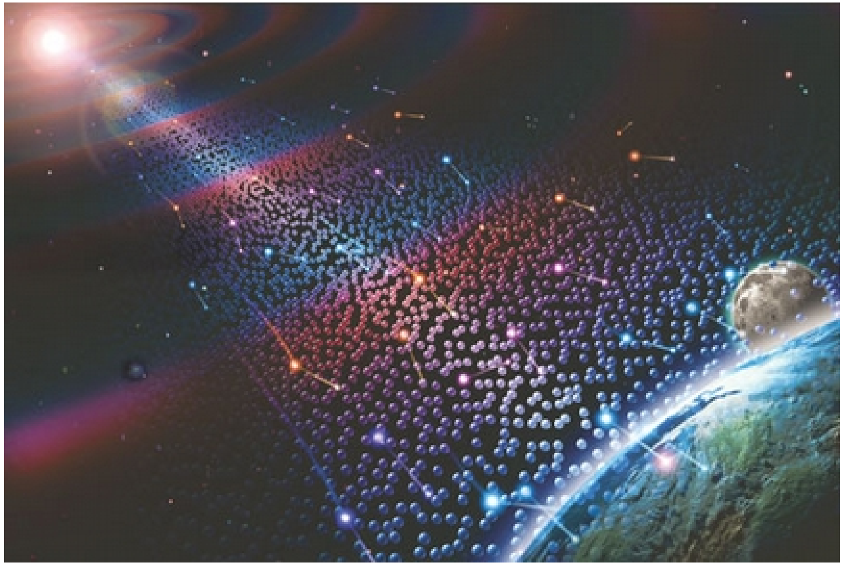
An overview of the current status of the neutrino mass measurements with a focus on the HOLMES experiment

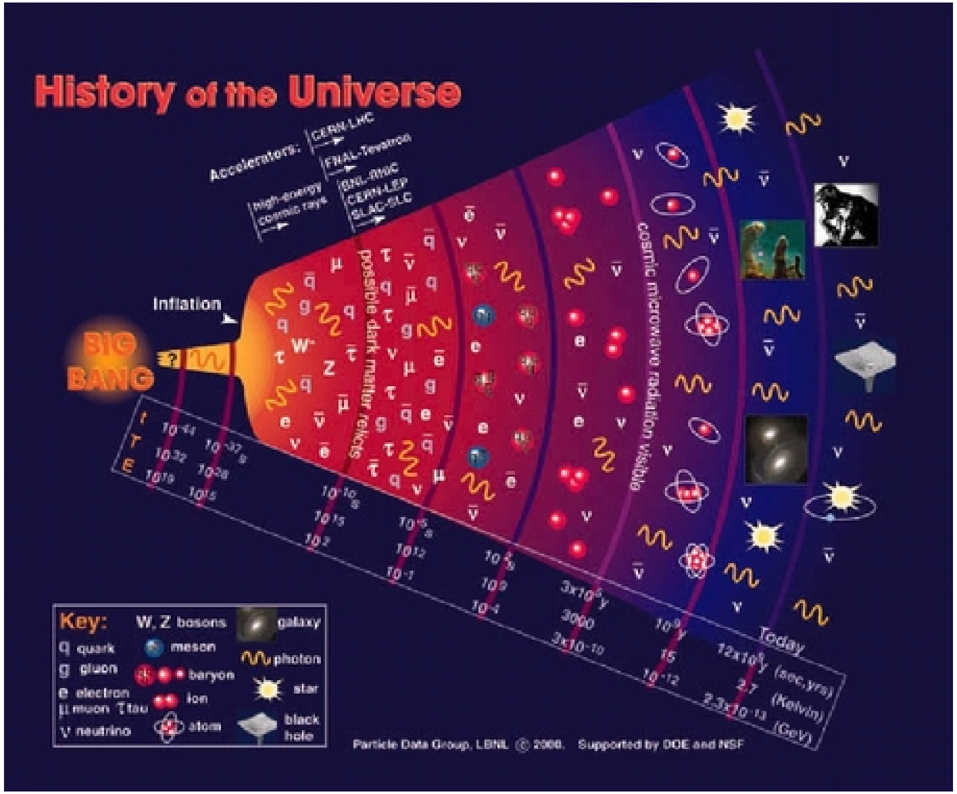
Andrei Puiu

Neutrinos



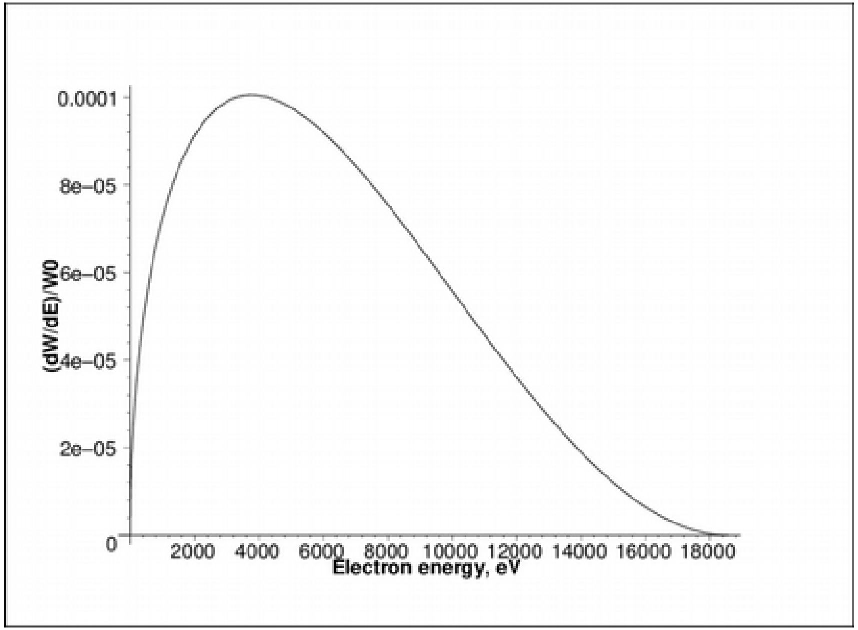
On average there are roughly one billion times more neutrinos than protons in the Universe.

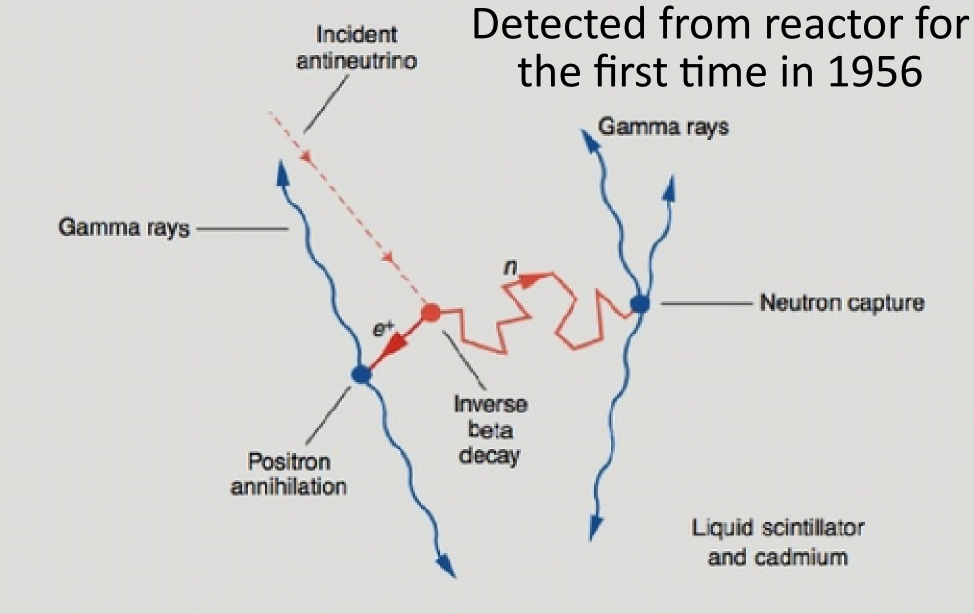
- Second most abundant particle in the universe
- Influenced the universe as we see it



Neutrino discovery

Needed to explain the continous spectrum of electrons emitted in beta decay





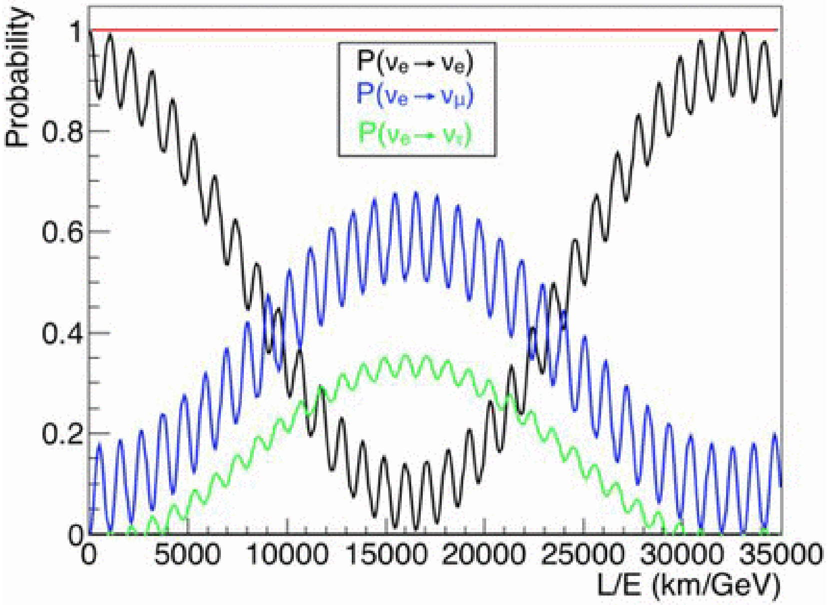
Detected from reactor for the first time in 1956

→ Opened a new era of experiments… and problmes to be solved

Still misterious

Neutrinos are peculiar particles

- Tiny mass
- Flavour oscillation

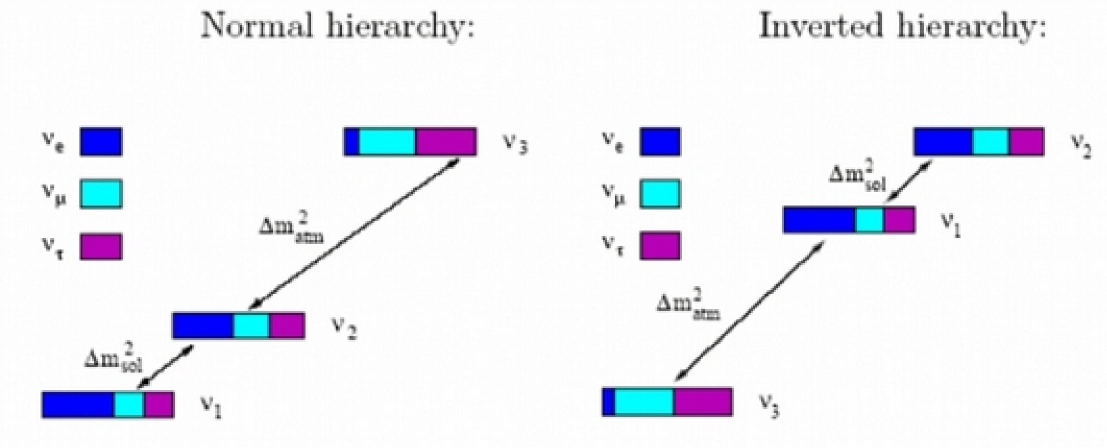


Open questions:

- What is the absolute scale of their mass ?
- Majorana or Dirac particle ?
- CP violating phase ?
- Sterile neutrinos ?

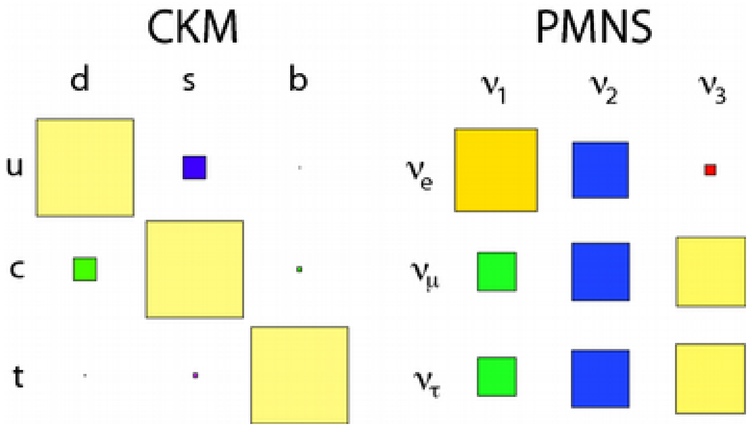
Facts on neutrinos

- A central goal in both cosmology and particle physics is to measure the mass of the neutrino particles. The neutrino sector is still poorly understood and the mechanism that gives rise to their mass is unknown.
- There are thought to be three active neutrino species, with mass differences measured through solar, atmospheric, reactor and accelerator neutrino oscillation experiments



The absolute mass scale is still unknown

Mixing matrix



$$
\begin{aligned}
U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \\
&= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
&= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix},
\end{aligned}
$$

How to assess the neutrino mass ?

- Cosmological measurements
- Neutrinoless Double Beta Decay
- Direct kinematic measurement from Beta or Electron Capture (EC) decay

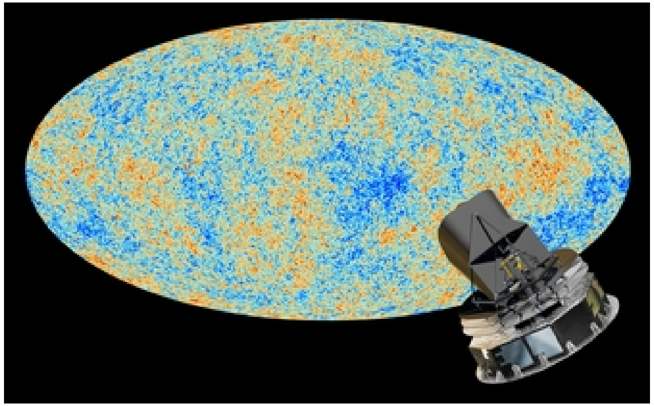
Since the the flavour oscillations paradigm has been established, a remarkable increase of interest has in investigating directly the absolute mass scale

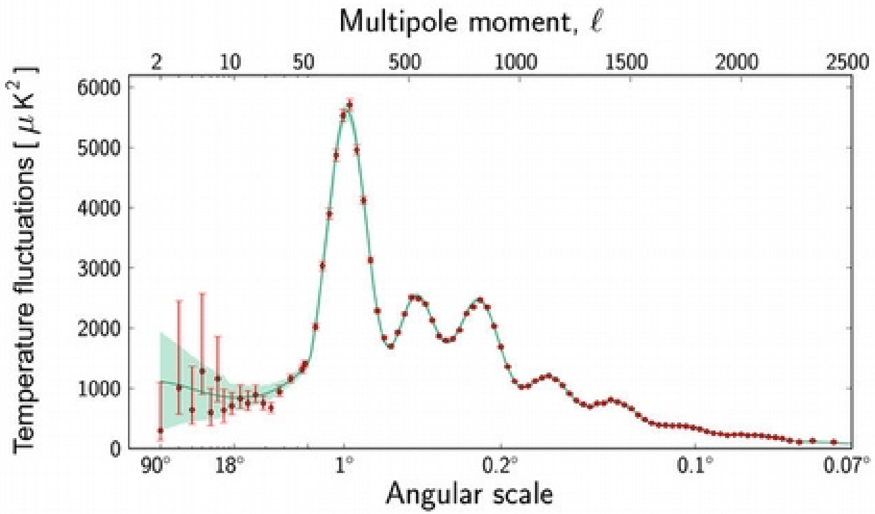
cosmology

$$m_{\Sigma} = \Sigma_i m_{\nu i}$$

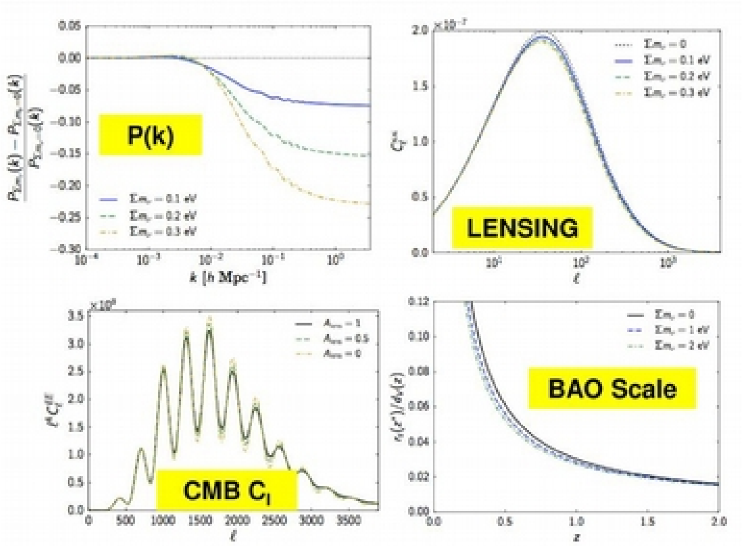
Massive neutrinos behave initially like non-interacting relativistic particles, and then later like cold dark matter. As such they affect the expansion rate of the Universe, compared to a pure radiation or pure matter component, as well as modifying the evolution of perturbations at early times

- $m_{\nu i} \neq 0$ affects CMB (multipole expansion and polarisation), Barionic Acoustic Oscillation and Lensing power spectrum
- $\Sigma_i m_{\nu i}$ is flavour mixing independent





Constraints from Cosmology



$$m_\Sigma = \Sigma_i m_{\nu i}$$

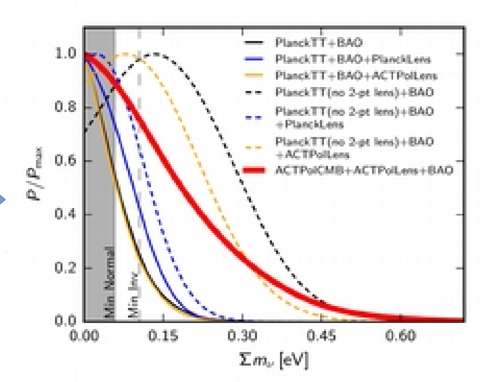
Assumptions:

- cosmological neutrinos are the same as the terrestrial ones
- ΛCDM + 3 interacting neutrinos

The current indirect 95% upper limit from cosmological data on the sum of the neutrino masses is

$$\Sigma_i m_{\nu i} < 130 \text{ meV}$$

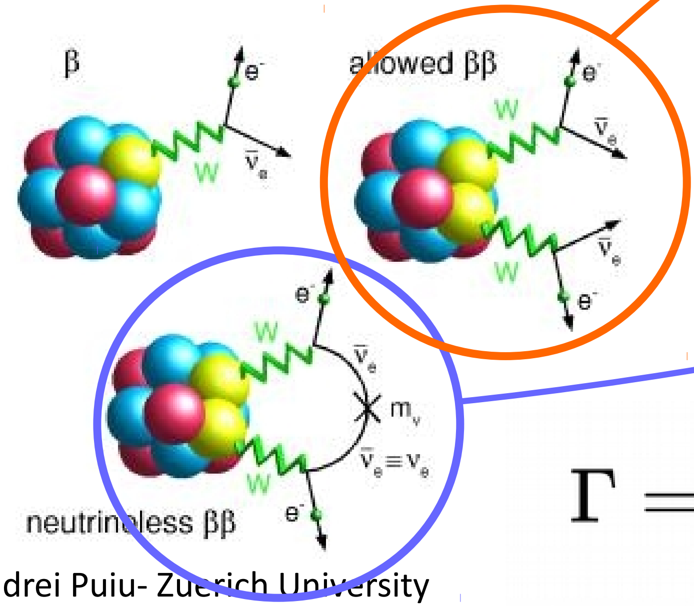
from the Planck measurements of the Cosmic Microwave Background (CMB), combined with Baryon Acoustic Oscillation (BAO) measurements from the Baryon Oscillation Spectroscopic Survey (BOSS)

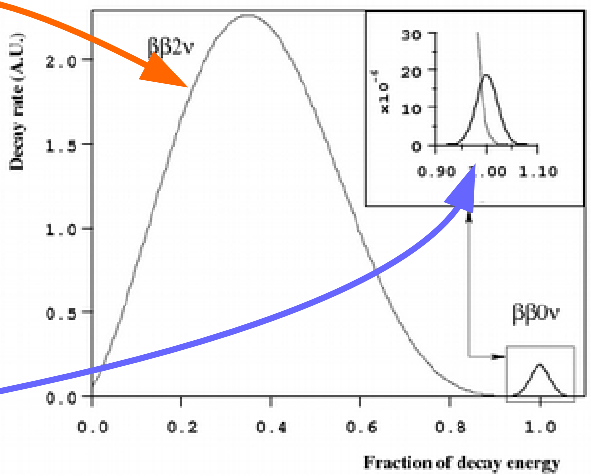


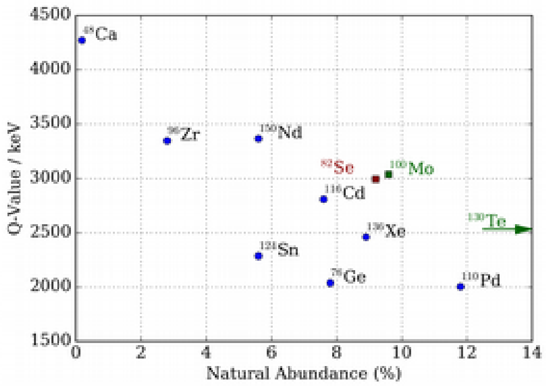
Neutrinoless Double Beta Decay

$$m_{\beta\beta} = \left|\Sigma_i m_{\nu i} U_{ei}^2\right|$$

- Not allowed in the Standard Model
- Possible only if neutrinos are Majorana particle
- Decay with halflife $\tau_{1/2} > 10^{26}$ y







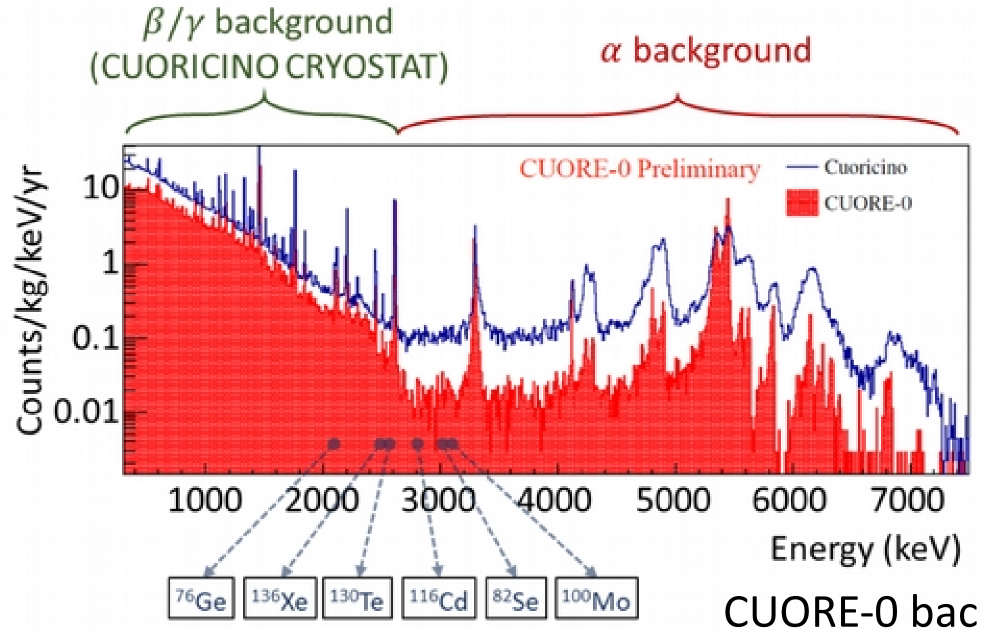
- $2\nu\beta\beta$ decay poses an unavoidable background
- High Q-value is desired
- High natural abudance → cheaper

$$\Gamma = G|M|^2|m_{\beta\beta}|^2$$

Neutrinoless Double Beta Decay Sensitivity

Very rare event search require a special experimental environment

- Low background is a must
  possibly 0 background
- High resolution for electron detection
- Very large masses with high isotopic abundance
- Undergound laboratories mandatory for cosmic ray shielding



CUORE-0 background

$$S^{0\nu} \propto \epsilon\, i.a. \sqrt{\frac{MT}{b\Delta E}} \qquad b \neq 0$$

$$S^{0\nu} \propto \epsilon\, i.a. MT \qquad b = 0$$

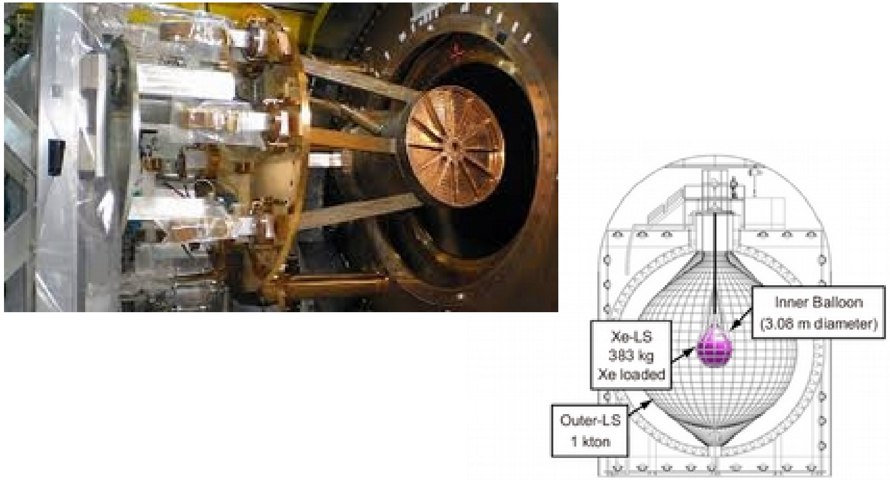
M:	Total active mass in kg
ϵ:	Detector efficiency
$i.a.$:	Isotopic abundance
b:	Background in c/keV/kg/y
ΔE:	Detector resolution @ ROI in keV
T:	Exposure time in y

Experimental approach

Calorimetric / Ge diodes

- Source = detector
- Extremely good energy resolution
- Crucial material selection
- Background discrimination techniquies
- Now at Ton scale

Liquid Xenon / Loaded scintillator

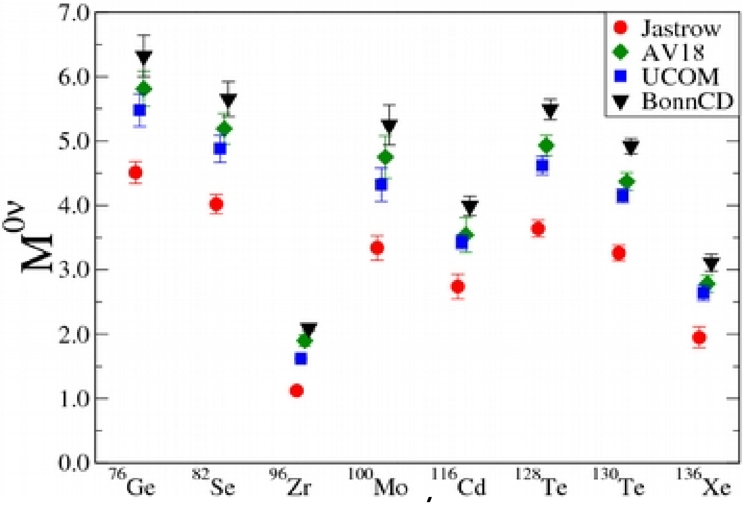


- Easily scalable to multi-ton scale
- Lower energy resolution
- Self shielding effect of liquid Xe

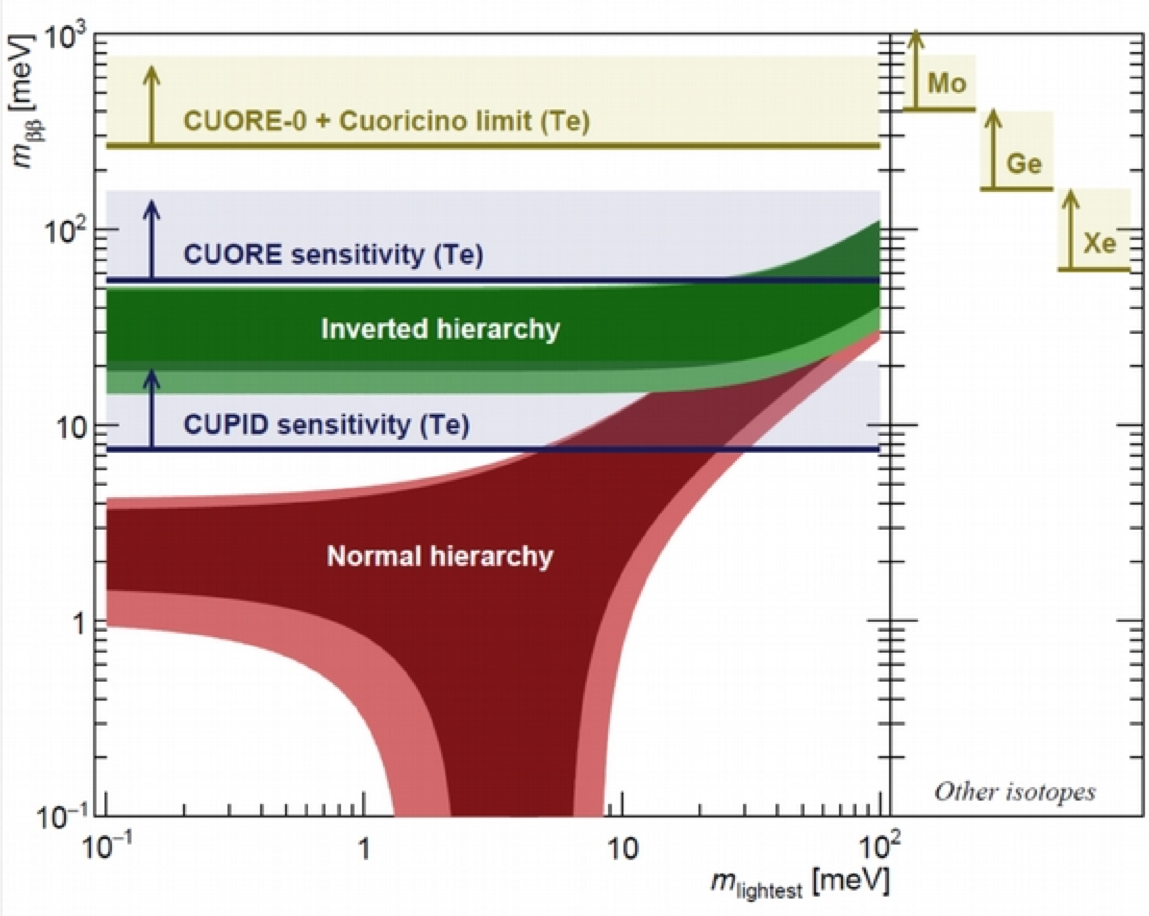
Current limit on $m_{\beta\beta}$ and neutrino mass

A non trivial issue is the evaluation of the nuclear matrix elements in order to assess mbb from the measured half life

$$\Gamma = G|M|^2\,|m_{\beta\beta}|^2$$

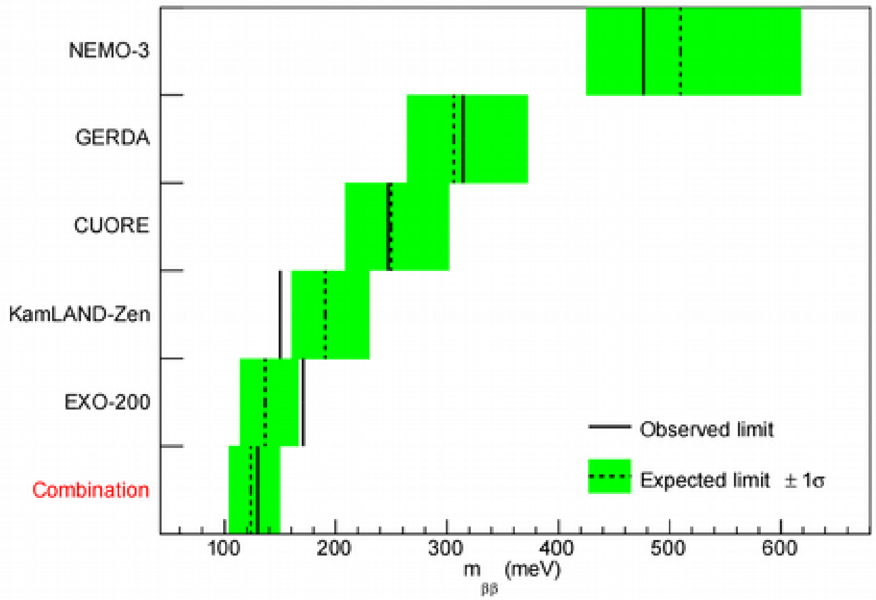


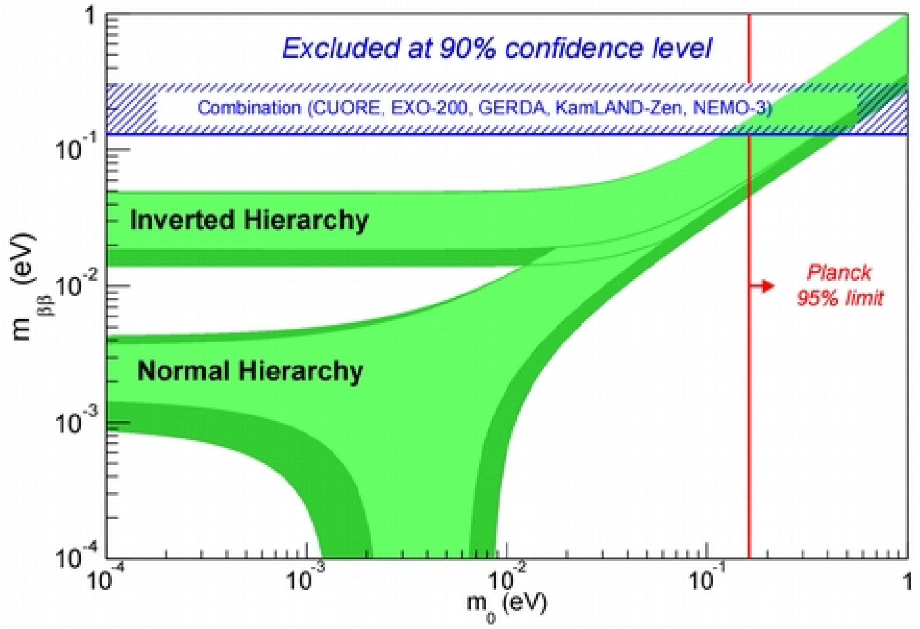
Ar



Current limit on m_ν from $0\nu\beta\beta$ decay

The main limits from experiments combined is 130 – 310 meV, depending on NME model



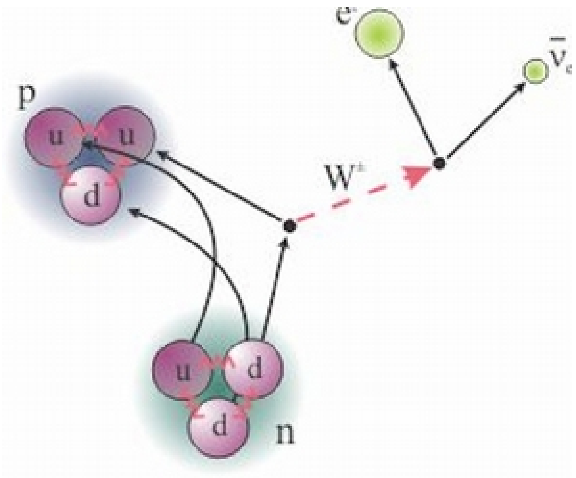


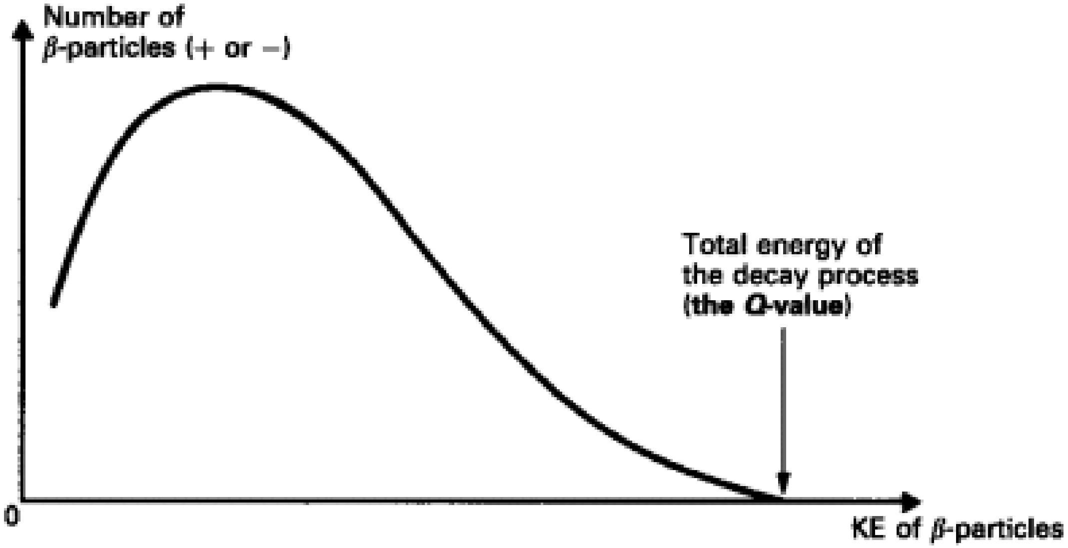
A

The model indepent tool

Kinematics of b decay: $E^2=p^2c^2+m^2c^4$
process involving neutrinos in the final state

$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$



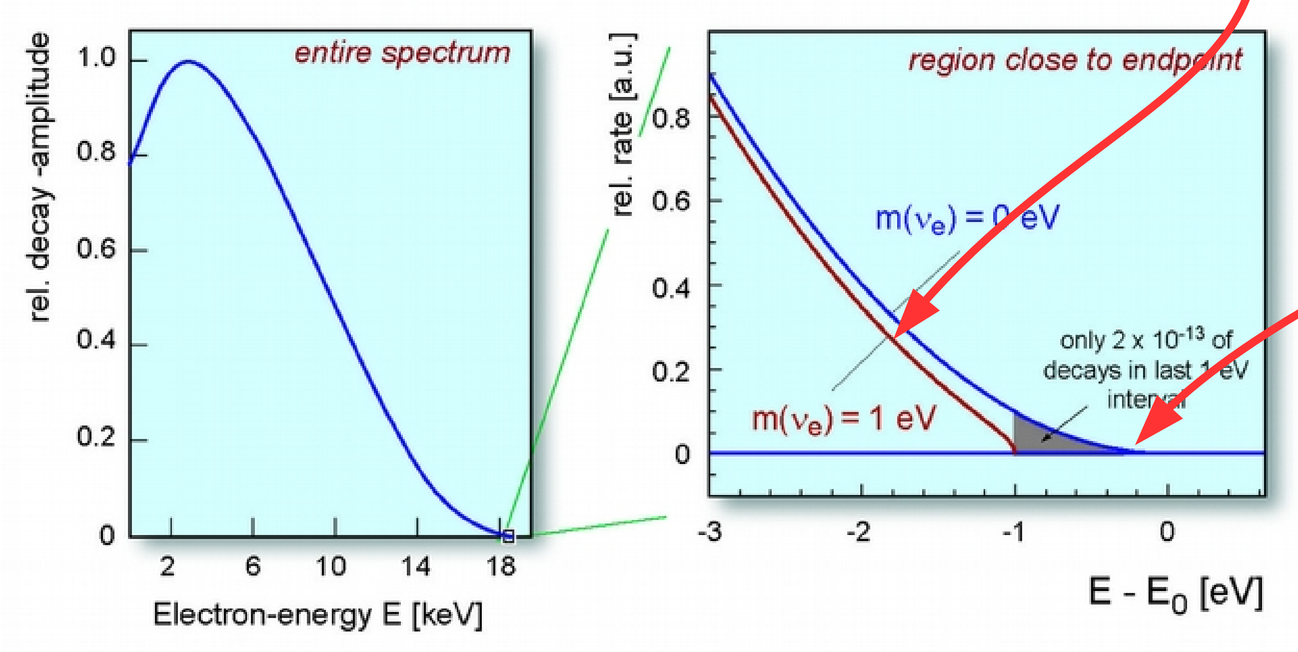


$$m_\beta = \left(\Sigma_i m_{\nu_i}^2 U_{ei}^2\right)^{1/2}$$

Andrei Puiu- Zuerich University

How to measure the neutrino

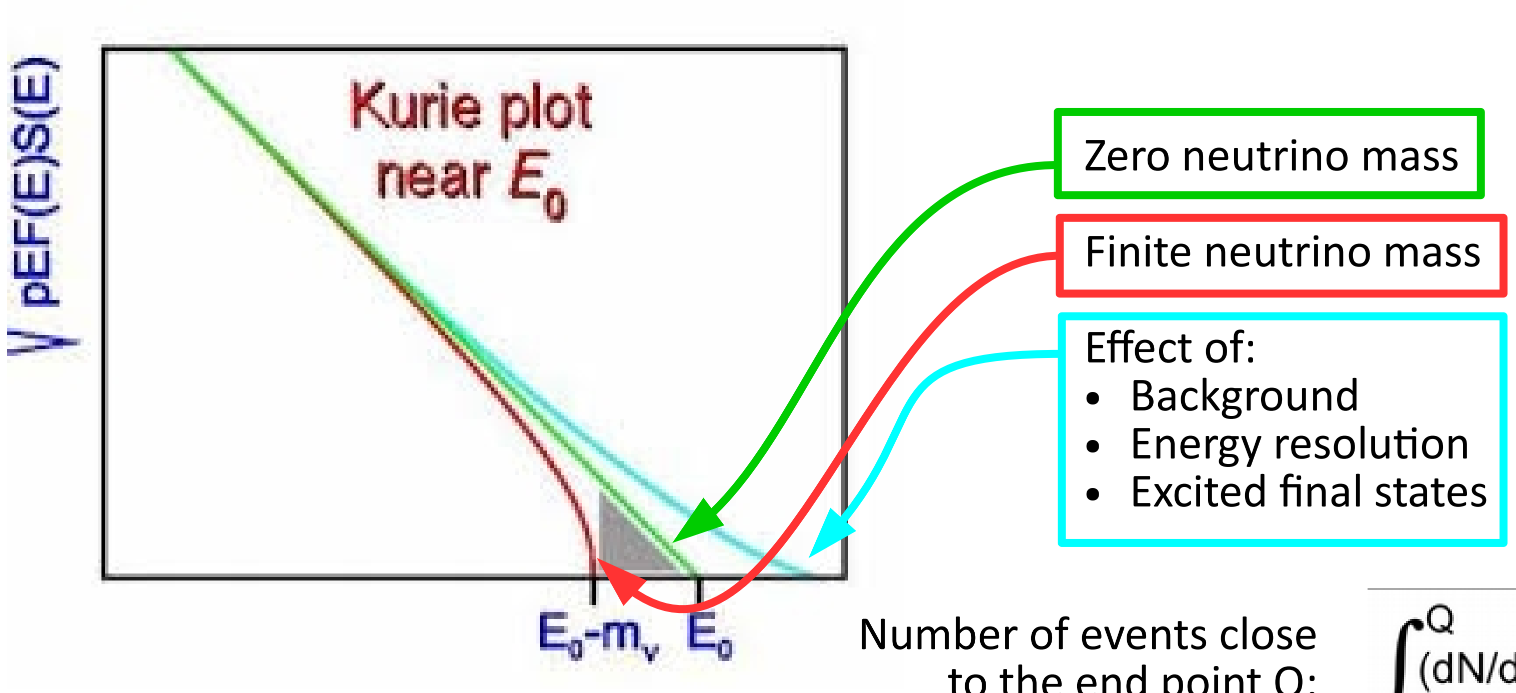
$$\frac{dN}{dE_e} = Cp(E+m_e)(E_0-E_e)\sqrt{(E_0-E_e)^2-\boxed{m_\nu^2}}\,F(E_e)\,\theta(E_0-E_e-\boxed{m_\nu})$$



Direct measurements search for the slight difference in shape right at the endpoint of the spectrum which may be indicative of a non-zero neutrino mass. They are difficult experiments to do, and can only be done under very special experimental circumstances.

Kurie plot

A common way to draw the beta decay spectrum is the Kurie plot: a convenient linearisation of the beta spectrum



Zero neutrino mass

Finite neutrino mass

Effect of:
- Background
- Energy resolution
- Excited final states

Number of events close to the end point Q:

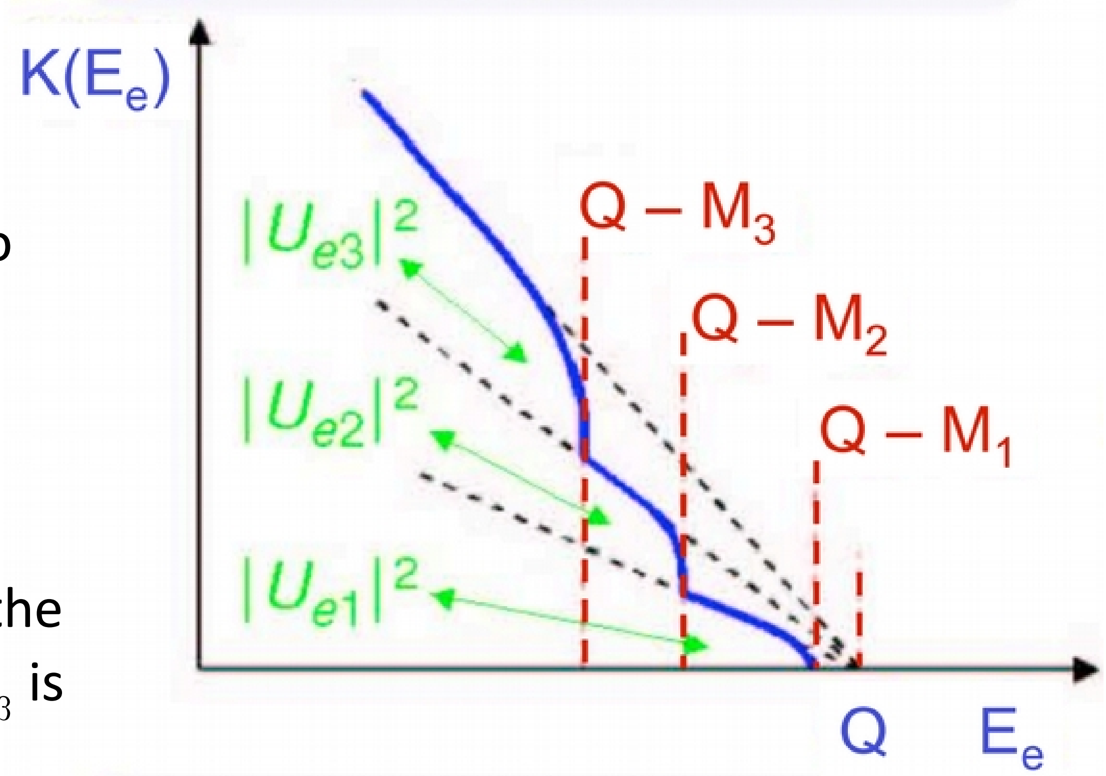
$$\int_{Q-\delta E}^{Q} (dN/dE)\, dE \cong 2(\delta E/Q)^3$$

Mass hierarchy effect

$$m_\beta = \left(\Sigma_i m_{\nu_i}^2 U_{ei}^2\right)^{1/2}$$

- the Kurie plot is an actual sum of three different sub-plots
- Each sub-Kurie plot corresponds to one of the three different mass eigenvalues
- The weight of each sub-Kurie plot will be given by $|U_{ei}|^2$

End point close-up



current experiments do not have the ability to resolve this feature → m_β is measured instead

Experimental approach

Two complementary approaches:

Spectrometers: source external to the detector

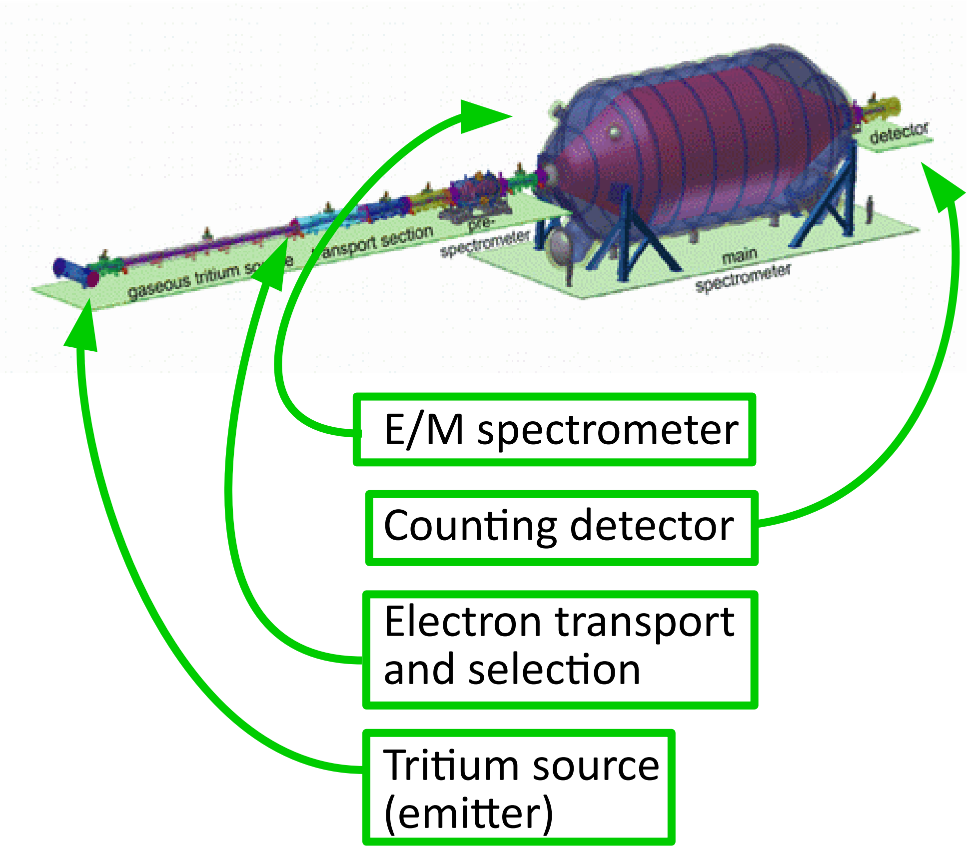
- Guide and select the electrons emitted from a beta source using high precision electric and magnetic fields
- measurement of the electron energy separated from the source
- present limit on m_β: ∼ 2 eV
- Katrin planned sensitivity: ∼ 0.2 eV

Calorimetry: source included in the detector

- measure all the visible energy of the decay with high resolution low energy electron detector
- → cryogenic microcalorimeters
- present limit on m_β: ∼ 10 eV
- Future sensitivity: 1 eV → easily scalable to 0.1 eV

Completely different systematic uncertainties

Quick overview

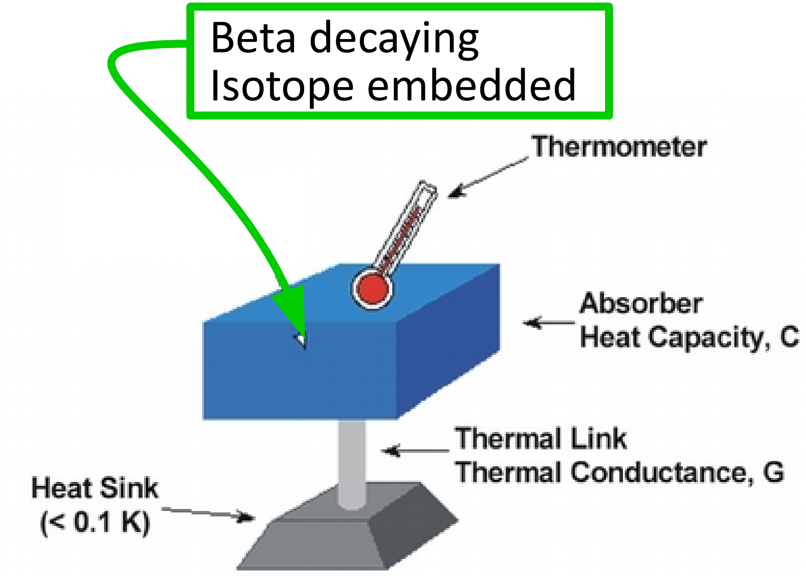


E/M spectrometer

Counting detector

Electron transport and selection

Tritium source (emitter)



Beta decaying Isotope embedded

Spectrometers and calorimeters

Spectrometers

PROs:

- High statistics
- Very good energy resolution

CONs:

- systematics due to source effects
- systematics due to decay to excitated states
- background

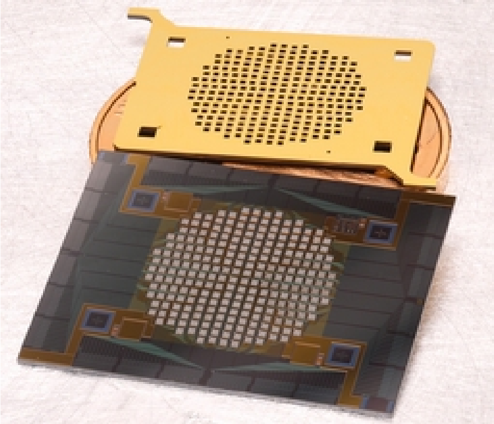
Calorimeters:

PROs:

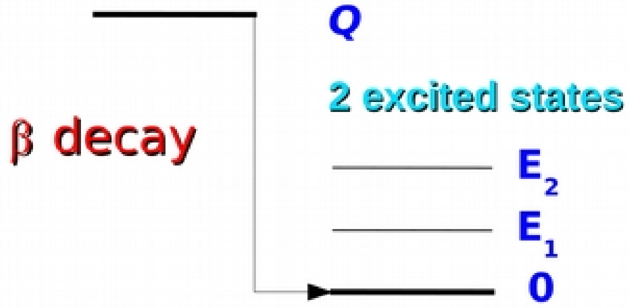
- no backscattering
- no energy losses in the source
- no solid state excitation
- no atomic/molecular final state effects

CONs:

- limiteted statistics
- systematics due to pile-up
- background

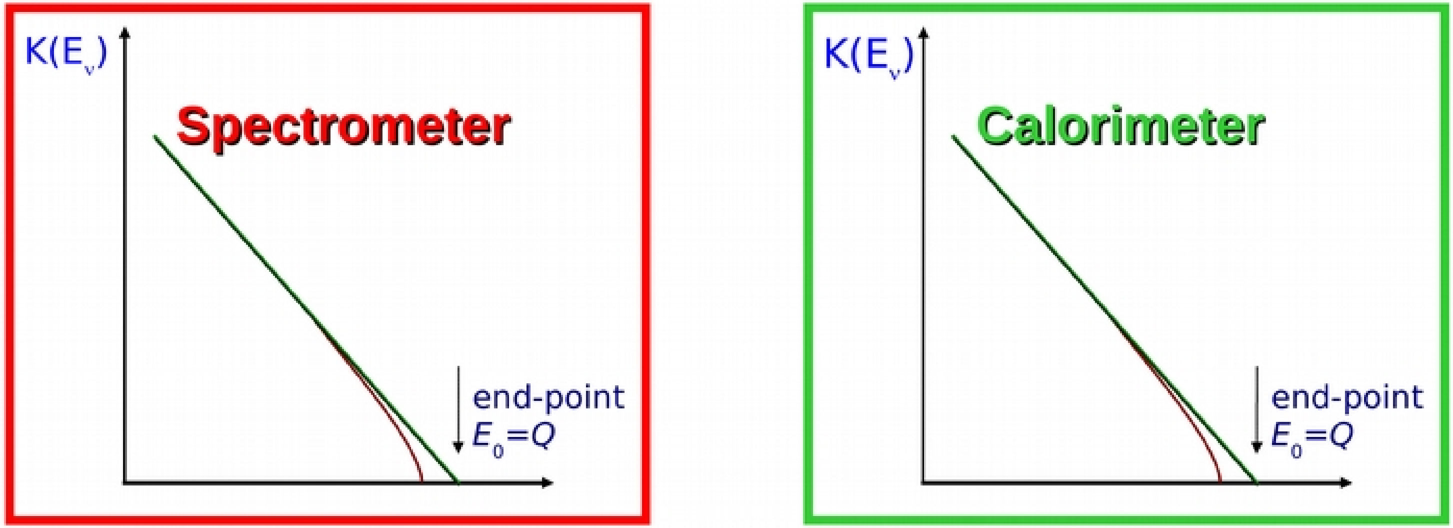


Spectrometry of beta sources -1-

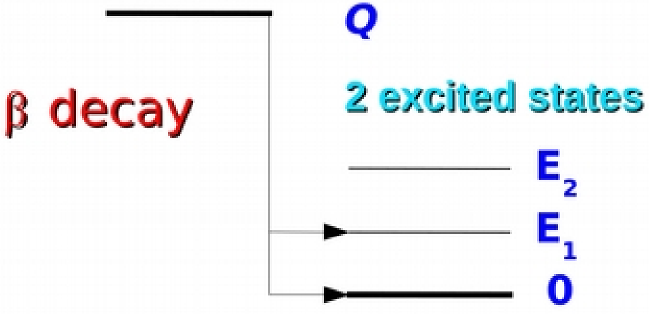


no excited state and $m_\nu = 0$

no excited state and $m_\nu > 0$

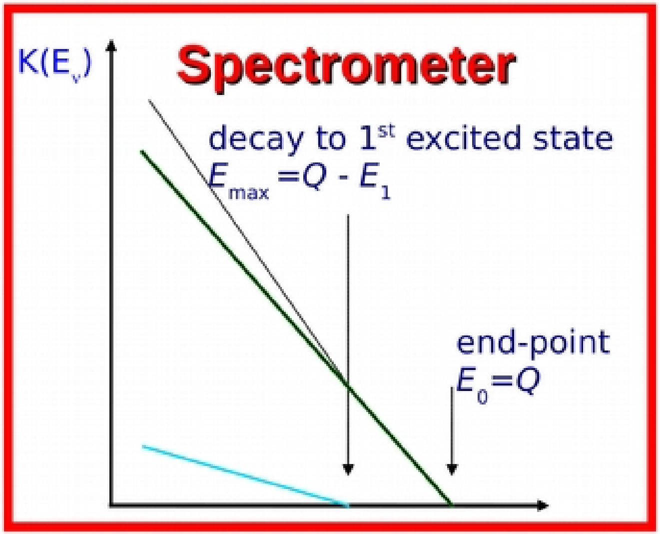


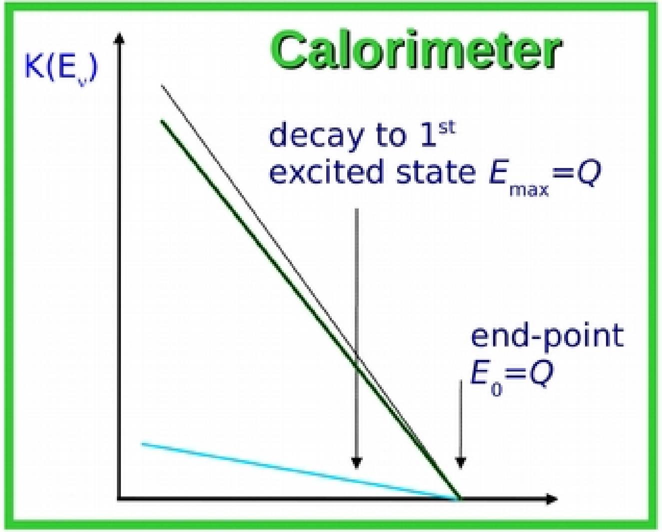
Spectrometry of beta sources -2-



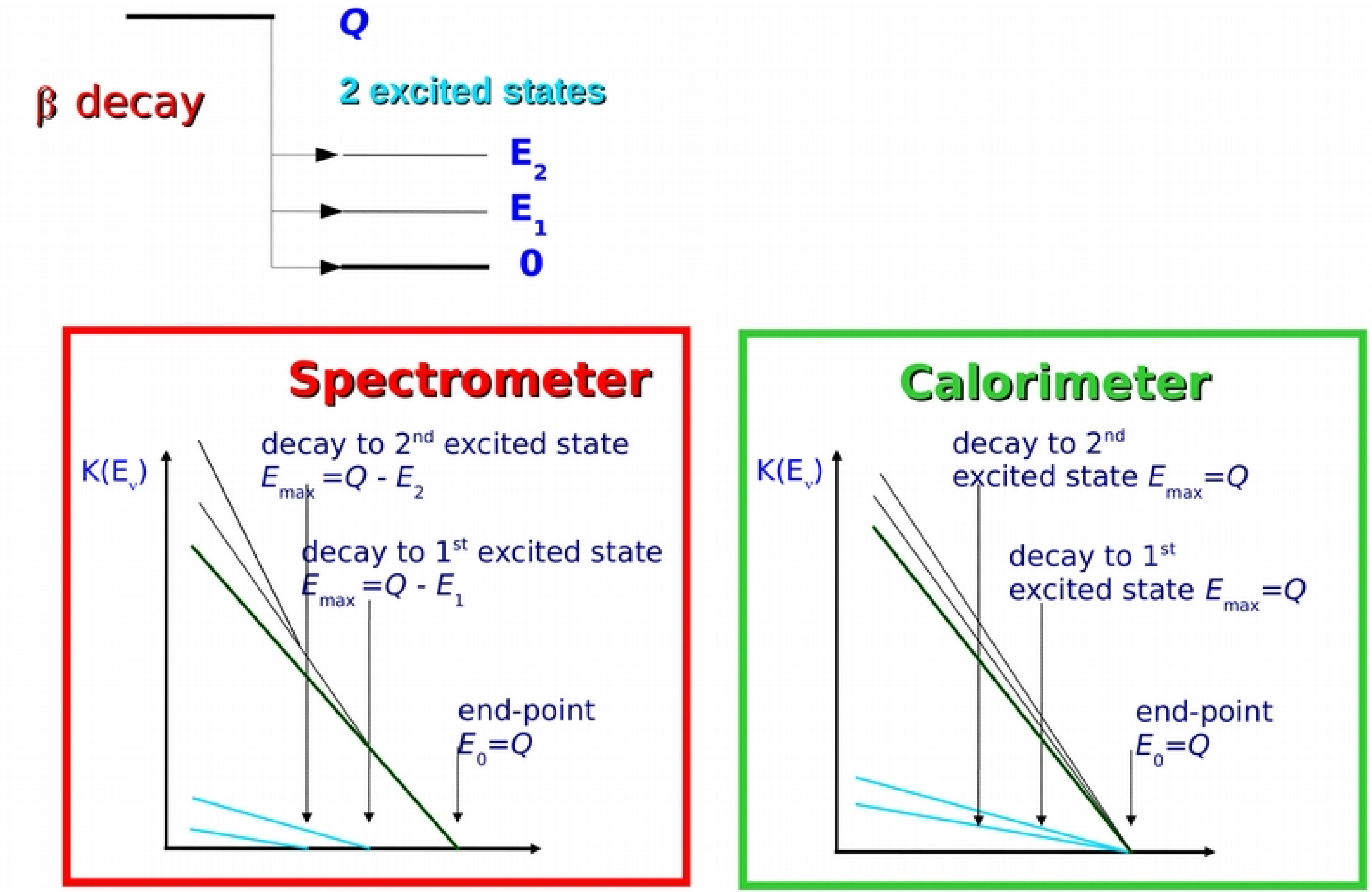
excitation energy is lost

de-excitation faster than
detector response time t_d~1 μs
⇩
excitation energy is
measured together with β energy

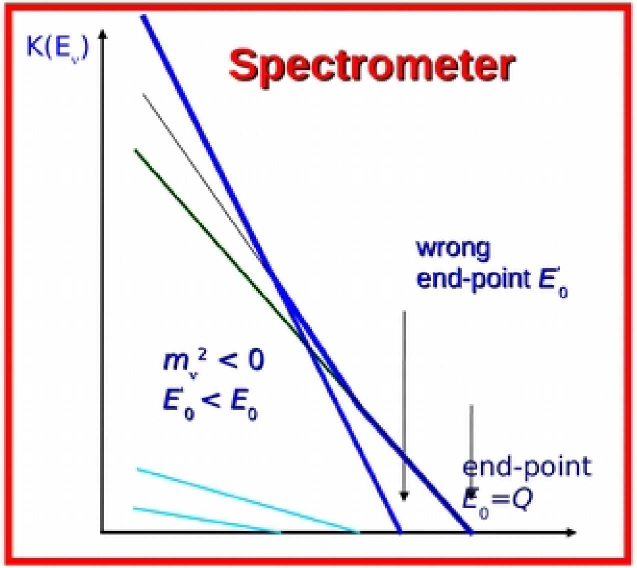


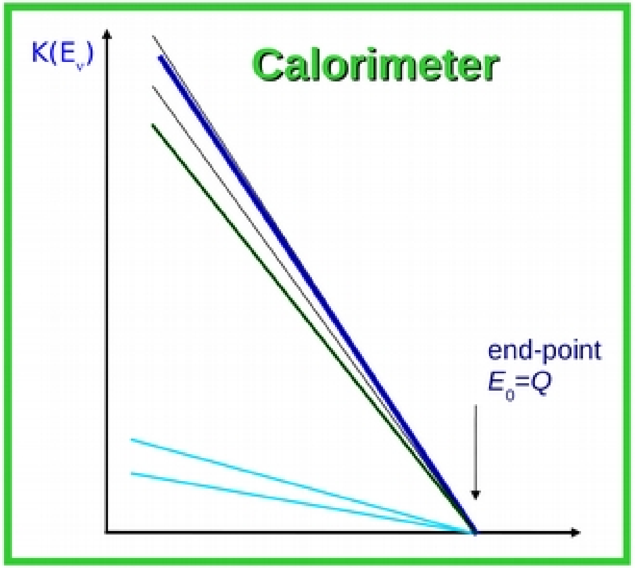


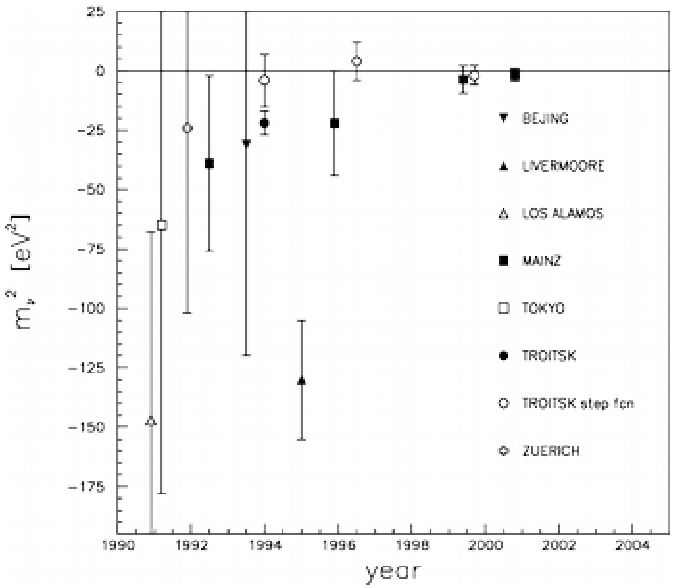
Spectrometry of beta sources -3-



Spectrometry of beta sources -4-







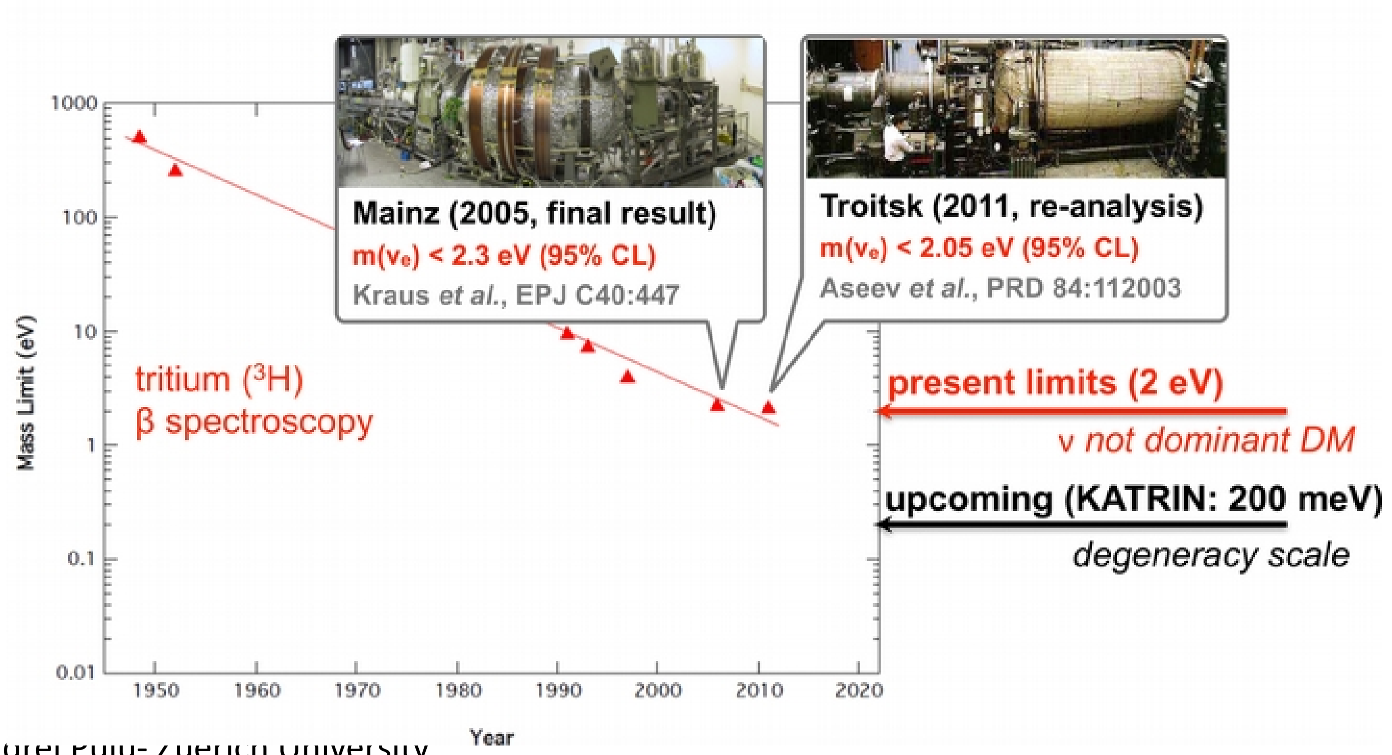
Wrong end point evaluation introduces systematics which, if not perfectly understood, can lead to a wrong estimation of the neutrino mass; such as $m_\nu^2<0$

Current spectrometer status

electrostatic integrating spectrometers (MAC-E filter)

- Mainz with solid ^{3}H source
- Troitsk with gaseous ^{3}H source

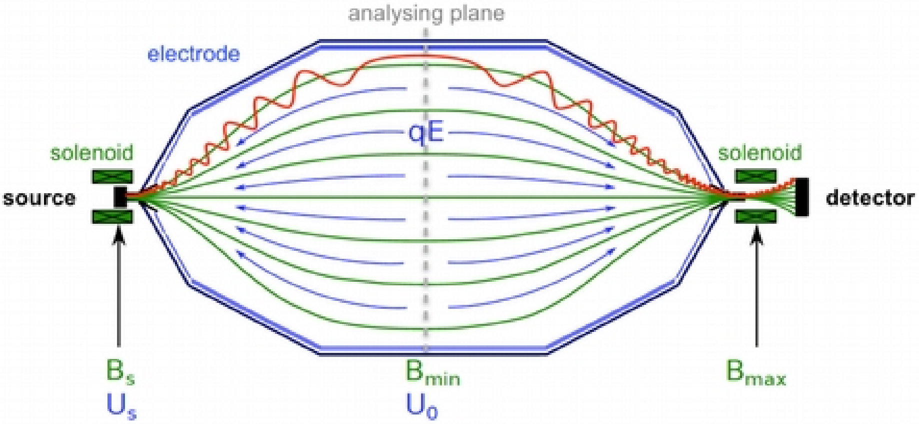
$m_\nu < 2.2$ eV 95% CL



KATRIN will push the limit down by an order of magnitude

MAC-E spectrometer for the neutrino mass

- Measure integral spectrum with moving threshold ($E_{kin} > eU_0$)
- **M**agnetic **A**diabatic **C**ollimation + **E**lectrostatic filter



[Beamson et al. 1980; Kruit & Read 1983; Lobashev 1985; Picard et al. 1992]

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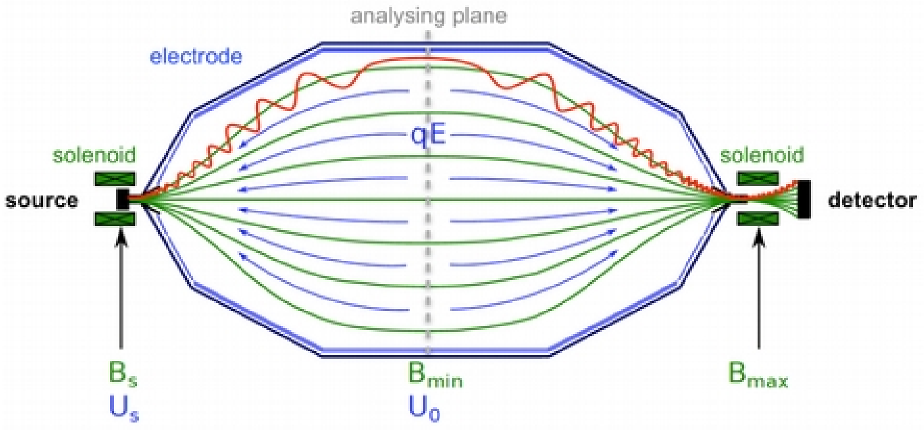
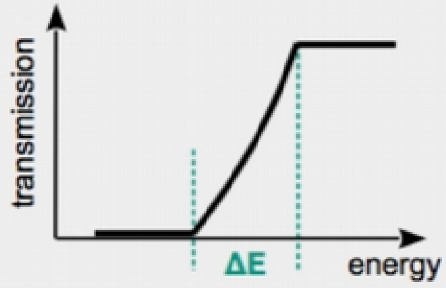


Sharp high-pass filter:



Steps of filter potential
→ integrated β spectrum

MAC-E spectrometer for the neutrino mass

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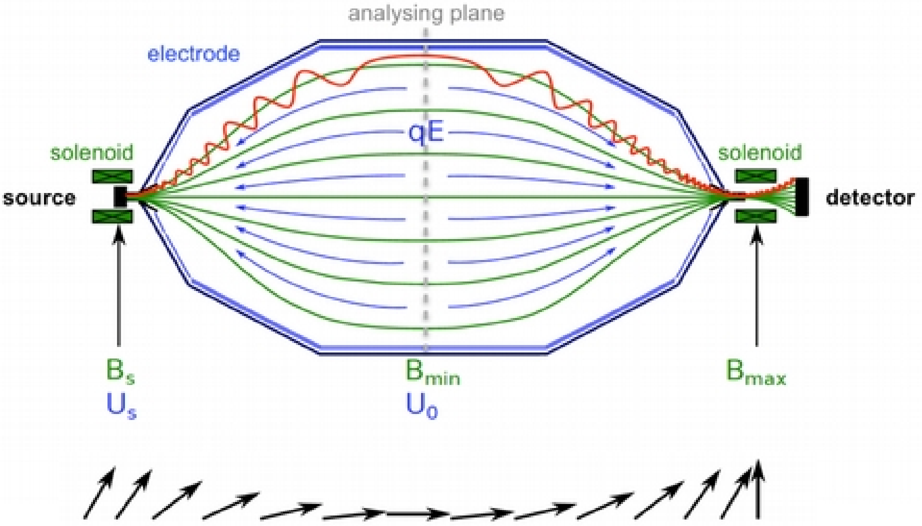
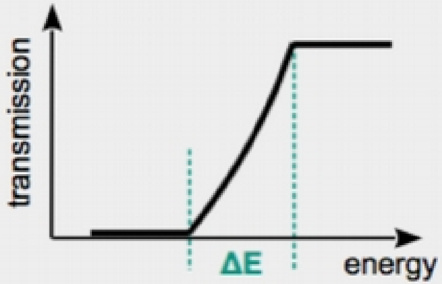


momentum transformation without E-field

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

Sharp high-pass filter:



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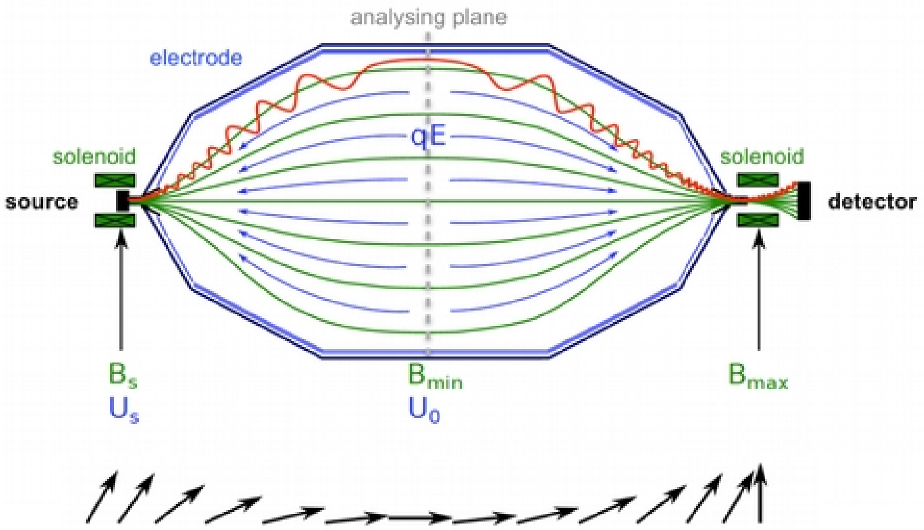

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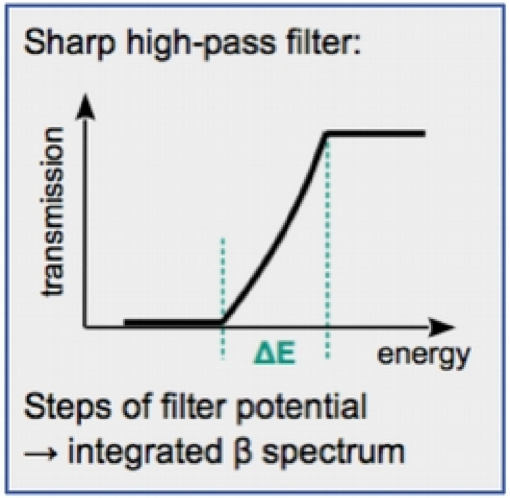

Sharp high-pass filter:

Steps of filter potential
→ integrated β spectrum

Energy Resolution $$\frac{\Delta E}{E} = \frac{B_{\mathrm{min}}}{B_{\mathrm{max}}}$$

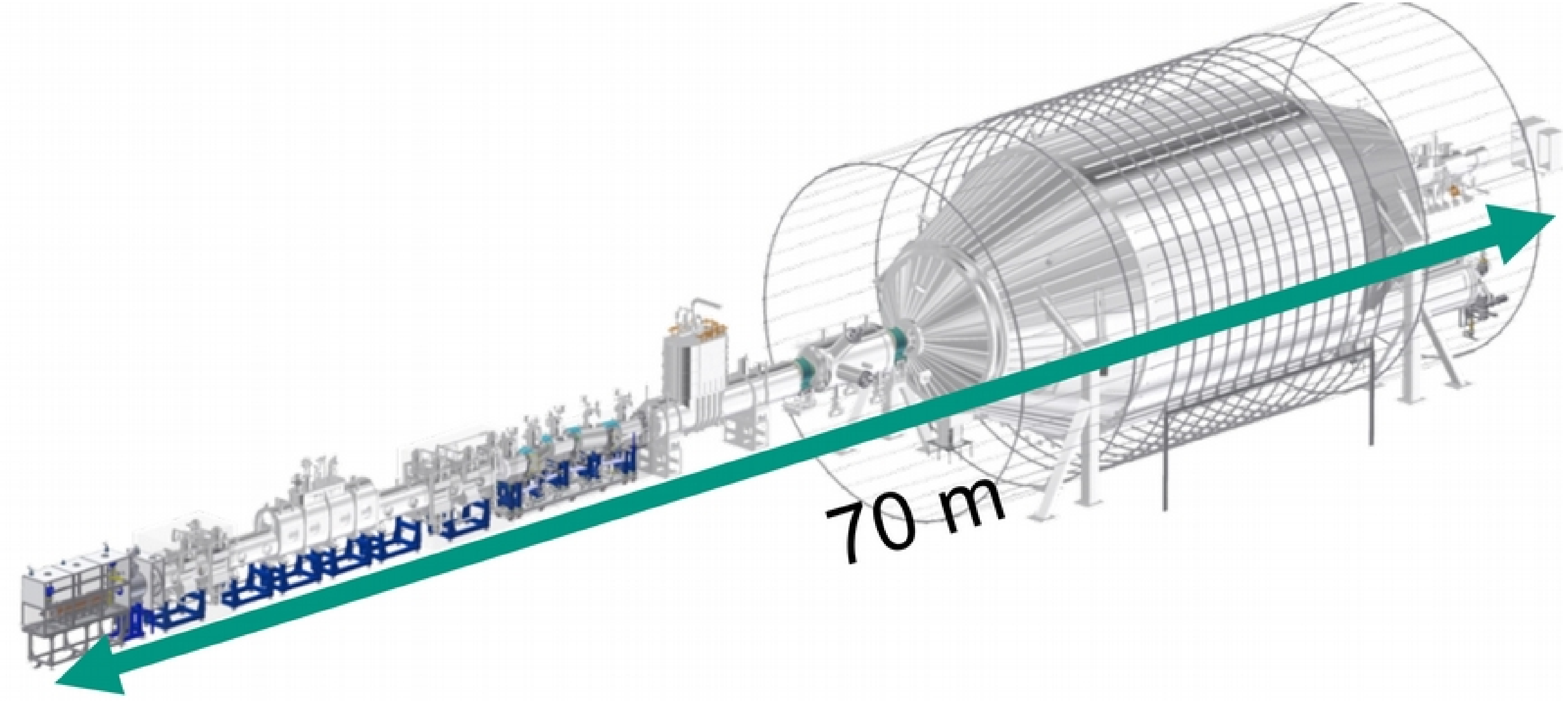
$B_{\mathrm{min}} = 0.3$ mT, $B_{\mathrm{max}} = 6$ T

$\Delta E < 1$ eV at 18.6 keV

[Kleesiek et al., arXiv:1806.00369]

KATRIN Spectrometer

KATRIN → 0.2 eV goal



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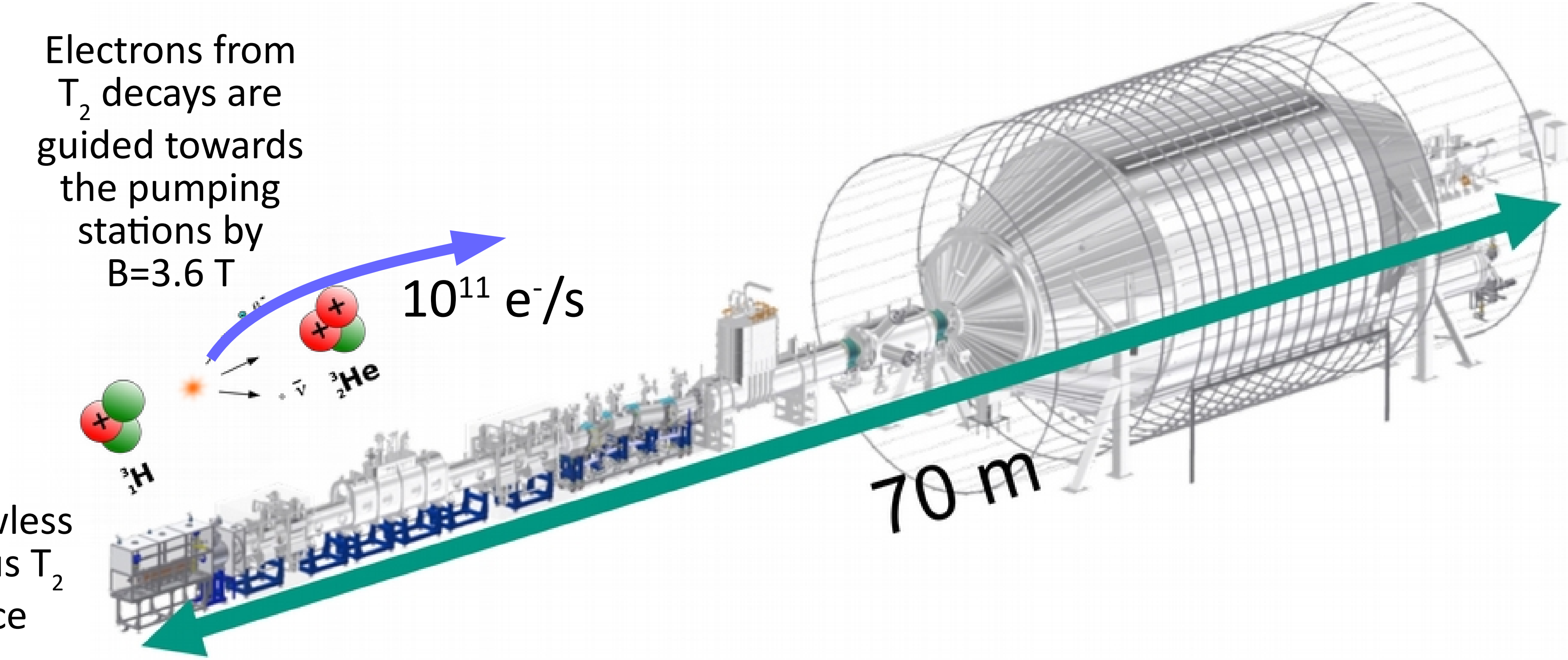


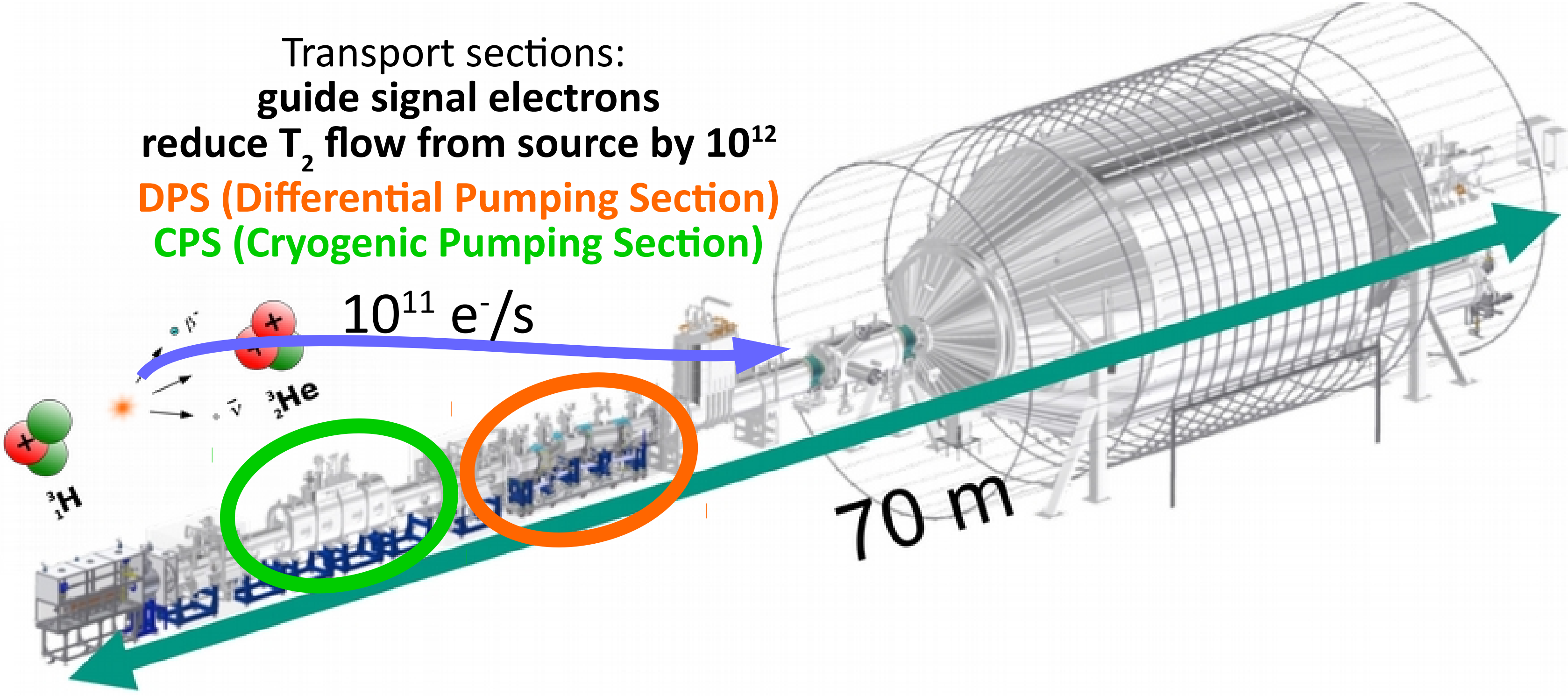
Electrons from T_2 decays are guided towards the pumping stations by B=3.6 T

10^{11} e^-/s

Windowless Gaseous T_2 Source

KATRIN Spectrometer

KATRIN → 0.2 eV goal



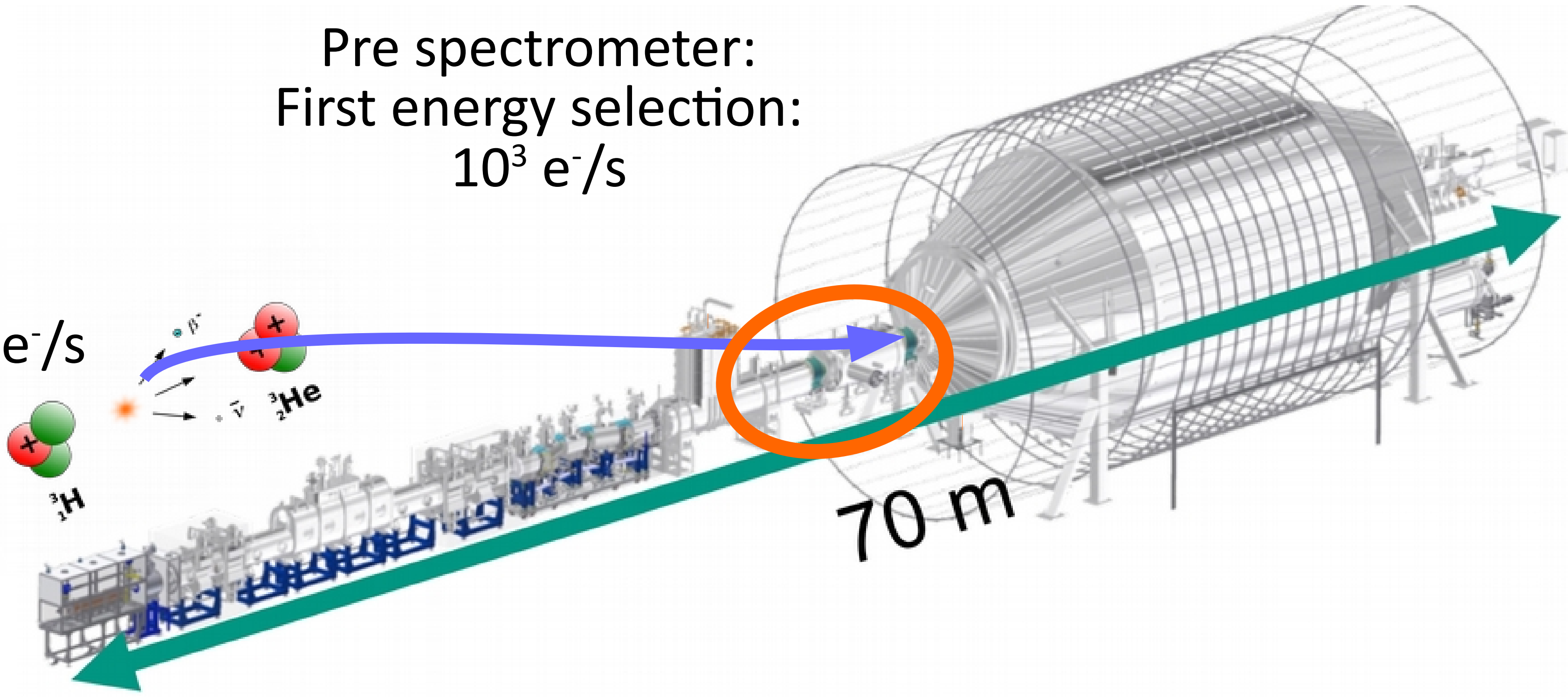
Transport sections:
guide signal electrons
reduce T_2 flow from source by 10^{12}
DPS (Differential Pumping Section)
CPS (Cryogenic Pumping Section)

10^{11} e^-/s

Windowless
Gaseous T_2
Source

KATRIN Spectrometer

KATRIN → 0.2 eV goal



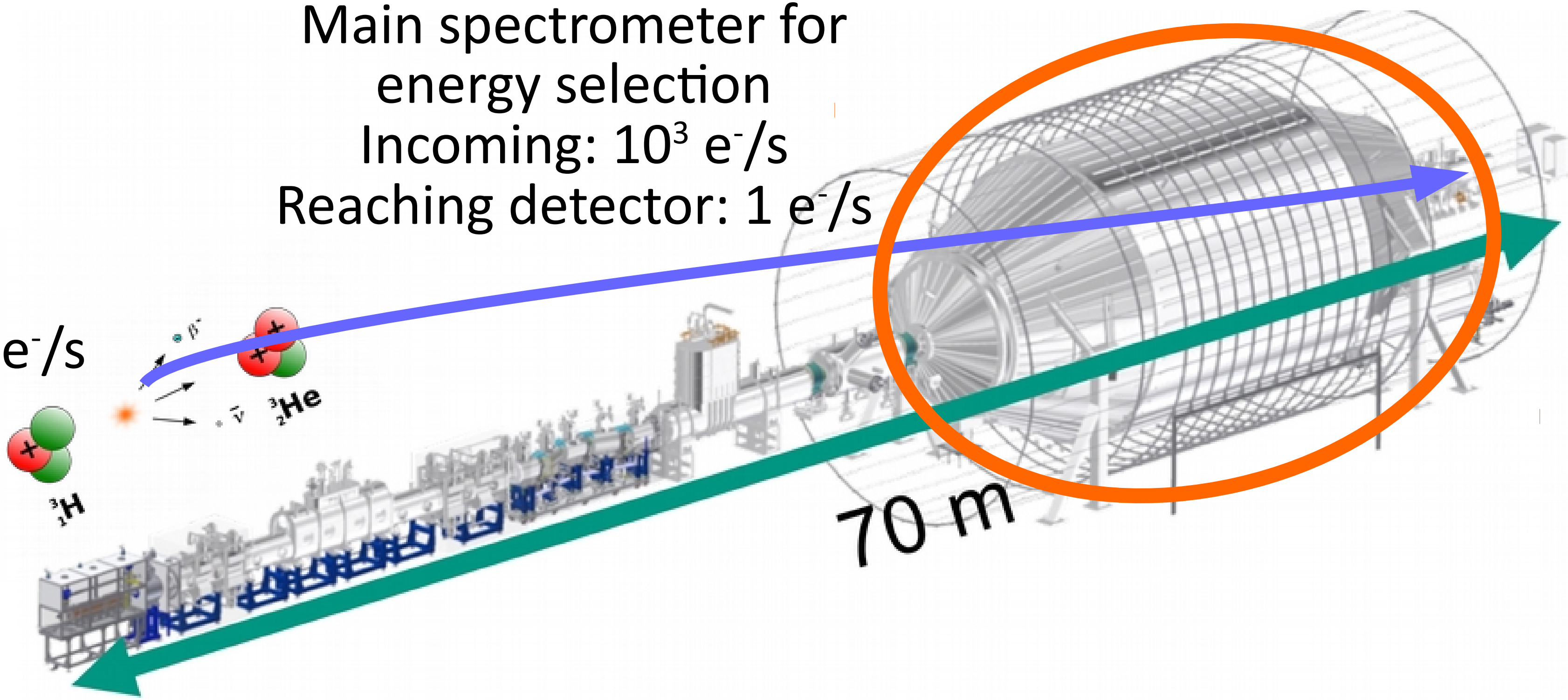
Pre spectrometer:
First energy selection:
10^3 e^-/s

10^{11} e^-/s

Windowless
Gaseous T_2
Source

KATRIN Spectrometer

KATRIN → 0.2 eV goal



Main spectrometer for energy selection
Incoming: 10^3 e^-/s
Reaching detector: 1 e^-/s

10^{11} e^-/s

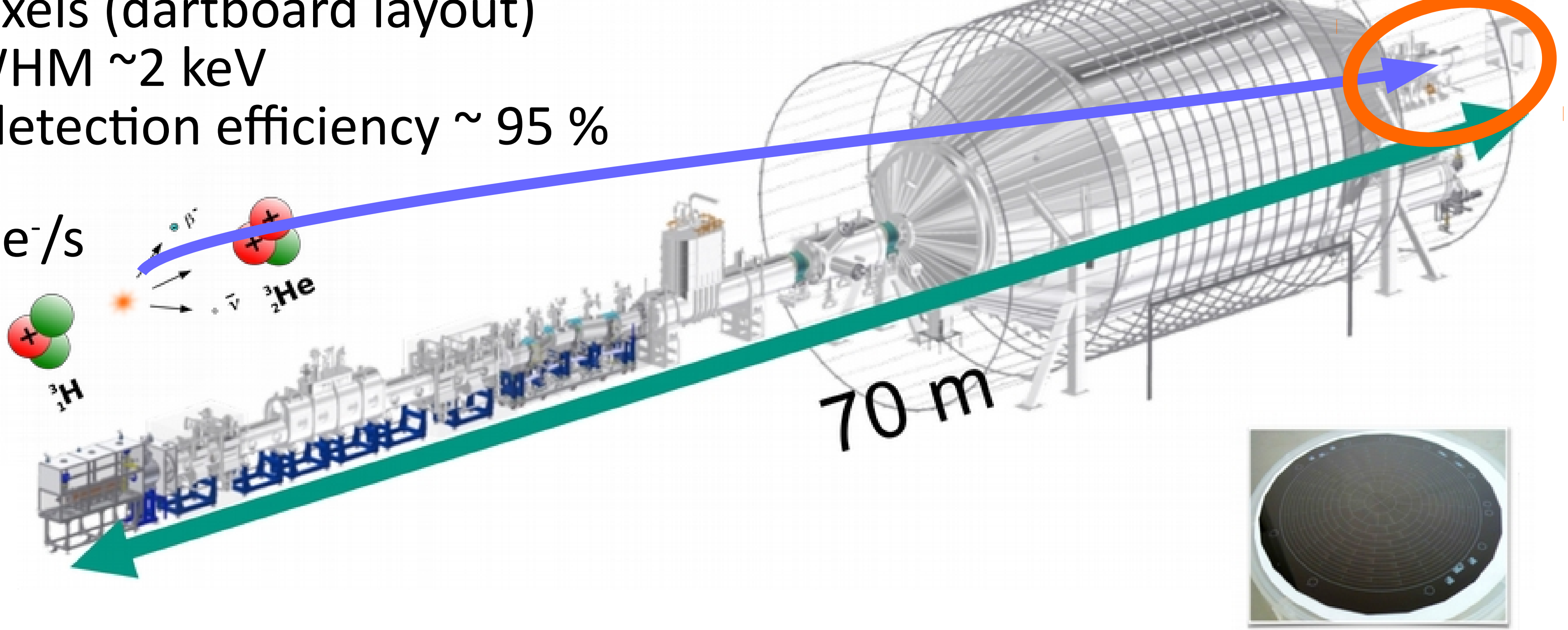
Windowless
Gaseous T_2
Source

KATRIN Spectrometer

KATRIN → 0.2 eV goal

Final e- couting facility:

- 90 mm diameter Si-PIN diode
- 148 pixels (dartboard layout)
- ΔE FWHM ~2 keV
- High detection efficiency ~ 95 %

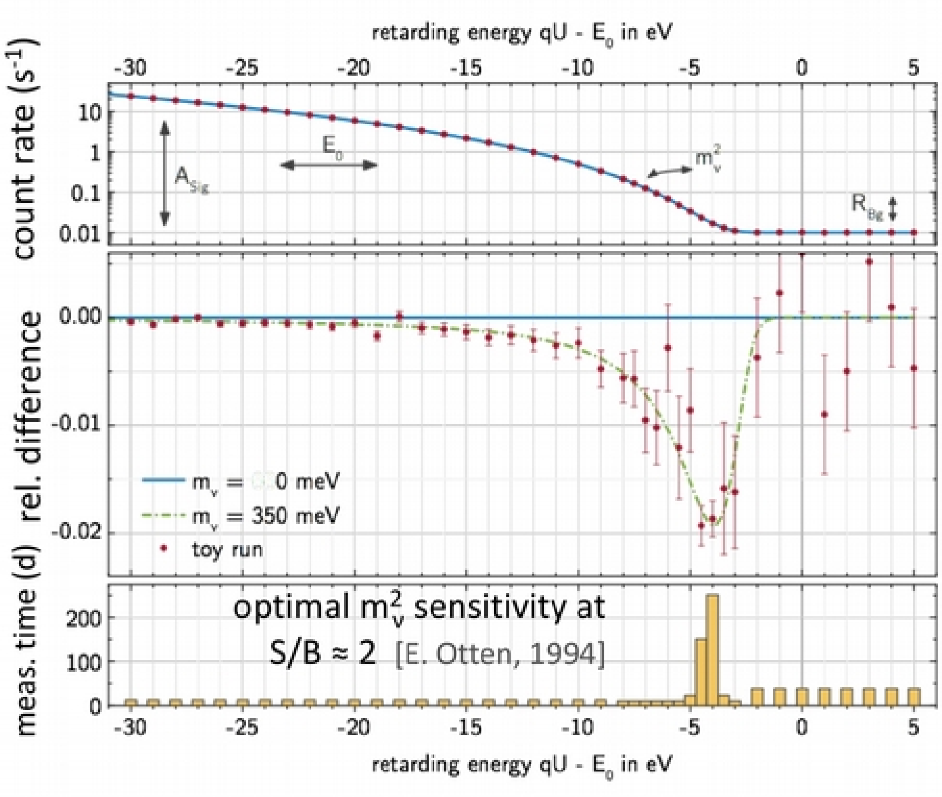


1 e^-/s

10^{11} e^-/s

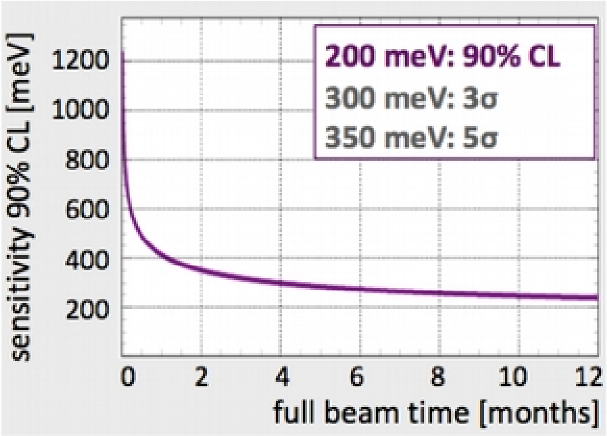
Windowless
Gaseous T_2
Source

KATRIN beta spectrum and sensitivity



- Fit of the integral spectrum
- 4 fit parameters:

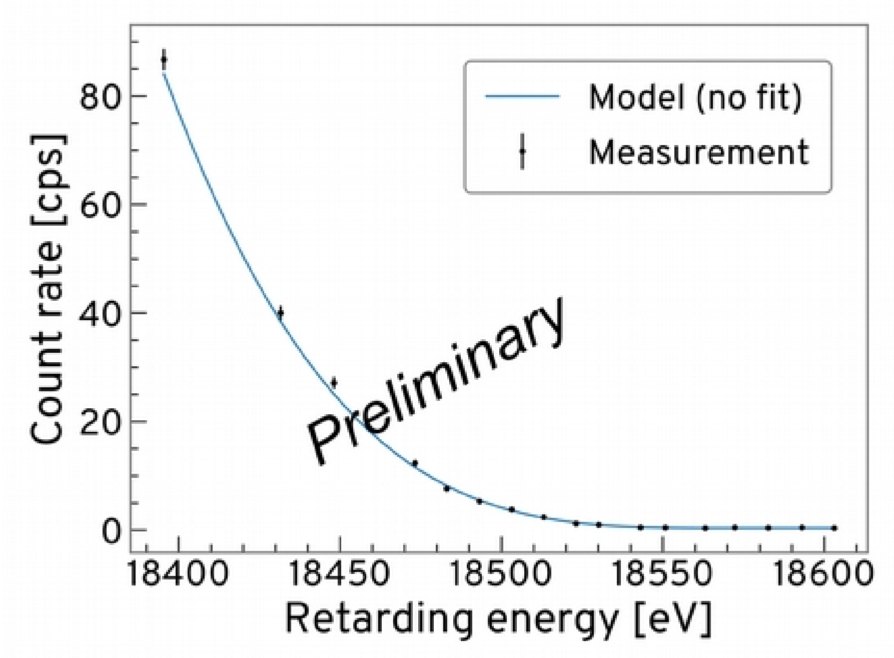
m_ν^2 , E_0 , A_{Sig} , R_{Bg}



3 yrs (5 calendar yrs) to balance statistics and systematics

β -decay spectrum:
Kleesiek et al., arXiv:1806.00369

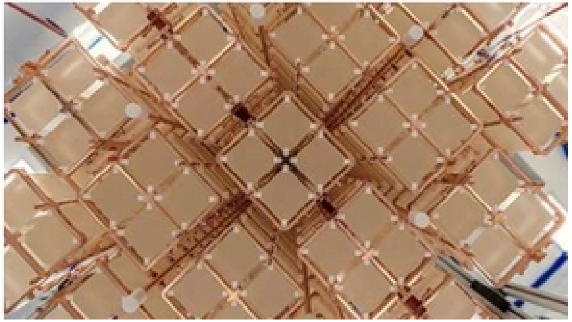
First spectrum

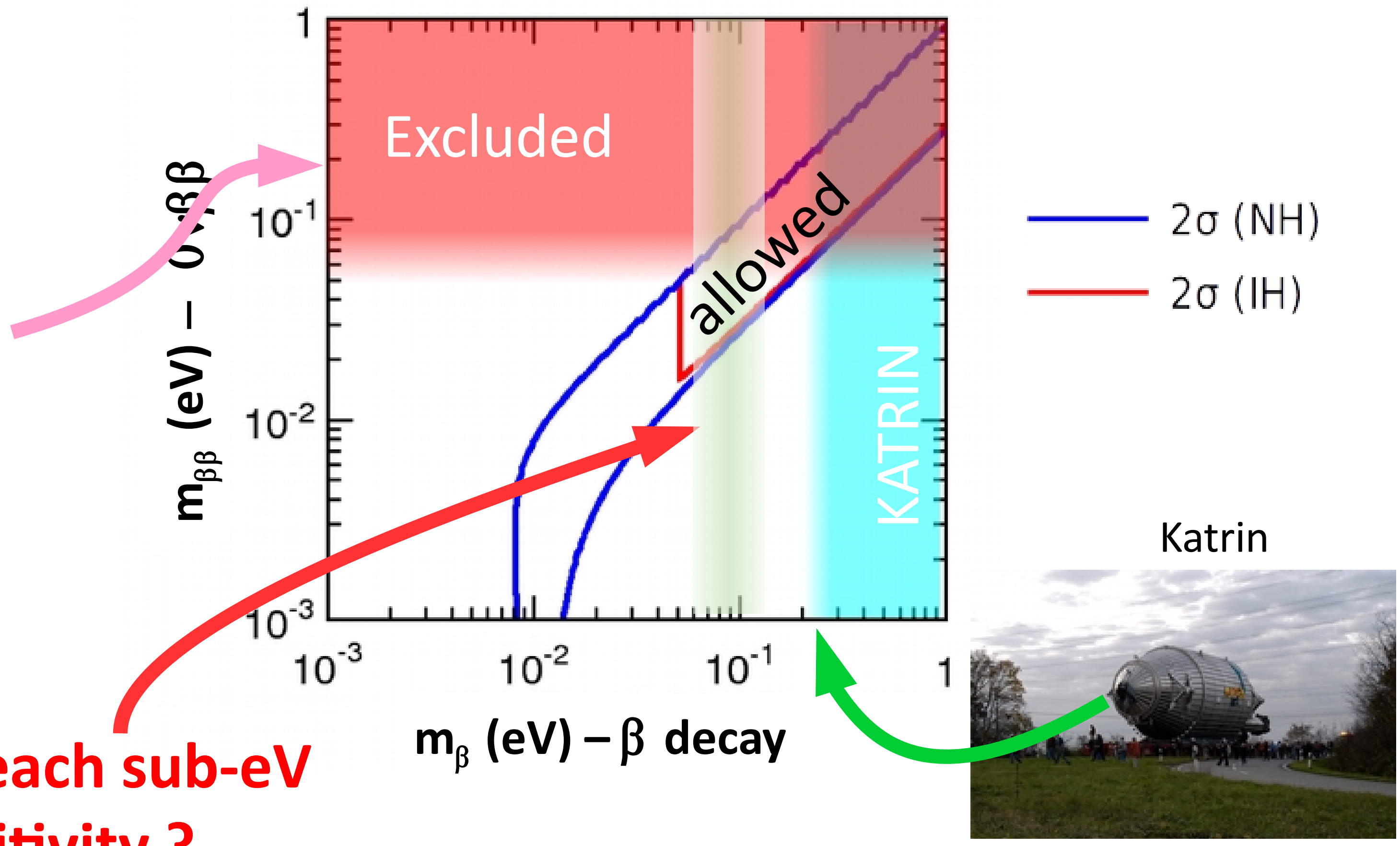


First end point scan in KATRIN
Great success !

Presented at NDM 2018 Daejeon | 29. June – 4. July 2018
Slides by Wonqook Choi | KIT-ETP

Limits are to be pushed





How to reach sub-eV sensitivity ?

Calorimetry

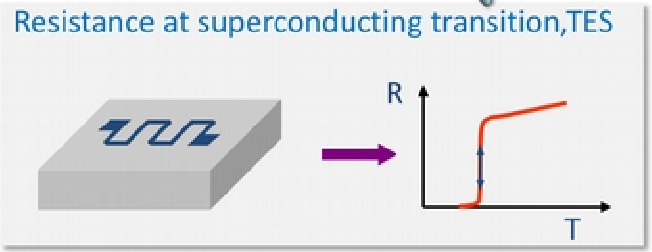
- Calorimetric detectors are a promising approach for confirmation of spectrometric measurements and for improving sensitivity in the near future
- Tritium is difficult to embed inside an absorber
- New isotope is needed. ^{187}Re at first
- Electron capture decaying ^{163}Ho is the latest candidate

HOLMES

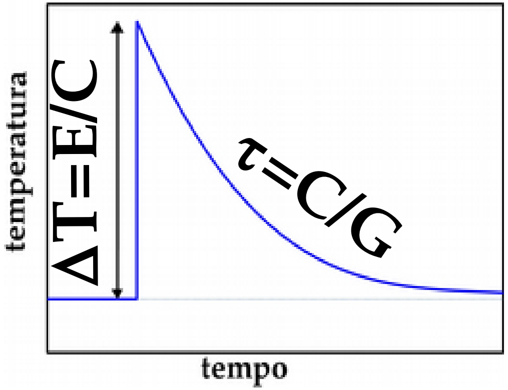
ECHo

Low temperature calorimeters

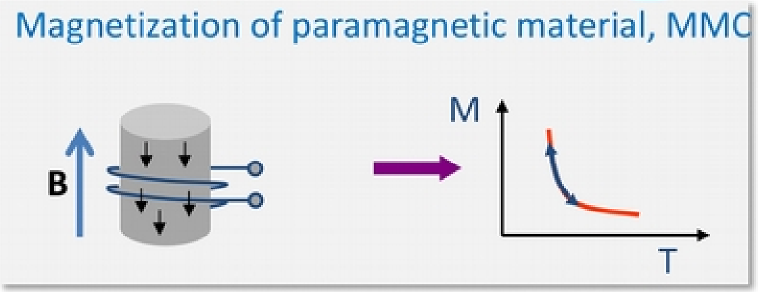
HOLMES


Resistance at superconducting transition,TES

K.D. Irwin and G.C. Hilton, Topics in Applied Physics 99 (2005) 63



ECHo


Magnetization of paramagnetic material, MMC

A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63

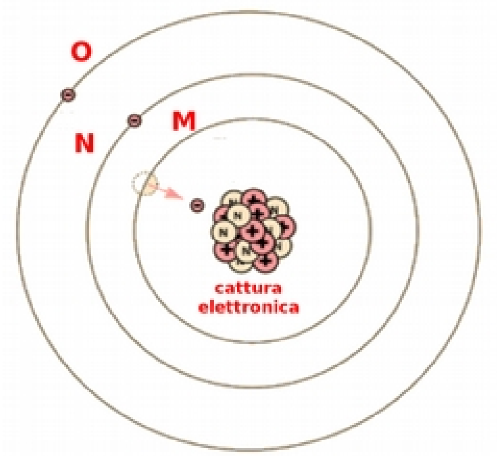
- The isotope of choice (^{163}Ho) is embedded in a gold absorber
- For each decay energy is released inside the absorber: the temperature increase is proportional to E/C → very low heat capacity for high signals → low temperature detectors
- All the released energy contributes to the formation of the signal, including eventual excited final states → no end point deformation

Calorimetric measurement with ^{163}Ho

$^{163}\mathrm{Ho} + e^- \longrightarrow {}^{163}\mathrm{Dy}^* + \nu_e$

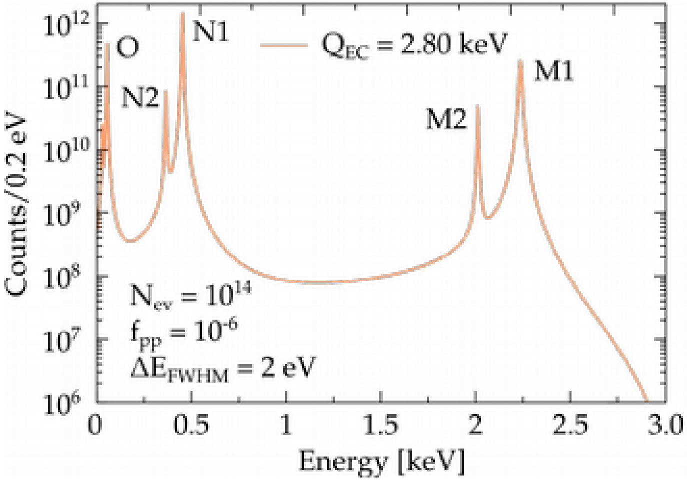
^{163}Ho decays via (EC) from shell ≥ M1, with $Q_{EC} \sim 2.8$keV

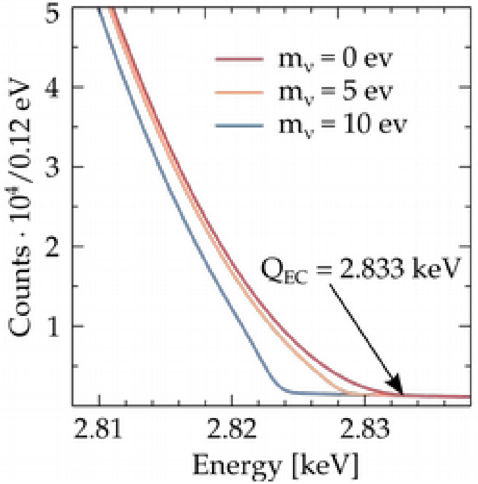
Proposed by A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429



$$\frac{d\lambda_{\mathrm{EC}}}{dE_c} = \frac{G_\beta^2}{4\pi^2} \boxed{(Q-E_c)\sqrt{(Q-E_c)^2 - m_\nu^2}} \times \Sigma_i n_i C_i \beta_i^2 \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4}$$

- calorimetric measurement of e- from Dy de-excitation
- end point close to M1 resonance enhances rate at the end point where m_ν is measured
- $\tau_{1/2} \sim 4570$ y: $2\mathrm{x}10^{11}$ nuclei ^{163}Ho = 1 Bq





Sentivity on neutrino mass and pile-up

Since all the events occurring within one detector are recorded without previous selection, pile-up becomes a crucial limiting factor

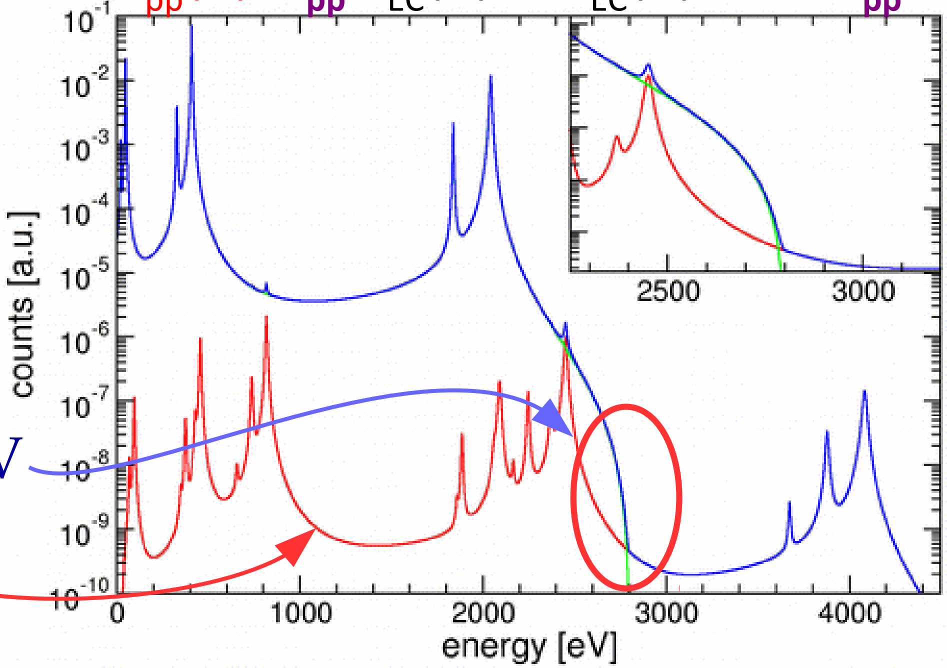
- events occurring closer in time than the timing resolution of the dector (τ_R)
- sets the limit on the maximum activity (A_{EC}) of each detector

$N_{pp}(E)=f_{pp}N_{EC}(E)\otimes N_{EC}(E)$ with $f_{pp}\approx A_{EC}\tau_R$

Super fast detectors with ~10 μs rise time pulses

Maximum activity ~ 300 Bq/riv

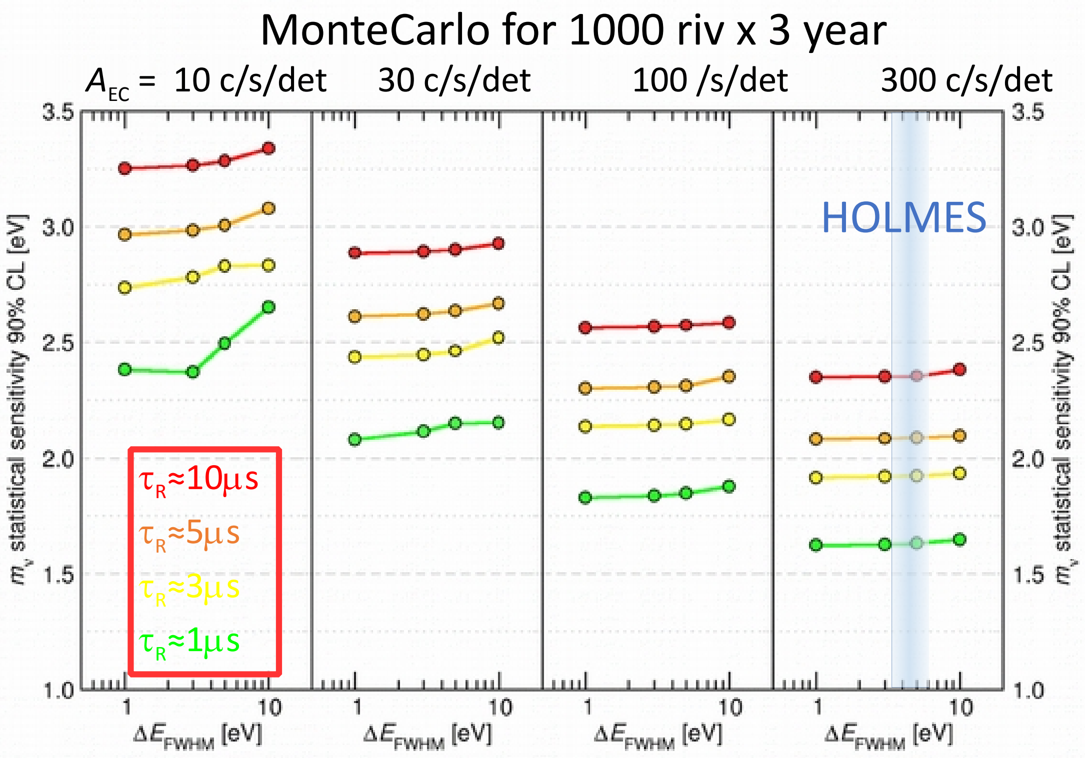
→ Very large arrays ~1000



$Q = 2800$ eV

$f_{pp} = 10^{-4}$

Number of events



(ERC-Adv. Grant 340321) PI:S.Ragazzi

HOLMES will:

- Measure m_ν with ~ 1 eV sensitivity
- Prove that calorimeters are a valid technique
- High precision *Q-vlaue* measurement of ^{163}Ho
- Systematic errors assesment

Short and medium terms

- 64 detectors array, t_M = 1 month (m_ν < 10 eV)
- Final measurement: 1000 detectors, 3×10^{13} events in 3 y
- 6.5×10^{16} ^{163}Ho nuclei needed (≈18 μg)

Five year plan started in 2014

Where to get ^{136}Ho

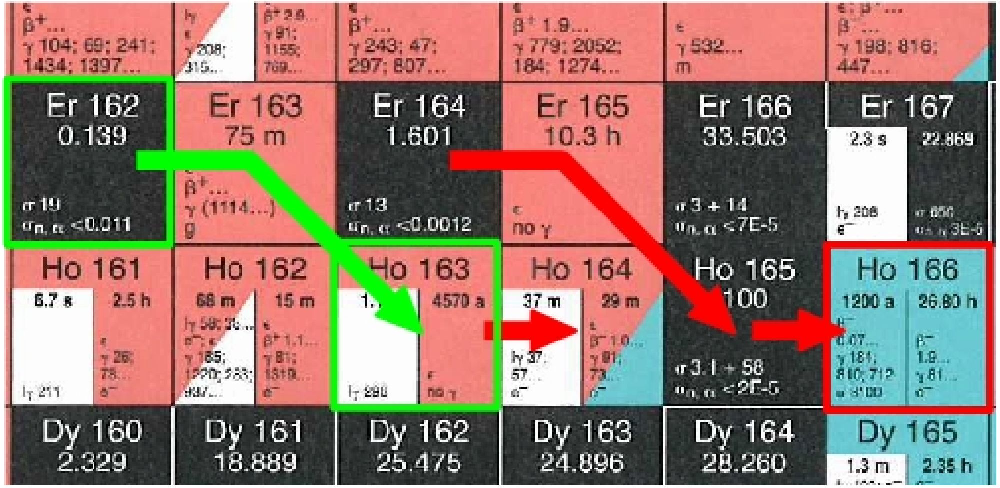
^{162}Er(n,γ)^{163}Er $\sigma_{thermal} \approx 20$b

^{163}Er ^{163}Ho + ν_e $\tau_{½}^{EC} \approx 75$min

- ILL at Grenoble: high neutron flux **n 1.3x10^{15} n/cm^2/s**
- Brun up cross section ^{163}Ho(n,γ)^{164}Ho non negligible (~ 200 b)
- ^{165}Ho(n,γ) (da ^{164}Er(n,γ)) → **^{166m}Ho, β^-, $\tau_{½}$ = 1200 y, Q = 1856 keV**
- A(^{163}Ho)/A(^{166m}Ho) = 100 ~ 1000
- Pre and post irradiation purification at PSI (Villigen, CH)

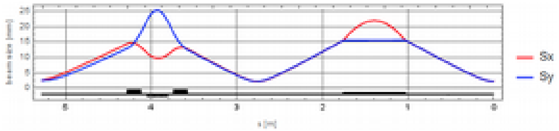
HOLMES needs ~ 200 MBq of ^{163}Ho

ECHO needs ~ 10 Mbq of ^{163}Ho

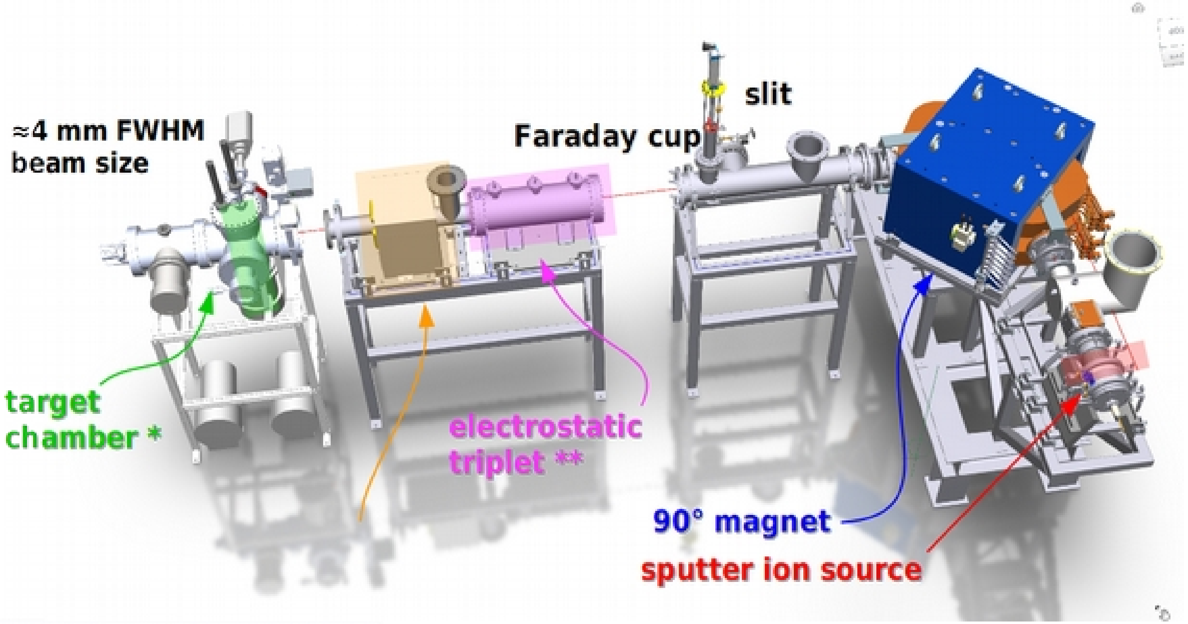


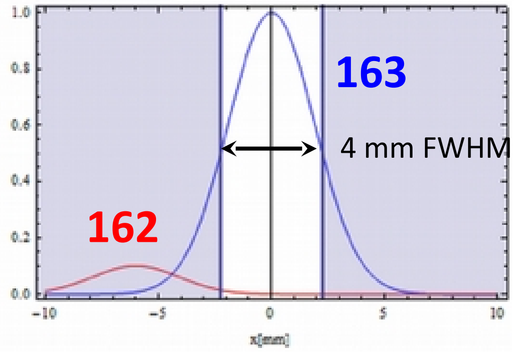
Getting ^{163}Ho inside the detectors

Ho beam width simulation



HOLMES

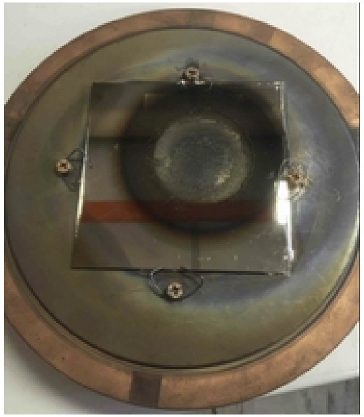




- Extraction tensions 30-50 kV
- Implantation depth in Au 10-100 nm
- **^{163}Ho/^{166m}Ho separation > 10^5**

Ho source (to be placed inside the implanter)

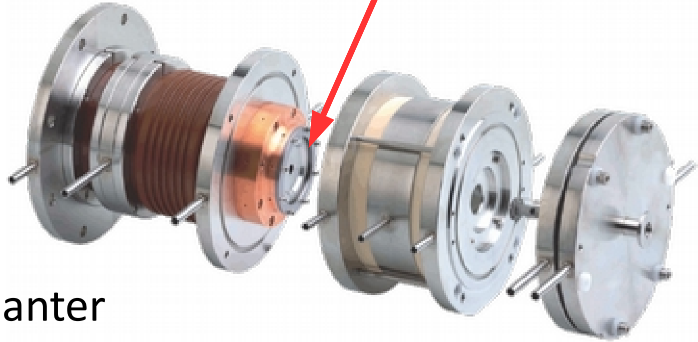
Thermoreduction/distillation inside special furnace:
$Ho_2O_3 + 2Y(\mathit{met}) \rightarrow 2Ho(\mathit{met}) + Y_2O_3$ at T > 1600 °Cc



Evaporated Ho → source production

Ho source production:

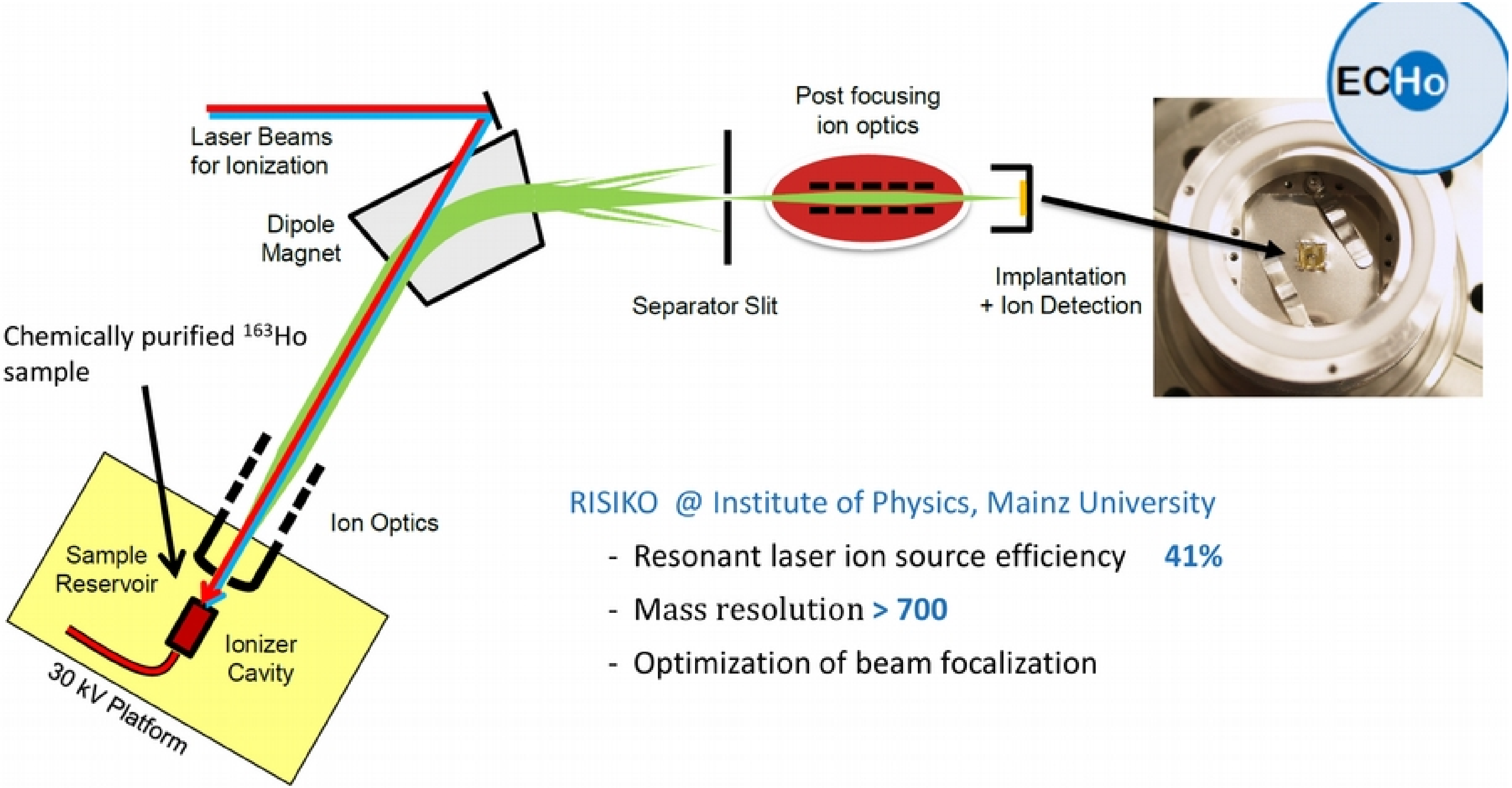
- Metallic Ho metallico mixed with Ti e Sn
- Extraction efficiency studies are in progress
- First extraction test



Source inside the implanter

HOLMES

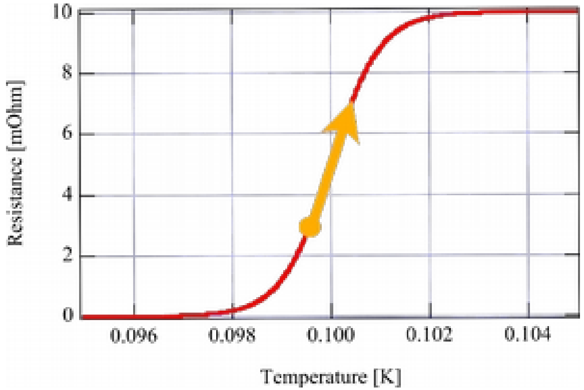
ECHo implanter system



RISIKO @ Institute of Physics, Mainz University

- Resonant laser ion source efficiency **41%**
- Mass resolution **> 700**
- Optimization of beam focalization

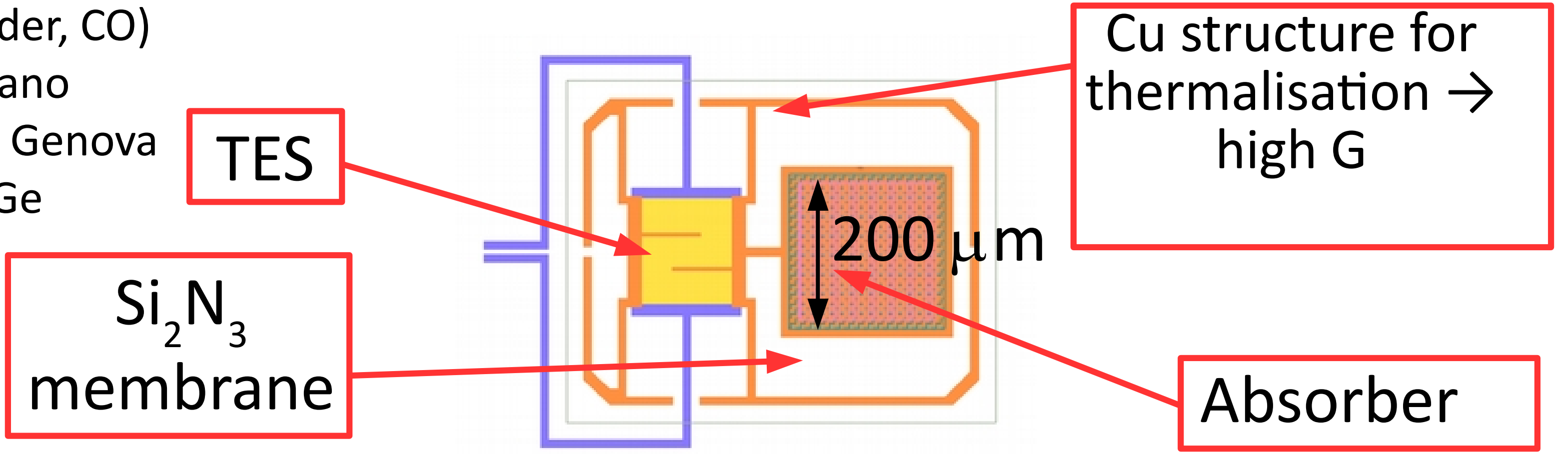
TES for HOLMES



Transition Edge Sensors Superconductive Detectors (TES)

- Very steep R vs T dependency in transition region
- Gold absorber with ^{163}Ho inside coupled to TES thermometer
- Ho sandwiched between two 1 μm thick gold layers for a total electron containment
- Fast detectors to reduce pile-up
  - tunable rise time ~ L/R
  - decay time dependent on detector characteristics C/G

✓ Production at NIST (Boulder, CO)
✓ tested at NIST and in Milano
➢ ^{163}Ho implating facility at Genova
➢ Final Au coverage at Mi-Ge



TES

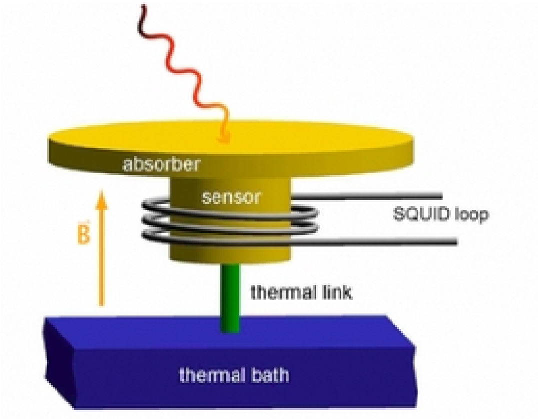
Si_2N_3 membrane

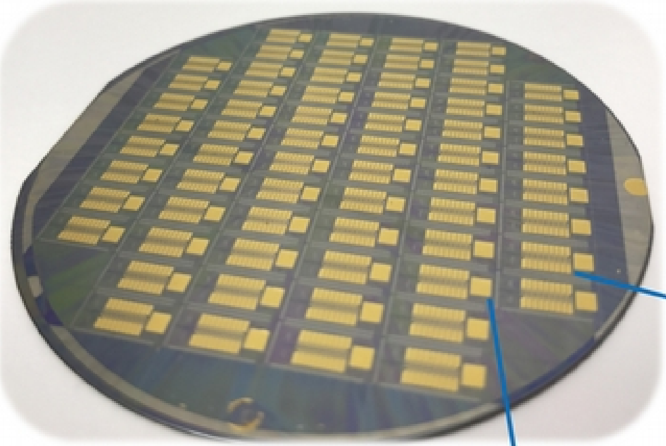
Cu structure for thermalisation → high G

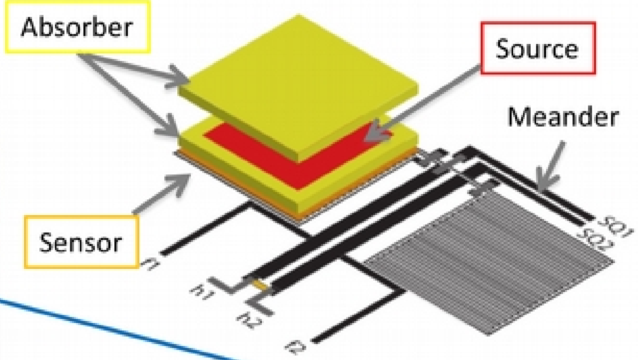
200 μm

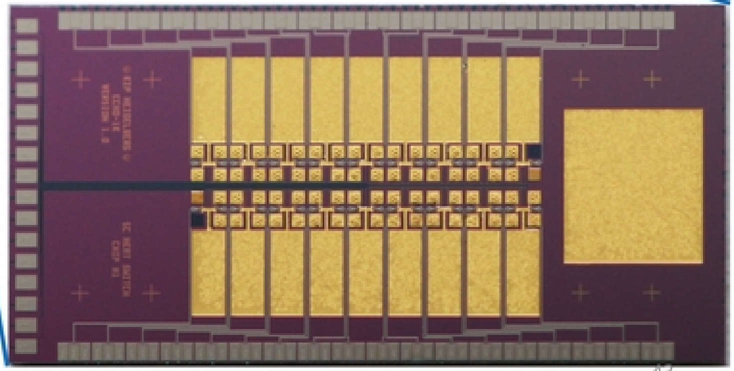
Absorber

MMC for ECHo









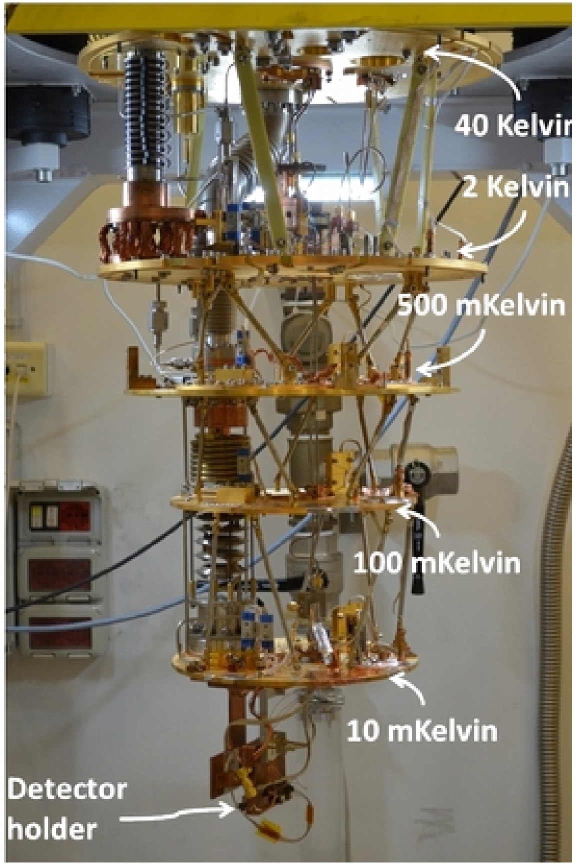
64 pixels which can be loaded with ^{163}Ho
+ 4 detectors for diagnostics

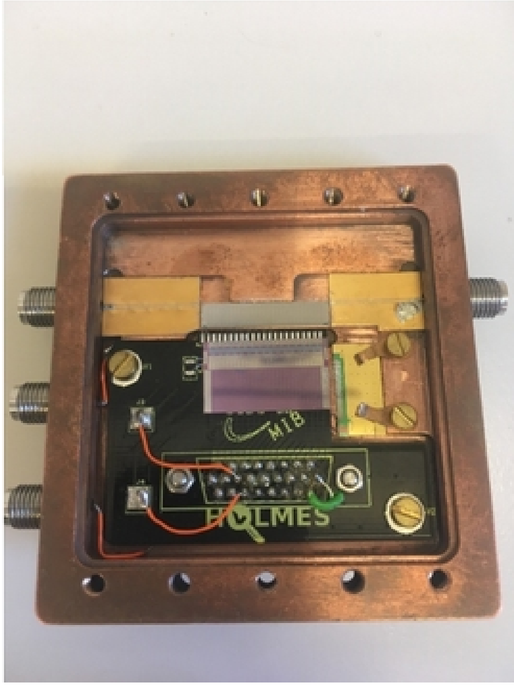
Design performance:
ΔE_{FWHM} ~ 5 eV
τ_r ~ 90 ns (single channel readout)
τ_r ~ 300 ns (multiplexed read-out)

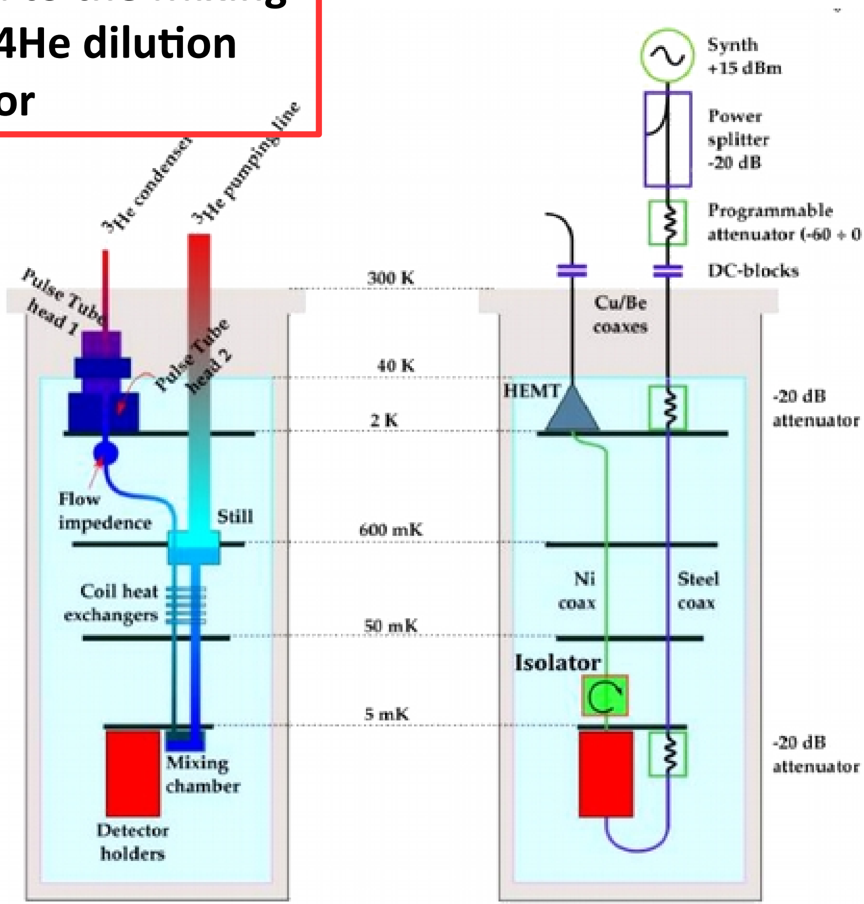
S.Kempf *et al.*, *J. Low. Temp. Phys.* **176** (2014) 426

The cryogenics - Milan

Detctor box is coupled to the Mixing Chamber of a 3He/4He dilution refrigerator



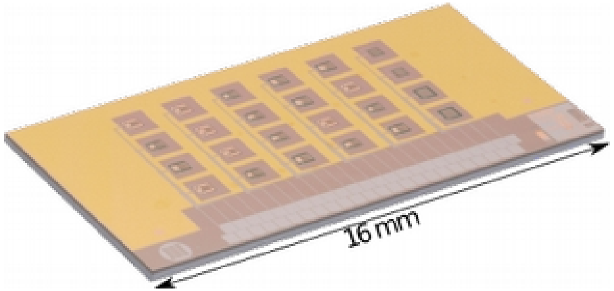


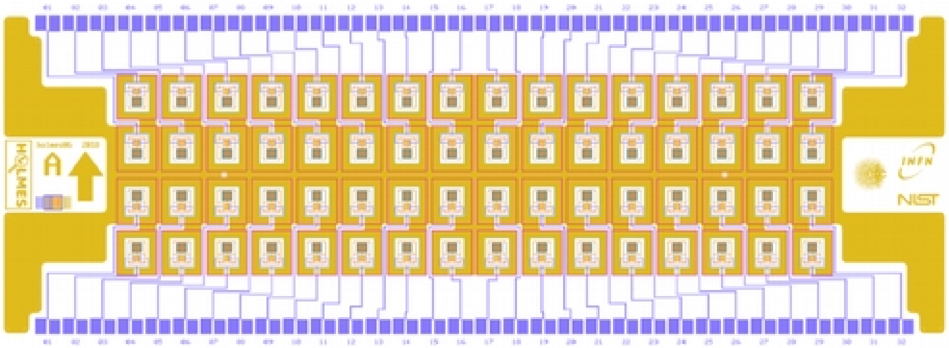


TES array

First Transition Edge Sensors array

- 6 different designs to be tested
- Different thermal conductances G
- Different TES intrinsic parameters

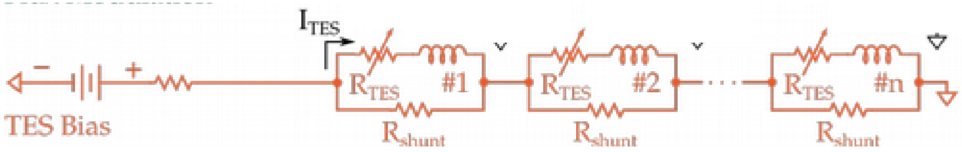


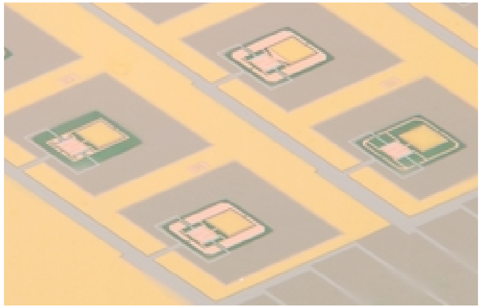


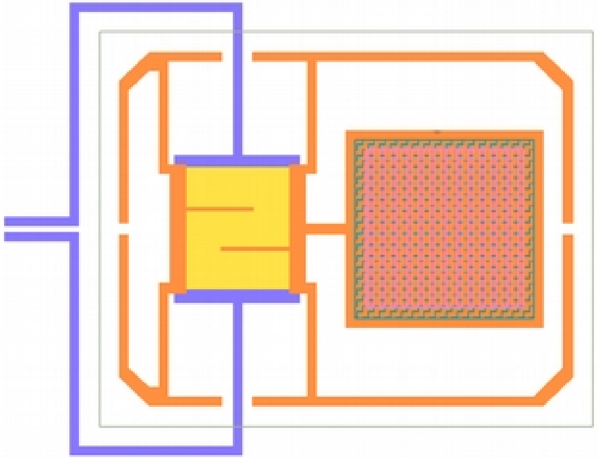
Readout

- Each TES is coupled to a RF-SQUID

$$E \rightarrow \delta T_{\text{TES}} \rightarrow \delta I_{\text{TES}}$$



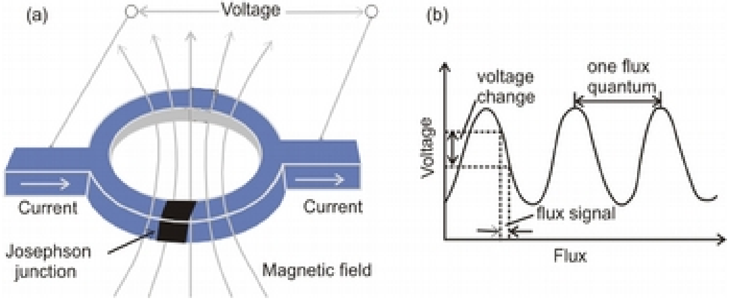


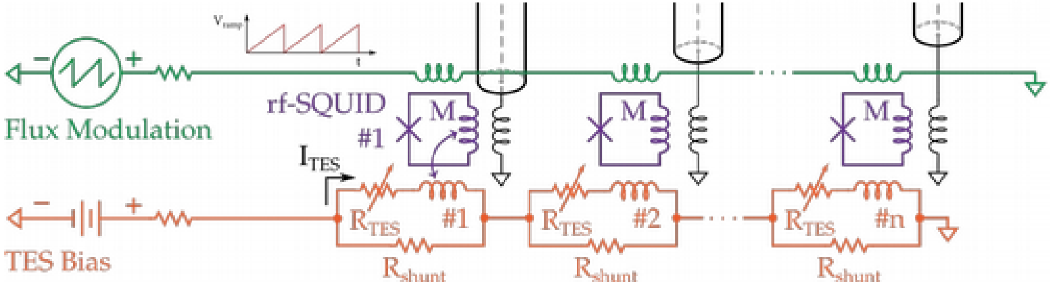


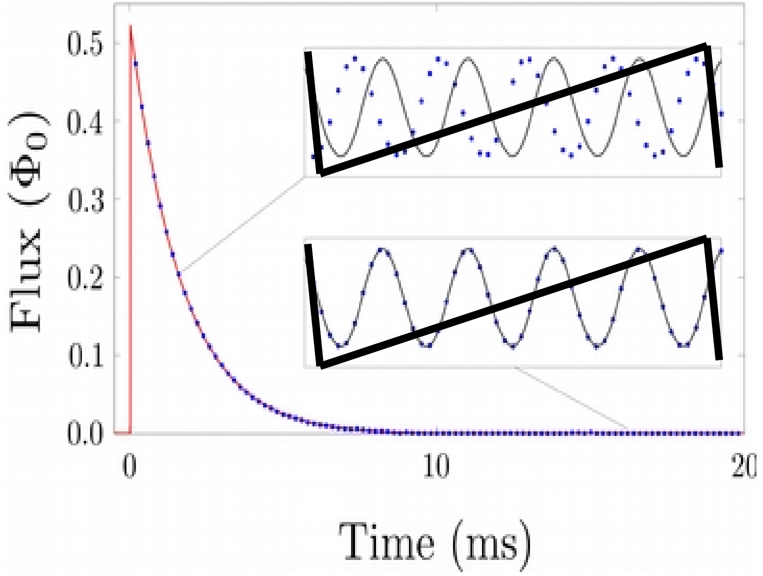
Readout

- Each TES is coupled to a RF-SQUID
- Every RF-SQUID is coupled to a common ramp

$$E \rightarrow \delta T_{\mathrm{TES}} \rightarrow \delta I_{\mathrm{TES}} \rightarrow \delta\phi_{\mathrm{squid}}$$

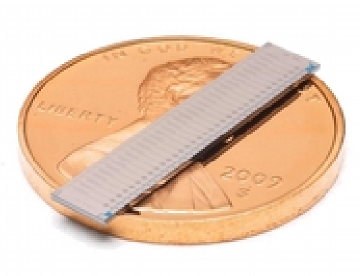


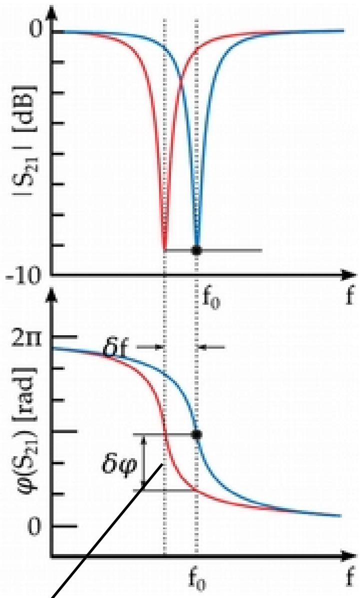




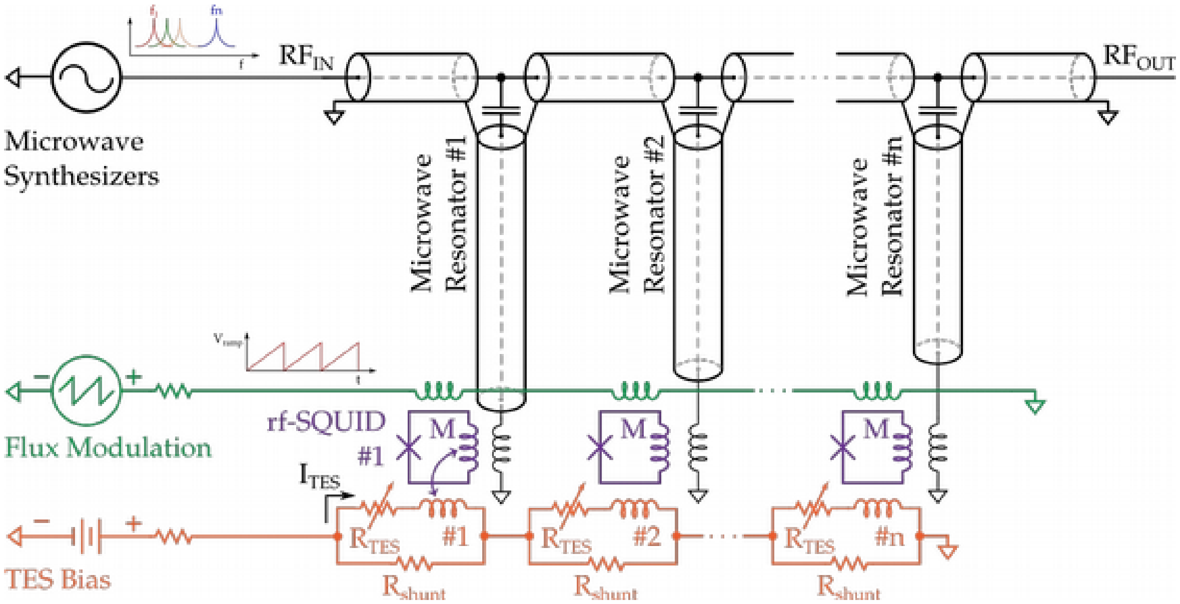
Readout

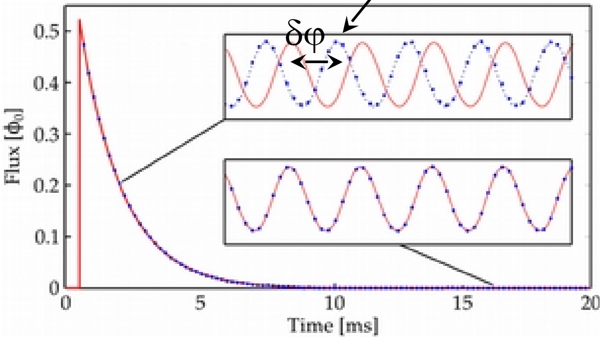
- Each TES is coupled to a RF-SQUID
- Every RF-SQUID is coupled to a common ramp
- Every RF-SQUID is coupled to a resonant circuit





$$E \rightarrow \delta T_{TES} \rightarrow \delta I_{TES} \rightarrow \delta\phi_{squid} \rightarrow \delta f_{resonator}$$



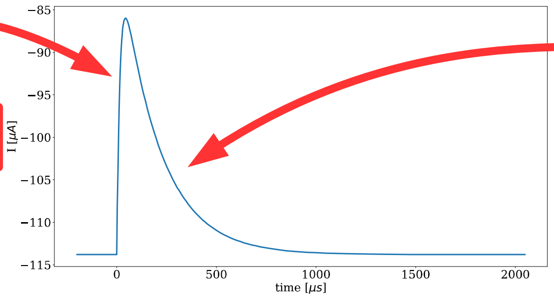


HOLMES final array detectors

HOLMES tested non implanted detectors → final design established

^{55}Fe (5.9 keV) + fluorescence from (Ca – 3.7 keV; **Cl – 2.6 keV**; Al – 1.5 keV)

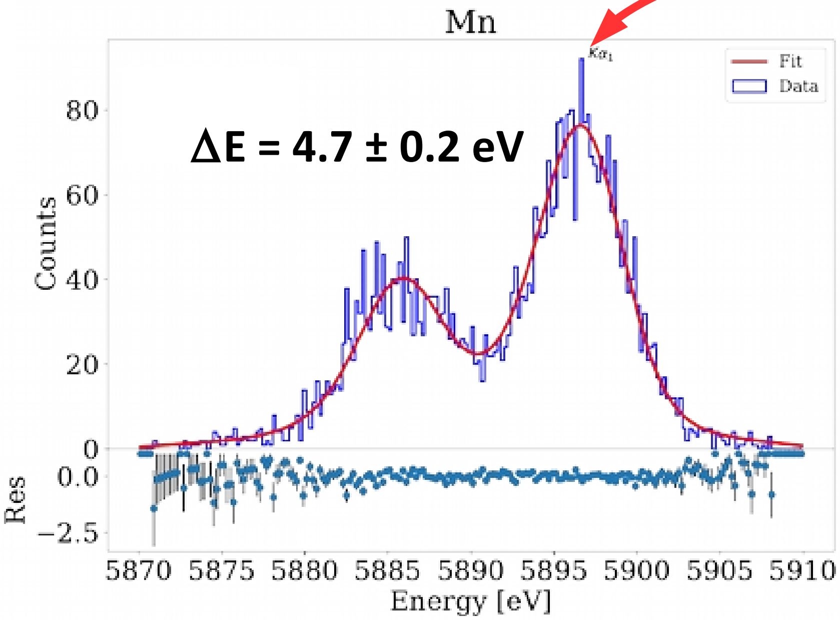
Stray iductance tuned to achieve pulse edge of $\tau_R \approx 10\ \mu s$



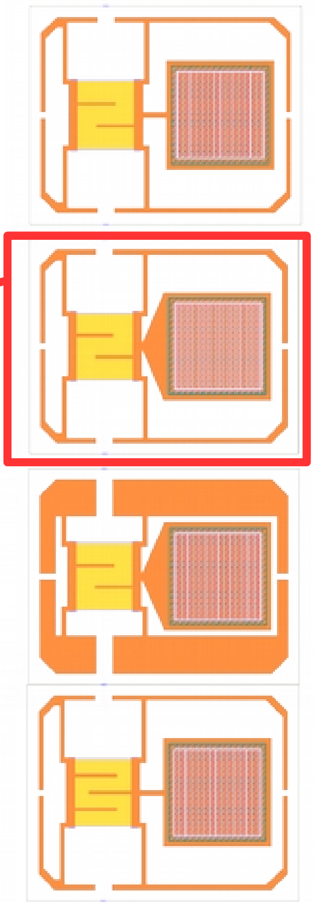
$\tau_R \approx 10\ \mu s$

$\tau_D \approx 190\ \mu s$

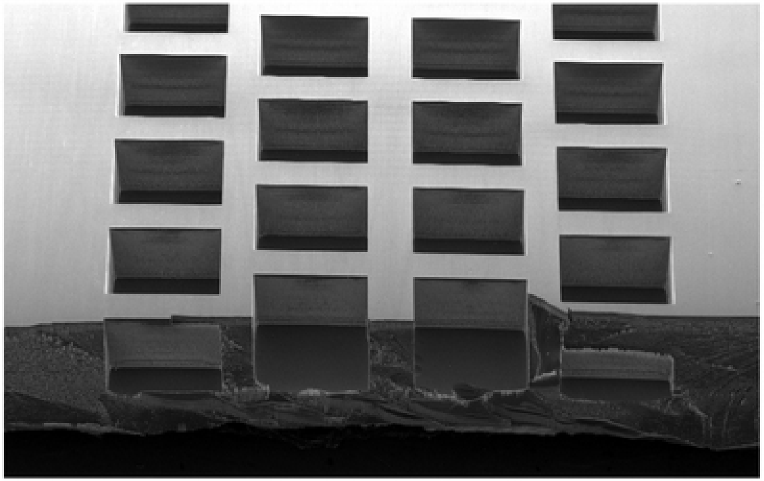
E [keV]	ΔE [eV]
1.49	3
2.62	4.6
3.69	4.6



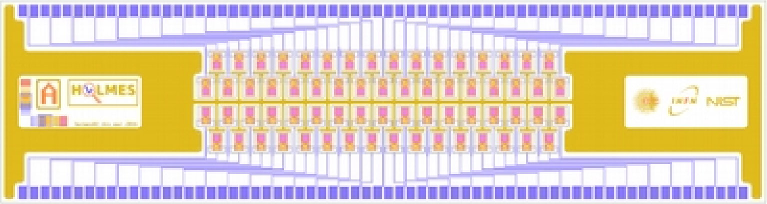
ΔE = 4.7 ± 0.2 eV

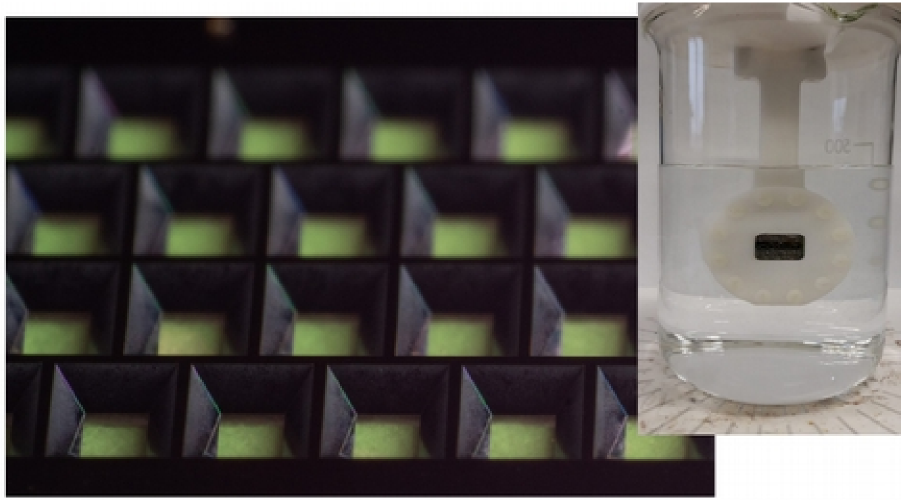


Final arrays – etching

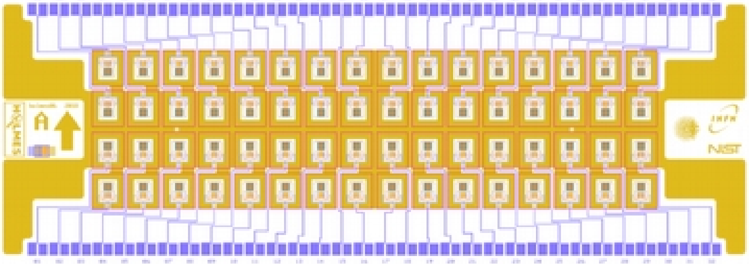


- Si Deep Reactive Ion Etching (DRIE)
- Closer detector packing → higher implant efficiency
- Still to be tuned





- Si KOH anisotropic wet etching
- Larger spacing between pixels
- Perfectly tuned→ HOLMES baseline



Next steps

→ The determination of the electron neutrino mass with ^{163}Ho is complementary to the determination of the neutrino mass with Tritium

→ spectral shape measurement is needed for theoreticians to refine the EC model of ^{163}Ho

→ ECHo and HOLMES have already demonstrated:

- production and purification of large amount of ^{163}Ho sample
- operation of large arrays of high resolution low temperature detector
- first low energy background studies

→ HOLMES detector modules will be soon tested for ^{163}Ho enclosure aiming at 300 Bq

→ ECHo is ready for upgrades to larger arrays with 1 Bq activity

Overall neutrino mass limits

$$m_\Sigma = \Sigma_i m_{\nu i}$$

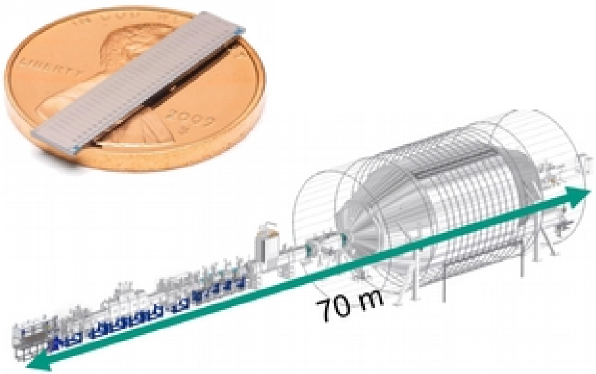
- Model dependent
- Orbital experiments
- Current limit 0.12 – 1 eV
- Future limit 15-50 meV

$$m_{\beta\beta} = \left|\Sigma_i m_{\nu i} U_{ei}^2\right|$$

- Model dependent
- Large underground experiments
- Current limit 100 – 300 meV
- Future limit 15-50 meV

$$m_\beta = \left(\Sigma_i m_{\nu_i}^2 U_{ei}^2\right)^{1/2}$$

- Model independent
- Surface experiments
- Current limit 2 eV
- Future limit 0.2 meV



Thank you for you patience and attention ;)