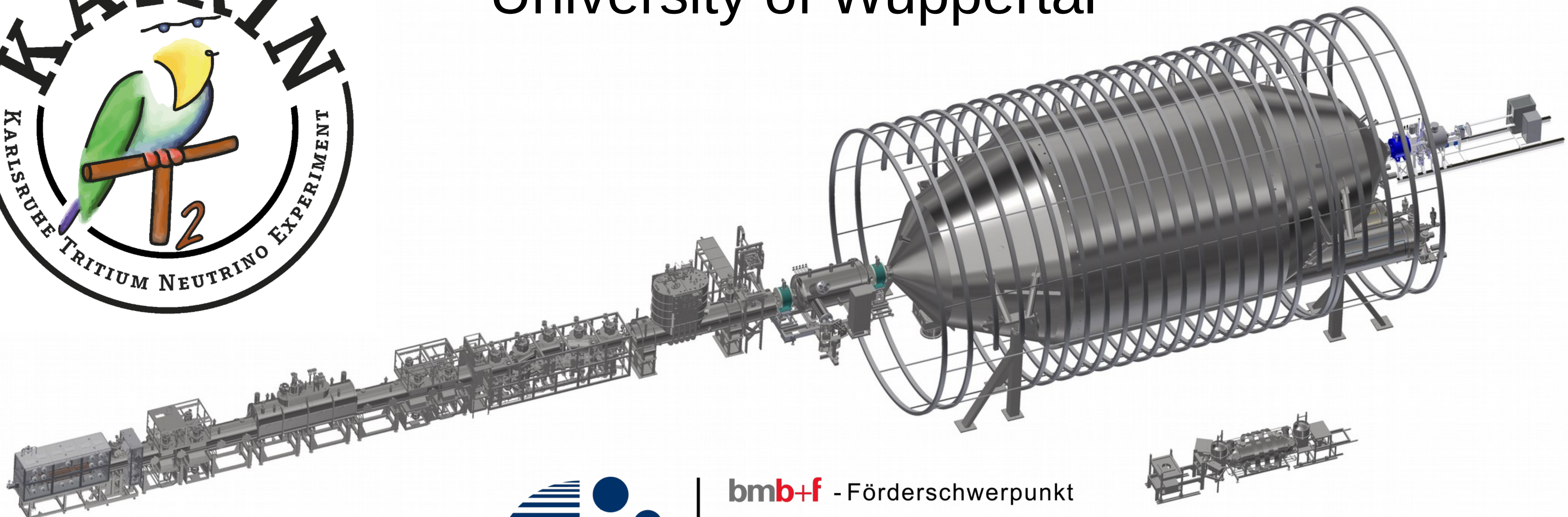
The mass of the neutrino – truly

… the KATRIN experiment and beyond

Klaus Helbing
University of Wuppertal



bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

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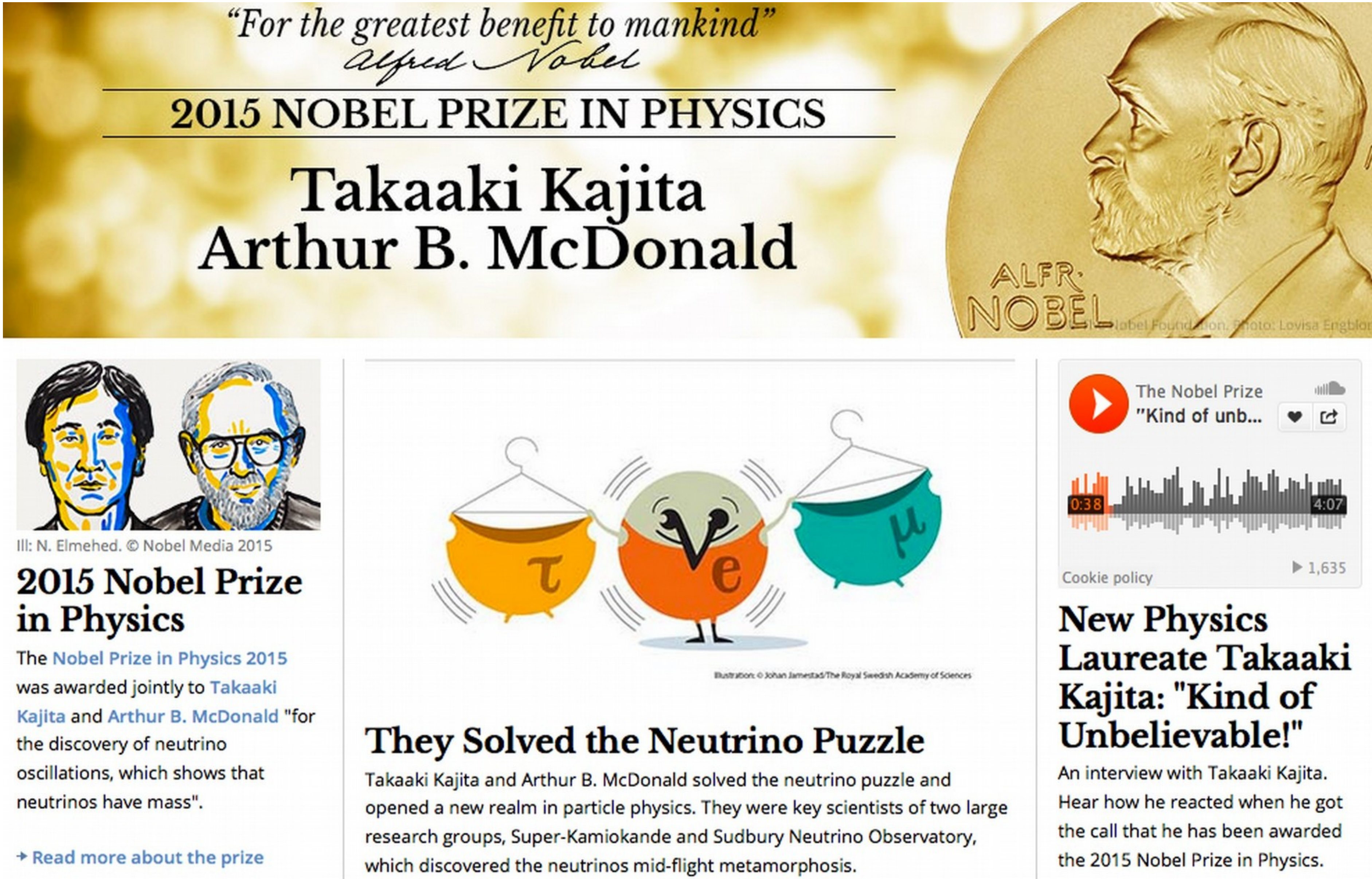


"For the greatest benefit to mankind"
Alfred Nobel

2015 NOBEL PRIZE IN PHYSICS

Takaaki Kajita
Arthur B. McDonald

Ill: N. Elmehed. © Nobel Media 2015

2015 Nobel Prize in Physics

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".

→ Read more about the prize

They Solved the Neutrino Puzzle

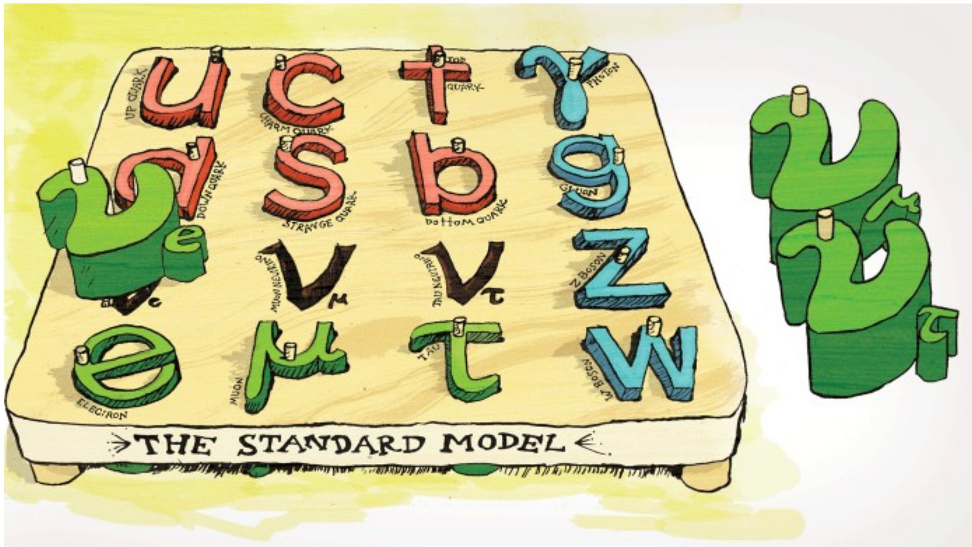
Takaaki Kajita and Arthur B. McDonald solved the neutrino puzzle and opened a new realm in particle physics. They were key scientists of two large research groups, Super-Kamiokande and Sudbury Neutrino Observatory, which discovered the neutrinos mid-flight metamorphosis.

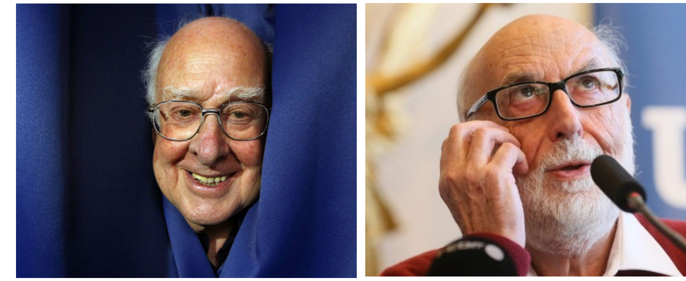
New Physics Laureate Takaaki Kajita: "Kind of Unbelievable!"

An interview with Takaaki Kajita. Hear how he reacted when he got the call that he has been awarded the 2015 Nobel Prize in Physics.

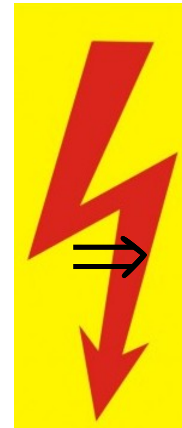
Kajita outreach talk: If neutrinos were massless they were traveling with c
→proper time does not pass any more, hence they cannot change

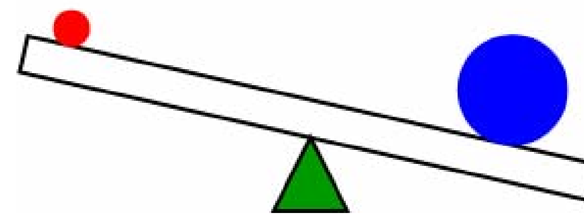
Neutrino versus Standard Model





$$H \Rightarrow m_\nu$$





- Does the Higgs give mass to the neutrinos? - **Actually Not in SM!**
- What are the masses of the known neutrino types?
- Are neutrinos their own antiparticles (Majorana)?
- More then three neutrino flavors (sterile)?
- Why did matter win over anti-matter?
- Current best fit for Dirac CP-violating phase maximal: ~ 270°

- Neutrinos 250,000 times lighter than electron
  - No simple extension of SM for 3 reasons:
    - No right-handed neutrinos → no Dirac mass term
    - Lepton number symmetry of SM → no Majorana mass term
    - Only renormalizable terms
  - Neutrino mass lowest order perturbation of BSM?
  - Seesaw mechanism: Neutrino mass suppressed by heavy partner

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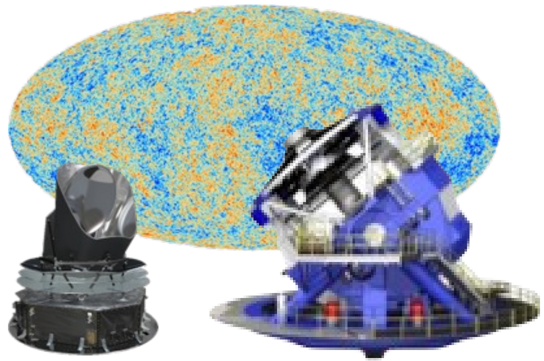
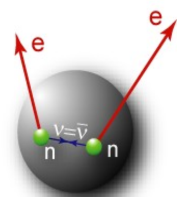
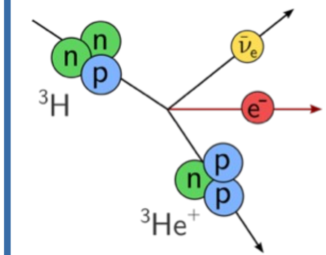
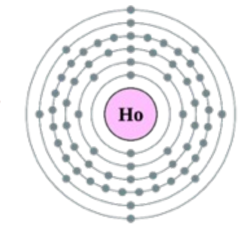
The absolute neutrino mass

Truly !









	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
Potential	15 – 50 meV	15 – 50 meV	200 meV
Model dependence	Multi-parameter cosmological model	- Majorana ν: LNV - BSM contributions other than m(ν)? - nucl. matrix elements - Incl. interferences	**Direct,** only kinematics; no cancellations in incoherent sum

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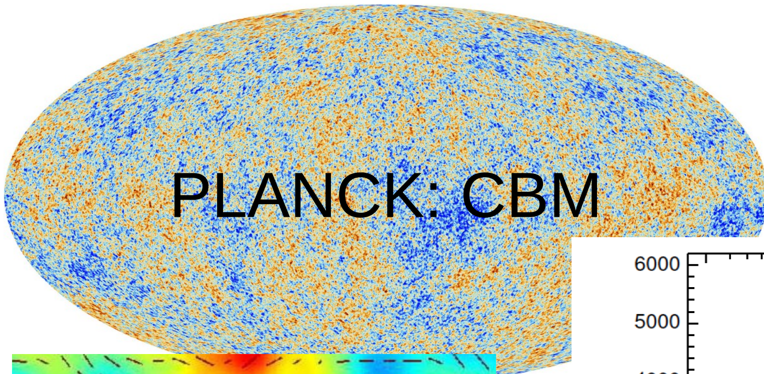
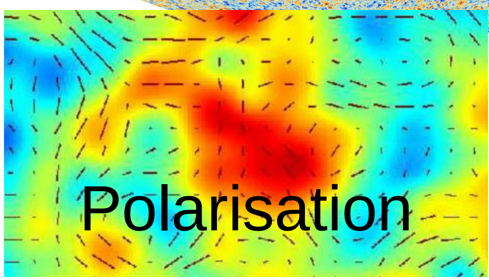
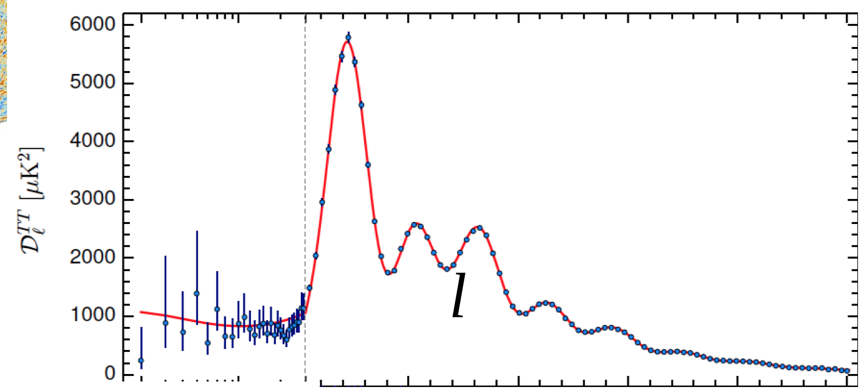
Neutrino mass from cosmology

BB model: ratio $\#\gamma/\#m(\nu)$ → m < 50 eV

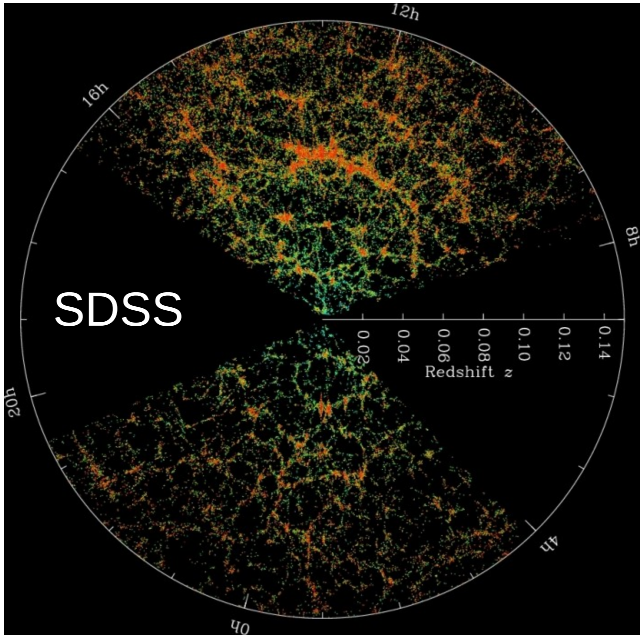


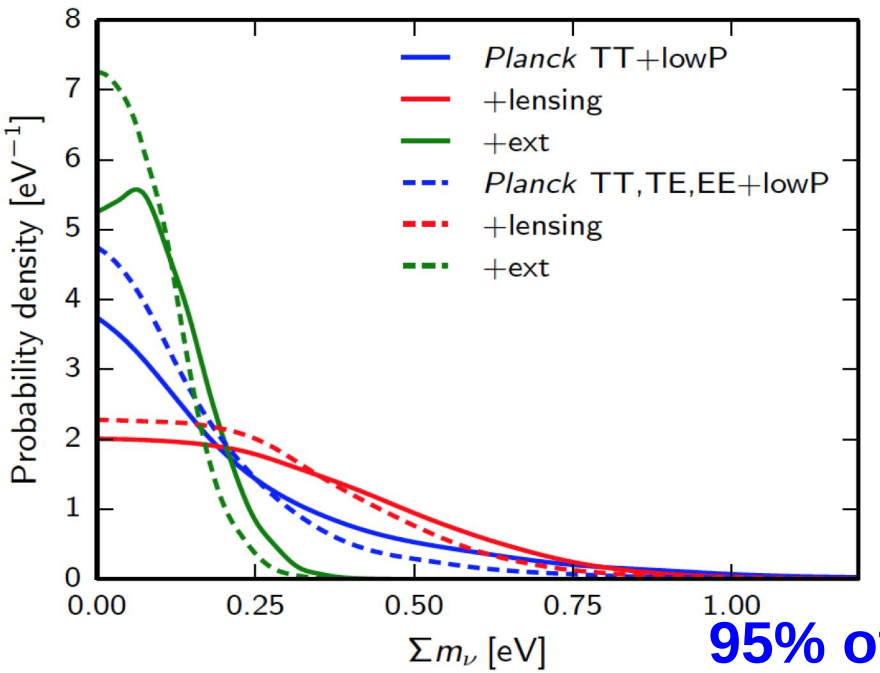


Planck Collaboration:
P. A. R. Ade et al., arXiv:1502.01589

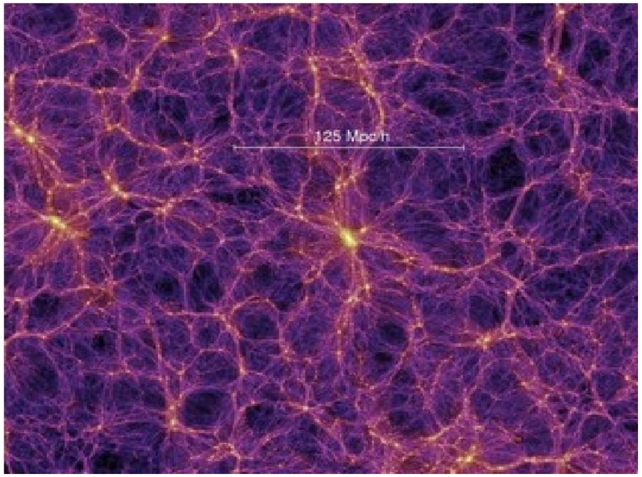


Large Scale Structure





numeric models
relic neutrinos
336 cm^{-3}



Alternative: arXiv:1606.00634

ΛCDM model …

very successful but

95% of universe not understood

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Fermi theory of beta decay

Fermi's Golden Rule: $\underbrace{\Gamma_{i\to f}}_{\text{decay rate}} = \frac{2\pi}{\hbar} \underbrace{|\langle f|H|i\rangle|^2}_{\text{interaction matrix}} \cdot \underbrace{\rho(E_f)}_{\text{density of final states}}$

$$dn = \frac{V}{h^3} \cdot p^2 dp \cdot d\Omega$$

$$\rho(E_e, E_\nu, d\Omega_e, d\Omega_\nu) = \frac{V^2}{(2\pi)^6} \cdot p_e E_e \cdot p_\nu E_\nu$$

$E := E_e - m_e$: kinetic electron energy

$E_0 = Q - E_{recoil}$: maximal kinetic electron energy

for $\mathbf{m_\nu = 0}$ and $Q \simeq E_0$

$$p_\nu = E_\nu = Q - E$$

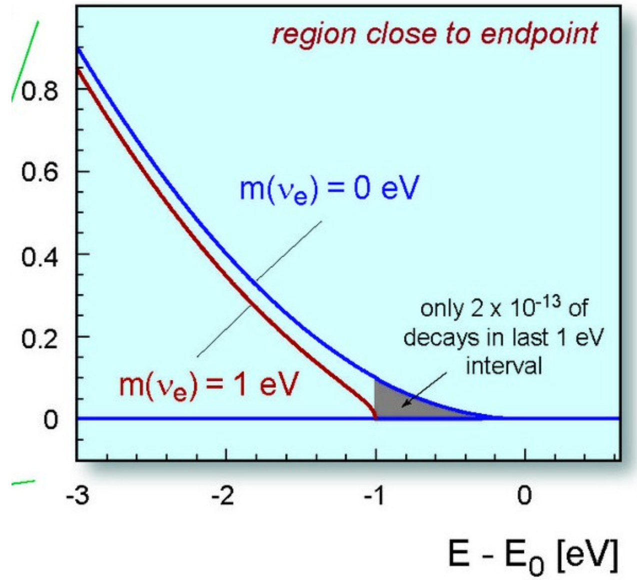
$$\frac{dN}{dE} \propto p_e E_e \cdot (Q-E)^2$$

$\sqrt{\frac{dN}{dE}}$ versus E : Kurie plot

$\Rightarrow \quad Q =$ abscissa

for $\mathbf{m_\nu \neq 0}$ and $E_{recoil} \neq 0$

$$\frac{dN}{dE} \propto p_e E_e \underbrace{(E_0 - E)}_{E_\nu} \underbrace{\sum_i |U_{ei}|^2 \sqrt{(E_0-E)^2 - m^2(\nu_i)}}_{p_{\nu_i}}$$



$$m^2(\nu_e) = \sum_i |U_{ei}|^2 m^2(\nu_i)$$

Observable:
Mass squared!
100x better meas.
→ 1/10 x m(ν)

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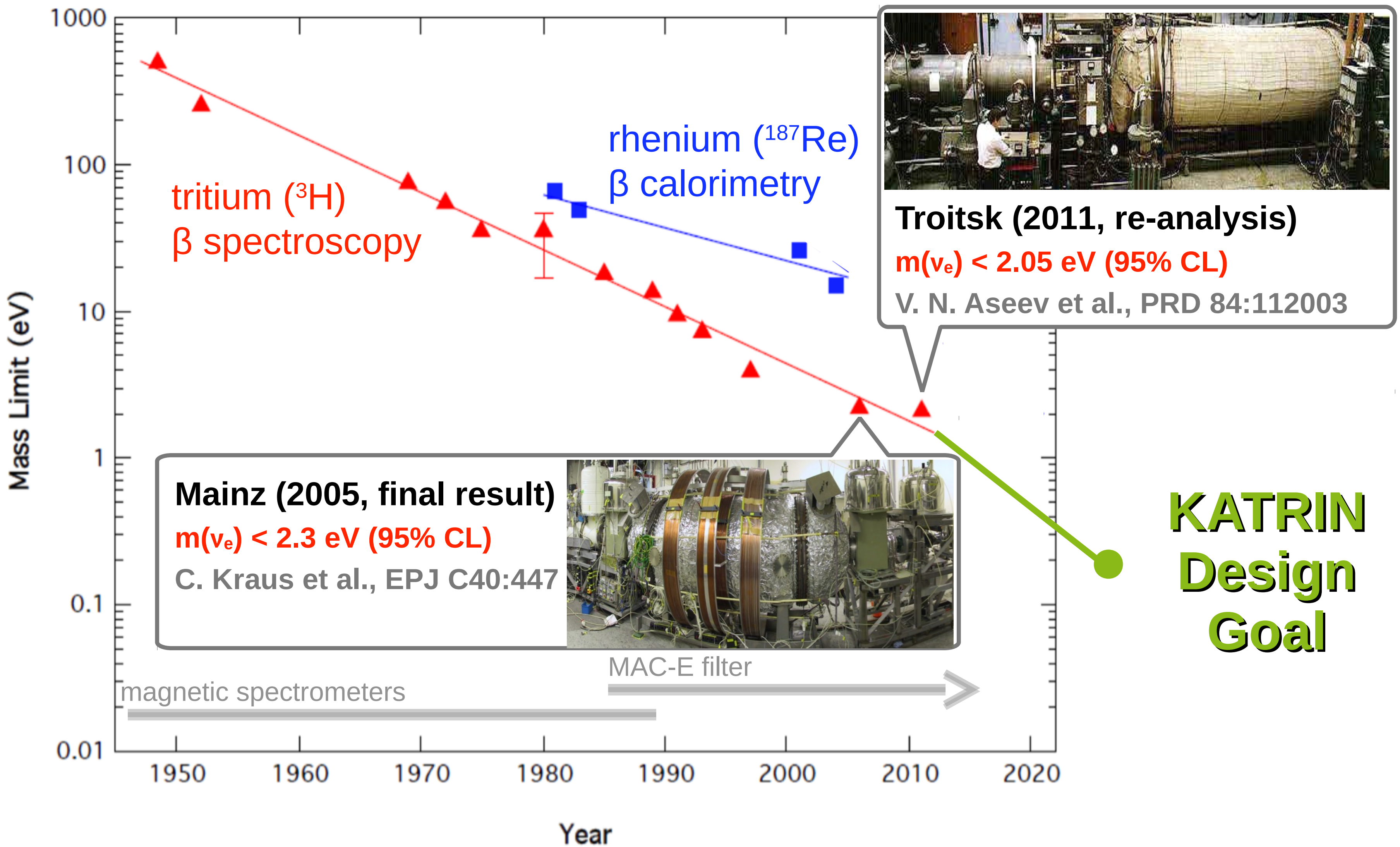
Moore's law for direct neutrino mass



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Recipe for improving sensitivity

- Improve statistics
  - Luminous beta source (10^{11} decays/s)
  - Excellent energy resolution (0.93 eV)
  - Low backgrounds (even at sea level)
- Improve systematics
  - Extensive commissioning
  - Molecular physics
  - **Column density (activity, scattering)**
  - …

Powers of Ten

- **5×10^{-5} energy resolution**
  → spectrometer volume: 1400 m^3
  → 3.5 Tesla superconducting magnets
- **10^{-3} stability of tritium source density**
  → temp. regulation by dual phase Ne
- **10^{-3} isotope content in source**
  → laser Raman spectroscopy
  → rapid circulation and purification system
- **10^{-5} non-adiabaticity in electron transport**
  → novel computational code KASSEIPEIA
  → pulsed and pointing electron gun
- **10^{-6} monitoring of HV-fluctuations**
  → ultra-precision HV divider
  → ^{83m}Kr energy standard
- **10^{-8} remaining ions after source**
  → dipole drift electrodes, FT-ICR
- **10^{-14} remaining flux of molecular tritium**
  → 3 Kelvin cryopumping with Argon frost
- **10^{7} dynamic range of rate**
  → electronics and DAQ
- **10^{-11} mbar ultrahigh vacuum**
  → huge getter and turbo molecular pumps

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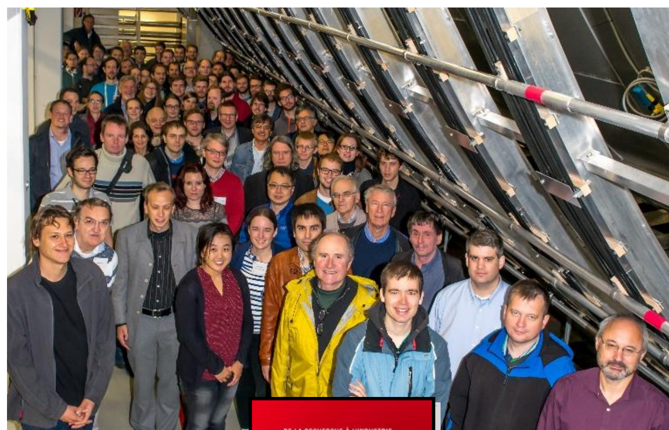
KATRIN collaboration

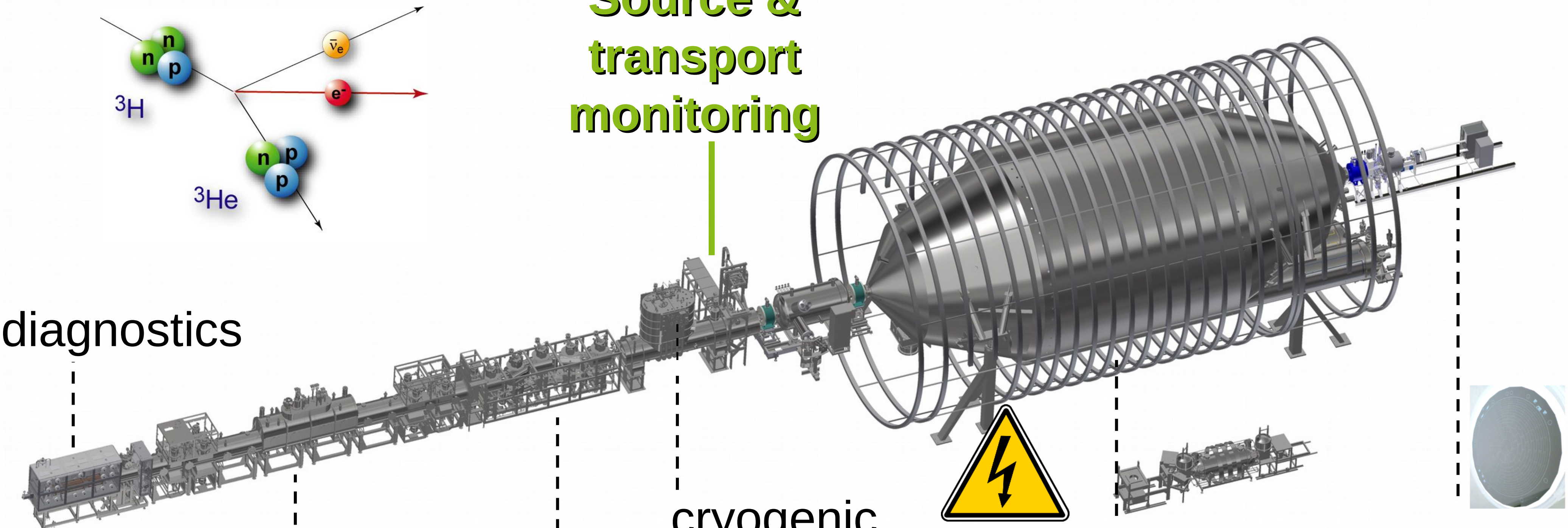
KArlsruhe TRitium Neutrino experiment

- **direct n-mass experiment**: at Tritium Laboratory (TLK), KIT
- international collaboration ~130 members
  from 6 countries: D, US, CZ, RUS, F, ES
- **uniting the world's expertise in tritium beta decy!**



■ **19 institutions:**

KATRIN beam line: 70 m



Recycling the tritium
Removing ions

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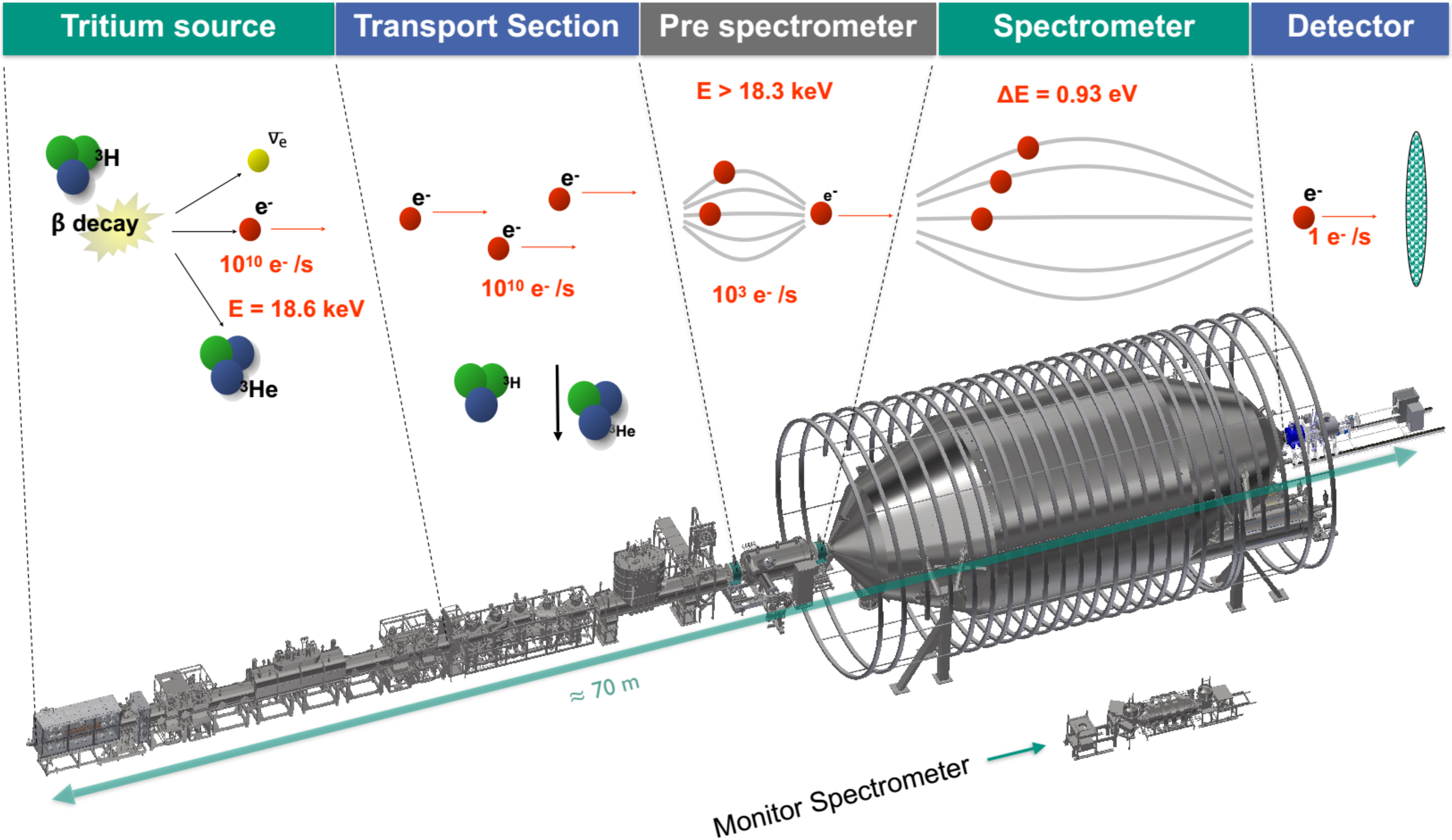
Tracking the beta-electrons



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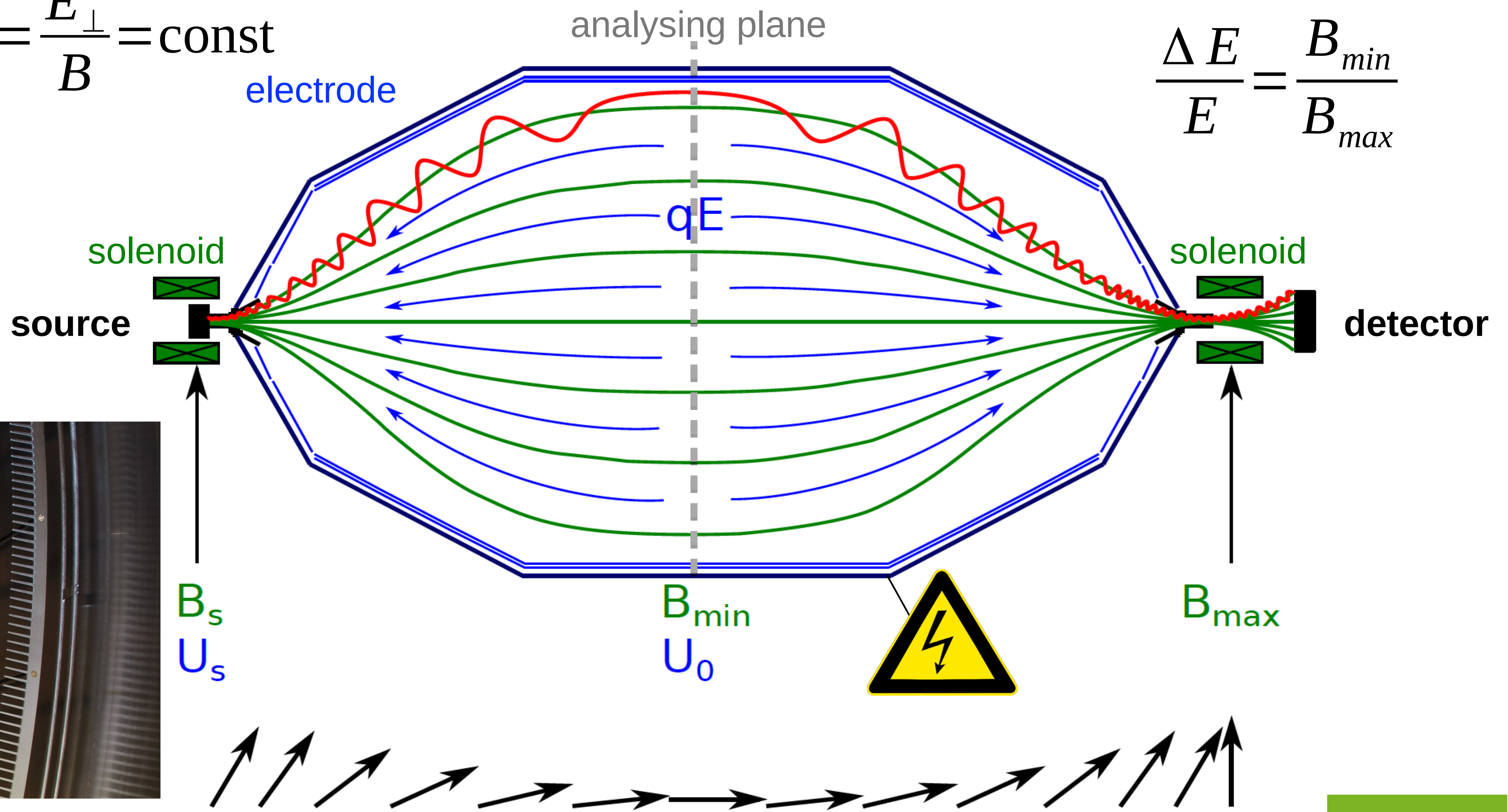
MAC-E filter principle

Magnetic Adiabatic Collimation & Electrostatic filter

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

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



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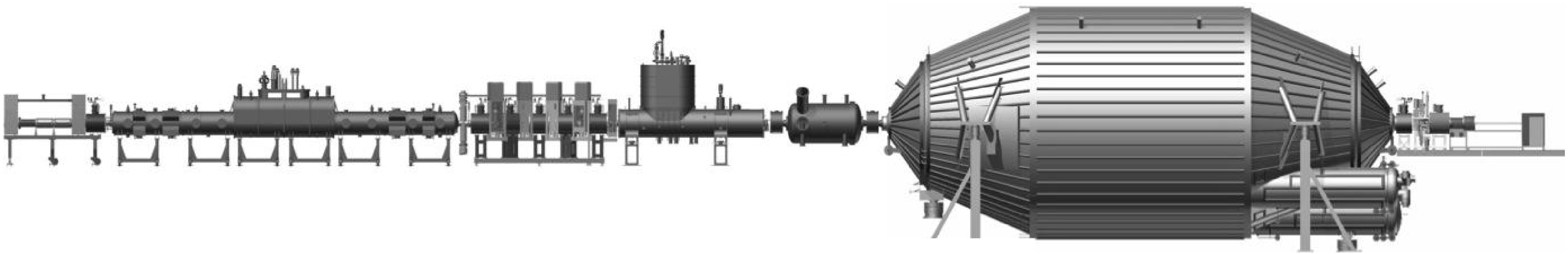
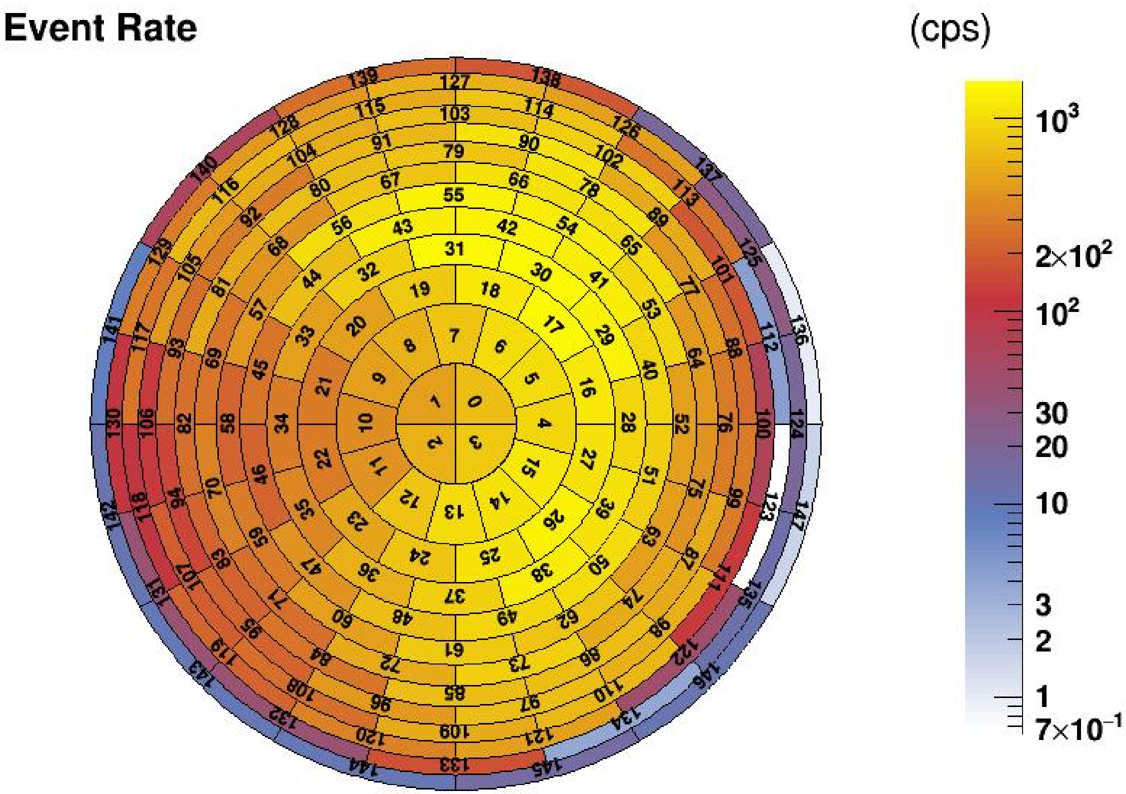
Technical start of KATRIN: "1st light": Oct. 14, 2016

Photo electrons over full 70m long beamline, but no tritium yet





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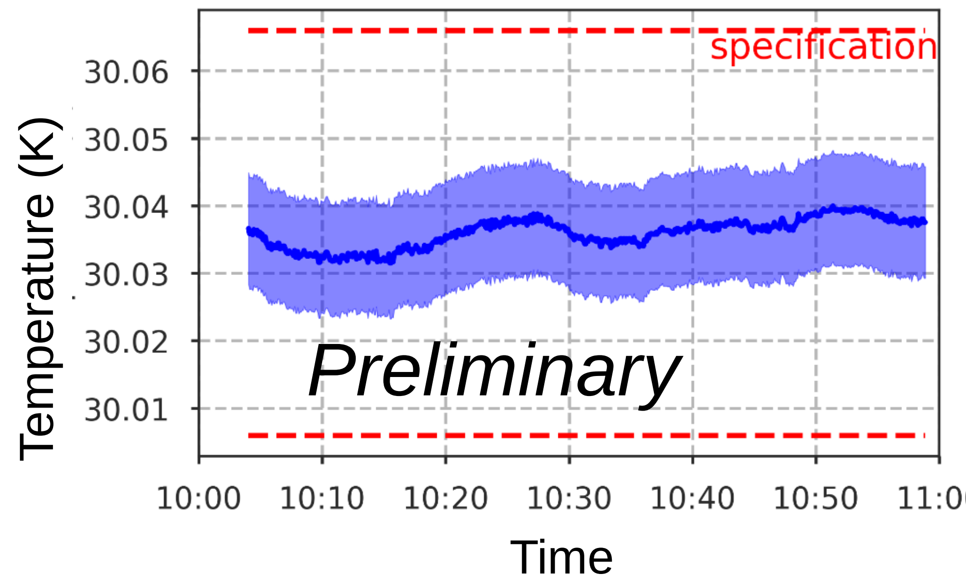
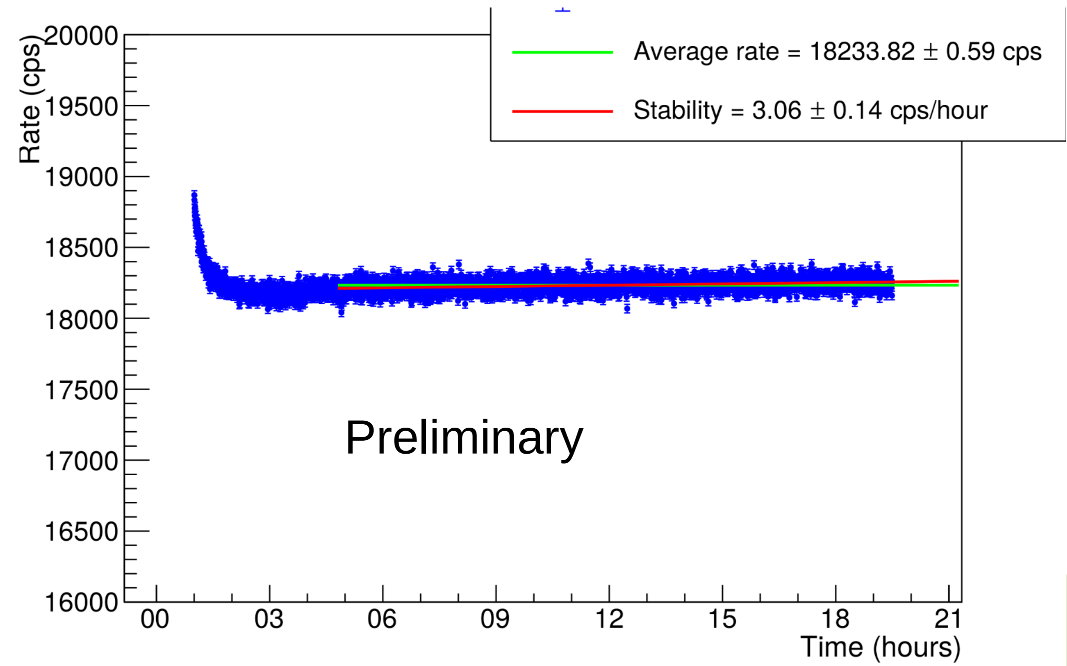
First tritium in KATRIN since 18 May

0.5% T atoms circulating in D_2 gas

- WGTS beam-tube temperature
  - Standard deviation less than 0.1% over 60 min



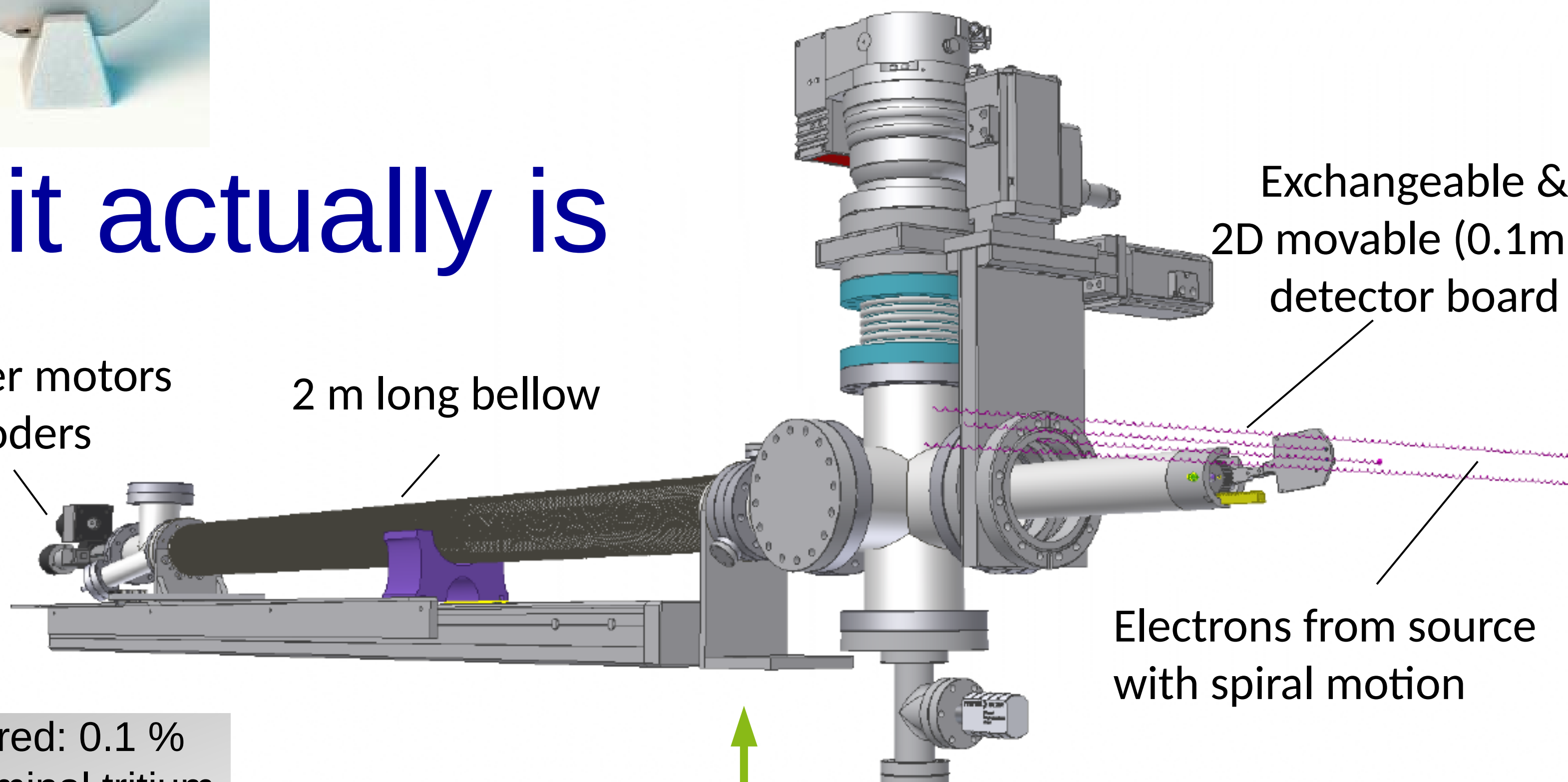
- Source and Transport System stability

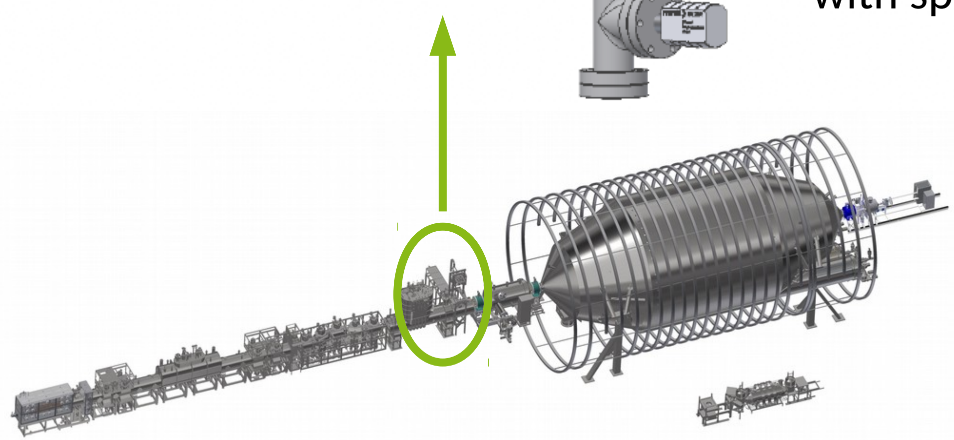


Beam monitoring: What I had thought of …

Fluorescent screens to be flipped into
> ~ GeV beams at moderate vacuum.

… what it actually is





- Rate stability required: 0.1 %
- Count rate with nominal tritium density: 1 MHz per 1 mm²
- Vacuum: 10^{-9} mbar
- Magnetic field: 1.2 Tesla
- Temp.: -190° – +150° C

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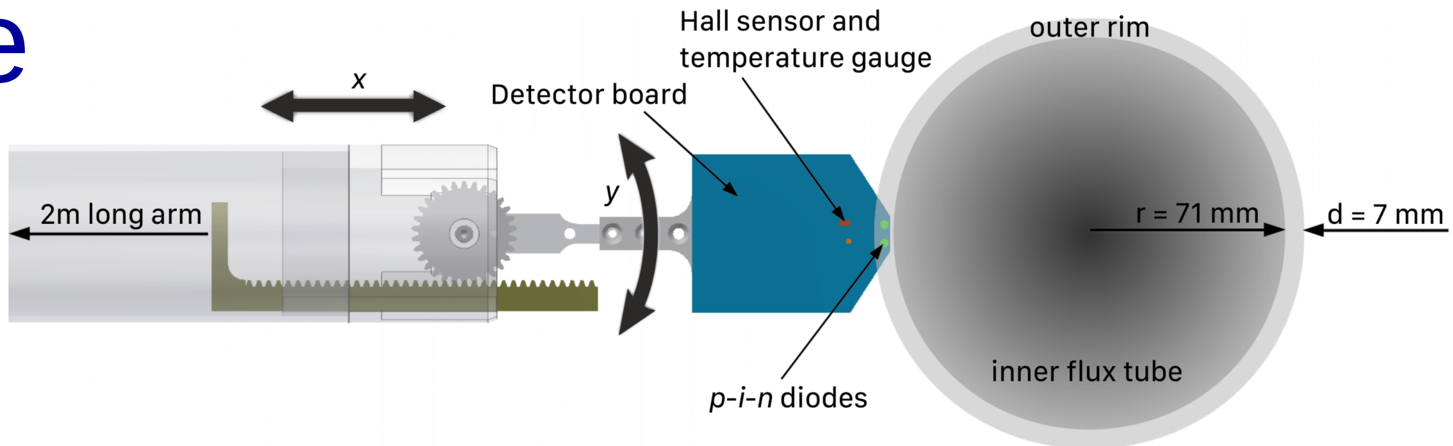
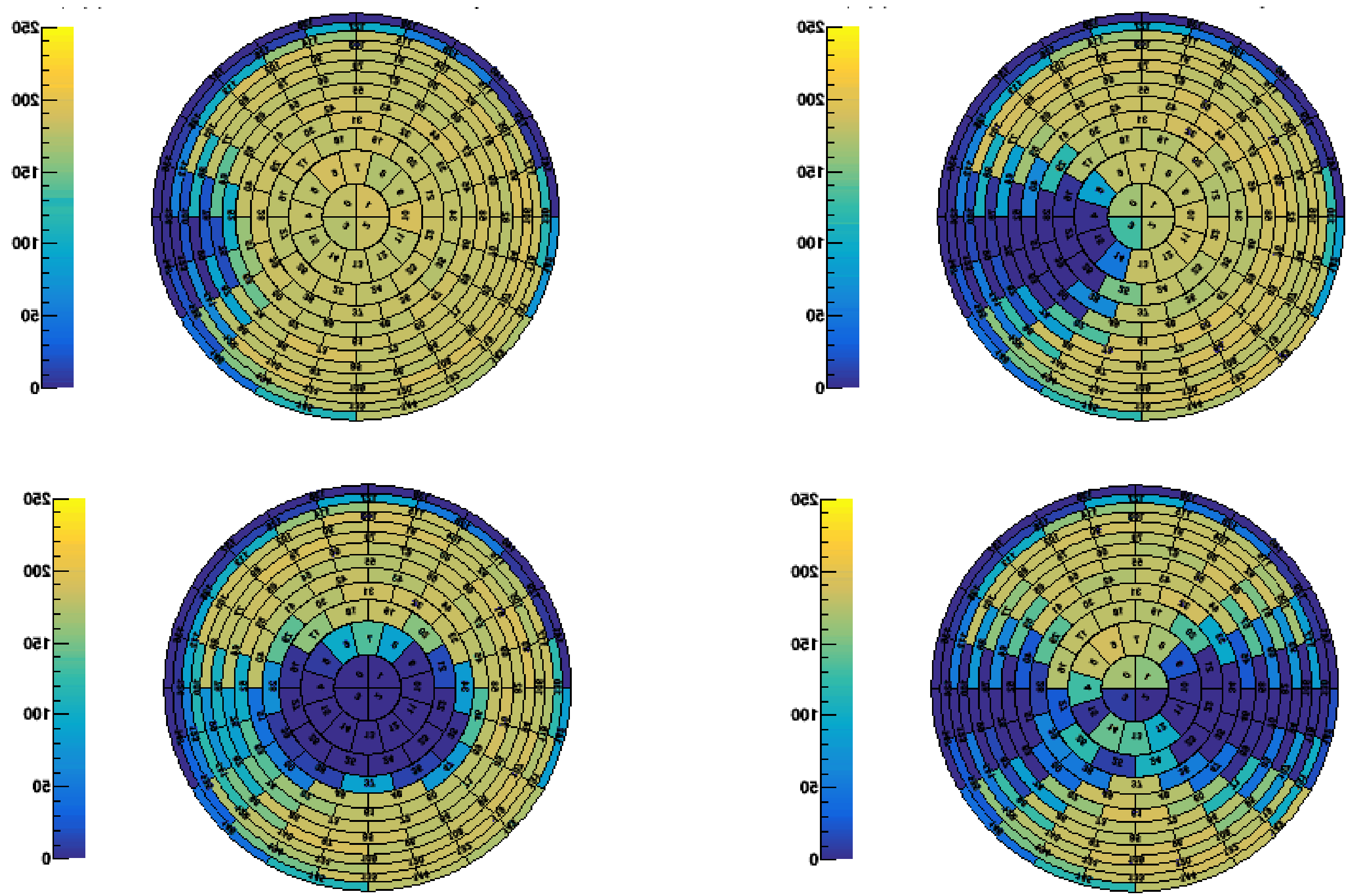
Seeing the β-electron flux





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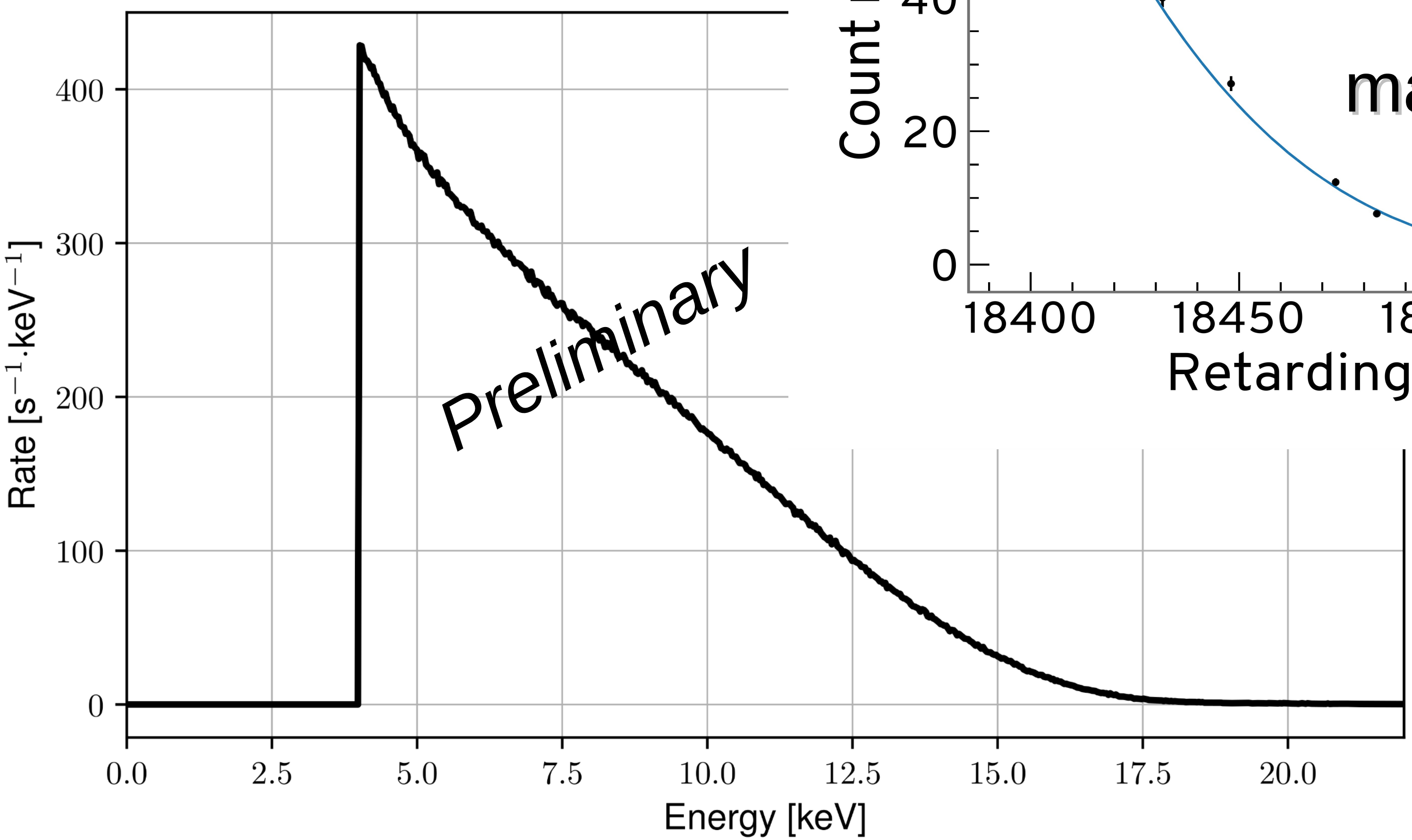
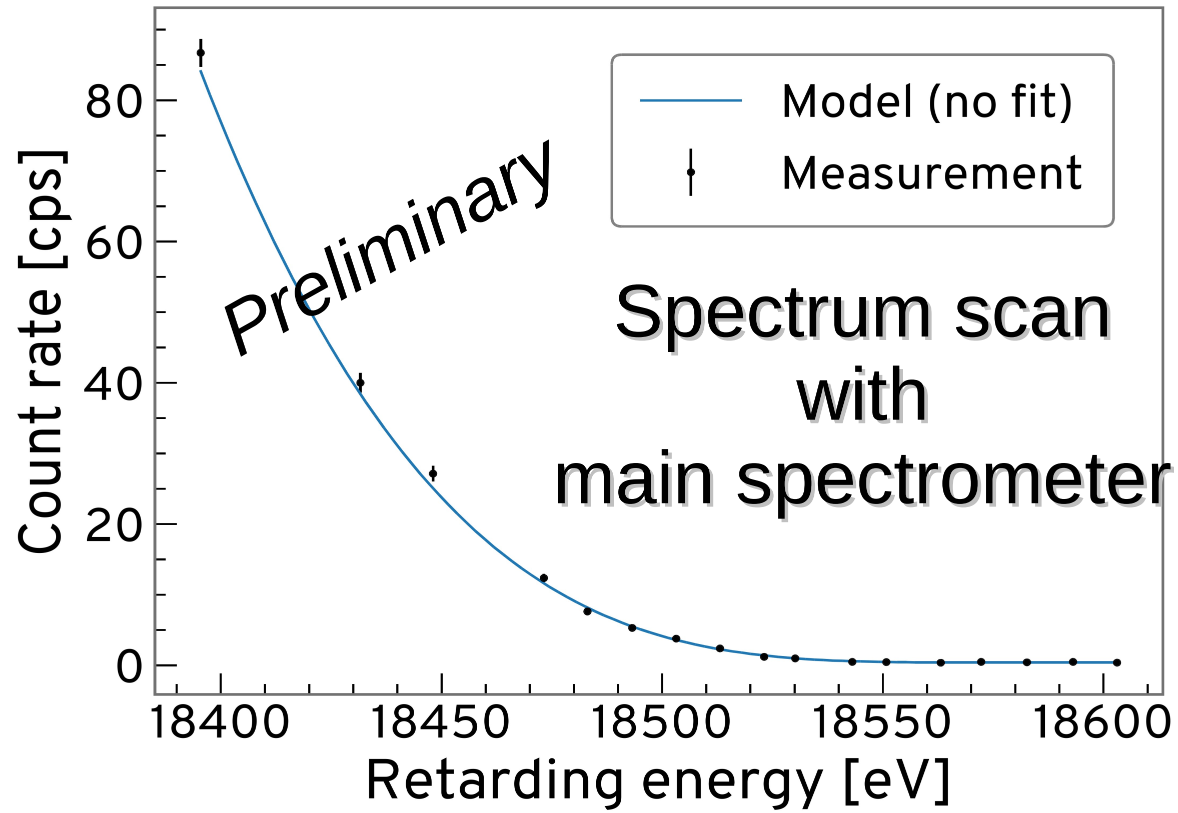
First tritium spectra

Spectrum from transport section PIN-diode



Spectrum scan with main spectrometer



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What's next

- KATRIN is now put to work
  - First full-beamline data, Oct. 2016
  - First spectral measurement of radioactive source, July 2017
  - First tritium since 5 weeks after ~ 20 year of preparation
  - Measurements this fall with D_2 gas
  - expect first neutrino mass data in early 2019
  - 5 year measurement campaign for neutrino mass
- Additional programme:
  - Sterile neutrinos at eV and keV scales
  - Right-handed weak currents
- Next steps:
  - KATRIN discovers neutrino mass → Stockholm ? , reconsider ΛCDM ?
  - … in the remote chance, it is not found … KATRIN is not immediately scalable → new ideas needed!
    - ECHo
    - Project-8

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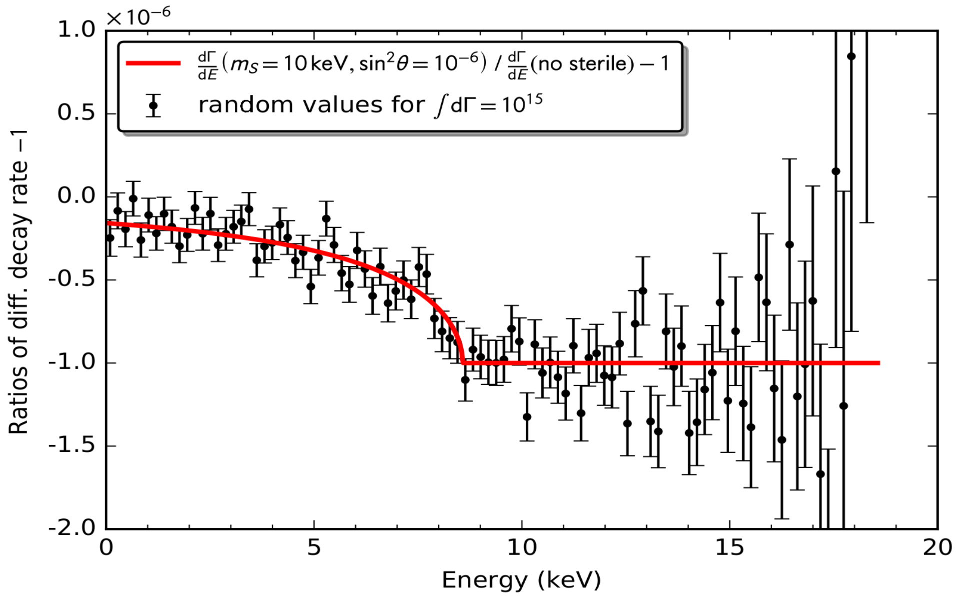
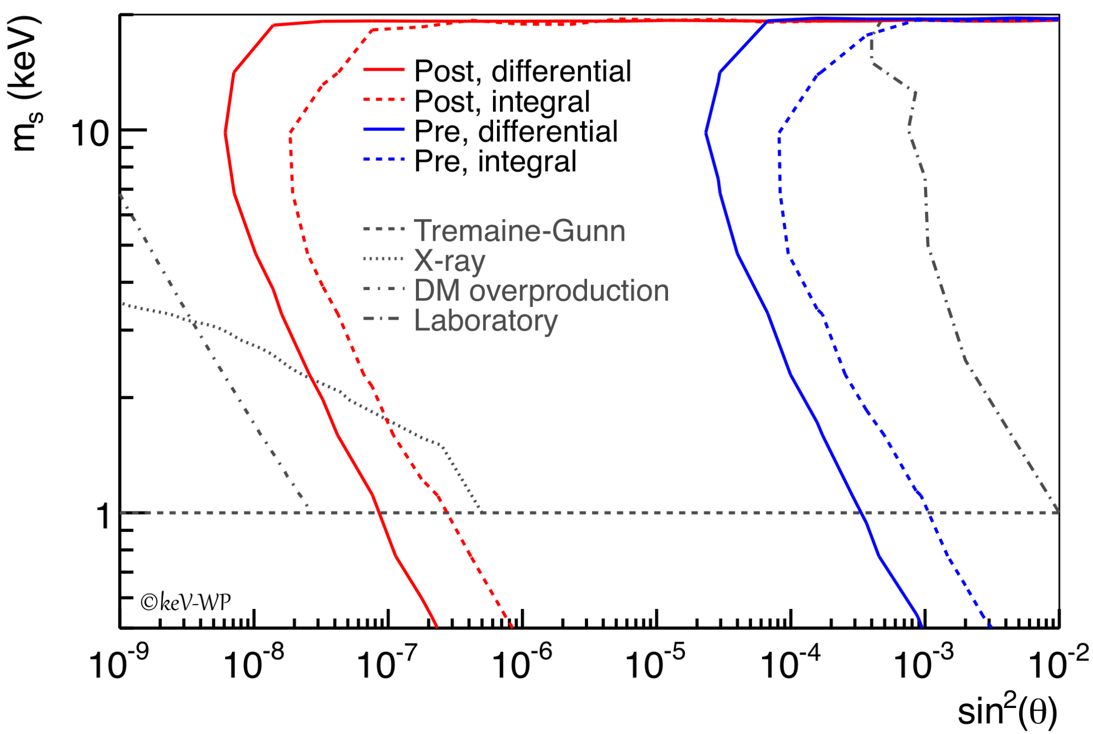
Sterile keV Neutrinos

Kinky spectrum



KATRIN projected sensitivity



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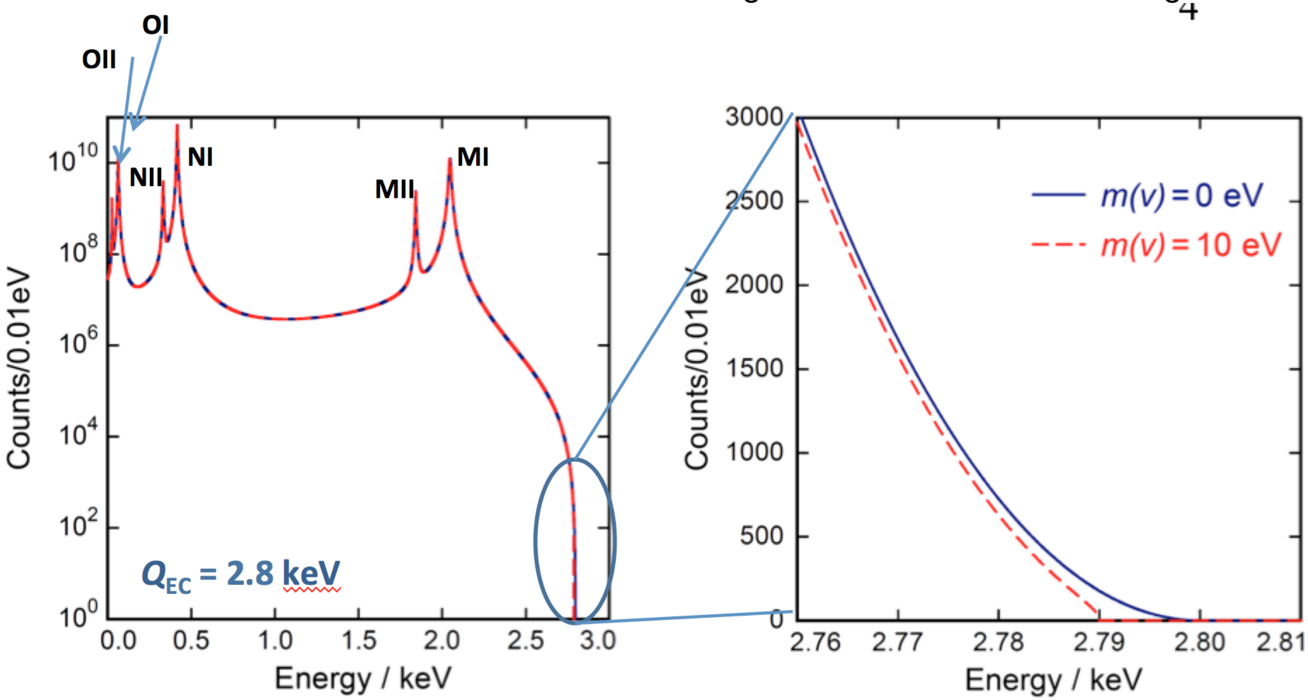
ECHo: ^{163}Ho electron capture with metallic magnetic calorimeters

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

4



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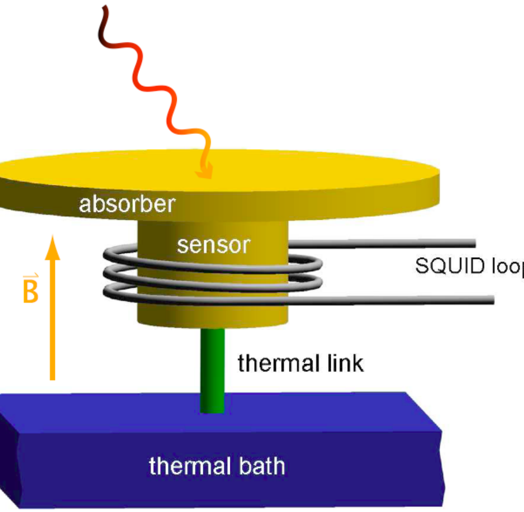
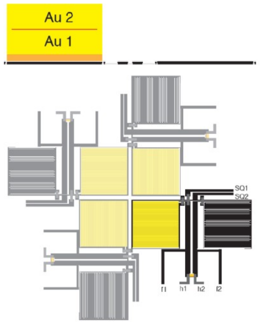
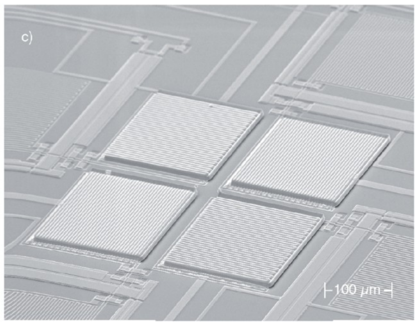






Project 8 goal: Measure coherent cyclotron radiation of tritium β electrons

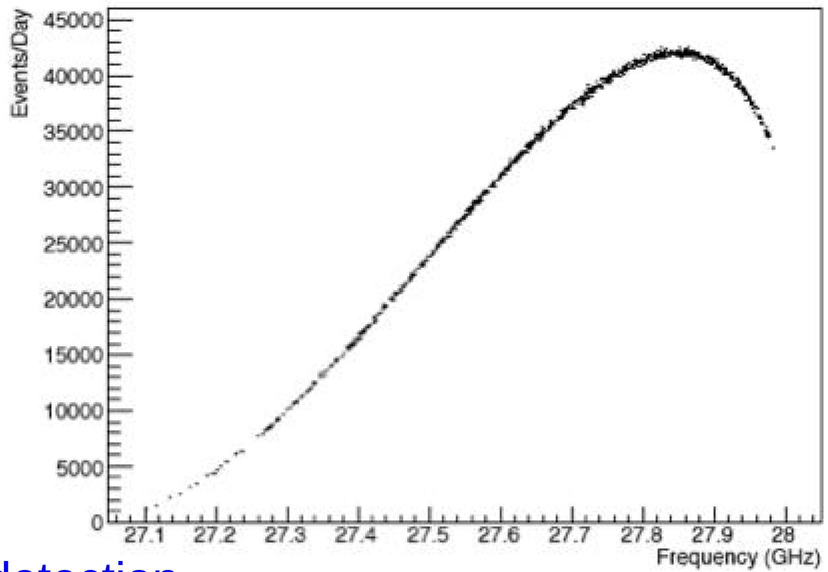
General idea:

- Source = KATRIN tritium source technology :

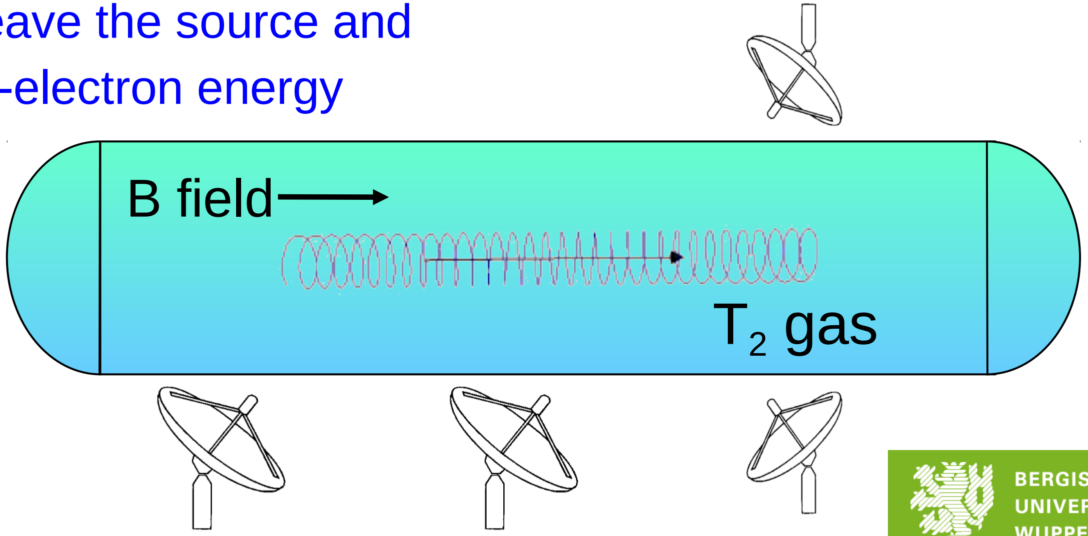
  uniform B field + low pressure T_2 gas

  β electron radiates coherent cyclotron radiation

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



- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation can leave the source and
  carries the information of the β-electron energy



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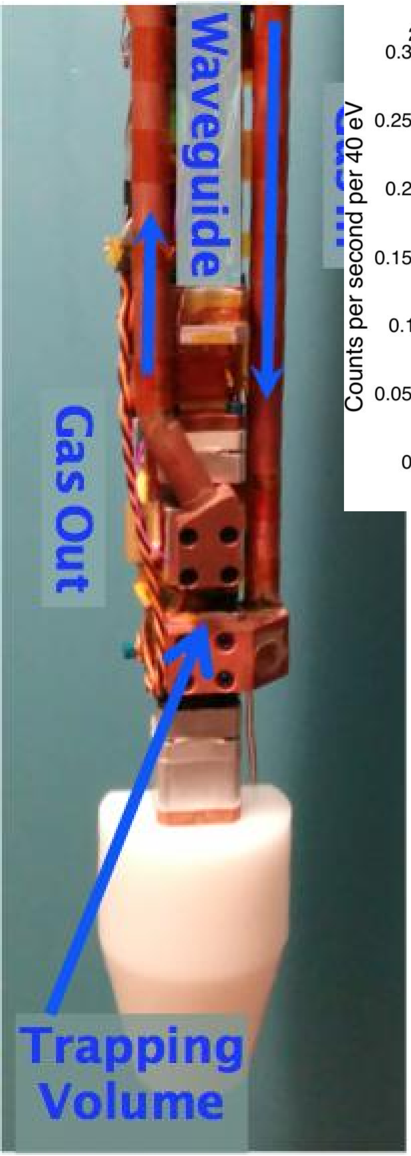
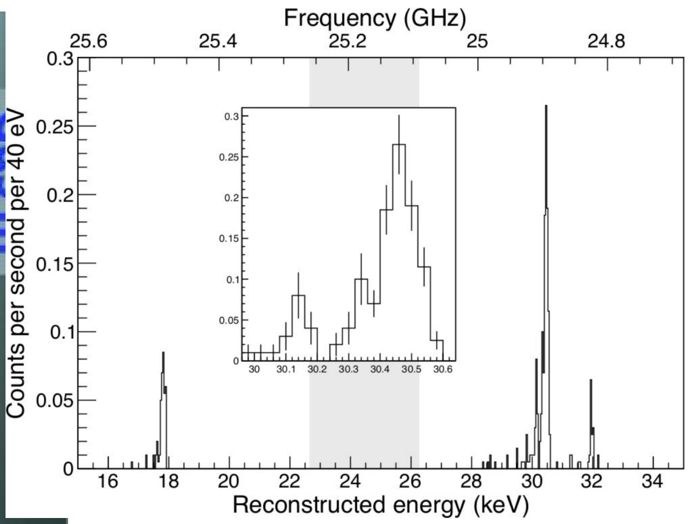
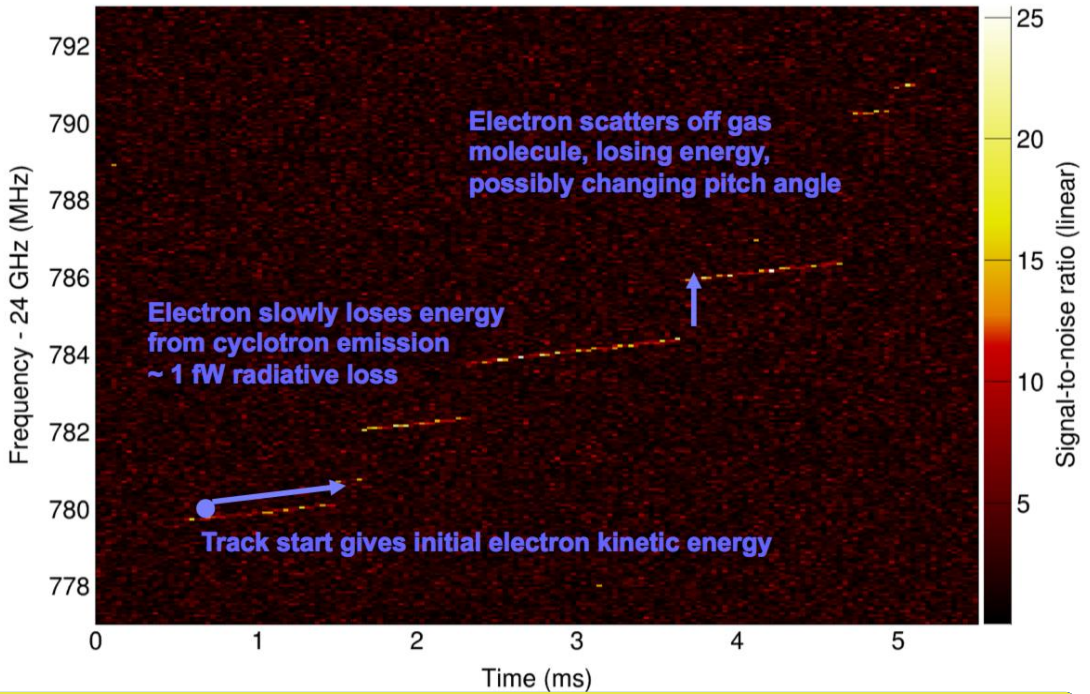
Project 8: Single electron detection from ^{83m}Kr







First detection of single electrons successfull
but still a lot of R&D necessary
- Is a large scale experiment possible ?
- What are the systematic uncertainties
& other limitations?

Thank you for your attention!

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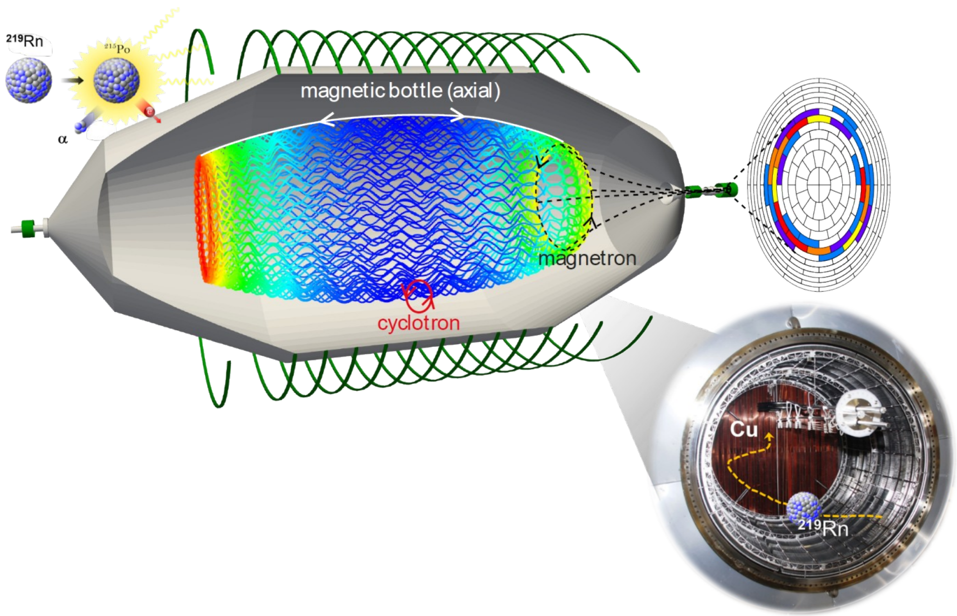
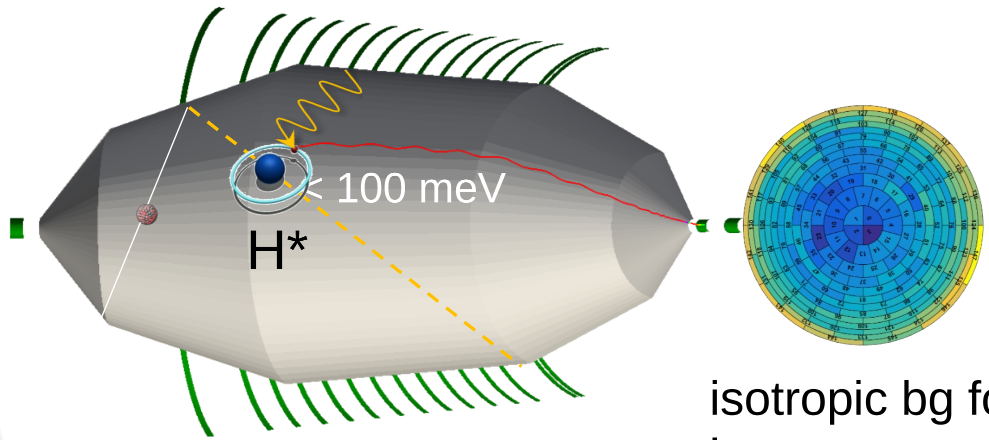
Backgrounds





isotropic bg for longer exposure

^{219}Rn atoms:

- ^{219}Rn emanates from NEG
- bg-rate: ~0.5 cps

countermeasure:

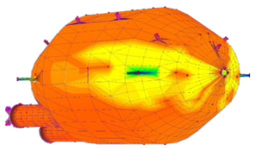
cryotraps in front of NEG

- 3 LN2-cooled Cu-baffles

H* Rydberg atoms:

- desorbed from walls due to ^{206}Pb recoil ions
- bg-rate: ~0.5 cps

countermeasures:

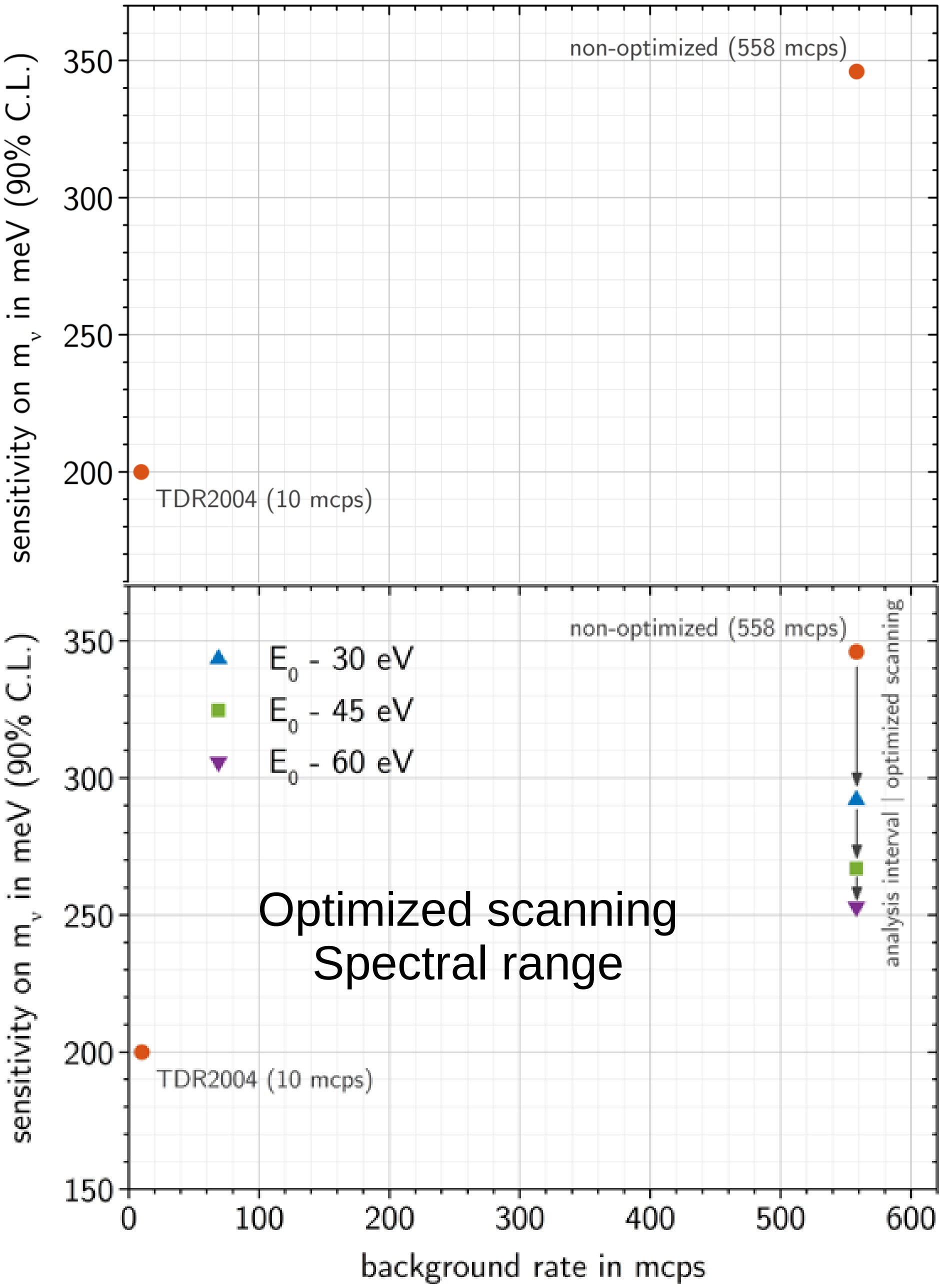


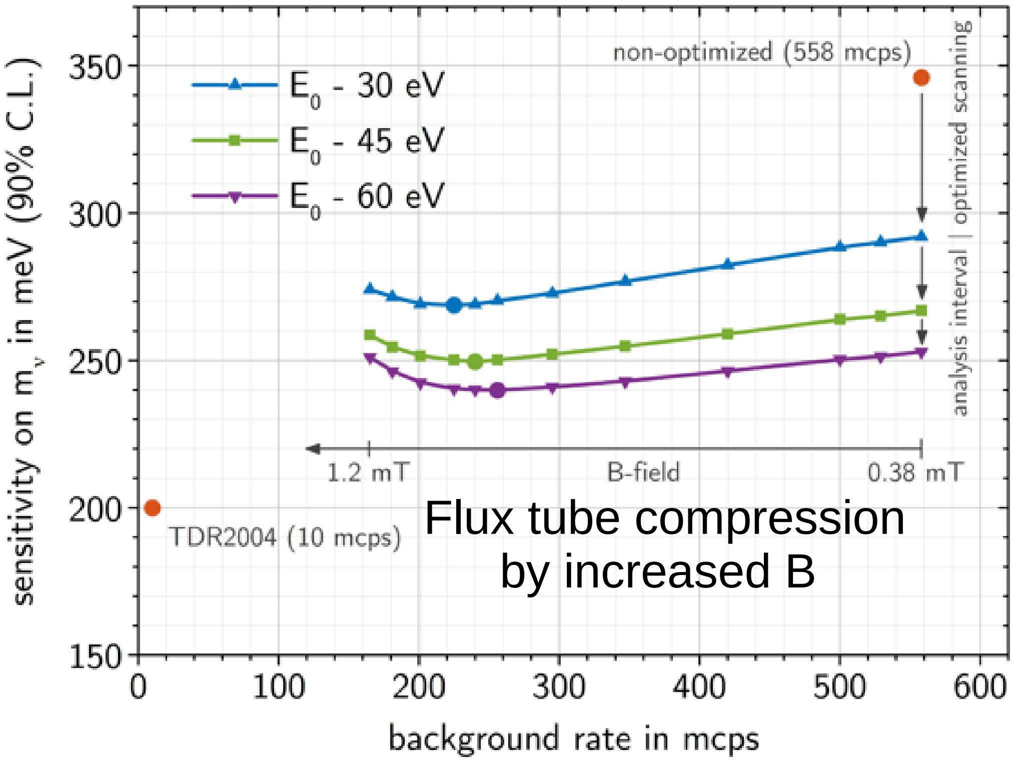
reduce H-atom surface coverage:

- extended bake-out phase
- strong UV illumination source

Can't we use Axions?

Background and sensitivity





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