Probing the absolute neutrino mass scale with the ^{163}Ho: the HOLMES project

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on behalf of the HOLMES collaboration

Neutrino Oscillation Workshop 2014
Conca Specchiulla, Sep. 7-14 2014

Outline

- ν mass direct measurement
- The ^{163}Ho electron capture spectrum calorimetric measurement
- The HOLMES project:
  - ^{163}Ho preparation
  - μ-calorimeter design, production and implantation with ^{163}Ho
  - Expected sensitivity and schedule
  - Conclusions

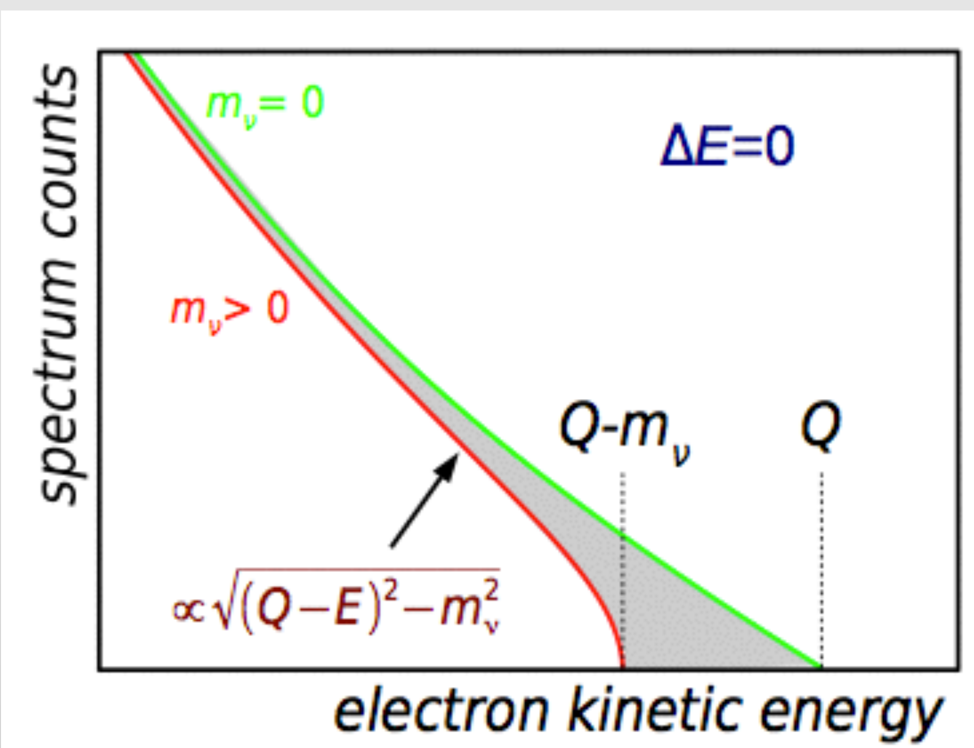
Direct ν mass measurement

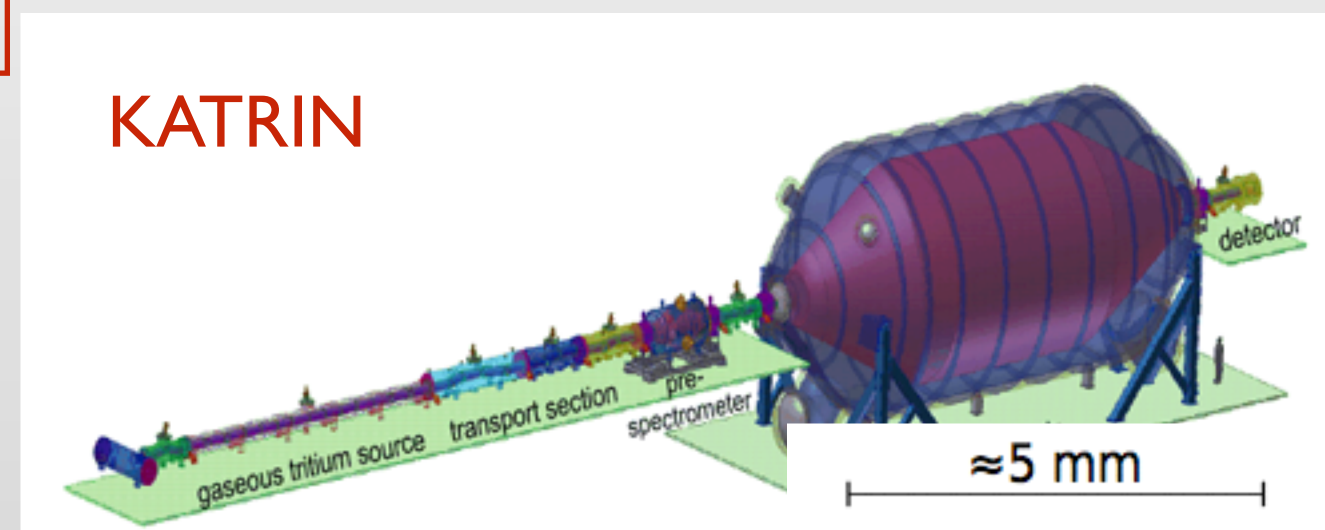
Kinematics of weak decay with ν emission:

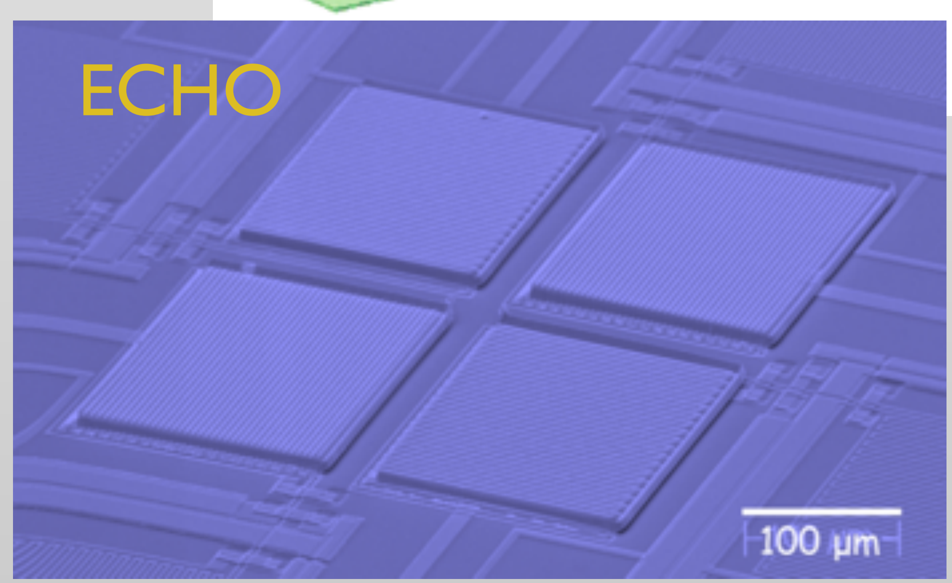
- low Q nuclear β decays (^{3}H, ^{187}Re, ^{163}Ho…)
- model independent: only E, p conservation
- ν mass appears as a distortion in the Kurie plot

2 different approaches:

- spectrometry: source placed outside the detector (KATRIN approach)
- calorimetry: source embedded inside the detector (ECHO, MARE, HOLMES approach) ⇒ low T μ-calorimeters







M. De Gerone, NOW 2014

The HOLMES project

ERC Advanced Grant 2013
Research proposal [Part B1]

Principal Investigator (PI): *Prof. Stefano Ragazzi*
PI's Host Institution for the project: *Istituto Nazionale di Fisica Nucleare*

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

HOLMES

INFN/Uni Mi-Bi: A. Nucciotti
INFN Ge: F. Gatti

Project started in Feb 2014

- Transition edge sensor with ^{163}Ho implanted Au absorber
- ~6.5×10^{13} nuclei/detector ⇒ A_{EC} ~300Bq;
- 1000 channels / array with multiplexed read-out
- $\Delta E \sim 1$eV and $\tau_r \sim 1\,\mu s$
- Probe the capability of this approach for a larger scale experiment

^{163}Ho electron capture

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

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

Q~2.55KeV, capture only from shell ≥ M1

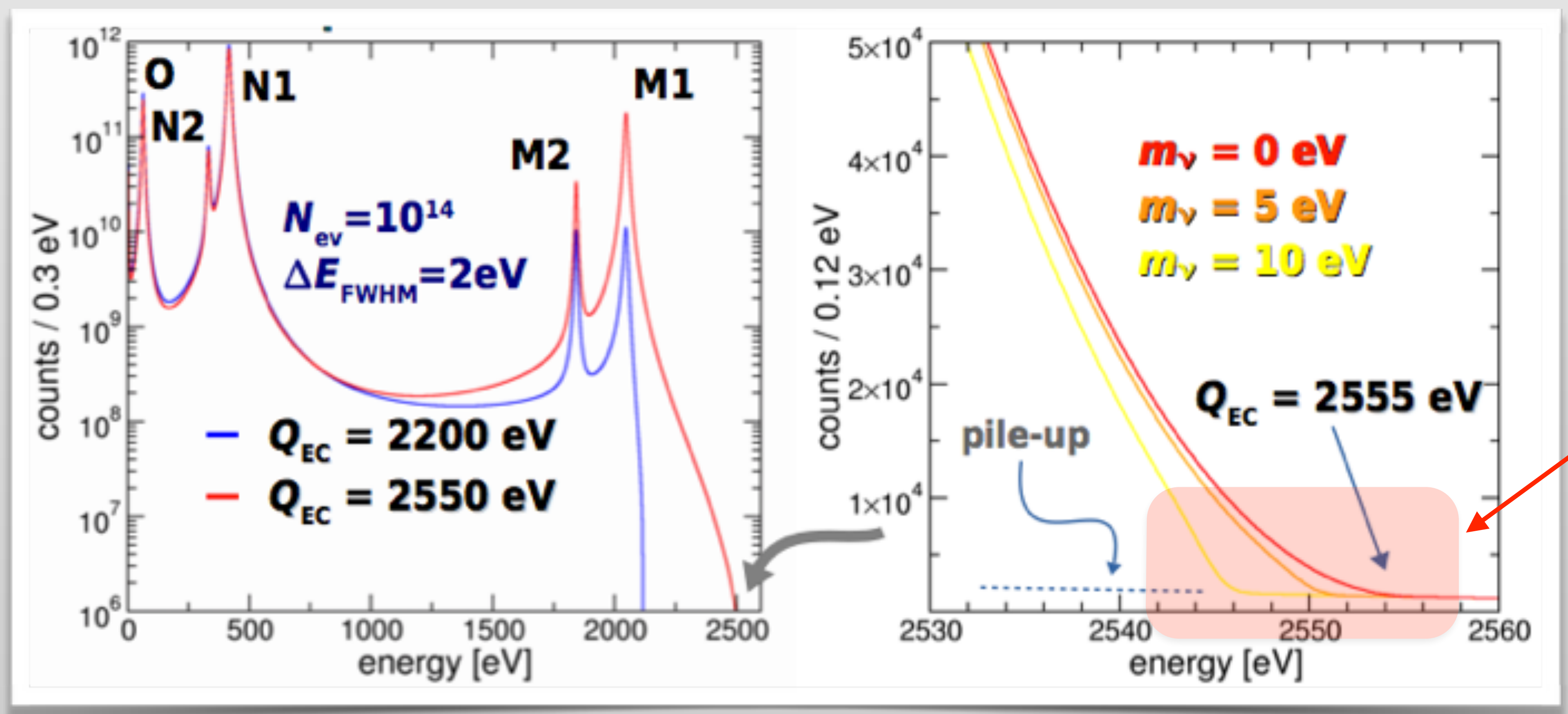
De Rujula & Lusignoli, Phys. Lett. B 118 (1982) 429

same factor as β decay
(total de-excitation energy E_c instead of E_e)

Breit-Wigner shapes

- calorimetric measurement of Dy* de-excitation
- "good" event rate and ν mass sensitivity depends on Q-value (~1/Q^3)
- $\tau_{1/2}$ ~ 4570 years → few active nuclei needed

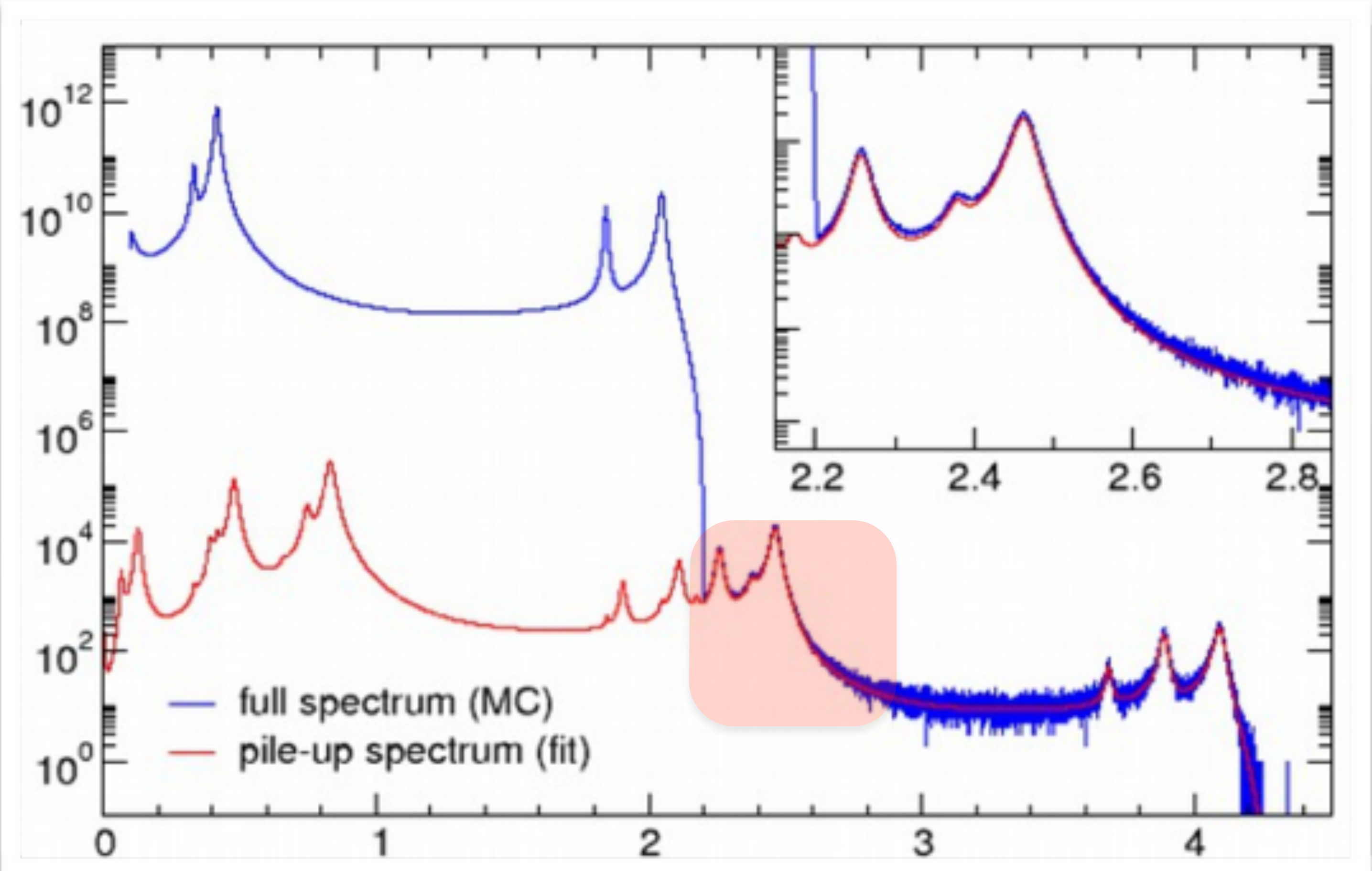
simulated spectra with different Q-value



expected ν mass effect

^{163}Ho electron capture: issues

- few Q value measurement so far
  - ratio of capture probability from different shells
  - measured Q-value: 2.2÷2.8KeV
  - "usually" Q = 2.55 KeV
- atomic de-excitation spectrum not well known
- complex pile-up spectrum
  - end-point is dominated by $\mathrm{sqrt}((Q-E_{EC})^2-m_\nu^2)$ but expected distortions due to pile-up

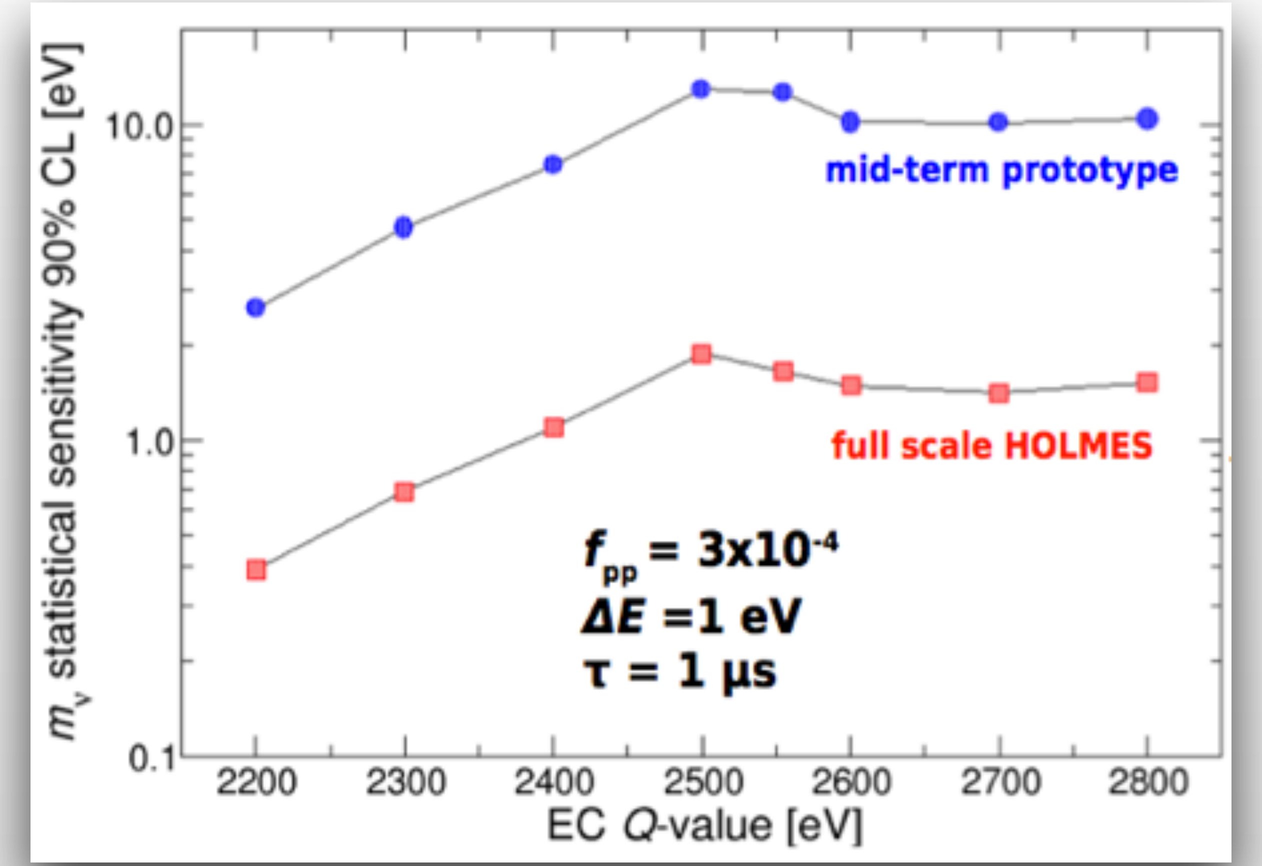


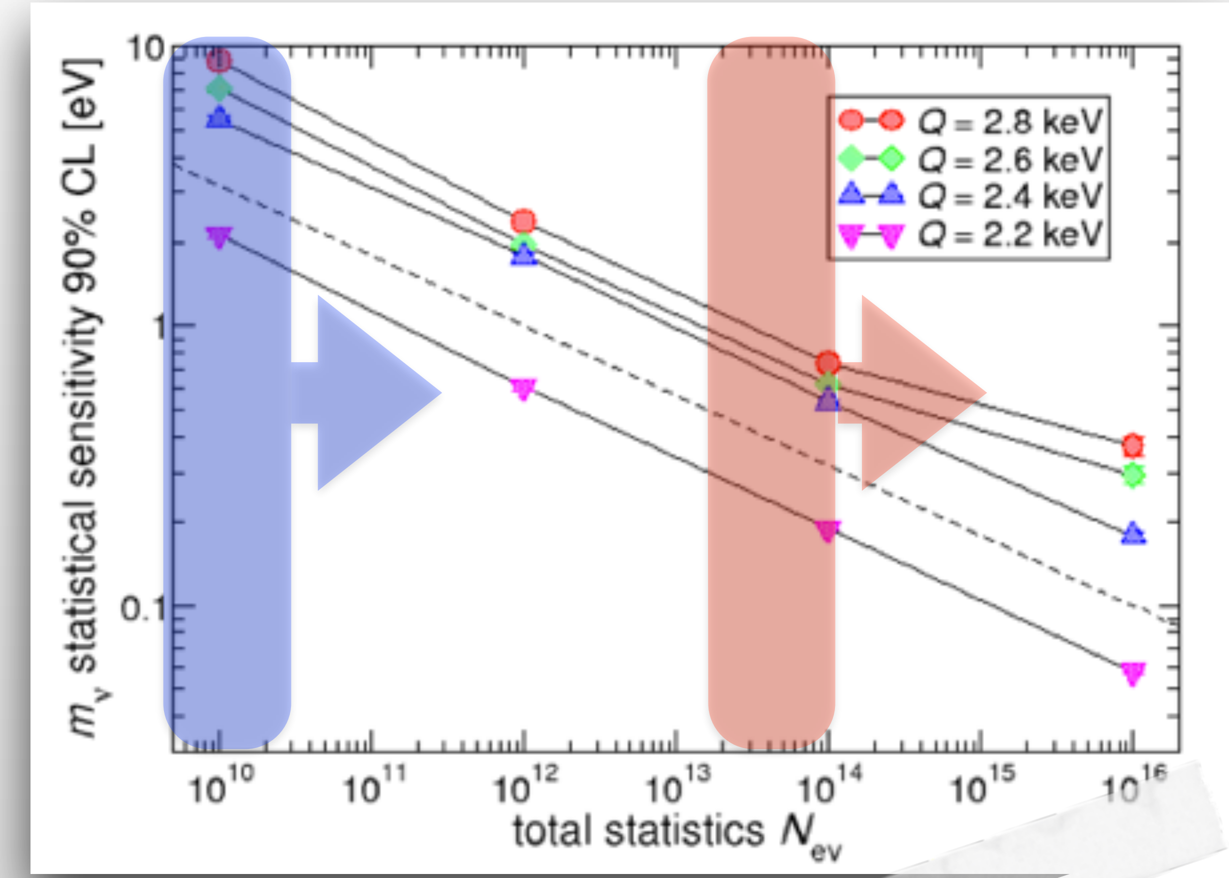
$Q=2.2\mathrm{keV}$ $f_{pp}=10^{-6}$ $N_{ev}=10^{14}$ $\Delta E=2\mathrm{eV}$ FWHM

Pile-up occurs when multiple events arrive within the temporal resolving time of the detector. In a first approximation, the fraction of unresolved pile up is given by $f_{pp} = \tau \times A_{EC}$

In order to reduce pile-up:
- trade-off between activity and statistic
- detector with fast signal rise time τ_r
- pile-up resolving algorithm

HOLMES baseline sensitivity





A. Nucciotti, submitted to EPJC, arXiv: 1405:5060

sub-ev sensitivity region: $N_{ev} > 10^{13}$

Mid-term prototype:
16x16 array, 1month of DAQ
A_{EC}=300Hz/ch
>10^{10} decays
expected mid 2016

Full scale HOLMES:
~1000 channels, exposure:
>10^3 det x year
A_{EC}=300Hz/ch
>10^{13} decays
expected 2017-2018

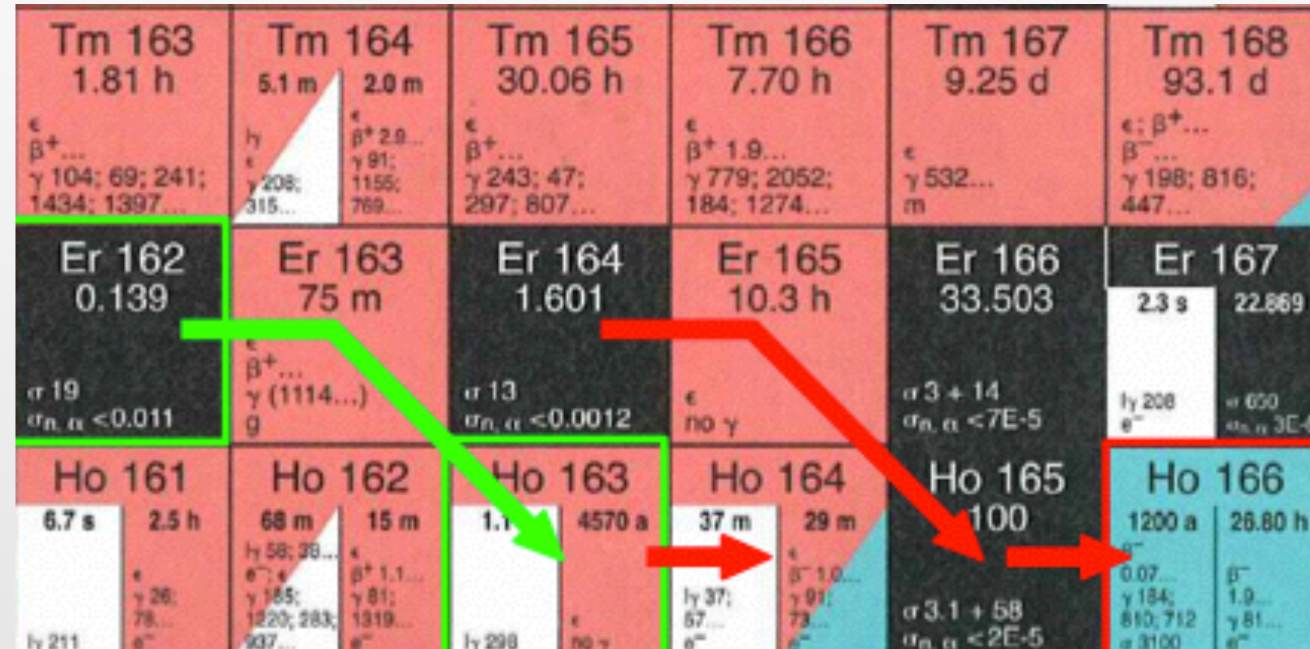
HOLMES tasks

- ^{163}Ho isotope production and purification;
- isotope embedding in detector;
- single TES design and optimization;
- array engineering;
- SQUID read-out and multiplexing optimization and testing;
- online/offline signal processing and analysis.

Ho production and purification

^{163}Ho from ^{162}Er neutron activation at nuclear reactor:

- ^{162}Er (n,γ) ^{163}Er, σ_{therm} ~ 20 b
- ^{163}Er + e^- → ^{163}Ho + ν_e ($\tau_{1/2}$ ~ 75 m)
- high yield (but not all cross sections are well known)
  - ~3x10^{12} ^{163}Ho nuclei/mg(^{162}Er)/h
- requires ^{162}Er enrichment and oxide chemical form (Er_2O_3)



But contamination from other isotopic species:

- ^{164}Ho from ^{163}Ho (n,γ) activation ?
- ^{165}Ho (n,γ) ^{166m}Ho (β, $\tau_{1/2}$~ 1200 years)
- from Ho contamination or ^{164}Er (n,γ)
- need high purification of sample

Collaboration with
ILL (Grenoble)
ITN (Lisboa)
Paul Scherrer Institute

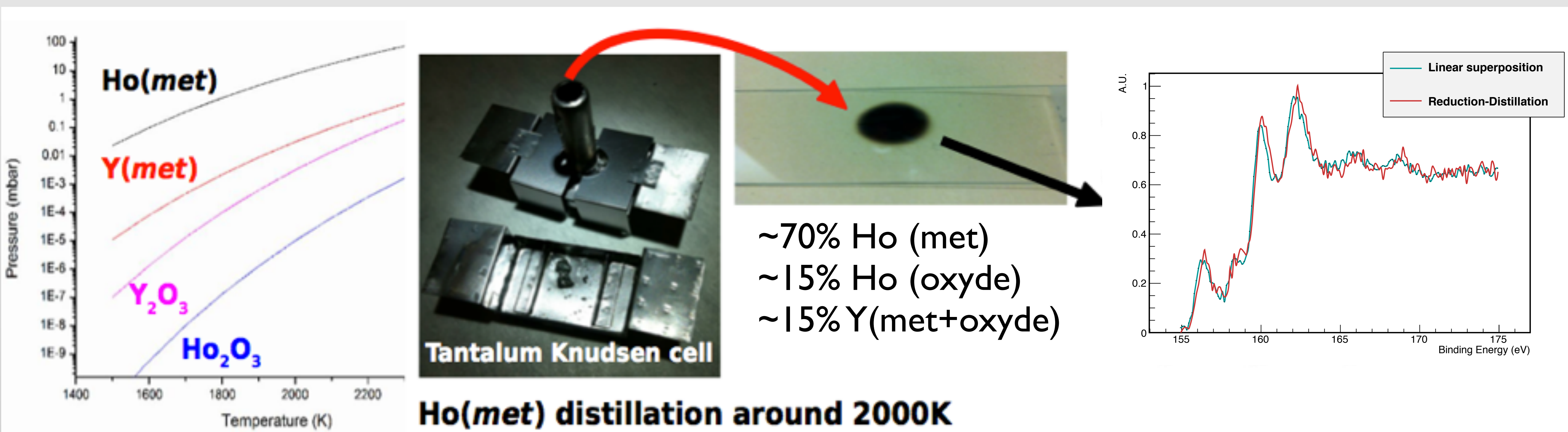
Ho production and purification

^{163}Ho separation from Dy, Er and others…

- radiochemistry (before/after activation process)
- magnetic mass separation

Ho_2O_3 thermo-reduction in Knudsen cell provides a metallic sample for the implantation:

- $Ho_2O_3 + Y(met) \rightarrow Ho(met) + Y_2O_3$ @2000K
- First test already performed in Genova

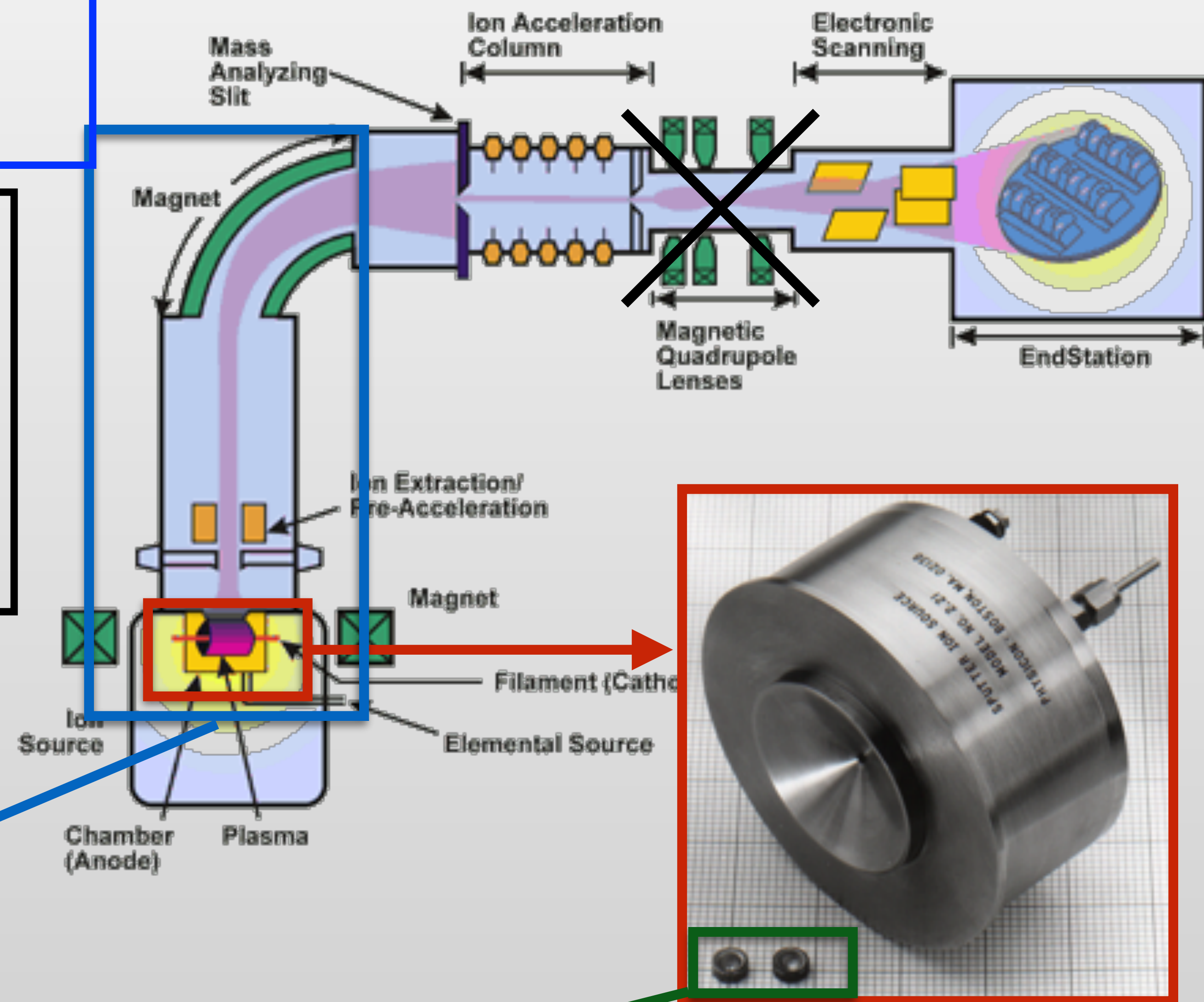


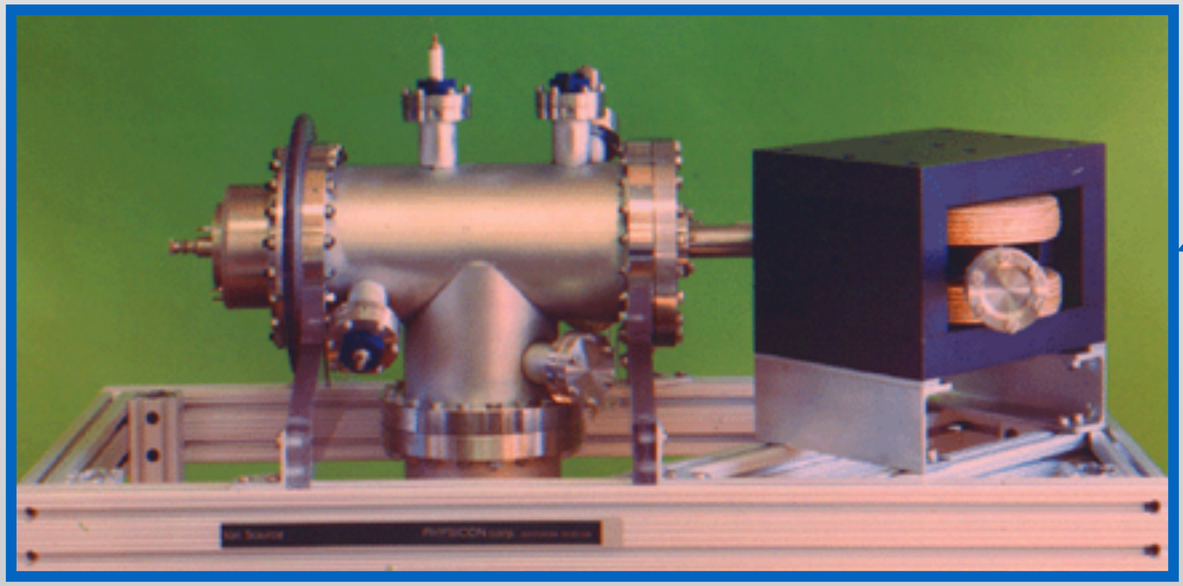
Ho production and embedding

^{163}Ho embedding in detector absorber
- implantation @30/40 nm depth
- magnetic separation of isotopic species (provides further purification)
- Au film deposition for full containment

Ad hoc beam line design on-going:
- high efficiency
- high mass resolving power
- implantation depth ~tens of nm (E~20/30KeV)

sketch of the ion implanter





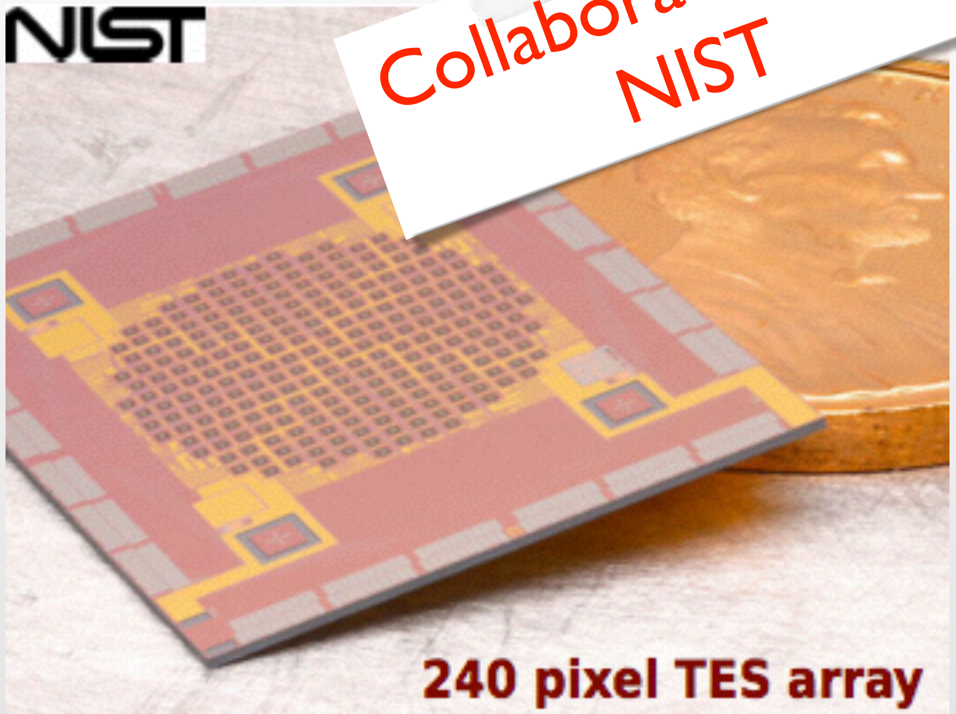
penning ion sputtering source

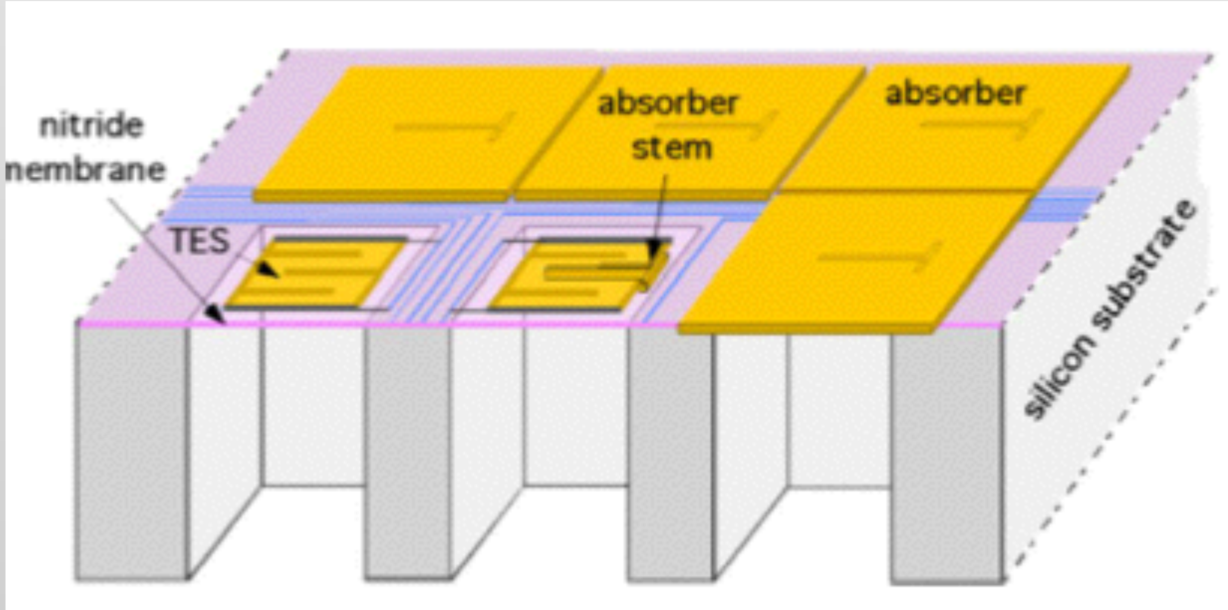
163Ho (metallic) cathode

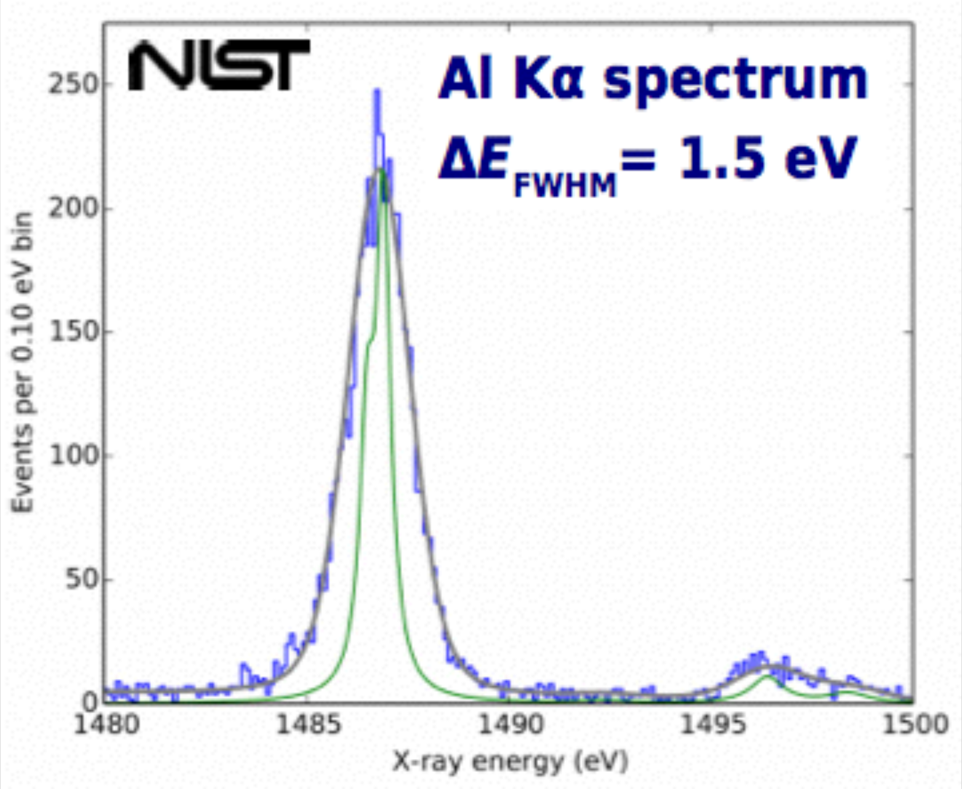
Single detector/array design

Collaboration with NIST

- Mo/Cu bilayers, T_c ~ 100mK
- μ-calorimeter with electrothermal feedback
- ~3μm thick Bi absorber with 163Ho/Au source for full absorption
- source: thin electrodeposited Au encapsulating implanted Holmium
- TES fabricated by NIST
- Ho implantation and membrane release in GE

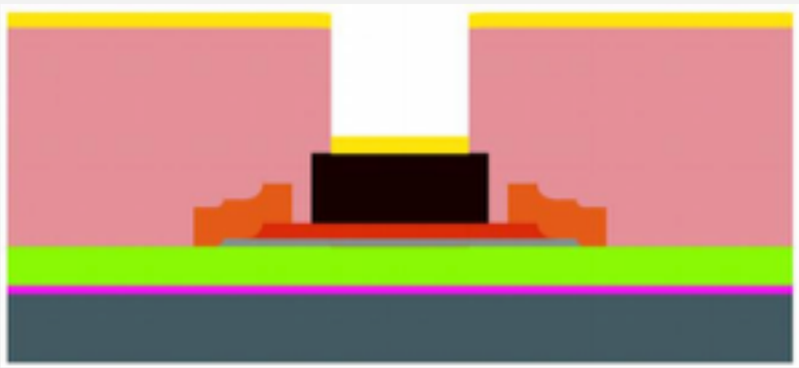






Detector production

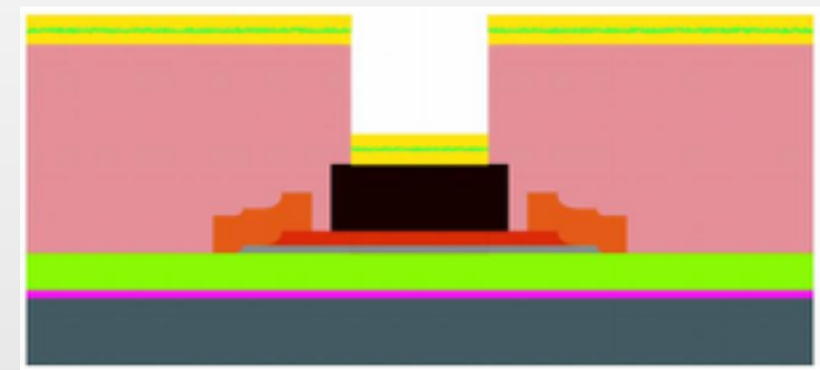
@NIST



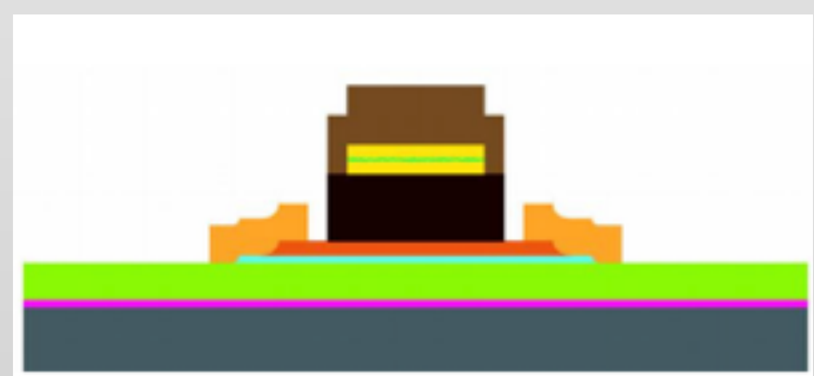
a) Array from NIST:
- complete Mo/Cu TES on Si/SiO/SiN substrate
- first Bi layer
- first Au layer
- do not finish lift off

@Genova

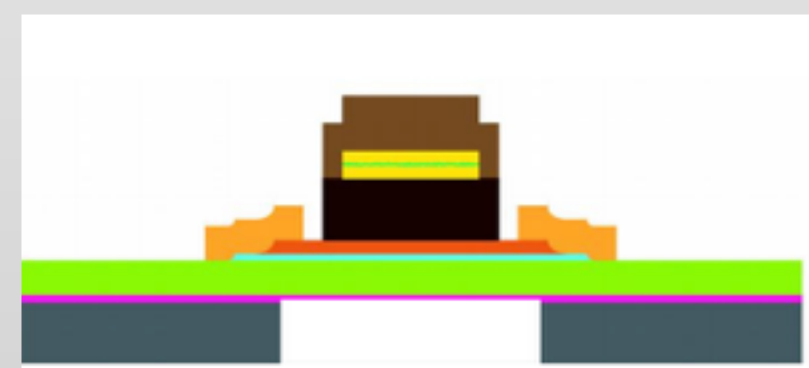
b) ^{163}Ho embedding



c) cap Ho with a second Au layer



d) lift off Au:Ho:Au layer second Bi layer (which fully encapsulate Au:Ho:Au)



e) Si etching

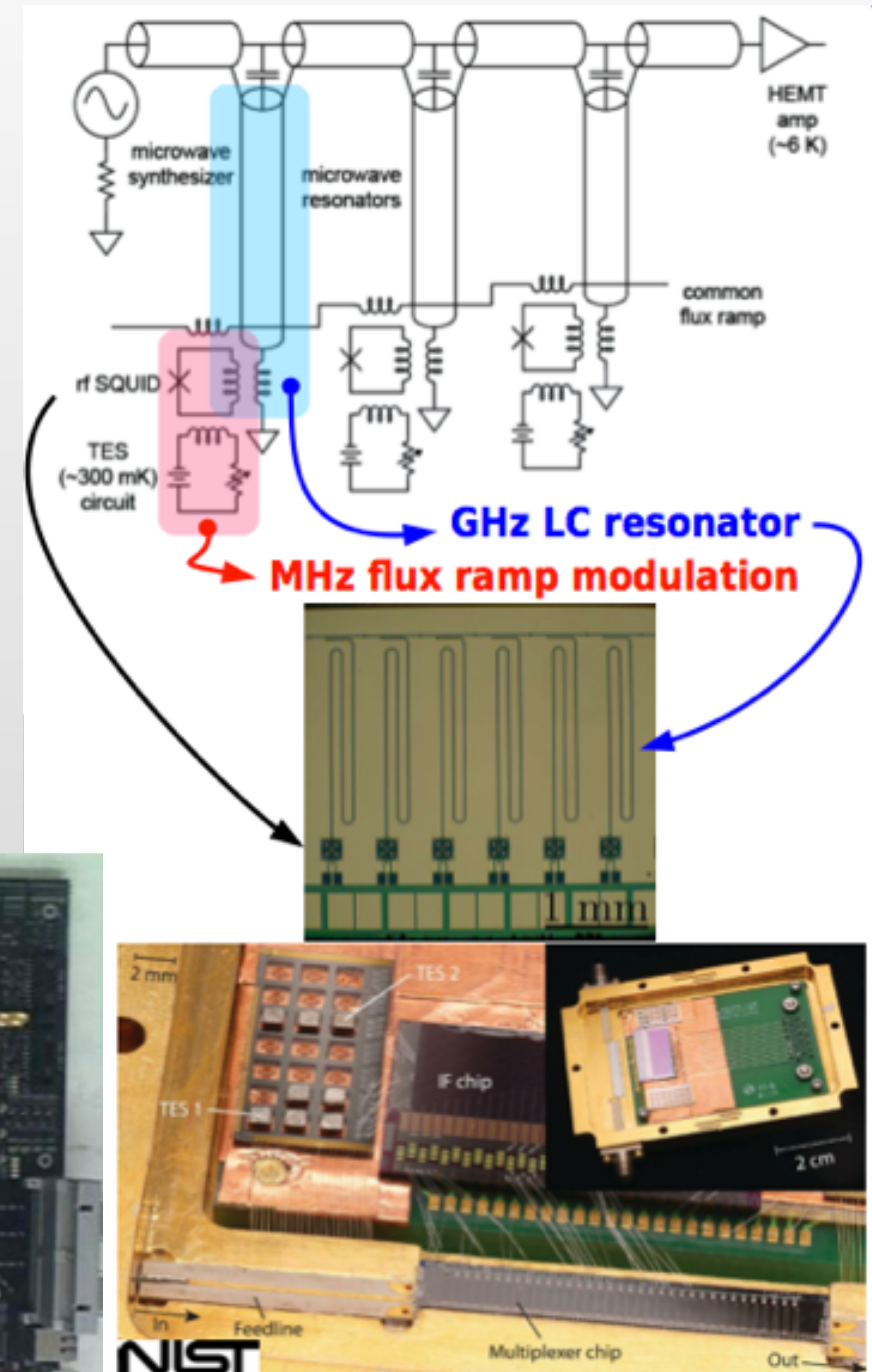
DAQ

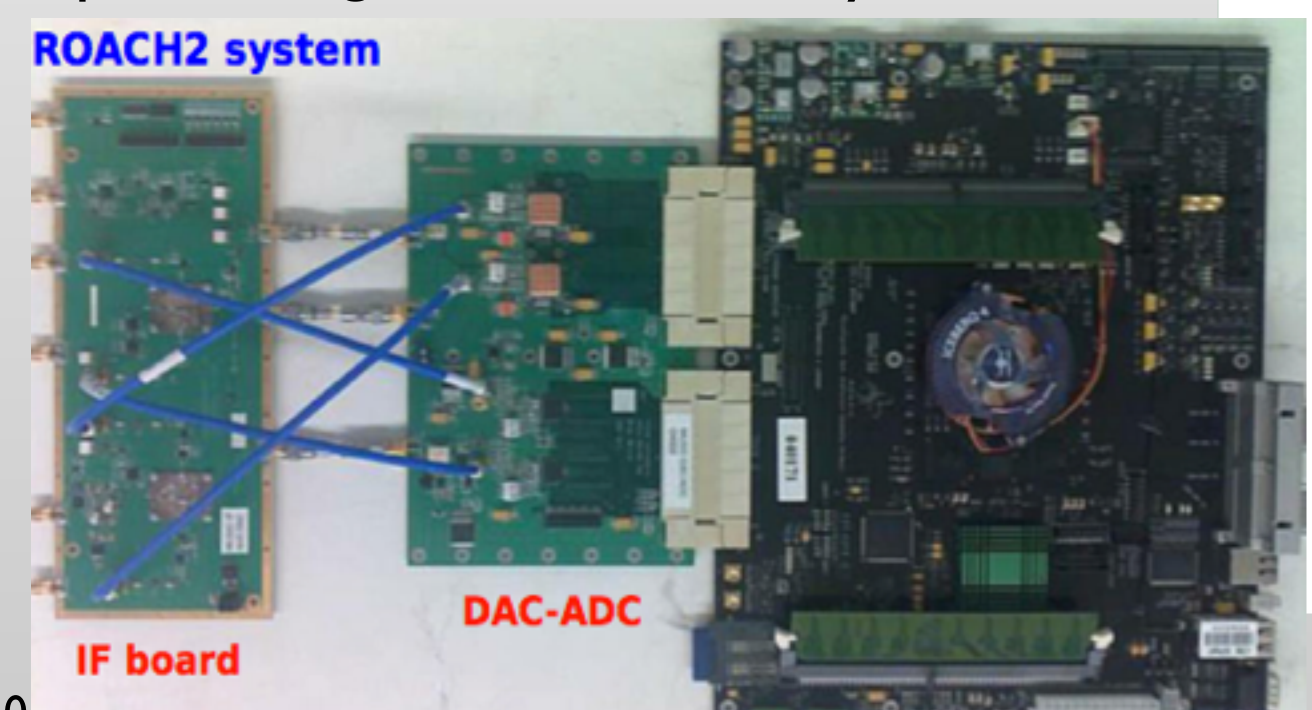
rf-SQUID readout with microwave MUX

- DC biased tes
- microwave rf-SQUID read out with flux ramp modulation

ROACH2-based MUX

- Xilinx FPGA based digital data processing
- frequency comb generation (up to 60 tones in 0-550MHz band)
- GHz band up/down conversion (5 - 5.5 GHz)
- I-Q signals (homodyne detection) de-multiplexing
- signal channelizing and rf-SQUID signal de-modulation
- real time signal processing → ~140TB in 3 years





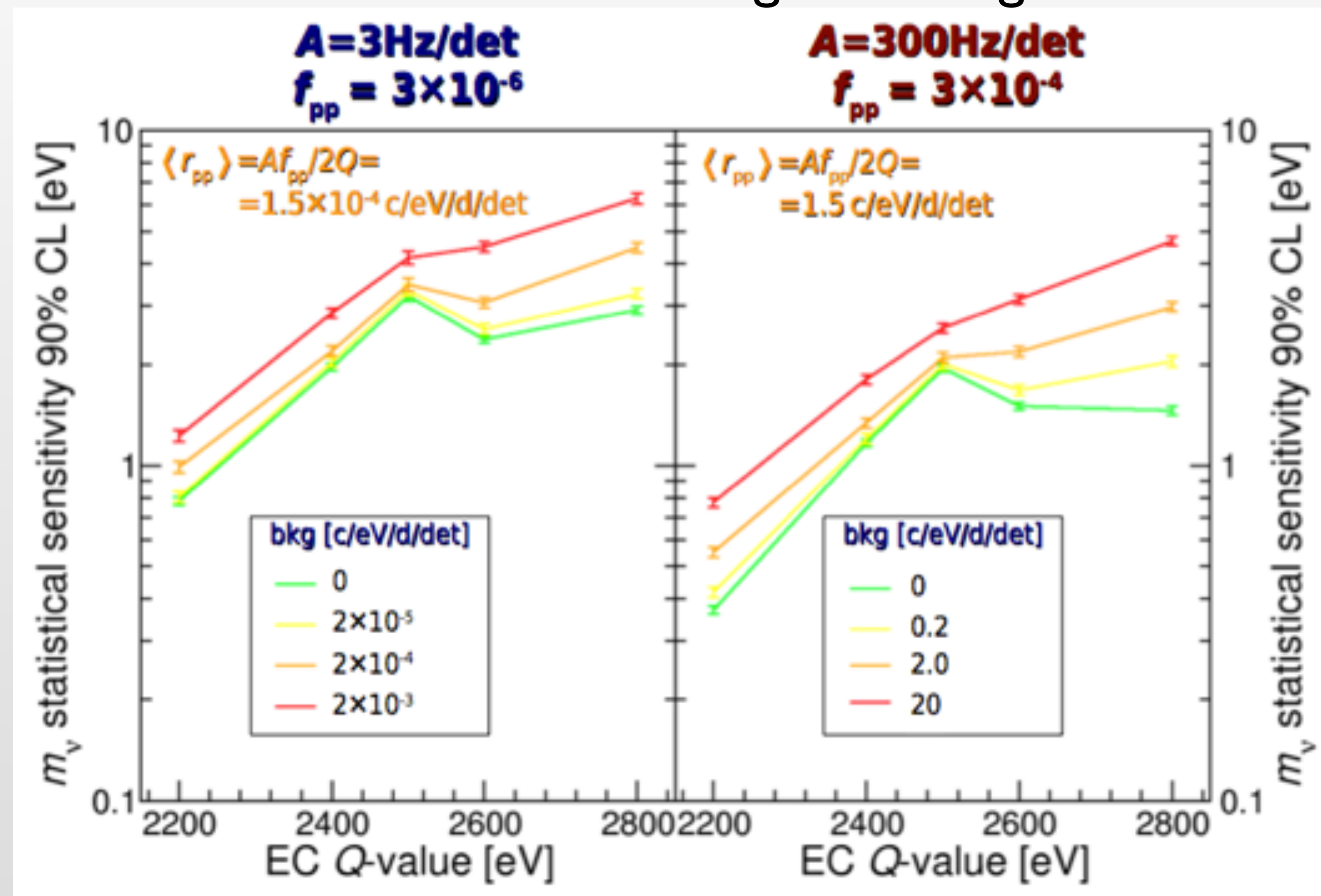
Source of background

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 at sea level (muons):
- TES@NIST(1600m):350×350×2.5μm^3 Bi absorbers:
  ⇒ b < 1 c/eV/d/det (preliminary);

MC simulations including flat background



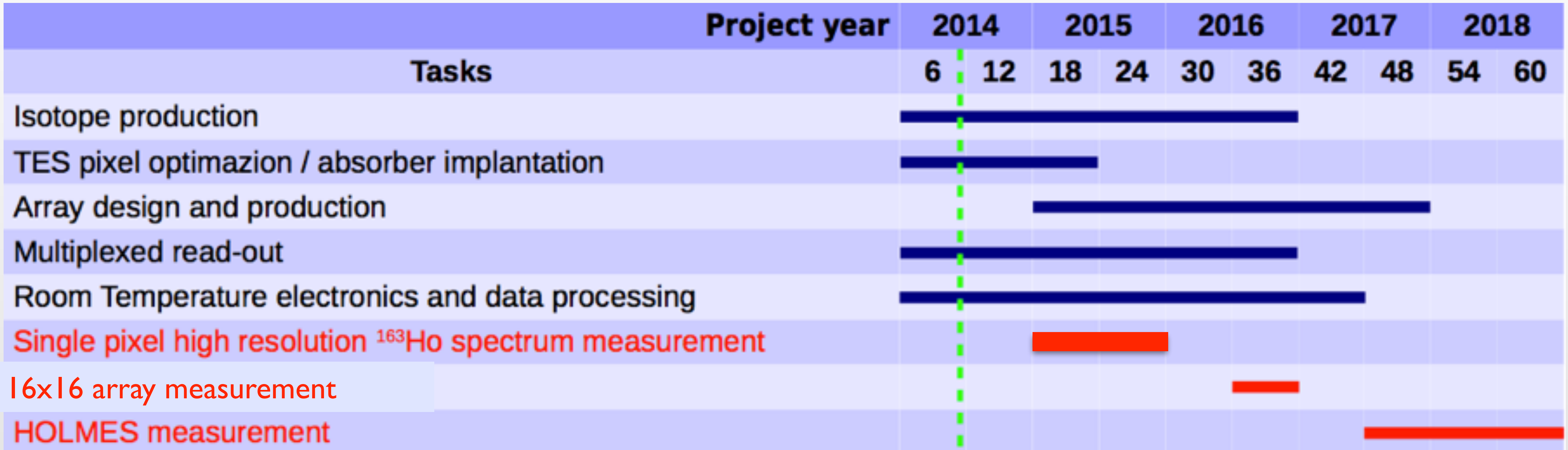
A. Nucciotti, submitted to EPJC, arXiv: 1405:5060

A flat background is negligible as long as it is smaller than the pile-up spectrum:

$$b < A_{EC} \times f_{pp} / 2Q$$

Other simulations are on-going to study the effect due to contaminations internal to the detector - mainly β and EC decaying isotopes ⇒ quality of Ho sample is crucial.

Status and schedule



- The HOLMES project started in Feb 2014.
- Current main activities:
  - test on isotope preparation (^{162}Er activation, sample purification)
  - ion implanter designing
    - first ^{163}Ho sample and implantation expected by mid 2015
  - single TES design and optimization (in collaboration with NIST)
    - single pixel test (^{163}Ho spectrum measurement) by fall 2015
  - development of the multiplexed read-out
  - development of the room temperature electronics and data processing

Conclusions

- HOLMES is a new project which aims to directly measure the ν mass
  - started in Feb 2014, funded by ERC Grant #340321.

- Its goal is to study the end-point of ^{163}Ho electron capture spectrum by using a ~1000 channels array of μ-calorimeters with ^{163}Ho implanted.
  - Probe this approach for a future larger scale experiment.

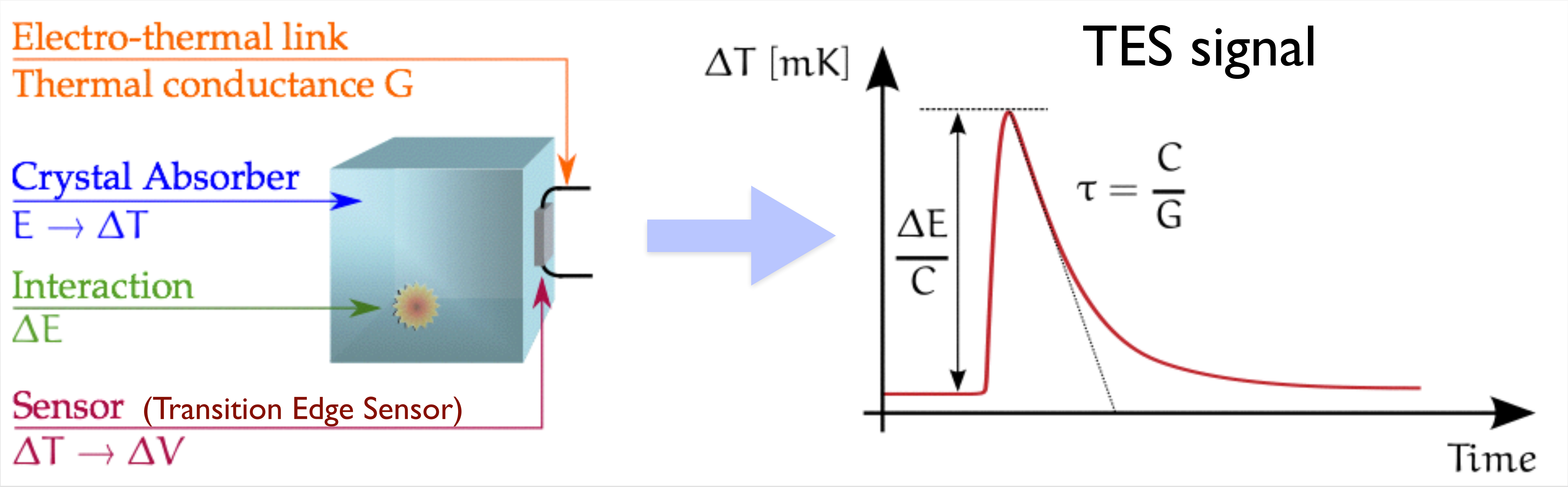
- The development of the first prototype is on-going:
  - Ho distillation, purification and embedding in the detector
  - single detector designing and optimization
  - first DAQ channels prototype

- We expect to measure the first Ho spectrum by end of 2015.

- Hope to see you again in NOW 2016 with the first results!

Back up slides

Low T calorimetry in a nutshell



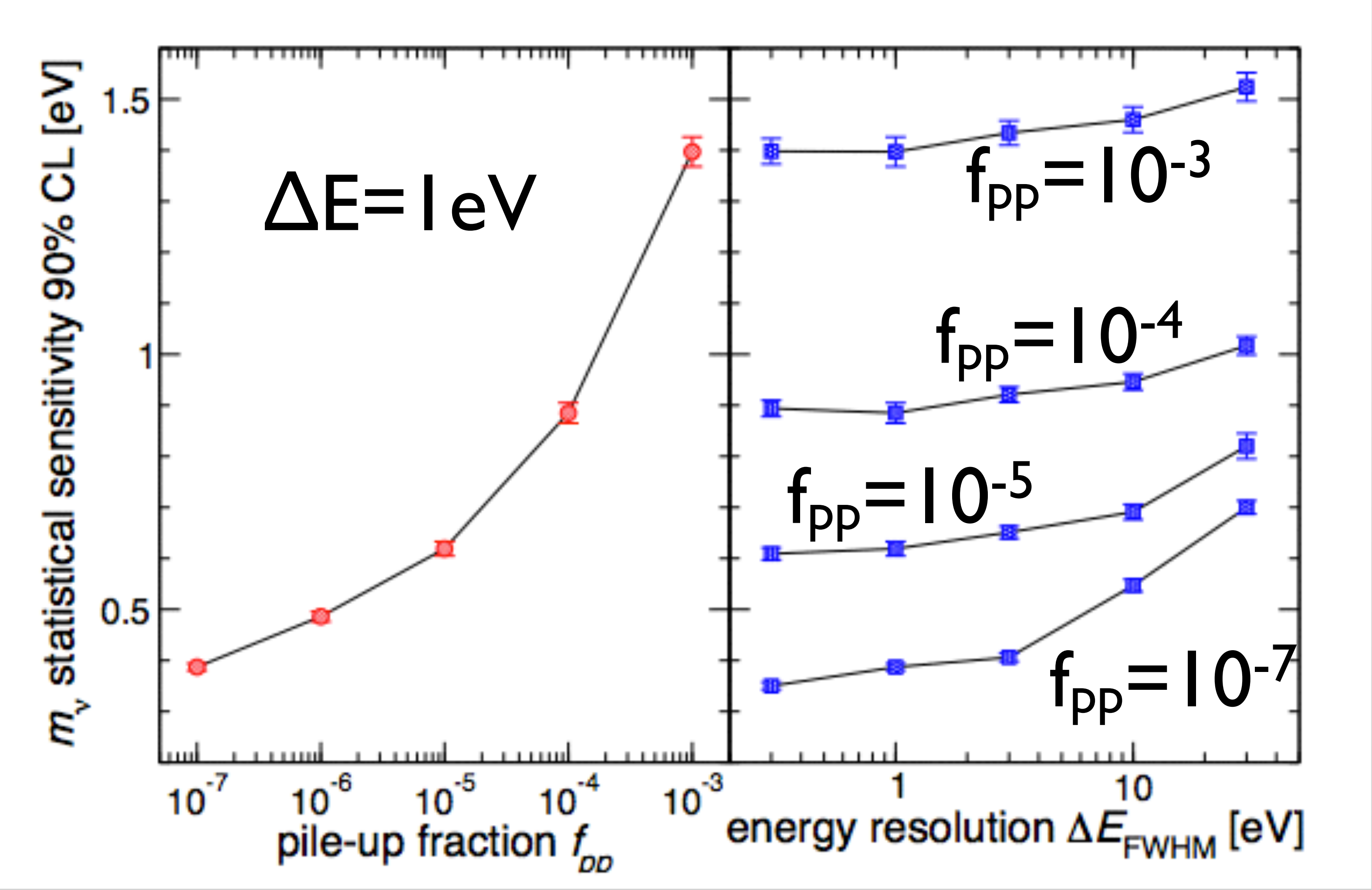
- Complete energy thermalization (ionization, excitation → heat → calorimetry)
- ΔT_{max} = E/C, C is the total thermal capacity
  - absorber with low thermal capacity
  - for superconductors below T_C and dielectric: $C \sim (T/\theta_D)^3$ (Debye law)
  - very low T is needed (10÷100mK)
- $\Delta E_{rms} = (k_b T^2 C)^{1/2}$ due to statistical fluctuations of internal energy
- $\Delta T(t) = E/C\ e^{-t/\tau}$, $\tau = C/G$ and G is the thermal conductance

Expected sensitivity

Q = 2600eV

b = 0 counts/s/eV/det

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



A. Nucciotti, submitted to EPJC, arXiv: 1405:5060

Expected sensitivity, Q~2.2KeV

required exposure for m_ν=0.2eV sensitivity

A [Hz]	τ [μs]	ΔE [eV]	N [counts]	Exposure [det*year]
1	1	1	2.8x10	9x10
1	0.1	1	1.3x10	4.3x10
100	0.1	1	4.6x10	1.5x10
10	0.1	1	2.8x10	9.0x10
10	1	1	4.6x10	1.5x10

→

- 5000 pixels/array;
- 3 arrays;
- 1 years of live-time;
- 2×10^{17} nuclei of ^{163}Ho

required exposure for m_ν=0.1eV sensitivity

A [Hz]	τ [μs]	ΔE [eV]	N [counts]	Exposure [det*year]
1	0.1	0.3	1.2x10	3.9x10
100	0.1	0.3	6.4x10	2.0x10
100	0.1	1	7.4x10	2.4x10
10	0.1	1	4.5x10	1.5x10
10	1	1	7.4x10	2.4x10

→

- 5000 pixels/array;
- 4 arrays;
- 10 years of live-time;
- 3×10^{17} nuclei of ^{163}Ho

background = 0

Expected sensitivity, Q~2.8KeV

required exposure for m_ν=0.2eV sensitivity

A [Hz]	τ [μs]	ΔE [eV]	N [counts]	Exposure [det*year]
1	1	1	0.2x10	7.6x10
1	0.1	1	1.6x10	5.3x10
100	0.1	1	9.8x10	3.1x10
10	0.1	1	3.8x10	1.2x10
10	1	1	9.8x10	3.1x10

→

- 60000 pixels/array;
- 5 arrays;
- 5 years of live-time;
- 4×10^{18} nuclei of ^{163}Ho

required exposure for m_ν=0.1eV sensitivity

A [Hz]	τ [μs]	ΔE [eV]	N [counts]	Exposure [det*year]
1	0.1	0.3	2.6x10	8.2x10
100	0.1	0.3	1.9x10	5.9x10
100	0.1	1	1.6x10	5.0x10
10	0.1	1	6.1x10	1.9x10
10	1	1	1.6x10	5.0x10

→

- 10^6 pixels/array;
- 6 arrays;
- 10 years of live-time;
- 8×10^{19} nuclei of ^{163}Ho

background = 0

Spectrometry vs calorimetry

General requirements for a ν mass experiment:

- High statistics near the end point
  - low Q-value (stat ~$1/Q^3$)
  - high activity/efficiency of the source
- Energy reso order ~eV or below (comparable with m_ν)
- S/N ratio
- small systematic effects

Spectroscopy: source $\not\subset$ detector

- high statistics
- high energy resolution (below eV)

- systematics due to the source (energy loss)
- systematics due to decay to excited states
- background

Calorimetry: source $\subset$ detector

- no backscattering
- no energy loss in source
- no solid state excitation
- no atomic/molecular final state effects
- good energy resolution (~eV)

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