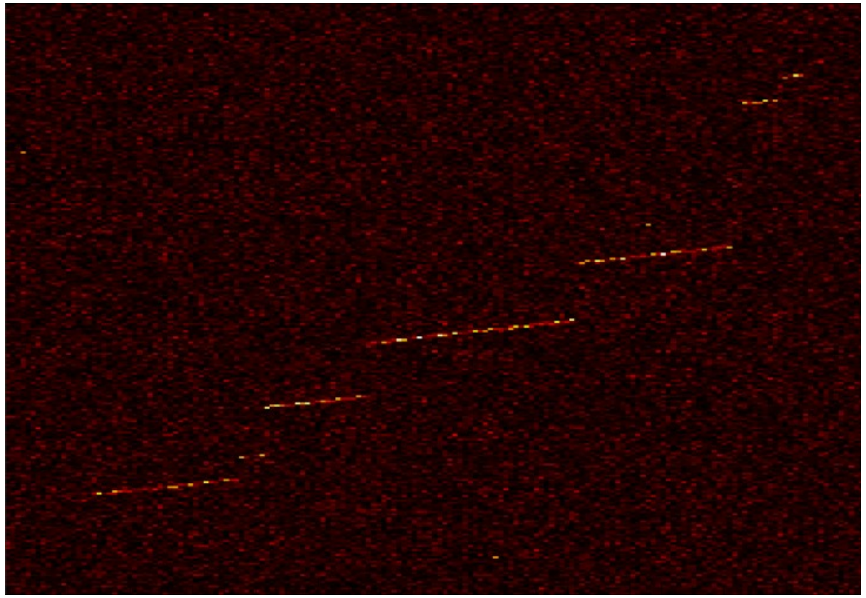
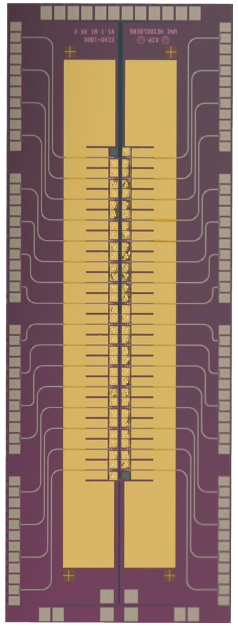
Karlsruher Institut für Technologie

Neutrino mass determination – Part II

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

Alexey Lokhov





Outline

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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, 0ν2β-decay, direct searches

Complementary observables

Direct laboratory measurements – least model dependent

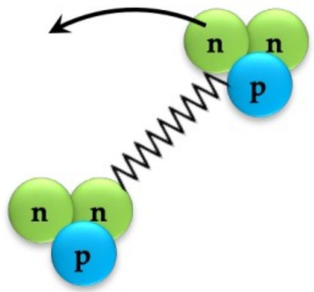
How to measure the mass without model dependencies?

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

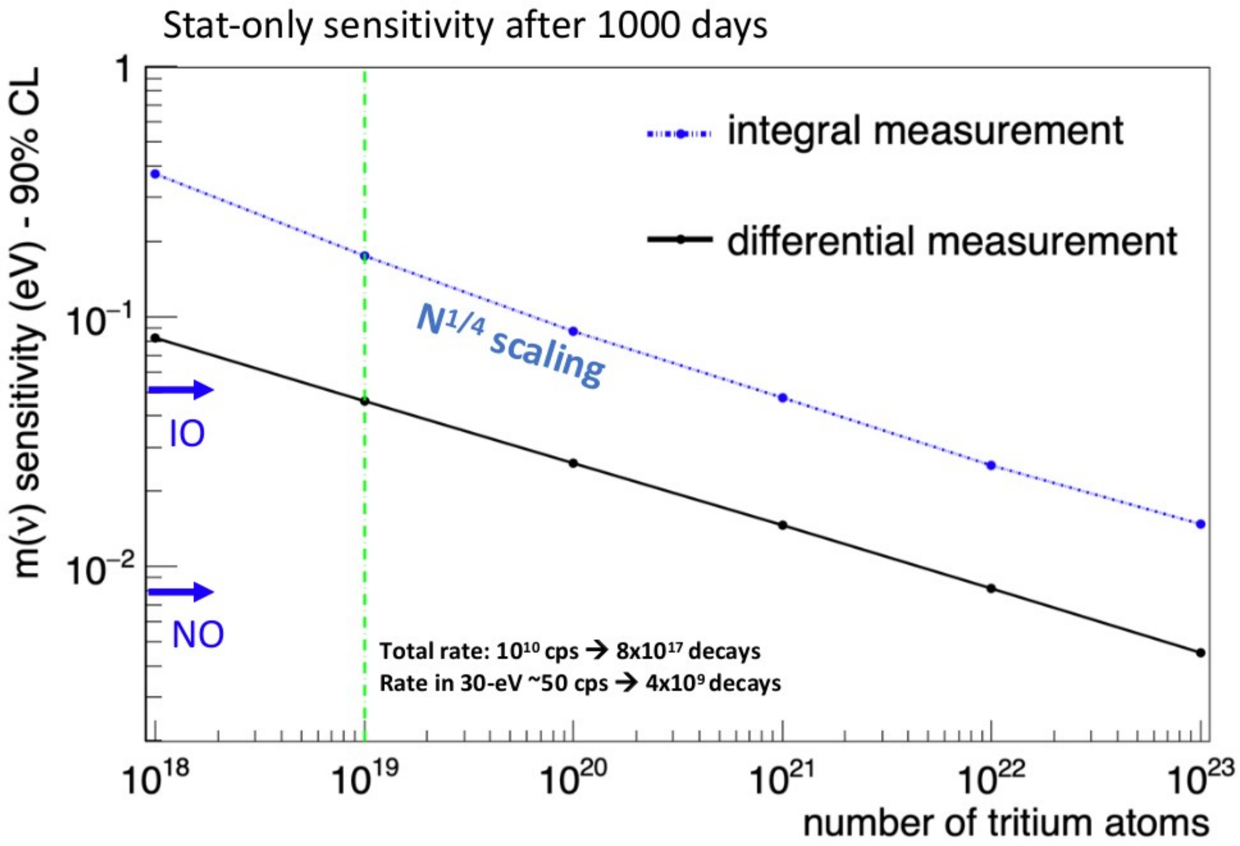
What other physics can we probe in the direct mass measurements?

What type of limitations are there?

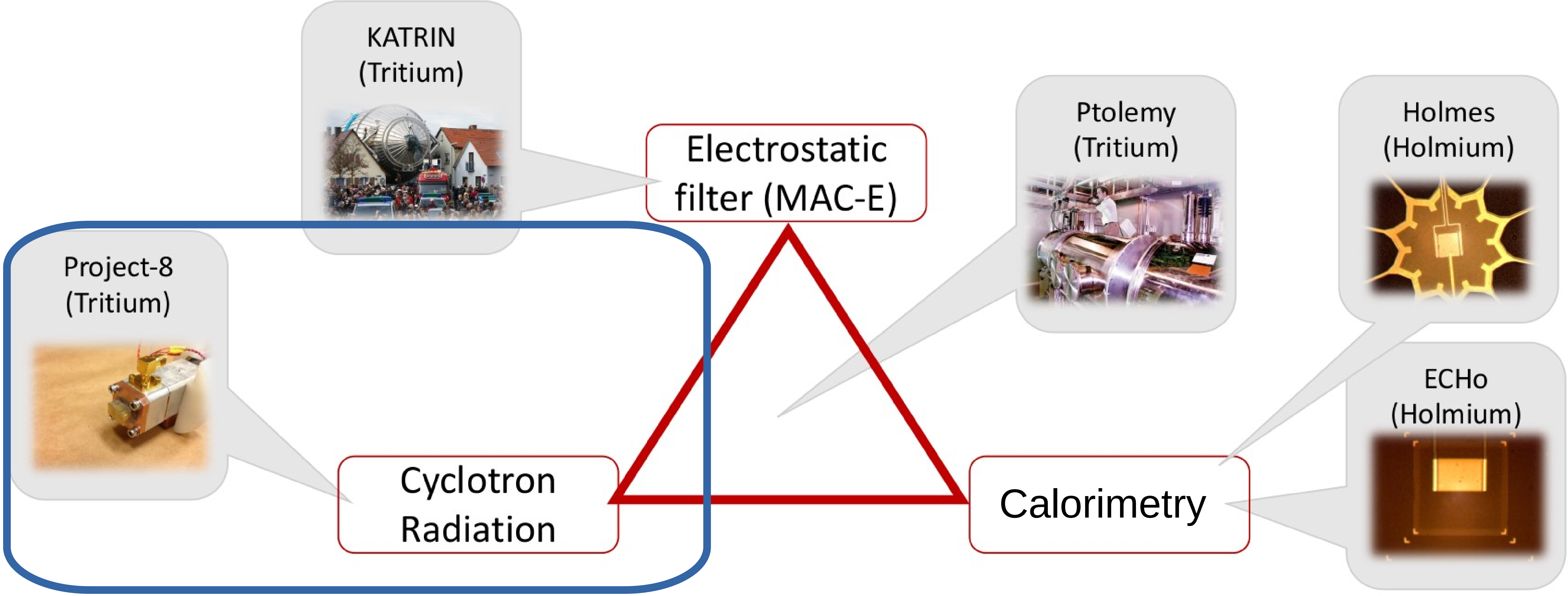
- Better statistics: more tritium
  - More scatterings → “Opaque” source
- “Different” tritium: atomic



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



Experimental techniques for direct ν-mass measurement



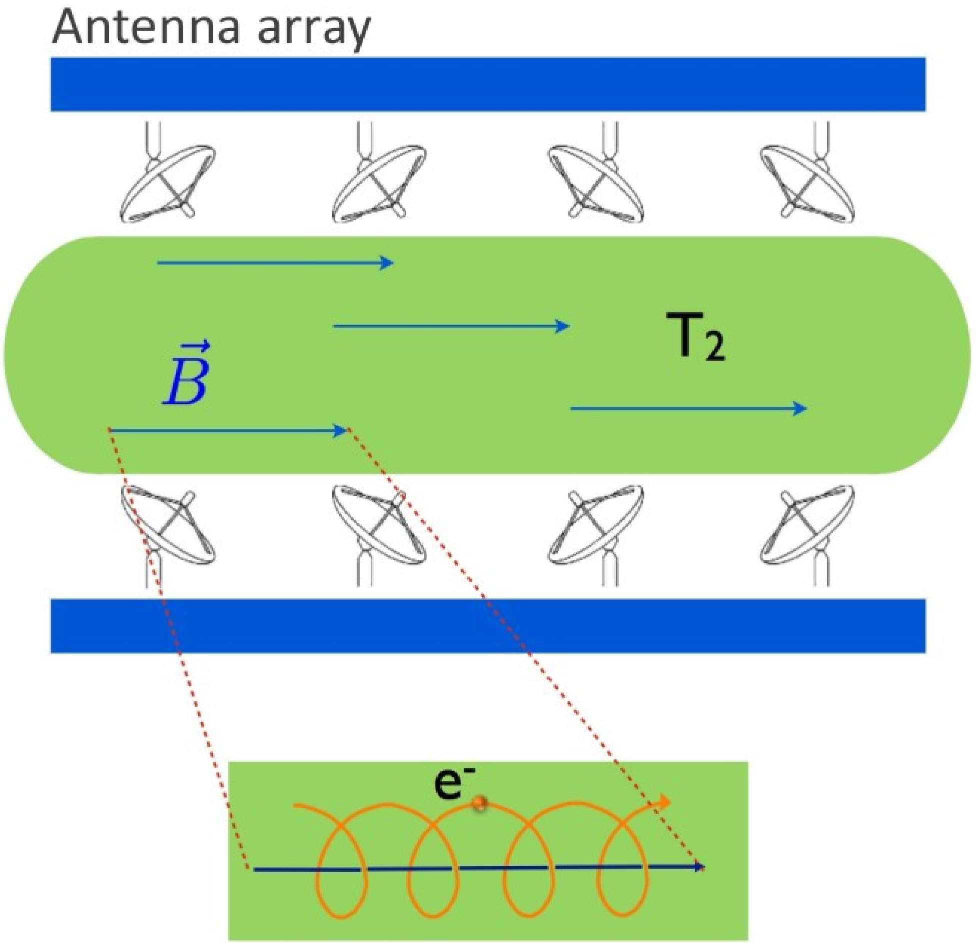
Energy measurement through cyclotron radiation

- Technology:

  Cyclotron Radiation Emission Spectroscopy

  (CRES)
- Non-destructive measurement of electron **energy** via **cyclotron frequency:**

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



"Never measure anything but frequency." — Arthur L. Schawlow

B. Monreal and Joe Formaggio, Phys. Rev D 80:051301

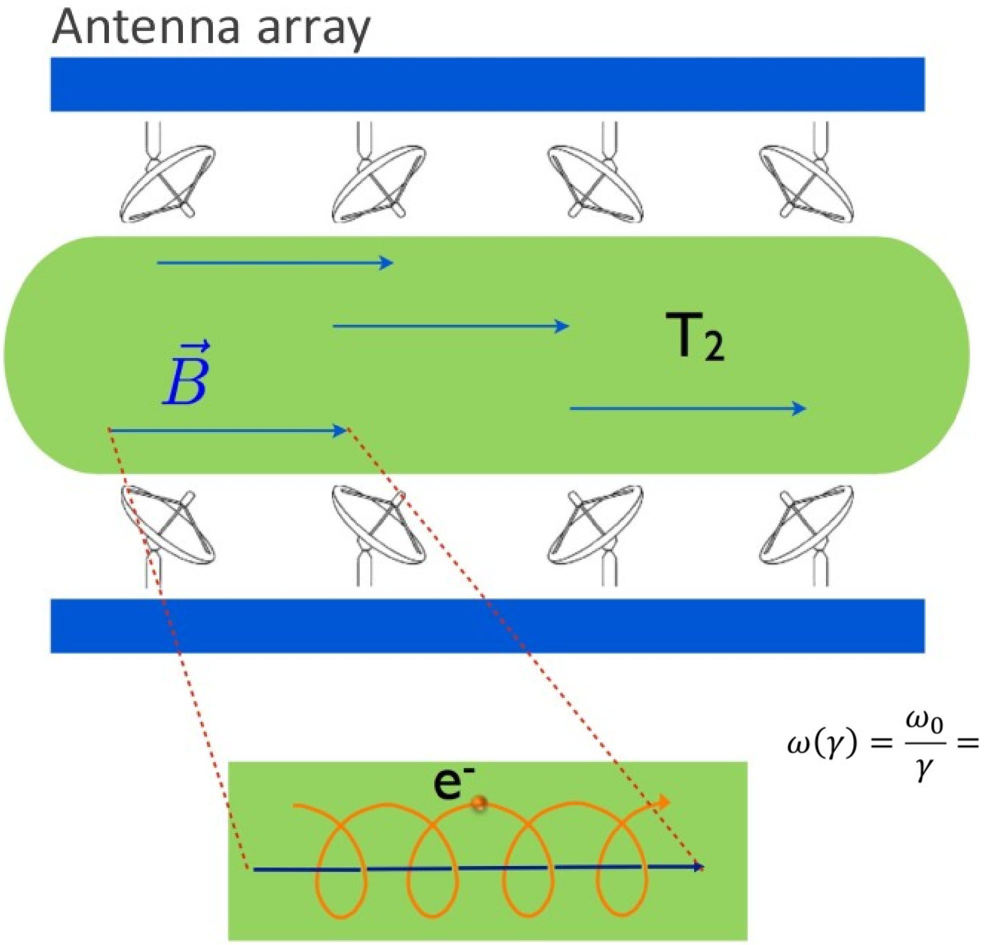
Energy measurement through cyclotron radiation

Advantages

- Source = detector concept, source is transparent to microwaves
- Differential measurement focusing on the endpoint region

Challenges

- Sub-eV energy resolution: **ΔE/E ~ Δω/ω ~ ppm**
  - B-field homogeneity at 10^{-7} level
- High statistics
  - large volume atomic trap ~m^3
- Long trapping



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

B. Monreal and Joe Formaggio, Phys. Rev D 80:051301

Energy measurement through cyclotron radiation – practical points

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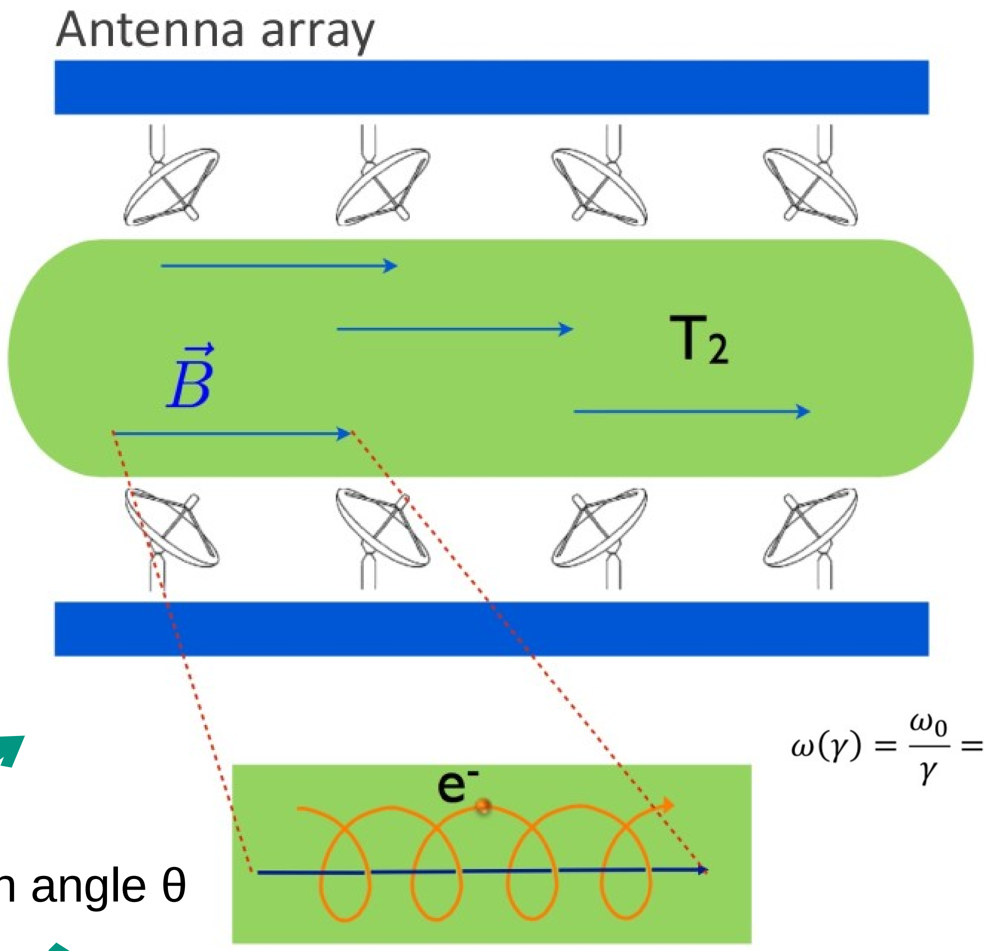
Larmor formula gives emitted power:

$$P(\gamma,\theta) = \frac{1}{4\pi\varepsilon_0}\frac{2}{3}\frac{q^4B^2}{m_\mathrm{e}^2}\left(\gamma^2-1\right)\sin^2\theta$$

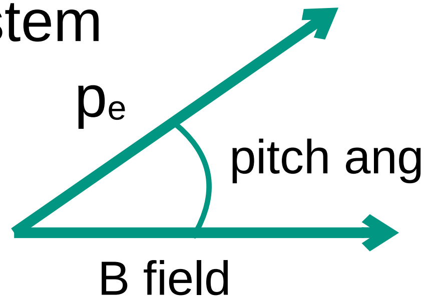


$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E+m_e}$$

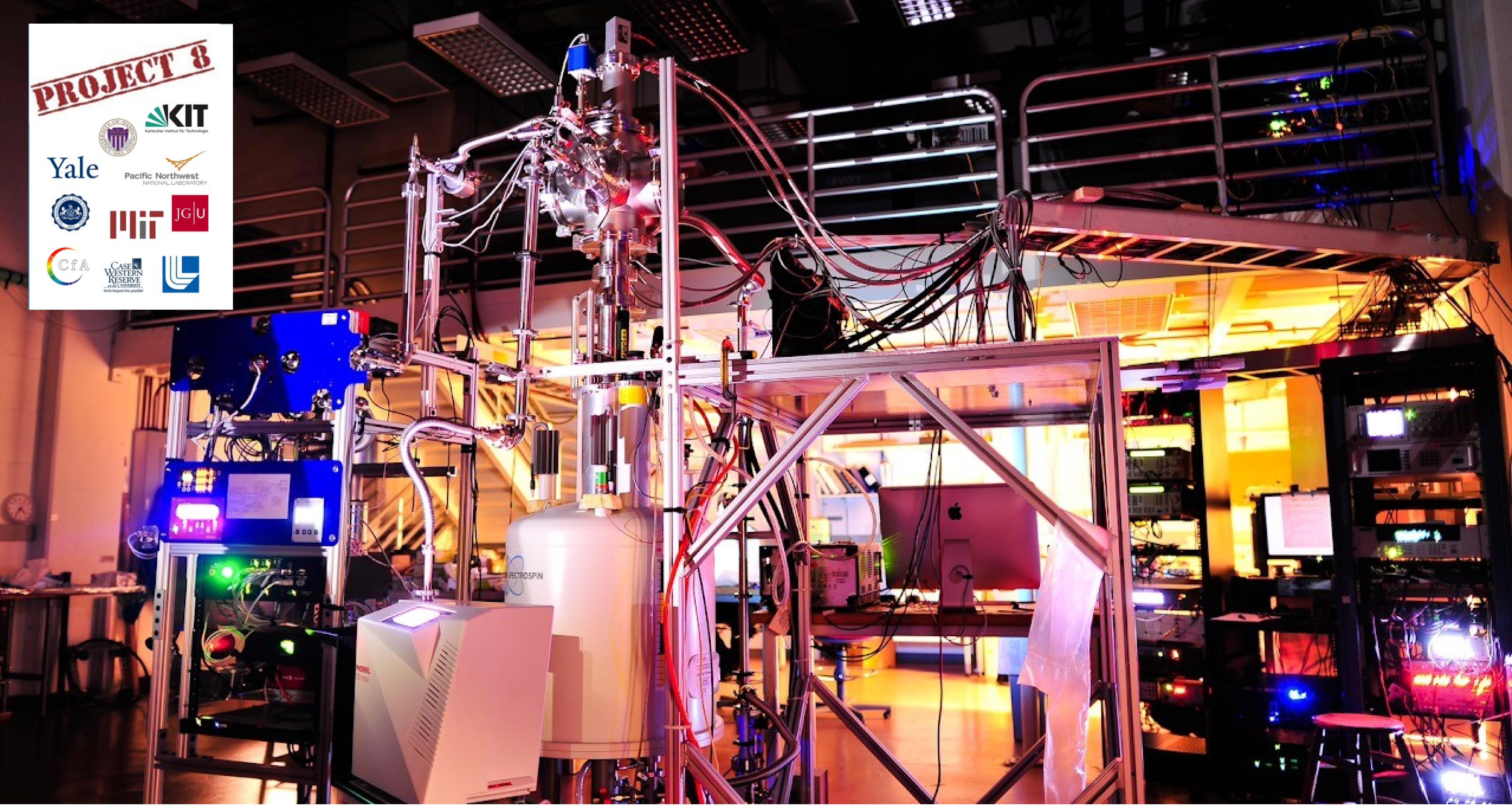
Realistic case:

- **1.7 fW** for 30.4 keV at θ = 90°
- **1.1 fW** for 18 keV at θ = 90°

➜ Need low-noise cryogenic RF system



B. Monreal and Joe Formaggio, Phys. Rev D 80:051301


PROJECT 8
KIT
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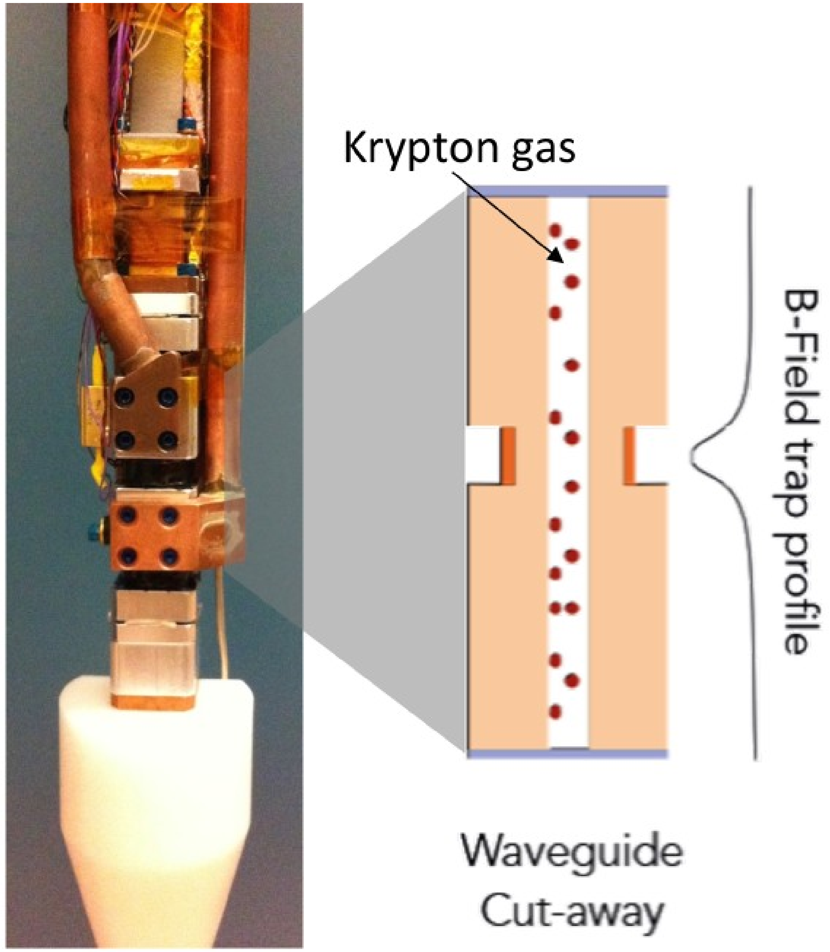
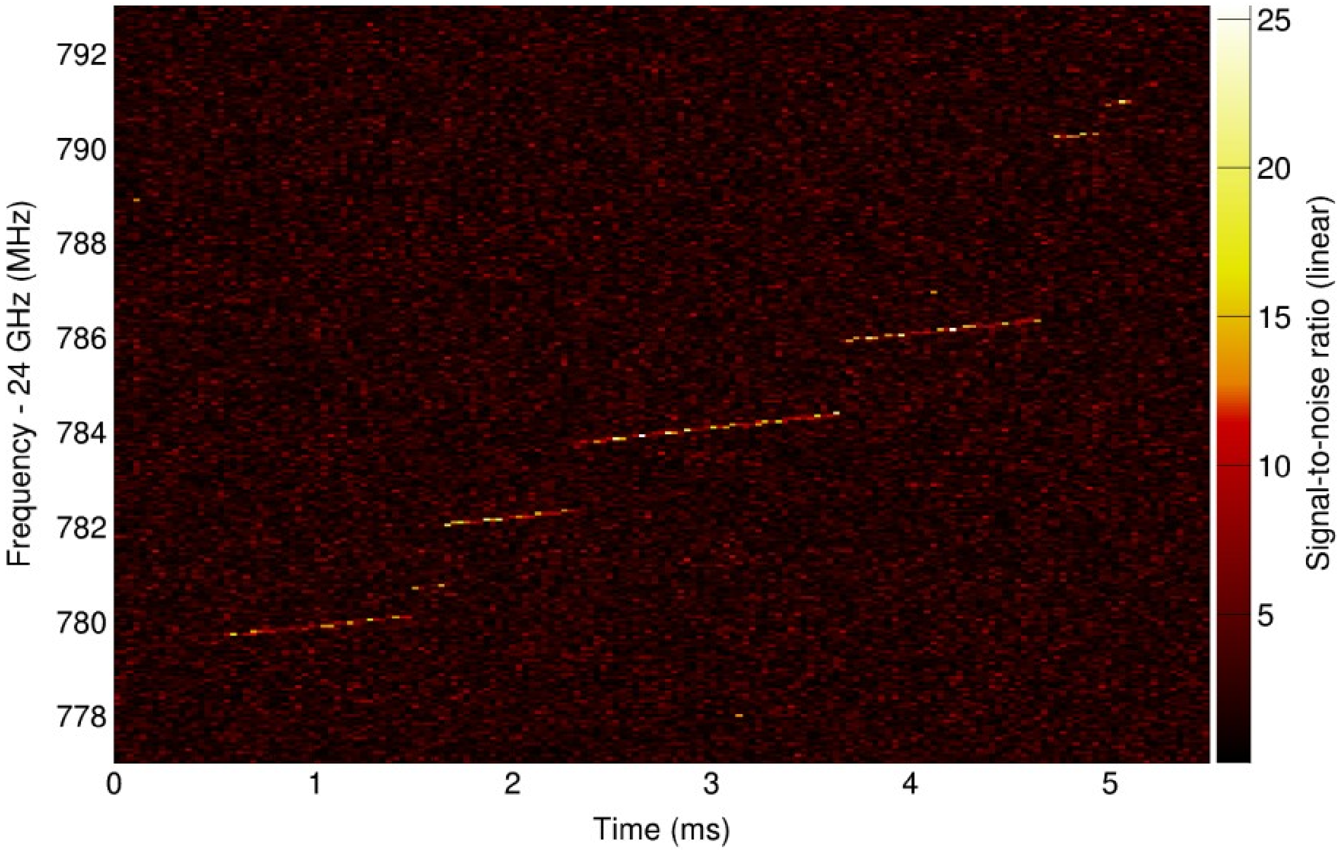
Yale
Pacific Northwest
NATIONAL LABORATORY
JG|U
CfA
CASE WESTERN RESERVE UNIVERSITY
think beyond the possible
SPECTROSPIN

Project 8: proof of concept





D.M. Asner et al., Phys. Rev. Lett. 114, 162501 (2015)

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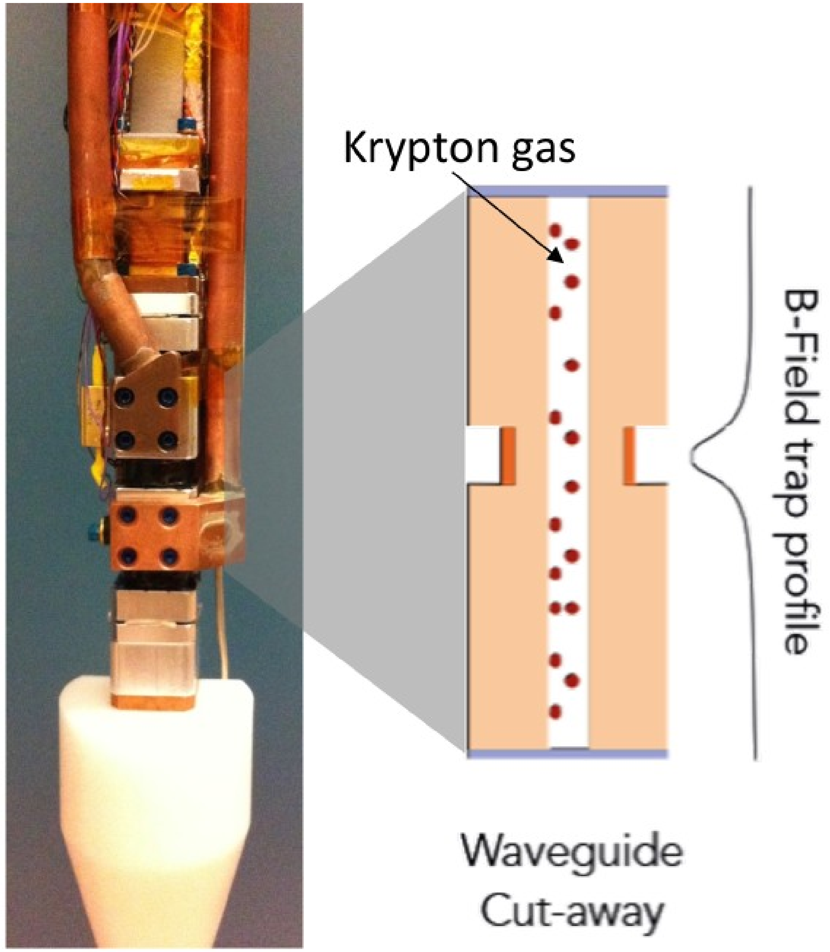
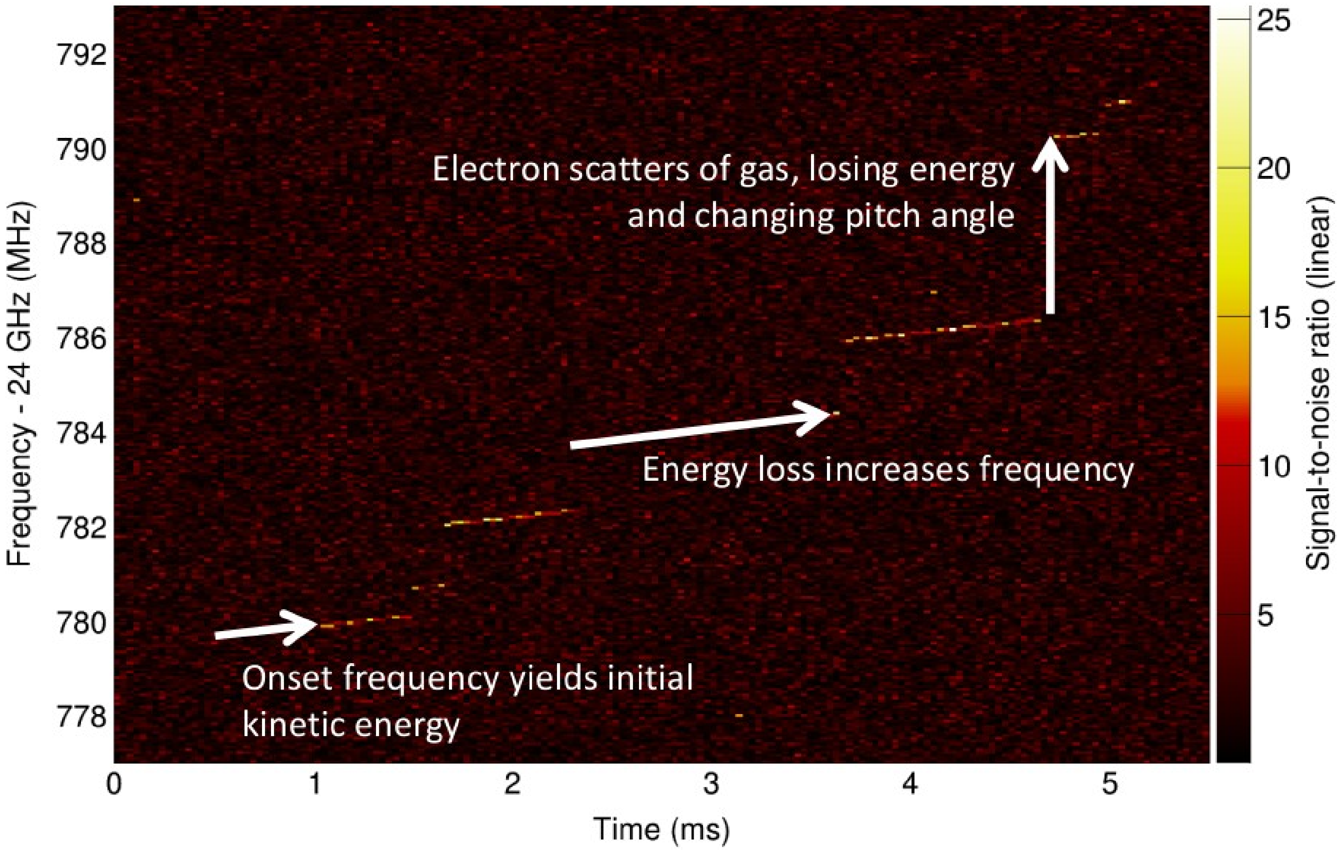




D.M. Asner et al., Phys. Rev. Lett. 114, 162501 (2015)

Project 8: recent results

Recent results

- First tritium spectra measured

  ΔE = 2 eV (FWHM), **bkg** < 3x10^{-11} eV^{-1} s^{-1}

- First neutrino mass limit: **m_ν < 185 eV (90% Cl.)**

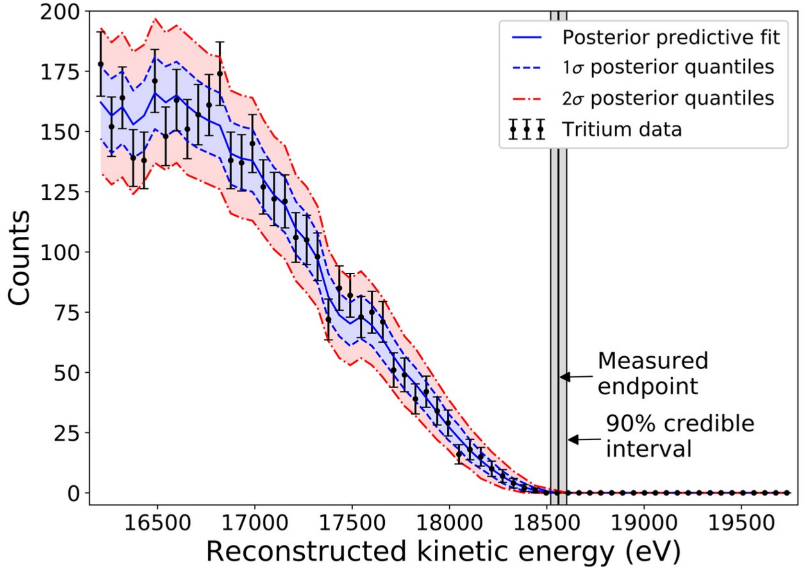
Next steps/challenges

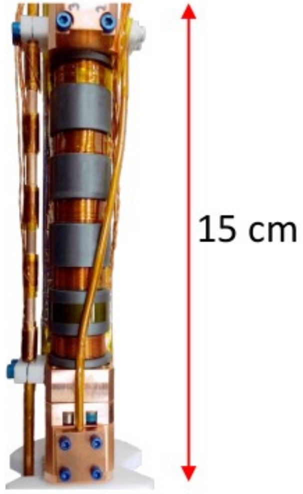
- large-volume traps (m^3)

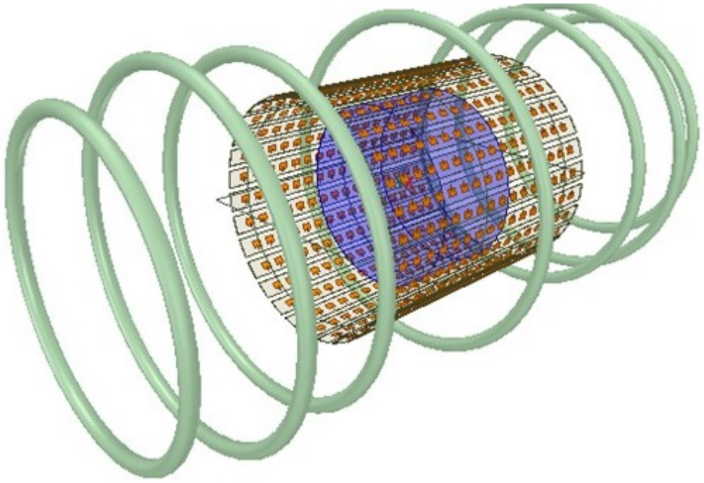
  (antenna array or cavity resonator)

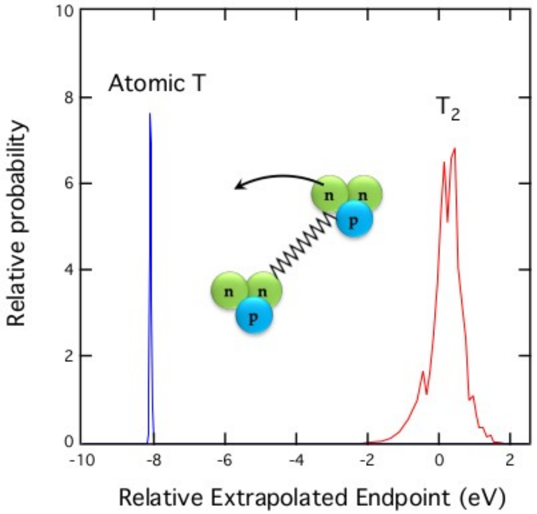
- develop atomic tritium source
- 0.4 eV sensitivity (phase-III)

Ultimate goal: 0.04 eV sensitivity



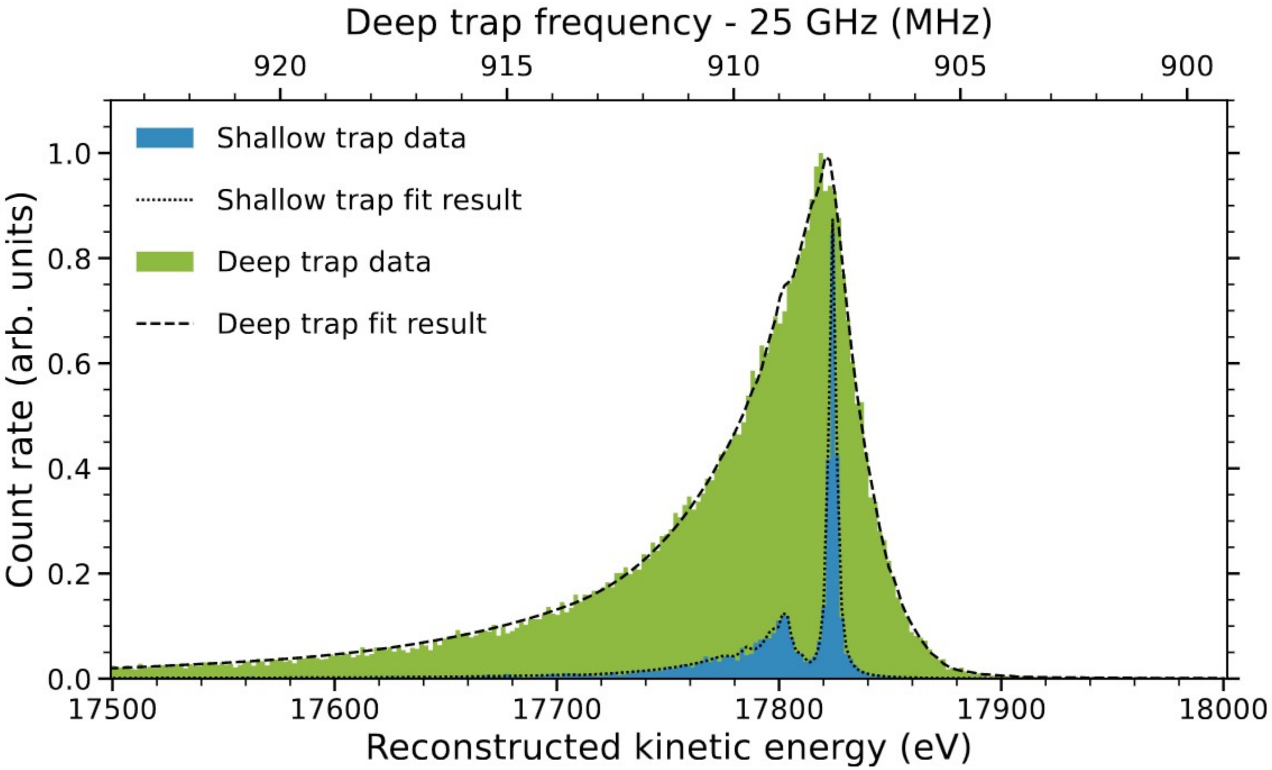


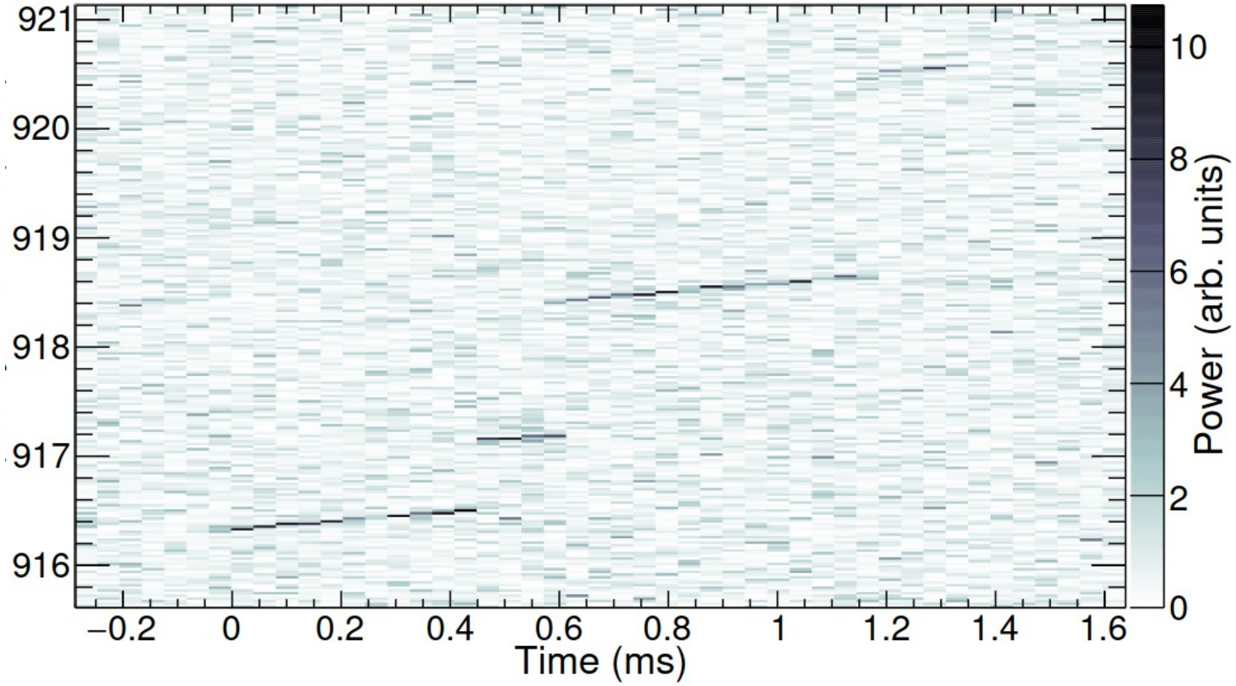




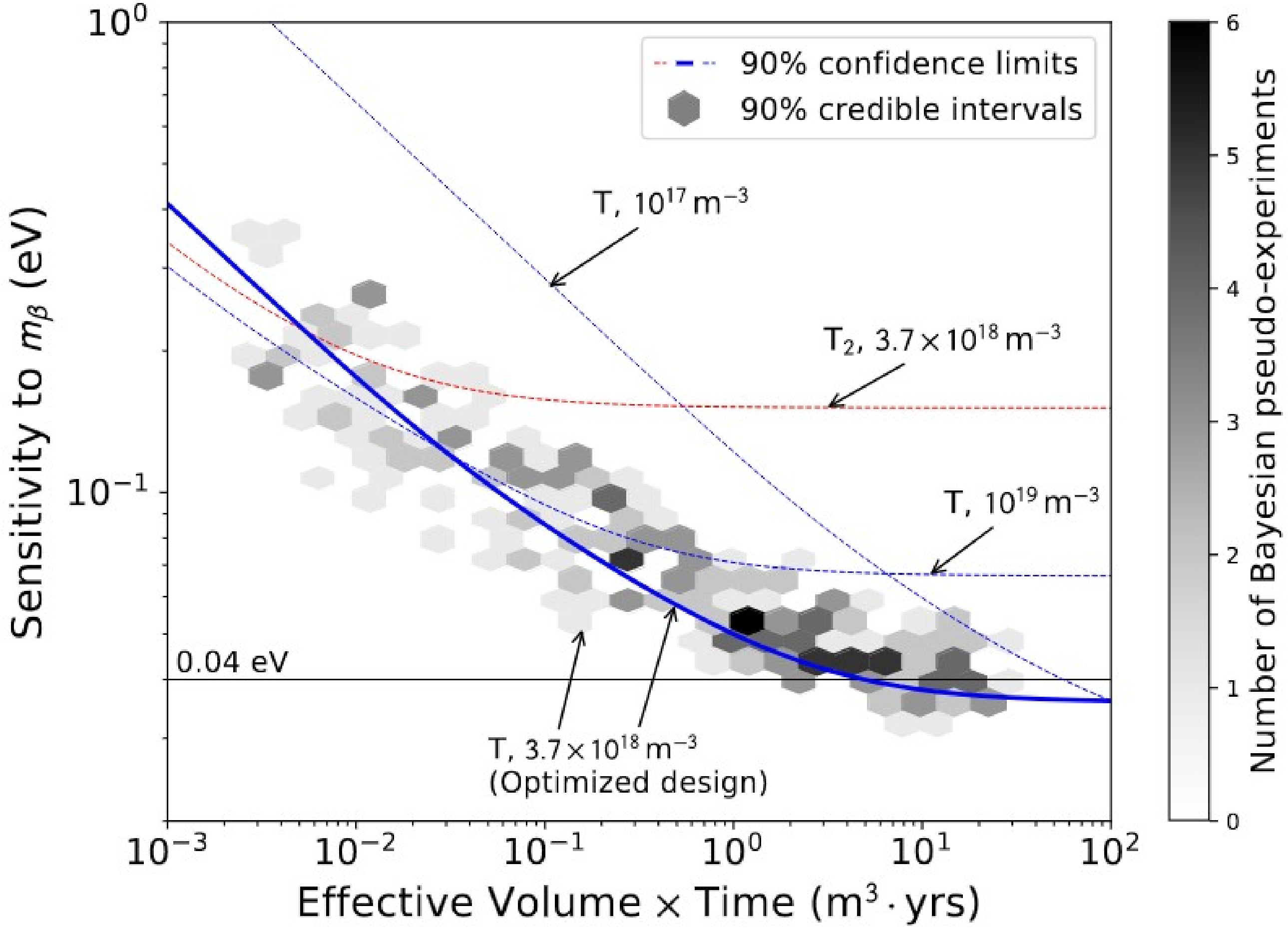
Project 8 collab., arXiv:2203.07349 (2022)

Project 8: phase II results



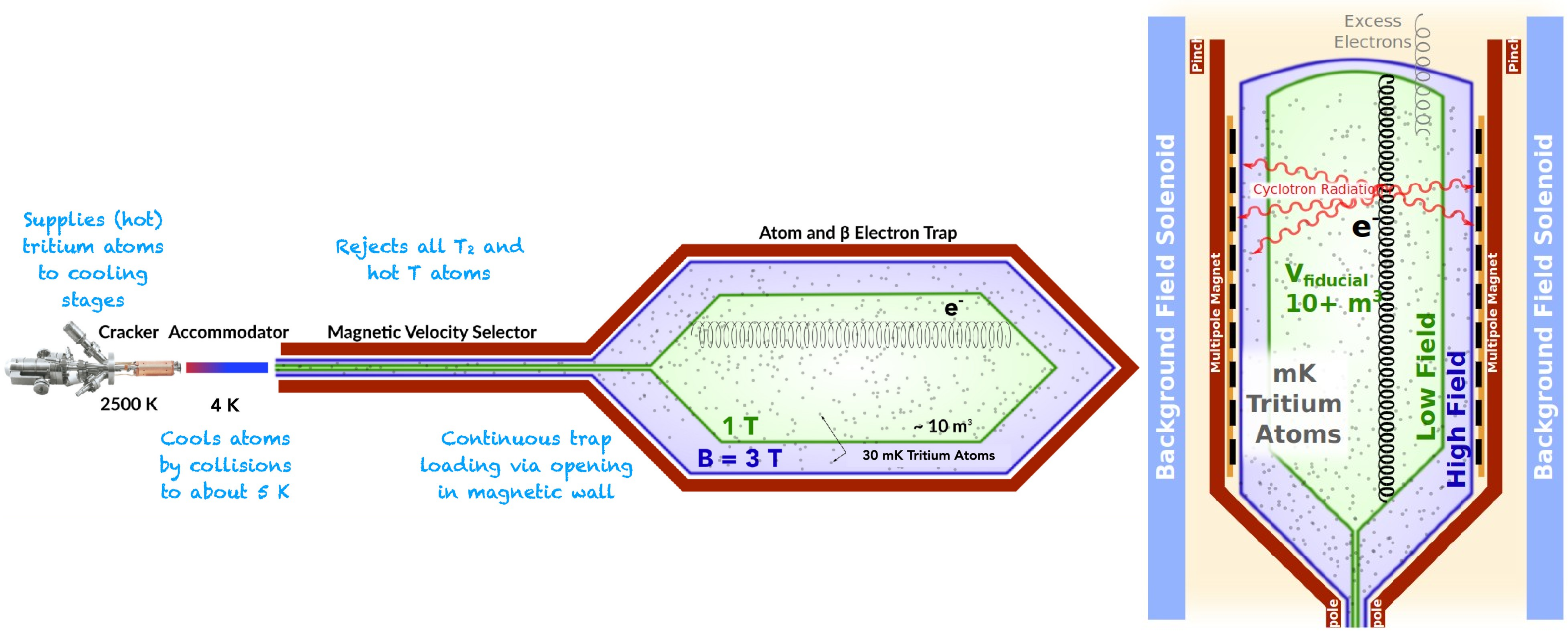


Project 8: next steps



- Demonstrate scalability of CRES to larger volumes
- Demonstrate possibility of high intensity atomic tritium source

Project 8: towards atomic tritium



from A. Lindman and S. Böser

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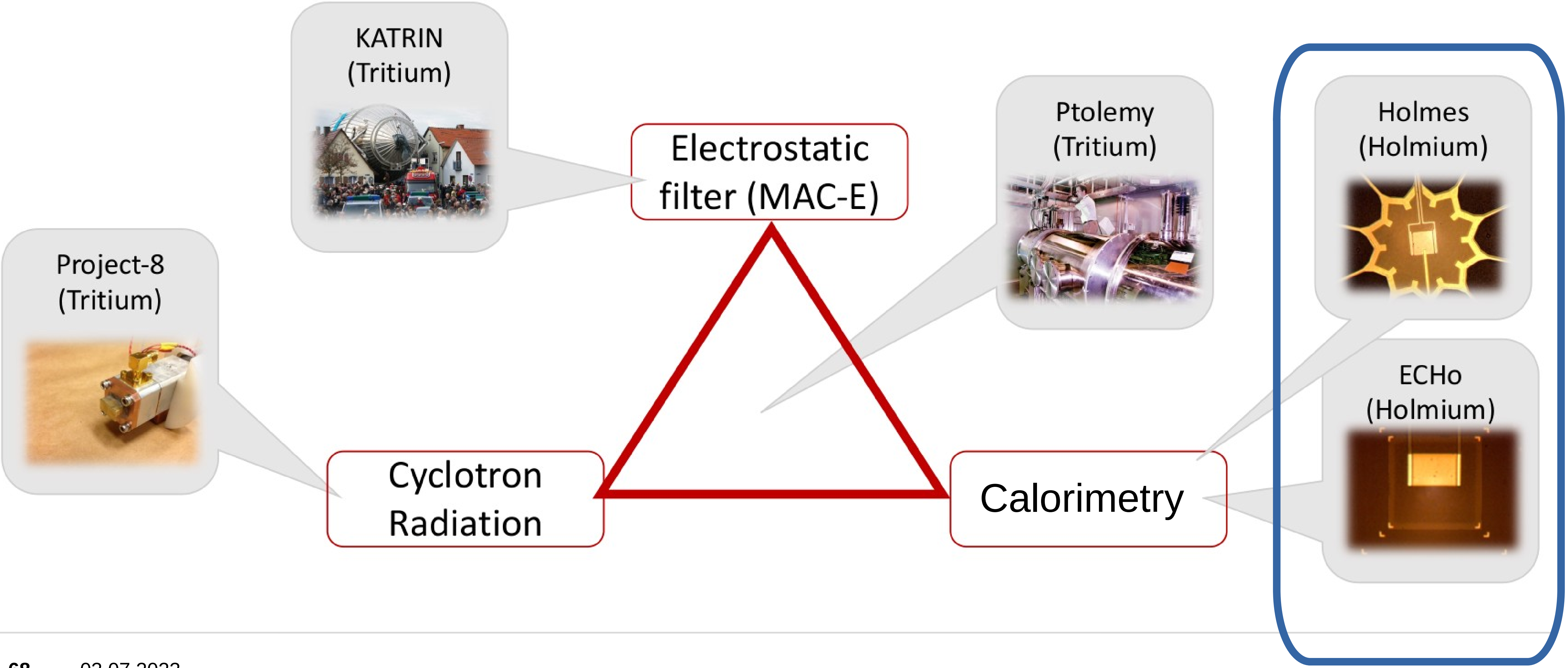
Current limit from KATRIN (MAC-E-Filter): <0.8 eV (90% CL)

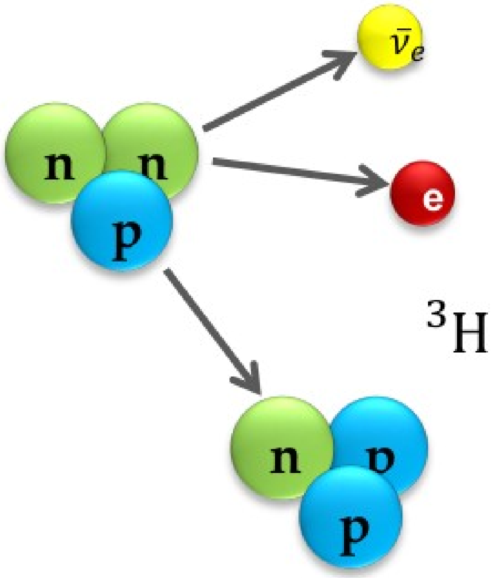
CRES technology: measuring the cyclotron frequency

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

Experimental techniques for direct ν-mass measurement

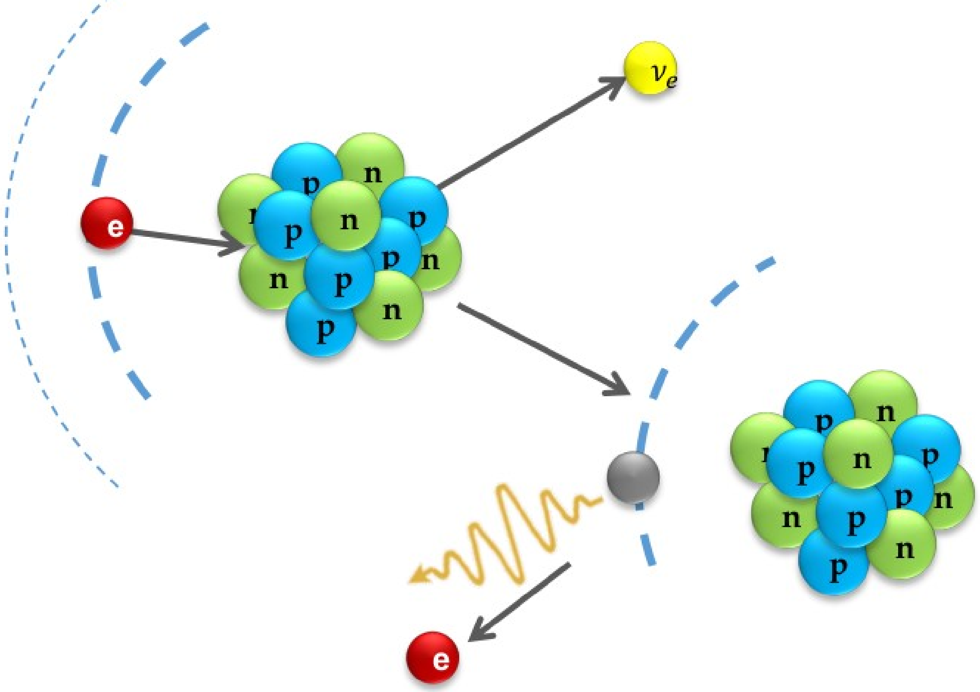


Tritium VS Holmium



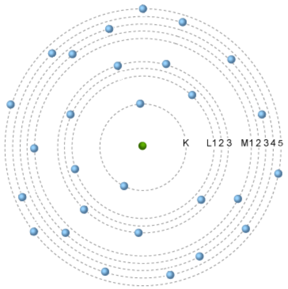
$$^{3}\mathrm{H} \rightarrow\ ^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e$$

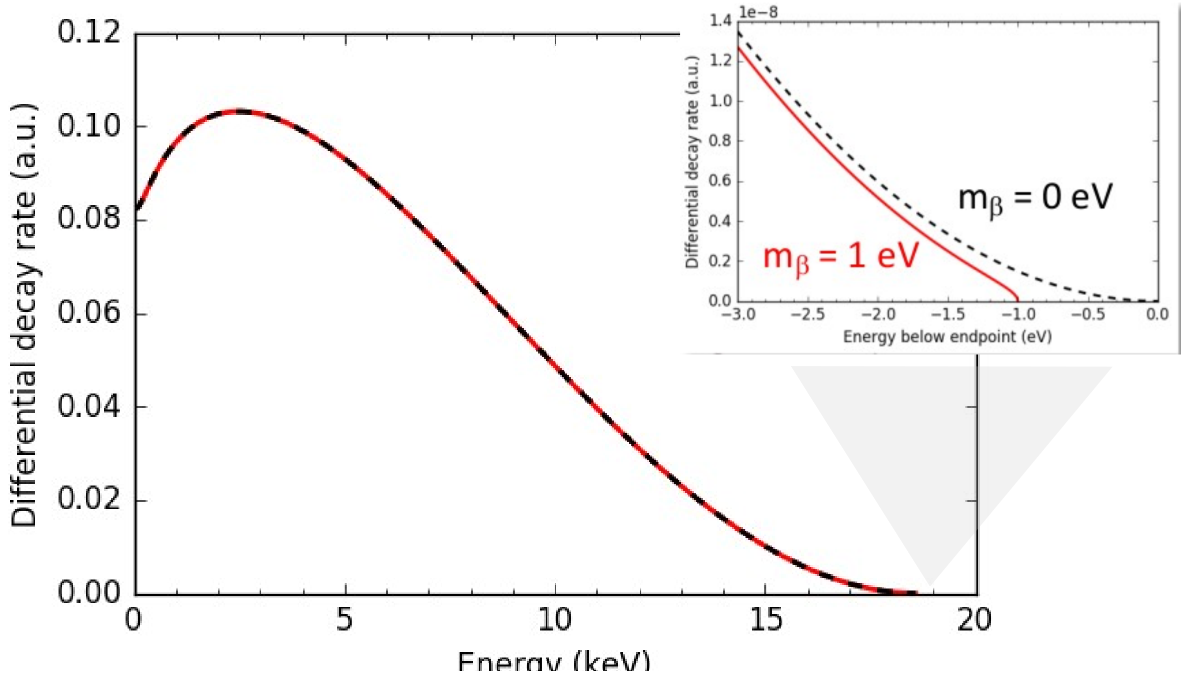
$$^{163}\mathrm{Ho} \rightarrow\ ^{163}\mathrm{Dy}^{*} + \nu_e$$
$$^{163}\mathrm{Dy}^{*} \rightarrow\ ^{163}\mathrm{Dy} + E_C$$

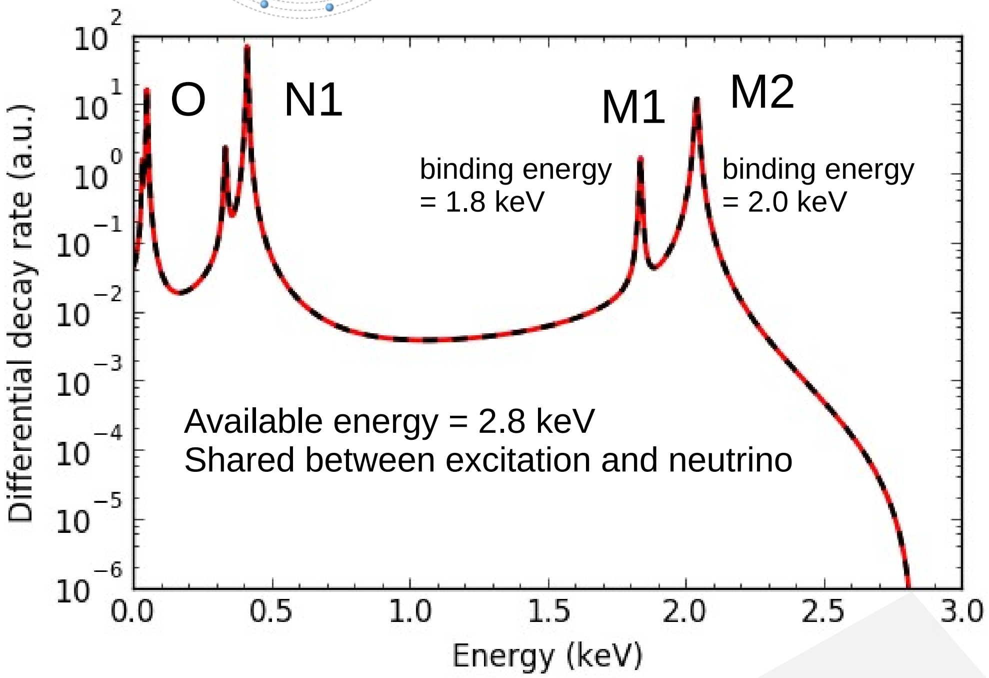


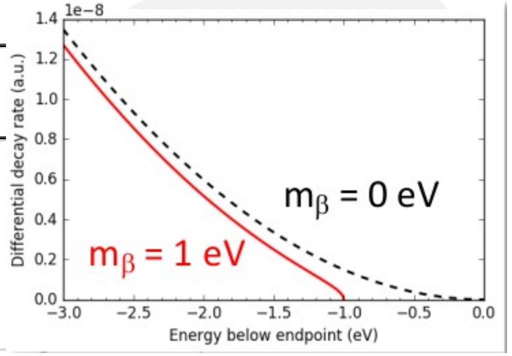
	^{3}H	^{163}Ho
	super-allowed β-decay	electron-capture decay
$T_{1/2}$	12.3 years	4500 years
E_0	18.6 keV	2.8 keV

Tritium VS Holmium









	^{3}H	^{163}Ho
	super-allowed β-decay	electron-capture decay
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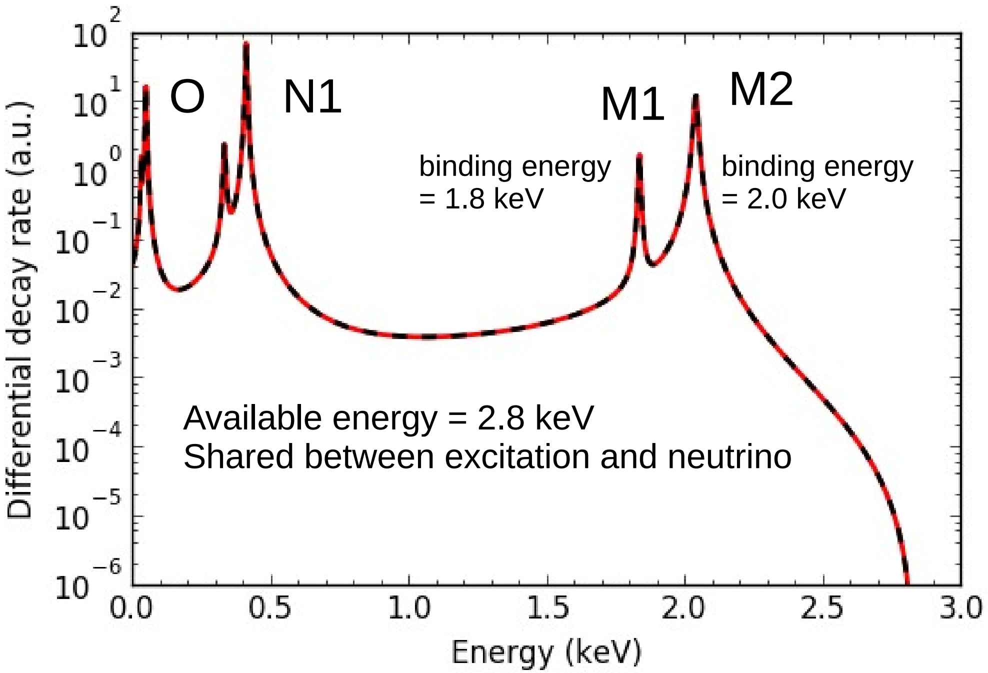
Calorimetric measurement of ^{163}Ho spectrum

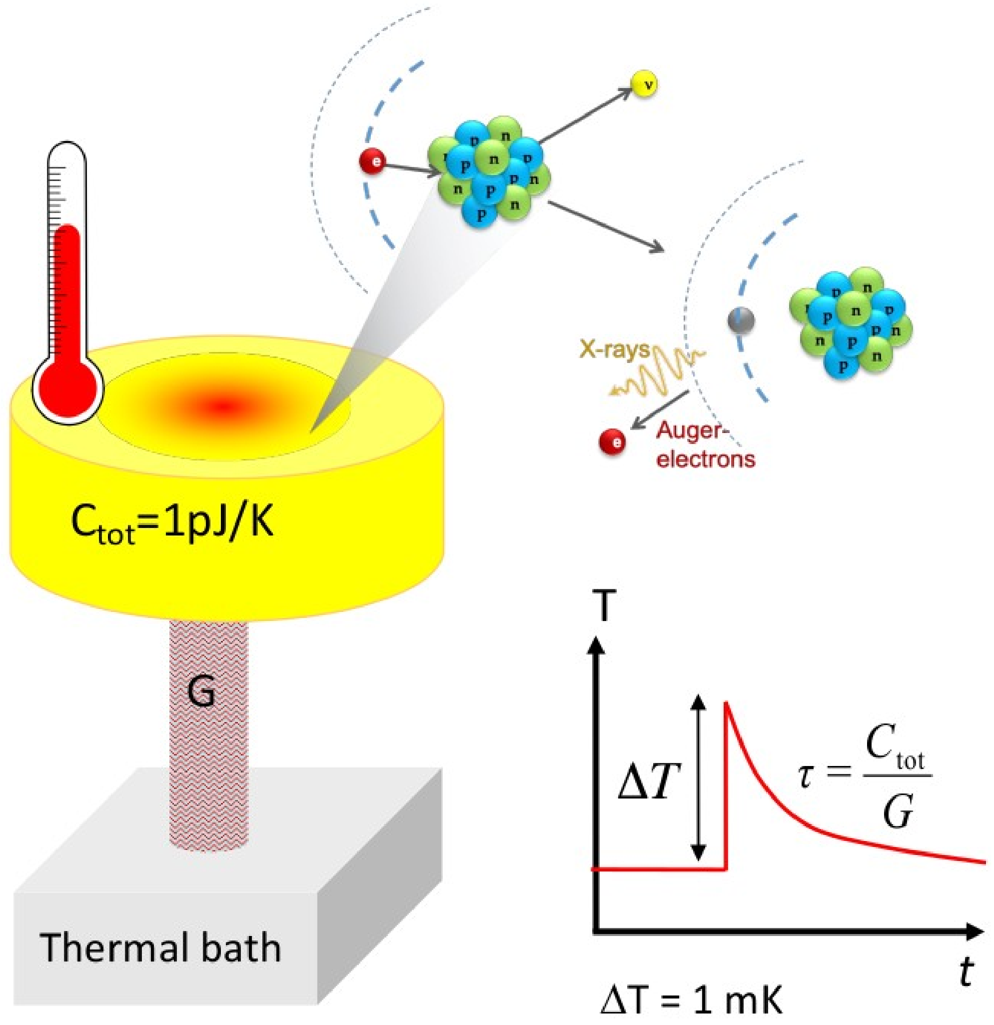
- Proposed by A. De Rujula and M. Lusignoli
  Phys. Lett. 118B (1982)
- Low-temperature micro-calorimetry
- Holmium enclosed in absorber
- Released energy → temperature increase



$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^2}{4}}$$

NB: Lorentzian shape →
Asymmetric Mahan shape

Calorimetric measurement



Advantages:

- “Source = detector” concept
- eV-scale differential measurement
  - total energy is measured

Challenges:

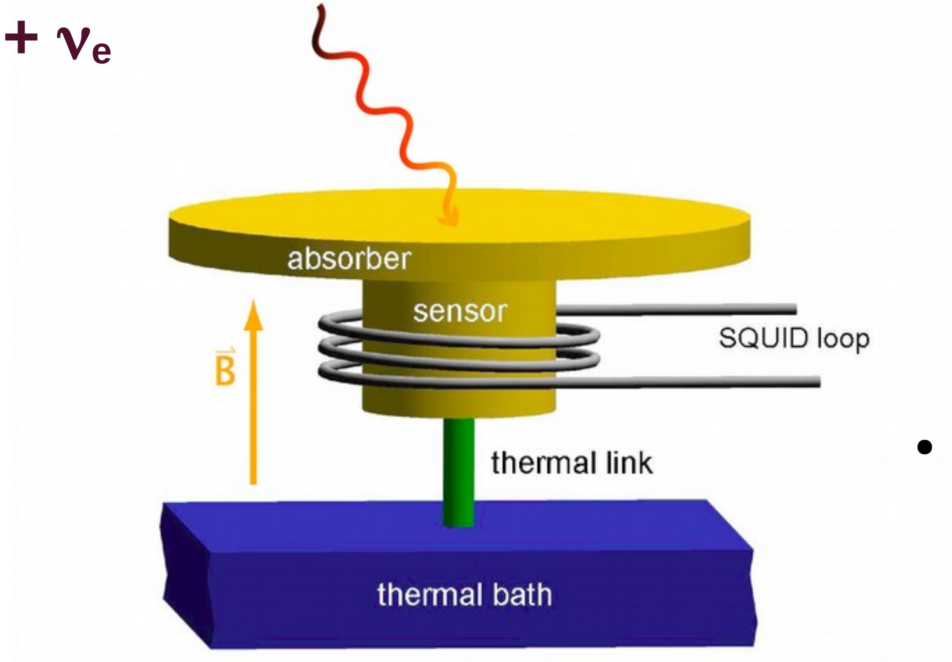
- High statistics (10^{13} decays for eV sensitivity)
  - increase activity per detector (10 Bq)
  - many detectors (>10000)
- Small heat capacity $\Delta T \approx \frac{E}{C_{tot}} \approx mK$
  - operation at low temperatures

Why the low temperatures?

$^{163}Ho + e^{-} \rightarrow$

$^{163}Dy^{*} + \nu_e \rightarrow$

$^{163}Dy + \gamma/e^{-} + \nu_e$



- What's the heat capacity of solid materials at low temperatures?

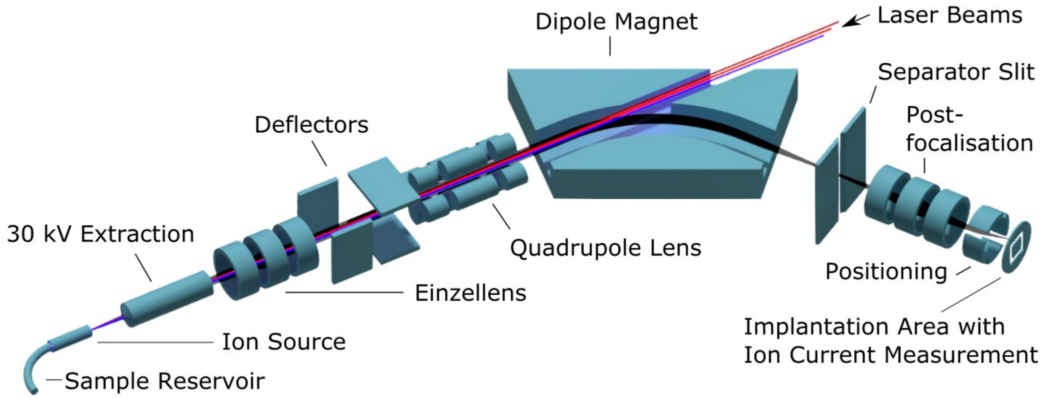
$$\Delta T = \Delta \frac{E}{C}, C \propto T^3$$

Peter Debye

- Typical signal readout: using a SQUID

Calorimetric measurement

Er161 3.21 h 3/2- EC	Er162 0+ 0.14	Er163 75.0 m 5/2- EC	Er164 0+ 1.61	Er165 10.36 h 5/2- EC	Er166 0+ 33.6
Ho160 25.6 m 5+ EC *	Ho161 2.48 h 7/2- EC *	Ho162 15.0 m 1+ EC *	Ho163 4570 y 7/2- EC *	Ho164 29 m 1+ EC,β- *	Ho165 7/2- 100



Experimental challenges

- Production and purification of ^{163}Ho
- Incorporate ~10^{11} Ho atoms into the high resolution detector
- Operation and readout of large arrays

Spectral shape and theory:

- Precise description of calorimetric spectrum and detector response
- Independent measurement of the Q-value of the decay by Penning trap mass-spectroscopy

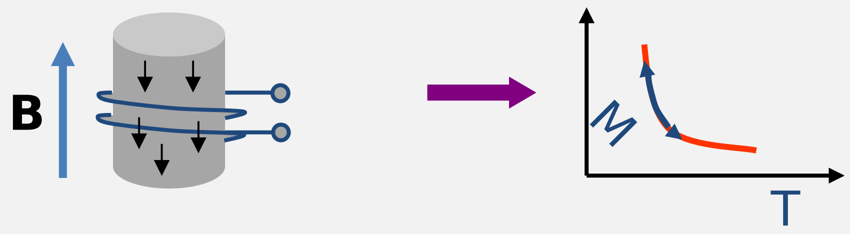
ν-mass from ^{163}Ho electron capture: technologies

- Two techniques for temperature sensing

ECHo approach:

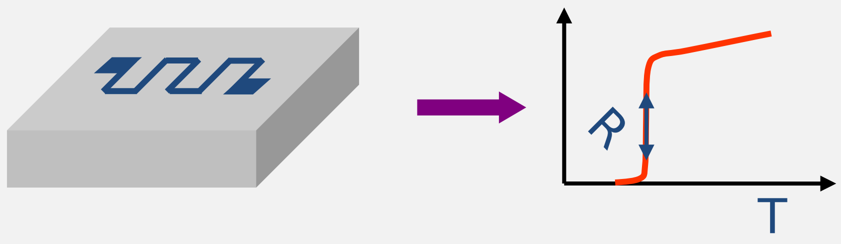
HOLMES approach:

Magnetization of paramagnetic material
Metallic Magnetic Calorimeters (MMC)



Resistance R at superconducting transition:

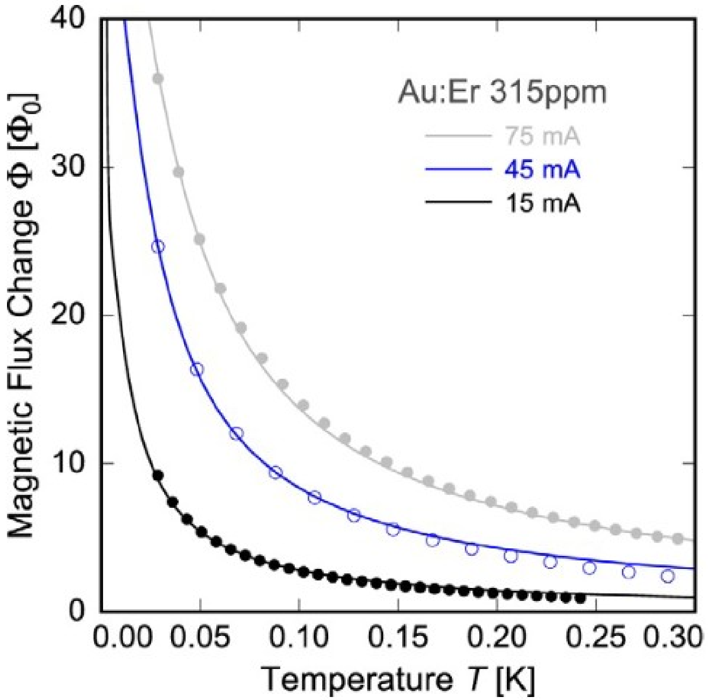
Transition Edge Sensors (TES)



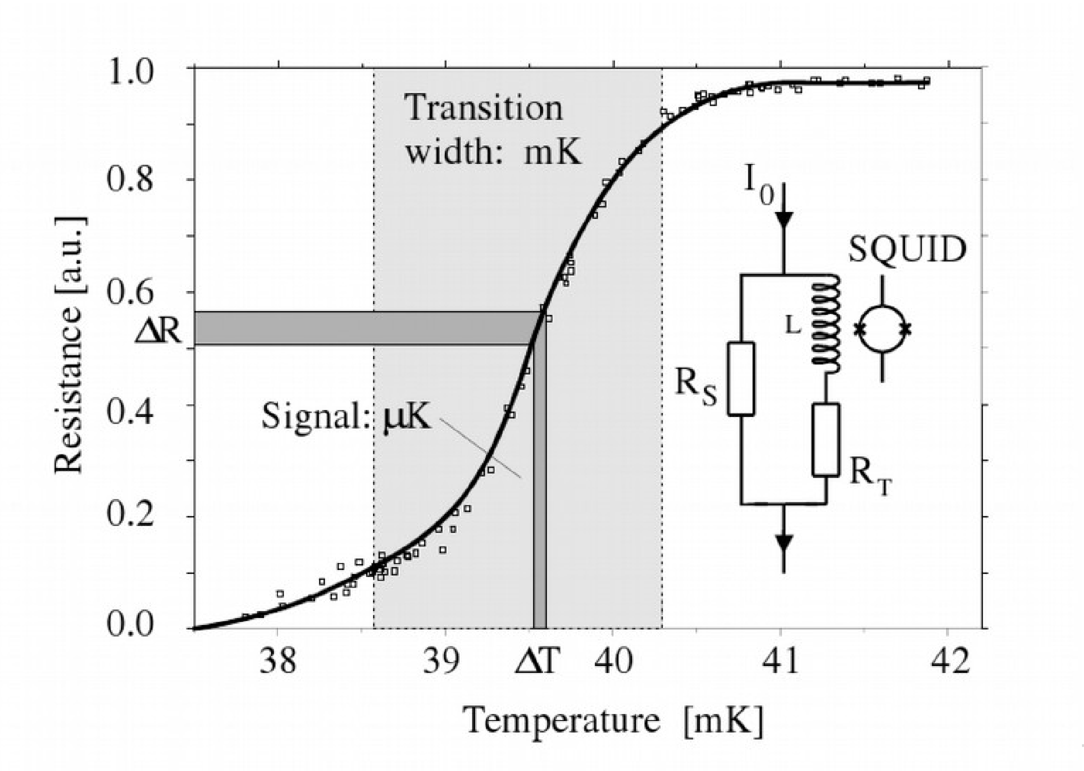
ν-mass from ^{163}Ho electron capture: technologies

- Two techniques for temperature sensing

ECHo approach:



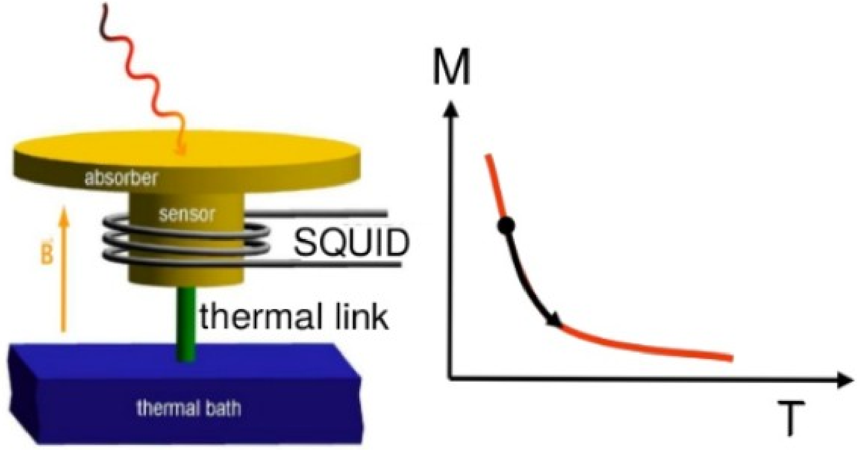
HOLMES approach:



ν-mass from ^{163}Ho electron capture: technologies

- Two techniques for temperature sensing

MMC: **m**etallic **m**agnetic **c**alorimeters with paramagnetic sensor Au:Er

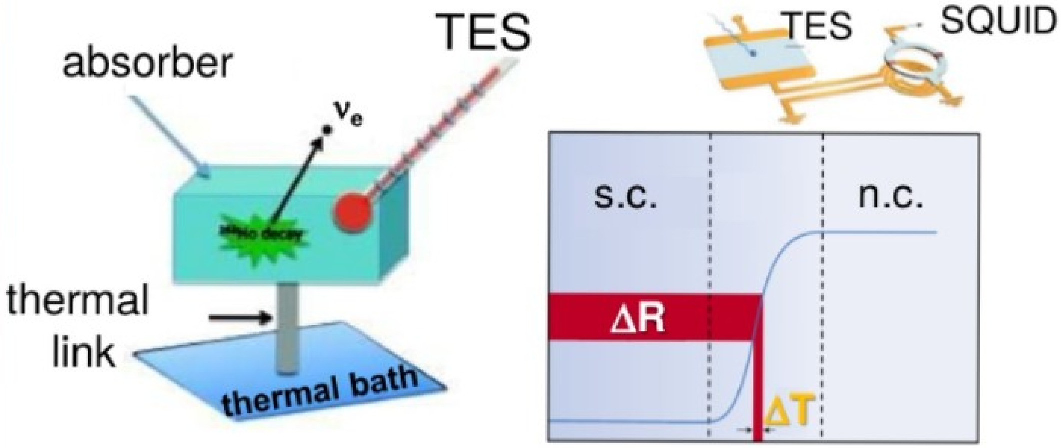


δT in absorber from EC-decay

⇨ change in **magnetism δM** of param. sensor

signal: $\delta\Phi_S \sim \frac{\partial M}{\partial T} \cdot \Delta T \sim \frac{\partial M}{\partial T} \cdot \frac{1}{C_{tot}} \cdot \delta E$

thermal micro-calorimeters with **TES** read-out



δT in absorber from EC-decay

⇨ change in temperature δT of TES thermistor

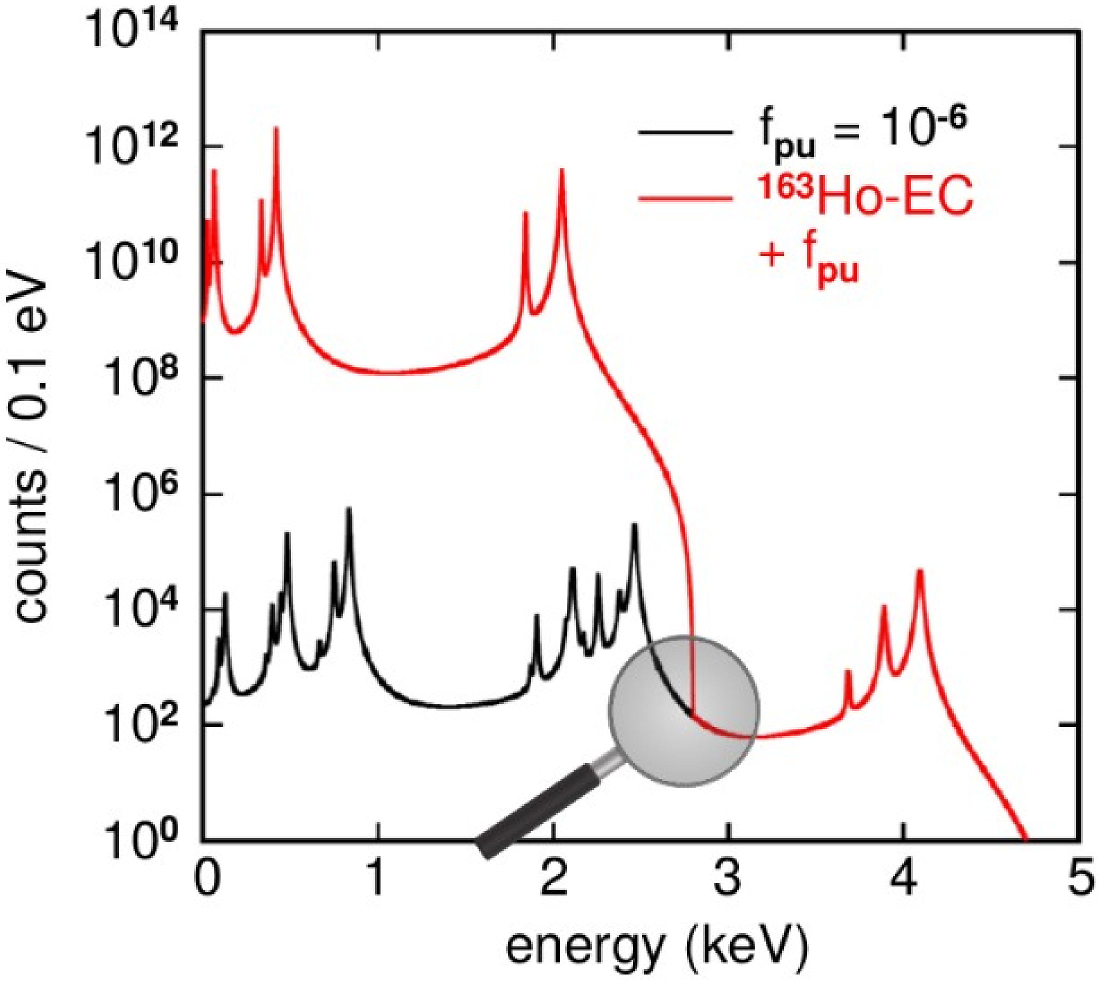
calorimeter signal: $\Delta T = \frac{\delta E}{V \cdot C_V}$

ν-mass from ^{163}Ho electron capture: numbers

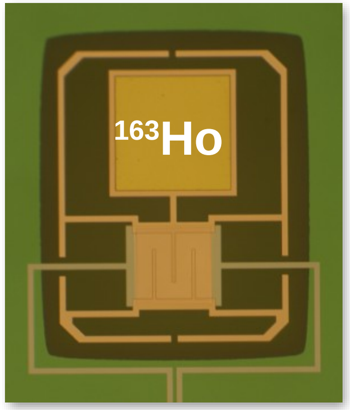
- Unresolved pile-up
  - Fraction of pile-up events $f_{pu} \sim a \cdot \tau_r$
  - for $f_{pu} < 10^{-6}$ with $\tau_r \sim 1 \mu s$

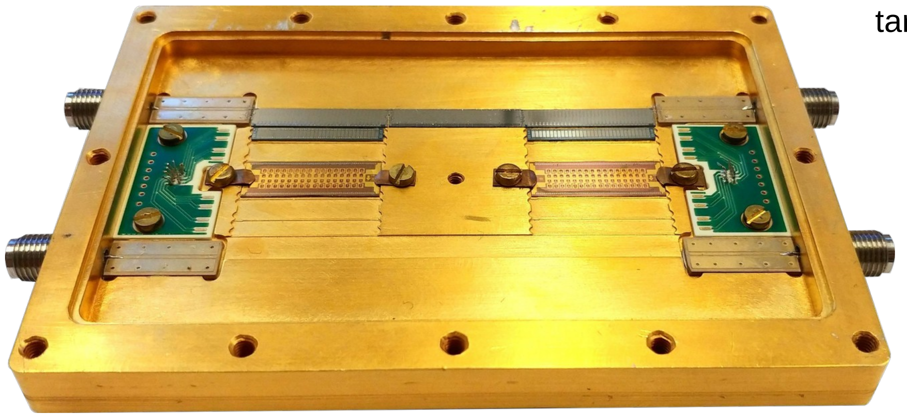
$$a_{per\ pixel} < 10\ Bq$$

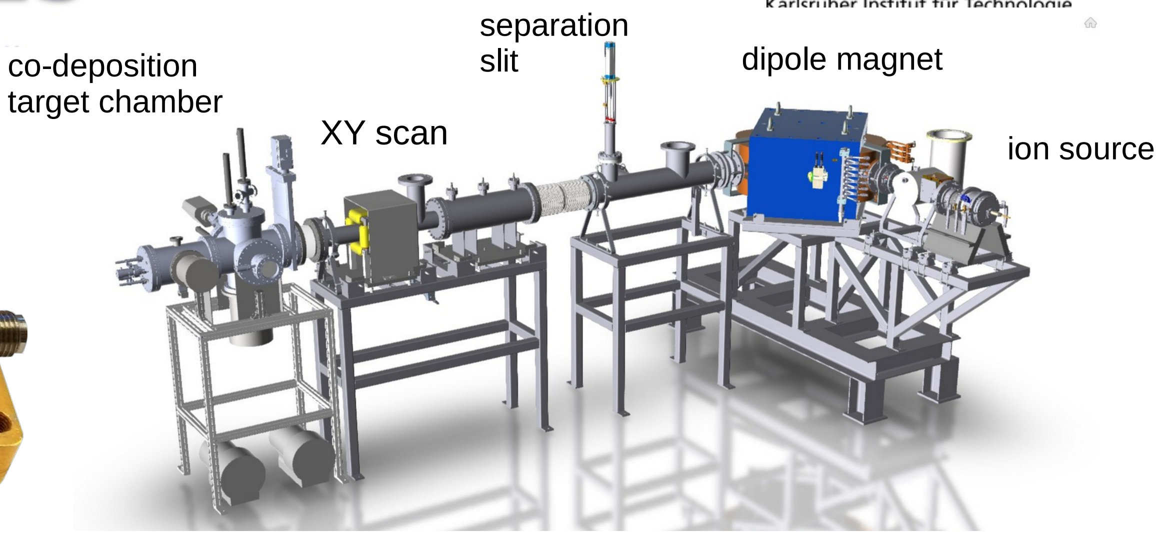
- Statistics at the endpoint:
  - 10^{14} events → $a_{total} > 1\ MBq$
- Very low background level:
  - $R_{bkg} < 10^{-5}\ events/eV/pixel/day$
- Energy resolution:
  - $\Delta E(FWHM) < 1\ eV$



TES technology with HOLMES

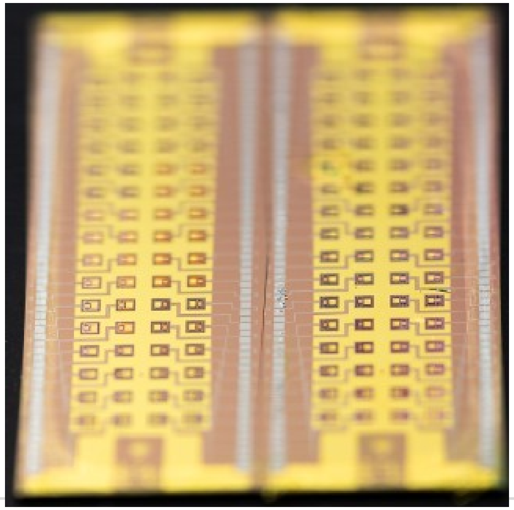


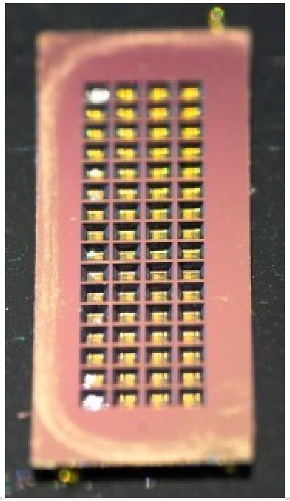


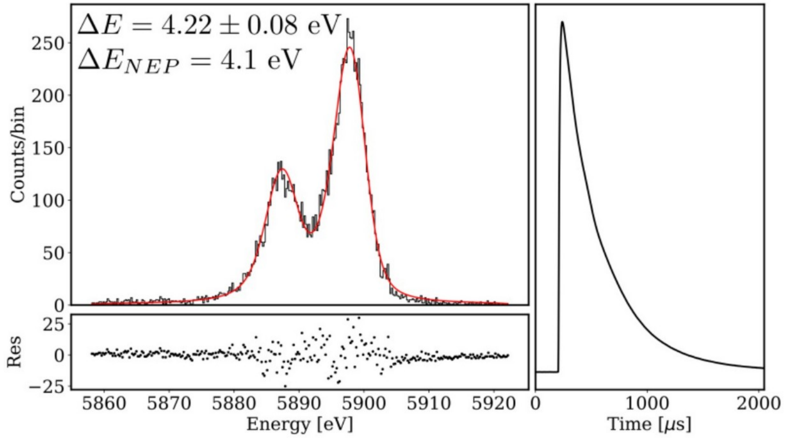


Detector design & fabrication at Milano

Mass separation and isotope embedding in Genova







- ΔE_{FWHM} ~ 4-6 eV, τ_{rise}~ 1.5 µs, τ_{decay}~ 300 µs

M. Borghesi et al., EPJ. C 81.5 (2021)

MMC technology with ECHo

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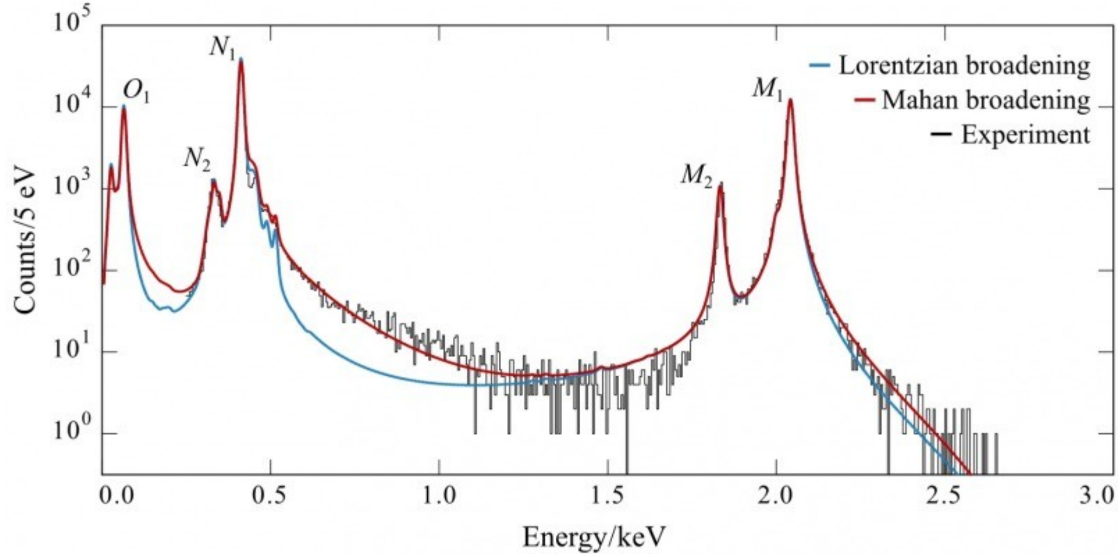
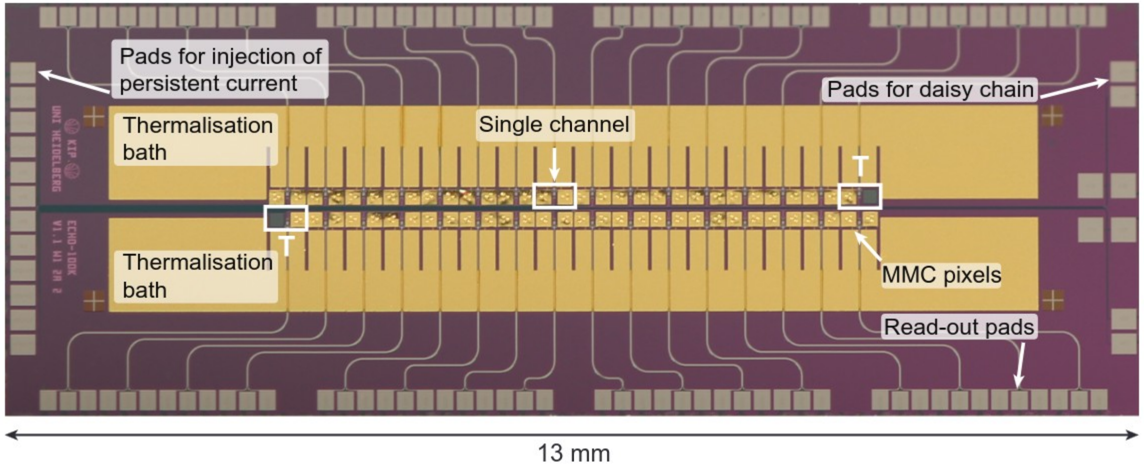
Achievements

- first holmium spectra measured
  - ΔE = 5 eV (FWHM), b <1.6x10^{-4} eV^{-1}pixel^{-1}day^{-1}
- first neutrino mass limit:
  - m < 150 eV (95% C.L.)
- refined theoretical calculations
- ECHo-1k completed: ~60 Bq (> 10^{8} events)
  - sensitivity on m < 20 eV

Next steps/challenges

- ECHo-100k: m < 2 eV



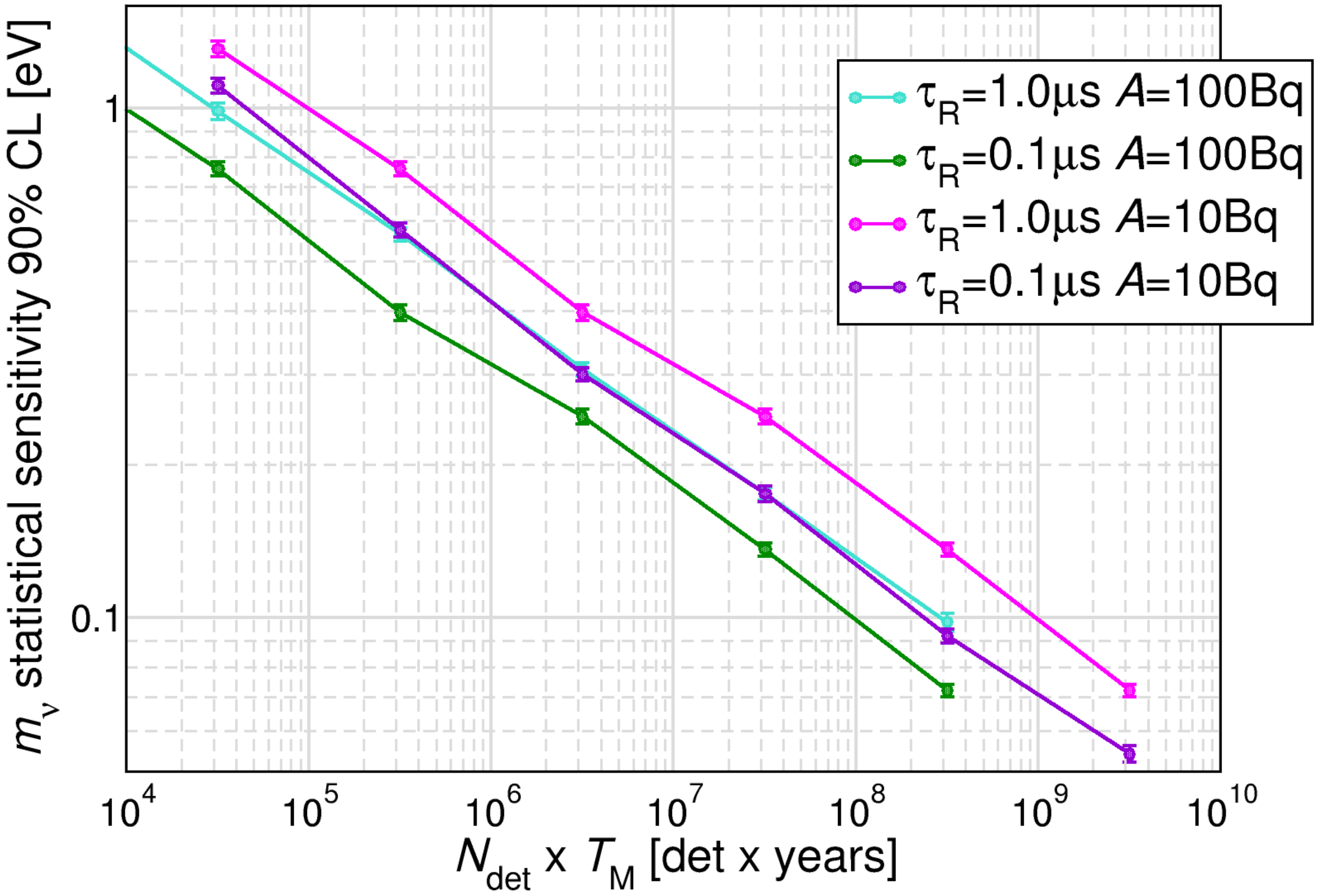


arXiv:2301.06455

EPJ-C 79 1026 (2019), Phys.Rev.C 97 (2018), New J. Phys. 22 (2020) 093018, EPJ-C 81, 963 (2021)

Towards ultimate sensitivity with ^{163}Ho

- pixel activity ≥100Bq/det
  - ^{163}Ho heat capacity
- time resolution below 0.1μs
- about 10M pixels
  - multiplexing and DAQ bandwidth



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CRES technology: measuring the cyclotron frequency

Calorimetry with quantum sensors

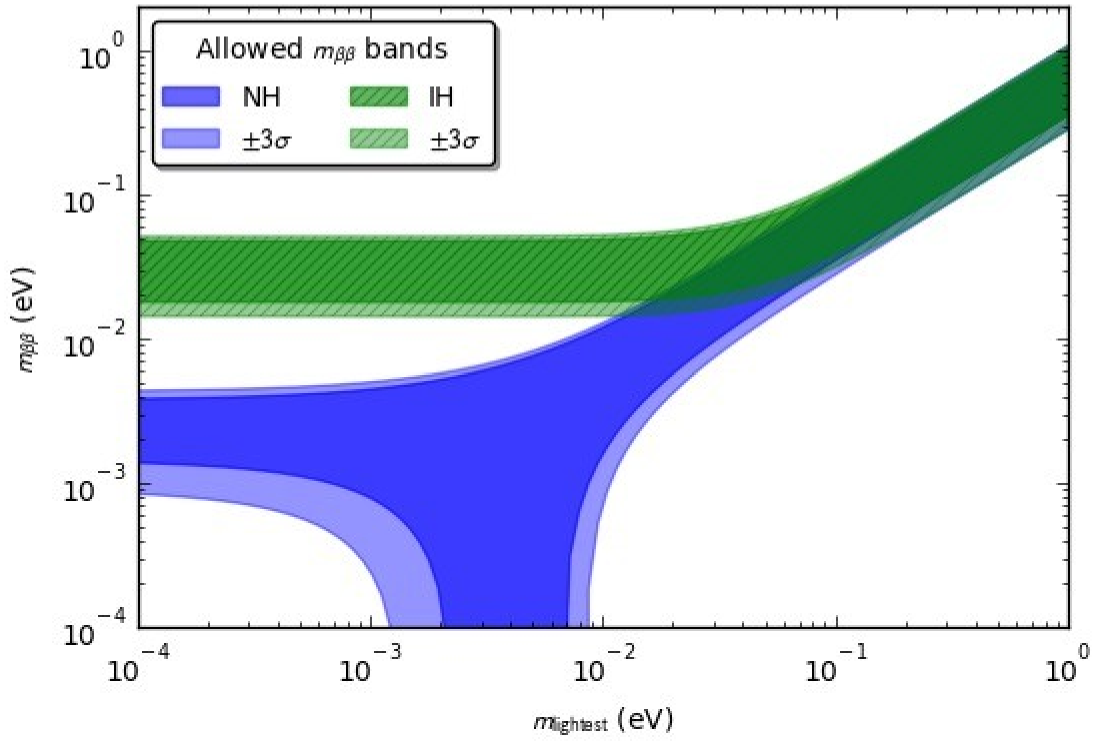
What other physics can we probe in the direct mass measurements?

Questions

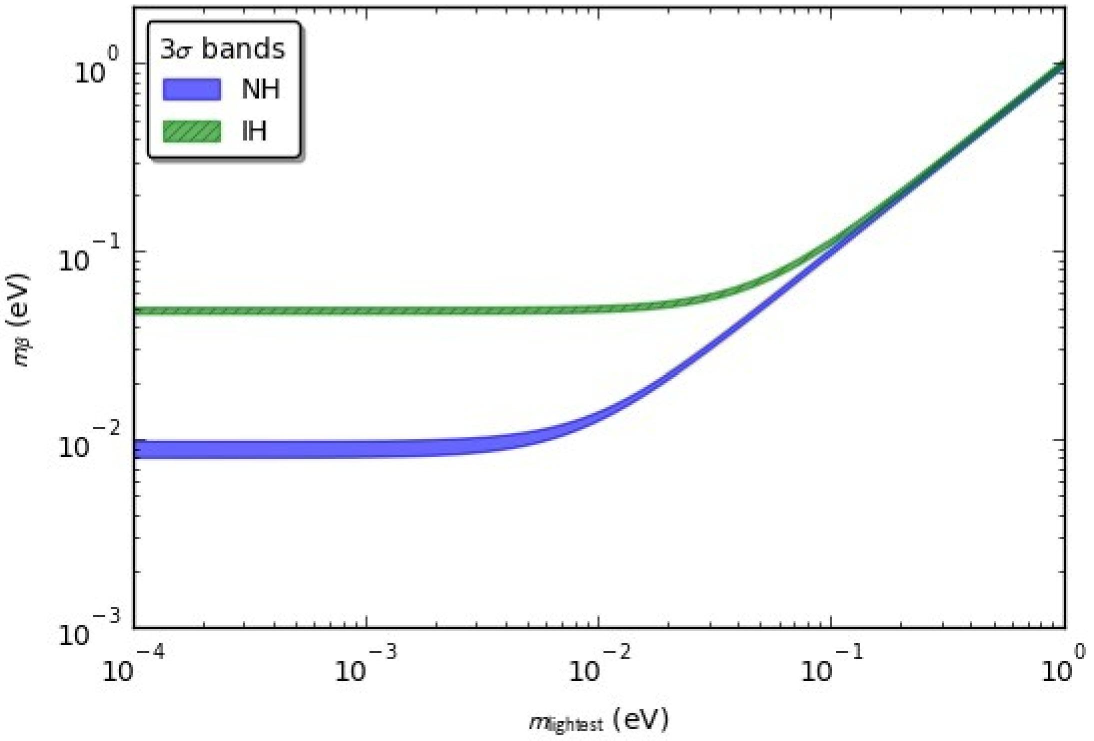
What do we measure?	Distortion of energy spectrum close to endpoint	Observable:	$m_\nu^2 = \sum_i \lvert U_{ei} \rvert^2 \cdot m_i^2$
How does KATRIN work?	Integrated spectrum	Electrostatic filtering + molecular tritium source	Now: <0.8 eV Goal: <0.3 eV
How can we go beyond KATRIN?	Differential energy measurement	Atomic tritium	New technologies: quantum sensors, CRES
What happens if we measure nothing?			

double β-decay vs single β-decay

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

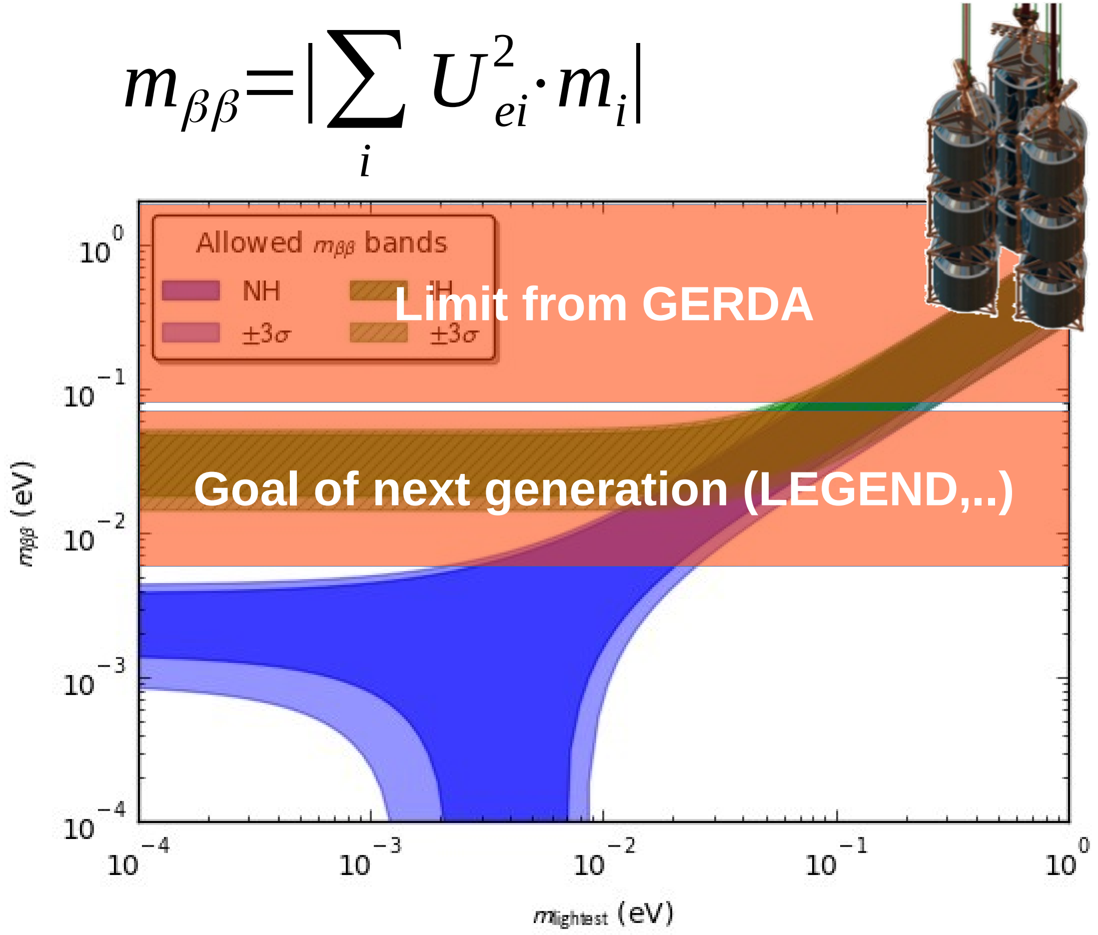


$$m_\nu^2=\sum_i |U_{ei}|^2 \cdot m_i^2$$

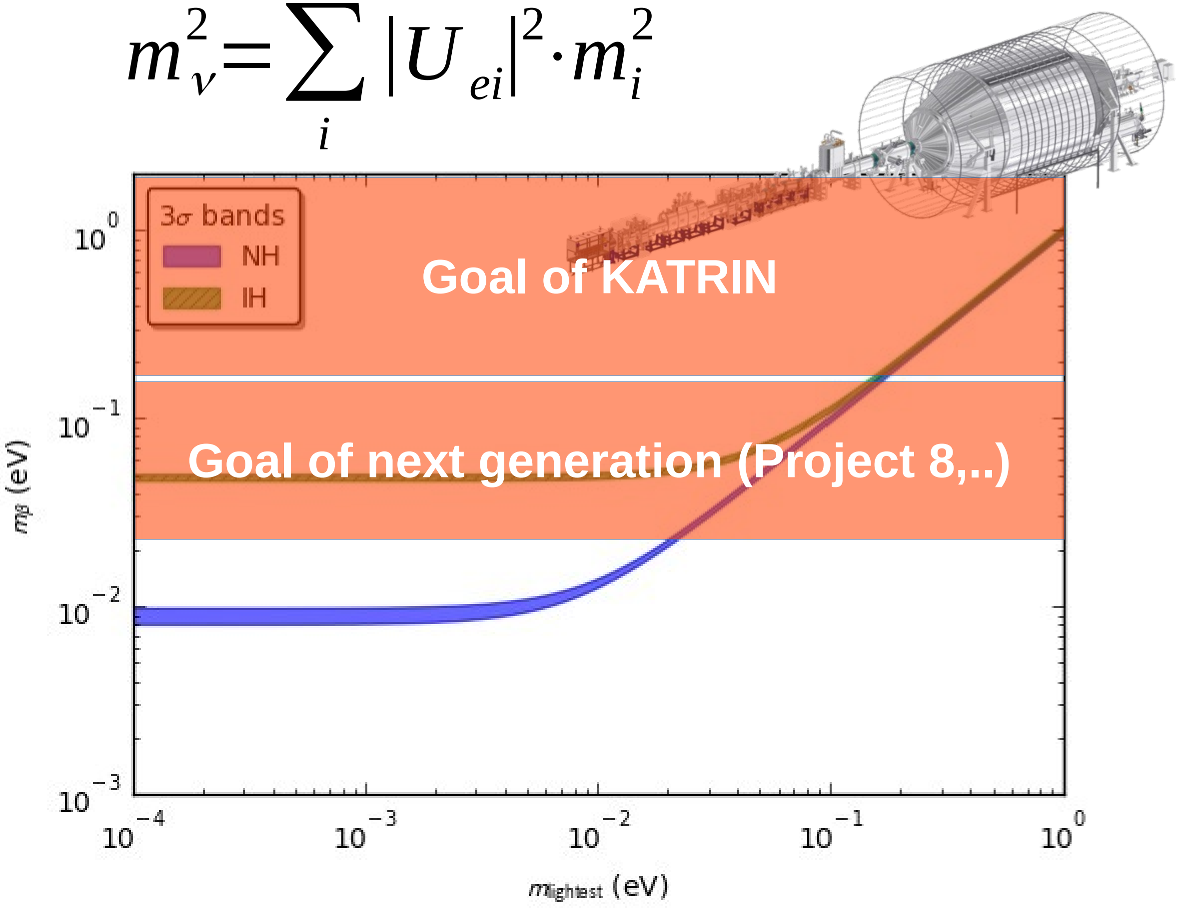


double β-decay vs single β-decay

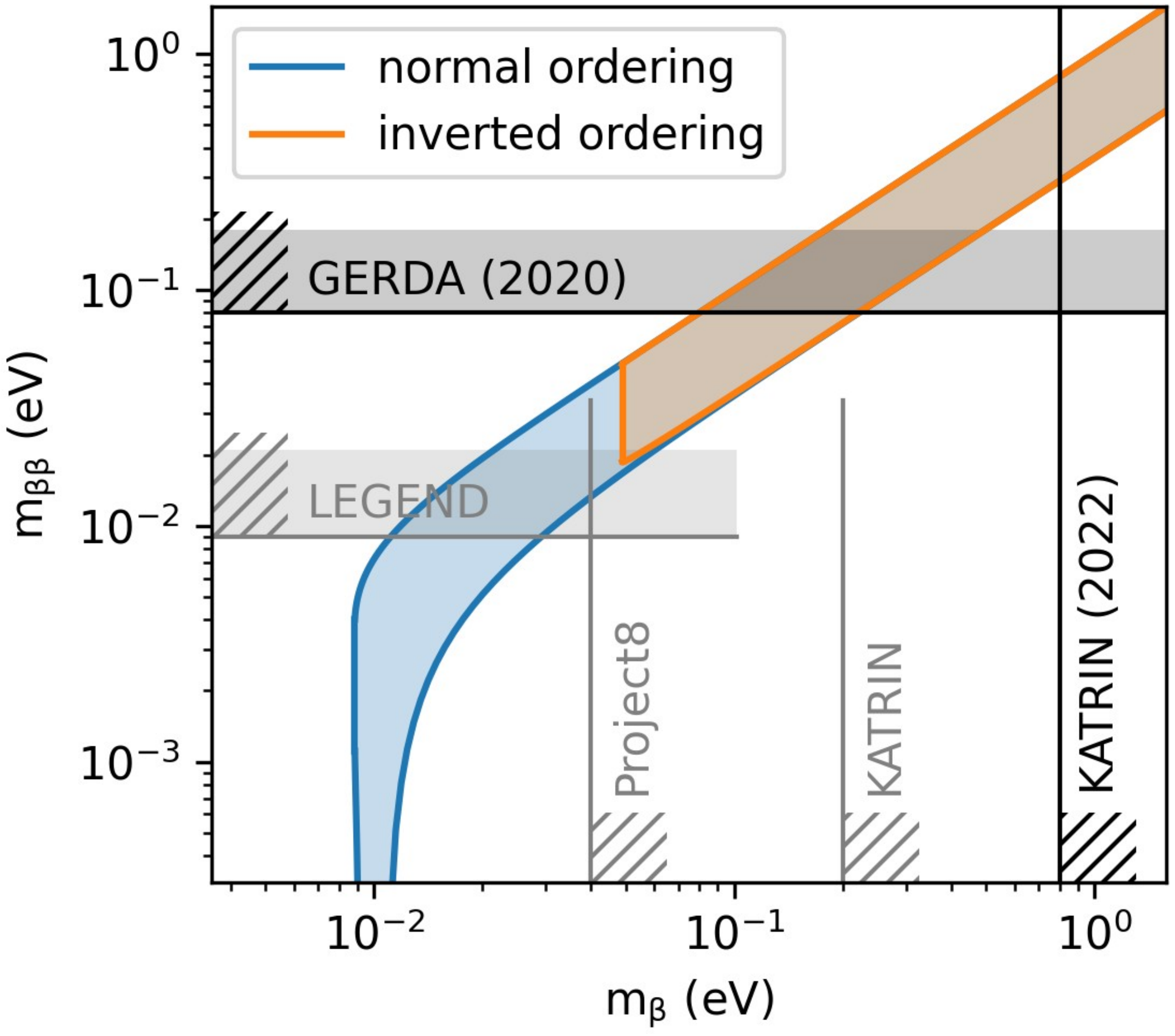
$$m_{\beta\beta} = |\sum_i U_{ei}^2 \cdot m_i|$$



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



Puzzles



- Option 1: KATRIN or Project 8 measures a neutrino mass but LEGEND sees no signal
  - Neutrino – Dirac particle
  - Cancellation in $0\nu2\beta$-decay and $m_{\beta\beta}$
- Option 2: LEGEND measures a $0\nu2\beta$-signal, but Project 8 measures no mass
  - a different mechanism for $0\nu2\beta$-decay

Questions

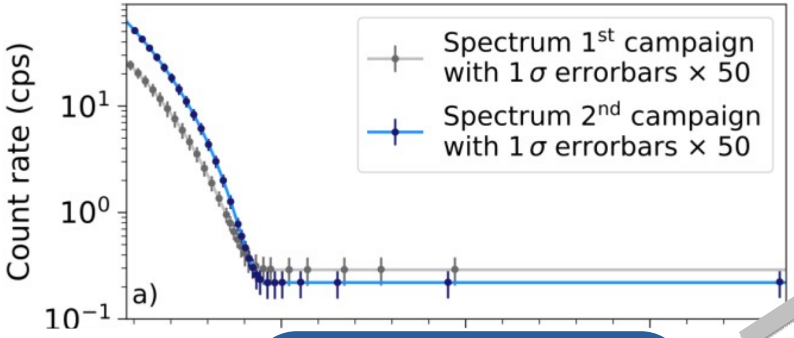
Karlsruher Institut für Technologie

What do we measure?	Distortion of energy spectrum close to endpoint	Observable:	$m_\nu^2 = \sum_i \lvert U_{ei} \rvert^2 \cdot m_i^2$
How does KATRIN work?	Integrated spectrum	Electrostatic filtering + molecular tritium source	Now: <0.8 eV Goal: <0.3 eV
How can we go beyond KATRIN?	Differential energy measurement	Atomic tritium	New technologies: quantum sensors, CRES
What happens if we measure nothing?	Direct measurements of mass are the least model dependent	Complementarity of 0ν2β, direct and cosmology	

Outline

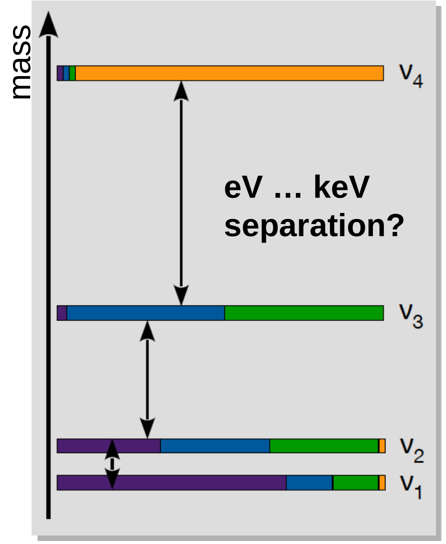
What do we know so far about neutrino masses?	Neutrinos are massive	The squared mass differences are known	The absolute scale is unknown
What are the three approaches to neutrino mass?	Cosmology, $0\nu2\beta$-decay, direct searches	Complementary observables	Direct laboratory measurements – least model dependent
How to measure the mass without model dependencies?	Current limit from KATRIN (MAC-E-Filter): <0.8 eV (90% CL)	CRES technology: measuring the cyclotron frequency	Calorimetry with quantum sensors
What other physics can we probe in the direct mass measurements?	Taking KATRIN as an example		

“Beyond neutrino mass” in KATRIN



β-spectrum of high statistics and precision

Is there a fourth (sterile) neutrino?

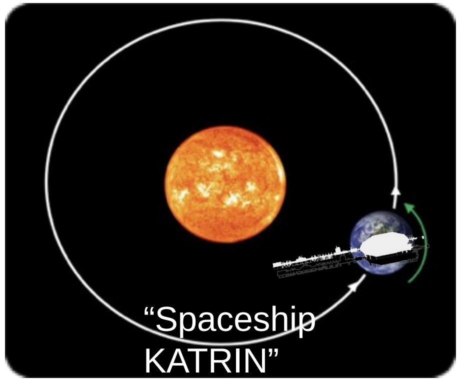


Neutrino mixing: “Kink” in regular β-spectrum tail (eV scale) or deep β-spectrum (keV scale)

Constrain local overdensity of cosmic relic neutrinos

Search for exotic interactions (spectrum shape)

Search for Lorentz invariance violation (sidereal modulation)



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, 0ν2β-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)

CRES technology: measuring the cyclotron frequency

Calorimetry with quantum sensors

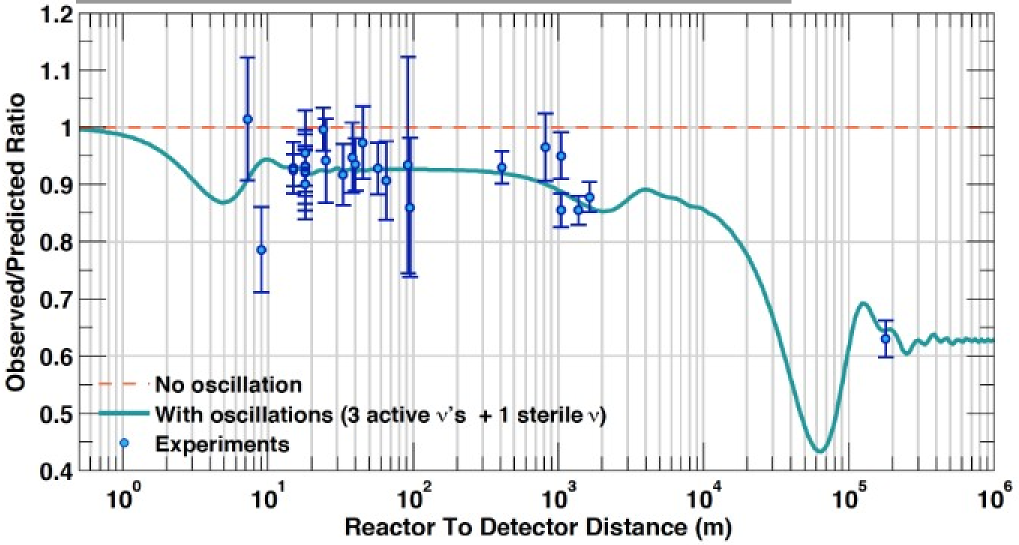
What other physics can we probe in the direct mass measurements?

Sterile neutrinos

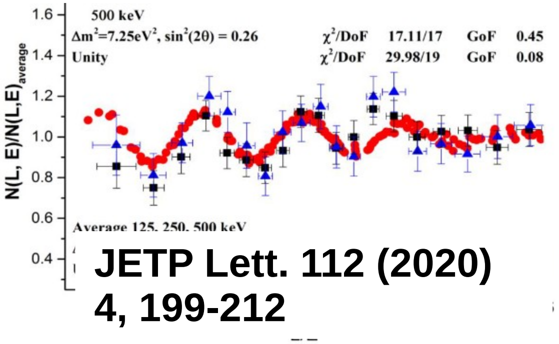
Light sterile neutrinos – Motivation

- Multiple (longstanding) anomalies in the oscillation data
- No universal explanation to all of them
- An oscillation-free measurement as an independent cross-check by KATRIN

Reactor antineutrino anomaly

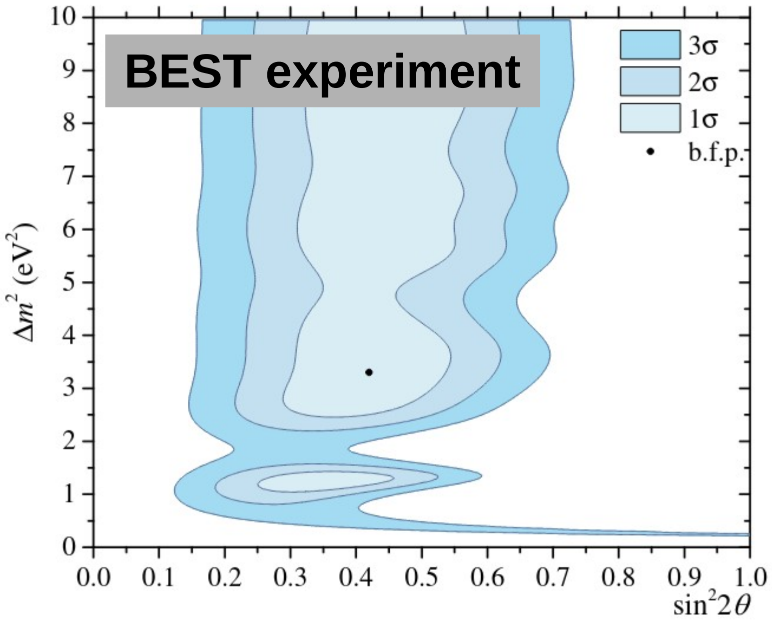


Neutrino-4 experiment



JETP Lett. 112 (2020) 4, 199-212

BEST experiment

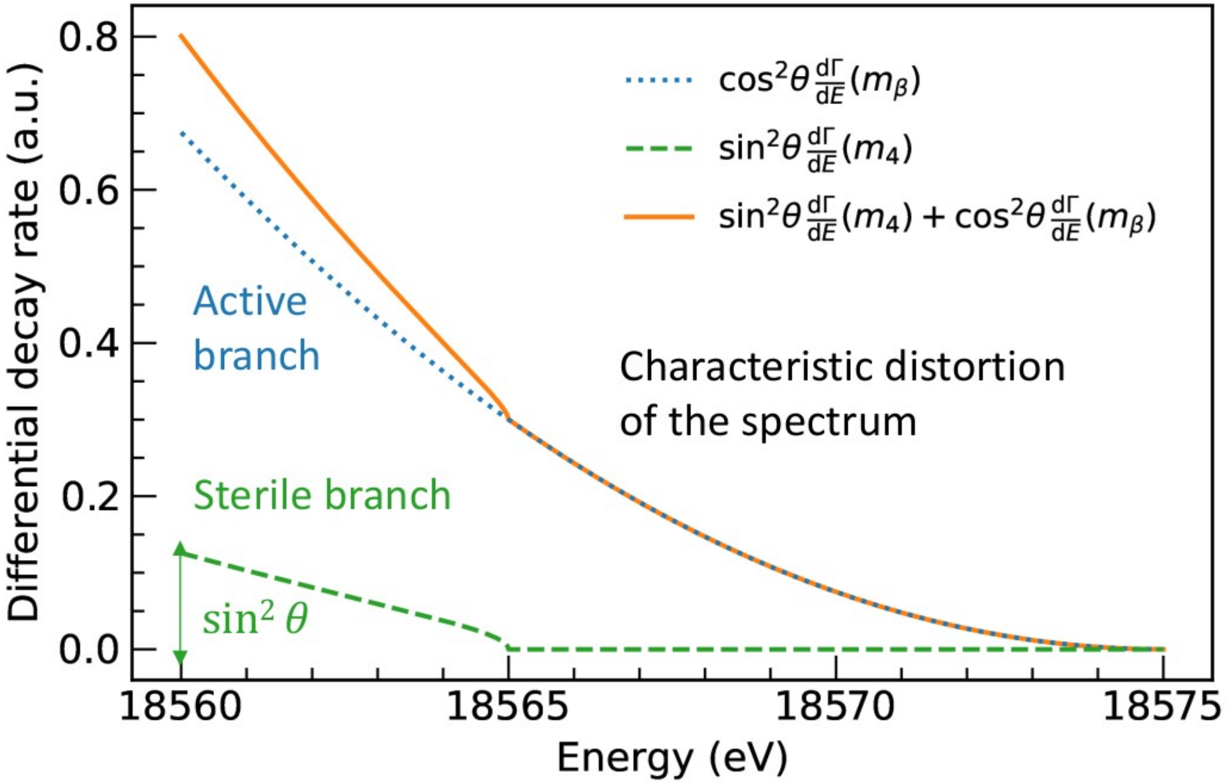


Phys.Rev.Lett. 128 (2022) 23, 232501

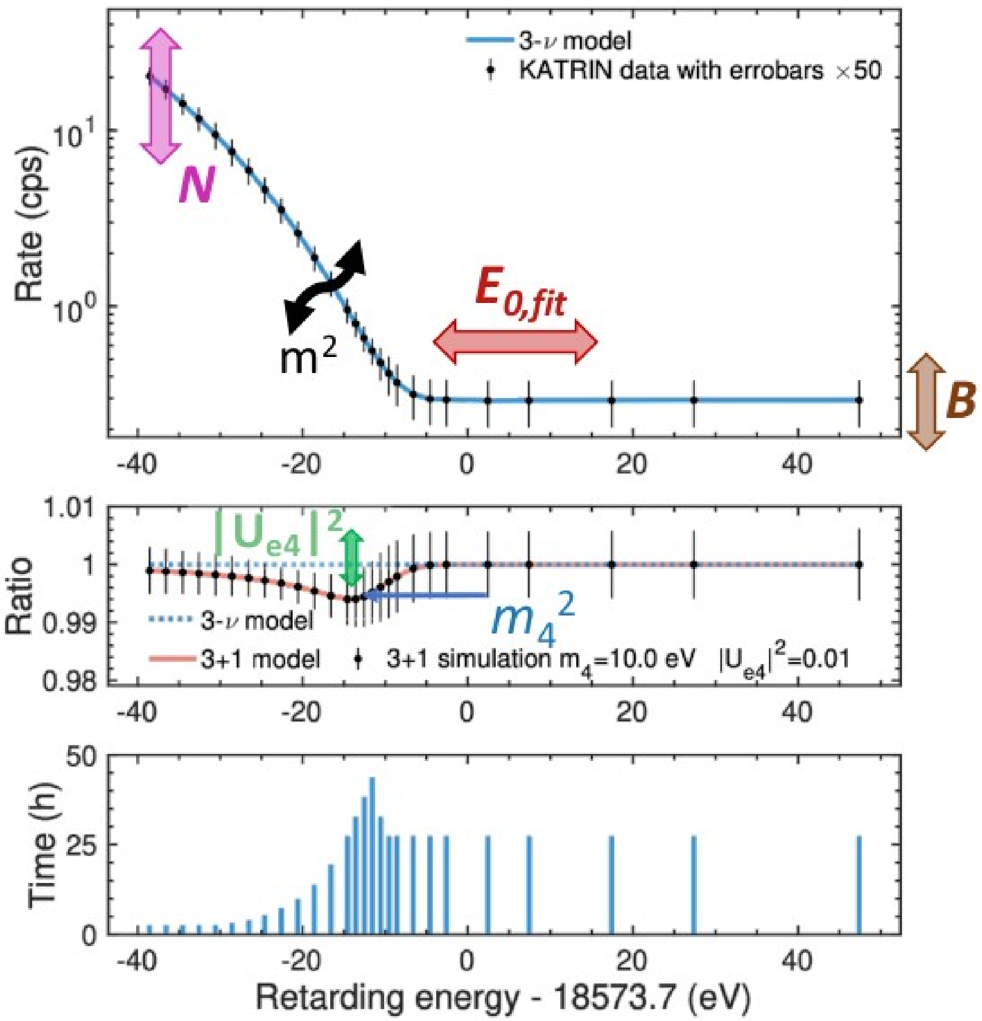
Sterile neutrinos signature in β-spectrum

- 3+1 sterile neutrino model
- Same data-set as for the neutrino mass
- Grid search in m_4, $|U_{e4}|^2$ plane

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



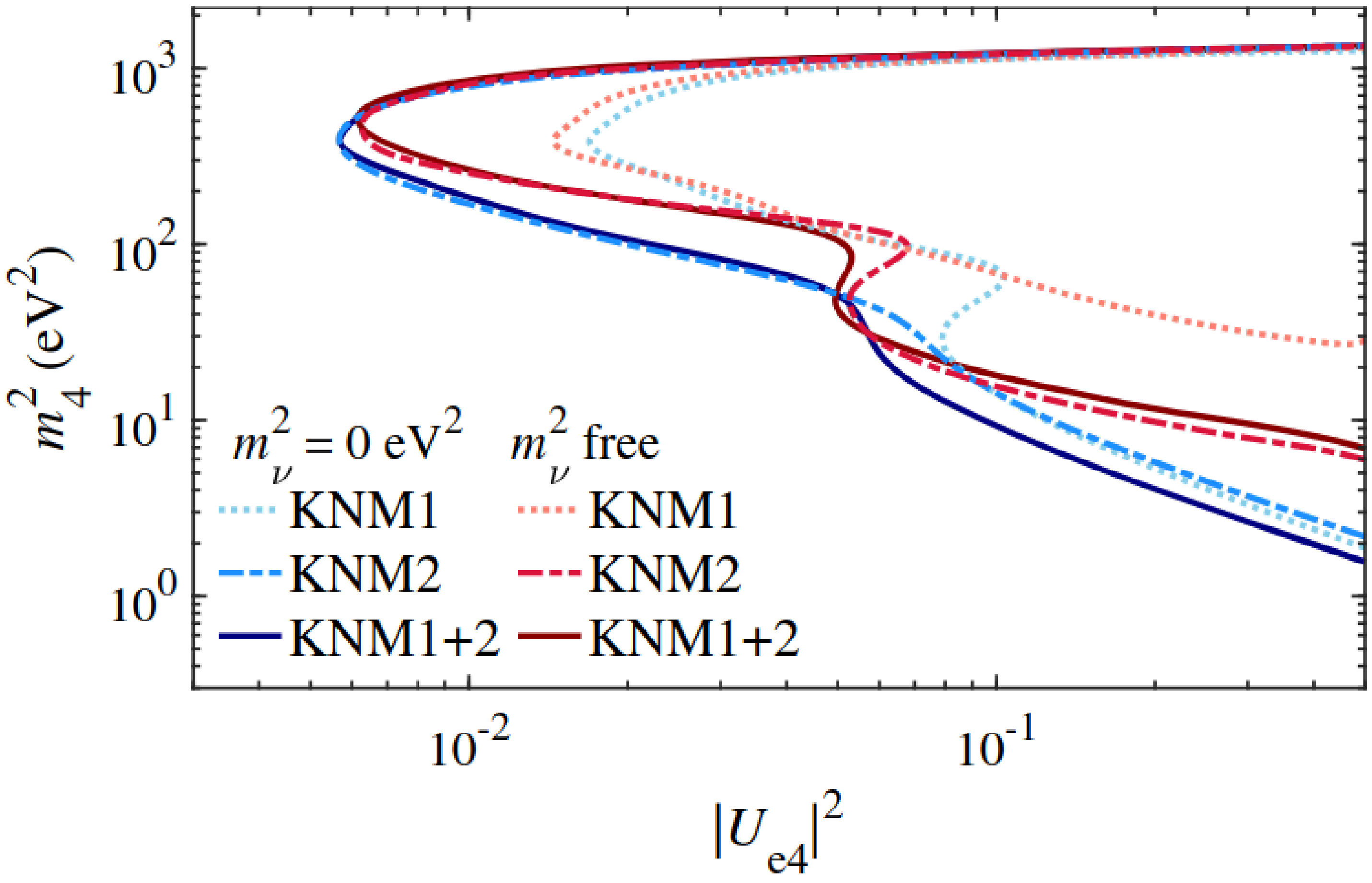
Sterile neutrinos signature in KATRIN



6 Fit parameters:

- N – amplitude of the signal
- E_0 – effective endpoint energy
- m^2 – effective mass of the electron antineutrino
- B – background rate
- $|U_{e4}|^2$ – 4th neutrino mixing
- m_4^2 – 4th neutrino mass

Combination of 1st and 2nd campaigns



Fixed $\boldsymbol{m_\nu^2 = 0}$

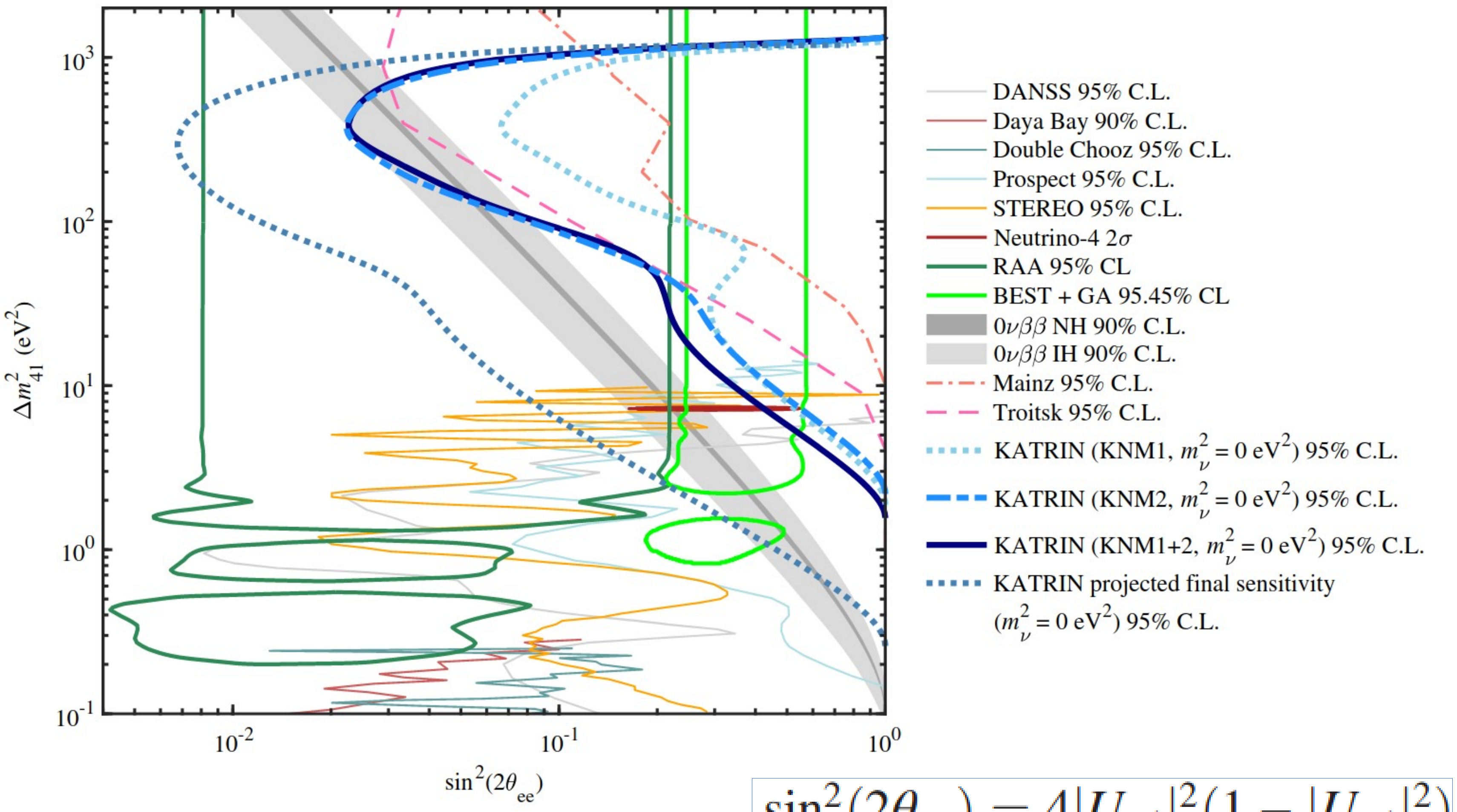
$$m_4^2 = 59.9\,\mathrm{eV}^2, |U_{e4}^2| = 0.011$$
$$\Delta\chi^2_{null} = 0.66$$

Free $\boldsymbol{m_\nu^2}$

$$m_4^2 = 87.4\,\mathrm{eV}^2, |U_{e4}^2| = 0.019$$
$$\Delta\chi^2_{null} = 1.69, m_\nu^2 = 0.57\,\mathrm{eV}^2$$

KATRIN Collab., PRD 105, 072004 (2022)

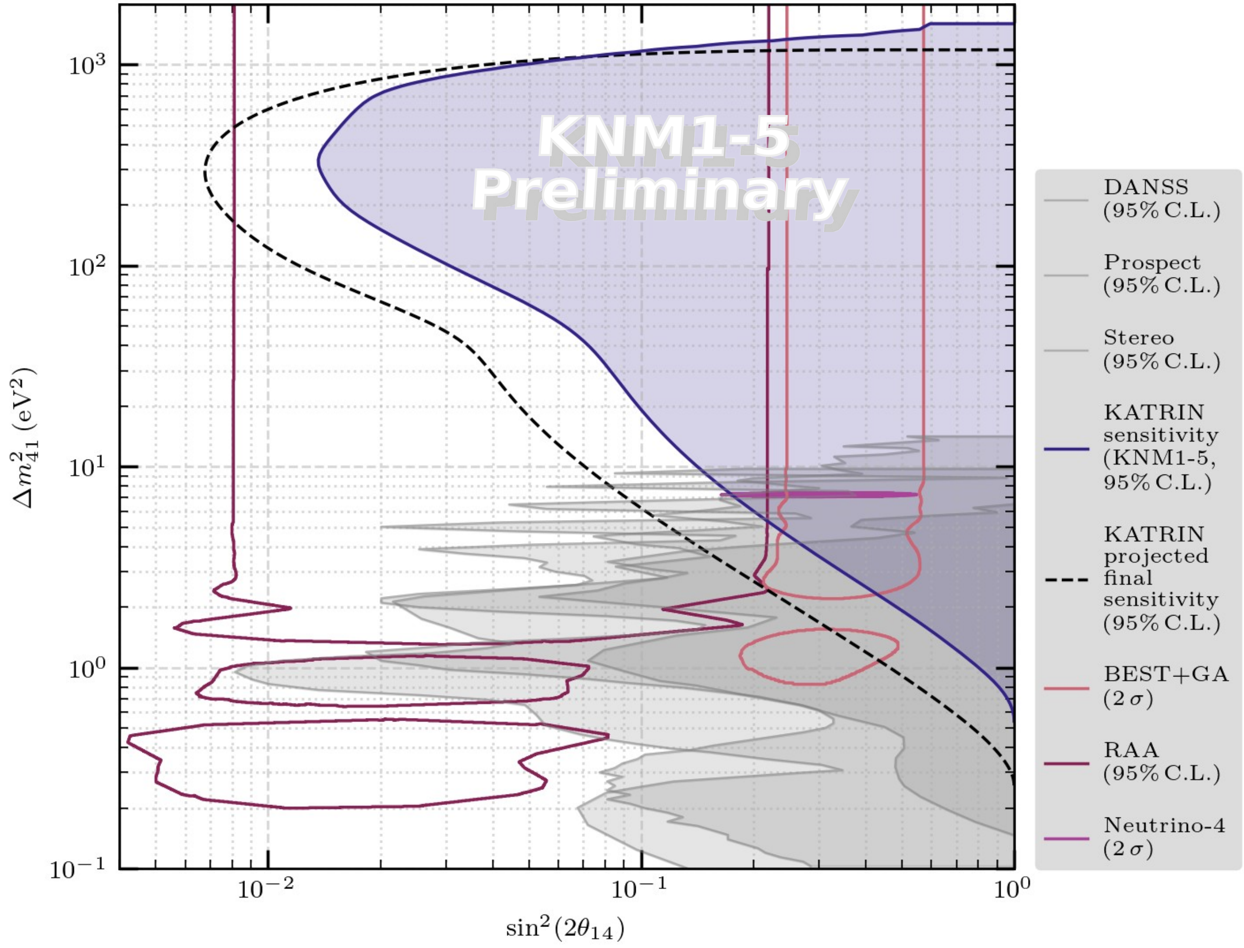
Sterile neutrinos – complimentarity



$$\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1 - |U_{e4}|^2)$$

- looking at the short baseline anomalies from a different perspective
- Signal-to-background up to 250
- More stringent limits than Troitsk and Mainz
- approaching the BEST allowed regions with **$\Delta m^2 \gtrsim$ 10 eV^2**
- complementary probe to oscillation-based experiments

Sterile neutrinos – prospects



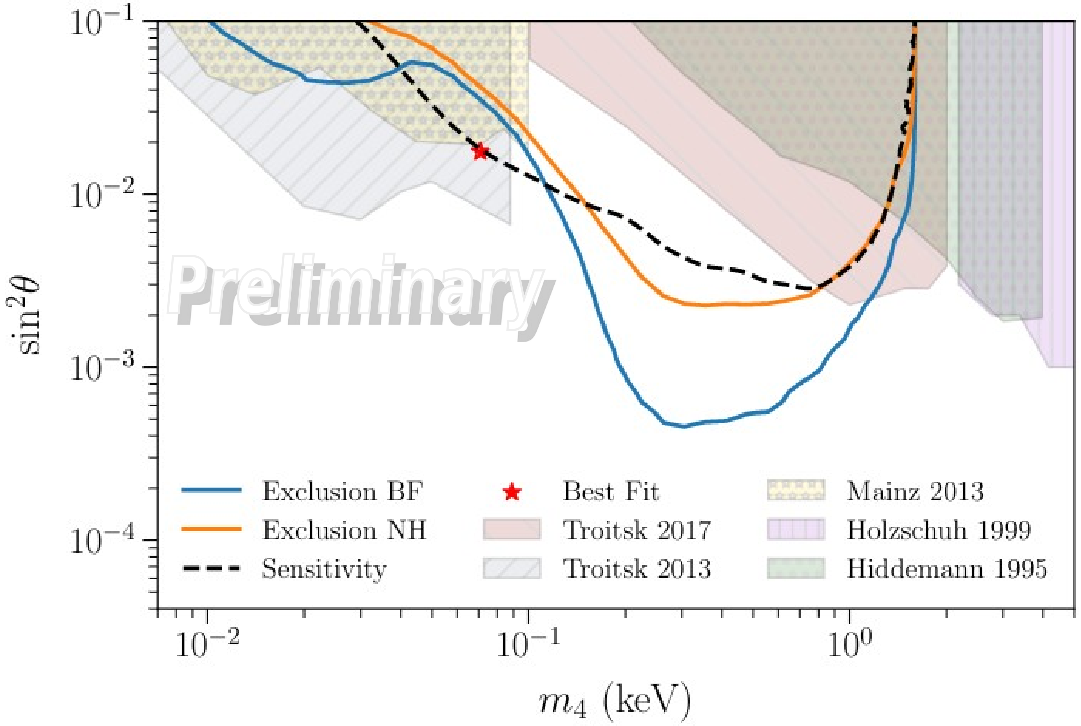
With first 5 datasets

- Probing large portion of the RAA, BEST and Neutrino-4

With full dataset

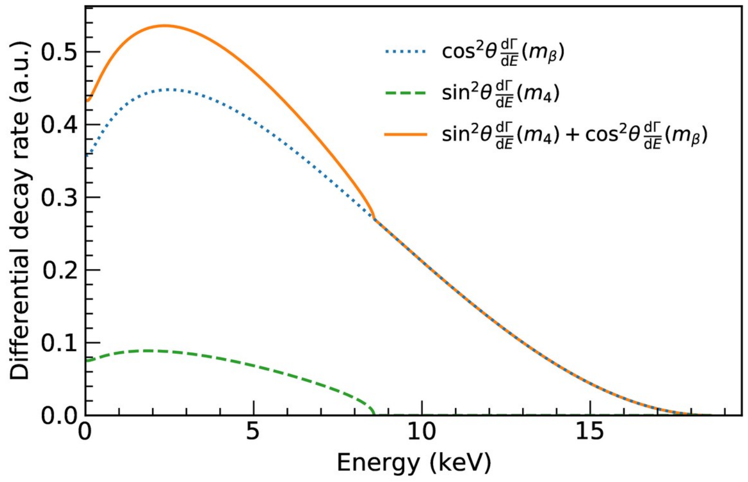
- Sensitive to interesting parameter range
- comparable sensitivities to neutrinoless double β-decay

keV sterile neutrinos



KATRIN Collab., arXiv:2207.06337

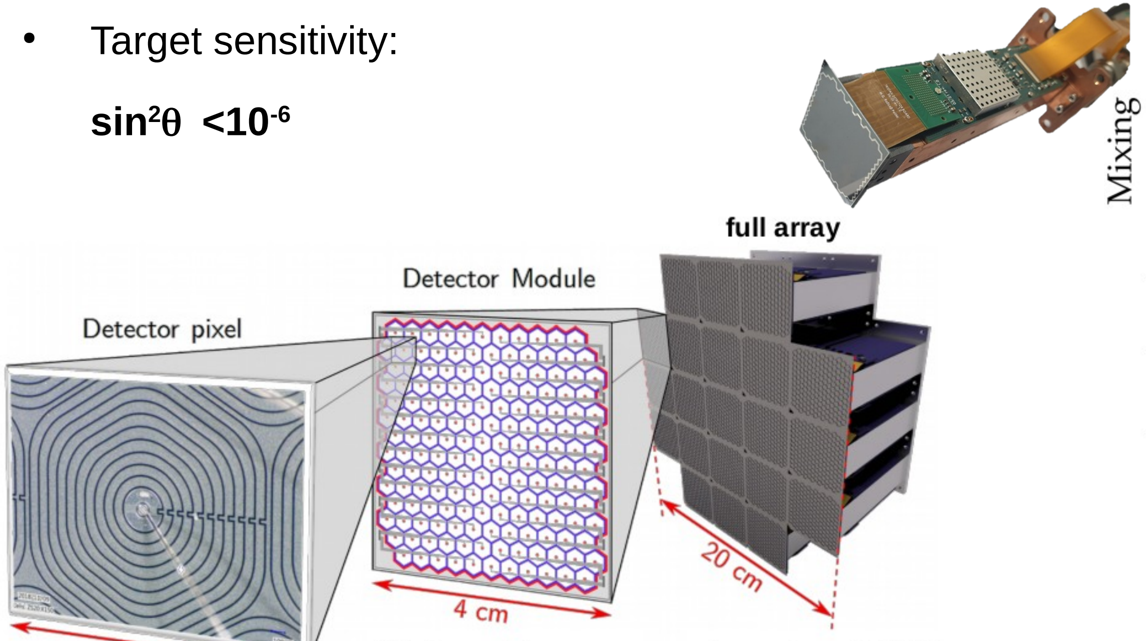
- Probing neutrinos with keV masses
  - using the first (technical) measurement phase
- Very high rates (mcps → Mcps)
- Several new effects to be taken into account
  - back-scattering of electrons
  - magnetic trapping

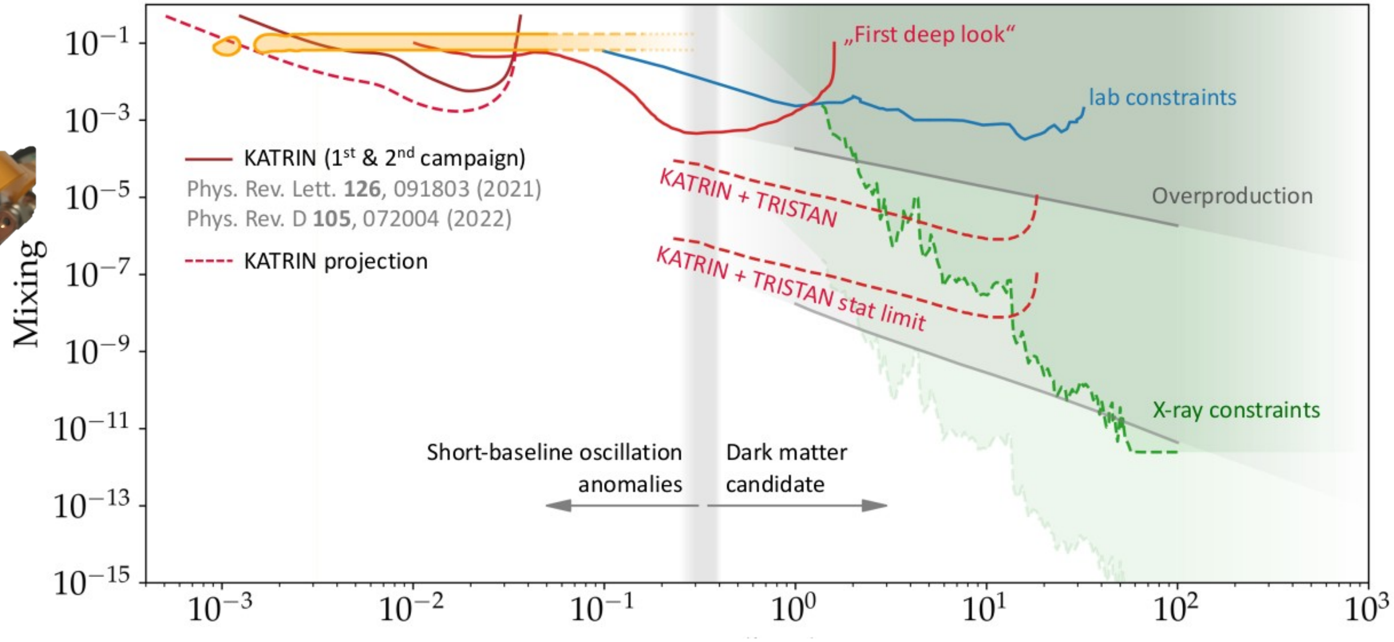


KATRIN with TRISTAN detector

- Novel multi-pixel Silicon Drift Detector array (>1000 pixels)
- Large count rates: 100 kcps/pixel
- Excellent energy resolution: 160 eV (FWHM) at 6 keV
- Target sensitivity:

  $\sin^2\theta$ <10^{-6}





- 9 modules of TRISTAN at KATRIN after 2025
- Several updates of the setup for reducing the systematics

S. Mertens et al., J.Phys.G 46 (2019) 6, 065203; T. Brunst et al.,JINST 14 (2019) 11, P11013, T. Houdy et al.,J. Phys.:C.Ser. 1468 (2020) 012177

Outline

What do we know so far about neutrino masses?	Neutrinos are massive	The squared mass differences are known	The absolute scale is unknown
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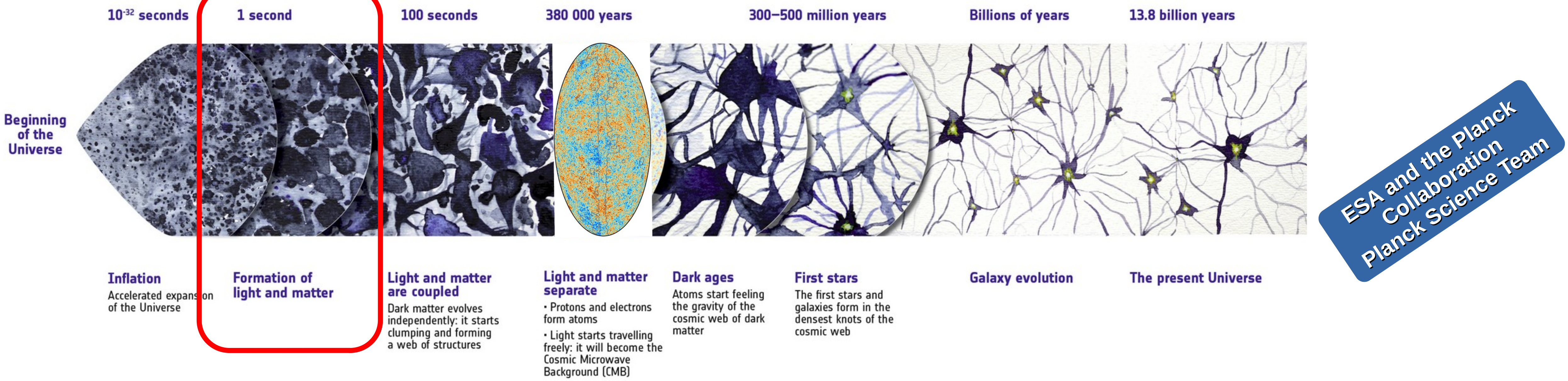
What other physics can we probe in the direct mass measurements?	Sterile neutrinos	Relic neutrinos	

Cosmic neutrino background: Motivation

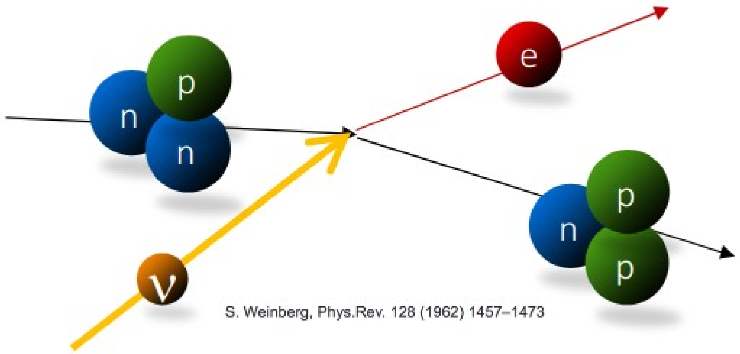


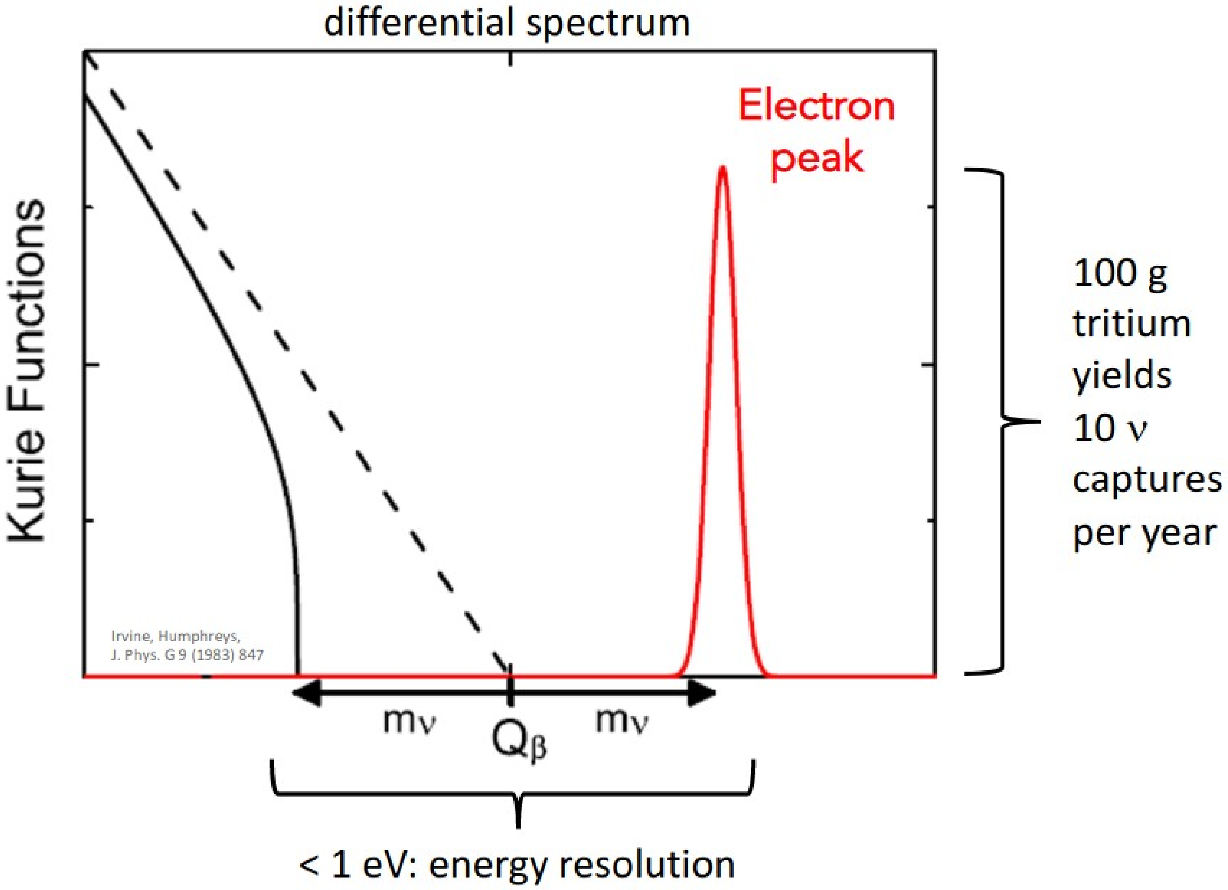
- ~340 relic neutrinos of all species /cm^3 in the Universe (56 /cm^3 per species)
- Decoupled the first second (1 MeV) after Big Bang
- Predicted overdensity $\eta \approx$ (1.2..20)
- Upper limits from previous kinematic neutrino mass measurements: 10^{13}

Relic neutrinos search with KATRIN

- relic neutrinos with meV energies
- neutrino capture on tritium (no energy threshold)
- Peak above the endpoint

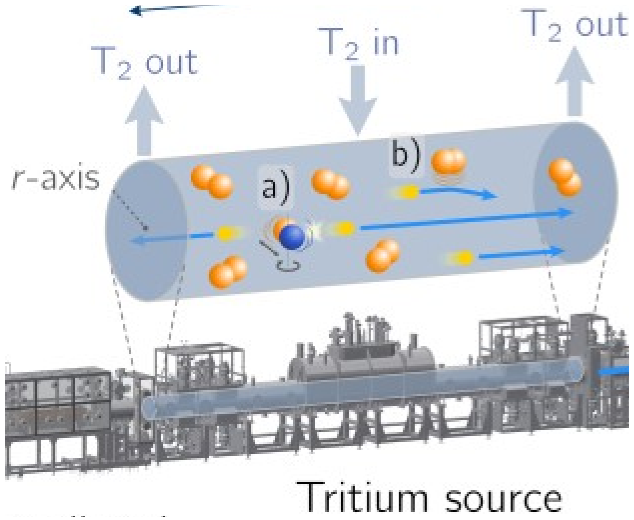
$$^{3}\mathrm{H} + \nu_e \longrightarrow \; ^{3}\mathrm{He}^{+} + e$$

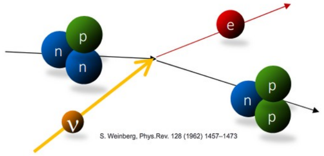




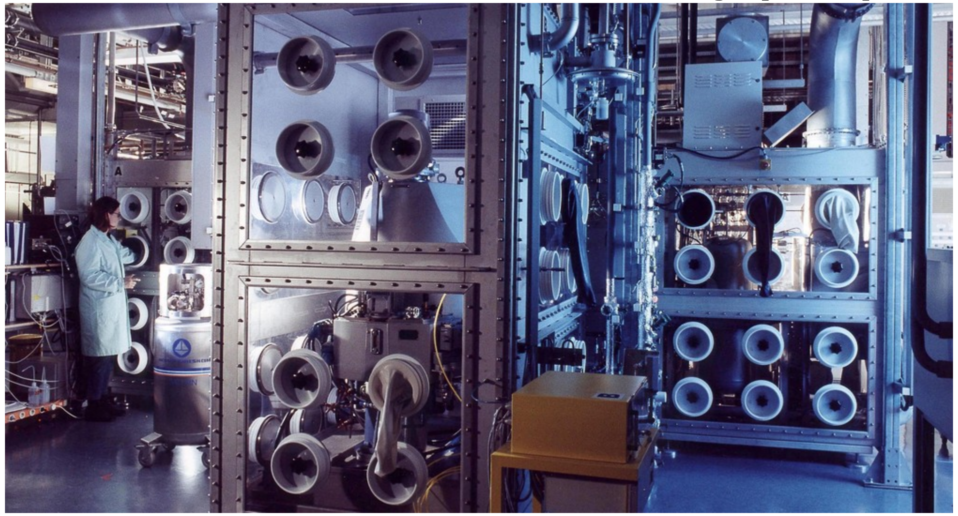
KATRIN Collab., PRL 129 (2022) 1, 011806

Relic neutrinos search with KATRIN





Karlsruhe Tritium Laboratory (TLK)



up to 40 g of tritium

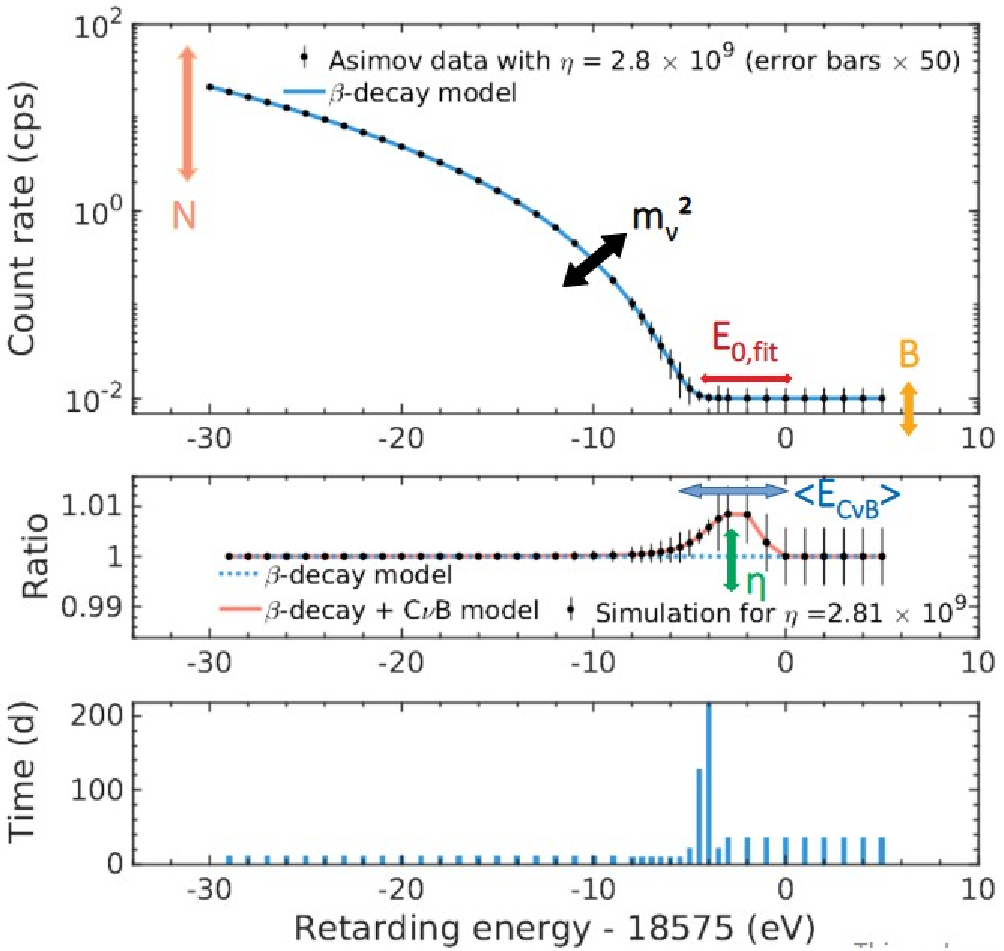
tens of μg of T_2 in the source
10^{-6} captures per year

KATRIN has the sensitivity to probe large clustering of cosmic neutrinos around the solar system

$$\eta = n_\nu / \langle n_\nu \rangle$$

KATRIN Collab., PRL 129 (2022) 1, 011806

Model for the relic neutrinos in KATRIN



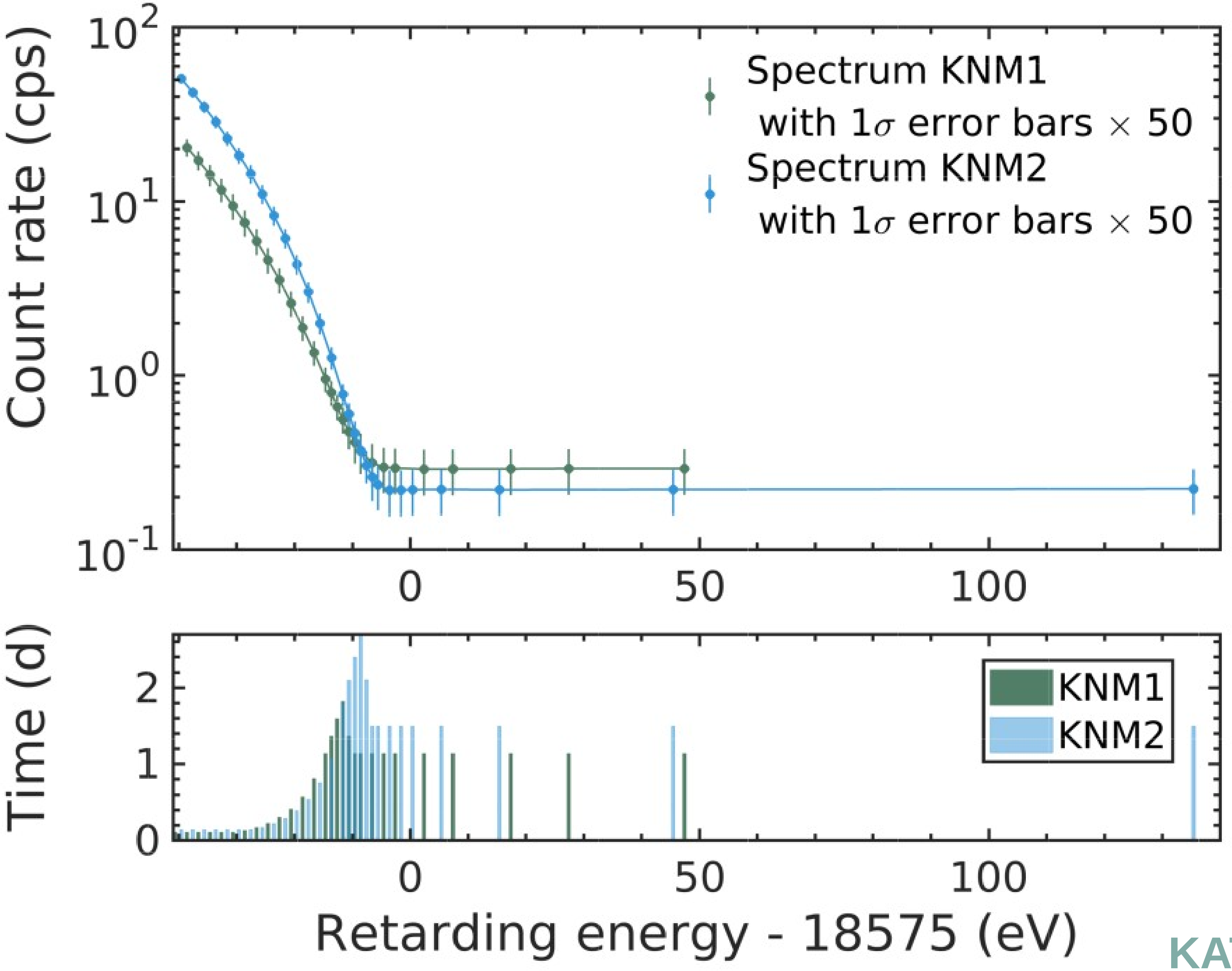
Fit parameters:

- N – amplitude of the signal
- E_0 – effective endpoint energy
- m^2 – effective mass of the electron antineutrino
- B – background rate
- η – local overdensity
- meV energy is neglected

$$R_{\mathrm{diff}}(E) = R_{\beta}(E) + R_{\mathrm{C\nu B}}(E)$$

KATRIN Collab., PRL 129 (2022) 1, 011806

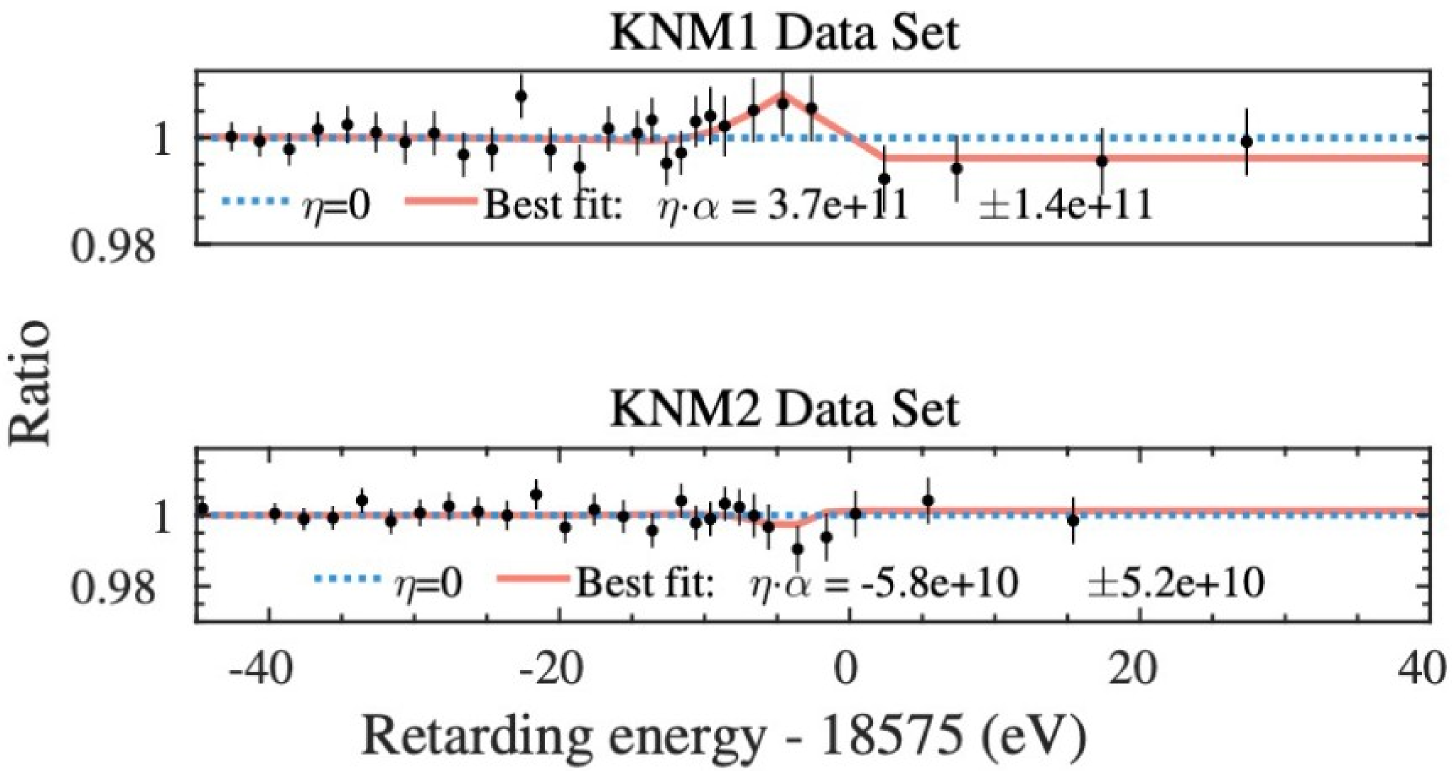
Relic neutrinos in the first science runs



- 1st campaign (2019)
  - 522 hours
  - 3.4 µg for capture on tritium
- 2nd campaign (2019)
  - 744 hours
  - 13.0 µg for capture on tritium

KATRIN Collab., PRL 129 (2022) 1, 011806

Relic neutrinos in the first science runs



- 1st campaign (2019)
  - 522 hours
  - 3.4 µg for capture on tritium
- 2nd campaign (2019)
  - 744 hours
  - 13.0 µg for capture on tritium
- no evidence for relic neutrino overdensity
  - upper limits

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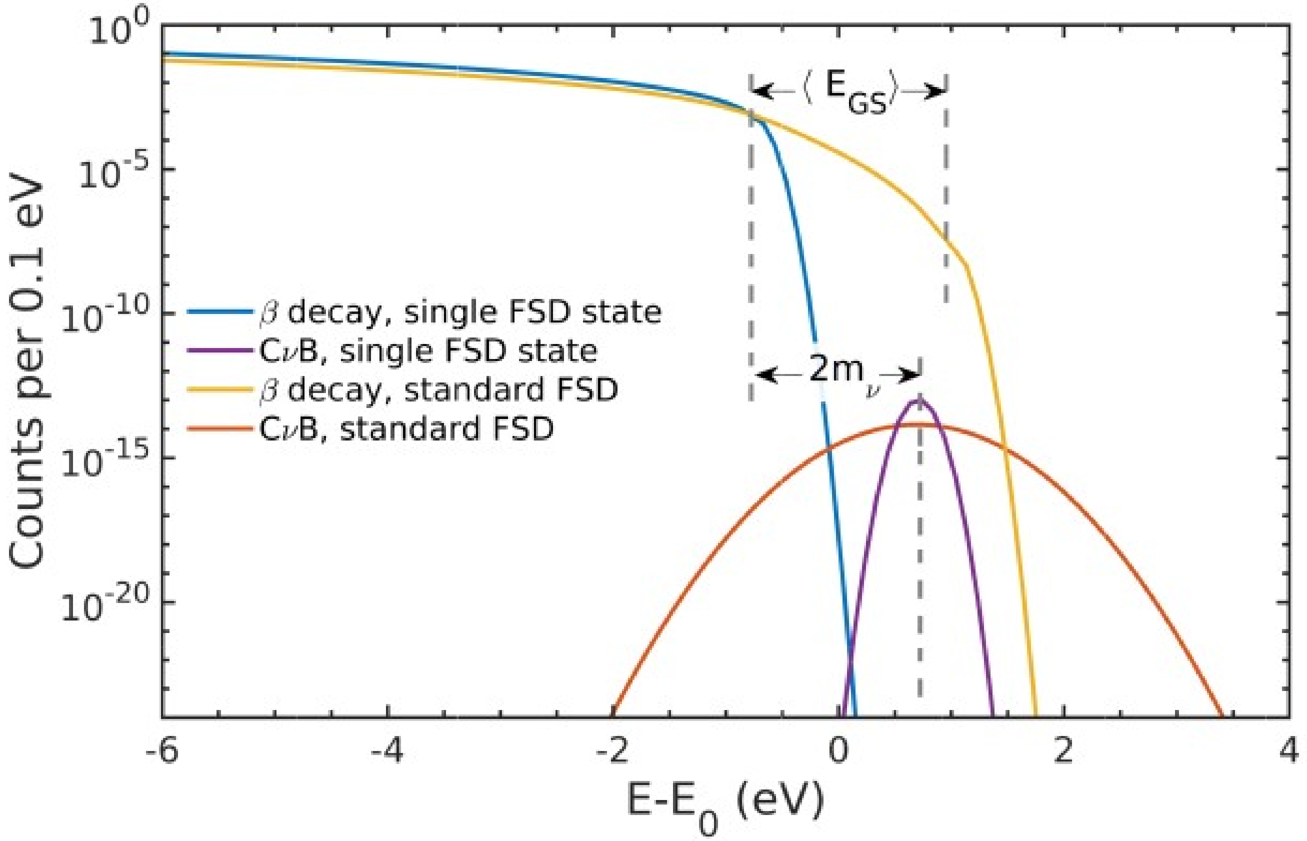
Relic neutrinos: challenges



- Background rate
  - order of magnitude higher
- T_2 β-spectrum creates irreducible background
  - $m_\nu < \langle E_{GS} \rangle /2 = 0.85$ eV
  - increase of the target mass does not increase the CνB sensitivity

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Relic neutrinos: results and prospects

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- search for large overdensity η of relic neutrinos near the Earth
- $\eta < 1.1 \cdot 10^{11}/\alpha$ at 95% C.L. – the search is statistically limited
- improved by 2 orders of magnitude compared to previous laboratory limits

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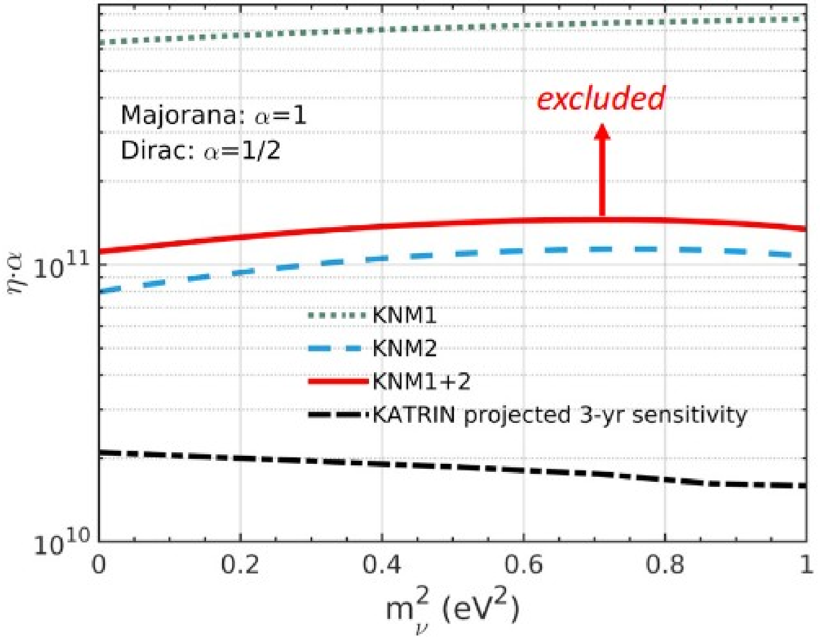

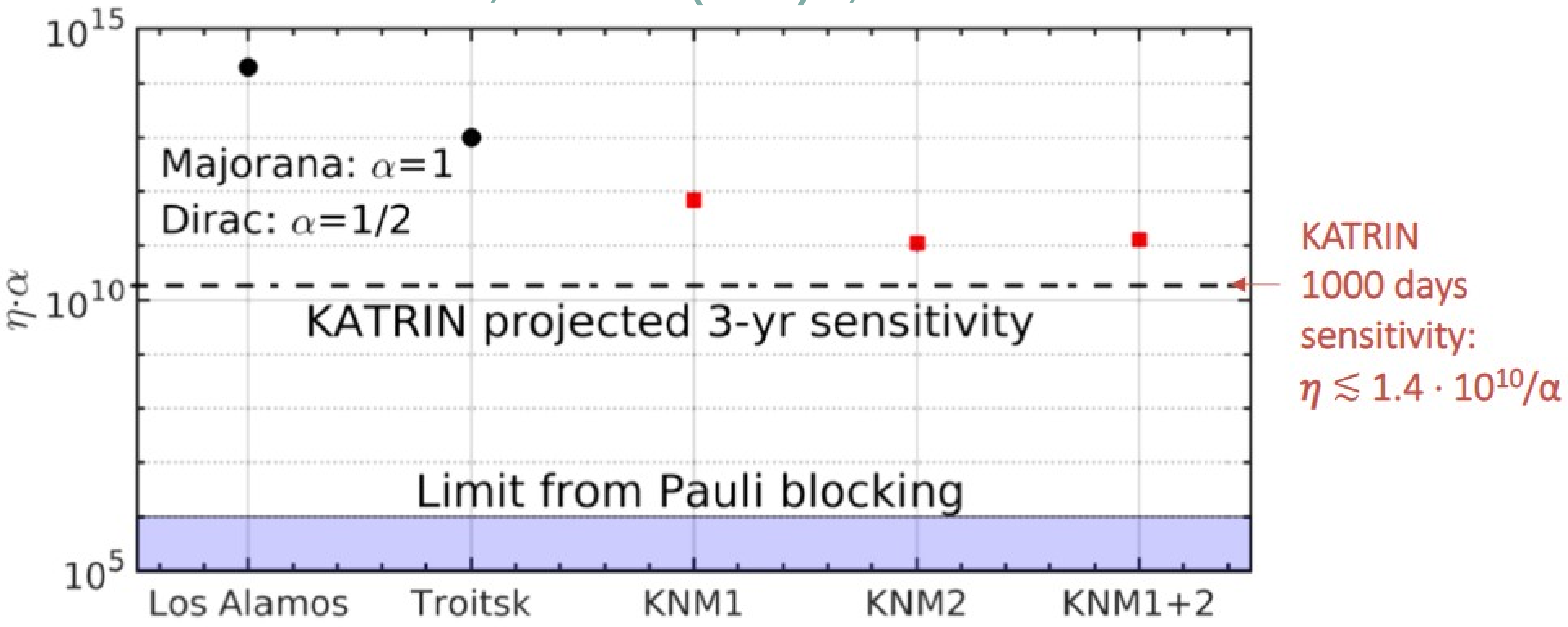

arXiv:2306.12366 → 10^4 – 10^7 might be possible

Outline

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What do we know so far about neutrino masses?	Neutrinos are massive	The squared mass differences are known	The absolute scale is unknown
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How to measure the mass without model dependencies?	Current limit from KATRIN (MAC-E-Filter): <0.8 eV (90% CL)	CRES technology: measuring the cyclotron frequency	Calorimetry with quantum sensors
What other physics can we probe in the direct mass measurements?	Sterile neutrinos	Relic neutrinos	BSM interactions & particles, Lorentz invariance

General Neutrino Interactions

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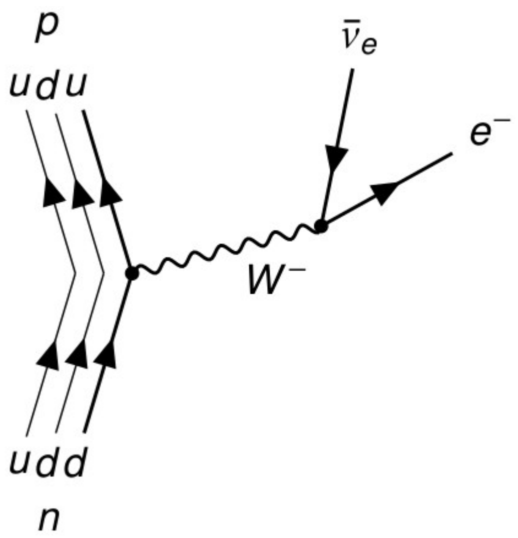
- Additional interactions which contribute to the weak interaction in the β-decay
- SM Effective Field Theory with additional right-handed neutrinos
  - Truncated at the order ***n* = 6**



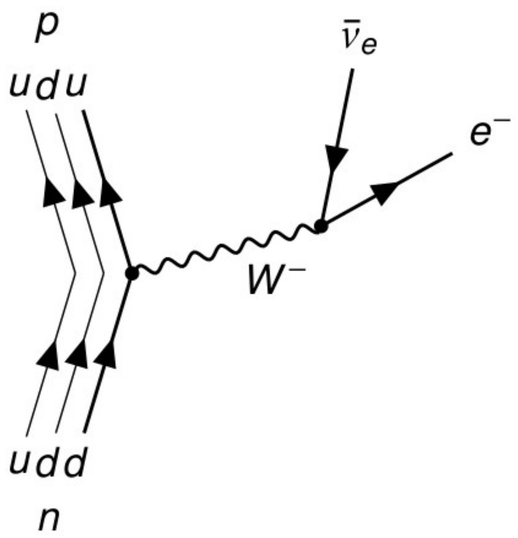
$$\mathcal{L}_{SMEFT}(\phi_{SM}) = \mathcal{L}_{SM}(\phi_{SM}) + \sum_{n\geq 5} \sum_{i} \frac{1}{\Lambda^{n-4}} C_i^{(n)} \mathcal{O}_i^{(n)}(\phi_{SM})$$

- GNI could modify the β-spectrum
  - Energy-dependent contributions to the rate could be studied with KATRIN

GNI Lagrangian for 4-fermion-interaction

$$\mathcal{L}_{GNI}^{CC} = -\frac{G_F V_{\gamma\delta}}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,ud} \right)^{\alpha\beta\gamma\delta} \left(\bar{e}_\alpha O_j \nu_\beta \right) \left(\bar{u}_\gamma O'_j d_\delta \right) + h.c.$$

- G_F : Fermi constant
- $V_{\gamma\delta}$: CKM matrix
- $\overset{(\sim)}{\epsilon}_{j,ud}$: Flavour space tensor describing **strength of interaction** type j with respect to SM Fermi interaction
  - $\epsilon_{L/R}$: Coupling for **left-/right-handed vector**-like interactions
  - ϵ_S: Coupling for **scalar** interactions
  - ϵ_P: Coupling for **pseudo-scalar** interactions
  - ϵ_T: Coupling for **tensor**-like interactions



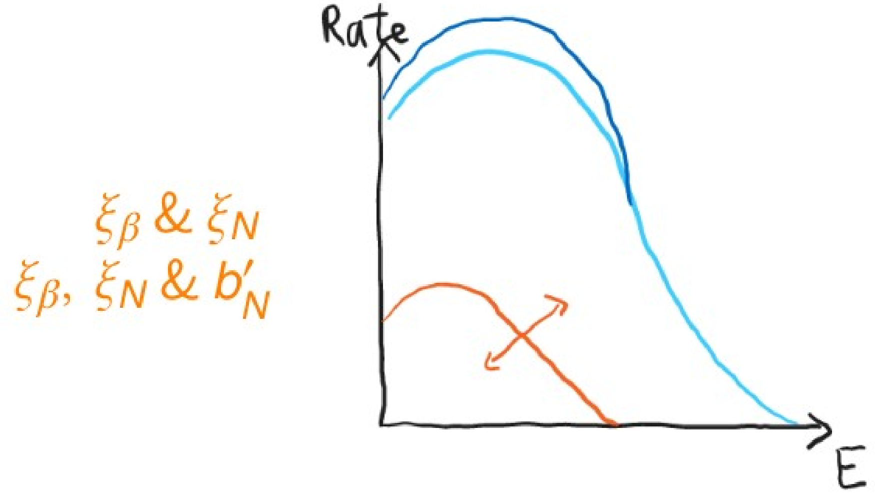
GNI in the tritium *β*-spectrum

$$\frac{d\Gamma}{dE} = \frac{G_F^2\, V_{ud}^2}{2\pi^3}\sqrt{(E+m_e)^2 - m_e^2}\,(E+m_e)(E_0 - E)$$

$$\times \left\{ \sum_{k=\beta,N} \sqrt{(E_0 - E)^2 - m_k^2} \cdot \xi_k \left[1 + \boldsymbol{b_k}\frac{m_e}{E+m_e} - \boldsymbol{b'_k}\frac{m_k}{E_0 - E} - \boldsymbol{c_k}\frac{m_e m_k}{(E+m_e)(E_0-E)} \right] \Theta(E_0 - m_k - E) \right\}$$

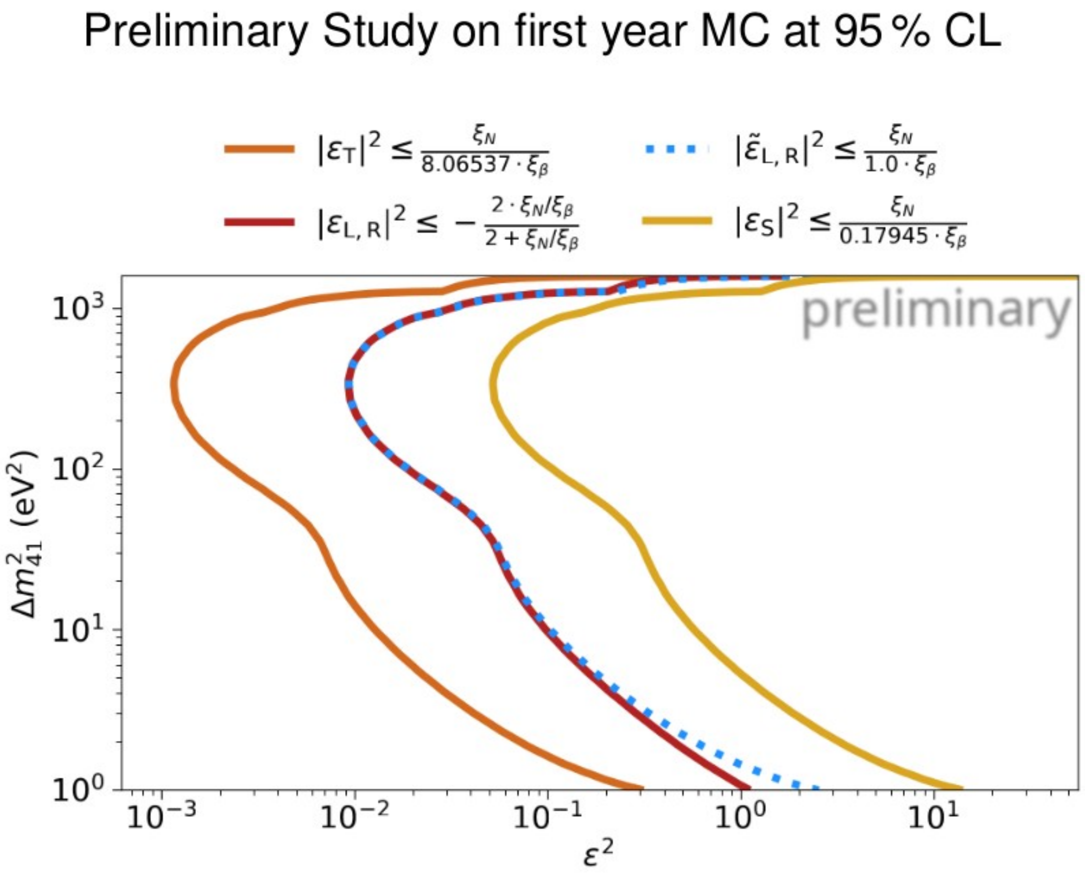
- Total decay rate for active and sterile neutrino
- ξ_k, b_k, b'_k, c_k are defined in terms of $\boldsymbol{\epsilon}$, $\boldsymbol{U_{e4}}$ and $\boldsymbol{g_V, g_S, g_T, g_A}$

  The SM case: $\xi_N = b_k = b'_k = c_k = 0$



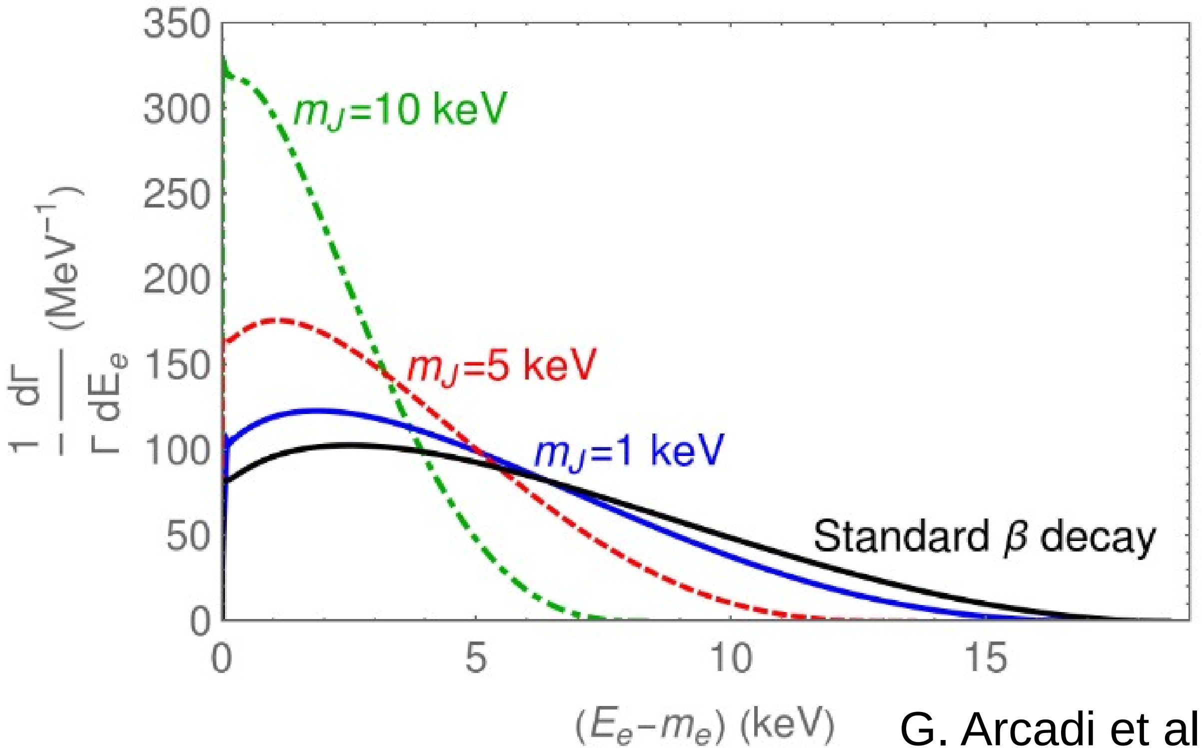
Sensitivity to GNI with the sterile branch

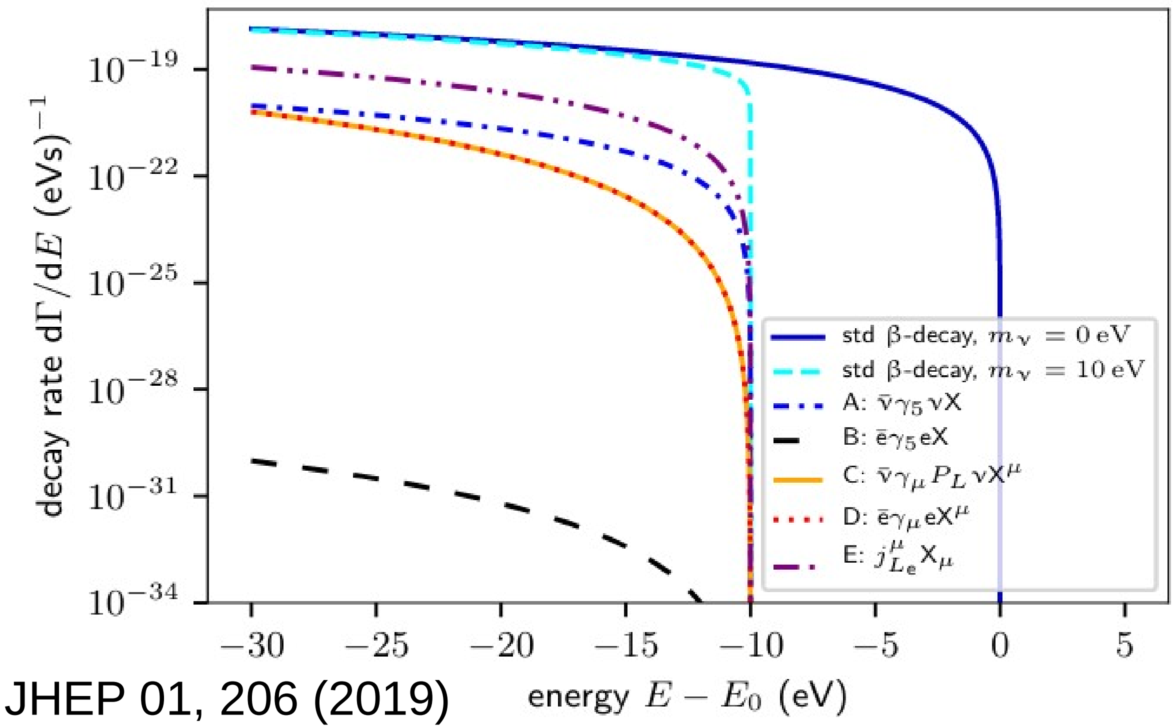
- Converting mixing $\frac{\xi_N}{\xi_\beta}$ into sensitivity to $\boldsymbol{\epsilon}$
- Strongest constraints on $\boldsymbol{\epsilon_T}$
- Other constraints:
  - neutrino oscillations
  - ν-e and ν-N scattering
  - charged lepton flavor violation



New light bosons

- Searching for new physics in the low-energy range
  - Light scalar or vector bosons can be emitted if their mass < Q_T
  - axions and axion-like particles, Majoron models, Z′





G. Arcadi et al. JHEP 01, 206 (2019)

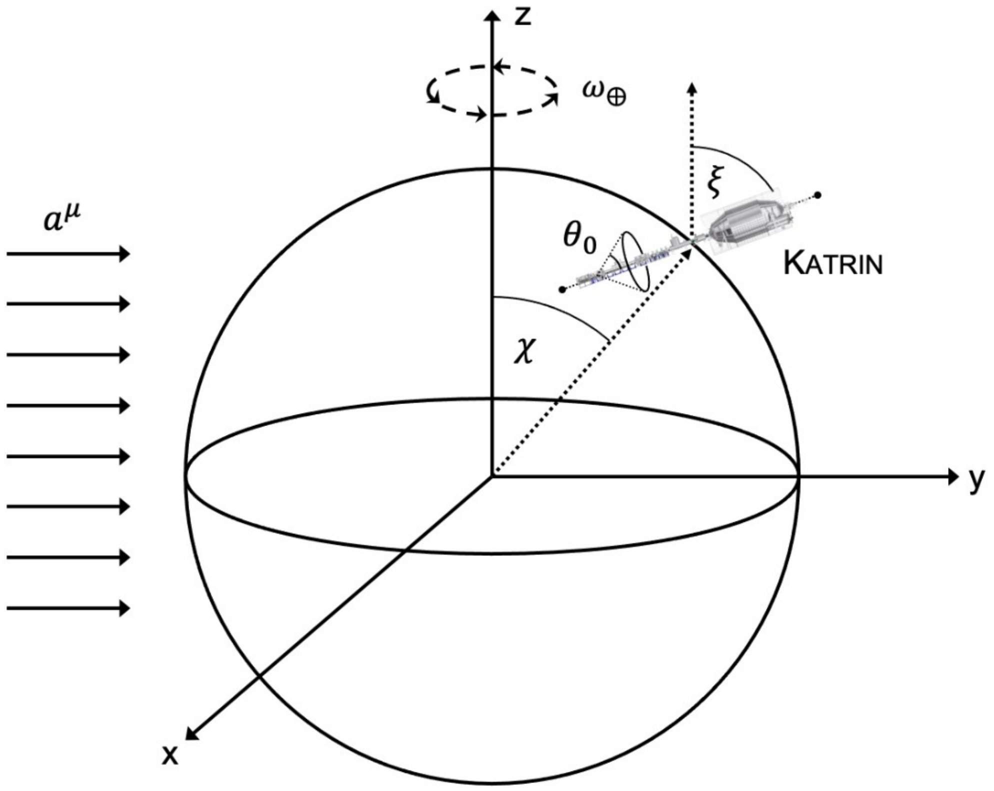
Search for Lorentz Invariance Violation

- Standard Model Extention: relativistic EFT with all possible LIV operators for neutrino propagation

$$L^a_{SME} = -\bar{\psi}_w a^\mu \gamma_\mu \psi_w$$

- for all particles in the β-decay
- terms $\propto a^\mu p_\mu = a^0 p_0 - \vec{a} \cdot \vec{p}$

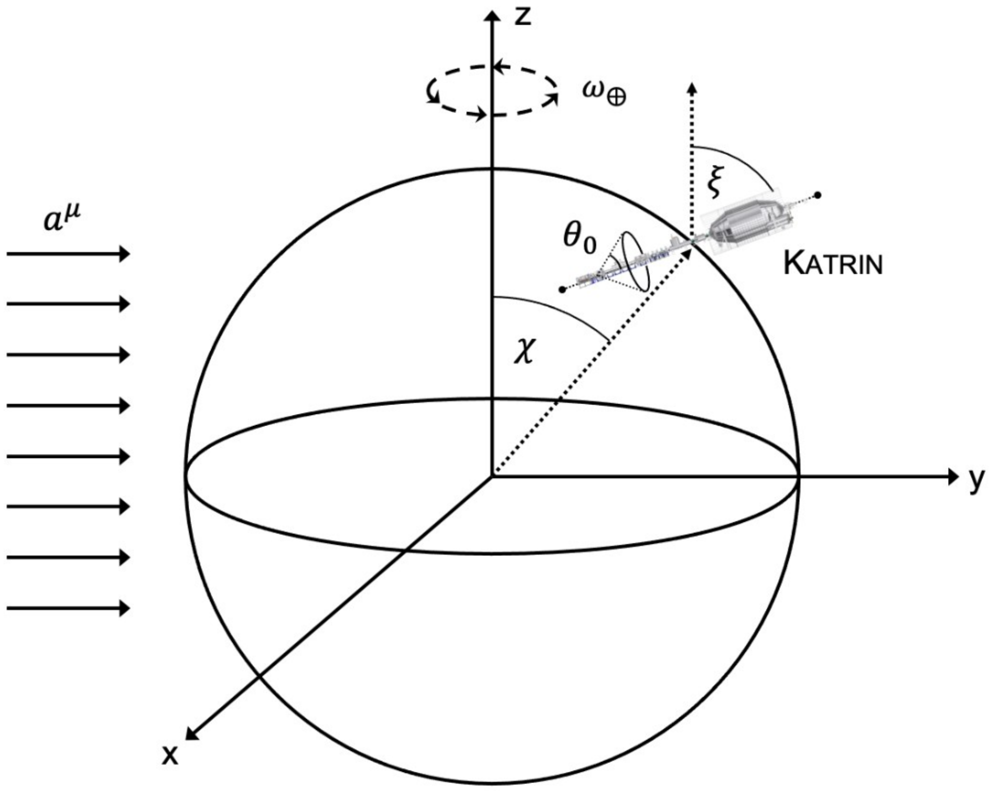
→ 1 sideral-day modulation of $\boldsymbol{E_0}$ and absolute shift of $\boldsymbol{E_0}$



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

Search for Lorentz Invariance Violation

- Time-dependent
  - Rotation of the Earth: change of intrinsic KATRIN direction w.r.t. $\mathbf{a}^{\mu}$
  - E_0 oscillates with *23 h 56 min* period
  - $\left|(a_{\text{of}}^{(3)})_{11}\right|$
- Time-independent
  - Measurements of E_0 at Mainz and KATRIN
  - $\left|(a_{\text{of}}^{(3)})_{00}\right|$ and $\left|(a_{\text{of}}^{(3)})_{10}\right|$



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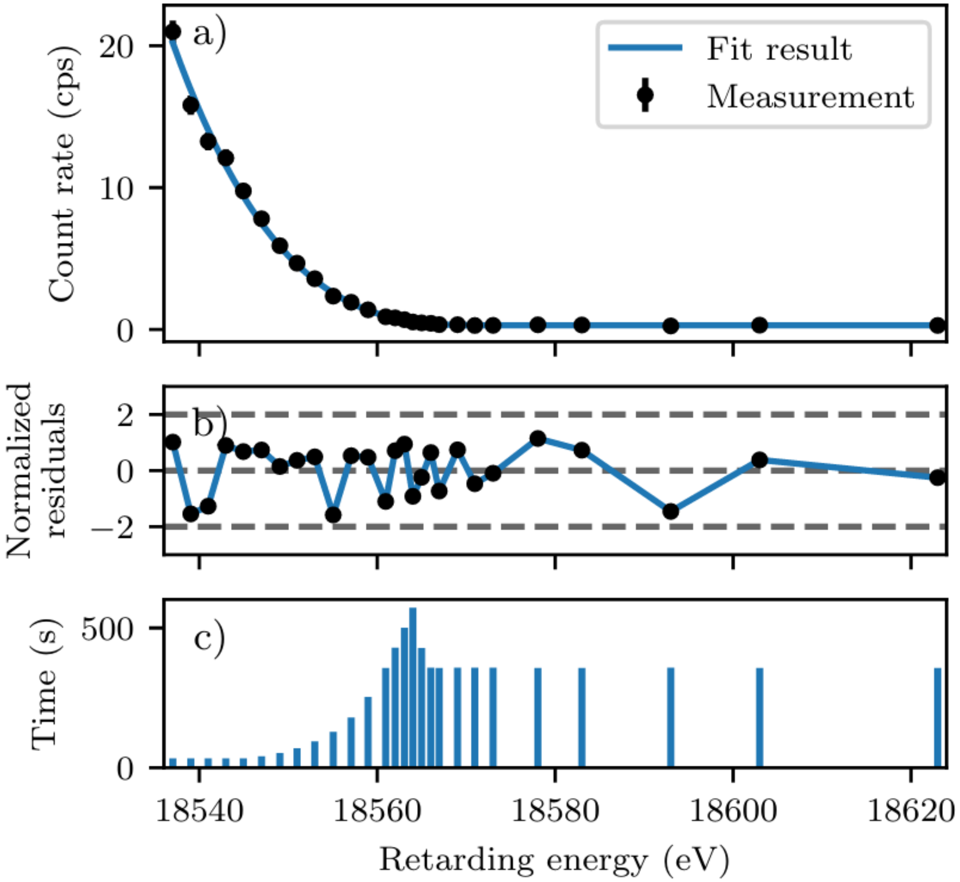
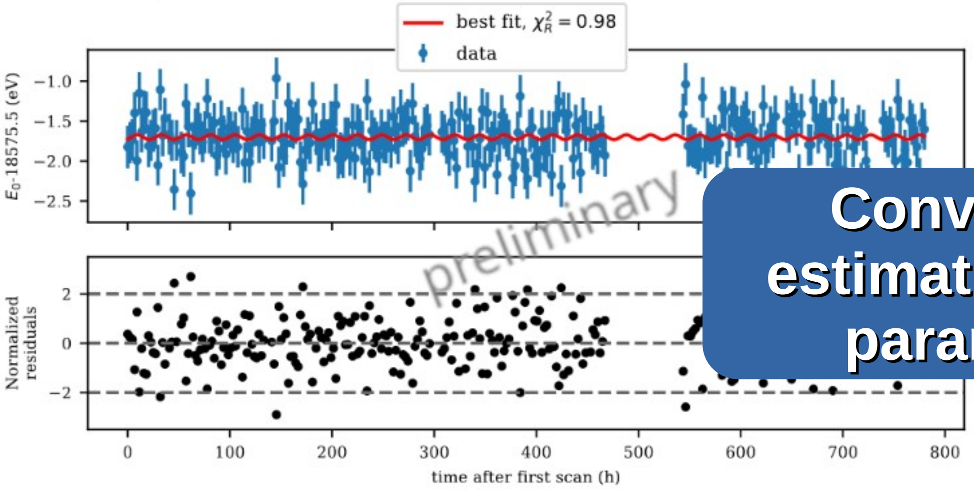
Lorentz invariance violation in KATRIN

Fit each 2h scan of β-spectrum



Estimate amplitude of E_0 oscillation



Convert into estimation of LIV parameters

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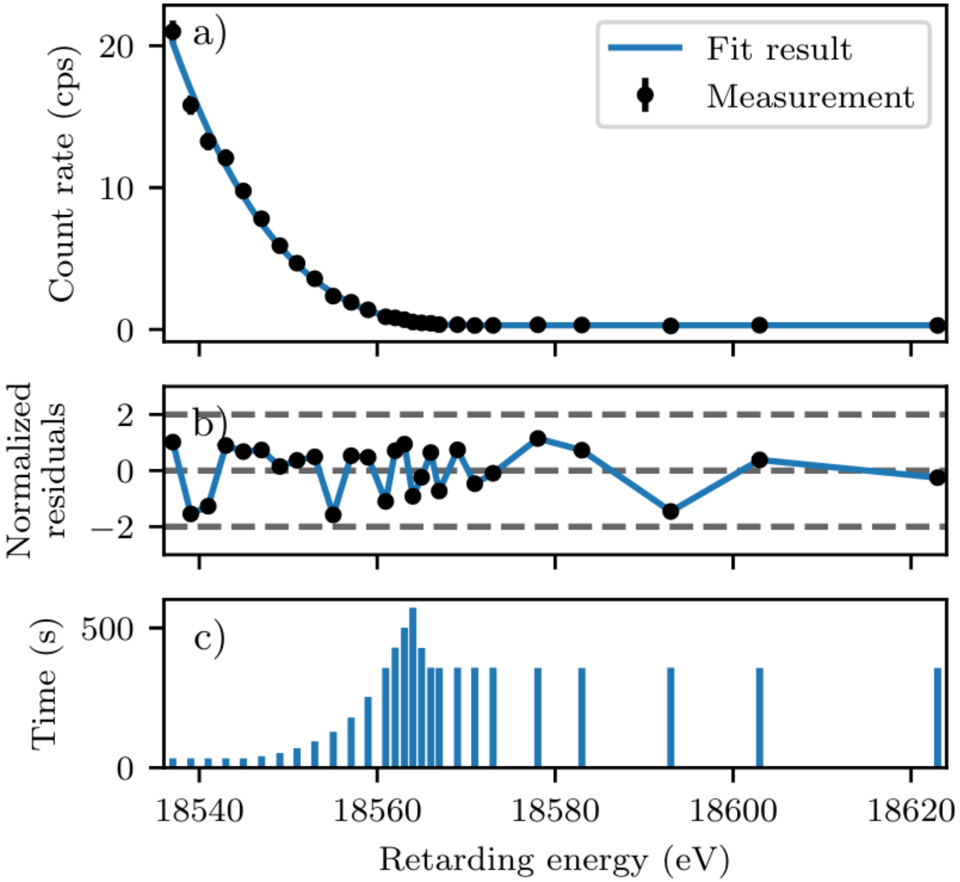
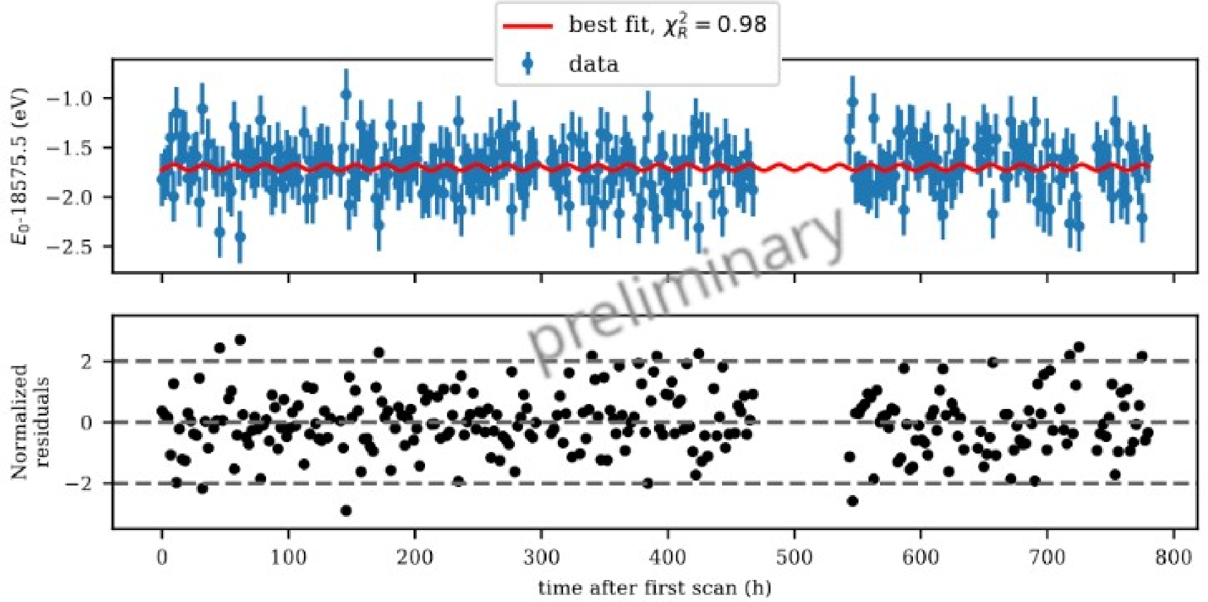
Lorentz invariance violation in KATRIN

Fit each 2h scan of β-spectrum



$$A = \sqrt{\frac{3}{2\pi}}\left|(a^{(3)}_{of})_{11}\right|\sqrt{B^2\cos^2\chi\cos^2\xi + (\beta_{rot} - B\sin\xi)^2}$$



$$E_0^{\text{fit}}(t_e) = D + A\cos(\omega t_e - \phi)$$

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Lorentz invariance violation in KATRIN

- No significant oscillation of E_0 observed

First upper limit:

$$\left|\left(a_{of}^{(3)}\right)_{11}\right| < 3.7 \times 10^{-6}\ GeV\ (90\,\%\ CL)$$

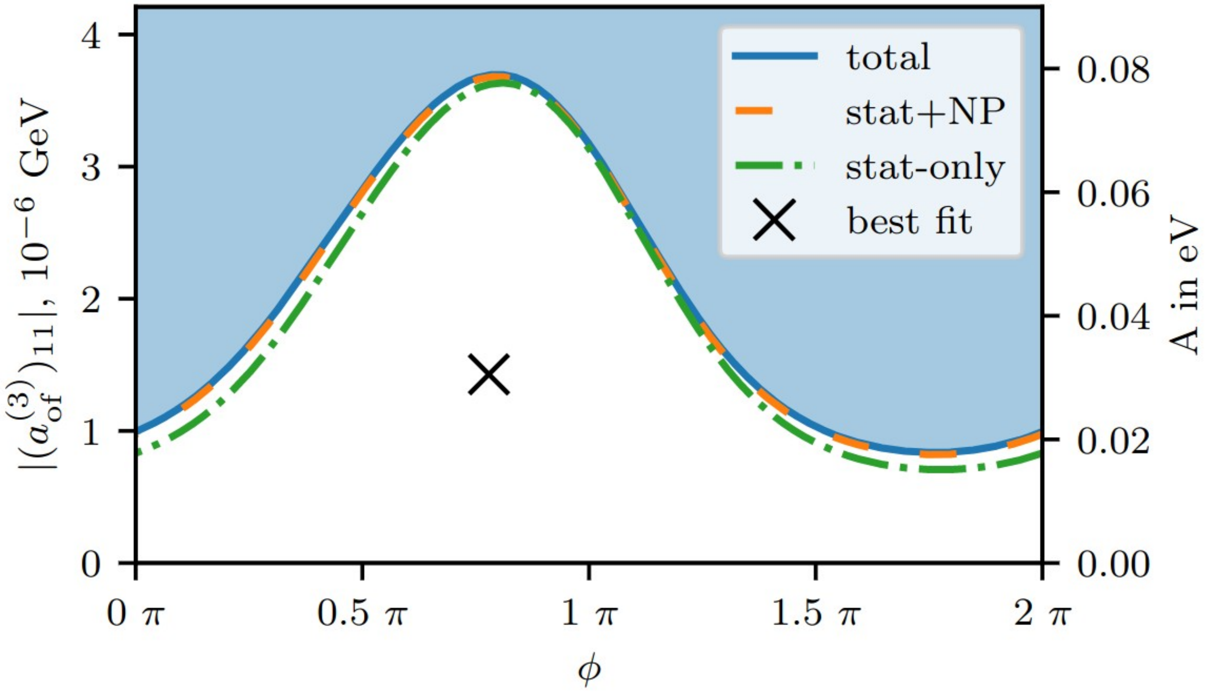
- No significant shift of E_0 observed

Improved upper limits:

$$\left|\left(a_{of}^{(3)}\right)_{00}\right| < 3.0 \times 10^{-8}\ GeV\ (90\,\%\ CL)$$

$$\left|\left(a_{of}^{(3)}\right)_{10}\right| < 6.4 \times 10^{-4}\ GeV\ (90\,\%\ CL)$$

$$A = \sqrt{\frac{3}{2\pi}}\left|\left(a_{of}^{(3)}\right)_{11}\right|\sqrt{B^2\cos^2\chi\cos^2\xi + (\beta_{rot} - B\sin\xi)^2}$$



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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, 0ν2β-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)	CRES technology: measuring the cyclotron frequency	Calorimetry with quantum sensors
What other physics can we probe in the direct mass measurements?	Sterile neutrinos	Relic neutrinos	BSM interactions & particles, Lorentz invariance

Summary & Outlook

- Ongoing hunt for the absolute neutrino mass scale with the laboratory experiments → KATRIN, Project 8, ECHo, HOLMES, ...
  - Current best limit: 0.8 eV (90% CL) from KATRIN
  - New technologies are developed for ultimate neutrino mass determination (~0.009 eV)
- Exciting physics ahead if there are contradictions between $0\nu2\beta$-decay, cosmology and direct neutrino mass measurements
- A variety of the “beyond neutrino mass” physics can be probed in the kinematic measurements of the weak decays

Thank you for your attention!