The HOLMES experiment

Angelo Nucciotti

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

on behalf of the **HOLMES** collaboration

HOLMES collaboration

Univ. Milano-Bicocca
INFN Milano-Bicocca
C.Brofferio
G.Ceruti
M.Faverzani
E.Ferri
A.Giachero
M.Maino
A.Nucciotti
G.Pessina
A.Puiu
S.Ragazzi
M.Sisti
F.Terranova

INFN Genova
M.Biasotti
V.Ceriale
D.Corsini
M.De Gerone
E.Fumagalli
F.Gatti
A.Orlando
L.Parodi
G.Pizzigoni
F.Siccardi

INFN Roma
M.Lusignoli

INFN LNGS
S.Nisi

NIST
B.Alpert
D.Becker
D.Bennett
J.Fowler
J.Gard
J.Hays-Wehle
G.Hilton
J.Mates
C.Reintsema
D.Schmidt
D.Swetz
J.Ullom
L.Vale

PSI
R.Dressler
S.Heinitz
D.Schumann

CENTRA-IST
M.Ribeiro-Gomes

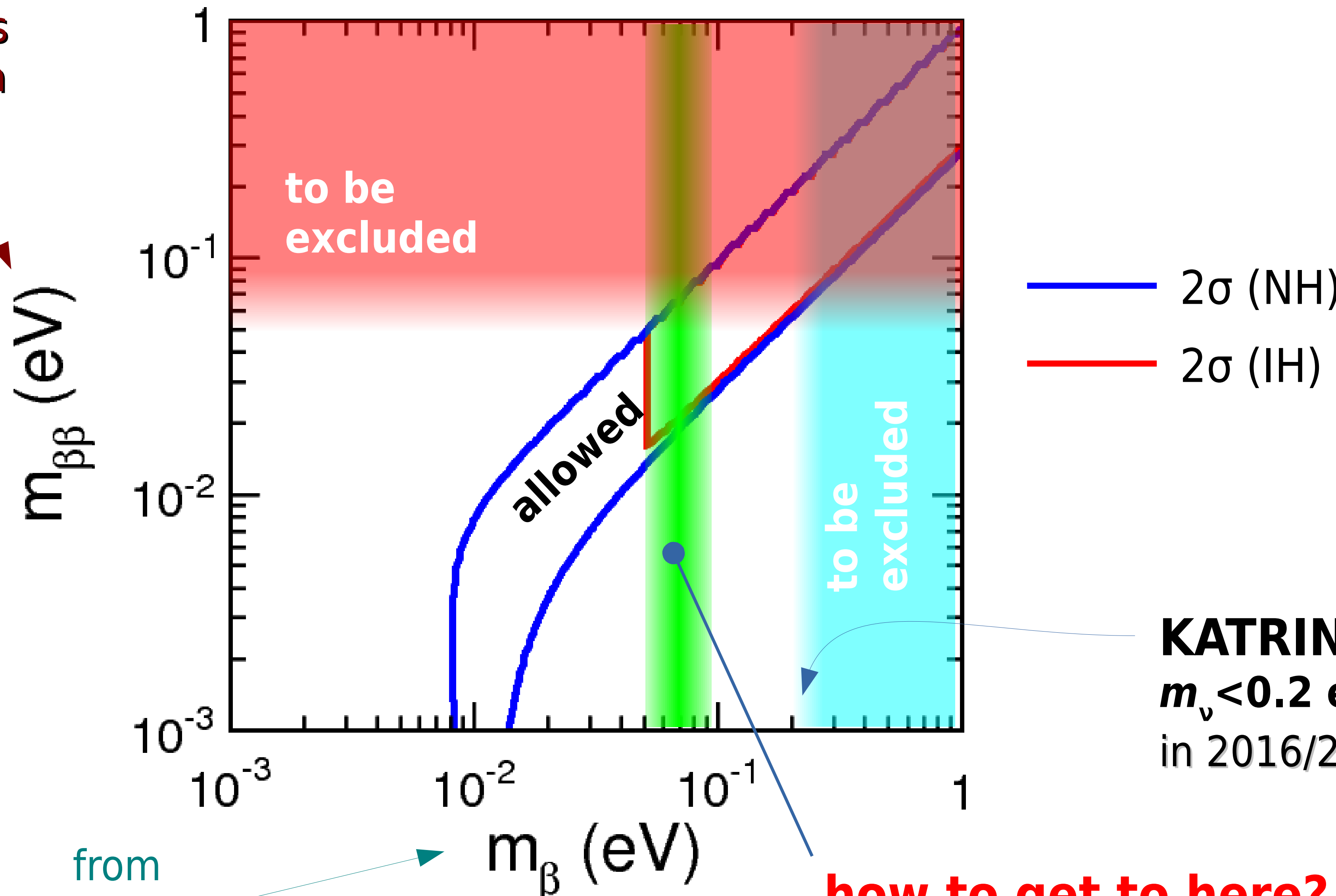
Caltech/JPL
P.K.Day

ILL
U.Koester

The Challenge: absolute neutrino mass

expected for the next few years

from
Neutrinoless Double Beta decay



KATRIN
m_ν<0.2 eV
in 2016/2017

from
Beta decay end-point

how to get to here?

Electron capture end-point experiment / 1

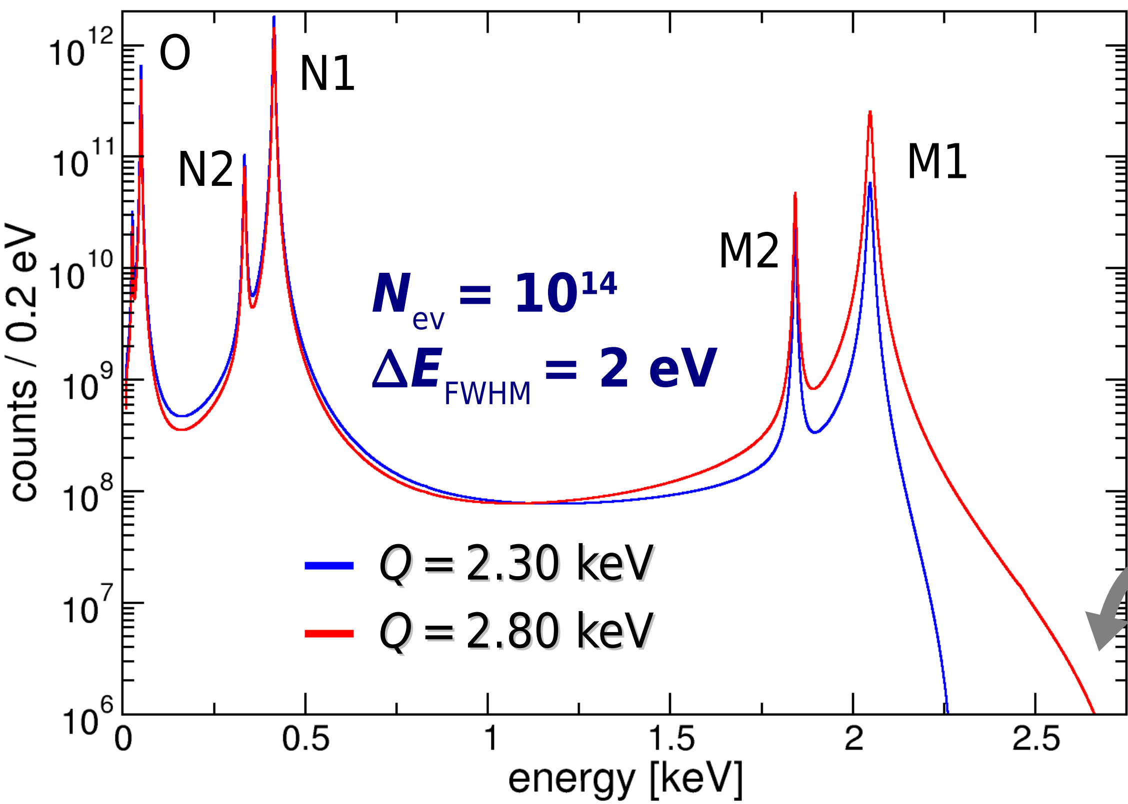
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

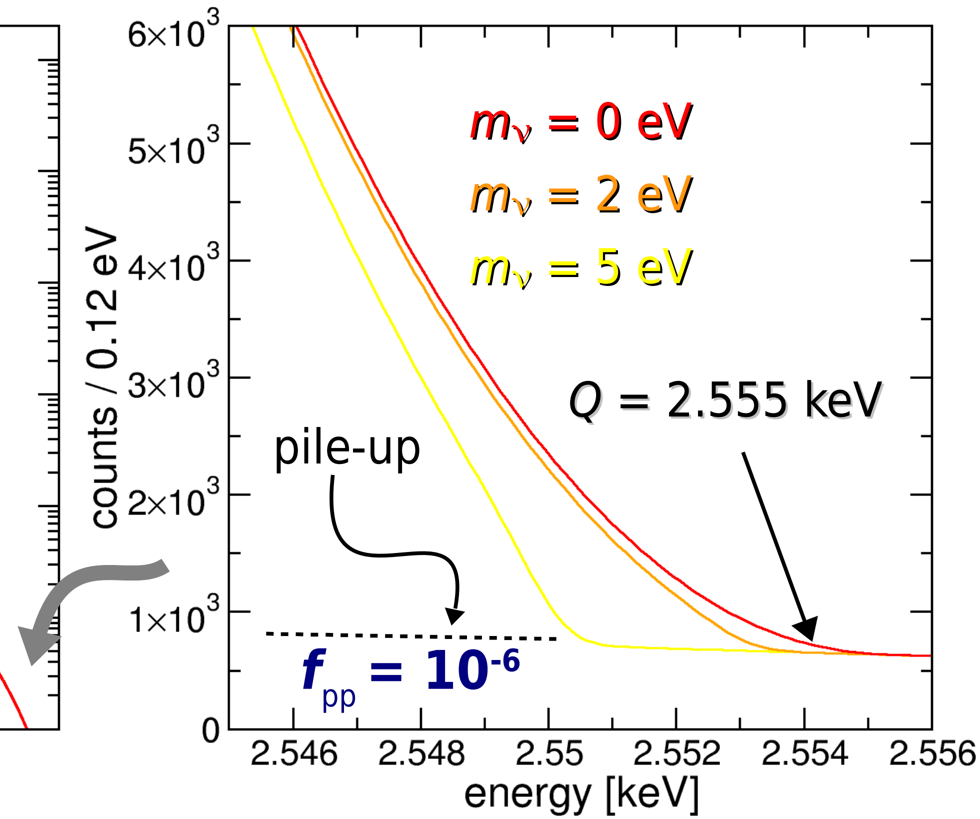
electron capture from shell ⩾ M1

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 = 2.3÷2.8 keV. Recommended: Q = ~~2.555 keV~~ **now 2.8 keV** ?
- $\tau_{1/2}$ ≈ **4570 years** → few active nuclei are needed

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



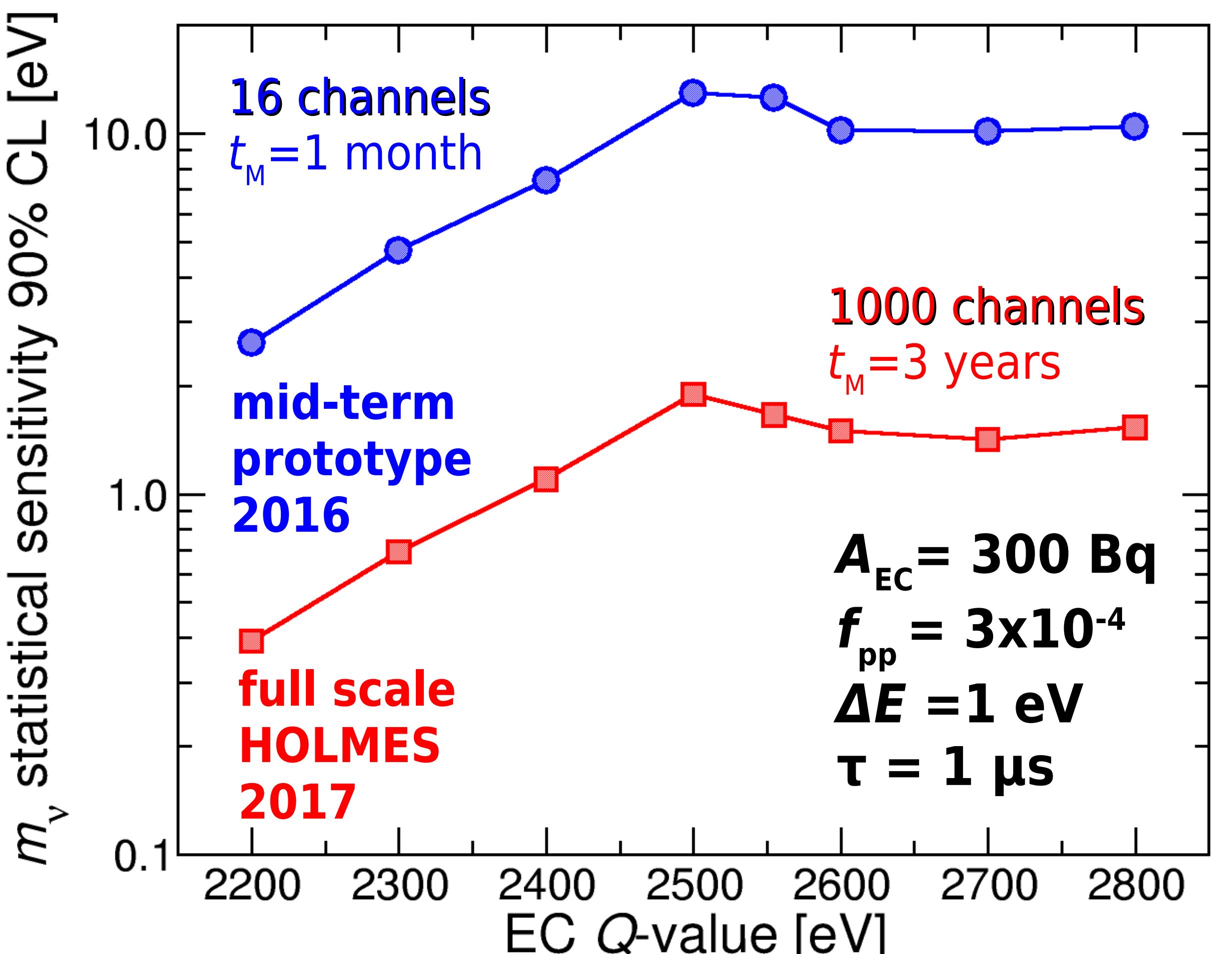


goal

- 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

- TES with **implanted** ^{163}**Ho**
  - $6.5\text{x}10^{13}$ nuclei per pixel
    → 300 dec/sec
  - $\Delta E \approx 1$eV and $\tau_R \approx 1\mu$s
- 1000 channel array
  - $6.5\text{x}10^{16}$ ^{163}Ho nuclei
    → ≈18μg
  - $3\text{x}10^{13}$ events in 3 years



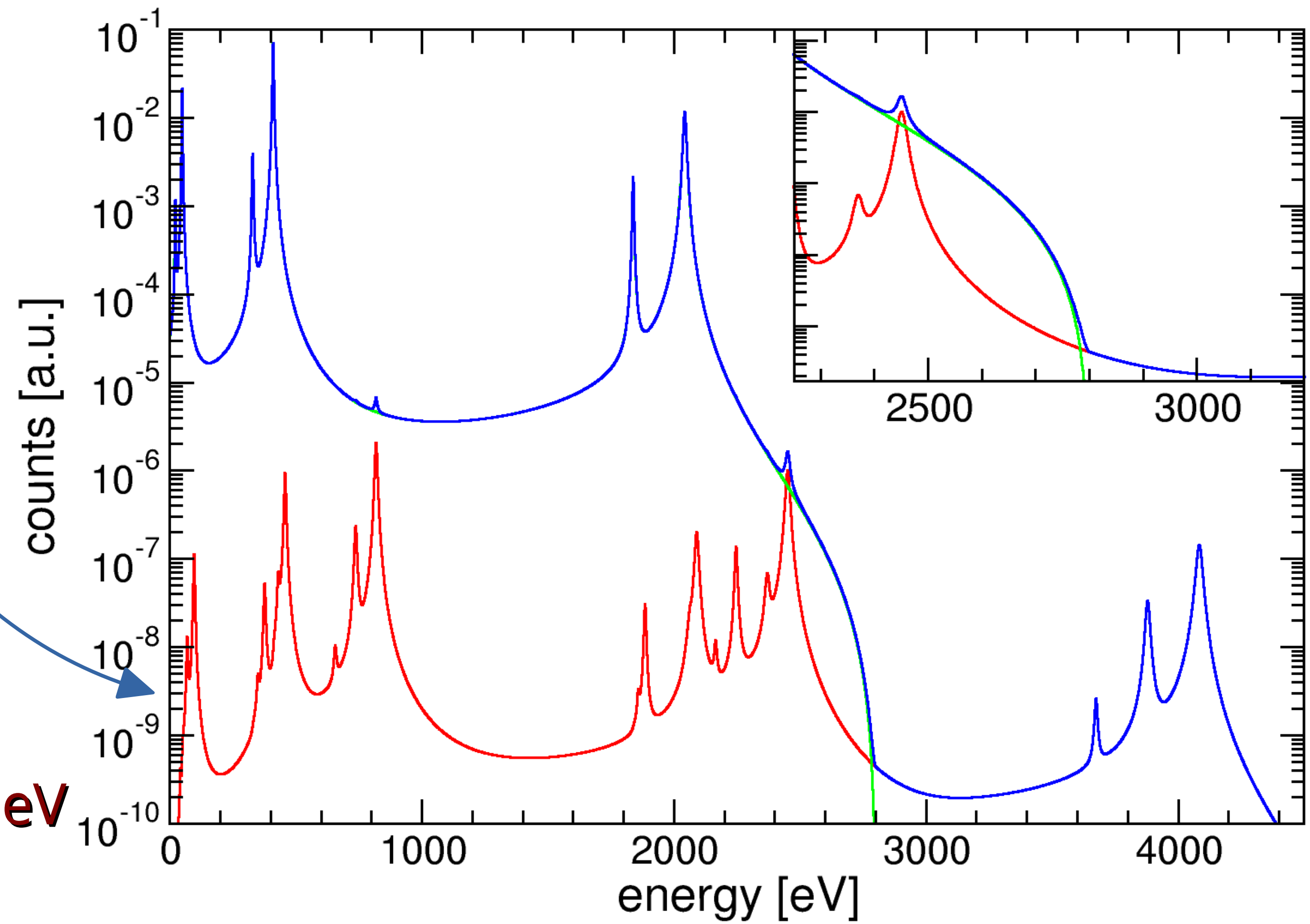
→ Project Started on February 1st 2014

B. Alpert et al., Eur. Phys. J. C, (2015) 75:112
http://artico.mib.infn.it/holmes

Electron capture end-point experiment / 2

- no direct **calorimetric** measurement of Q (end-point) so far
- complex **pile-up spectrum**
  - $N_{pp}(E) = f_{pp} N_{EC}(E) \otimes N_{EC}(E)$ with $f_{pp} \approx A_{EC} \tau_R$

A_{EC} EC activity per detector
τ_R time resolution (≈rise time)

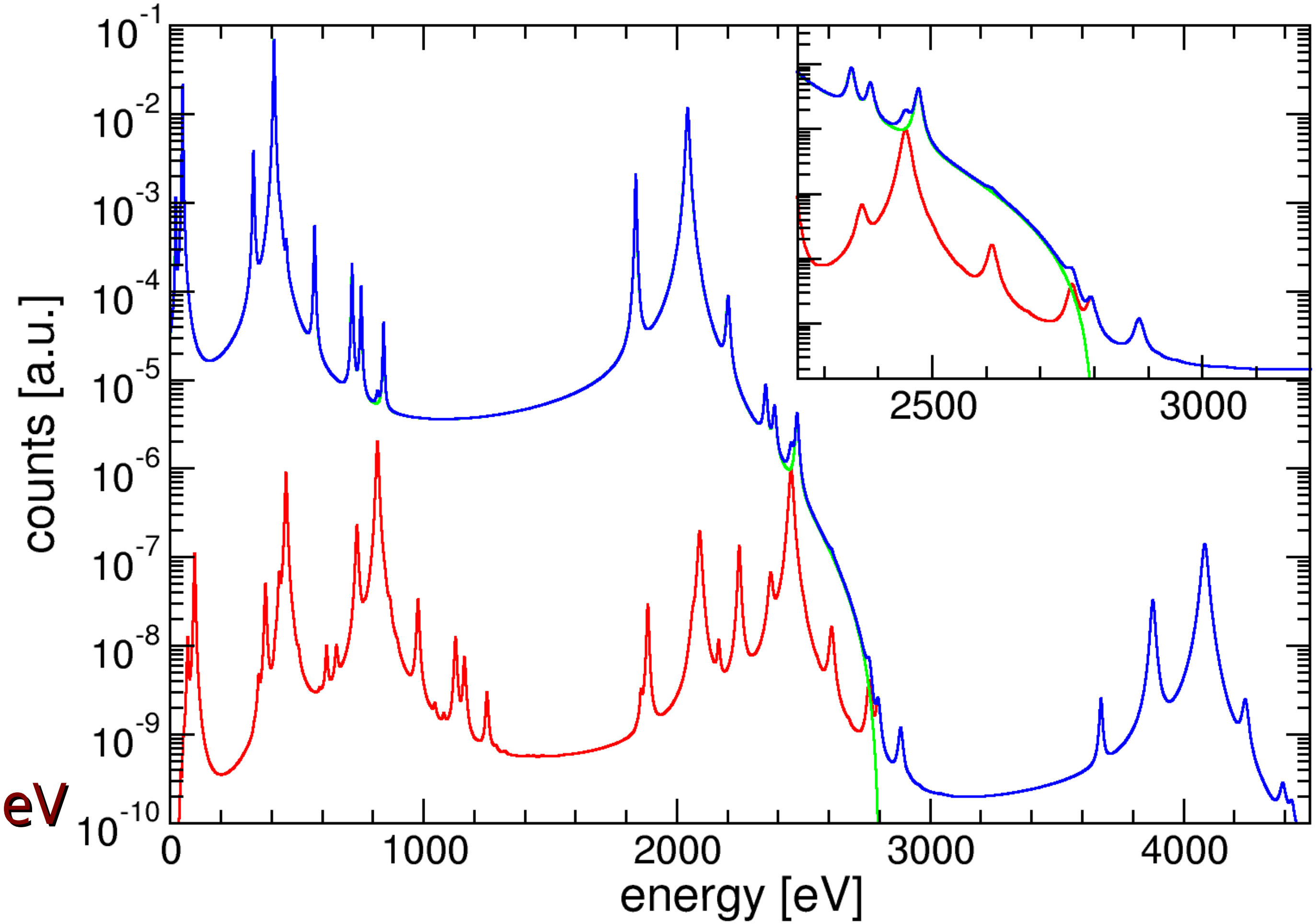


$Q = 2800$ eV
$f_{pp} = 10^{-4}$

Electron capture end-point experiment / 3

- shake-up/shake-off → **double hole excitations**
  - *n*-hole excitations possible but less probable
  - authors do not fully agree on energies and probabilities
- even more complex **pile-up spectrum**
  - it may be worth keeping **f_{pp} smaller than 10^{-4}**

A.De Rujula, arXiv:1305.4857
R.G.H.Robertson, arXiv:1411.2906
A.Faessler et al., PRC 91 (2015) 45505

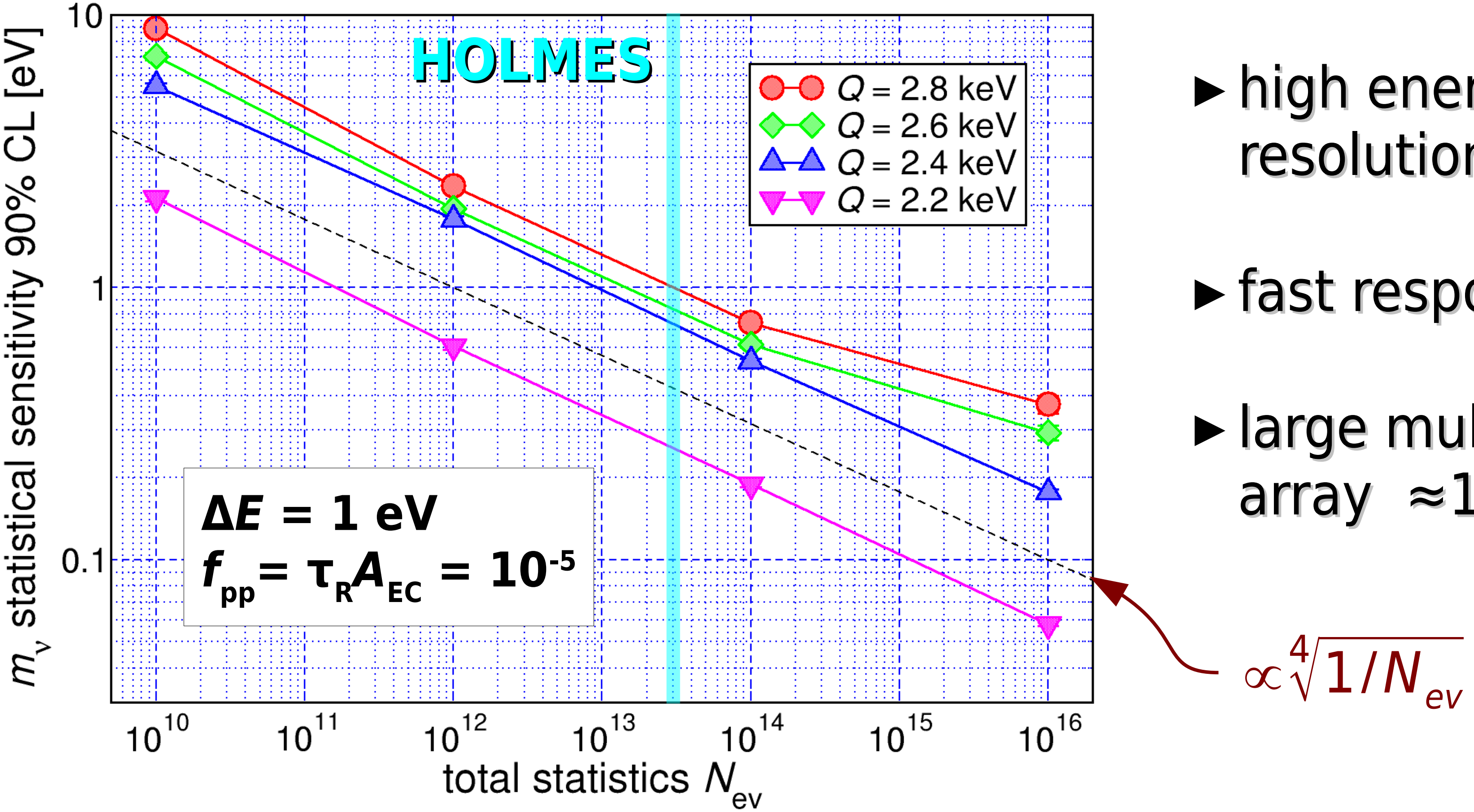


$Q = 2800$ eV

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

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

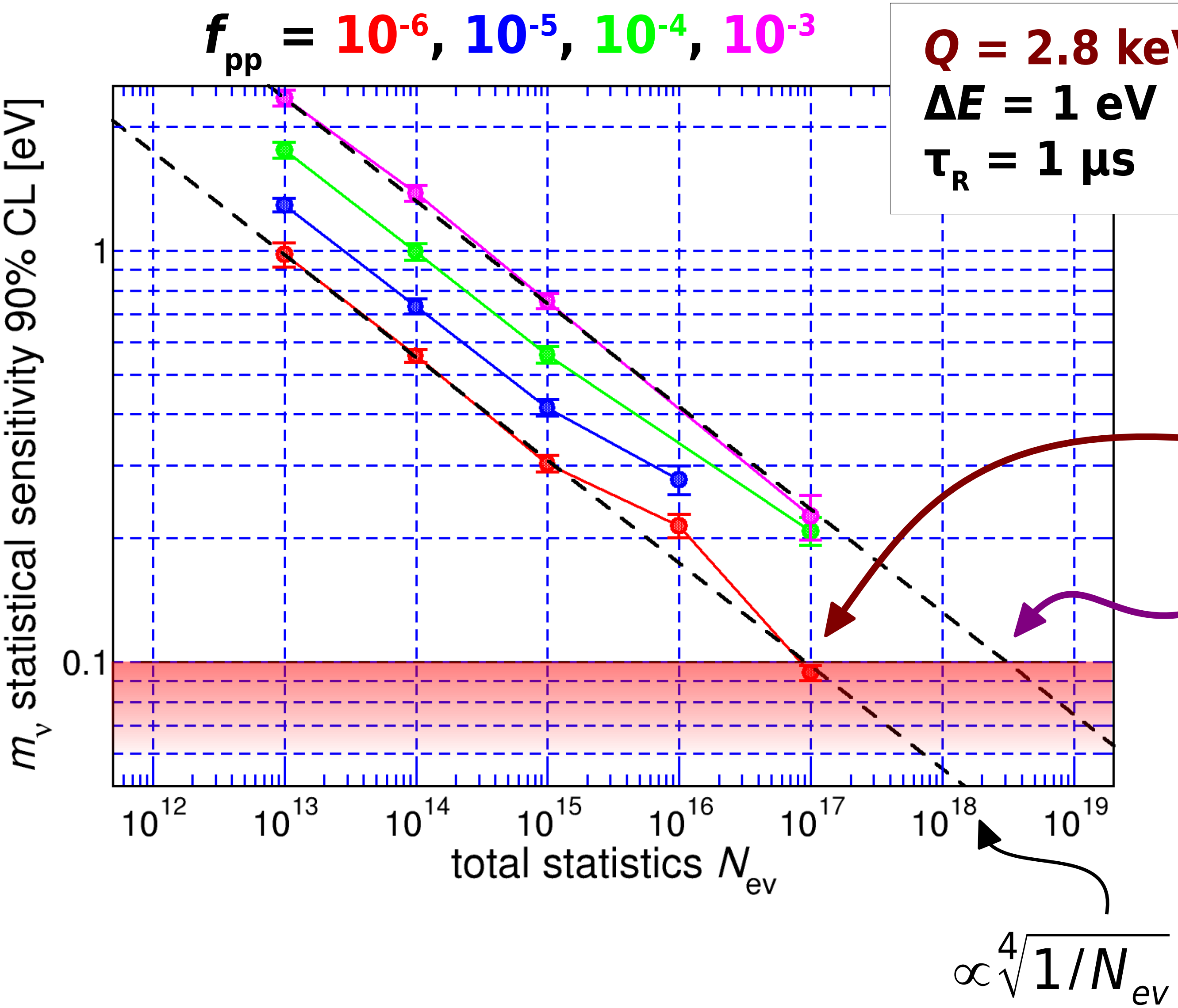


- ▸ high energy resolution ≈1eV
- ▸ fast response ≈1μs
- ▸ large multiplexable array ≈1000

M. Galeazzi et al., arXiv:1202.4763v2

A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

Statistical sensitivity: Montecarlo simulations / 2



Q = 2.8 keV
ΔE = 1 eV
τ_R = 1 μs

A = 1Bq
$N_{det}t_M \approx 3\times10^9$ det x y

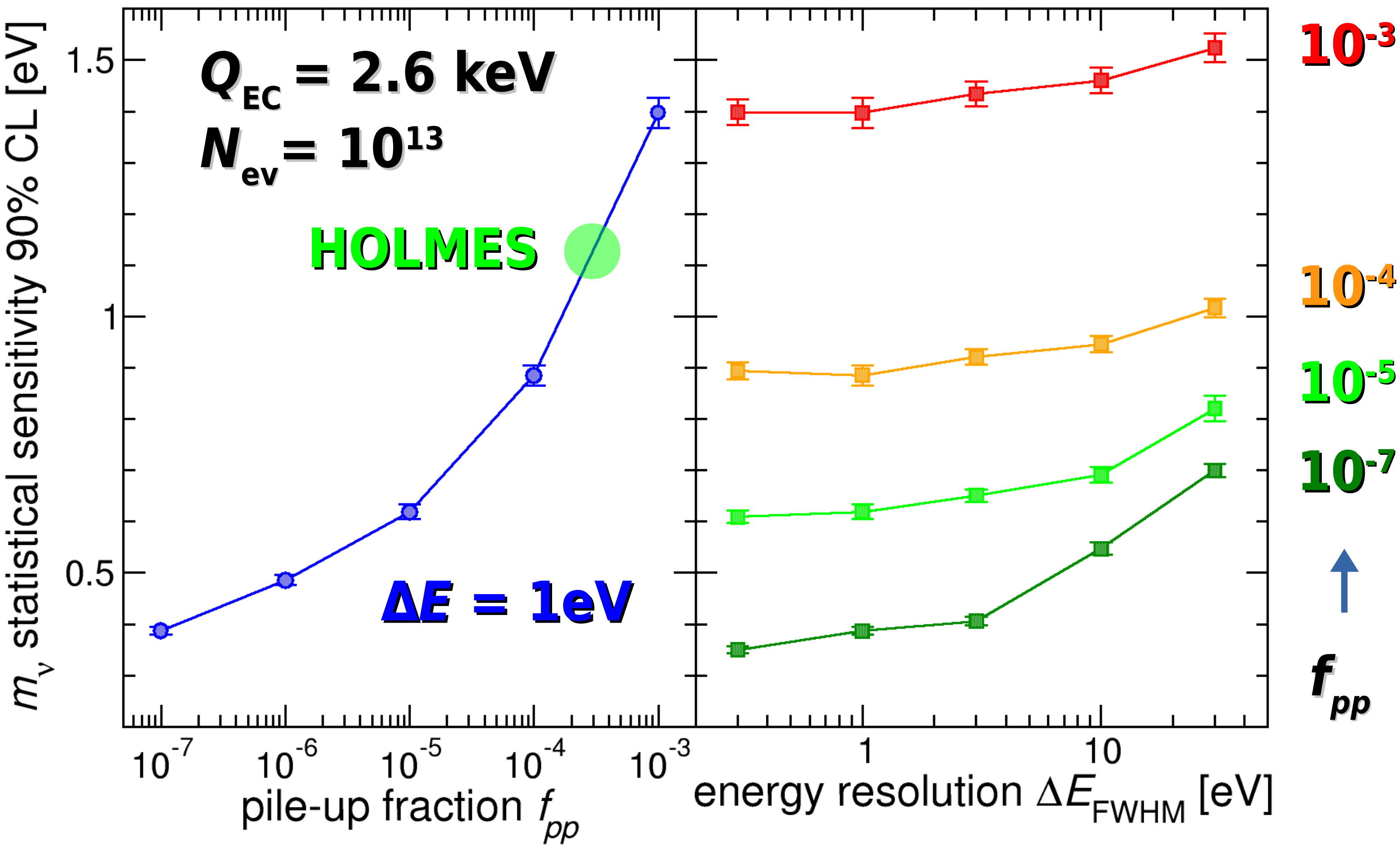
A = 1000Bq
$N_{det}t_M \approx 10^7$ det x y

HOLMES design: more MC simulations...

Statistical sensitivity $\Sigma(m_\nu)$ dependencies from MC simulations

- strong on statistics $N_{ev}=A_{EC}N_{det}t_M$: $\Sigma(m_\nu) \propto N_{ev}^{1/4}$
- strong on rise time pile-up (probability $f_{pp} \approx A_{EC}\tau_R$)
- weak on energy resolution ΔE

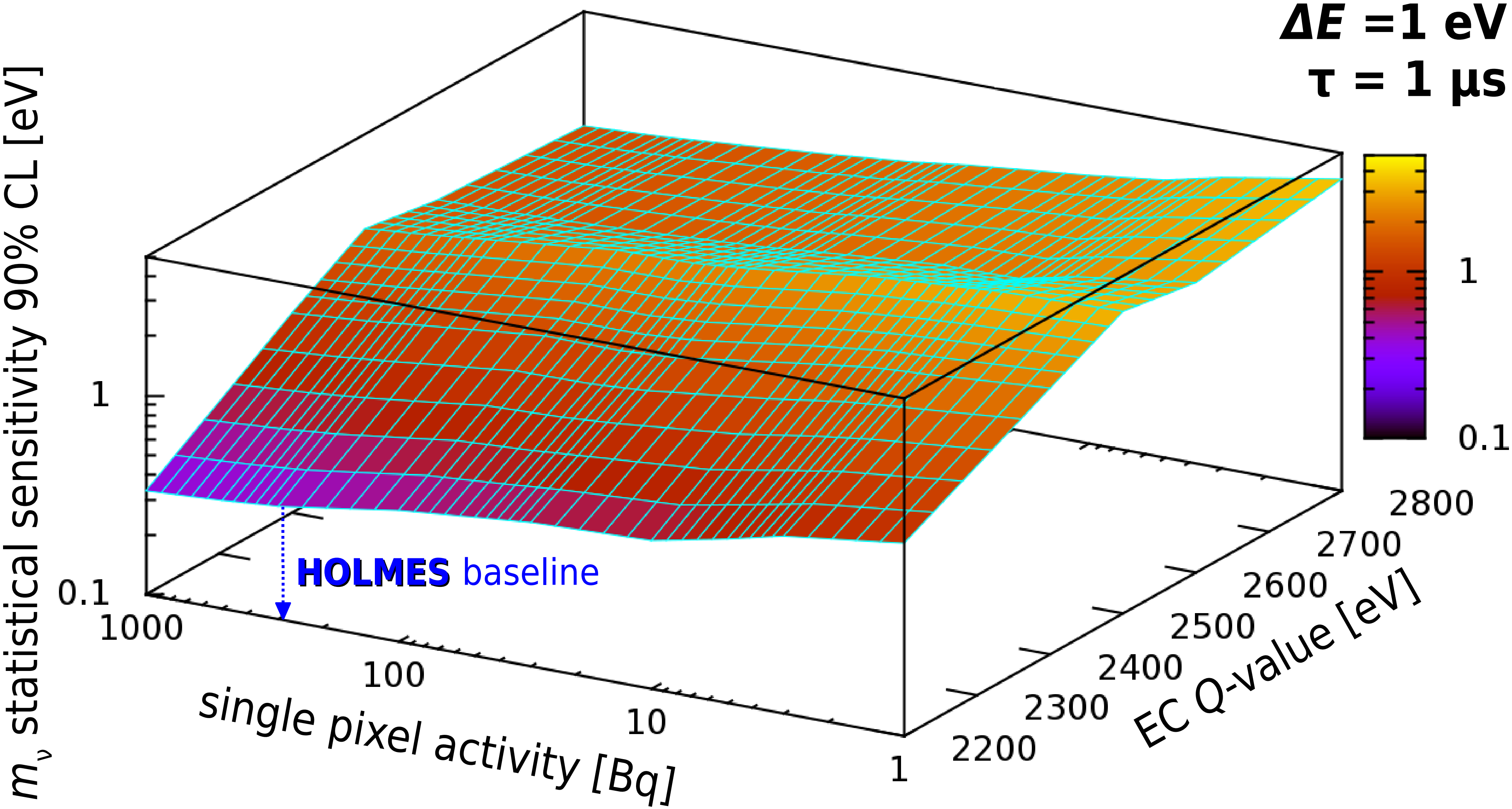
t_M measuring time
N_{det} number of detectors
A_{EC} EC activity per detector
τ_R time resolution (≈rise time)



Statistical sensitivity and single pixel activity

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

fixed exposure $N_{det}t_M$



high activity → robustness against (flat) background
***A*=300Bq → *b*<≈0.1 counts/eV/day/det**

Effective time resolution

- for subsequent (Δt) events with energy E_1 and E_2: time resolution $\boldsymbol{\tau_R = \tau_R(E_1, E_2)}$

$$N_{pp}(E) = A_{EC}\int_0^{\infty}\tau_R(E,\epsilon)N_{EC}(\epsilon)N_{EC}(E-\epsilon)d\epsilon$$

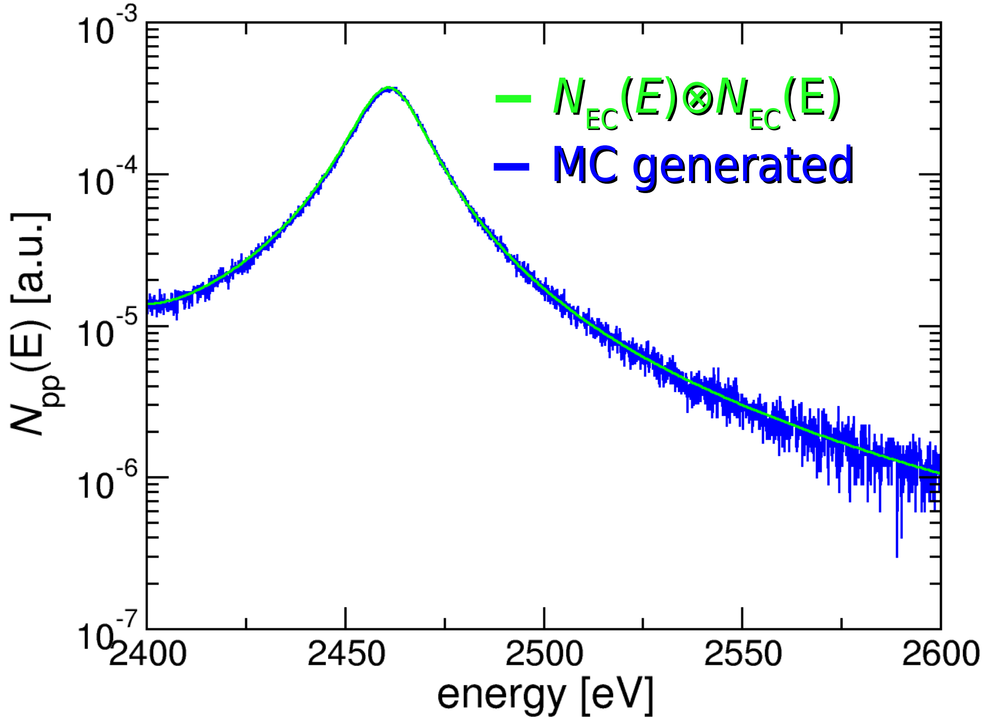
- Montecarlo pile-up spectrum simulations
  - ▷ event pairs with $E_1+E_2 \in [2.4\text{ keV}, 2.6\text{ keV}]$ (drawn from ^{163}Ho spectrum), $\Delta t \in [0, 8\tau_{rise}]$
  - ▷ realistic pulse shapes and noise, sampled with f_{sampl}, record length, and n bit
  - ▷ process simulated pulses with pile-up detection algorithms
- evaluate **effective time resolution τ_{eff}** from **pile-up detection efficiency $\eta(\Delta t)$**

$$f_{pp} = A_{EC}\Delta t_{max}\left[1-\int_0^{\Delta t_{max}}\frac{\eta(x)}{\Delta t_{max}}dx\right] = A_{EC}\tau_{eff}$$

Filter	f_{sampl} [MHz]	L [nH]	τ_{rise} [µs]	τ_{eff} [µs]	ΔE OF [eV]
WF *	**1.0**	24	2.3	**1.0**	3.0
WF *	**1.0**	48	4.5	**1.3**	2.1
SVD **	**1.0**	48	4.5	**0.6**	
SVD **	**0.5**	48	4.5	**1.1**	

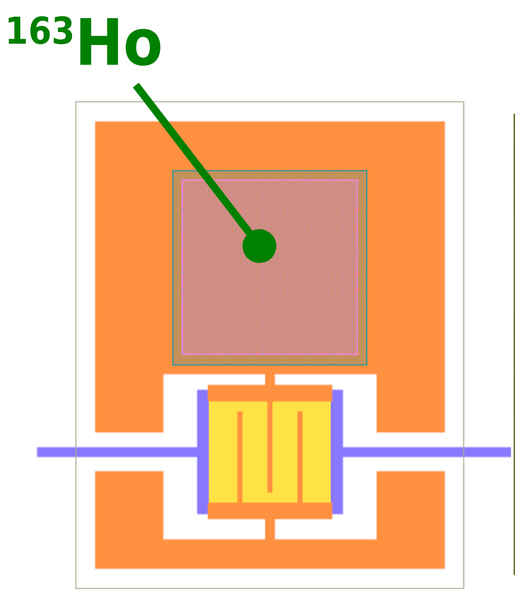
* Wiener Filter → T1.6 E.Ferri

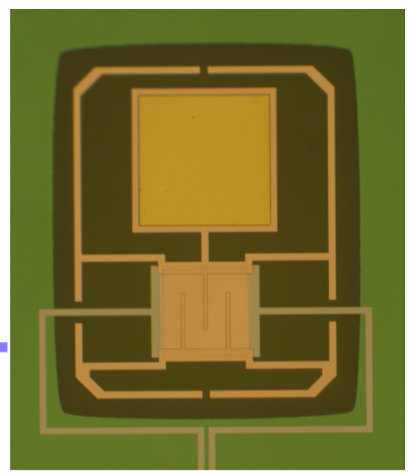
** Single Value Decomp. → G2.7 B.Alpert

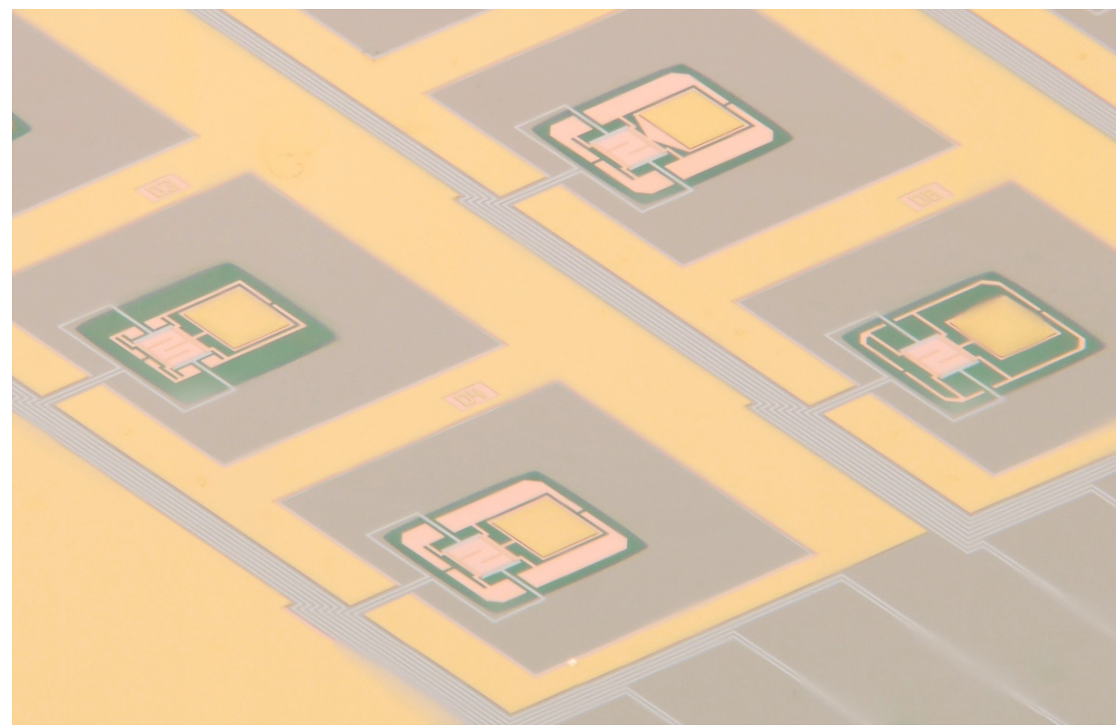


HOLMES pixel design

- optimize design for speed and resolution **→ G1.1 J.Hays-Wehle**
  - **specs @2.5keV : ΔE_{FWHM} ≈ 1eV, τ_{rise} ≲ 5μs, τ_{decay} ≈ 100μs** (* exponential time constants)
- **2 μm Au** thickness for *full* electron and photon absorption
  - GEANT4 simulation: 99.99998% / 99.927% full stopping for 2 keV electrons / photons
- *side-car* design to avoid TES proximitation and *G* engineering for speed
- define process for ^{163}Ho implantation vs. excess heat capacity



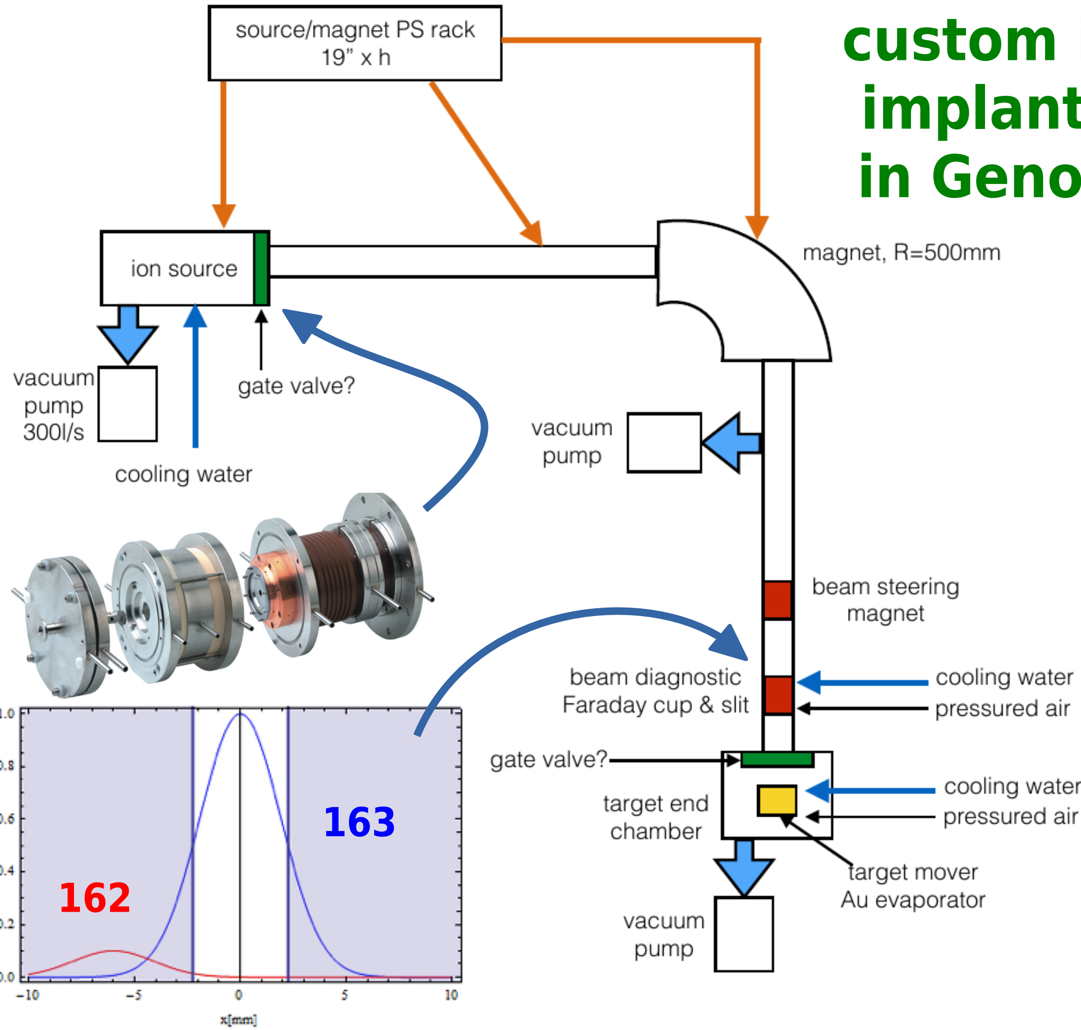


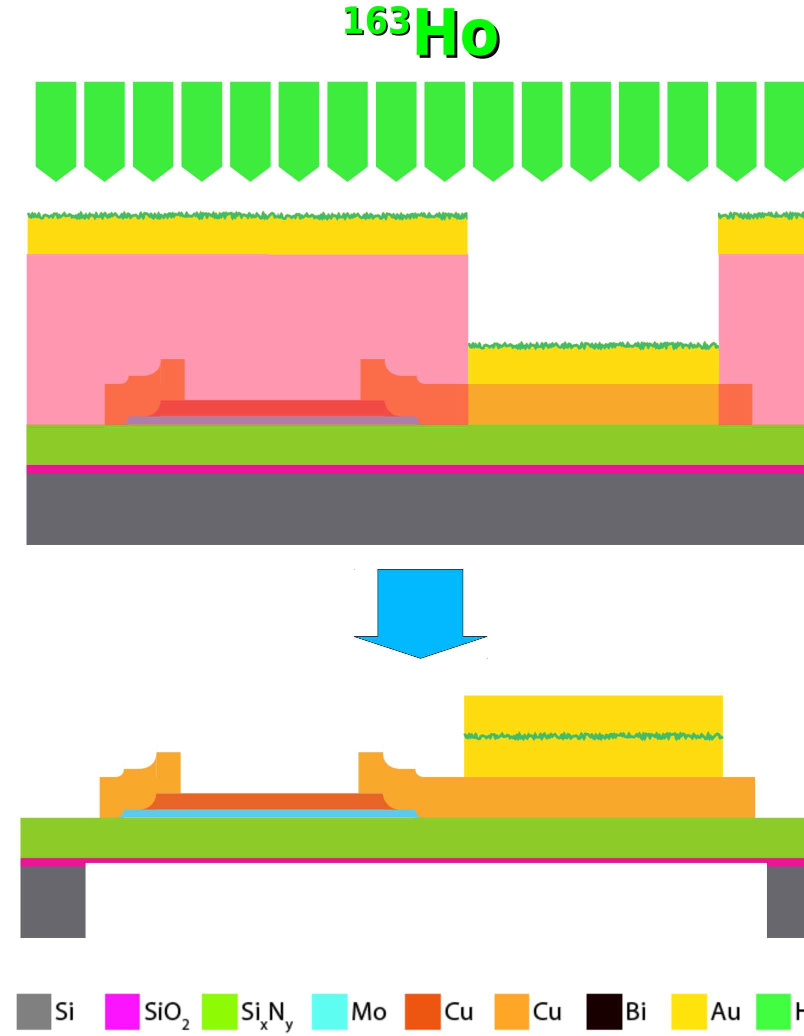


- **tests at NIST are in progress**
  - from preliminary static measurements model predicts:
  - **ΔE_{FWHM} ≈ 3 eV, τ_{rise} ≈ 6 μs, τ_{decay} ≈ 130 μs** (*L* = 35 nH)

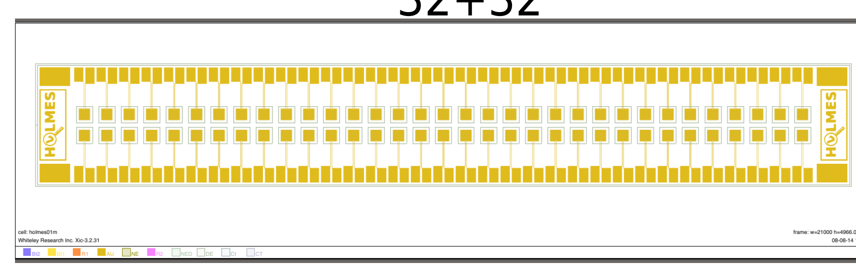
HOLMES detector array fabrication

custom ion implanter in Genova





32+32

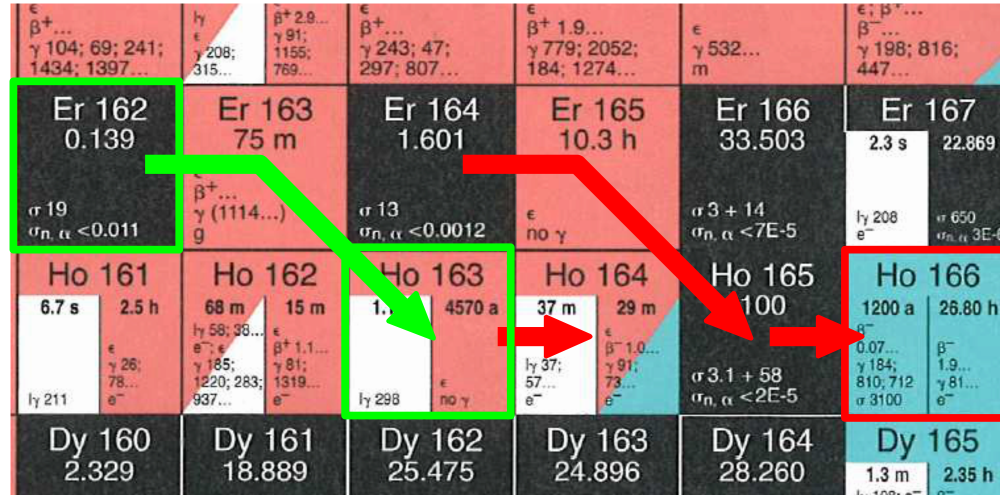


- 2 µm thick Au encapsulating implanted ^{163}Ho
- TES fabricated at NIST, Boulder, CO, USA
- ^{163}Ho implantation and
  Si_2N_3 membrane release at INFN Genova

→ T4.4 A.Orlando

^{163}Ho production by neutron activation

HOLMES needs ≈150MBq of ^{163}Ho

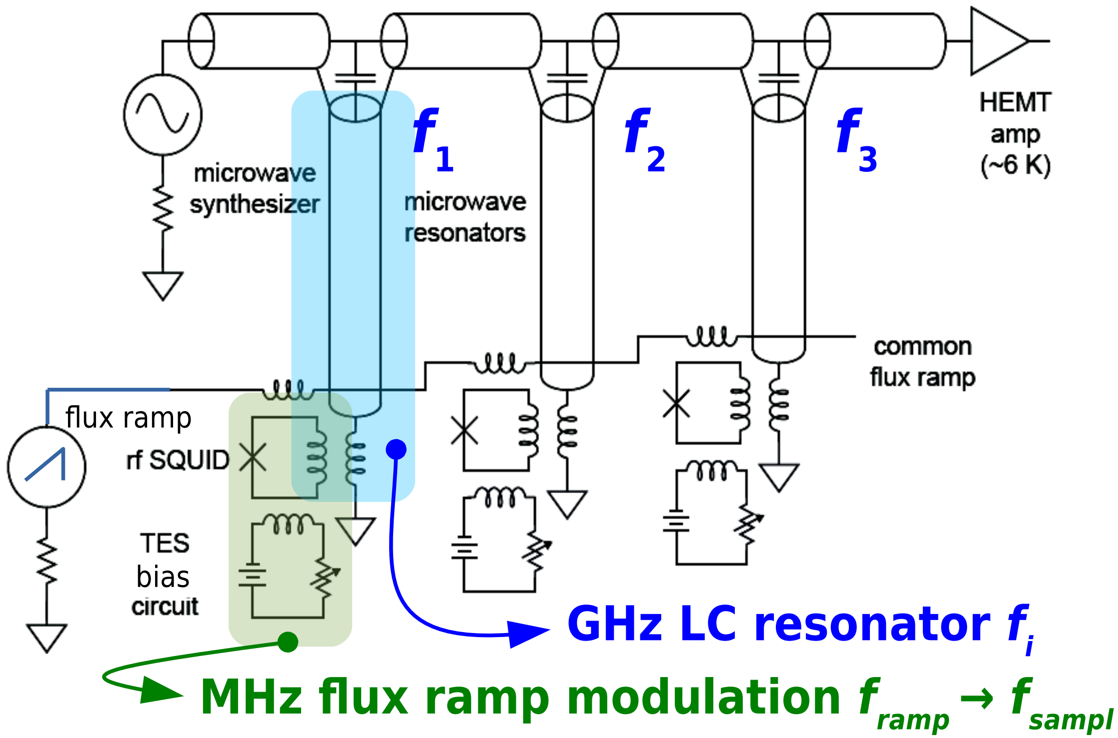


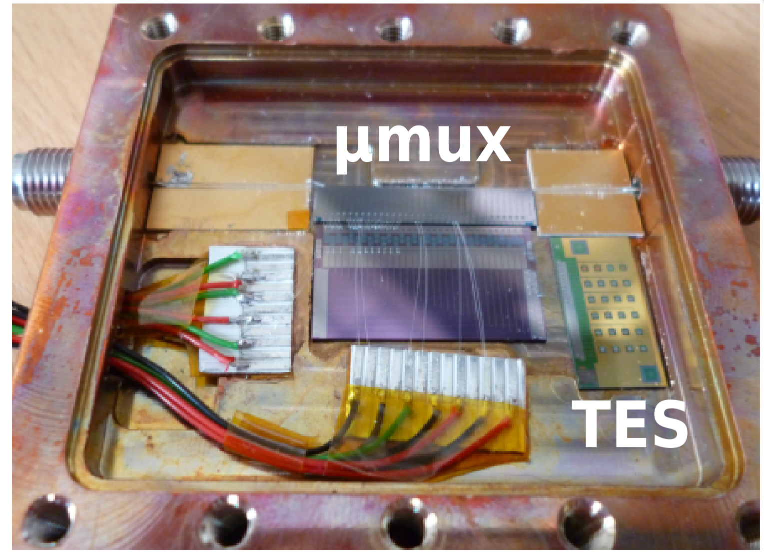
^{162}Er (n,γ) ^{163}Er $\sigma_{thermal} \approx 20$b

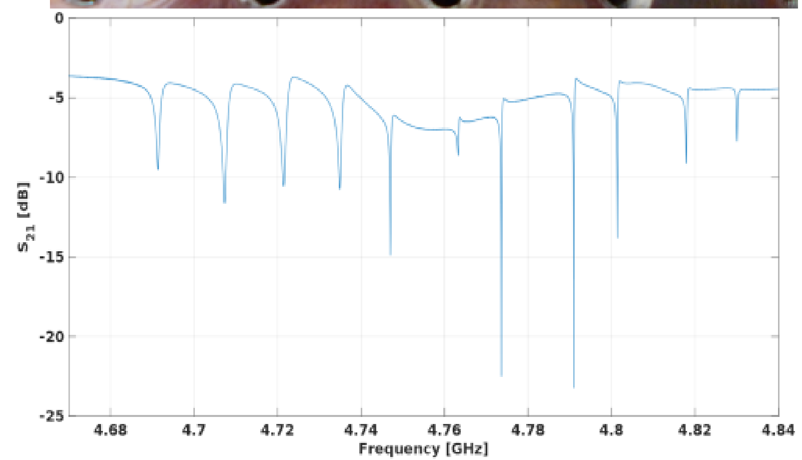
^{163}Er → ^{163}Ho + ν_e $\tau_{½}^{EC} \approx 75$min

- **high yield** (σs must be checked)
  - ILL reactor (Grenoble, France): thermal neutron flux 1.3×10^{15} n/cm^2/s
  - ≈270 kBq(^{163}Ho)/mg(^{162}Er)/week at ILL (→ 80mg(^{162}Er) for 7 weeks → ≈150MBq of ^{163}Ho)
- burn up ^{163}Ho(n,γ)^{164}Ho: **cross section not known**
  - may reduce yield: $\sigma_{burn\text{-}up} \approx 100$b → 80mg(^{162}Er) for 7 weeks → ≈120MBq of ^{163}Ho
- **^{165}Ho(n,γ)** (mostly from ^{164}Er(n,γ)) → **^{166m}Ho, β $\tau_{½}$=1200y**
  - 80mg(^{162}Er) for 7 weeks → order of 100kBq of ^{166m}Ho (depends on ^{164}Er abundance)
- **30% enriched** Er_2O_3 → Ho_2O_3 thermoreduction required
  - Ho_2O_3+2Y(*met*) → 2Ho(*met*)+Y_2O_3 at 2000°C → **G2.3 V.Ceriale**
- **chemical pre-purification** and **post-separation** at PSI (Villigen, Switzerland)
- irradiated and processed samples are under investigation with ICP-MS
- **150mg of enriched Er_2O_3 are at ILL** since 2014 (56 days → **≈70-80MBq**)

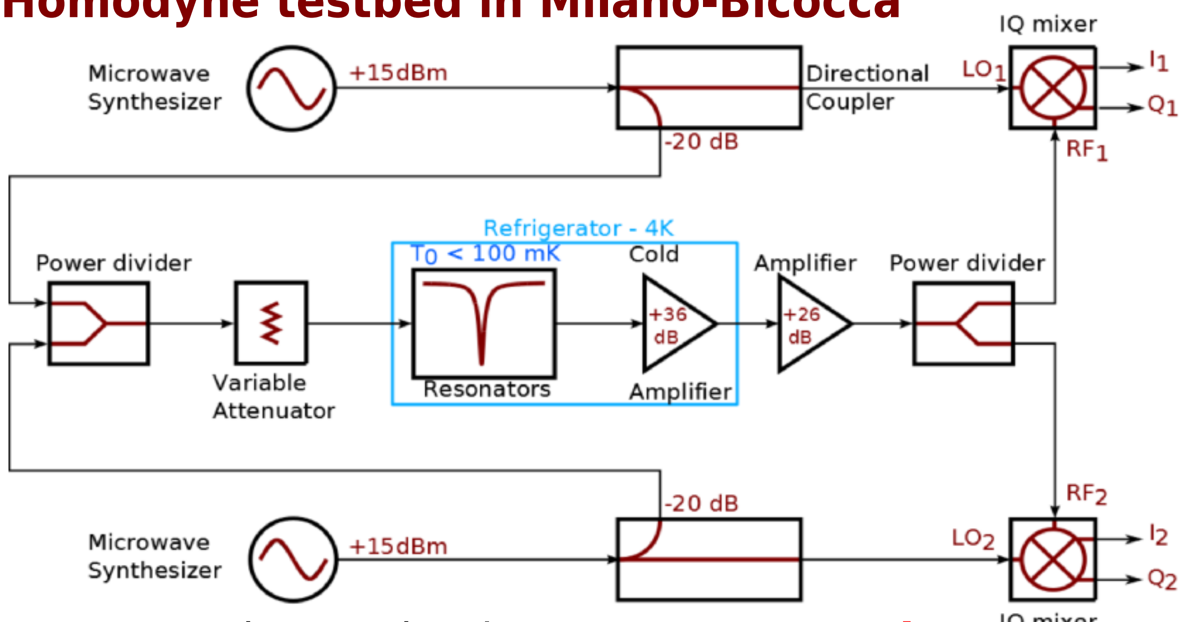
HOLMES array read-out: rf-SQUID μwave mux

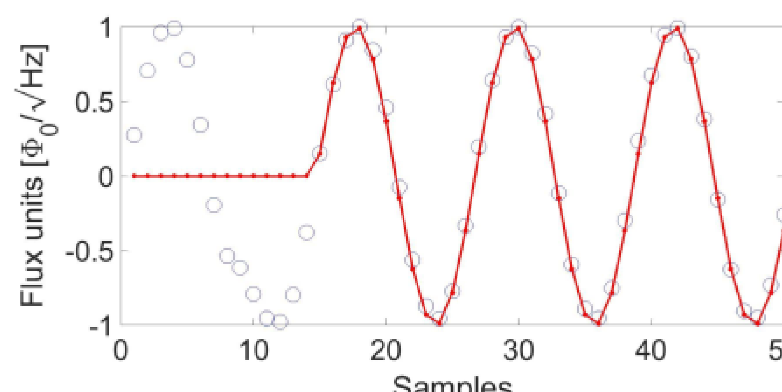






Homodyne testbed in Milano-Bicocca

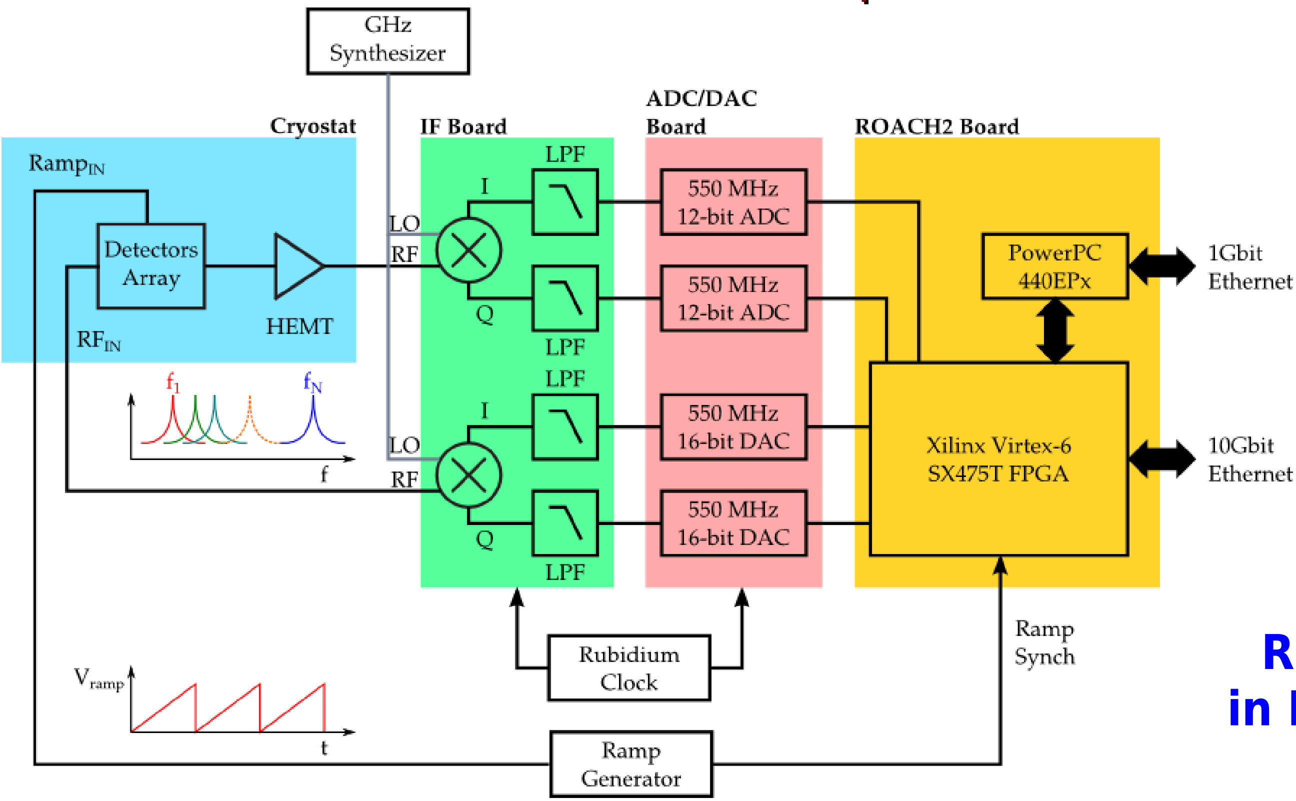


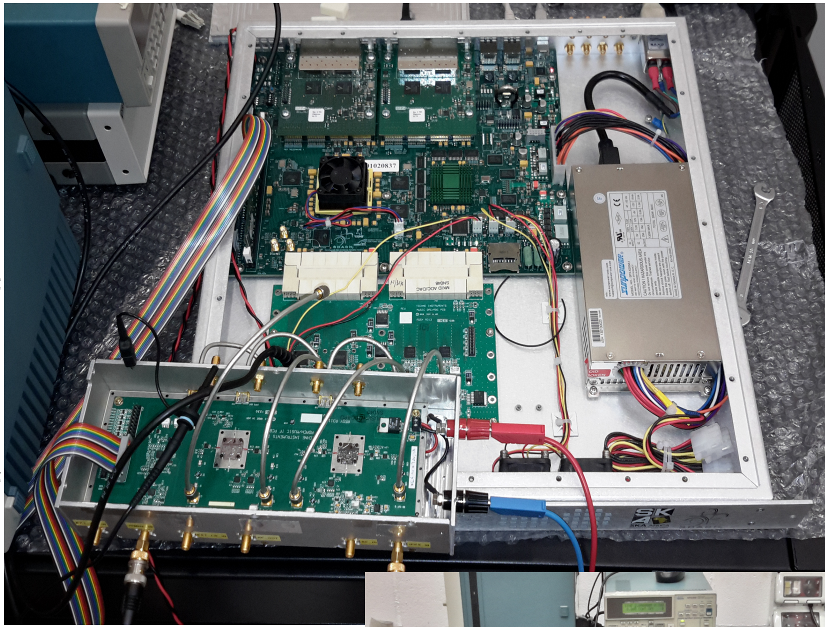


IV curves, noise, and pulses → **G1.14 A.Puiu**

HOLMES DAQ

Software Defined Radio + flux ramp modulation based on **ROACH-2**





ROACH2 system in Milano-Bicocca

- **multiplexing factor**
- f_{TES} required bandwidth per channel

$f_{TES} = 2n_{\Phi_0}f_{sampl}$ (f_{sampl} from pile-up simulations)

$$N_{mux} = \frac{f_{ADC}}{5 f_{TES}}$$

$f_{sampl} = 0.5\text{MHz}$, $n_{\Phi_0} = 2 \rightarrow N_{mux} \approx 50$

→ T2.4 J. Mates / G.29 J.Gard / G1.14 A.Puiu

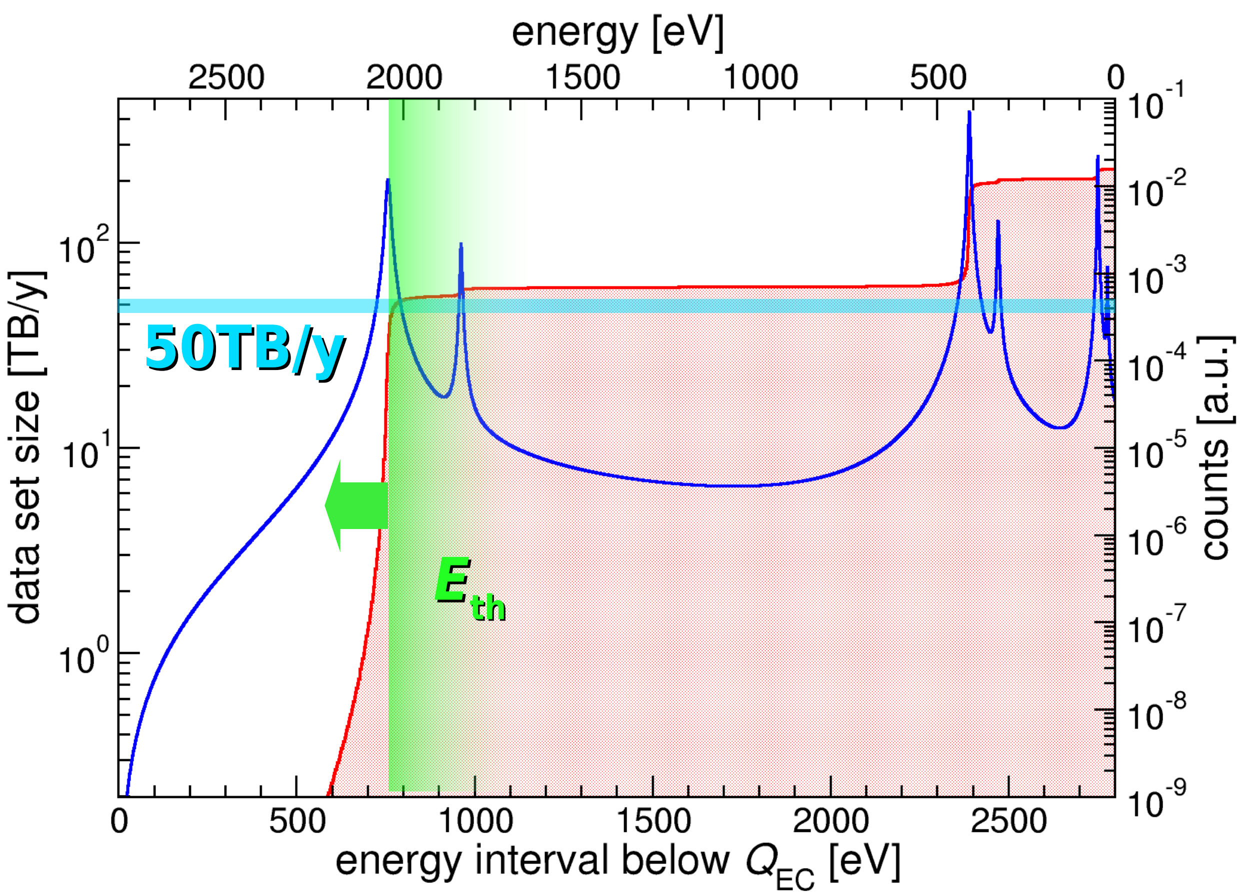
HOLMES signal processing and in-line analysis

* hypothetical configurations

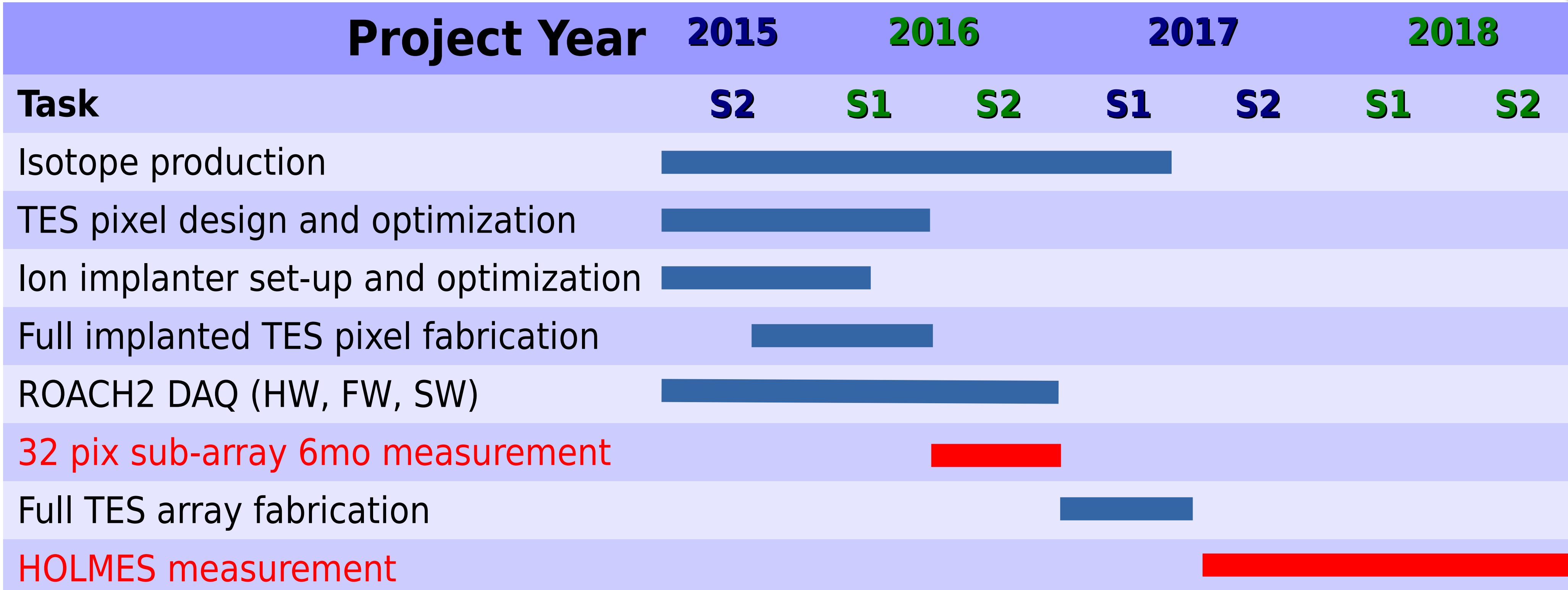
- **normal data taking (permanent RAID storage)**
  - save only *n*-tuples (6 × 4 byte words) *
  - high threshold (E_{th}≈2.022keV, E_{M1}=2.041keV, Q_{EC}=2.8keV, 21% of spectrum) *
  - **about 150TB in 3 years** (un-compressed)
- **periodic minimum bias samples (temporary storage)**
  - tune parameters for real time pulse processing
  - full waveform (512 samples at 12 bit) for immediate off-line analysis *
  - full spectrum → **20TB/day**
  - combined with high threshold data
- **lower threshold is possible with compression**

ROACH2 FW real-time pulse processing:
- threshold cut
- ...

SERVER *quasi* real-time pulse processing:
- OF analysis → *n*-tuples
- pile-up detection
- ...



HOLMES schedule and conclusions



- **HOLMES project is taking off…**
  - many technical challenges are being addressed in parallel
  - design phase is almost complete
  - setting up is in progress
  - spectrum measurements are coming in ≈1 year

Open post-doc position with HOLMES

The group at Università di Milano-Bicocca works on
Low Temperature Detectors for Neutrino Physics and has one postdoctoral fellowship available in the framework of the HOLMES experiment.

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

For more information contact Angelo Nucciotti at angelo.nucciotti@mib.infn.it