Neutrino mass measurements

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Introduction

KATRIN: tritium beta spectroscopy at the endpoint
- possible upgrades of KATRIN

Options beyond KATRIN:
- ^{163}Ho EC cryo bolometers ECHo and HOLMES
- detection of synchrotron radiation from tritium: Project 8

R&D for the future: Ptolemy

Conclusions

Photo: M. Zacher

Searches for neutrino mass

β-decay: absolute ν-mass

model independent, kinematics

status: $m_\nu < 2$ eV

potential: $m_\nu \approx 0.2$ eV

e.g.: KATRIN, ECHO, HOLMES, Project-8, ...

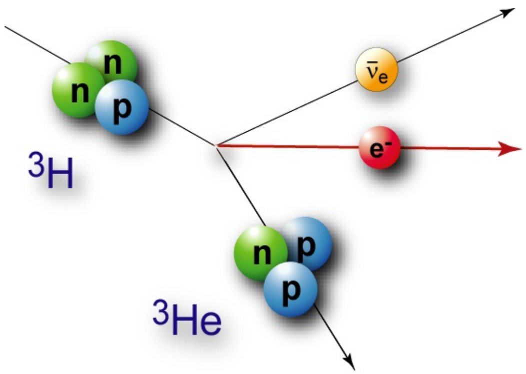
0νββ-decay: eff. Majorana mass

model-dependent (CP-phases)

status: $m_{\beta\beta} < 0.1$ eV

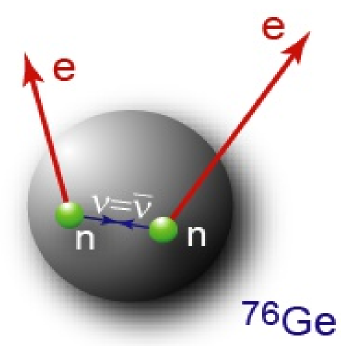
potential: $m_{\beta\beta} \approx$ 20-50 meV

e.g.: GERDA, KamLAND-Zen, CUORE, EXO, Majorana, Nemo 3, ...



neutrino mass measurements

m_ν | $m_{\beta\beta}$ | Σm_i

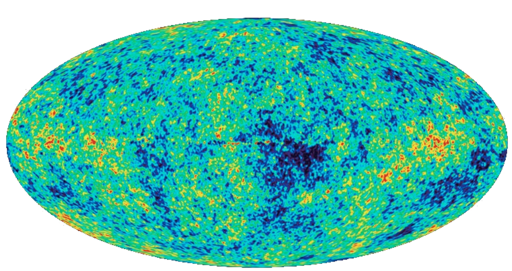


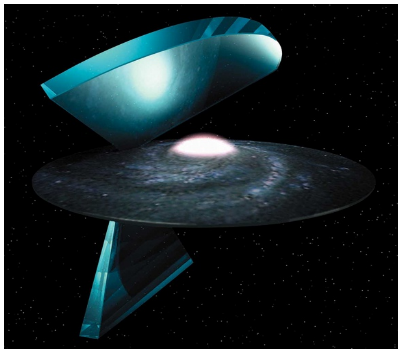
cosmology: ν hot dark matter Ω_ν

model dependent, analysis of CMB and structure formation data

status: $\Sigma m_\nu < 0.23$ eV

(Planck Collaboration, A&A 594 (2016) A13)





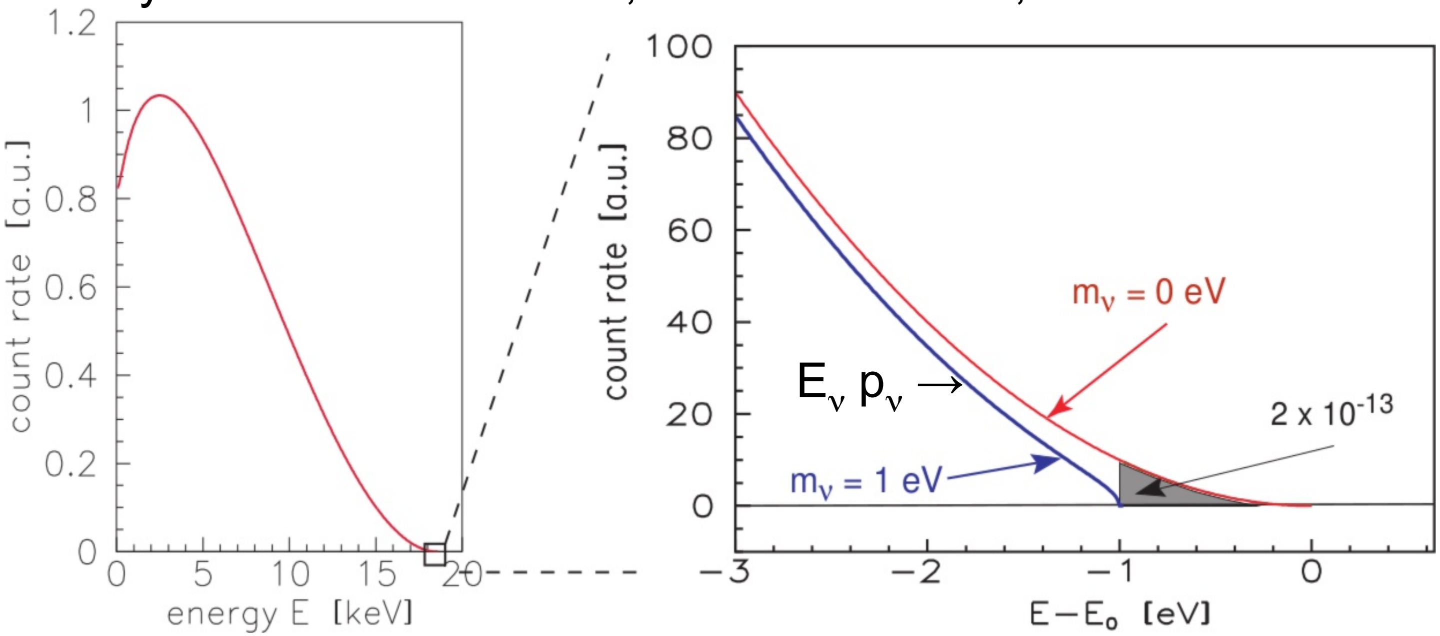
Direct determination of "$m(\nu_e)$" from β-decay (and EC)

β: $dN/dE = K\ F(E,Z)\ \underbrace{p}_{p_e}\ \underbrace{E_{tot}}_{E_e}\ \underbrace{(E_0-E_e)}_{E_\nu}\ \underbrace{\Sigma\,|U_{ei}|^2\sqrt{(E_0-E_e)^2 - m(\nu_i)^2}}_{p_\nu}$

essentially phase space: p_e E_e E_ν p_ν

with "electron neutrino mass": **"$m(\nu_e)^2$":=** $\Sigma\,|U_{ei}|^2$ **$m(\nu_i)^2$**, complementary to $0\nu\beta\beta$ & cosmol.

(modified by electronic final states, recoil corrections, radiative corrections)



Need: low endpoint energy ⇒ **Tritium ^{3}H (^{163}Ho)**

very high energy resolution &
very high luminosity &
very low background

⇒ **MAC-E-Filter (or cryobolometer for ^{163}Ho)**

The KATRIN experiment at Karlsruhe Institute of Technology

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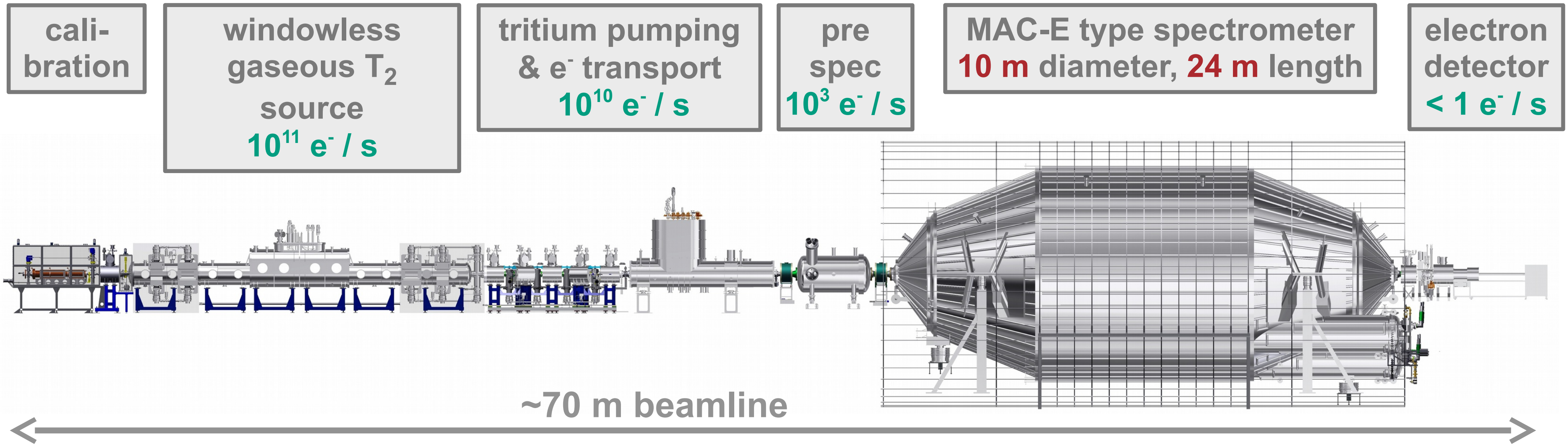


Basic ideas of KATRIN:

- Windowless gaseous molecular tritium source

→ ultra-high luminosity and small systematics

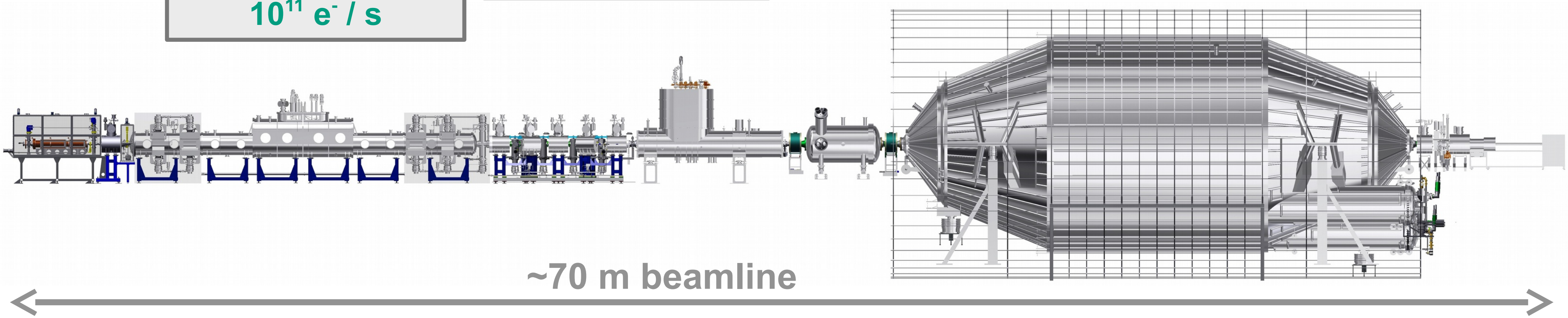
- Huge spectrometer of MAC-E-Filter type

→ ultra-high energy resolution

Sensitivity on m(ν_e):
2 eV → 200 meV

The KATRIN experiment at Karlsruhe Institute of Technology

cali-bration	windowless gaseous T_2 source 10^{11} e⁻ / s	tritium pumping & e⁻ transport 10^{10} e⁻ / s	pre spec 10^3 e⁻ / s	MAC-E type spectrometer 10 m diameter, 24 m length	electron detector < 1 e⁻ / s

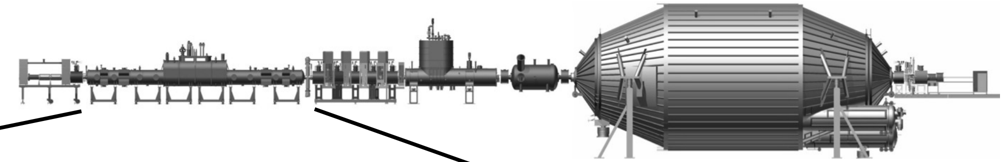


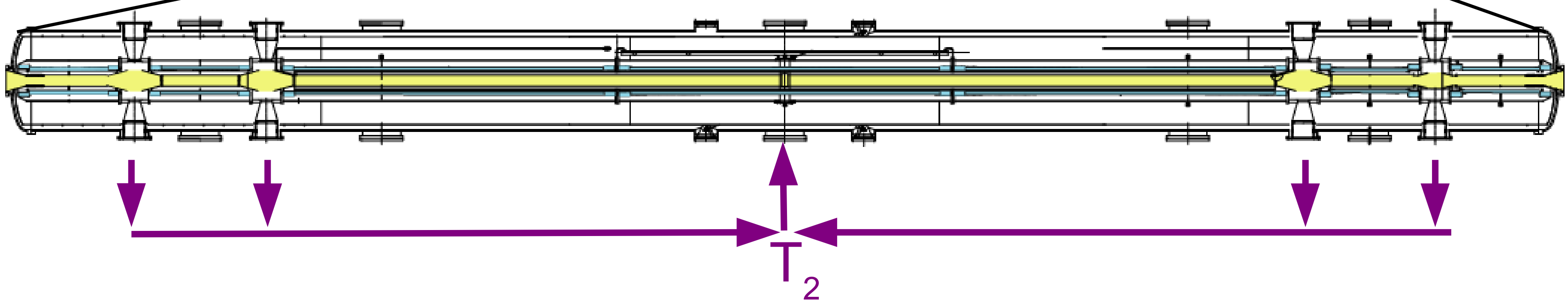
Windowless Gaseous Molecular Tritium Source WGTS

per mill stability source strength request:

$dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p \;\; V / R \, T$

tritium fraction f_T & ideal gas law





WGTS:

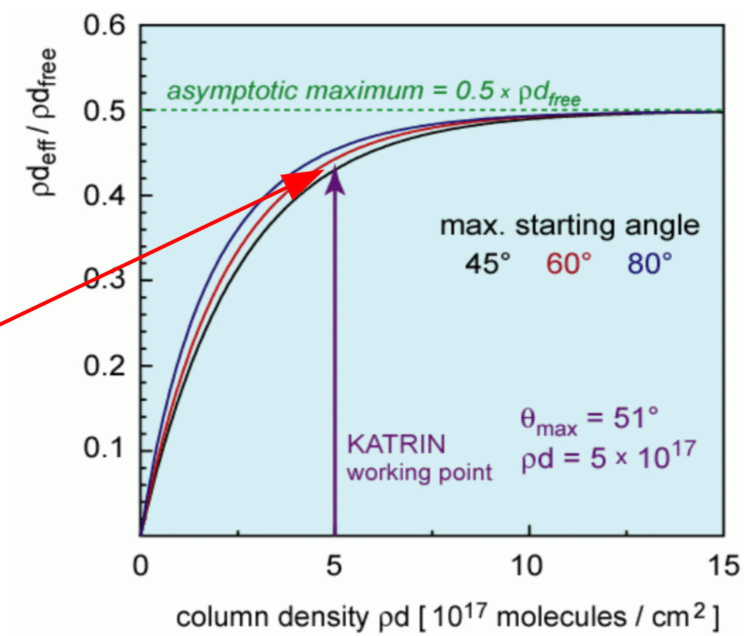
tube in long superconducting solenoids
⊘ 9cm, length: 10m, T = (30 ± 0.03) K

Tritium recirculation (and purification)
p_{inj} = (3 ± 0.003) μbar, q_{inj} = 4.7Ci/s

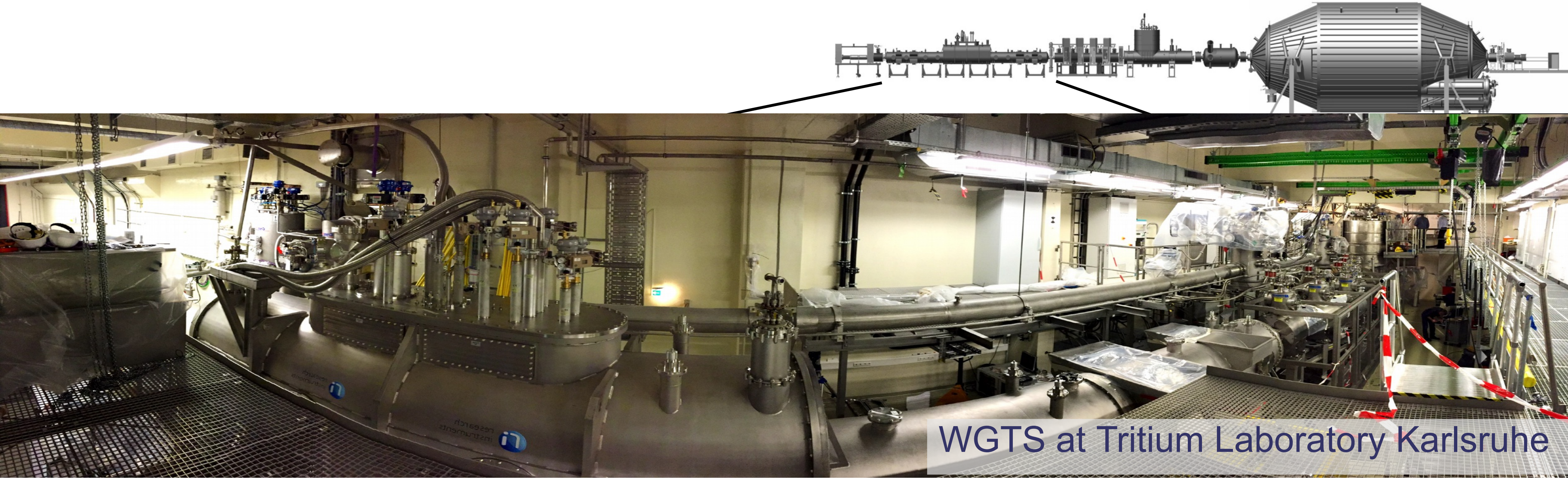
T_2 purity f_T by laser Raman spectr.

→ $\rho d = 5 \cdot 10^{17}/cm^2$
measure with near to maximum count rate with small systematics

check column density by e-gun



Windowless Gaseous Molecular Tritium Source WGTS



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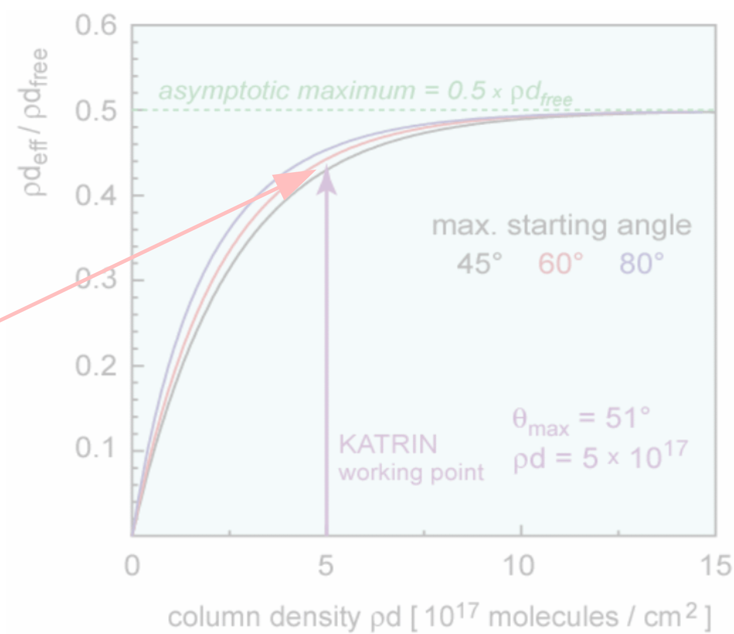
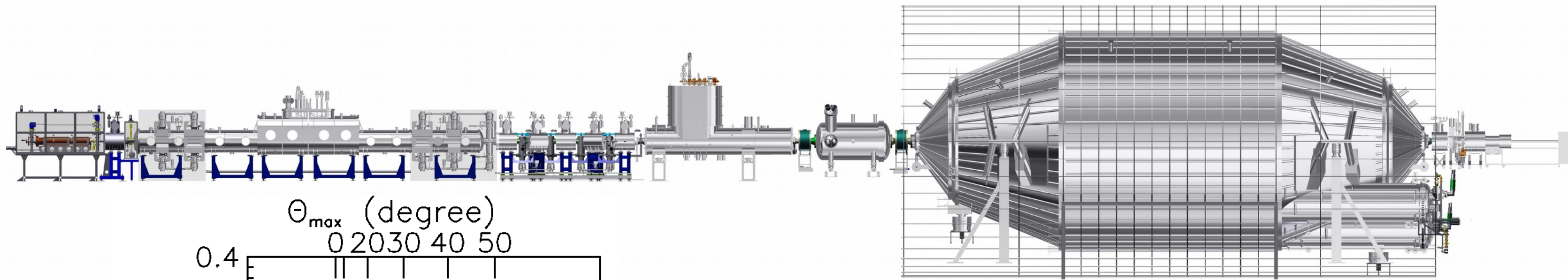
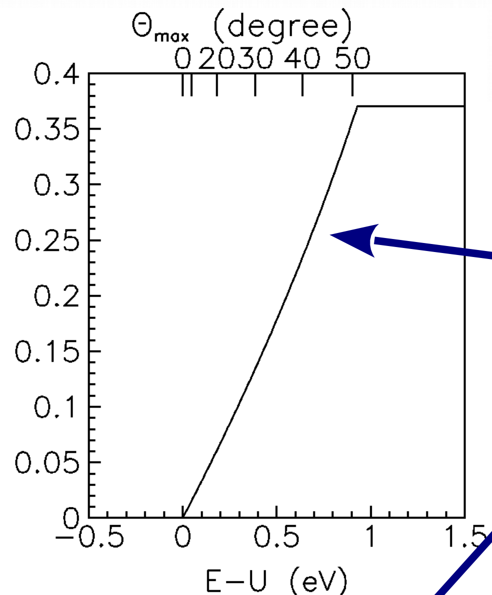


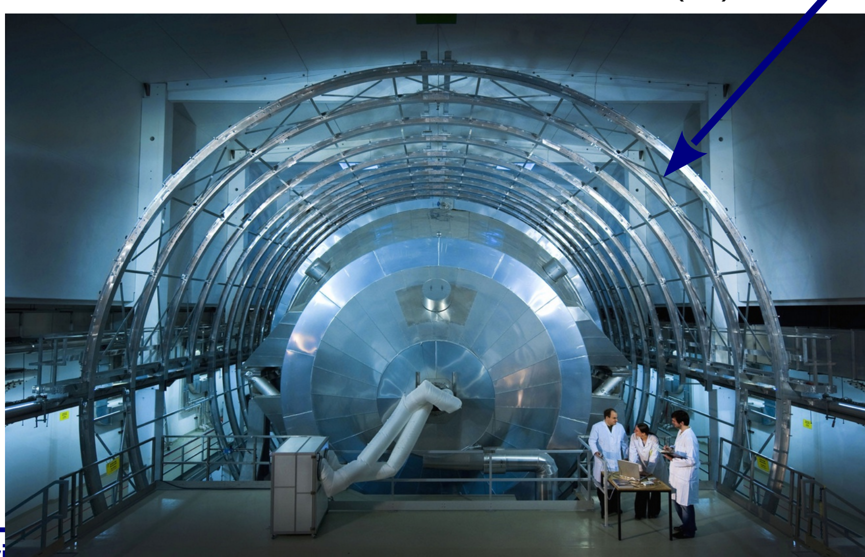
The KATRIN Main Spectrometer: an integrating high resolution MAC-E-Filter



Integral transmission function:
$\Delta E = E \cdot B_{min}/B_{max}$ = 0.93 eV



- 18.6 kV retardation voltage, σ < 60 meV/years
- Energy resolution (0% → 100% transmission): 0.93 eV
- Ultra-high vacuum, pressure < 10^{-11} mbar
- Air coils for earth magnetic field compensation
- Double layer wire electrode for background reduction and field shaping



Focal Plane Detector

Focal plane detection system

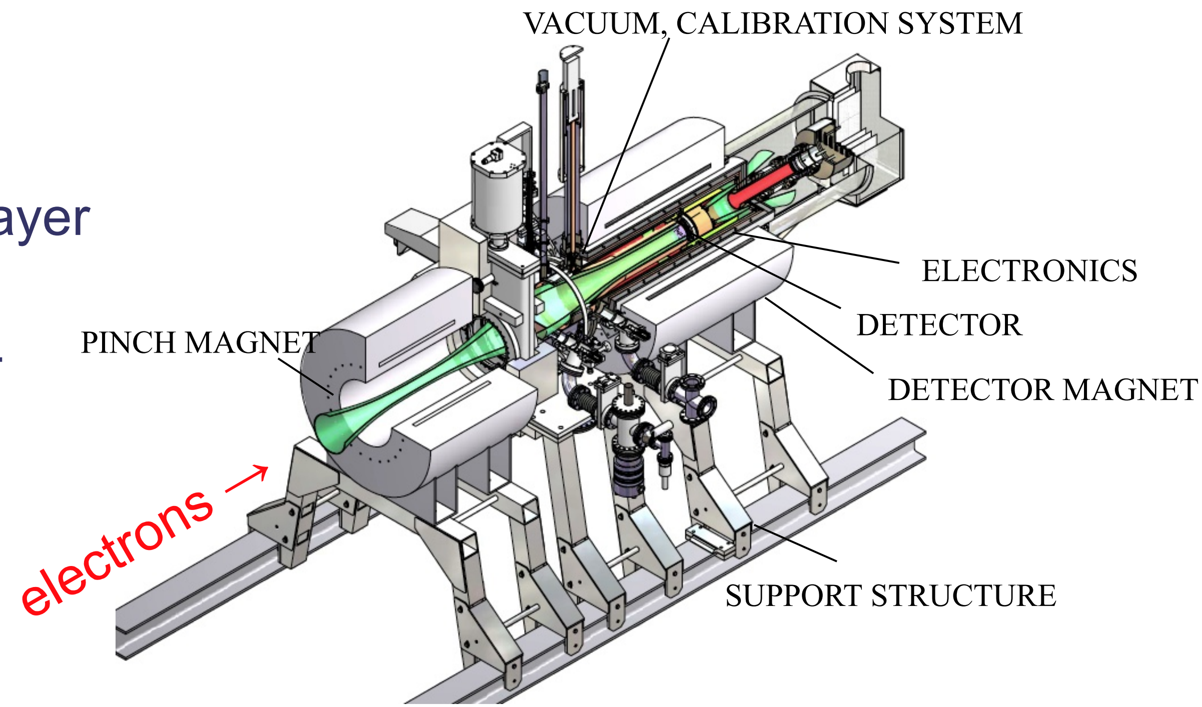
segmented Si PIN diode:
90 mm Ø, 148 pixels, 50 nm dead layer

energy resolution ≈ 1 keV

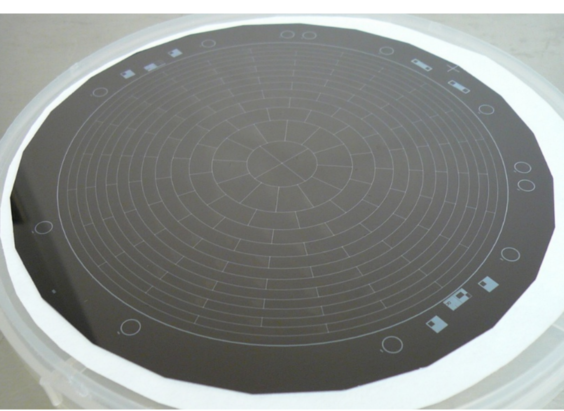
pinch and detector magnets up to 6 T

post acceleration (10kV)

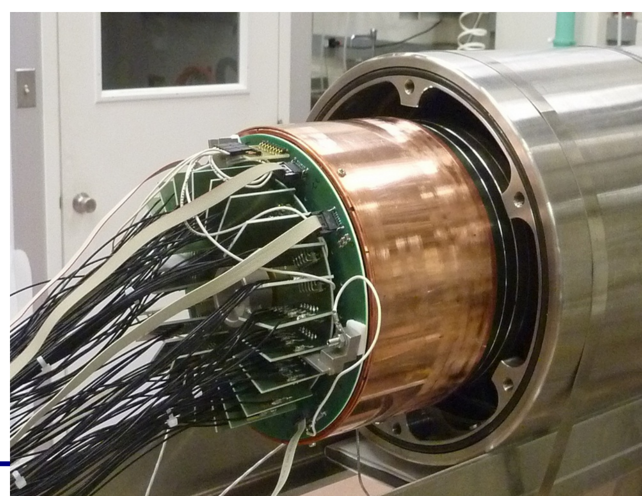
active veto shield



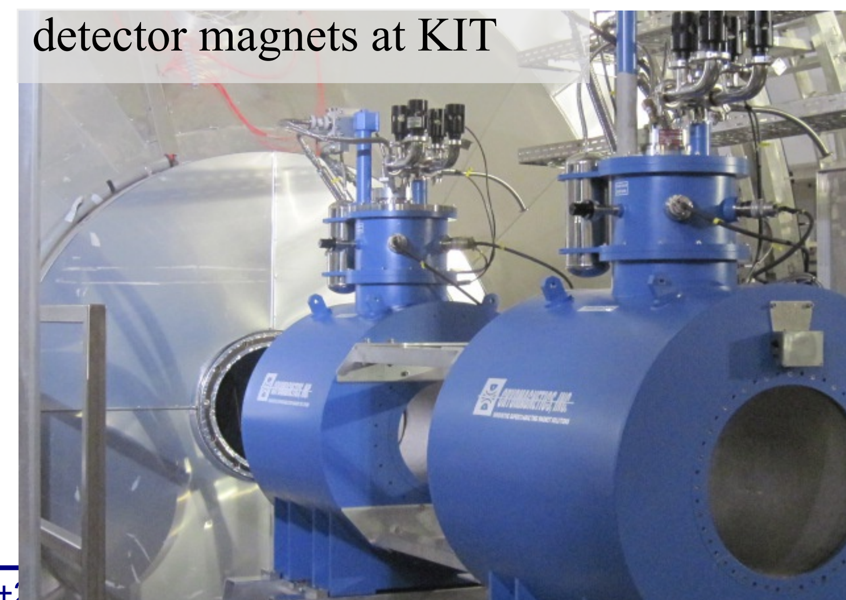
segmented Si-PIN wafer



pre-amplifier wheel

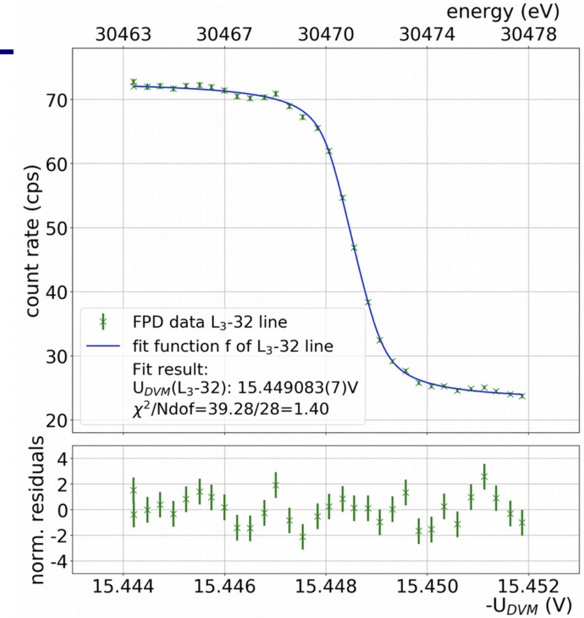


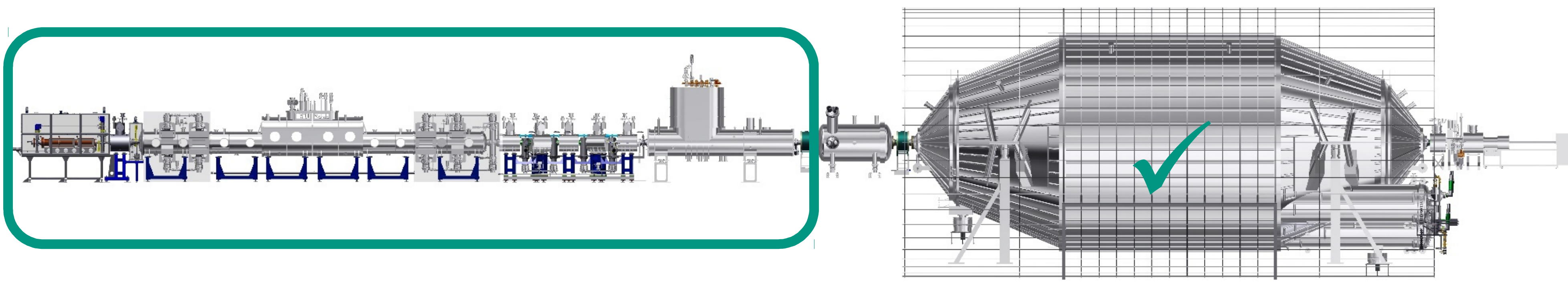
detector magnets at KIT



Status of KATRIN before May/June 2018

- KATRIN will investigate $m(\nu_e)$ with 200 meV sensitivity by employing
  - a high-resolution MAC-E filter with < 1 eV energy resolution (e.g. M. Arenz et al., EPJ C 78 (2018) 368)
  - and an ultra-stable high-luminosity windowless gaseous molecular tritium source





Inner loop buffer vessel pressure	WGTS Temperature	Gas composition	Source activity
Active regulation Stability <0.05%	**Two-phase Ne cooling** Stability <1.5mK/h @ 30 K	**Raman spectroscopy** Precison <0.1% in 20 s	**Not yet demonstrated**
Priester et al. Vacuum 116 (2015) 42	*Grohmann et al. Cryogenics 55-56, (2013) 5*	*M. Schlösser et al. J. Mol. Struct. 1044, 24 (2013) 61*	

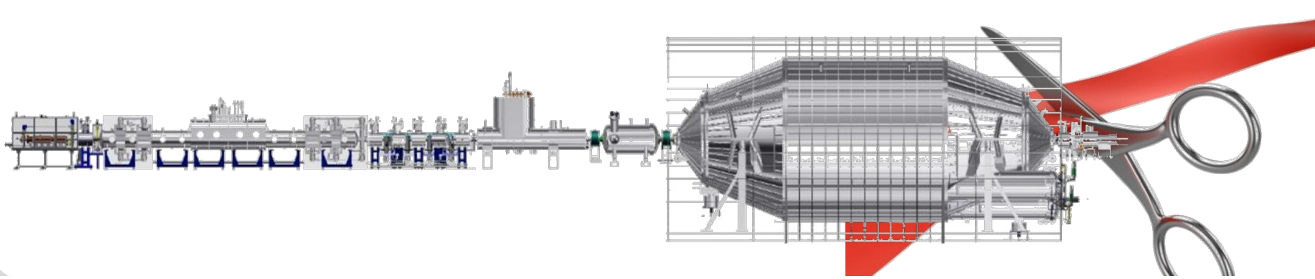
May/June 2018: KATRIN inauguration & first tritium campaign (commissioning)

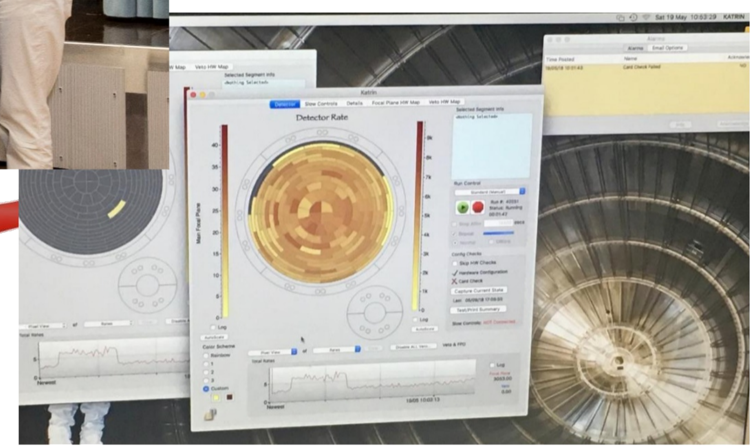
Motivation:

method: inject known gas mix from prepared cylinders (80% of nominal ρd, ~1% DT and ~99% D_2 corresponds to <1% of nominal activity ≈ 500 MBq)

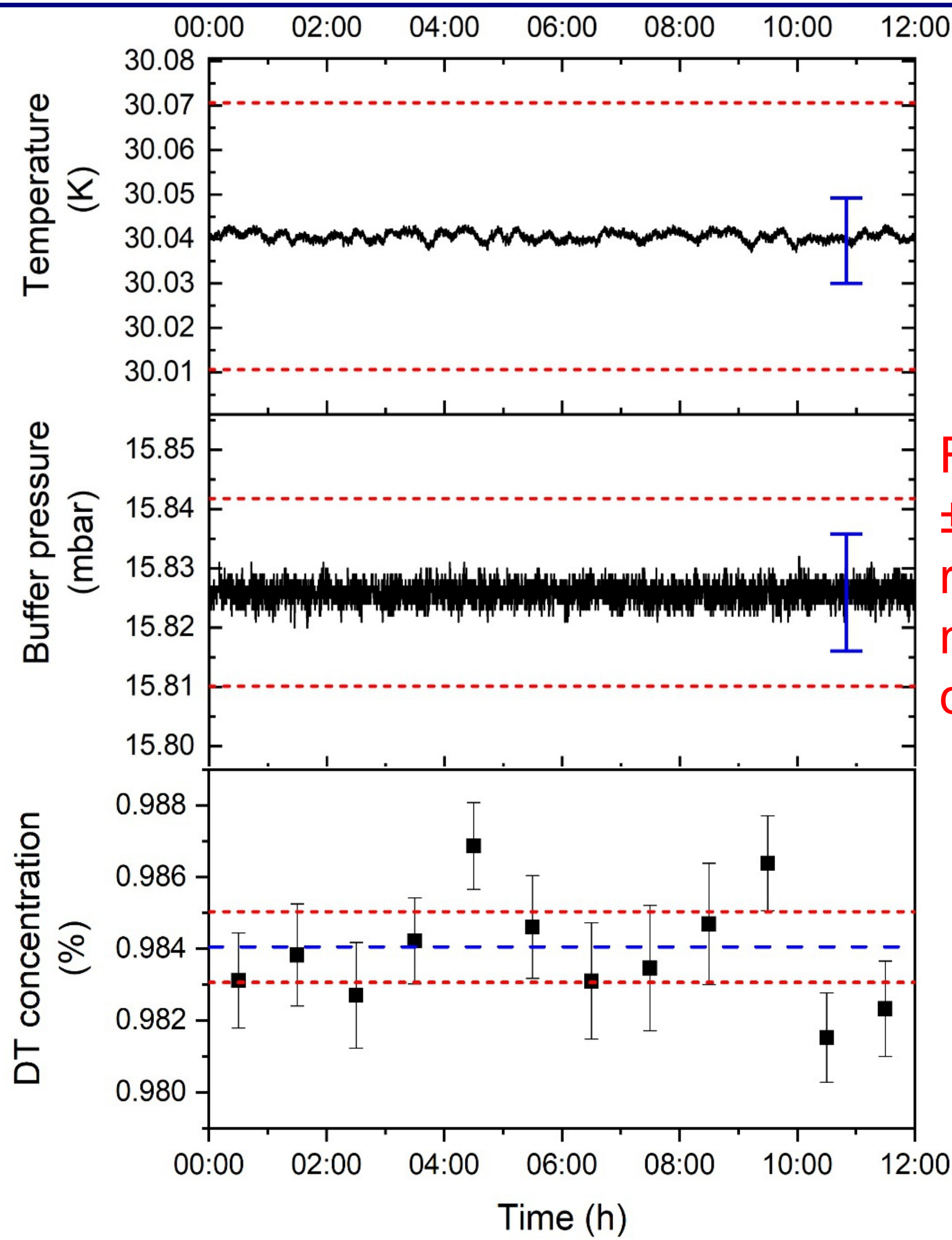
verify functionality of all system components and demonstrate 0.1% global stability

study beta spectrum for systematic effects and test analysis strategies





First tritium campaign: Stability of source parameters during 12 h

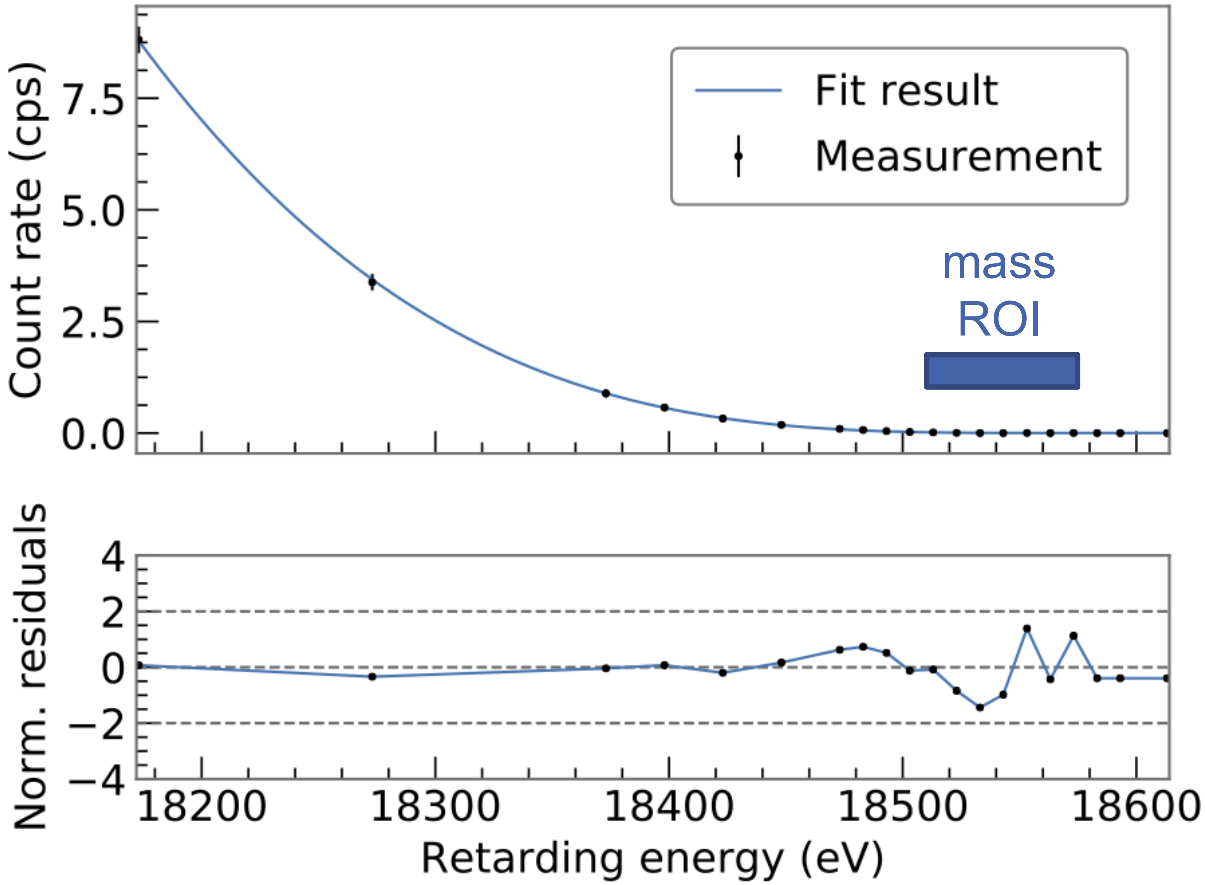


Blue arrow: systematic uncertainty

Red dashed line: ± 0.1 % stability required for neutrino mass data taking

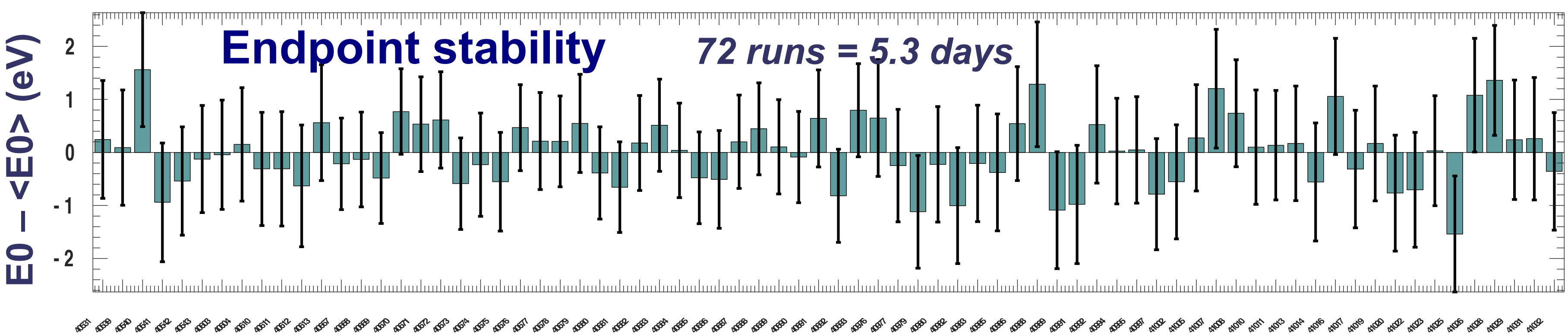
→ source parameters were proven to be stable and within the specifications

Tritium spectrum fit (example)



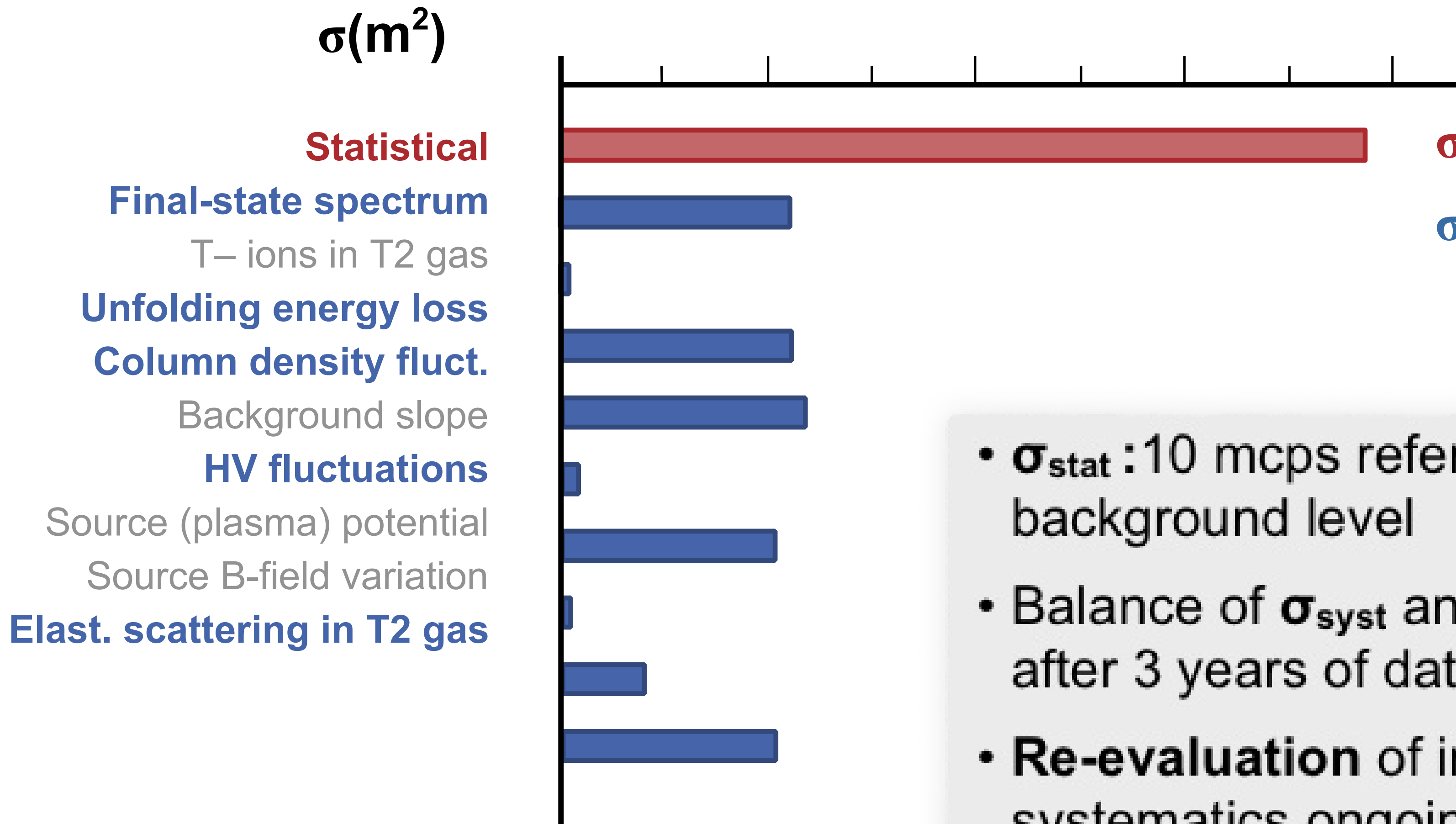
- **Single run (3h), analysis of single detector pixel**
- **ROI extended to 400 eV**
- **Statistics only**

→ very good agreement between data and fit (shape and estimated absolute rate!) & very stable



Statistical & systematic uncertainties

KATRIN's uncertainty budget (design sensitivity, ~2004):



$\sigma(m^2)_{stat} = 0.018\ eV^2$

$\sigma(m^2)_{syst} = 0.017\ eV^2$

- σ_{stat} : 10 mcps reference background level
- Balance of σ_{syst} and total σ_{stat} after 3 years of data
- **Re-evaluation** of individual systematics ongoing during system characterisation

Statistical & systematic uncertainties

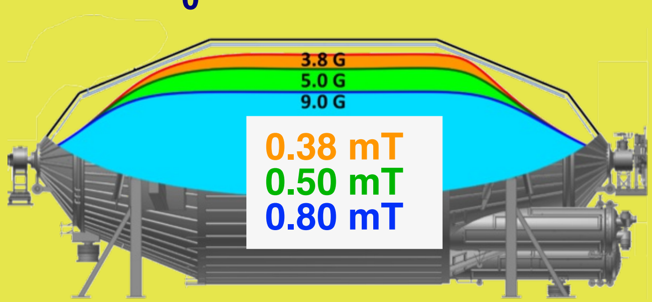
3 yr of data taking

sensitivity on the neutrino mass (stat.+sys. uncertainties):

→ 200 meV (design value)

Higher (Rydberg) background rate

→ using larger data range (E_0-60 eV) and a bit less energy res.:



→ 240 meV (without further mitigation of the Rydberg background)

„Science“ data taking 2019 – 2023

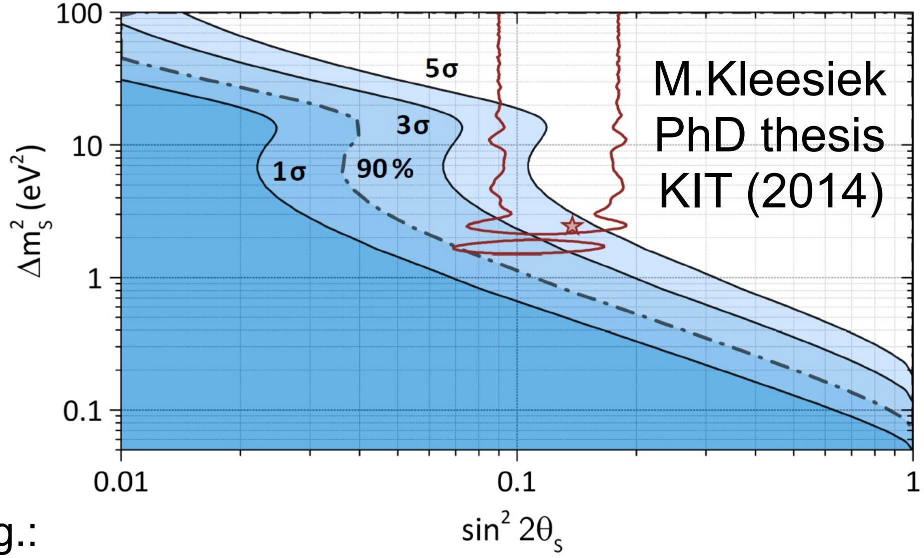
and hopefully beyond with upgrades

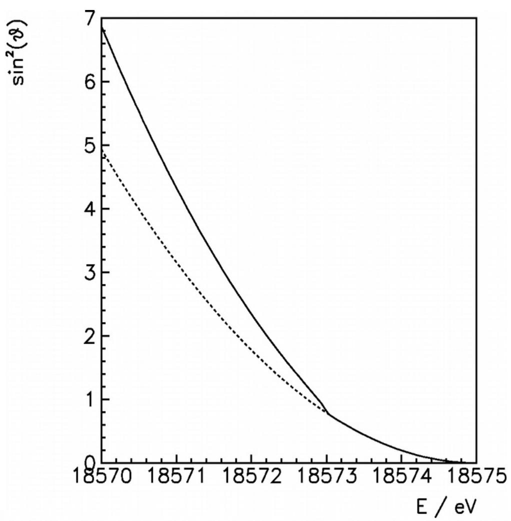
KATRIN will measure an ultra-precise β-spectrum → search for physics beyond the SM

Sterile neutrinos

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \left(\cos^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_{1,2,3})^2} + \sin^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_4)^2}\right)$$

eV ν:

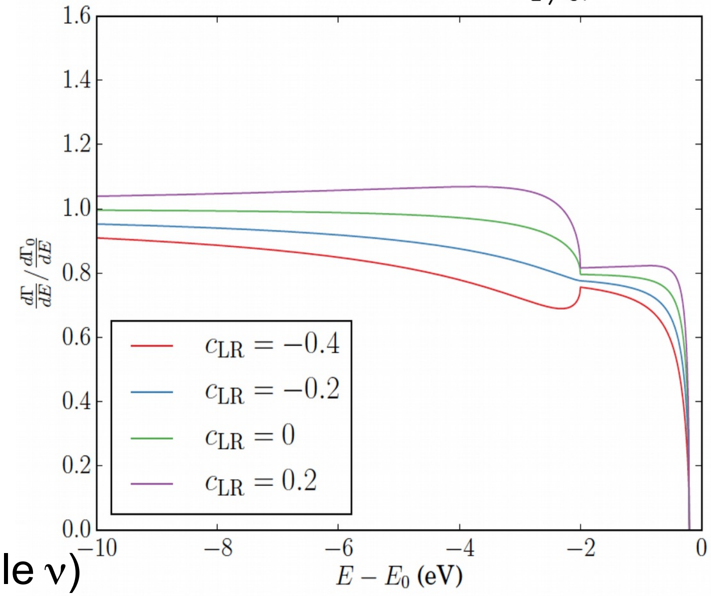




see e.g.:
J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

keV ν:

see e.g.
S. Mertens et al., JCAP 02 (2015) 020
M. Drewes et al. JCAP 01 (2017) 025



non SM currents, ...

see e.g.: N. Steinbrink et al., JCAP 6 (2017) 15 (RH currents & sterile ν)

Sterile neutrino search with KATRIN: upgrading detector by the project TRISTAN

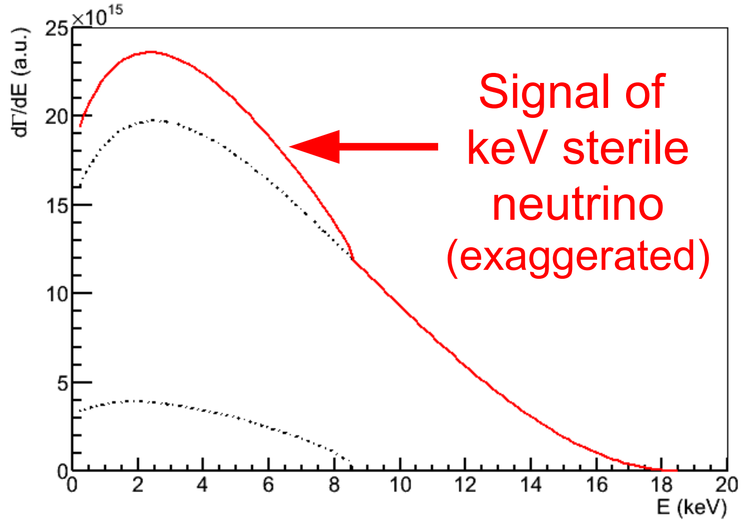
Extension of KATRIN to search for eV – keV sterile neutrinos

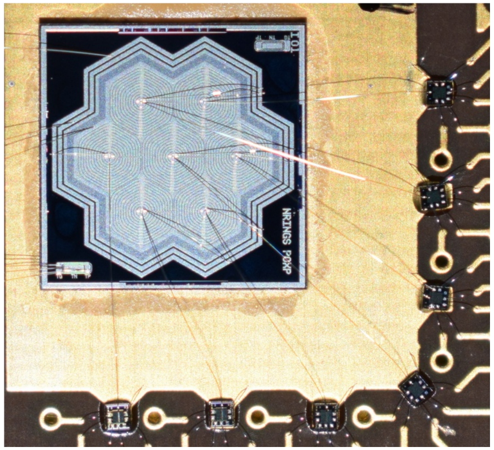
Tiny, but characteristic signal further away from the endpoint

Challenge:
ppm sensitivity needed (high statistics, small systematics)
→ New detector system!

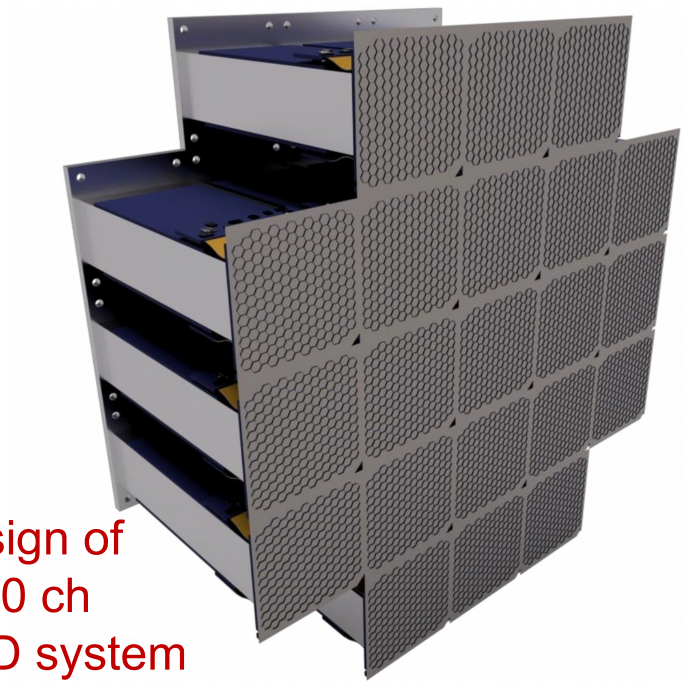
R&D of multi-pixel Silicon Drift Detector (SDD) system ongoing

Excellent performance demonstrated with prototype detector system





7 pixel TRISTAN prototype

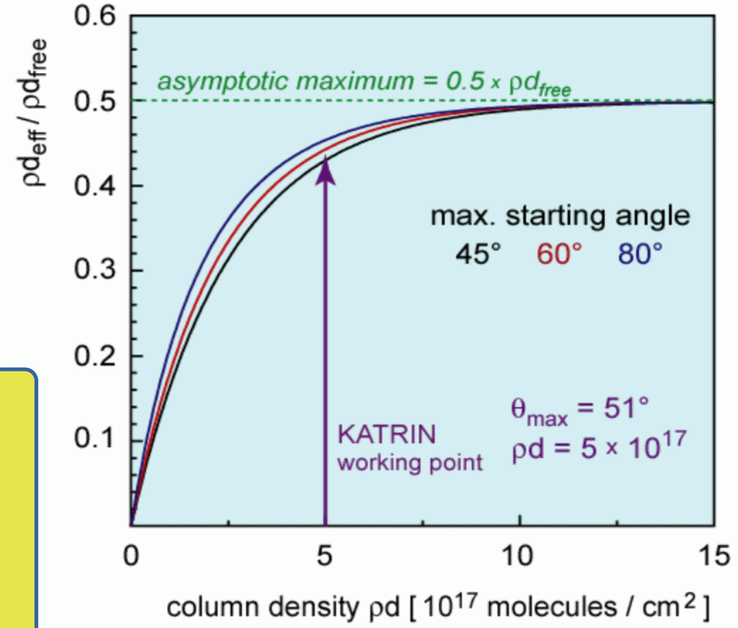


Design of 3500 ch SDD system

S. Mertens, T. Lasserre *et. al.* Phys.Rev. D91 (2015) 4, 042005
S. Mertens, K. Dolde, M. Korzeczek, *et al.* JCAP 1502 (2015) 02, 020
K. Dolde, S.Mertens, D. Radford et. al. NIM-A 848 (2017)
M. Drewes *et. al.*, JCAP 1701 (2017) no.01, 025
A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens, O. Ruchayskiy, arXiv:1807.07938
S. Mertens, et al.: arXiv:1810.06711 [physics.ins-det] (2018)

KATRIN's sensitivity of 200 meV might not be enough
Can we go beyond or improve KATRIN ?

Problem: The KATRIN source is already opaque
→ need to increase size transversally
magnetic flux tube conservation
requests larger spectrometer too
but a Ø100m spectrometer is not feasible

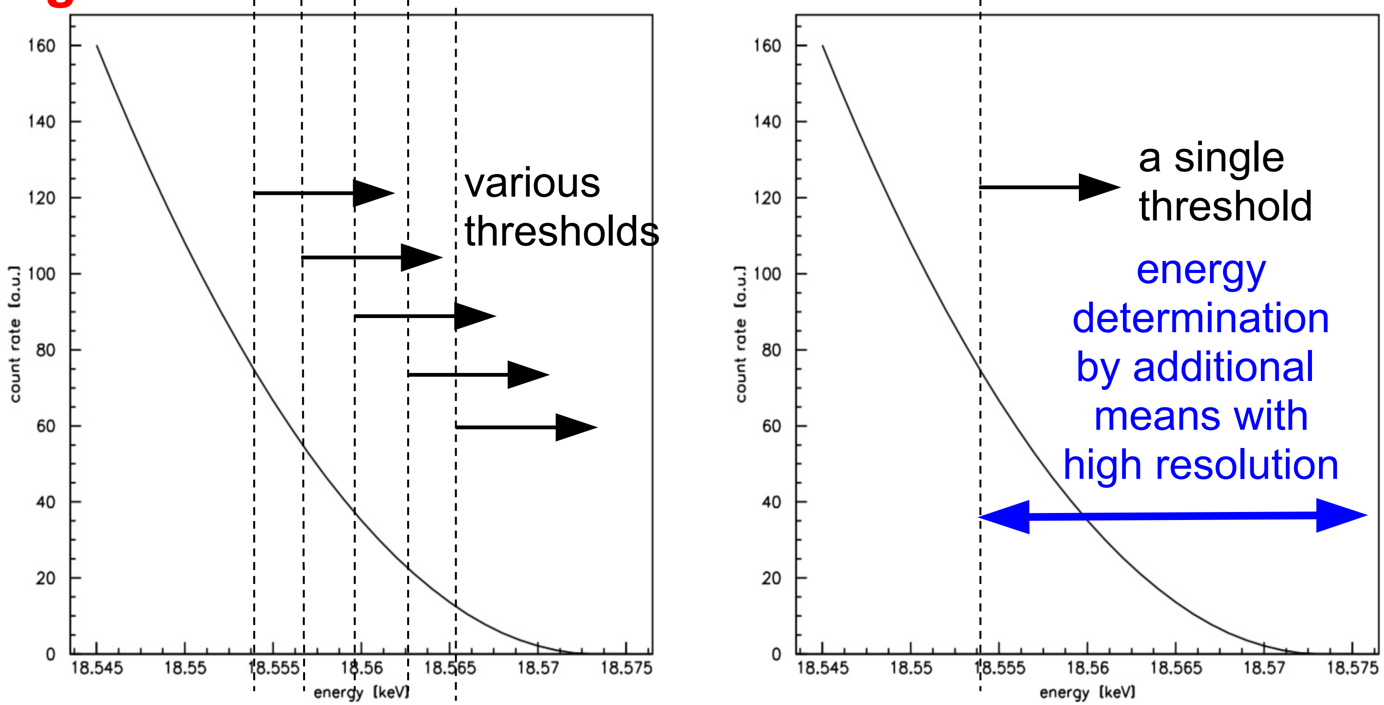


Possible ways out:

a) make better use of the electrons by differential measurement (e.g. cryo bolometer array or TOF) additional to integral threshold:
→ measure all retarding voltage settings at once
additional benefit: possible background reduction

Gain of additional differential method
avoiding loss of statistics by many filter settings

Integral MAC-E-Filter method | **add. differential measurement**



need many retardation voltages, about 40 different settings, to obtain spectral information

need one retardation voltage to limit count rate and use other means, e.g. high-res. detector to obtain spectral information

→ Differential method: expect naively statistical improvement in m_ν^2 of up to a factor $\sqrt{40}$ w.r.t. standard KATRIN,

i.e. up to a factor of 2.5 in m_ν w.r.t. standard KATRIN !

→ KATRIN could reach < 100 meV with such a method

Numbers are in agreement with simulations in dipl. thesis of A. Mertens, KIT, 2012

Possible ways for an add. differential method at KATRIN

1) Cryo bolometer detector array

Problem: In the KATRIN setup the electons are guided and adiabatically collimated by axial magnetic fields with conserved magnetic flux: 134 Tcm^2 (70% of KATRIN default magnetic fields)

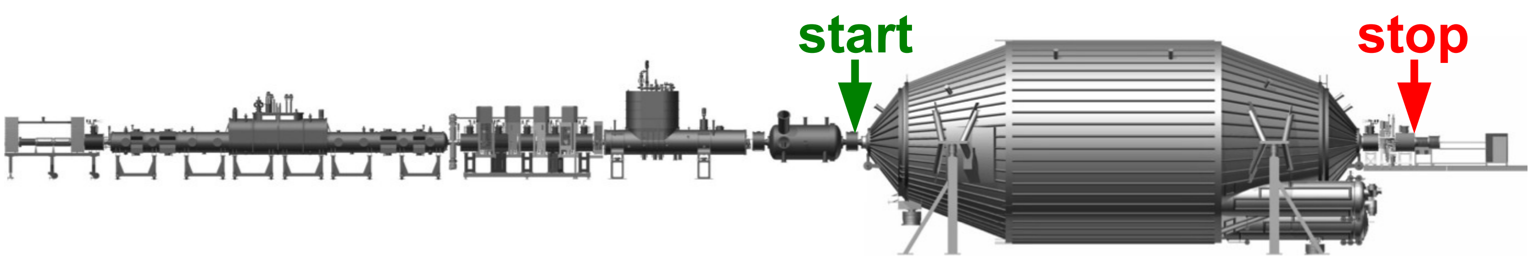
→ Tesla magnetic fields at cryo-bolometer array

Is there a cryo bolometer technology compatible with this?

Or can we separate magnetically the electron absorber from the temperature read-out?

2) Measurement of time of flight

Works in principle since electrons are strongly retarded by the MAC-E-Filter, please see *N. Steinbrink et al., NJP 15 (2013) 113020*



Problem: Can we build an electron tagger to measure the time of start with only little disturbance?

There are some ideas, which are not excluded by first principles ..

Bonus of any differential method: could significantly lower background !

KATRIN's sensitivity of 200 meV might not be enough
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magnetic flux tube conservation
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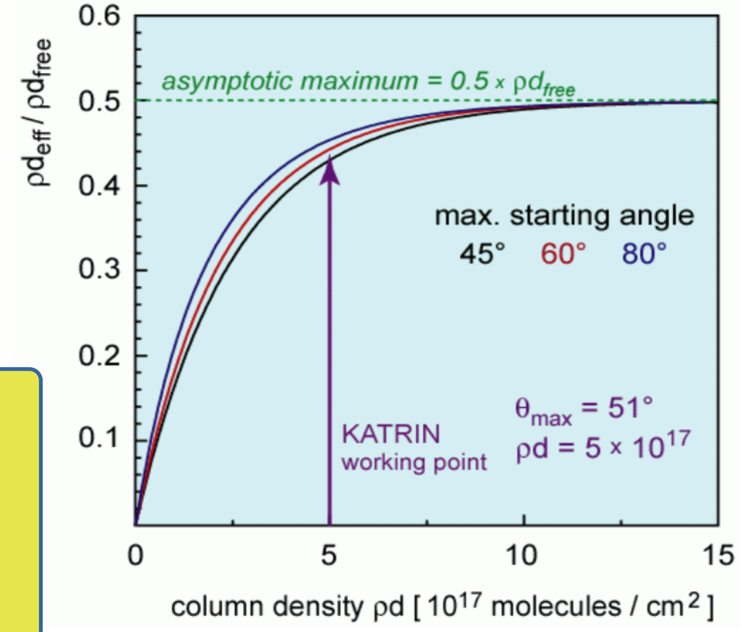


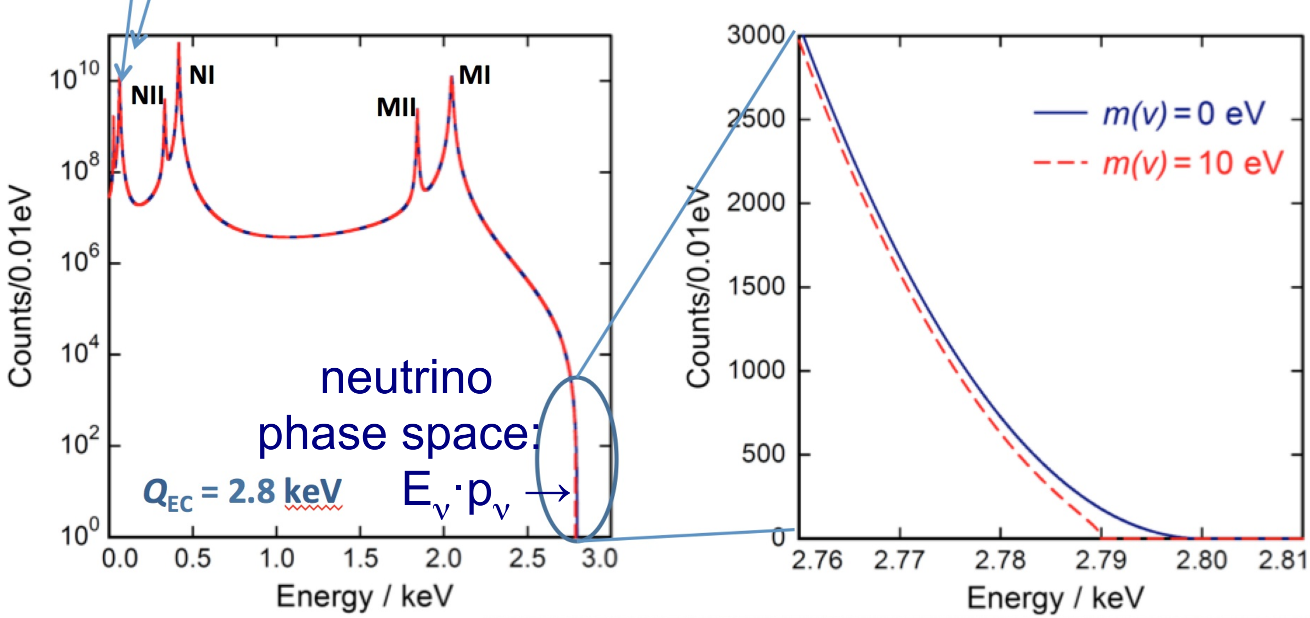
Possible ways out:

a) make better use of the electrons by differential measurement (e.g. cryo bolometer array or TOF) additional to integral threshold:
→ measure all retarding voltage settings at once
additional benefit: possible background reduction

b) source inside detector (compare to $0\nu\beta\beta$)
using cryogenic bolometers (ECHo, HOLMES, ..)

Direct ~~anti~~ neutrino mass measurement from ^{163}Ho electron capture: ECHo, HOLMES

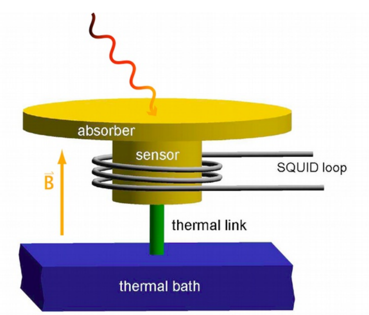
$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e \rightarrow {}^{163}\mathrm{Dy} + \gamma/e^- + \nu_e$$



^{163}Ho source inside cryo calorimeter → determine ΔE by temp change ΔT:

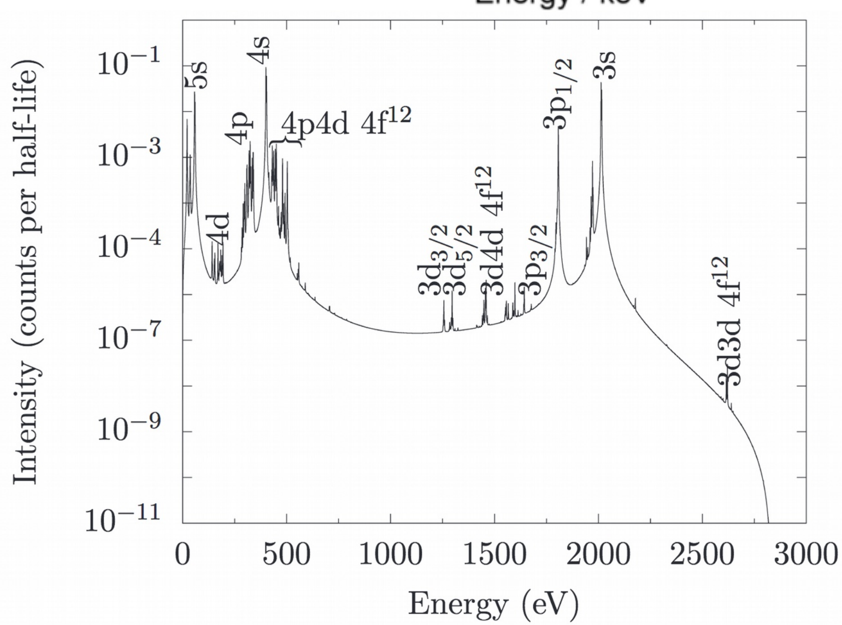
$\Delta T = \Delta E / C,\ C \propto T^3$

ECHo:
metallic magnetic calorimeters: change of magnetic properties

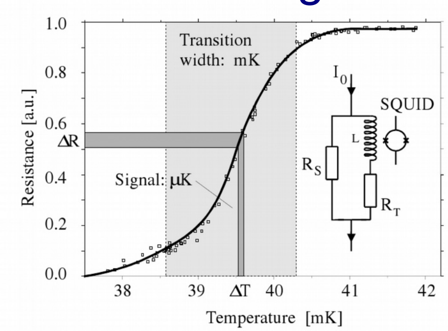


New ab initio spectral calculation: M. Braß et al., PRC **97** (2018) 054620

→ much better agreement with experimental data from ECHo



HOLMES:
sc. transition edge sensors



Direct ~~anti~~ neutrino mass measurement from ^{163}Ho electron capture: ECHo, HOLMES

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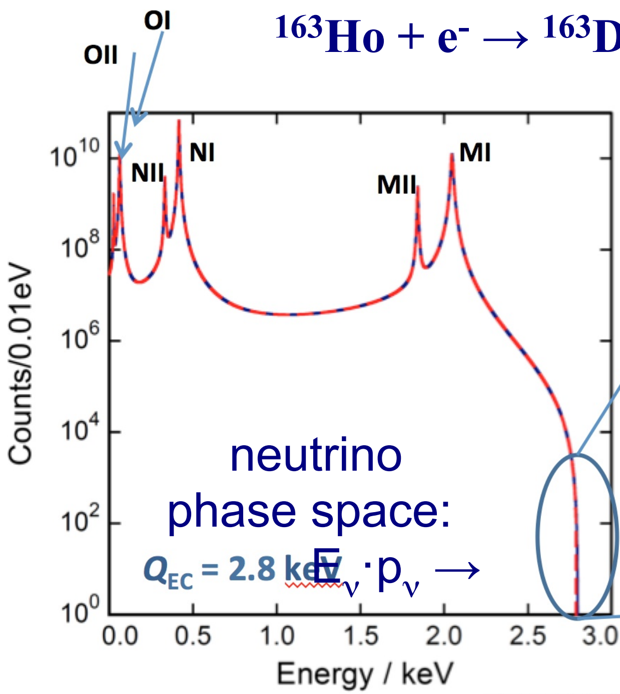
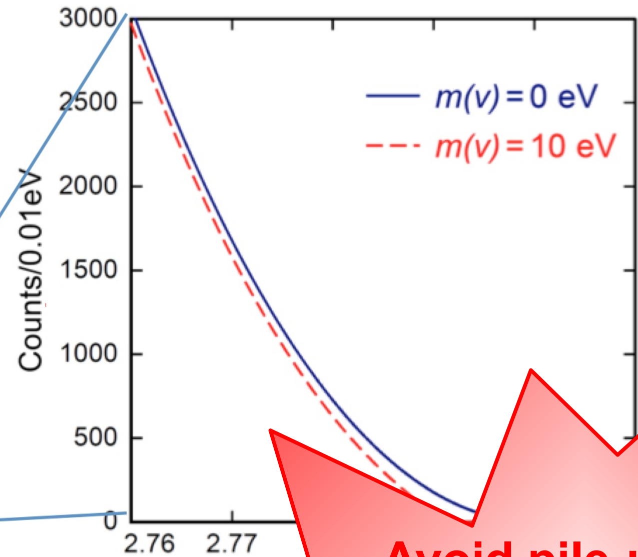
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e \rightarrow {}^{163}Dy + \gamma/e^- + \nu_e$



neutrino phase space: $E_\nu \cdot p_\nu \rightarrow$

Q_{EC} = 2.8 keV



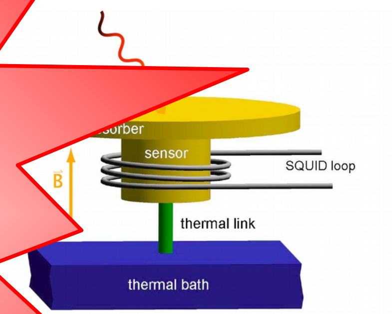
^{163}Ho source inside cryo calorimeter
→ determine ΔE
by temp change ΔE:

$\Delta T = \Delta E / C, \; C \propto T^3$

Avoid pile-up
→ require
O(10000) channels

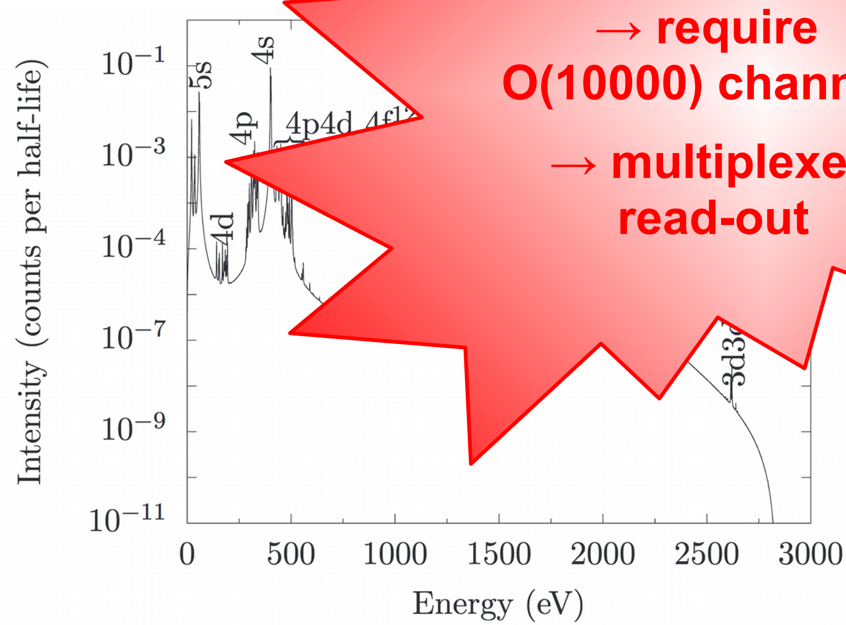
→ multiplexed
read-out

ECHo:
etallic magnetic calorimeters:
hange of magnetic properties

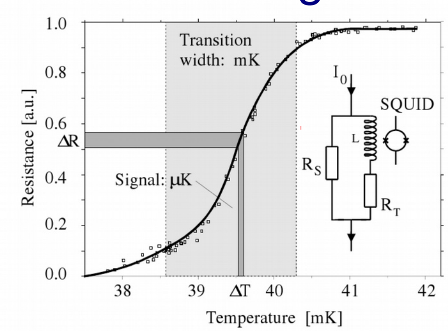


New ab initio spectral calculation:
M. Braß et al.,
PRC **97** (2018) 054620

→ much better agreement with experimental data from ECHo

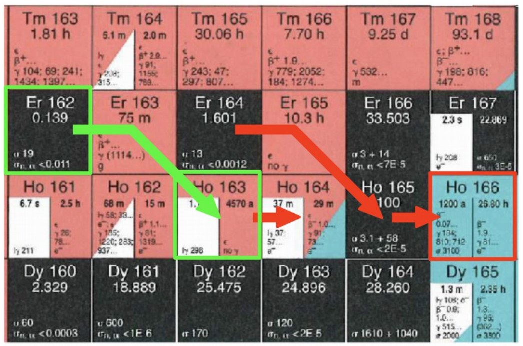


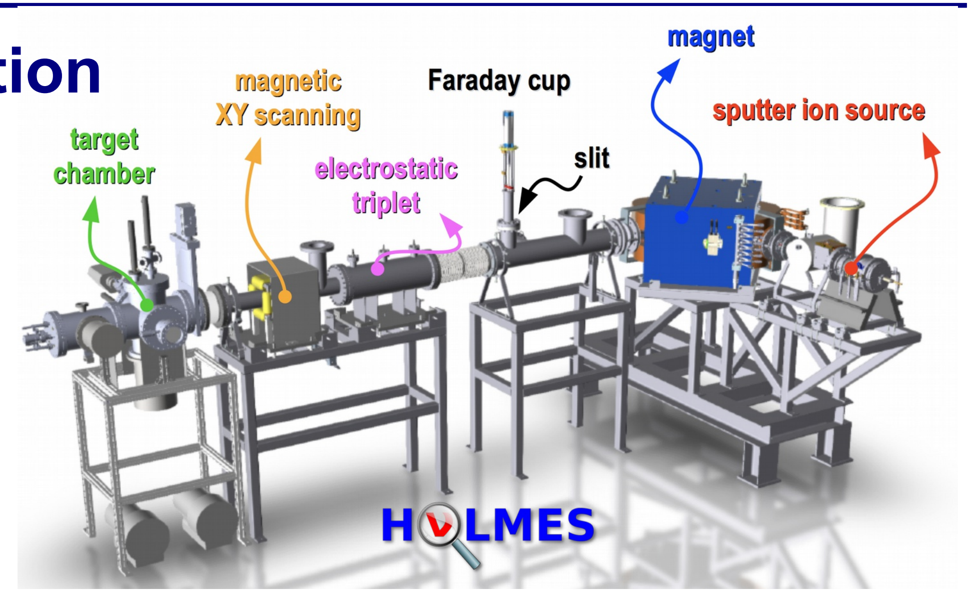
HOLMES:
sc. transition edge sensors



Direct ~~anti~~ neutrino mass measurement from ^{163}Ho electron capture: add. technical challenges

Source by n irradation and implantation





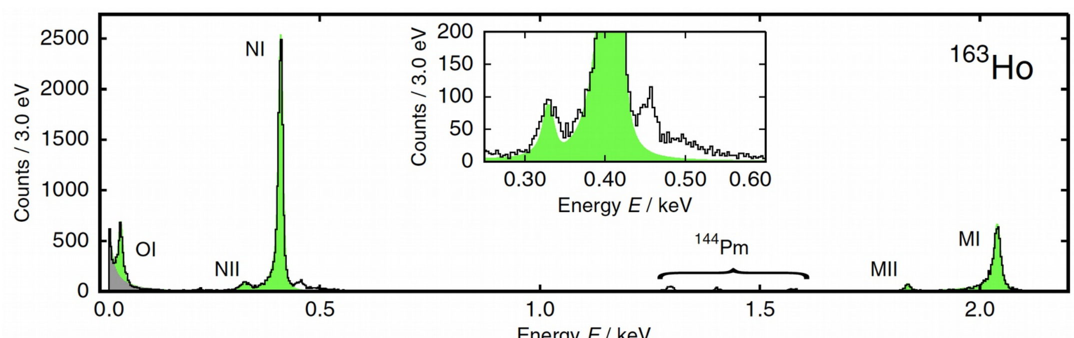
Q-value of ^{163}Ho:
→ long debate of values around 2.5 and 2.8 keV solved:

SHIPTRAP Penning trap measurement:
S. Eliseev et al., PRL ***115*** *(2015) 062501*

$$Q_{EC} = (2.833 \pm 0.030^{stat} \pm 0.015^{syst})\ \text{keV}$$

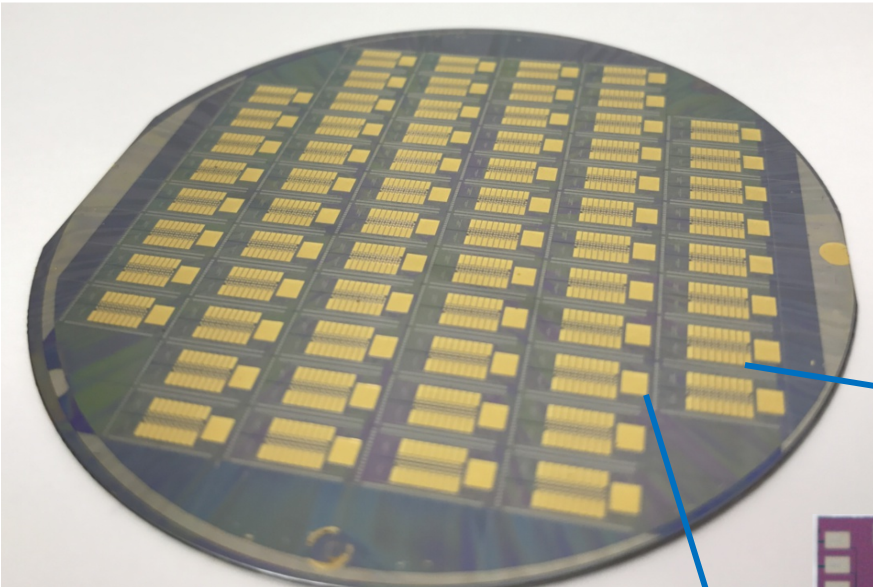
ECHo precision ^{163}Ho EC spectrum:
P. C.-O. Ranitzsch et al., PRL ***119*** *(2017) 122501*

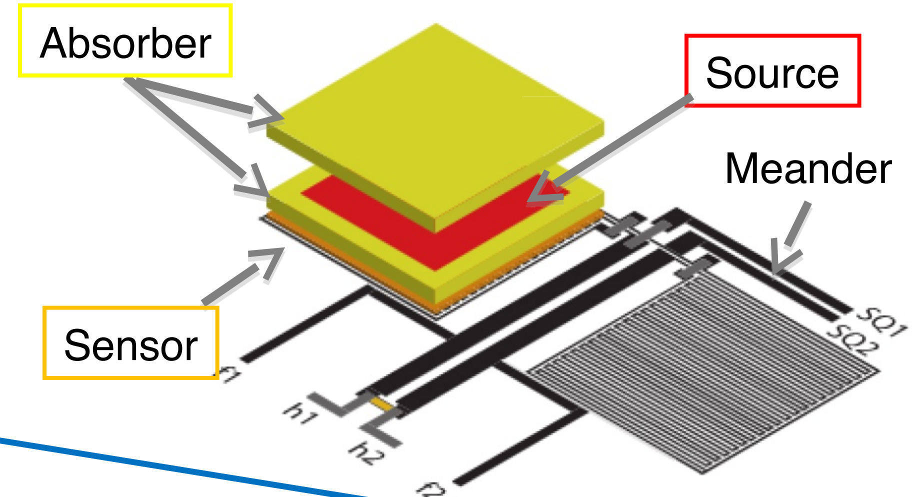
$$Q_{EC} = (2.858 \pm 0.010^{stat} \pm 0.05^{syst})\ \text{keV}$$

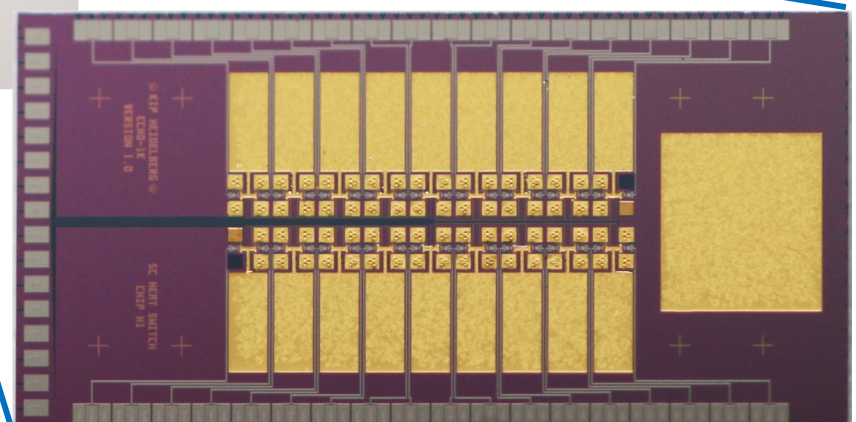


courtesy: L. Gastaldo, A. Nucciotti

Present status of ECHo





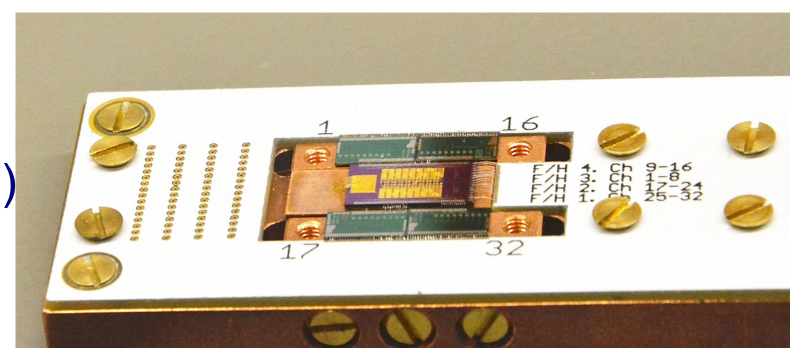


64 pixels which can be loaded with ^{163}Ho
+ 4 detectors for diagnostics

Design performance:
ΔE_{FWHM} ~ 5 eV
τ_r ~ 90 ns (single channel readout)
τ_r ~ 300 ns (microwave-multiplexed read-out)

ECHo-1k chip implanted at RISIKO at Univ. of Mainz
→ ^{163}Ho activity per pixel $a \approx 1$ Bq (total activity A ≈ 100 Bq)

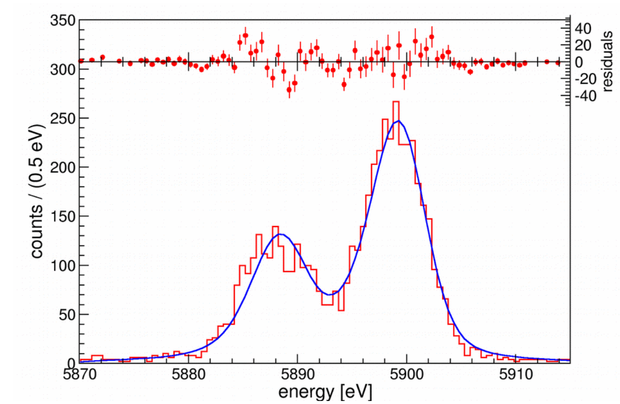
4 Front-end chips each with 8 dc-SQUIDs
→ **ECHo has taken spectra with 10^7 counts this summer**



courtesy: L. Gastaldo

Present status of HOLMES

Source production and purification:
130 MBq available for tests and experiments ✓

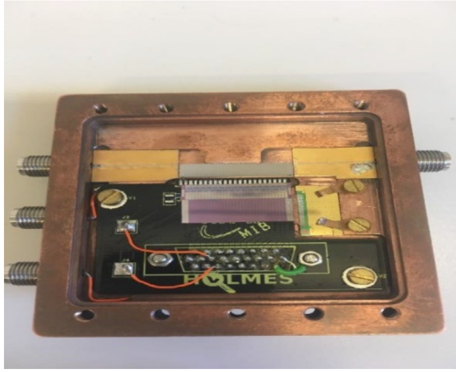


Detector arrays characterization:
very good single pixel performance ✓

ΔE_{FWHM} = 4.5±0.1 eV @ 6 keV

$\tau_{rise} \approx$ 13 μs

operating microwave SQUID multiplexing
next challenge → load TES arrays with ^{163}Ho !



Dedicated mass separator:
facility installed
tests of the ion source on-going
commissioning on-going !

courtesy: L. Gastaldo, A. Nucciotti

Future plans of ECHo & HOLMES

ECHo

ECHo-1k – revised (2015 – 2018)

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

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

ECHo-100k (2018 – 2021)

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

$\rightarrow m(\nu_e) < 2$ eV 90% C.L.

HOLMES

Activity per pixel: 300 Bq (6×10^{13} ^{163}Ho atoms)
Number of detectors: 64 → 1000

Proof of concept (end of 2019):

64 channels mid-term prototype
t_M= 1 month
$\rightarrow m(\nu_e) < 10$ eV

Full scale (starting shortly later):

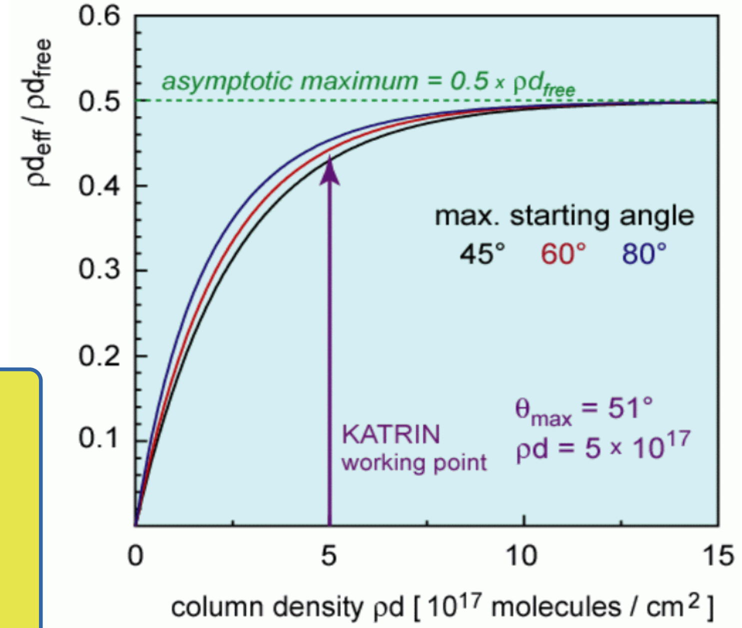
1000 channels
t_M= 3 years (3×10^{13} events)
$\rightarrow m(\nu_e) \approx 1$ eV

Sub-eV sensitivity

maybe possible if mass production of multiplexed detectors works
and if no other showstoppers appear ...

KATRIN's sensitivity of 200 meV might not be enough
Can we go beyond or improve KATRIN ?

Problem: The KATRIN source is already opaque
→ need to increase size transversally
magnetic flux tube conservation
requests larger spectrometer too
but a Ø100m spectrometer is not feasible



Possible ways out:

a) make better use of the electrons by differential measurement (e.g. cryo bolometer array or TOF) additional to integral threshold:
→ measure all retarding voltage settings at once
additional benefit: possible background reduction

b) source inside detector (compare to 0νββ) using cryogenic bolometers (ECHo, HOLMES, ..)

c) hand-over energy information of β electron to other particle (radio photon), which can escape tritium source (Project 8)

Project 8's goal: Measure coherent cyclotron radiation of tritium β electrons

General idea: *B. Monreal and J. Formaggio, PRD 80 (2009) 051301*

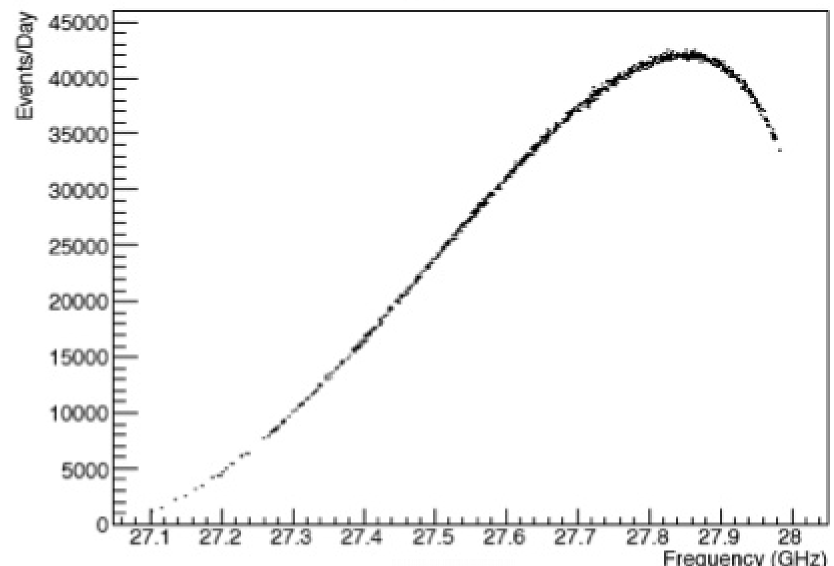
- Source = KATRIN tritium source technology :

  uniform B field + low pressure T_2 gas

  β electron radiates coherent cyclotron radiation

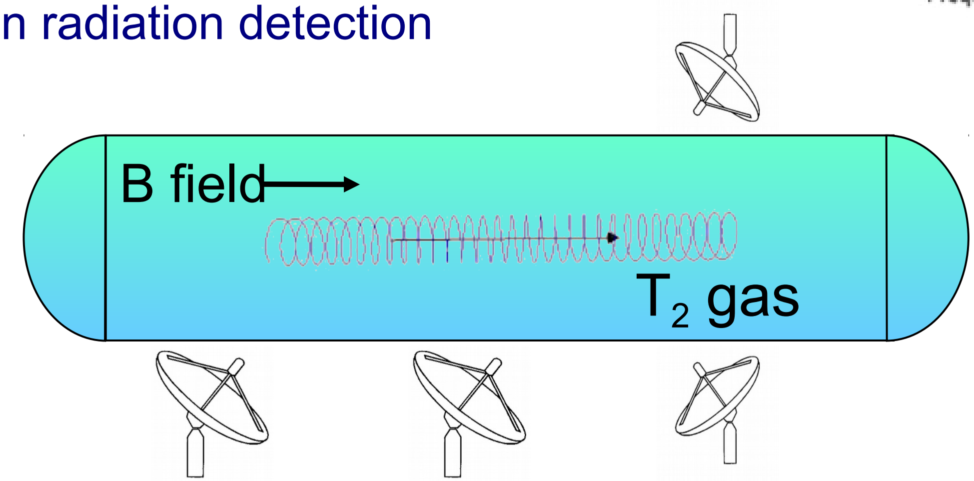
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

  But tiny signal: P (18 keV, θ=90°, B=1T) = 1 fW



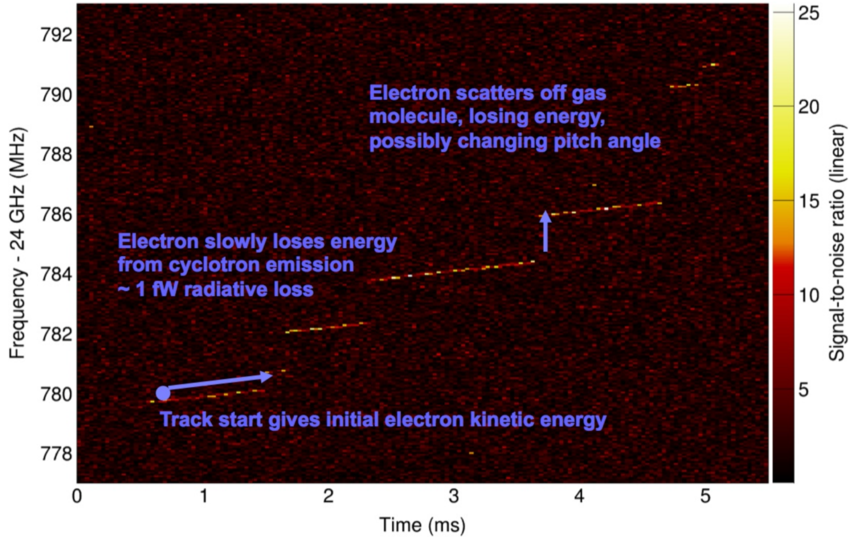
- Antenna array (interferometry) for cyclotron radiation detection

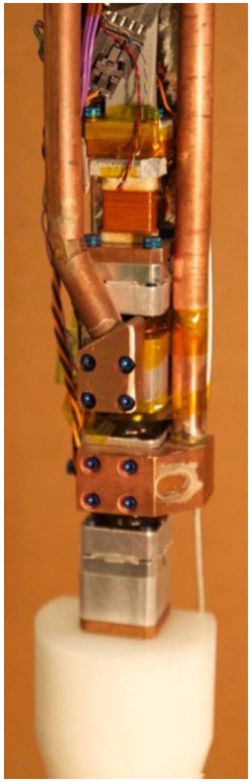
  since cyclotron radiation can leave the source and carries out the information of the β-electron energy



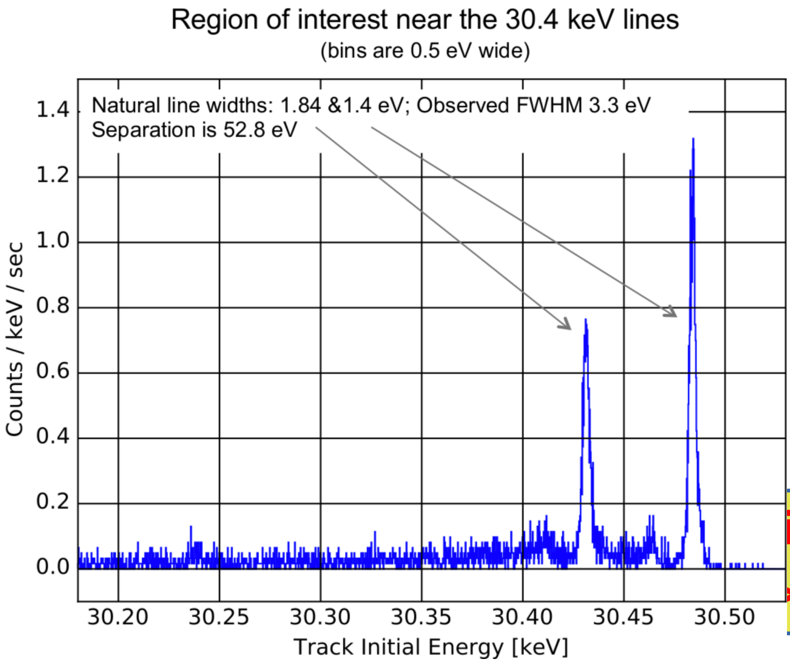
Project 8: phase I (^{83m}Kr) and II (tritium) Proof of principle

Phase I (^{83m}Kr)



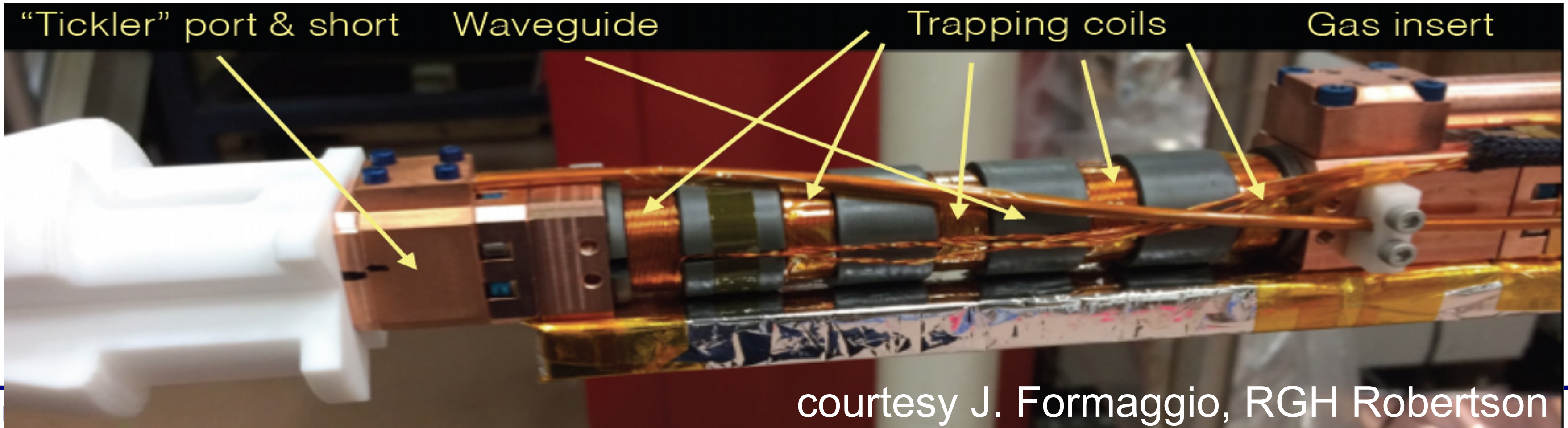


magnetic bottle to trap decay electrons long enough



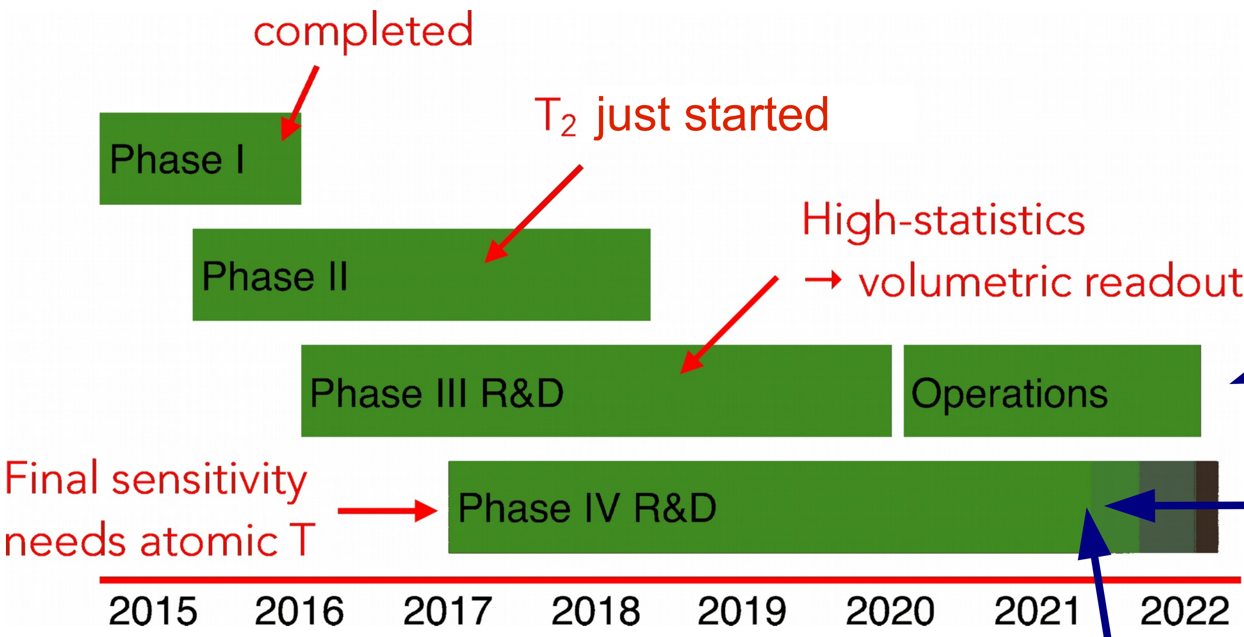
D. M. Asner et al., Phys. Rev. Lett. 114, 162501

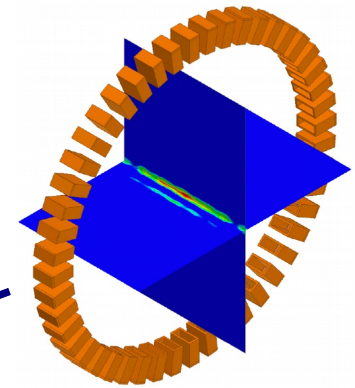
Phase II (tritium, just started)

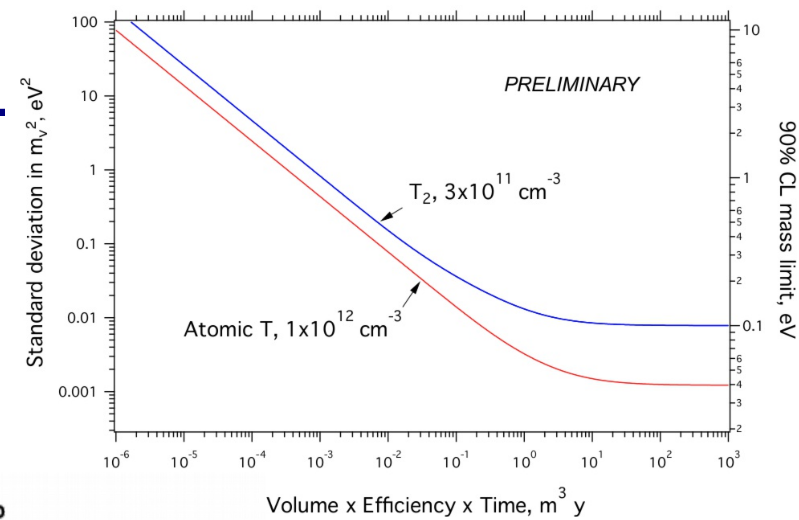


courtesy J. Formaggio, RGH Robertson

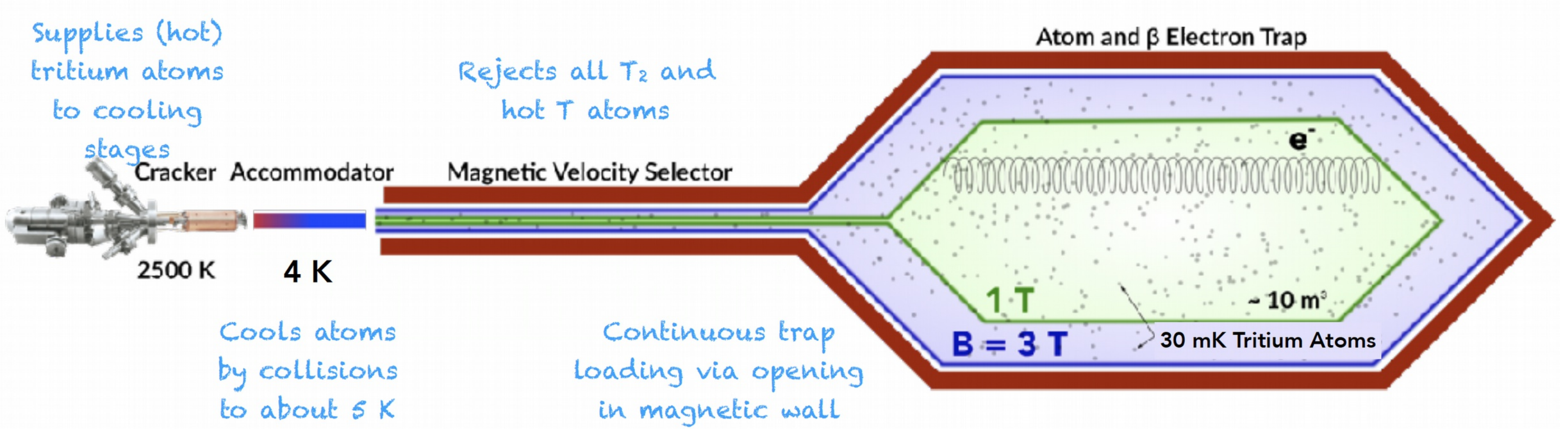
Project 8: longterm perspective







atomar tritium source (higher resolution)



→ 40 - 100 meV should be possible with ≈$10 m^3$ setup

courtesy: S. Böser

KATRIN's sensitivity of 200 meV might not be enough
Can we go beyond or improve KATRIN ?

Problem: The KATRIN source is already opaque
→ need to increase size transversally
magnetic flux tube conservation
requests larger spectrometer too
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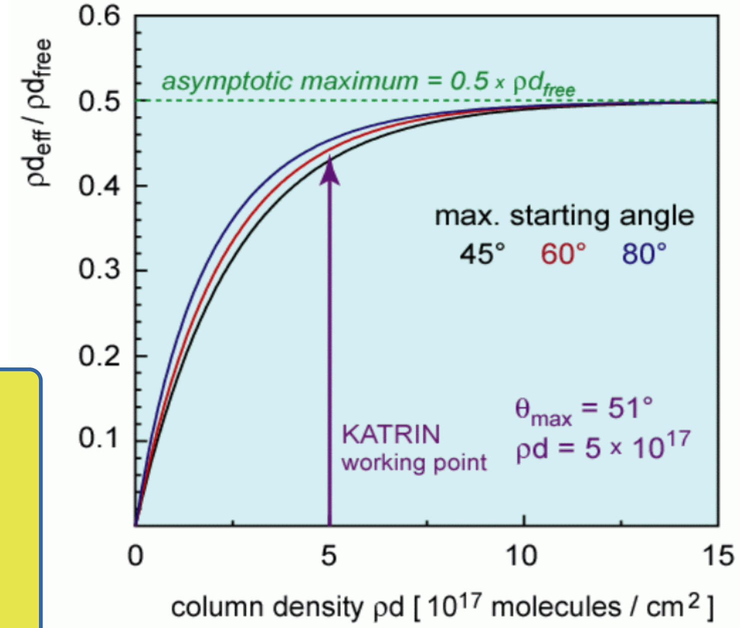

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additional benefit: possible background reduction

b) source inside detector (compare to $0\nu\beta\beta$)
using cryogenic bolometers (ECHo, HOLMES, ..)

hand-over energy information of β electron to other particle (radio photon), which can escape tritium source (Project 8)

d) combine all technologies and add new (PTOLEMY)

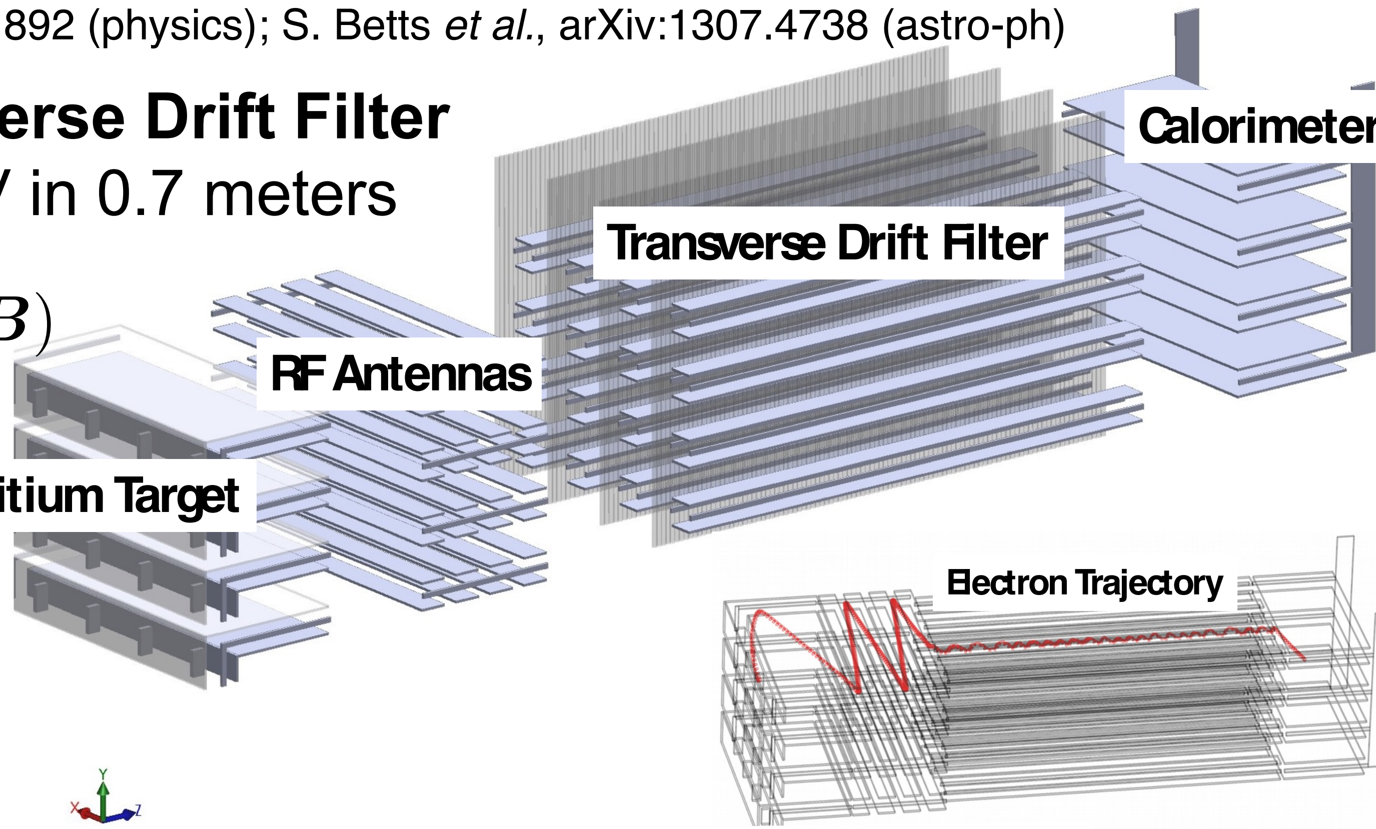
PTOLEMY

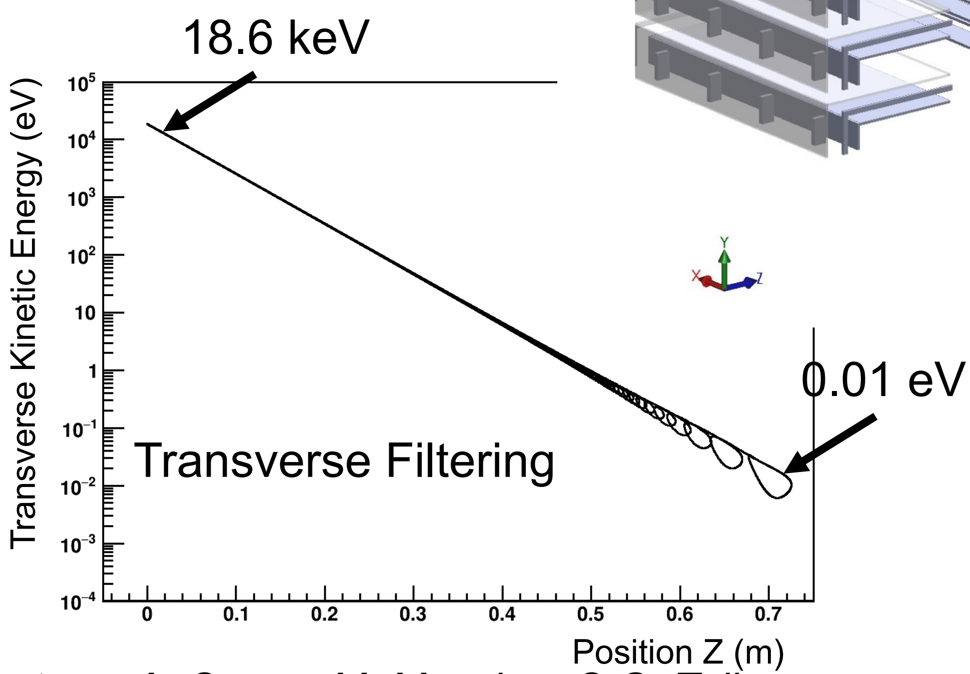
PTOLEMY Collaboration, M.G. Betti *et al.* *(51 authors)*, arXiv:1810.06703 (astro-ph);
E. Baracchini *et al.*, arXiv:1808.01892 (physics); S. Betts *et al.*, arXiv:1307.4738 (astro-ph)

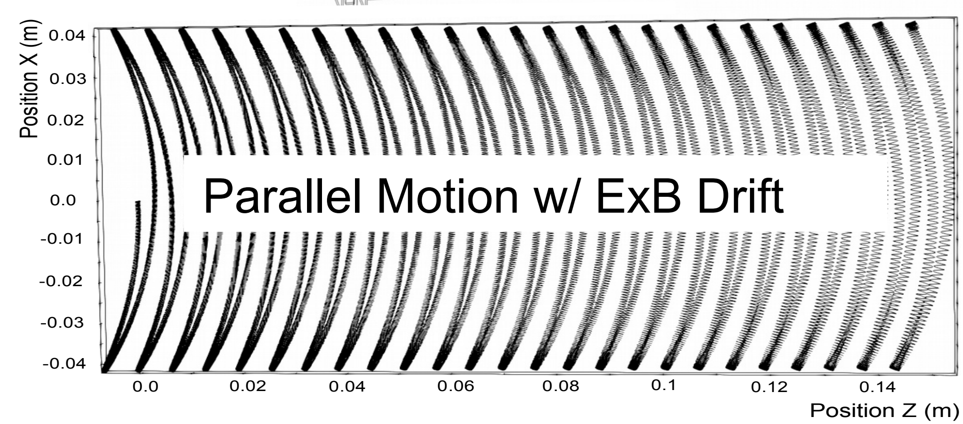
New Concept: **Transverse Drift Filter**

18.6 keV → 0.01 eV in 0.7 meters

$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\boldsymbol{E}\cdot(\boldsymbol{\nabla}B \times \boldsymbol{B})$$







courtesy: A. Cocco, M. Messina, C.G. Tully

WWU MÜNSTER

Conclusions

Direct neutrino mass determination is complementary to $0\nu\beta\beta$ and cosmology

- KATRIN: has started, successful tritium commissioning & inauguration run
science runs in 2019 – 2023, 240 meV sensitivity

Beyond KATRIN:

- Possible KATRIN upgrades: TRISTAN (keV sterile ν)
and differential (100 meV sensitivity)

- Cryo bolometers with ^{163}Ho:

ECHO: ECHo-1k is taken data with 60 pixels, 1st results soon
ECHo-100k will start 2020 with multiplexing readout, < 2 eV sensit.

HOLMES: start data taking with 64 pixels end of 2019
upgrade to 1024 channels with $\approx$1 eV sensitivity

- Coherent synchrotron radiation electron spectroscopy: Project 8

concept proven with ^{83m}Kr, tritium run started recently,
preparation for phase III/IV with 40-100 meV sensitivity

Far future:

- PTOLEMY: R&D on new concepts, tritium-loaded graphene, new filter