The KATRIN Neutrino Mass Experiment

Joachim Wolf (KATRIN Collaboration)

Institute of Experimental Nuclear Physics

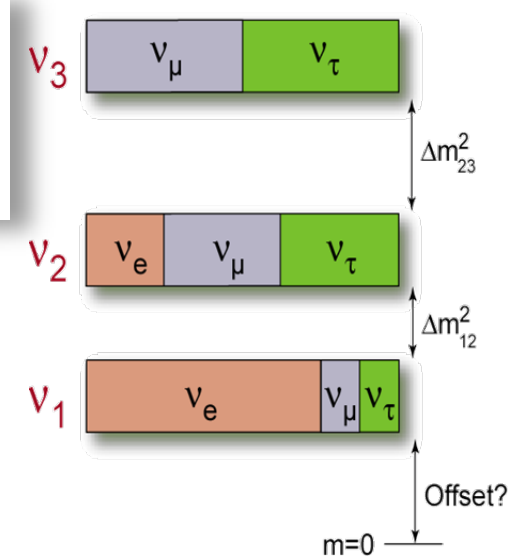
NPB 2012

- Neutrino mass measurement
- β-decay and MAC-E-Filter
- KATRIN experiment
  - setup
  - test measurements
  - sensitivity
  - schedule and future goals
- Conclusions

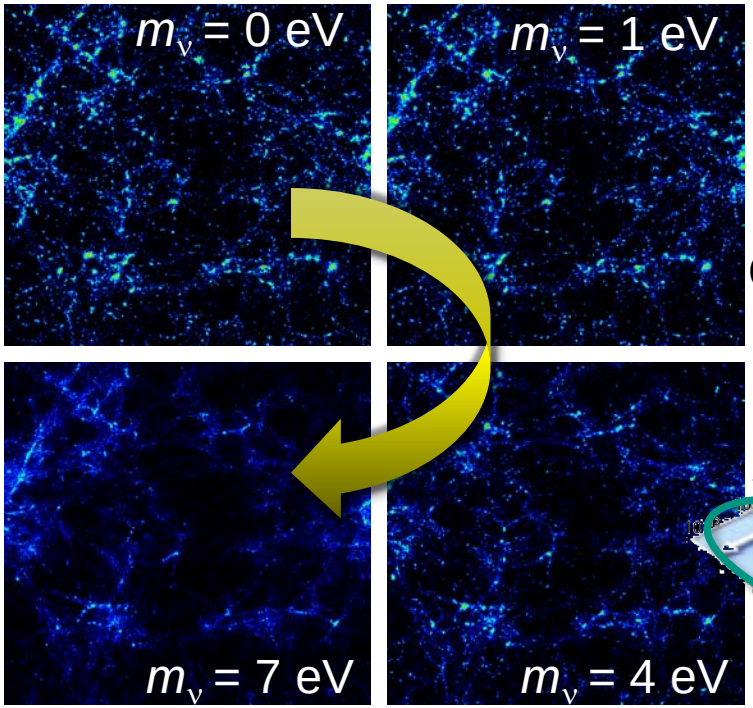
Motivation: ν´s in Astroparticle Physics

cosmology: role of ν´s as hot (warm) dark matter?

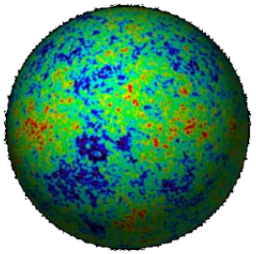
particle physics: origin and hierarchy of the ν-mass?
Majorana/Dirac, CP, sterile ν, ... ?



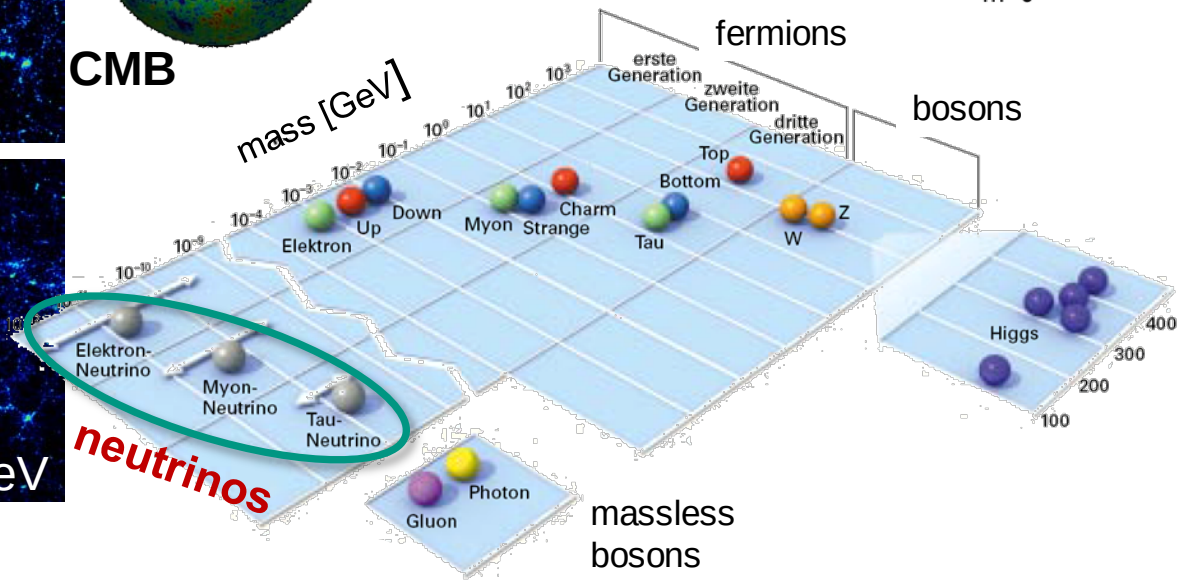
cosmology ⇔ **particle physics**



LSS



CMB



Current limits for the neutrino mass

Cosmology:
- LSS, CMB, …
- model dependent
- status: $\Sigma m_\nu < 0.4$ eV (0.3 – 2.0 eV)
- future sensitivity: 0.1 – 0.6 eV

$$\sum_{j=1}^{3} m_j$$

S. Hannestad et al., *JCAP 08* (2010) 001

Supernova:
- ToF measurement SN 1987A
- status: $m_\nu < 5.7$ eV (PDG 2006)
- future sensitivity: sub-eV ?

neutrino mass measurements

complementary measurements

0νββ-decay:
- eff. Majorana mass
- model dependent (NME)
- cancellation ? (Majorana phase α)
- status: $m_{\beta\beta} = 0.32$ eV ? (K.-K.)
- future sensitivity: 20 – 50 meV

$$\sum_{j=1}^{3} \left|U_{ej}\right|^2 \cdot e^{i\alpha_j} \cdot m_j$$

β-decay:
- eff. neutrino mass
- model independent (kinematics)
- status: $m_\beta < 2$ eV (Mainz, Troitsk)
- future sensitivity: 200 meV

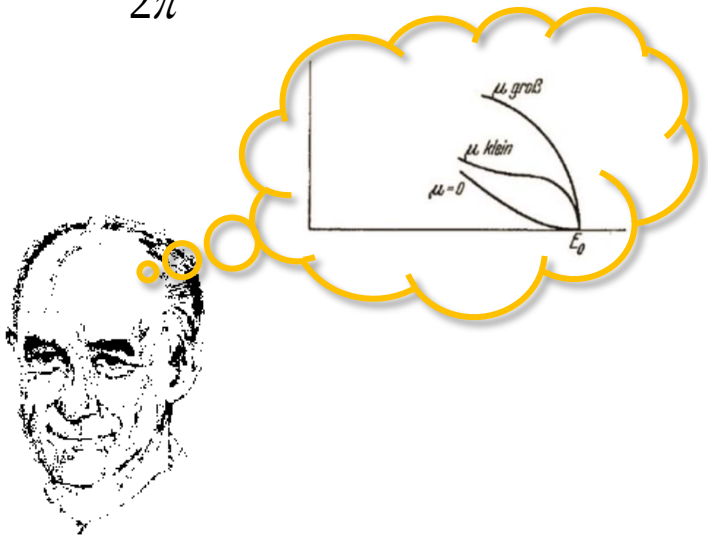
$$\sum_{j=1}^{3} \left|U_{ej}\right|^2 \cdot m_j$$

β-decay – Fermi theory & neutrino mass

β-decay kinematics close to endpoint E_0: model independent measurement of $m(\nu_e)$, based solely on **kinematic parameters & energy conservation**

$$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$$

$$G_F^2 \cdot \frac{m_e^5}{2\pi^3} \cdot \cos^2\theta_C \cdot |M|^2$$



observable m_β^2 effective ´electron-ν-mass´

$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$

´incoherent´ sum of the mass eigenstates m_i

Fermi function F(E,Z)

small modifications by final states, radiative & recoil corrections

E W Otten and C Weinheimer
Rep. Prog. Phys. **71** 086201 (2008)

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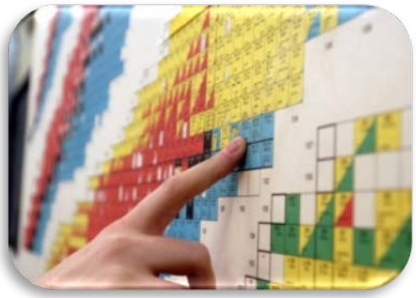
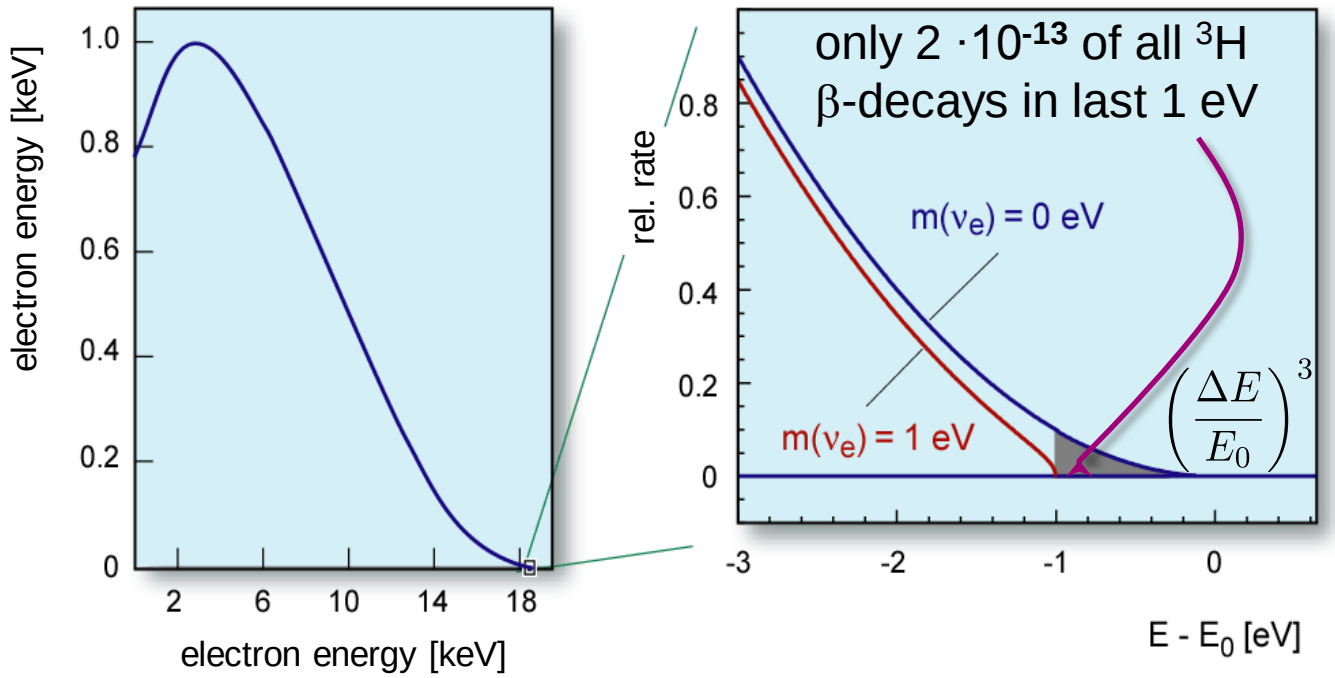
which isotope yields the highest β-intensity & ν-mass sensitivity?





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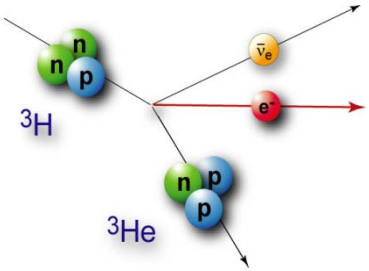
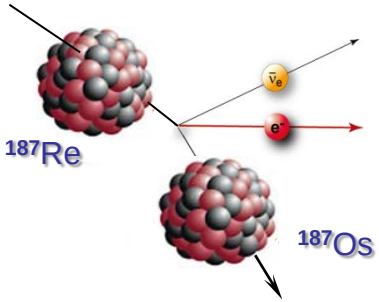


$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

ß-source requirements
short half life $t_{½}$ ↯ high luminosity
low endpoint energy E_0
superallowed/allowed transition
simple atomic/molecular structure

^{3}H: super-allowed	
E_0	18.6 keV
$t_{1/2}$	12.3 y

^{187}Re: unique 1st	
E_0	2.47 keV
$t_{1/2}$	43.2 Gy



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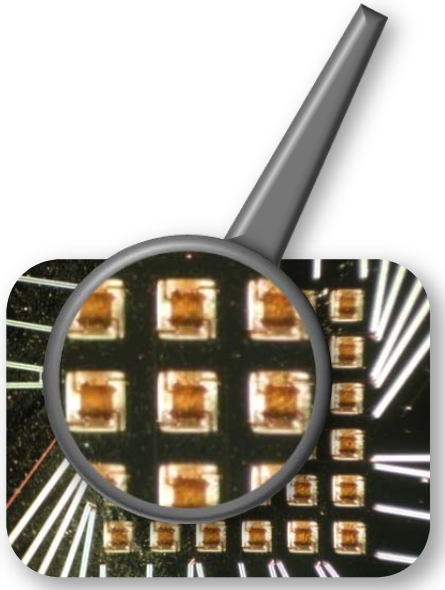
which detector?

β-detection requirements
large solid angle (~2π)
low background rate
high energy resolution (~eV)
short dead time, no pile up

spectrometer	calorimeter
external β-source	β-source = detector
β-source: ^{3}H	β-source: ^{187}Re, ^{163}Ho

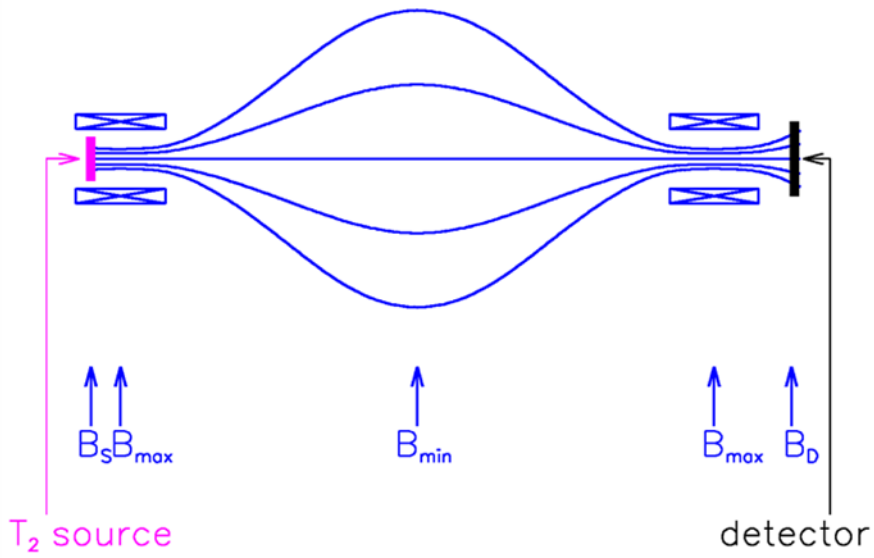


Principle of the MAC-E-Filter

Magnetic Adiabatic Collimation + Electrostatic Filter

A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345

- **Two supercond solenoids compose magnetic guiding field**
- **Electron source (T_2) in left solenoid**
- **Detector in right solenoid**



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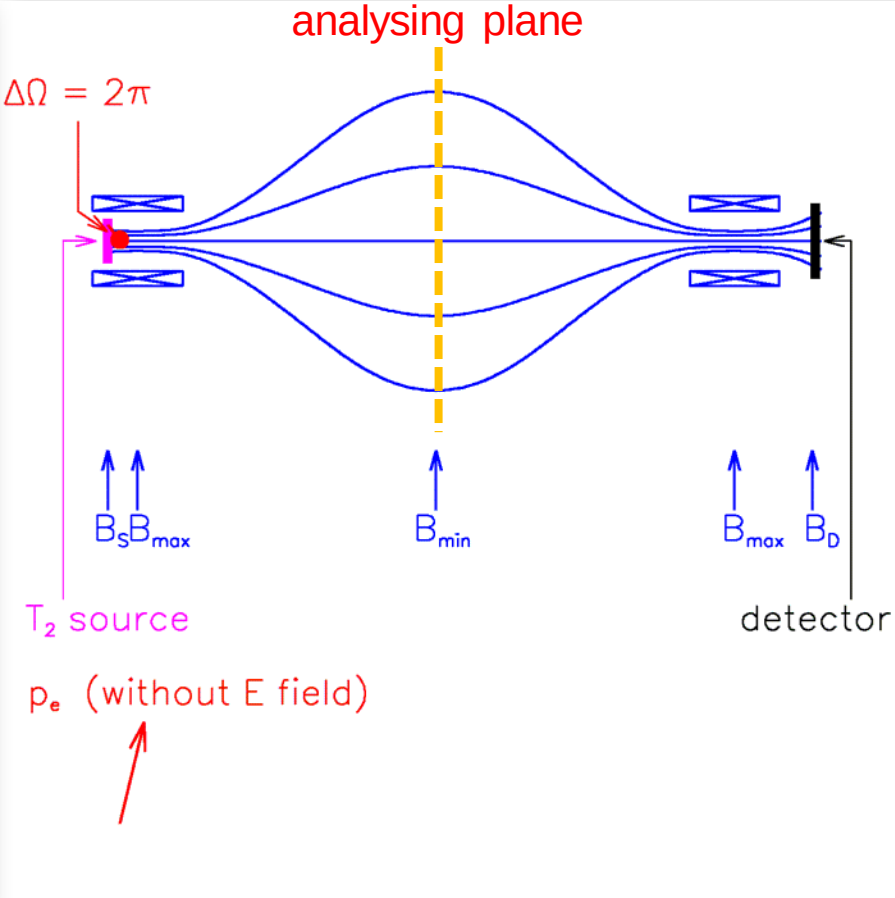
- **e^- magnetically guided**
  - **cyclotron motion**
- **adiabatic transformation:**
  - **$\mu = E_\perp/B$ = const. (magn. moment)**
  - **parallel e^- beam (analysing plane)**



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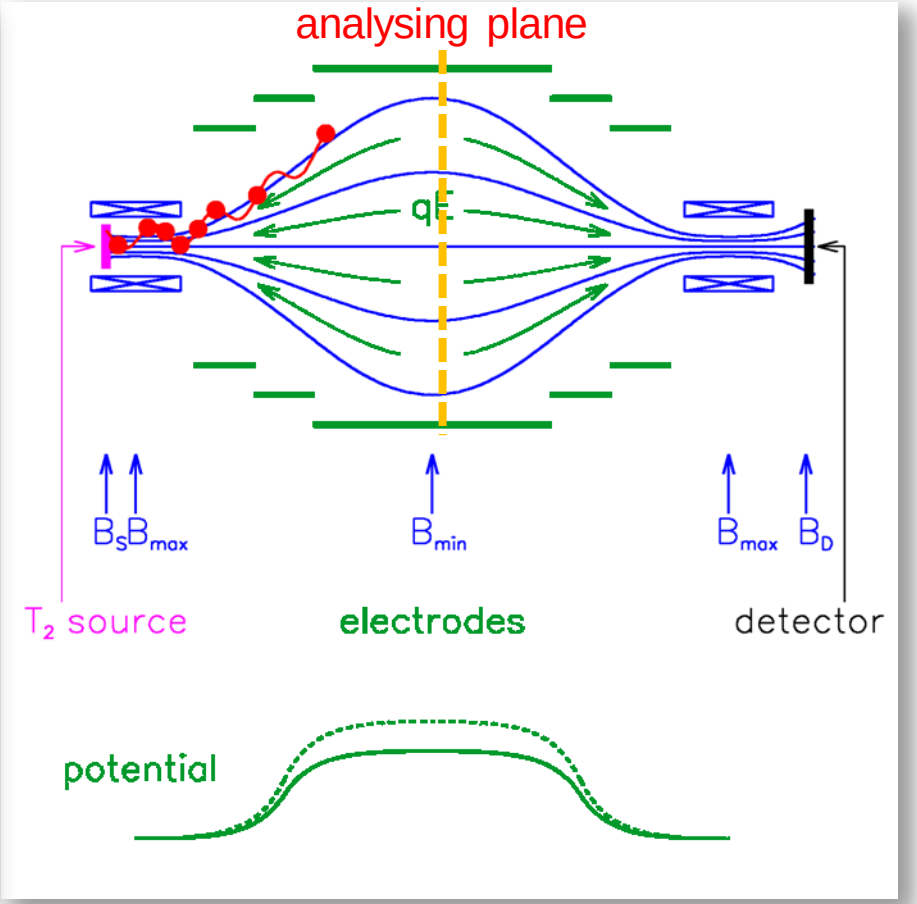
  - **parallel e^- beam (analysing plane)**
- **Energy analysis by electric field**
  - **$\Delta E = E \cdot B_{min}/B_{max}$ (magn. moment)**
  - **$\Delta E = E \cdot A_{src}/A_{ana}$ (magn. fluxtube)**

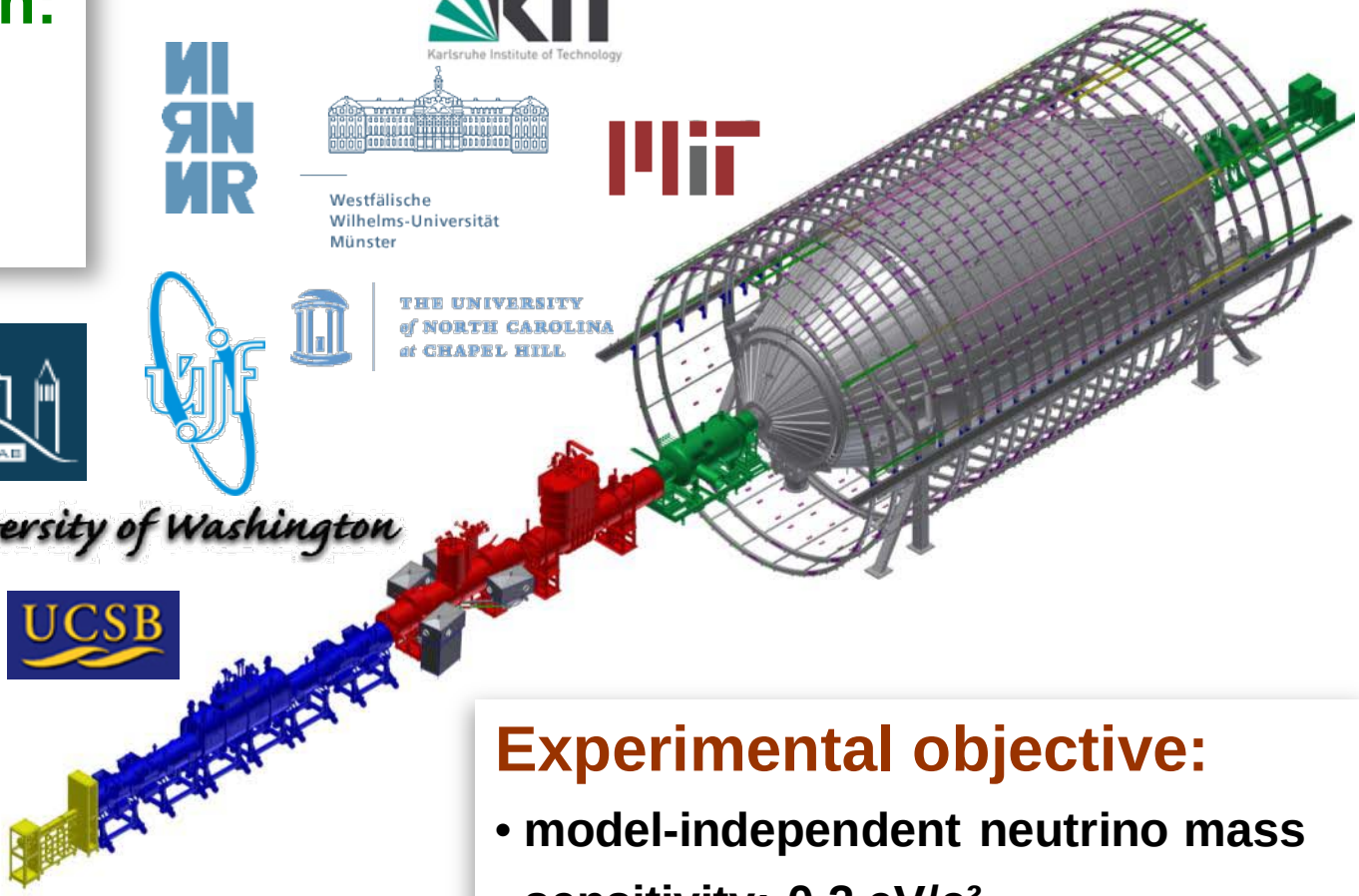


The KATRIN Experiment @ KIT

(KArlsruhe TRItium Neutrino experiment)

Collaboration:

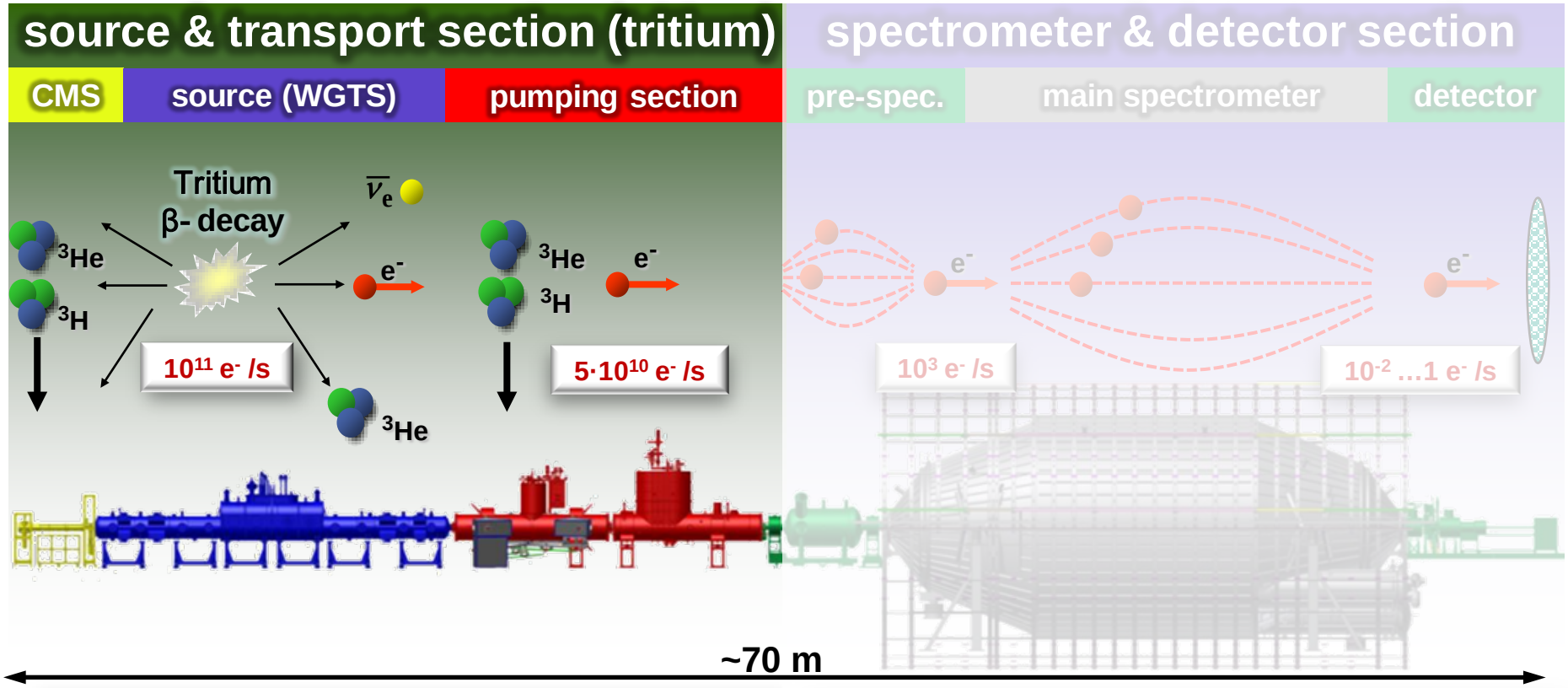
- 130 scientists
- 5 countries
- 14 institutions



Experimental objective:

- model-independent neutrino mass
- sensitivity: 0.2 eV/c²
- source: gaseous tritium (β-decay)

KATRIN Setup and Requirements



- $<10^{-3}$ stability of tritium column density ρd
- tritium suppression factor $>10^{14}$
- effective removal of ions ($R = 10^8$)
- fully adiabatic (meV scale) transport of e^-

- energy resolution = 0.93 eV
- absolute energy scale: ppm accuracy
- avoid particle storage in Penning-like traps
- background rate $< 10^{-2}$ cps

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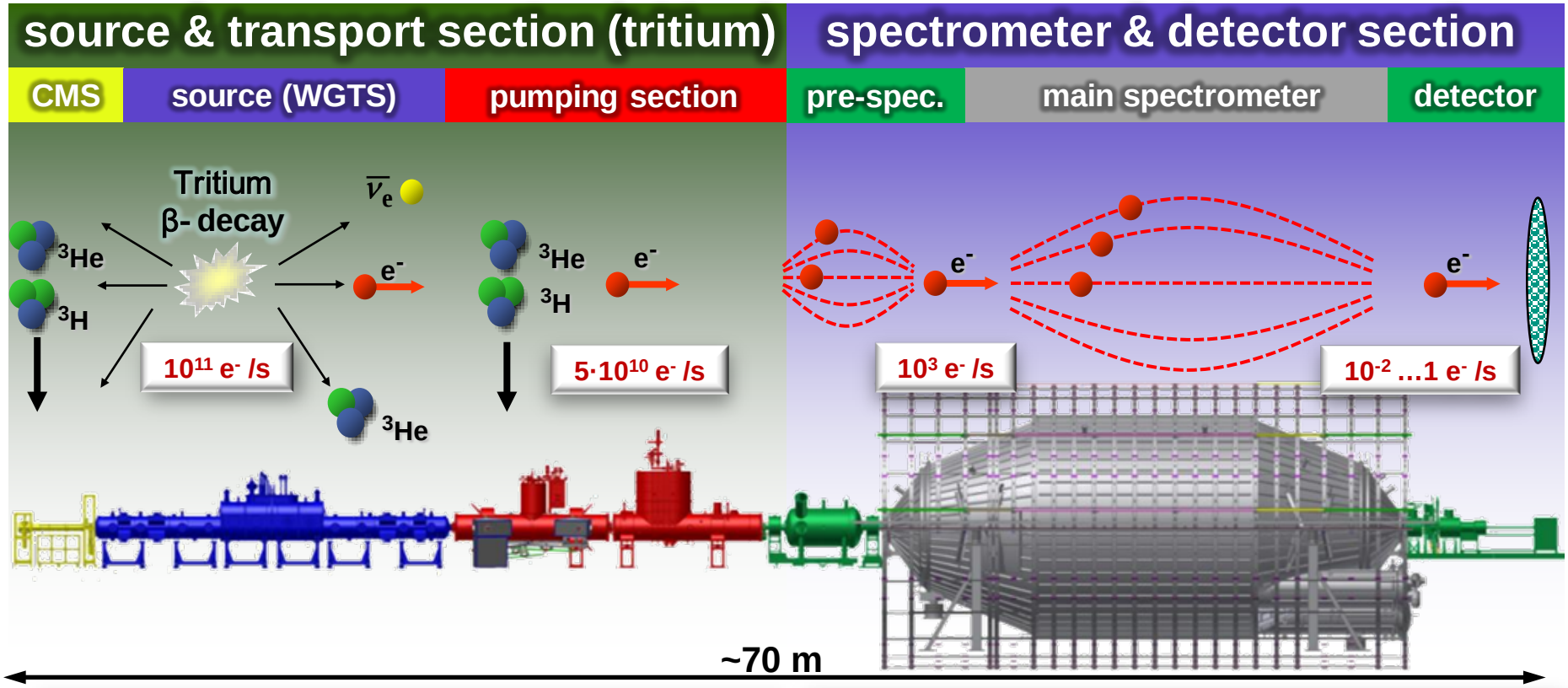

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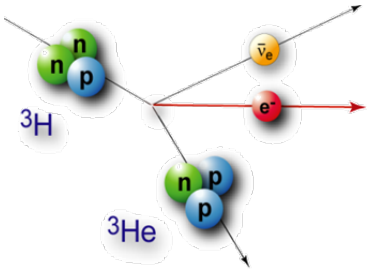
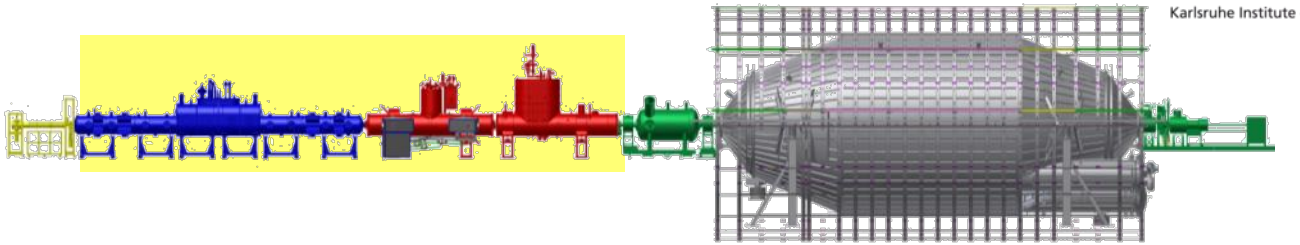
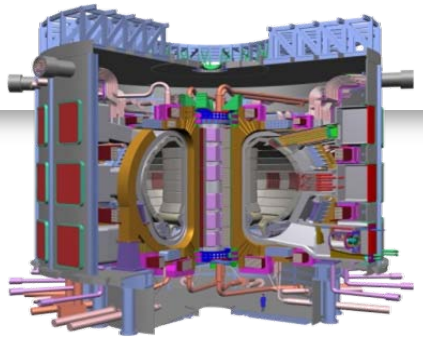


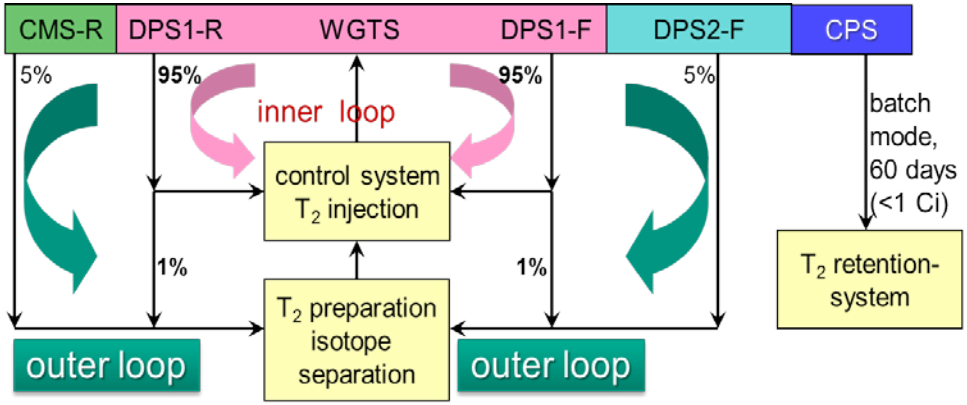
Tritium Source: Loop System



KATRIN tritium throughput per year is equivalent to ITER fusion facility

- tritium source is operated as closed cycle:
- thoughput of 40 kg/year





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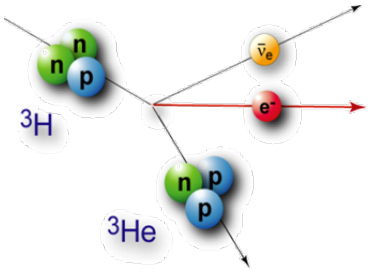
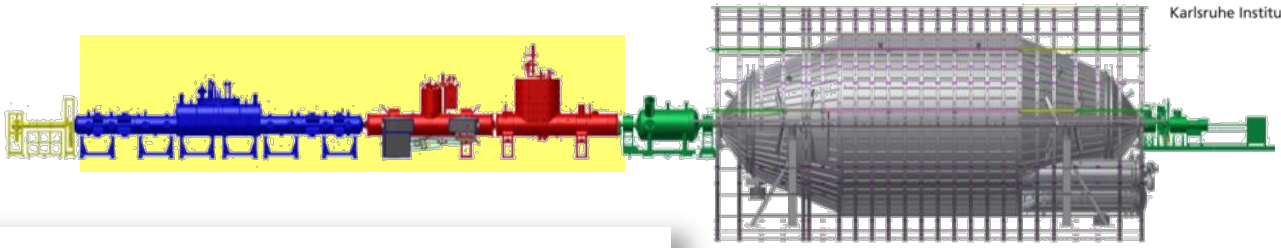
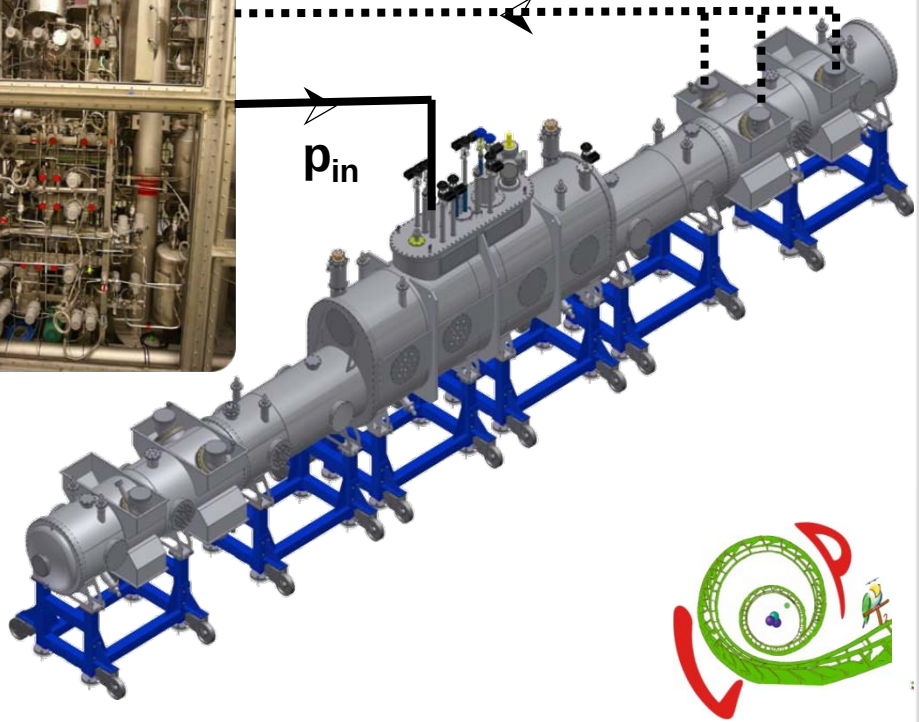




10^{-4} stability for p_{in} achieved in test set-up



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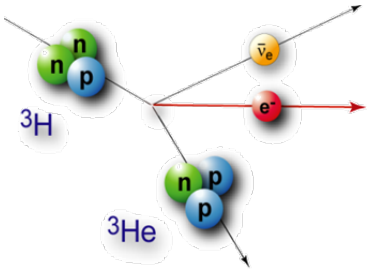
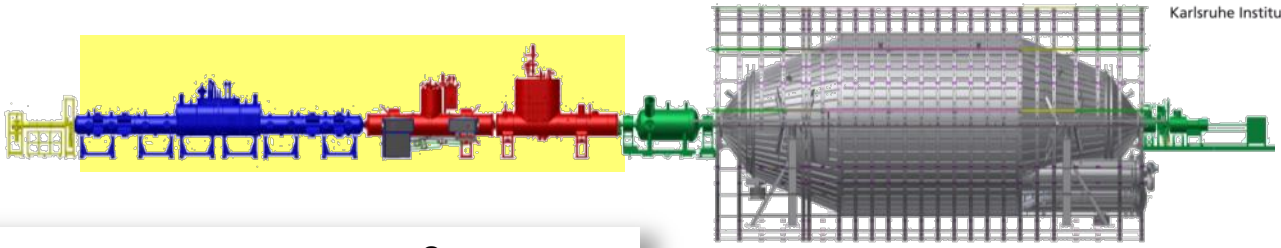
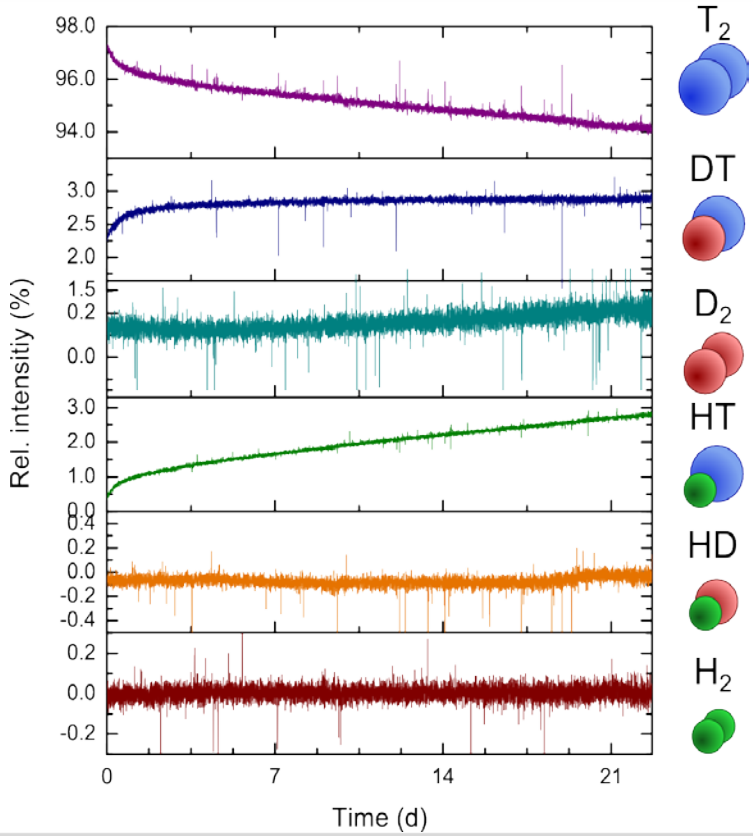
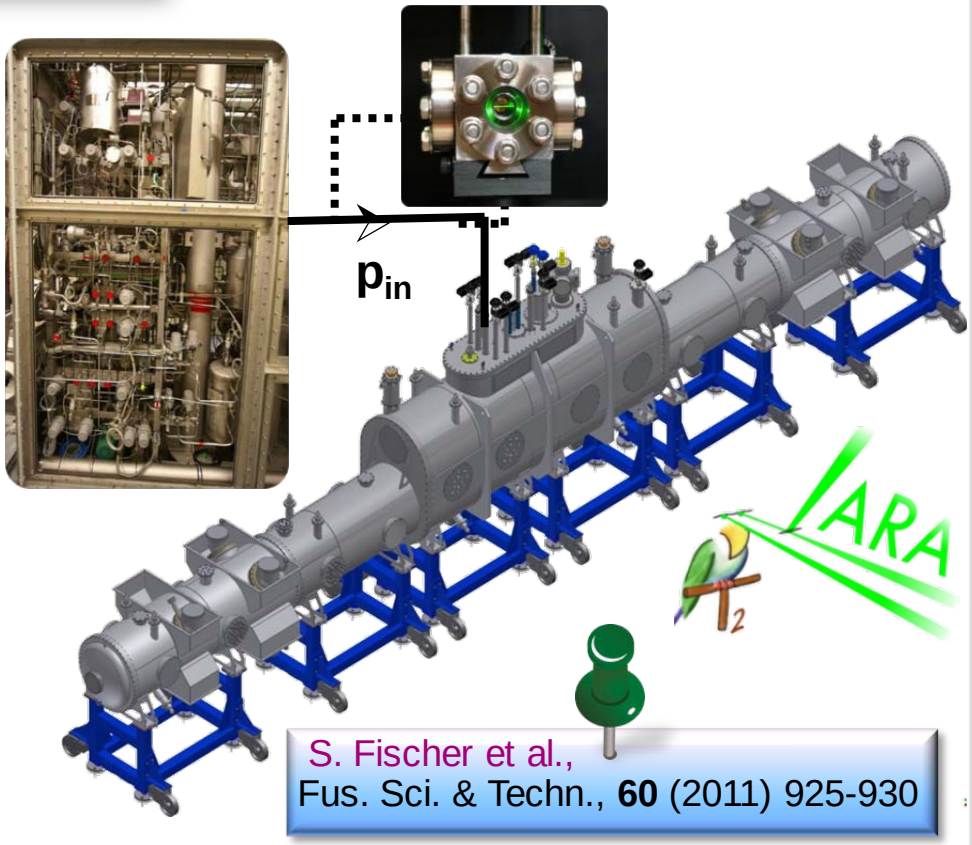


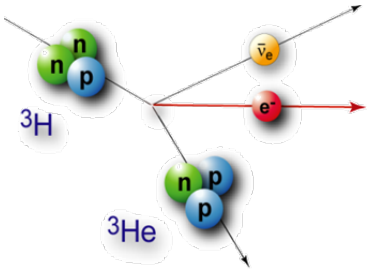


Laser-Raman spectroscopy: 10^{-3} in 60 s

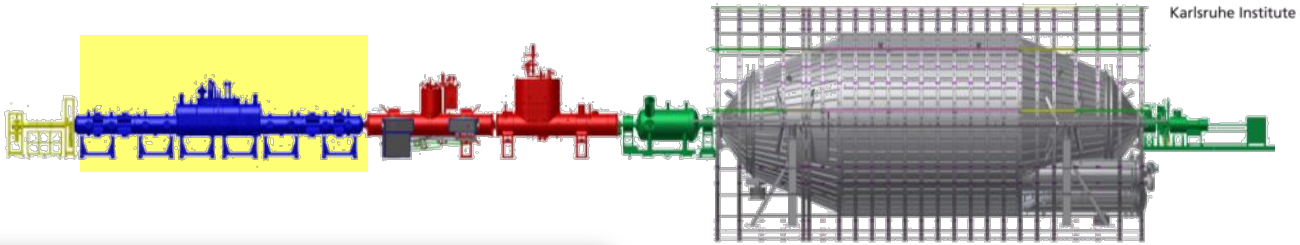




S. Fischer et al.,
Fus. Sci. & Techn., **60** (2011) 925-930



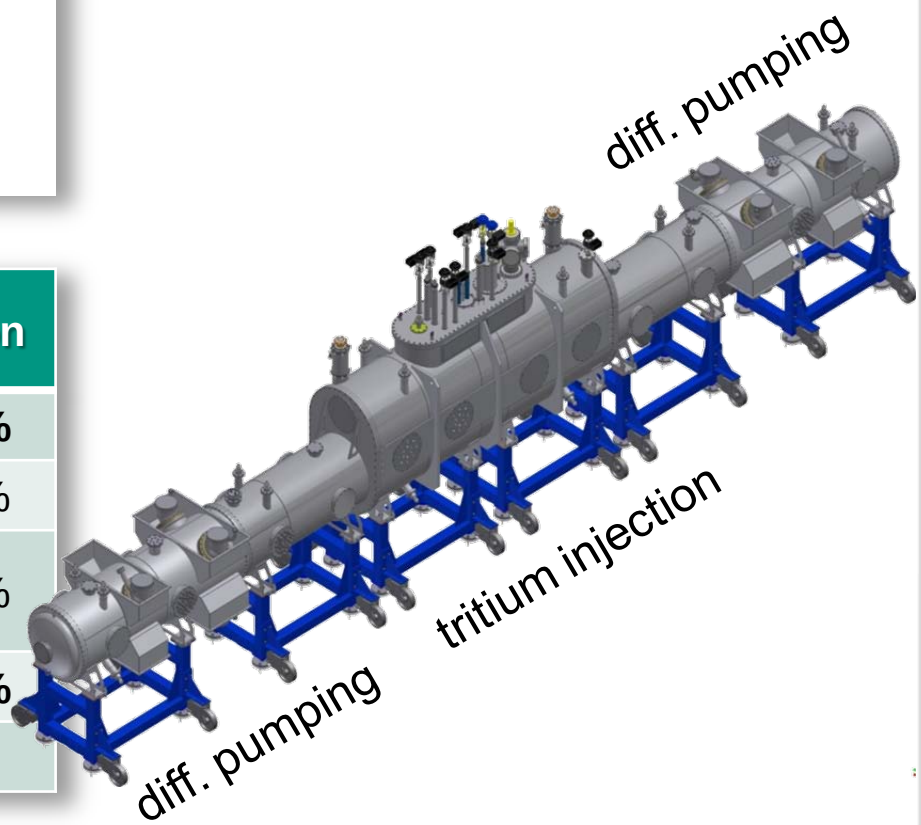
Tritium Source: WGTS



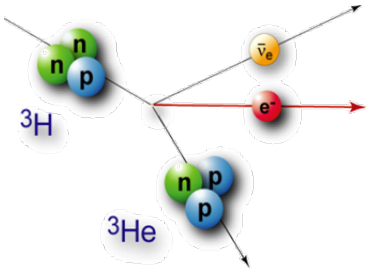
Windowless Gaseous Tritium Source

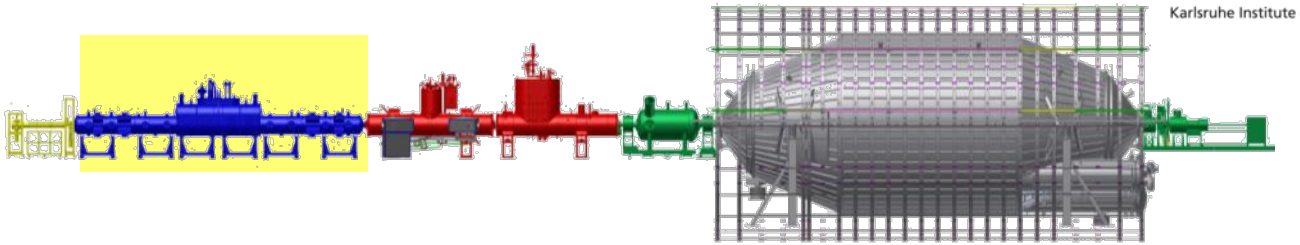
- **molecular tritium source**
- **high luminosity**
- **high stability**

WGTS	design value	precision
luminosity	**1.7×10^{11} Bq**	**± 0.1 %**
injection rate	5×10^{19} mol/s	± 0.1 %
column density ρd	5×10^{17} mol/cm^2	± 0.1 %
tritium purity	**> 95%**	**± 0.1 %**
magnetic field	3.6 T	± 2%



Tritium Source: Demonstrator





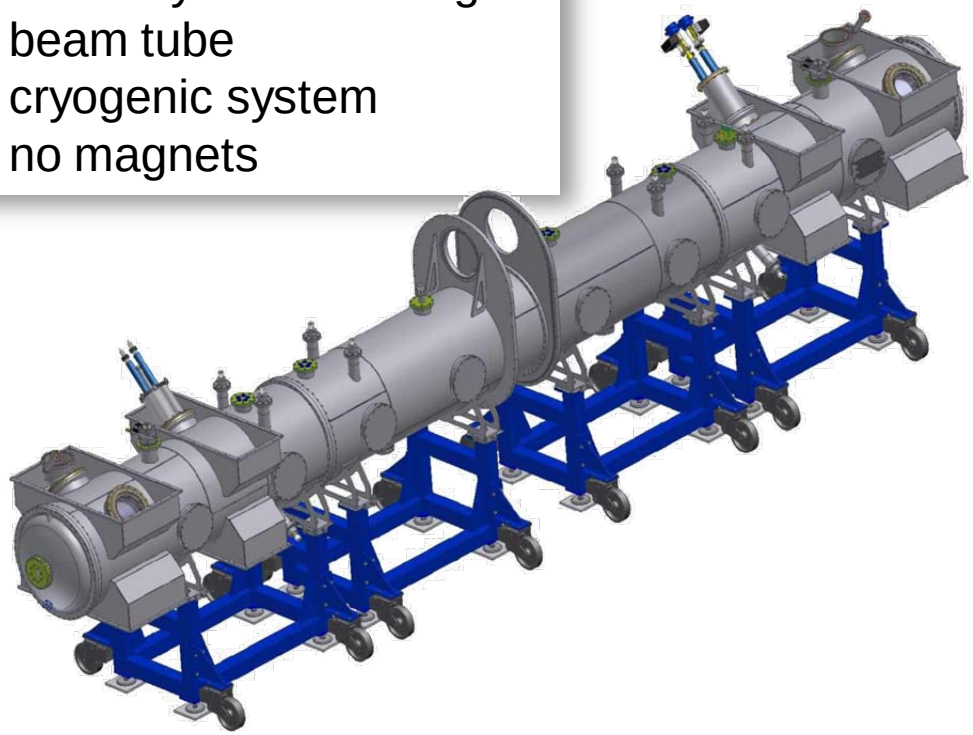
stainless steel beam tube Ø=90mm

2-phase Neon

2-phase Neon

Components of WGTS:

- outer cryostat housing
- beam tube
- cryogenic system
- no magnets



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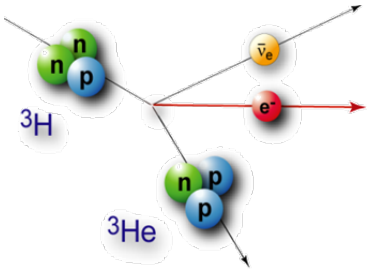
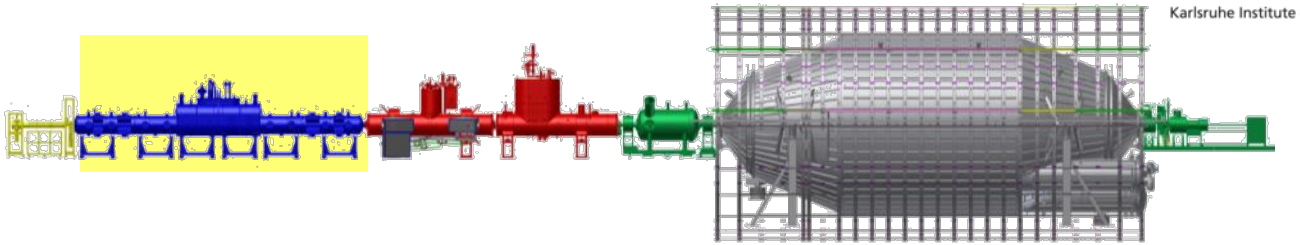
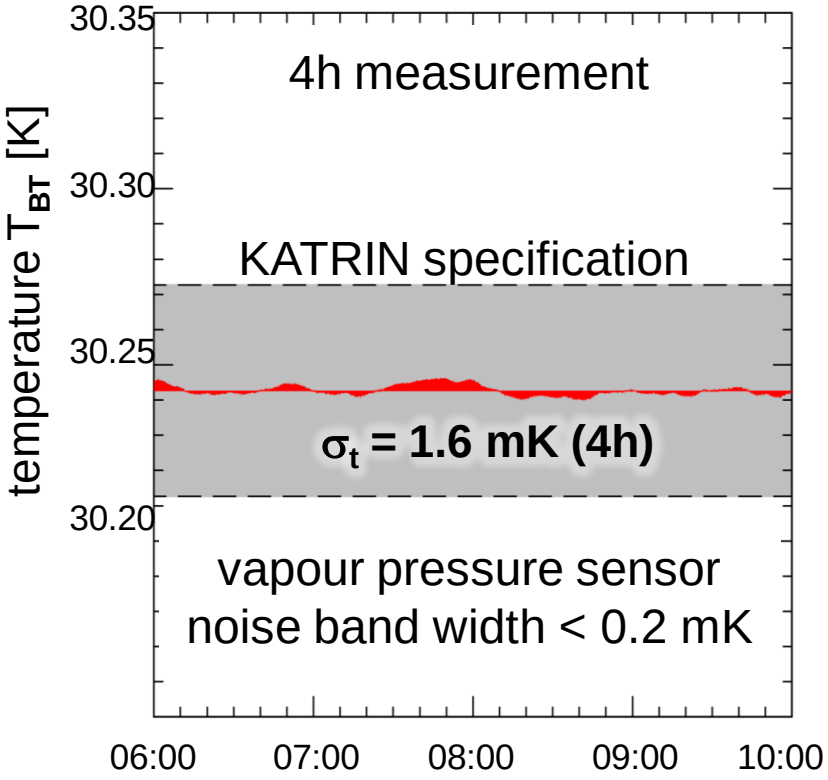
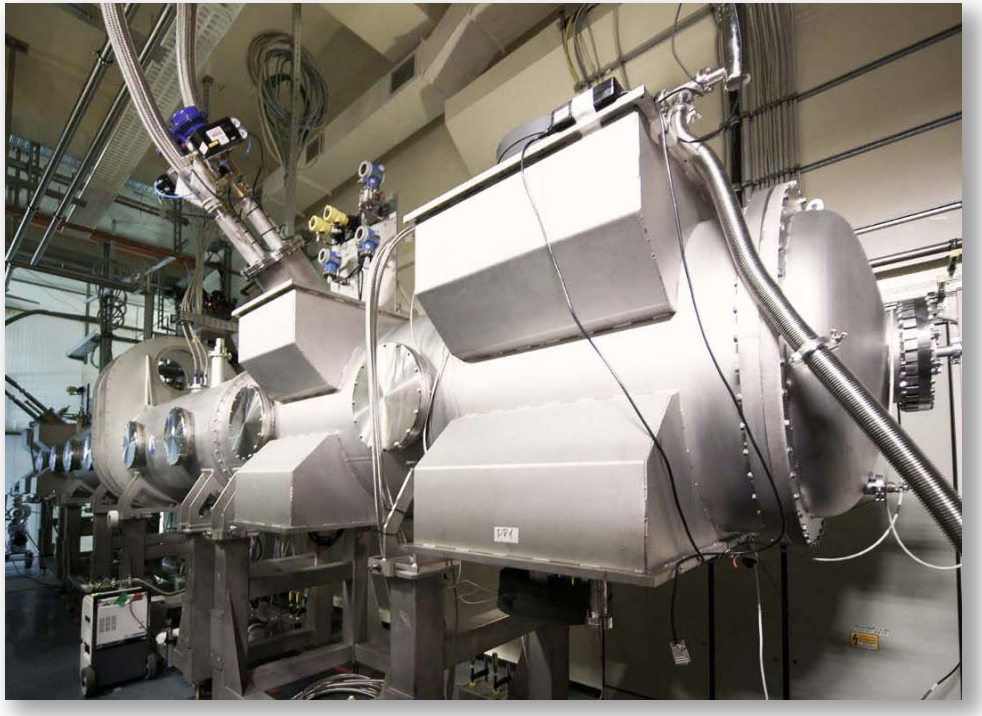
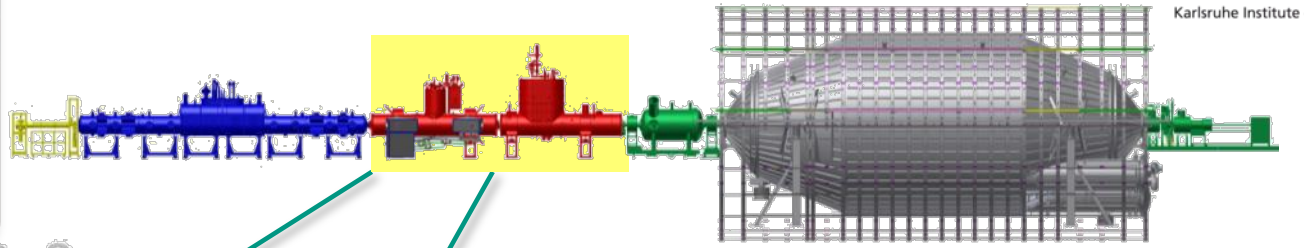


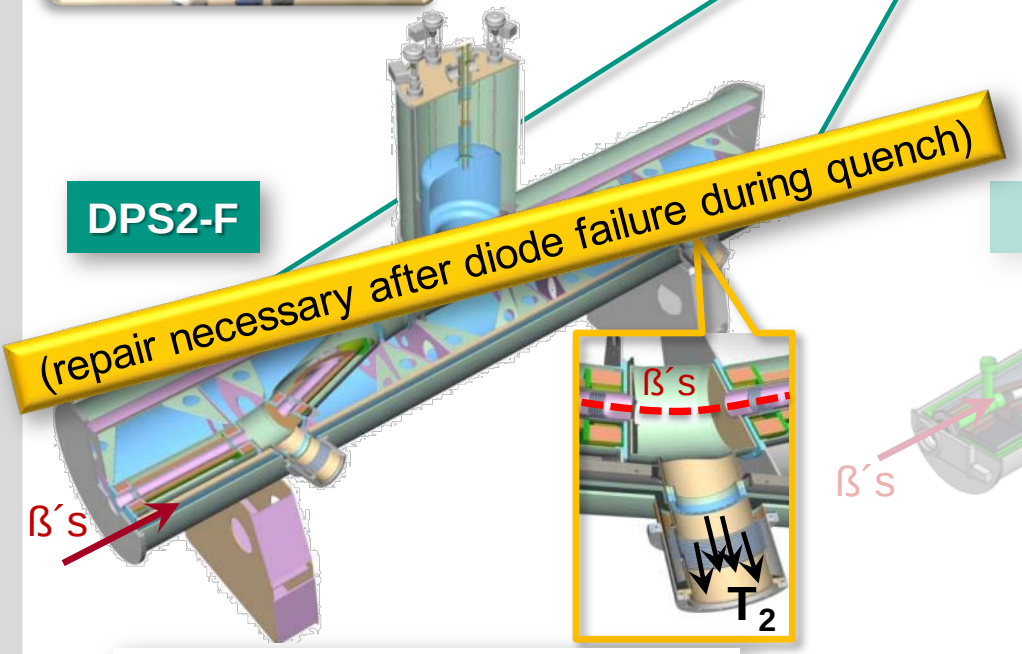


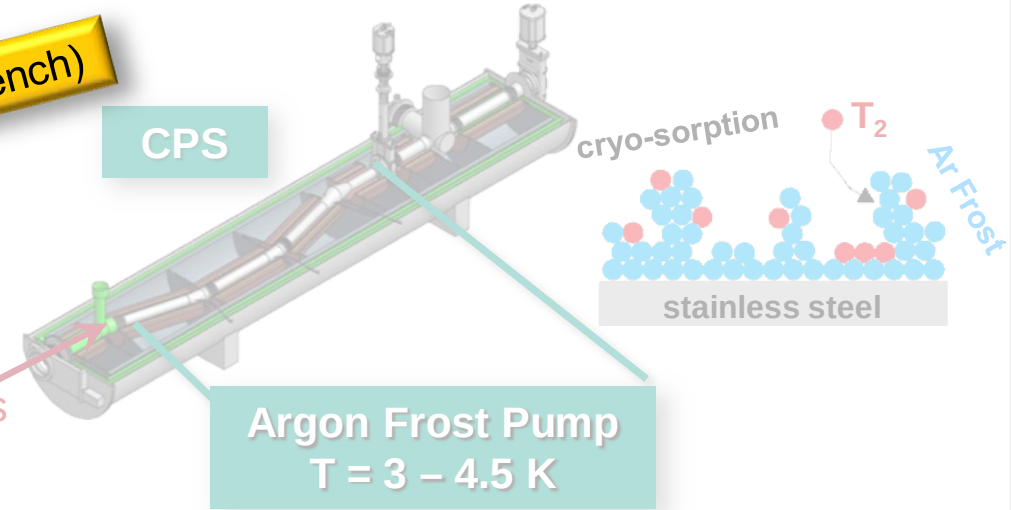




Transport & Pumping Sections







- active pumping, 4 TMPs
- Tritium retention 10^5
- magnetic field: 5.6 T
- on-site since 08/2009

- pumping by cryo-sorption
- Tritium retention $>10^7$
- magnetic field: 5.6 T
- on schedule: delivery 2013

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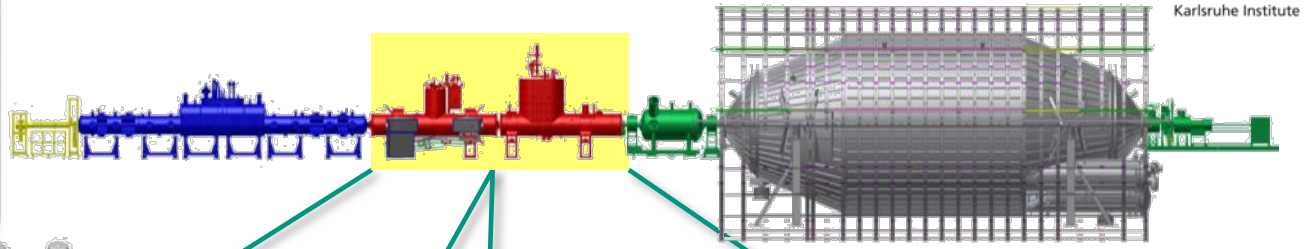
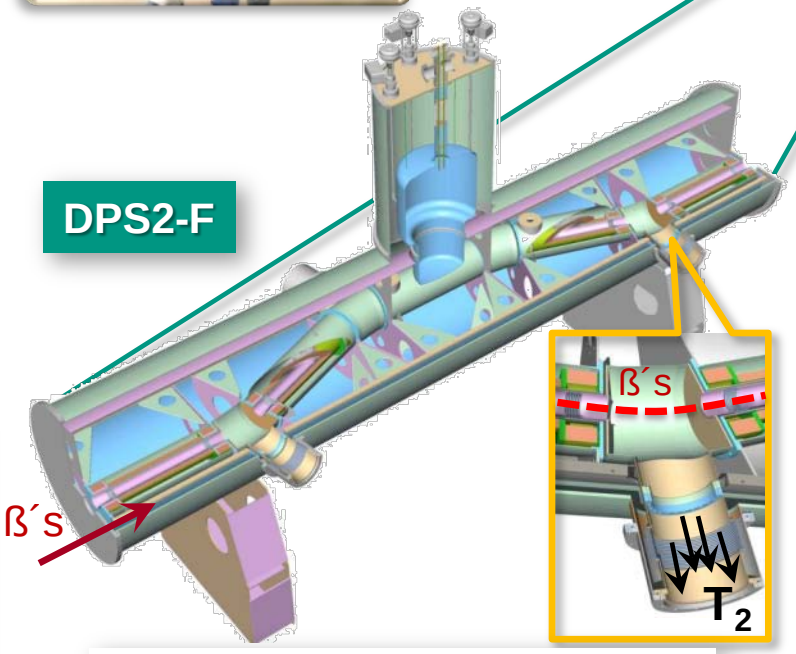
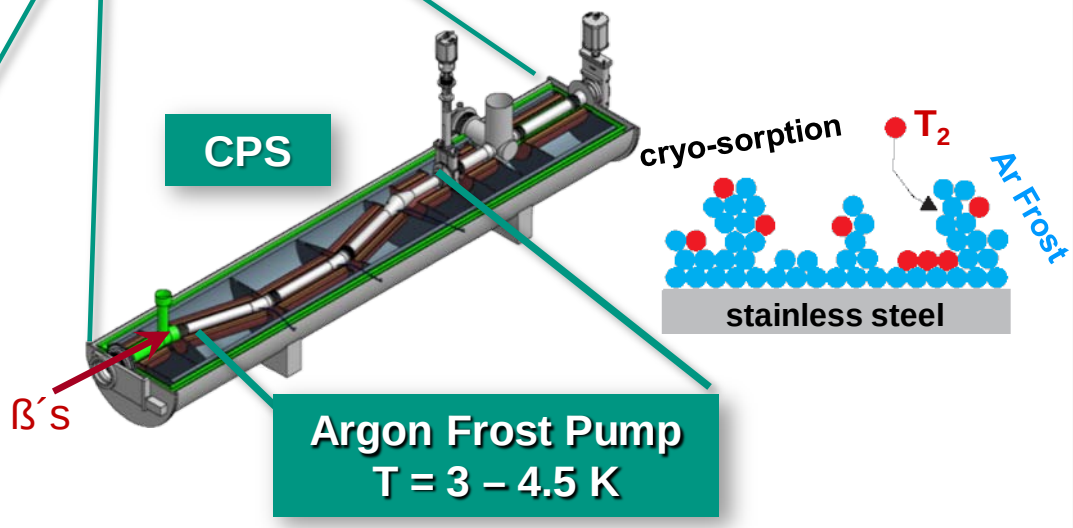


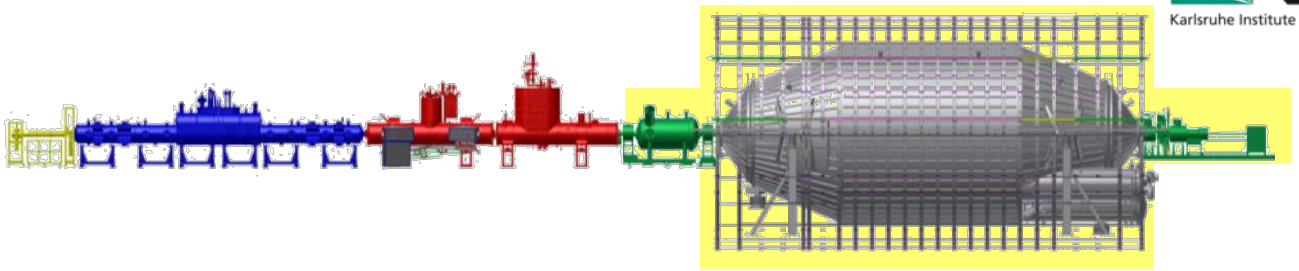




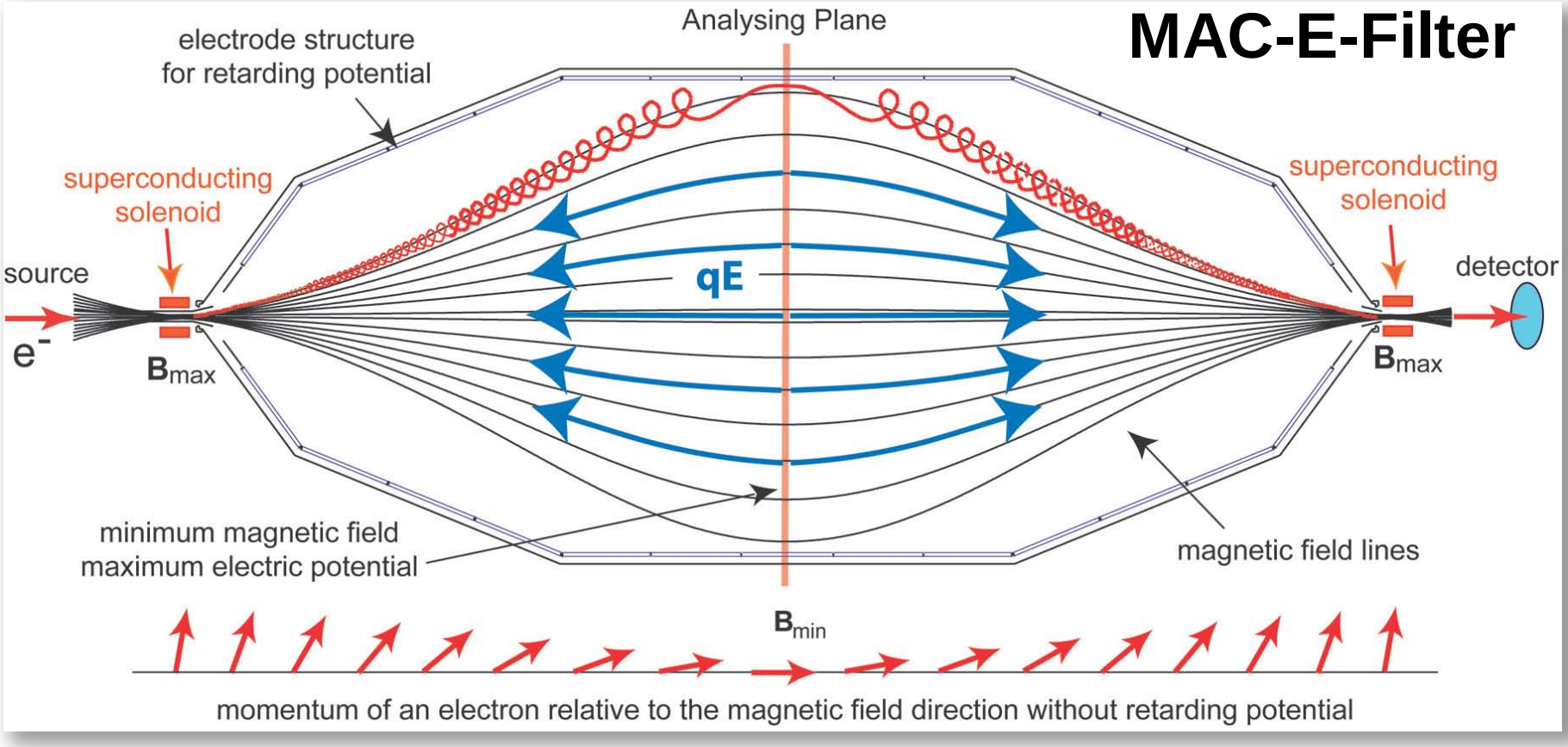
- active pumping, 4 TMPs
- Tritium retention 10^5
- magnetic field: 5.6 T
- on-site since 08/2009

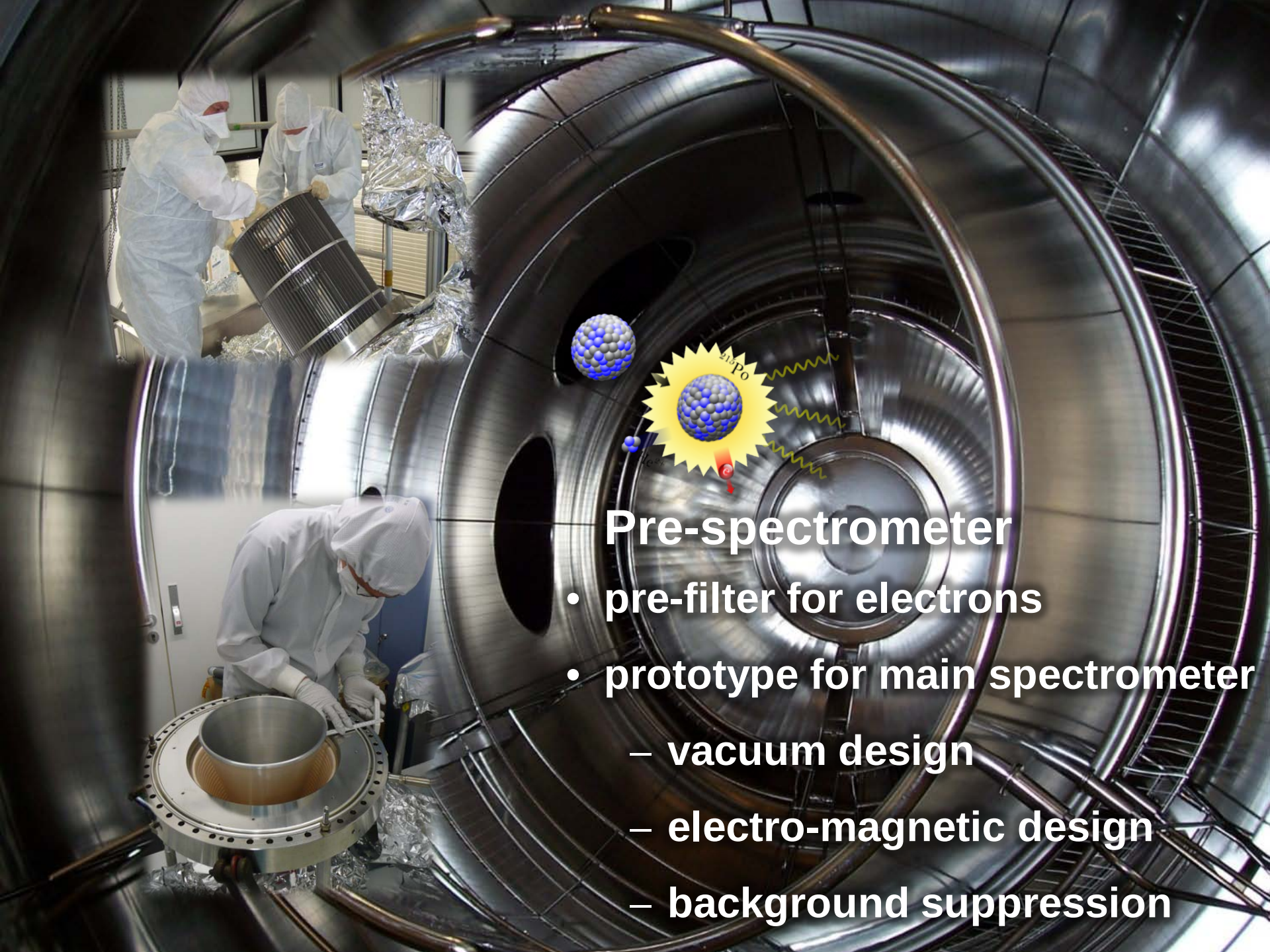
- pumping by cryo-sorption
- Tritium retention $>10^7$
- magnetic field: 5.6 T
- on schedule: delivery 2013

Spectrometer and Detector Section



MAC-E-Filter



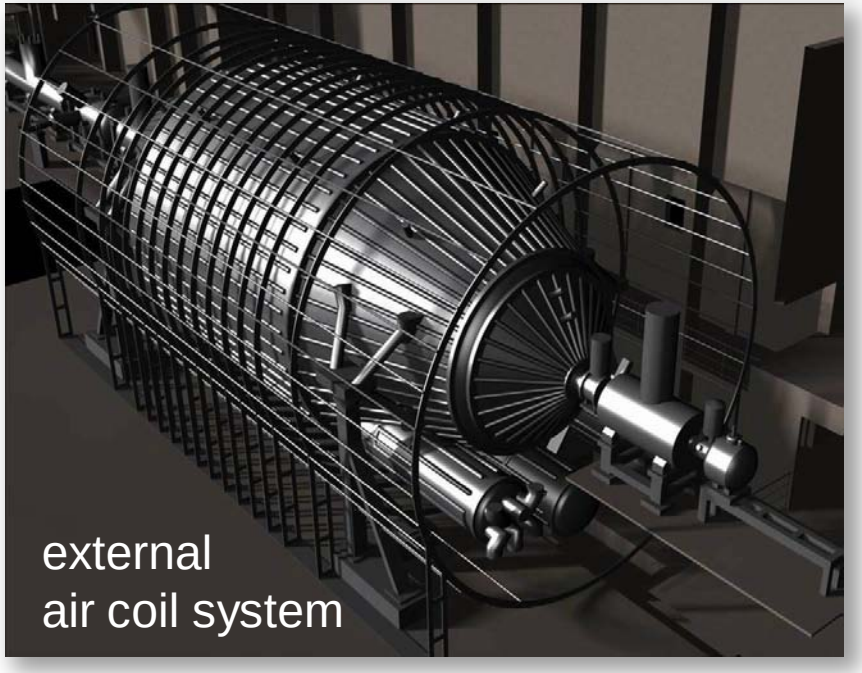


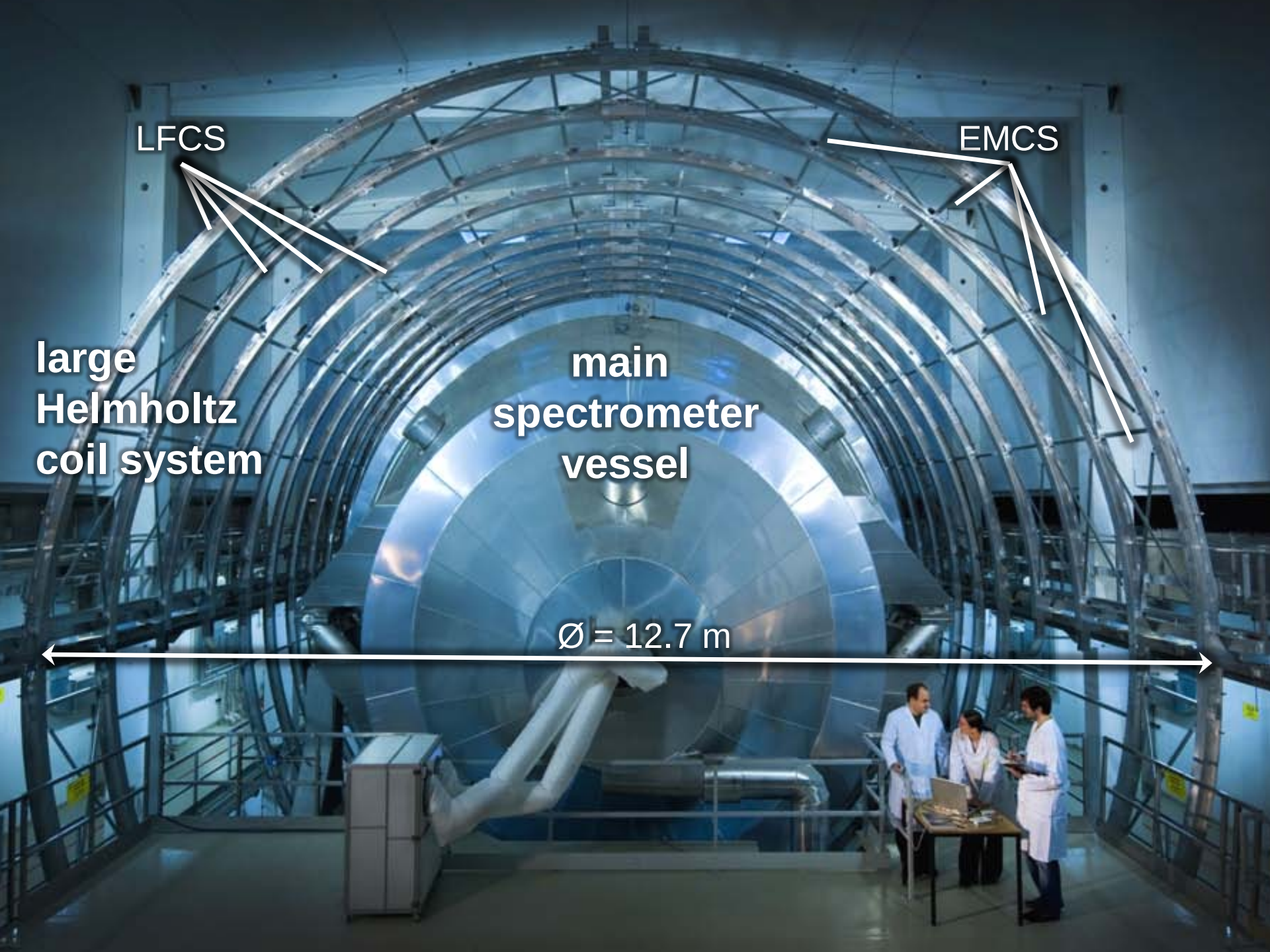
Pre-spectrometer

- pre-filter for electrons
- prototype for main spectrometer
  - vacuum design
  - electro-magnetic design
  - background suppression

Main Spectrometer

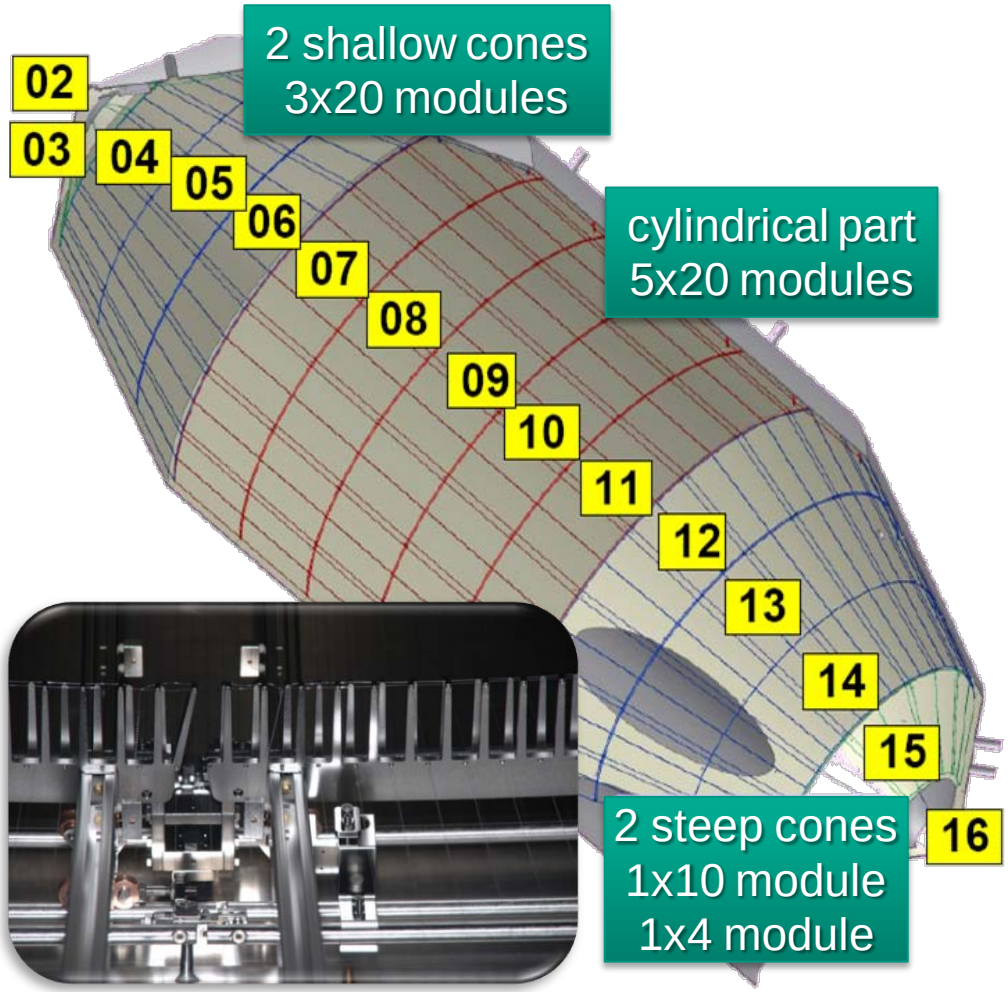
- **Ultra-precise energy analysis of electrons close to endpoint E_0**
  - energy resolution: **ΔE = 0.93 eV** (0% → 100% transmission) @ 18.6 keV
- **Features:**
  - Ø = 10 m, length = 24 m, surface = 690 m², volume = 1240 m³,
  - p < 10^{-11} mbar (world´s largest UHV recipient)
  - inner wire electrode system & external Helmholtz-type air coil system




LFCS
EMCS
large
Helmholtz
coil system
main
spectrometer
vessel
Ø = 12.7 m

Inner Electrode System – Objectives

double-layered inner wire electrode system



#1: background suppression

inelastic reactions of cosmic μ

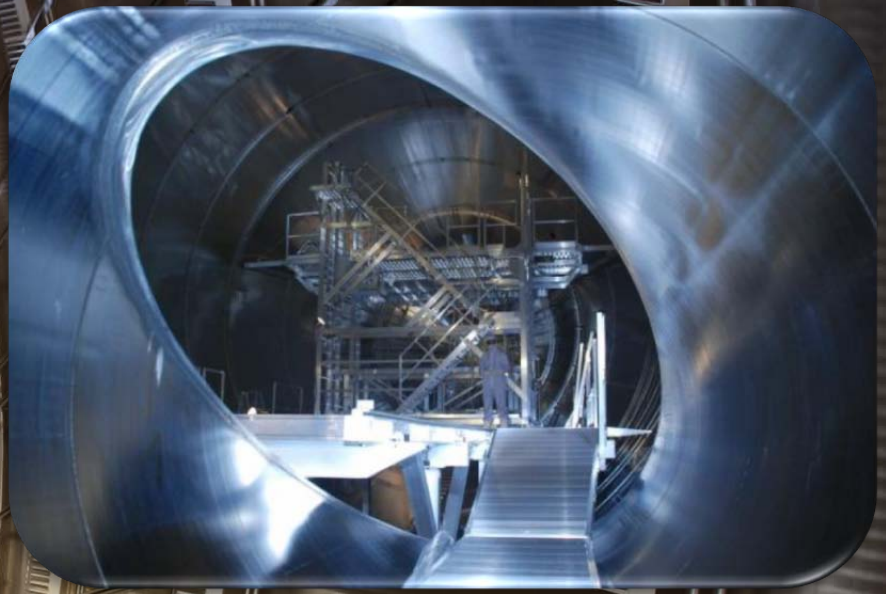
↳ low-energy secondary electrons from the 690 m² inner surface are **repelled** electrostatically

#2: fine forming of retarding field

- **precision HV power supplies:** intrinsic HV precision ~**1 ppm**
- **dipole/ECR mode**: eject particles stored in **Penning traps**

≈24,000 wires (in 248 frames)

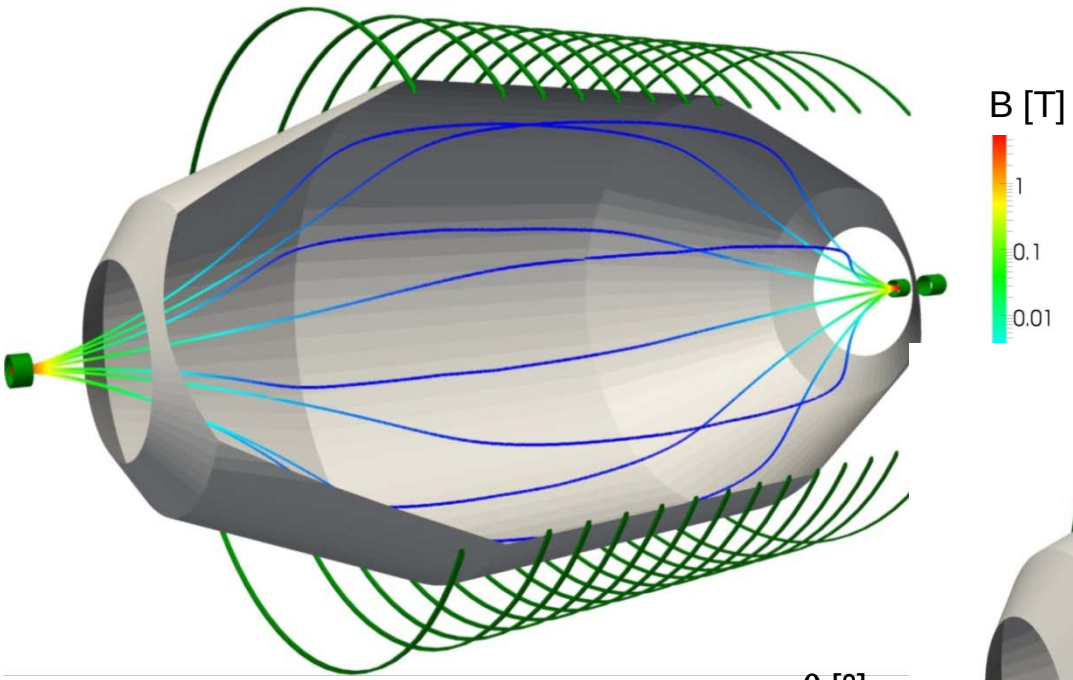
Main Spectrometer: Inner Electrode System



Jan. 31, 2012

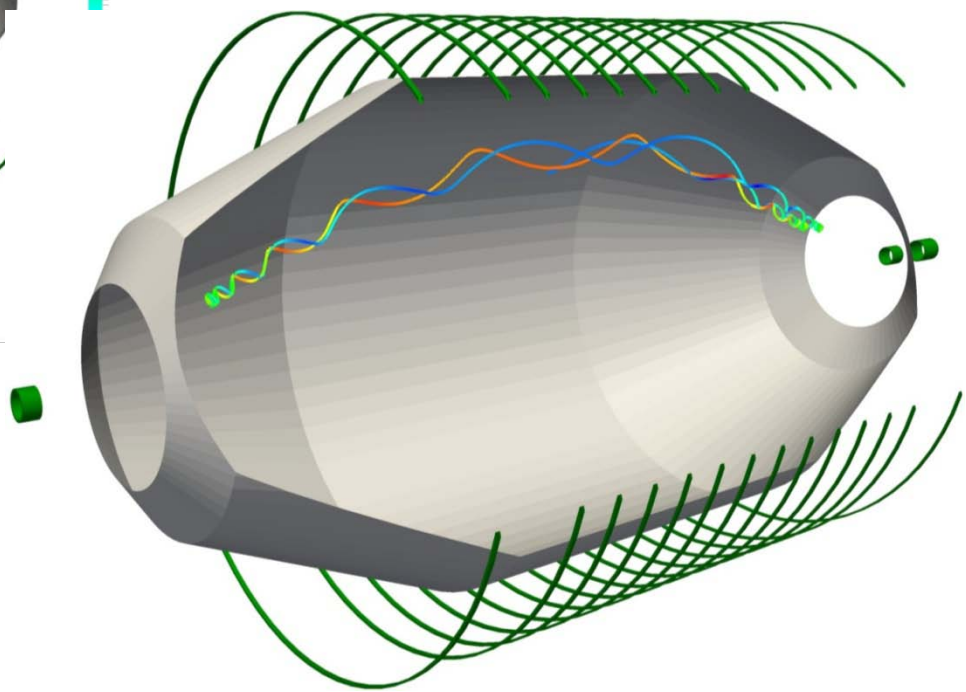
KASSIOPEIA: signal & background

KASSIOPEIA: KATRIN simulation code for electron trajectories



transmission of β-electrons:

- magnetic guiding
- electrostatic retardation



trapping of bg-electrons:

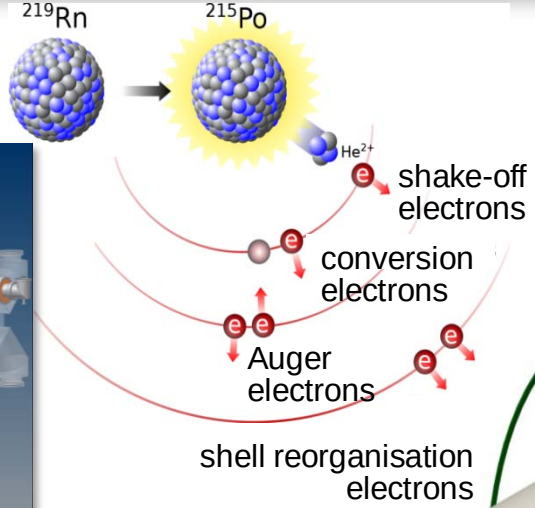
- spectrometer acts as a magnetic bottle,
- long storage time (h)

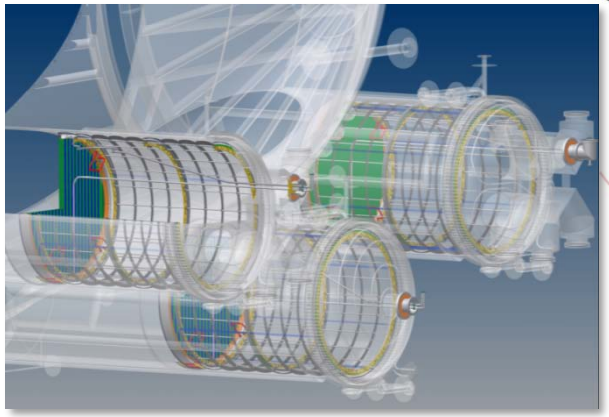
Radon induced background

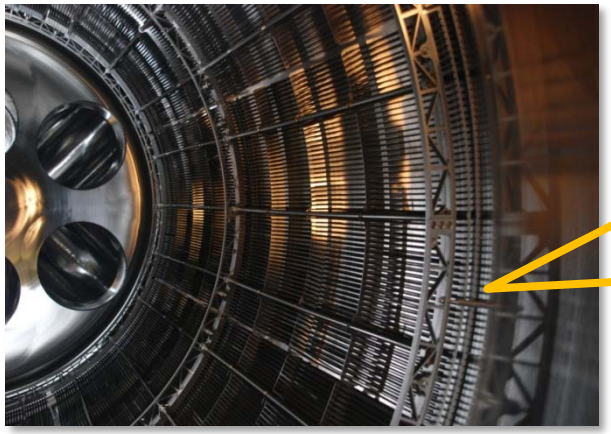
^{219}Rn emanation from St707 NEG getter strips (3 x 1 km) in pump ports of spectrometer

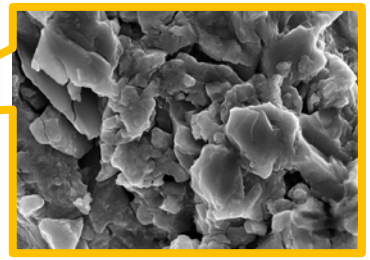
F.M. Fränkle et al., Astropart. Phys. **35** (2011) 128

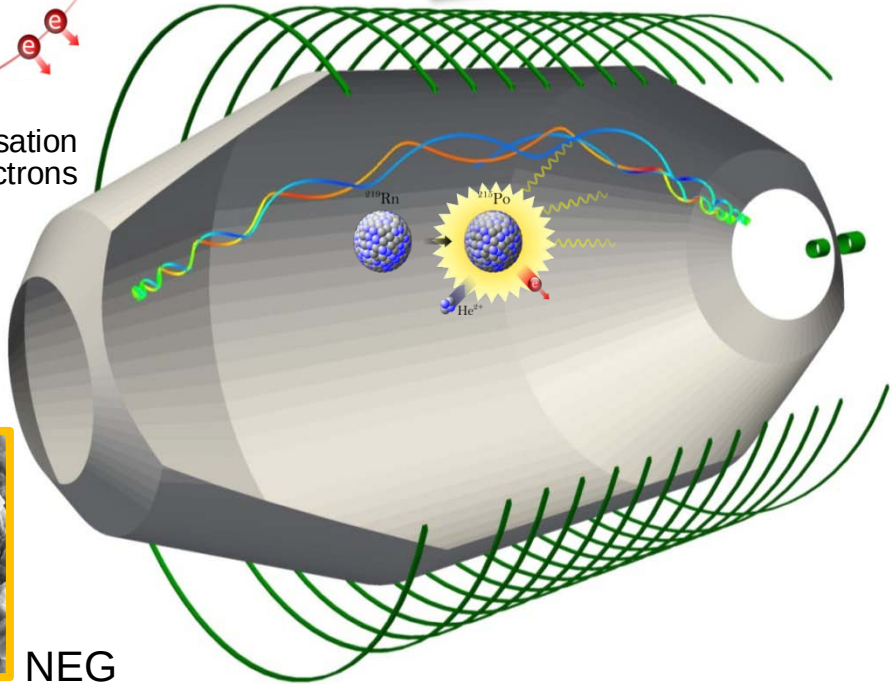
S. Mertens, PhD thesis KIT (2012)







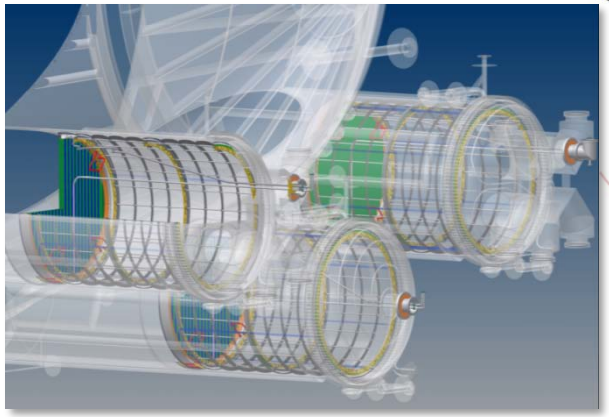


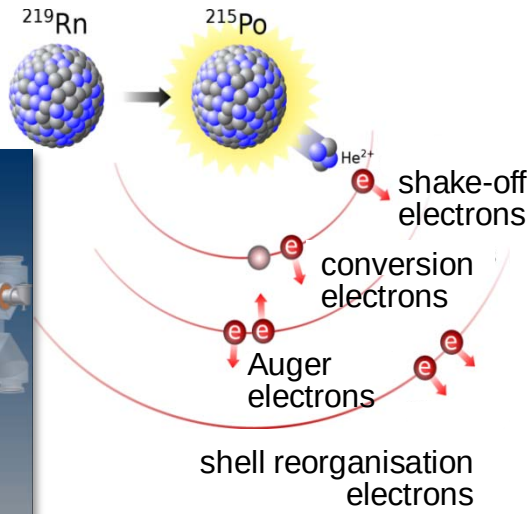


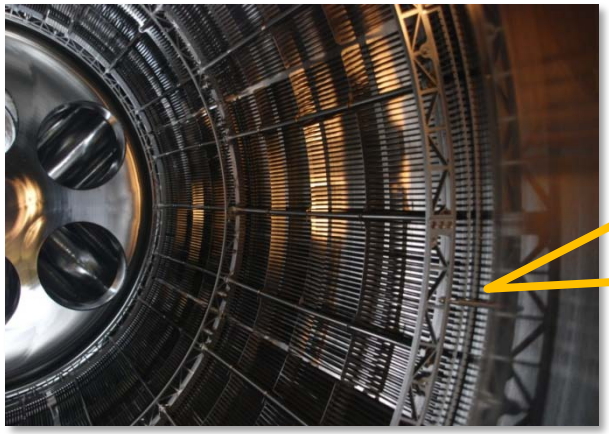
NEG

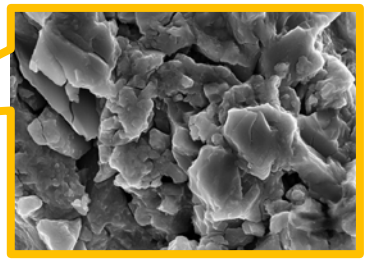
Radon induced background

Passive background reduction: **LN2-cooled baffles** to cryosorb ^{219}Rn

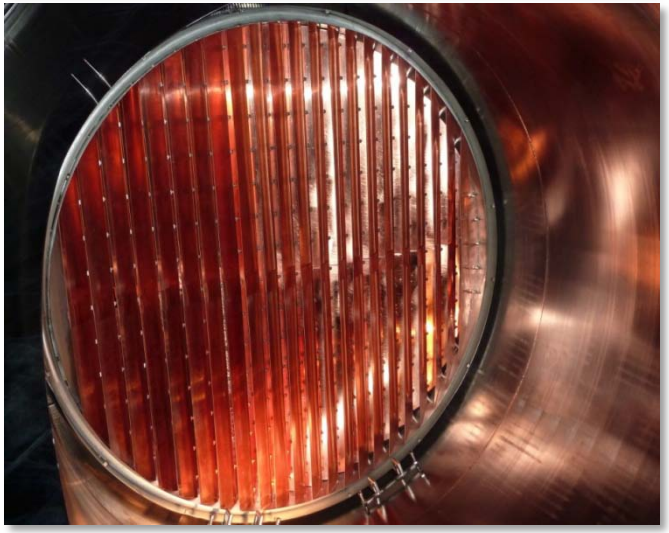








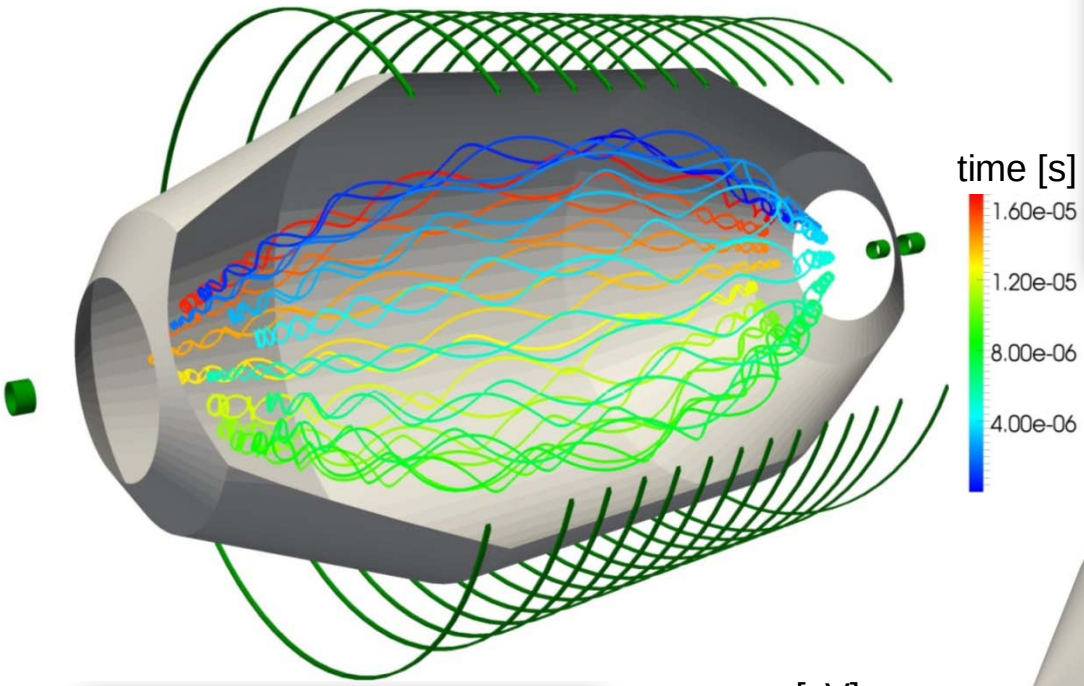
NEG

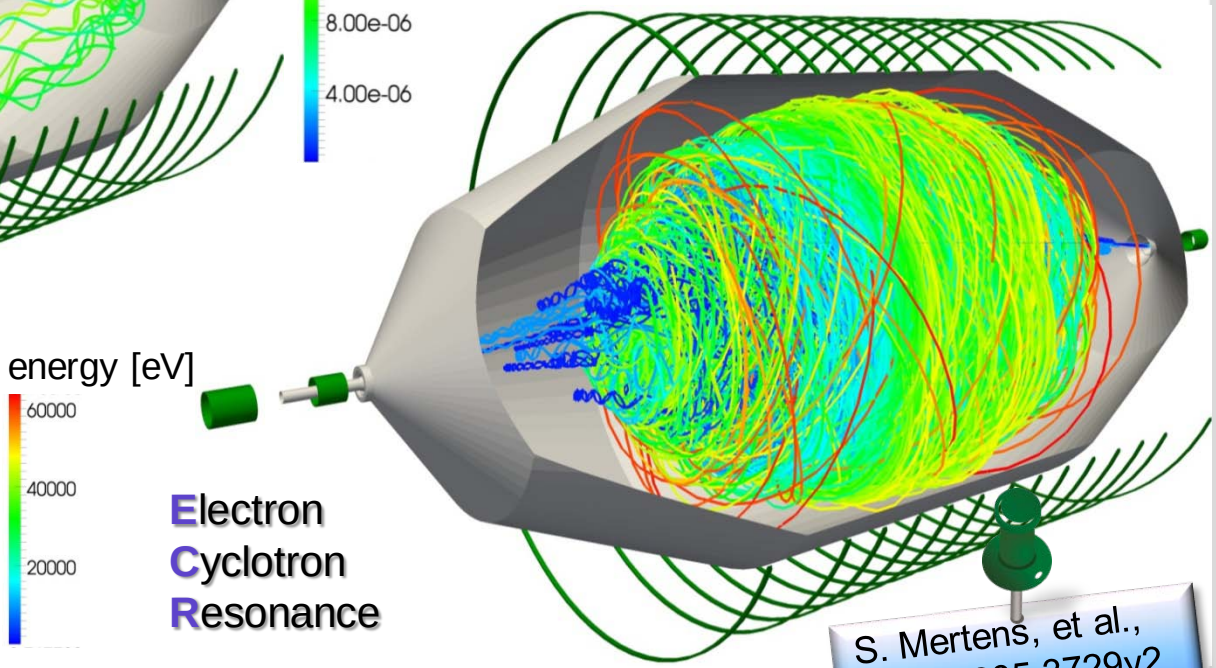


KASSIOPEIA: background reduction

^{219,220}Rn emanation from bulk material of vessel: need active bg-suppression

- **stored multi-keV electrons**:
  rapid cyclotron motion
  intermediate axial oscillation
  slow magnetron drift



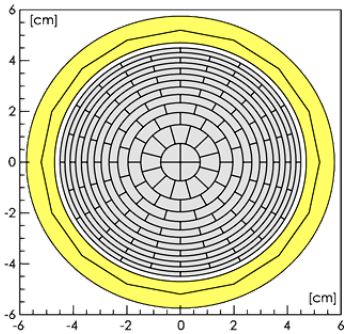


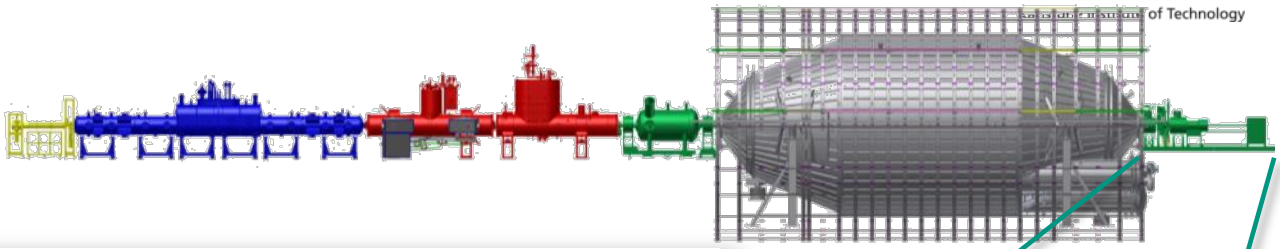
- **ECR technique**:
  stochastic heating
  by short RF pulses
  with $\omega_{RF} = \omega_{cycl}$

Electron
Cyclotron
Resonance

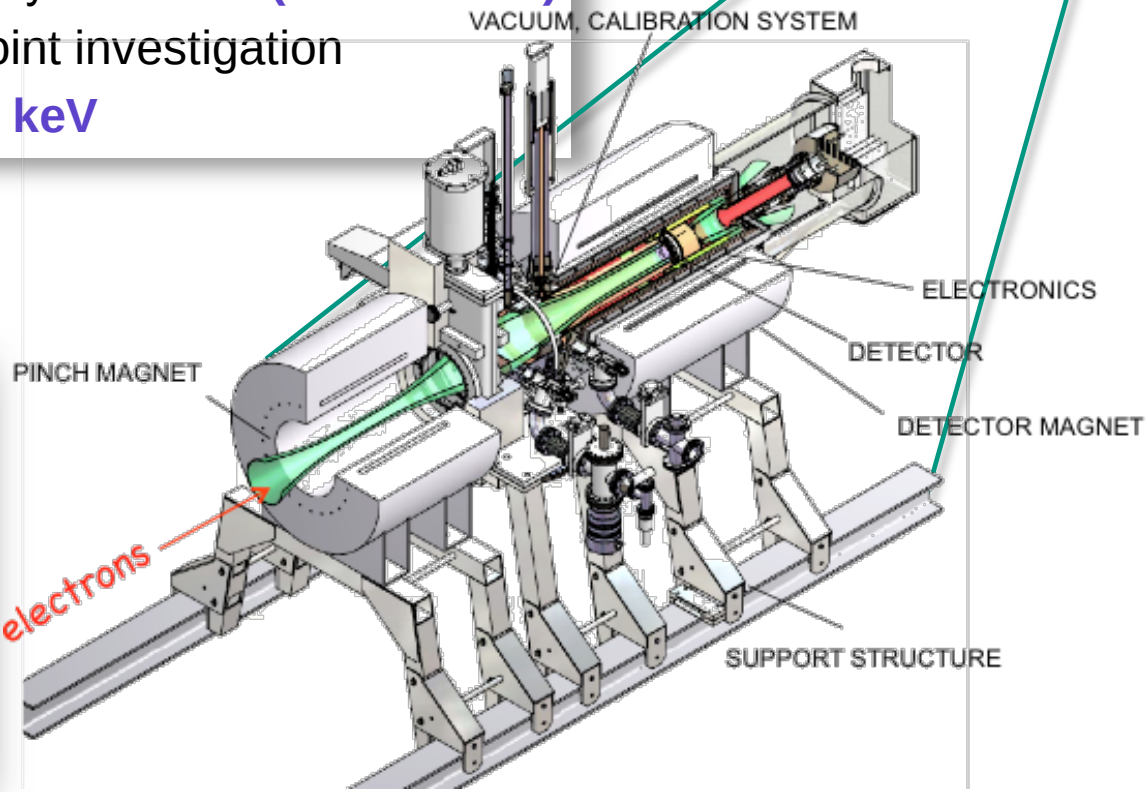
S. Mertens, et al., arXiv:1205.3729v2

Main Detector





- segmented Si-PIN diode **(148 pixel)**
- detection of transmitted β decay electrons **(mHz to kHz)**
- **low background** for T_2 endpoint investigation
- high energy resolution **ΔE ≈ 1 keV**



commissioning at KIT in 2011

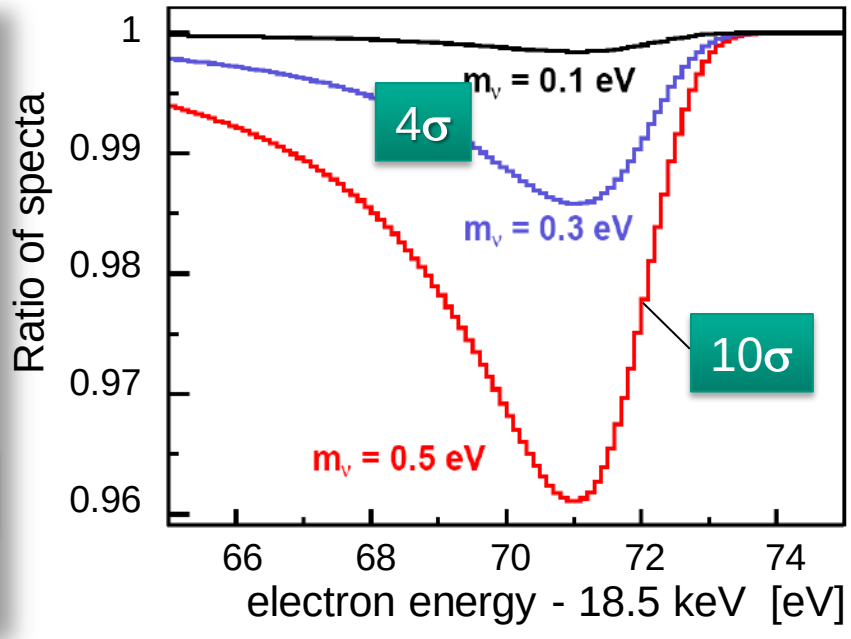
KATRIN sensitivity

reference ν-mass sensitivity
for 3 ´full beam´ years:

- statistical & systematic errors contribute equally:
  - statistics σ_{stat} = 0.018 eV²
  - systematics σ_{syst} < 0.017 eV²

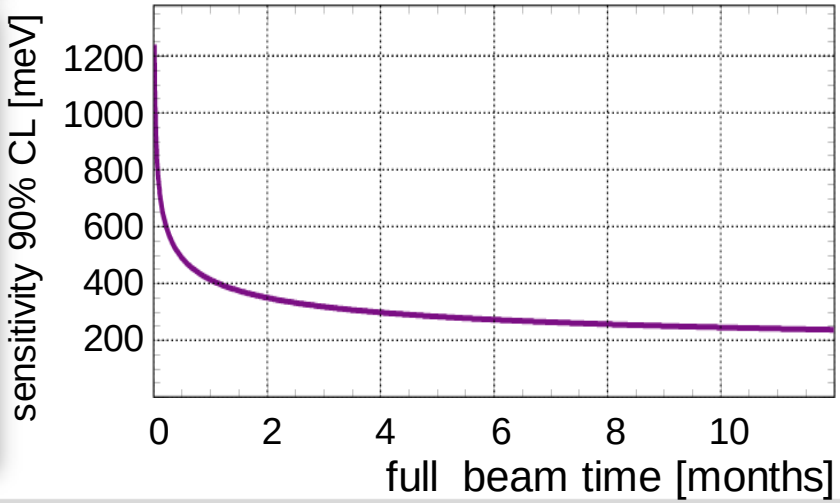
sensitivity m(ν) = 200 meV (90% CL)

350 meV (5σ)



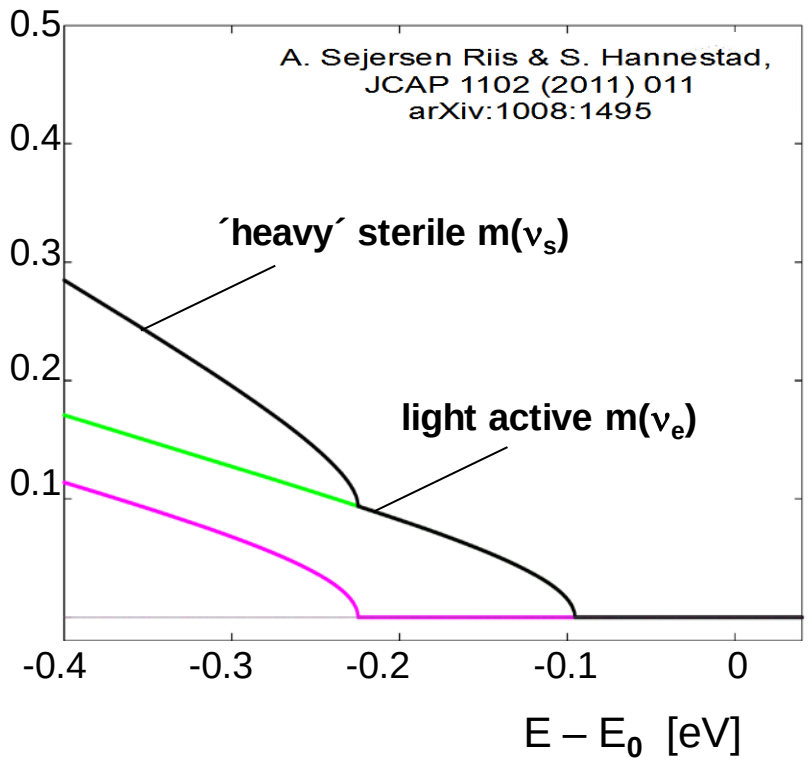
plans for a later KATRIN phase II:

- differential β-energy spectrum:
  - cryo-bolometer array with ΔE ~ 1eV?
  - synchrotron emission (GHz-range)?
- precision external value end point E_0
- atomic tritium source?

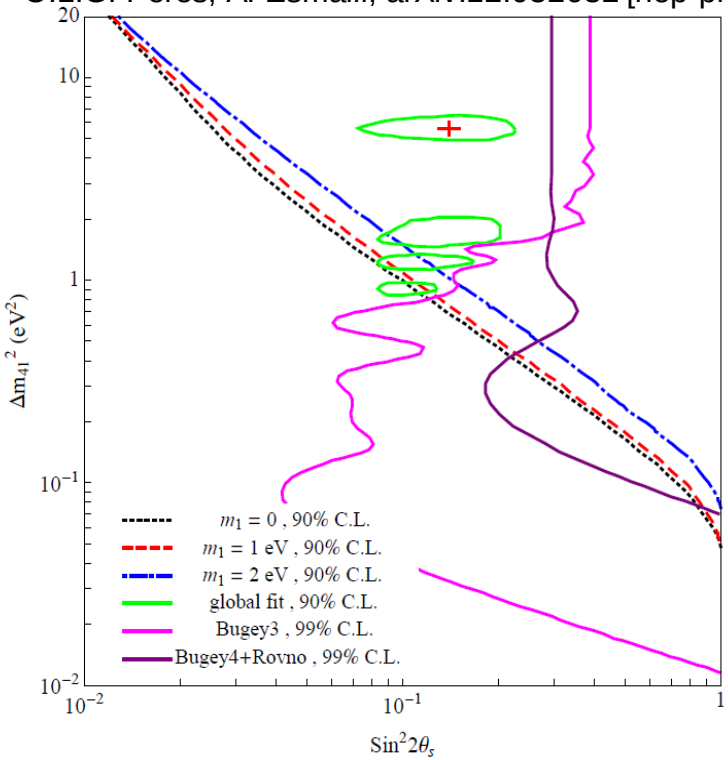


Sterile neutrinos: (sub-)eV scale

- Hannestad et al. - initial estimates of KATRIN sensitivity for sterile ν´s assume **very light active neutrinos m(ν_e) ~ 0 eV, mixed with sterile m (ν_s)**
- 3 σ detection of ´kink´ by $m_{sterile}$ if active-sterile mixing **$|U_{es}|^2 \geq 0.055$**
- 3+2 scenarios can also be disentangled**, measure absolute value m (ν_s)**



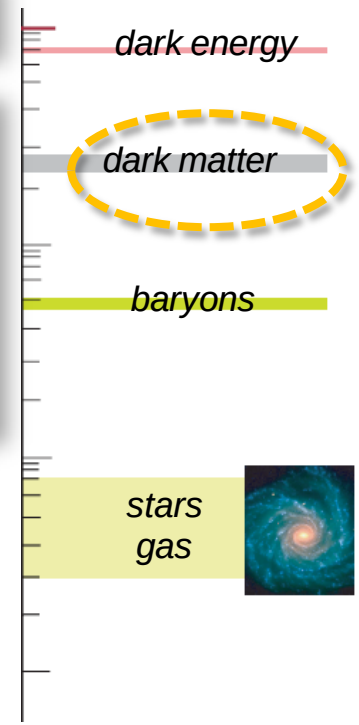
O.L.G. Peres, A. Esmaili, arXiv:12.032632 [hep-ph]

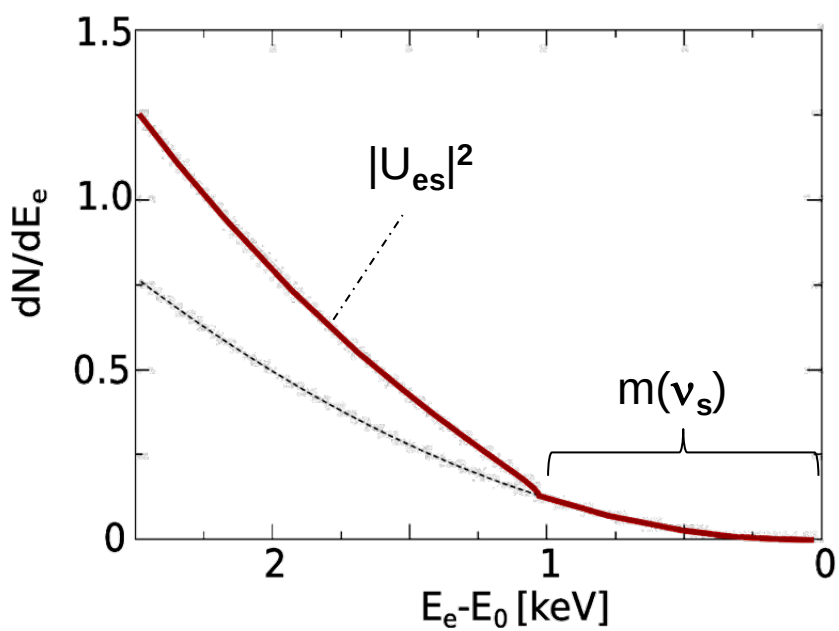


Sterile neutrinos in astroparticle physics

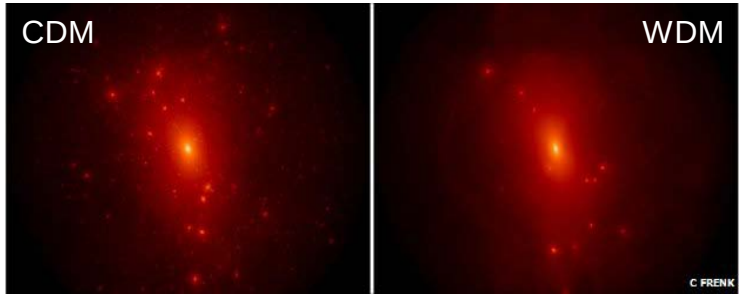
Cosmology: role of sterile ν´s as warm dark matter

- idea: sterile ν´s in the **1-10 keV** mass regime would constitute **warm dark matter**
- sterile neutrino ν_s would manifest itself as a **kink (10^{-7}-10^{-10}) deep in the ß-spectrum**
  ↳need reliable calculation of spectral shape





DM & dwarf statellites

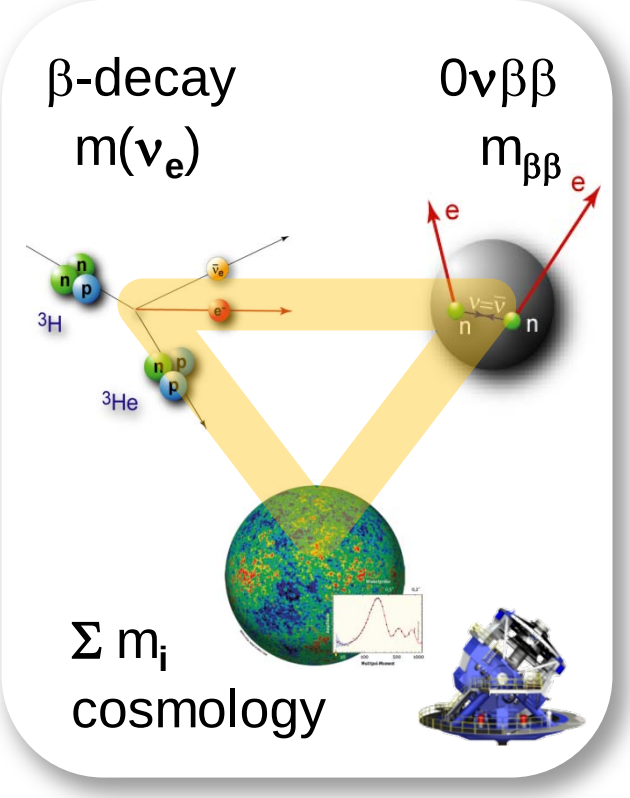


Conclusions

- **Studies of β-decay/EC kinematics**
  - only model-independent method to determine absolute ν-mass scale
  - KATRIN will probe cosmologically relevant scale down to $m(\nu_e)$ = 200 meV
  - studies for phase II to go beyond this value
- **Calorimetric experiments will provide an independent check**
  - **MARE**: ^{187}Re (β-decay); **ECHO**: ^{163}Ho (electron capture)
  - advantage: scalable approach
  - still a lot of R&D work for $m(\nu_e)$ = 200 meV
- New ideas: **Project 8** and others
- **KATRIN next steps**:
  - electromagnetic tests of main spectrometer (start in Oct. 2012)
  - commissioning of CPS (end of 2013) and WGTS (end of 2014)
  - beginn of neutrino measurement: 2015

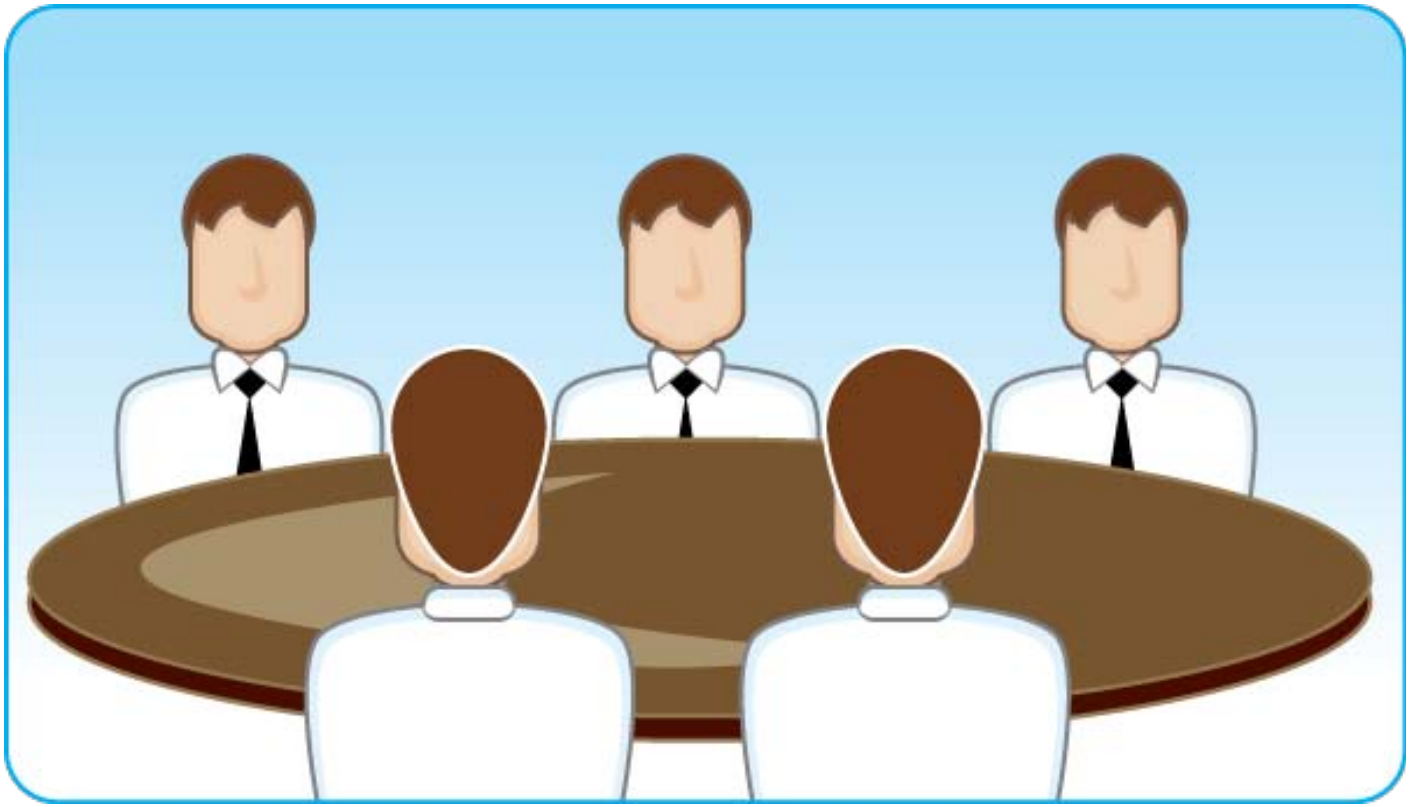
Conclusions

The **complete picture** of neutrino masses is obtained only by comparing high-precision results from **direct neutrino mass searches** with **0νββ experiments** and **cosmological studies**



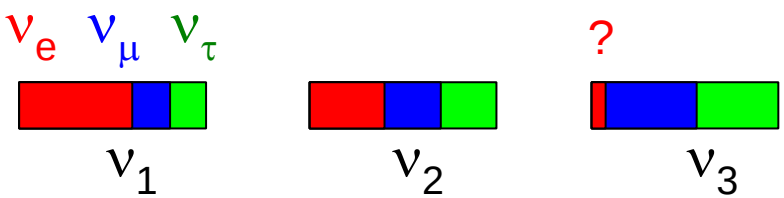

Thank you for your attention

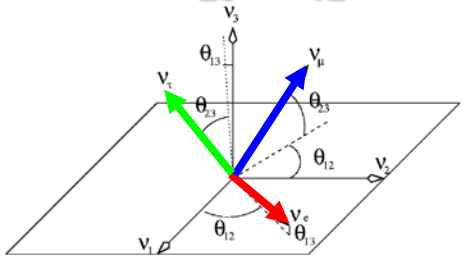
Discussion



Absolute neutrino mass

Results of recent oscillation experiments: Θ_{23}, Θ_{12}, Δm^2_{23}, Δm^2_{12}





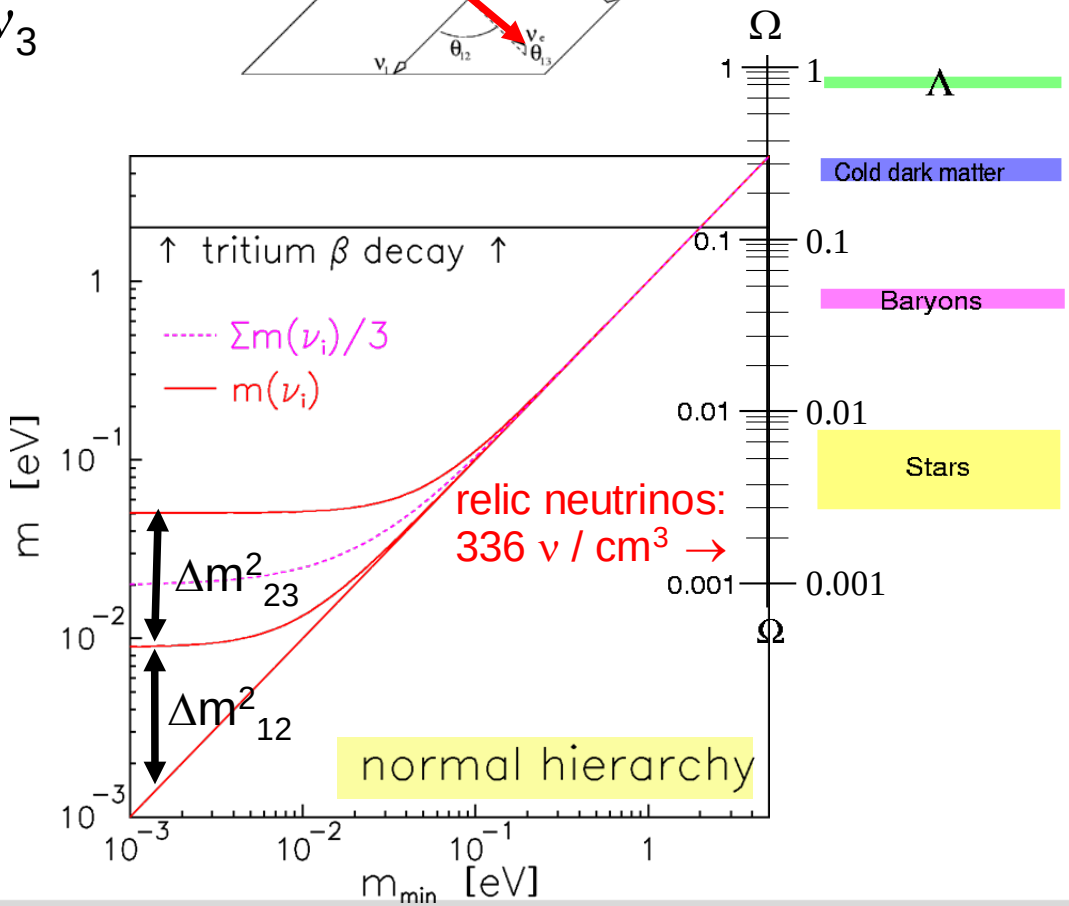
degenerated masses

accessible to β-experiments

cosmologically relevant:

- HDM
- large scale structure formation

hierarchical masses



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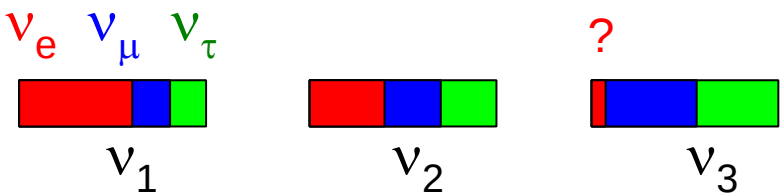

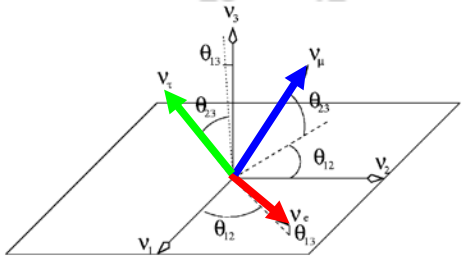

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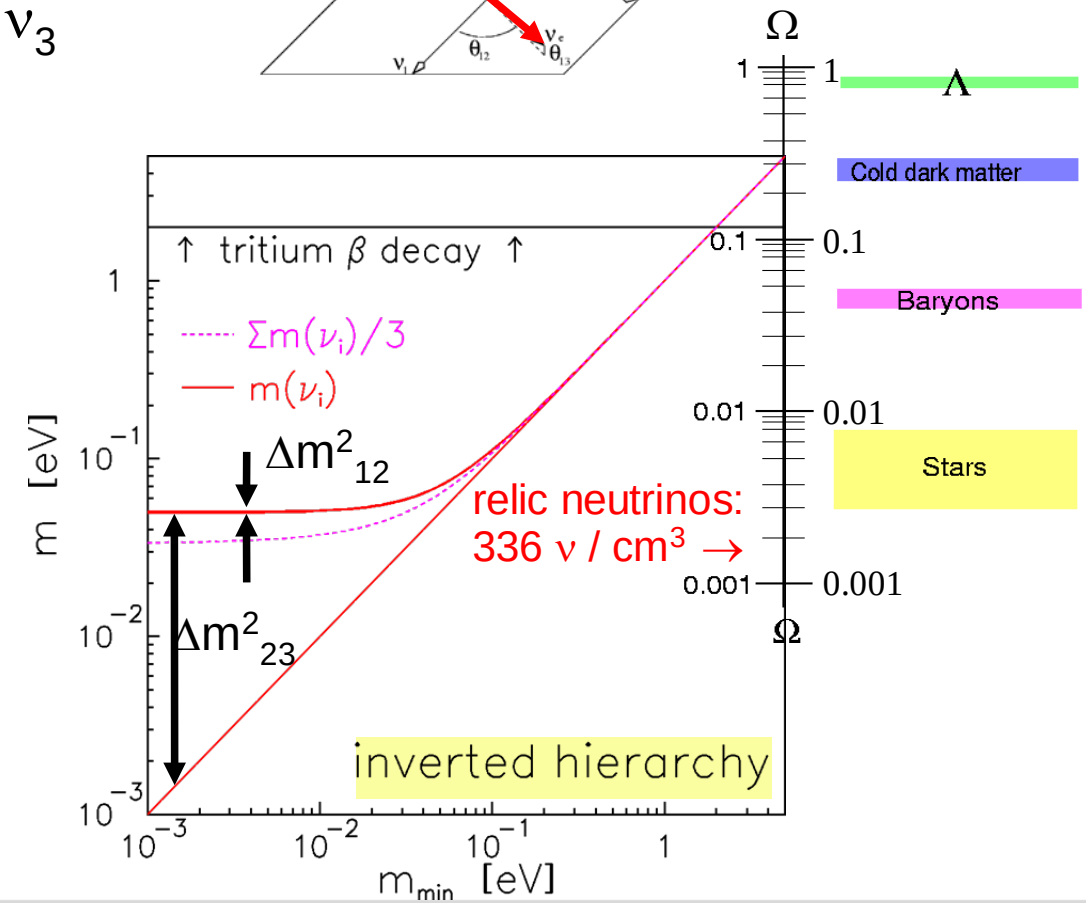
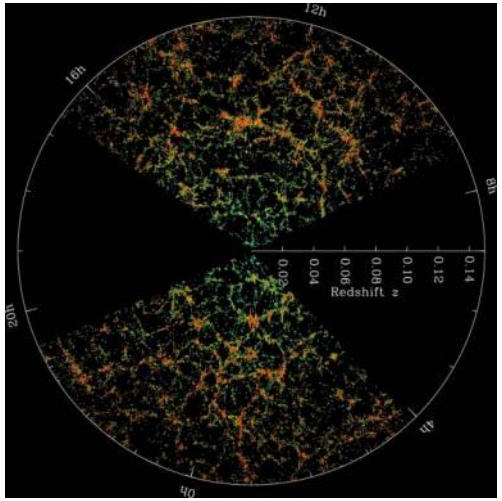


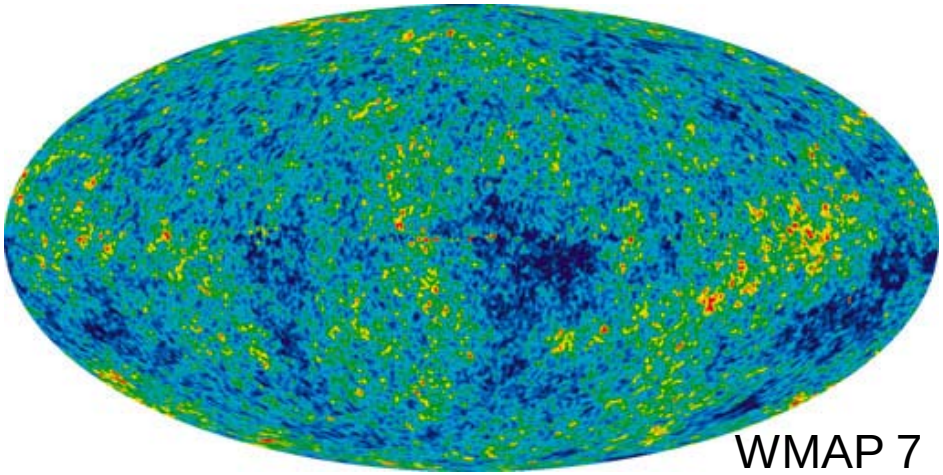
Cosmology and neutrino mass

- massive neutrinos contribute to **hot dark matter**
- kinematic effect of HDM on **structure formation**
- sensitive to **total energy density** of neutrinos **(Σm_i)**
- **different models** using various sets of parameters and data
- minimal ΛCDM plus m_ν : $\Sigma m_i < 0.4$ eV (CMB + LSS)
- current bounds: $0.3 \text{ eV} \leq \Sigma m_j \leq 2 \text{ eV}$

S. Hannestad: arXiv:1007.0658v2



SDSS DR7

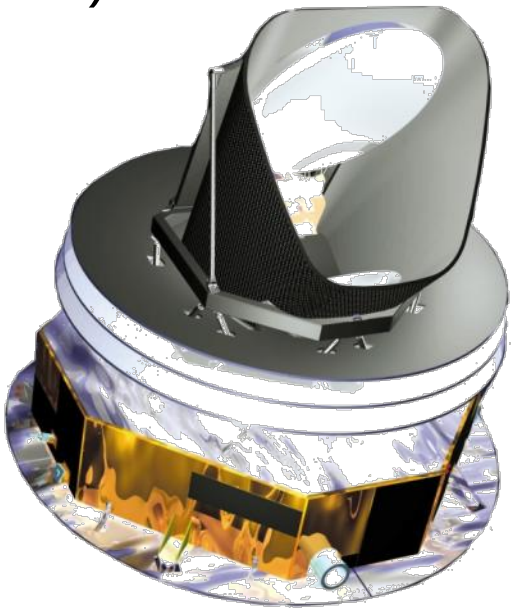


WMAP 7

Cosmology and neutrino mass

Future probes of neutrino mass:

- new galaxy redshift surveys (BOSS, HETDEX, WFMOS,…)
- weak lensing surveys
- CMB: PLANCK satellite (launched: 14.May 2009)
- Lyman-α forest measurements (BOSS)
- cluster surveys
- 21 cm measurements



Expected sensitivity:

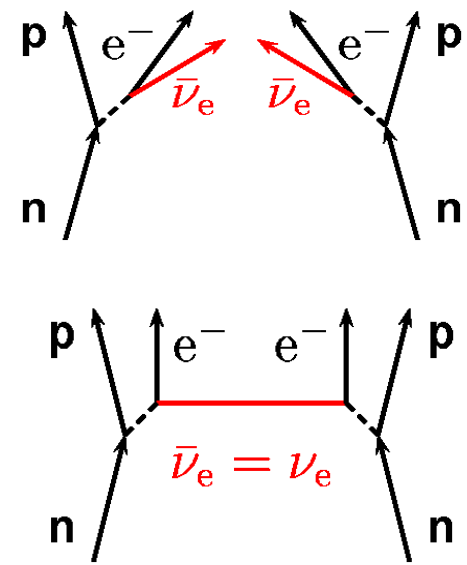
- short term (5-7 y): $0.1\ \mathrm{eV} \leq \Sigma m_j \leq 0.6\ \mathrm{eV}$
- long term (7-15 y): $0.05\ \mathrm{eV} \leq \Sigma m_j \leq 0.4\ \mathrm{eV}$

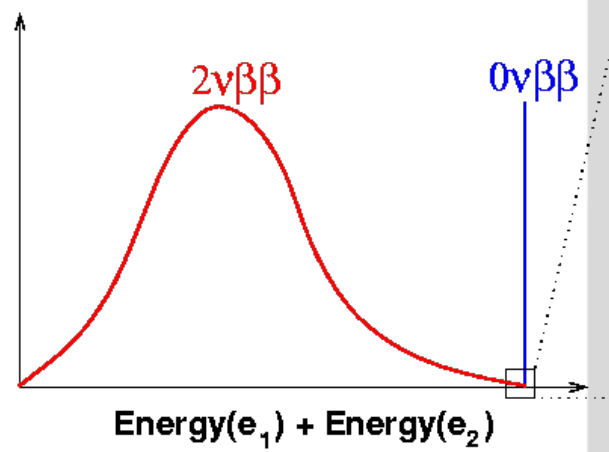
S. Hannestad: arXiv:1007.0658v2

Neutrino-less double-β-decay and neutrino mass

O. Cremonesi: arXiv: 1002.1437v1

- **2 decay modes in double-β-decay**:
  - **normal (2ν2β)**
    - $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$
    - **allowed** by standard model
    - **continuous energy spectrum**
    - has been **observed** (t ~ 10^{-19} – 10^{-21} y)
  - **neutrinoless (0ν2β)**
    - $(A,Z) \rightarrow (A,Z+2) + 2\overline{\nu}_e$
    - needs **massive Majorana neutrinos**
    - **energy peak at endpoint**
    - **$\tau > 10^{25}$ y**
    - violation of total lepton number conservation





Neutrino-less double-β-decay and neutrino mass

- **Measurement: decay rate**

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \left|m_{\beta\beta}\right|^2$$

– $G^{0\nu}$ **phase space integral**
(exactly calculable)

– $M^{0\nu}$ **nuclear matrix element**
(wide range of different calculations)

– $m_{\beta\beta}$ **effective neutrino mass with Majorana phases α**
(cancellation of mass terms possible)

$$m_{\beta\beta} = \sum_{j=1}^{3} \left|U_{ej}\right|^2 \cdot e^{i\alpha_j} \cdot m_j$$

Neutrino-less double-β-decay and neutrino mass

accuracy limited by nuclear matrix element calculation

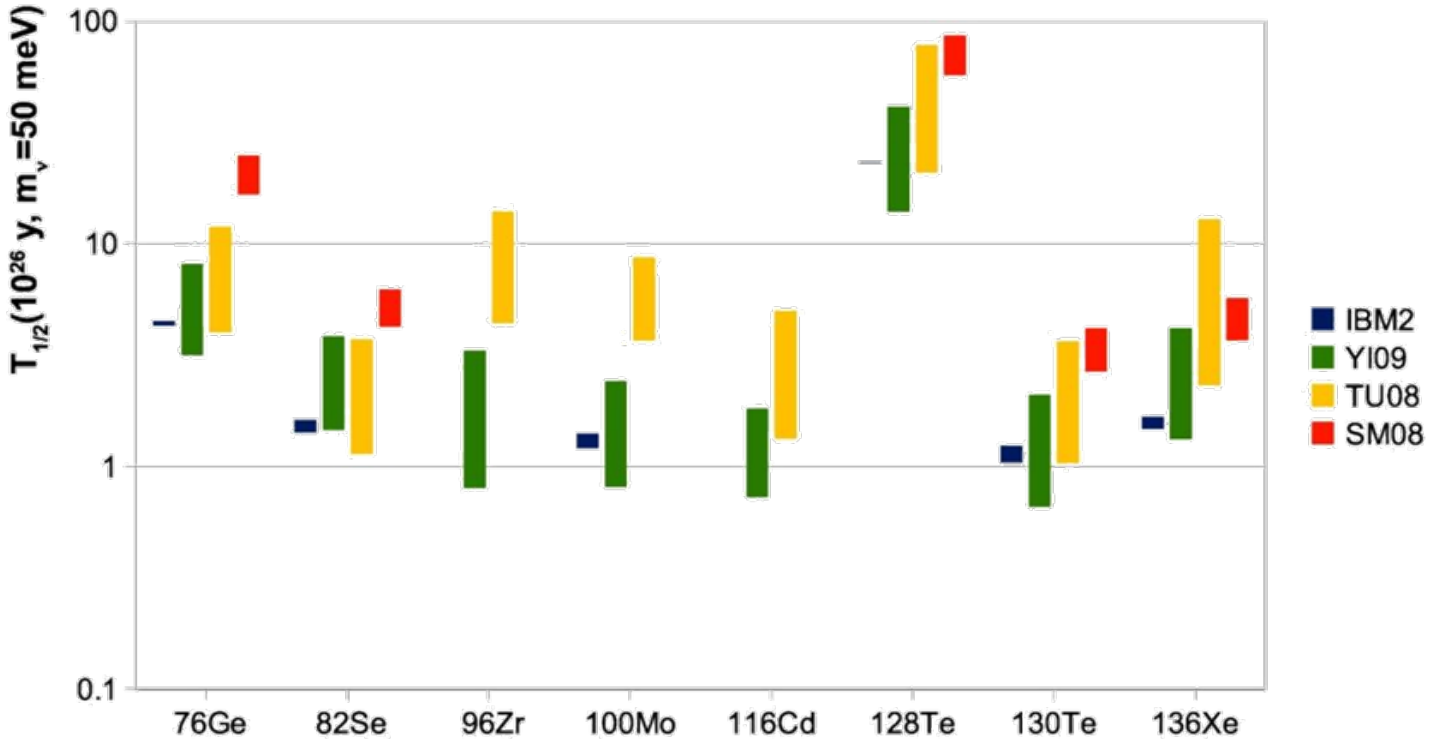
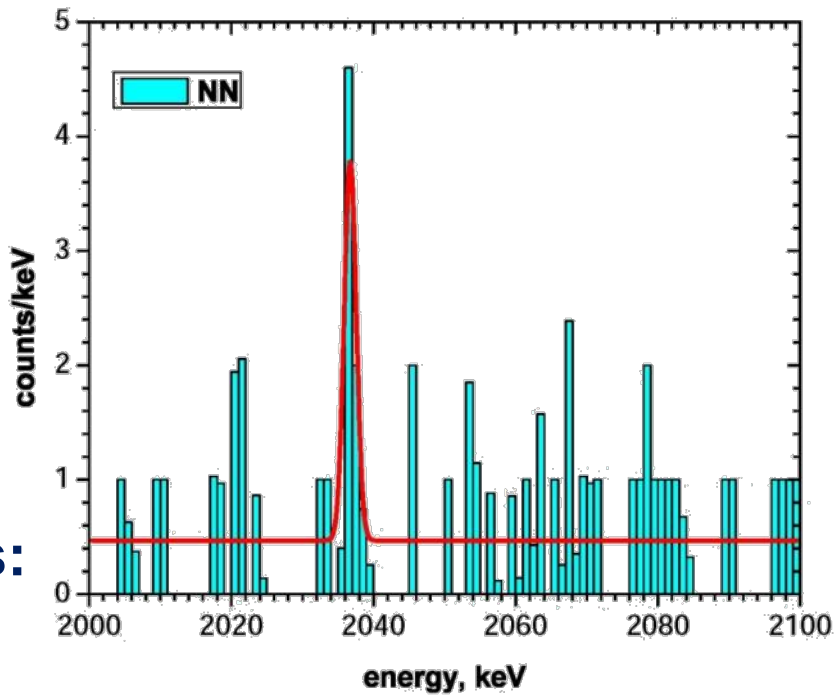


Figure 1: Expected $\beta\beta(0\nu)$ half lives for 50 meV effective neutrino mass and different NME calculations: IBM2 [17], YI09 [18], TU08 [19] and SM08 [20].

O. Cremonesi: arXiv: 1002.1437v1

Neutrino-less double-β-decay and neutrino mass

- **Current results:**
  - **Heidelberg-Moskau (^{76}Ge)**
  - **KHDH analysis:**
    - **$T_{1/2}$ = 2.23 x 10^{25} y (6σ)**
    - **$m_{\beta\beta}$ = 0.32 ± 0.03 eV**
  - **physics beyond the SM ?**
  - **right-handed weak parameters:**
    - **<η> = 3.05 ± 0.26 x 10^{-9}**
    - **<λ> = 6.92 ± 0.58 x 10^{-7}**



- **0ν2β only provides upper limit on neutrino mass**

H. V. Klapdor-Kleingrothaus and I. V. Krivoshein, Mod. Phys. Let. A, Vol. 21, No. 20 (2006) 1547

Standard β-decay and neutrino mass

kinetic measurement of the effective neutrino mass

E W Otten and C Weinheimer
Rep. Prog. Phys. **71** 086201 (2008)

Fermi's golden rule:

$$\frac{d\Gamma}{dE} = C \cdot F(E) \cdot p \cdot (E + m_e)(E_0 - E) \cdot \sum_i |U_{ei}|^2 \cdot \sqrt{(E_0 - E)^2 - m_{\nu_i}^2}$$

If the energy resolution is much larger than Δm_ν
we see only an **effective neutrino mass m_β**:

$$\sqrt{(E_0 - E)^2 - \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2} \quad \text{with} \quad m_\beta^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$

measurement: look for missing energy close to the endpoint

- high energy resolution
- high activity source

Measurement of the β-spectrum

Spectrometer (tritium)

- energy selected by electric or magnetic fields
- external β-source
- energy loss due to scattering
- energy resolution 0.93 eV (100%)
- low count rate in detector
- lower energies rejected
- event fraction in last 10 eV: $3 \cdot 10^{-10}$
- present sensitivity: 2 eV
- planned sensitivity: 0.2 eV

KATRIN

Micro-calorimeter (^{187}Re)

- energy measured by cryogenic bolometer
- β-source = detector
- measures entire β-decay energy
- energy resolution ≈ 5 –10 eV (FWHM)
- full count rate (pile-up !)
- many small detectors needed
- event fraction in last 10 eV: $1.3 \cdot 10^{-7}$
- present sensitivity: 15 eV
- planned sensitivity I: 2 eV
- planned sensitivity II: 0.2 eV

MARE

bolometer experiments for ^{187}Re

^{187}Re-experiments (MANU, MIBETA, MARE)

^{187}Re as ß-emitter: natural isotope content = 62.8 %

$$^{187}_{85}\mathrm{Re} \rightarrow {}^{187}_{86}\mathrm{Os} + e^- + \bar{\nu}_e$$

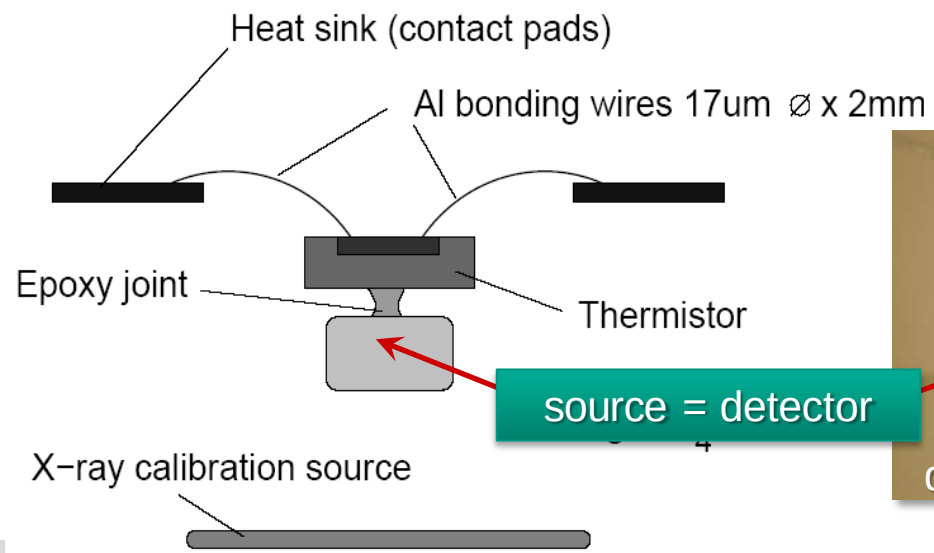
$5/2^+ \rightarrow 1/2^-$ ´unique´ 1st forbidden transition (shape factor), BEFS

^{187}Re: unique 1st	
E_0	2.47 keV
$t_{1/2}$	43.2 Gy

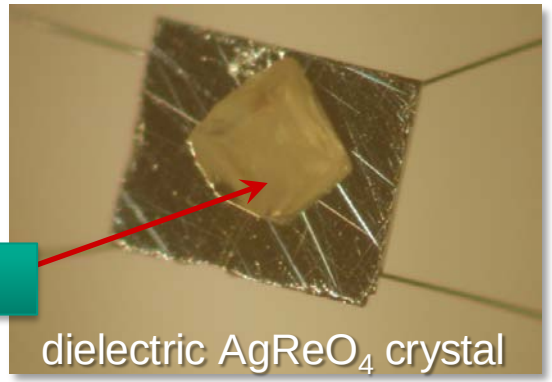
previous ^{187}Re-experiments MANU, MIBETA

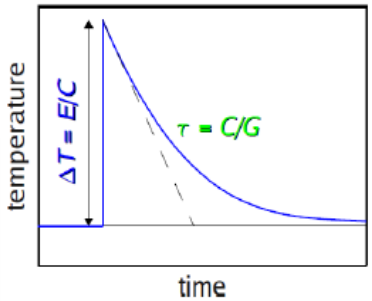
MANU: metallic Rhenium — group in Genova

MIBETA: dielectric $AgReO_4$ crystals — group in Milano



measure entire ß-decay energy





MIBETA:
10 crystals

MARE experiment

- **M**icrocalorimeter **A**rrays for a **R**henium **E**xperiment

- **general strategy to increase sensitivity to sub-eV regime**:
  - deploy large arrays of cryogenic micro-bolometers
    up-scaling of source intensity with 1 mg Re ≈ 1 decay/s
  - avoid pulse pile-up: develop faster detectors
  - develop multiplexed read-out technologies
  - improve energy resolution to 1 eV-level

MARE-I ~ 10^9-10^{10} ß-decays

- set-up small bolometer array: ν-mass sensitivity $m(\nu_e)$ ~ few eV
- test & select different isotopes (^{163}Ho-EC/^{187}Re-ß-decay) and read-out/sensor techniques (TES, Si-thermistor, MMC, …)

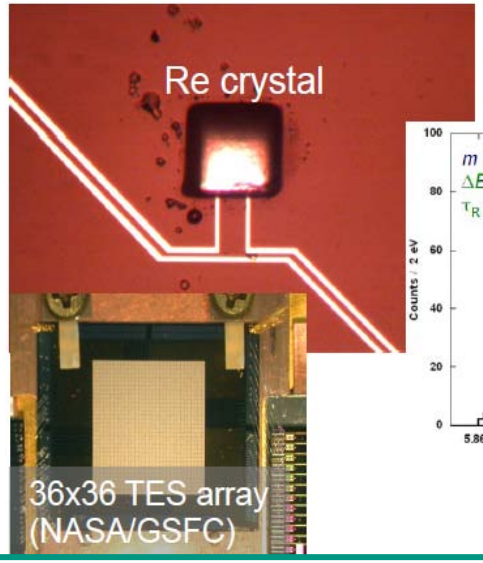
MARE-II ~ 10^{14} ß-decays

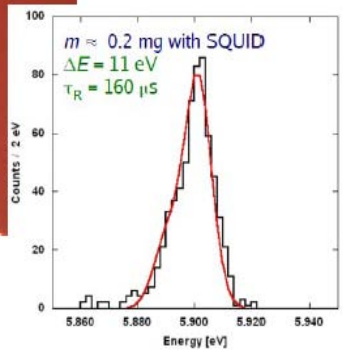
- full set-up, large bolometer array with 10^4-10^5 pixels
- aim for statistical ν-mass sensitivity $m(\nu_e)$ ~ 0.1-0.2 eV

MARE experiment: phase-I

Genova — $m(\nu_e) \sim 2$ eV

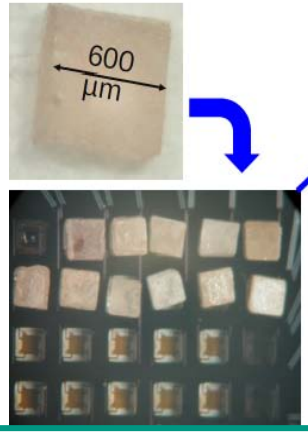
- metallic Re absorbers, up to 300
- m = (0.2-0.3) g ↳ ~0.25 Bq
- TES sensors (Ir-Au bi-layer), multiplexed SQUID read-out
- $\Delta E \sim 11$ eV
- $\tau_{rise} \sim 160$ µs

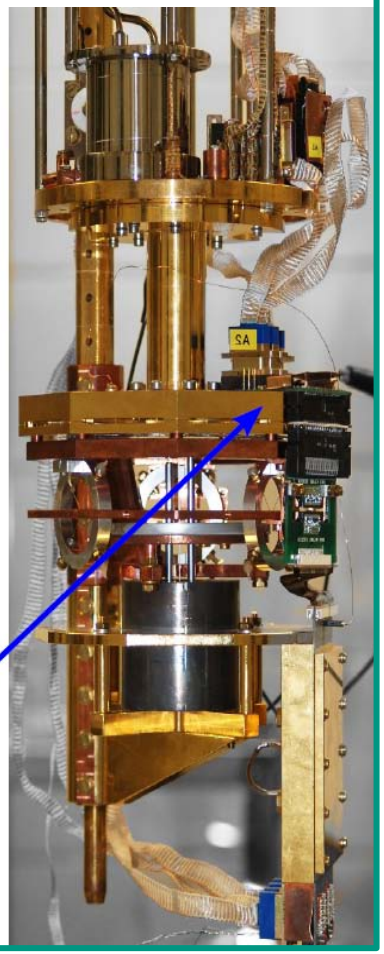




Milano-Bicocca — $m(\nu_e) \sim 3$-4 eV

- 6x6 arrays of AgReO4 crystals (up to 8 arrays can be housed in cryostat)
- m = 0.5 mg ↳ 0.27 Bq
- readout: Si-implanted thermistors
- $\Delta E \sim 25$ eV
- $\tau_{rise} \sim 250$ µs



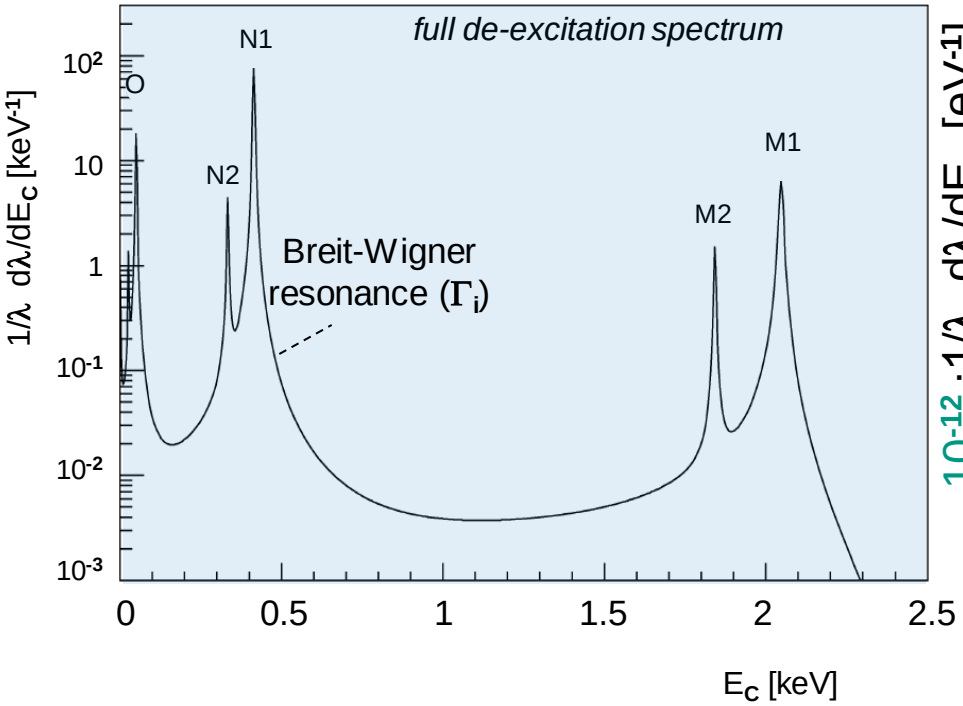


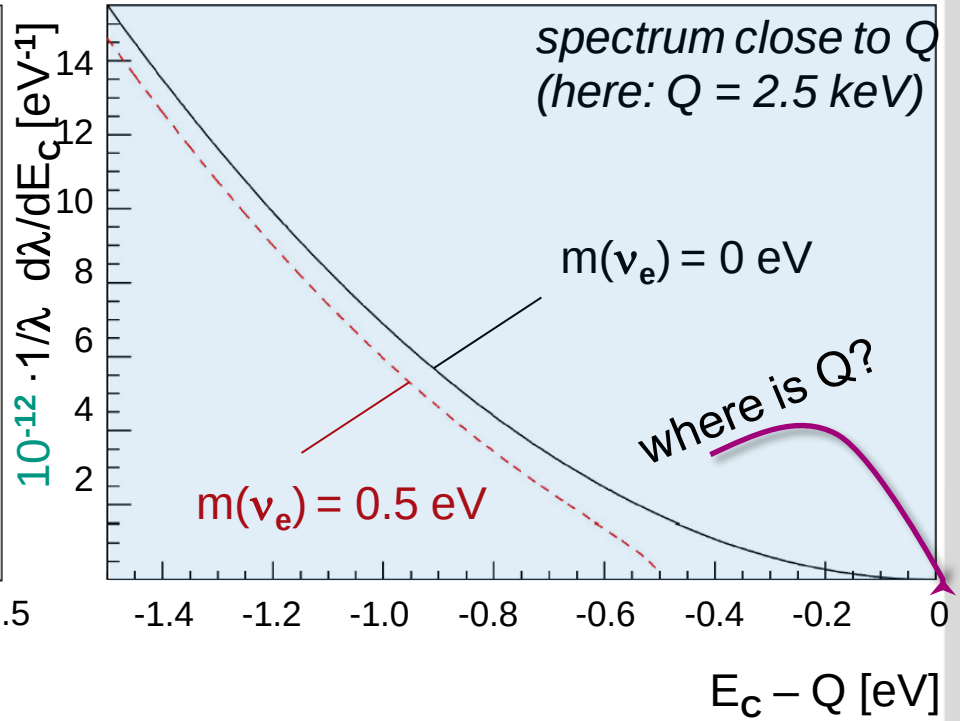
electron capture & ν-mass

- electron capture: non-zero m(ν_e) value affects the EC de-excitation spectrum

EC of ^{163}Ho is suitable candidate: $^{163}Ho + e^- \rightarrow \nu_e + {}^{163}Dy^* \rightarrow {}^{163}Dy + E_C$

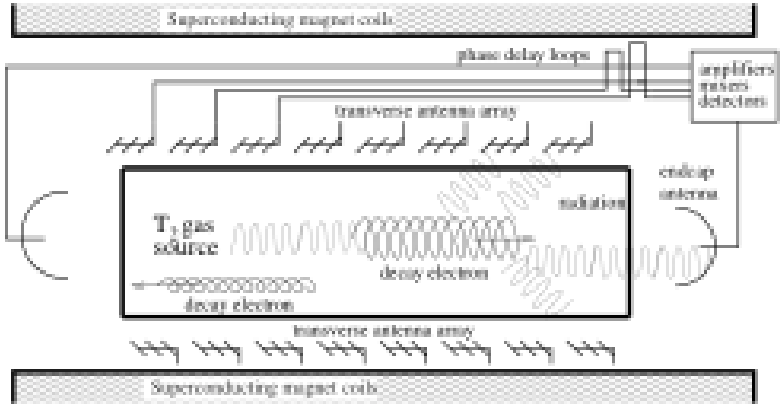
$$\frac{d\lambda_{EC}}{dE_C} \sim (Q-E_C)\cdot\sqrt{(Q-E_C)^2 - m^2(\nu_e)}\cdot\sum_i n_i\cdot C_i\cdot\beta_i^2\cdot B_i\cdot\frac{\Gamma_i}{2\pi}\cdot\frac{1}{(E_C-E_i)^2+\Gamma_i^2/4}$$





Measuring the Neutrino Mass

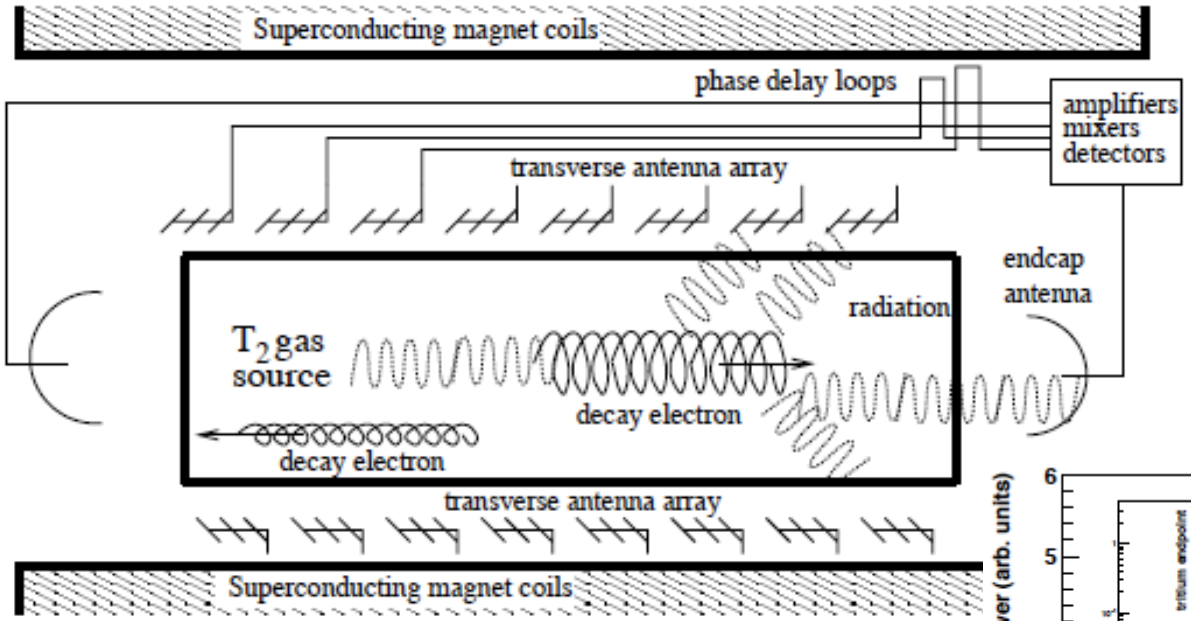
3rd approach, proposed recently: Project 8



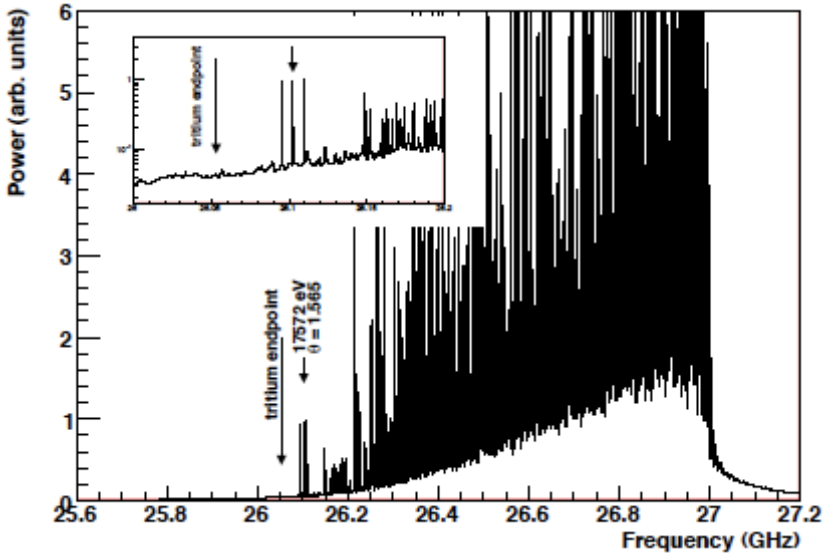
- source: gaseous T_2
- technique: radio-frequency spectroscopy of coherent cyclotron radiation of β decay electrons
- more details: arXiv:0904.2860v1 [nucl-ex]
- design values: projected energy resolution: 1 eV
  estimated sensitivity on $m(\nu_e)$: 0.1 eV
- status: preparations for a proof-of-principle experiment

Project 8 collaboration

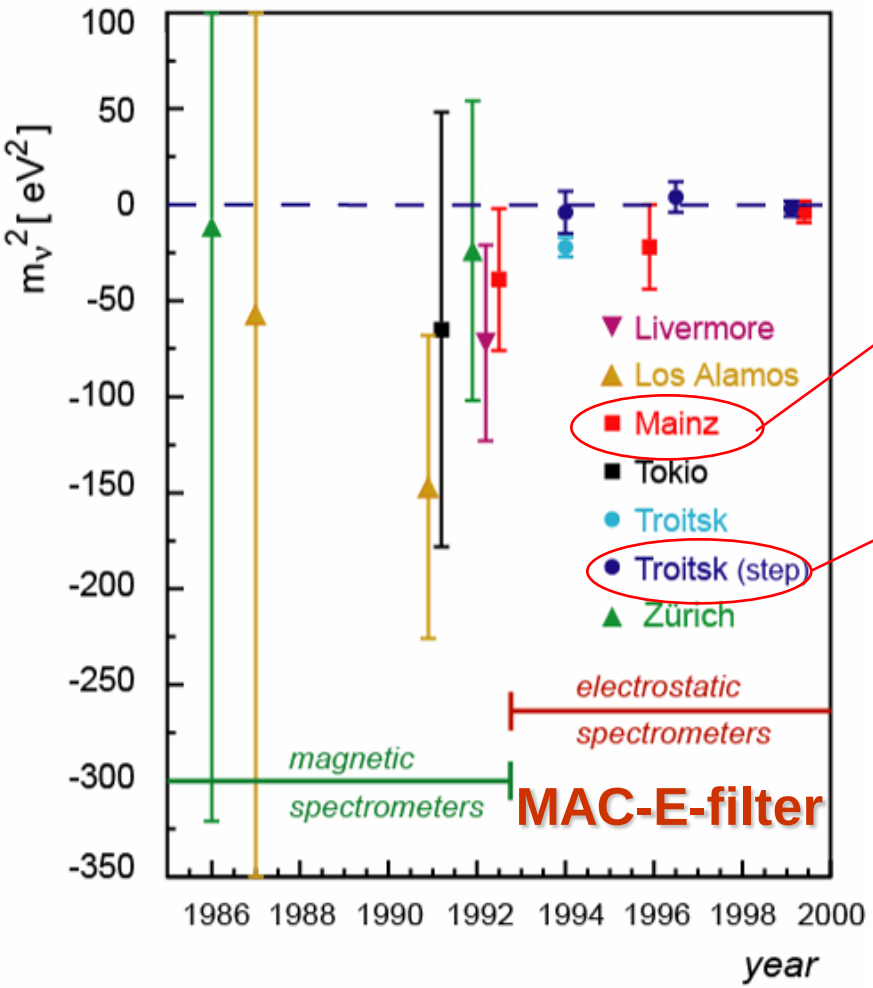
- Cyclotron radiation from T_2
- first prototype at UW, Seattle



$$\omega = \frac{eB}{\gamma m_e} = \frac{\omega_c}{\gamma} = \frac{\omega_c}{1 + \frac{K_e}{m_e c^2}}$$



History of ^{3}H β-decay experiments



$$m_\nu^2 = -0.6 \pm 2.2_{stat} \pm 2.1_{syst}\,\mathrm{eV}^2$$
$$m_\nu \leq 2.3\,\mathrm{eV}(95\%CL)$$

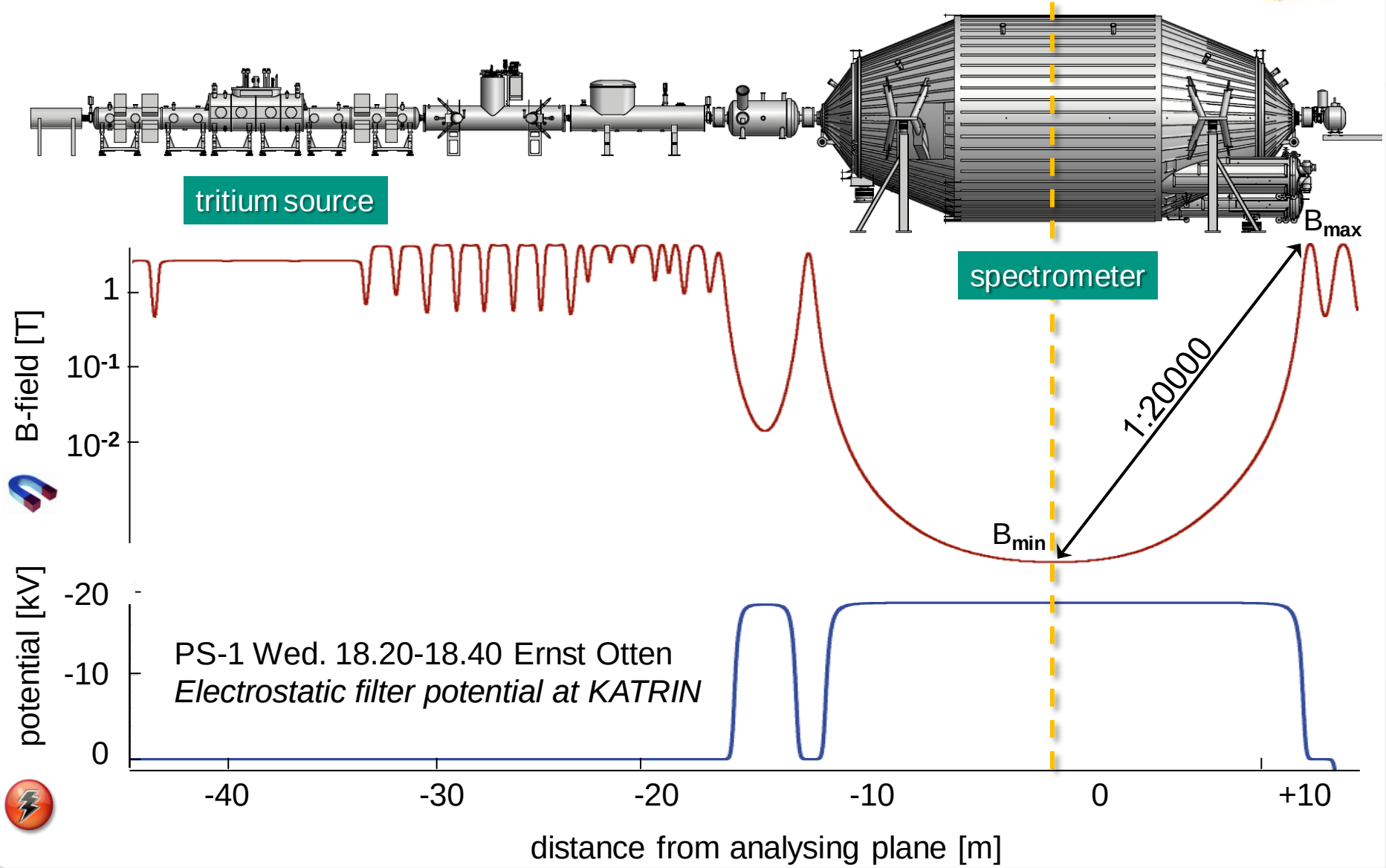
$$m_\nu^2 = -1.2 \pm 2.2_{stat} \pm 2.1_{syst}\,\mathrm{eV}^2$$
$$m_\nu \leq 2.2\,\mathrm{eV}(95\%CL)$$

Mainz & Troitsk have reached the limit of their sensitivity

both experiments are used now to conduct systematic studies for the next generation:

KATRIN

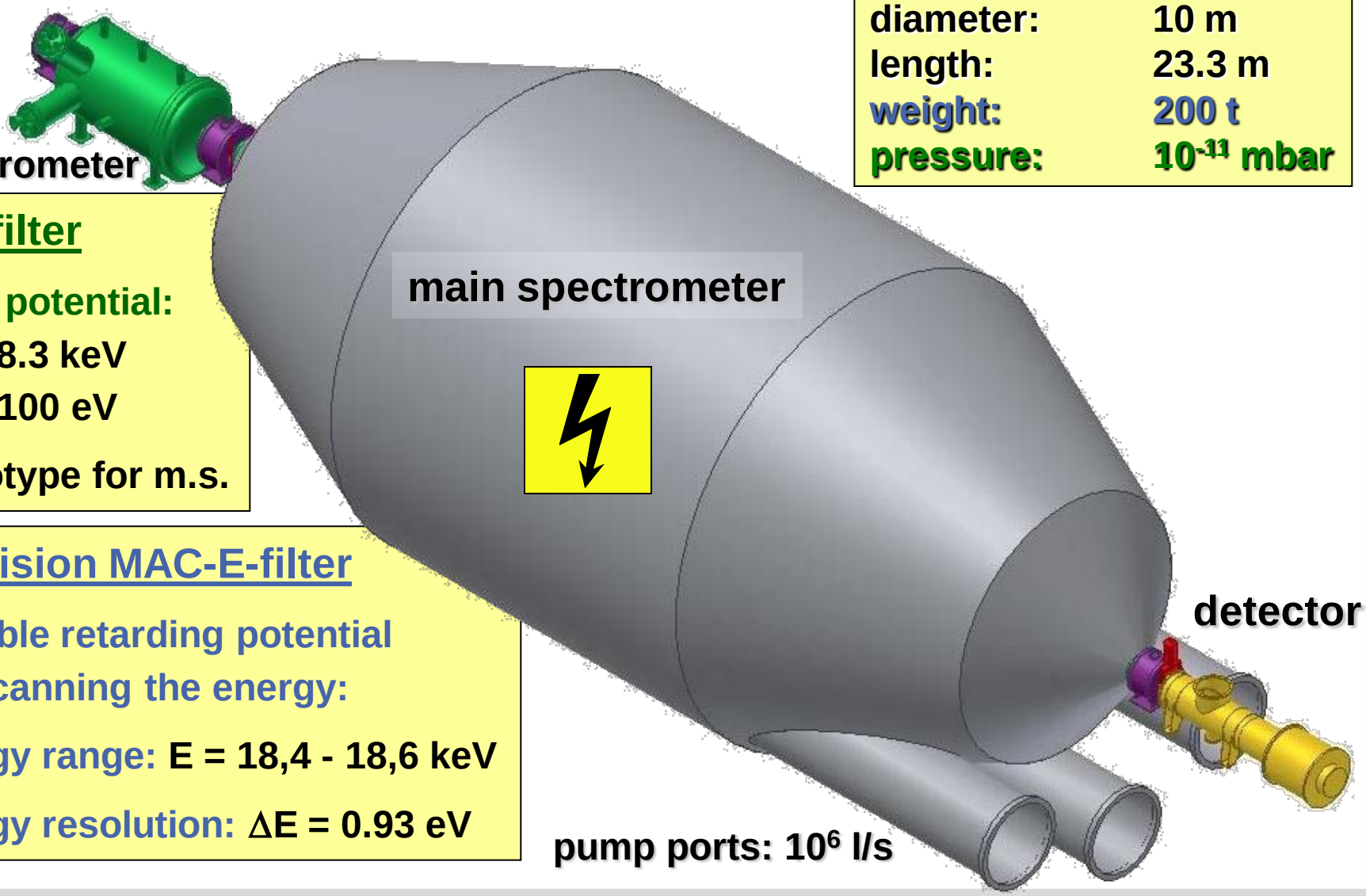
magnetic field & electrostatic potential



PS-1 Wed. 18.20-18.40 Ernst Otten
Electrostatic filter potential at KATRIN

The electro-static tandem-spectrometer

diameter:	10 m
length:	23.3 m
weight:	200 t
pressure:	10^{-11} mbar



Pre-filter

fixed potential:

E = 18.3 keV

$\Delta E \approx 100$ eV

prototype for m.s.

Precision MAC-E-filter

variable retarding potential for scanning the energy:

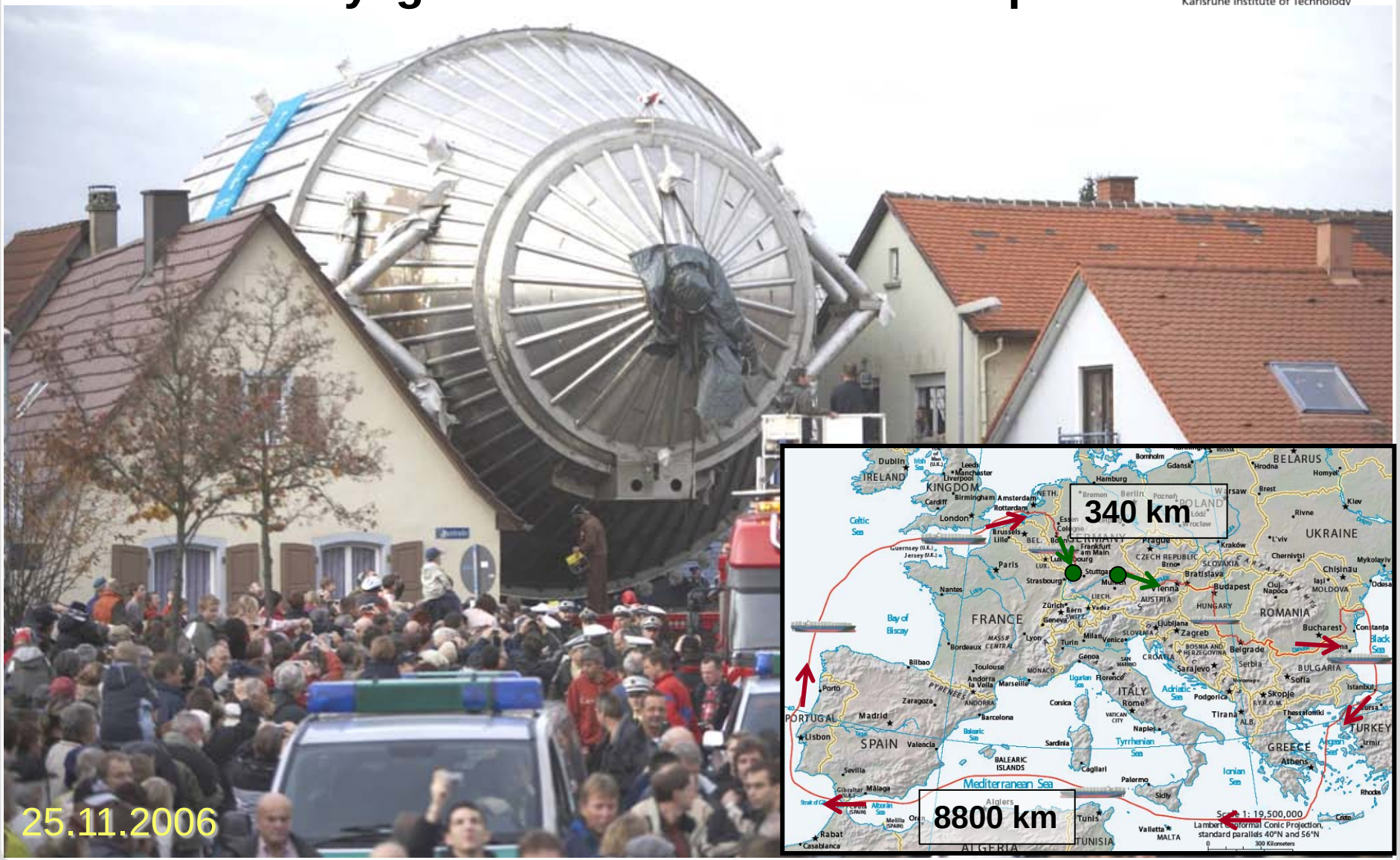
energy range: E = 18,4 - 18,6 keV

energy resolution: $\Delta E = 0.93$ eV

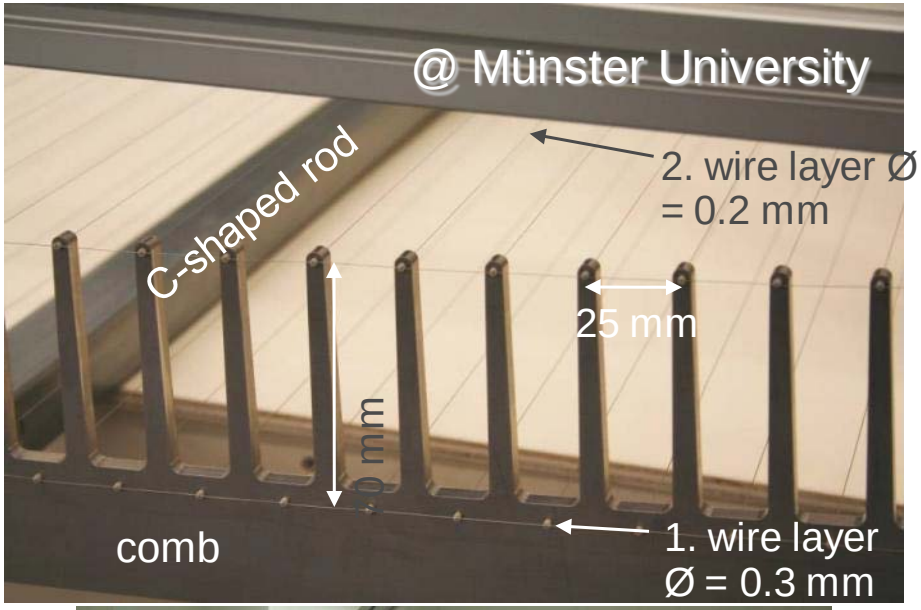
Requirements for the vacuum system

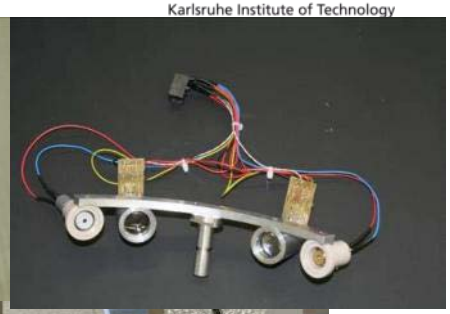
- **final pressure:** < 10^{-11} mbar
- **outgassing:** < 10^{-12} mbar l/s cm² (innere surface: *690 m²*)
- **effective pumping speed**
  - **3000m getter strips: 1 000 000 l/s (H_2 and other active gases)**
  - **6 turbo-molecular pumps: 8 400 l/s (all gases)**
- **max. allowed gasload**
  - **H_2 < 10^{-5} mbar l/s**
    - **outgassing vessel: <6 x 10^{-6} mbar l/s**
    - **outgassing electrodes: <3 x 10^{-6} mbar l/s**
    - **6 TMPs, beamline, gauges: < 10^{-6} mbar l/s**
  - **non-getterable gases < 10^{-7} mbar l/s (hydrocarbons, noble gases,...)**

Arrival of the main spectrometer after a voyage of 8800 km around Europe



KATRIN: ≈ 240 double layer wire electrode modules





Systematic uncertainties

any unaccounted variance σ^2 leads to negative shift of m_ν^2: $\Delta m_\nu^2 = -2\sigma^2$

1. inelastic scatterings of ß´s inside WGTS
   - requires dedicated e-gun measurements, unfolding techniques for response fct.

2. fluctuations of WGTS column density (required < 0.1%)
   - rear detector, Laser-Raman spectroscopy, T=30K stabilisation, e-gun measurements

3. transmission function
   - spatial resolved e-gun measurements

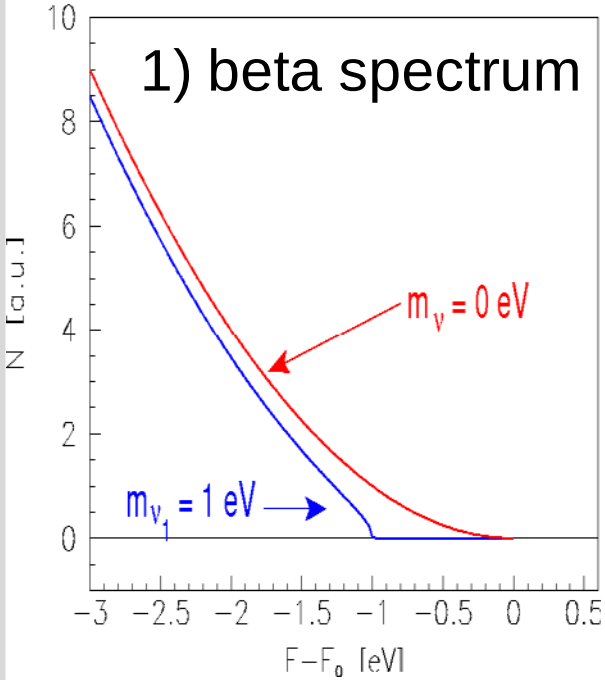
4. WGTS charging due to remaining ions (MC: ϕ < 20mV)
   - inject low energy meV electrons from rear side, diagnostic tools available

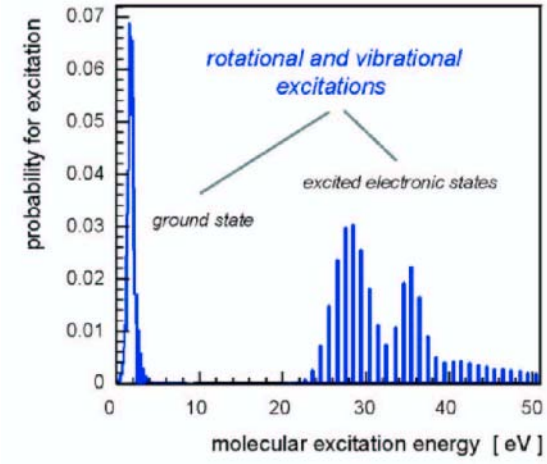
5. final state distribution
   - reliable quantum chem. calculations

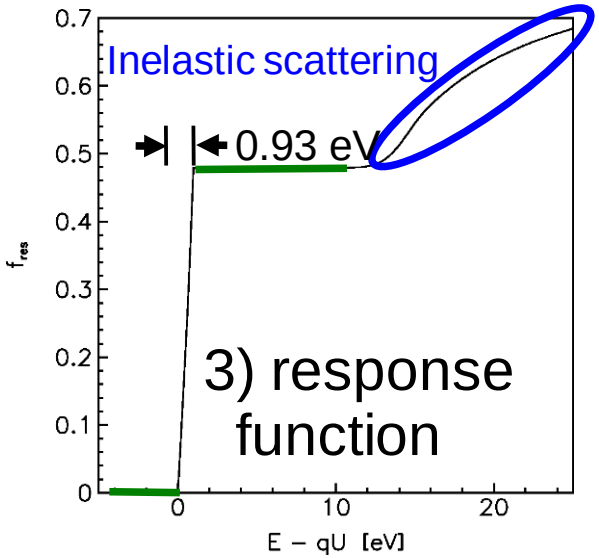
6. HV stability of retarding potential on ~3ppm level required
   - precision HV divider (PTB), monitor spectrometer beamline

some contributions each with $\Delta m_\nu^2 \leq 0.007\ eV^2$

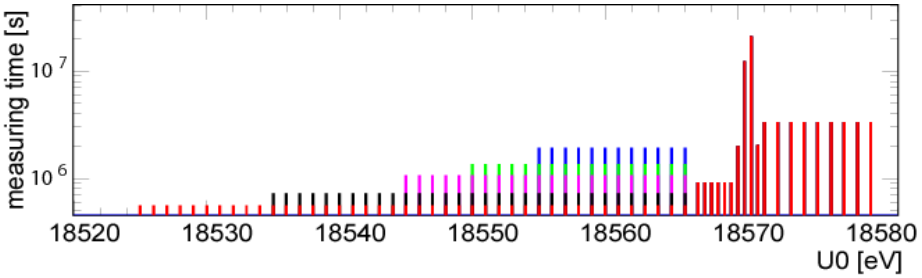
Statistics

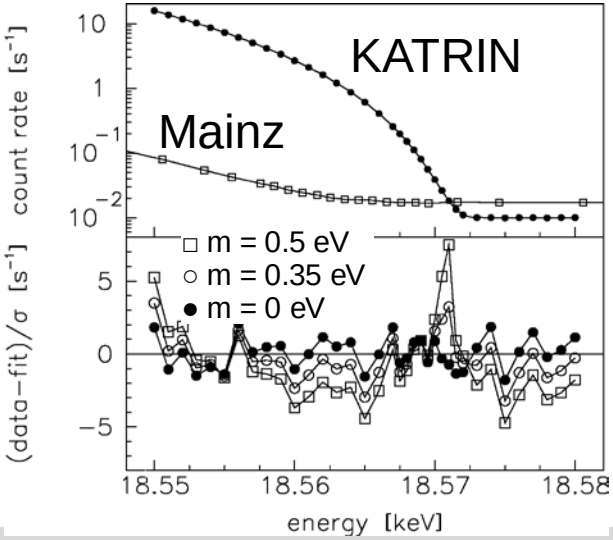






4) measurement point distrib. ⇒ MC data





Recent developments in β-spectroscopy

- **Sterile neutrinos *not* disfavoured by cosmology**
  - might be seen by KATRIN — Hamann et al.: arXiv: 1006.5276
    - if mass of ν_s is large enough (for instance LSND neutrinos)
    - mixing with $\bar{\nu}_e$ is large enough — Riis, Hannestad: arXiv: 1008.1495
- **New ideas**
  - **Project 8**: measures E_β via cyclotron radiation — Monreal, Formaggio, Phys. Rev. D80, 051301(R) (2009)
  - search for **ultra-low Q value** isotopes — Kopp, Merle: arXiv: 0911.3329v2
    - decay in excited daughter states
    - partial ionization of parent isotope
  - **radioactive ions in storage ring** — Lindroos et al.: arXiv: 0904.1089
  - **ultra-cold atoms in trap** (E_β, p_β, p_{rec}) — Jerkins et al.: arXiv: 0901.3111v4
  - **direct mass difference and heat** — Matsuzaki et al.: arXiv: 0908.4163v3