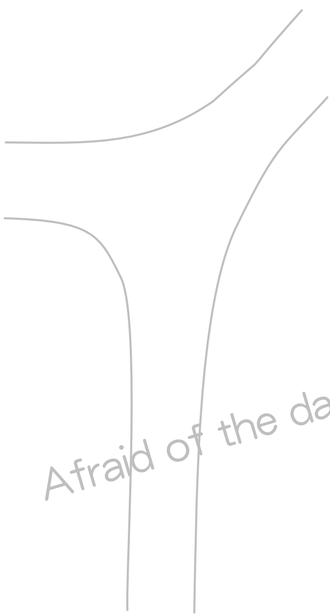
Don’t know Dirac or Majorana?
No problem !!

# Direct Neutrino Mass Measurement with KATRIN



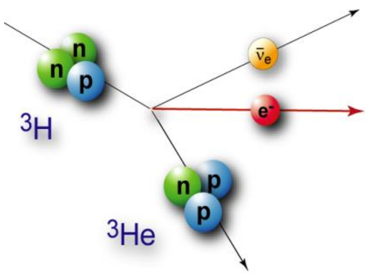
Afraid of the dark well?

Sanshiro Enomoto (University of Washington)
for the KATRIN Collaboration

DBD16, Osaka, Japan, 8 Nov 2016

# Neutrino Mass Measurement with Single Beta Decay

Use Kinematics only, look at the end-point shape

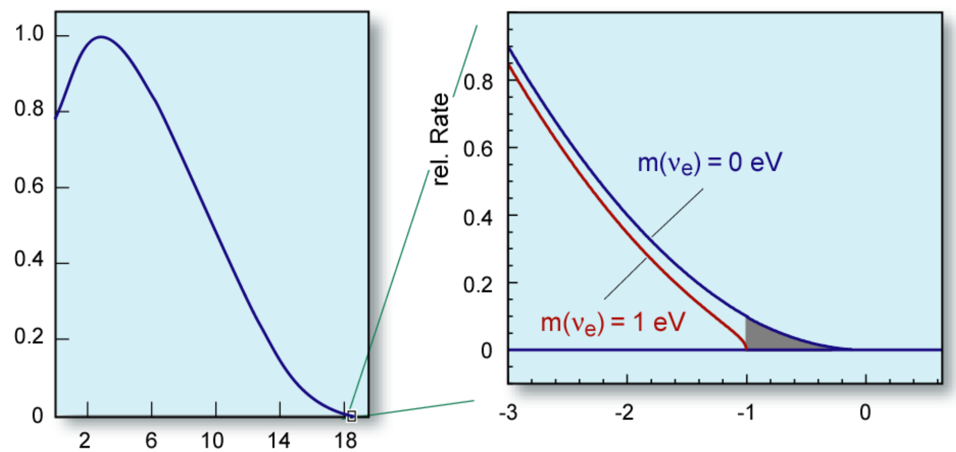



$$\frac{dN}{dE_e} = C \cdot F(E,Z) \cdot P_e \cdot (E_e + m_e c^2) \cdot (E_o - E_e)\sqrt{(E_o - E_e)^2 - m_{\nu_e}{}^2}$$

$$\sum_i |U_{ei}|^2 \cdot m_i{}^2 \sim m_i{}^2$$

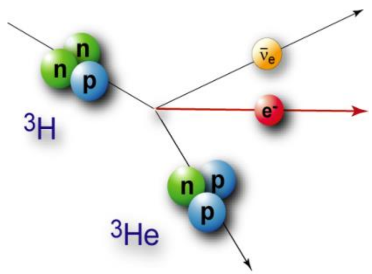
in degenerated region

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



# Neutrino Mass Measurement with Single Beta Decay

## Use Kinematics only, look at the end-point shape




$$\frac{dN}{dE_e} = C \cdot F(E,Z) \cdot P_e \cdot (E_e + m_e c^2) \cdot (E_o - E_e)\sqrt{(E_o - E_e)^2 - m_{\nu_e}{}^2}$$

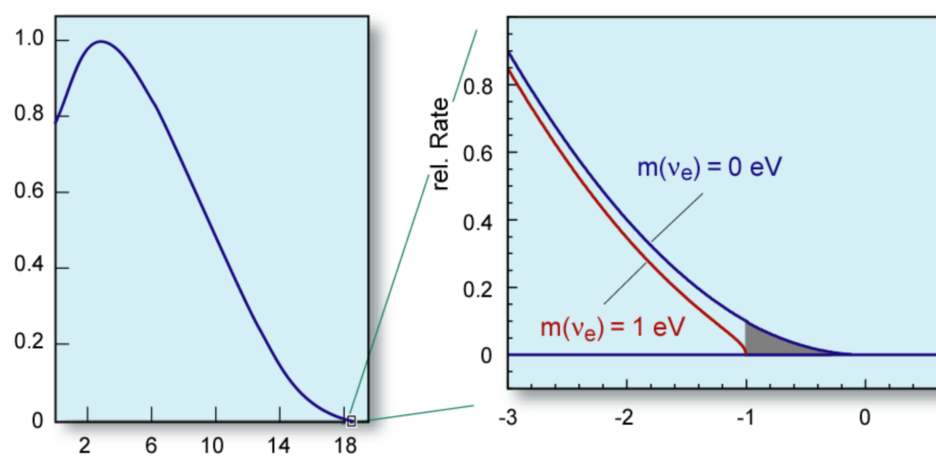
$$\sum_i |U_{ei}|^2 \cdot m_i{}^2 \sim m_i{}^2$$

in degenerated region

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

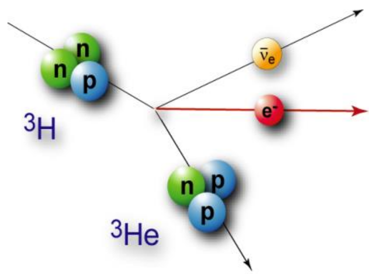
## Tritium as beta-source

- low end-point (18.6 keV)
  - → relatively large deformation
  - → electro-statically reachable
- short life (12.3 y):
  - → small source amount
  - → less scattering in source
- super-allowed transition
  - → matrix element reliably calculable
- simplest molecular:
  - → molecular states calculable



# Neutrino Mass Measurement with Single Beta Decay

## Use Kinematics only, look at the end-point shape




$$\frac{dN}{dE_e} = C \cdot F(E,Z) \cdot P_e \cdot (E_e + m_e c^2) \cdot (E_o - E_e) \sqrt{(E_o - E_e)^2 - m_{\nu_e}^{\ 2}}$$

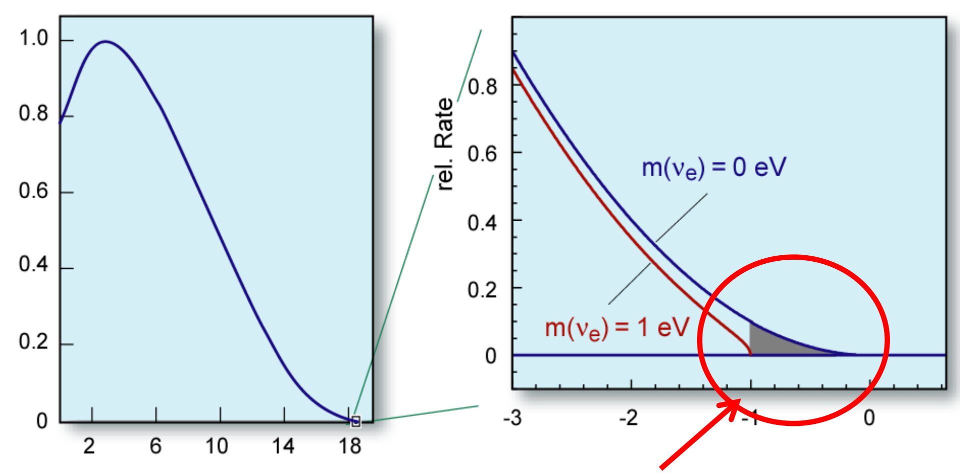
$$\sum_i |U_{ei}|^2 \cdot m_i^{\ 2} \sim m_i^{\ 2}$$

in degenerated region

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

## Tritium as beta-source

- low end-point (18.6 keV)
  - → relatively large deformation
  - → electro-statically reachable
- short life (12.3 y):
  - → small source amount
  - → less scattering in source
- super-allowed transition
  - → matrix element reliably calculable
- simplest molecular:
  - → molecular states calculable

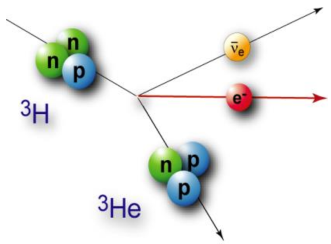



only $2\times10^{-13}$ of all beta in last 1 eV

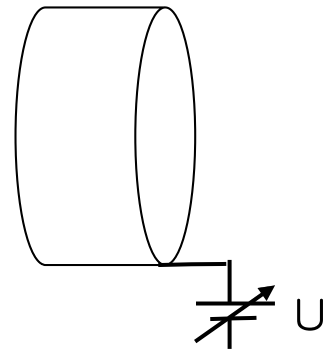
## Needs:

- strong source
- high precision spectroscopy

# Electron Spectroscopy with Electro-Static Filter

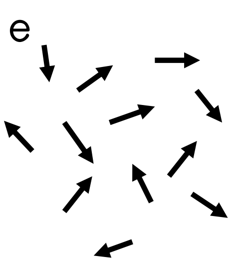


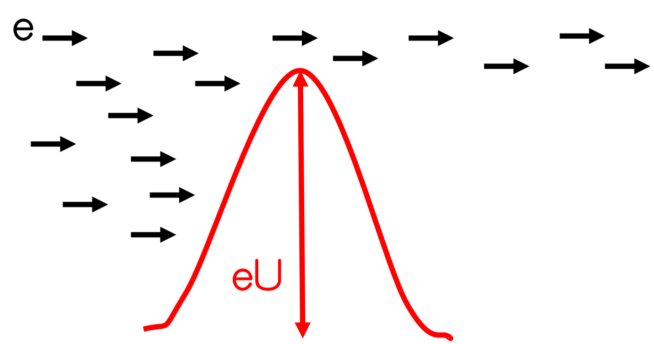

tritium
source




electro-static
retarding potential

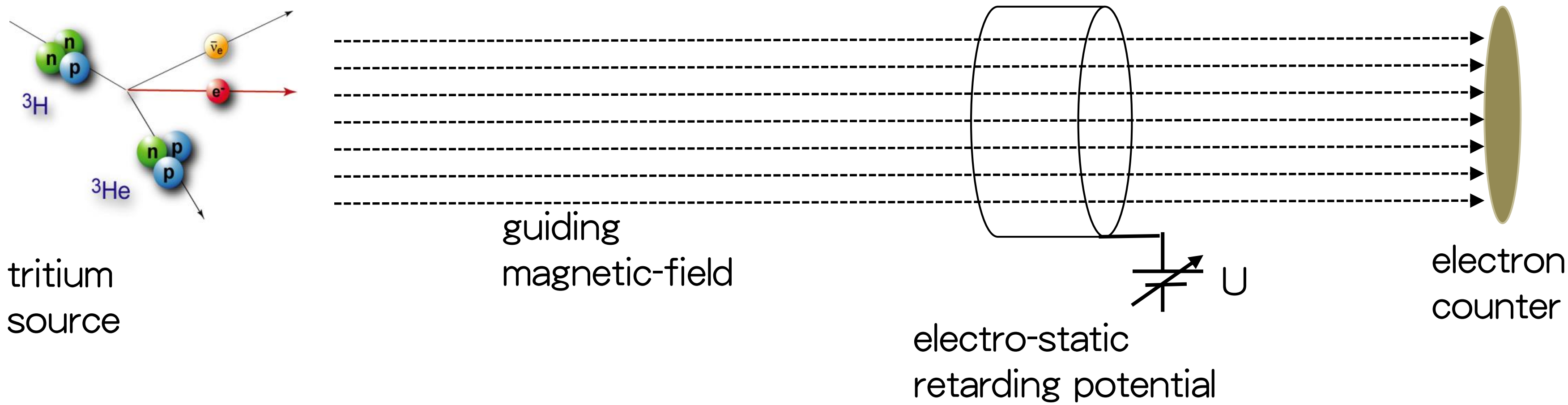
electron
counter

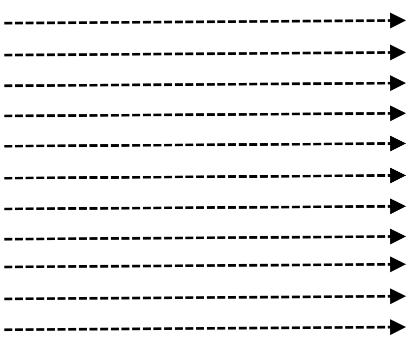


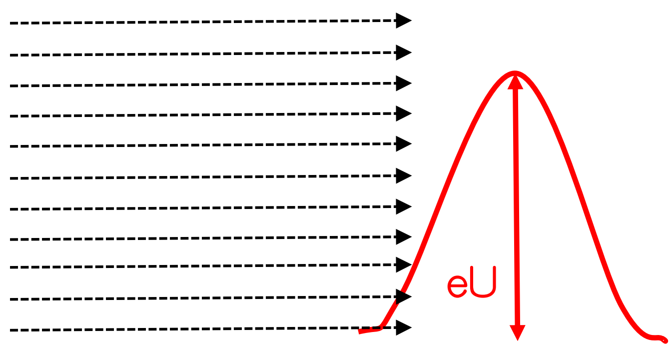




Problem: only small fraction of electrons reach this
→ guiding magnetic field

# Electron Spectroscopy with Electro-Static Filter



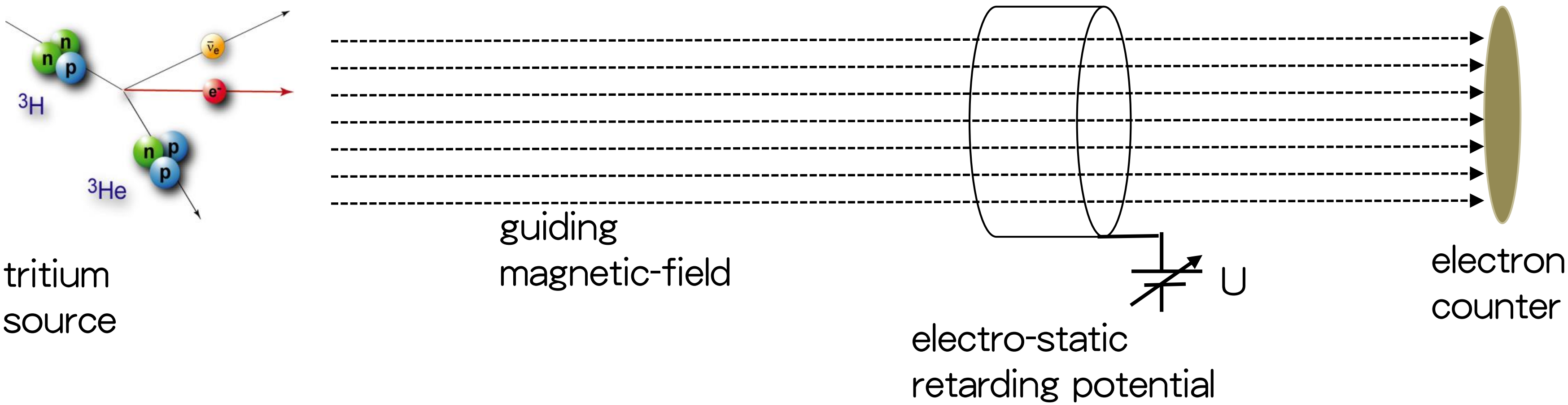



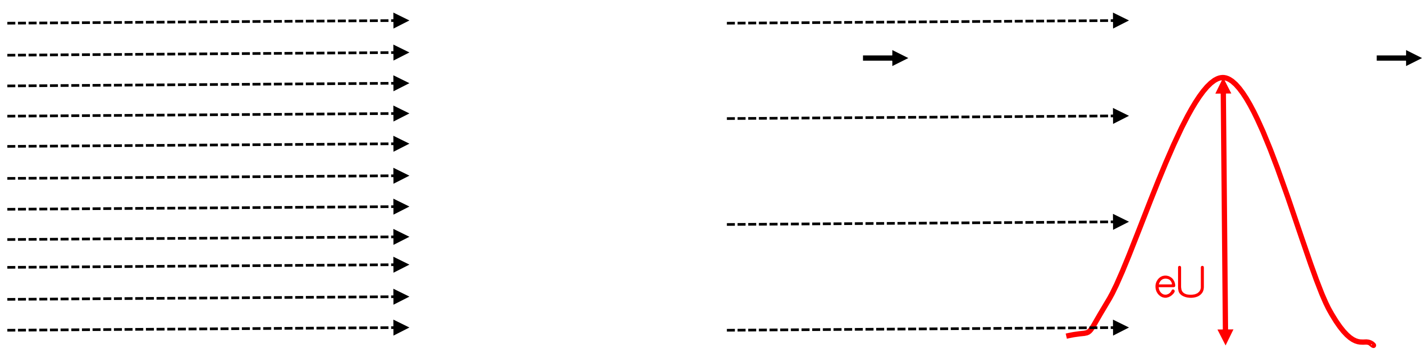



$E_{parallel}$ / $E_{transversal}$ depends on initial emission angle

Problem: only $E_{parallel}$ is measured
→ adiabatic collimation

# Electron Spectroscopy with Electro-Static Filter



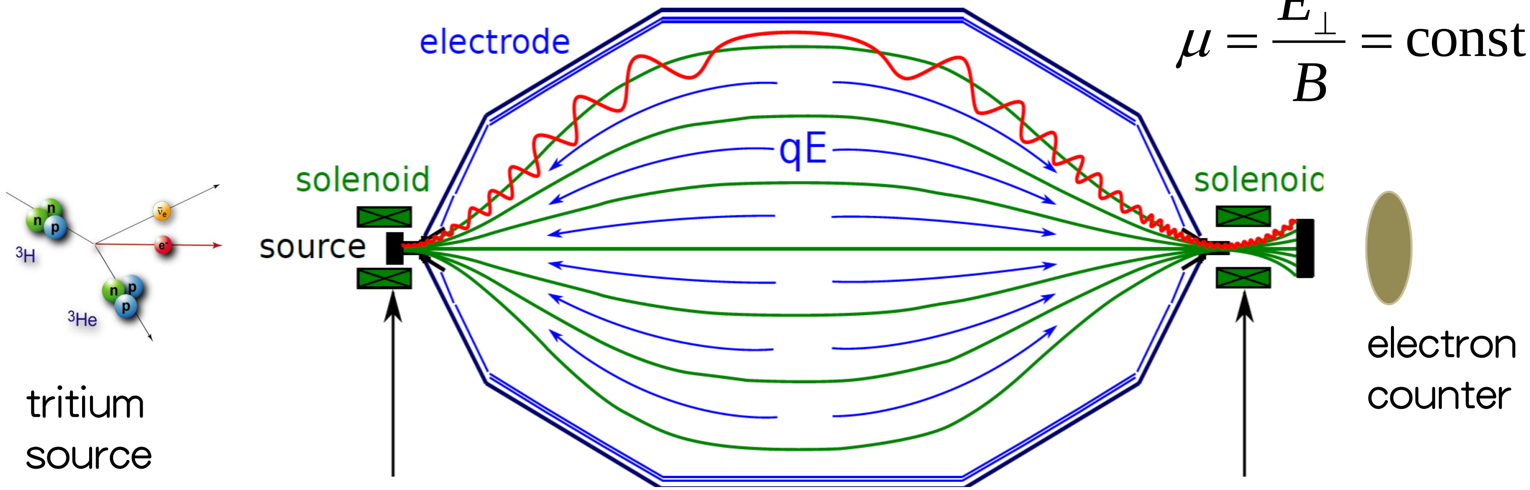



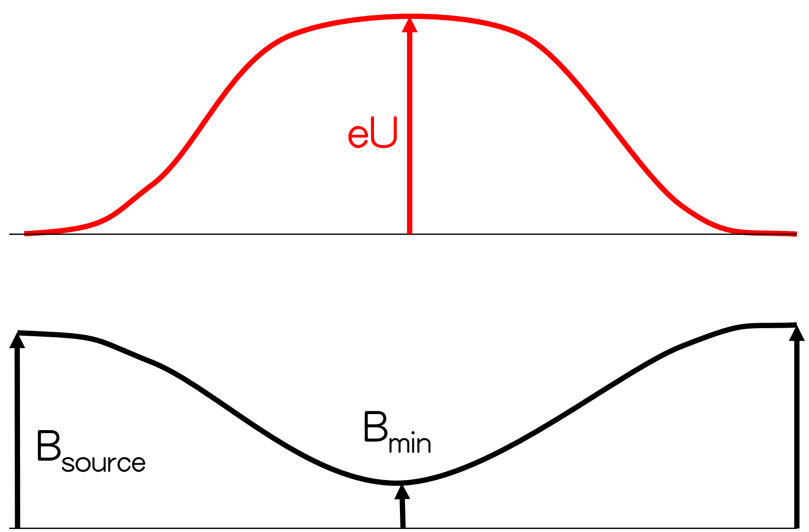

reduce magnetic field adiabatically

⇒ magnetic moment conserves: $\mu = \frac{E_\perp}{B} = \mathrm{const}$ ⇒ collimation

# MAC-E (Magnetic-Adiabatic-Collimation Electro-static) Filter

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

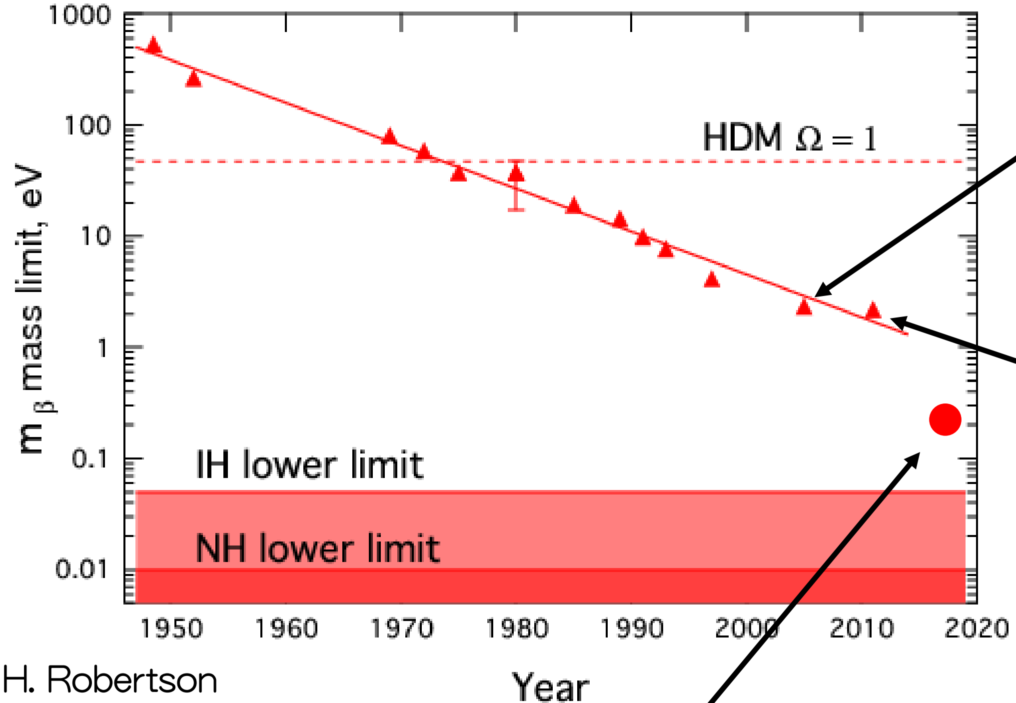


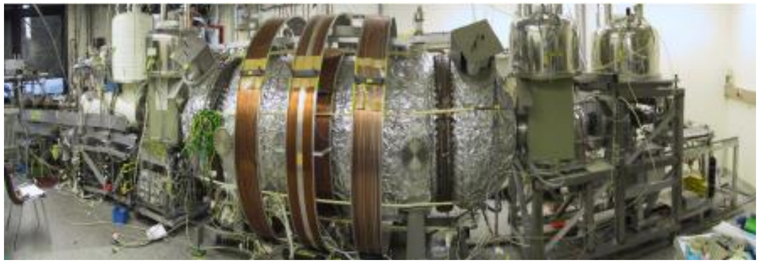

Energy resolution is determined by B-Ratio

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

# Present Mass Limit and KATRIN Experiment




H. Robertson



Mainz (2005, final result)
$m(\nu_e) < 2.3$ eV (95%CL)

Triosk (2011, re-analysis)
$m(\nu_e) < 2.05$ eV (95%CL)

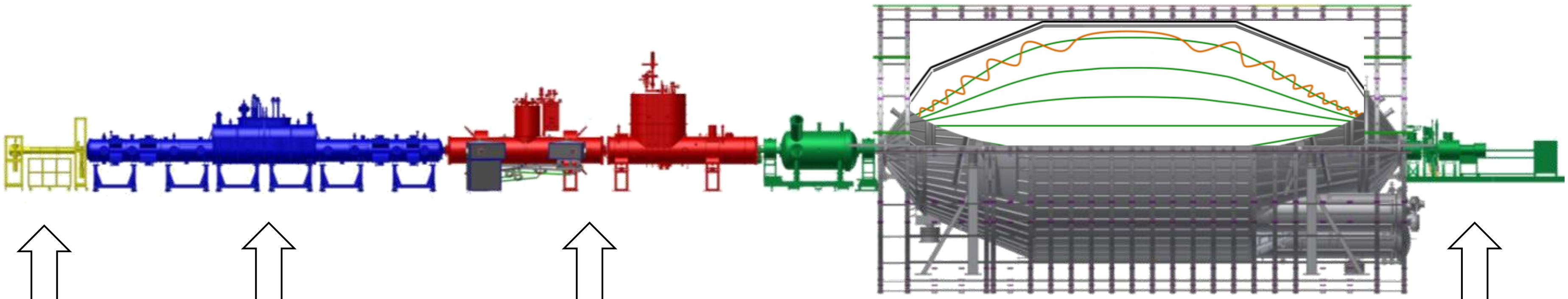
KATRIN
design sensitivity: $m(\nu_e) < 0.2$ eV (90%CL)

1/10 sensitivity on $m_e$
- ⇒ 1/100 sensitivity on $m_e^2$
- ⇒ ×100 statistics, 1/100 systematics

# KATRIN Experiment

## KArlsruhe TRItium Neutrino Experiment

- located at Karlsruhe Institute of Technology, Karlsruhe, Germany
- design sensitivity: $m(\nu_e) < 0.2$ eV (90%CL, 3 years)

Calibration
E-Gun etc

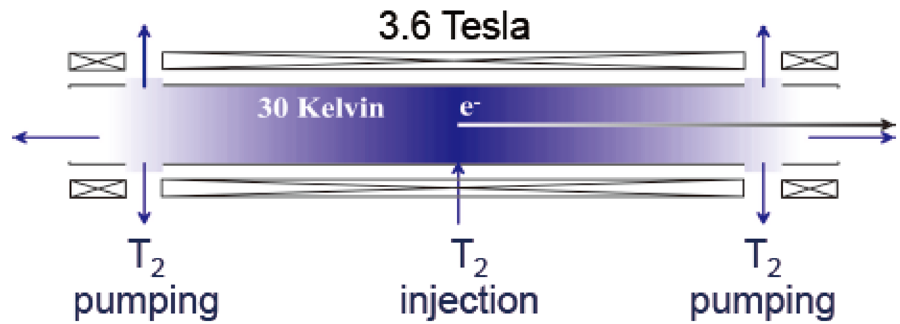
$10^{11}$ Bq Gaseous Tritium Source

Tritium Retention
(electrons guided by B)

0.93 eV Resolution
MAC-E Filter

Electron Counter
(~10 mHz)

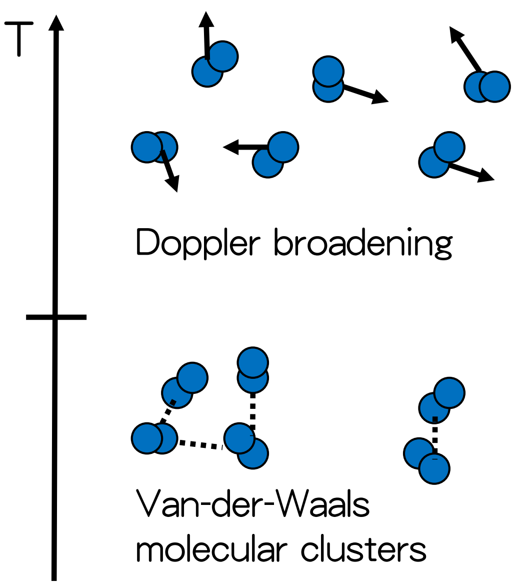
# Windowless Gaseous Tritium Source



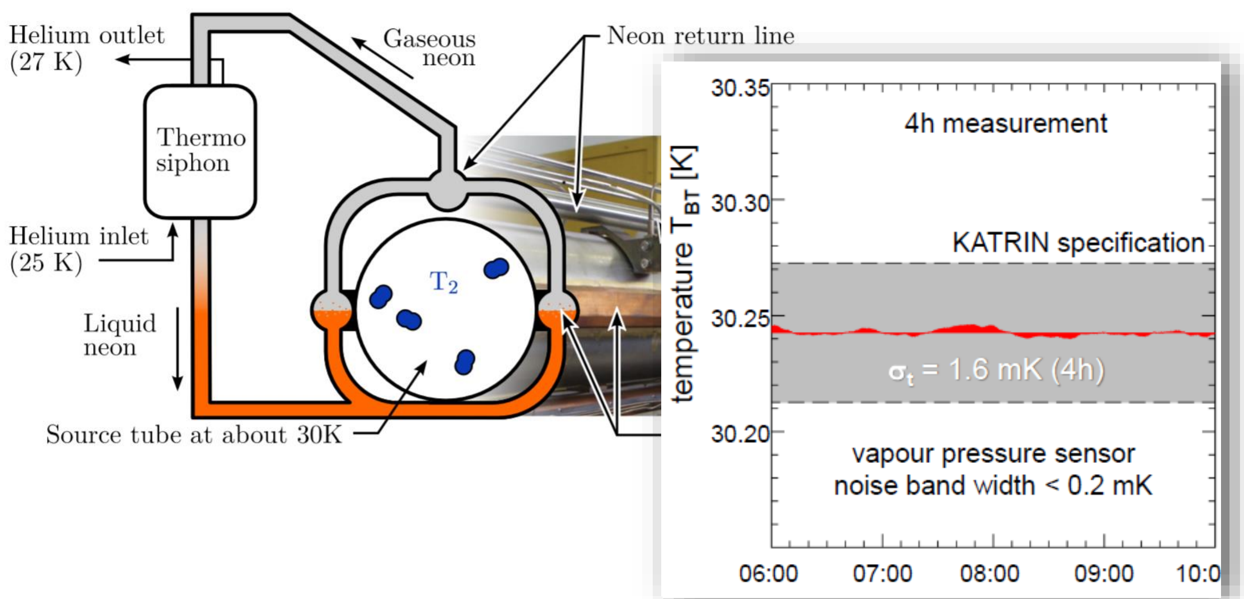

- 100 GBq Gaseous Tritium Source
- 40 g/day circulation

- 0.1% Pressure Stability
- 0.1% Temperature Stability

## Cooled at 30 ± 0.003 K

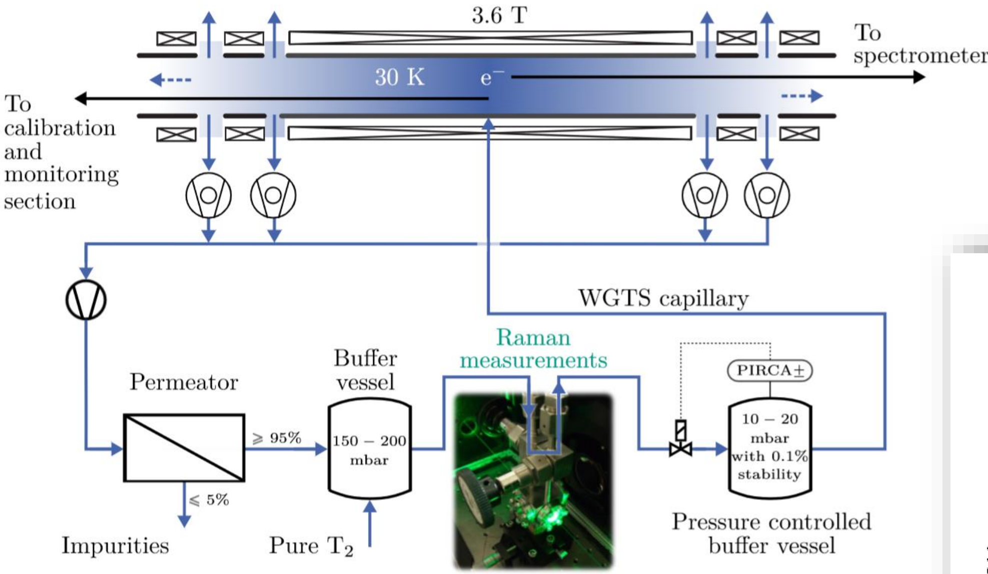


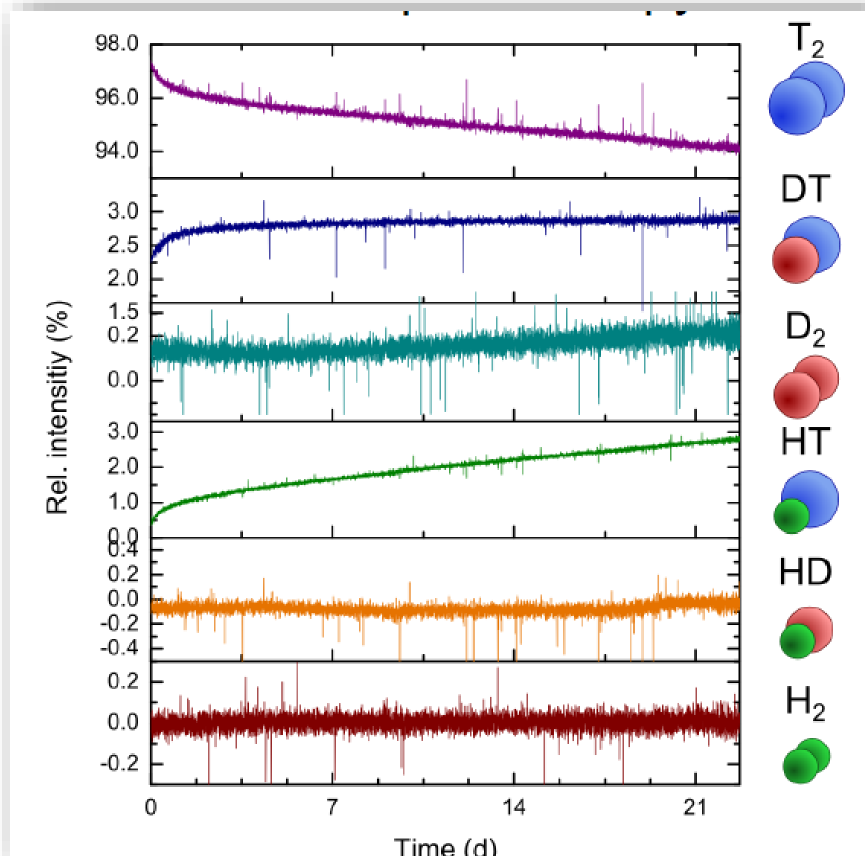

## Two Phase (LNe/GNe) Cooling



# Gas Composition Monitoring

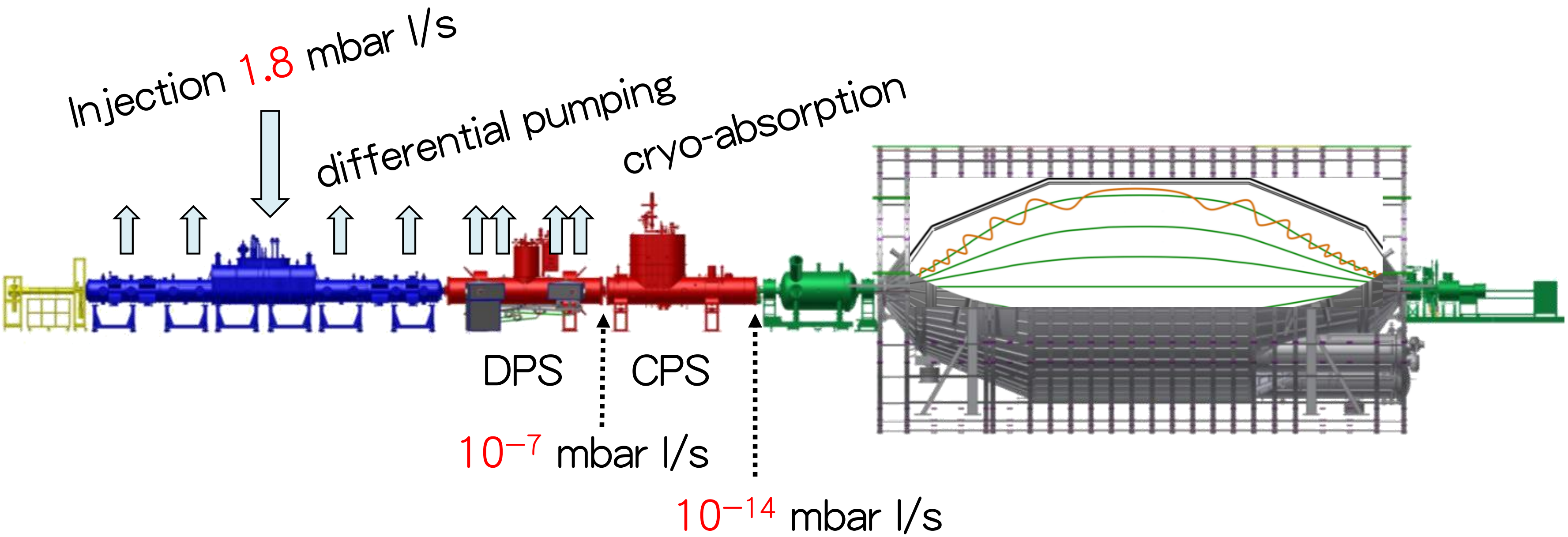
## Laser Raman Spectroscopy (in embedded the tritium loop)



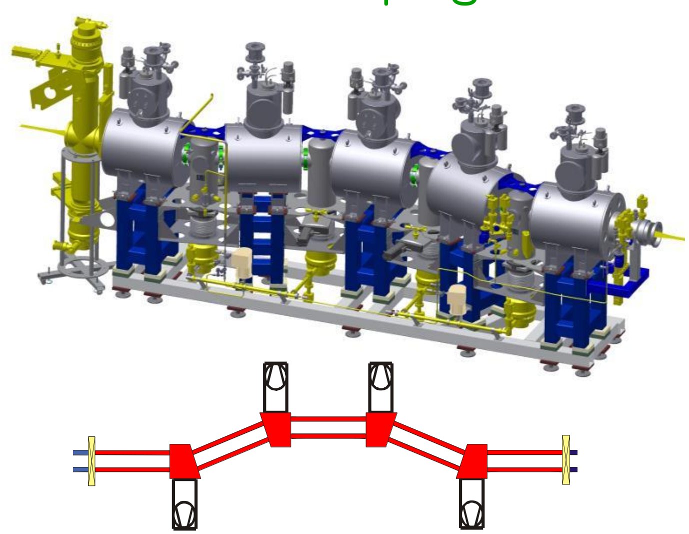




- 0.1 % precision in 60 sec

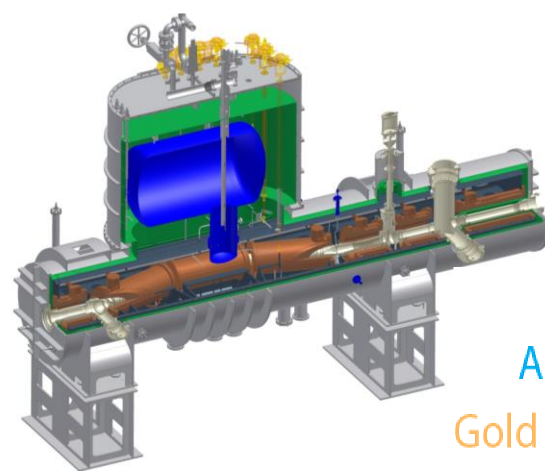
# Tritium Retention



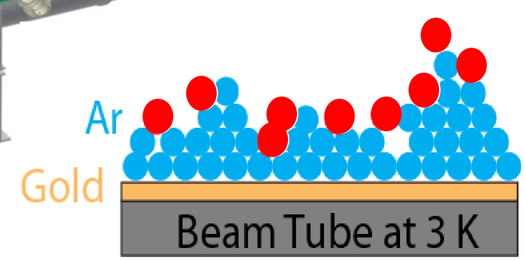

Differential Pumping Section



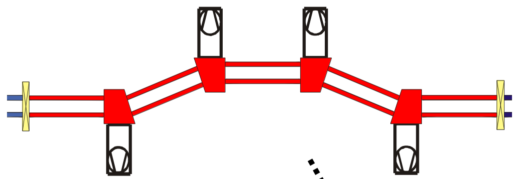
Cryo-Pumping Section



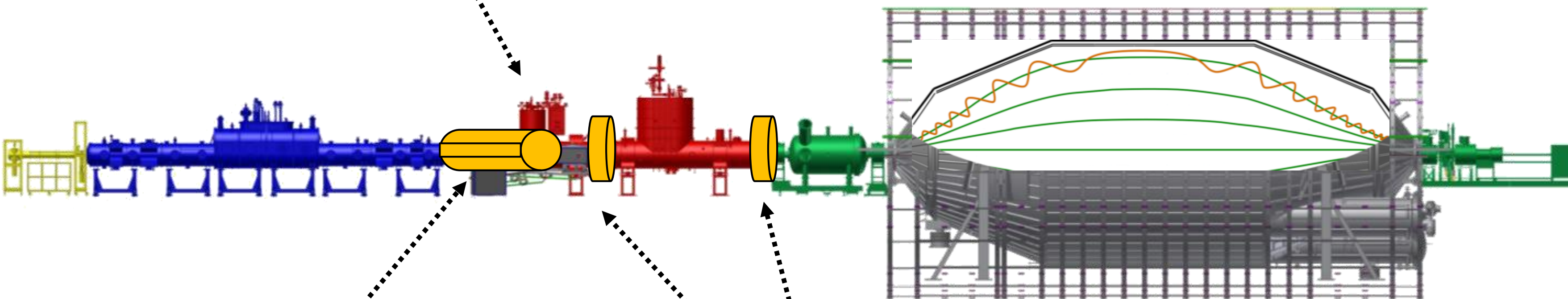
Ar frost for large surface



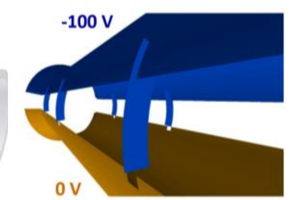
# Tritium Retention: ion blocking and removal

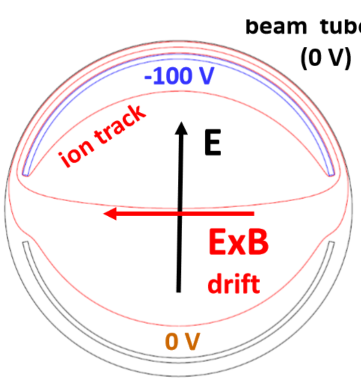


- No straight path for molecules
- Electrons adiabatically guided by B-field



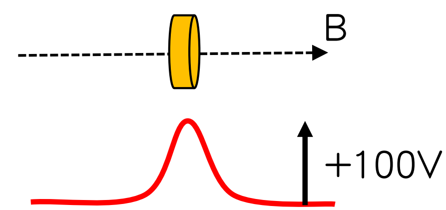
## Dipole Electrodes



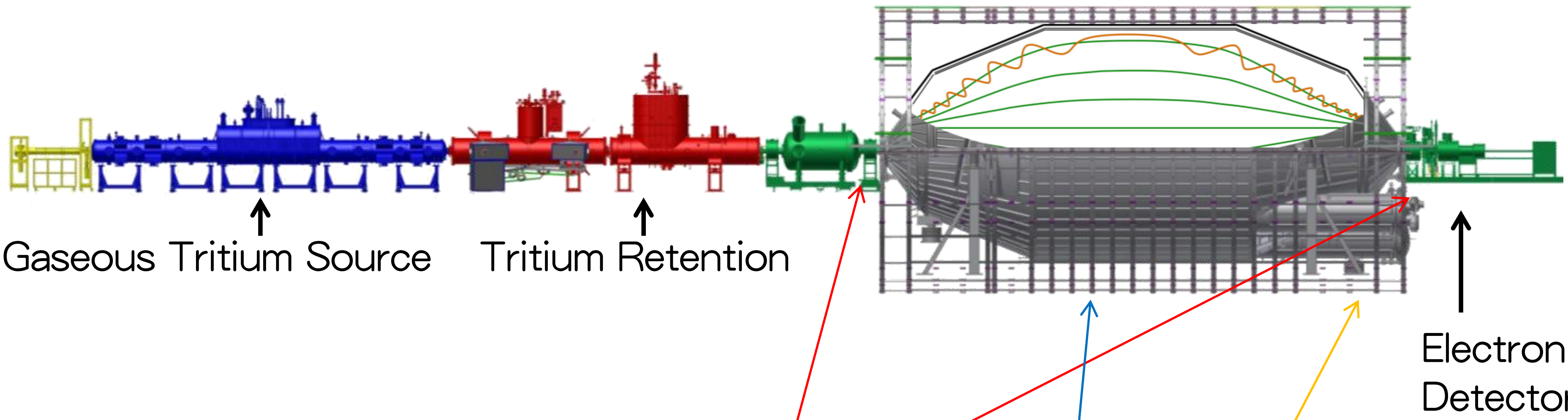

- Remove ions by $\vec{E} \times \vec{B}$ drift

## Ring Electrodes




- Reflect positive ions

# Main Spectrometer (MAC-E Filter)




KATRIN MAC-E Filter

- B max: 6 T by super conducting magnets
- B min: 3 G (=0.0003 T) by 24m × 9m UHV vessel
  ⇒ $\Delta E$ = 0.93 eV @18.6 keV

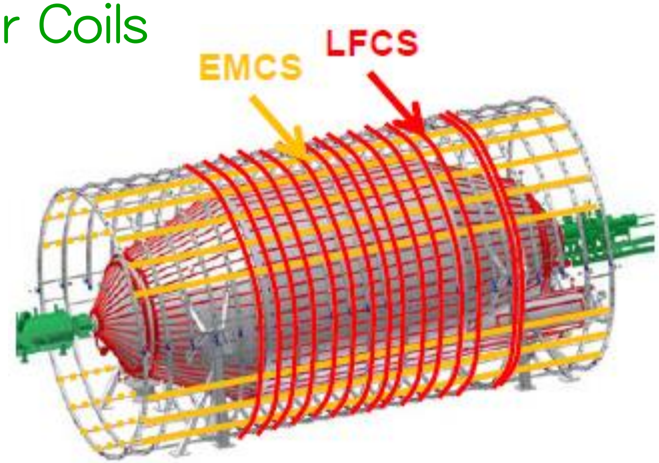
- 1240 $m^3$ UHV vessel
- $10^{-11}$ mbar pressure (6 TMP and 3 km NEG strips)

- ppm-level precision retarding high-voltage (control and monitor)

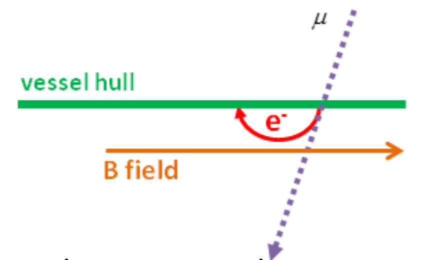
# Field Shaping & EM Shielding

✓ satisfy transmission condition (adiabatic guidance, precise retarding)
✓ avoid penning traps

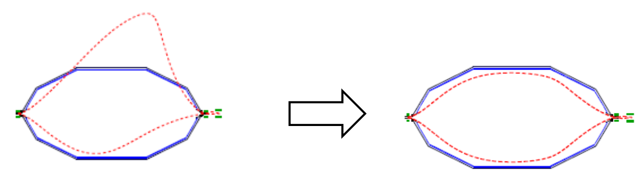
## Air Coils



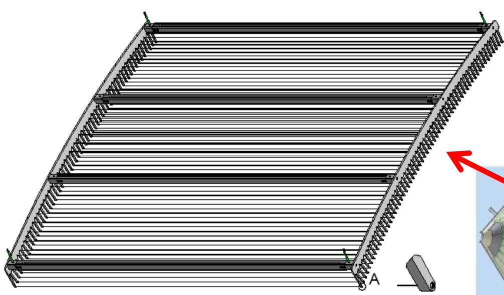

- B-field shaping
- magnetic shielding



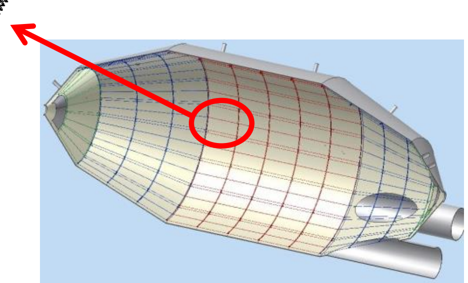

- background removal (B-pulsing)
- geomagnetism compensation



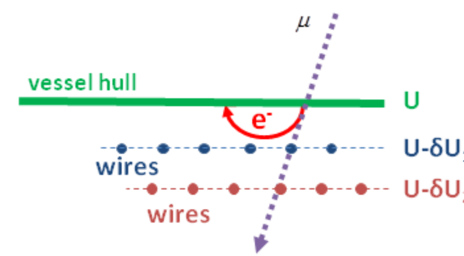
## Inner Wire Electrodes



double-layer wire
mass-less electrode



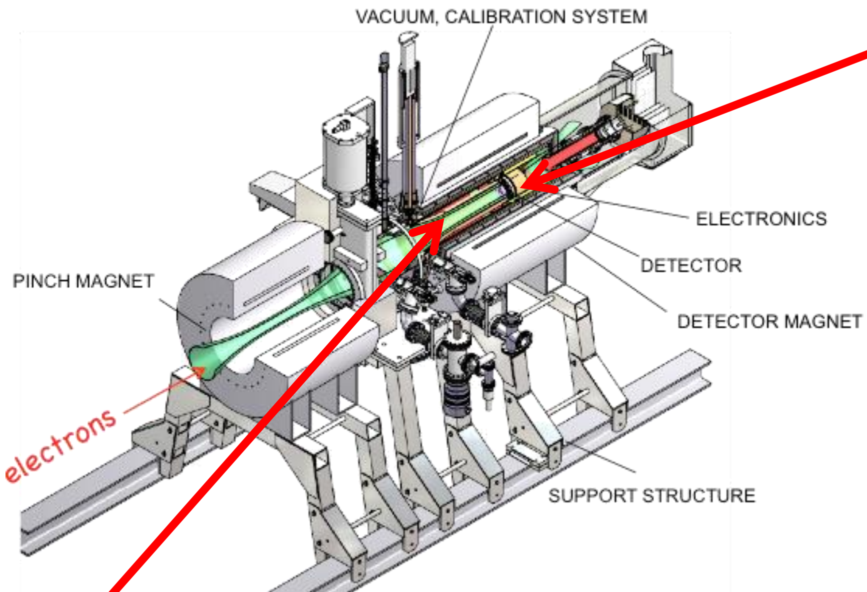
- E-field shaping
- electric shielding



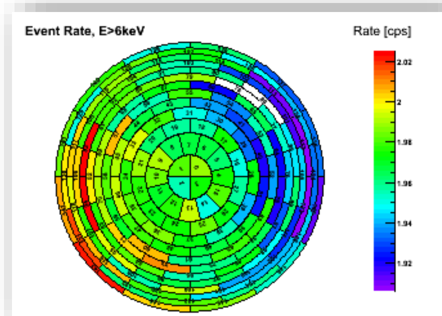

- background removal (dipole mode)
- vessel HV noise screening

# Electron Detector

148 pixel Si PIN diode




9 cm

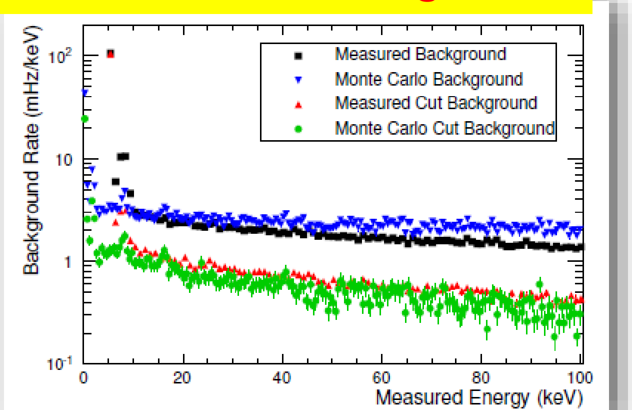



Position sensitivity on flux-tube cross section

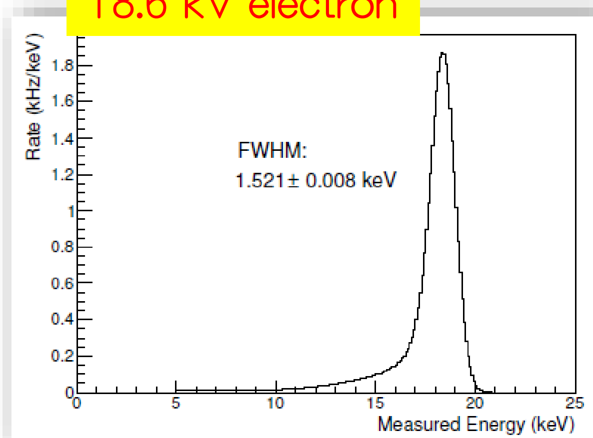
Post-Acceleration Electrode

shifts electrons to lower background region

detector section backgrounds




18.6 kV electron



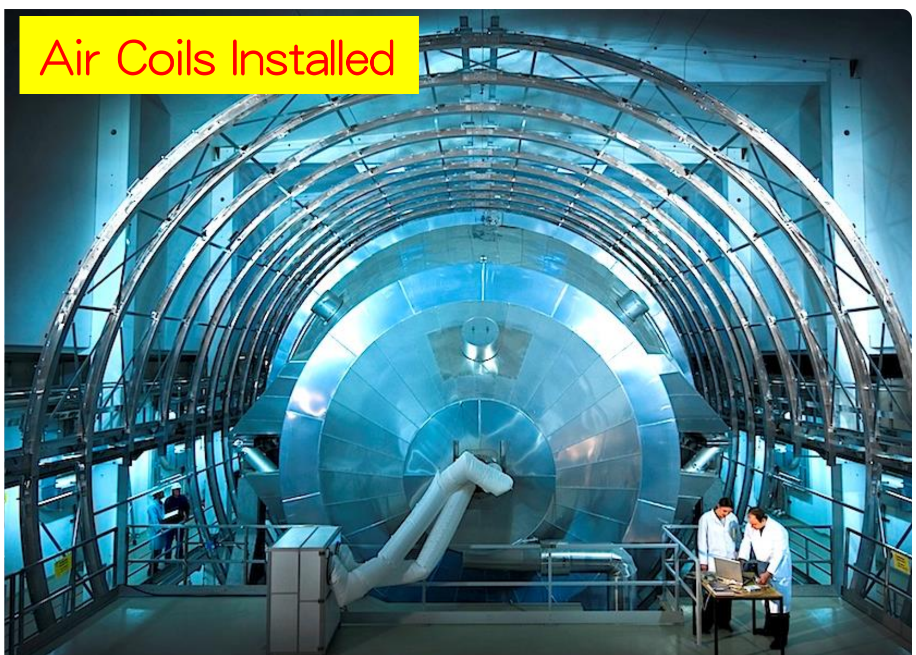

$\Delta E$ = ~1.5 keV

$E_{thresh}$ : ~4 keV

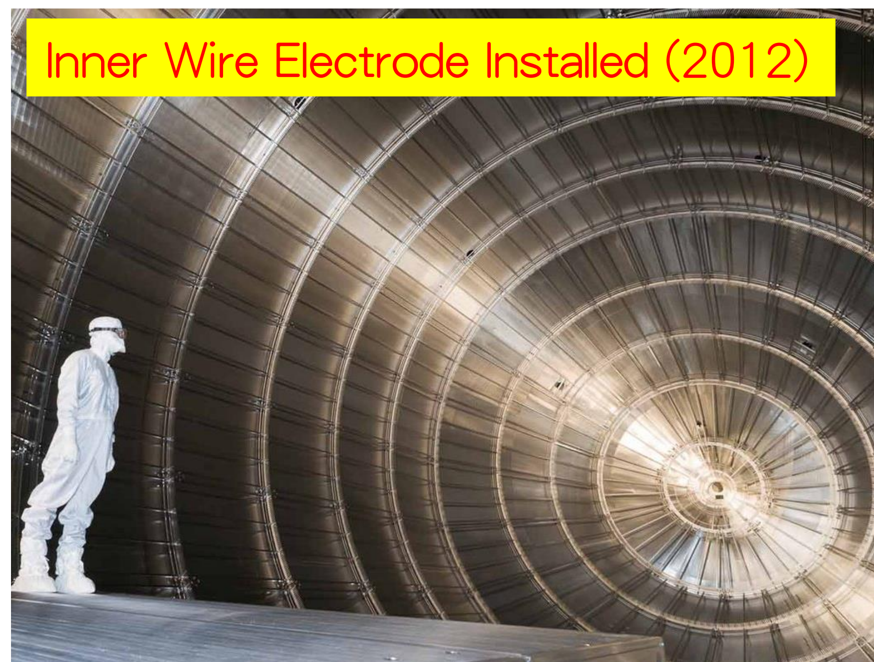
# Spectrometer Construction and Commissioning

Aug 2006

Oct 2006

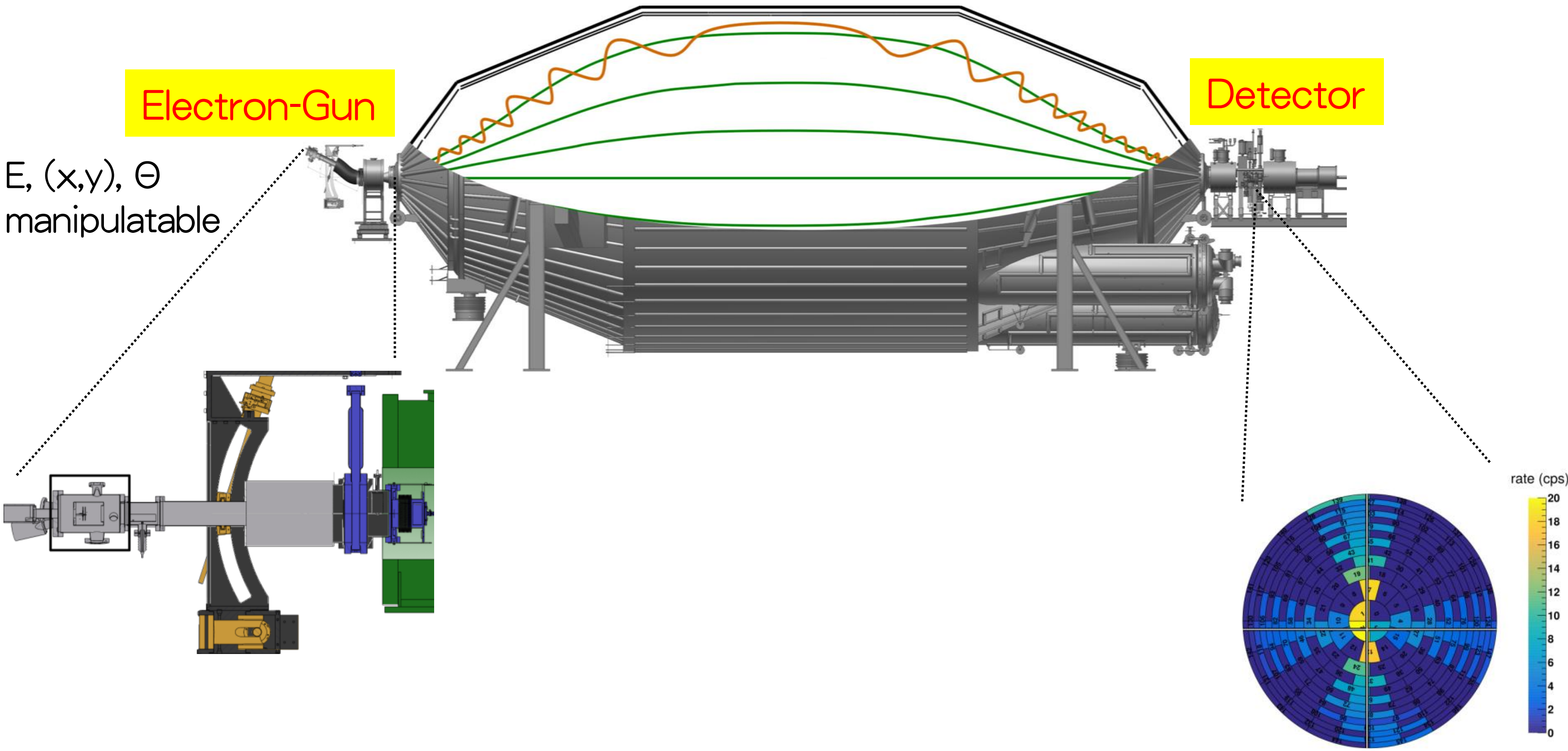


Air Coils Installed



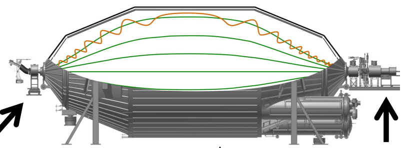
Inner Wire Electrode Installed (2012)

# EGun-Spectrometer-Detector Commissioning (2013~)




- MAC-E filter transmission characterization
- Background measurements
- HV stability test
- and more (alignment, active background removal, detector characterization, …)

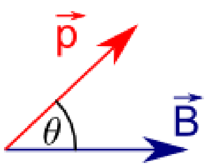
# MAC-E Transmission Characteristics



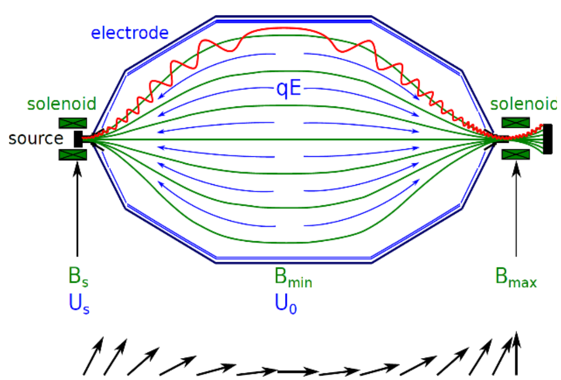
Detector

E-Gun
- E fixed
- Θ variated

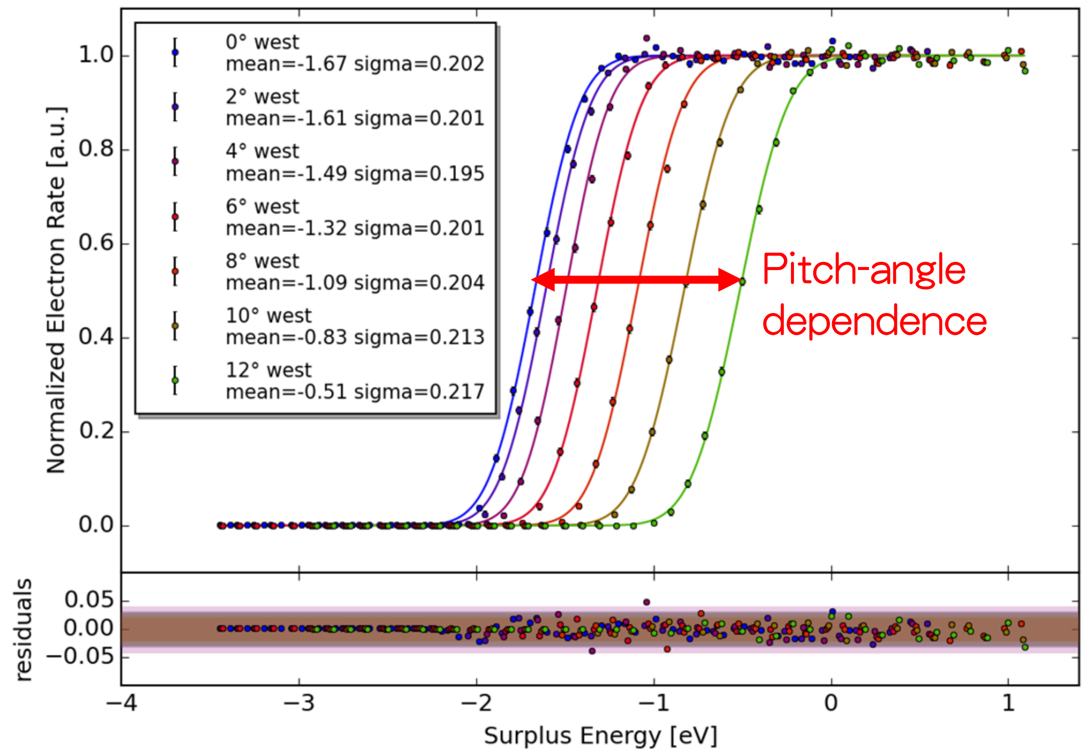
Spectrometer
- U variated




Transmission depends on pitch angle



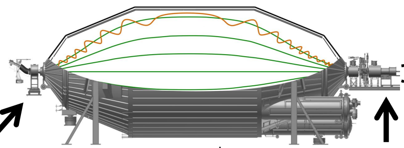

Transmission Function Measurement




retarding potential decreased

blocking → transmitting

# MAC-E Characteristics (potential penetration)



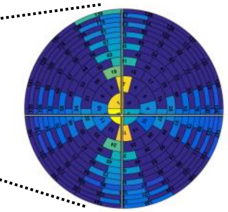
Detector

E-Gun

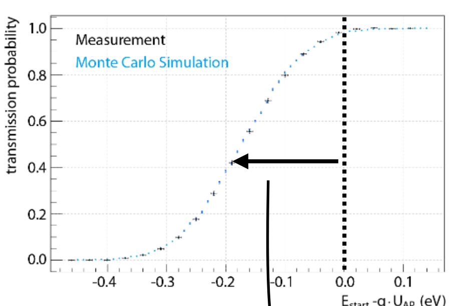
- E fixed
- Θ = 0
- (x,y) variated

Spectrometer

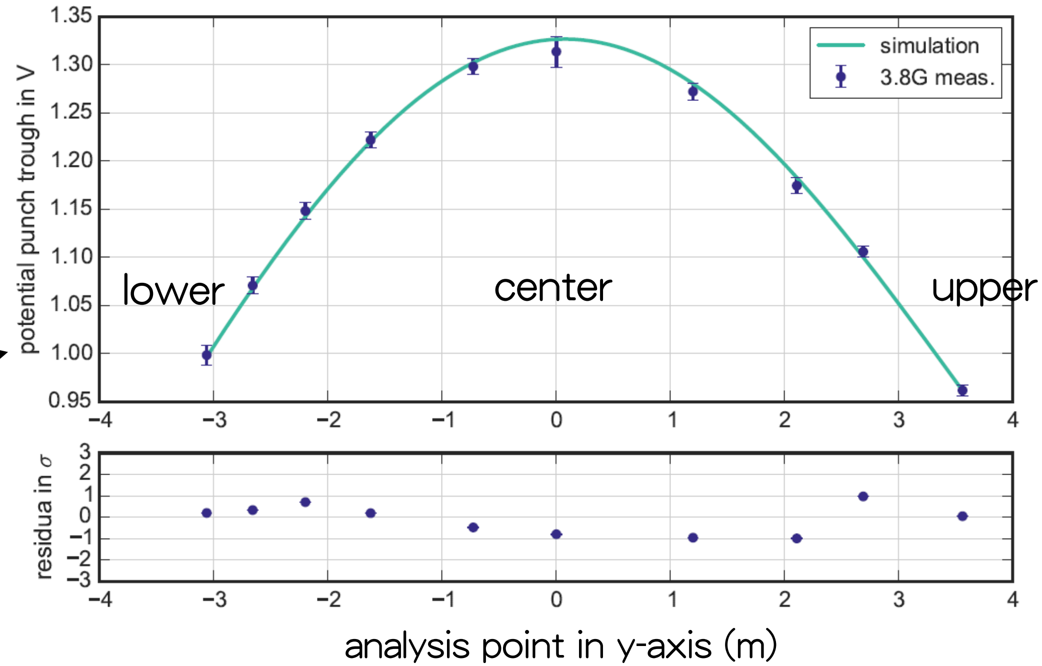
- U variated



Measure transmission function at various points



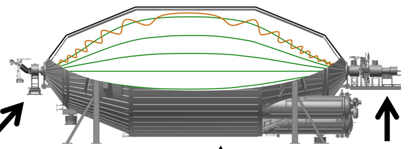

Analyzing Plane Potential Structure




more retarding

M. Erhard

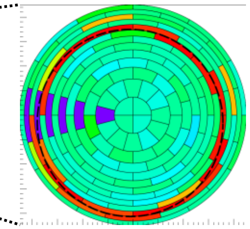
# Time-of-flight Measurements



E-Gun: start
- Pulsed
- Position varied

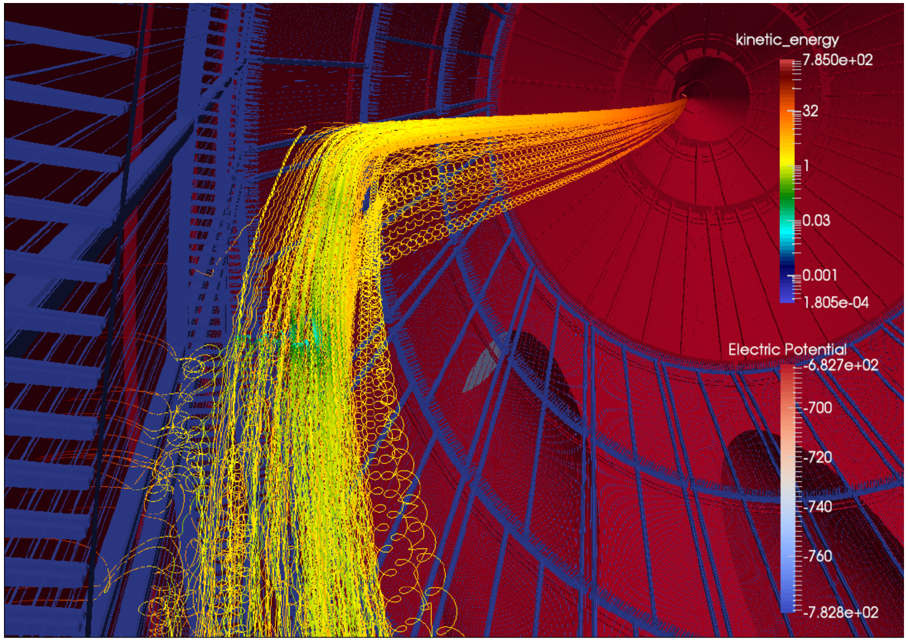
Spectrometer

Detector: stop



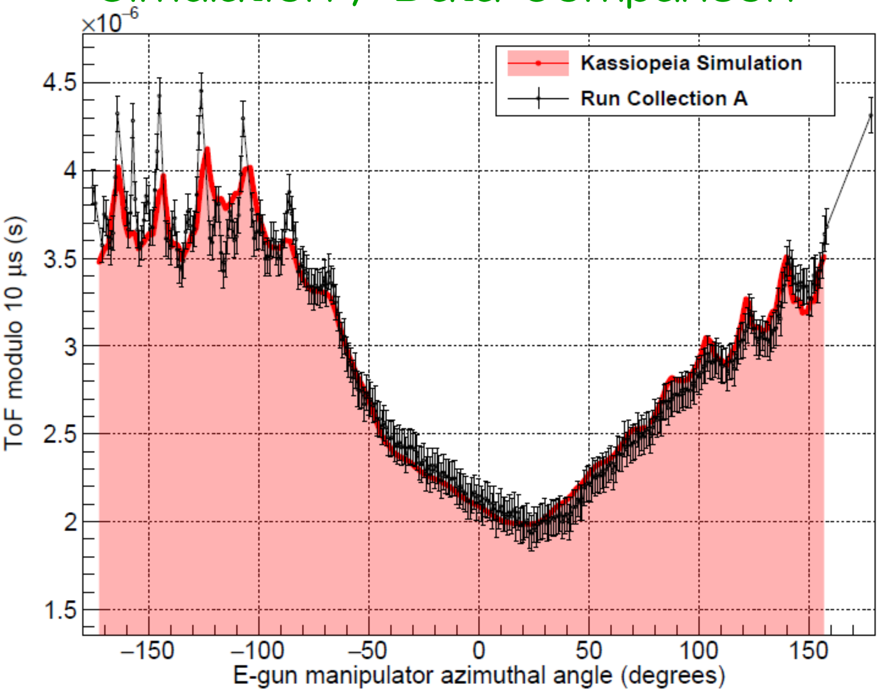
Scanning outer region

## Simulation




J. Barrett

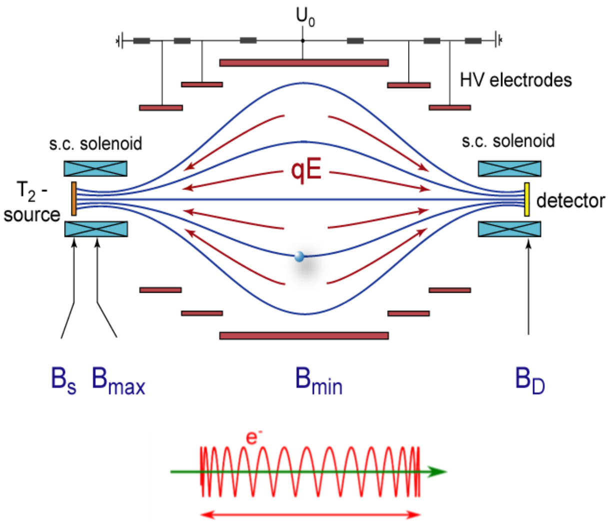
## Simulation / Data Comparison



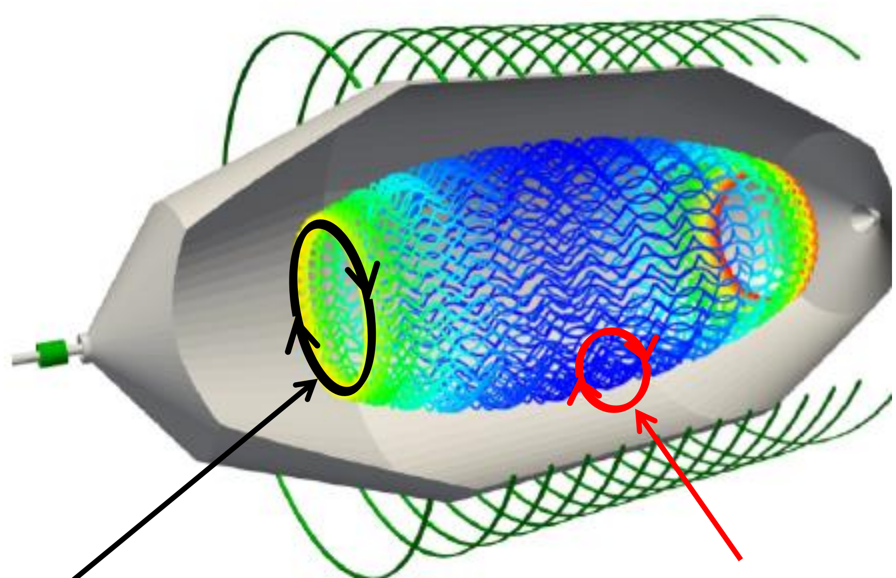

J. Barrett

# Potential Background Source: Trapped Particles

MAC-E filter is a magnetic bottle for particles generated inside (w/ large angle)




Large-angle particles are magnetically reflected



magnetron drift due to $\vec{\nabla} B \times \vec{B}$ and $\vec{E} \times \vec{B}$

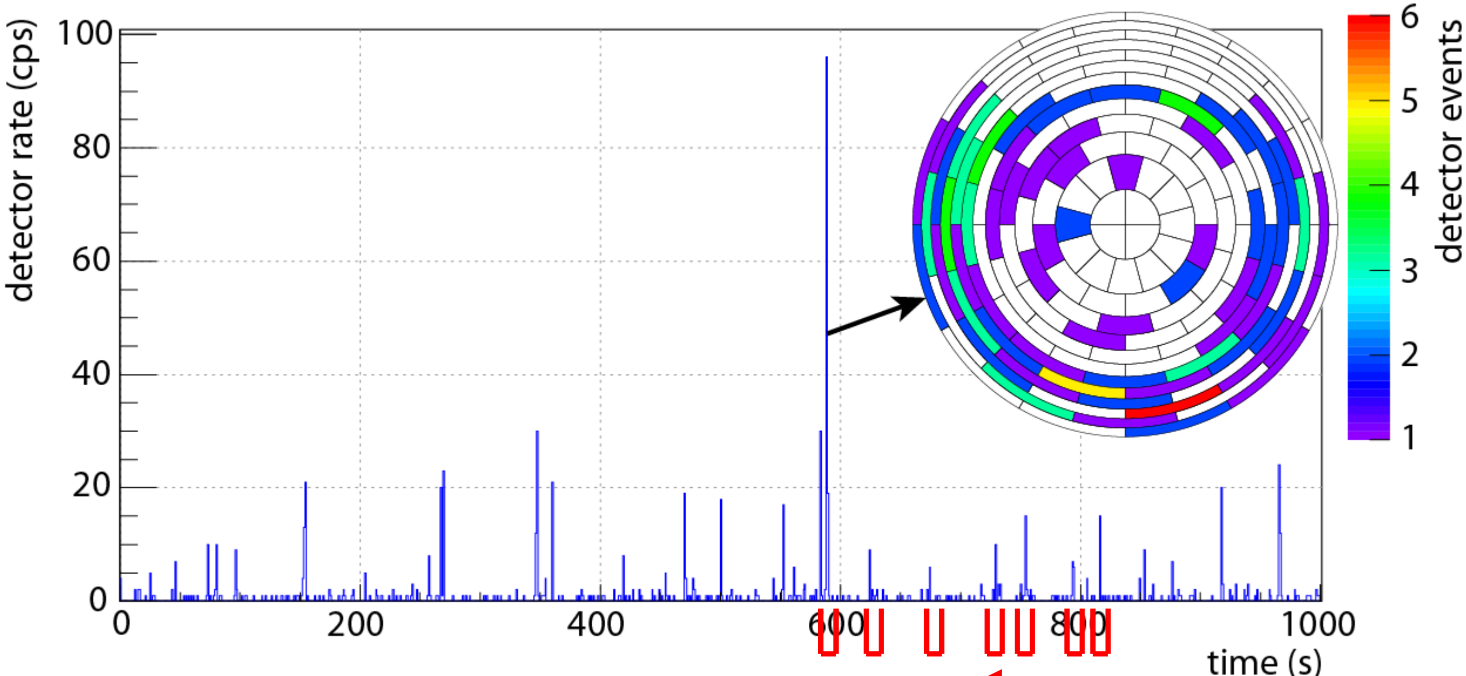
cyclotron motion

Stored particles could be a major background source

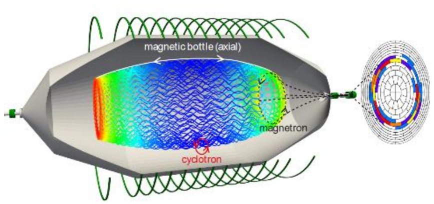
- stay in the vessel for ~min ~hours
- ionize residual gas, generating low-energy secondary electrons
- the secondaries reach the detector, just look like signals

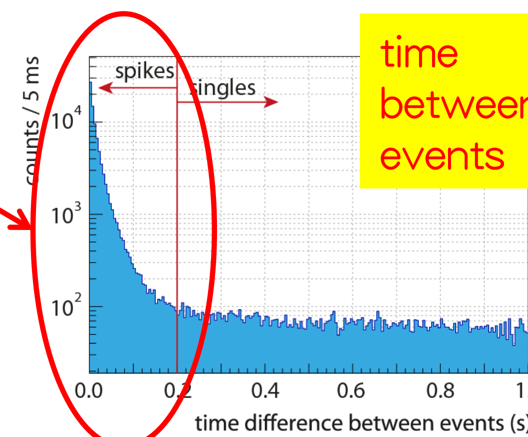
# Imaging the Stored Particles

by injecting Ar to increase *residual* gas (pressure: $10^{-11}$ mbar → $10^{-8}$ mbar)




storage time is reduced,
rate spikes with <200 ms duration



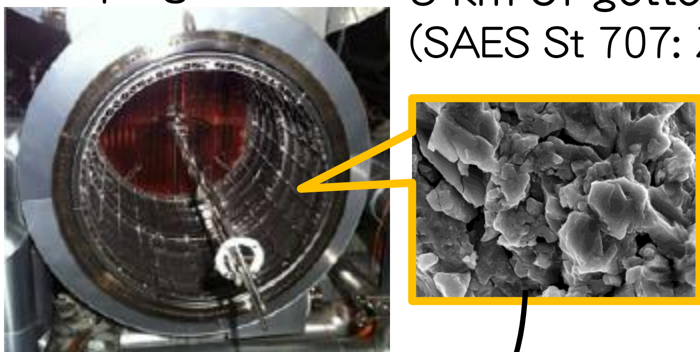

time between events

Ring pattern from stored particles is visible

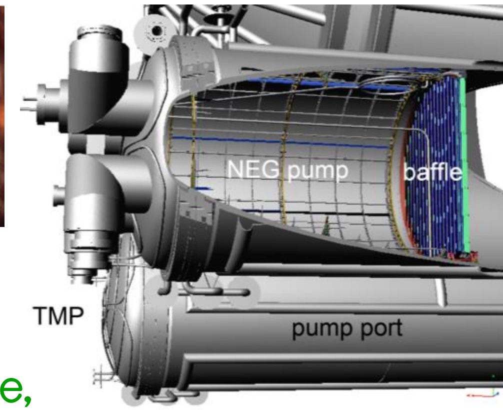
# We had known the source: it' s Radon, as always

Pumping Port

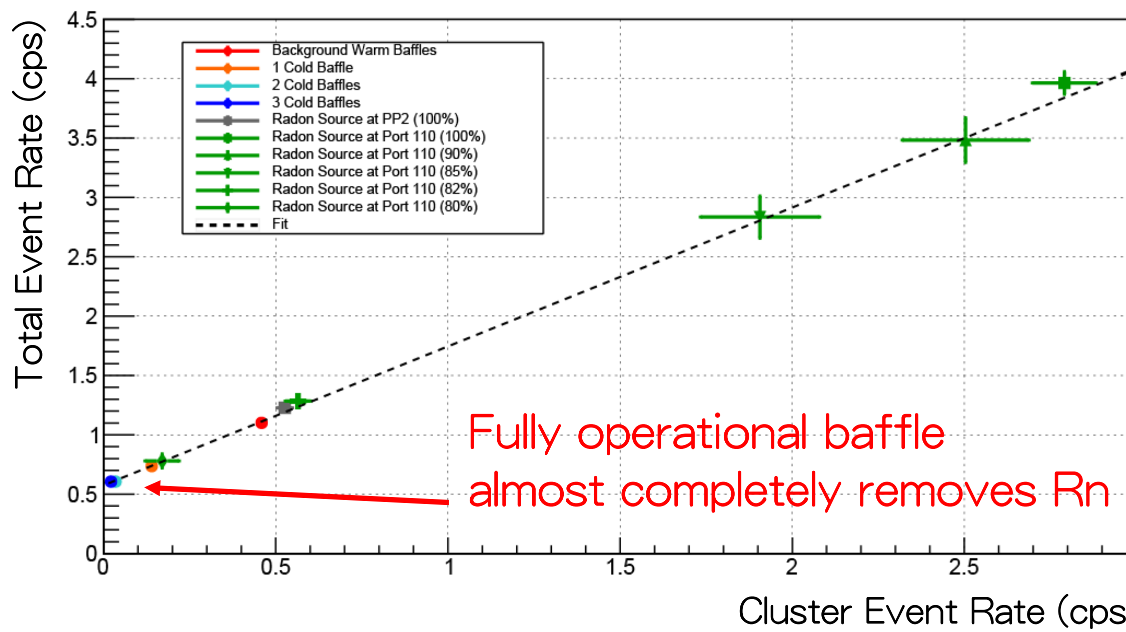
3 km of getter material
(SAES St 707: Zr-V-Fe)




Cryo-Baffle is installed
between NEG and Vessel

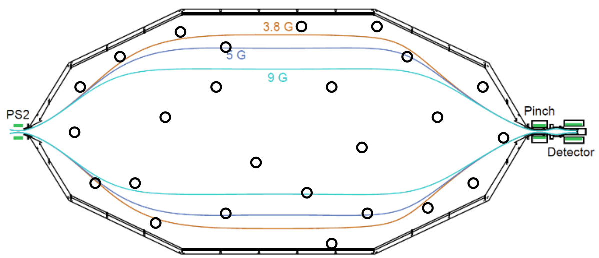



Cluster rate and total BG rate,
for various Baffle configurations

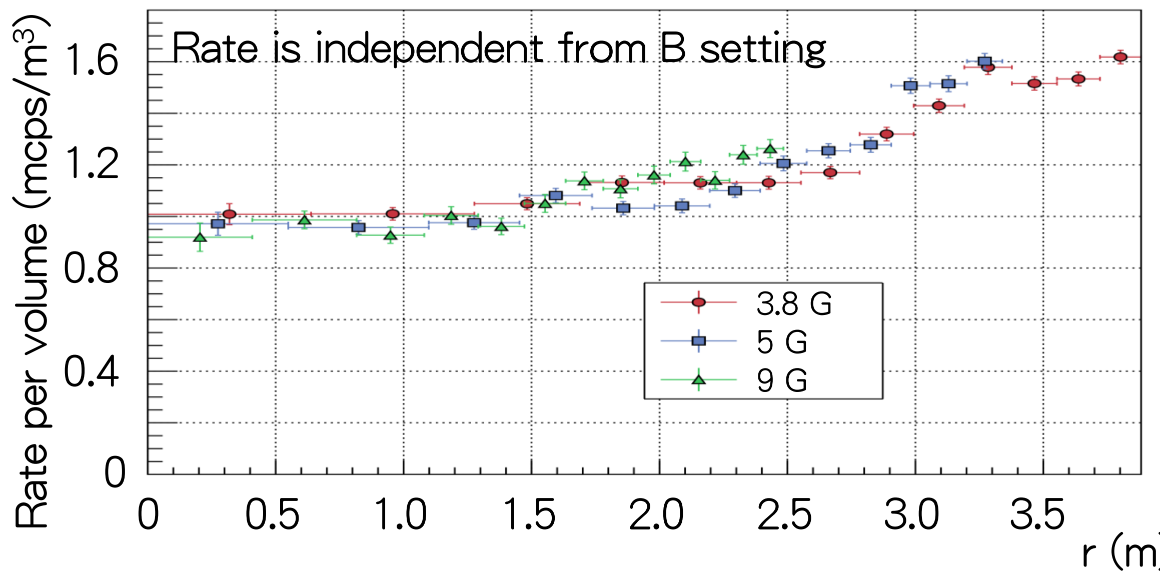


# Unexpected: 0.5 cps Electrons; from where?

## Sources are in the volume (not from the wall)




Low-energy electrons (~eV) generated in the volume??




## Other observations

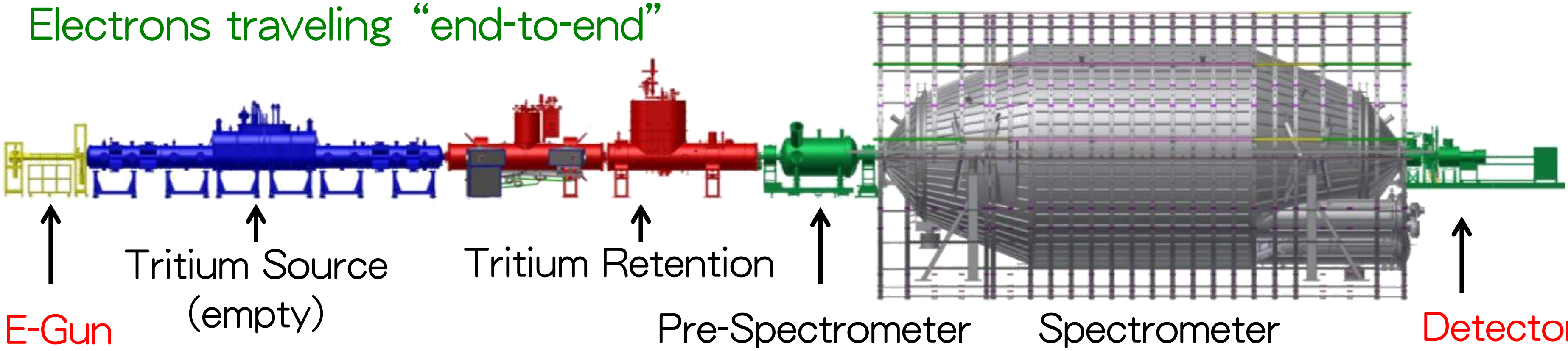
- Dependence on temperature, cleanness of vessel wall, and inner-wire E-field
- Not correlated to cosmic muon rates
- 30 keV and 42 keV electrons observed from the vessel wall ($^{210}$Pb EC ??)

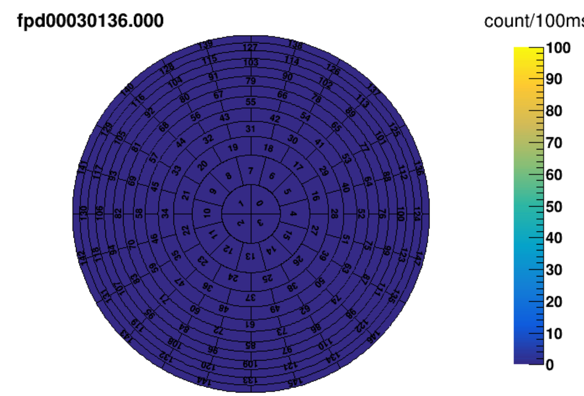
## Our Best Hypothesis: Rydberg Hydrogen (neutral excited hydrogen atoms)

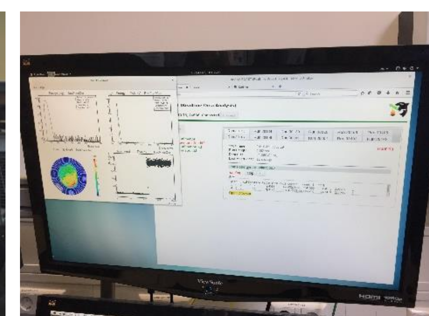
- Rn progeny $^{210}$Pb are embedded in the vessel wall
- Alpha-decay of $^{210}$Po ($^{210}$Po progeny) somehow excites hydrogen on the wall
- Excited H* atoms (Rydberg Hydrogen) are ionized in volume by black-body radiation

# KATRIN "First Light" (Oct 2016)

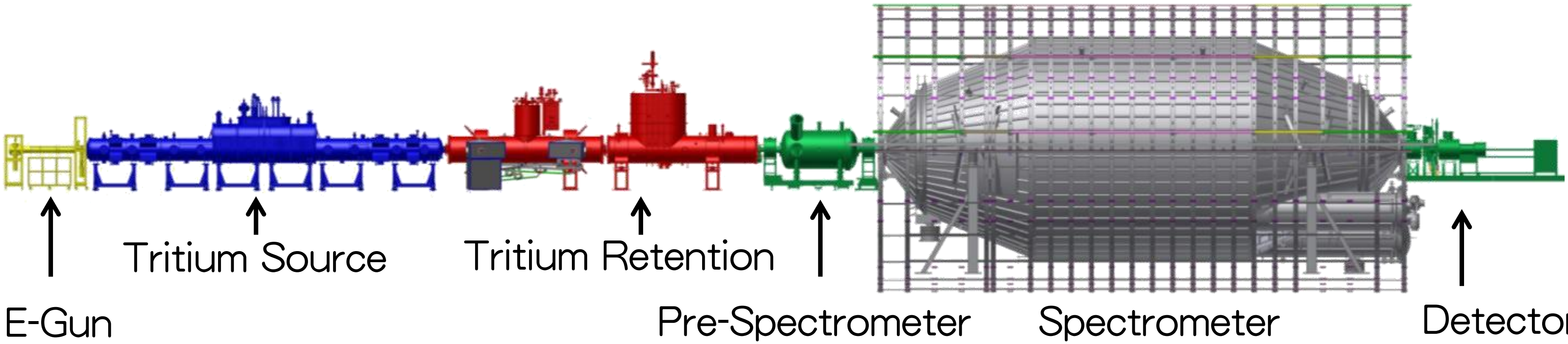
Electrons traveling "end-to-end"



# Final Commissioning in 2017




2013~

Measurements Started Last Week

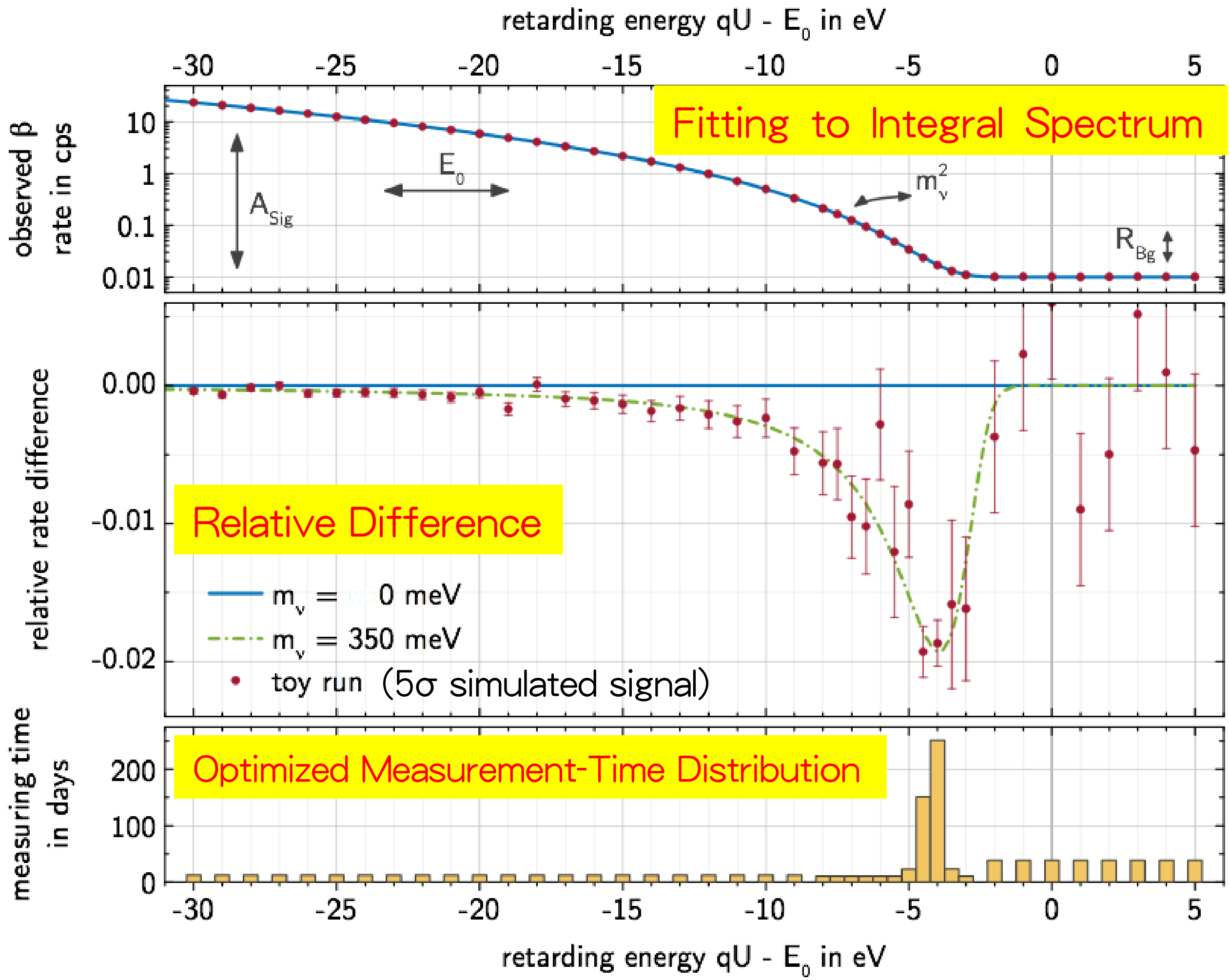
Commissioning Measurements March 2017 ~ … $D_2$+$T_2$ run by end of 2017

## 2017 Commissioning Plans

- Characterization of components, completion of tritium loops
- Test/calibration with gaseous Kr source
- Test with $D_2$ gas, then $D_2$+$T_2$
- Measurement of energy-loss in source with E-Gun

# Scanning Optimization and Spectrum Fitting

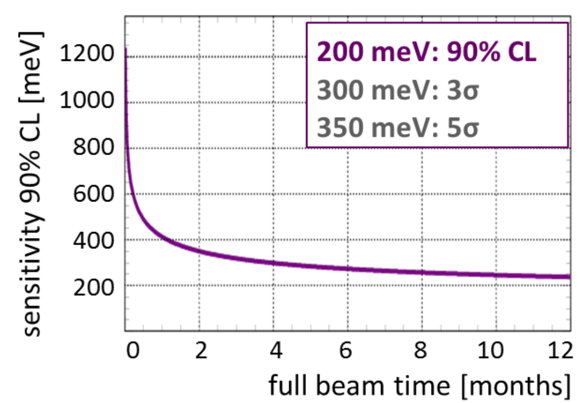
## Scanning Optimization with Toy MC




Four Parameter Fitting:
$m_\nu^2$, $E_0$, $A_{sig}$, $R_{bg}$

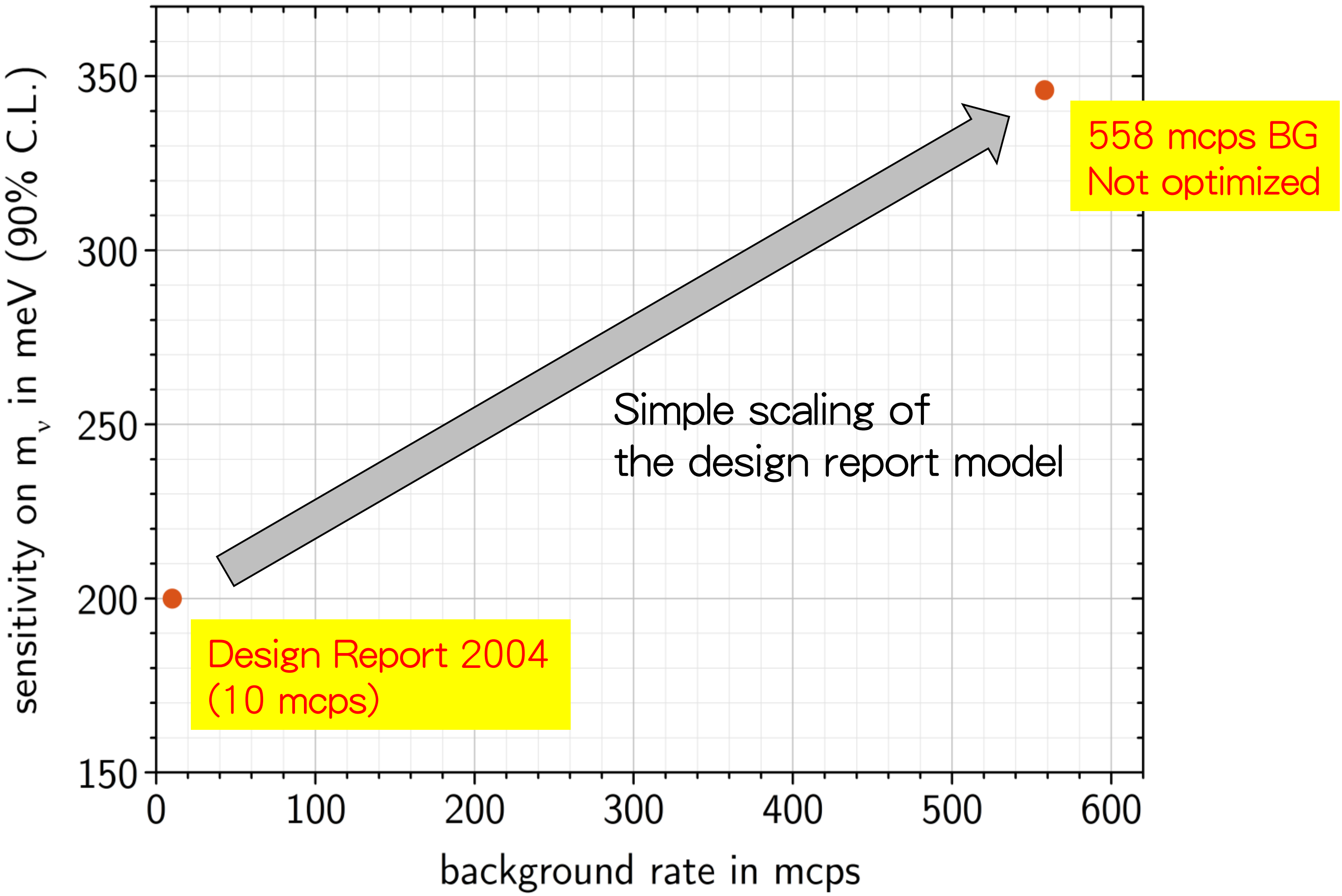
End-point is unconstrained

Design Sensitivity:
200 meV (90%CL) in 3 yr



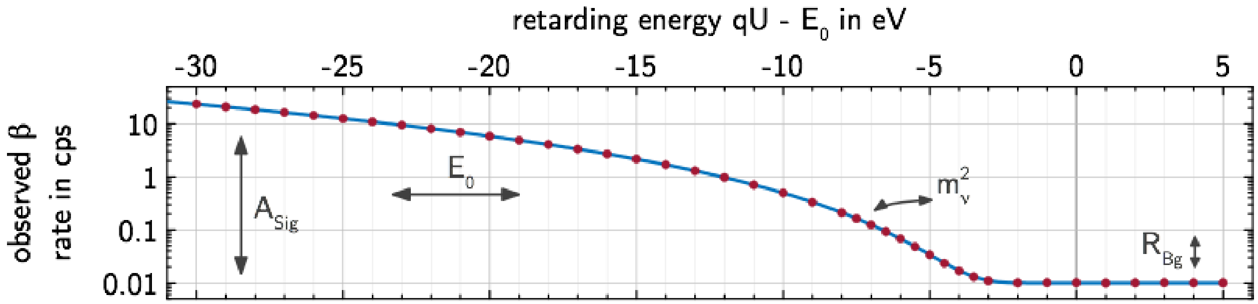

M. Kleesiek

# If the 500 mcps BG cannot be removed



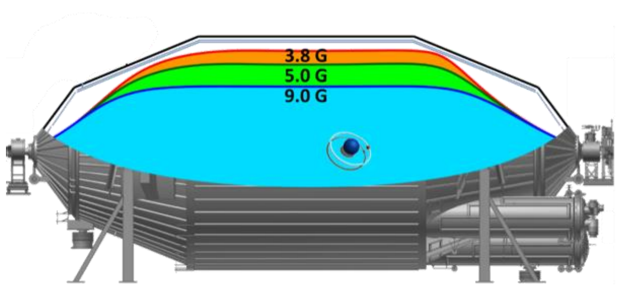
# KATRIN Sensitivity in case the BG cannot be removed

## Optimization on Scanning Range

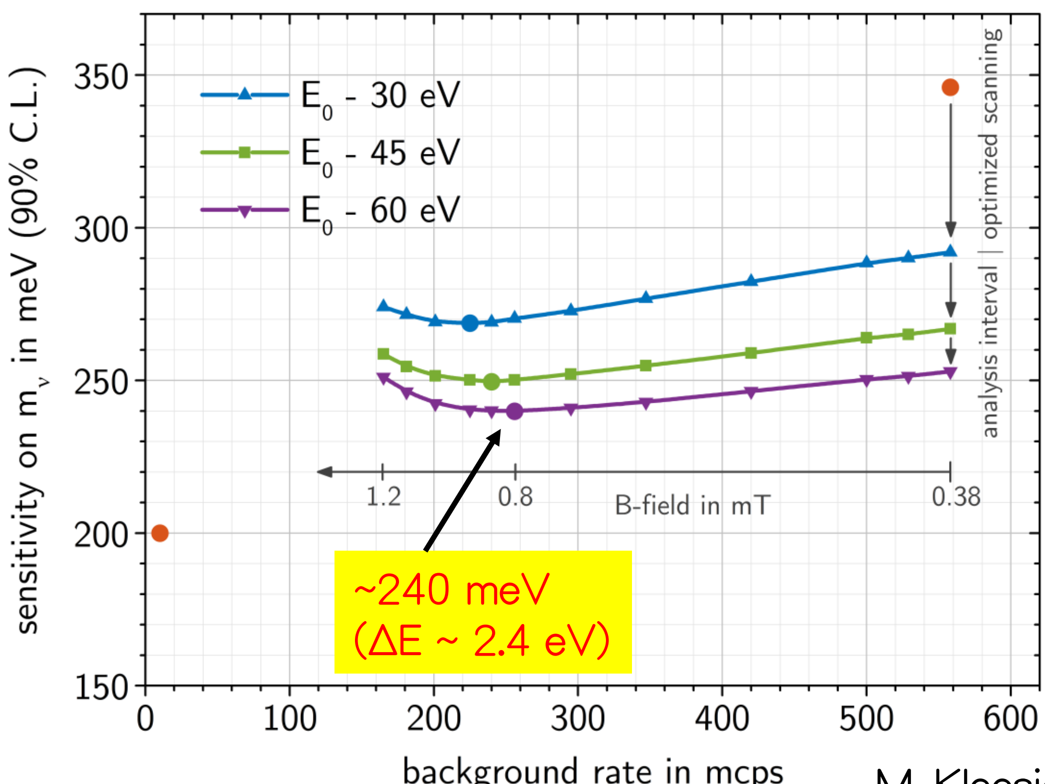



Extended Analysis Interval
- More signal
- Less "clean" part

## Optimization on Flux Volume




Shrunk flux volume
- Reduced BG
- Worse ΔE




M. Kleesiek

# Summary and Outlook

## KATRIN: Model-Independent Neutrino Mass Measurement

- Only uses beta-decay kinematics
- 100 GBq gaseous tritium + 0.9 eV resolution MAC-E filter
- Design sensitivity 0.2 eV (90%CL) in 3 years

## Status

- Main spectrometer commissioned and characterized
- "First light" last month: everything assembled
- Source section commissioning in 2017

## FAQ: When will KATRIN start?

~~In two years~~ → First tritium data in one year

# KATRIN Collaboration

- ~130 Collaborators
- 18 Institutions
- 6 Countries
  DE, US, CZ, RU, UK, FR

# KATRIN Error Budget

(KATRIN Design Report 2004)