HOLMES

The Electron Capture Decay of ^{163}Ho to Measure the Electron Neutrino Mass with sub-eV sensitivity

ERC-Advanced Grant 2013

PI: Stefano Ragazzi

Host Institution: INFN

Additional Beneficiary: Univ. di Milano-Bicocca

INFN Sez. Milano-Bicocca, INFN Sez. Genova, LNGS,
INFN Sez. Roma, Univ. Lisboa, Miami Univ., NIST, JPL, ...

Angelo Nucciotti

Università di Milano-Bicocca e INFN - Sezione di Milano-Bicocca

Outline

- Neutrino physics
- Direct neutrino mass measurements
- ^{187}Re calorimetry with thermal detectors
- ^{163}Ho calorimetry with thermal detectors
- **HOLMES** experiment
- Conclusions

Neutrino properties

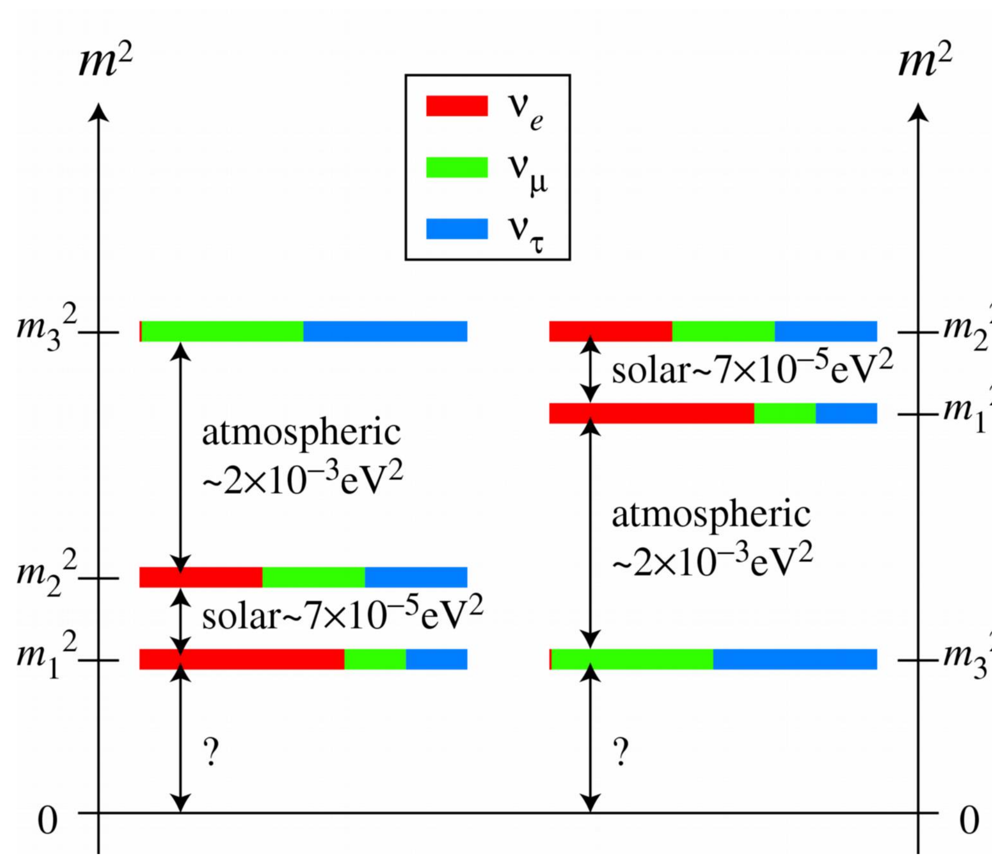
- neutrinos are massive fermions
- there are 3 active neutrino flavors
- neutrino flavor states are mixtures of mass states

neutrino mixing matrix

neutrino mass eigenstate

$$|\nu_l\rangle = \sum_k U_{lk} |\nu_k\rangle$$

neutrino flavor weak eigenstate



→ neutrino oscillation experiments measure

$\Delta m_{ik}^2 = |m_i^2 - m_k^2|$

$\sin^2 2\vartheta_{ik} = f(|U_{lk}|^2)$

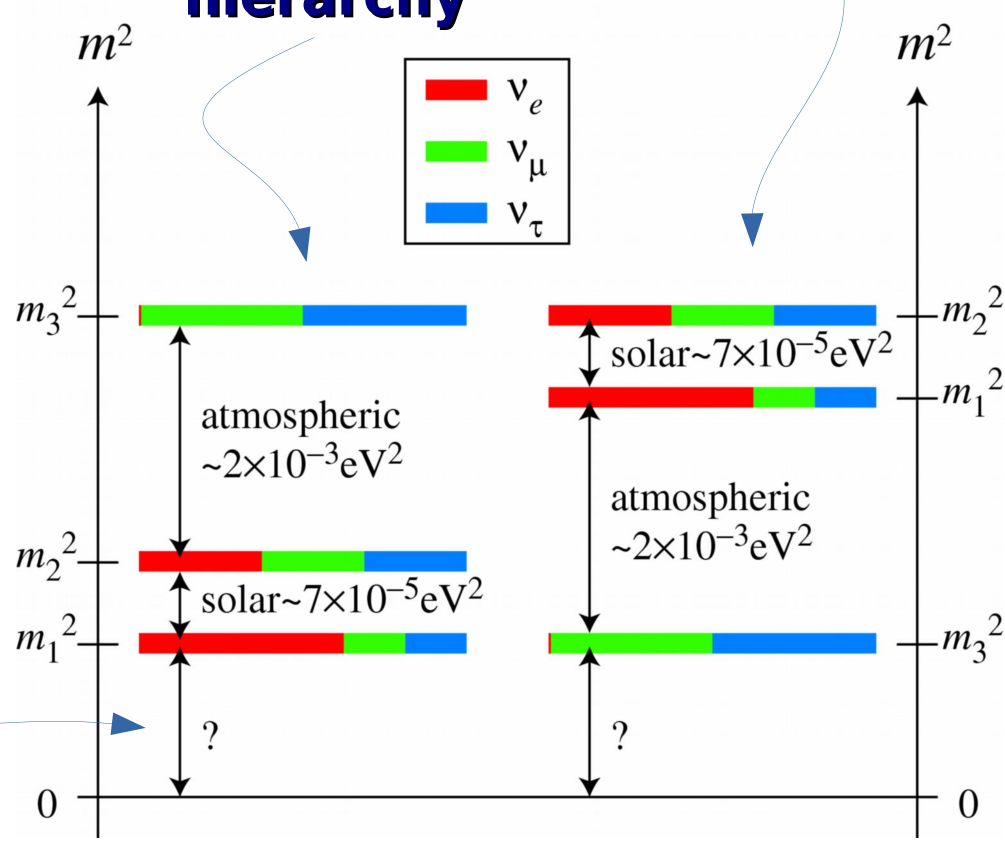
Neutrino open questions

- mass scale: i.e. mass of the lightest ν
- degenerate ($m_1 \approx m_2 \approx m_3$) or hierarchical masses
  - mass hierarchy: $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 \approx m_2$?
- $\nu = \bar{\nu}$? i.e. Dirac or Majorana particle?
- CP violation in the lepton sector

inverted hierarchy

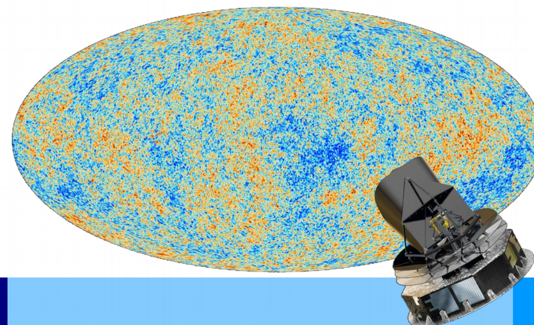
normal hierarchy

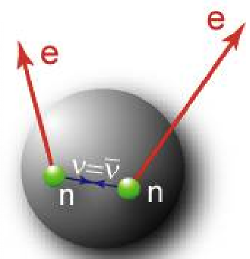
mass scale

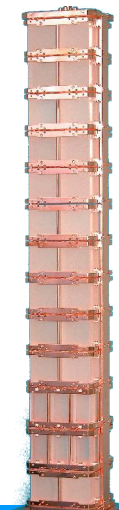


Mass scale: experimental tools / 1

three complementary tools available
→ low temperature detectors play key role
(E. Fiorini and T. Niinikoski, Nucl. Instrum. and Meth. 224, p.83 (1984))





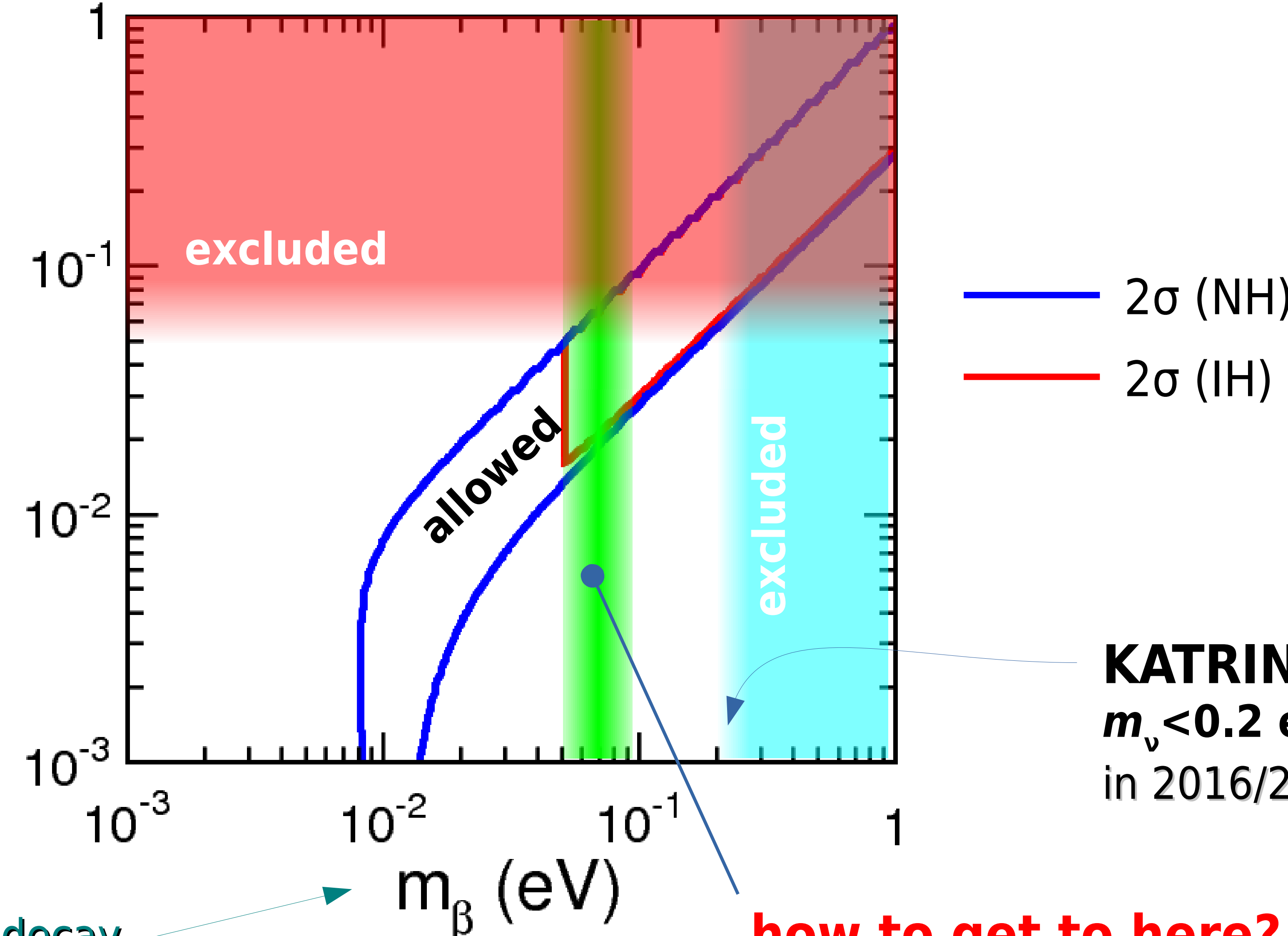


tool	Cosmology CMB+LSS+...	Neutrinoless Double Beta decay	Beta decay end-point
observable	$m_\Sigma=\sum_k m_{\nu_k}$	$m_{\beta\beta}=\lvert\sum_k m_{\nu_k} U_{ek}^2\rvert$	$m_\beta=(\sum_k m_{\nu_k}^2 \lvert U_{ek}\rvert^2)^{1/2}$
present sensitivity	≈0.1 eV	≈0.1 eV	2 eV
future sensitivity	**0.05 eV**	**0.05 eV**	**0.2 eV**
model dependency	yes ☹	yes ☹	no ☺
systematics	large ☹	yes 😐	large ☹

The Challenge: absolute neutrino mass

expected in the next ≈5 years

Neutrinoless Double Beta decay



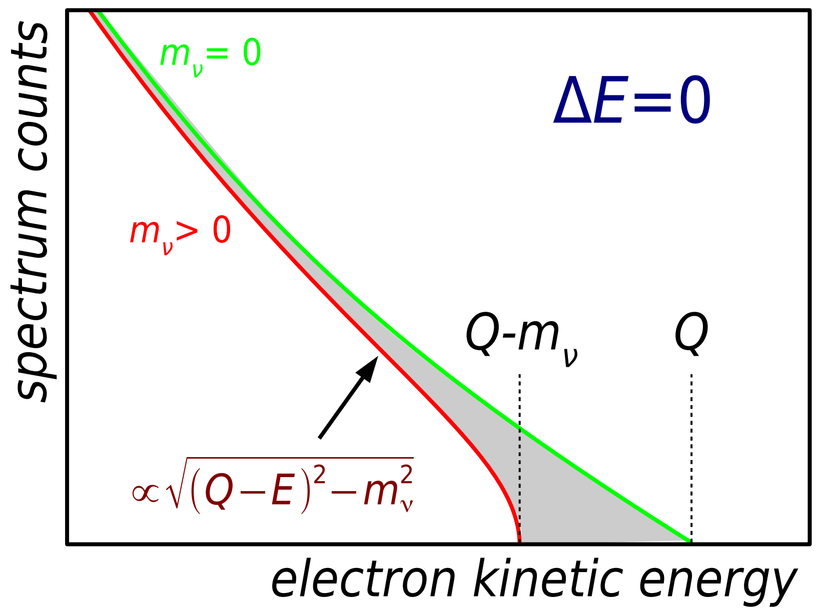
KATRIN
***m_ν*<0.2 eV**
in 2016/2017

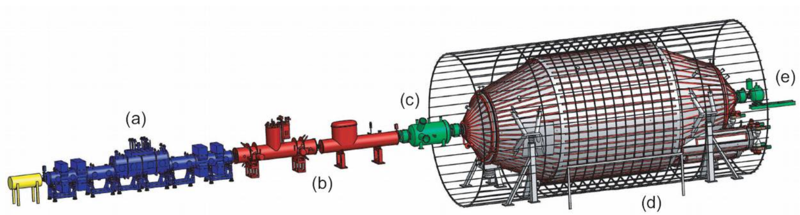
Beta decay end-point

how to get to here?

Direct neutrino mass measurements

- **kinematics of weak decays with ν emission**
  - low Q nuclear beta decays (^{3}H, ^{187}Re...)
  - only energy and momentum conservation
  - no further assumptions
- **2 approaches with different systematics:**
  - spectrometry: the β source is outside the detector
  - calorimetry: the β source is contained in the detector which measures all the energy released except the ν energy



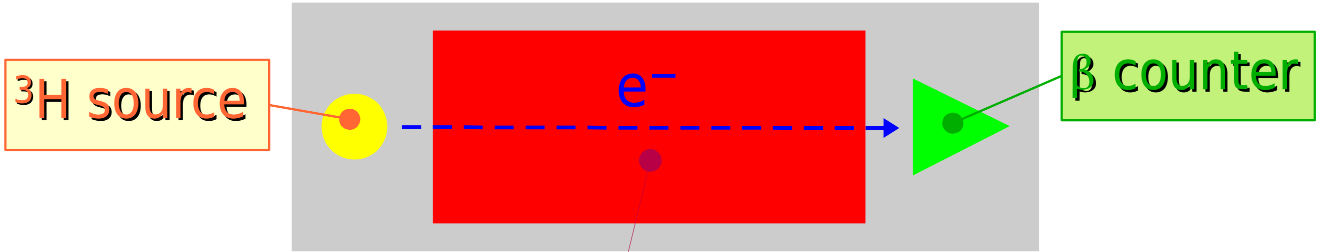


KATRIN
large MAC-E filter spectrometer with ^{3}H

MARE/ECHO/HOLMES
array of low temperature microcalorimeters with ^{187}Re or ^{163}Ho

Experimental approaches

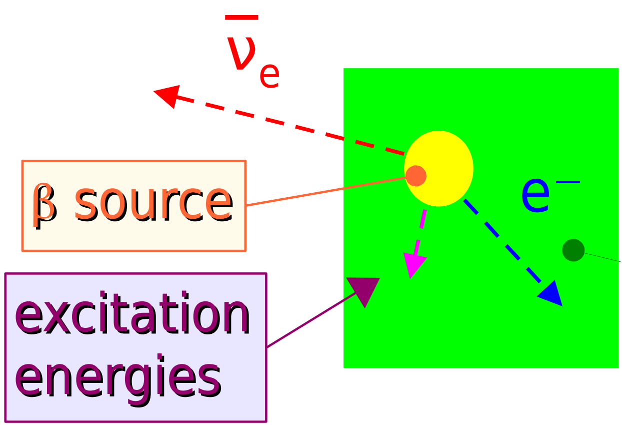
Spectrometers: source ≠ detector



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

- ▲ high statistics
- ▲ high energy resolution
- ▼ large systematics
  - ▶ source effects
  - ▶ decays to excited states
- ▼ background

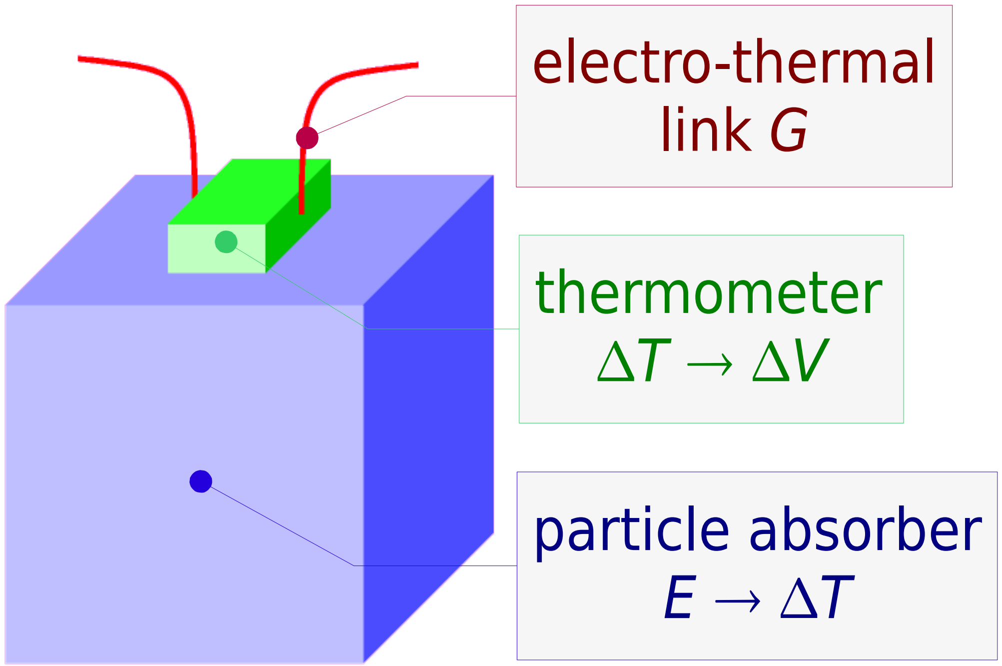
Calorimeters: source ⊆ detector

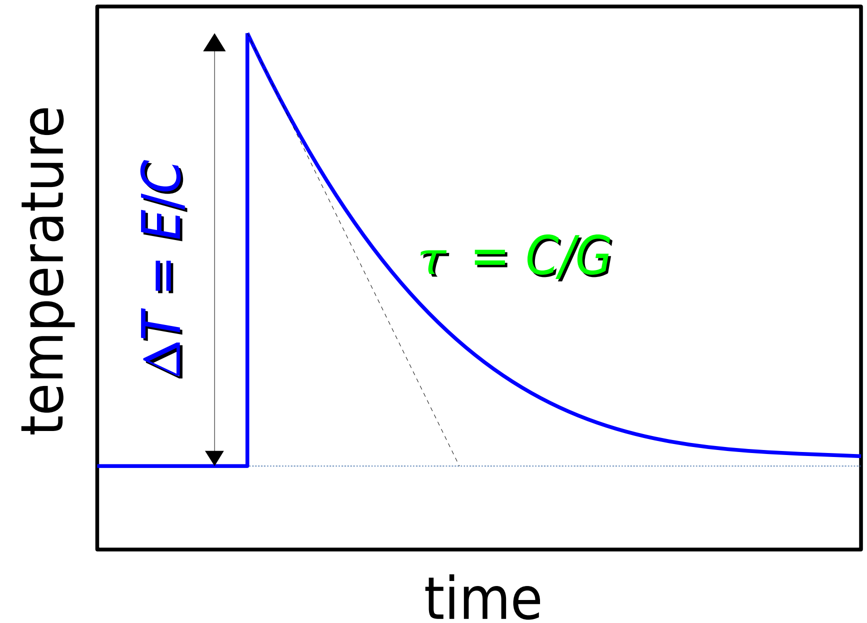


β calorimeter
ideally measures all the energy E released in the decay except for the $\bar{\nu}_e$ energy: $E=E_0-E_\nu$

- ▲ no backscattering
- ▲ no energy losses in the source
- ▲ no atomic/molecular final state effects
- ▲ no solid state excitation
- ▼ limited statistics
- ▼ pile-up background
- ▼ spectrum related systematics

Calorimetry with low temperature detectors (LTD)





1 mg of Re @ 100 mK
$C \sim T^3$ (Debye) → $C \sim 10^{-13}$ J/K
→ $\Delta E_{rms} \sim$ **1 eV**
6 keV x-ray → $\Delta T \sim$ **10 mK**
$G \sim 10^{-11}$ W/K → $\tau = C/G \sim$ **10 ms**

- complete energy *thermalization* (ionization, excitation → heat) → **calorimetry**
- $\Delta T = E/C$ with C total thermal capacity (phonons, electrons, spins...) phonons: $C \sim T^3$ (Debye law) in dielectrics or superconductors below T_c → low T (i.e. $T \ll 1$K)
- $\Delta E_{rms} = (k_B T^2 C)^{1/2}$ due statistical fluctuations of internal energy E
- $\Delta T(t) = E/C\, e^{-t/\tau}$ with $\tau = C/G$ and G thermal conductance

Calorimeter statistical sensitivity

resolving time τ_R analysis interval ΔE

source activity A_β number of detectors N_{det}

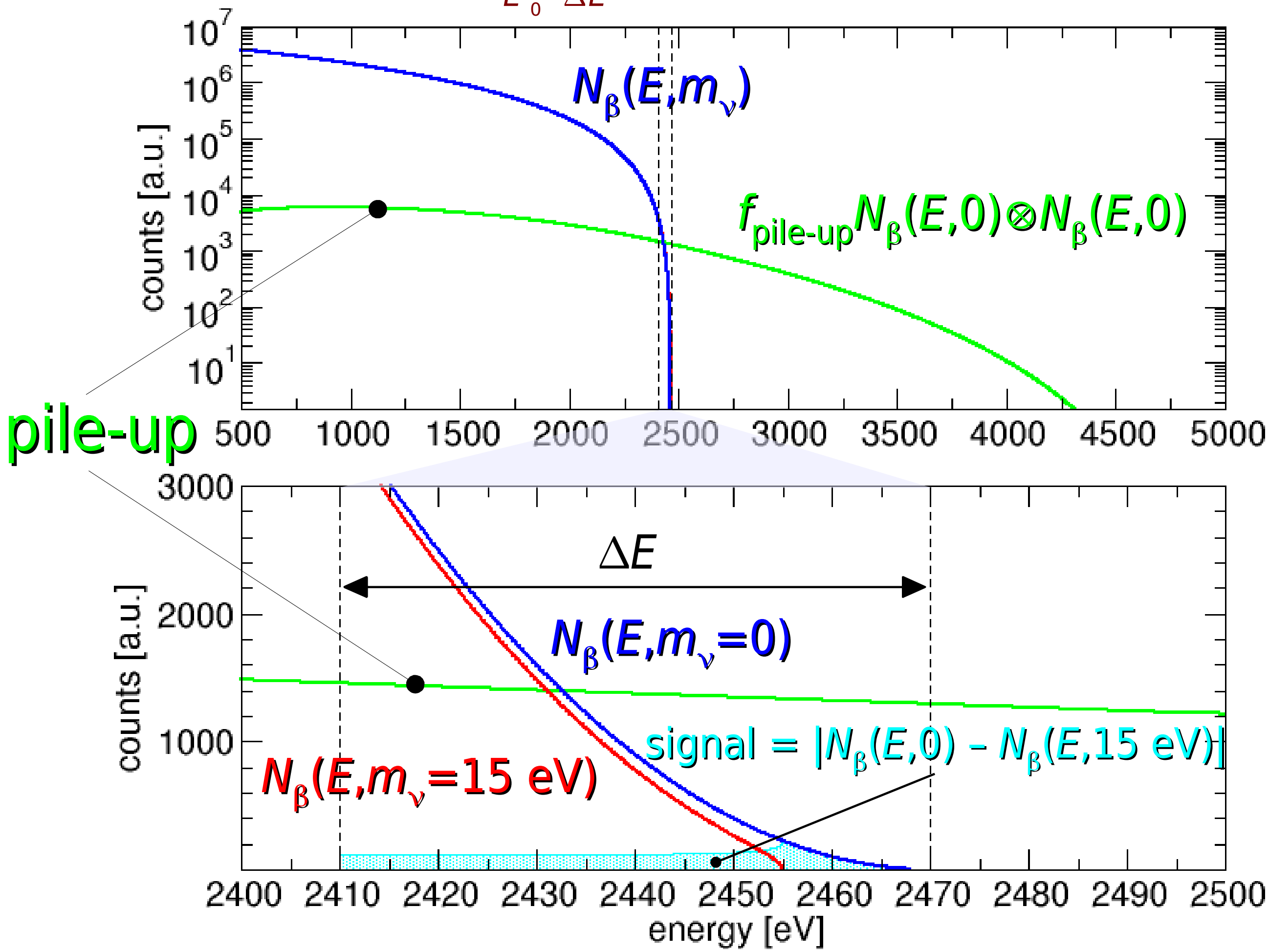
pile-up fraction $f_{pile\text{-}up}=\tau_R A_\beta$

experimental exposure $t_M=T\times N_{det}$

$$N_\beta(E,m_\nu)\approx\frac{3}{E_0^3}(E_0-E)^2\sqrt{1-\frac{m_\nu^2}{(E_0-E)^2}}$$

$$F_{\Delta E}(m_\nu)=A_\beta N_{det}\int_{E_0-\Delta E}^{E_0} N_\beta(E,m_\nu)dE \qquad F_{\Delta E}(0)\approx A_\beta N_{det}\frac{\Delta E^3}{E_0^3}$$

→ ^{187}Re E_0=2.5keV



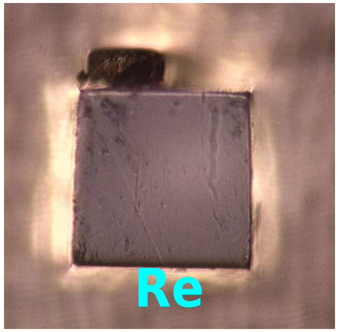
$$f_{pile-up}=\tau_R A_\beta \ll \frac{\Delta E^2}{E_0^2}$$ negligible pile-up

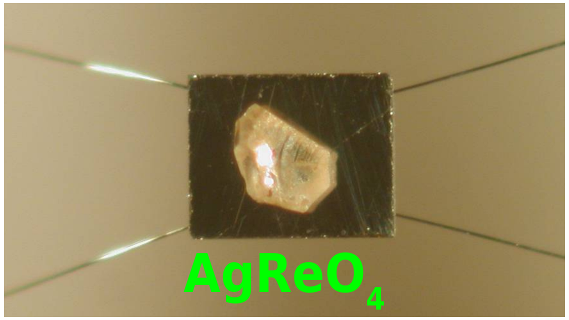
$$\Sigma_{90}(m_\nu)\approx 0.89\sqrt[4]{\frac{E_0^3\Delta E}{A_\beta t_M}}$$

experimental challenges

- energy resolution ΔE_{FWHM}
- time resolution τ_R
- exposure $t_M = N_{det}\times T$
- single channel activity A_β

^{187}Re experiments: MANU-MIBETA ... MARE

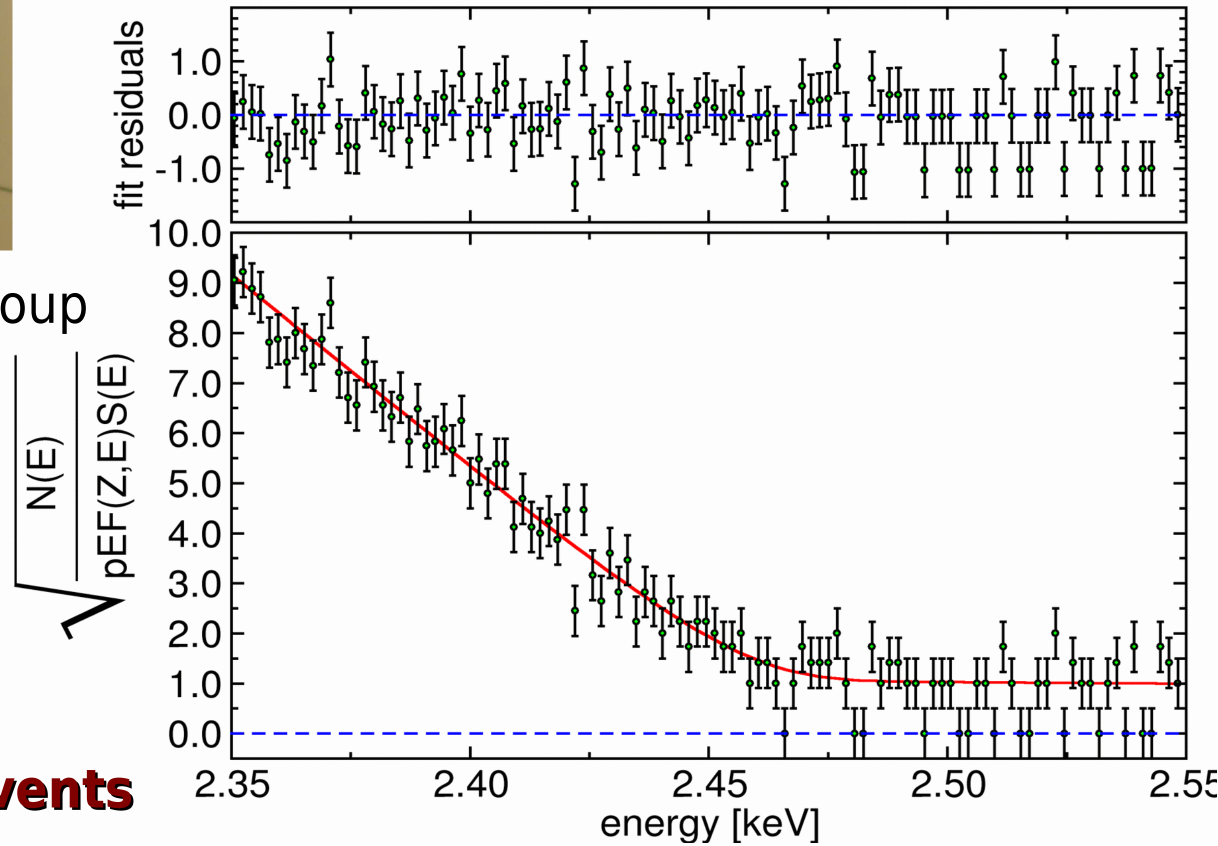




- proposed since 1985 by Genova group
- **MIBETA** @ MiB with $AgReO_4$
  - m_ν < 15 eV 90% C.L.

    M.Sisti et al., NIM A 520 (2004) 125
- **MANU** @ Ge with metallic Re
  - m_ν < 26 eV 95% C.L.

    F.Gatti, Nucl. Phys. B91 (2001) 293
- first ^{187}Re experiments: $N_{ev} \approx 10^7$ events



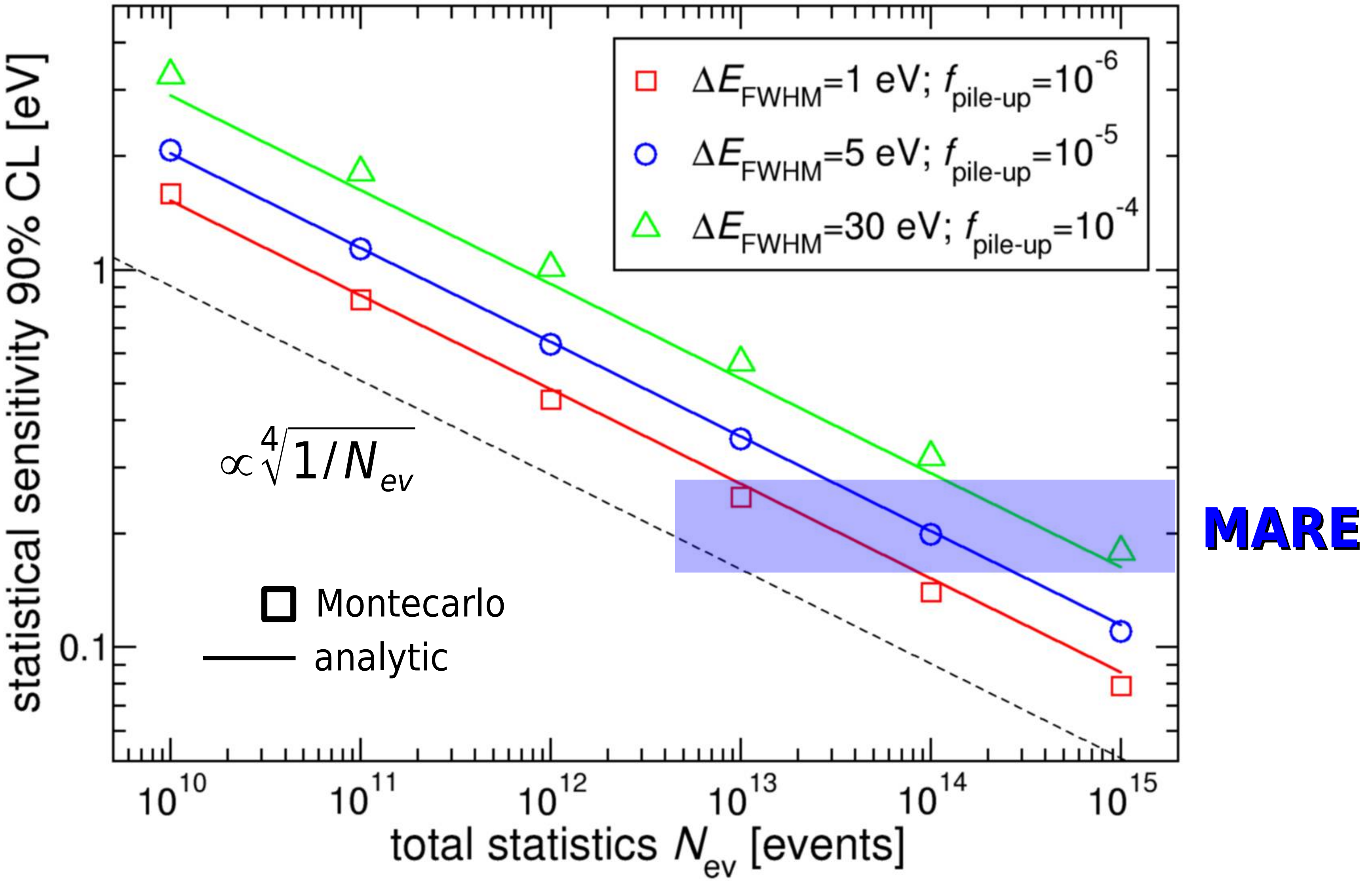
MARE (Microcalorimeter arrays for a Rhenium Experiment)

- project for a sub-eV direct neutrino mass measurement
- wide international interest since Orlando (USA) meeting in 2007
- phased approach to optimize detectors technology

^{187}Re experiment statistical sensitivity / 1

^{187}Re past mesurements

- total statistics $N_{ev} \approx 10^7$ events



A.Nucciotti et al., Astropart. Phys., 34 (2010) 80 (arXiv:0912.4638v1)

^{187}Re experiment statistical sensitivity / 2

exposure required for 0.2 eV m_ν sensitivity

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

exposure required for 0.1 eV m_ν sensitivity

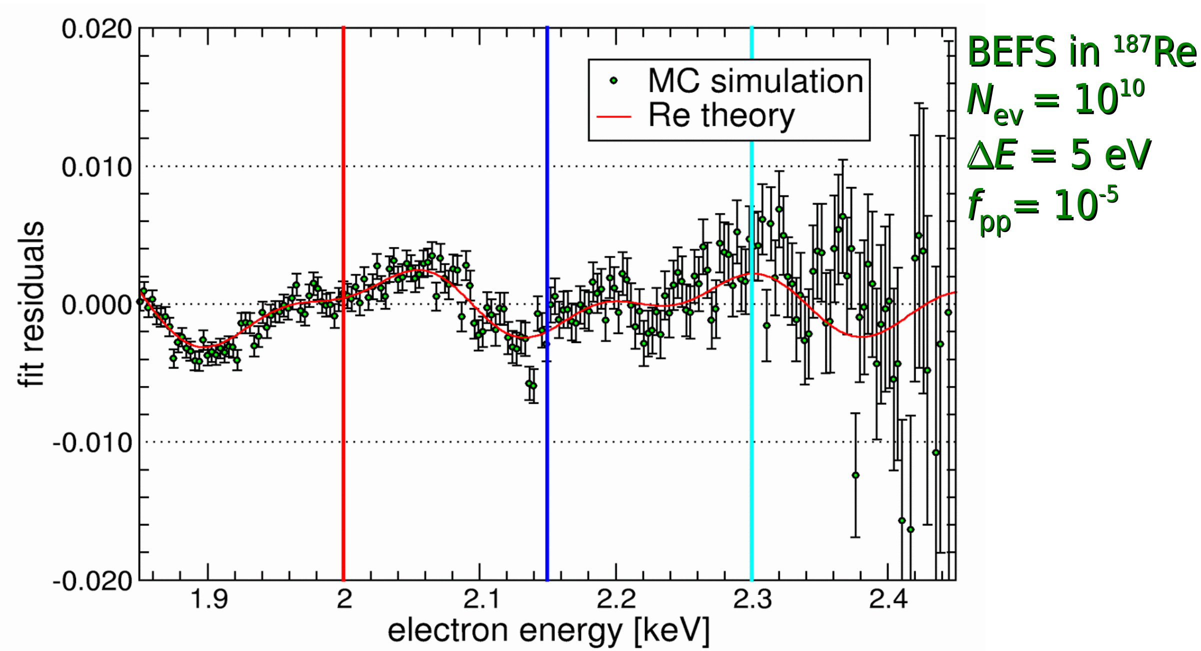
A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.1	1.7×10^{14}	5.4×10^6
10	0.1	0.1	5.3×10^{14}	1.7×10^6
10	1	1	10.3×10^{14}	3.3×10^6
10	3	3	21.4×10^{14}	6.8×10^6
10	5	5	43.6×10^{14}	13.9×10^6

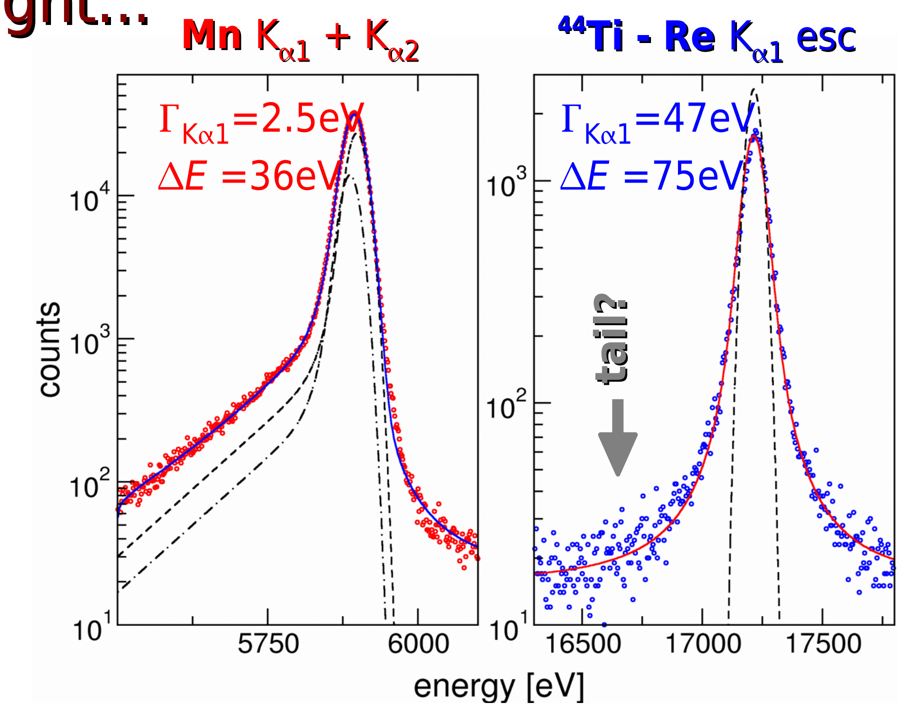
^{187}Re half-life time
$\tau_{1/2}$ = 43.2 Gy
^{187}Re natural abundance
a.i. = 63%
metallic Rhenium
→ ≈1.0 Hz/mg/s

20000 pixels/array
16 arrays
10 years
3.2 kg ^{nat}Re

Rhenium experiment status and future

- Re detector development → no good results after **20+ years** of R&D
  - no clear understanding of Re absorber physics
  - purity and superconductivity?
  - extra heat capacity *C* due to nuclear quadrupole moment?
- low specific activity → “large” masses → fabrication issues
- possible large systematics
  - Beta Environmental Fine Structure (BEFS)
  - detector energy response function
- **future of Re experiments is not very bright...**





Electron capture end-point experiment / 1

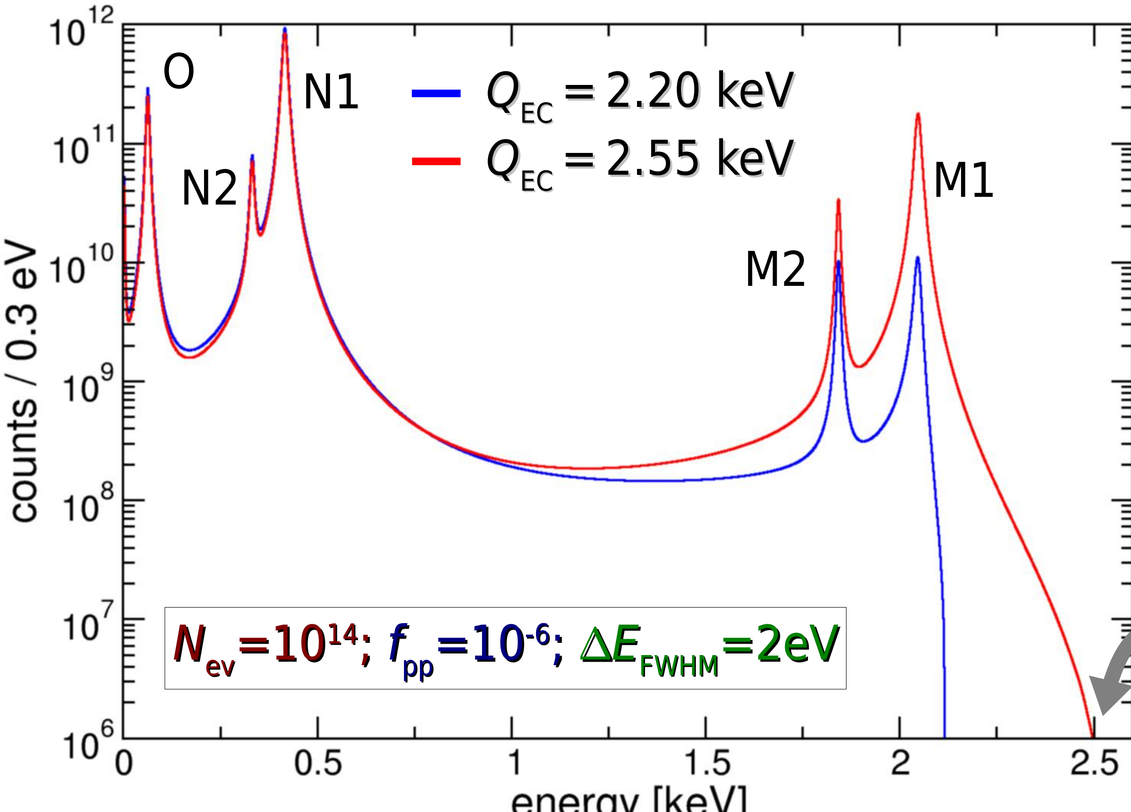
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

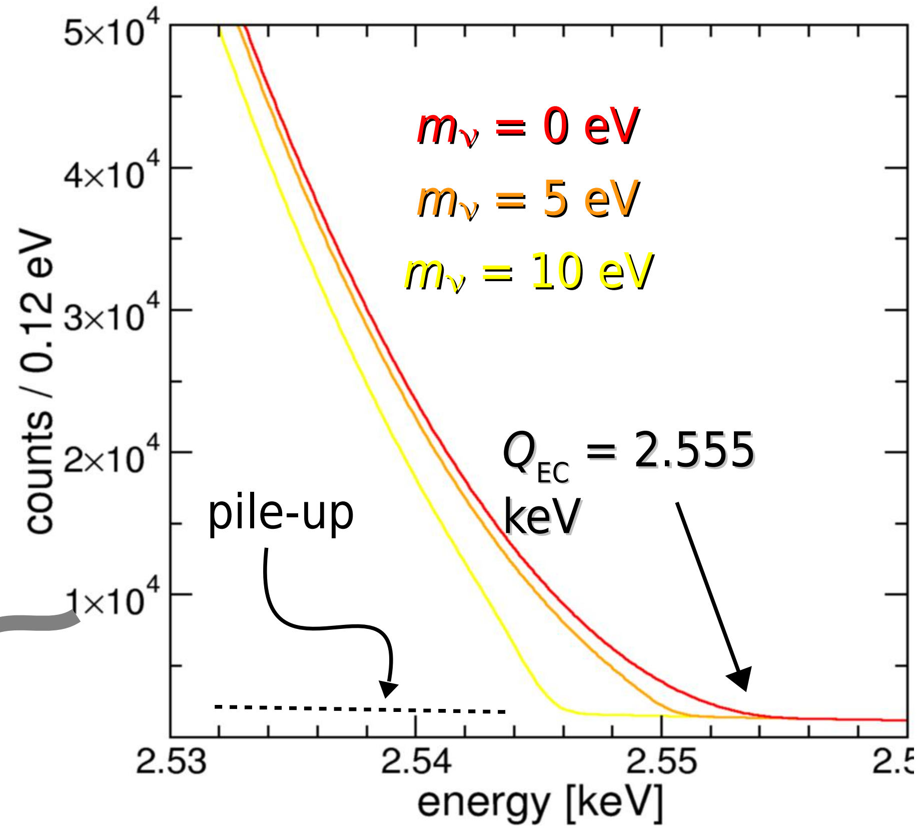
electron capture from shell ⩾ M1

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

- **calorimetric measurement of Dy atomic de-excitations** (mostly non-radiative)
- rate at end-point and ν mass sensitivity depend on *Q*
  - ▶ Measured: **Q_{EC} = 2.2÷2.8 keV**. Recommended: **Q = 2.555 keV**
- **$\tau_{1/2}$ ≈4570 years** → few active nuclei are needed

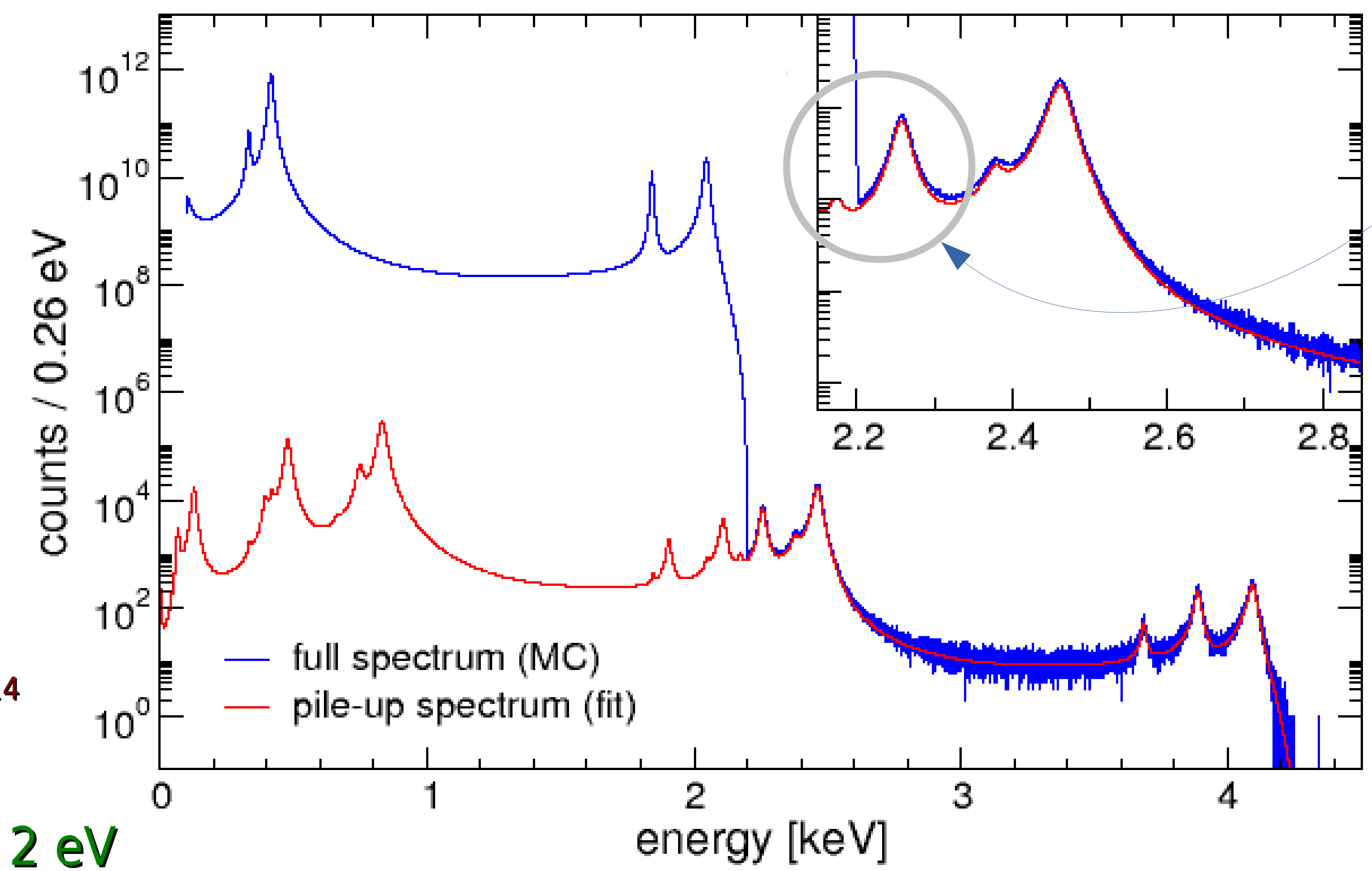
$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c-E_i)^2+\Gamma_i^2/4}$$





Electron capture end-point experiment / 2

- no direct **calorimetric** measurement of Q so far
- Q and atomic de-excitation spectrum poorly known
- complex **pile-up spectrum**
  - end-point spectrum shaped by $(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2}$ but...



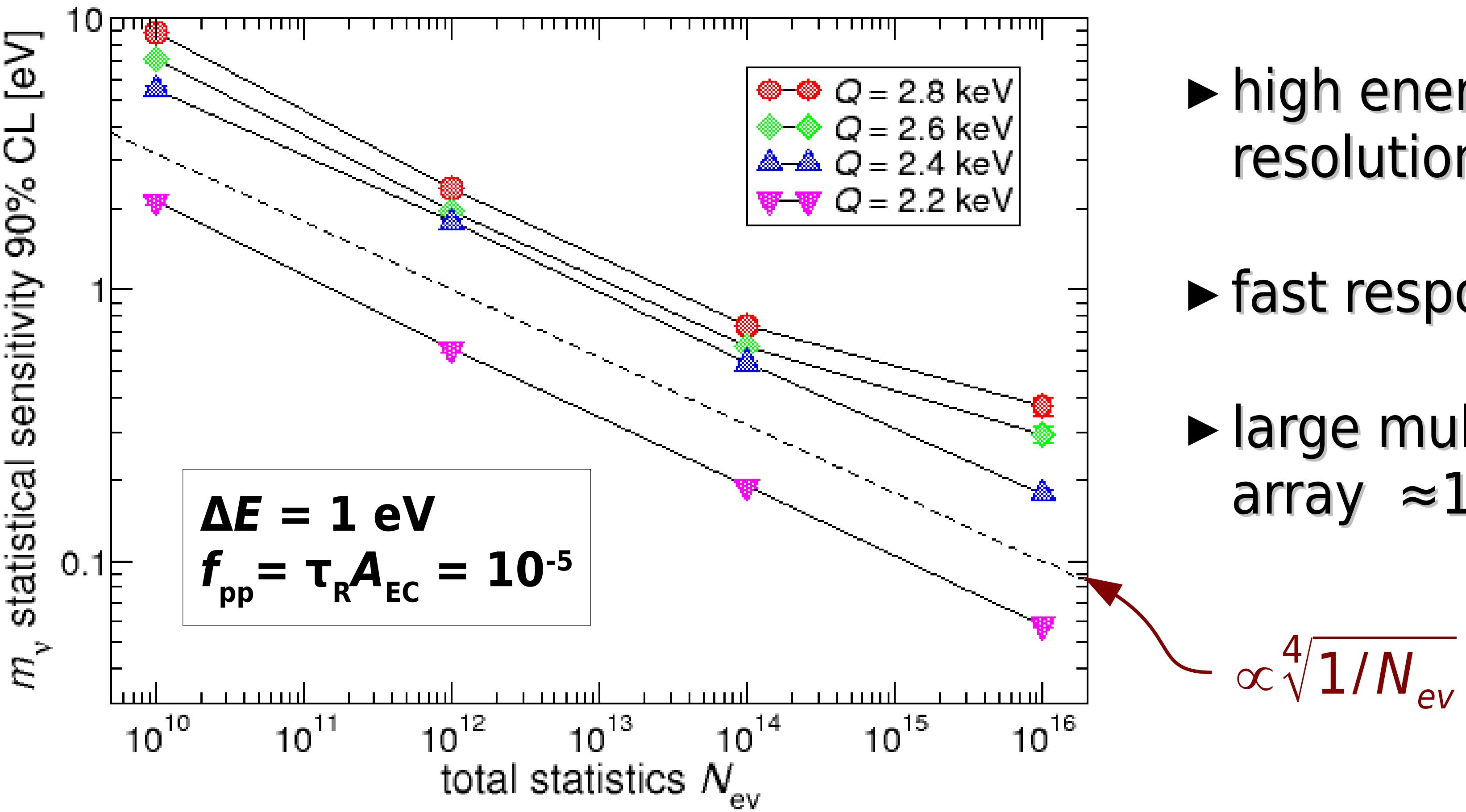
$N_{ev} = 10^{14}$

$f_{pp} = 10^{-6}$

$\Delta E_{FWHM} = 2$ eV

Statistical sensitivity: Montecarlo simulations

- 2×10^{11} ^{163}Ho nuclei → 1 decay/s
- ^{163}Ho production: p.e. neutron irradiation of ^{162}Er enriched Er
- embed ^{163}Ho in thermal detectors for low energy X-rays spectroscopy



- ▸ high energy resolution ≈1eV
- ▸ fast response ≈1μs
- ▸ large multiplexable array ≈1000

M. Galeazzi et al., accepted for publication by PRD, arXiv:1202.4763v2

^{163}Ho experiment statistical sensitivity / 1

exposure required for 0.2 eV m_ν sensitivity

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
$\approx 2\times10^{17}$ ^{163}Ho nuclei

exposure required for 0.1 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.3	1.2×10^{14}	3.9×10^{6}
100	0.1	0.3	6.4×10^{14}	2.0×10^{5}
100	0.1	1	7.4×10^{14}	2.4×10^{5}
10	0.1	1	4.5×10^{14}	1.5×10^{6}
10	1	1	7.4×10^{14}	2.4×10^{6}

5000 pixels/array
4 arrays
10 years
$\approx 3\times10^{17}$ ^{163}Ho nuclei

^{163}Ho experiment statistical sensitivity / 2

exposure required for 0.2 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	1	1	3.8×10^{15}	1.2×10^{8}
1	0.1	1	1.6×10^{15}	5.3×10^{7}
100	0.1	1	9.8×10^{15}	3.1×10^{6}
10	0.1	1	3.8×10^{15}	1.2×10^{7}
10	1	1	9.8×10^{15}	3.1×10^{7}

Q_{EC} = 2800 eV
***bkg* = 0**

60000 pixels/array
5 arrays
5 year
$\approx 4\times10^{18}$ ^{163}Ho nuclei

exposure required for 0.1 eV m_ν sensitivity

A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.3	2.6×10^{16}	8.2×10^{8}
100	0.1	0.3	1.9×10^{17}	5.9×10^{7}
100	0.1	1	1.6×10^{17}	5.0×10^{7}
10	0.1	1	6.1×10^{16}	1.9×10^{8}
10	1	1	1.6×10^{17}	5.0×10^{8}

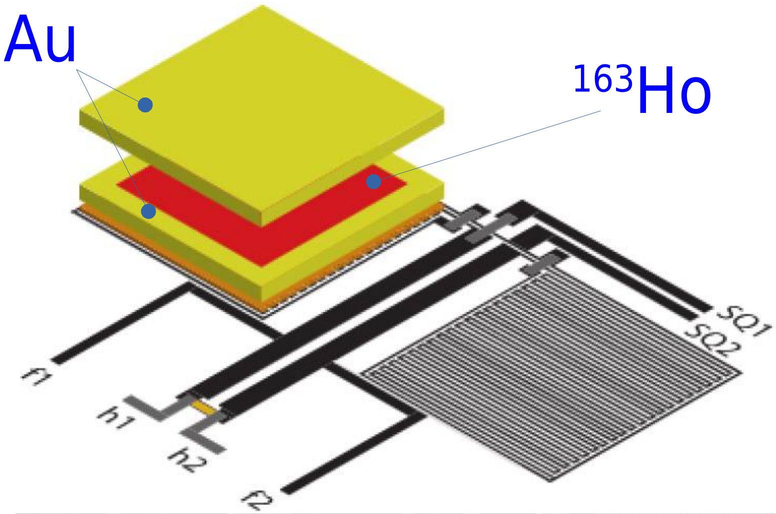
10^{6} pixels/array
6 arrays
10 years
$\approx 8\times10^{19}$ ^{163}Ho nuclei

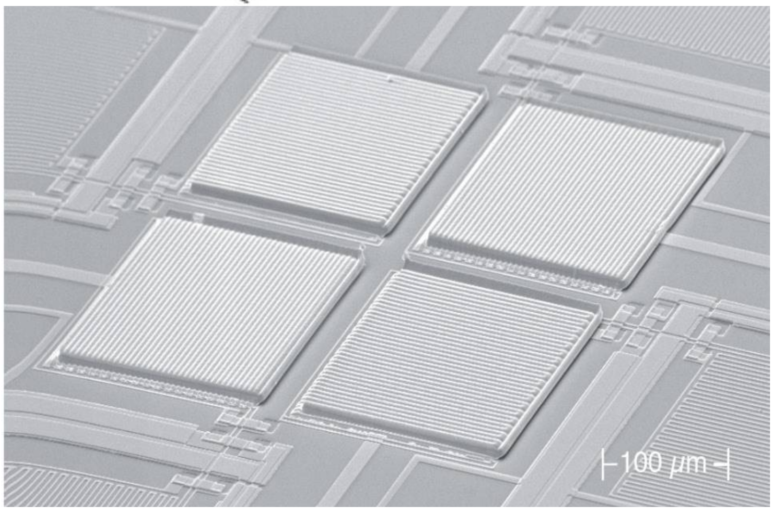
Holmium experiment status

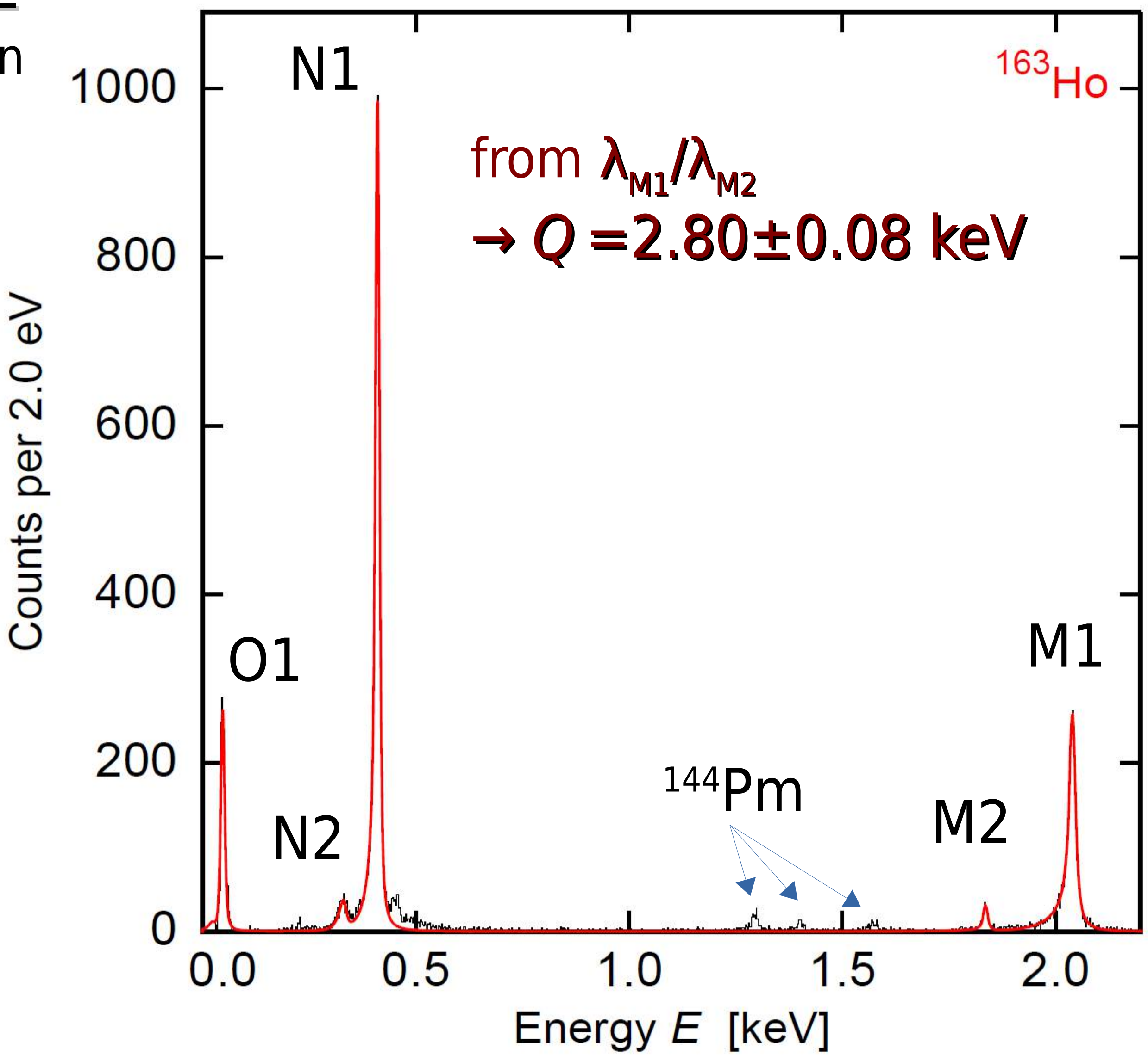
- **^{163}Ho seems to be better than ^{187}Re**
  - higher specific activity → don't need a “Holmium detector”
  - *self calibrating* → better systematics control
  - but
    - higher Q → maybe less sensitive
    - pile-up spectrum
    - chemical effects on Q
- (at least) **two projects**
  - **ECHO** (Heidelberg)
  - **MARE** (→ now HOLMES)
  - Los Alamos National Lab., Standford University ?, ...
- **common technical challenges**
  - clean ^{163}Ho production
  - ^{163}Ho incorporation
  - large channel number → high speed multiplexing
  - data handling (processing, storage, ...)

ECHO experiment

- Magnetic Metallic Calorimeters with Au absorbers (2 pixels)
  - $\Delta E \approx 8$ eV and $\tau_{rise} \approx 130$ ns
- p on W/Ta target at ISOLDE
  - online separation/implantation
  - $\approx 10^{10}$ ^{163}Ho nuclei







HOLMES (ERC-Advanced Grant n. 340321)

goal

- neutrino mass measurement: m_ν statistical sensitivity as low as 0.4 eV
- prove technique potential and scalability:
  - assess EC *Q*-value
  - assess systematic errors

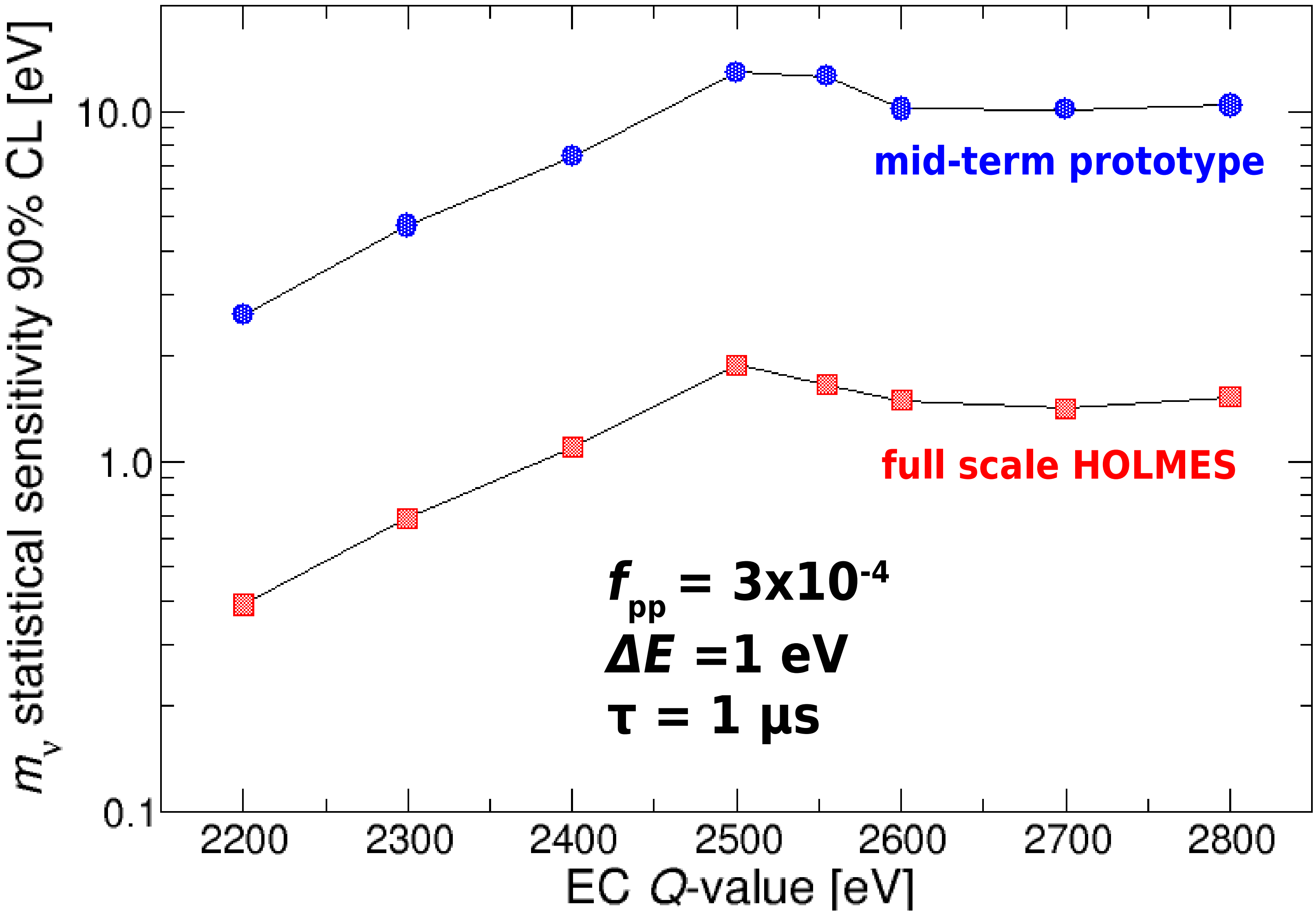
baseline

- Transition Edge Sensors (TES) with ^{163}Ho implanted Au absorbers
  - 6.5×10^{13} nuclei per detector → 300 dec/sec
  - $\Delta E \approx 1$eV and $\tau_R \approx 1\mu s$
- 1000 channel array
  - 6.5×10^{16} ^{163}Ho nuclei → ≈18μg
  - 3×10^{13} events in 3 years

→ Project Start: 1 Feb 2014

http://artico.mib.infn.it/nucriomib/experiments/holmes

HOLMES baseline statistical sensitivity

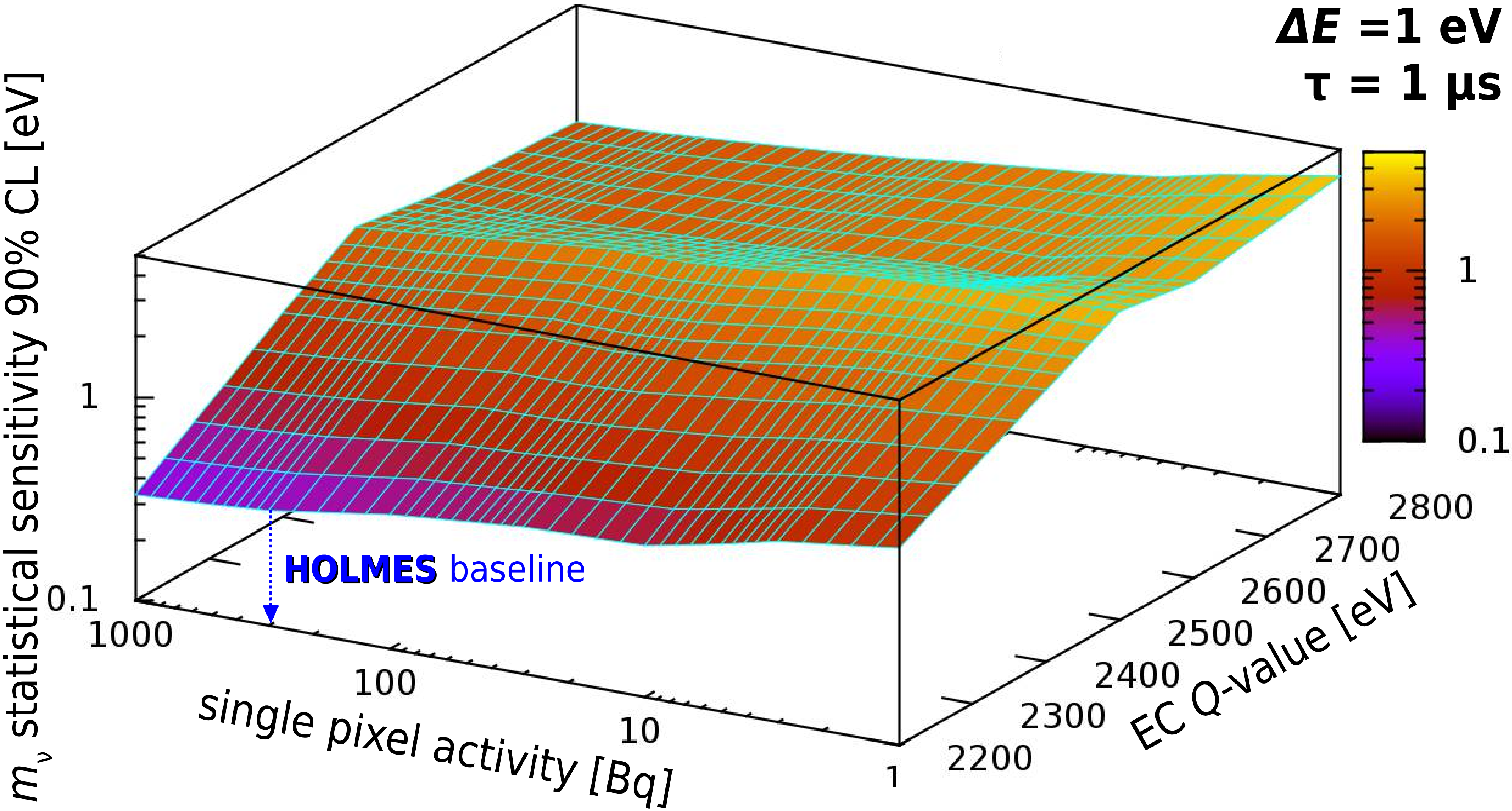


16 channels
t_M=1 month
A=300Hz/ch
→ 10^{10} decays

1000 channels
t_M=3 years
A=300Hz/ch
→ 3×10^{13} decays

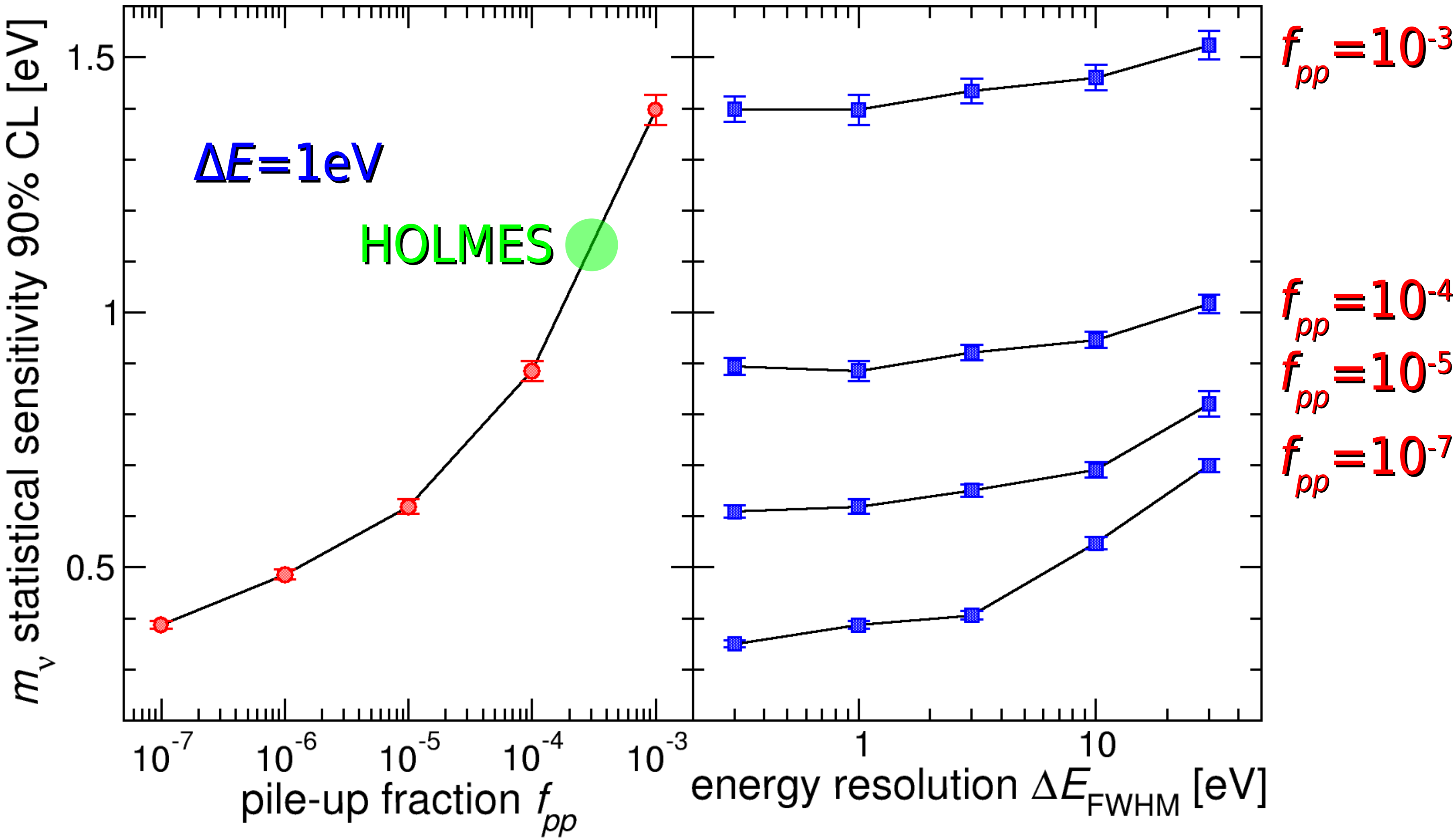
Statistical sensitivity and single pixel activity

1000 channels
t_M=3 years
ΔE =1 eV
τ = 1 µs



More MC simulations...

Q_{EC} = 2.6 keV
N_{ev} = 10^{13}



Low energy background sources / 1

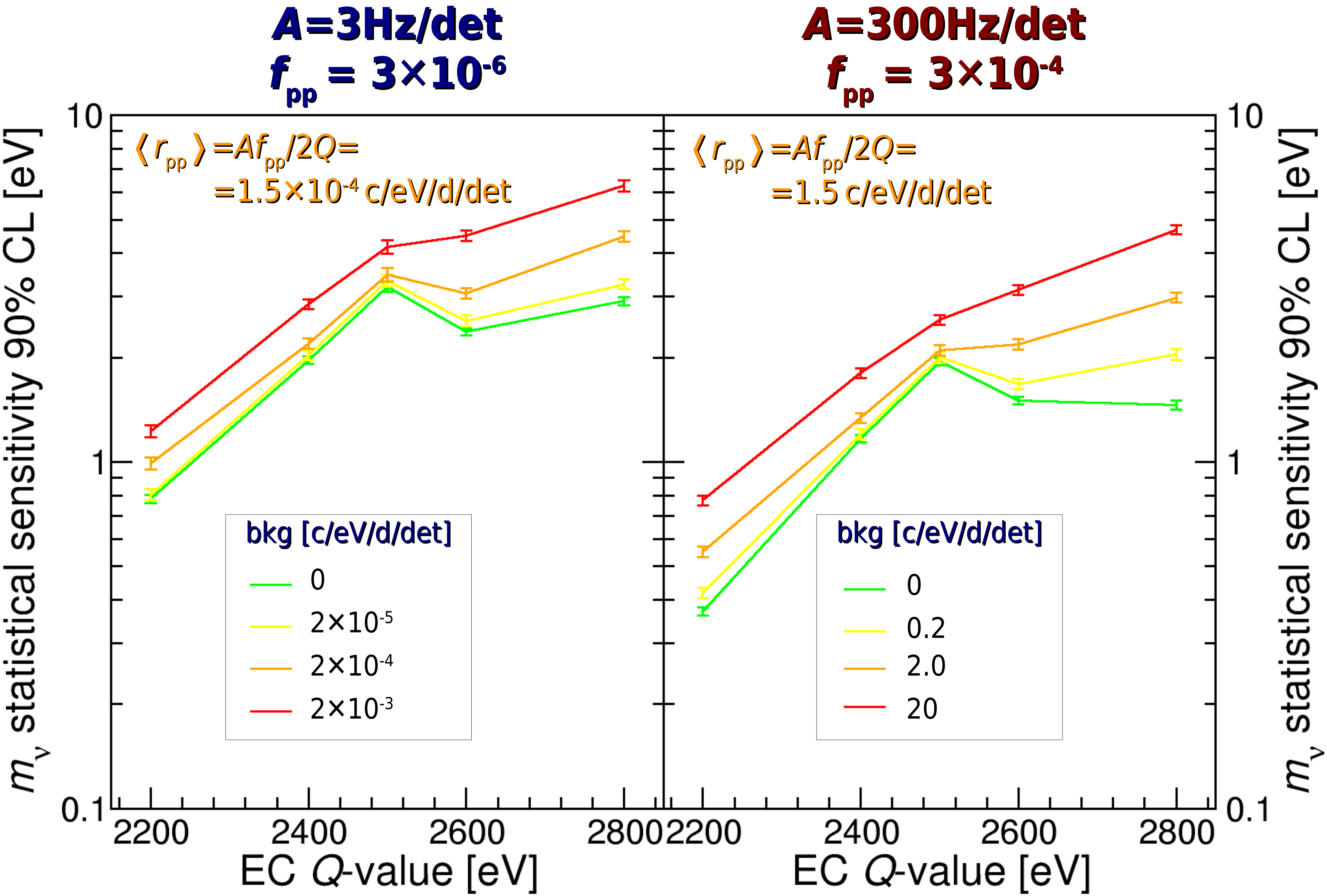
- environmental γ radiation
  - Compton interactions
  - Photoelectric interactions with photoelectron escape
  - fluorescent X-rays and X-ray escape lines
- γ and β from close surroundings
- cosmic rays
  - muons, ...
  - EM showers
- ...

Cosmic rays at sea level (muons)

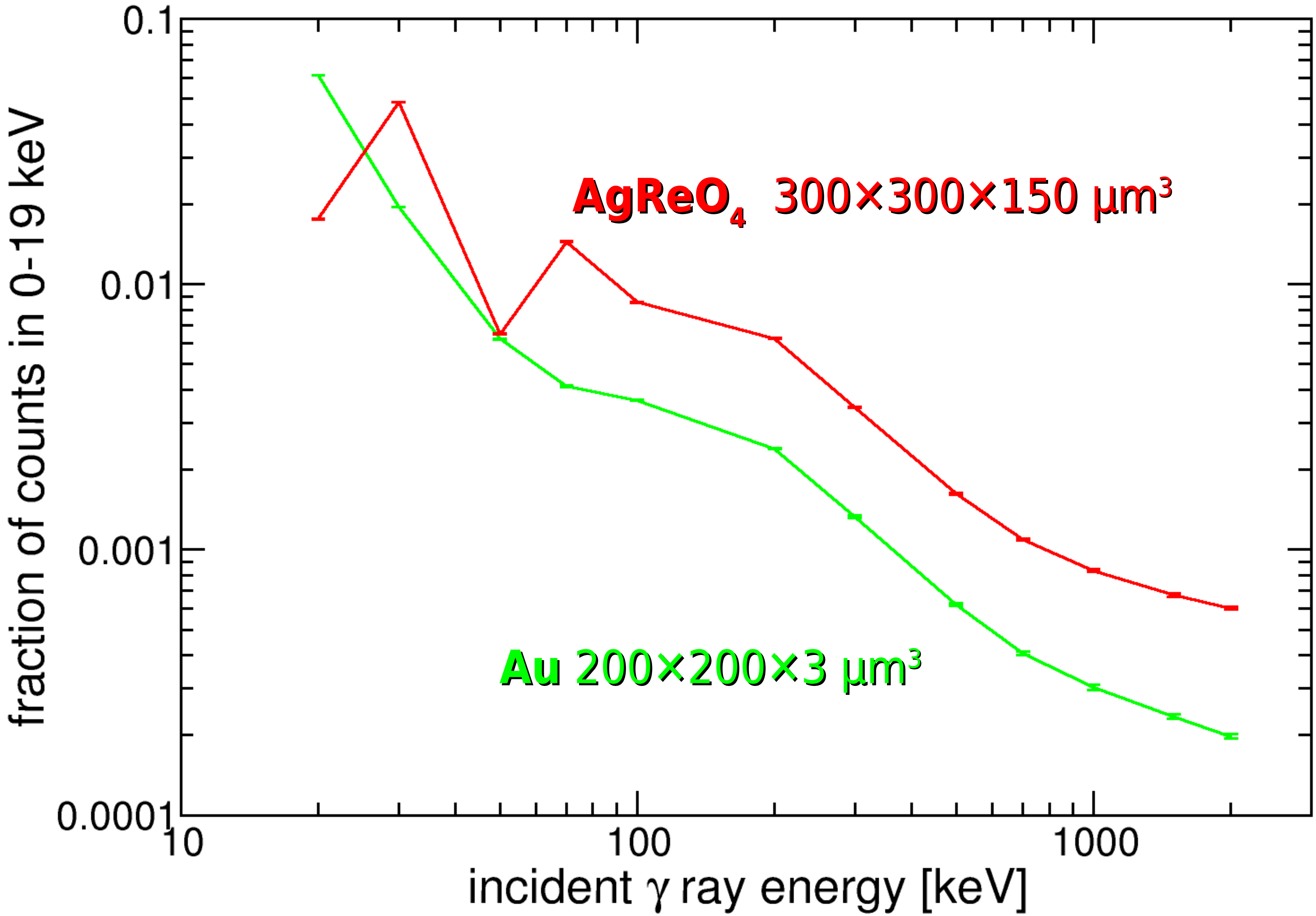
- Au pixel: 200×200×3 μm^3
  - ▷ $\langle \Delta E \rangle \approx$ 10keV, $r \approx 1\ d^{-1}$
- array Si substrate: 20×20×0.5 mm^3
  - ▷ $\langle \Delta E \rangle \approx$ 300keV, $r \approx 7000\ d^{-1}$

- **MIBETA**: 300×300×150 μm^3 $AgReO_4$ crystals
  - ▸ bkg(2..5keV)≈1.5×10^{-4} c/eV/d/det
- **TES @NIST** (1600m): 350×350×2.5 μm^3 Bi absorbers
  - ▸ bkg<1 c/eV/d/det (preliminary measurement: not conclusive...)

Effect of background on sensitivity



Low energy background sources / 2



HOLMES tasks

- ^{163}Ho isotope production
- ^{163}Ho isotope embedding in detector
- single TES optimization and testing
- TES array design, engineering and testing
- SQUID read-out and multiplexing optimization and testing
- room temperature signal processing and in-line analysis
- cryogenic set-up

^{163}Ho production and embedding

^{163}Ho production by nuclear reaction

- high yield
- low by-products contaminations (in particular ^{166m}Ho, β $\tau_{½}$=1200y)
- not all cross sections are well known
  - → neutron activation of enriched ^{162}Er (nuclear reactor)
  - → ^{163}Dy(p,n)^{163}Ho E_p>10 MeV (direct, low yield → PSI?)
  - → ^{nat}Dy(α,xn)^{163}Er and ^{159}Tb(^{7}Li, 3n)^{163}Er

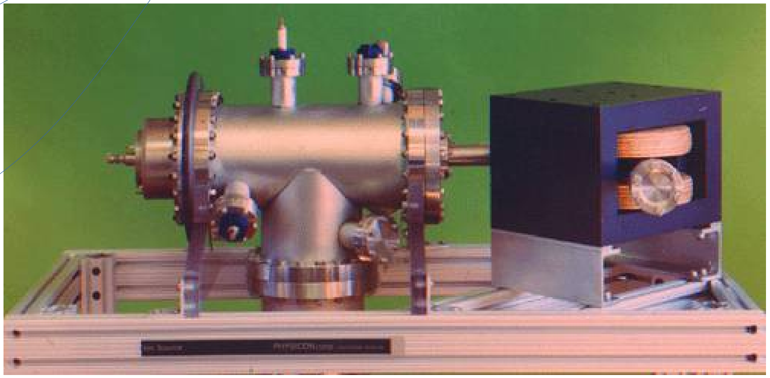
HOLMES baseline

^{163}Ho Separation from Dy, Er and more ...

- radiochemistry (before and/or after irradiation)
- magnetic mass separation
- resonance ionization laser ion source (RILIS)?

^{163}Ho embedding in detector absorber

- implantation (+magnetic separation)
- Au film deposition for full containment



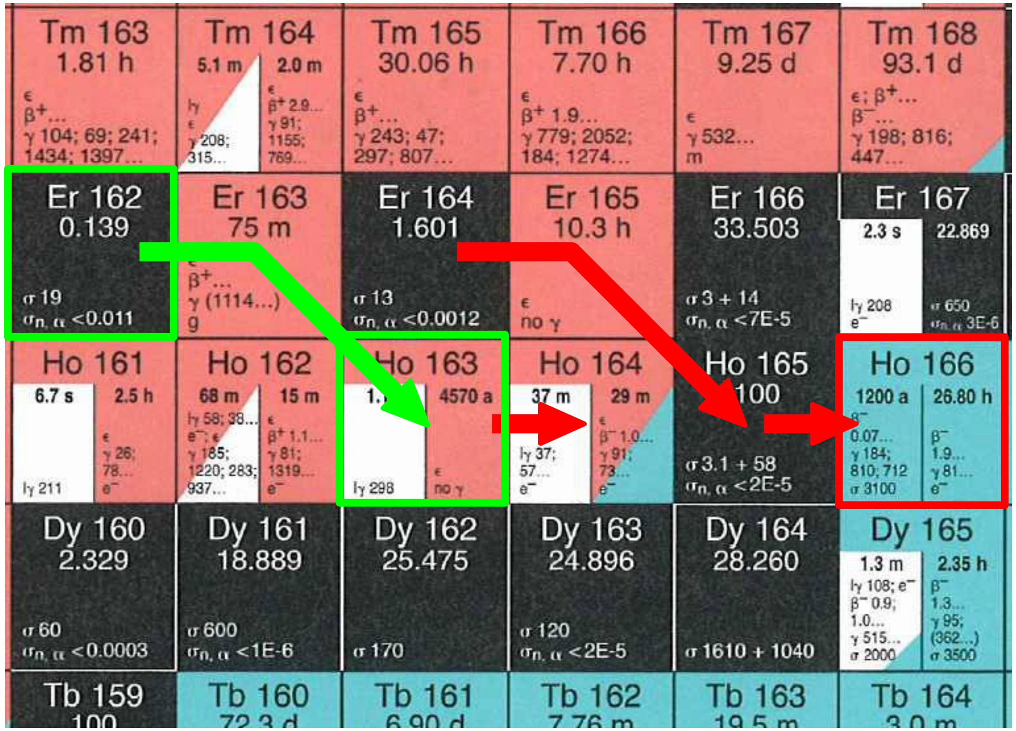
ECHO

J.W. Engle et al., NIM B 311 (2013) 131–138

particle	p	n 10^{14} n/cm2/s	p 16 MeV 80 μA	p 24 MeV 240 μA	α 40 MeV 30 μA
target	W/Ta	^{162}Er (40%)	^{nat}Dy 200mg/cm^2	^{nat}Dy 20g	^{nat}Dy "thick"
^{163}Ho prod rate [nuclei/h]	10^{14}	10^{13-15}/ mg ^{162}Er	10^{14}	10^{15}	10^{13}

U. Koester @NuMass 2013

^{163}Ho production by neutron activation



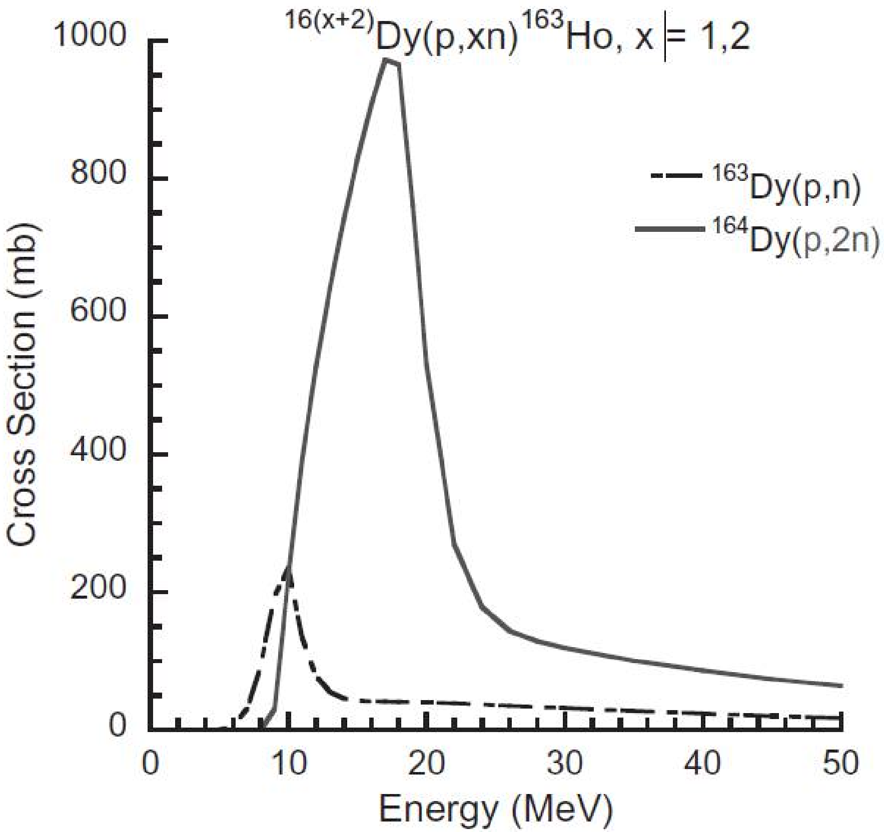
^{162}Er (n,γ) ^{163}Er $\sigma_{thermal} \approx 20$b

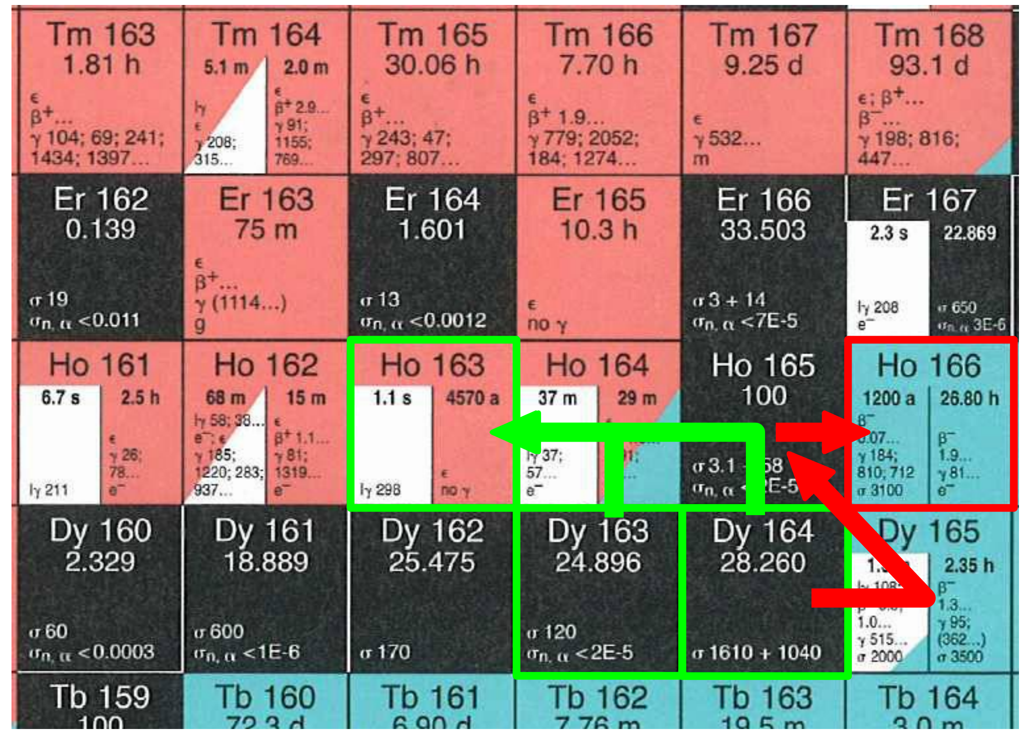
^{163}Er → ^{163}Ho + ν_e $\tau_{½}^{EC} \approx 75$min

- only few experimental data for almost all cross sections involved
- possibly high yield
  - ≈3×10^{12} ^{163}Ho nuclei/mg(^{162}Er)/h for a thermal neutron flux of 10^{13} n/cm^2/s
- ^{163}Ho(n,γ)^{164}Ho (burn-up)?
- ^{165}Ho(n,γ) (from Ho contaminations or ^{164}Er(n,γ)) → ^{166m}Ho, β $\tau_{½}$=1200y
- analyse ^{163}Ho content in MARE-RD activated samples → ICPMS
- requires enrichement and oxide chemical form (Er_2O_3)

^{163}Ho production by p irradiation

^{163}Dy (p,n) ^{163}Ho and ^{164}Dy (p,2n) ^{163}Ho



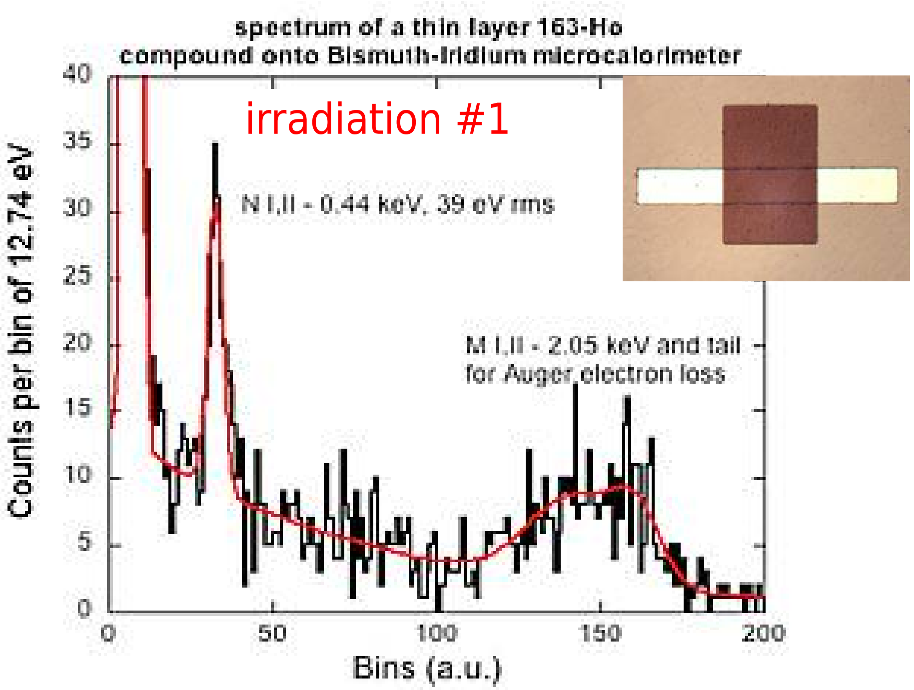


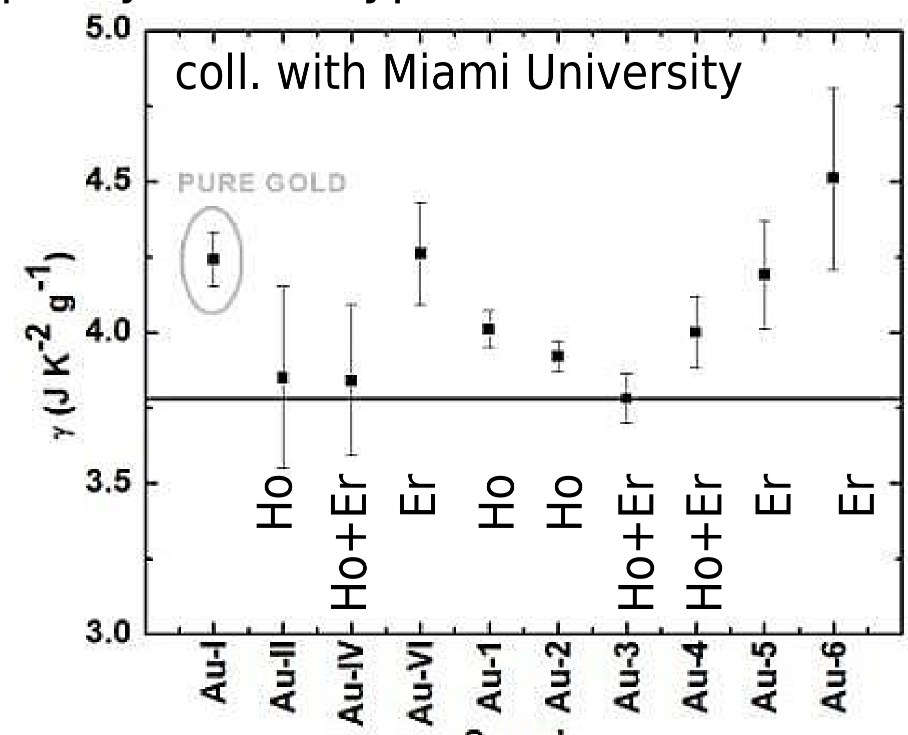
- only few experimental data for almost all cross sections involved
- metallic Dy target with natural composition
- lower yield
- many high energy neutrons produced by (p,*x*n) on Dy isotopes
  - ^{165}Ho(n,γ) (from Ho contaminations or ^{164}Dy(n,γ)) → ^{166m}Ho, β $\tau_{1/2}$=1200y

MARE-RD: ^{163}Ho production

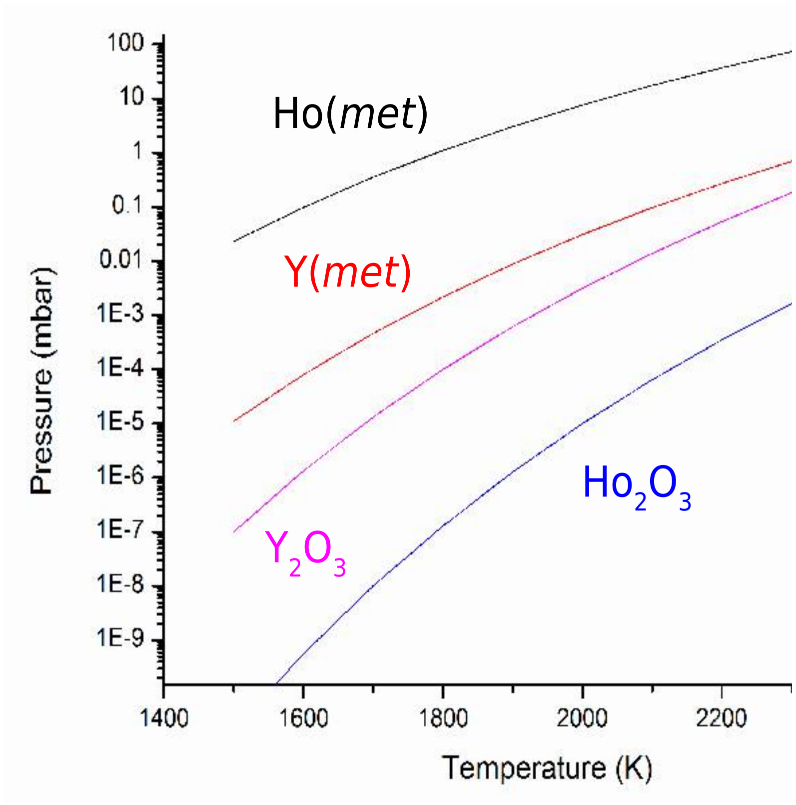
- ^{163}Ho production by Er:^{162}Er enriched neutron irradiation
  - ▹ 3 irradiatons at Lisboa research reactor (ITN)
  - ▹ 1 irradiation at Grenoble reactor (ILL) → >10MBq of ^{163}Ho (now *cooling*...)
- Er_2O_3/Ho_2O_3 thermoreduction→ metallic target for implantation
  - ▹ $Y_5Si_3+Ho_2O_3 \rightarrow Y_{5-x}Ho_xSi_3$ a 600-800°C: didn't work out...
  - ▹ $Ho_2O_3+2Y(met) \rightarrow 2Ho(met)+Y_2O_3$ at 2000°C: it worked...

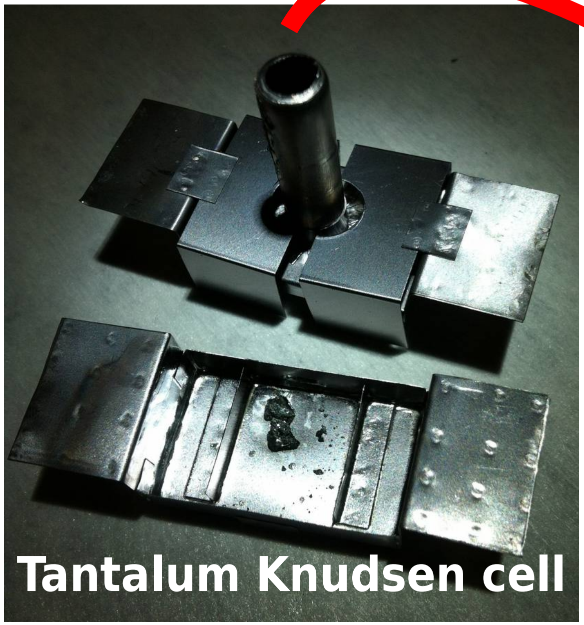
- effect of Ho/Er implantation in Au absorbers
  - ▹ magnetic contributions to Au heat capacity due to hyperfine interactions

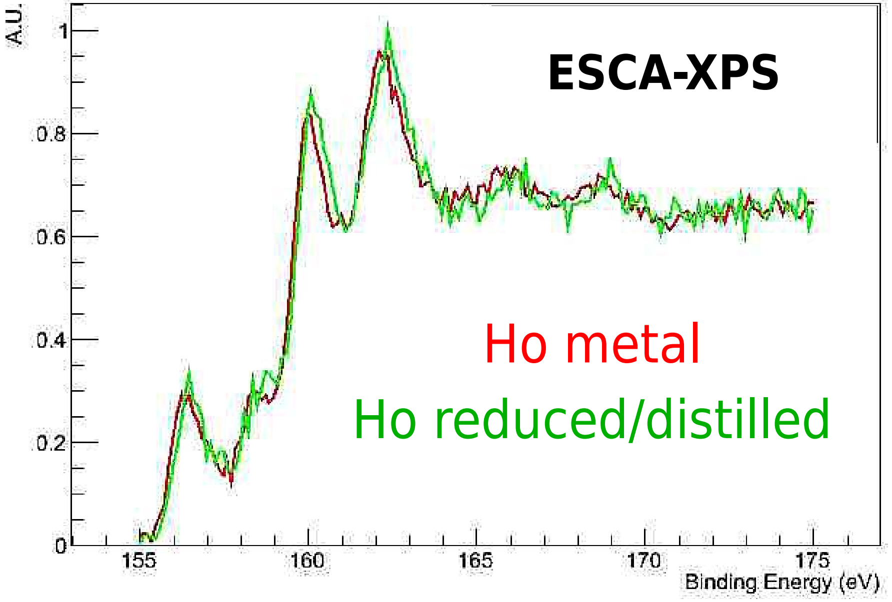




MARE-RD: Ho oxide reduction



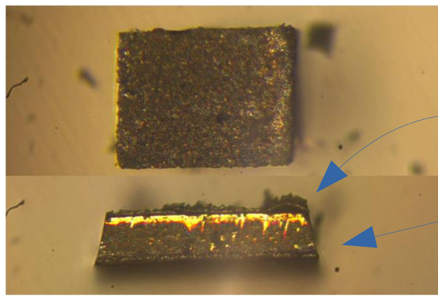




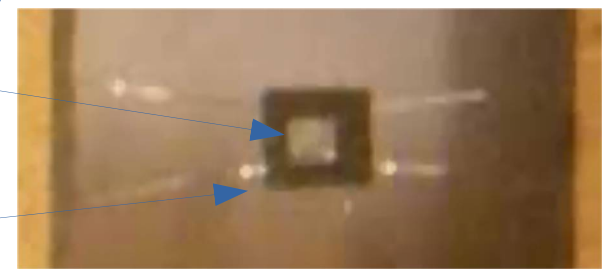
- Ho_2O_3 distillation around 2000K
- XPS on deposited film:
  - 80% metallic Ho
  - 20% re-oxidized Ho

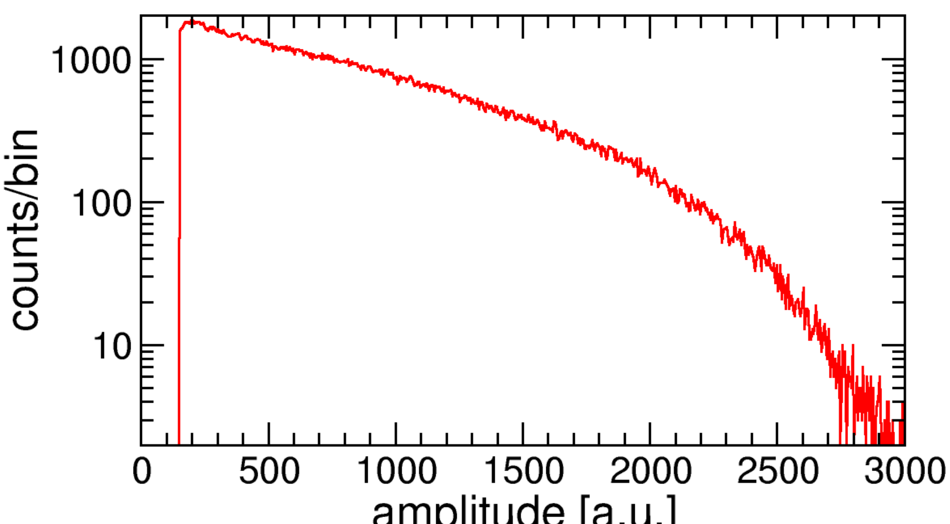
MARE-RD: tests on irradiated samples

- sample from irradiated Er_2O_3 (^{162}Er enriched at 20%) powder (#2)
- Er_2O_3/Ho_2O_3 distillation at ≈2000K
- deposition on thinned Sn single crystal



sandwiched Sn absorbers
coupled to
Si implanted thermistors

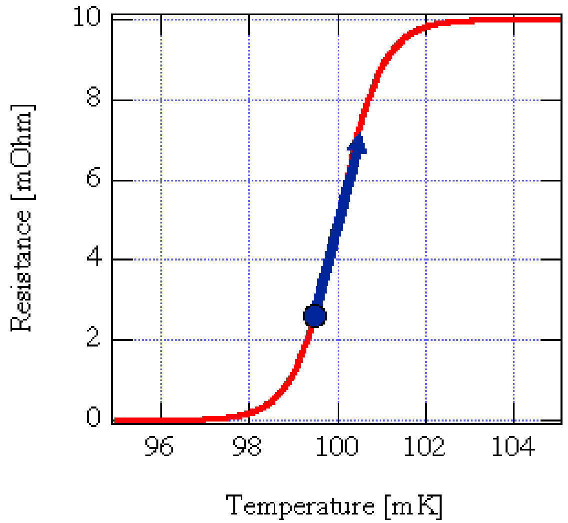


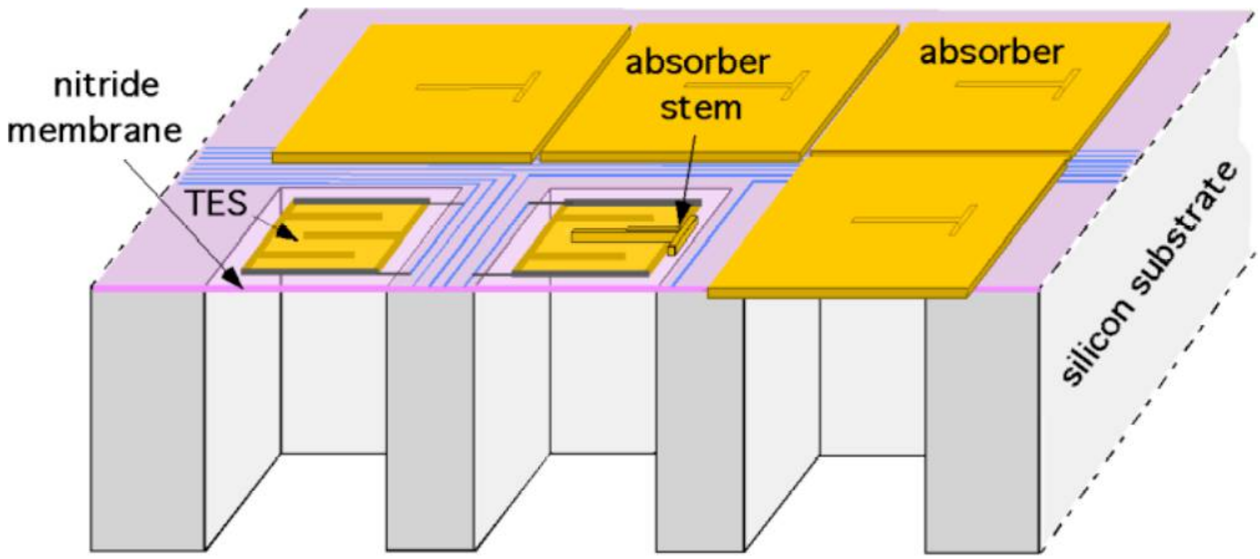


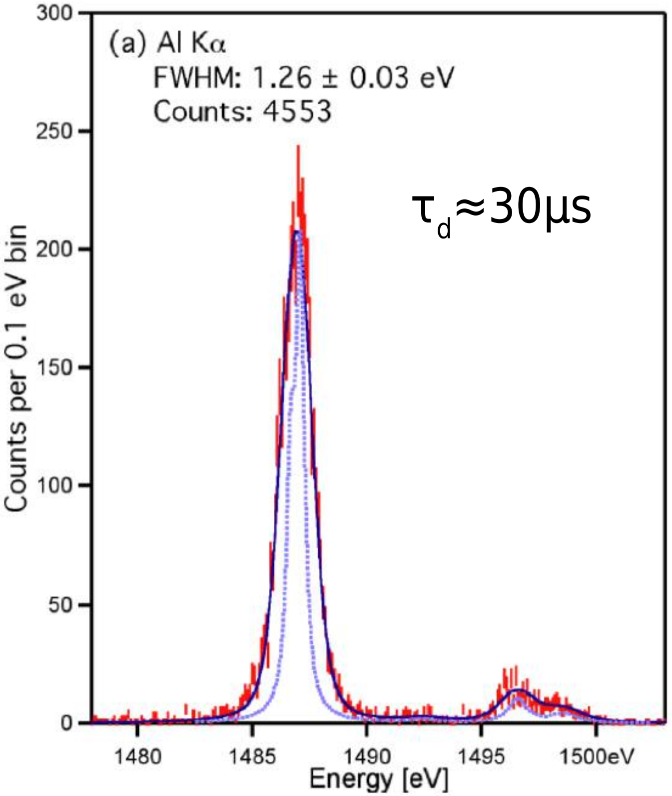
- no ^{163}Ho peaks
- continuum ≈1c/s
  → β from ^{152}Eu in irradiated sample?
- more tests...
- sample analysis ICPMS (@LNGS), ...
- sample purification

HOLMES detectors

- Transition Edge Sensors (TES) with Bi/Au absorber
  - ▷ hot electron microcalorimeters with electro-thermal feedback
  - ▷ 2 µm thick electrodeposited Au for full absorbtion
- MoAu or MoCu proximity TES → $T_c \approx 100$mK
- on Si_2N_3 membrane



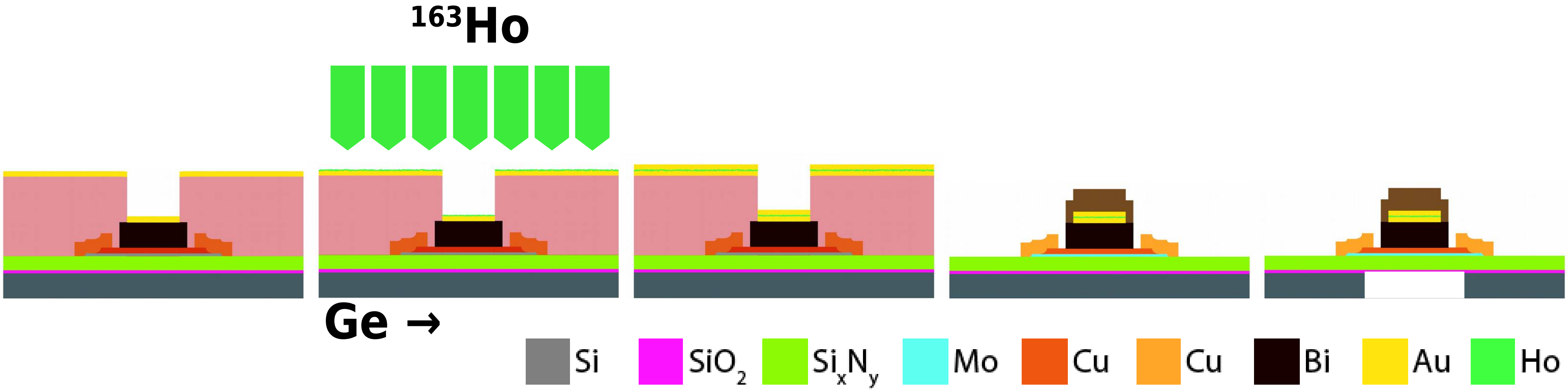




NASA/GSFC

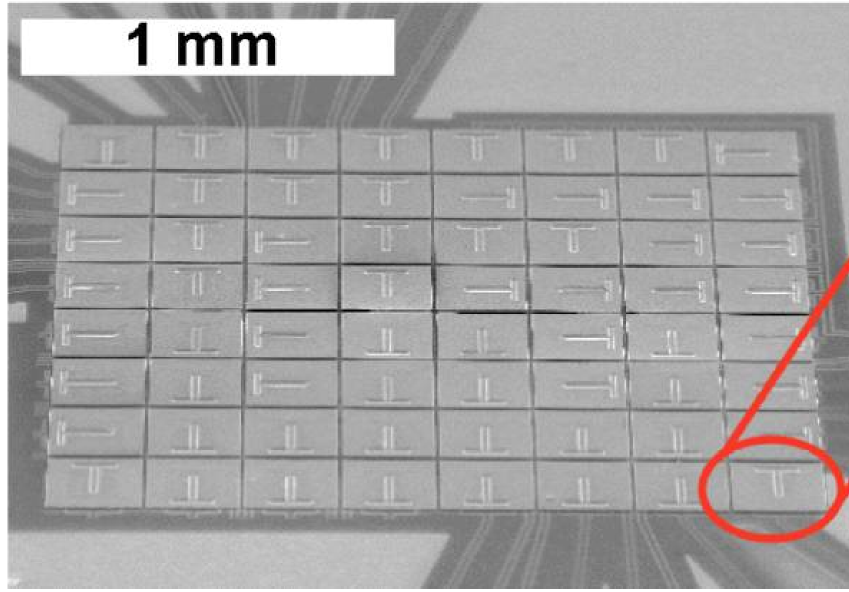
HOLMES detector array fabrication

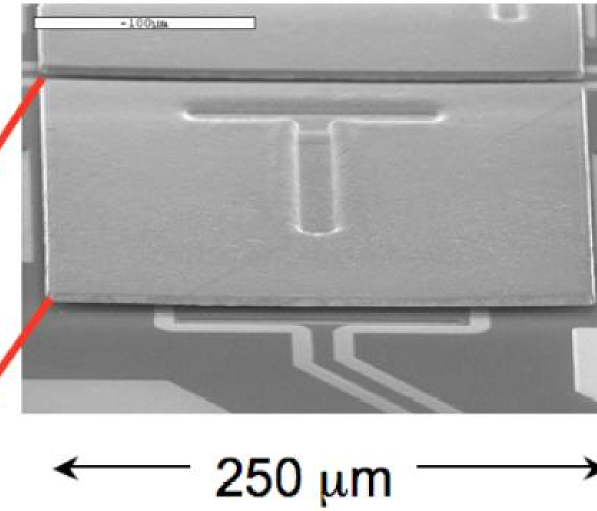
- single pixel development @Genova
  - ▷ optimize design for speed and resolution
  - ▷ define process for ^{163}Ho implantation
- array design @Genova
- subcontract array fabrication (NIST, Boulder, USA)
  - ▷ subcontractor fabricates array with 1 μm Au absorber
- Genova completes array fabrication
  - ▷ Genova implants ^{163}Ho at shallow depth (≈100Å)
  - ▷ Genova covers implant with 1 μm Au absorber
  - ▷ Genova completes array fabrication (Si_2N_3 release)

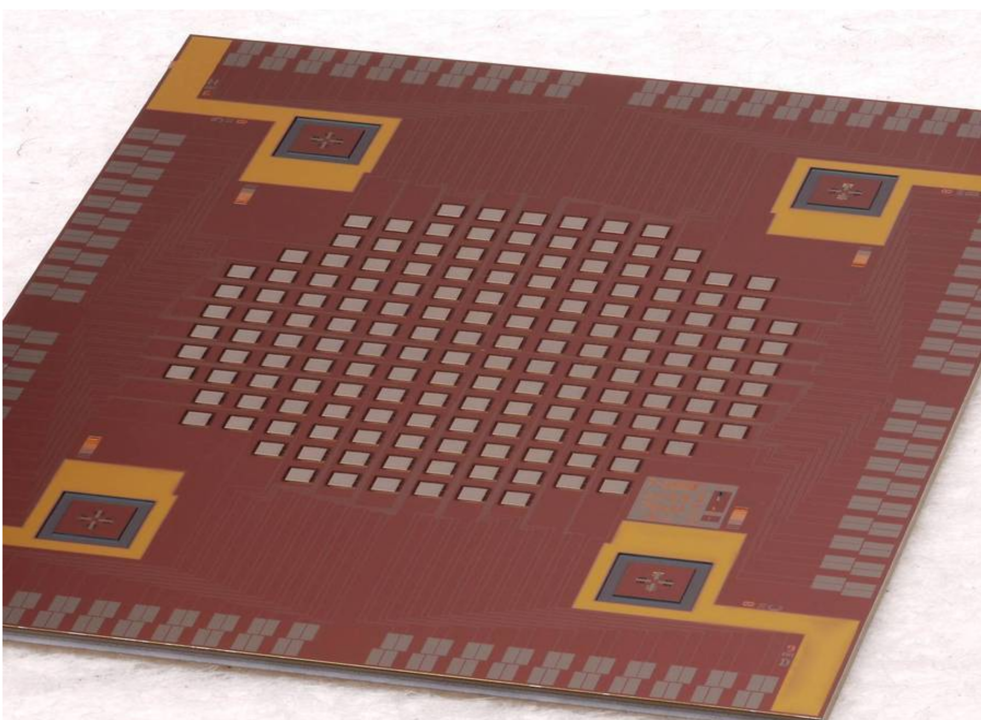


HOLMES detector array

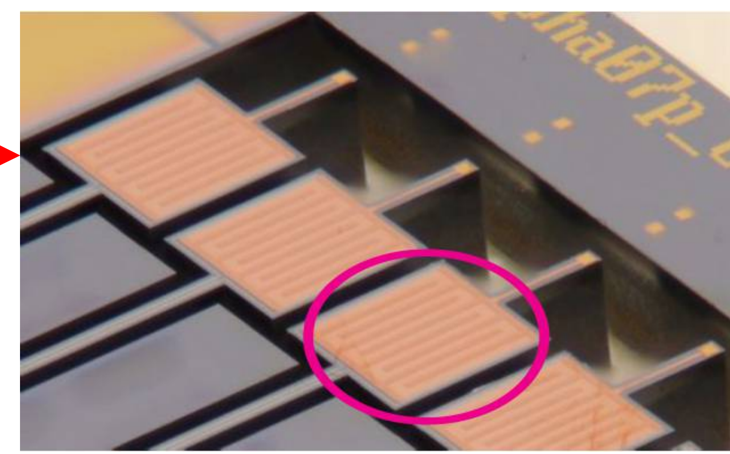
NASA/GSFC







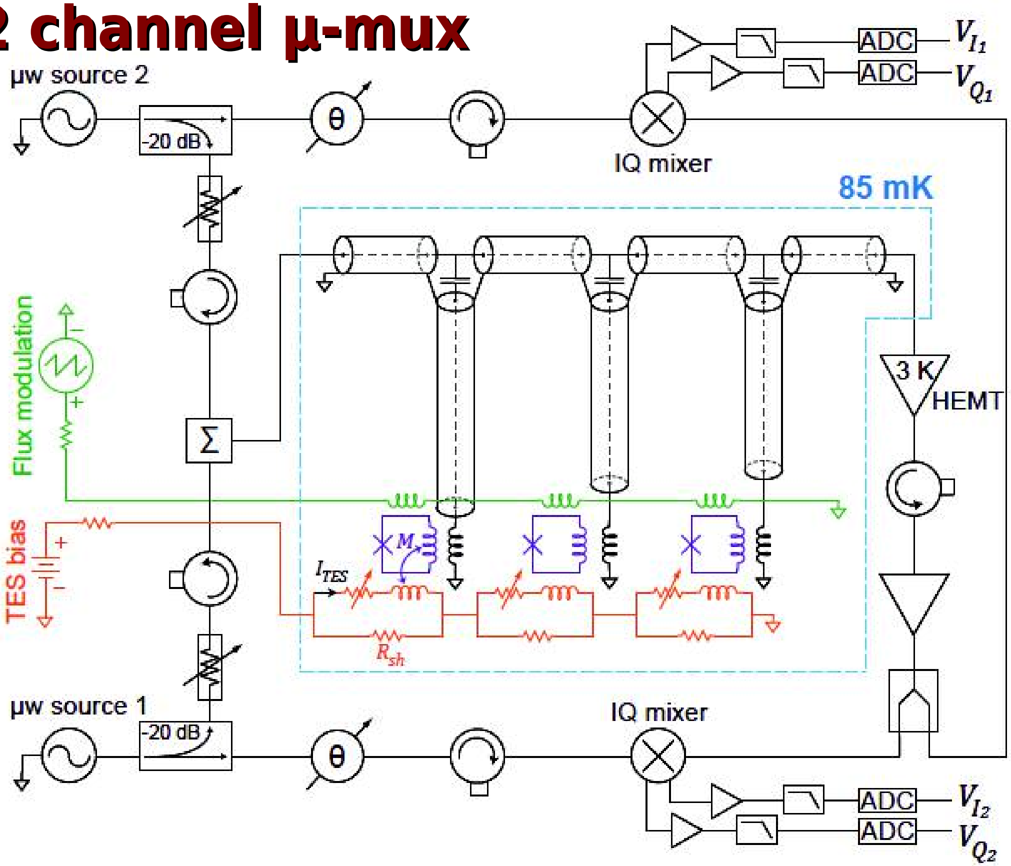
NIST

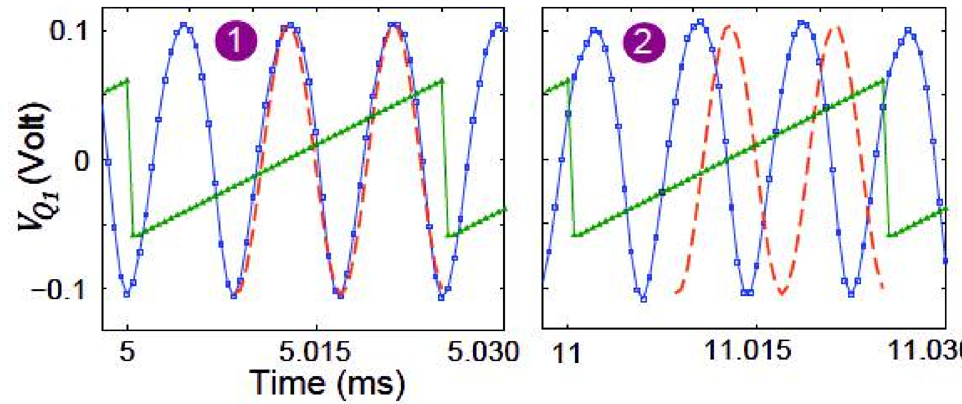


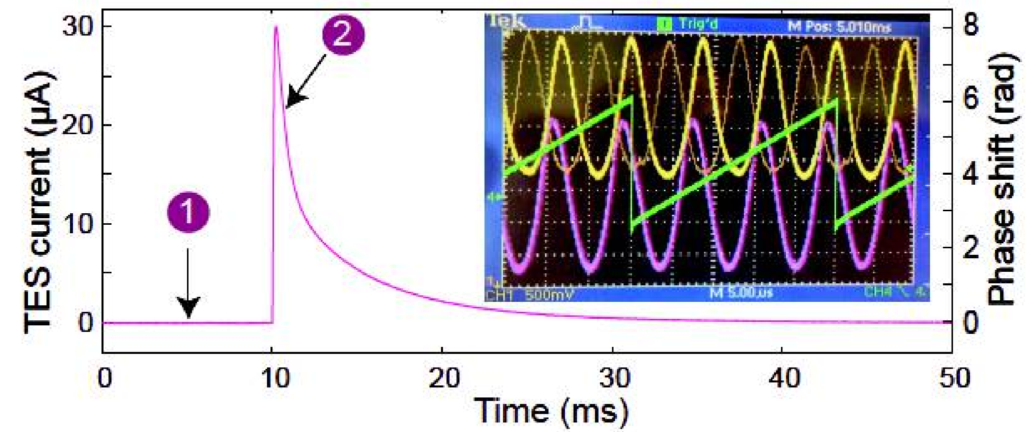
→ **HOLMES array**: 256 sparse pixels (4x)

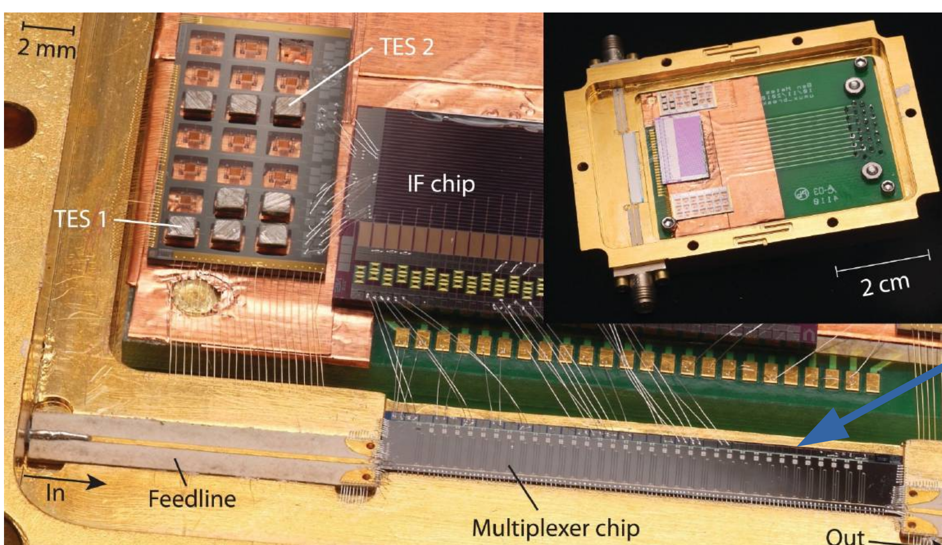
HOLMES array multiplexing: RF SQUID mw-mux

2 channel μ-mux

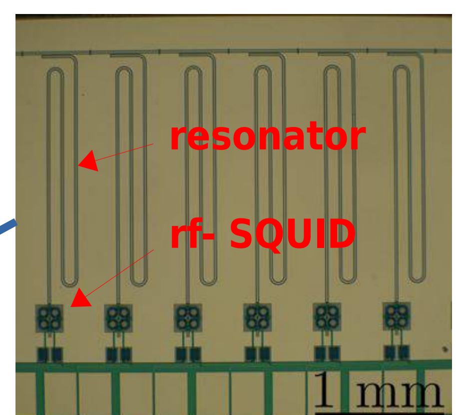








O. Noroozian et al., "High-resolution gamma-ray spectroscopy with a microwave-multiplexed transition-edge sensor array", proceedings LTD-15 arXiv:1310.7287



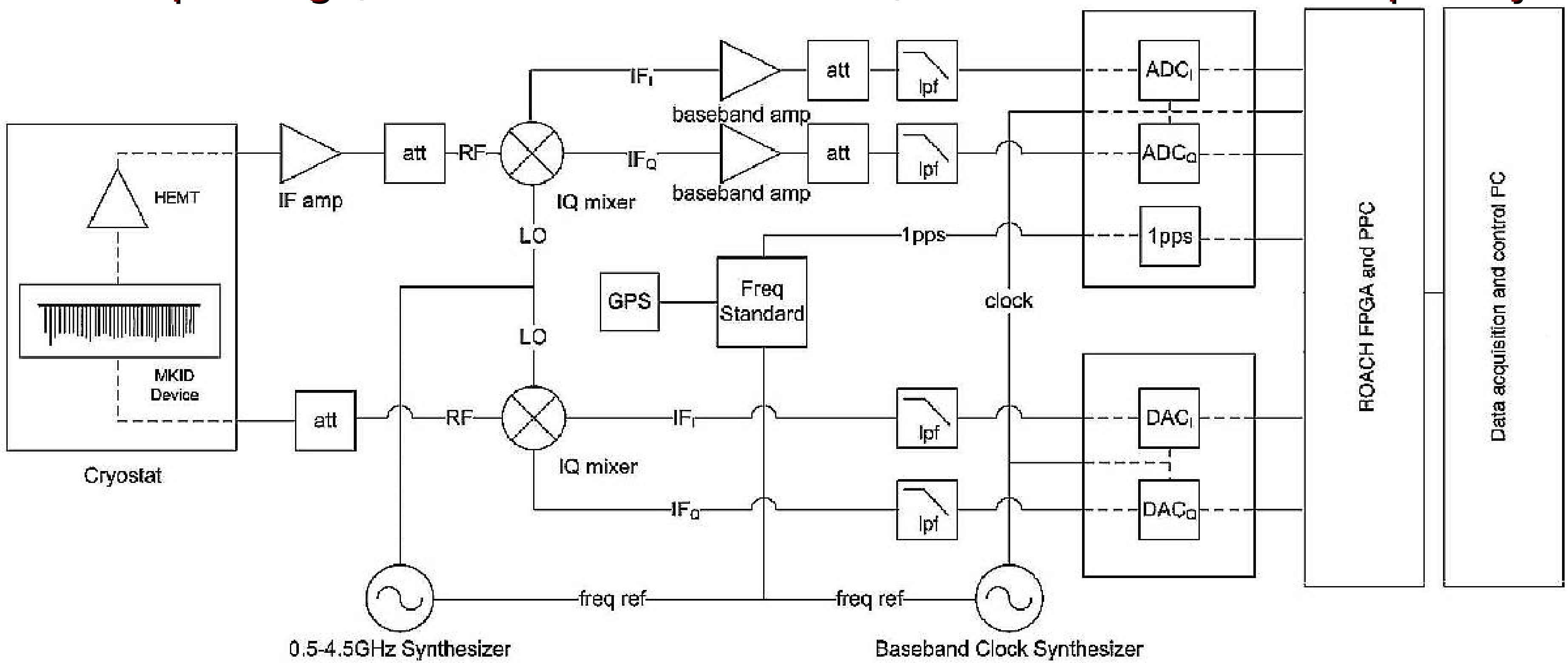
- **dc TES biasing**
- **always ON TESs**

$$\phi = \frac{2\pi M}{\Phi_0} I_{\mathrm{TES}}$$

$$\phi = \arctan\left(\frac{\sum V_Q \sin \omega_m t}{\sum V_Q \cos \omega_m t}\right)$$

HOLMES array multiplexing: DAQ

Digital multiplexing (Software Defined Radio) based on ROACH-2 open system



mux factor: 64

ADC: 550MS/s 12 bit

bandwidth/channel: 8.6MHz

bandwidth for 1µs rise time: 160kHz

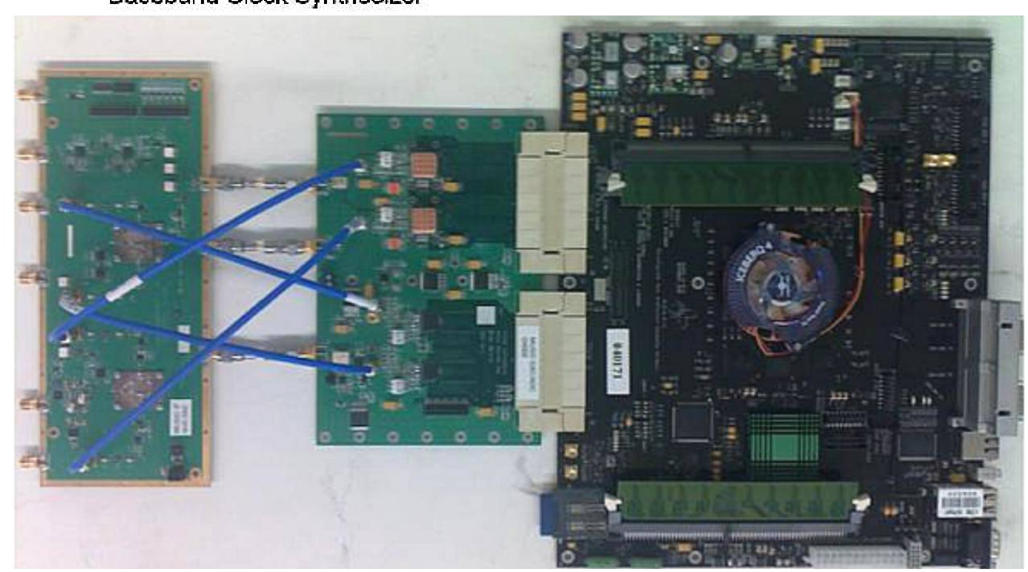
→ 64 resonances between 0 and 550MHz

→ up-conversion → 5-5.5GHz

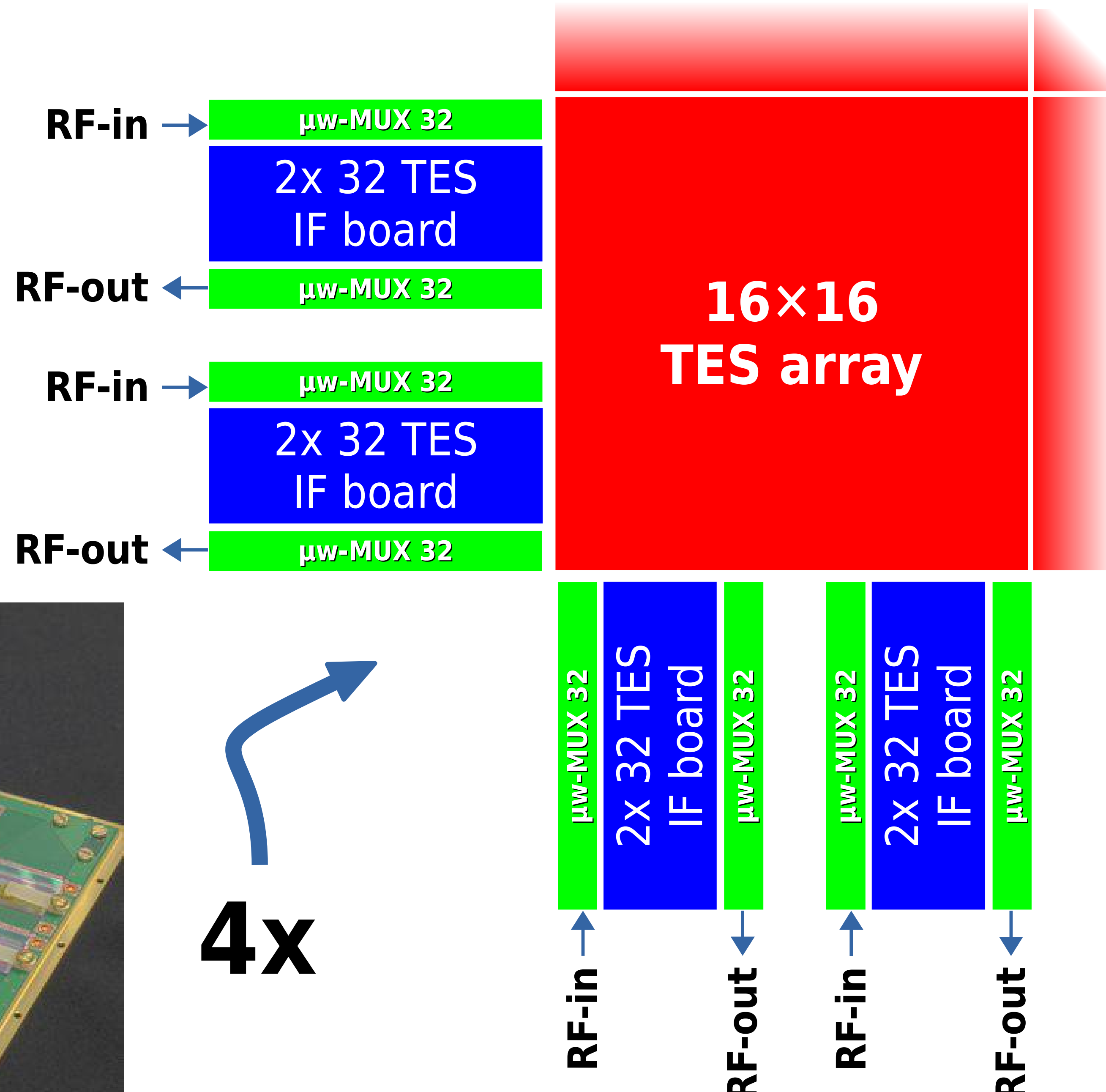
→ down-conversion → 0-500MHz

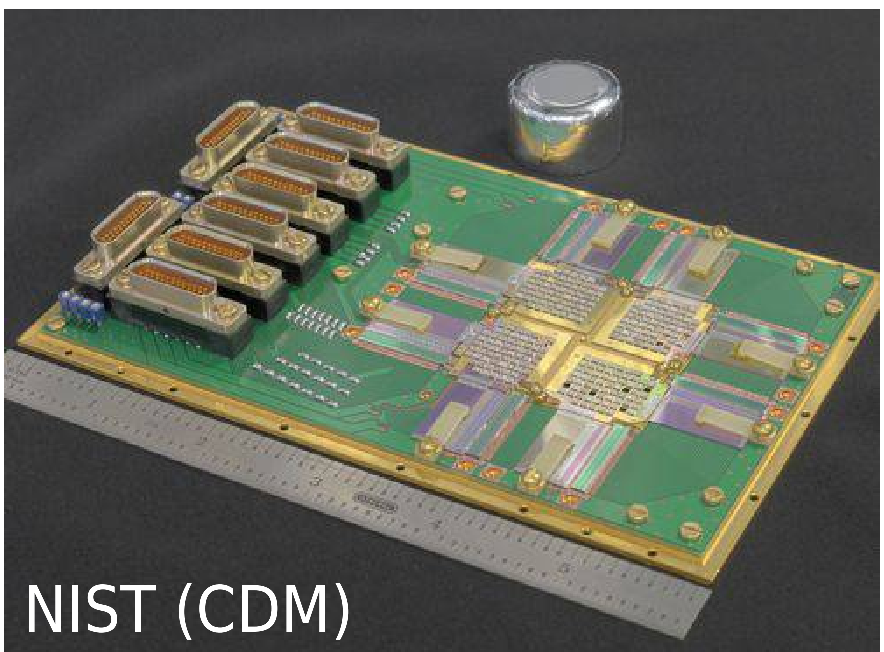
→ IQ signal demux

→ rfSQUID signal demodulation



HOLMES array multiplexing / 3





HOLMES signal processing and in-line analysis

data throughput with digitized pulses
3×10^5 decay/s x 2k (rec len) x 16 bit = 2.5GB/s

- reduce resolution (12 bit) and record length (256)
- use variable sampling time
- **real time pulse processing**
  - optimal filtering, pile-up detection, pulse shape analysis
- commissioning and periodic minimum bias samples
  - tune parameters for real time pulse processing in normal data taking
  - full waveform saved to disk for immediate off-line analysis
  - full spectrum (10% live time) and with ≈2.0keV thershold (90%)
  - **2TB/day** (to be stored only temporary)
- normal data taking
  - save only n-tuples (8 × 4 byte words) for each event above ≈2.0keV
  - **140TB in 3 years**

Alternatives to HOLMES baseline

- **^{163}Ho production route** (baseline: neutron activation of ^{162}Er)
  - ^{163}Dy(p,n)^{163}Ho E_p>10 MeV at PSI
- **Detector tecnology** (baseline: TES with multiplexed SQUID read-out)
  - Thermal mode microresonators with microwave multiplexing (FBK)
- **Detector read-out** (baseline: ~~Code Division Multiplexing with dcSQUID~~)
  - microwave rfSQUID multiplexing
  - microwave mux with Kinetic inductance parametric up-converter

Broader impact

large arrays for high flux high resolution X-rays spectroscopy

- astrophysics → ATHENA, ...
- material science → XAS, XAS imaging, XRF, XES ...
  - chemistry and biology
  - archeometry
  - ...
- time resolved sub-picosecond XAS
- nuclear safeguard and nuclear reactor fuel diagnostic

HOLMES schedule

	Project year	Y1		Y2		Y3		Y4		Y5	
Activities	**Tasks**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**48**	**54**	**60**
Isotope production	Production optimization	■	■	■							
	Final production				■	■					
Pixel optimization	TES sensor design optimization and tests	■	■	■							
	Absorber ^{163}Ho embedding	■	■ 2								
	Absorber with isotope optimization		■	■	■						
Array	Prototype production and testing		■	■							
	4x4 array production				■						
	32x32 array engineering and production					■	■				
Multiplexed read-out	SQUID/MUX development and tests	■ 1	■	■							
	SQUID/MUX prototype				■						
	SQUID and MUX production					■	■				
RT electronics and data processing	Analog/digital signal processing R&D and tests	■	■	■	■						
	Analog/digital signal processing for prototype					■					
	Analog/digital signal processing for HOLMES						■	■			
	Server and storage system					■	■	■			
Software Tools	Neutrino mass analysis package	■	■	■	■						
	In-line signal processing algorithm development			■	■	■	■				
Cryogenics	Temporary set-up for testing	■									
	Dilution refrigerator installation	■	■								
	Set-up for prototype measurement					■					
	HOLMES setu-up					■	■				
Physics Measurements	4x4 array commissioning and data taking					■ 3					
	32x32 array commissioning						■				
	Engineering run							■			
	HOLMES data taking								■ 4	■	■
	Preliminary analysis and physics results									■	■

Project Start: 1 Feb 2014

HOLMES schedule (updated)

		2014		2015		2016		2017		2018	
	Project year	Y1		Y2		Y3		Y4		Y5	
Activities	**Tasks**	6	12	18	24	30	36	42	48	54	60
Isotope production	Production optimization										
	Final production										
Pixel optimization	TES sensor design optimization and tests										
	Absorber ^{163}Ho embedding system		2								
	Absorber with isotope optimization										
Array	Prototype production and testing			●							
	4x4 array production										
	32x32 array engineering and production										
Multiplexed read-out	SQUID/MUX development and tests	1									
	SQUID/MUX prototype										
	SQUID and MUX production										
RT electronics and data processing	Analog/digital signal processing R&D and tests										
	Analog/digital signal processing for prototype										
	Analog/digital signal processing for HOLMES										
	Server and storage system										
Software Tools	Neutrino mass analysis package										
	In-line signal processing algorithm development										
Cryogenics	Temporary set-up for testing										
	Dilution refrigerator installation										
	Set-up for prototype measurement										
	HOLMES setu-up										
Physics Measurements	4x4 array commissioning and data taking						● 3				
	32x32 array commissioning										
	Engineering run										
	HOLMES data taking								4	●	
	Preliminary analysis and physics results										

Project Start: 1 Feb 2014

● key measurements

HOLMES present status

- irradiated Er_2O_3 sample with 10MBq ^{163}Ho **cooling** at ILL reactor
- irradiated Er_2O_3 samples ICP-MS analysis **in progress**
- Ho distillation/reduction system assembly **in progress**
- custom ion implanter design **in progress**
- optimized TES design **in progress** (with NIST)
- upgrade of TES fab facility @Genova **in progress**
- cryogen free OxfInst Triton200 refrigerator **in production**
- TES testbed with muxed micro-wave read-out installation **in progress**
- microwave multiplexed rfSQUID read-out design **in progress**
- ROACH-2 system for testing **delivered**

first TES detectors with implanted ^{163}Ho: July 2015

Conclusions

- **HOLMES is challenging project!**
  - it will assess the real potential of ^{163}Ho experiments
  - it will give interesting limits on the neutrino mass
  - it may be a technology demonstrator for an experiment with ≤0.1 eV sensitivity