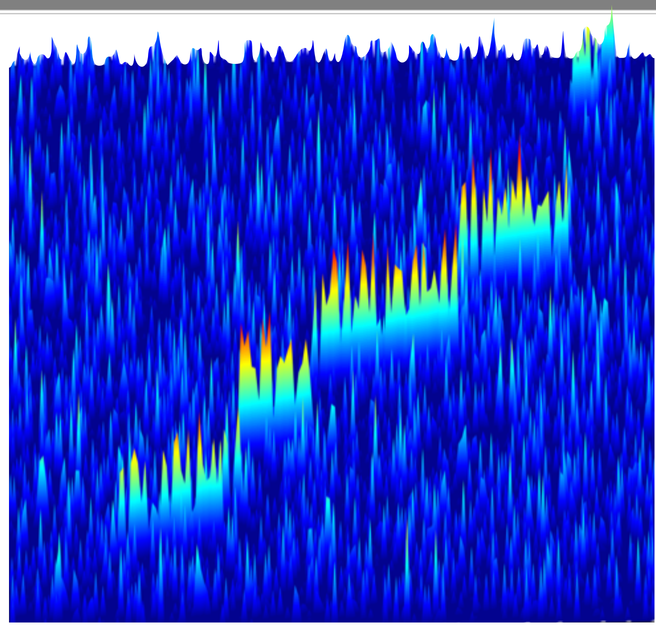
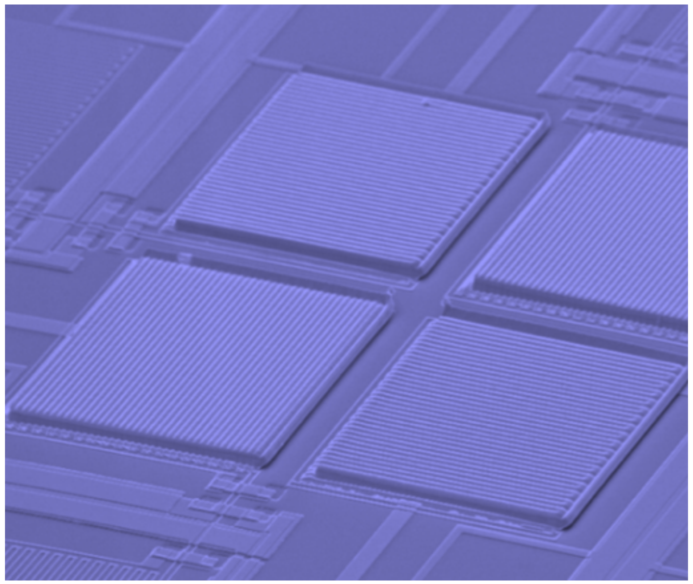
Direct probes of neutrino mass

Tritium β-decay and EC of ^{163}Ho

KATHRIN VALERIUS | KIT-IKP (Institute for Nuclear Physics)





4 Nobel Prizes for Neutrino Physics

Karlsruhe Institute of Technology

1995

Martin L. Perl
Prize share: 1/2

© University of California Regents

Frederick Reines
Prize share: 1/2

The Nobel Prize in Physics 1995 was awarded *"for pioneering experimental contributions to lepton physics"* jointly with one half to Martin L. Perl *"for the discovery of the tau lepton"* and with one half to Frederick Reines *"for the detection of the neutrino"*.

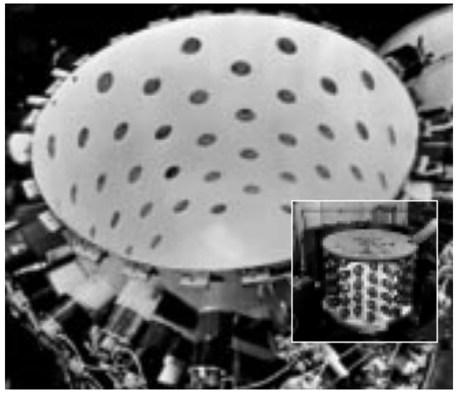
1988

Leon M. Lederman
Prize share: 1/3

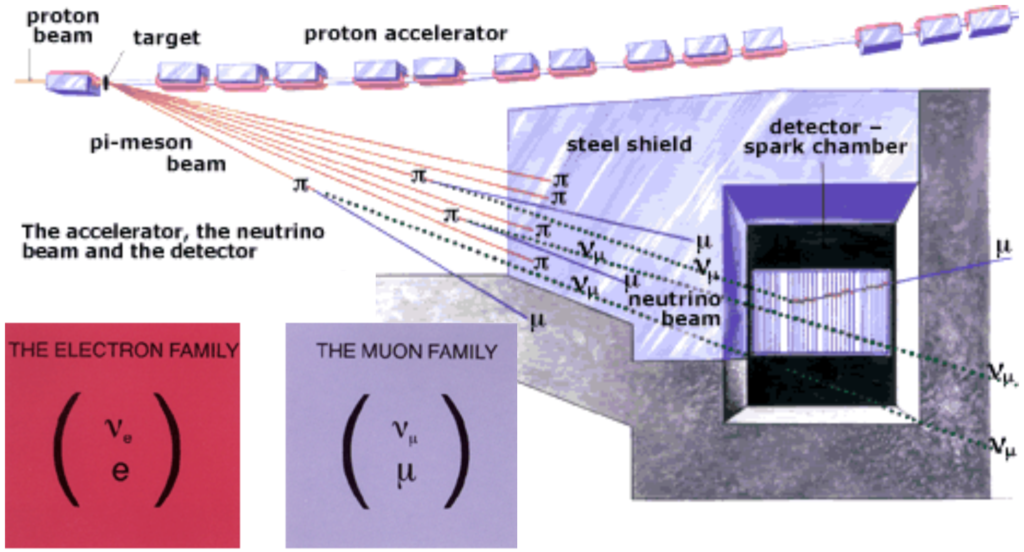
Melvin Schwartz
Prize share: 1/3

Jack Steinberger
Prize share: 1/3

The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz and Jack Steinberger *"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"*.



"Herr Auge"



4 Nobel Prizes for Neutrino Physics

Karlsruhe Institute of Technology

2002

Raymond Davis Jr.
Prize share: 1/4

Masatoshi Koshiba
Prize share: 1/4

Riccardo Giacconi
Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

2015

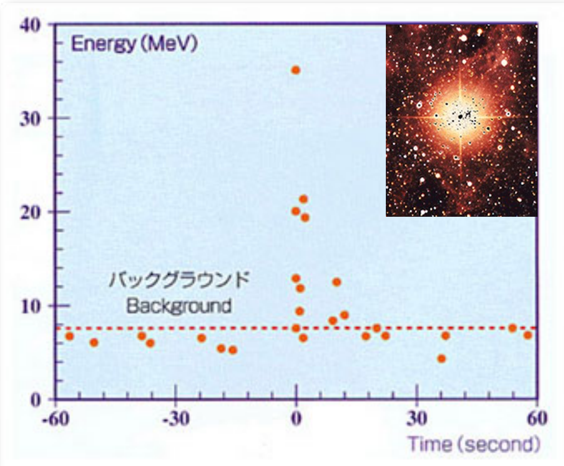
Photo © Takaaki Kajita
Takaaki Kajita
Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB
Arthur B. McDonald
Prize share: 1/2

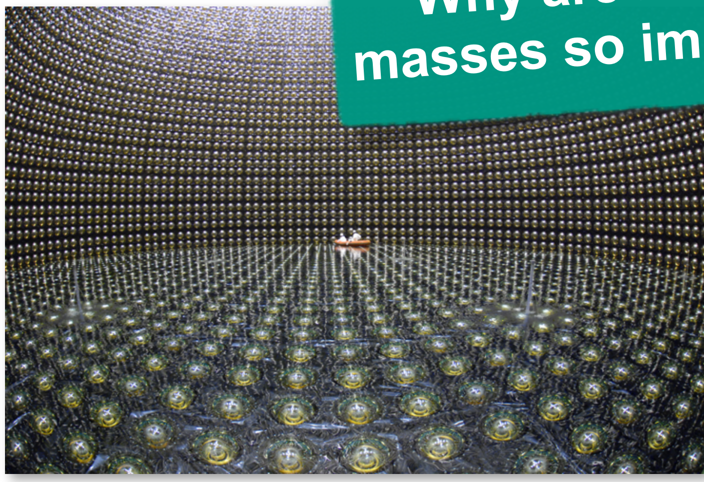
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Why are neutrino masses so important?

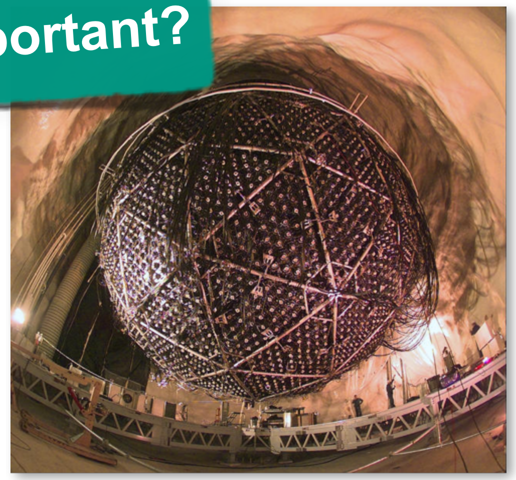
Homestake



KamiokaNDE



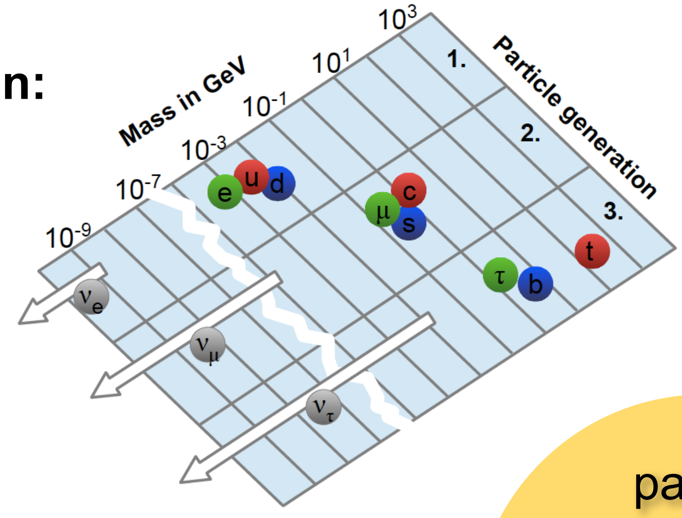
Super-KamiokaNDE



SNO

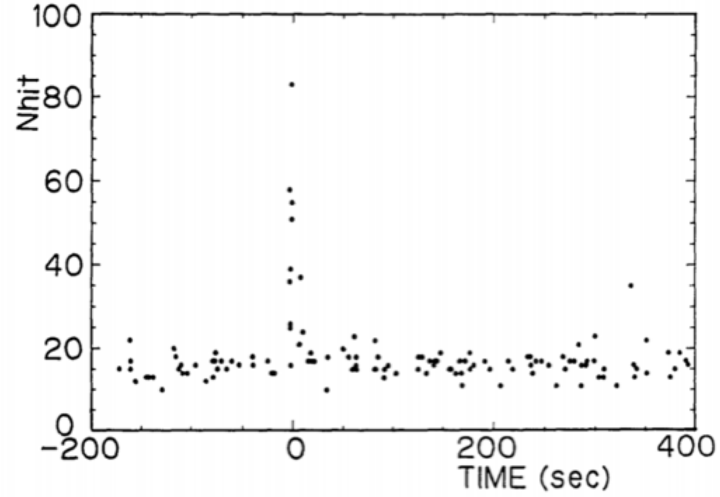
The role of massive neutrinos

mass generation: new concepts

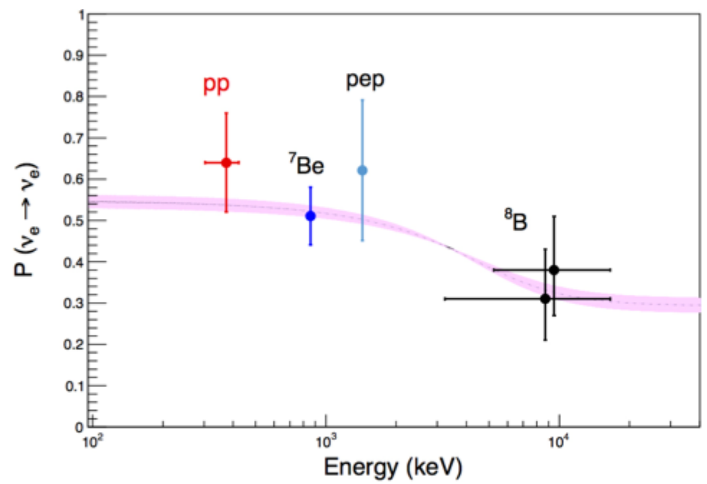


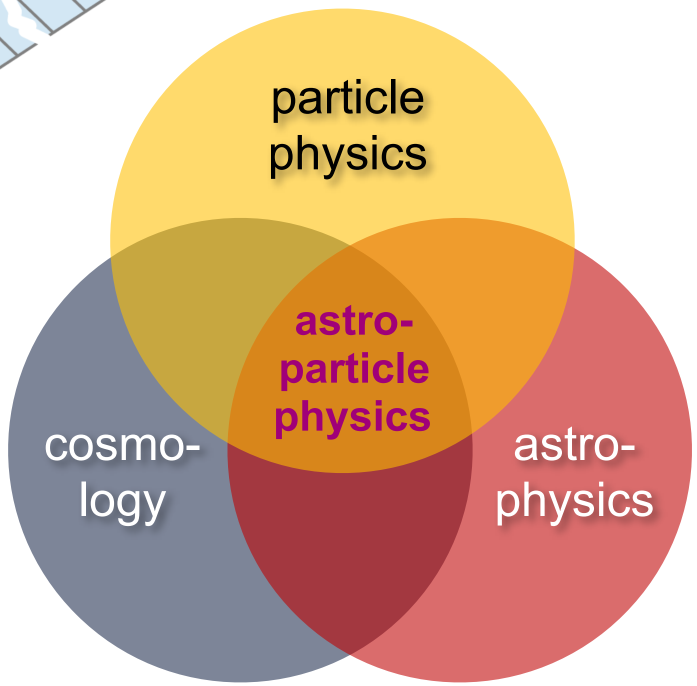
understanding astrophysical processes

Neutrino burst from SN 1987a

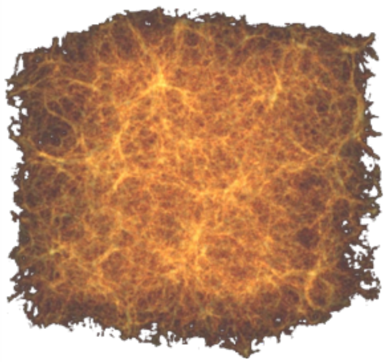


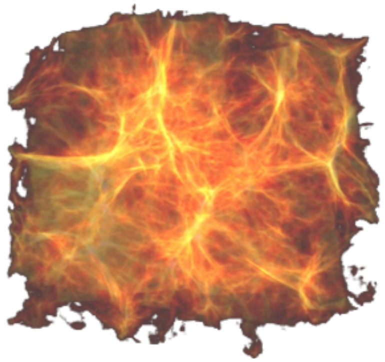
Matter effects in the sun





massive neutrinos as “cosmic architects”





$\Sigma\, m_\nu$ = **0 eV** **6.9 eV**

What's on the menu today?

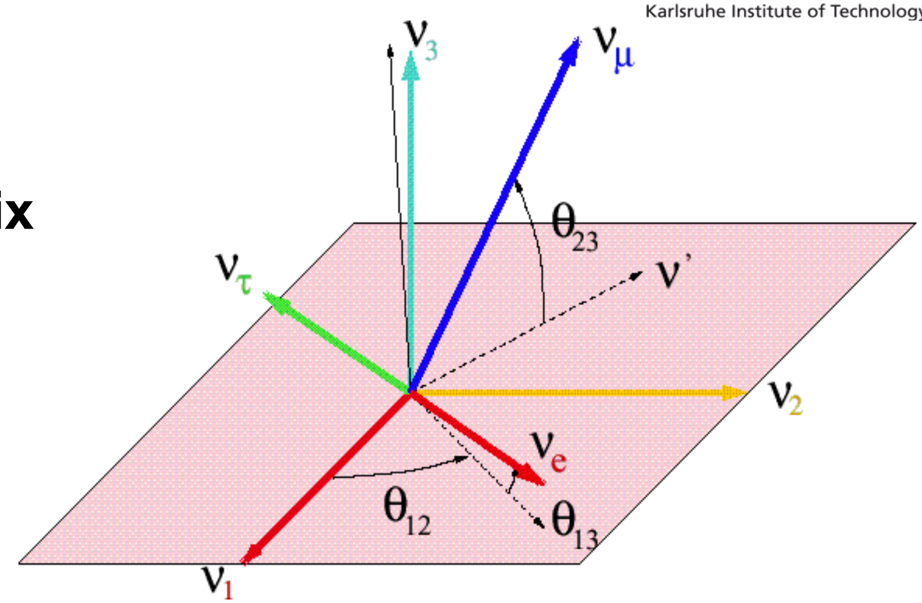
- Introduction:
  - Neutrino masses & mixing
  - Methods to measure neutrino masses
- Neutrino mass searches using kinematics:
  - Beta decay of Tritium (^{3}H)
  - Electron capture in Holmium (^{163}Ho)
- Summary & outlook

Three-flavour neutrino mixing

3 x 3 unitary mixing matrix analogous to CKM:

"Pontecorvo Maki Nakagawa Sakata"

(PMNS)



- 3 mixing angles: θ_{12}, θ_{23}, θ_{13},
- 1 CP-violating phase: δ
- 2 independent Δm^2 scales:

$$\boxed{\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2}$$

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

Three-flavour neutrino mixing — present experimental values

Karlsruhe Institute of Technology

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

2. & 3. generation	1. & 3. generation	1. & 2. generation	
$\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV^2	$\Delta m_{13}^2 = 2.5 \times 10^{-3}$ eV^2	$\Delta m_{12}^2 = 7.6 \times 10^{-5}$ eV^2	
± 6%	± 6%	± 7%	3σ uncertainty, including ordering
$\theta_{23} \approx 45°$ (maximal)	$\theta_{13} \approx 8.5°$ (small)	$\theta_{23} \approx 34°$ (large)	
± 16%	± 5%	± 7%	3σ uncertainty, including ordering

➜ Structure of leptonic mixing matrix very different from CKM matrix:

$$U_{PMNS} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

How do we know all this?

➜ collected "world data" from many different experiments

2. & 3. generation	1. & 3. generation	1. & 2. generation
$\Delta m_{23}^2 = 2.5 \times 10^{-3}\ eV^2$	$\Delta m_{13}^2 = 2.5 \times 10^{-3}\ eV^2$	$\Delta m_{12}^2 = 7.6 \times 10^{-5}\ eV^2$
$\theta_{23} \approx 45°$ *(maximal)*	$\theta_{13} \approx 8.5°$ *(small)*	$\theta_{23} \approx 34°$ *(large)*

atmospheric & long-baseline accelerator exp.

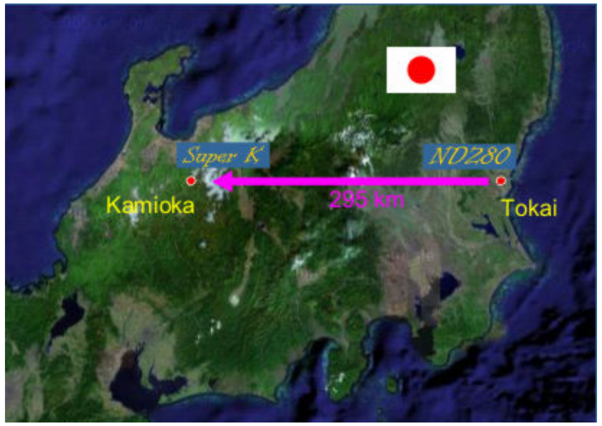
GeV, ν_μ ($\bar{\nu}_\mu$)

reactor & long-baseline accelerator exp.

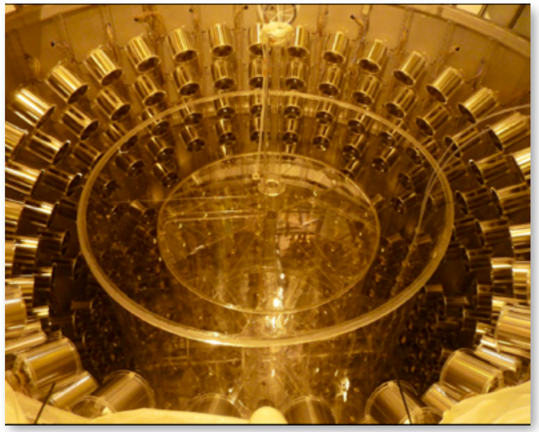
MeV, $\bar{\nu}_e$
GeV, ν_μ ($\bar{\nu}_\mu$)

solar & reactor exp.

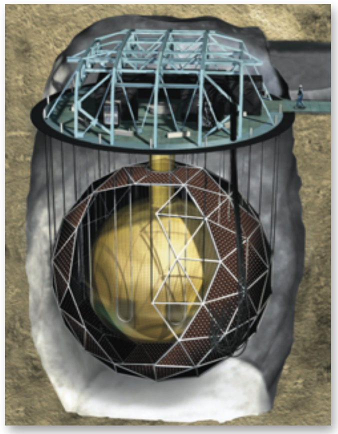
MeV, ν_e ($\bar{\nu}_e$)



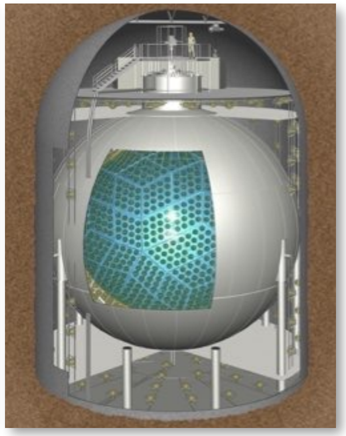
Tokai - Kamioka (T2K)



Double Chooz



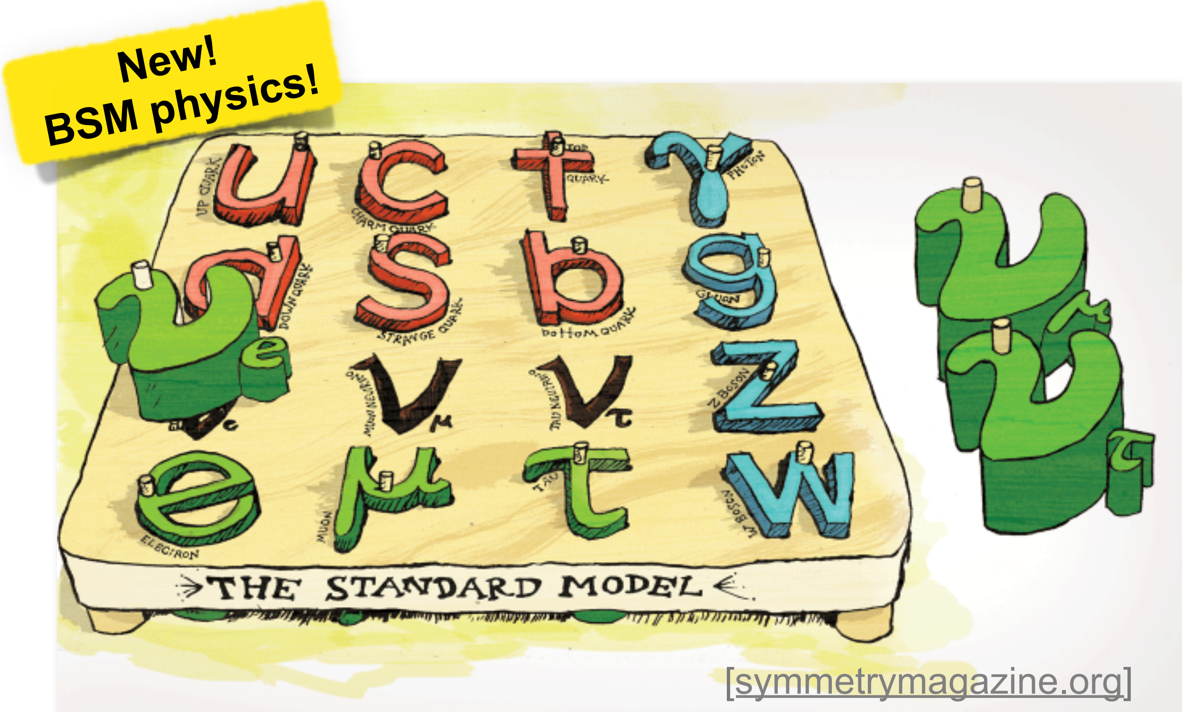
SNO

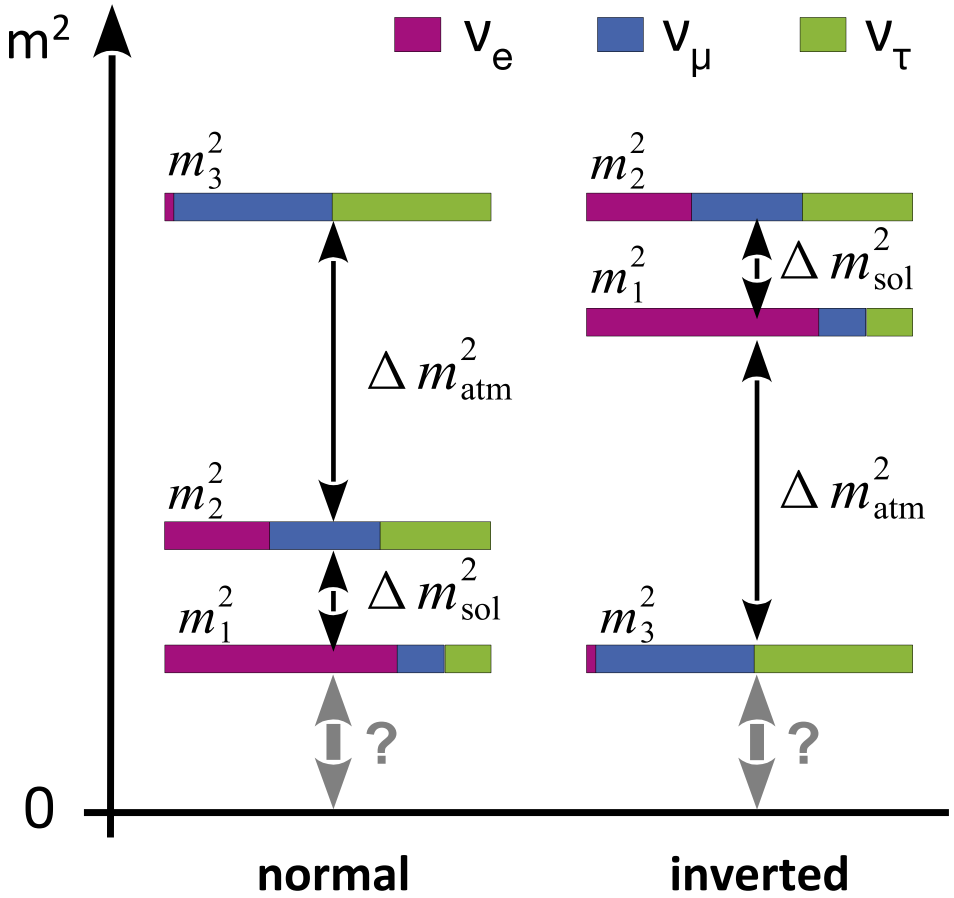


KamLAND

Results of ν-oscillation experiments

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





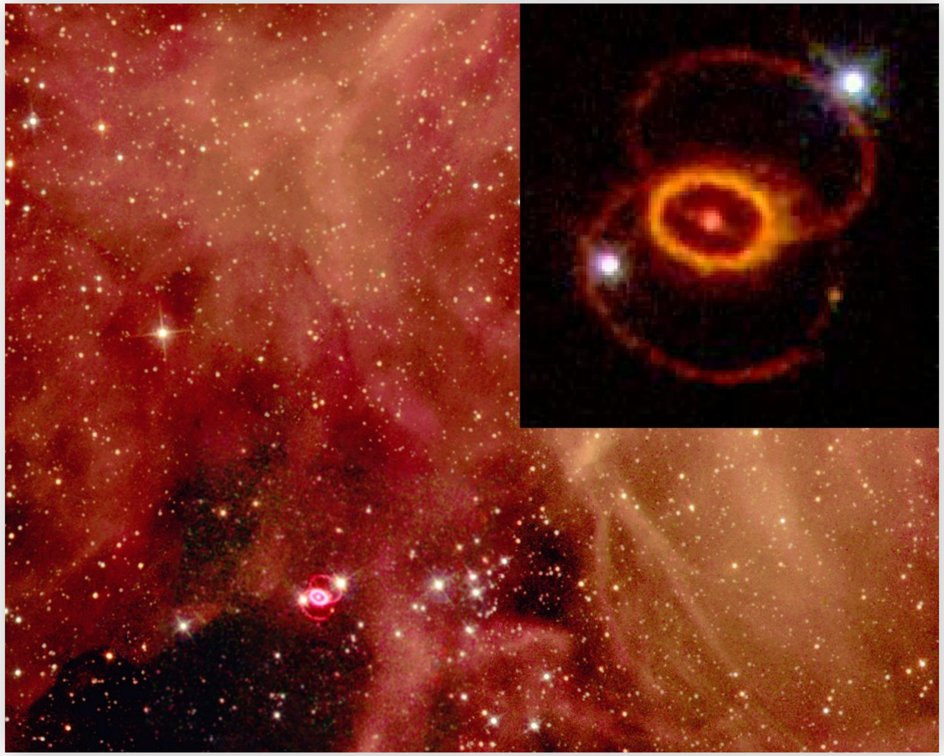
- *Which mass ordering (normal, inverted)?*
- ***What is the absolute ν mass scale?***

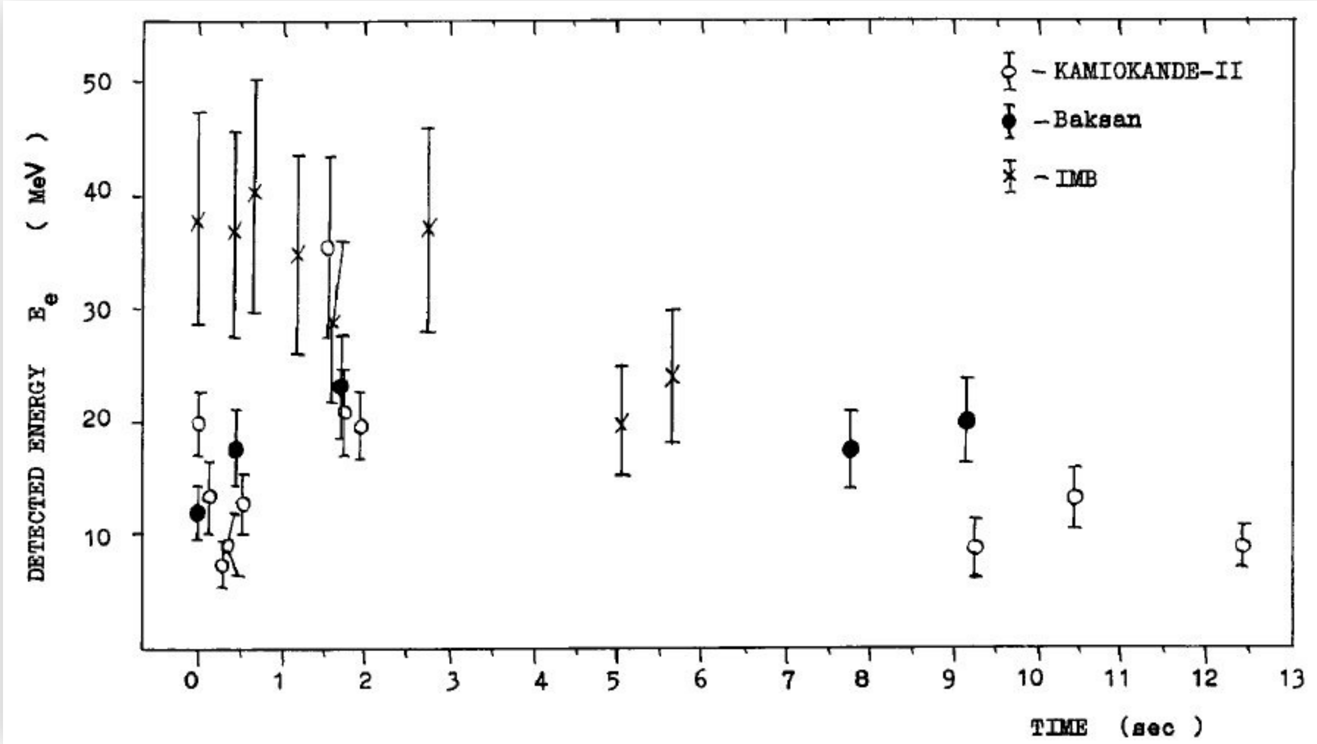
So far: only **upper** (< 2 eV) and **lower bounds** (>0.01 resp. >0.05 eV)

Well, then,
how to determine the neutrino mass scale?

Astrophysicist's answer: Use astrophysical data! **Core-collapse SN 1987a in LMC**

today **24. Feb. 1987**

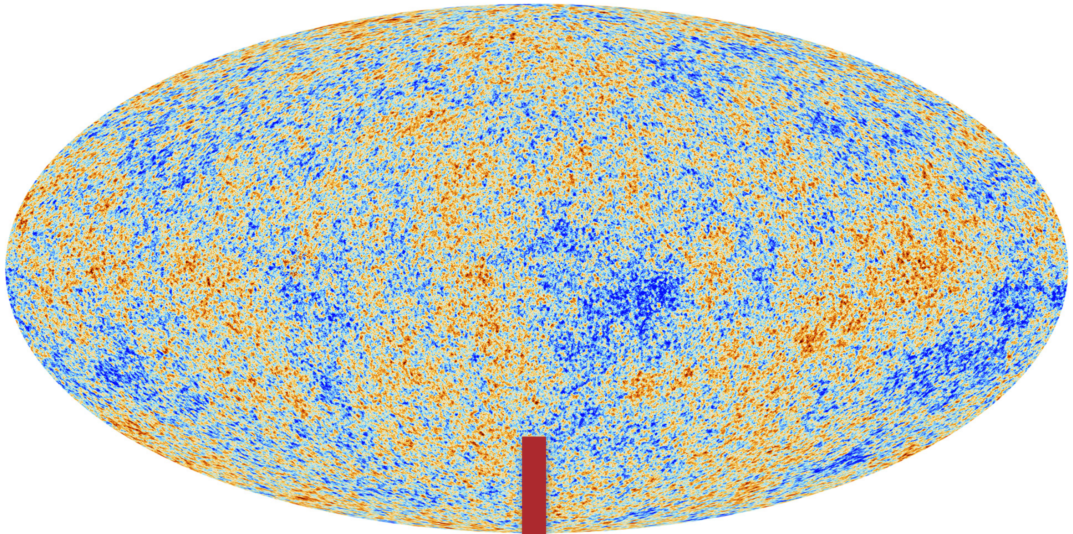


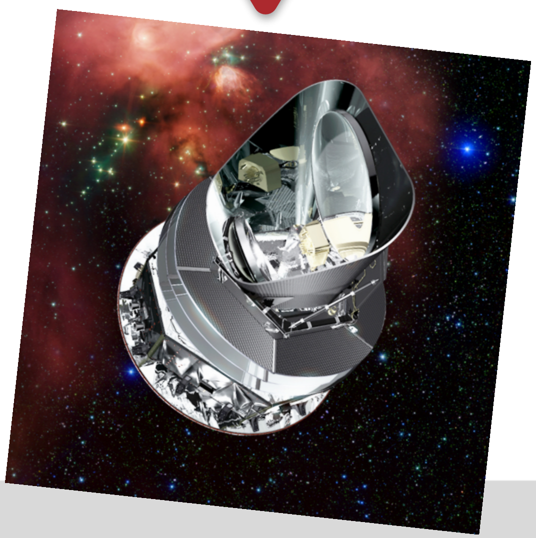


- ➡ Estimate ν mass from energy-dependent time of flight. Current limit: $m(\nu_e) < 5.7$ eV.
- ➡ Purely kinematical. Main difficulties: (a) rare! (b) emission model! [Loredo et al., 2005]

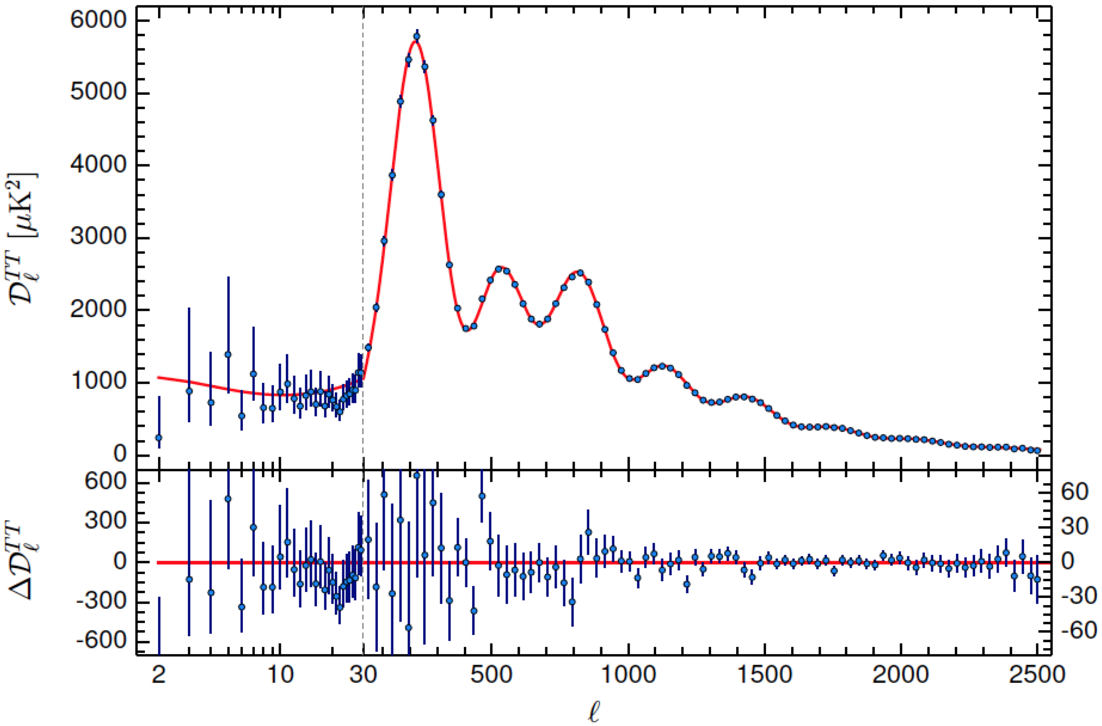
Well, then,
how to determine the neutrino mass scale?

Cosmologist's answer: Use cosmological data!

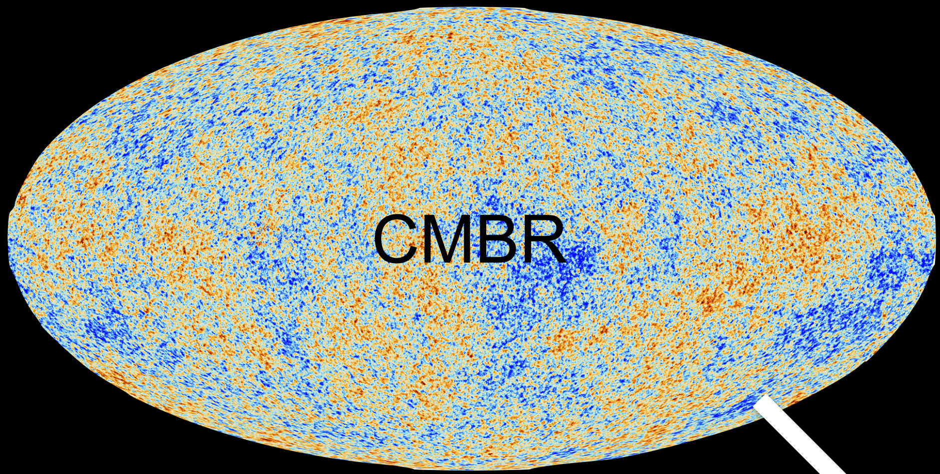




Ade et al. (Planck Coll.), arXiv:1502.01589

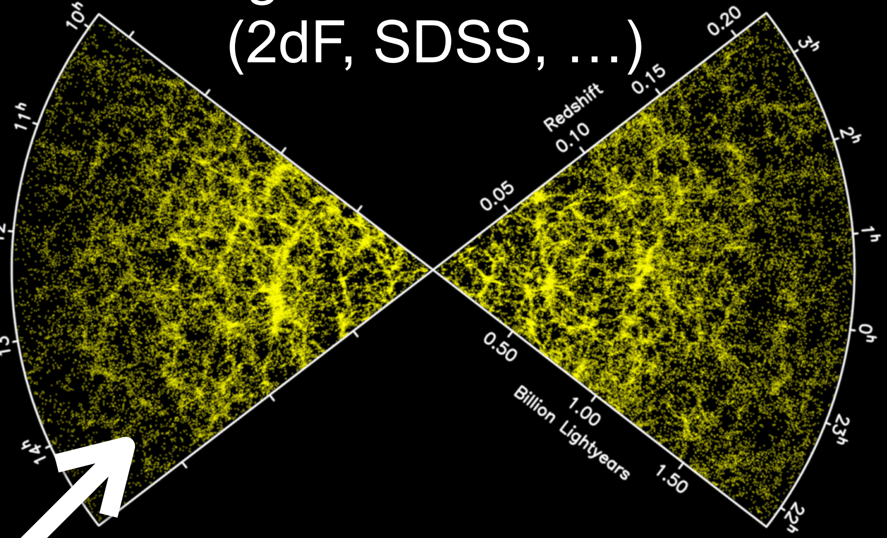


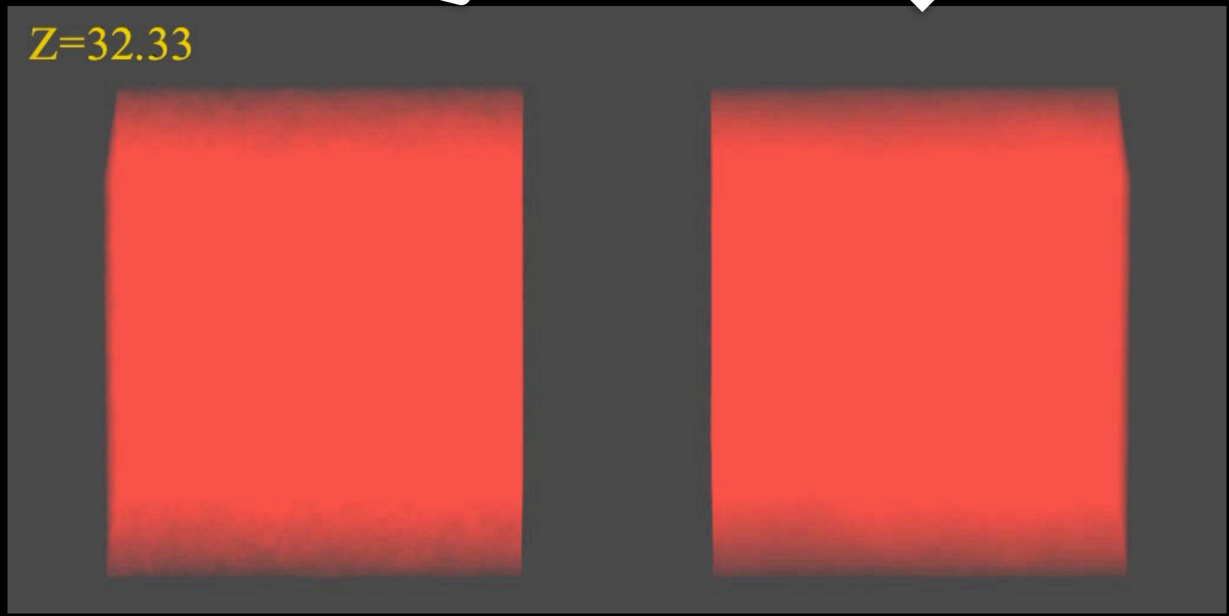
Neutrino mass from cosmology



cold dark matter
+
relic neutrino
density:
336 ν /cm³

Large scale structure
(2dF, SDSS, …)





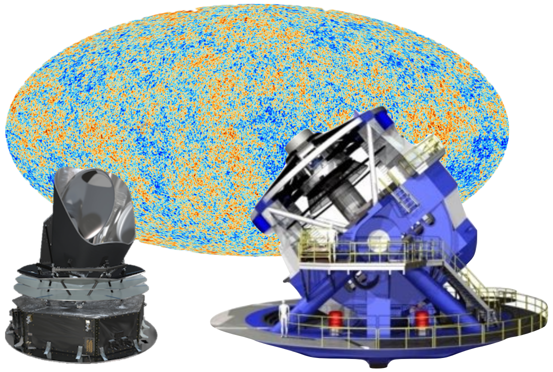
$\Sigma\, m_\nu$ = 0 eV 6.9 eV *

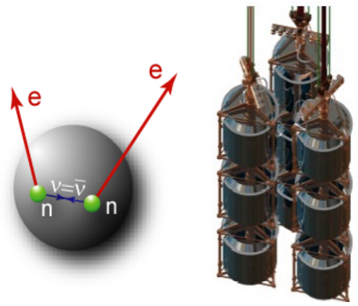
[T. Haugbølle, Univ. of Aarhus]

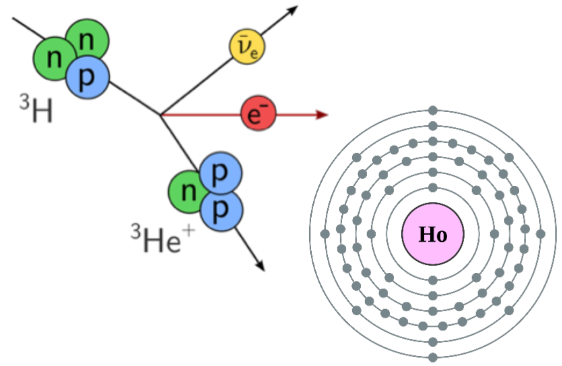
Well, then,
how to determine the neutrino mass scale?

Karlsruhe Institute of Technology

Experimentalist's answer:
3 complementary paths!







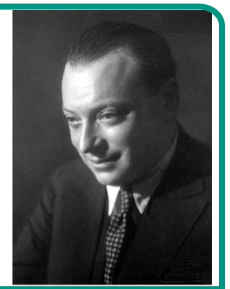
Tool	Cosmology CMB + LSS + ...	Neutrinoless double β-decay	β-decay endpoint and EC
Observable	$\sum m_\nu = \sum_{i=1}^{3} m_i$	$\langle m_{\beta\beta} \rangle = \left\| \sum_{j=1}^{3} \|U_{ej}\|^2 \, m_j \, e^{i\alpha_j} \right\|$	$m_\beta^2 = \sum_{i=1}^{3} \|U_{ei}^2\| \, m_i^2$
Present upper limit	0.15 – 1 eV	0.2 – 0.4 eV	2 eV
Potential	20 – 50 meV	20 – 50 meV	200 meV
Model dependence	Multi-parameter cosmological model	- Majorana vs. Dirac - phase cancellations possible - nucl. matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum

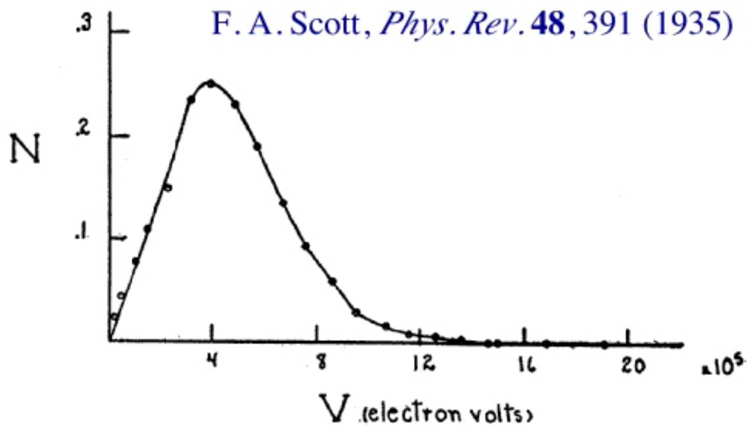
Kinematics of weak decays:
“direct” ν mass search

β decay and neutrino mass

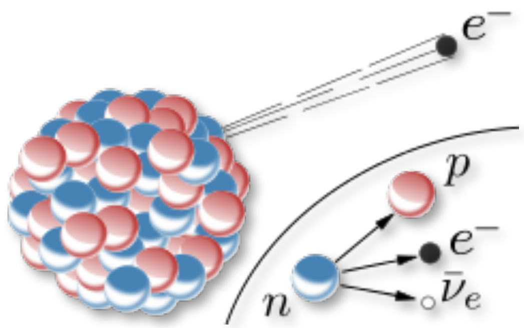
1930: Wolfgang Pauli's "desperate remedy" to solve the problem of apparent violation of energy & momentum conservation in β decay

postulation of **new particle**: neutral, spin ½, weak interaction





Energy distribution curve of the beta-rays.



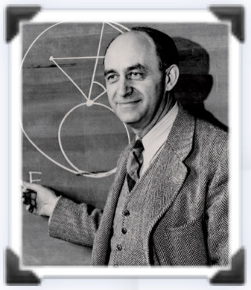
4 December 1930
Gloriastr.
Zürich

Physical Institute of the
Federal Institute of Technology (ETH)
Zürich

Dear radioactive ladies and gentlemen,

As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem"* of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons,** which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.

β decay and neutrino mass



E. Fermi, 1934

Versuch einer Theorie der β-Strahlen. I[1]).

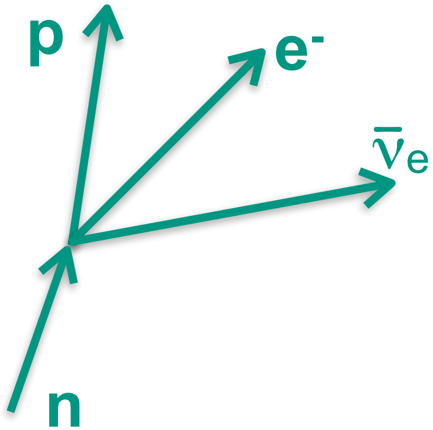
Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

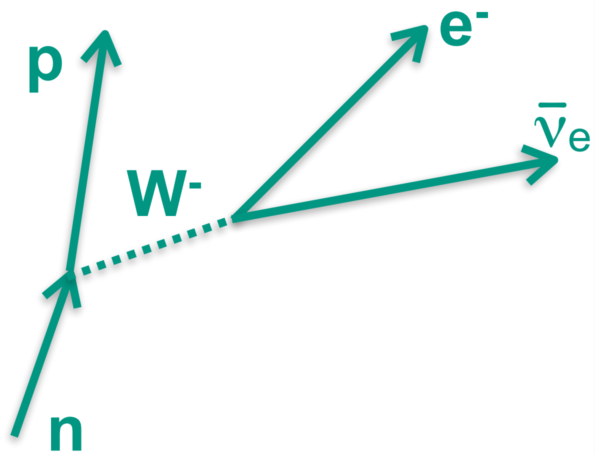
Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

1. Grundannahmen der Theorie.

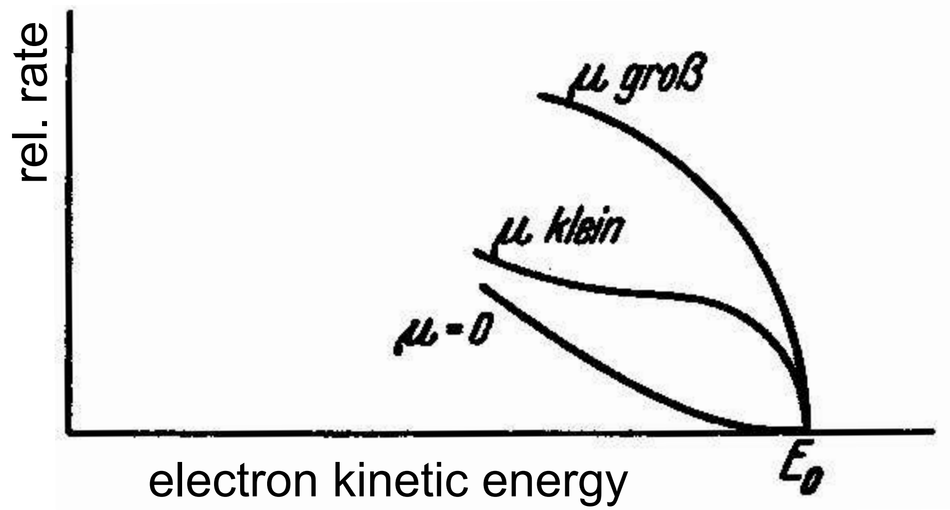
Bei dem Versuch, eine Theorie der Kernelektronen sowie der β-Emission aufzubauen, begegnet man bekanntlich zwei Schwierigkeiten. Die erste ist durch das kontinuierliche β-Strahlenspektrum bedingt. Falls der Erhaltungssatz der Energie gültig bleiben soll, muß man annehmen, daß ein Bruchteil der beim β-Zerfall frei werdenden Energie unseren bisherigen Beobachtungsmöglichkeiten entgeht. Nach dem Vorschlag von W. Pauli kann man z. B. annehmen, daß beim β-Zerfall nicht nur ein Elektron, sondern auch ein neues Teilchen, das sogenannte „Neutrino" (Masse von der Größenordnung oder kleiner als die Elektronenmasse; keine elektrische



1934: Fermi 4-point int.



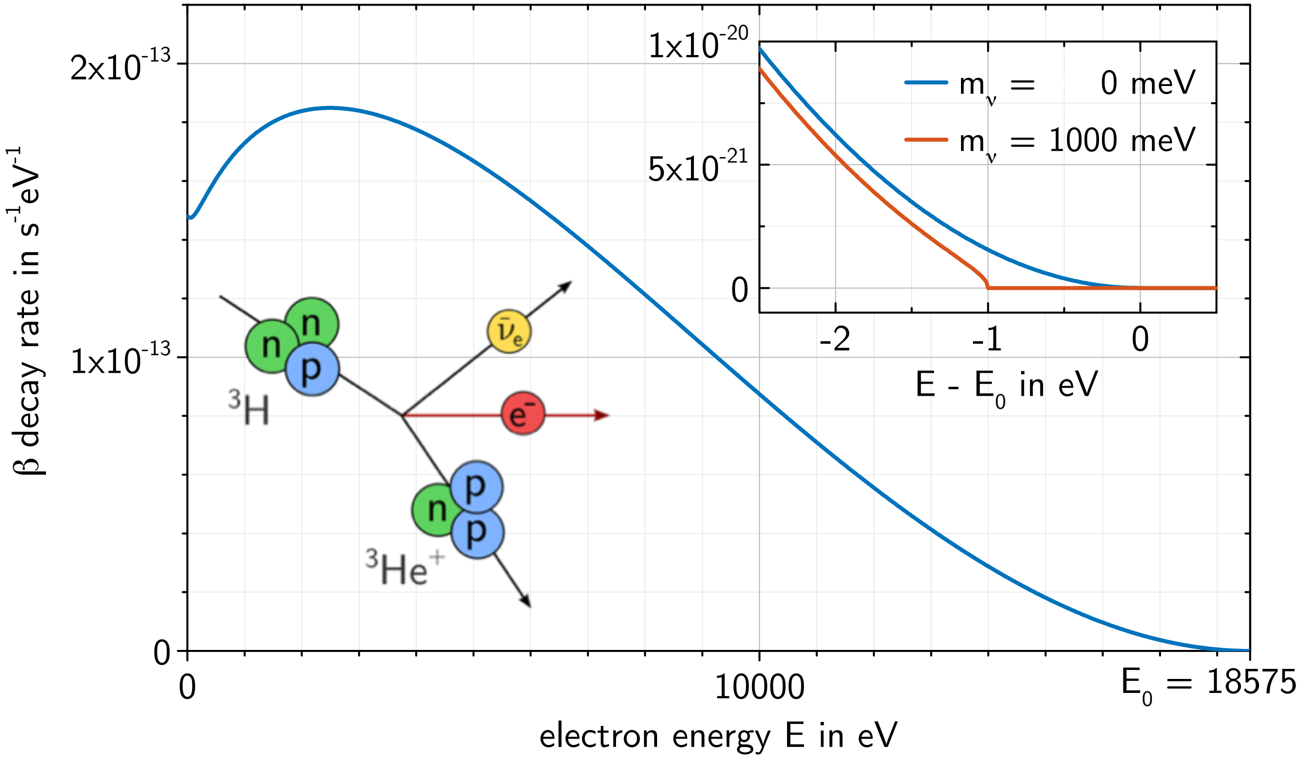
1938 (Yukawa, Klein et al.): boson-mediated weak int.



- Model independent neutrino mass measurement: based solely on **kinematic variables** (E_0, E_e, p_e, m_e) and **energy conservation**
- Elusive neutrino escapes undetected, only electron energy is measured

Direct kinematic determination of m(ν_e)

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = C\,F(Z,E)\,p\,(E+m_\mathrm{e})\,(E_0-E)\,\sum_i |U_{\mathrm{e}i}|^2 \sqrt{(E_0-E)^2 - m^2(\nu_i)}$$



Key requirements:

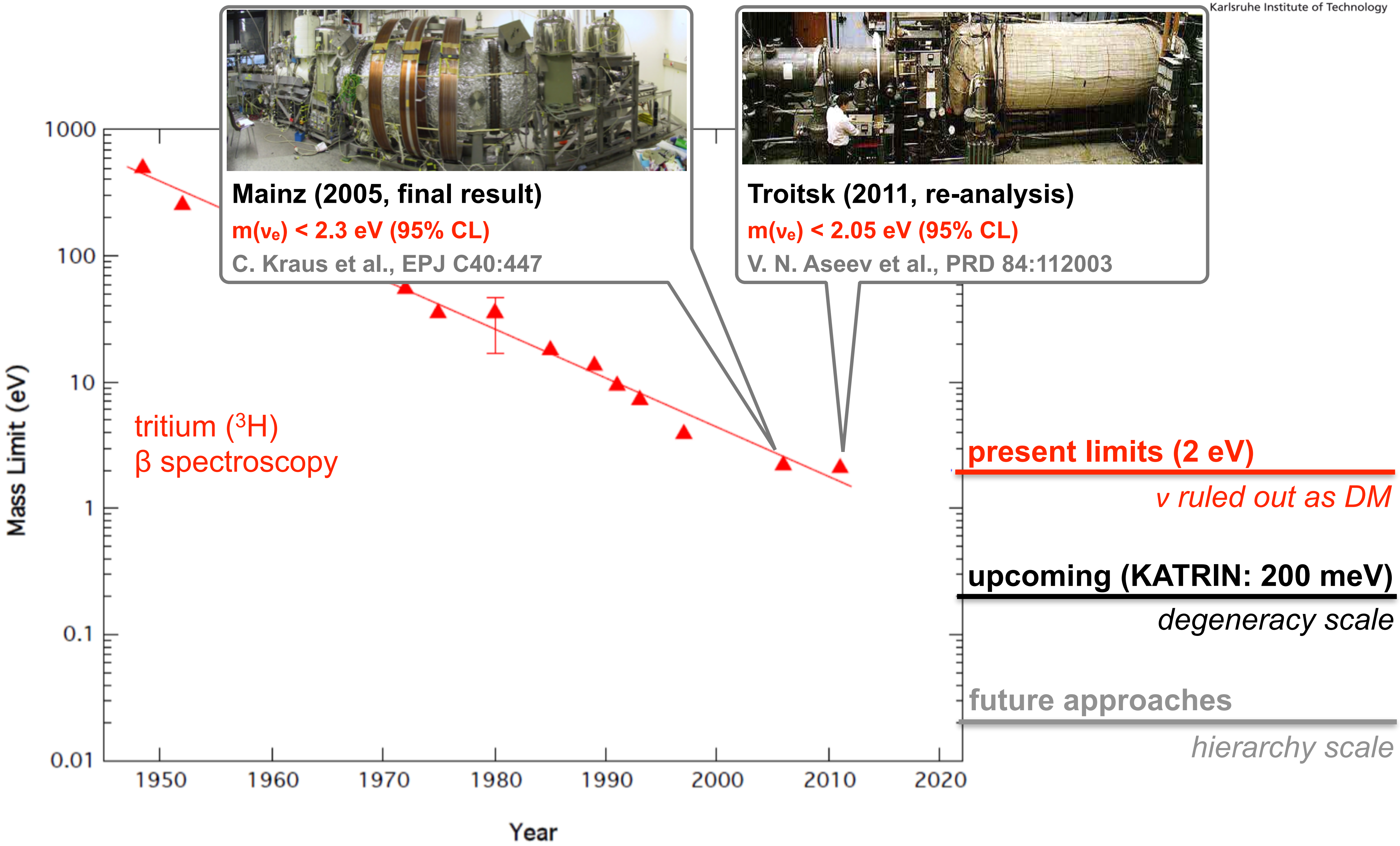
- high-activity source
- low-endpoint β emitter (^{3}**H**) or EC isotope (^{163}**Ho**)
- excellent energy resolution (MAC-E filter or calorimeter)

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

spectral distortion measures **“effective” mass square:**

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

Moore's Law of direct neutrino mass searches

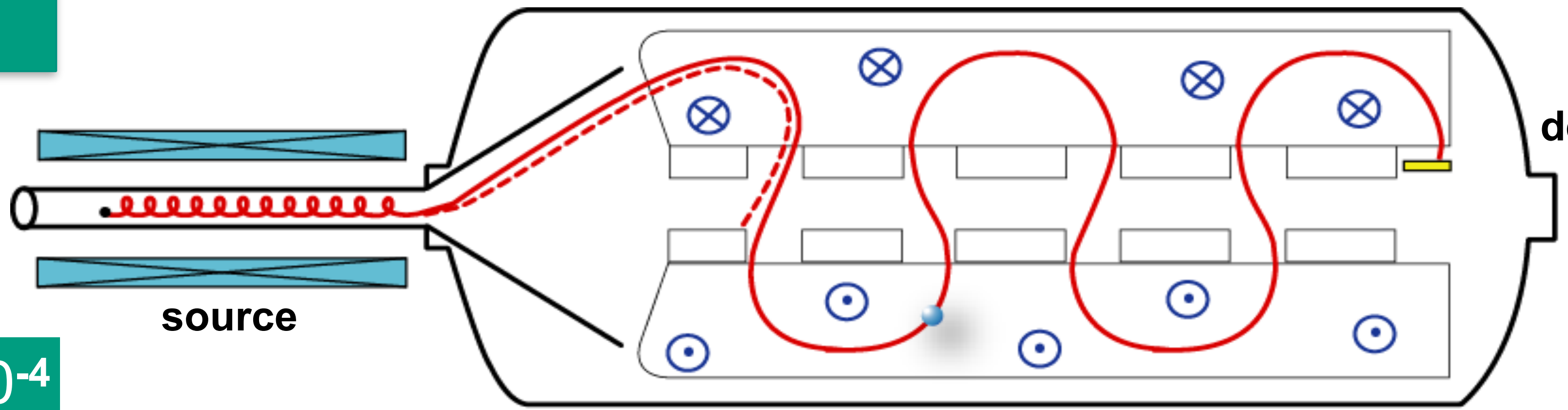


Courtesy J.F. Wilkerson/R.G.H. Robertson

Magnetic vs. electrostatic spectrometers

Karlsruhe Institute of Technology

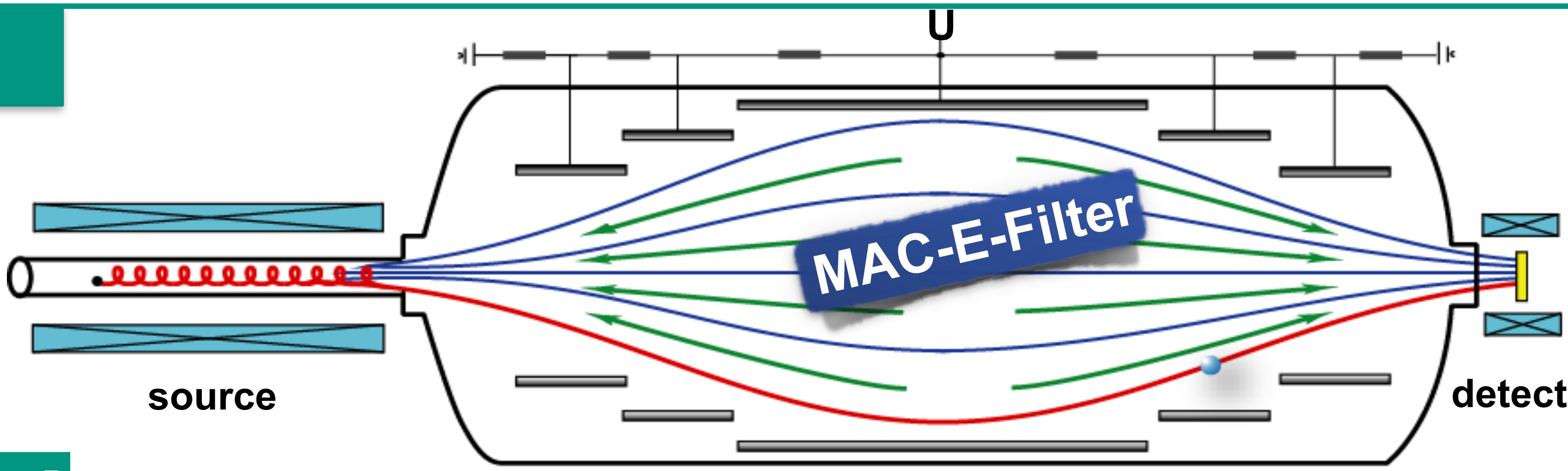
magnetic



$\Delta p/p = 7 \times 10^{-4}$
$\delta\Omega$ small

Principle: magnetic guiding, **momentum analysis**

electrostatic

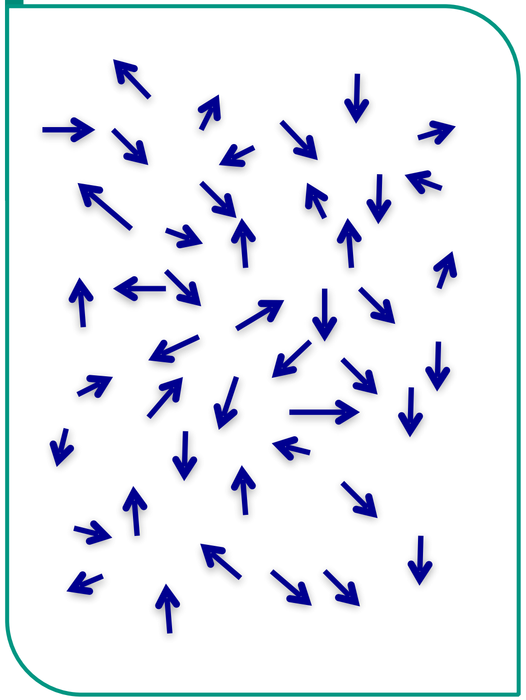


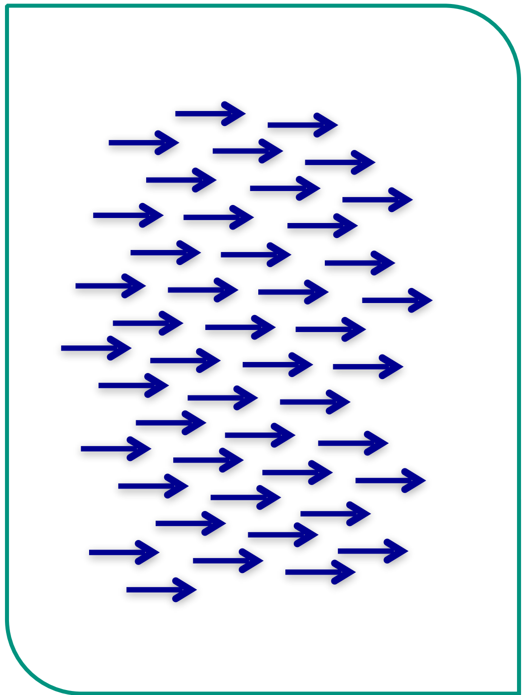
$\Delta E/E = 1 \times 10^{-5}$
$\delta\Omega \sim 2\pi$

Principle: magnetic guiding, transformation cycl. → long. energy, **energy analysis** by retardation potential

MAC-E principle: Mainz, Troitsk, KATRIN

isotropic emission of e$^-$



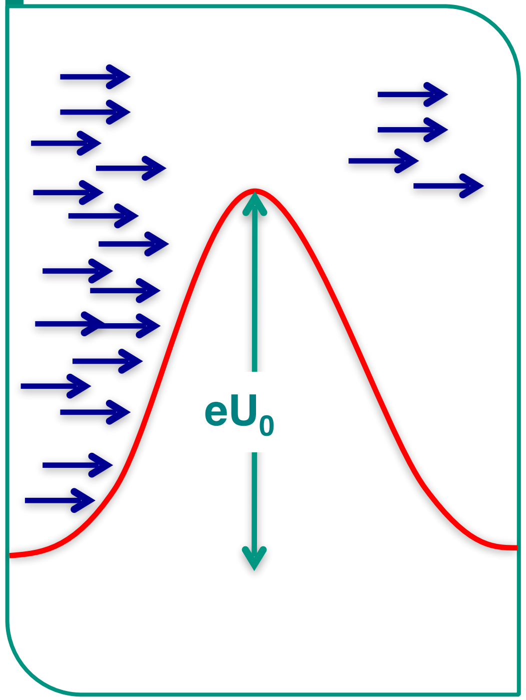


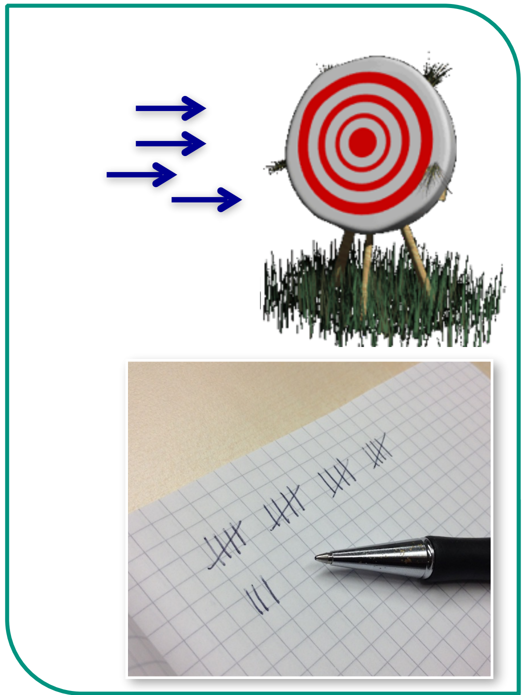
magnetic guiding
& adiabatic collimation

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

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

electrostatic filtering





counting

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

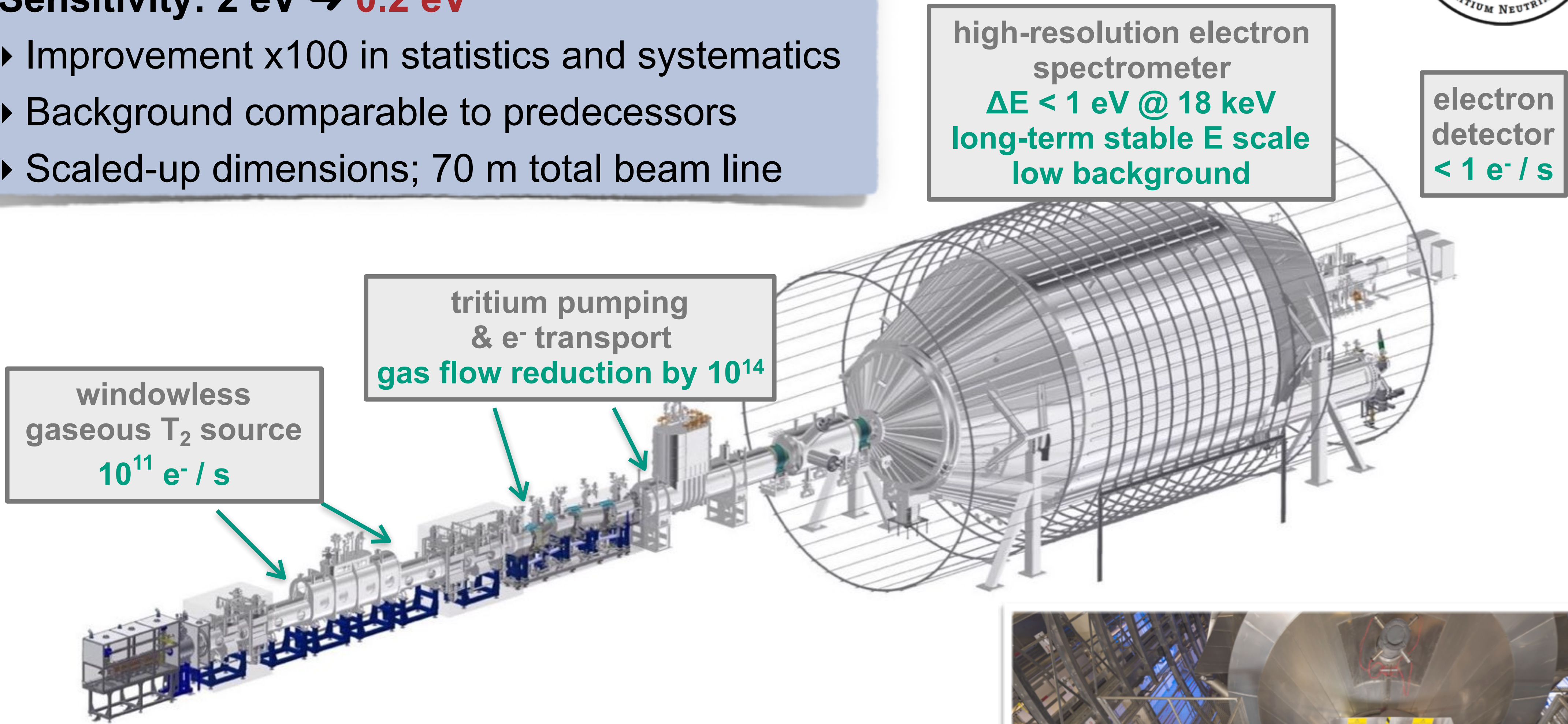
filter width ΔE:

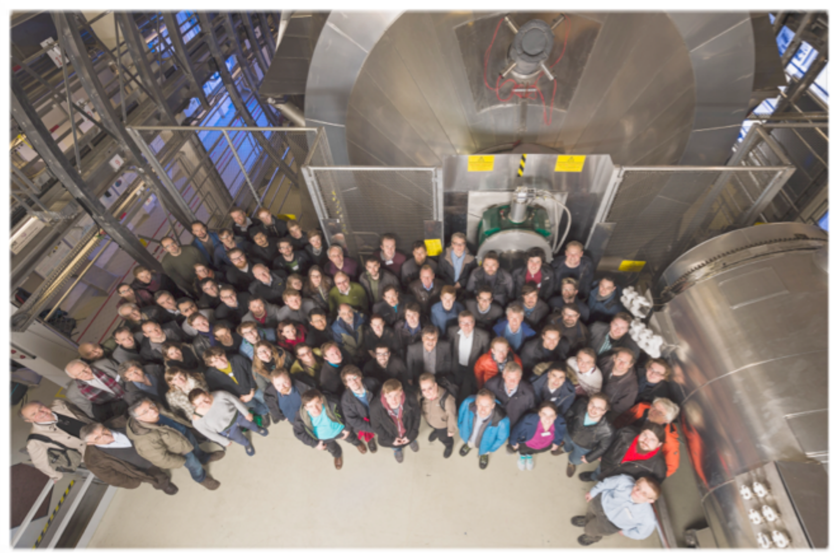
$$\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}}$$

The Karlsruhe Tritium Neutrino Experiment

Sensitivity: 2 eV ➜ 0.2 eV

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





Looks good on paper, but …

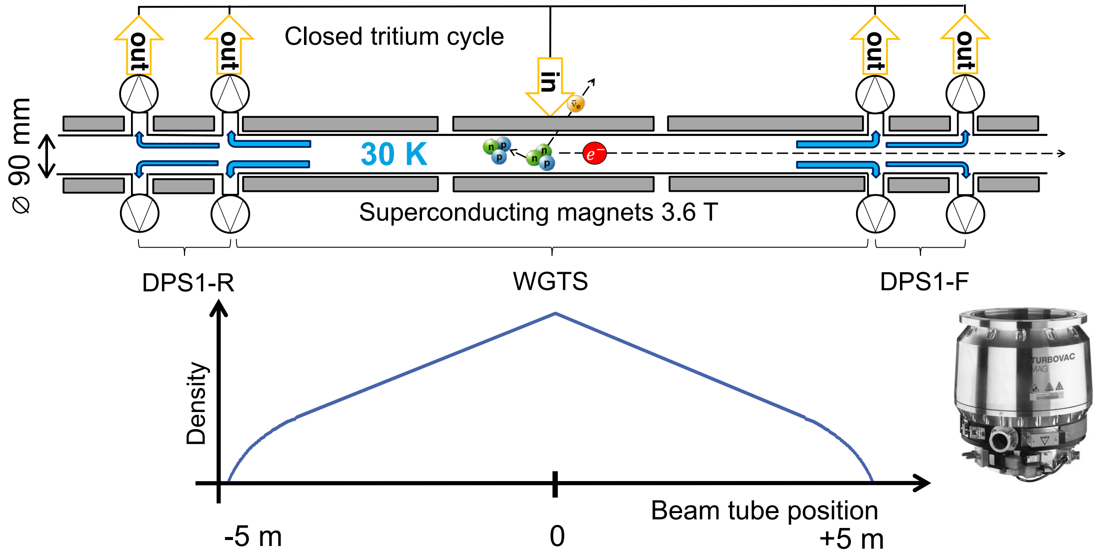
Status of the KATRIN source

Gaseous molecular tritium source of

- high activity (~170 GBq)
- high isotopic purity (ε_T > 95%)
- high stability (0.1%)

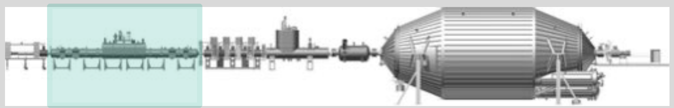
Extensive control of systematics

Gas column: 40% no-loss electrons

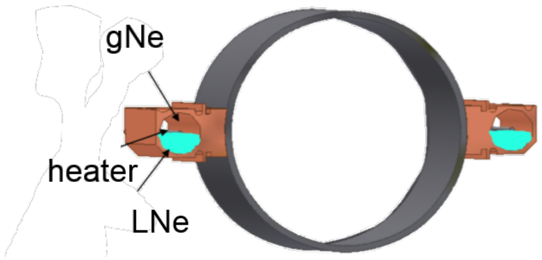


✓ Mechanical and cryo-infrastructure complete

✓ Test of 800 sensors & valves

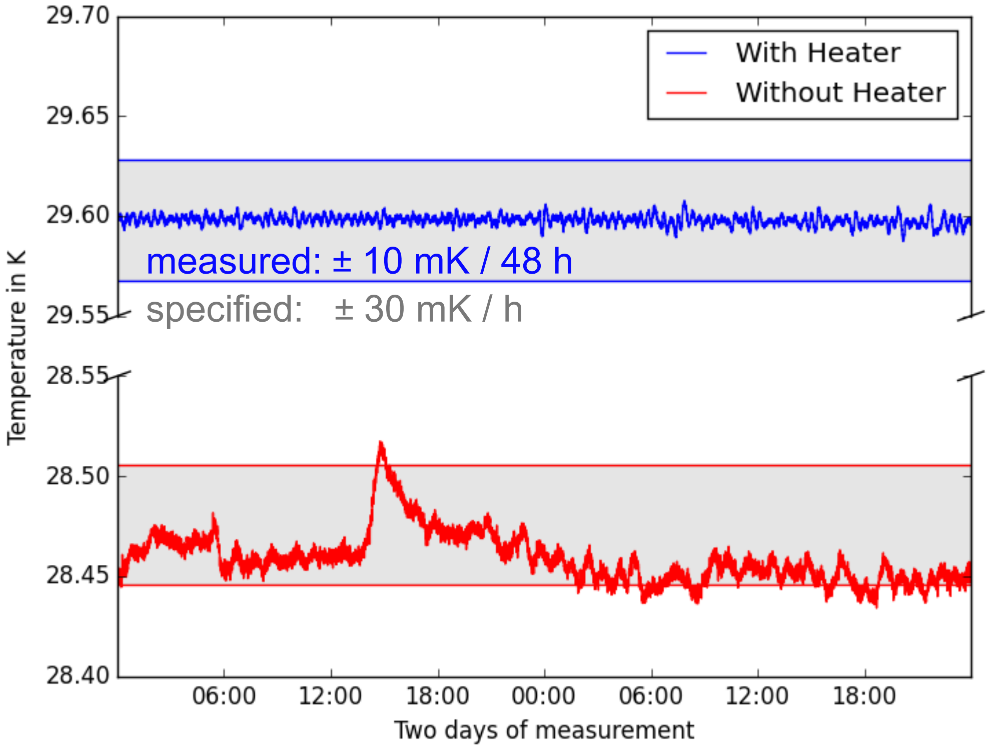


Source: Beam-tube cooling performance

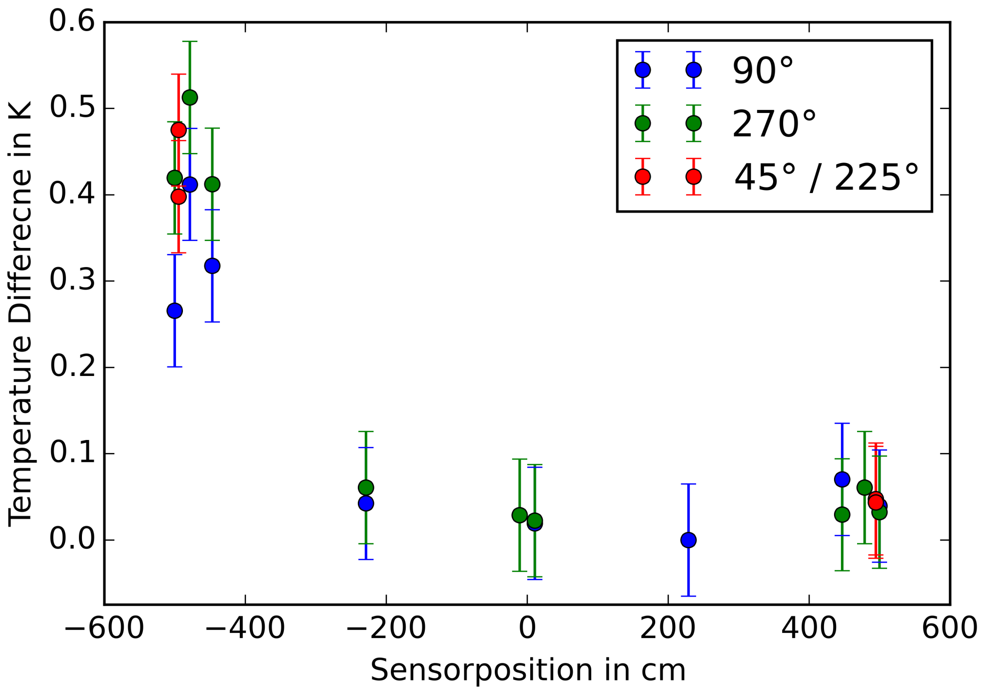


Novel 2-phase neon beam tube cooling system successfully tested (Nov. 2016)

Stability of beam tube temperature surpassing specifications



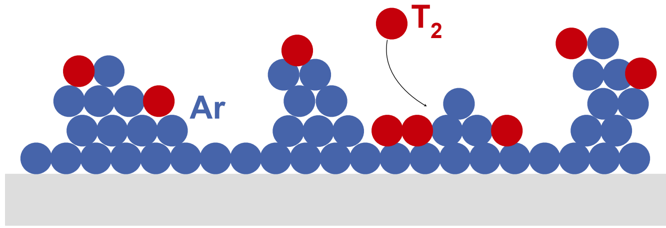
Axial temperature profile along 10 m beam tube



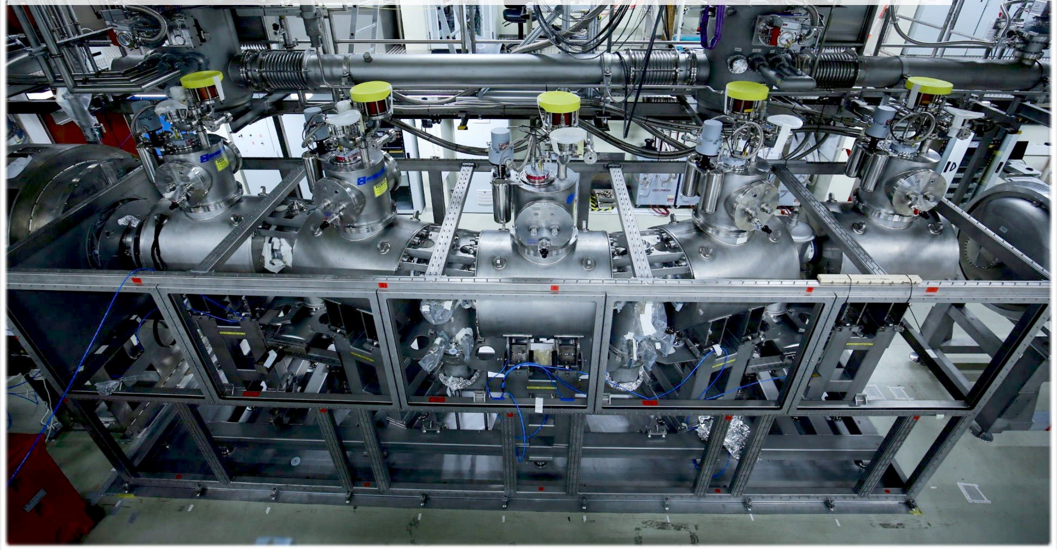
[A. Marsteller, H. Seitz-Moskaliuk]

Status of transport & pumping sections

- fully adiabatic, **lossless electron transport** in 5.6 T magnetic field
- **reduction of T_2 flow rate** towards spectrometers by factor **$>10^{14}$** by magnetic chicane with **differential** and **cryo-pumping**
- **blocking of ion flux** by electrostatic barrier



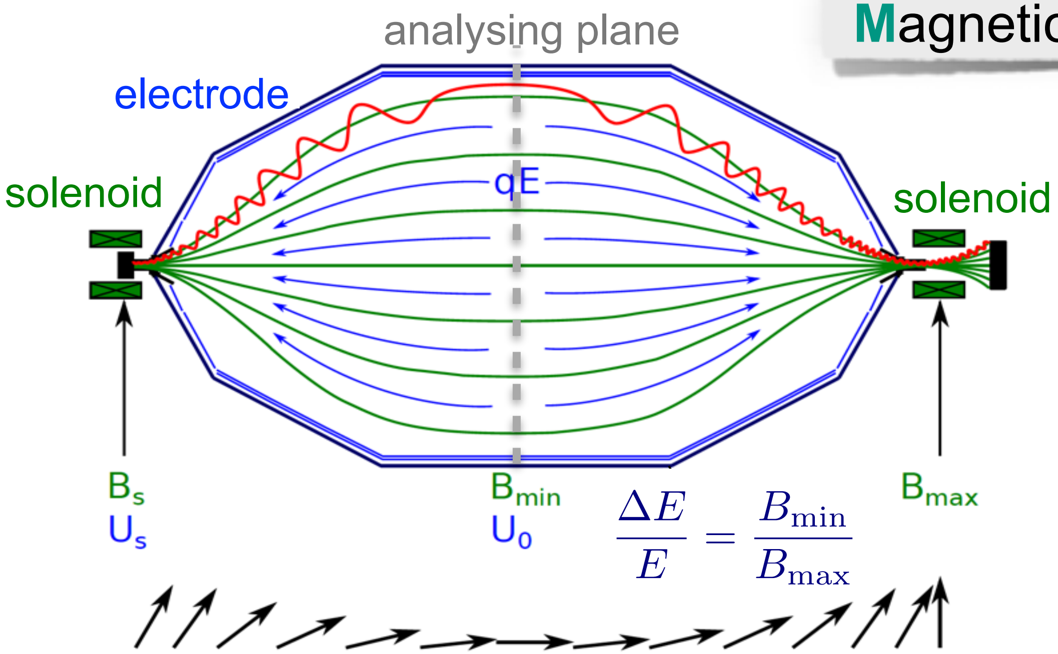
active differential pumping with TMPs
status: magnets, beam tubes installed & tested,
next: instrumentation (FT-ICR)



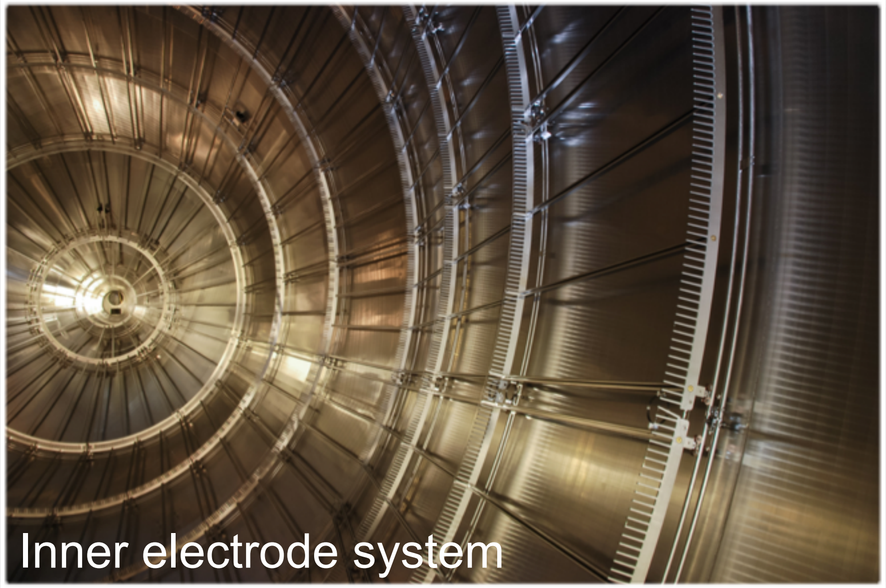
passive cryo-pumping with Ar frost at 3-4 K
status: cool-down to 3.5 K successful, s.c. magnets operational; ***next:*** Ar operation tests

KATRIN spectrometer status

Magnetic **A**diabatic **C**ollimation and **E**lectrostatic **Filter**

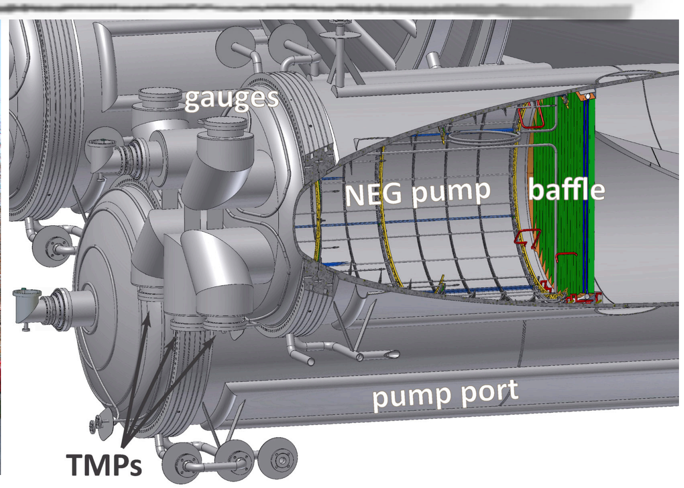


$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$



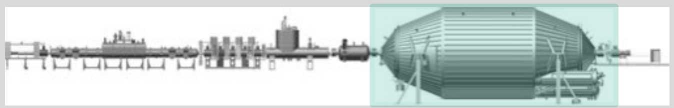
Inner electrode system

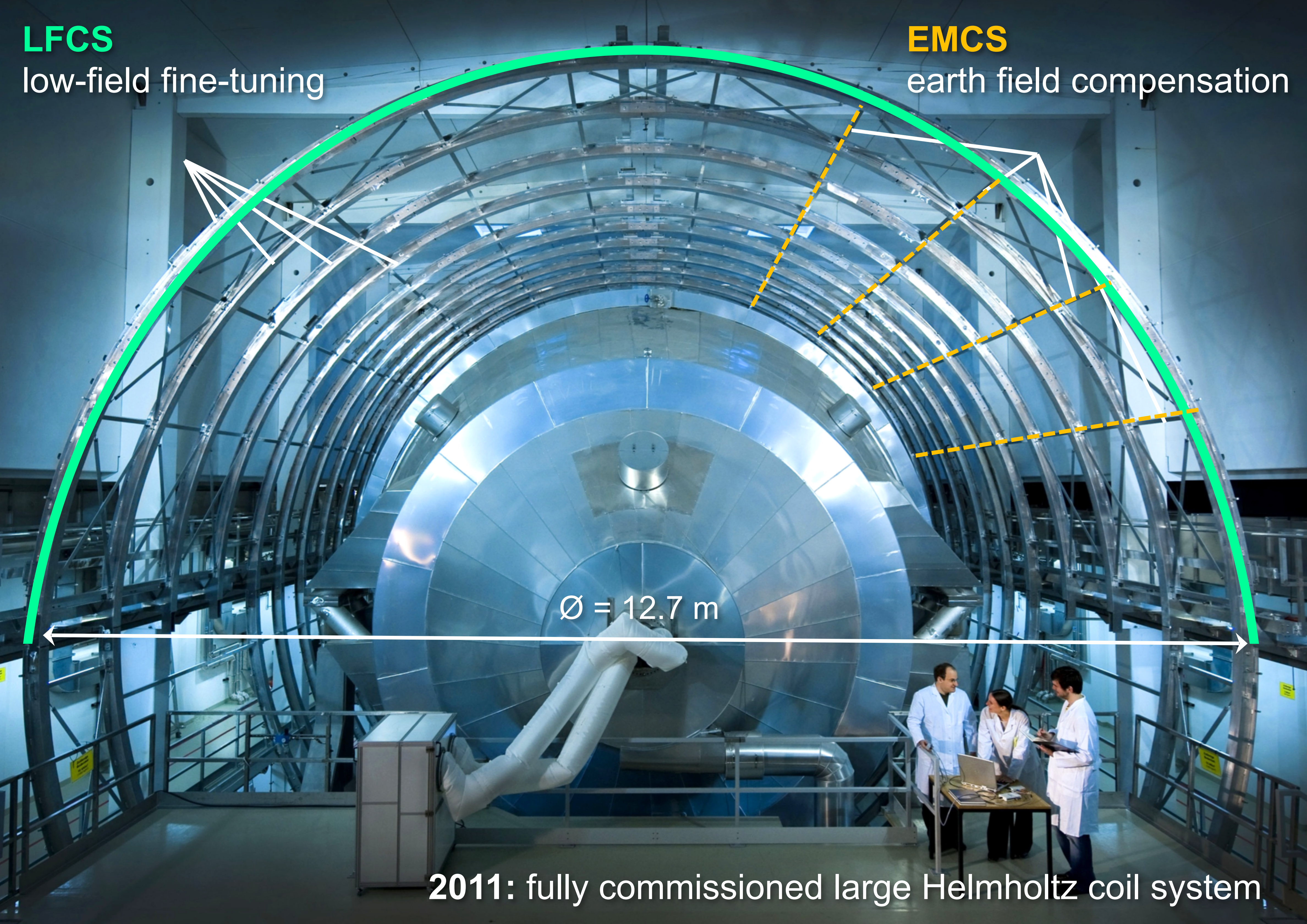
UHV system for ~1500 m^3 spectrometer
p ~ 10^{-11} mbar

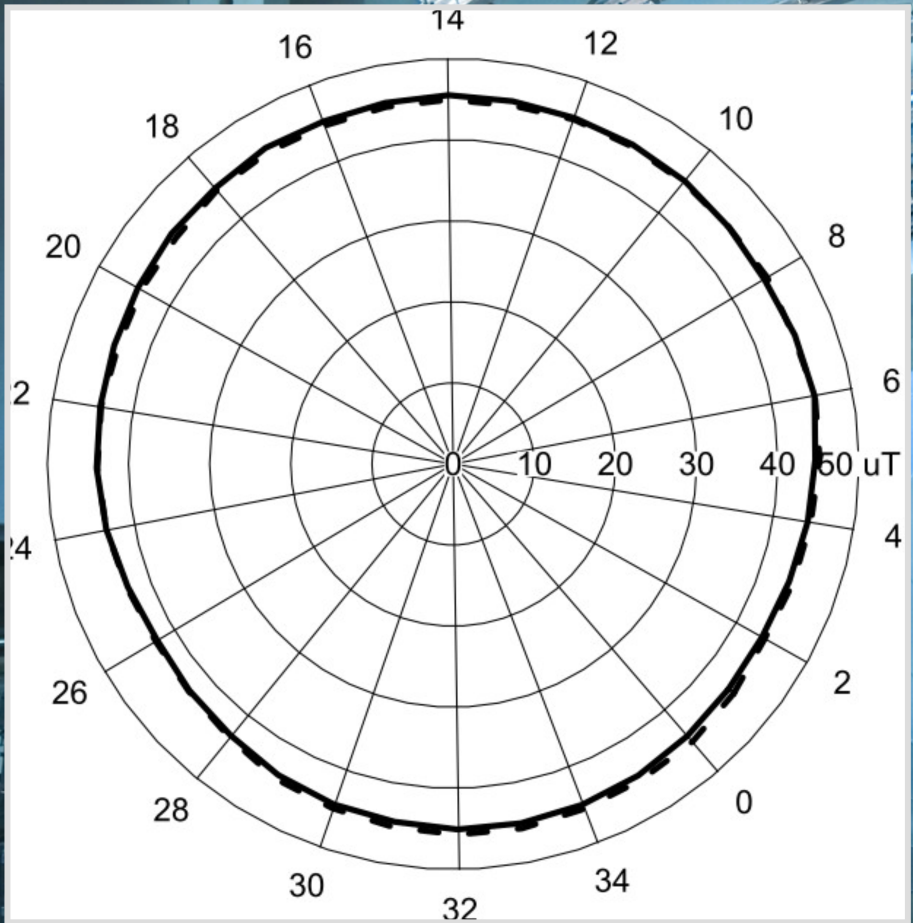


[Arenz *et al.*, JINST 2016]

Large Helmholtz coil system




LFCS
low-field fine-tuning
EMCS
earth field compensation
Ø = 12.7 m
2011: fully commissioned large Helmholtz coil system

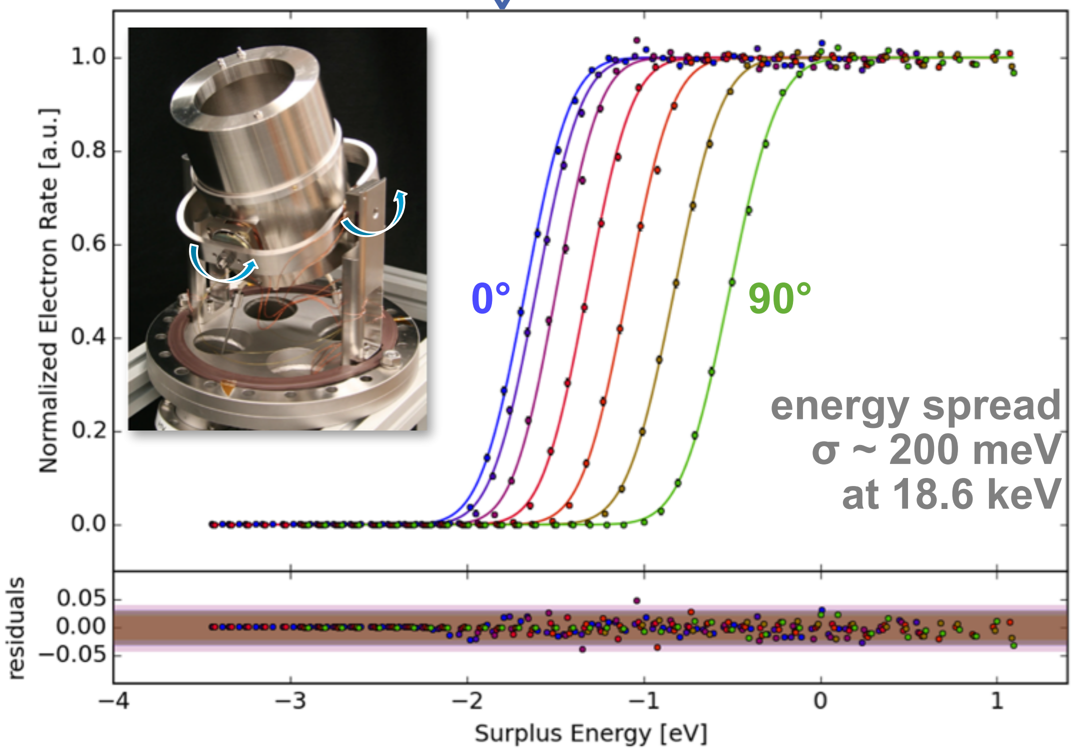


9/2014: de-gaussing of experimental hall

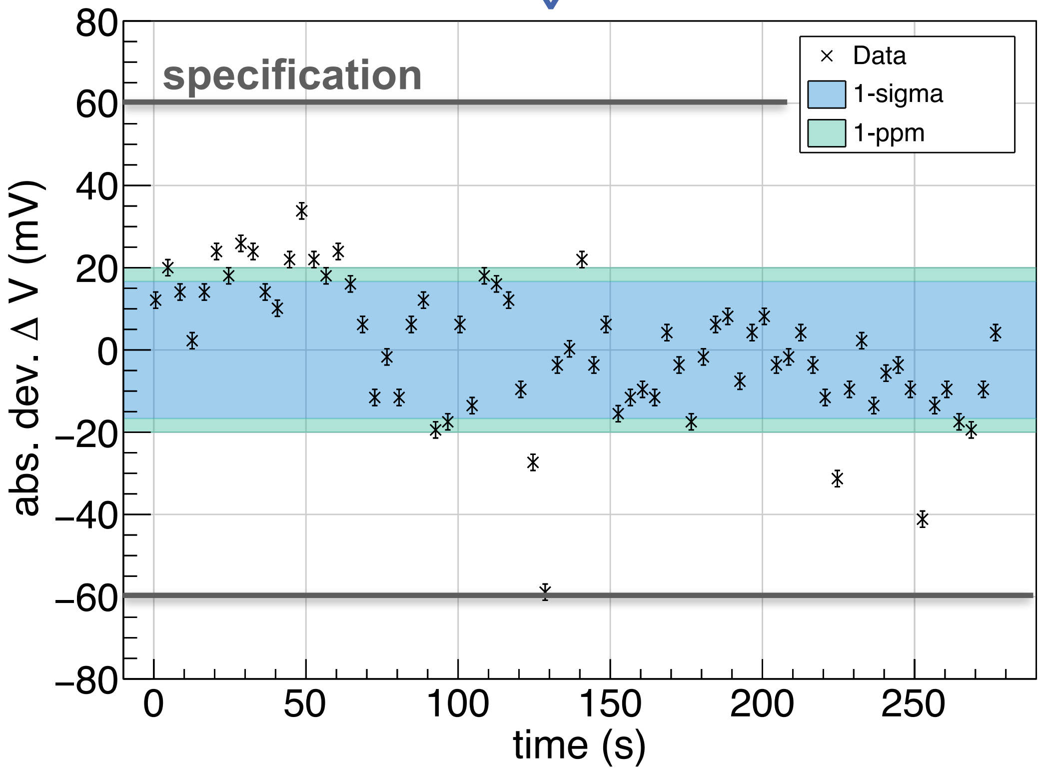
KATRIN spectrometer: filter characteristics

2013-2015

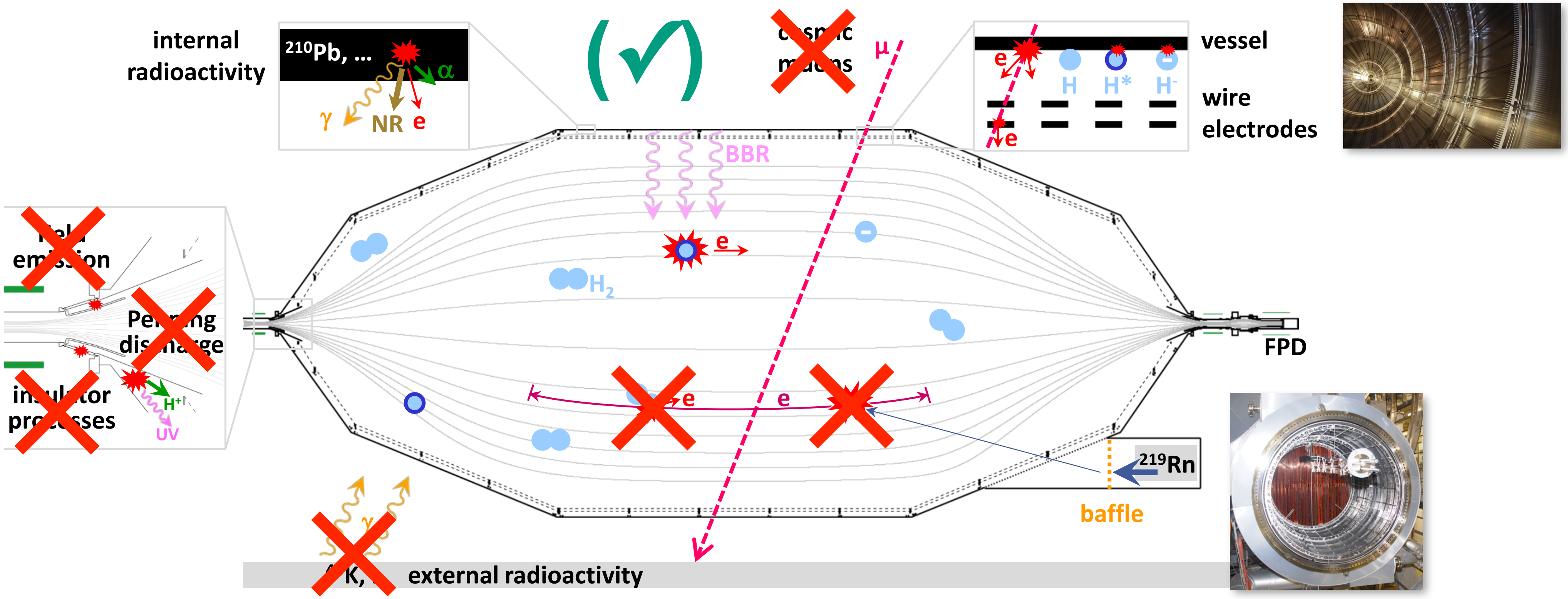
energy filter works as expected (limited by e-gun)



HV stability (post-regulation): $\Delta U/U \sim 1$ ppm



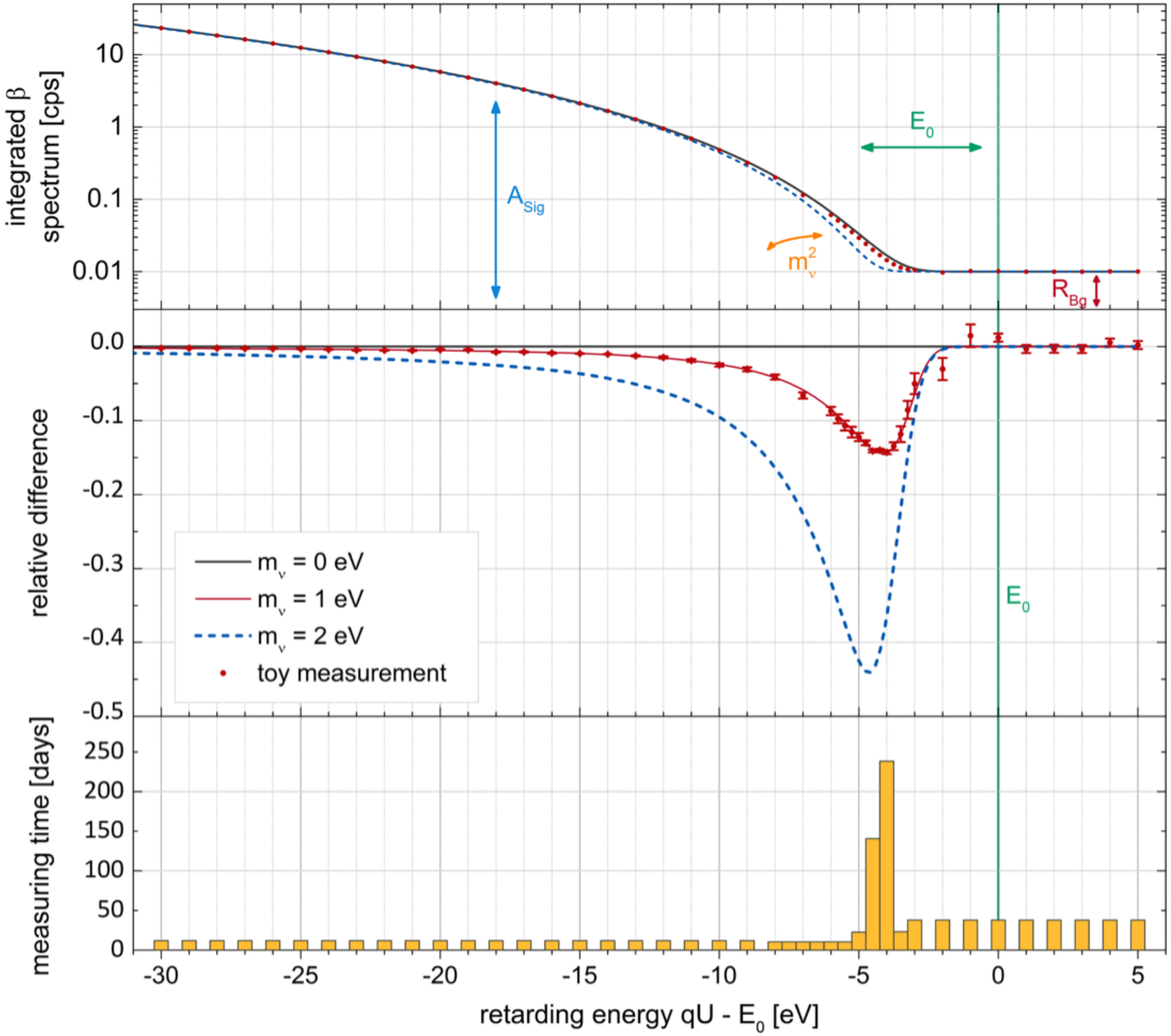
Background mitigation in MAC-E filters



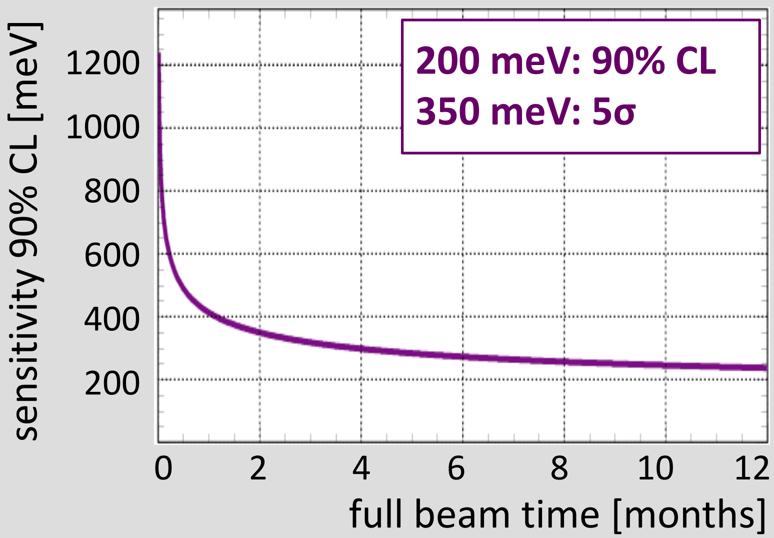
- **8 sources of background investigated and understood**
- **7 out of 8 avoided or actively eliminated by**
  - fine-shaping of special electrodes
  - symmetric magnetic fields
  - LN_2-cooled baffles (cold traps)
  - wire electrode grids

- **1 out of 8 remaining:**
  caused by ^{210}Pb on spectrometer walls (neutral H* atoms ionised by black-body radiation in spectrometer)

KATRIN: ν-mass sensitivity



- Relative **shape** measurement of **integrated β spectrum**
- 4 fit parameters:
  m^2_ν , E_0 , A_S , R_{Bg}
- After **3 yrs** of data (~5 cal. yrs): balance of statistics and systematics



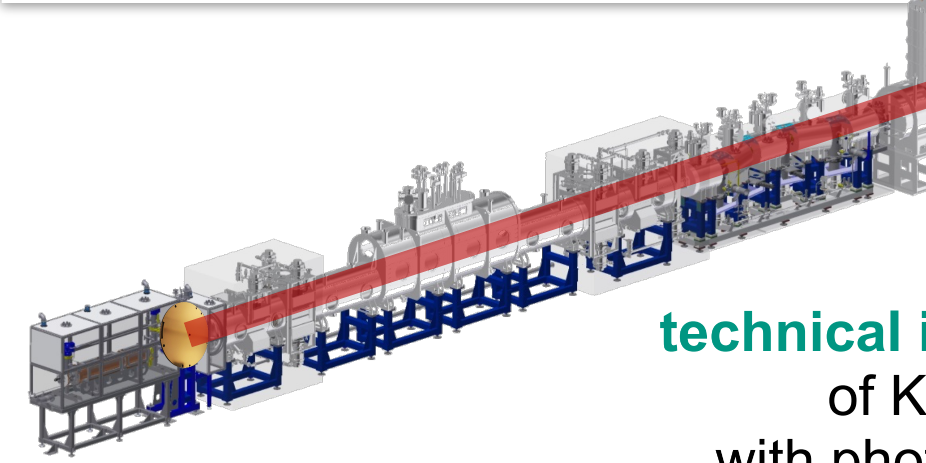
KATRIN milestone: “First Light”

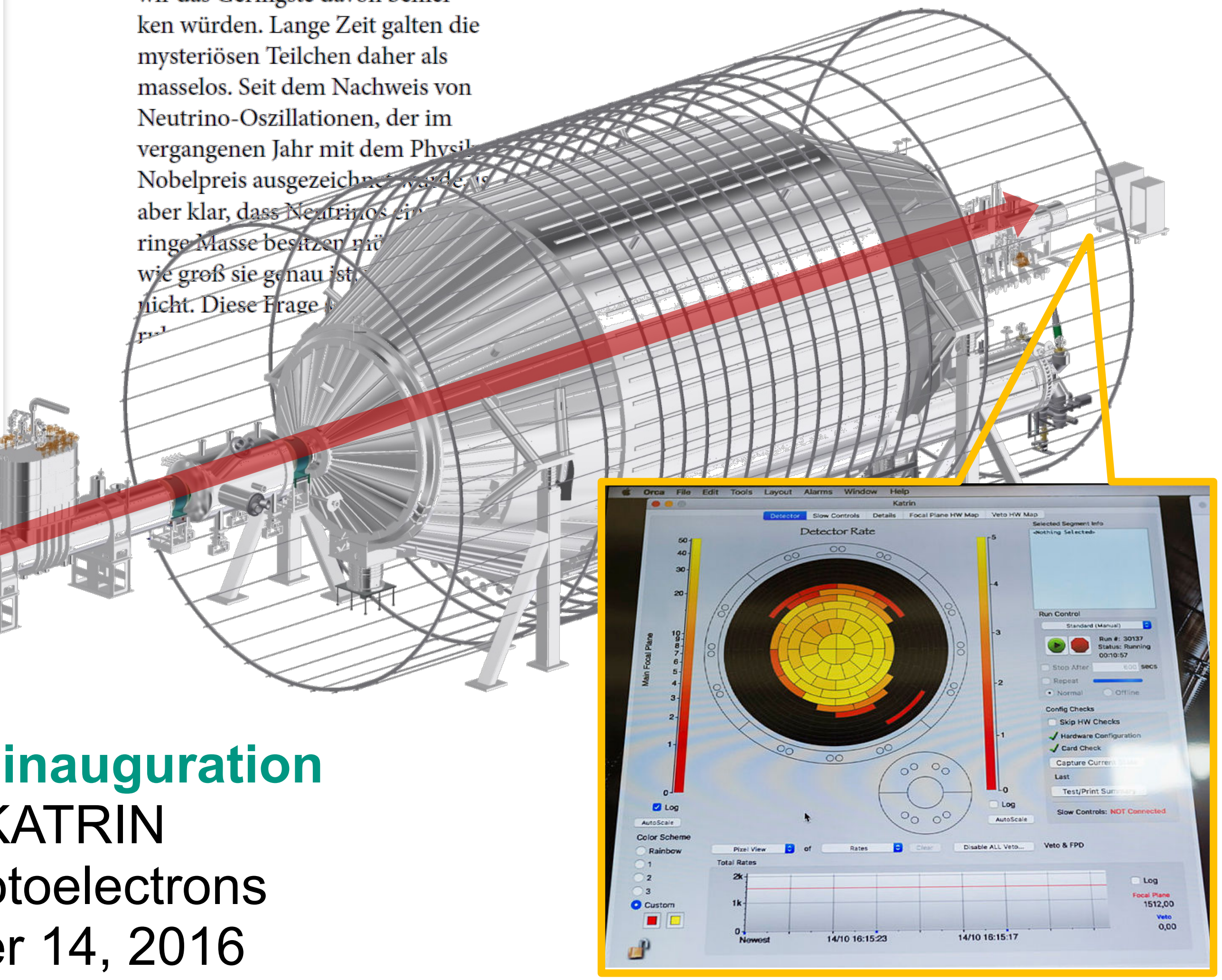
Karlsruhe Institute of Technology

Neutrinos auf der Waage DPG

Am 14. Oktober durchflogen erstmals Elektronen das Experiment KATRIN am Karlsruher Institut für Technologie

Neutrinos durchdringen uns jede Sekunde milliardenfach, ohne dass wir das Geringste davon bemerken würden. Lange Zeit galten die mysteriösen Teilchen daher als masselos. Seit dem Nachweis von Neutrino-Oszillationen, der im vergangenen Jahr mit dem Physi Nobelpreis ausgezeichn aber klar, dass Neutrinos ei ringe Masse besitzen m wie groß sie genau ist nicht. Diese Frage





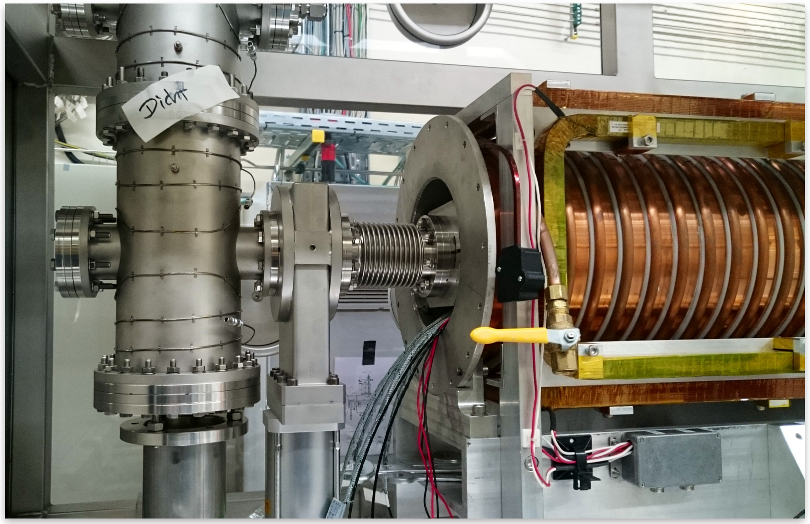
technical inauguration
of KATRIN
with photoelectrons
October 14, 2016

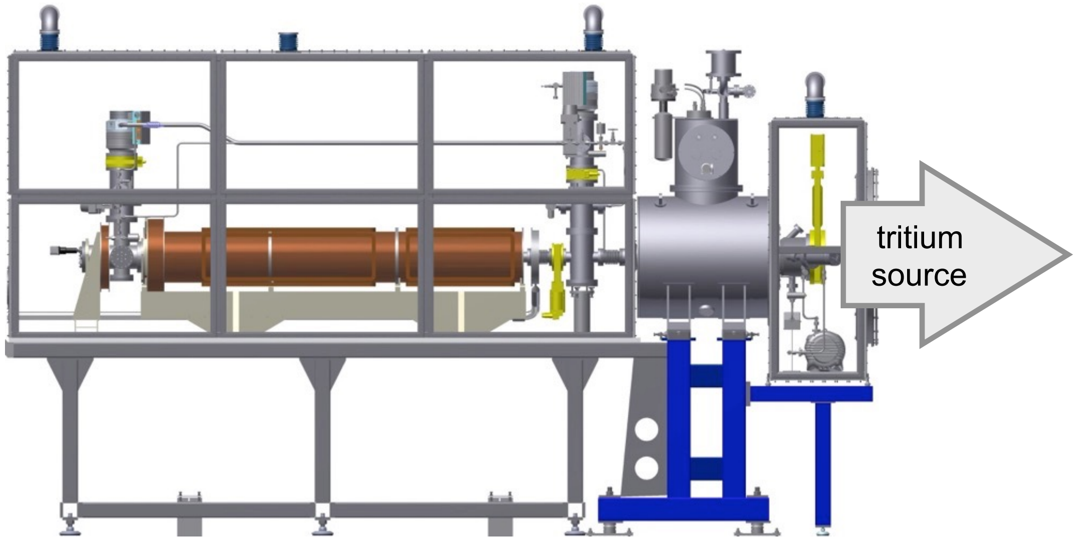
KATRIN: Next steps

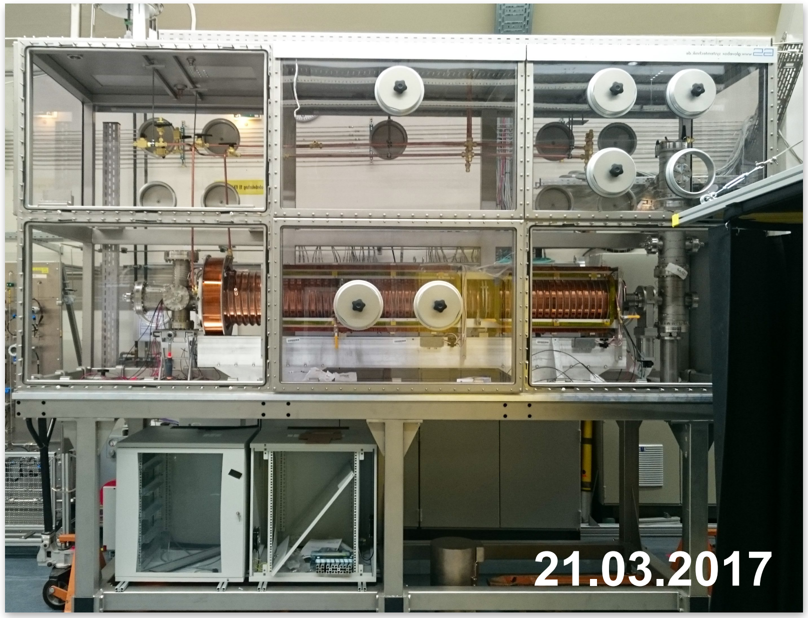
Installation of precision electron source ("e-gun")

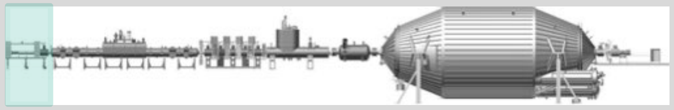
Major importance for systematics:

- precision determination of overall transmission function (requirements: ~few degree angular selectivity and ~100 meV energy resolution)
- determination of energy loss function
- in-line column density monitoring







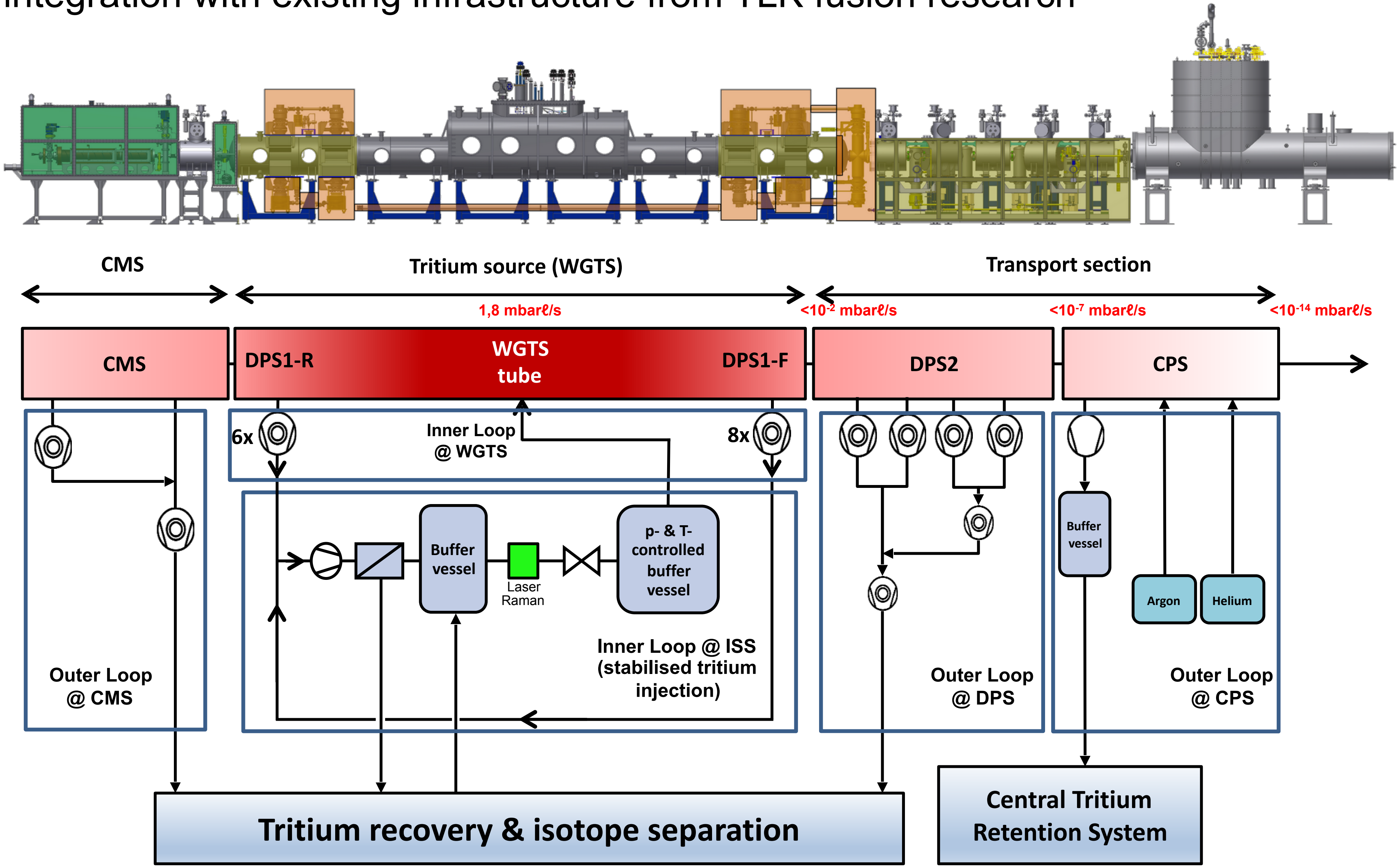


[K. Valerius et al., JINST 6 (2011) P01002;
J. Behrens et al., arXiv:1703.05272]

KATRIN: Next steps

Connection & testing of tritium gas circuits

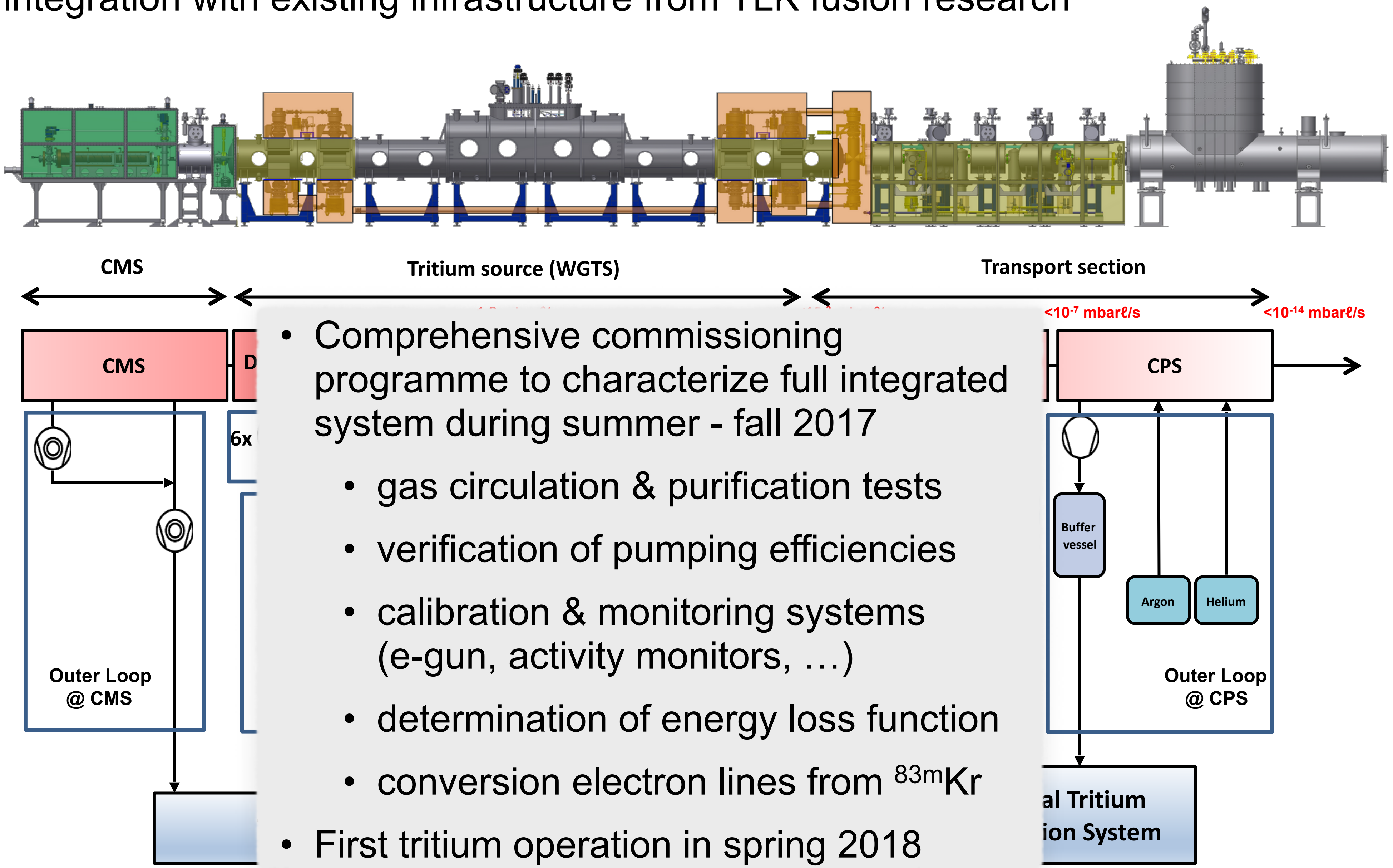
integration with existing infrastructure from TLK fusion research



KATRIN: Next steps

Connection & testing of tritium gas circuits

integration with existing infrastructure from TLK fusion research



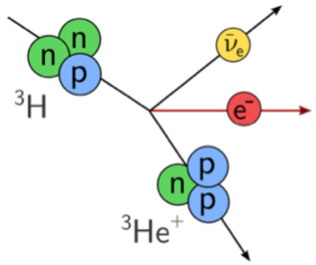
- Comprehensive commissioning programme to characterize full integrated system during summer - fall 2017
  - gas circulation & purification tests
  - verification of pumping efficiencies
  - calibration & monitoring systems (e-gun, activity monitors, …)
  - determination of energy loss function
  - conversion electron lines from ^{83m}Kr
- First tritium operation in spring 2018

Intermediate summary

- Discovery of non-zero neutrino masses ➜ incompleteness of the Standard Model

- Mass scale & pattern remain to be uncovered!
- Increasingly stringent bounds from cosmology ➜ ΛCDM paradigm

- Direct neutrino mass determination using kinematics (^{3}H β decay)



- KATRIN experiment in final commissioning phase
  ➜ start data-taking in spring 2018

Stay tuned!

How to further improve ν-mass sensitivity?

Problems:

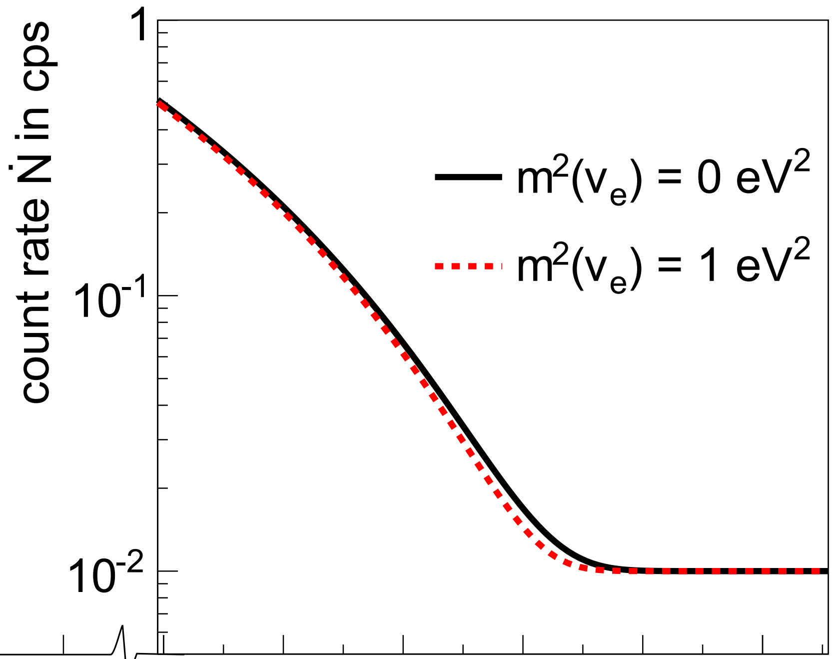
MAC-E technique does not scale further

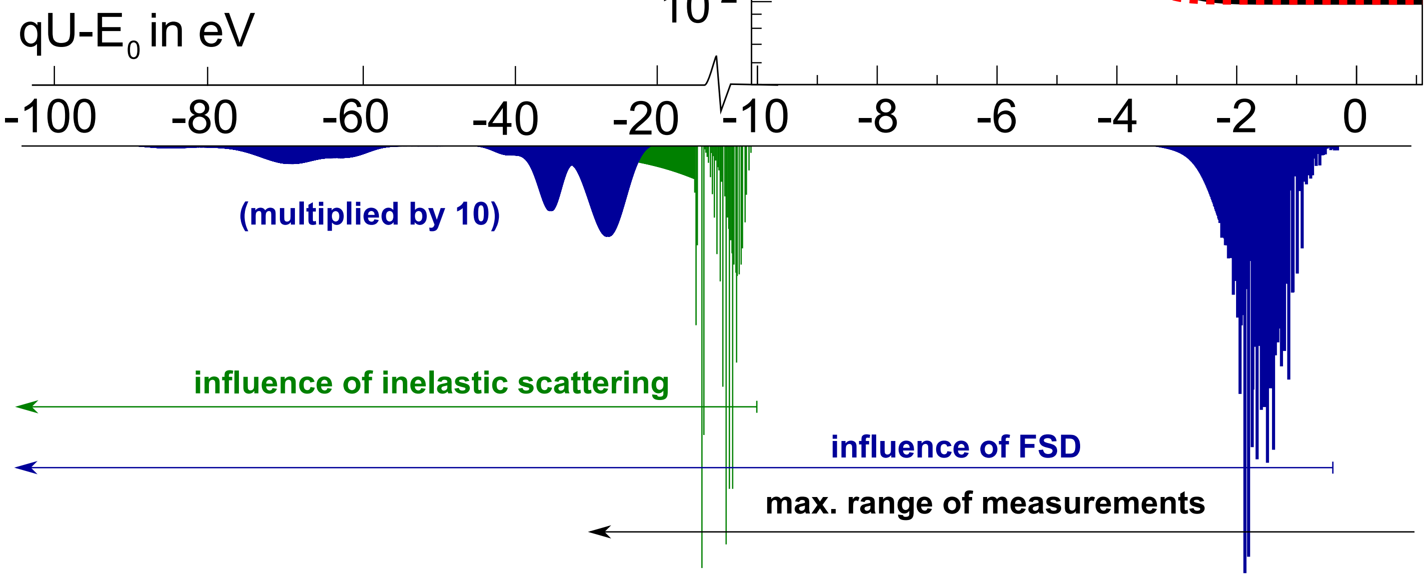
- energy resolution
- source luminosity

∅100 m spectrometer ???

Integrated β spectrum: loss of information

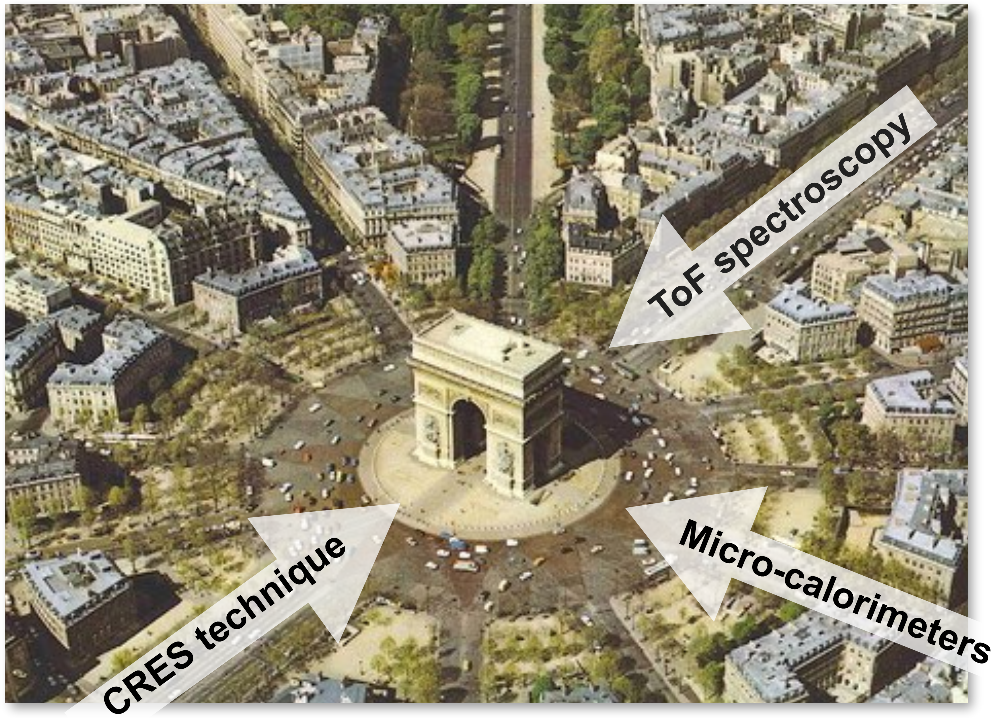
Final state uncertainty in molecular T_2





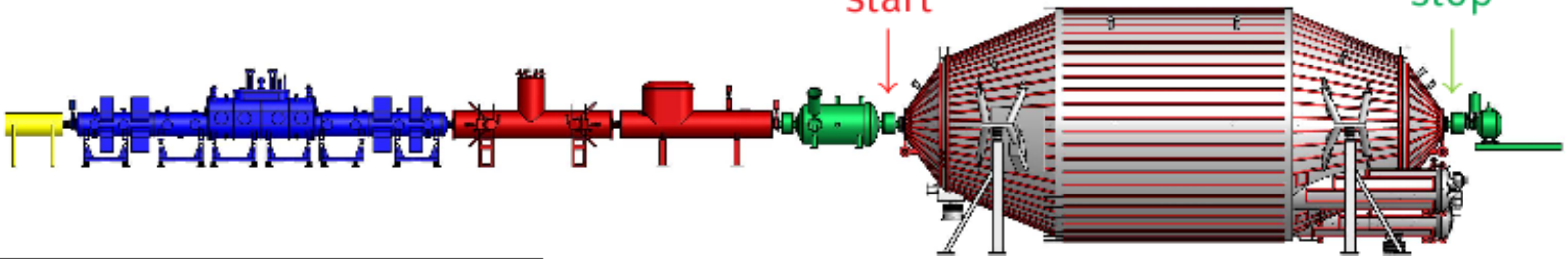
New developments

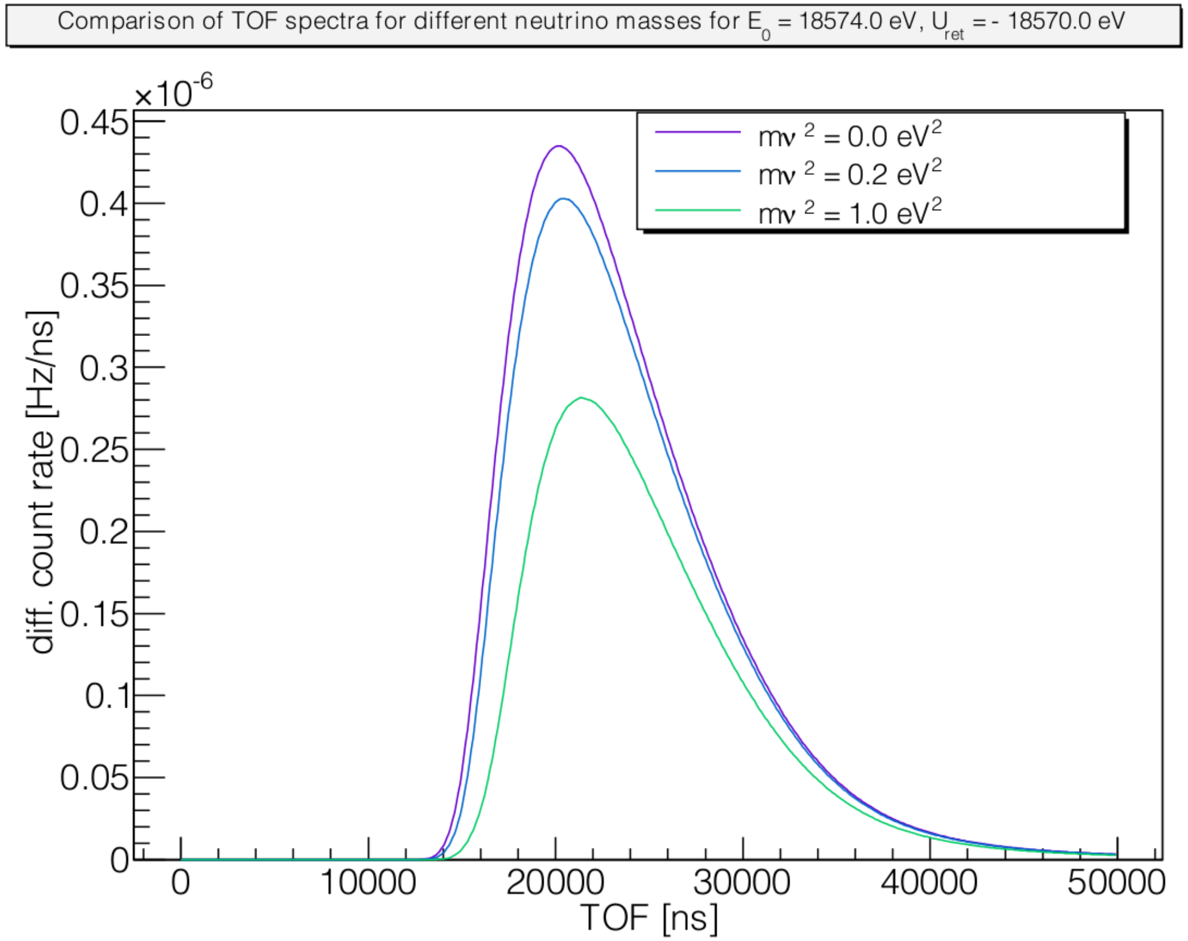
Several avenues towards improvement:



1st avenue: exploit differential β spectrum

Idea: Upgrade to MAC-E-TOF spectrometer





Spectrometer as 24 m long "delay line"
➜ very sensitive to small differences in surplus energy

TOF spectrum records full β spectrum
➜ save meas. time by using only few voltage settings of MAC-E filter

Coincidence requirement
➜ add. background suppression

Technical realization?
(a) pre-spectrometer as gated filter
(b) radio frequency tagger

[Bonn et al. (1999), Steinbrink et al. (2013), Robertson et al. (in prep.)]

2nd avenue: alternative spectroscopic technique

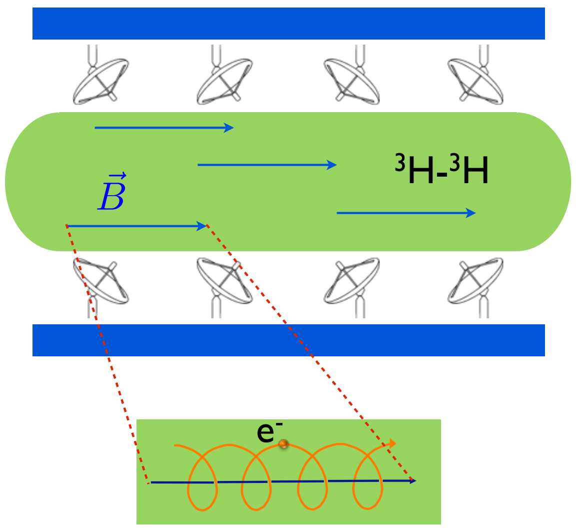
PROJECT 8

UW Seattle, MIT, UCSB,
Pacific NW, CfA, Yale,
Livermore, KIT, U Mainz

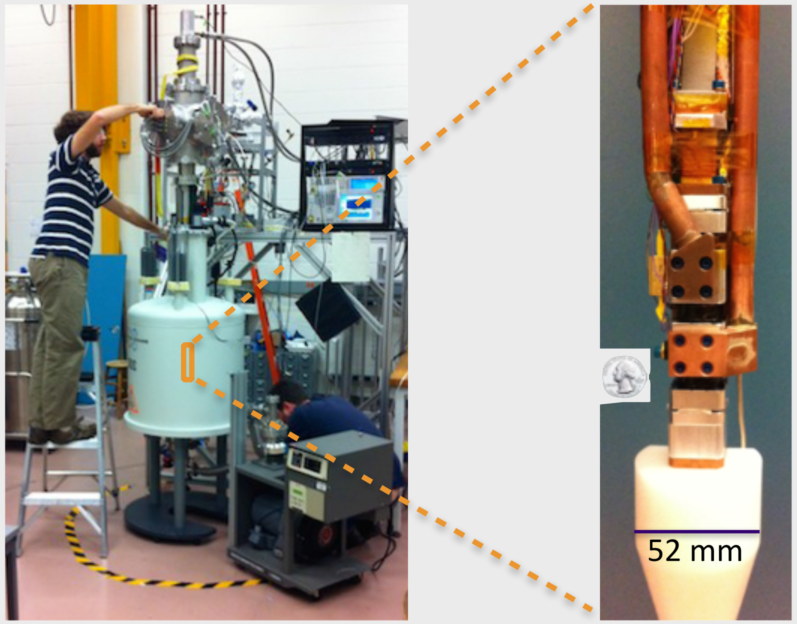
Idea: Cyclotron Radiation Emission Spectroscopy (CRES)

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

$$\omega(\gamma) = \frac{\omega_c}{\gamma} = \frac{eB}{E_{\mathrm{kin}} + m_e}$$



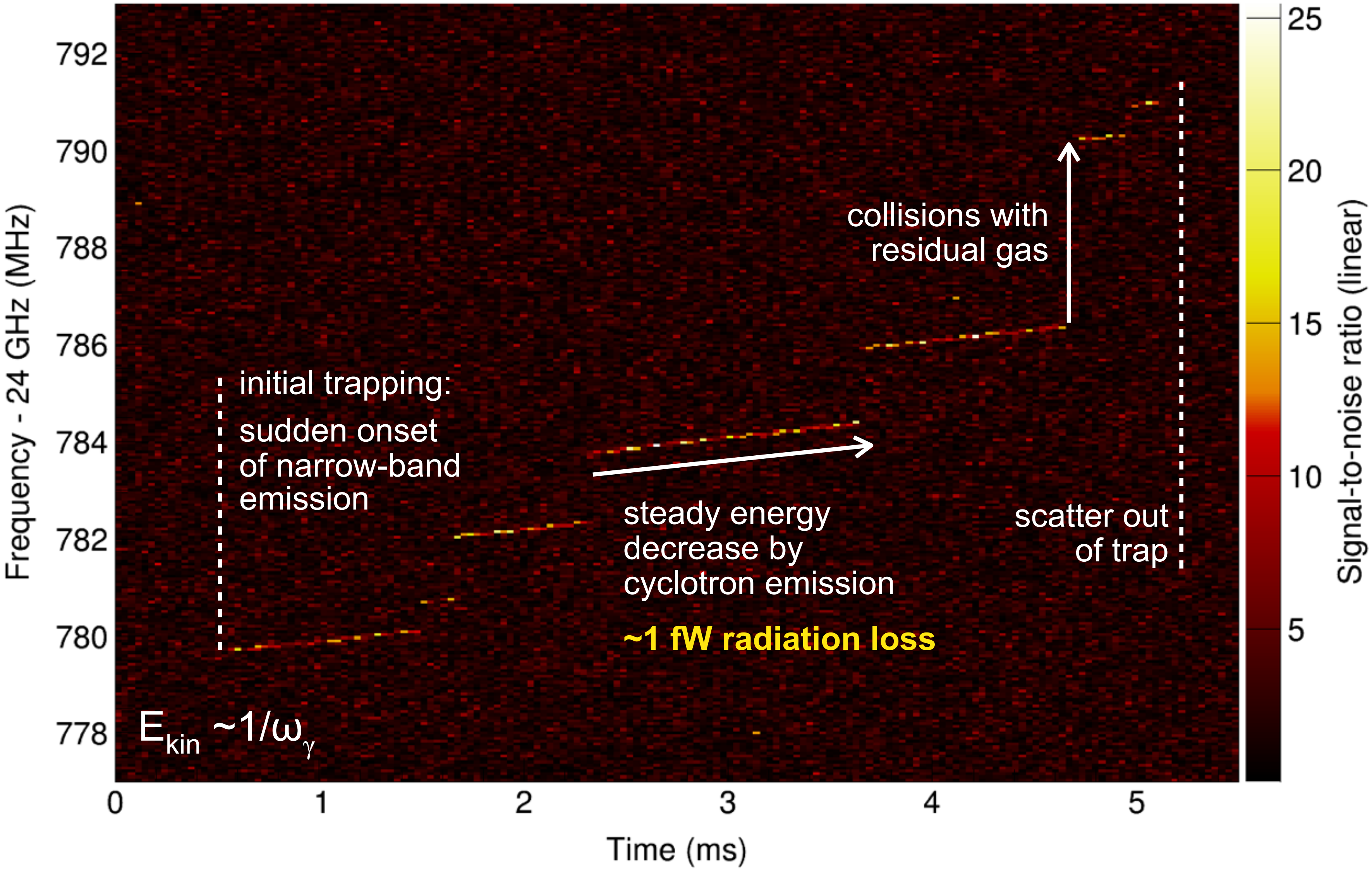
Phase I system



➜ Proof of principle of CRES technique

Project 8 – phase I results

First observation of cyclotron radiation from single electrons

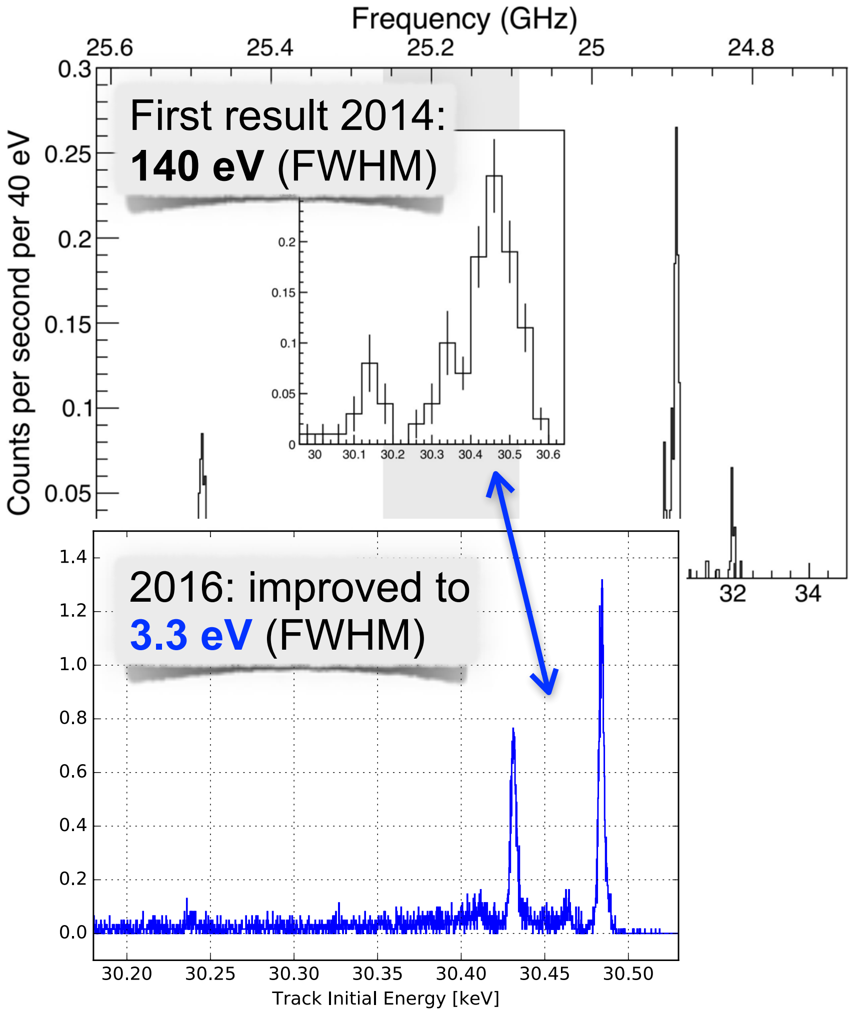


[Asner *et al.*, PRL 114 (2015) 162501]

Project 8 – next goals

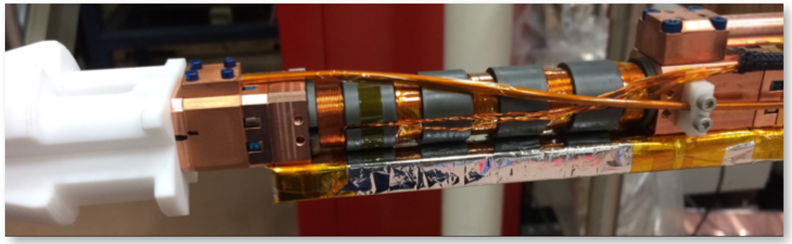
Karlsruhe Institute of Technology

- **Phase I (2010-2016)**
  - Demonstration of CRES method
  - Conversion electron lines from ^{83m}Kr



- **Phase II (2015-2017)**
  - Spectroscopy of continuous T_2 spectrum
  - Systematics, energy resolution

R&D



- **Phase III (2016-2020)**

  10-20 cm^3 eff. source volume (1 yr)
  phased-array antenna
  sensitivity goal: 2 eV (90% CL)

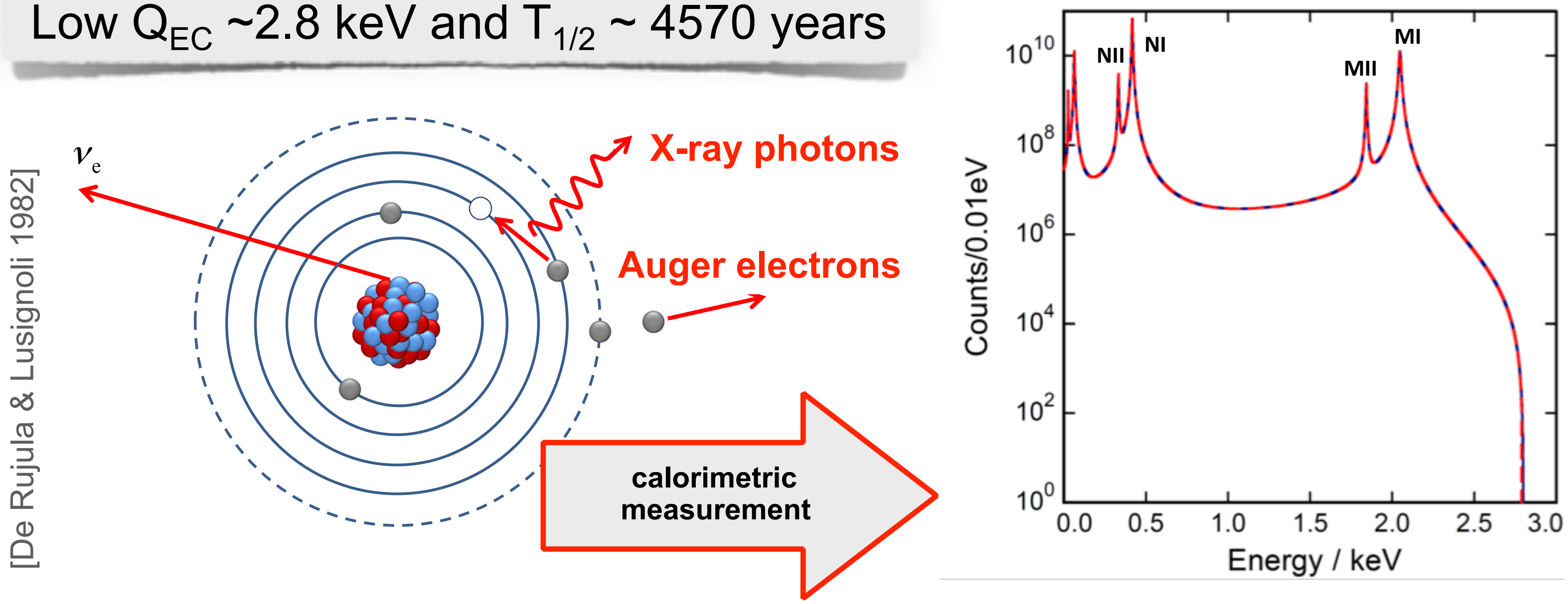
- **Phase IV**

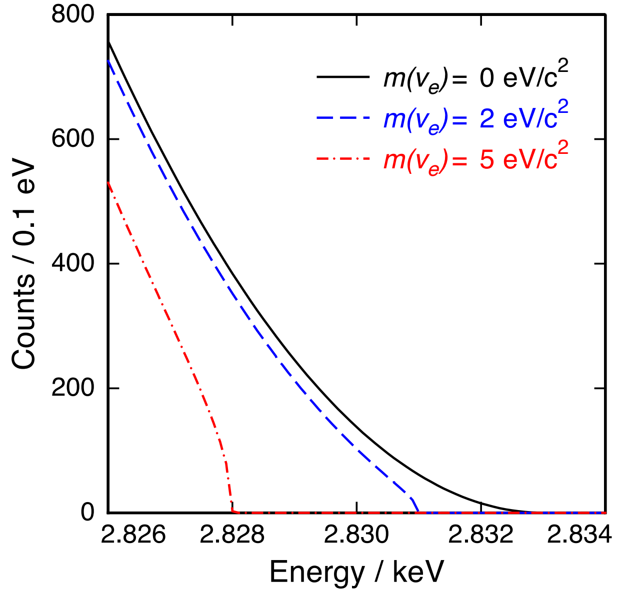
  Large-scale exp., with atomic tritium source,
  for sub-eV sensitivity (hierarchy scale)

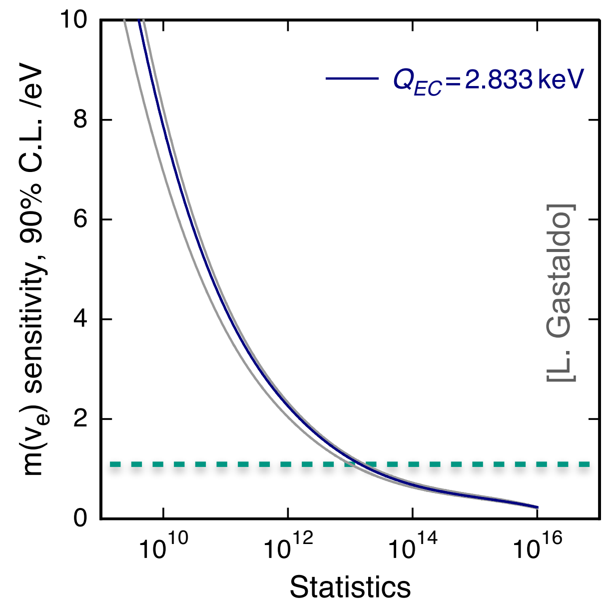
3rd avenue: calorimetric measurement with ^{163}Ho

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

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





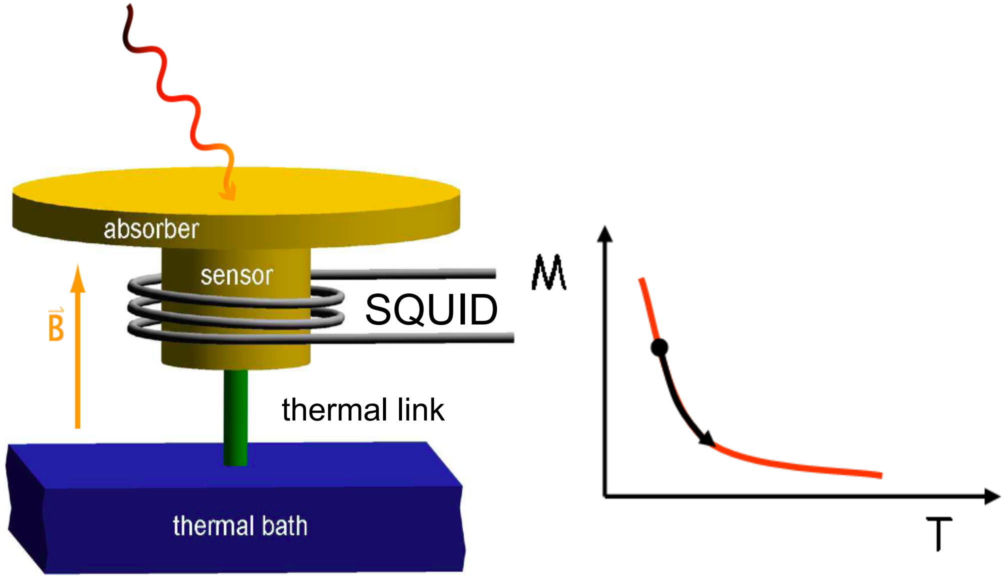


Challenges:

- production & purification of isotope ^{163}Ho
- incorporation of ^{163}Ho into high-resolution detectors
- operation & readout of large calorimeter arrays
- detailed understanding of calorimetric spectrum (nuclear & atomic physics + detector response)

Calorimeters to measure ^{163}Dy* atomic de-excitation

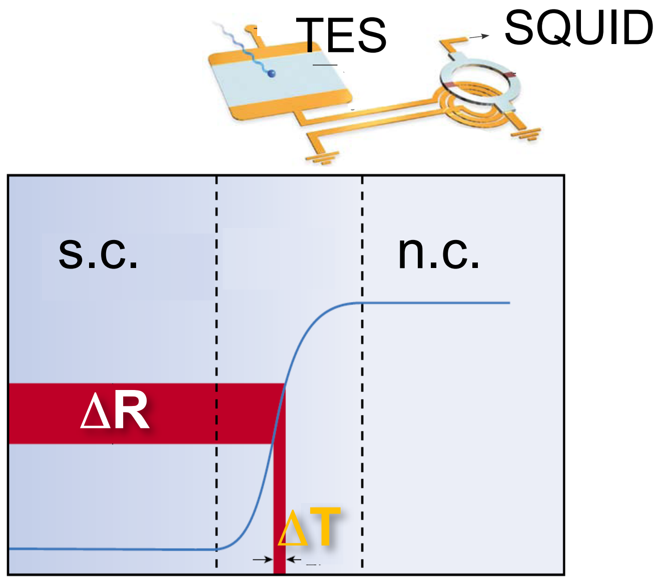
MMC: **m**etallic **m**agnetic **c**alorimeters
with paramagnetic sensor Au:Er



δT in absorber from EC-decay
⇨ change in magnetization M of sensor

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

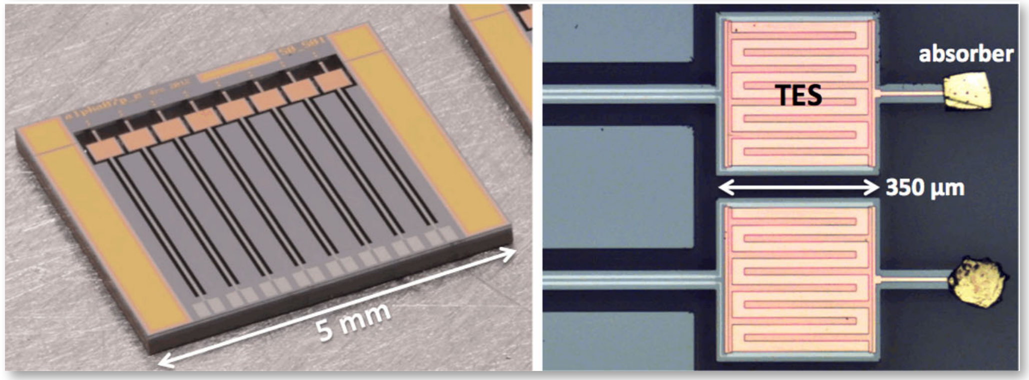
thermal micro-calorimeters
with **t**ransition **e**dge **s**ensor (**TES**)

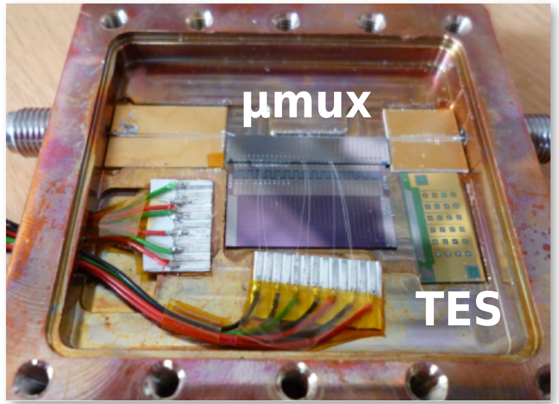


δT in absorber from EC-decay
⇨ change in temperature T and resistance R of thermistor

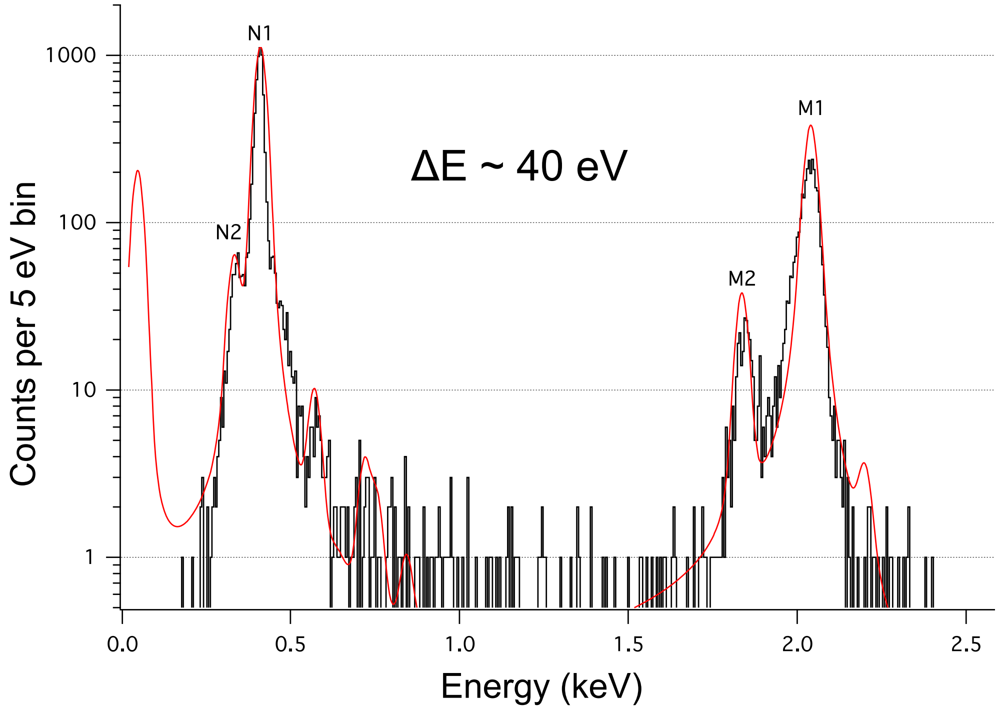
signal: current change measured by SQUID array

TES technology: NuMECS and HOLMES





[Croce *et al.*, J. Low Temp. Phys. 2016]



HOLMES design & timeline

- ΔE ~1 eV at 2.5 keV, t_{rise} = 1…10 µs, 300 Bq per pixel (tests at NIST in progress: prelim. ΔE ~4 eV)
- demonstrator array in 2017
- full ~1000 channel array operation expected for 2018

[Alpert *et al.*, Eur. Phys. J. C 75 (2015) 112]

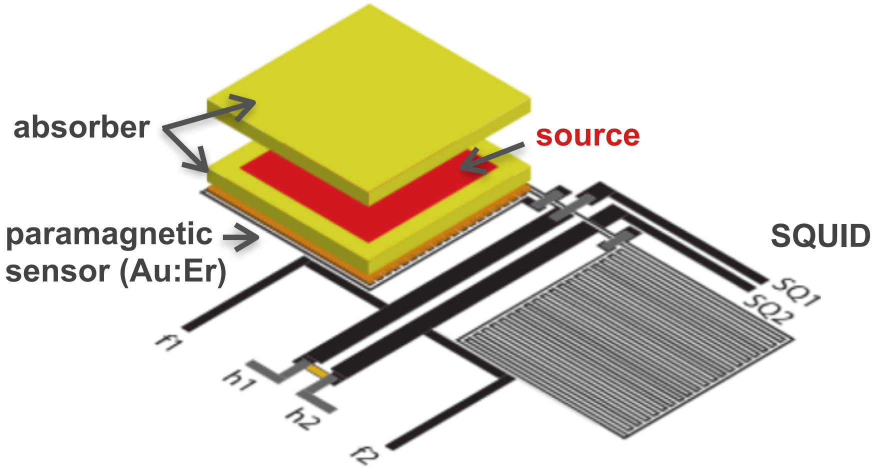
MMC technology: ECHo

Heidelberg (Univ., MPIK), U Mainz, U Tübingen, TU Dresden, U Frankfurt, HU Berlin, ILL Grenoble, PNPI St Petersburg, U Bratislava, IIT Roorkee, Saha Inst. Kolkata

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

FOR 2202 ECHo

[Fleischmann *et al.* 2009; Gastaldo *et al.* 2013]

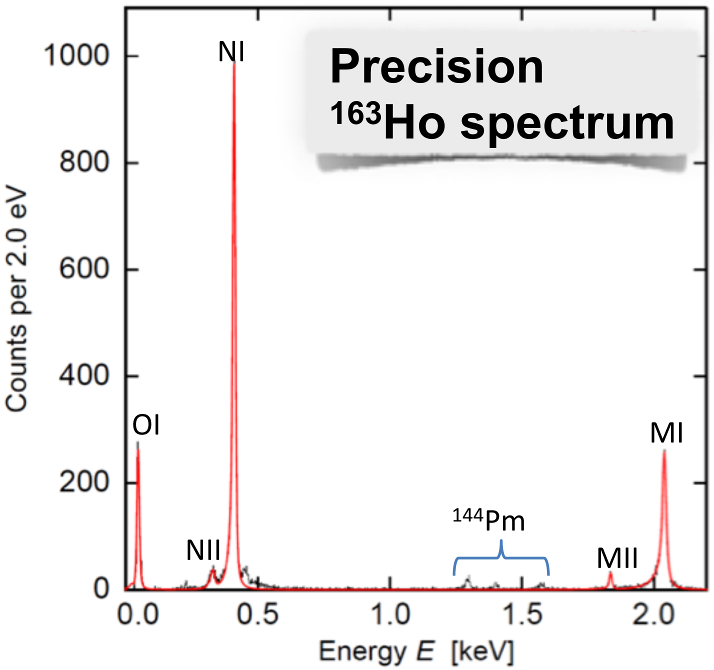


Technology

- magnetic micro-calorimeter (MMC) arrays with microwave SQUID multiplexing readout
- fast rise time (~130 ns) and excellent linearity & resolution (ΔE ~ 5 eV)
- isotope production: $^{162}Er(n,\gamma)^{163}Ho$ offline mass separation

[Ranitzsch et al., arXiv:1409:0071; Gastaldo *et al.* 2014]

Precision ^{163}Ho spectrum



- ☑ new improved detectors
- ☑ improved implantation with purified source
- ☑ proof of multiplexed readout
- ☑ first underground meas.

ECHo Timeline

- **Phase I: ECHo-1k**
  to be completed by 2018
  2 x 50 pixel x 10 Bq,
  4 months: $m(\nu_e) < 10$ eV
- **Phase II: ECHo-1M**
  array of 10^5 detectors
  50 x 2000 pixel x 10 Bq,
  2 years: sub-eV sensitivity

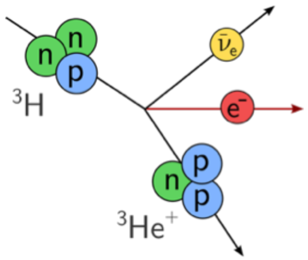
[L. Gastaldo *et al.*, J. Low Temp. Phys. 176 (2014) 876]

Direct ν-mass determination: status and outlook

Karlsruhe Institute of Technology

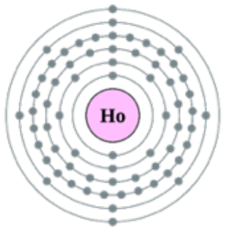
Current achievements

- **KATRIN:** under commissioning, preparing for first tritium runs
- **Project 8:** successful prototype, CRES proof of principle with ^{83m}Kr



ECHo, HOLMES, NuMECS:

- Detector development (MMC, TES)
- Test of scalable arrays
- High-purity ^{163}Ho production and implantation into absorber



Next goals

- Long-term data-taking in integral spectroscopy mode (0.2 eV)
- Develop CRES towards first tritium measurement (2 eV) and beyond

- Operate medium-size arrays ($\sim 10^{10}$ counts) for 10 eV sens.
- Prepare large arrays ($\sim 10^{14}$ counts) for sub-eV range

NECKARZIMMERN 2017

NEUTRINO 2018

Bonus material:

Other fun physics
with precision β spectroscopy

KATRIN: ν-mass sensitivity … and more:

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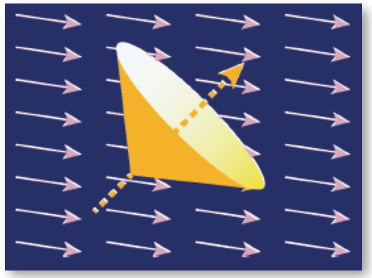
Explore physics potential

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

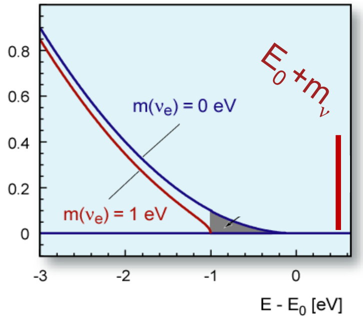
standard operation mode for KATRIN

RH currents
Bonn et al. (2011)

Violation of Lorentz symmetry
e.g. Blasone et al. (2005)
Diaz, Kostelecky & Lehnert (2013)

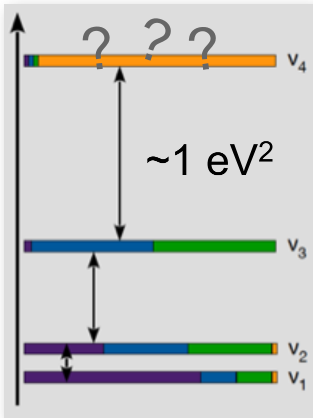


Constraining local CνB
e.g. Kaboth & Formaggio (2010),
Fässler et al. (2013)



capture of relic ν on β-instable nuclei

Search for eV-scale sterile ν
e.g. Formaggio & Barrett (2011)



- **and further away from E_0:**

  search for keV-mass scale sterile ν as WDM candidates

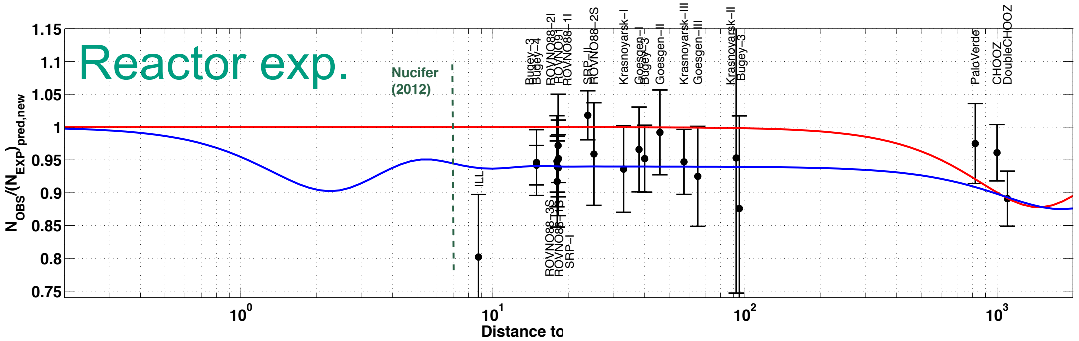
  Mertens et al. (2015); see also Barry, Heek & Rodejohann (2014)

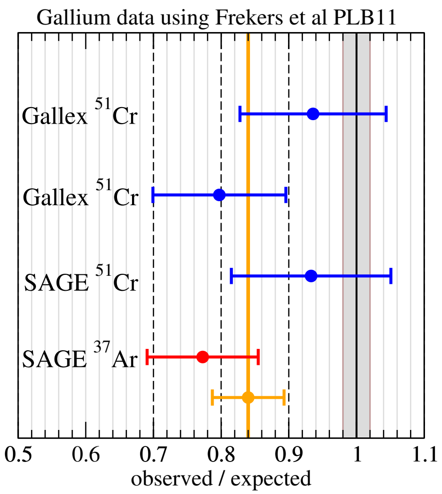
non-standard operation, novel detector concepts

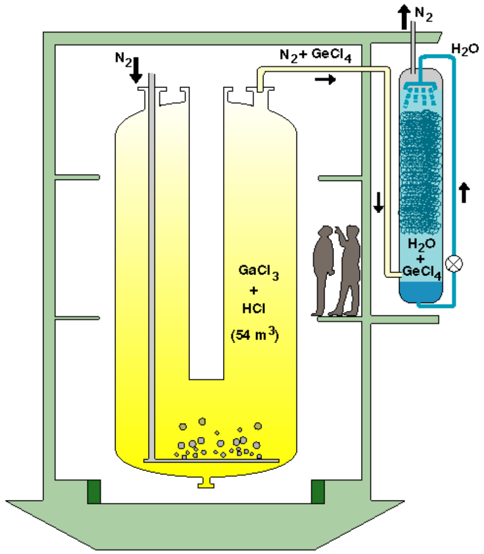
Why sterile neutrinos?

Hints of eV-scale sterile neutrinos?

May explain anomalous short-baseline oscillation results:







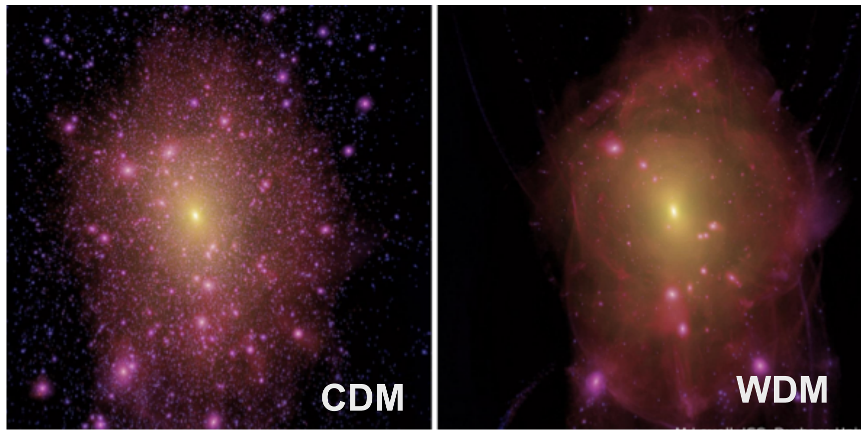
Gallium experiments

Hints of keV-scale sterile neutrinos?

Pure (Λ)CDM scenario:

- Missing satellites problem
- Too-big-to-fail problem
- “Core” vs. “cusp” problem

KeV-scale sterile ν as viable WDM candidate

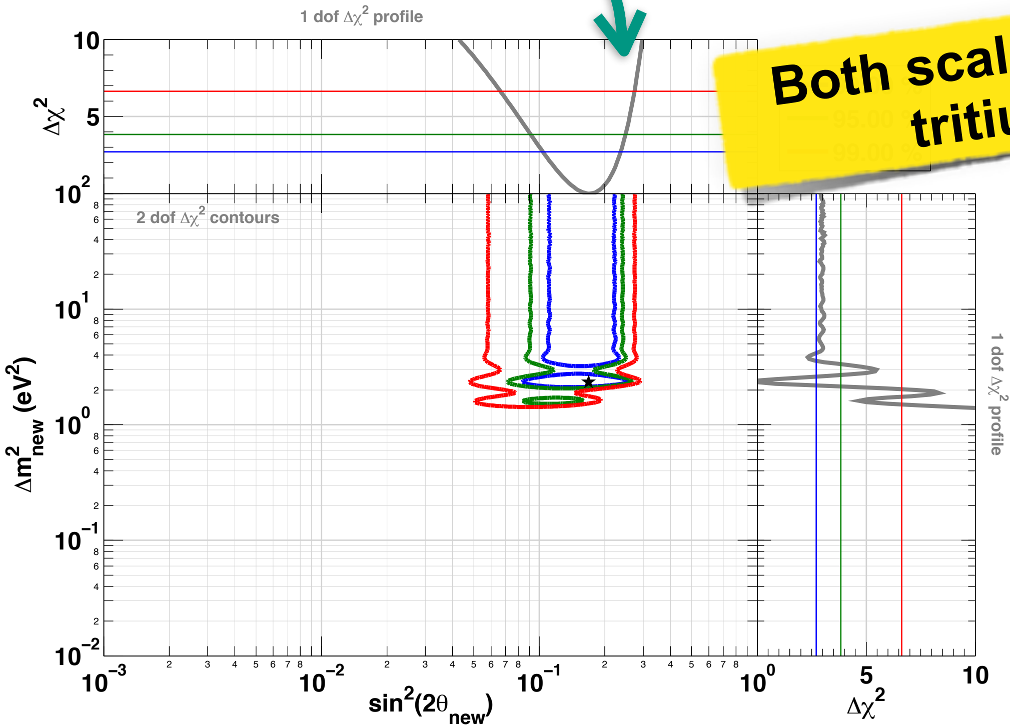


M. Lovell, ICC Durham

Why sterile neutrinos?

Hints of eV-scale sterile neutrinos?

May explain anomalous oscillation results from
- Short baseline accelerator experiments
- Gallium experiments
- Reactor experiments



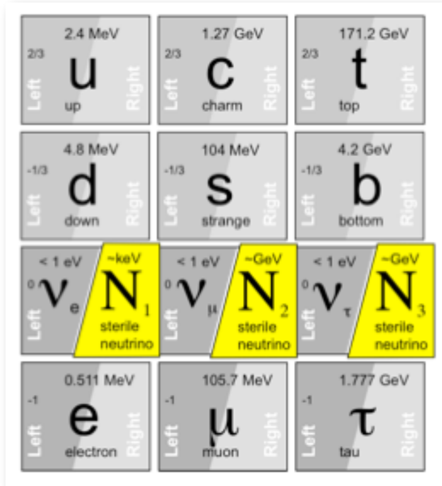
[G. Mention et al. (2011), updated in White Paper (2014)]

Both scales accessible in tritium β decay

Hints of keV-scale sterile neutrinos?

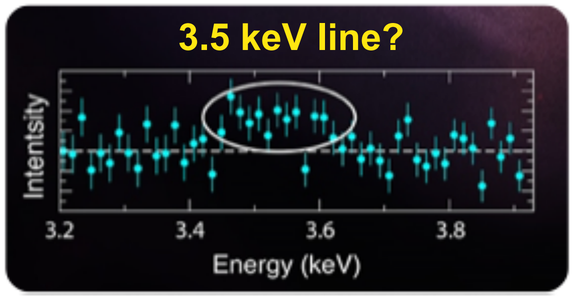
Well motivated as natural extension of Standard Model (νMSM)

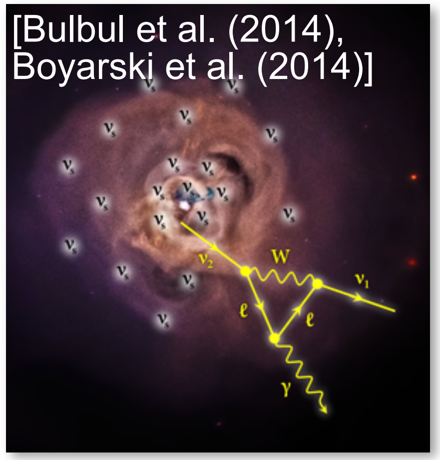
[e.g., Canetti, Drewes, Shaposhnikov (2013)]



In agreement with cosmological observations from small to large scales [e.g., Shi & Fuller (1999)]

Recent indirect hints from X-ray astronomy?





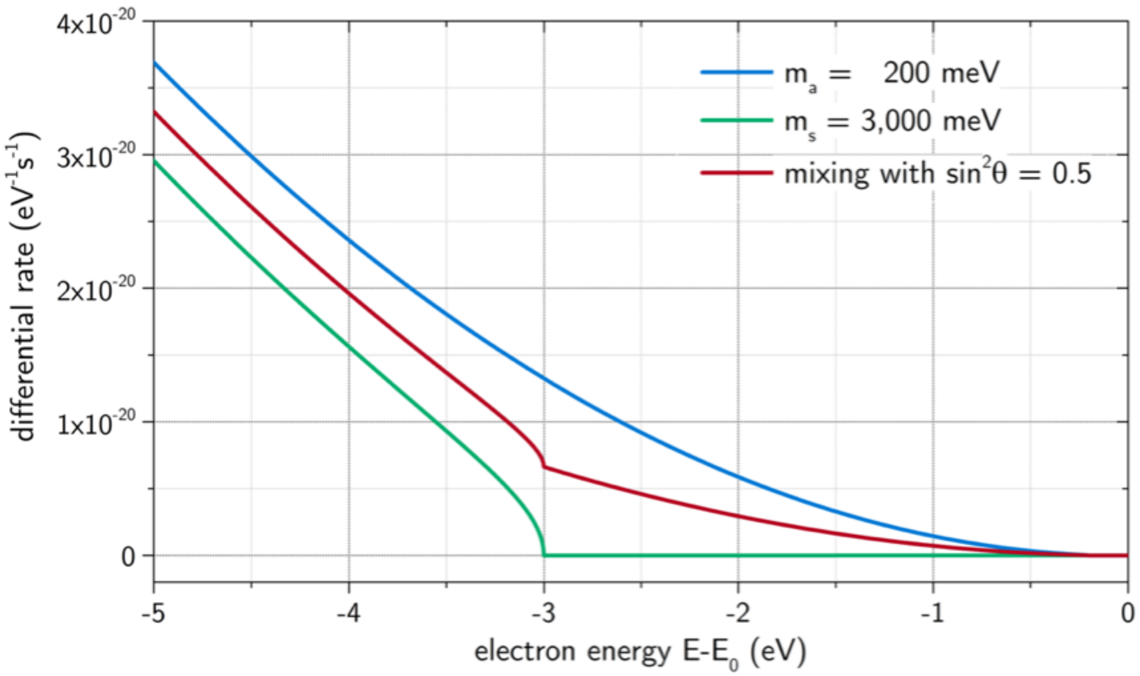
Imprint of sterile neutrinos on β spectrum

Shape modification below E_0 by active $(m_a)^2$ and sterile $(m_s)^2$ neutrinos:

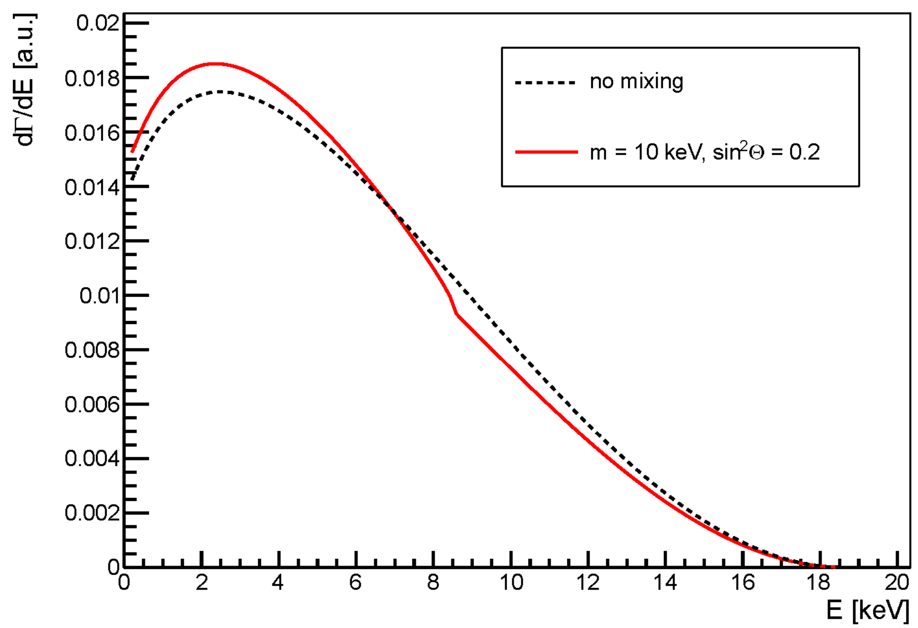
$$\frac{dN}{dE} = \boxed{\cos^2\theta_s \frac{dN}{dE}(m_a^2)} + \boxed{\sin^2\theta_s \frac{dN}{dE}(m_s^2)}$$

⇒ additional kink in β spectrum at $E = E_0 - m_s$

light sterile ν, m_s = 3 eV

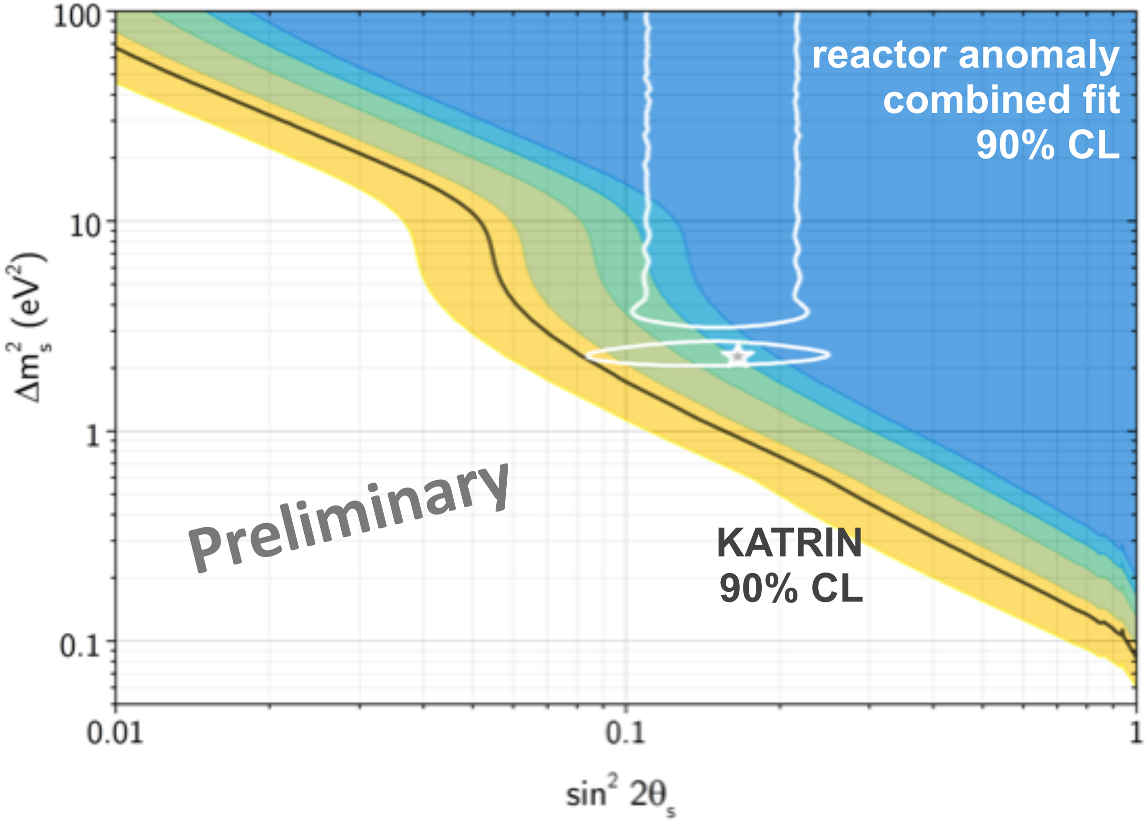


keV sterile ν, m_s = 10 keV



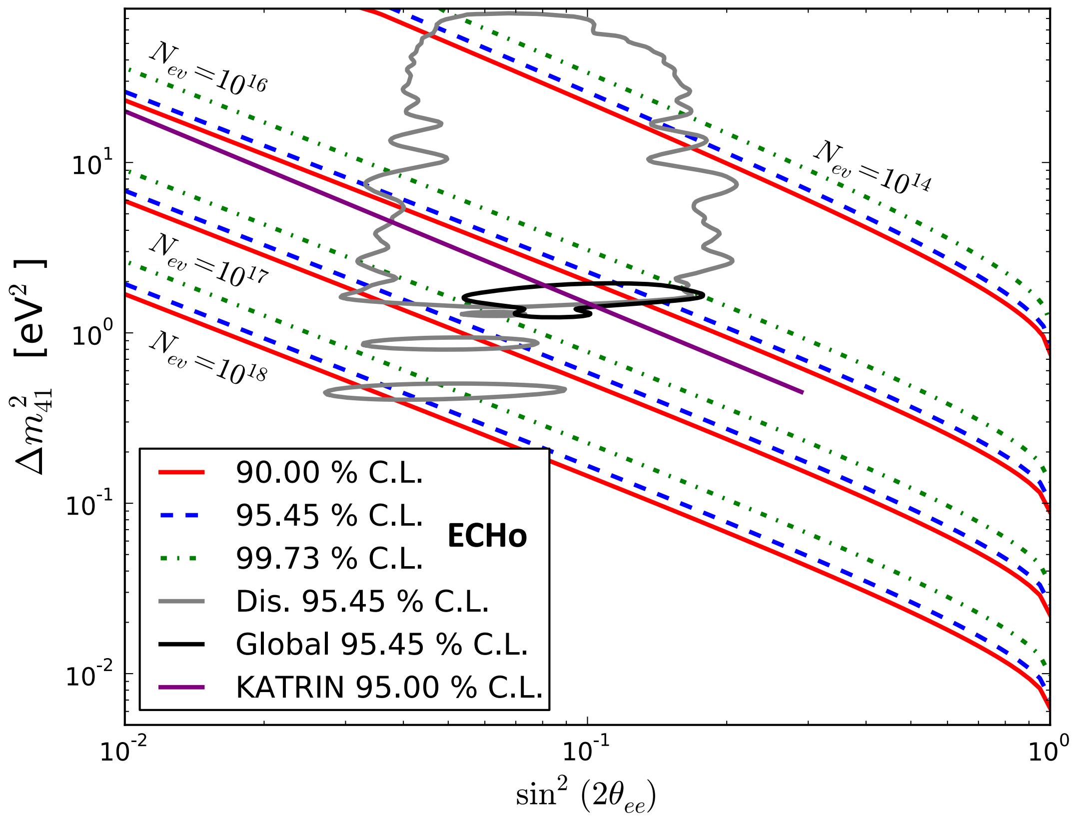
Search for eV-scale sterile ν with direct mass

Tritium: KATRIN



[Kleesiek *et al.*, in prep.]

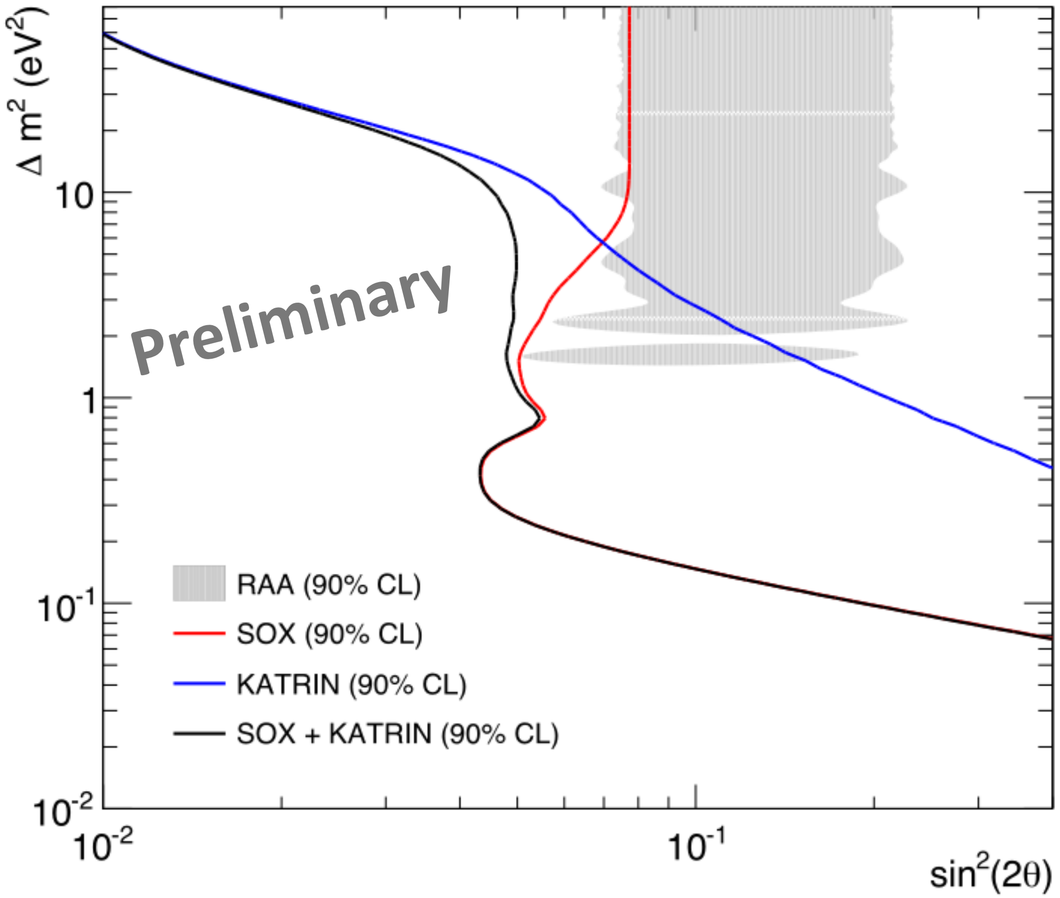
Holmium: ECHo



[Gastaldo et al., arXiv:1605.05497]

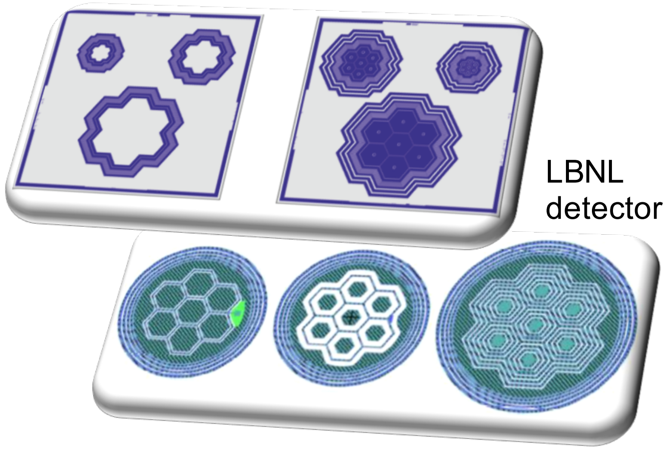
Search for eV-scale sterile ν with direct mass experiments

Combined sensitivity of direct neutrino mass exp. and SBL oscillation searches



Search for keV-scale sterile ν with direct mass experiments

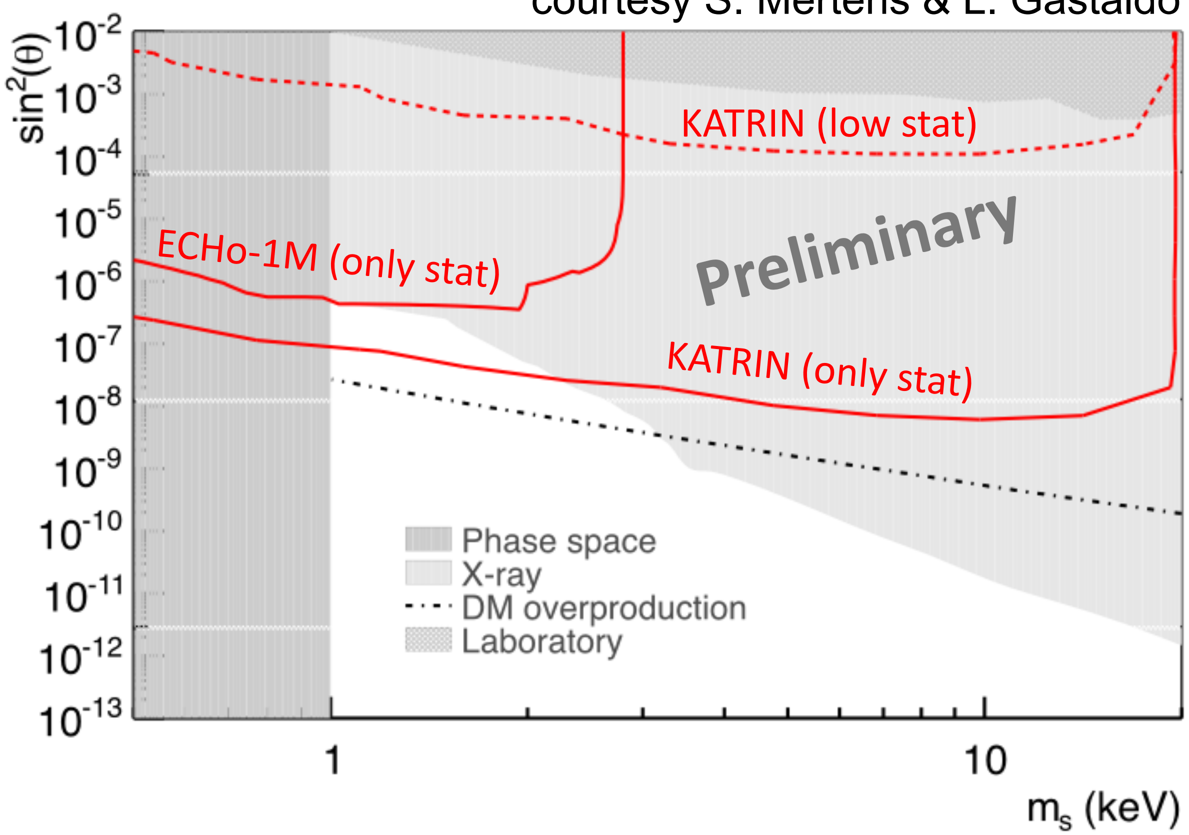
- First measurements with KATRIN “baseline” set-up at reduced source strength
- Prototyping and sensitivity studies for upgraded detector system under way
- Sensitivity of holmium experiments restricted by low Q-value (2.8 keV)



TRISTAN detector prototypes for KATRIN

P4.040, S. Mertens
P4.041, A. Huber

courtesy S. Mertens & L. Gastaldo



Search for keV-scale sterile ν with KATRIN

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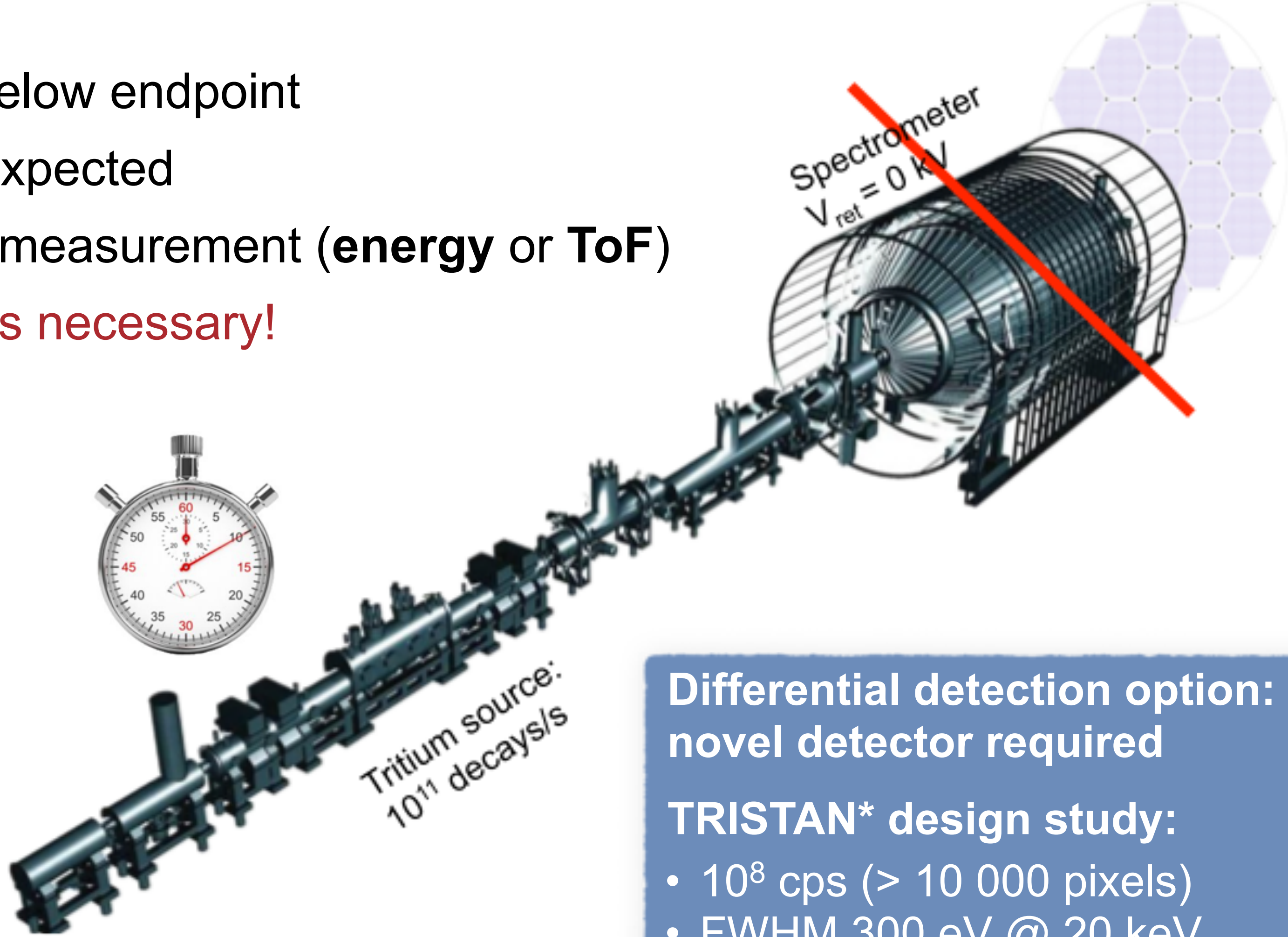
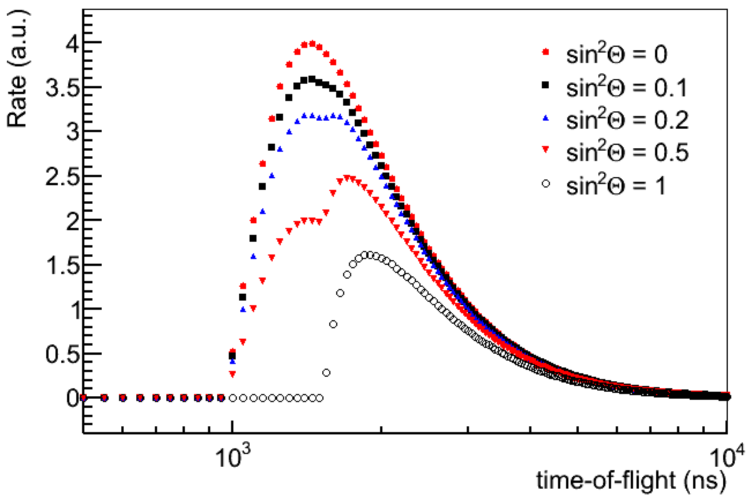
The challenge:

- High count rates at ~few keV below endpoint
- Tiny sterile admixture $\sin^2(\theta_s)$ expected
- Best sensitivity for **differential** measurement (**energy** or **ToF**)

➡ Development of new techniques necessary!



ToF option:
electron tagger required



[Steinbrink et al. (2013), Robertson et al. (in prep.)]

Differential detection option:
novel detector required

TRISTAN* design study:

- 10^8 cps (> 10 000 pixels)
- FWHM 300 eV @ 20 keV
- > 20 cm diameter

[Mertens et al. (2015)]

*) **TR**itium beta decay **I**nvestigation on **S**terile **T**o **A**ctive **N**eutrino mixing

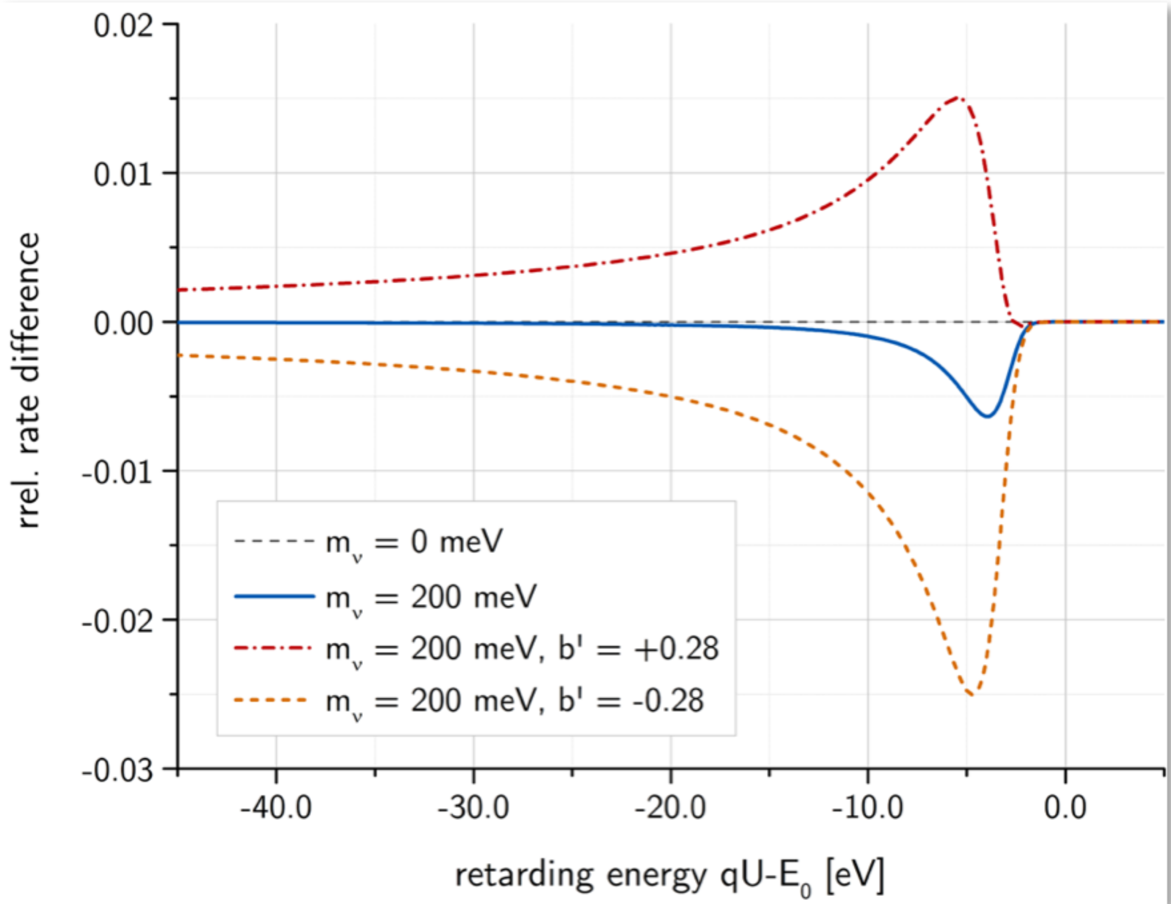
Effect of RH current contributions

$$\frac{d\Gamma}{dE\,dt} \propto E_\nu \sqrt{E_\nu^2 - m_\nu^2}\left(1 + \boxed{b'}\frac{m_\nu}{E_\nu}\right)$$

[J. Bonn et al., *Phys. Lett. B* 703 (2011) 310]

Fierz-like parameter *b'* enters differential rate

$$\boxed{b'} \approx -2\,\frac{\mathfrak{Re}(L_V R_V^* + L_V R_S^*)|\mathcal{M}_F|^2 + \mathfrak{Re}(L_A R_A^* + L_A R_T^*)|\mathcal{M}_{GT}|^2}{|L_V|^2|\mathcal{M}_F|^2 + |L_A|^2|\mathcal{M}_{GT}|^2}$$



Imprint on integrated spectrum:

- Only small sensitivity on *b'* if endpoint E_0 left free in fit
  ➜ good for determination of $m^2(\nu_e)$
- Improvement of present bounds on *b'* with KATRIN for small $m(\nu_e)$ if
  - external E_0 value with accuracy < 50 meV as input*
  - absolute energy scale in KATRIN U_{spec} - U_{source} known to same accuracy of < 50 meV

*) 70 meV accuracy:
E. G. Myers et al., *PRL* 114 (2015) 013003

Figure: M. Kleesiek

Probing Lorentz invariance in β decay

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[Kostelecky & Mewes (2004, 2009)]

Standard Model Extension (SME) framework:

Neutrinos satisfy Dirac-like equation

$$\boxed{(i\mathbf{\Gamma}^\alpha \partial_\alpha - \mathbf{M})\,\psi = 0}$$

with $\mathbf{\Gamma}$, $\mathbf{M}$ including momentum-dependent coefficients

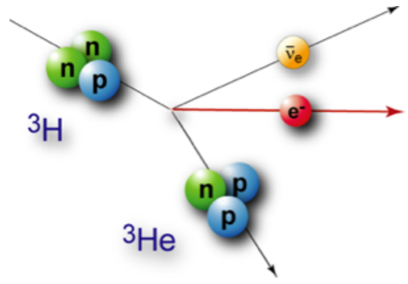
[review: Diaz (2014)]

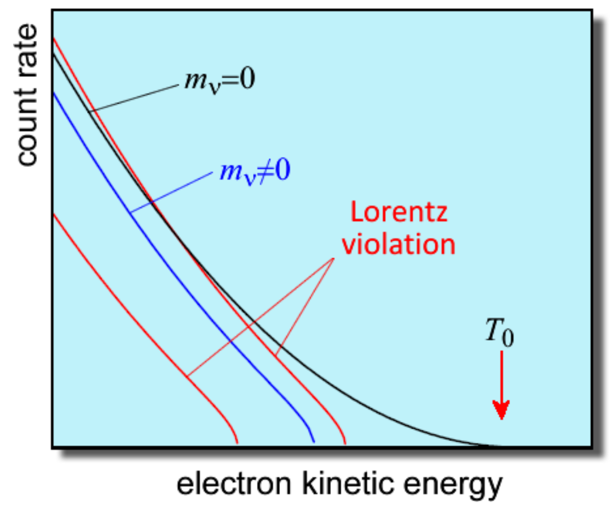
Experimental searches:

- Neutrino oscillations
- Neutrino velocity (ToF)
- Weak decays

probe oscillation-free parameters

Tritium β decay:





- Modified energy dependence of decay rate
- Spectral shape dependent on sidereal time and experiment orientation
- Effective dim-3 coefficient: osc. shift of endpoint $T_{0,\mathrm{eff}}$ with $\omega_{\mathrm{sidereal}}$
- Effective dim-2 coefficient: osc. of m^2 parameter (can mimic tachyonic ν)

[Diaz, Kostelecky, & Lehnert 2013]