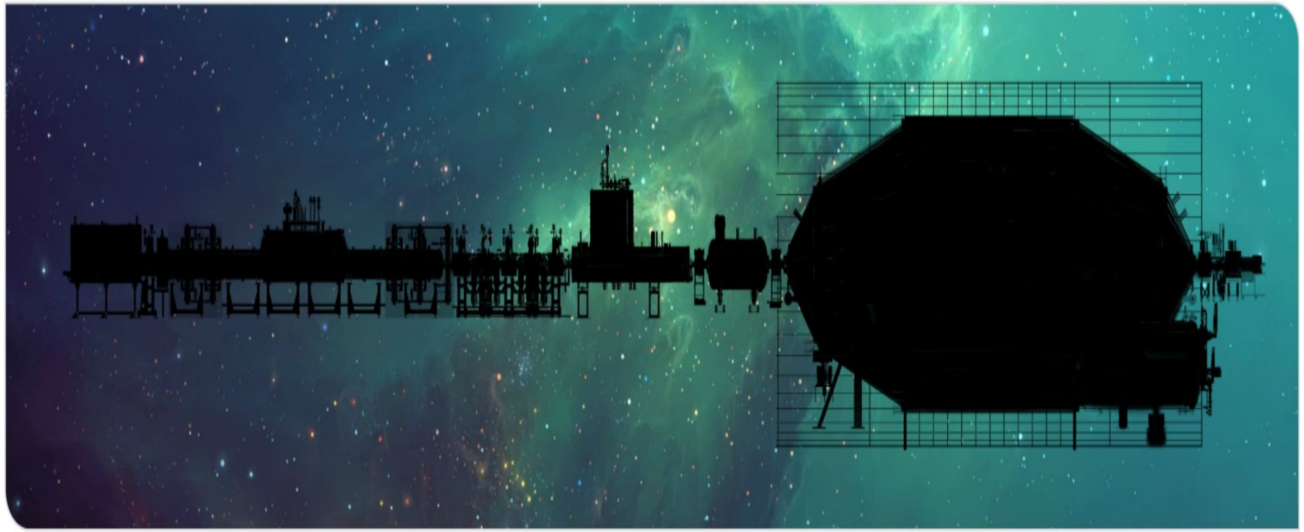
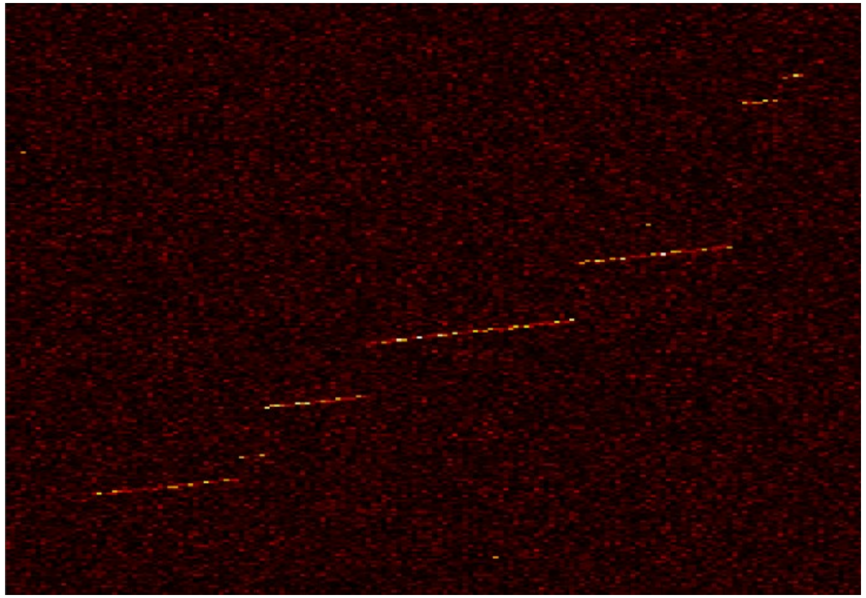
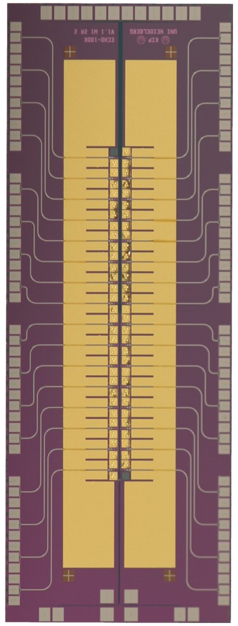
Neutrino mass determination – Part I

International School on Astroparticle Physics (ISAPP 2023) – Varenna, Italy

Alexey Lokhov







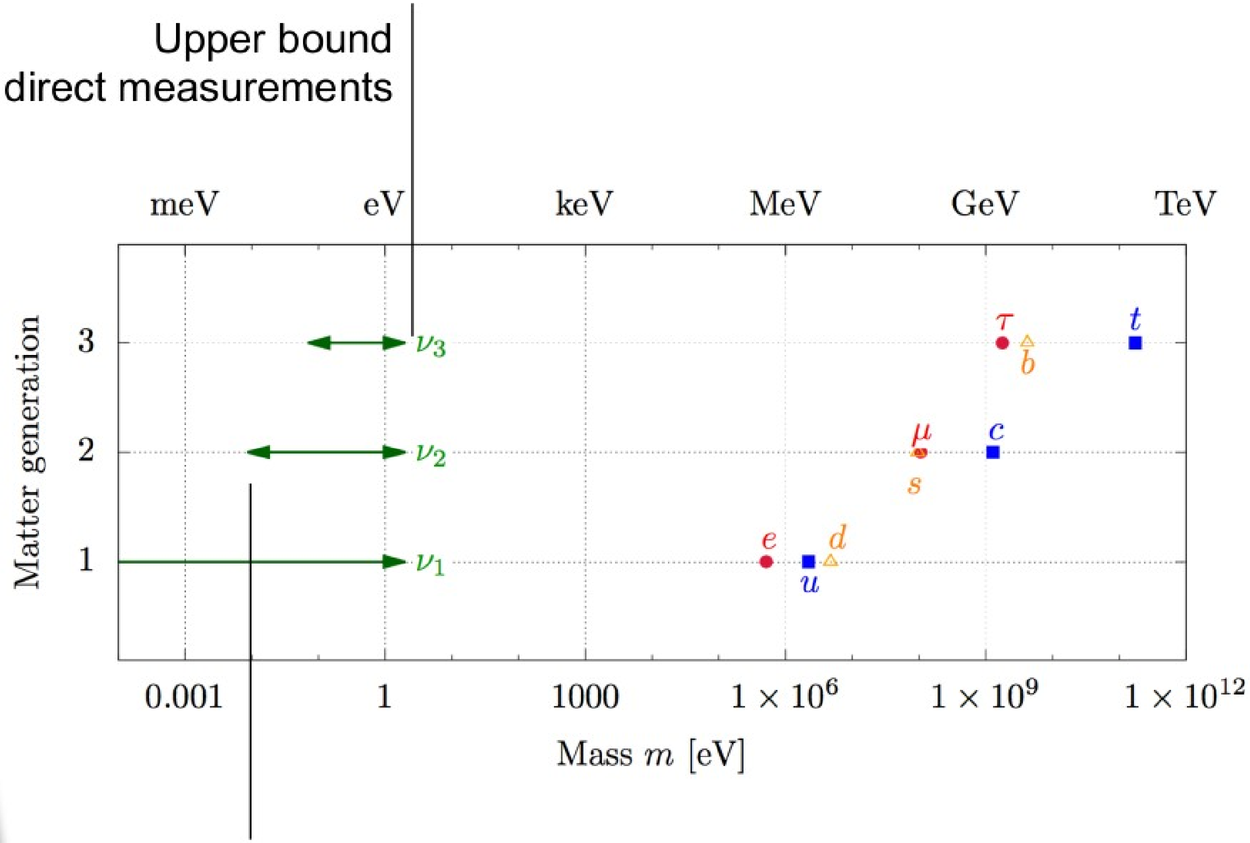
Outline

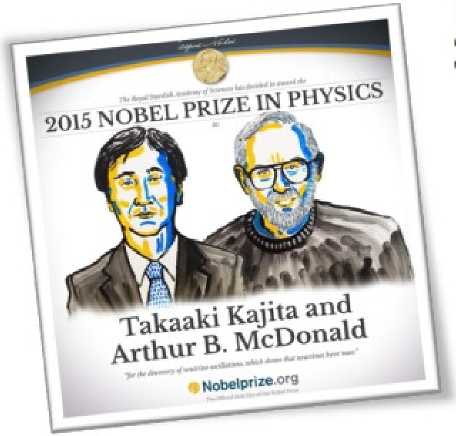
Karlsruher Institut für Technologie

- What do we know so far about neutrino masses?
- What are the three approaches to neutrino mass?
- How to measure the mass without model dependencies?
- What other physics can we probe in the direct mass measurements?
- Status of direct neutrino mass measurements
- Next generation of experiments

Neutrino mass

Upper bound
from direct measurements

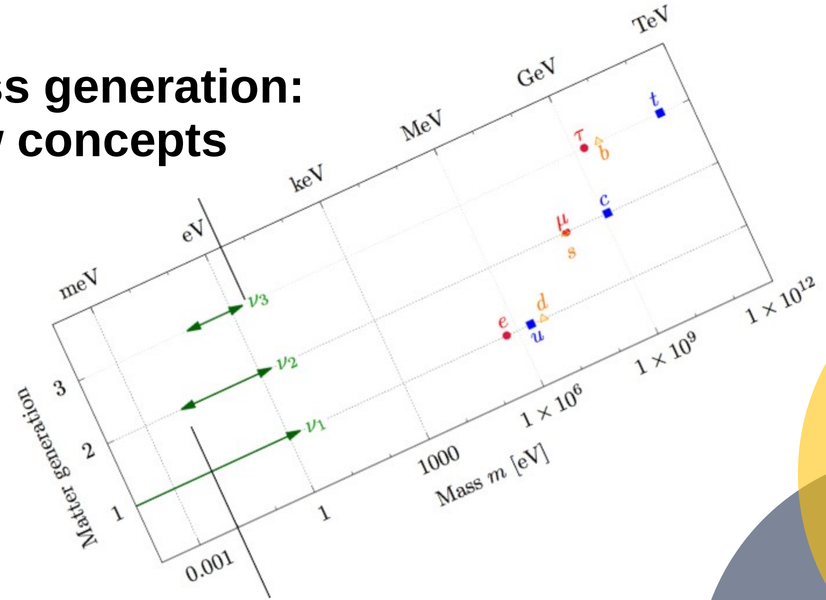




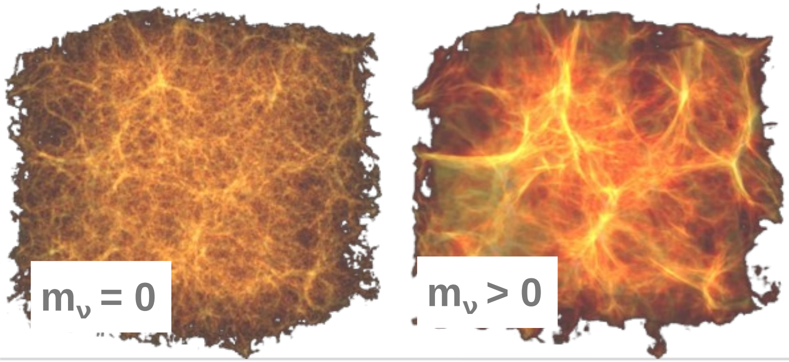
Lower bound
from oscillation experiments

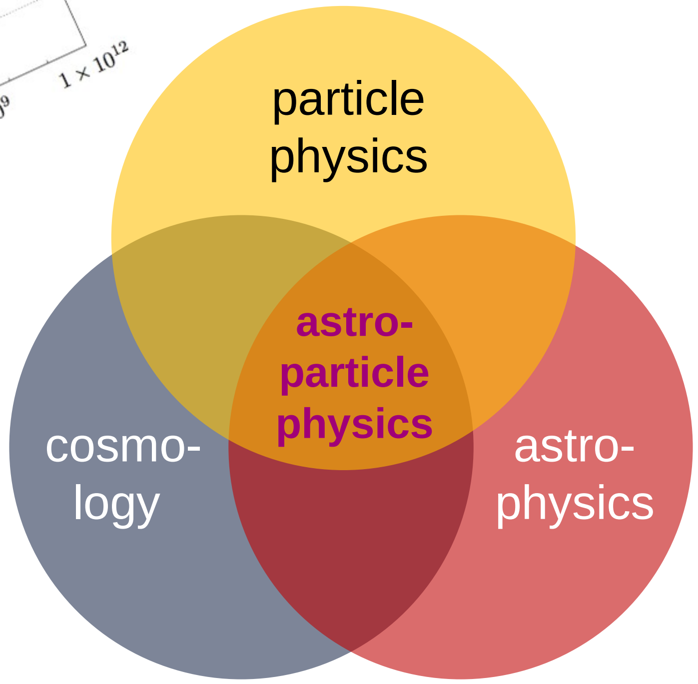
Role of massive neutrinos

Mass generation: new concepts



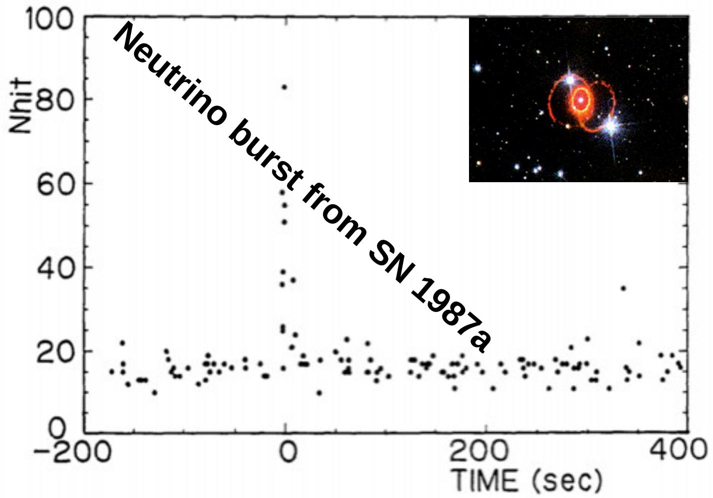
Massive neutrinos as “cosmic architects”



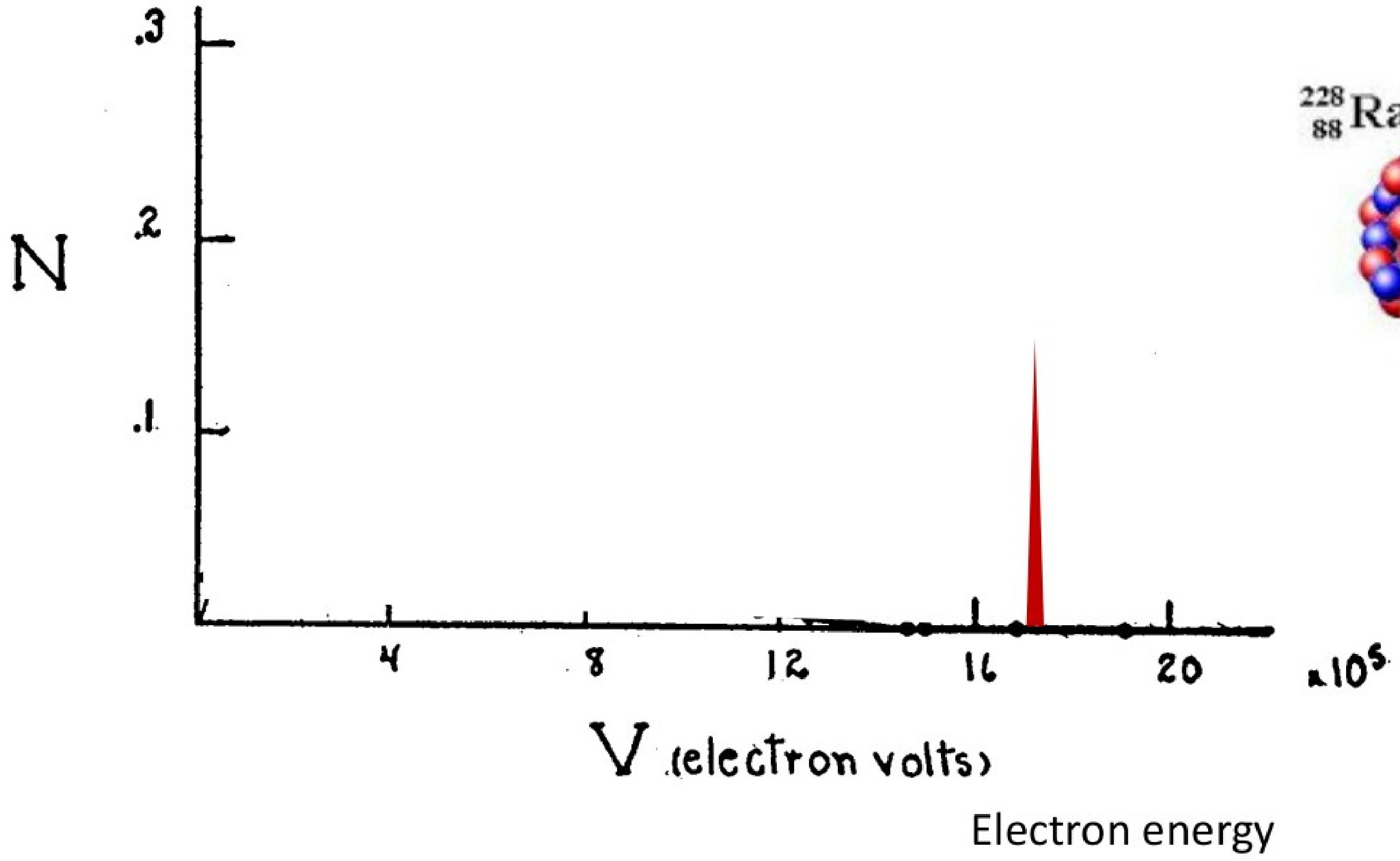


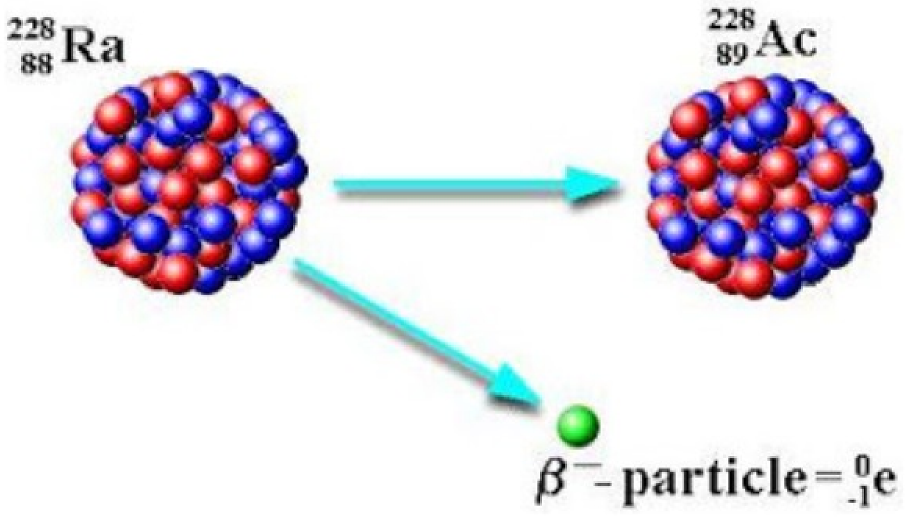
Mass measurement: new concepts

Understanding astrophysical processes



1930: Neutrino postulation and mass





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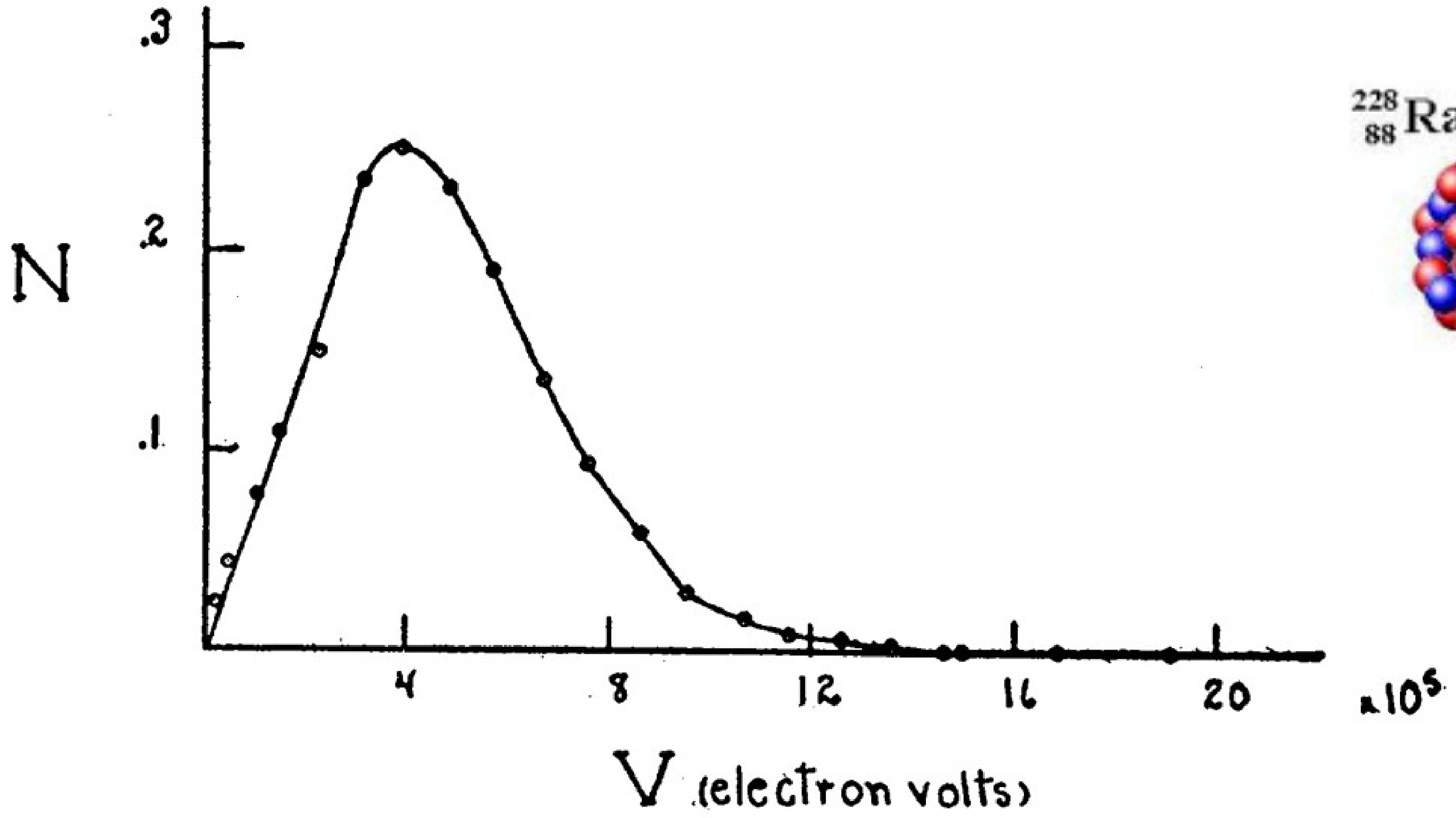

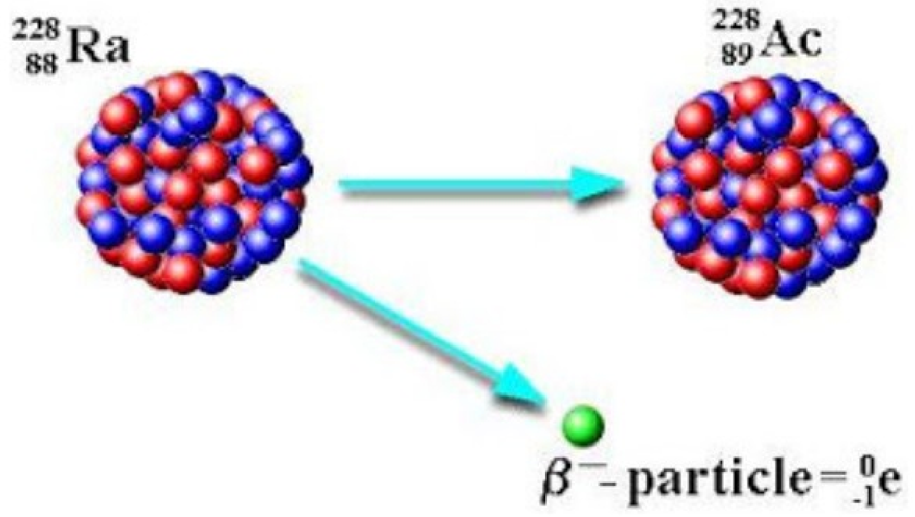

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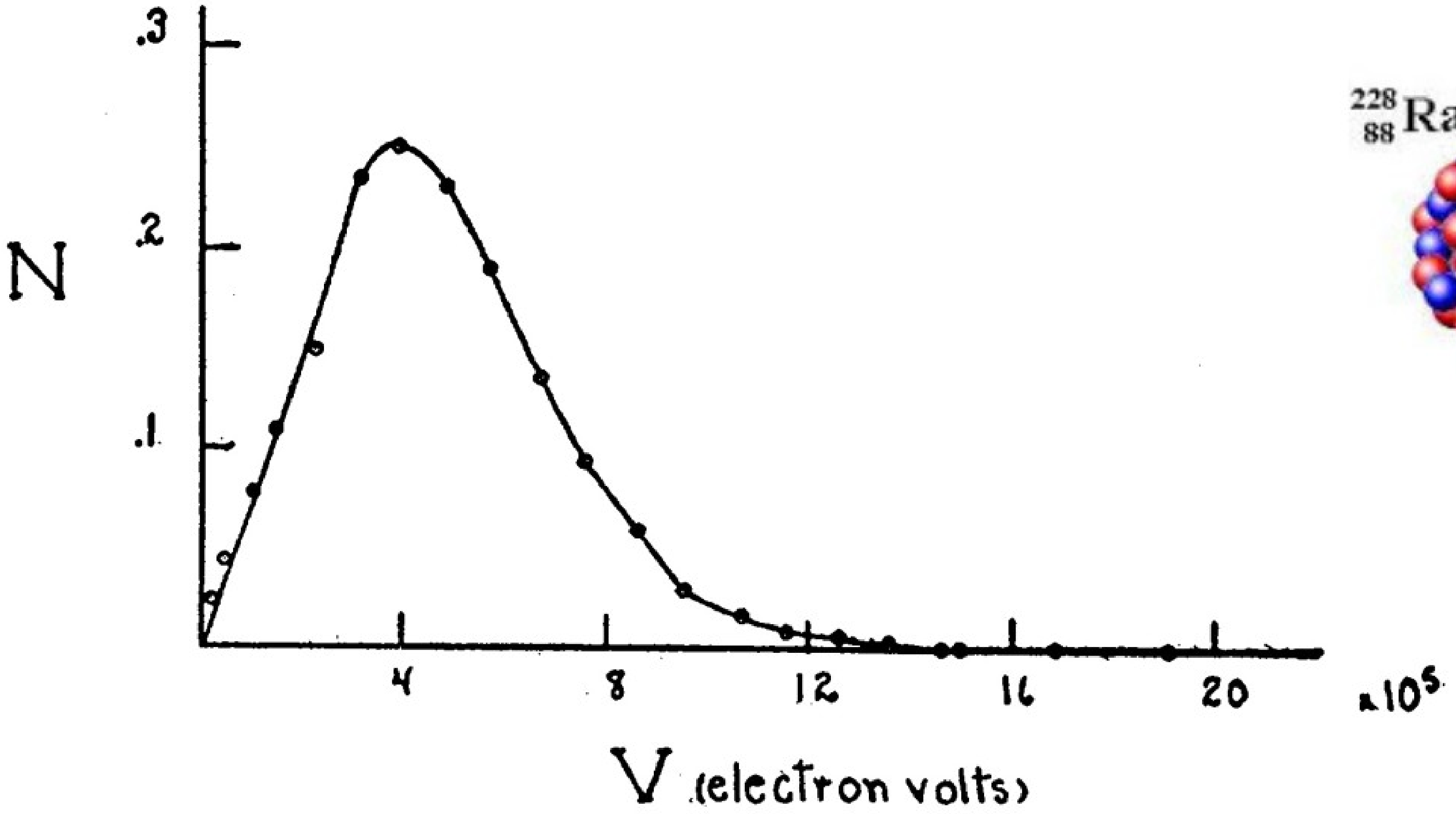

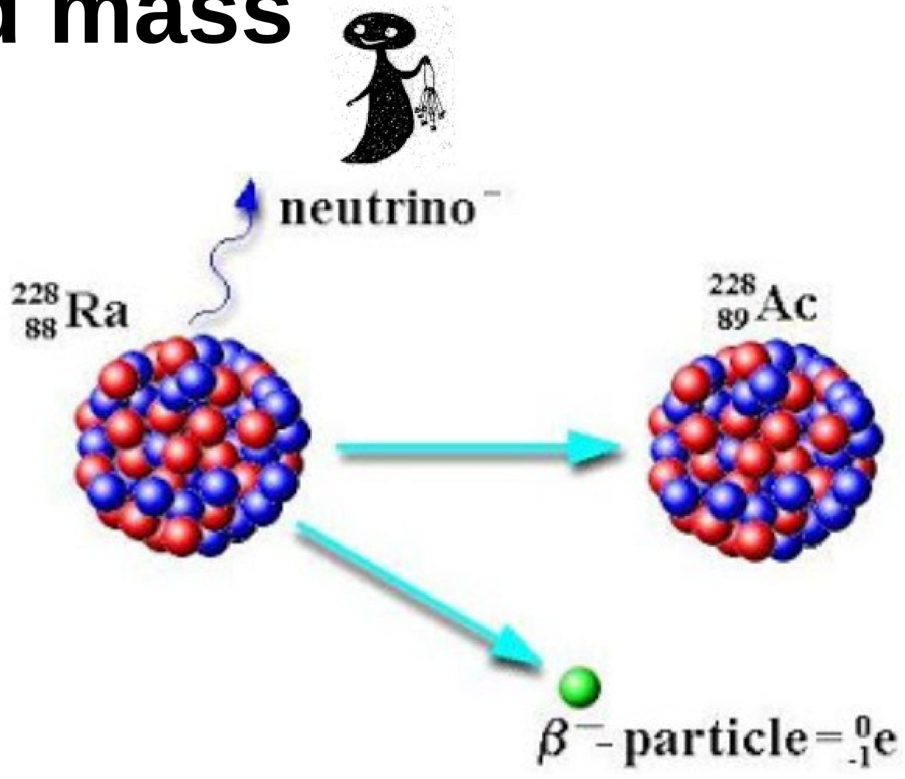

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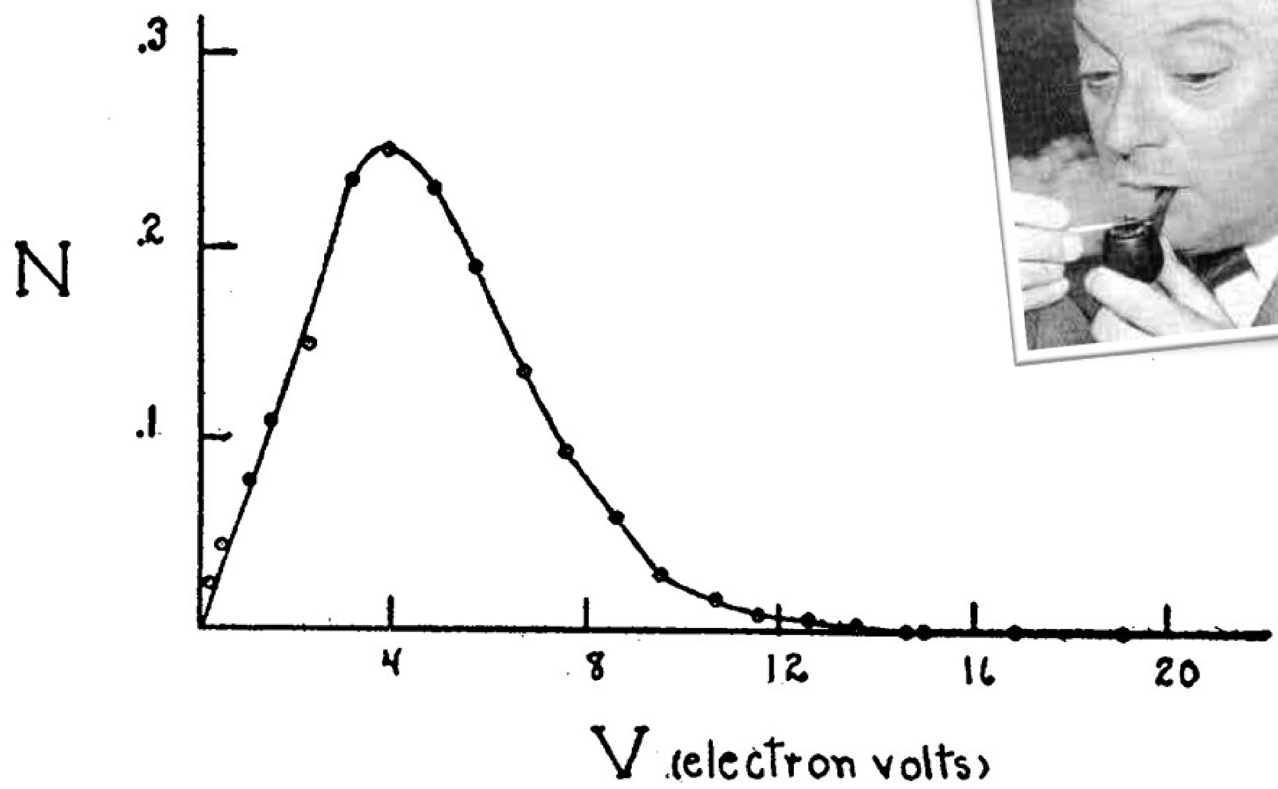
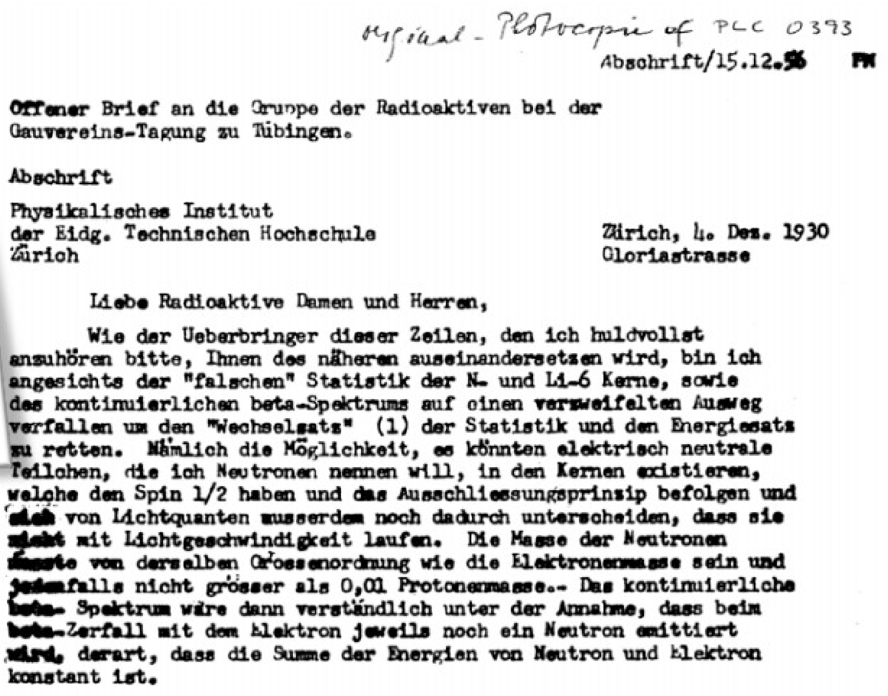




Original - Photocopie of PLC 0393
Abschrift/15.12.56 FW

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

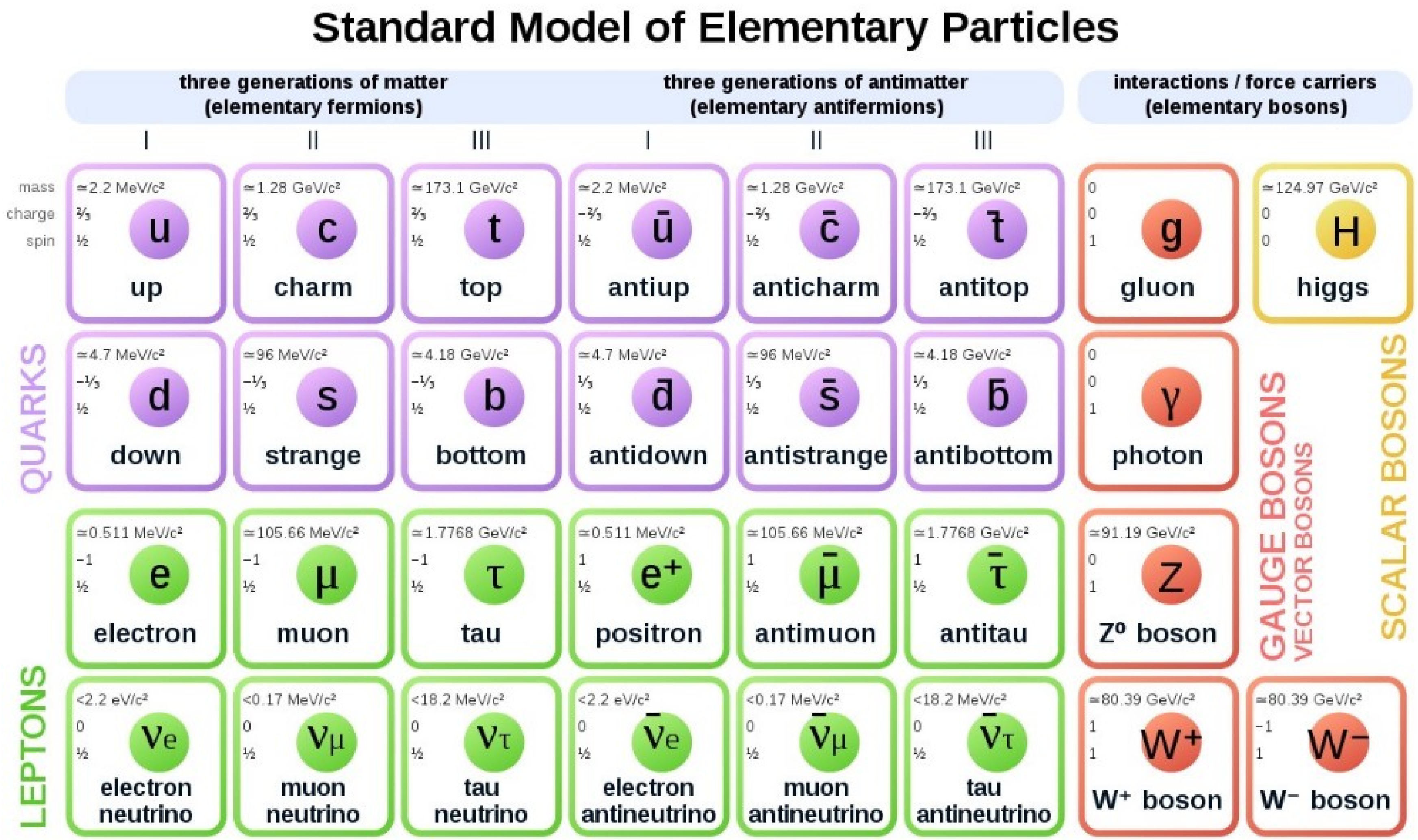
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

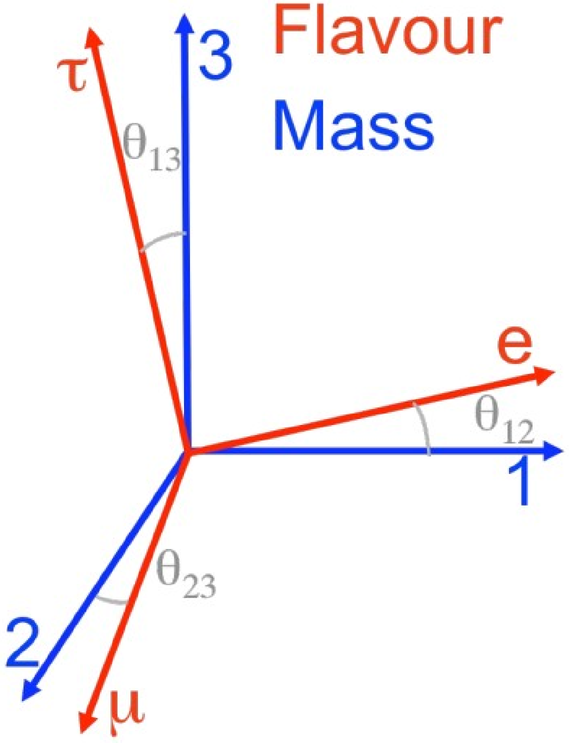
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

$m_\nu < 0.01 m_p \sim 10$ MeV

Neutrino in the Standard Model



Neutrino mixing, masses and oscillations



PMNS matrix

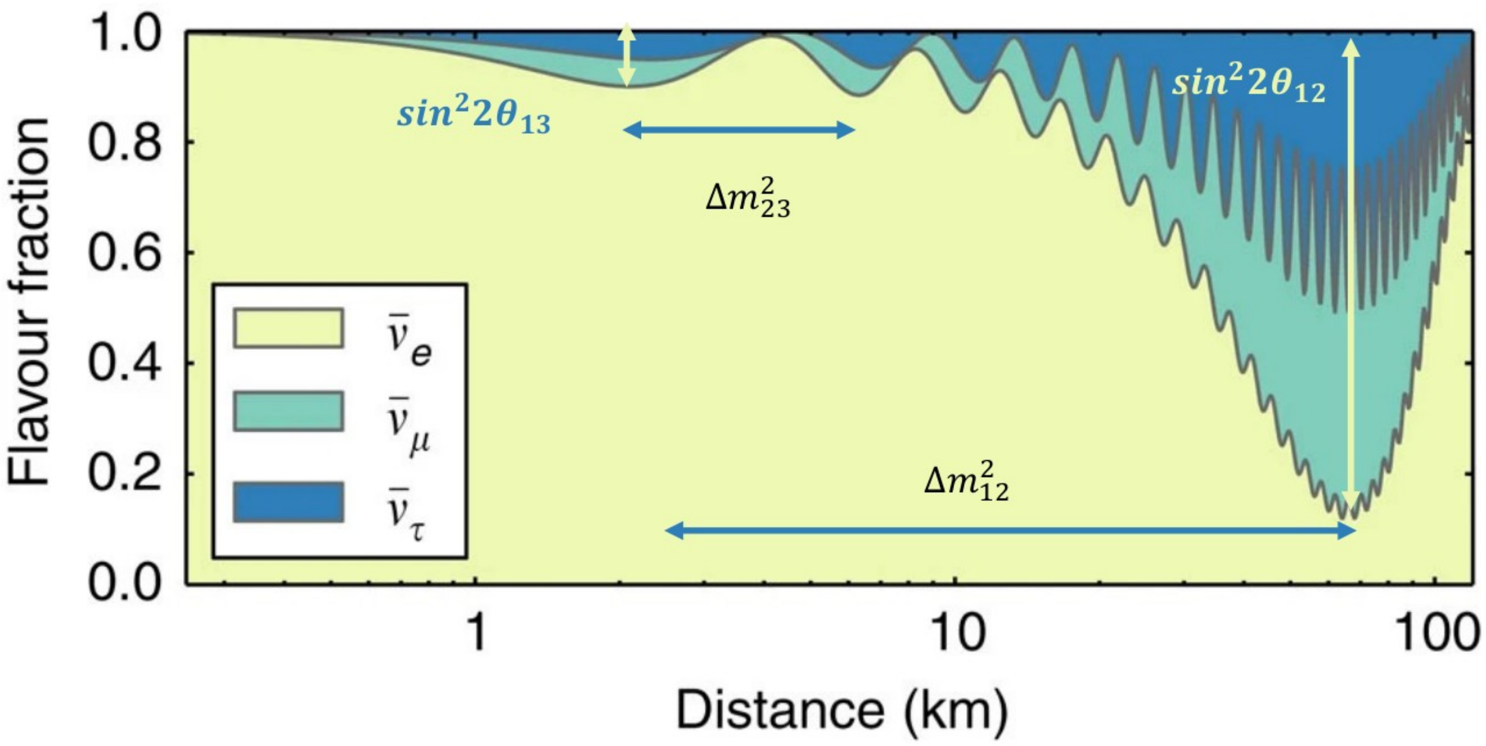
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

➔ Eligio Lisi
Marco Pallavicini

Neutrino oscillations

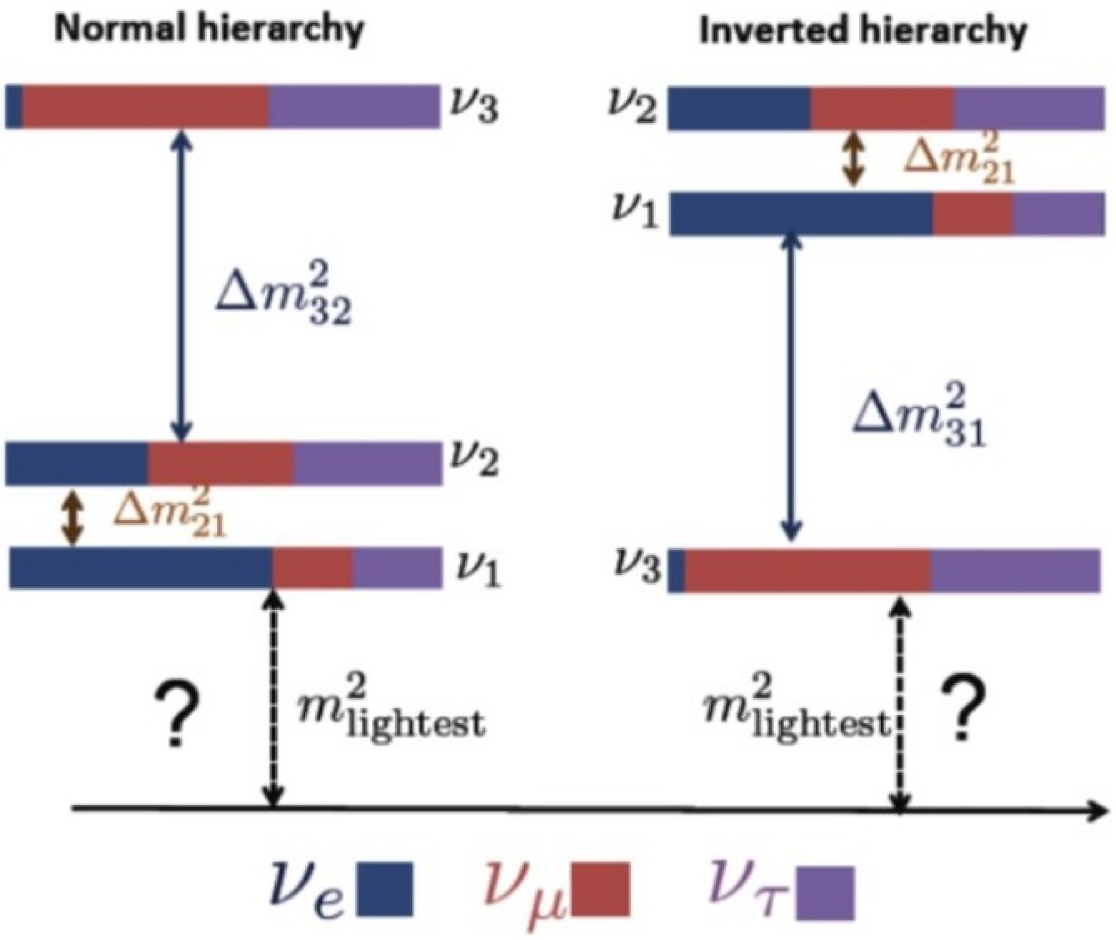
For two flavors:

$$P(\nu_e \rightarrow \nu_\mu) = sin^2 2\theta \cdot sin^2\left(\Delta m^2 \cdot \frac{L}{E_\nu}\right)$$



- 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- 1 Dirac phase: δ
  - possibly 2 Majorana phases $\alpha_{1,2}$
- 2 independent “splittings” Δm^2 and lightest mass $m_{lightest}$

What have we learned from oscillation data?



- At least two neutrinos have mass
- $\Delta m^2_{21} = 8 \cdot 10^{-5}\,\text{eV}^2, \Delta m^2_{32} = 2.5 \cdot 10^{-3}\,\text{eV}^2$
- ν_1 is lighter than ν_2 (matter effects)

- Which neutrino is the lightest?
- What in the mass of the lightest neutrino?

Outline

What do we know so far about neutrino masses?

Neutrinos are massive

The squared mass differences are known

The absolute scale is unknown

What are the three approaches to neutrino mass?

How to measure the mass without model dependencies?

What other physics can we probe in the direct mass measurements?

How can we measure the neutrino masses?

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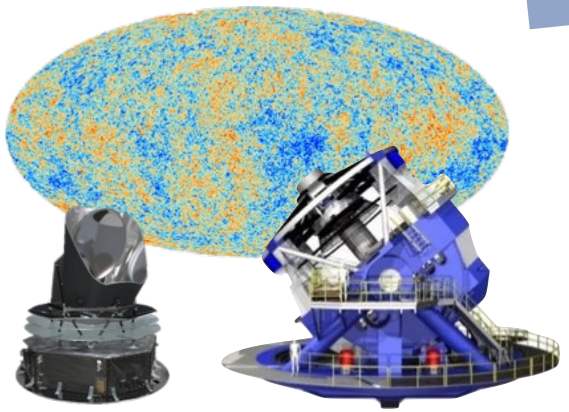
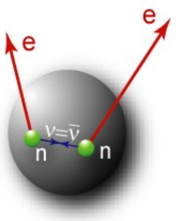
Indirect (model-dependent) probes:

- Observational cosmology
- Search for 0νββ

→ Matteo Viel
Enzo Branchini
Douglas Scott
Nicola Bartolo

→ Ezio Previtali



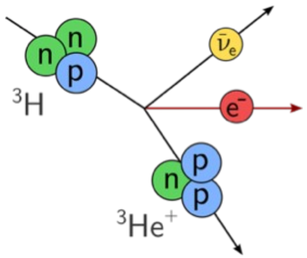


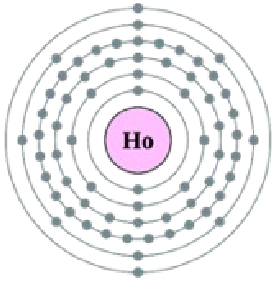
Direct probes:

→ Aldo Ianni

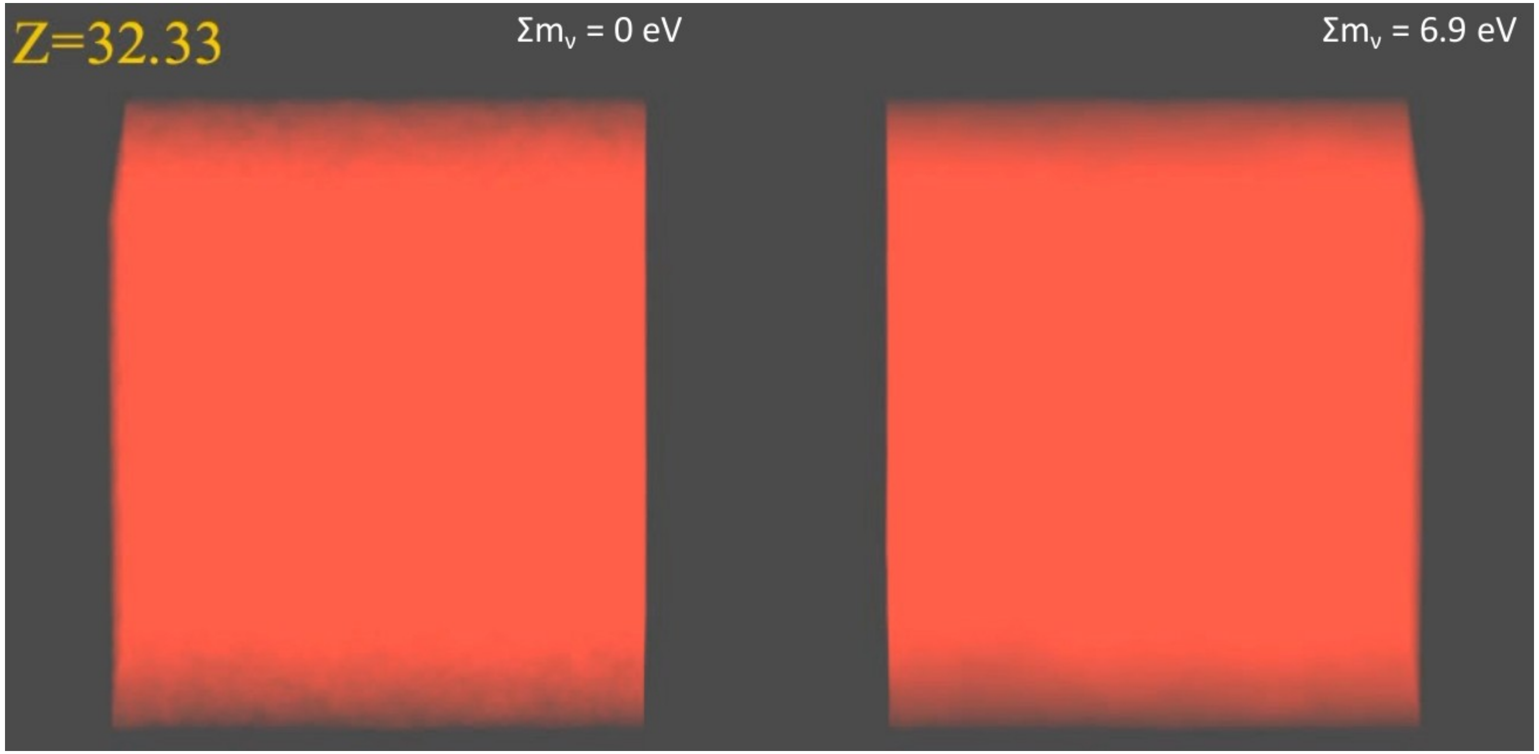
- Supernova ν time-of-flight
- Kinematics of weak decays (^{3}H β-decay, ^{163}Ho electron capture)

→ this lecture





Observational cosmology



- Neutrinos are the most abundant matter particle in the universe
- Even if light they can impact the structure formation

Observational cosmology

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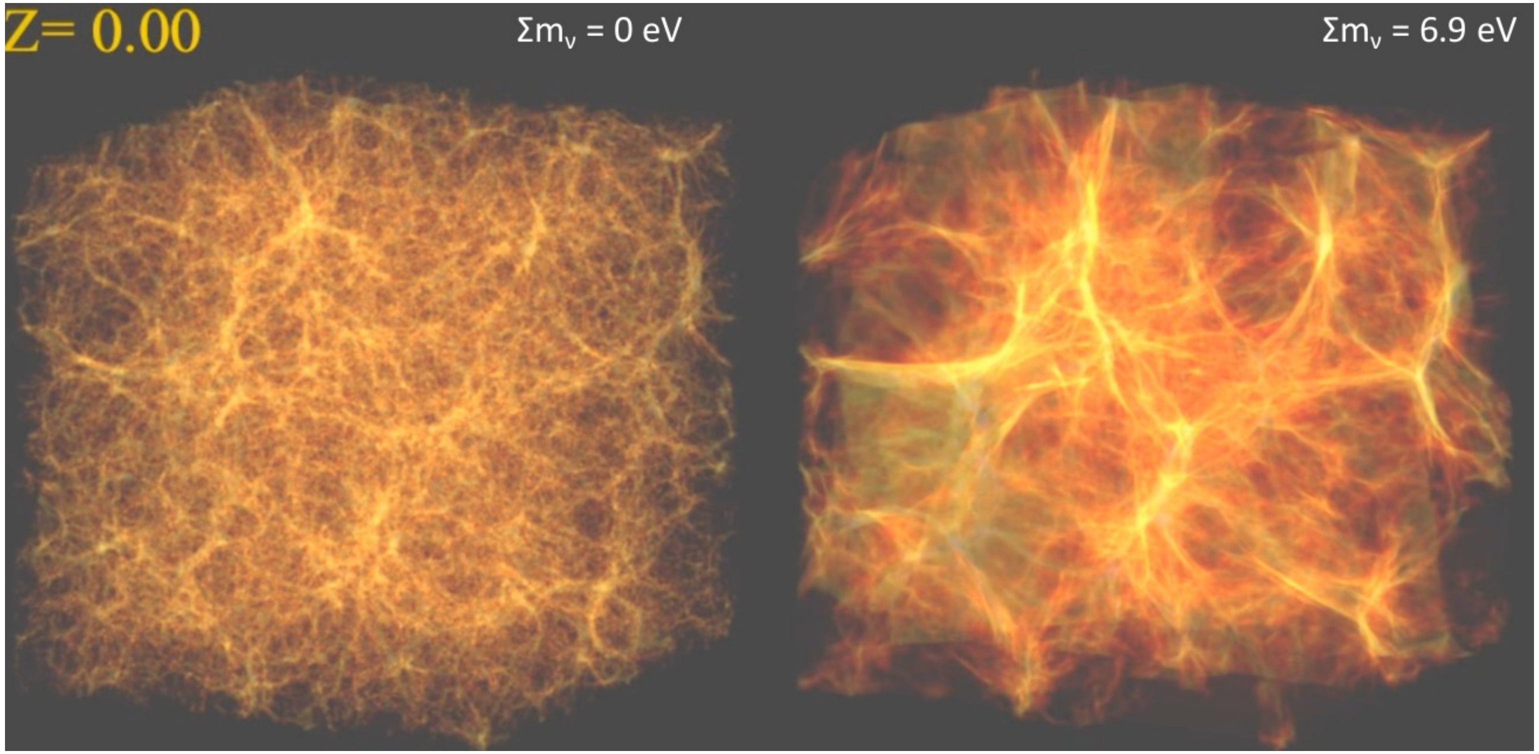

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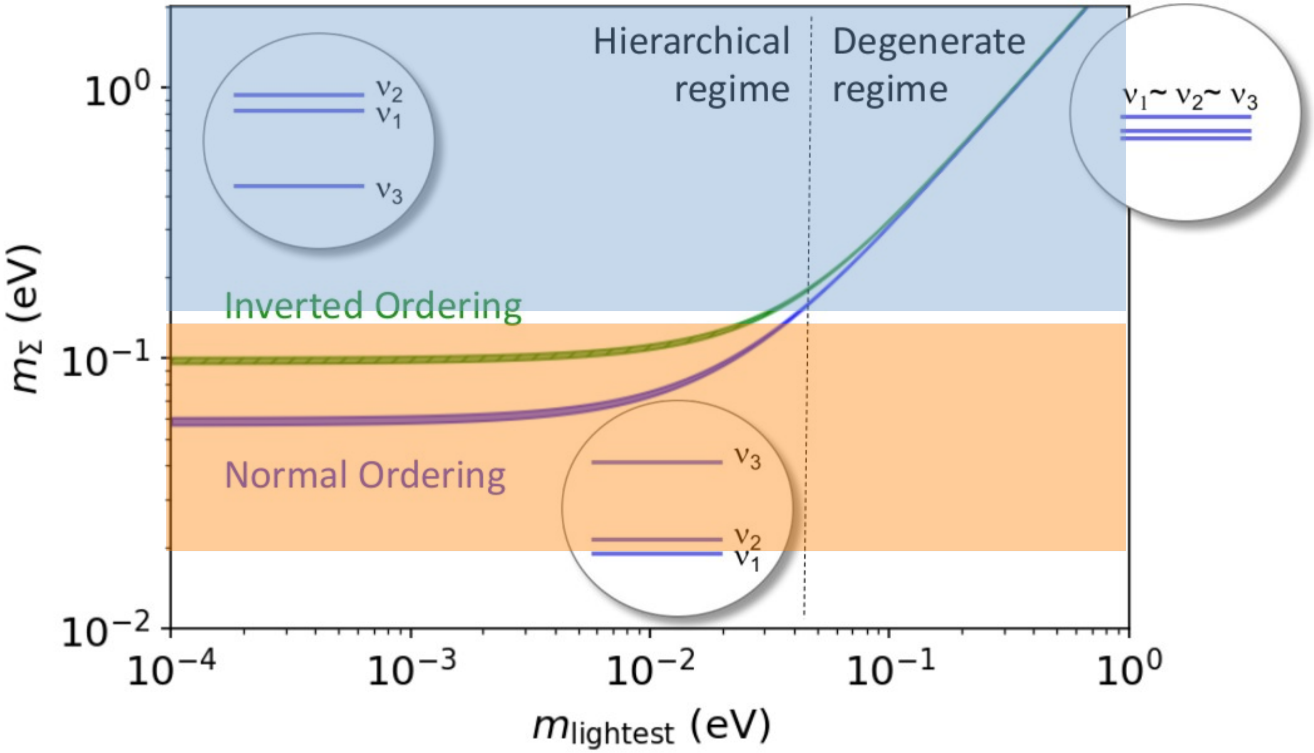
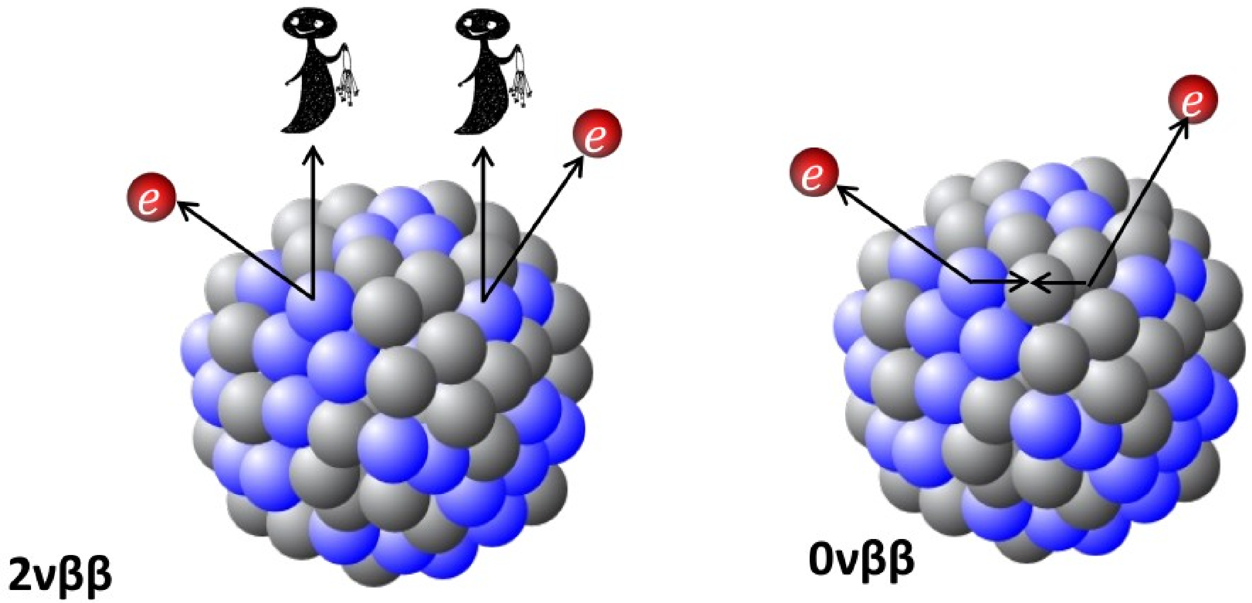
Observational cosmology



- $\sum m_\nu$ < 120 meV (Planck)
- Future missions
  - 10 meV precision
- Various ways to relax the limits:
  - Beyond ΛCDM
  - New neutrino physics

Search for 0νββ decay



$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$n + \nu_e \rightarrow p + e^-$$

- Proof that neutrinos are Majorana particles and that Lepton number is violated
- Depends on the nuclear matrix calculation
- $m_{\beta\beta}$ < 79–180 meV (90% CL)

GERDA collaboration
Science 365, 1445 (2019)
PRL. 125, 252502 (2020)

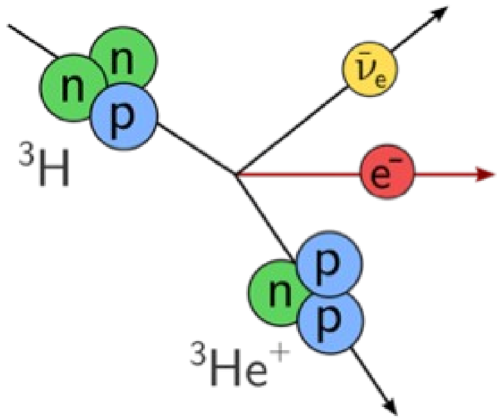
$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q,Z) \cdot |M^{0\nu}|^2 \cdot \boldsymbol{m_{\beta\beta}^2}$$

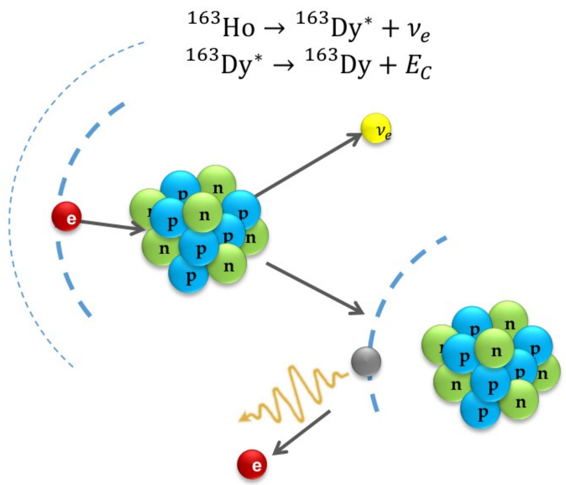
Direct neutrino mass measurement

- No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4$

  $\Rightarrow m_\nu^2$

- Time-of-flight measurements (ν from supernova)
- Kinematics of weak decays / beta decays, e.g. T, ^{163}Ho





Overview: neutrino mass observables

Cosmology

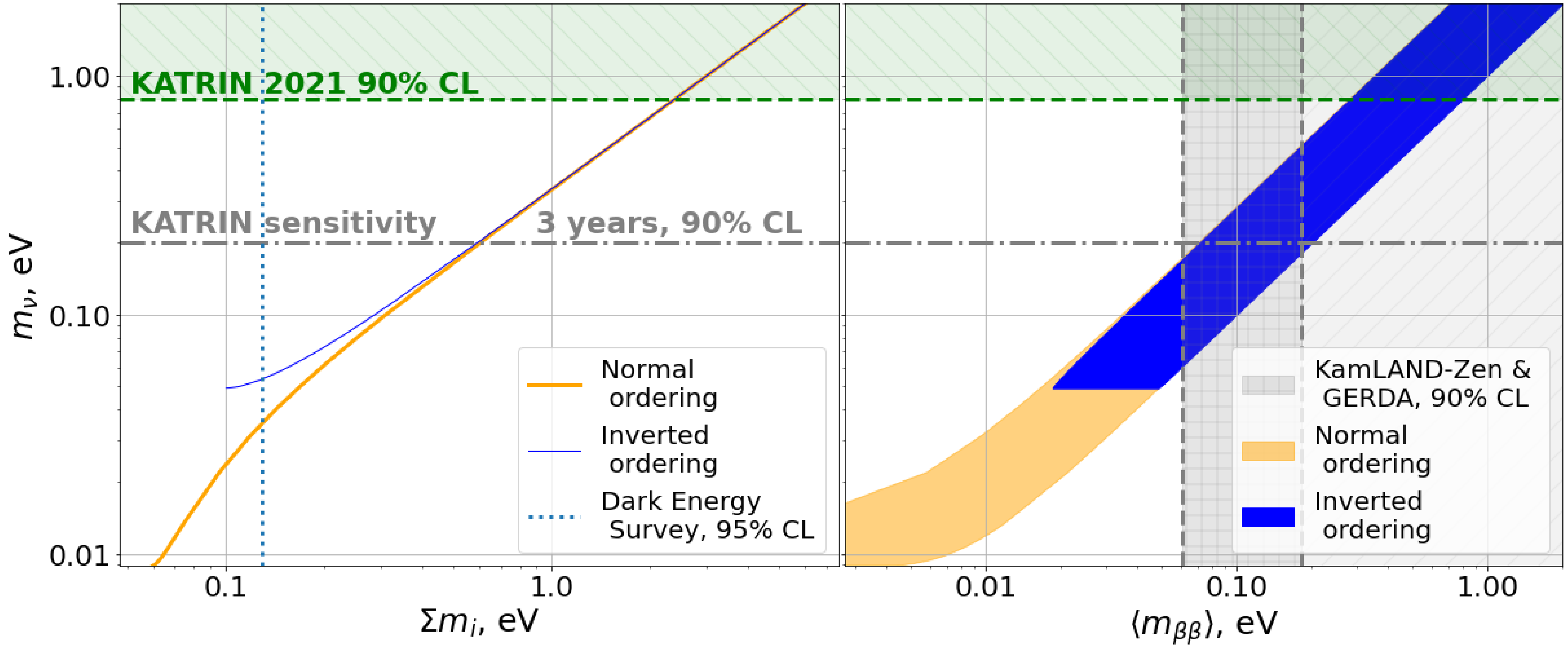
$M_\nu = \sum_i m_i$

0νββ decay

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

β decay and EC

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



Outline

What do we know so far about neutrino masses?

Neutrinos are massive

The squared mass differences are known

The absolute scale is unknown

What are the three approaches to neutrino mass?

Cosmology, $0\nu2\beta$-decay, direct searches

Complementary observables

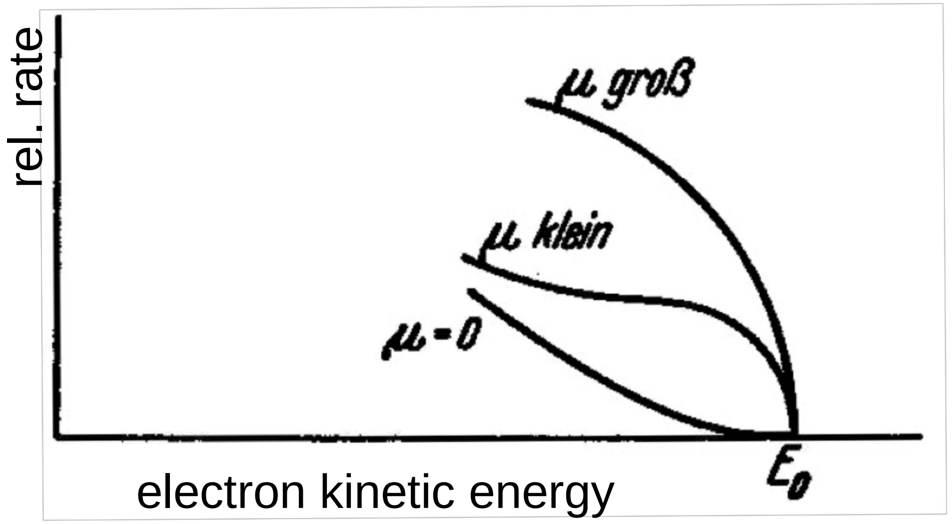
Direct laboratory measurements – least model dependent

How to measure the mass without model dependencies?

What other physics can we probe in the direct mass measurements?

Neutrino mass from β-decay kinematics

Theory: Starting from Fermi's seminal paper (Z. Phys., 1934)



Experiment: Tritium identified early on as most suitable β-emitter

NATURE August 21, 1948 Vol. 162

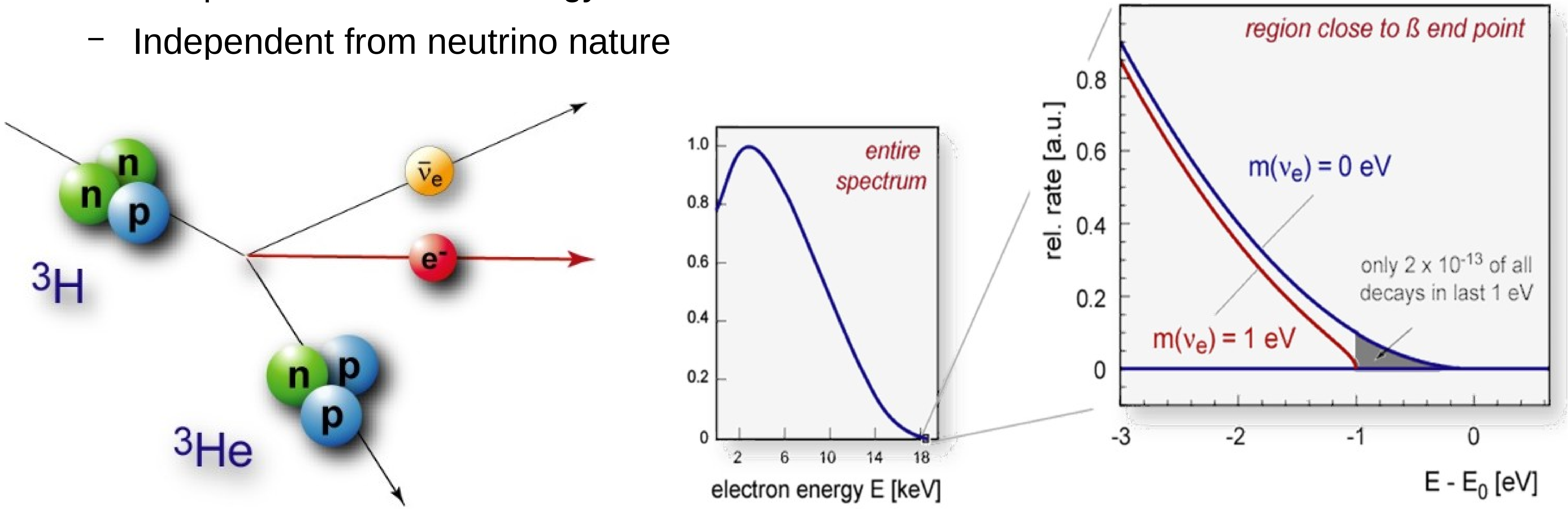
Beta Spectrum of Tritium

THE β-spectrum of tritium ($_1H^3$) is of particular interest because: (1) the relatively simple structure of the $_1H^3$ nucleus makes it well suited to a test of the Fermi theory of β-decay; (2) the unusually low energy of the β-particles means that the shape of the spectrum near the upper limit is an extremely sensitive function of the rest mass of the neutrino if the Fermi theory is confirmed; (3) a theoretical discrepancy[1] exists between the half-life[2] and the upper energy limit, as recently measured[3]; (4) the mass difference ($_1H^3$ — $_2He^3$) can be accurately determined.

Curran *et al.*

Neutrino mass from β-decay kinematics

- Non-zero neutrino mass distorts the spectrum of electrons
  - Independent from cosmology
  - Independent from neutrino nature



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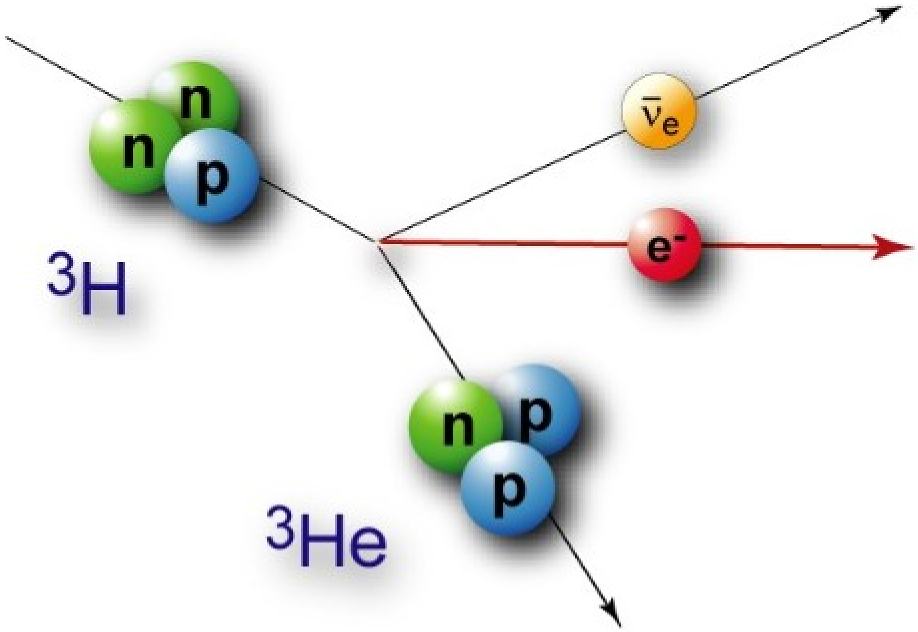
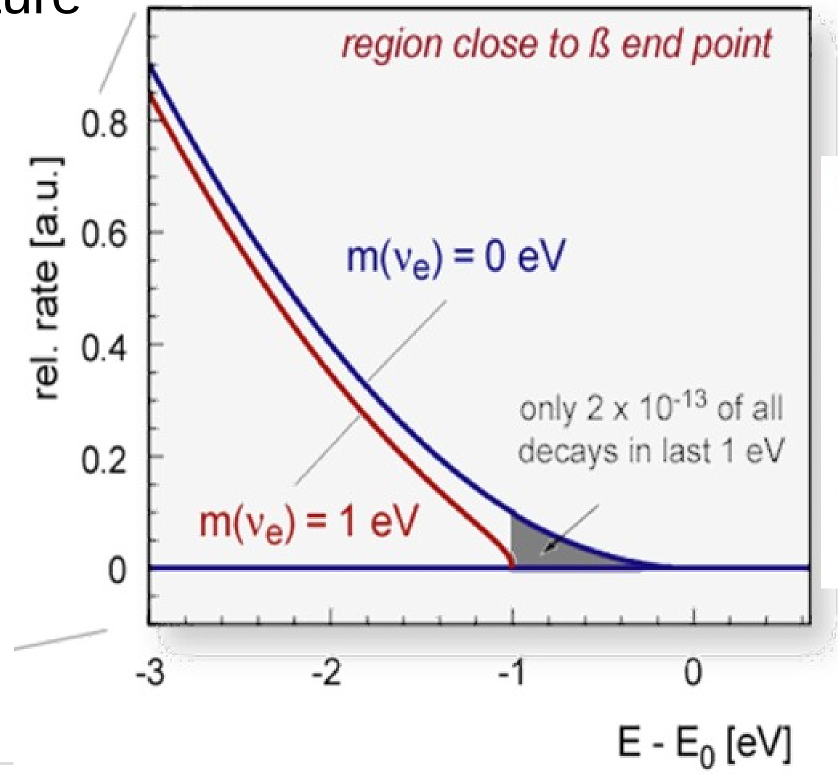
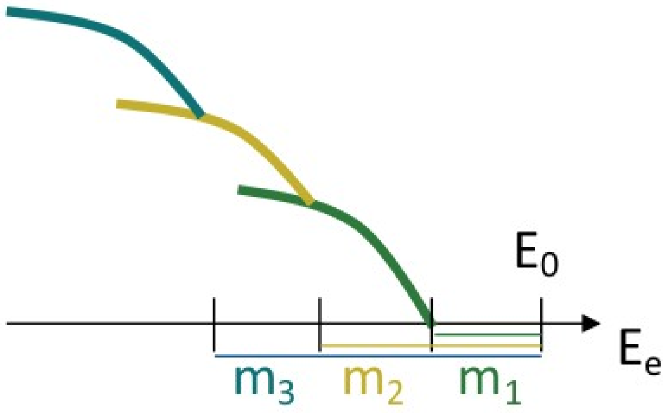
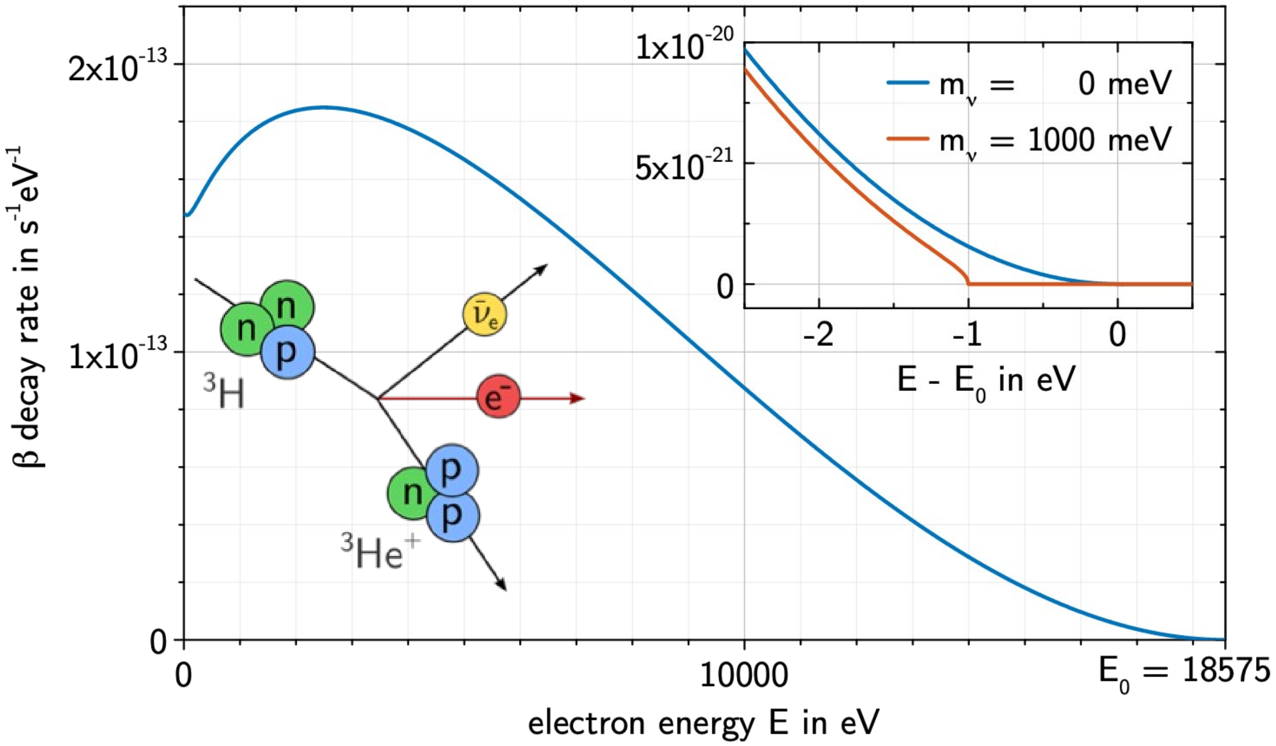






Neutrino mass from β-decay kinematics

$$\frac{d\Gamma}{dE} = K \cdot F(Z,E) \cdot \underbrace{p}_{p_e} \cdot \underbrace{E_{tot}}_{E_e} \cdot \underbrace{(E_0 - E)}_{E_\nu} \cdot \underbrace{\sum_i |U_{ei}|^2 \sqrt{(E_0-E)^2 - m_i^2}}_{p_\nu}$$



Key requirements & technologies

- Low-endpoint β/EC nuclide: E_0 = 18.6 keV for ^{3}H
- High-activity source: $T_{1/2}$ = 12.3 yr for ^{3}H
- Excellent energy resolution

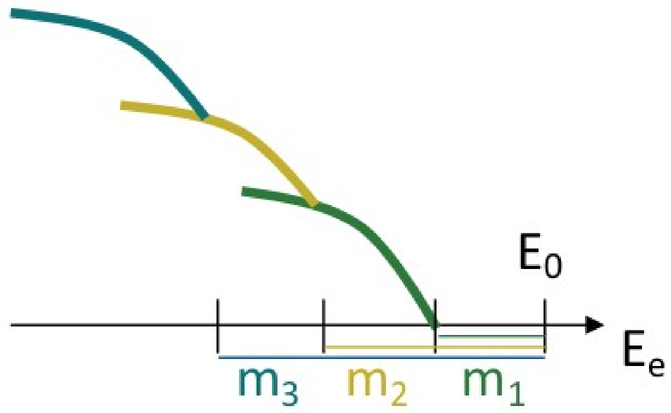
Spectral distortion measures **"effective" mass square:**

$$m^2(\nu_e) := \sum_i |U_{ei}|^2 m_i^2$$

Effective neutrino mass parameter

$$\frac{d\Gamma}{dE}=\sum_i |U_{ei}|^2 C\cdot F(E,Z)\cdot(E+m_e)\cdot(E_0-E)\cdot\sqrt{(E+m_e)^2-m_e^2}\cdot\sqrt{(E_0-E)^2-m_i^2}$$

- Assume that we are measuring “far away” from E_0



$$\sum_i |U_{ei}|^2\cdot(E_0-E)\cdot\sqrt{1-\frac{m_i^2}{(E_0-E)^2}}$$

$$\approx\sum_i |U_{ei}|^2\cdot(E_0-E)\cdot(1-\frac{1}{2}\cdot\frac{m_i^2}{(E_0-E)^2})$$

$$=(E_0-E)\cdot(1-\frac{1}{2}\cdot\frac{\sum_i |U_{ei}|^2\cdot m_i^2}{(E_0-E)^2})$$

$$\approx\sqrt{(E_0-E)^2-\sum_i |U_{ei}|^2\cdot m_i^2}$$

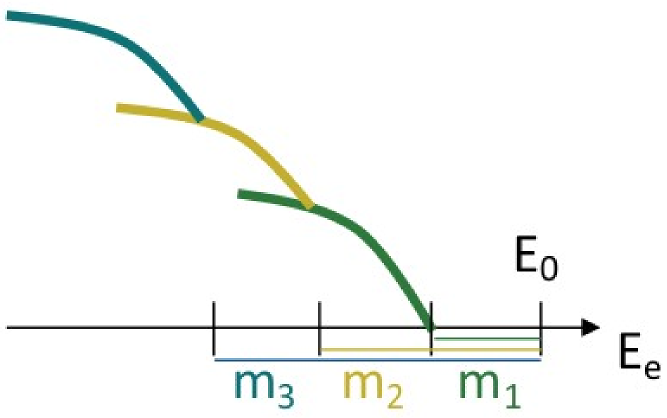
Effective neutrino mass parameter

$$\frac{d\Gamma}{dE} = \sum_i |U_{ei}|^2 C \cdot F(E,Z) \cdot (E+m_e) \cdot (E_0 - E) \cdot \sqrt{(E+m_e)^2 - m_e^2} \cdot \sqrt{(E_0-E)^2 - m_i^2}$$

- Assume that we are measuring “far away” from E_0

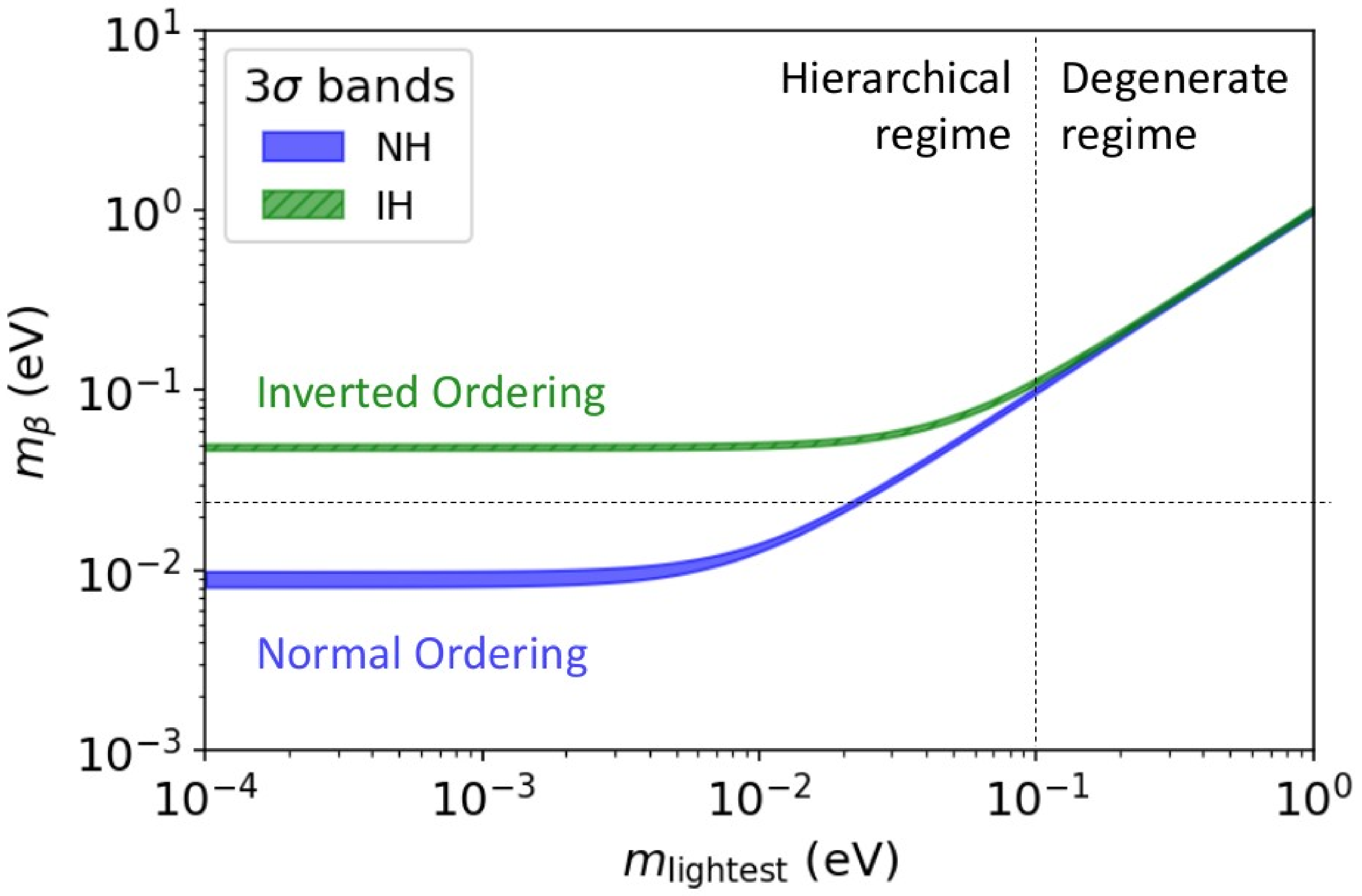
$$\frac{d\Gamma}{dE} = C \cdot F(E,Z) \cdot (E+m_e) \cdot (E_0 - E) \cdot \sqrt{(E+m_e)^2 - m_e^2} \cdot \sqrt{(E_0-E)^2 - \sum_i |U_{ei}|^2 \cdot m_i^2}$$

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

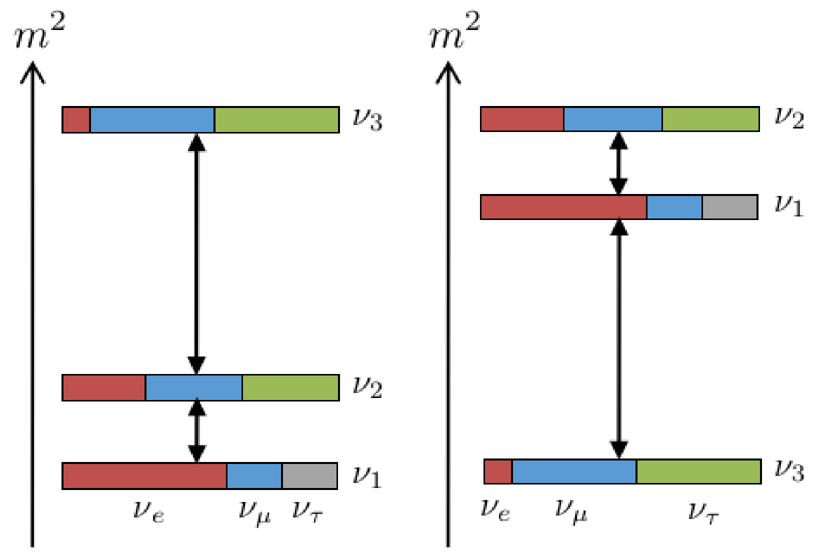


- Incoherent sum of neutrino masses
- Effective squared mass of electron antineutrino

Effective neutrino mass

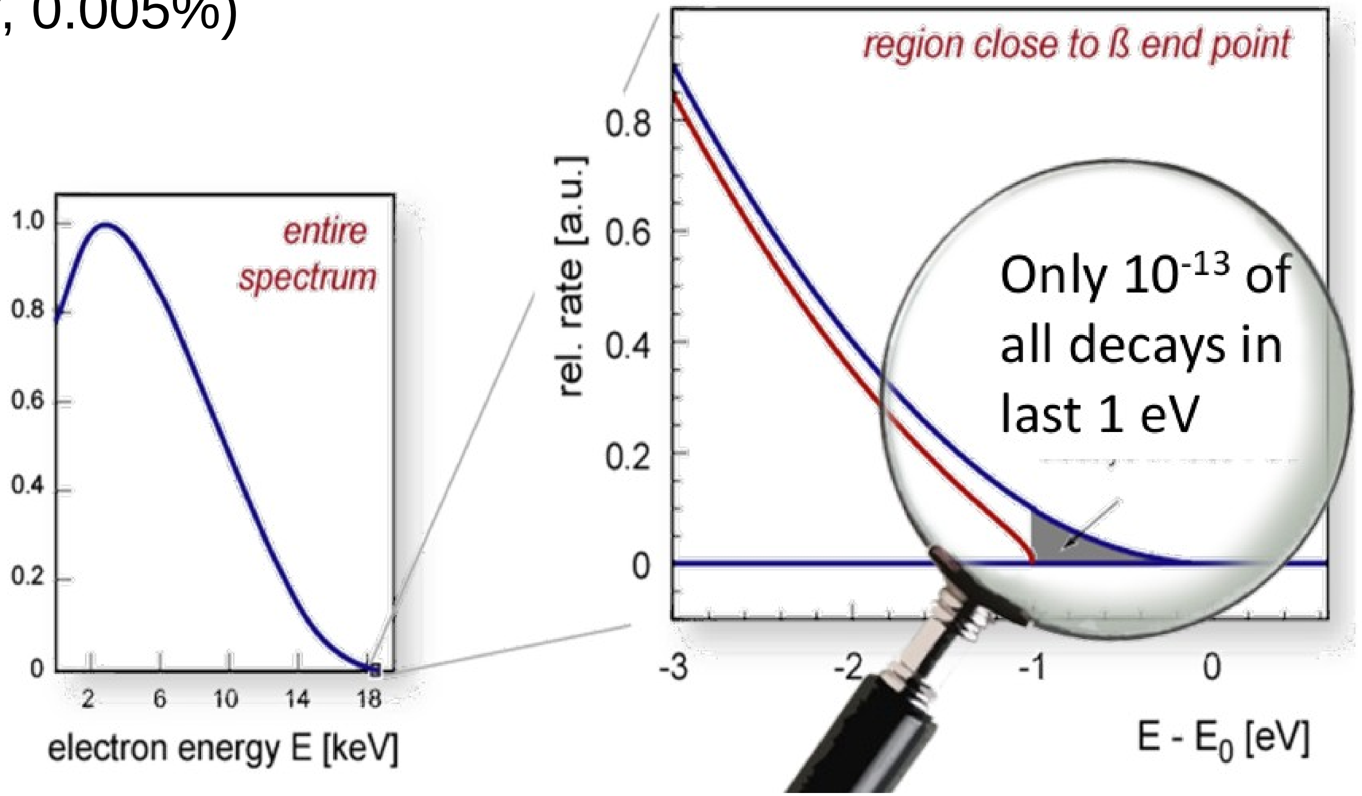


$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$$

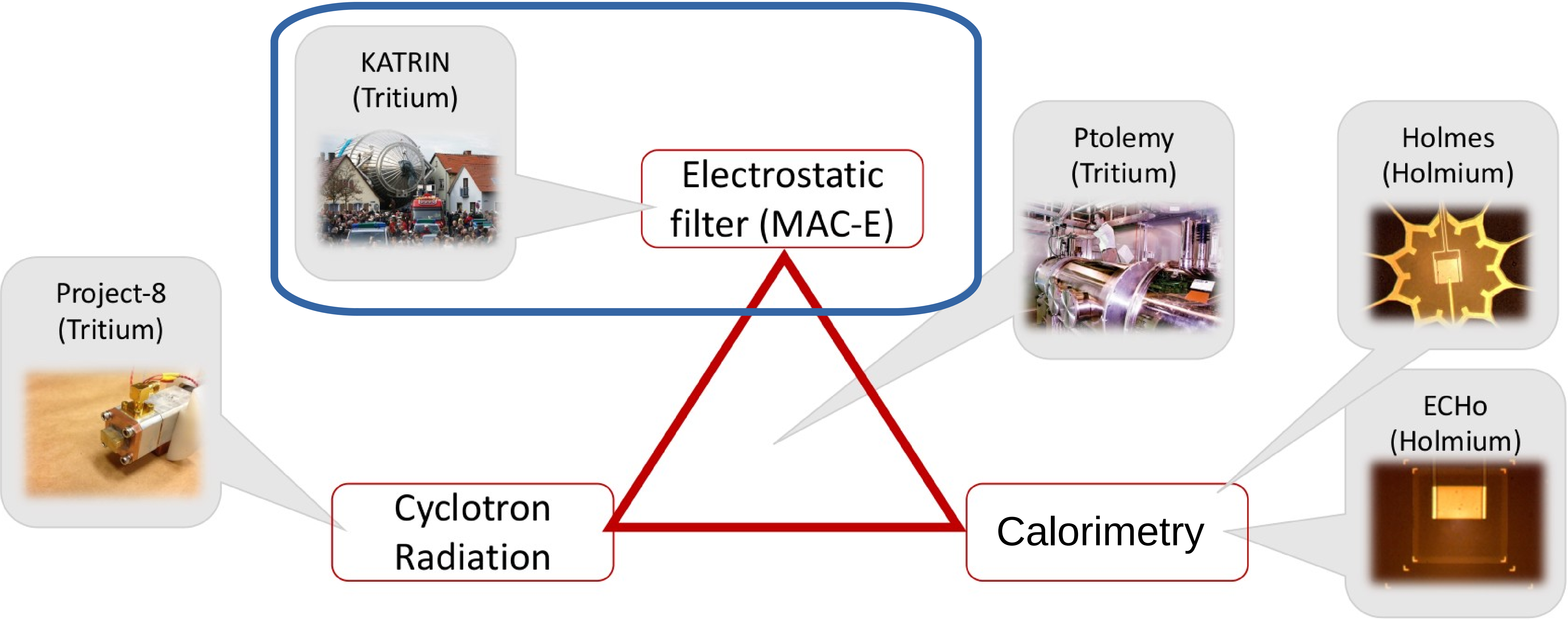


Experimental challenges

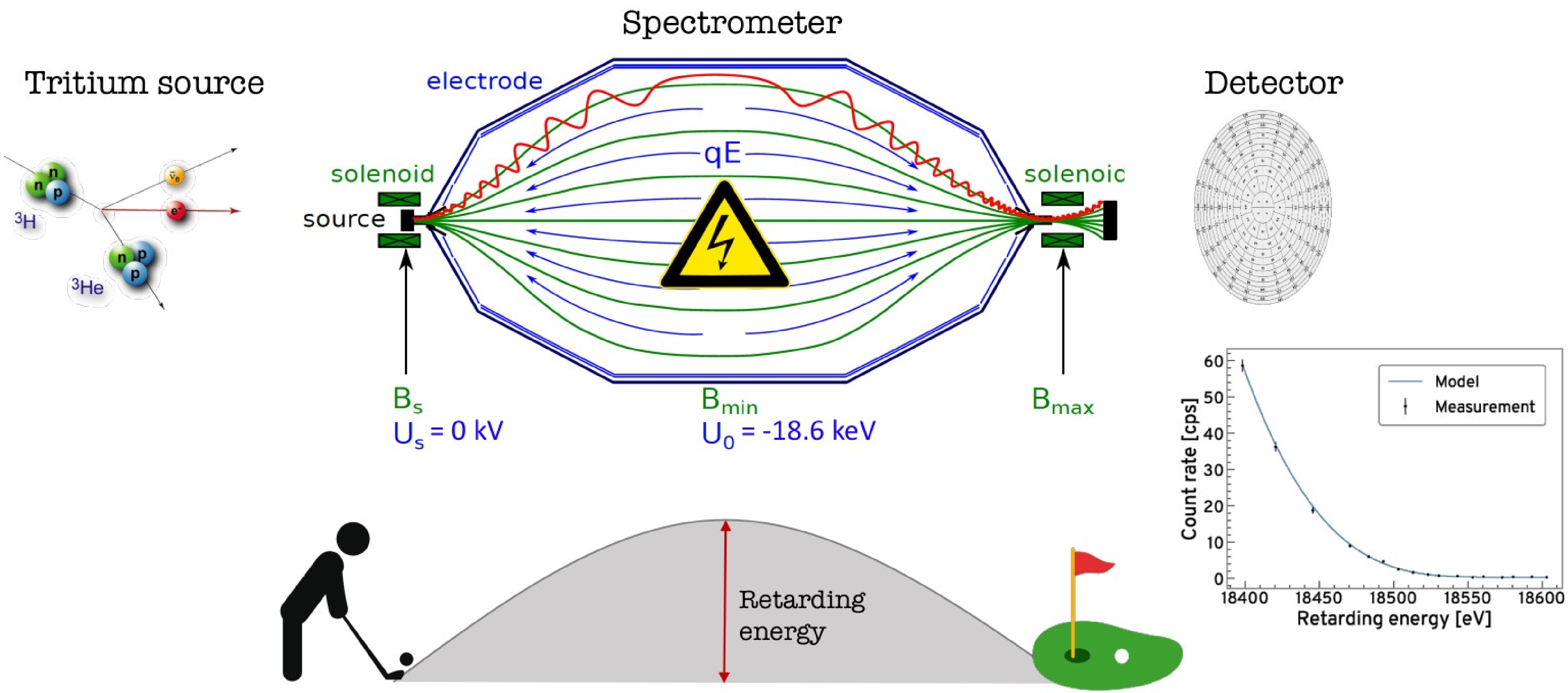
- How to realize such experiment?
  - Ultra-strong radioactive source (10^{11} decays/s)
  - Excellent energy resolution (~ 1 eV, 0.005%)
  - Low background (< 100 mcps)



Experimental techniques for direct ν-mass measurement



MAC-E filter technique



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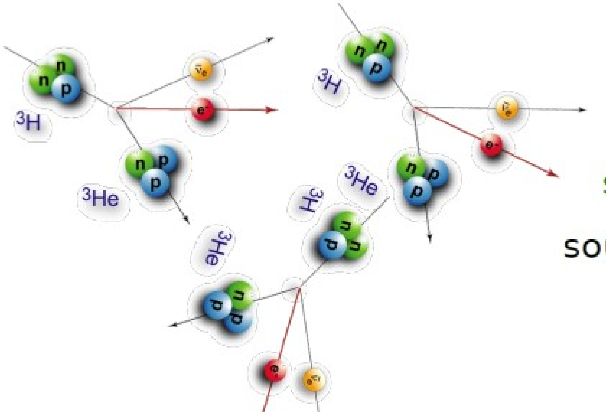
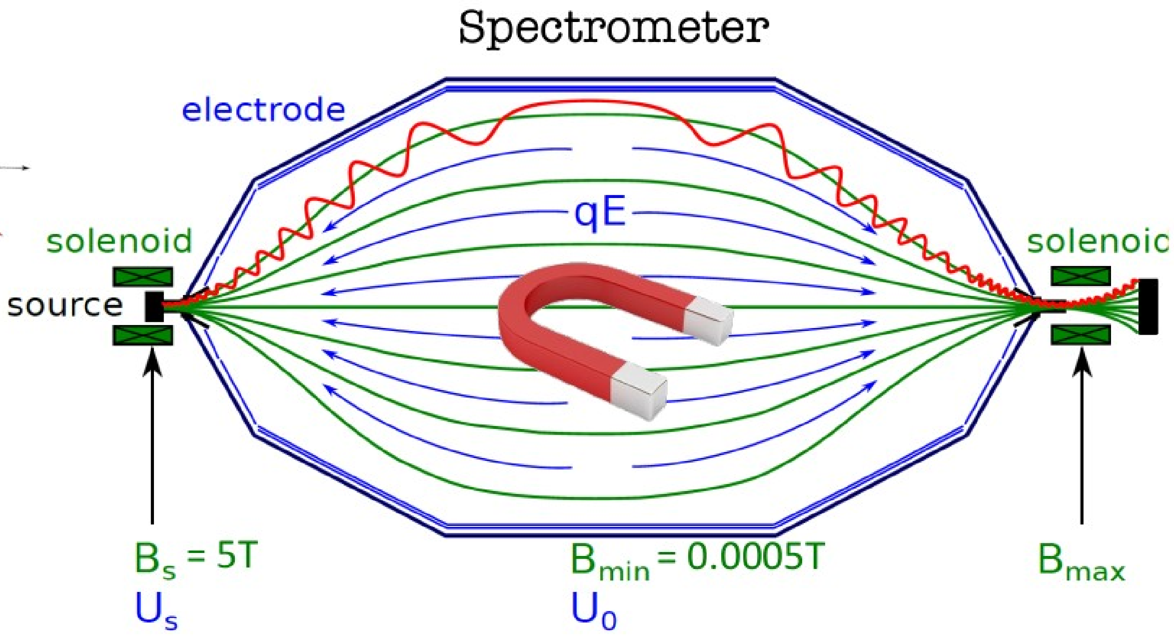
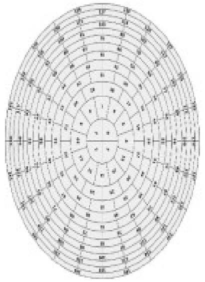


Isotropic source

$$E_{kin} = E_L + E_T$$

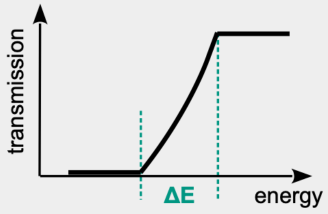


Detector



✓ Large angle acceptance
✓ eV-scale E-resolution

Sharp high-pass filter:



Steps of filter potential
→ integrated β spectrum

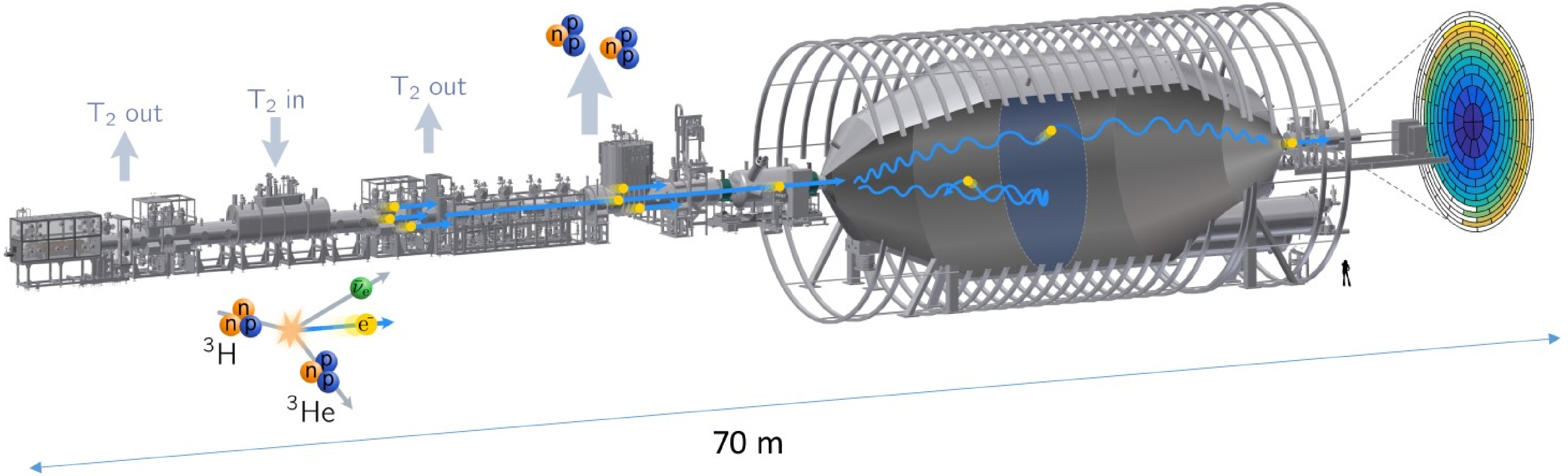
$$E_T^{center} = E_T^{start} \cdot \frac{B^{center}}{B^{start}} \quad \rightarrow \quad E_T^{center,max} = E \cdot \frac{B^{center}}{B^{start}} \approx 2 \text{ eV}$$

KATRIN: Karlsruhe Tritium Neutrino Experiment

KATRIN’s epic voyage

Karlsruher Institut für Technologie

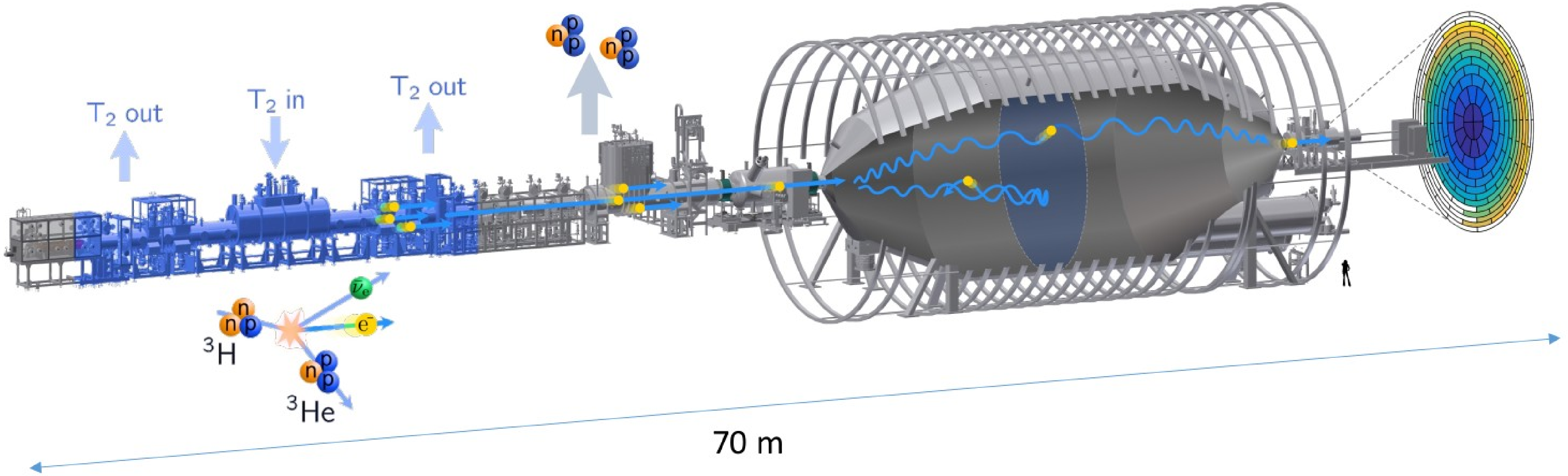
Measurement principle of KATRIN



Measurement principle of KATRIN

Tritium source

- 100 μg of gaseous T_2
- 10^{11} T_2 decays/s



Measurement principle of KATRIN

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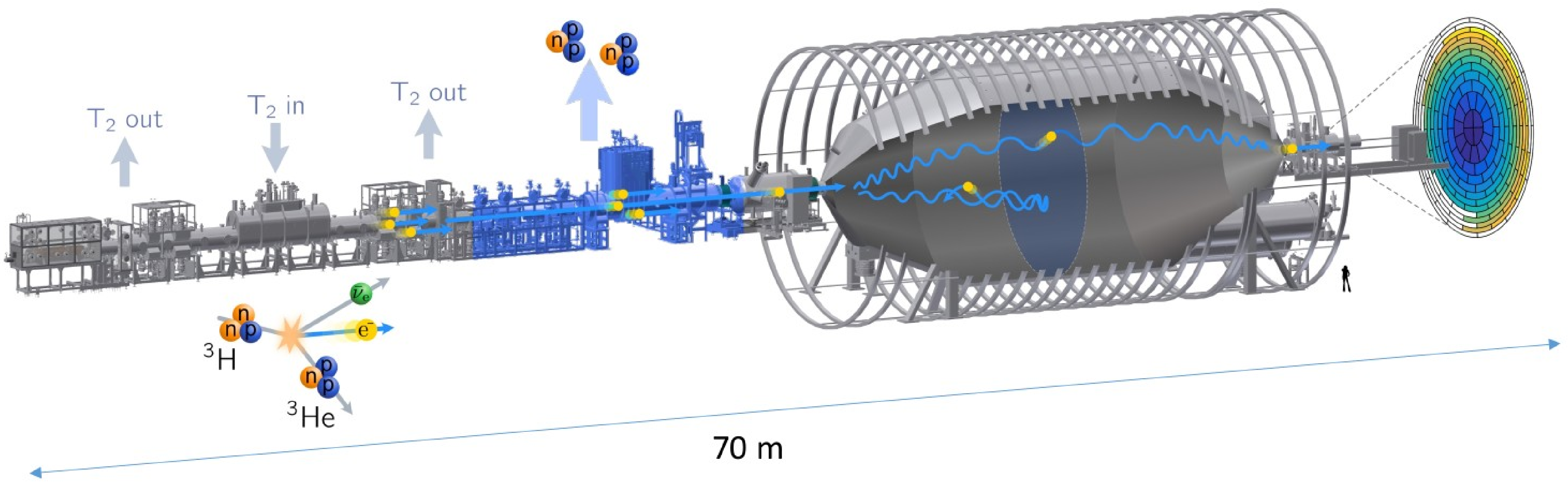
Transport section
- Guidance of electrons
- Removal of tritium



Measurement principle of KATRIN

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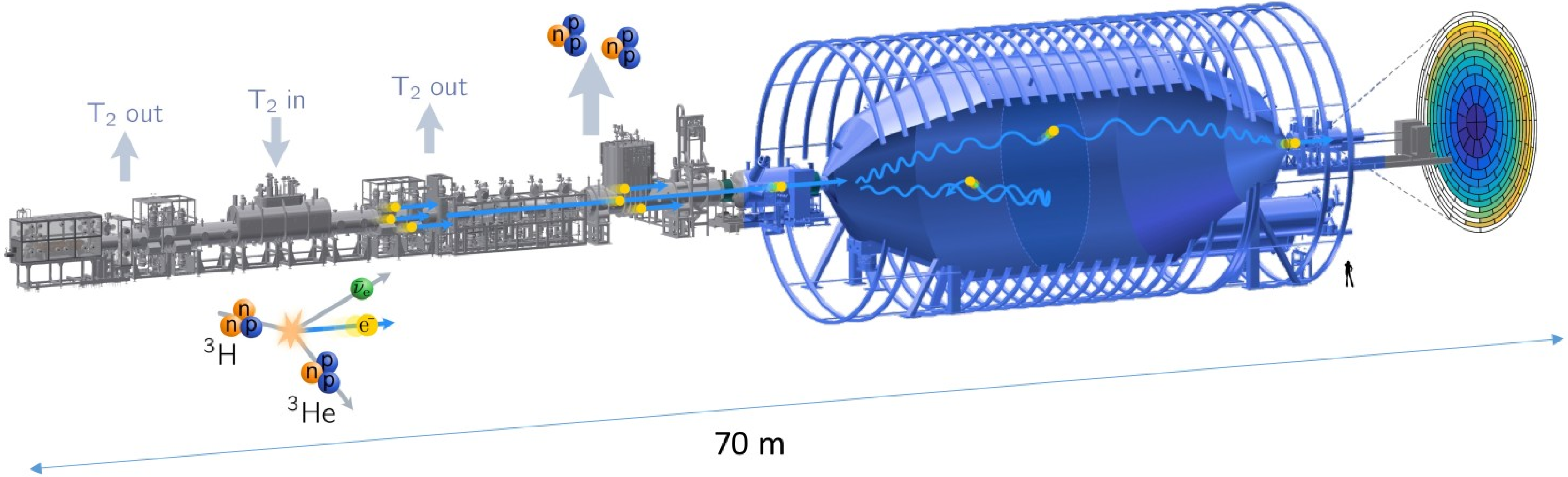
- Guidance of electrons
- Removal of tritium

Spectrometer
- Electrostatic filter
- MAC-E filter principle



Measurement principle of KATRIN

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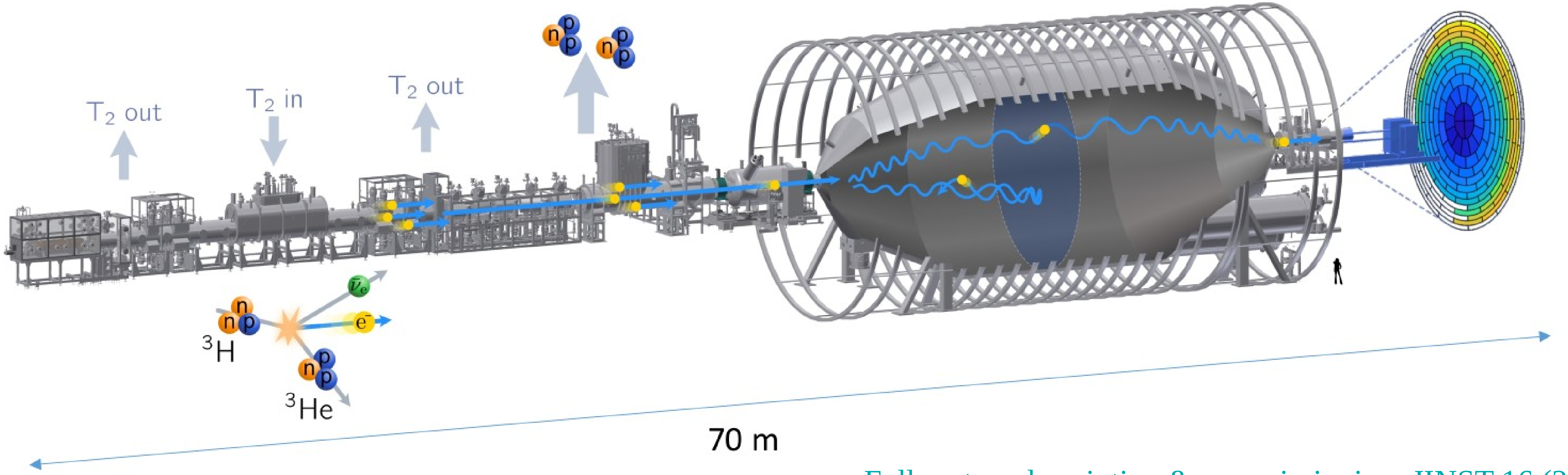
- 100 µg of gaseous T_2
- 10^{11} T_2 decays/s

Transport section
- Guidance of electrons
- Removal of tritium

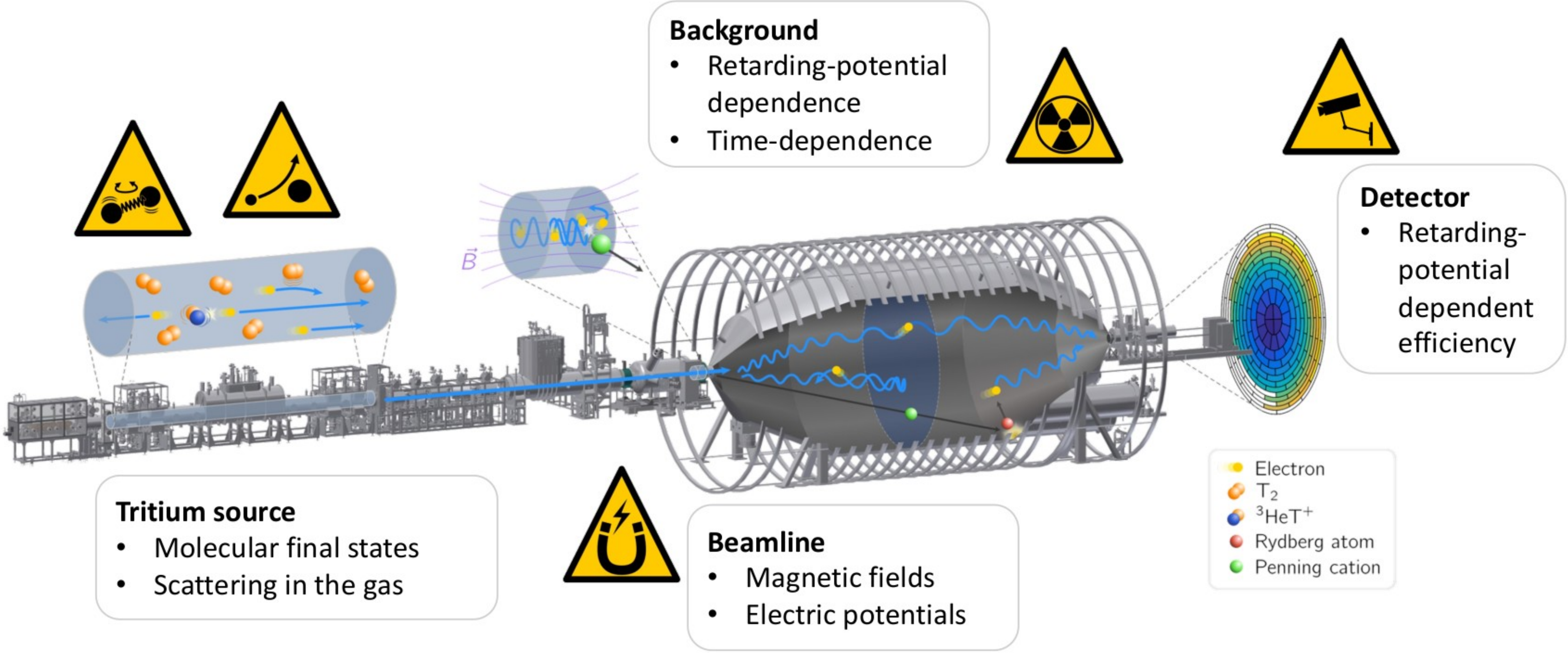
Spectrometer
- Electrostatic filter
- MAC-E filter principle

Detector
- Counts electrons
- Rate vs potential

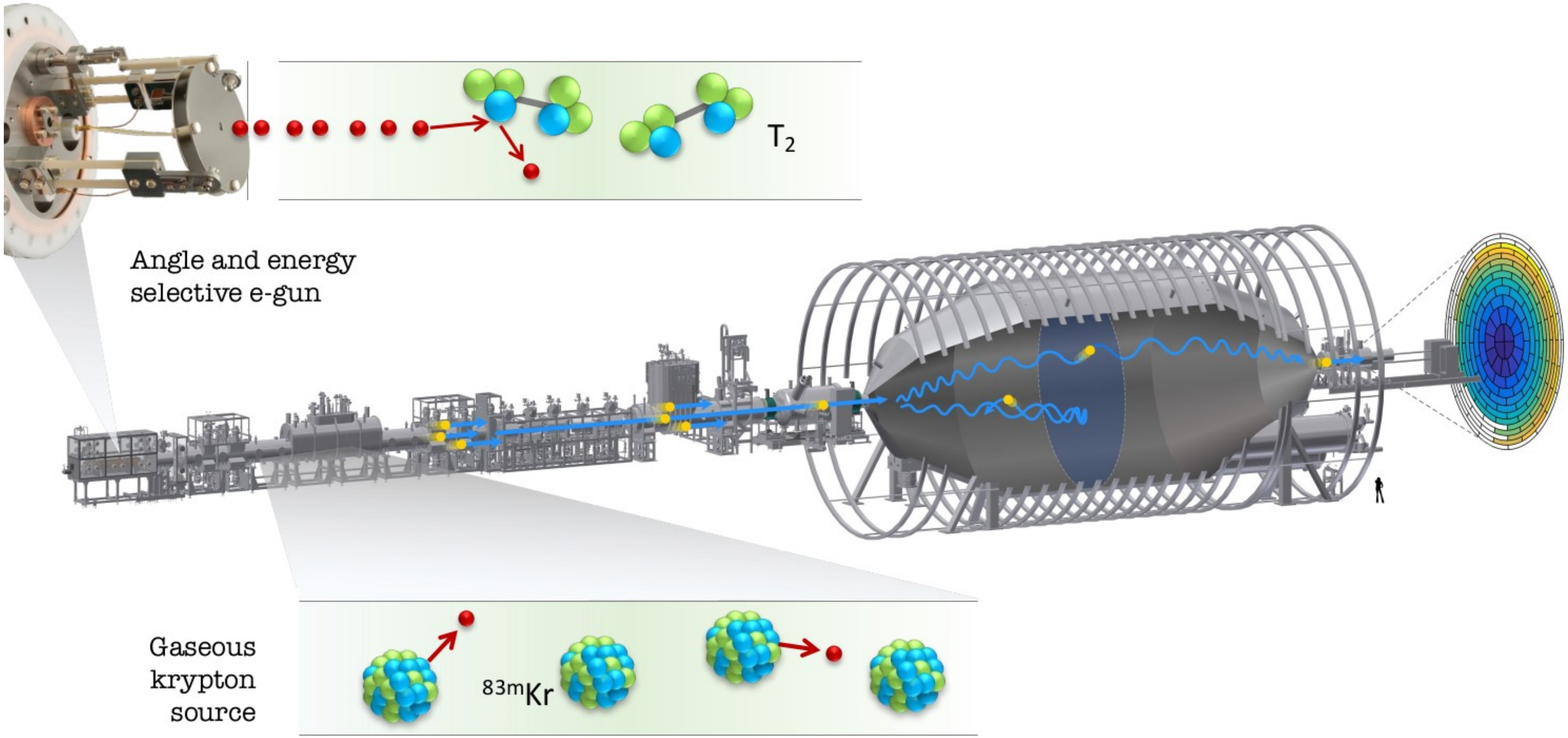


Full system description & commissioning, [JINST 16 (2021) T08015]

Systematic effects

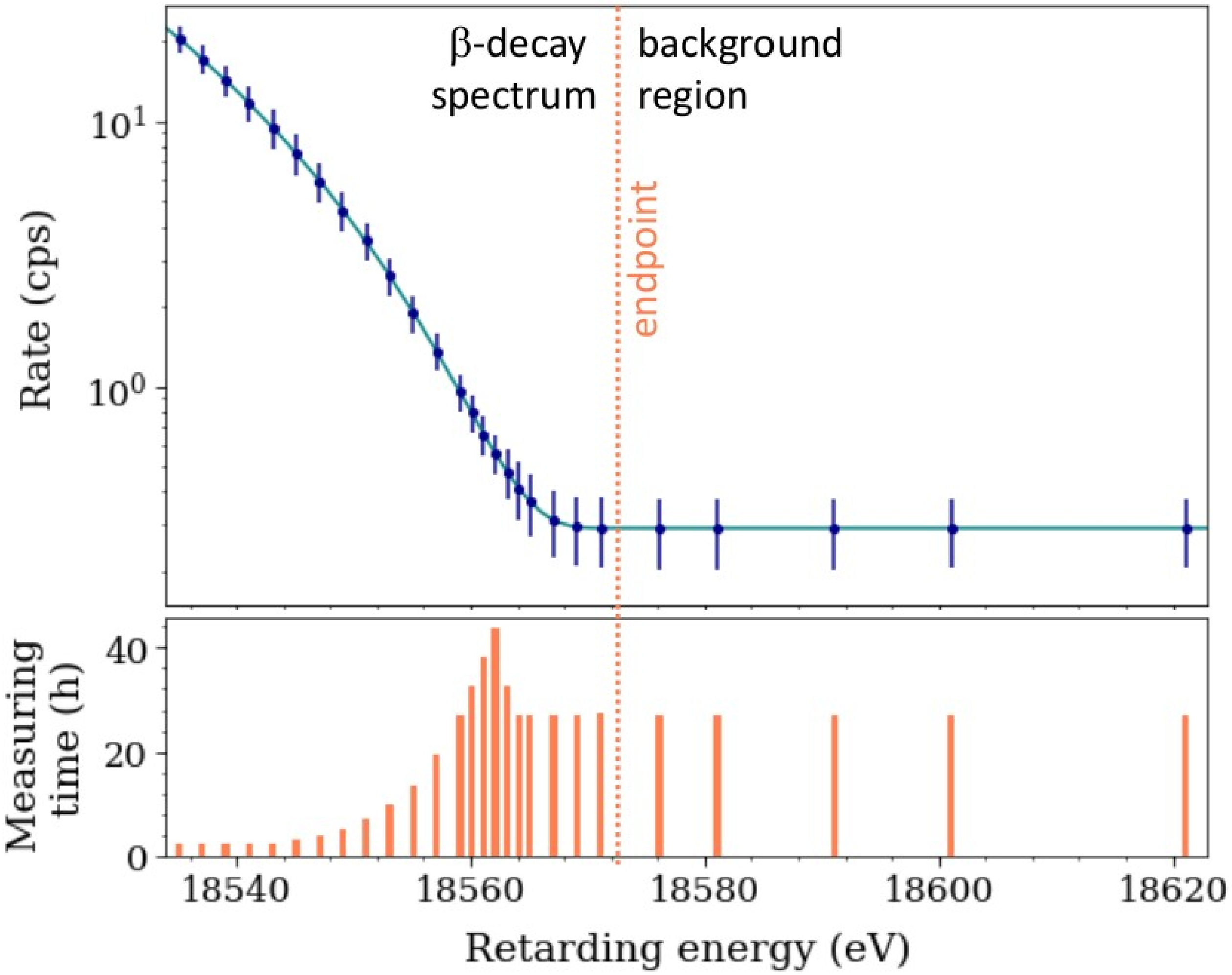


Calibration sources



Measurement strategy

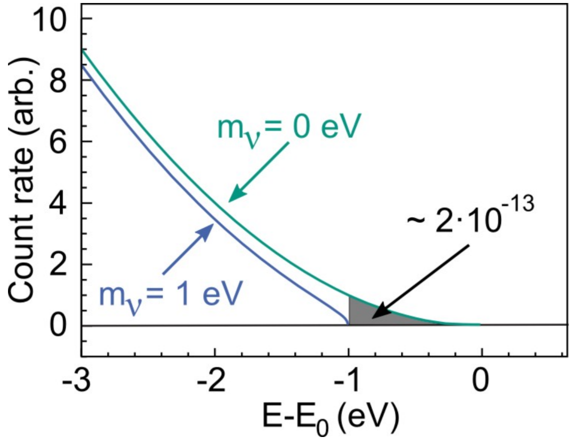
- Scan: ~40 HV set points
- Scan length: 2-3 hours
- Analysis interval:
  - E_0 - 40 eV, E_0 + 135 eV
- Hundreds of scans per campaign



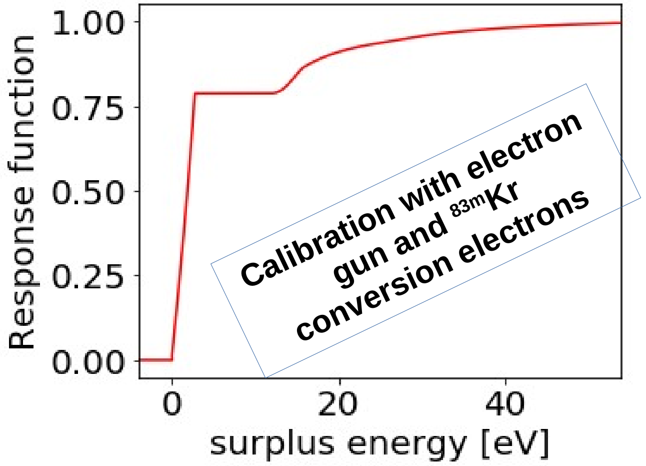
Beta-spectrum and neutrino mass

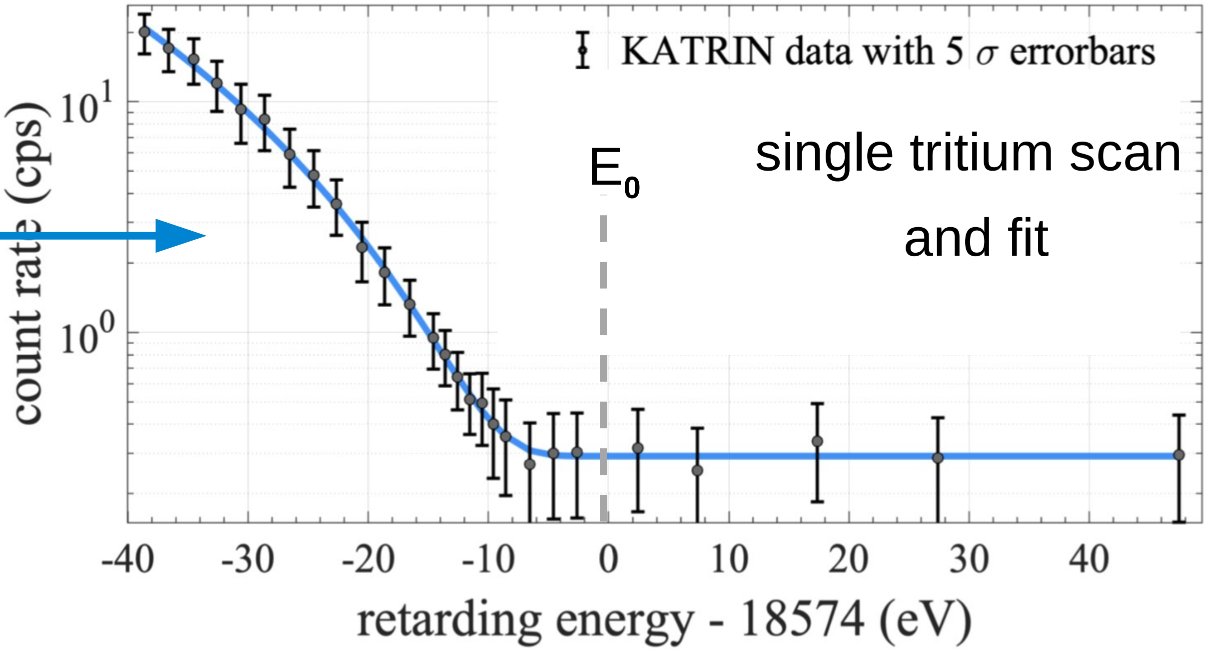
Karlsruher Institut für Technologie

- **Beta spectrum: $R_\beta(E, m^2(\nu_e))$**



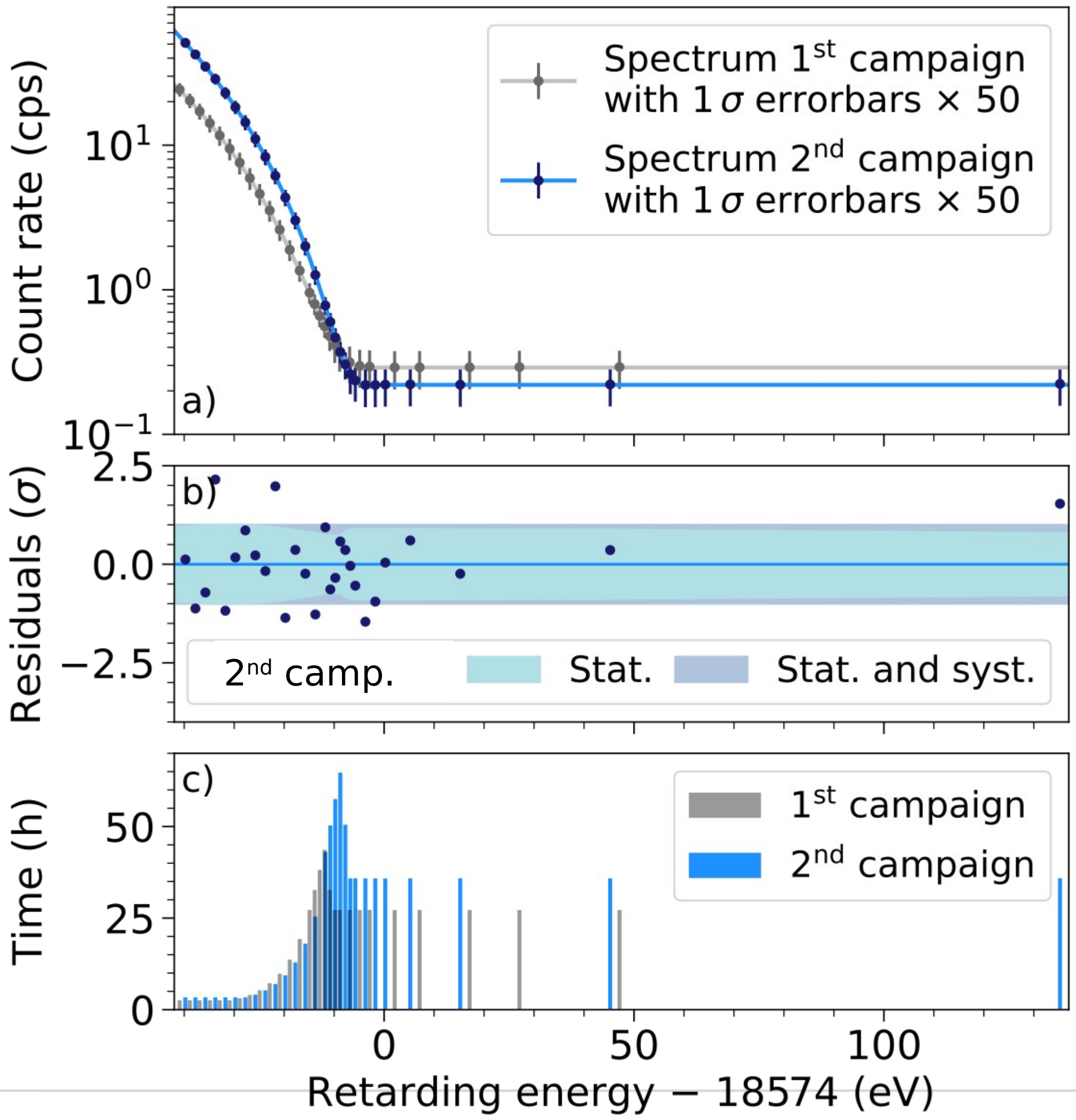
- **Experimental response: f(E-qU)**





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

Recent ν-mass results



First campaign (spring 2019):

✓ total statistics: 2 million events

✓ best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ eV² (stat. dom.)

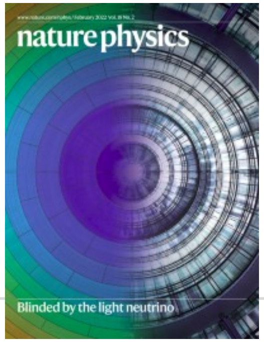
✓ limit: $m_\nu < 1.1$ eV (90% CL)

Second campaign (autumn 2019):

✓ total statistics: 4.3 million events

✓ best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$ eV² (stat. dom.)

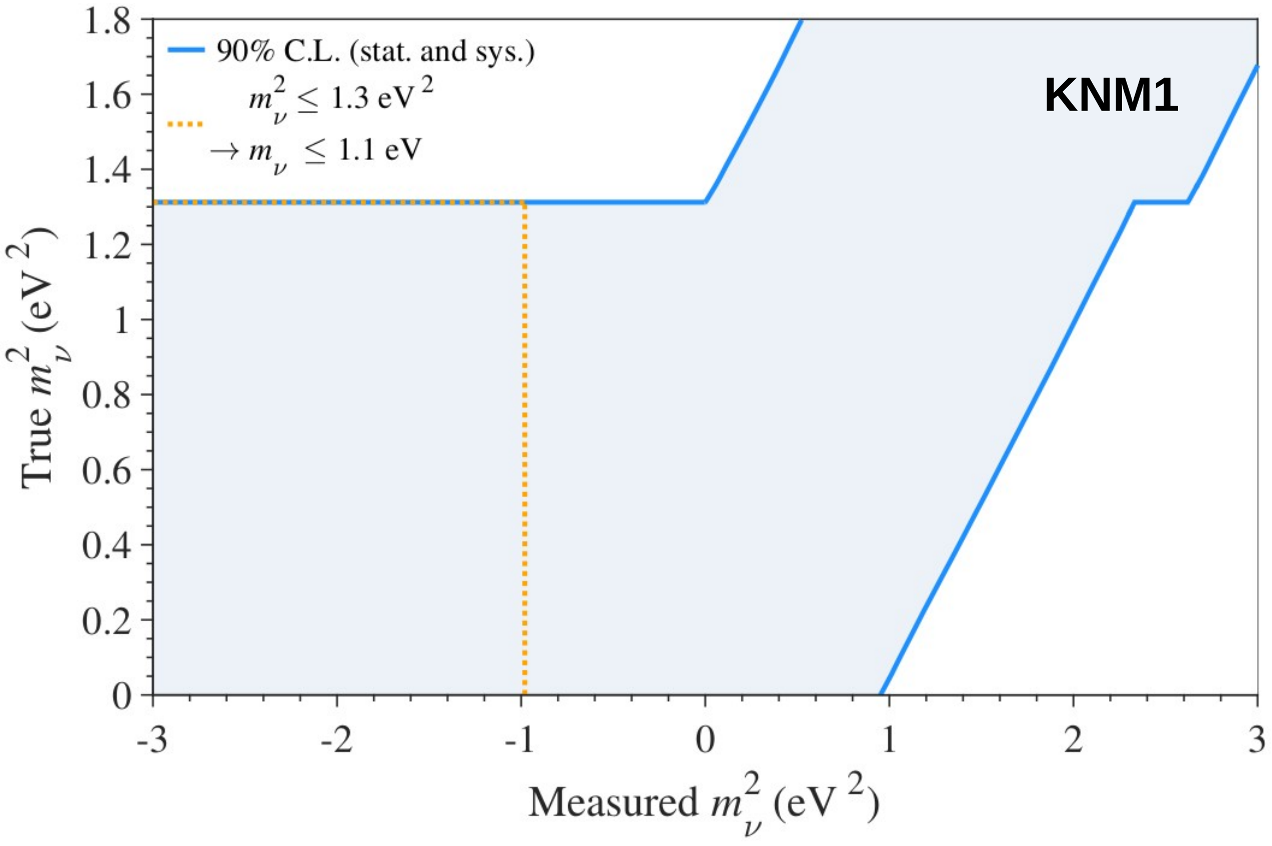
✓ limit: $m_\nu < 0.9$ eV (90% CL)

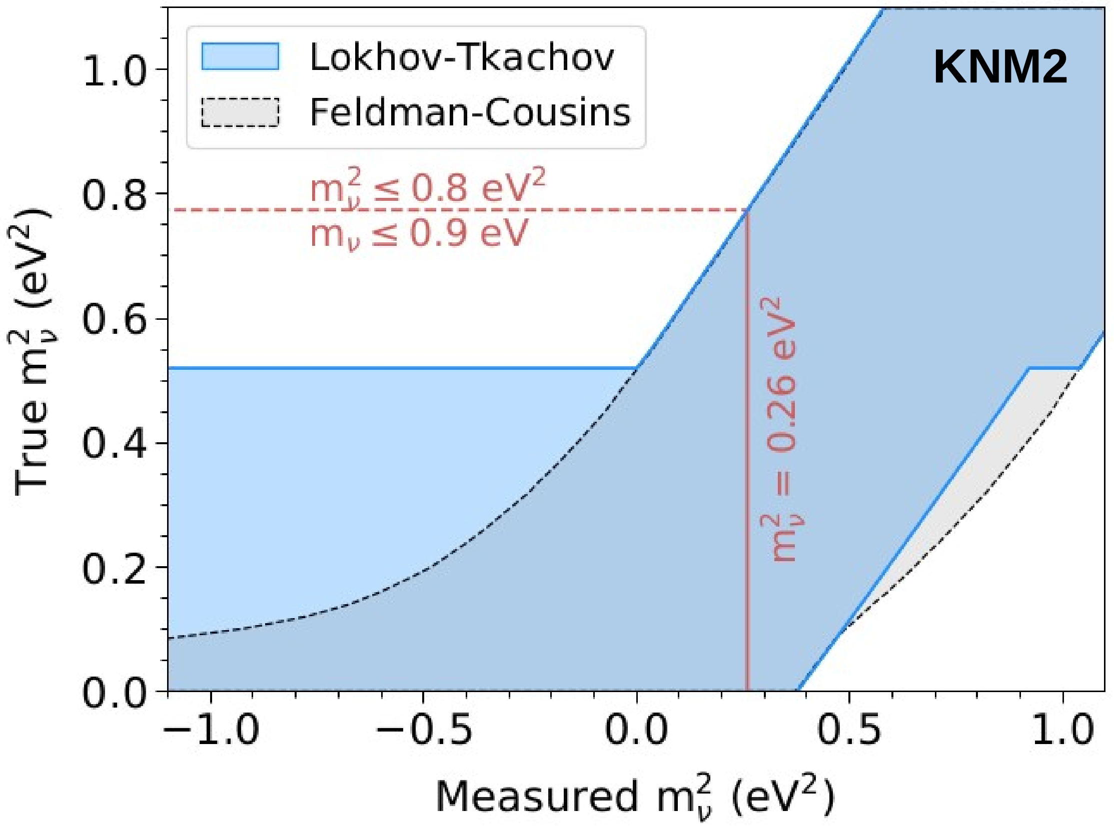


Combined result: $m_\nu < 0.8$ eV (90% CL)

KATRIN Collab, Nature Phys. 18 (2022) 160

Confidence intervals construction

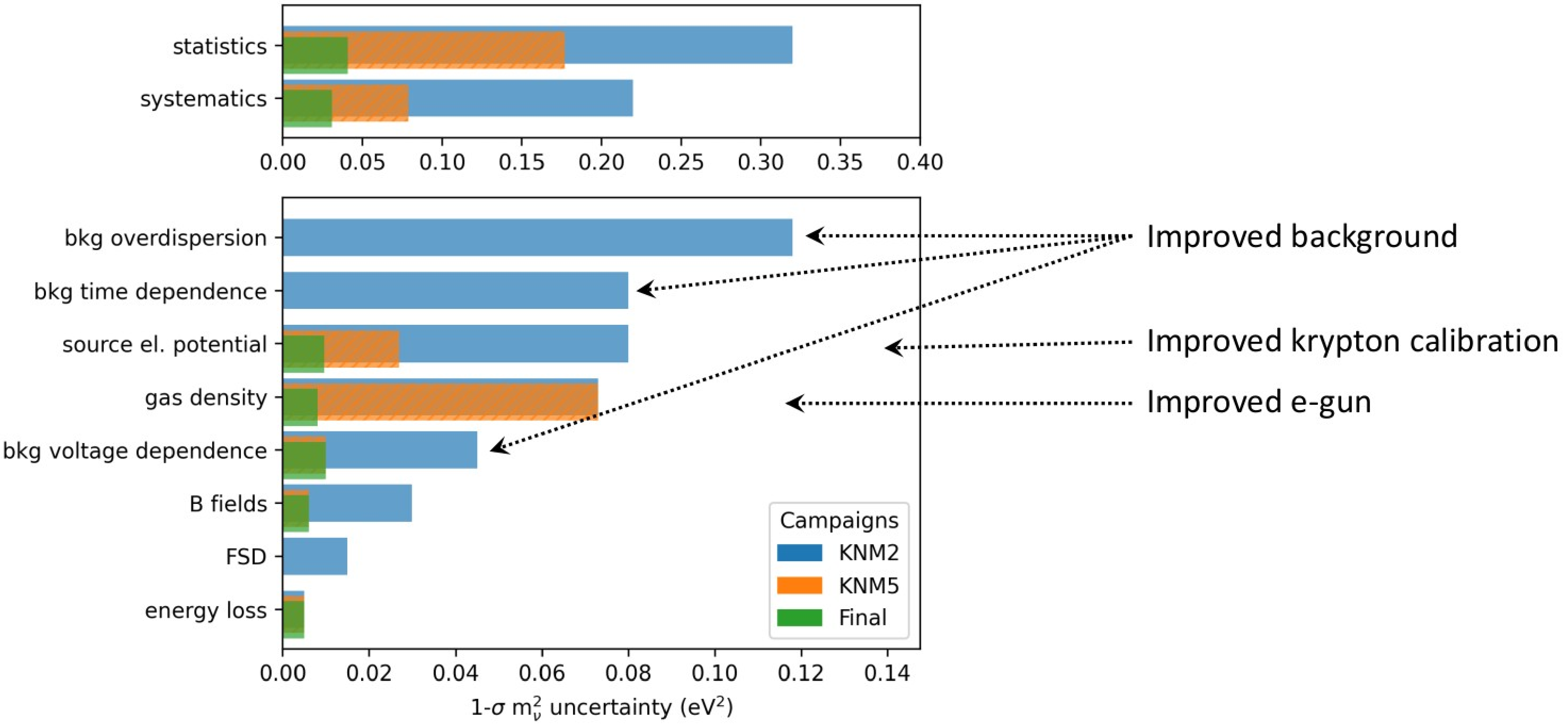




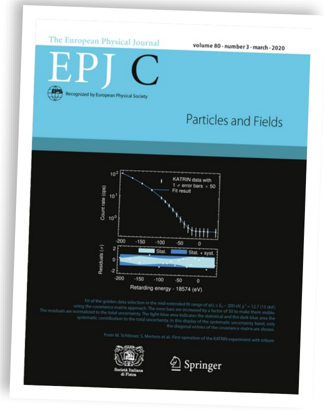
Phys. Part. Nucl. 46, 347–365

Phys. Rev. D 57, 3873–3889

Systematics

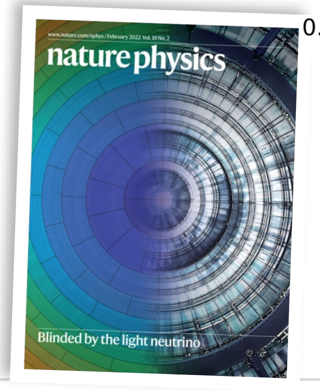


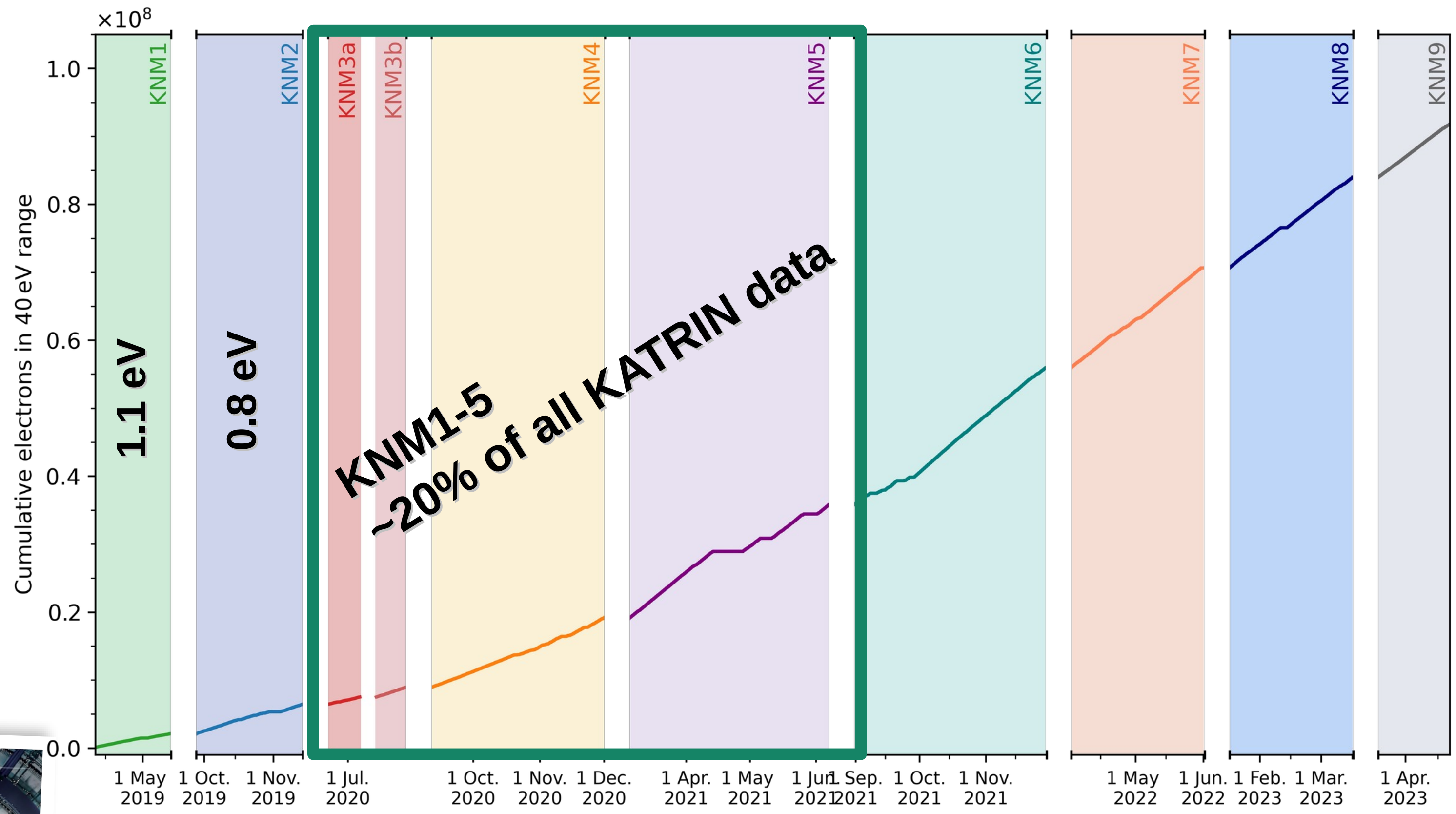
KATRIN Data taking



EPJ C 80, 264 (2020)

PRL 123 (2019) 221802
PRD 104 (2021) 012005





Analysis of 5 scientific runs → to be published soon

Statistical sensitivity ~ 0.5 eV (90% CL)

Nature Phys. 18 (2022) 160

New data

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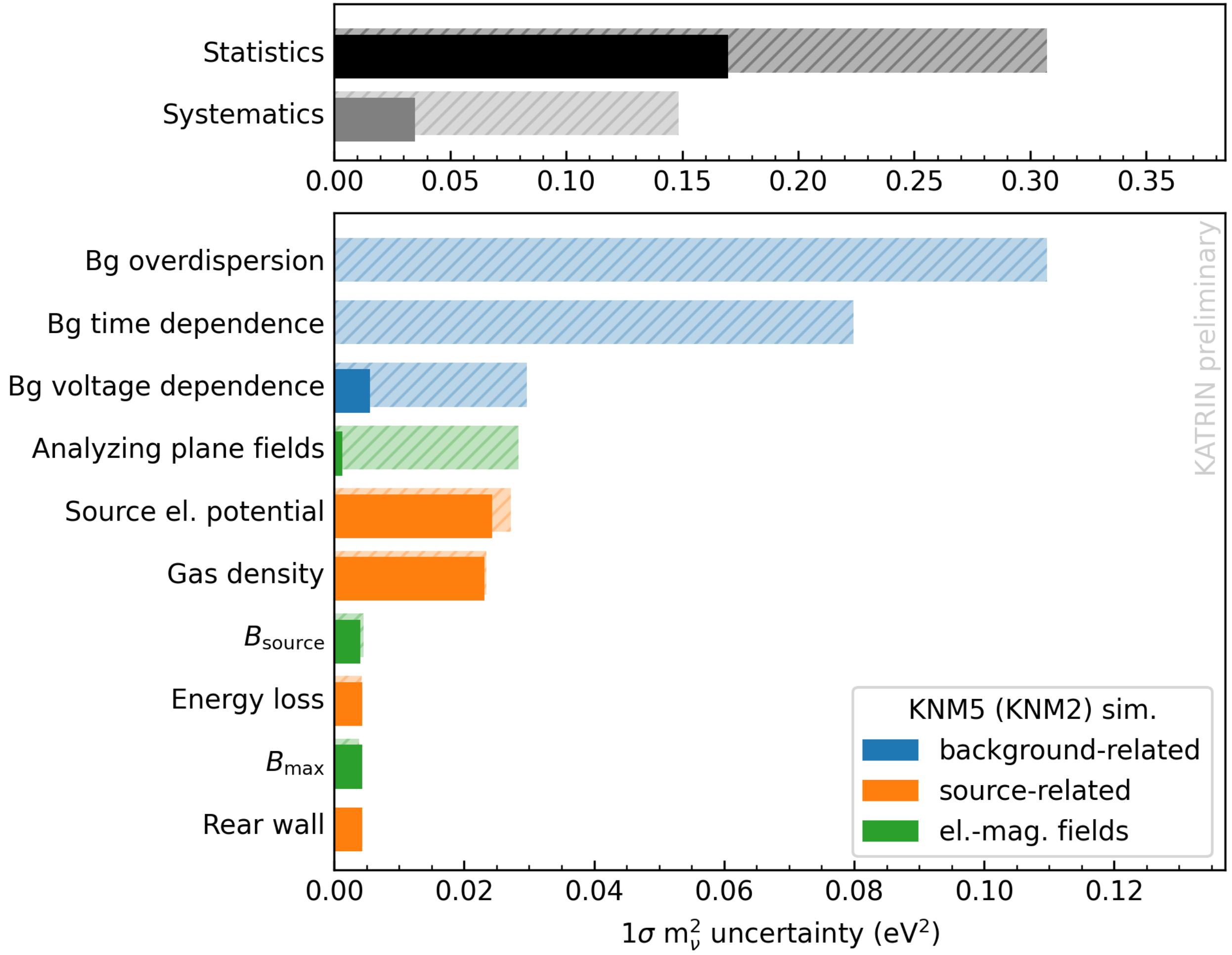
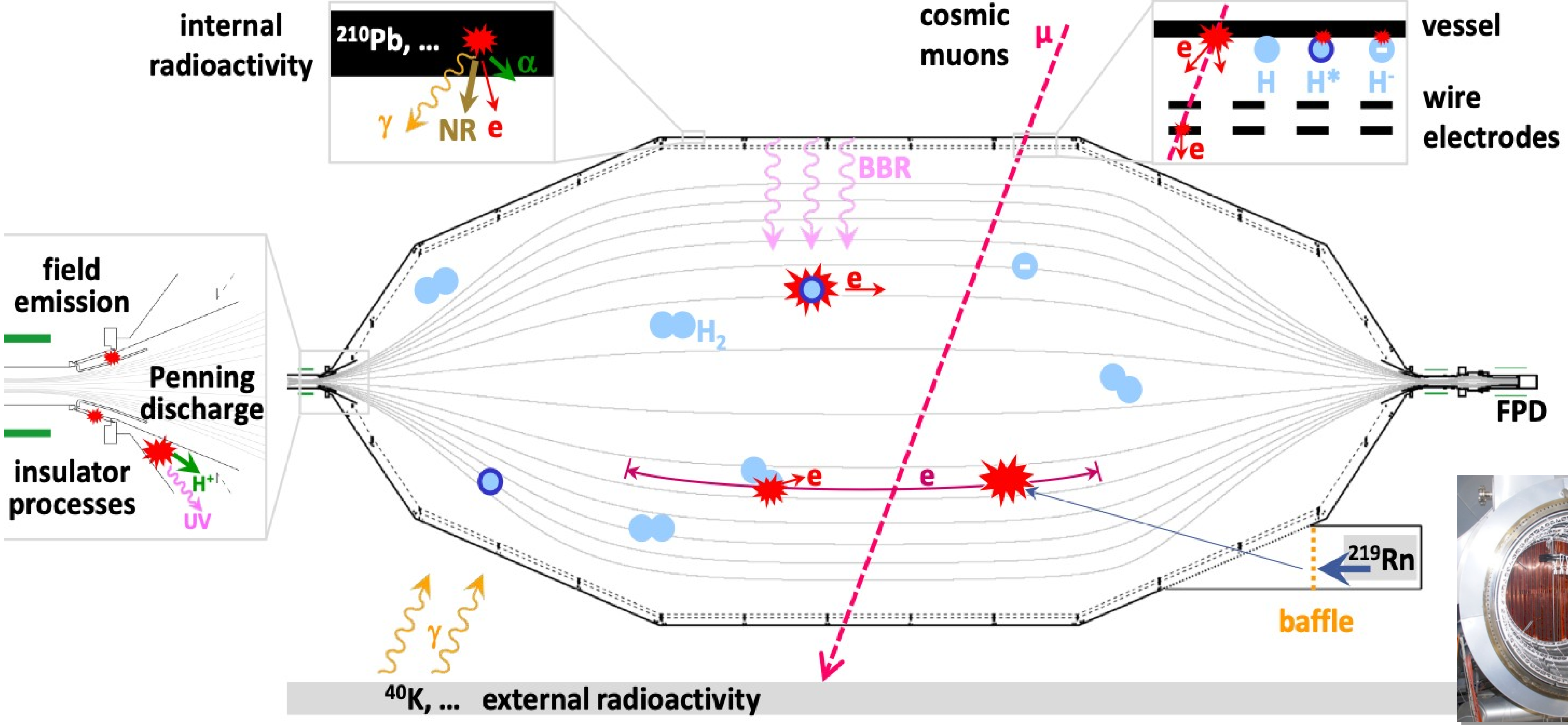
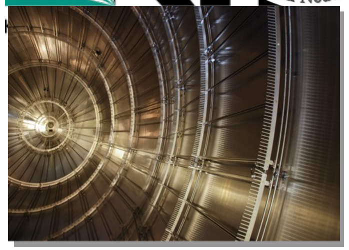
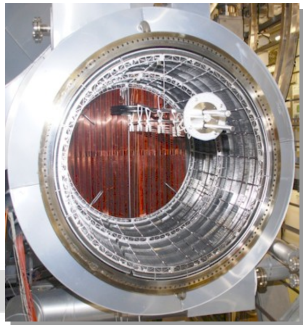
- More statistics and lower systematics



Challenge: Background





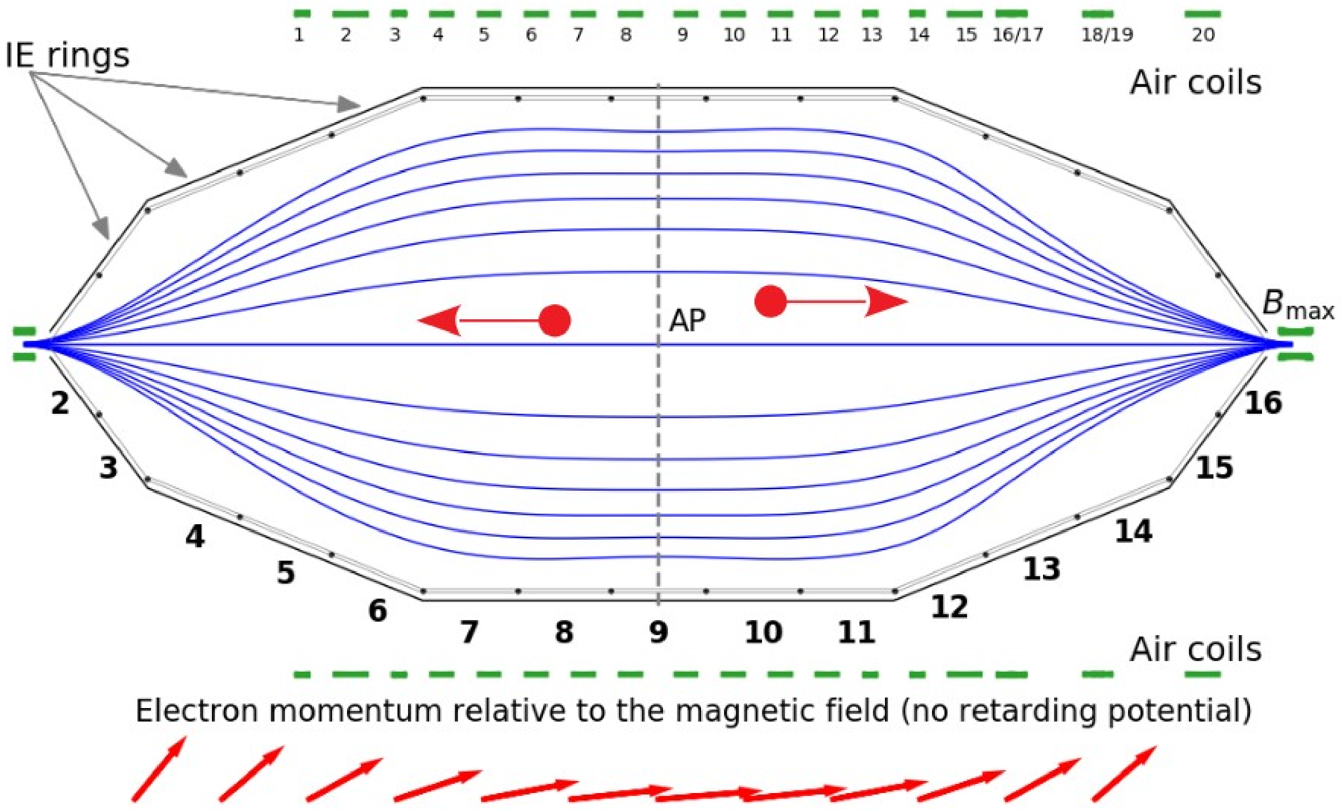


- **Various sources of backgrounds identified**

- **All but one known sources are supressed**

Background reduction

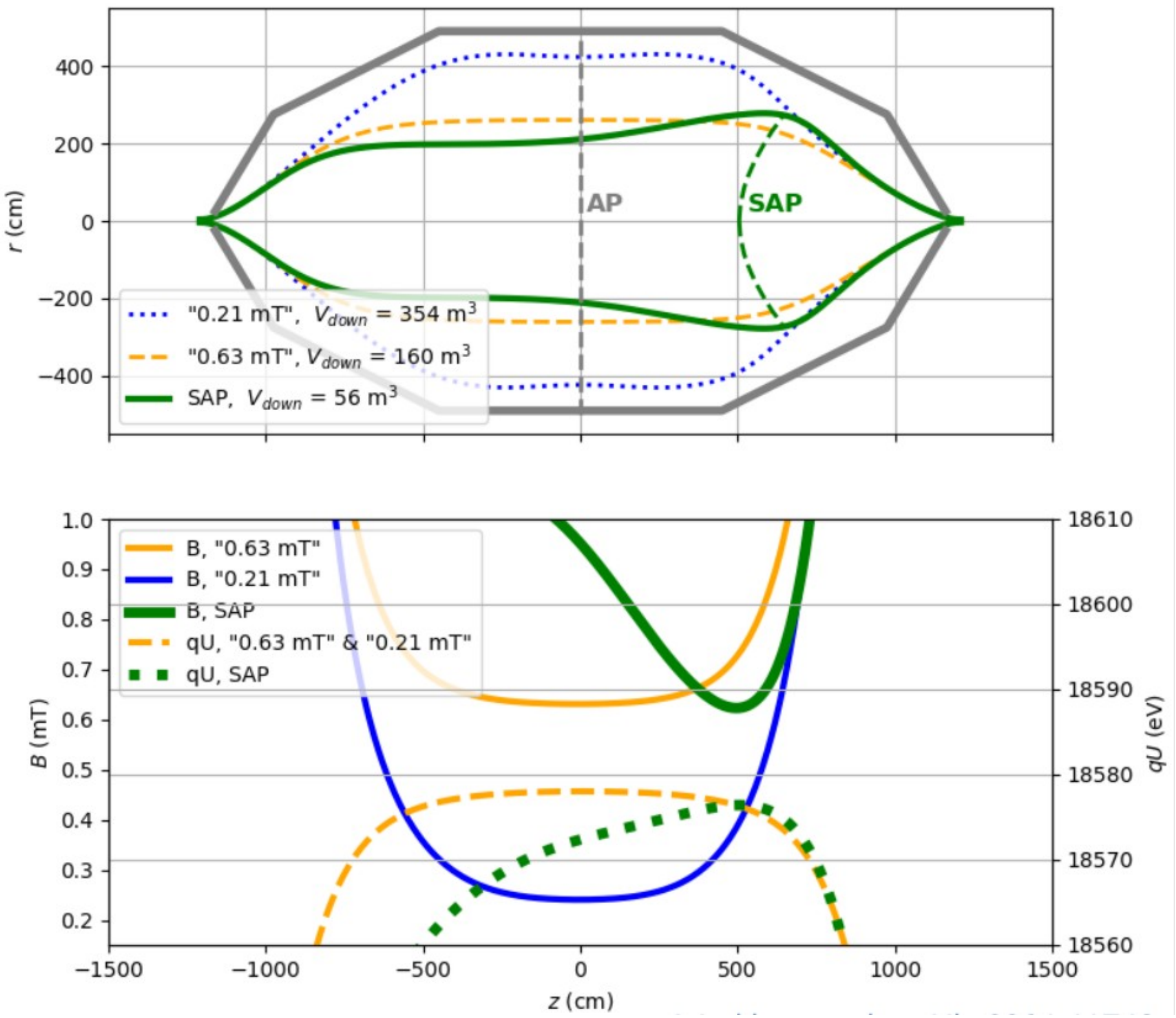
- Main component:
  - Highly excited (Rydberg) atoms
  - Uniformly distributed in the spectrometer
- Reducing volume –> reducing background
  - Shifted analysing plane mode



$$\Delta E = \frac{B_{\text{min}}}{B_{\text{max}}} \cdot E$$

Background reduction

- Main component:
  - Highly excited (Rydberg) atoms
  - Uniformly distributed in the spectrometer
- Reducing volume –> reducing background
  - **Shifted analysing plane** mode
- Factor 2 reduction of the background rate



Eur.Phys.J.C 82 (2022) 3, 258

Historical overview

2022:

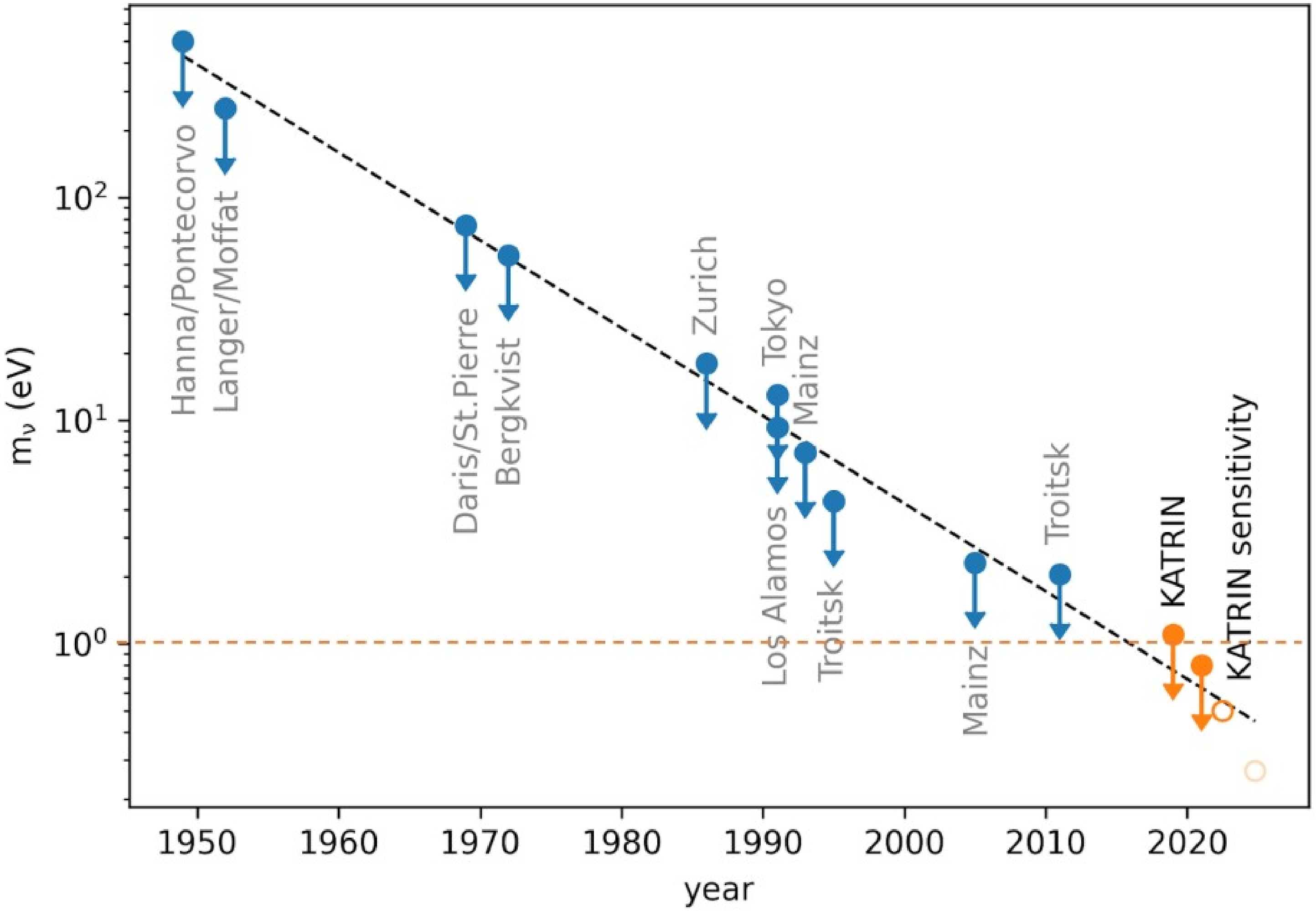
- first direct neutrino-mass experiment to reach sub-eV sensitivity and limit
- $m_\nu < 0.8$ eV (90% CL)
  KATRIN Collab. Nat. Phys. **18,** 160–166 (2022)

2023:

- Sensitivity: $m_\nu < 0.5$ eV (90% CL)

2025:

- Final goal: $m_\nu < 0.3$ eV (90% CL)



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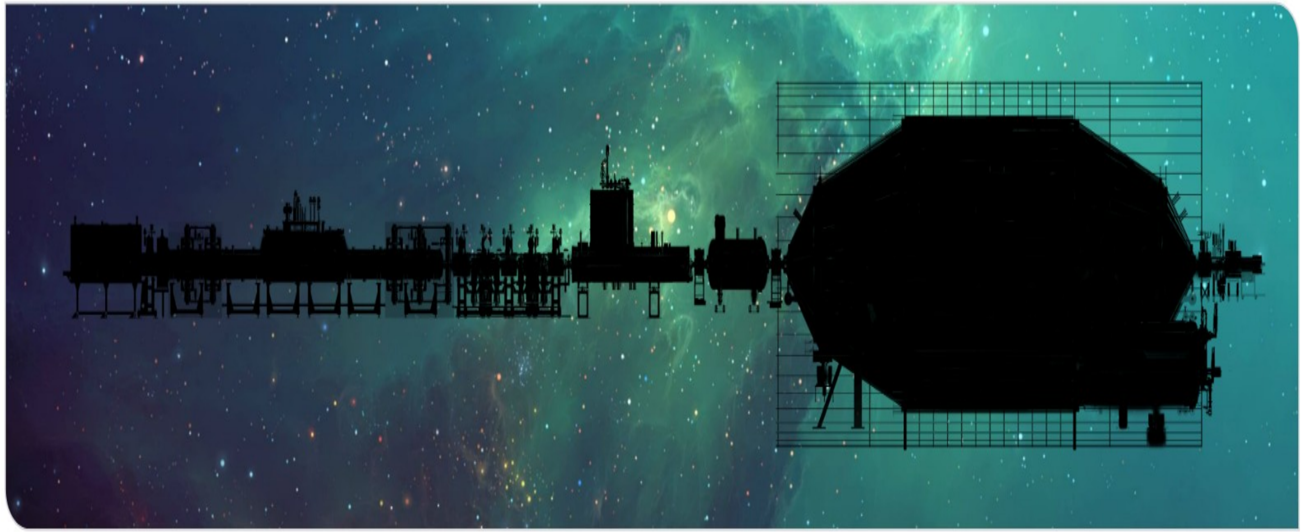
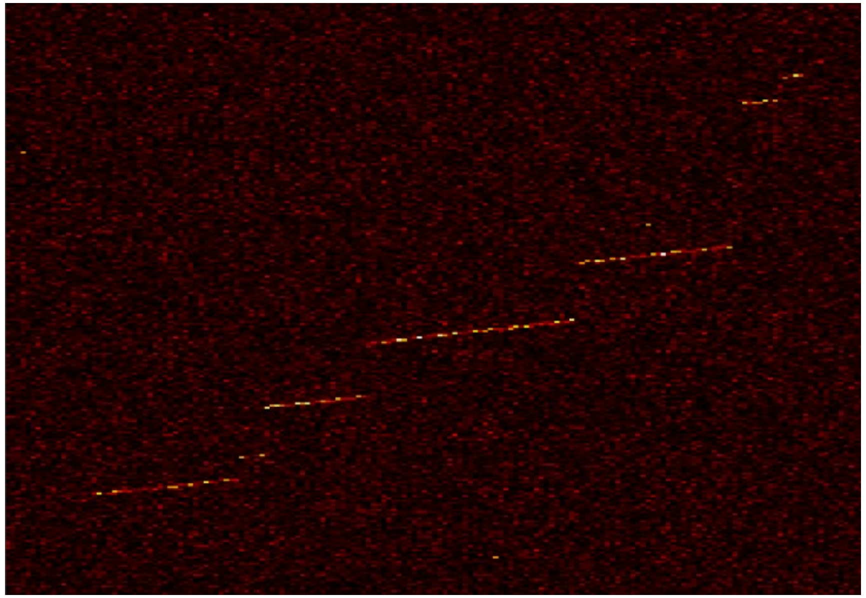
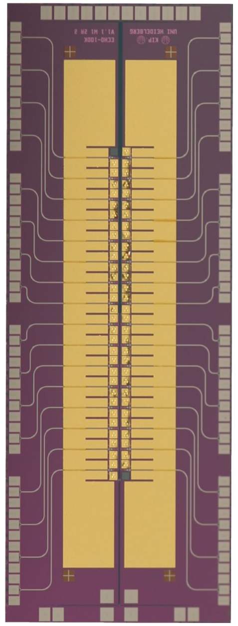
Neutrino mass determination – Part II

International School on Astroparticle Physics (ISAPP 2023) – Varenna, Italy

Alexey Lokhov







Outline

Karlsruher Institut für Technologie

What do we know so far about neutrino masses?

Neutrinos are massive

The squared mass differences are known

The absolute scale is unknown

What are the three approaches to neutrino mass?

Cosmology, $0\nu2\beta$-decay, direct searches

Complementary observables

Direct laboratory measurements – least model dependent

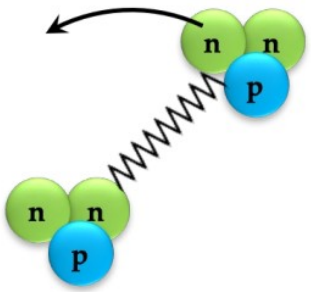
How to measure the mass without model dependencies?

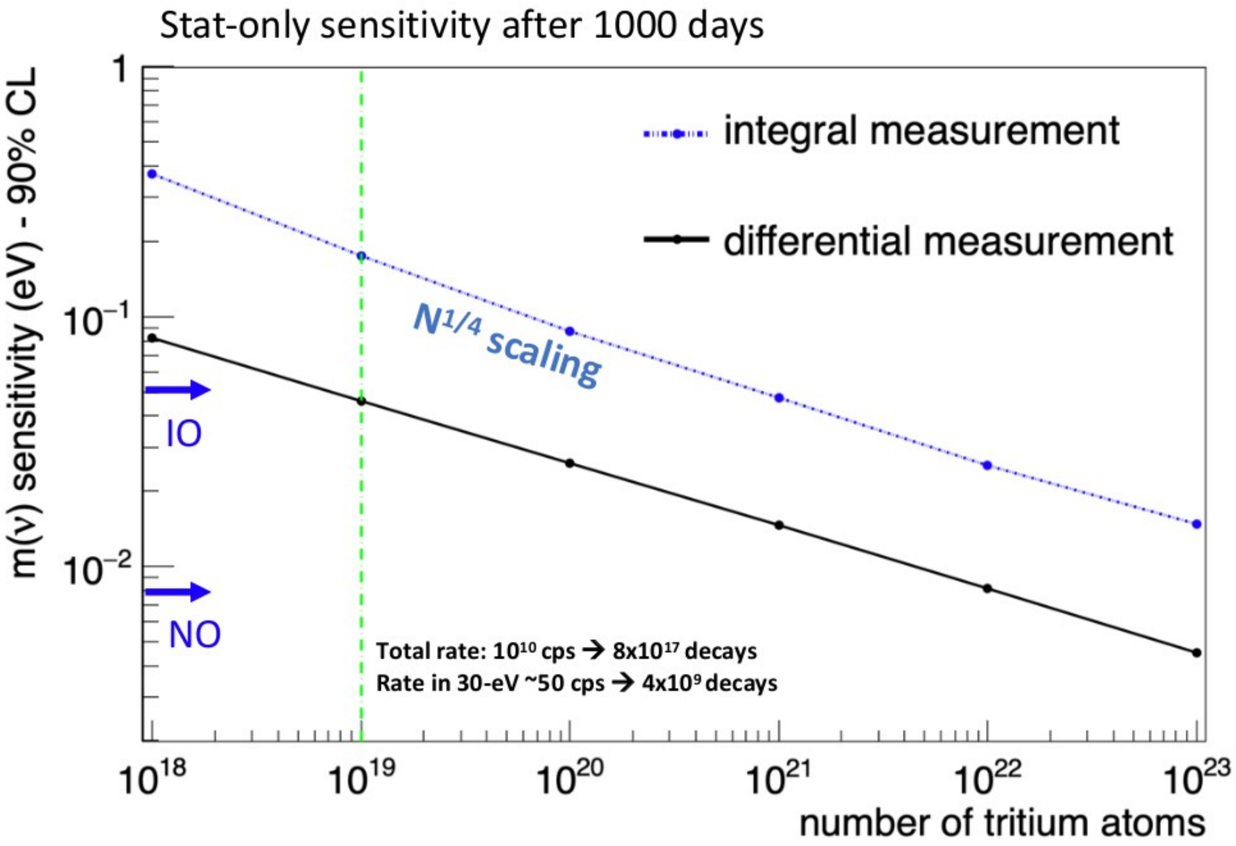
Current limit from KATRIN (MAC-E-Filter): <0.8 eV (90% CL)

What other physics can we probe in the direct mass measurements?

What type of limitations are there?

- Better statistics: more tritium
  - More scatterings → "Opaque" source
- "Different" tritium: atomic





- Differential measurement
  - Better use of statistics
  - Intrinsically less background