The HOLMES experiment

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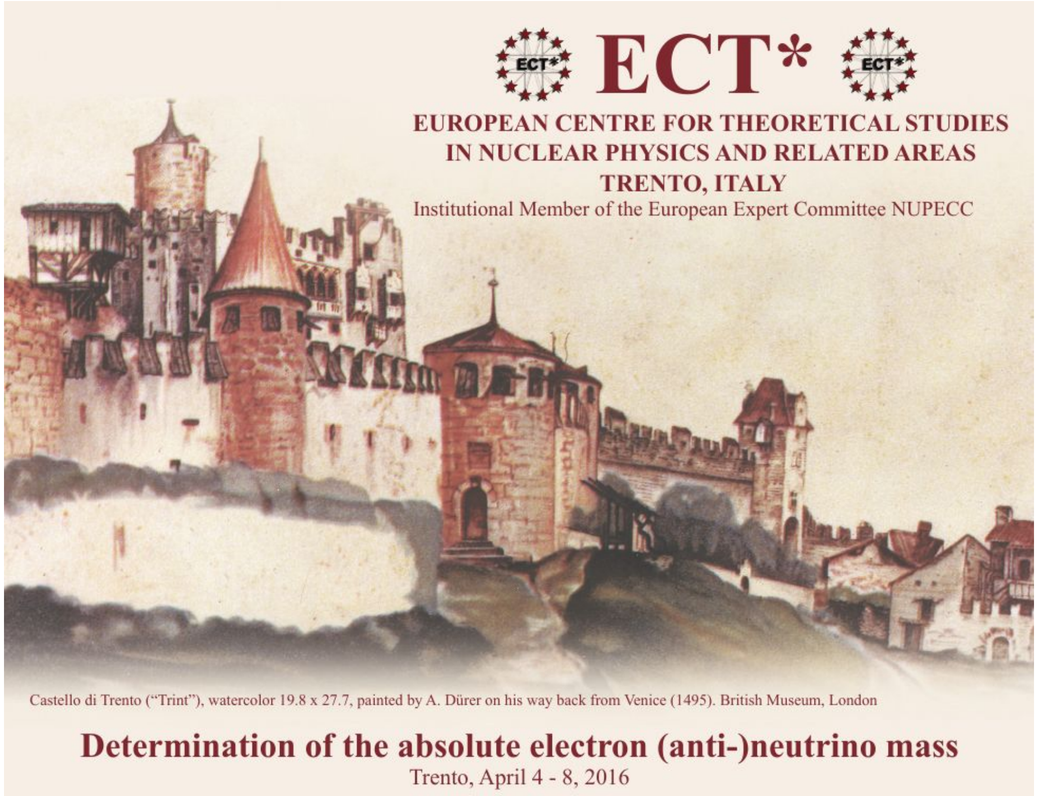
on behalf of the **HOLMES** collaboration



Outline

- Absolute neutrino mass
- ^{163}Ho EC decay for direct neutrino mass measurements
- **HOLMES** experiment
  - sensitivity MC simulations
  - experiment design
  - technical task development status
- Conclusions

HOLMES collaboration

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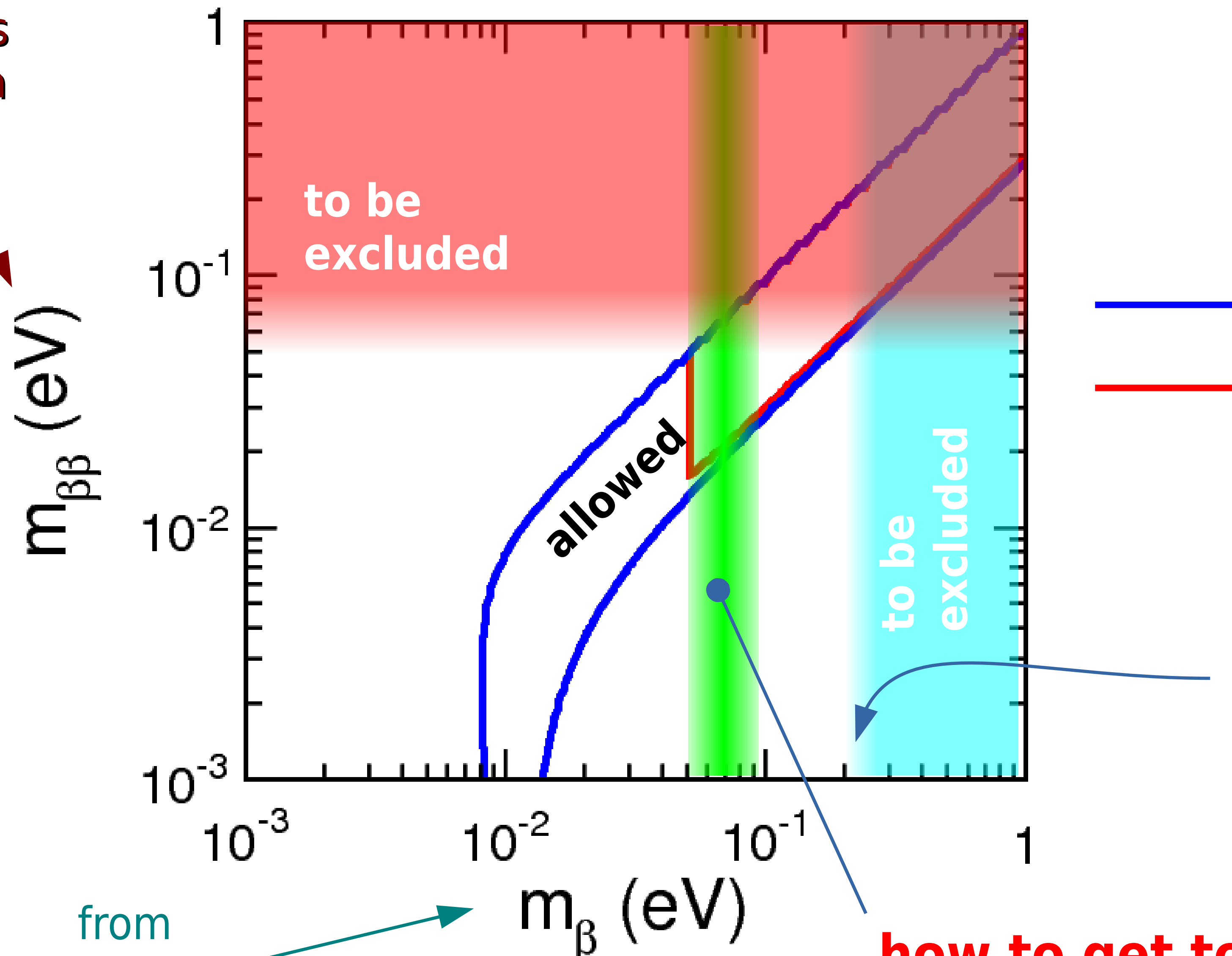
U.Koester

The Challenge: absolute neutrino mass

expected for the next few years

from
Neutrinoless
Double Beta
decay



from
Beta decay
end-point

KATRIN
***m_ν*<0.2 eV**
in 2016/2017

how to get to here?

Electron capture end-point experiment / 1

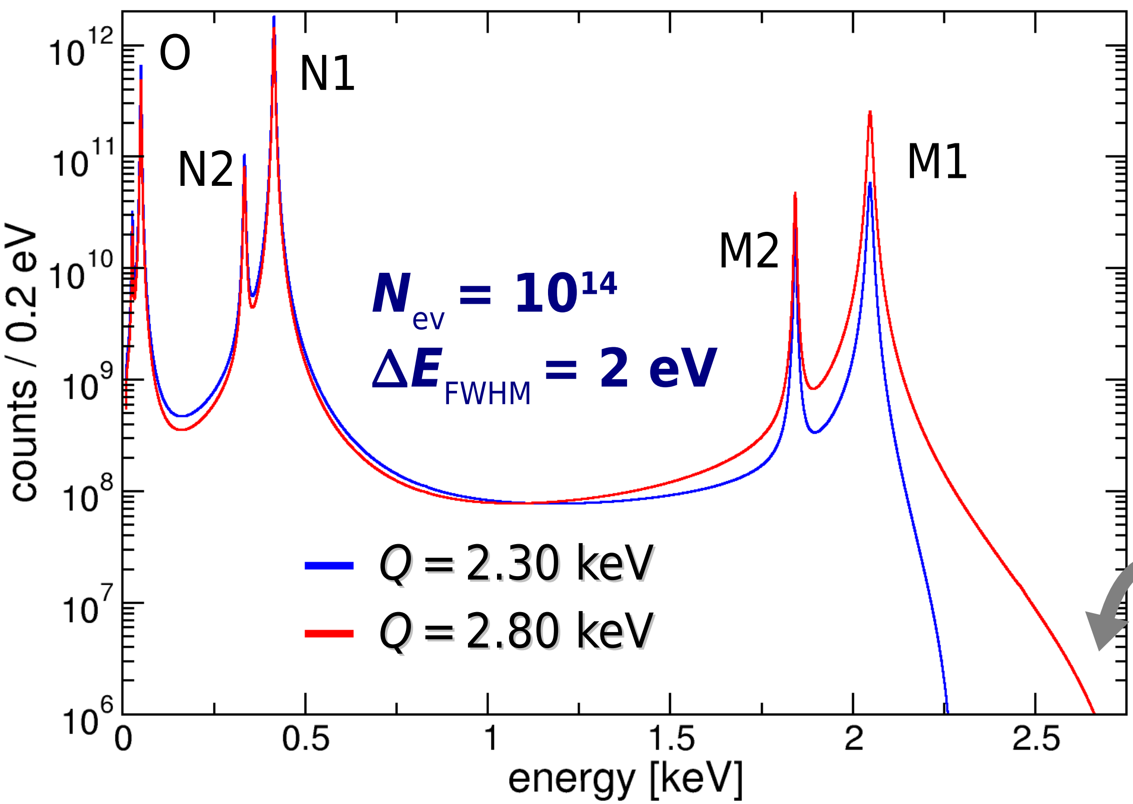
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

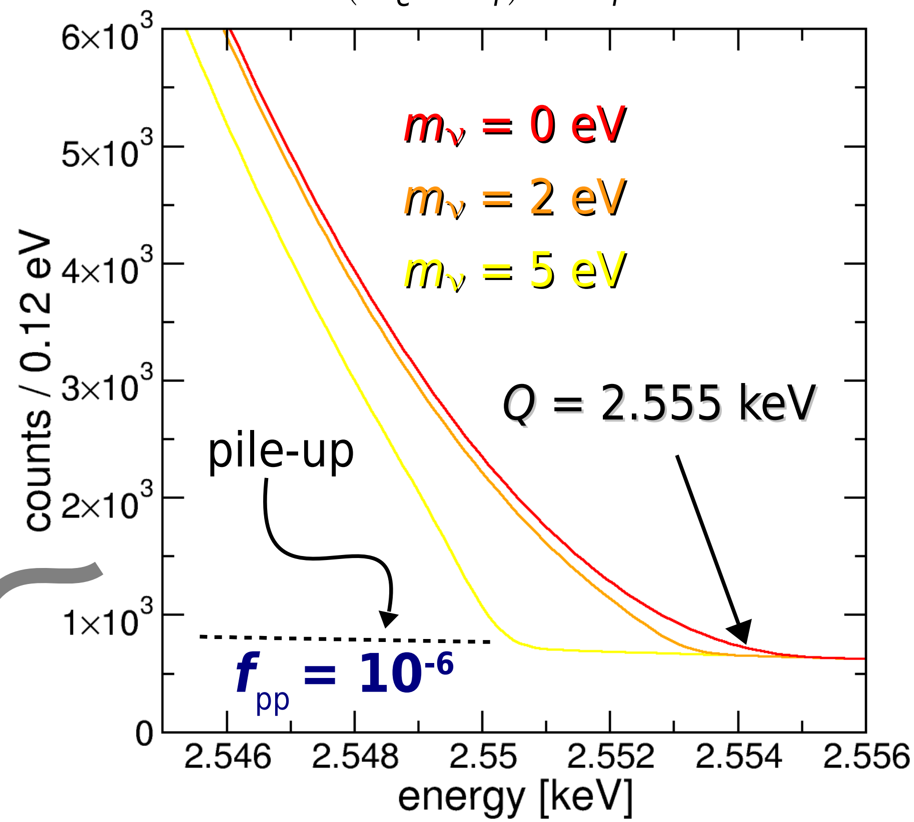
electron capture from shell ⩾ M1

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

- **calorimetric measurement of Dy atomic de-excitations** (mostly non-radiative)
- **Q = 2.8 keV** (recent measurement with Penning trap)
  - rate at end-point and ν mass sensitivity depend on $Q - E_{M1}$
- **$\tau_{1/2}$ ≈ 4570 years** → few active nuclei are needed (2×10^{11} ^{163}Ho nuclei ↔ 1Bq)

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

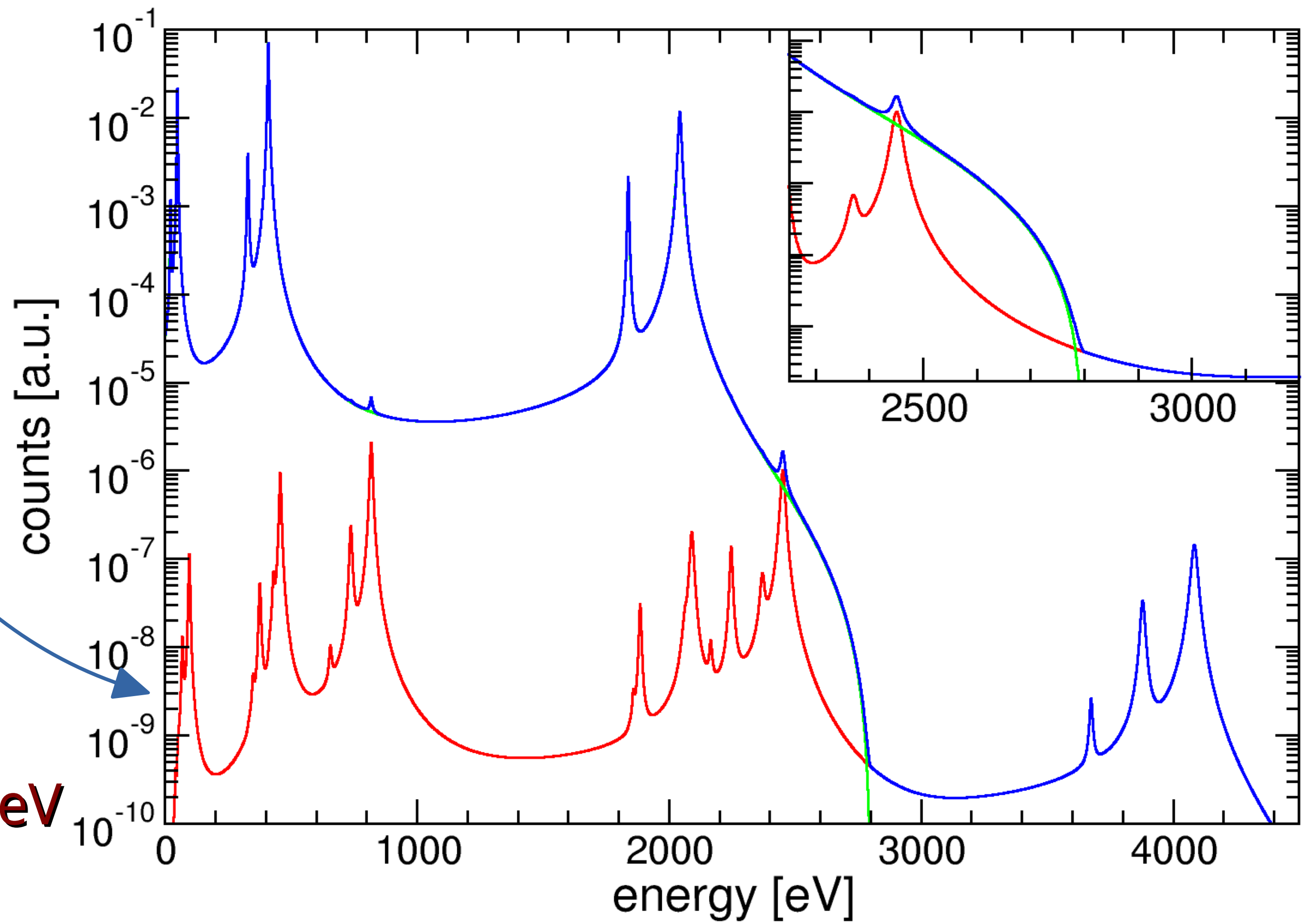




Electron capture end-point experiment / 2

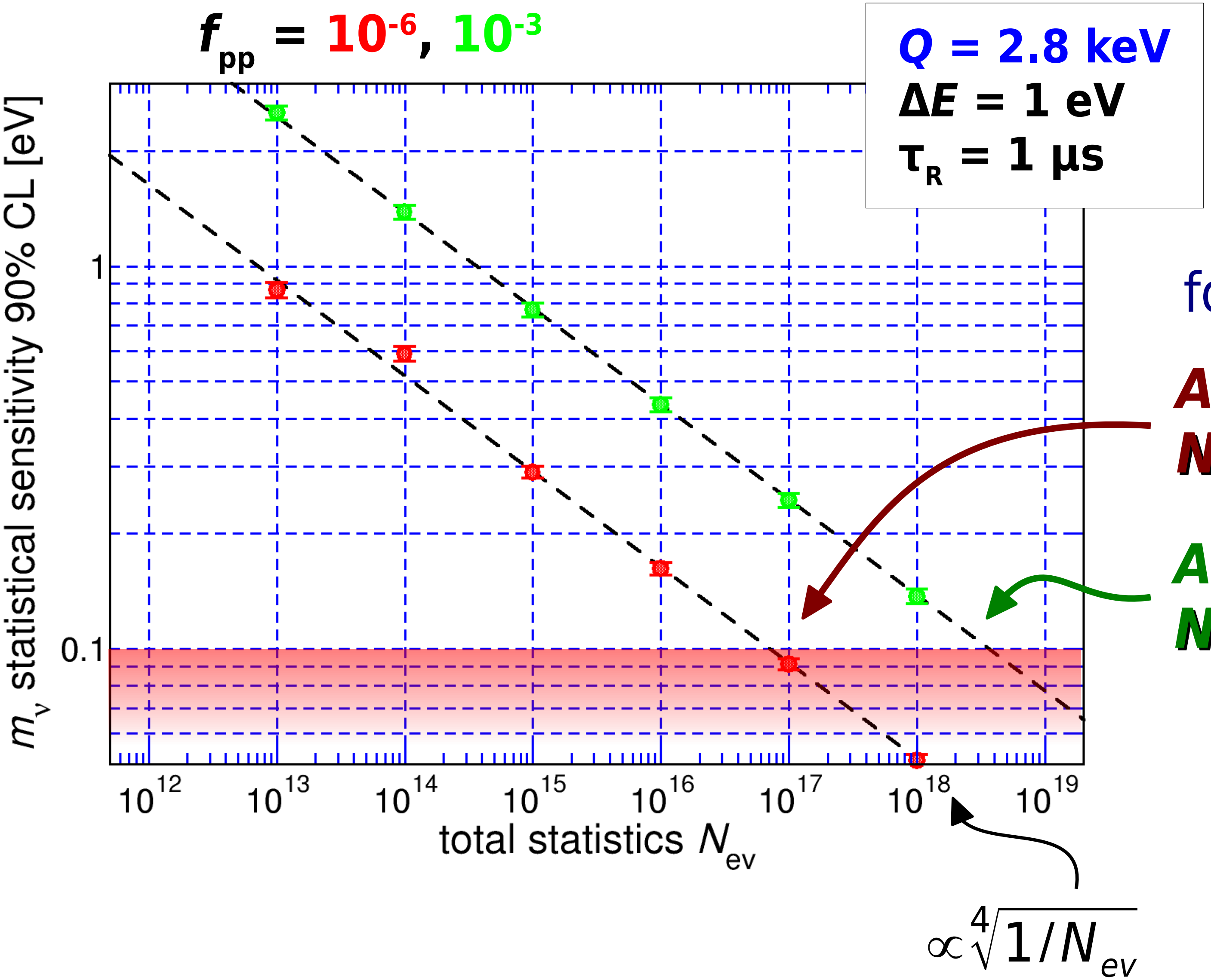
- no direct **calorimetric** measurement of Q (end-point) so far
- complex **pile-up spectrum**
  - $N_{pp}(E) = f_{pp} N_{EC}(E) \otimes N_{EC}(E)$ with $f_{pp} \approx A_{EC} \tau_R$

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



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

Statistical sensitivity: Montecarlo simulations



for $\Sigma(m_\nu) \leq 0.1$ eV

A = 1Bq
$N_{det} t_M \approx 2\times10^9$ det×y

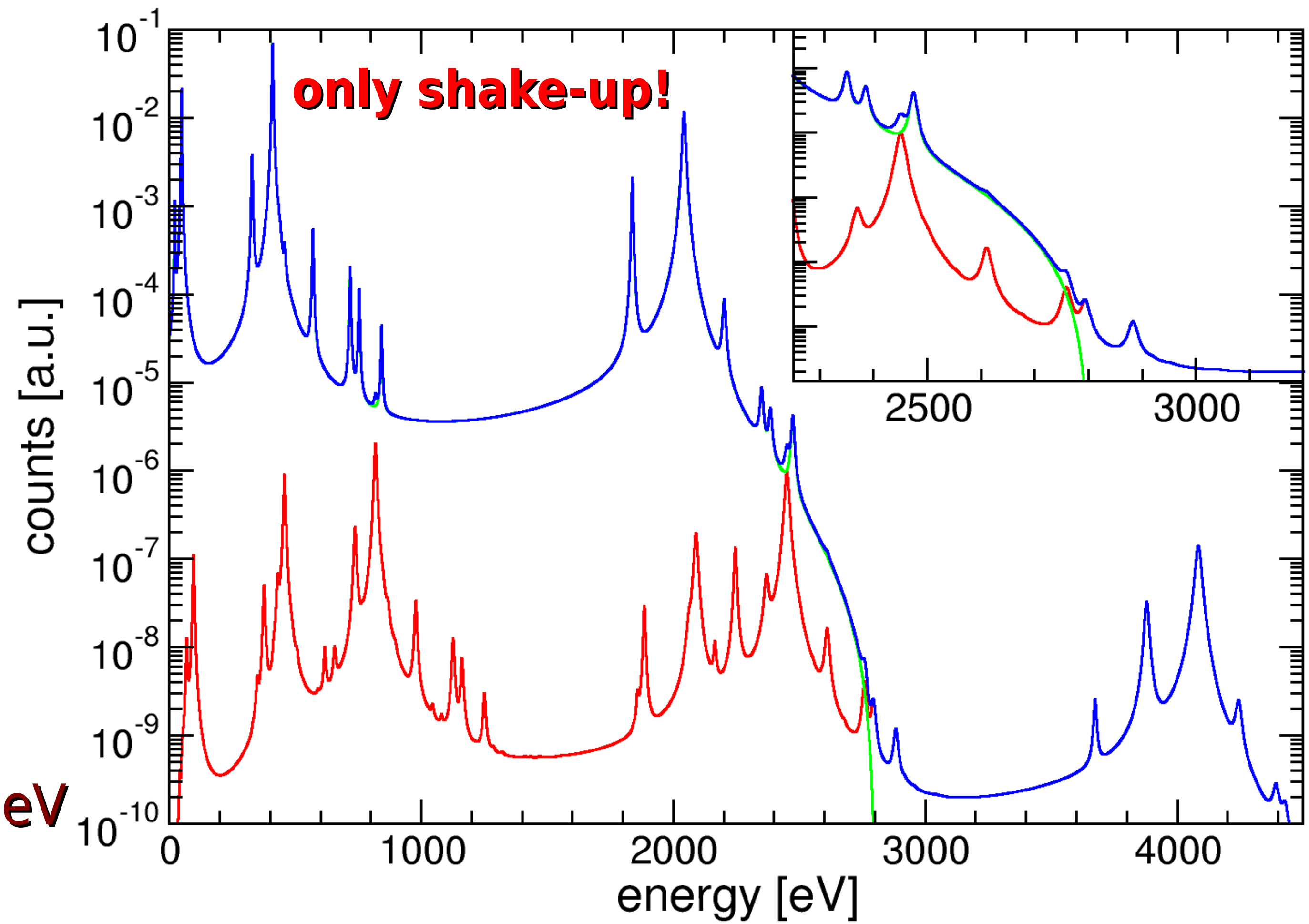
A = 1000Bq
$N_{det} t_M \approx 10^8$ det×y

M. Galeazzi et al., arXiv:1202.4763v2
A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

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}**

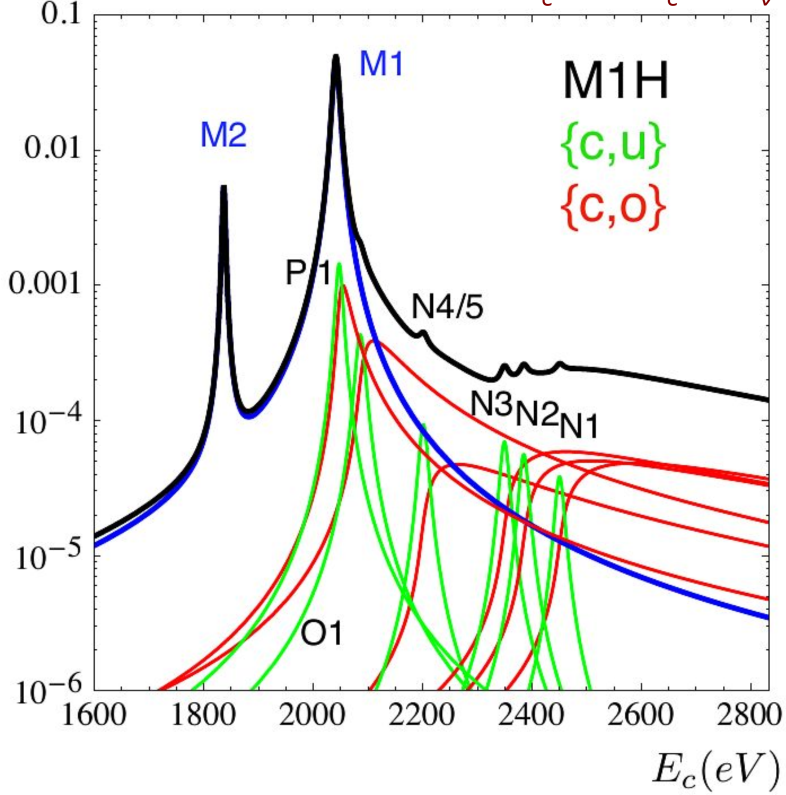
A.De Rújula, arXiv:1305.4857
R.G.H.Robertson, arXiv:1411.2906
A.Faessler et al., PRC 91 (2015) 45505



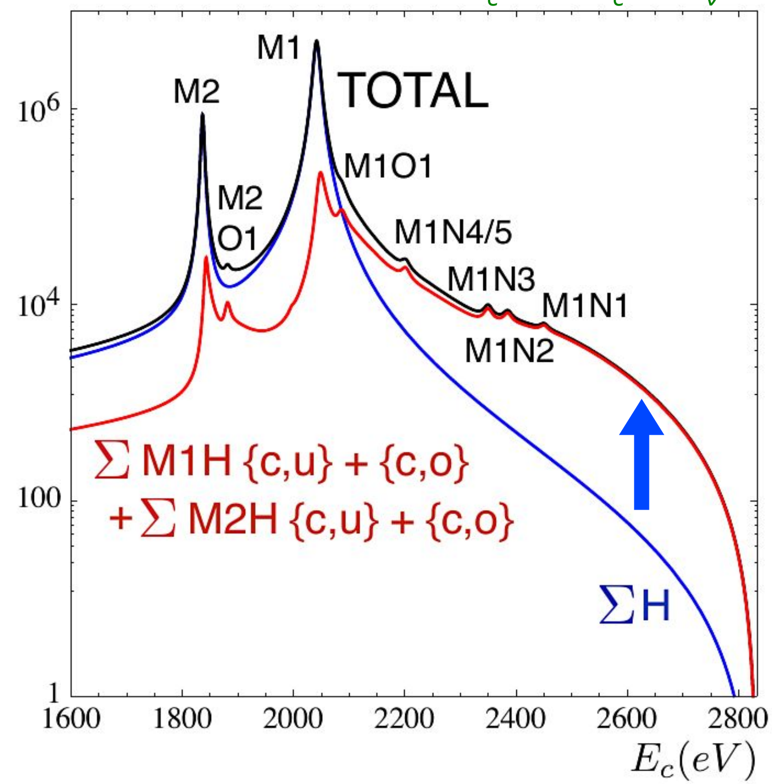
$Q = 2800$ eV
$f_{pp} = 10^{-4}$

Electron capture end-point experiment / 4

without kinematic factor $(Q\text{-}E_c)((Q\text{-}E_c)^2\text{-}m_\nu^2)^{1/2}$



with kinematic factor $(Q\text{-}E_c)((Q\text{-}E_c)^2\text{-}m_\nu^2)^{1/2}$



- including **2-hole shake-off processes** → **A. De Rújula**

$$^{163}\text{Ho} \rightarrow {}^{163}\text{Dy}^{H1\ H2} + e^- + \nu_e$$

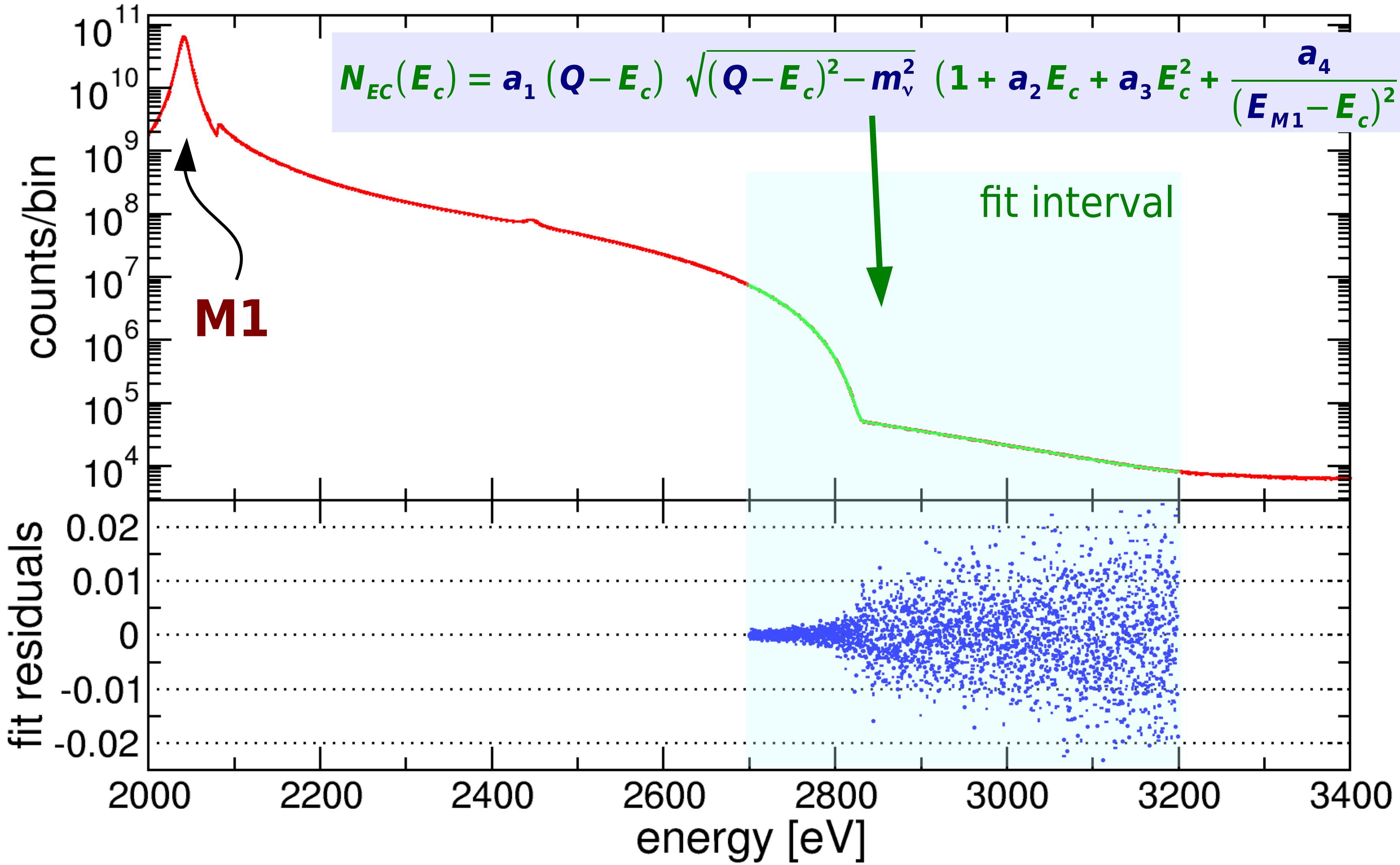
- dominate rate at end-point
  - **optimistic**: factor **~40** increase (A.De Rújula and M. Lusignoli, arXiv:1601.04990)
  - no analytic description of spectral shape at end-point
- make pile-up less important

Statistical sensitivity: shake-off processes

MC simulation with the *optimistic* spectrum in arXiv:1601.04990

Q = 2833 eV, N_{ev} = 3x10^{13}, f_{pp} = 3.0×10^{-4}, ΔE = 1.0 eV

$$N_{EC}(E_c) = a_1\,(Q-E_c)\,\sqrt{(Q-E_c)^2-m_\nu^2}\,\left(1+a_2E_c+a_3E_c^2+\frac{a_4}{(E_{M1}-E_c)^2}\right)+f_{pp}N_{pp}(E_c)$$

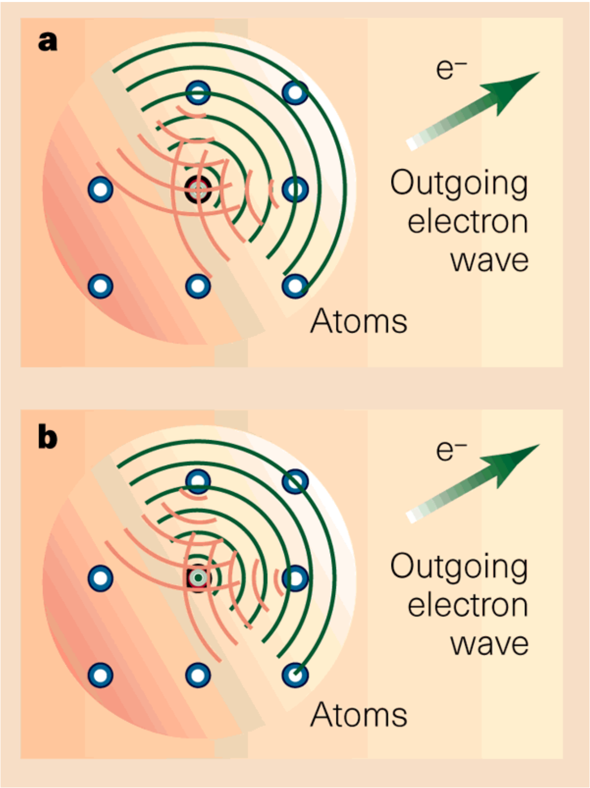


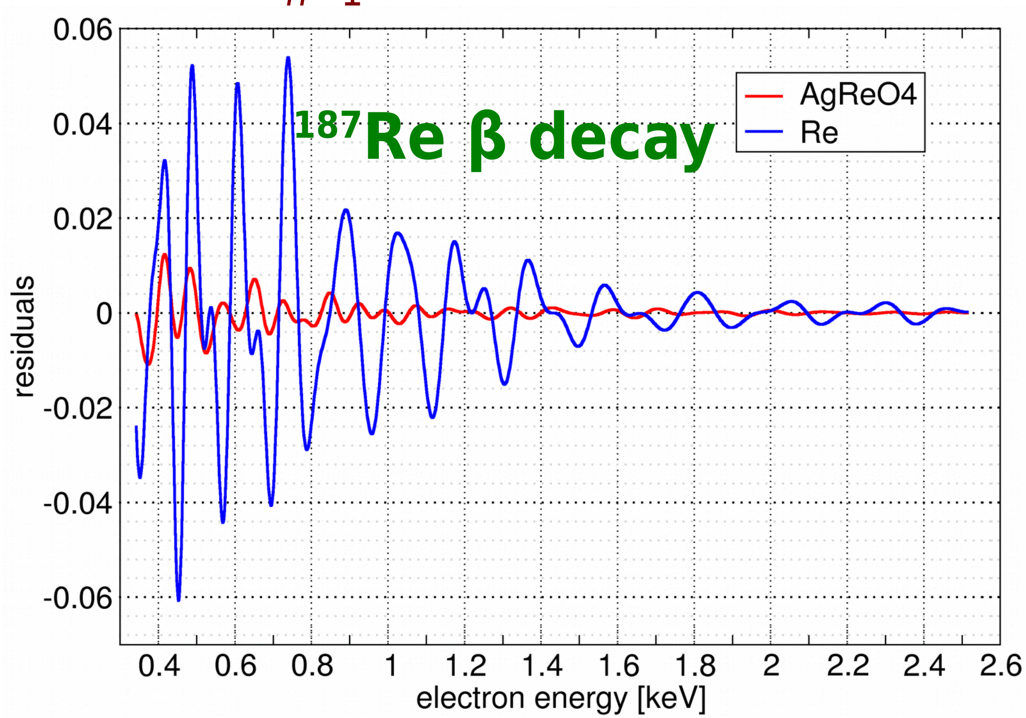
statistical sensitivity **$\Sigma(m_\nu) \approx 0.64 \pm 0.03$ eV**

Beta Environmental Fine Structure in ^{163}Ho?

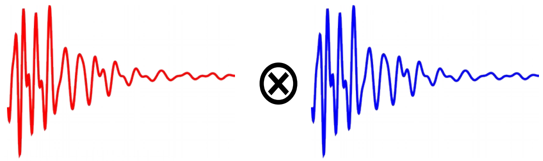
$$\chi_{BEFS}(k_e) = F_s \chi_{EXAFS}^{l=0} + F_p \chi_{EXAFS}^{l=1}$$

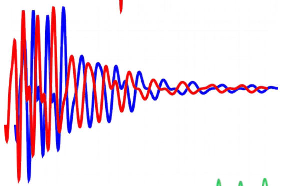
$$\chi_{EXAFS}^{l}(k_e) = (-1)^l \sum_{n=1}^{N} B_{nl}(k_e, R_n) e^{-2k_e^2\sigma_n^2} \sin(2k_e R_n + \delta_{0l} + \delta_{nl})$$





- what about **BEFS in ^{163}Ho** spectra?
  - E_c deposited by cascade processes → **convolution**?
  - different transition sequences → **cancellation**?
  - smeared position of ^{163}Ho in host lattice → **attenuation**?



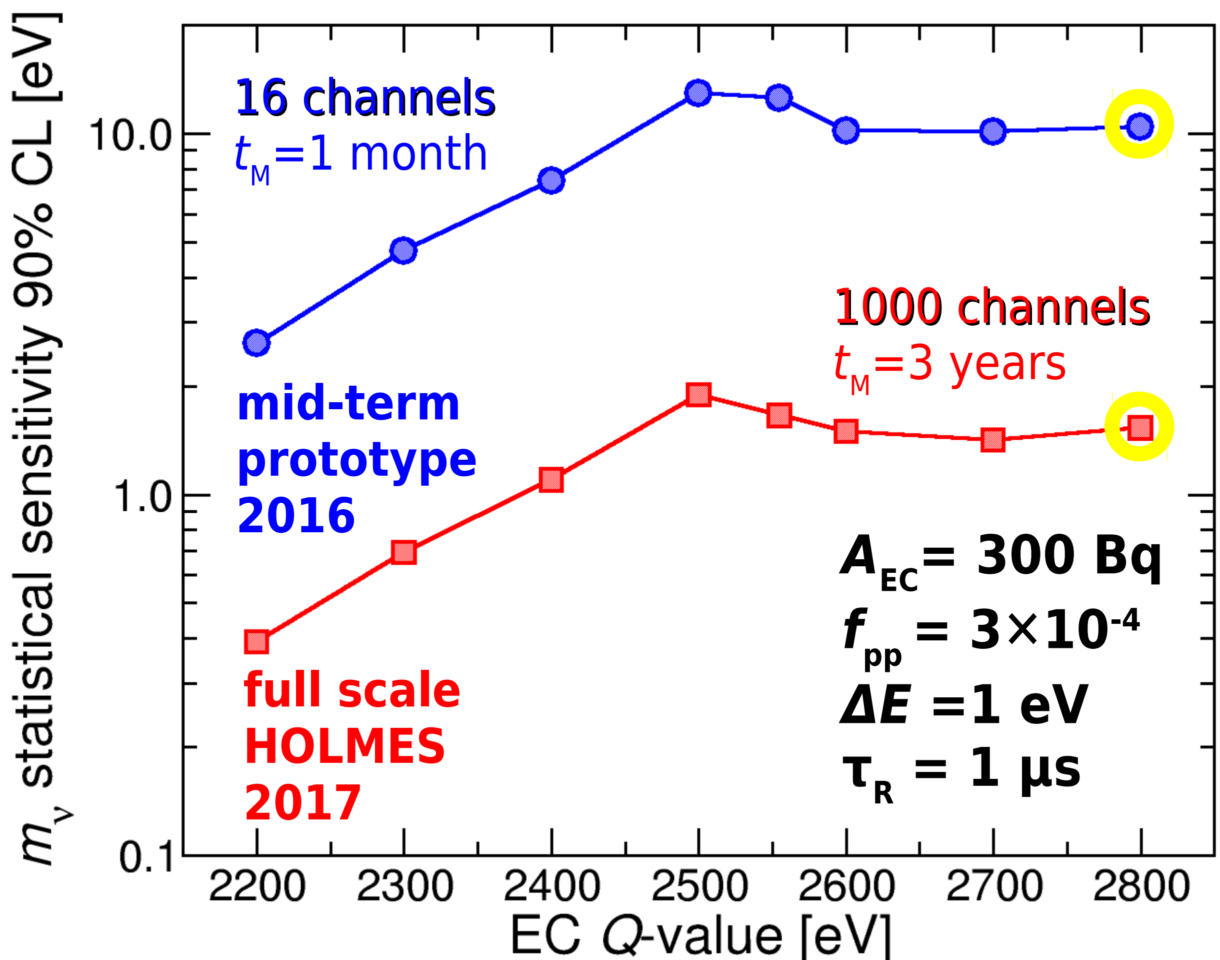


goal

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

baseline

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



→ Project Started on February 1st 2014

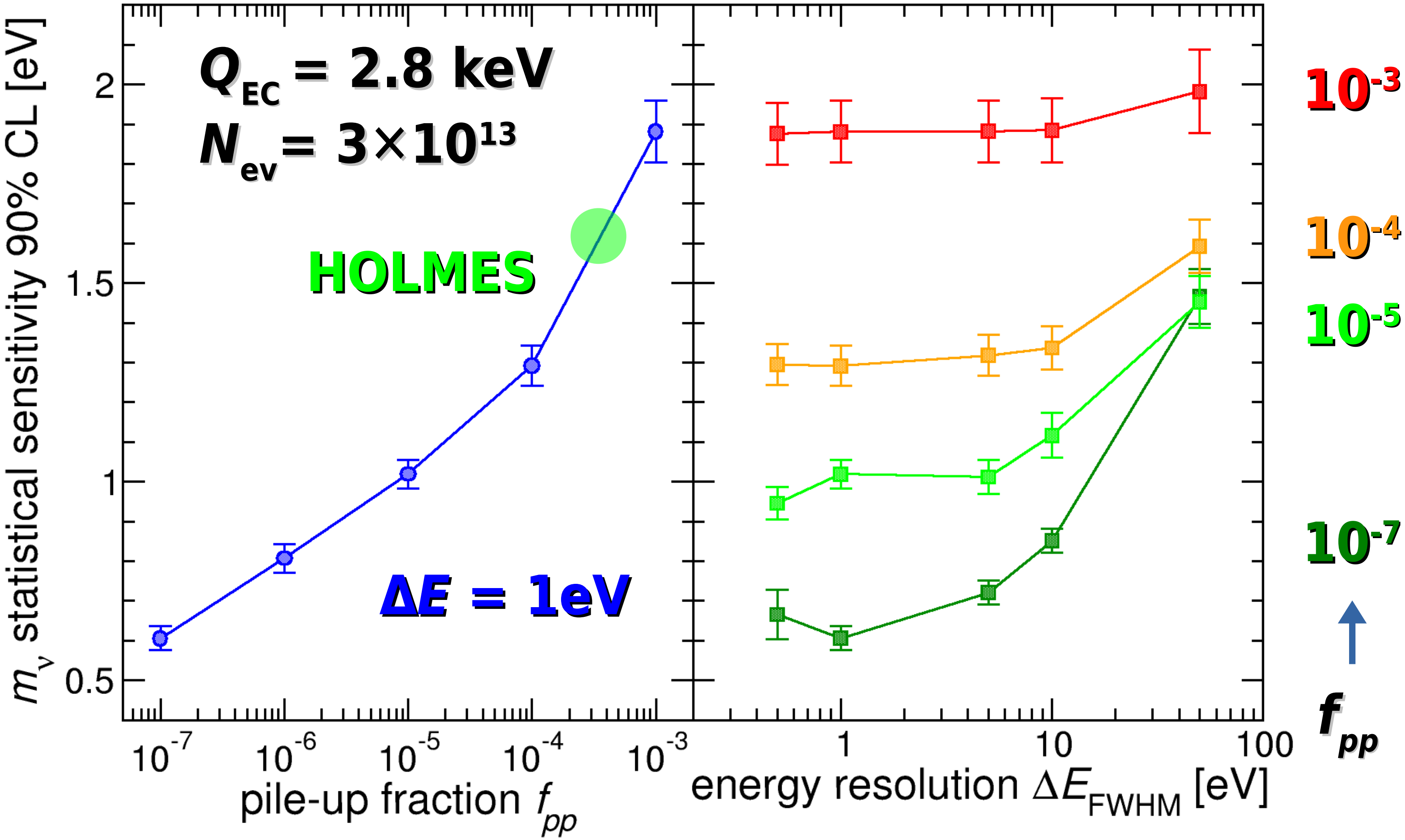
B. Alpert et al., Eur. Phys. J. C, (2015) 75:112
http://artico.mib.infn.it/holmes

HOLMES design: more MC simulations...

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

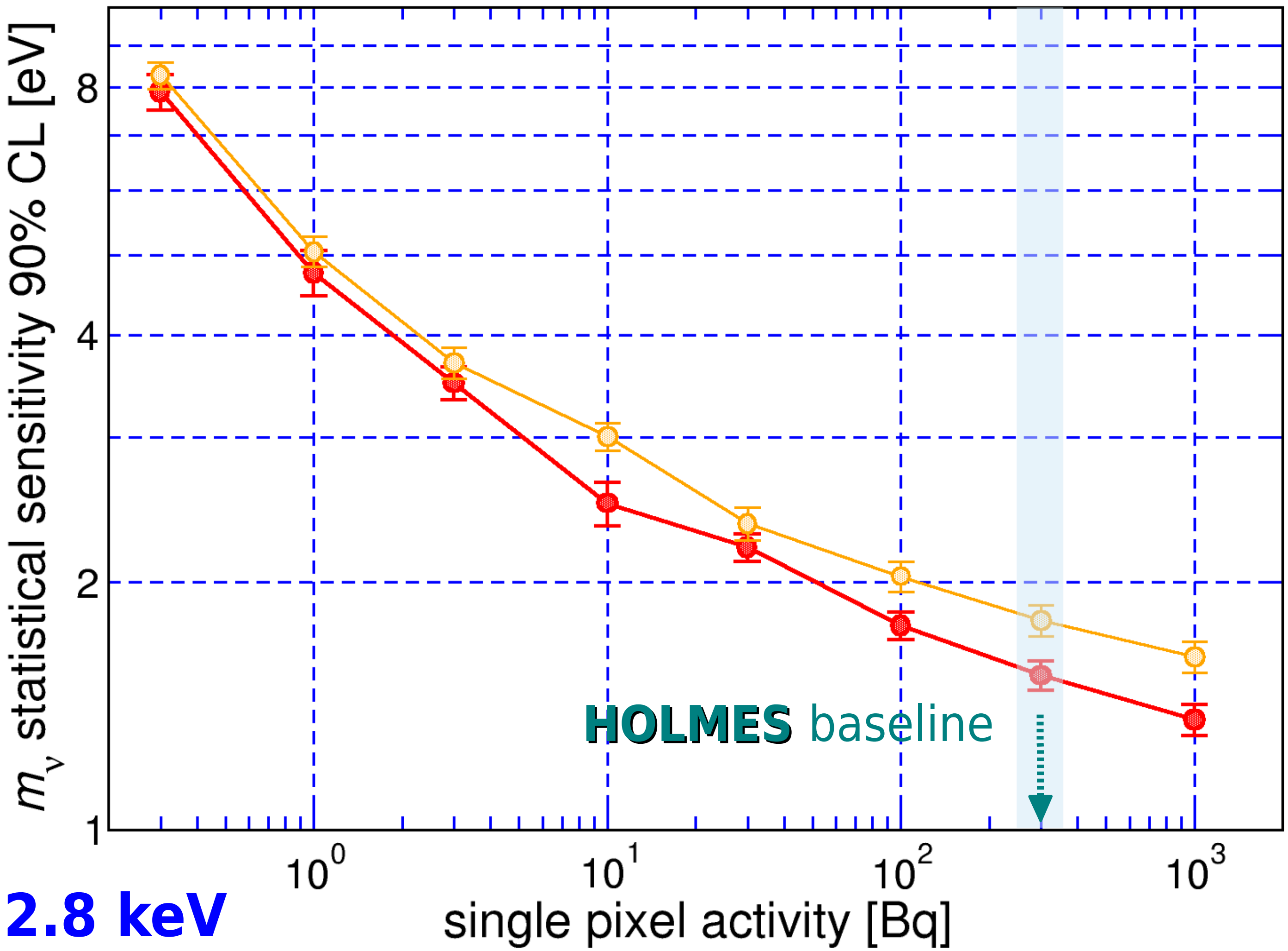
- strong on statistics $N_{ev}=A_{EC}N_{det}t_M$: $\Sigma(m_\nu) \propto N_{ev}^{-1/4}$
- strong on rise time pile-up (probability $f_{pp}\approx A_{EC}\tau_R$)
- weak on energy resolution ΔE

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

fixed exposure $N_{det}t_M$



1000 channels
t_M=3 years

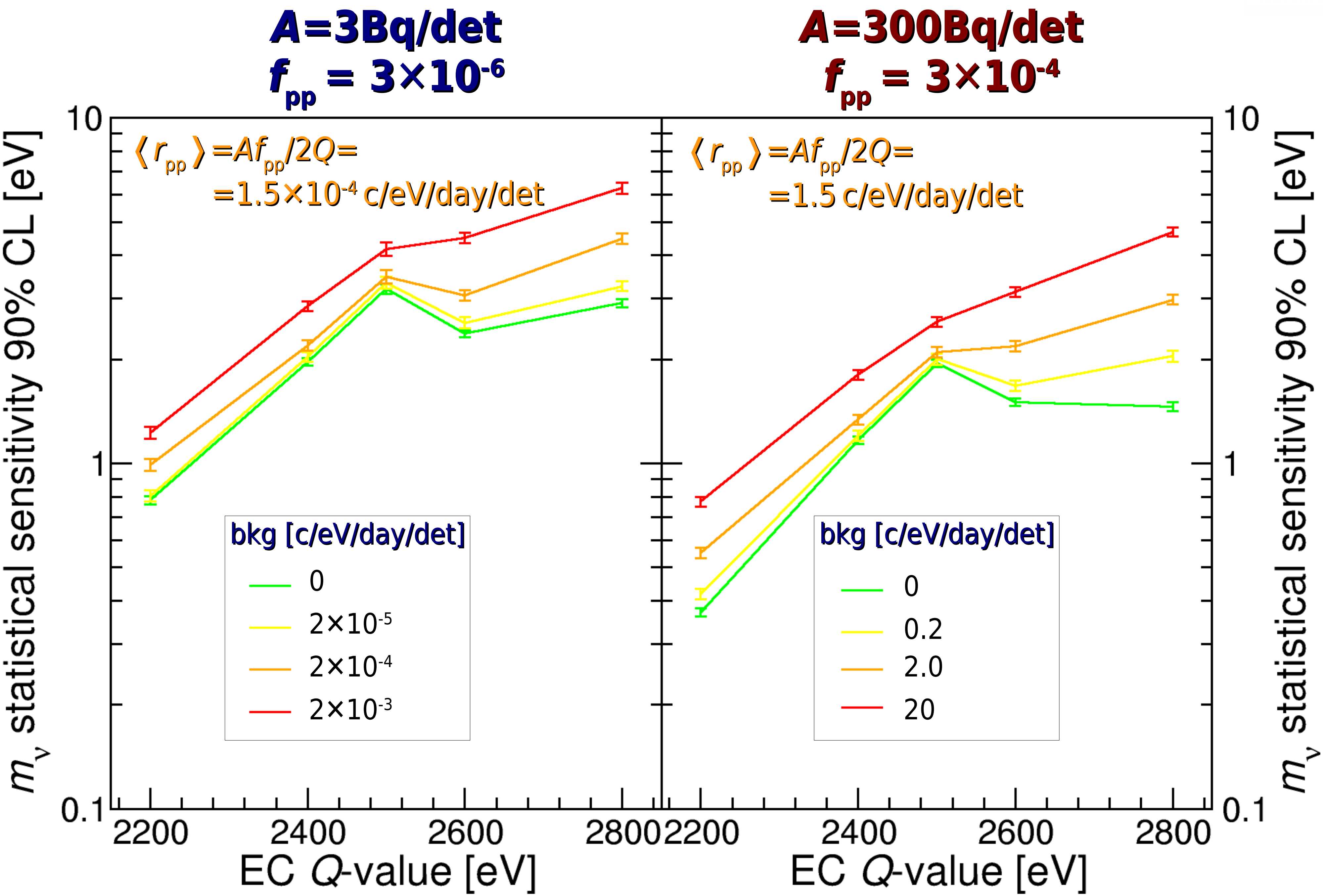
***ΔE* =1 eV**
τ_R = 1 µs

ΔE =3 eV
τ_R = 3 µs

***Q* = 2.8 keV**

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

Effect of background on sensitivity



Low energy background sources

- environmental γ radiation
- γ, X and β from close surroundings
- **cosmic rays**
  - GEANT4 simulation for CR at sea level (**muons**)
  - **Bi pixel 200×200×3 μm^3 → *bkg* ≈ 5×10^{-5} c/eV/day/det (0 - 4 keV)**
- **internal radionuclides**
  - GEANT4 simulation for **^{166m}Ho** (β$^-$, $\tau_{1/2}$ = 1200 y, produced along with ^{163}Ho)
  - **Bi pixel 200×200×3 μm^3 → *bkg* ≈ 10^{-11} c/eV/day/det/(^{166m}Ho nucleus)**
  - *bkg* ≈ 0.5 c/eV/day/det/Bq(^{166m}Ho)
  - *A*(^{163}Ho) = 300Bq/det: for *bkg*(^{166m}Ho)<0.1 c/eV/day/det

    → *N*(^{163}Ho)/*N*(^{166m}Ho)>6000

    → *A*(^{163}Ho)/*A*(^{166m}Ho)>1500

MIBETA experiment with 300×300×150 μm^3 $AgReO_4$ crystals
bkg(2..5keV)≈1.5×10^{-4} c/eV/day/det

HOLMES experiment design

- design mostly driven by **read-out bandwith** requirements
  - TES microwave multiplexing with rf-SQUID ramp modulation + Software Defined Radio (SDR)

read-out specs
SDR ADC f_{ADC}
multiplexing factor n_{TES}

→

signal sampling f_{samp}
signal rise time τ_{rise}

→

HOLMES targets
τ_R ΔE N_{det}

$$f_{samp} \geq \frac{R_d}{\tau_{rise}} \approx \frac{5}{\tau_{rise}}$$ detector signal sampling (signal BW)

$$f_{res} \geq 2 n_{\Phi_0} f_{samp}$$ flux ramp modulated signal BW (resonator BW)

$$f_n \geq g_f f_{res} = \frac{2 R_d g_f n_{\Phi_0}}{\tau_{rise}}$$ microwave tones separation

multiplexing factor

$$n_{TES} = \frac{f_{ADC}}{f_n} \leq \frac{f_{ADC} \tau_{rise}}{2 R_d g_f n_{\Phi_0}} \approx \frac{f_{ADC} \tau_{rise}}{200}$$

for fixed f_{ADC}**=550MHz** and n_{TES}**≈30** ↔ τ_{rise}**≈10µs** with f_{samp}**=0.5MHz**

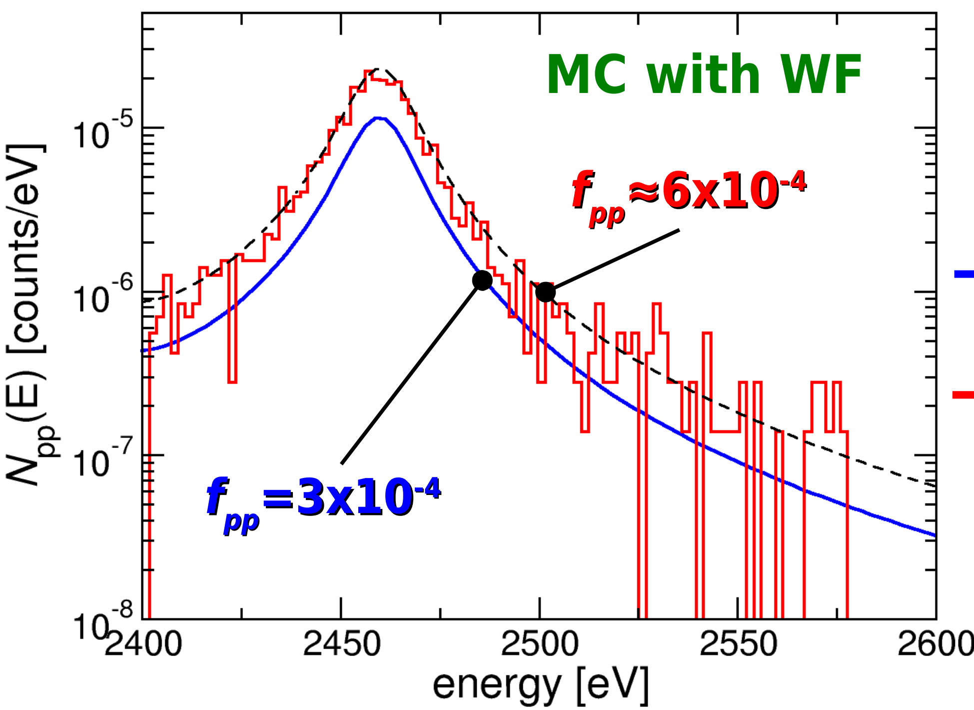
→ **check for τ_R and ΔE...**

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), $\Delta t \in [0, 16\mu s]$ *
  - ▷ pulse shape and noise from NIST TES model, sampled with f_{sampl}, record length, and n bit
  - ▷ process pulses with pile-up detection algorithms:
    - Wiener Filter WF (→ **E. Ferri**) or Single Value Decomposition SVD (→ **B. Alpert**)
- evaluate **effective time resolution τ_{eff}** from **pile-up detection efficiency $\eta(\Delta t)$**



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

— $f_{pp}\, N_{EC}(E) \otimes N_{EC}(E)$ with A = 300 Bq and τ_R = 1 μs

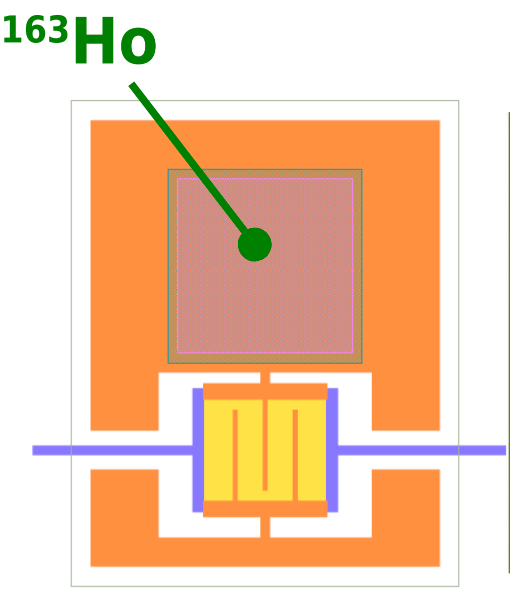
— **WF simulation** with f_{samp} = 1 MHz, $\tau_{rise} \approx$ 10 μs, and A = 300 Bq

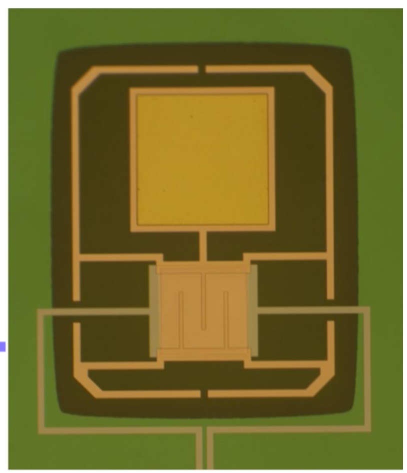
→ estimated $\tau_{eff} \approx$ 3 μs

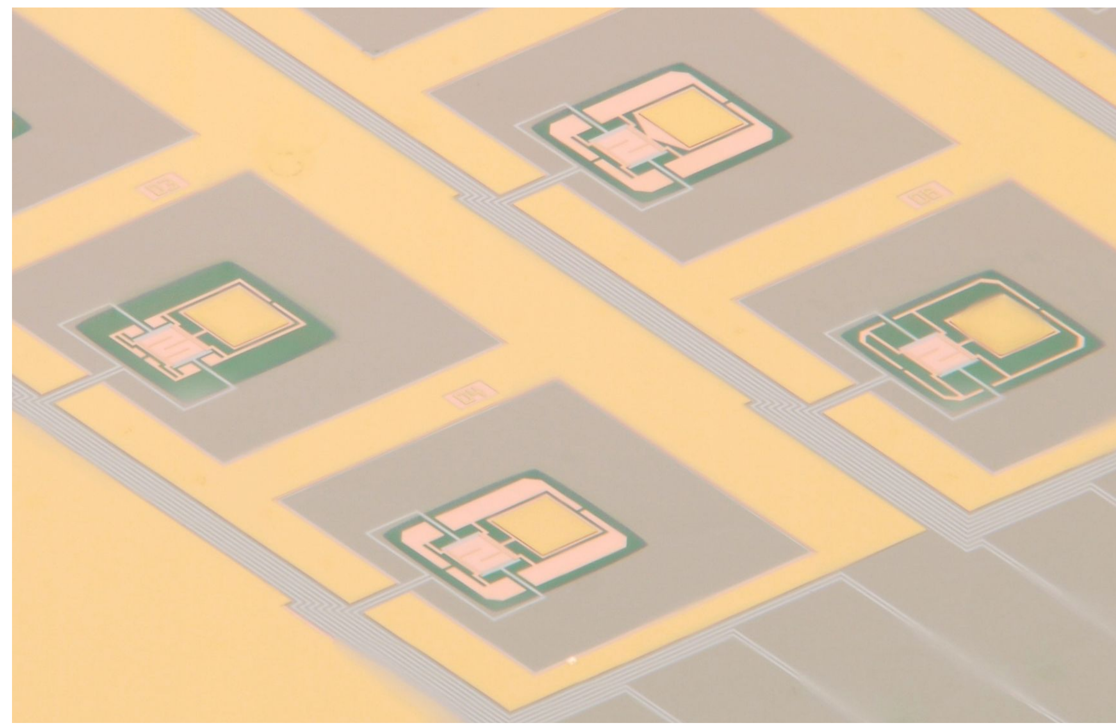
* for WF simulations

HOLMES pixel design

- optimize design for speed and resolution → **J.Hays-Wehle**
  - **specs @2.5keV : ΔE_{FWHM} ≈ 1eV, τ_{rise} ≈ 10μs, 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 τ_{decay} control
- define process for ^{163}Ho implantation vs. excess heat capacity





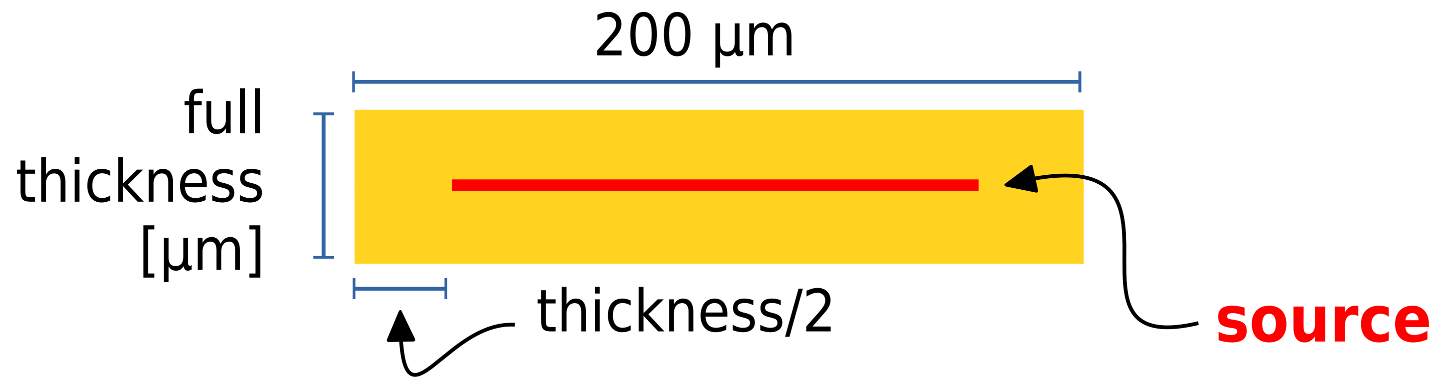


- **tests at NIST are in progress**
  - preliminary measurements agree with model predictions:
  - **ΔE_{FWHM} ≲ 4 eV, τ_{rise} ≈ 6 μs** (with L=38nH → to be slowed), **τ_{decay} ≈ 130 μs** (tunable)

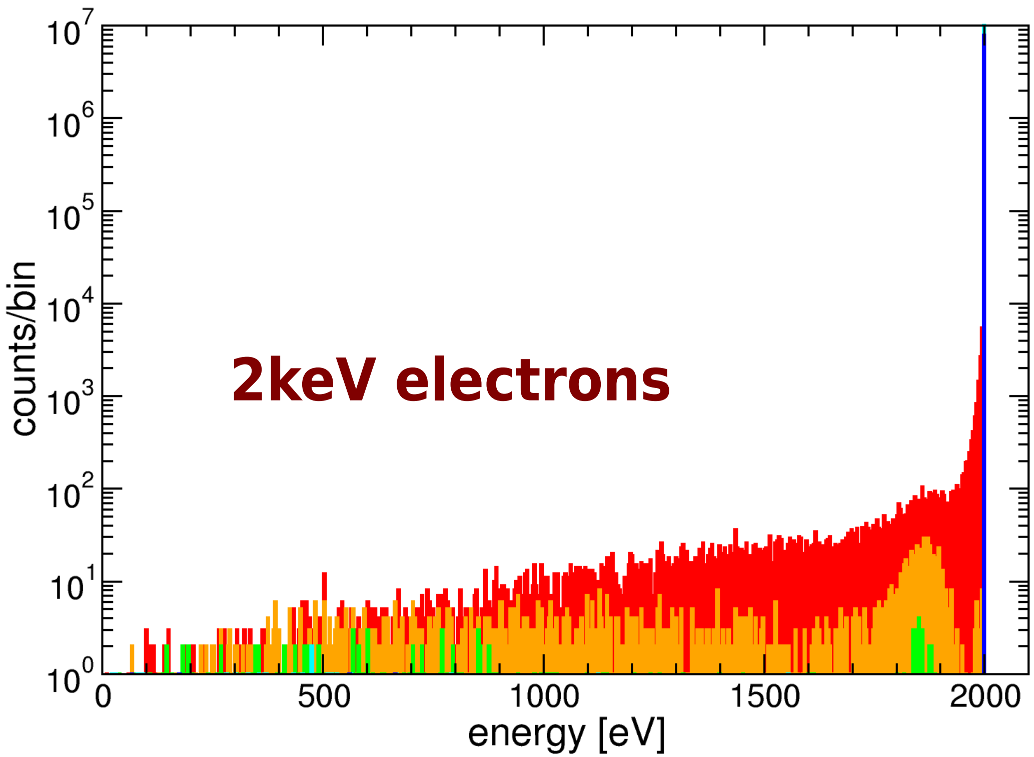
→ **J.Hays-Wehle**

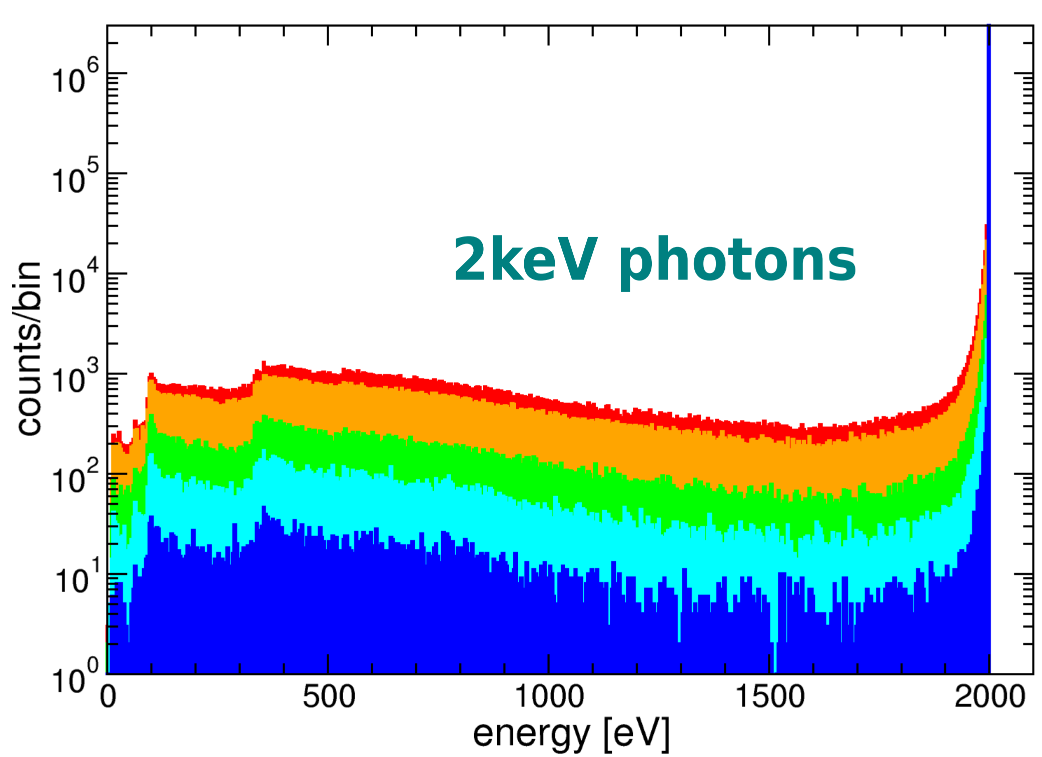
Stopping EC radiation in TES absorber / 1

Geant4 + LowEnergyEM: 10^7 events

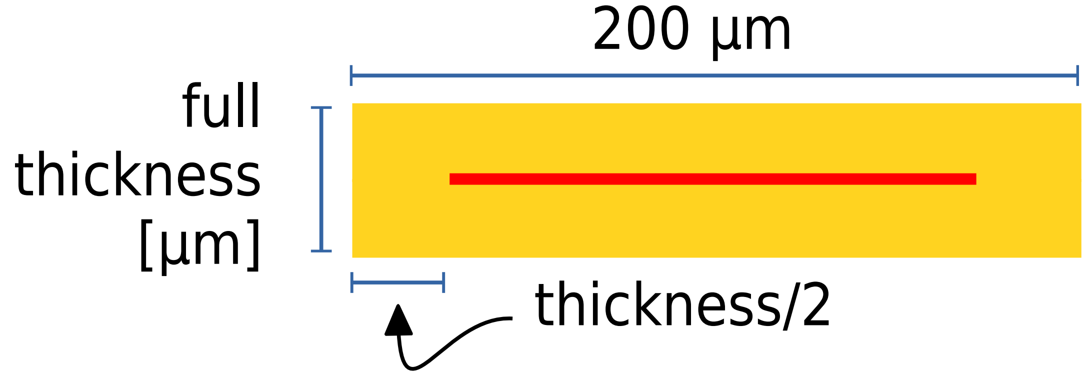


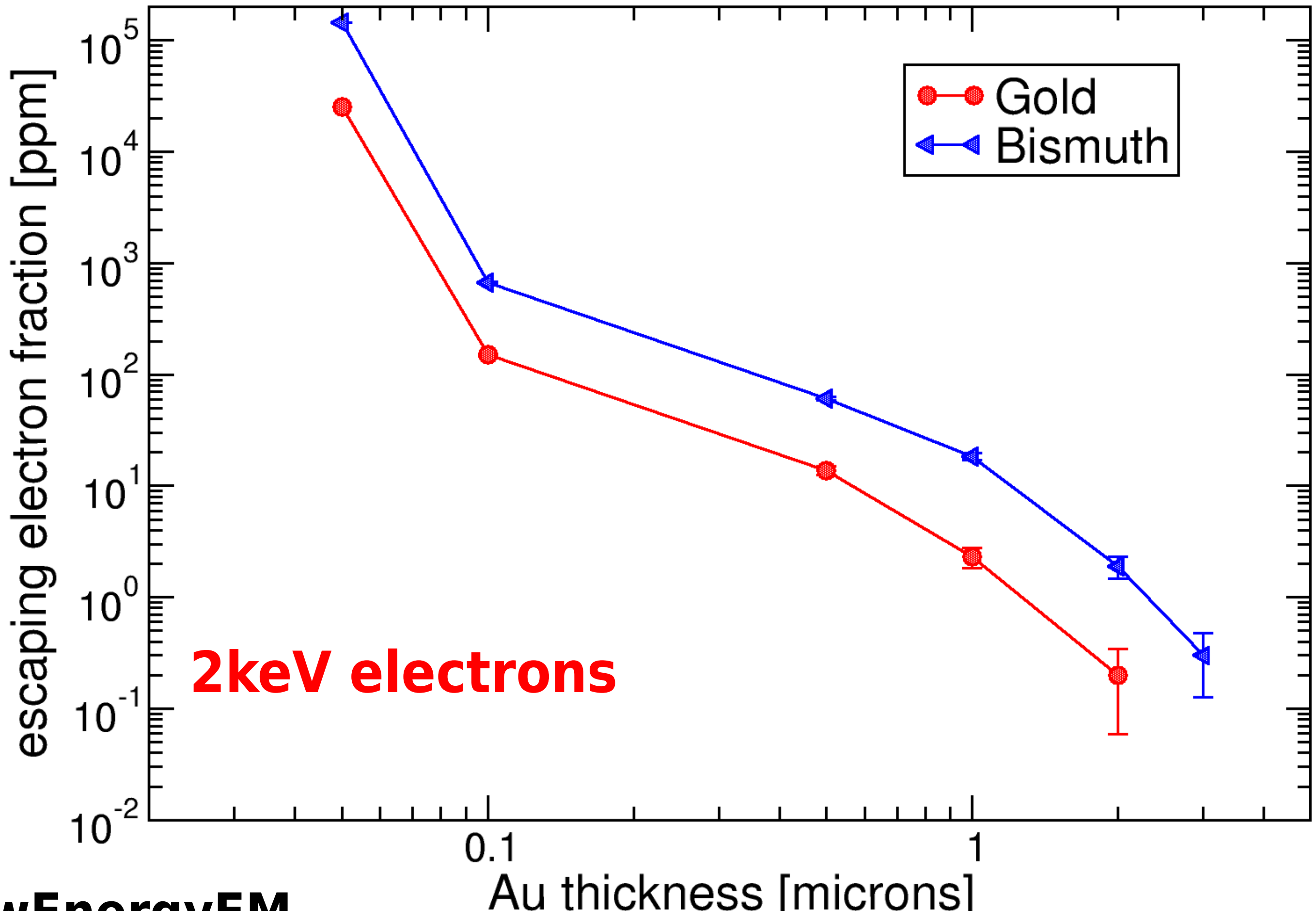
full thickness: 0.05, 0.1, 0.5, 1, 2 µm





Stopping EC radiation in TES absorber / 2

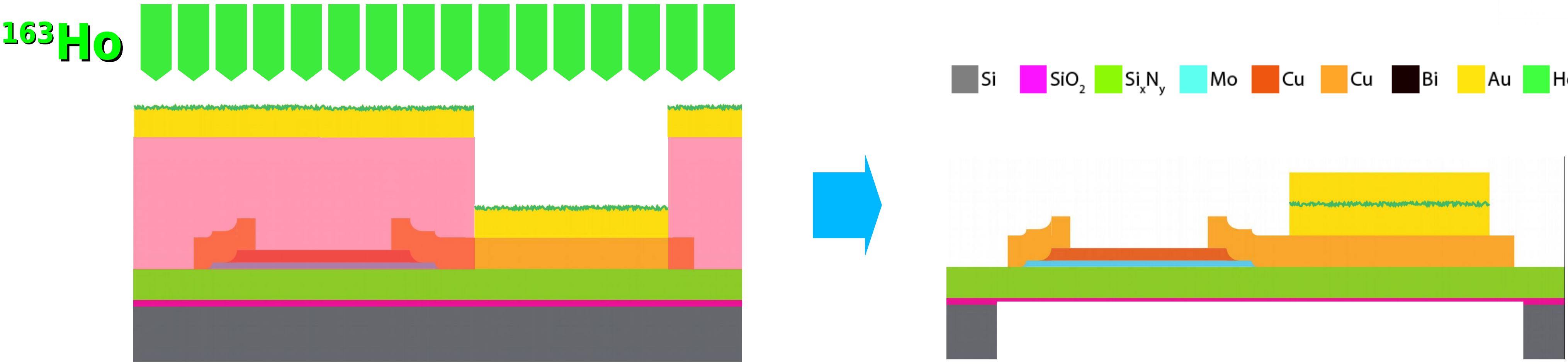




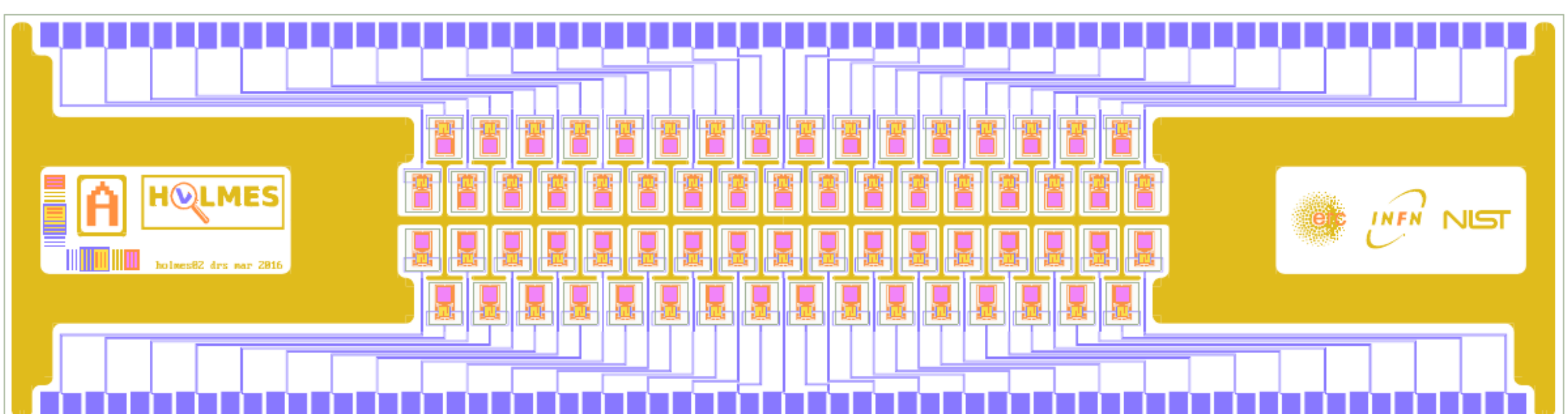
Geant4 + LowEnergyEM

10^7 events

HOLMES detector array fabrication

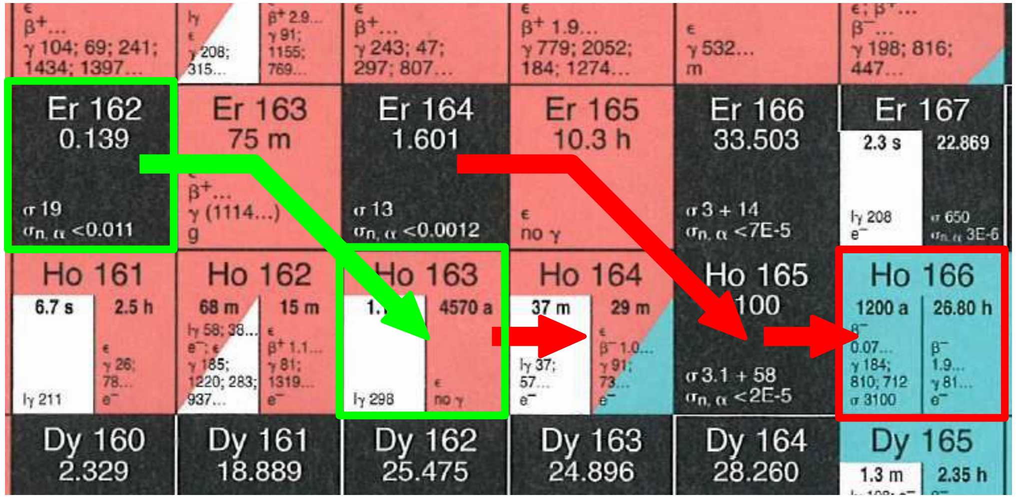


- TES array fabricated at **NIST**, Boulder, CO, USA
- ^{163}**Ho** implantation at **INFN**, Genova, Italy
- 1 µm **Au** final layer deposited at INFN Genova
- fabrication process details under investigation
  - ion implant before/after Si_2N_3 membrane release
- HOLMES **4×16 linear sub-array** for low parasitic *L* and high implant efficiency



^{163}Ho production by neutron activation

HOLMES needs ≈200MBq of ^{163}Ho



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

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

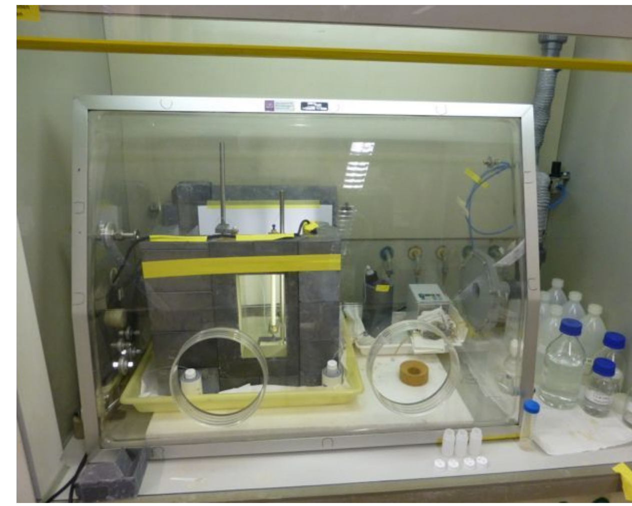
→ U.Koester

- **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 (→ 100mg(^{162}Er) for 7 weeks → ≈200MBq of ^{163}Ho)
- **burn up** ^{163}Ho(n,γ)^{164}Ho: **cross section not known**
  - may reduce yield: $\sigma_{burn\text{-}up} \approx 100b$ → 100mg(^{162}Er) for 7 weeks → ≈190MBq of ^{163}Ho
- **^{165}Ho(n,γ)** (mostly from ^{164}Er(n,γ)) → **^{166m}Ho, β $\tau_{½}$=1200y**
  - 100mg(^{162}Er) for 7 weeks → order of 100kBq of ^{166m}Ho (depends on ^{164}Er abundance)
- analysis of 2 samples irradiated at ILL with **ICP-MS** at LNGS is in progress
- **HOLMES needs ≈500mg Er_3O_2 enriched at 30%**
- **chemical pre-purification** and **post-separation** at PSI (Villigen, Switzerland)

HOLMES source chemical processing

- **enriched Er_2O_3** samples* irradiated at ILL and pre-/post-processed at **PSI**
  - ▸ 25 mg irradiated for 55 days → $A(^{163}\mathrm{Ho})_{theo}$≈**10MBq** ($A(^{166m}\mathrm{Ho})_{meas}$≈10kBq)
  - ▸ 150mg irradiated for 50 days → $A(^{163}\mathrm{Ho})_{theo}$≈**70MBq** ($A(^{166m}\mathrm{Ho})_{meas}$≈500kBq)
- **Ho chemical separation** with ion-exchange resins in hot-cell
  - ▸ **efficiency ≈79%**

* from CENTRA, Lisbon

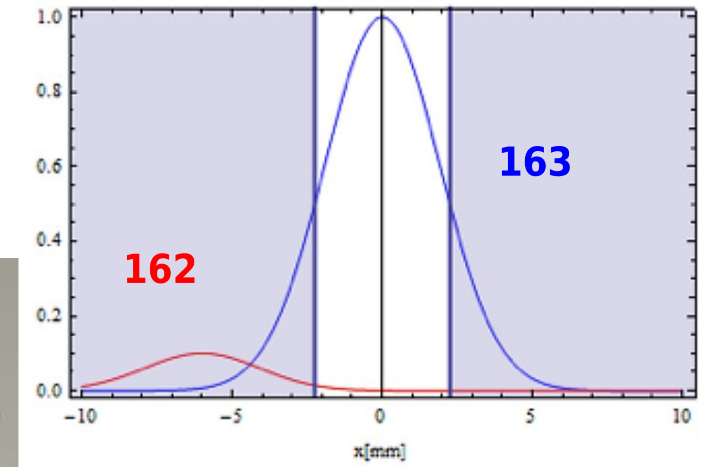


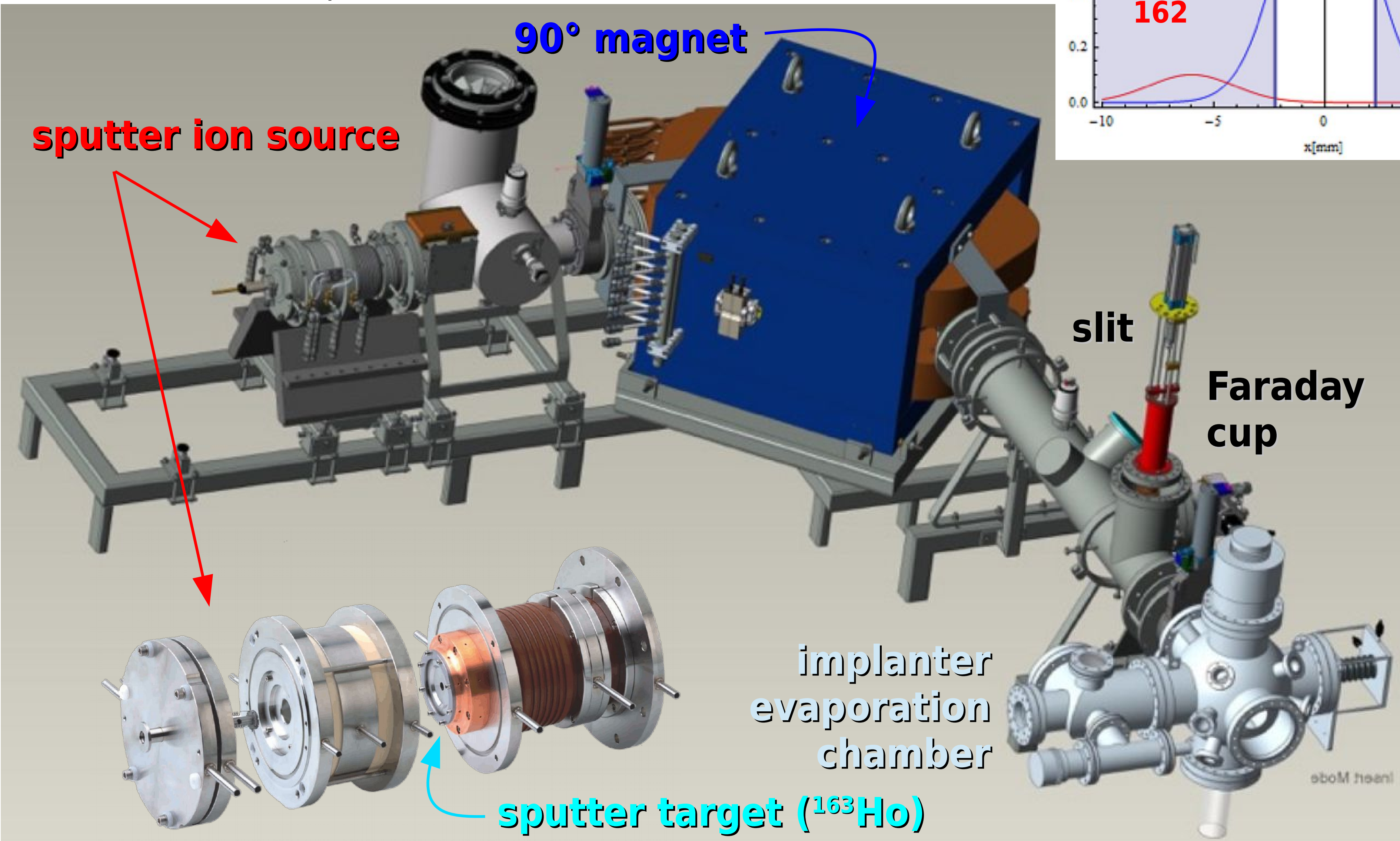
- **Metallic holmium sputter target** for implanter ion source
- 30% enriched Er_2O_3 → Ho_2O_3
- thermoreduction/distillation in furnace (Genova)
  - ▸ Ho_2O_3+2Y(*met*) → 2Ho(*met*)+Y_2O_3 at 2000°C

→ **V.Ceriale** (poster)

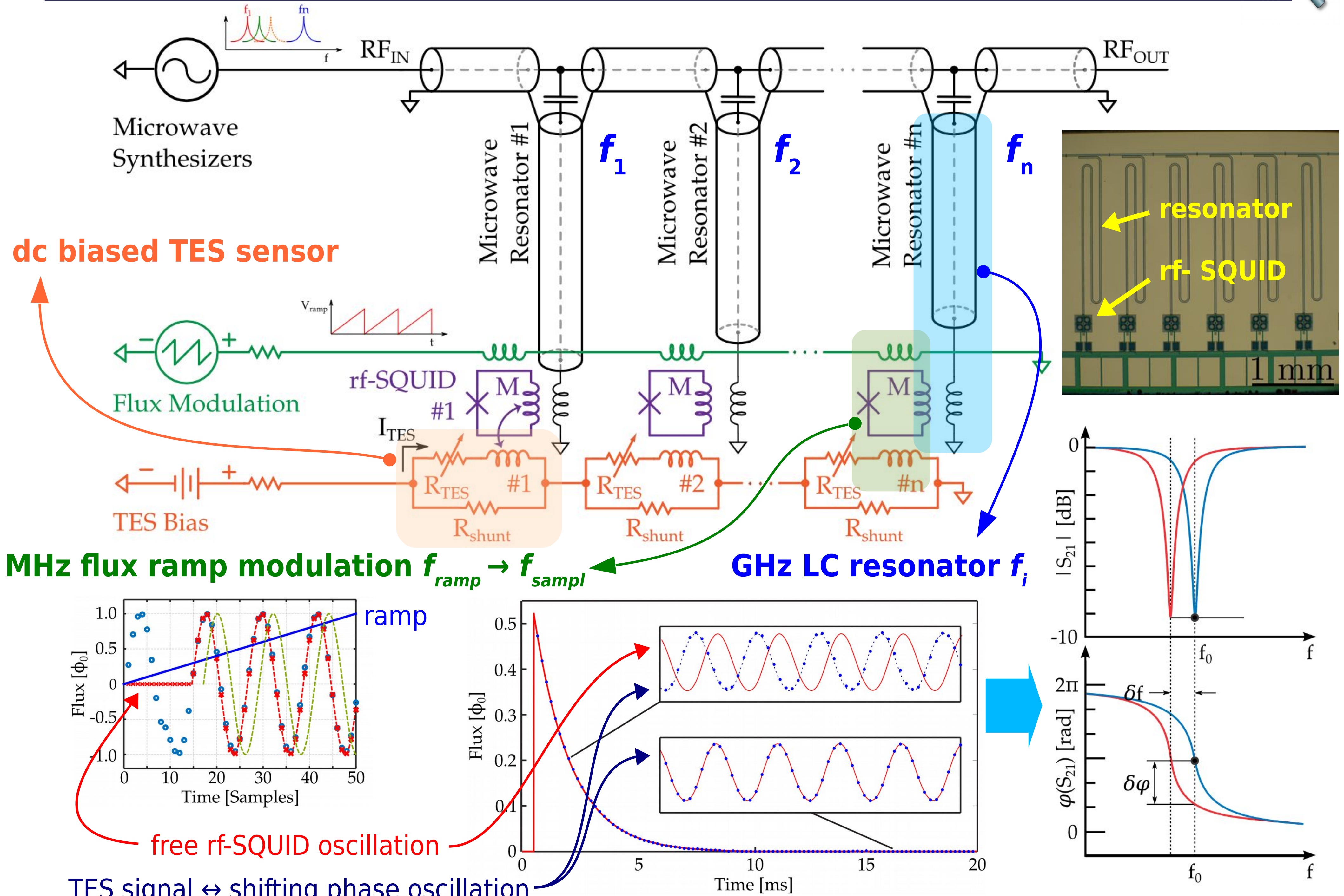
HOLMES ion implantation system

- ordered to **Danfysik** (DK). Delivery before Sept 2016
- ion current 5 mA
- extraction voltage 30 - 50 kV → 10 - 100 nm implant depth
- ^{163}Ho / ^{166m}Ho separation better than 10^5

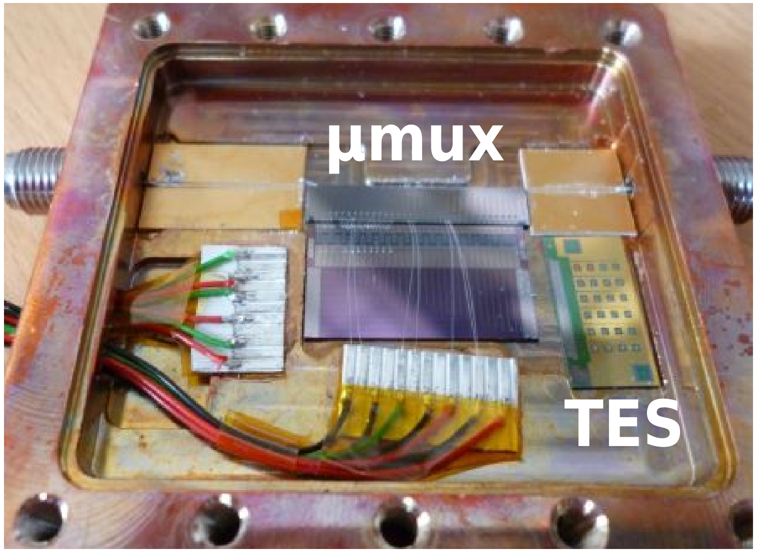


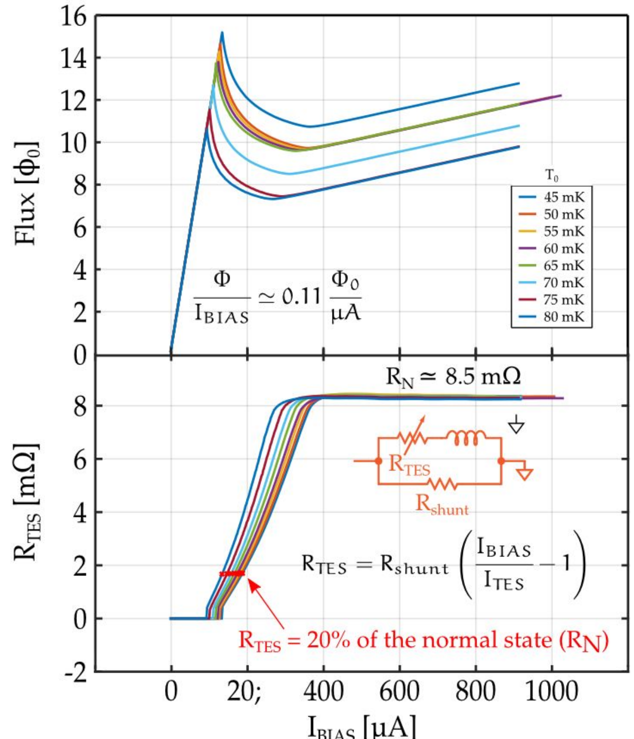


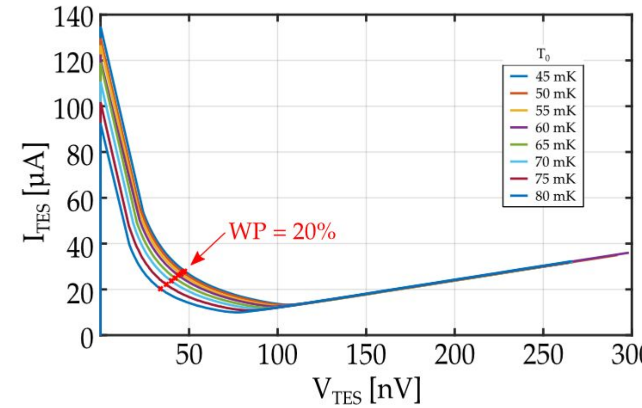
HOLMES array read-out: rf-SQUID μwave mux

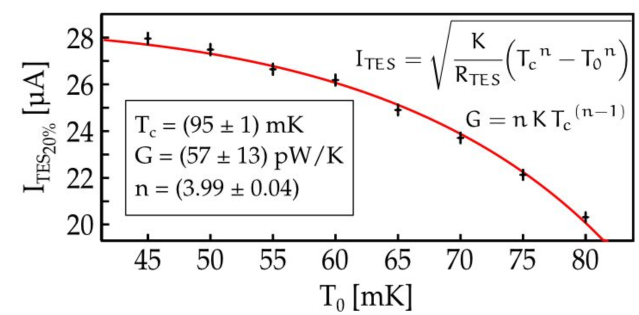


TES with rf-SQUID µwave read-out testing

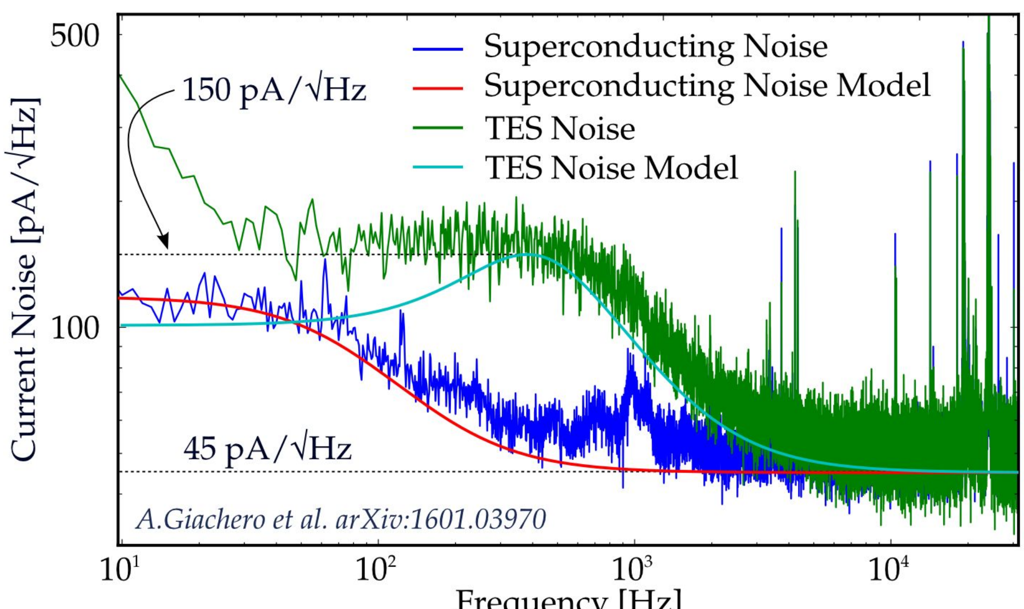


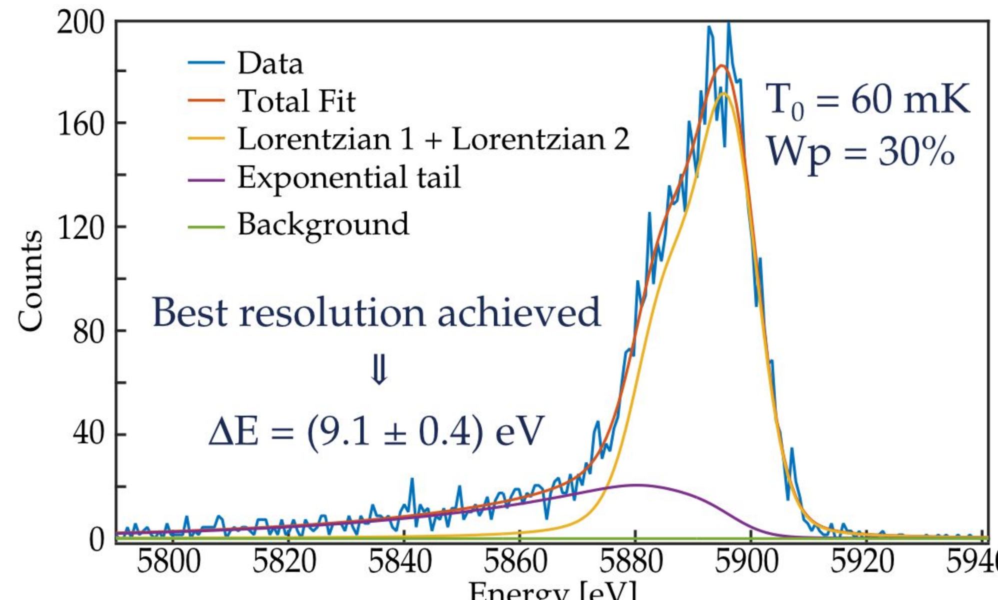






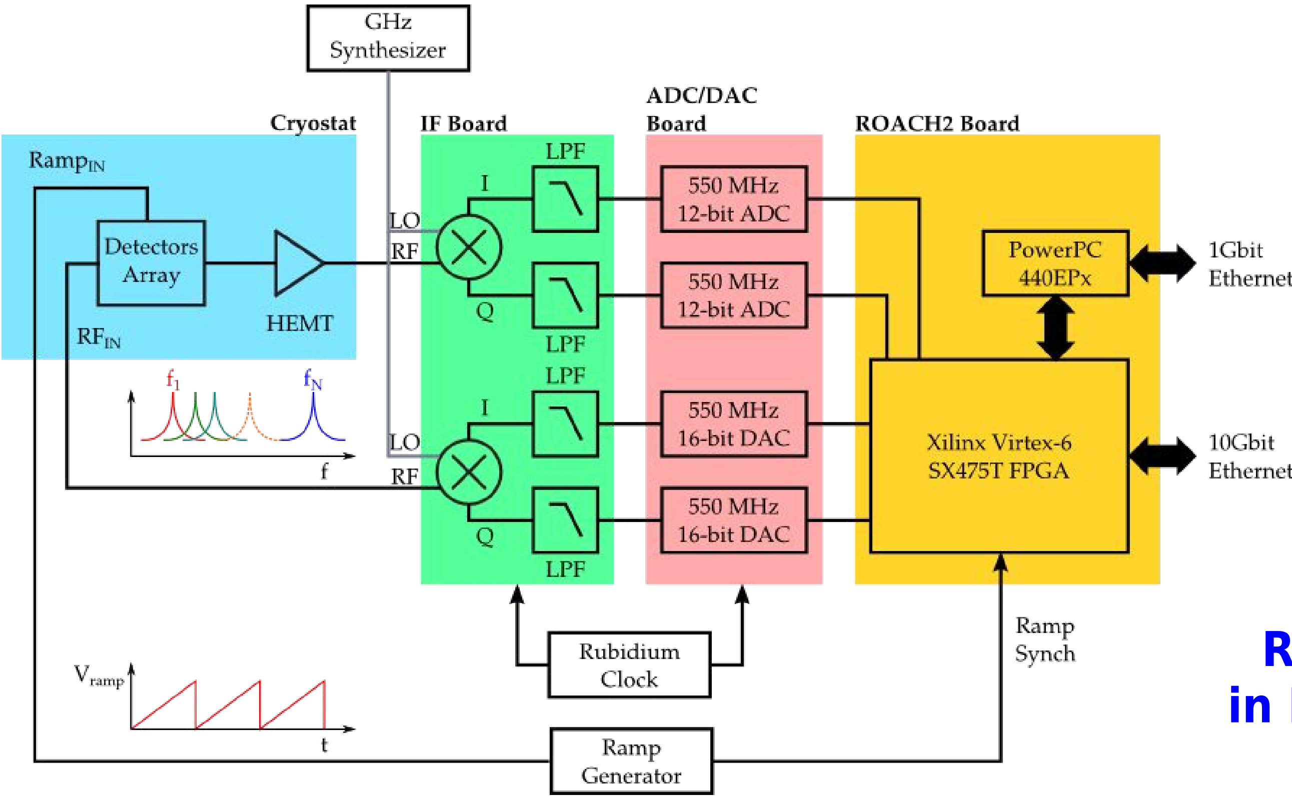
Tests in **Milano-Bicocca**
with **Bismuth TES** coupled to
µwave mux (from **NIST**) → **A. Giachero** poster

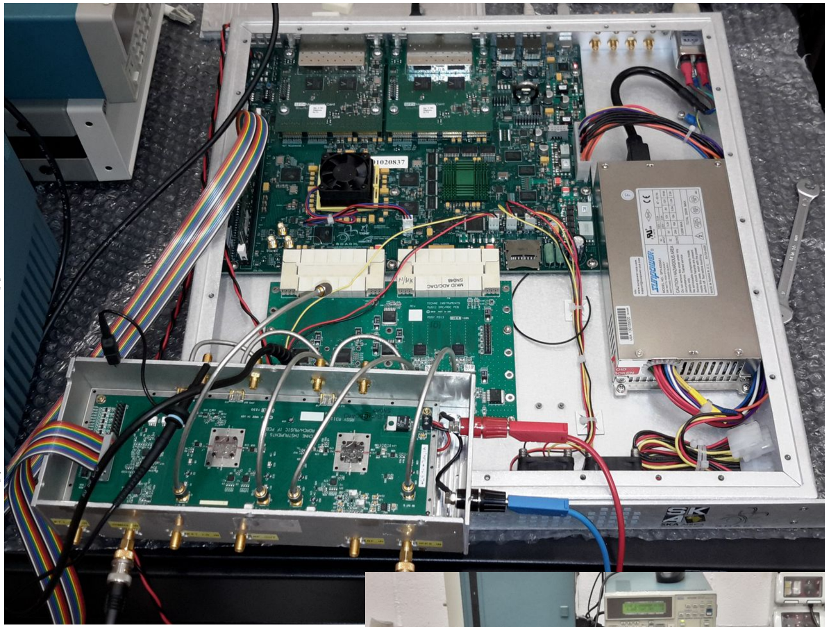




HOLMES DAQ

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





ROACH2 system in Milano-Bicocca

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

$$f_{TES} = 2 n_{\Phi_0} f_{sampl}$$

$f_{sampl} = 5/\tau_{rise}$ (f_{sampl} and τ_{rise} from pile-up simulations)

$$N_{mux} = \frac{f_{ADC}}{10 f_{TES}}$$

$f_{sampl} = 0.5\text{MHz}$, $n_{\Phi_0} = 2 \rightarrow N_{mux} \approx 28$

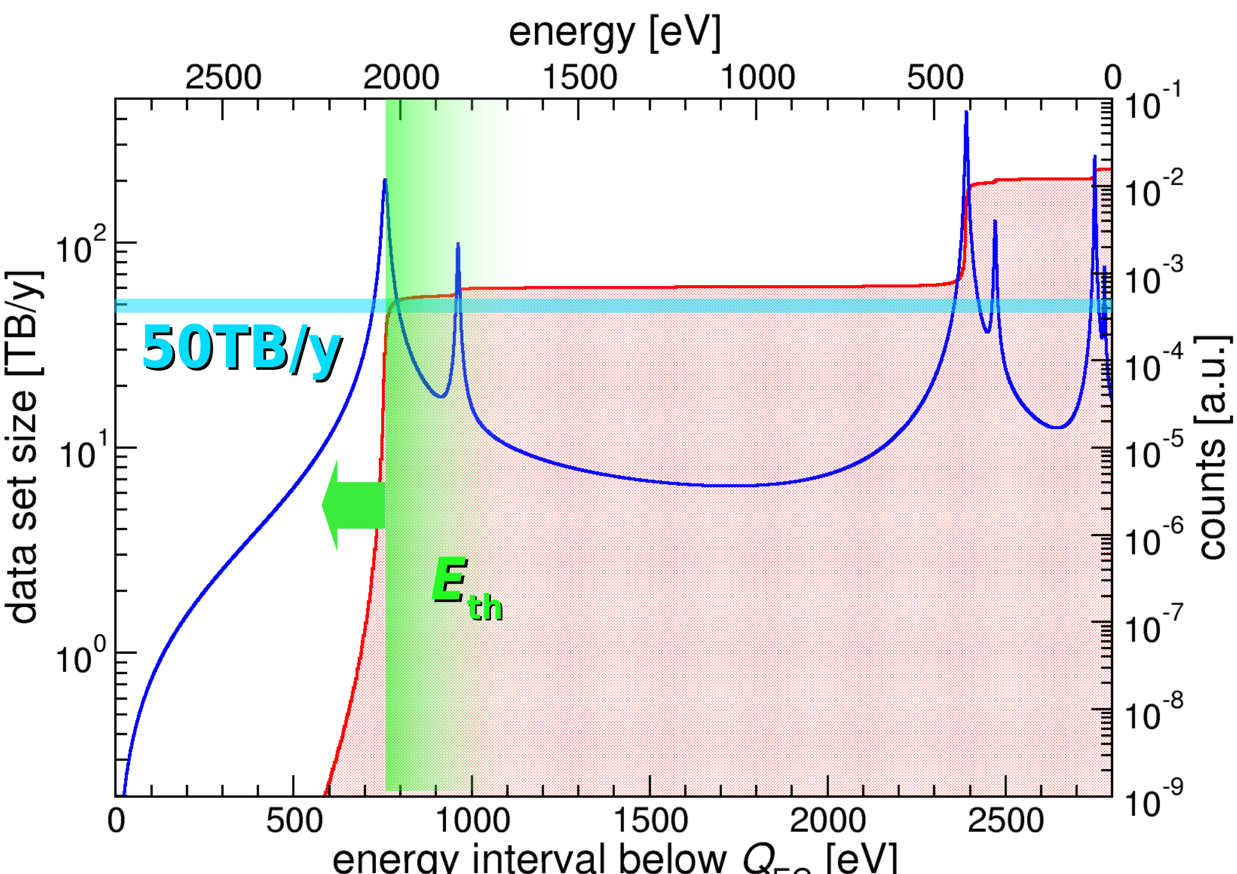
HOLMES signal processing and in-line analysis

* hypothetical configurations

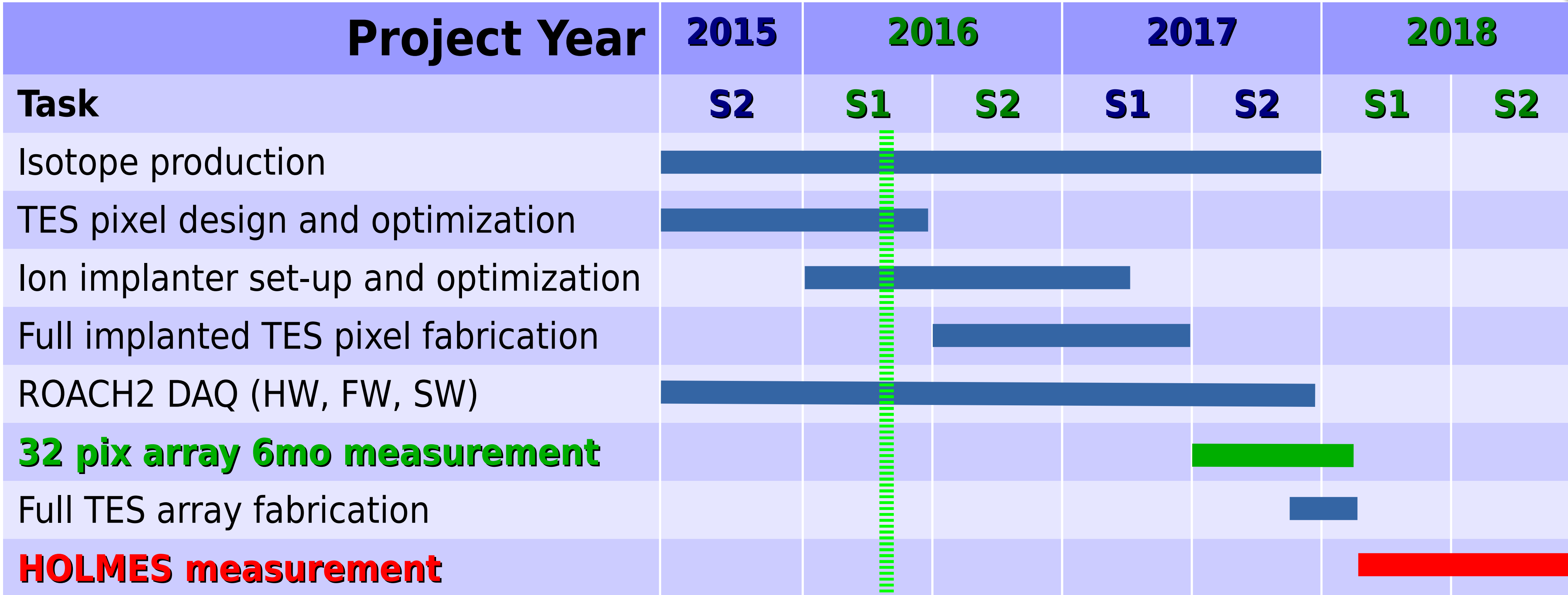
- **normal data taking (permanent RAID storage)**
  - save only *n*-tuples (6 × 4 byte words) *
  - high threshold (E_{th}≈2.022keV, E_{M1}=2.041keV, Q_{EC}=2.8keV, 21% of spectrum) *
  - **about 150TB in 3 years** (un-compressed)
- **periodic minimum bias samples (temporary storage)**
  - tune parameters 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 status**
  - 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

Backup slides

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