MAX-PLANCK-INSTITUT
FÜR PHYSIK

Technical
University
of Munich

Latest results from KATRIN

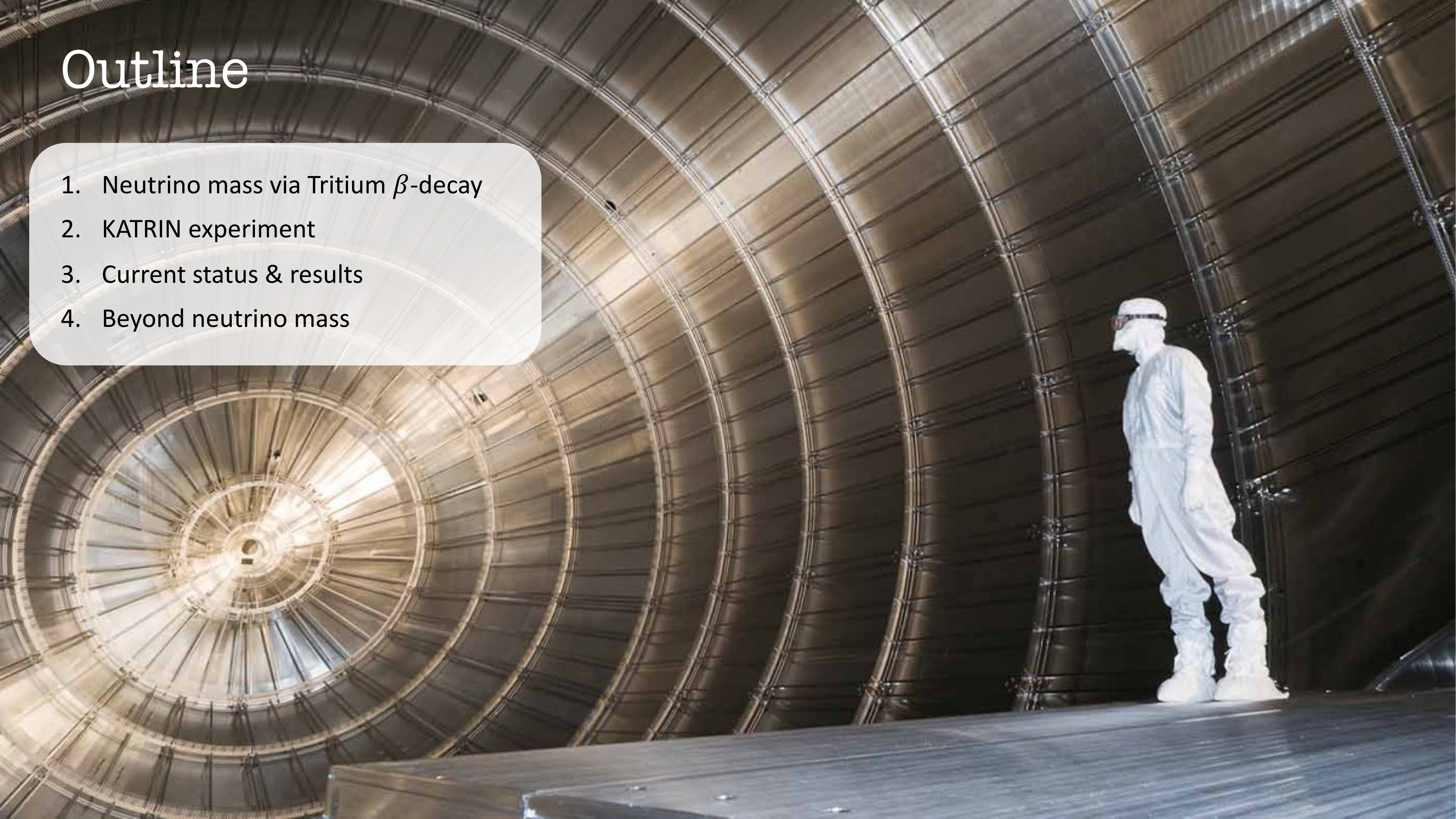
IRN Neutrino meeting at LAPP

Lisa Schlüter - on behalf of the KATRIN collaboration

2022, June 30

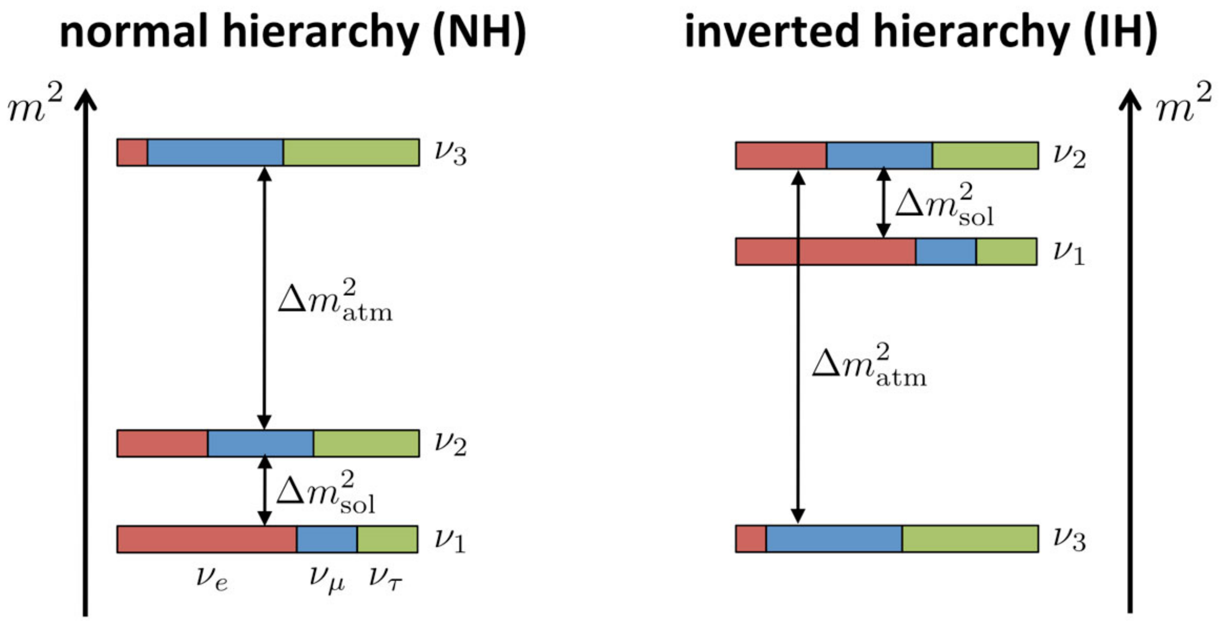
Outline

1. Neutrino mass via Tritium β-decay
2. KATRIN experiment
3. Current status & results
4. Beyond neutrino mass



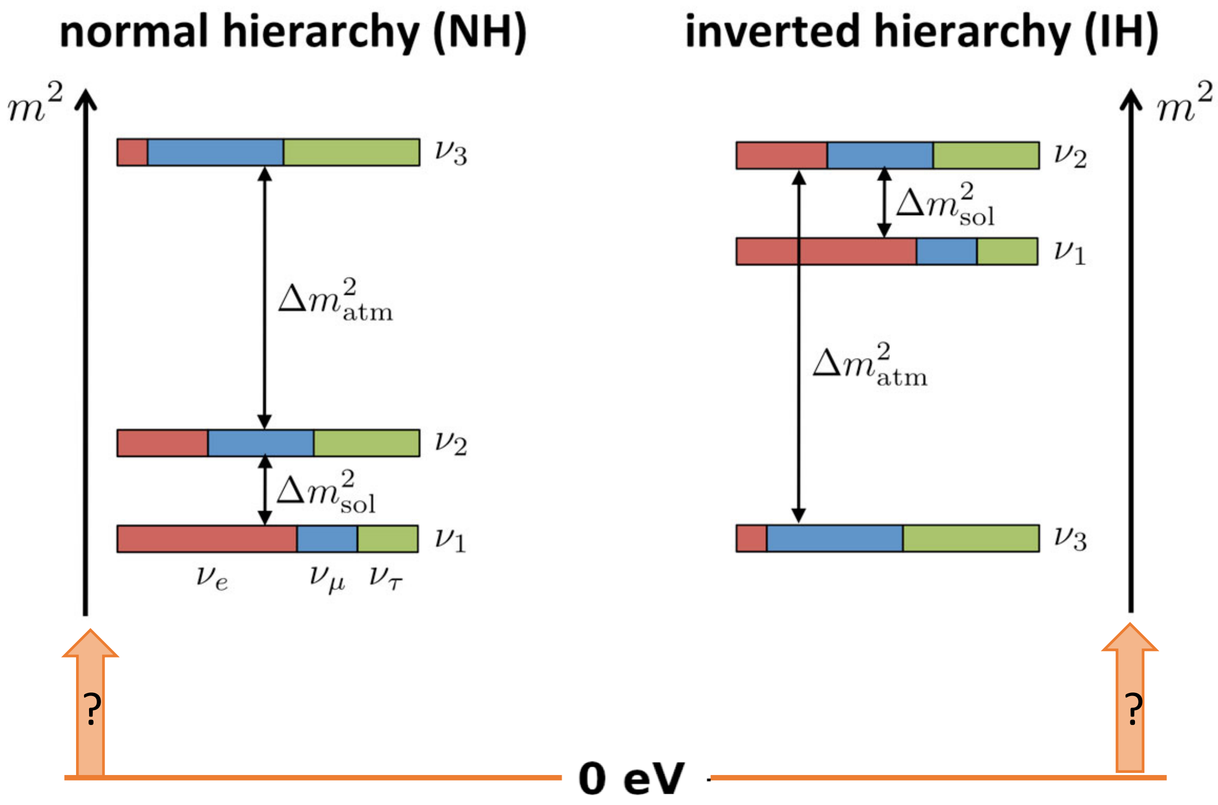
Absolute neutrino mass scale

- Neutrino oscillations
  - ➢ They have a mass
  - ➢ Mass splittings Δm_{ij}^2 and mixing

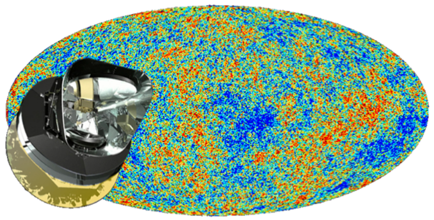


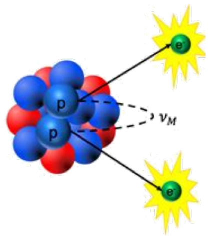
Absolute neutrino mass scale

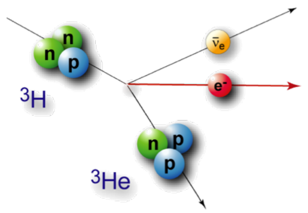
- Neutrino oscillations
  - ➢ They have a mass
  - ➢ Mass splittings Δm^2_{ij} and mixing
- Absolute mass scale?



Neutrino mass determination



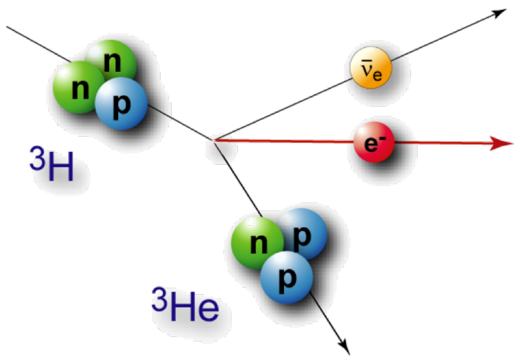


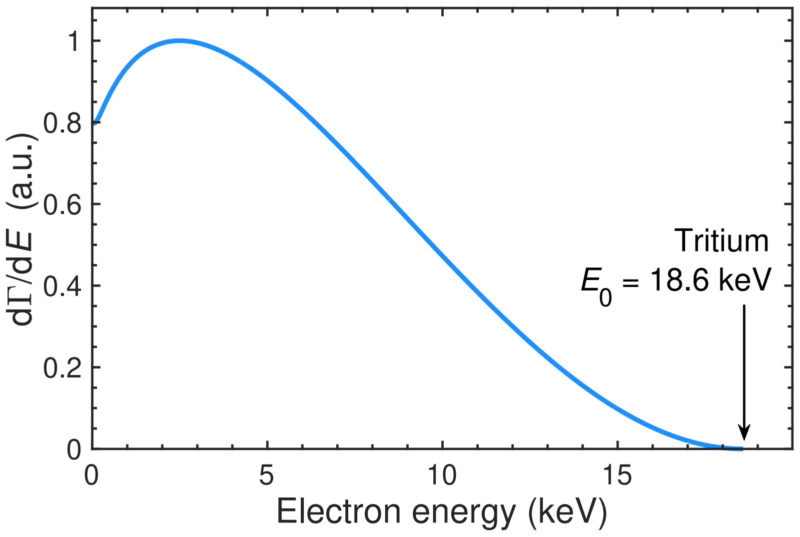


	Cosmology	Search for $0\nu\beta\beta$	β-decay and electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta} = \left\| \sum_i U_{ei}^2 \; m_i \right\|$	$m_\beta^2 = \sum_{i=1} \|U_{ei}\|^2 \, m_i^2$
Present upper limit	0.11 – 0.54 eV*	0.061 – 0.165 eV**	0.8 eV
Model dependence	• Multi-parameter cosmological model	• Majorana nature • Possible cancellations in coherent sum	• Direct, only kinematics • No cancellation in incoherent sum
Experiments	• Planck satellite	• GERDA, KAMLAND-Zen, MAJORANA, LEGEND, (n)Exo,…	• KATRIN, Project8, PTOLEMY • ECHo, HOLMES

*source: PDG 2020: Neutrinos in Cosmology **source: PDG 2020 Neutrino masses

Tritium β-decay





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

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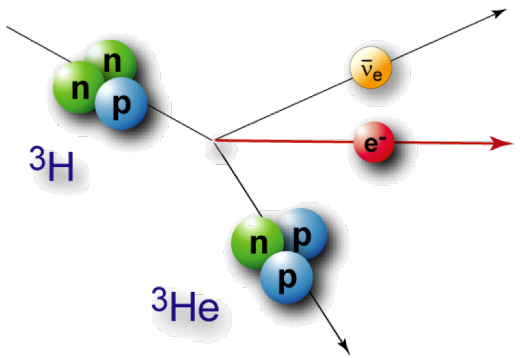

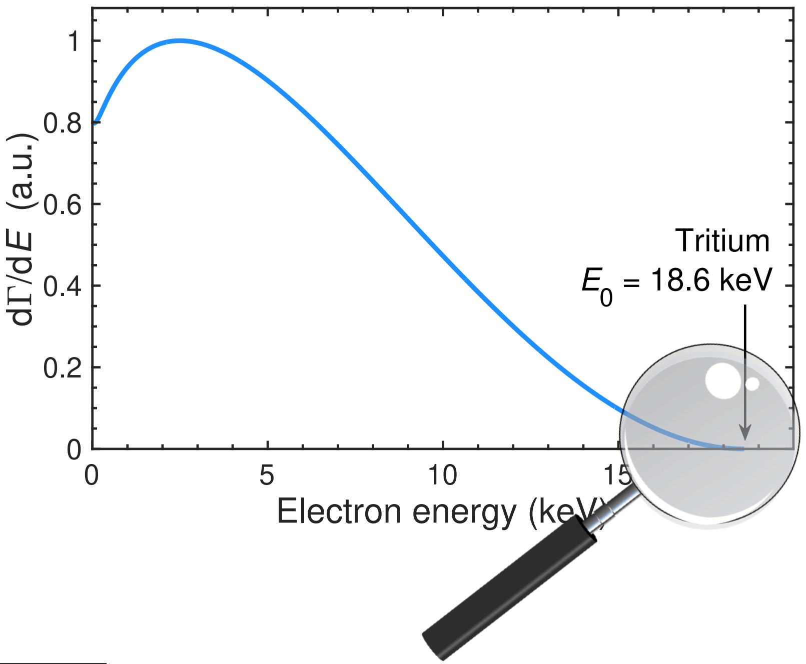

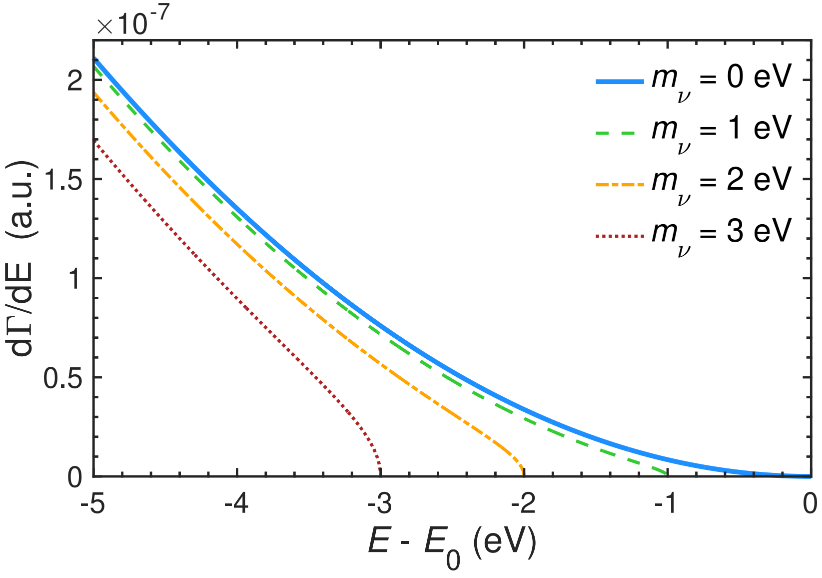

	^{3}H
	Super-allowed β-decay
$T_{1/2}$	12.3 years
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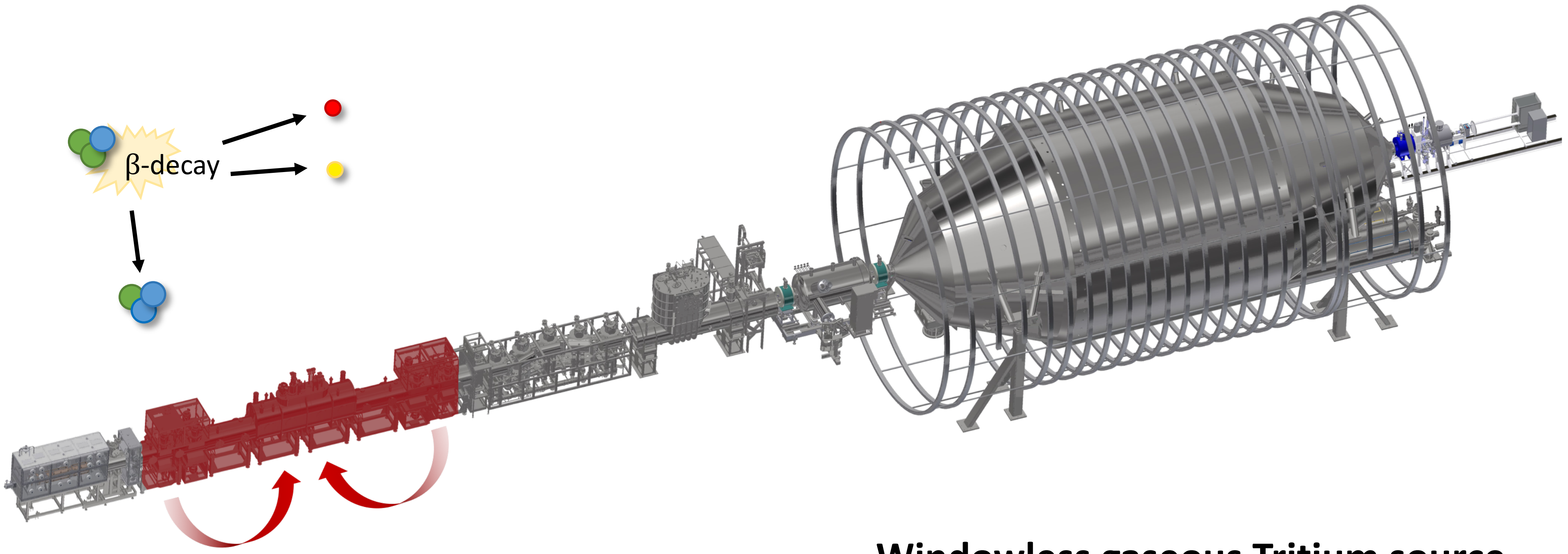
$$m_\nu^2 = \sum_{i=1}^{3} |U_{ei}|^2 \, m_i^2$$

KATRIN Measurement Principle



Windowless gaseous Tritium source

- Molecular tritium in closed loop system
- 10^{11} decays/s

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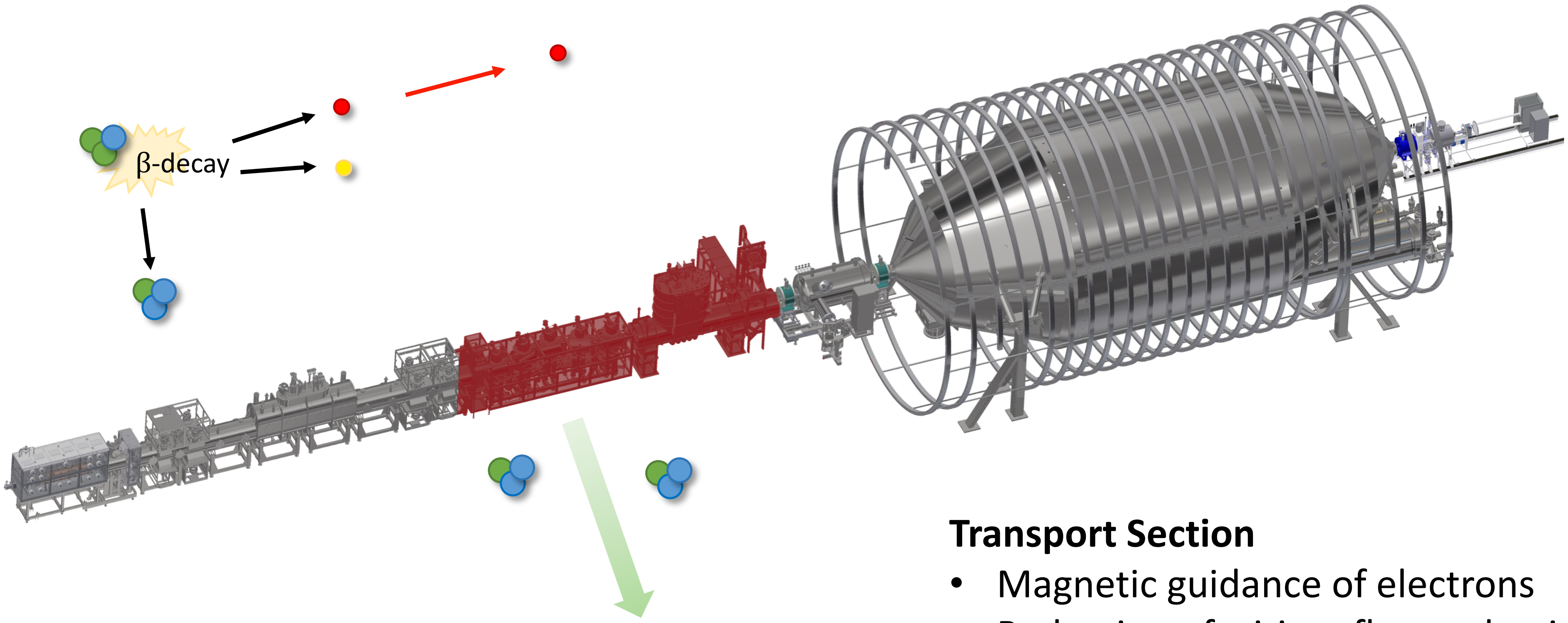

Transport Section
- Magnetic guidance of electrons
- Reduction of tritium flow reduction by 14 orders of magnitude

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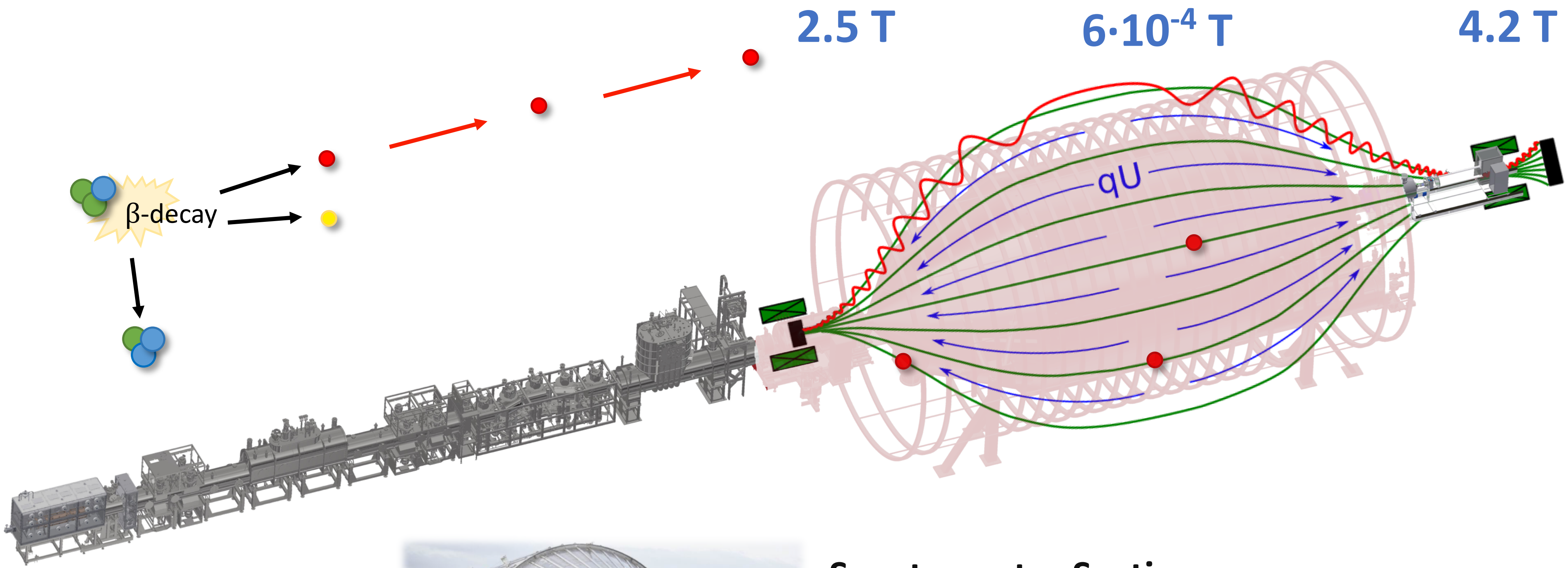
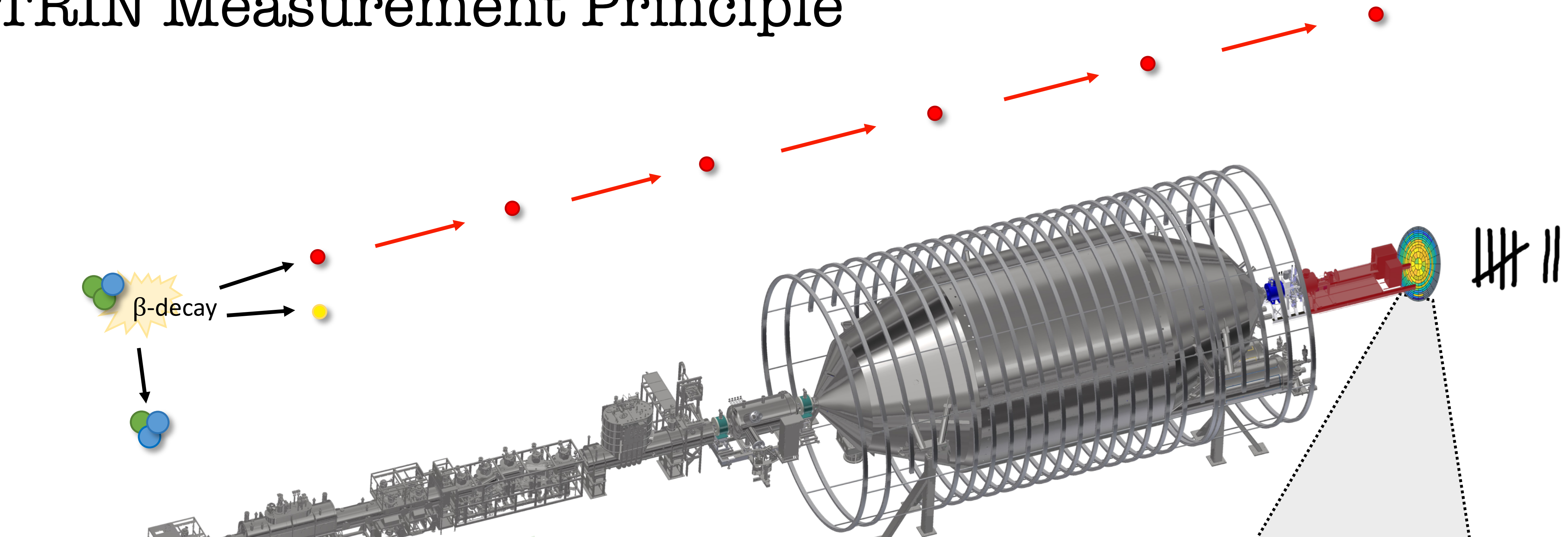


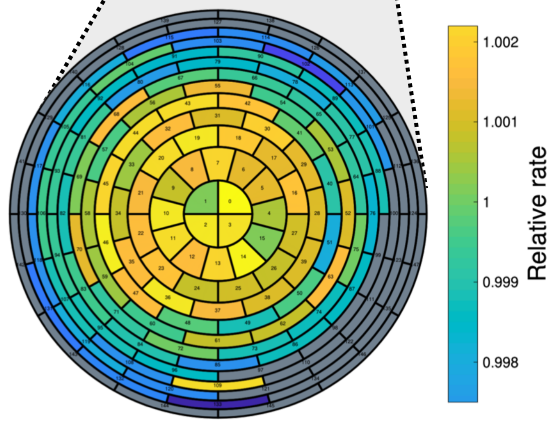
Spectrometer Section

- Magnetic adiabatic collimation (MAC) + electrostatic (E) filter
- Energy resolution 2.7 eV

KATRIN Measurement Principle



Focal Plane Detector
- Silicon detector
- 148 pixels in 13 rings
- Counts electrons



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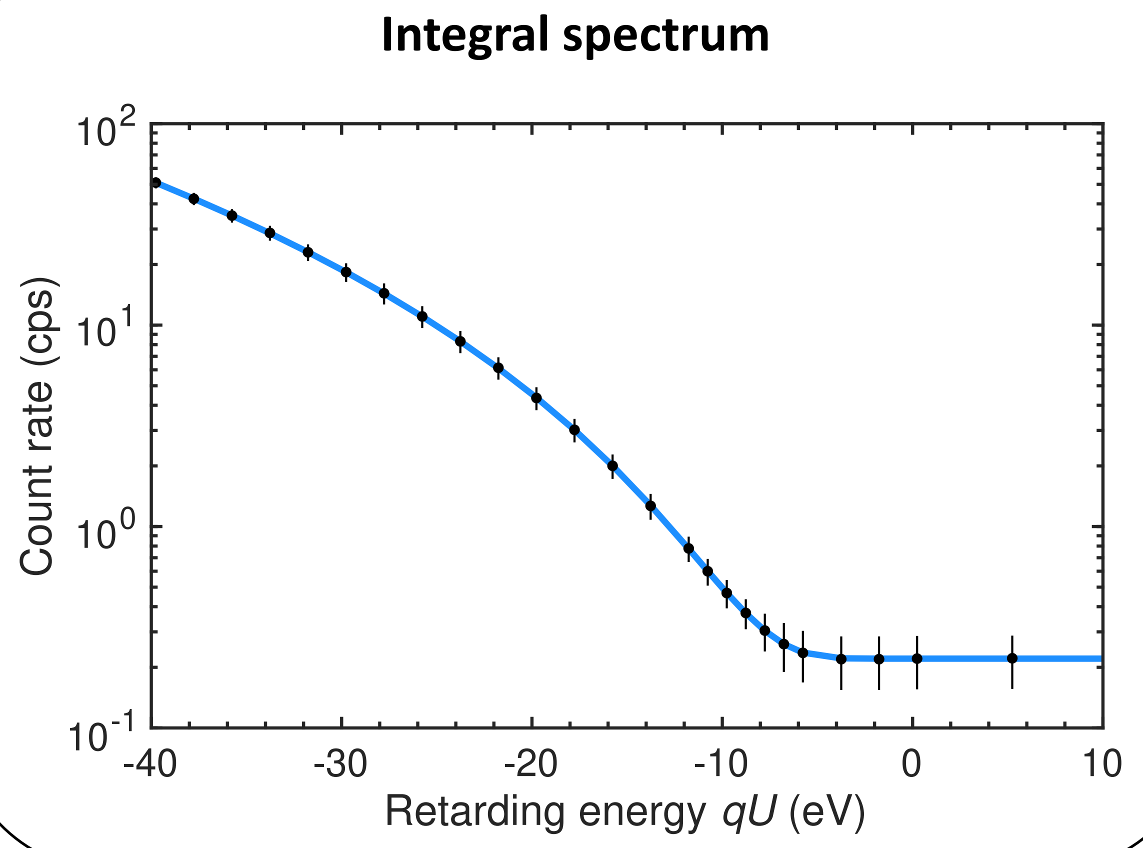

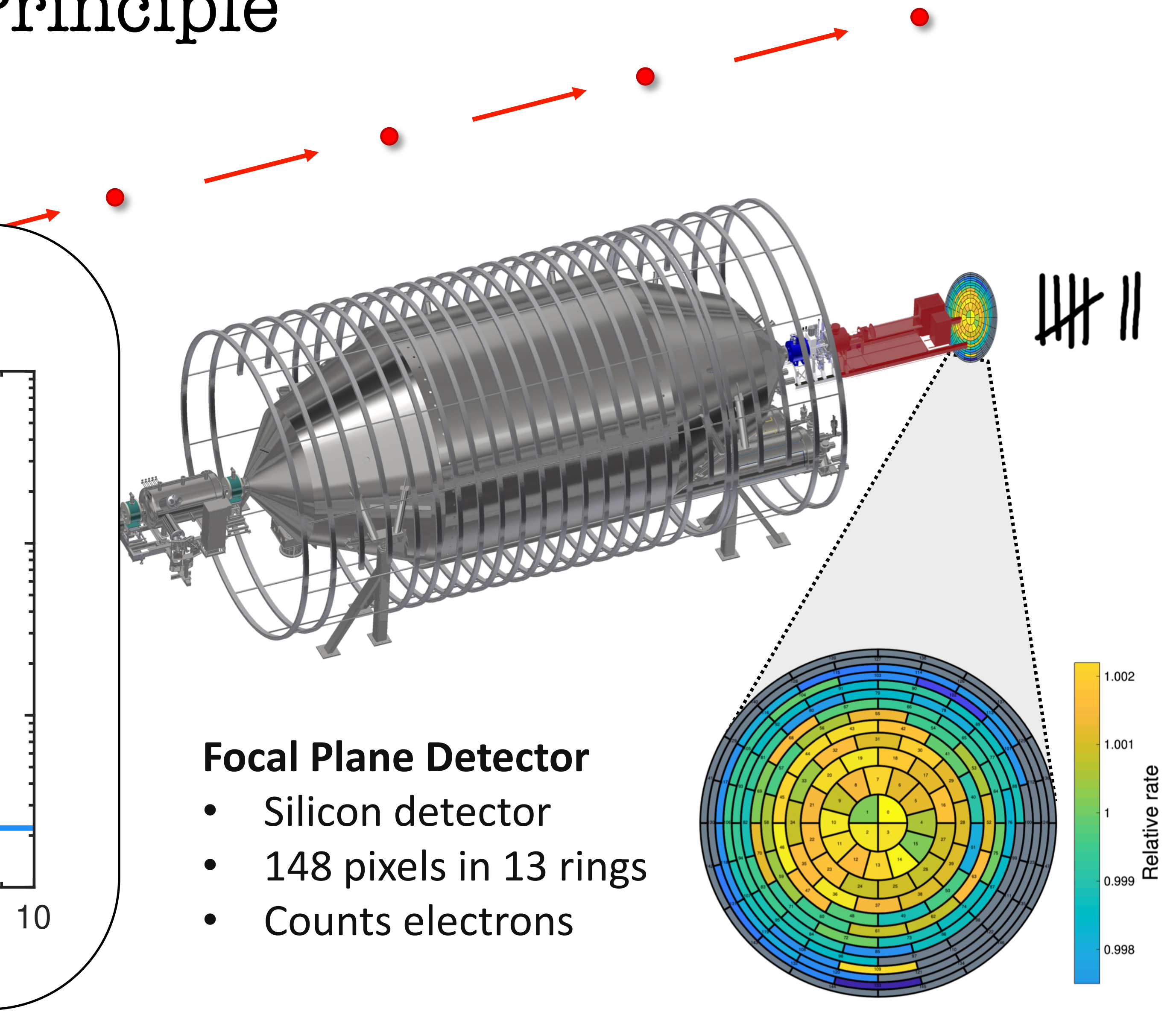

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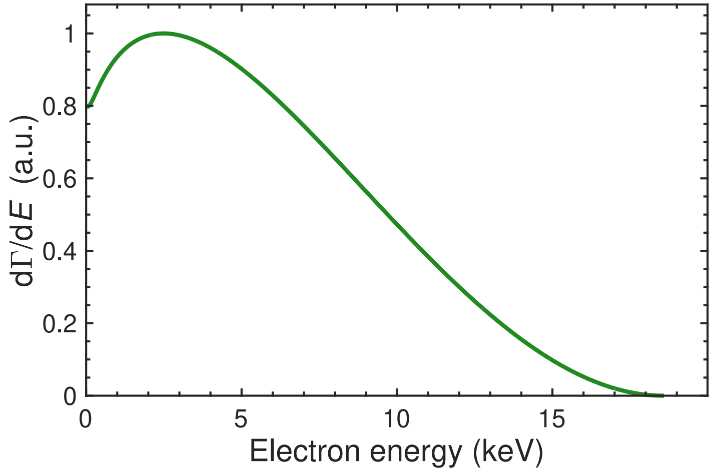
Model prediction

Differential β-spectrum



Theoretical input:
- Fermi theory
- Theo. corrections
- Final-state distribution

Experimental response function

Experimental input:
- Spectrometer transmission
- Energy-loss in the source

Integral β- spectrum

Model function:
- Describes data
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Model prediction

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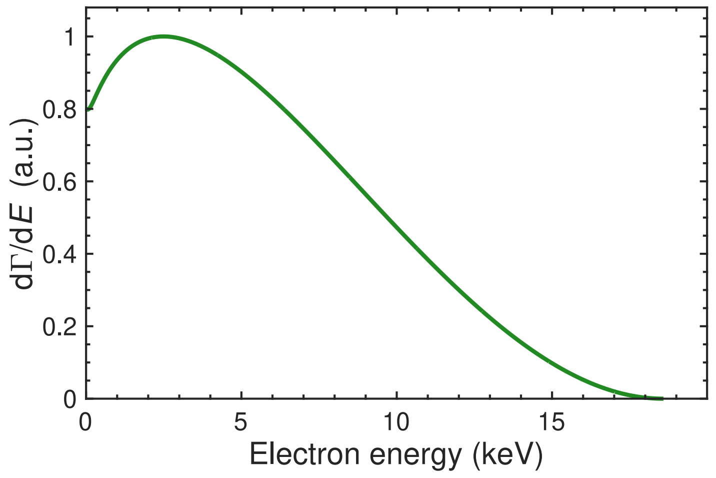

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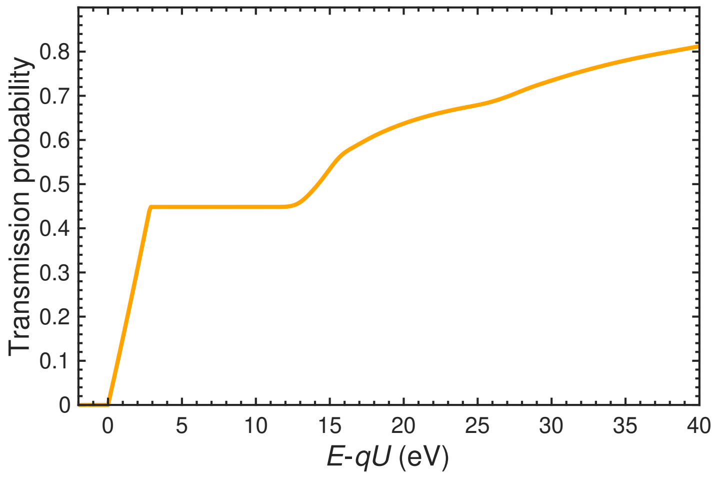

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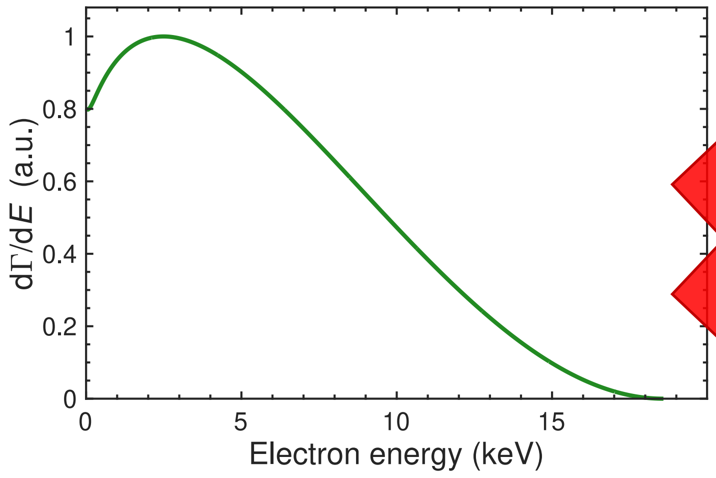

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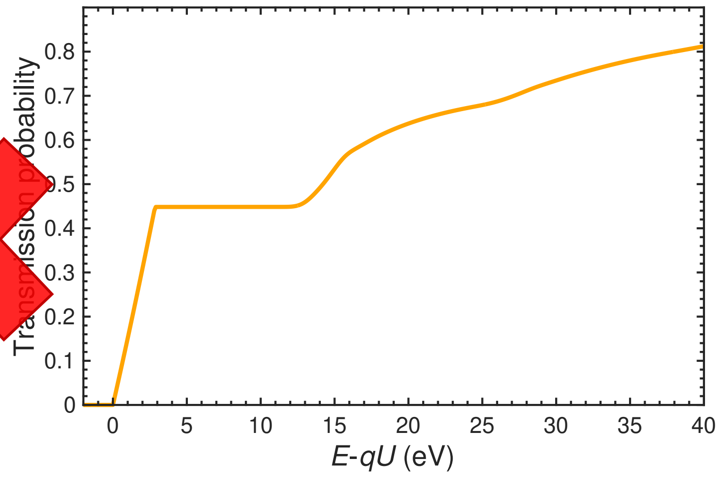

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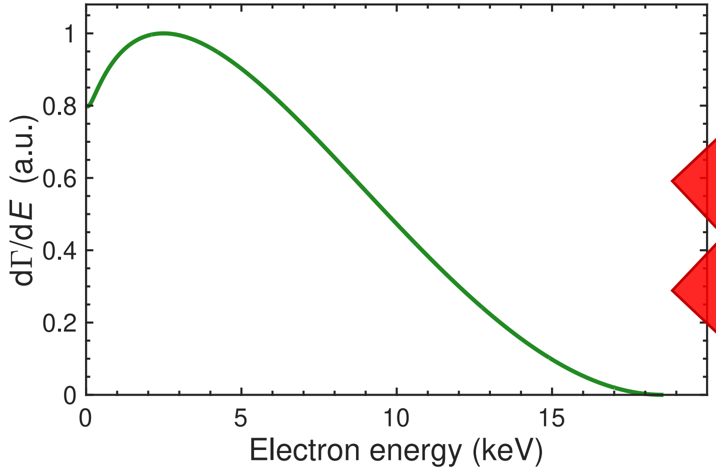

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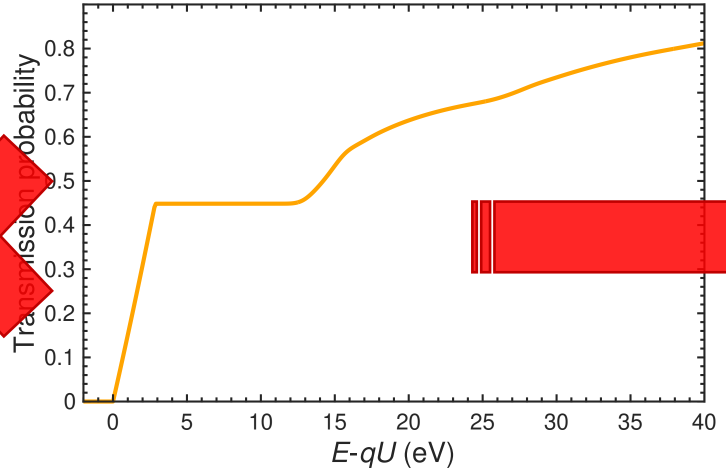

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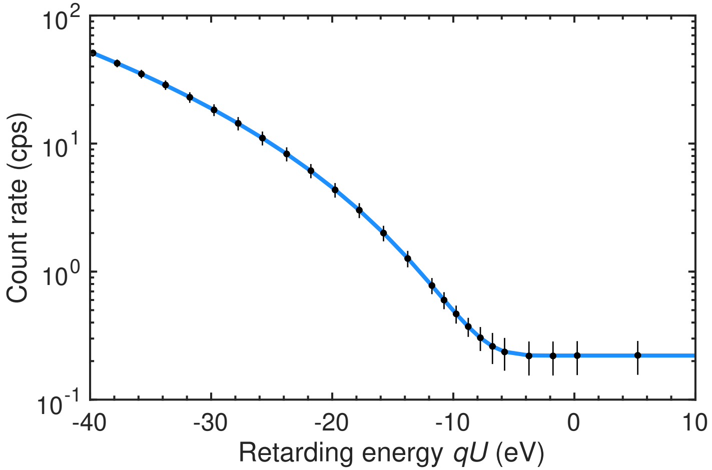

Model function:

- Describes data
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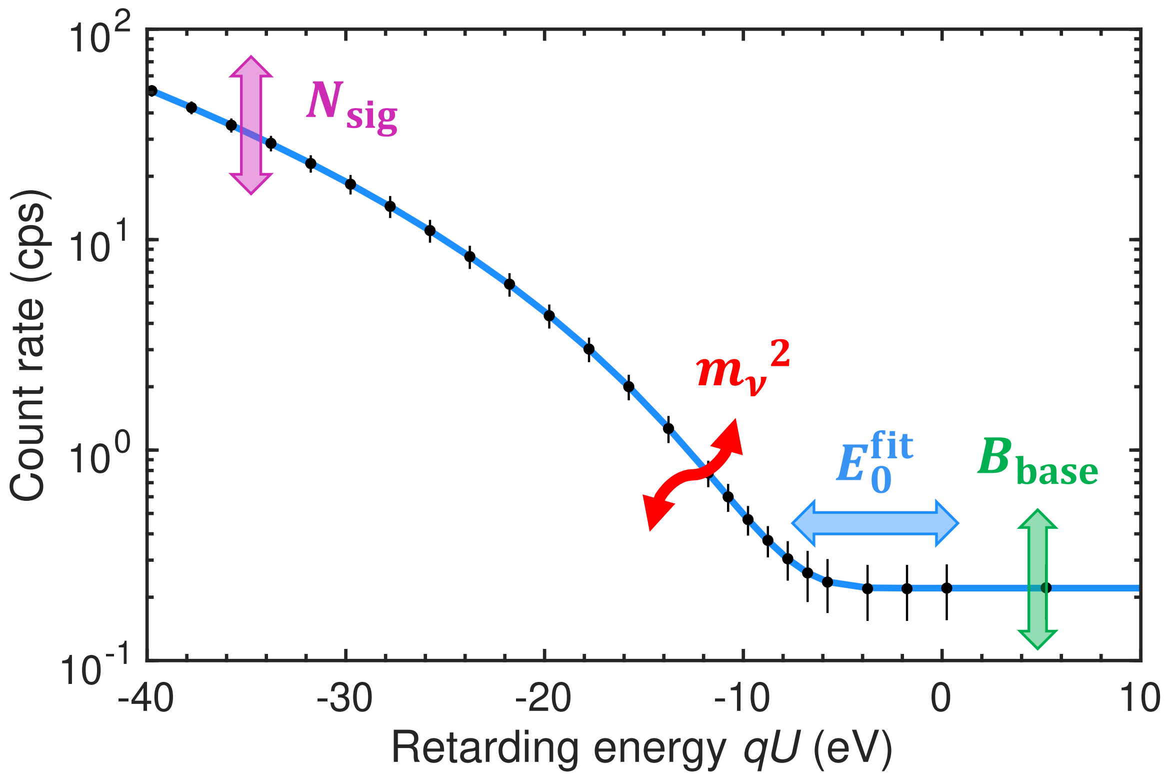
Spectrum and Fit

Fit Parameter

1. $m_\nu{}^2$ neutrino mass
2. E_0^{fit} endpoint
3. N_{sig} signal normalization
4. B_{base} energy-independent background rate



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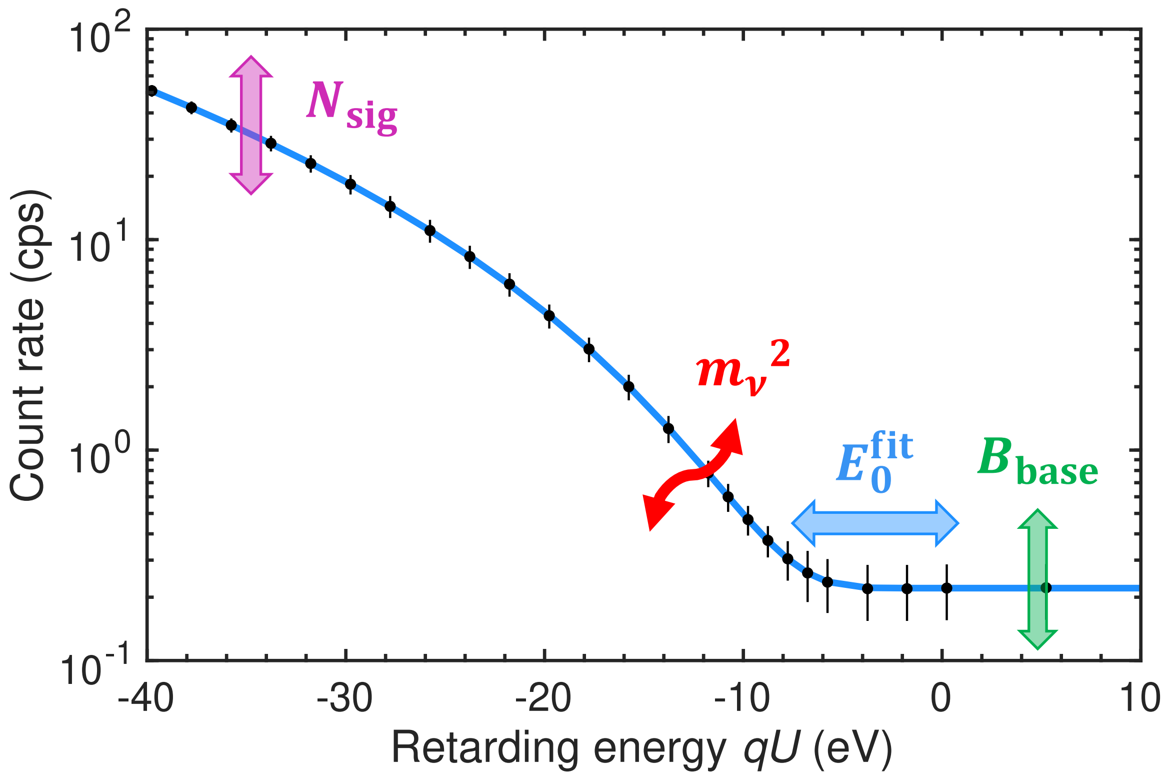


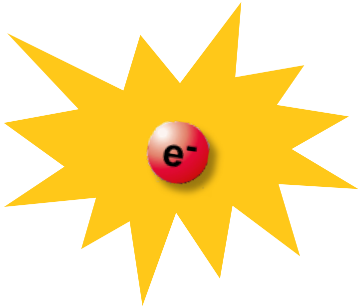
Three complementary analysis strategies

- Different statistics:
  - Least-squares
  - Maximum-likelihood
- Different systematics treatments:
  - Covariance matrices
  - MC error propagation
  - Pull terms
- Independent implementation

Timeline

2001
Founding of KATRIN

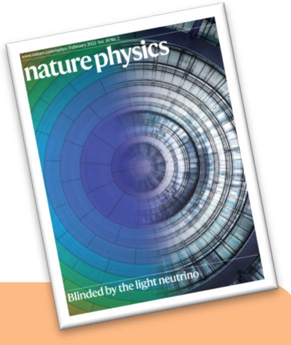
2006
Spectrometer arrives in Karlsruhe



2016
First electrons

2018
KATRIN inauguration
First Tritium

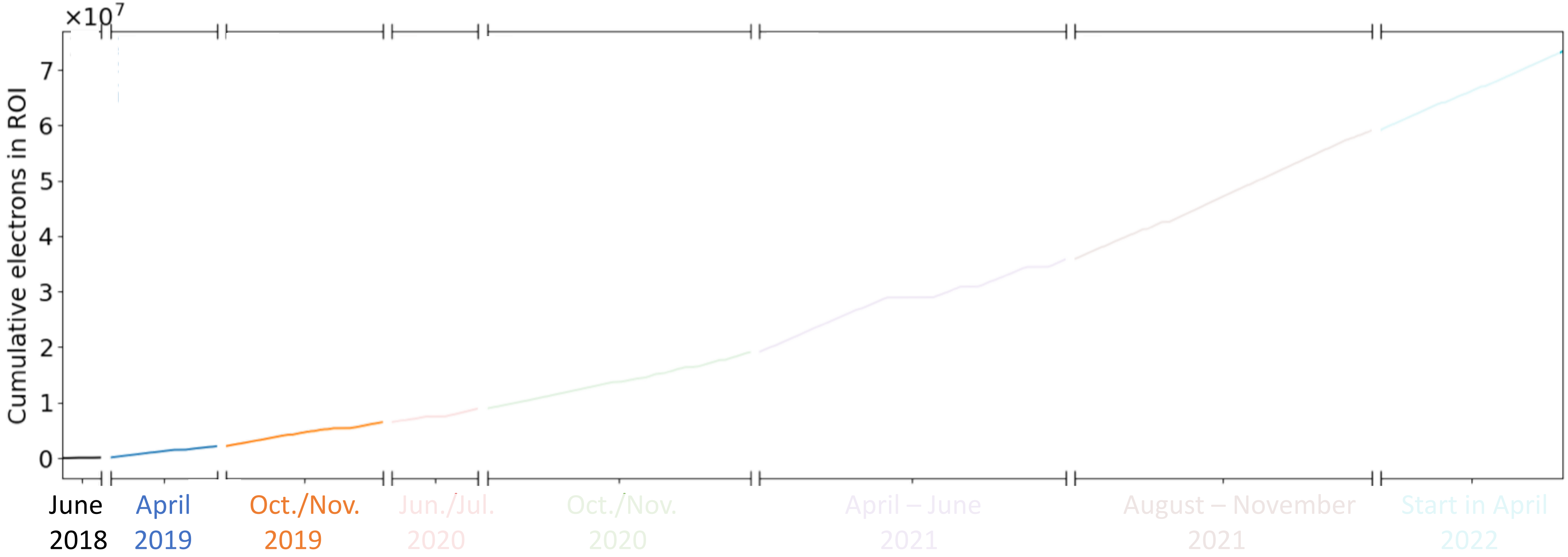
2019
First upper limit
m_β < 1.1 eV (90% C.L.)



2021
First sub-eV limit
m_β < 0.8 eV (90% C.L.)

Until 2024
Measurements

Analyzed measurement campaigns



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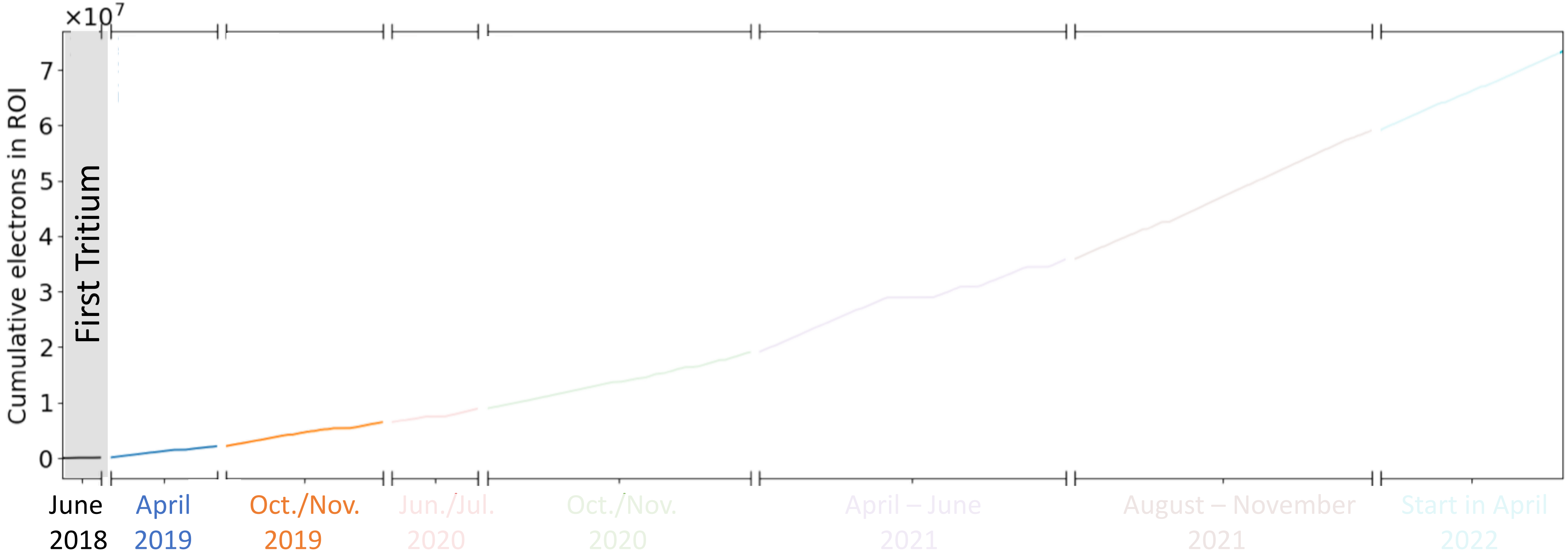
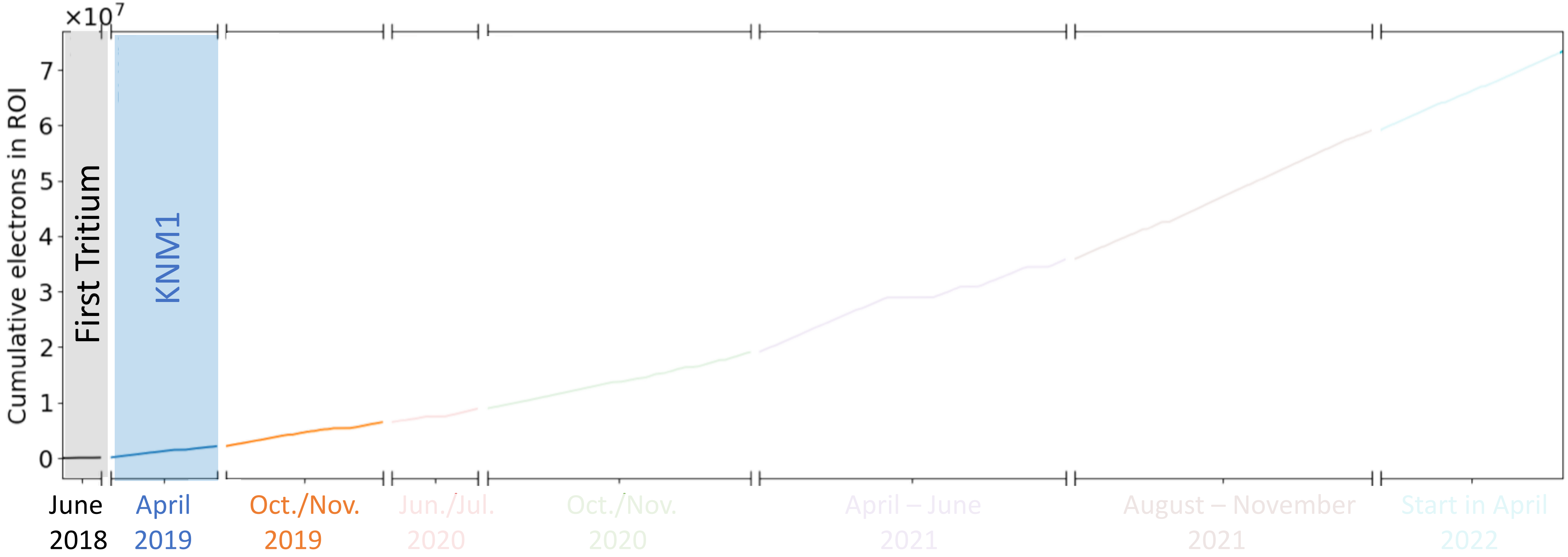


- Commissioning
- Only 0.5% tritium

Analyzed measurement campaigns



- Commissioning
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- 1st campaign
- $1.5 \cdot 10^6$ β-electrons
- $m_\nu < 1.1$ eV

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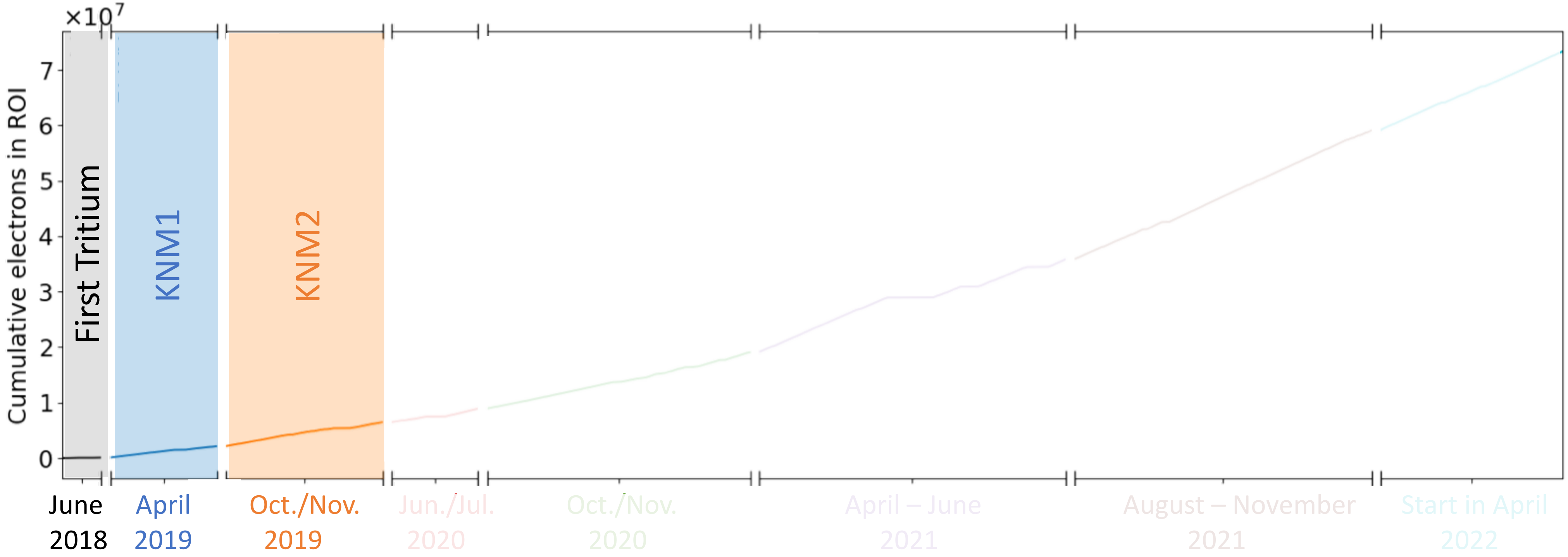


- Commissioning
- Only 0.5% tritium

- 1^{st} campaign
- $1.5 \cdot 10^6$ β-electrons
- $m_\nu < 1.1$ eV

- 2^{nd} campaign
- $3.7 \cdot 10^6$ β-electrons
- $m_\nu < 0.9$ eV

Blinding

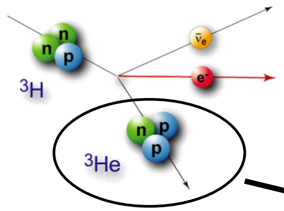
- Prevent human-induced bias
- History of negative neutrino mass squared

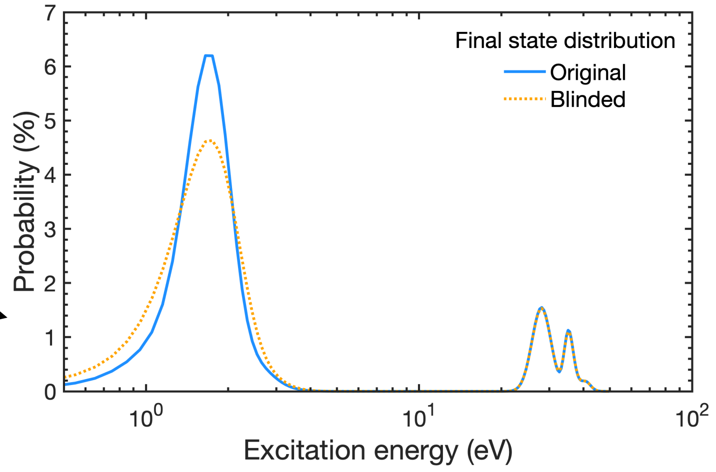
1. full analysis on MC data

Systematics studies,
cross checks, fitter comparison, …

Blinding

- Prevent human-induced bias
- History of negative neutrino mass squared
- Final State distribution of parent & daughter molecule
  - Rotational and Vibrational excitations
  - Electronic excitations





1. full analysis on MC data

Systematics studies,
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2. data analysis with *"blind"* FSD

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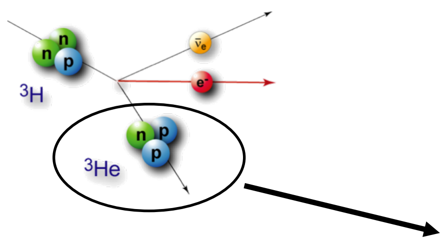
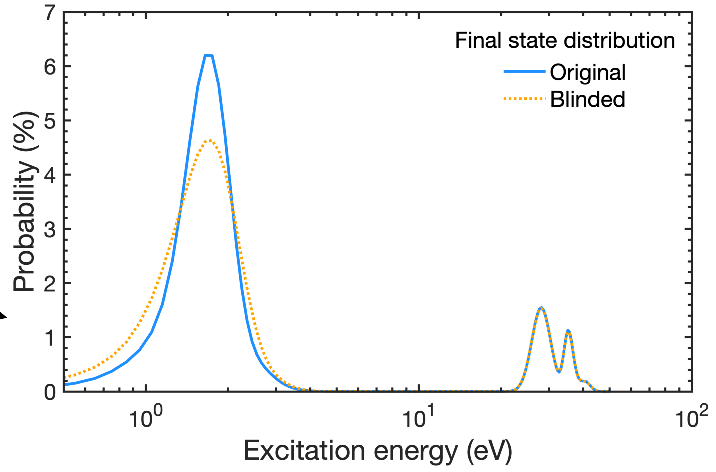




1. full analysis on MC data

Systematics studies,
cross checks, fitter comparison, …

2. data analysis with *"blind"* FSD

Systematics studies,
cross checks, fitter comparison, …

3. final data analysis with original FSD

Neutrino-mass results

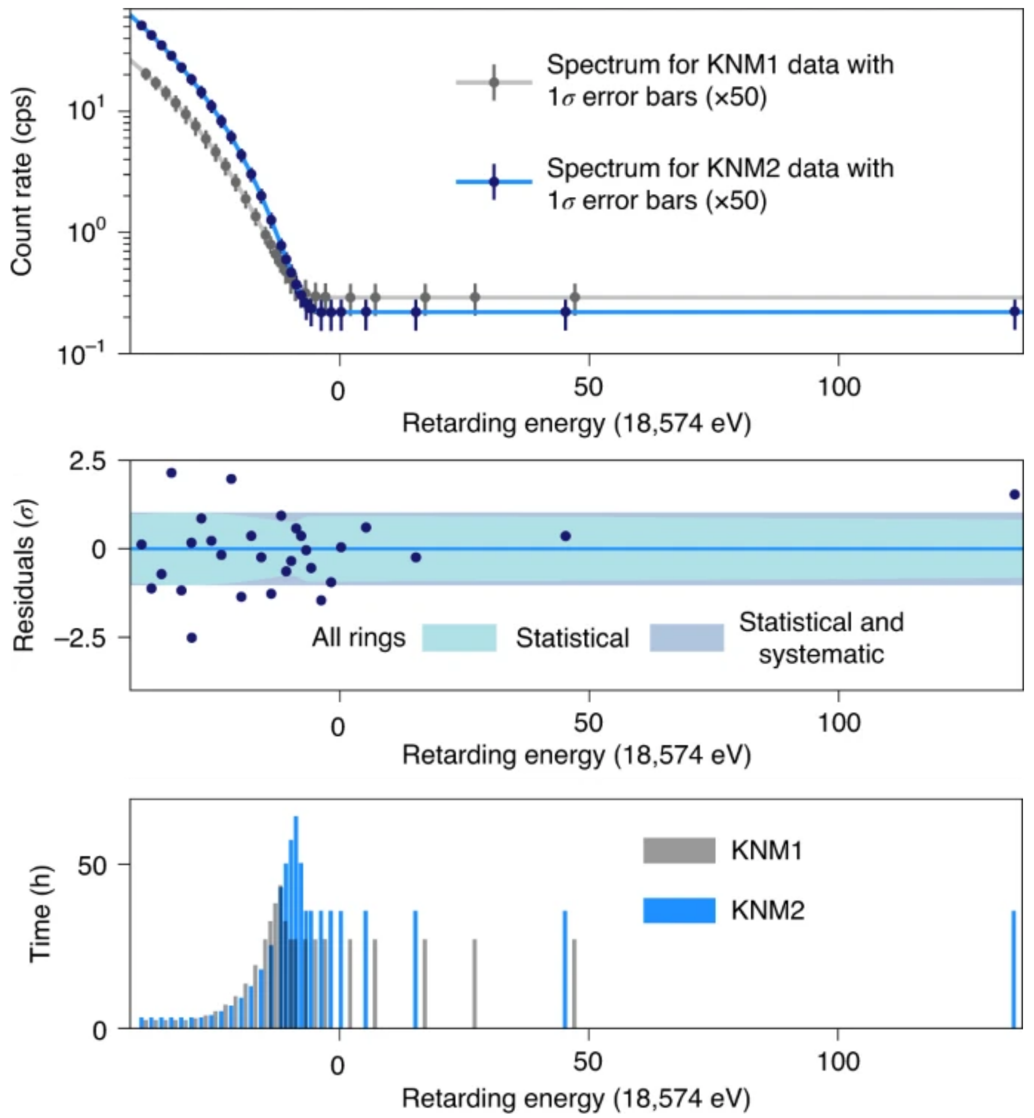
1st campaign (spring 2019):

- Best fit: $m_\nu^2 = (-1.0 \pm 1.0)\ \mathrm{eV}^2$
- Upper limit: $m_\nu \leq 1.1\ \mathrm{eV}\ \ (90\%\ \mathrm{C.L.})$

2nd campaign (autumn 2019):

- Best fit: $m_\nu^2 = (0.26 \pm 0.32)\ \mathrm{eV}^2$
- Upper limit: $m_\nu \leq 0.9\ \mathrm{eV}\ \ (90\%\ \mathrm{C.L.})$

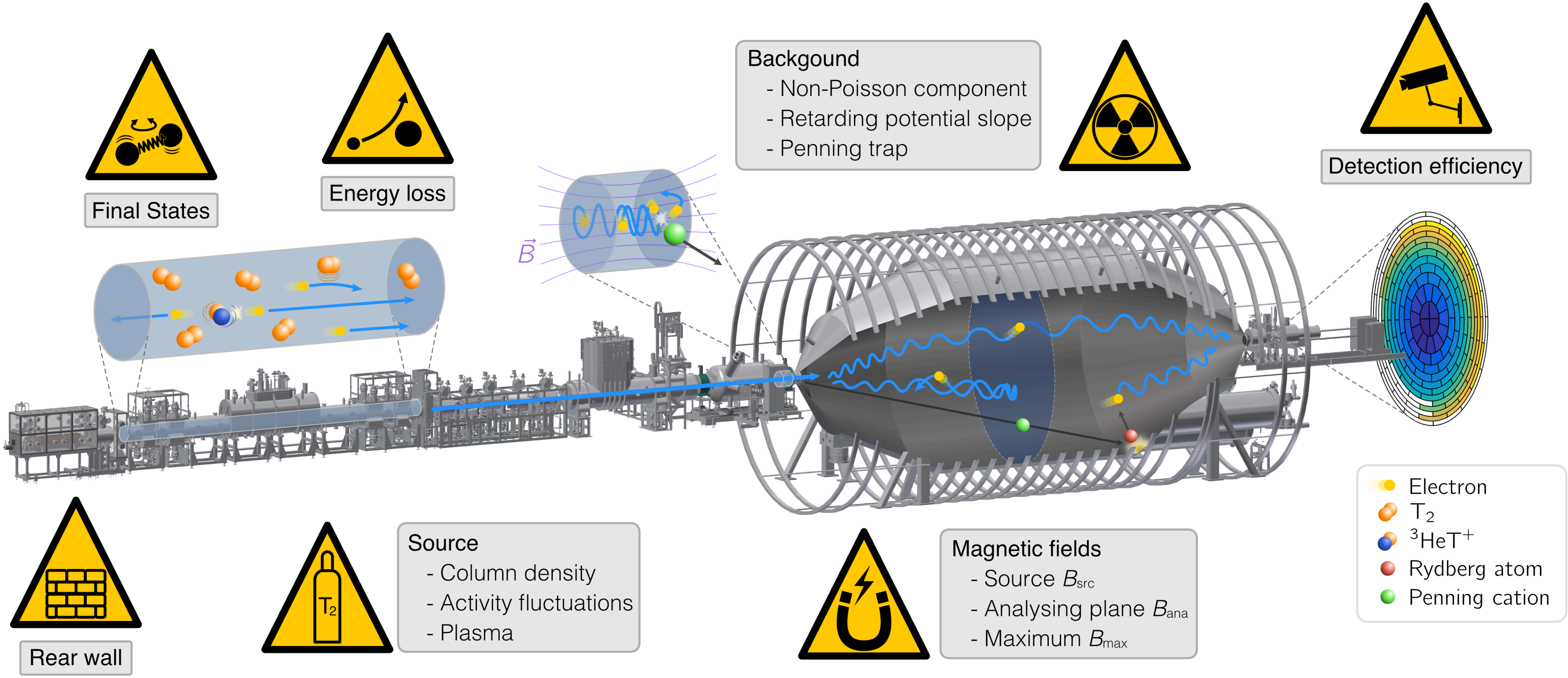
➢ Combined upper limit: $\boldsymbol{m_\nu \leq 0.8\ \mathrm{eV}\ \ (90\%\ \mathrm{C.L.})}$



More details:

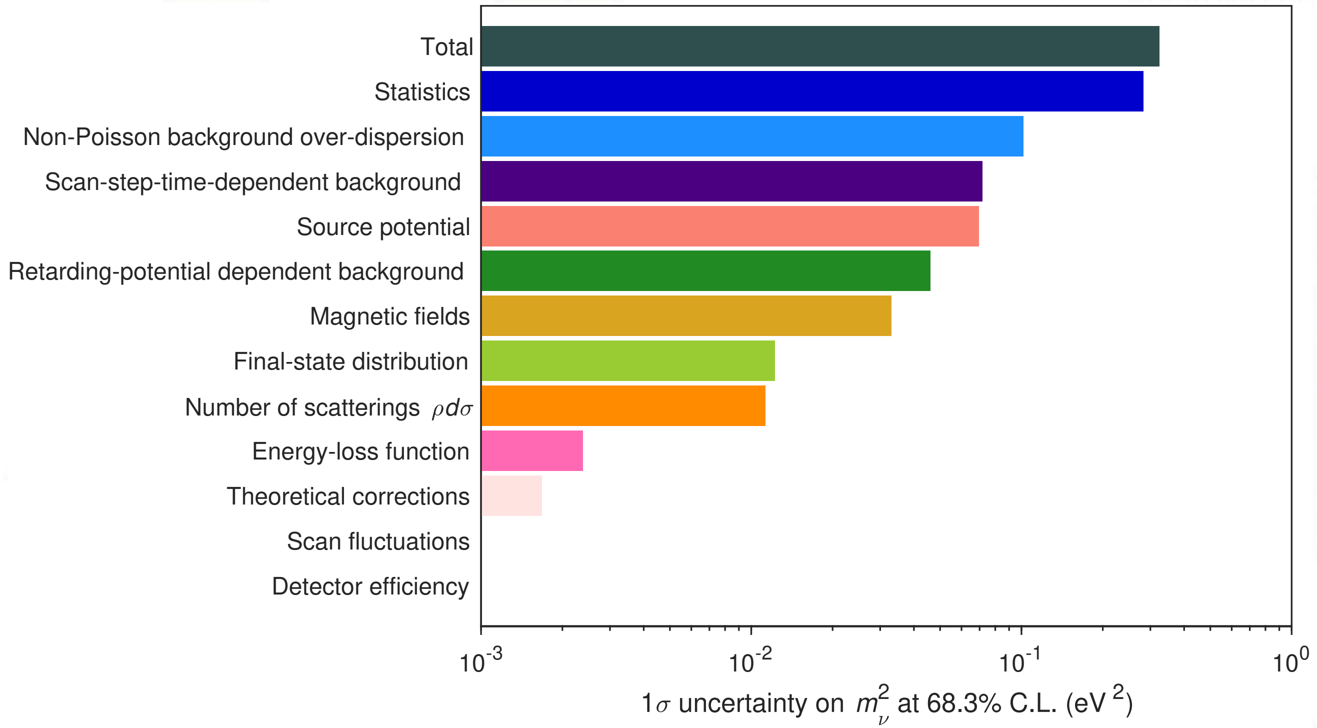
➢ Phys. Rev. Lett. 123, 221802 (2019)
➢ Phys. Rev. D 104, 012005 (2021)
➢ Nature Physics 18, 160–166 (2022)

Systematic effects overview

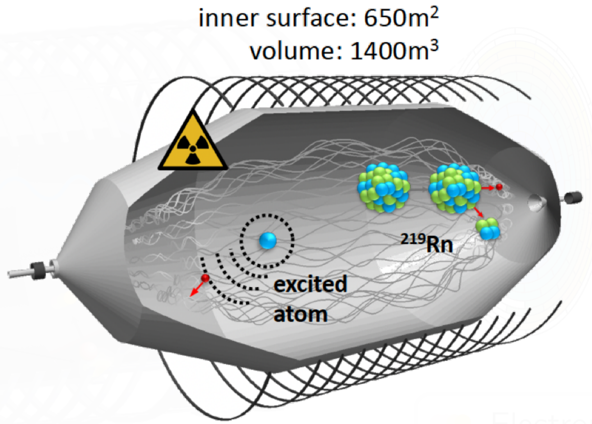


Systematic effects overview

Uncertainty breakdown in KNM2

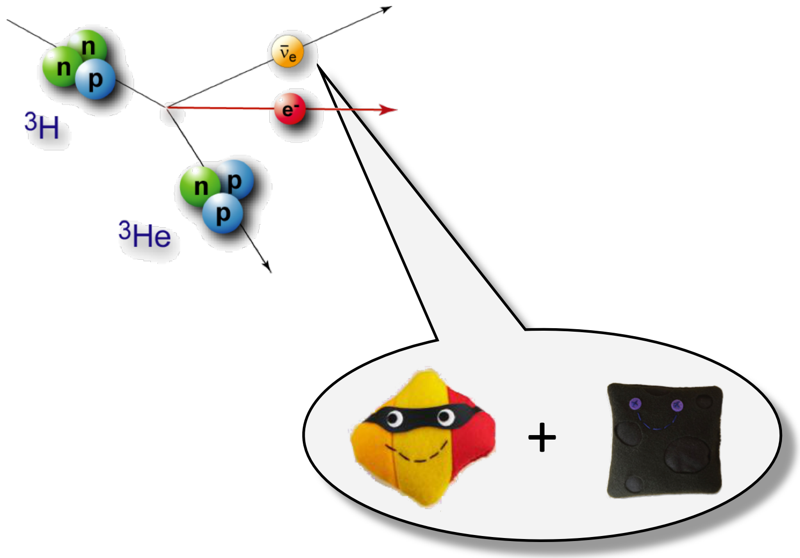


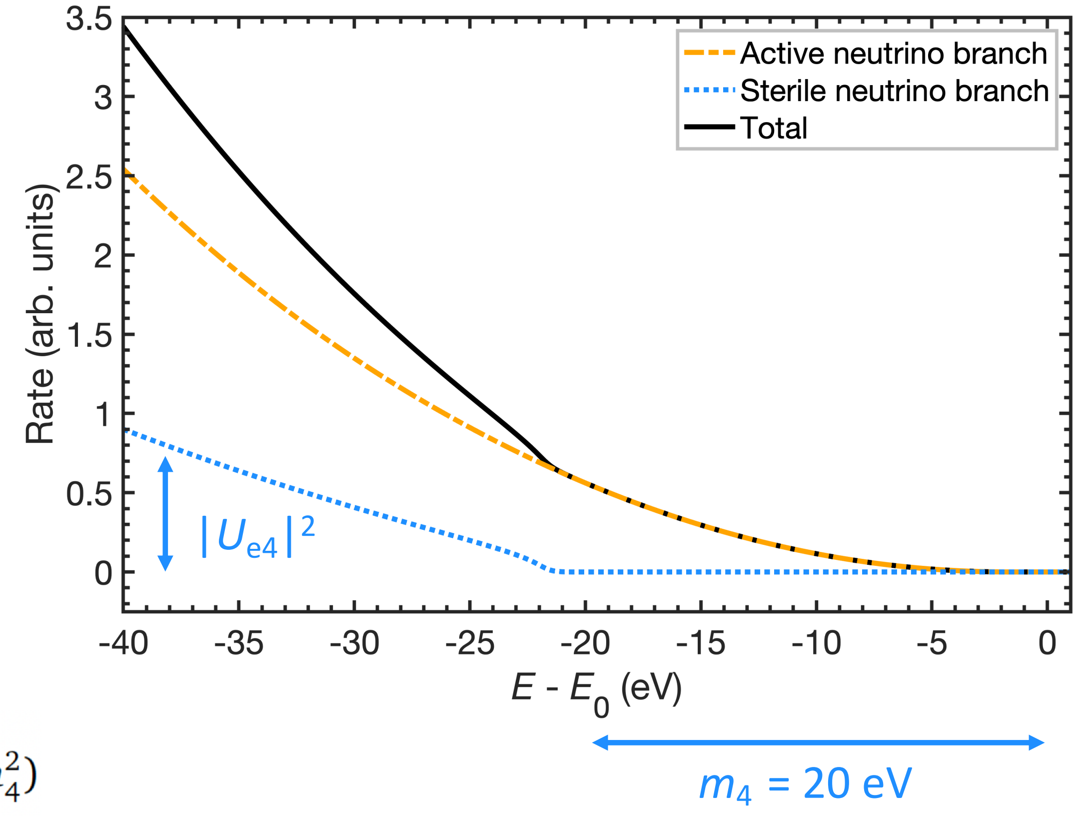
- First and second data set:
  - Dominated by statistical uncertainties
  - Largest systematic: uncertainty on background



- Improvement by 2022:
  - New magnetic field configuration
  - ✓ Background rate reduction ×2
  - ✓ No more bg rate over-dispersion

Sterile neutrinos in KATRIN





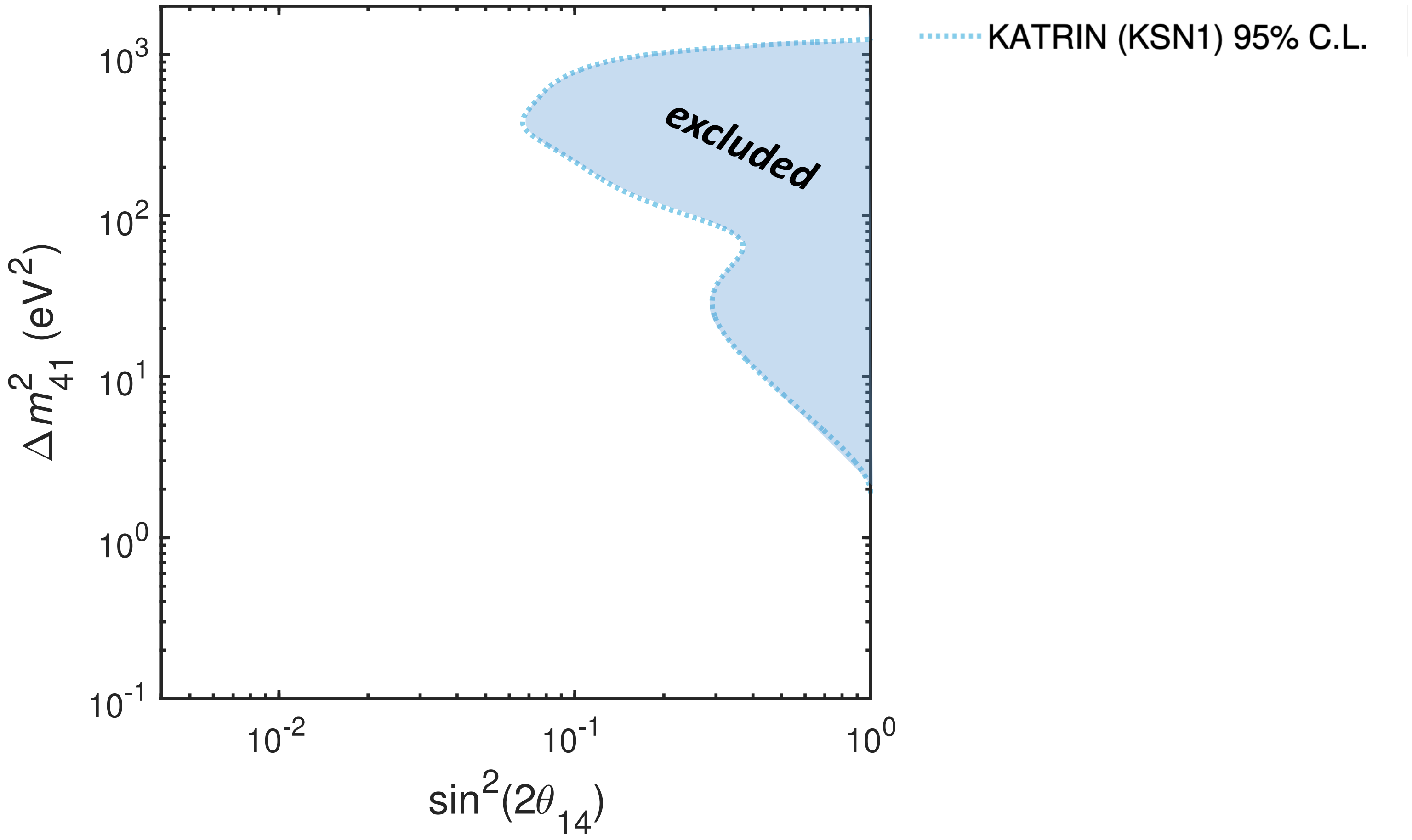
$$\frac{d\Gamma}{dE}(E, m_\nu^2, m_4^2, |U_{e4}|^2) = \underbrace{(1 - |U_{e4}|^2) \cdot \frac{d\Gamma}{dE}(E, m_\nu^2)}_{\text{Active branch}} + \underbrace{|U_{e4}|^2 \cdot \frac{d\Gamma}{dE}(E, m_4^2)}_{\text{Sterile branch}}$$

Result 1st campaign

- **No sterile neutrino signal at 95% C.L.**
- Calculate exclusion contour

- Sensitive to $m_4^2 \leq 40^2\ \mathrm{eV}^2$
- ➢ Restricted by measurement energy range

- Loose sensitivity small m_4^2
- ➢ Small signal/background ratio



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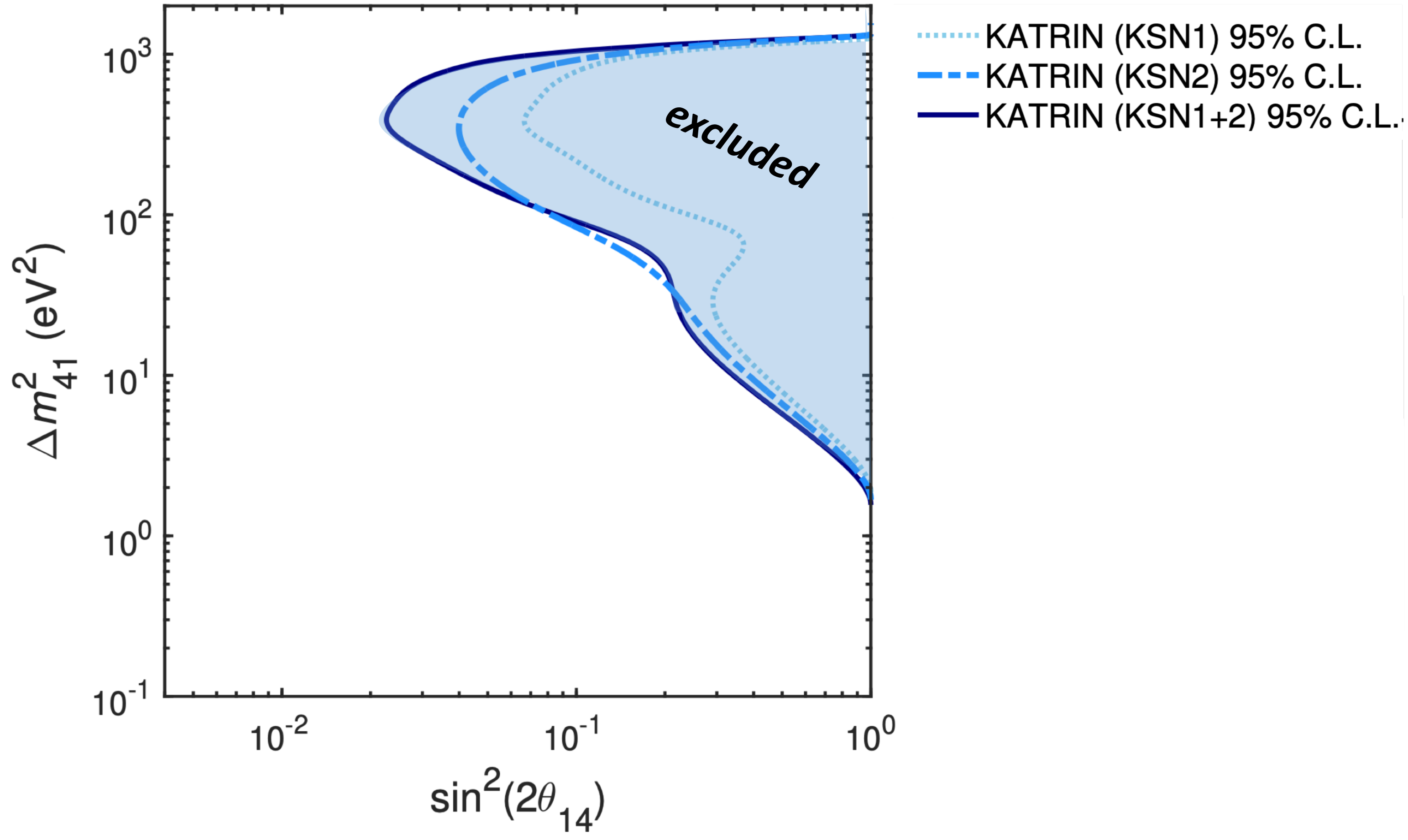

Current status

- **No sterile neutrino signal at 95% C.L.**
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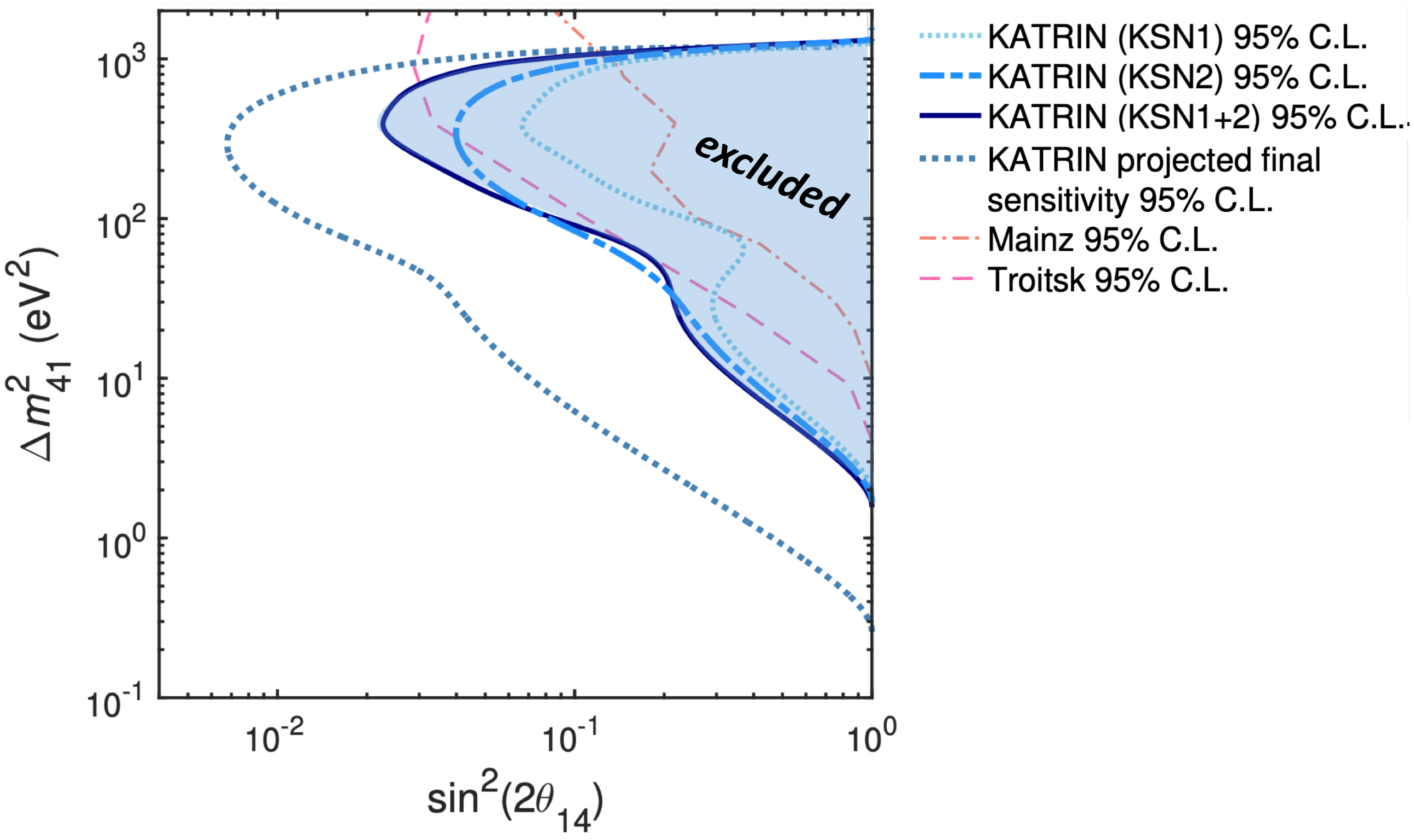
- Exclude partially parameter space:
  - Reactor Anomaly (RAA)
  - Gallium anomaly (GA) + BEST
  - Neutrino-4



More details:

- Phys. Rev. Lett. 126, 091803 (2021)
- Phys. Rev. D 105, 072004 (2022)

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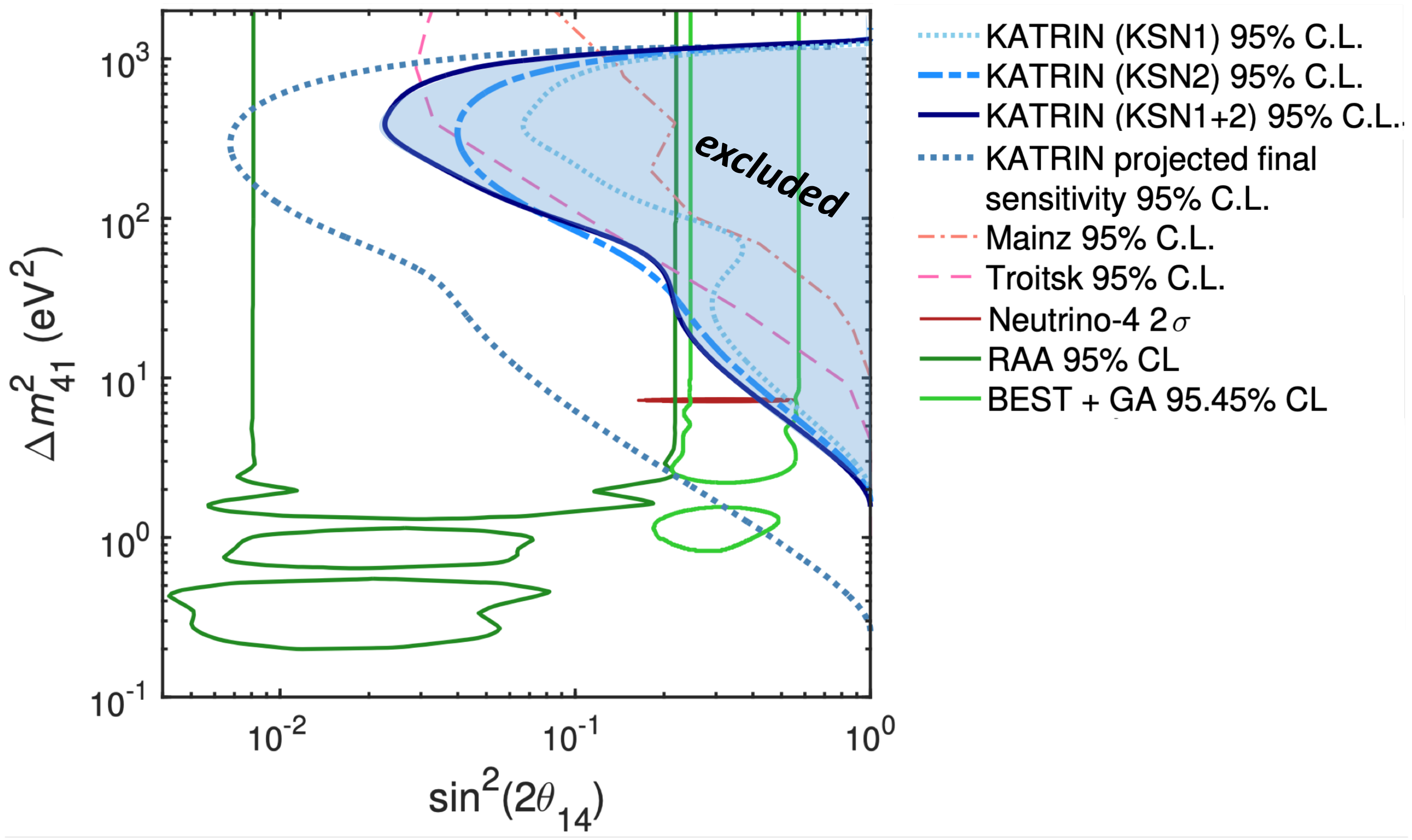

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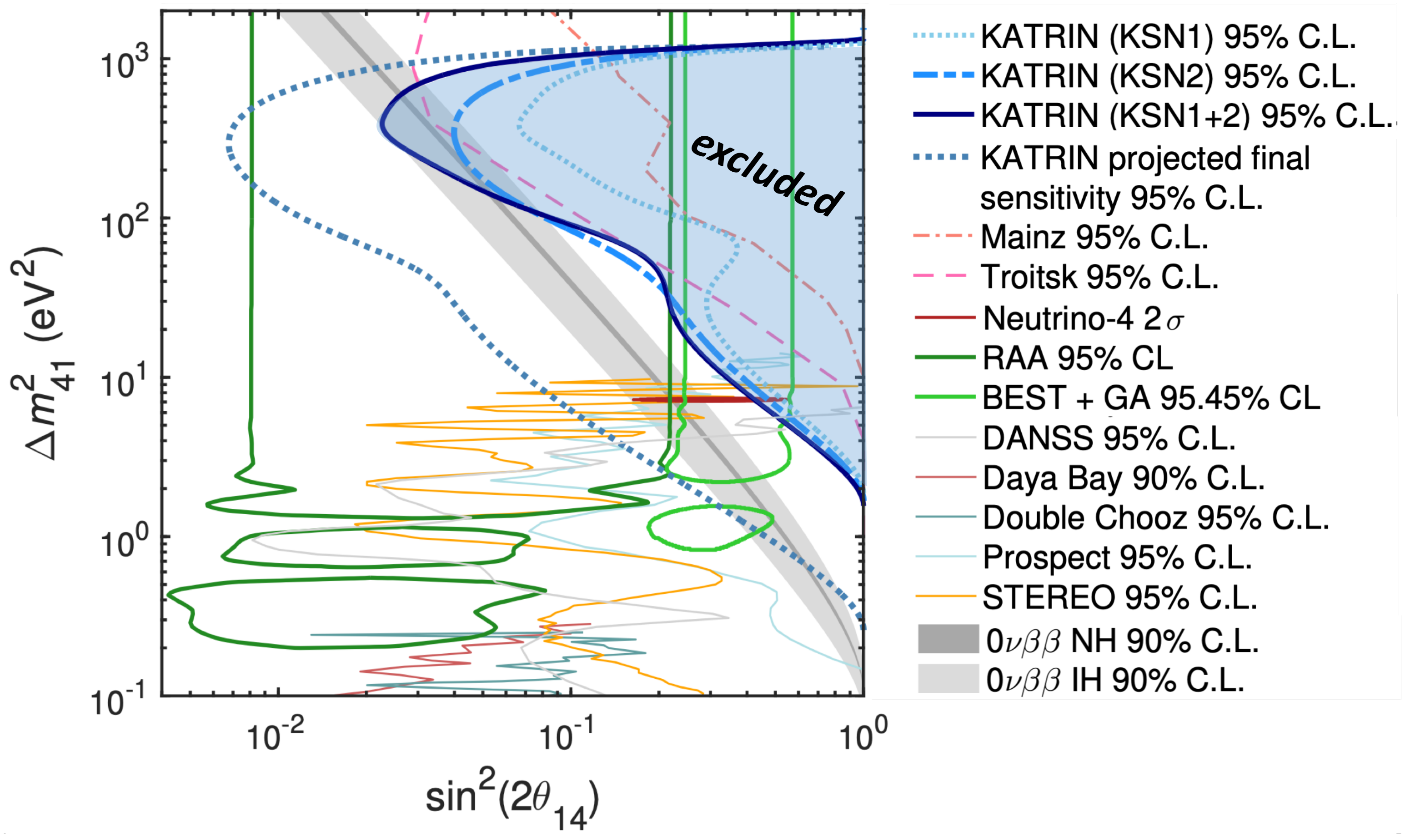
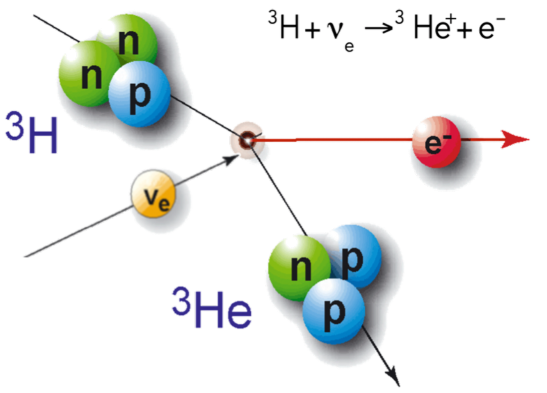
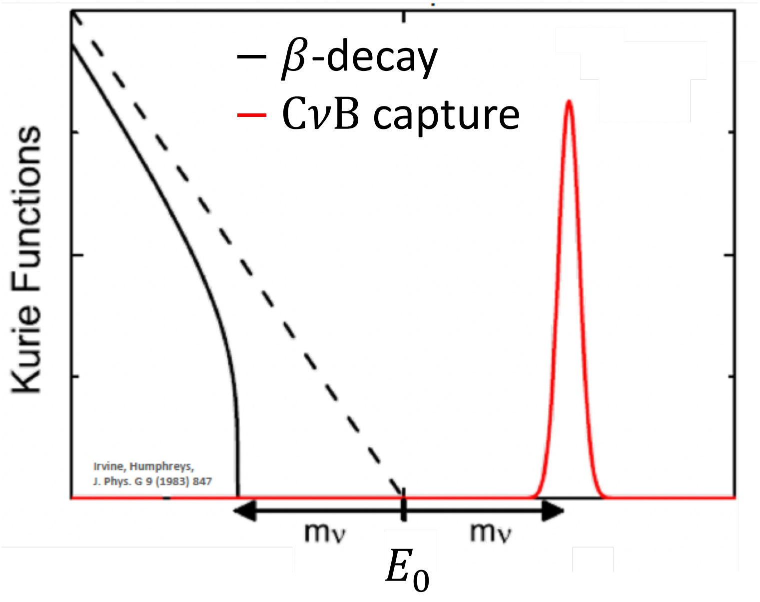


Relic neutrino capture

- 56 cm^{-3} *relic* neutrinos per species from the Big Bang
- $\langle E_{\text{kin}} \rangle \approx 0.2$ meV
- To date no observation
- In KATRIN expected rate: $R_\nu^{\text{eff}} = 10^{-6}\ \text{yr}^{-1} \cdot \eta$

  ...depends on neutrino nature: ×½ for Dirac particles, ×1 for Majorana



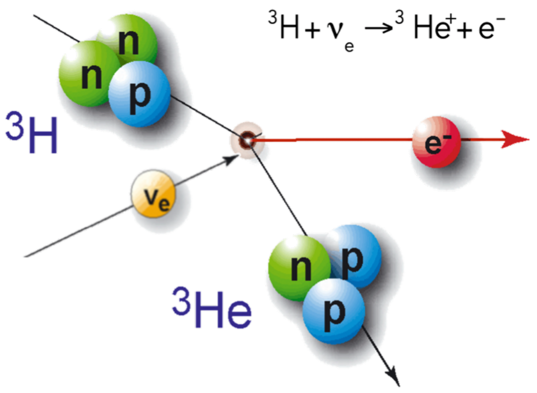


Relic neutrino capture

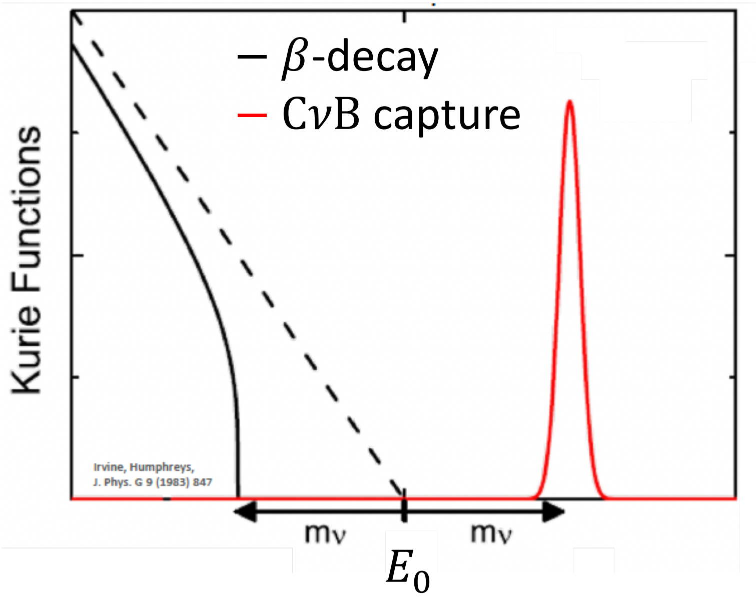
- 56 cm^{-3} *relic* neutrinos per species from the Big Bang
- $\langle E_{\text{kin}} \rangle \approx 0.2 \text{ meV}$
- To date no observation
- In KATRIN expected rate: $R_\nu^{\text{eff}} = 10^{-6} \text{ yr}^{-1} \cdot \boldsymbol{\eta}$

… local gravitational clustering possible: $\boldsymbol{\eta}$ overdensity

…depends on neutrino nature: ×½ for Dirac particles, ×1 for Majorana



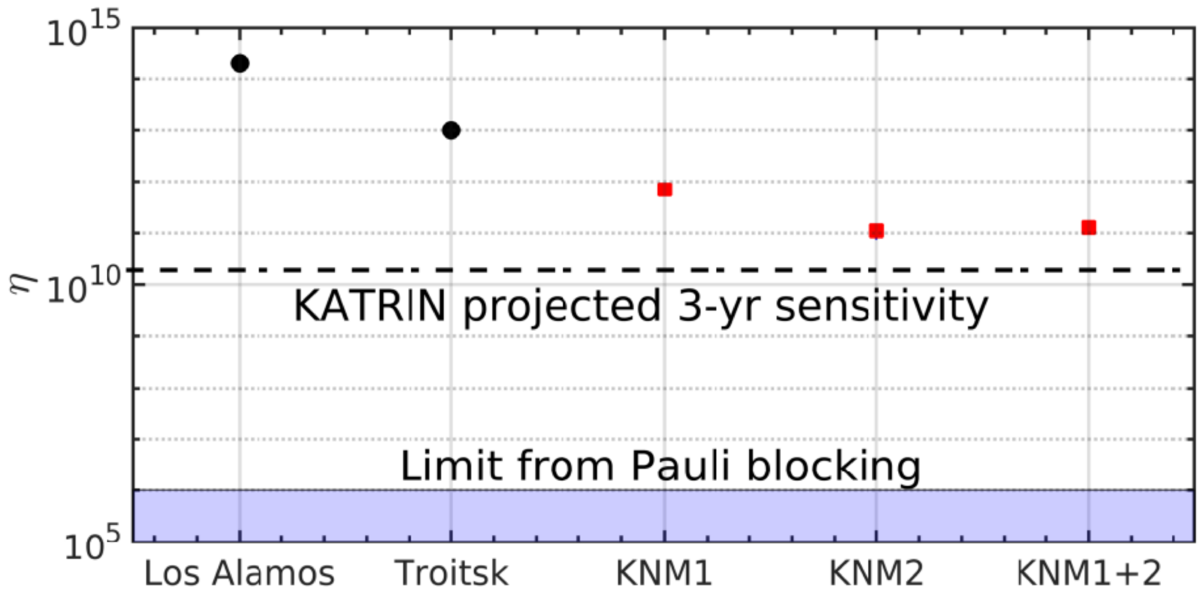
No energy threshold! Allows for relic ν detection



Current Status

- No evidence for <u>large</u> relic neutrino overdensity
- Upper limit: $\boldsymbol{\eta < 1.1 \cdot 10^{11}}$ (95% C.L.)

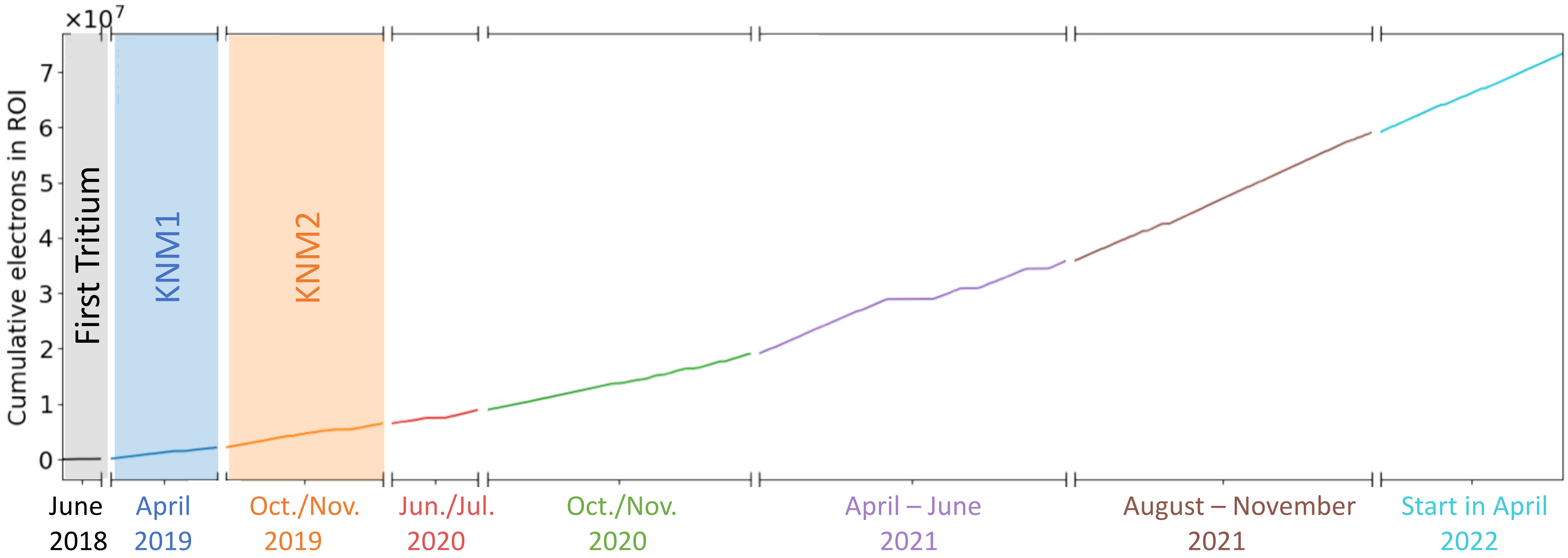
- Limited by statistical uncertainties
- Improved constraints from other laboratory experiments by 2 orders of magnitude



More details:

➢ [Phys. Rev. Lett. 129, 011806 (2022)]

Measurement campaigns

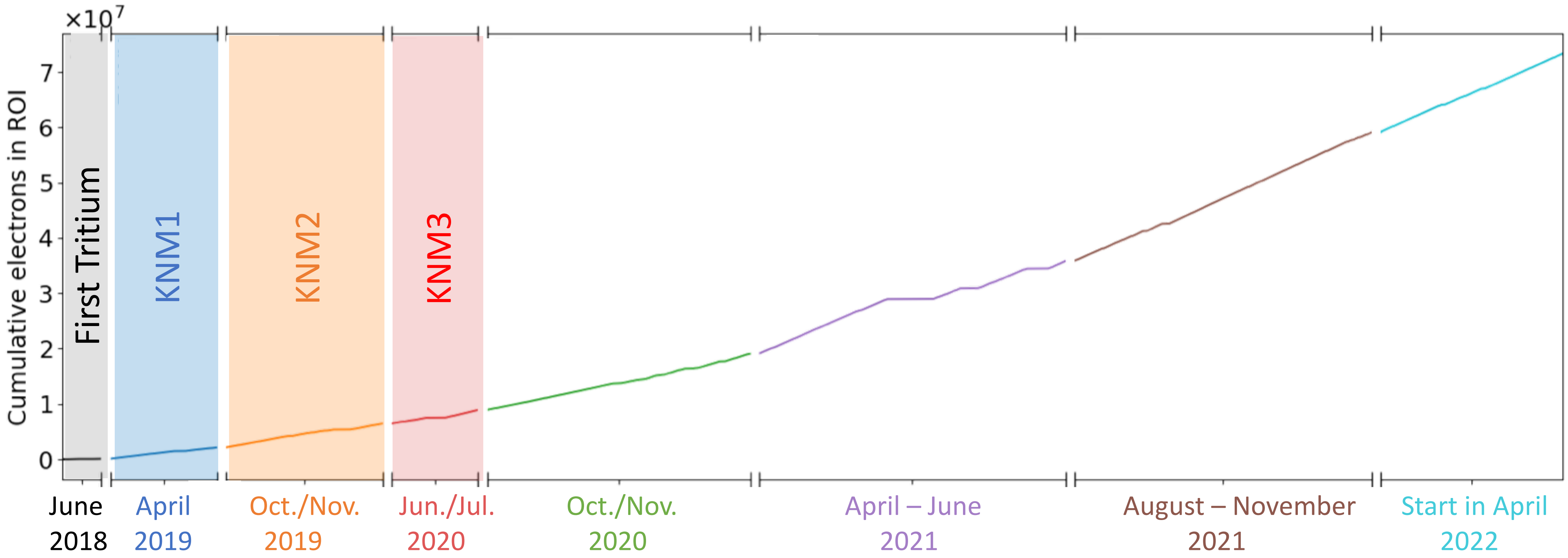


- Commissioning
- Only 0.5% tritium

- 1st campaign
- $1.5 \cdot 10^6$ β-electrons
- $m_\nu < 1.1$ eV

- 2nd campaign
- $3.7 \cdot 10^6$ β-electrons
- $m_\nu < 0.9$ eV

Measurement campaigns



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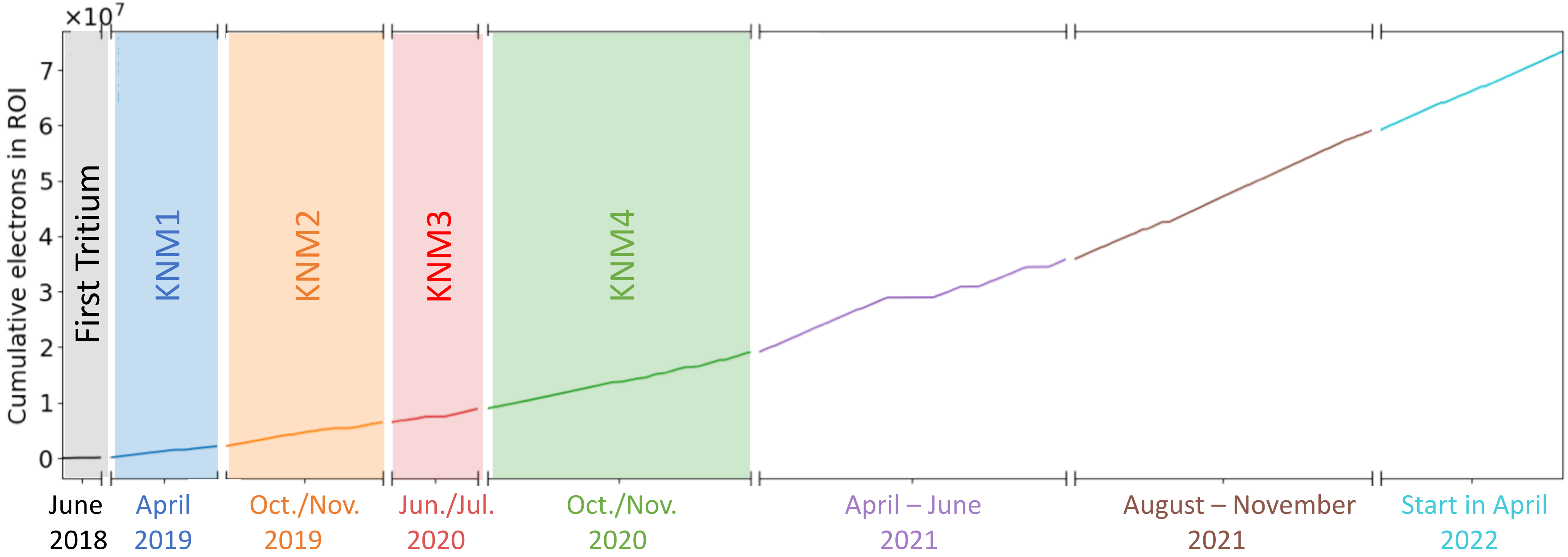

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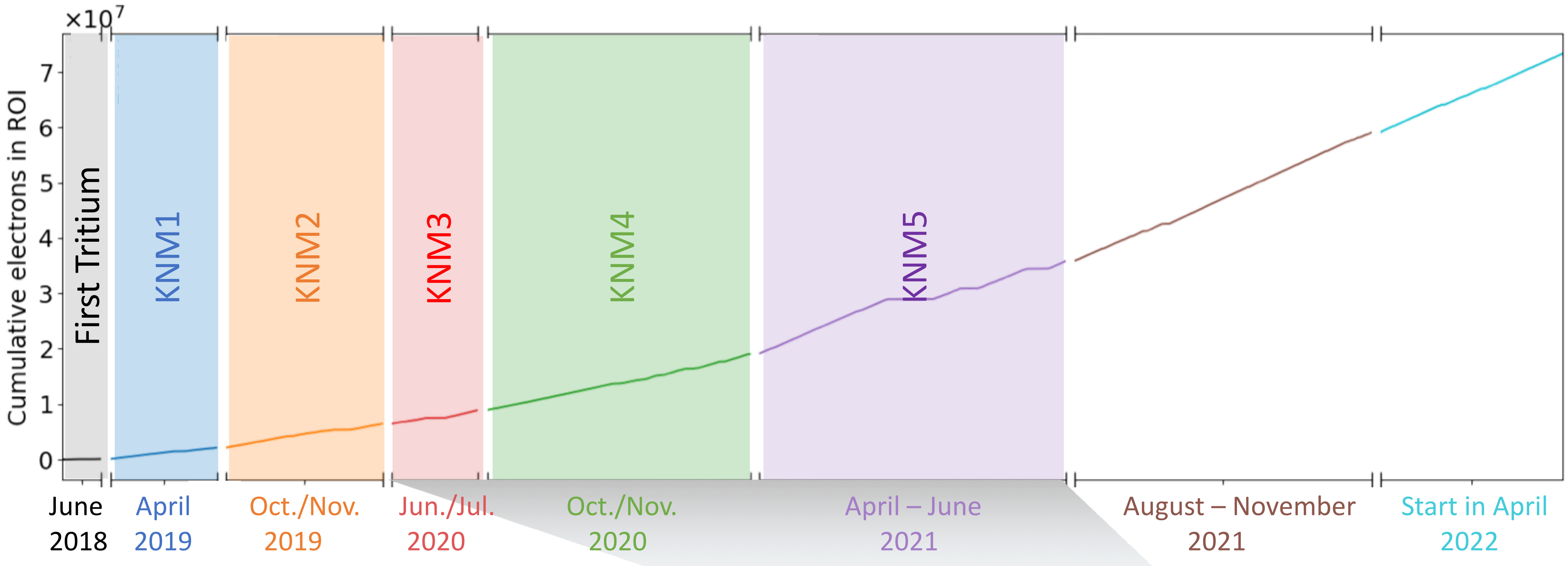
Measurement campaigns



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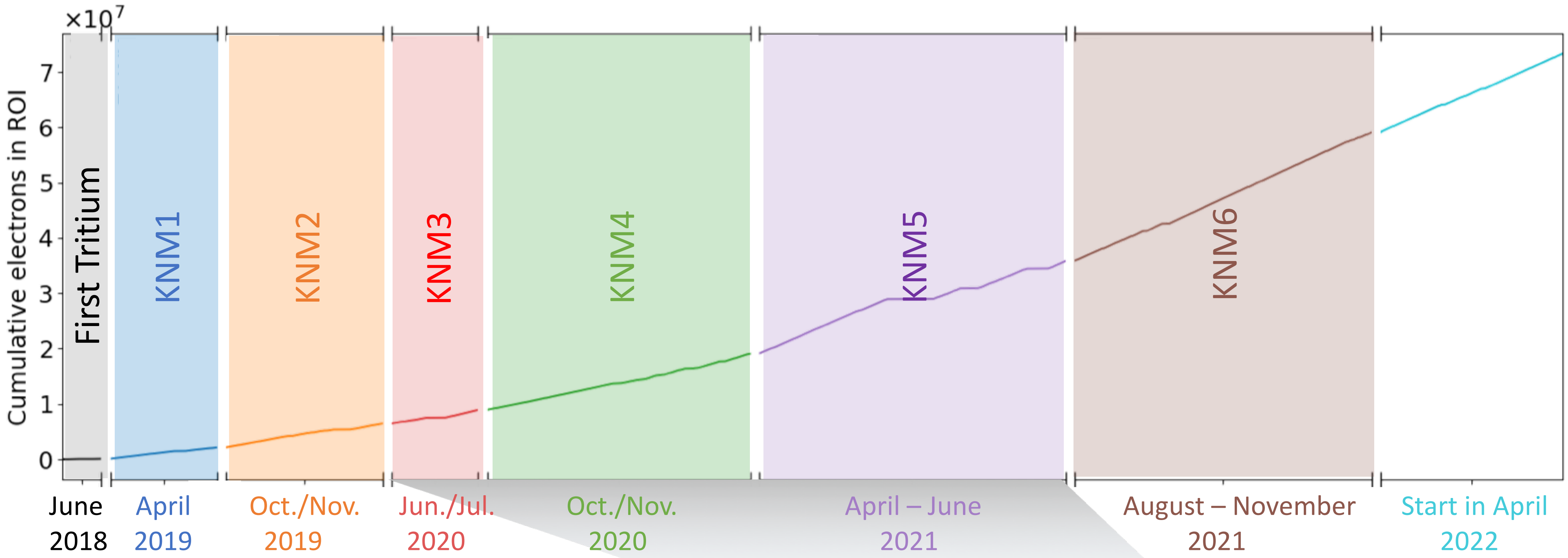
- 3rd + 4th + 5th campaigns
- Unblinding this summer

Measurement campaigns



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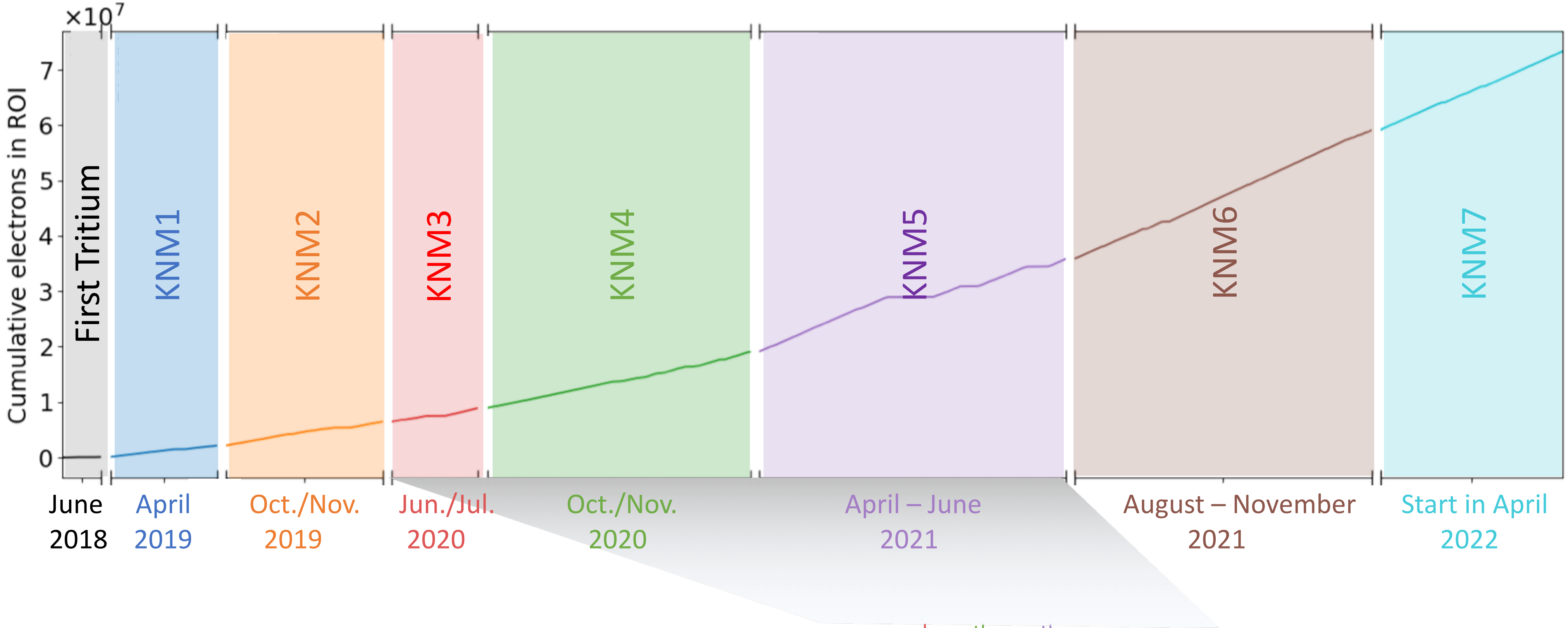

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- 3rd + 4th + 5th campaigns
- Unblinding this summer

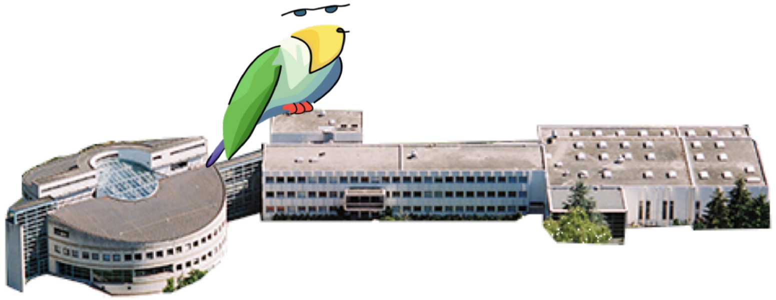
- 6th + 7th campaigns
- data taking completed

Take home message

- KATRIN is taking tritium data since 2018
- Neutrino mass measurement via kinematics of tritium β-decay
- Current upper limit $m_\nu \leq 0.8\ \mathrm{eV}\ (90\%\ \mathrm{C.L.})$

- Beyond nu-mass
  - Constraints on eV-scale sterile neutrinos
  - Constraints on relic neutrino over-density

Thank you for your attention!



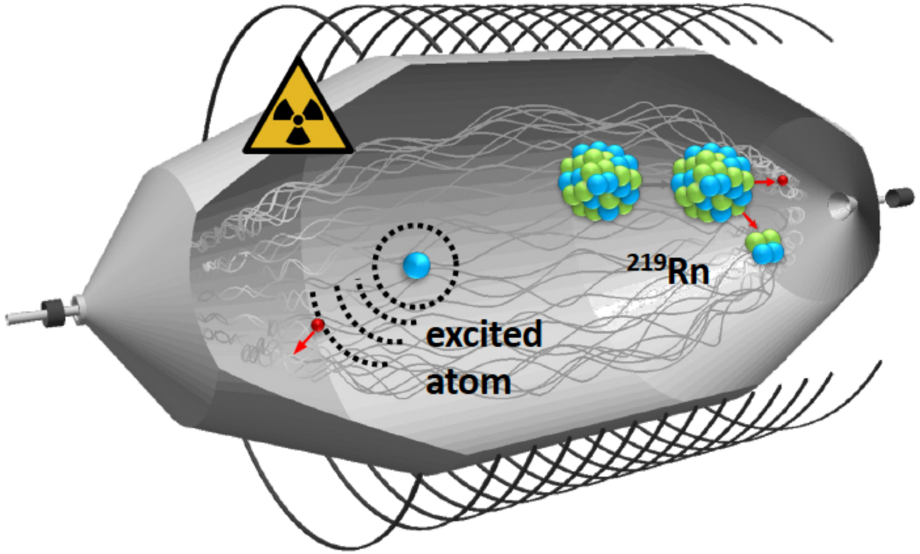
Backup

Background in KATRIN

1. **Rydberg background**:
   - Radioactive decay in spectrometer walls
   - neutral Rydberg atoms enter spectrometer
   - Ionization through thermal radiation
   - low-energetic electrons are accelerated toward detector
   - ➢ energy and time independent

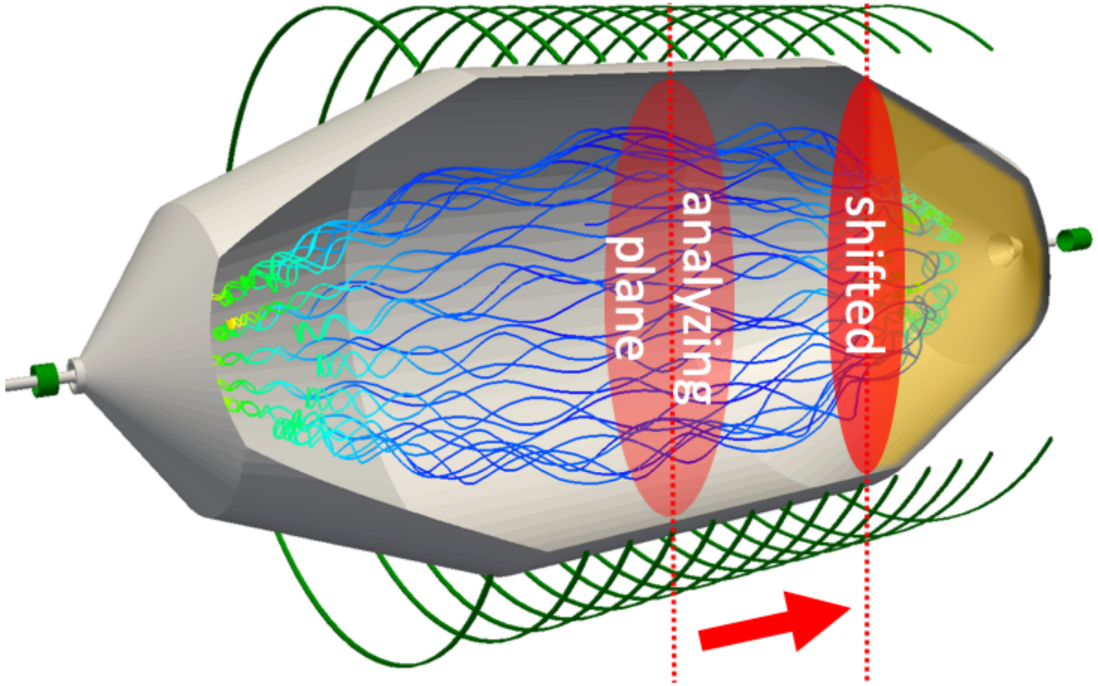
2. **Radon background:**
   - α-decay of Radon isotopes in spectrometer pumps
   - Multiple high-energetic electrons (relaxation processes, etc.)
   - Large transversal momentum → become trapped in spectrometer
   - Scatter on residual gas → produce low energetic electrons
   - Acceleration toward FPD → energy and time independent background
   - Varies more than expected from Poisson statistics
3. **Penning trap background**
   - Penning trap between pre- and main spectrometer
   - Traps electrons, discharge → background
   - increases as a function of time
4. Further backgrounds
   - intrinsic FPD background
   - ...

inner surface: 650m²
volume: 1400m³



Shifted analyzing plane

- Background scale with active flux tube volume downstream of analyzing plane
- New magnetic field configuration:
  - *"Shifted Analyzing Plane"*
  - Reduce flux tube volume
  - ✓ Background rate reduction ×2

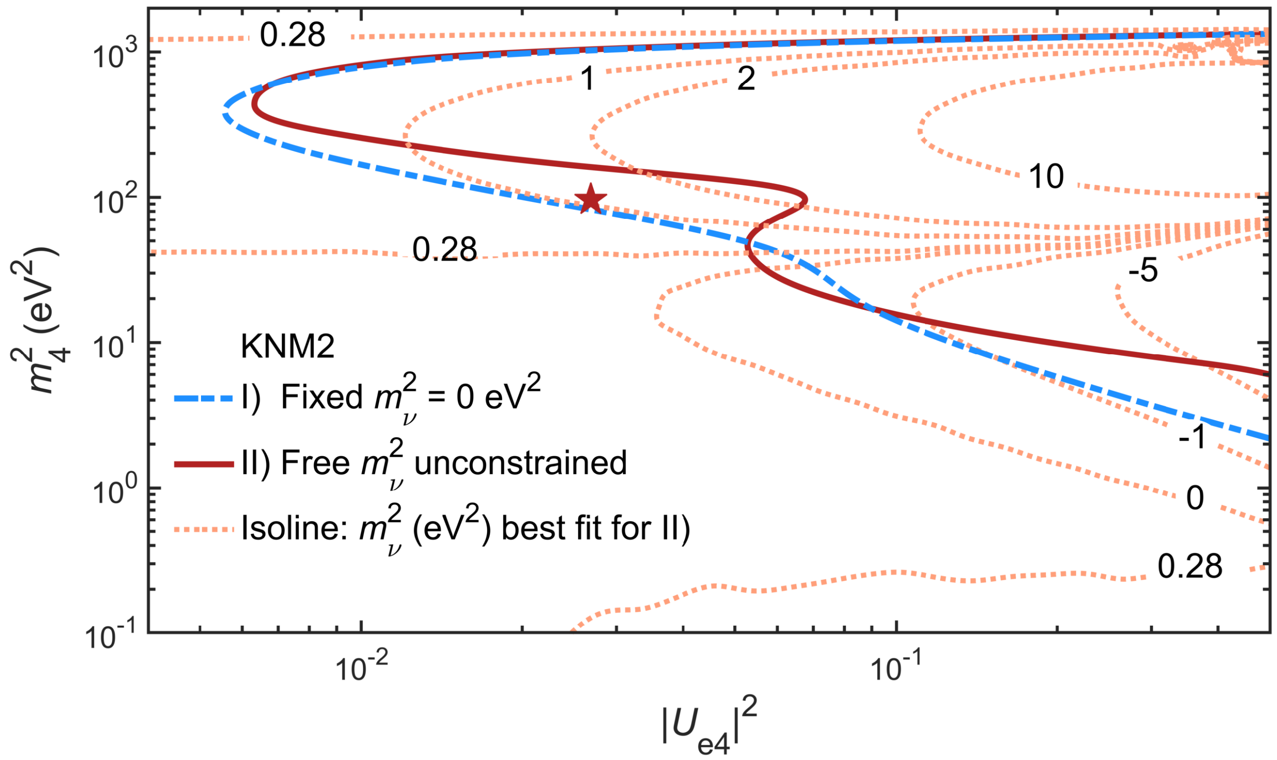


Sterile Neutrino Search

Two analysis cases:

I. Hierarchical scenario
   - $m_4^2 \gg m_1, m_2, m_3$
   - $m_\nu^2 = 0 \text{ eV}^2$ fixed

II. Generic scenario:
   - m_ν^2 as free nuisance parameter
   - correlation between active and sterile decay branches

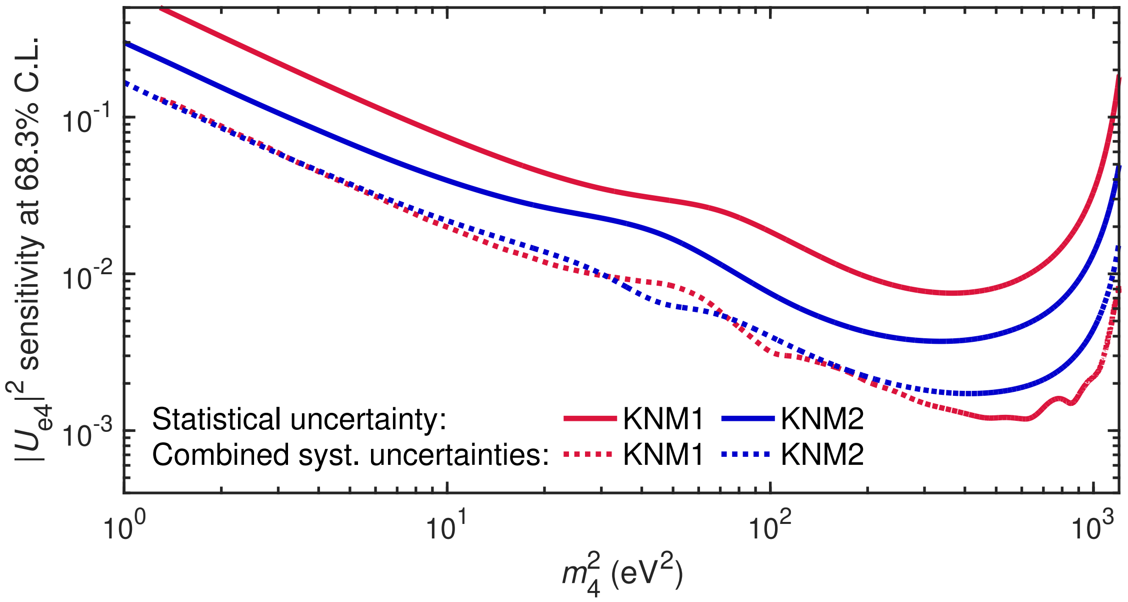


Systematic uncertainties in sterile-neutrino search

- Investigate systematic effects
- 1σ uncertainty on $|U_{e4}|^2$ for fixed m_4^2 values via raster scan

$$\sigma_{\text{syst}} = \sqrt{\sigma^2_{\text{total}} - \sigma^2_{\text{stat}}}$$

- Result:
  - Both campaigns are statistics dominated
  - Similar influence of systematic uncertainties



Systematic uncertainty breakdown sterile-neutrino search

Dominant syst. effects:

- Source-potential variations
- Scan—step-duration dependent background
- Background rate over-dispersion