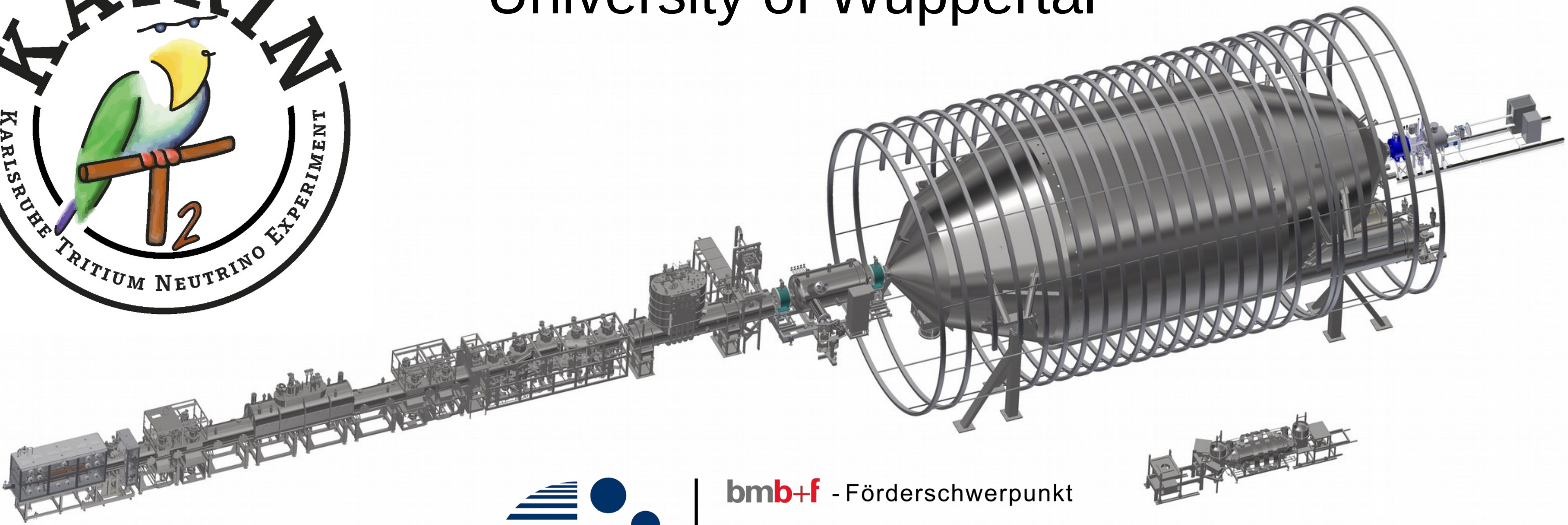
The mass of the neutrino
… KATRIN (and beyond)

Klaus Helbing
University of Wuppertal



bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

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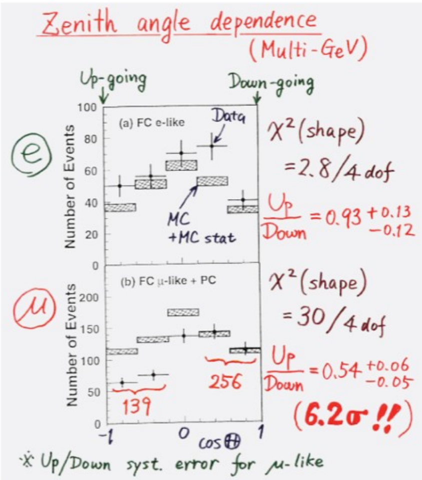
Beyond the Standard Model of particle physics

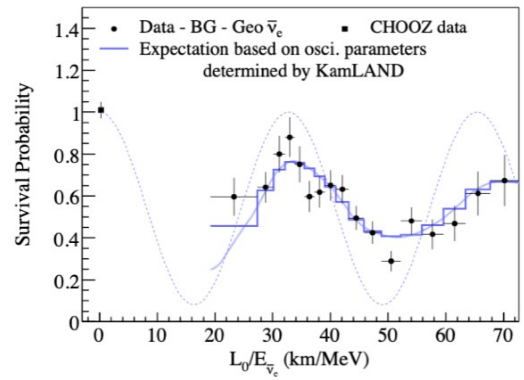
- Theoretical view
  - Symmetry → Matter and Antimatter are produced in equal amounts but the universe only consists of matter
  - The Standard Model cannot predict masses of particles
  - Extrapolation of coupling constants don't meet at $\boldsymbol{E_{GUT}}$
  - Why three generations of quarks and leptons?
- Experimental status
  - Standard Model describes all observations at man made accelerators
  - No Magnetic Monopoles, Neutralinos, HNLs, CHAMPs, … found
  - Indirect hints from Dark Matter and Dark Energy … may be “just” gravity beyond GRT on cosmological scales
  - **Neutrino is not massless!**

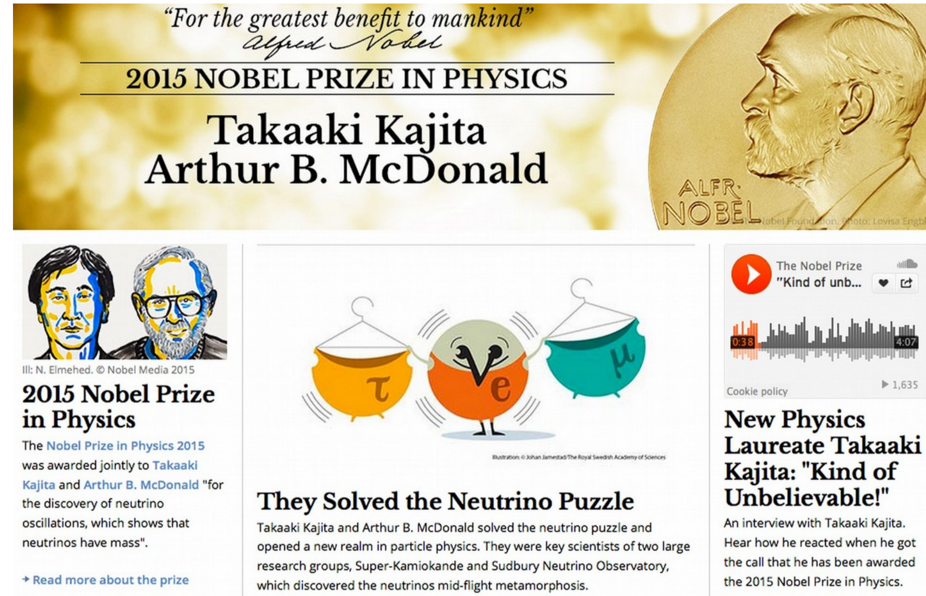
Neutrinos oscillate

SuperK 1998 atmospheric neutrinos

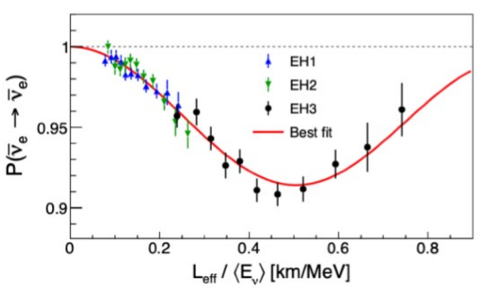


KamLAND 2006
reactor neutrinos ~ 180 km

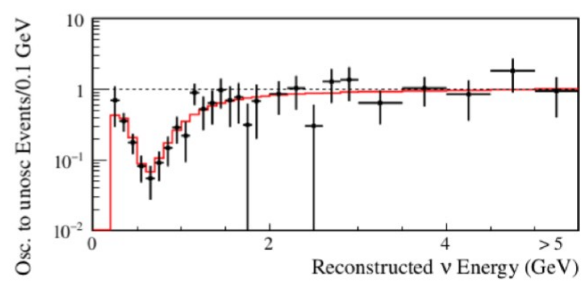




DayaBay, 2015
$\bar{\nu}_e \to \bar{\nu}_e$, $\langle L \rangle \sim 2$ km



T2K, 2015
$\nu_\mu \to \nu_\mu$, $\langle L \rangle \sim 295$ km



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

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The Standard Model flavor puzzle

Lepton mixing:

$$\theta_{12} \approx 33^\circ$$
$$\theta_{23} \approx 45^\circ$$
$$\theta_{13} \approx 9^\circ$$

$$U_{PMNS} = \frac{1}{\sqrt{3}} \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \epsilon \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}$$

Quark mixing:

$$\theta_{12} \approx 13^\circ$$
$$\theta_{23} \approx 2^\circ$$
$$\theta_{13} \approx 0.2^\circ$$

$$U_{CKM} = \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

Why care about the neutrino mass?

Rumor has it ...

…. “the classic Standard Model can easily be modified to include neutrino mass.”

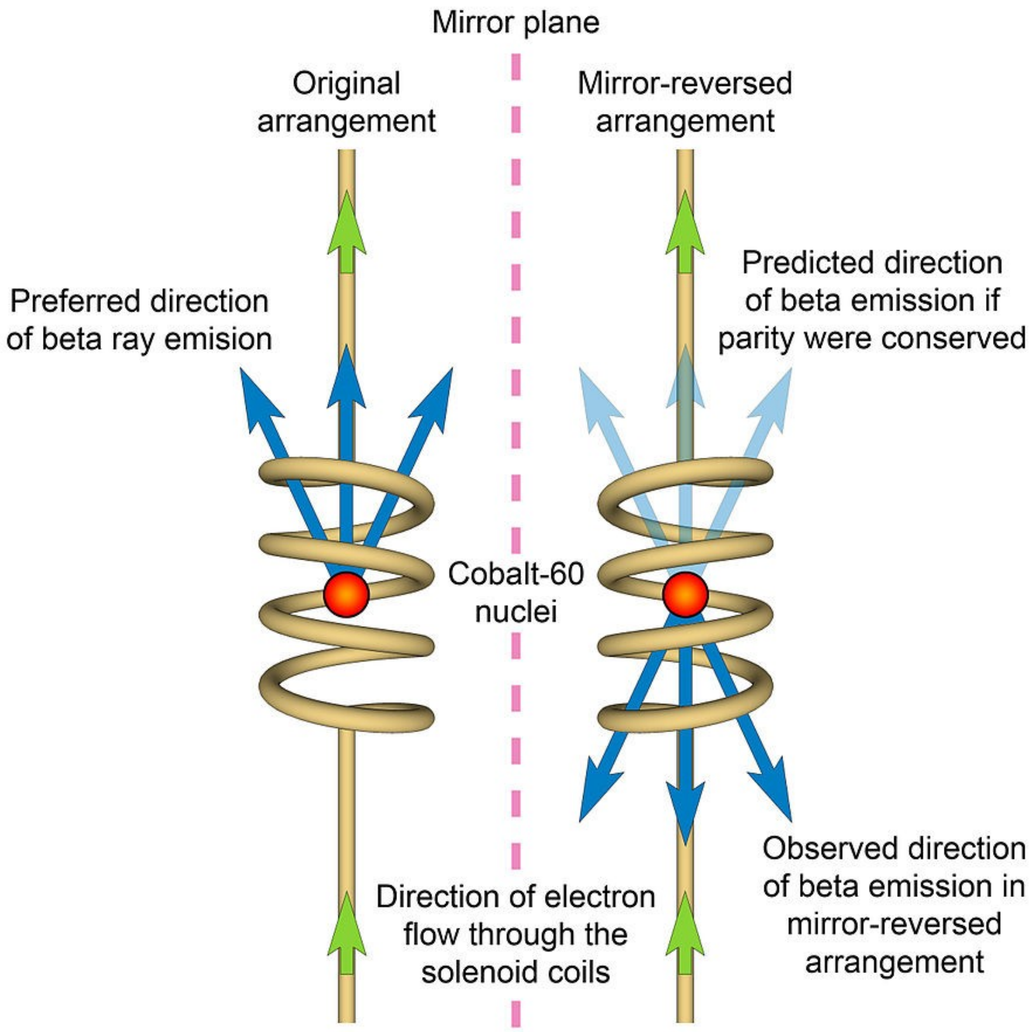
…. well, that's not quite correct!

Reminder: V-A-Theory

- Vector "minus" Axialvector theory:
  - Low energy description of weak interactions (i.e. part of SM)
  - Nuclear physics lecture → W^+, W^-, Z^0
  - Describes parity violation found in "Wu-Experiment"
  - No right-handed neutrinos
  - No left-handed anti-ν

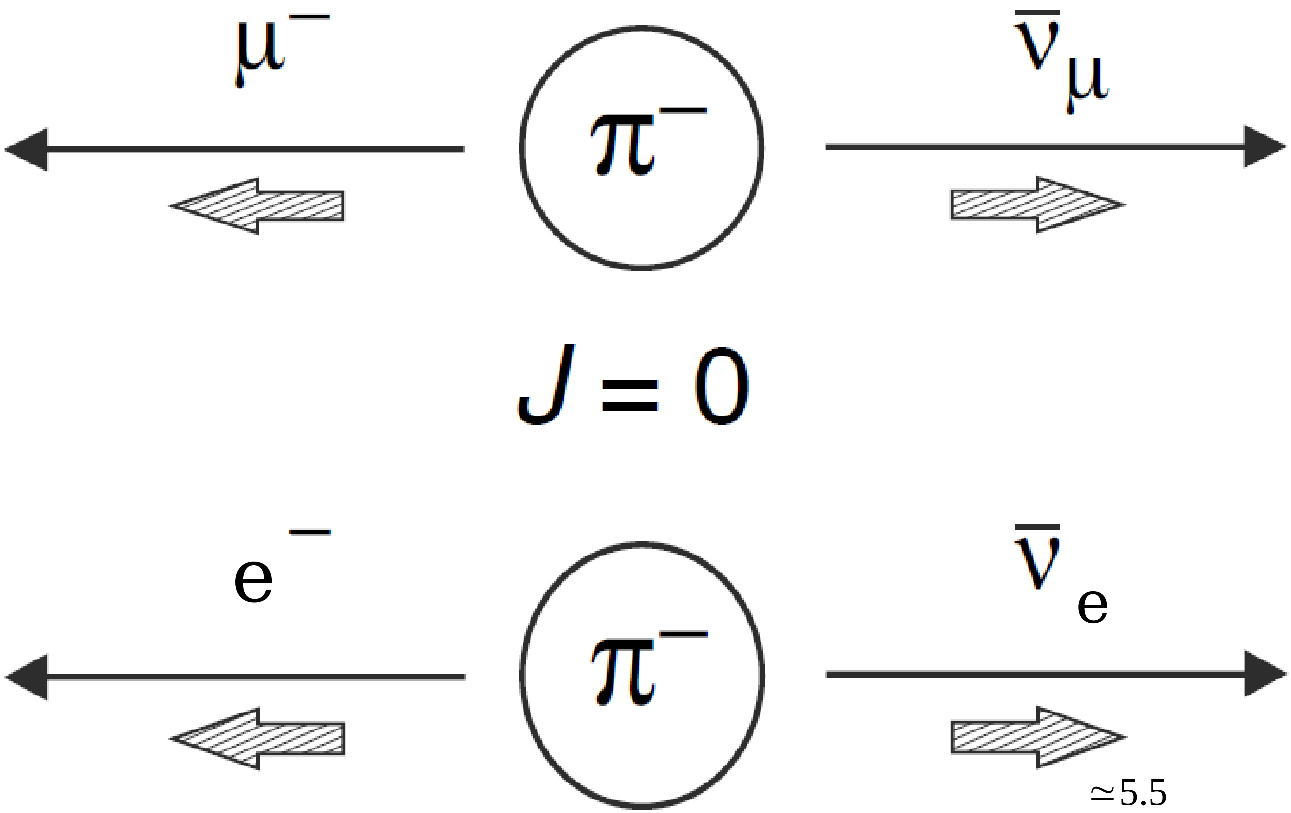
Wu-Experiment:

$$^{60}_{27}\mathrm{Co} \rightarrow \, ^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e + 2\gamma$$



Example/Reminder: Pion decay

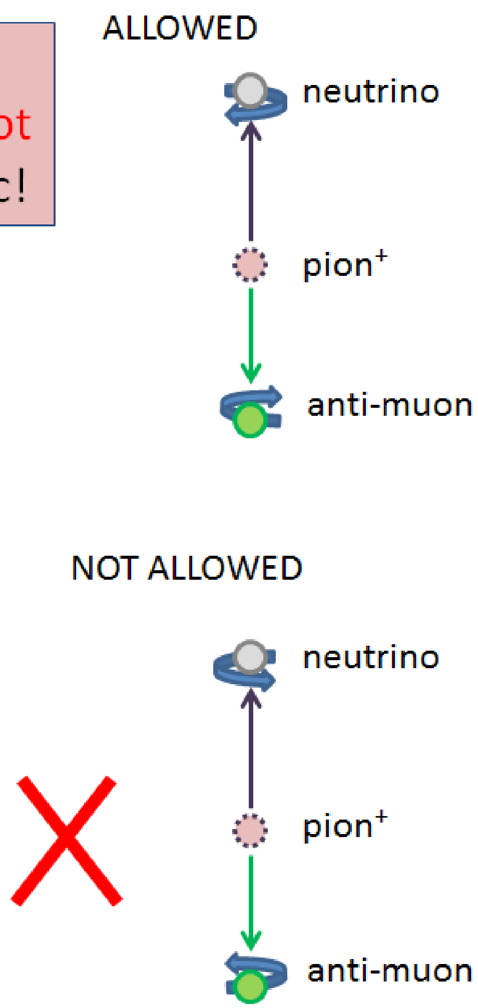
Involved anti-neutrinos purely right-handed
for massless anti-neutrinos



$$R_\pi \equiv \frac{\Gamma(\pi^+ \rightarrow e^+ + \nu_e)}{\Gamma(\pi^+ \rightarrow \mu^+ + \nu_\mu)} = \underbrace{\left(\frac{m_e}{m_\mu}\right)^2}_{\text{Probablility for left handed anti-leptons}} \underbrace{\overbrace{\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2}^{\simeq 5.5}}_{\text{Phase space factor}} = 1.28 \cdot 10^{-4}$$

V-A theory and neutrino helicity

In Fact The Laws Of Nature Are Not Parity-Symmetric!



- Standard model:
  - Neutrinos left-handed
  - Anti-Neutrinos right-handed
  - Neutrinos need to be **massless** for this to be always true
  - Otherwise reference frame exists with different helicity

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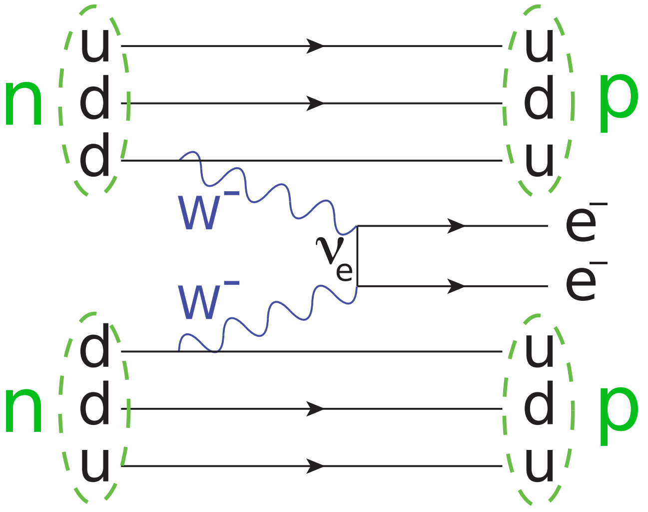
Majorana masses and lepton number violation

- Lepton number conservation is symmetry in SM
- Massive Majorana neutrino
  → neutrinoless double $\boldsymbol{\beta}$-decay

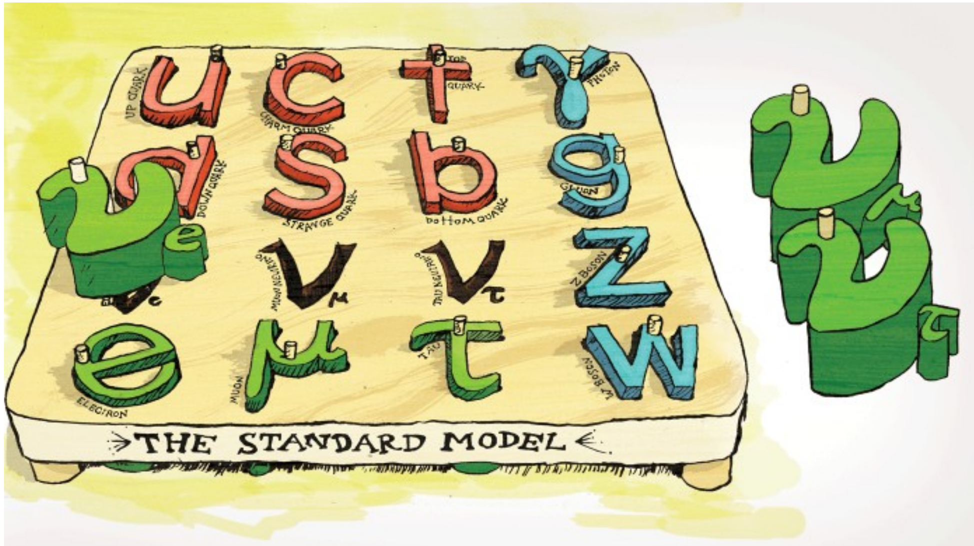


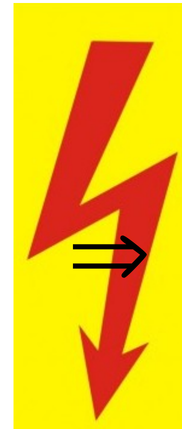
- Large neutrino mixing
  → significant decay rates plausible

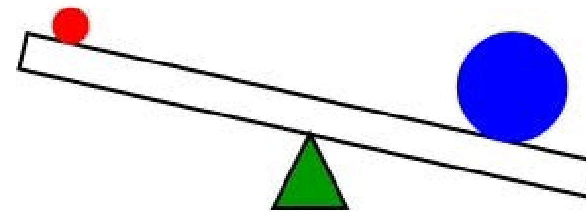
  $\tau \rightarrow \mu + \gamma \ , \mu \rightarrow e + \gamma$

  …. but has not been observed!

Neutrino versus Standard Model



H  $\Rightarrow$ m_ν



- 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 than three neutrino flavors (sterile)?
- Why did matter win over anti-matter? **Current best fit for Dirac CPV phase: ~ 270° (IO), ~ 195° (NO)**

- 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

Seesaw mechanism – a primer

- SM may be effective low energy theory
- Seesaw mechanism: generic model for eV neutrino masses
- Assuming additional right-handed neutrinos and existence of a very large mass scale:
  - grand unification
  - Planck scale

- matrix arising from adding neutrino mass;
  M_D: Dirac mass, M_N: Neutrino mass before symmetry breaking

$$A = \begin{pmatrix} 0 & M_D \\ M_D & M_N \end{pmatrix}$$

- Eigenvalues:

$$\lambda_\pm = \frac{M_N \pm \sqrt{M_N^2 + 4 M_D^2}}{2}$$

$$\text{if } M_N \gg M_D \ : \ |\lambda_+| \simeq M_N \ ; \ |\lambda_-| \simeq \frac{M_D^2}{M_N}$$

Lower mass shrinks with unification scale

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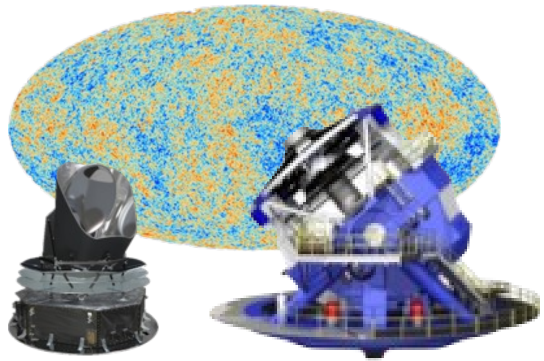
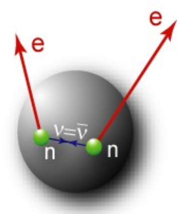
Nobel prices on Neutrinos

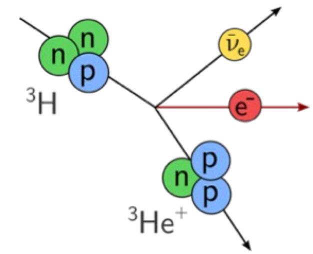
- 1979: Glashow, Salam, Weinberg
  → prediction of neutral currents
- 1988: Lederman, Schwartz, Steinberger
  → 2 neutrinos, detection of ν_μ
- 1995: Reines → detection of the neutrino
- 2002: Davis, Koshiba
  → astrophysical (solar) neutrinos
- 2015: Kajita, McDonald → $m_\nu > 0$

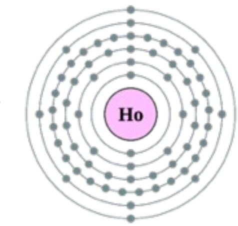
The absolute neutrino mass

Truly !





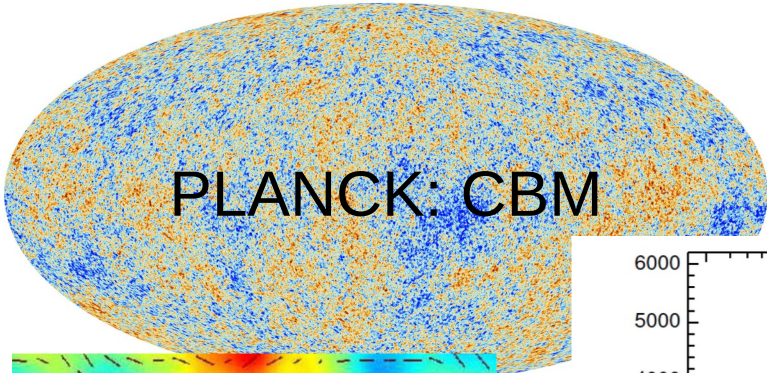


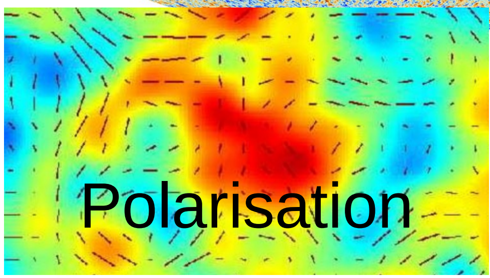


	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m^2_{\beta\beta} = \left\|\sum_i U^2_{ei}\, m_i\right\|^2$	$m^2_\beta = \sum_i \|U_{ei}\|^2\, m^2_i$
Present upper limit	0.12 – 1 eV	0.2 – 0.4 eV	2 eV
Potential	15 – 50 meV	15 – 50 meV	200 meV
Model dependence	Multi-parameter cosmological model	- Majorana ν: LNV - BSM contributions other than m(ν)? - nucl. matrix elements - Incl. interferences	**Direct,** only kinematics; no cancellations in incoherent sum

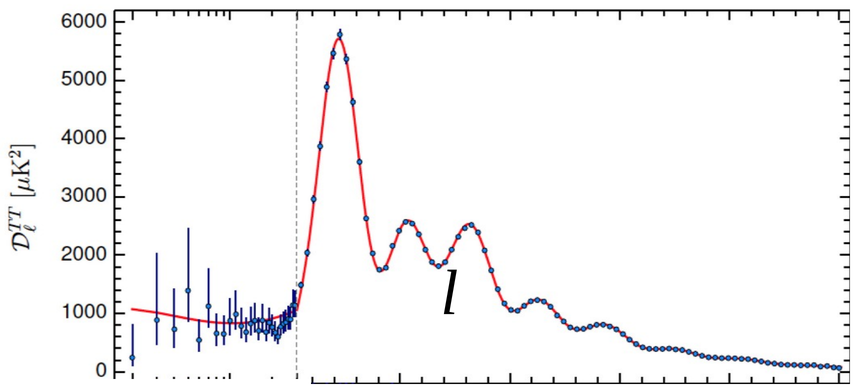
Neutrino mass from cosmology

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

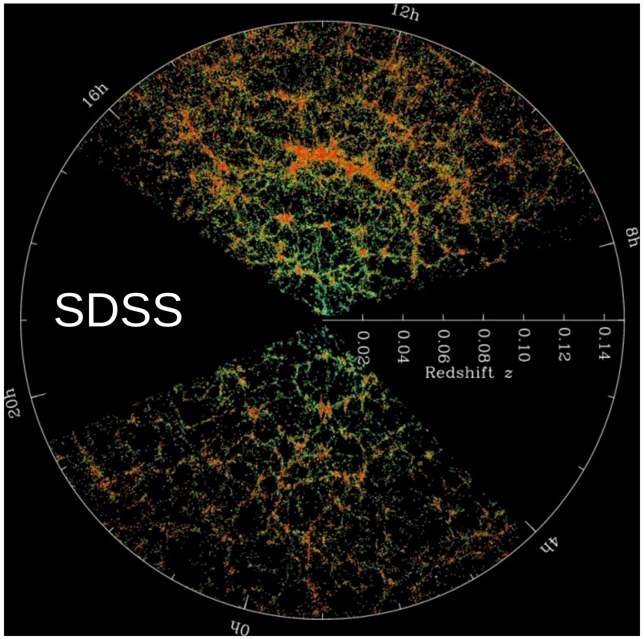


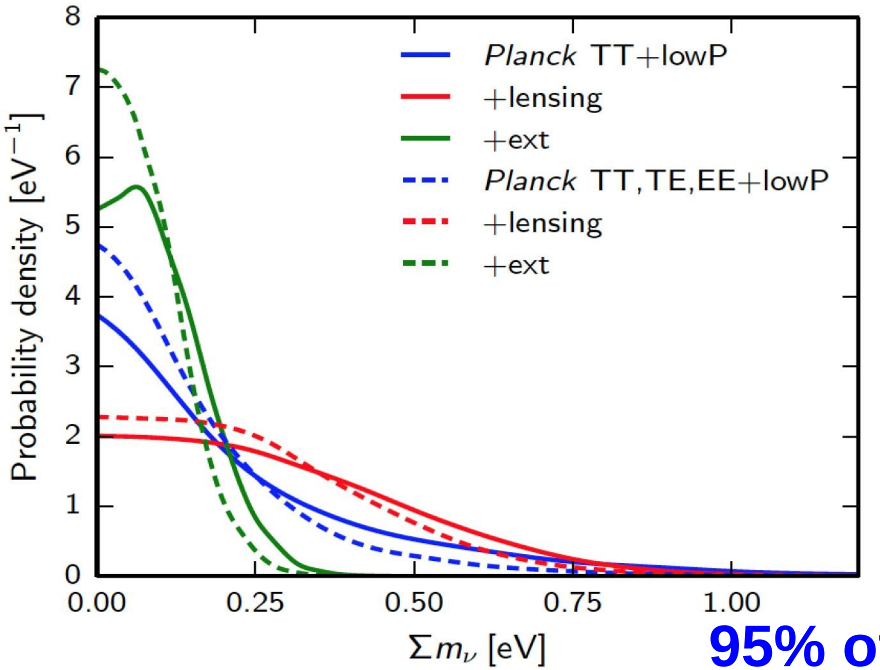


Planck Collaboration:
P. A. R. Ade et al., arXiv:1502.01589

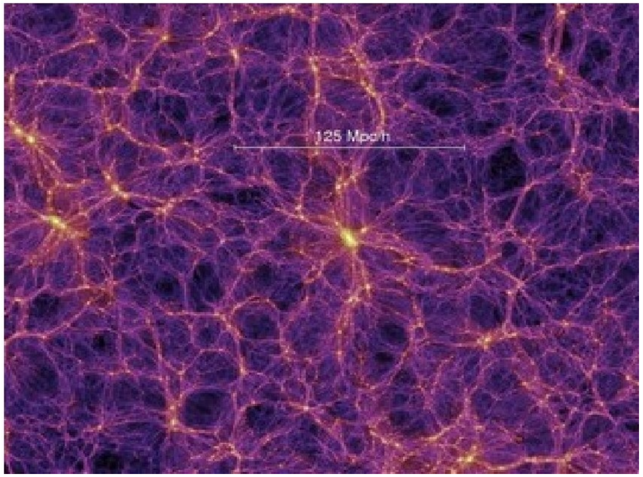


Large Scale Structure





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: $\underbrace{\Gamma_{i\to f}}_{\text{decay rate}} = \frac{2\pi}{\hbar} \underbrace{|<f|H|i>|^2}_{\text{interaction matrix}} \cdot \underbrace{\rho(E_f)}_{\text{density of final states}}$

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

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

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

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

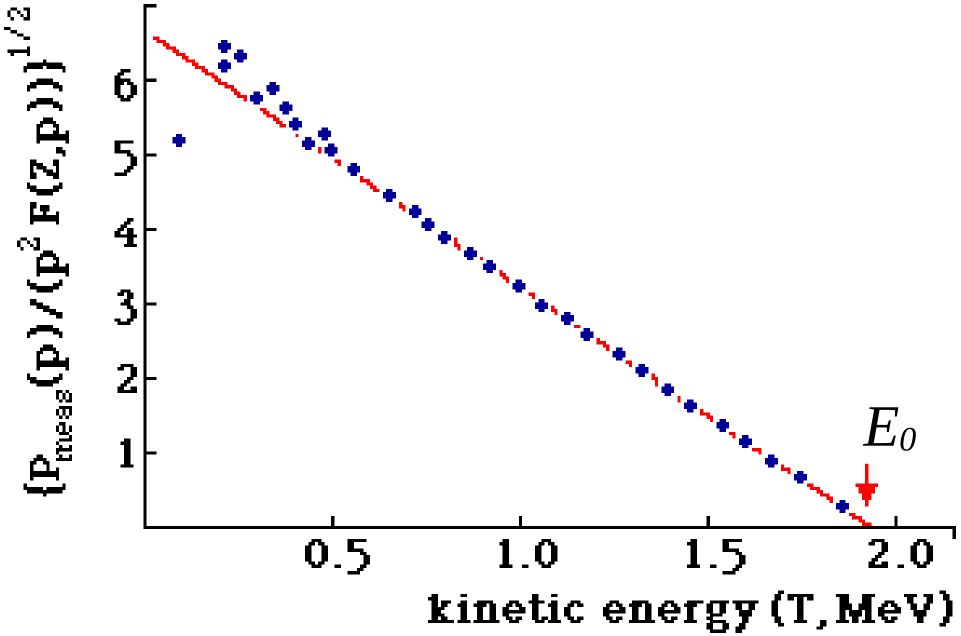
for $\boldsymbol{m_\nu = 0}$ and $Q \simeq E_0$

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

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

$\sqrt{\frac{dN}{dE} \cdot \frac{1}{p_e^2}}$ versus E : Kurie plot

$\Rightarrow$ $Q =$ abscissa



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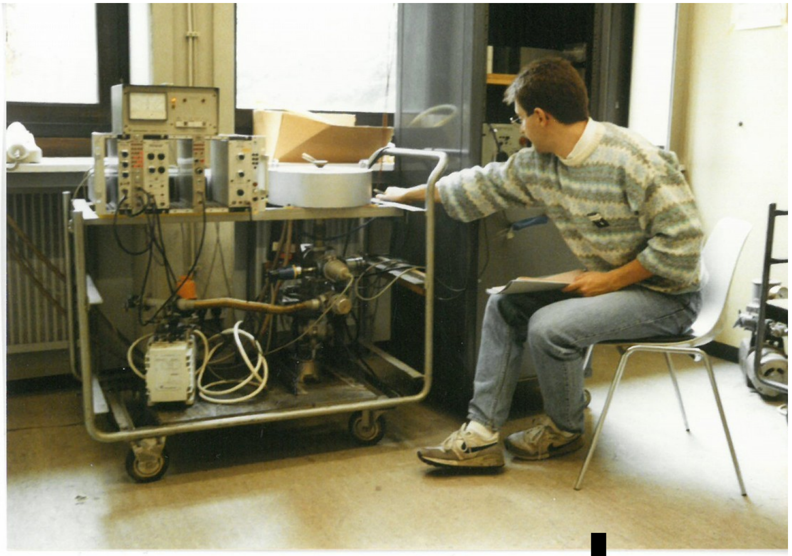
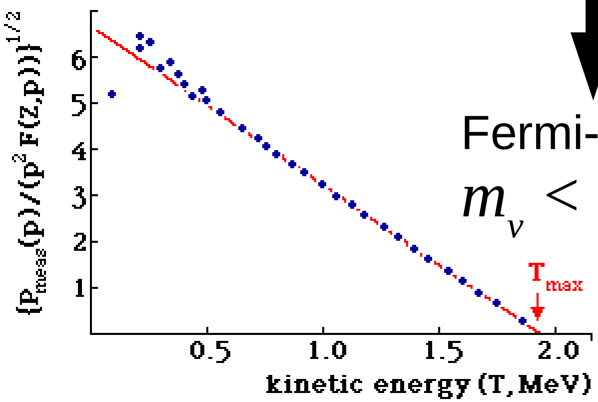
Beta-spectra, lab class – How I got attracted ☺ –





Fermi-Kurie-Plot

$m_\nu < 100$ keV

Hans-Christian Schultz-Coulon
Heidelberg University, LHC, Atlas

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Fermi theory of beta decay

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

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

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

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

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

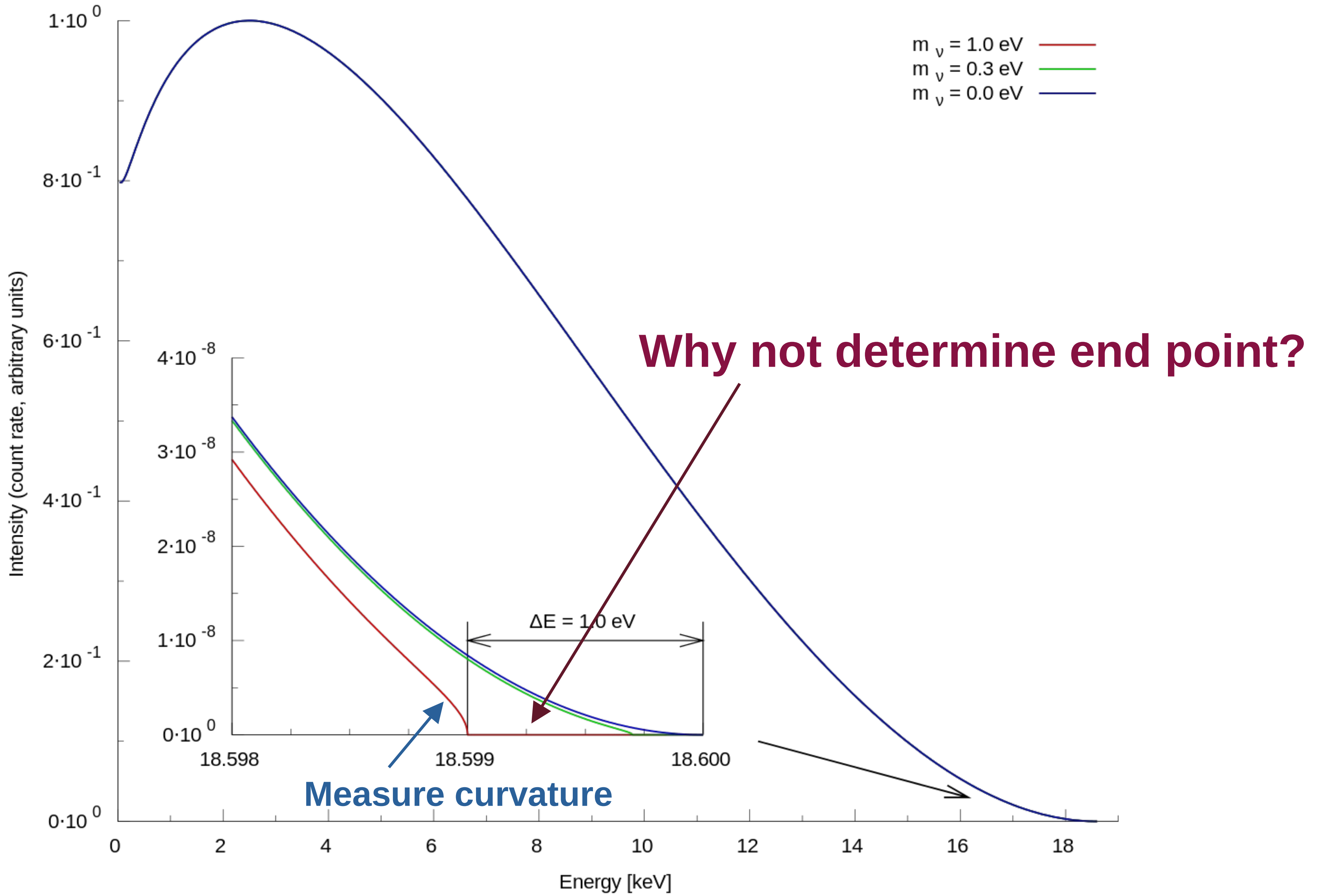
for $\boldsymbol{m_\nu \neq 0}$ and $E_{recoil} \neq 0$

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

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

Beta-mass:
Incoherent sum of mass eigenstates!

Measurement approach



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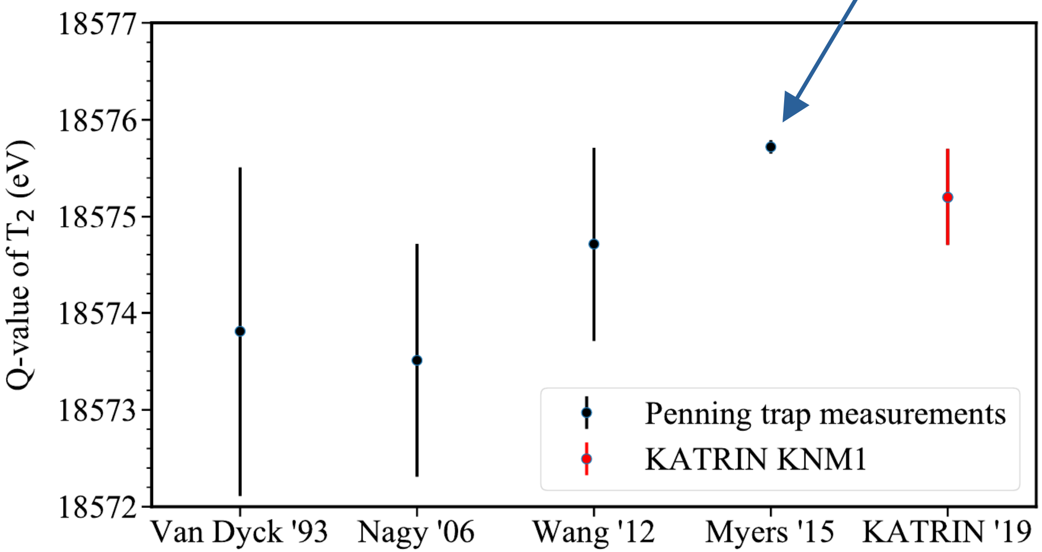
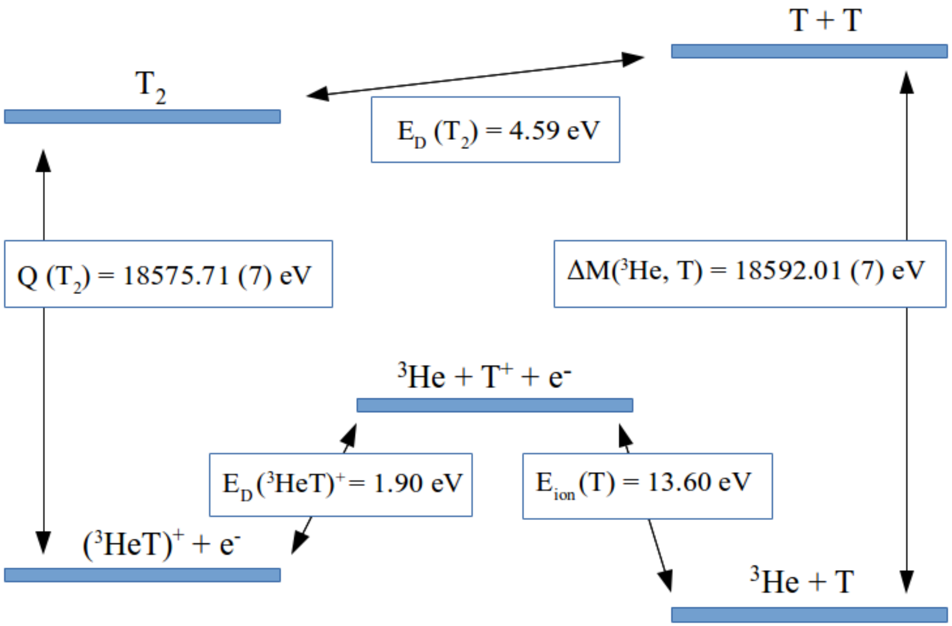
Why not just determine mass through end point E_0?

$$Q(\mathrm{T}_2) = E_0 - E_{\mathrm{rec}} - \boldsymbol{m_\nu} \quad ; \quad E_{\mathrm{rec}} = \frac{E_0^2 + 2E_0 m_e}{m_{\mathrm{HeT+}}}$$

Q values only now available with sufficient precision below 1eV

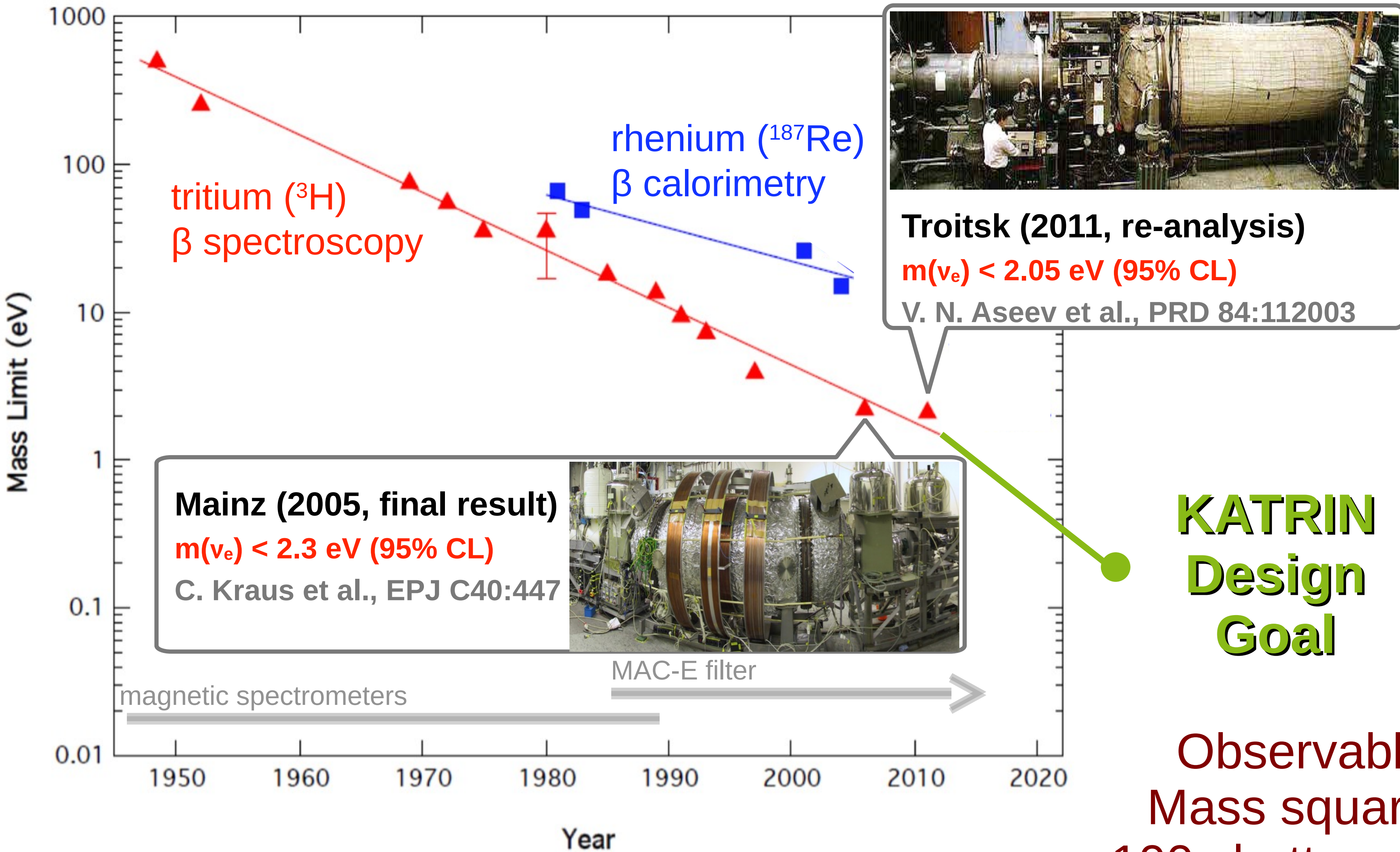




In reality even more details:

- “grounding” of beta source
- Work function
- Plasma ….

Moore's law for direct neutrino mass



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

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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

KATRIN collaboration

KArlsruhe TRitium Neutrino experiment

- **direct ν-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 – Karlsruhe Tritium Neutrino Experiment

University of Washington

Carnegie Mellon University – Pittsburgh Pennsylvania 1900

Case Western Reserve University – Est. 1826

CEA – De la recherche à l'industrie

MIT

Berkeley Lab

KIT – Karlsruher Institut für Technologie

TUM

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

universität bonn

Hochschule Fulda – University of Applied Sciences

The University of North Carolina at Chapel Hill

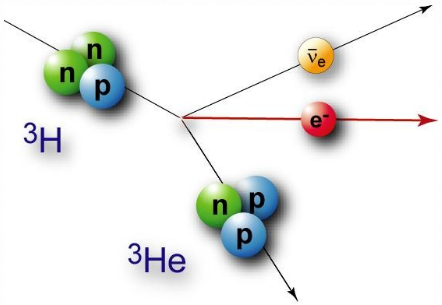
Westfälische Wilhelms-Universität Münster

Bergische Universität Wuppertal

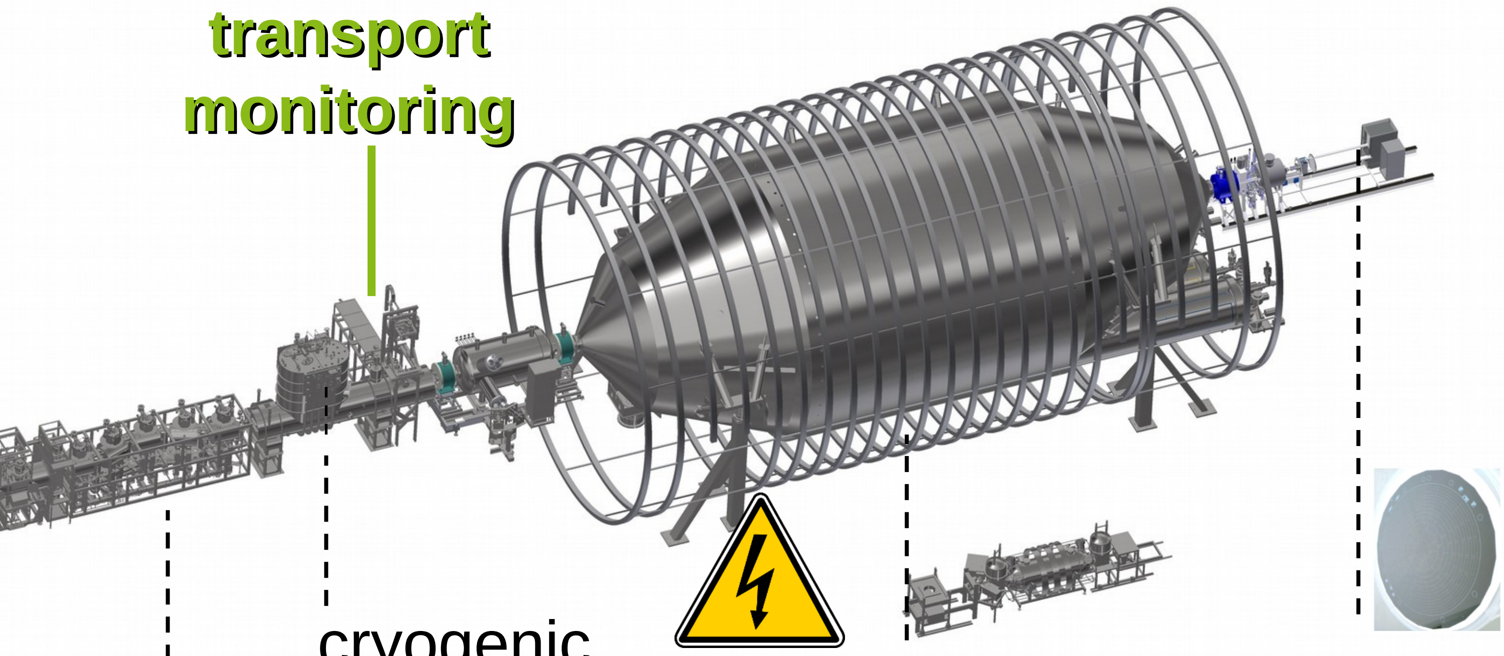
JG|U – Johannes Gutenberg Universität Mainz

Universidad Complutense Madrid

KATRIN beam line: 70 m

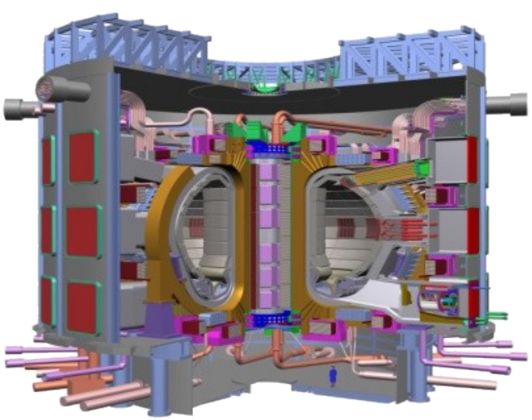


Source & transport monitoring

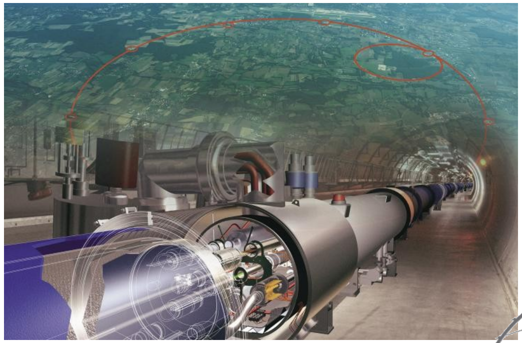


Recycling the tritium
Removing ions

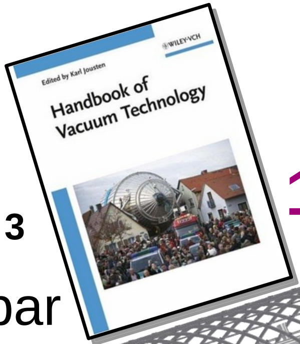
KATRIN vacuum



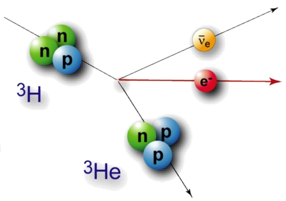
ITER
(2035)

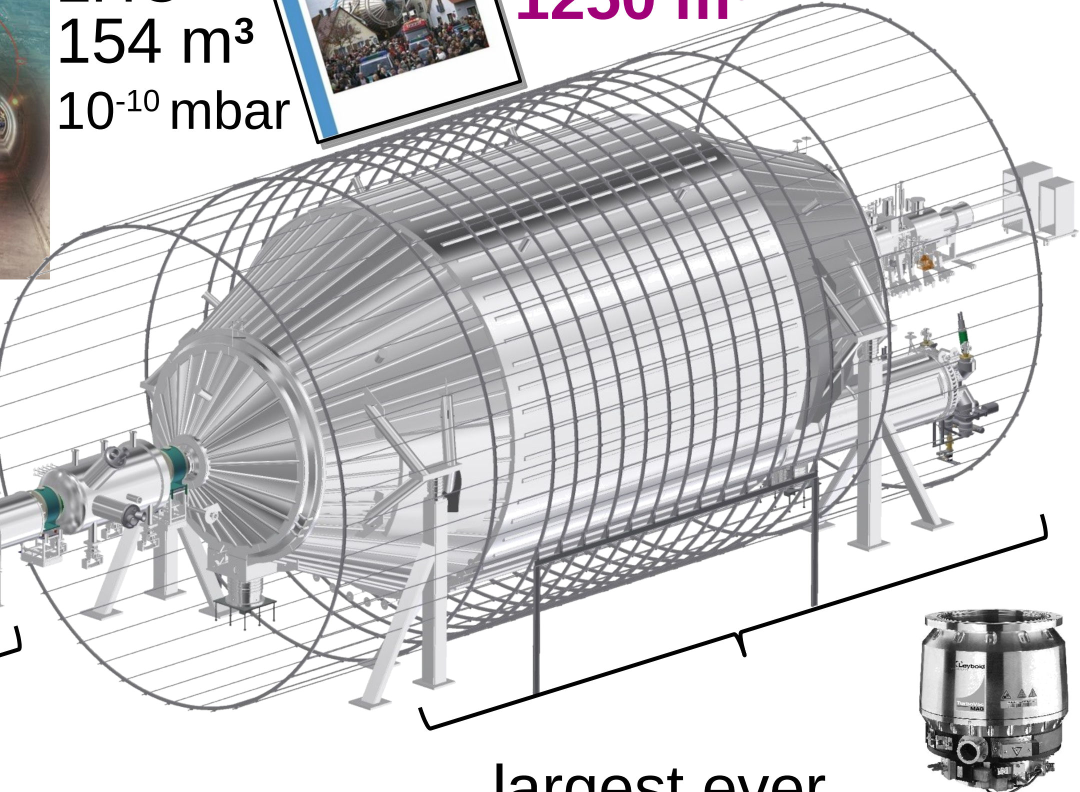


LHC
154 m³
10^{-10} mbar



1250 m³

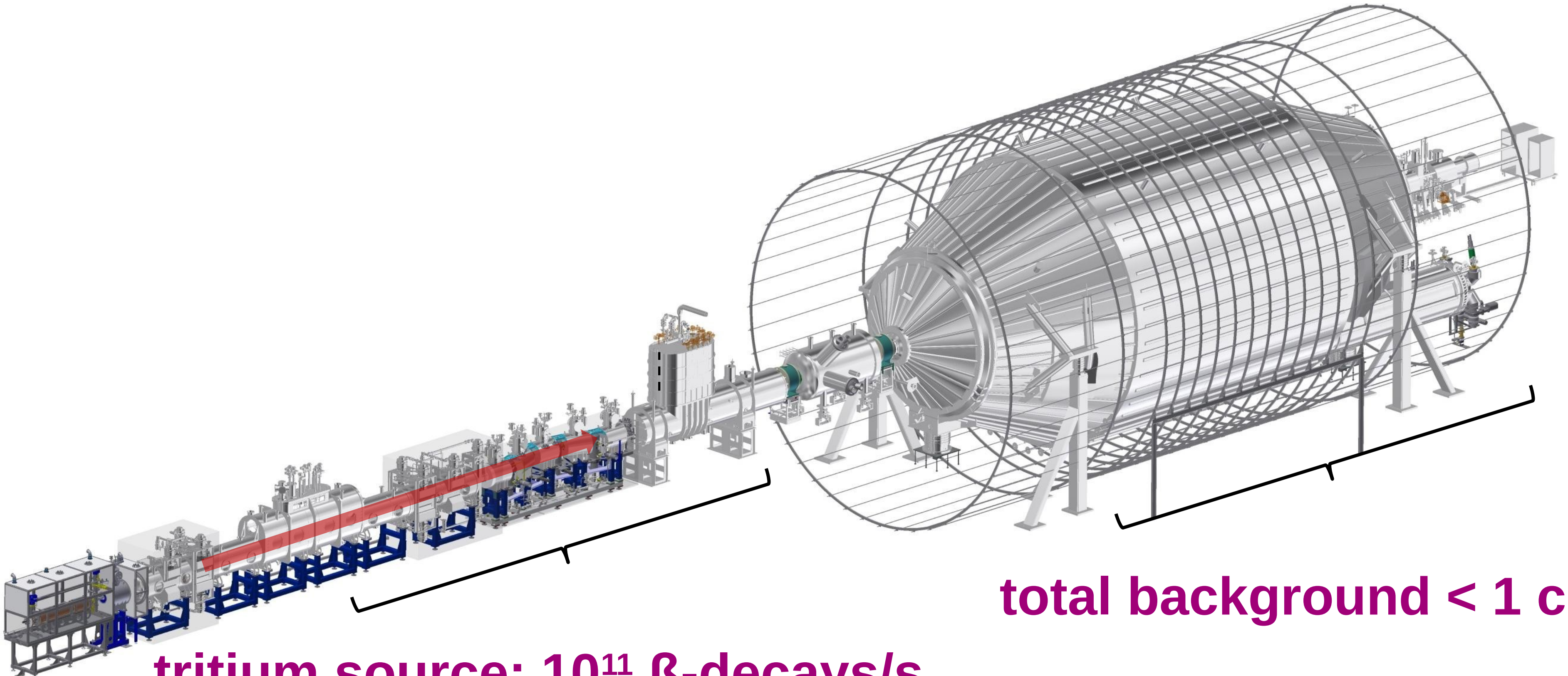




largest ever tritium
throughput ~ **10 kg/a** (2018)

largest ever
UHV recipient:
p ~ 10^{-11} mbar
(2013)

Background reduction



total background < 1 cps

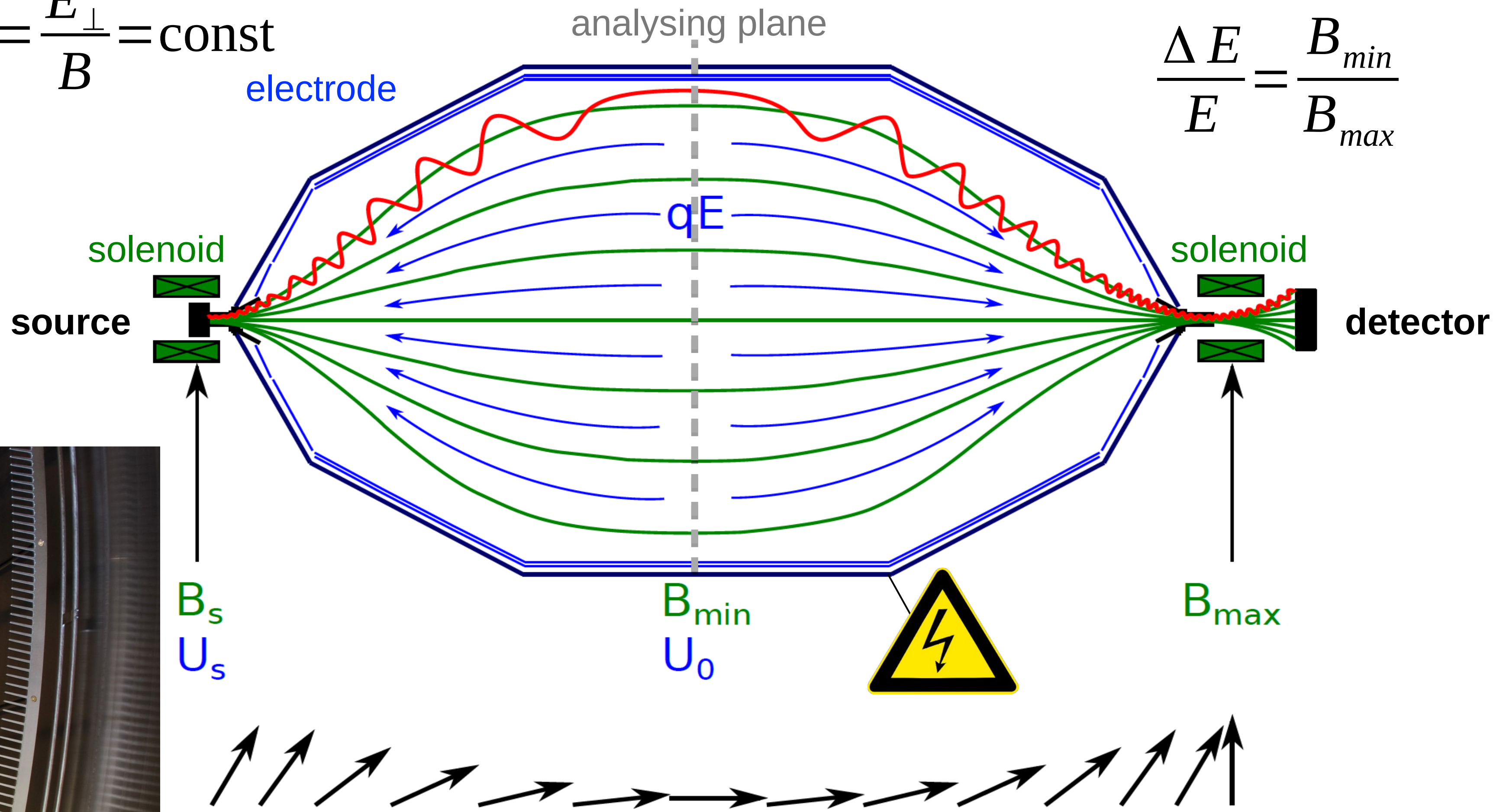
tritium source: 10^{11} ß-decays/s

MAC-E filter principle

Magnetic Adiabatic Collimation & Electrostatic filter

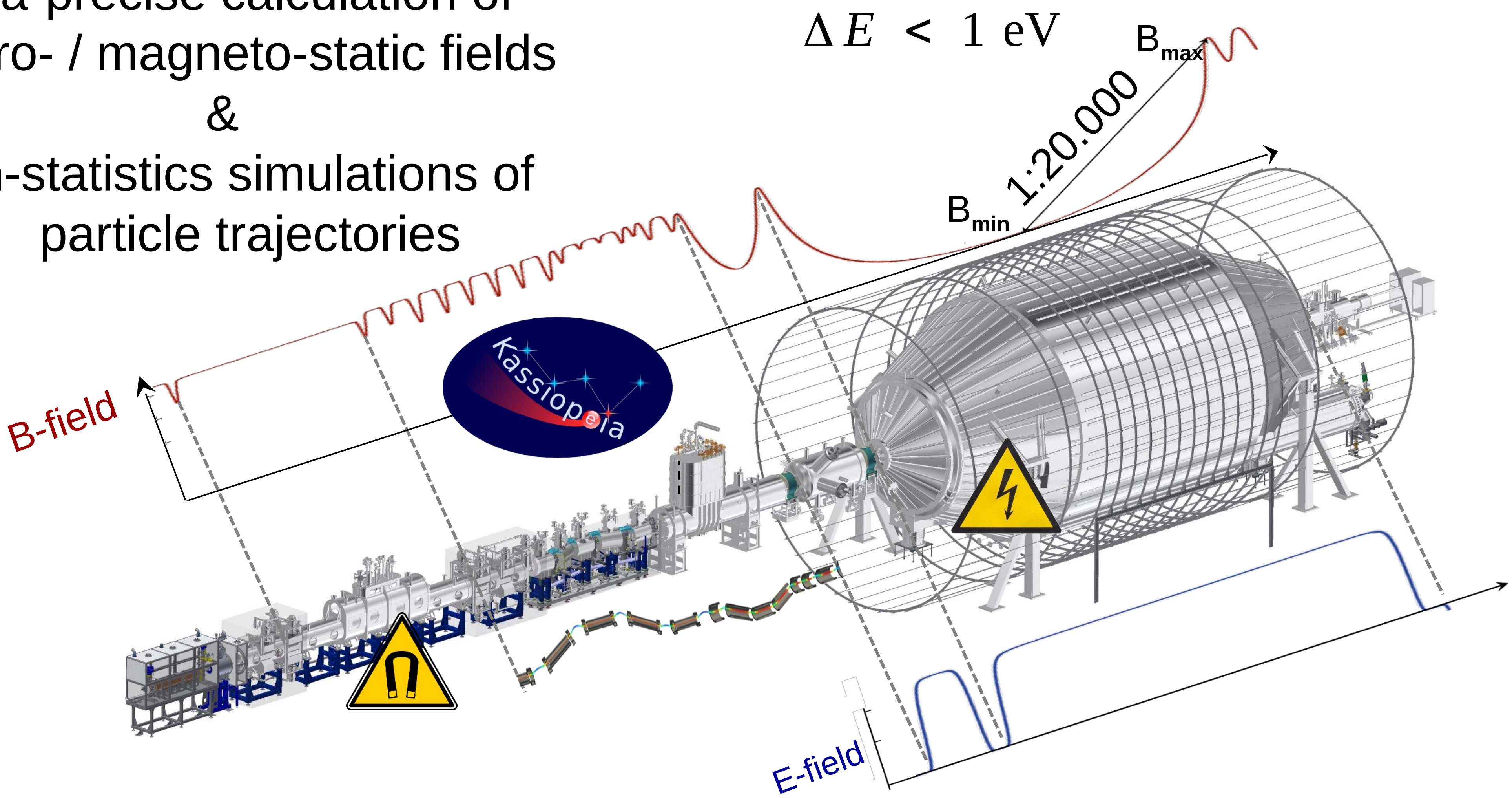
Magnetic moment $\mu = \frac{E_\perp}{B} = \text{const}$

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



Electric and magnetic fields

ultra-precise calculation of
electro- / magneto-static fields
&
high-statistics simulations of
particle trajectories



Journey of the main spectrometer

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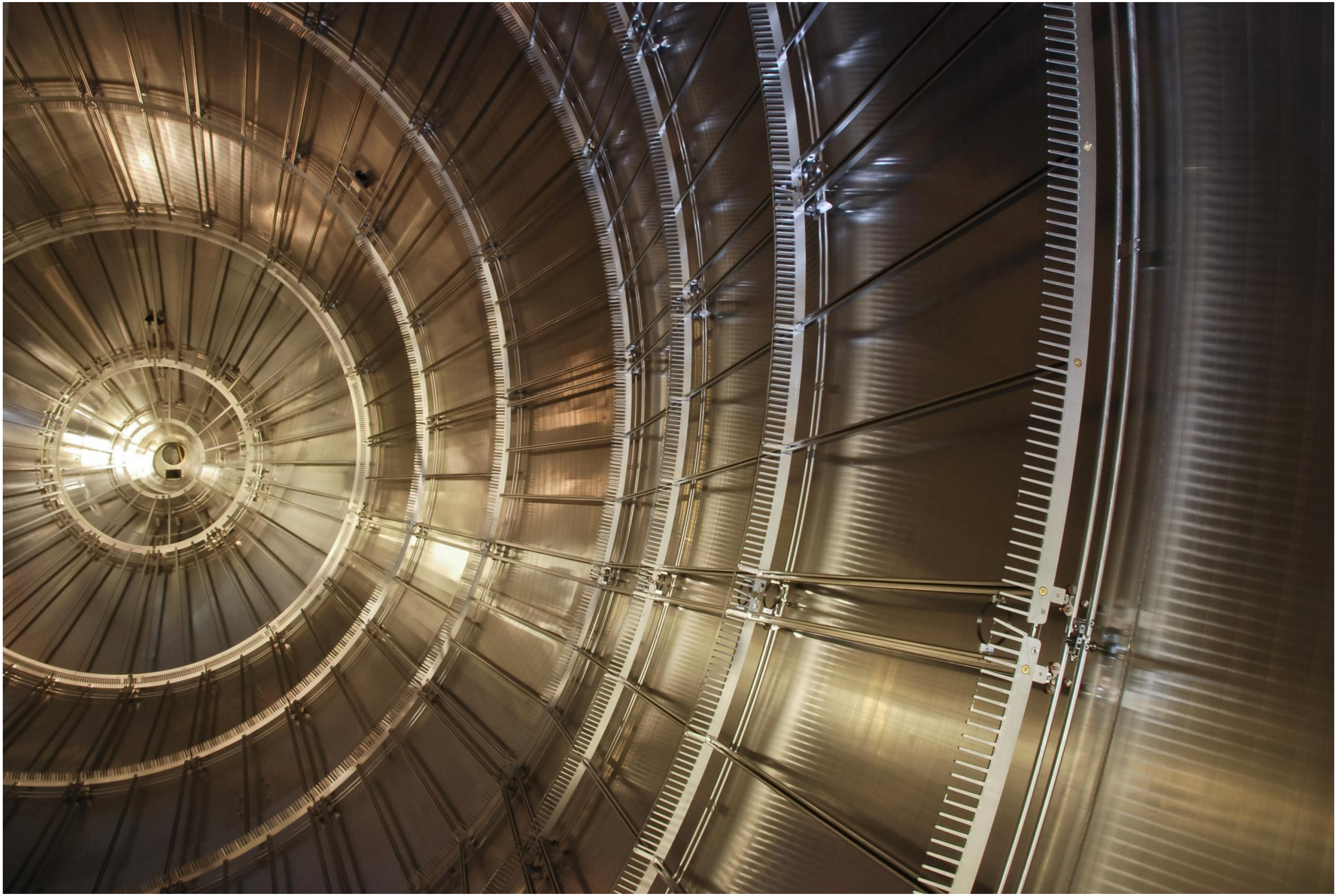
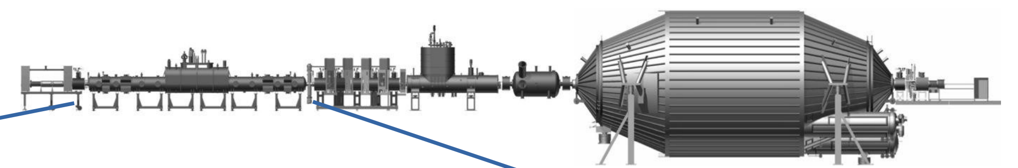
Main spectrometer

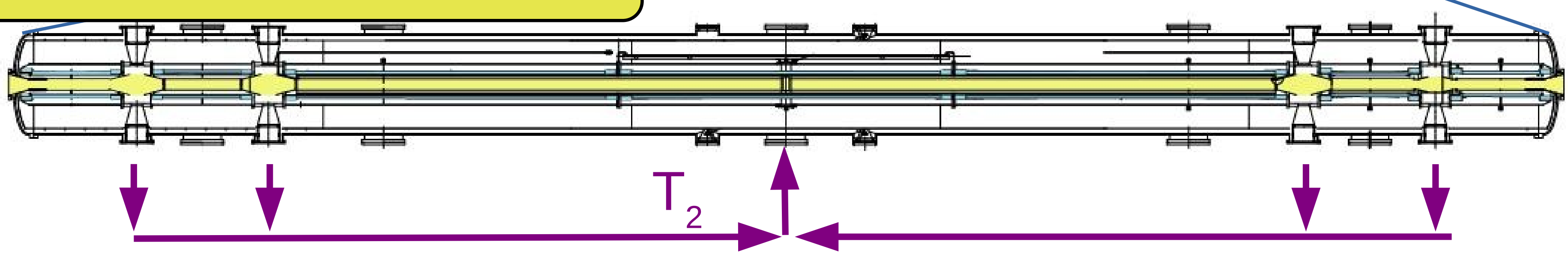
Ernst Otten: “feels like entering the Cologne Cathedral”



molecular Windowless Gaseous Tritium Source (WGTS)

per mill stability source strength request:
$dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p\, V / R\, T$
tritium fraction f_T & ideal gas law





WGTS: tube in long superconducting solenoids ⌀ 9cm, length: 10m, T = 30 K

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

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

check column density by e-gun, beam monitors, T_2 purity by laser Raman

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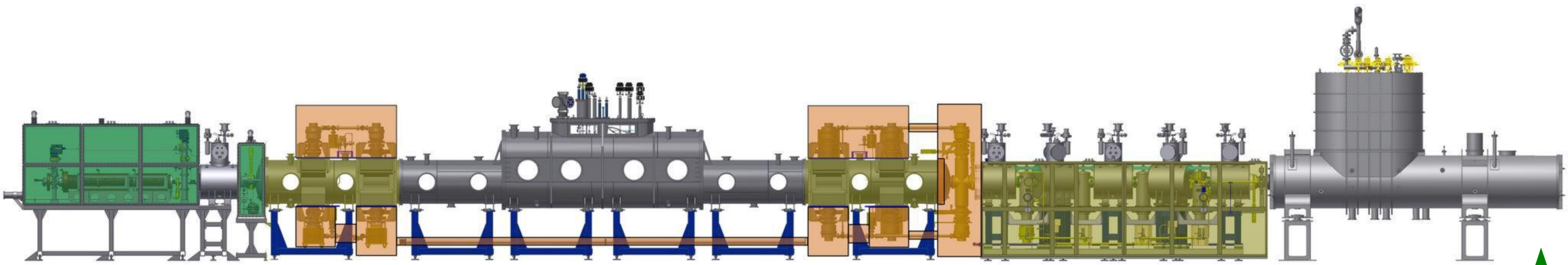
Transport, differential and cryogenic pumping sections

Monitoring & calibration system

Molecular windowless gaseous tritium source

Differential pumping

Cryogenic pumping
with Argon snow
at LHe temperatures



T_2-injection 1.8 mbar l/s
= $1.7*10^{11}$ Bq/s

FT-ICR Penning traps to measure ions from WGTS

$\approx 10^{-7}$ mbar l/s

$< 2.5\ 10^{-14}$ mbar l/s

⇒ adiabatic electron guiding & T_2 reduction factor of $\sim 10^{14}$

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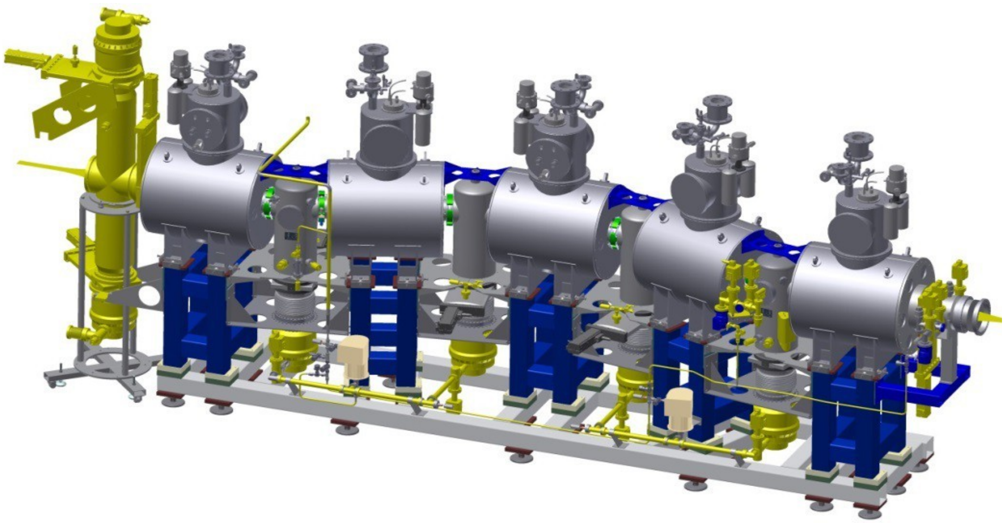
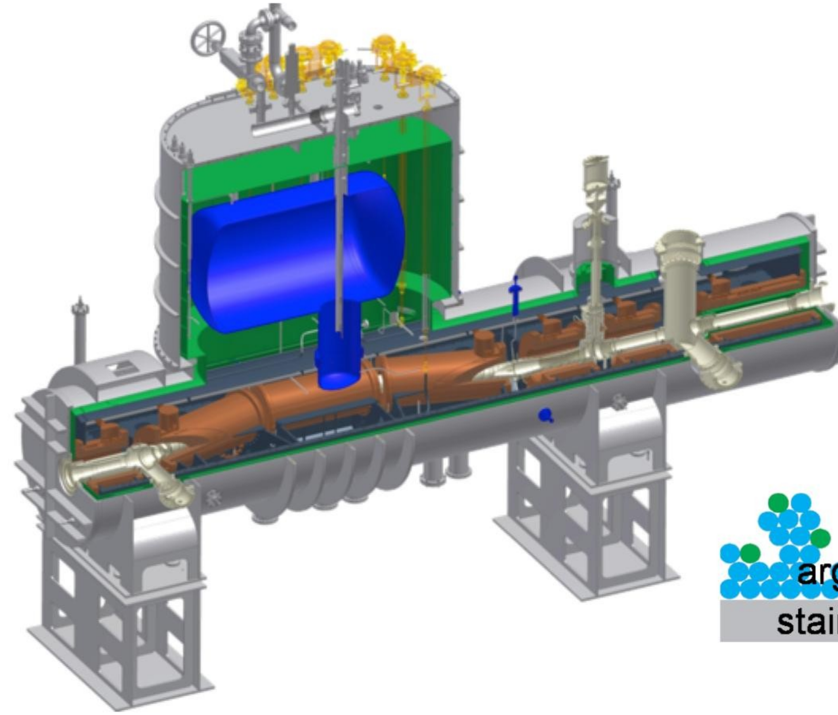
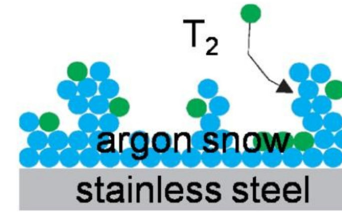
Differential and cryo pumping sections



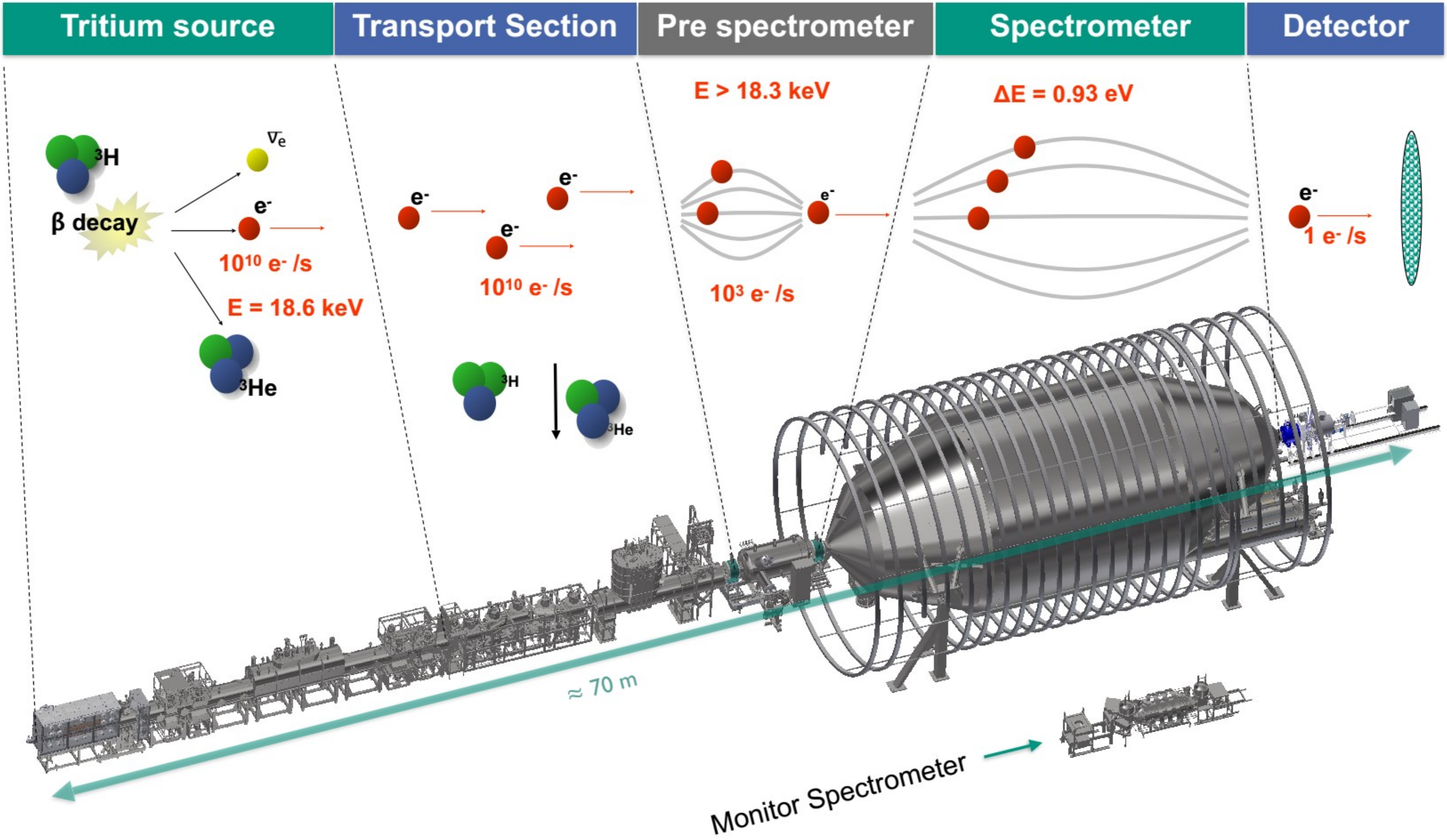




- based on by cryo-sorption at Ar snow at 3-4 K
- Tritium retention: >10^7
- magnetic field: 5.6 T

- active pumping: 4 TMPs
- Tritium retention: 10^5
- magnetic field: 5.6 T
- **Ion monitoring by FTICR and ion manipulation by dipole and monopole electrodes inside**

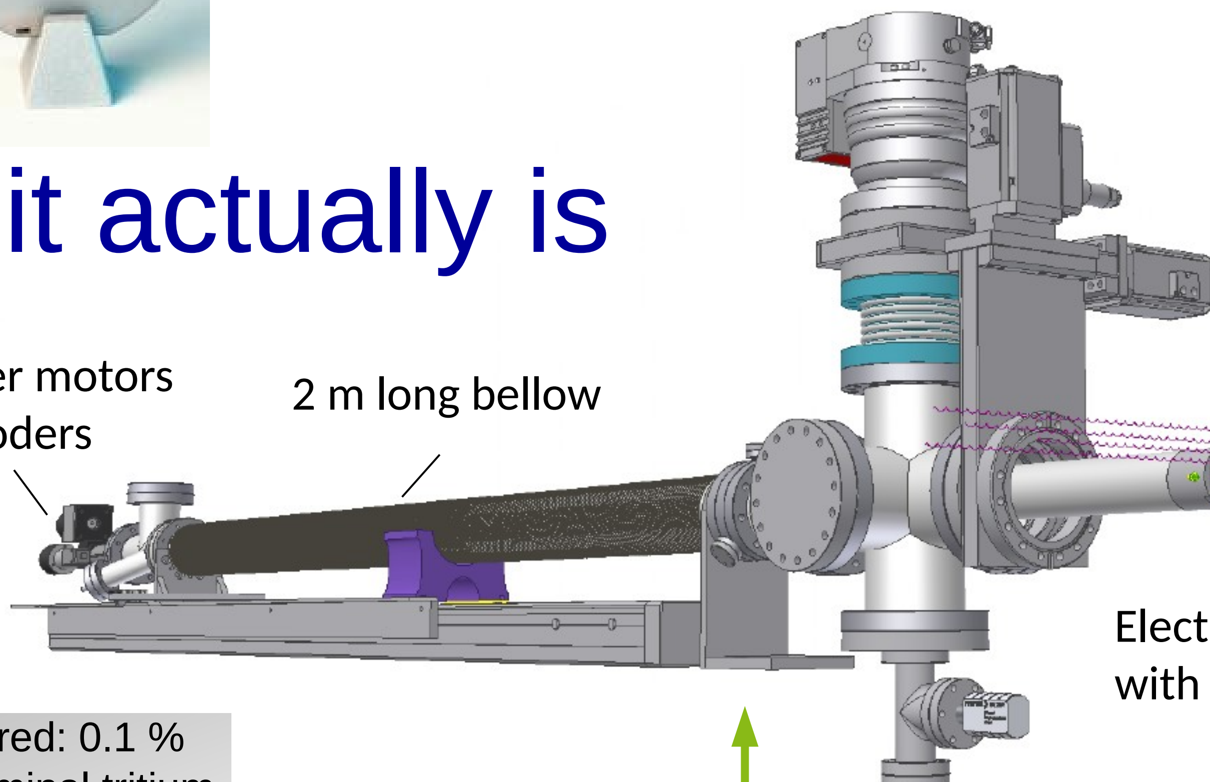
Tracking the beta-electrons



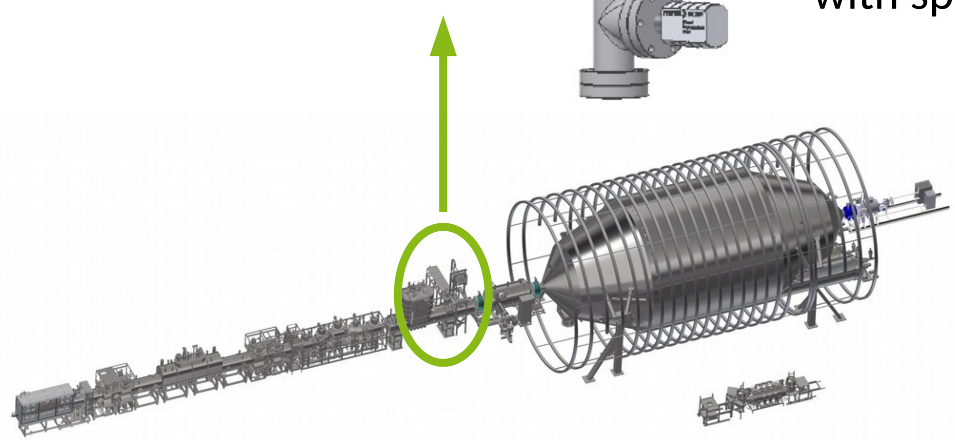
Beam monitoring: What I had thought of …

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

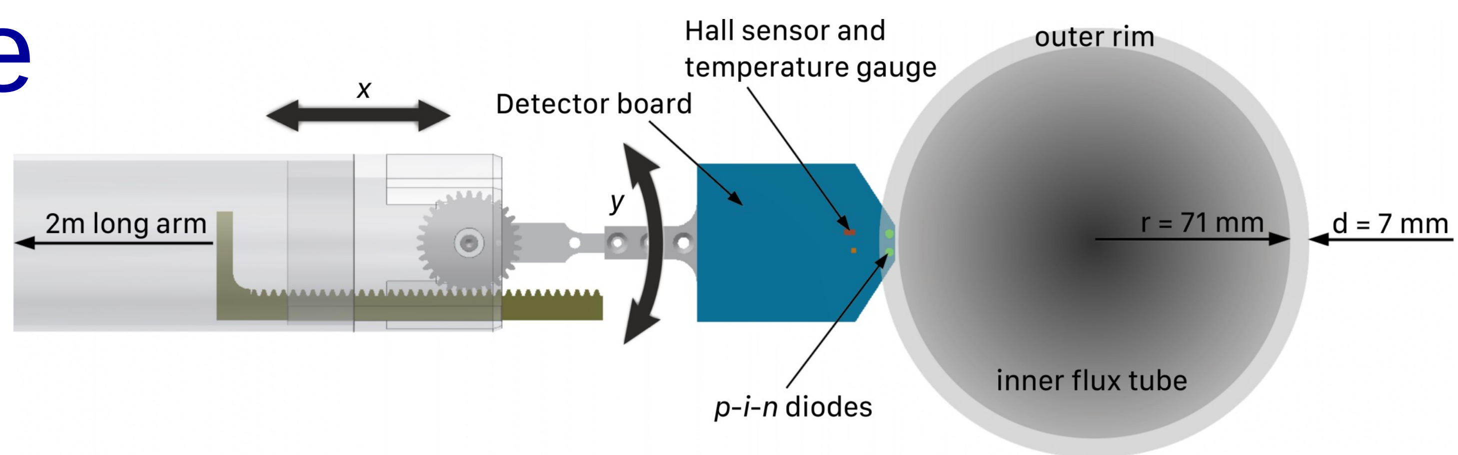
… what it actually is

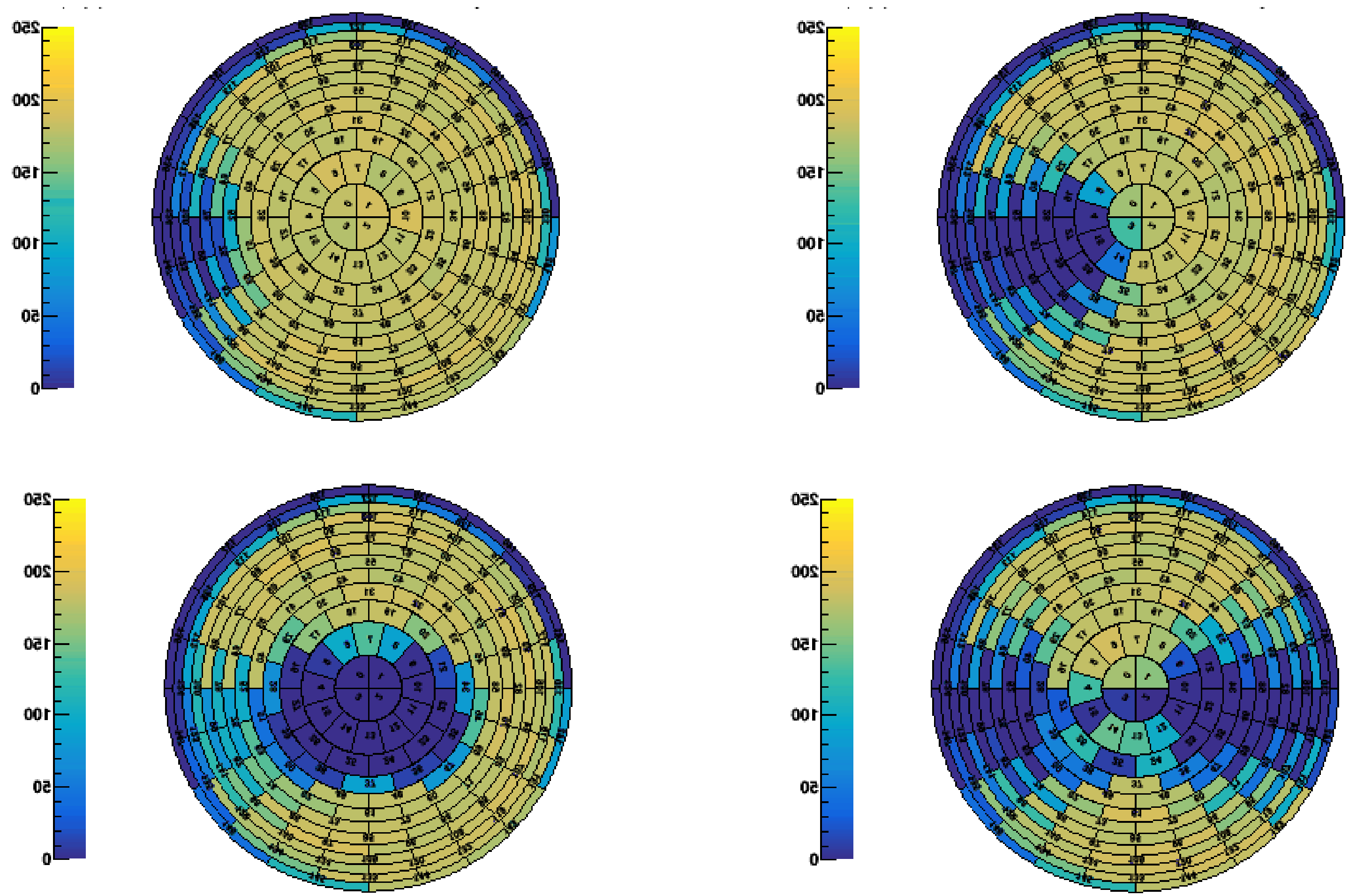


- Rate stability required: 0.1 %
- Count rate with nominal tritium density: 1 MHz per 1 mm²
- Vacuum: 10^{-9} mbar
- Magnetic field: 1.2 Tesla
- Temp.: -190° – +150° C



Seeing the β-electron flux

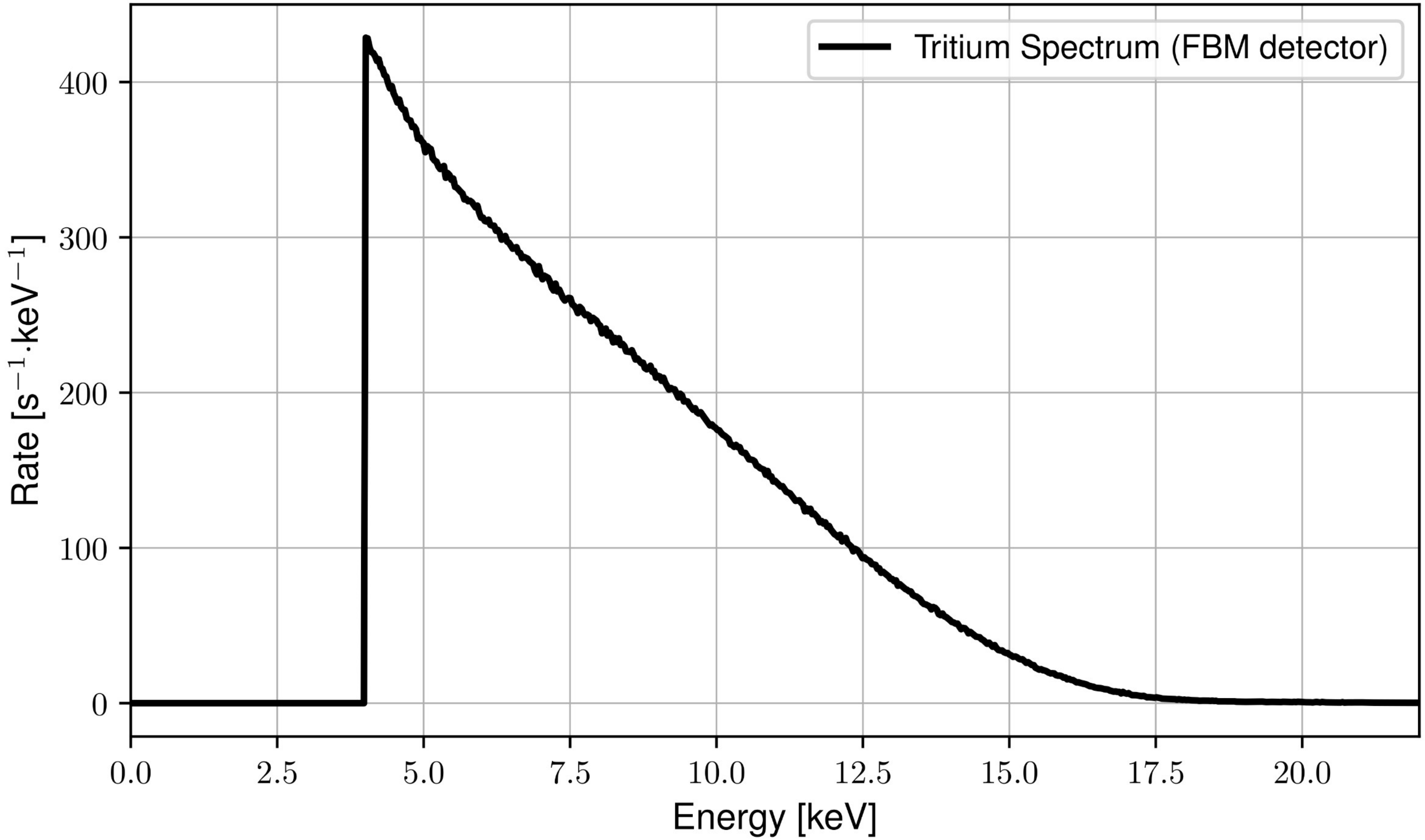




Shadow of detector board on focal plane behind main spectrometer.

First tritium spectra

Spectrum from transport section PIN-diode



First ν-mass result

- **ν-mass: best fit result**

$$m_{\nu_e}^2 = -1.0^{+0.9}_{-1.1}\,\mathrm{eV}^2$$

- **ν-mass: new upper limit**

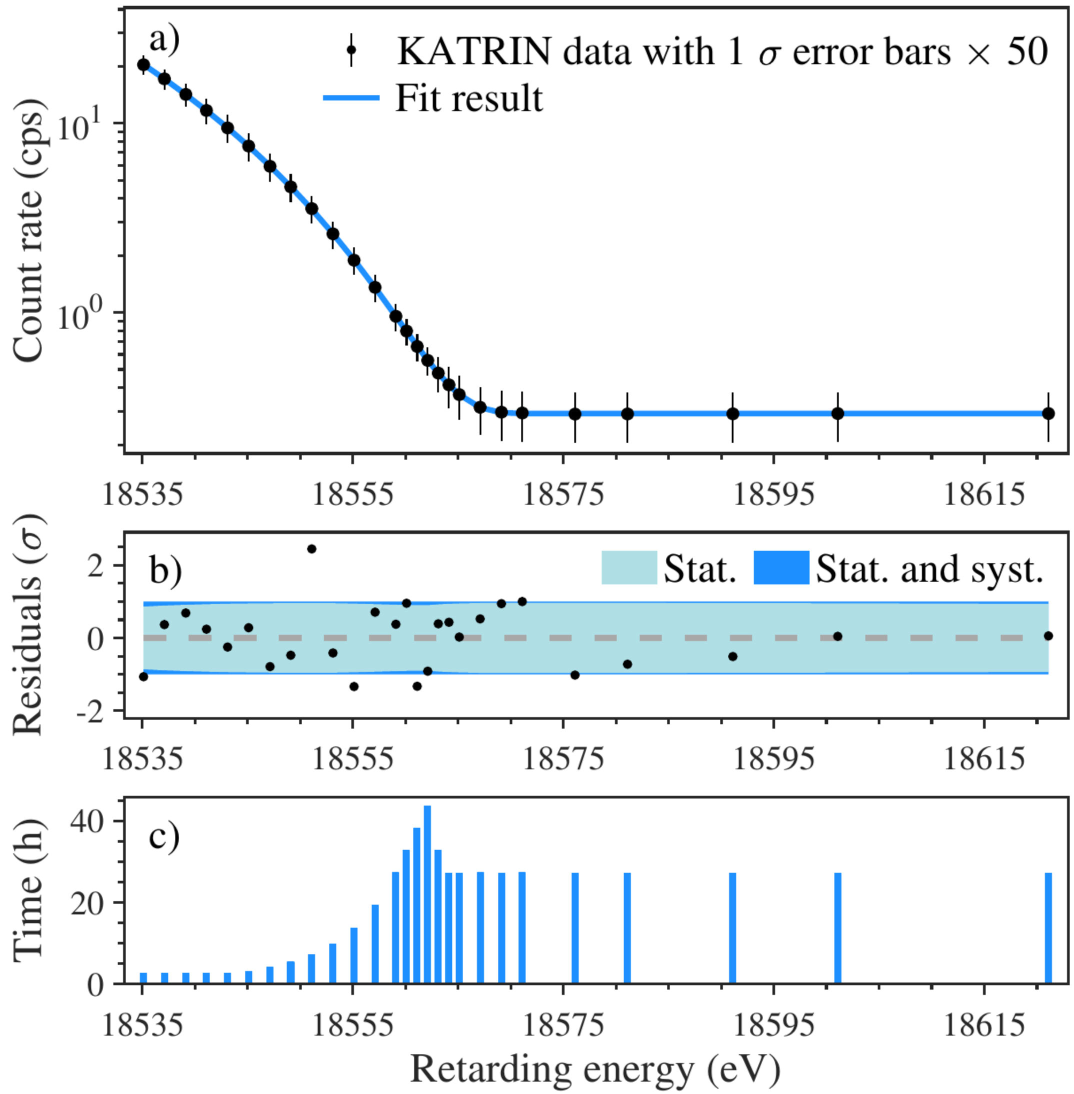
$$m_{\nu_e} < 1.1\,\mathrm{eV}\,(90\,\%\,\mathrm{CL})$$

Lokhov - Tkachov

Feldman-Cousins $m_{\nu_e} < 0.8\,\mathrm{eV}\,(90\,\%\,\mathrm{CL})$

Bayesian $m_{\nu_e} < 0.9\,\mathrm{eV}\,(90\,\%\,\mathrm{CI})$

flat prior, $m^2>0$



Statistics:
5 days live time
out of 1000

Limit 2x better than
previous results

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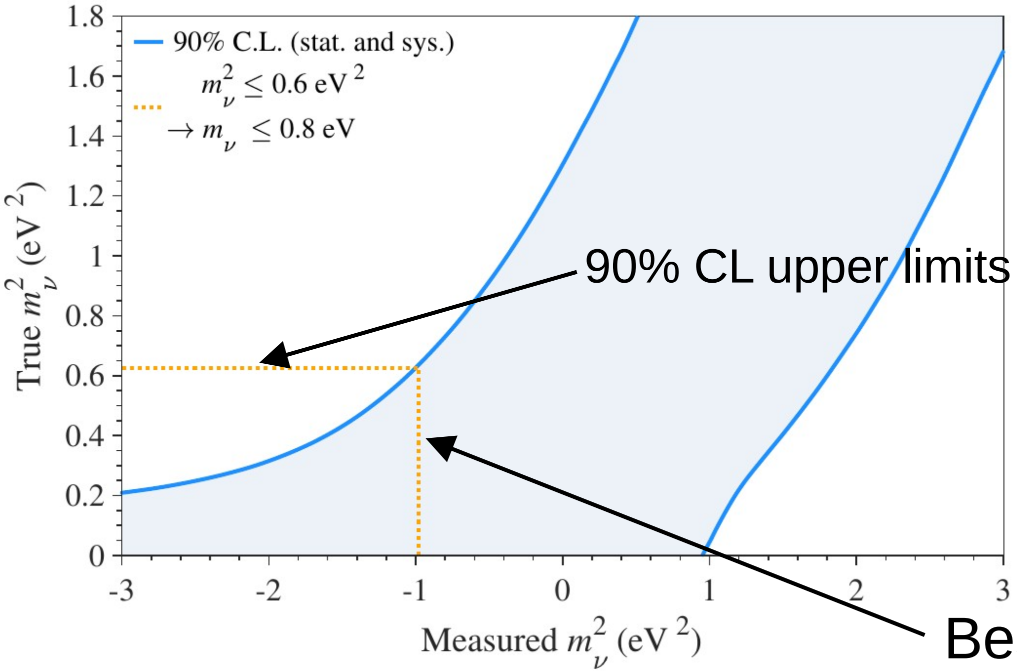
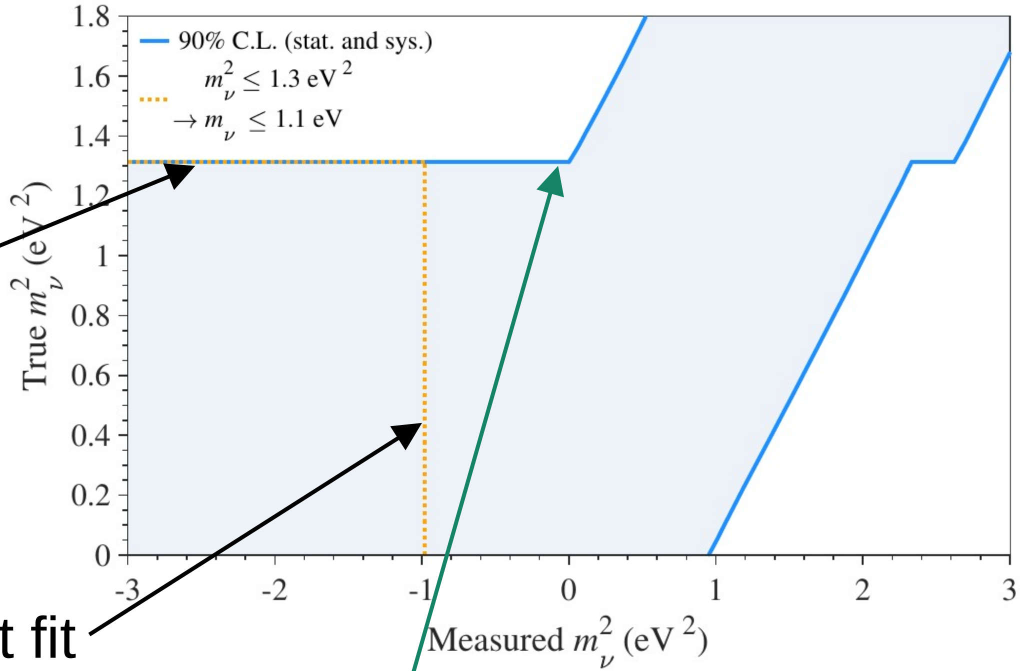
What is Lokhov-Tkachov ?

Feldman and Cousins



Lokhov and Tkachov

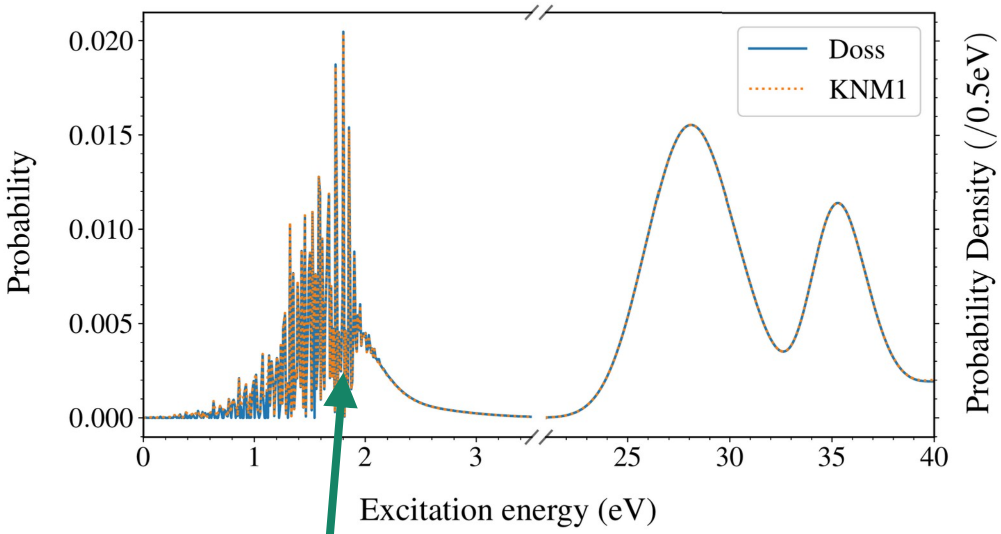


90% CL upper limits

Best fit

Truncate unphysical region
→ no gain from negative m²
for limit setting

Blindness strategy



- Final-state distribution (FSD) for transitions from decay of T_2 to He_3T in electronic ground state (below 4 eV) and bound rovibrational molecular states

- Blindness difficult since systematics needs to be studied with full statistics.
  1) fix data selection, analysis cuts before fitting on MC.
  2) Model blinding rather than data blinding: replace FSD with Gaussian of undisclosed width → **inject unknown shift for m^2**

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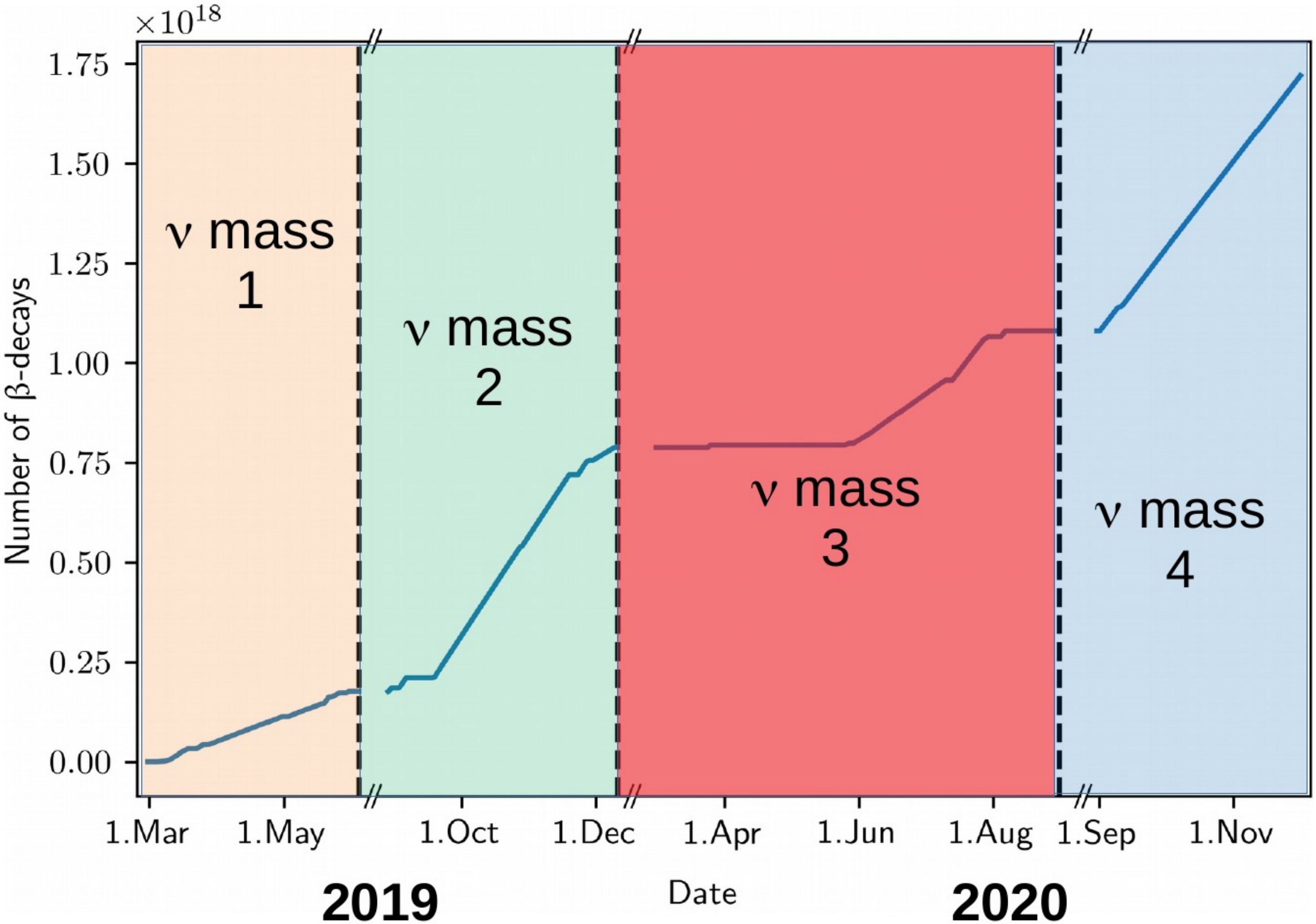
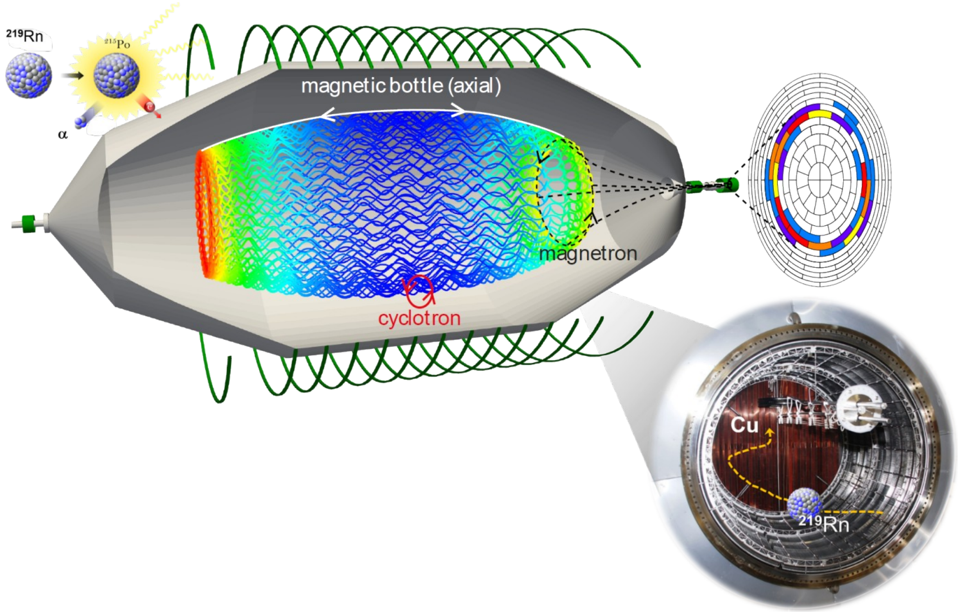
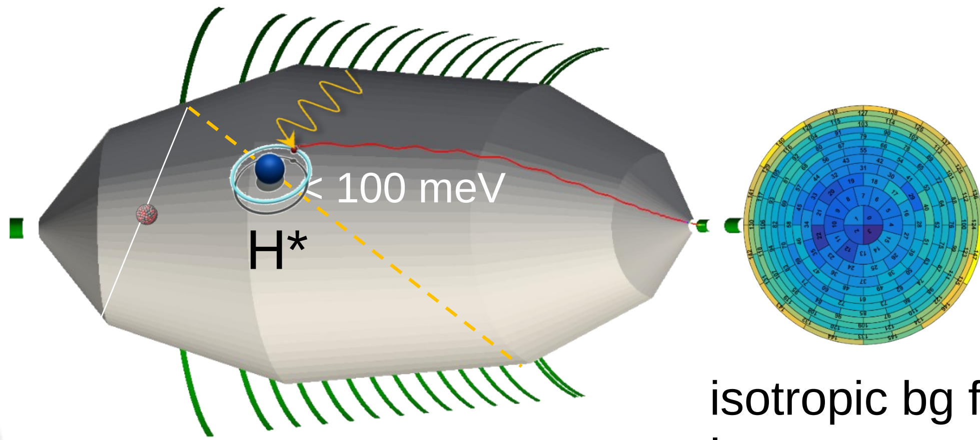
… and counting



KATRIN is taking data through Corona in 2020

Backgrounds





isotropic bg for
longer exposure

^{219}Rn atoms:

- ^{219}Rn emanates from NEG
- bg-rate: ~500 mcps

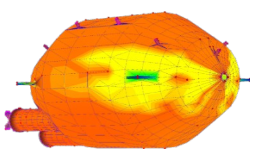
countermeasure:

cryotraps in front of NEG
- 3 LN2-cooled Cu-baffles

✓

H* Rydberg atoms:

- desorbed from walls
  due to ^{206}Pb recoil ions
- bg-rate: ~500 mcps



countermeasures:

reduce H-atom surface coverage:
- extended bake-out phase
- strong UV illumination source

… and more challenging ideas … !

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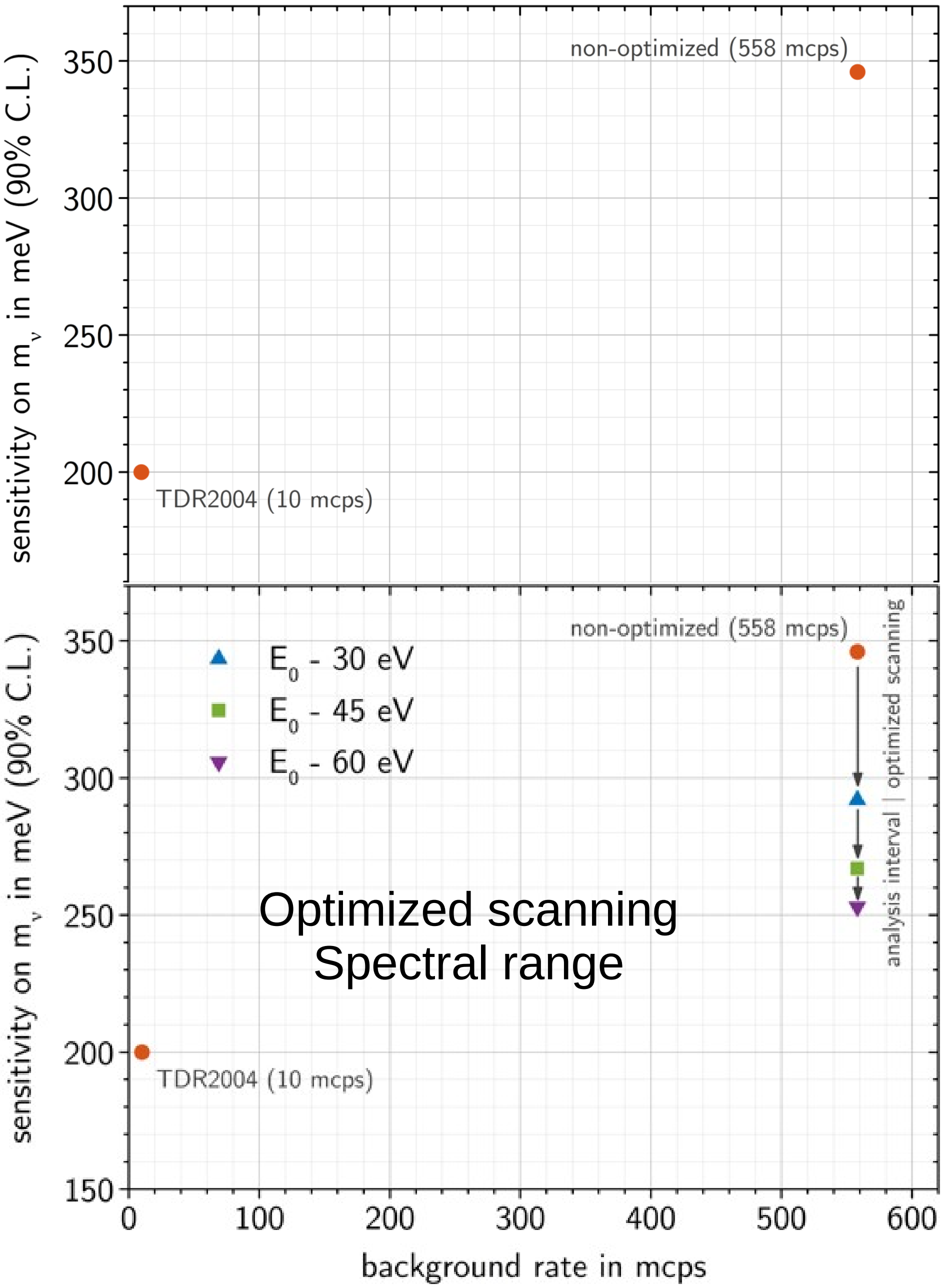
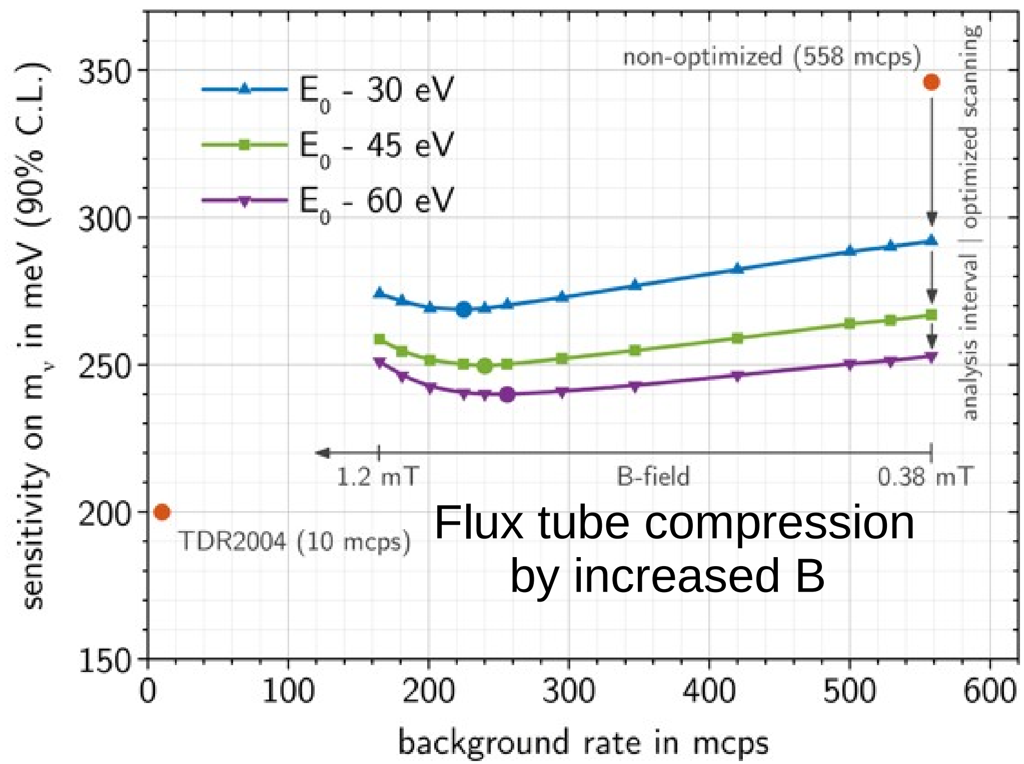
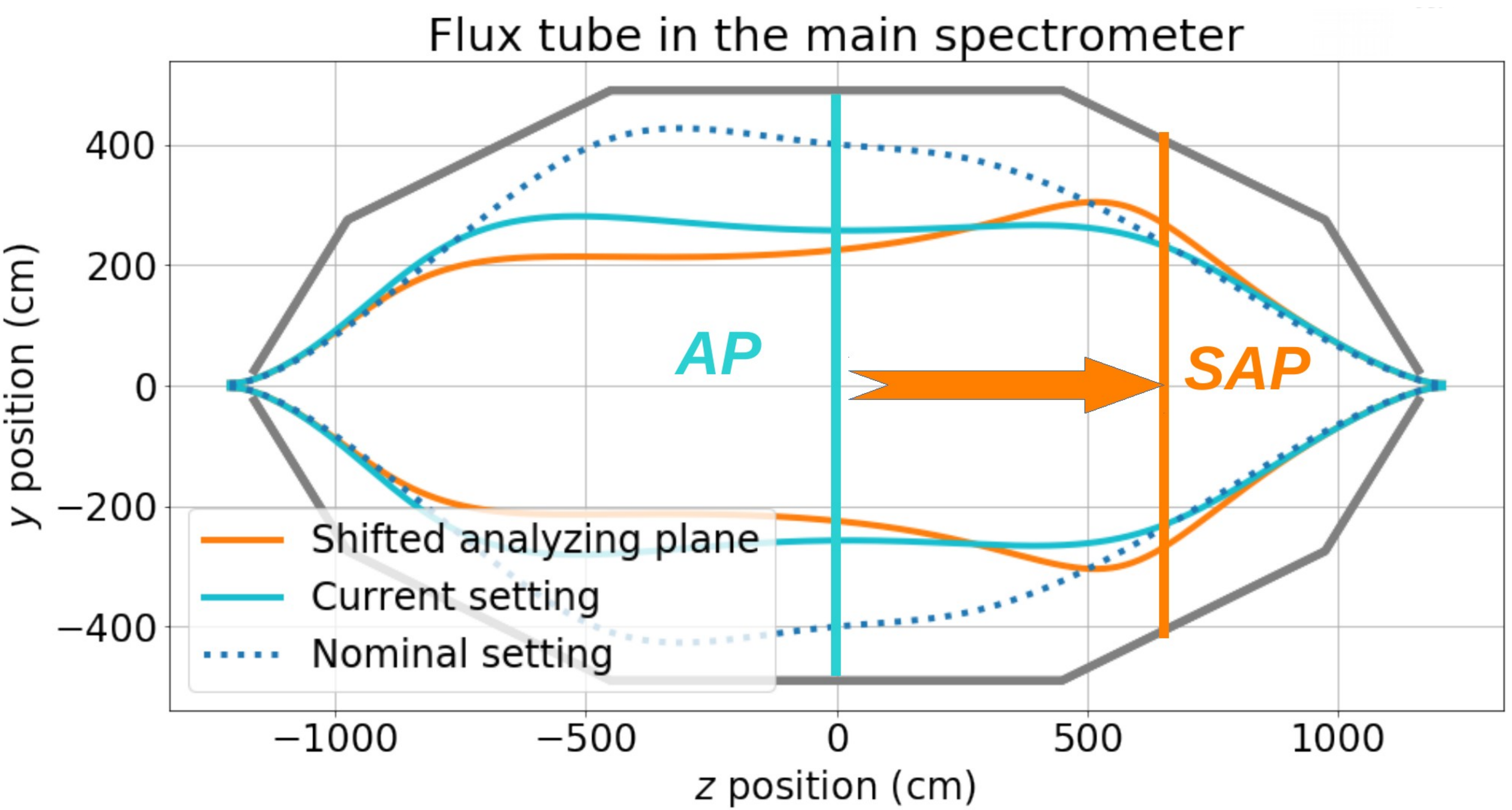
Background and sensitivity





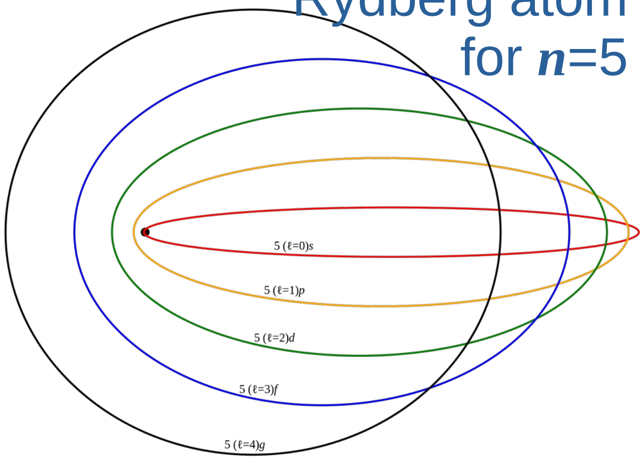
Background is volume effect → Flux tube tweaking

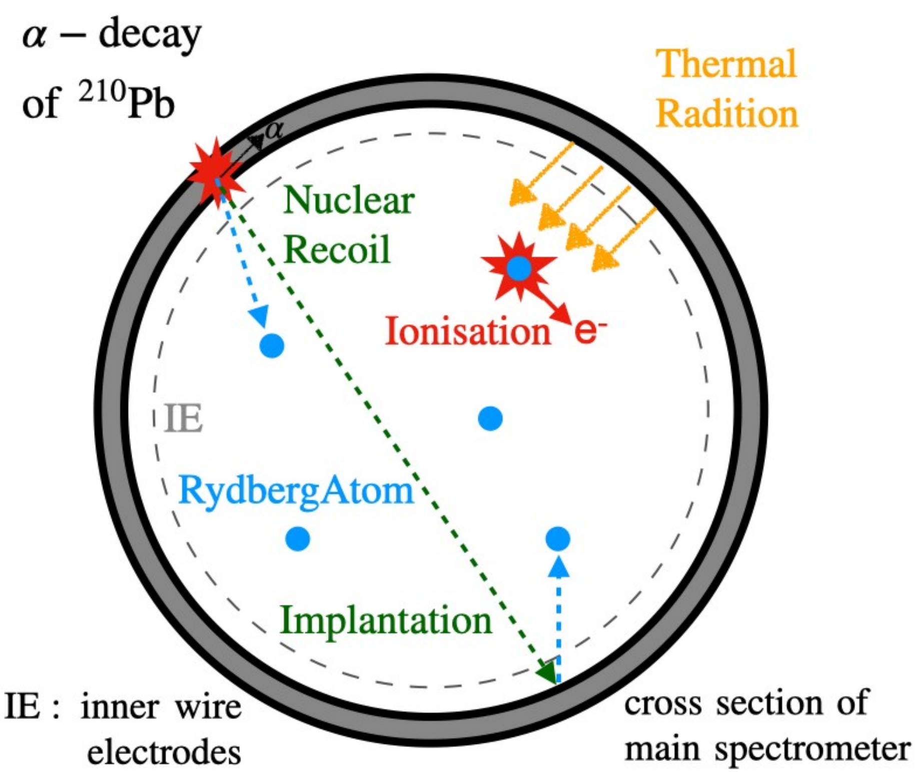


Rydberg background

During installation:
Ambient air: 222-Rn → 210-Pb ($t_{1/2}$ = 22.3 year)
210-Pb implanted in main spectrometer steel walls
measured 210-Pb surface activity: 1 mcps/m^2
210-Pb → 210-Po → α
α → probability to eject neutral atoms in a highly excited state ("Rydberg" atoms) into the vacuum passing all electric and magnetic barriers on their way into the relevant magnetic flux tube of the spectrometer.

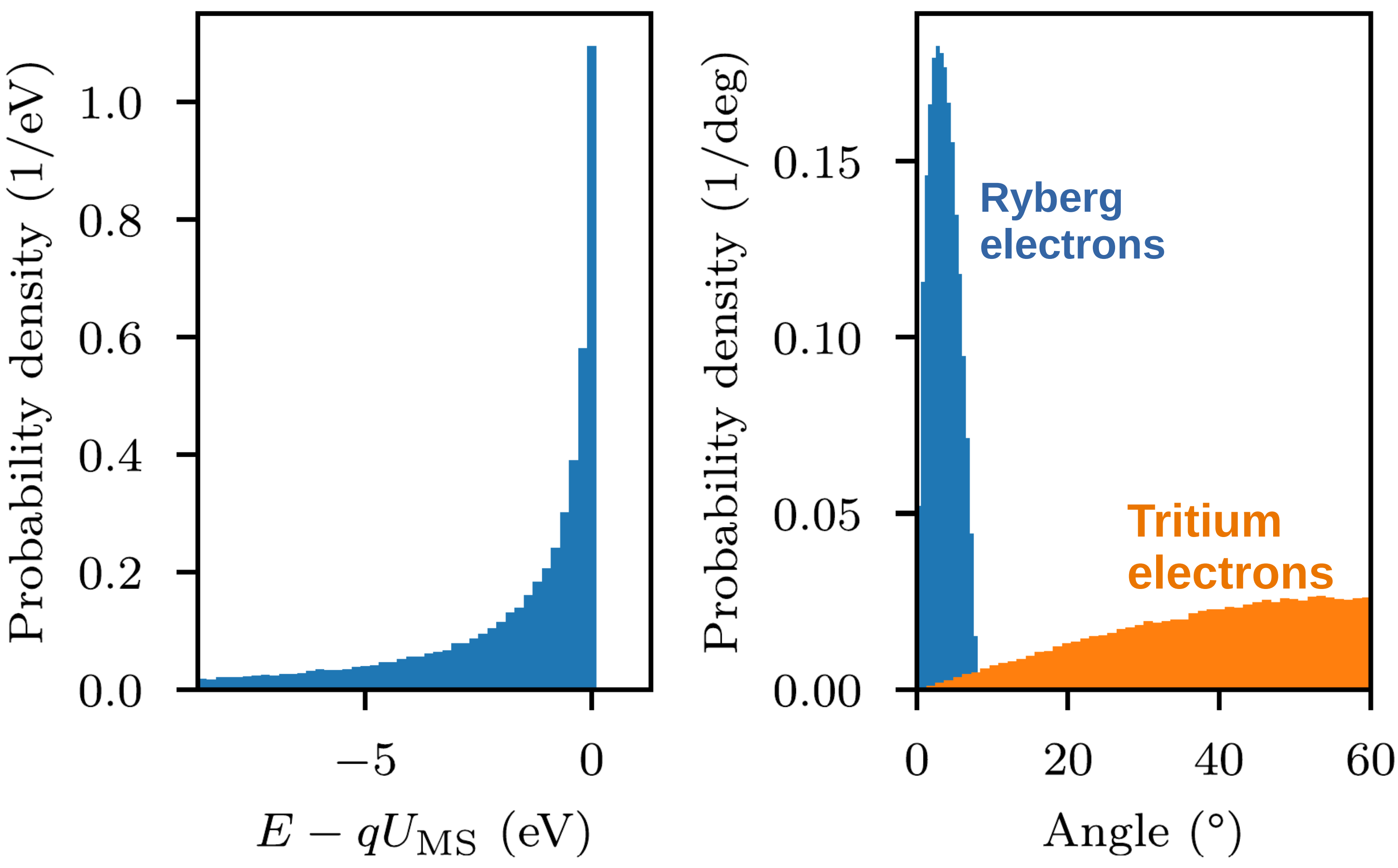
Semiclassical orbits of a Rydberg atom for ***n***=5



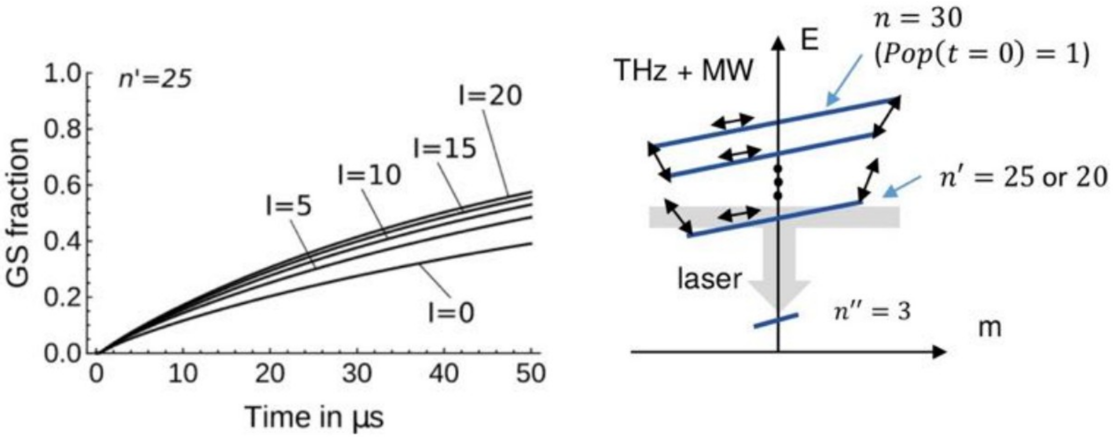


- Rydberg atoms get ionized by black body radiation (BBR) even at room temperature!
- Resulting free electron gets accelerated towards the detector and counted
- Characteristics of Rydbergs:
  - Recoil nucleus sputters off highly excited Rydberg atoms with high principal quantum number ***n***
  - unknown distribution of ***n*** and angular quantum number ***l***

Rydberg R&D
Angular electron separation



R&D: Active deexitation with THz/MW radiation

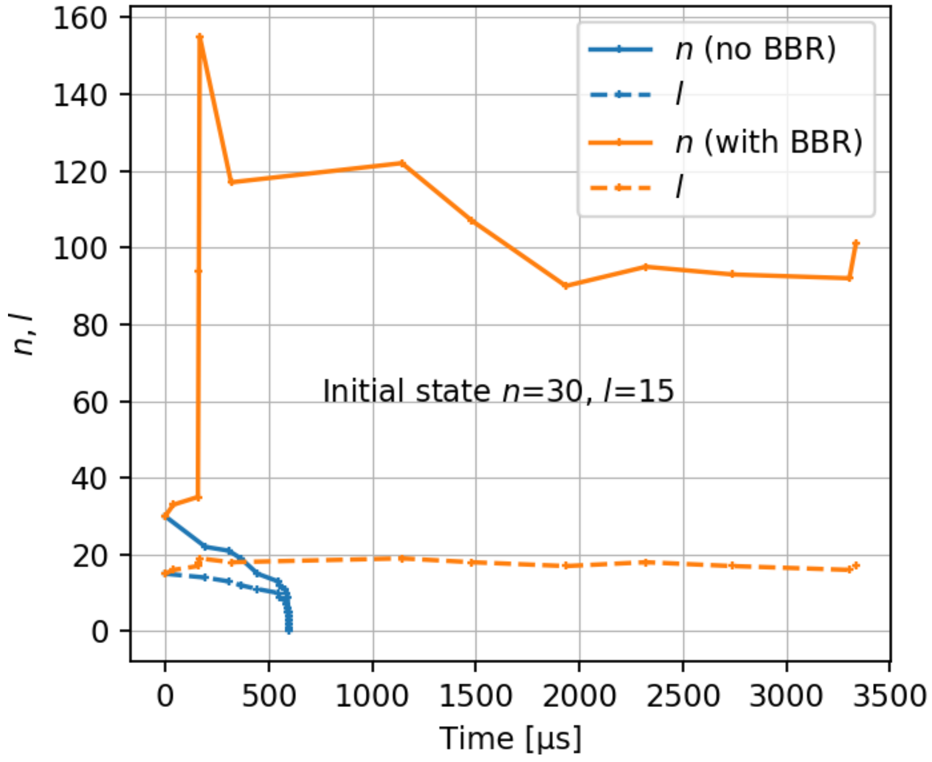


Idea inherited from ASACUSA & Anti-Hydrogen community

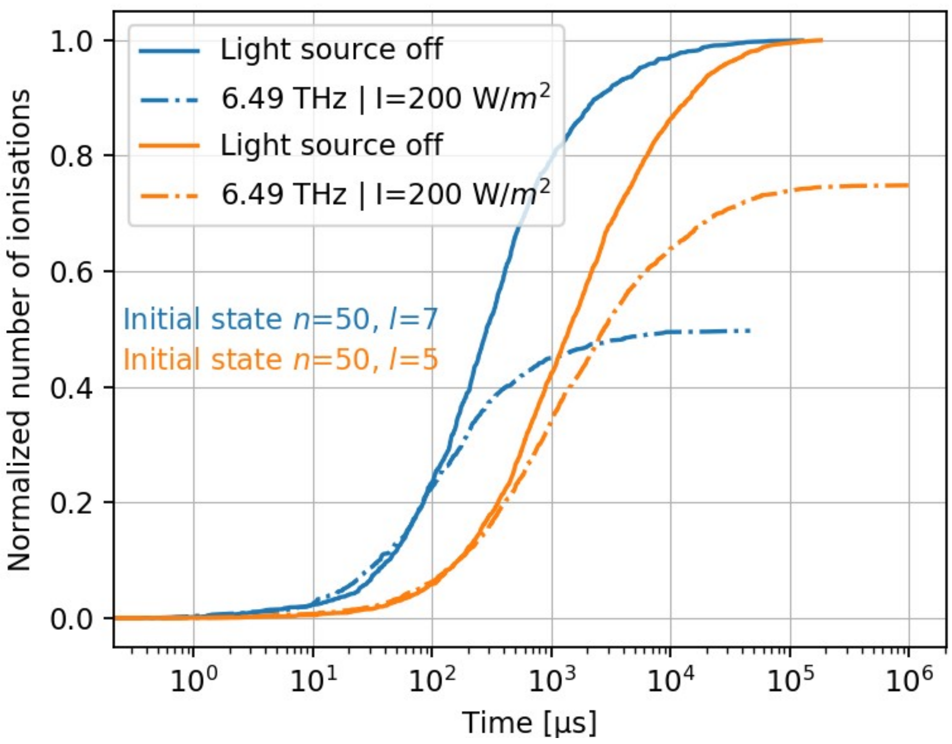
Pursued now for KATRIN in Wuppertal

Rydberg R&D
THz radiation for deexcitation

Effect of Black Body Radiation



Effect of THz radiation



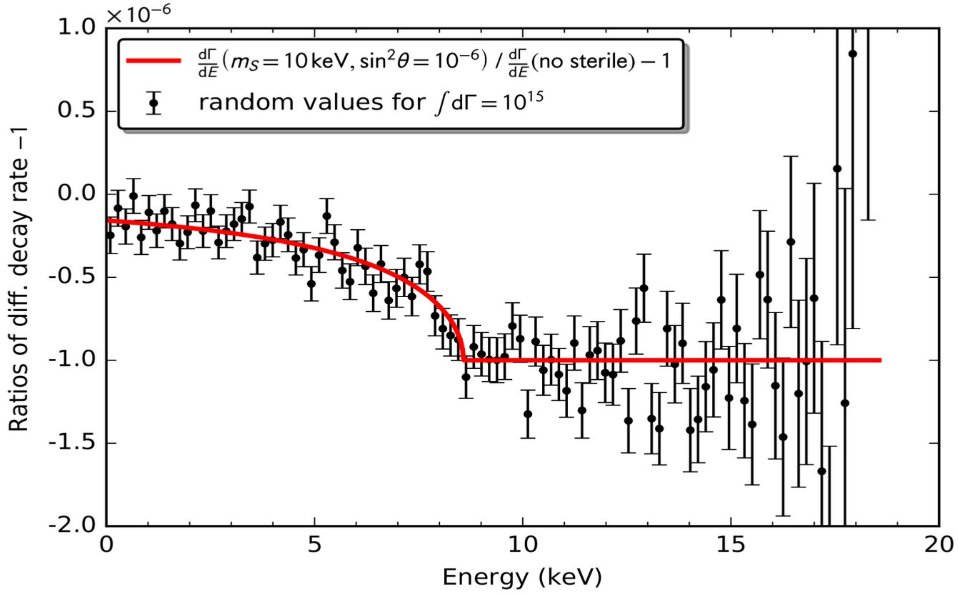
Summary

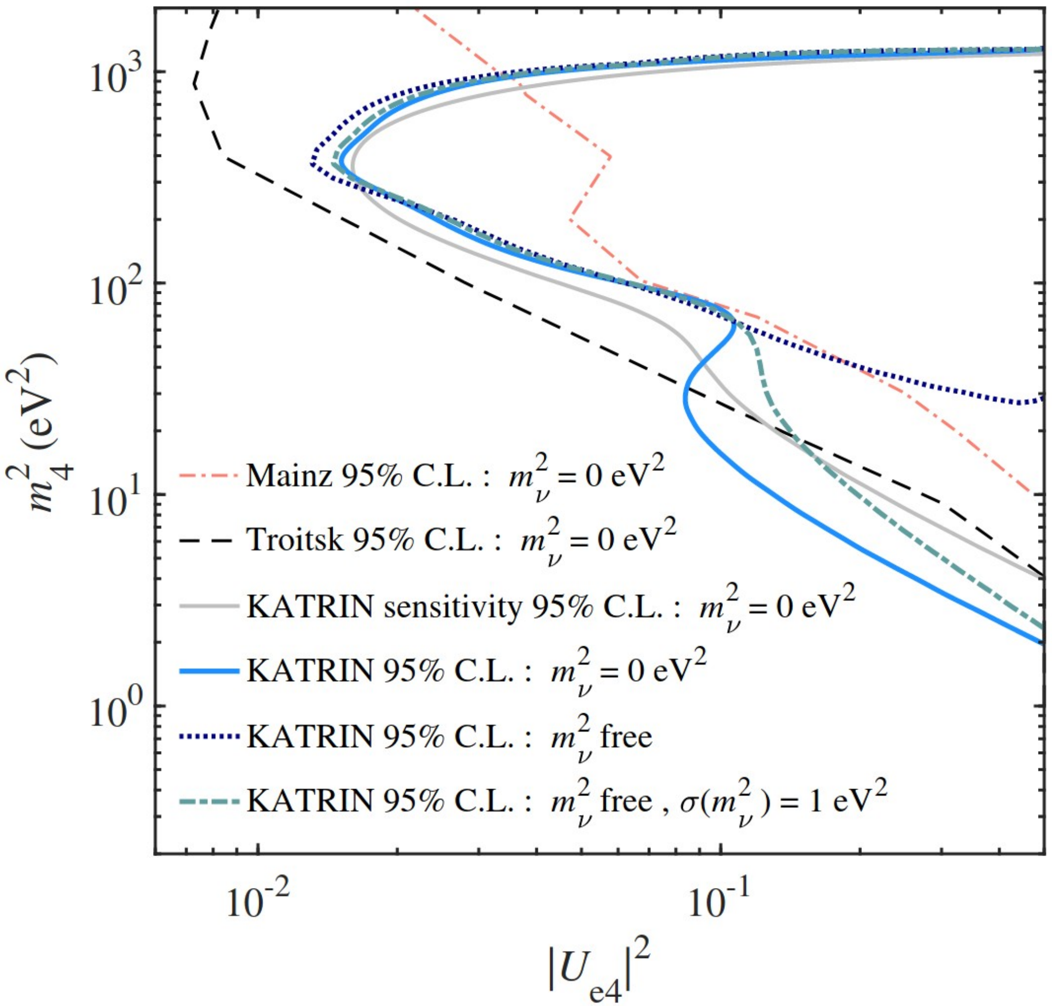
- Direct neutrino mass experiments focus on the single failure of the Standard Model of particle physics.
- Extremely diverse range of technologies (atomic, laser, vacuum, theory detector physics) need all be pushed beyond current applications.
- Next steps:
  - KATRIN discovers Nu-Mass → Stockholm ! reconsider ΛCDM !
  - … in the remote chance, it is not found: KATRIN is not scalable
    - Squeeze it: new ideas wrt backgrounds and tweaks on spectral analysis
    - new experimental concepts: ECHo, Project-8

Thank you for your attention!

Sterile keV Neutrino result

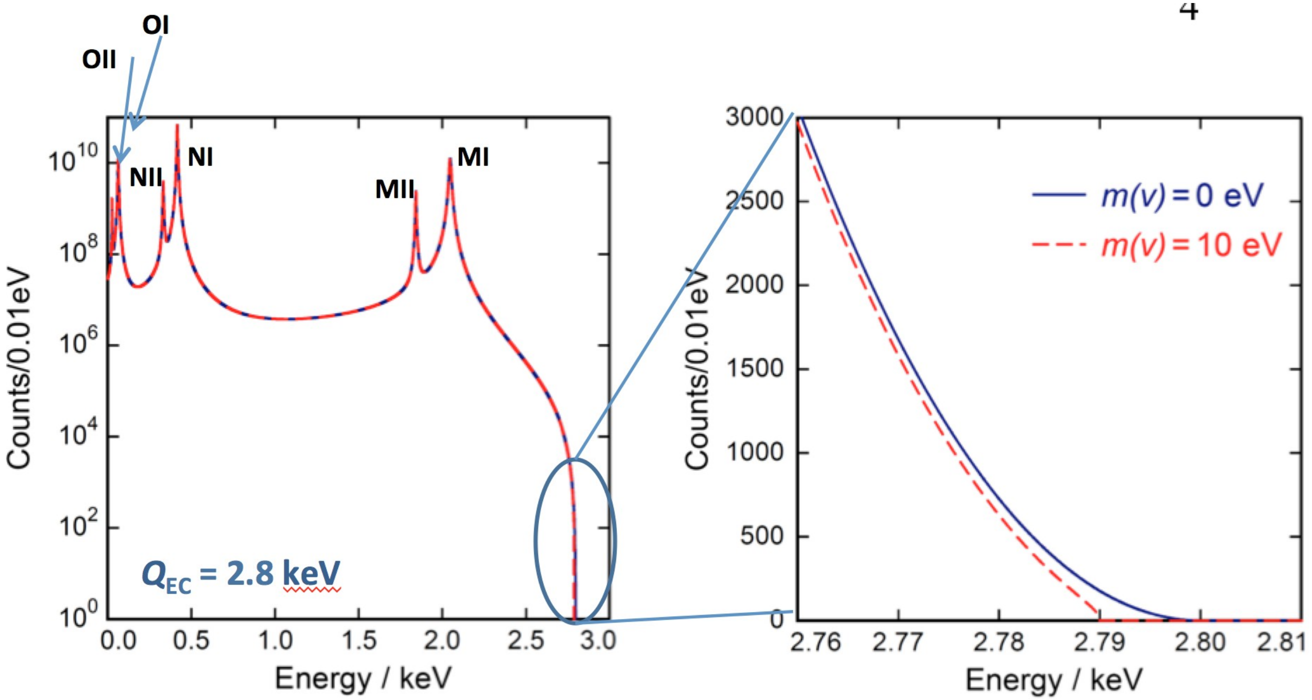
Kinky spectrum

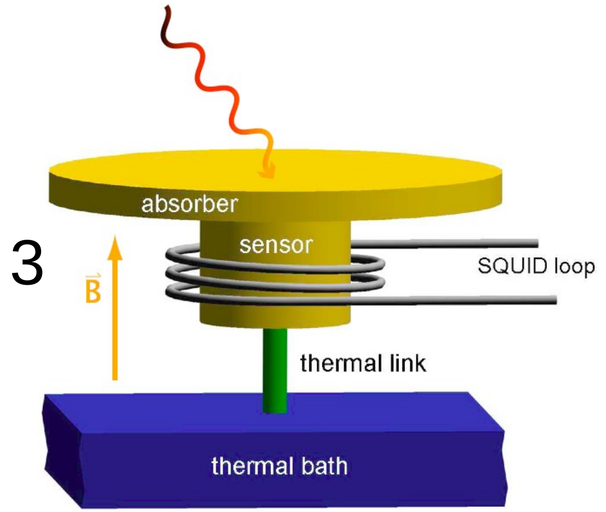


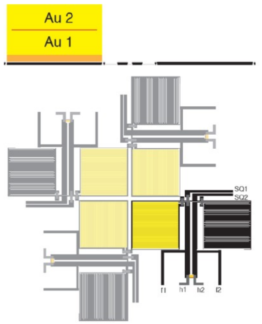


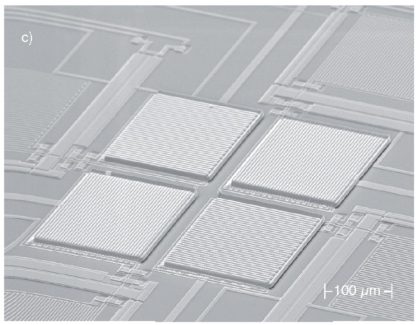
ECHo: ^{163}Ho electron capture with metallic magnetic calorimeters

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









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

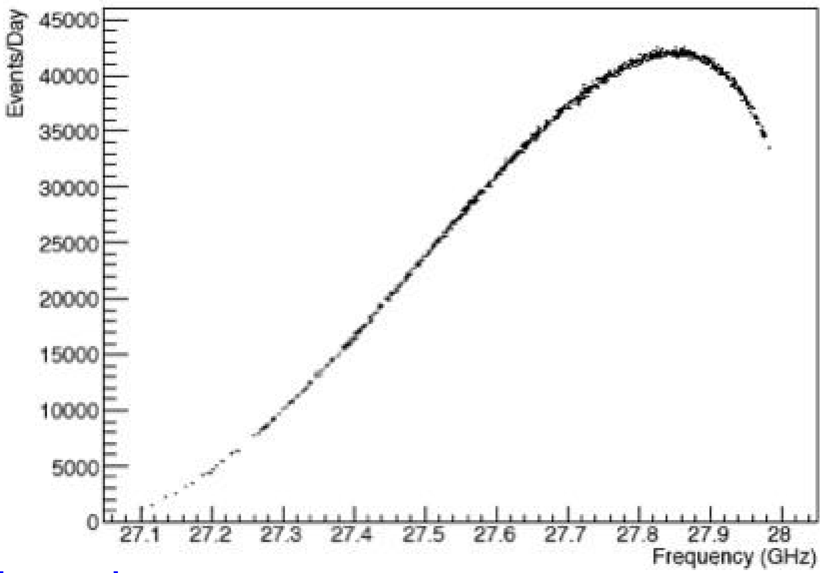
General idea:

- Source = KATRIN tritium source technology :

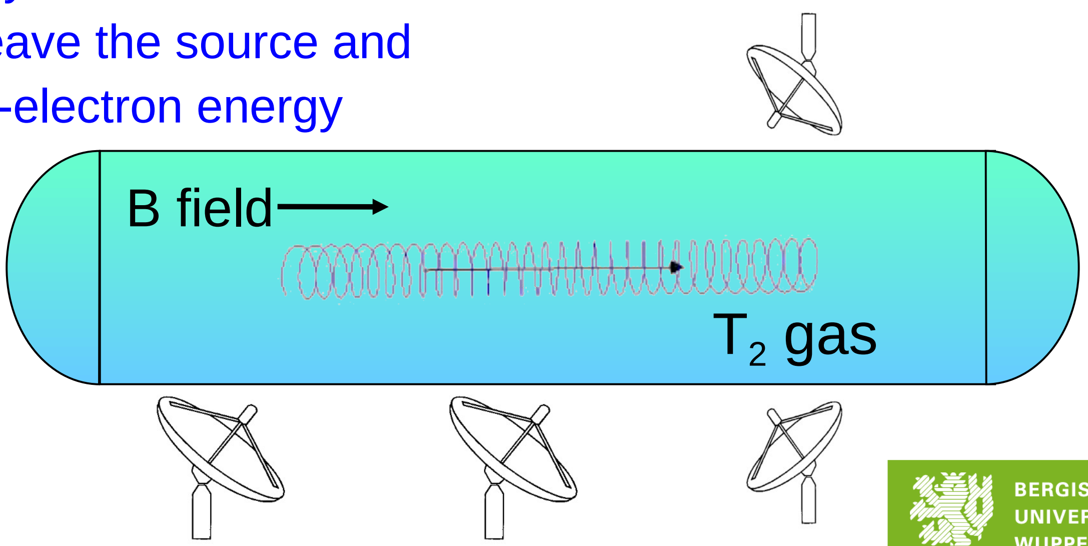
  uniform B field + low pressure T_2 gas

  β electron radiates coherent cyclotron radiation

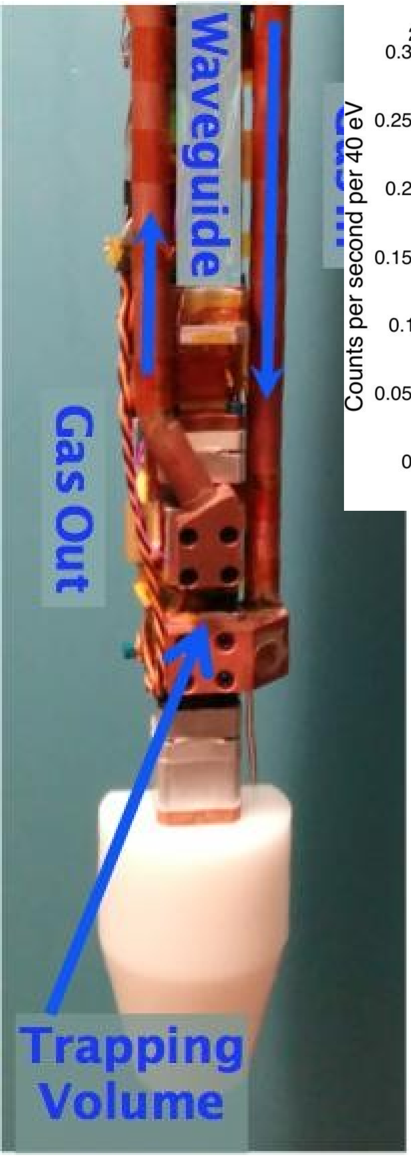
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

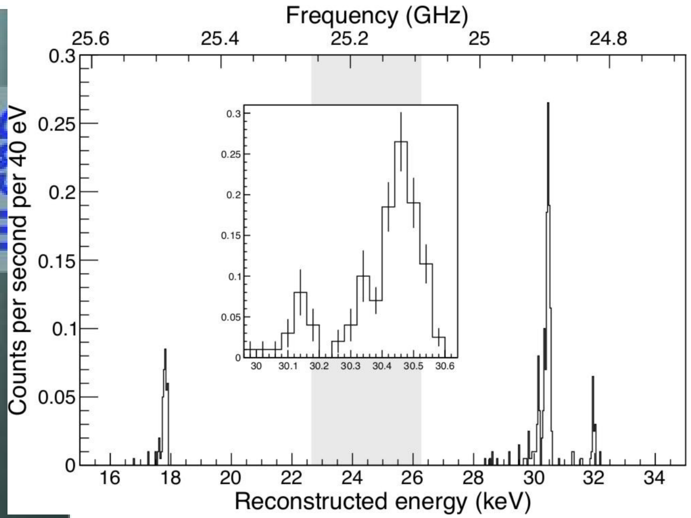


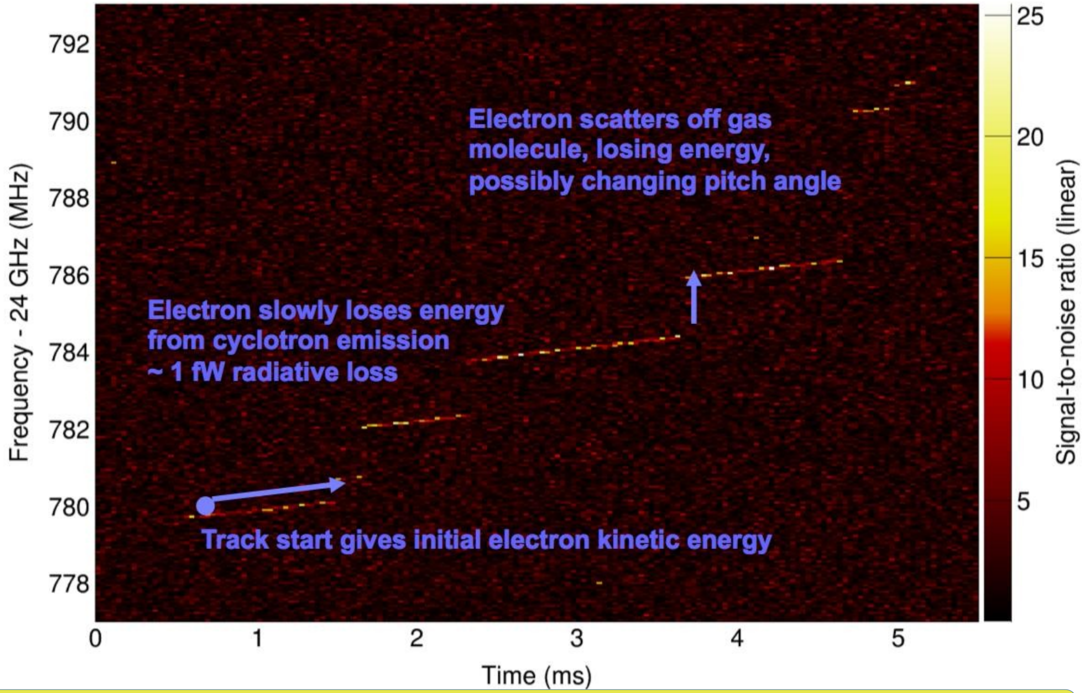
- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation can leave the source and carries the information of the β-electron energy



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?

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