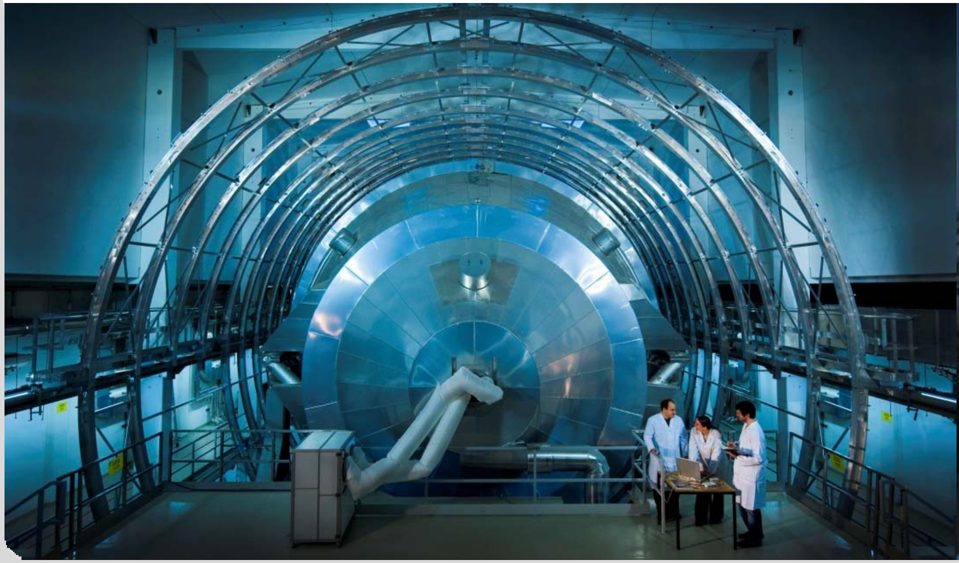
Karlsruhe Institute of Technology

Absolute Neutrino Mass Measurements

Joachim Wolf (KATRIN Collaboration)

Institute of Experimental Nuclear Physics

NuFact10, Mumbai / India

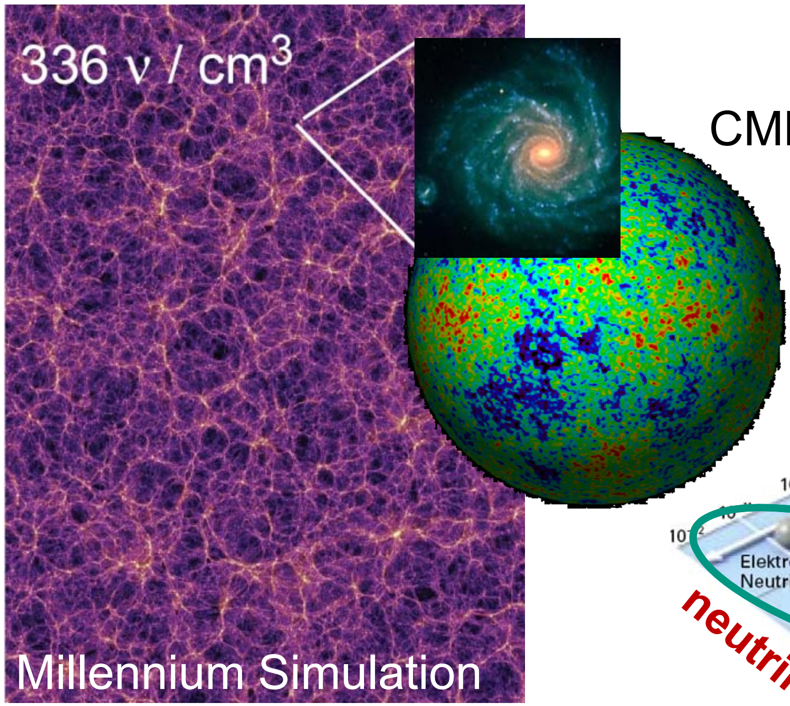


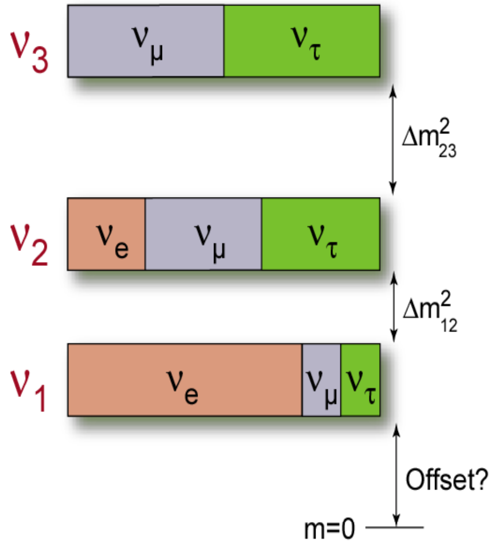
Motivation: ν´s in Astroparticle Physics

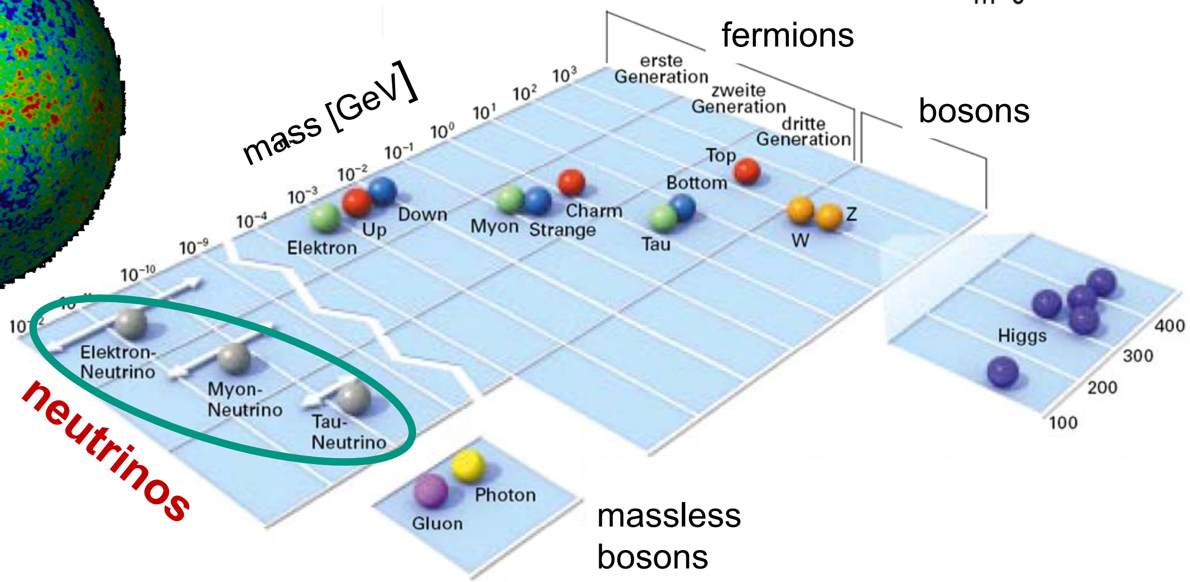
cosmology: role of ν´s as hot dark matter?

particle physics: origin and hierarchy of the ν-mass?

cosmology ⇔ **particle physics**







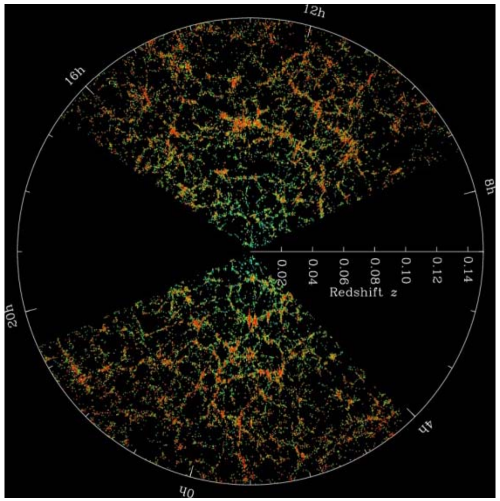
Methods to determine the neutrino mass scale

- **Cosmology**
  effect of neutrinos on structure formation
- **Search for $0\nu\beta\beta$ decays**
  decay only possible for massive Majorana neutrinos
- **Direct neutrino mass detection:**
  No further assumptions needed ($E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$)
  - **Time-of-flight measurements** (ν from supernova)
    SN1987a $\Rightarrow m(\nu_e) < 5.7$ eV (PDG 2006)
  - **Kinematics of weak decays** (β-decay search for $m_{\nu e}$)
    - tritium β-decay spectrometers
    - ^{187}Re β-decay bolometers
    - search for other low-Q isotopes ?

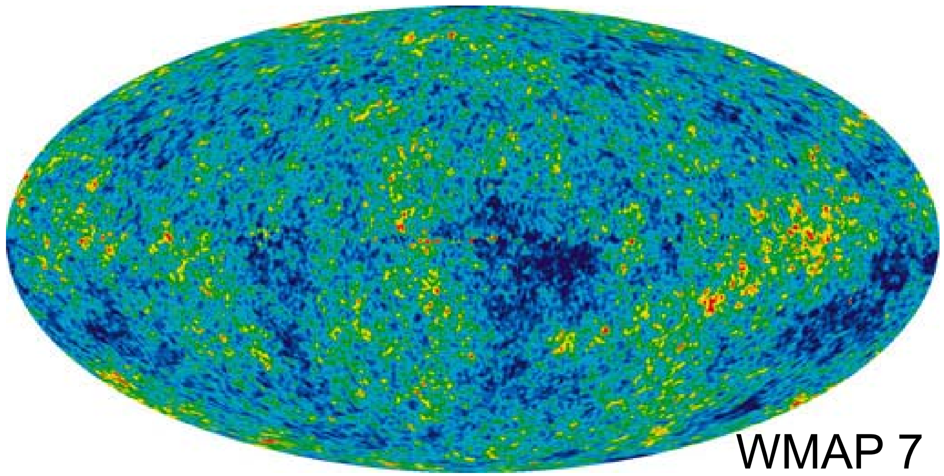
Cosmology and neutrino mass

- 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: $0.3\ \mathrm{eV} \leq \Sigma m_i \leq 2\ \mathrm{eV}$

S. Hannestad: arXiv:1007.0658v2



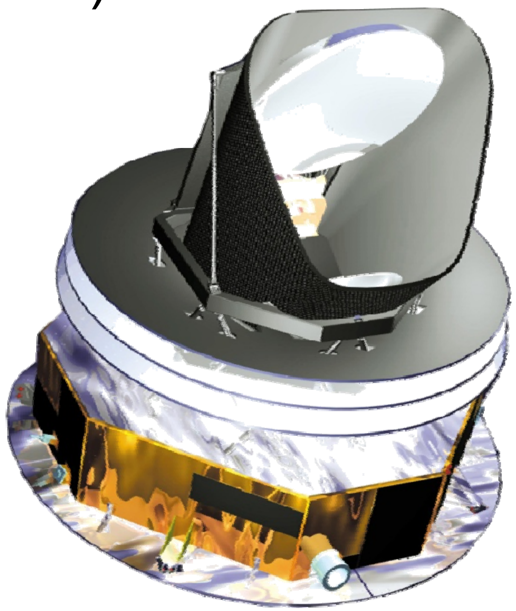
SDSS DR7


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:

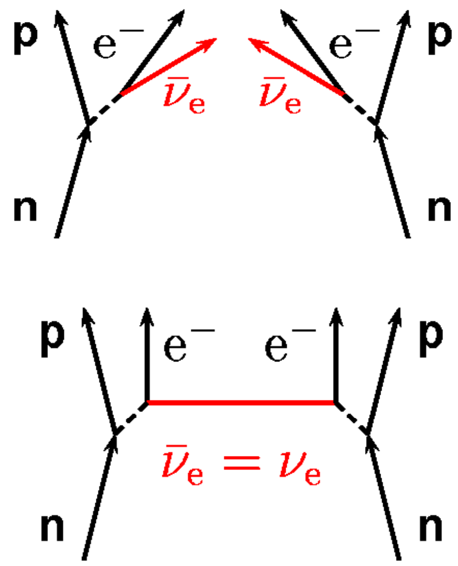
- short term (5-7 y): $0.1\ \mathrm{eV} \leq \Sigma m_j \leq 0.6\ \mathrm{eV}$
- long term (7-15 y): $0.05\ \mathrm{eV} \leq \Sigma m_j \leq 0.4\ \mathrm{eV}$

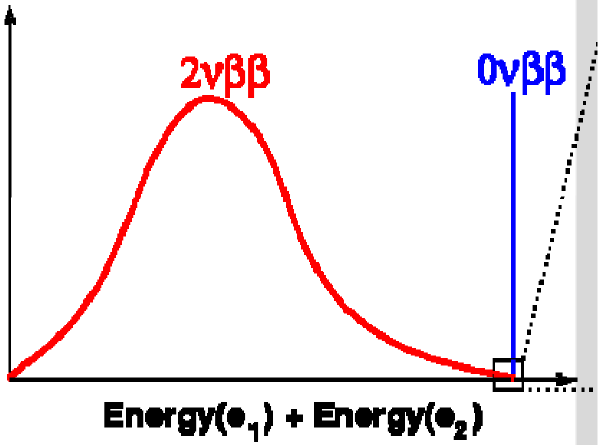
S. Hannestad: arXiv:1007.0658v2

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

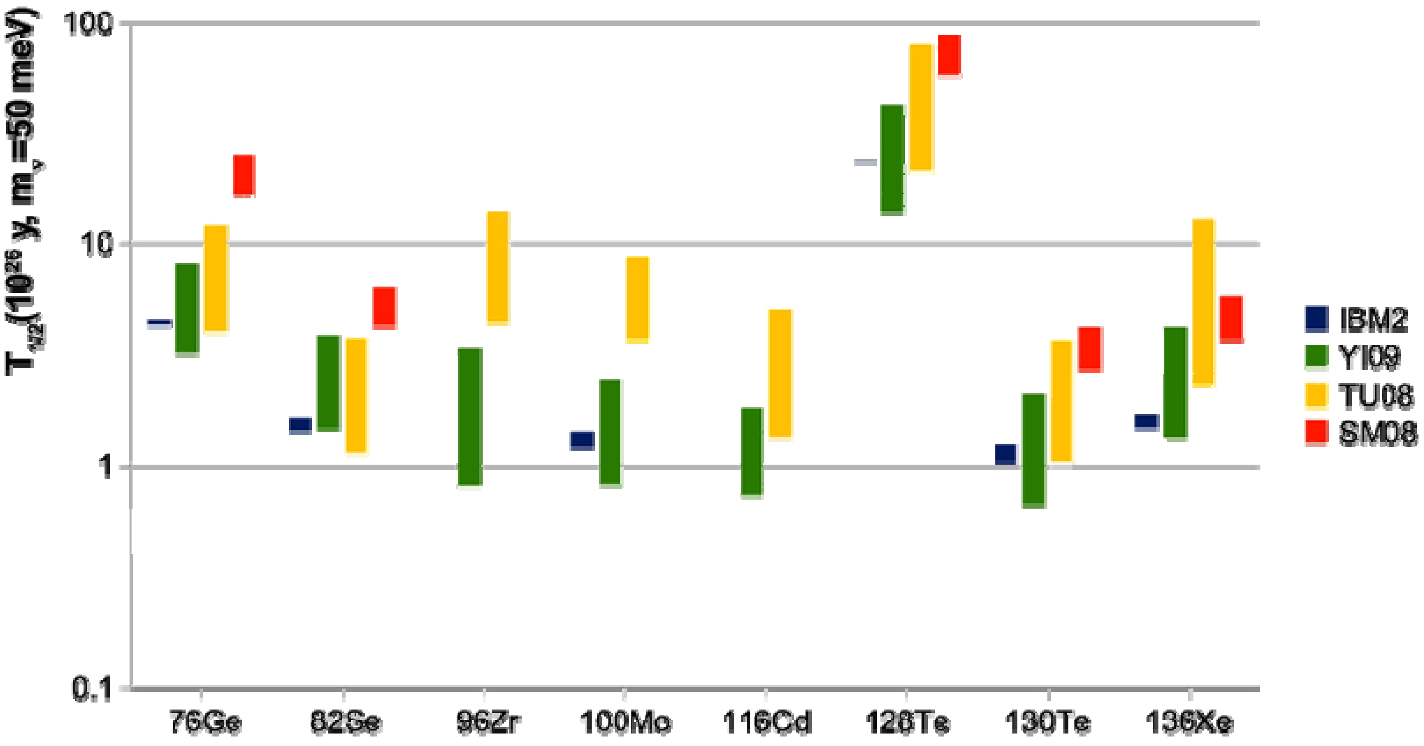


Figure 1: Expected $\beta\beta(0\nu)$ half lives for 50 meV effective neutrino mass and different NME calculations: IBM2 [17], YI09 [18], TU08 [19] and SM08 [20].

O. Cremonesi: arXiv: 1002.1437v1

Neutrino-less double-β-decay and neutrino mass

- **Current results:**
  - **Heidelberg-Moskau (^{76}Ge)**
    - **KHDH analysis:** $T_{1/2} = 2.23 \times 10^{25}$ y, $m_{\beta\beta} = 0.32$ eV (6σ)

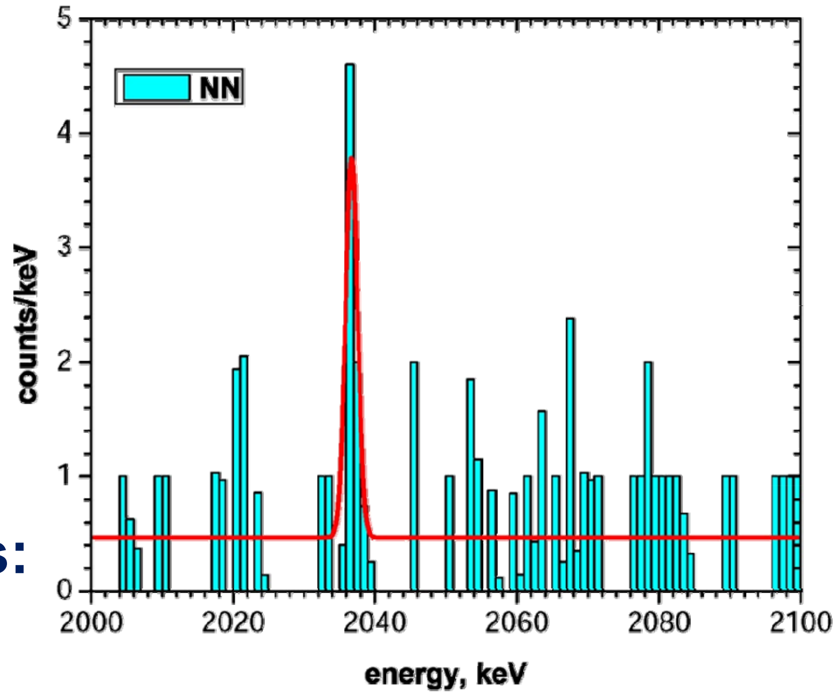
H. V. Klapdor-Kleingrothaus and I. V. Krivoshein, Mod. Phys. Let. A, Vol. 21, No. 20 (2006) 1547

  - **IGEX (^{76}Ge)** $T_{1/2} > 1.57 \times 10^{25}$ y, $m_{\beta\beta} < 0.33 – 1.35$ eV
  - **Cuoricino (^{130}Te)** $T_{1/2} > 3.0 \times 10^{25}$ y, $m_{\beta\beta} < 0.19 – 0.68$ eV
  - **NEMO 3**
    - ^{159}Nd $T_{1/2} > 1.8 \times 10^{22}$ y, $m_{\beta\beta} < 4.0 – 6.3$ eV
    - ^{100}Mo $T_{1/2} > 2.7 \times 10^{22}$ y, $m_{\beta\beta} < 0.19 – 0.68$ eV
    - ^{116}Cd, ^{82}Se, ^{96}Zr, ^{48}Ca and ^{130}Te

- **positive signal can also come from physics beyond the SM**

Neutrino-less double-β-decay and neutrino mass

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



- **$0\nu2\beta$ 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

Neutrino-less double-β-decay and neutrino mass

Future scenarios and branching points in terms of discovery

sensitivity to $\langle M_{\beta\beta} \rangle$	experimental situation
100 - 500 meV	degenerate hierarchy 100-200 kg isotope – 1-5 year scale
15 - 50	
2 - 5 n	discovery if neutrino is a Majorana particle unpredictable time scale

if this range holds (and/or ^{76}Ge claim is confirmed):

- CUORE will see it in ^{130}Te and may do multi-isotope searches simultaneously (^{130}Te - ^{116}Cd - ^{100}Mo)
- GERDA phase I / II will see it 0ν-DBD ^{76}Ge
- EXO-200 will see it in ^{136}Xe
- SNO+ could see it in ^{150}Nd
- SuperNEMO may investigate the mechanism (^{82}Se or ^{150}Nd)

reduction of uncertainties in NME

precision measurement era for 0ν-DBD!

slide from A. Giuliani: NOW2010

Neutrino-less double-β-decay and neutrino mass

Future [title partly covered by overlay box]

if this range holds:
- CUORE could marginally see it, but could clearly detect it in ^{130}Te if enriched or in ^{82}Se / ^{116}Cd / ^{100}Mo if upgraded to LUCIFER-mode
SuperNEMO could marginally see it in ^{82}Se or ^{150}Nd
- SNO+ could see it in ^{150}Nd only if enriched
- GERDA phase III / MAJORANA could see it in ^{76}Ge

large scale enrichment required

discovery in 3 or 4 isotopes necessary (and possible...) to confirm the observation and to improve $\langle M_{\beta\beta} \rangle$ estimate

sensitivity	
100 - 50	
15 - 50 meV	inverted hierarchy - atmospheric ΔM^2 region 1000 kg isotope – 5-10 year scale
2 - 5 meV	direct hierarchy - solar ΔM^2 region 100 tons of isotopes is the typical scale discovery if neutrino is a Majorana particle unpredictable time scale

slide from A. Giuliani: NOW2010

Standard β-decay and neutrino mass

kinetic measurement of the effective neutrino mass

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

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

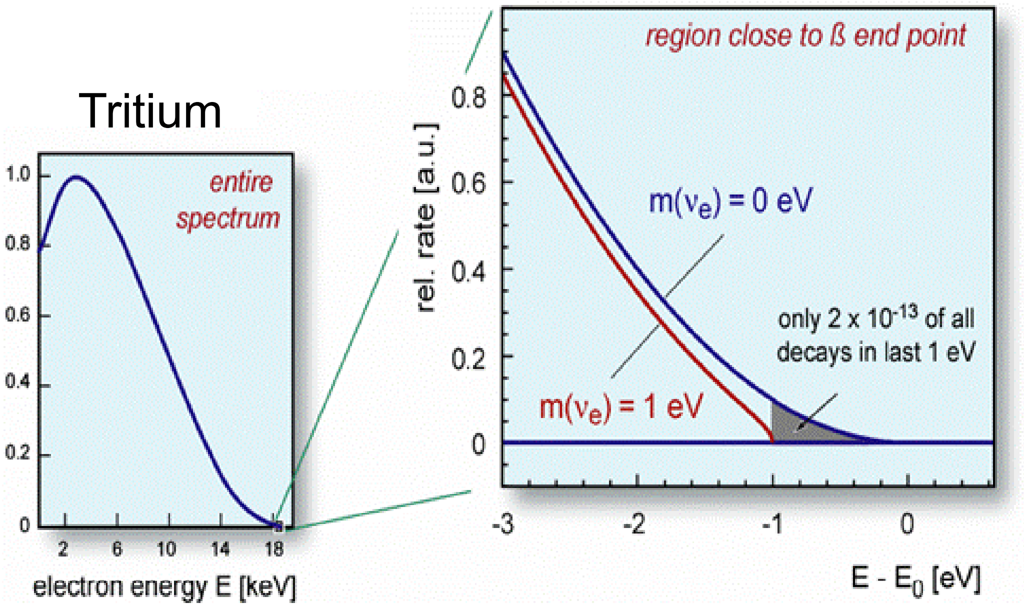
Standard β-decay and neutrino mass

kinetic measurement of the effective neutrino mass

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

Fermi's golden rule:

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



Low Q value necessary

Tritium as β-emitter:

- high specific activity ($t_{1/2}$=12.3a)
- endpoint energy E_0=18.6 keV
- super allowed transition

Rhenium as β-emitter:

- low spec. activity ($t_{1/2}=4.3 \cdot 10^{10}$a)
- endpoint energy E_0=2.47 keV
- uniquely forbidden transition

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

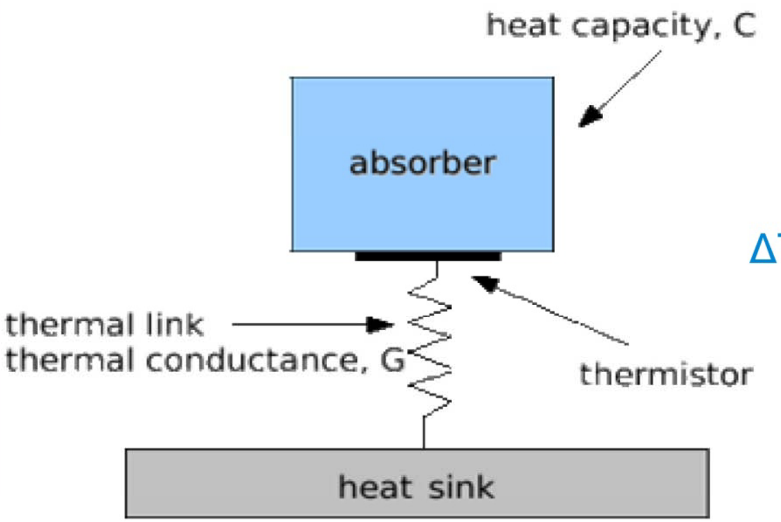
→ **KATRIN**

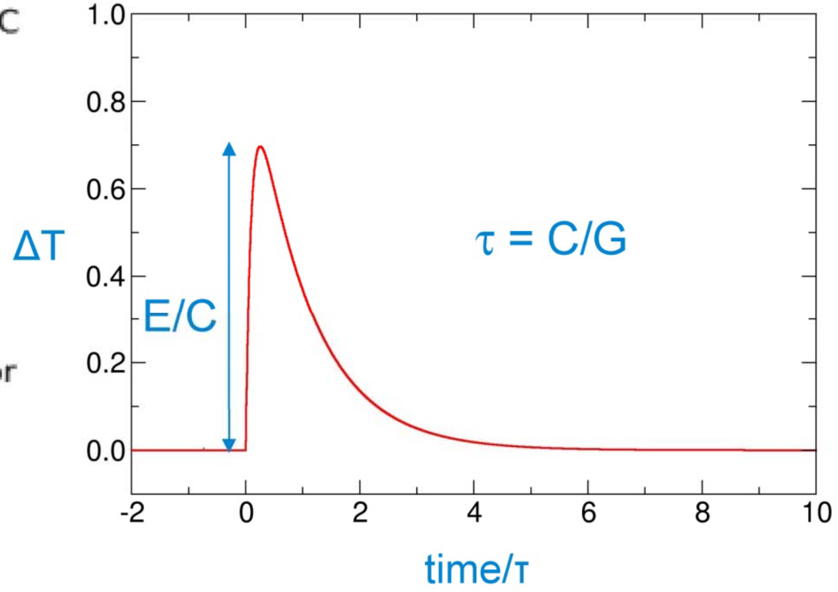
Micro-calorimeter (^{187}Re)

- 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**

Cryogenic Detectors





Detection Principle:

- $\Delta T = E/C$ where C is the total thermal capacity
  - low C: $C \sim (T/\Theta_D)^3$ in superconductors & dieletric below T_C
    - low T (10 ÷ 100 mK)
- ultimate limit to energy resolution:
  - statistical fluctuation of internal energy $\Delta E = (k_B T^2 C)^{1/2}$
- detect all deposited energy, including short-lived excited states (100 μs)
- achieve very good energy resolution in the keV range

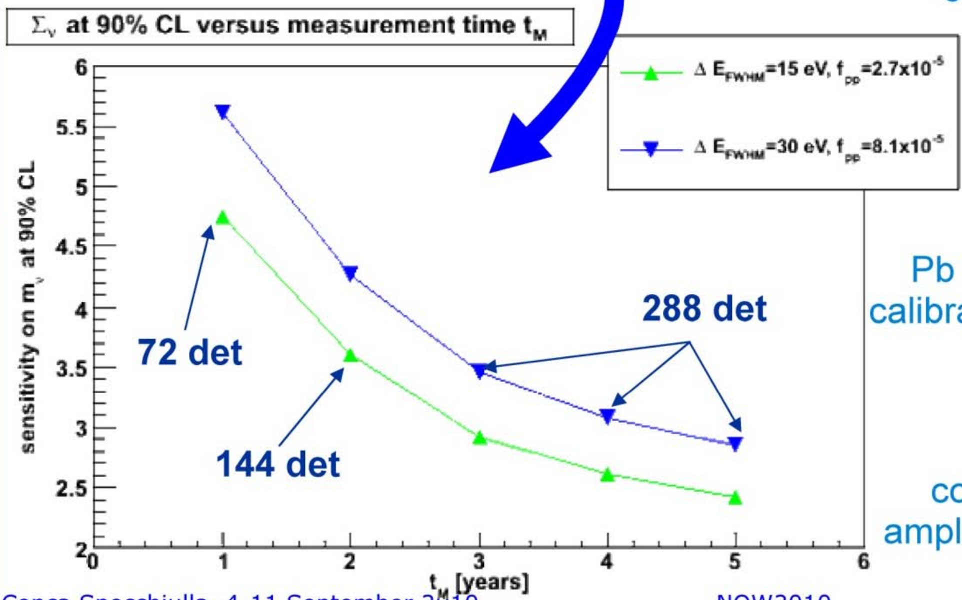
MARE 1 in Milan: MC sensitivity

Detectors

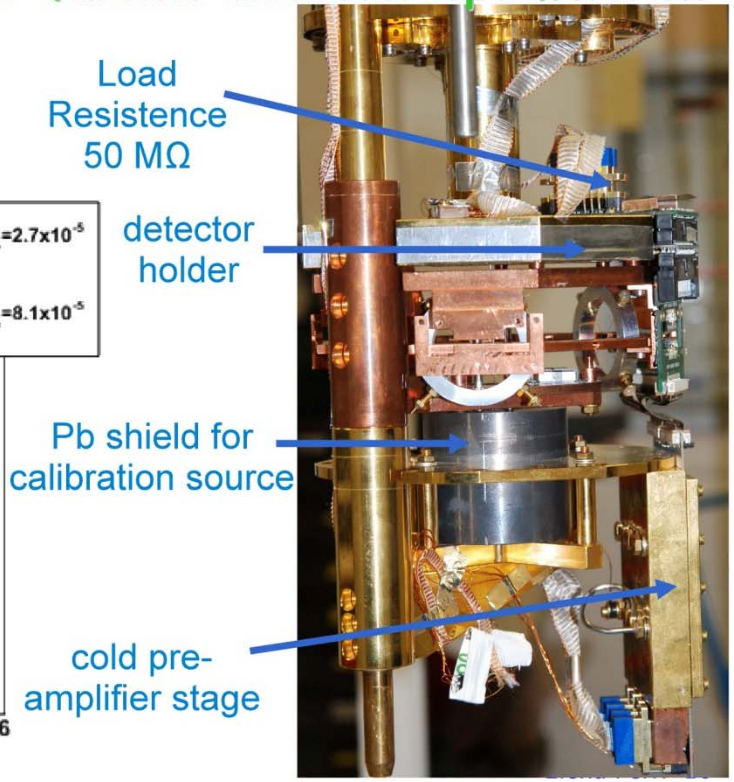
ΔE_{FWHM} ~ 15 eV e τ_R ~ 100 μs
1 year and 72 channels → $\Sigma(m_\nu)$ ~5eV
3 years and 288 channels → $\Sigma(m_\nu)$ ~ 3eV

ΔE_{FWHM} ~ 30 eV e τ_R ~ 300 μs
1 year and 72 channels → $\Sigma(m_\nu)$ ~6eV
3 years and 288 channels → $\Sigma(m_\nu)$ ~ 3eV

- setup designed for 8 arrays
- 288 $AgReO_4$ crystals
- now starting with 2 arrays (72 ch.)
- gradual deployment
  - ▷ **further detector optimization**



Conca Specchiulla, 4-11 September 2010 NOW2010



MARE 1 activities

- **Isotope physics investigation and systematics assessment**
  - ^{163}Ho + Si-impl/TES (U Genova - U Milano-Bicocca – U Lisbon/ITN)
  - $AgReO_4$ + Si-impl (U Milano-Bicocca - U Como - NASA/GSFC – UW Madison)
- **Sensor-Absorber coupling (^{187}Re/^{163}Ho) and single pixel design**
  - ^{187}Re + TES (U Genova – U Miami – U Lisbon/ITN)
  - ^{187}Re + MMC (U Heidelberg)
  - ^{163}Ho + TES (U Genova)
  - ^{163}Ho + MMC (U Heidelberg)
  - ^{163}Ho/^{187}Re + MKID (U Milano-Bicocca -JPL/Caltech - U Roma - FBK)
- **Multiplexed sensor read-out**
  - SQUID multiplexing (U Genova - PTB)
  - SQUID microwave multiplexing (U Heidelberg)
- **Software tools**
  - Data Analysis (U Miami)
  - Montecarlo simulations (U Miami - U Milano-Bicocca)

MARE 2 statistical sensitivity: Re & Ho options

- only statistical analysis
- 50000+ detectors gradually deployed
  - ▷ arrays distributed in many laboratories around the world
  - ▷ about $10^{13} \div 10^{14}$ events after 5 years

Exposure required for 0.2 eV m_ν sensitivity

^{187}Re

A_β [Hz]	τ_R [µs]	ΔE [eV]	N_{ev} [counts]	exposure [det × year]
1	1	1	0.2×10^{14}	7.6×10^5
10	1	1	0.7×10^{14}	2.1×10^5
10	3	3	1.3×10^{14}	4.1×10^5
10	5	5	1.9×10^{14}	6.1×10^5
10	10	10	3.3×10^{14}	10.5×10^5

bkg = 0

5000 pixels/array
8 arrays
10 years
400 g ^{nat}Re

^{163}Ho

A_β [Hz]	τ_R [µs]	ΔE [eV]	N_{ev} [counts]	exposure [det × year]
1	1	1	2.8×10^{13}	9.0×10^5
1	0.1	1	1.3×10^{13}	4.3×10^5
100	0.1	1	4.6×10^{13}	1.5×10^4
10	0.1	1	2.8×10^{13}	9.0×10^4
10	1	1	4.6×10^{13}	1.5×10^5

Q_{EC} = 2200 eV
bkg = 0

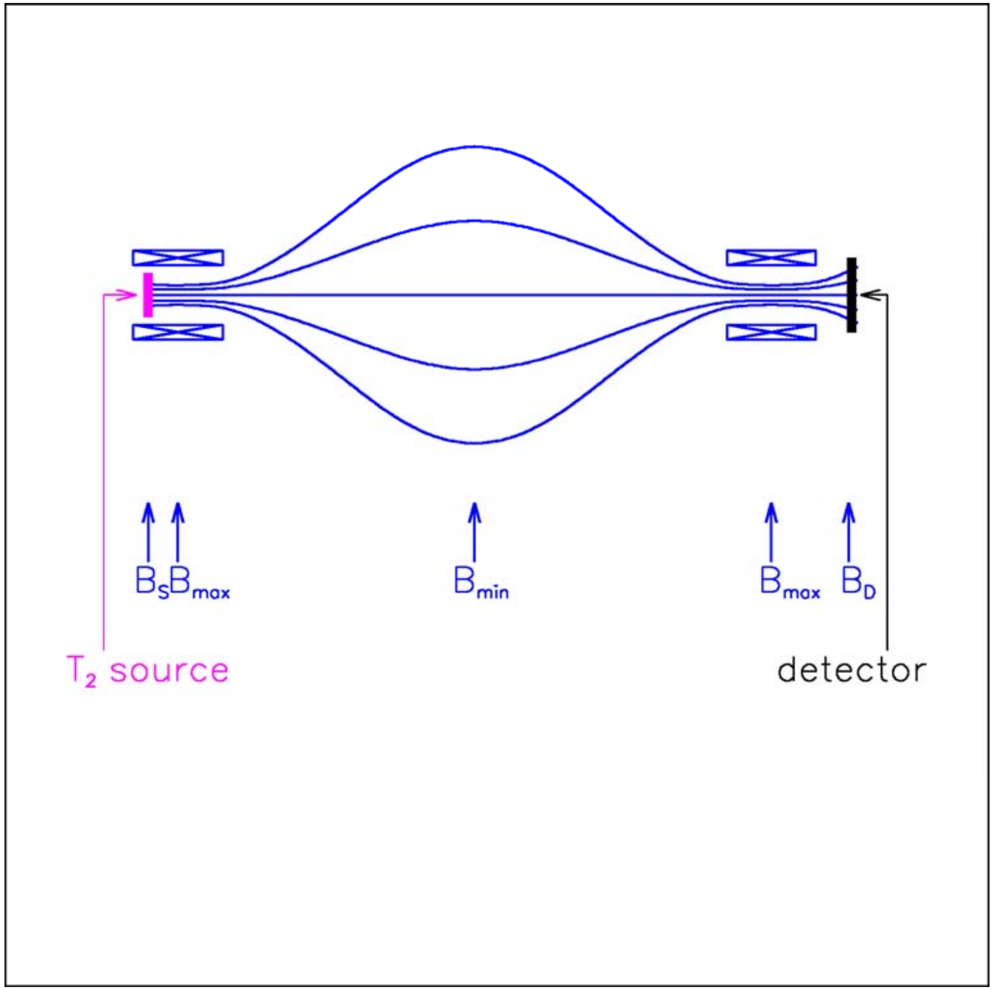
5000 pixels/array
3 arrays
1 year
~2×10^{17} ^{163}Ho nuclei

need for new sensor R&D and new read-out techniques

Principle of the MAC-E-Filter

Magnetic Adiabatic Collimation + Electrostatic Filter
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

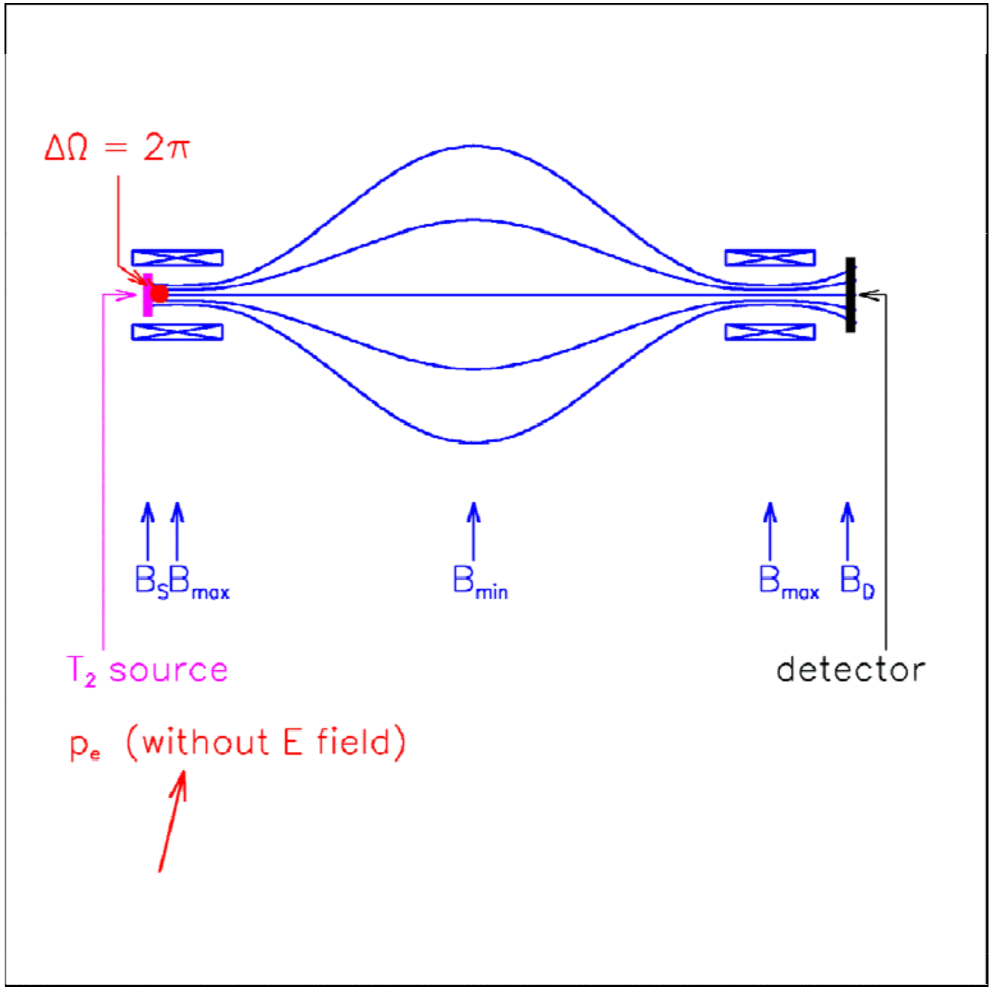
- Two supercond. solenoids compose magnetic guiding field
- Electron source (T_2) in left solenoid



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
- e^- in forward direction: magnetically guided
- adiabatic transformation: $\mu = E_\perp / B = \text{const.}$ $\Rightarrow$ parallel e^- beam

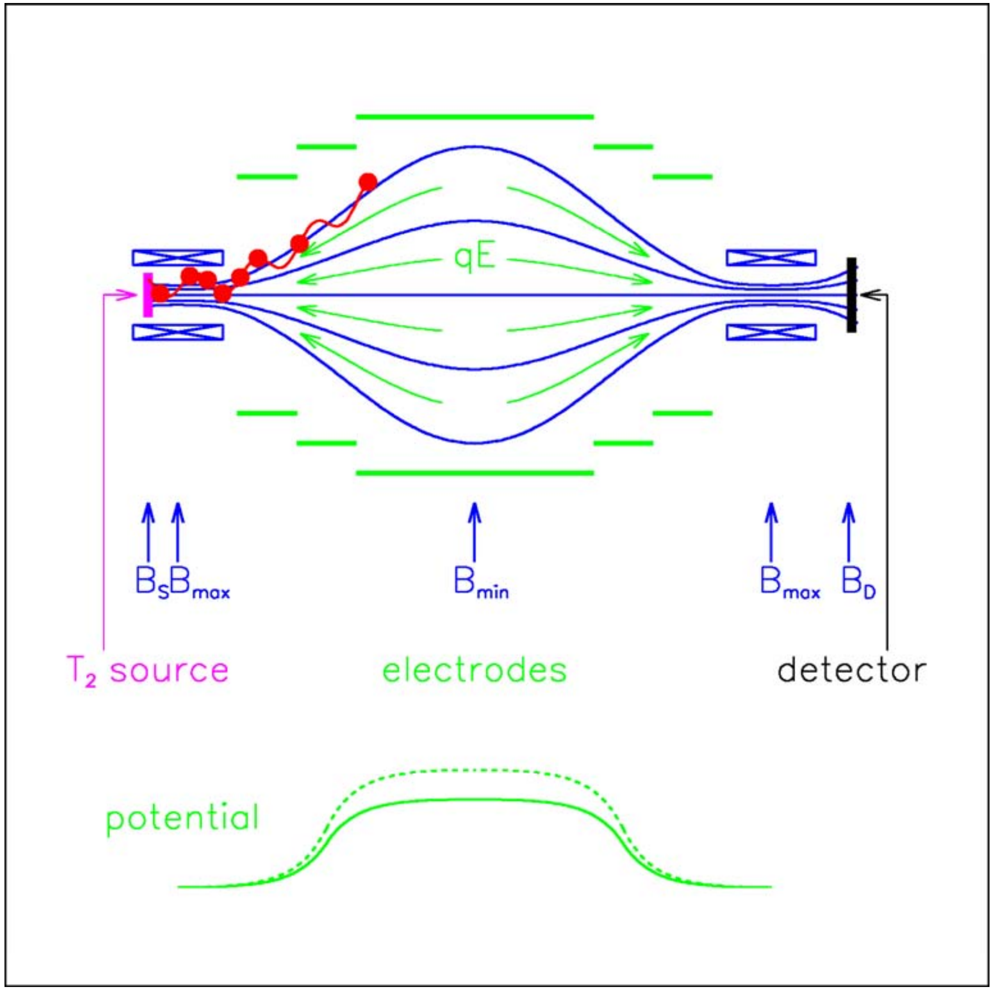


Principle of the MAC-E-Filter

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
- e^- in forward direction: magnetically guided
- adiabatic transformation: $\mu = E_\perp / B = \text{const.}$
  $\Rightarrow$ parallel e^- beam
- Energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min} / B_{max} = E \cdot A_{s,eff} / A_{analyse}$

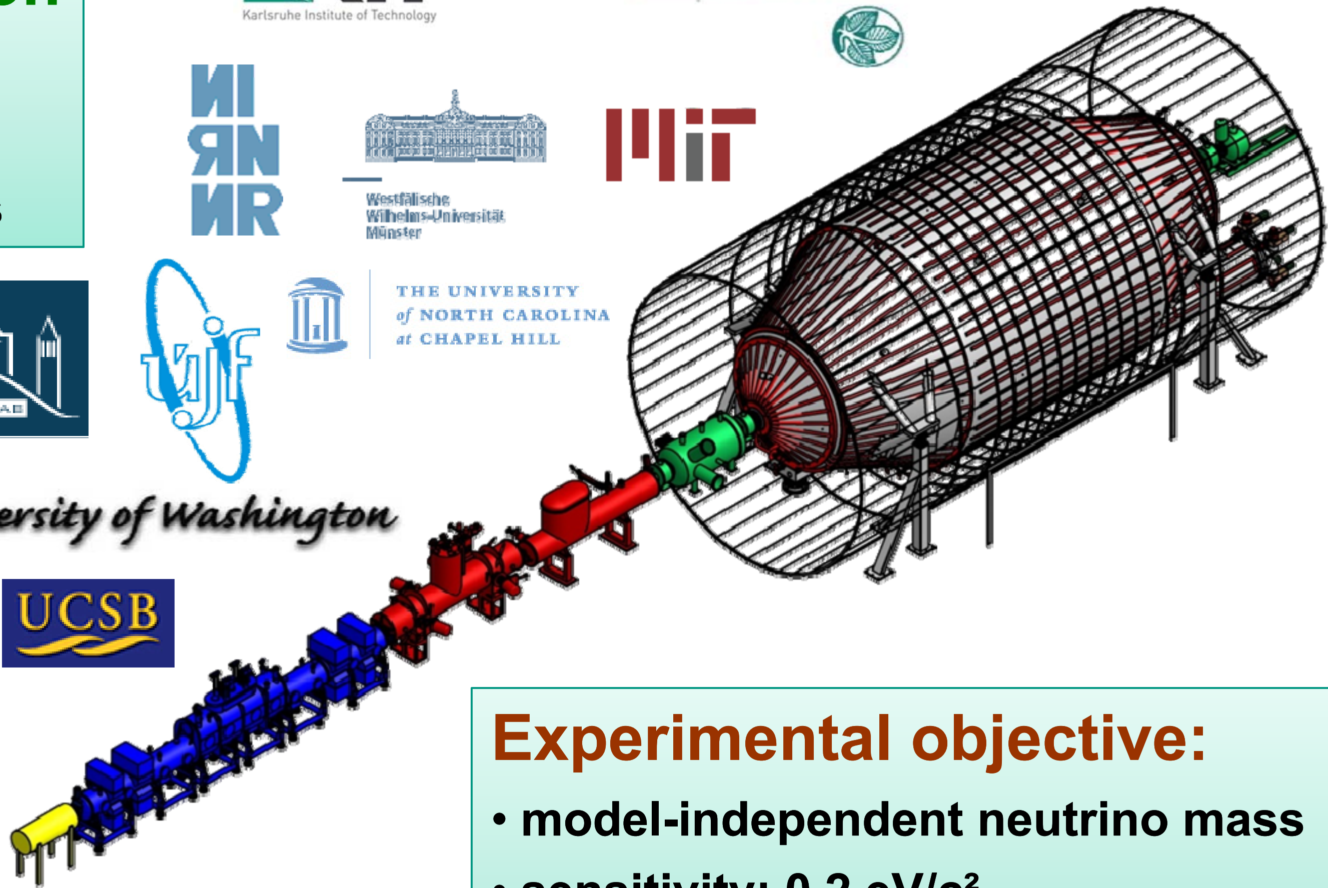
Mainz ≈ 4.8 eV; KATRIN = 0.93 eV



The KATRIN experiment

Collaboration

- 130 scientists
- 5 countries
- 14 institutions



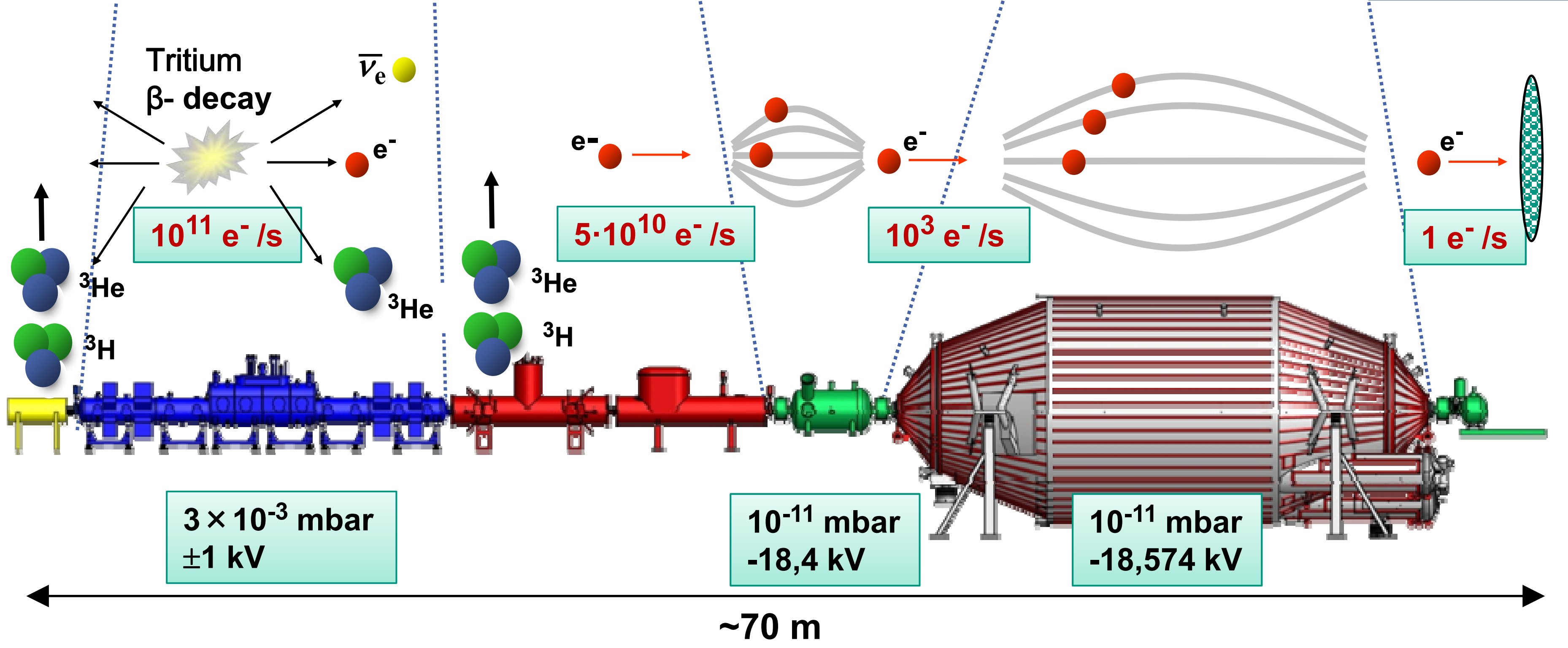
Experimental objective:

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

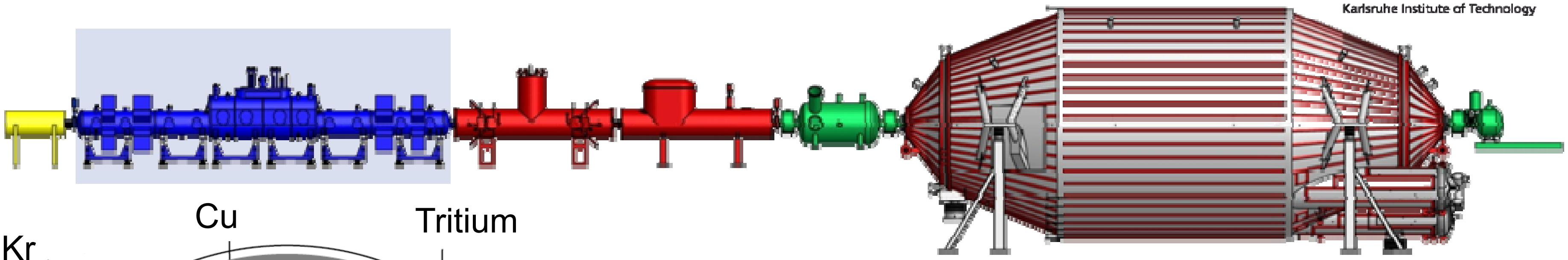
The KATRIN Setup

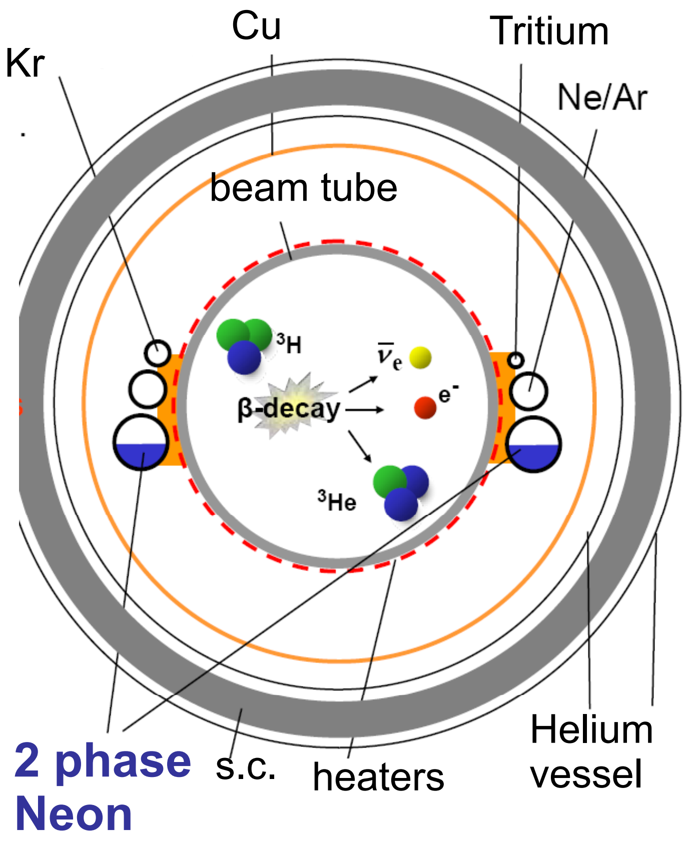
source & transport section | spectrometer & detector section

source monitoring	stable tritium column density	electron transport tritium retention	reflection of low energy electrons	high precision energy analysis of electrons	electron counter
rear	source (WGTS)	diff. pumping	pre-spectrometer	main spectrometer	detector



Windowless Gaseous Tritium Source WGTS



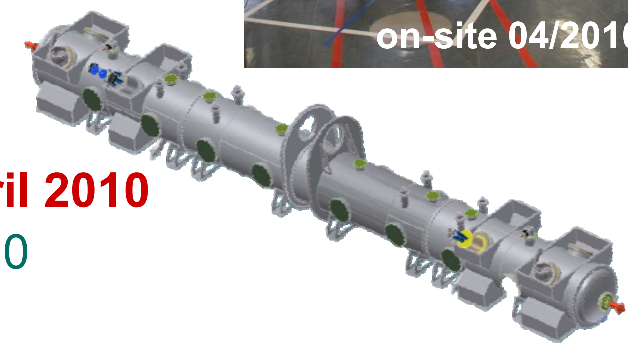


KATRIN requirement:

T = 27 K with ΔT < 30 mK

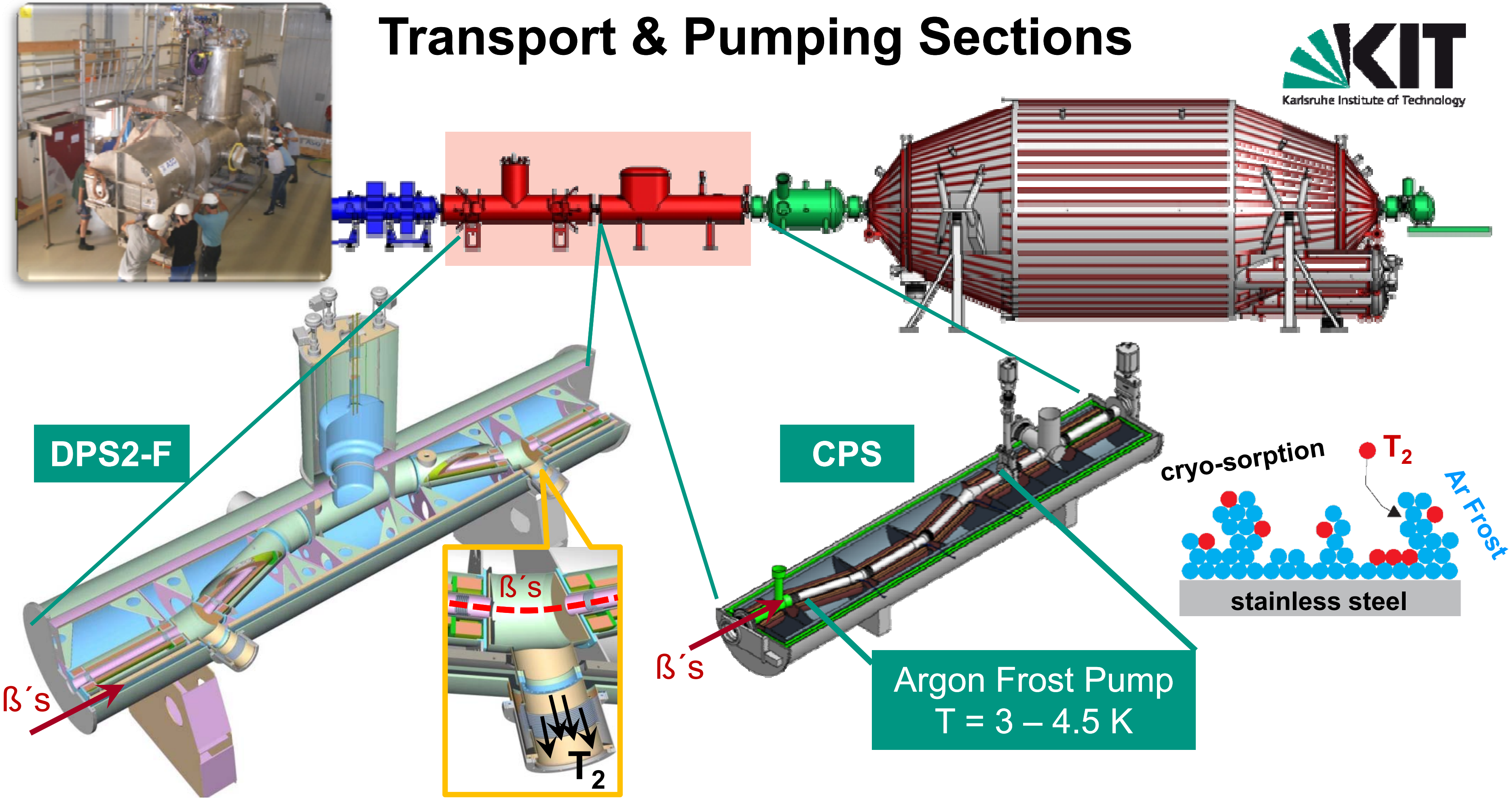
Control system designed for 10^{-4} level.

Demonstrator:



- **on-site since April 2010**
- tests until Fall 2010
- upgrade to WGTS

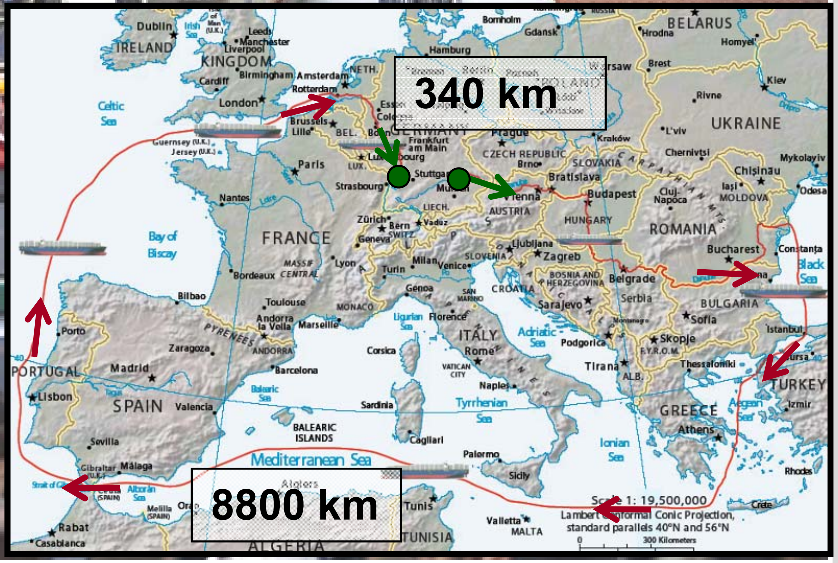
Transport & Pumping Sections



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

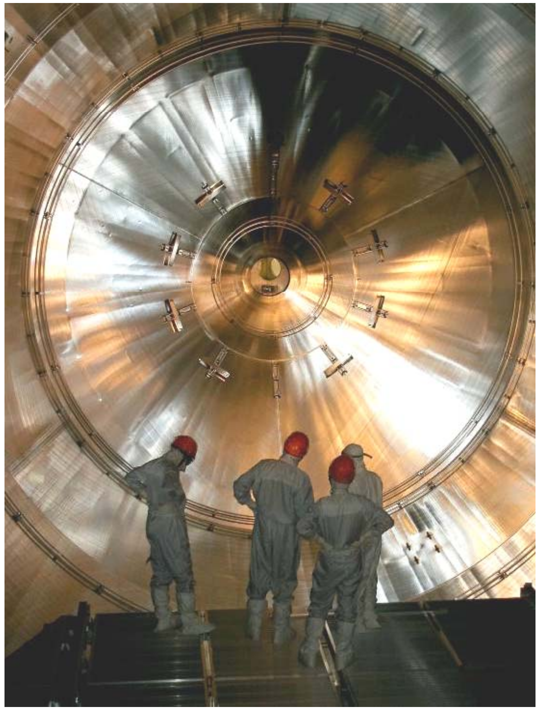
- pumping by cryo-sorption
- Tritium retention $>10^7$
- magnetic field: 5.6 T
- on schedule: delivery 2011

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

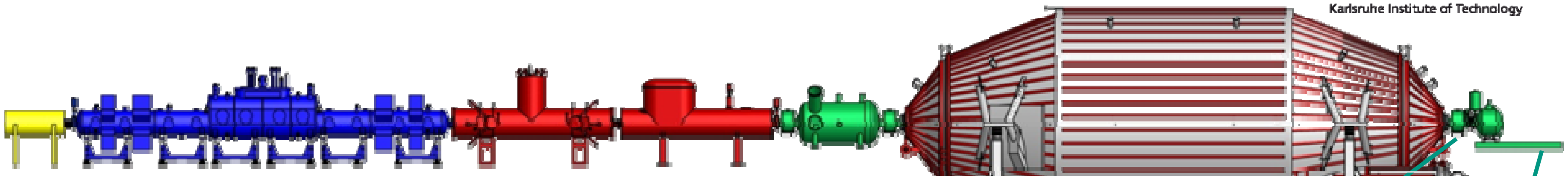


Status of the main spectrometer

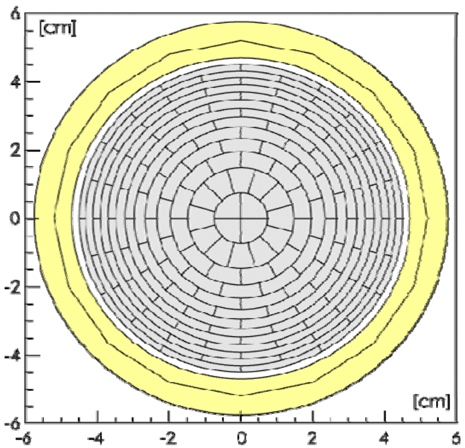
- successfull bake-out (350°C) and vacuum tests
- inner electrode system being prepared for installation
  - 23440 individual wires in 248 frames (University Münster)
- Helmholtz coils with 12.6 m diameter installed
- first electromagnetic tests planned in 2011

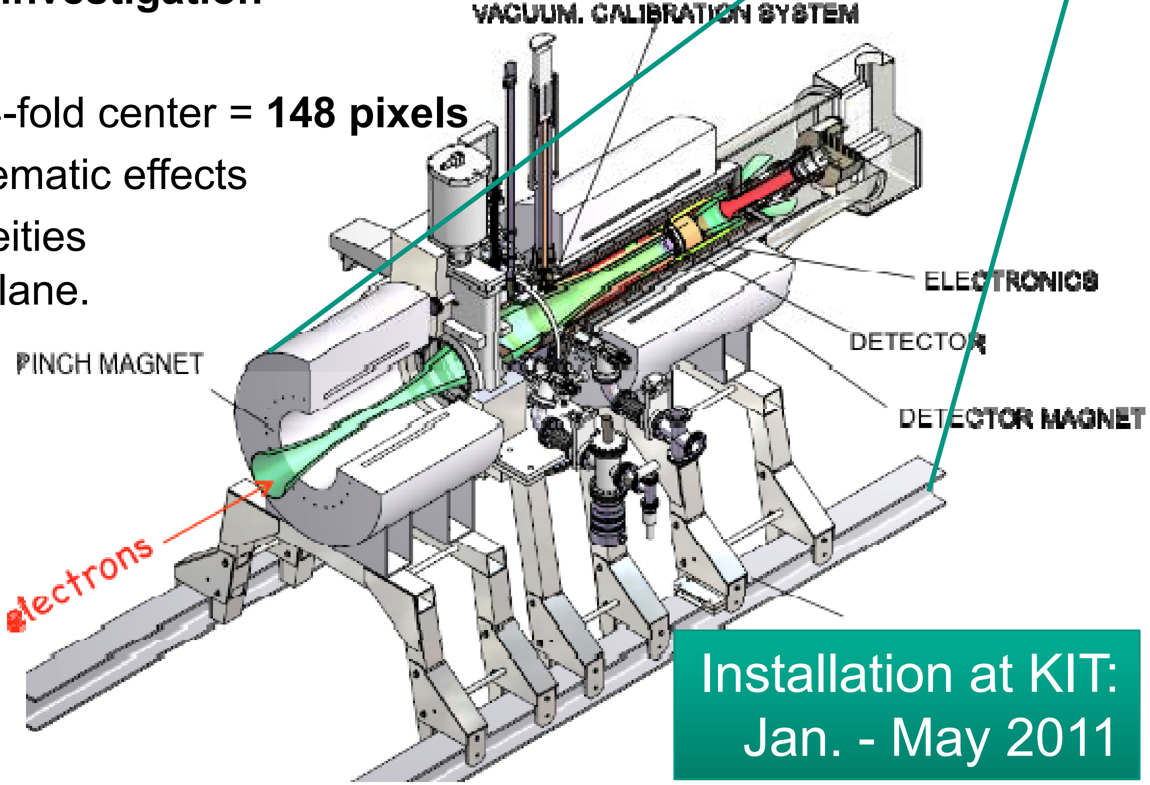


Main Detector



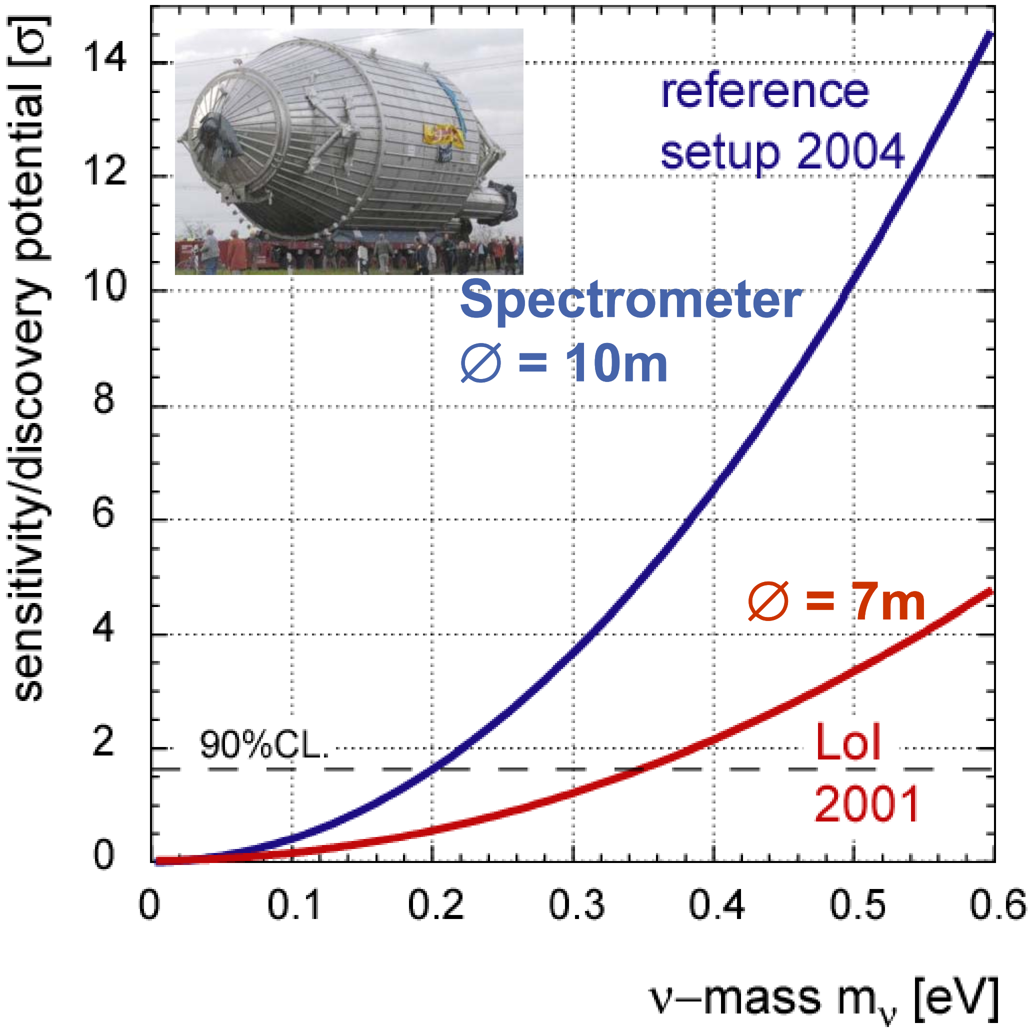
- Si-PIN diode
- detection of transmitted β decay electrons (mHz to kHz)
- **low background for T_2 endpoint investigation**
- high energy resolution ΔE ≈ 1 keV
- 12 rings with 30° segmentation + 4-fold center = **148 pixels**
  - minimize bg, investigate systematic effects
  - compensate field inhomogeneities of spectrometer's analyzing plane.





Installation at KIT:
Jan. - May 2011

KATRIN sensitivity and discovery potential



sensitivity (90% CL)

m(ν) < 0.2 eV

discovery potential

m(ν) = 0.35 eV (5σ)

begin of measurements

2011 (test runs with spectrometer)

201x (full system integration)

final results after 5-6 years

KATRIN Design Report 2004

http://bibliothek.fzk.de/zb/berichte/**FZKA7090.pdf**

Recent developments in β-spectroscopy

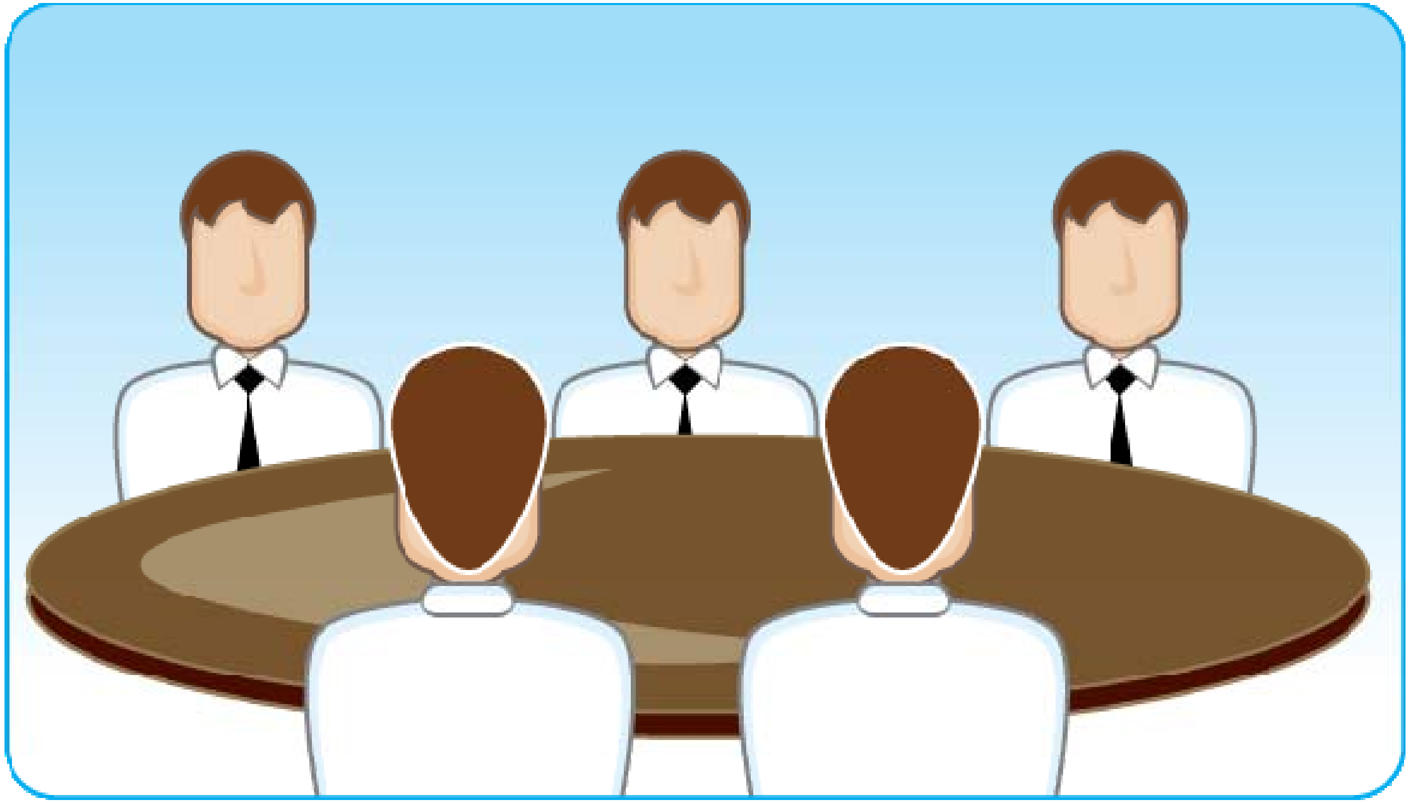
- **Sterile neutrinos *not* disfavoured by cosmology**
  - might be seen by KATRIN — Hamann et al.: arXiv: 1006.5276
    - if mass of ν_s is large enough (for instance LSND neutrinos)
    - mixing with $\bar{\nu}_e$ is large enough — Riis, Hannestad: arXiv: 1008.1495
- **New ideas**
  - **Project 8**: 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

Conclusions

- **Three methods to determine the neutrino mass**
  - **cosmology (LSS, CMB, BBN)**
    - currently most sensitive probe to m_{ν},
    - model dependent
    - no access to source (relic neutrinos, other HDM non-SM particles ?)
    - next generation: $\Sigma m_j < 0.1$ eV (0.05 eV)
  - **$2\beta0\nu$**
    - very sensitive
    - model dependent (nuclear matrix element, non-SM couplings ?)
    - next generation: $m_{\beta\beta} = \Sigma|U_{ej}|^2 e^{i\alpha} m_j < 0.1$ eV (0.05 eV)
  - **β-decay**
    - sensitivity reached limit, new ideas needed
    - not model dependent (kinematics)
    - next generation: $m_{\beta} = (\Sigma|U_{ej}|^2 m_j^2)^{1/2} < 0.2$ eV (0.1 eV ?)
- **methods complement one another (Σm_j , $m_{\beta\beta}$, m_{β})**
- **next decade should become very interesting for m_{ν}**

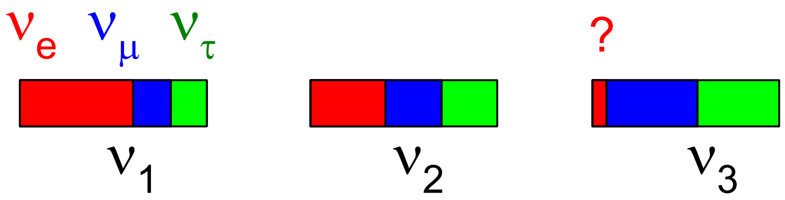

Thank you for your attention

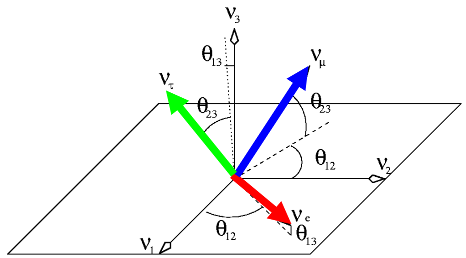
Discussion



Absolute neutrino mass

Results of recent oscillation experiments: $\Theta_{23}, \Theta_{12}, \Delta m^2_{23}, \Delta m^2_{12}$





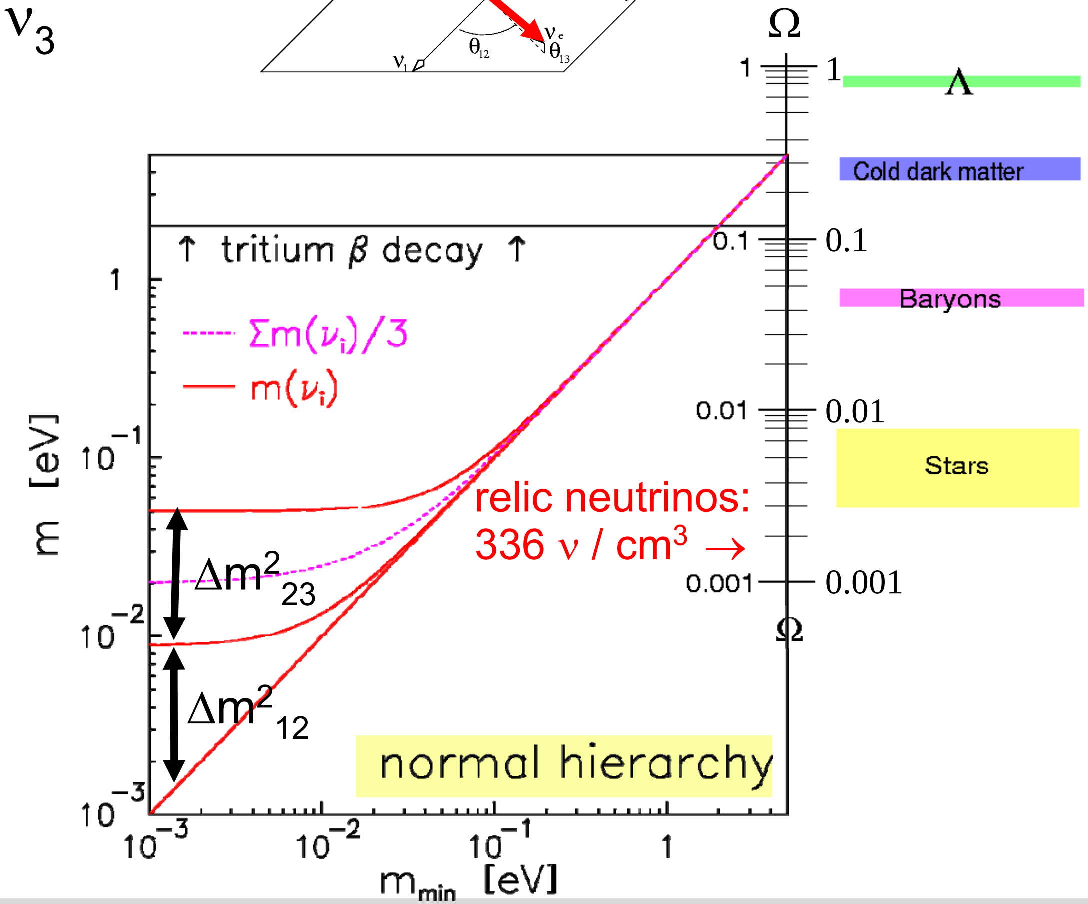
degenerated masses

accessible to β-experiments

cosmologically relevant:

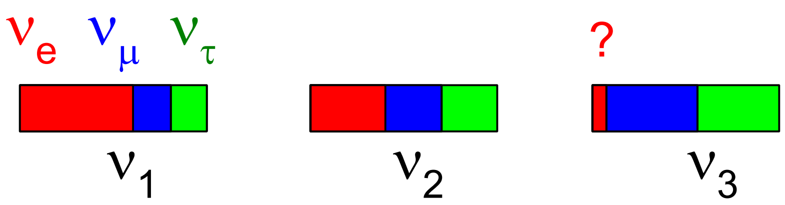
- HDM
- large scale structure formation

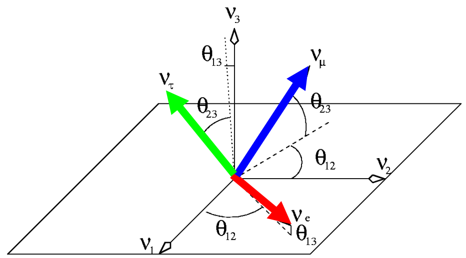
hierarchical masses



Absolute neutrino mass

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





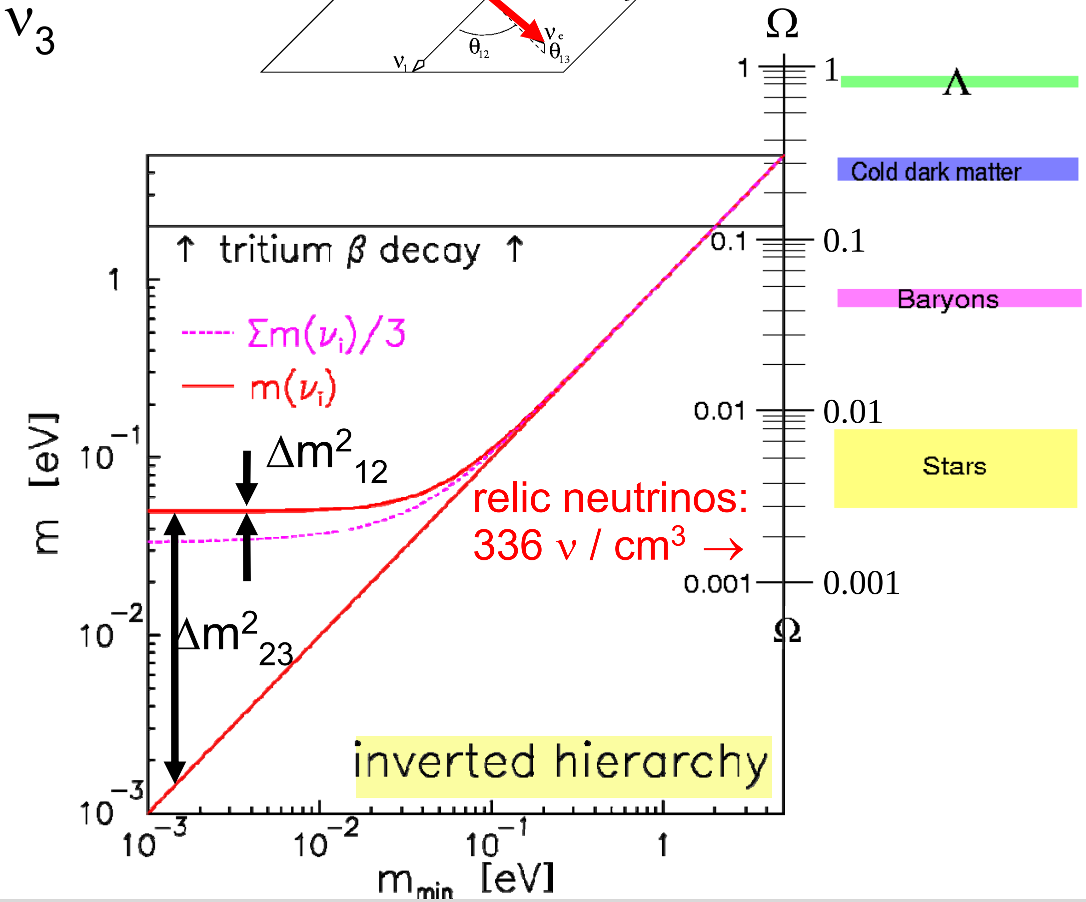
degenerated masses

accessible to β-experiments

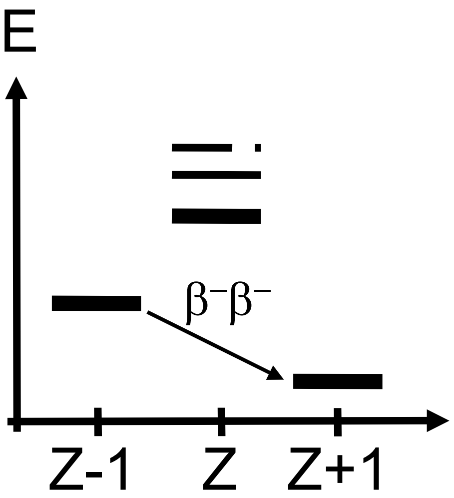
cosmologically relevant:

- HDM
- large scale structure formation

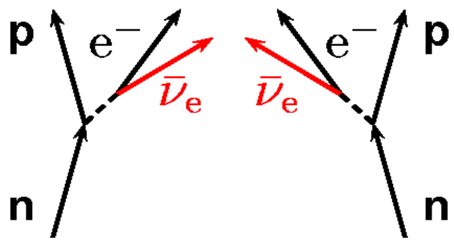
hierarchical masses



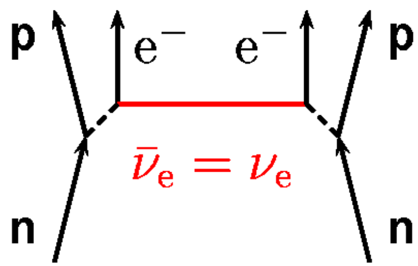
Double β decay



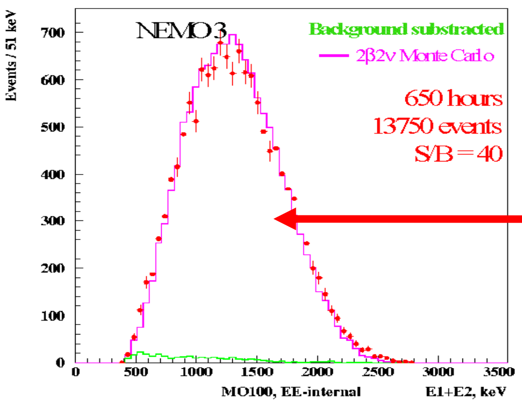
normal (2νββ)

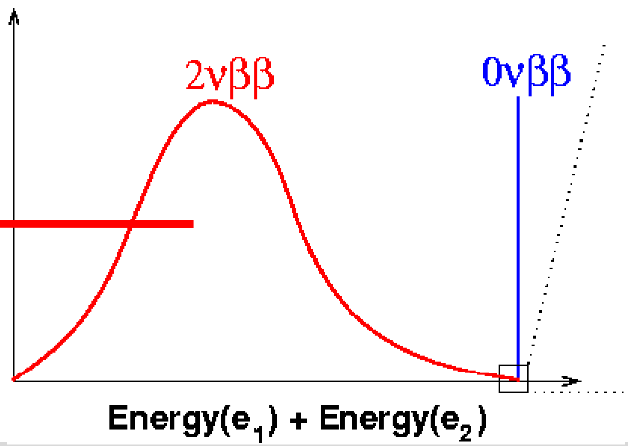


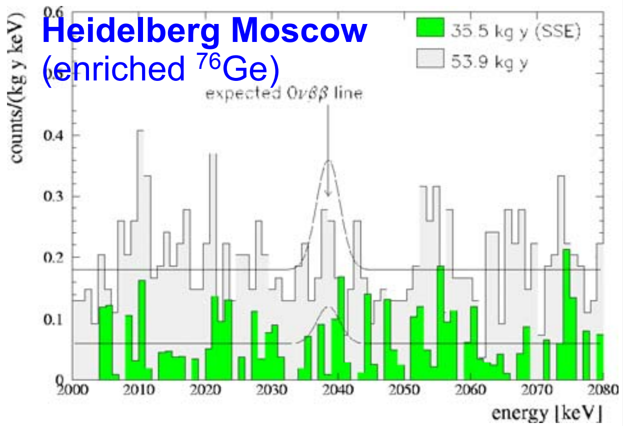
neutrinoless (0νββ)



needed: a) $\bar{\nu} = \nu$ (Majorana)
b) helicity flip: $m(\nu) \neq 0$
or other new physics







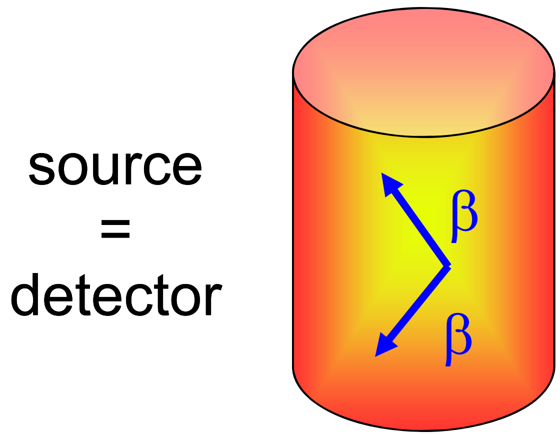
Current and future double β decay experiments

$m_{ee} \sim (1/\text{enrichment})^{1/2} \cdot (\Delta E \cdot bg/M \cdot t)^{1/4}$

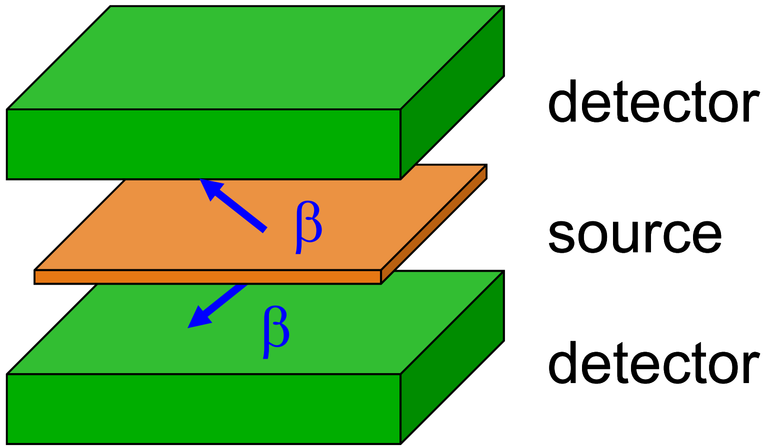
⇒ mass → 1t, high enrichment, very low background *bg*

2 ways to measure both β-electrons:

semiconductor or cryogenic bolometer



tracking calorimeter

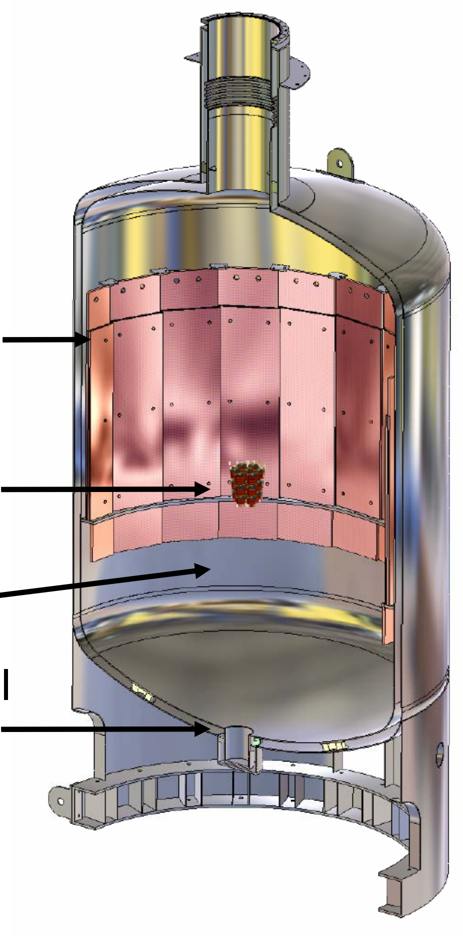


running:	CUORICINO
setting up:	GERDA, CUORE, EXO-200
planned:	Majorana, EXO, COBRA, ...

running:	NEMO-3
setting up:	SuperNEMO
planned:	MOON

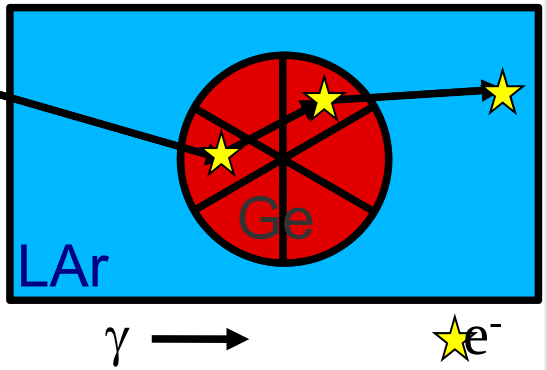
GERDA experiment

MPIK, MPI Munich, Tübingen, Dresden + groups from Italy, Russia, Poland, Switzerland



New background reduction methods:

- naked Germanium detectors in noble liquid
- segmented detectors to identify multi-side events
- identify escaping Compton photons by scintillation light in LAr



3 Phases of GERDA

Phase 1: reuse old detectors of Hd-Moscow and IGEX

Phase 2: new segmented detectors (40 kg)

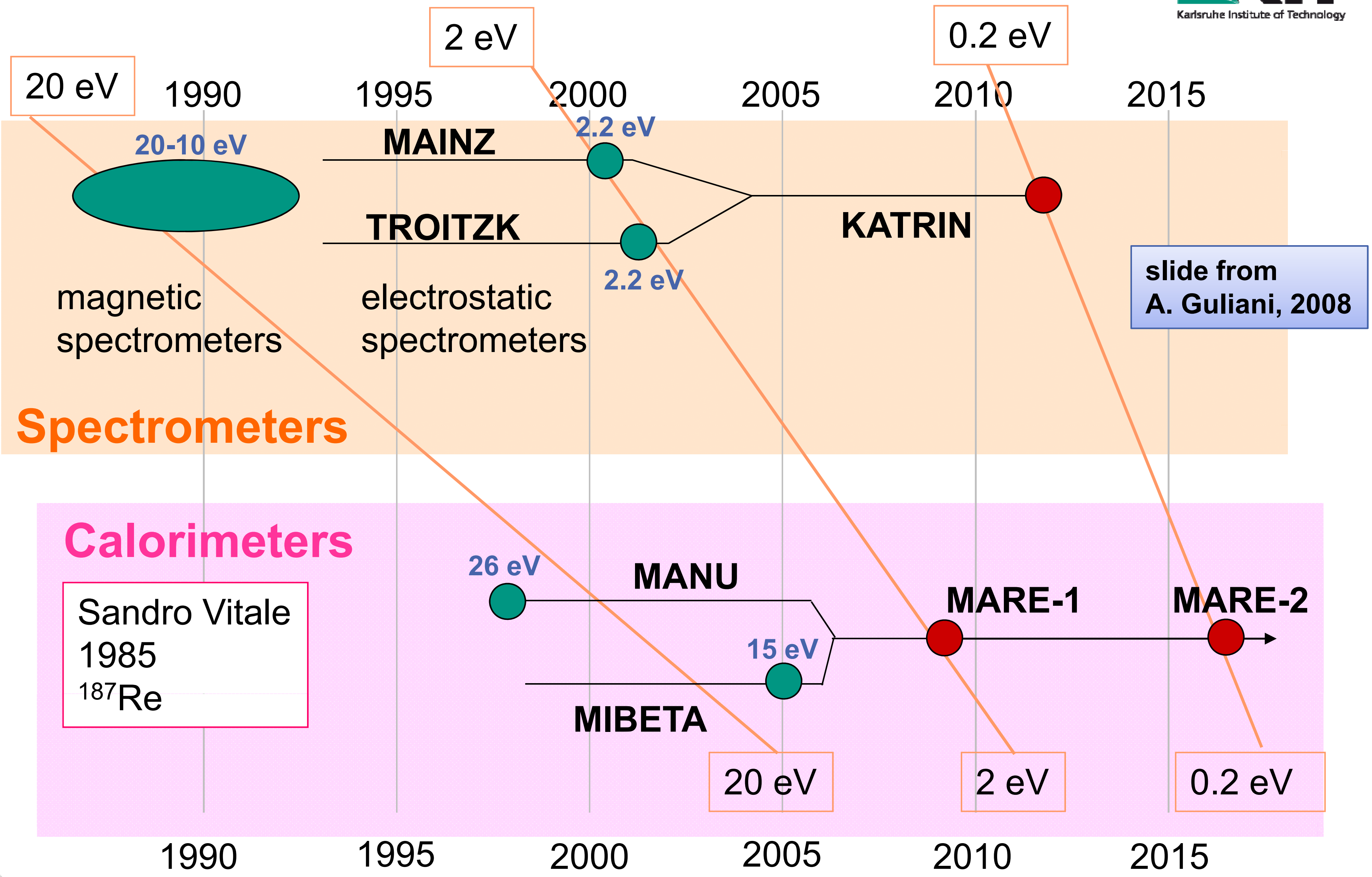
Phase 3: many more detectors (500 kg) (together with MAJORANA-exp.)

Status:

cryostat delivery now

start of GERDA phase 1 in 2010

Microcalorimeters and spectrometers

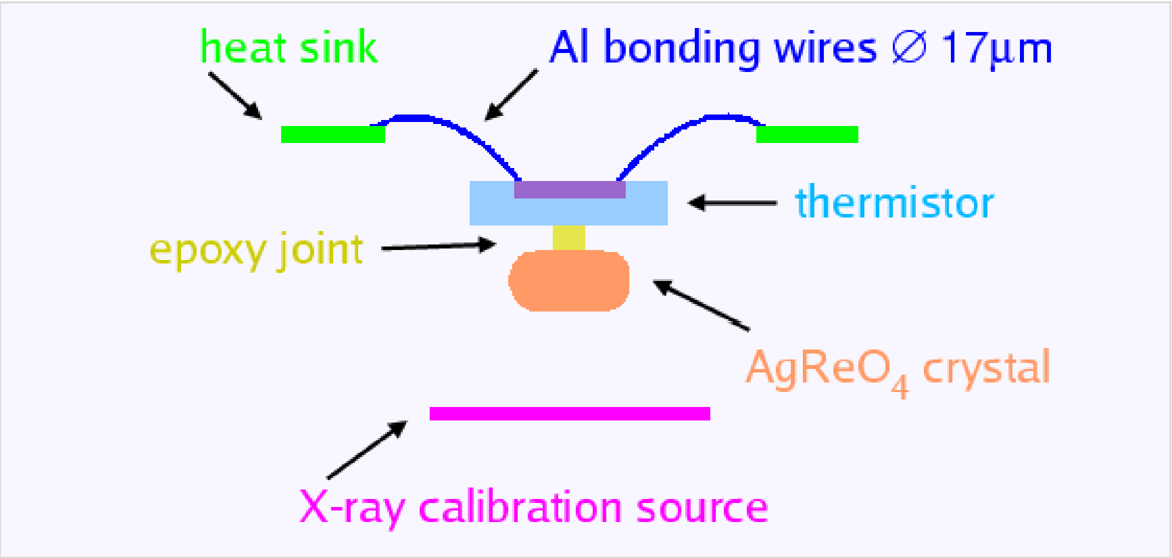


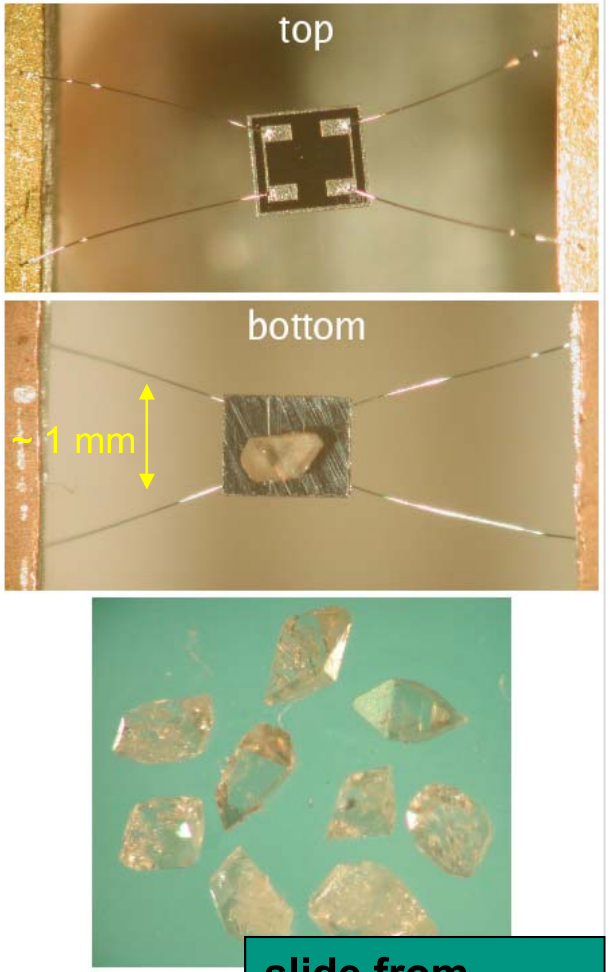
MIBETA (Milano/Como) experiment: the detectors

Energy absorbers
- $AgReO_4$ single crystals
- ^{187}Re activity ≅ 0.54 Hz/mg
- M ≅ 0.25 mg ⇒ A ≅ 0.13 Hz

Thermistors
- Si-implanted thermistors
- high sensitivity
- many parameters to play with
- high reproducibility ⇒ array
- possibility of μ-machining

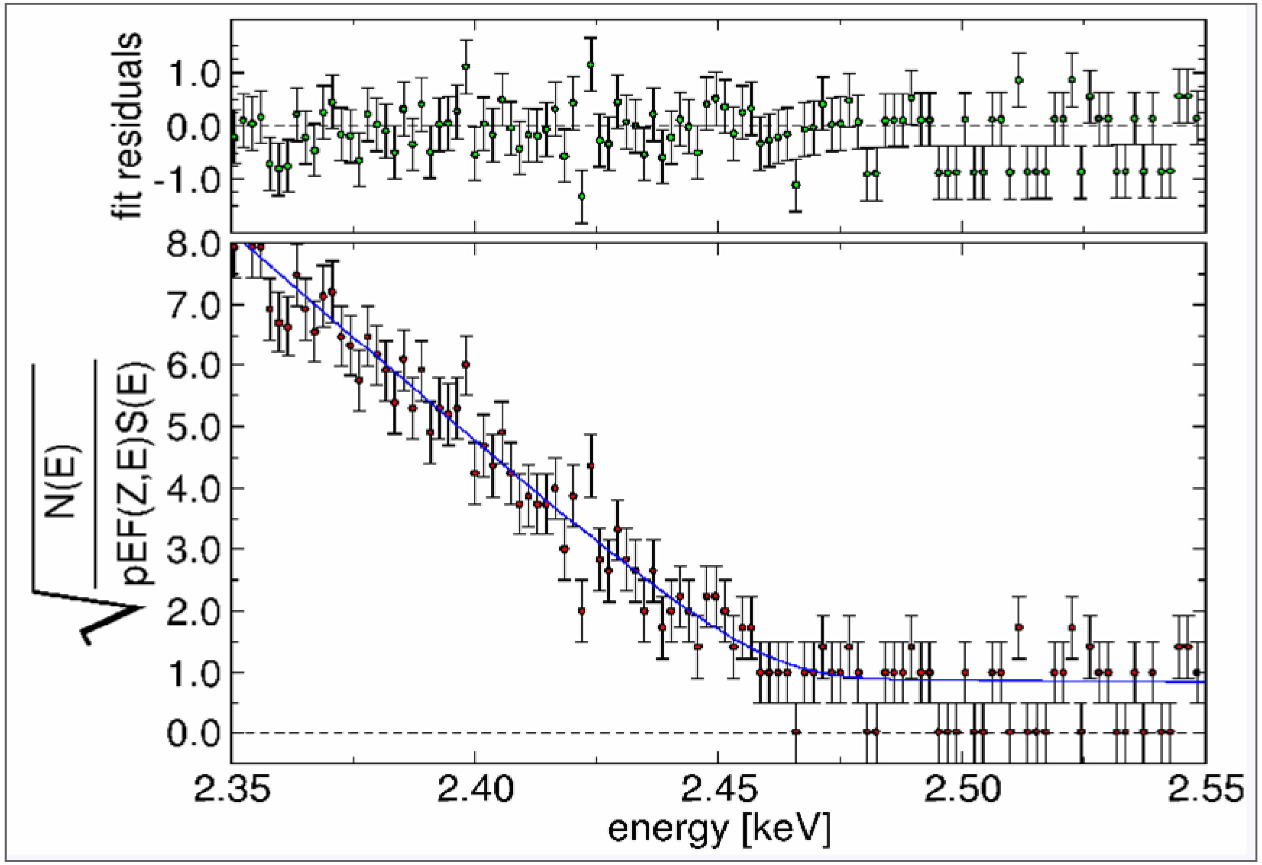
typically, array of 10 detectors
lower pile up & higher statistics





slide from A. Guliani, 2008

MIBETA experiment: the neutrino mass



Fit parameters

single gaussian:
ΔE_{FWHM} = 27.8 eV

fitting interval:
0.8 – 3.5 keV

free constant background:
6 x 10^{-3} c/keV/h

free pile-up fraction:
1.7 x 10^{-4}

$\langle M_\beta \rangle^2 = -141 \pm 211_{stat} \pm 90_{sys}\ eV^2$

$\langle M_\beta \rangle < 15.6$ eV (90% c.l.)

slide from A. Guliani, 2008

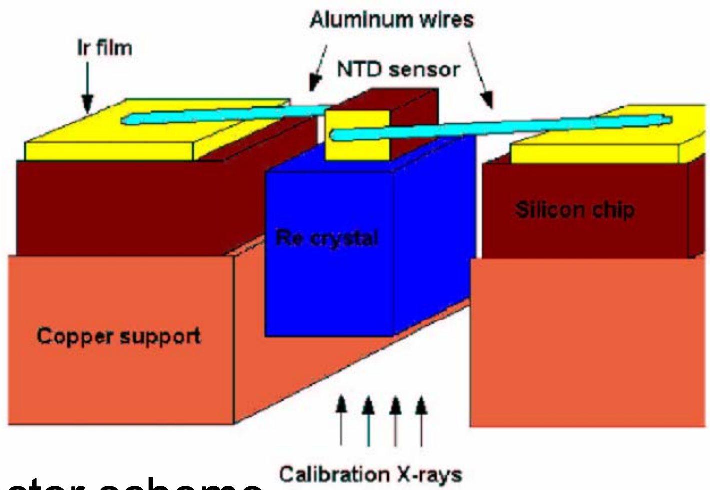
MANU experiment (Genoa)

Similar technique as MIBETA

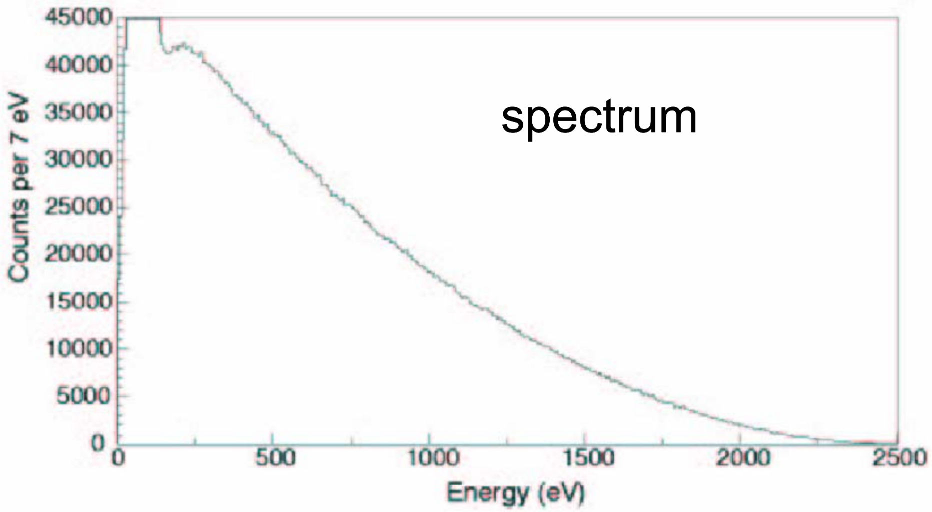
- One detector only
- Metallic Rhenium
- $\Delta E_{FWHM} = 96$ eV
- $Q = 2470 \pm 1 \pm 4$ eV
- $\tau_{1/2} = 41.2 \pm 0.02 \pm 0.11$ Gy

$\langle M_\beta \rangle < 26$ eV (95 % c.l.)

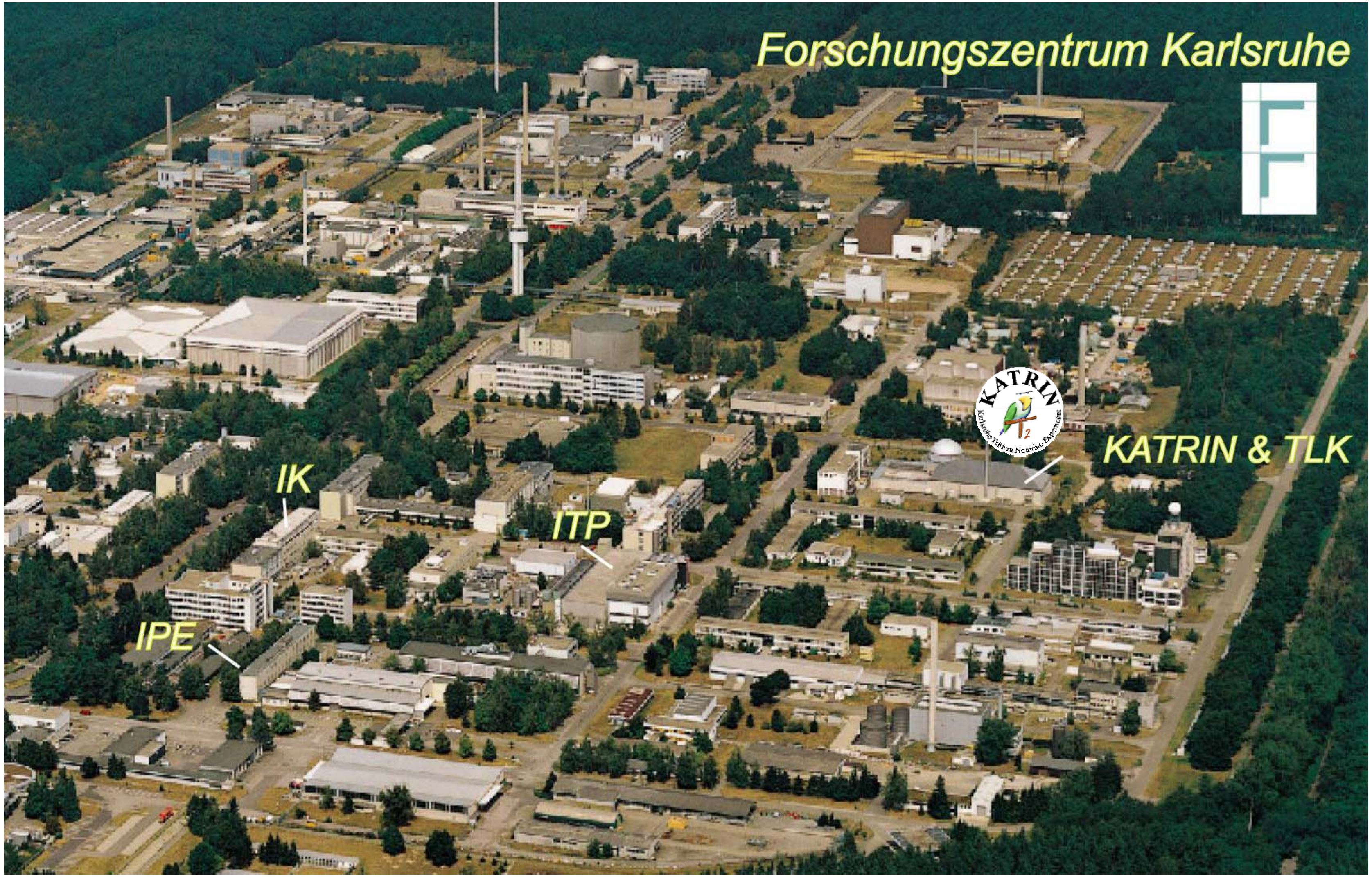
slide from A. Guliani, 2008



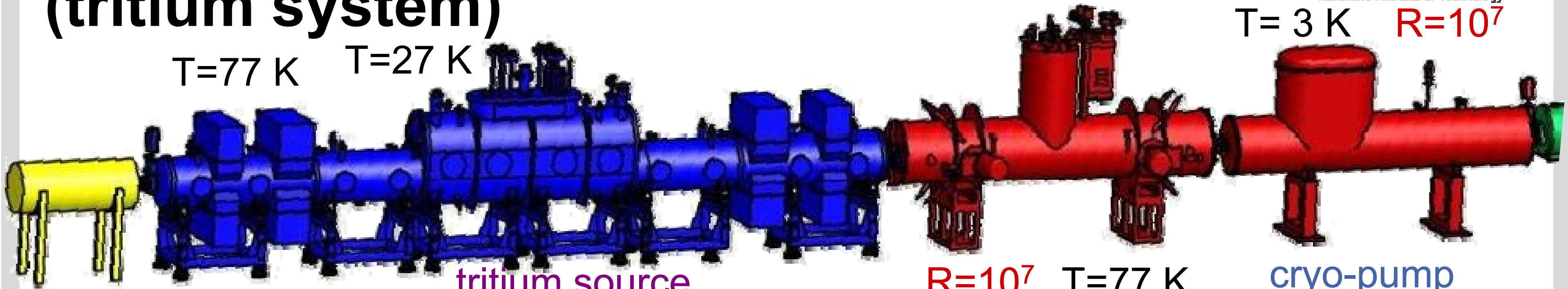
detector scheme



KATRIN @ Karlsruhe



Source and transport section (tritium system)

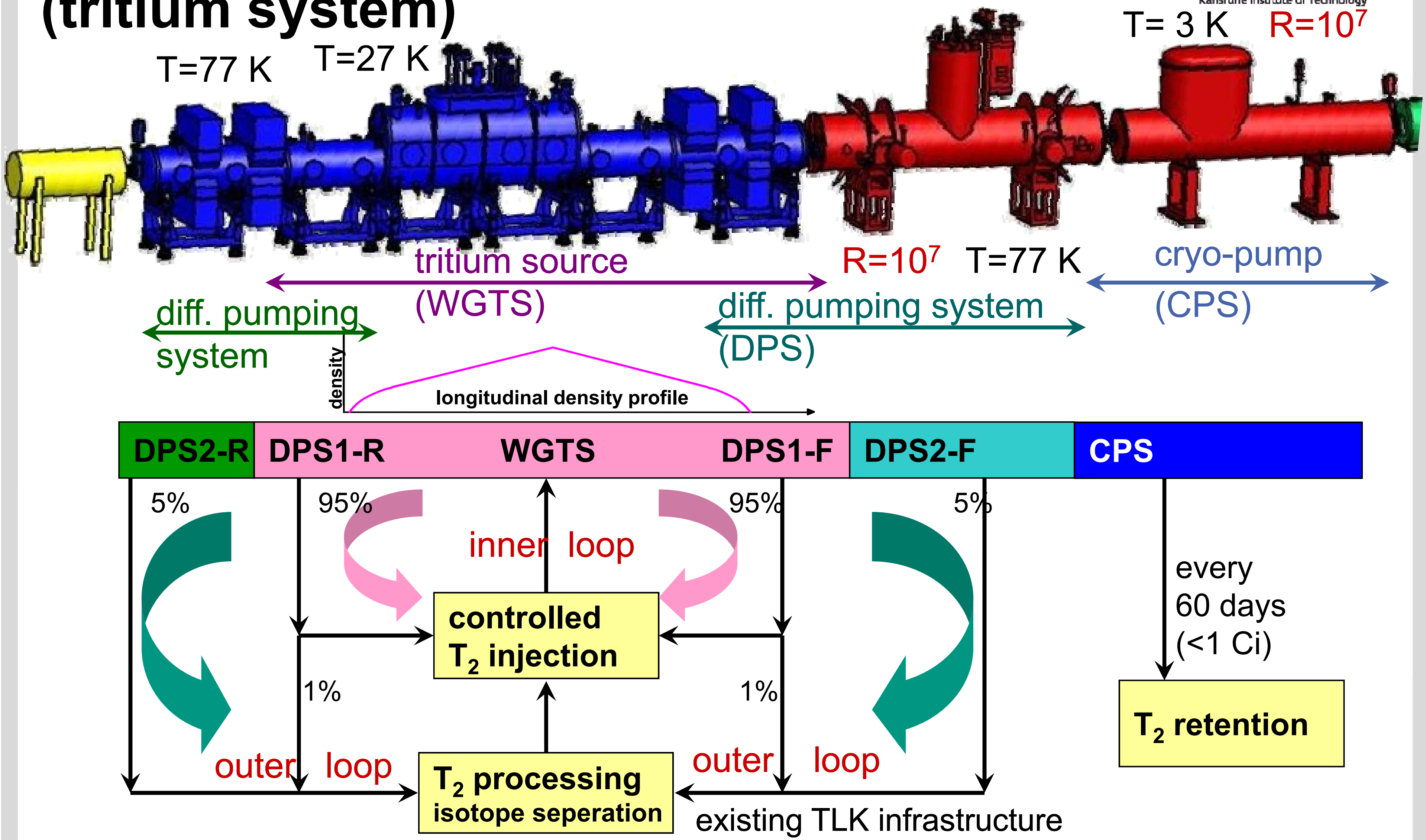


Main requirements for the tritium section

stability: 0.1%

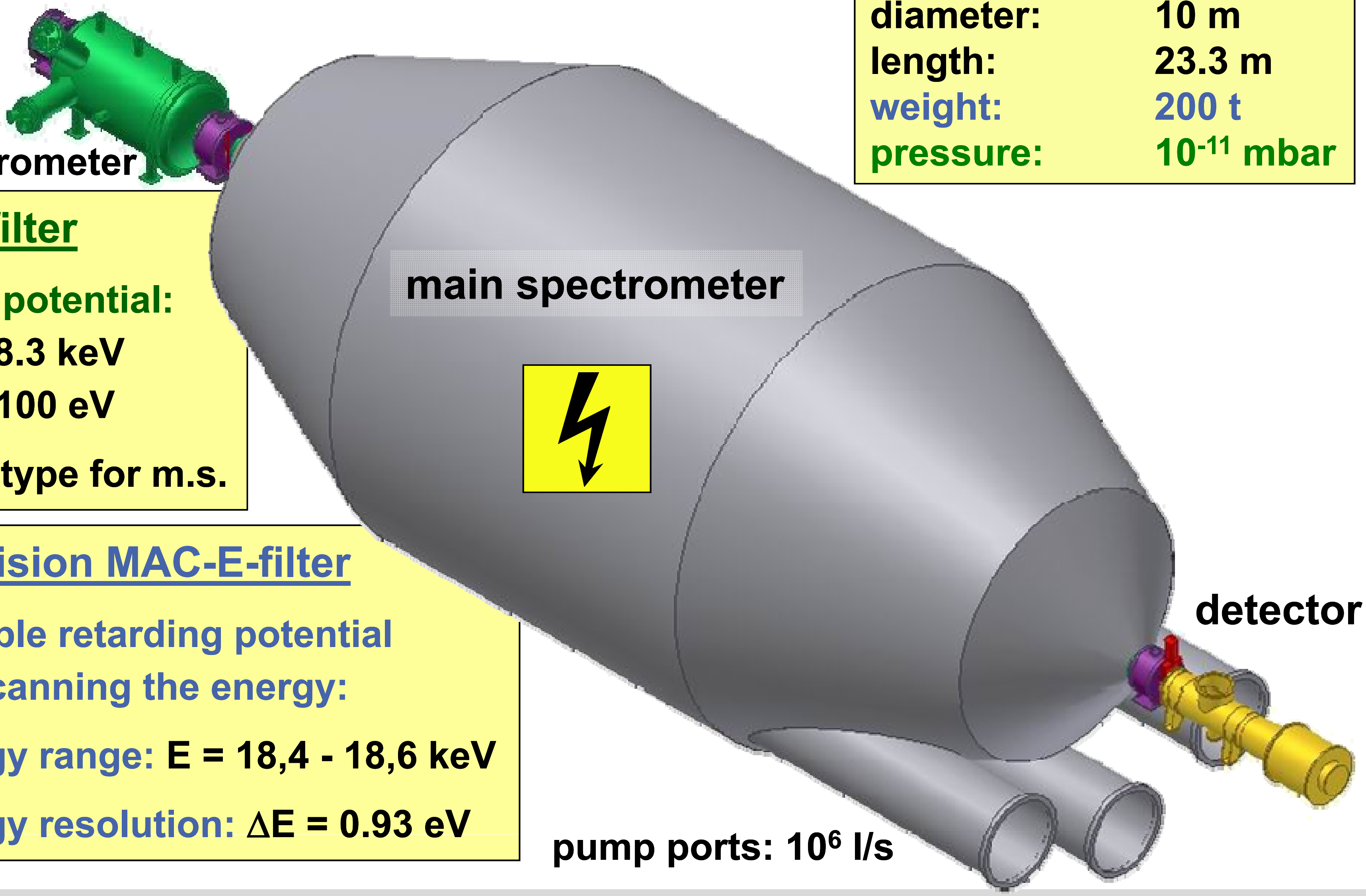
- activity in WGTS: 10^{11} Bq
- high molecular tritium purity: > 95 %
- flow rate: 5×10^{19} molecules/s ± 0.1% (40 g T_2/day)
- column density ρd: 5×10^{17} molecules/cm^2 ± 0.1%
  - Ø temperature stability 0,1 %
- magnetic field strength: WGTS: 3.6 T ± 2% DPS/CPS: 5.6 T
- **tritium flow reduction: 10^{14} (DPS and CPS): 10^{-20} mbar in M.S.**

Source and transport section (tritium system)



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

ΔE ≈ 100 eV

prototype for m.s.

Precision MAC-E-filter

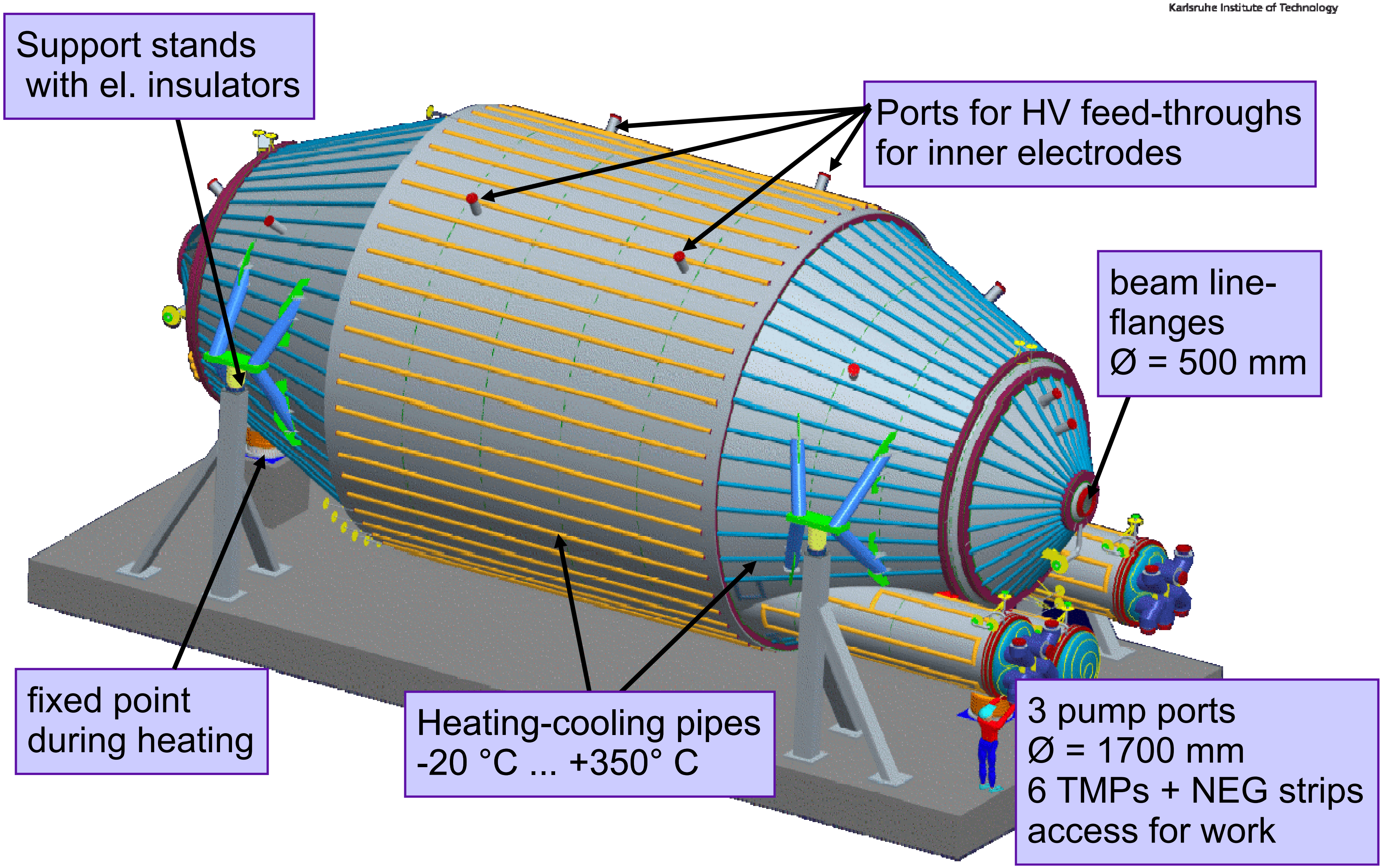
variable retarding potential

for scanning the energy:

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

energy resolution: ΔE = 0.93 eV

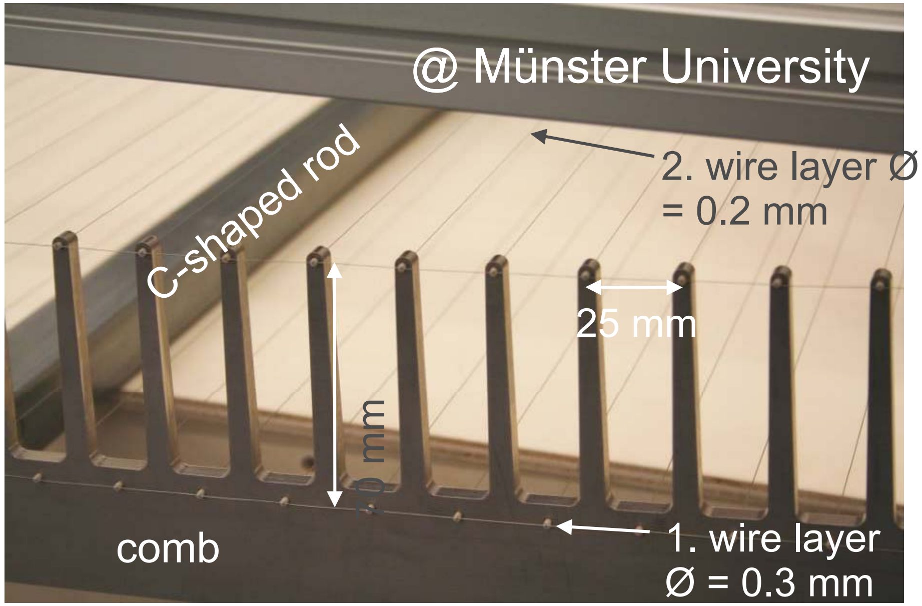
Design of the main spectrometer

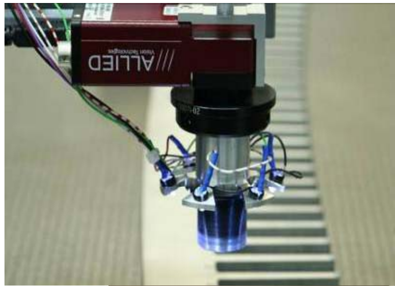


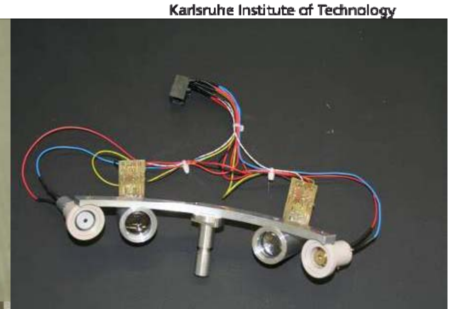
Requirements for the vacuum system

- **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,...)**

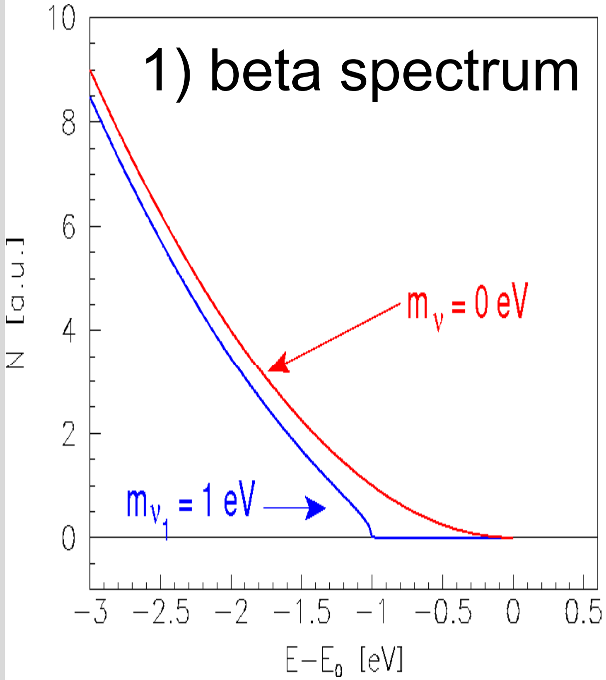
KATRIN: ≈ 240 double layer wire electrode modules



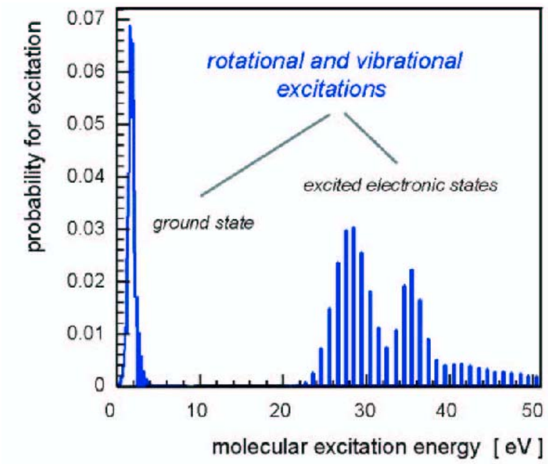


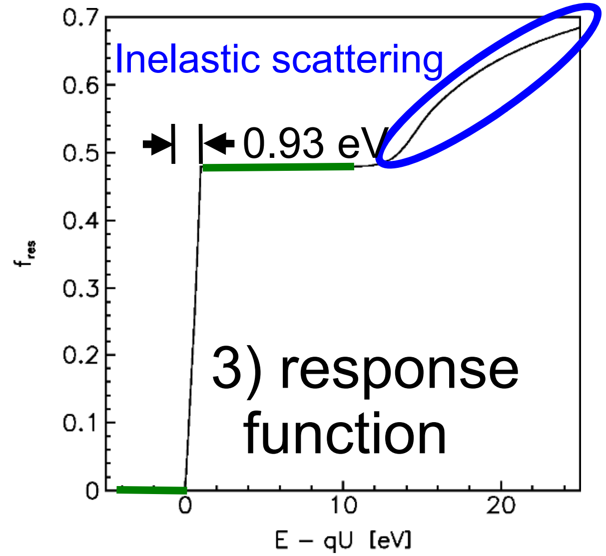


Statistics

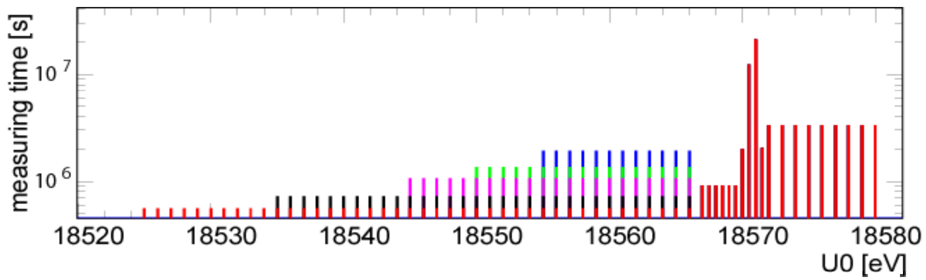


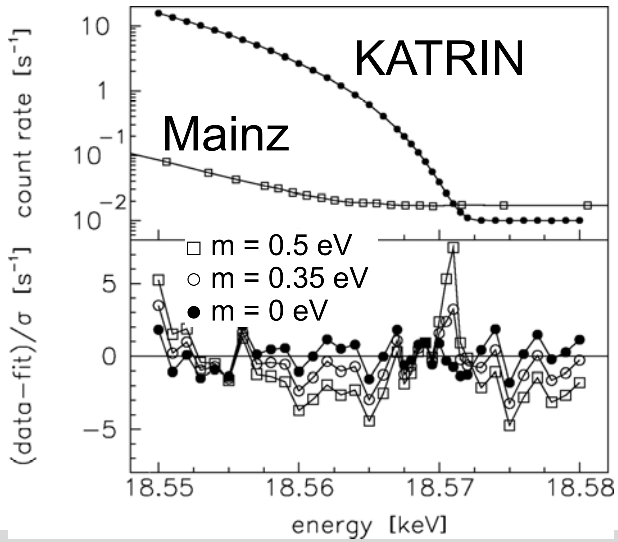
2) final states





4) measurement point distrib. ⇒ MC data





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

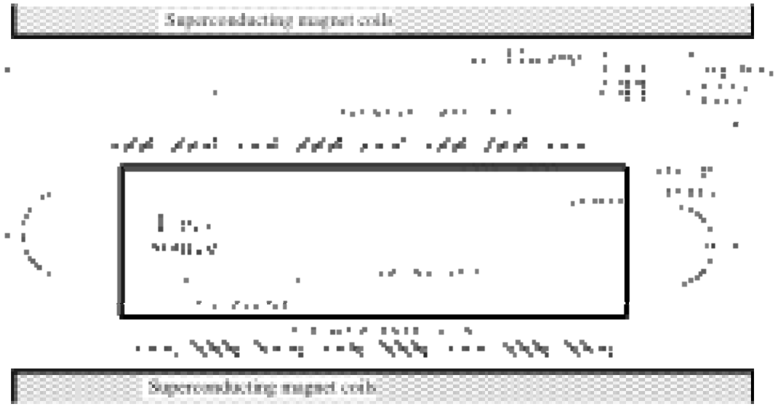
5. final state distribution
   - reliable quantum chem. calculations

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

Measuring the Neutrino Mass

3rd approach, proposed recently: Project 8



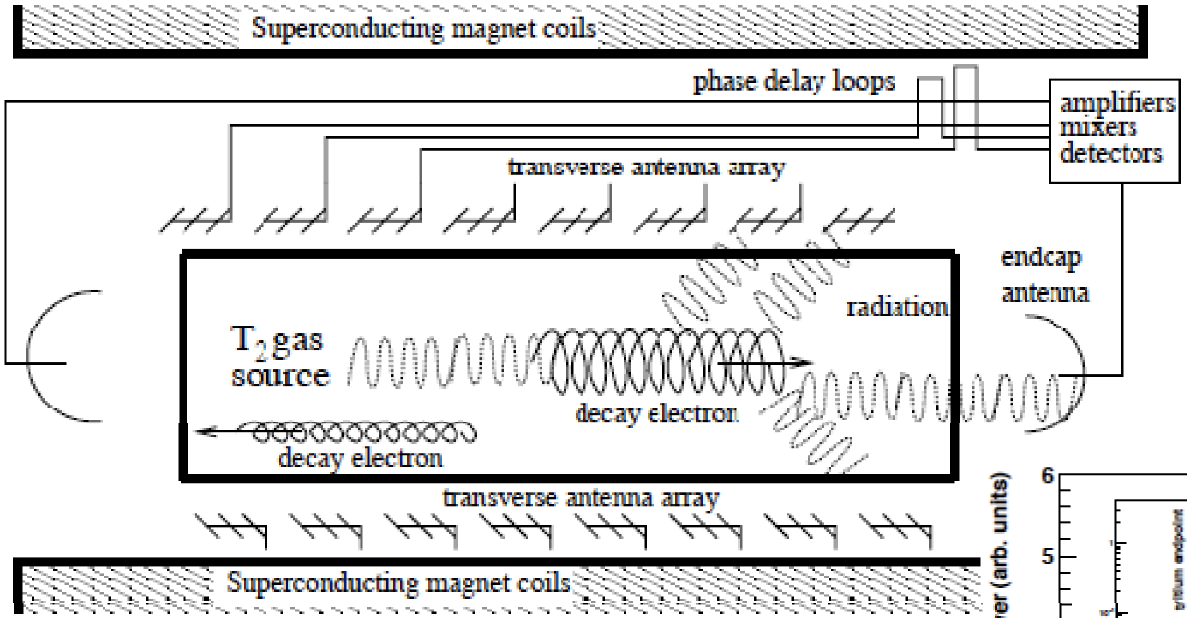
- source: gaseous T_2
- technique: radio-frequency spectroscopy of coherent cyclotron radiation of β decay electrons
- more details: arXiv:0904.2860v1 [nucl-ex]

- 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



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