The HOLMES experiment

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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Outline

- absolute neutrino mass
- neutrino mass measurements
- low temperature detectors
- ^{163}Ho EC decay for direct neutrino mass measurements
- **HOLMES** experiment
  - sensitivity MC simulations
  - experiment design
  - task development status
- conclusions

Neutrino properties

- neutrinos are massive fermions
- there are 3 active neutrino **flavors: e, μ, τ**
- neutrino flavor states are mixtures of 3 **mass states**

neutrino mixing matrix

neutrino **mass** eigenstate

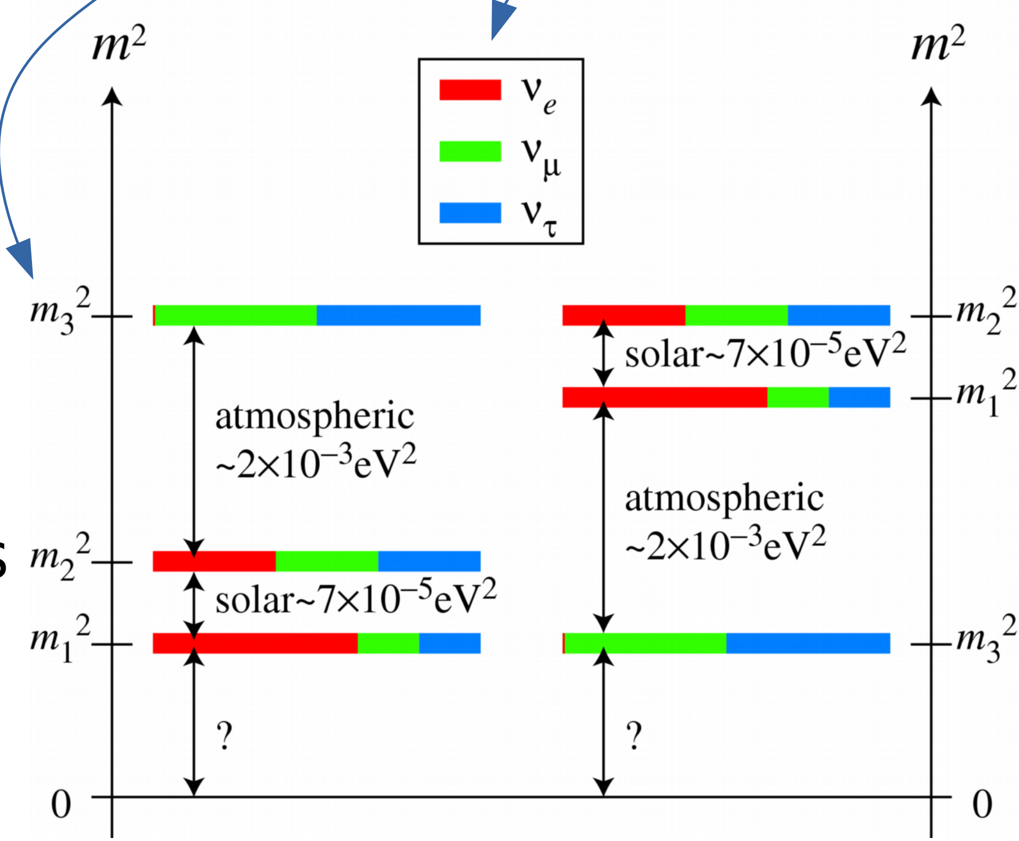
$$|\nu_l\rangle = \sum_k U_{lk} |\nu_k\rangle$$

neutrino **flavor** weak eigenstate

from neutrino oscillation experiments

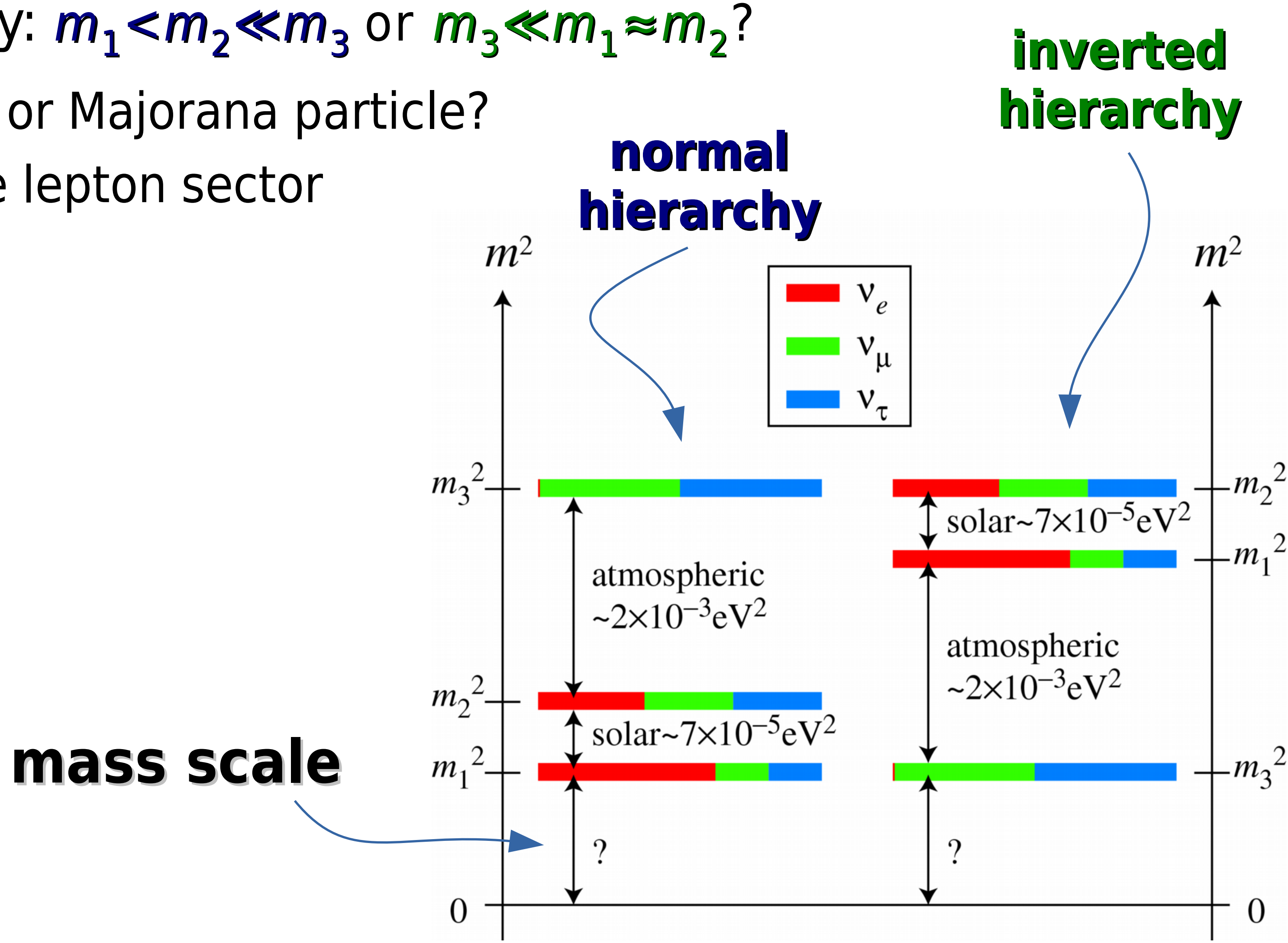
$$\Delta m_{ik}^2 = |m_i^2 - m_k^2|$$

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



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

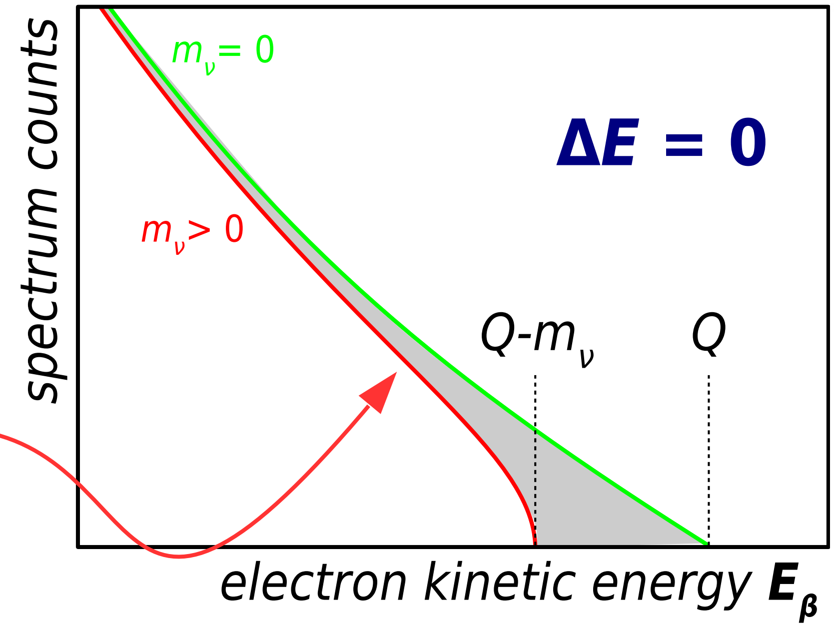


Direct neutrino mass measurements

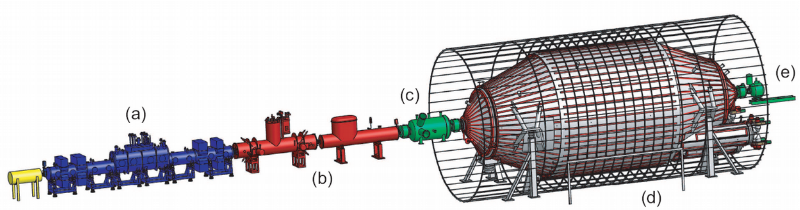
- **kinematics of weak decays with ν emission**
  - low *Q* nuclear beta decays (^{3}H, ^{187}Re...)
  - only energy and momentum conservation
  - no further assumptions

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$

$$N(E_\beta) \propto p_\beta E_\beta (Q-E_\beta)\sqrt{((Q-E_\beta)-m_\nu^2)}\,F(z,E_\beta)\,S(E_\beta)$$

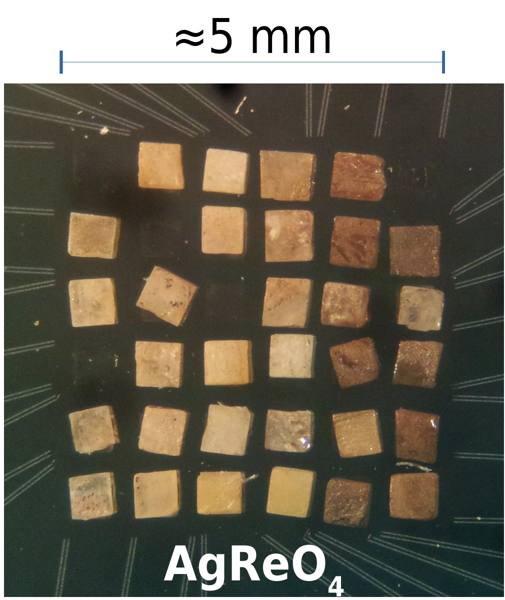


- **2 approaches with different systematics:**
  - **spectrometry** with the β source outside
  - **calorimetry** with the β source inside



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

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



Direct neutrino mass measurements / 2

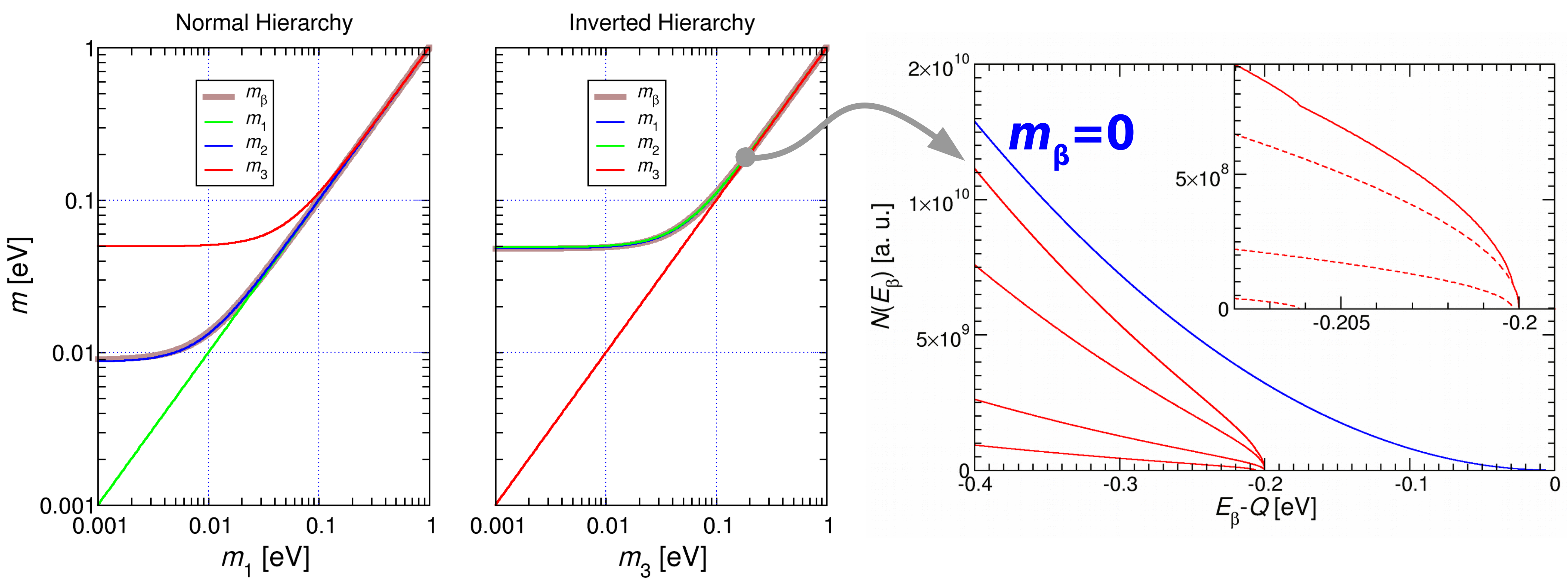
- **kinematics of weak decays**
  - observable in nuclear beta decays with $\bar{\nu}_e$ (ν_e) emission

$$|\nu_e\rangle = \sum_k U_{ek} |\nu_k\rangle$$

$$N(E) \propto p_\beta E_\beta (Q-E_\beta) \sum_k |U_{ek}|^2 \sqrt{(Q-E_\beta)^2 - m_{\nu_k}^2}\, F(Z,E_\beta) S(E_\beta)$$

$$m_\beta = \sqrt{\sum_k m_{\nu_k}^2 |U_{ek}|^2}$$

$$N(E) \approx p_\beta E_\beta (Q-E_\beta) \sqrt{(Q-E_\beta)^2 - m_\beta^2}\, F(Z,E_\beta) S(E_\beta)$$

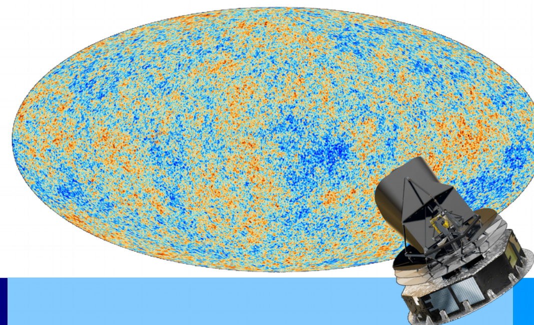


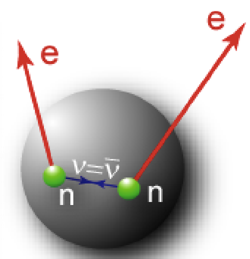
Mass scale: experimental tools / 1

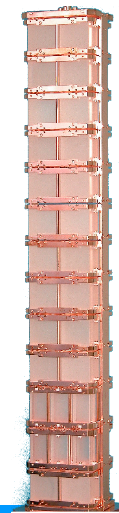
three complementary tools available

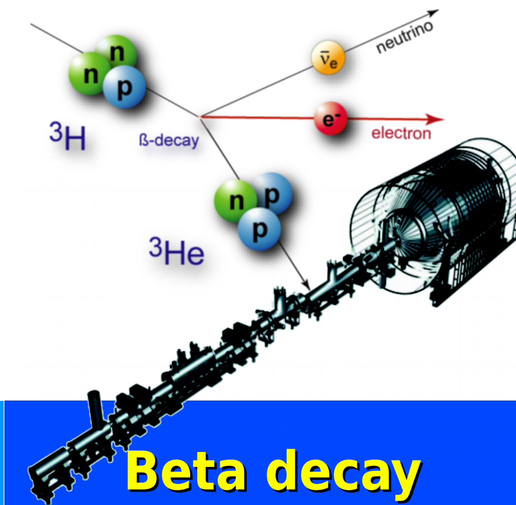
→ low temperature detectors play key role

(E. Fiorini and T. Niinikoski, Nucl. Instrum. and Meth. 224, p.83 (1984))







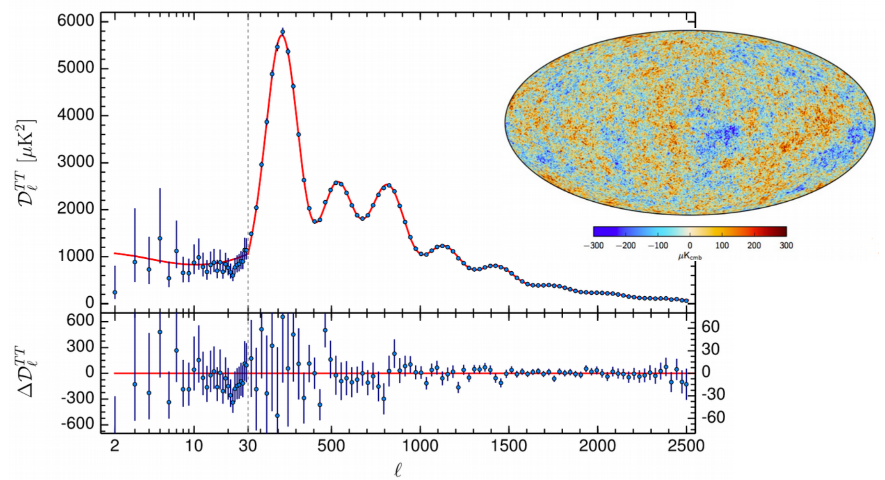


tool	Cosmology CMB+LSS+...	Neutrinoless Double Beta decay	Beta decay end-point
observable	$m_\Sigma=\Sigma_k m_{\nu_k}$	$m_{\beta\beta}=\lvert\Sigma_k m_{\nu_k} U_{ek}^2\rvert$	$m_\beta=(\Sigma_k m_{\nu_k}^2 \lvert U_{ek}\rvert^2)^{1/2}$
present sensitivity	≈0.1 eV	≈0.1 eV	2 eV
future sensitivity	**0.05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

Experimental status for neutrino mass / 1

Cosmological measurements:

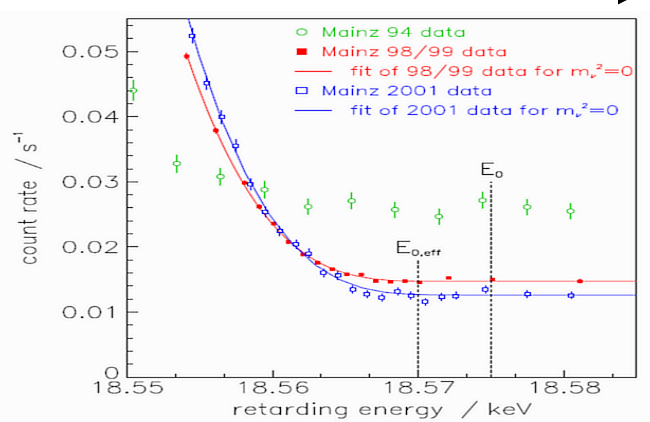
- Planck TT, TE, EE+lowP+BAO:
  m_Σ**<0.17 eV** (95%)
  P. A. R. Ade et al., A&A 594, A13 (2016)



Tritium beta decay end-point measurements:

- Troitsk + Mainz experiments: m_β**<2.2 eV** (95%)

Ch. Kraus et al., Eur. Phys. J. C 73, (2013) 2323;
V. N. Aseev, Phys. Rev. D 84, (2011) 112003.

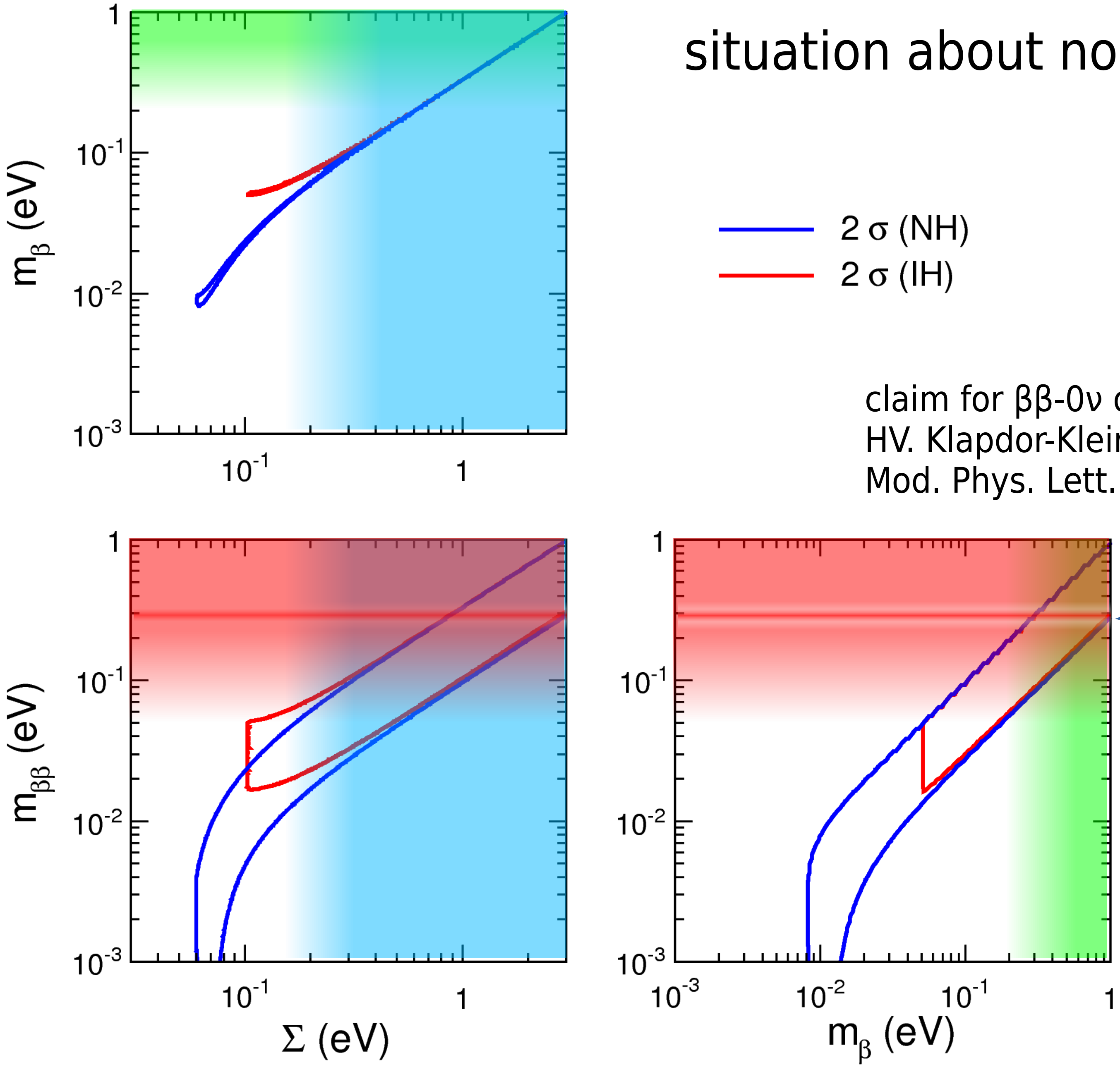


Neutrinoless double-beta decay searches:

- GERDA (^{76}Ge): $m_{\beta\beta}$**<0.15÷0.33 eV** (90%) Nature 544 (2017) 7648
- KamLAND-Zen (^{136}Xe): $m_{\beta\beta}$**<0.06÷0.16 eV** (90%) Phys. Rev. Lett. 117 (2016) 082503
- CUORE-0 (^{130}Te): $m_{\beta\beta}$**<0.27÷0.76 eV** (90%) Phys. Rev. Lett. 115 (2015) 102502

Direct ν mass measurements: the status

situation about now



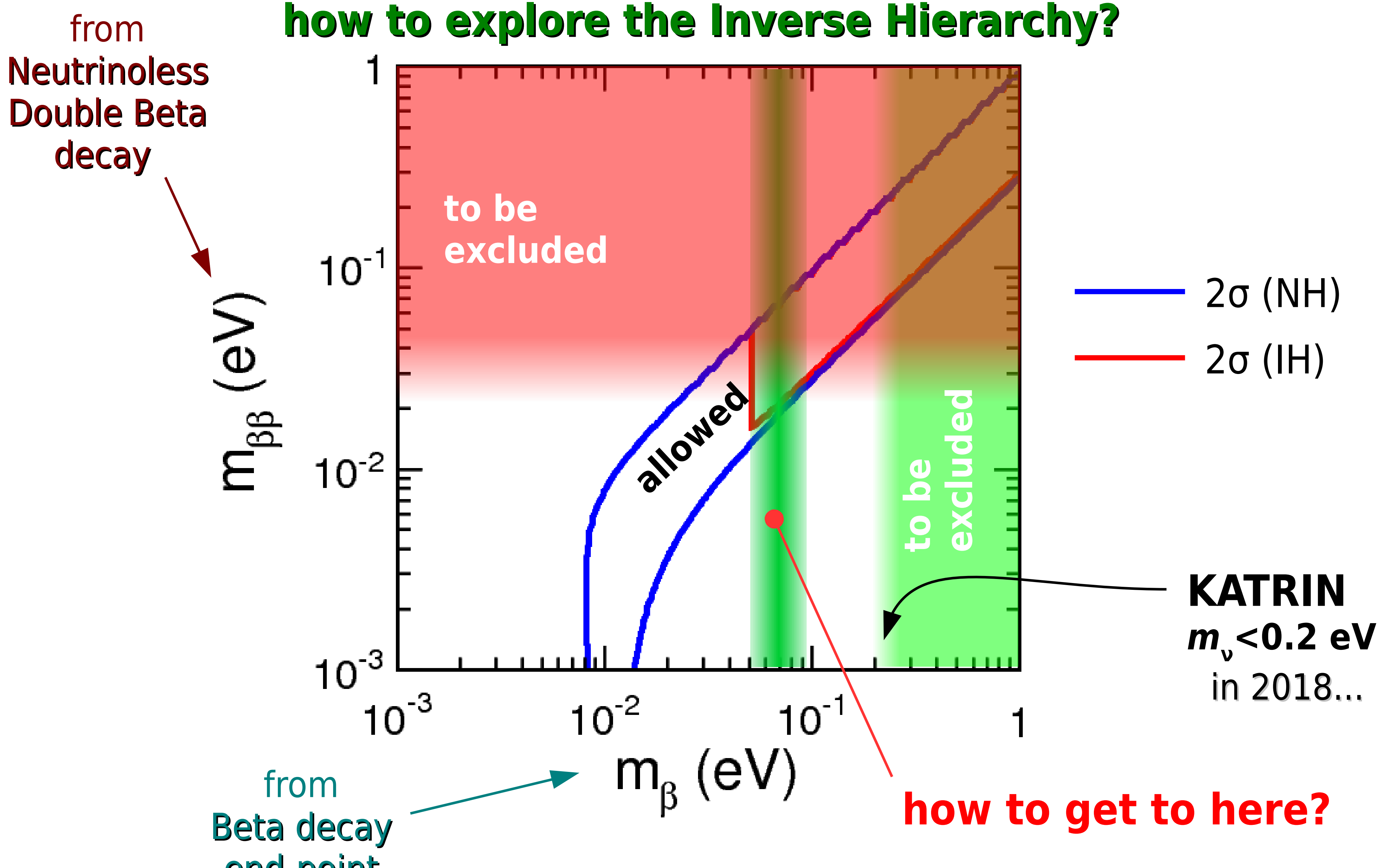
claim for ββ-0ν observation in ^{76}Ge
HV. Klapdor-Kleingrothaus et al.
Mod. Phys. Lett. A, 21 (2006) 1547

G.L.Fogli et al., Phys. Rev. D 86 (2012) 013012

Direct ν mass measurements: the challenge

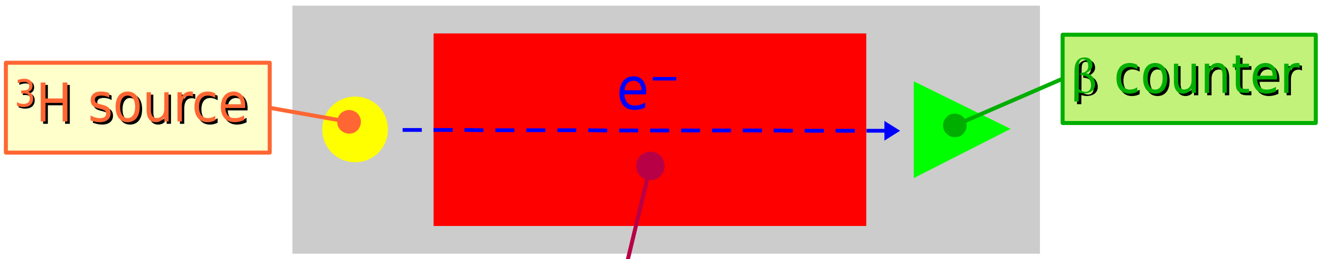
expected for the next few years

how to explore the Inverse Hierarchy?



Direct ν mass measurements: experimental

Spectrometers: source ≠ detector

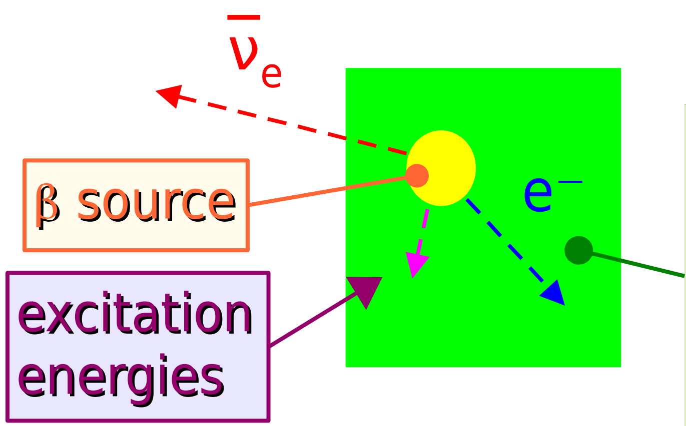


β differential or integral spectrometer

βs from the ^{3}H spectrum in 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

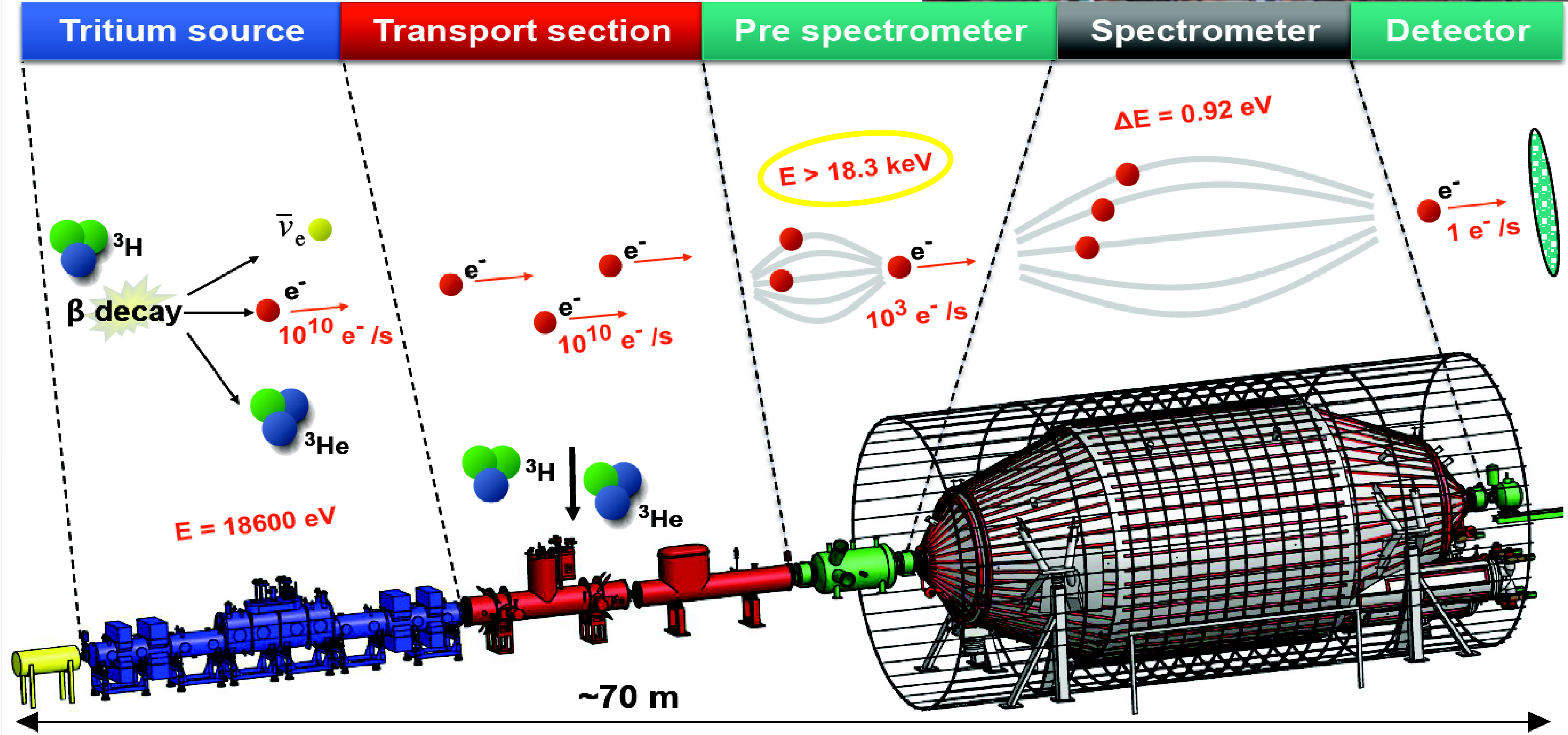
ideally measures all the energy E released in the decay except for the $\bar{\nu}_e$ energy: $\boldsymbol{E=Q-E_\nu}$

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

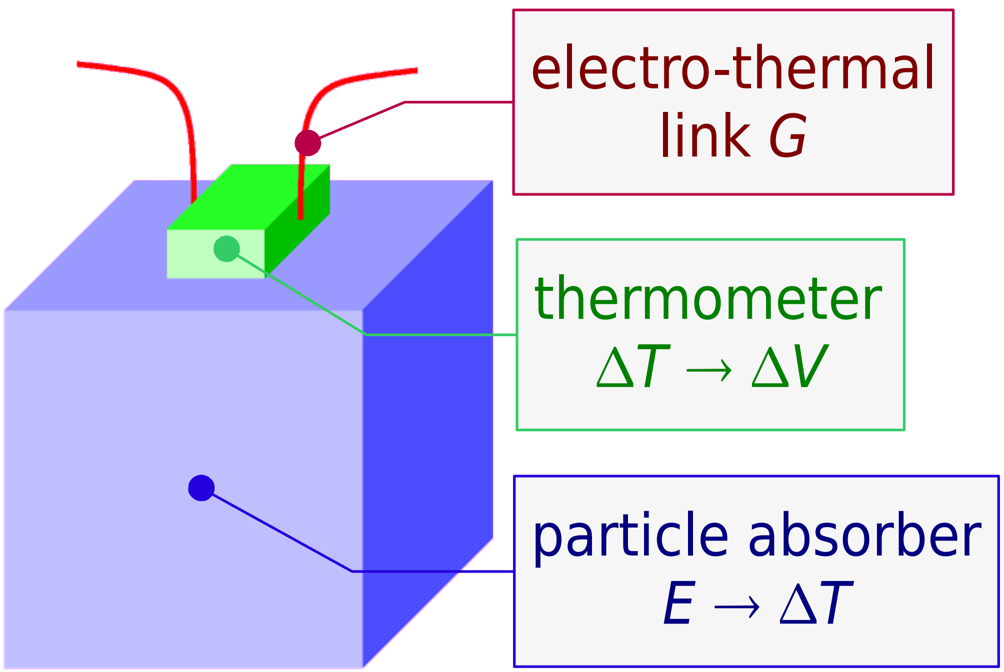
Spectrometers: KATRIN

largest electrostatic spectrometer with gaseous ^3H source (E_0=18.6keV)

- expected statistical sensitivity **$m_{\nu e}$ < 0.2 eV 90% CL**
- start data taking in **2017**

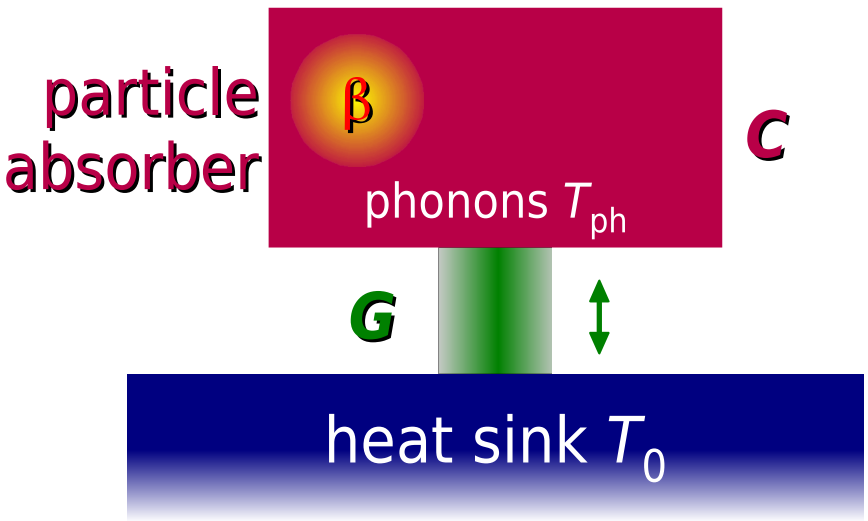


Low temperature detectors as calorimeters



- (quasi-)equilibrium thermal detector
- complete energy *thermalization*
  - **calorimetry**
- **$\Delta T = E/C$** (C thermal capacity)
  - low C
    - low T (i.e. $T \ll 1$K)
    - dielectrics, superconductors
- Pros and cons
  - ▲ high energy resolution
  - ▲ large choice of absorber materials
  - ▲ true calorimeters
  - ▼ only energy and time informations
  - ▼ slow time response

Low temperature detector principles



$$C(T_{ph})\frac{dT_{ph}}{dt}+G(T_{ph},T_0)=P(t)$$

$$P(t)=\Delta E\,\delta(t)\;\rightarrow\;T_{ph}(t)=T_0+\frac{\Delta E}{C}e^{-t/\tau}$$

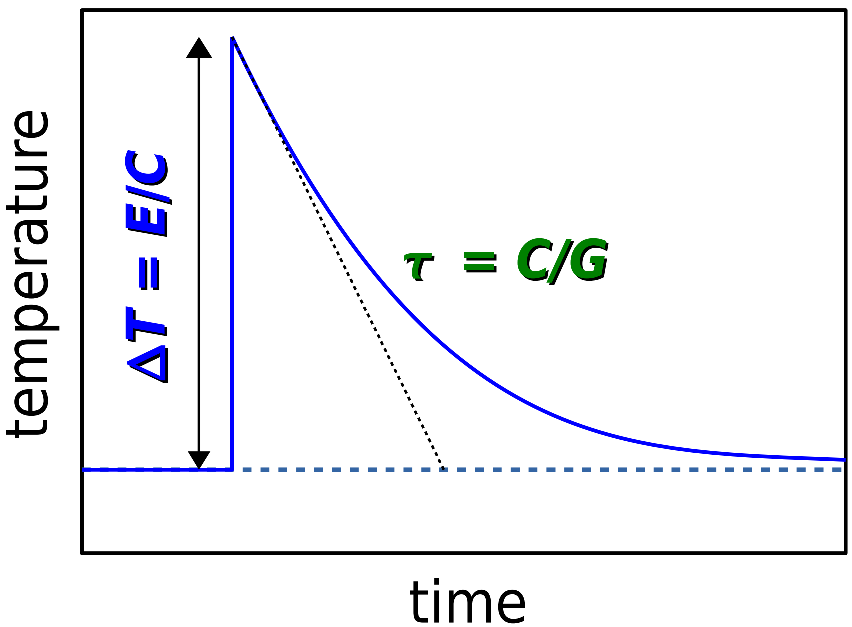
for $t>0$ and with $\tau = C/G$

- resolution limit: random energy flow through ***G***
- statistical fluctuations of internal energy ***U***

$$U=\langle U\rangle \pm \Delta U_{rms}$$

$$N_{ph}=\frac{\langle U\rangle}{\langle E_{ph}\rangle}=\frac{CT}{k_B T}$$

$$\Delta U_{rms}=\sqrt{N_{ph}}(k_B T)=\sqrt{k_B T^2 C}$$



1 mg of Re @ 100 mK

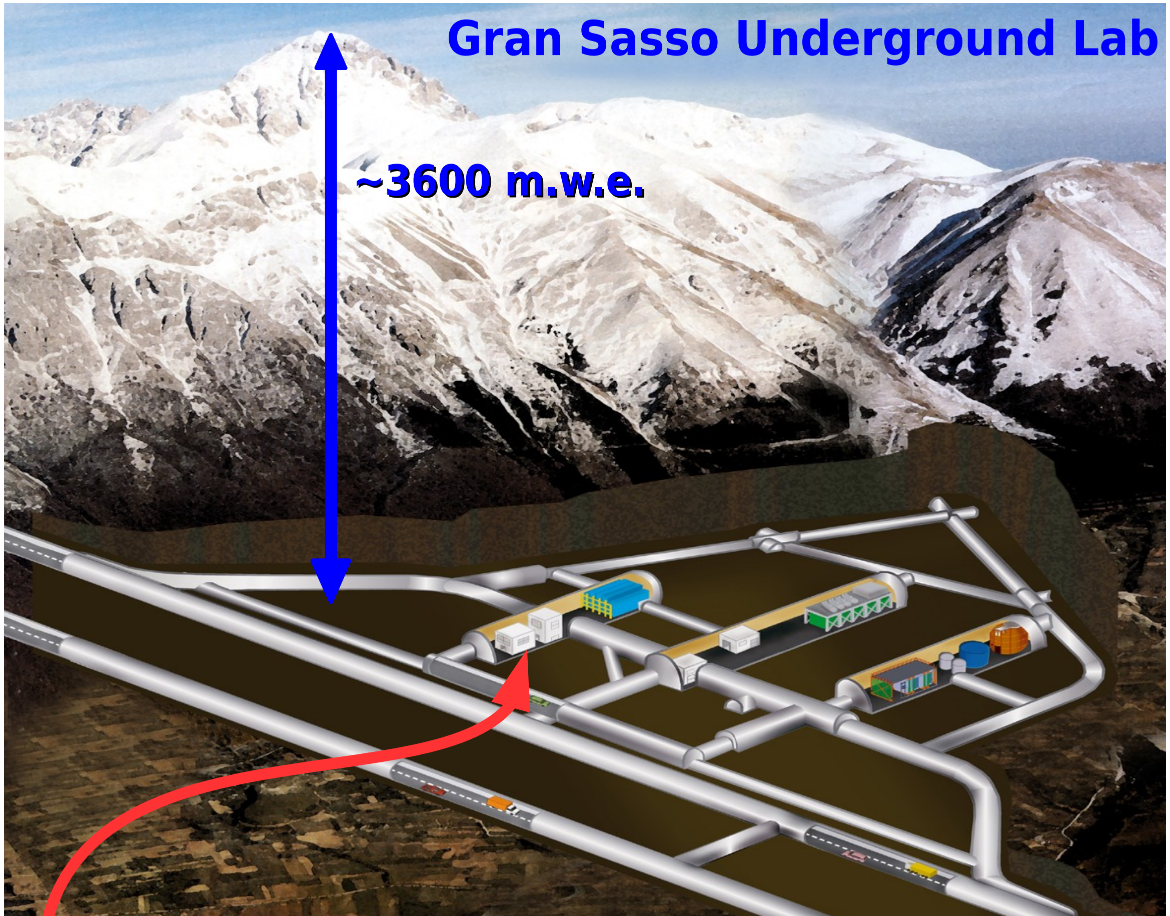
$C \sim T^3$ (Debye) ⇒ $C \sim 10^{-13}$ J/K

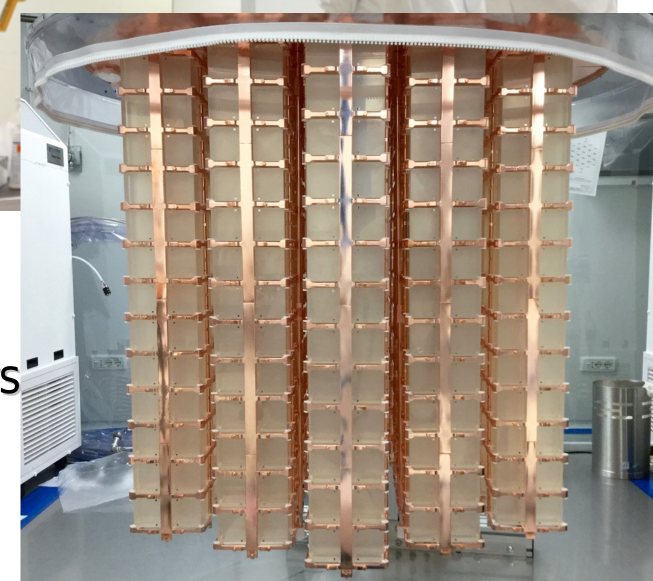
6 keV X-ray ⇒ **ΔT ~ 10 mK**

$G \sim 10^{-11}$ W/K ⇒ **$\tau = C/G$ ~ 10 ms**

ΔU_{rms} ~ 1 eV

CUORE experiment



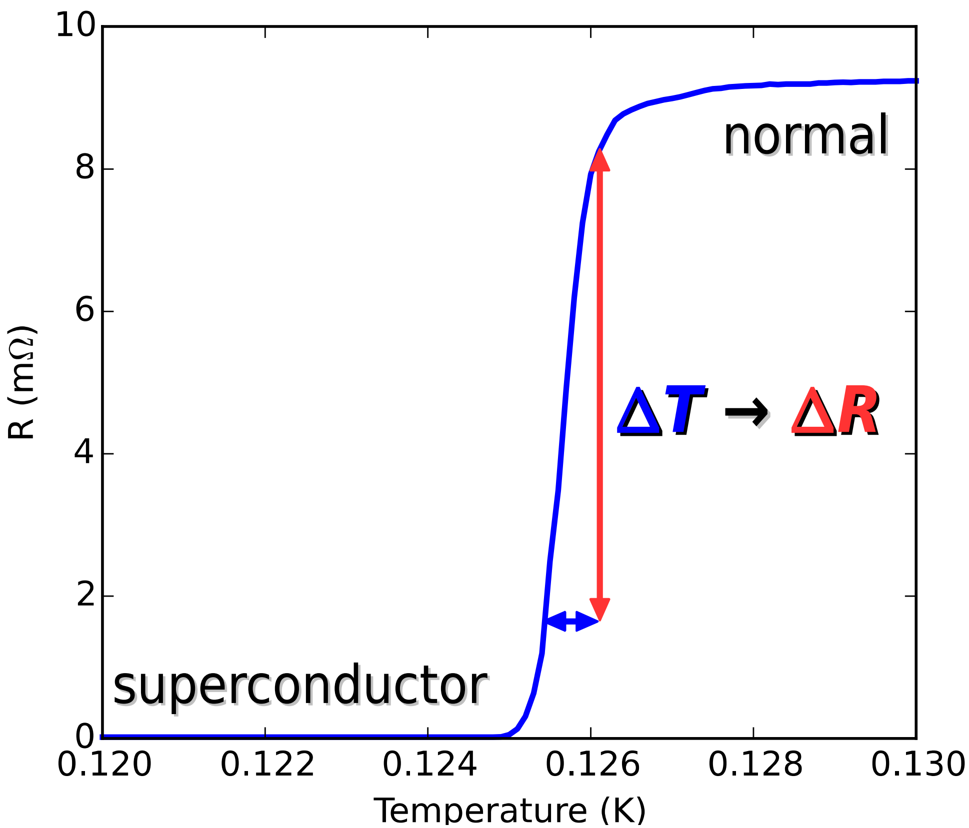


CUORE: Cryogenic Underground Observatory for Rare Events

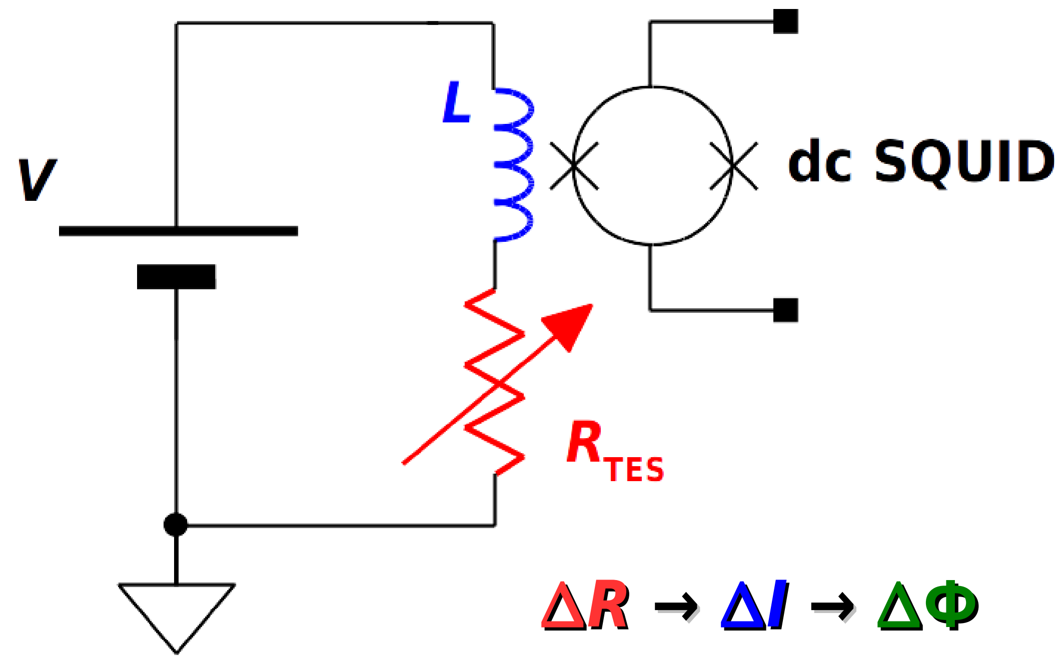
- searches for ^{130}**Te neutrinoless double-beta decay**
- 988 natural **TeO_2** 750 g crystals as low temperature detectors
- total mass **740 kg TeO_2** ⇒ 206 kg of ^{130}Te
- **now cold at about 10 mK**

Superconducting transition edge sensors (TES)

- superconductor thin films operated inside the phase transition at T_c
  - elemental superconductors: Ir (T_c= 112 mK), W (T_c= 15 mK), ...
  - metal-superconductor bilayers ⇒ tunable T_c (20÷200 mK) : Mo/Cu, Ti/Au, Ir/Au, ...
- high sensitivity $TdR/(RdT)\approx 100$) ⇒ high energy resolution
  - as **thermal sensors** → $\sigma_E^2 \approx \xi^2 k_B T^2 C$
- strong electron-phonon coupling ⇒ high intrinsic speed
- low impedance ⇒ SQUID read-out ⇒ multiplexing for large arrays



TES read-out: costant voltage bias



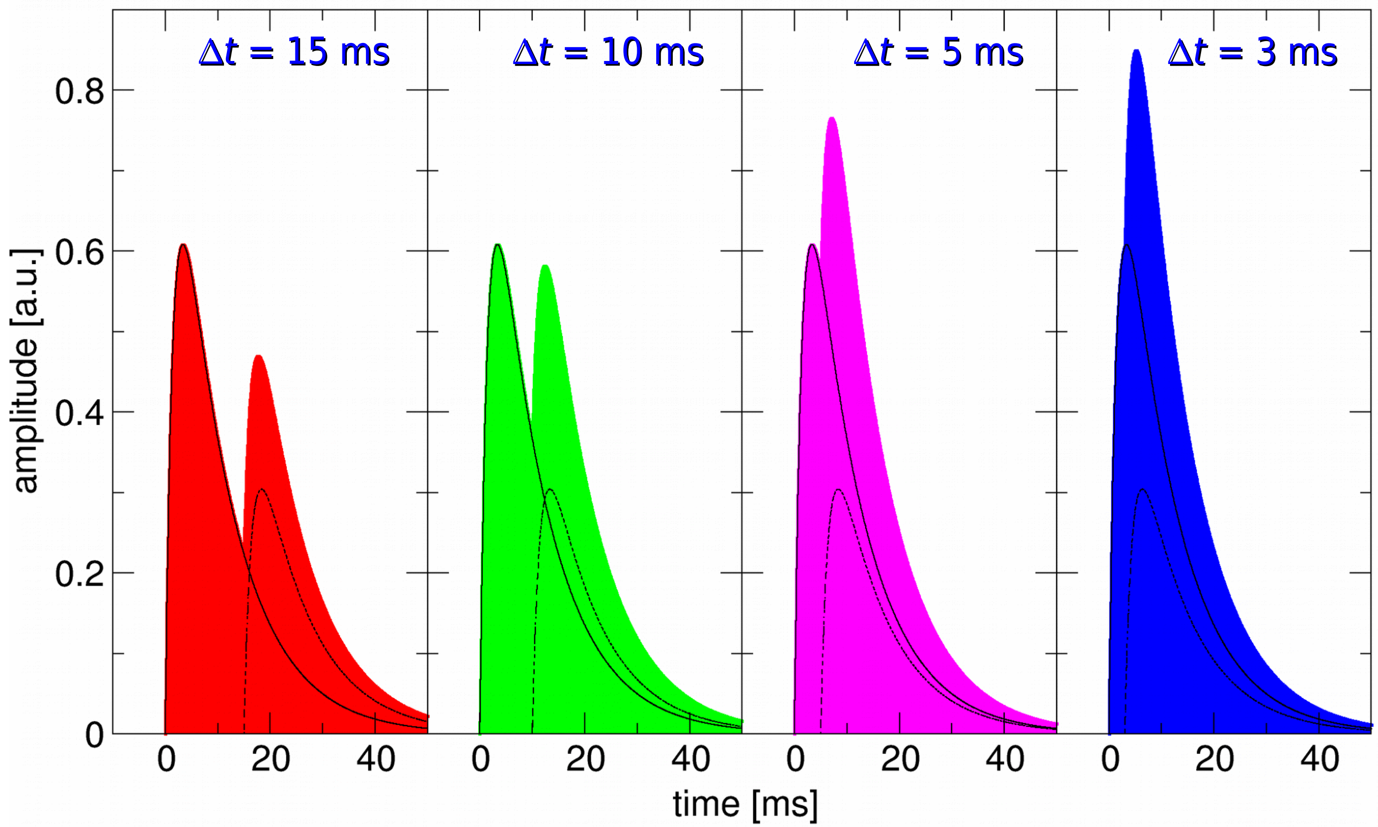
Rise time pile-up

simple pulse model

$$A(t)=A\left(e^{-t/\tau_{decay}}-e^{-t/\tau_{rise}}\right)$$

2 pulses with:

- τ_{rise}= 1.5 ms
- τ_{decay}= 10 ms
- A_2/A_1 = 0.5



resolving time τ_R ≈ pulse rise time τ_{rise}

Calorimetry of beta sources

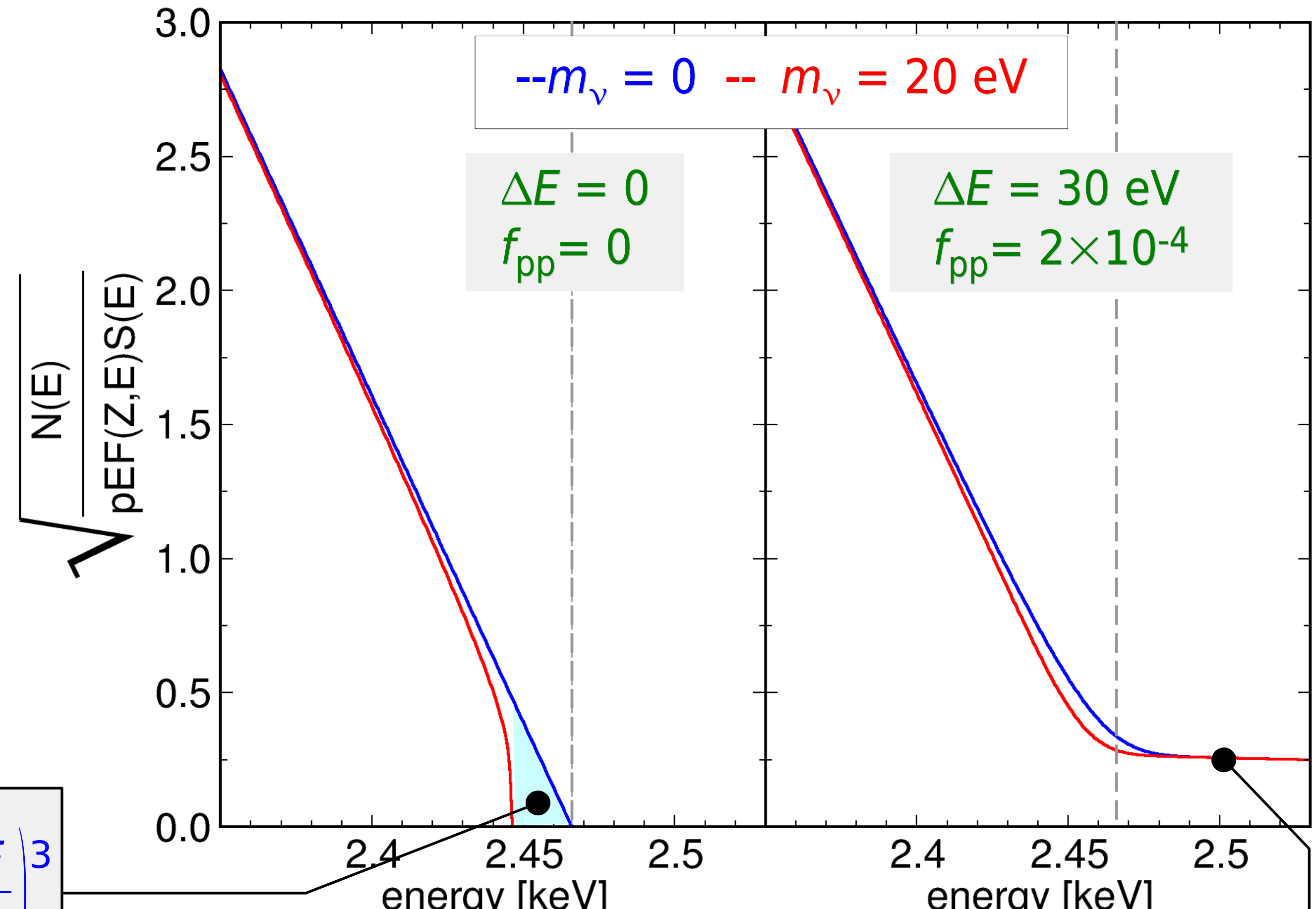
- calorimeters measure the **entire spectrum** at once
  - low E_0 β decaying isotopes for more statistics near the end-point
  - best choice ^{187}Re: Q = 2.5 keV, $\tau_{½} \approx 4\times10^{10}$ y ⇒ $F(\Delta E=10\text{ eV}) \approx (\Delta E/Q)^3 = 7\times10^{-8}$
  - other option ^{163}Ho electron capture: $Q \approx 2.6$ keV, $\tau_{½} \approx 4600$ y

advantages

- ▲ no back-scattering
- ▲ no energy losses in the source
- ▲ no atomic/molecular final state effects
- ▲ no solid state excitation

drawbacks

- ▼ limited statistics
- ▼ pile-up background
- ▼ spectrum related systematics



$$F(\Delta E) \approx \left(\frac{\Delta E}{Q}\right)^3$$

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

β decay calorimetry statistical sensitivity

resolving time τ_R analysis interval ΔE

source activity A_β number of detectors N_{det}

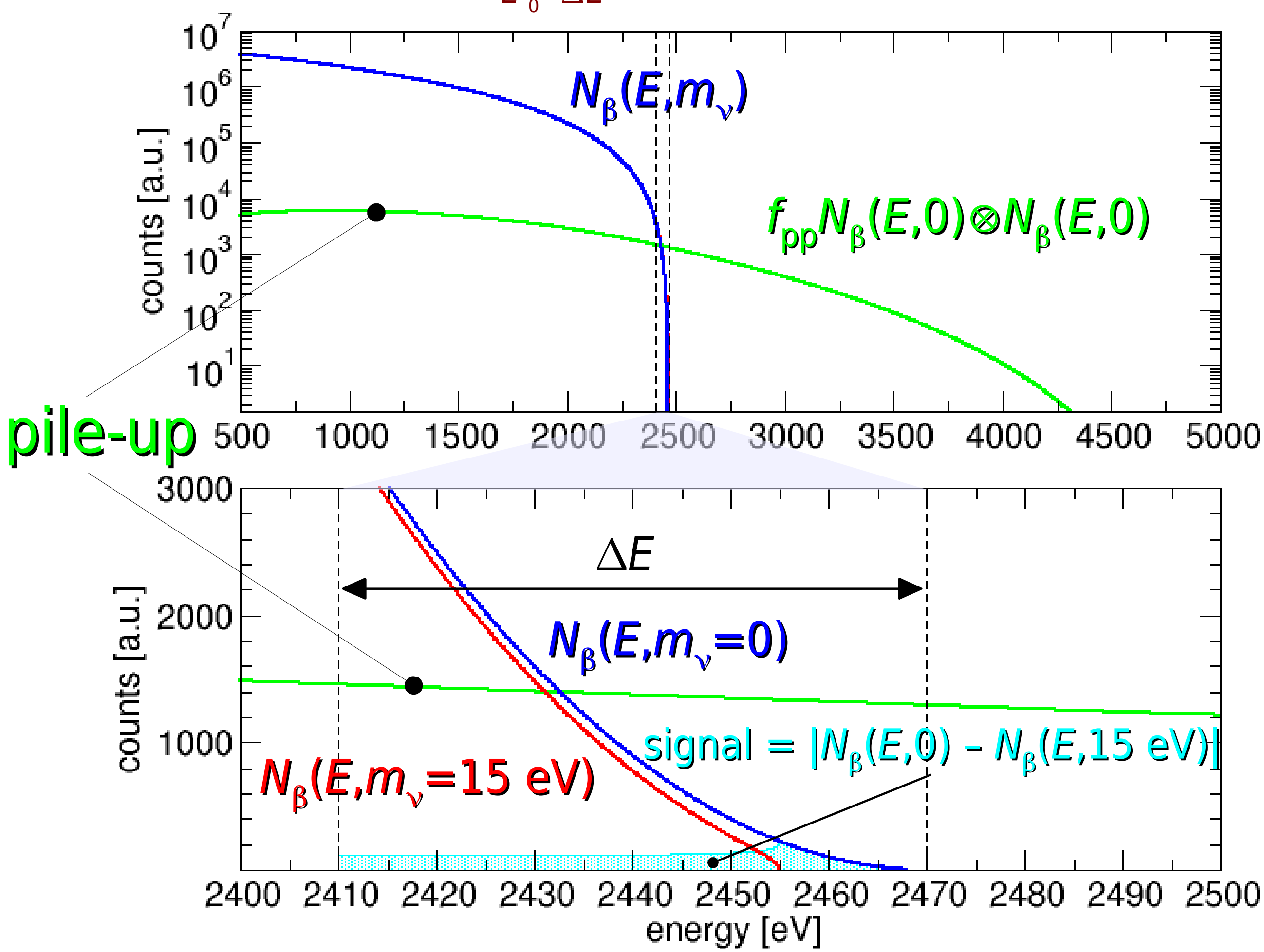
pile-up fraction $f_{pp}=\tau_R A_\beta$

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

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

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

→ ^{187}Re Q=2.5keV



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

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

experimental challenges

- energy resolution ΔE
- time resolution τ_R
- exposure $t_M = N_{det} \times T$
- detector activity A_β

A.Nucciotti et al., Astropart. Phys. 24 (2010) 80

Thermal detectors for calorimetric experiments

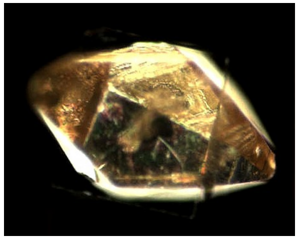
^{187}Re β decay

$$^{187}_{75}Re \rightarrow ^{187}_{76}Os + e^- + \bar{\nu}_e$$

- $5/2^+ \rightarrow 1/2^-$ unique first forbidden transition ⇒ $S(E)$
- end point Q = 2.47 keV
- half-life time $\tau_{1/2}$ = 43.2 Gy
- natural abundance a.i. = 63%
  - 1 mg metallic Rhenium ⇒ ≈1.0 decay/s

- **metallic rhenium** single crystals
  - superconductor with T_c=1.6K
  - NTD thermistors
  - **MANU experiment (Genova)**

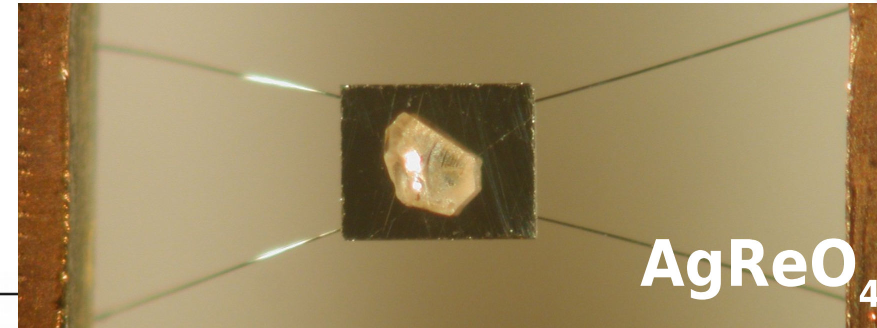
- **dielectric rhenium compound** ($AgReO_4$) crystals
  - Silicon implanted thermistors
  - **MIBETA experiment (Milano)**

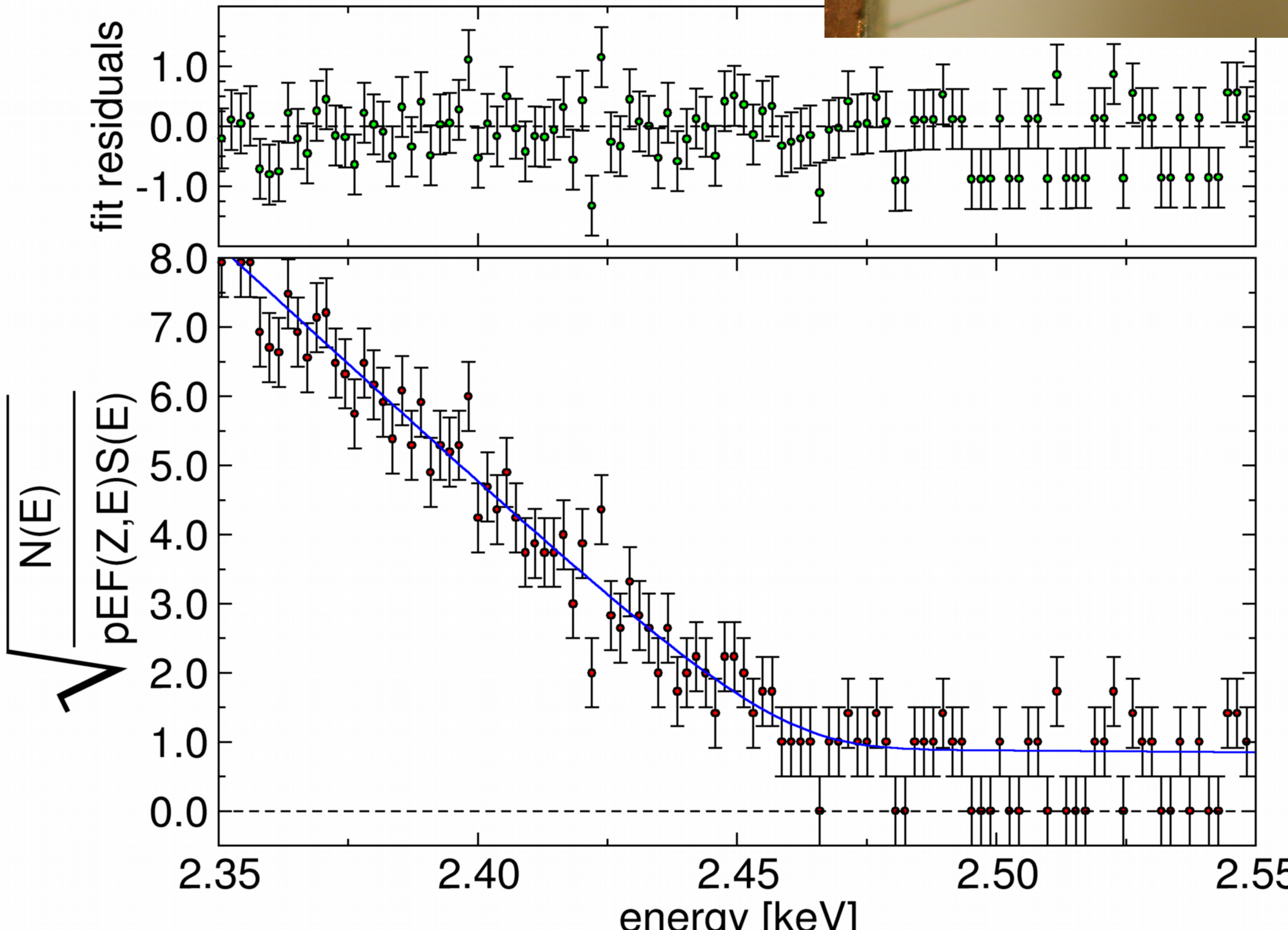


→ $m_\nu < \approx$15 eV

MIBETA experiment results

- 0.6 years live time (0.45 years only β)
- 6.2×10^{6} ^{187}Re decays above 700 eV
- $m_\nu^2 = -96 \pm 189_{stat} \pm 63_{sys}$ eV^2
  - ▸ **$m_\nu < 15.2 \pm 2.0_{sys}$ eV (90 % C.L.)**





M.Sisti et al., NIM A 520 (2004) 125

Electron capture calorimetric experiments

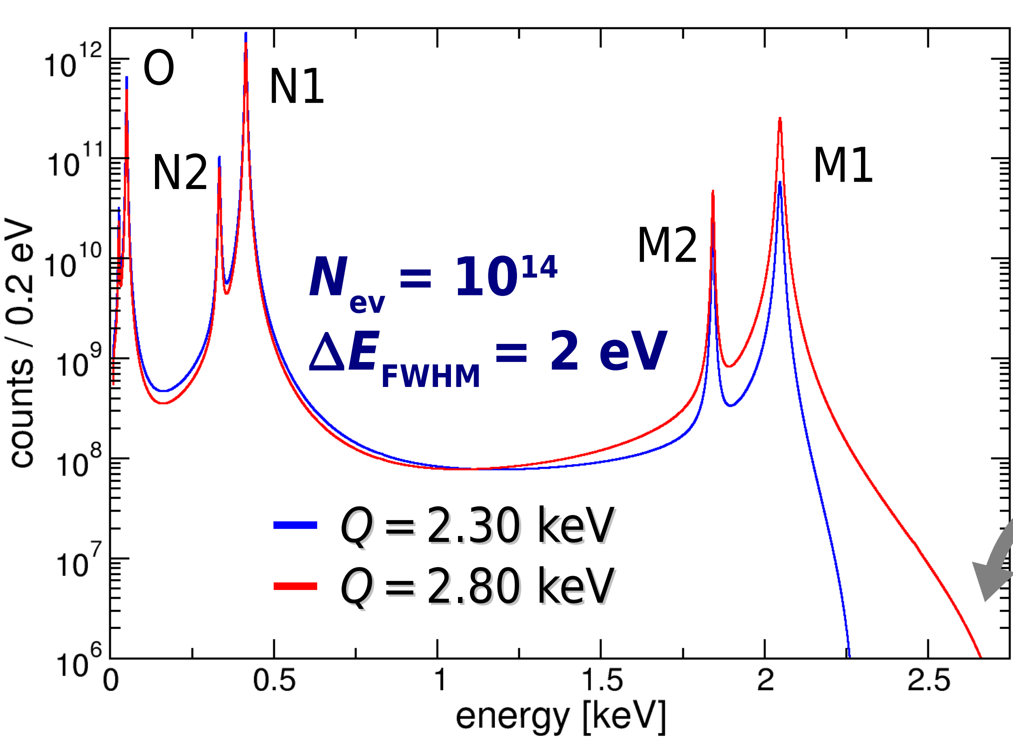
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

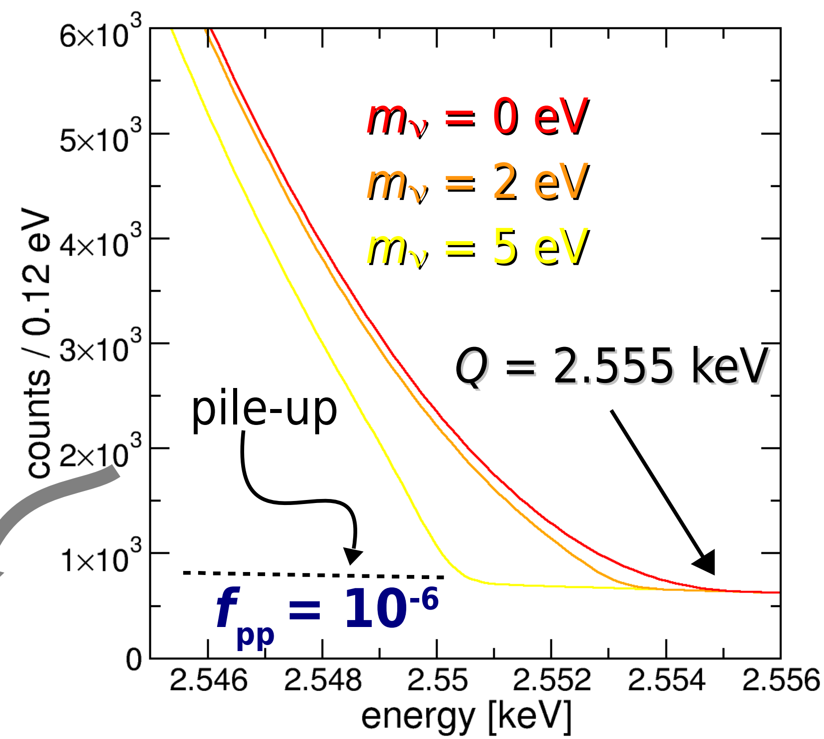
electron capture from shell ≥ M1

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** (recently measured with Penning trap)
  - end-point rate and ν mass sensitivity depend on $\boldsymbol{Q - E_{M1}}$
- $\boldsymbol{\tau_{1/2}} \approx$ **4570 years** → few active nuclei are needed (2×10^{11} ^{163}Ho nuclei ↔ 1Bq)

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





From ^{187}Re to ^{163}Ho calorimetric experiments

- **scaling up ^{187}Re experiments for sub-eV sensitivity**

  → **MARE** (**M**icrocalorimeter **A**rray for a **R**henium **E**xperiment)

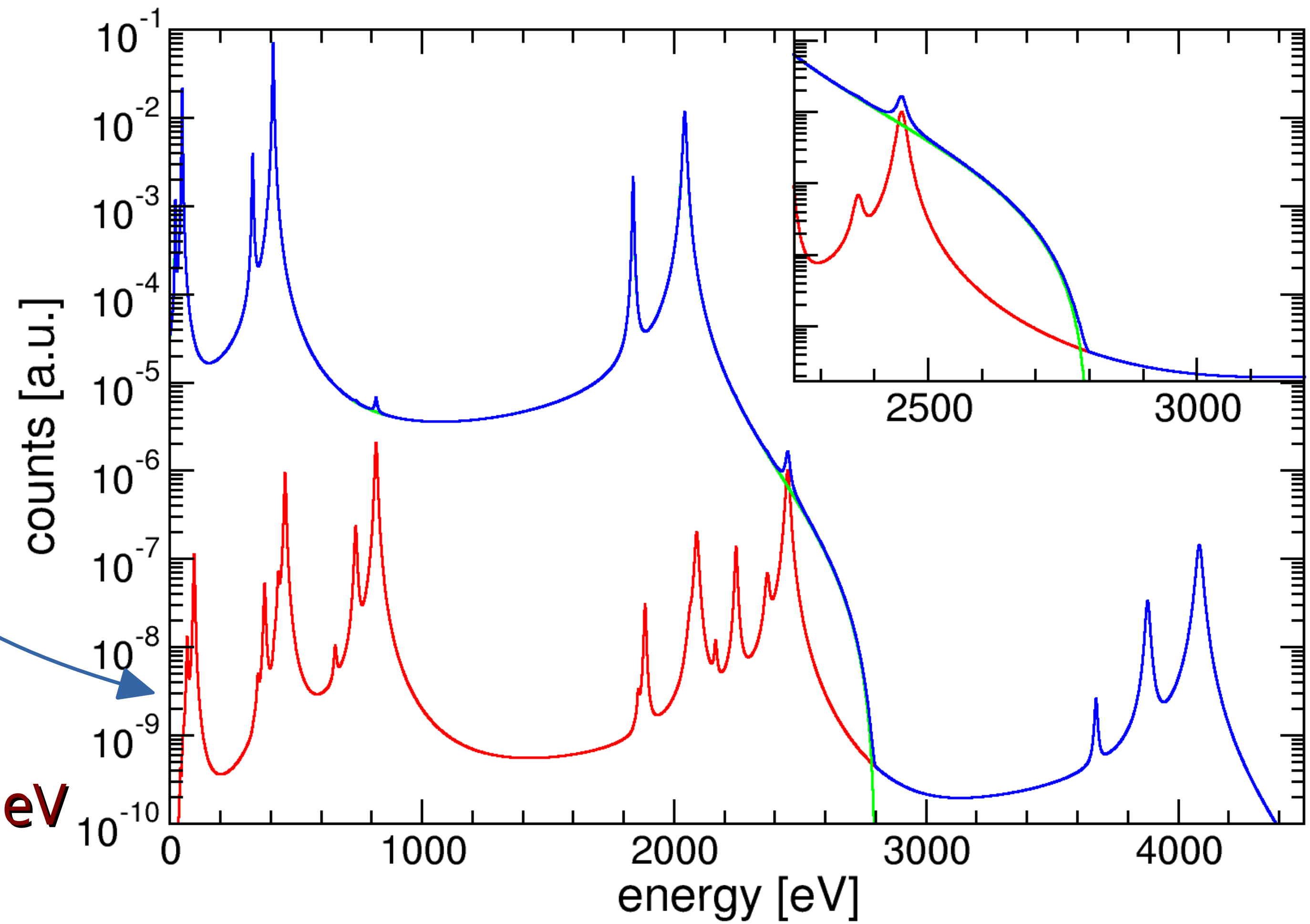
  - no clear understanding Re absorber physics in spite of 20 years of R&D
  - low ^{187}Re specific activity → “large” masses → fabrication issues
  - possible large systematics → Beta Environmental Fine Structure (BEFS)
- **^{163}Ho seems to be better than ^{187}Re**
  - higher specific activity → *Holmium detector* not needed
  - *self calibrating* → better control of systematics
  - but
    - higher Q → maybe less sensitive
    - pile-up spectrum
    - chemical effects on Q
- **two active projects** presently
  - **ECHo** (Heidelberg)
  - **MARE** (→ now **HOLMES**)
  - Los Alamos National Lab., Standford University ?, ...

A. Nucciotti, Adv. High Energy Physics, 2016, 915304

Electron capture end-point experiment

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

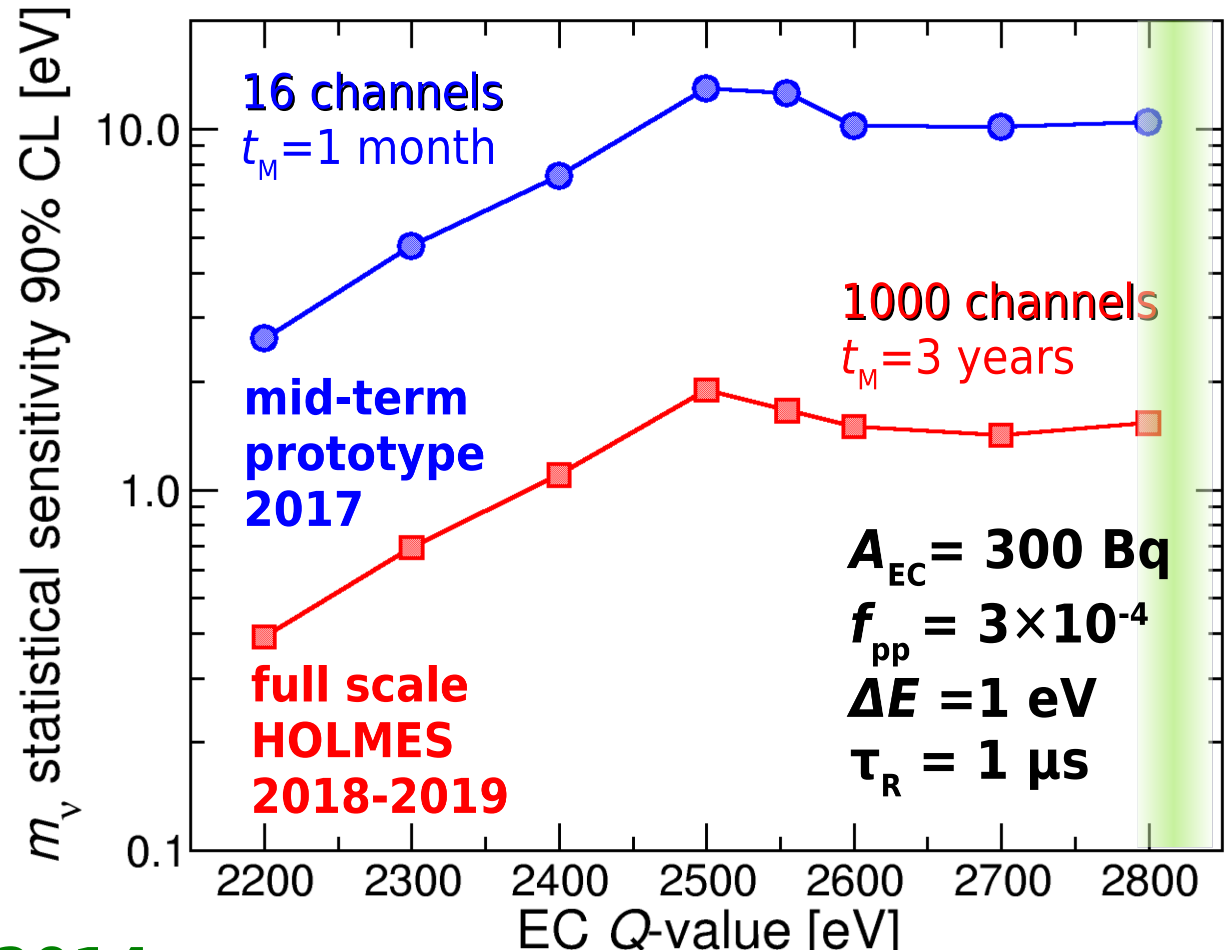
goal

- 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 microcalorimeters** with **implanted ^{163}Ho**
  - 6.5×10^{13} nuclei per pixel
    A_{EC} **= 300 dec/sec**
  - $\Delta E\approx1$**eV** and $\tau_R\approx1\mu s$
- **1000 channel** array
  - 6.5×10^{16} ^{163}Ho nuclei
    → ≈18μg
  - 3×10^{13} events in **3 years**

→ started on February 1st 2014



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

HOLMES collaboration

Univ. Milano-Bicocca INFN Milano-Bicocca	INFN Genova	NIST	PSI
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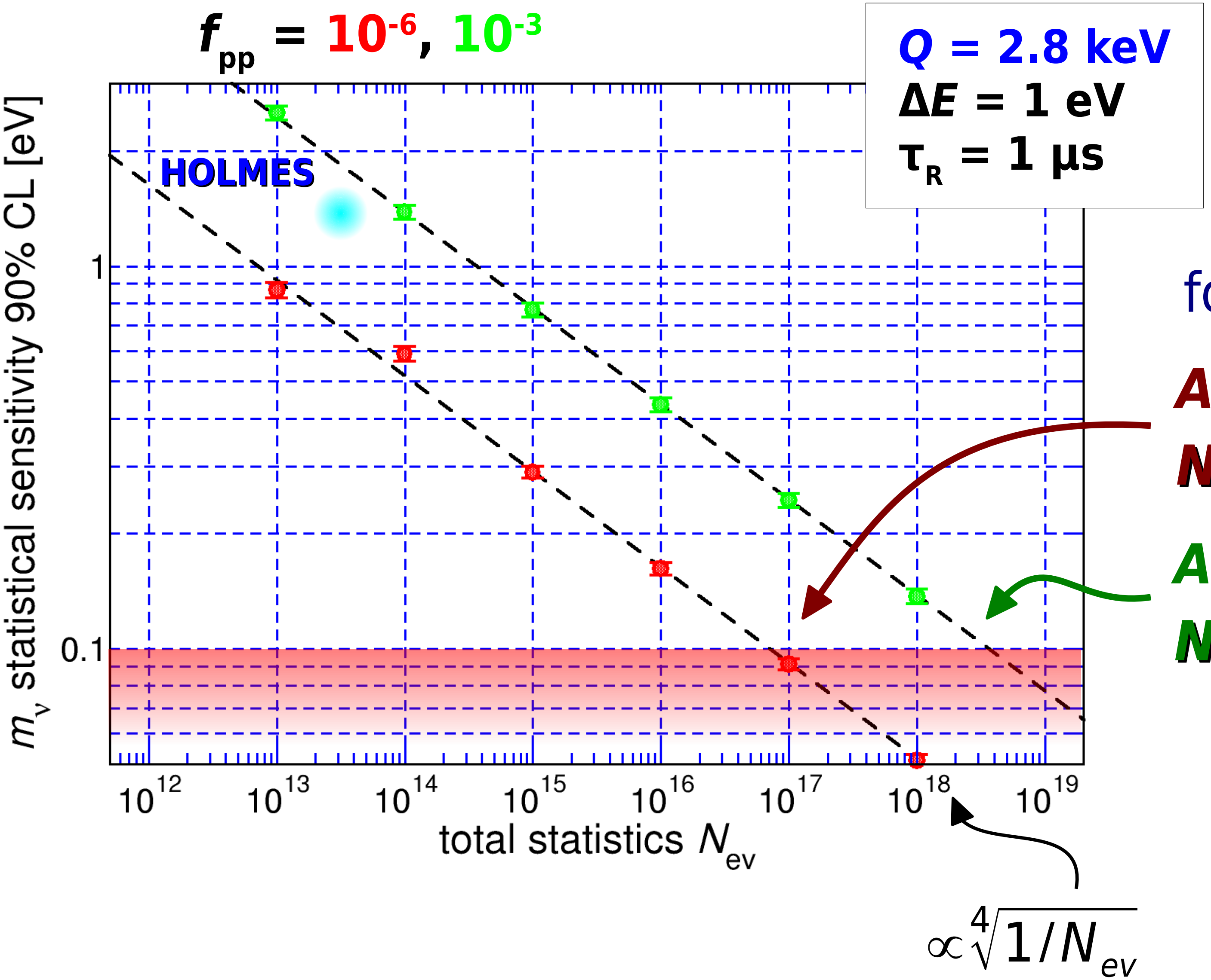
E.Ferri	G.Gallucci	D.Bennett	D.Schumann
A.Giachero	M.De Gerone	J.Fowler	
A.Nucciotti	F.Gatti	J.Gard	**CENTRA-IST**
A.Orlando	L.Parodi	J.Hays-Wehle	M.Ribeiro-Gomes
G.Pessina	F.Siccardi	G.Hilton	
A.Puiu		J.Mates	**ILL**
S.Ragazzi	**INFN Roma**	C.Reintsema	U.Koester
	M.Lusignoli	D.Schmidt	
		D.Swetz	
	INFN LNGS	J.Ullom	
	S.Nisi	L.Vale	

Potential sensitivity: Montecarlo simulations



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

A_{EC} = 1 Bq

$N_{det} t_M \approx 2\times10^9$ det×y

A_{EC} = 1000 Bq

$N_{det} t_M \approx 10^8$ det×y

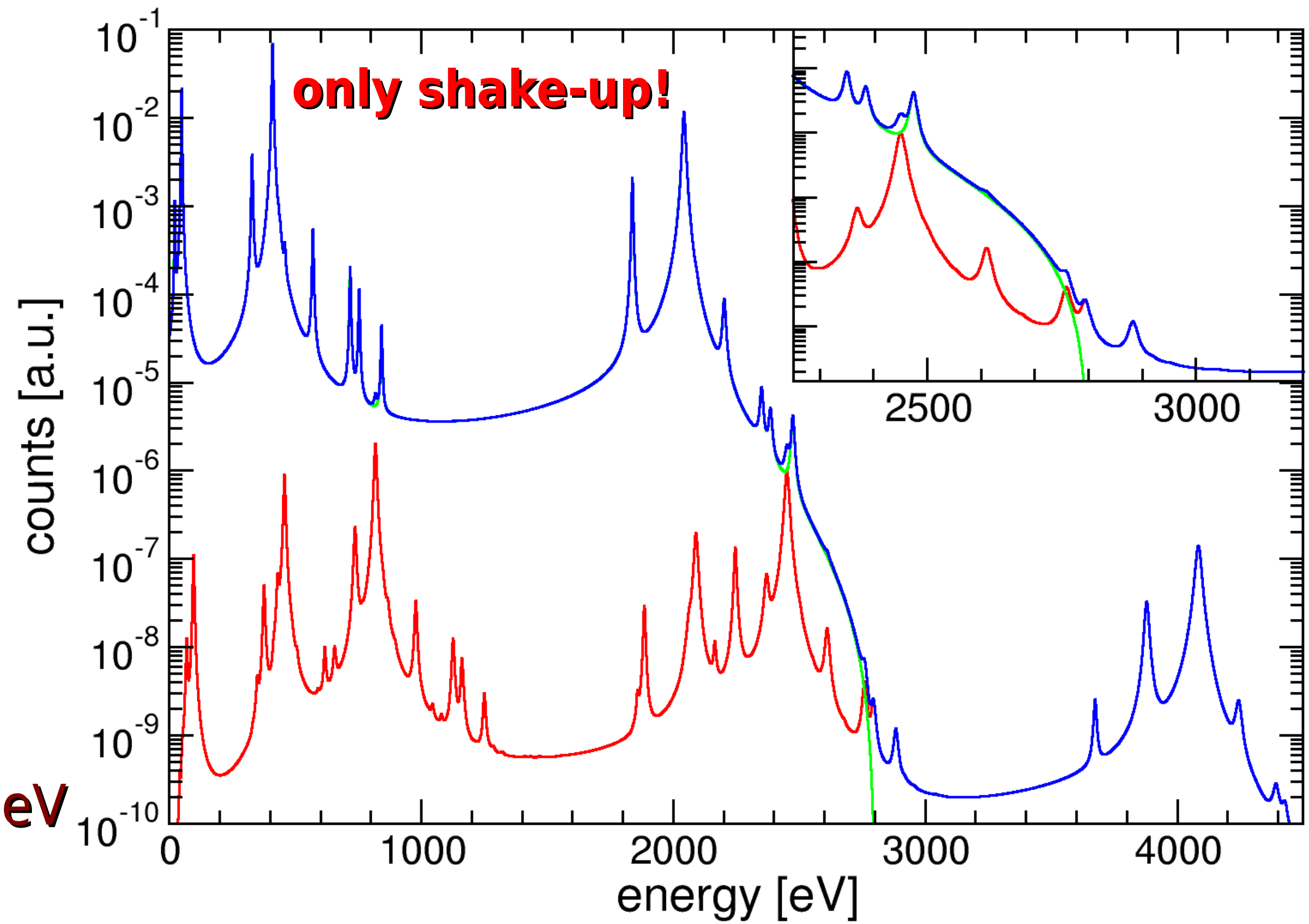
A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

More on EC end-point experiments / 1

- **shake-up/shake-off** → double hole excitations
  - *n*-hole excitations possible but less probable
  - authors do not fully agree on energies and probabilities

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

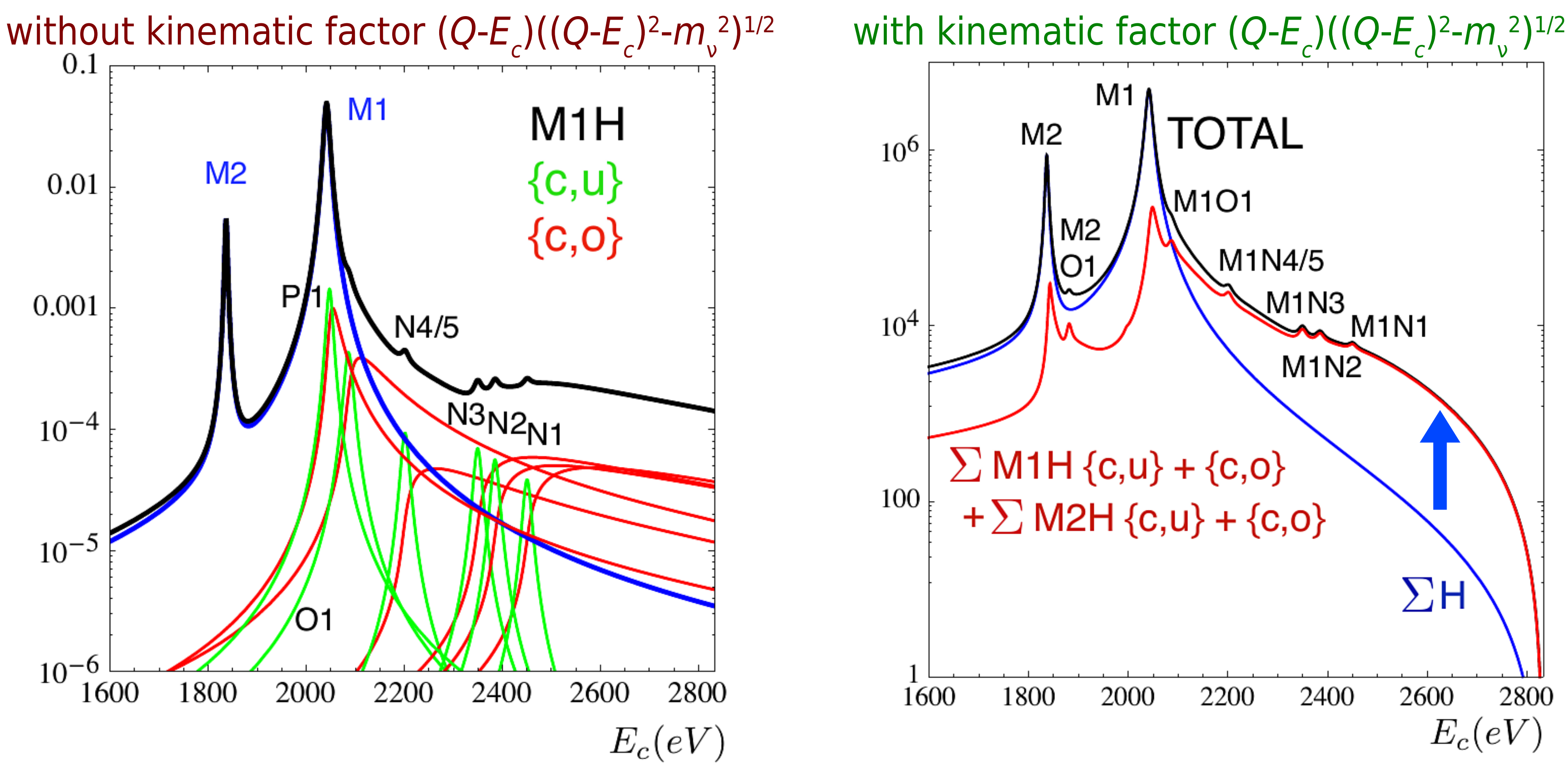
- even more complex pile-up spectrum
  - it may be worth keeping f_{pp} smaller than 10^{-4}



$Q = 2800$ eV

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

More on EC end-point experiments / 2



A.De Rújula & M. Lusignoli, J. High Energ. Phys. (2016) 2016: 15

- including **2-hole shake-off processes**

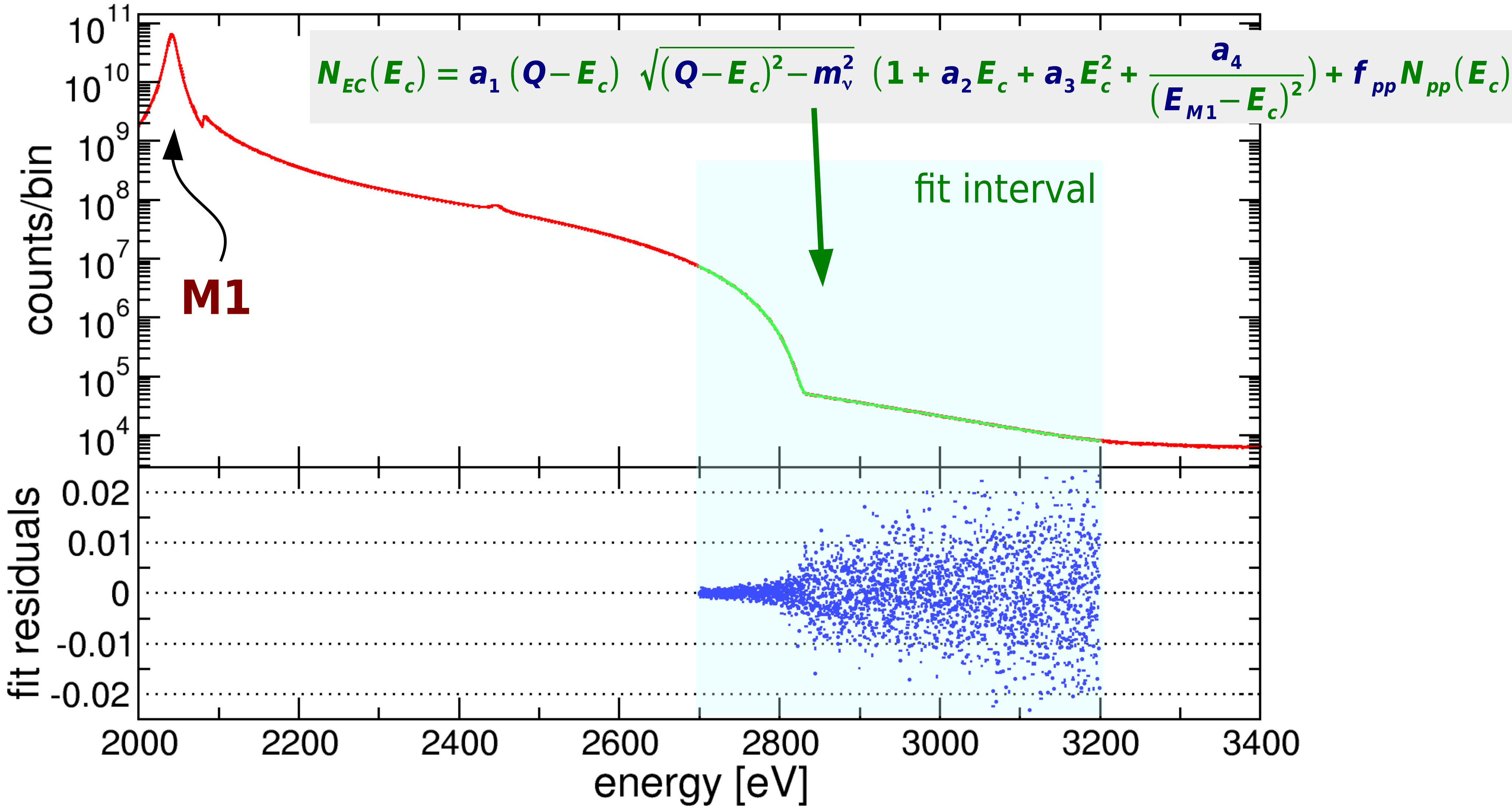
$$^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}^{H1\ H2} + e^- + \nu_e$$

- dominate rate at end-point
  - **optimistic**: factor **~40** increase
  - no analytic description of spectral shape at end-point
- make pile-up less important

Statistical sensitivity: shake-off processes

HOLMES simulation with the *optimistic* spectrum from A.De Rújula & M. Lusignoli

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



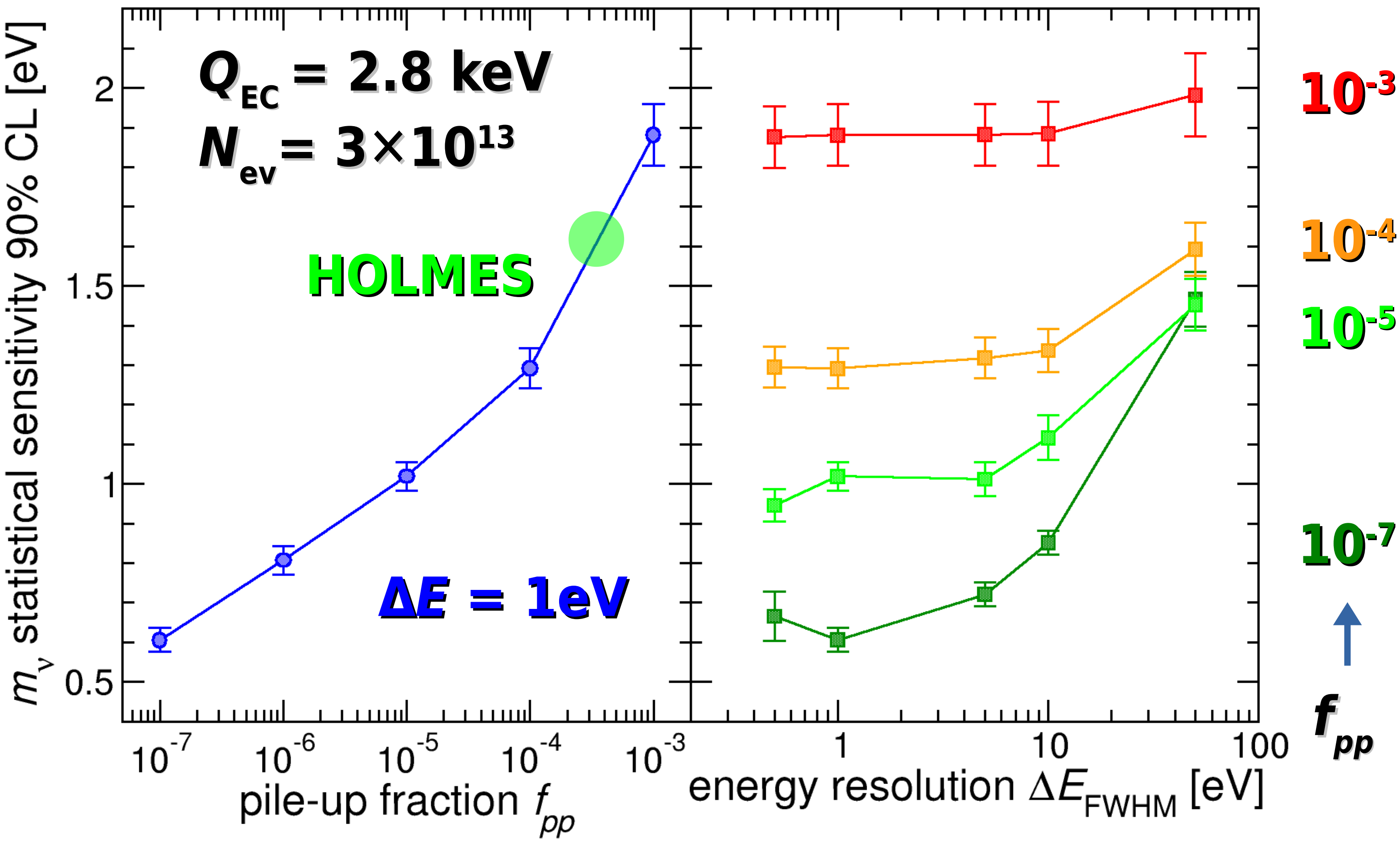
statistical sensitivity **$\Sigma(m_\nu) \approx 0.64 \pm 0.03$ eV**

HOLMES design: more MC simulations...

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

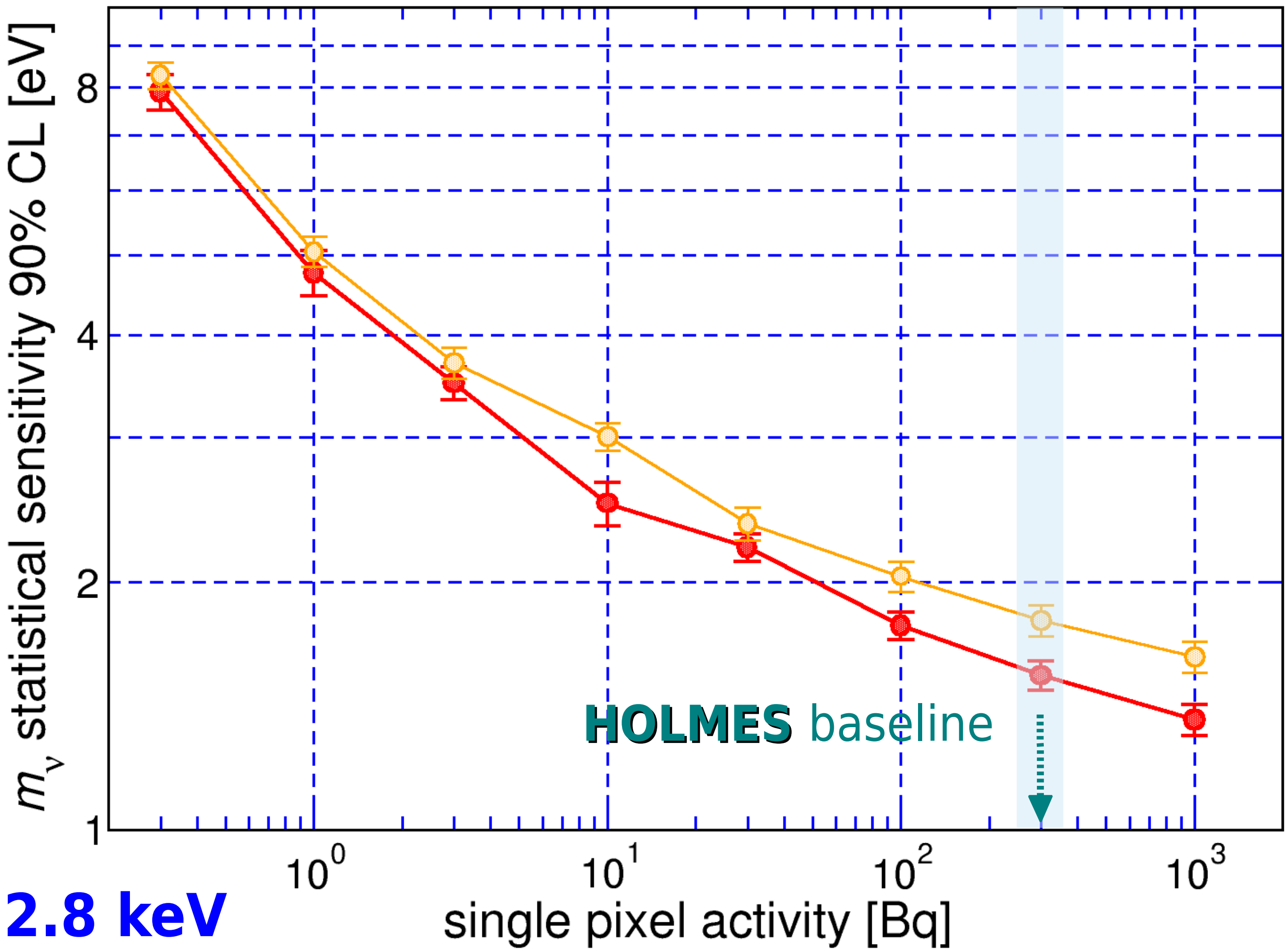
- strong on statistics $N_{ev}=A_{EC}N_{det}t_M$: $\Sigma(m_\nu) \propto N_{ev}^{-1/4}$
- strong on rise time pile-up (probability $f_{pp} \approx A_{EC}\tau_R$)
- weak on energy resolution ΔE

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

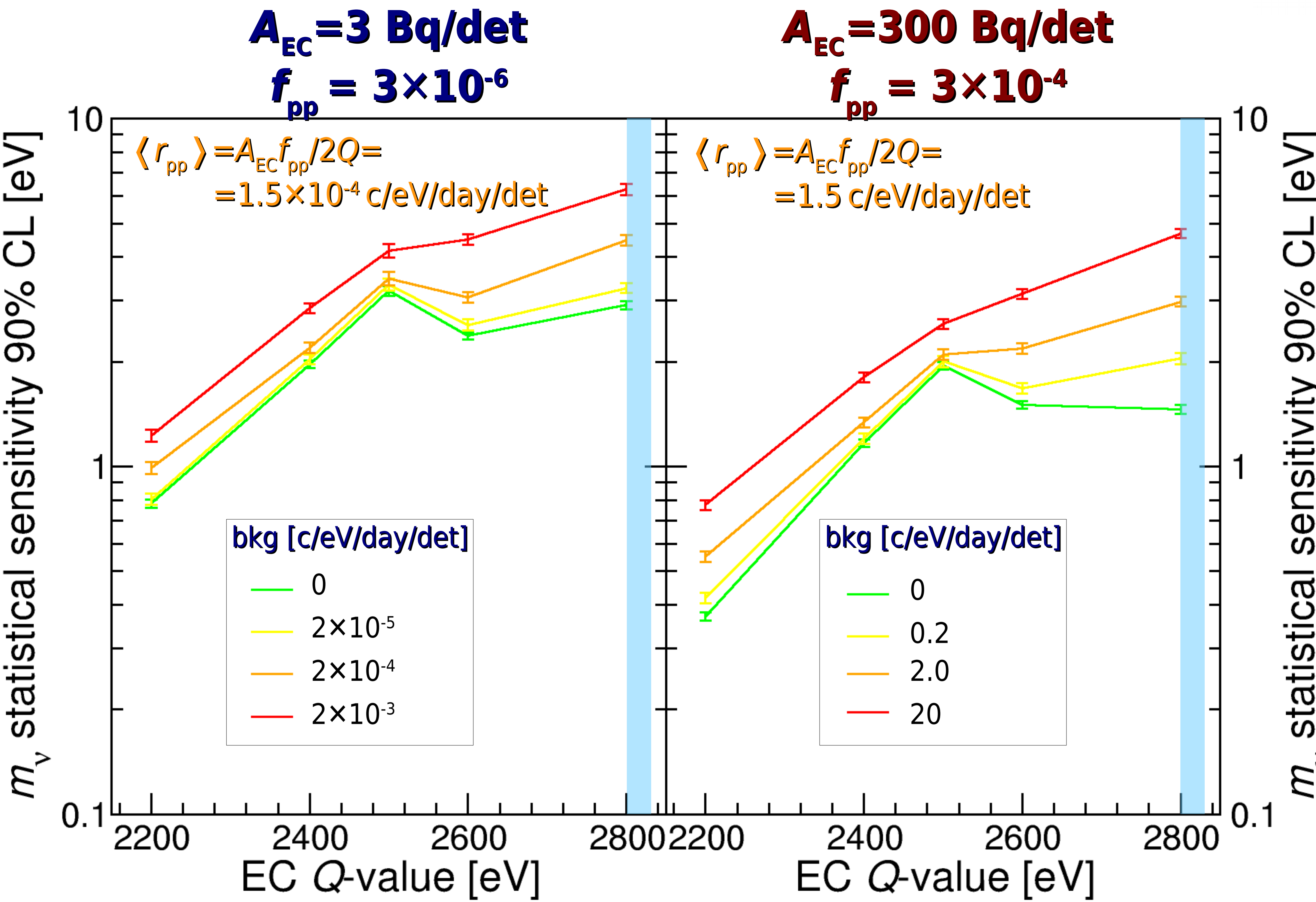
ΔE =1 eV
τ_R = 1 μs

ΔE =3 eV
τ_R = 3 μs

Q = 2.8 keV

high activity → robustness against (flat) background
A_{EC}=300 Bq → *bkg*<≈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 (only **muons**)
  - ▷ **Au pixel 200×200×2 μm^3 → *bkg* ≈ 5×10^{-5} c/eV/day/det (0 - 4 keV)**
- **internal radionuclides**
  - ▷ **^{166m}Ho** (β$^-$, $\tau_{½}$ = 1200 y, produced along with ^{163}Ho)
  - ▷ **Au pixel 200×200×2 μm^3**

    GEANT4 simulation → ***bkg* ≈ 0.5 c/eV/day/det/Bq(^{166m}Ho)**
  - ▷ *A*(^{163}Ho) = 300Bq/det (↔ ≈6.5×10^{13} nuclei/det)

    ***bkg*(^{166m}Ho)<0.1 c/eV/day/det → *A*(^{163}Ho)/*A*(^{166m}Ho) > 1500**

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

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

HOLMES tasks

- ^{163}Ho isotope production
- ^{163}Ho embedding system
- TES pixel R&D
- TES array design and fabrication
- TES array multiplexed read-out
- Data Acquisition System

^{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

- ^{162}Er irradiation at **ILL nuclear reactor** (Grenoble, France)
  - thermal neutron flux at **ILL**: 1.3×10^{15} n/cm^2/s
  - burn up ^{163}Ho(n,γ)^{164}Ho: $\sigma_{burn\text{-}up} \approx 200$b (preliminary result from **PSI** analysis)
  - ^{165}Ho(n,γ) (mostly from ^{164}Er(n,γ)) → ^{166m}Ho (β, $\tau_{½}$=1200y) → $A(^{163}\text{Ho})/A(^{166m}\text{Ho})$=100~1000
- chemical pre-purification and post-separation at **PSI** (Villigen, CH)
- **HOLMES needs ≈ 200 MBq of ^{163}Ho**

  with reasonable assumptions on the (unknown) global embedding process efficiency...

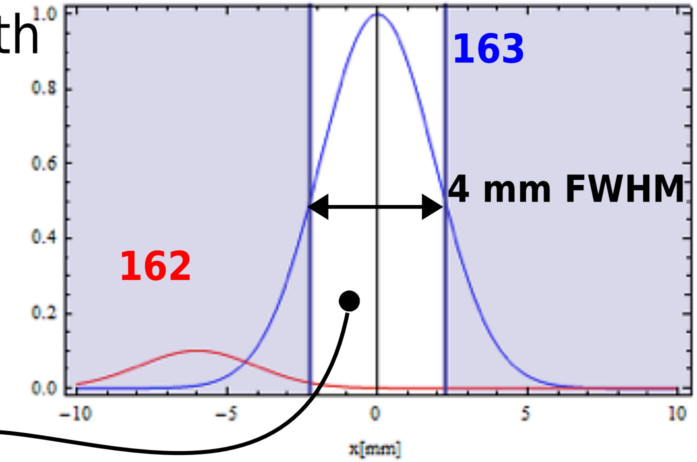
HOLMES source production

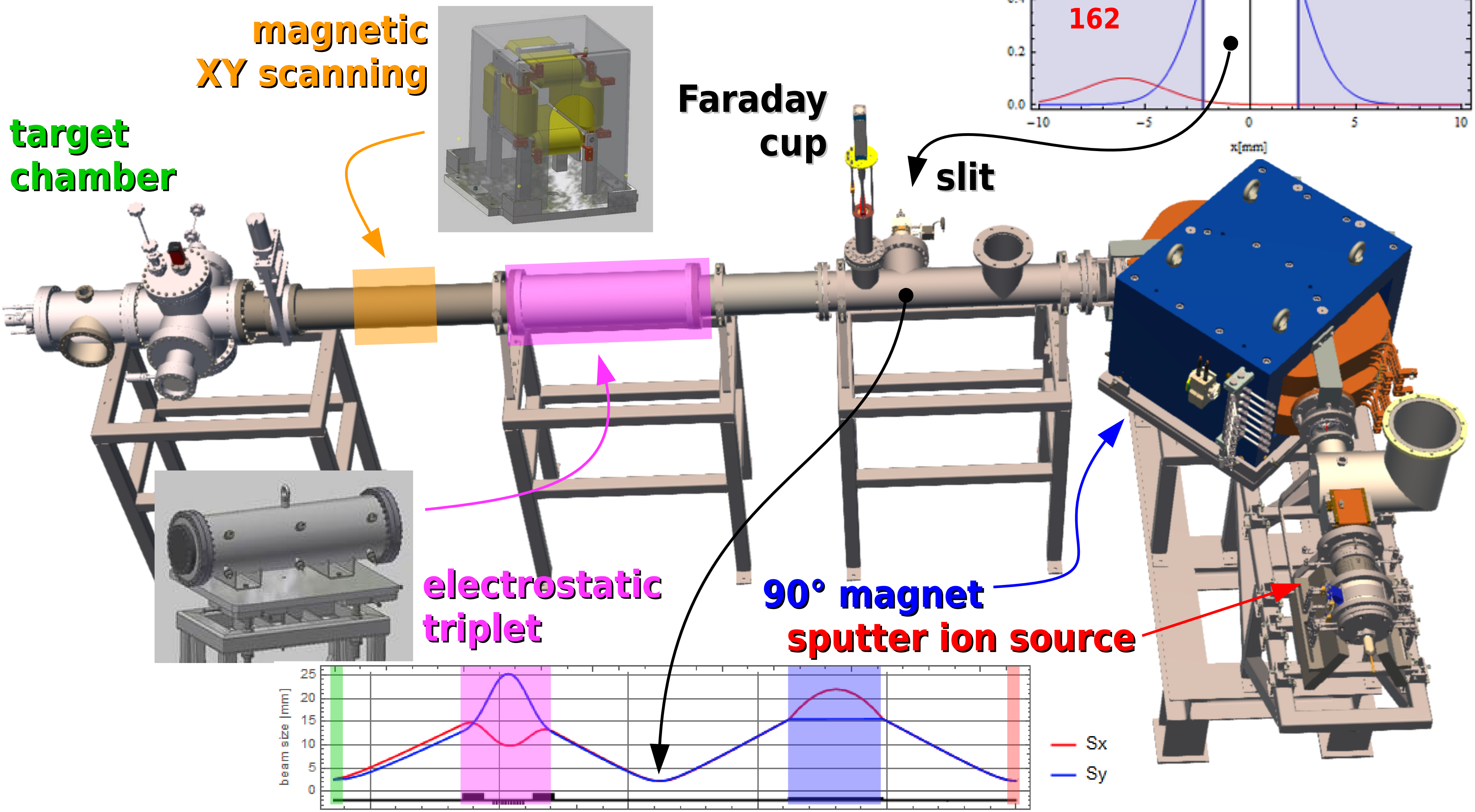
- **enriched Er_2O_3** samples* irradiated at **ILL** and pre-/post-processed at **PSI**
  - 25 mg irradiated for 55 days (2014) → ***A*(^{163}Ho) ≈ 5 MBq** (*A*(^{166m}Ho)≈10kBq)
  - 150 mg irradiated for 50 days (2015) → ***A*(^{163}Ho) ≈ 38 MBq** (*A*(^{166m}Ho)≈37kBq)
- **Ho chemical separation** with ion-exchange resins in hot-cell at **PSI**
  - **efficiency ≳79%** (preliminary)
- **540 mg of 25% enriched Er_2O_3** irradiated 50 days at **ILL** early in 2017
  - ***A*(^{163}Ho)$_{theo}$ ≈ 130 MBq** (enough for R&D and 500 pixels) (*A*(^{166m}Ho)≈180kBq)

* from INFN and CENTRA (Lisbon)

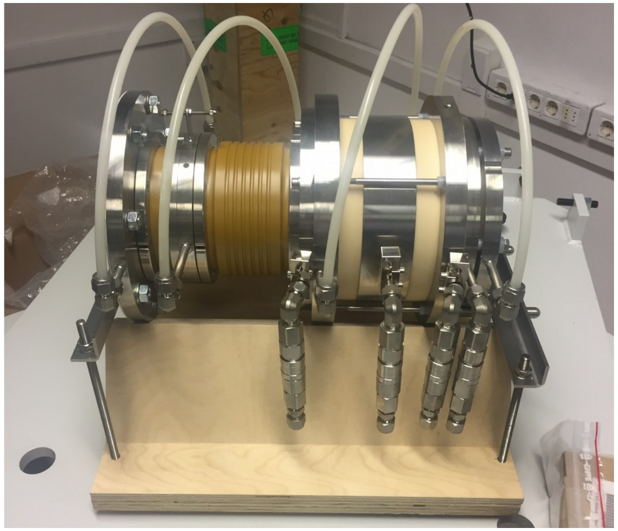
HOLMES mass separation and ion implantation

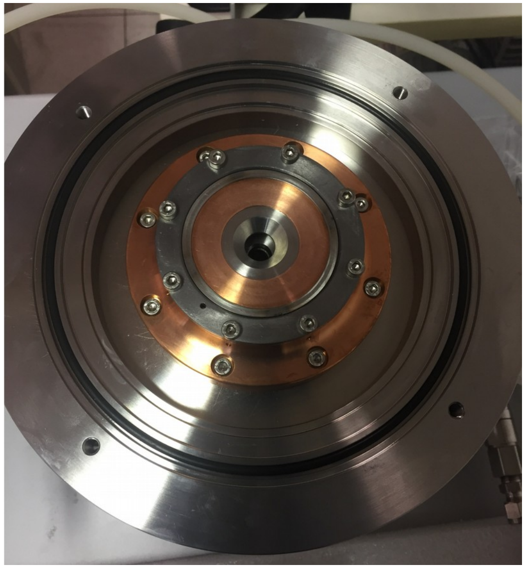
- extraction voltage 30-50 kV → 10-100 nm implant depth
- ^{163}**Ho** / ^{166m}**Ho** separation better than 10^5
- **ion source**, **magnet** and **slit** delivered end **2016**



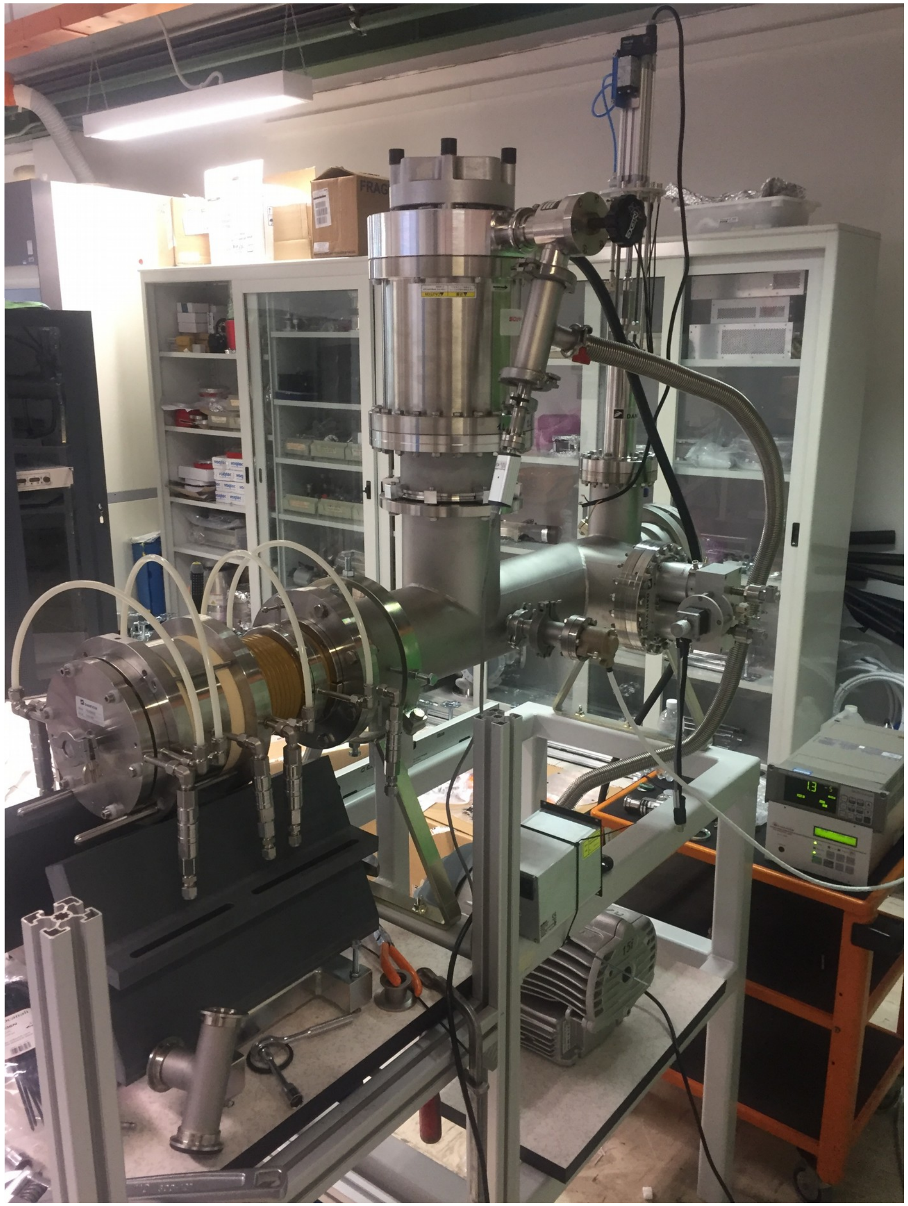


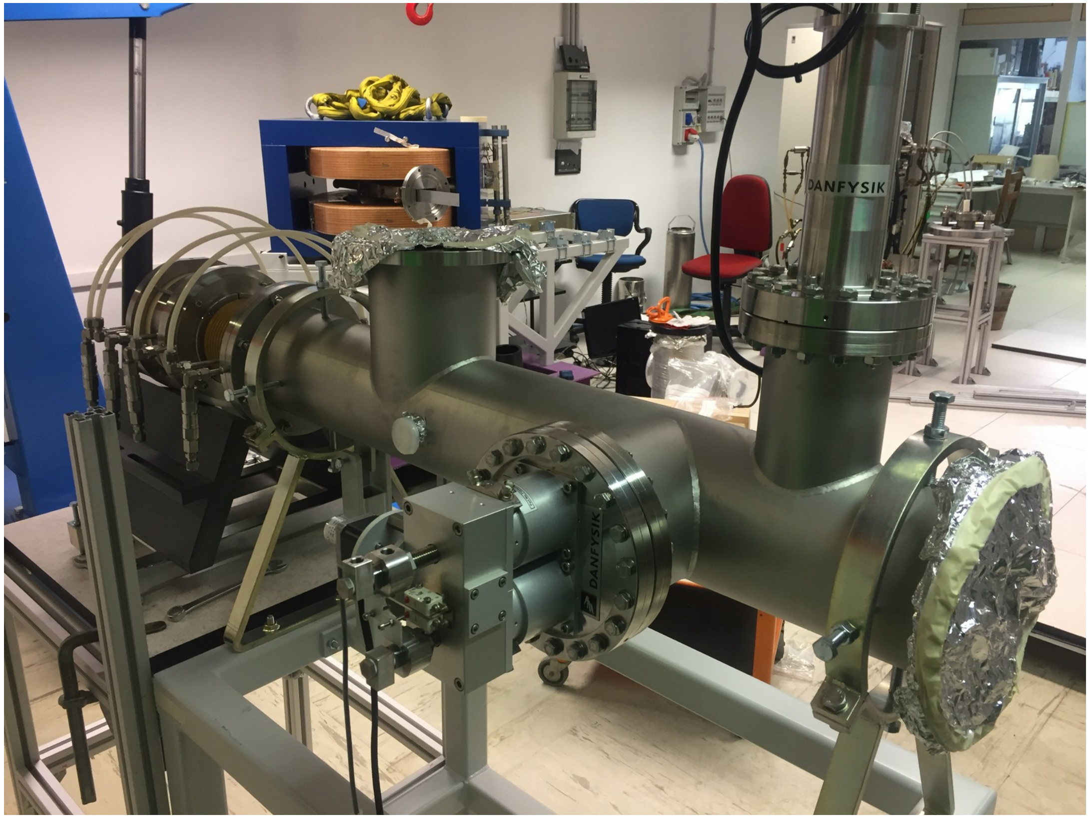
HOLMES ion implantation system / 2





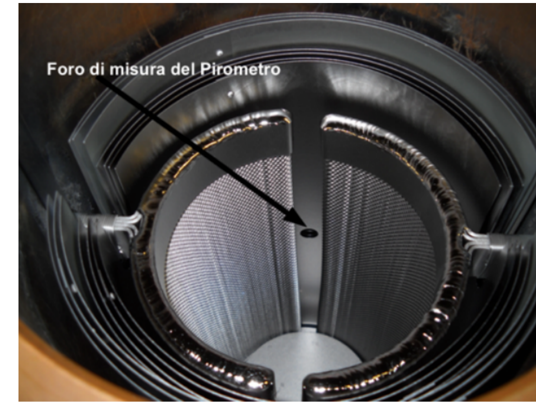
testing the ion source

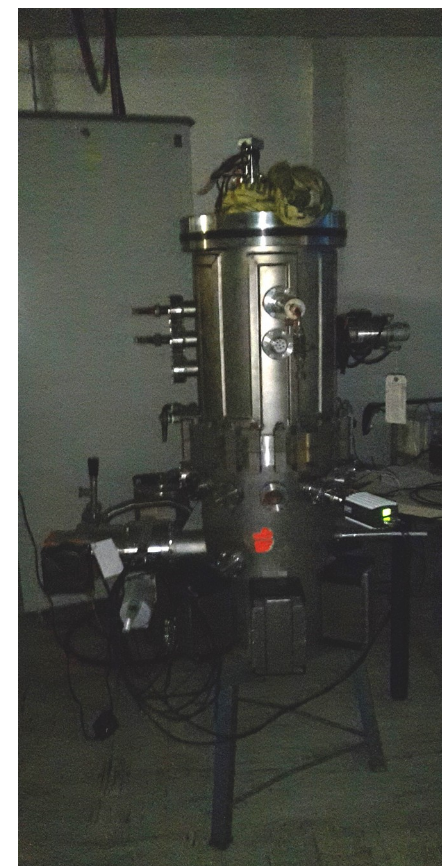


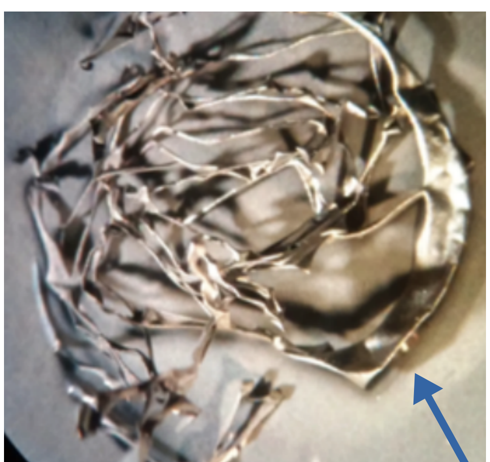


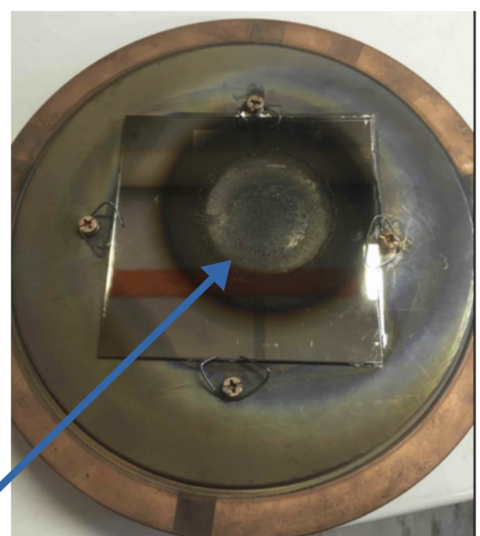
Ion source sputter target production / 1

- **Metallic holmium sputter target** for implanter ion source
- 30% enriched $Er_2O_3 \rightarrow Ho_2O_3$
- thermoreduction/distillation in furnace
  - $\mathbf{Ho_2O_3+2Y(\mathit{met}) \rightarrow 2Ho(\mathit{met})+Y_2O_3}$ **at $\mathbf{\mathit{T}>1600°C}$**
- new furnace set-up in 2016
- work in progress to
  - optimize the process
  - measure efficiency (≈**70%**, preliminary)





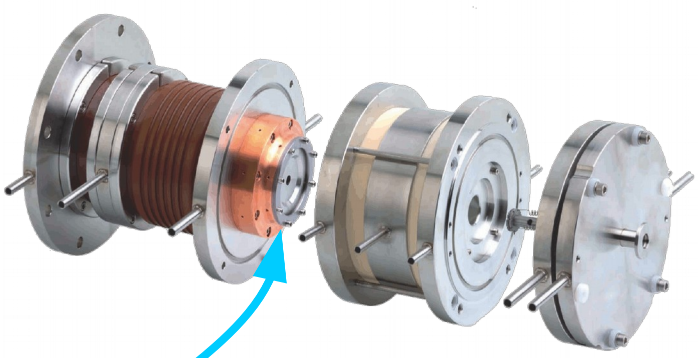




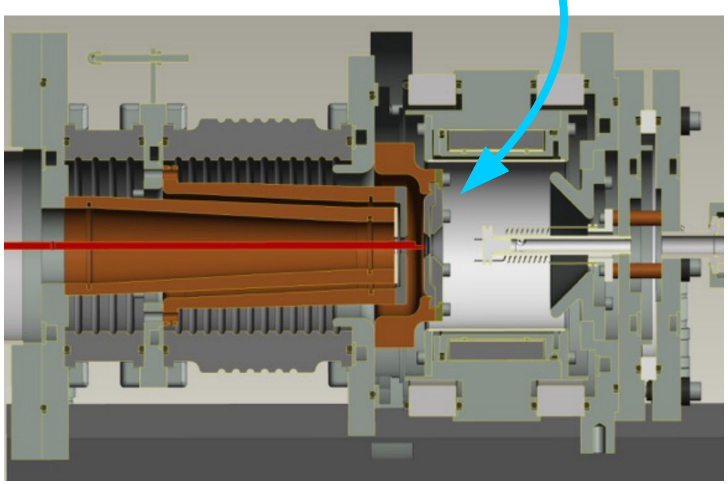
evaportated metallic holmium

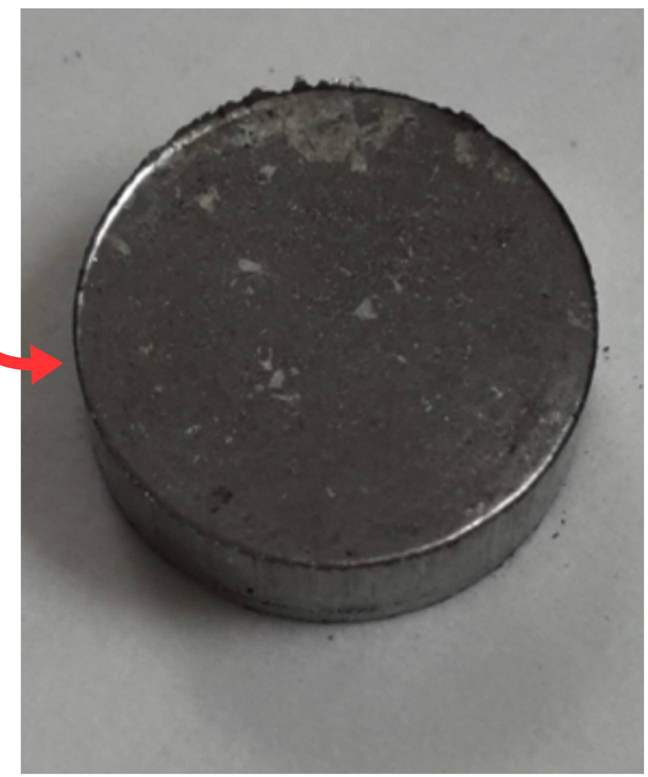
Ion source sputter target production / 2

- **Metallic holmium sputter target** for implanter ion source
  - work is in progress to produce the sputter target
  - sintering Ho with other metals

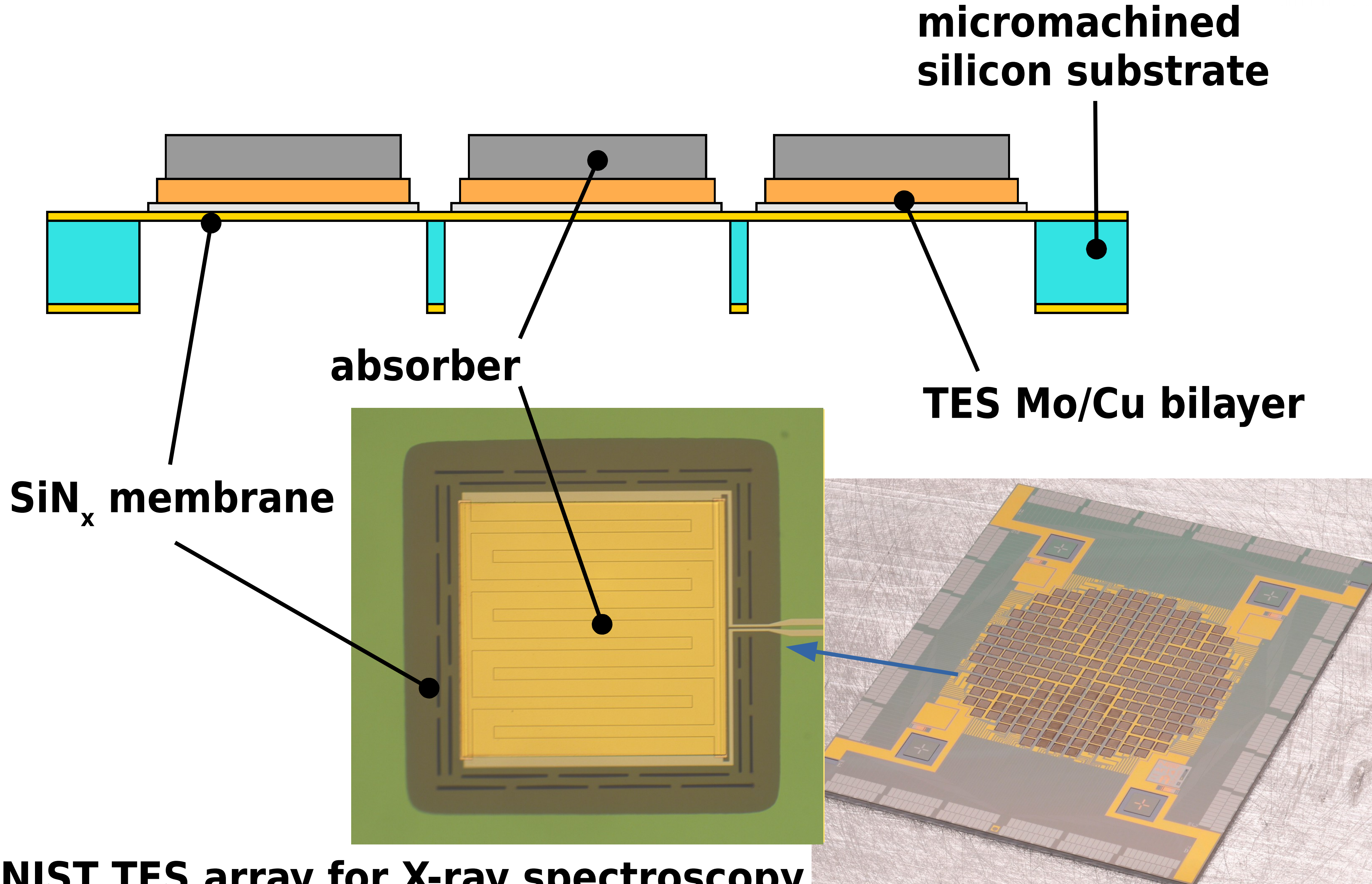


target





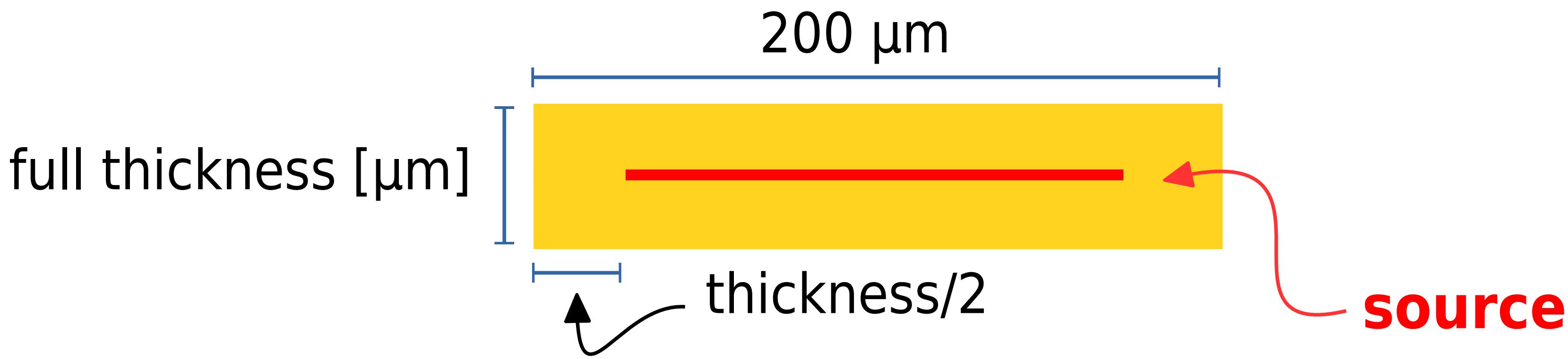
TES microcalorimeters



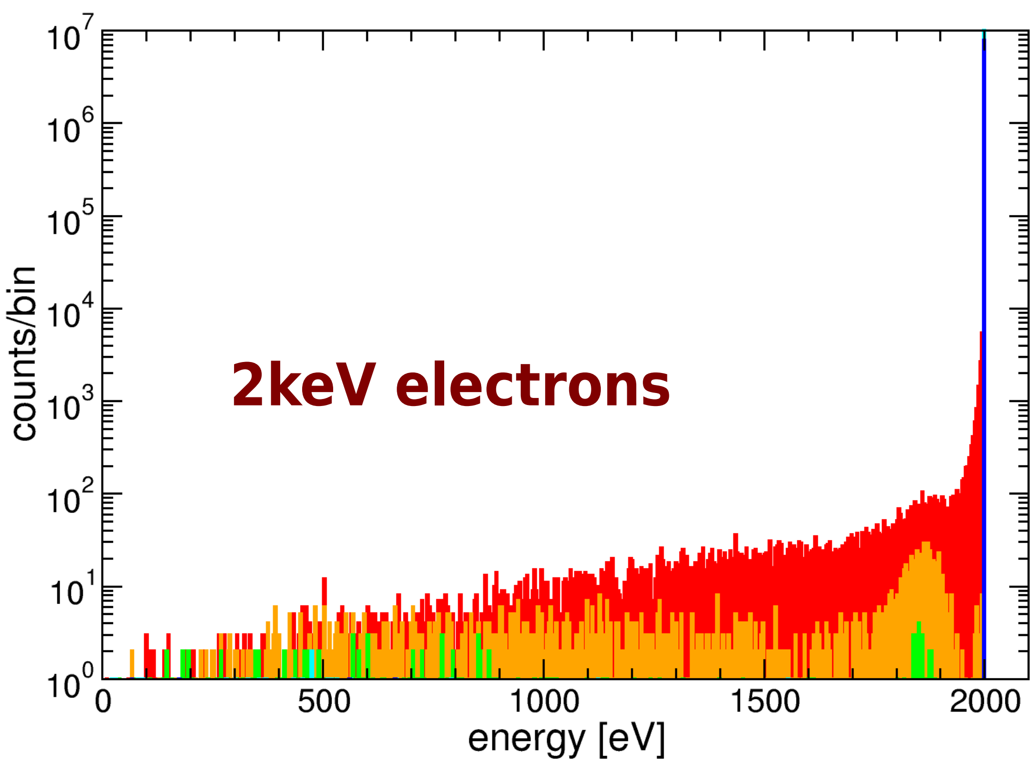
NIST TES array for X-ray spectroscopy

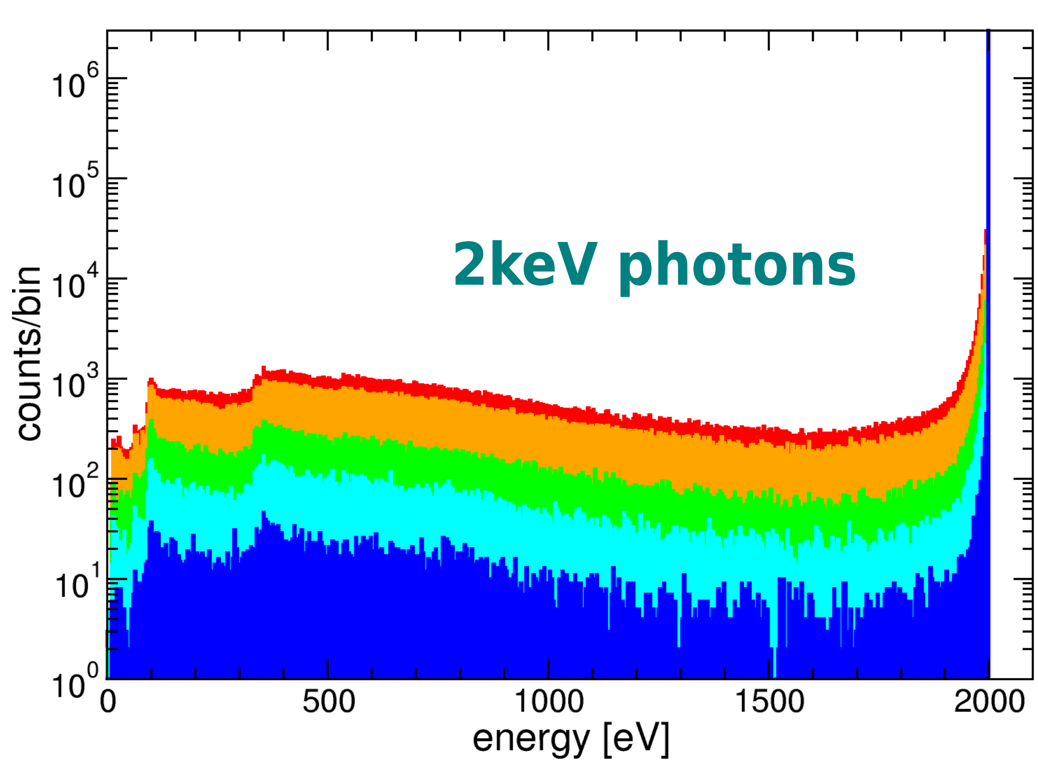
TES absorber design: stopping EC radiation / 1

Geant4 + LowEnergyEM MC simulation



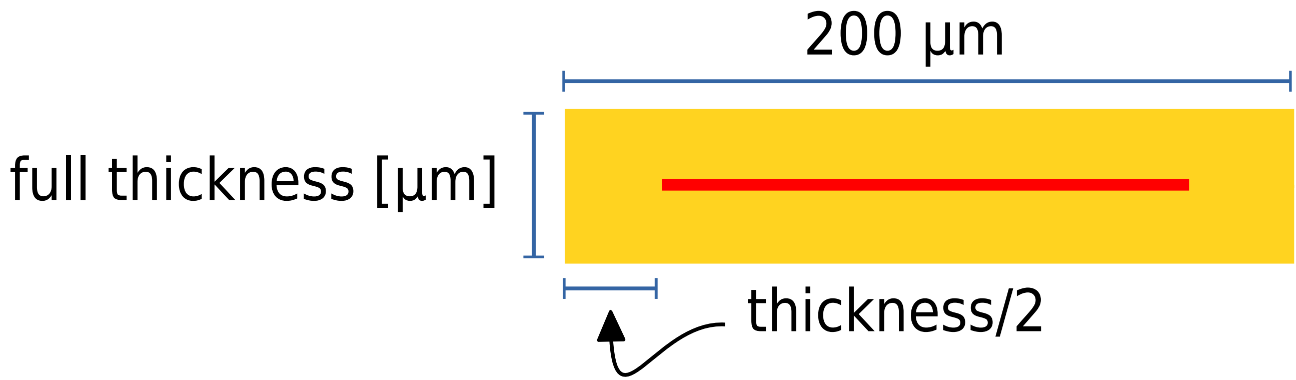
full thickness: 0.05, 0.1, 0.5, 1, 2 µm

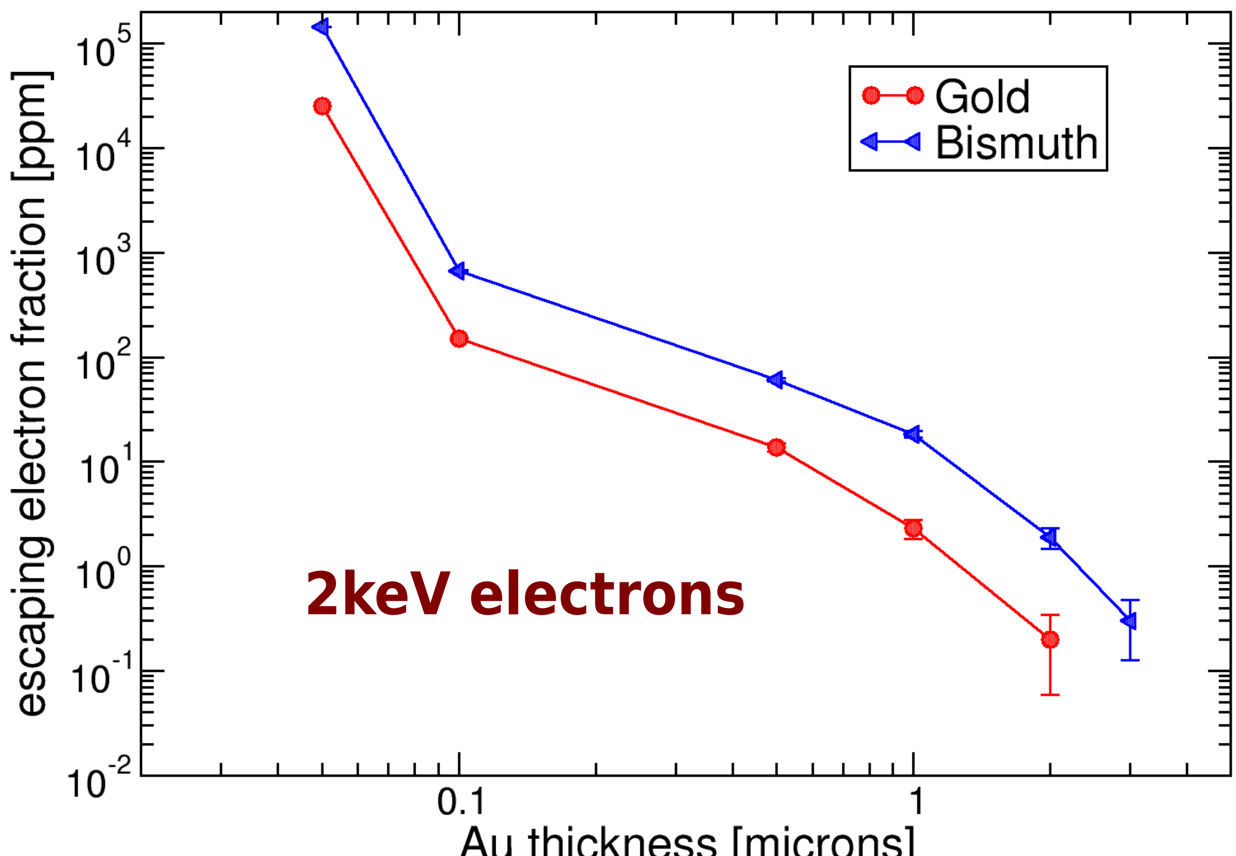




TES absorber design: stopping EC radiation / 2

Geant4 + LowEnergyEM MC simulation





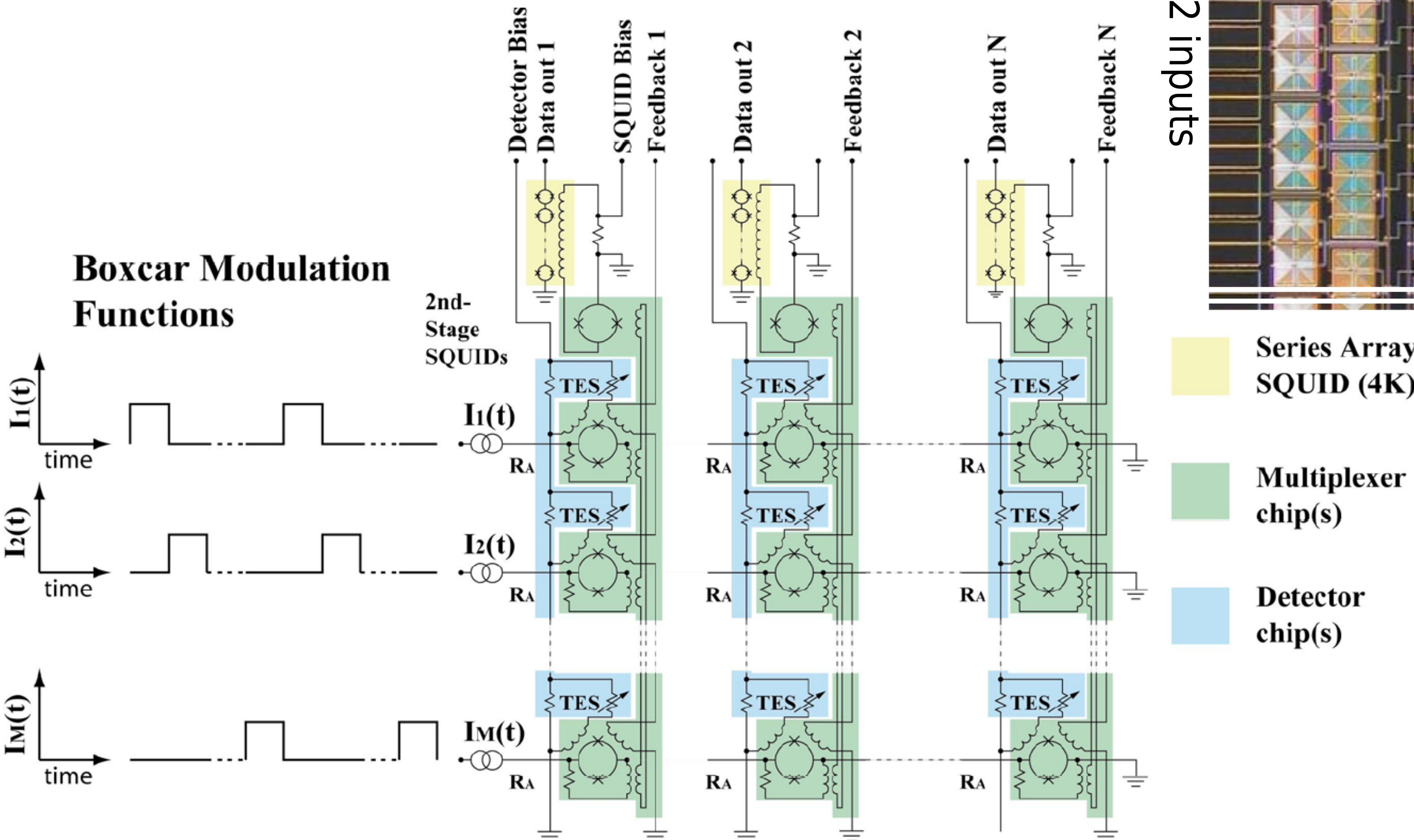
Multiplexed TES array read-out

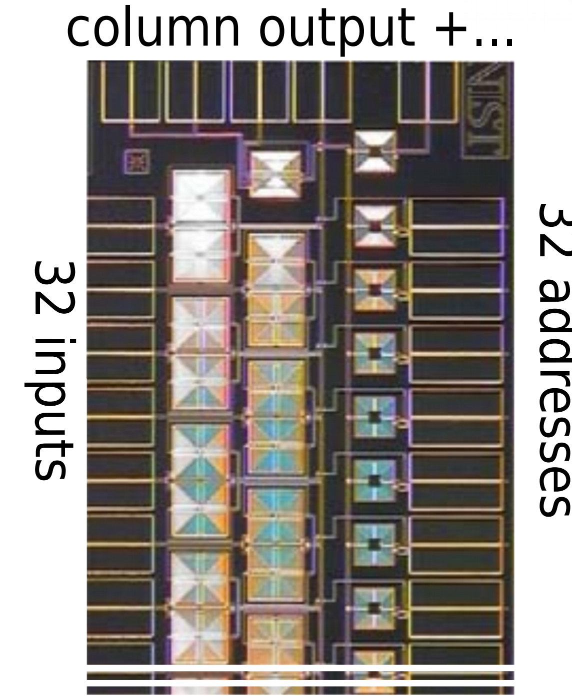
TDM Time Division Multiplexing

$N \times N$ TES array

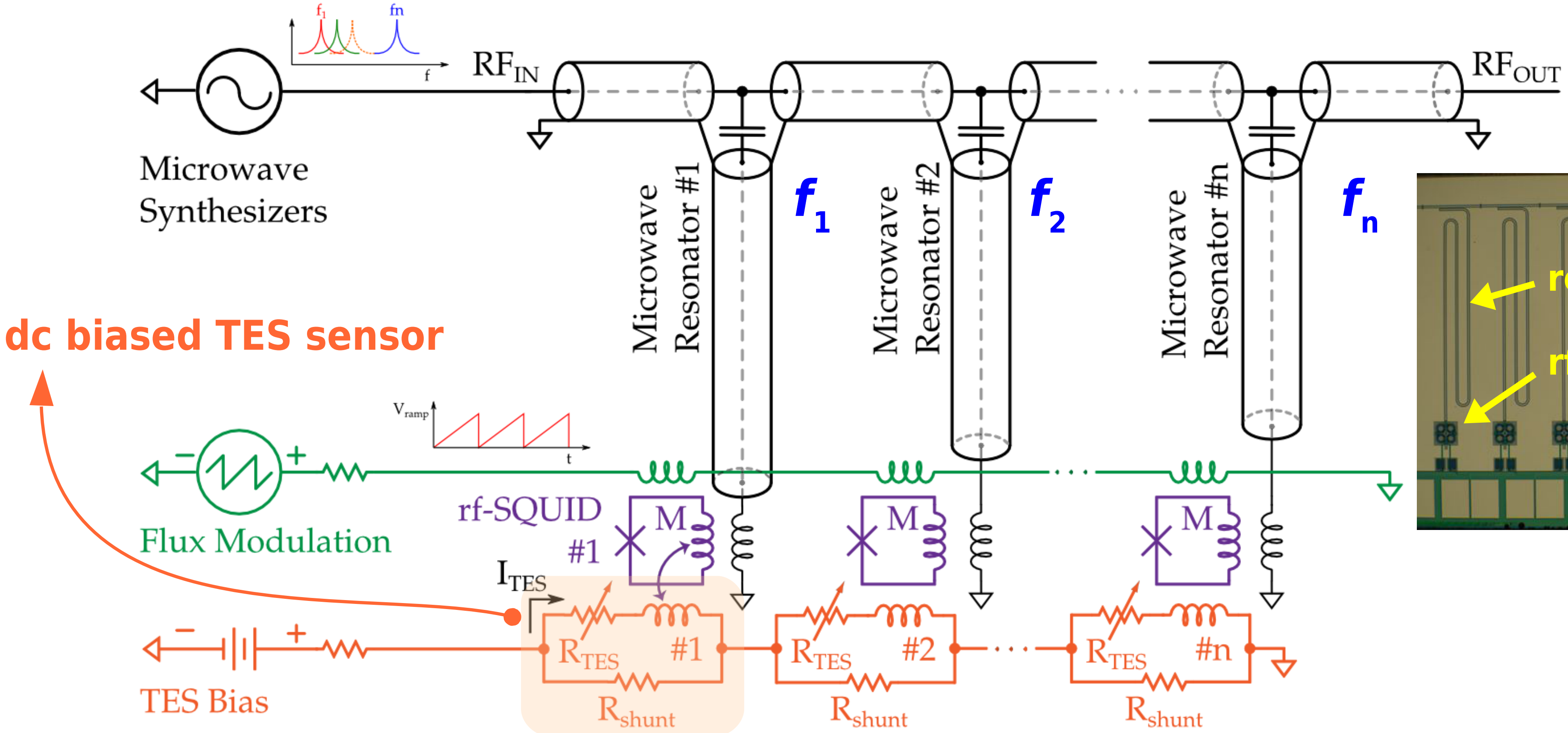
without *mux* → $N \times N$ readout channels

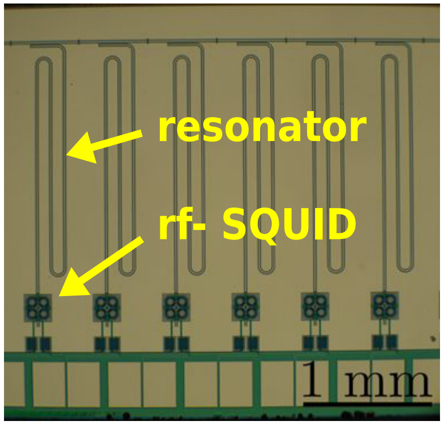
with *mux* → N addresses + N outputs



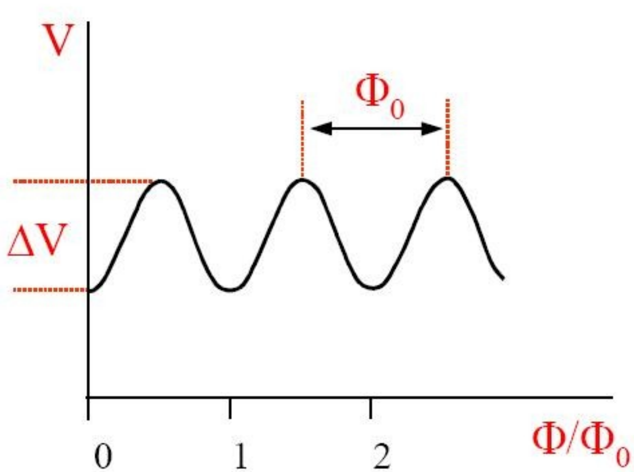


HOLMES array read-out: rf-SQUID μwave mux

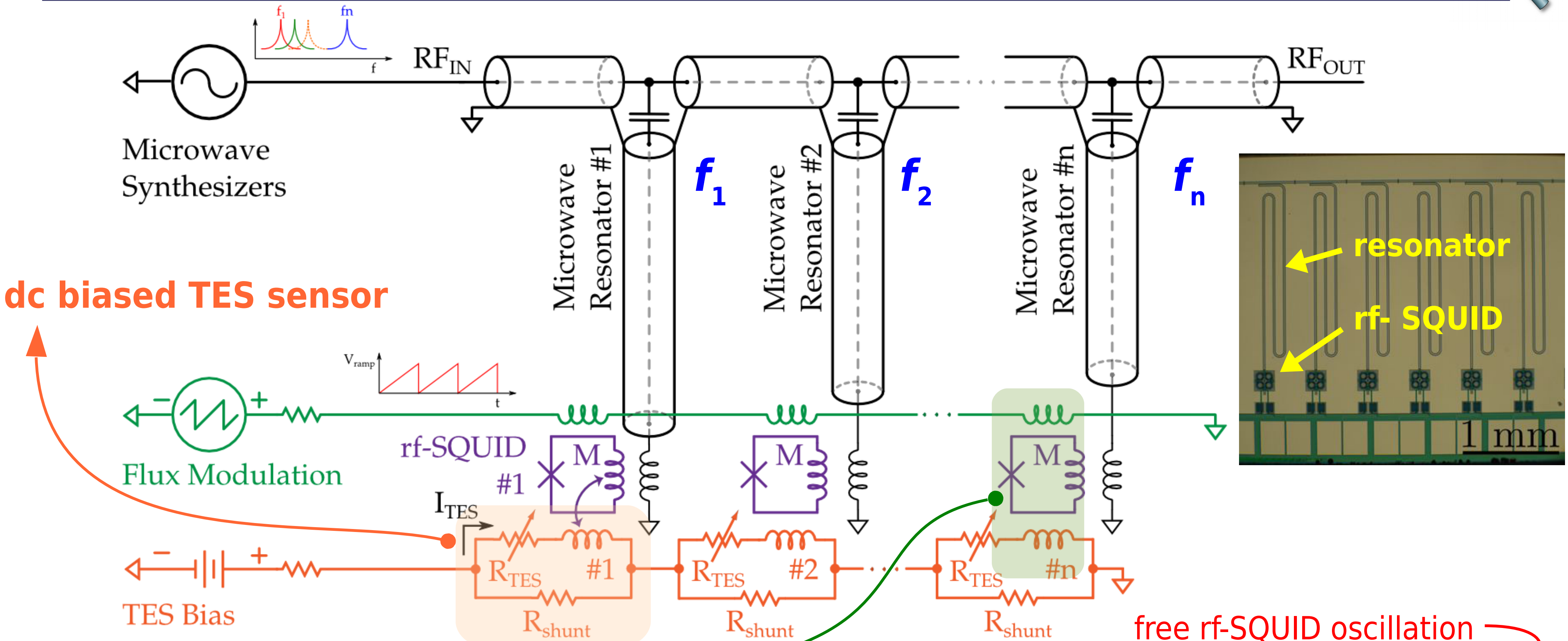


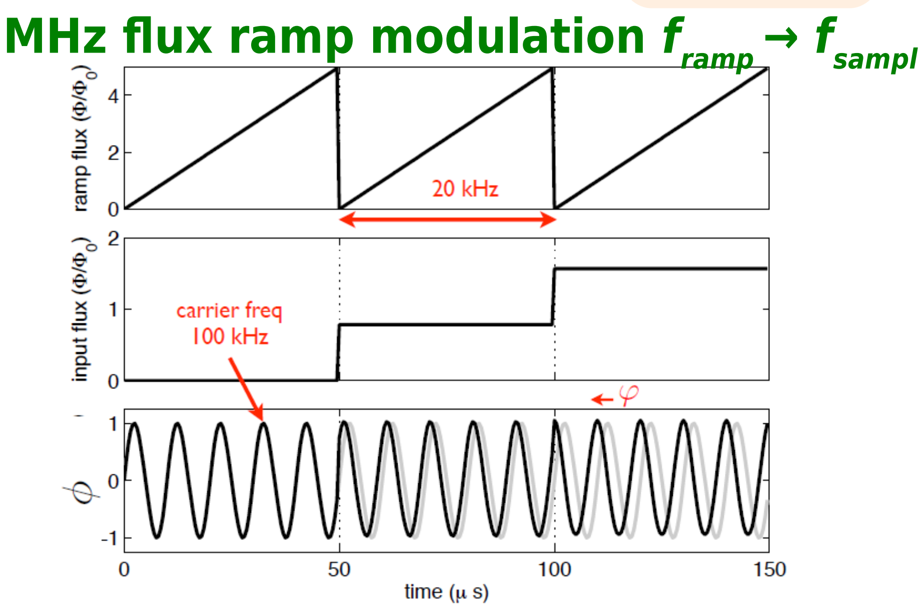


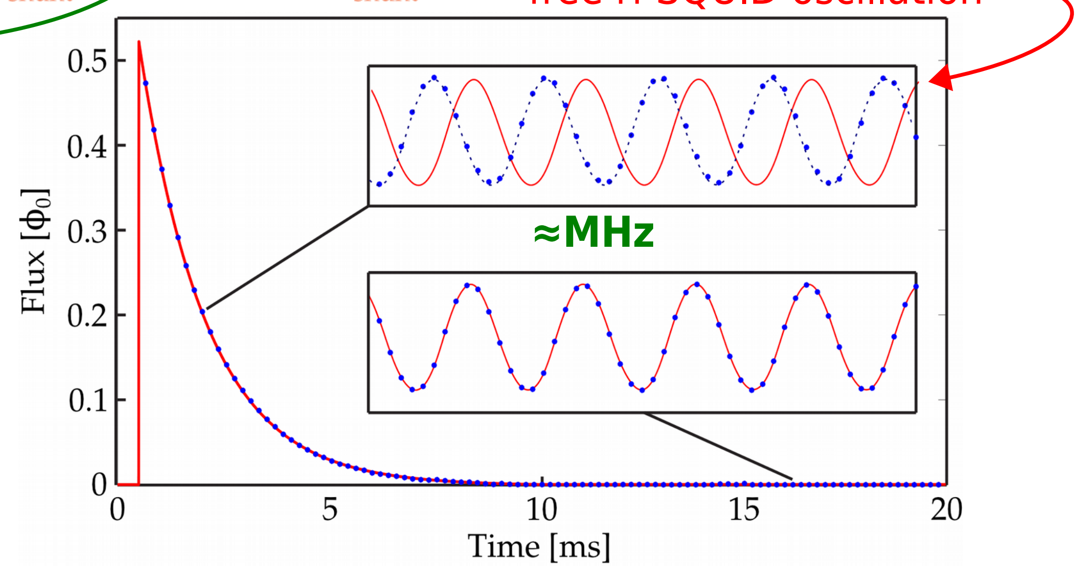
periodic SQUID response



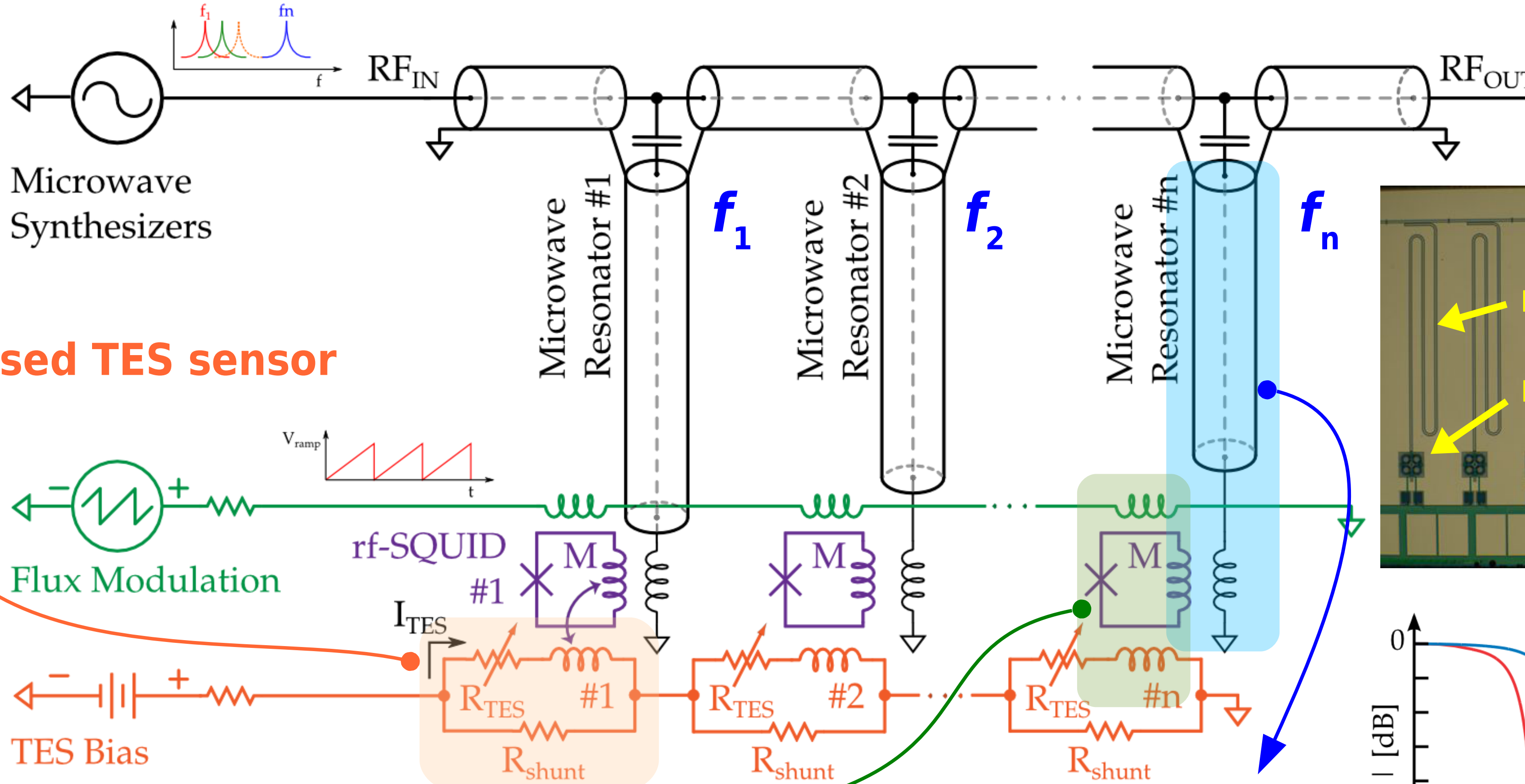
HOLMES array read-out: rf-SQUID μwave mux

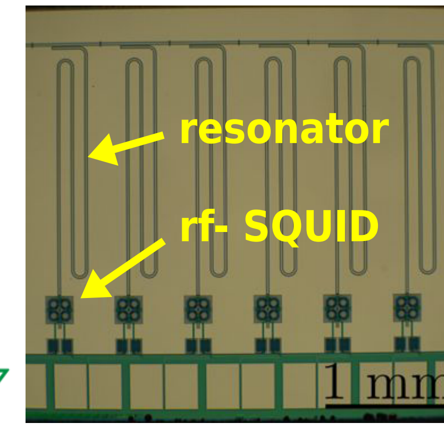






HOLMES array read-out: rf-SQUID µwave mux

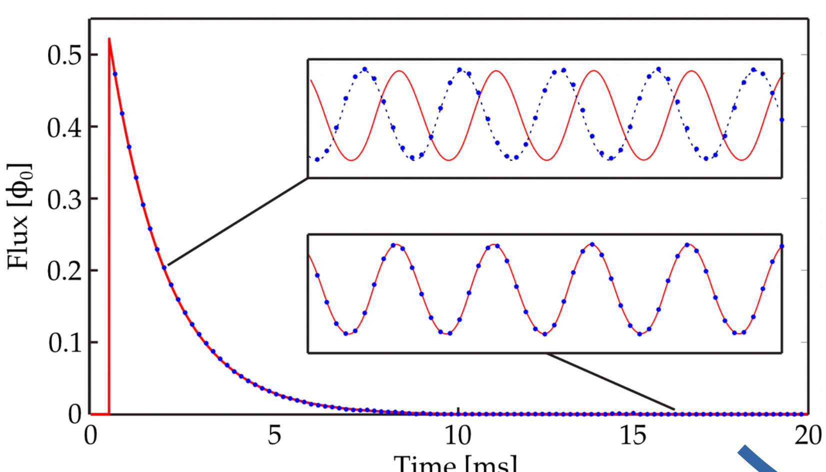




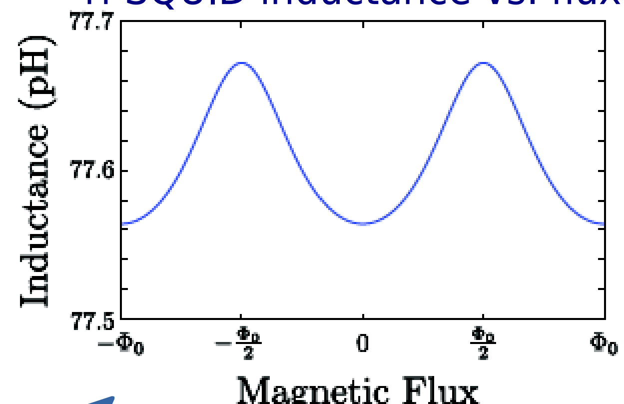
dc biased TES sensor

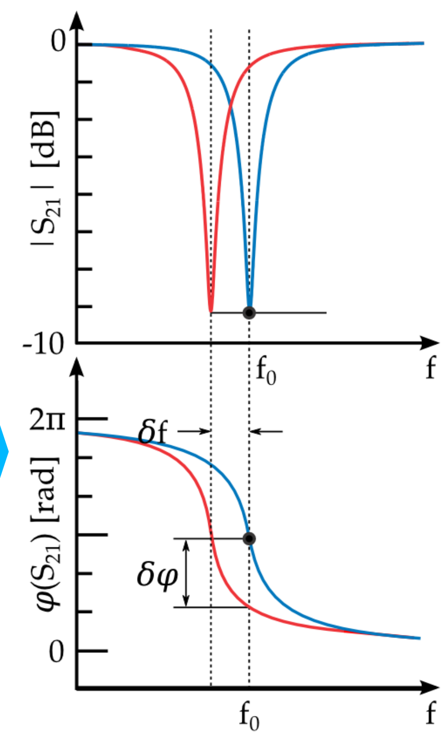
MHz flux ramp modulation $f_{ramp} \rightarrow f_{sampl}$

GHz LC resonator f_i

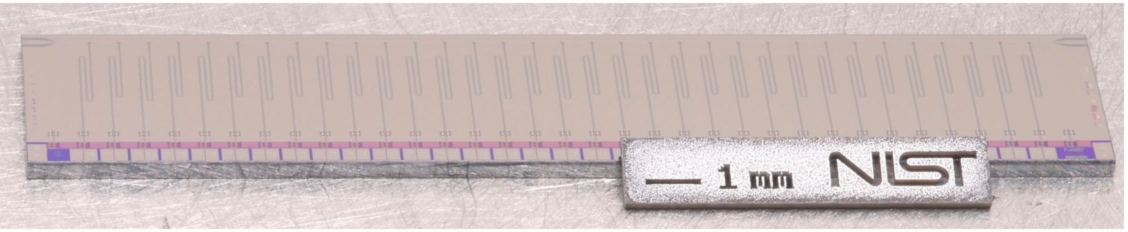


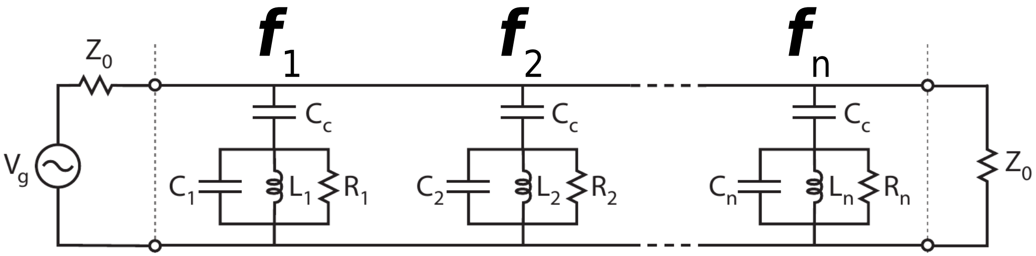
rf-SQUID inductance vs. flux



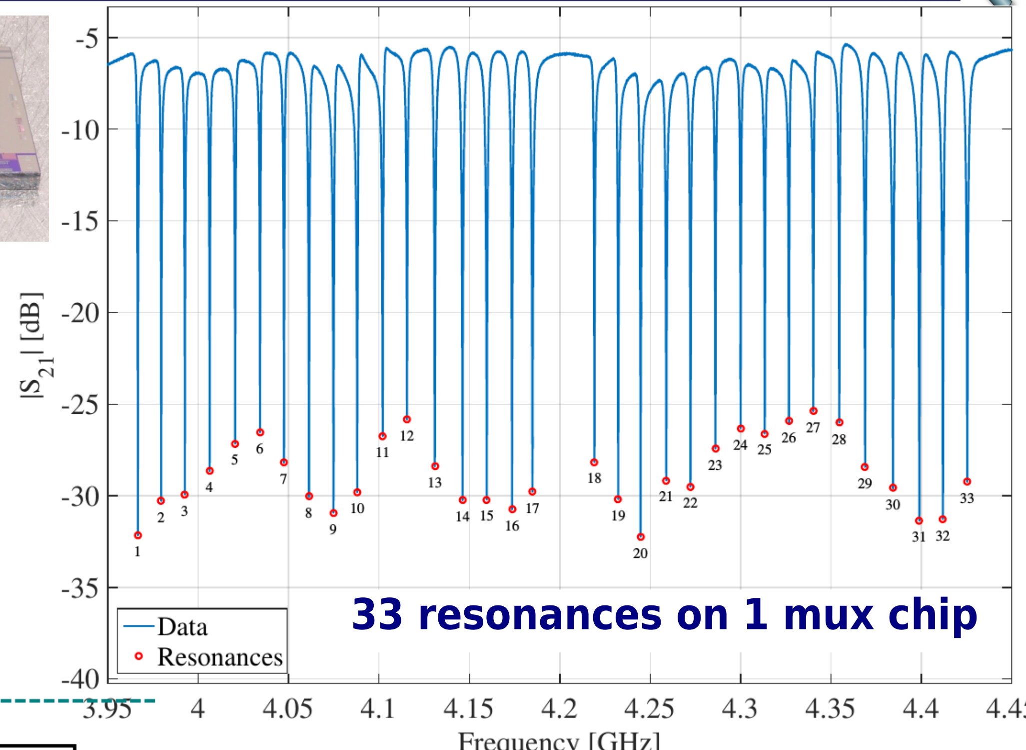


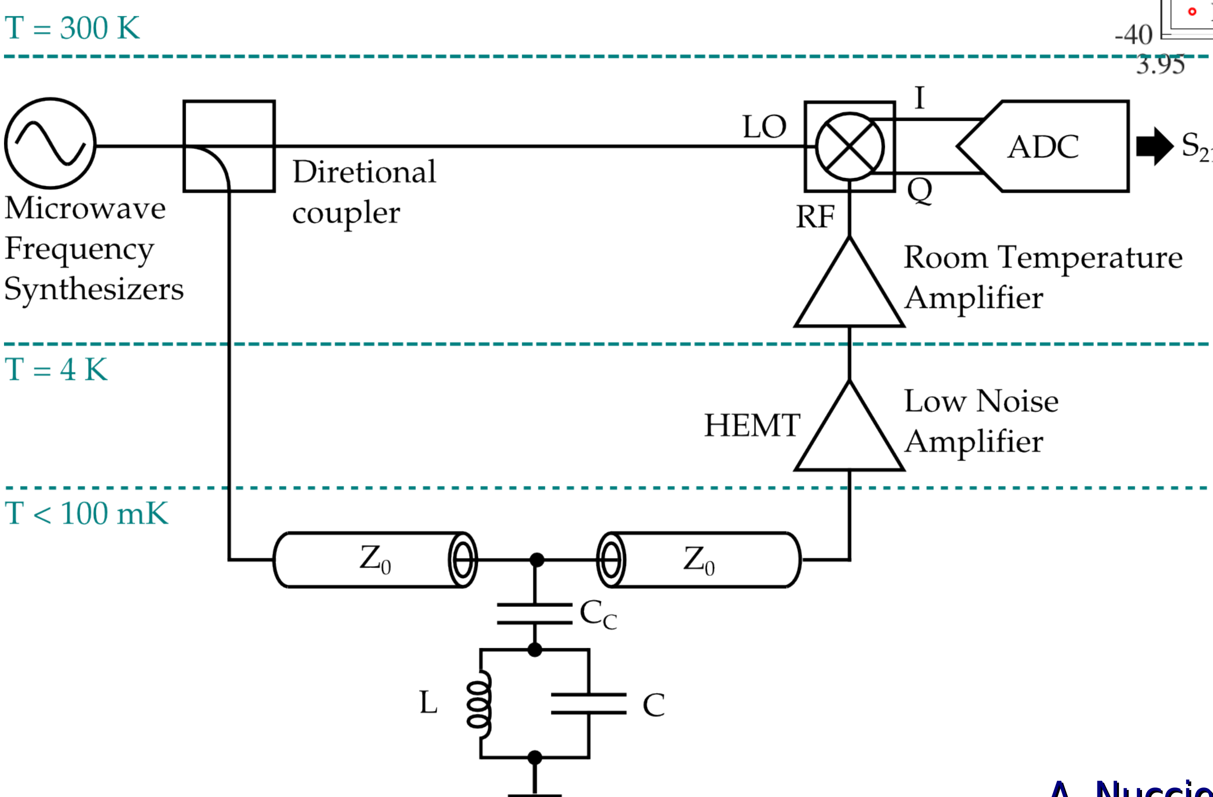
μwave with RF carrier homodyne read-out

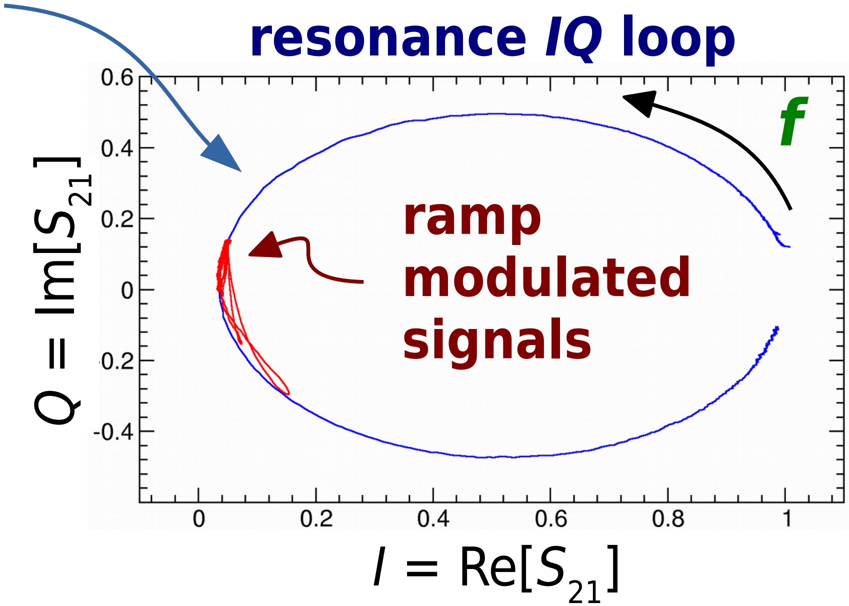




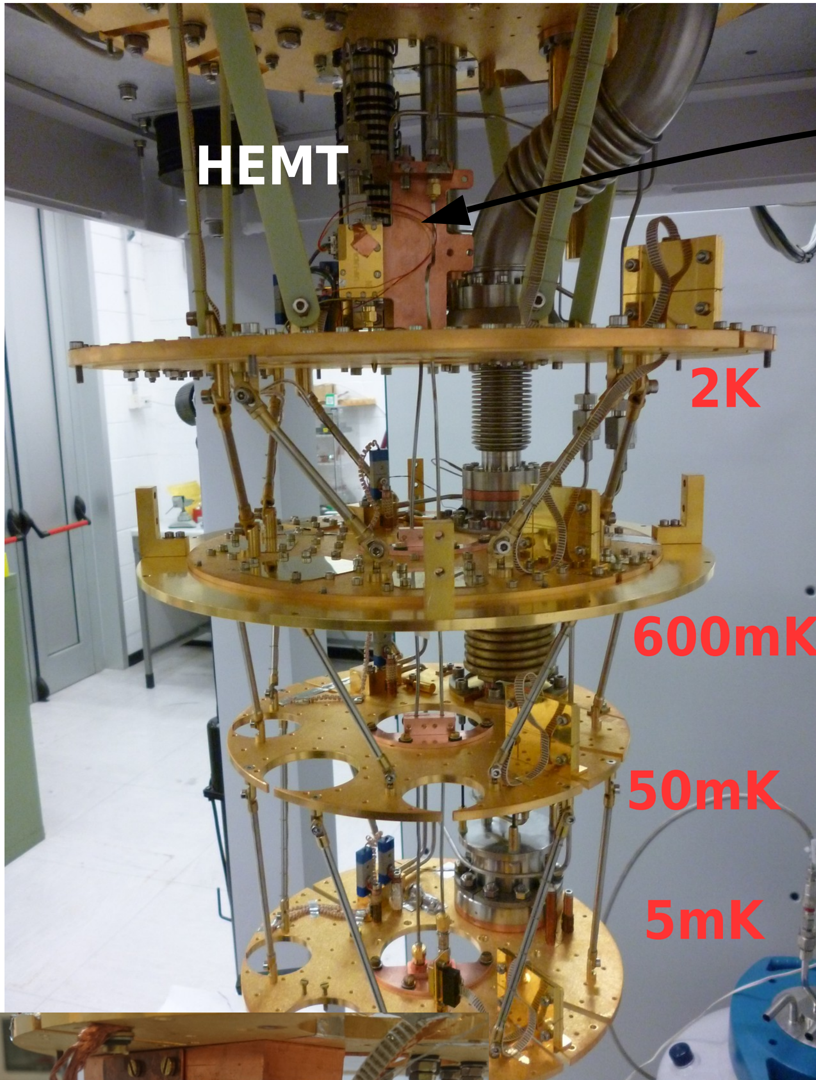
device ***i*** is read out tuning the RF carrier to f_i



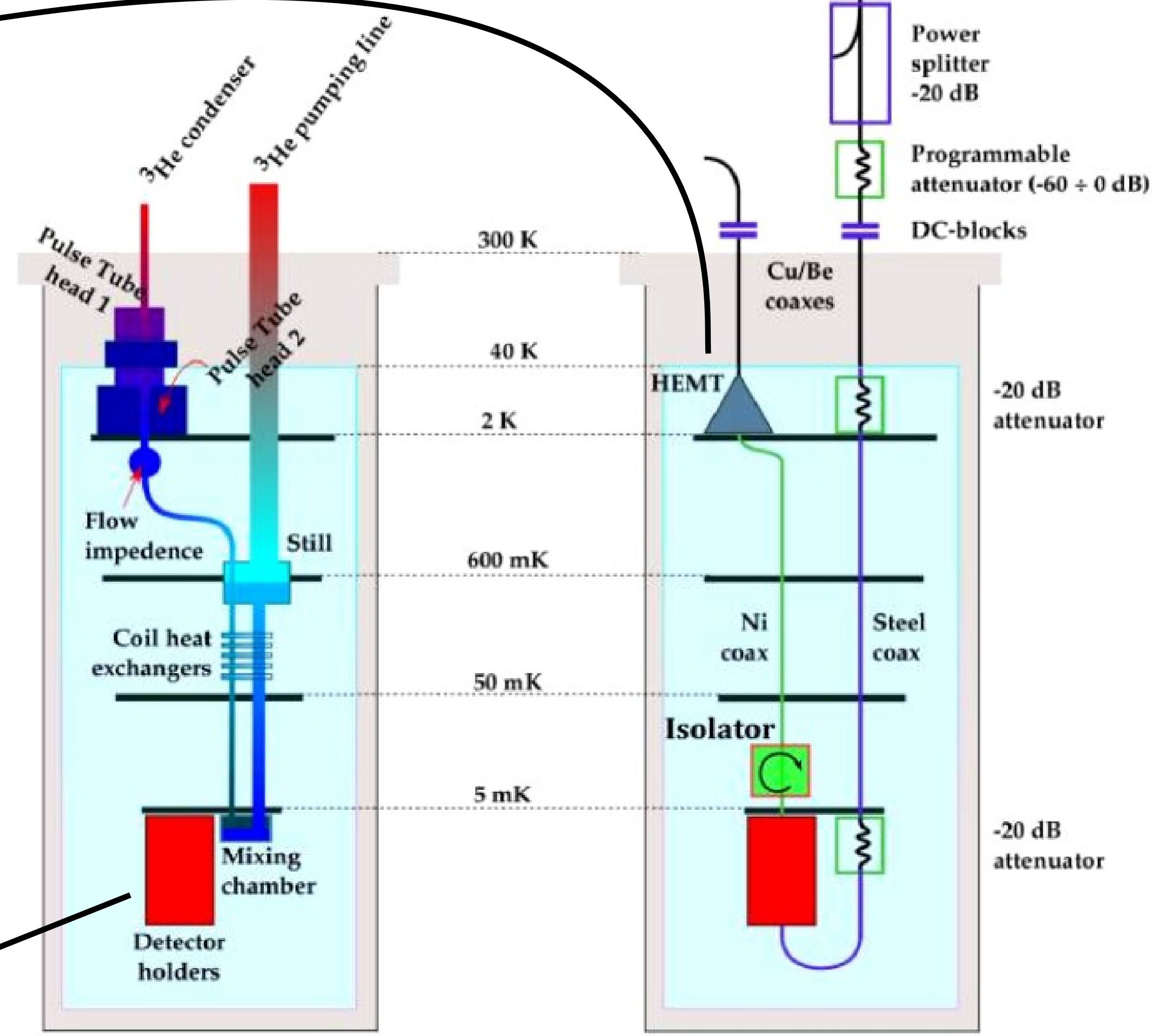


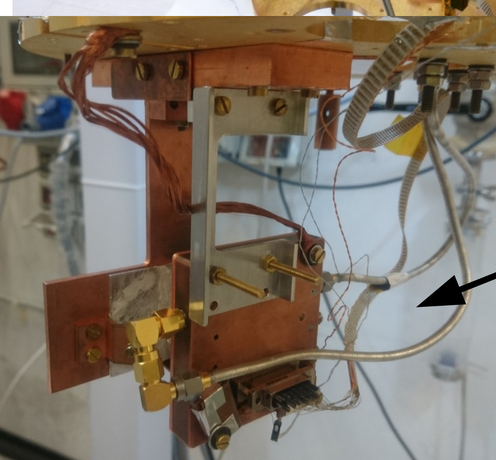


Cryogenic set-up



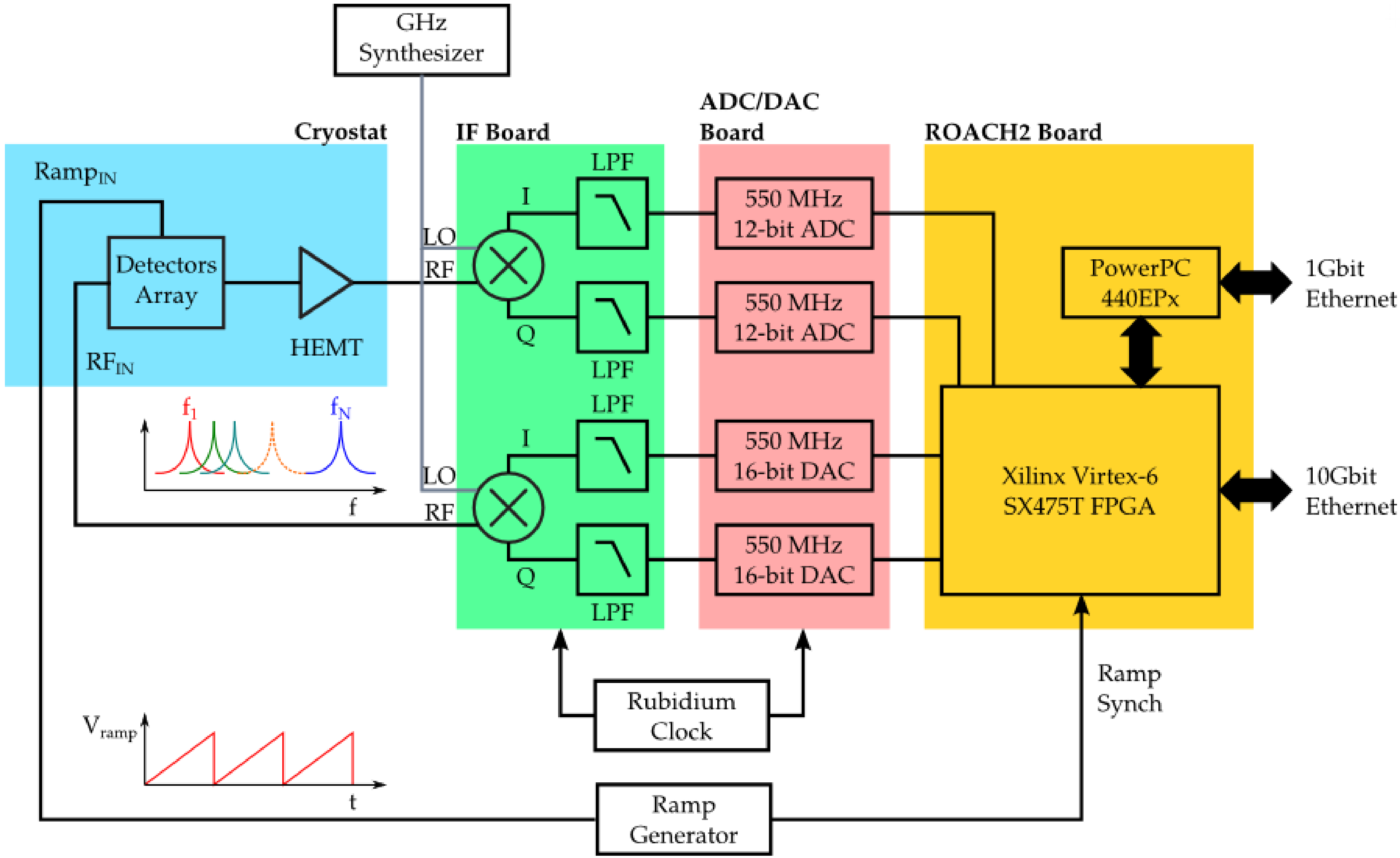
LHe-free dilution refrigerator





detector holder

HOLMES DAQ: Software Defined Radio



multiplexing factor n_{TES}

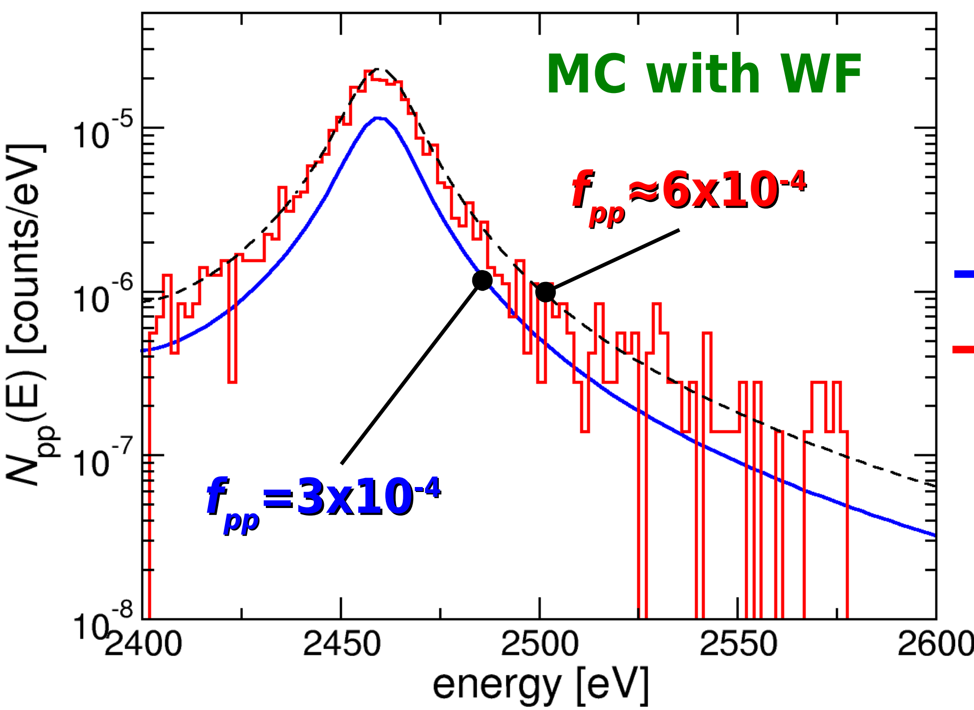
f_{BW} required bandwidth per channel $\approx 1/\tau_{rise}$ → $n_{TES} \approx \frac{f_{ADC}}{10 f_{BW}}$

Detector 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 with pile-up detection algorithms:
    - **Wiener Filter WF** or **Single Value Decomposition SVD**
- evaluate **effective time resolution $\boldsymbol{\tau_{eff}}$** from **pile-up detection efficiency $\boldsymbol{\eta(\Delta t)}$**



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

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

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

best time resolution

SVD (f_{samp}= 0.5MHz, τ_{rise}≈ 10µs) → τ_{eff}≈ 1 µs

HOLMES detector design

design mostly driven by **read-out bandwith** requirements

- TES microwave multiplexing with rf-SQUID ramp modulation + Software Defined Radio (SDR)

read-out specs			→	HOLMES targets
SDR ADC f_{ADC} multiplexing factor n_{TES}	→	signal sampling f_{samp} signal rise time τ_{rise}	→	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 ($g_f \gtrsim 10$)

multiplexing factor

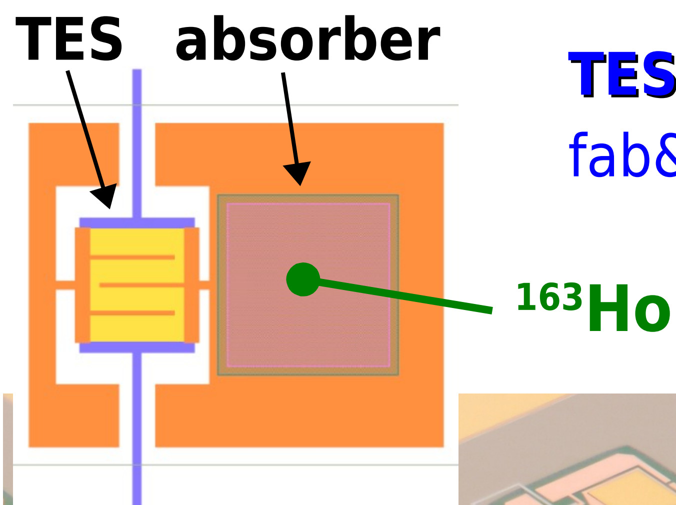
$$n_{TES} = \frac{f_{ADC}}{f_n} \leq \frac{f_{ADC} \tau_{rise}}{2 R_d g_f n_{\Phi_0}} \approx \frac{f_{ADC} \tau_{rise}}{200}$$

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

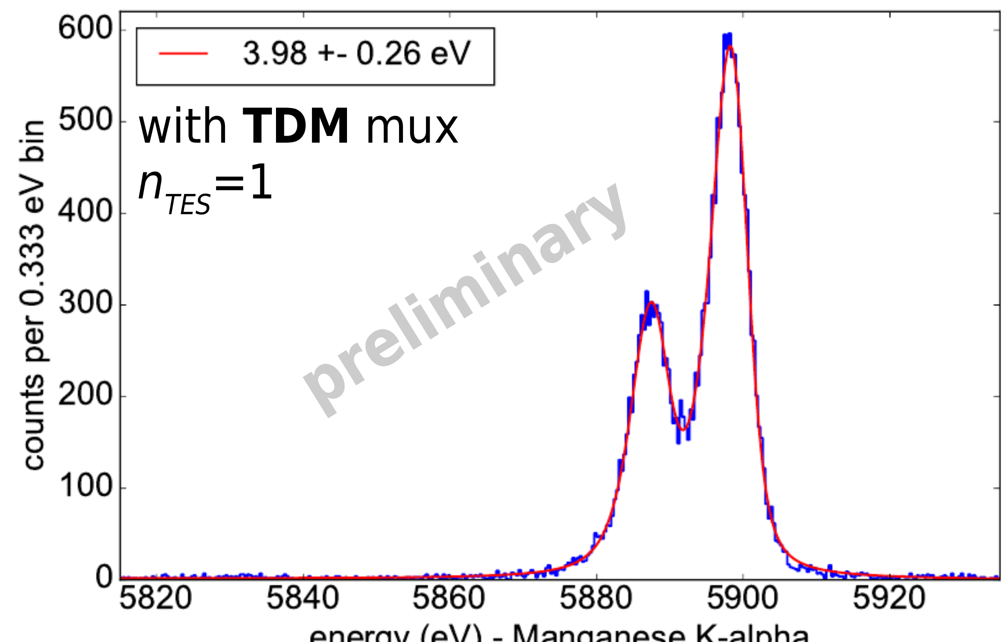
→ check for τ_R and ΔE...

HOLMES pixel design and test

- optimize design for speed and resolution
  - ▷ **specs @3keV : $\Delta E_{FWHM} \approx$ 1eV, $\tau_{rise} \approx$ 10μs, $\tau_{decay} \approx$ 100μs**
- **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

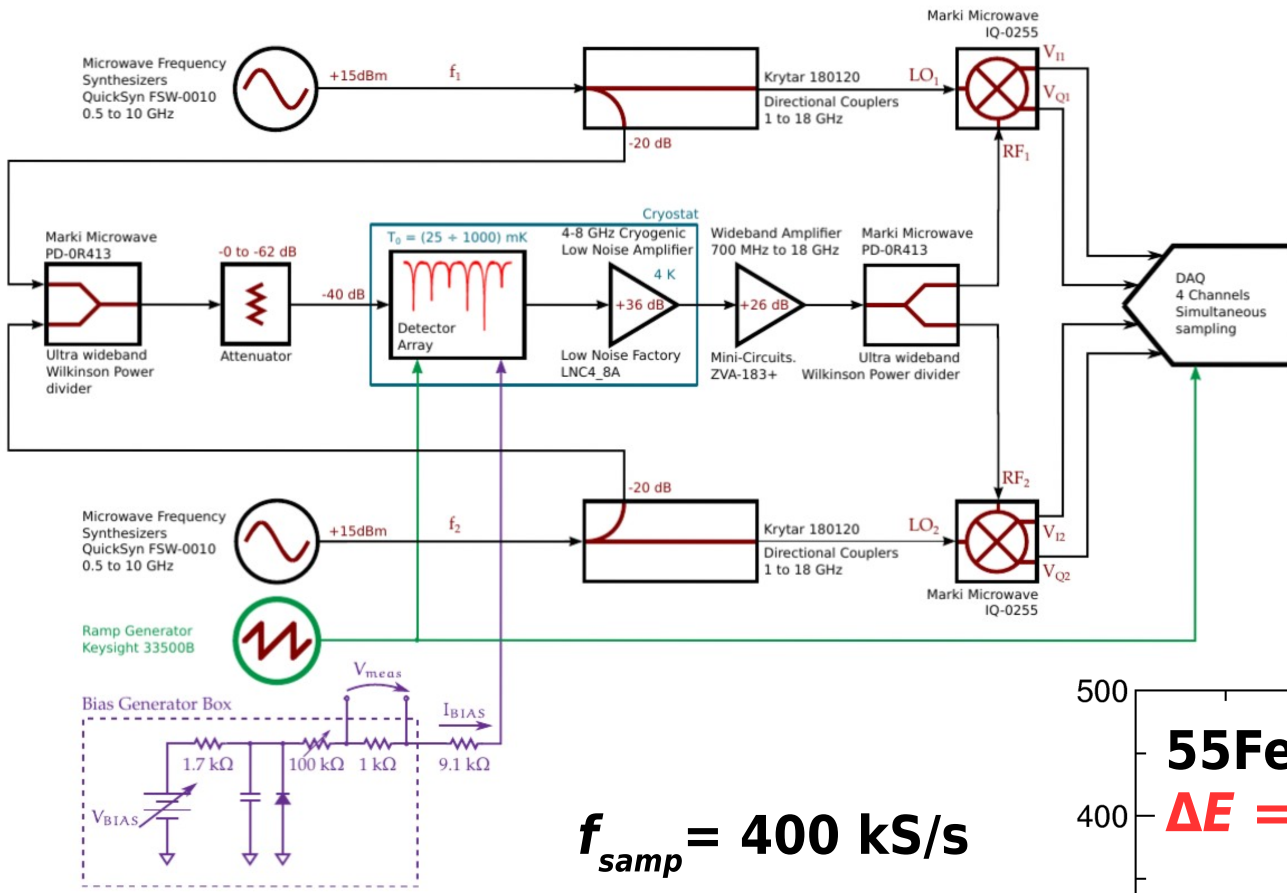


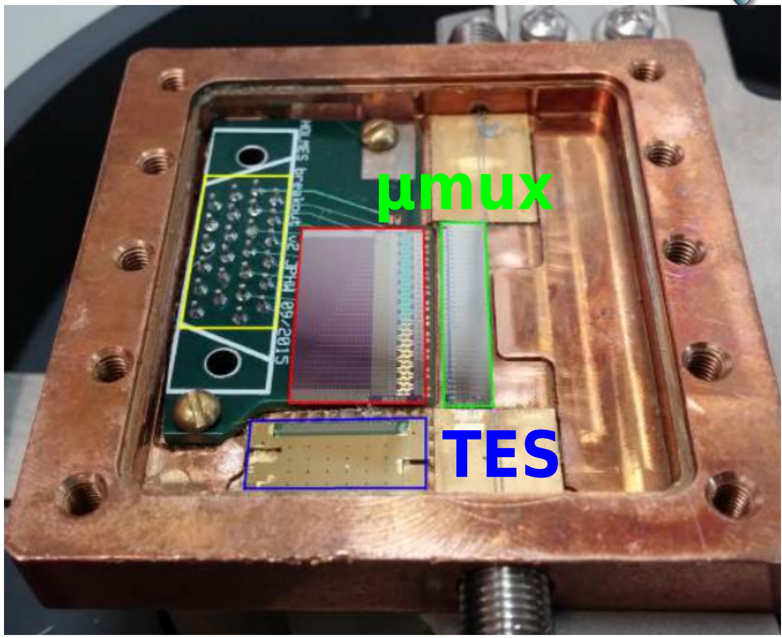
TES prototypes
fab&test @ **NIST**



- ▷ $\Delta E_{FWHM} \lesssim$ **4 eV** @ 6 keV (→ **≈3 eV** @ Q_{EC})
- ▷ $\tau_{rise} \approx$ **6 μs** (with *L*=38nH → to be slowed)
- ▷ $\tau_{decay} \approx$ **130 μs** (still tunable)

Detector testing with homodyne read-out



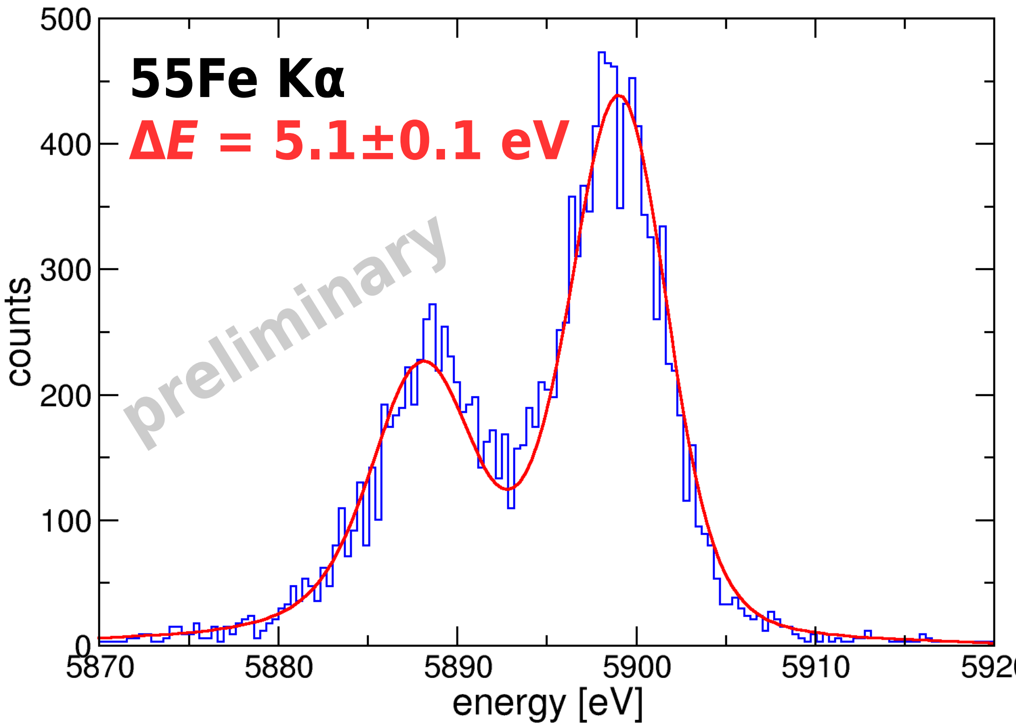


f_{samp} = 400 kS/s

ΔE_0 = 4.0 eV

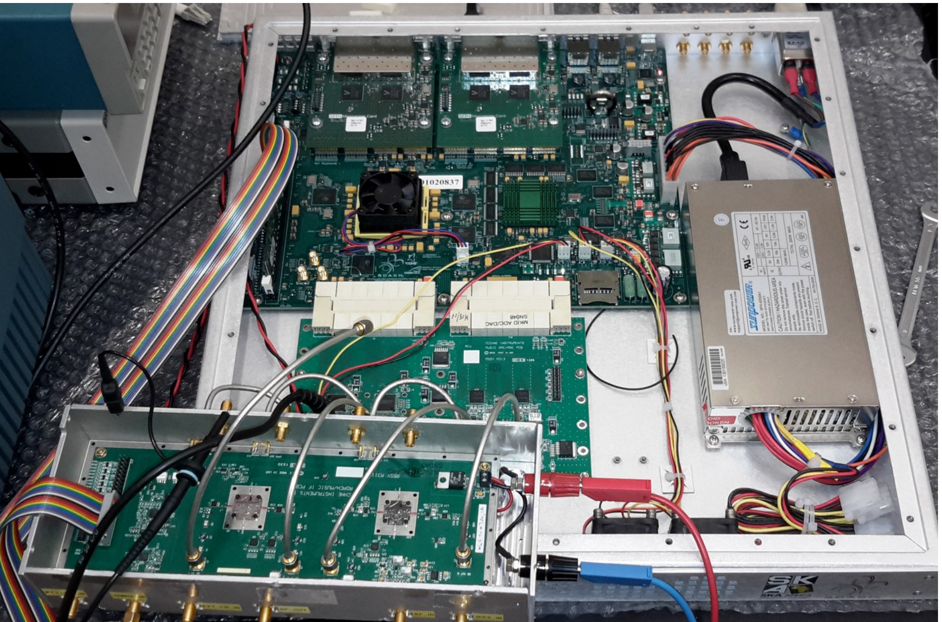
τ_{rise} = 35 µs

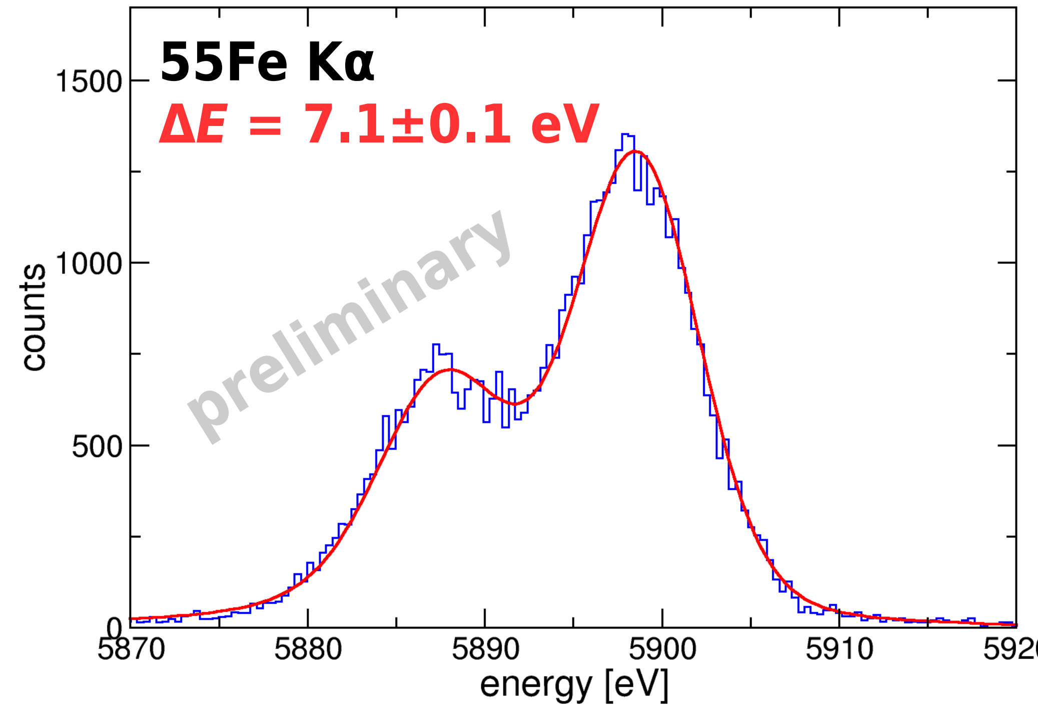
τ_{decay} = 141 µs

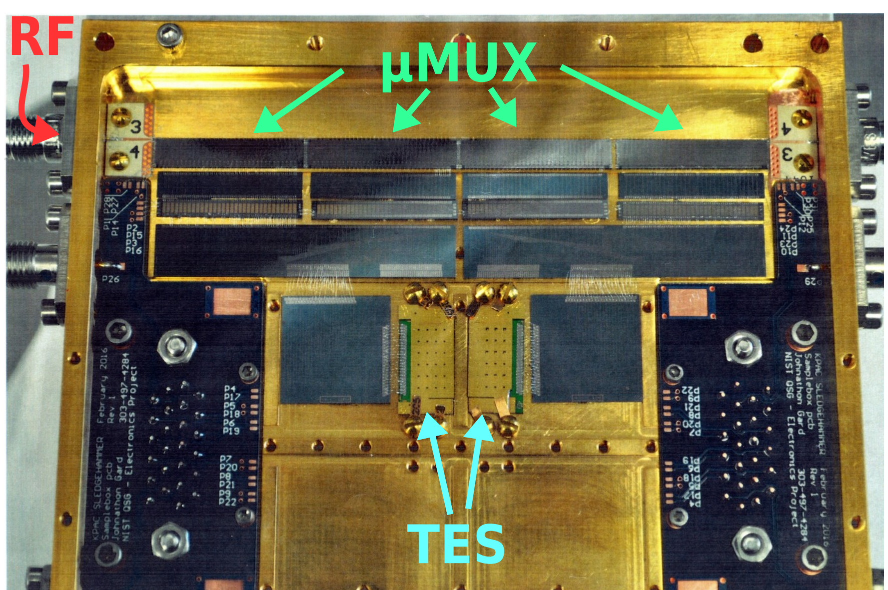


Detector testing with HOLMES DAQ

ROACH-2 based Software Defined Radio







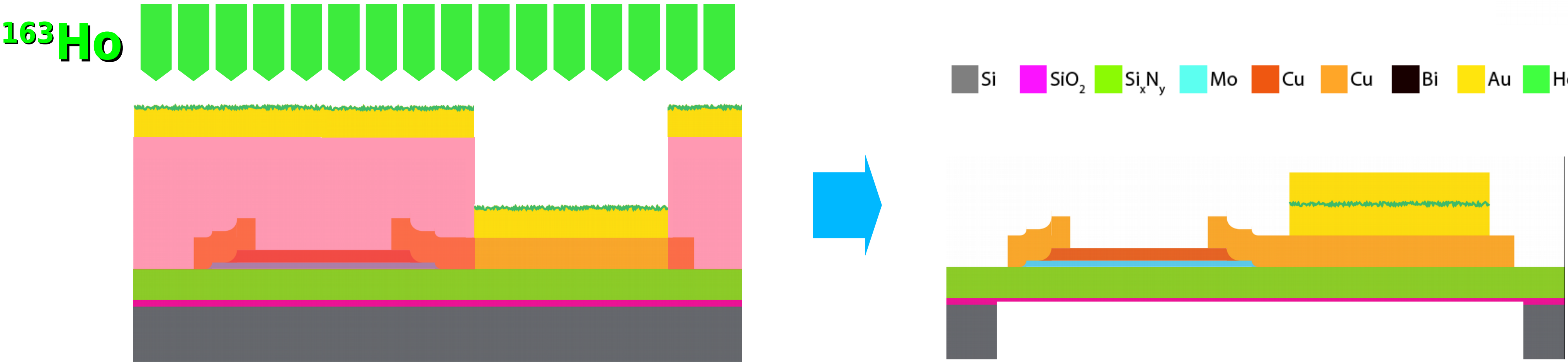
f_{samp} = 500 kS/s

ΔE_0 = 5.6 eV

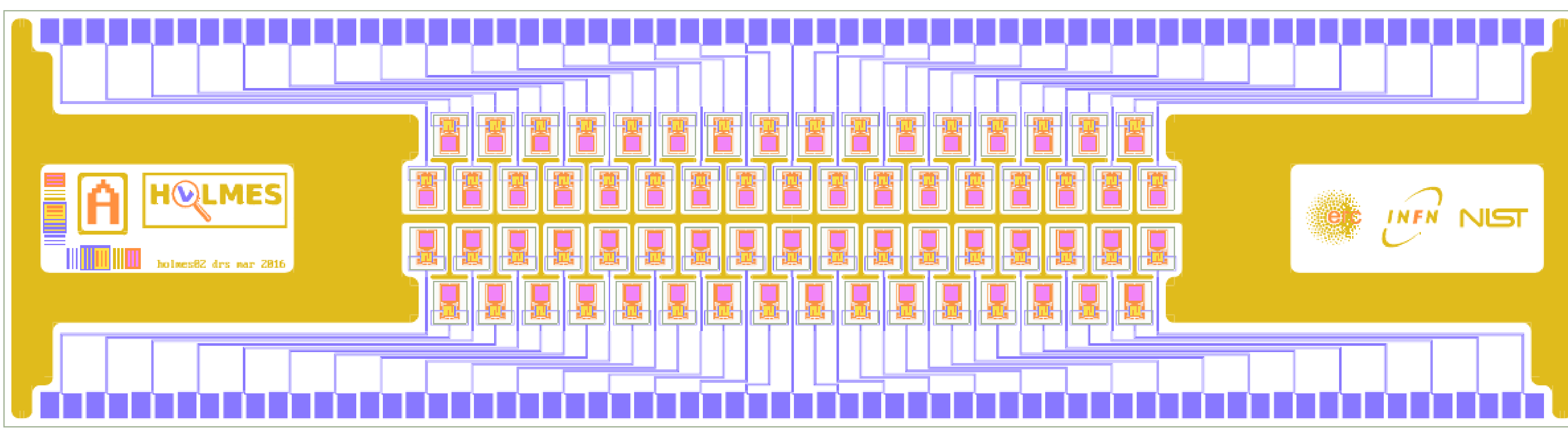
τ_{rise} = 6.5 μs

τ_{decay} = 67 μs

HOLMES detector design and fabrication

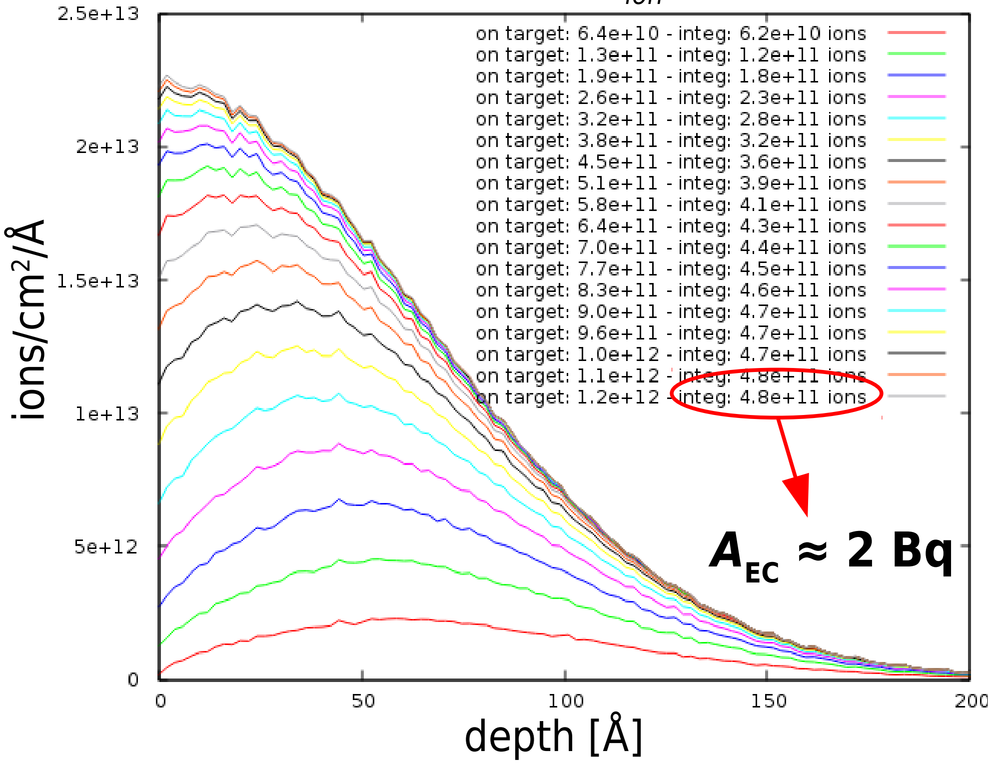


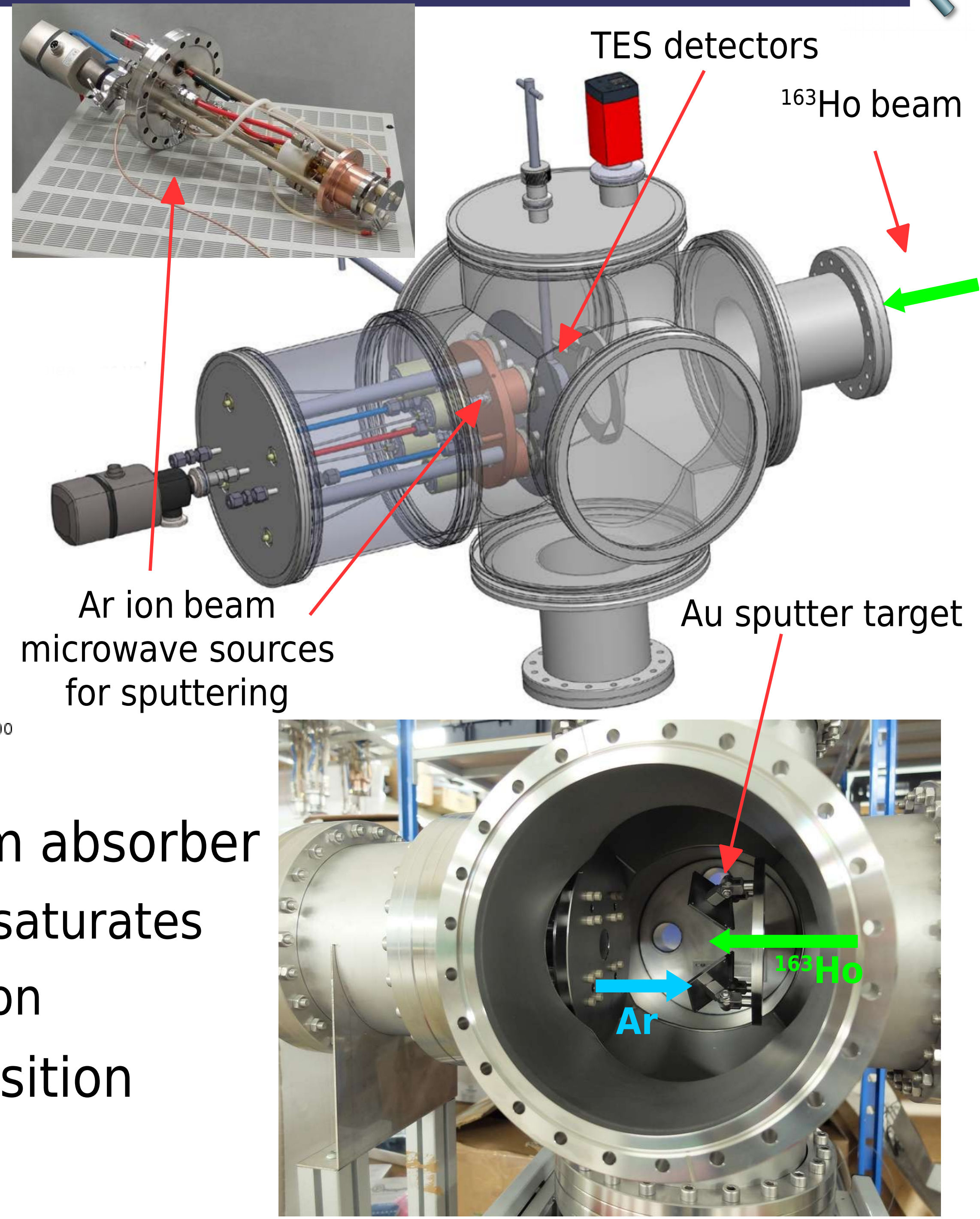
- TES array fabricated at **NIST**, Boulder, CO, USA
- ^{163}**Ho** implantation at **INFN**, Genova, Italy
- 1 μm **Au** final layer deposited at INFN Genova
- fabrication process definition in progress
- HOLMES **4×16 linear sub-array** for low parasitic *L* and high implant efficiency



Target chamber for absorber fabrication

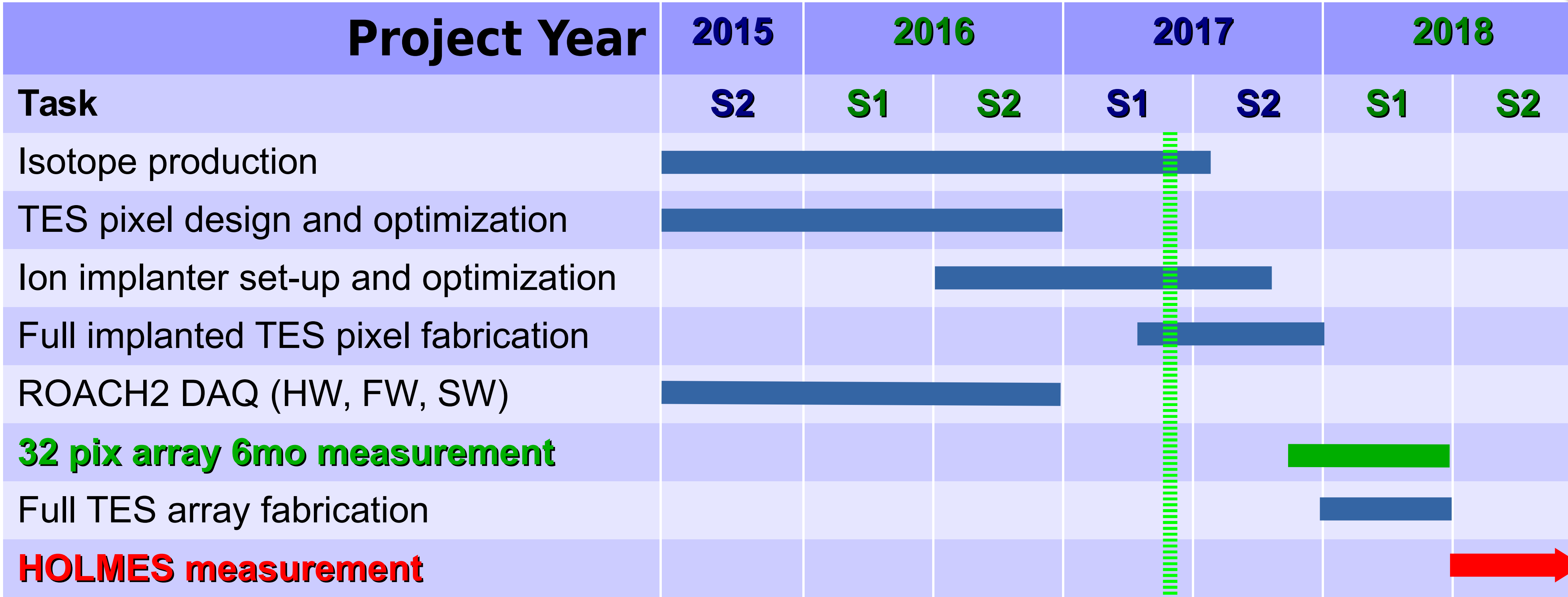
ion implant simulation with SRIM2013
^{163}Ho ions on Au (E_{ion} = 50 keV)





- ^{163}Ho ion beam sputters Au from absorber
  - ^{163}Ho concentration in absorber saturates
  - compensate by Au co-evaporation
- final 1 µm Au layer in situ deposition
- **tests are in progress**

HOLMES schedule and conclusions

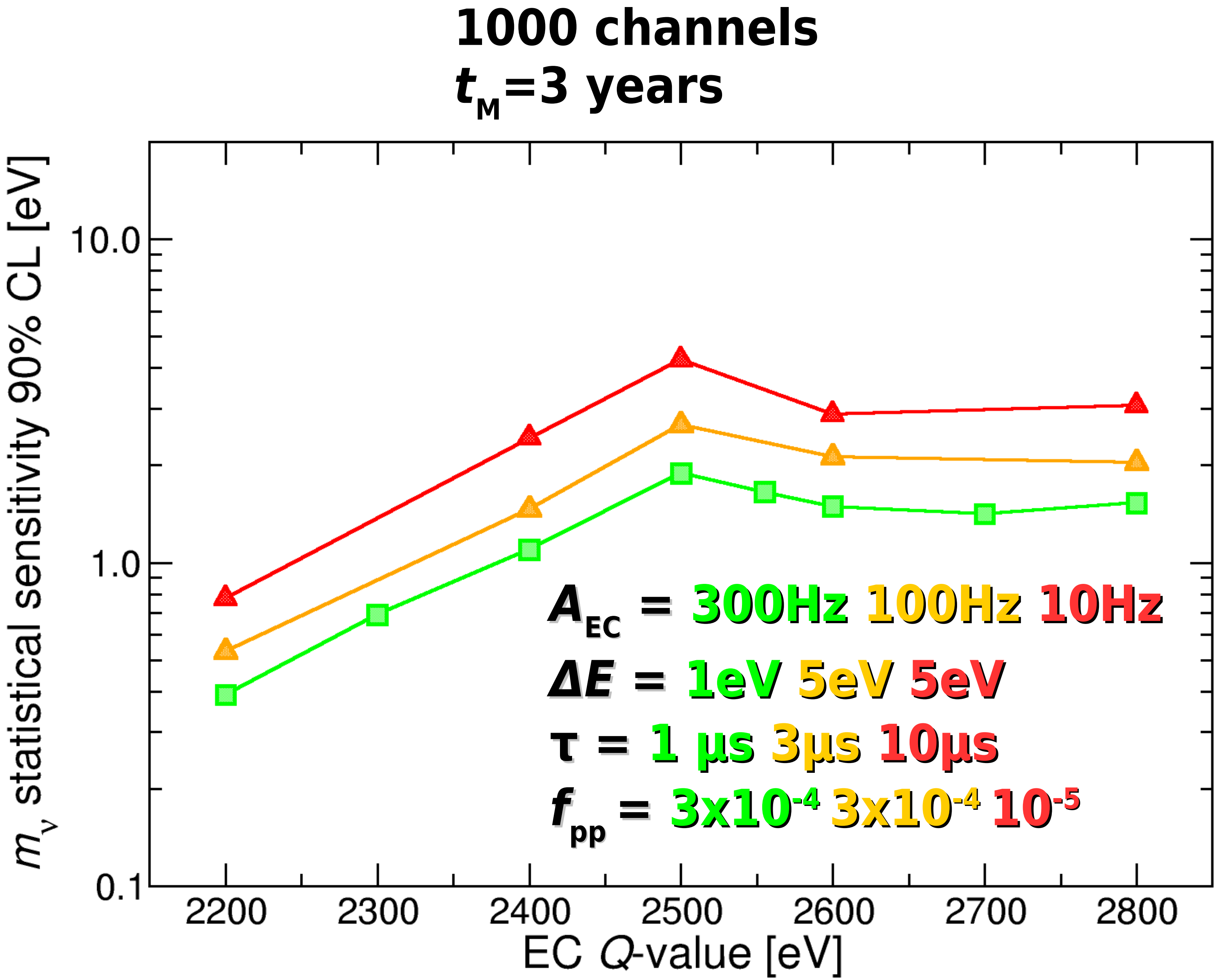


- **HOLMES project status**
  - many technical challenges are being addressed in parallel
  - design phase is complete
  - ion implanter setting up is in progress
  - first ^{163}Ho implantation coming shortly
  - spectrum measurements will begin late in 2017

Backup slides

...

Worst case scenarios…

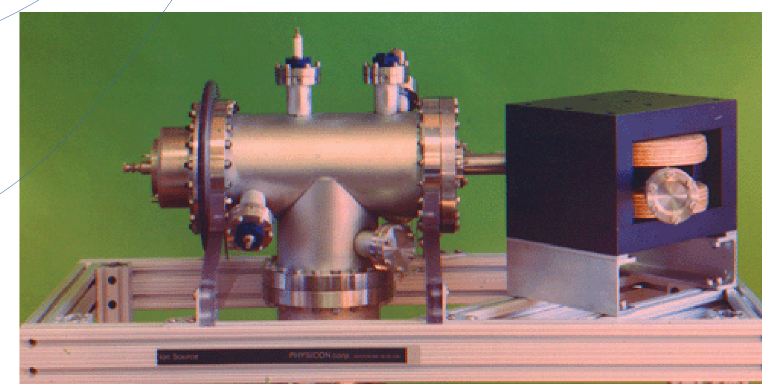


^{163}Ho production and embedding

- **^{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



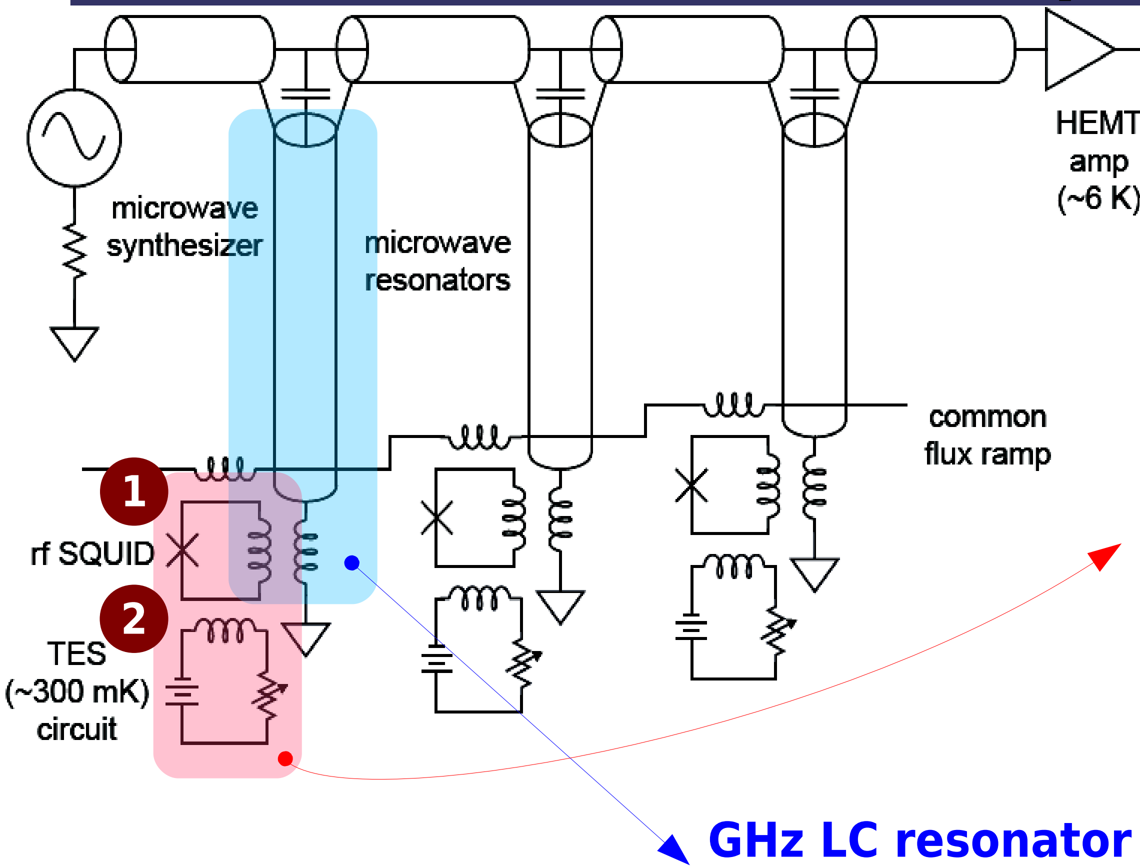
ECHO

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}

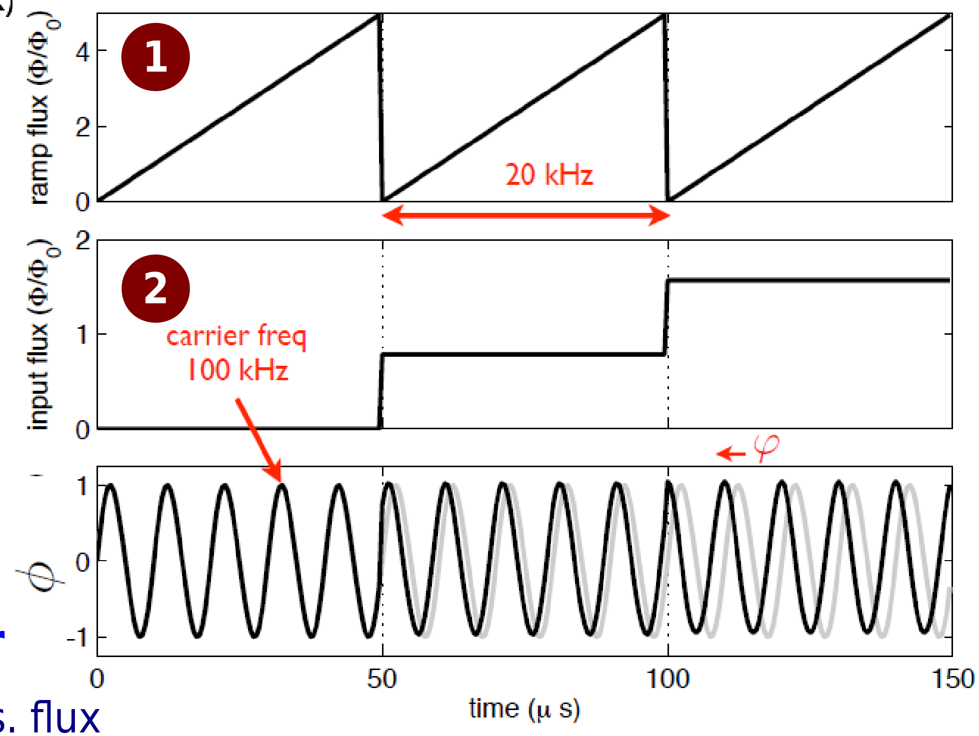
U. Koester @NuMass 2013

rf-SQUID microwave multiplexing

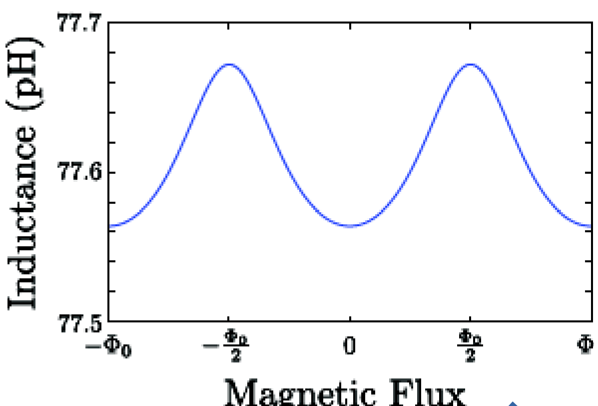


GHz LC resonator

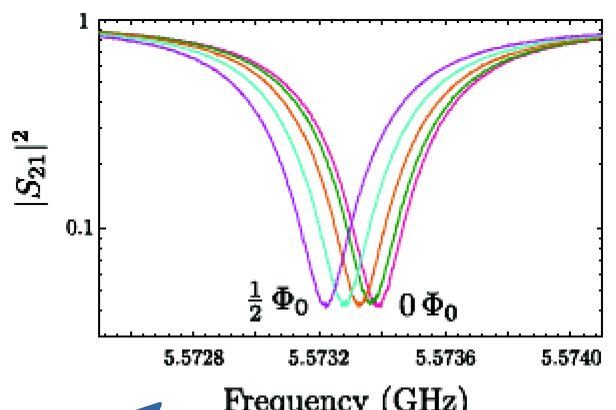
MHz flux ramp modulation



rf-SQUID inductance vs. flux



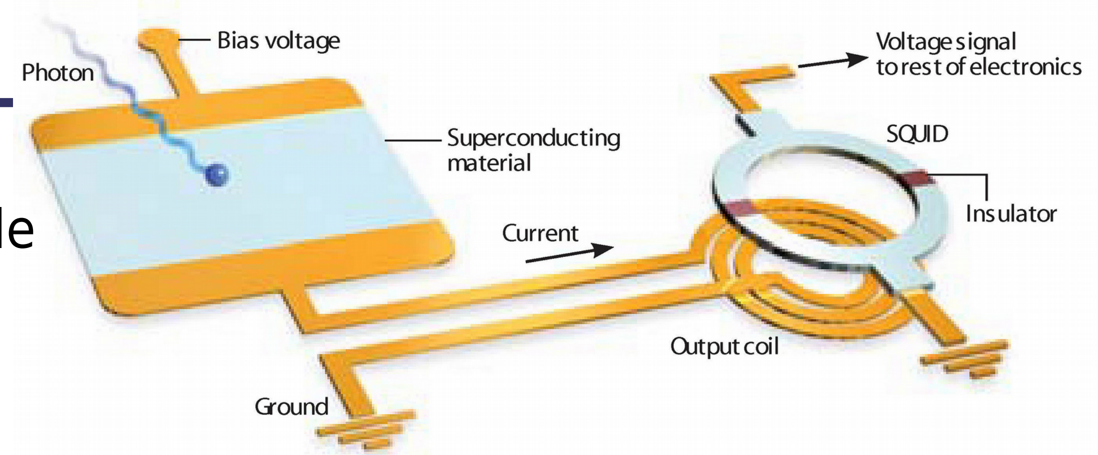
resonance frequency vs. flux

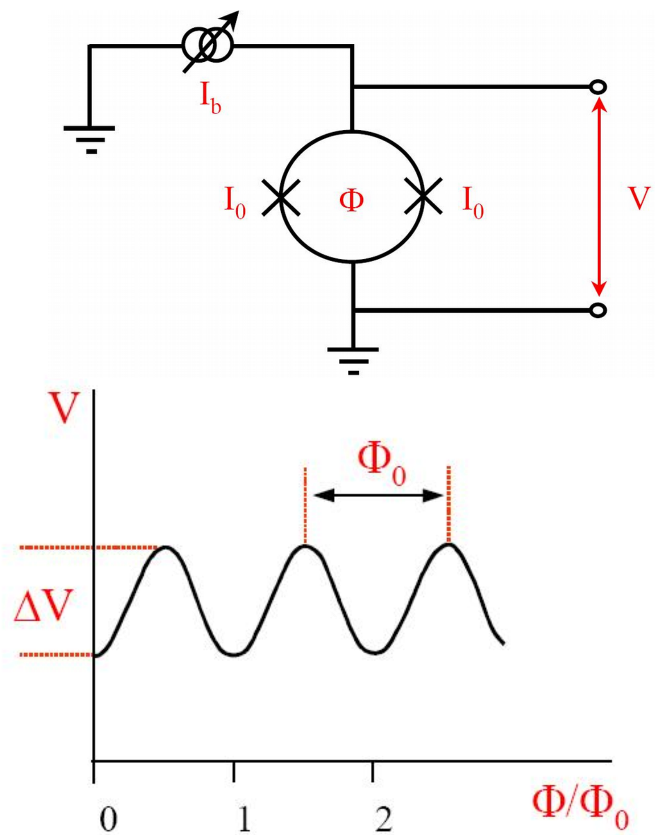


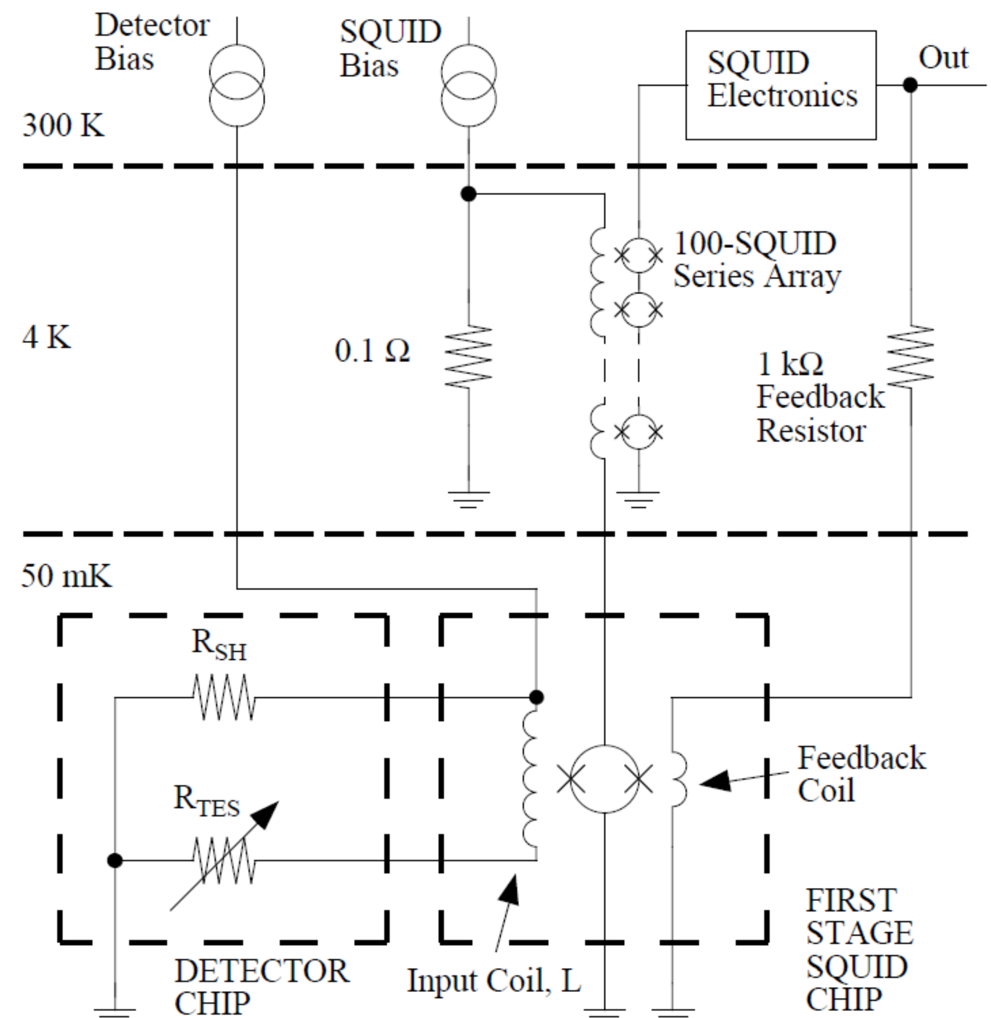
J. Brevik @ LTD15

TES read-out: SQUID

- low impedance suitable for multiplexable dc-SQUID magnetometers
- current amplifier configuration
  - ▷ $\Delta I \rightarrow \Delta \Phi \rightarrow \Delta V$
- feedback linearized response







The holmium experiments

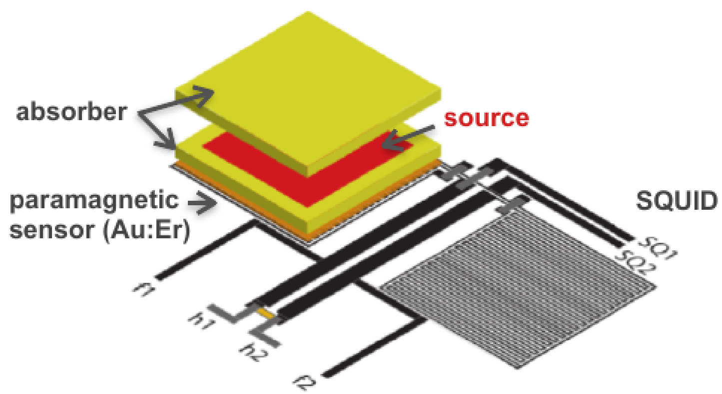
	ECHo	HOLMES	NUMECS
^{163}Ho production	^{162}Er (n, γ)	^{162}Er (n, γ)	Dy (p, nx)
Absorber	Gold	Gold	Nanoporous gold
Sensor	Au:Er magnetic	TES Mo/Cu	TES Mo/Cu
	Present status		
ΔE at M1 peak [eV]	12	—	43 (incl. Γ_{M1})
τ_{rise} [μs]	0.13	—	—
A_{EC} [Bq]	0.2	—	0.1
	Projected (E_0 = 2800 eV)		
N_{det}	100	1000	4096
ΔE [eV]	<5	1	—
τ_{rise} [μs]	<1	1	—
A_{EC} [Bq/detector]	10	300	100
f_{pp}	10^{-6}	3×10^{-4}	—
t_M [y]	1	3	1
$\Sigma_{90}(m_{\nu_e})$ [eV]	10	1.5	1

dal talk di Kathrin Valerius a Neutrino 2016

The ECHo Experiment

Heidelberg (Univ., MPIK), U Mainz, U Tübingen, TU Dresden, U Frankfurt, HU Berlin, ILL Grenoble, PNPI St Petersburg, U Bratislava, IIT Roorkee, Saha Inst. Kolkata

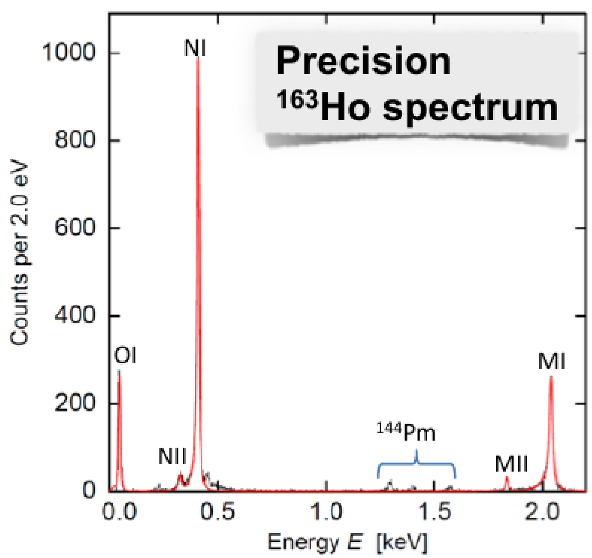
[Fleischmann et al. 2009; Gastaldo et al. 2013]



Technology

- magnetic micro-calorimeter (MMC) arrays with microwave squid multiplexing readout
- fast rise time (~130 ns) and excellent linearity & resolution (ΔE ~ 5 eV)
- isotope production: $^{162}Er(n,\gamma)^{163}Ho$ offline mass separation

[Ranitzsch et al., arXiv:1409:0071; Gastaldo et al. 2014]



- ☑ new improved detectors
- ☑ improved implantation with purified source
- ☑ proof of multiplexed readout
- ☑ first underground meas.

Timeline

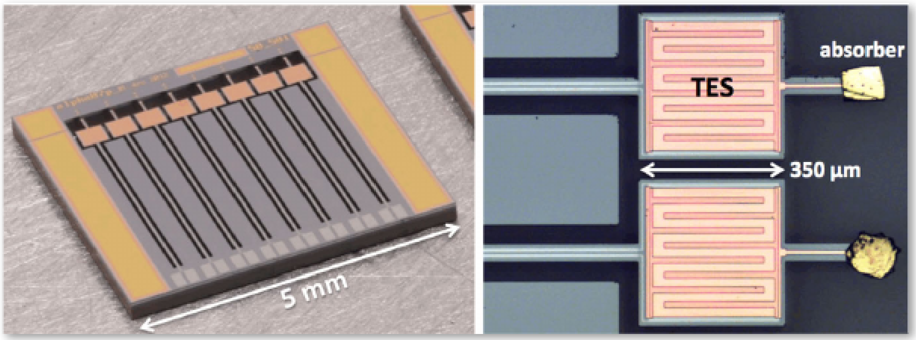
- **Phase I: ECHo-1k**
  to be completed by 2018
  2 x 50 pixel x 10 Bq,
  4 months: $m(\nu_e) < 10$ eV
- **Phase II: ECHo-1M**
  array of 10^5 detectors
  50 x 2000 pixel x 10 Bq,
  2 years: sub-eV sensitivity

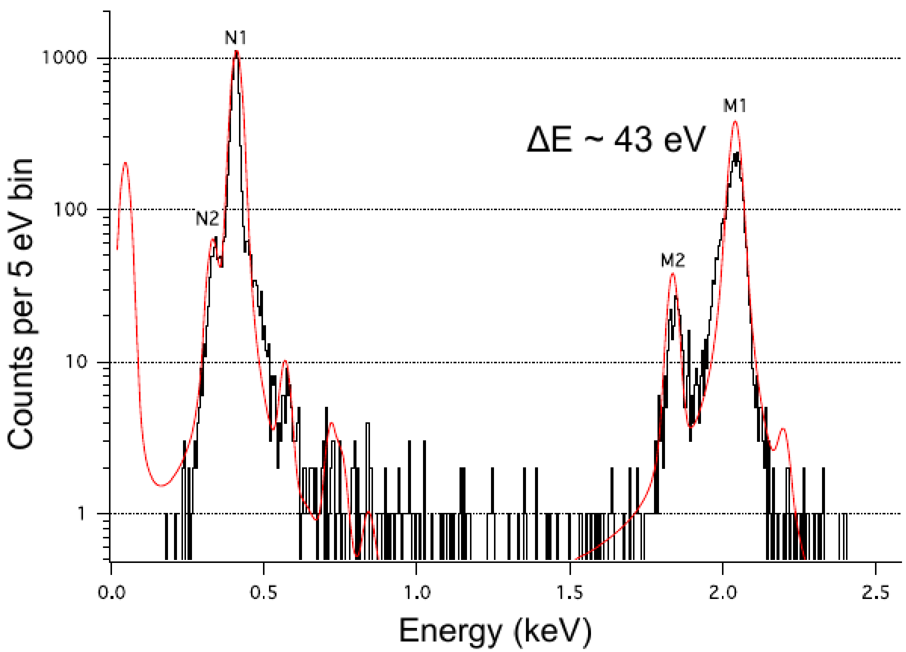
23 [L. Gastaldo *et al.*, J. Low Temp. Phys. 176 (2014) 876]

P1.046, C. Enss | P4.037, S. Scholl | P4.038, L. Gastaldo

The NuMECS Experiment

Los Alamos National Laboratory · NIST · Wisconsin





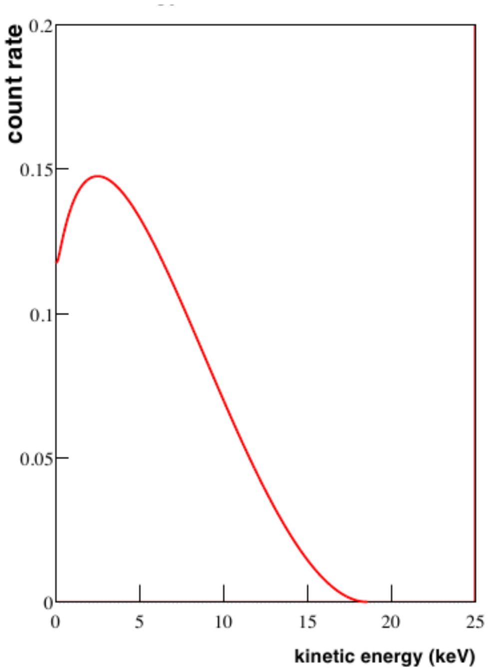
Technology

- transition-edge sensors (TES, Mo-Cu bilayer)
- gold foil absorbers with dried solution containing ^{163}Ho
- ^{163}Ho production by proton irradiation of natural dysprosium

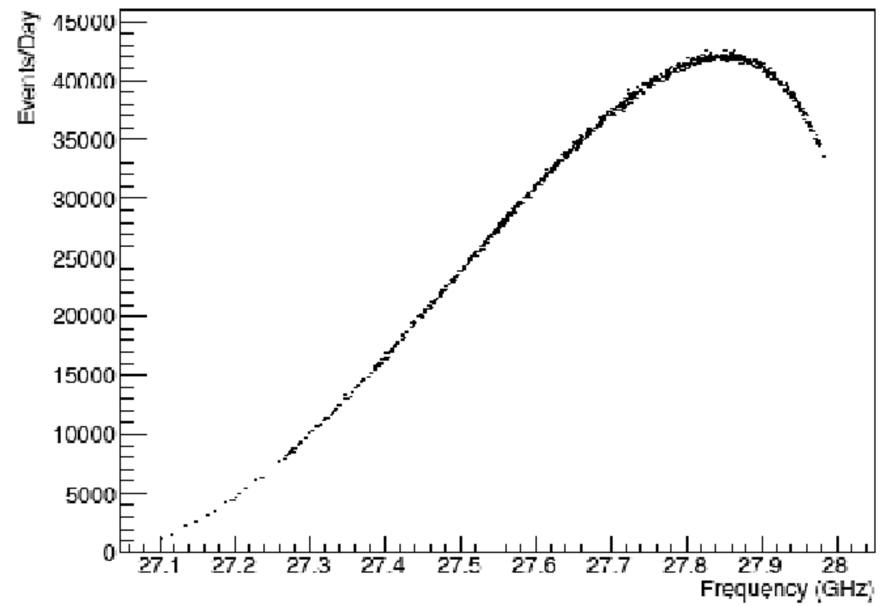
^{163}Ho spectrum

- obtained after systematic improvement of absorber production
- still limited statistics (40 hrs, 0.1 Bq) and resolution

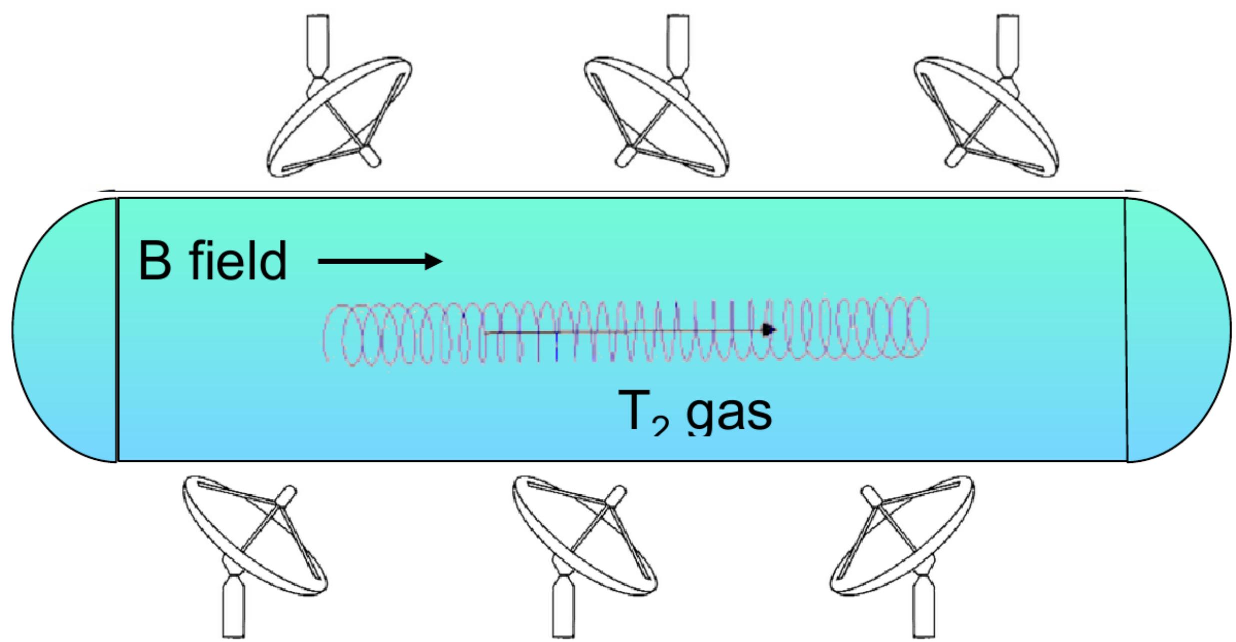
21 [Croce *et al.*, J. Low Temp. Phys. 2016] K. Valerius, KIT | Direct probes of neutrino mass | NEUTRINO 2016



$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$



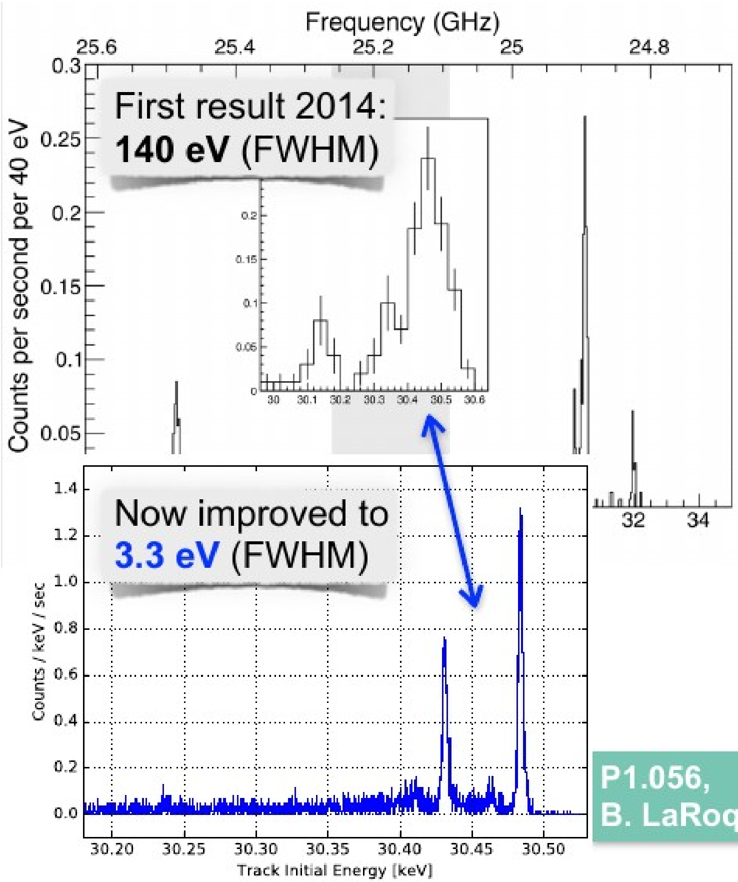
GHz cyclotron radiation detection to measure *K*



uniform B field + low pressure T2 gas

Project 8 – next goals

- **Phase I (2010-2016)**
  - Demonstration of CRES method
  - Conversion electron lines from ^{83m}Kr



P1.056, B. LaRoque

- **Phase II (2015-2017)**
  - Spectroscopy of continuous T_2 spectrum
  - Systematics, energy resolution

P1.057, N. Oblath

- **Phase III (2016-2020)**

  10-20 cm^3 eff. source volume (1 yr)
  phased-array antenna
  sensitivity goal: 2 eV (90% CL)

P4.047, B. VanDevender

- **Phase IV**

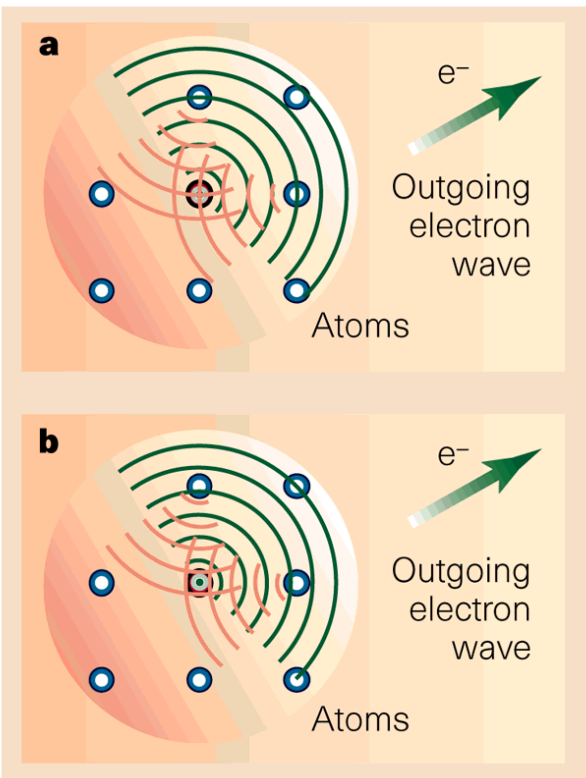
  Large-scale exp., with atomic tritium source, for sub-eV sensitivity (hierarchy scale)

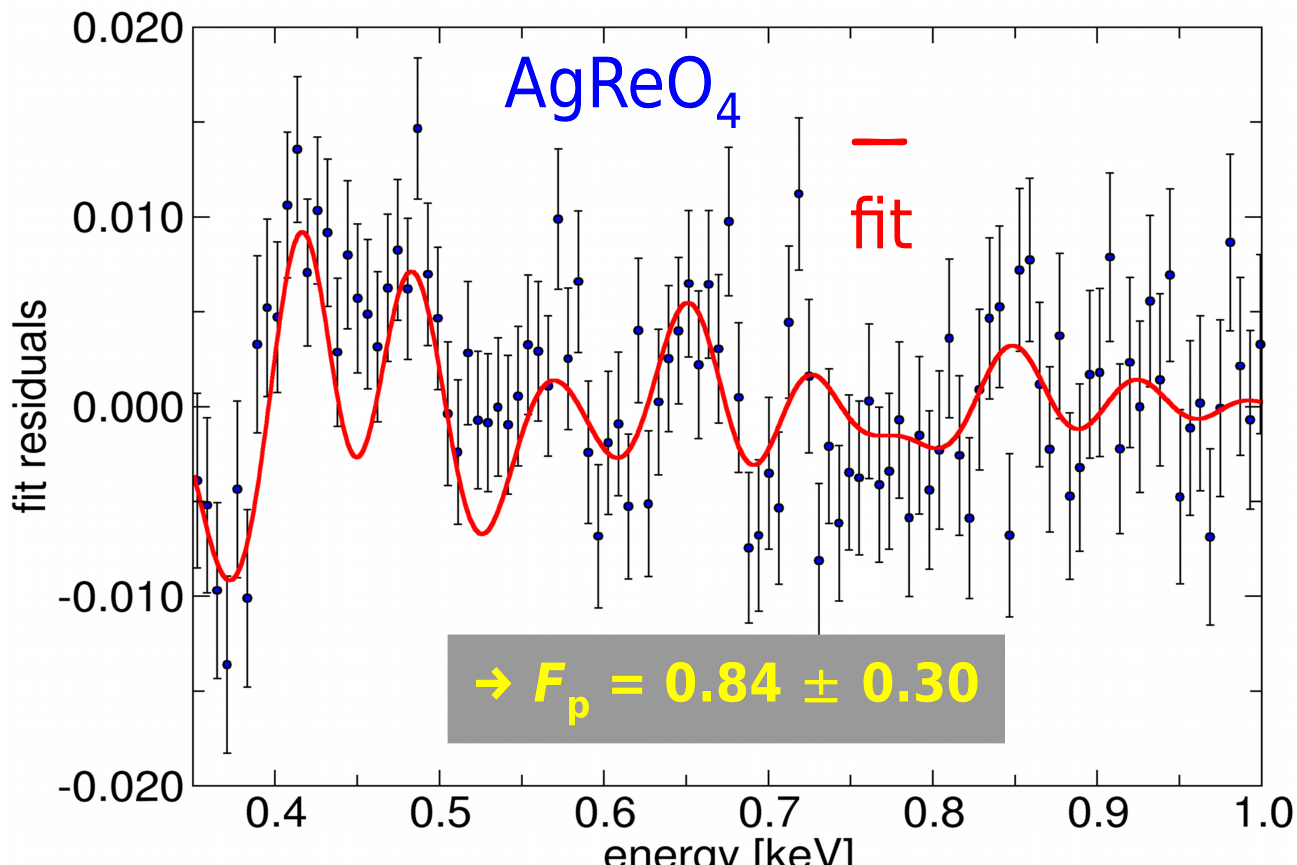
BEFS: Beta Environmental Fine Structure

Modulation of the electron emission probability due to the atomic and molecular surrounding of the decaying nucleus: it is explained by the wave structure of the electron (analogous of EXAFS)

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

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



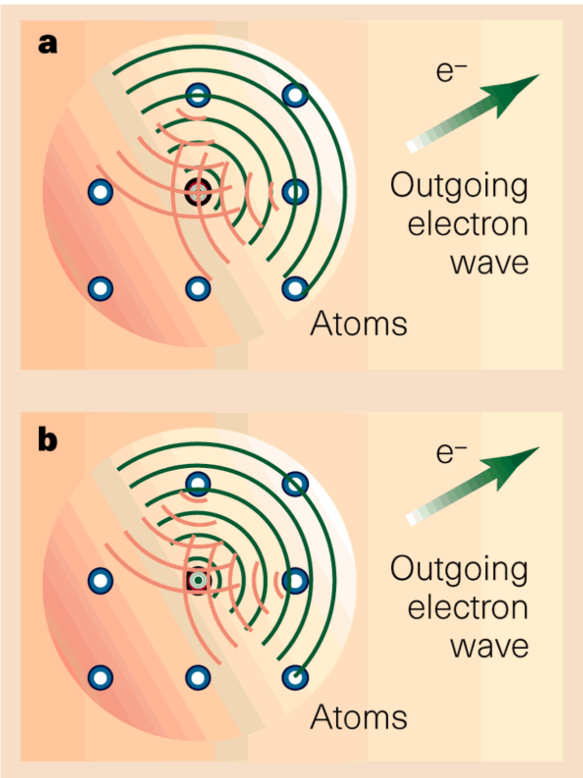


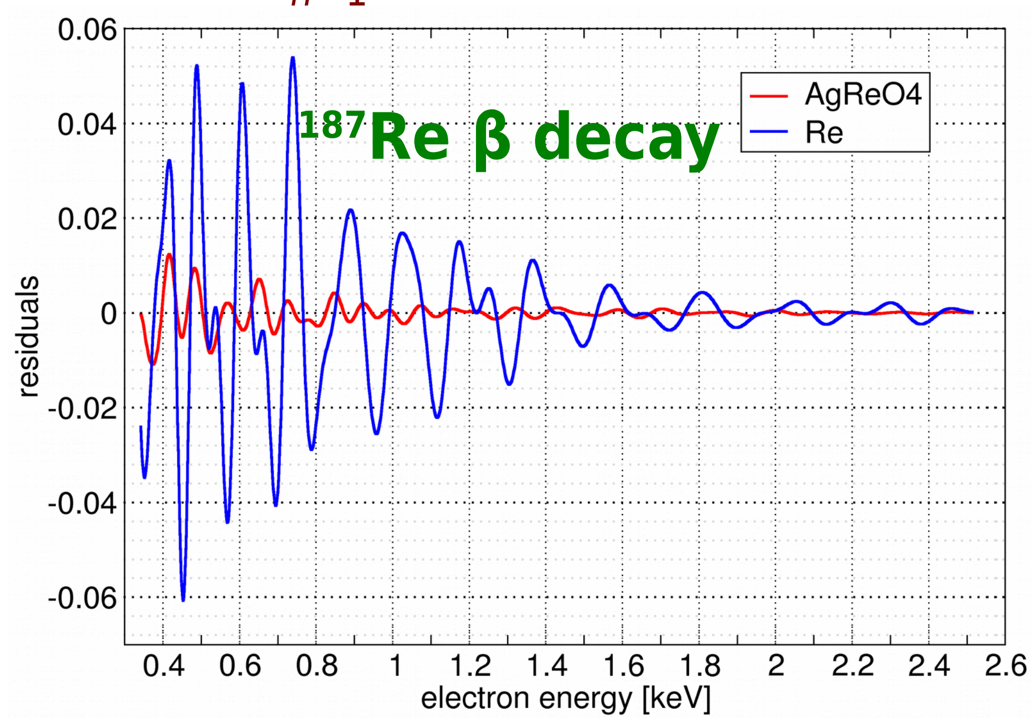
C. Arnaboldi et al., Phys. Rev. Lett. 96 (2006) 042503 (for BEFS in Rhenium: F. Gatti et al. Nature, 397 (1999) 137)

Beta Environmental Fine Structure in ^{163}Ho?

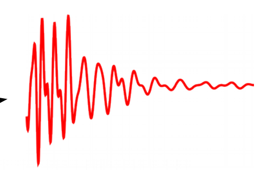
$$\chi_{BEFS}(k_e) = F_s \chi_{EXAFS}^{l=0} + F_p \chi_{EXAFS}^{l=1}$$

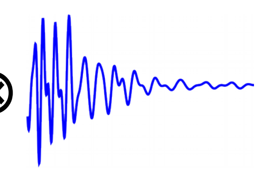
$$\chi_{EXAFS}^{l}(k_e) = (-1)^l \sum_{n=1}^{N} B_{nl}(k_e, R_n) e^{-2k_e^2 \sigma_n^2} \sin(2k_e R_n + \delta_{0l} + \delta_{nl})$$



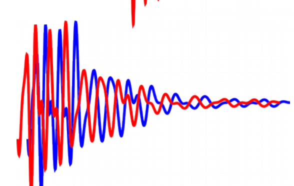


- what about **BEFS in ^{163}Ho** spectra?
  - E_c deposited by cascade processes → **convolution**?





  - different transition sequences → **cancellation**?



  - smeared position of ^{163}Ho in host lattice → **attenuation**?

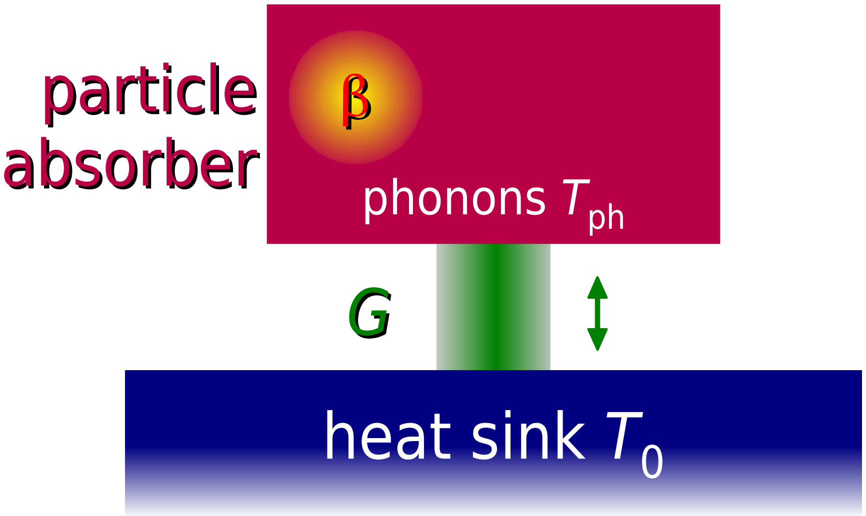
Resolution limit: LTD vs. ionization detectors

Ionization detectors

- measure only the energy that goes into ionization ($\sim$1/3)
  - in semiconductors: energy to create an *e-h* pair $W_0 \approx 3$ eV $\Rightarrow N_{eh} = E/W_0$
  - statistical fluctuations on N_{eh} limit the energy resolution: $\sigma_E = \sqrt{F\, N_{eh}}\, W_0 = \sqrt{F\, E\, W_0}$
  - in practice: $\Delta E_{FWHM} \approx$ **115 eV at 6 keV for silicon**
- other limitations from electron transport properties (material restriction, purity...)

Cryogenic detectors

- measure the energy that goes into heat (100%)
  - no branching $\Rightarrow$ no statistical fluctuations
  - resolution limit: random energy flow through G
  - statistical fluctuations of internal energy $U = \langle U \rangle \pm \Delta U_{rms}$



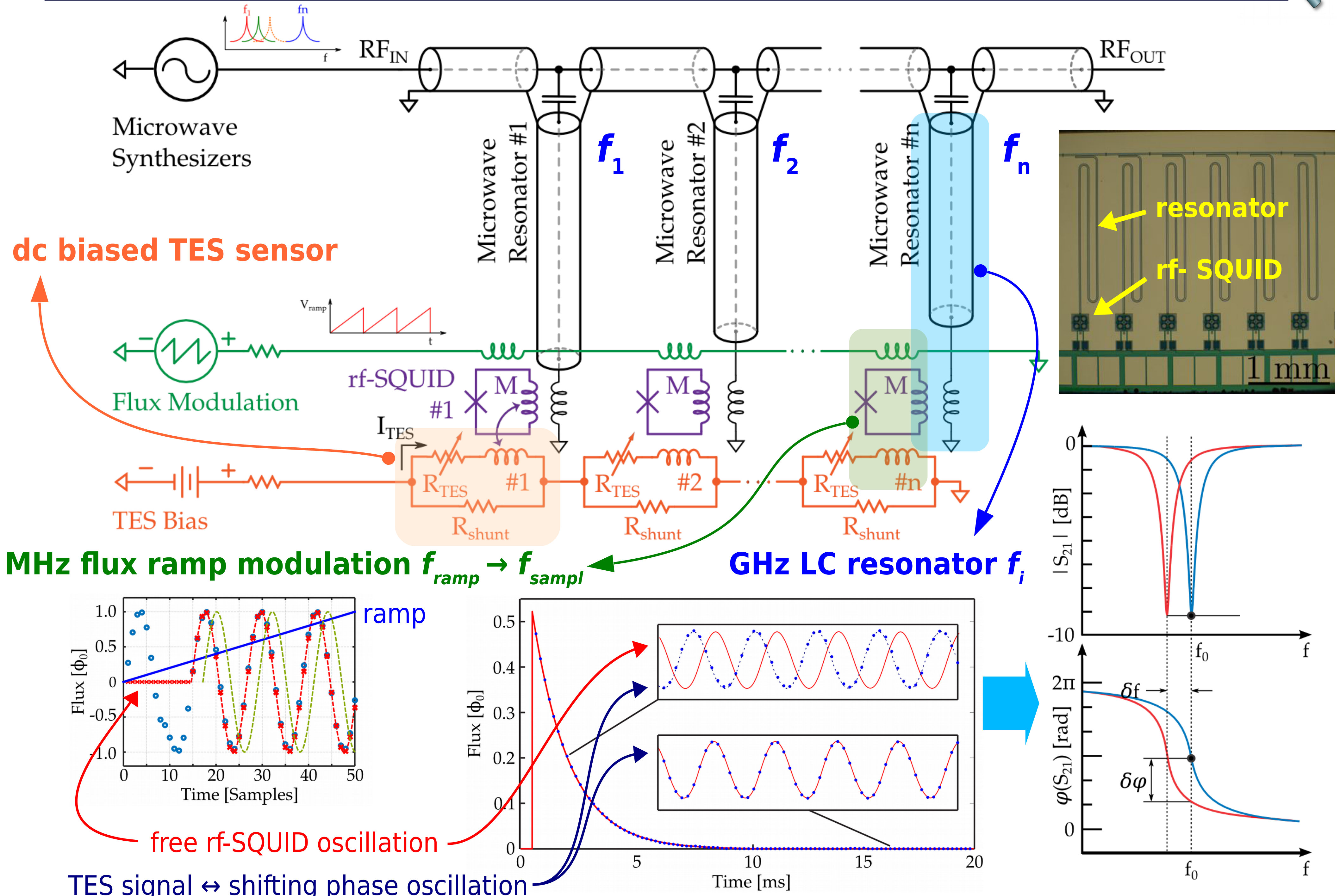
$$N_{ph} = \frac{\langle U \rangle}{\langle E_{ph} \rangle} = \frac{CT}{k_B T}$$

$$\Delta U_{rms} = \sqrt{N_{ph}}\,(k_B T) = \sqrt{k_B T^2 C}$$

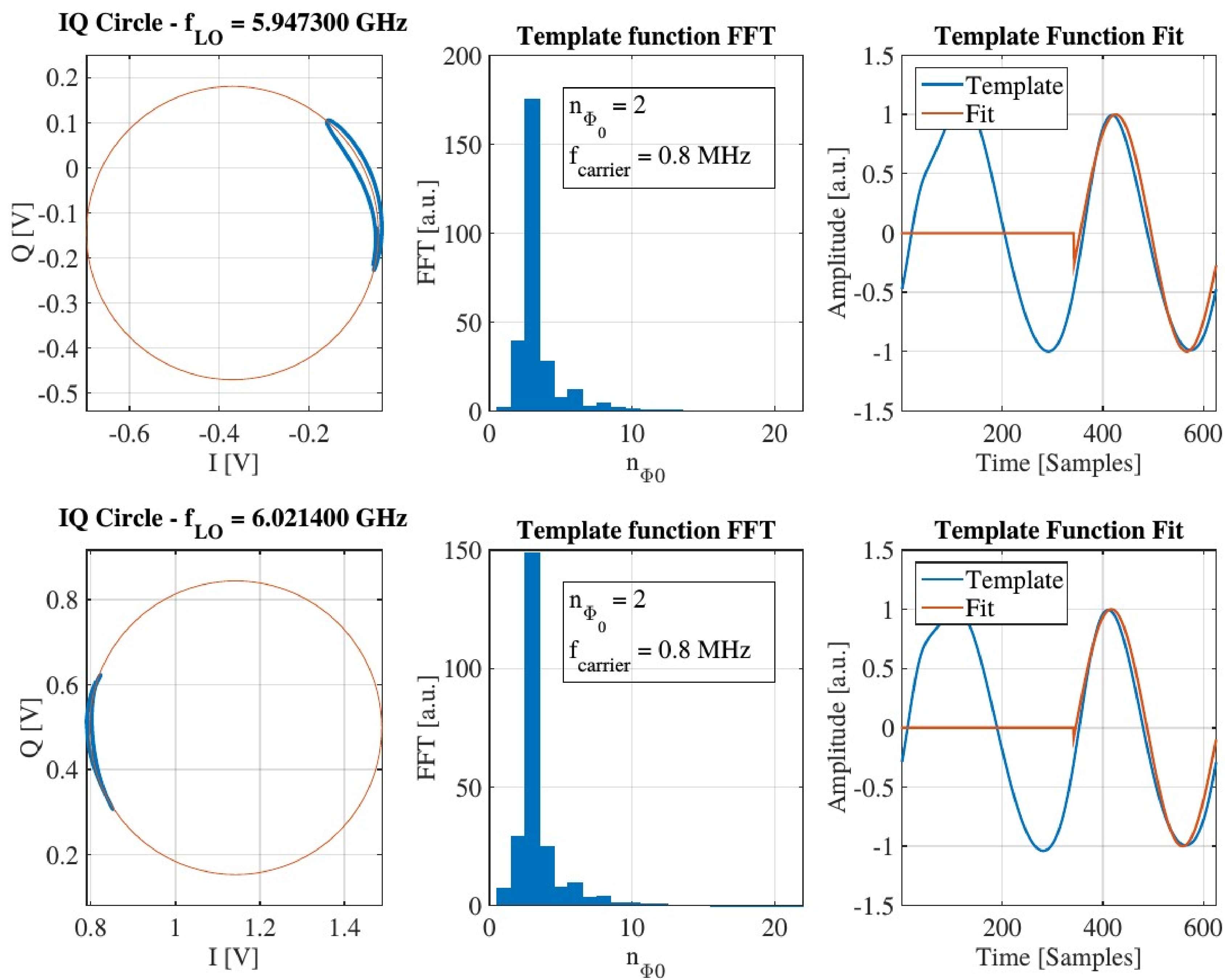
1 mg of Re @ 100 mK

$C \sim 10^{-13}$ J/K $\Rightarrow$ $\Delta U_{rms} \sim$ **1 eV**

HOLMES array read-out: rf-SQUID µwave mux



Ramp demodulation

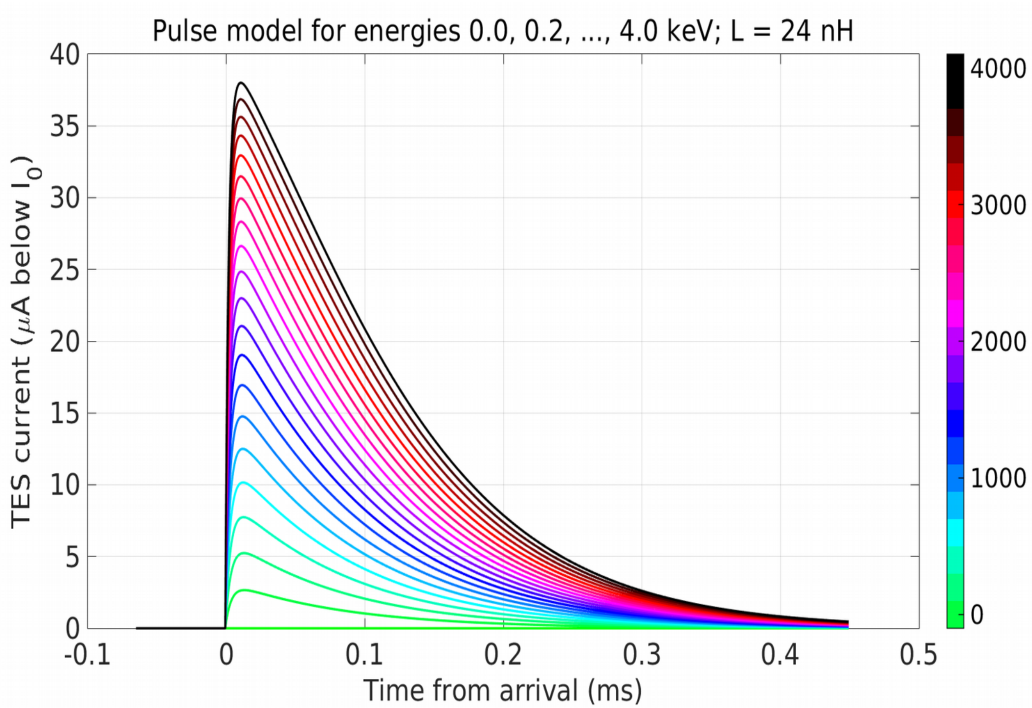


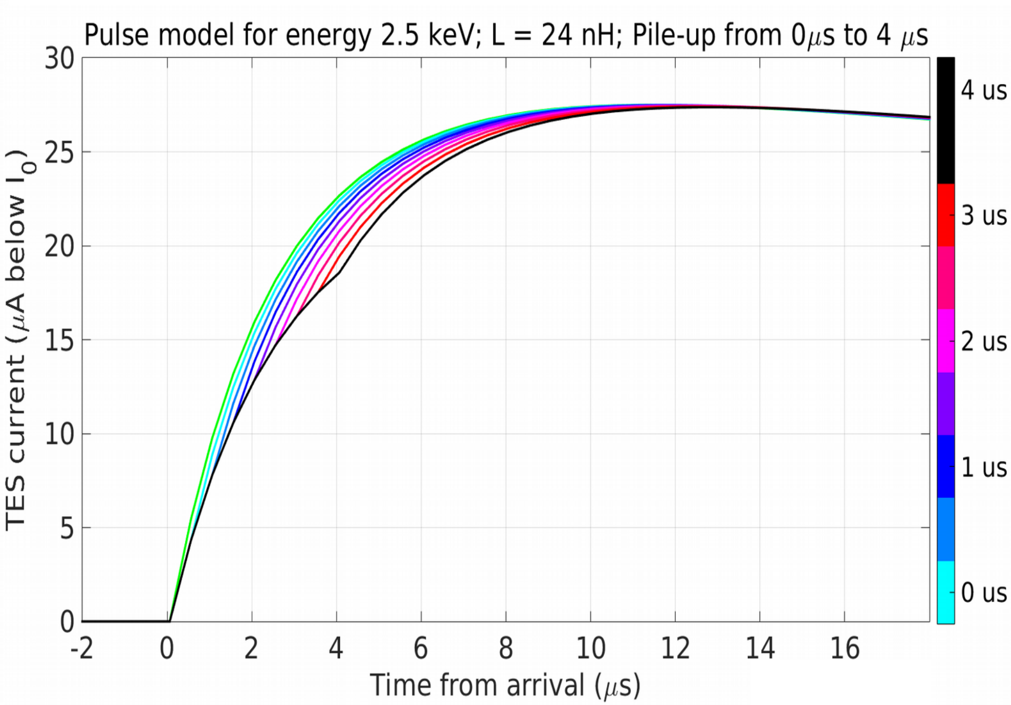
Rise time pile-up

2 pulses with:

- τ_{rise}= 1.5 ms
- τ_{decay}= 10 ms
- A_2/A_1 = 0.5

$$A(t)=A\left(e^{-t/\tau_{decay}}-e^{-t/\tau_{rise}}\right)$$





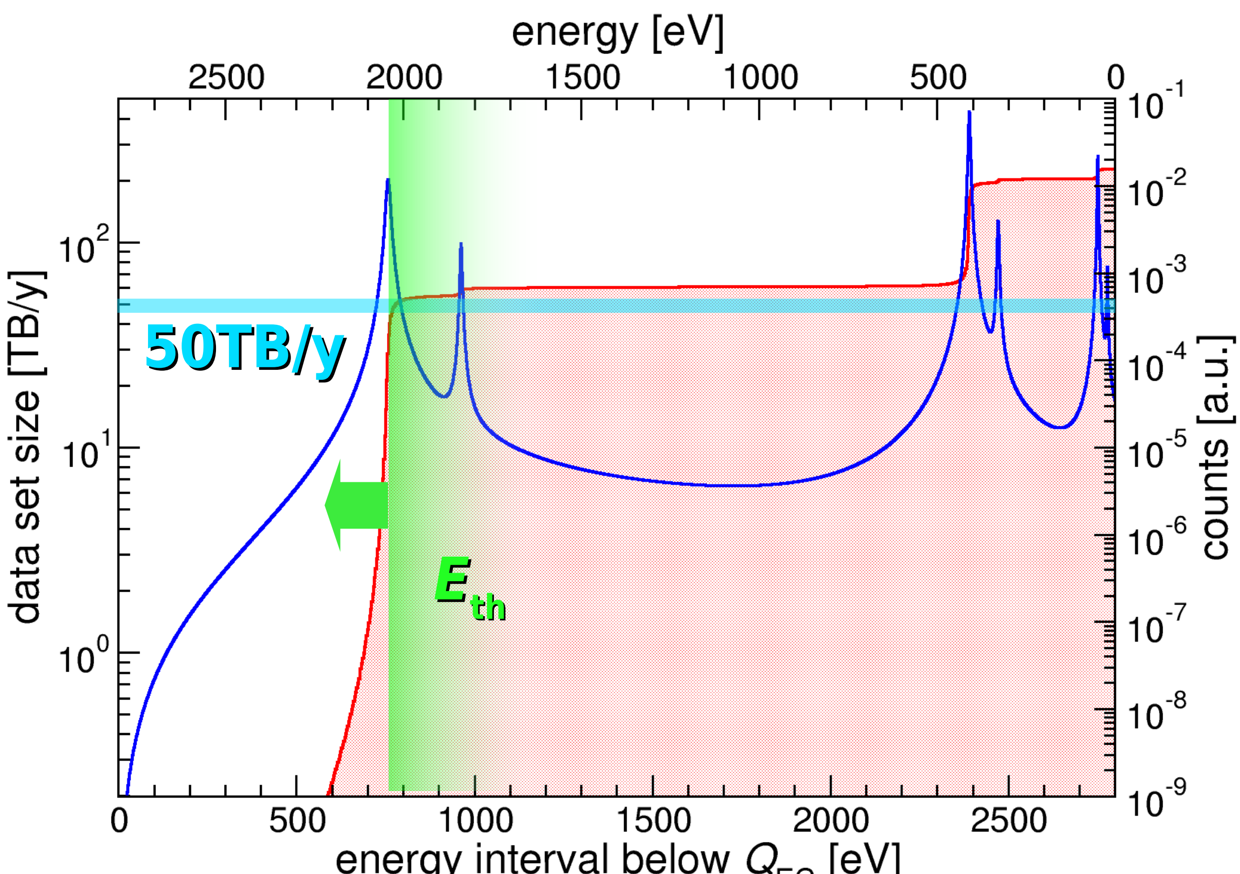
HOLMES signal processing and in-line analysis

* 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
- …

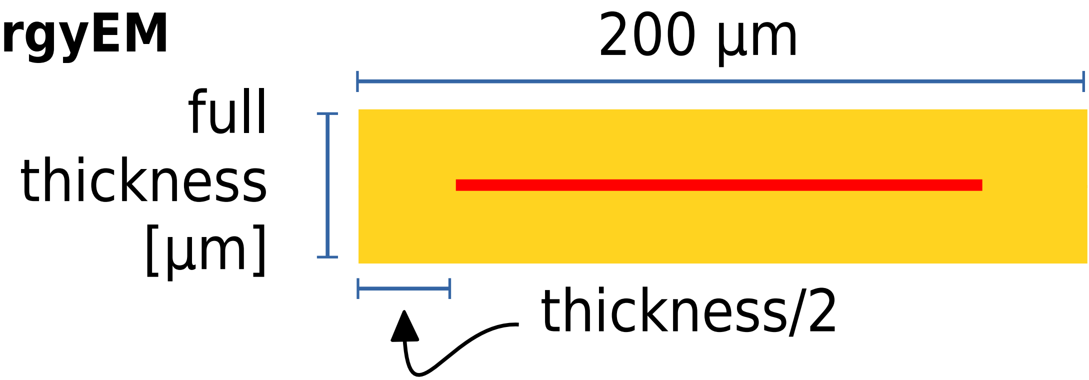
SERVER *quasi* real-time pulse processing:
- OF analysis → *n*-tuples
- pile-up detection
- …

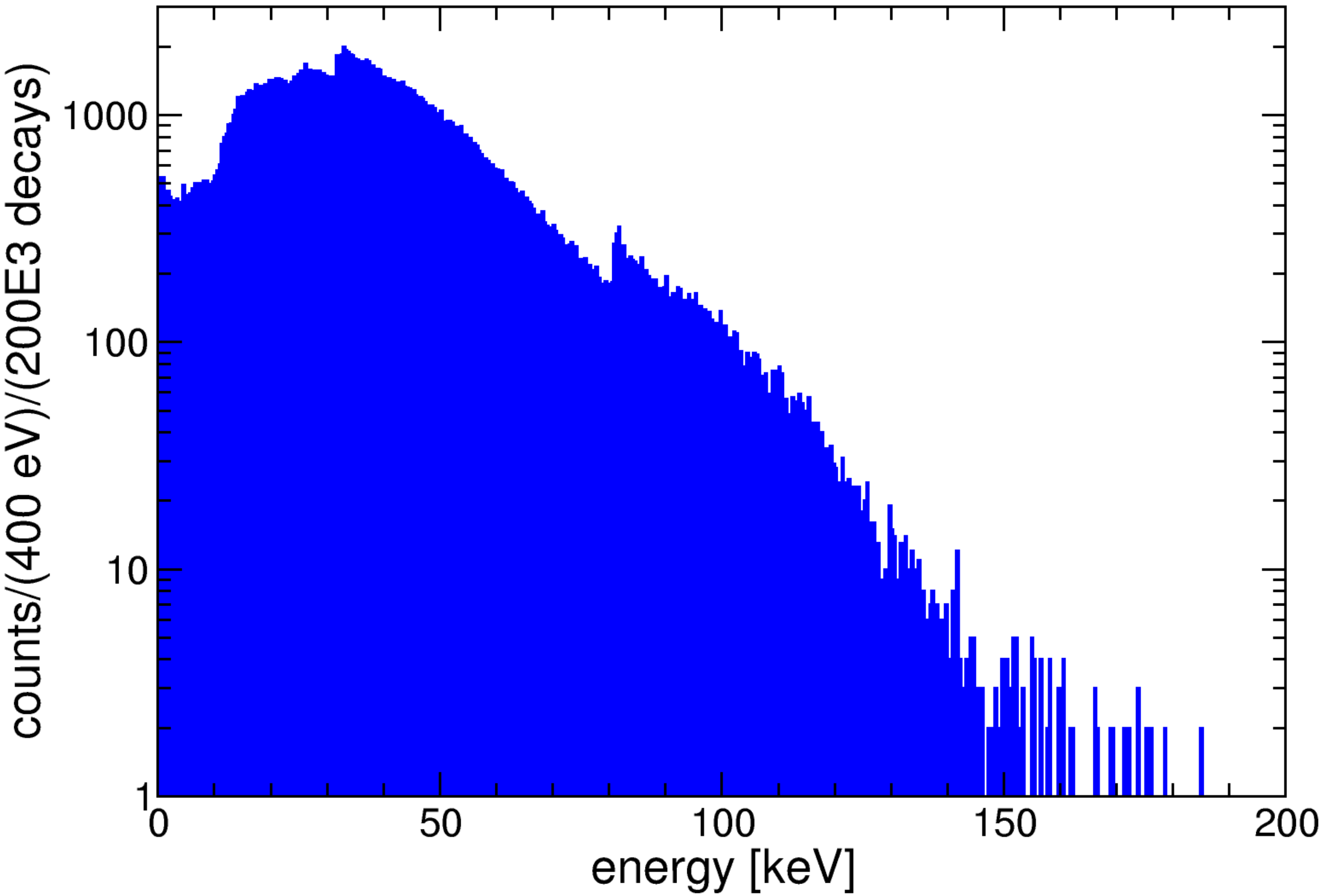


^{166m}Ho backgroun

Geant4 + LowEnergyEM

2 10^5 events





Low energy background sources / 2