Karlsruhe Institute of Technology

KATRIN
the Karlsruhe Tritium Neutrino Experiment

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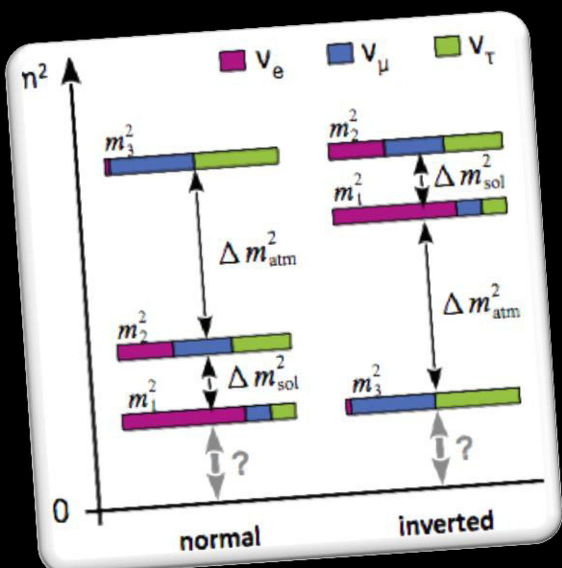
MPIA, Heidelberg, 02.02.2018

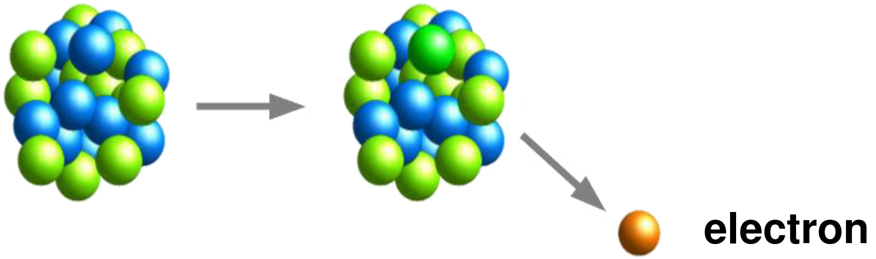
- A brief history of neutrinos
- Neutrino mass measurement
- The KATRIN experiment
- Future projects

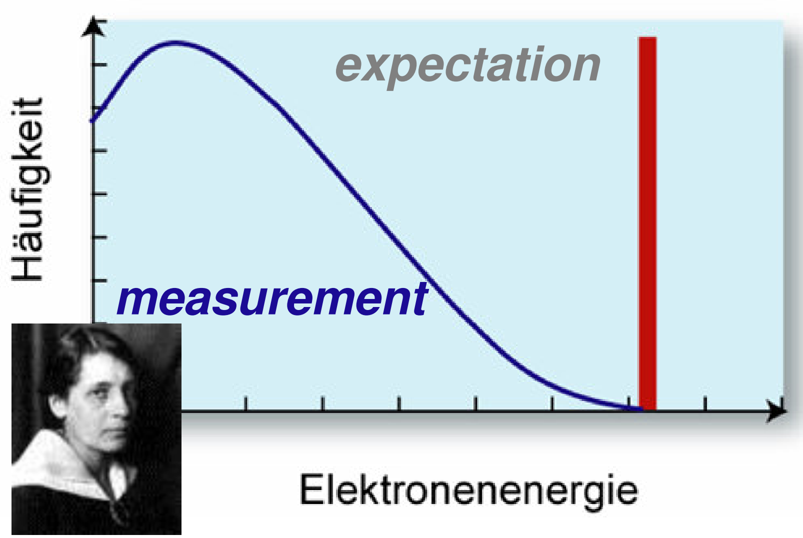
A brief history of neutrinos



Discovery of the neutrinos

β-decay





1912-1930

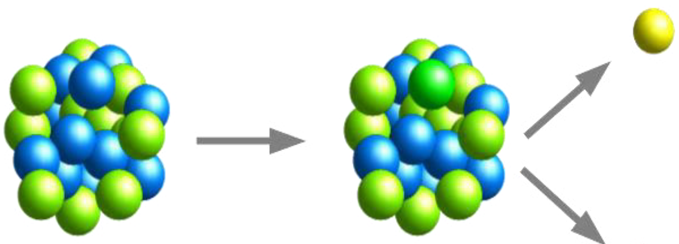
Investigation of **radioactive materials**, which emit **electrons**.

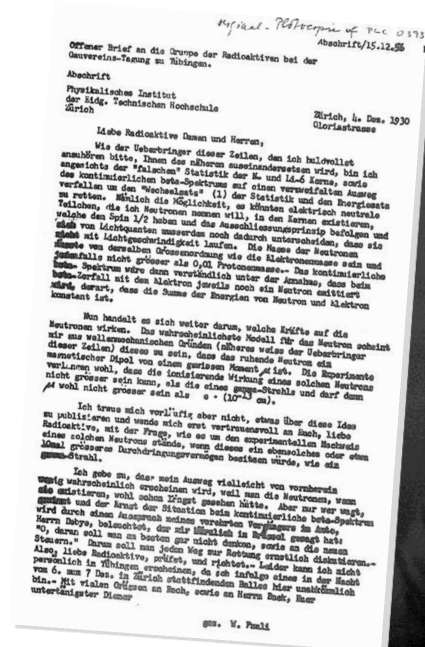
+ energy conservation
+ momentum conservation

?

Discovery of the neutrinos

β-decay




Mysical - Photocopie of PLC 0393
Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

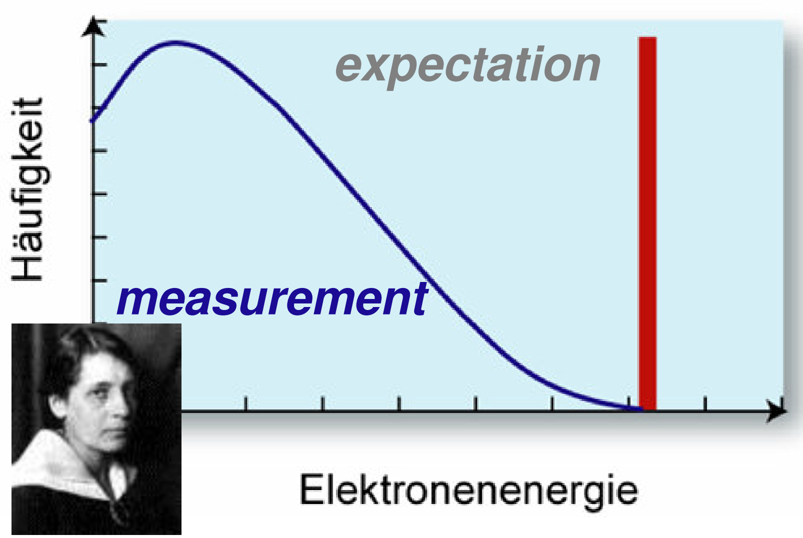
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als e · (10⁻¹³ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Wolfgang Pauli (1900-1958)

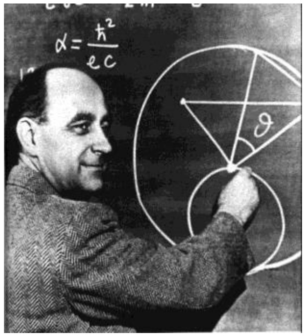


1930

Proposal: in addition to the electron another, neutral and very light particle is emitted, sharing the energy.

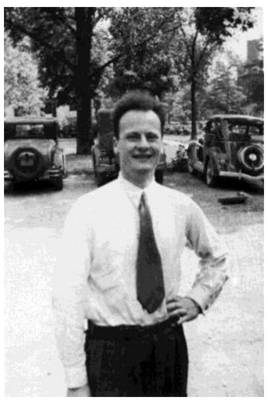
+ energy conservation
+ momentum conservation

Discovery of the neutrinos



1934

Enrico Fermi develops a successful theorie for β-decay, including the neutrino.



1935

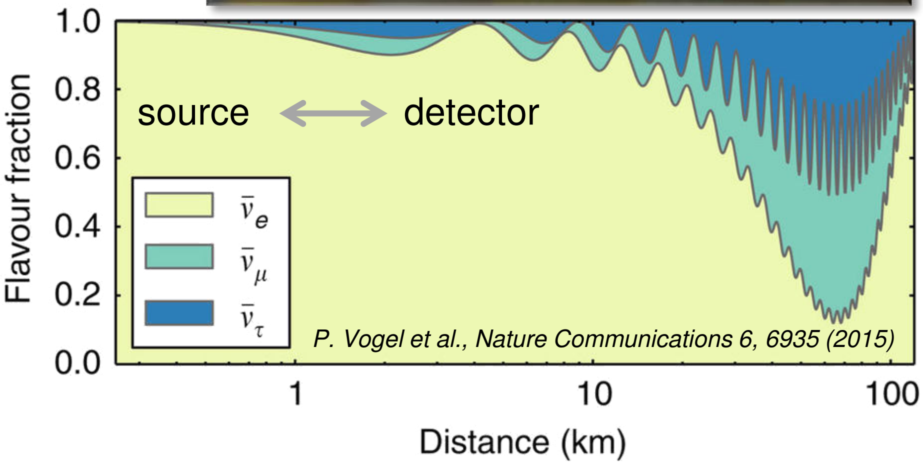
Hans Bethe calculates the probability to detect neutrinos. Absorber has to be 10‘000‘000‘000‘000‘000‘000 m (1000 LJ) thick to stop a neutrino !

1957

Reines & Cowan are the first to detect neutrinos at a nuclear reactor.

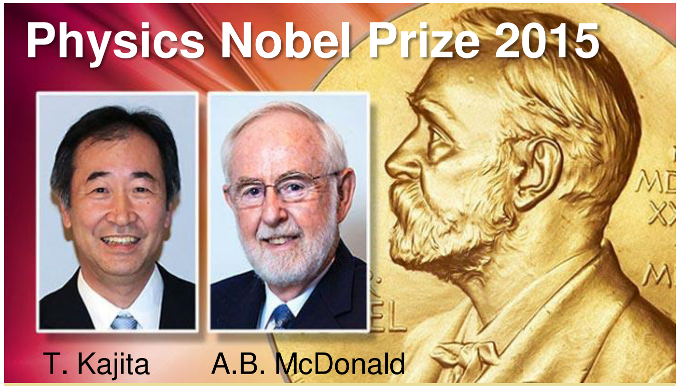
Neutrino mass and flavor-oscillation

- Neutrinos come in three flavors: ν_e ν_μ ν_τ
- Heisenberg: **mass** and **flavor** cannot be measured at the same time
- Neutrino properties can assume **three Eigenvalues** for **mass** (ν_1 ν_2 ν_3) and **flavor** (ν_e ν_μ ν_τ)
- Neutrino with a **unique flavor**: **mix of three mass Eigenvalues**
- Three **mass eigenfunctions** with different velocities ➔ phase shift
- **ν–oscillation** along the path of flight
- Oscillation length depends on:
  - $\Delta m^2 = m_{\nu 1}^2 - m_{\nu 2}^2$
  - **neutrino energy**

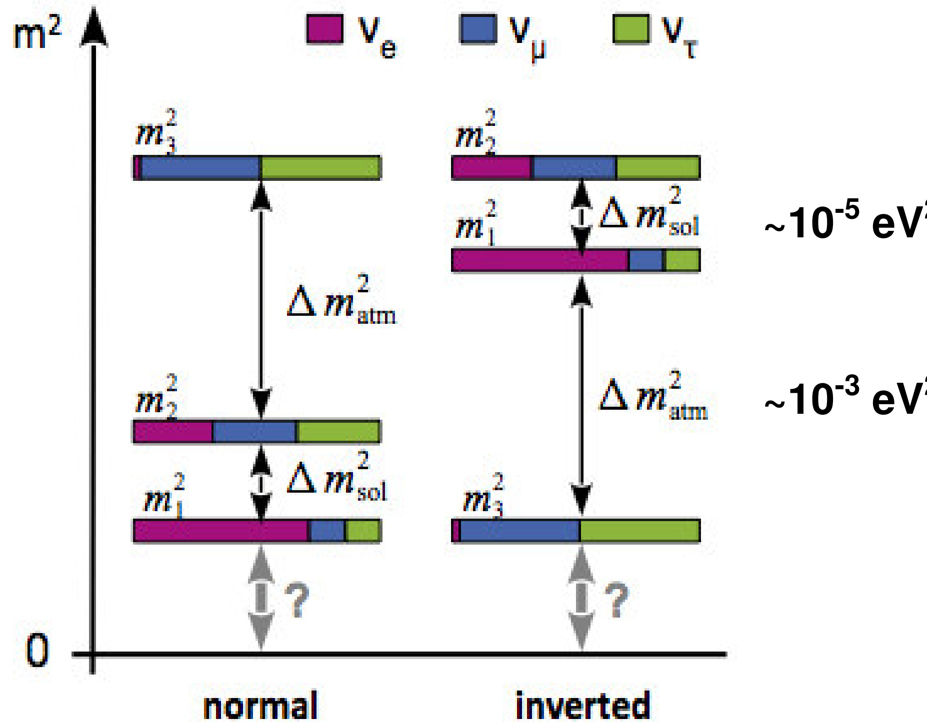


P. Vogel et al., Nature Communications 6, 6935 (2015)

Neutrino mass and flavor-oscillation



"for the discovery of neutrino oscillations, which show that neutrinos have mass"



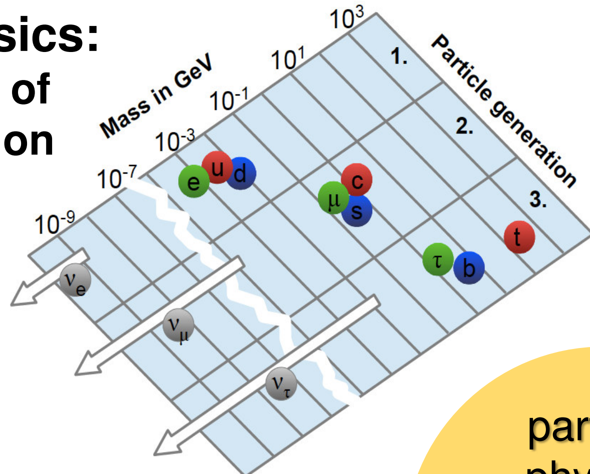
Neutrino oscillations observed:

- solar neutrinos
- atmospheric neutrinos (cosmic rays)
- neutrinos from nuclear reactors
- accellerator neutrinos

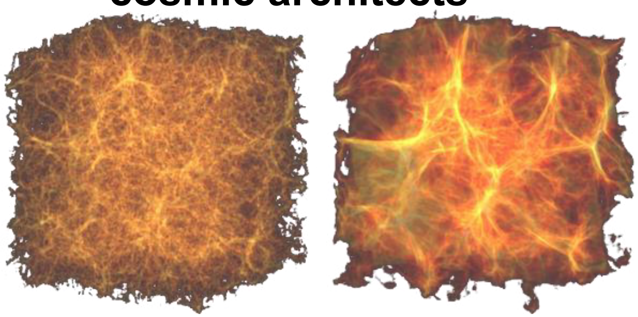
- Large neutrino mixing and tiny neutrino masses m(ν_i) ≠ 0 established
- ν oscillation depends on $\Delta m^2 = {m_1}^2 - {m_2}^2$
- **What is the absolute ν mass scale?**

The role of massive neutrinos

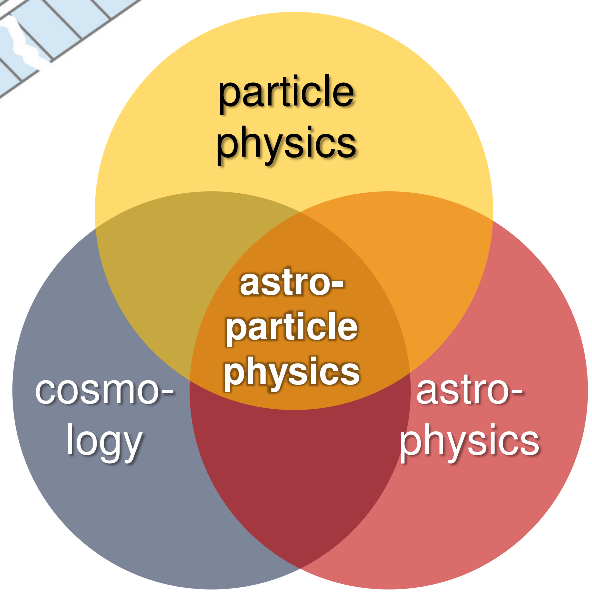
Particle Physics:
new concepts of mass generation



Cosmology:
massive neutrinos as “cosmic architects”

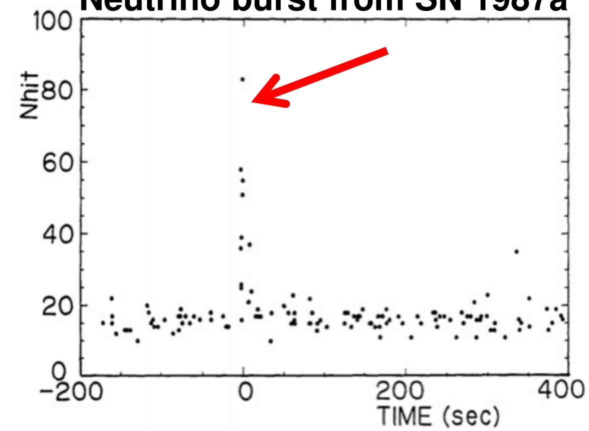


$m_\nu = 0$ $m_\nu > 0$

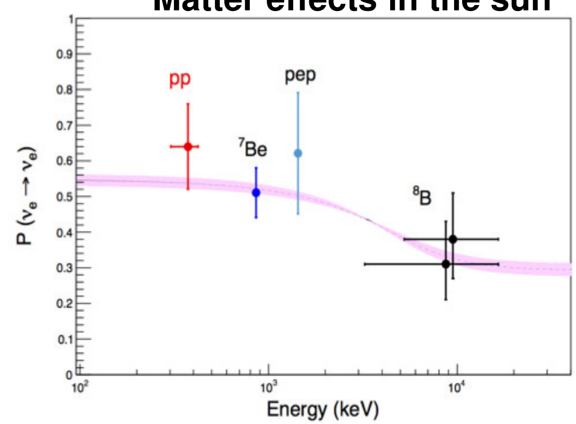


Astrophysics:
understanding ν-related processes

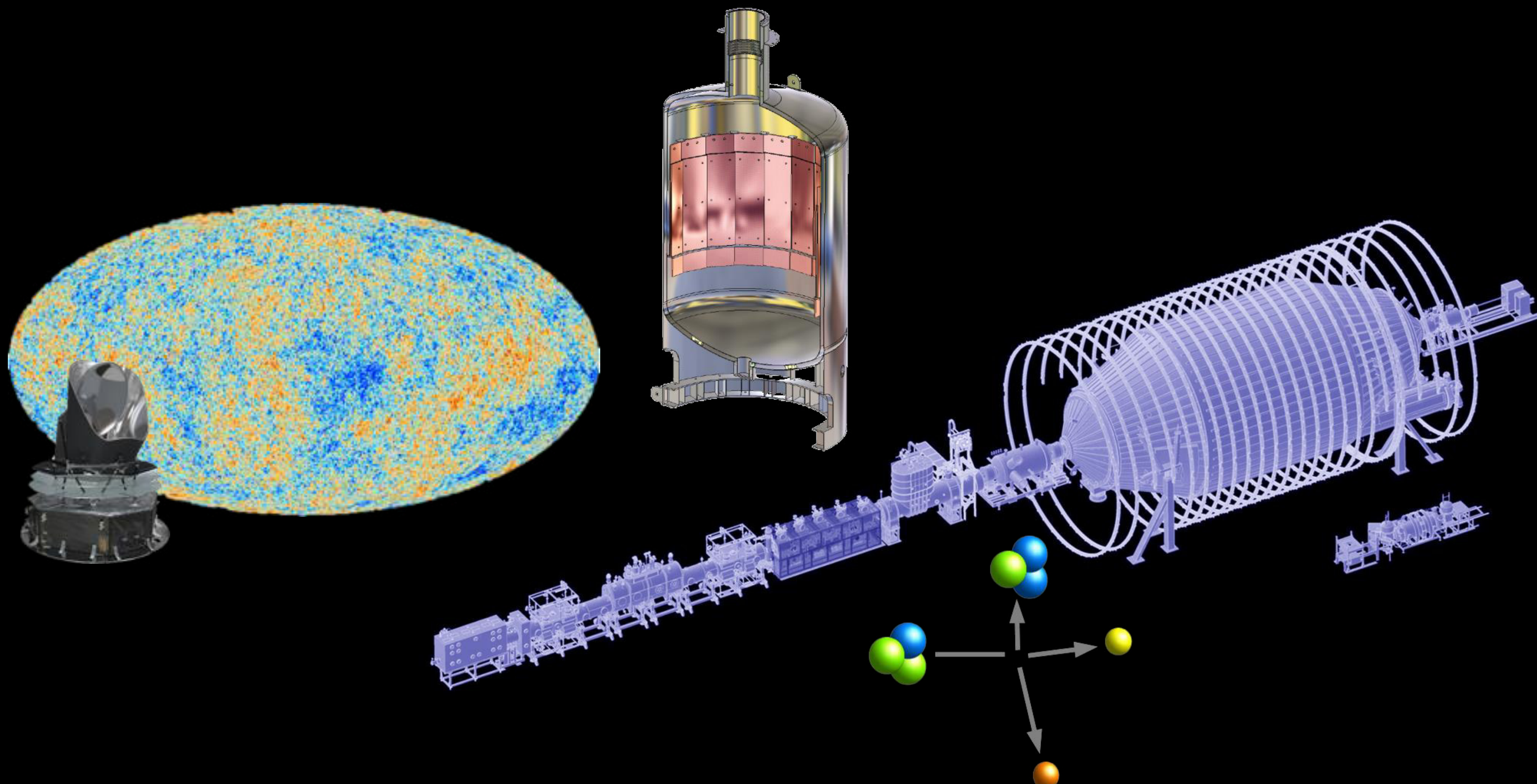
Neutrino burst from SN 1987a



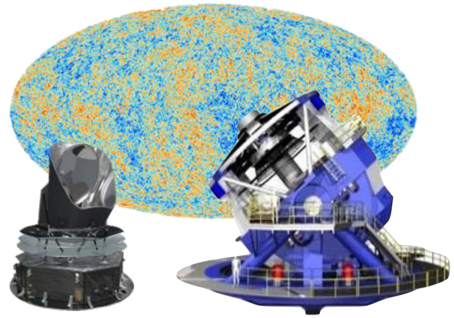
Matter effects in the sun

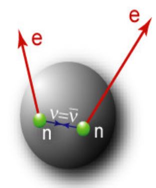


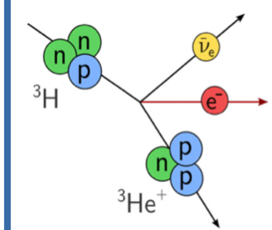
Neutrino mass measurement

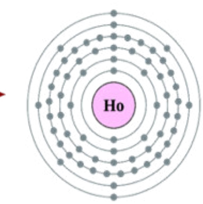


Complementary paths to the ν mass scale





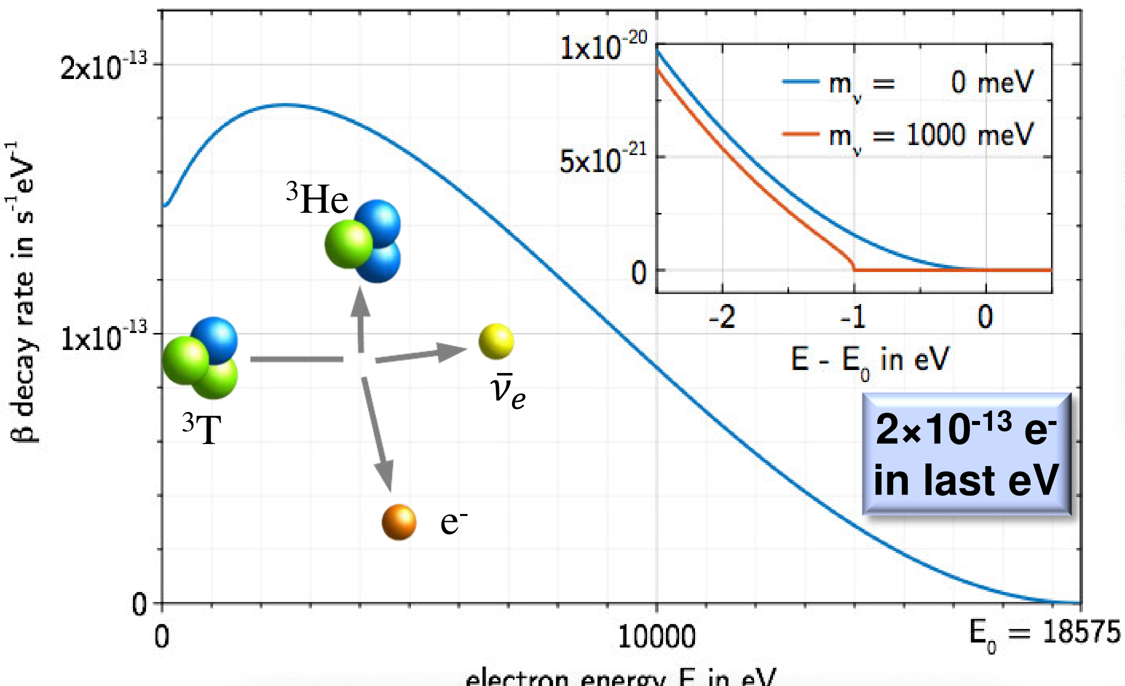




	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\|\sum_i U^2_{ei}\, m_i\right\|^2$	$m^2_\beta = \sum_i \|U_{ei}\|^2\, m^2_i$
Present upper limit	0.12 – 1 eV	0.2 – 0.4 eV	2 eV
Model dependence	Multi-parameter cosmological model	- Majorana ν - contributions other than m(ν)? - nuclear matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum ➜ this talk

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:

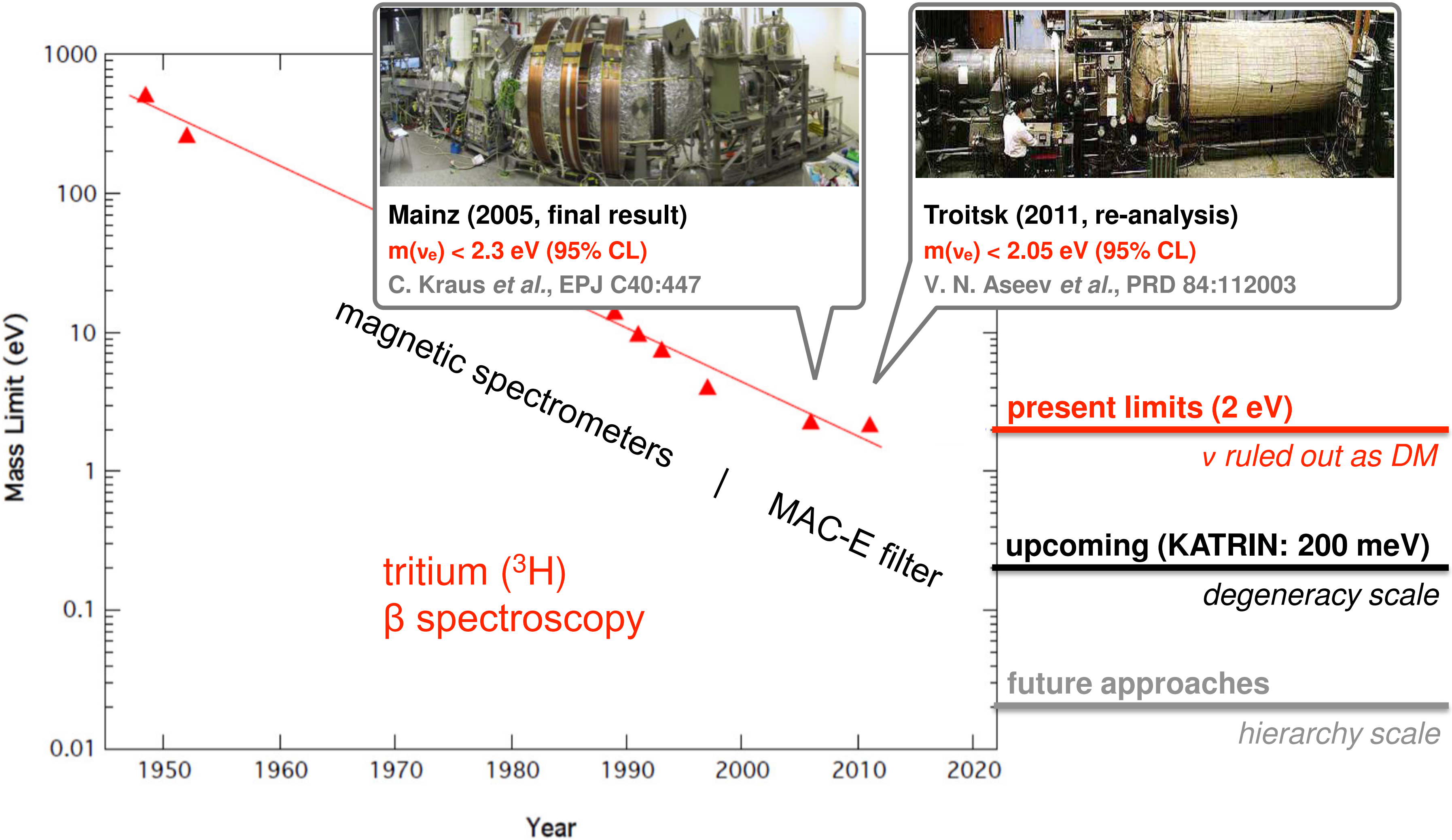
- high-activity source
- low-endpoint β emitter (**^{3}H**) or EC isotope (**^{163}Ho**)
- excellent energy resolution (MAC-E filter or calorimeter)

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 ν mass searches



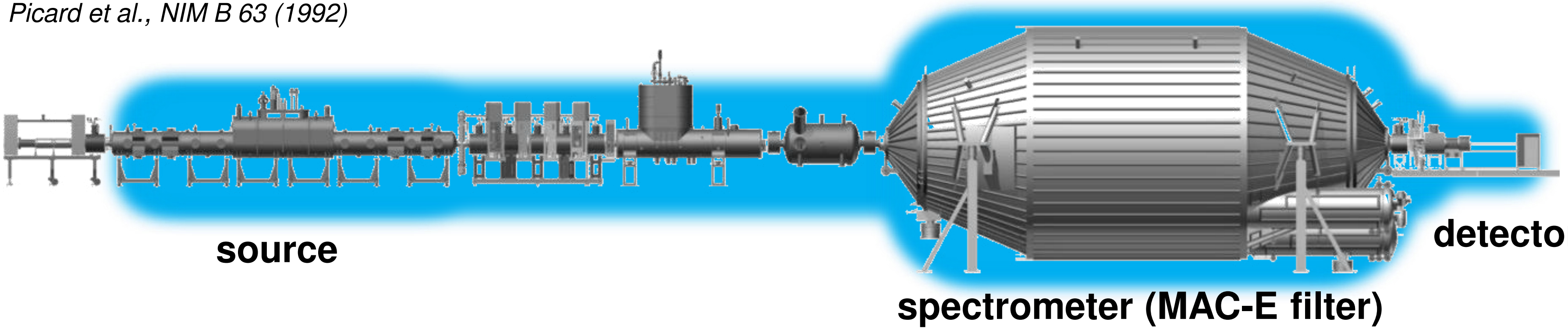
[courtesy J.F. Wilkerson/R.G.H. Robertson]

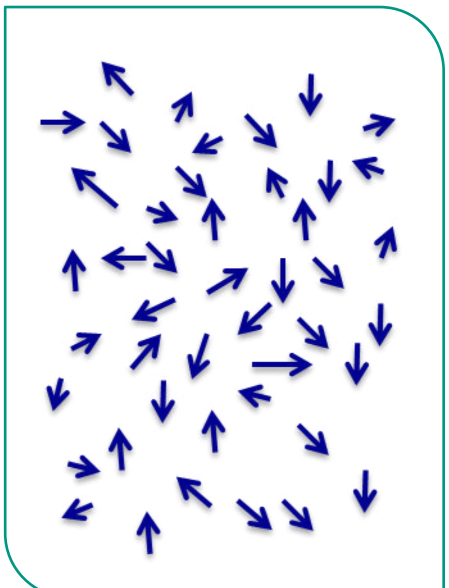
The MAC-E Filter

A. Picard et al., NIM B 63 (1992)

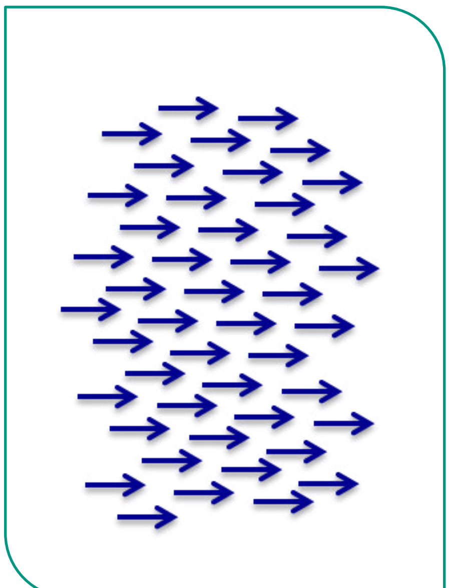
Magnetic Adiabatic Collimation with Electrostatic Filter

Karlsruhe Institute of Technology

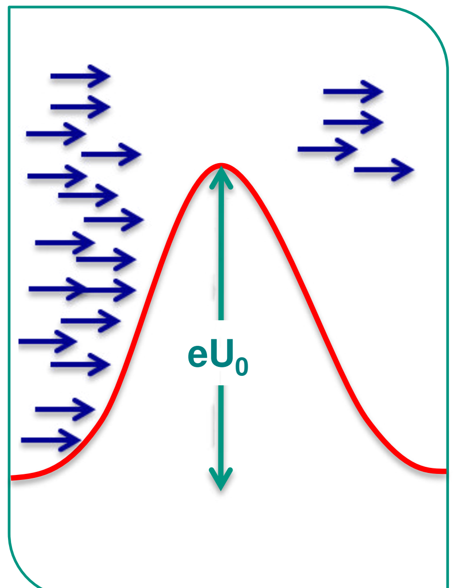




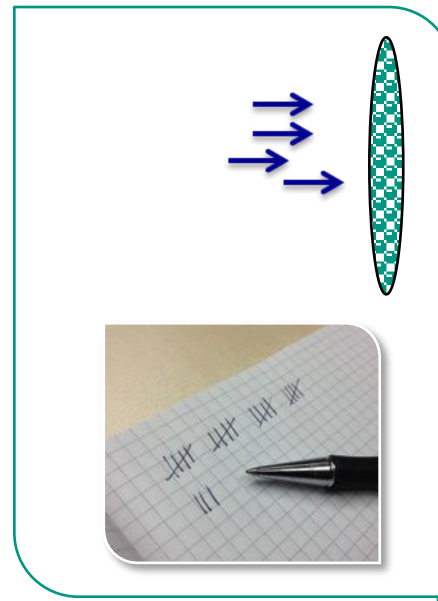
isotropically emitted tritium β-electrons



adiabatically collimated by magnetic field



electrons filtered by electric potential

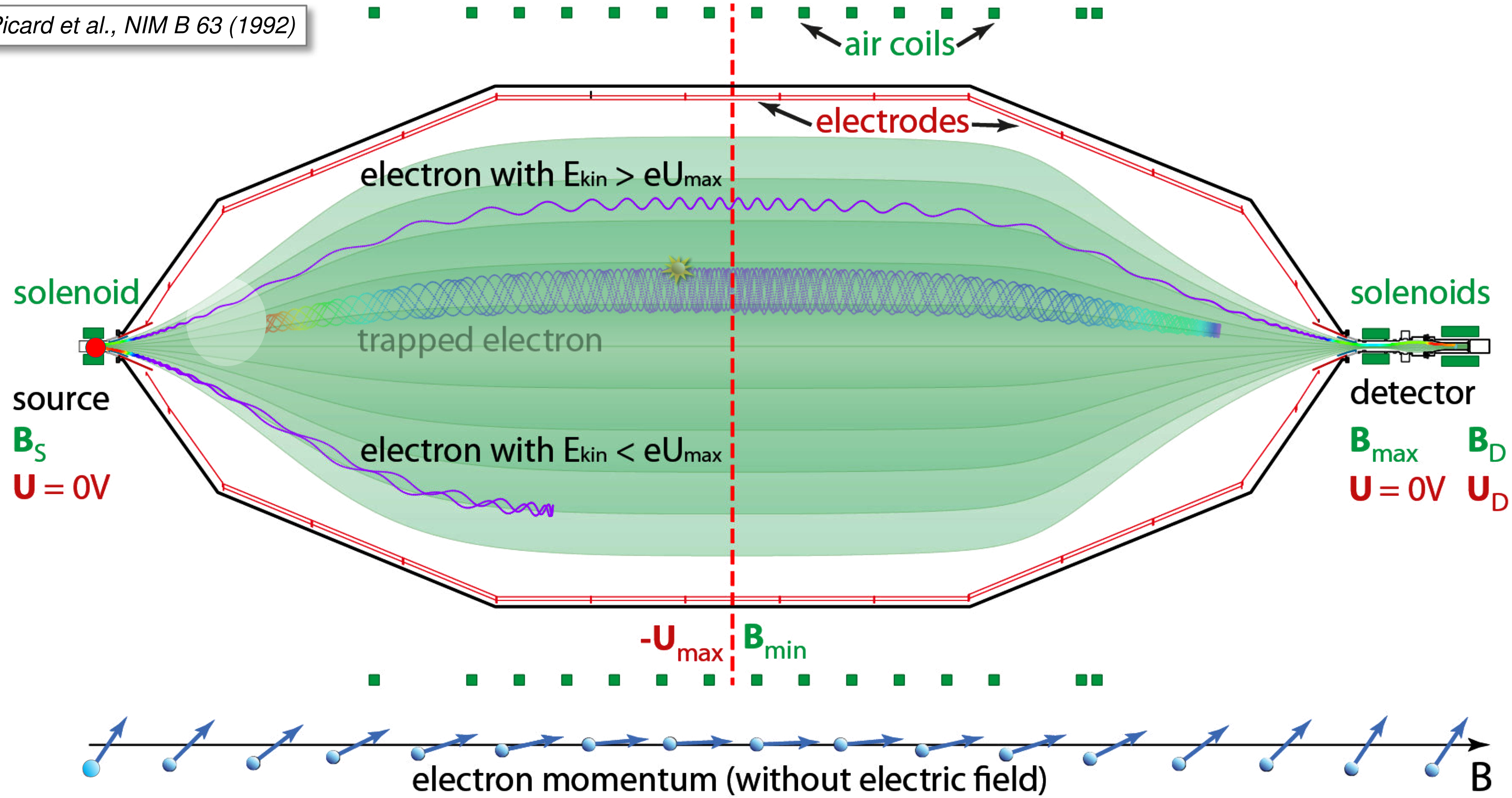


remaining electrons counted after filtering

The MAC-E Filter

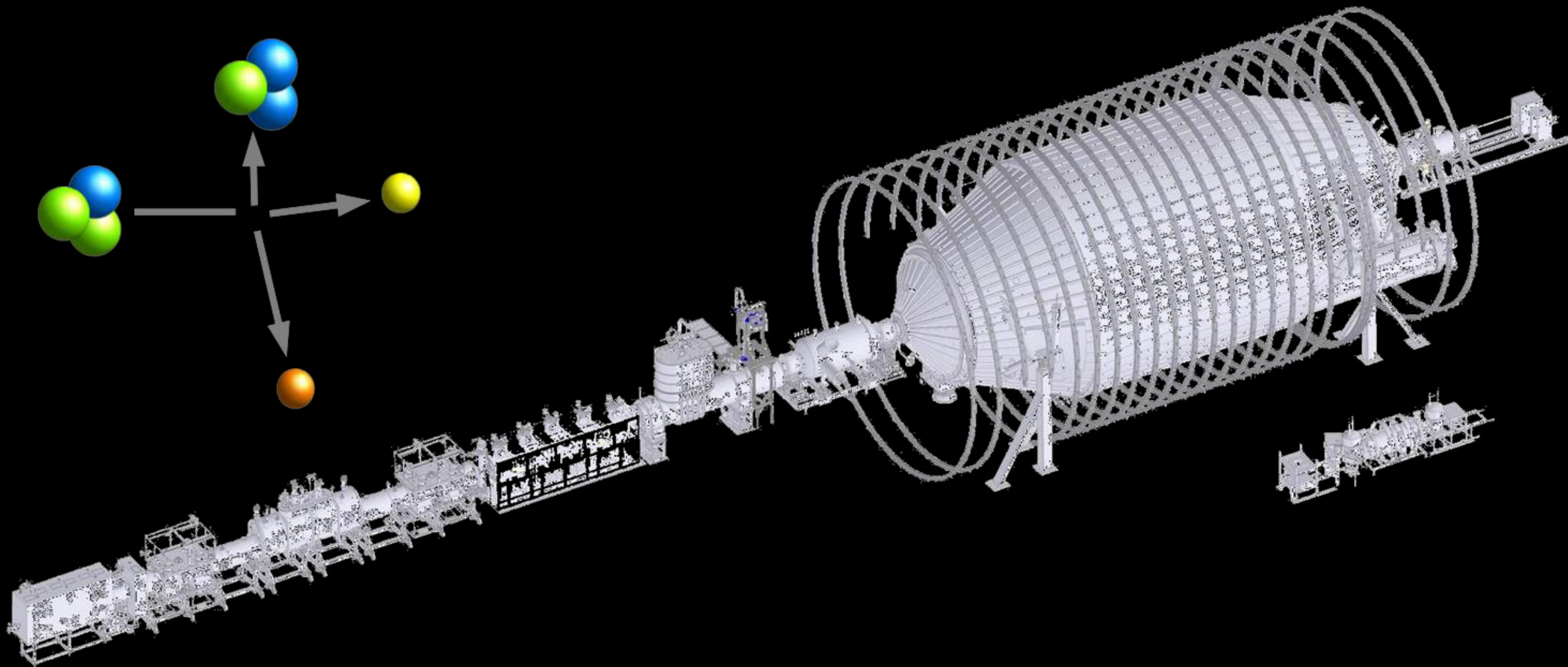
***M**agnetic **A**diabatic **C**ollimation with **E**lectrostatic Filter*

A. Picard et al., NIM B 63 (1992)



- **collimation:** $\mu = E_\perp / B = const$, ➔ $E_\perp \rightarrow E_{||}$ for $B = 6\ T \rightarrow 3mT$
- **energy analysis:** transmission condition: $E_{||} > eU_{max}$ (retarding potential)
- **energy resolution:** $\Delta E = E \cdot B_{min} / B_{max} = 18.6\ keV \cdot 0.3\ mT / 6\ T = 0.93\ eV$

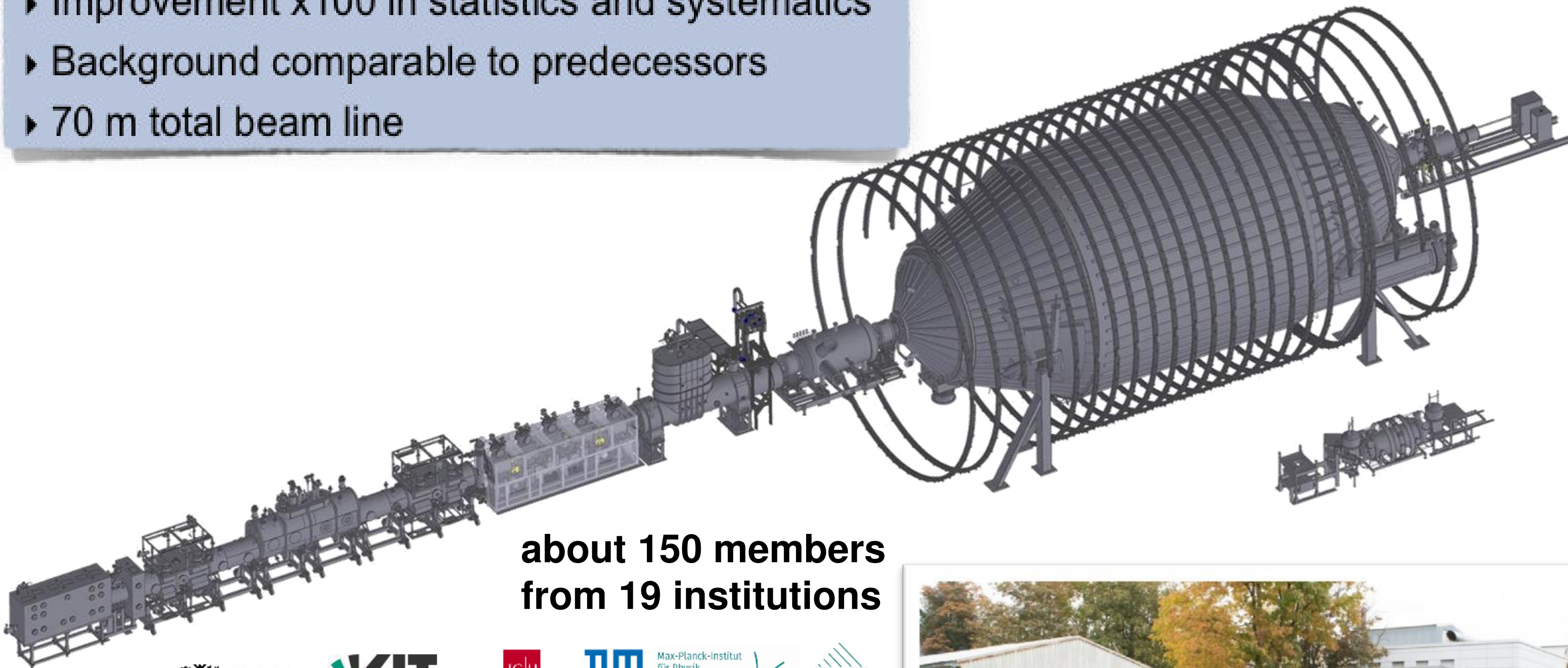
The KATRIN experiment



The Karlsruhe Tritium Neutrino Experiment

Sensitivity: 2 eV ➜ 0.2 eV

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

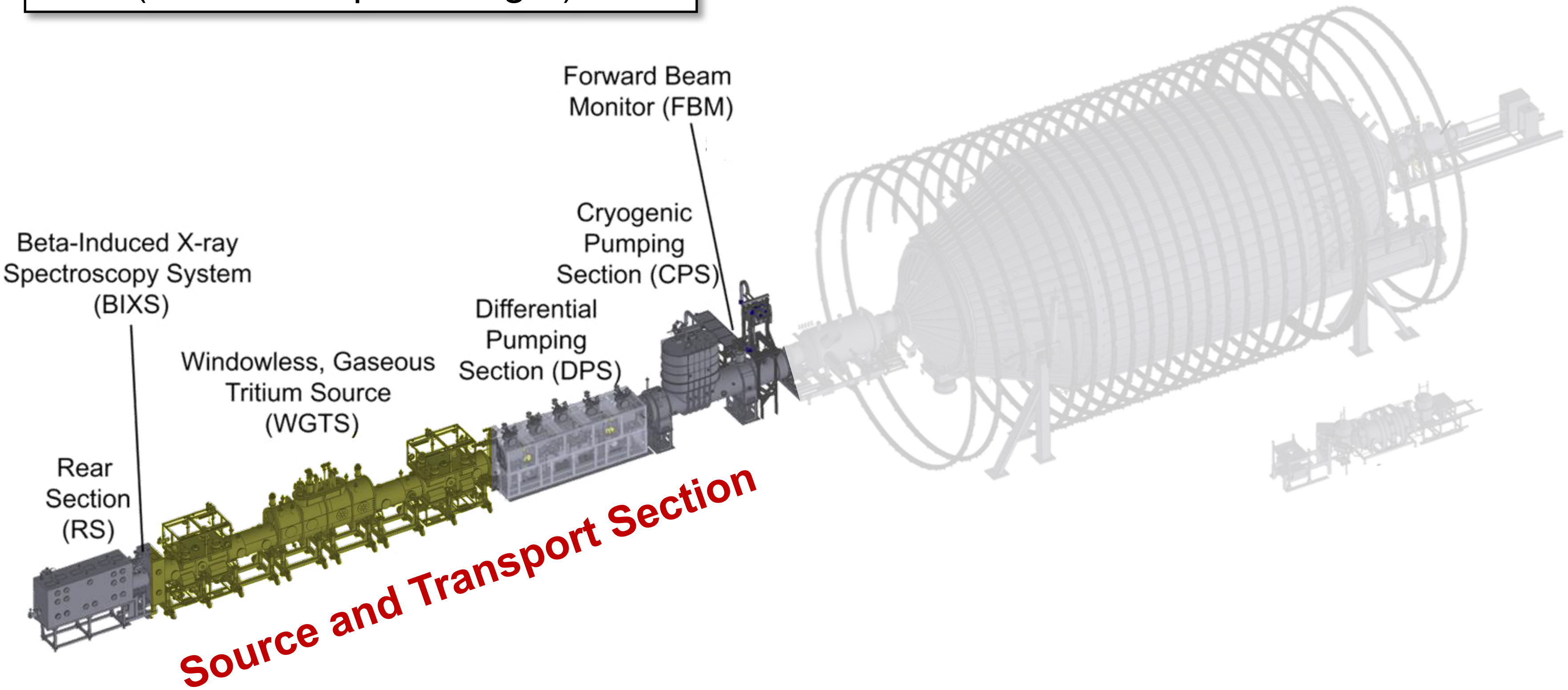


about 150 members from 19 institutions

Bergische Universität Wuppertal
KIT Karlsruhe Institute of Technology
JGU Johannes Gutenberg Universität Mainz
TUM Technische Universität München
Max-Planck-Institut für Physik
Max-Planck-Institut für Kernphysik
Westfälische Wilhelms-Universität Münster
universität bonn
Hochschule Fulda University of Applied Sciences
Case Western Reserve University
University of Washington
The University of North Carolina at Chapel Hill
MIT
Berkeley Lab
Carnegie Mellon University
cea
Universidad Complutense Madrid

The Karlsruhe Tritium Neutrino Experiment

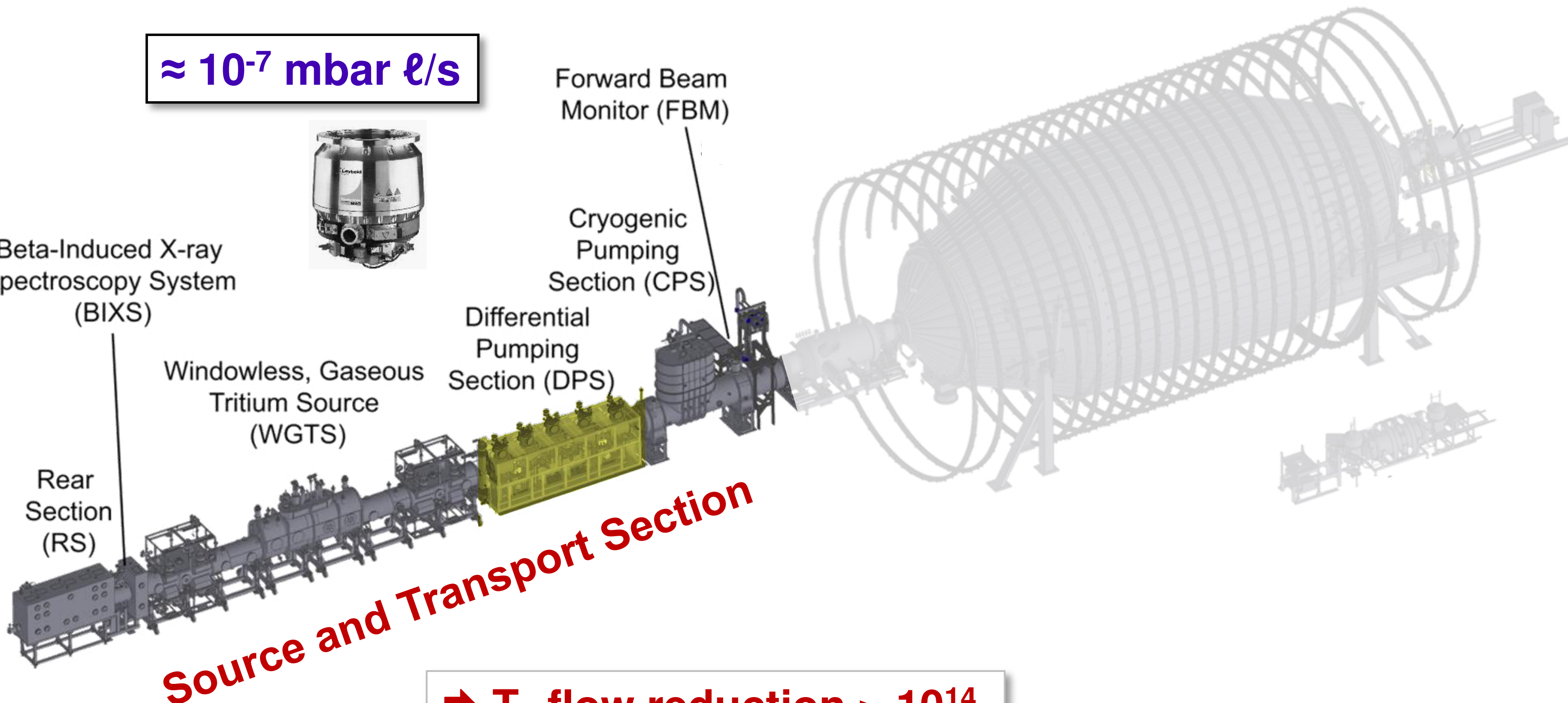
T_2-injection: 1.8 mbar ℓ/s (STP)
($1.7 \cdot 10^{11}$ Bq/s = 40 g/d)



➡ **processing-system: "tritium loops"**

The Karlsruhe Tritium Neutrino Experiment

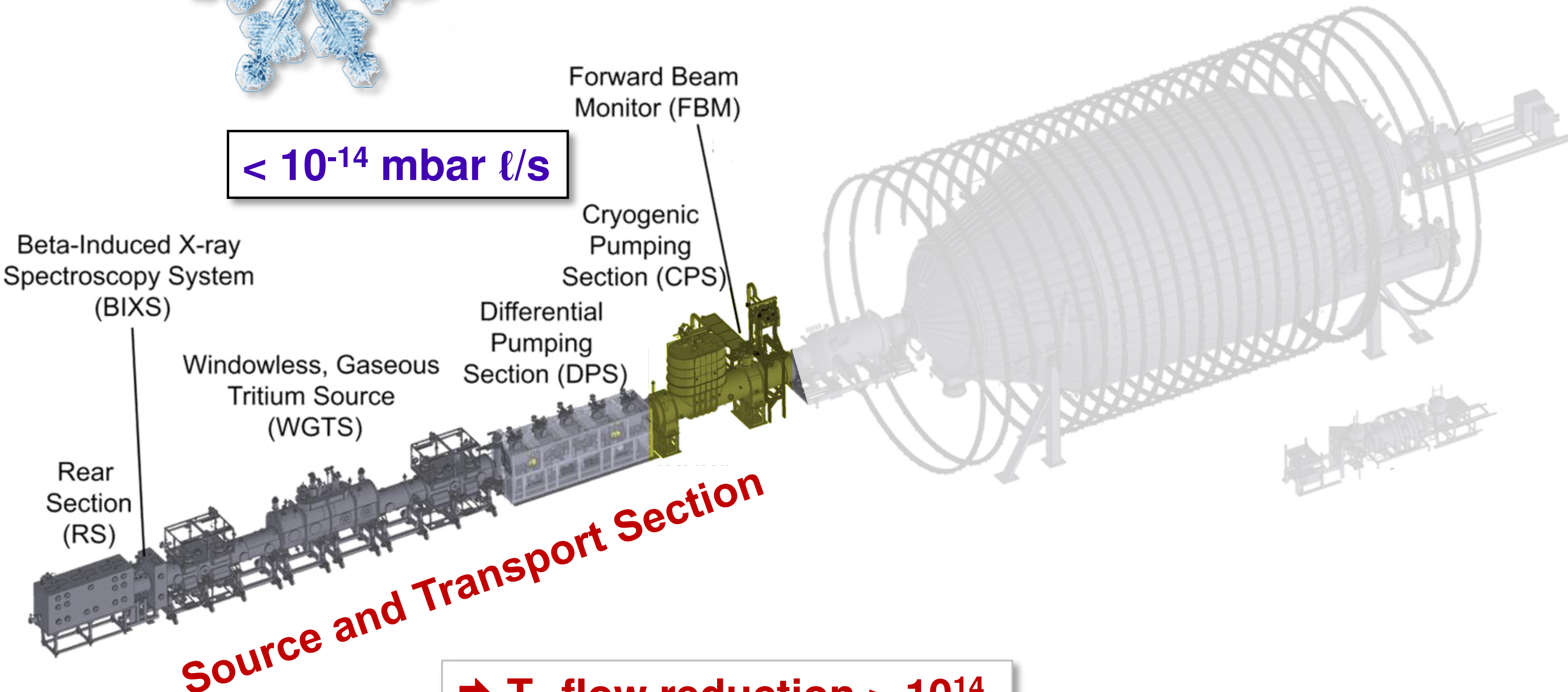
≈ 10^{-7} mbar ℓ/s



➡ **T_2 flow reduction > 10^{14}**

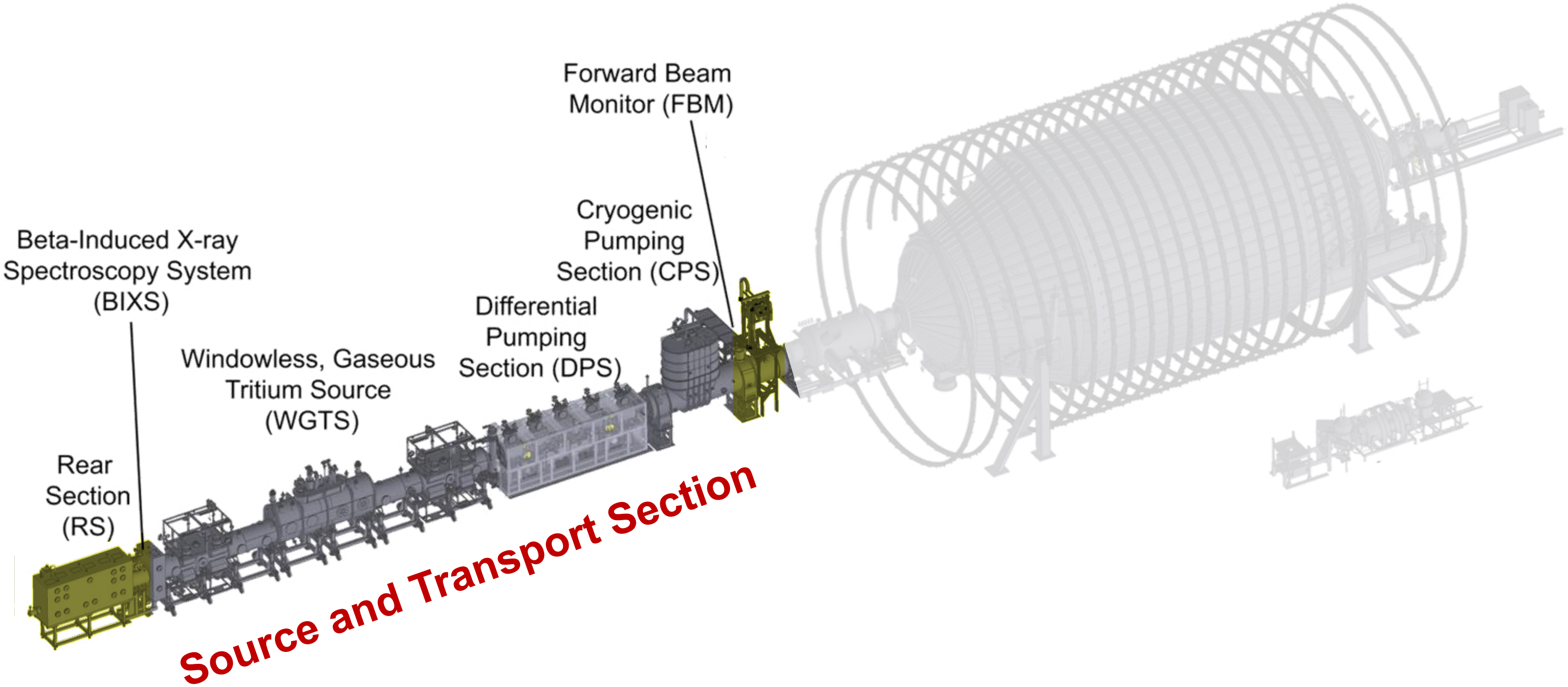
The Karlsruhe Tritium Neutrino Experiment

$< 10^{-14}$ mbar ℓ/s



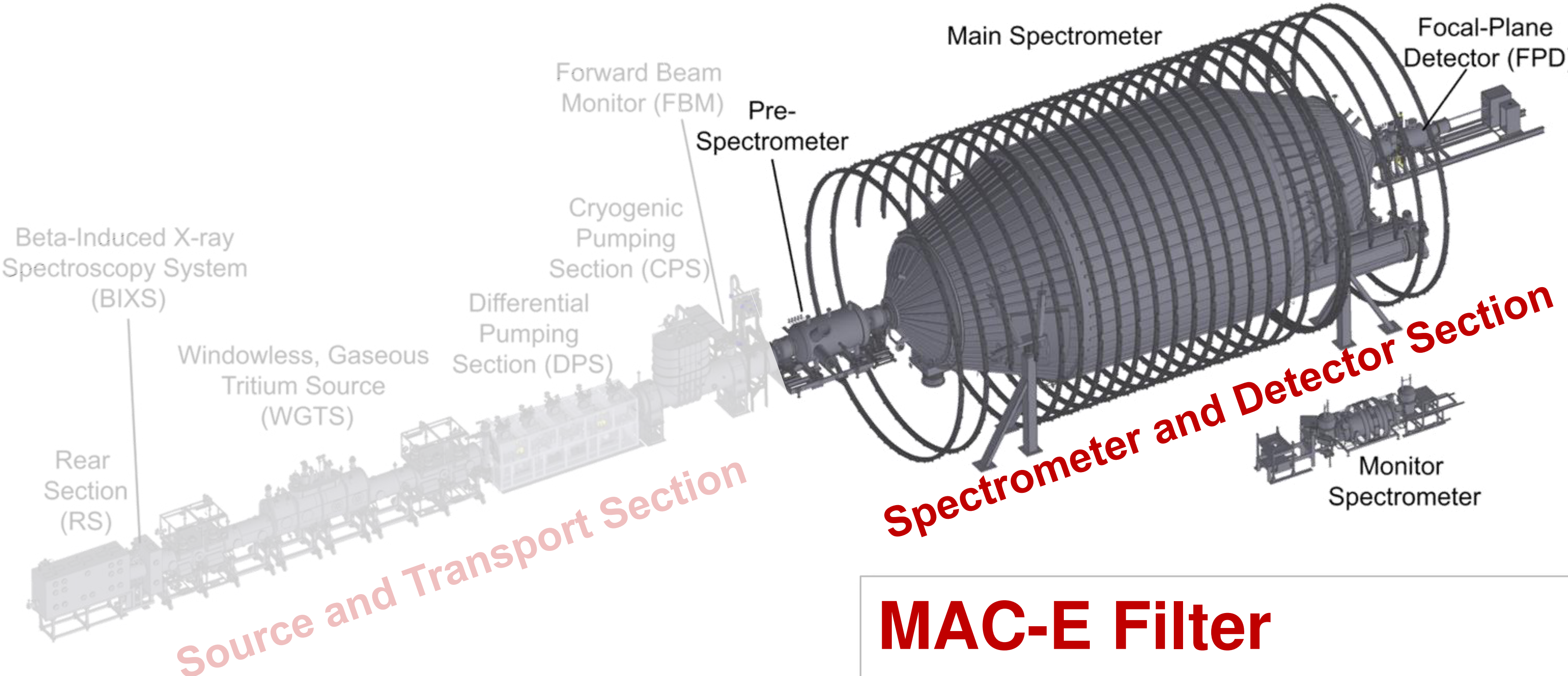
➡ T_2 flow reduction > 10^{14}

The Karlsruhe Tritium Neutrino Experiment



➡ **Calibration and monitoring system**

The Karlsruhe Tritium Neutrino Experiment



MAC-E Filter

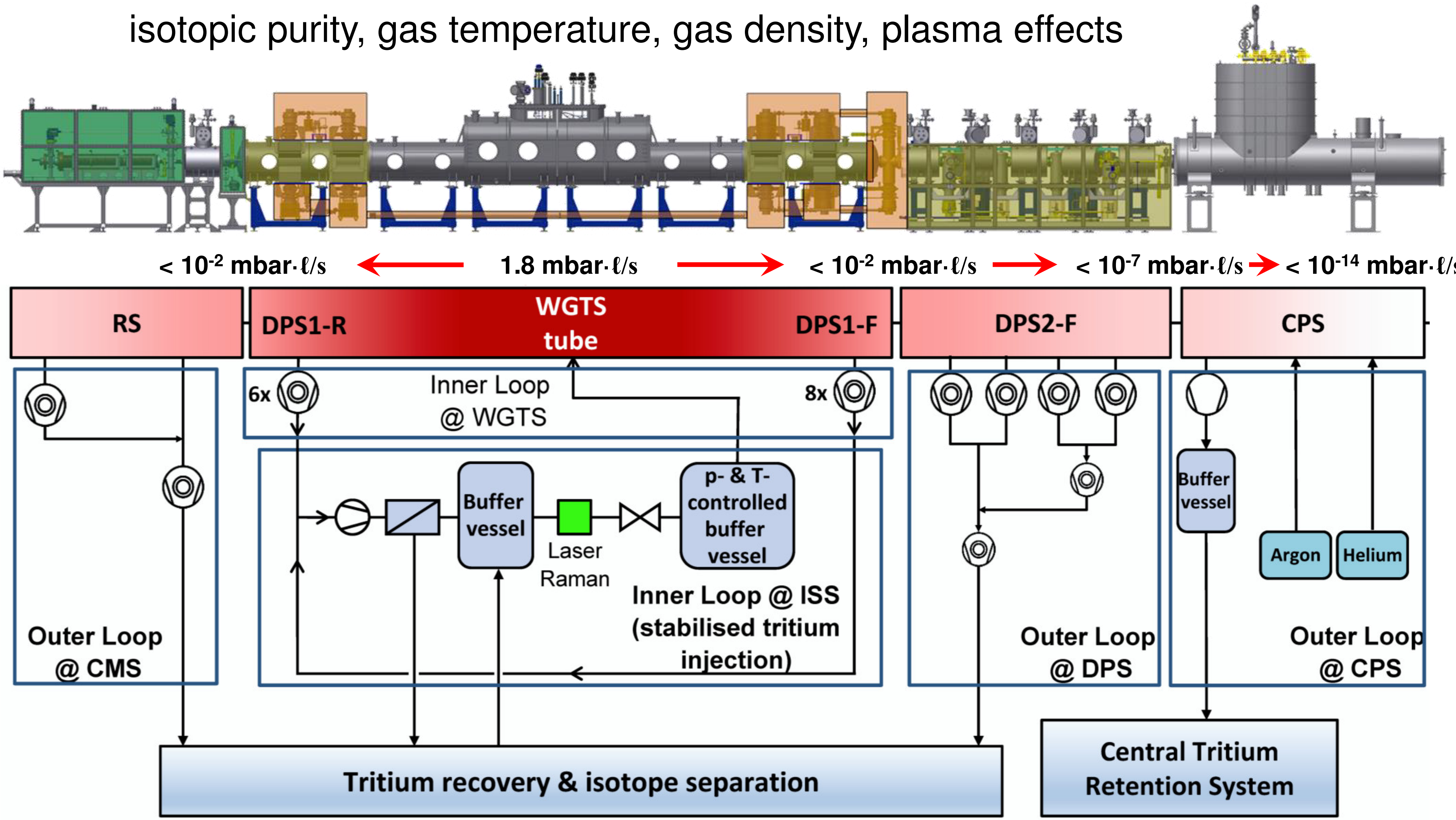
➔ energy resolution 1 eV at 18600 eV

➔ low background (design: 10 mcps)

KATRIN Source and Transport Section

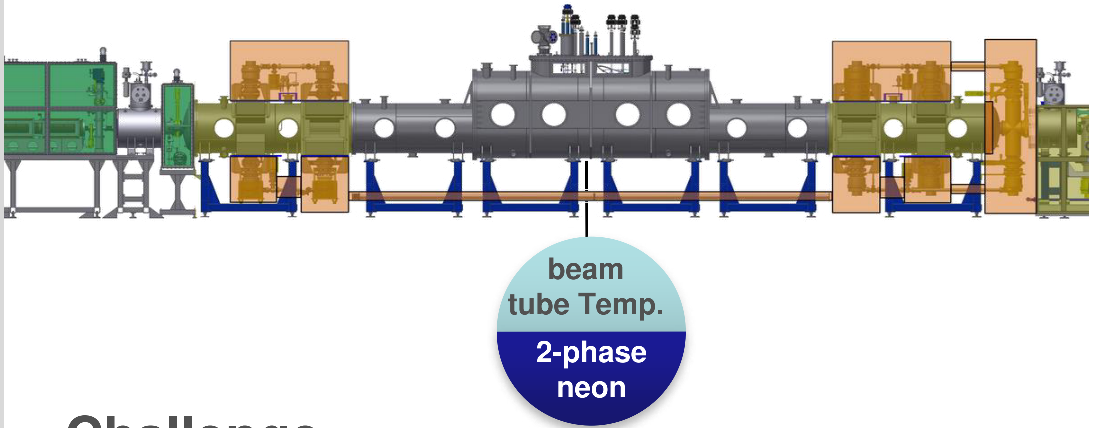
- **Source - stringent control of systematic effects**:

  isotopic purity, gas temperature, gas density, plasma effects



Windowless Gaseous Tritium Source WGTS

Beam tube temperature



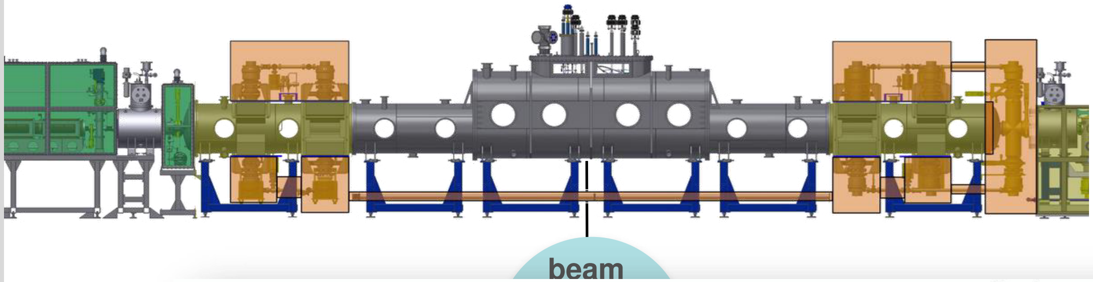
Challenge

- temperature stability on $\mathbf{10^{-3}}$ level

Windowless Gaseous Tritium Source WGTS

Karlsruhe Institute of Technology

Beam tube temperature



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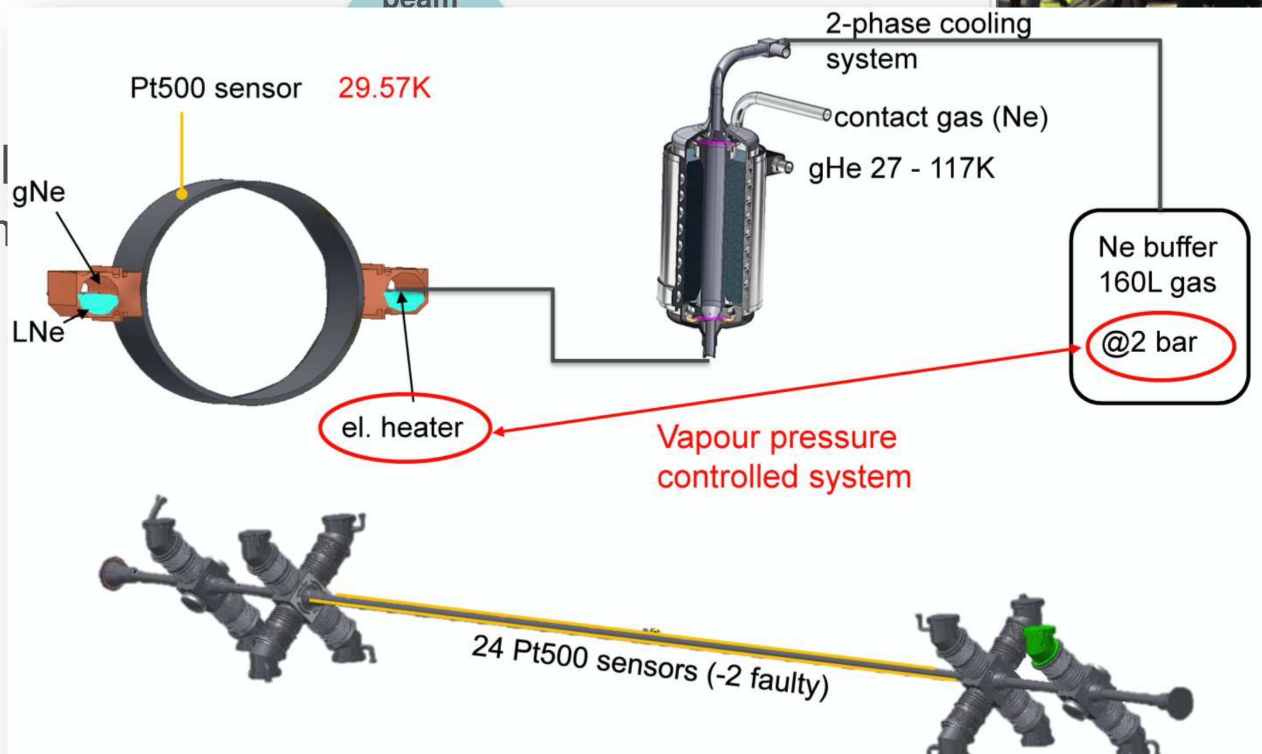
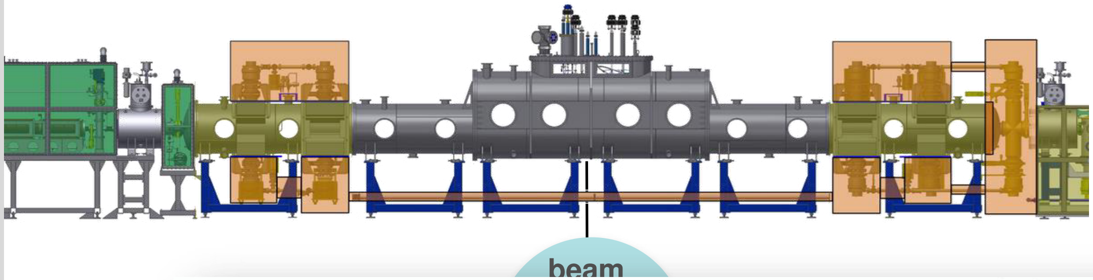


Windowless Gaseous Tritium Source WGTS

Beam tube temperature



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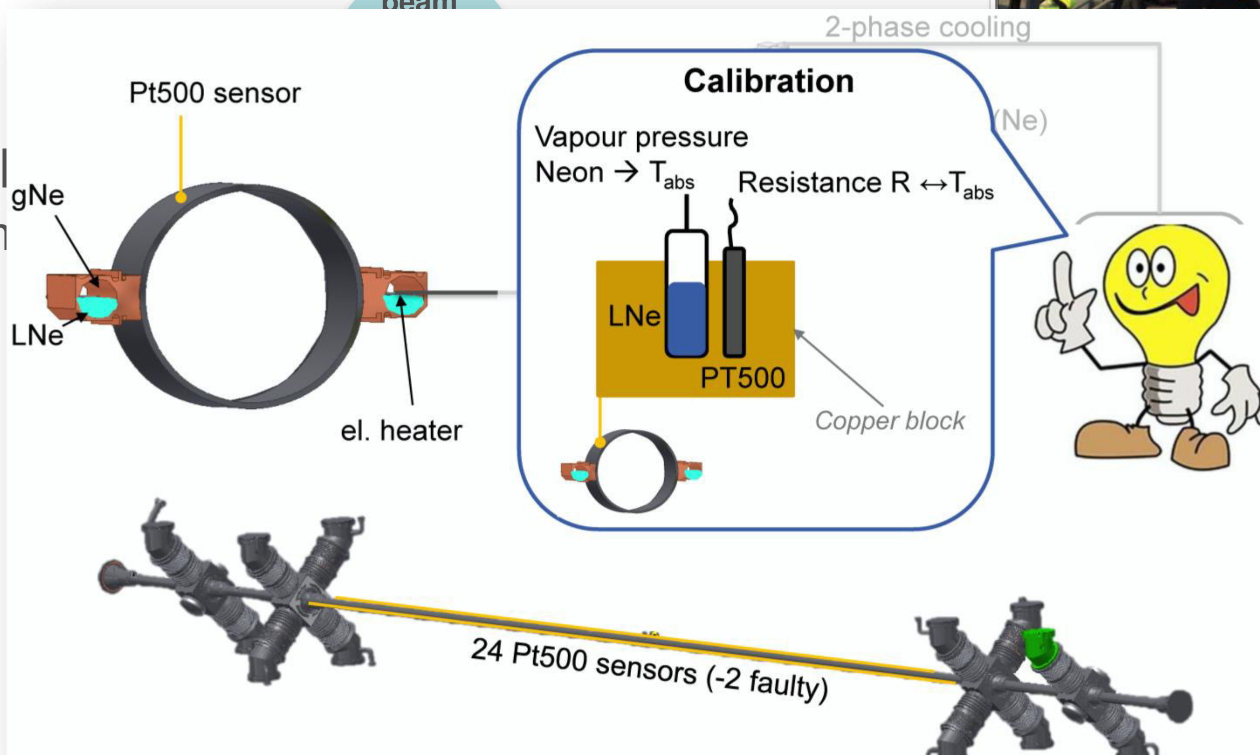
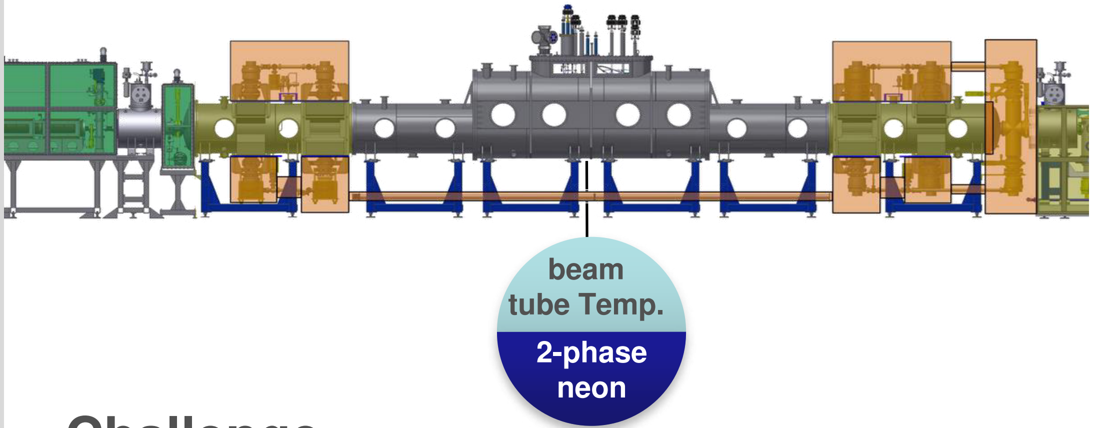


Windowless Gaseous Tritium Source WGTS

Beam tube temperature



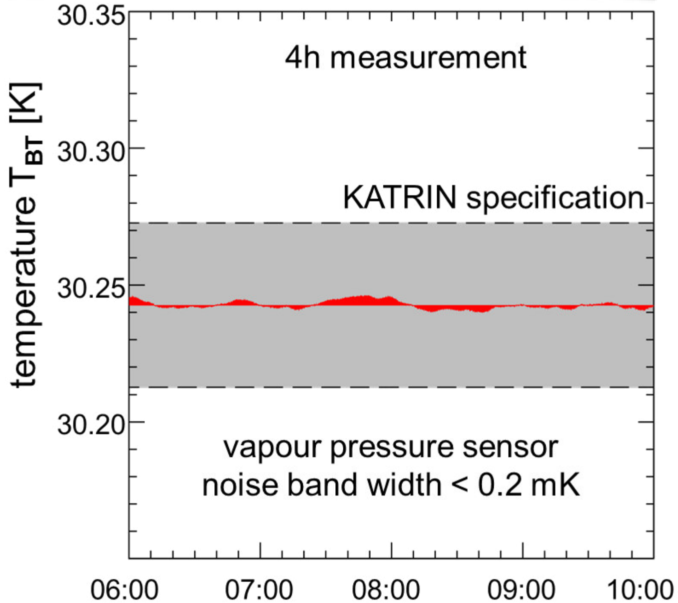
Challenge

- temperature stability on **10^{-3}** level

Technological development

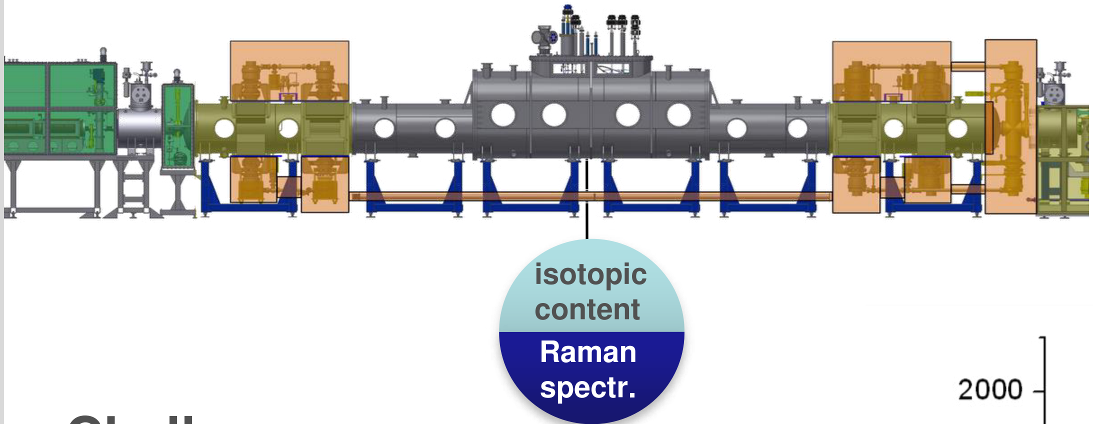
- novel **2-phase neon** cooling system
- required: $\Delta T = \pm$ 30 mK (1 h)
- **achieved: $\Delta T = \pm$ 1.5 mK (1 h)**

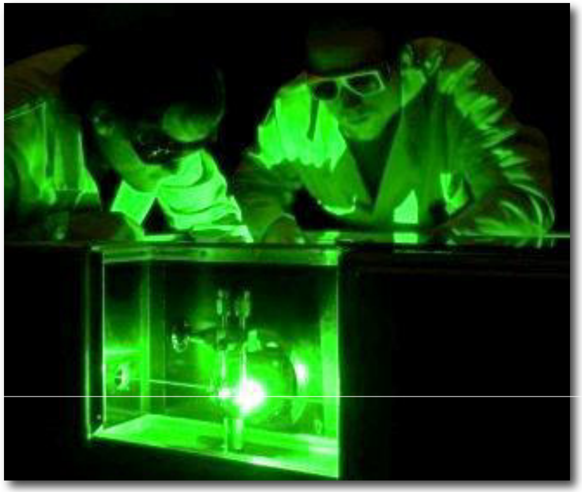
→ **stability surpassing specifications**



Windowless Gaseous Tritium Source WGTS

Raman spectroscopy



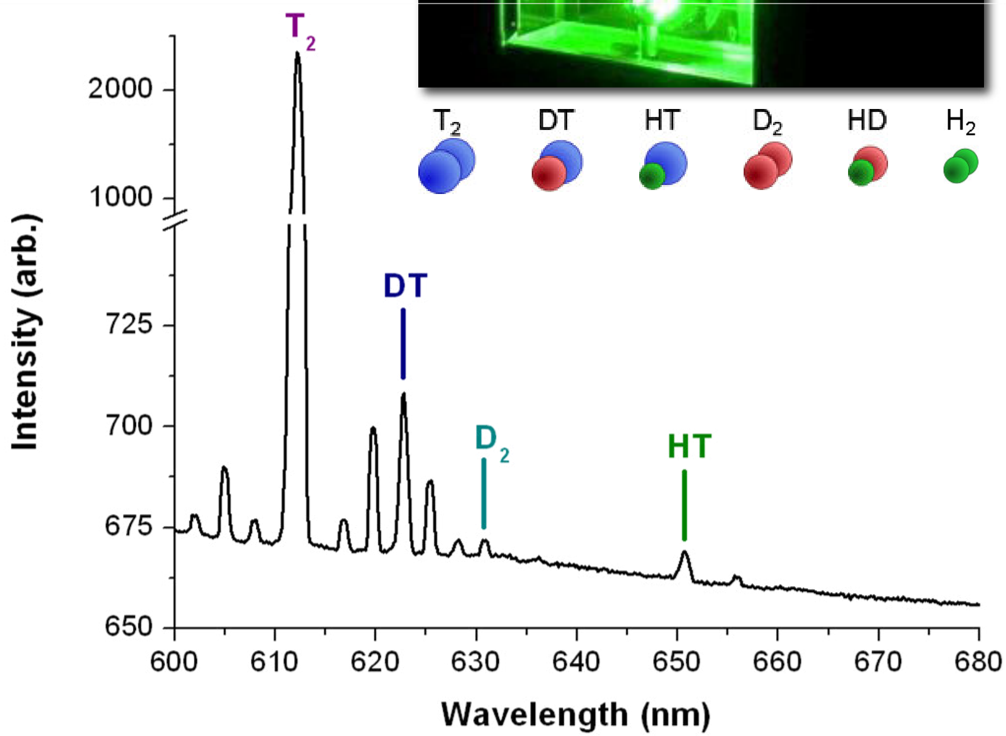


Challenge

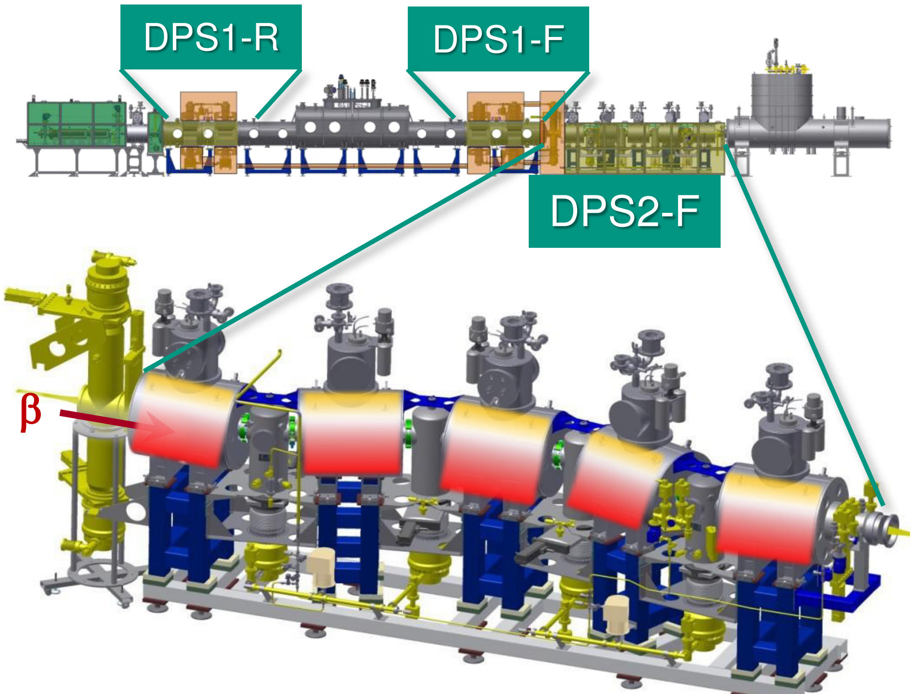
- measure isotopic source content with **10^{-3}** accuracy in **100 s**

Technological development

- calibrated **Laser-Raman system** for all 6 hydrogen isotopologues
- achieved: **< 10^{-3}** accuracy in **60 s**

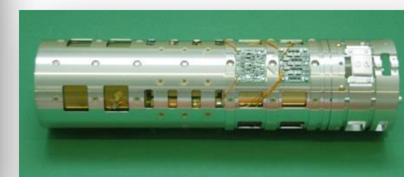


Transport and Pumping Section: DPS



Tritium ion removal

- 4 dipole electrodes: drift to wall
- Split-ring electrodes: ion rejection



Differential Pumping Section (DPS)

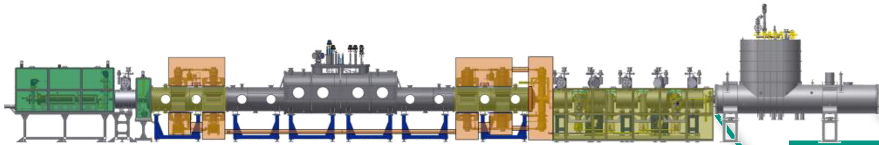
- magnetic field: 5.6 T
- active pumping: 18 TMPs
- tritium retention: **10^7**
- tritium ion removal and monitoring
- built at KIT, commissioning 2016/17

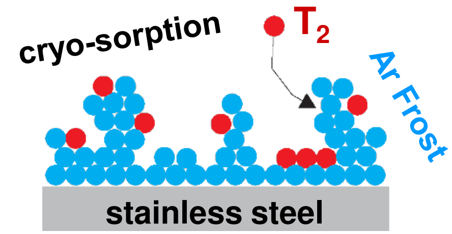
Tritium ion monitoring

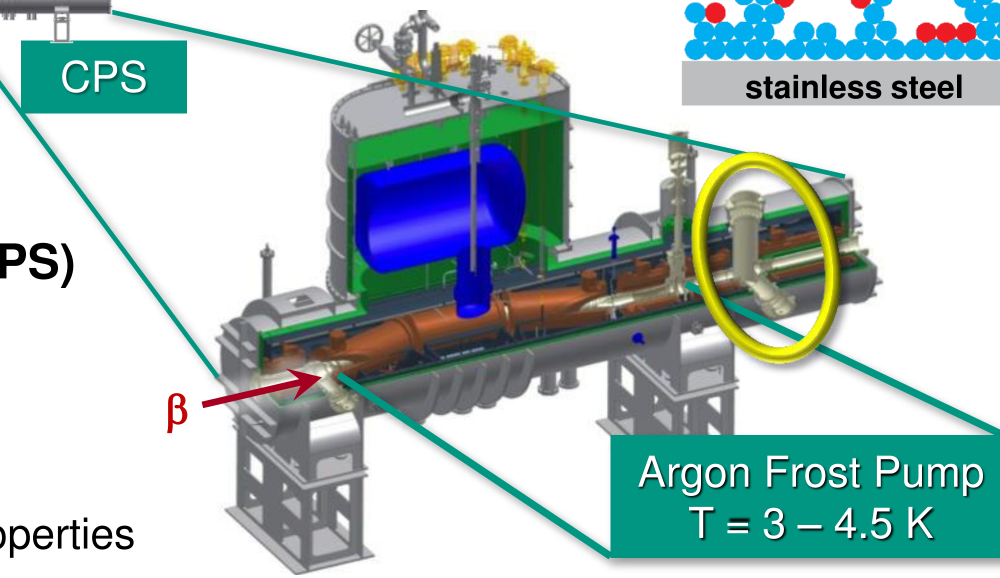
- FT-ICR: ion trap

(Fourier Transform – Ion Cyclotron Resonance mass spectrometer)

Transport and Pumping Section: CPS







Cryogenic Pumping Section (CPS)

- magnetic field: **5.6 T**
- based on cryo-sorption **Ar at 3K**
- tritium retention: **$>10^7$**
- beam diagnostics, spectrometer properties
- successful commissioning: 2016/2017

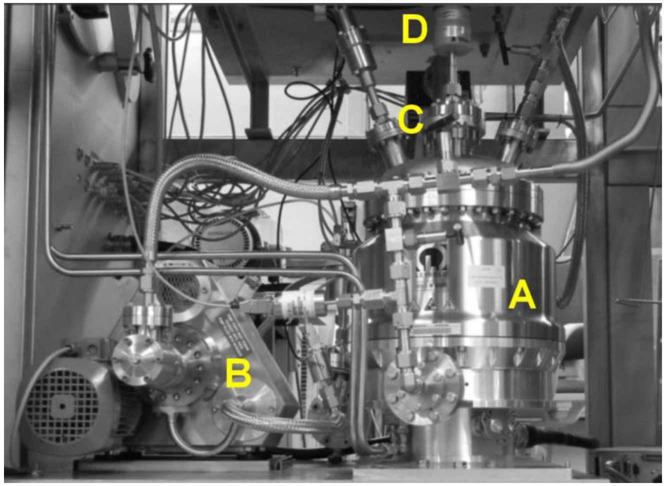
Calibration and monitoring

- Forward beam monitor (retractable photo diode)
- Condensed ^{83m}**Kr** source (conv. electron peaks)

Risks for turbo-molecular pumps?

Endurance test for TMP with tritium

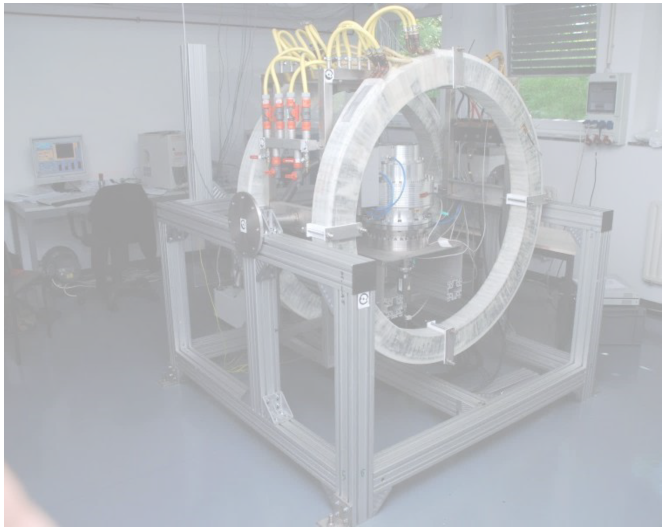
- tritium can affect non-metal parts of pump
- TMP type: Leybold MAG-W 2800
- tested at Tritium Laboratory Karlsruhe (TLK)
- **398 days** operation with tritium
- throughput: **1106 g tritium**



F. Priester, PhD thesis at KIT (2013)

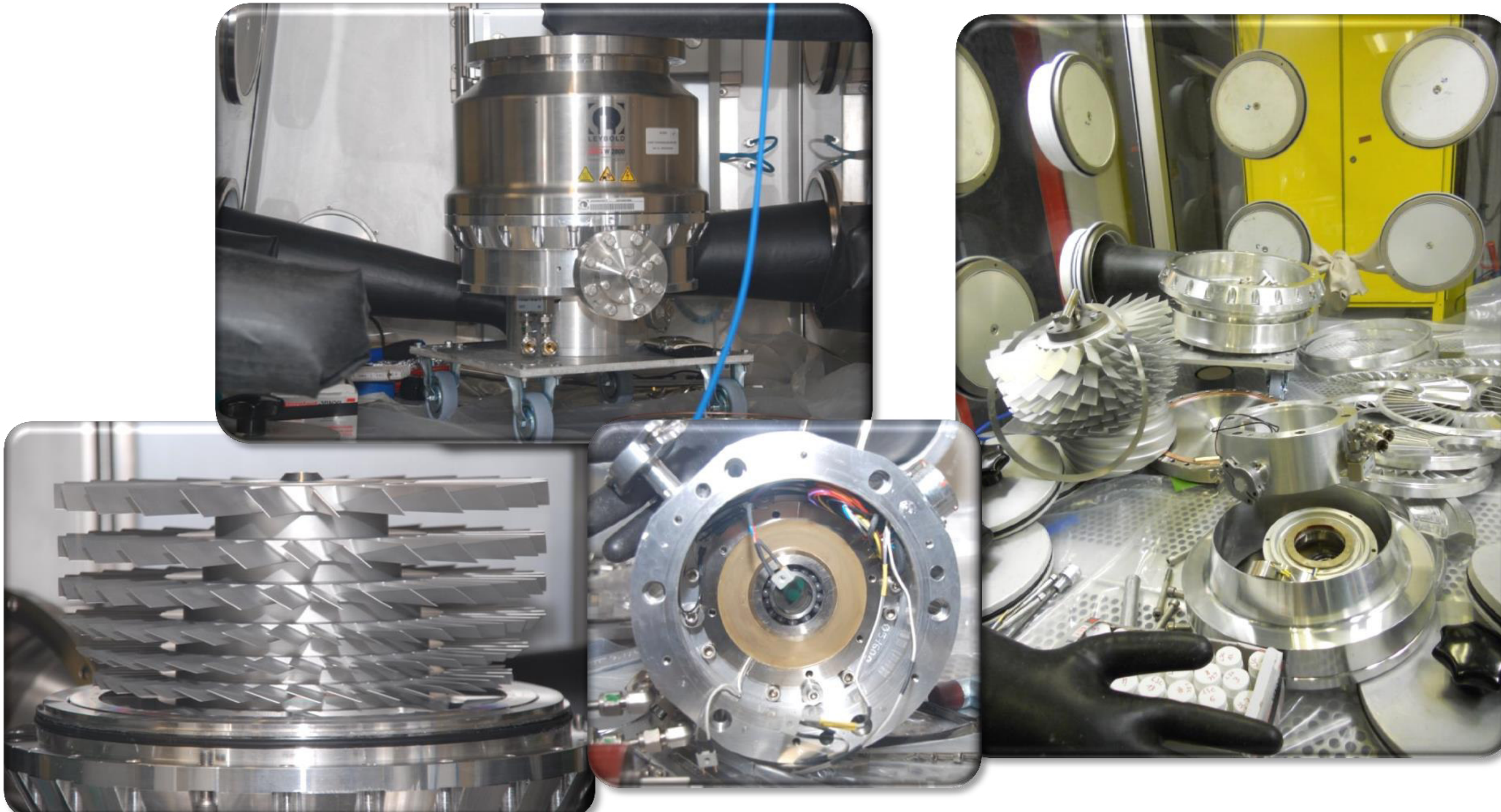
TMP in a magnetic field

- eddy currents can over-heat rotor
- high mag. field can slow down rotor
- failure of magnetic bearing
- test setup built at KIT for large TMPs
- math. model developed for prediction



R. Größle et al., Vacuum 86 (2012) 985-989

Complete dismantling of a MAG W 2800



- parts were highly contaminated with tritium, but …
- … parts looked like new, no indication of wear, cables and O-rings ok

Risks for turbo-molecular pumps?

Endurance test for TMP with tritium

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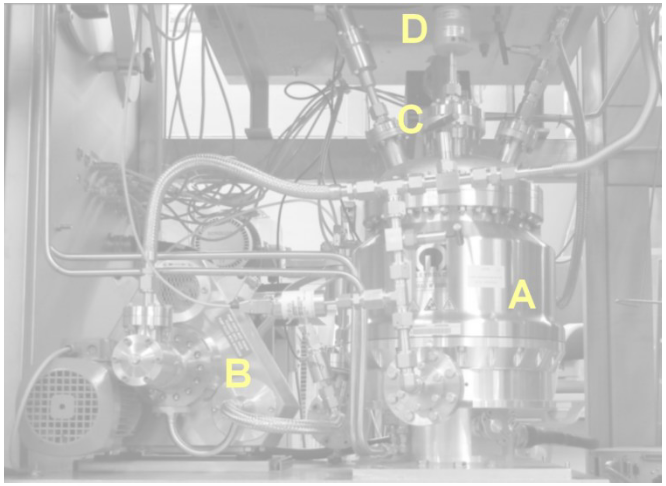

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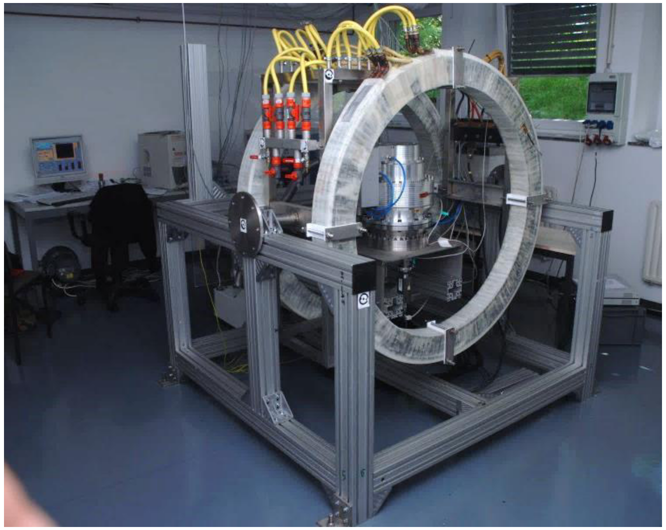
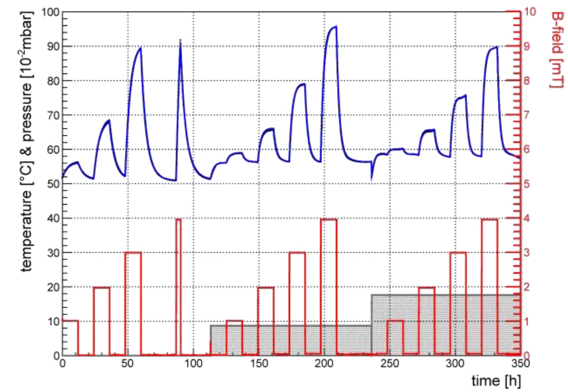
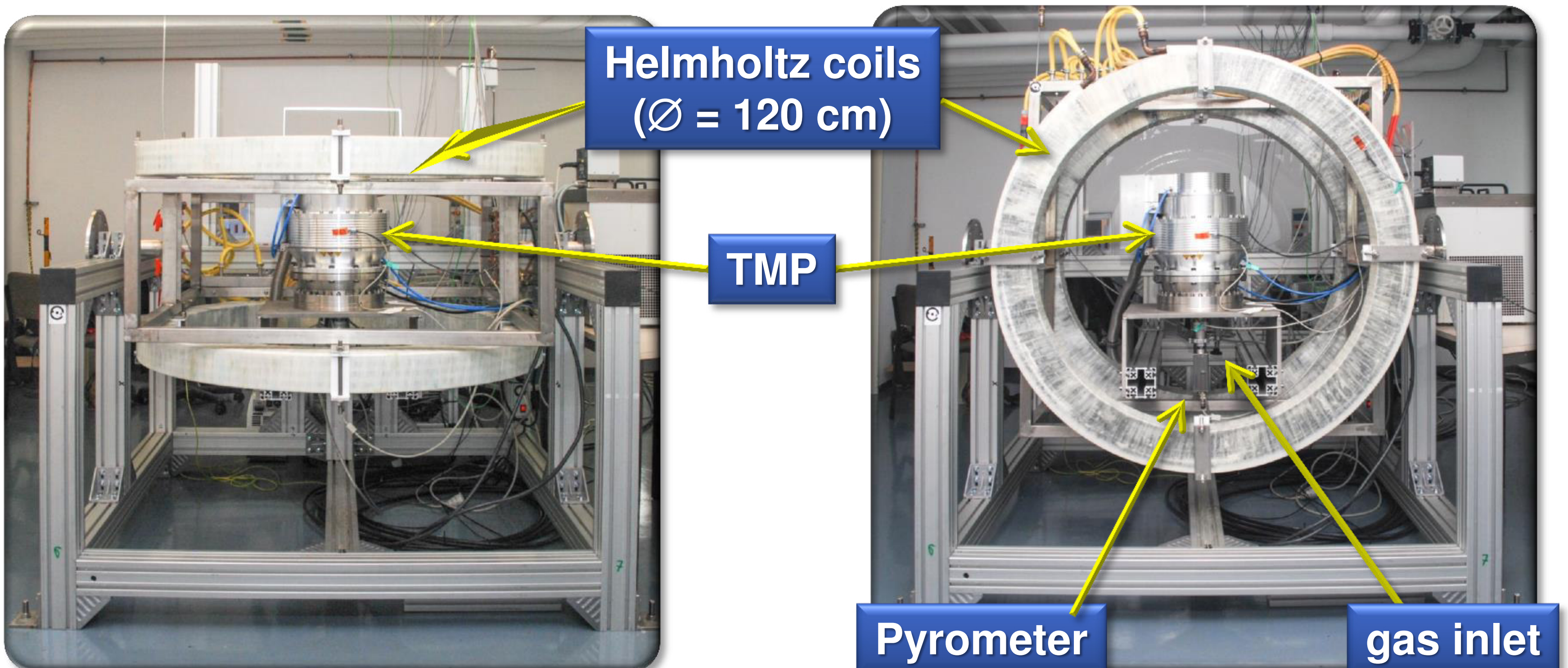


R. Größle et al., Vacuum 86 (2012) 985-989

TMP in a magnetic field

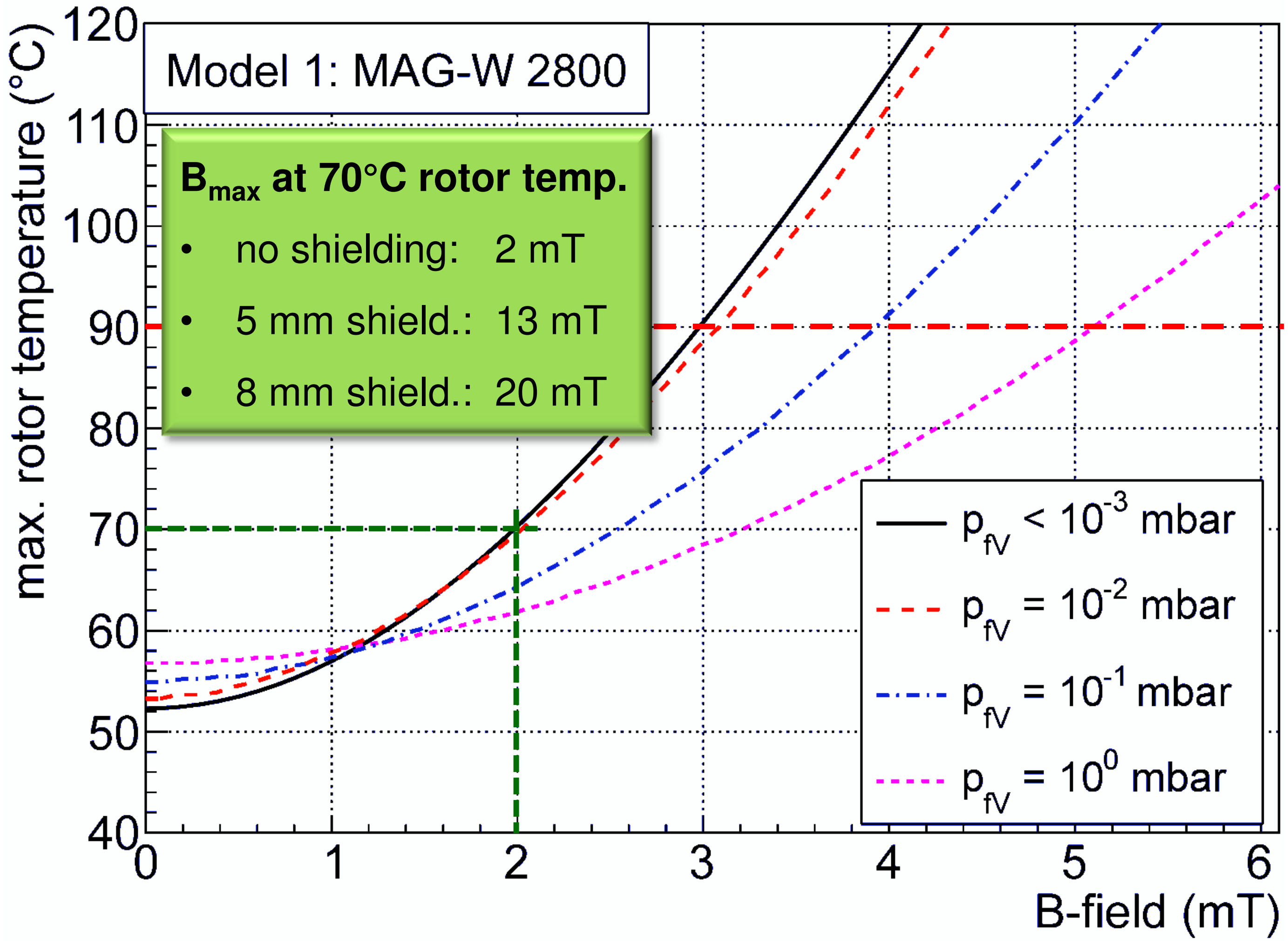
- Helmholtz coils: radius = 60 cm
- B-field: 0 – 50 mT
- coils can be turned by 90°
- pyrometer used for rotor temperature
- gas flow possible
- measures parameters for empirical model





TMP in a magnetic field

- WGTS: TMPs operated in 18.5 mT
- 8 mm St37 steel shielding: < 70°C



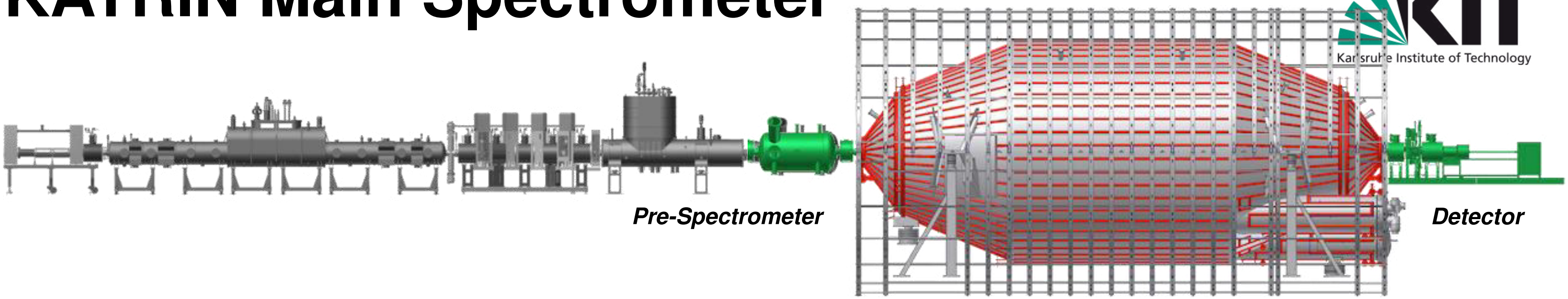
The KATRIN Main Spectrometer

Manufacturing of the Main Spectrometer

Karlsruhe Institute of Technology

KATRIN Main Spectrometer Journey to KIT

KATRIN Main Spectrometer

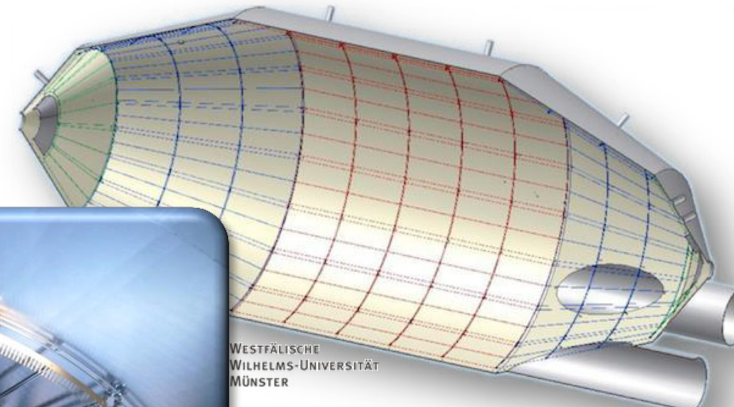


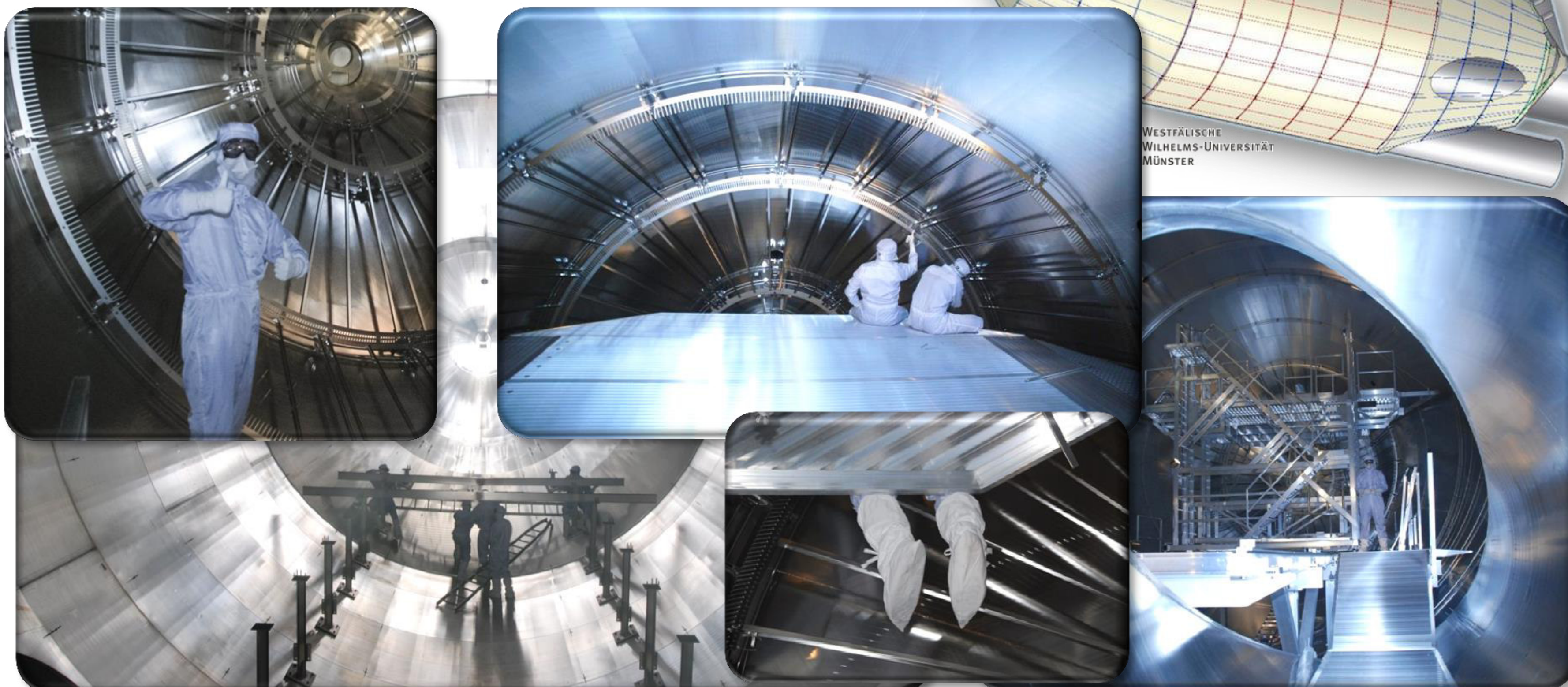
- **MAC-E Filter** principle → precise electron energy measurement
  - Vacuum vessel & electrodes on **variable retarding potential (18.6 kV)**
  - Magnetic guiding field: **0.3 mT – 6 T**
  - High resolution: **ΔE = 0.93 eV @ 18.6 keV**
- **Stainless steel (~200 to, 316LN)**
- **Dimensions:**
  - diameter: 10 m
  - Length: 23 m
  - volume: 1240 m^3
  - inner surface: 1222 m^2 (including wire electrodes)

arrival at KIT: 26.11.2006

Wire Electrode Installation (2008 – 2012)

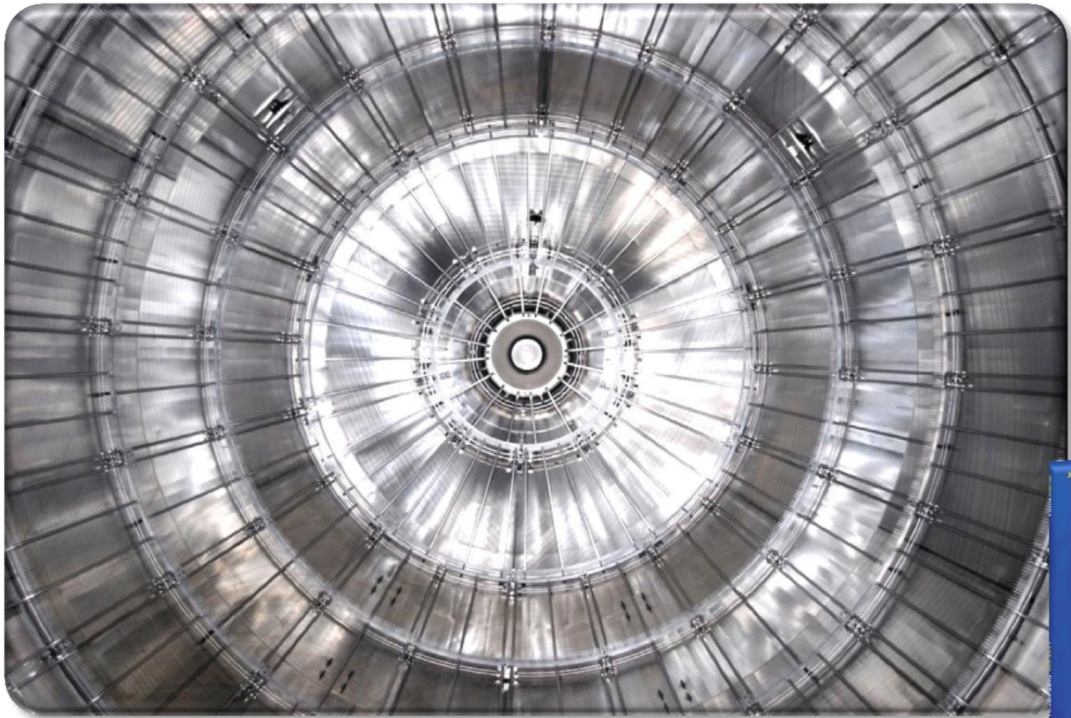
- **248 wire electrodes cover the inner surface of the Main Spectrometer**
  - 23 440 insulated wires
  - ~ 120 000 individual parts
- **Installed under cleanroom conditions**

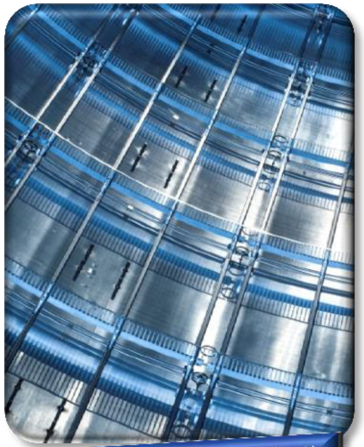




Wire Electrode Installation (2008 – 2012)

Karlsruhe Institute of Technology

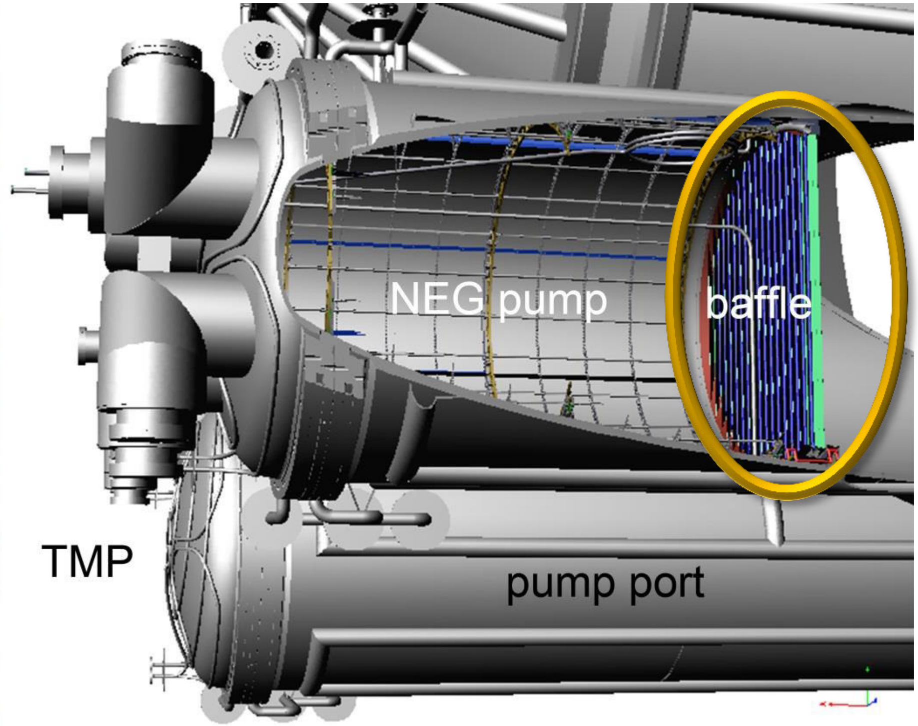




- 2012: Electrode installation completed
- 2013: bakout at 300°C
- first commissioning runs
  - 2013
  - 2015
  - 2017/18

Westfälische Wilhelms-Universität Münster

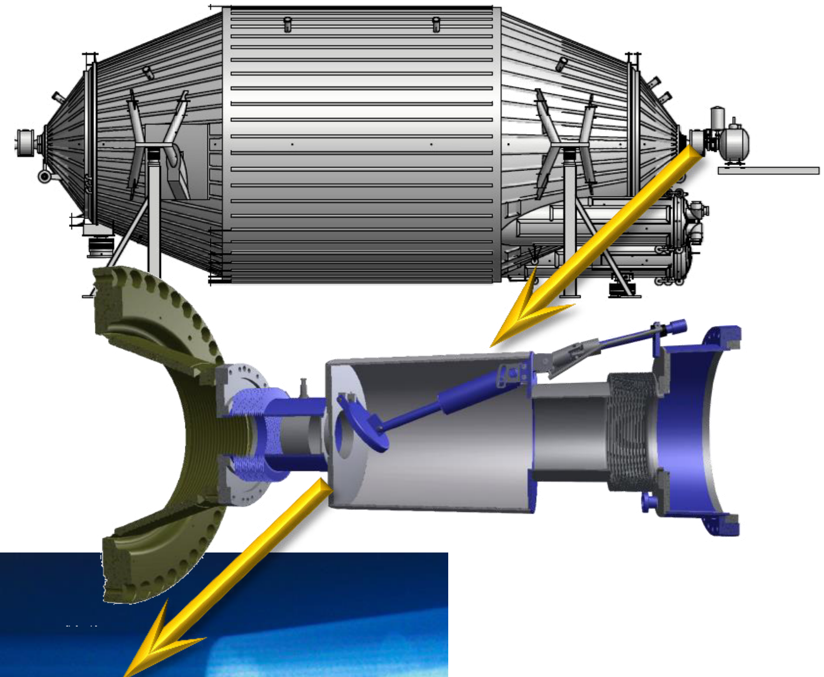
KATRIN Main Spectrometer Vacuum

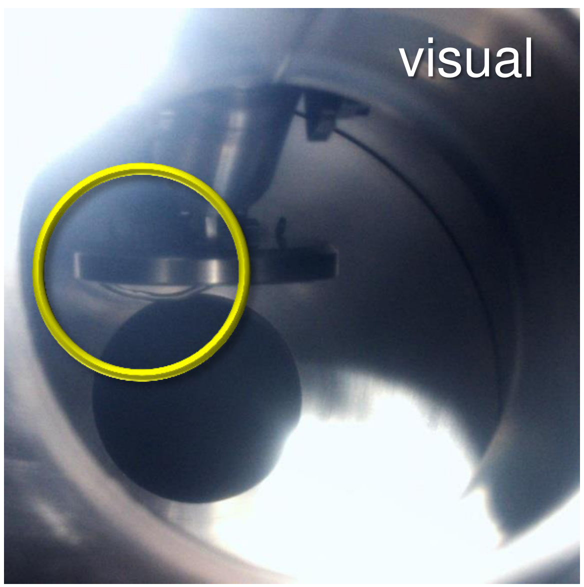


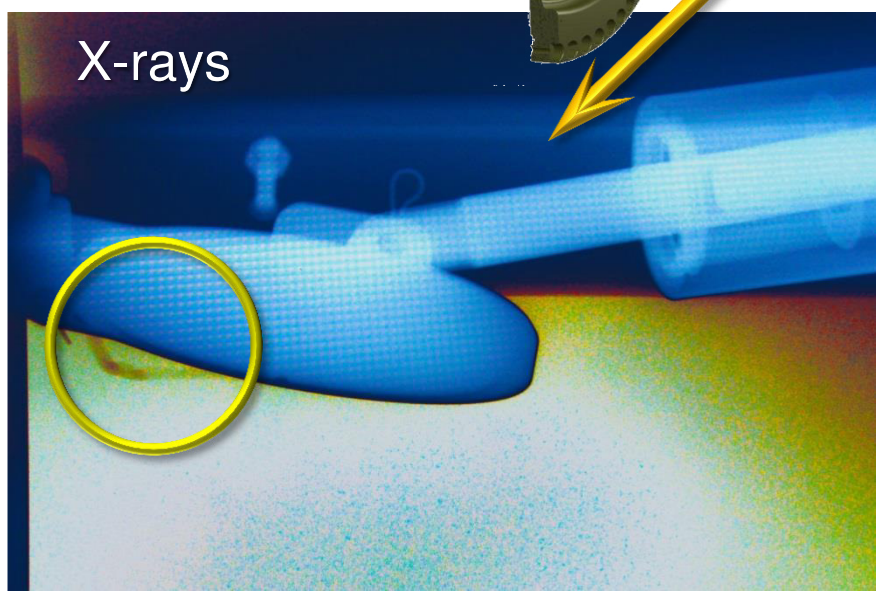
- Roughing pump: 640 m^3/h screw-pump
- 6 turbo-molecular pumps (Leybold MAG-W 2800): 10 000 ℓ/s (H_2)
- 2 ~~3~~ NEG-pumps (3000 m SAES St707 getter strips): ~~~10^6 ℓ/s (H_2)~~ 250 000 ℓ/s
- 3 cryogenic LN_2 baffles (radon): ~160 000 ℓ/s (Rn)
- ultimate pressure: 10^{-11} mbar

Coupling of Spectrometer and Detector

- Detector de-coupled during bake-out
- Requires valve inside magnet bore
- O-ring partly slipped out during baking
- **Challenge:** attach detector without saturation of the activated NEG-pump

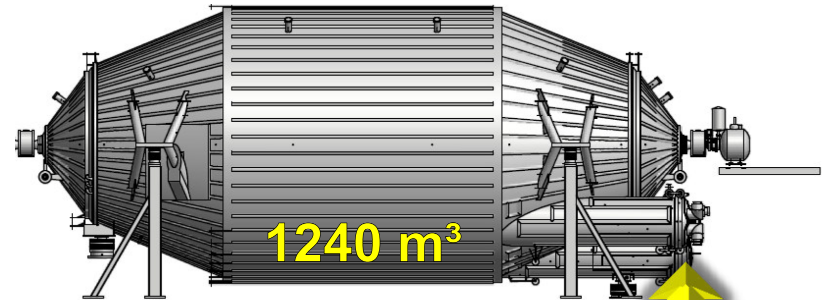






Coupling of Spectrometer and Detector

- **Solution:** replacing the O-ring under inert gas atmosphere (Ar)
- Gas quality N9.0 required to prevent contamination of NEG



Ar 9.0

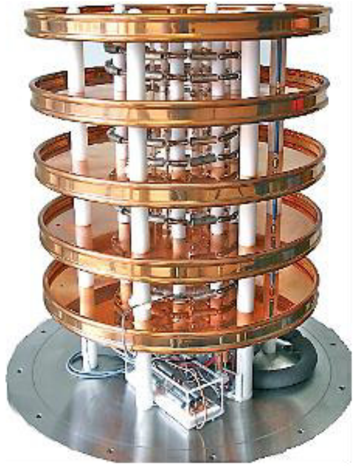
144 bottles Argon N6.0

Ar 6.0

XENON 1t
gas purification system (SAES)

☑ O-ring exchanged in Ar atmosphere
☑ beam-line valve now leak tight
☑ detector section attached

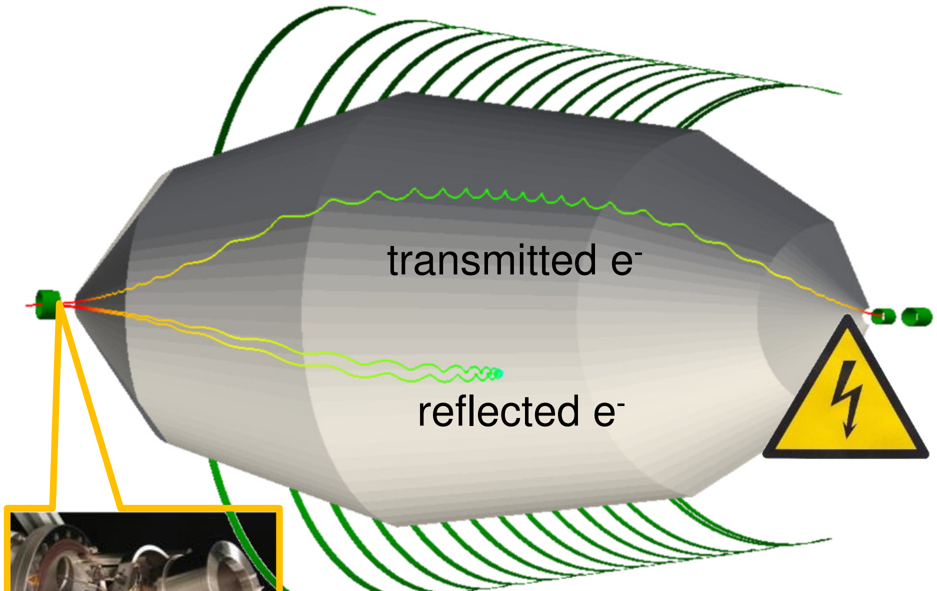
KATRIN - MAC-E filter characteristics



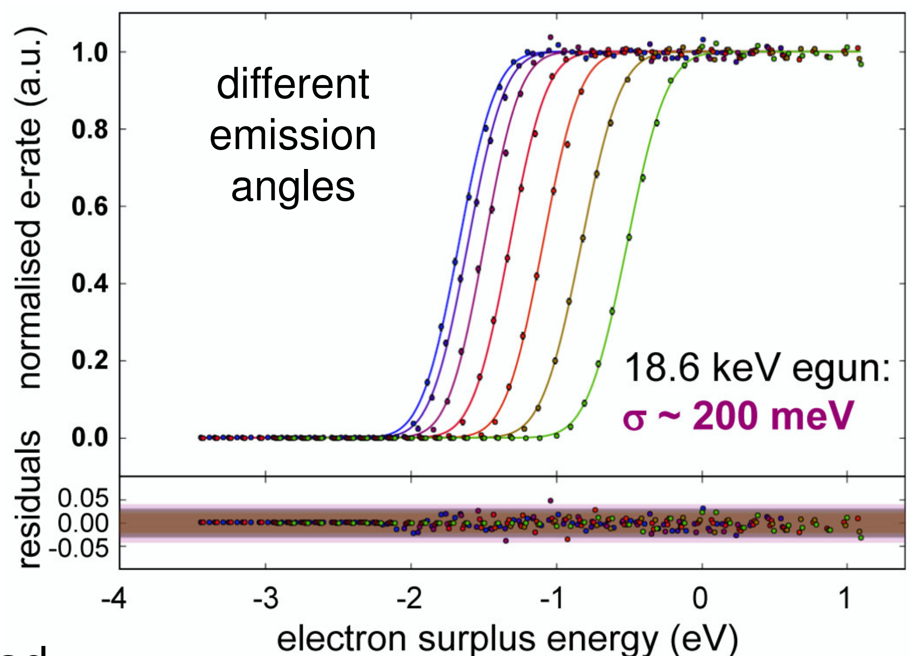
- **main spectrometer** works as high-resolution MAC-E filter:
  - **sharp transmission function** for 18.6 keV e^- from e-gun
  - width limited by egun emission spectrum
  - **HV stability on ppm-scale**

Westfälische Wilhelms-Universität Münster

In cooperation with German national metrology institute PTB

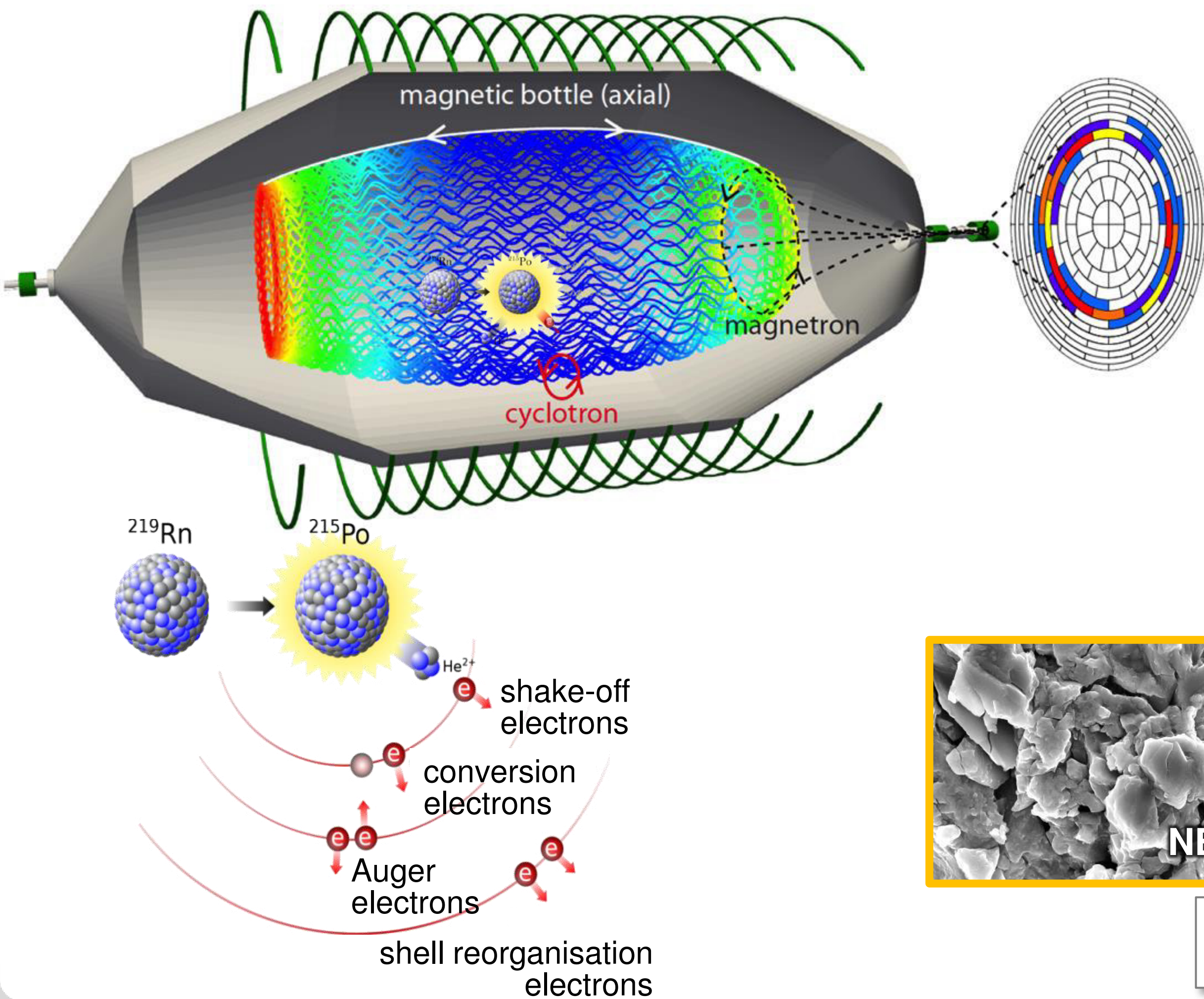


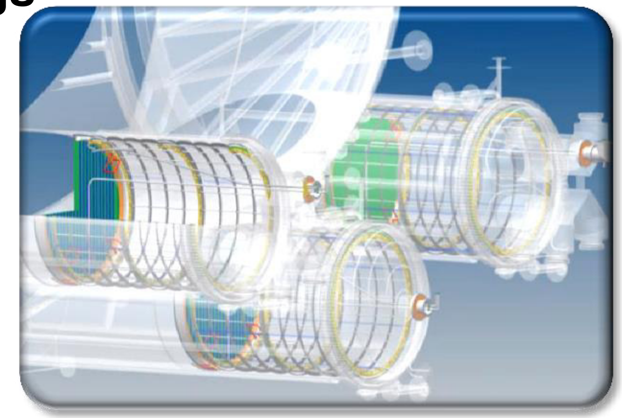
e-gun with small angular spread

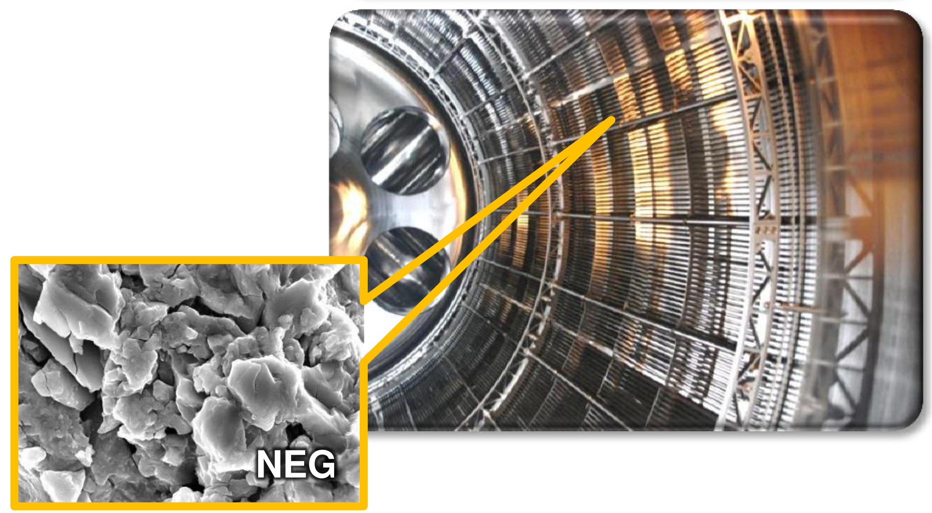


Radon as source of background (problem)

- ^{219}Rn emanation from St707 NEG getter strips (2000 m) in pump ports
- ^{220}Rn emanation from stainless steel walls/weldings



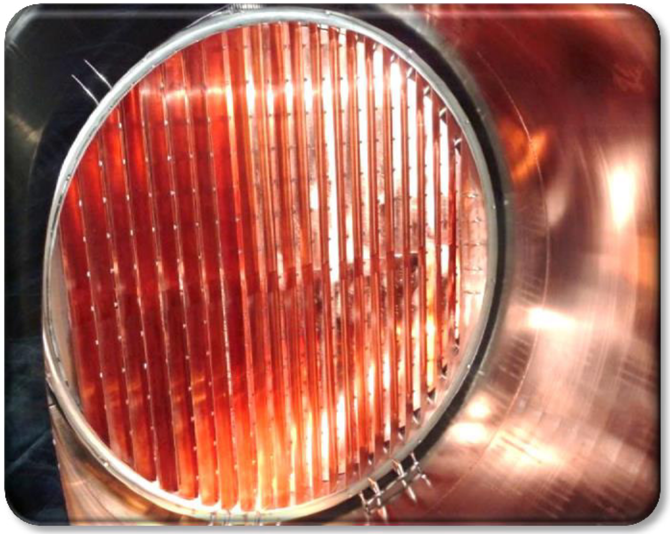


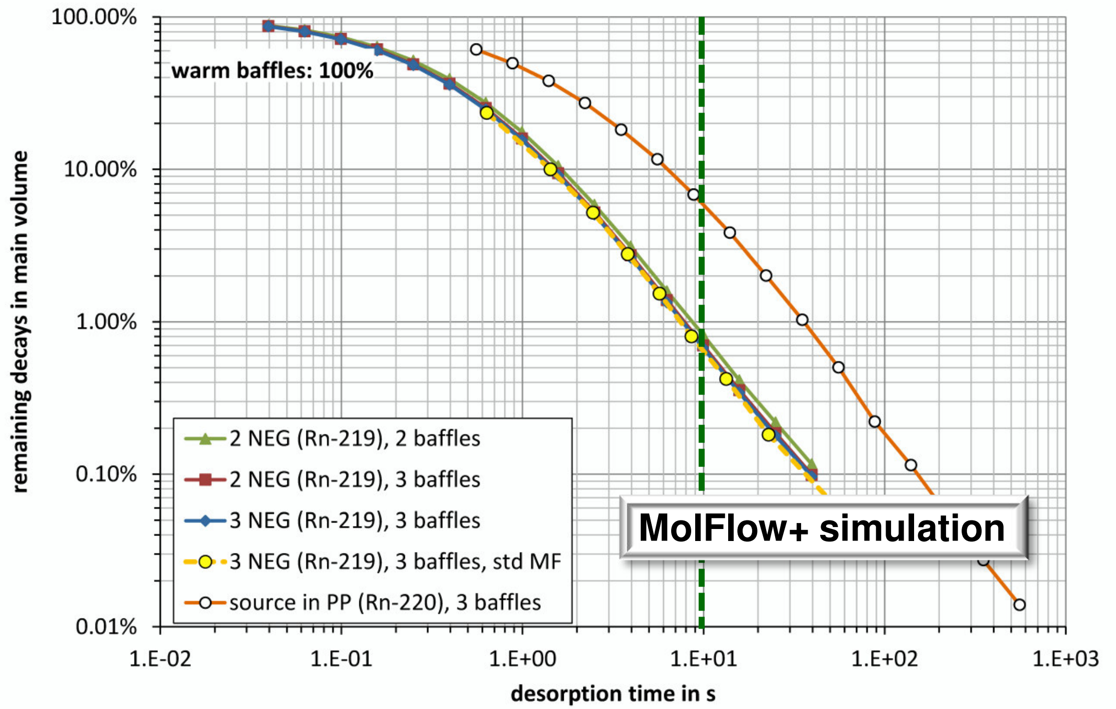


F.M. Fränkle et al., Astropart. Phys. 35 (2011) 128
S. Mertens et al., Astropart. Phys. 41 (2013) 52

Radon as source of background (solution)

- passive background reduction: LN$_2$-cooled baffles to cryo-sorb ^{219}Rn, ^{220}Rn



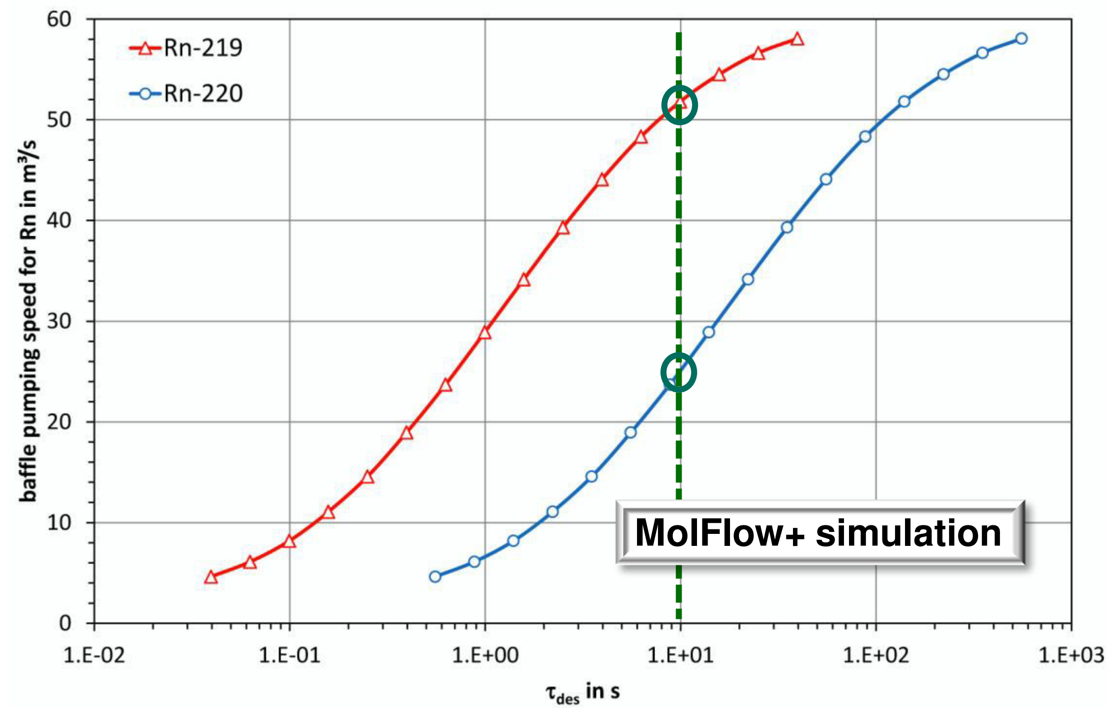


- Reduction of effective NEG pumping speed: 38%
- Reduction of ^{219}Rn flow into main vol. : ~ 0.6%
- Reduction of ^{220}Rn flow into main vol. : ~ 6%

G. Drexlin et al., Vacuum 138 (2017), 165–172

Radon as source of background (solution)

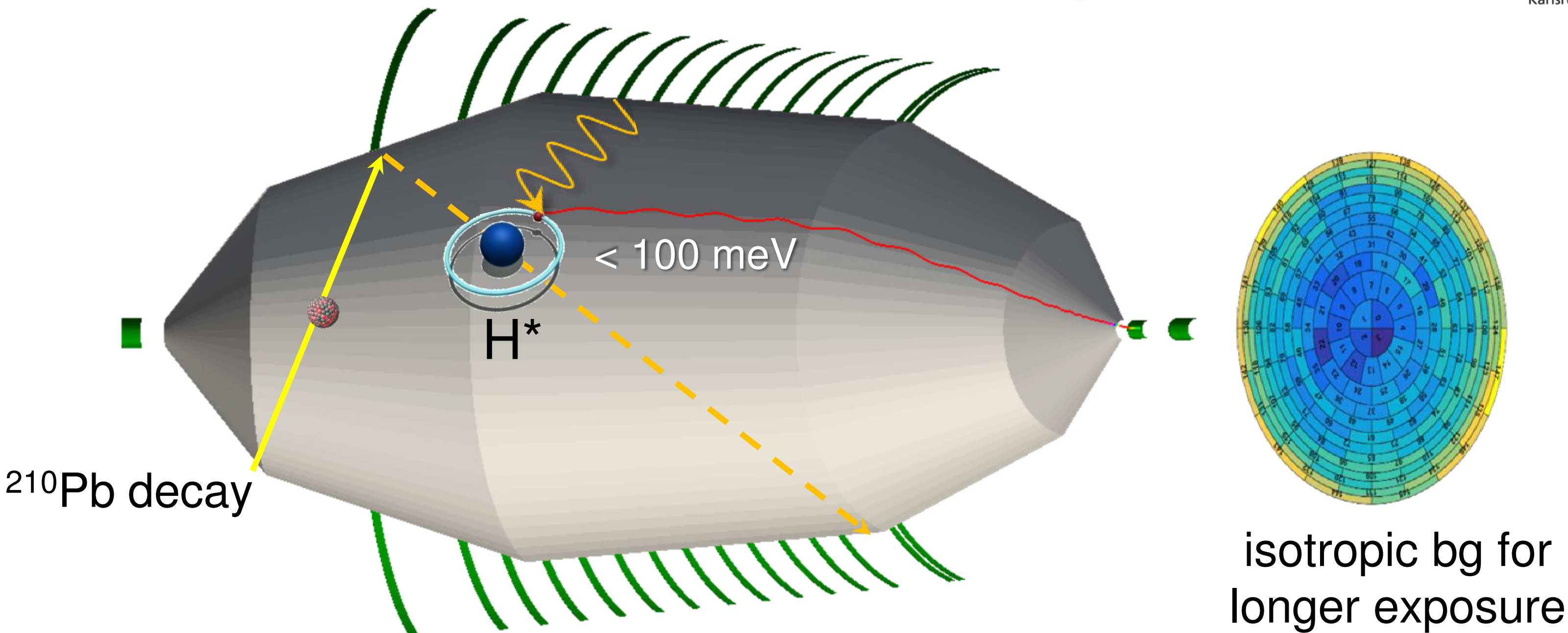
- passive background reduction: LN2-cooled baffles to cryo-sorb ^{219}Rn, ^{220}Rn



- Reduction of effective NEG pumping speed: 38%
- Reduction of ^{219}Rn flow into main vol. : ~ 0.6%
- Reduction of ^{220}Rn flow into main vol. : ~ 6%
- Pumping speed for ^{219}Rn from walls: 160 000 ℓ/s
- Pumping speed for ^{220}Rn from walls: 75 000 ℓ/s

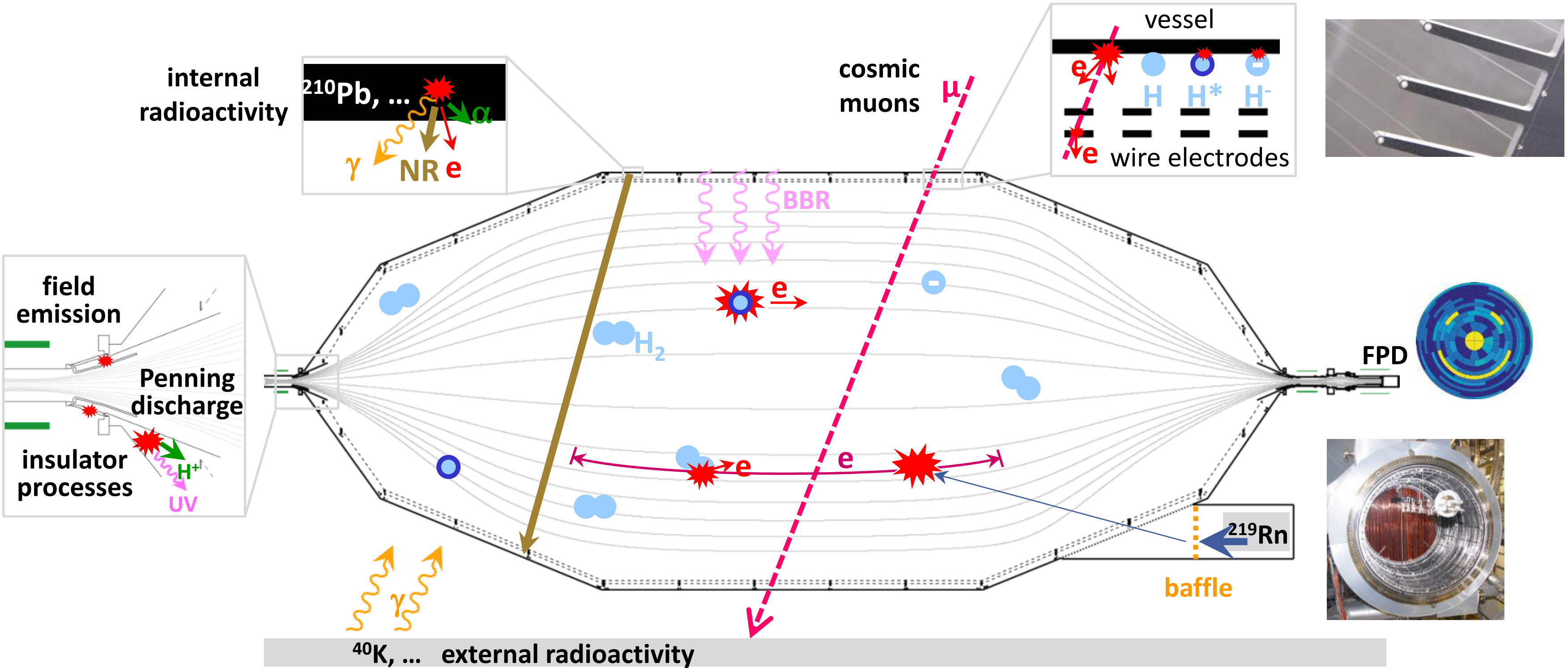
G. Drexlin et al., Vacuum 138 (2017), 165–172

Remaining background (0.5 cps) ?



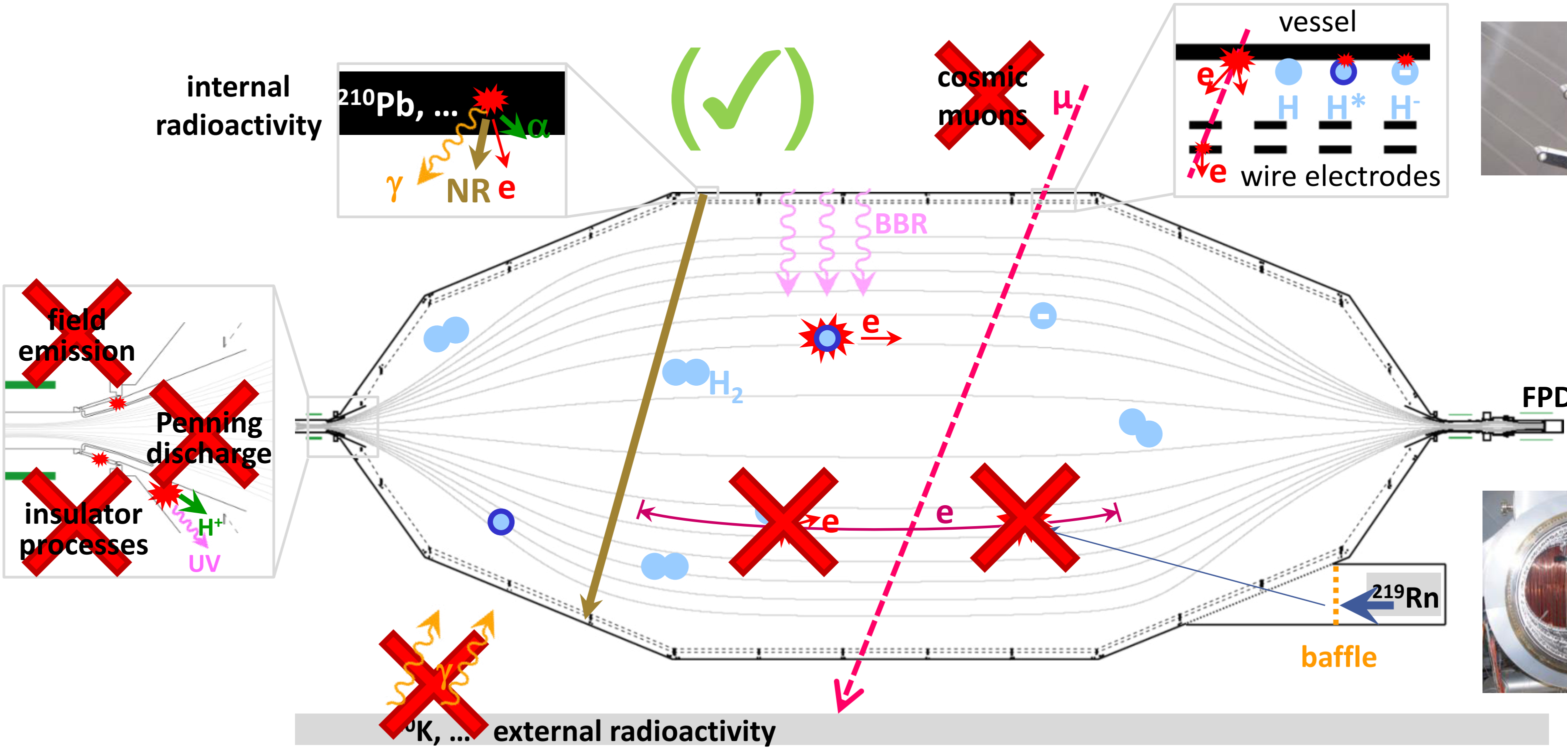
- **H* Rydberg atoms:**
  - desorbed from walls due to ^{206}Pb recoil ions
  - non-trapped electrons on meV-scale
  - **bg-rate: ~0.5 cps**
  - **positive test with short-lived ^{220}Rn (^{212}Pb)**
  - **countermeasures** (work in progress):
    - reduce H-atoms on surface: extended bake-out ➔ 0.3 cps
    - strong B-field in center (smaller flux tube volume) ➔ 0.2 cps

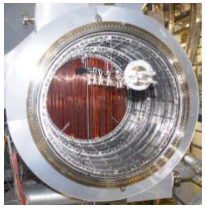
KATRIN main spectrometer backgrounds



- Various processes can contribute to the spectrometer background
- Spectrometer backgrounds were investigated in detail during two measurement phases

KATRIN main spectrometer backgrounds

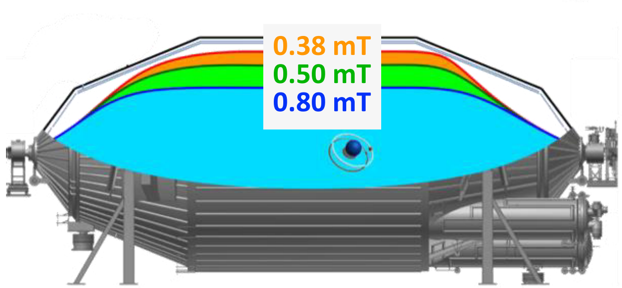


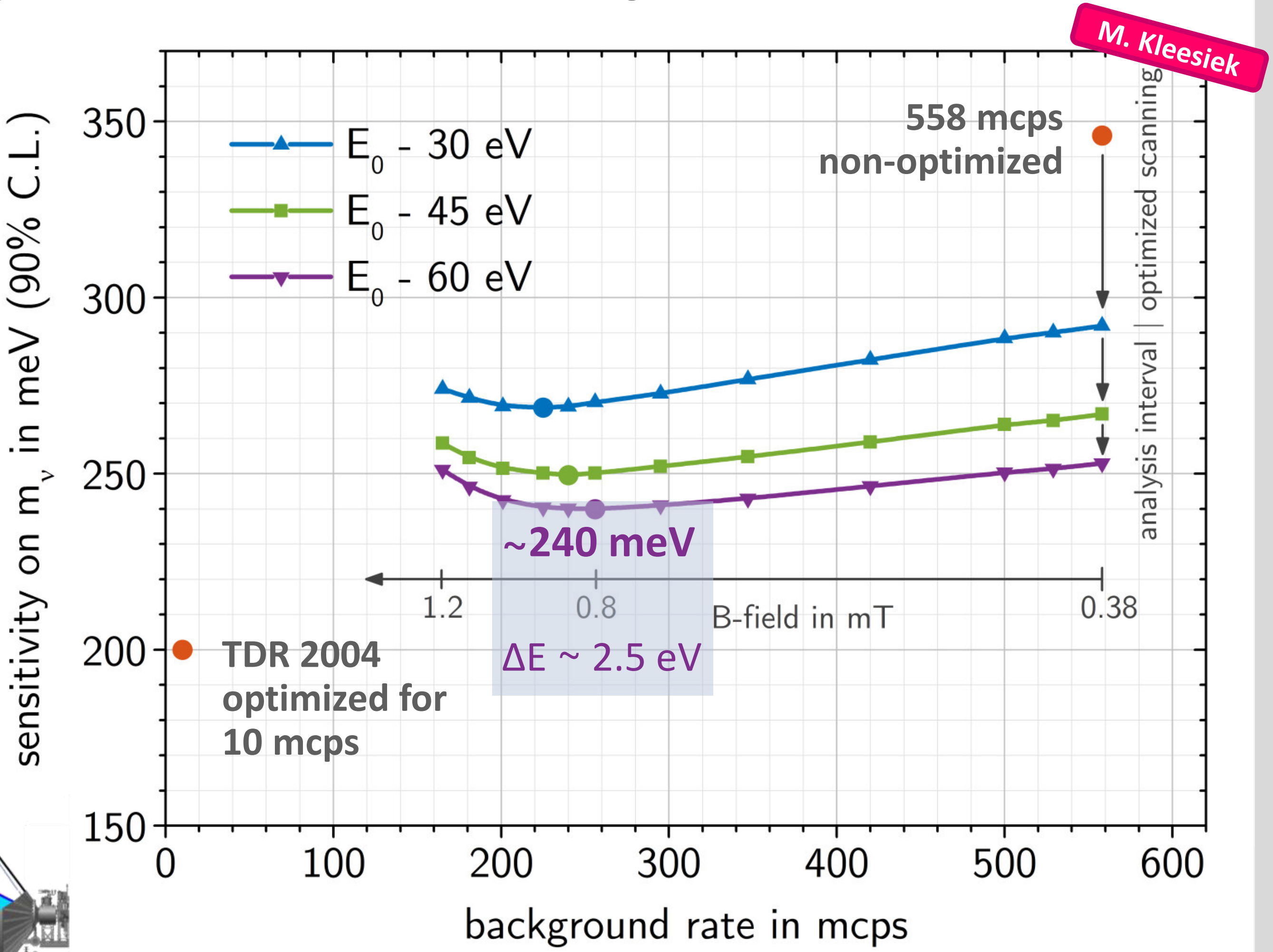


- All previously known background processes are efficiently suppressed
- Background rate about 50 times larger then design value (10 mcps), presumably due to ionization of Rydberg atoms by black body radiation

KATRIN background & sensitivity

- Further background reduction measures under investigation
- In addition: several mitigation strategies
  - optimized scanning
  - energy range of spectral analysis
  - flux tube compression by increasing B





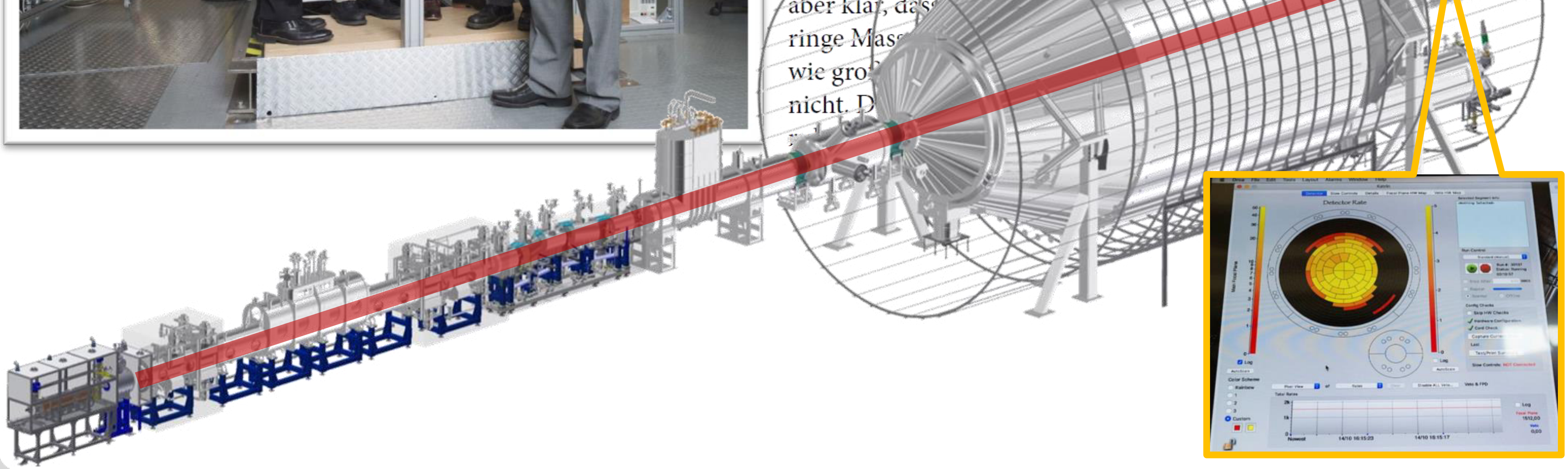
KATRIN milestone 2016 – first light

■ Neutrinos auf der Waage

DPG

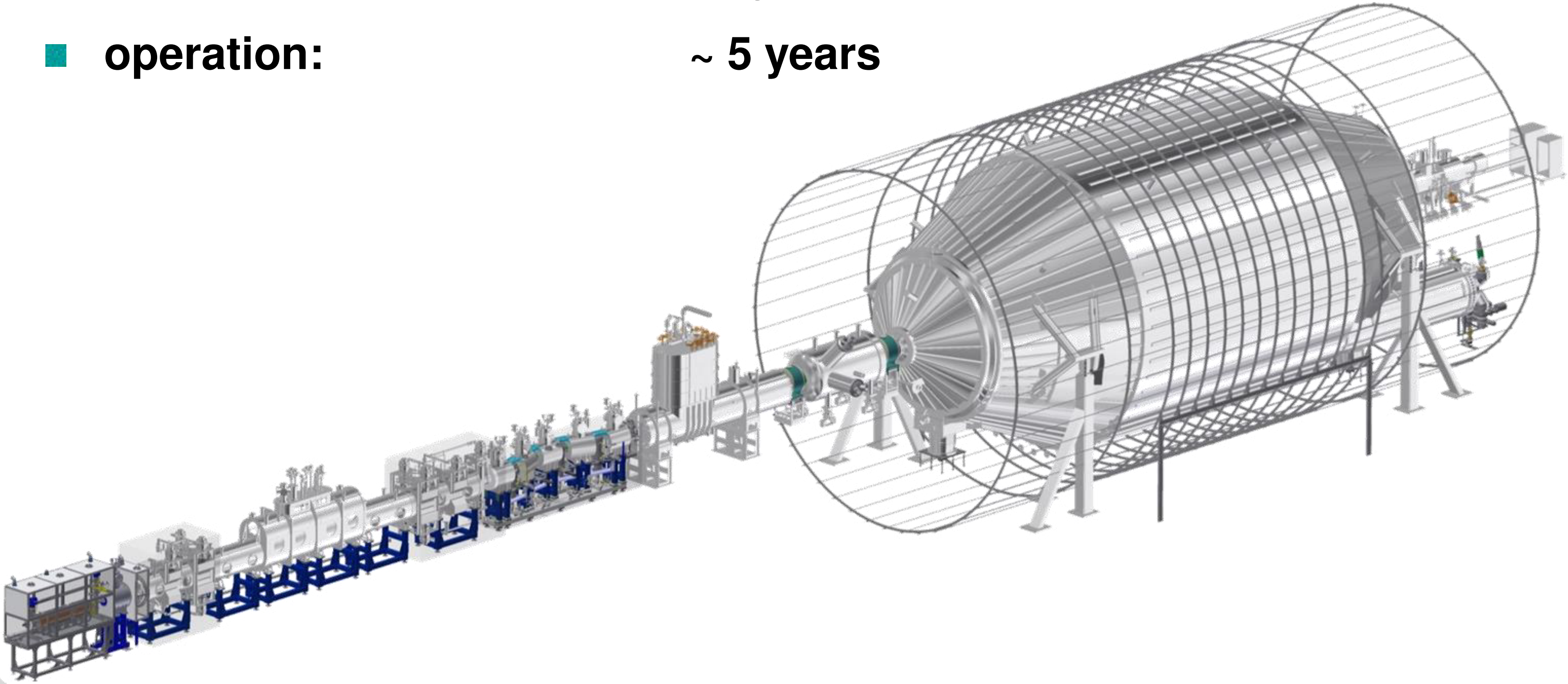
Am 14. Oktober durchflogen erstmals Elektronen das Experiment KATRIN

Neutrinos durchdringen uns jede
Sekunde milliardenfach, ohne dass
wir das Geringste davon bemer-
ken würden. Lange Zeit galten die
mysteriösen Teilchen daher als
masselos. Seit dem Nachweis
Neutrino-Oszillation
vergangen
Nobelpreis
aber klar, das
ringe Mas
wie gro
nicht. D

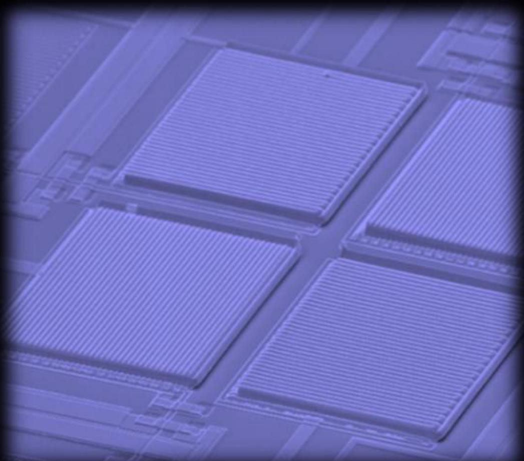


KATRIN – next steps

- final commissioning tests: now
- first tritium data May 2018
- operation: ~ 5 years

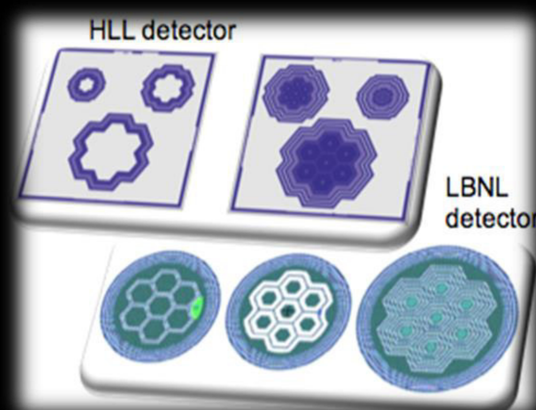


The Future of Neutrino Mass Measurements

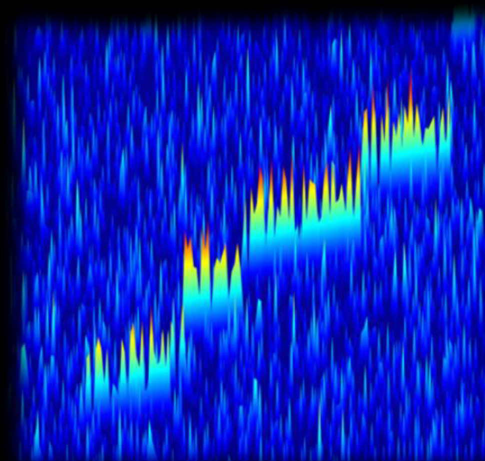


© ECHo Collaboration

cryogenic bolometer with Holmium 163



TRISTAN detector for KATRIN



© Project 8 Collaboration

Cyclotron Resonance Emission Spectroscopy (CRES)

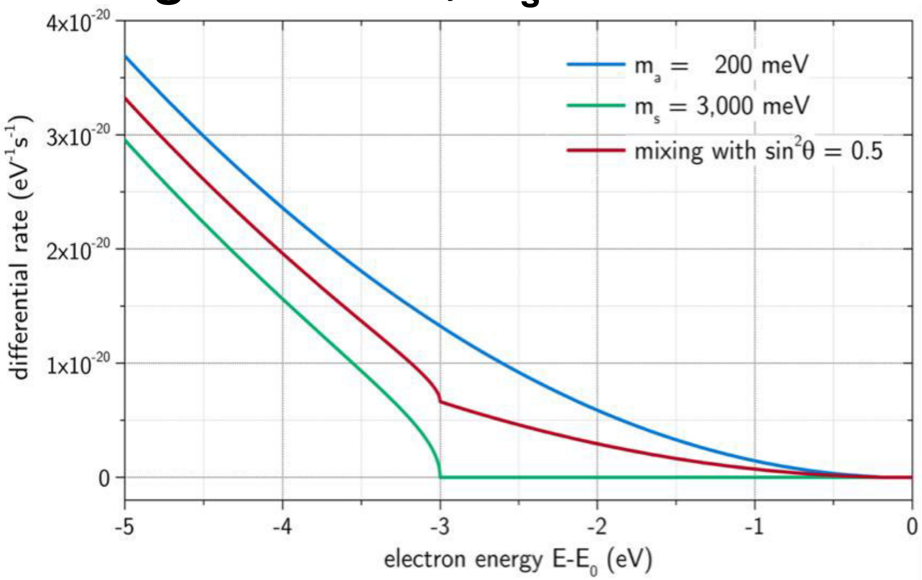
Imprint of sterile neutrinos on β spectrum

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

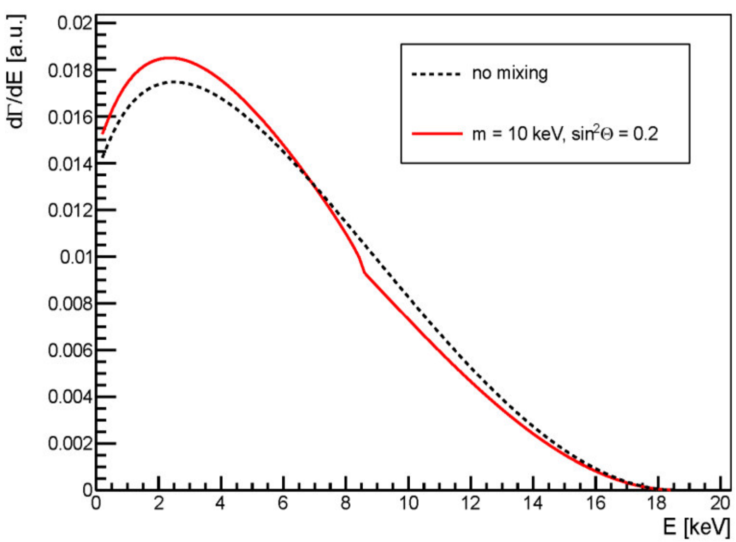
$$\frac{dN}{dE} = \cos^2\theta_s \frac{dN}{dE}(m_a^2) + \sin^2\theta_s \frac{dN}{dE}(m_s^2)$$

⇒ 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



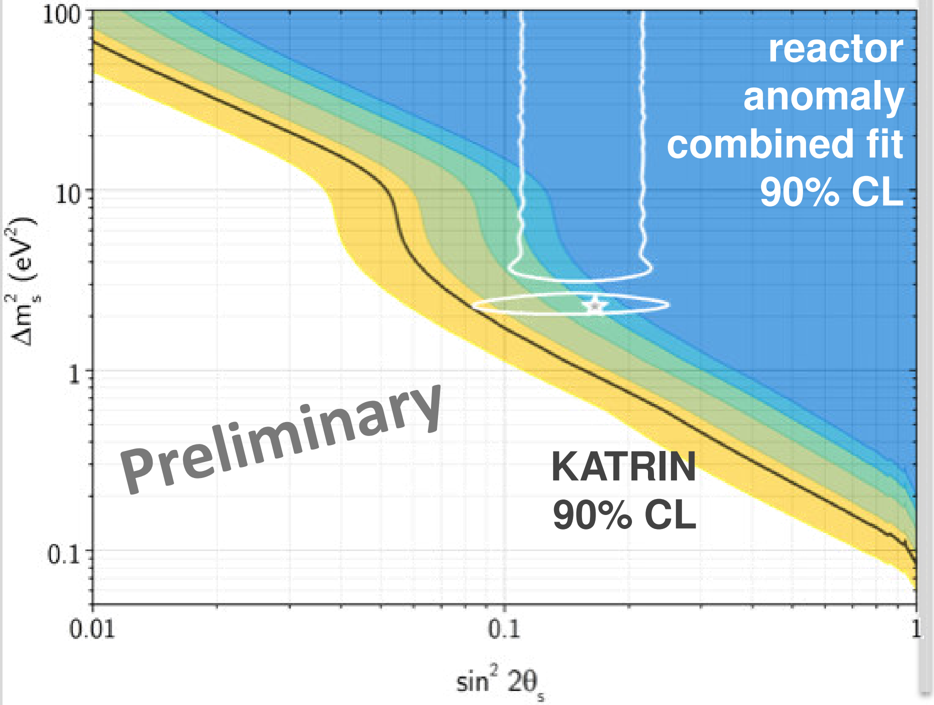
Why sterile neutrinos?

Both scales accessible in tritium β decay

Karlsruhe Institute of Technology

Hints of eV-scale sterile neutrinos?

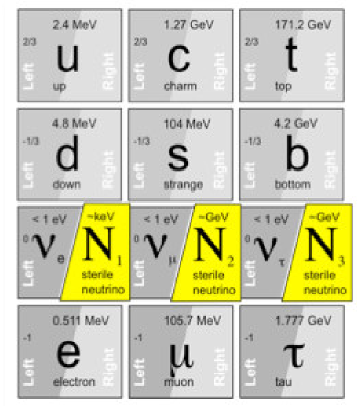
May explain anomalous oscillation results from
- Short baseline accelerator experiments
- Gallium experiments
- Reactor experiments



[M. Kleesiek, PhD thesis (KIT), 2014;

Hints of keV-scale sterile neutrinos?

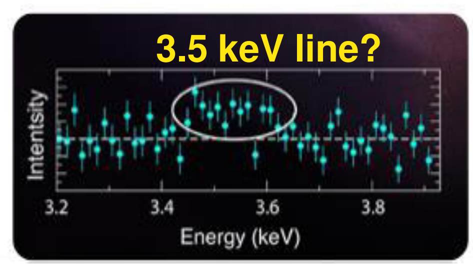
Well motivated as natural extension of Standard Model (νMSM)

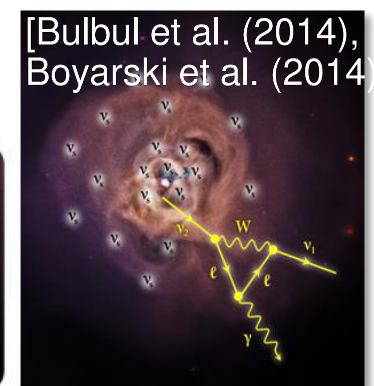


[e.g., Canetti, Drewes, Shaposhnikov (2013)]

In agreement with cosmological observations from small to large scales

Recent indirect hints from X-ray astronomy?

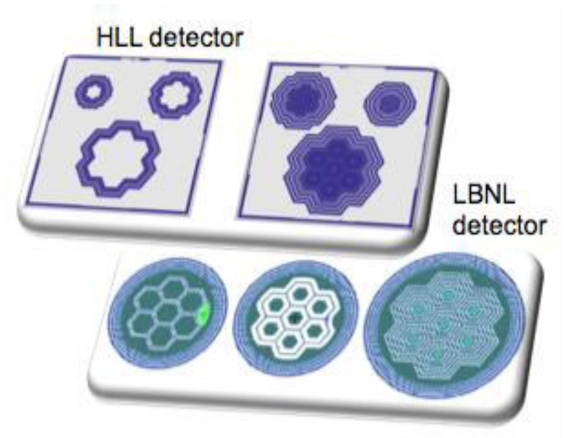


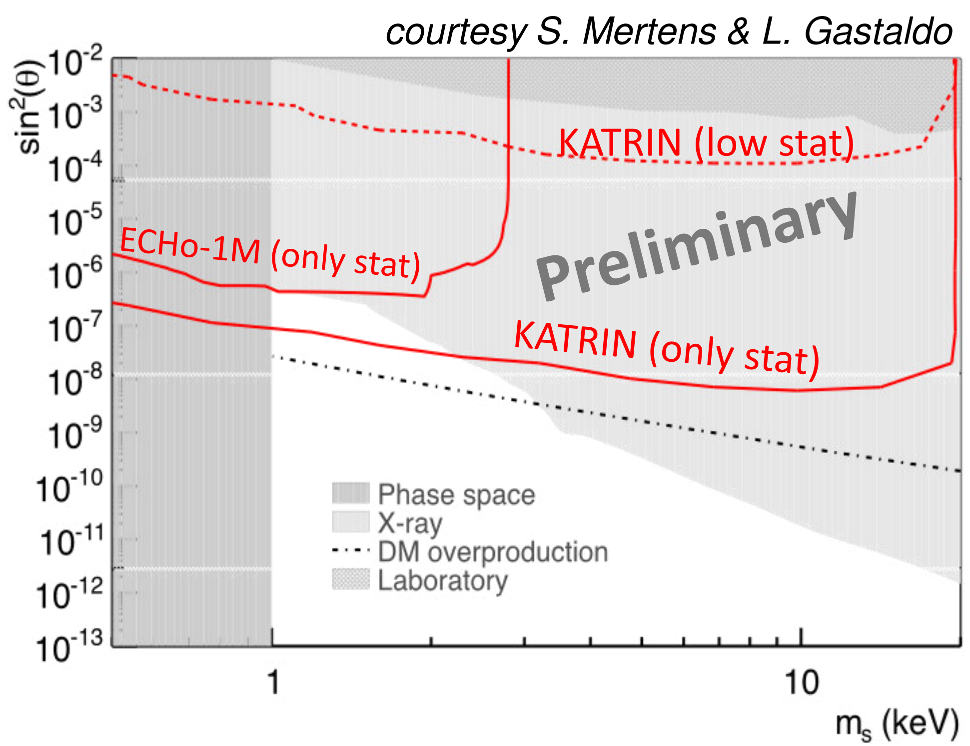


Search for keV-scale sterile ν with KATRIN

Karlsruhe Institute of Technology

- First measurements with KATRIN "baseline" set-up at reduced source strength
- Develope new multi-pixel SDD detector for differential energy measurement



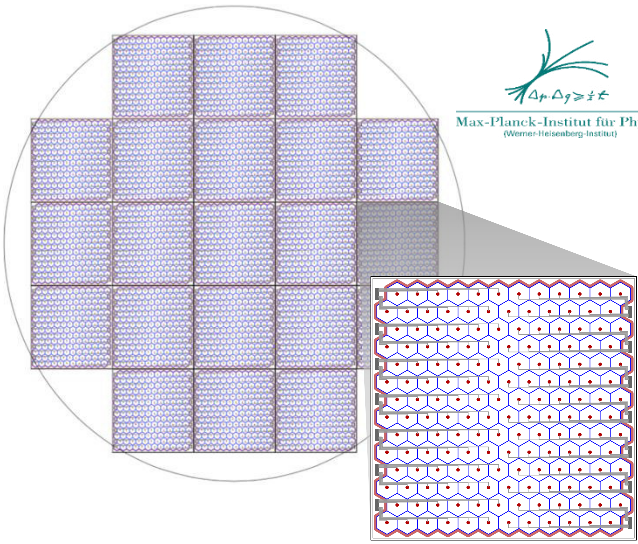


TRISTAN SDD prototypes for KATRIN

- thin dead-layer (< 100 nm)
- good resolution (300 eV @ 20 keV)
- low threshold (1 keV)
- high rates (70‘000 cps/pixel)

Search for keV-scale sterile ν with KATRIN

- First measurements with KATRIN “baseline” set-up at reduced source strength
- Develope new multi-pixel SDD detector for differential energy measurement
- Handling of high rates (> 10^9 cps) with 3000 – 4000 pixels

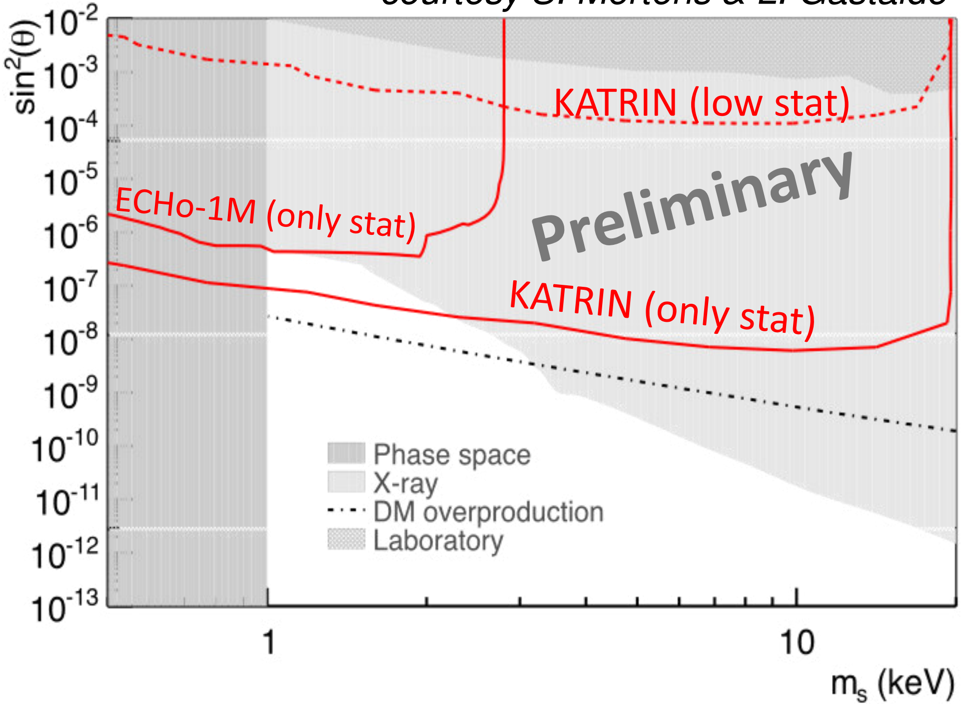


Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

TRISTAN SDD prototypes for KATRIN

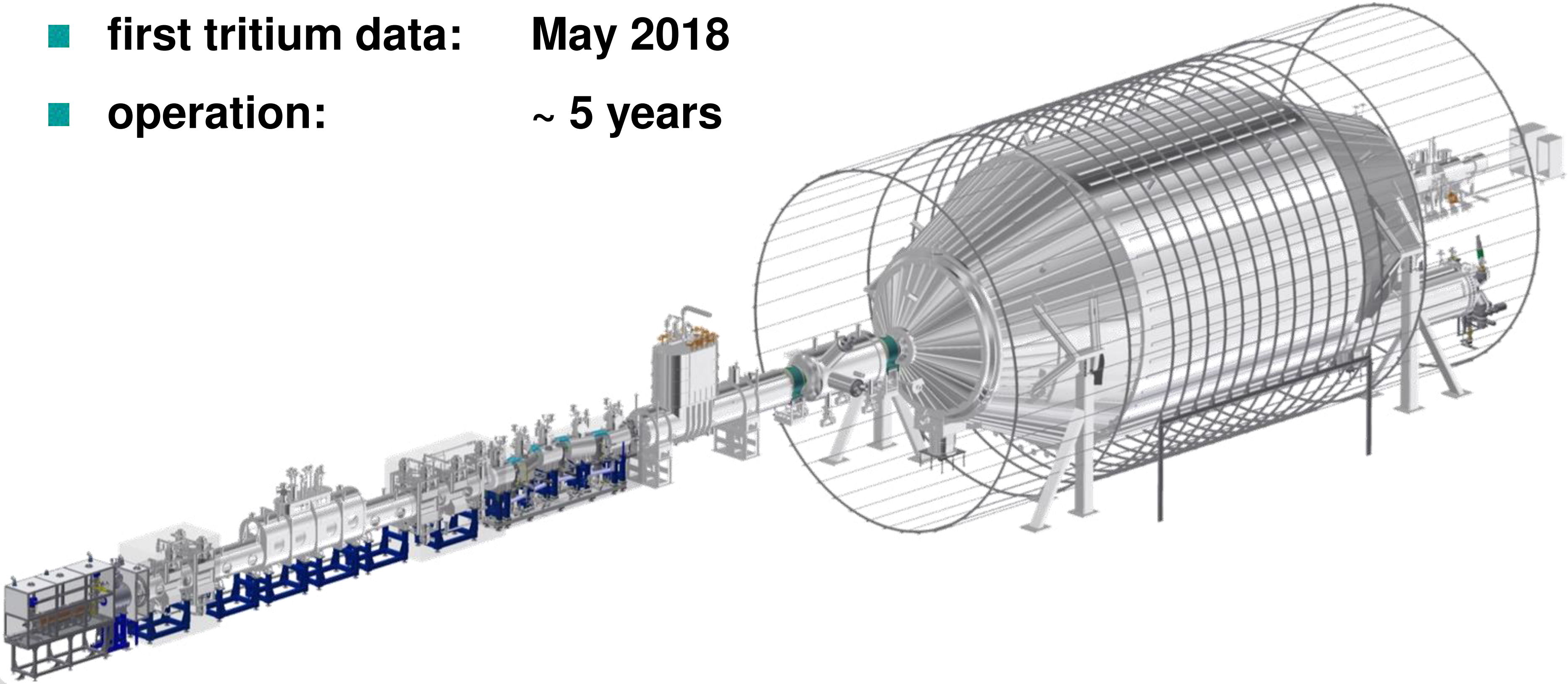
- thin dead-layer (< 100 nm)
- good resolution (300 eV @ 20 keV)
- low threshold (1 keV)
- high rates (70‘000 cps/pixel)

courtesy S. Mertens & L. Gastaldo



Conclusions

- **KATRIN will be the ultimate MAC-E Filter**
- **many technical challenges solved**
- **final commissioning tests ongoing**
- **first tritium data: May 2018**
- **operation: ~ 5 years**



Thank you for your attention
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