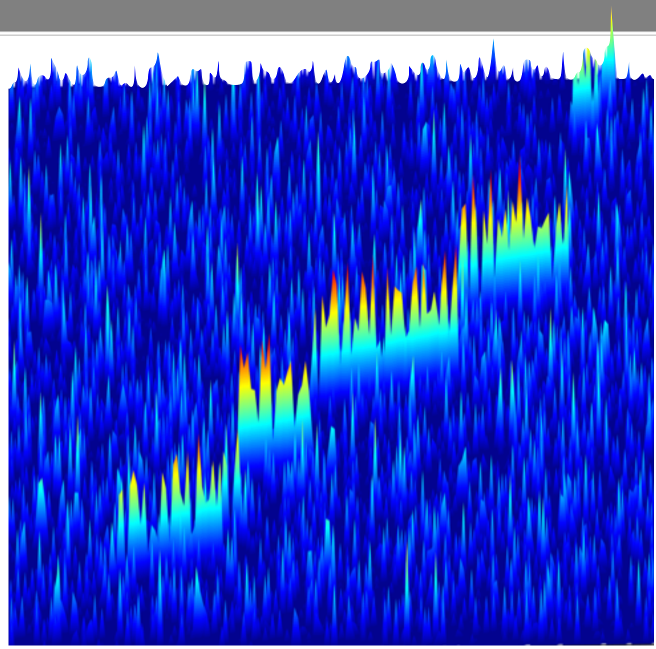
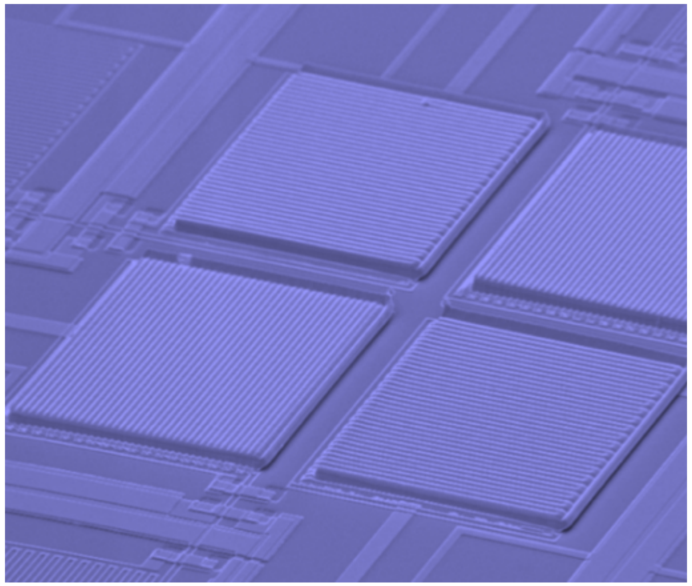
VIII. International Pontecorvo Neutrino Physics School
Sinaia, Romania | Sept. 1-10, 2019

Direct probes of neutrino mass

β-decay and electron capture

Kathrin Valerius | KIT, Institute for Nuclear Physics

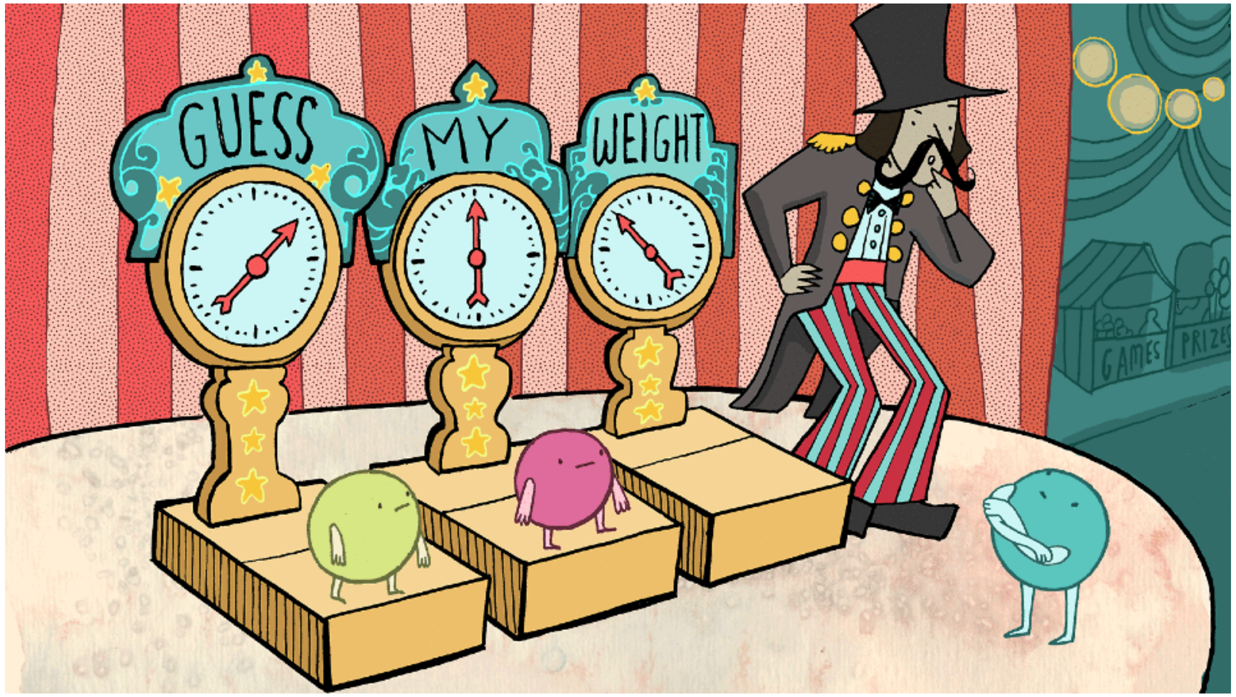




What’s on the menu?

- *I. Introduction*
  Why measure the ν mass scale?
- *II. Overview*
  Methods: How can we access the ν mass scale?
- *III. Main*
  Direct kinematic neutrino mass measurement using weak decays:
  Reach of current experiments and prospects for the future
- *IV. Extra*
  Other interesting physics
  in precision weak decays

I. Motivation

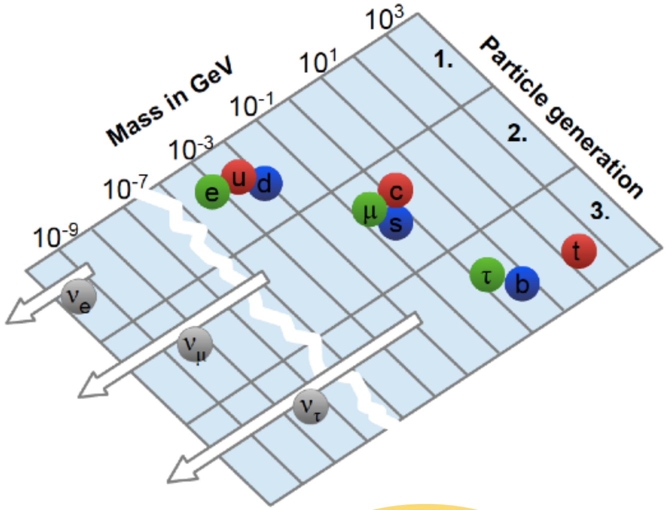
Why is the neutrino mass scale important?



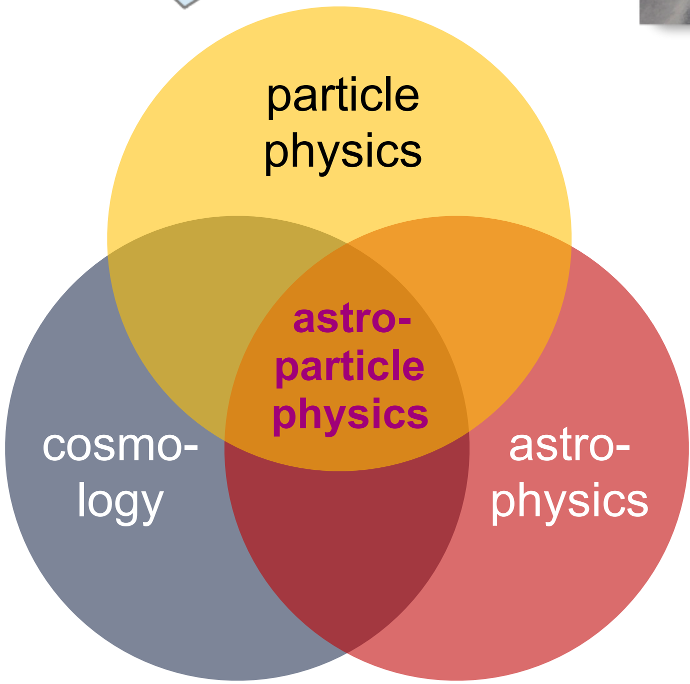
[symmetrymagazine.org]

The role of massive neutrinos

Mass generation: new concepts

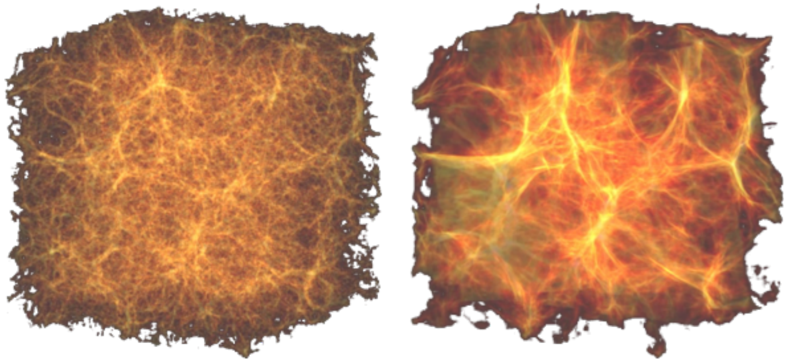


Mass measurement: new concepts



Massive neutrinos as "cosmic architects"

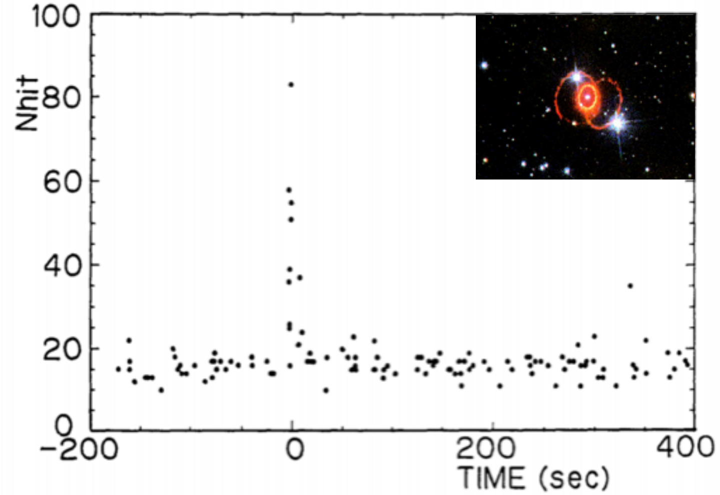
336 ν / cm³ in the Universe today



$m_\nu = 0$ $m_\nu > 0$

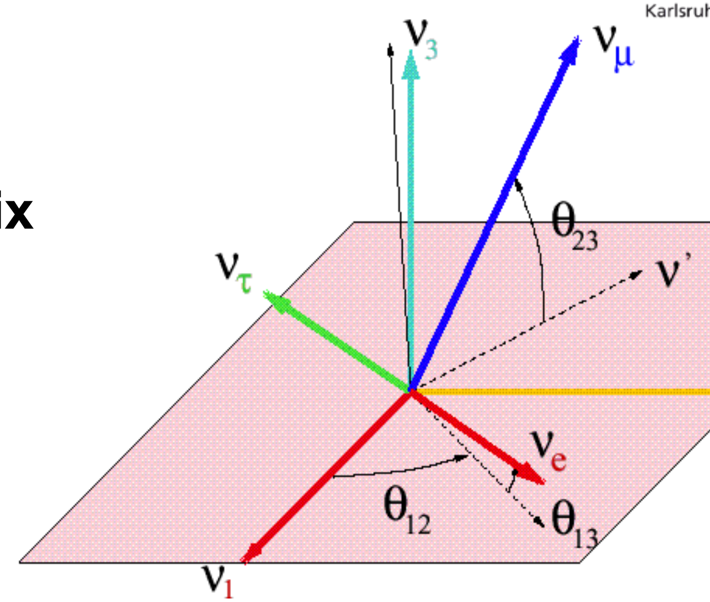
Understanding astrophysical processes

Neutrino burst from SN 1987a



Three-flavour neutrino oscillations

3 x 3 unitary mixing matrix analogous to CKM:
"Pontecorvo Maki Nakagawa Sakata"
(PMNS)



- 3 mixing angles: θ_{12}, θ_{23}, θ_{13},
- 1 Dirac phase: δ, possibly 2 Majorana phases $\alpha_{1,2}$
- 2 independent "splittings" Δm^2 and lightest mass m_0

→ Several lectures at this School

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The big picture: What have we learned from oscillation data?

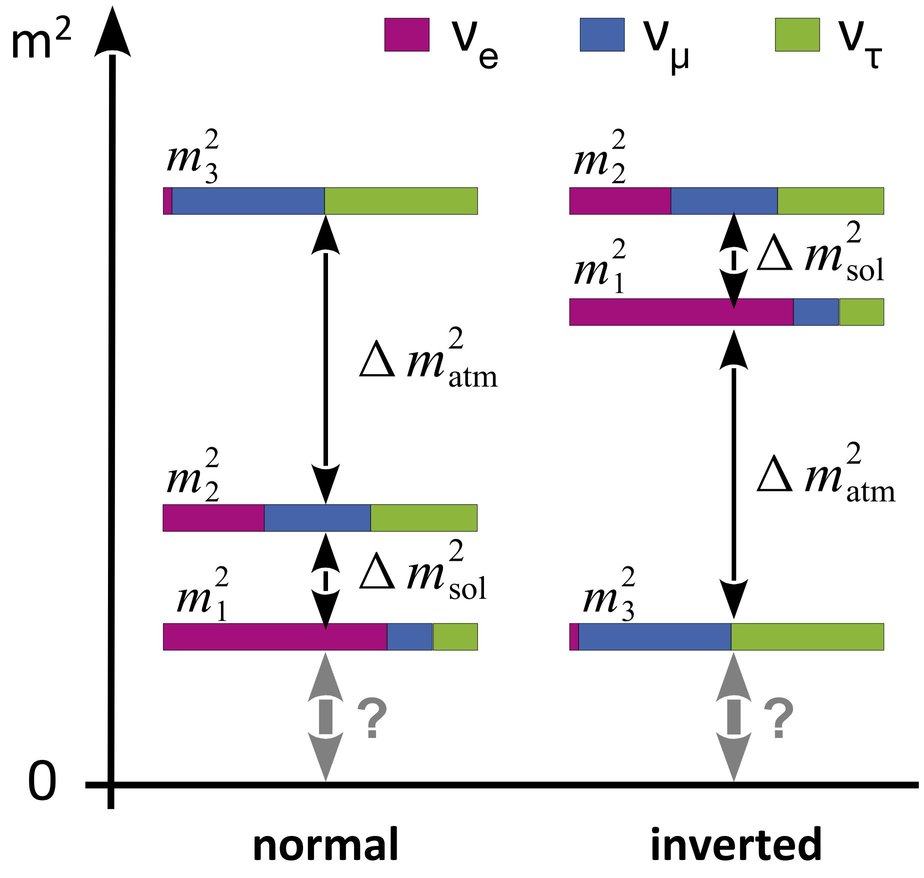
➜ Several lectures at this School

- Large neutrino mixing and tiny neutrino masses $m(\nu_i) \neq 0$:

New! BSM physics!

- Non-zero θ_{13} measured
- Hints for non-maximal $\theta_{23} \neq \pi/4$
- Expectation of CP-violating phase δ

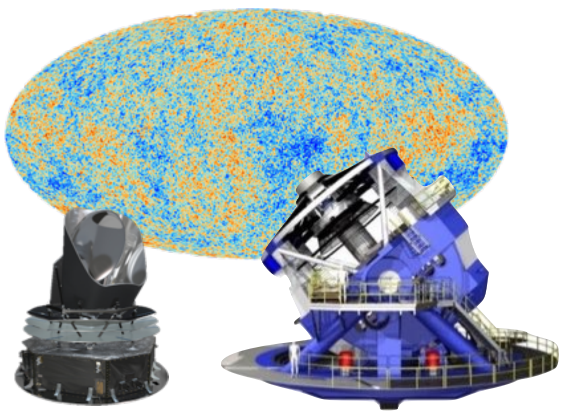
- Majorana vs Dirac nature of neutrinos?
- Absolute mass scale cannot be determined from oscillations
- Expect m_ν > 10 meV for normal ordering, m_ν > 50 meV for inverted ordering

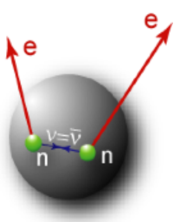


II. How can we measure neutrino masses?

Indirect (model-dependent) probes:

- Observational cosmology → R. Battye
- Search for $0\nu\beta\beta$ → A. Giuliani, J. Menendez

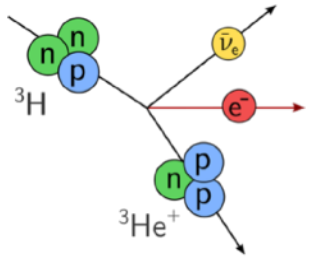


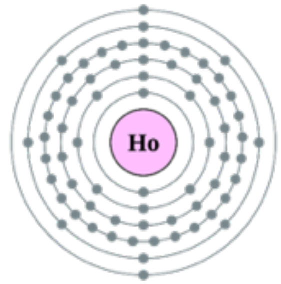


Direct (less model-dep.) probes:

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

→ this lecture





Overview: Neutrino mass observables

Cosmology

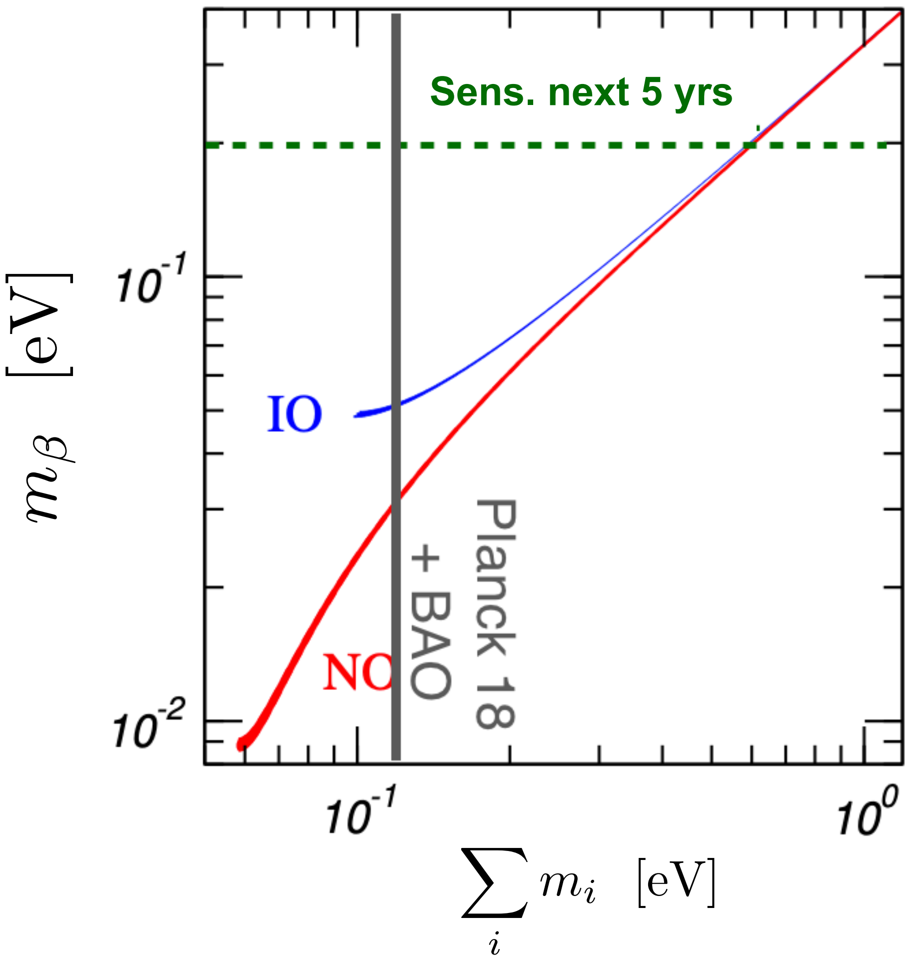
$M_\nu = \sum_i m_i$

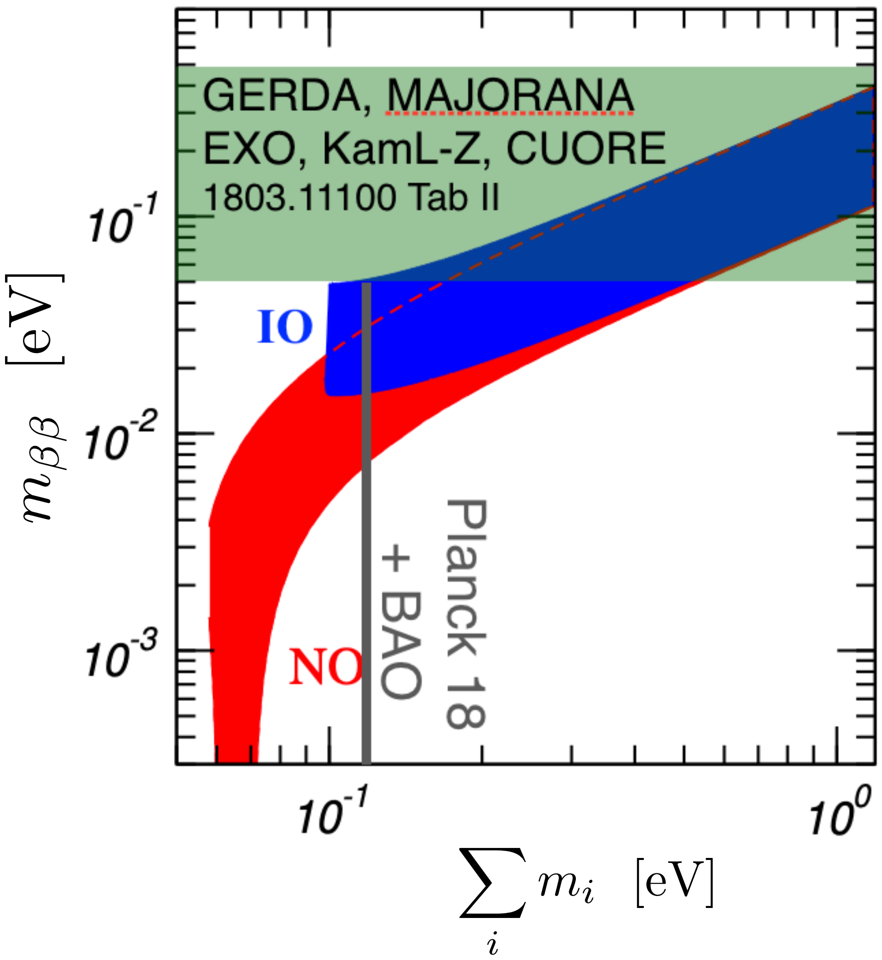
0νββ decay

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

β decay and EC

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

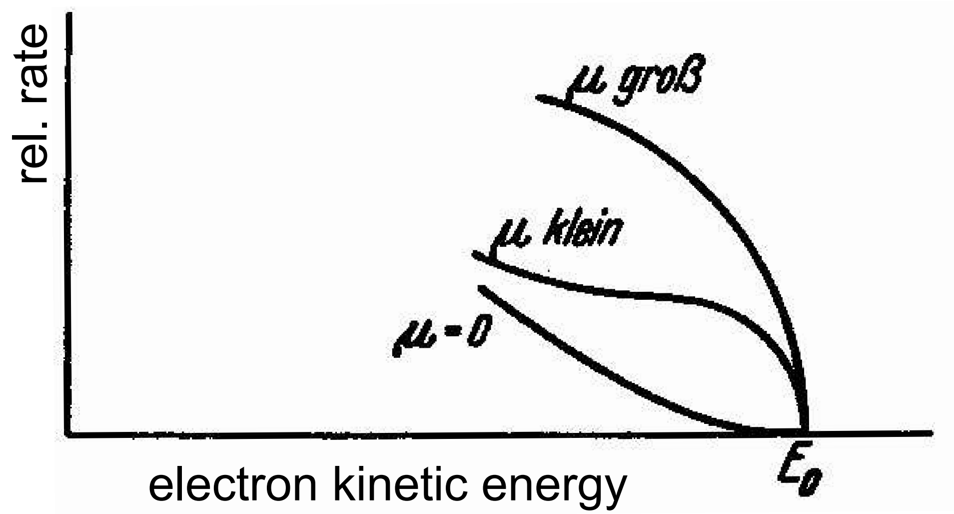


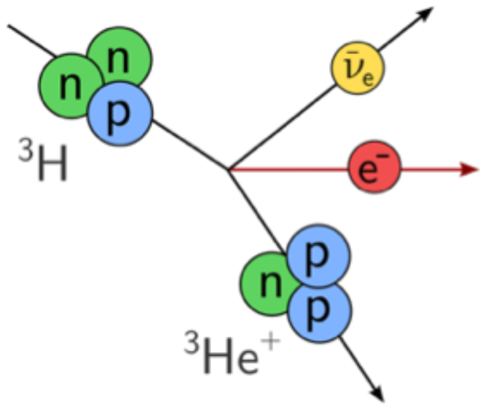


NuFIT 4.0 (2018)
from Th. Schwetz-Mangold

Neutrino mass from β-decay kinematics

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





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

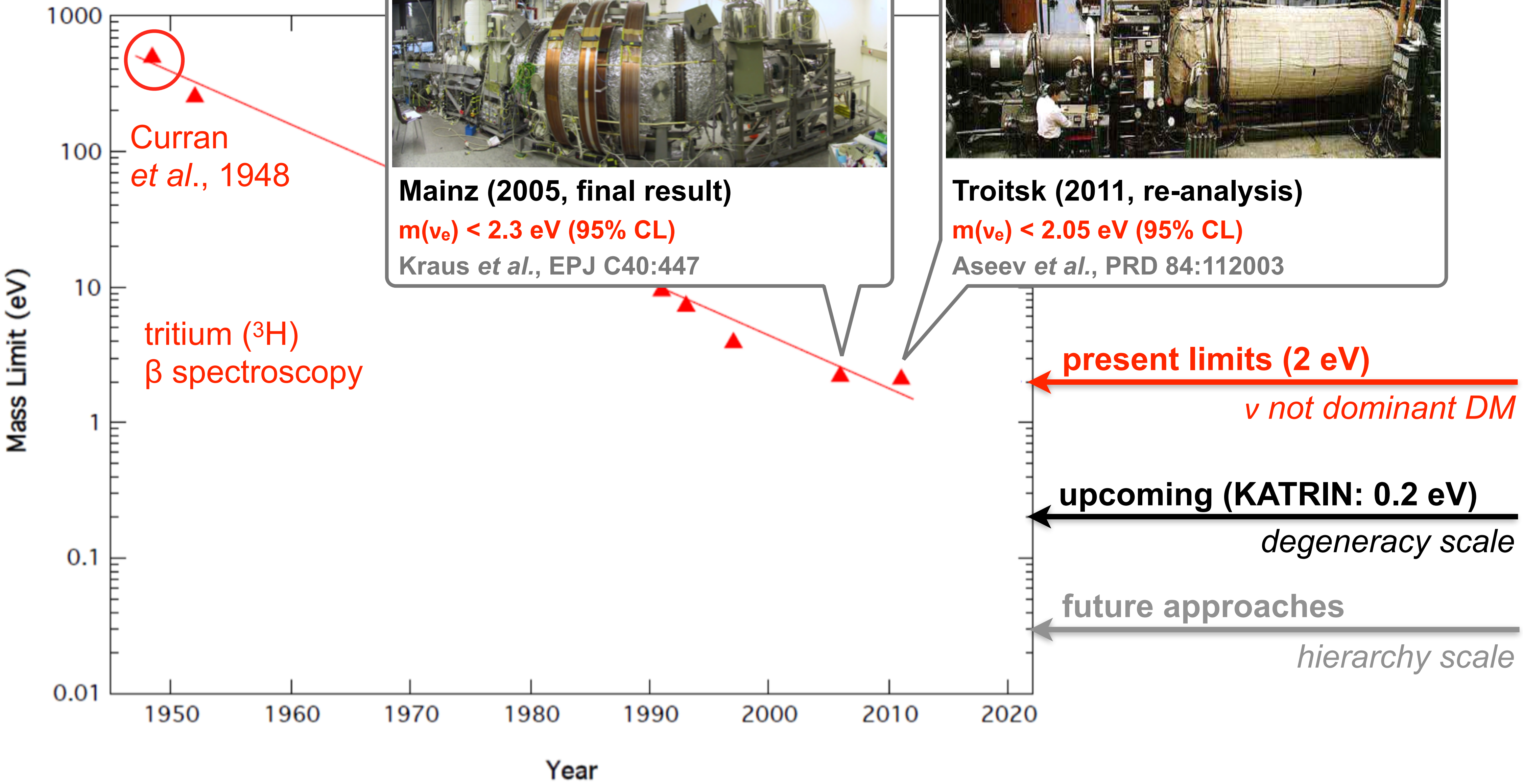
NATURE August 21, 1948 Vol. 162

Beta Spectrum of Tritium

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

Curran *et al.*

Neutrino mass from β-decay kinematics



Mainz (2005, final result)

$m(\nu_e) < 2.3$ eV (95% CL)

Kraus *et al.*, EPJ C40:447

Troitsk (2011, re-analysis)

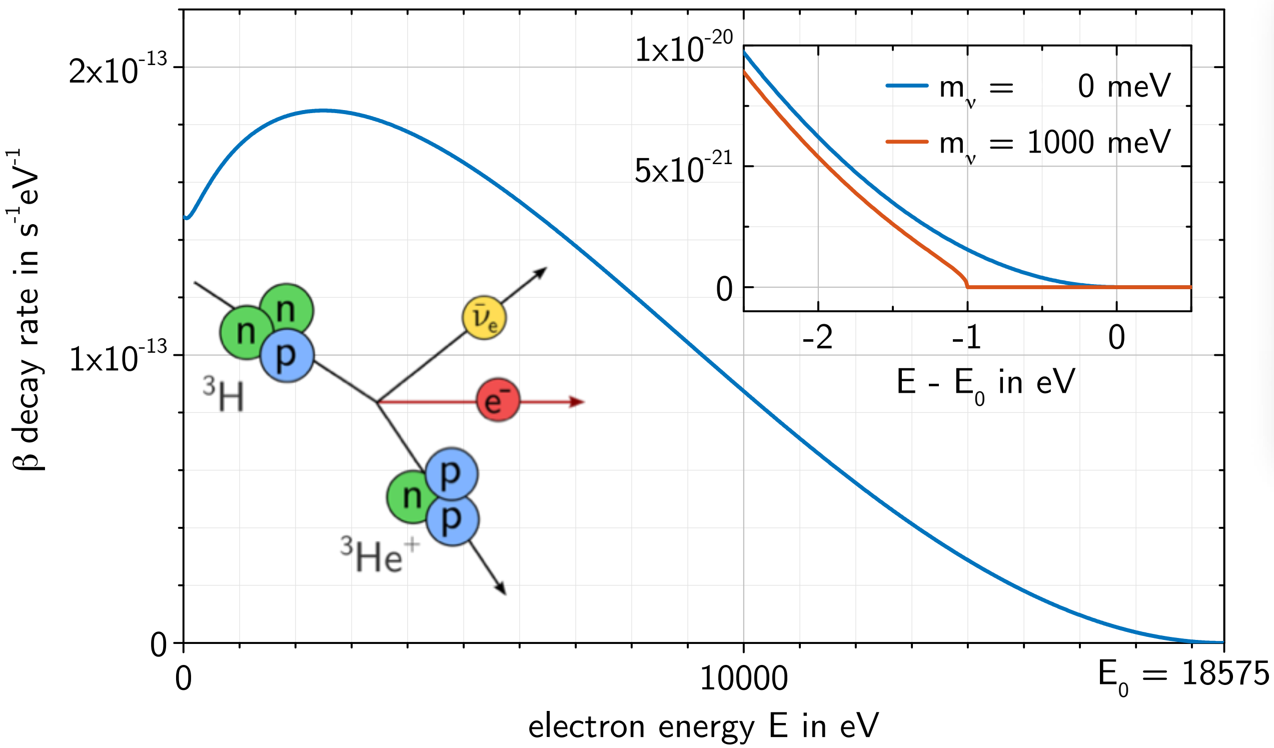
$m(\nu_e) < 2.05$ eV (95% CL)

Aseev *et al.*, PRD 84:112003

[courtesy J.F. Wilkerson/R.G.H. Robertson]

Neutrino mass from β-decay kinematics

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



Key requirements & technologies

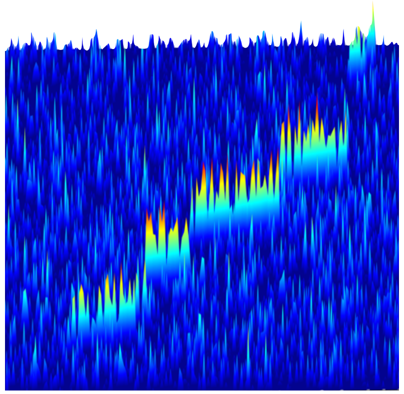
- Low-endpoint β/EC nuclide: E_0 = 18.6 keV for **^{3}H**
- High-activity source: $T_{1/2}$ = 12.3 yr for **^{3}H**
- Excellent energy resolution

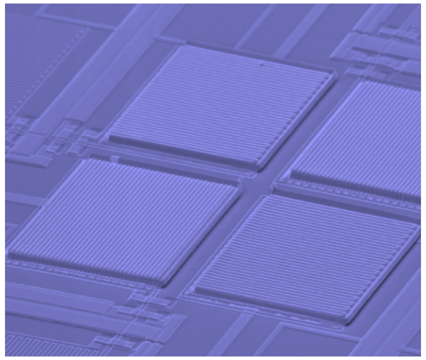
Kinematic measurement can probe for **heavier neutrino states**
➜ eV-scale and keV-scale sterile ν

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

$$m^2(\nu_\mathrm{e}) := \sum_i |U_{\mathrm{e}i}|^2\, m_i^2$$

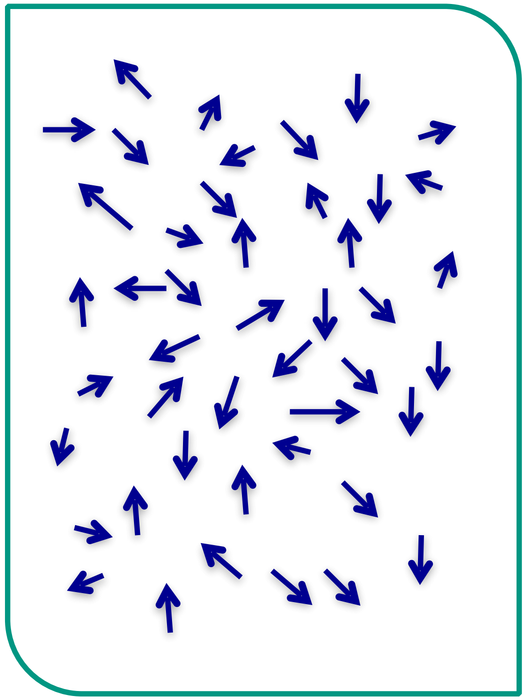
III. Experimental techniques for direct ν-mass measurement



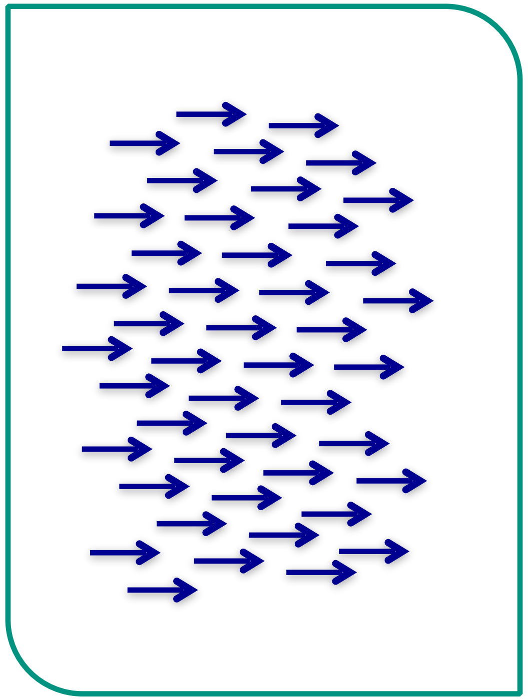


High-resolution spectroscopy with electric and magnetic fields

Source: isotropic emission of β-electrons



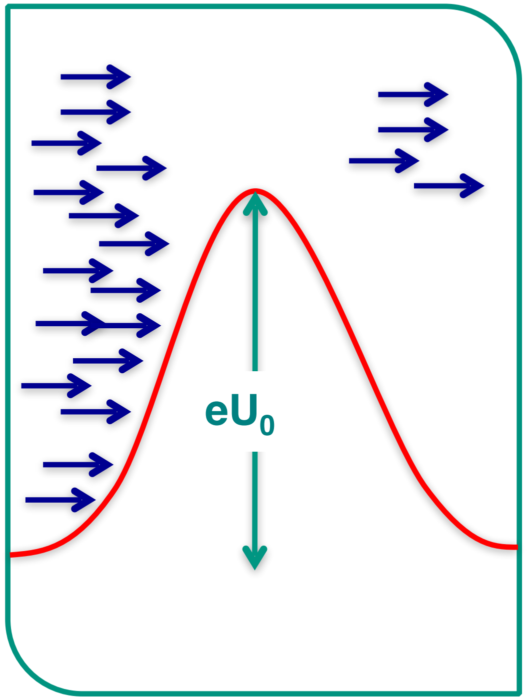
Transport: magn. guiding and adiabatic collimation



$$\mu = \frac{E_\perp}{B} = \mathrm{const.}$$

$$E_\perp \longrightarrow E_\parallel$$

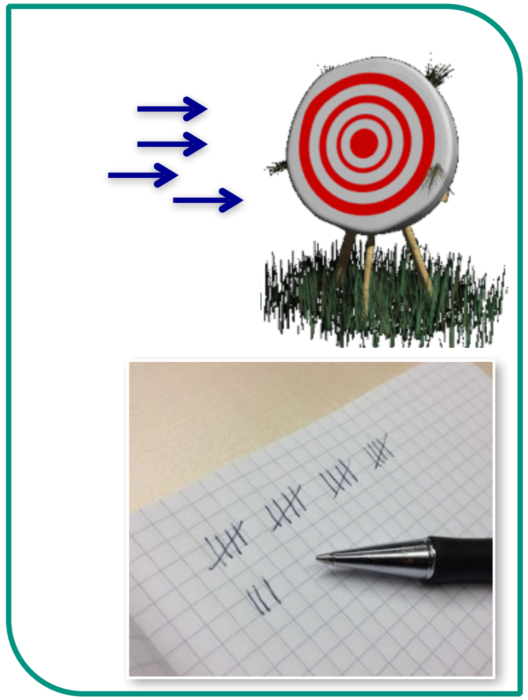
Spectrometer: variable electrostatic filter



high-pass filter for $E_{||} > eU_0$

$$\frac{\Delta E}{E} = \frac{B_{\mathrm{min}}}{B_{\mathrm{max}}}$$

Detector: electron counter



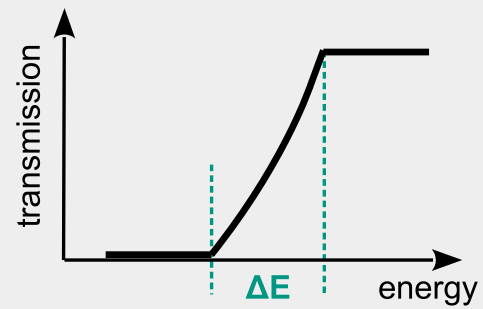
MAC-E filter technique

Magnetic Adiabatic Collimation & Electrostatic Filter

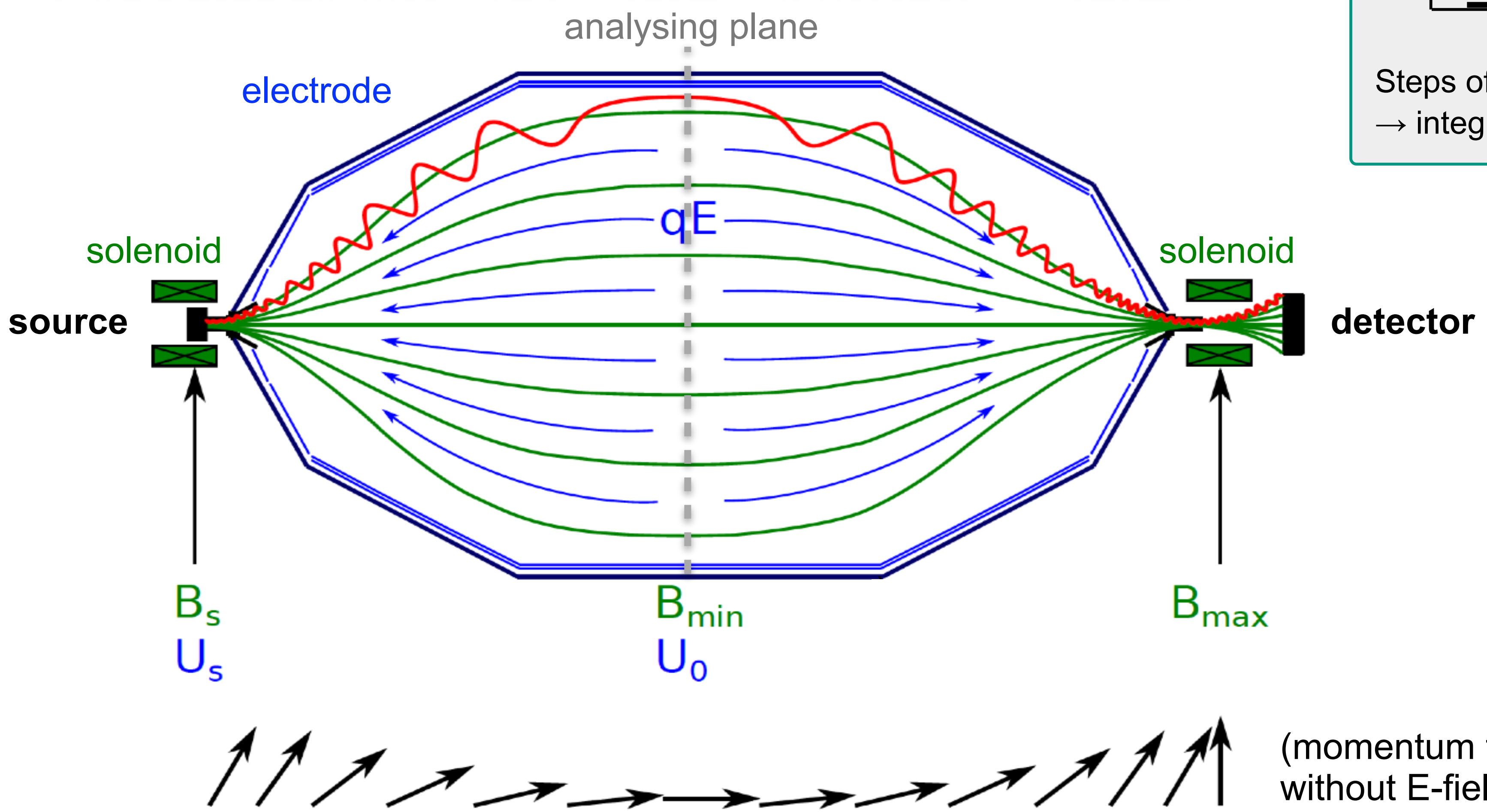
- ➜ integrating electrostatic filter ($E_{kin} > eU_0$)
- ➜ “clean” analytic response function
- ➜ **ΔE < 1 eV** at 18.6 keV

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

Sharp high-pass filter:



Steps of filter potential
→ integrated β spectrum



(momentum transformation
without E-field)

[Beamson *et al.* 1980; Kruit & Read 1983; **Lobashev 1985; Picard *et al.* 1992**]

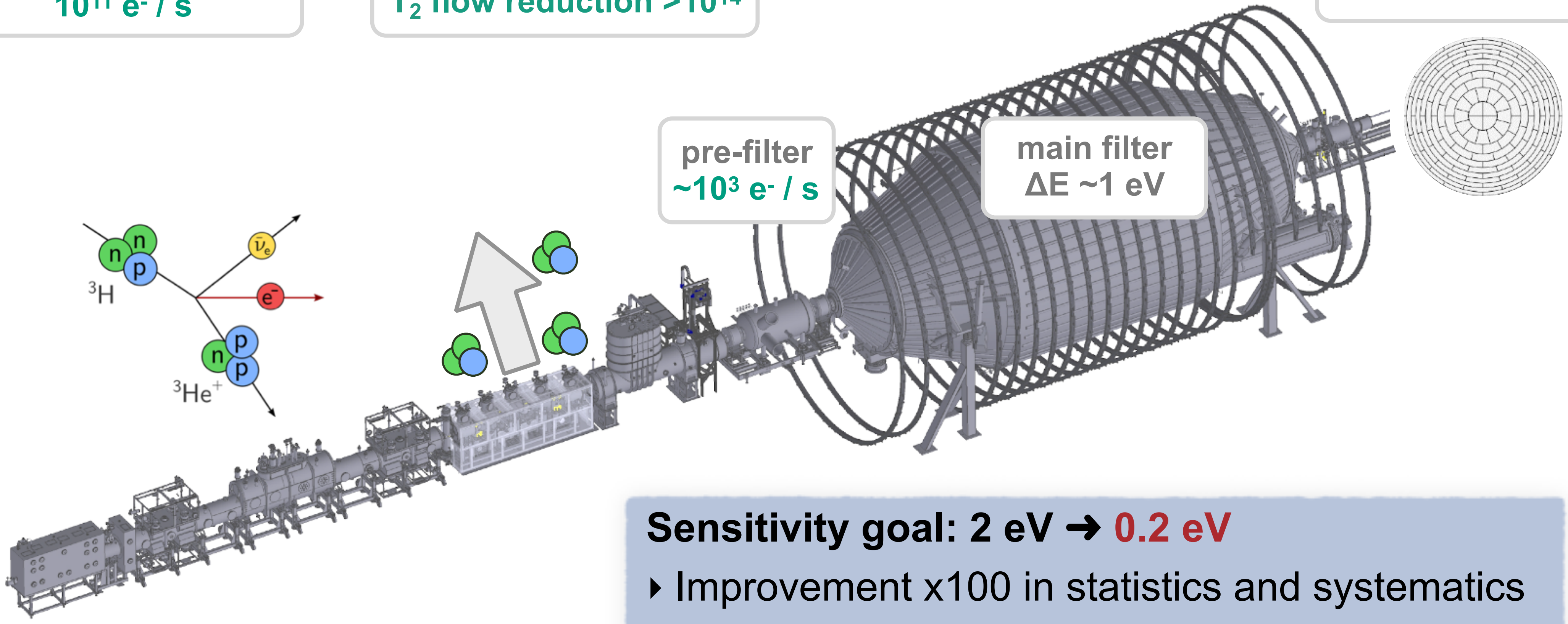
The Karlsruhe Tritium Neutrino Experiment: working principle

windowless gaseous T_2 source
10^{11} e^- / s

tritium pumping & e^- transport
T_2 flow reduction $>10^{14}$

high-pass energy filters

counting detector
< 1 e^- / s



pre-filter
~10^3 e^- / s

main filter
ΔE ~1 eV

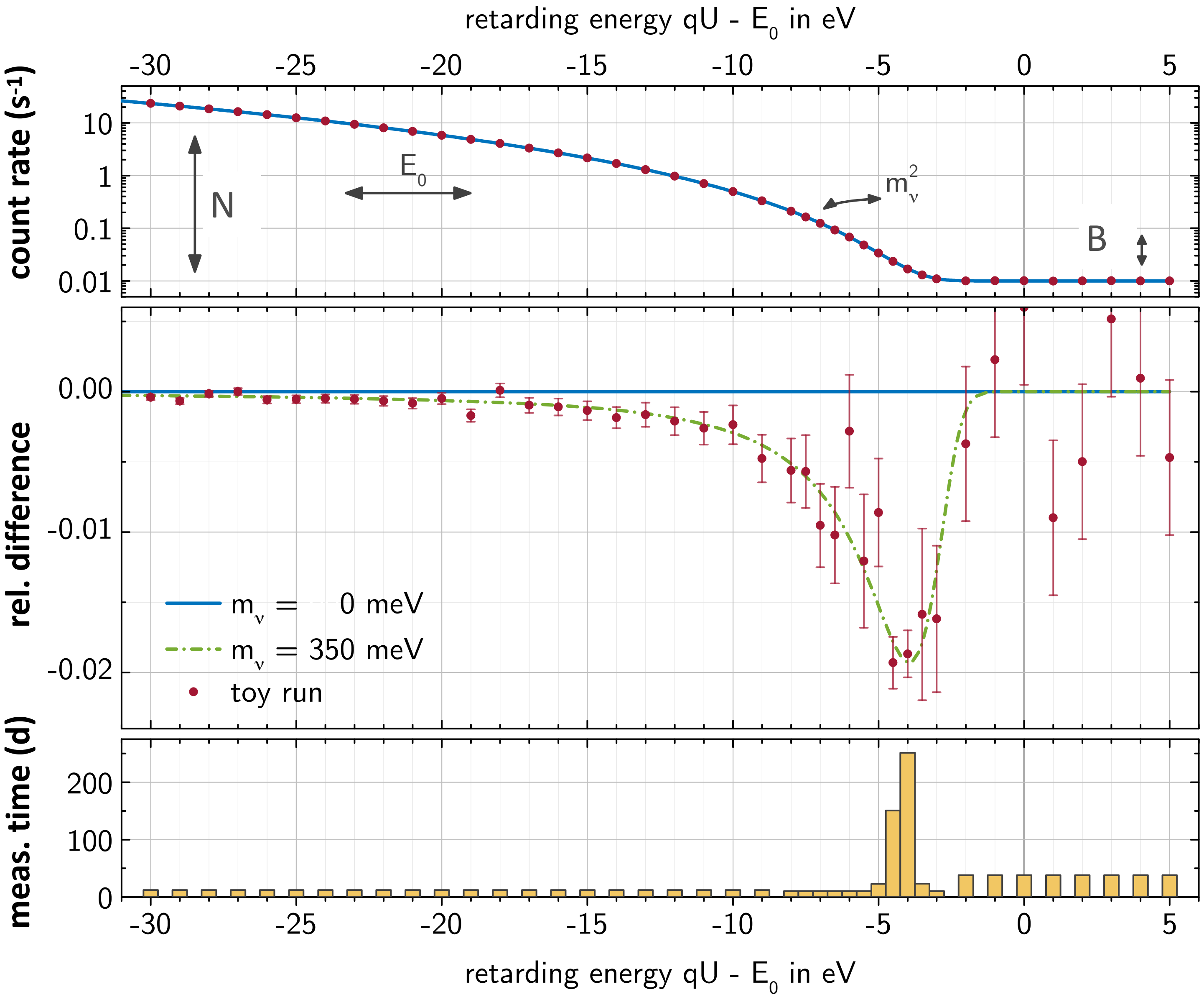
Sensitivity goal: 2 eV ➜ 0.2 eV

- Improvement x100 in statistics and systematics
- Background comparable to predecessors
- Scaled-up dimensions; 70 m total beam line


Looks simple on paper, but …

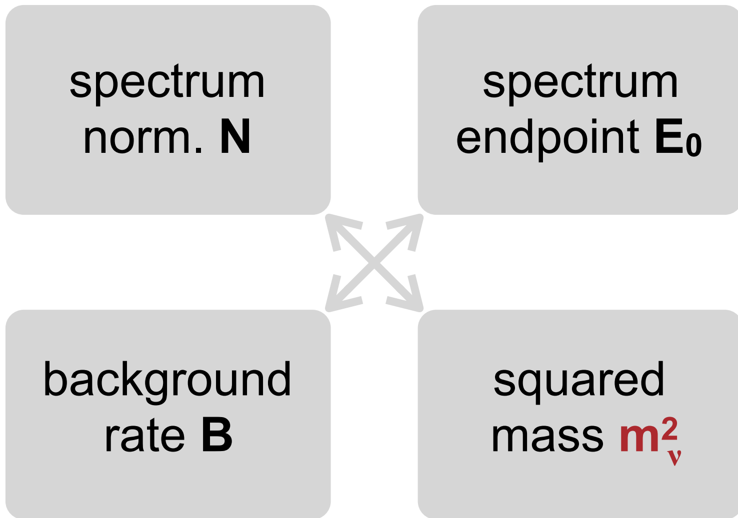
KATRIN's epic voyage

Measurement principle of KATRIN



Direct **shape** measurement of **integrated β spectrum**

Four fit parameters:



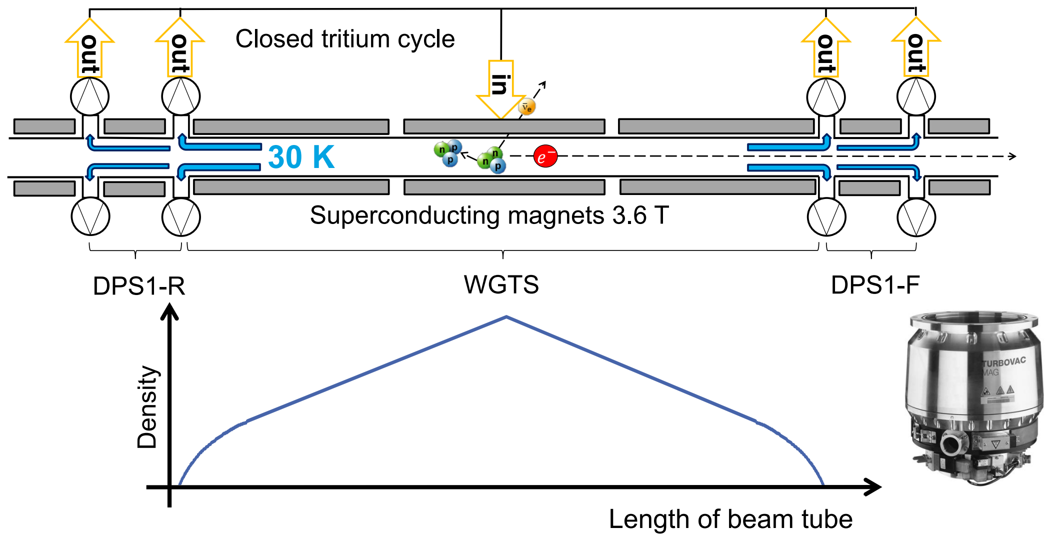
Windowless gaseous tritium source

Gaseous molecular tritium (T_2) source:

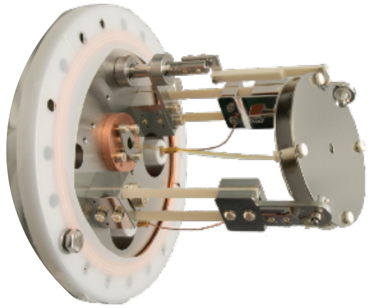
- high activity (~100 GBq)
- high isotopic purity (ε_T > 95%)

Challenge: gas column stability (0.1%)

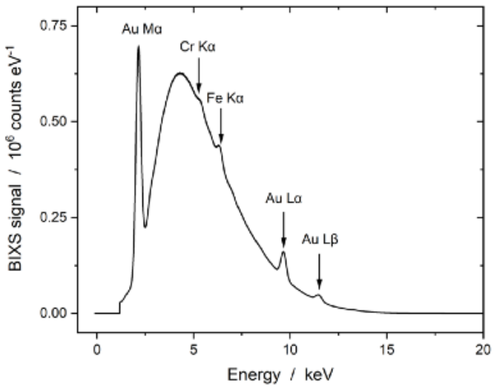
$n \sim \varepsilon_T \cdot p \cdot V / (R \cdot T)$



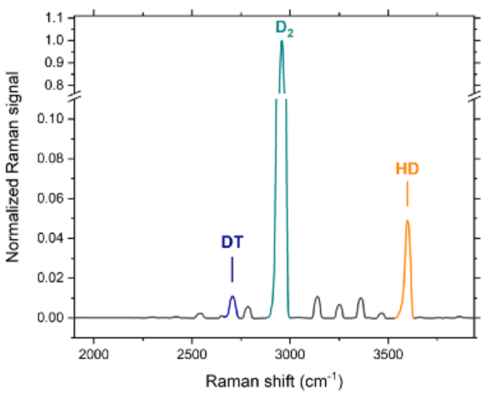
precision "electron gun" to measure scattering of electrons in source

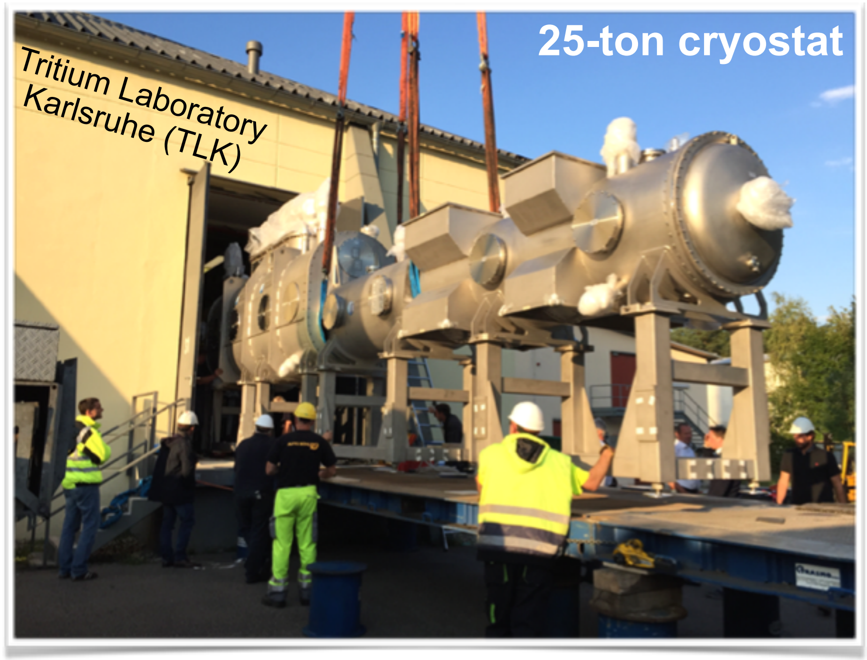


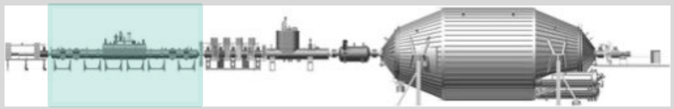
activity monitoring (BIXS)



gas composition (laser Raman spec.)

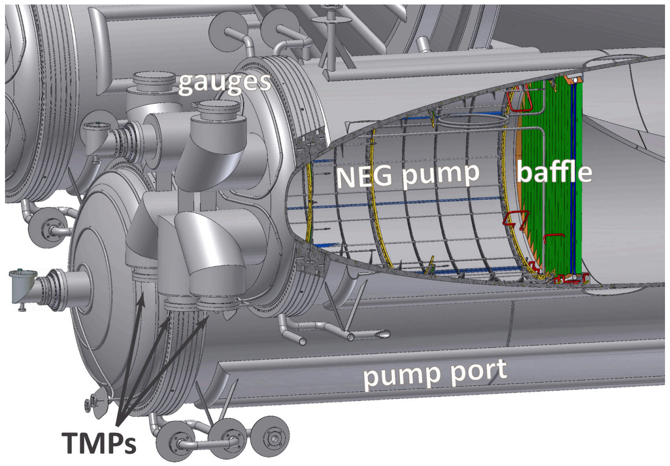






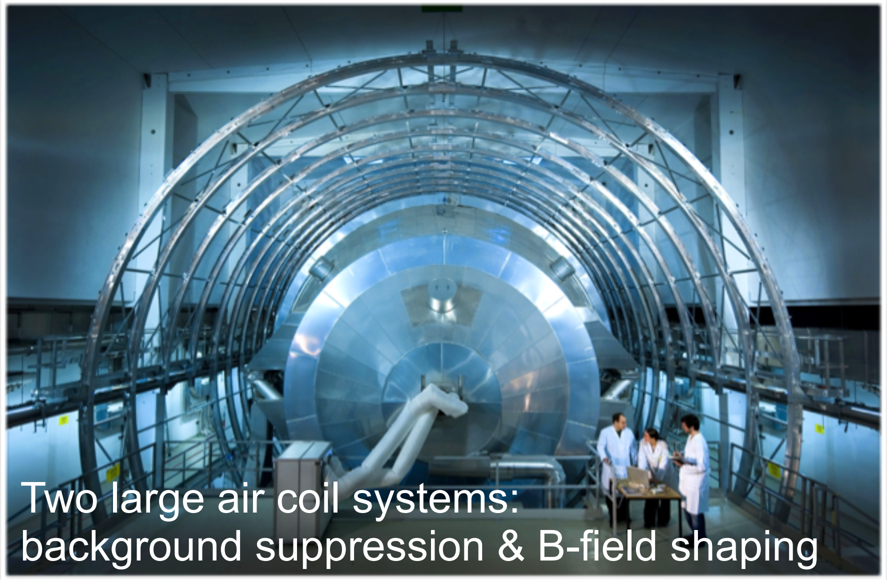
➜ Posters by M. Aker, A. Marsteller

KATRIN main spectrometer

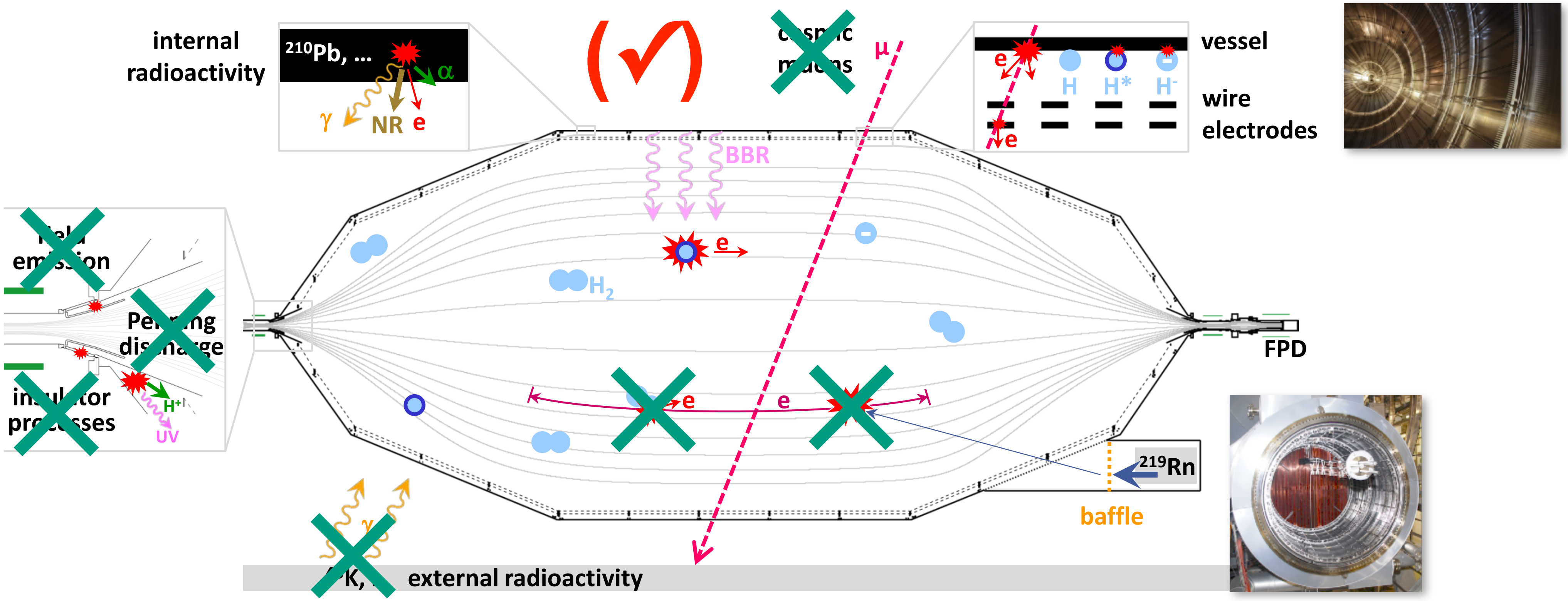


UHV system for spectrometer (~1240 m^3)

Large NEG pumps to reach p~10^{-11}mbar and LN_2-cooled baffles for radon trapping



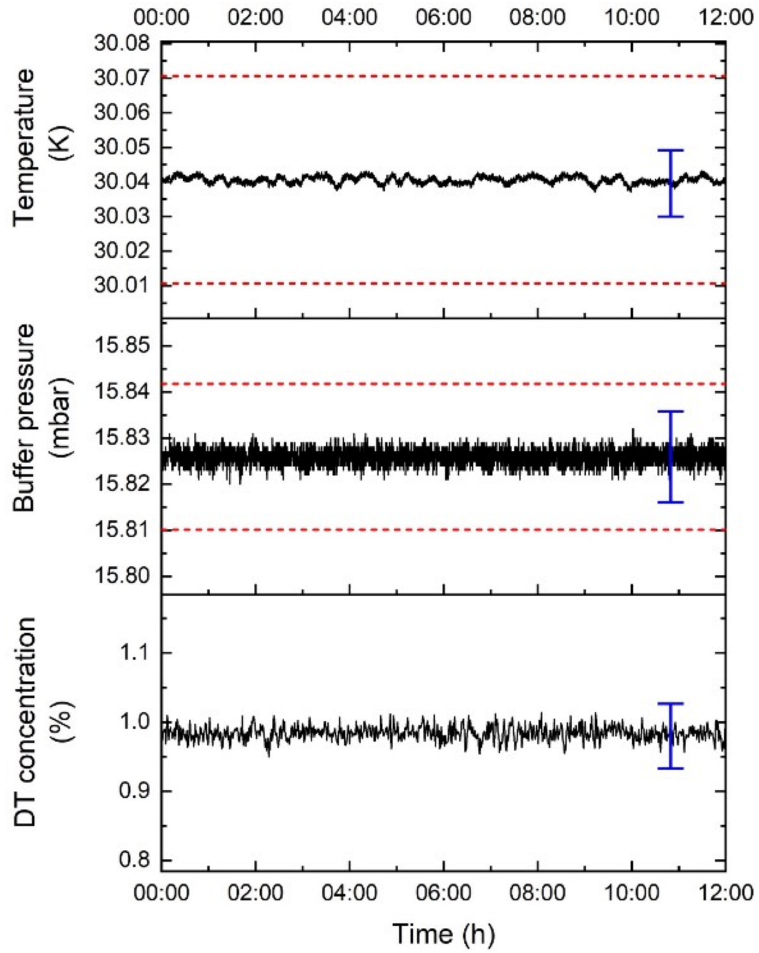
Background sources in KATRIN

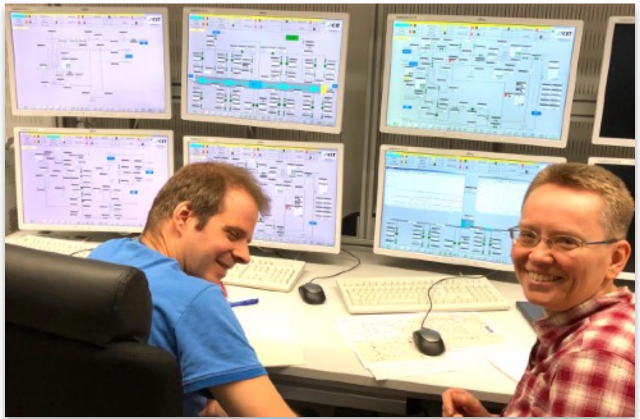


- Actively eliminated 7 out of 8 known sources of background.
- Remaining backgrounds predominantly originate from main spectrometer: stored particles from radon decays, ionisation of Rydberg states.
- Currently investigating how to mitigate these further (e.g. field configuration).

2018 milestone: *First Tritium* campaign

- Commissioning of the system with traces of tritium, but nominal loops operation: **D_2 (99%) + DT (1%)**
- Demonstrate **0.1%** global system stability
- Obtain high-quality beta spectra with good statistics (~500 MBq), large energy window (few 100 eV)
- Study systematic effects, verify analysis tools & model

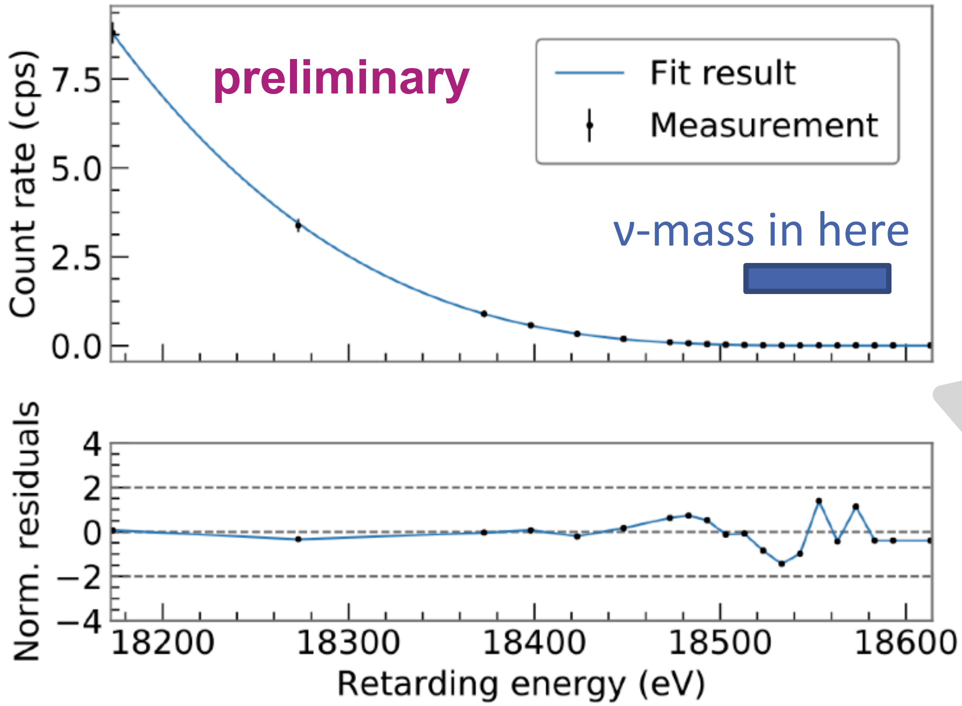




First tritium injection
Friday, May 18th,
7:48 UTC

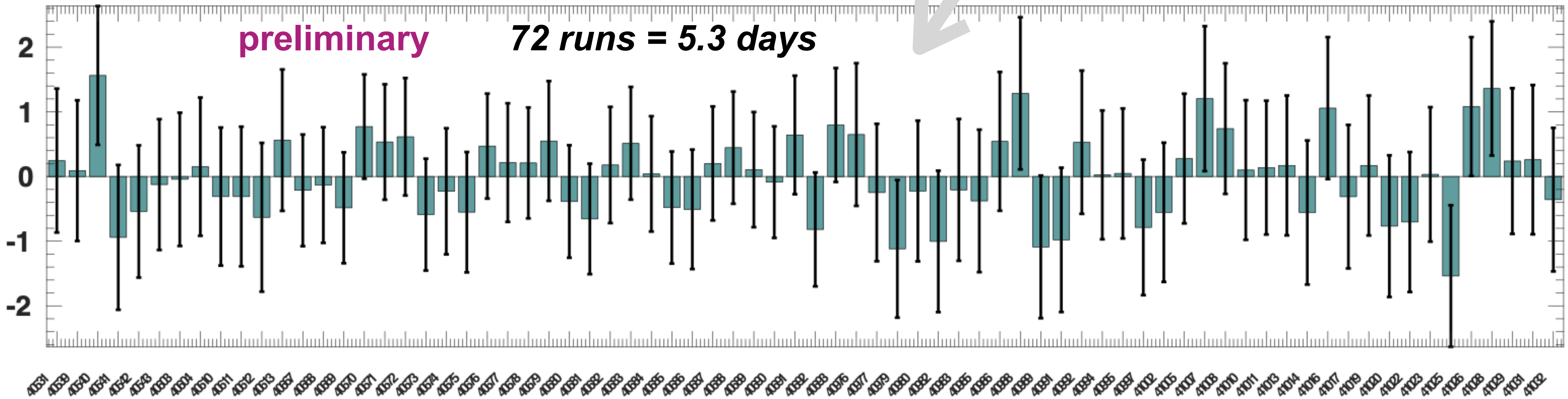
14 days
of stable,
reliable operation

Analysis of the first tritium beta spectra



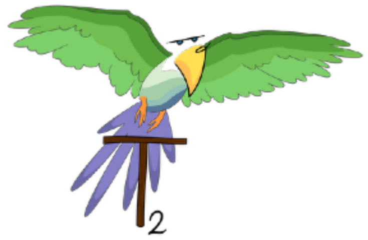
- Shown: single run (3 h), single pixel
- Extended energy range out to 400 eV
- Three-parameter fit: $m^2(\nu) = 0$ fixed
- Here: only statistical uncertainty

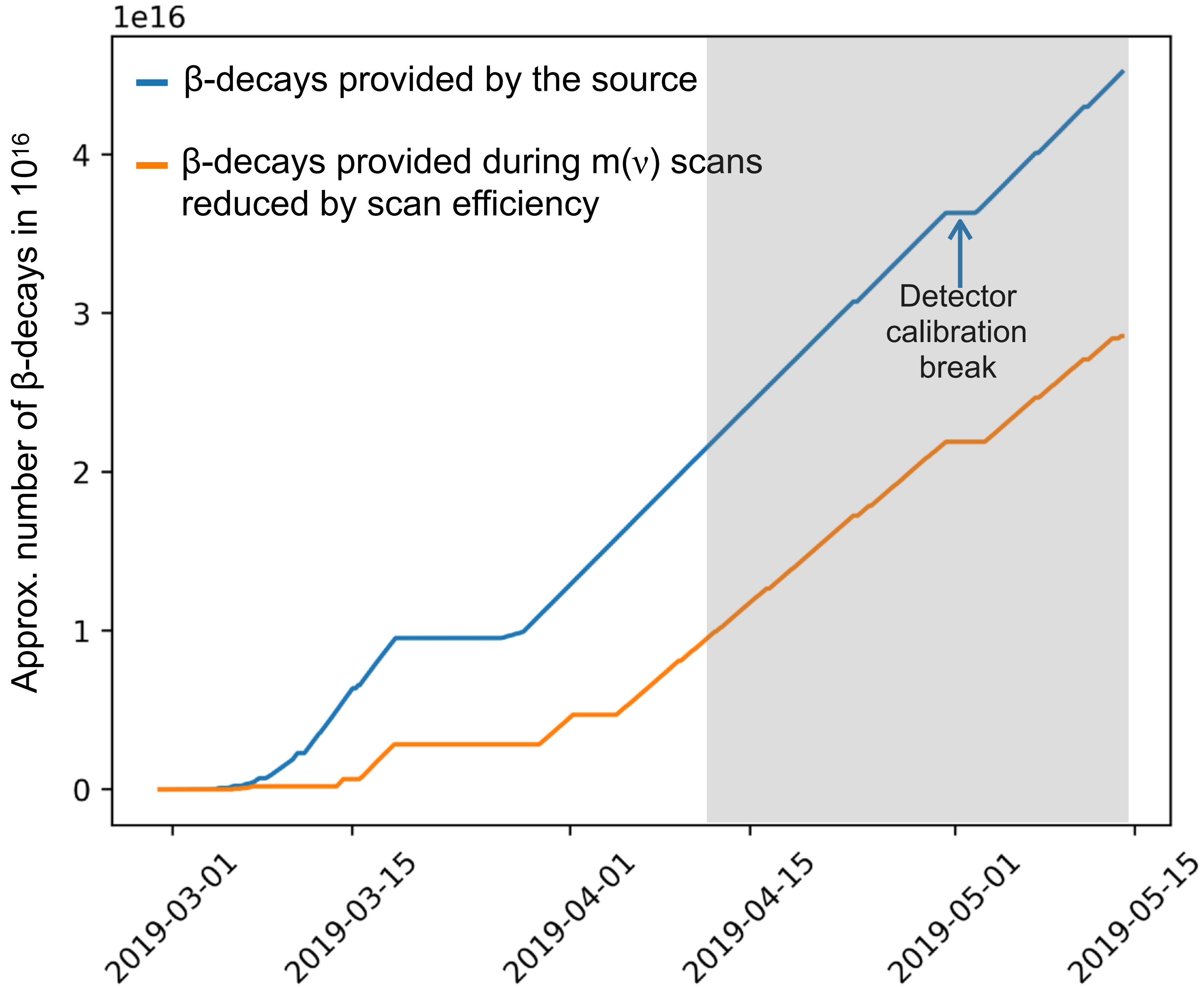
- Excellent match of model expectation and data in rate and spectral shape.
- Endpoint is stable and agrees with expectation within errors.



➜ “First Tritium” paper in preparation

2019 milestone:
Start of ν-mass data-taking of KATRIN





Ca. 300 spectrum scans recorded

April 10 - May 13: spectrum scans at $\sim 2 \cdot 10^{10}$ β-decays/sec

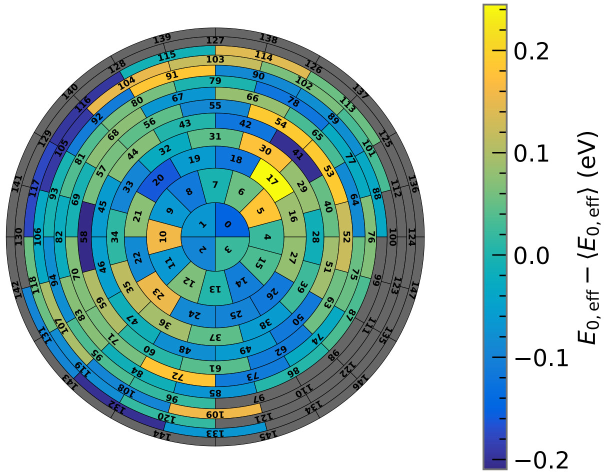
Gradual ramp-up to source strength 50x “First Tritium”

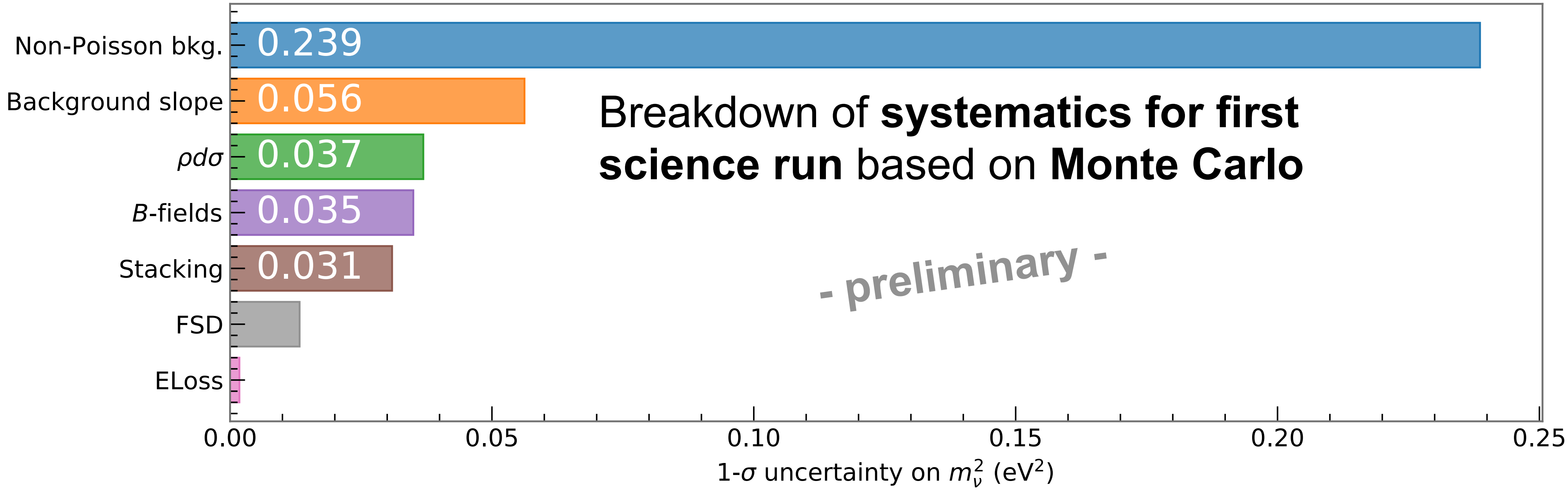
March 4th: Start of tritium circulation

What to expect from this first science run?

First release of results coming up at TAUP 2019!

- Excellent quality of data: Endpoint value observed to be stable in time and over pixels.
- About 2 million counts in region of interest close to endpoint E_0 ➜ stat. error dominates.
- Expected m_ν sensitivity including systematics estimate: ~1.13 eV (90% C.L.)





Breakdown of **systematics for first science run** based on **Monte Carlo**

➜ Poster by Ch. Karl

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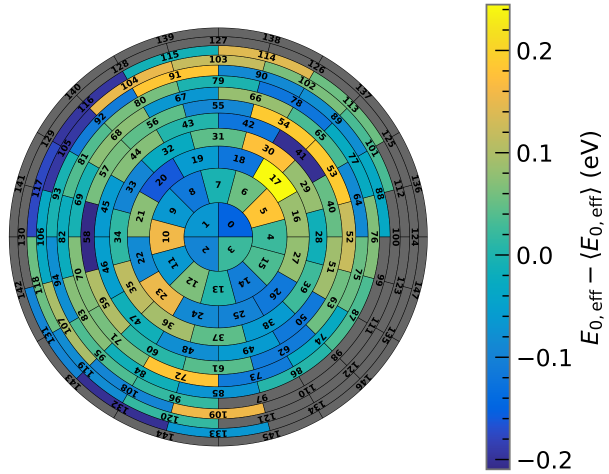
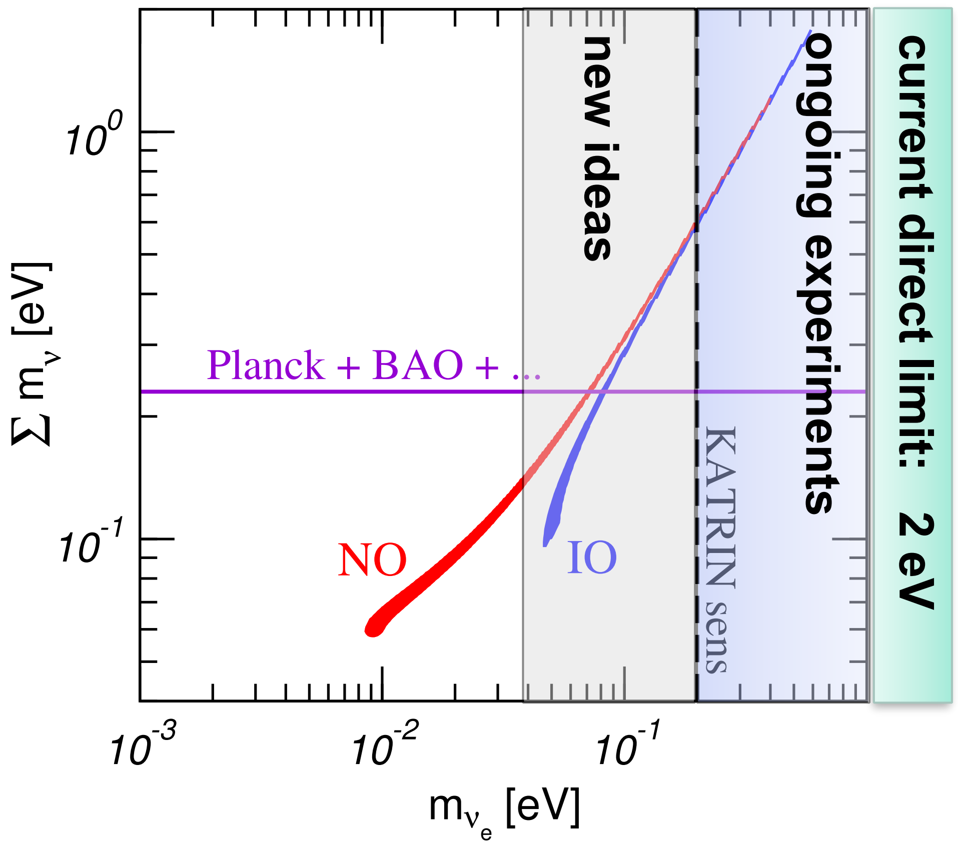


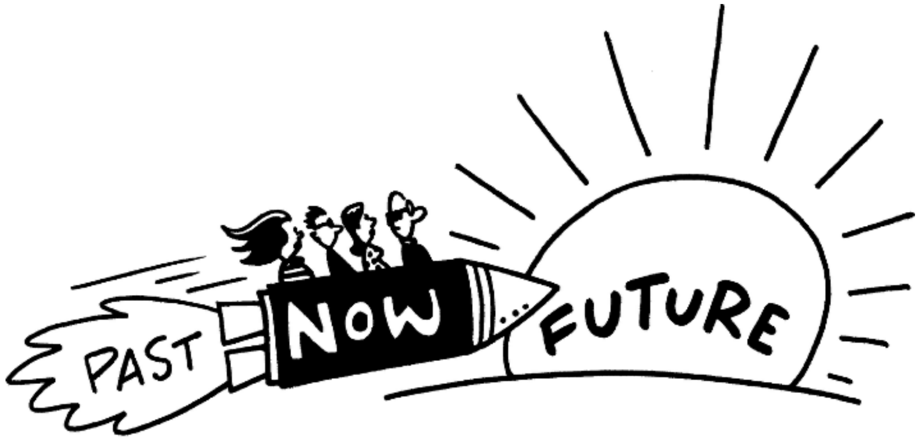
Outlook:

- Next ν-mass run (at full source strength) coming this Fall.
- Expect to be running until 2024 for target m_ν sensitivity of 200 meV.

maintenance	β-spectrum scans	cryotrap regeneration, calibration, background	β-spectrum scans	cryotrap regeneration, calibration, background	β-spectrum scans	maintenance
	60 days		60 days		60 days	

III b. Novel approaches

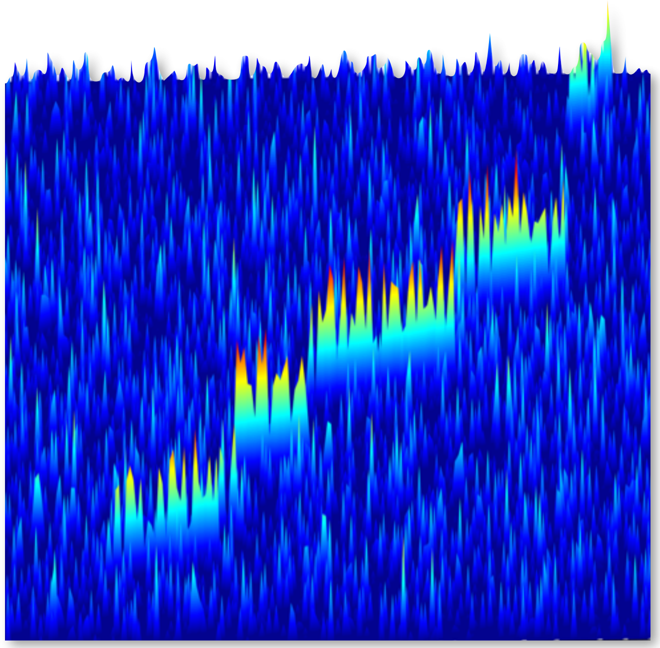




Challenges for further improvement:

- Upscaling requires much larger dimensions (resolution, source opacity)
- MAC-E filter measures integral spectrum
- Molecular final state excitations (vib: ~100 meV) as ultimate limitation for T_2

Energy measurement through cyclotron radiation



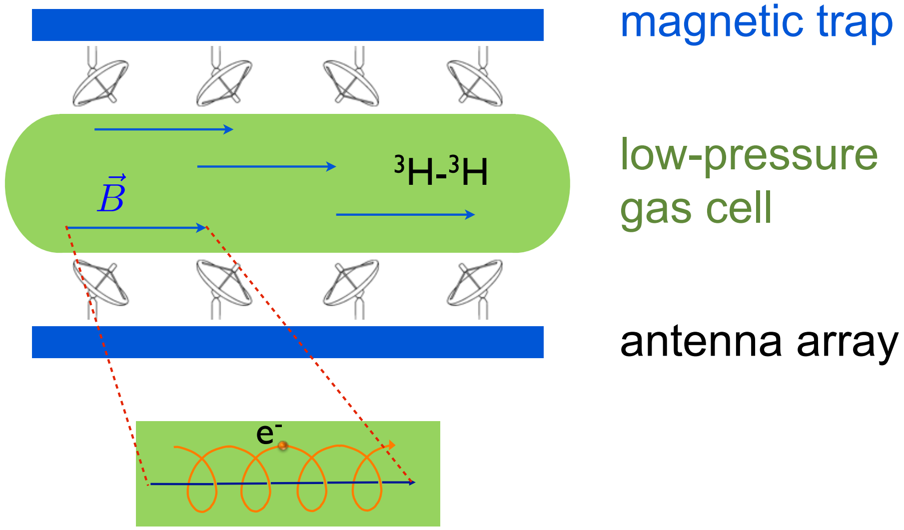
"Never measure anything but frequency." — Arthur L. Schawlow

Cyclotron Radiation Emission Spectroscopy (CRES)

PROJECT 8
UW Seattle, MIT, Case Western Reserve, Pacific NW, CfA, Yale, Penn State, Livermore, U Mainz, KIT

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

$$f(\gamma) = \frac{1}{2\pi}\frac{f_c}{\gamma} = \frac{eB}{m_e + E_{kin}}$$



Appeal of the method:

- Source transparent to microwaves
- No e^- transport from source to detector
- Precision inherent in frequency techniques

Challenges of the method:

- Energy resolution: **ΔE/E ~ Δf/f ~ ppm**
- Frequency resolution: **Δf ~ 1/Δt**
  Δt ~20 μs → 1400 m at 18 keV
  need multiple passes in a trap

[Monreal & Formaggio, PRD 80 (2009) 051301]

Cyclotron Radiation Emission Spectroscopy (CRES)

PROJECT 8

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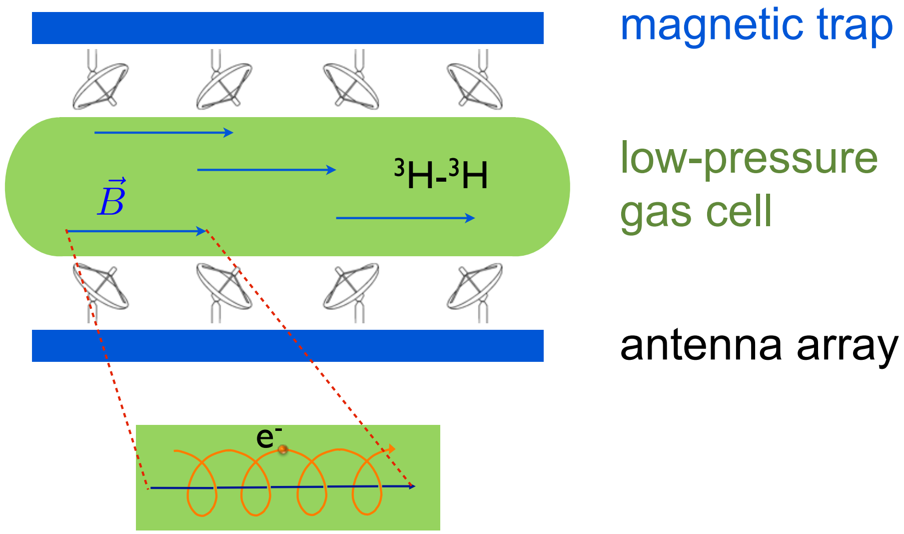
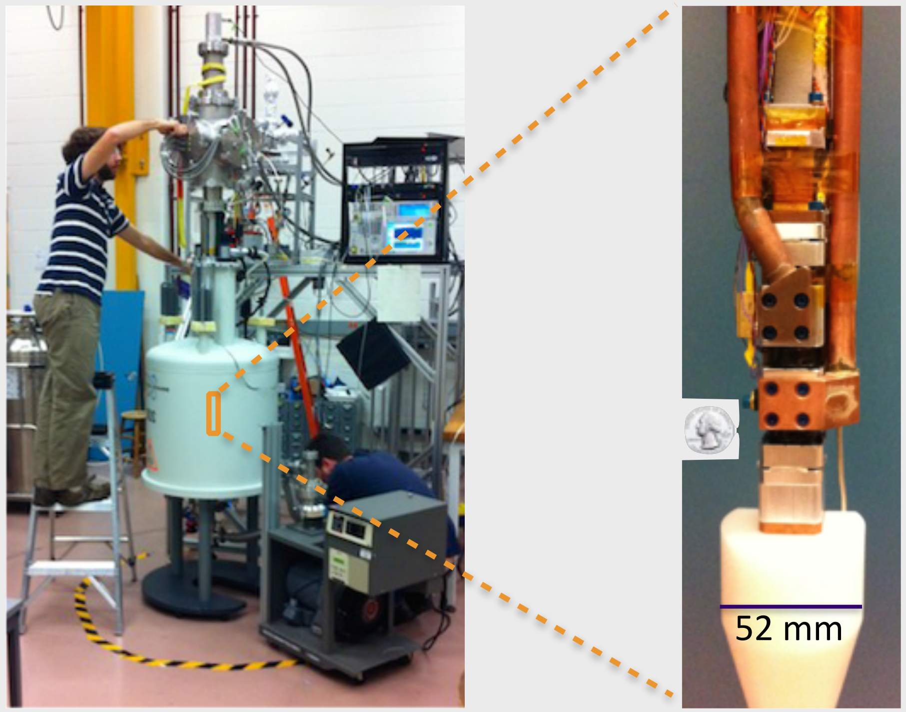


From theoretical idea to experimental reality within 5 years



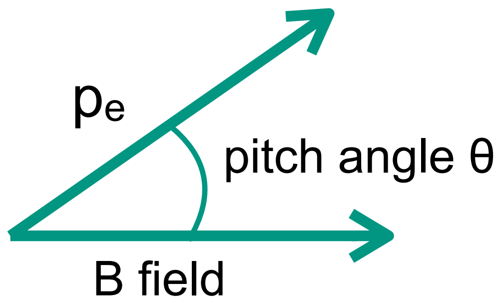
➜ Proof of principle of CRES technique

[Monreal & Formaggio, PRD 80 (2009) 051301]

Cyclotron Radiation Emission Spectroscopy — some practical points

Larmor formula gives emitted power:

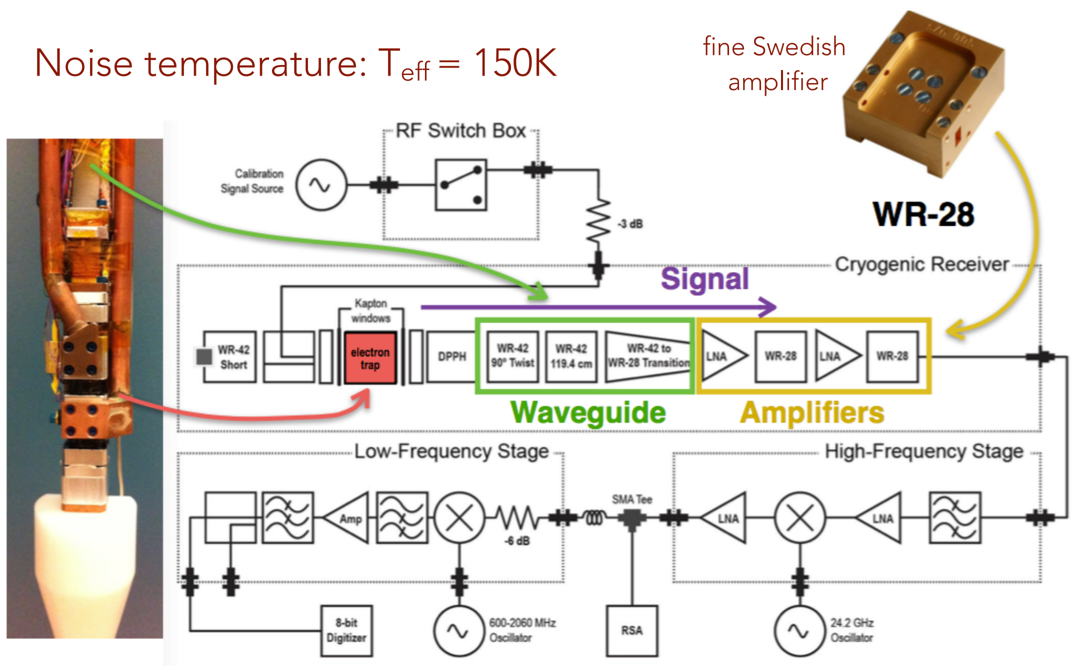
$$P(\gamma,\theta) = \frac{1}{4\pi\varepsilon_0}\frac{2}{3}\frac{q^4B^2}{m_\mathrm{e}^2}\left(\gamma^2-1\right)\sin^2\theta$$



Realistic case:

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

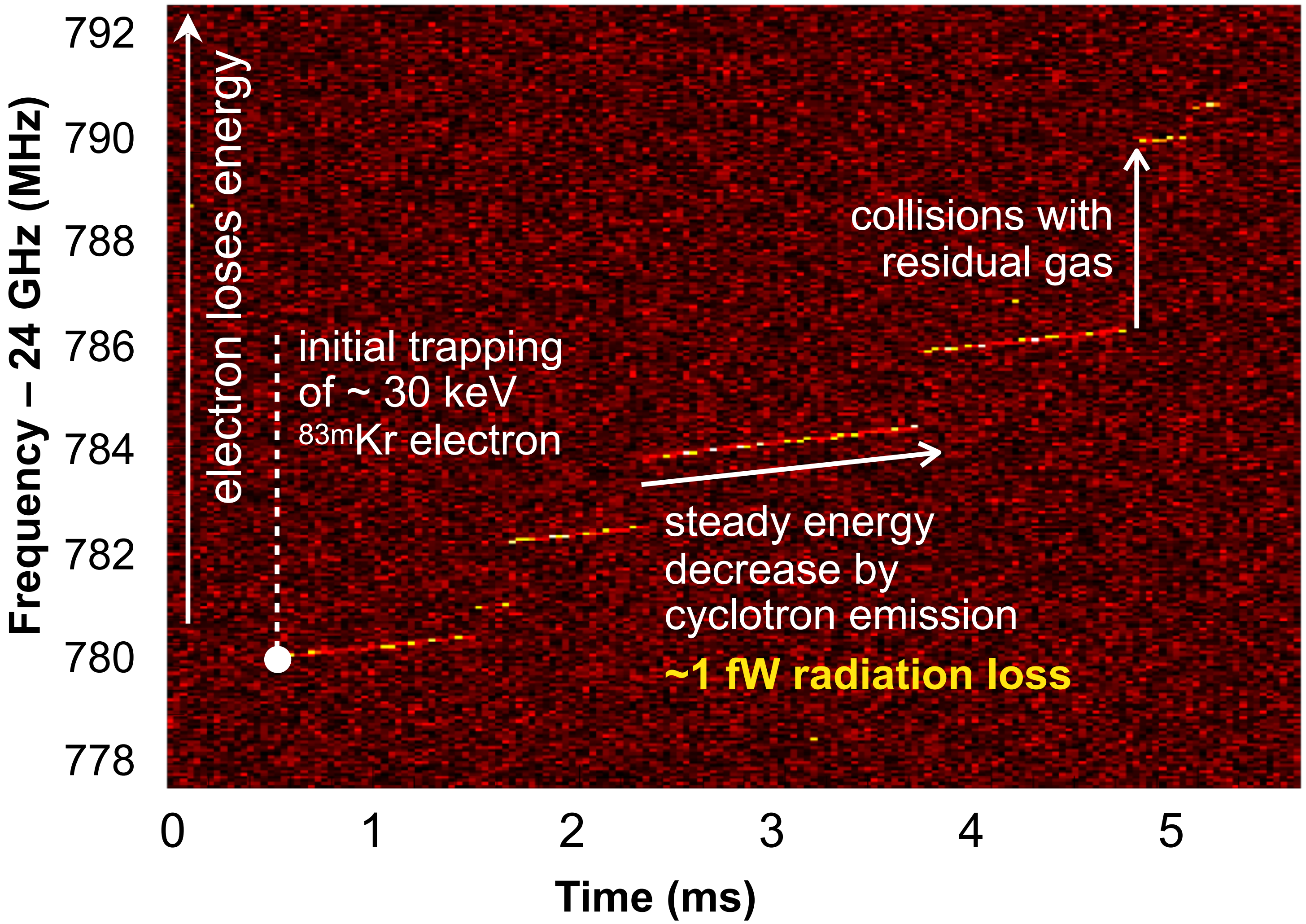
➜ Need low-noise cryogenic RF system



from S. Böser

Project 8: phased approach

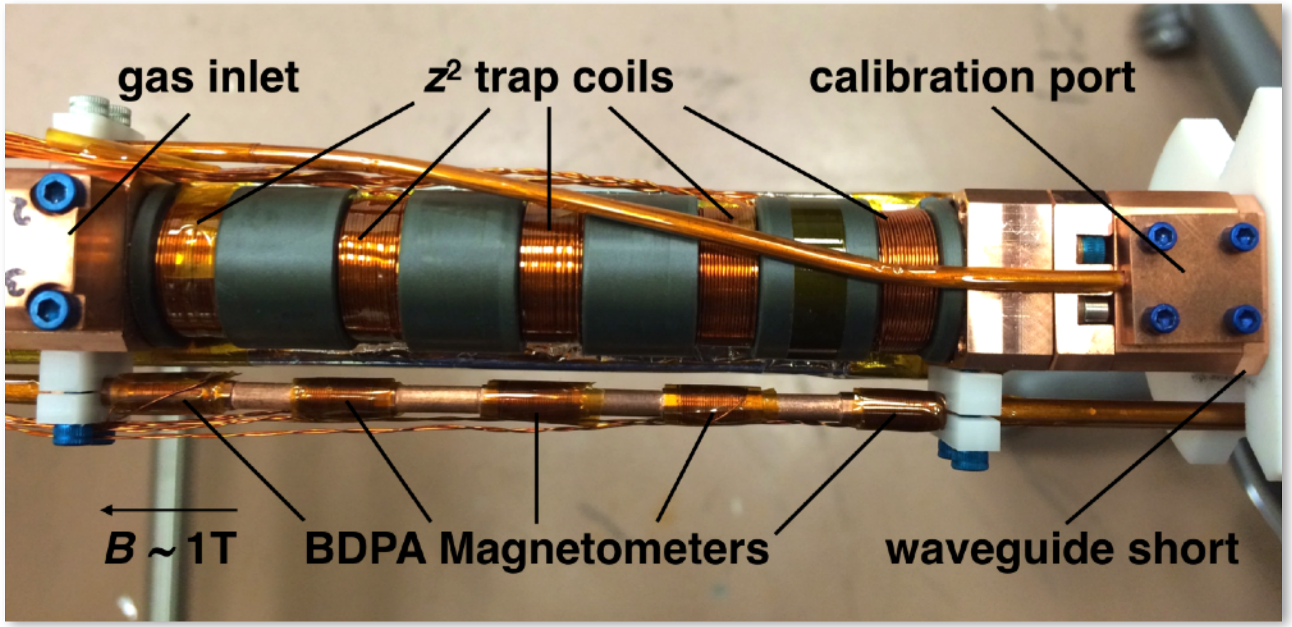
- **Phase I (2010-2016): proof of principle**
  Single-electron CRES demonstrated with conversion electron lines from ^{83m}Kr



[Asner *et al.*, PRL 114 (2015) 162501]

Project 8: phased approach

- **Phase I (2010-2016): proof of principle**
  Single-electron CRES demonstrated with conversion electron lines from ^{83m}Kr
- **Phase II (2015-2019): tritium demonstrator**
  - Improved waveguide, read-out, energy resolution, systematics studies
  - Continuous T_2 β-spectrum, $m(\nu_e)$ ~ 100 …10 eV

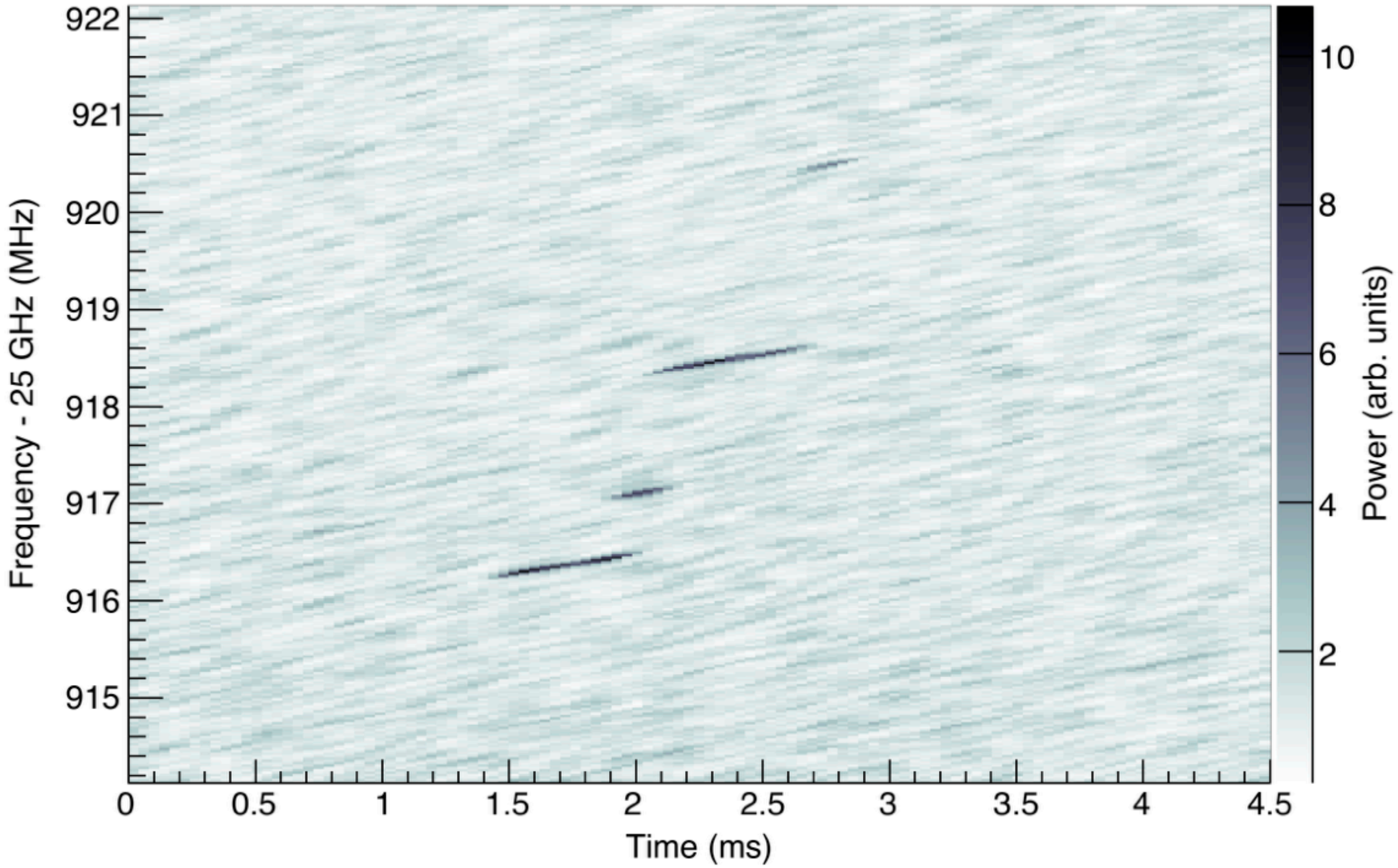


Phase II set-up

T_2 data-taking started in fall 2018

Project 8: phase II results

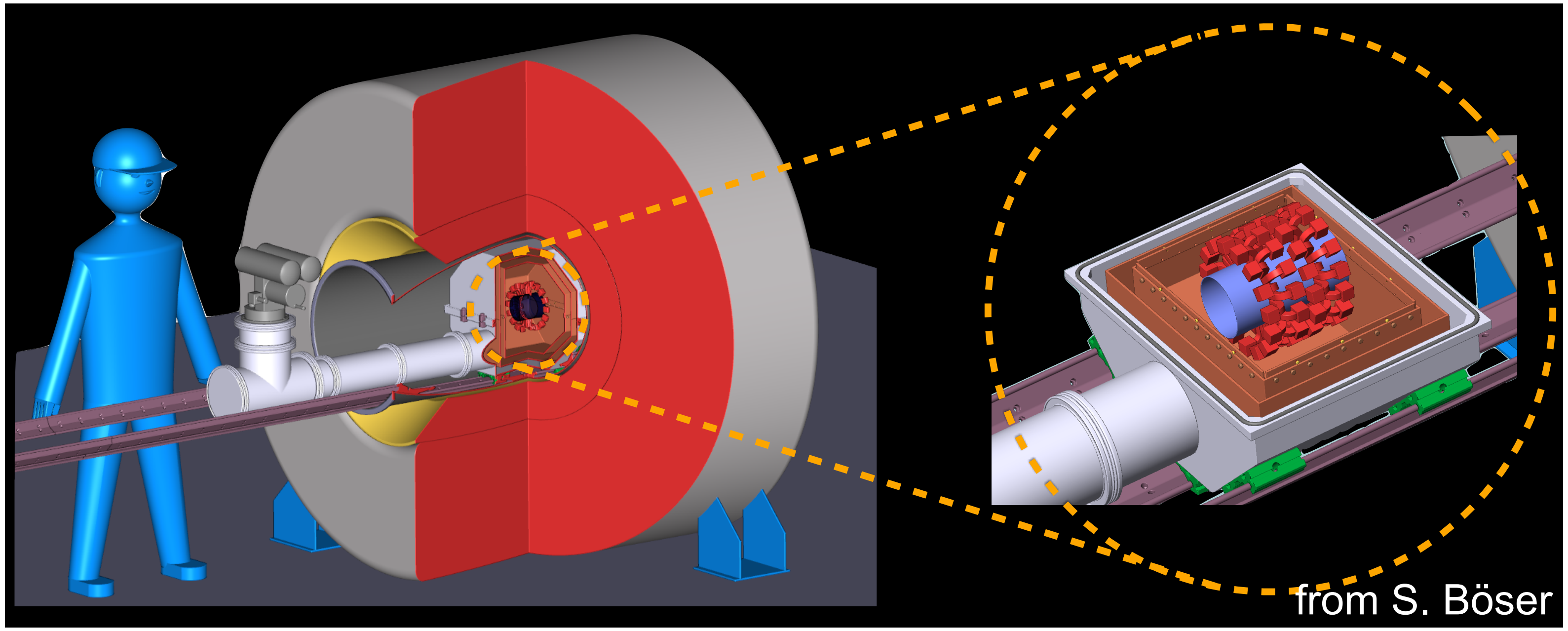
- First tritium CRES events observed in October 2018
- Spectrum describes the data well; no events recorded above endpoint E_0
- Currently taking another 100-day run to complete phase II

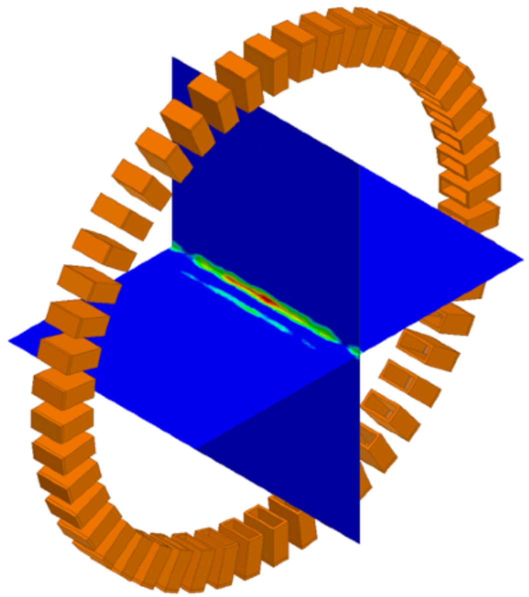


Project 8: next steps

Phase III (2016-2020): large volume demonstrator

- 10^5 Bq in 200 cm^3 volume (10-20 cm^3 effective) ➜ 1 yr for $m(\nu_e)$ ~ 2 eV
- Open-bore MRI magnet: cryostat moved in on rails
- Phased-array read-out, digital beam-forming
- Ongoing design for trap, cryo-system, antenna array

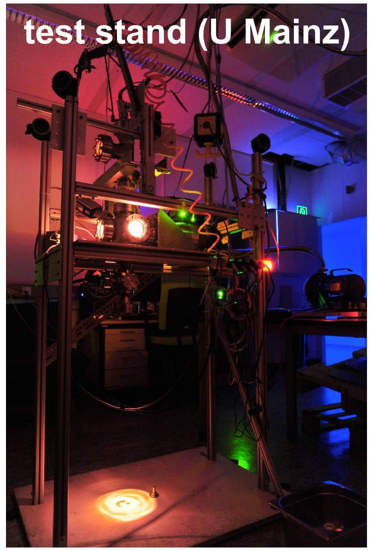


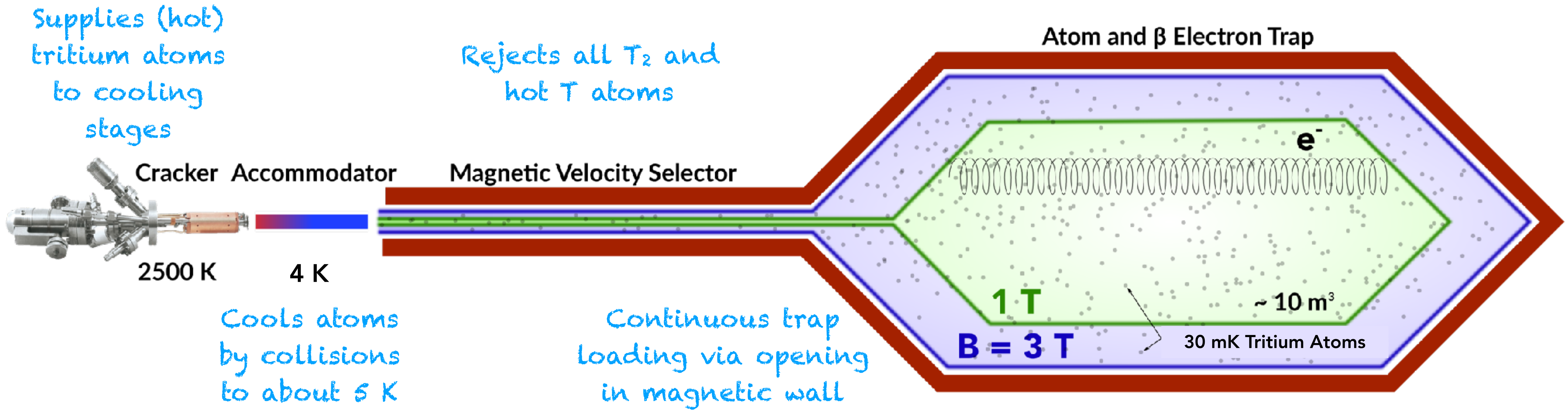


Project 8: towards atomic tritium

Phase IV (2017+): development of source concepts

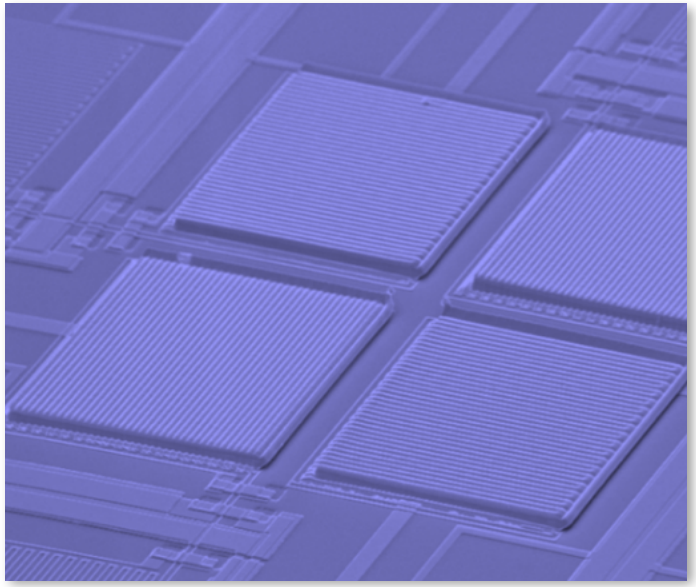
- goal: sub-eV sensitivity at inverted hierarchy scale
- R&D for large-volume magnetic trap for atomic tritium (< 50 mK)
- 10^{18} atoms (~10^{9} Bq activity) in fiducial volume of 10+ m^3





from A. Lindman

Calorimetric approach using ^{163}Ho



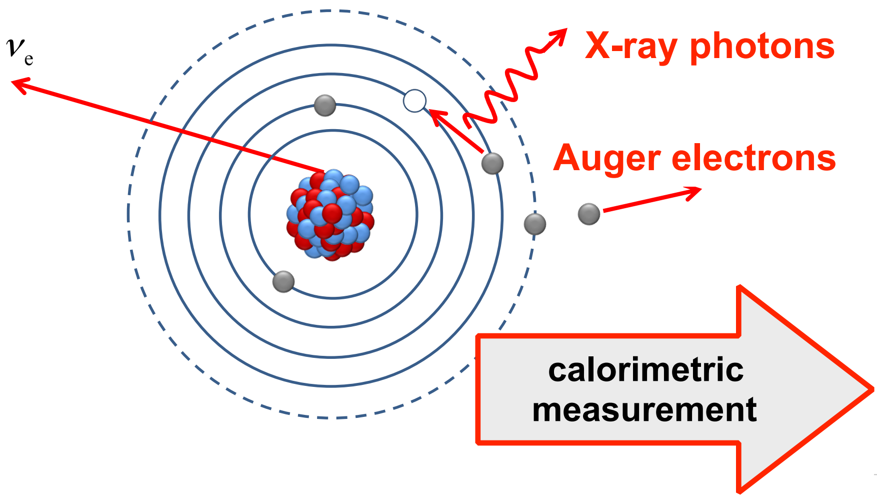
ν-mass from ^{163}Ho electron capture

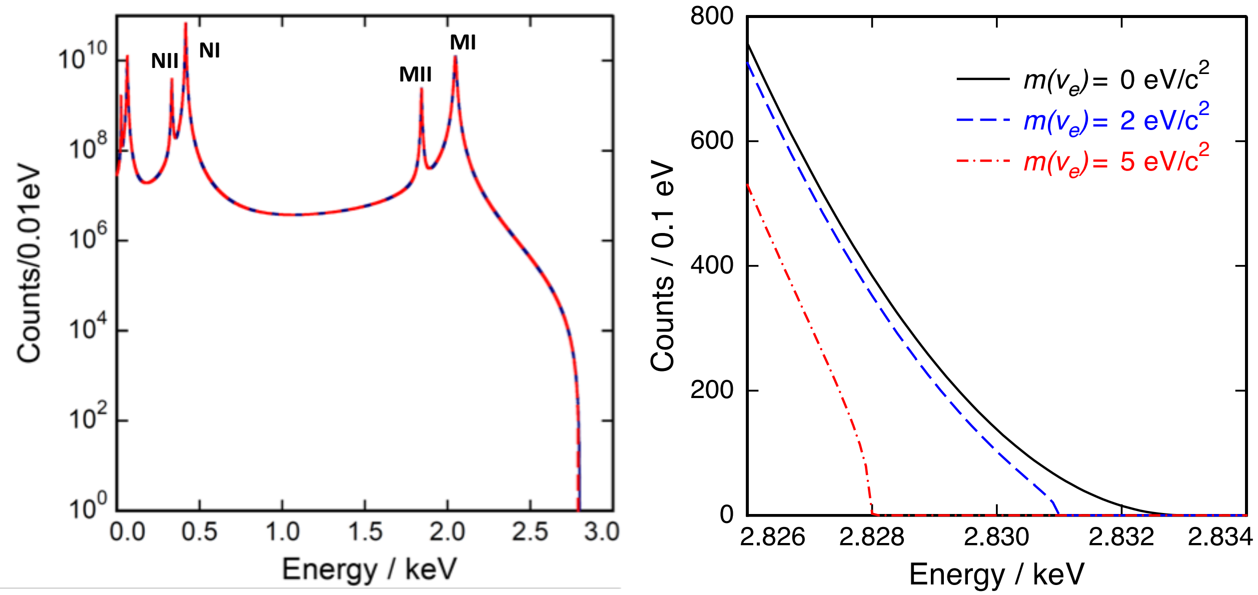
$^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}^{*} + \nu_e$

Low Q_{EC} ~2.8 keV and $T_{1/2}$ ~ 4570 years

Proposed by de Rujula & Lusignoli (1982)

Present limit: $m(\nu_e) < 225$ eV (90% C.L.)





[L. Gastaldo]

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

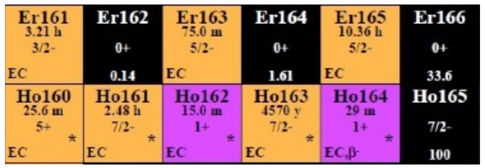
ν-mass from ^{163}Ho electron capture

Challenges (experiment):

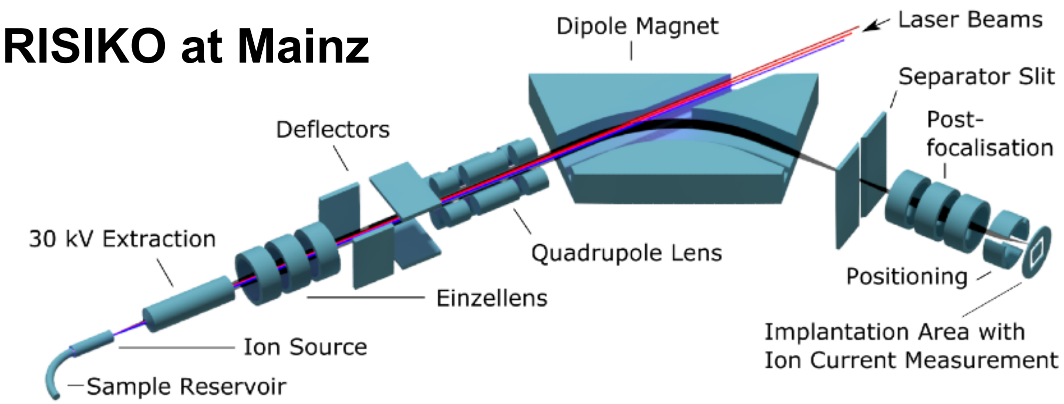
- Production & purification of isotope ^{163}Ho
- Incorporation of ^{163}Ho into high-resolution detectors ($2 \cdot 10^{11}$ atoms for 1 Bq)
- Operation & readout of large arrays

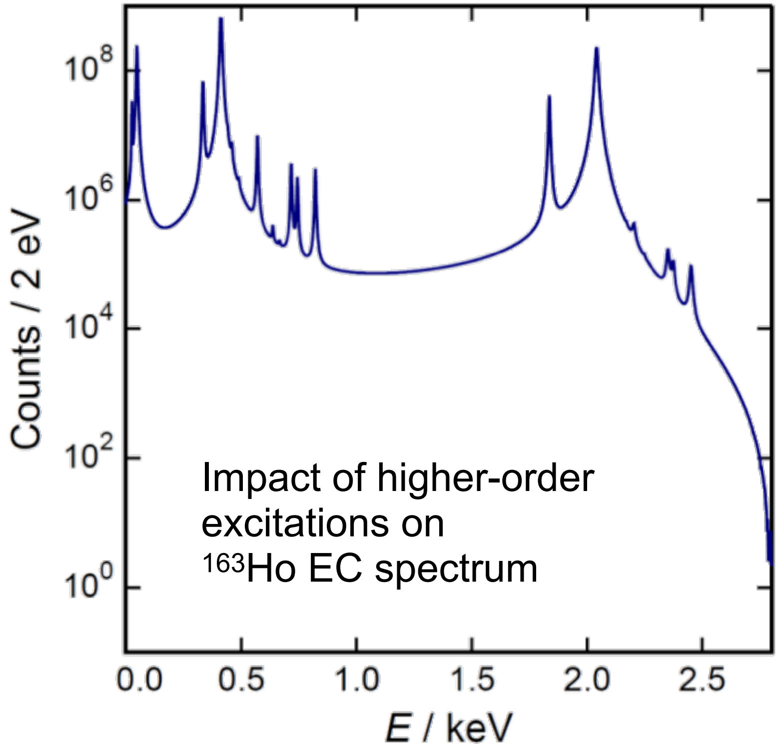
Challenges (theory & spectral shape):

- Precise understanding of calorimetric spectrum (nuclear/atomic physics + detector response)
- Independent determination of Q_{EC} by Penning-trap mass spectrometry



RISIKO at Mainz





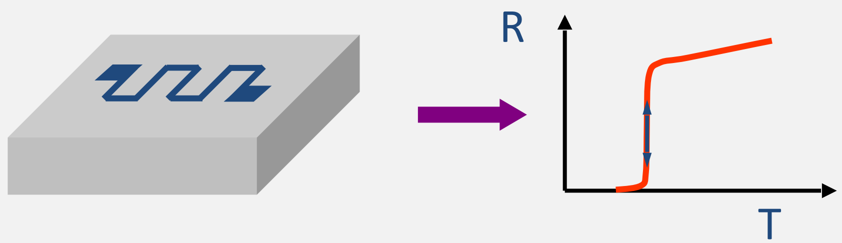
[A. Faessler et al., PRC 91 (2015) 045505, 064302]

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

- Two experiments to address sub-eV neutrino masses by calorimetric spectrum
- Two different techniques for temperature sensing

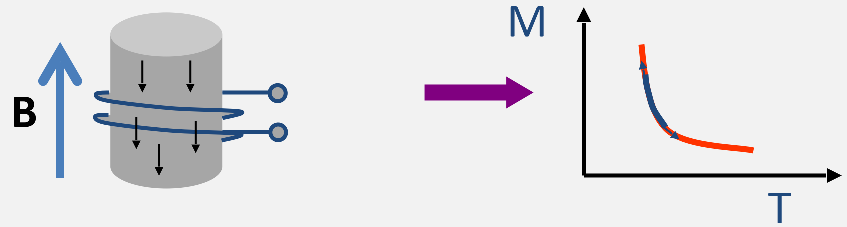
HOLMES approach:

Resistance R at superconducting transition:
Transition Edge Sensors (TES)



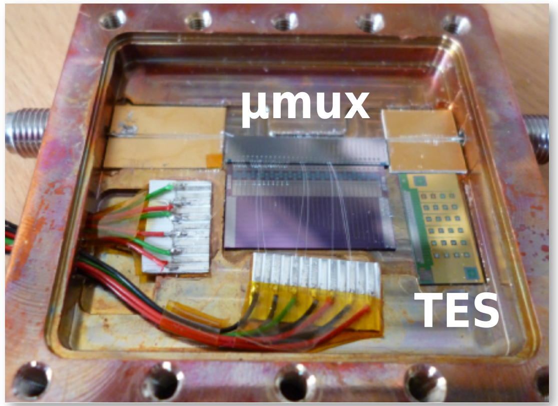
ECHo approach:

Magnetization of paramagnetic material
Metallic Magnetic Calorimeters (MMC)

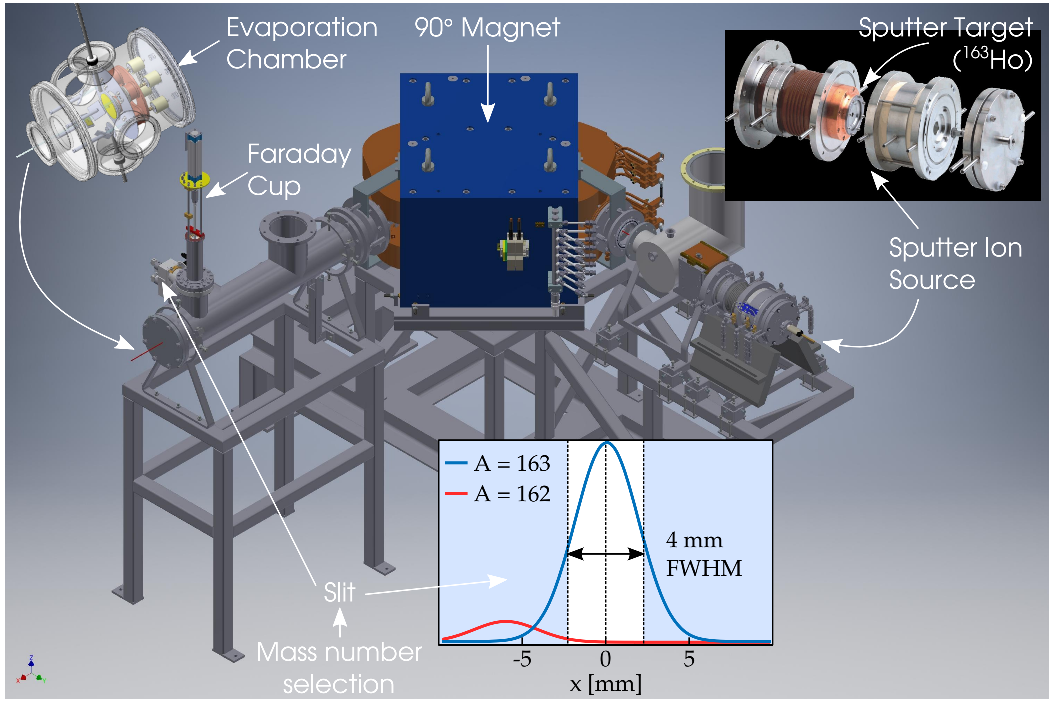


[Cryogenic Particle Detection, (ed. C. Enss), Topics Appl. Phys. 99 (Springer, 2005)]

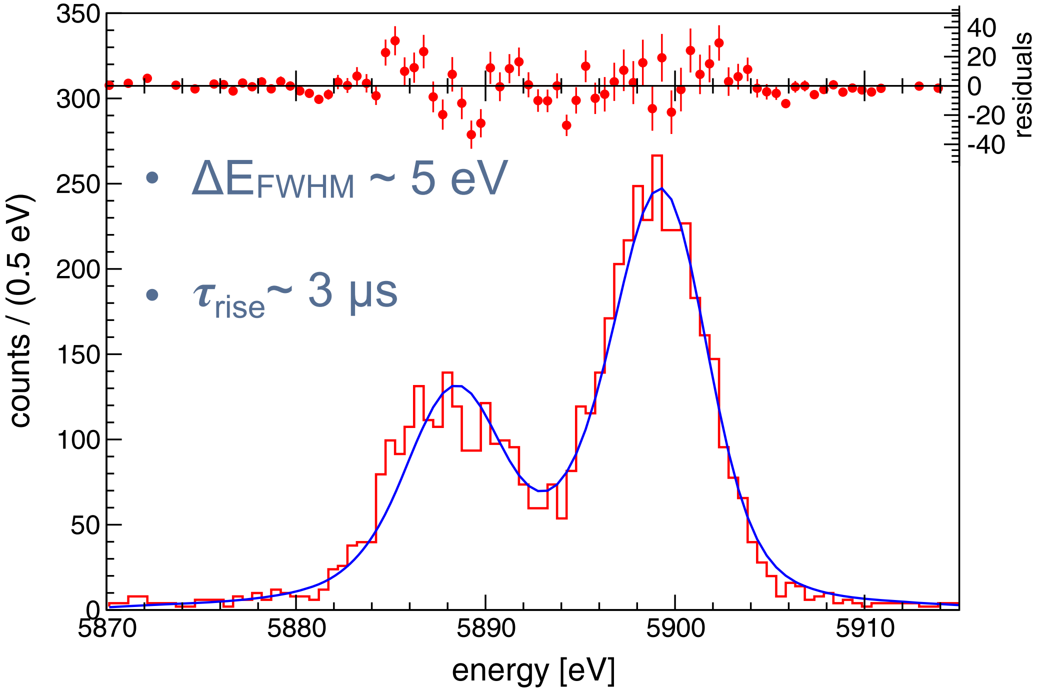
TES technology: HOLMES



Detector design & fabrication at Milano



Custom mass-separator ion implanter at Genova



HOLMES design & timeline:

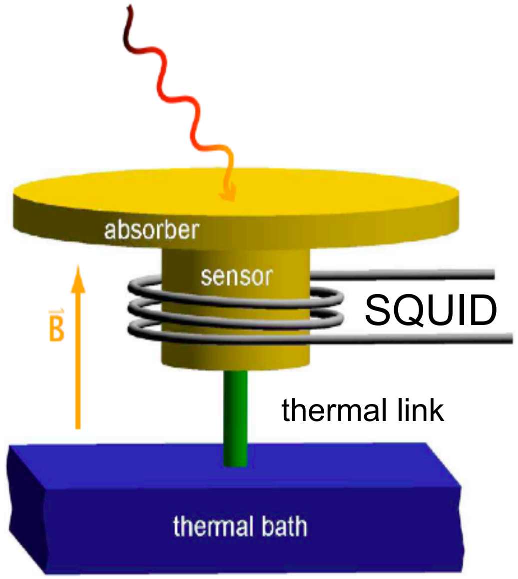
- 6.5 x 10^{13} nuclei ^{163}Ho (~300 Bq) per pixel
- ΔE ~ 1 eV (FWHM), τ_{rise}~ 1 µs; **1000-pix** array for **1 eV goal**
- TES array + DAQ ready, first implant. coming up
- **32 pixels for 1 month ➜ m_ν sensitivity ~10 eV**

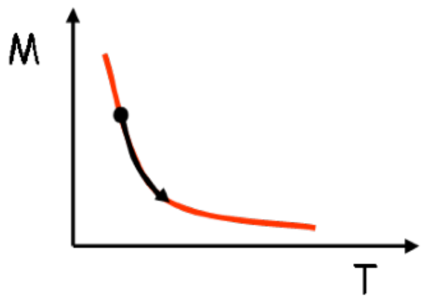
[B. Alpert *et al.*, EPJ C79 (2019) 304]

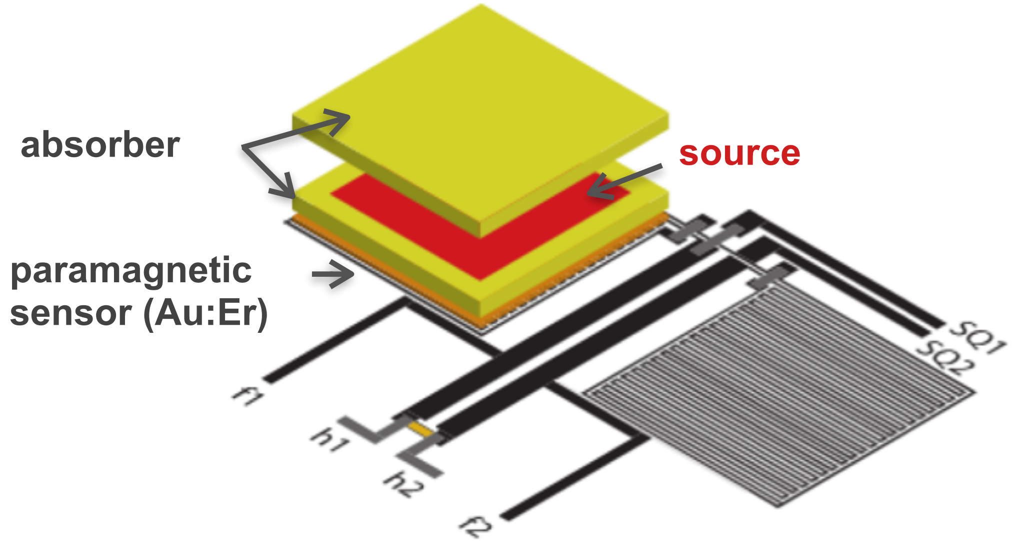
MMC technology: ECHo

Karlsruhe Institute of Technology

Metallic **M**agnetic **C**alorimeters (**MMC**) with paramagnetic Au:Er sensor read out by SQUID







δT in absorber from EC-decay

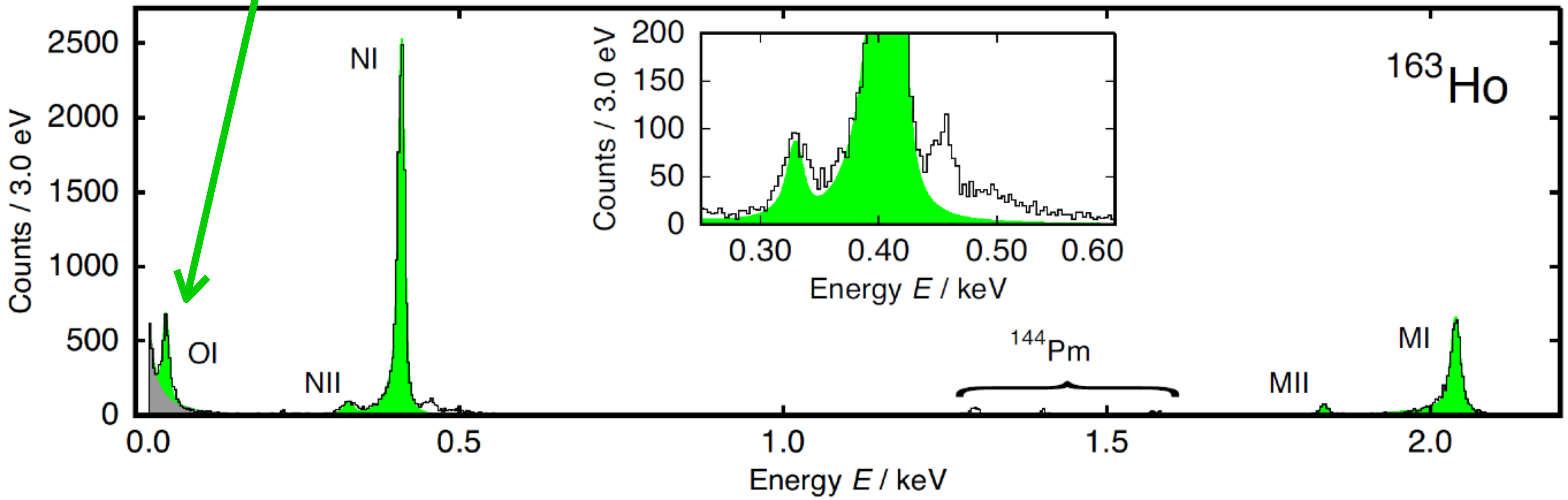
⇨ change in magnetization M of sensor

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

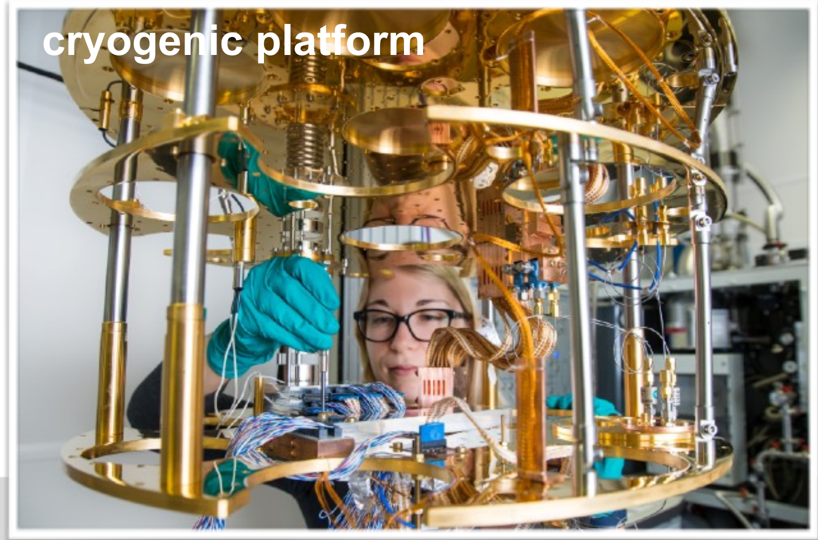
- Fast rise time (~130 ns) and excellent linearity & resolution ($\Delta E_{FWHM} < 5$ eV)
- Multiplexed readout of MMC arrays

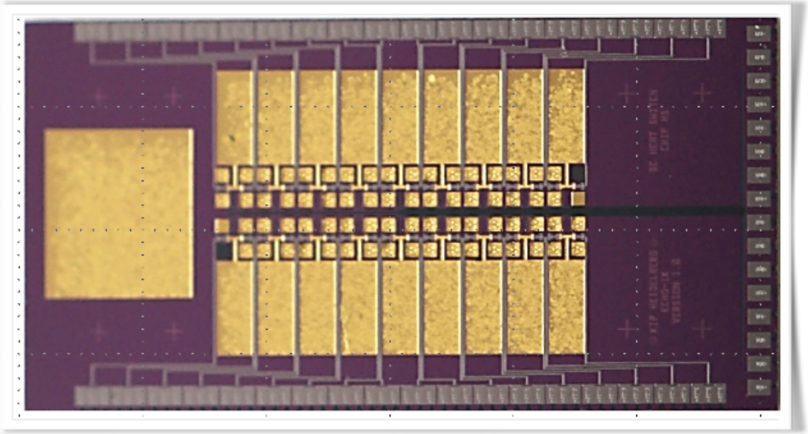
MMC technology: ECHo

Precision ^{163}Ho spectrum
first calorimetric measurement of OI-line



Ranitzsch *et al.*, PRL 119 (2017) 122501





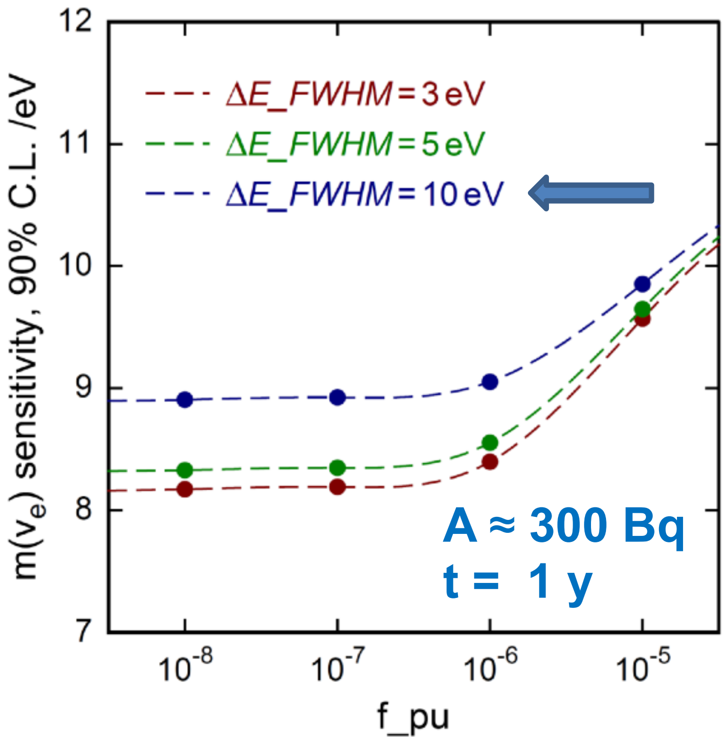
64-pix detectors optimized for implantation

microwave SQUID multiplexing readout

ECHo timeline

ECHo-1k – revised (2015 – 2018)

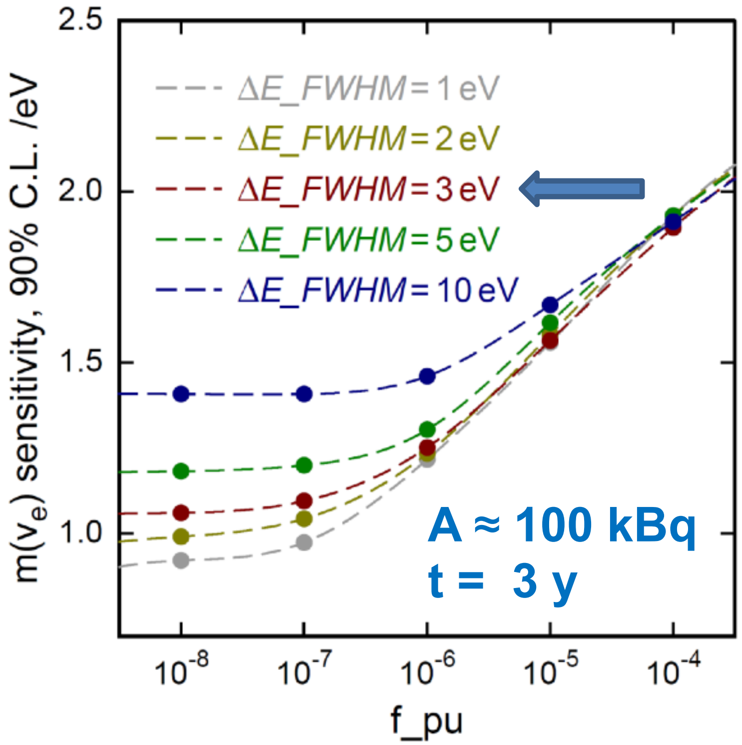
Activity per pixel: 5 Bq
Number of detectors: 60
Readout: parallel two-stage SQUID



$m(\nu_e)$ < 10 eV 90% C.L.

ECHo-100k (2018 – 2021)

Activity per pixel: 10 Bq
Number of detectors: 12000
Readout: microwave SQUID multiplexing



$m(\nu_e)$ < 1.5 eV 90% C.L.

[ECHo collaboration, EPJ-ST 2017]

Improved neutrino mass limit from ECHO-1k is under way!

Direct ν-mass experiments: status and outlook

Karlsruhe Institute of Technology

current achievements → **next goals**

KATRIN

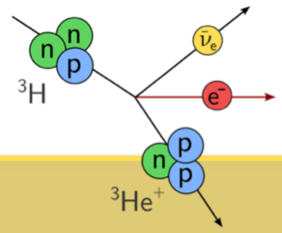
First ν-mass result from 2019 science run about to be released!

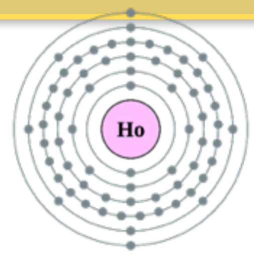
Long-term data-taking (5 yrs) for full sensitivity **(0.2 eV)**

Project 8

CRES proof of principle in 2014, T_2 operation started in fall 2018

Develop CRES for **10 → 2 eV,** and towards IH (atomic source)





ECHo
HOLMES

- Advanced detector development (MMC and TES technologies)
- Test of scalable arrays, readout
- First ν-mass result from ECHo-1k is coming up

- Operate medium-size arrays (~10^{10} counts) for **10 eV** sens.
- Prepare large arrays (~10^{14} counts) for **sub-eV** sens.

IV. Extra course

More physics questions for direct kinematic experiments

- How many neutrino states are there?

- Can kinematic experiments probe novel forms of interaction?

left-right symmetric model

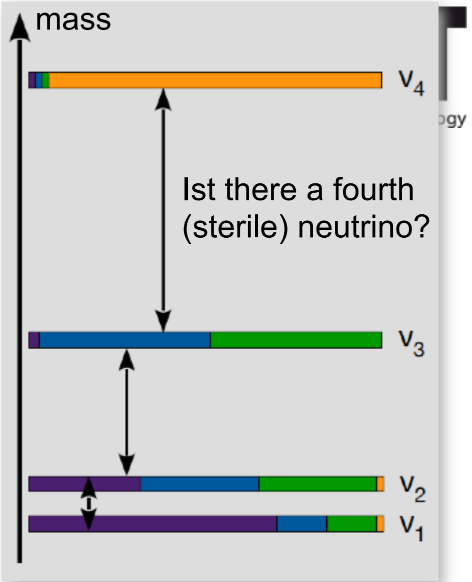
right-handed charged currents

non- V-A interactions

Pontecorvo School logo by M. Bilenky

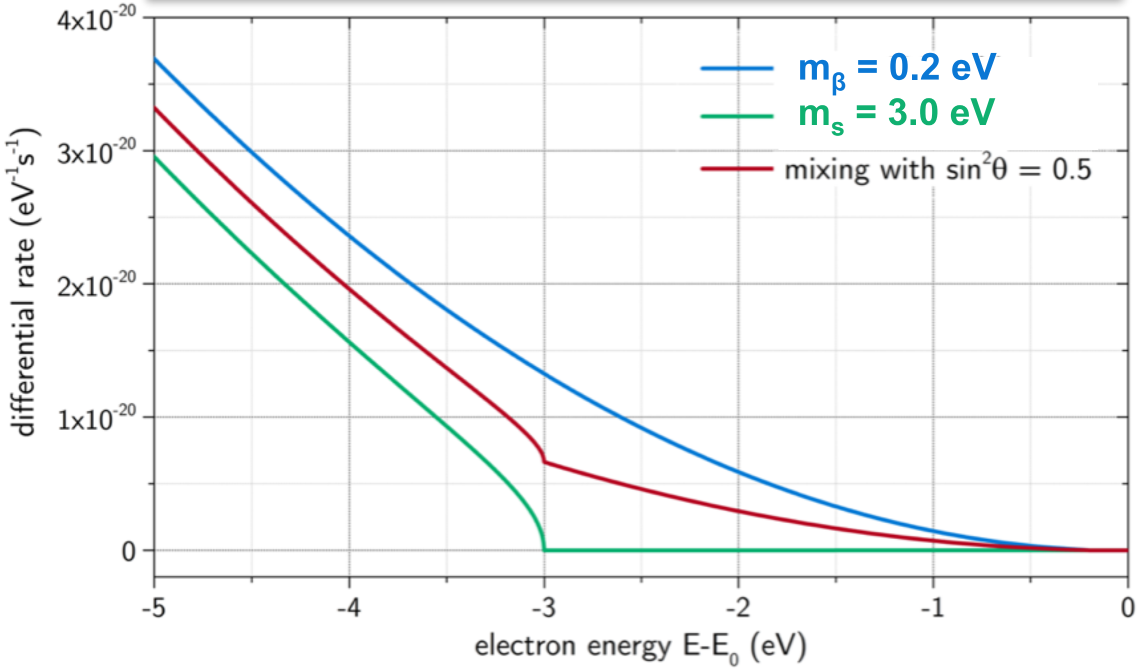
Imprint of sterile neutrinos on β spectrum

$$\frac{d\Gamma}{dE} = \cos^2(\theta_s)\,\frac{d\Gamma}{dE}(m_\beta^2) + \sin^2(\theta_s)\,\frac{d\Gamma}{dE}(m_s^2)$$

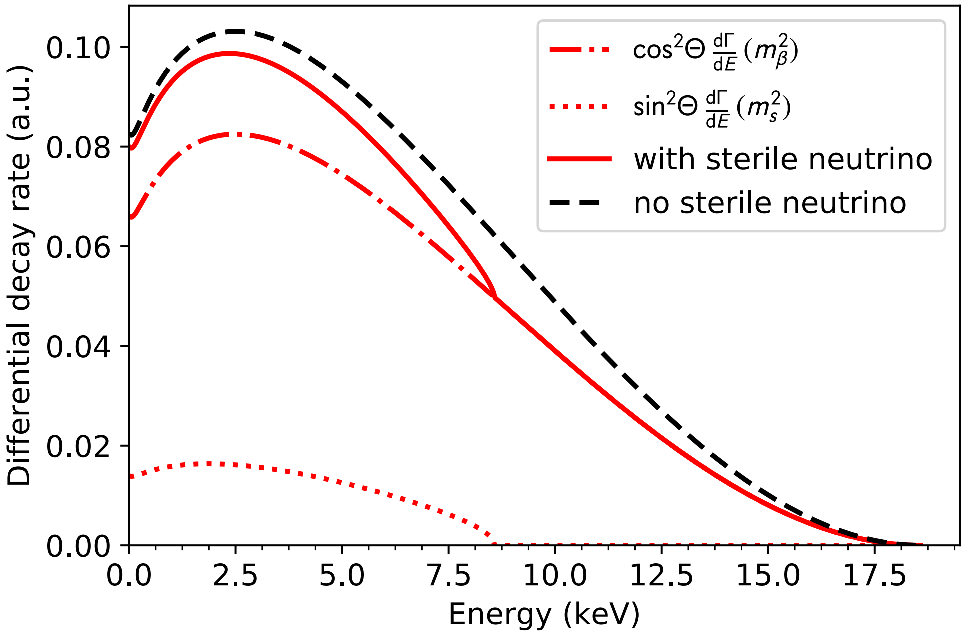


Mixing: sterile ν generates "kink" in β spectrum at $E = E_0 - m_s$

light sterile ν, m_s ~ few eV
motivated by oscillation anomalies



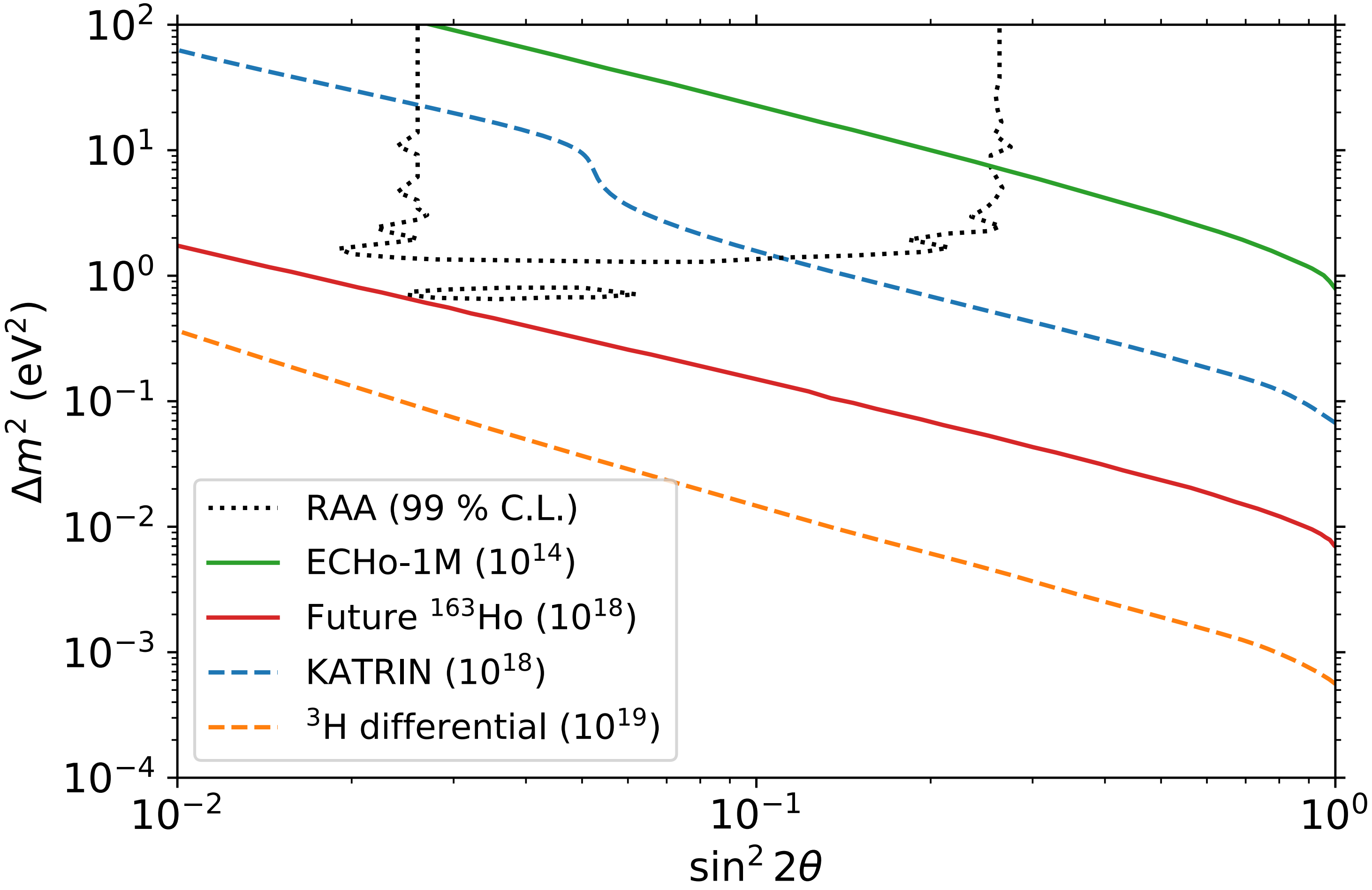
heavy sterile ν, m_s ~ few keV
motivated as DM candidate



Imprint of sterile neutrinos on β spectrum

… close to the **spectral endpoint E_0**:

light sterile neutrinos



Reactor anti-nu anomaly

ECHo-1M experiment

KATRIN experiment

future ^{163}Ho experiment

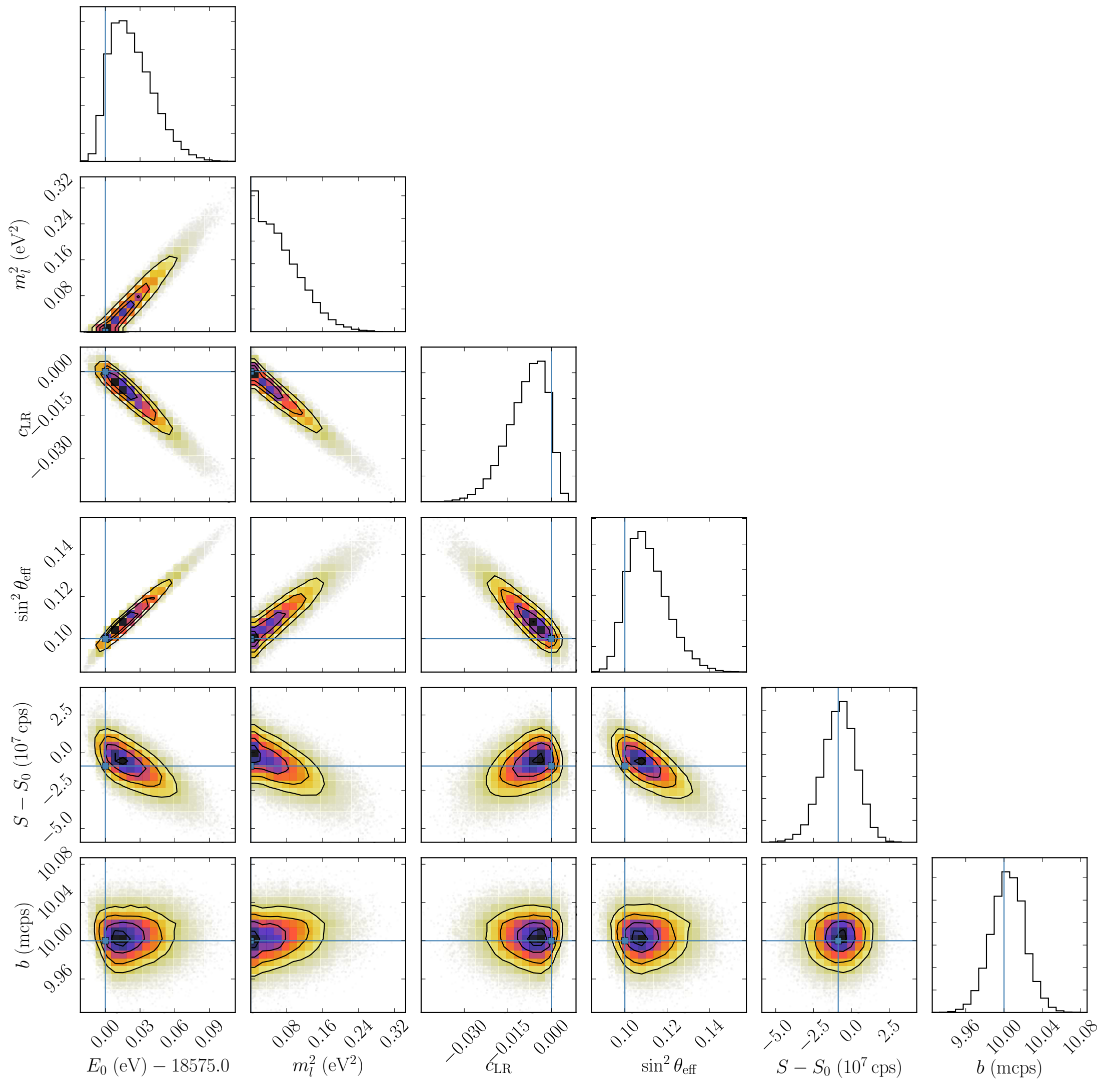
future atomic tritium exp.

[compilation: Böser et al., arXiv:1906.01739]

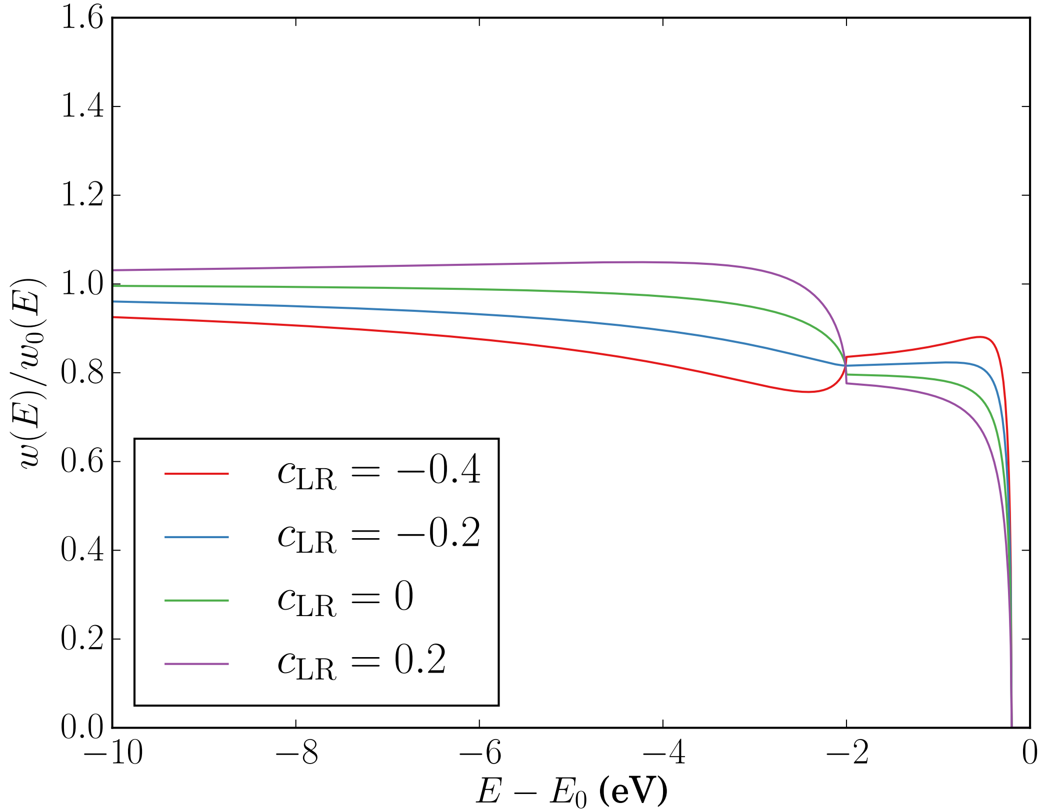
Imprint of sterile neutrinos on β spectrum

light sterile neutrinos
+ novel interactions

… close to the **spectral endpoint E_0**:



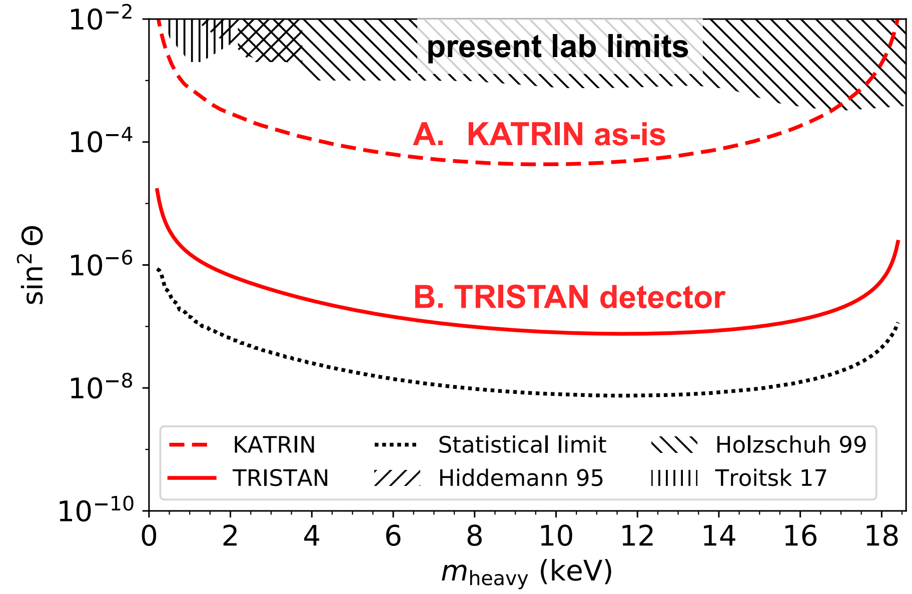
Spectral shape distortion close to E_0 due to interference term in left-right symmetric model



[Steinbrink *et al.*, JCAP 06 (2017) 015]

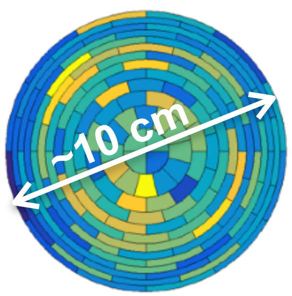
Search for keV-scale sterile ν with TRISTAN at KATRIN

- High count rates at ~few keV below endpoint
- Tiny sterile admixture $\sin^2(\theta_s)$ expected
- Best sensitivity for differential measurement, need energy resolution ~300 eV or better



A. KATRIN Phase-0

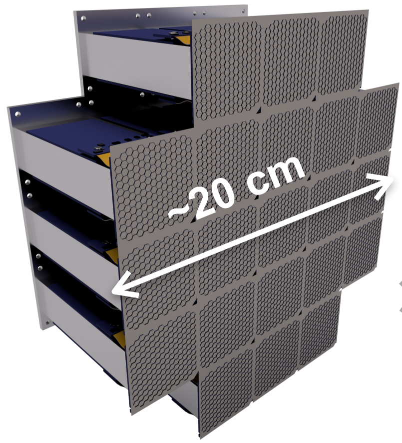
initial ramp-up phase of KATRIN at reduced source strength



148 pixels
KATRIN 2018/19

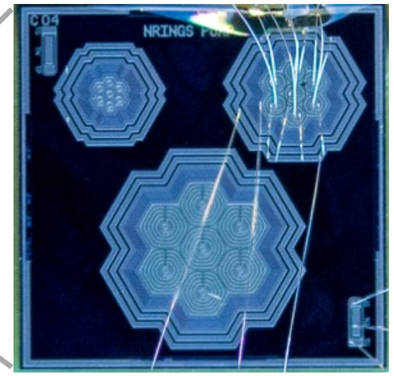
B. TRISTAN project

detector upgrade after completion of 5-year KATRIN running



~ 3500 pixels
KATRIN ca. 2024

7-pixel SDD prototype (MPP/HLL Munich)



166-pix module test at KATRIN in 2019

Concept paper: Mertens et al., J. Phys. G 46 (2019) 065203

➜ Poster by M. Lebert

Summary

- The absolute neutrino mass scale is one of the big open questions in astroparticle physics.
- Complementary sources of information: cosmology, $0\nu\beta\beta$ search, direct kinematic experiments (^{3}H, ^{163}Ho).
- Several experiments have just started and are delivering first results!
- Much larger data sets and refined analyses are expected during the next years. In parallel, new technologies are being developed.
- Bonus: Precision β/EC spectra give access to a broad range of physics topics, e.g. heavy neutrinos at eV and keV scales, exotic weak interactions, …

➜ Stay tuned and/or join us!