Neutrinos

Lecture 2

TRISEP 2024 Summer School

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Outline

Lecture 1:
Historical overview –
What we know

- Birth and discovery of neutrinos
- Neutrino sources
- Wu and Goldhaber experiment
- Solar neutrino problem
- Neutrino oscillations

Lecture 2:
What we would like to know

- Neutrino mass measurements
  - KATRIN
  - PROJECT 8
- Sterile neutrinos

Lecture 3
Neutrinos as messengers –
What we can learn from
studying neutrinos

- Neutrinos as messenger particles in astrophysics

Nuclear Stability

- For many nuclei, it is energetically favorable to decay to a lower energetic state with spontaneous emission of one or more particles.
- The nucleus is generally most stable for $Z \approx N$. For larger nuclei, more neutrons are required to compensate the Coulomb force between protons.
- For an excess of n or p, β decay occurs:
    - β^- decay: ${}^{A}Z \rightarrow {}^{A}(Z+1) + \beta^- + \bar{\nu}_e$
    - β^+ decay: ${}^{A}Z \rightarrow {}^{A}(Z-1) + \beta^+ + \nu_e$
    - EC: ${}^{A}Z + e^- \rightarrow {}^{A}(Z-1) + \nu_e$
- In heavy nuclei: α decay where ^{4}He is emitted from the nucleus
- Fission → break up of nucleus in two lighter nuclei
- Decay daughter not required to be stable!

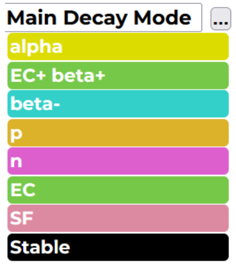
Table of Isotopes

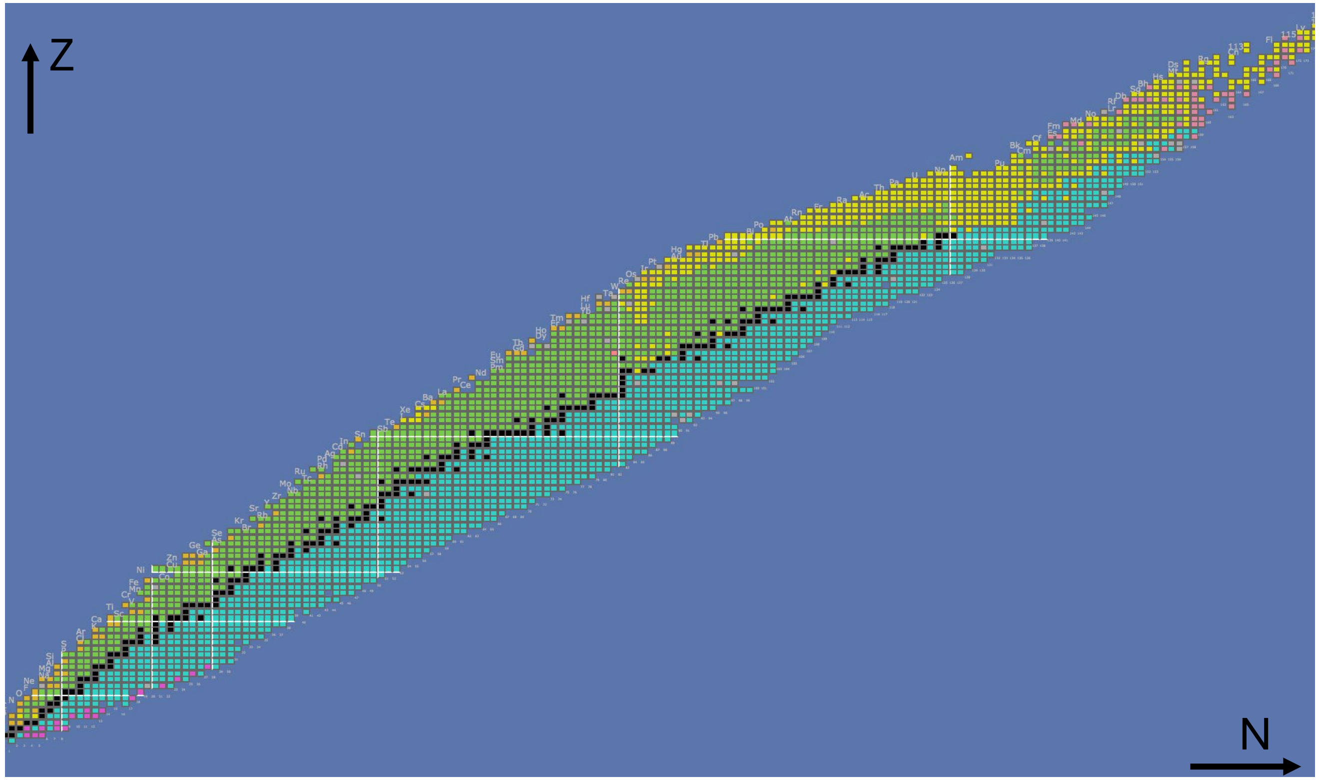
- Isotopes: same Z
- Isotones: same N
- Isobars: same A = N + Z

- 284 stable nuclei of 83 stable elements

- Common features:
    - Light nuclei: $Z \approx N$
    - Heavier nuclei: $Z < N$
    - Stable even Z and even N nuclei are more common than odd Z or odd N nuclei
    - Even-A nuclei are more common than odd-A nuclei
    - Only stable odd-odd nuclei are ^{2}H, ^{6}Li, ^{10}B, ^{14}N
    - Of the 20 elements that only have one stable isotope, only ^{9}Be has even-Z
    - Isotope with the most stable isotopes is $_{50}$Sn (10 stable isotopes)

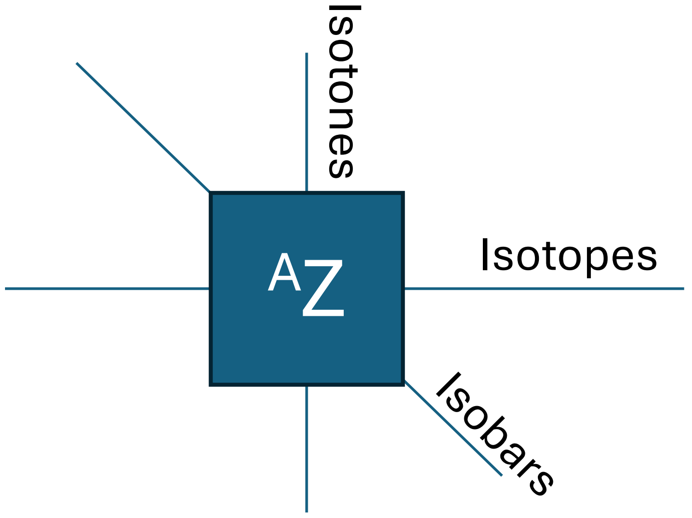
Magic nuclear numbers: 2, 8, 20, 28, 50, 82, and 126

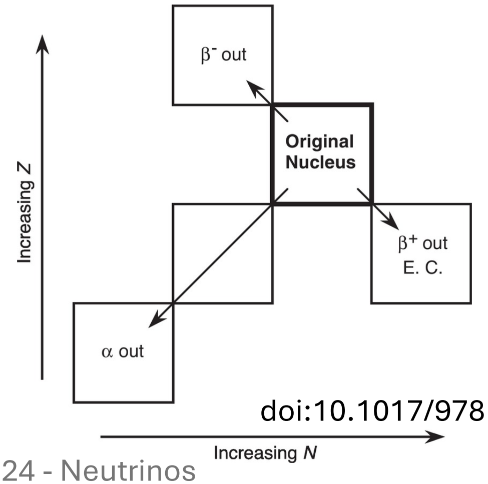




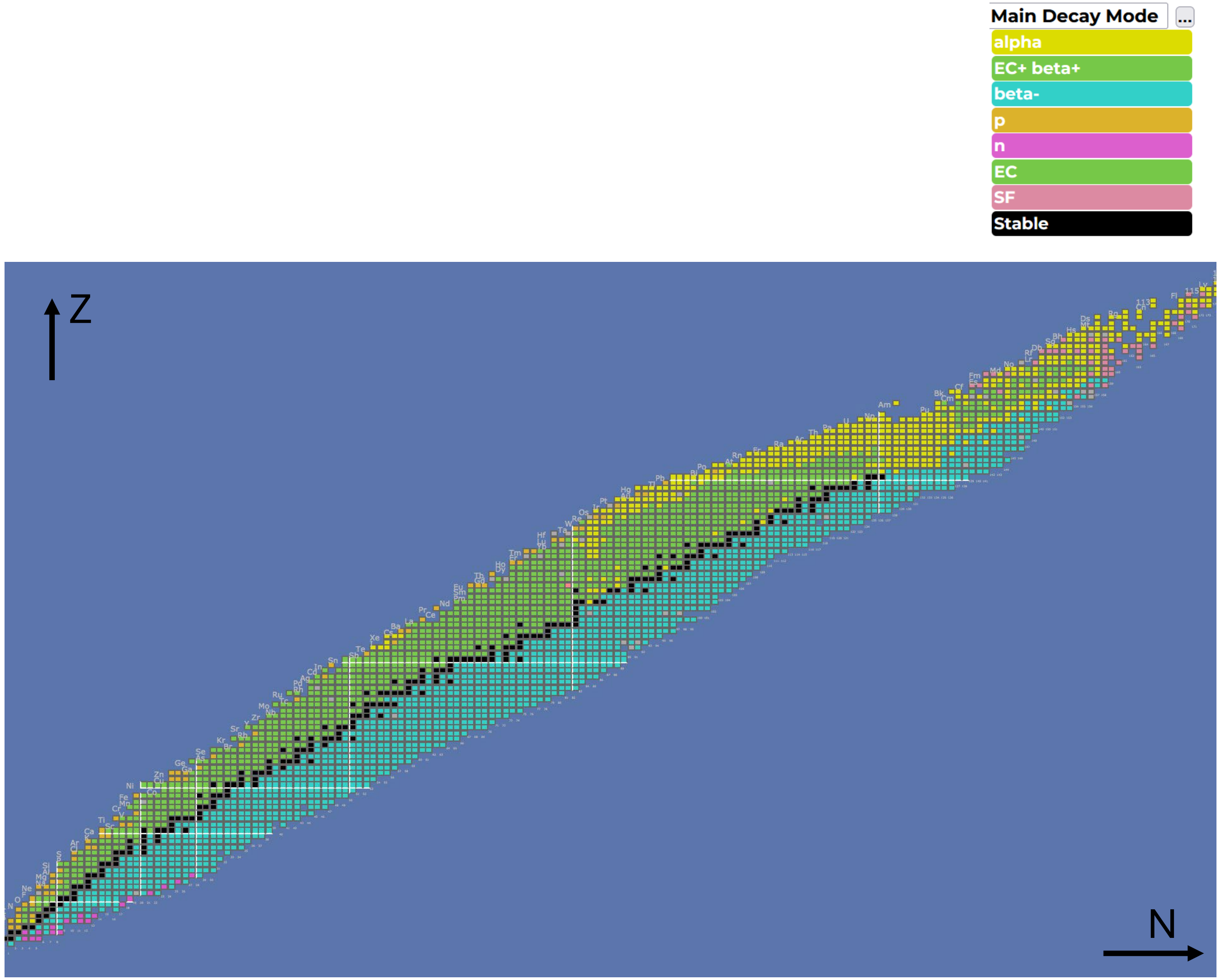
From: https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html
Also great: https://www.nndc.bnl.gov/

Table of Isotopes





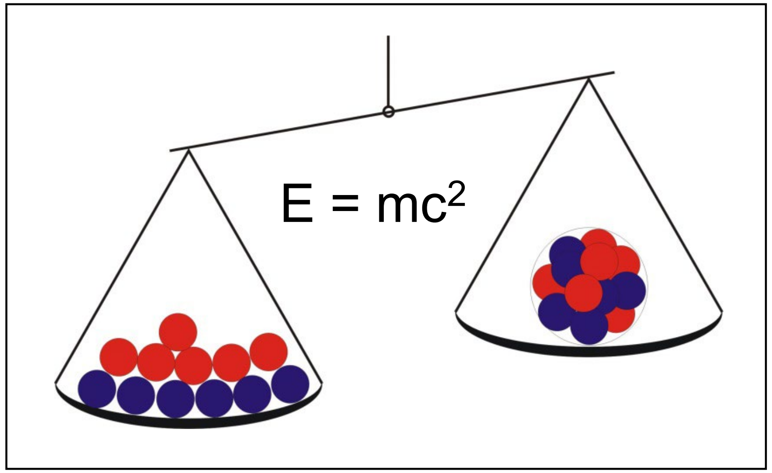
doi:10.1017/9781108885263.003



From: https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html
Also great: https://www.nndc.bnl.gov/

Mass and Binding Energy

The mass of an atomic nucleus reflects its binding energy and hence its stability and structure



Z Protons (Proton number)

N Neutrons (Neutron number)

A = N + Z (Mass number)

B: Binding energy

Q: Charge state

Nuclear mass $M(N, Z)\, c^2 = Z\cdot m_p\, c^2 + N\cdot m_n\, c^2 - B_{nucl}(N, Z)$

Atomic mass $M_{at}(N, Z)\, c^2 = Z\cdot m_p\, c^2 + N\cdot m_p\, c^2 + Z\cdot m_{el}\, c^2 - B_{nucl}(N, Z) - B_{el}(Z)$

Ionic mass $M_{ion}(N, Z)\, c^2 = Z\cdot m_p\, c^2 + N\cdot m_p\, c^2 + (Z-Q)\cdot m_{el}\, c^2 - B_{nucl}(N, Z)^2 - B_{el}(Q)/c^2$

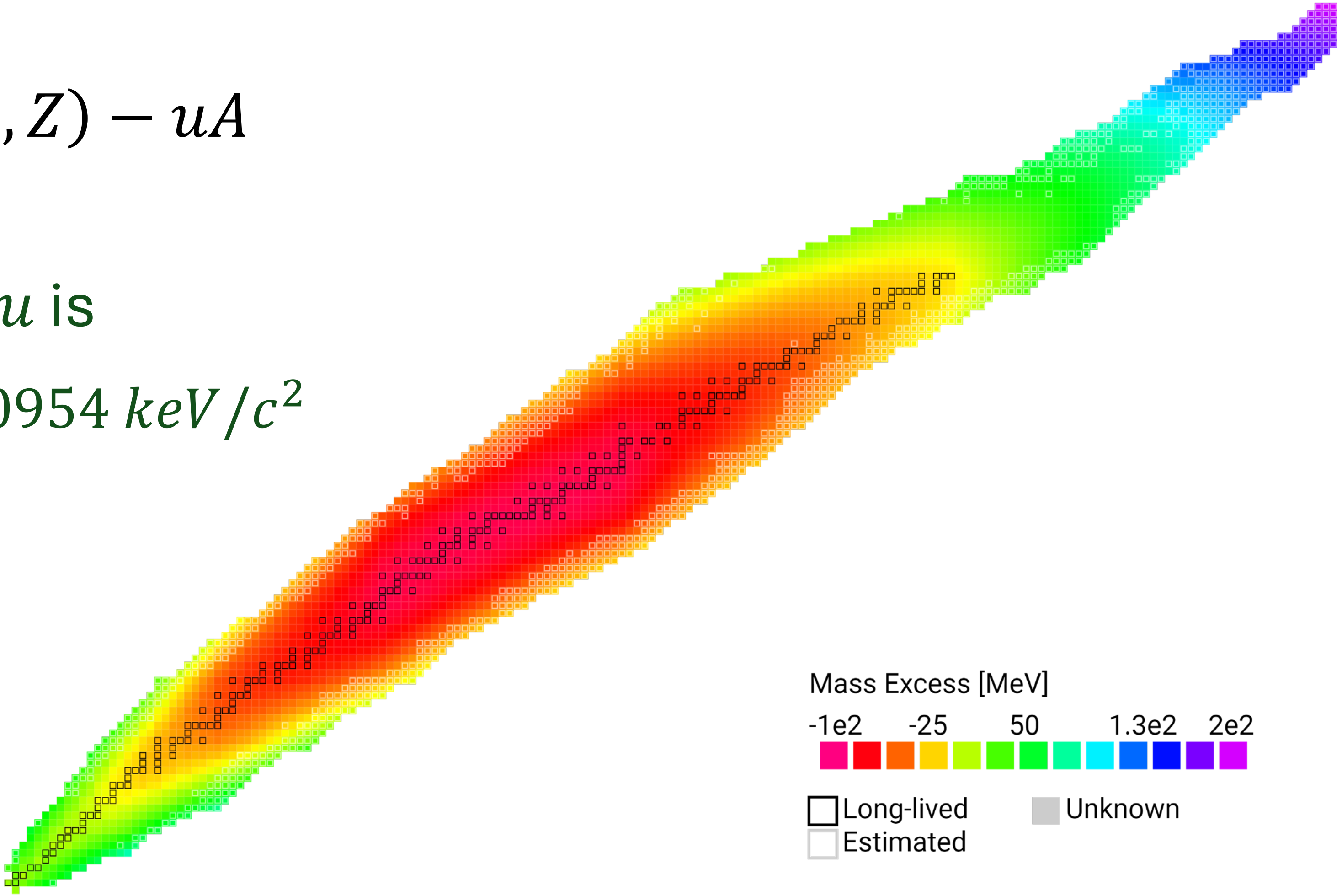
Slide courtesy of A. Kwiatkowski

Typically the mass excess (or defect) is used instead of the mass.

Mass excess $\Delta(N,Z) \equiv M(N,Z) - uA$

where the atomic mass unit u is

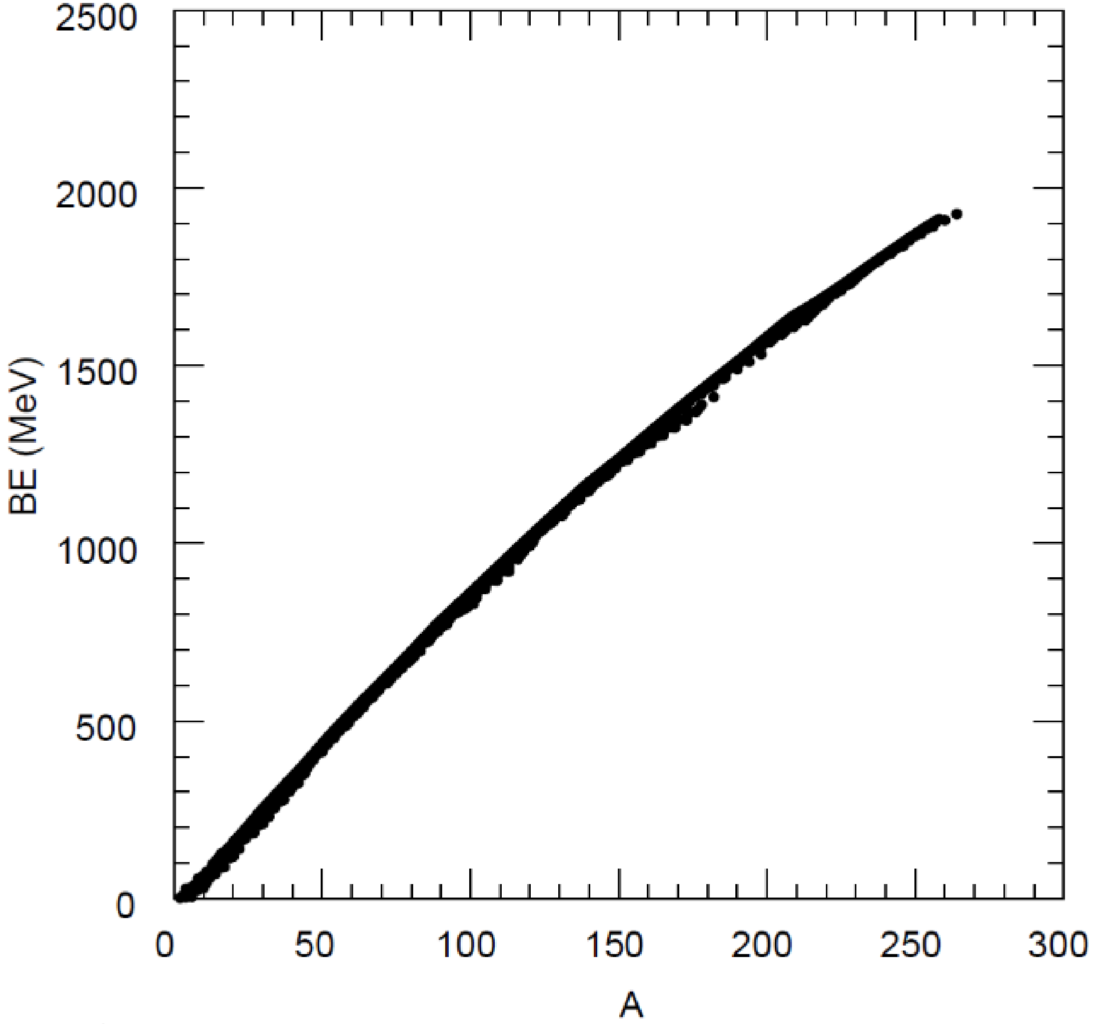
$$1\,u = {}^{M(^{12}C)}\!\big/_{12} = 931\,494.0954\ keV/c^2$$

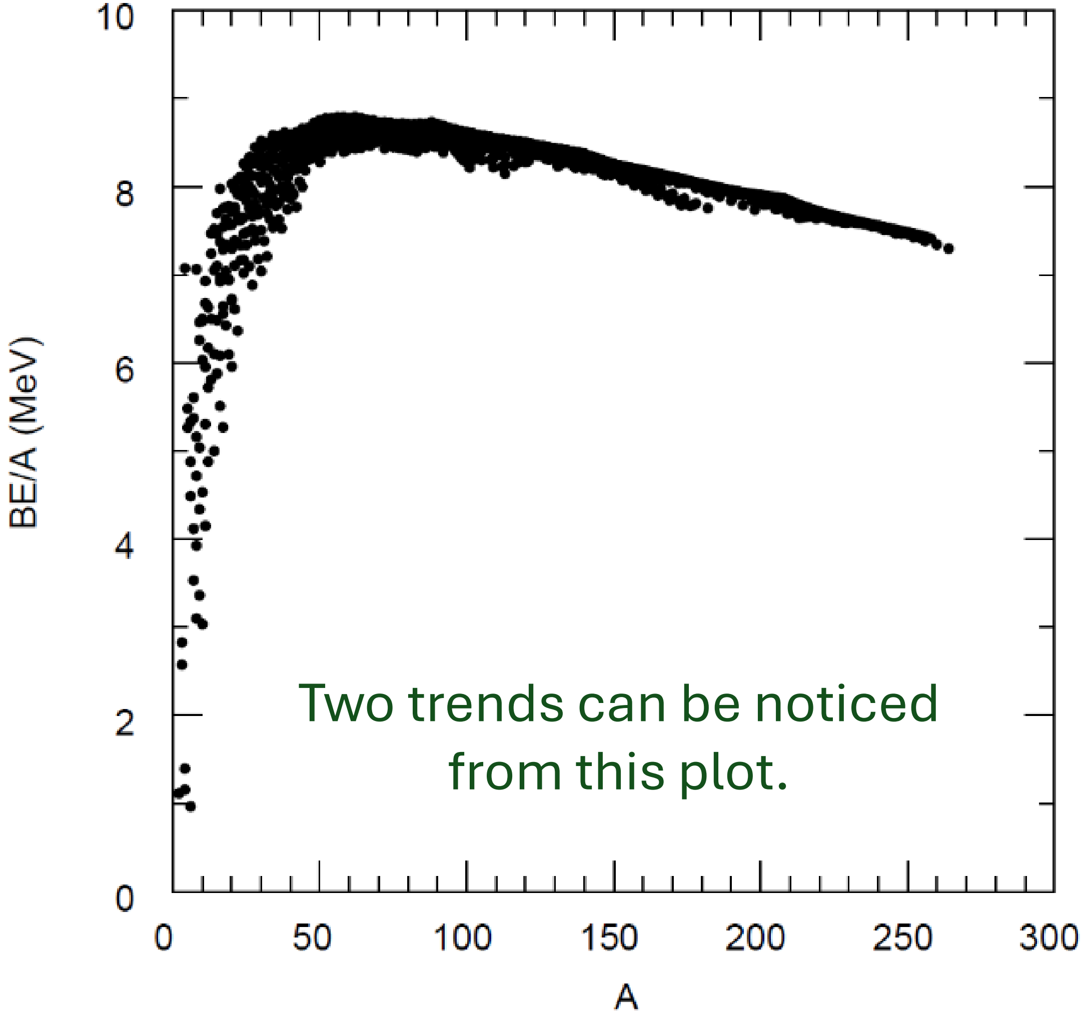


AME 2020, Chin. Phys. C 45 (2020) 030002, (https://www-nds.iaea.org/amdc/)

Slide courtesy of A. Kwiatkowski

We want to understand binding energy as a function of N & Z.





Two trends can be noticed from this plot.

Figures taken from B.A. Brown

Slide courtesy of A. Kwiatkowski

The achievable precision and accuracy depends on the measurement technique.

Indirect

- Decay measurements & kinematics

Direct

- Conventional mass spectrometry
- Time of flight
- Frequency based

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decays:

$A \rightarrow B + b$

$Q_a = M_A - M_B - m_b$

reactions:

$A(a,b)B$

$Q = M_A + M_a - M_B + M_b$

Slide courtesy of A. Kwiatkowski

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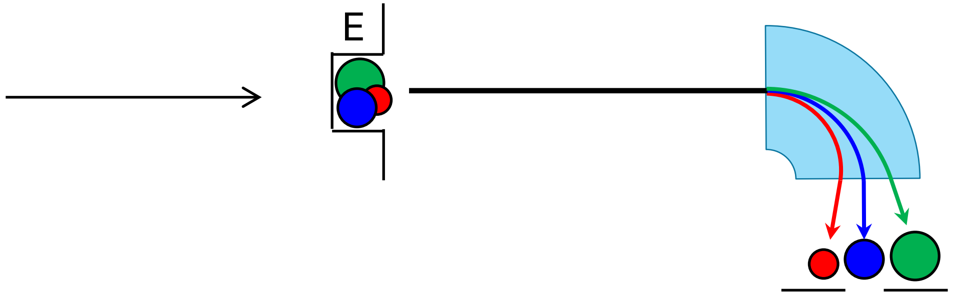
mass separator:
(spectrograph /
spectrometer)

dispersion
$D = \Delta x \cdot m/\Delta m$



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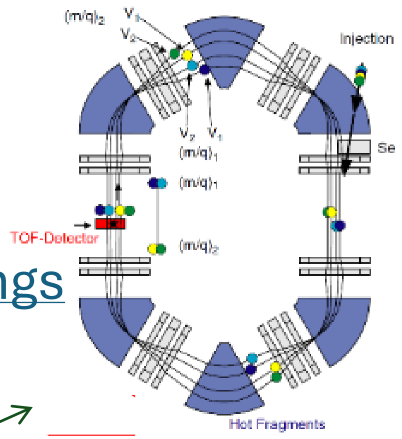
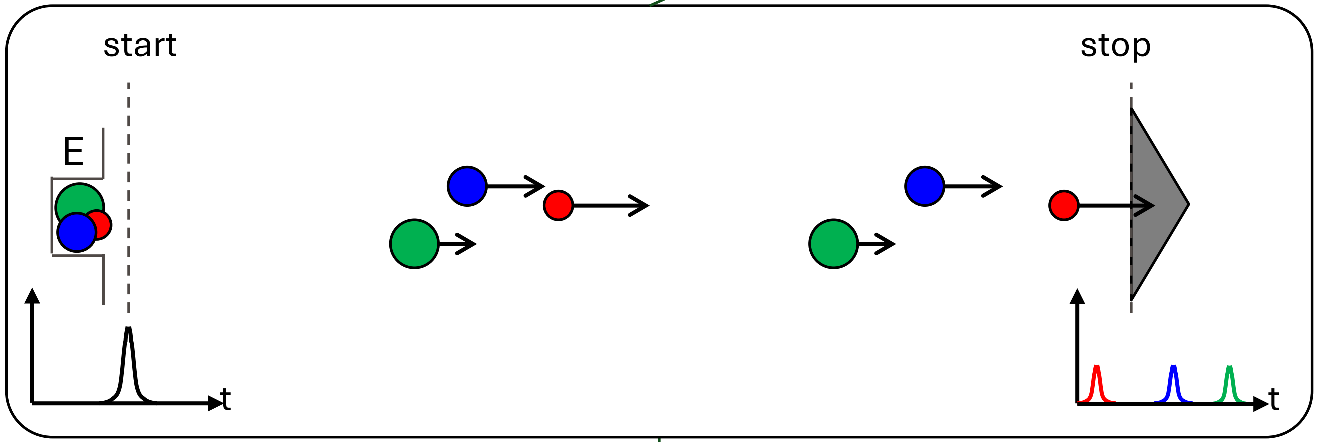


storage rings



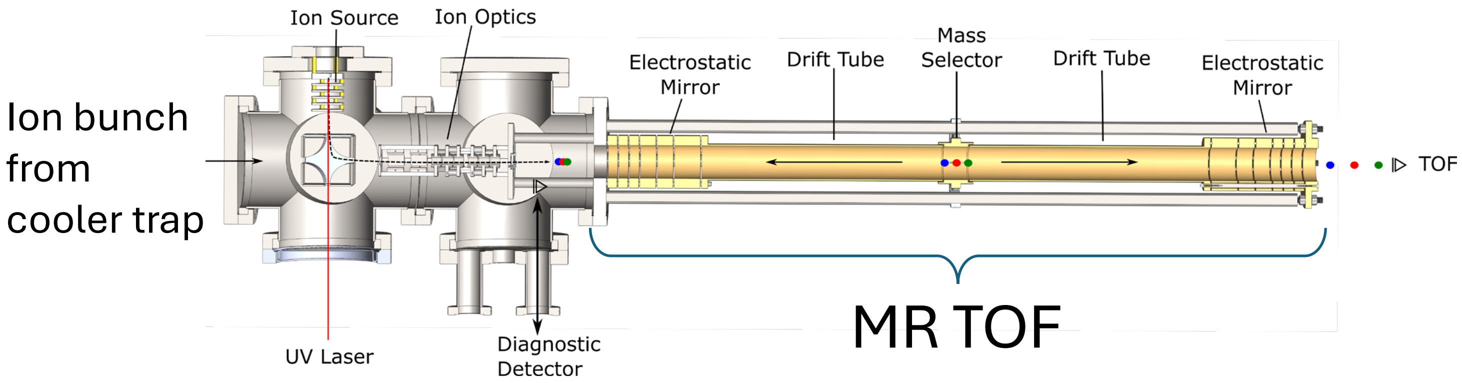
MR-TOF ion traps
multi pass

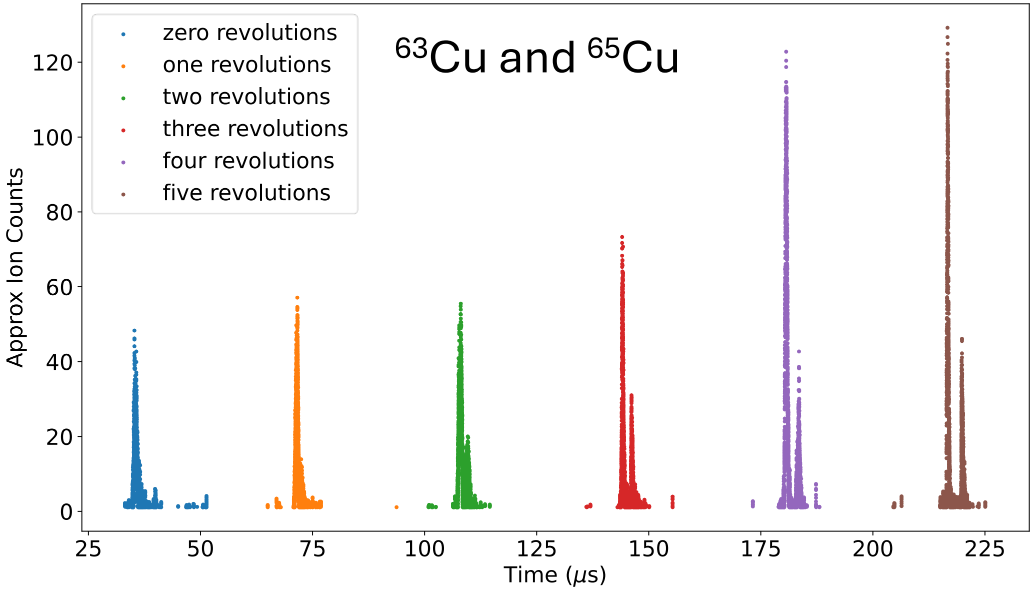
TOF: Z. Meisel & S. George, IJMS 349 (2013) 145;
ESR: F. Bosch, LNP 651 (2004) 137; MR-TOF: W. Plass, T. Dickel, C. Scheidenberger, IJMS IJMS 349 (2013), 134

The MRTOF

Operating Principle

- Ions accelerated by potential U gain kinetic energy $E_{kin} = z_i eU = mivi^2/2$
- Ions with different mass-to-charge separate in time, and can be resolved if $\Delta t_{ij} > \Delta t_i, \Delta t_j$
- Calculated with mass-resolving power (MRP), $R = m/\Delta m = t/(2\,\Delta t)$
- Current devices achieve R > 100,000
- For mass 64, R=100,000 results in Δm = 640 keV

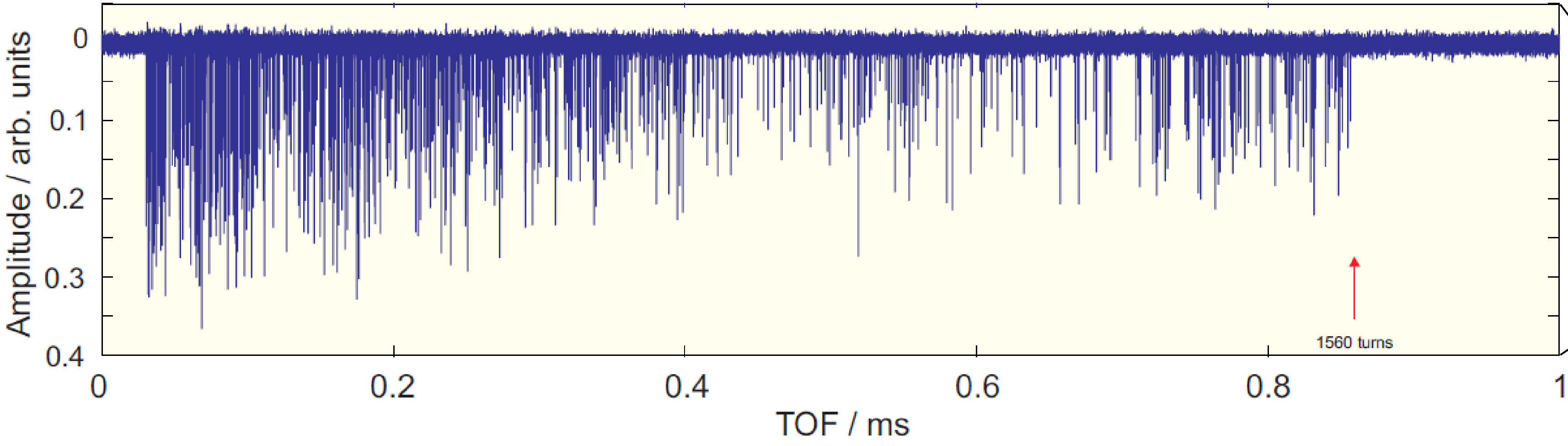


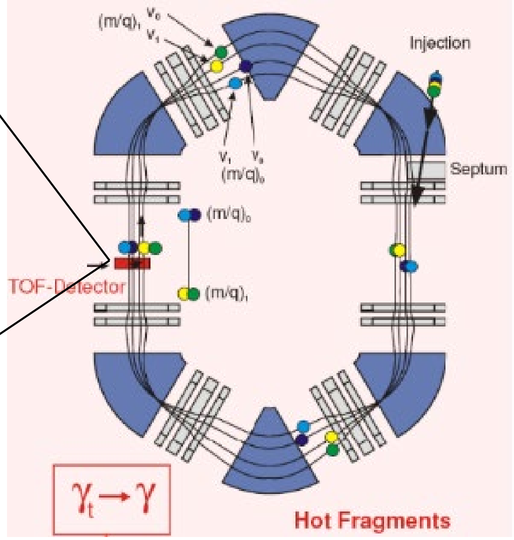


As revolutions increase, ToF peak splits!
Cu has two stable isotopes...

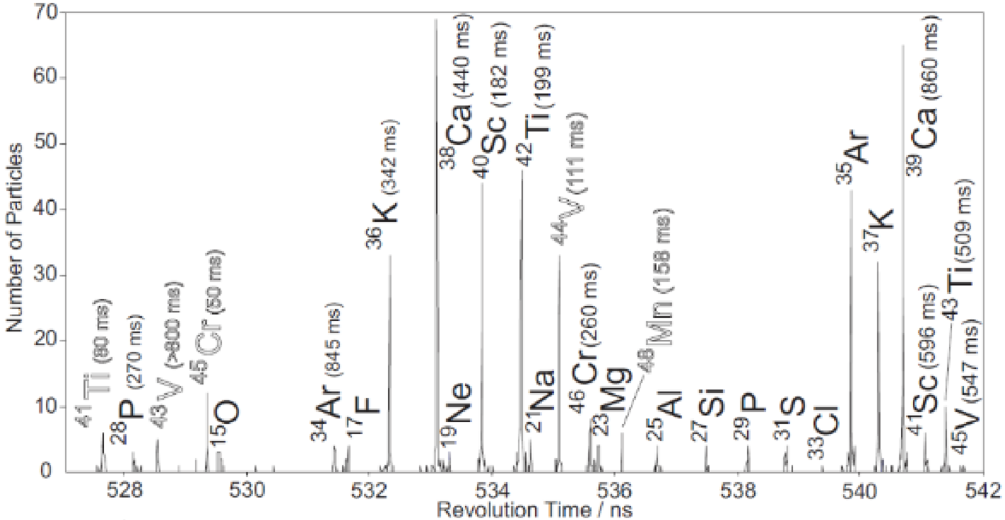
Slide courtesy of A. Kwiatkowski

Isochronous mass spectrometry is a time-of-flight measurement.





optics tuned to counteract beam divergence



δm ~ 100-300 keV

single-ion sensitivity

hundreds of ions simultaneously

$T_{1/2} \geq 10$ μs

Figures: F. Bosch, LNP 651 (2004) 137; K. Blaum, Phys. Rep. 425 (2006) 1

Slide courtesy of A. Kwiatkowski

The achievable precision and accuracy depends on the measurement technique.

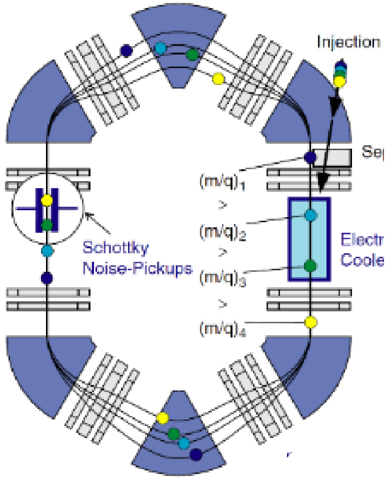
Indirect

- Decay measurements & kinematics

Direct

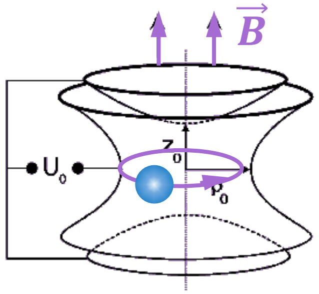
- Conventional mass spectrometry
- Time of flight
- Frequency based

storage rings



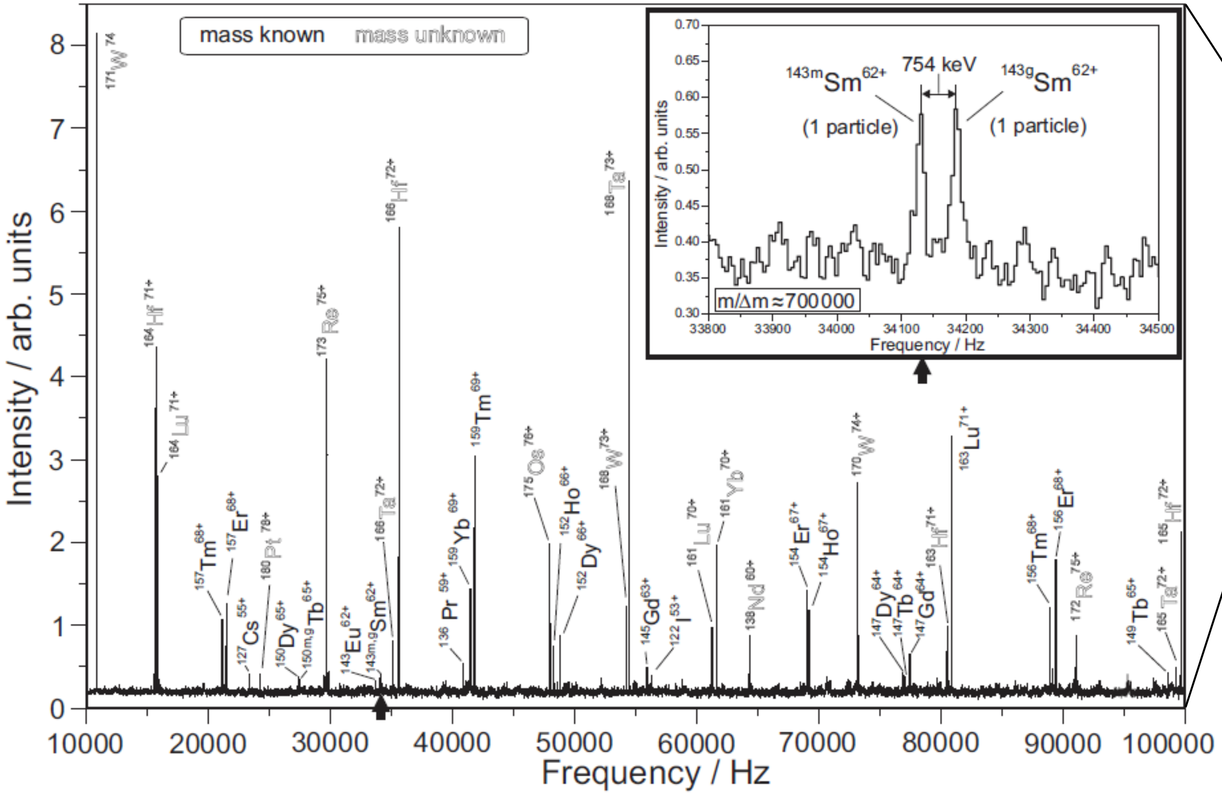
Penning traps

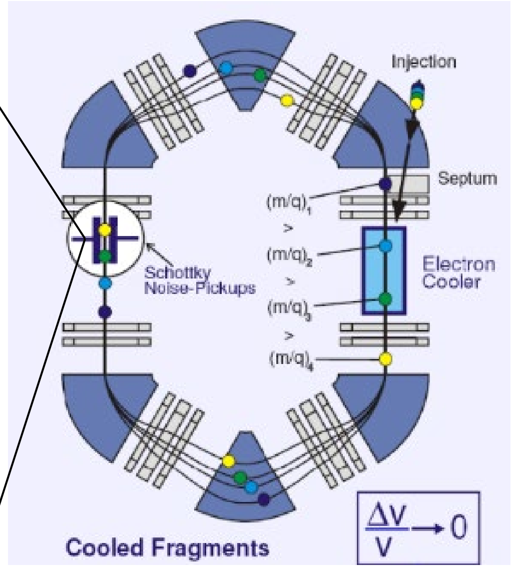
$$\omega_c = \frac{q}{m} \cdot B$$



Slide courtesy of A. Kwiatkowski

Schottky mass spectrometry is a frequency-based measurement.





beam cooled in electron cooler to “eliminate” beam divergence

signal induced in pair of plates & Fourier transformed

$\delta m \sim 10$ keV

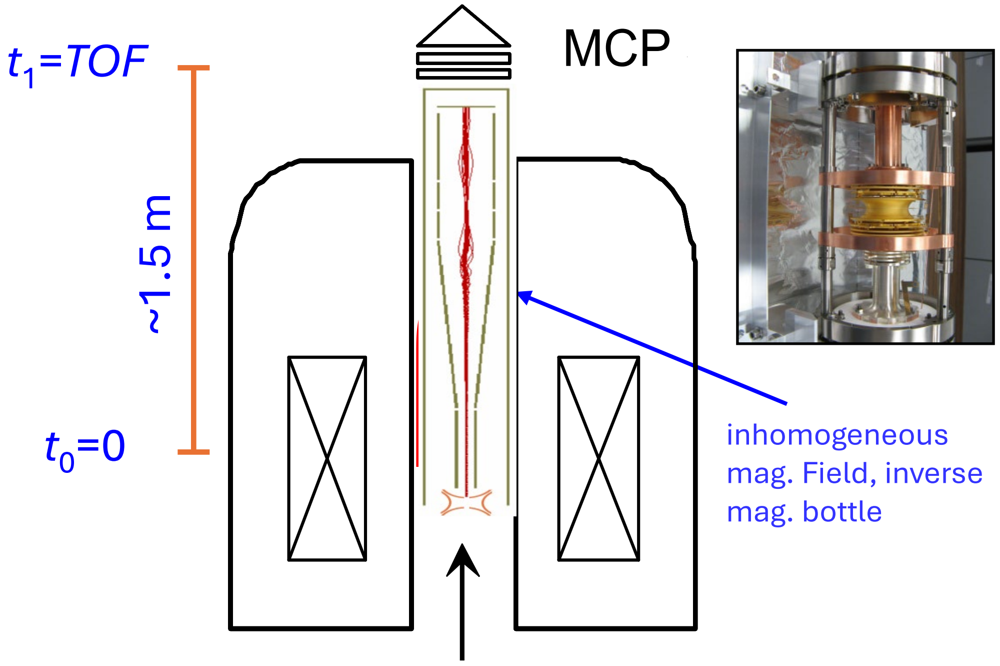
single-ion sensitivity

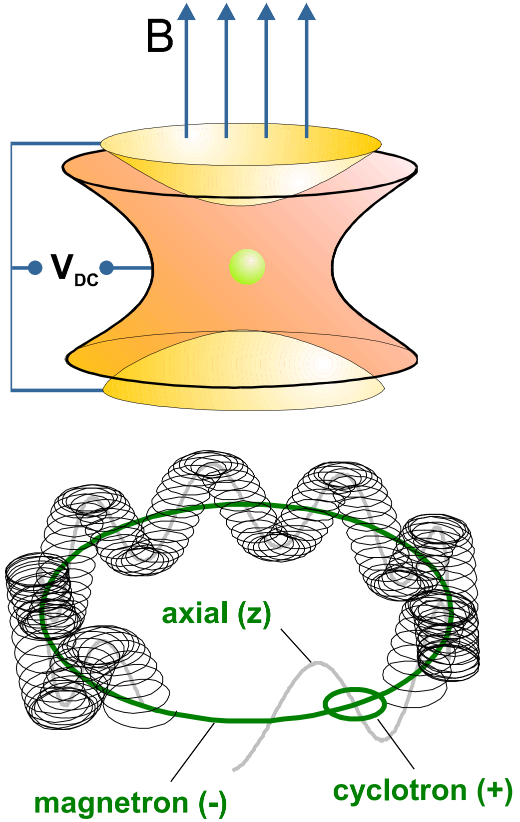
hundreds of ions simultaneously

$T_{1/2} \geq 1$ s due to cooling

Figures: F. Bosch, LNP 651 (2004) 137; K. Blaum, Phys. Rep. 425 (2006) 1

Mass measurement – Time of Flight method





Cyclotron frequency: $$\nu_c = \nu_+ + \nu_- = \frac{1}{2\pi}\frac{q}{m}B$$

$$\vec{F} = -\frac{E_r(\omega_{rf})}{B}\frac{\partial B(z)}{\partial z}\hat{z}$$

Determine atom mass from frequency ratio with a well known reference

Time-of-flight cyclotron resonance detection → suited for radioactive isotopes
Experiment is carried out with one ion in the trap!

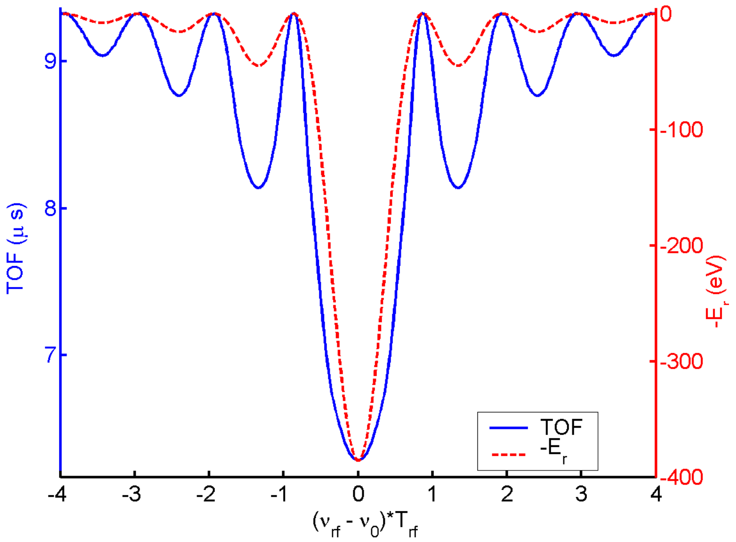
Mass measurement – Time of Flight method

Ions in the trap are

- exposed to an rf-excitation ω_{rf} of duration T_{rf}
- accelerated by the magnetic field gradient:
- stopped by an MCP detector, TOF is recorded
- Comparison to well known isotope

$$\vec{F} = -\frac{E_r(\omega_{rf})}{B}\frac{\partial B(z)}{\partial z}\hat{z}$$

Large E_r = shorter TOF



Resolution:

$$\frac{\delta m}{m} \propto \frac{m}{q}\frac{1}{BTN^{1/2}}$$

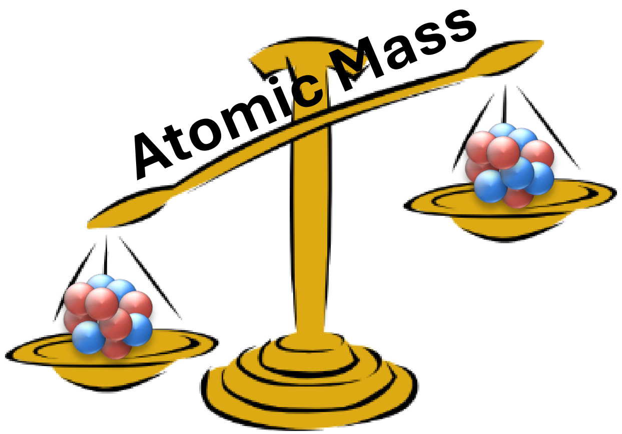
$\Rightarrow$ longer excitation time
$\Rightarrow$ larger B
$\Rightarrow$ more ions
$\Rightarrow$ highly charged ions

The mass is found by a scan of ω_{rf} around the resonance:

$$\omega_{rf} = \omega_c = \frac{qB}{m}$$

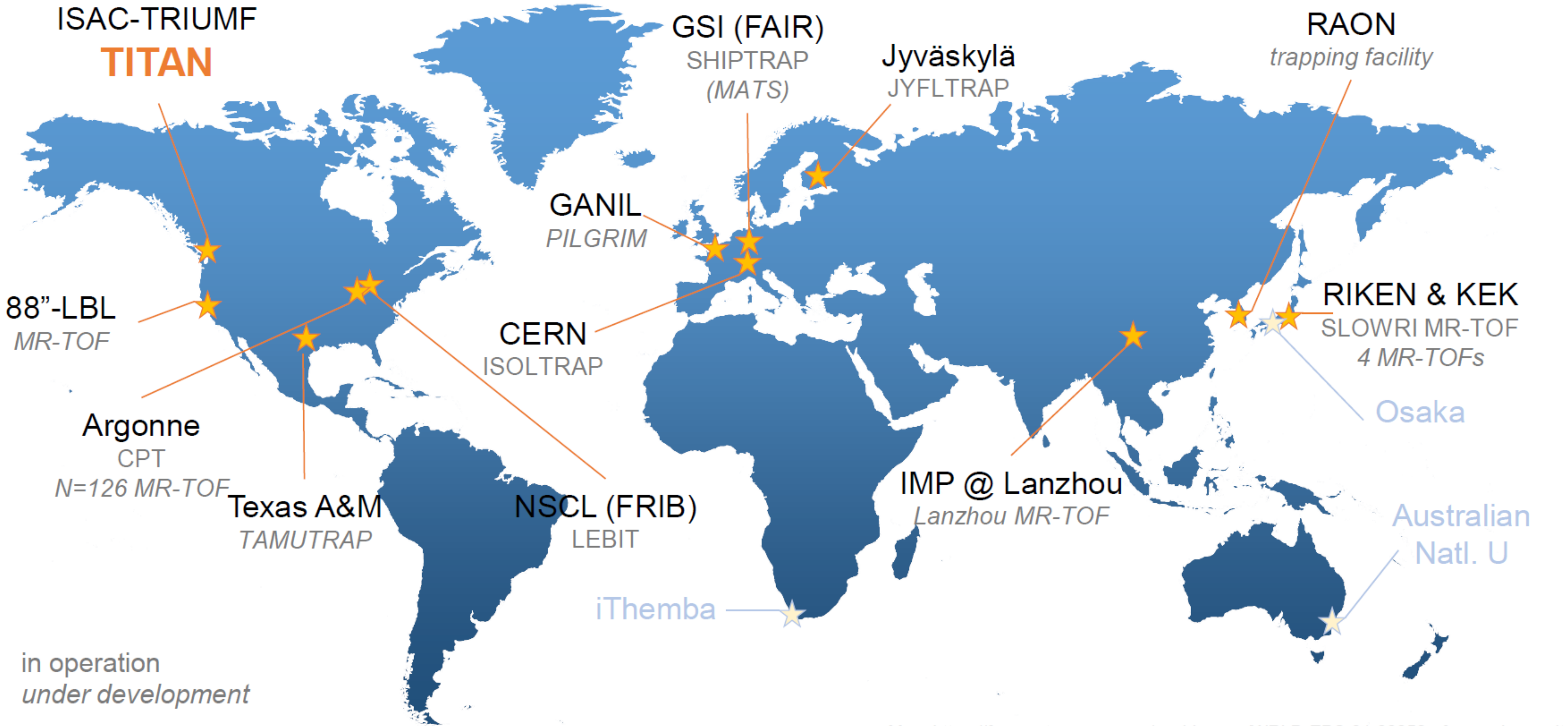
- Penning trap TOF method achieves $\delta m/m \sim 10^{-(8\text{-}9)}$
- Specialized Penning traps achieve better resolution

Precision required determines on the application



Field	**$\delta m/m$**
Chemistry: ID molecules	10^{-5}-10^{-6}
Nuclear structure: shells	10^{-6}
Nuclear fine structure: halos	10^{-7}-10^{-8}
Astrophysics: r-process	10^{-7}
Nuclear predictions: IMME	10^{-7}-10^{-8}
Weak interaction: CVC, CKM	10^{-8}
Atomic physics: B_e, QED	10^{-9}-10^{-11}
Metrology: CPT	$\leq 10^{-11}$

You can submit proposals for nuclear physics measurements, too!



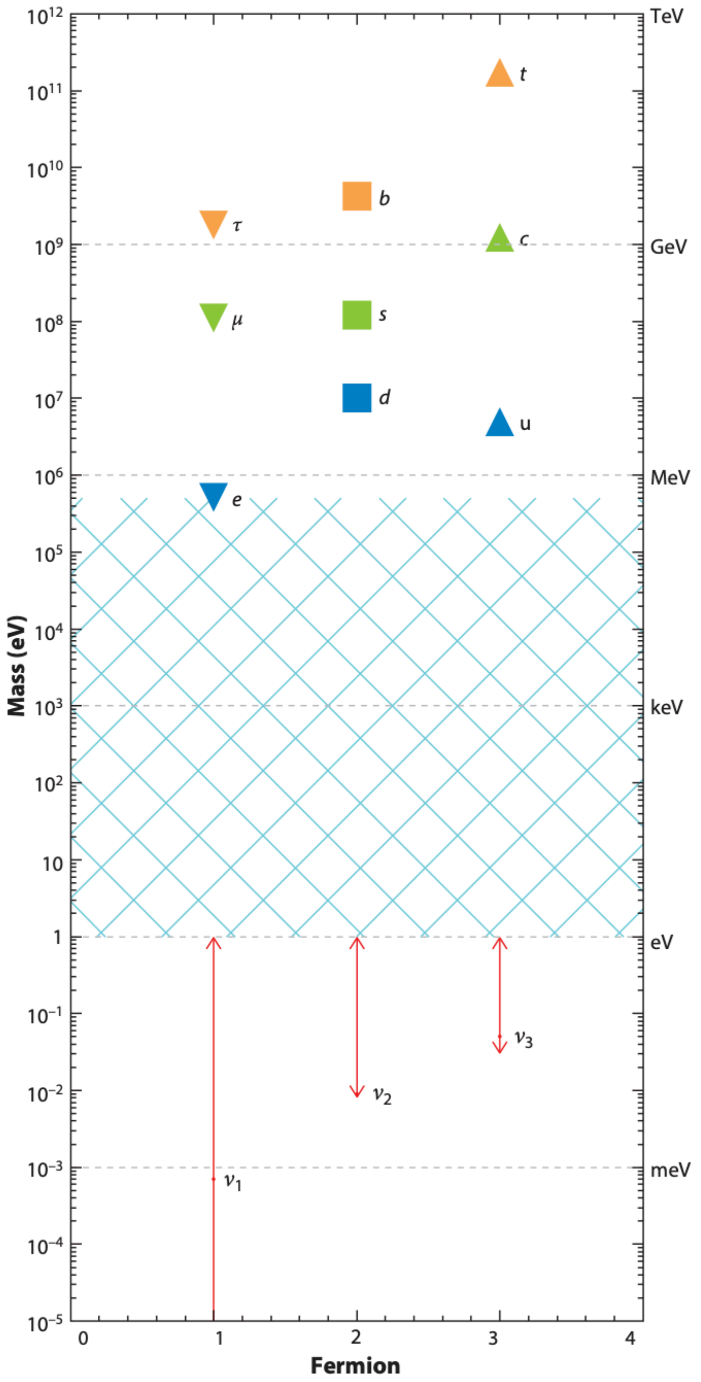
Map: https://freevectormaps.com/world-maps/WRLD-EPS-01-0005?ref=search_result

Neutrino mass

- Oscillation experiments prove neutrinos have mass
- However, they do not provide any explanation for the origin of this mass
  - In particular, why the masses are so much smaller than the charged leptons
- There are basically 3 possibilities:
  - Neutrinos get their masses through the Higgs mechanism, but their couplings are very weak (***Dirac neutrinos***)
  - There is another mass scale, which suppresses the masses of the light neutrinos (***Majorana neutrinos*** with “see-saw”)
  - Neutrinos couple to a different Higgs boson than the charged fermions (typically also ***Majorana neutrinos***)

- Further discussion of these possibilities is at:

  https://arxiv.org/pdf/hep-ph/0211134.pdf



https://www.annualreviews.org/doi/pdf/10.1146/annurev-nucl-102115-044600

Neutrino mass

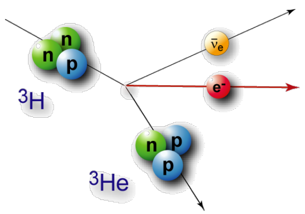
- How would you devise an experiment to measure the neutrino mass?

Measuring Neutrino Masses

Direct measurement ← → Indirect measurements

Kinematic measurement

$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i}$$

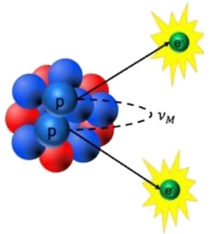


- Muon and tau decay
- Direct measurement m of ν_e from β endpoint
- Upper limit from beta decay: 0.8 eV [Nature 2022]
- KATRIN, Project8, ECHo, HOLMES

Effective ββ mass

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}{}^2 m_i \right|$$

virtual ν exchange

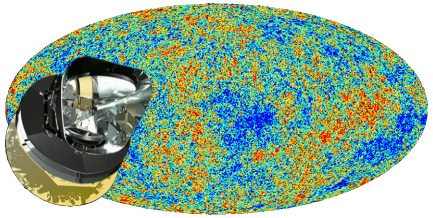


- Majorana nature
- Upper limit: ~0.05 – 0.2 eV
- GERDA, KamLAND-ZEN, MAJORANA, LEGEND, nEXO, CUORE, CUPID, NEXT, …

Model dependent

Observational Cosmology

$$\sum = \sum m_i$$



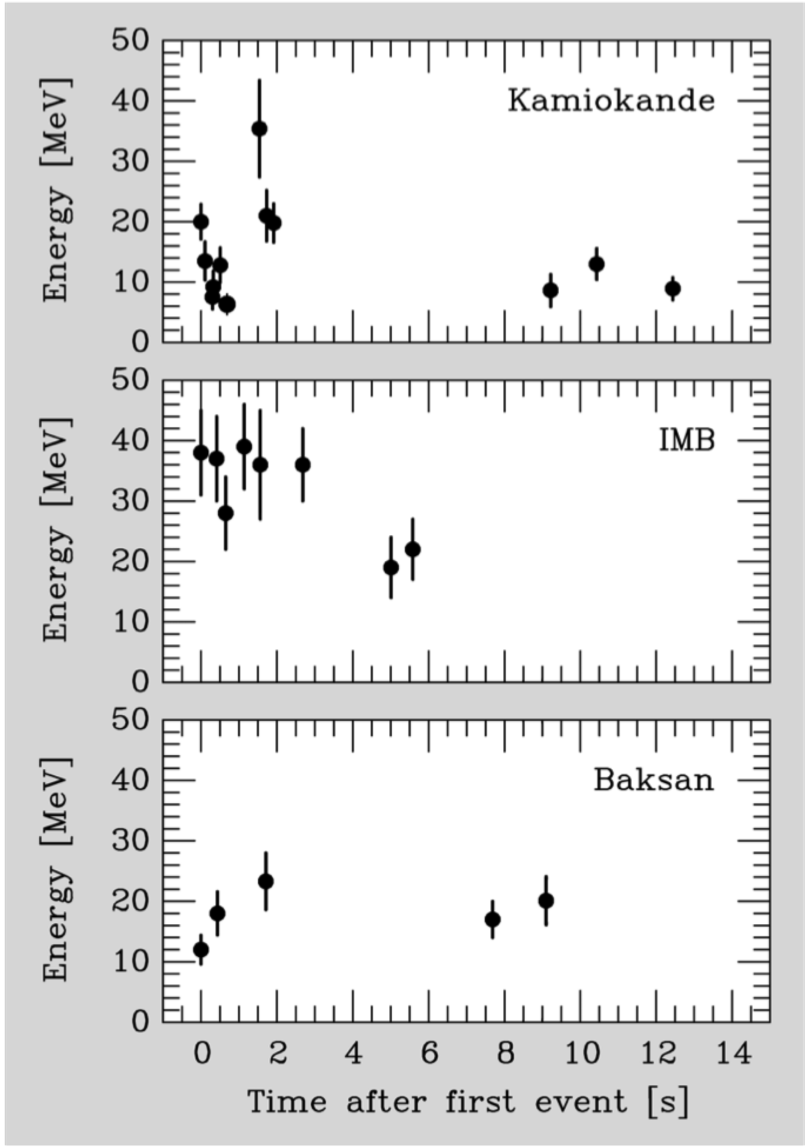
- Multi-parameter cosmological model
- Upper limit: ~0.11 – 0.54 eV*
- Planck satelite

*source: PDG 2020: Neutrinos in Cosmology

Neutrino mass

- What are the challenges in measuring the neutrino mass directly?

Time of flight from SN1987A



Based on the information on this slide, calculate the mass of the neutrino. (for help see arXiv 0909.2104)

ernova

in

Flight time: $t \approx 5\times10^{12}\ \mathrm{s}$

Signal spread: $\Delta t \approx 10\,\mathrm{s}$

Neutrino energy: $E_{tot,min} \sim 10$ MeV to $E_{tot,max} \sim 40$ MeV

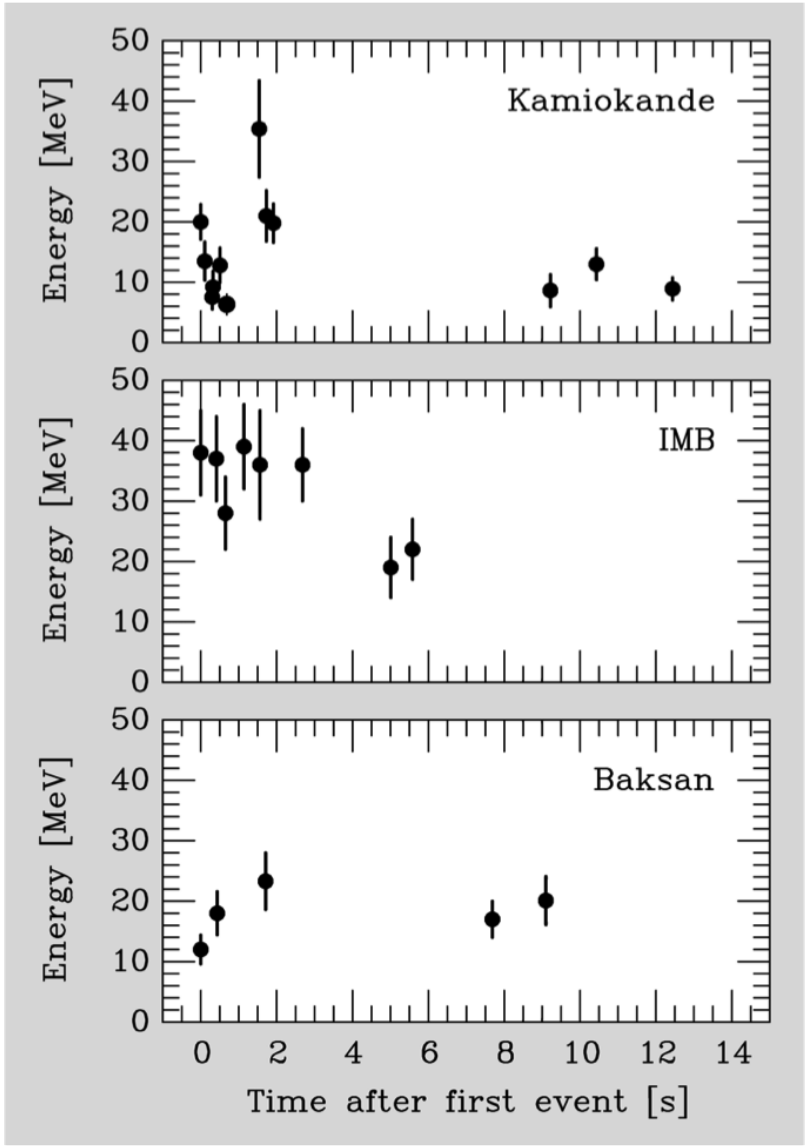
Assumptions: more energetic particles arrive earlier

$$\beta_{\max} \approx 1 \approx \beta_{\min} \text{ and } E_{\text{tot max}}{}^{2} >> E_{\text{tot min}}{}^{2}$$

$$m^2 = E_{tot}^2 - p^2 = E_{tot}^2\left(1-\beta^2\right) = E_{tot}^2\left(1-\beta\right)\left(1+\beta\right) \approx 2E_{tot}^2\left(1-\beta\right)$$

$$\Rightarrow \quad \beta \approx 1 - \frac{m^2}{2E_{tot}^2}$$

Time of flight from SN1987A



Supernova neutrino mass estimation

Flight time: $t \approx 5\times10^{12}$ s

Signal spread: $\Delta t \approx 10$ s

Neutrino energy: $E_{tot,min} \sim 10$ MeV to $E_{tot,max} \sim 40$ MeV

Assumptions: more energetic particles arrive earlier

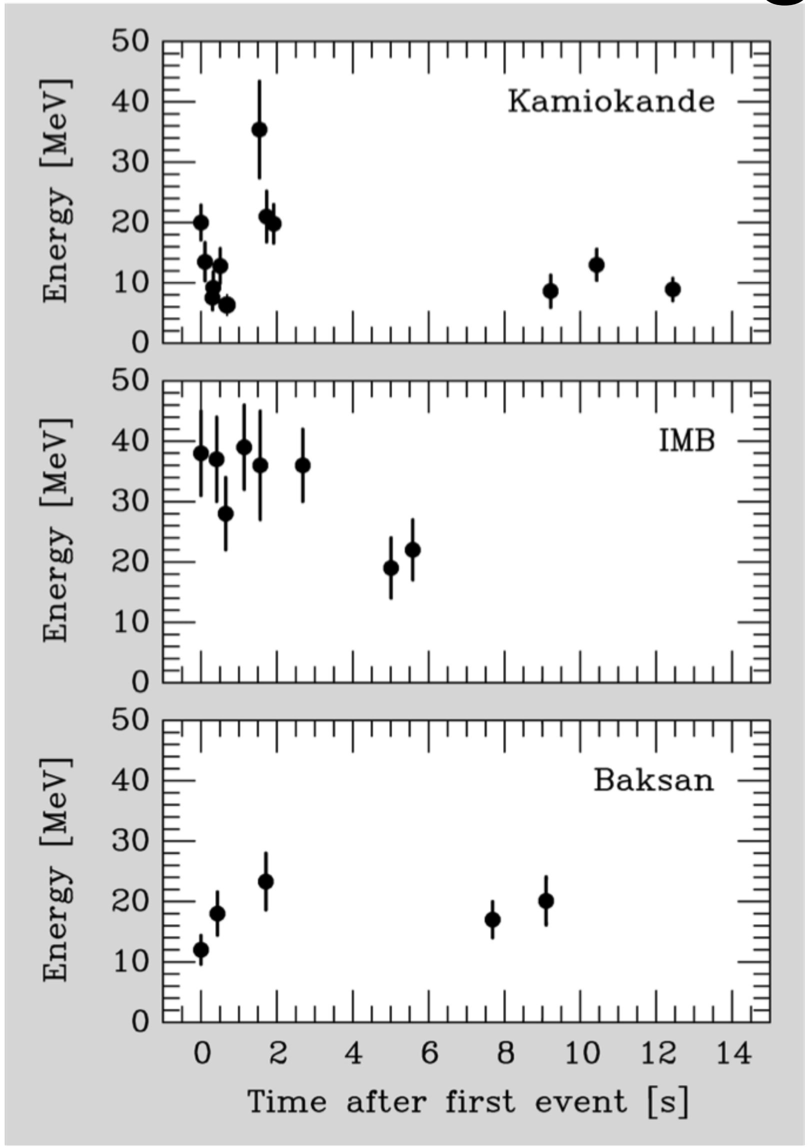
$$\beta_{\max} \approx 1 \approx \beta_{\min} \text{ and } E_{\text{tot max}}{}^{2} >> E_{\text{tot min}}{}^{2}$$

$$\frac{\Delta t}{2t} = \frac{L/\beta_{\min} - L/\beta_{\max}}{L/\beta_{\min} + L/\beta_{\max}} = \frac{\beta_{\max} - \beta_{\min}}{\beta_{\max} + \beta_{\min}} \approx \frac{\beta_{\max} - \beta_{\min}}{2} = \frac{1}{2}\left(-\frac{m^2}{2E^2_{tot\max}} + \frac{m^2}{2E^2_{tot\min}}\right) \approx \frac{m^2}{4E^2_{tot\min}}$$

$$\Rightarrow \quad m \approx E_{\min tot}\sqrt{\frac{2\Delta t}{t}} = 10\,\text{MeV}\sqrt{\frac{20\,\text{s}}{5\cdot10^{12}\,\text{s}}} = 20\,\text{eV}$$

Source: arXiv 0909.2104

Time of flight from SN1987A



Neutrino events (~20 events globally) from supernova 1987A (Large Magellanic Cloud) were detected in KamiokaNDE, IMB, and Baksan observatories.

With a model for neutrino production and detector response model, it is possible to look for smearing due to neutrino mass. Early analyses gave limits ~20 eV.

Improved supernova modeling and Bayesian statistical approaches do better:

< 5.7 eV @ 95% C.L.
Loredo and Lamb, *PRD* 65 (2002)

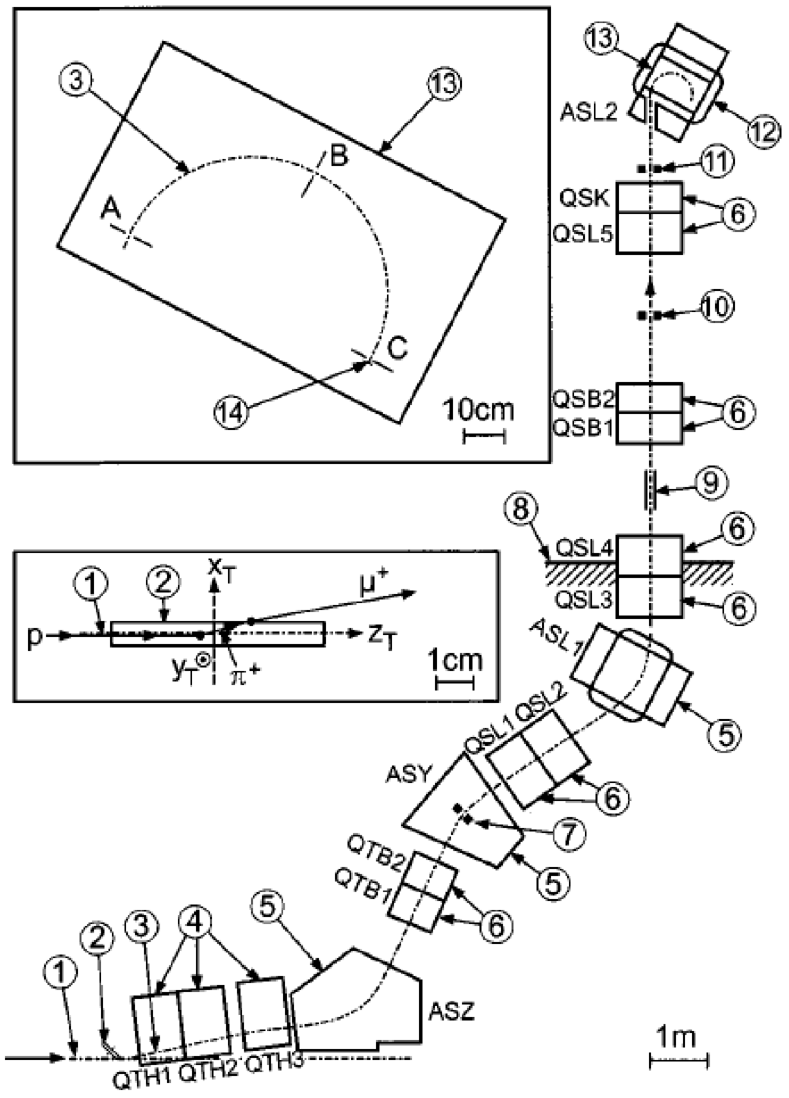
Pion decay

Current best limit from studies of the kinematics of $\pi \rightarrow \mu\nu_\mu$ decay.

$$p_\mu^2 + m_\mu^2 = (m_\pi^2 + m_\mu^2 - m_\nu^2)^2 / 4m_\pi^2$$

$$m_{\nu_\mu}^2 = m_{\pi^+}^2 + m_{\mu^+}^2 - 2m_{\pi^+}\sqrt{p_{\mu^+}^2 + m_{\mu^+}^2}$$

- Pion decay in flight is limited in practice by momentum resolution.
- Pion decay at rest is limited by pion mass uncertainty. This currently gives the best limits from PSI



Pion decay

Current best limit from studies of the kinematics of $\pi \rightarrow \mu\nu_\mu$ decay.

$$m^2_{\nu_\mu} = m^2_{\pi^+} + m^2_{\mu^+} - 2m_{\pi^+}\sqrt{p^2_{\mu^+} + m^2_{\mu^+}}$$

- Pion mass from X-ray measurements on pionic atoms:

$$m_\pi = 139.567\,82 \pm 0.000\,37\ \mathrm{MeV}$$

$$m_\pi = 139.569\,95 \pm 0.000\,35\ \mathrm{MeV}$$

- Muon mass from ratio of magnetic moments from muon and proton:

$$m_\mu = (105.658\,3668 \pm 0.000\,0038)\ \mathrm{MeV}$$

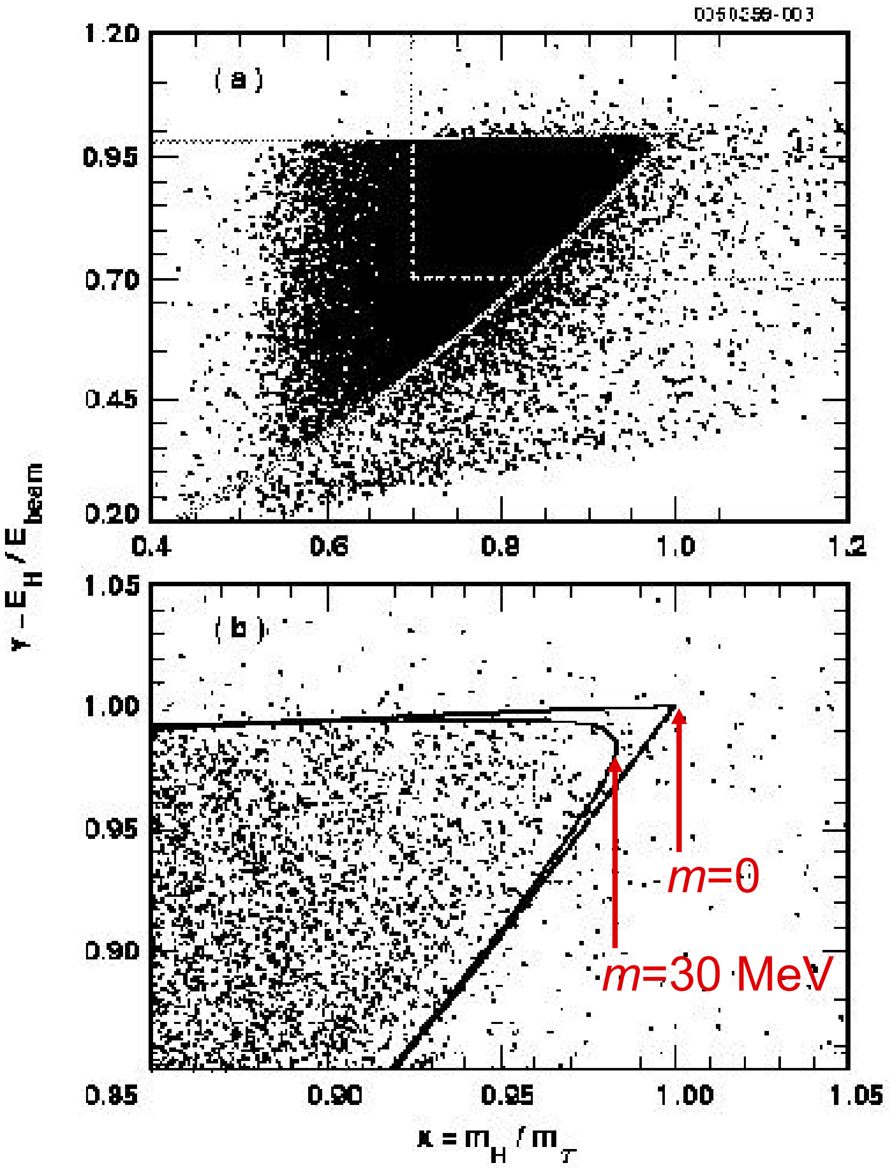
- Muon momentum:

$$p_\mu = (29.792\,00 \pm 0.000\,11)\ \mathrm{MeV}$$

$$\boxed{m^2_{\nu_\mu} = (-0.016 \pm 0.023)\ \mathrm{MeV}^2 \rightarrow}$$

m_ν<170 keV @ 90% C.L.
Assamagan et al., *PRD* (1996)

τ decay



Tau produced at accelerators:

$$e^+e^- \rightarrow \tau^+\tau^- \qquad E_\tau = \sqrt{s}/2$$

$$m_{\mathrm{had}} = m_\tau - m_\nu$$

Best limit from studies of the kinematics of τ decays.

$$\tau^- \rightarrow 2\pi^- \pi^+ \nu_\tau$$
$$\tau^- \rightarrow 3\pi^- \; 2\pi^+ (\pi^0) \nu_\tau$$

Fit to scaled visible (hadronic) energy

$$E_{\mathrm{had}} = \frac{(m_\tau^2 + m_{\mathrm{had}}^2 - m_\nu^2)}{2m_\tau}$$

vs. scaled invariant mass.

Best limit <18.2 MeV @ 95% C.L.
Aleph, EPJ C2 395 1998

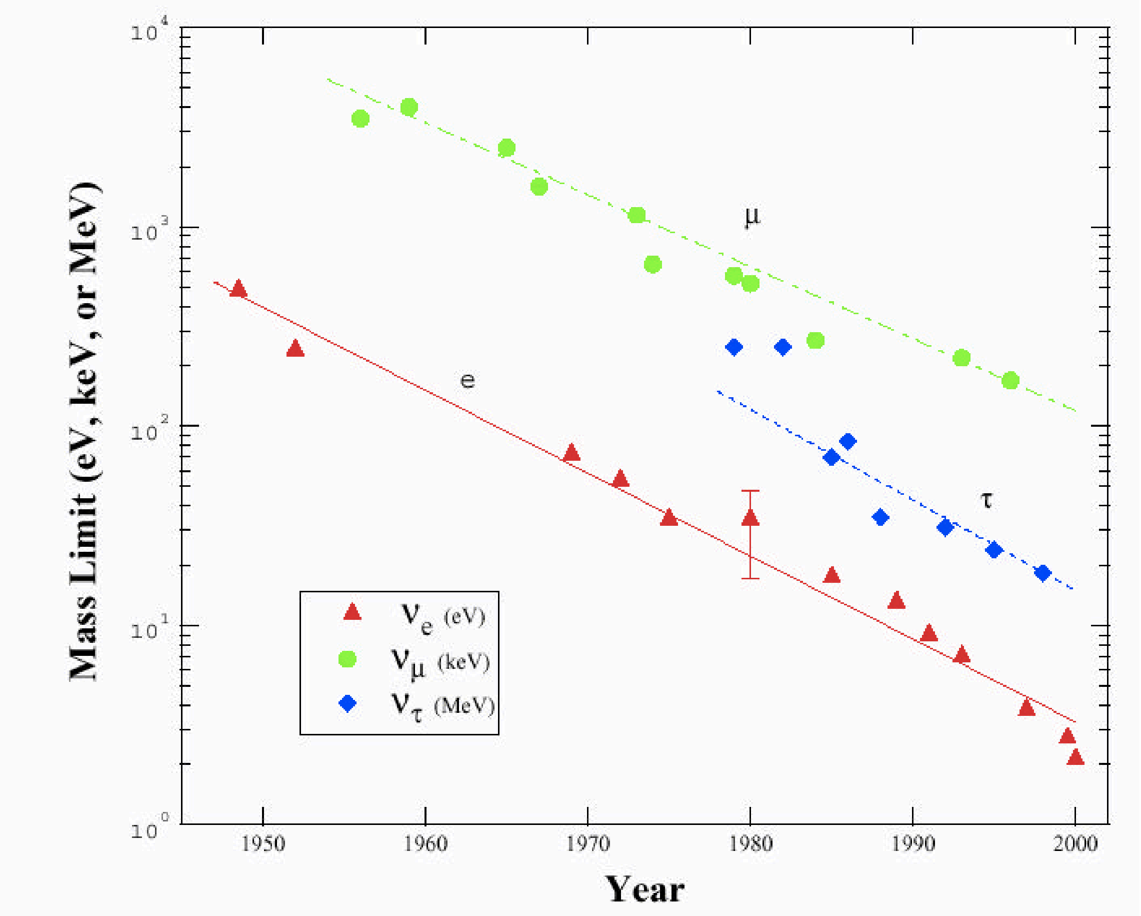
Decay kinematics measurements

Look at the impact of non-zero ν mass on the following decays.

ν_e: beta decay

ν_μ: pion decay

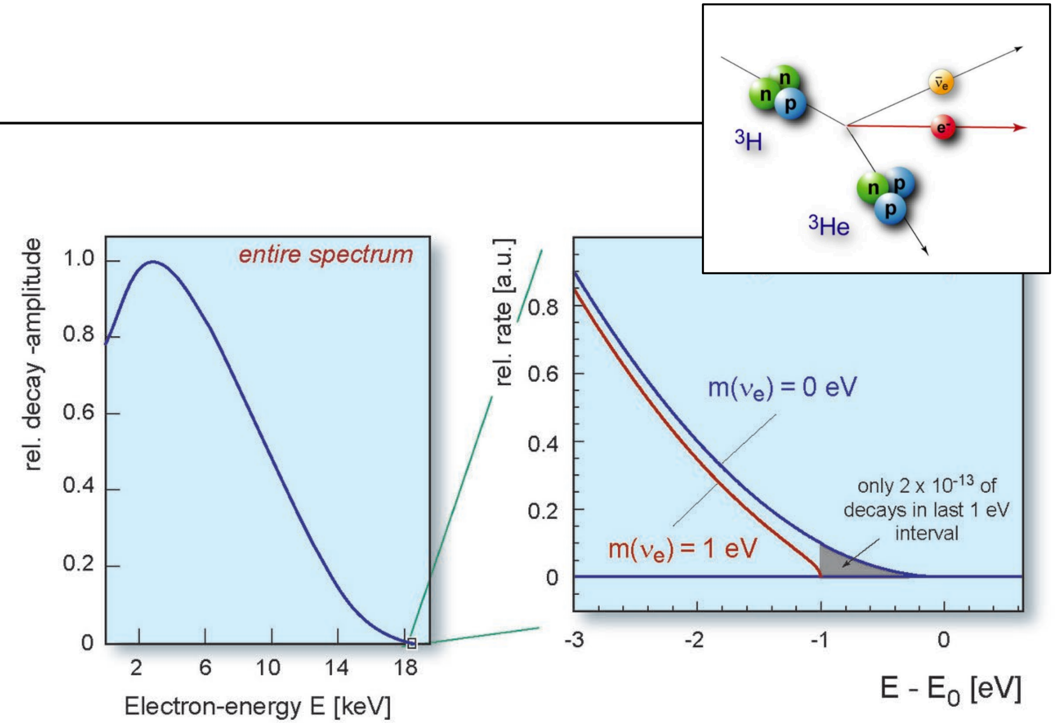
ν_τ: tau decay



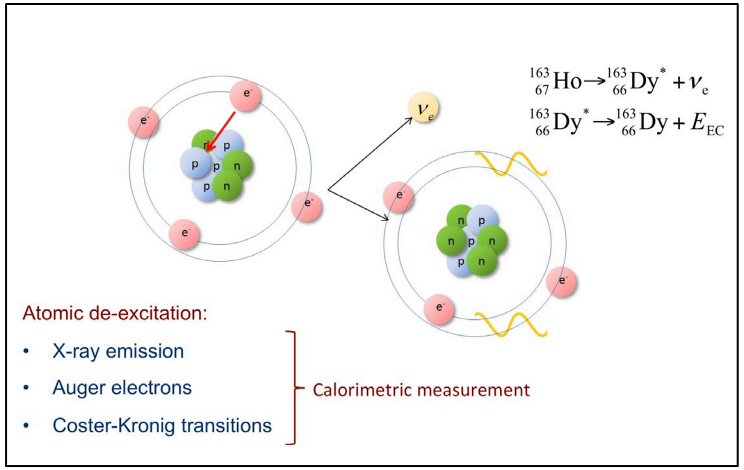
$$m^2(\nu_e) = \sum_{i=1}^{3} |U_{ei}^2|^2 m_i^2 \qquad m^2(\nu_\mu) = \sum_{i=1}^{3} |U_{\mu i}^2|^2 m_i^2 \qquad m^2(\nu_\tau) = \sum_{i=1}^{3} |U_{\tau i}^2|^2 m_i^2$$

Isotopes

- Basically only two isotopes are of interest for endpoint measurements
- Want as low an end-point as possible, and short enough half-life to get required statistics



	^{3}H	^{163}Ho
Type	superallowed β-decay	electron-capture decay
$T_{1/2}$	12.3 years	4500 years
E_0	18.6 keV	2.5 keV



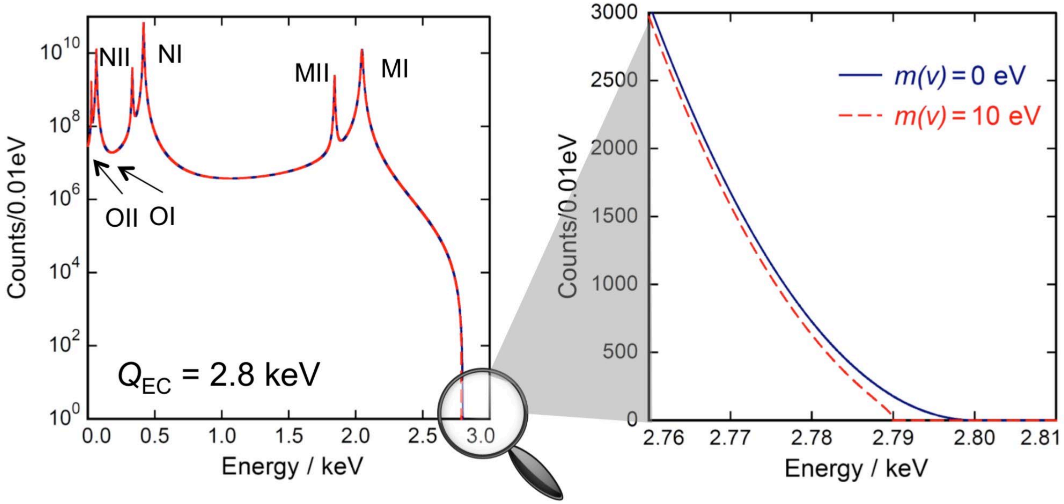
$${}^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$

$${}^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_{EC}$$

Atomic de-excitation:

- X-ray emission
- Auger electrons
- Coster-Kronig transitions

Calorimetric measurement



Required precision for neutrino mass measurements

- We want to determine the Q value of ^{3}H decay. What do we need to measure?

→ We need to measure the masses of decay mother and daughter, i.e., ^{3}H and ^{3}He

- To what precision do we need to measure the Q-value so that its uncertainty does not dominantly contribute to KATRIN's measurement? Say 30 meV?

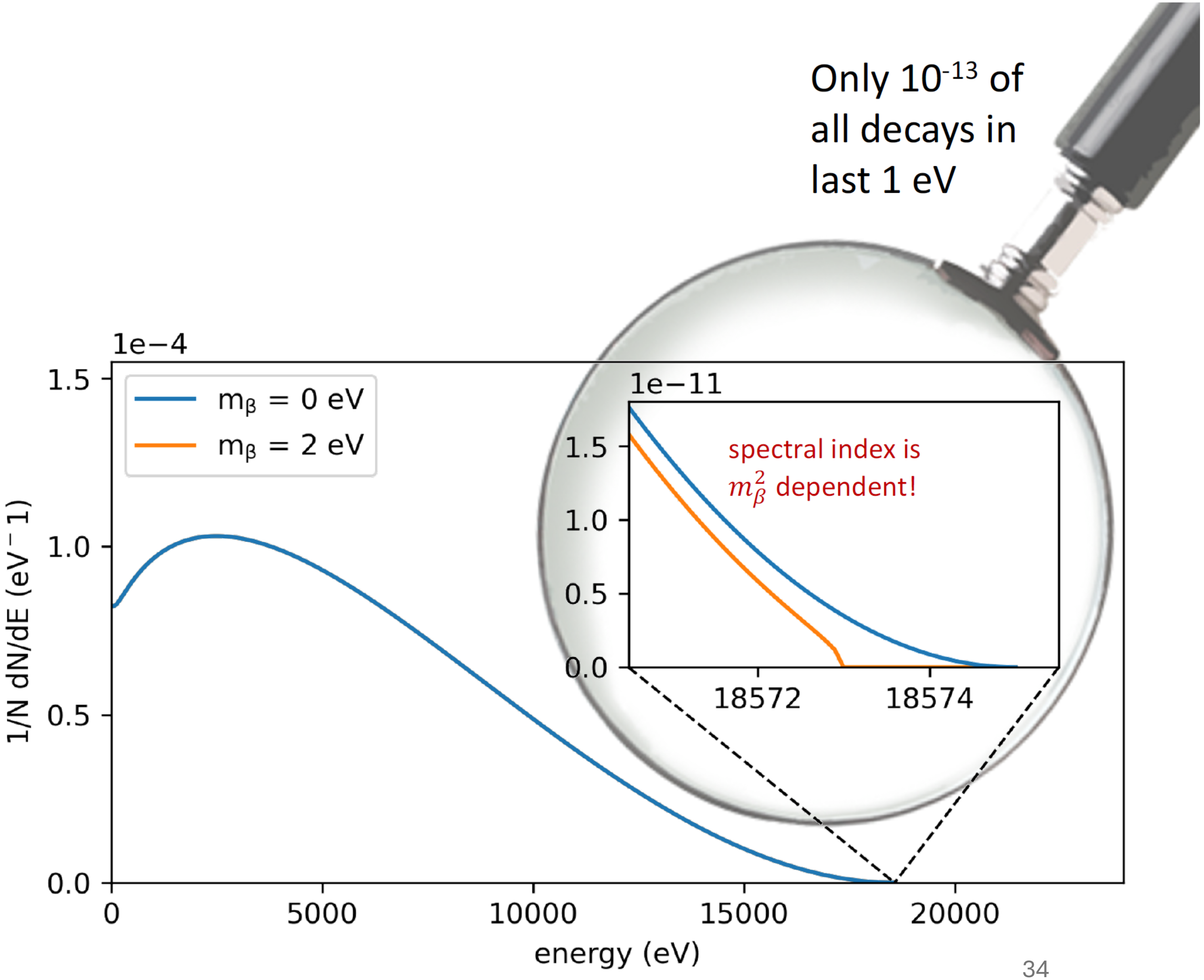
→ A relative uncertainty of 10 parts per trillion in the mass ratio would allow determining the *Q* value with a precision of 30 meV.

Measured Q(T) = 18 592.071(22) eV

Phys. Rev. Lett. 131, 243002 (2023)

Precision Tritium Endpoint Measurement with KATRIN

- ✓ strong tritium source: 10^{11} decays/s
- ✓ < 0.1 cps background level
- ✓ ~1 eV energy resolution
- ✓ 0.1% level understanding of the spectrum shape
- ✓ 0.1% level hardware stability controlled over the years



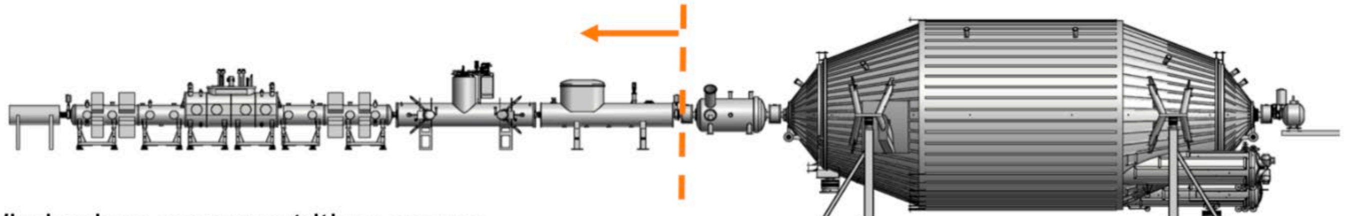
Only 10^{-13} of all decays in last 1 eV

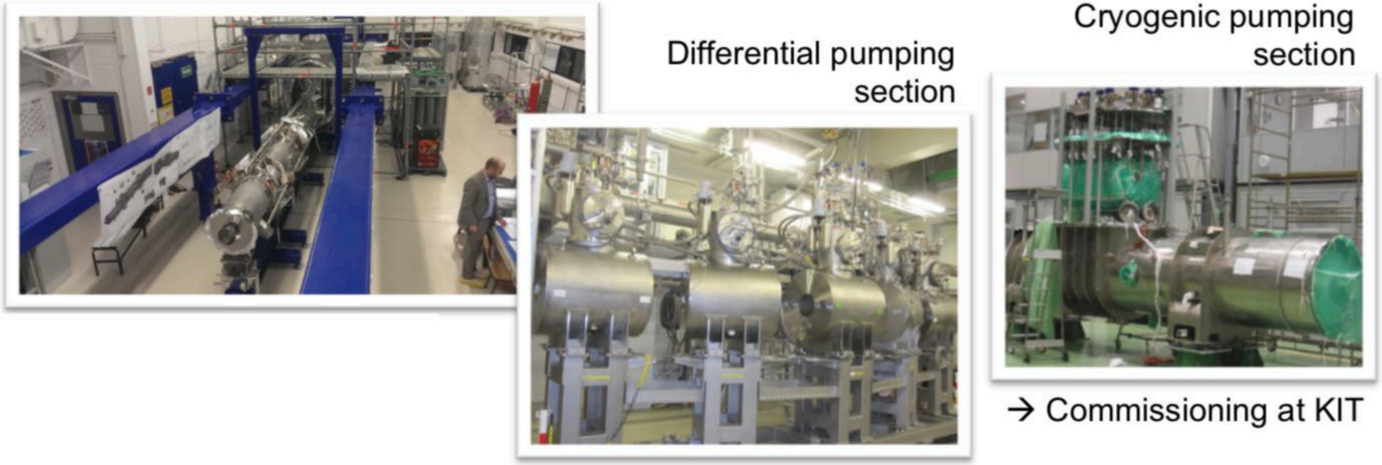
spectral index is m_β^2 dependent!

Slide Courtesy Thierry Lasserre

KATRIN

- Extremely large electrostatic filter only transmits electrons within ~30 eV of the endpoint
- Magnetic adiabatic collimation (MAC-E filter) allows high acceptance of βs for 10^{11} Bq source
- Overall length: 70 m, spectrometer: 23 m long, 10 m diameter
- UHV below 10^{-11} mbar





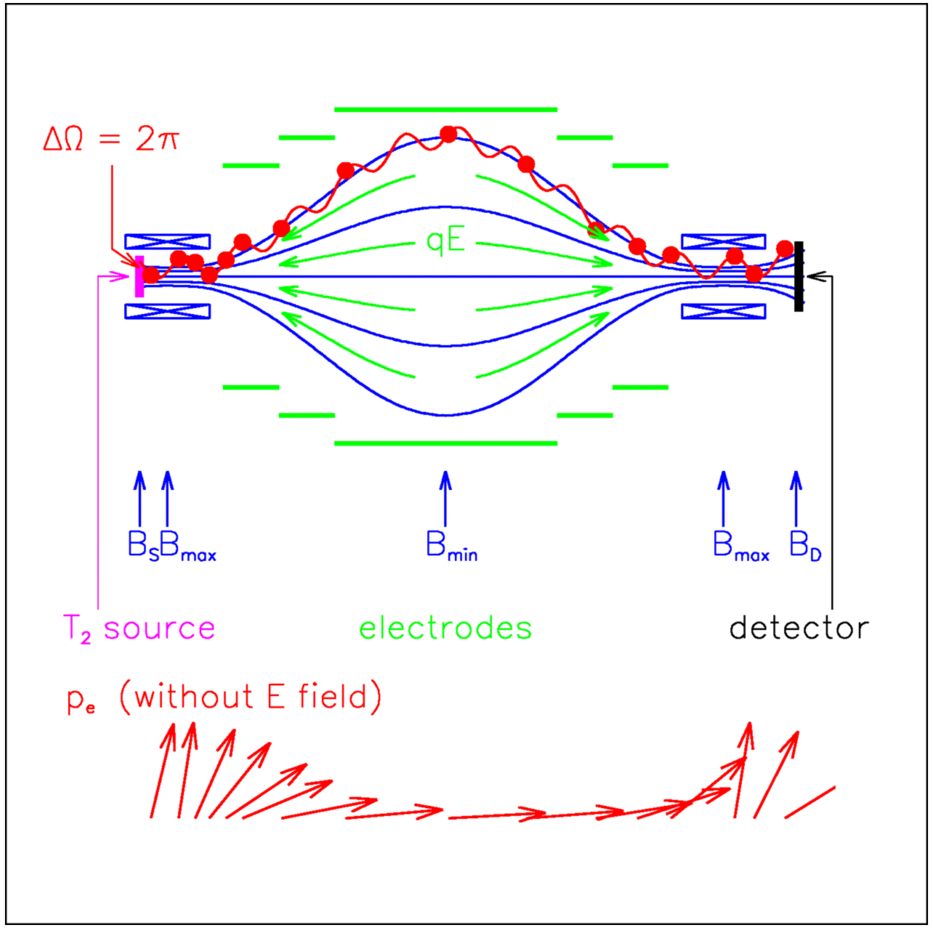
Windowless gaseous tritium source

Differential pumping section

→ Commissioning at KIT

Cryogenic pumping section

→ Commissioning at KIT



High acceptance and sub-eV resolution in principle possible

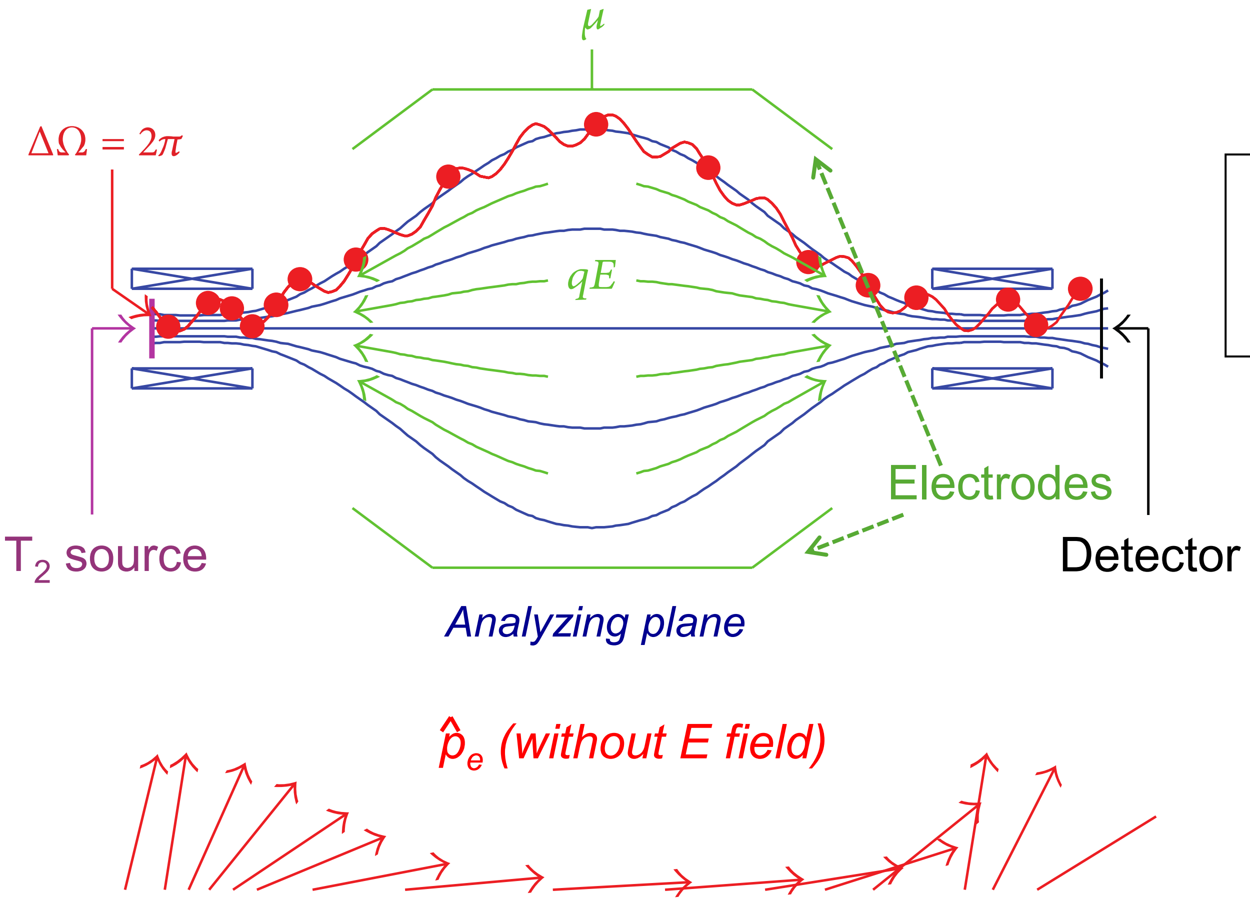
https://www.katrin.kit.edu/79.php

MAC-E filter

Magnetic Adiabatic Collimation and Electrostatic filter

The MAC-E filter allows measurement of integral spectrum with an adjustable threshold. Only see the endpoint of the decay!

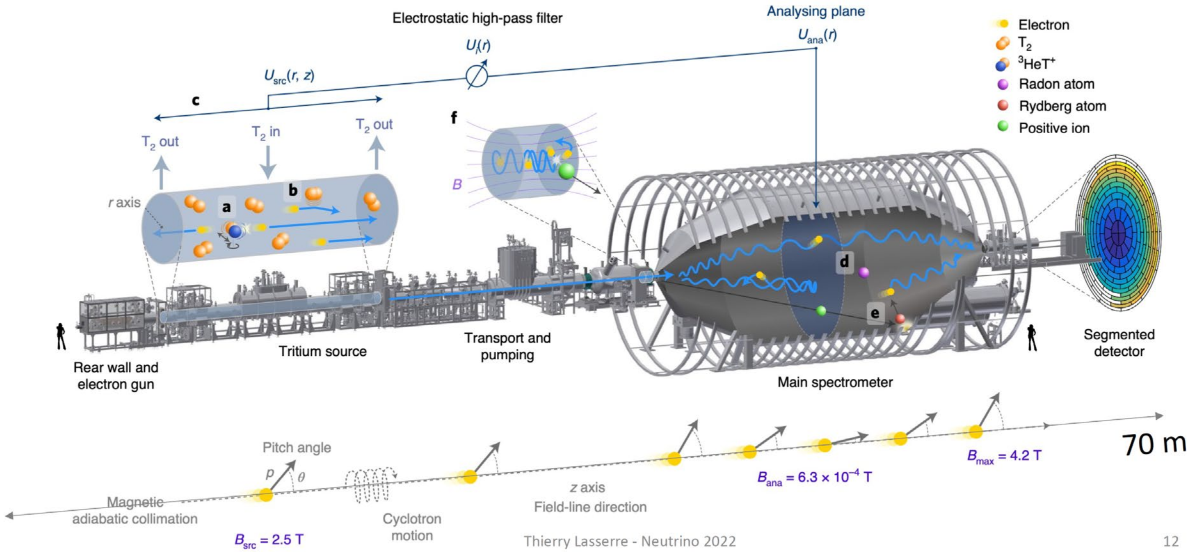
Transverse kinetic energy is converted to longitudinal kinetic energy by magnetic adiabatic collimation.



$$\boxed{\mu = \frac{E_\perp}{B} = \text{const}}$$

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

KATRIN

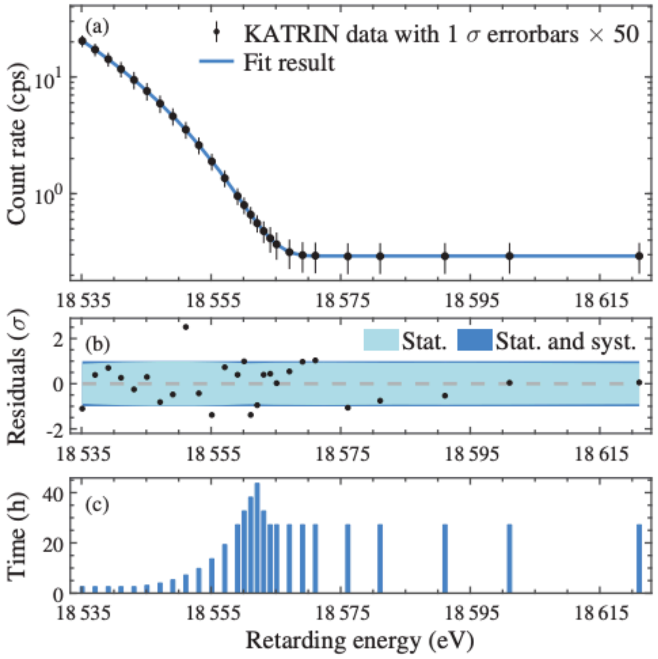


The main spectrometer traveled a near-9000-kilometer route to cover a distance of only 400 km.
https://www.symmetrymagazine.org/article/march-2007/deconstruction-katrin?language_content_entity=und

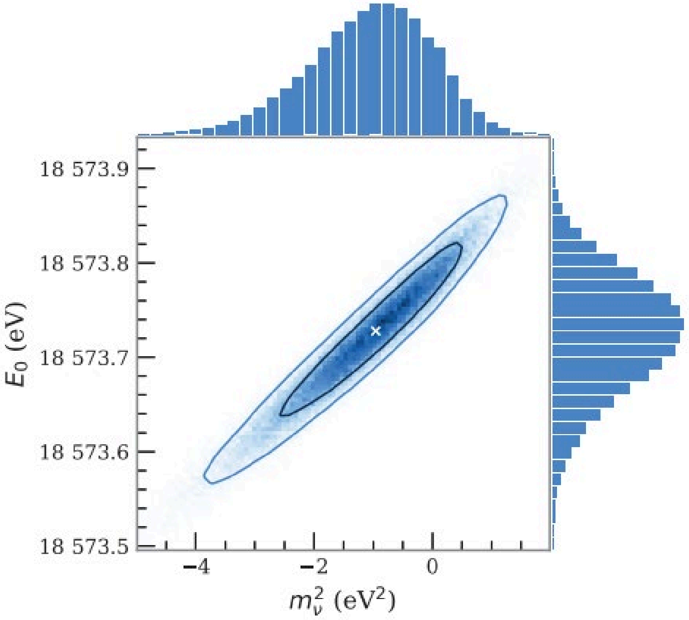
KATRIN

- First results reported in 2019, gave $m_{\nu_e} < 1.1$ eV (limited by statistics, now 0.8 eV limit from 2022)
- Expect to reach sensitivity ~0.2 eV (3σ discovery potential ~ 0.28 eV) after 3 years of running

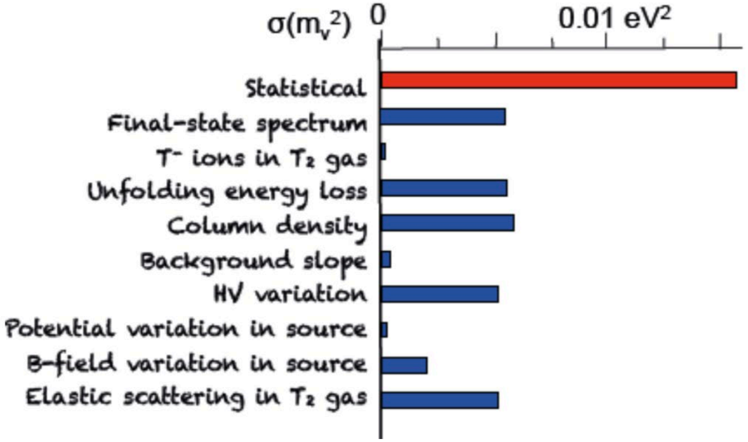
Observed spectrum near endpoint:

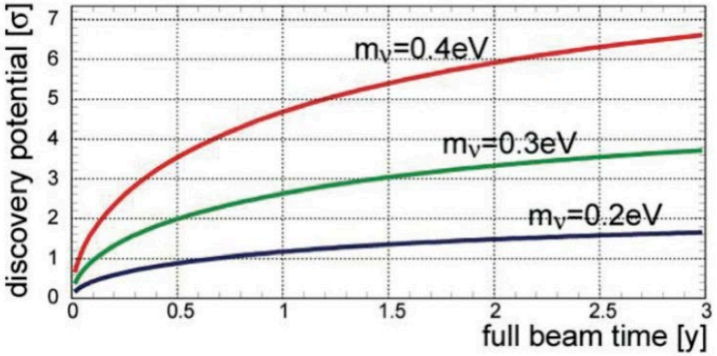


Joint posterior PDF for *m*, E_0:



Error budget and projected discovery potential:





https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.123.221802

Slide from Alexey Lokhov, NEUTRINO 2024

Preprint →
https://www.katrin.kit.edu/130.php#Anker0

Conclusion and Outlook

New KATRIN release improves direct neutrino-mass bound by a factor of 2:

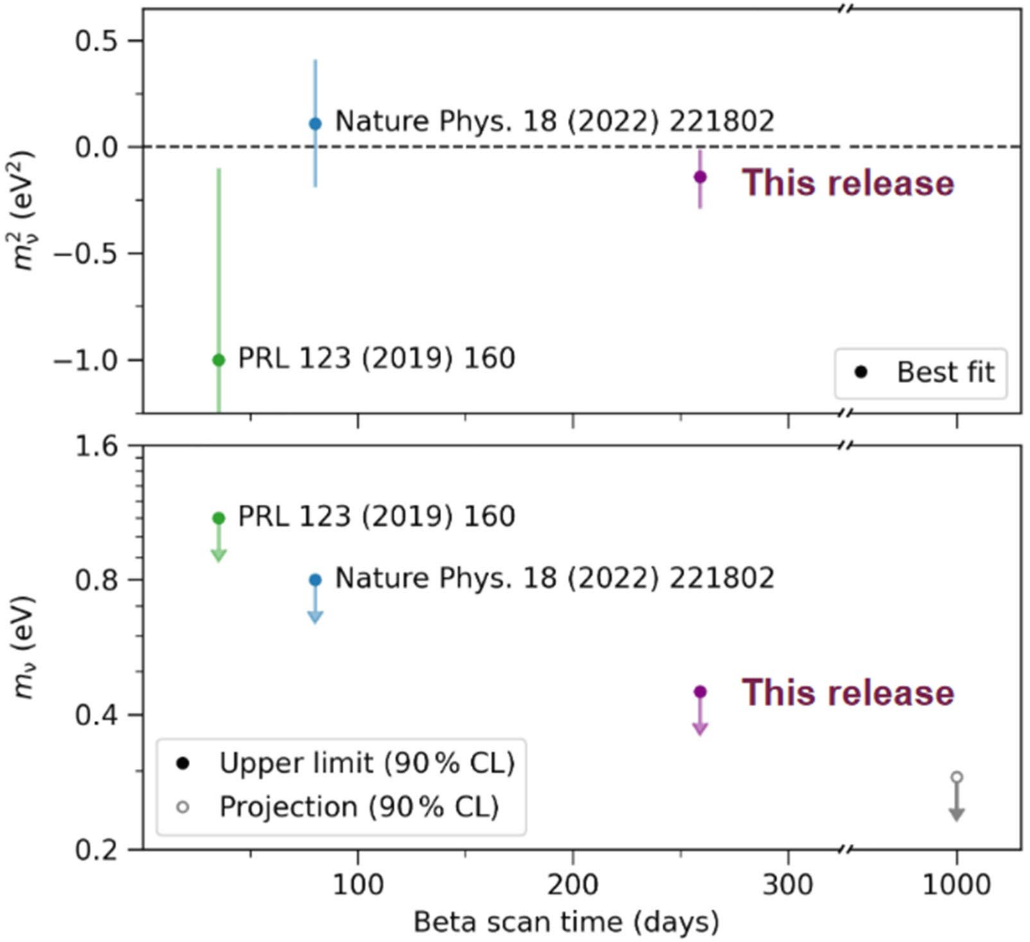
$$\boxed{m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})}$$

Ongoing analysis:

- 70 % of total anticipated data recorded, improvements in systematics
- Several BSM physics searches: eV-sterile, exotic interactions, light bosons, relic ν… ⇒ stay tuned!

Ongoing data taking through **2025 → Σ 1000 days**

- target sensitivity below 0.3 eV



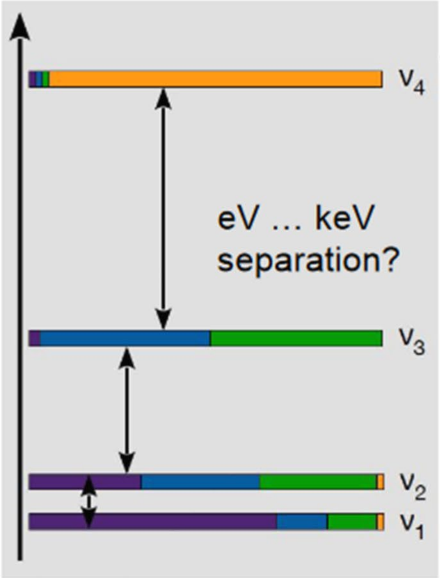
Slide from Alexey Lokhov, NEUTRINO 2024

KATRIN “beyond neutrino mass”

β-spectrum of high statistics and precision

Is there a fourth (sterile) neutrino?
(search for a kink)

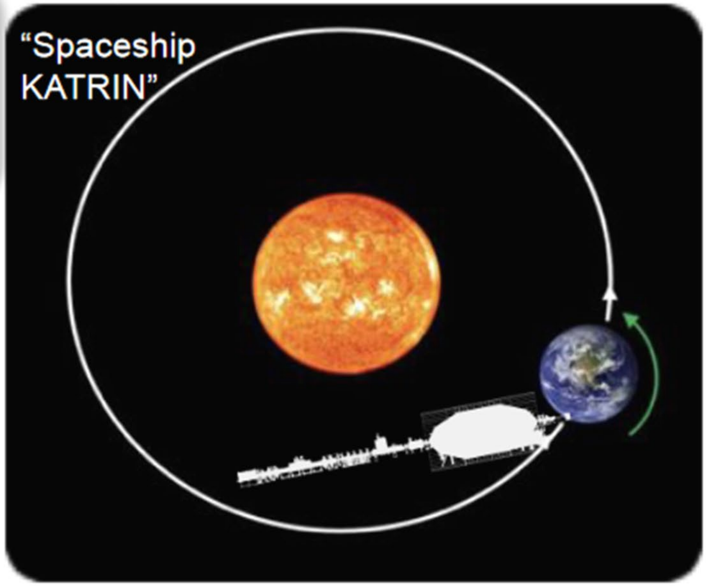
Phys.Rev.Lett. 126 (2021) 9, 091803
Phys.Rev.D 105 (2022) 7, 072004



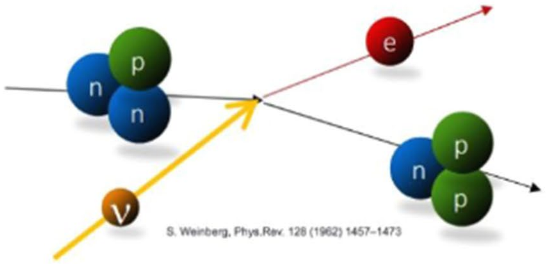
Posters by S. Mohanty & X. Stribl

Search for Lorentz invariance violation
(sidereal modulation)

Phys.Rev.D 107 (2023) 8, 082005



Constrain local density of cosmic relic neutrinos
(peak search)



S. Weinberg, Phys.Rev. 128 (1962) 1457–1473

Phys. Rev. Lett. 129 (2022) 1, 011806

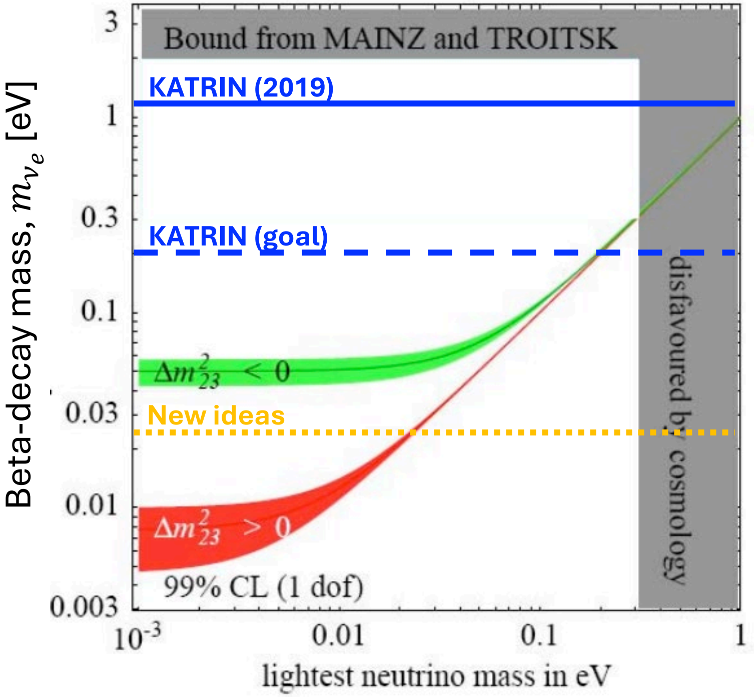
Search for exotic interactions
(spectrum shape)

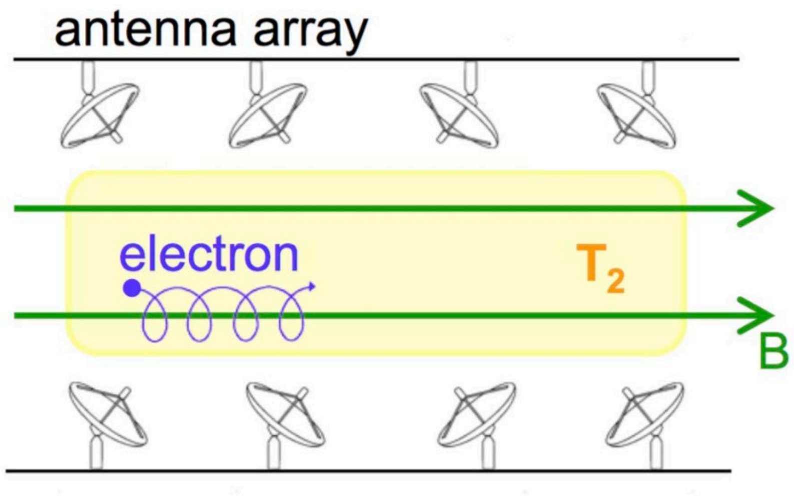
Poster by C. Fengler

Project 8

- New ideas are needed beyond KATRIN, which is probably the largest such spectrometer feasible

- Project 8 aims to perform non-destructive measurement of electron energy from cyclotron radiation:



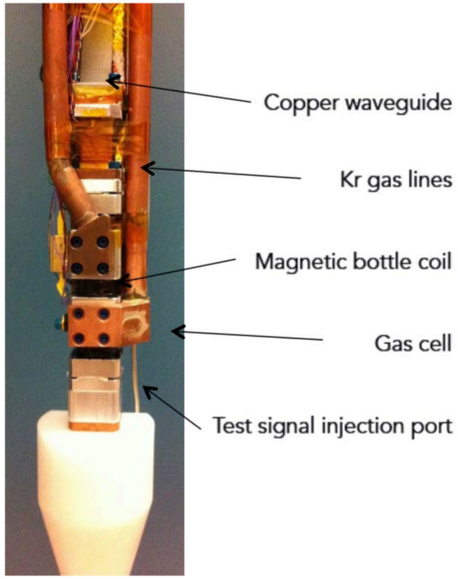


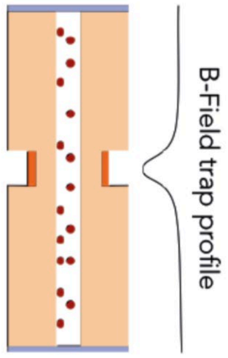
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

- This technique may in principle be scaled to a large, atomic ^{3}H source capable of covering the IH

Project 8

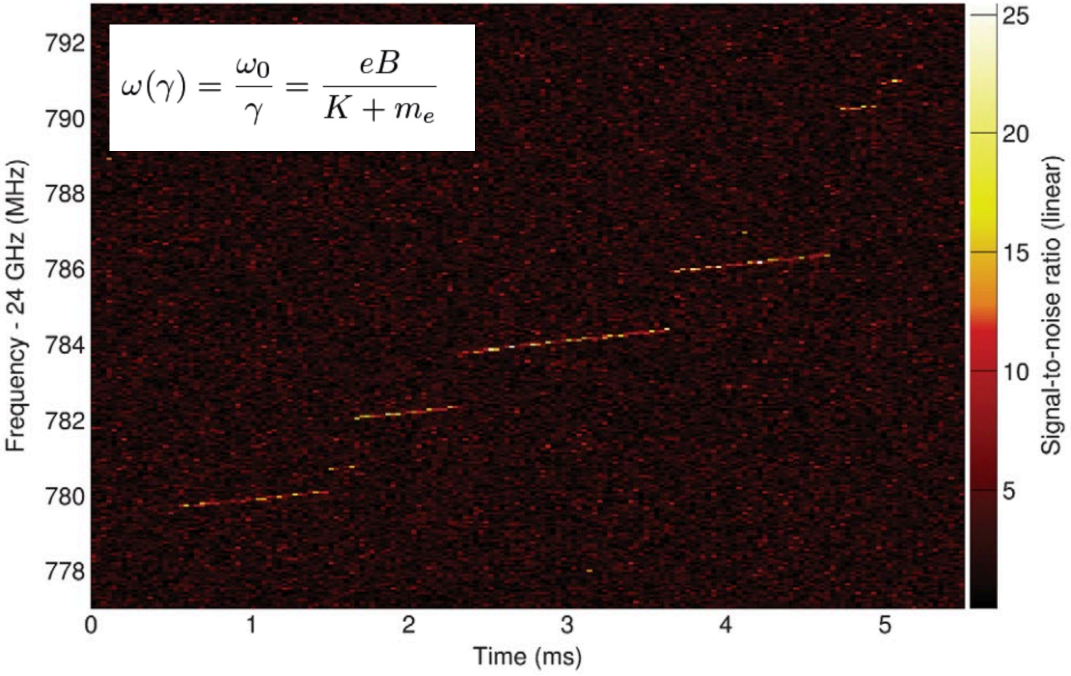
- First demonstration of measuring cyclotron radiation from single electron in 2015
- Working on scaling up to larger demonstrators:
  - Phase II: first ^{3}H test (not yet competitive mass constraints)
  - Phase III: large volume system with competitive (~eV mass) sensitivity
  - Phase IV: large experiment with atomic ^{3}H at IH sensitivity





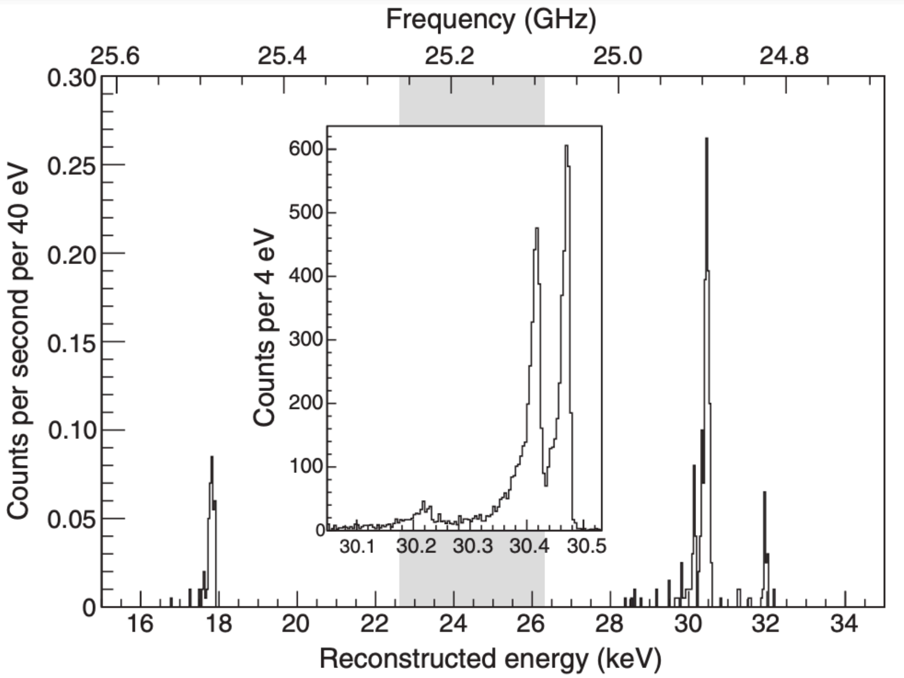
Waveguide Cut-away

Observed single e^- vs time:



$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

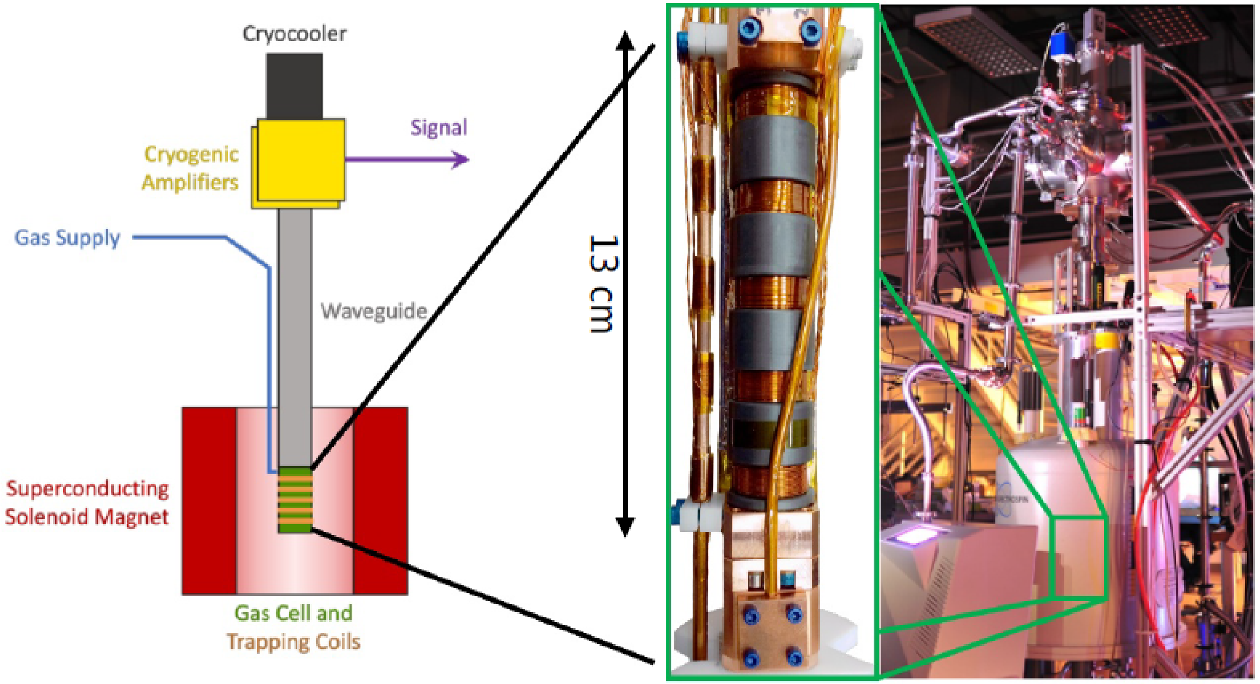
Measured electron energy spectrum (^{83m}Kr):



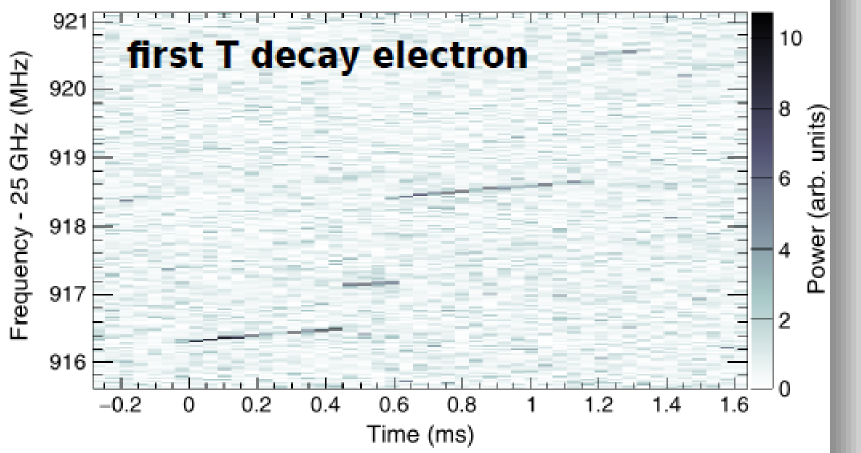
https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.114.162501

From NEUTRINO 2024 talk

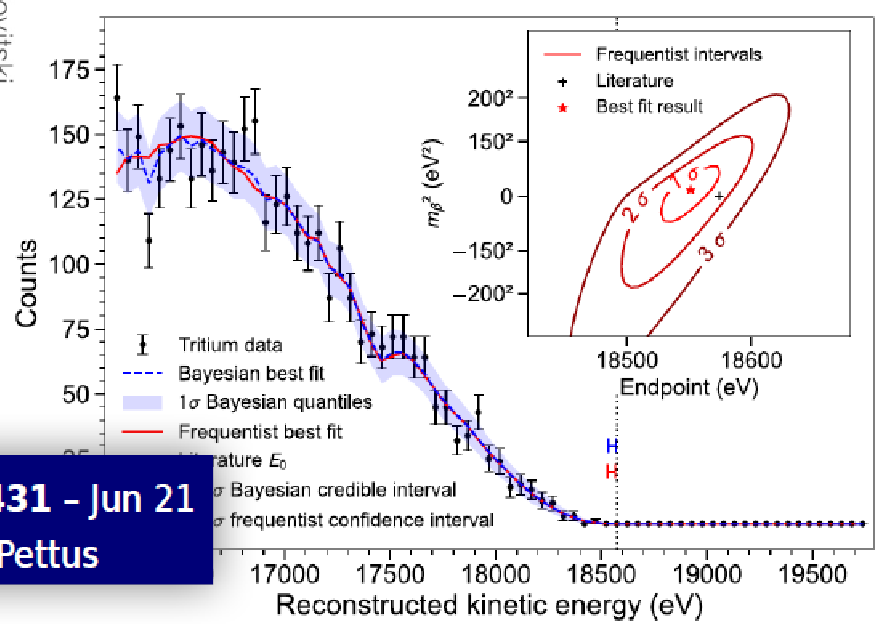
Project8: phase II results



Credit: A. Lindman, E. Novitski



A. Ashtari Esfahani et al. Phys. Rev. C 109, 035503



4 different experimental phases since 2009

long term sensitivity goal: 40 meV 90% CL (phase IV)

phase II with T_2 adsorbed in getter

- demonstrated T decay spectroscopy with **0 background**
- ΔE_{FWHM}=54 eV (deep trap configuration)
- 3770 T decays within wave guide in 82 days
- → **m_ν < 152 eV** 90% CL *Project 8 Collaboration, PRL 131 (2023) 102502*

poster 431 – Jun 21
W. Pettus

From NEUTRINO 2024 talk

Project8: phase III and IV

PROJECT 8

Phase III (in progress now)

CRES with T_2 or magnetogravitationally trapped T atoms

goal $m_\nu < 0.2$ eV (with T_2)

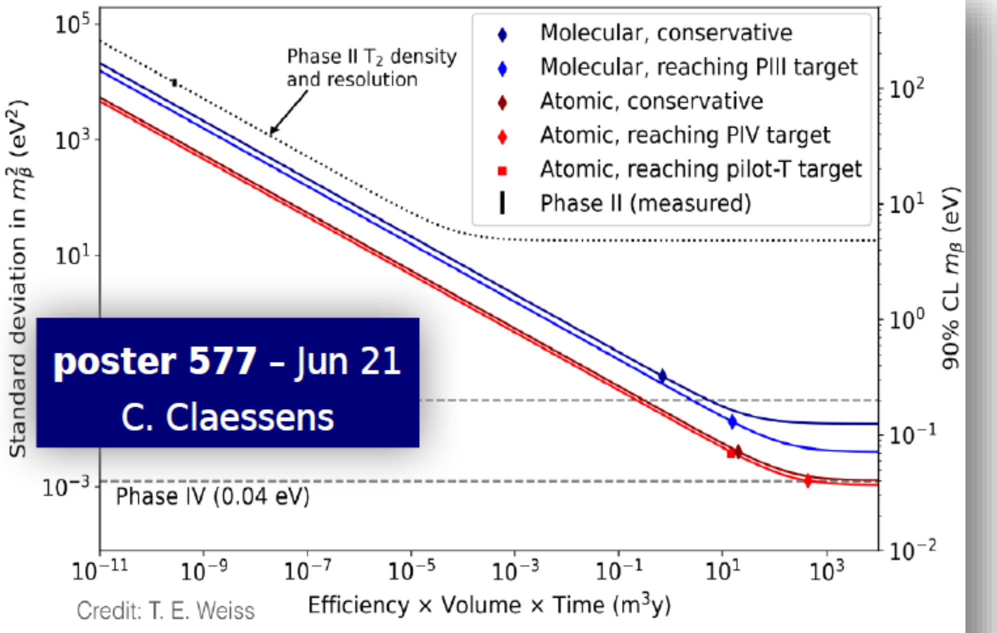
R&D on atomic Tritium source well advanced

R&D on cavity RF readout (f_c <1GHz for T trapping)

Phase IV

scaling up phase III trap

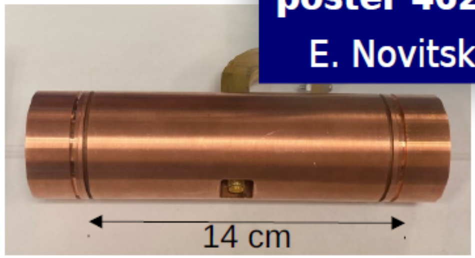
goal $m_\nu < 0.04$ eV



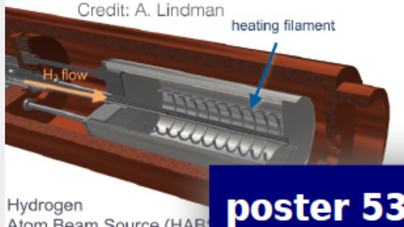
Credit: T. E. Weiss

poster 577 – Jun 21
C. Claessens

poster 462 – Jun 21
E. Novitski, et al.



CRES cavity prototype at 26GHz

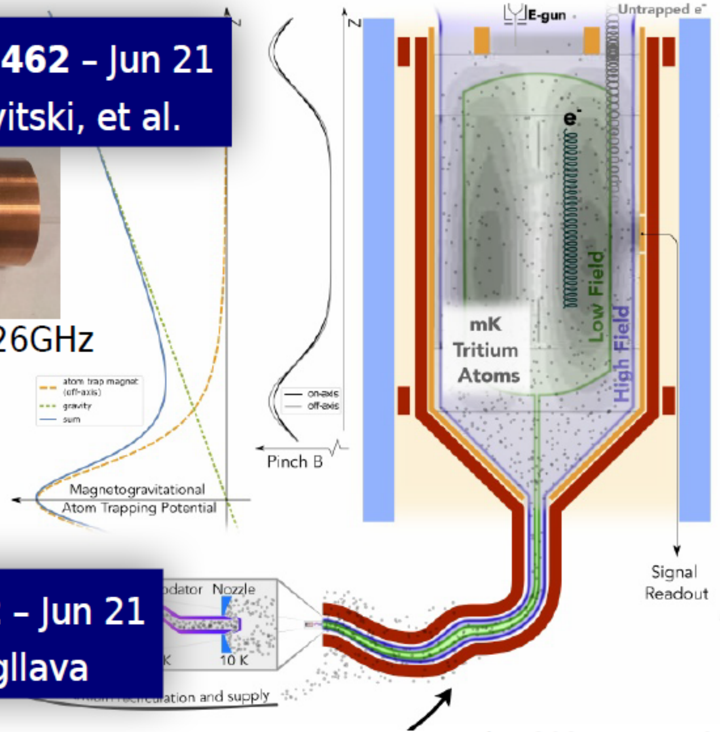


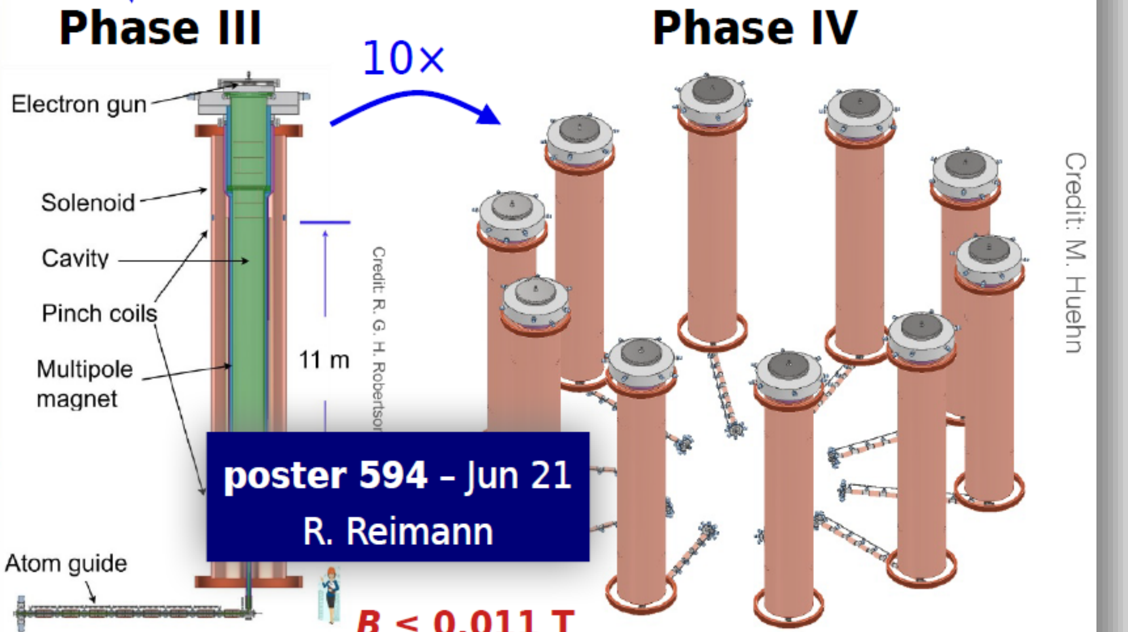
Credit: A. Lindman

Hydrogen Atom Beam Source (HABS

poster 532 – Jun 21
B. Muçogllava

conceptual design





Credit: M. Huehn

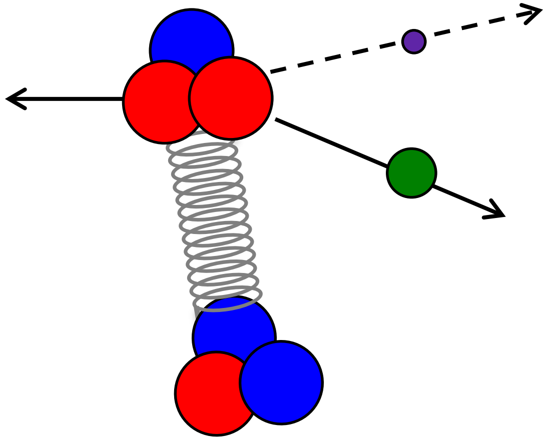
poster 594 – Jun 21
R. Reimann

$B \lesssim 0.011$ T
$f_c \lesssim 325$ MHz

Tritium gas sources

Gas sources give the best results, but we're limited to using molecular tritium.

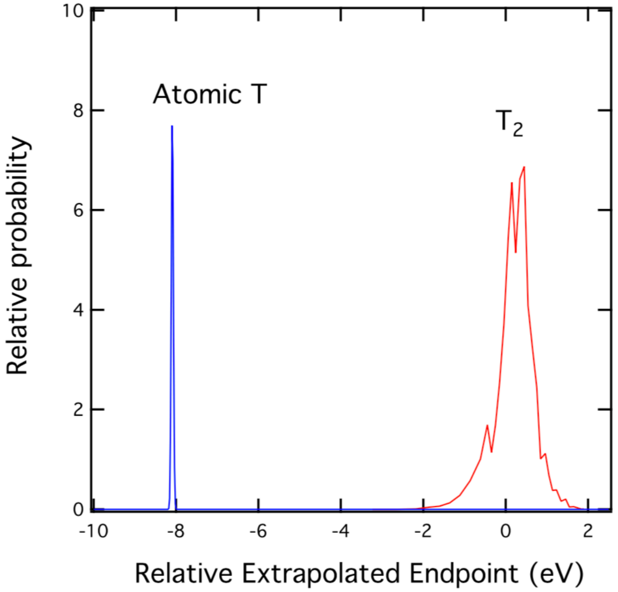
- Electronic excitations in T atoms
- Excitations in T_2 gas
  - Electronic: 20 eV
  - Vibrational: ~0.1 eV
  - Rotational: ~0.01 eV
- Beta spectrum depends on excitation energies V_k and probabilities P_k
- KATRIN needs 1% uncertainties on final state distribution.



$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7}|M_{\text{nuc}}|^2 F(Z,E_e) p_e E_e \times \sum_{i,k} |U_{ei}|^2 P_k (E_{\max} - E_e - V_k)$$
$$\times \sqrt{(E_{\max} - E_e - V_k)^2 - m_{\nu i}^2} \times \Theta(E_{\max} - E_e - V_k - m_{\nu i})$$

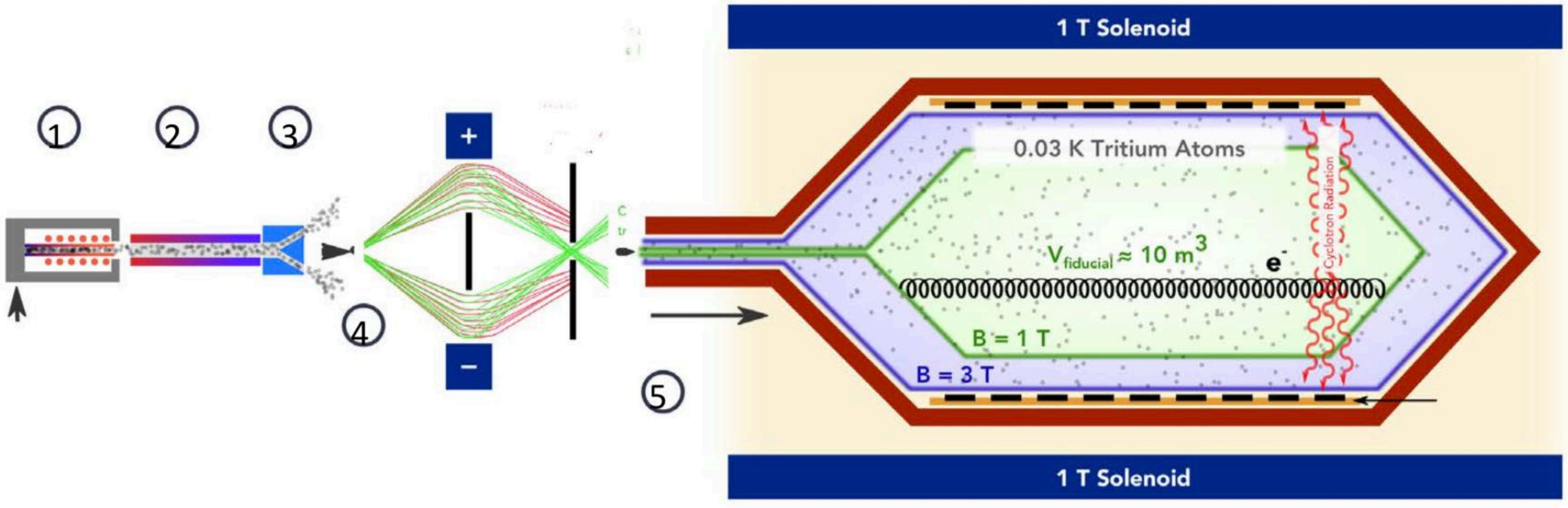
Project 8

- Major systematic for any sufficiently sensitive ^{3}H experiment is the need for atomic tritium (to avoid smearing from rotational/vibrational states in molecular tritium)



Final state energy distribution relative to tritium endpoint

Concept for large atomic tritium experiment:



1: Molecular tritium thermally cracked

2: Atomic tritium cooled in accommodator

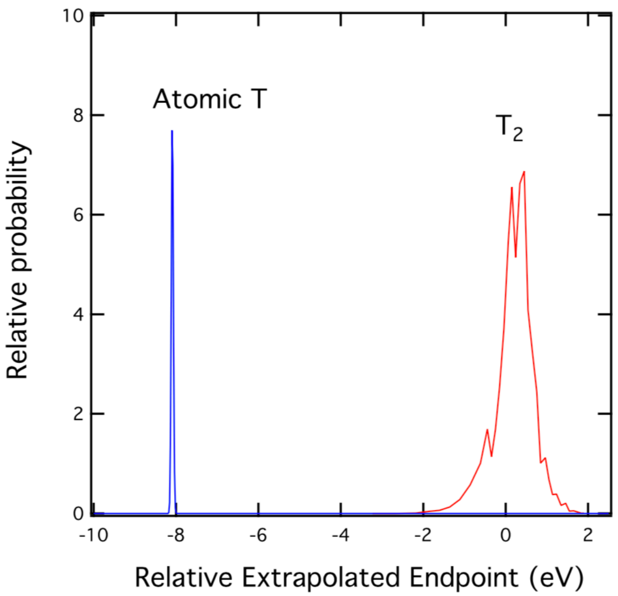
3: Cool atoms sprayed into velocity and state selector

4: Cold low-field seeking spin tritium selected

5: Atoms cooled to millikelvin temperatures by magnetic step, linger in decay volume

Project 8

- Major systematic for any sufficiently sensitive ^{3}H experiment is the need for atomic tritium (to avoid smearing from rotational/vibratio



Final state energy distribution relative to tritium endpoint

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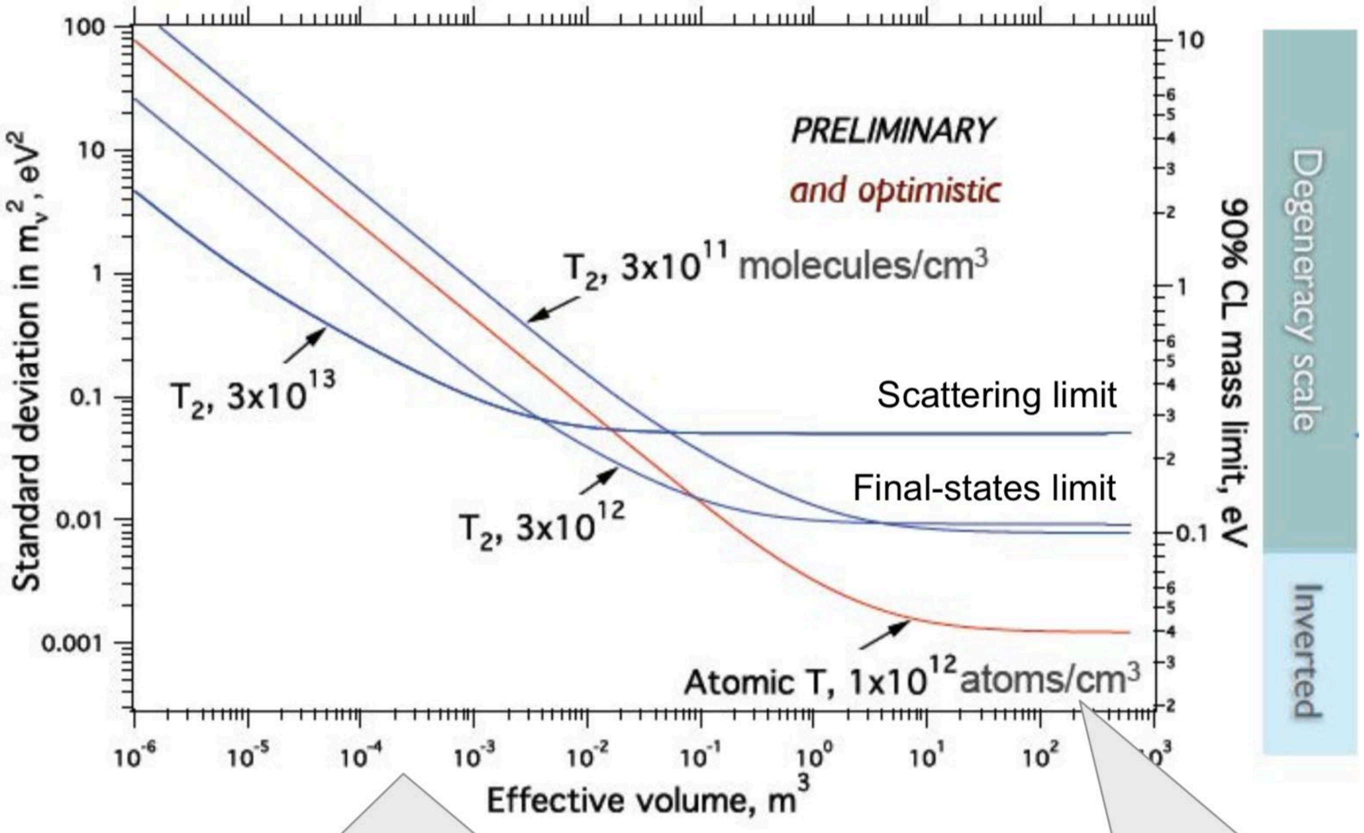
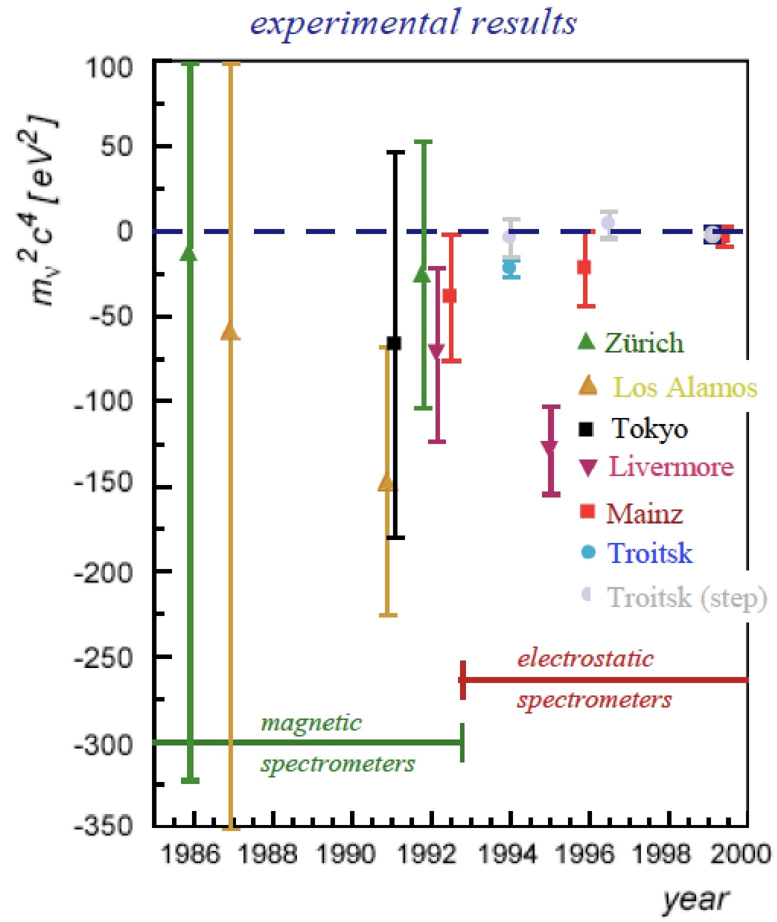


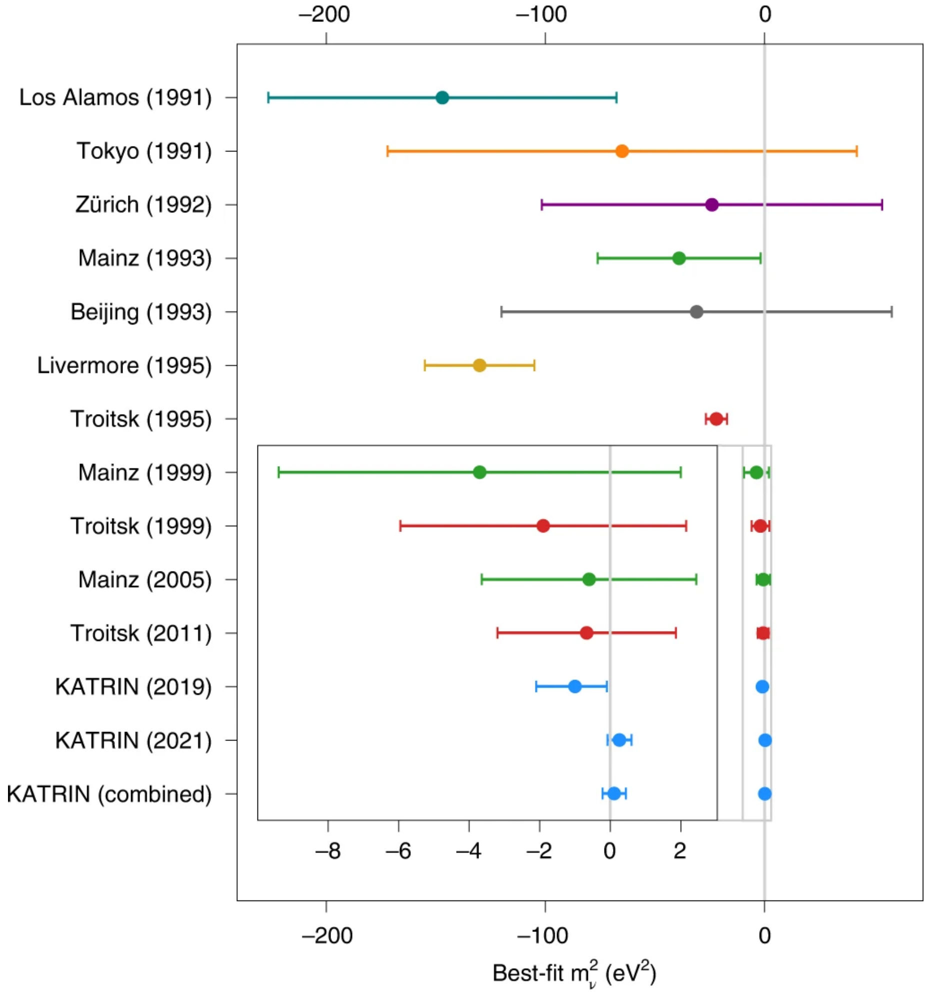
smaller volume than KATRIN (but scalability has to be demonstrated)

eventually atomic tritium will be needed

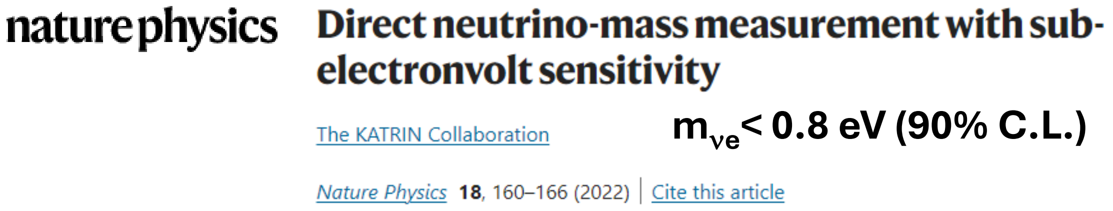
Tremendous progress in T-decay

		m_ν
ITEP	T_2 in complex molecule magn. spectrometer (Tret'yakov)	17-40 eV
Zürich	T_2 - source impl. on carrier magn. spectrometer (Tret'yakov)	< 11.7 eV
Los Alamos	gaseous T_2 - source magn. spectrometer (Tret'yakov)	< 9.3 eV
Tokyo	T - source magn. spectrometer (Tret'yakov)	< 13.1 eV
Livermore	gaseous T_2 - source magn. spectrometer (Tret'yakov)	
Mainz (1994-today)	frozen T_2 - source electrostat. spectrometer	< 2.2 eV
Troitsk (1994-today)	gaseous T_2 - source electrostat. spectrometer	(< 2.5 eV)





Where do we stand on Neutrino Masses from Tritium Decay?

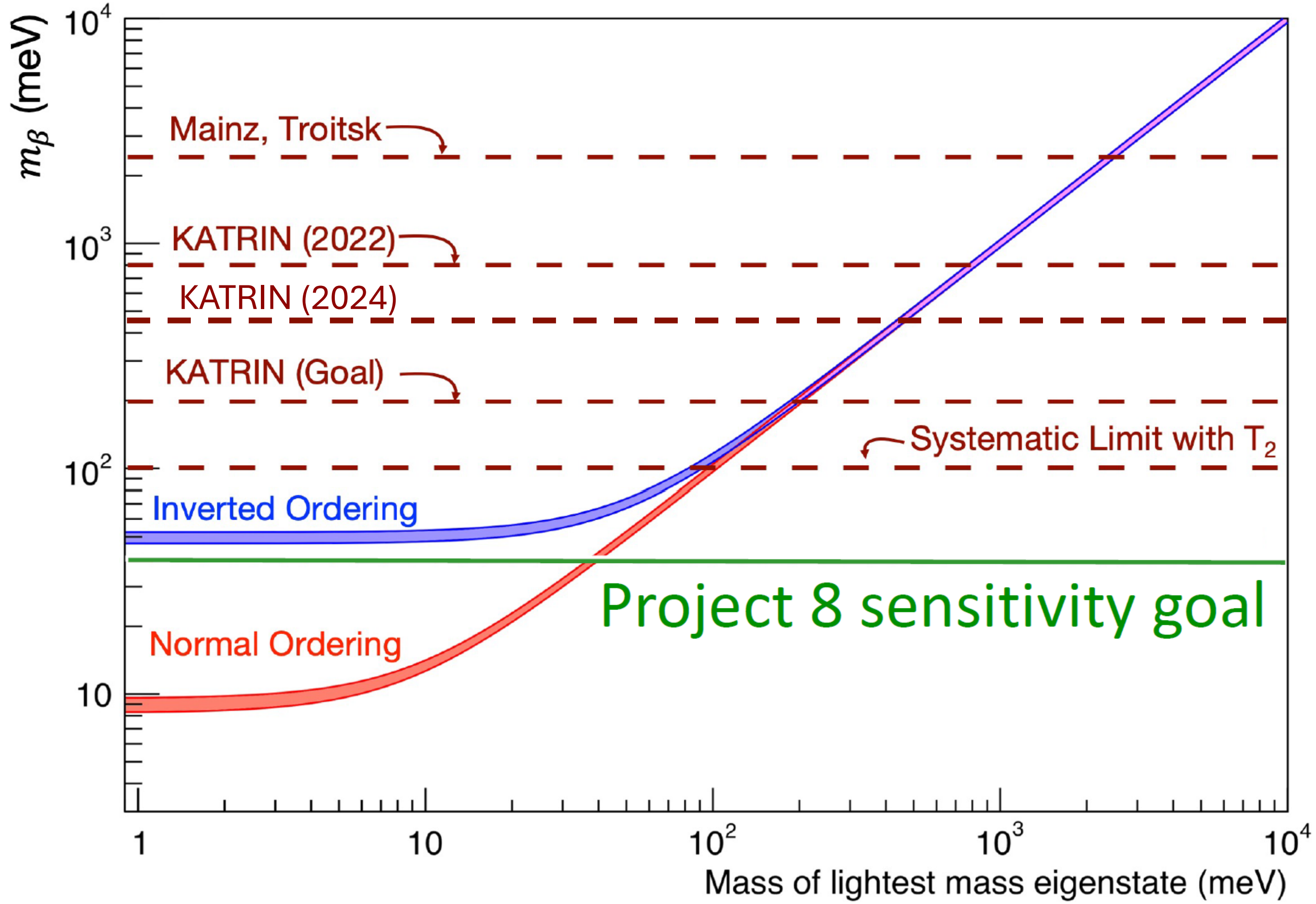


nature physics **Direct neutrino-mass measurement with sub-electronvolt sensitivity**

The KATRIN Collaboration

Nature Physics **18**, 160–166 (2022) | Cite this article

$m_{\nu e} < 0.8$ eV (90% C.L.)

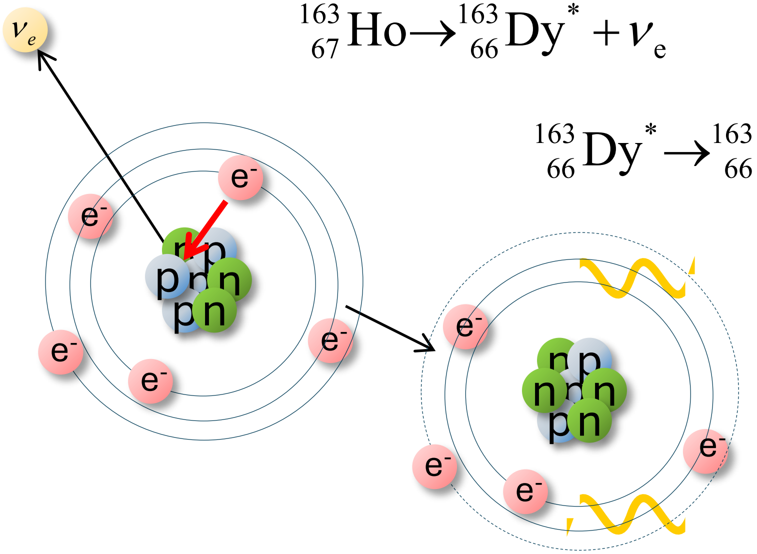


Goals:

- Sensitivity to 40 meV/c^2 neutrino mass
- Measure neutrino mass or exclude inverted hierarchy
- Simultaneous sensitivity to active and sterile neutrinos

Slide Courtesy Elise Novitzki

Precision Holmium EC Decay: ECHo and HOLMES

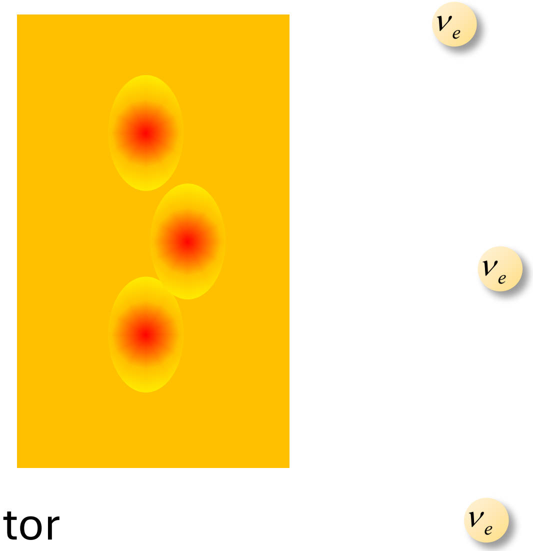


$${}^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_\mathrm{e}$$

$${}^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_\mathrm{C}$$

Atomic de-excitation:

- X-ray emission
- Auger electrons
- Coster-Kronig transitions



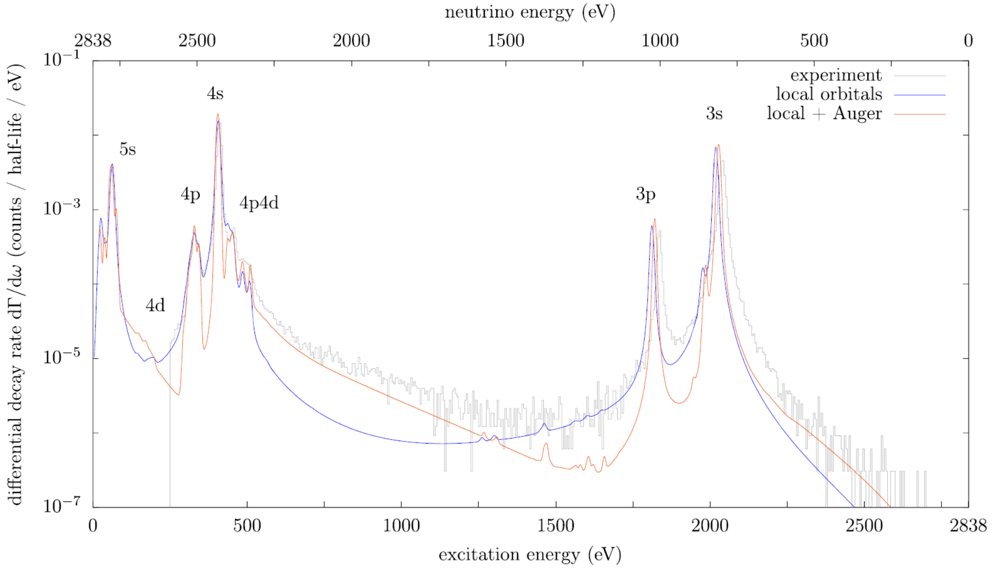
Calorimetric measurement Source = Detector

A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

- $\tau_{1/2} \cong$ 4570 years (2*10^{11} atoms for 1 Bq)
- Q_{EC} = $(2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Ab-initio calculations foresee a smooth shape at the endpoint region

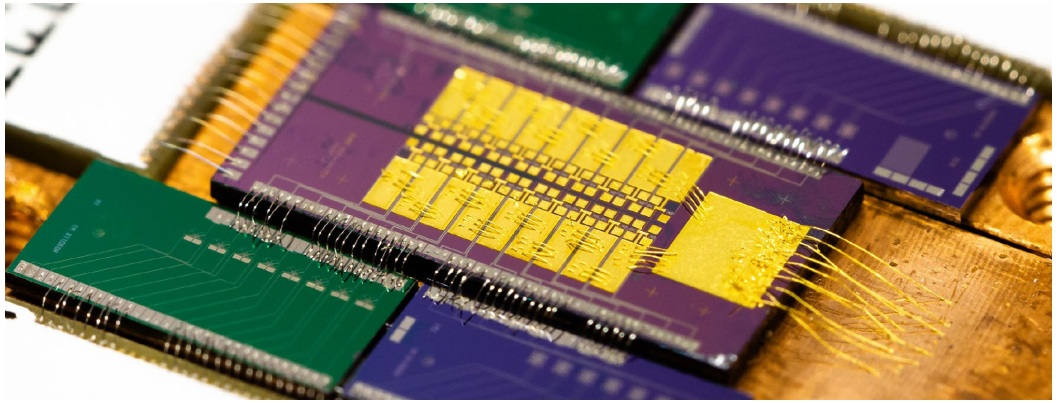


Slide Courtesy: Loredana Gastaldo

M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018

ECHO-1K

Precision Holmium EC Decay - $m_{\nu e}$



60 MMC pixels with about 1 Bq ^{163}Ho: Achievable sensitivity

$m(\nu_e) < 20$ eV (95% C.L.)

4-day measurement with 4 pixels loaded with ~0.2 Bq ^{163}Ho

Energy resolution $\Delta E_{FWHM} = 9.2$ eV

Background level $b < 1.6 \times 10^{-4}$ events/eV/pixel/day

- $Q_{EC} = (2838 \pm 14)$ eV
- $m(\nu_e) < 150$ eV (95% C.L.)

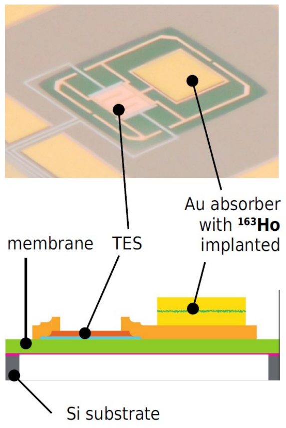
!

low T microcalorimeters with implanted ^{163}Ho

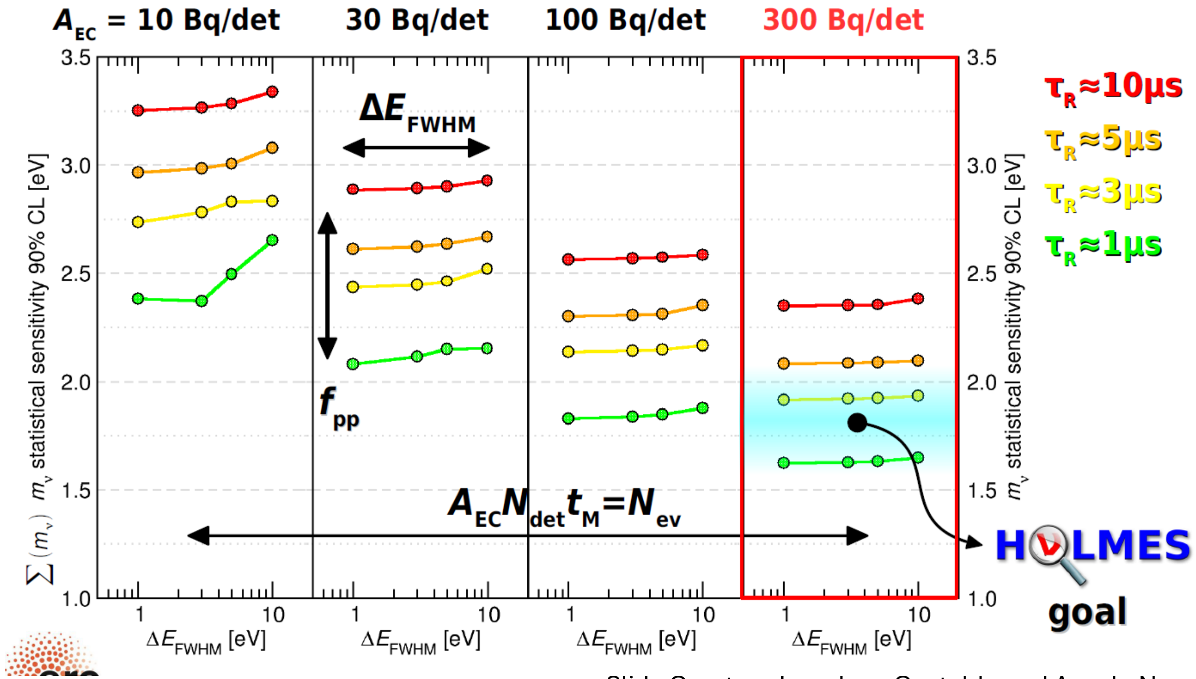
- 6.5×10^{13} atom/det → A_{EC}=300 Bq/det
- $\Delta E \approx 1$ eV and $\tau_R \approx 1$ μs

1000 channel array

- 6.5×10^{16} ^{163}Ho nuclei → ≈18 μg
- 3×10^{13} events in 3 years



exposure $N_{det}t_M$ = 1000 det × 3 y



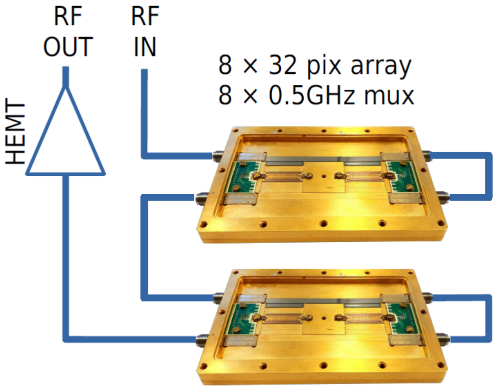
Slide Courtesy Loredana Gastaldo and Angelo Nucciott

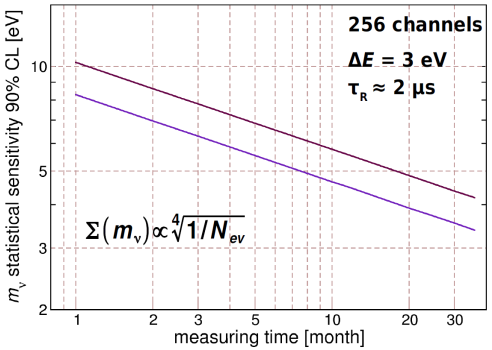
The Future of Neutrino Masses from Ho Decay?

HOLMES

***A* = 1 Hz/det** ***A* = 3 Hz/det**	low dose

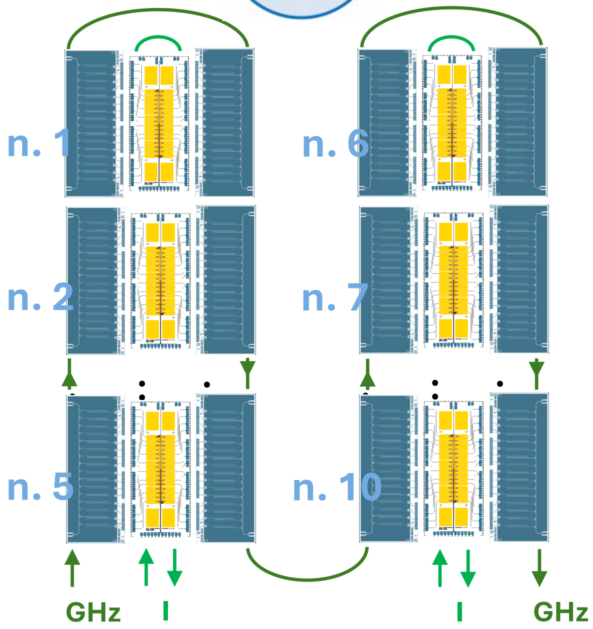
8 × ROACH2+IF boards





erc INFN Università degli Studi di Milano Bicocca NIST PSI centra

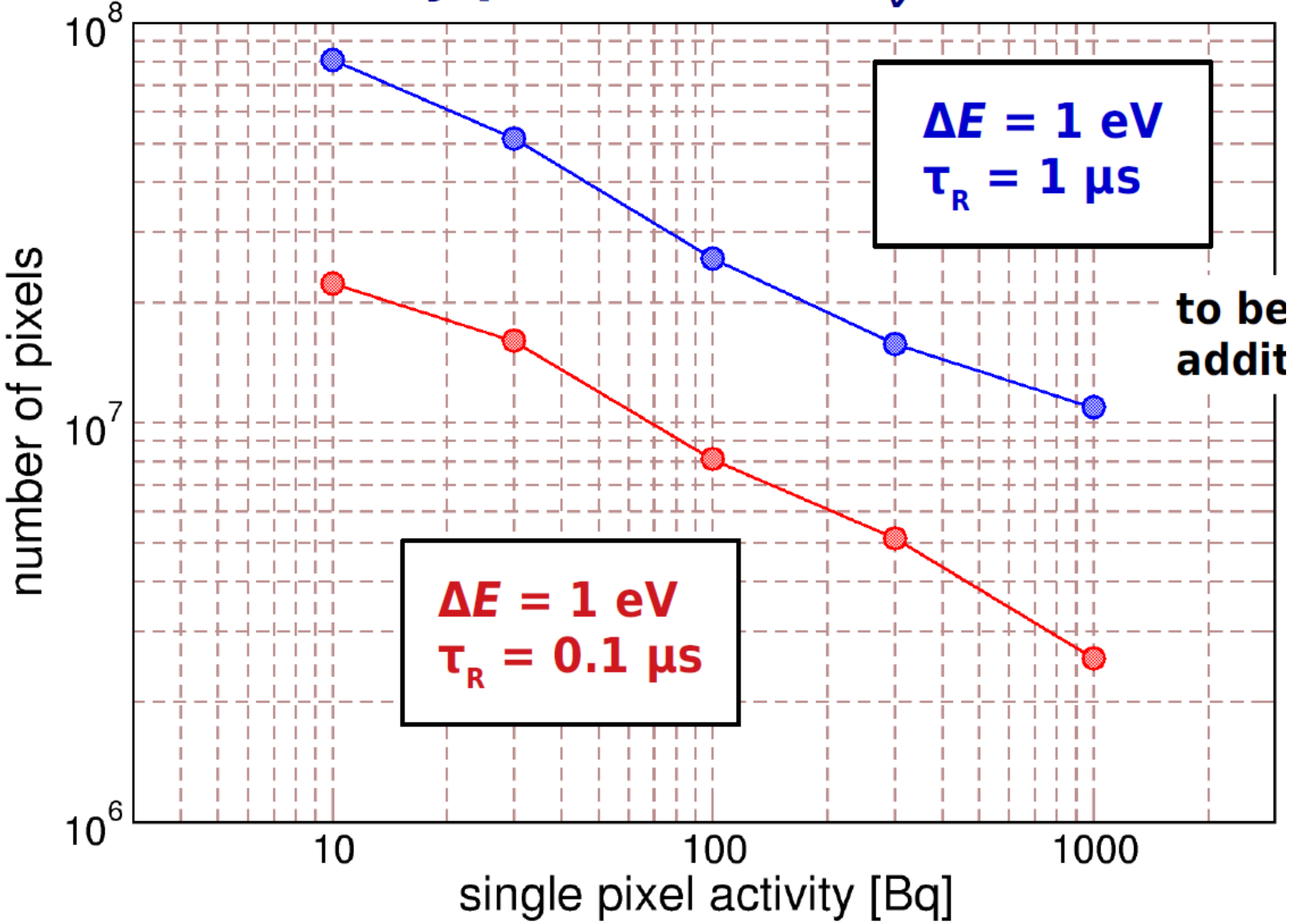
ECHo



DFG Deutsche Forschungsgemeinschaft

The ECHo Collaboration EPJ-ST 226 8 (2017) 1623

how many pixels for $\Sigma(m_\nu) \leq 0.1$ eV ?

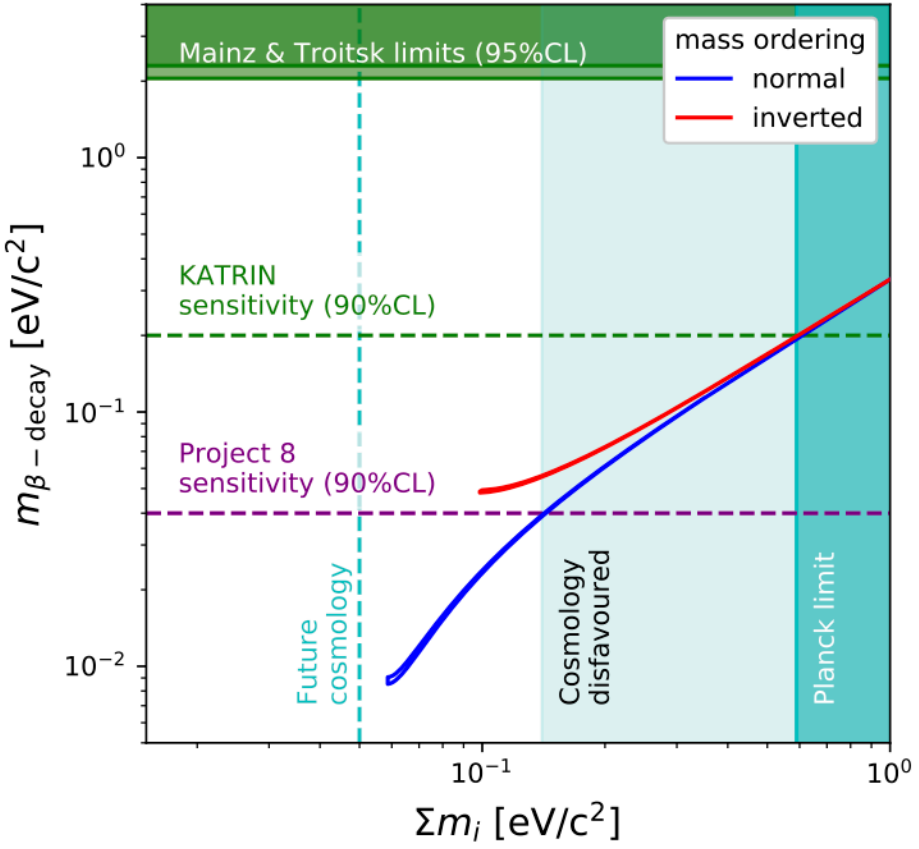


Snowmass LOI: Measuring the electron neutrino mass using the electron capture decay of ^{163}Ho

Cosmology

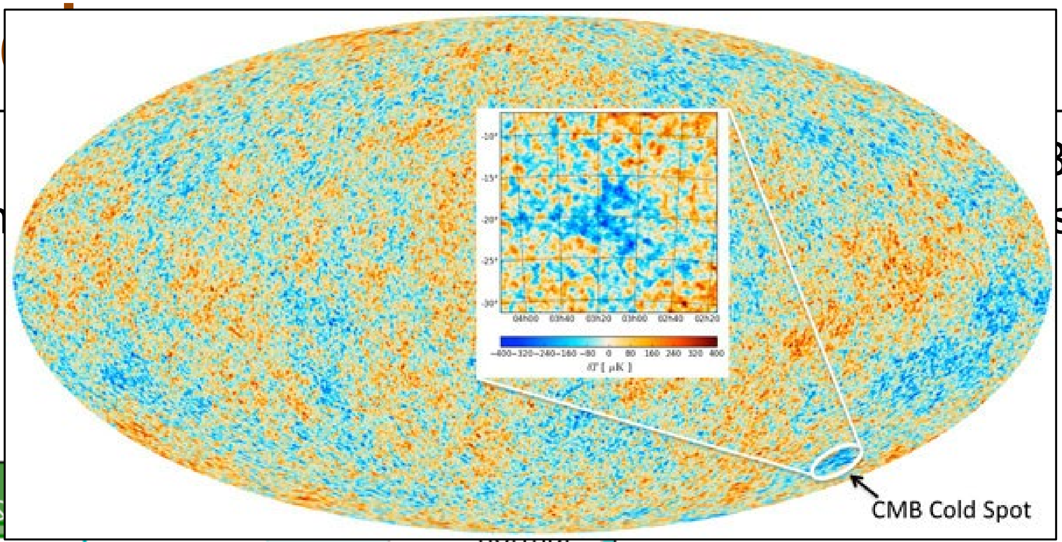
- In parallel to the direct measurements, next-generation CMB experiments aim to measure the sum of the neutrino masses:

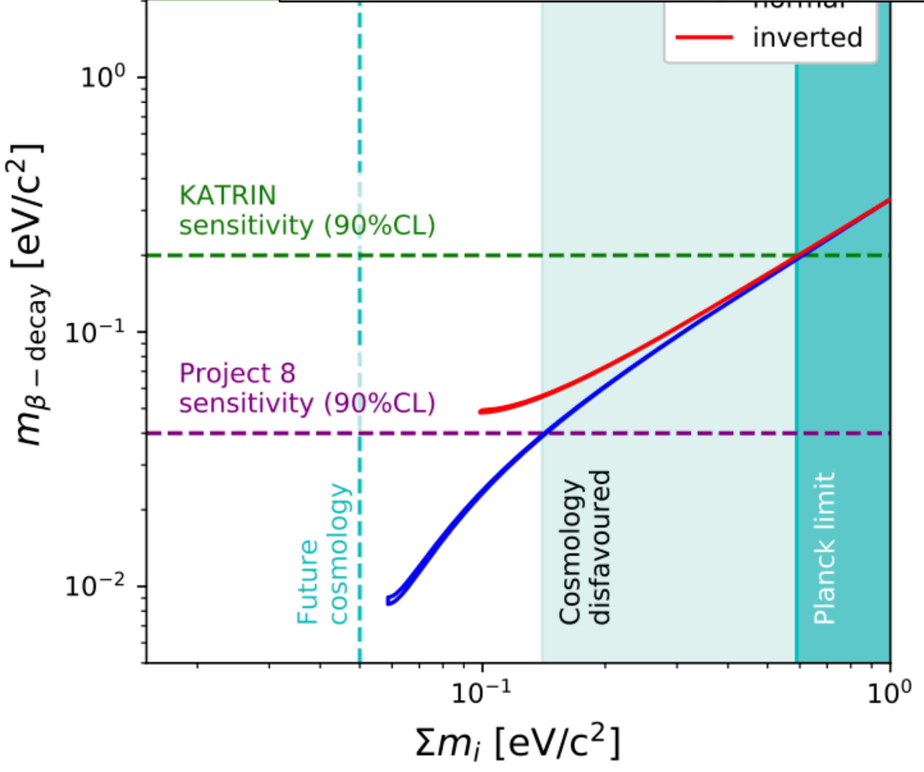
$$m_\nu = \sum_i m_i$$



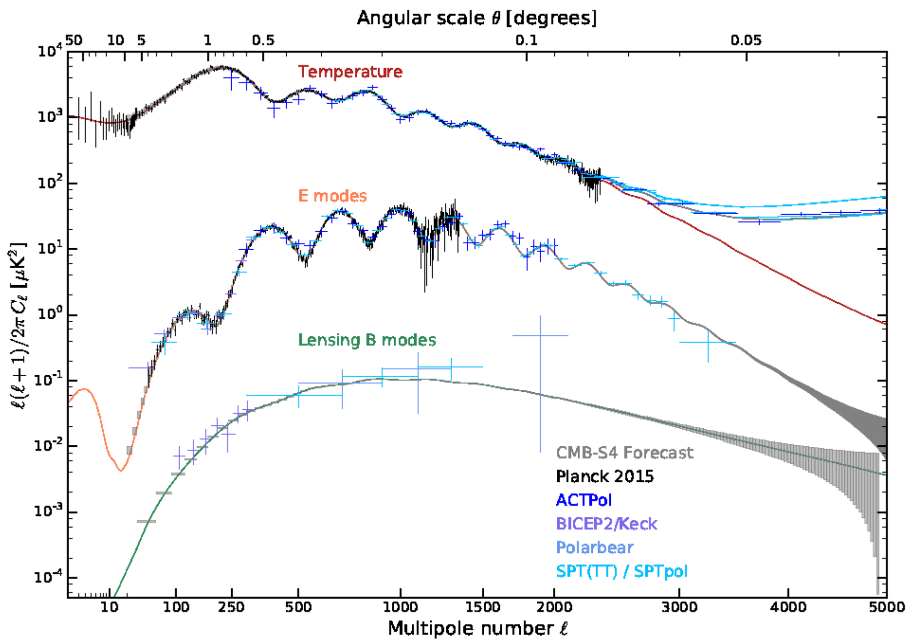
Cosm

- In parallel B
  experimen s:

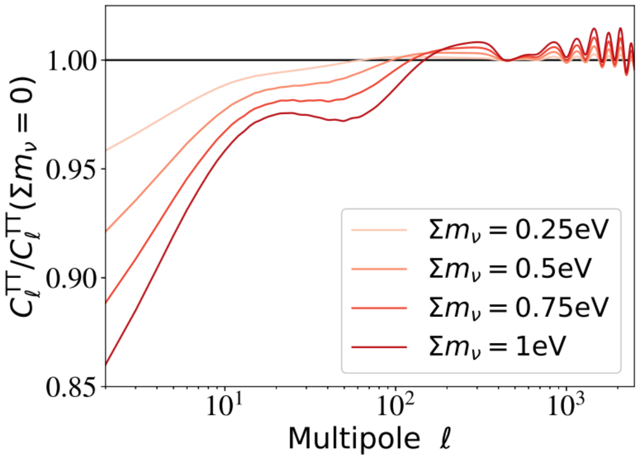




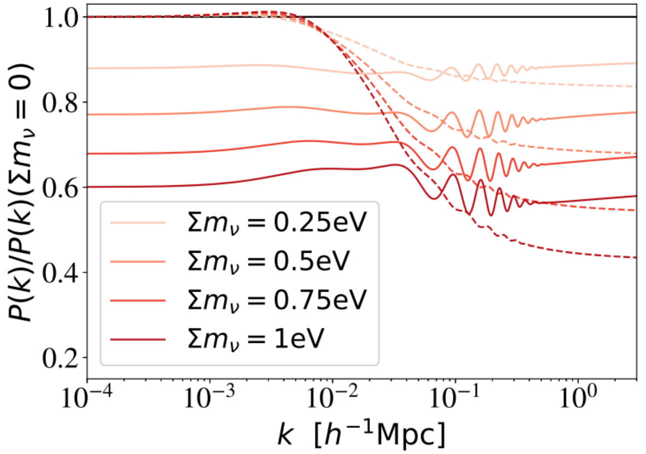
Projected sensitivity for CMB S4:



Temperature anisotropies:

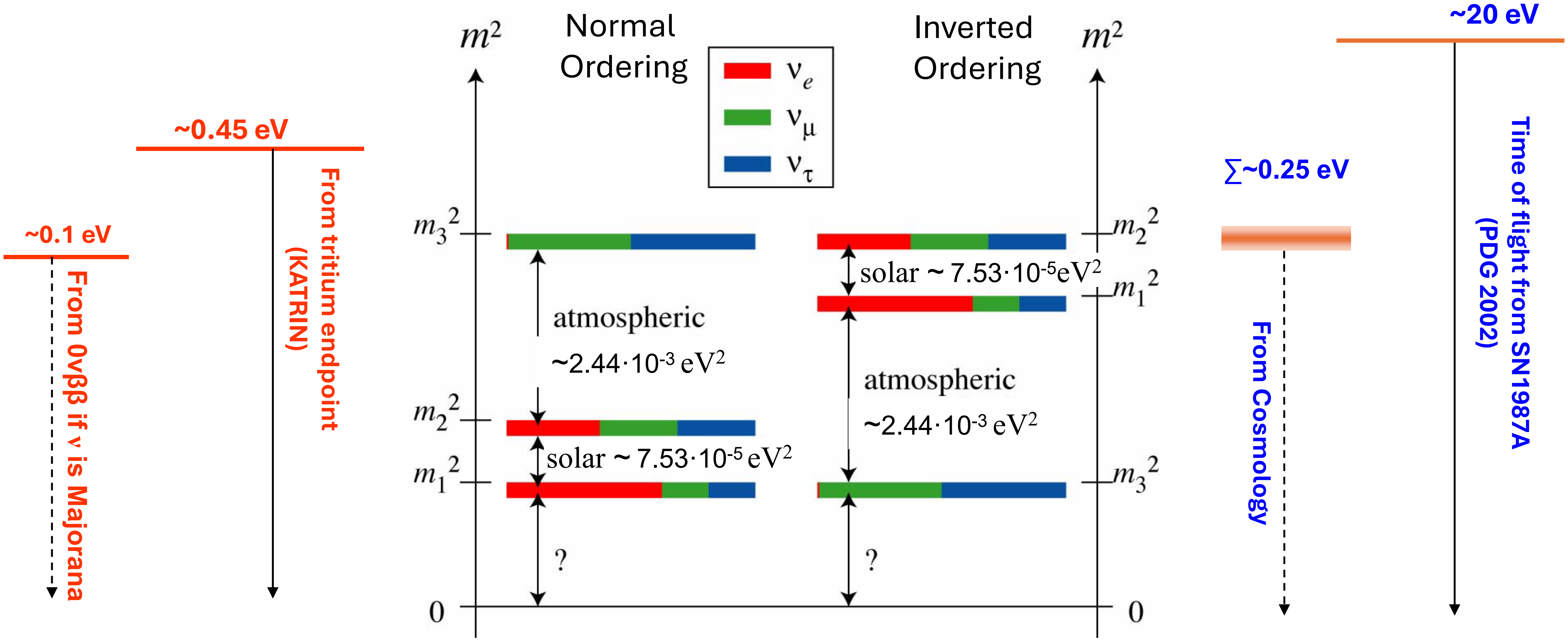


Matter power spectrum:



https://pdg.lbl.gov/2019/reviews/rpp2019-rev-neutrinos-in-cosmology.pdf

What we know about neutrinos



Search for Heavy (Mostly Sterile) Neutrino Mass States

Mostly Sterile keV Neutrino Mass States

- Beta decay is particularly sensitive to keV-MeV mass states

- Mass states in this region have $\tau \approx \tau_{\text{universe}}$ and could thus serve as some fraction of the observed DM in our universe
  - Excellent candidates for warm dark matter Dodelson and Widrow, **PRL** 72, 17 (1994)

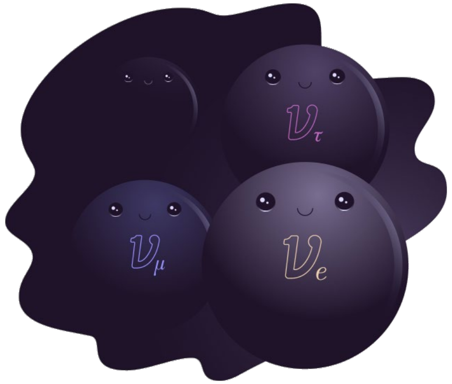


Image Courtesy: Symmetry Magazine

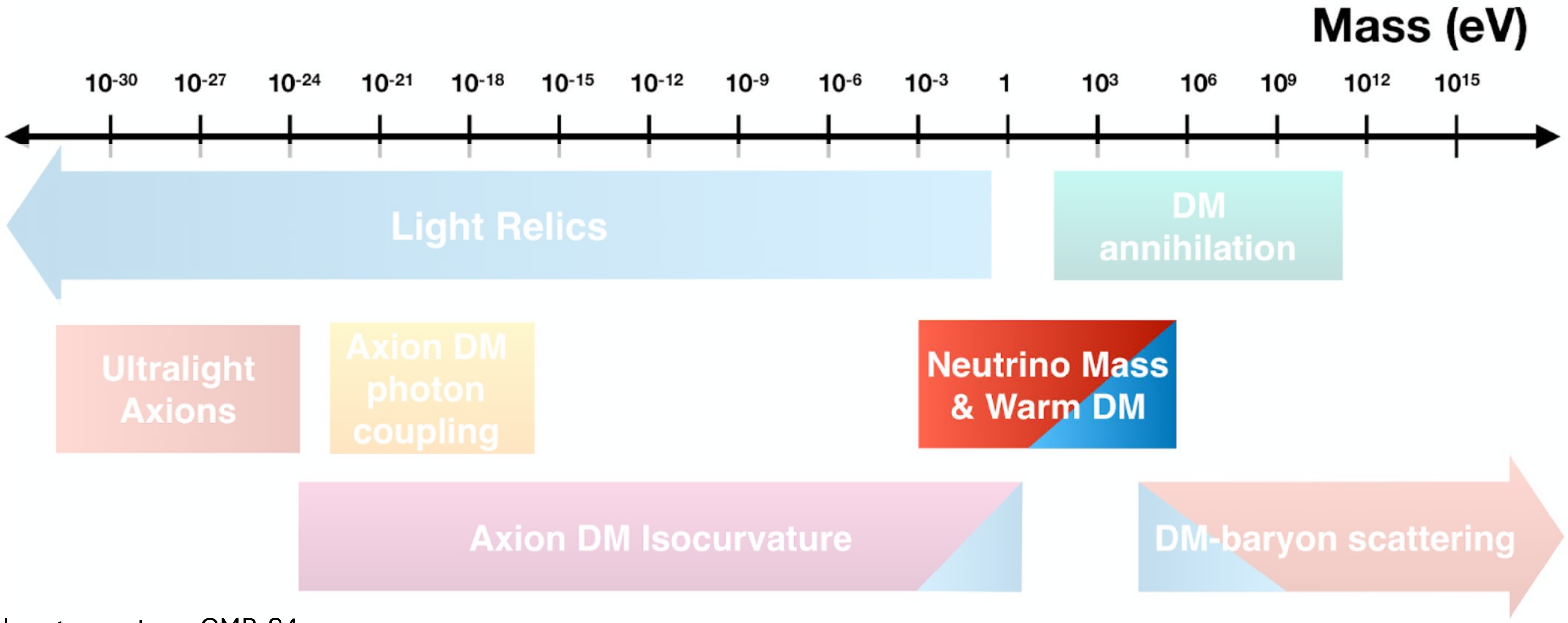
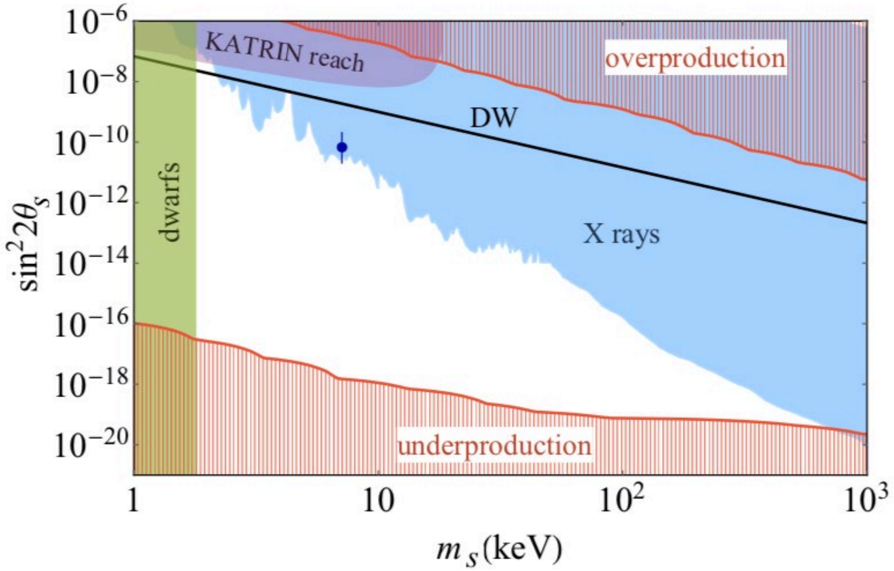


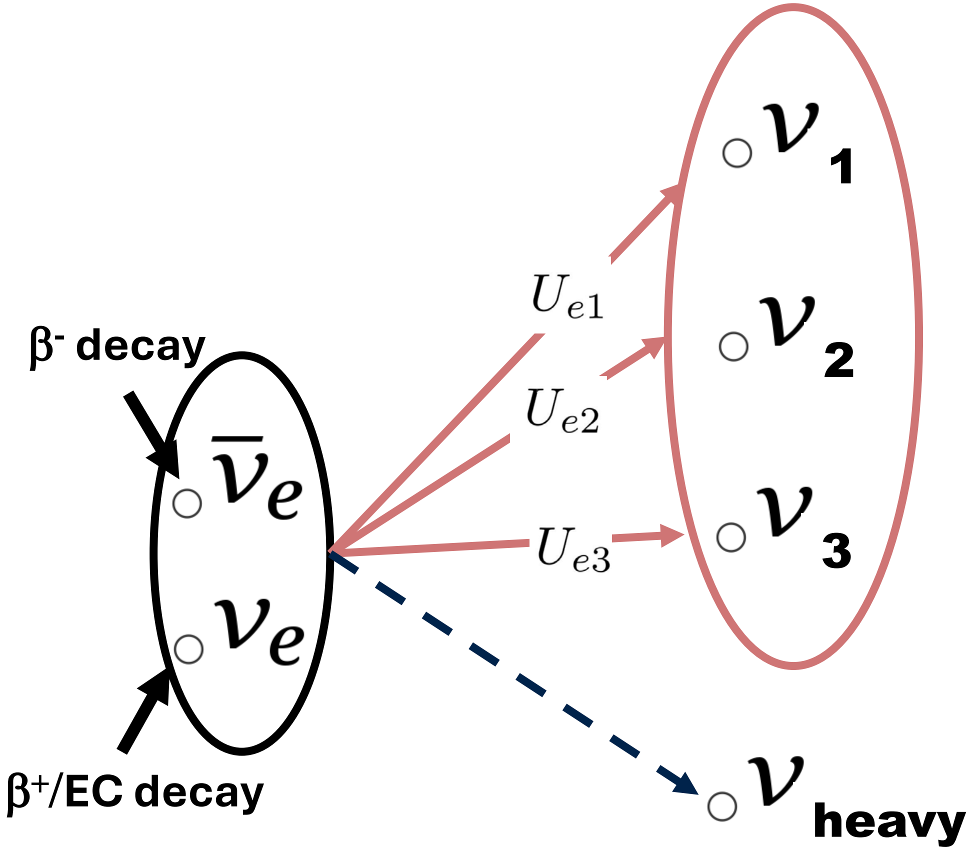
Image courtesy: CMB-S4

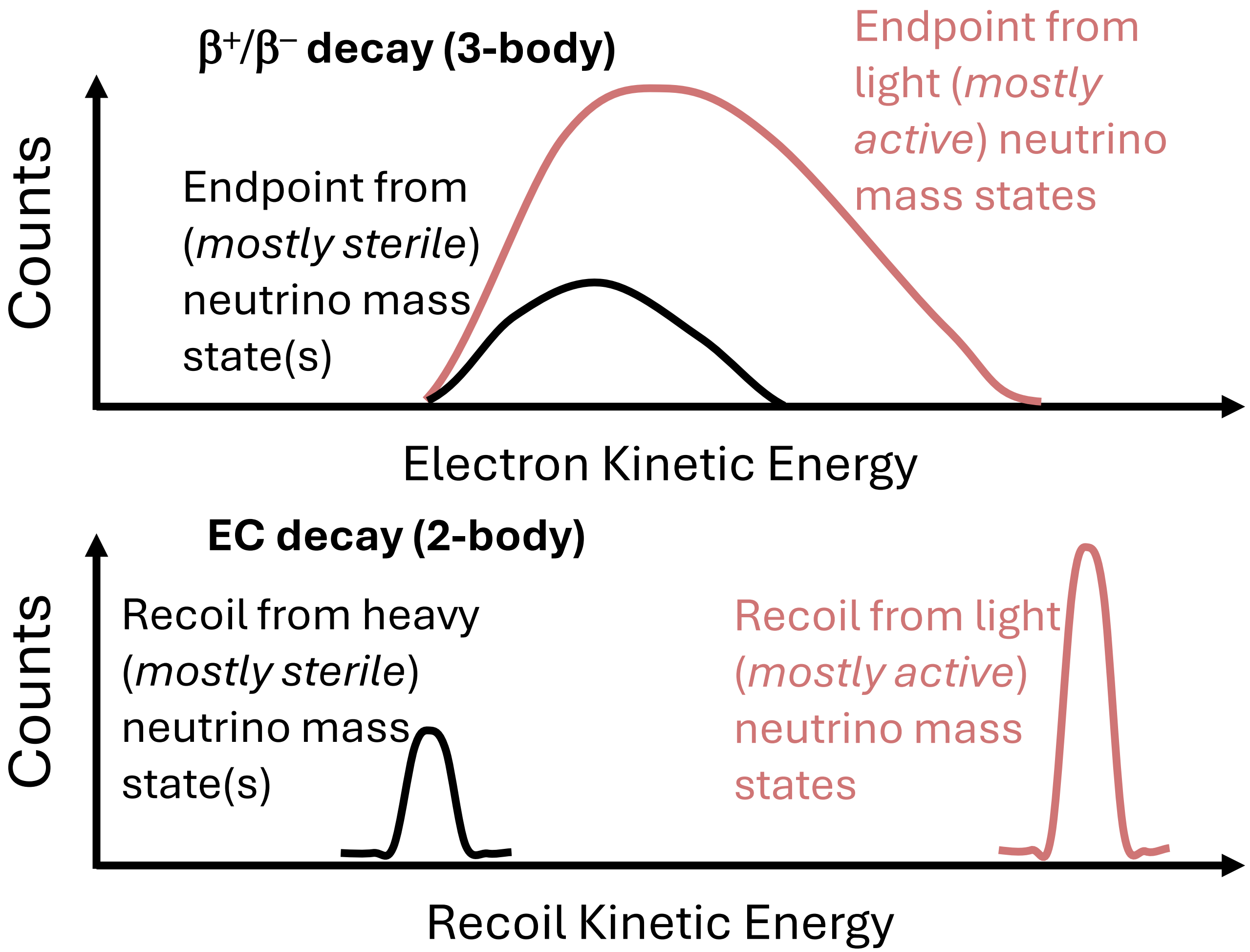


B. Dasgupta and J. Kopp, Phys. Rep. **928**, 1-63 (2021)

Heavy Neutrino Mass Studies via Coupling to ν_e

- In EC/β^+ and β^- decay, we study the relative coupling of the mass states to $\bar{\nu}_e$ (ν_e)
- Momentum is conserved with the mass states, not flavor states

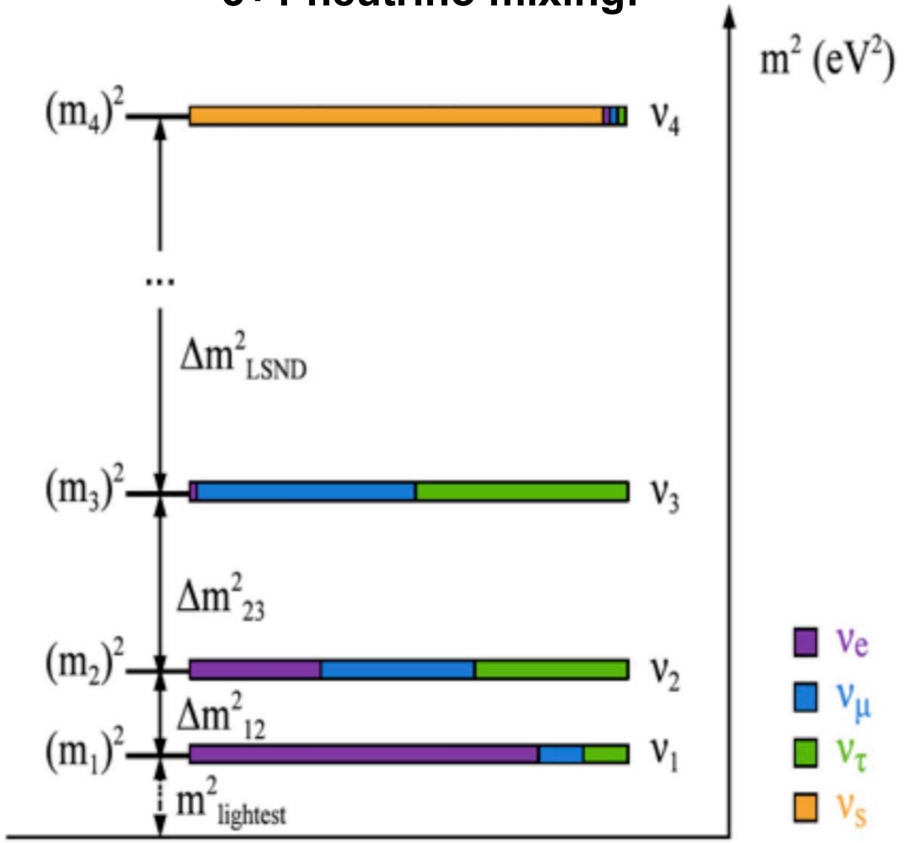




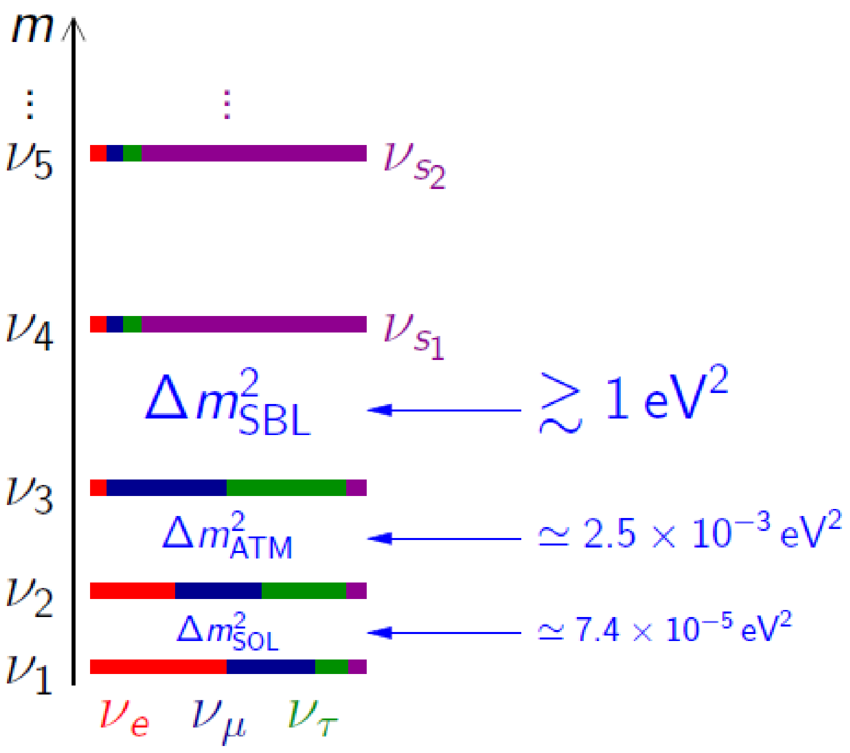
Sterile νs

- Potential explanation for the short baseline data is a small mixing with a light (~eV scale) sterile ν
  - Or maybe 2 more sterile νs are needed to fit the data? (or *n* more?)

3+1 neutrino mixing:



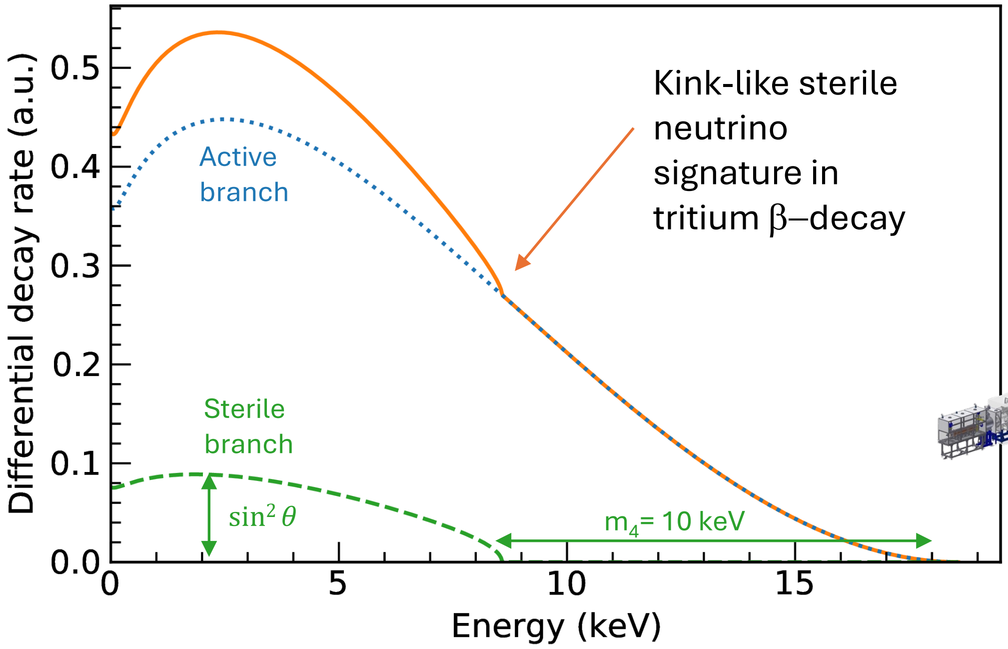
3+*n* (*n*=2?) neutrino mixing:



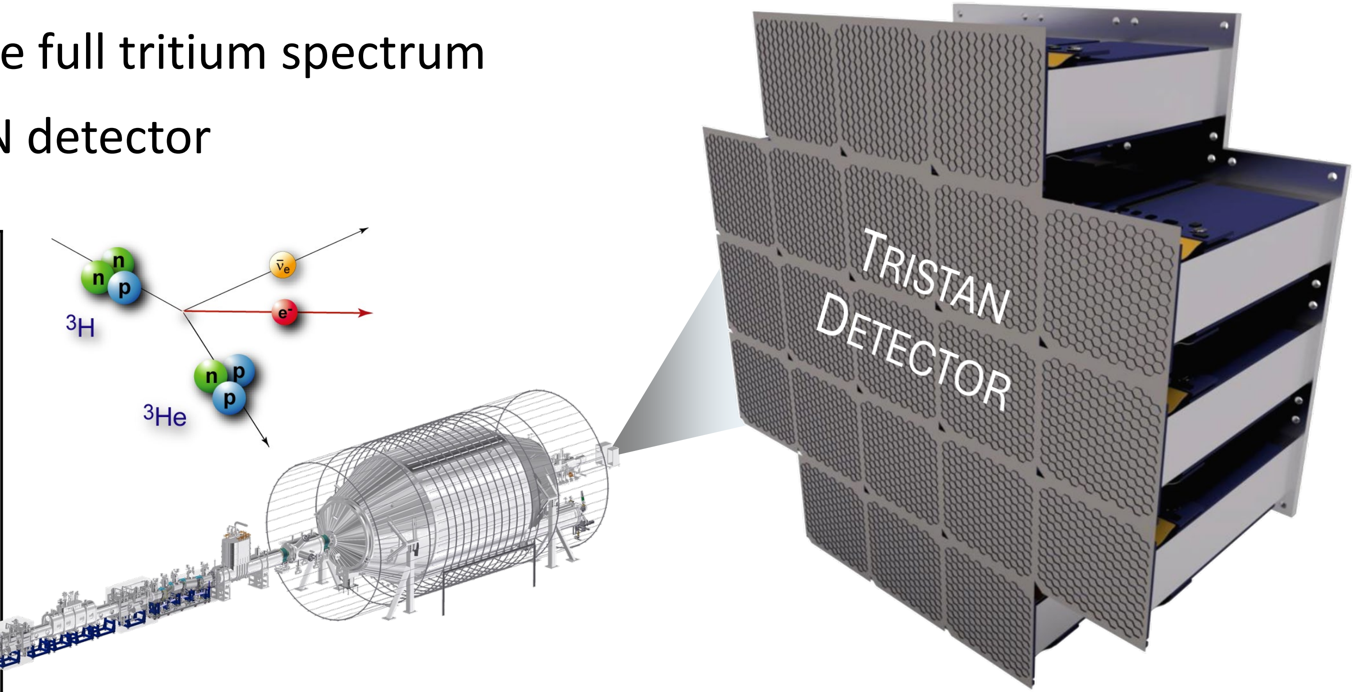
Tritium Endpoint Measurements – KATRIN/TRISTAN

Idea:

- Make use of the strong KATRIN tritium source and beamline
- Perform a differential measurement of the full tritium spectrum
- Requires new detector system → TRISTAN detector



Kink-like sterile neutrino signature in tritium β–decay



S. Mertens et al. JCAP 1502 (2015)
S. Mertens et al, PRD 91 (2015)

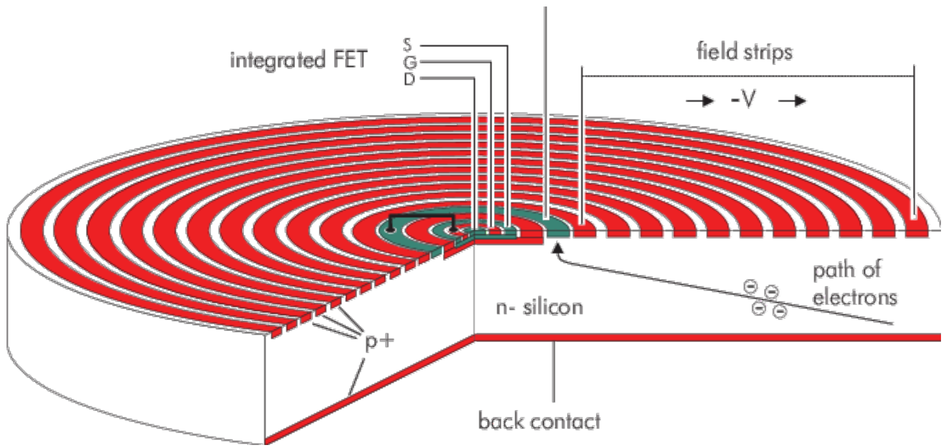
Tritium Endpoint Measurements – KATRIN/TRISTAN

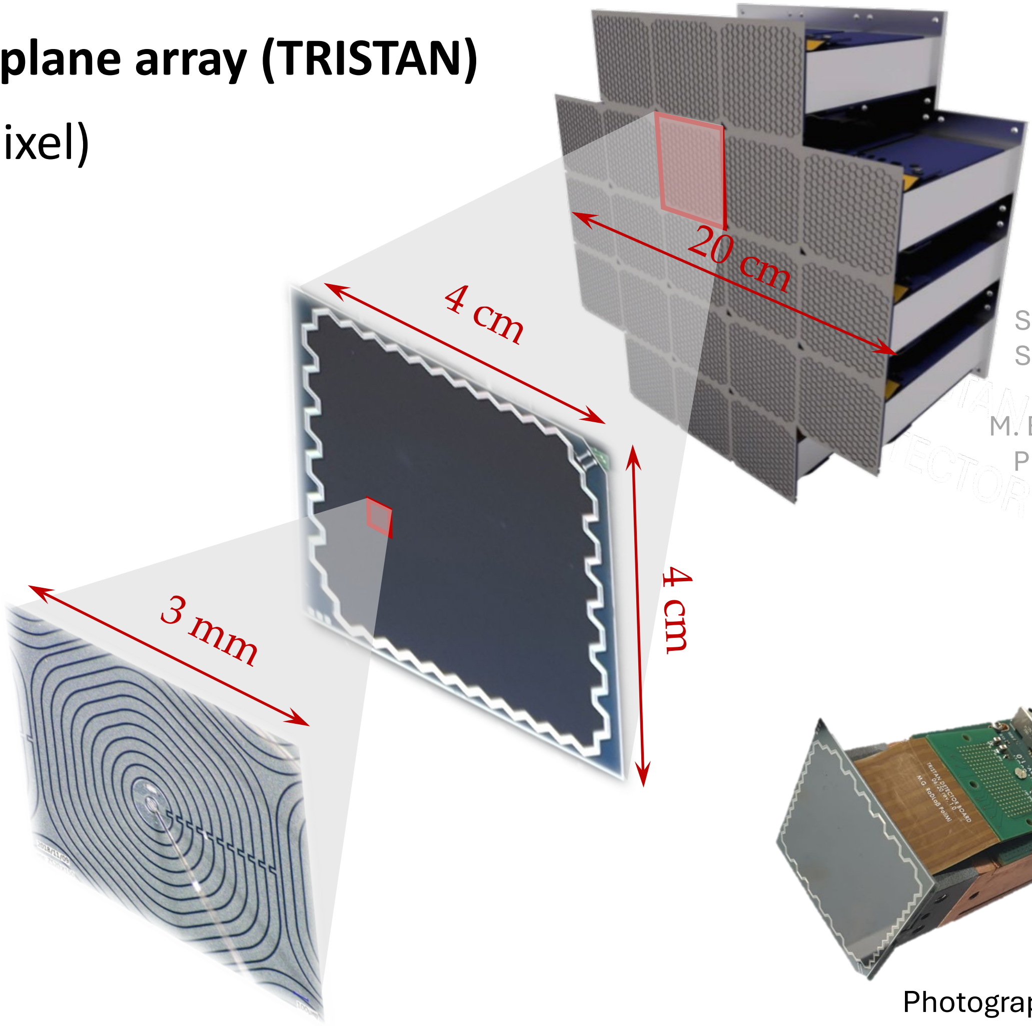
Multi-pixel (>1000) silicon drift detector focal plane array (TRISTAN)

✓ Capability of handling high rates (> 10^5 cps/pixel)

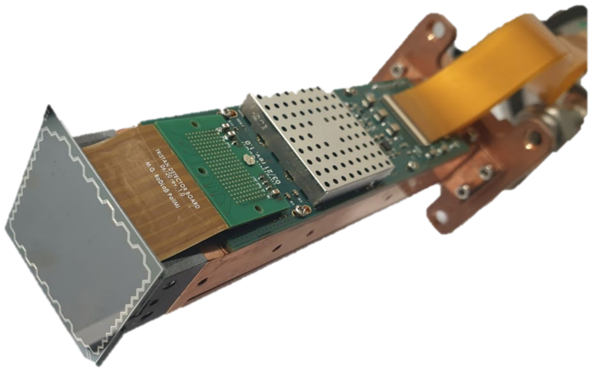
✓ Good energy resolution (300 eV @ 20 keV)

✓ Large focal plane area coverage





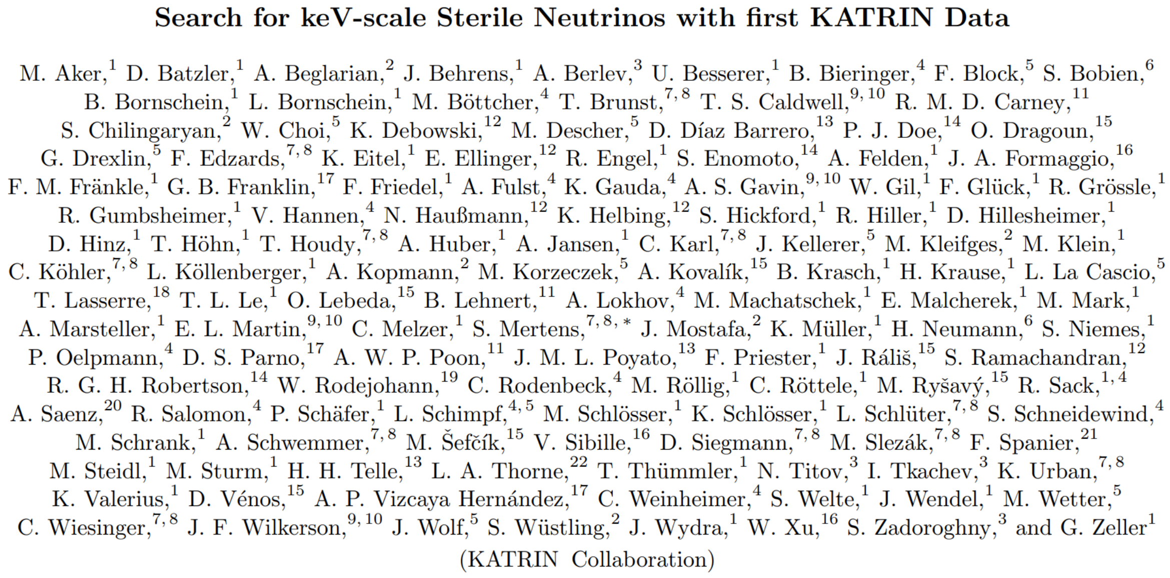
S. Mertens et al, J. Phys. G46 (2019)
S. Mertens et al, J. Phys. G48 (2020)
M. Gugiatti et al, NIM-A 979 (2020)
M. Biassoni et al, EPJ. Plus 136 (2021)
P. King et al JINST 16 T07007 (2021)



Photograph of TRISTAN module

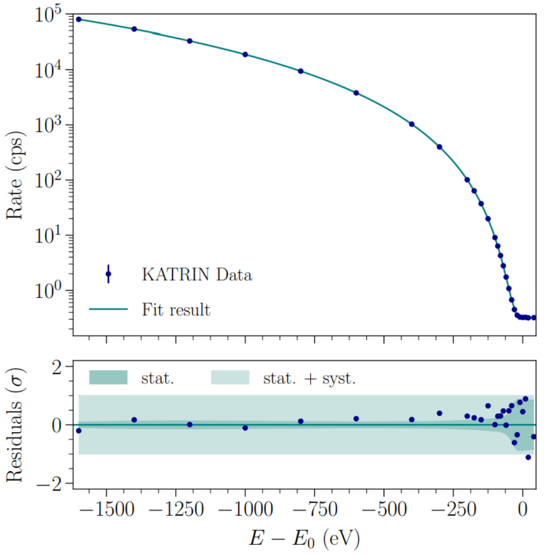
First keV-Mass Neutrino Search with KATRIN Data

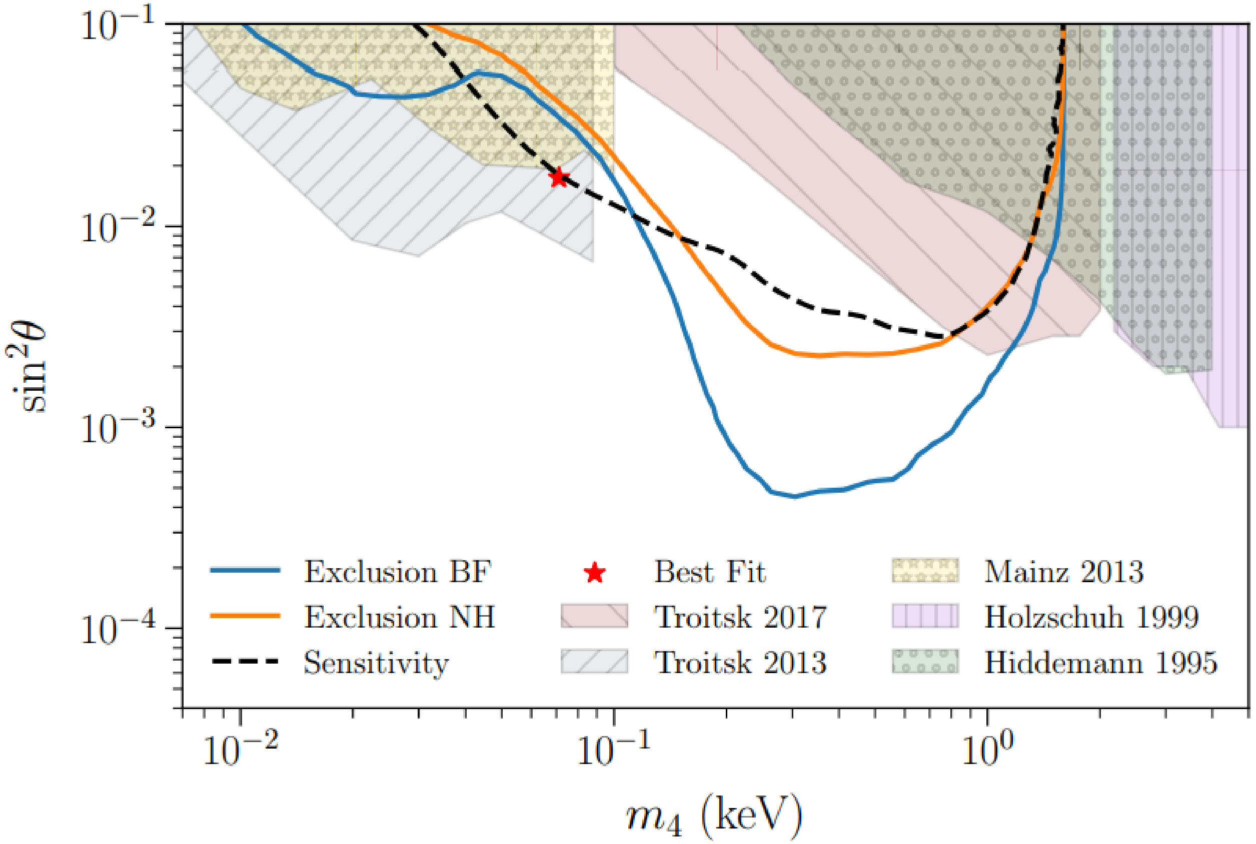
2207.06337



Search for keV-scale Sterile Neutrinos with first KATRIN Data

M. Aker,[1] D. Batzler,[1] A. Beglarian,[2] J. Behrens,[1] A. Berlev,[3] U. Besserer,[1] B. Bieringer,[4] F. Block,[5] S. Bobien,[6]
B. Bornschein,[1] L. Bornschein,[1] M. Böttcher,[4] T. Brunst,[7,8] T. S. Caldwell,[9,10] R. M. D. Carney,[11]
S. Chilingaryan,[2] W. Choi,[5] K. Debowski,[12] M. Descher,[5] D. Díaz Barrero,[13] P. J. Doe,[14] O. Dragoun,[15]
G. Drexlin,[5] F. Edzards,[7,8] K. Eitel,[1] E. Ellinger,[12] R. Engel,[1] S. Enomoto,[14] A. Felden,[1] J. A. Formaggio,[16]
F. M. Fränkle,[1] G. B. Franklin,[17] F. Friedel,[1] A. Fulst,[4] K. Gauda,[4] A. S. Gavin,[9,10] W. Gil,[1] F. Glück,[1] R. Grössle,[1]
R. Gumbsheimer,[1] V. Hannen,[4] N. Haußmann,[12] K. Helbing,[12] S. Hickford,[1] R. Hiller,[1] D. Hillesheimer,[1]
D. Hinz,[1] T. Höhn,[1] T. Houdy,[7,8] A. Huber,[1] A. Jansen,[1] C. Karl,[7,8] J. Kellerer,[5] M. Kleifges,[2] M. Klein,[1]
C. Köhler,[7,8] L. Köllenberger,[1] A. Kopmann,[2] M. Korzeczek,[5] A. Kovalík,[15] B. Krasch,[1] H. Krause,[1] L. La Cascio,[5]
T. Lasserre,[18] T. L. Le,[1] O. Lebeda,[15] B. Lehnert,[11] A. Lokhov,[4] M. Machatschek,[1] E. Malcherek,[1] M. Mark,[1]
A. Marsteller,[1] E. L. Martin,[9,10] C. Melzer,[1] S. Mertens,[7,8,*] J. Mostafa,[2] K. Müller,[1] H. Neumann,[6] S. Niemes,[1]
P. Oelpmann,[4] D. S. Parno,[17] A. W. P. Poon,[11] J. M. L. Poyato,[13] F. Priester,[1] J. Ráliš,[15] S. Ramachandran,[12]
R. G. H. Robertson,[14] W. Rodejohann,[19] C. Rodenbeck,[4] M. Röllig,[1] C. Röttele,[1] M. Ryšavý,[15] R. Sack,[1,4]
A. Saenz,[20] R. Salomon,[4] P. Schäfer,[1] L. Schimpf,[4,5] M. Schlösser,[1] K. Schlösser,[1] L. Schlüter,[7,8] S. Schneidewind,[4]
M. Schrank,[1] A. Schwemmer,[7,8] M. Šefčík,[15] V. Sibille,[16] D. Siegmann,[7,8] M. Slezák,[7,8] F. Spanier,[21]
M. Steidl,[1] M. Sturm,[1] H. H. Telle,[13] L. A. Thorne,[22] T. Thümmler,[1] N. Titov,[3] I. Tkachev,[3] K. Urban,[7,8]
K. Valerius,[1] D. Vénos,[15] A. P. Vizcaya Hernández,[17] C. Weinheimer,[4] S. Welte,[1] J. Wendel,[1] M. Wetter,[5]
C. Wiesinger,[7,8] J. F. Wilkerson,[9,10] J. Wolf,[5] S. Wüstling,[2] J. Wydra,[1] W. Xu,[16] S. Zadoroghny,[3] and G. Zeller[1]
(KATRIN Collaboration)

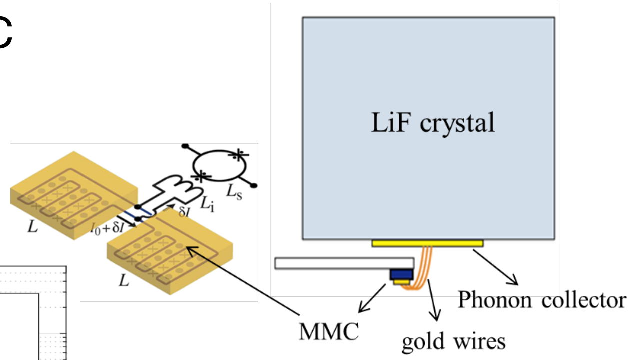


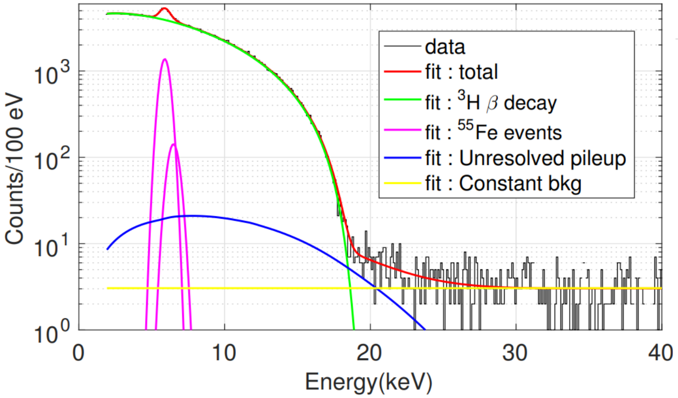


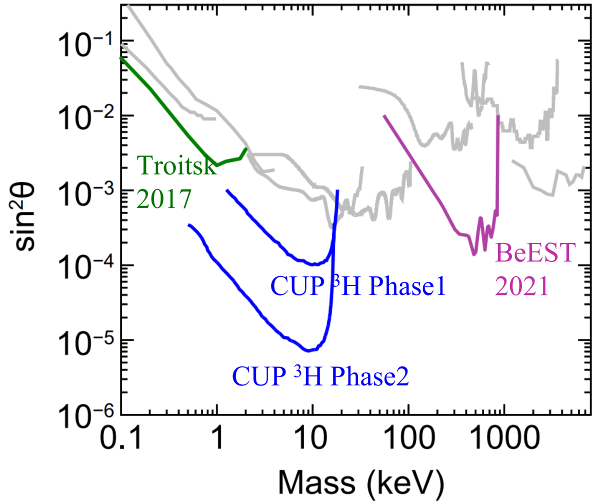
Rare Isotopes in Superconducting Sensors for keV Searches

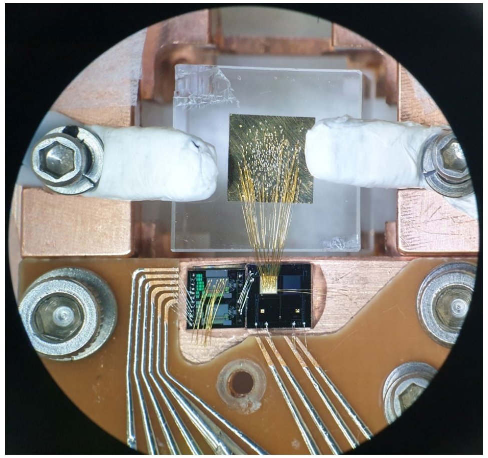
^{3}H in LiF Bolometer + MMC

YC Lee, LTD-19 2021

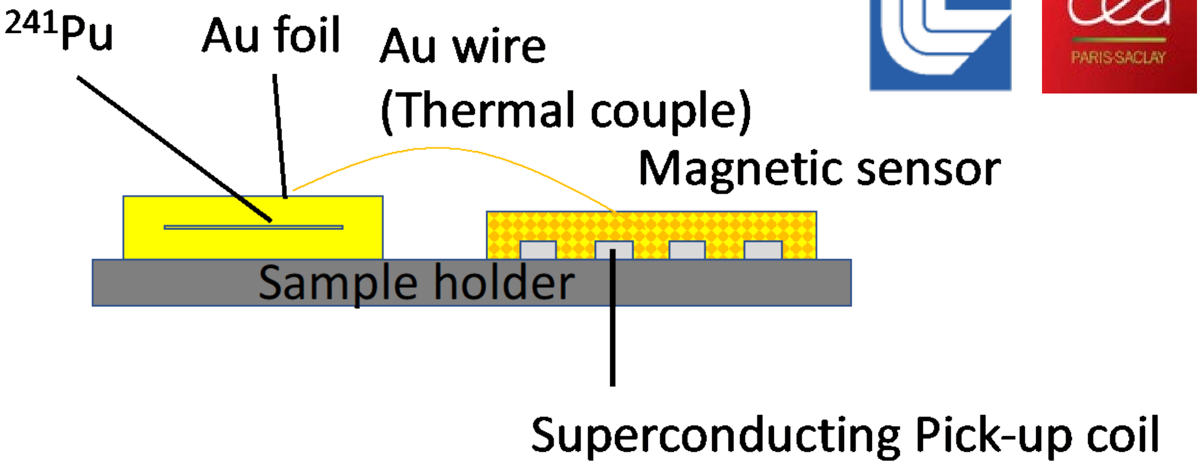


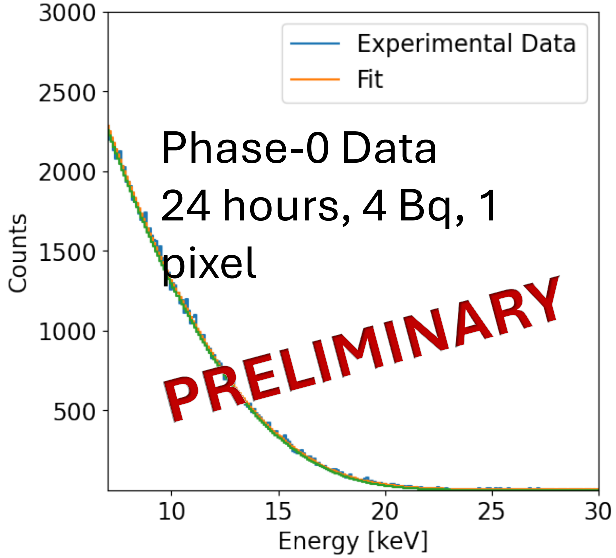


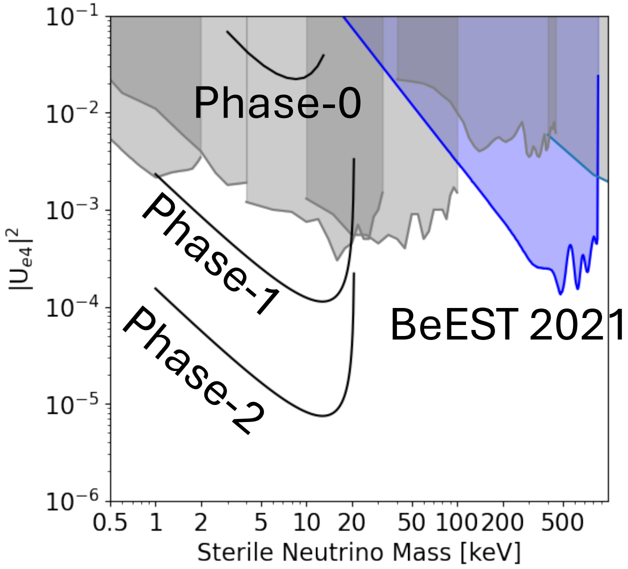




^{241}Pu in Au + MMC : Magneto-ν Experiment

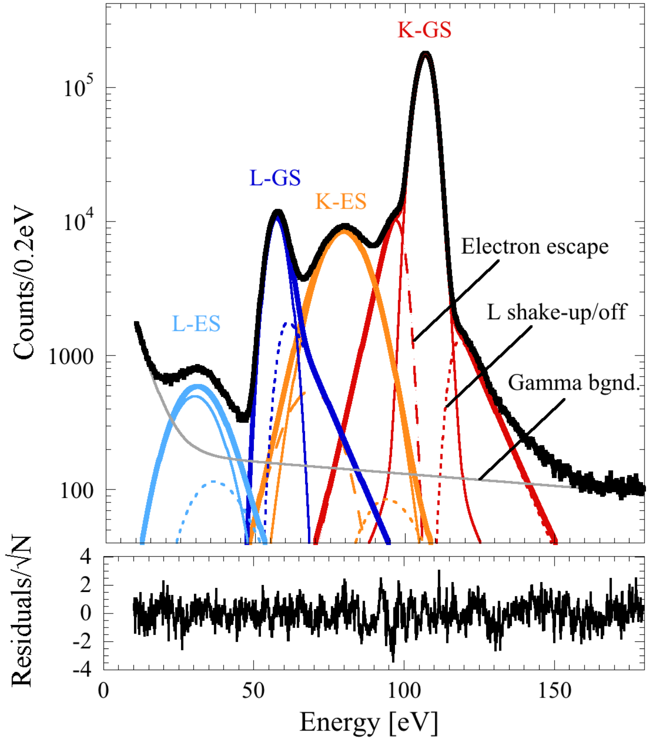




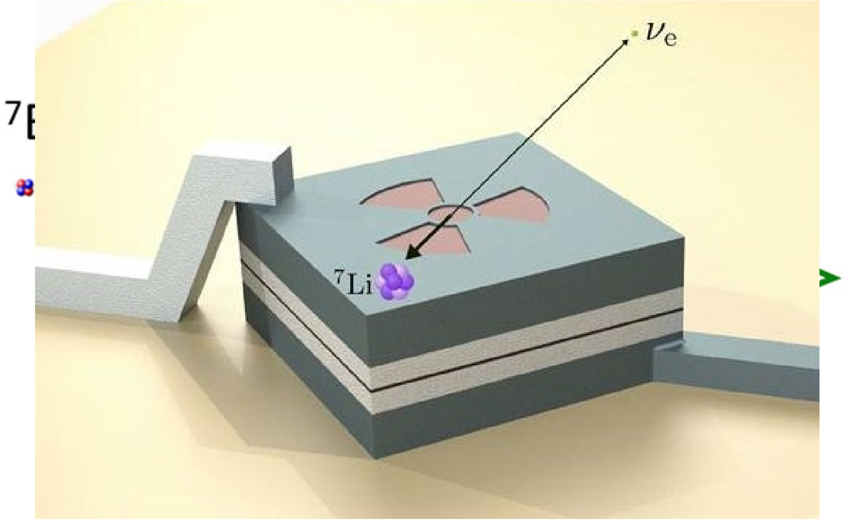


^{7}Be EC Decay - The BeEST Experiment

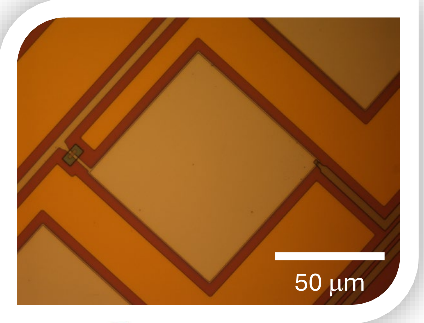
Rare-isotope implantation at TRIUMF-ISAC

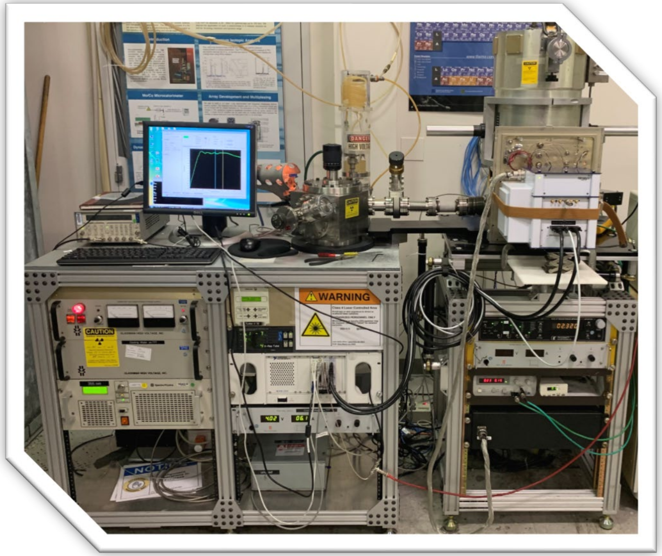


A. Samanta *et al.*, Phys. Rev. Mat. (*in press*) (2022)
S. Friedrich *et al.*, J. Low Temp. Phys. (*in press*) (2022)
C. Bray *et al.*, J. Low Temp. Phys. (*in press*) (2022)
K.G. Leach and S. Friedrich, J. Low Temp. Phys. (*in press*) (2022)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)
S. Friedrich *et al.*, J. Low Temp. Phys. **200**, 200 (2020)

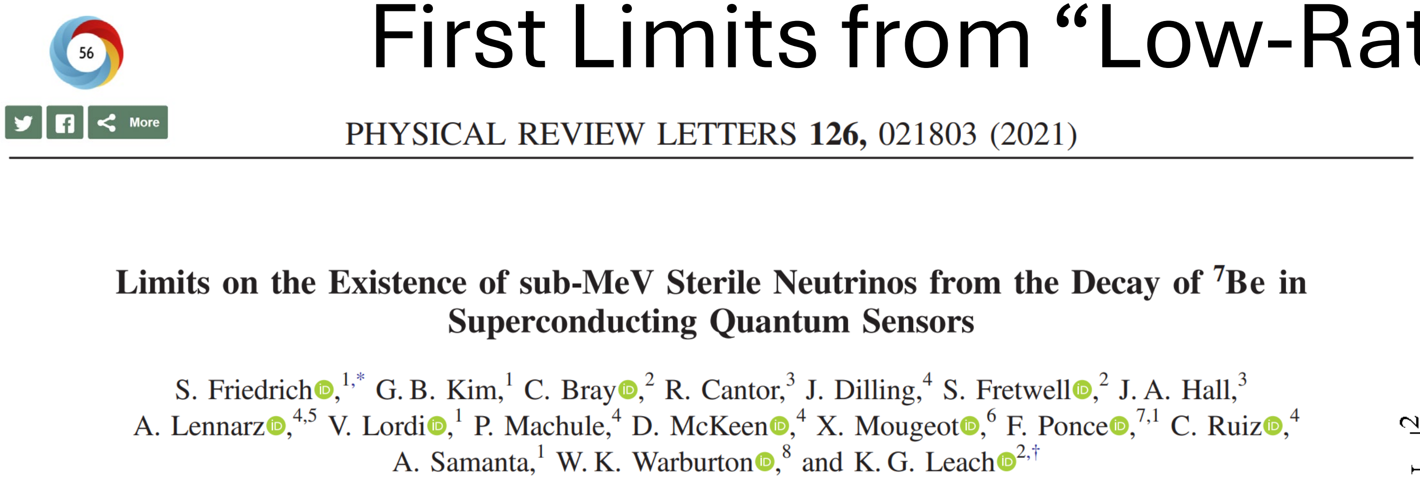


Ta, Al, and Nb-based STJ Sensors





First Limits from “Low-Rate” Phase-II Data

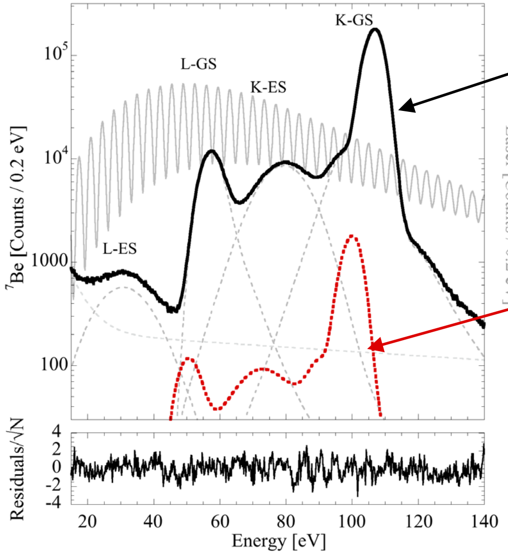


PHYSICAL REVIEW LETTERS **126,** 021803 (2021)

Limits on the Existence of sub-MeV Sterile Neutrinos from the Decay of ^{7}Be in Superconducting Quantum Sensors

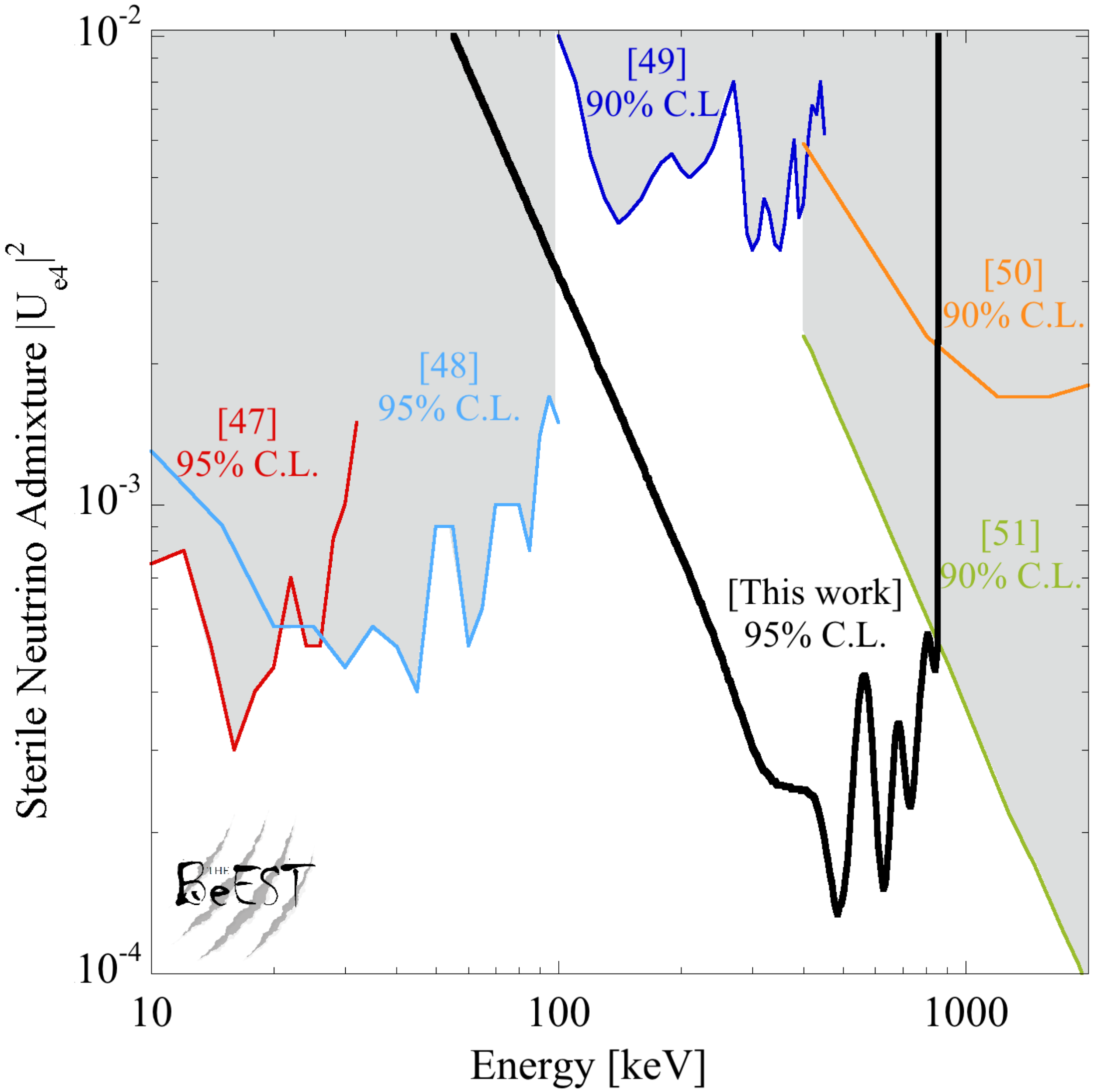
S. Friedrich,[1,*] G. B. Kim,[1] C. Bray,[2] R. Cantor,[3] J. Dilling,[4] S. Fretwell,[2] J. A. Hall,[3]
A. Lennarz,[4,5] V. Lordi,[1] P. Machule,[4] D. McKeen,[4] X. Mougeot,[6] F. Ponce,[7,1] C. Ruiz,[4]
A. Samanta,[1] W. K. Warburton,[8] and K. G. Leach[2,†]

Phase-II data from a single 138x138 μm^2 STJ counting at low rate (~10 Bq) for 28 days



Recoil spectrum generated by pseudo-degenerate mass states from ~28 days of counting

Example of signal that would be generated by 300 keV neutrino with 1% mixing



Future Projections for keV-MeV Mass Searches

- Nuclear decay provides a powerful, model-independent probe in the keV – MeV mass range
- Significant progress in measurements over the past 3 years – enabled by quantum sensing
- Experiments poised to increase sensitivity by 5+ orders of magnitude in the next decade

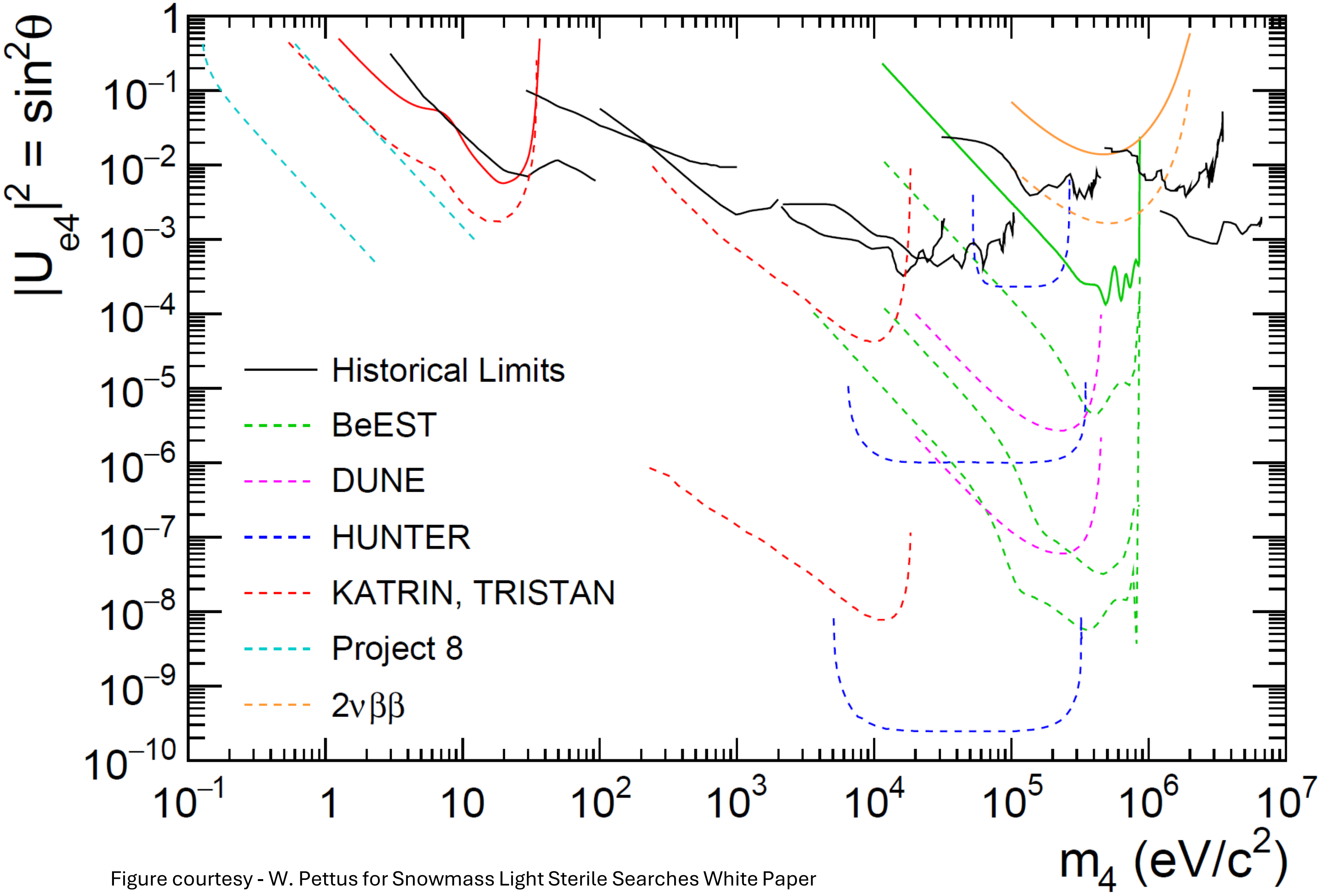


Figure courtesy - W. Pettus for Snowmass Light Sterile Searches White Paper