HOLMES

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

ERC-Advanced Grant 2013

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Additional Beneficiary: Univ. di Milano-Bicocca

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

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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

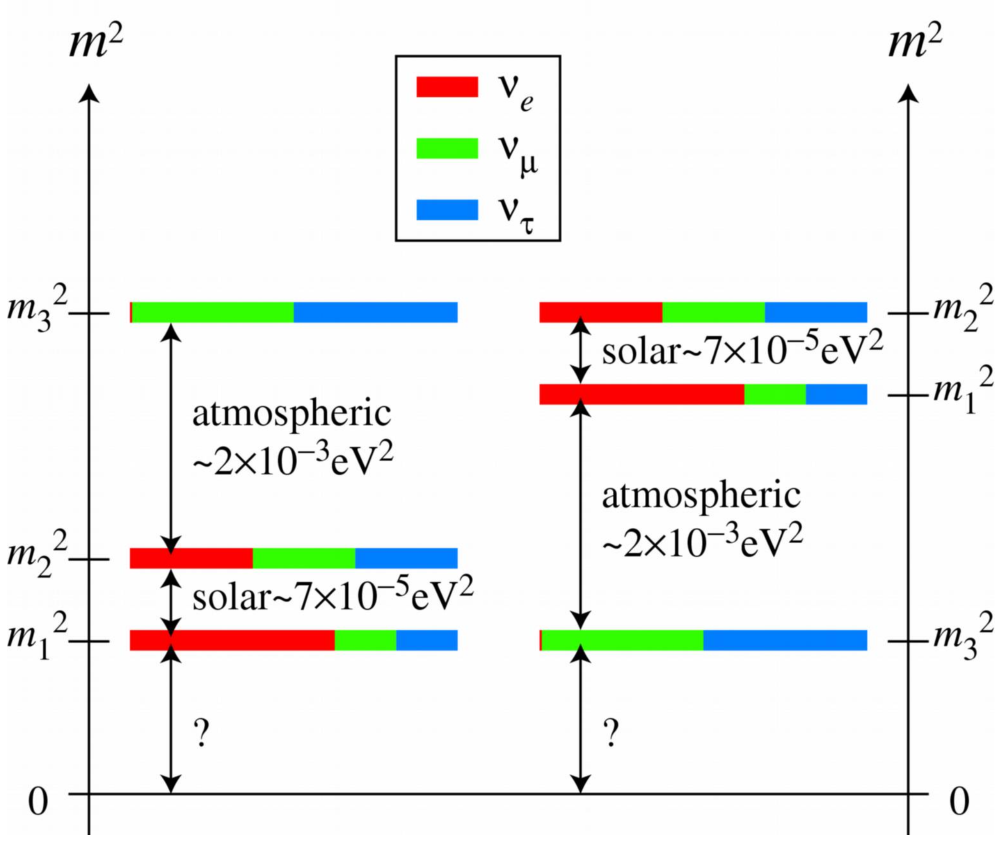
$$|\nu_l\rangle = \sum_k U_{lk} |\nu_k\rangle$$

neutrino flavor weak eigenstate

→ neutrino oscillation experiments measure

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

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



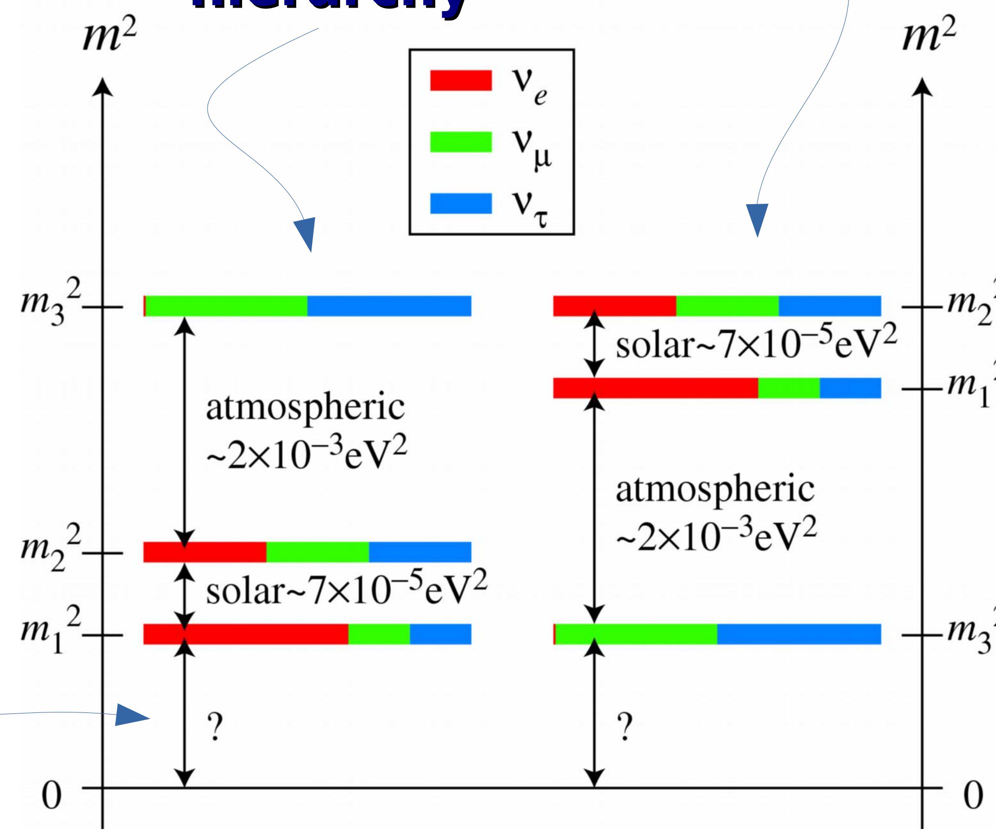
Neutrino open questions

- 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

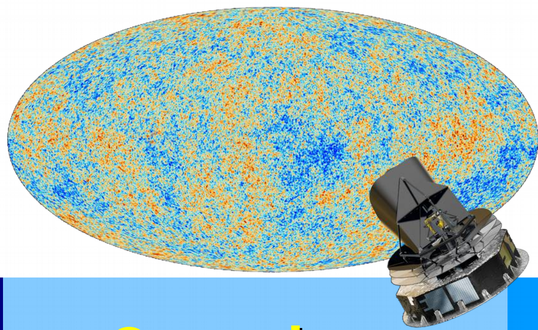
normal hierarchy

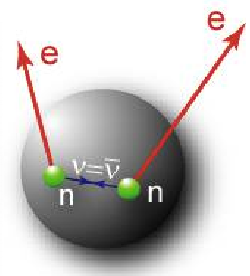
mass scale

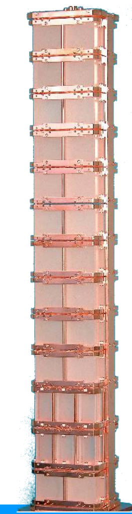


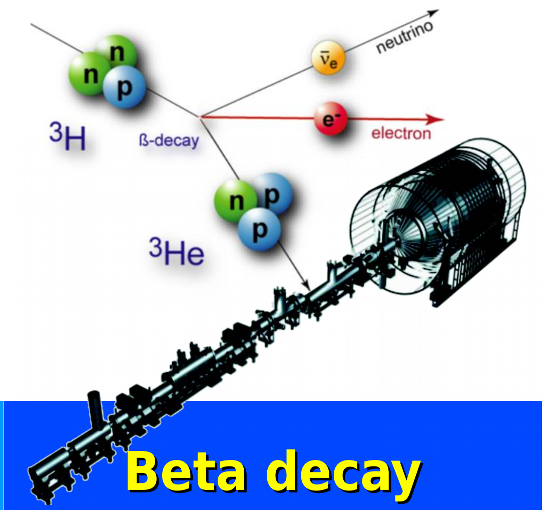
Mass scale: experimental tools / 1

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







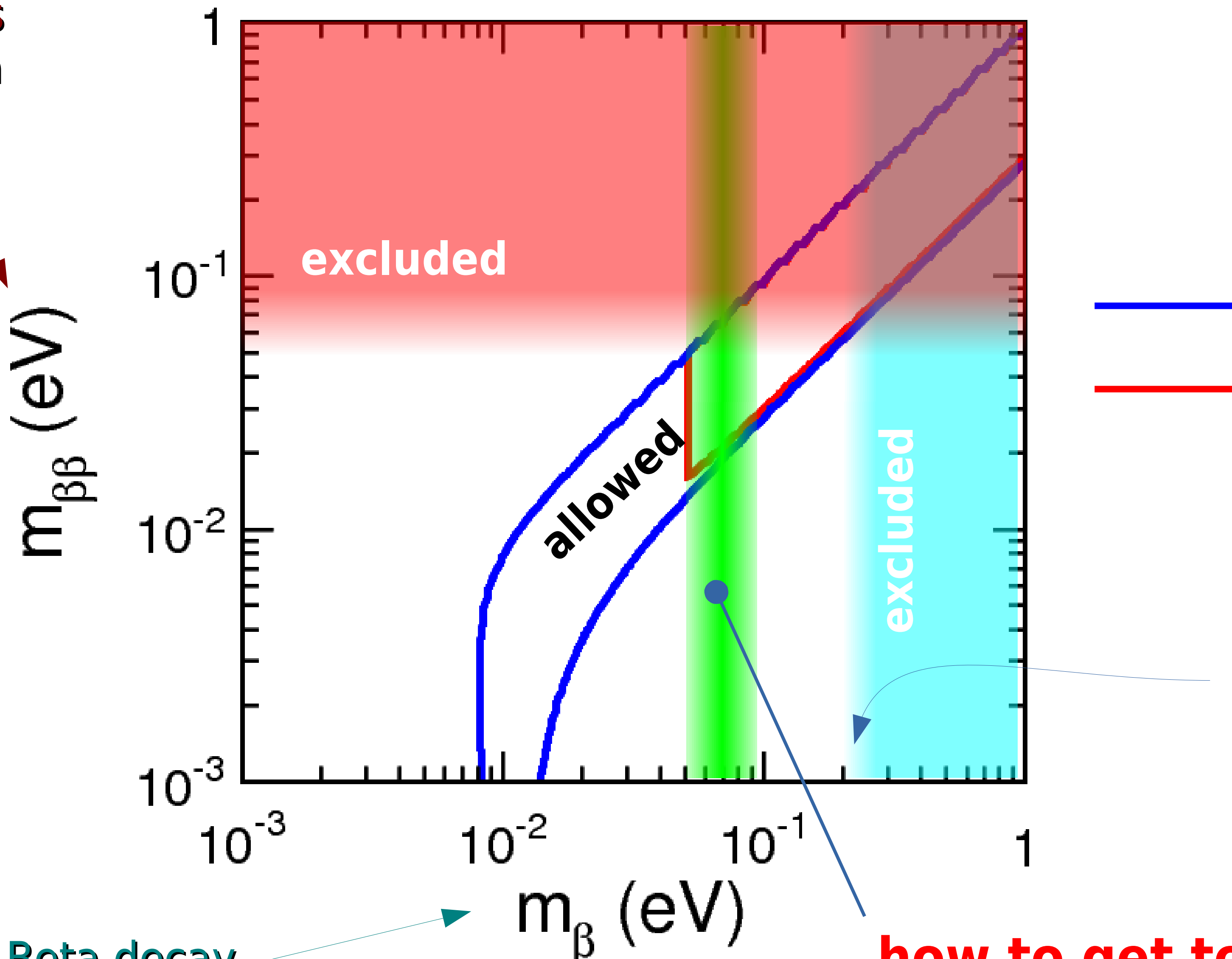


tool	Cosmology CMB+LSS+...	Neutrinoless Double Beta decay	Beta decay end-point
observable	$m_\Sigma=\Sigma_k m_{\nu_k}$	$m_{\beta\beta}=\lvert\Sigma_k m_{\nu_k} U_{ek}^2\rvert$	$m_\beta=(\Sigma_k m_{\nu_k}^2 \lvert U_{ek}\rvert^2)^{1/2}$
present sensitivity	≈0.1 eV	≈0.1 eV	2 eV
future sensitivity	**0.01 eV**	**0.01 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



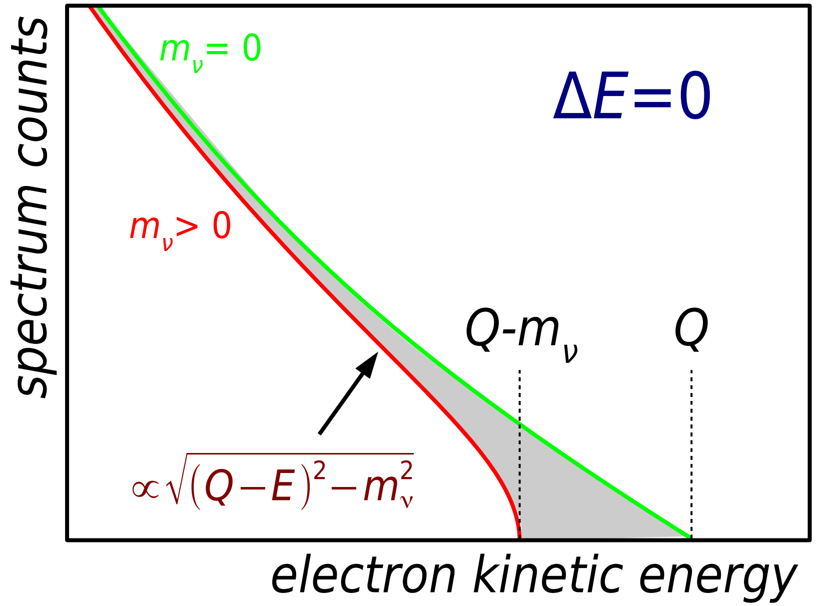
KATRIN
***m_ν*<0.2 eV**
in 2016/2017

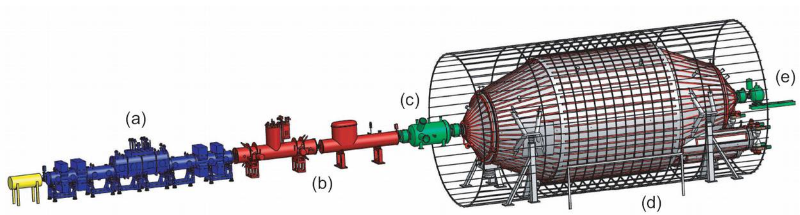
Beta decay end-point

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

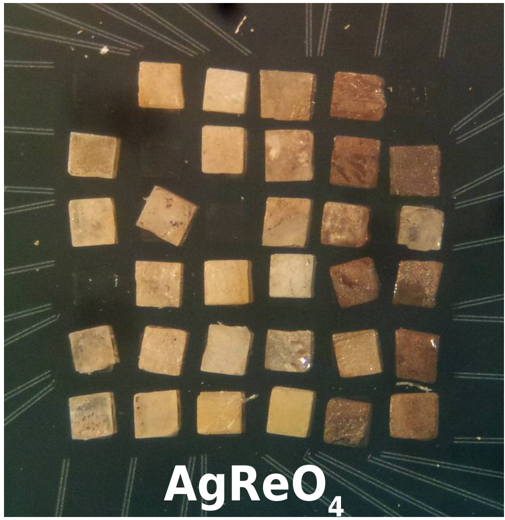




KATRIN
large MAC-E filter spectrometer with ^{3}H

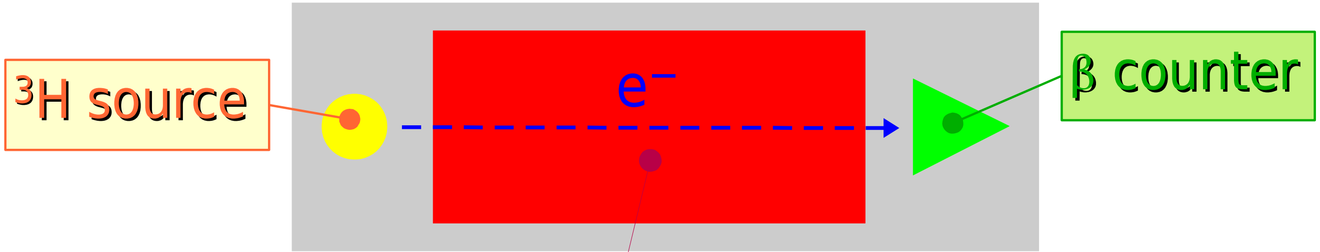
MARE/ECHO/HOLMES
array of low temperature microcalorimeters with ^{187}Re or ^{163}Ho

≈5 mm



Experimental approaches

Spectrometers: source ≠ detector

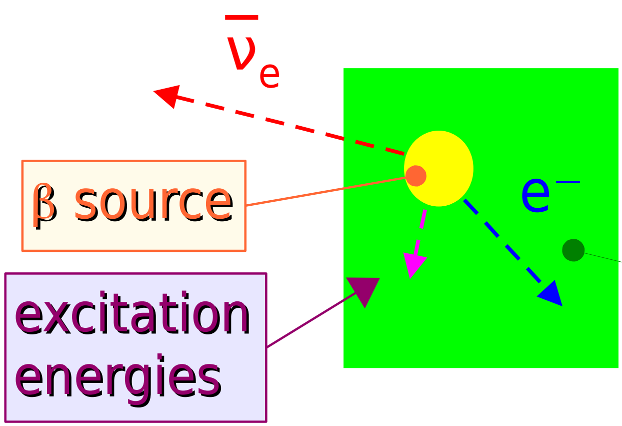


β analyzer

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

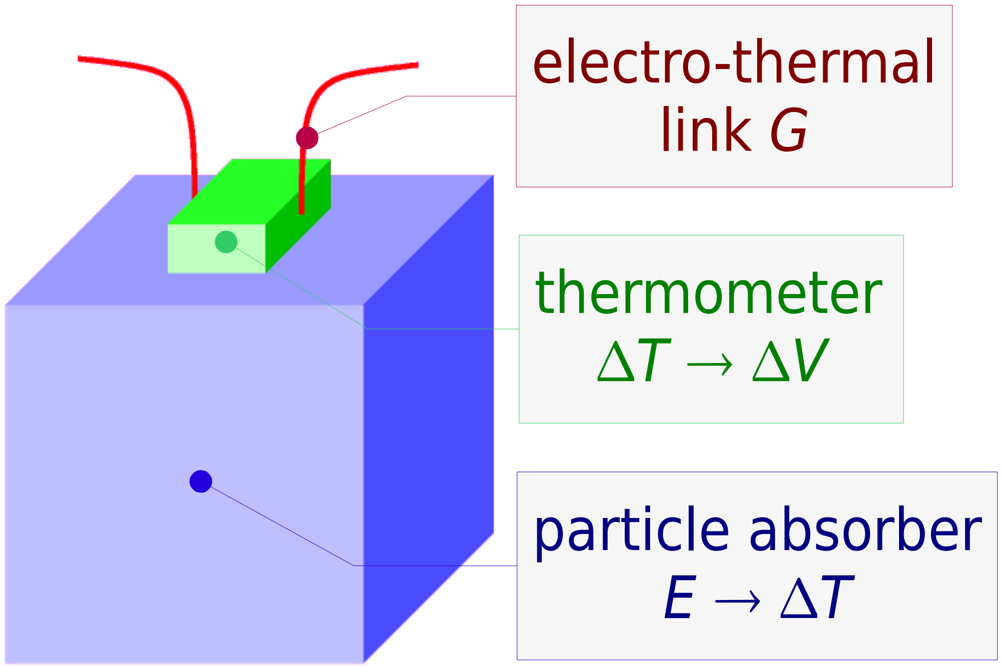


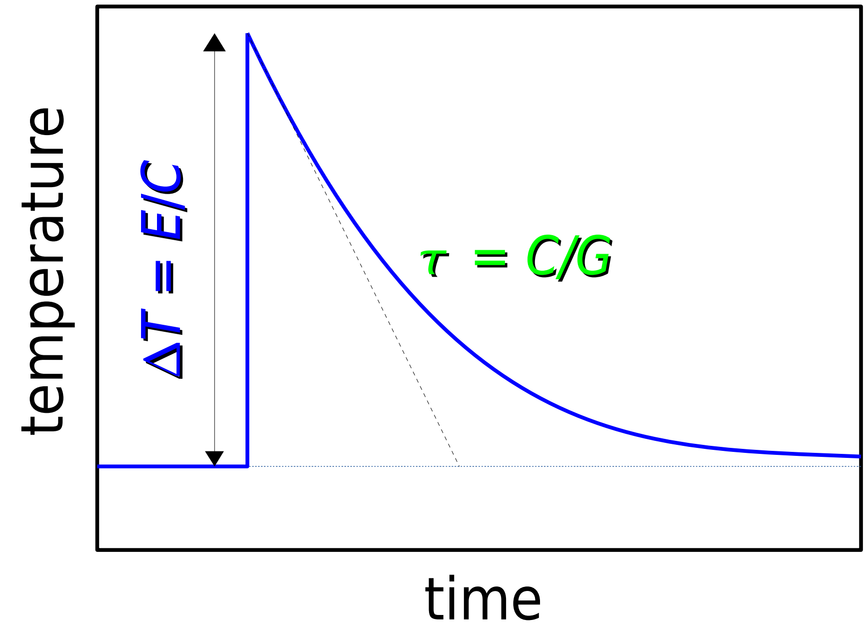
β calorimeter

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}

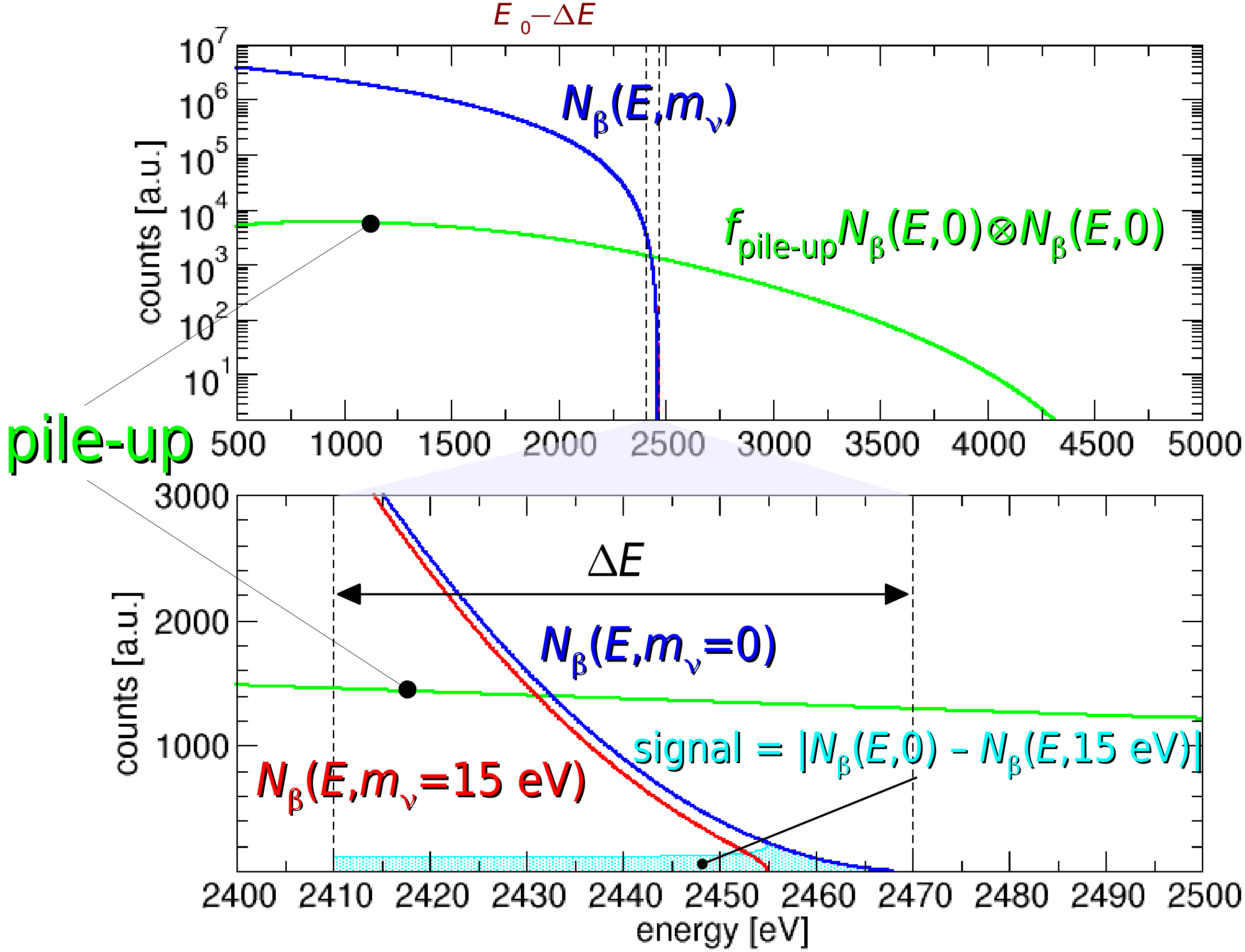
pile-up fraction $f_{pile\text{-}up}=\tau_R A_\beta$

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



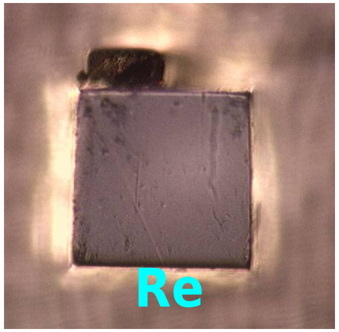
$$f_{pile-up} = \tau_R A_\beta \ll \frac{\Delta E^2}{E_0^2}$$ negligible pile-up

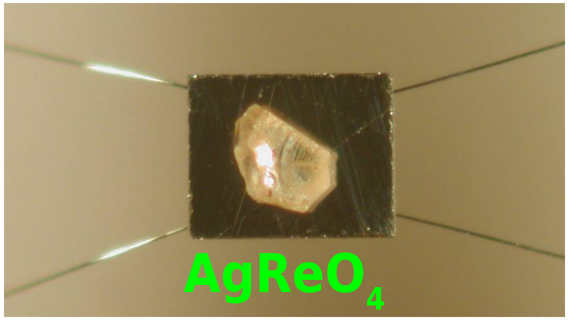
$$\Sigma_{90}(m_\nu) \approx 0.89\sqrt[4]{\frac{E_0^3\,\Delta E}{A_\beta t_M}}$$

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

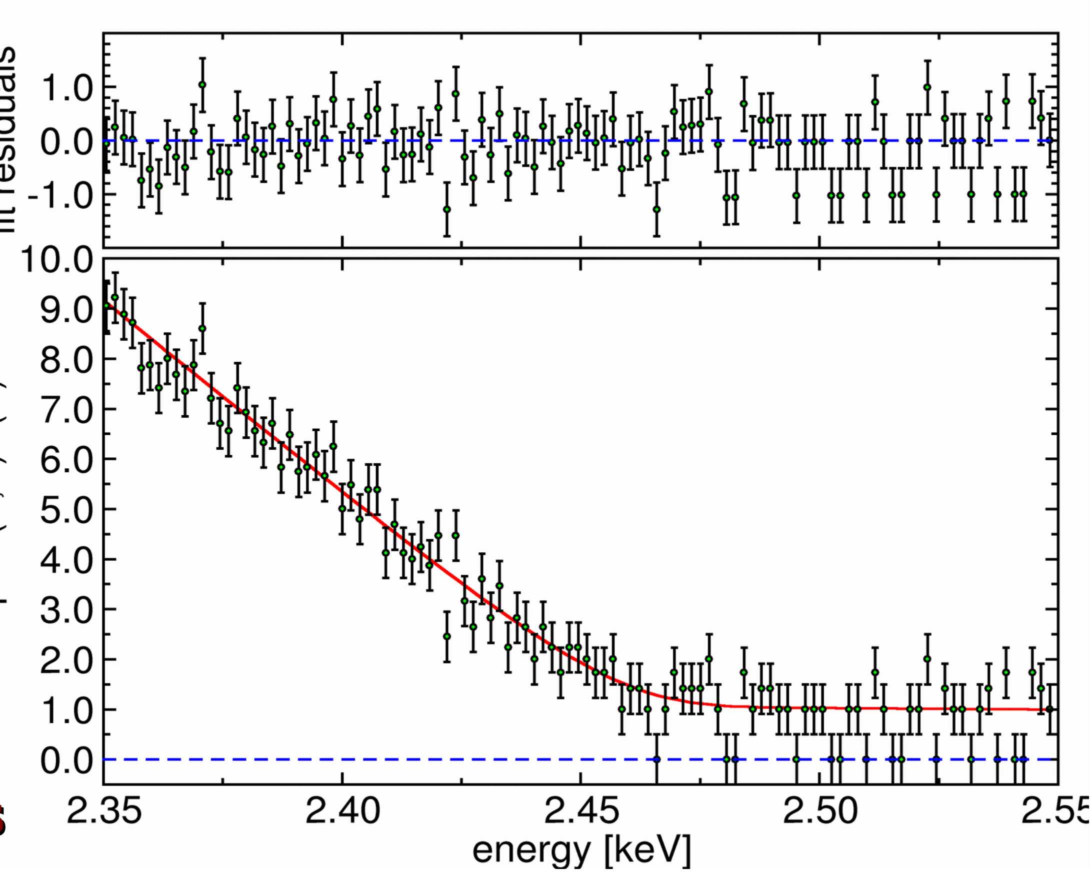




- proposed since 1985 by Genova group
- **MIBETA** @ MiB with $AgReO_4$
  - m_ν < 15 eV 90% C.L.

    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



$$\sqrt{\frac{N(E)}{pEF(Z,E)S(E)}}$$

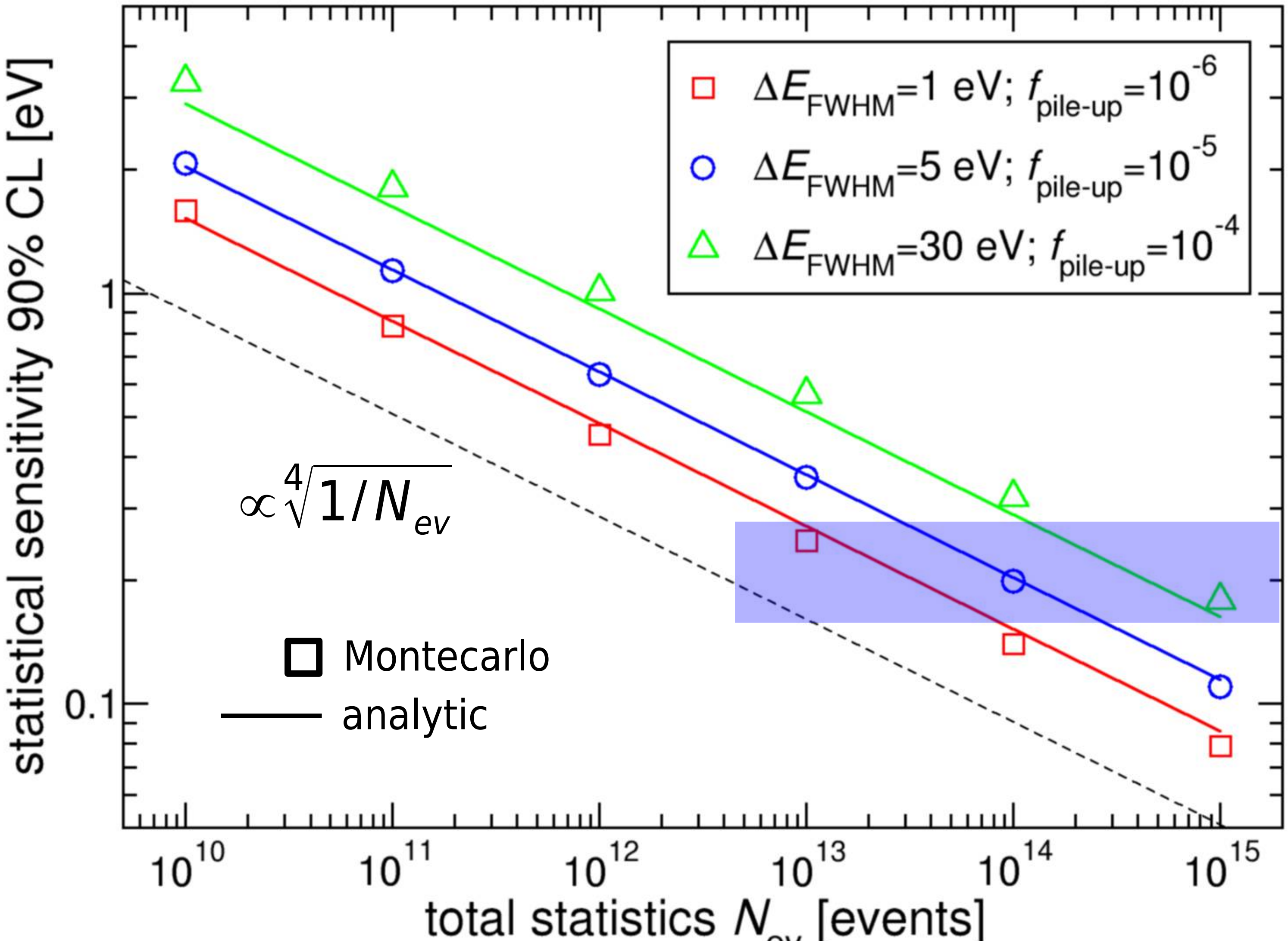
MARE (Microcalorimeter arrays for a Rhenium Experiment)

- 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



MARE

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

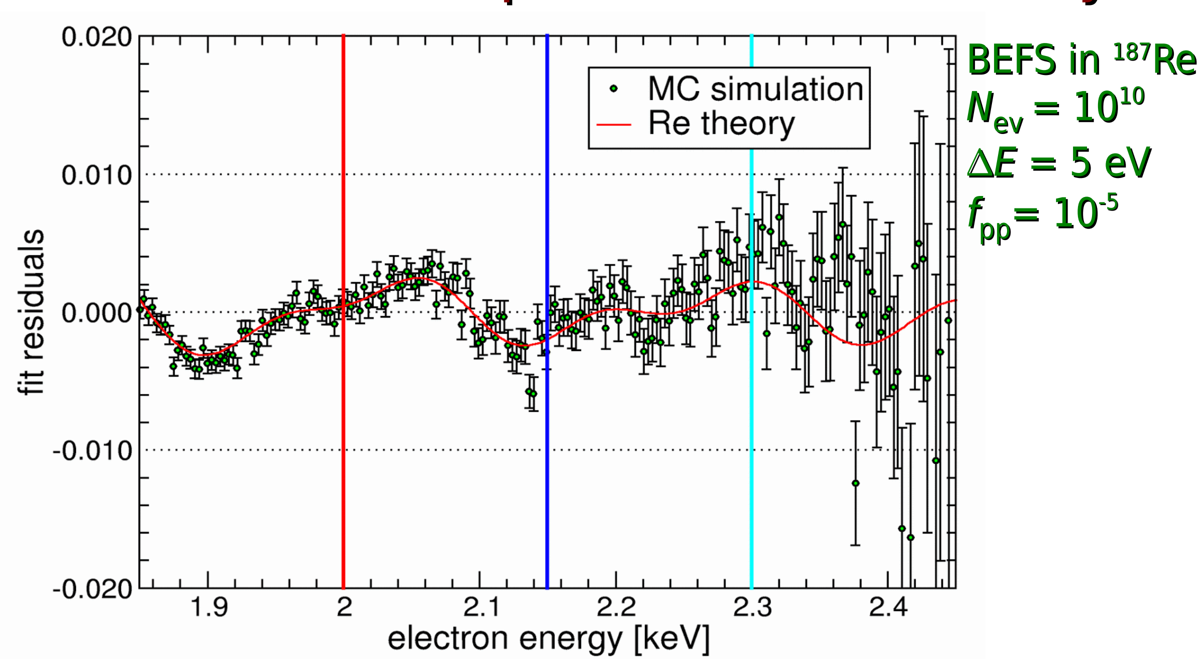
exposure required for 0.1 eV m_ν sensitivity

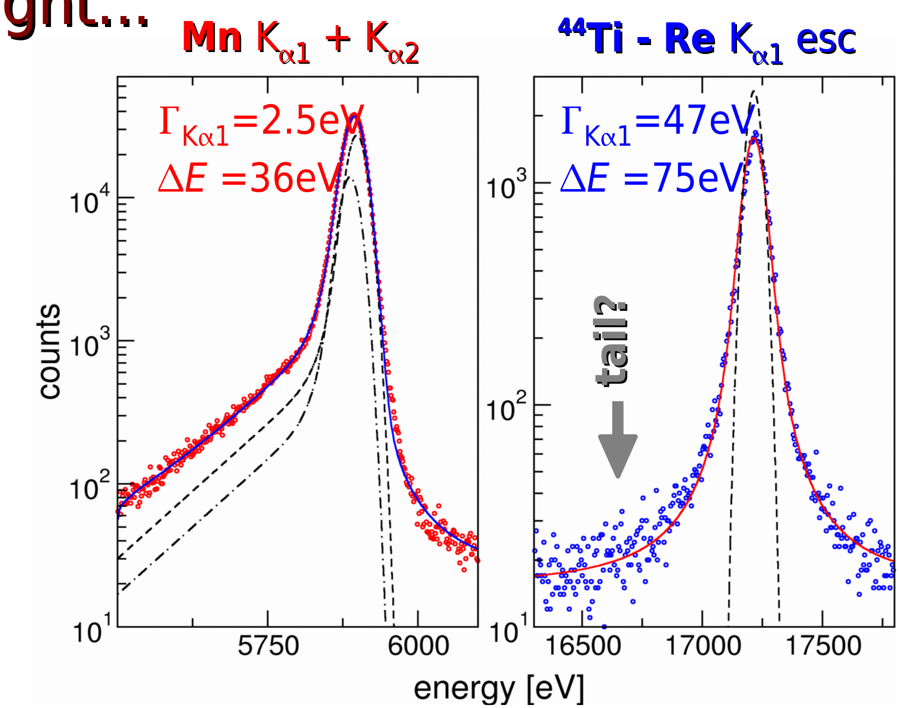
A_β [Hz]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.1	1.7×10^{14}	5.4×10^{6}
10	0.1	0.1	5.3×10^{14}	1.7×10^{6}
10	1	1	10.3×10^{14}	3.3×10^{6}
10	3	3	21.4×10^{14}	6.8×10^{6}
10	5	5	43.6×10^{14}	13.9×10^{6}

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

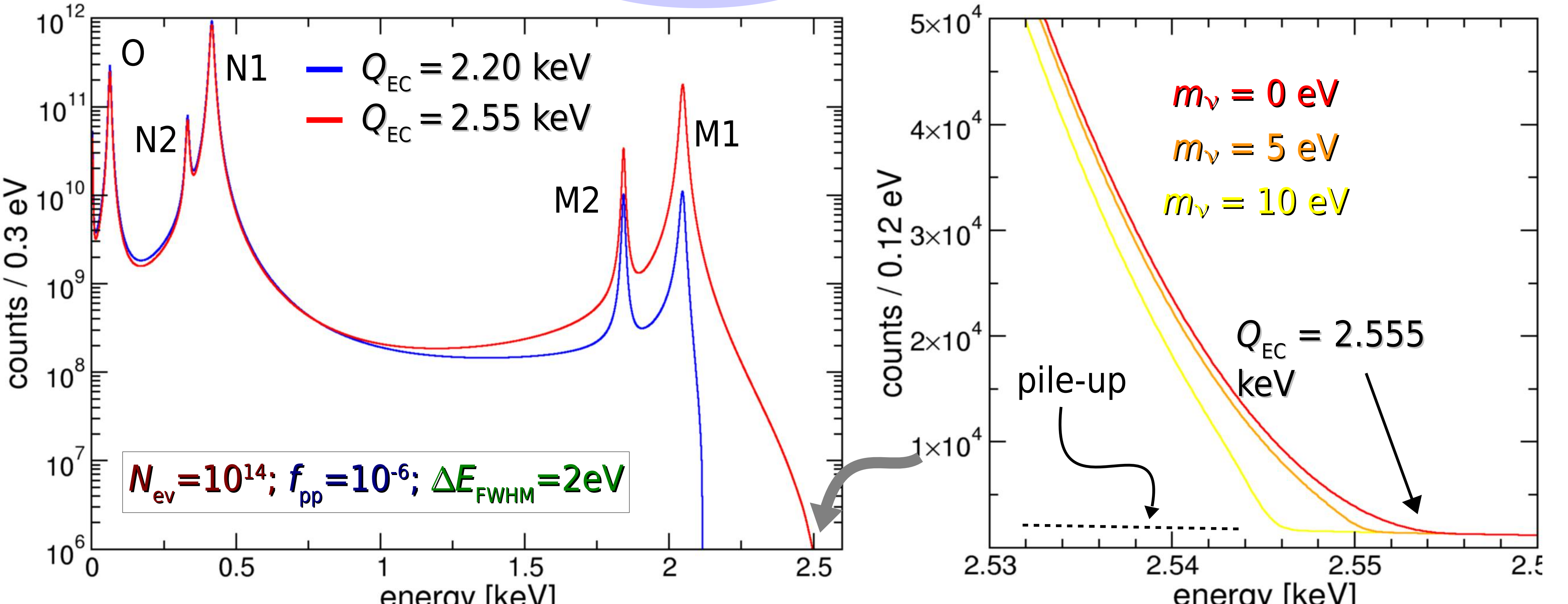
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

electron capture from shell ⩾ M1

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

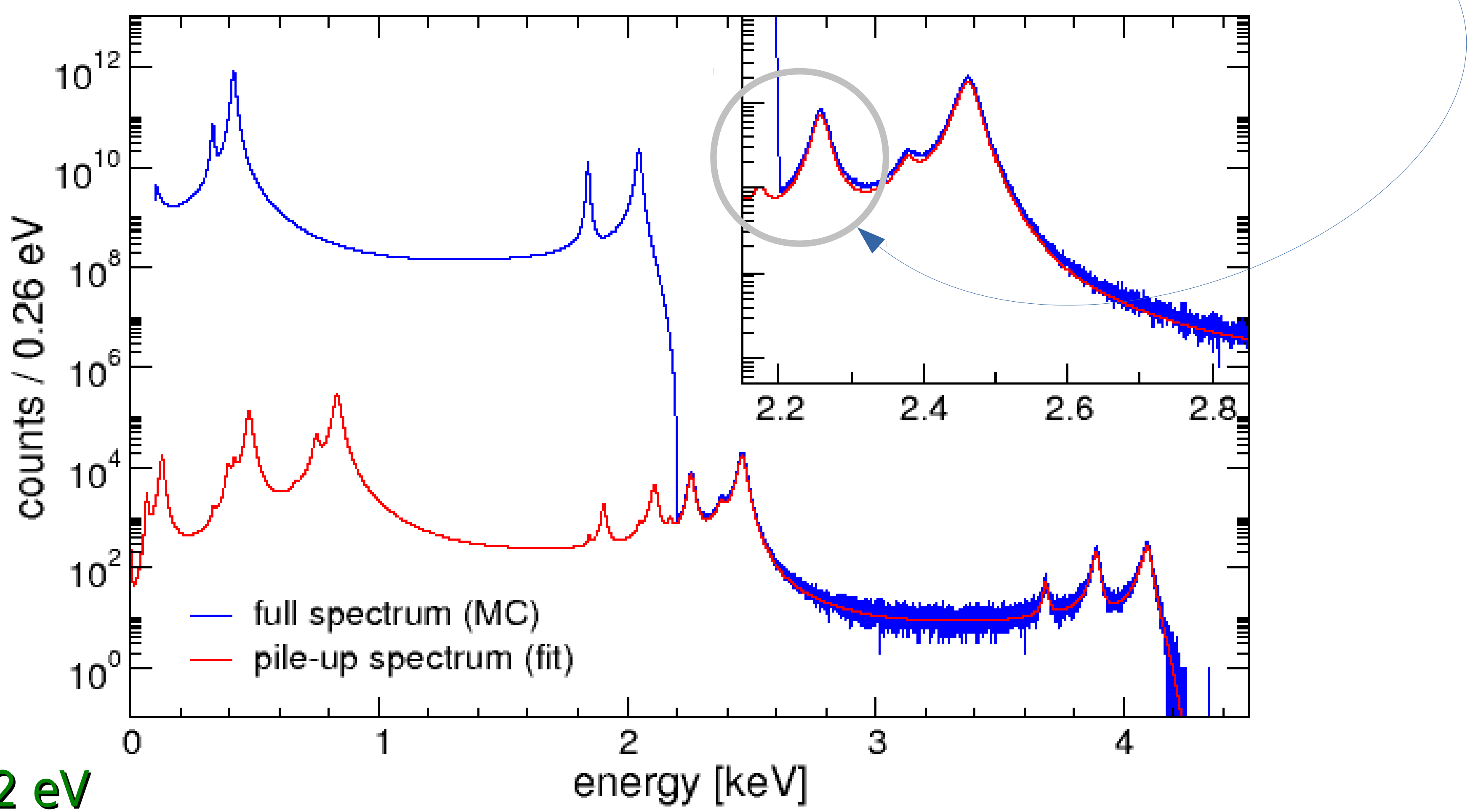
- **calorimetric measurement of Dy atomic de-excitations** (mostly non-radiative)
- rate at end-point and ν mass sensitivity depend on Q
  - Measured: Q_{EC} = **2.2÷2.8 keV**. Recommended: Q = **2.555 keV**
- **$\tau_{½}$ ≈4570 years** → few active nuclei are needed

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



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 spectral shape dominated by $(Q-E_c)\sqrt{(Q-E_c)^2-m_\nu^2}$ but...



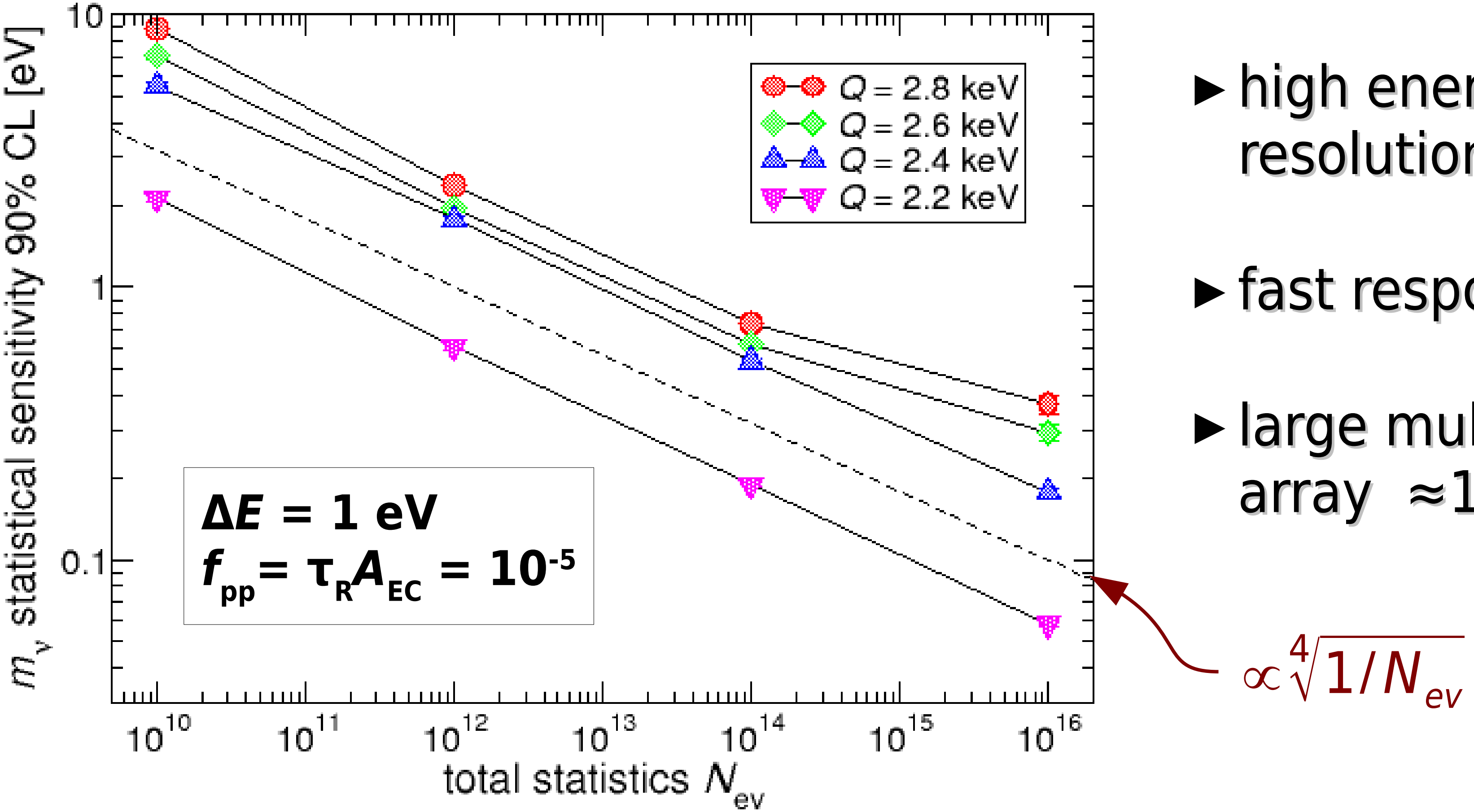
$N_{ev} = 10^{14}$

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

$\Delta E_{FWHM} = 2$ 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}

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}

Q_{EC} = 2200 eV
***bkg* = 0**

5000 pixels/array
3 arrays
1 year
$\approx 2\times10^{17}$ ^{163}Ho nuclei

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}

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}

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

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

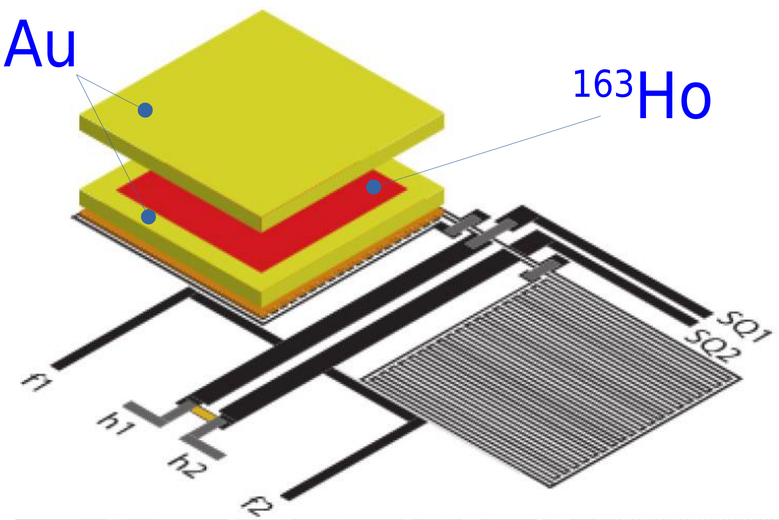
10^6 pixels/array
6 arrays
10 years
$\approx 8\times10^{19}$ ^{163}Ho nuclei

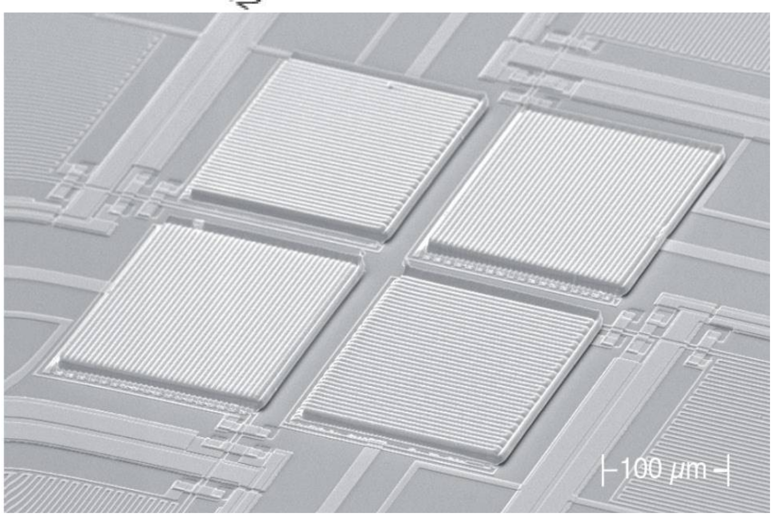
Holmium experiment status

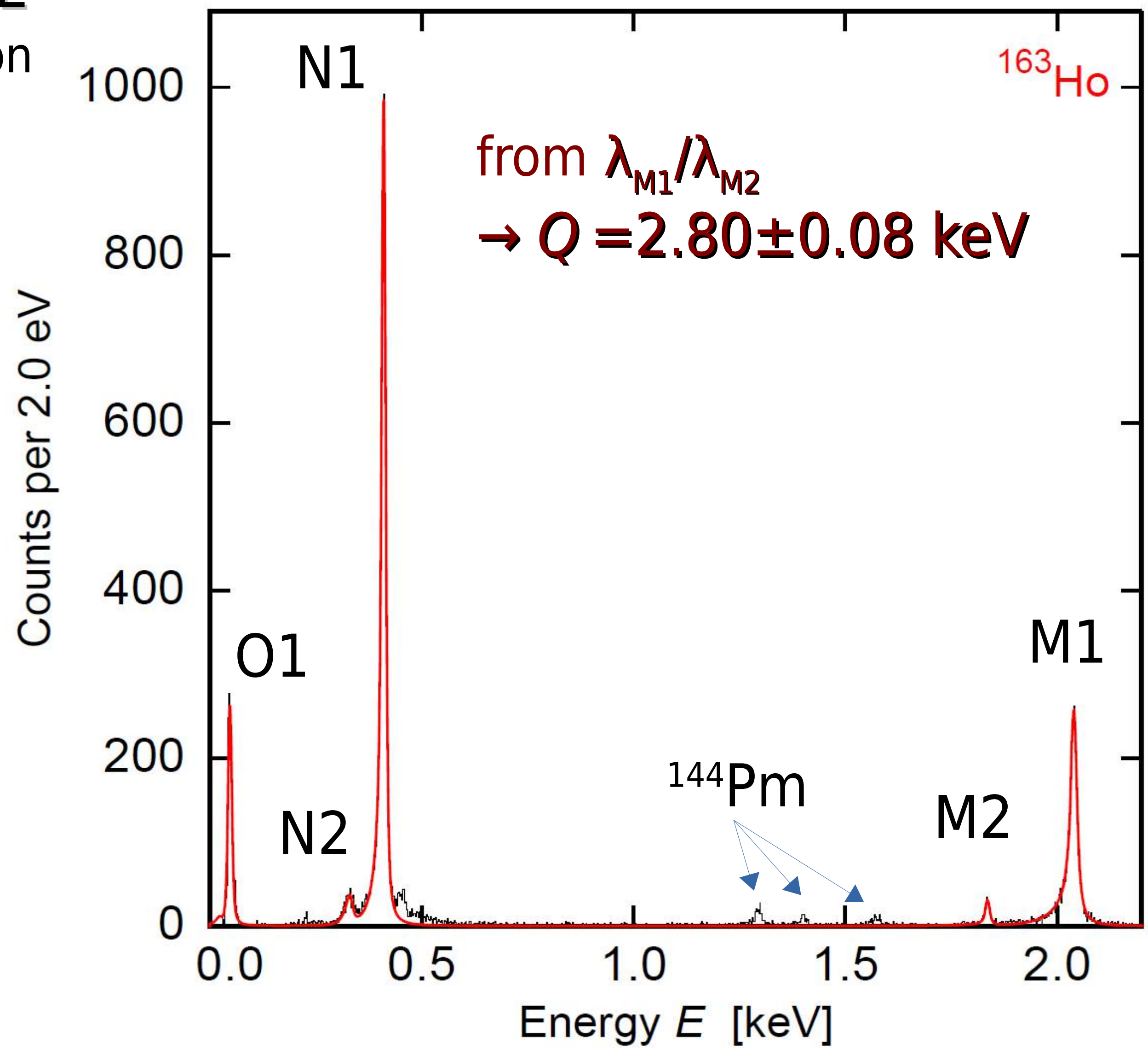
- **^{163}Ho seems to be better than ^{187}Re**
  - higher specific activity → don't need a “Holmium detector”
  - *self calibrating* → better systematics control
  - but
    - higher *Q* → maybe less sensitive
    - pile-up spectrum
    - chemical effects on *Q*
- (at least) **two projects**
  - **ECHO** (Heidelberg)
  - **MARE** (→ will become 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

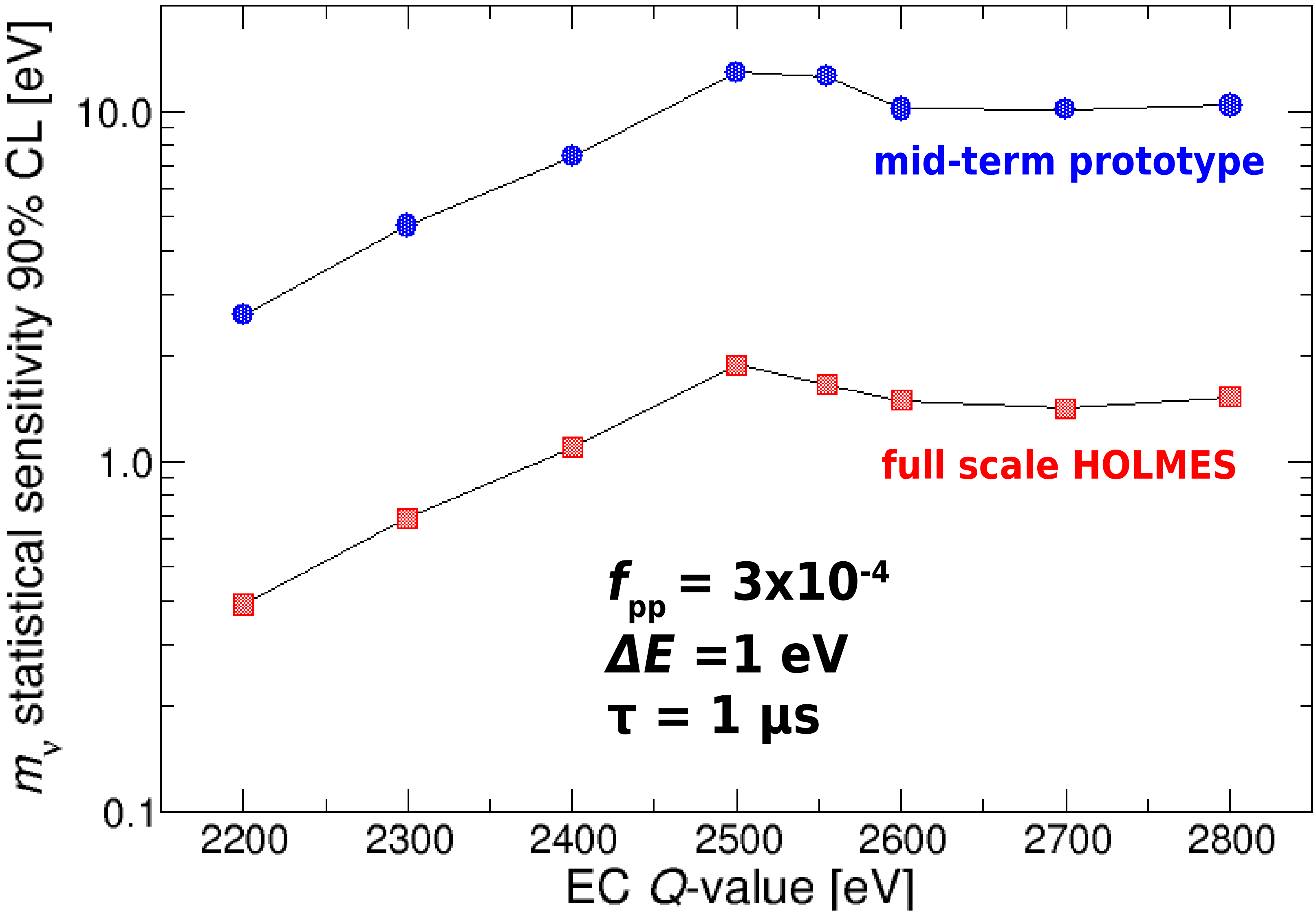
baseline

- 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

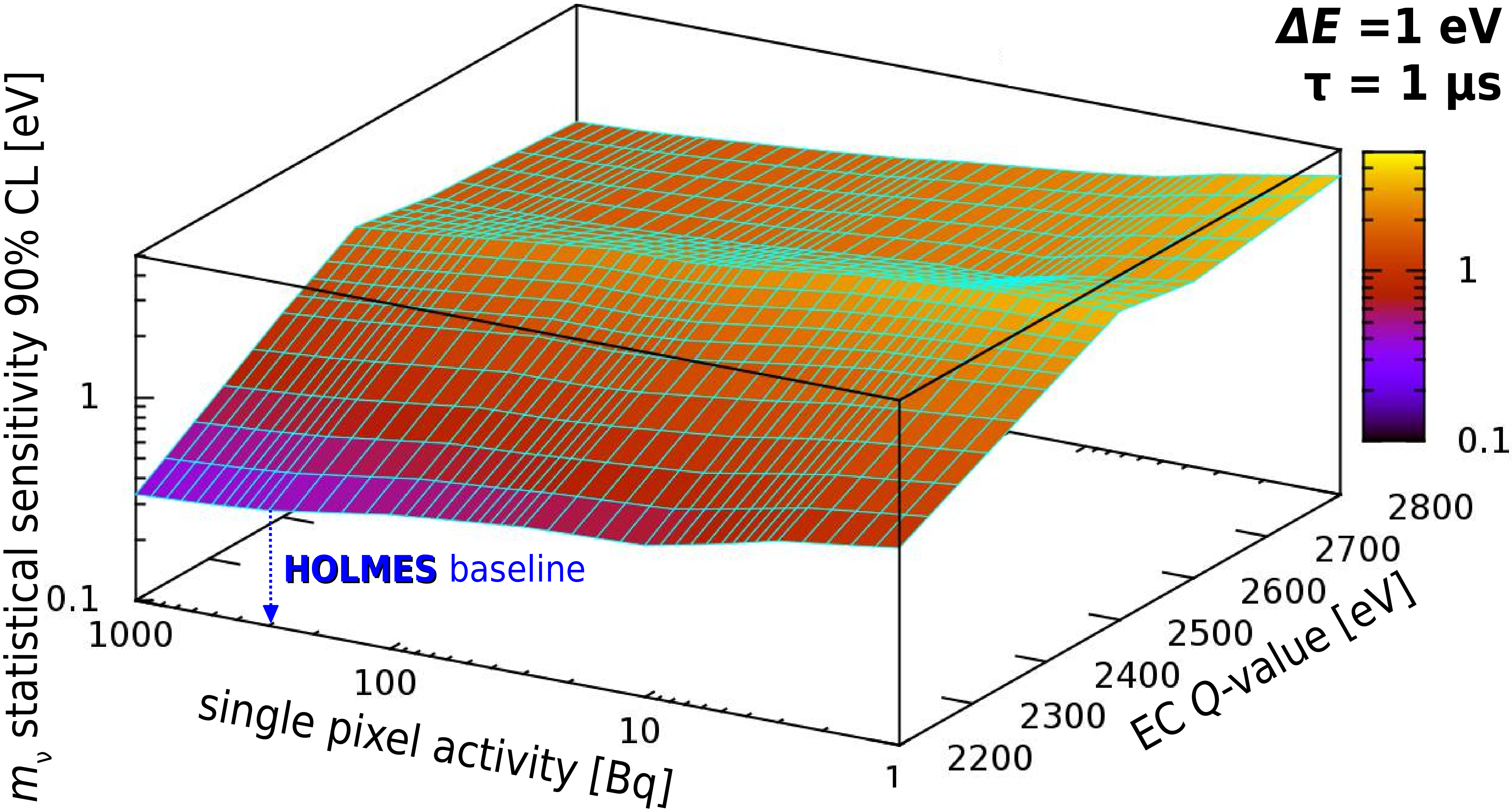


16 channels
t_M=1 month
A=300Hz/ch
→ 10^{10} decays

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

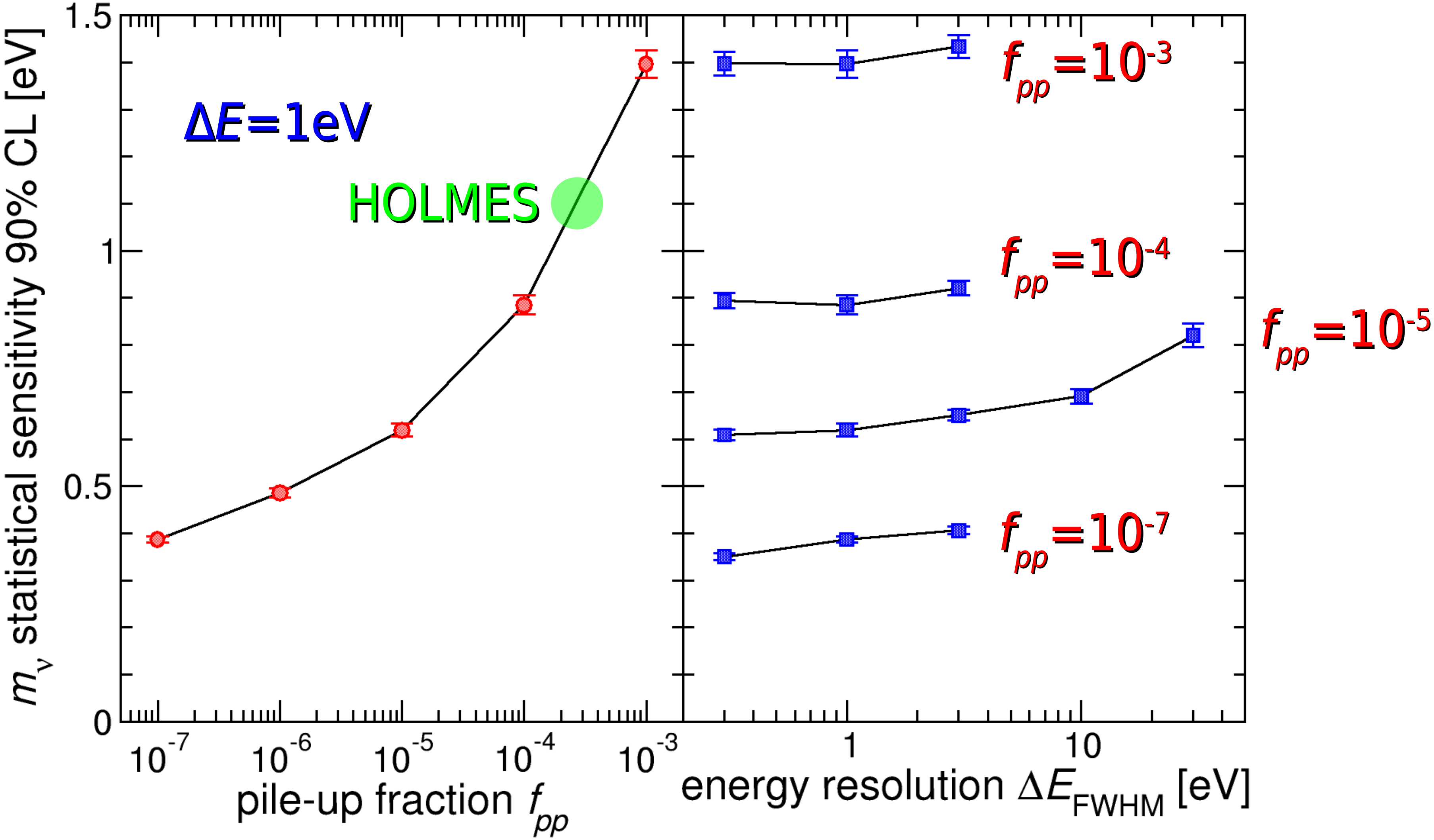
Statistical sensitivity and single pixel activity

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

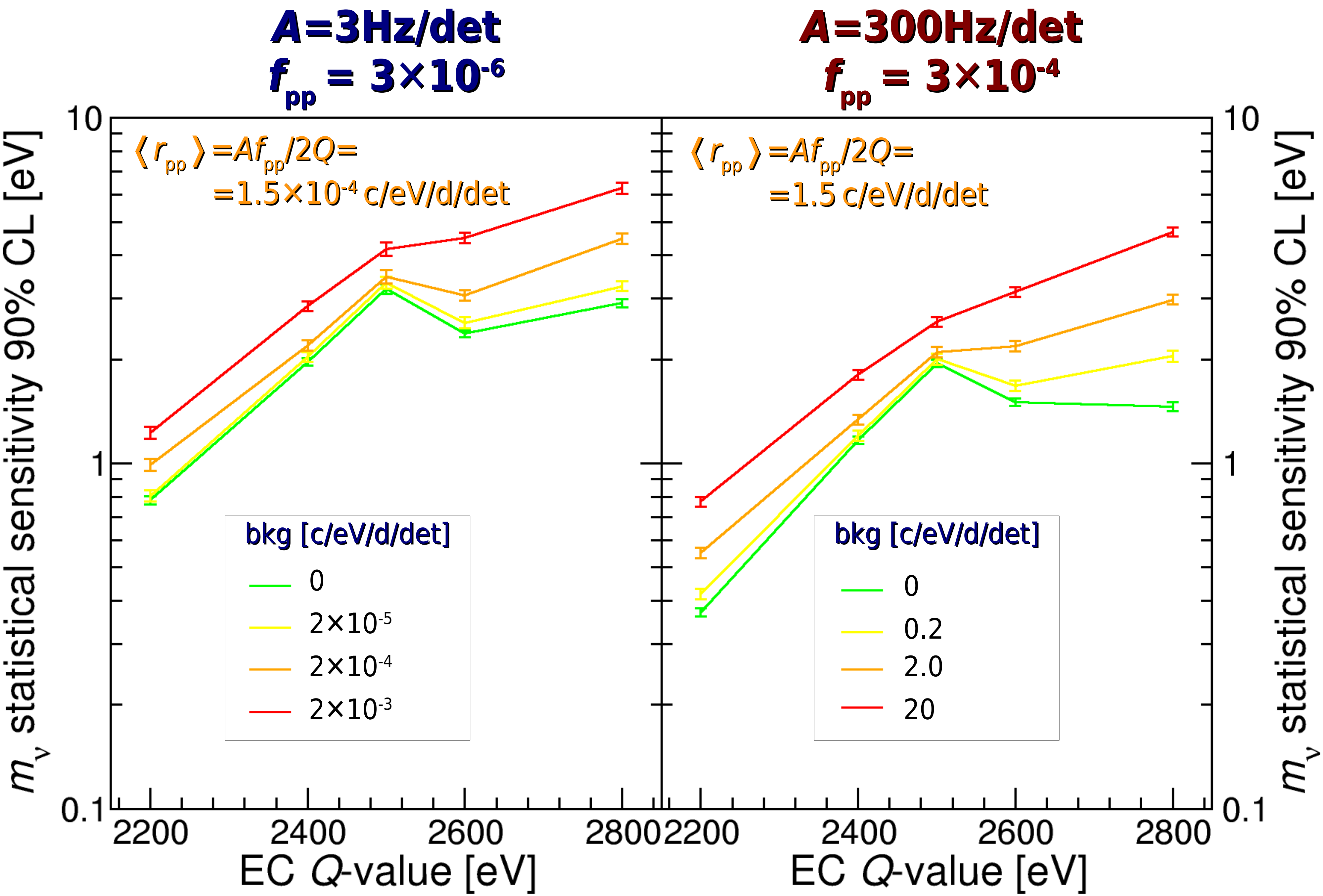
- environmental γ radiation
  - Compton interactions
  - Photoelectric interactions with photoelectron escape
  - fluorescent X-rays and X-ray escape lines
- γ and β from close surroundings
- cosmic rays
  - muons, ...
  - EM showers
- ...

Cosmic rays at sea level (muons)

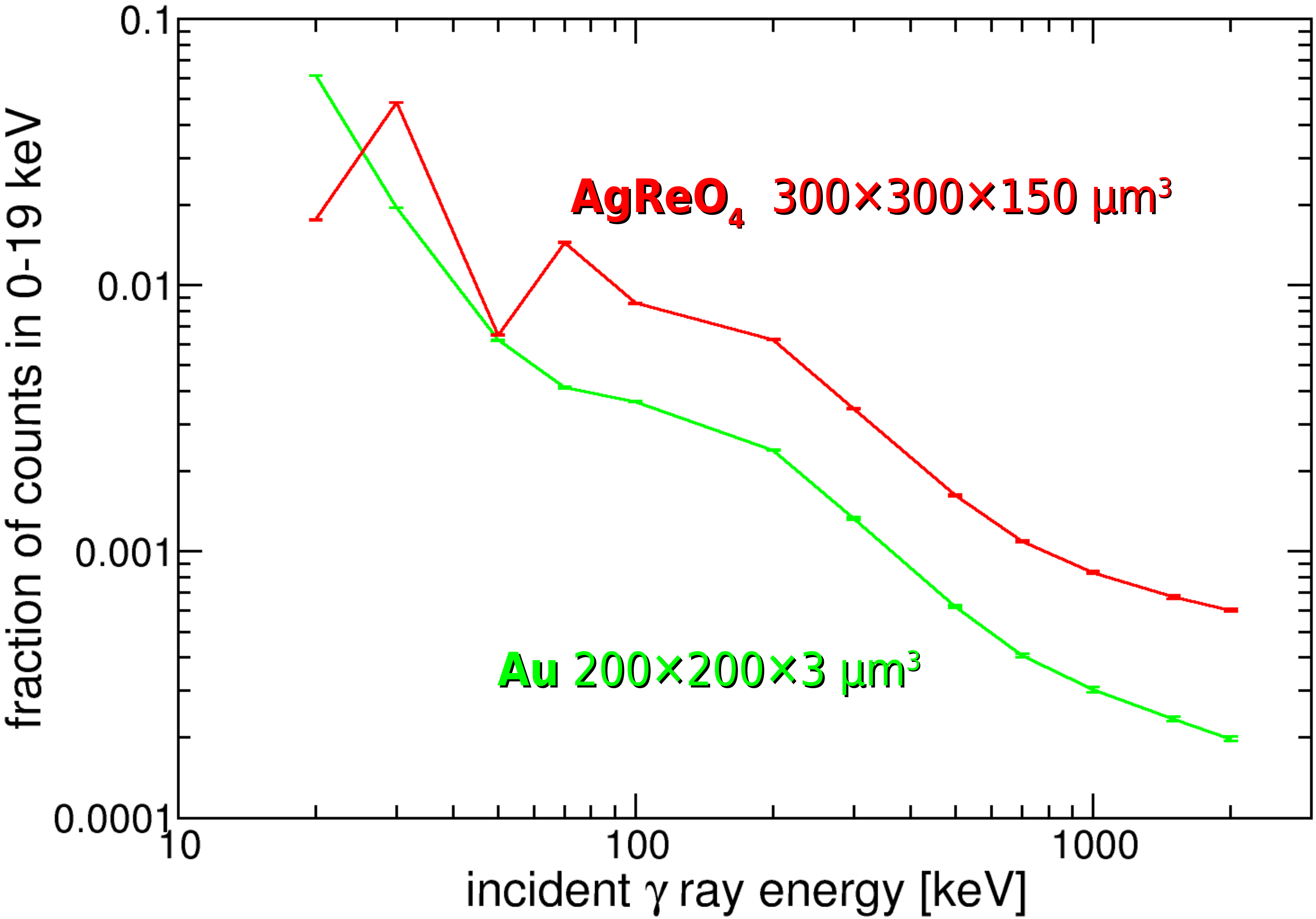
- Au pixel: 200×200×3 μm^3
  - ▷ $\langle \Delta E \rangle \approx$ 10keV, $r \approx 1\ d^{-1}$
- Si chip: 20×20×0.5 mm^3
  - ▷ $\langle \Delta E \rangle \approx$ 300keV, $r \approx 7000\ d^{-1}$

- **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

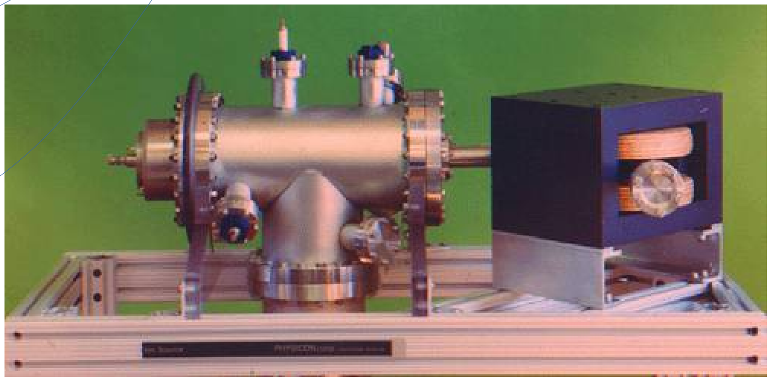
- ^{163}Ho isotope production
- ^{163}Ho isotope embedding in detector
- single TES optimization and testing
- TES array design, engineering and testing
- SQUID read-out and multiplexing optimization and testing
- room temperature signal processing and in-line analysis
- cryogenic set-up

^{163}Ho production and embedding

- **^{163}Ho production by nuclear reaction**
  - high yield
  - low by-products contaminations (in particular ^{166m}Ho, β $\tau_{1/2}$=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

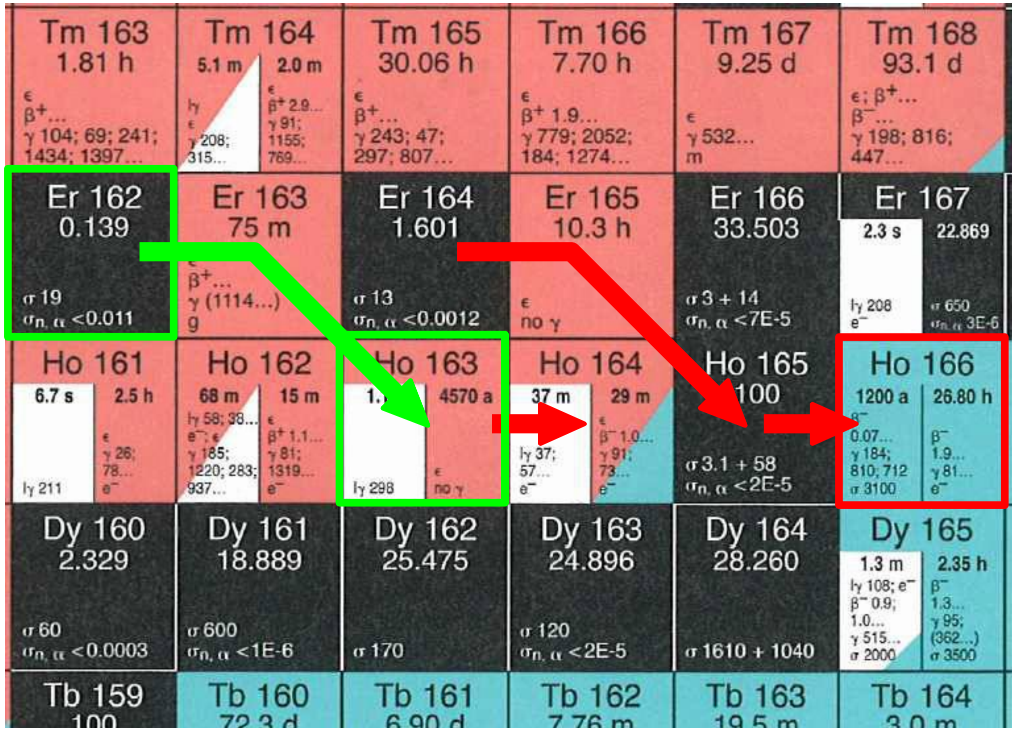
particle	p	n 10^{14} n/cm2/s	p 16 MeV 80 µA	p 24 MeV 240 µA	α 40 MeV 30 µA
target	W/Ta	^{162}Er (40%)	^{nat}Dy 200mg/cm^2	^{nat}Dy 20g	^{nat}Dy “thick”
^{163}Ho prod rate [nuclei/h]	10^{14}	10^{13-15}/ mg ^{162}Er	10^{14}	10^{15}	10^{13}

U. Koester @NuMass 2013

^{163}Ho production by neutron activation

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

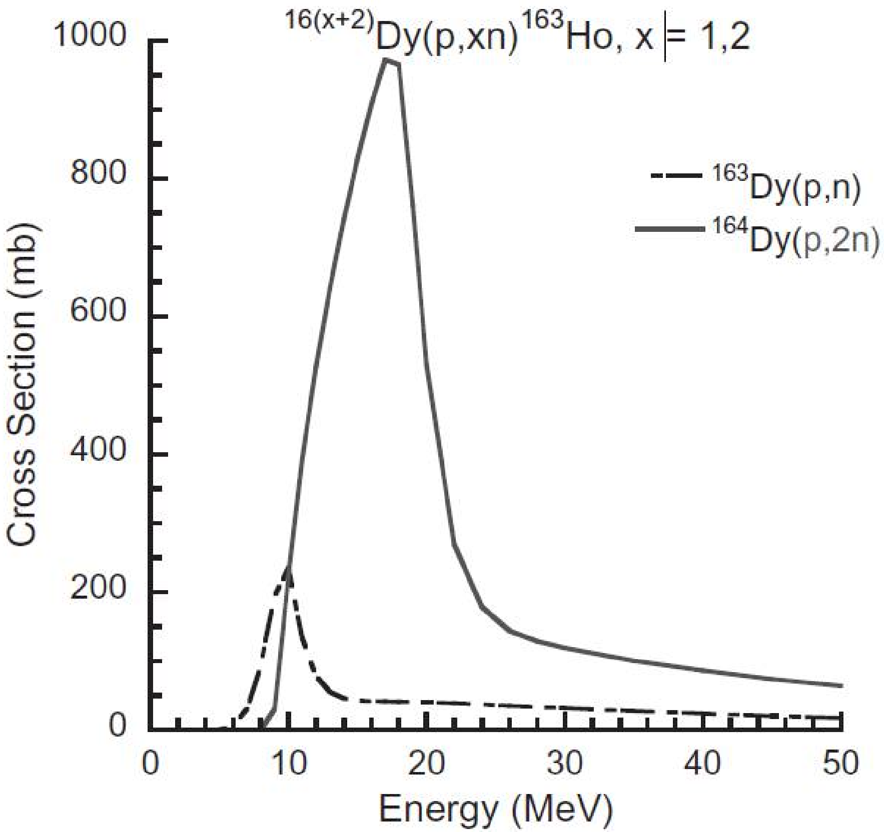
^{163}Er → ^{163}Ho + ν_e $\tau_{½}^{EC} \approx 75$min

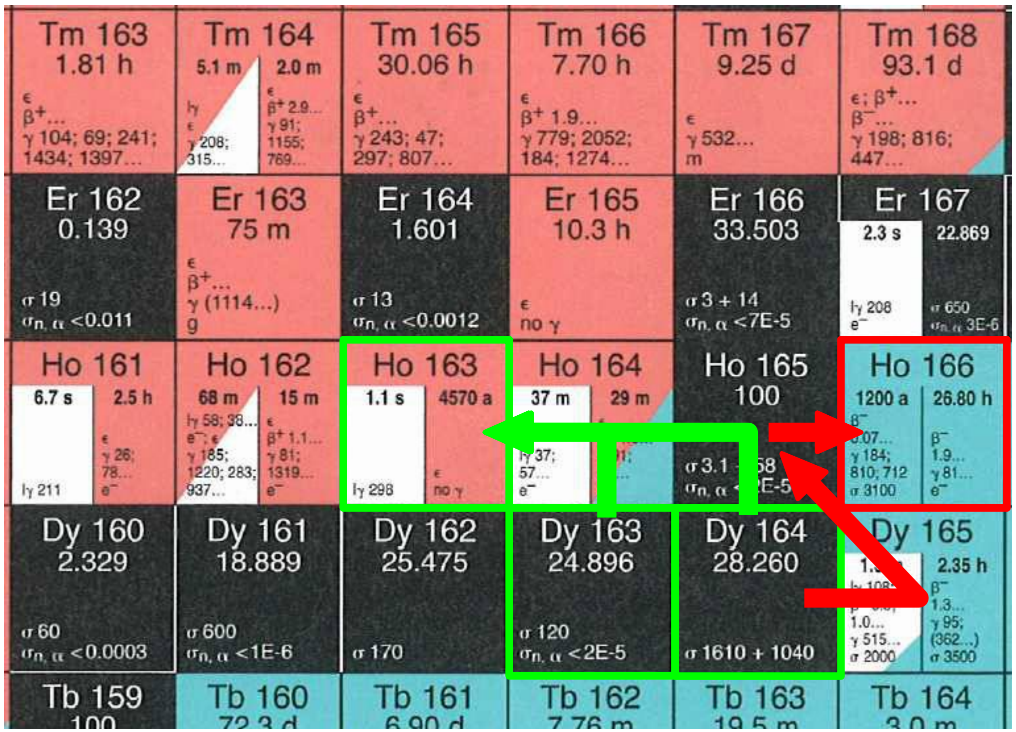


- only few experimental data for almost all cross sections involved
- possibly high yield
  - ≈3×10^{12} ^{163}Ho nuclei/mg(^{162}Er)/h for a thermal neutron flux of 10^{13} n/cm^2/s
- ^{163}Ho(n,γ)^{164}Ho (burn-up)?
- ^{165}Ho(n,γ) (from Ho contaminations or ^{164}Er(n,γ)) → ^{166m}Ho, β $\tau_{½}$=1200y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



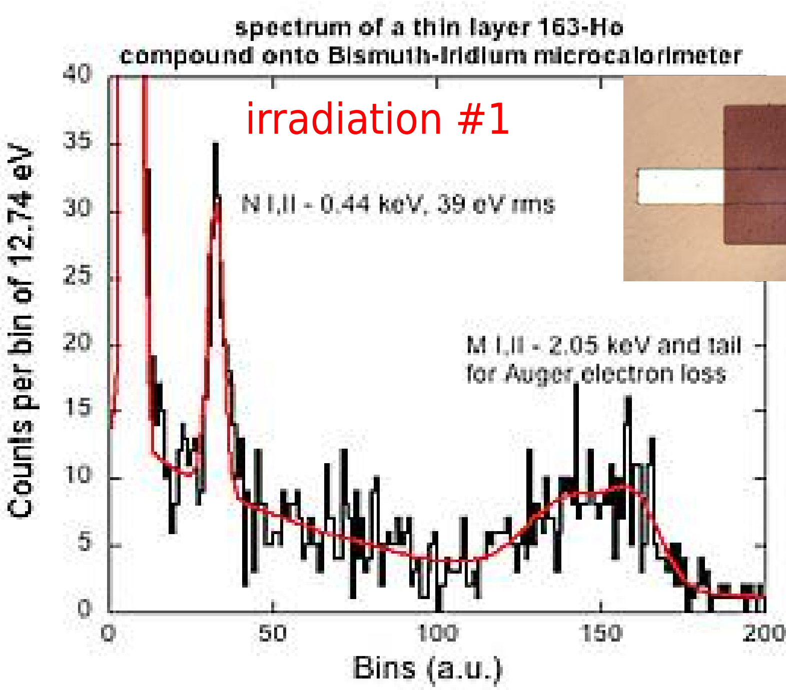


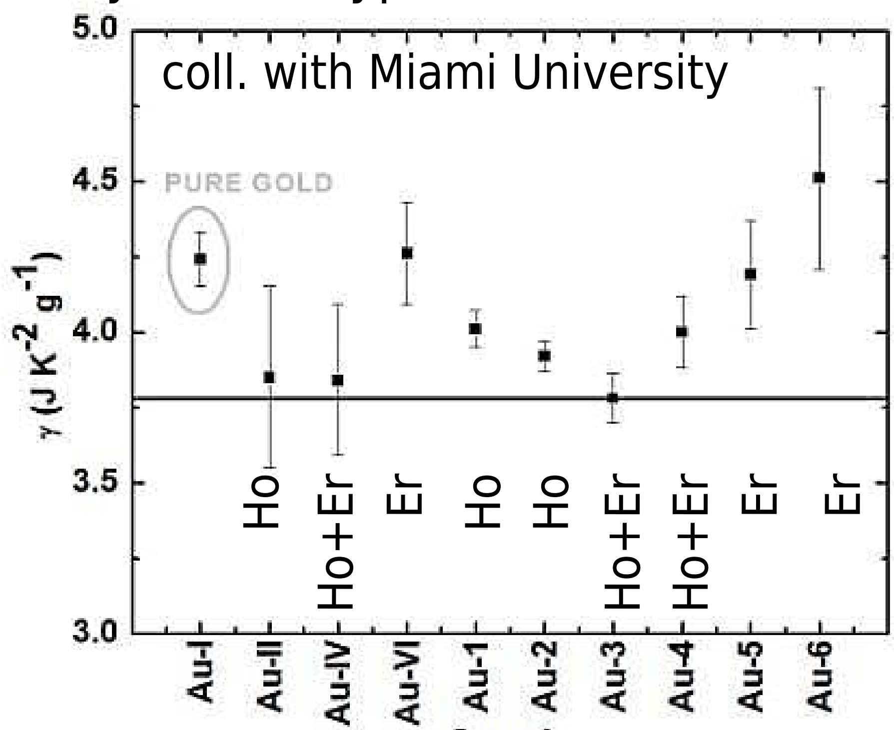
- only few experimental data for almost all cross sections involved
- metallic Dy target with natural composition
- lower yield
- many high energy neutrons produced by (p,*x*n) on Dy isotopes
  - ▸ ^{165}Ho(n,γ) (from Ho contaminations or ^{164}Dy(n,γ)) → ^{166m}Ho, β $\tau_{½}$=1200y

MARE-RD: ^{163}Ho / 1

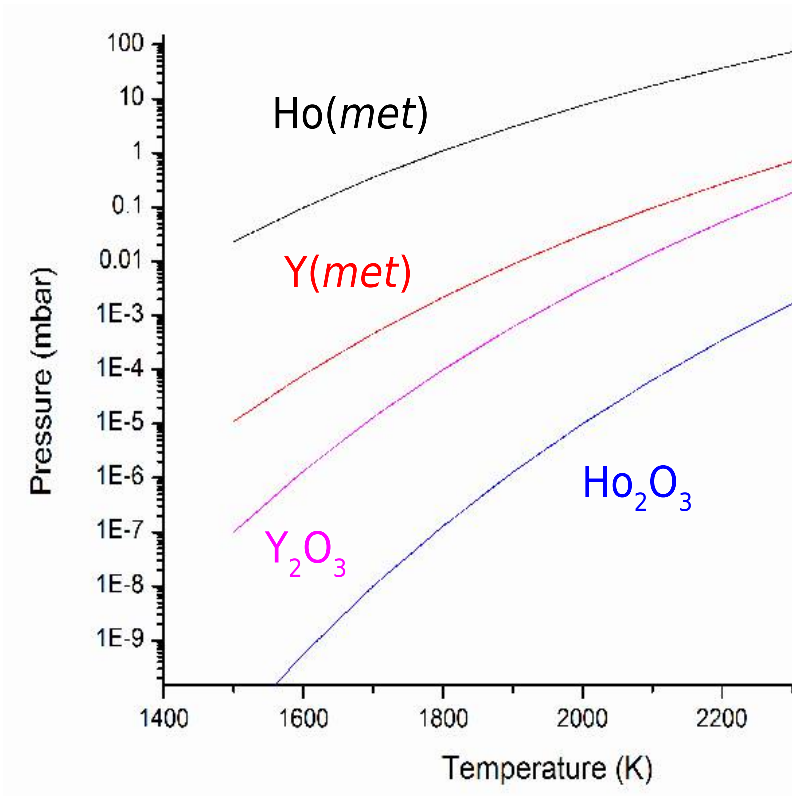
- ^{163}Ho production by Er:^{162}Er enriched neutron irradiation
  - ▹ 3 irradiatons at Lisboa research reactor (ITN)
  - ▹ 1 irradiation at Grenoble reactor (ILL) → 1MBq of ^{163}Ho (now *cooling*...)
- Er_2O_3/Ho_2O_3 thermoreduction→ metallic target for implantation
  - ▹ $Y_5Si_3+Ho_2O_3 \rightarrow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

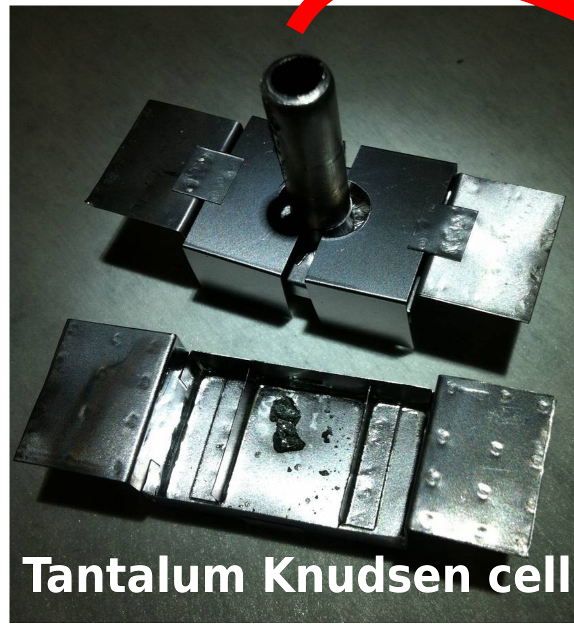
- effect of Ho/Er implantation in Au absorbers
  - ▹ magnetic contributions to Au heat capacity due to hyperfine interactions

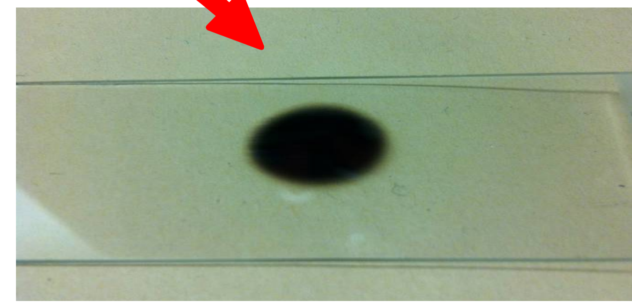


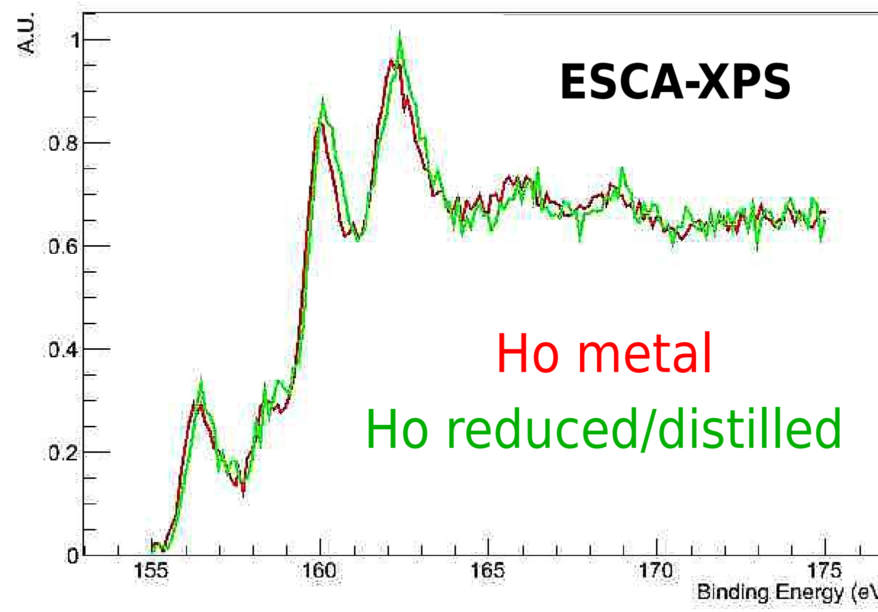


MARE-RD: Ho oxide reduction





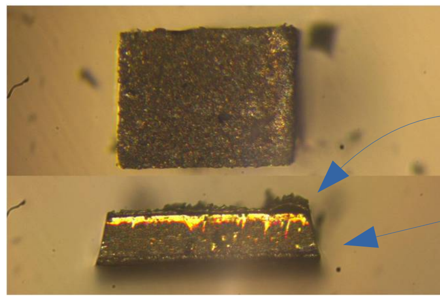




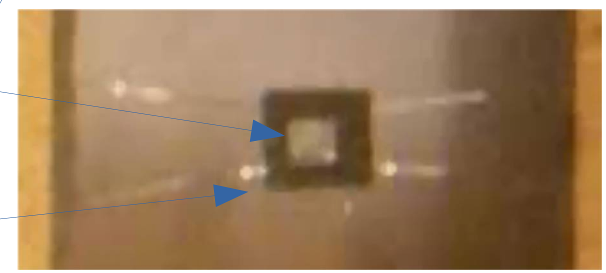
- Ho_2O_3 distillation around 2000K
- XPS on deposited film:
  - 80% metallic Ho
  - 20% re-oxidized Ho

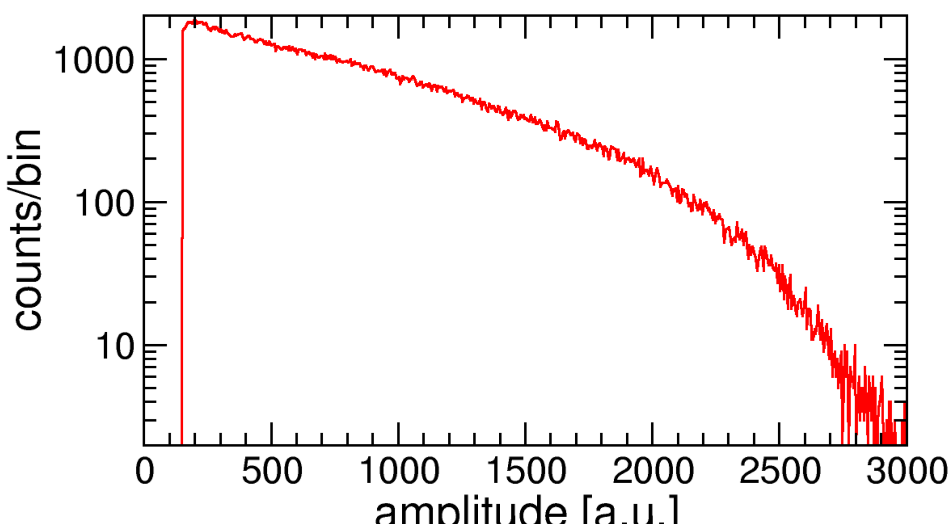
MARE-RD: tests on irradiated samples

- 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

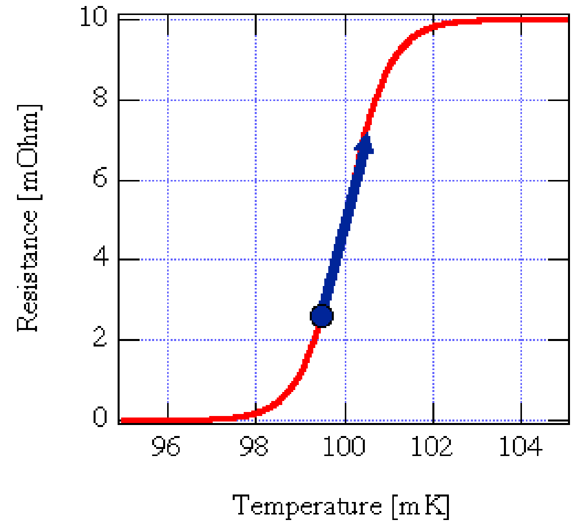


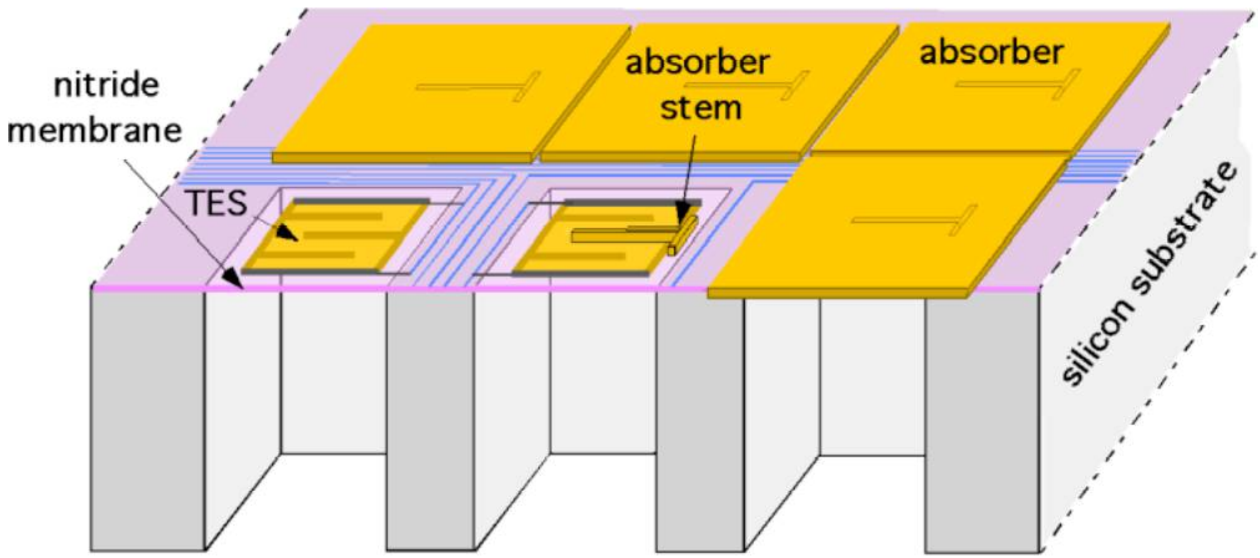


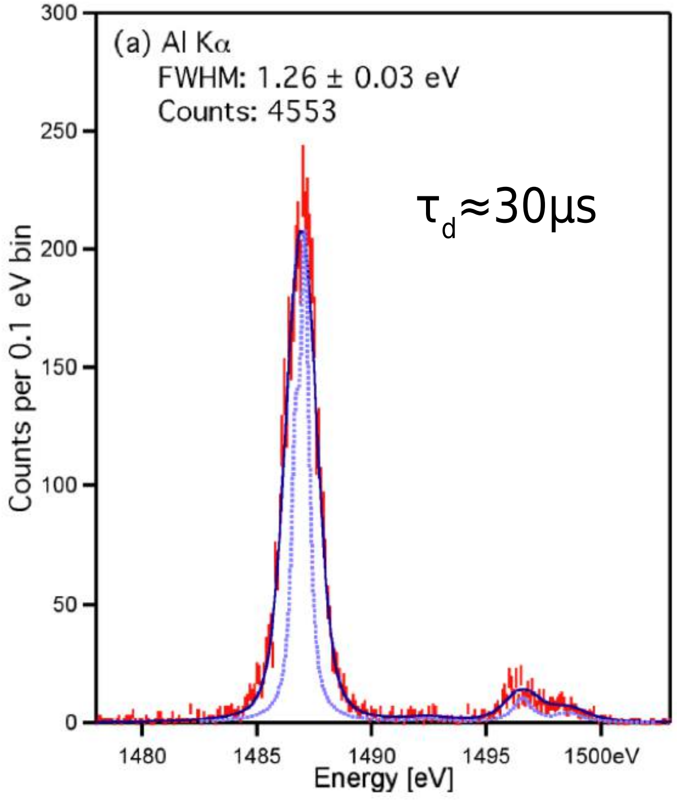
- no ^{163}Ho peaks
- continuum ≈1c/s
  → β from ^{152}Eu in irradiated sample?
- more tests...
- sample analysis ICPMS (@LNGS), ...
- sample purification

HOLMES detectors

- Transition Edge Sensors (TES) with 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



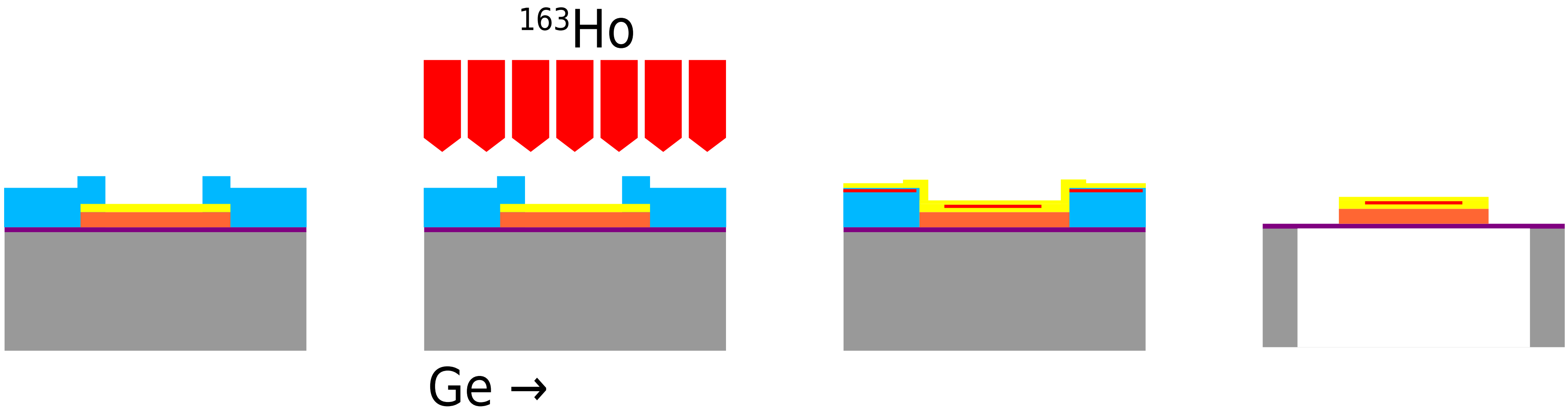




NASA/GSFC

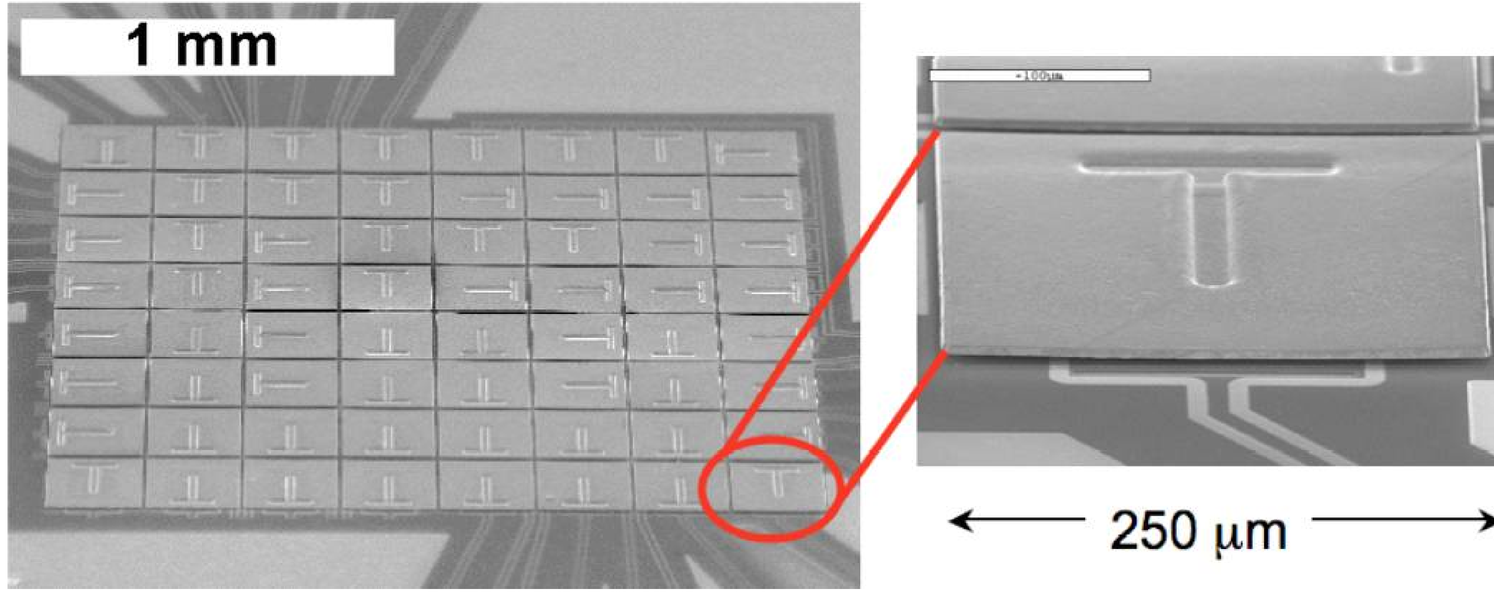
HOLMES detector array fabrication

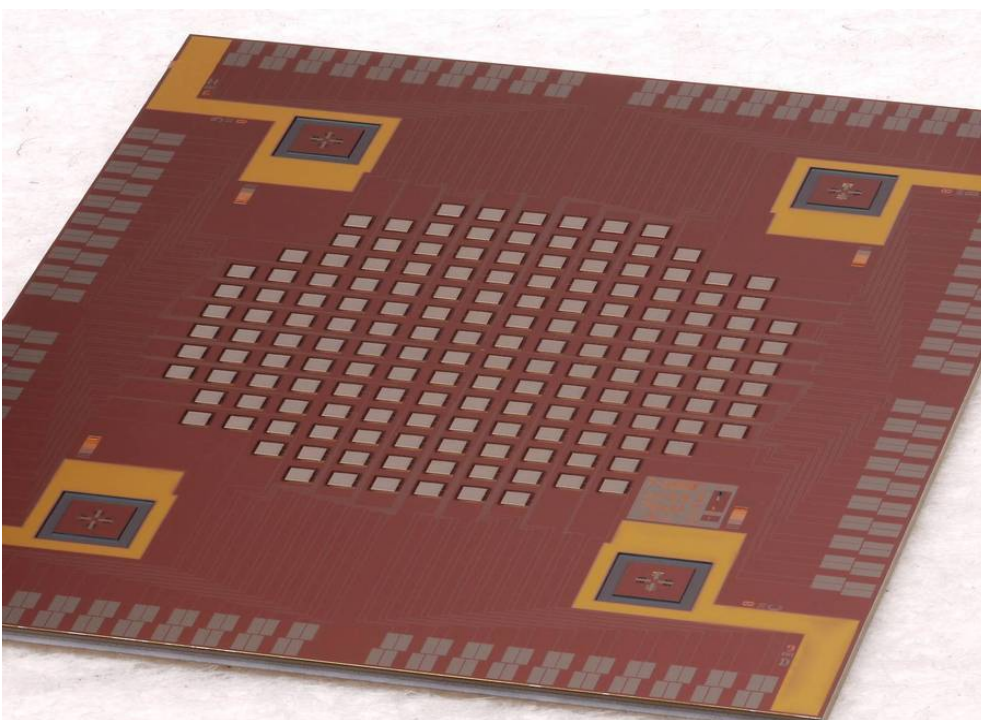
- single pixel development @Genova
  - ▷ optimize design for speed and resolution
  - ▷ define process for ^{163}Ho implantation
- array design @Genova
- subcontract array fabrication
  - ▷ subcontractor fabricates array with 1 µm Au absorber
- Genova completes array fabrication
  - ▷ Genova implants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



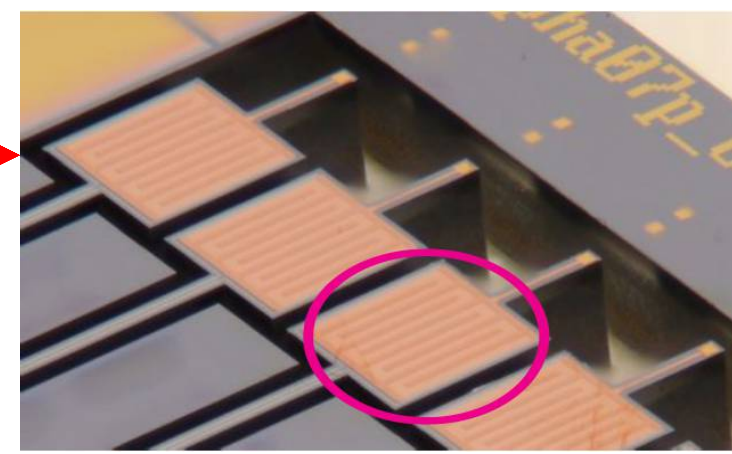
HOLMES detector array

NASA/GSFC





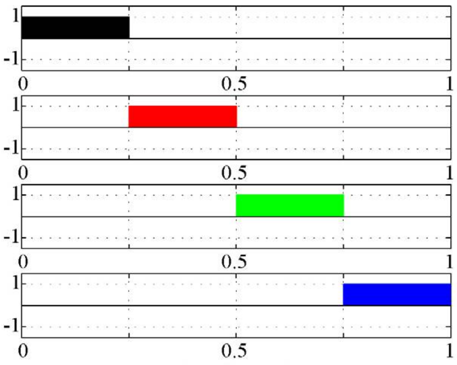
NIST



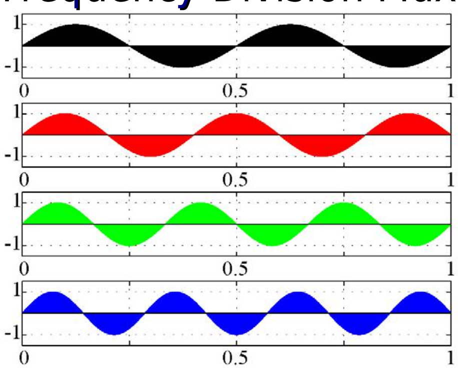
→ **HOLMES array**: 256 sparse pixels (4x)

HOLMES array multiplexing

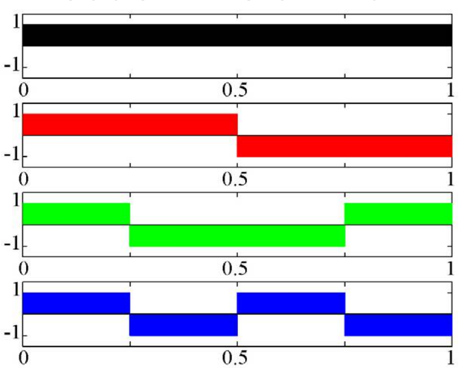
Time Division Mux

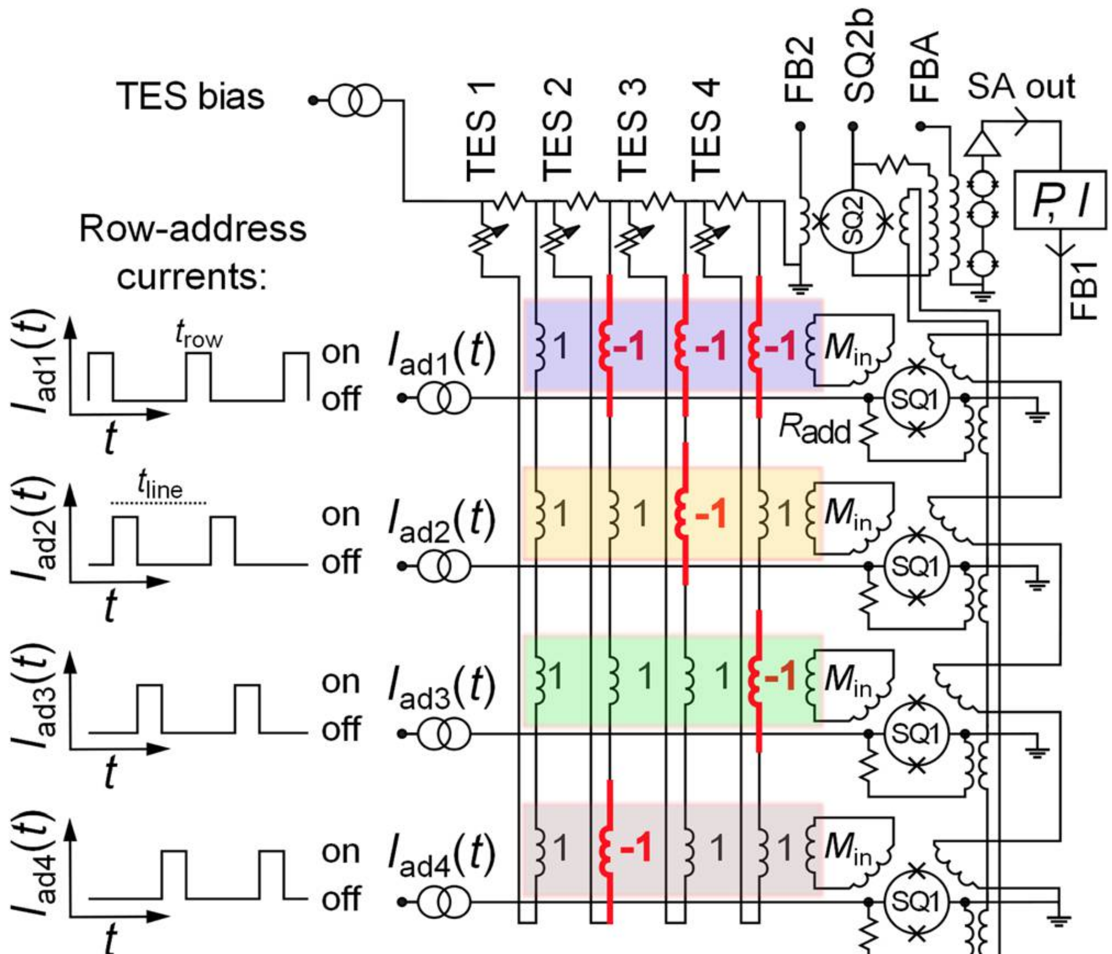


Frequency Division Mux

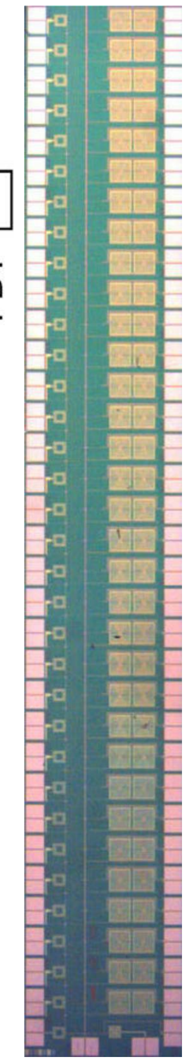


Code Division Mux





M. Niemack et al.,Appl. Phys. Lett. 96, 163509 (2010)
G.M. Stiehl et al., Appl. Phys. Lett. 100, 072601 (2012)

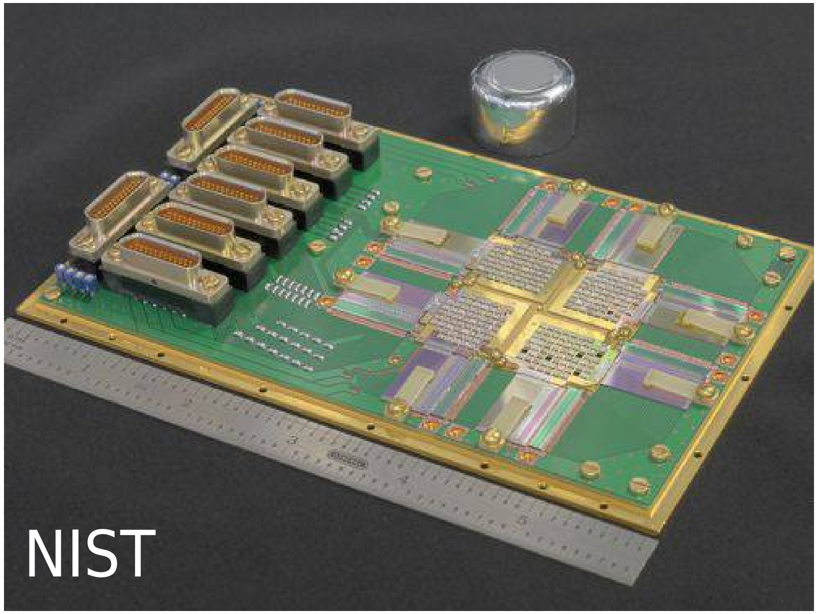


NIST 32 row Φ-CDM chip (1 column)

→ **HOLMES mux**: Φ-CDM with 16 row columns (64x)

→ 900 wires

HOLMES array multiplexing / 2



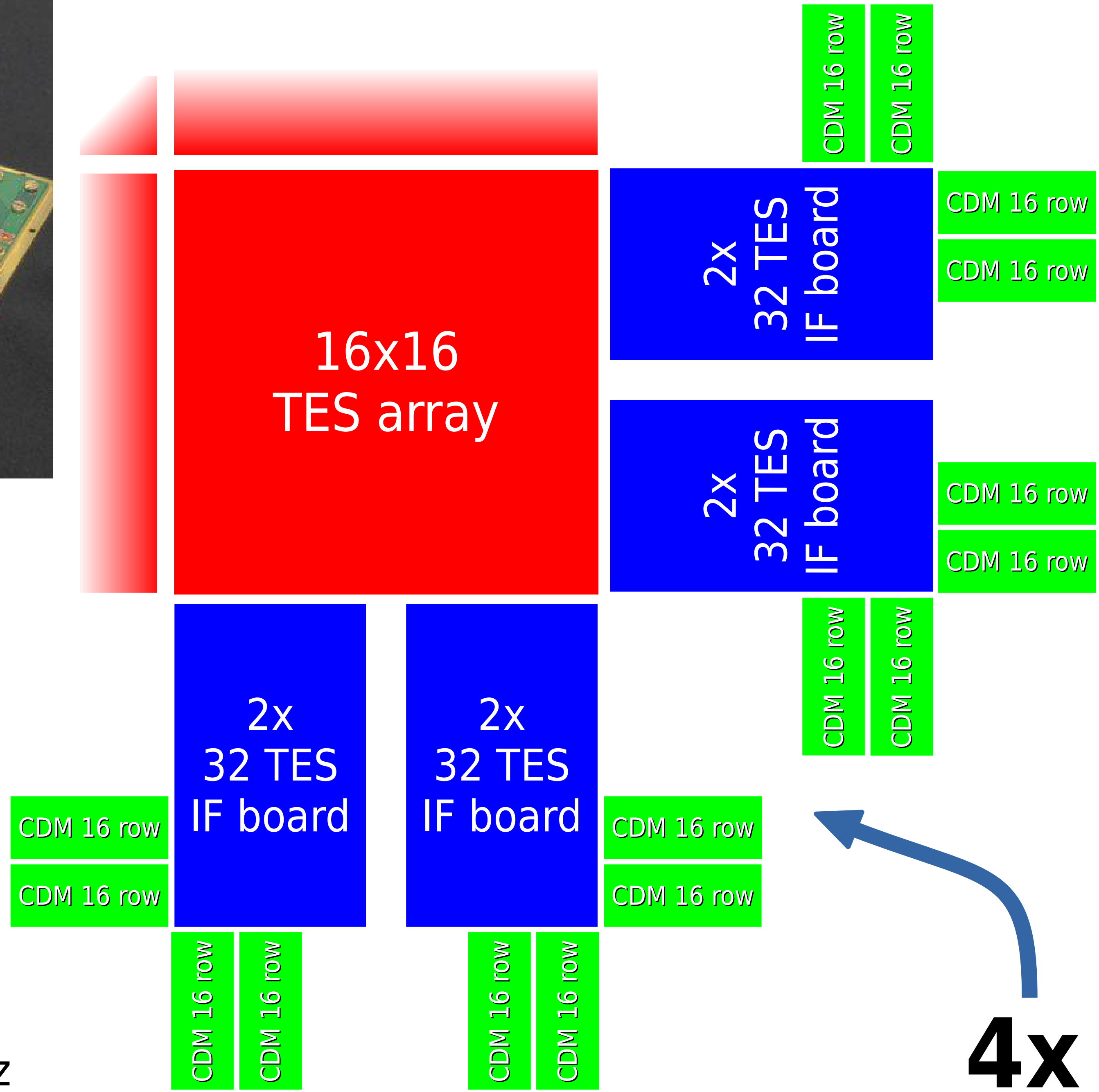
64x **CDM-MUX 16 row**

↓

DFB
160ns row time

↓

12.5MB/s data stream
→ demux, filter, trigger...
→ pulses from 16 ch at 5×10^3Hz

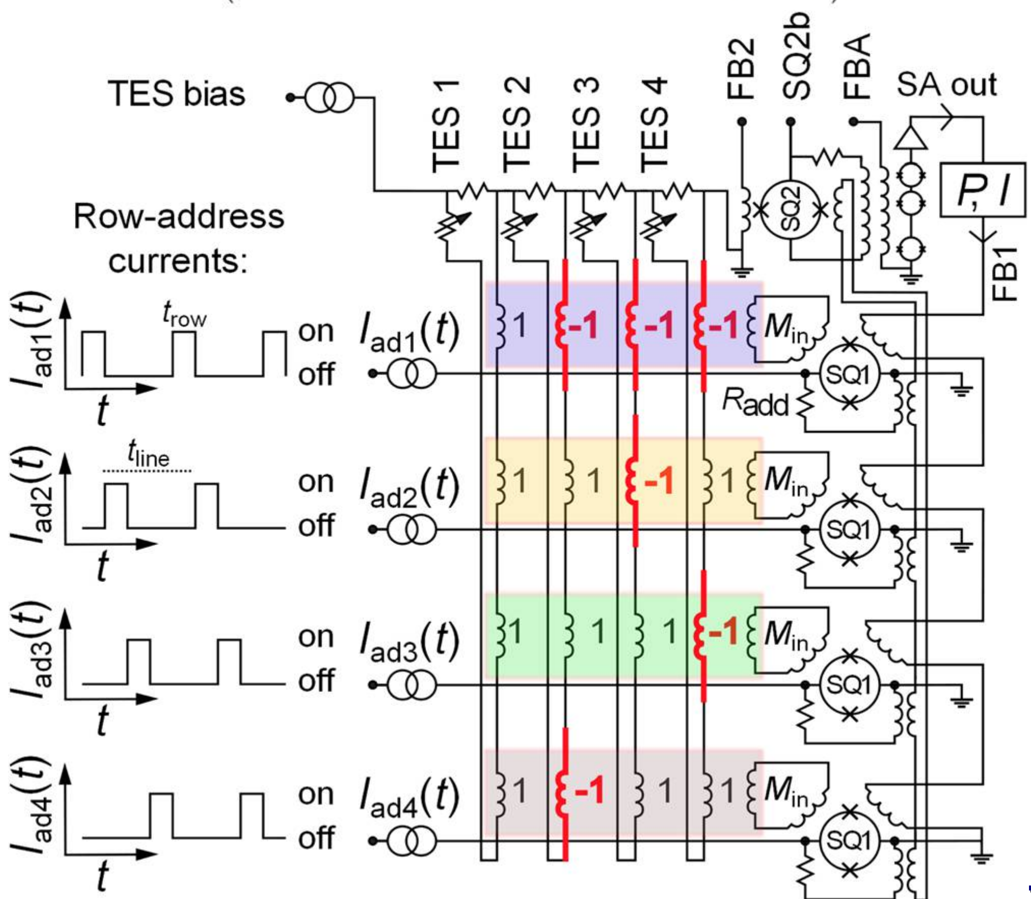


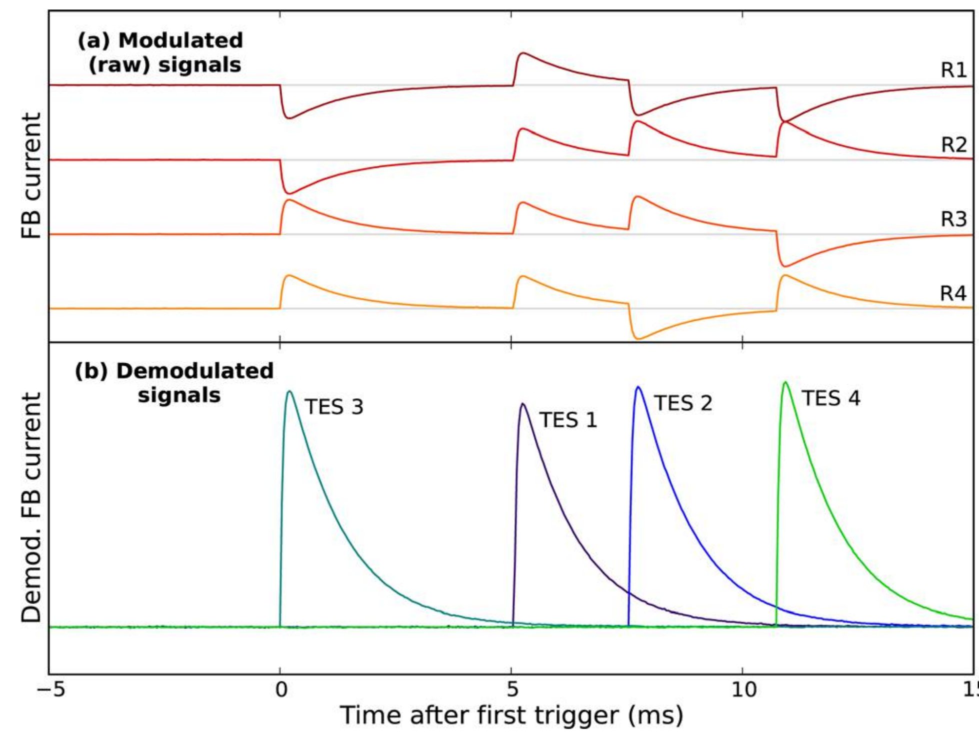
Φ-CDM

$$W_4 \equiv \begin{pmatrix} 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & 1 \\ 1 & 1 & 1 & -1 \\ 1 & -1 & 1 & 1 \end{pmatrix},$$

$$W_8 \equiv \begin{pmatrix} 1 & -1 & 1 & -1 & -1 & 1 & -1 & -1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & 1 \\ 1 & 1 & 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & -1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & -1 & 1 & 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & -1 & 1 & 1 & -1 & 1 \\ 1 & 1 & -1 & 1 & -1 & 1 & 1 & -1 \\ 1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 \end{pmatrix}$$

- TES DC biasing
- always ON TESs
- sub-frame sampling

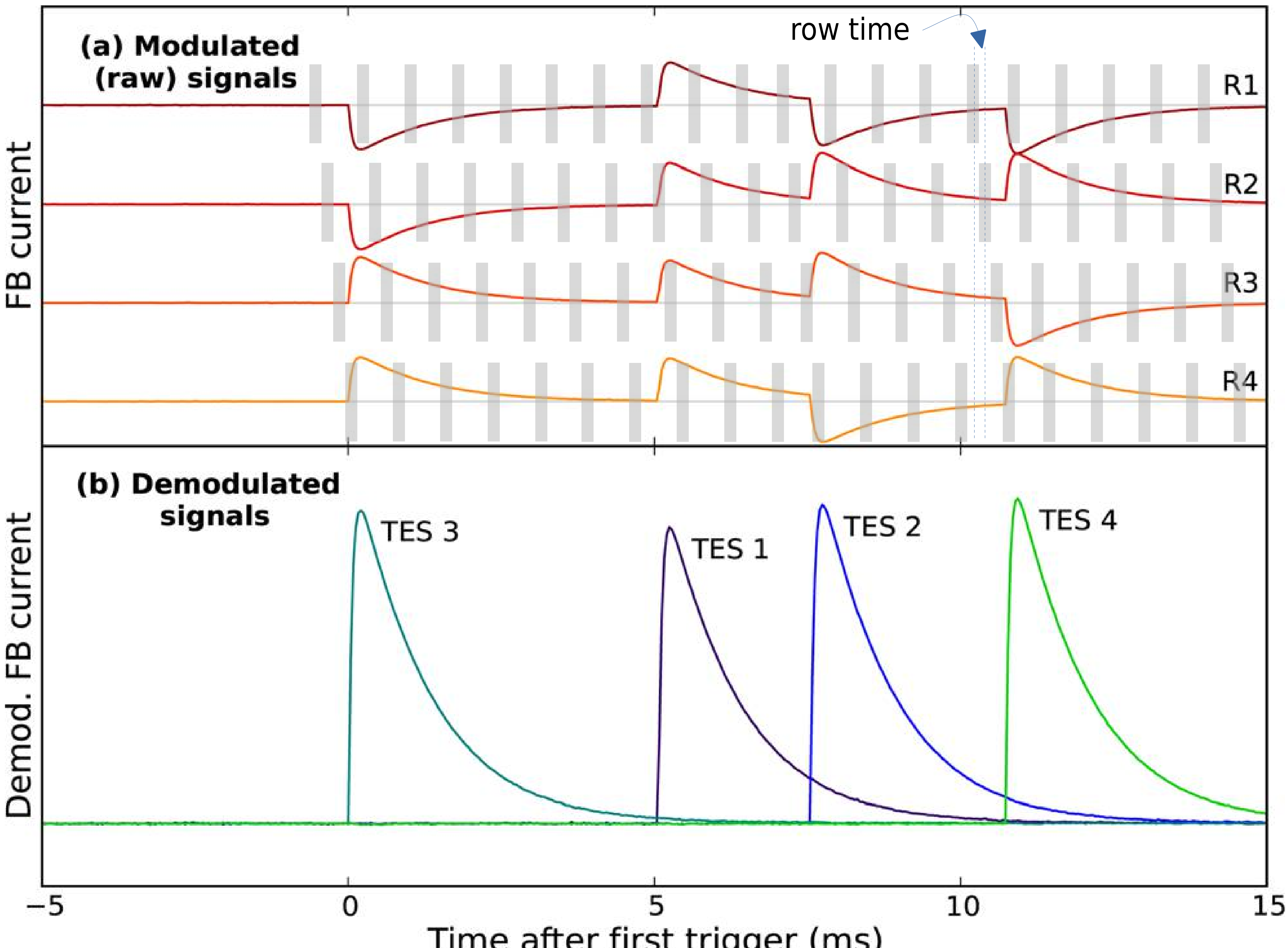




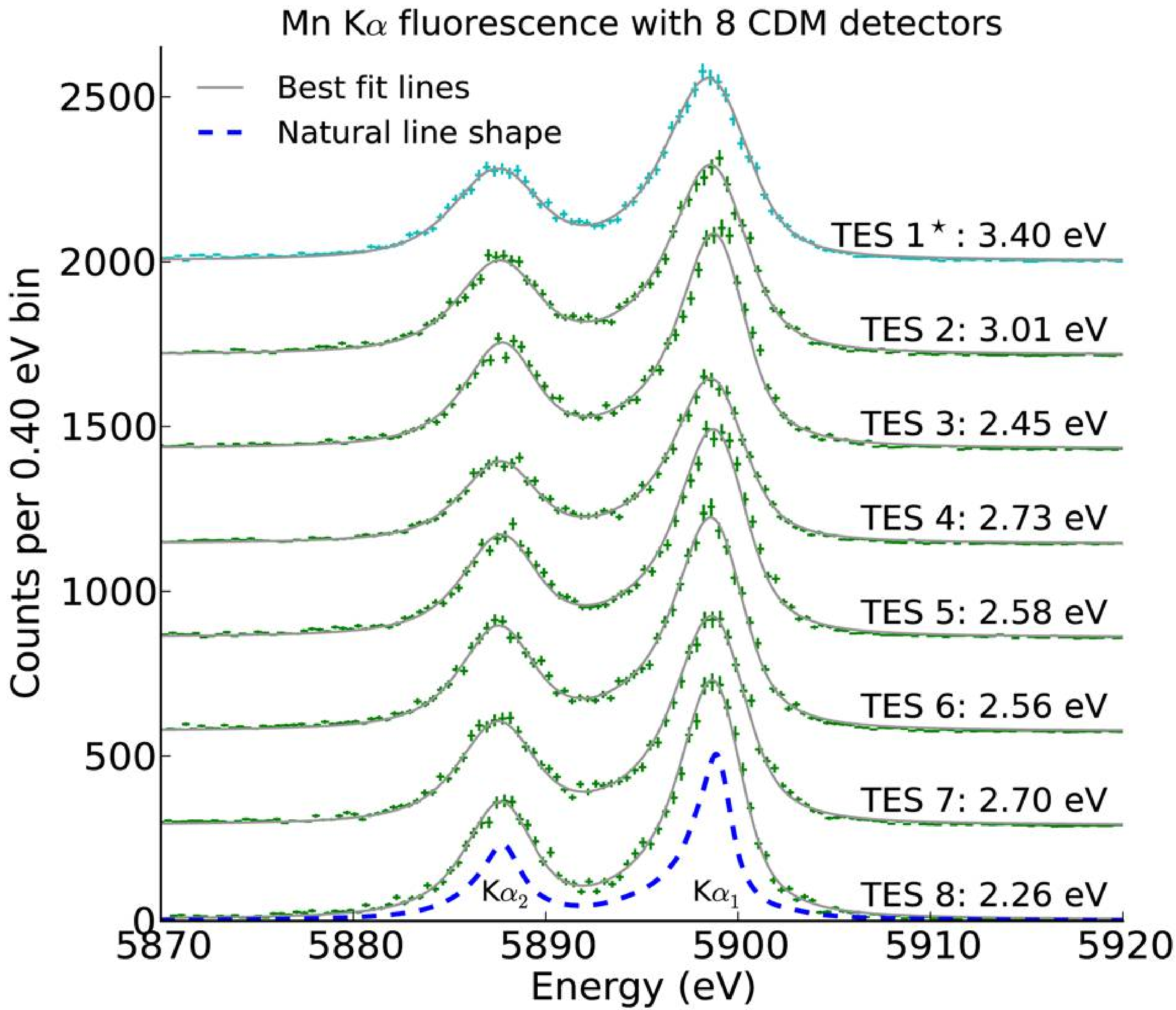
- speed?
- cross-talk?

Sub-frame sampling

modulated signal sampling time (frame time) = 4 * row time



Φ-CDM / 2



Mn Kα fluorescence with 8 CDM detectors
Best fit lines
Natural line shape
TES 1*: 3.40 eV
TES 2: 3.01 eV
TES 3: 2.45 eV
TES 4: 2.73 eV
TES 5: 2.58 eV
TES 6: 2.56 eV
TES 7: 2.70 eV
TES 8: 2.26 eV
Kα2
Kα1
Counts per 0.40 eV bin
Energy (eV)
0
500
1000
1500
2000
2500
5870
5880
5890
5900
5910
5920

HOLMES signal processing and in-line analysis

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

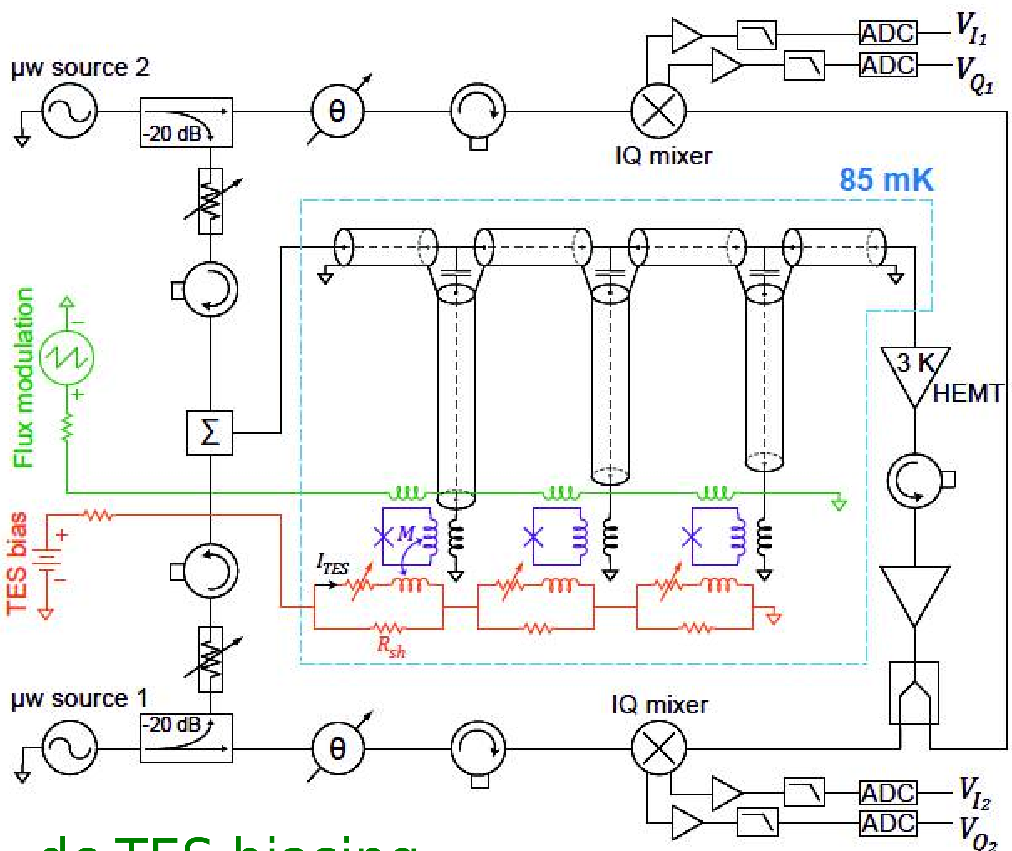
- reduce resolution (14 bit) and record length (256)
- **real time pulse processing**
  - optimal filtering, pile-up detection, pulse shape analysis
- commissioning and periodic minimum bias samples
  - full waveform saved to disk for off-line analysis
  - full spectrum (10% live time) and with 1.5keV thershold (90%)
  - 2.2TB/day
- normal data taking
  - save only n-tuples (16 16 bit words) for each event above 1.5keV
  - 90TB in 3 years
- **140TB total**

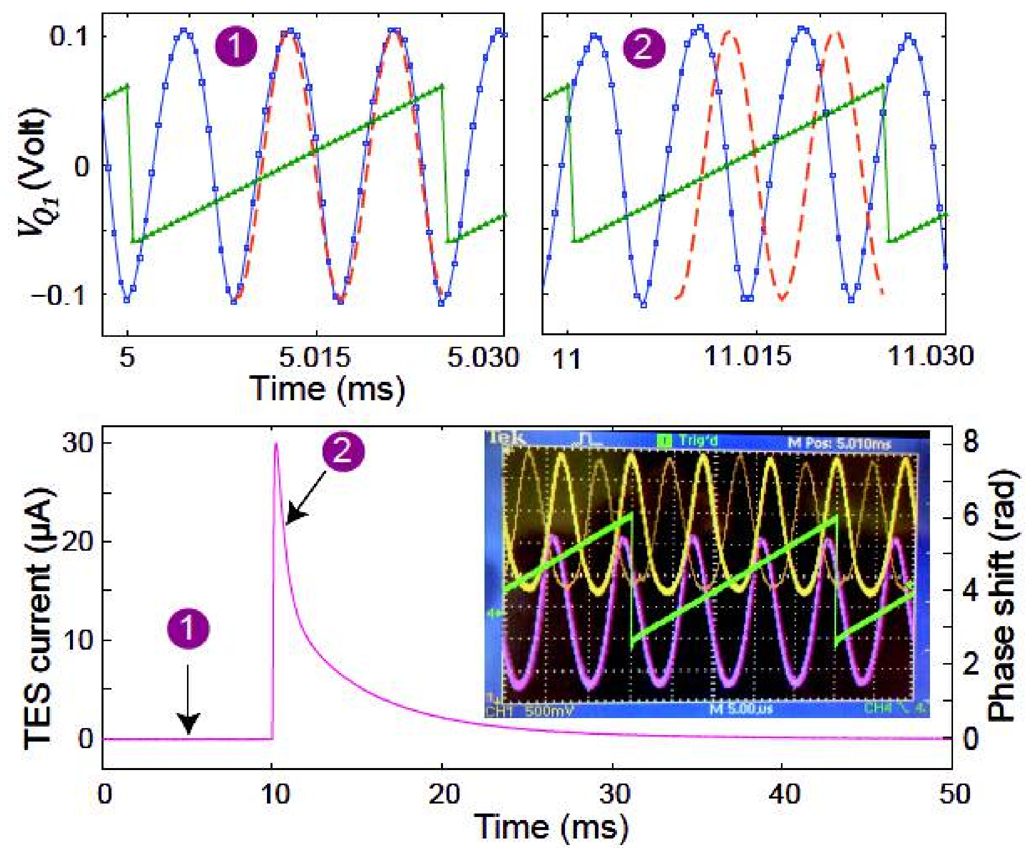
Alternatives to HOLMES baseline

- **^{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

RF SQUID multiplexing

2 channel µmux



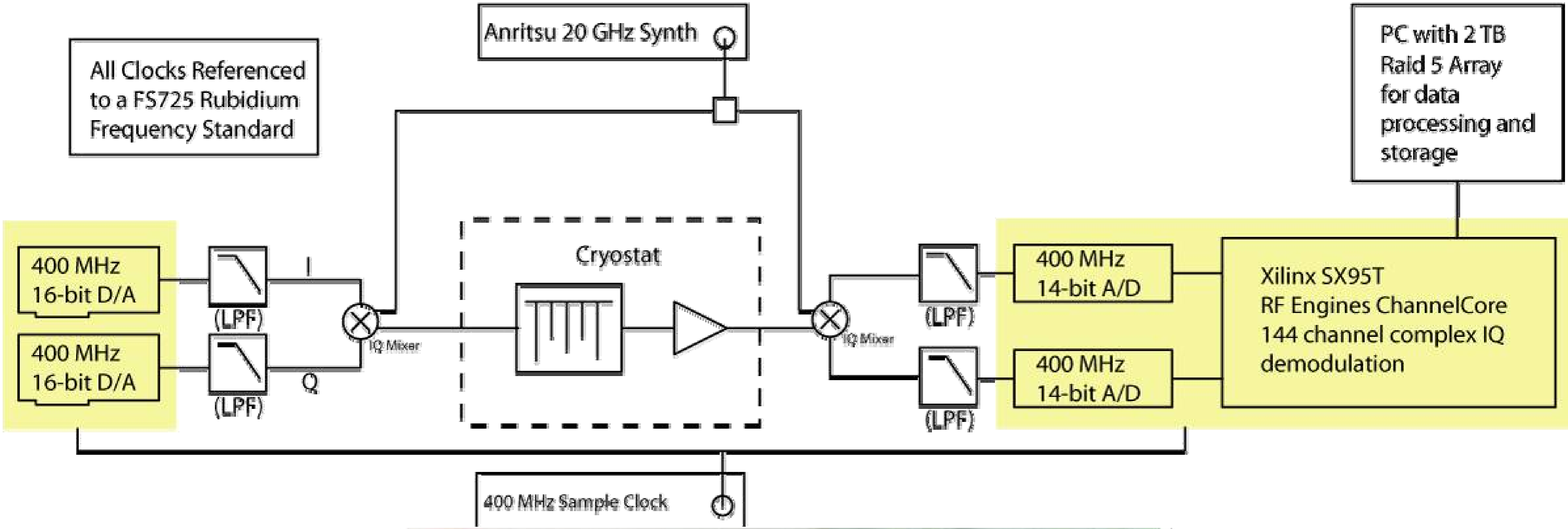


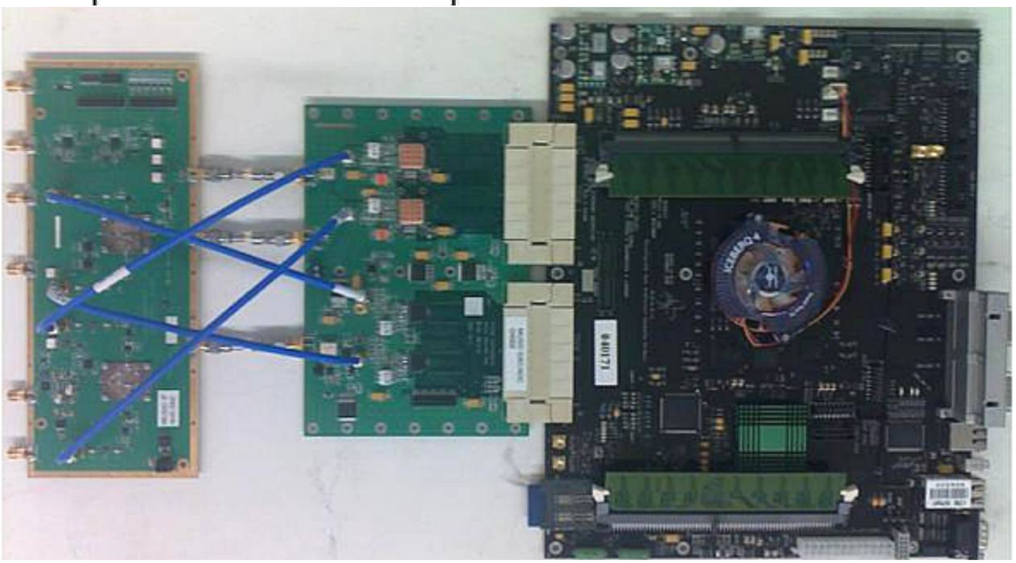
- dc TES biasing
- always ON TESs

bandwidth/pix 10MHz
→ 50 resonances beteween 0 and 500MHz
→ up-conversion → 5-5.5GHz
→ down-conversion → 0-500MHz → demux

RF SQUID multiplexing / 2

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





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

Conclusions

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