22nd International Workshop on

Weak Interactions and Neutrinos WIN'09

Electroweak Symmetry Breaking
Weak Decays, CP Violation and CKM
Neutrino Physics
Dark Matter

September 14-19, 2009 - Relais San Clemente, Perugia - ITALY

Direct neutrino mass measurements

Monica Sisti

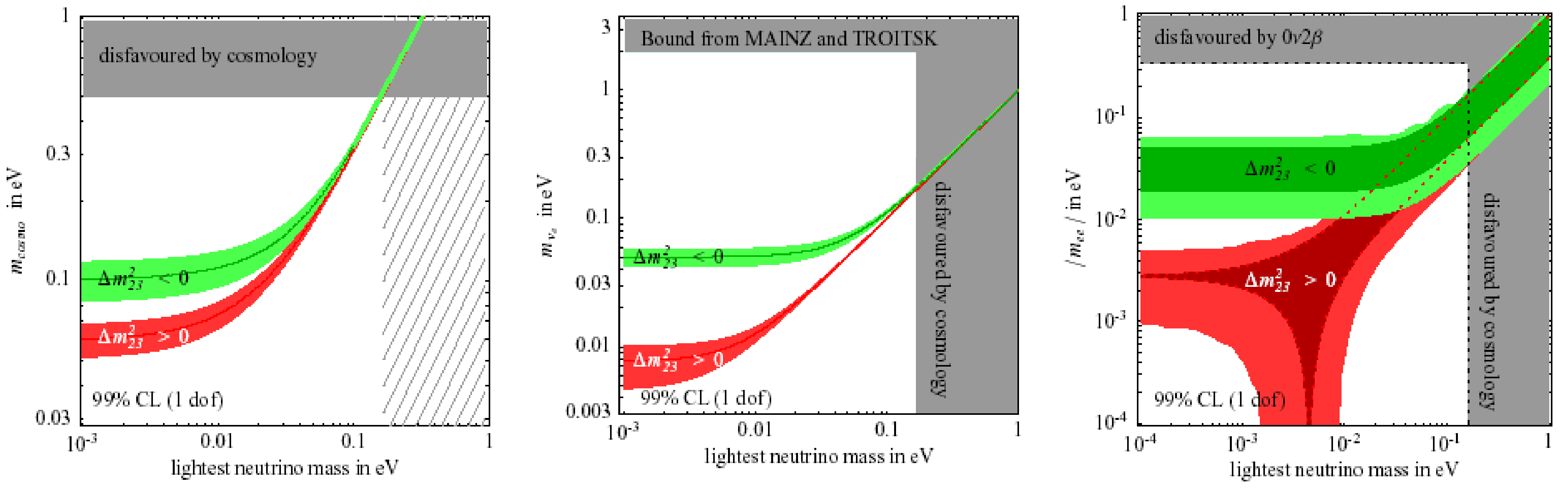
Università and INFN – Milano Bicocca

Outlook

- Crucial time for neutrino physics
- Importance of direct neutrino mass measurements
- Comparing the techniques: spectrometers vs. calorimeters and current state-of-the-art
- KATRIN: the future of spectrometer experiments
- Prospects for ^{187}Re experiments: the MARE project

Our knowledge about neutrino properties

Strumia and Vissani: hep-ph/0606054



🟩 inverse hierarchy: $m_3 \ll m_1 \approx m_2$

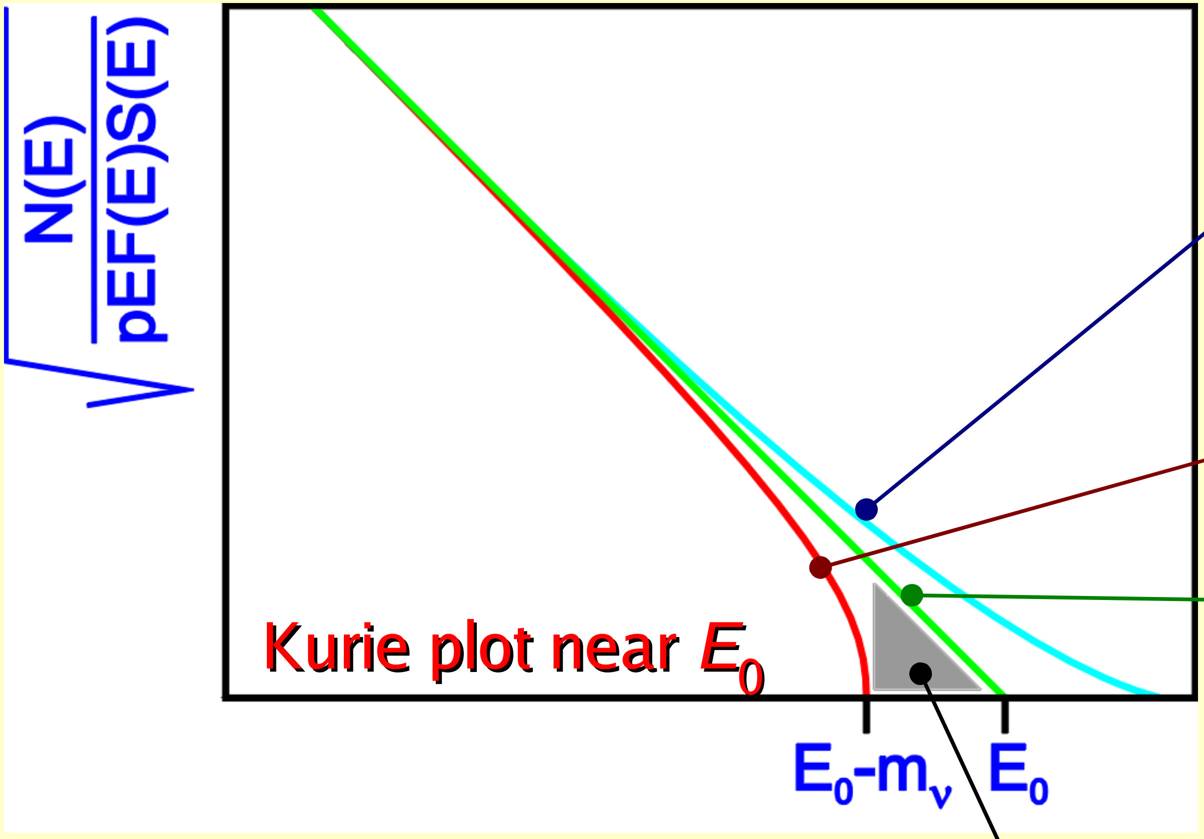
🟥 normal hierarchy: $m_1 \approx m_2 \ll m_3$

degeneration: $m_1 \approx m_2 \approx m_3$

Tool	Measured quantity	Sensitivity (eV) present	future	
Cosmology (CMB+LSS)	$m_\Sigma \equiv \sum m_i$	0.7÷1	0.07	yes
0ν double beta decay	$m_{ee} \equiv \lvert\sum m_i \lvert U_{ei}\rvert^2 e^{i\alpha_i}\rvert$	0.5	0.05	yes
Beta decay	$m_\beta \equiv (\sum m_i^2 \lvert U_{e\,i}\rvert^2)^{1/2}$	2	0.2	no

model dependency

Assessing absolute neutrino mass scale



effect of:
- detector energy resolution
- background counts
- other systematics...

effect of $m_\nu \neq 0$

$N(E_\beta, m_{\bar{\nu}_e} = 0)$

fraction *F* of decays below the end-point

$$F(\delta E) = \int_{E_0 - \delta E}^{E_0} N(E_\beta, m_{\bar{\nu}_e} = 0)\, dE \approx \left(\frac{\delta E}{E_0}\right)^3$$

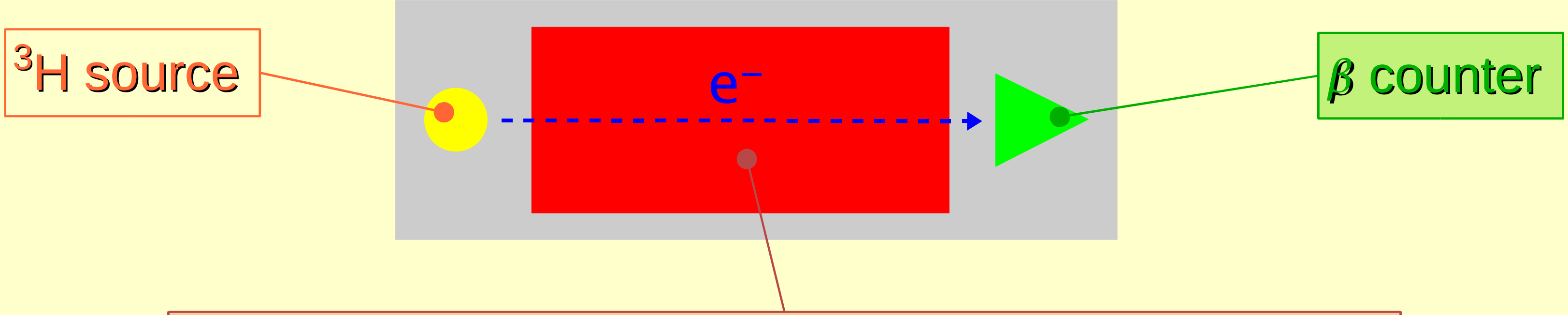
for ^{3}H β-decay $F(10\ \text{eV}) \approx 2 \times 10^{-10}$

General experimental requirements

- low endpoint energy E_0
- high statistics at the β spectrum end-point
- high energy resolution ΔE
- high signal-to-background ratio at the end-point
- small systematic effects

Experimental approaches to direct measurement

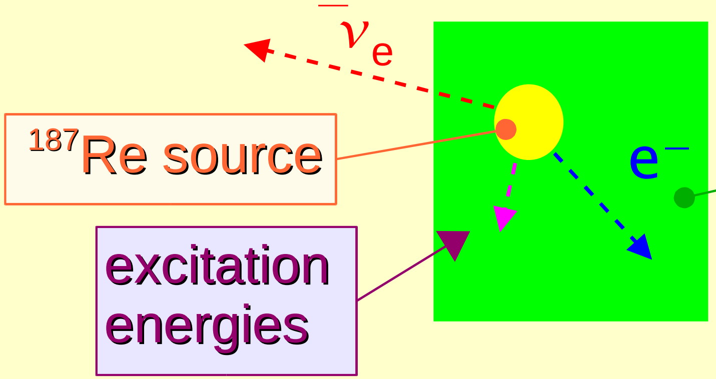
- **Spectrometers: source ≠ detector**



β analyzer

- **differential or integral spectrometer**: βs from the ^{3}H spectrum δE are magnetically and/or electrostatically selected and transported to the counter

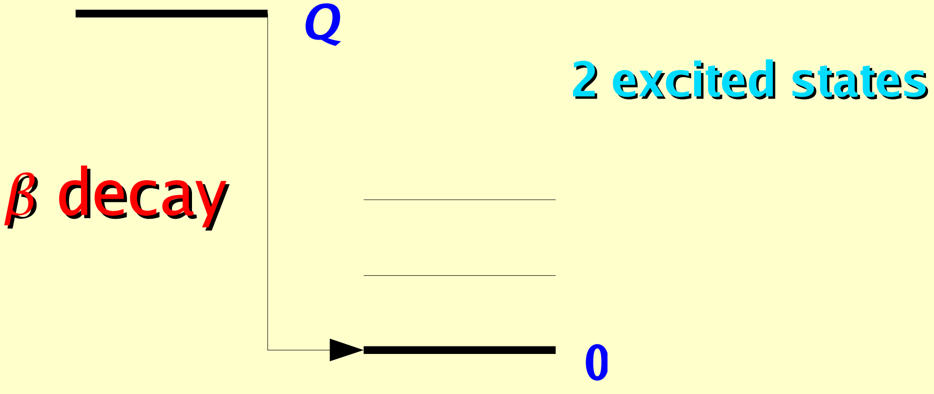
- **Calorimeters: source ⊆ detector**



β calorimeter

ideally measures all the energy E released in the decay except for the $\bar{\nu}_e$ energy: $E=E_0-E_\nu$

Spectrometry of beta sources

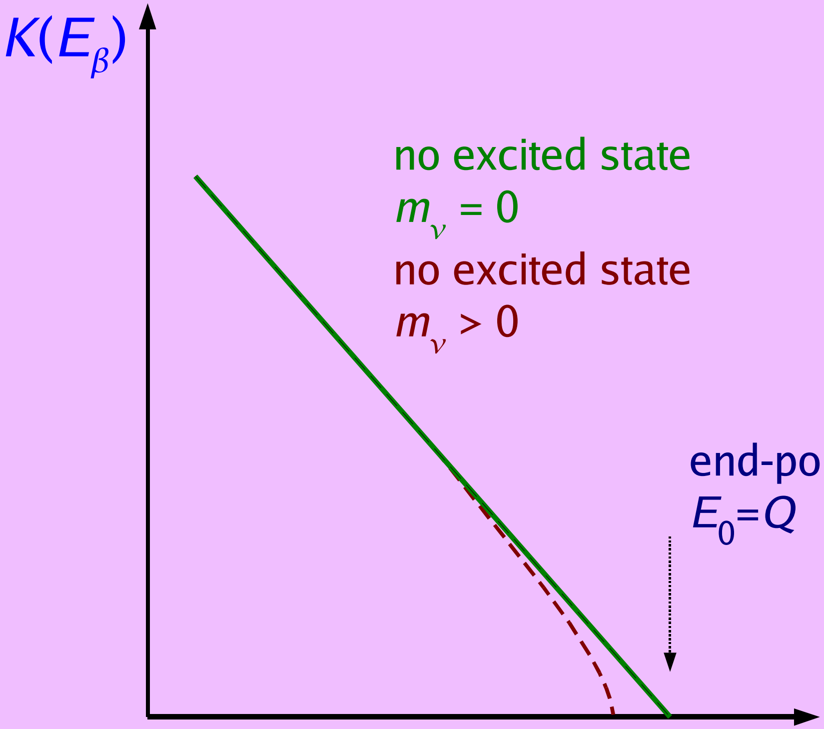

Q

2 excited states

β decay

0

Spectrometers


$K(E_\beta)$

no excited state

$m_\nu = 0$

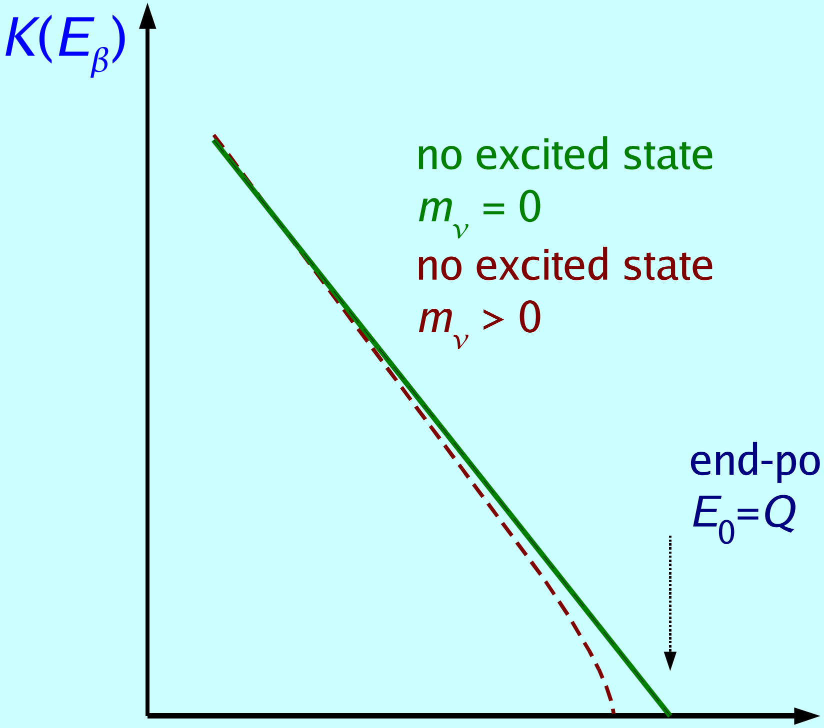
no excited state

$m_\nu > 0$

end-point

$E_0 = Q$

Calorimeters


$K(E_\beta)$

no excited state

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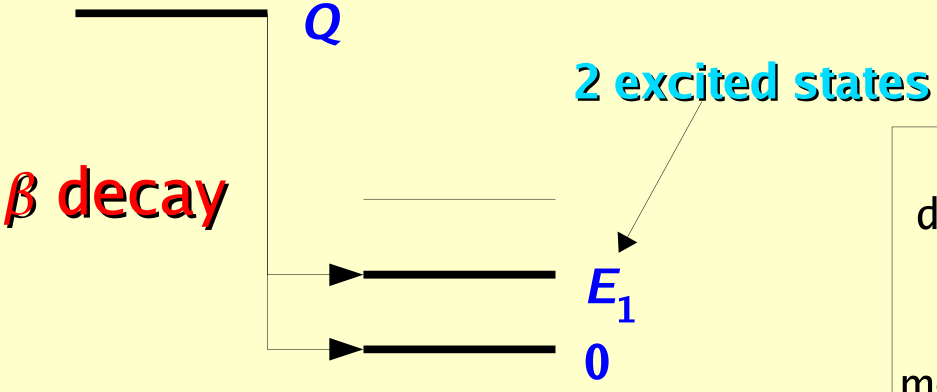
no excited state

$m_\nu > 0$

end-point

$E_0 = Q$

Spectrometry of beta sources



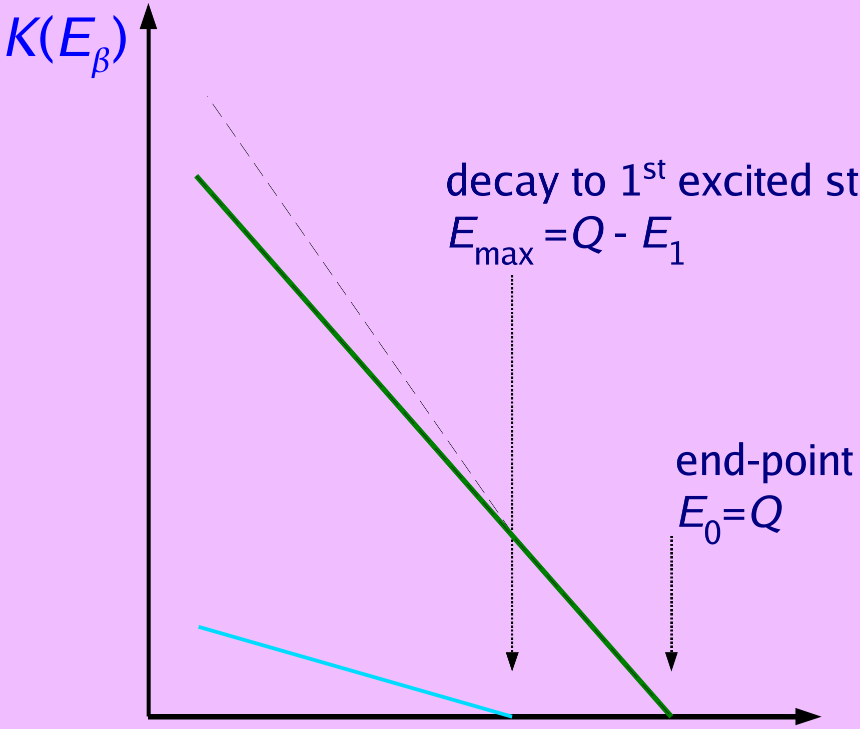
excitation energy is lost

de-excitation faster than detector response time $t_d \sim 1\ \mu s$

⇩

excitation energy is measured together with β energy

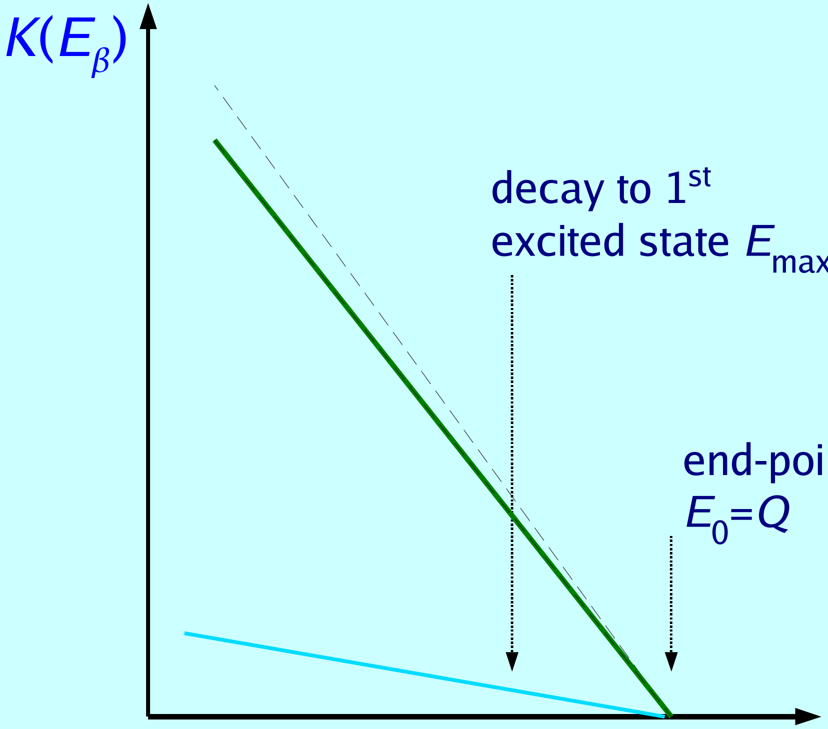
Spectrometers



decay to 1st excited state $E_{max} = Q - E_1$

end-point $E_0 = Q$

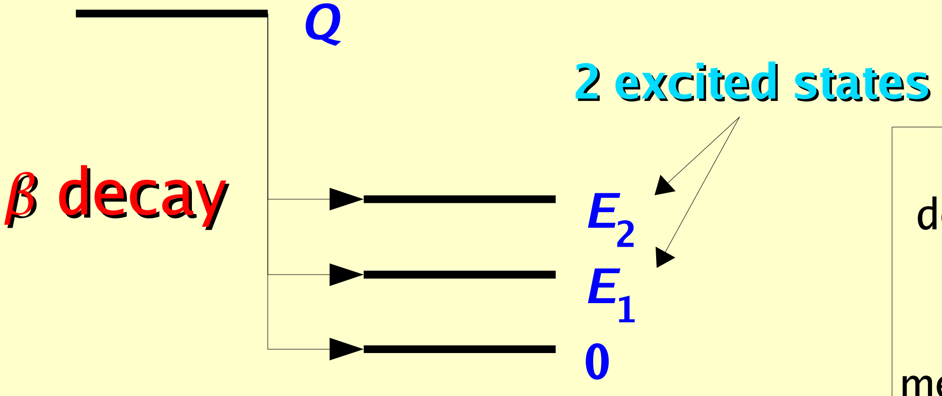
Calorimeters



decay to 1st excited state $E_{max} = Q$

end-point $E_0 = Q$

Spectrometry of beta sources



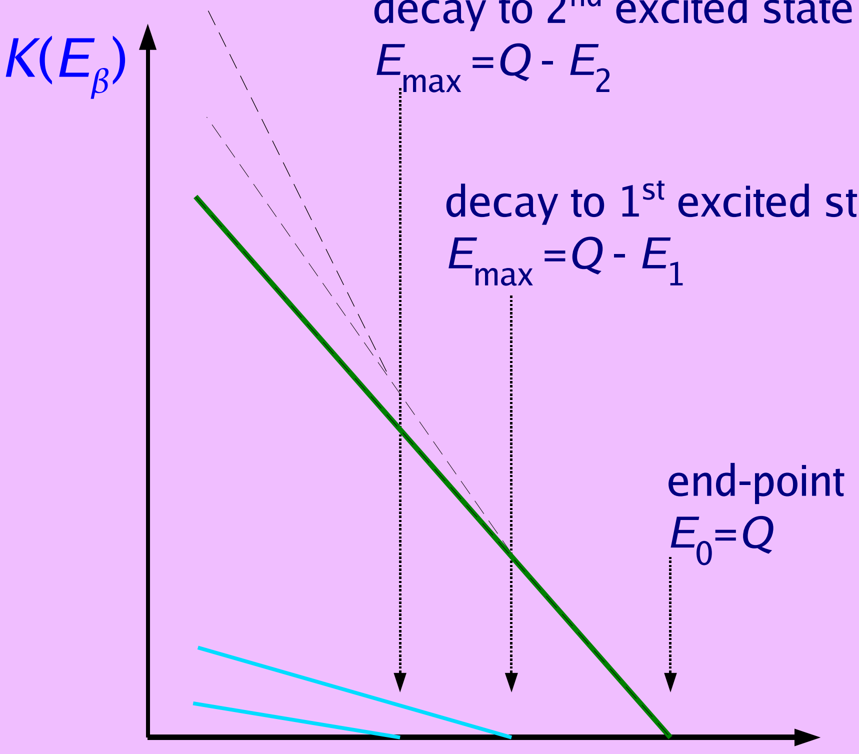
excitation energy is lost

de-excitation faster than detector response time $t_d \sim 1\ \mu$s

⇩

excitation energy is measured together with β energy

Spectrometers

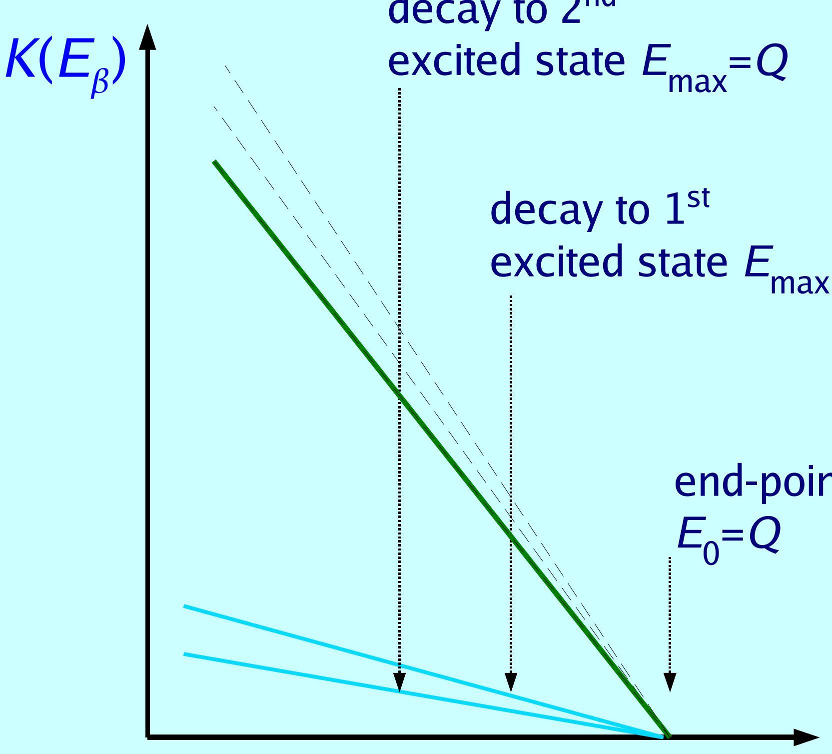


decay to 2nd excited state $E_{max} = Q - E_2$

decay to 1st excited state $E_{max} = Q - E_1$

end-point $E_0 = Q$

Calorimeters

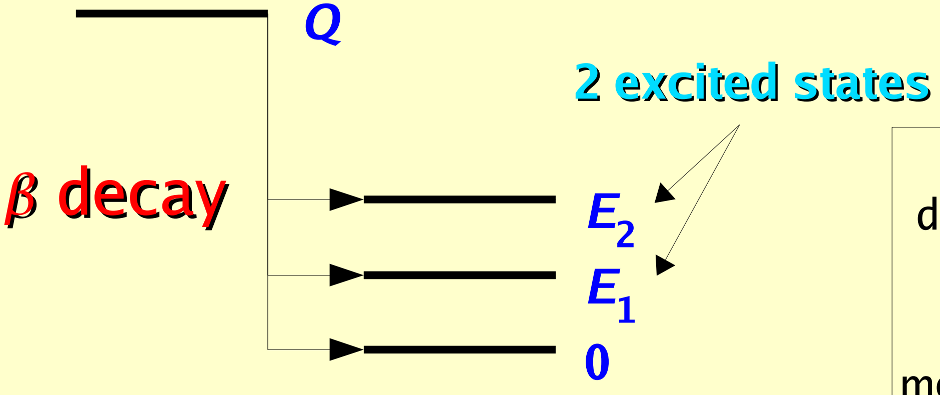


decay to 2nd excited state $E_{max} = Q$

decay to 1st excited state $E_{max} = Q$

end-point $E_0 = Q$

Spectrometry of beta sources



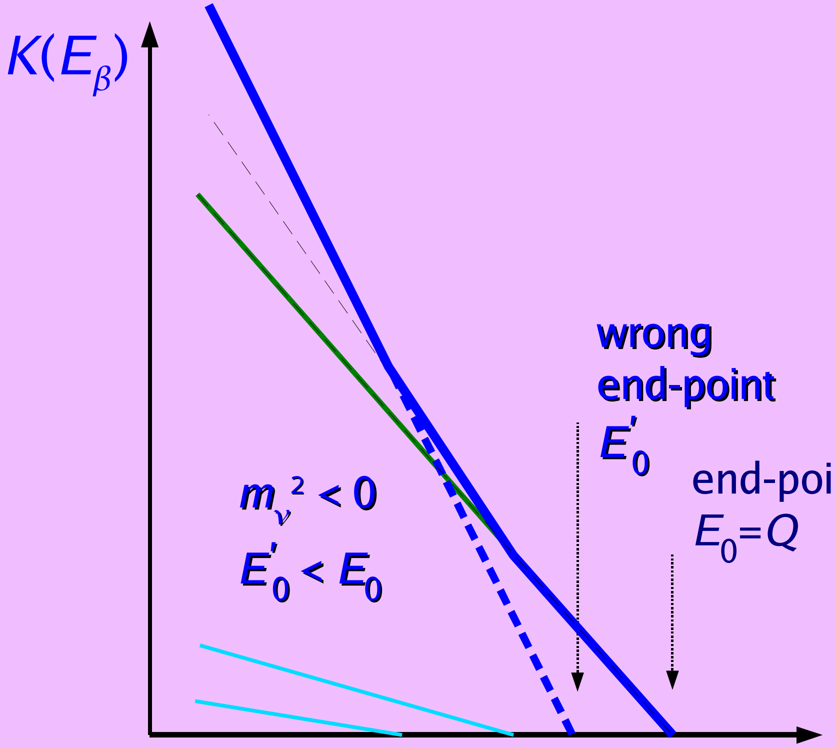
excitation energy is lost

de-excitation faster than detector response time $t_d \sim 1\ \mu s$

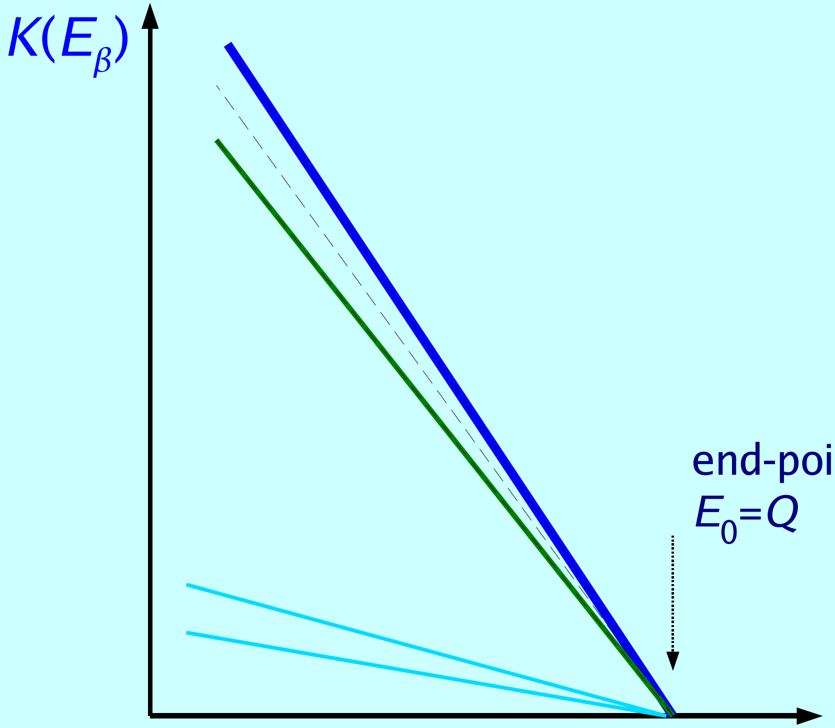
⇩

excitation energy is measured together with β energy

Spectrometers



Calorimeters



Calorimetry of beta sources

Calorimeters measure the entire spectrum at once

- **use low E_0 β decaying isotopes to achieve enough statistics close to E_0**
- **best choice ^{187}Re: E_0 = 2.47 keV** $\Rightarrow F(\delta E = 10\ \text{eV}) \approx (\delta E/E_0)^3 = 7 \times 10^{-8}$

Pile-up

- time unresolved superposition of β decays
- for a source activity A_β, a time resolution τ_R and an energy resolution function $R(E_\beta)$

$$N^{exp}(E_\beta) \approx (N(E_\beta) + \tau_R A_\beta \cdot N(E_\beta) \otimes N(E_\beta)) \otimes R(E_\beta)$$

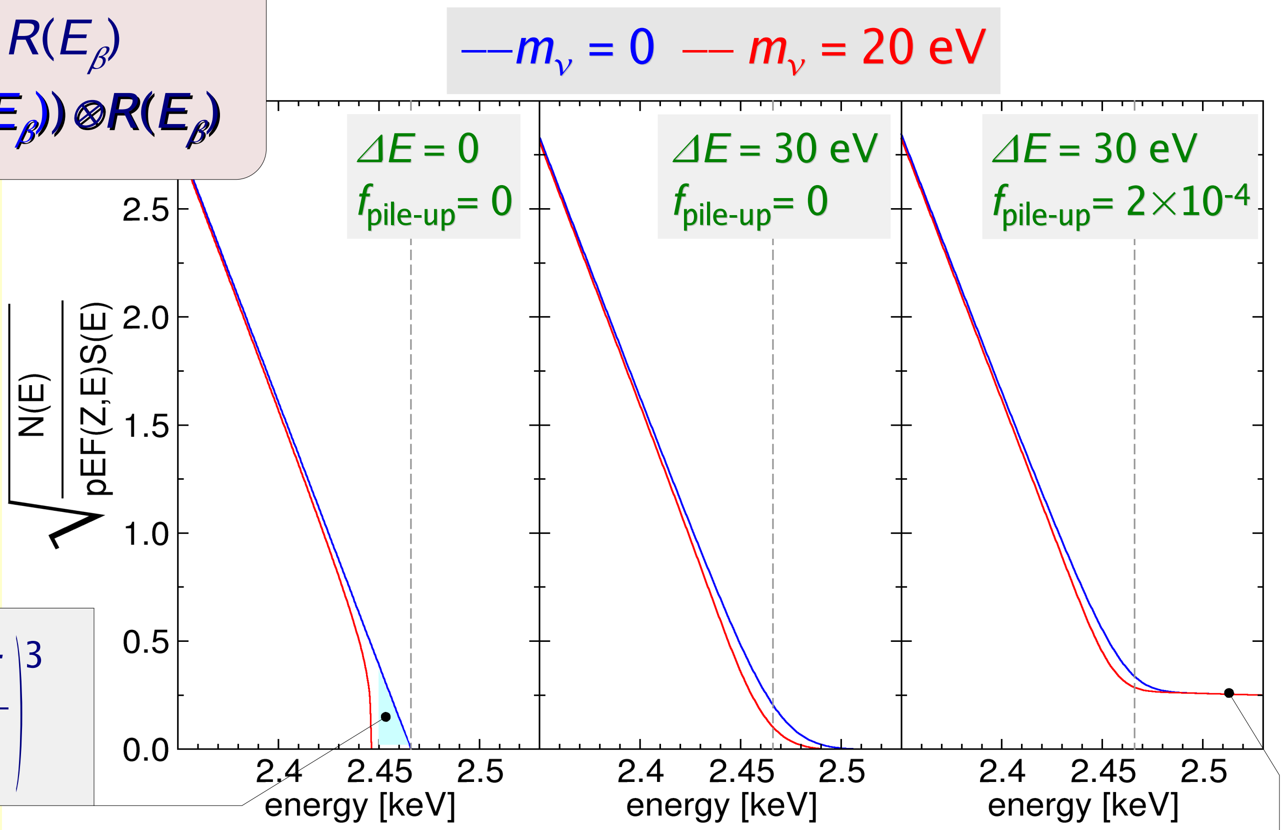
Arrays of microcalorimeters

$$F(\delta E) \approx \left| \frac{\delta E}{E_0} \right|^3$$

$$^{187}_{75}\text{Re} \rightarrow ^{187}_{76}\text{Os} + e^- + \bar{\nu}_e$$

natural isotopic abundance: 63%

→ 1 mg metallic Re ≈ 1.0 dec/s



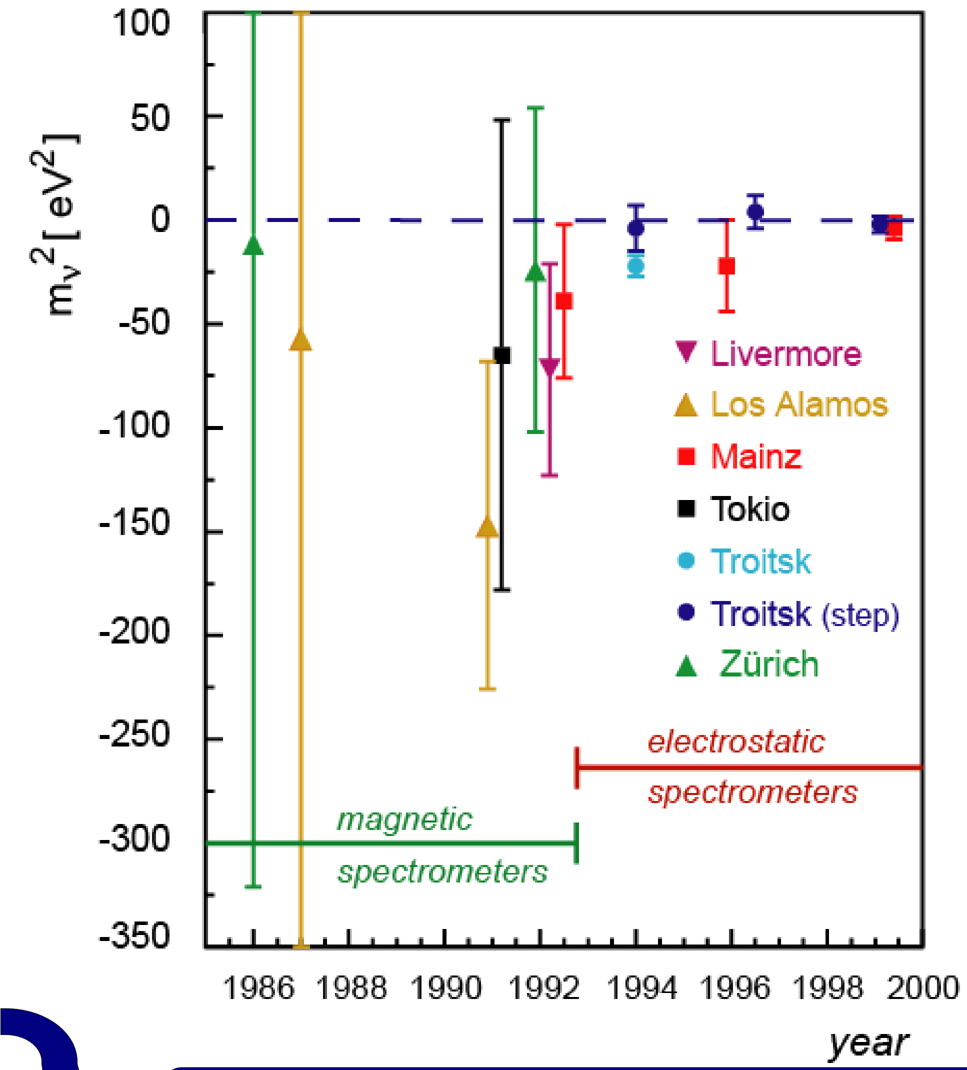
pile-up fraction: $f_{pp} = \tau_R A_\beta$

^{3}H beta decay in the last twenty years

	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	< 2.5 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.3 eV

PDG 2008:

experimental results



PDG evaluation: < 2 eV (95% C.L.)

Electrostatic filter with Magnetic Adiabatic Collimation

MAC-technique

adiabatic guiding of ß-particles along the magnetic field lines

inhomogen. B-Feld: stray field of 2 super-conducting magnets

$B_{max} = 3 - 6\ \mathrm{T}$

$B_{min} < 1\ \mathrm{mT}$

very large solid angle !

$\Delta\Omega \sim 2\pi$

E-technique

energy analysis by electro static retarding field (electrodes)

integral particle transmission $E > U_0$

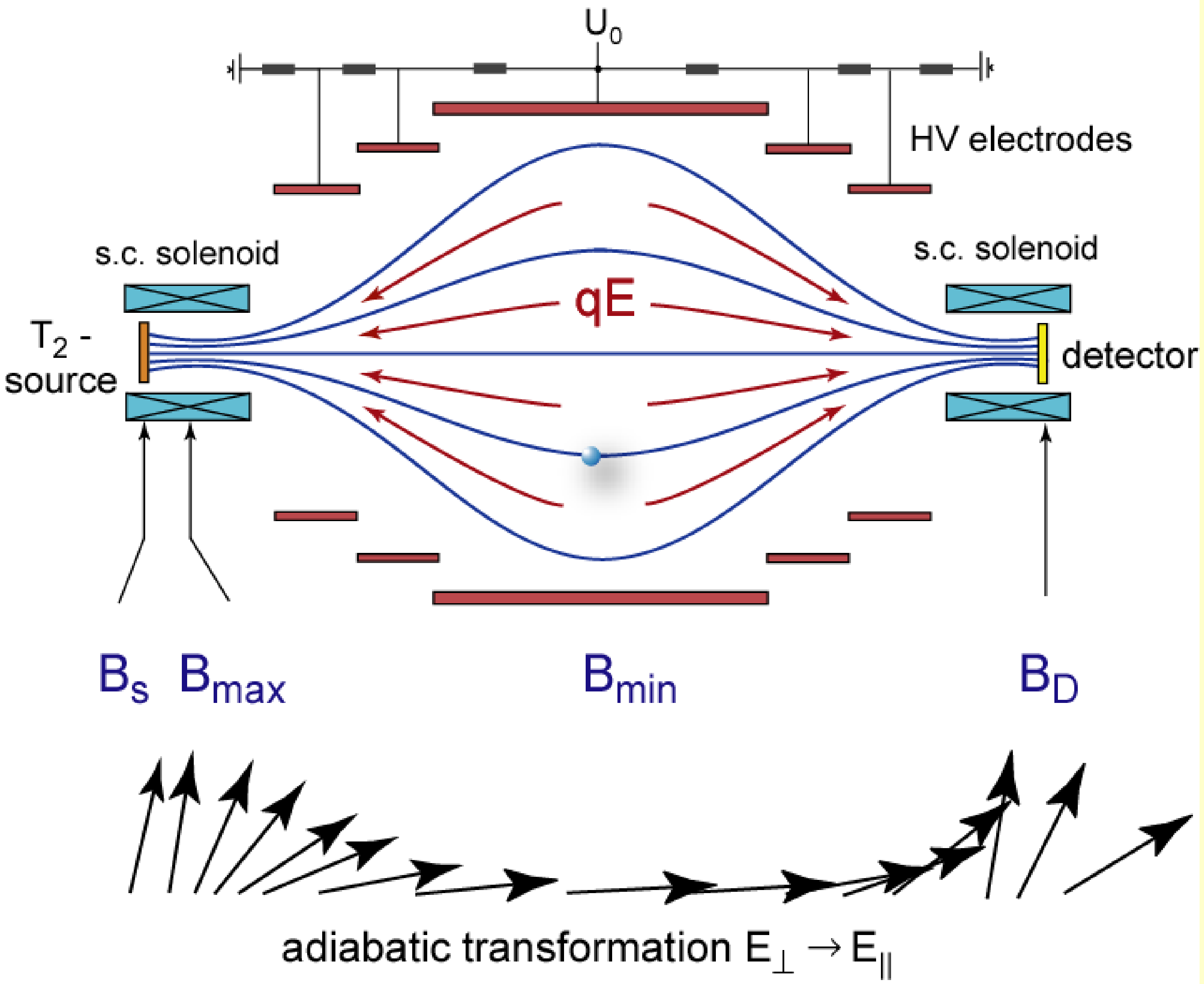
high pass filter !

MAC-E filter

$$\vec{F} = (\vec{\mu}\cdot\vec{\nabla})\,\vec{B} + q\,\vec{E}$$

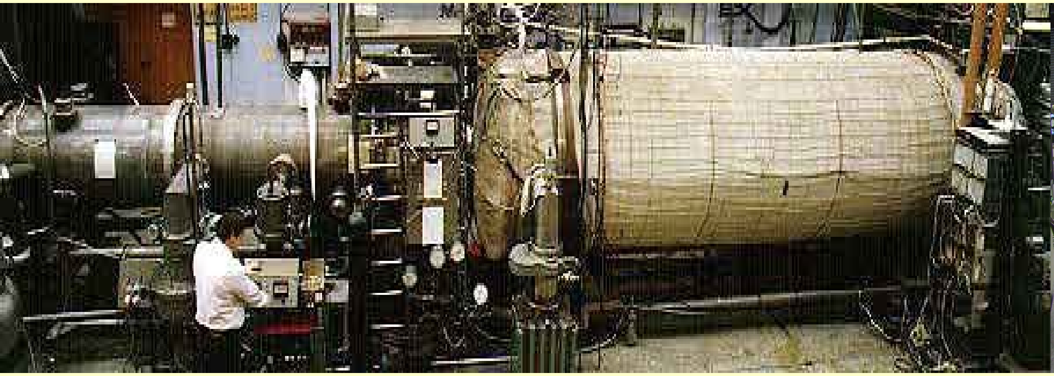
$$\mu = E_\perp / B = \mathrm{const}$$

$U_0 < 30\ \mathrm{kV}$



The most sensitive neutrino mass experiments

Mainz & Troitsk have reached their intrinsic limit of sensitivity



Troitsk

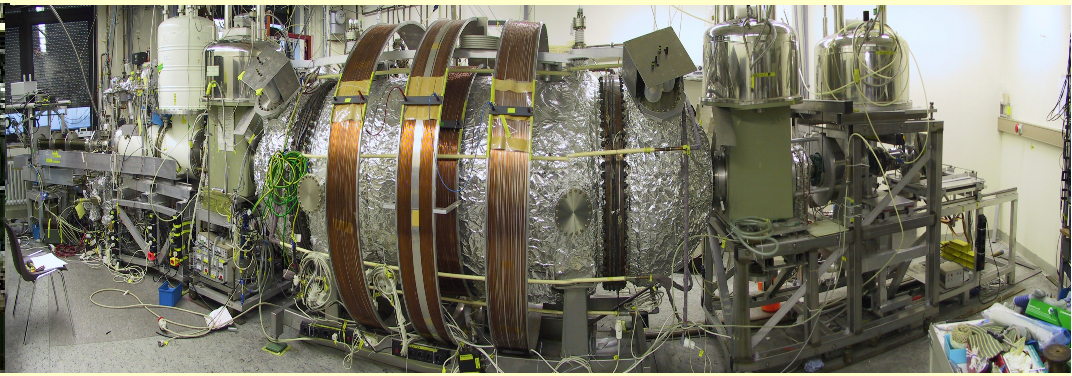
windowless gaseous T_2 source

$m_\nu^2 = -2.3 \pm 2.5_{stat} \pm 2.0_{sys}$ eV^2

$m_\nu \leq 2.05$ eV (95 % C.L.)

Lobashev, Nucl. Phys. A 719 (2003) 153

with a phenomenological corrrection for yet unexplained small anomaly in the spectrum



Mainz

quench condensed solid T_2 source

$m_\nu^2 = -0.6 \pm 2.2_{stat} \pm 2.1_{sys}$ eV^2

$m_\nu \leq 2.3$ eV (95 % C.L.)

Kraus et al., Eur. Phys. J. C 40 (2005) 447

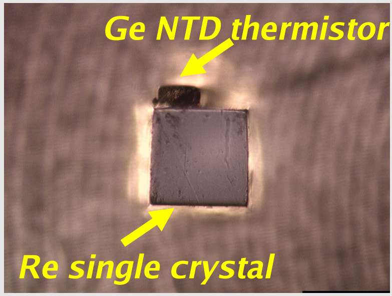
both experiments now used for systematic investigations

Precursor ^{187}Re experiments

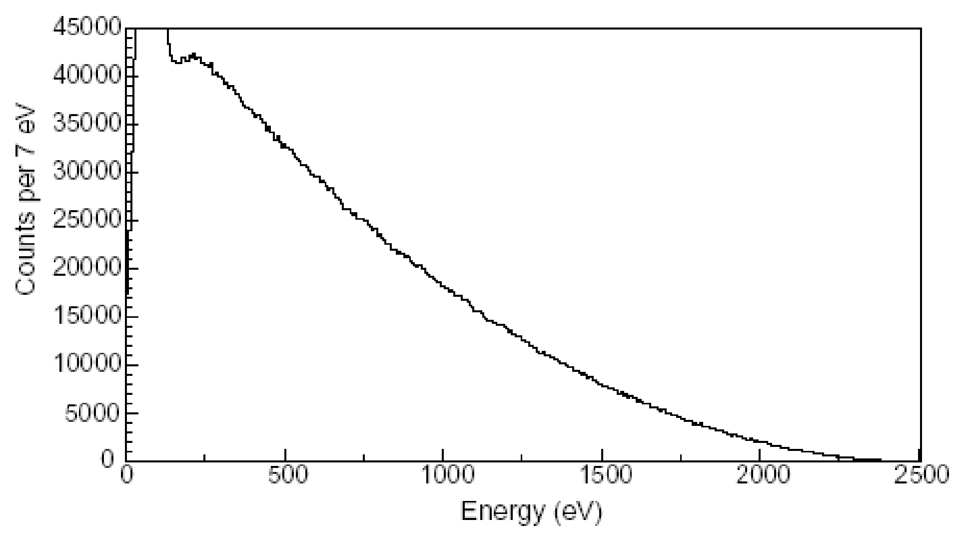
MANU (1999)

Genova

- 1 crystal of metallic Re: 1.6 mg
- ^{187}Re activity ≈ 1.6 Hz
- Ge-NTD thermistor
- ΔE=96 eV FWHM
- 0.5 years live-time
- $m_\nu{}^2 = -462\ ^{+579}_{-679}\ \mathrm{eV}^2$
- $m_\nu < 26$ eV (95 % C.L.)



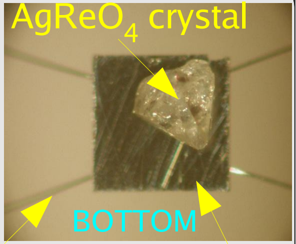
6.0×10^6 ^{187}Re decays above 420 eV

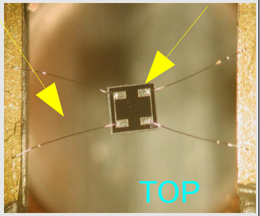


MIBETA (2002-2003)

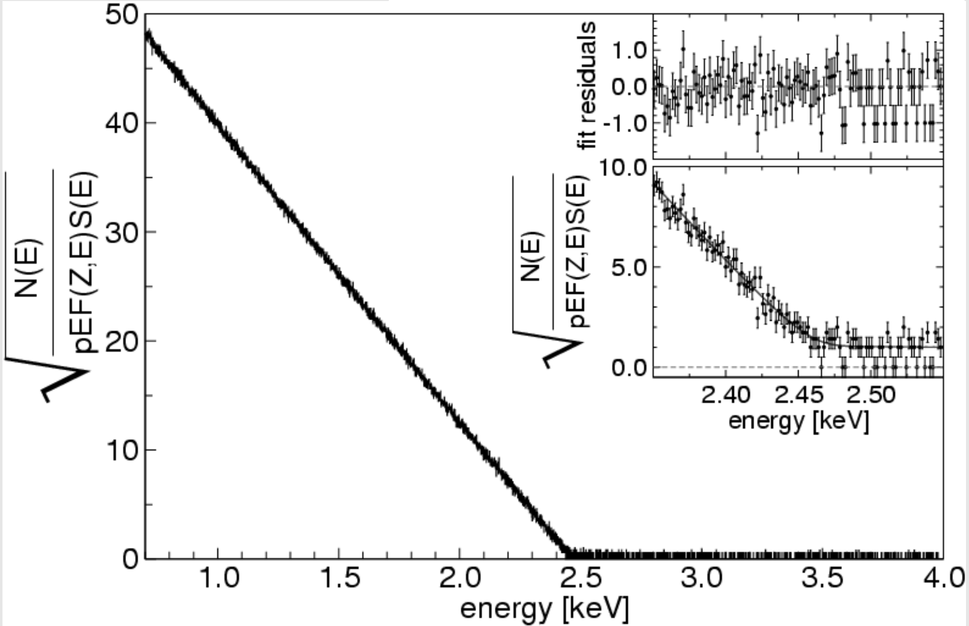
Milano, Como, Trento

- 10 AgReO$_4$ crystals: 2.71 mg
- ^{187}Re activity = 0.54 Hz/mg
- Si thermistors (ITC-irst)
- ΔE= 28.5 eV FWHM
- 0.6 years live time
- $m_\nu{}^2 = -112 \pm 207_{stat} \pm 90_{sys}\ \mathrm{eV}^2$
- $m_\nu < 15$ eV (90 % C.L.)





6.2×10^6 ^{187}Re decays above 700 eV



Comparing techniques in β decay

Spectrometers

- **Choice of β-emitter: ^{3}H**
  - E_0 = 18.6 keV
  - $\tau_{1/2}$ = 12.3 y
  - $1/2^{+} \rightarrow 1/2^{+}$ superallowed transition

Achieved sensitivity: ~ 2 eV

- **Advantages**
  - ▲ high statistics
  - ▲ high energy resolution
  - ▲ simple atomic/molecular structure
- **Drawbacks**
  - ▼ systematics due to source effects
  - ▼ systematics due to excited final states
  - ▼ background
  - ▼ spectrometer stability
  - ▼ ...

Calorimeters

- **Choice of β-emitter: ^{187}Re**
  - E_0 = 2.5 keV
  - $\tau_{1/2}$ = 43.2 Gy
  - $5/2^{+} \rightarrow 1/2^{-}$ unique 1st forbidden

Achieved sensitivity: ~ 15 eV

- **Advantages**
  - ▲ measure neutrino energy
  - ▲ no backscattering/self-absorption
  - ▲ no excited final state effects
- **Drawbacks**
  - ▼ limited statistics
  - ▼ systematics due to pile-up
  - ▼ energy dependent background
  - ▼ ^{187}Re spectral shape
  - ▼ ...

Future planned sensitivity:

KATRIN ➔ 0.2 eV (data taking: 2012)

Future planned sensitivity:

MARE-1 ➔ 2÷4 eV (data taking: 2009)

MARE-2 ➔ 0.2 eV (2015???)

Complementary techniques –Different systematics

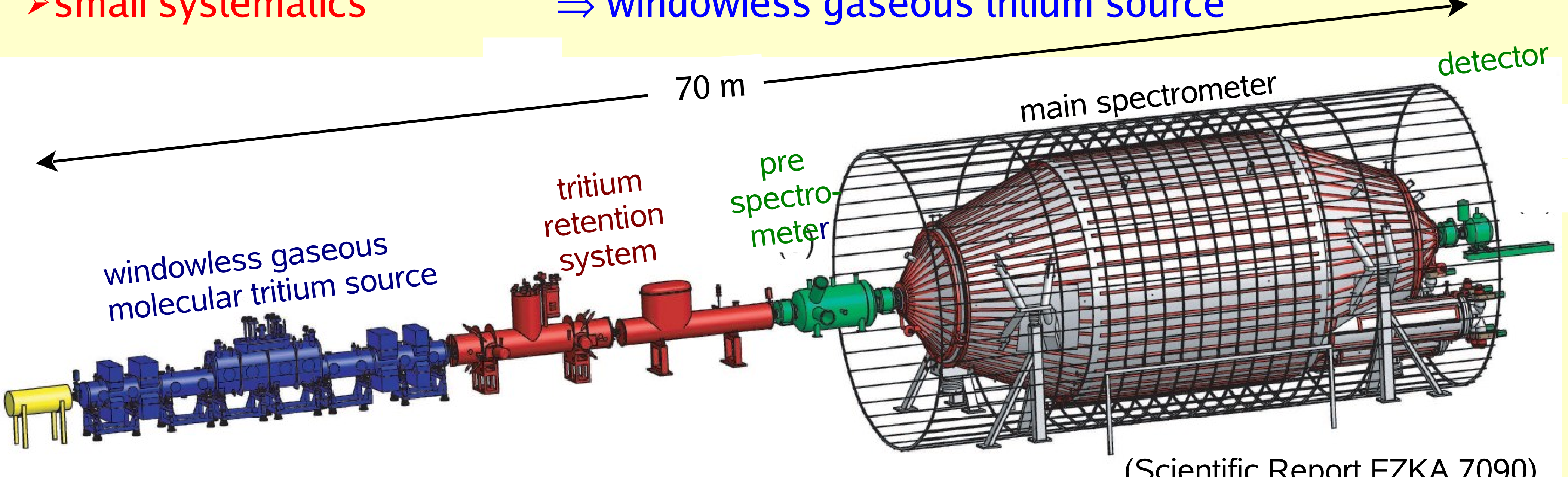
The Karlsruhe Tritium Neutrino experiment: KATRIN

Physics goal: one order of magnitude improvement on m_ν

2 eV → 0.2 eV

- higher energy resolution: $\Delta E \approx 1\,\text{eV}$
  since $E/\Delta E \sim A_{\text{spectrometer}}$ ⇒ larger spectrometer
- higher statistics
  $dN/dt \sim A_{\text{source}} \sim A_{\text{spectrometer}}$ ⇒ larger spectrometer
  longer measuring time: ⇒ 100 d → 1000 d
- small systematics ⇒ windowless gaseous tritium source

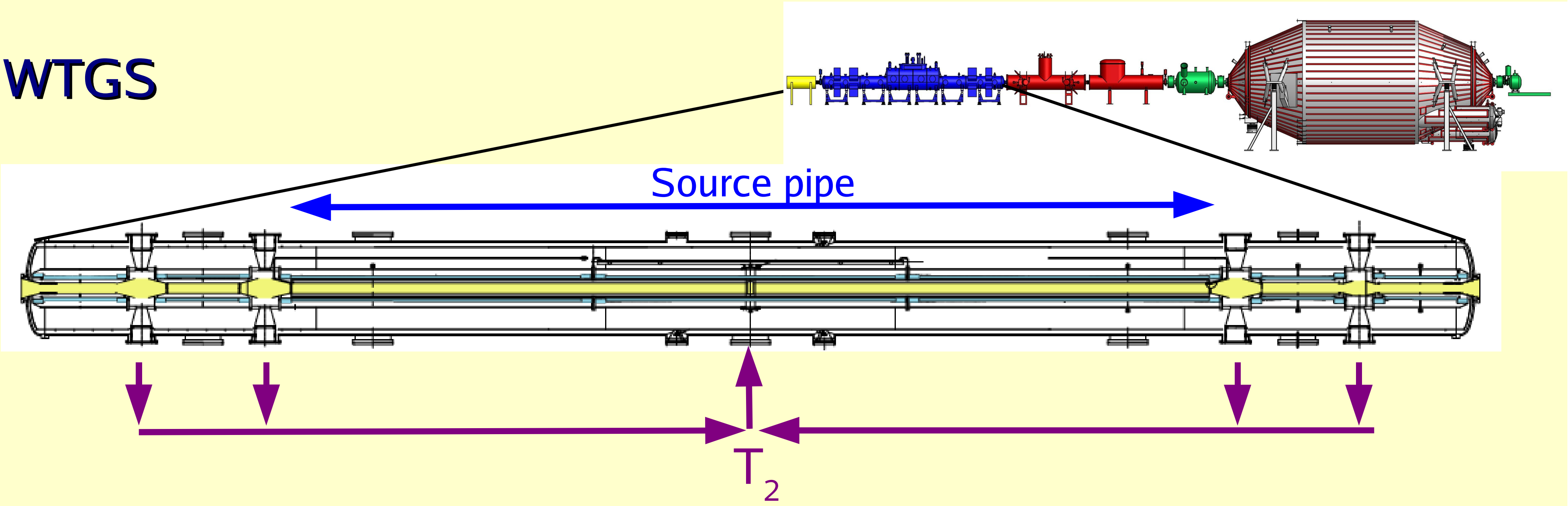
$\Big\}$ ∅ 10m



(Scientific Report FZKA 7090)

Molecular Windowless Gaseous Tritium Source

WTGS



stainless steel tube in long superconducting solenoids

$\varnothing$ 9 cm, length 10 m, T = 30 K (± 0.1%)

Magnetic field: 3.6 Tesla (± 2%)

Tritium recirculation (and purification)

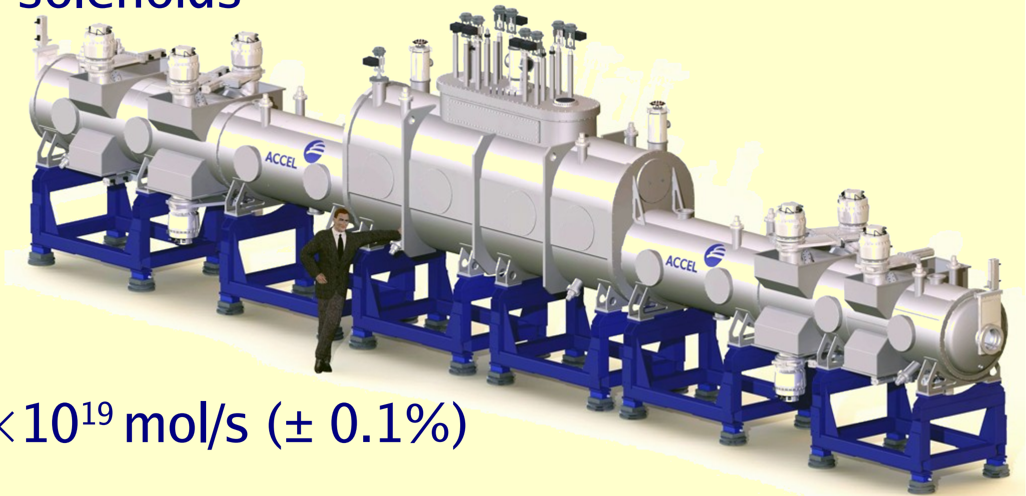
Tritium purity > 95%

Tritium injection: p_{inj}= 0.003 mbar, $rate_{inj}$= 5×10^{19} mol/s (± 0.1%)

Integral column density: $\rho d = 5\times10^{17}/cm^2$ (± 0.1%)

for high signal rate with small systematics

(maximum accepted solid angle: 51°)



WGTS-demonstrator
will arrive early 2010

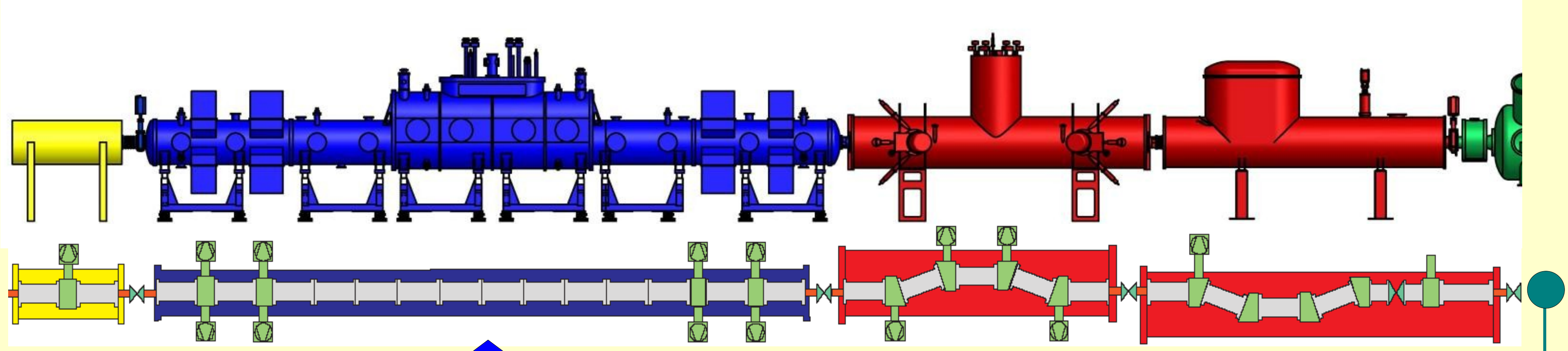
Transport and pumping sections

adiabatic electron guiding & T_2 flow reduction factor of ~10^{14}

Molecular windowless gaseous tritium source

Differential pumping

Cryogenic pumping



T_2-injection 1.8 mbar l/s (STP)

= 1.7×10^{11} Bq/s = 40 g/d

$R > 10^7$

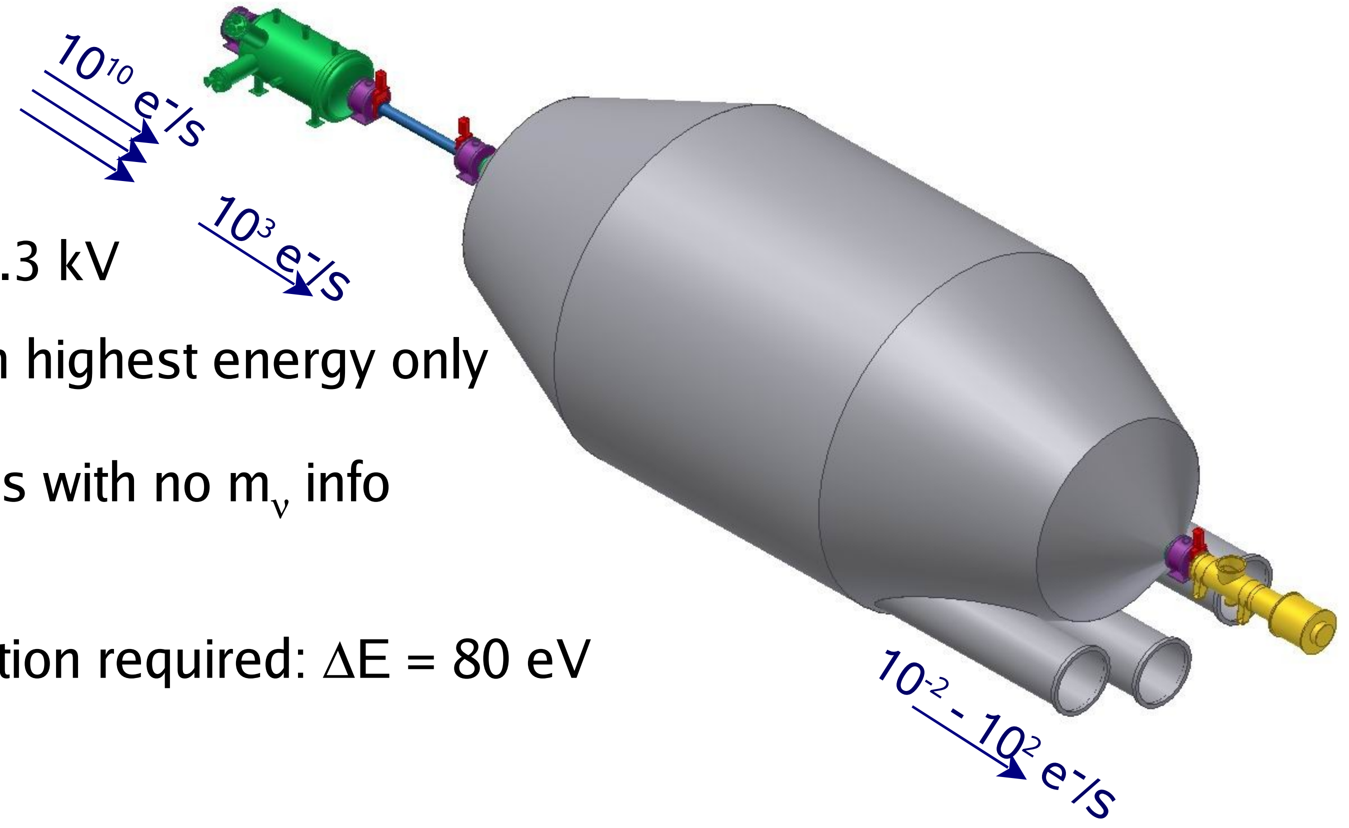
$\approx 10^{-7}$ mbar l/s

$R > 10^7$

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

$p(T_2) < 10^{-20}$ mbar

Pre and main electrostatic spectrometers



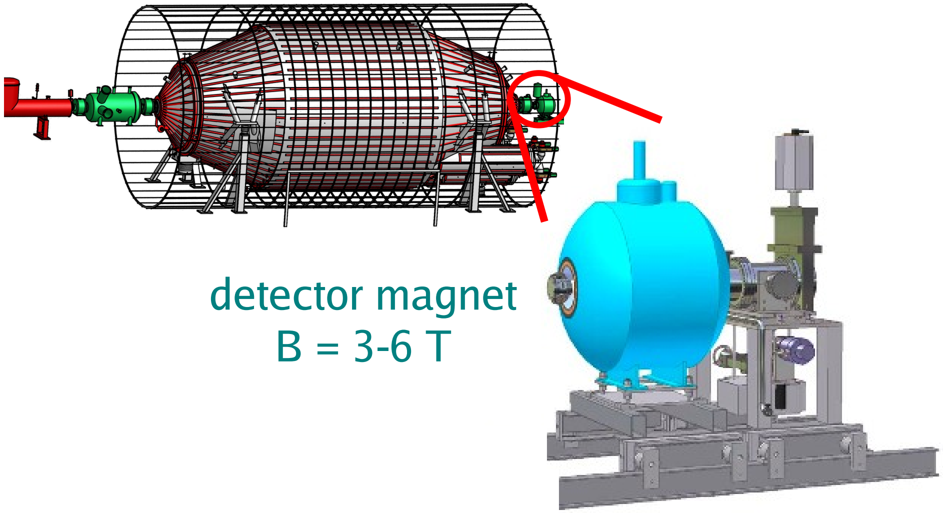
Pre spectrometer

- ∅ 1.7 m, length 3.5 m
- Fixed retarding potential: -18.3 kV
- Transmission of electron with highest energy only
  (10^{-7} part in last 100 eV)
  m→ Filter all β-decay electrons with no m_ν info
  → Reduction of background
- only moderate energy resolution required: $\Delta E = 80$ eV

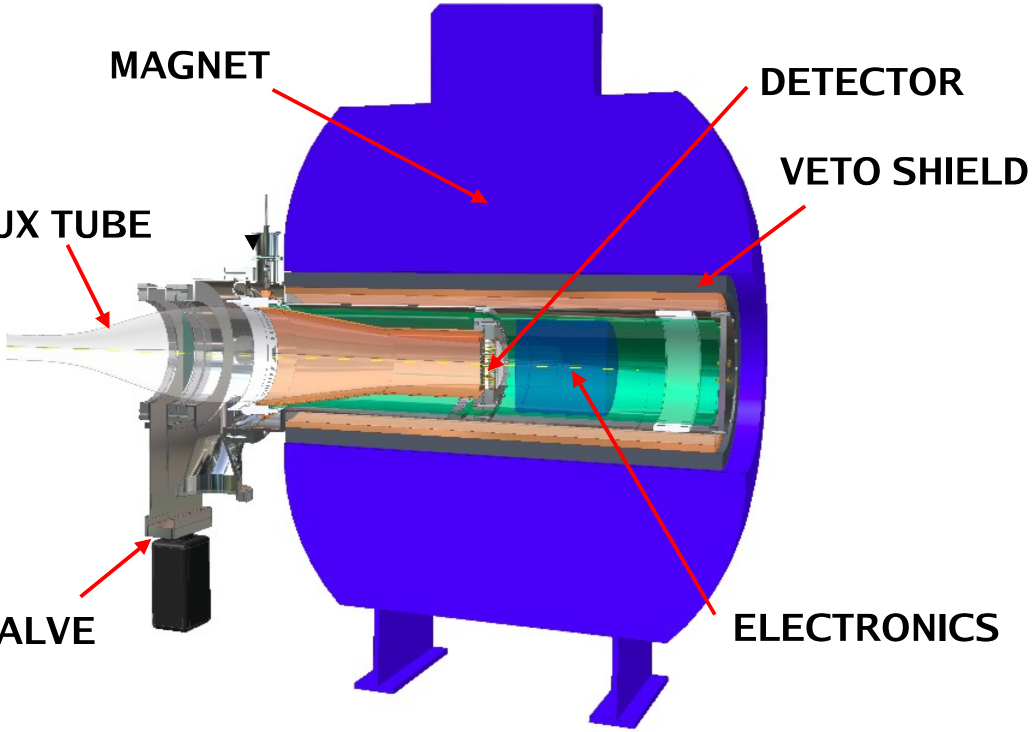
Main spectrometer:

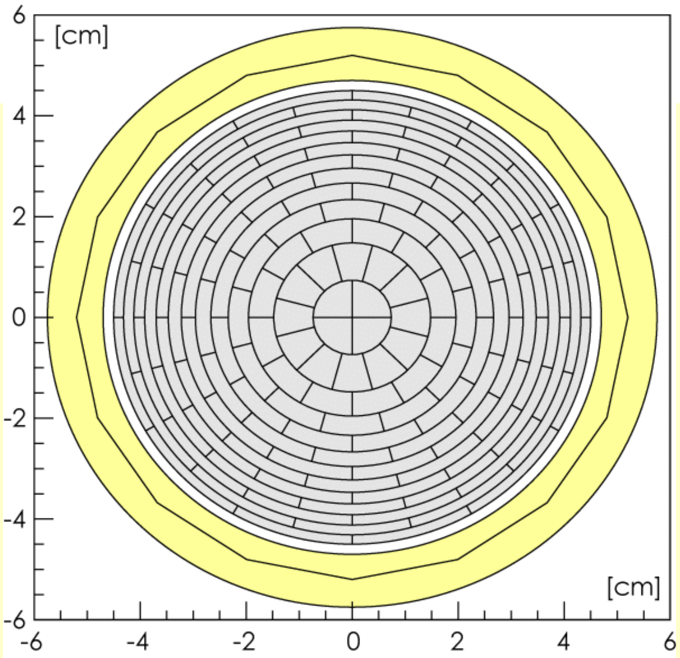
- ∅ 10 m, length 24 m
  ⇒ large energy resolution: $\Delta E = 0.93$ eV
  ⇒ high luminosity: $L = A_{\mathrm{Seff}}\ \Delta\Omega/4\pi = A_{\mathrm{analyse}}\ \Delta E/(2E) = 20\ \mathrm{cm}^2$
- Variable retarding potential: -18.4–18.6 kV
- ultrahigh vacuum requirements (background) $p < 10^{-11}$ mbar (EHV)
- „simple“construction: vacuum vessel at HV + „massless“screening electrode

Detector setup



detector magnet
B = 3-6 T





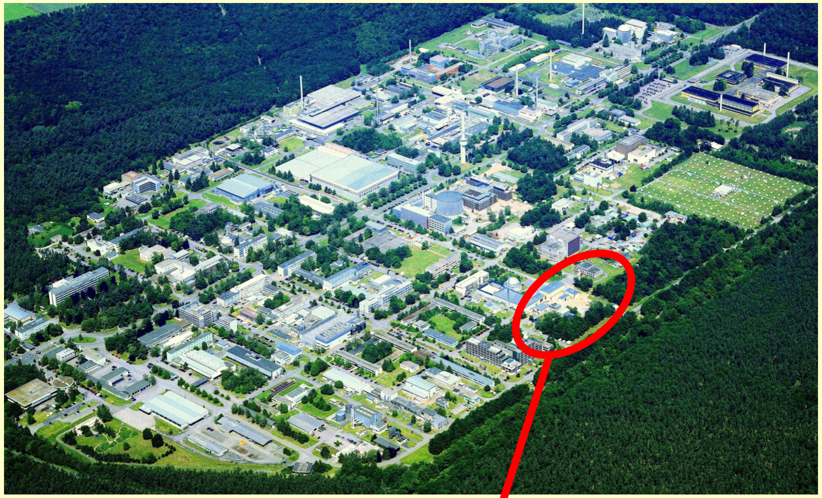
- Si-Pin diode
- Detection of transmitted β-decay electrons (mHz to kHz)
- **Low background for endpoint investigation**
- High energy resolution ΔE < 1 keV
- 12 rings with 30° segmentation + 4 fold center = **148 pixels**

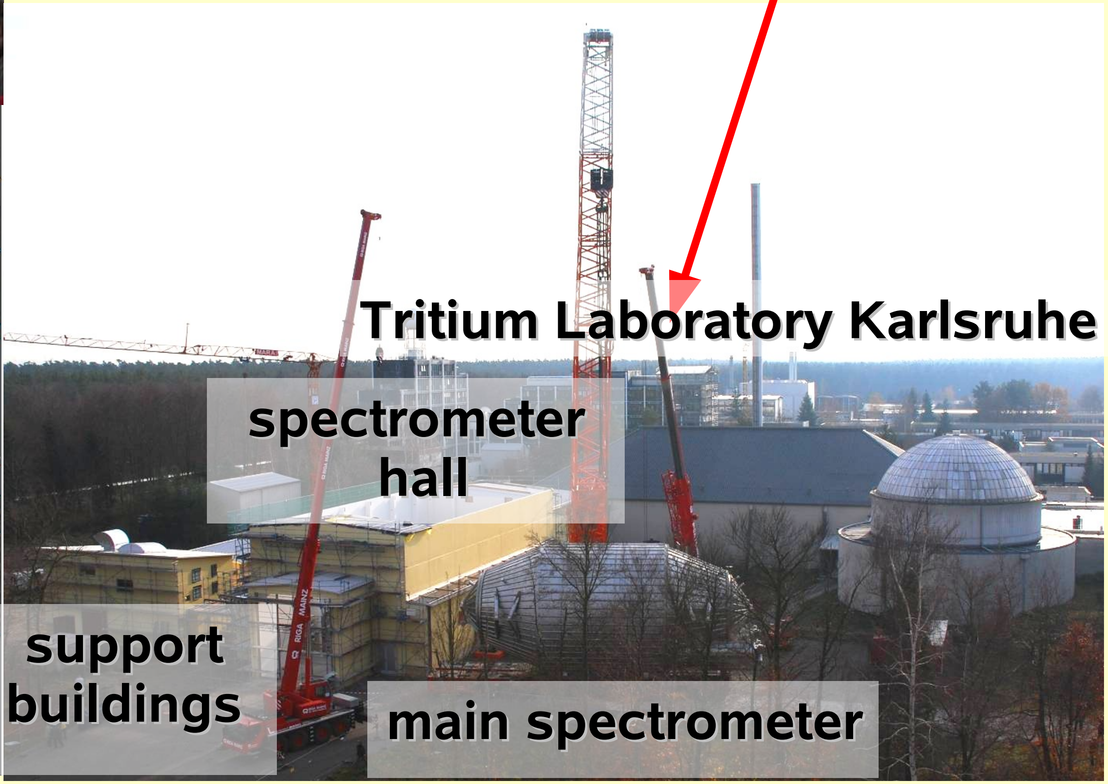
➔ record azimuthal and radial profile of flux tube

KATRIN @ Forschungzentrum Karlsruhe

Leopoldshafen, 25.11.06

8800 km





Tritium Laboratory Karlsruhe

spectrometer hall

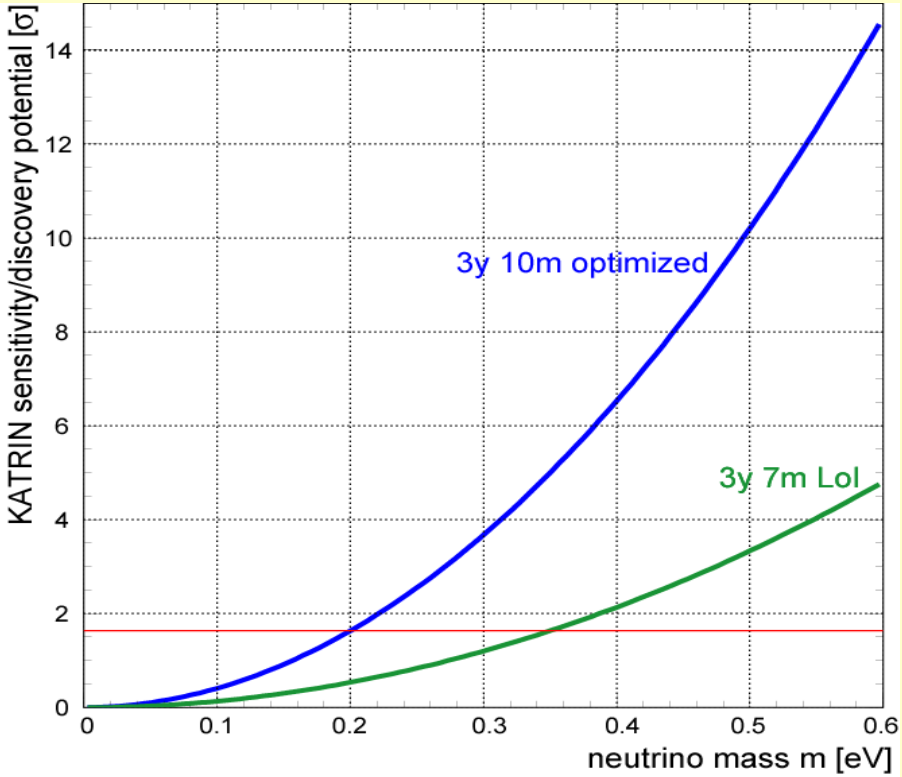
support buildings

main spectrometer

KATRIN time schedule

KATRIN: 0.2 eV sensitivity:

2009-11	commissioning of main spectrometer and detector
2009-12	commissioning of tritium source and tritium elimination lines
2012-	regular data taking for 5-6 years (3 full-beam-years)



Expectation for 3 full beam years: $\sigma_{syst} \sim \sigma_{stat}$

sensitivity:

$m_\nu < 0.2$eV (90%CL)

KATRIN pictures and plots: thanks to C. Weinheimer

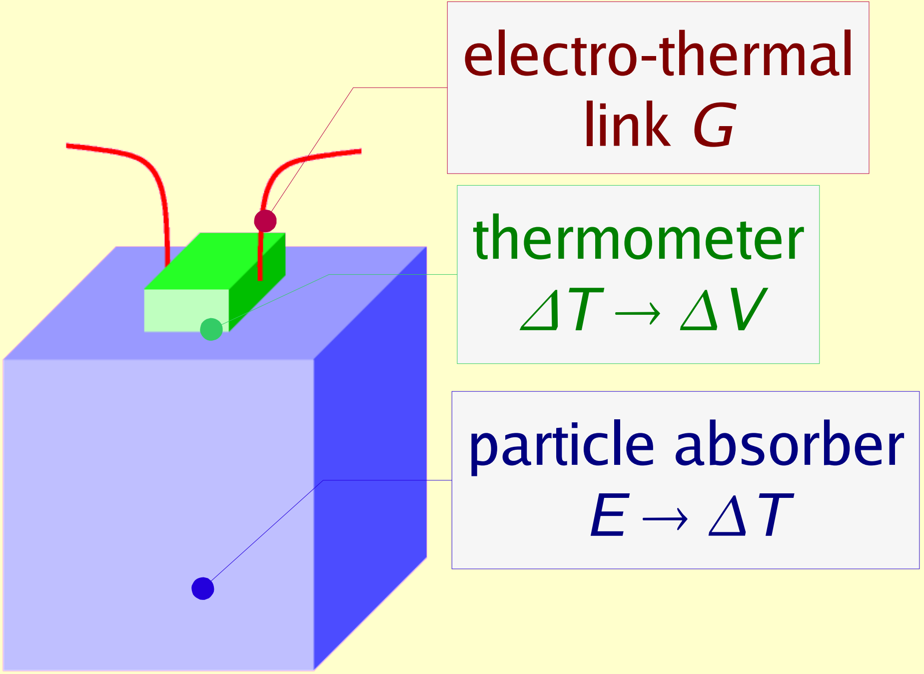
A project for a new ^{187}Re experiment: MARE

http://crio.mib.infn.it/wig/silicini/proposal/

MARE: Microcalorimeter Arrays for a Rhenium Experiment

Università di Genova, and INFN-Genova, Italy
Goddard Space Flight Center, NASA, Maryland, USA
Kirkhhof-Institute Physik, Universität Heidelberg, Germany
Università dell'Insubria, and INFN-Milano-Bicocca, Italy
Università di Milano-Bicocca,and INFN-Milano-Bicocca, Italy
NIST, Boulder, Colorado, USA
ITC-irst, Trento, and INFN-Padova, Italy
PTB, Berlin, Germany
University of Miami, Florida, USA
Università di Roma ‘La Sapienza”, and INFN-Roma1, Italy
SISSA, Trieste, Italy
Wisconsin University, Madison, Wisconsin, USA

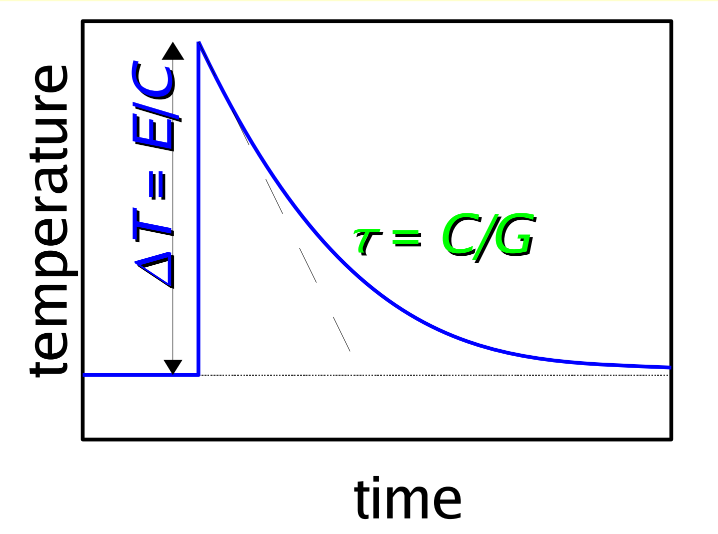
Cryogenic detectors



electro-thermal link *G*

thermometer
$\Delta T \rightarrow \Delta V$

particle absorber
$E \rightarrow \Delta T$



- example: 1 mg of Re @ 100 mK
  $C \sim T^3$ (Debye) ⇒ $C \sim 10^{-13}$ J/K
  6 keV X-ray ⇒ $\Delta T \sim 10$ mK
  ⇒ $\Delta U \sim 1$ eV
  G ~ 10^{-11} W/K ⇒ $\tau \sim 10$ ms

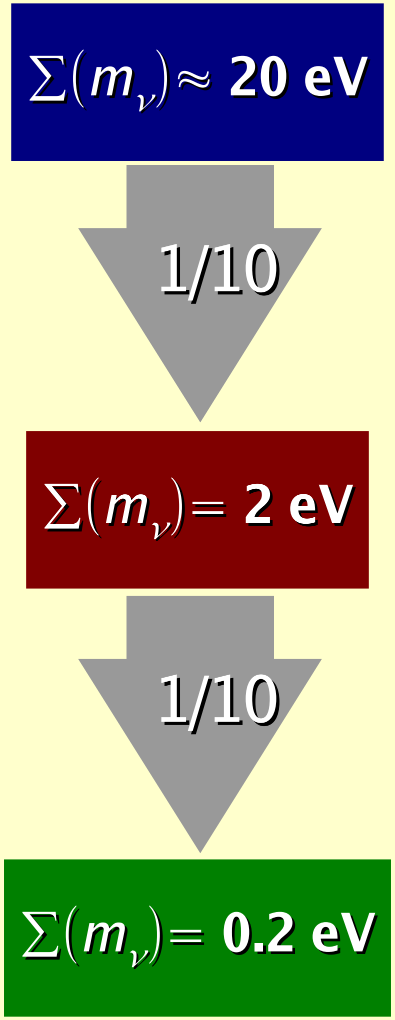
Detection principle:

- $\boldsymbol{\Delta T = E/C}$ where C is the total thermal capacity
  - low C: $\boldsymbol{C \sim T^3}$ in dielectrics or superconductors below T_C
    - → low T (i.e. $T \ll 1$K)
- time response: $\boldsymbol{\tau = C/G}$
- ultimate limit to energy resolution:

statistical fluctuation of internal energy U: $\langle \Delta U^2 \rangle = k_B T^2 C$

- **All the deposited energy is measured**
- **The detector is fully sensitive**

^{187}Re experiment statistical sensitivity



$\Sigma(m_\nu) \approx$ **20 eV**

1/10

$\Sigma(m_\nu) =$ **2 eV**

1/10

$\Sigma(m_\nu) =$ **0.2 eV**

- MIBETA detectors with $\Delta E_{\mathrm{FWHM}} = 30$ eV, $\tau_R = 1.5$ ms
  - ▷ $A_\beta = 0.15$ Hz → $f_{pp} = 2\times10^{-4}$
  - ▷ $t = 3.6$ y×det → 1.6×10^{7} events
  - ▷ $\Sigma_{\mathrm{exp}}(m_\nu) = 15$ eV
- detectors with $\Delta E_{\mathrm{FWHM}} = 10$ eV, $\tau_R = 100\ \mu$s
  - ▷ for $A_\beta = 0.3$ Hz → $f_{pp} = 3\times10^{-5}$
  - ▷ $\Sigma_{\mathrm{MC}}(m_\nu) = 2$ eV with 2×10^{10} events
  - ▷ $t = 2000$ y×det
- detectors with $\Delta E_{\mathrm{FWHM}} = 1$ eV, $\tau_R = 1\ \mu$s
  - ▷ for $A_\beta = 1$ Hz → $f_{pp} = 10^{-6}$
  - ▷ $\Sigma_{\mathrm{MC}}(m_\nu) = 0.2$ eV with 2.5×10^{13} events
  - ▷ $t = 8\times10^{5}$ y×det

The MARE project

Goal: a **sub-eV** direct neutrino mass measurement complementary to the KATRIN experiment

MARE is divided in two phases:

MARE-1

new experiments with large arrays using available technology and ready to start as soon as possible

2÷4 eV m_ν sensitivity

MARE-2

very large experiment with a m_ν statistical sensitivity close to KATRIN but still improvable: 5 years from now for further detector R&D

0.2 eV m_ν sensitivity

phase I is needed:

- because it's the only possible one with present technology
- to investigate systematics in thermal calorimeters

very important to cross-check spectrometer results

MARE-1: TES vs. Silicon thermistors

- **aim**: high statistics measurement with a *ready-to-use* technology
  - ▷ few eV statistical sensitivity in few years
  - ▷ investigate systematics in thermal calorimeters with $10^9 \div 10^{10}$ events
  - ▷ cross-check spectrometer results

MARE-1 SEMICON (MIBETA2)

U. Milano-Bicocca / INFN Sez. Mi-Bicocca
U. Insubria / INFN Sez. Mi-Bicocca
ITC-Irst / INFN Sez. Padova
U. Wisconsin, Madison
NASA/Goddard

- ○ about 300 element arrays
- ○ well known Si implanted thermistors
- ○ AgReO$_4$ crystals

MARE-1 TES (MANU2)

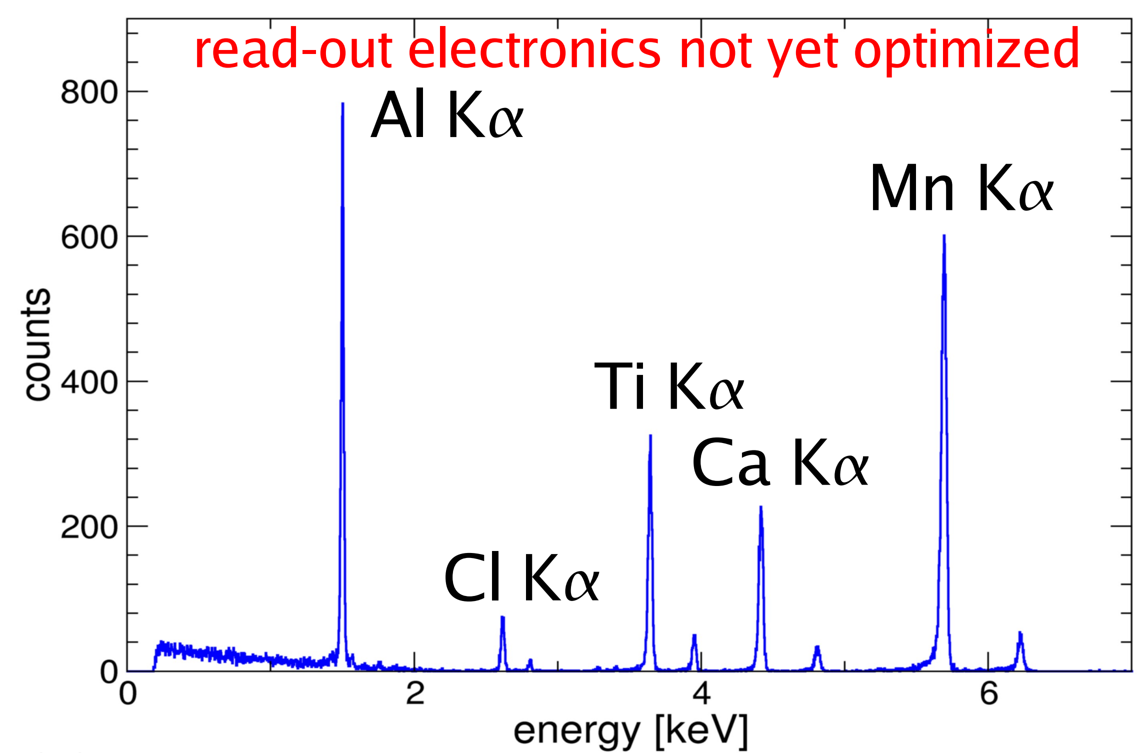
U. Genova / INFN Sez. Genova
U. Miami, Florida
PTB Berlin, Germany

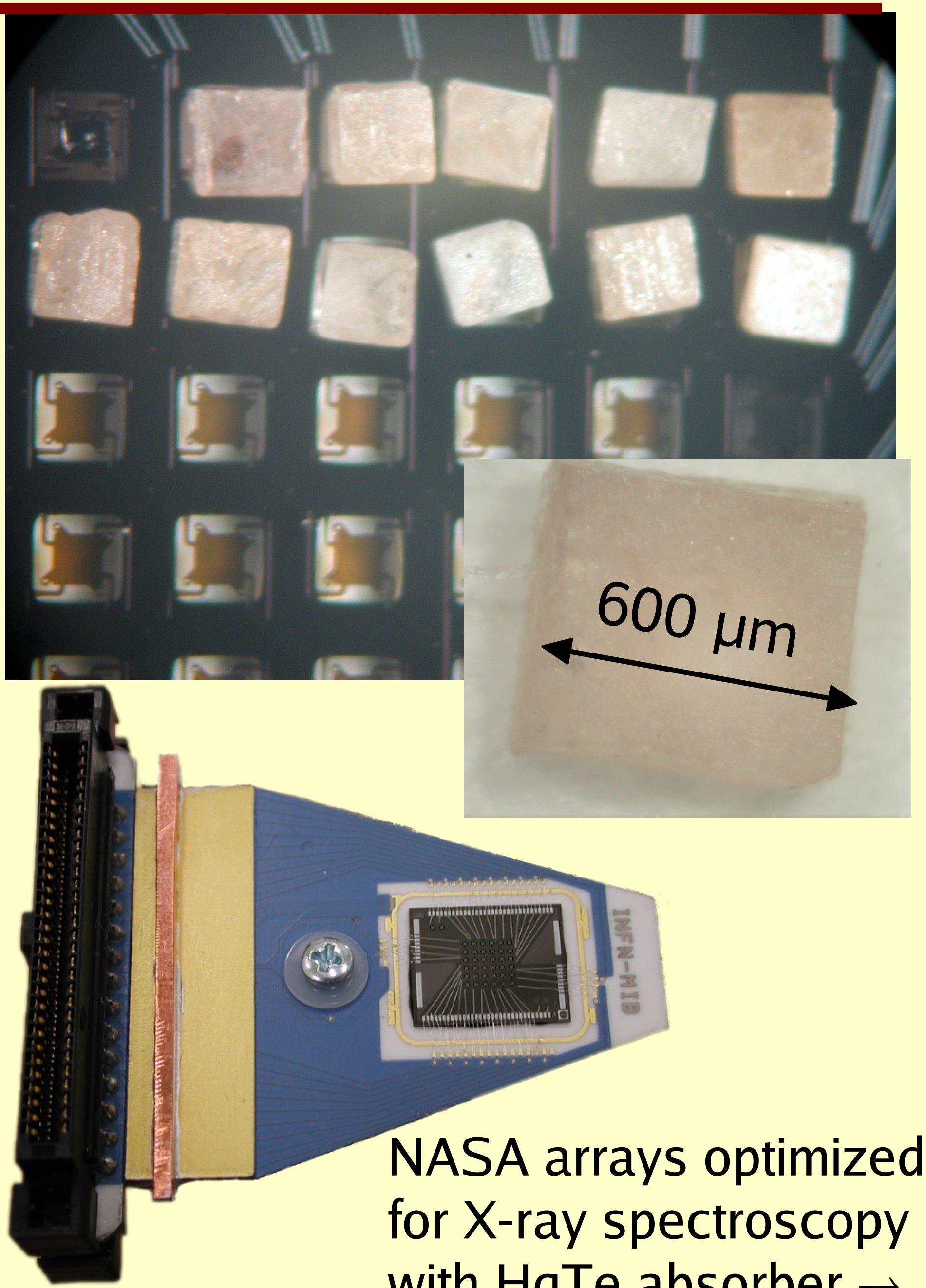
- ○ about 300 element arrays
- ○ newly developed transition edge sensors
- ○ Re crystals

- ▷ cross check
- ▷ common effort on systematics
- ▷ joint analysis to improve limit

MARE-1 SEMICON

- ○ **NASA/GSFC XRS2-2 arrays**
  - ▷ 6x6 pixels
- ○ flat $AgReO_4$ single crystals
  - ▷ $m \approx 0.5$ mg
- ○ detector R&D phase results
  - ▷ best operating $T \approx 90$mK
  - ▷ **$\Delta E \approx 30$ eV, $\tau_R \approx 250$ µs**

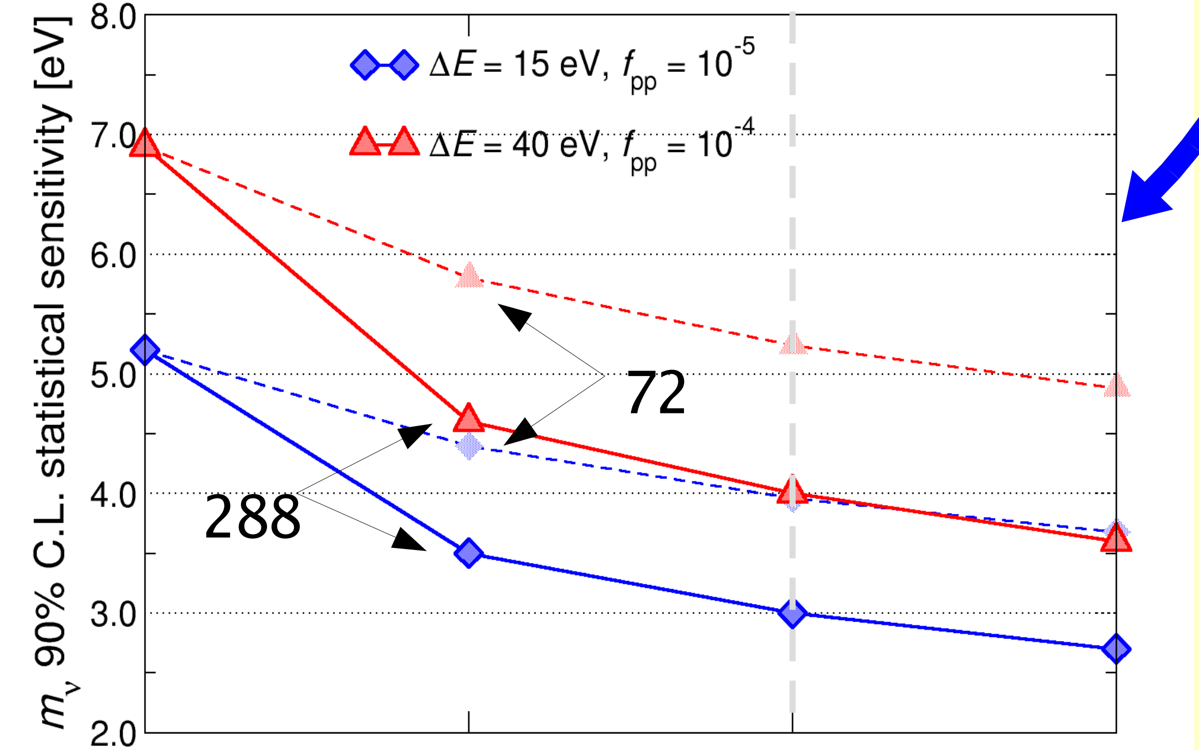

read-out electronics not yet optimized



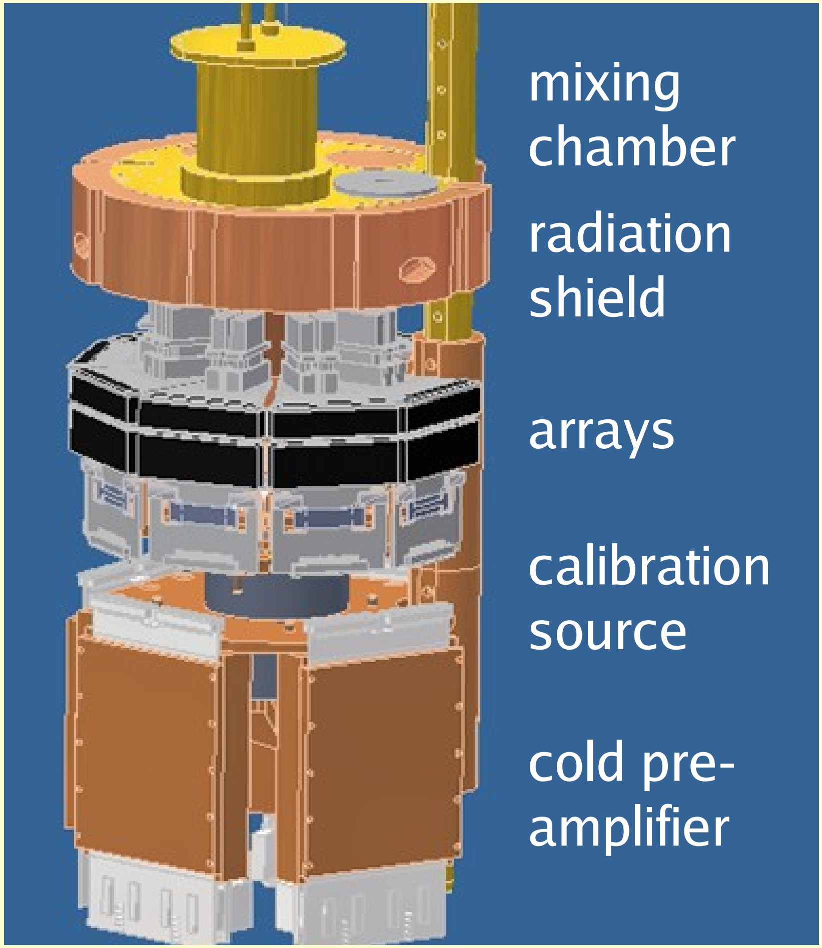
NASA arrays optimized for X-ray spectroscopy with HgTe absorber → ASTRO-E2 mission

MARE-1 SEMICON: MC statistical sensitivity

year	1	2	3	4
new detectors	72	216	0	0
total detectors	72	288	288	288
statistics [det*y]	72	360	648	936
activity [c/s]	0.27	m_{AgReO4} = 500 μg		
statistics [events]	6.10E+08	3.05E+09	5.49E+09	7.94E+09
ΔE = 40 eV	τ = 400μ s	f_{pp} = 1.0E-4		
m_ν sensitivity (90%)	6.9	4.6	4.0	3.6
ΔE = 15 eV	τ = 50μ s	f_{pp} = 1.0E-5		
m_ν sensitivity (90%)	5.2	3.5	3.0	2.7

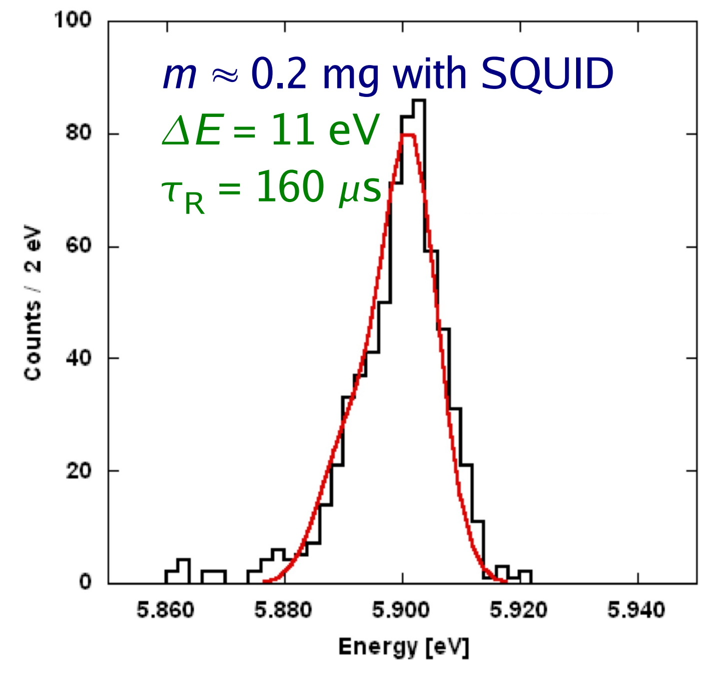


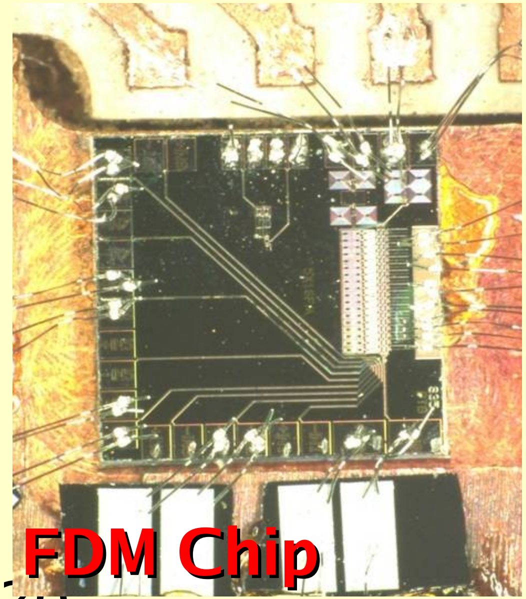
- ○ setup ready for 8 arrays
- ○ 288 $AgReO_4$ crystals
- ○ **now starting with 2 arrays (72 ch.)**
- ○ gradual deployment
  - ▷ further detector optimization

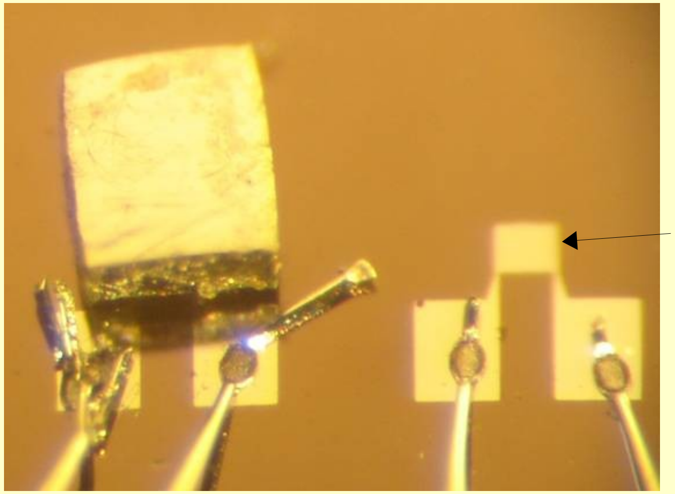


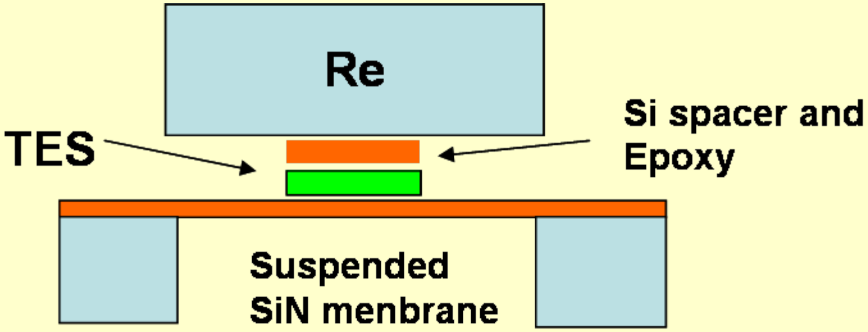
MARE-1 TES

- Pulsed Laser Deposition of thin films: pure **Ir** or **Ir bilayers**
- detectors with **metallic rhenium** absorbers
- **300 channel array**
- detector R&D goal:
  - **1 mg** Re crystals with: **ΔE = 5 eV, τ_R = 10 μs**
  - a further step towards MARE-2
- two read-out options
  - JFETs with **cold impedance transformer**
  - frequency **multiplexed SQUIDs (FDM)**
    - **first 3x3 FDM chip is under test now**

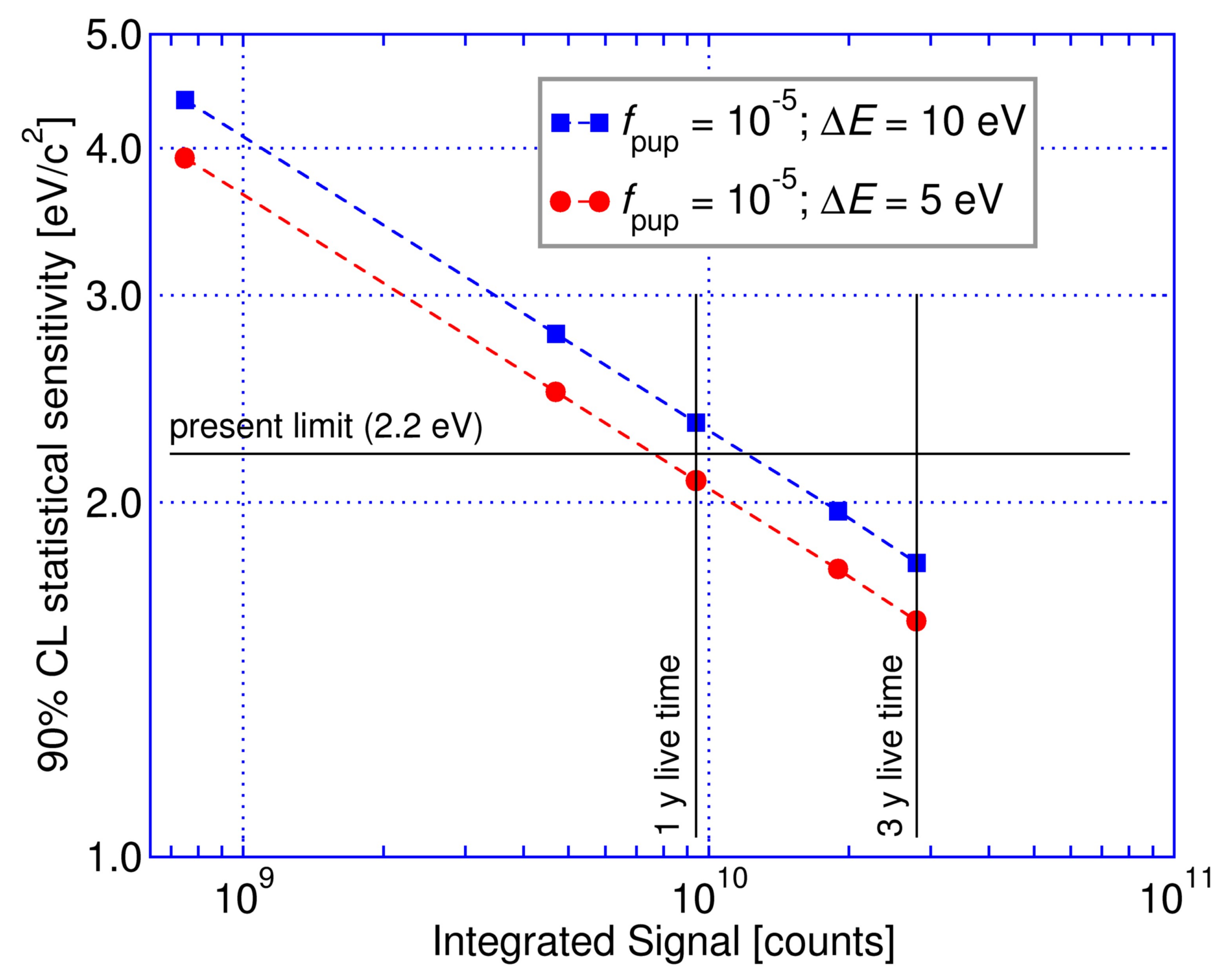








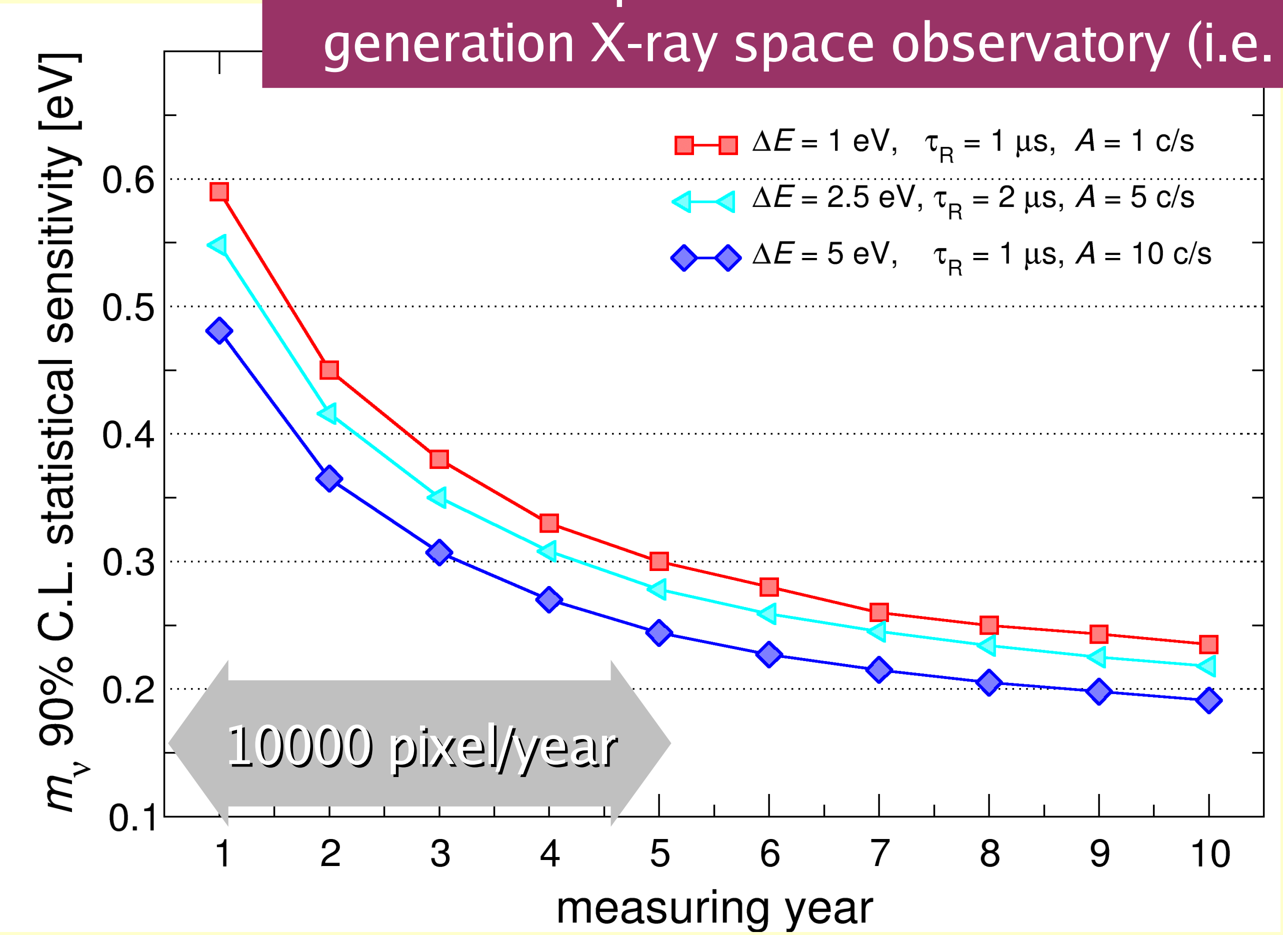
MARE-1 TES statistical sensitivity



- ○ 300 rhenium crystals in 2 refrigerators
  - ▷ $m \approx$ 1 mg
- ○ Ir/Au or Al/Ag TES at 100 mK
  - ▷ **ΔE = 10 eV, τ_R = 10 μs, f_{pp} = 10^{-5}**
- ▸ about 3×10^{10} events in 3 years ⇒ **m_ν<1.8 eV**

MARE-2

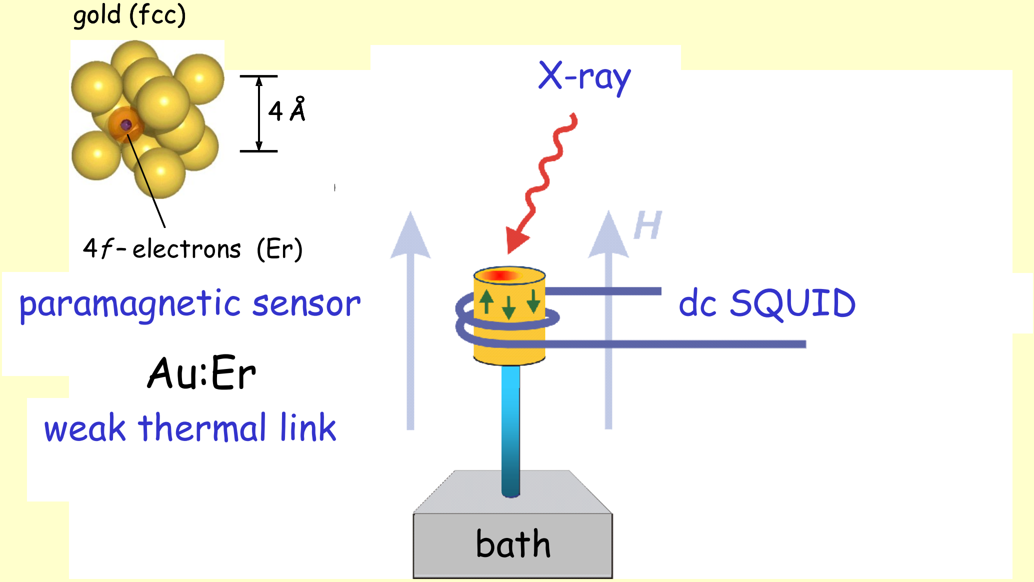
- only statistical analysis
- 50000+ detectors gradually deployed
  - 5 arrays with 10000 detectors each
  - one array deployed per year for the first 5 years
  - arrays distributed in many laboratories around the world
  - about $10^{13} \div 10^{14}$ events after 5 years
- technical requirements not far from that for next generation X-ray space observatory (i.e. XEUS, Con-X)

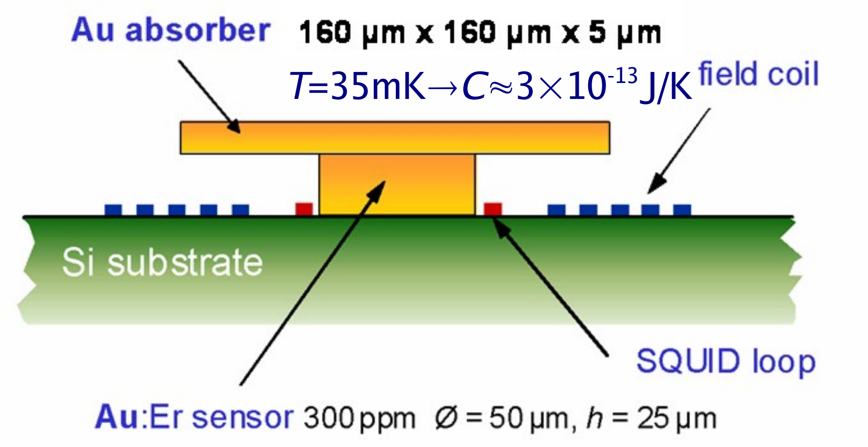


10000 pixel *kits*
$\Delta E \approx 1$ eV
$\tau_R \approx 1\ \mu s$
$A_\beta \approx 1 \div 10$ Hz

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

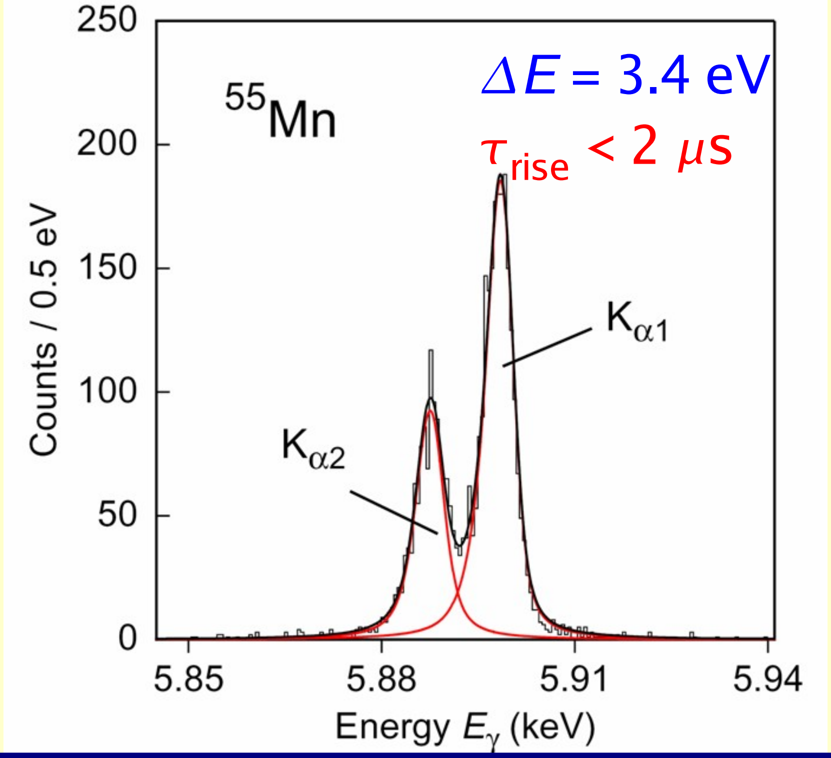
MMC - Magnetic Micro Calorimeters (Heidelberg)

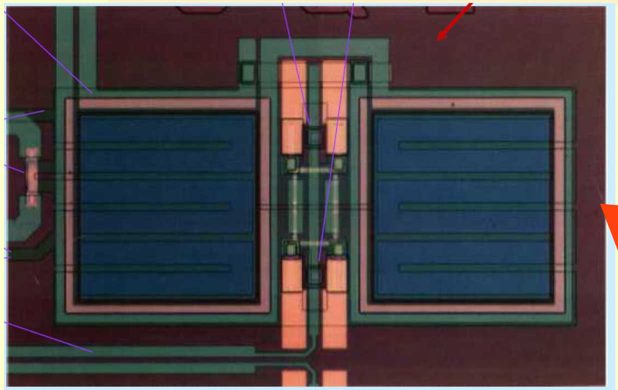




$$\delta M = \frac{\partial M}{\partial T}\,\delta T = \frac{\partial M}{\partial T}\,\frac{E_\gamma}{C_{\mathrm{ges}}}$$

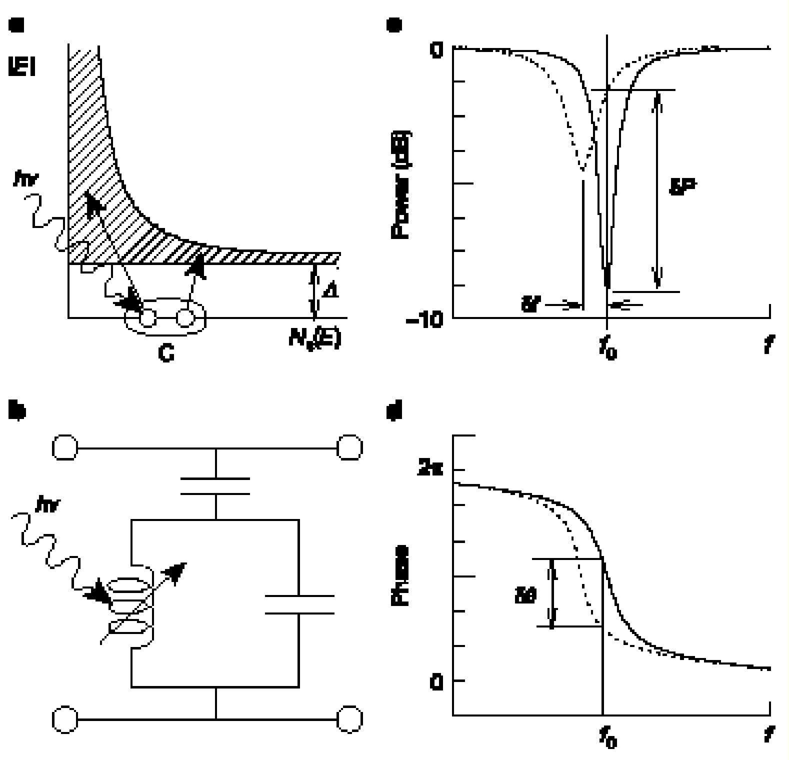
- suitable for **large capacity absorbers**
- **very fast** $\sim\mu$s
- **high energy resolution** $\sim$eV

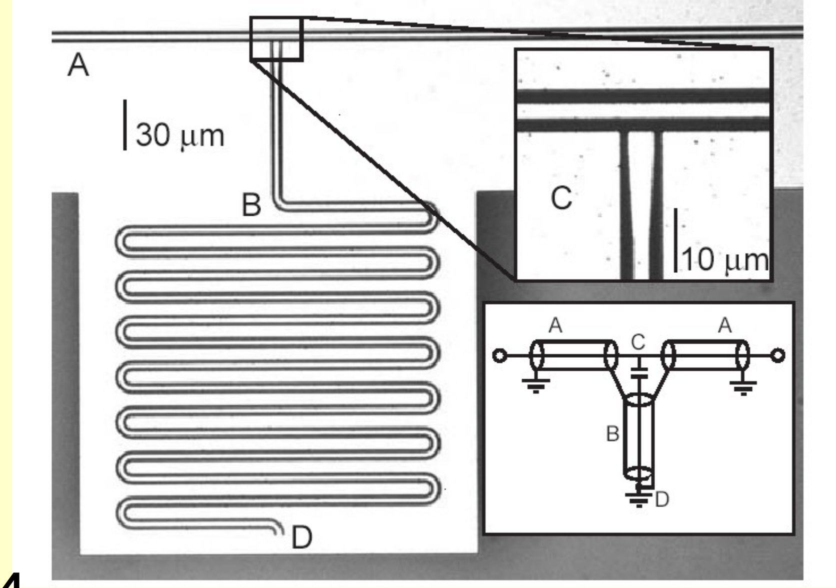




sensor design optimization for MARE-2
rhenium absorbers in progress
⇨ meander pick-up coils without external *B* field

MKIDs –Multiplexed Kinetic Inductance Detectors





- resonator exploiting the *T* dependence of inductance in a superconducting film
  - **qp detectors** suitable for large absorbers
  - **fast** devices for high single pixel activity A_β and low pile-up f_{pp}
  - **high energy resolution**
  - **multiplexing** for very large number of pixel

Sensitivity

$\Delta E = 5$ eV

t_M = 36000 detectors x 3 years

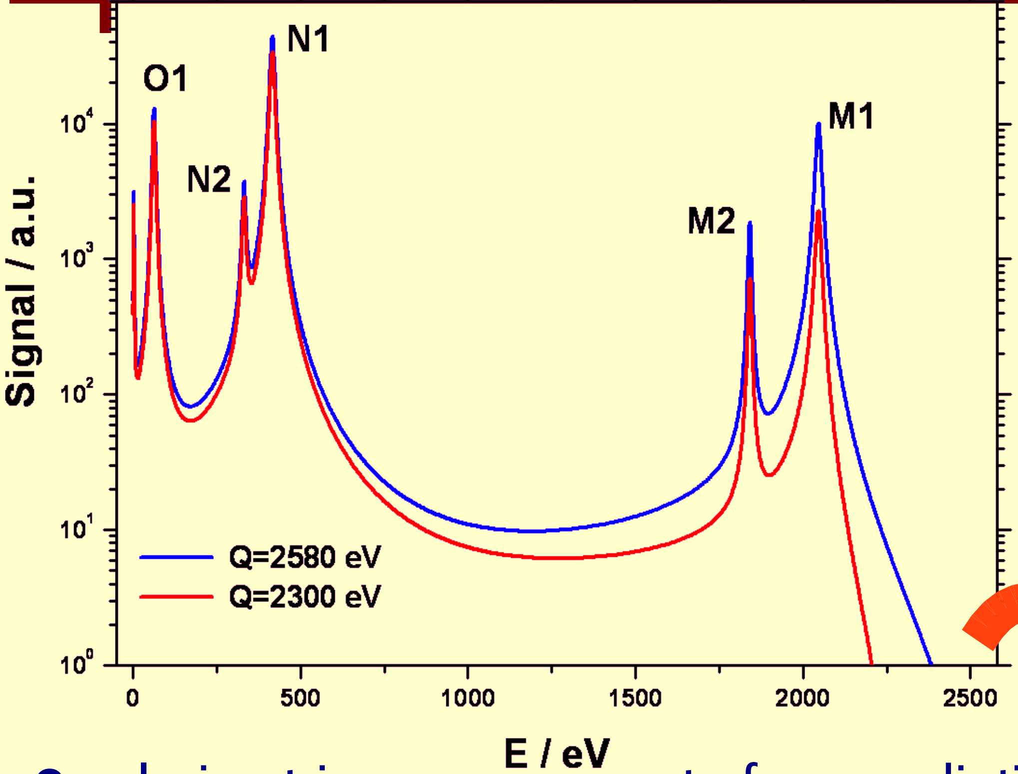
A_β = 20 c/s/det

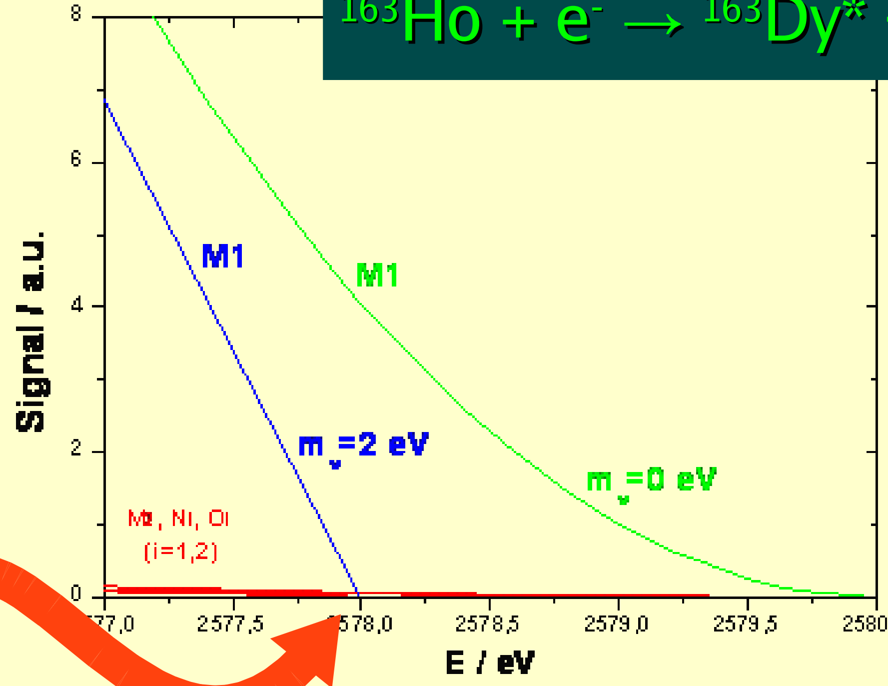
- $\tau_{rise} = 1\ \mu s \Rightarrow m_\nu < 0.2$ eV
- $\tau_{rise} = 100\ \mu s \Rightarrow m_\nu < 0.4$ eV

- KIDs developed for astrophysics
- application to bulky absorber still requires further efforts

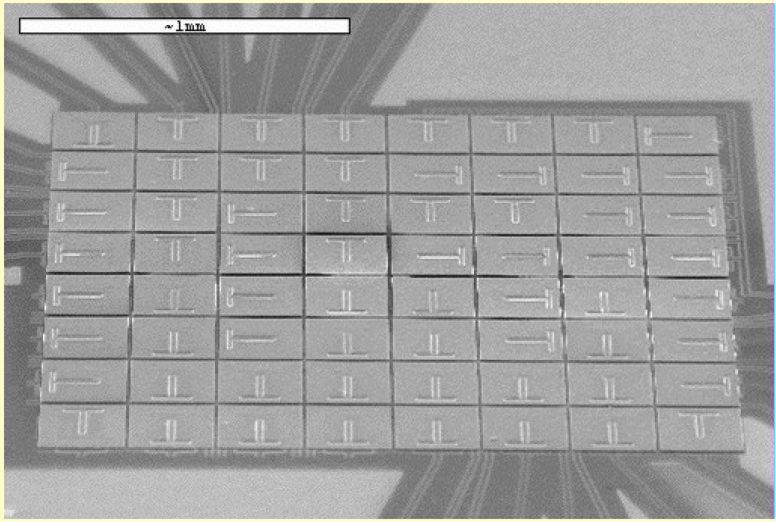
^{163}Ho electron capture measurement

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





- calorimetric measurement of non-radiative Dy atomic de-excitations (Coster-Kronig, Auger...)
- fraction of events at end-point may be as high as for ^{187}Re: depends on Q_{EC} (≈2.5 keV)
  - ► Q_{EC}?
- fewer active nuclei are needed ($\tau \approx$ 4000 y)
  - ►can be implanted in any suitable absorber
  - ►first implantation tests at ISOLDE are encouraging
- new NASA/Goddard TES arrays (ΔE = 2eV) can be implanted with ^{163}Ho



Conclusions

Investigation of β-decay kinematics is the only model-independent approach to the absolute neutrino mass scale.

KATRIN is the ultimate tritium β-decay experiment: it will reach a sensitivity of 0.2 eV on m_ν. Expected data taking in 2012.

^{187}Re calorimetry is complementary to tritium experiments and can give sub-eV sensitivity to m_ν.

The **MARE** project 1st phase is just starting. R&D improvements on the detector technology are crucial for the 2nd phase.