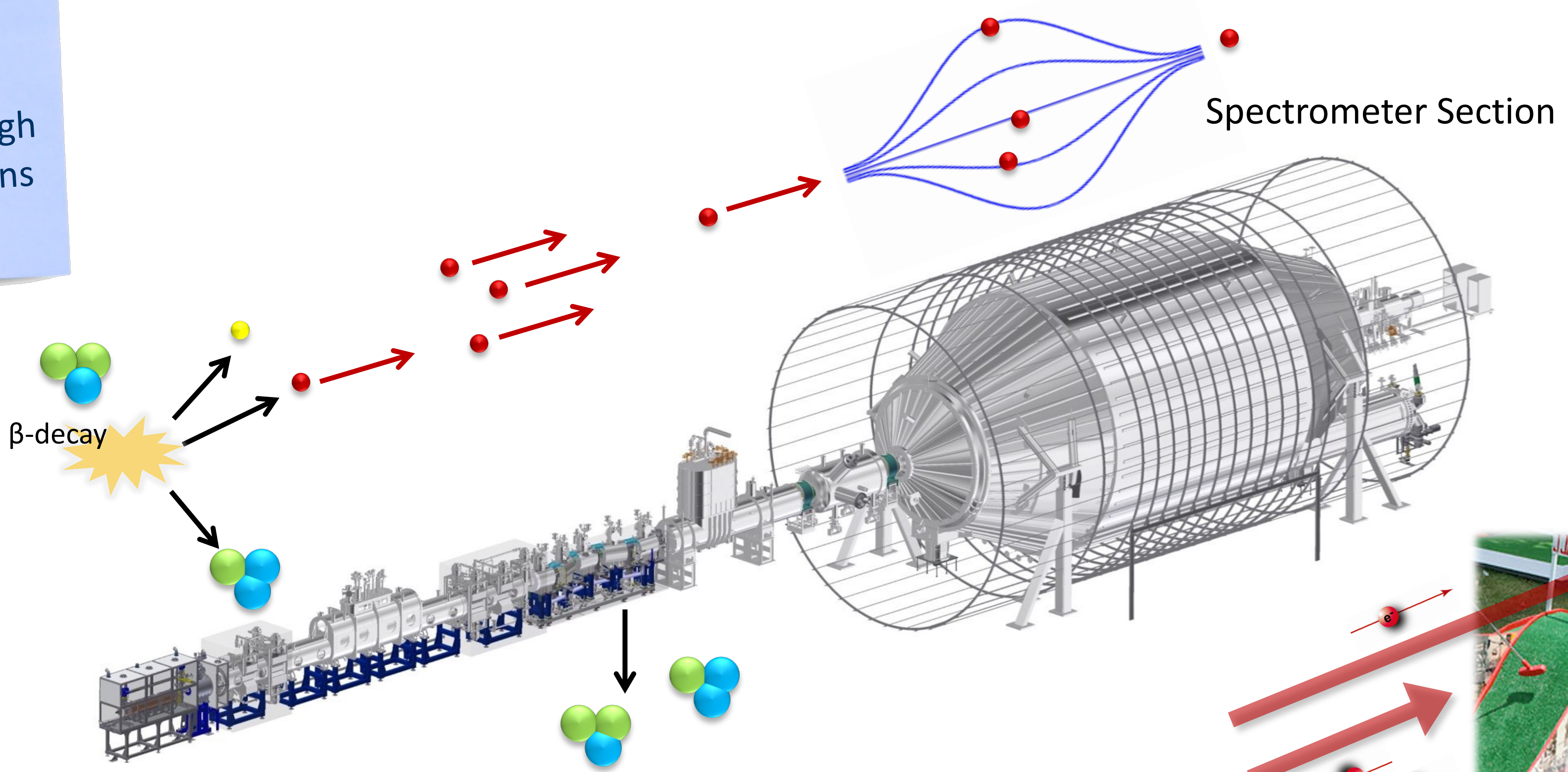
Tritium flow reduction by 14 orders of magnitude



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

KATRIN Working Principle

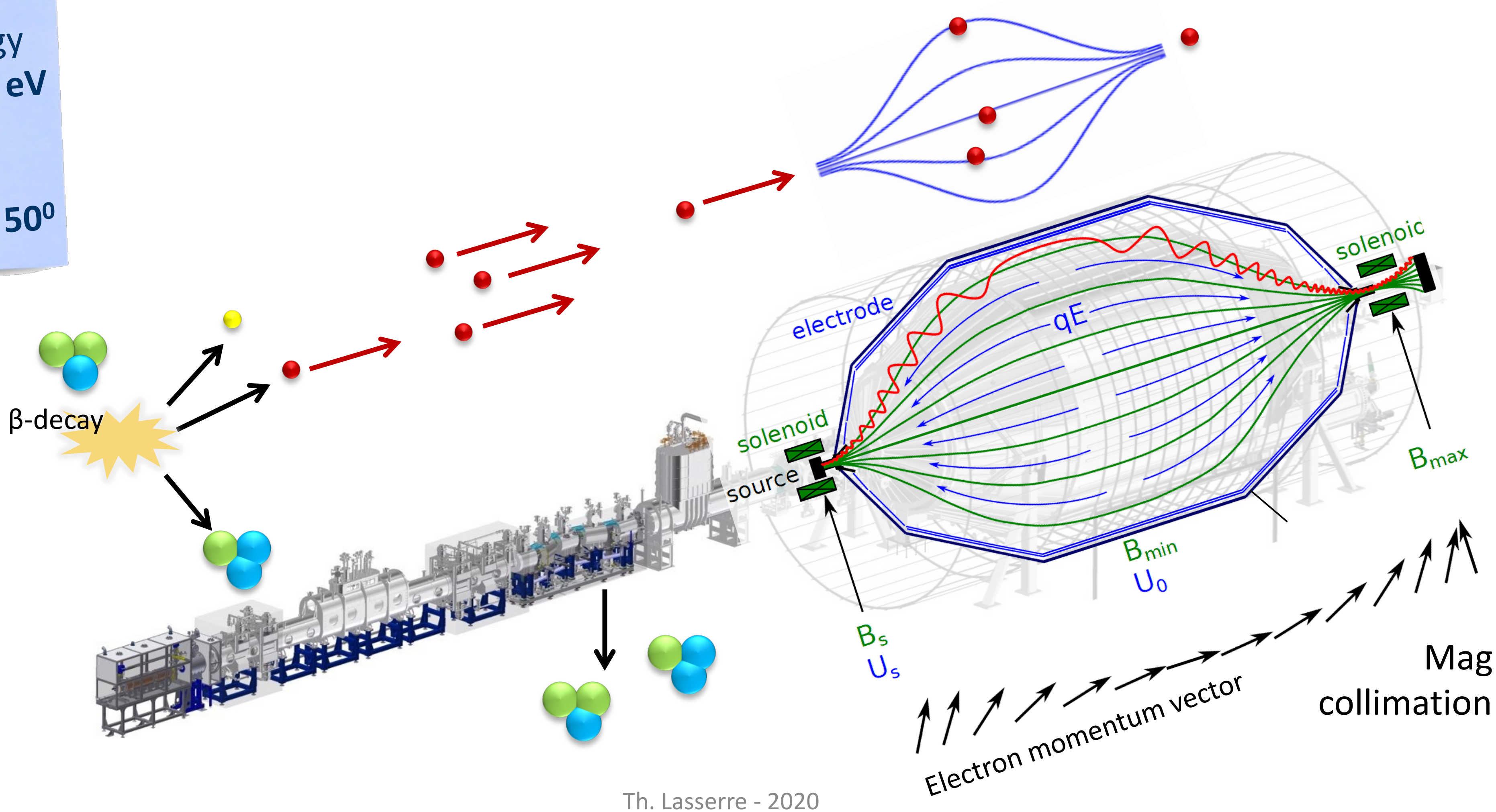
Electrostatic filter selects high energy electrons



KATRIN Working Principle

excellent energy resolution: **~ 3 eV**

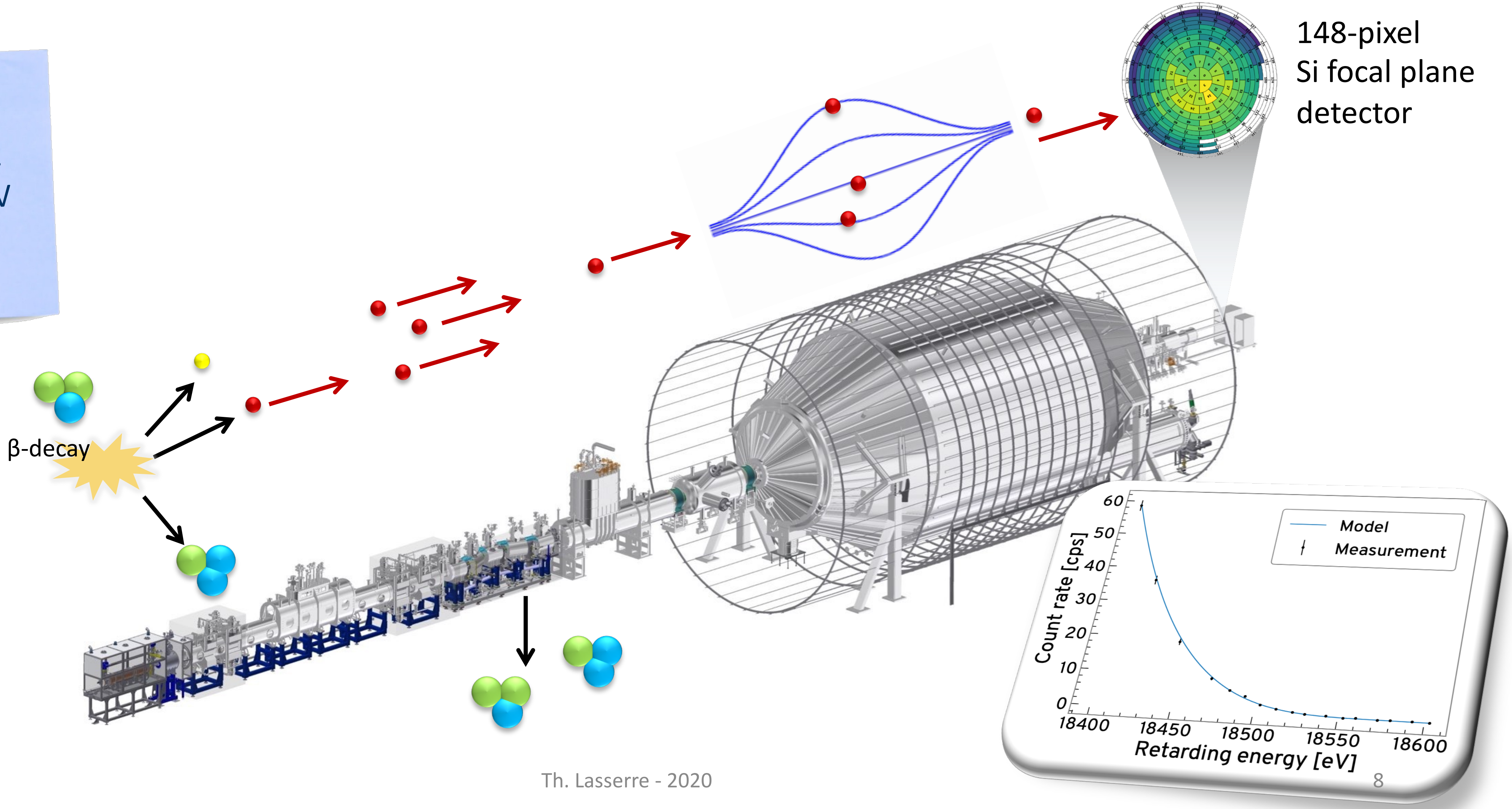
large angle acceptance: **~ 50⁰**



Magnetic adiabatic collimation + electrostatic filter (MAC-E)

KATRIN Working Principle

Integral measurement down to 40 eV below the endpoint

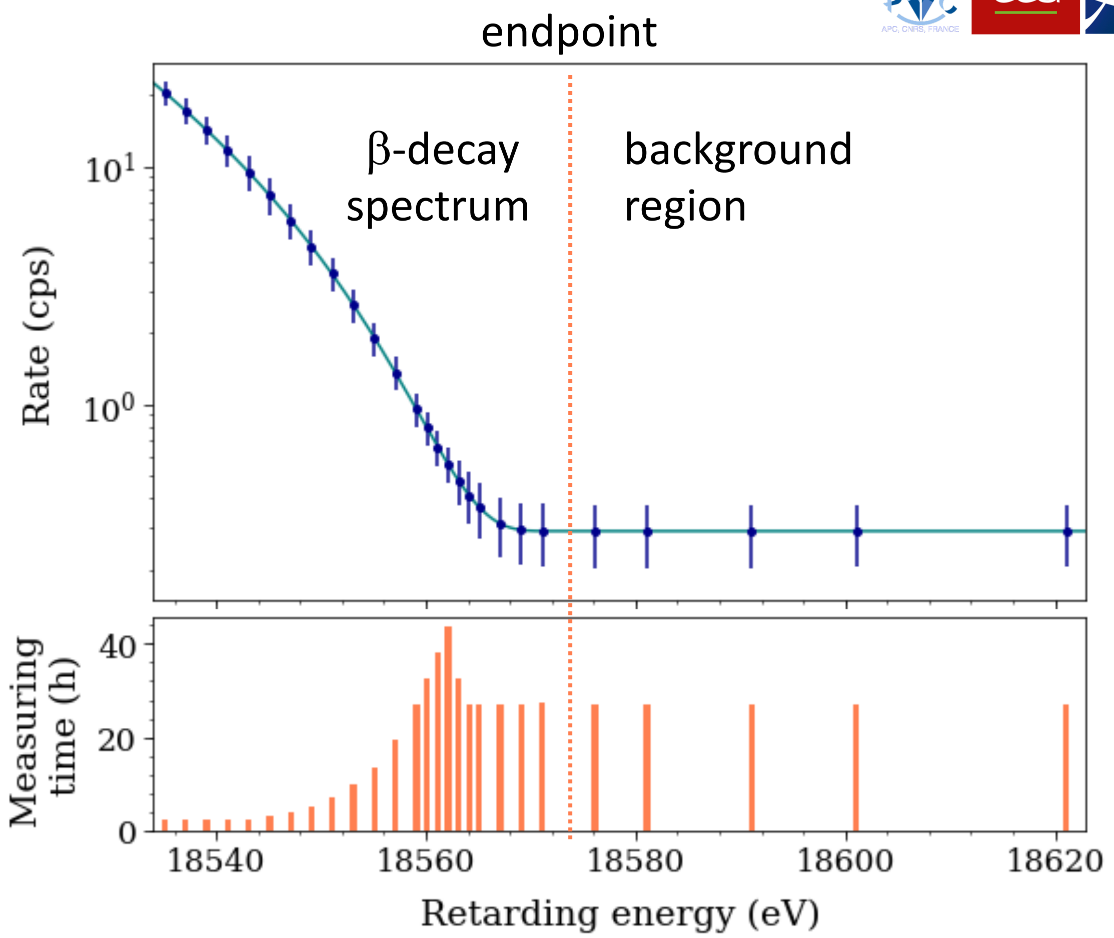


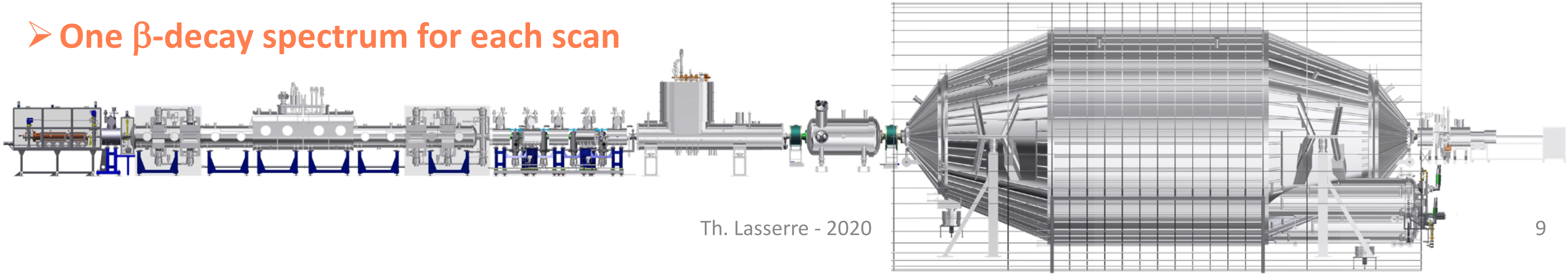
Scanning Strategy

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

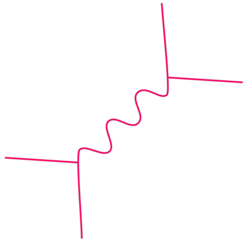
➢ One β-decay spectrum for each scan

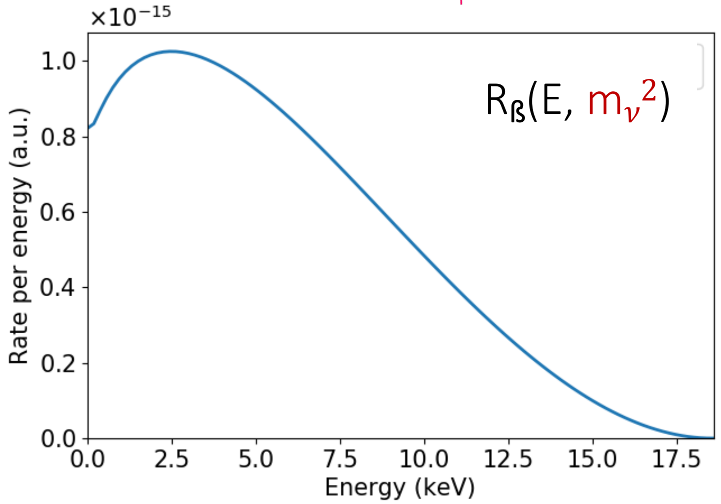




Integral spectrum modeling

tritium β-decay theory

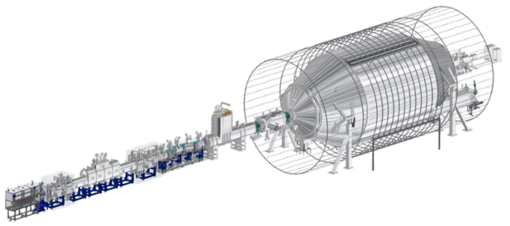


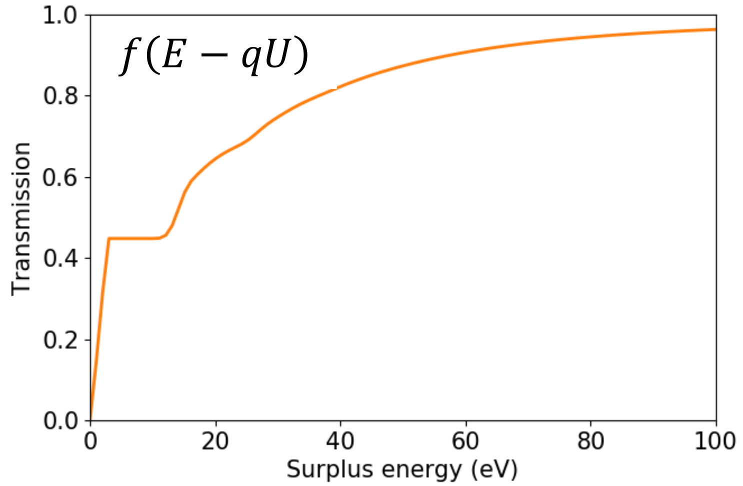


$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C \cdot p_e E_e \cdot \sqrt{(E_e - E_0)^2 - m_{\nu_i}^2} \cdot (E_e - E_0) \cdot F(E_e, Z)$$

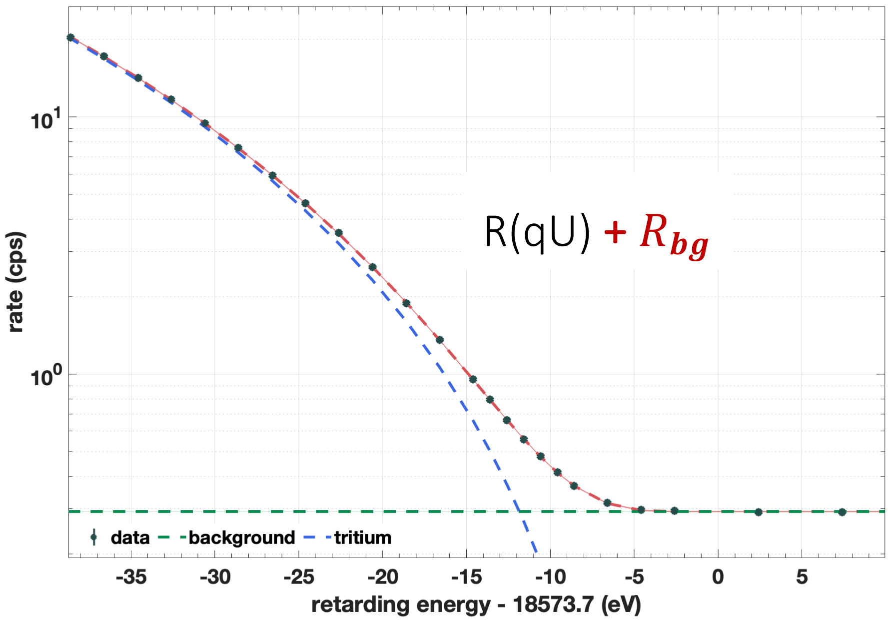
$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_ß(E, m_\nu^2) \cdot f(E - qU)\, dE + R_{bg}$$

experimental setup



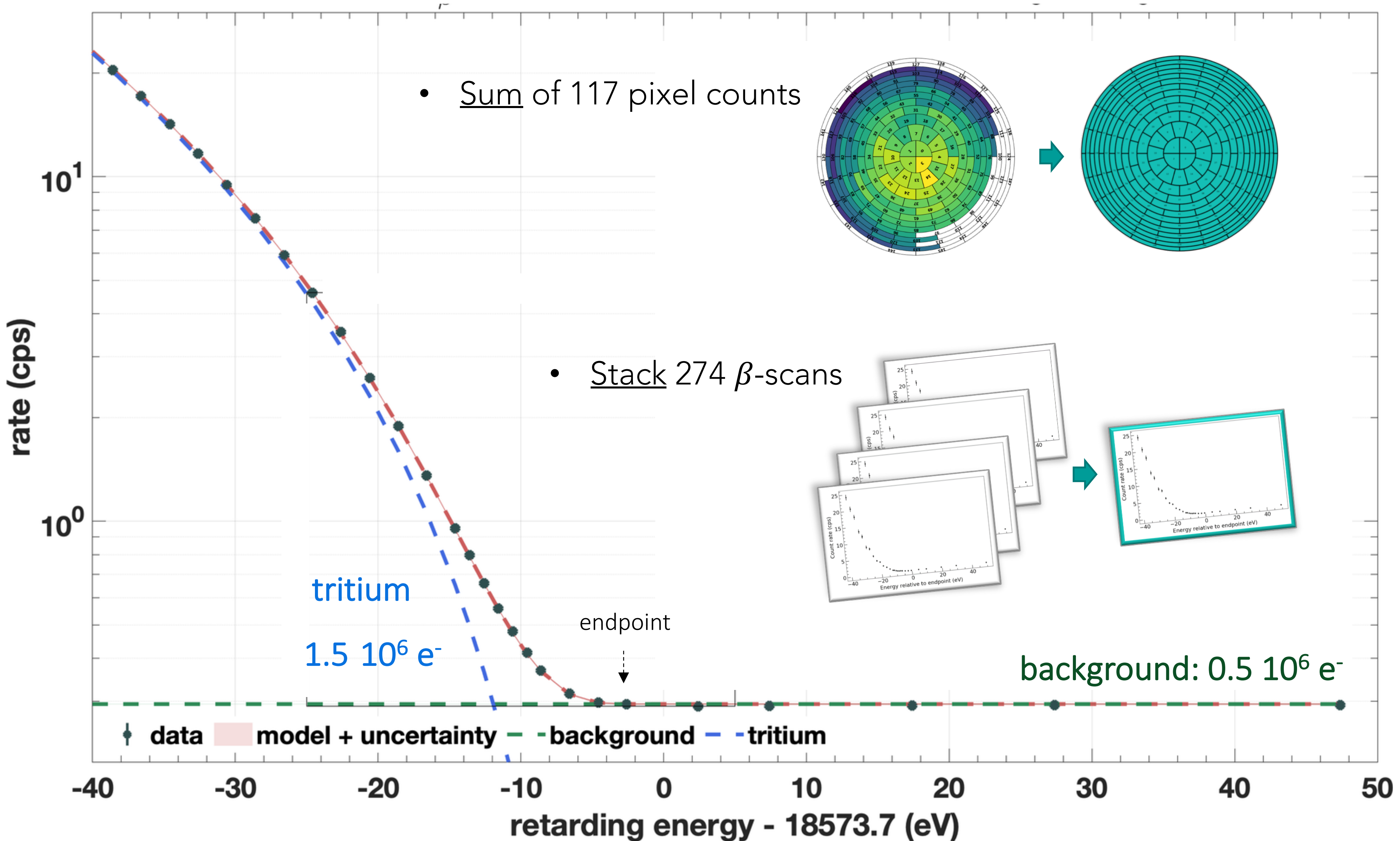


integral β-spectrum



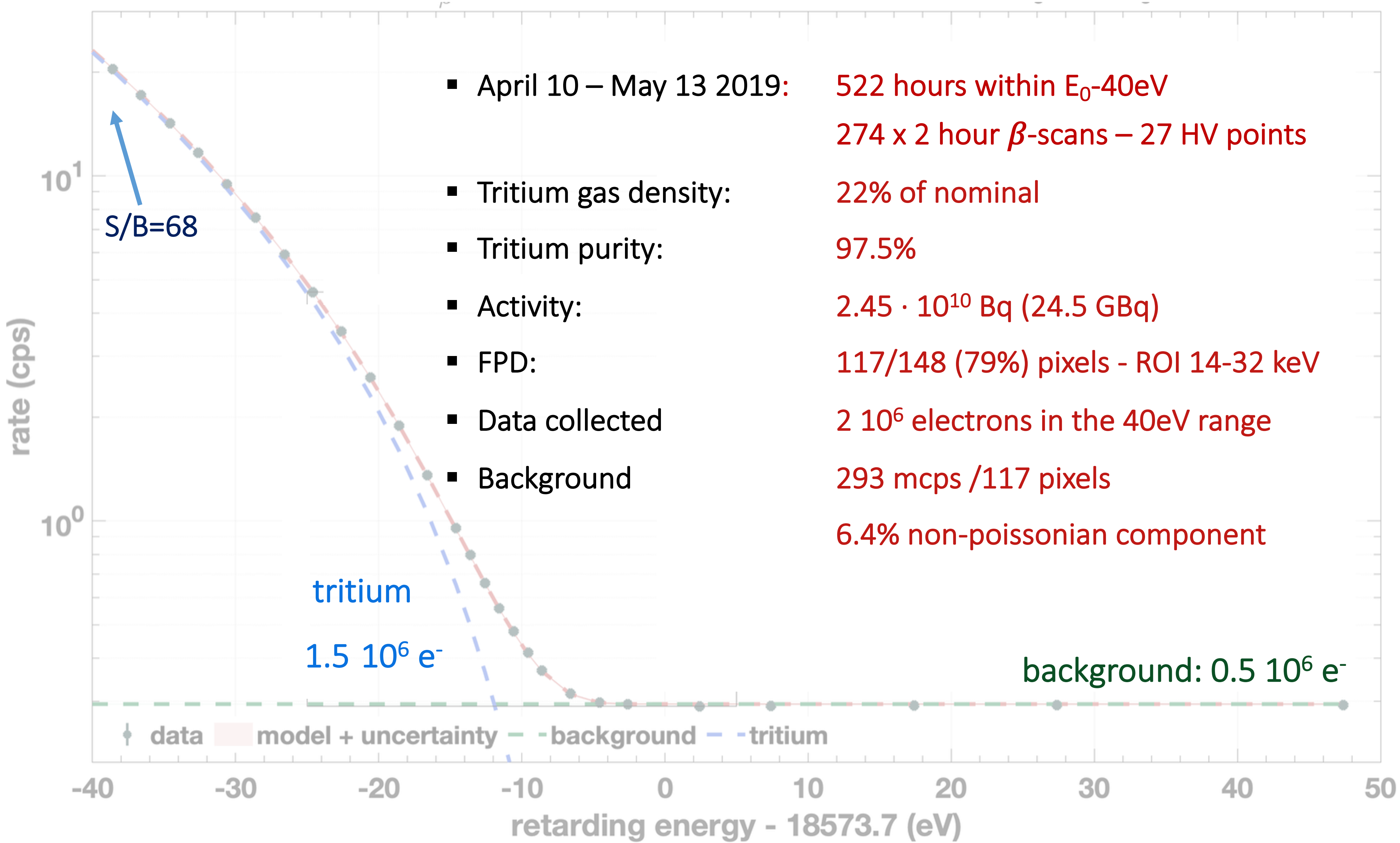
← R_{bg}

… combination of 32058 spectra

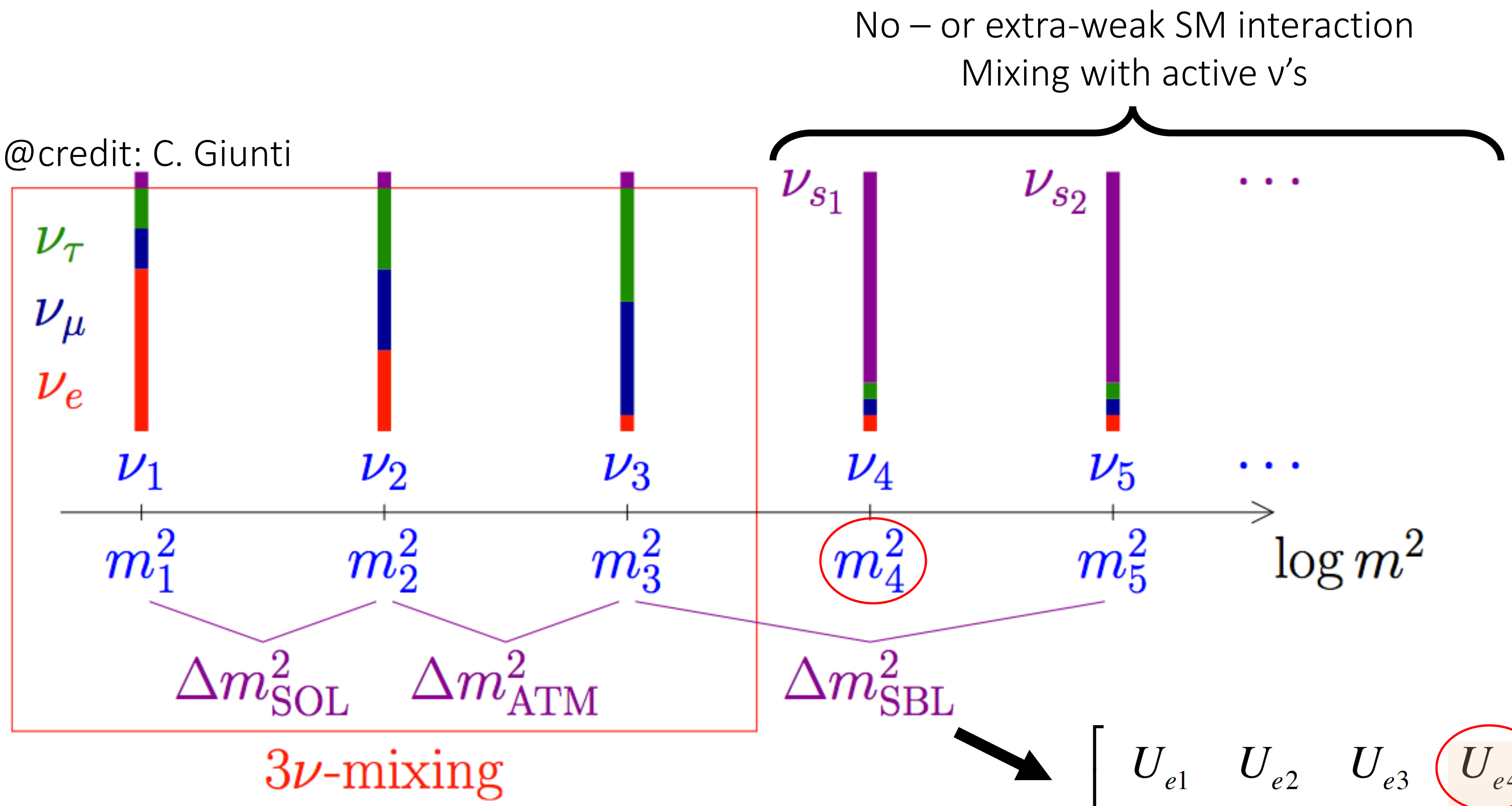


Sterile Neutrino Search Dataset

- April 10 – May 13 2019: 522 hours within E_0-40eV
  274 x 2 hour β-scans – 27 HV points
- Tritium gas density: 22% of nominal
- Tritium purity: 97.5%
- Activity: $2.45 \cdot 10^{10}$ Bq (24.5 GBq)
- FPD: 117/148 (79%) pixels - ROI 14-32 keV
- Data collected $2\ 10^6$ electrons in the 40eV range
- Background 293 mcps /117 pixels
  6.4% non-poissonian component

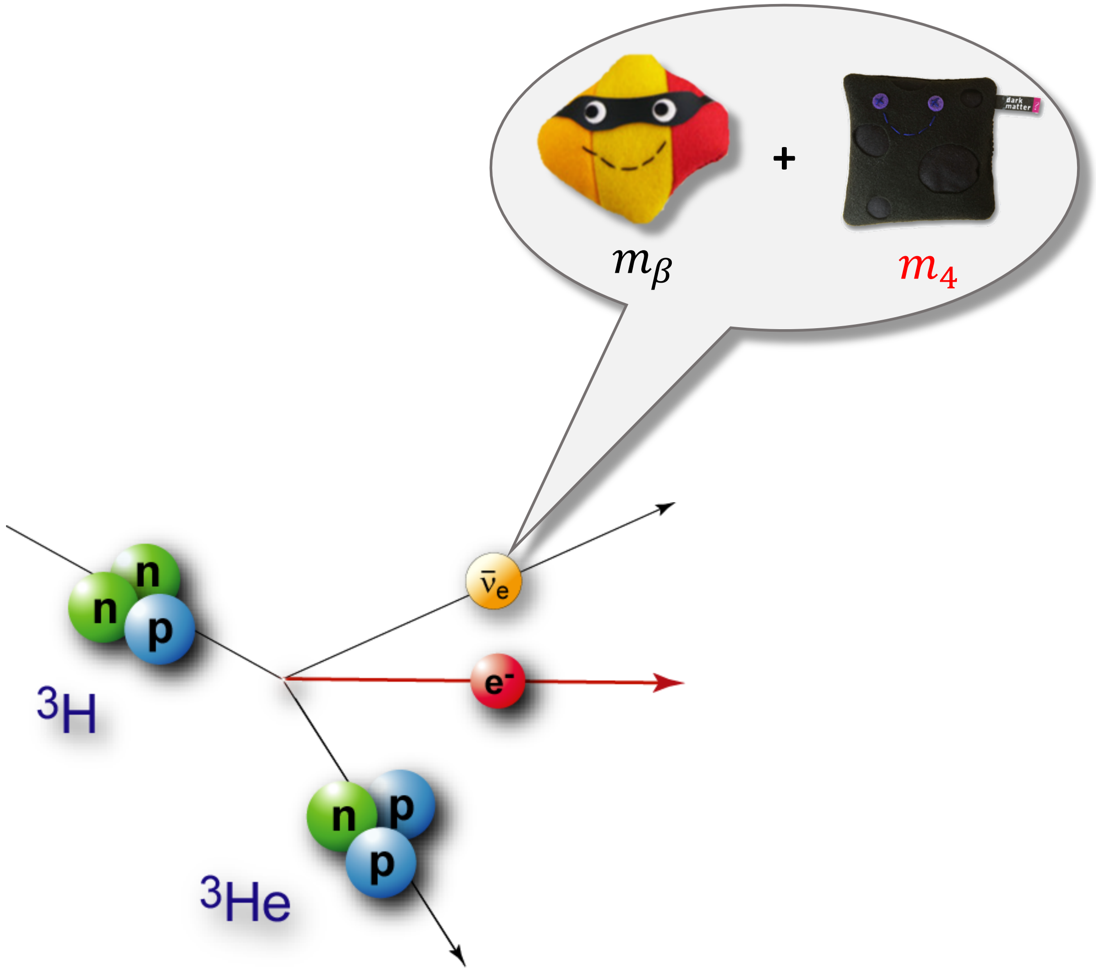


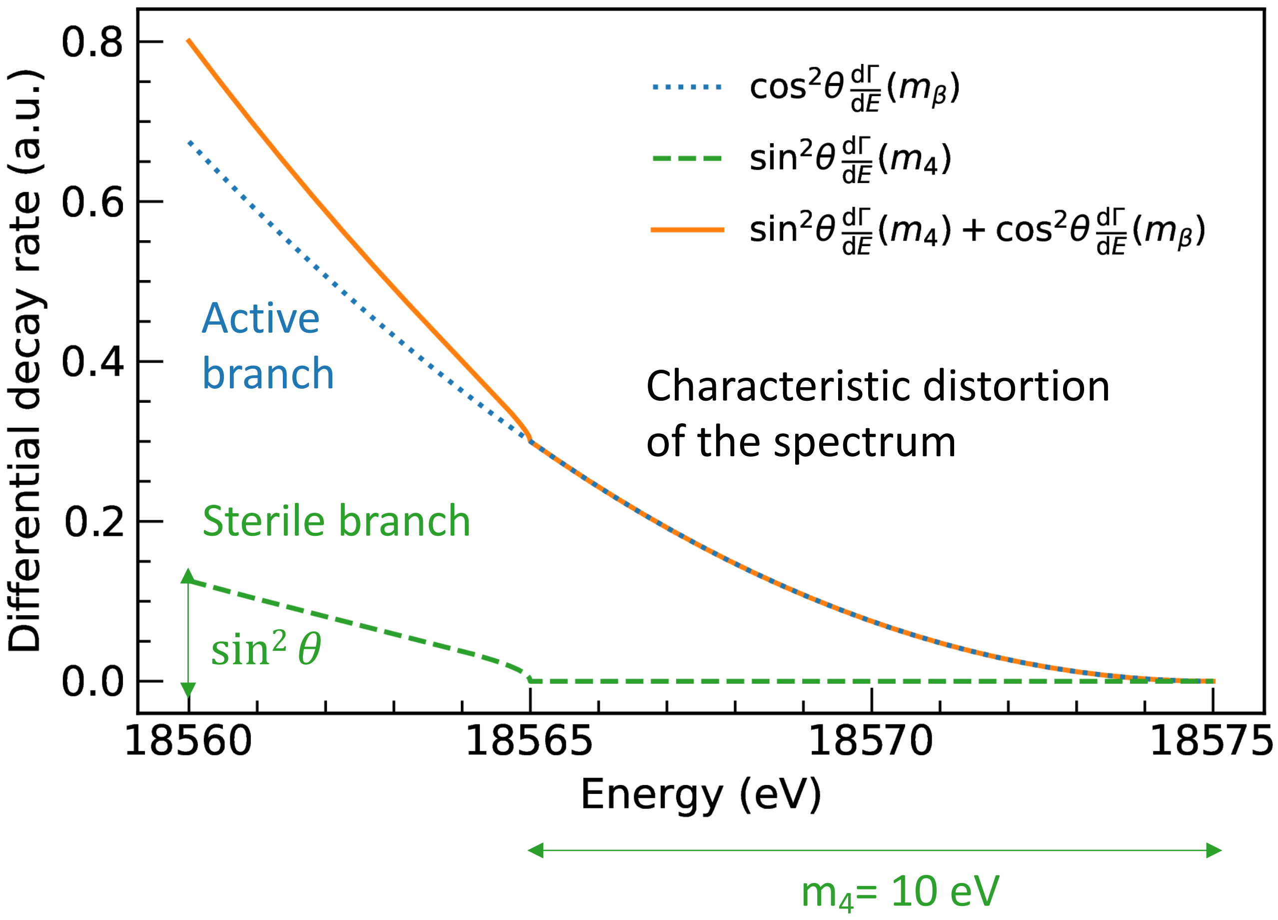
Sterile Neutrinos – General Idea



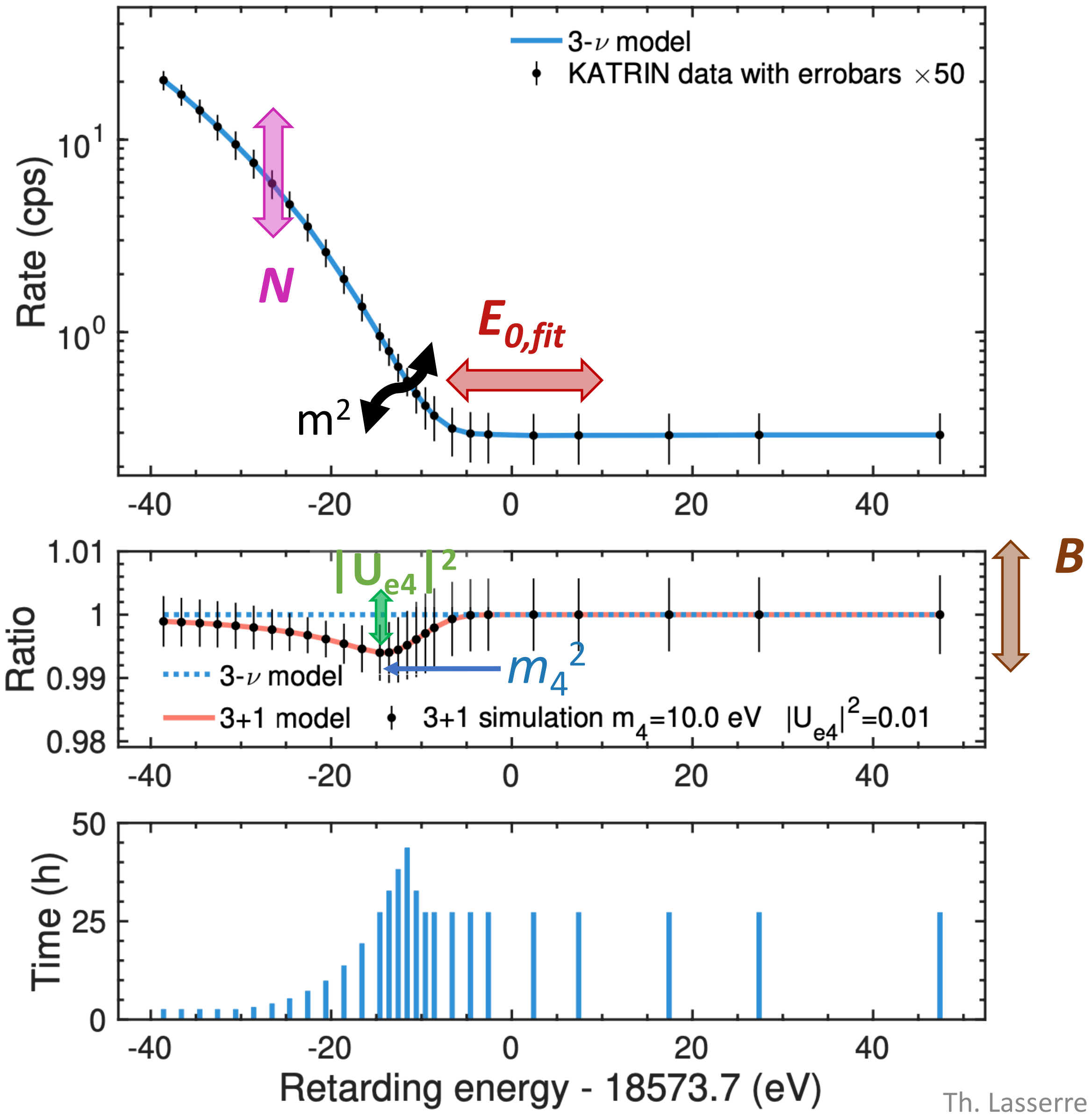
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

eV-Sterile neutrino signature in KATRIN





Sterile Neutrino Modeling

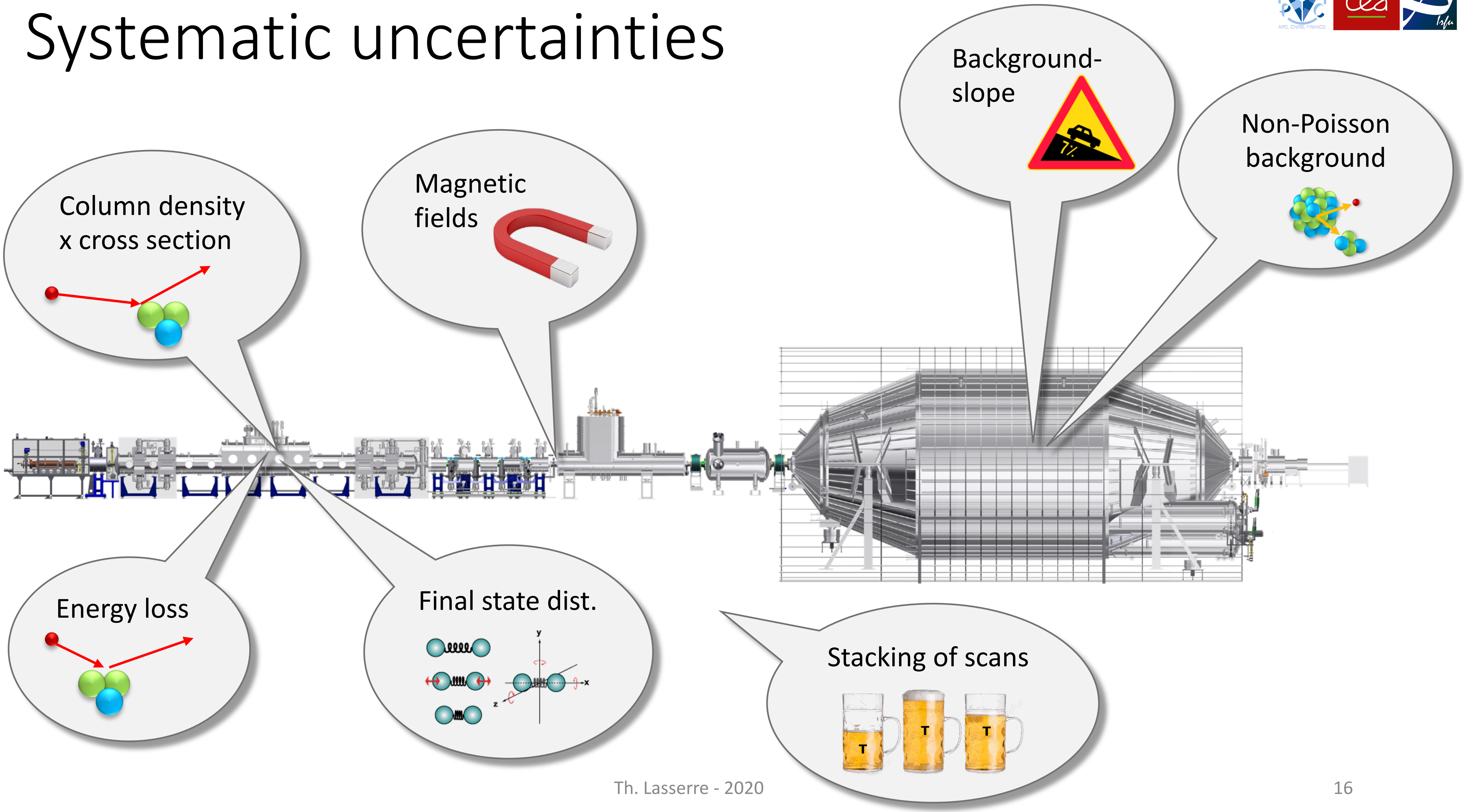


$$\frac{d\Gamma}{dE} = \underbrace{\left(1 - |U_{e4}|^2\right) \frac{d\Gamma}{dE}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$

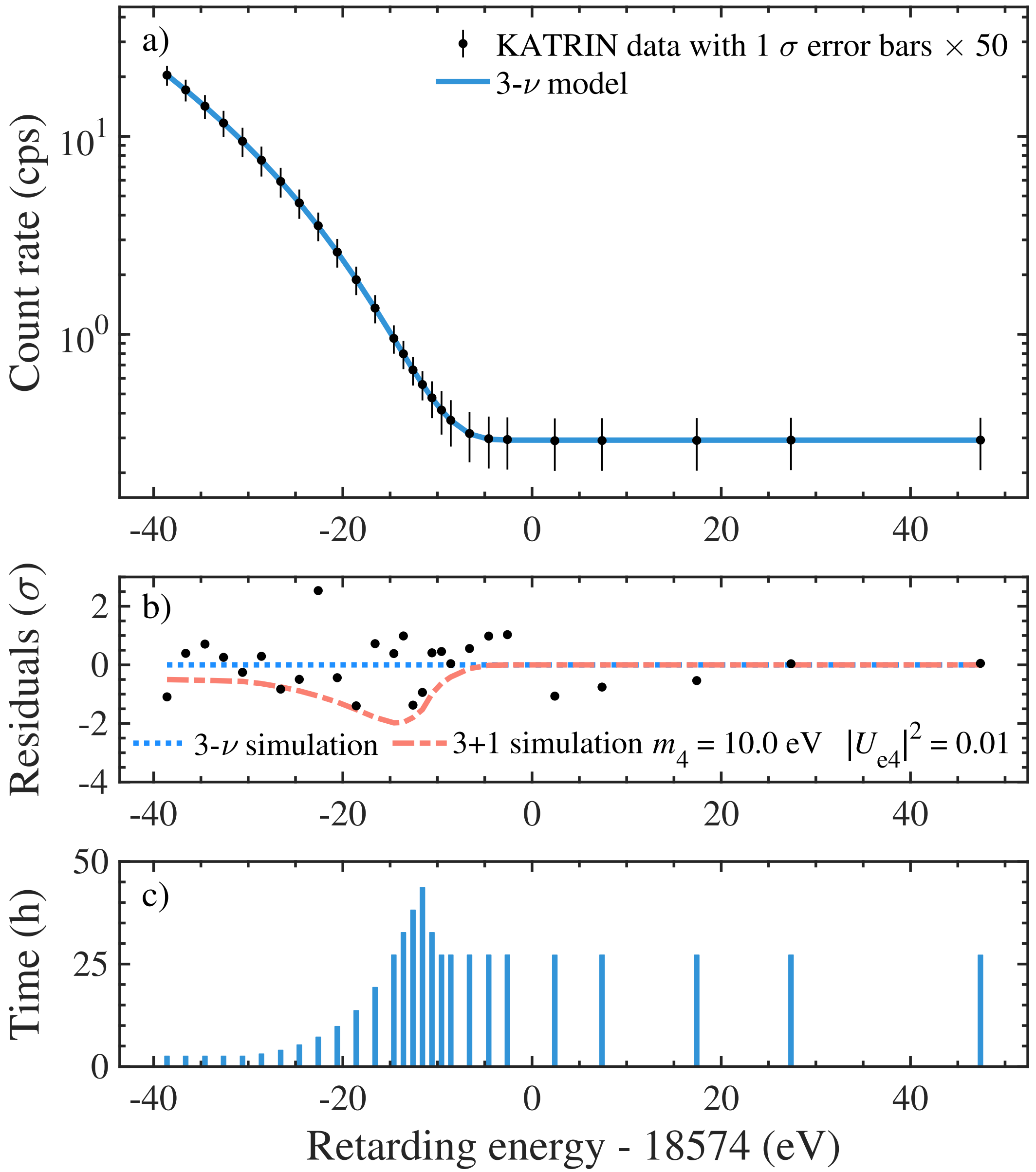
<u>Fit Parameters:</u>

m^2	neutrino mass (fixed/free/constrained)
$E_{0,fit}$	endpoint
N	signal normalization
B	energy-independent background rate
m_4^2	4^{th} neutrino mass
$\lvert U_{e4}\rvert^2$	4^{th} neutrino mixing

Systematic uncertainties



KATRIN 3+1 Neutrino Fit (40 eV range)

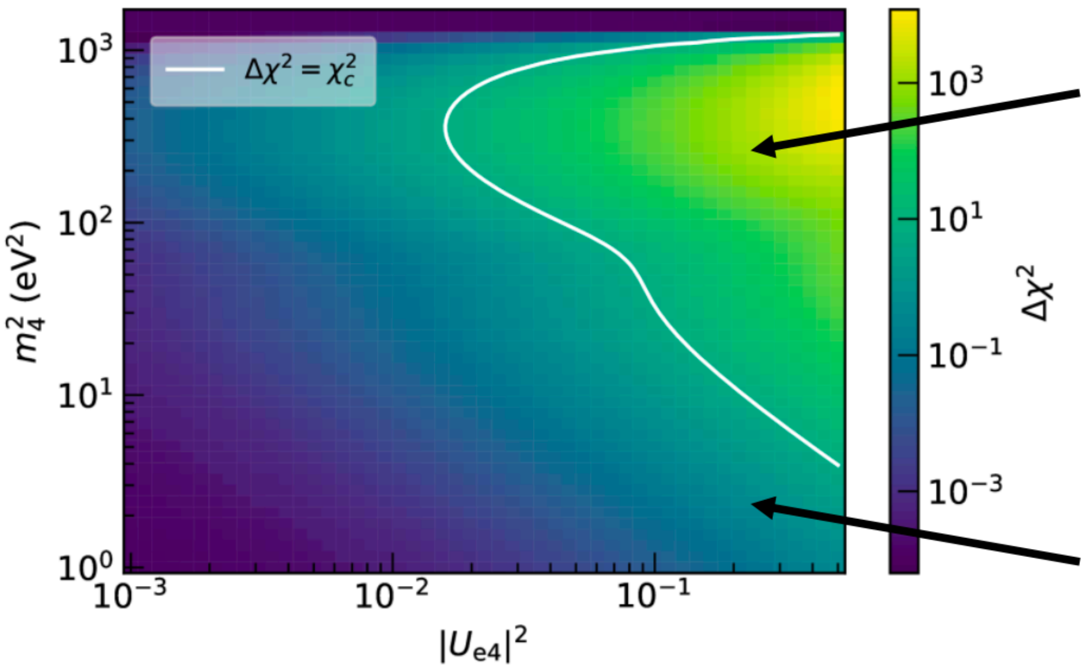


No evidence for sterile neutrino signal

Best fit	3ν (NH)	3+1
m_4^2	-	73.0
$\|Ue_4{}^2\|$	-	0.034
p − value	0.41	0.50
χ^2	22.9	21.3
$\Delta\chi^2$	1.6 (54.5% C.L)	

Confidence Interval (95 % C.L.)

- χ^2 analysis, systematic effects included via covariance matrix
- Likelihood ratio for given sterile parameters: $\Delta\chi^2\left(|U_{e4}|^2, m_4^2\right) = \chi^2\left(|U_{e4}|^2, m_4^2\right) - \chi^2_{\text{best}}$



parameters for which $\Delta\chi^2 > \Delta\chi^2_c$ are excluded

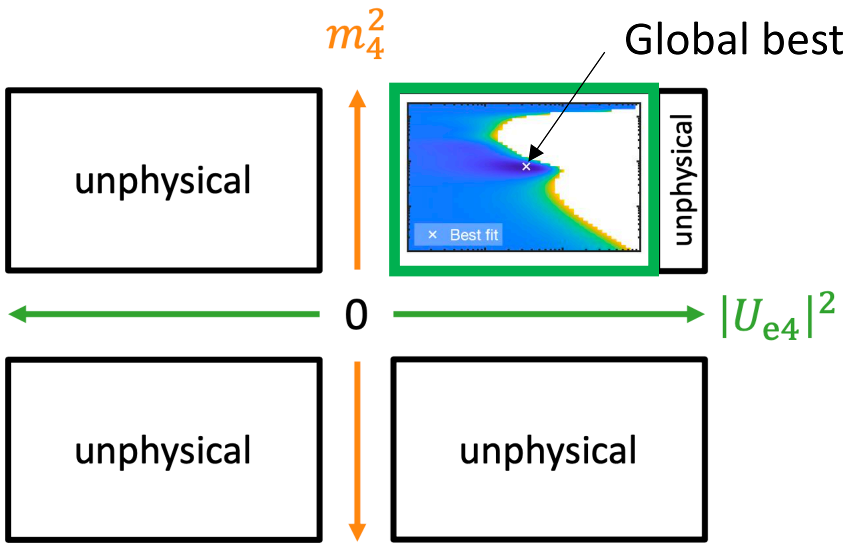
accepted

- Good approximation by Wilks' theorem: $\Delta\chi^2_c$ = 5.99 for the 95% C.L.
  95 % quantile of χ^2 distribution with 2 dof was verified with >5000 MC simulations ($\Delta\chi^2_c$ = 6.18)

Complementary Investigations

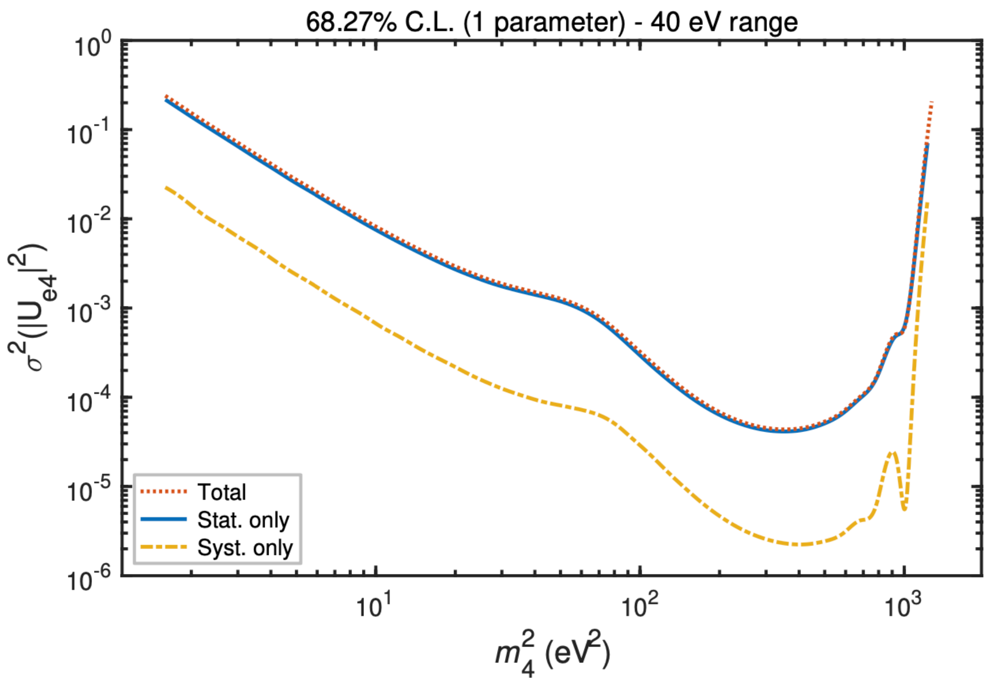
Analysis performed in non-physical regions

- $|Ue_4{}^2| < 0$ — negative β-decay rate at the heavy neutrino branch
- $|Ue_4{}^2| > 0.5$ — unphysical mixing
- $m_4^2 < 0$ — tachyonic sterile neutrino



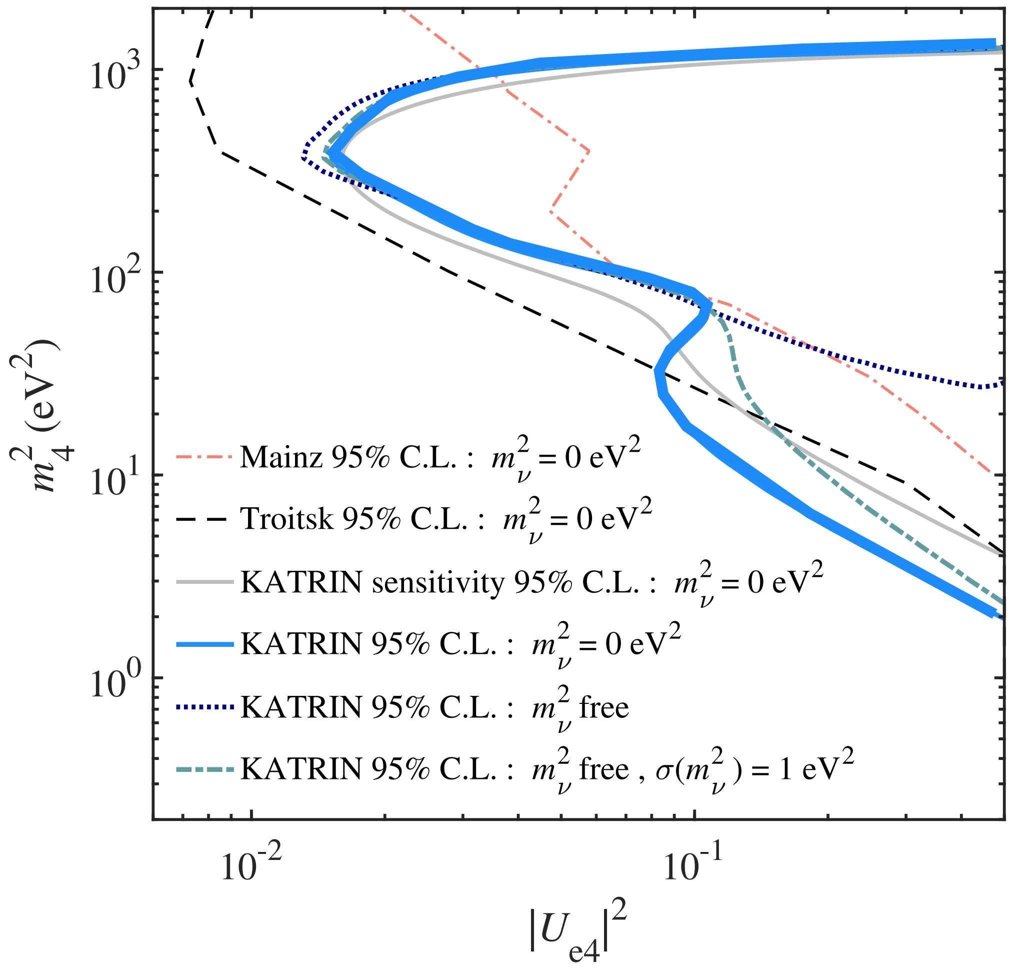
Raster scan

- choose a fixed value of m_4^2 and extract a $|Ue_4{}^2|$
- repeat for all physical m_4^2 - extract $\sigma(|Ue_4{}^2|)$



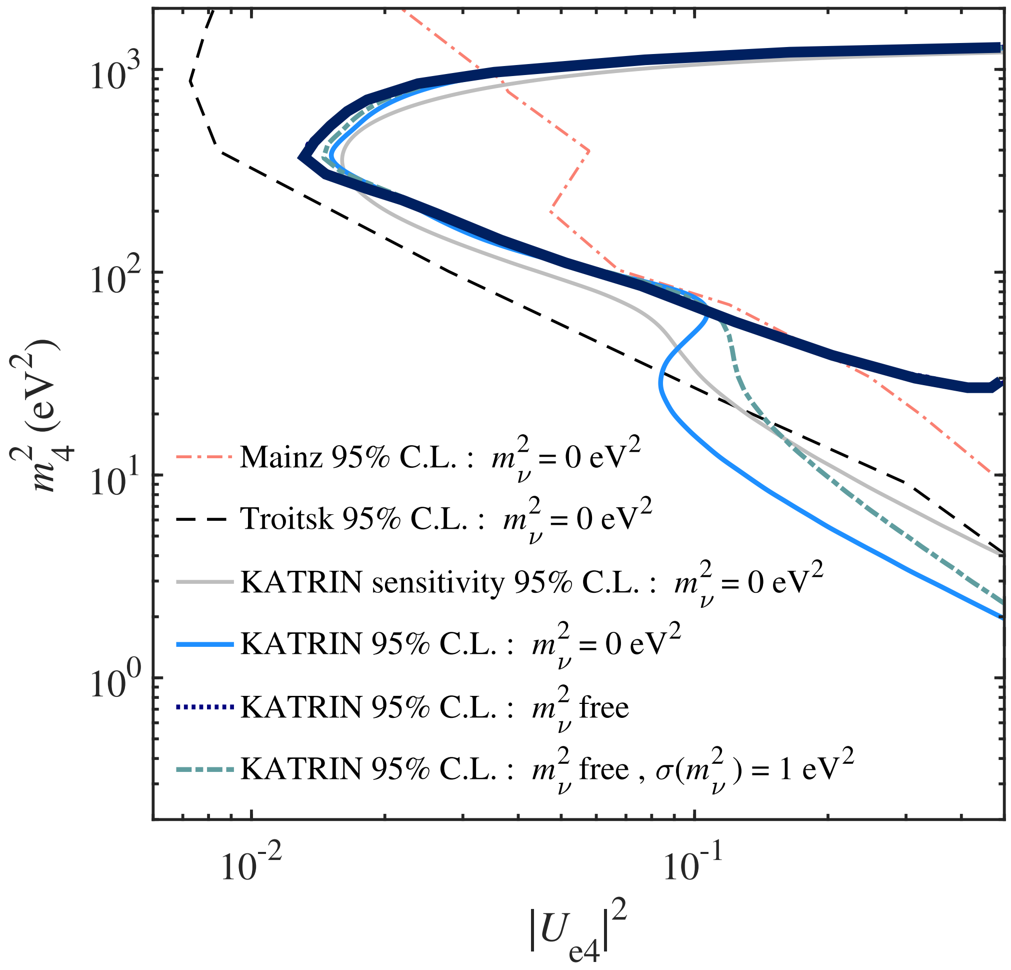
Systematic uncertainties are negligible for all m_4

Case i) 40 eV fit range, m_β= 0 eV fixed



- Results in the $|U_{e4}{}^2|$ - m_4^2 plane
- m_β= 0 eV fixed
- Sensitive to
  - m_4^2 < 1000 eV^2
  - $|U_{e4}|^2$ > 0.02
- Limit directly comparable to Mainz/Troitsk

Case ii) 40 eV fit range, free m_β



- **Free m_β**

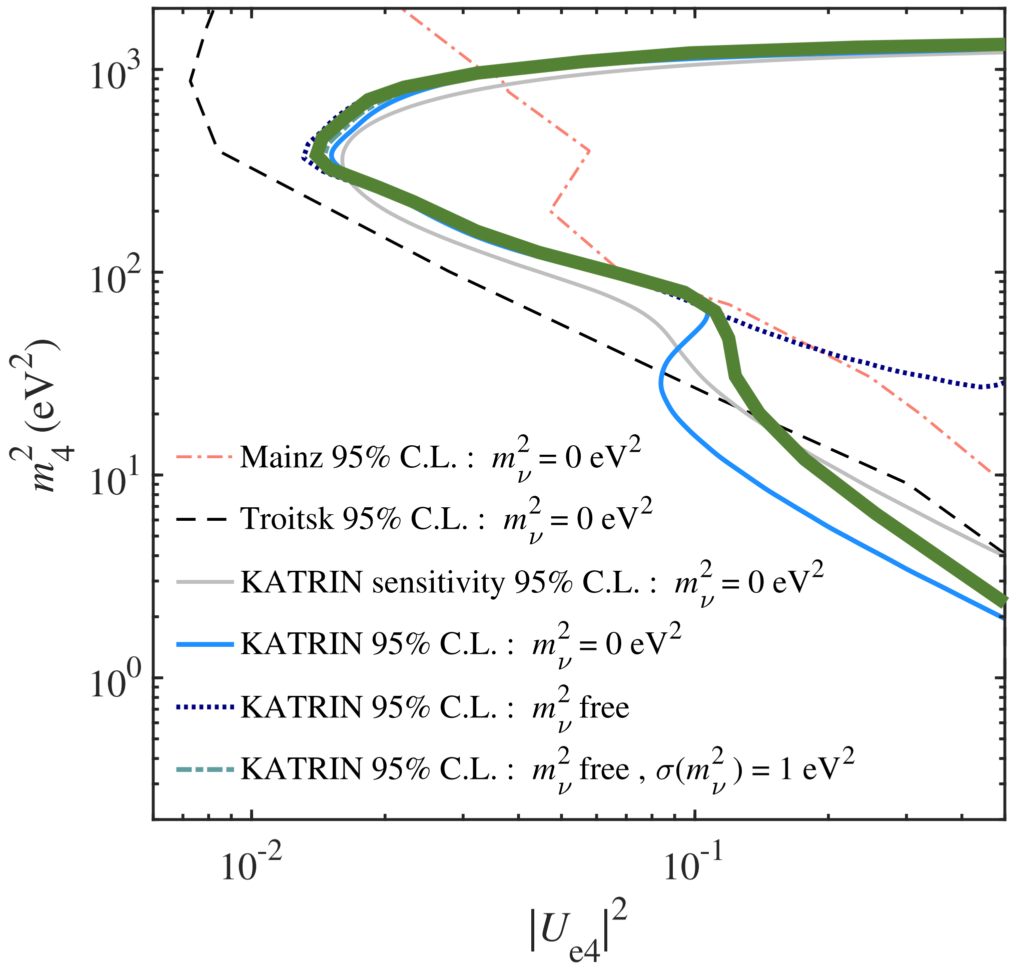
  → m_β can be negative

- The most generic analysis

- Loosing sensitivity w.r.t. case i) for $m_4^2 < 60$ eV^2

  → m_β and m_4 correlation at large $|\mathrm{Ue}_4{}^2|$

Case iii) 40 eV fit range, constrained m_β



- Constrained m_β

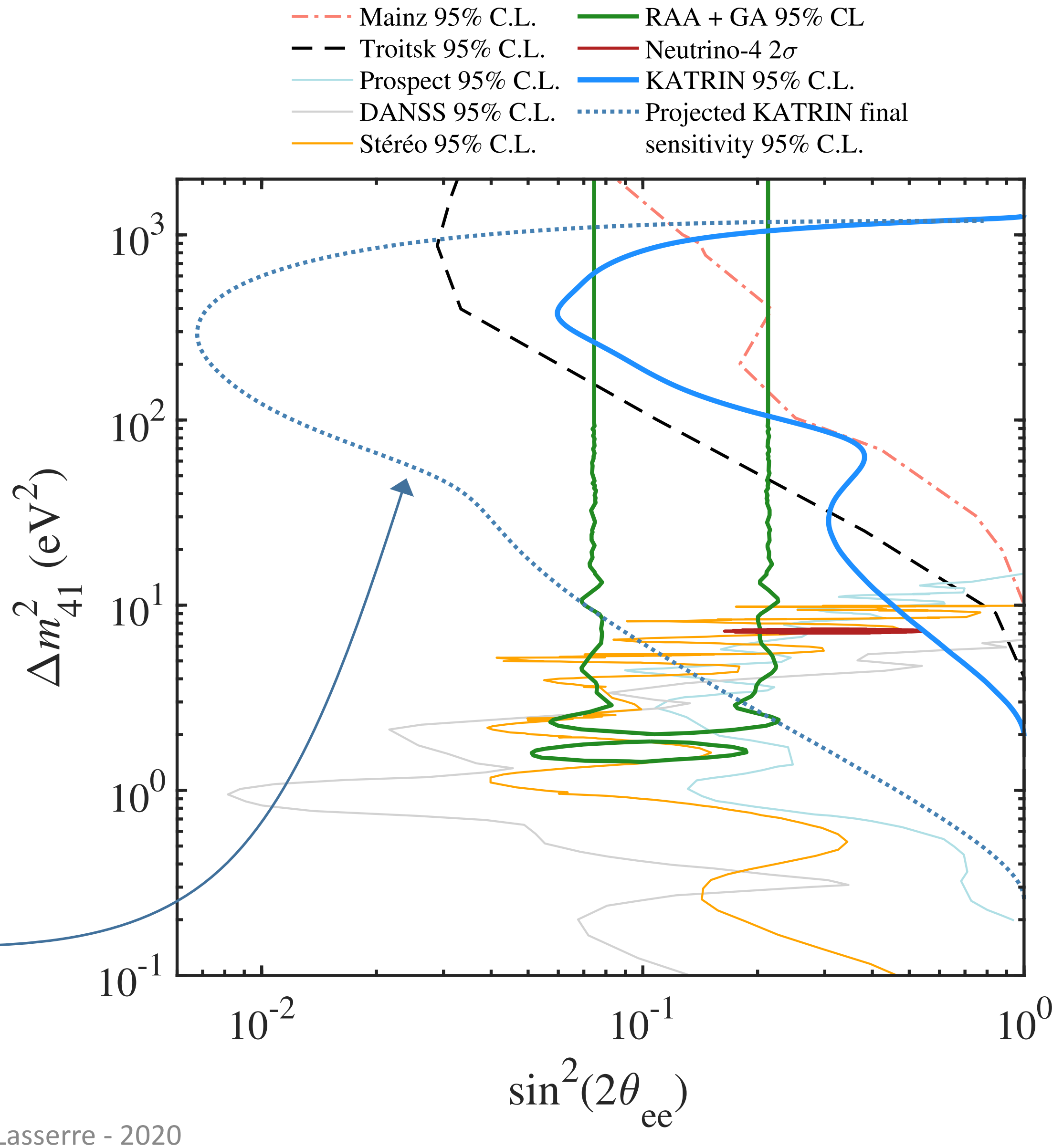
  Arbitrary constraint value, for illustration : 1 eV^2

- Intermediate case, for illustration of the impact of an external constraint (here m_β < 1 eV)

- Could be later used with with a bound from cosmology for instance

Synergy with oscillation experiments

- Oscillation Electron Disappearance Experiments
  - $\Delta m_{41}^2 = m_4^2 - m_1^2 \approx \Delta m_{42}^2 \approx \Delta m_{43}^2$
  - $\sin^2 2\Theta = 4|U_{e4}|^2(1-|U_{e4}|^2)$
- KATRIN
  - m_β and m_4
  - $\sin^2\Theta = |U_{e4}|^2$
- Conversion KATRIN -to- Oscillation
  - $\Delta m_{41}^2 \simeq m_4^2 - m_\beta^2$
  - $\sin^2 2\Theta = 4 \sin^2\Theta(1- \sin^2\Theta)$
- Projected KATRIN final sensitivity (1000 days of data – reduced background)

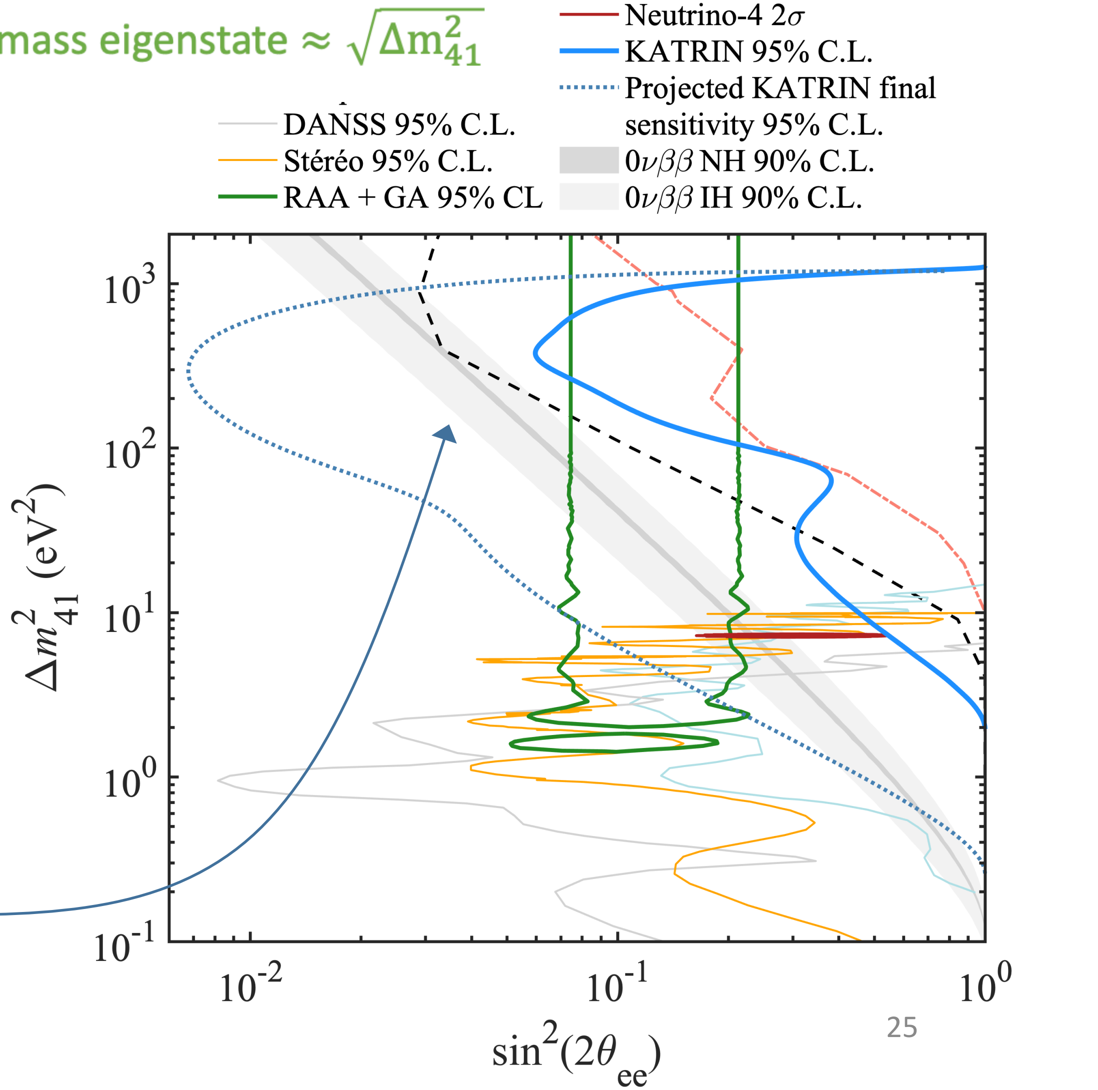


Interplay with $0\nu\beta\beta$ experiments

- $m_{\beta\beta}^{4\nu} = \left|(1 - |U_{e4}|^2) \cdot m_{\beta\beta}^{3\nu} + e^{i\varphi}\, |U_{e4}|^2\ m_4 \right|$

complex phase with $\varphi \in [-\pi, \pi]$ — active-to-sterile mixing — 4th mass eigenstate $\approx \sqrt{\Delta m_{41}^2}$

- Experimental constraint: $m_{\beta\beta}^{exp} < 0.165$ eV at 90% C. L.
- $m_{\beta\beta}^{exp} = m_{\beta\beta}^{4\nu} = \left|(1 - |U_{e4}|^2) \cdot m_{\beta\beta}^{3\nu} + e^{i\varphi}\, |U_{e4}|^2\ \sqrt{\Delta m_{41}^2}\right| < 0.165$ eV
- MC: Calculate $m_{\beta\beta}^{exp}$ for each each grid point, sampling
  - $m_{\beta\beta}^{3\nu} \in [0, 0.005\ eV]$ (NH), $m_{\beta\beta}^{3\nu} \in [0.01, 0.05\ eV]$ (IH)
  - $\varphi \in [-\pi, \pi]$
- Grey bands show all $(\Delta m_{41}^2, |U_{e4}|^2)$ combinations for which $m_{\beta\beta}^{exp}$ <0.165 eV



Conclusion

- High-quality data collected over 780 hours @25 GBq in 2019

- 2019: World Best Direct Neutrino Mass Measurement:

  m_ν < 1.1 eV (90% C.L.), Phys. Rev. Lett. 123, 221802

- 2020: First Results on the light sterile neutrino search, Arxiv

- x 10 more statistics already acquired

arXiv:2011.05087v1 [hep-ex] 10 Nov 2020

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(Dated: November 11, 2020)

We report on the light sterile neutrino search from the first four-week science run of the KATRIN experiment in 2019. Beta-decay electrons from a high-purity gaseous molecular tritium source are analyzed by a high-resolution MAC-E filter down to 40 eV below the endpoint at 18.57 keV. We consider the framework with three active neutrinos and one sterile neutrino of mass m_4. The analysis is sensitive to a fourth mass state $m_4^2 \lesssim 1000$ eV^2 and to active-to-sterile neutrino mixing

Thanks for your attention