Advances in holmium-based neutrino mass experiments

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International School of Nuclear Physics - 43rd Course

Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics

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Outline

- direct neutrino mass measurements
- calorimetric measurements with low temperature detectors
- low *Q* beta decay experiments
- ^{163}Ho EC decay calorimetric experiments
  - decay spectrum
  - statistical sensitivity
- HOLMES and ECHo experiments
  - detectors
  - isotope production and embedding
  - arrays readout, data acquisition and processing
  - present results
- future of holmium based experiments

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

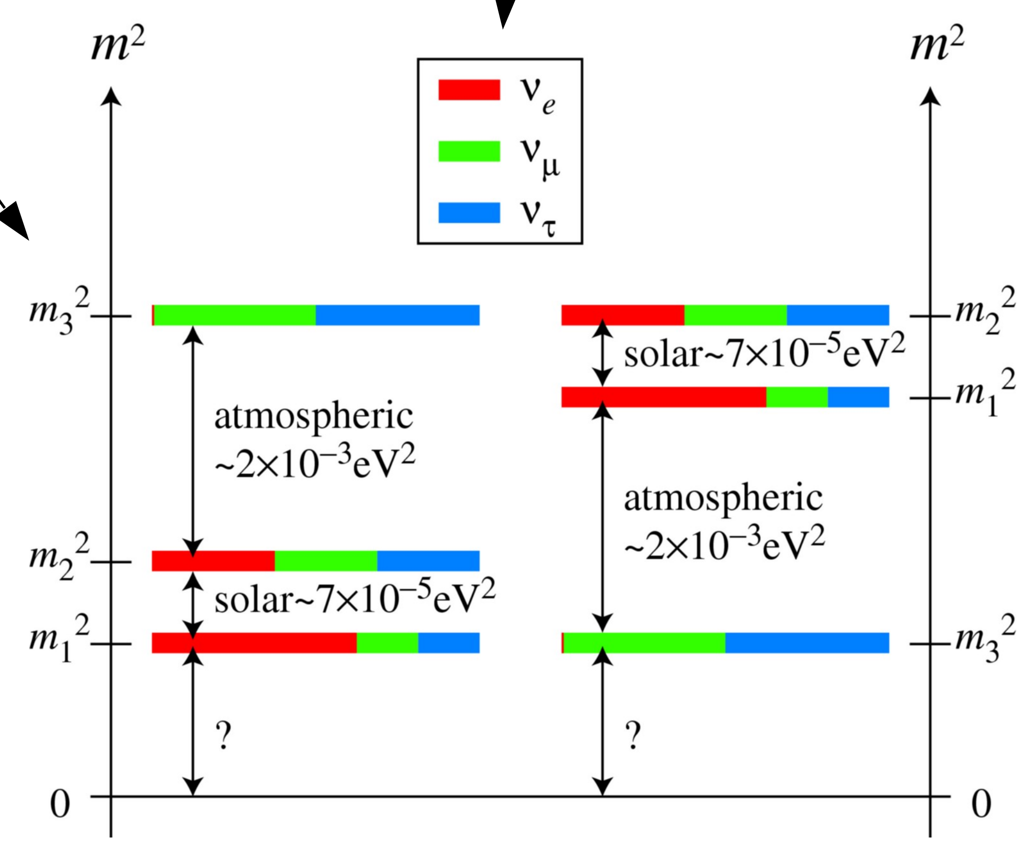
$$|\nu_l\rangle = \sum_k U_{lk} |\nu_k\rangle$$

neutrino **flavor** weak eigenstate

from neutrino oscillation experiments

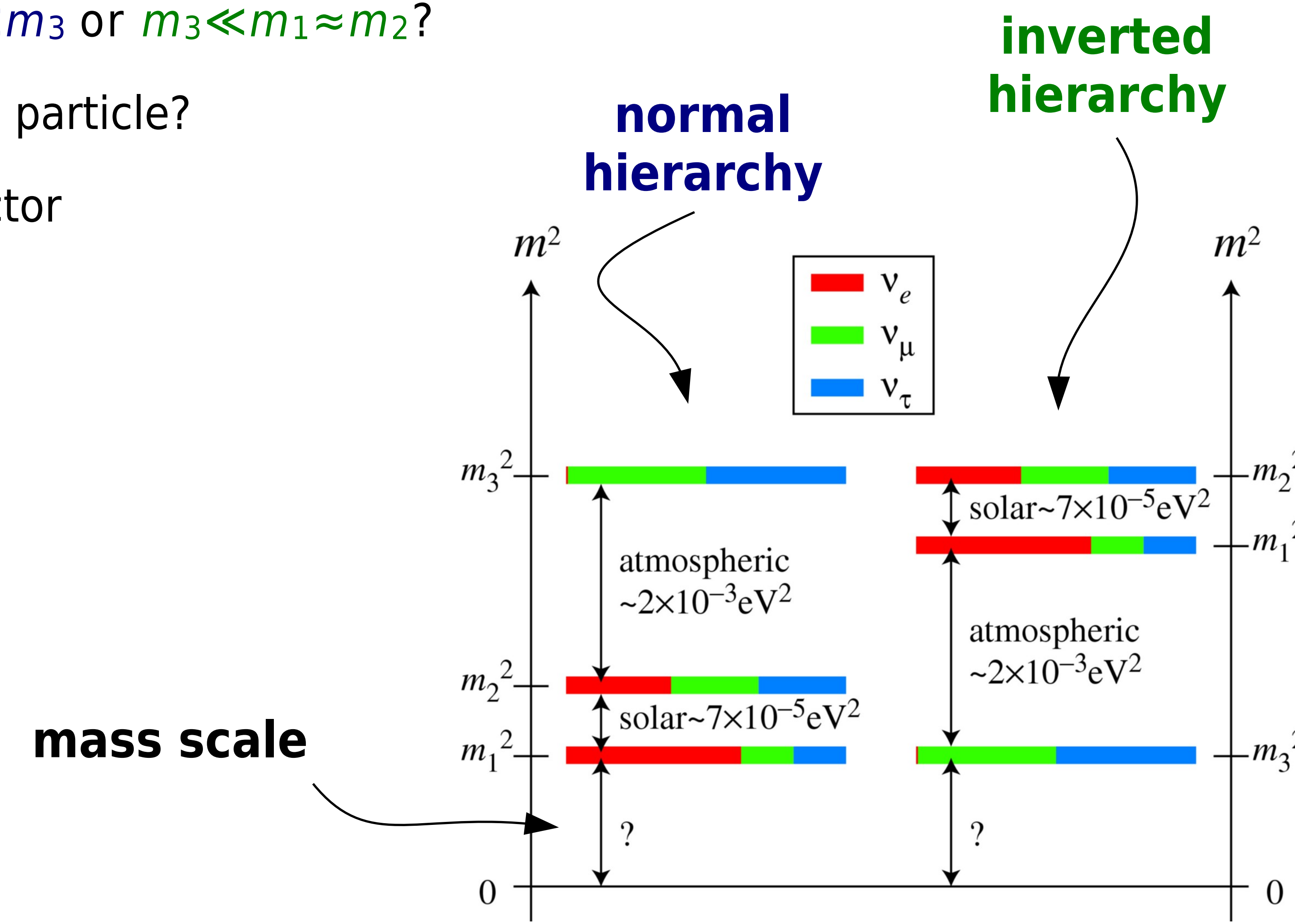
$$\Delta m_{ik}^2 = |m_i^2 - m_k^2|$$

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



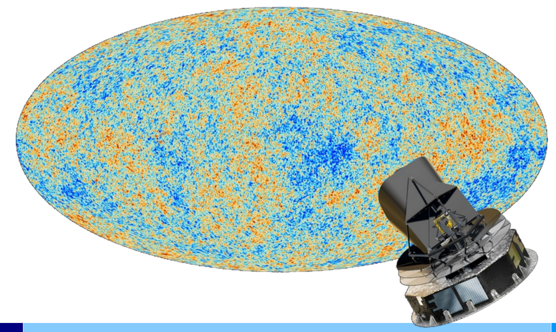
Neutrino open questions

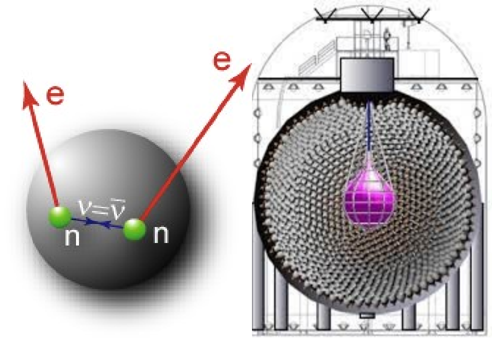
- mass scale: i.e. mass of the lightest ν
- degenerate ($m_1 \approx m_2 \approx m_3$) or hierarchical masses
  - mass hierarchy: $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 \approx m_2$?
- $\nu = \bar{\nu}$? i.e. Dirac or Majorana particle?
- CP violation in the lepton sector



Direct ν mass measurements: the status

three complementary tools available



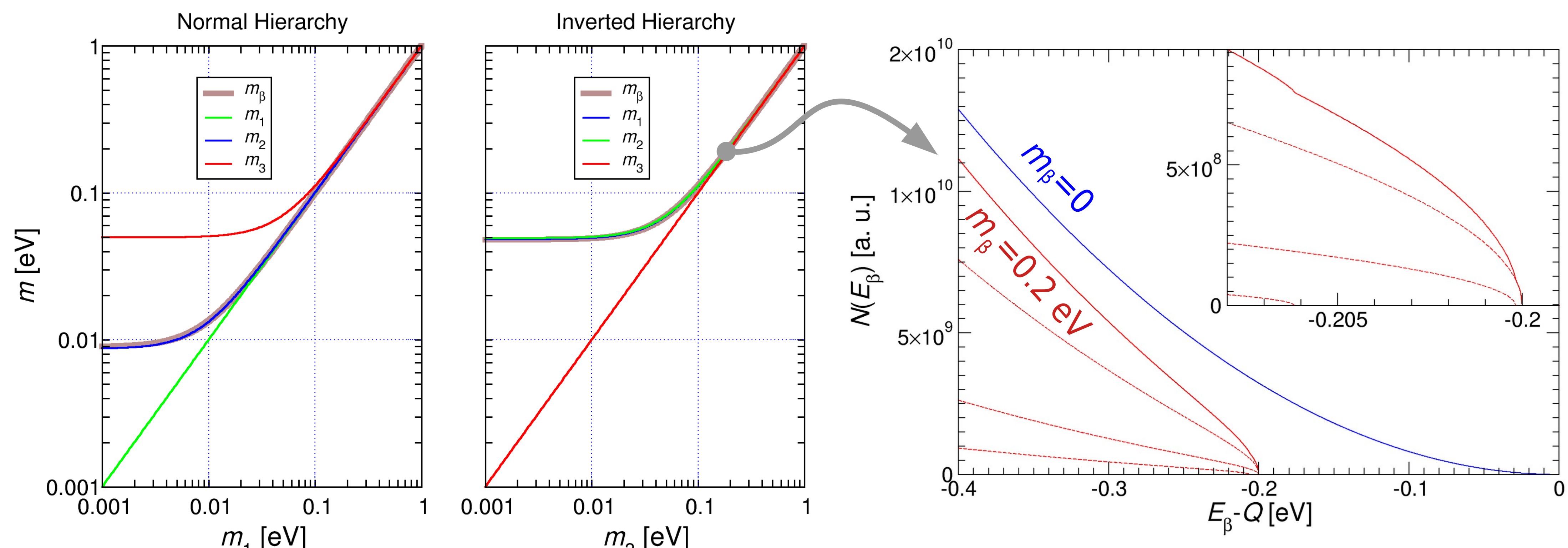


tool	Cosmology CMB+LSS+...	Neutrinoless Double Beta decay	Beta decay end-point
observable	$m_\Sigma=\sum_k m_{\nu_k}$	$m_{\beta\beta}=\lvert\sum_k m_{\nu_k} U_{ek}^2\rvert$	$m_\beta=(\sum_k m_{\nu_k}^2 \lvert U_{ek}\rvert^2)^{1/2}$
present sensitivity	≈0.1 eV	≈0.1 eV	≈1 eV
≈10y future sensitivity	**≈0.05 eV**	**≈0.01 eV**	**≈0.1 eV**
model dependency	yes ☹	yes ☹	no ☺
systematics	large ☹	some 😐	large ☹

Direct neutrino mass measurements

- **kinematics of weak decays**
  - in beta and electron capture decays where $\bar{\nu}_e$ or ν_e are emitted $|\nu_e\rangle = \sum_k U_{ek}|\nu_k\rangle$
  - non zero neutrino masses $m_{\nu k}$ modify the phase space
  - for nuclear β decay $N(E) \propto p_\beta E_\beta (Q-E_\beta) \sum_k |U_{ek}|^2 \sqrt{(Q-E_\beta)^2 - m_{\nu_k}^2}\, F(Z,E_\beta) S(E_\beta)$
- for degenerate masses ($m_{\nu 1} \approx m_{\nu 2} \approx m_{\nu 3}$)

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

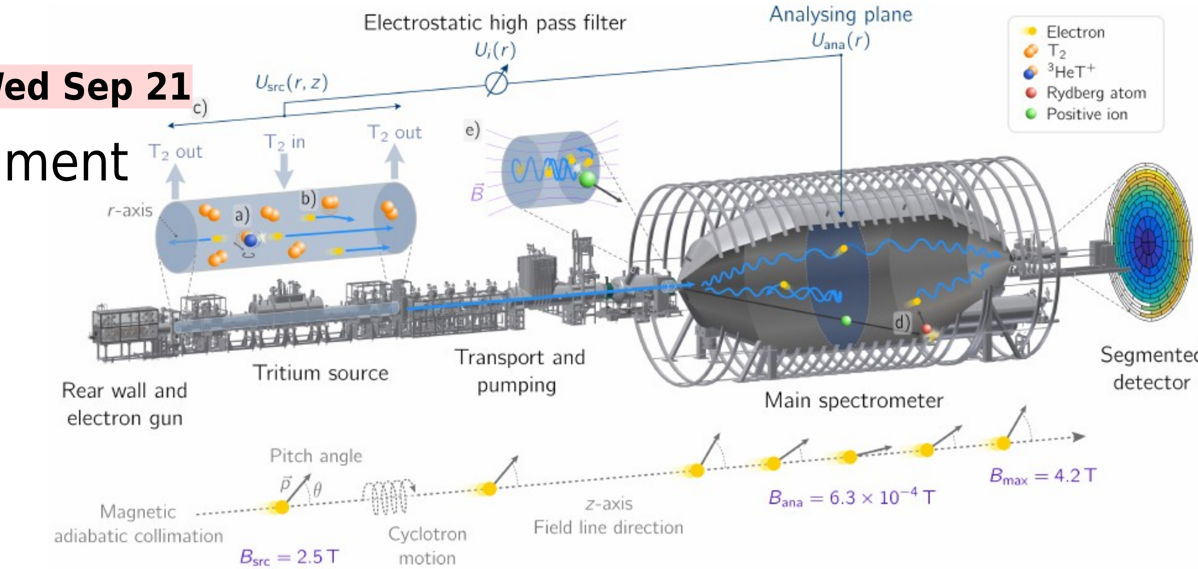


Tritium experiments

KATRIN *Nat. Phys. 18, 160–166 (2022)* **Lokhov + Schwemmer on Wed Sep 21**

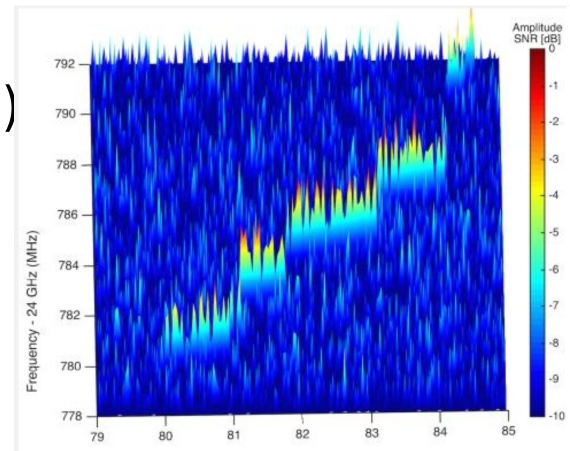
- MAC-E filter: ultimate integral spectrometer experiment
- sensitivity goal: 0.2 eV 90% CL
- energy resolution <3 eV @18 keV.
- first high-purity tritium campaign in 2019

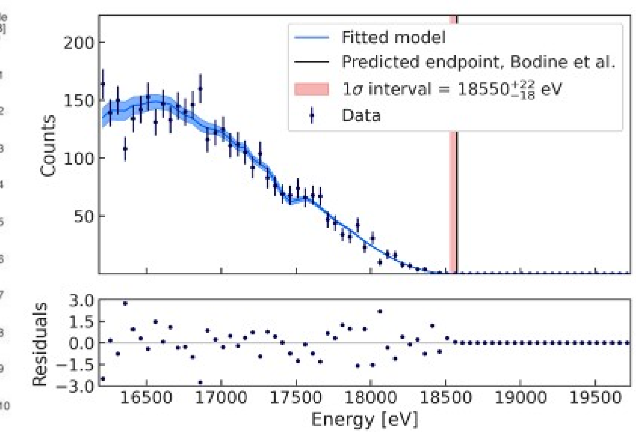
  → $\boldsymbol{m_\nu < 0.8}$ **eV** 90% CL



Project8 *arXiv:2203.07349*

- Cyclotron Resonance Electron Spectrometry (CRES)
- sensitivity goal: 40 meV 90% CL
- 4 different experimental phases: phase III ongoing
- energy resolution ≈2 eV @18 keV

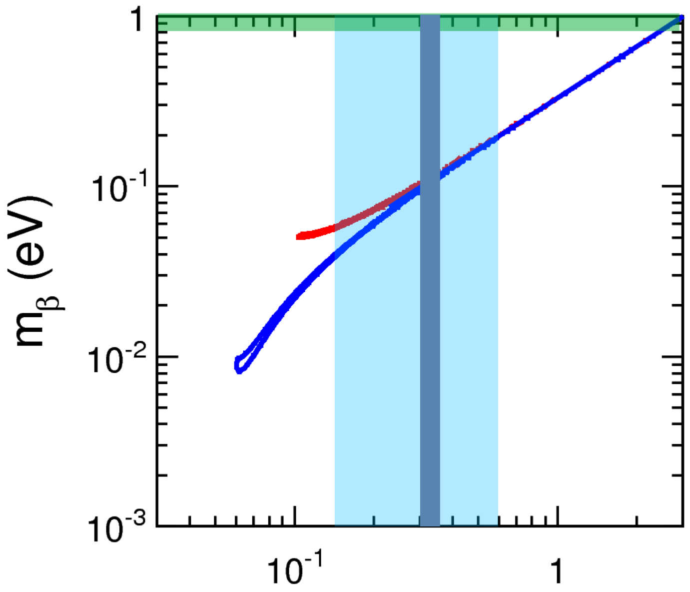




PTOLEMY *M.G. Betti et al., Prog. Part. Nucl. Phys, 106 (2019)*

- project to measure the Cosmic Neutrino Background via neutrino capture on tritium
- differential spectrometer combining CRES with an EM dynamic filter and hi-res microcalorimeters
- sensitivity potential: $O(10)$ meV
- presently: small prototype R&D

Direct ν mass measurements: 2022 status



NH and **IH** 2σ bands from oscillation parameters

G.Fogli et al., Phys. Rev. D 86 (2012) 013012 (only minor updates in 2022)

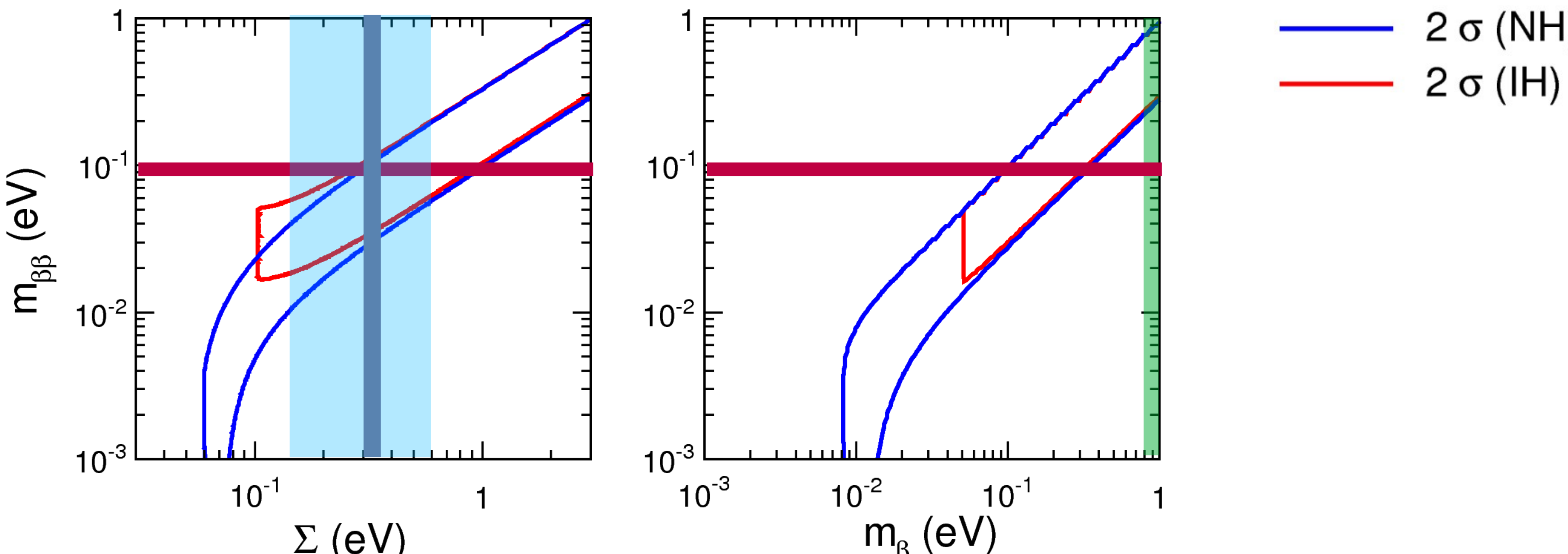
$m_{\beta\beta}$ from 0ν double beta decay experiments

E. Lisi, A. Marrone, Phys.Rev.D 106 (2022) 1, 013009. arXiv:2204.09569

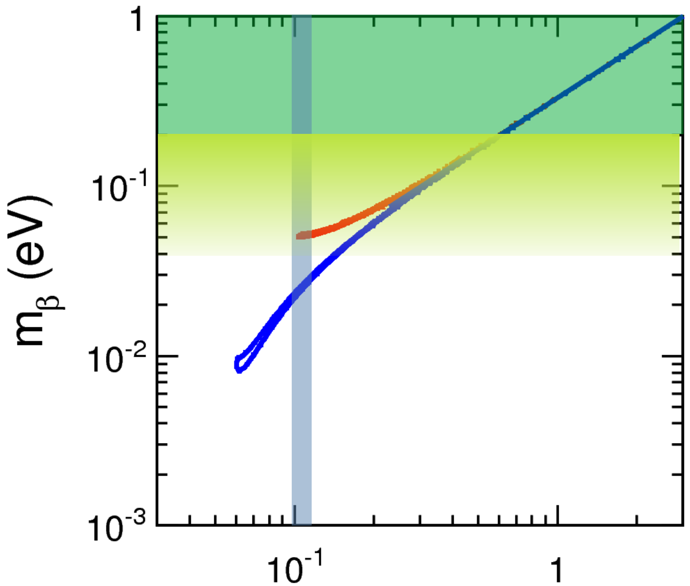
Σ from cosmic microwave background measurements

F. Capozzi, et al. Phys. Rev. D 104, 083031. arXiv:2107.00532

m_β from KATRIN *KATRIN Coll., Nat. Phys. 18, 160–166 (2022)*



Direct ν mass measurements: role of kinematic exp.

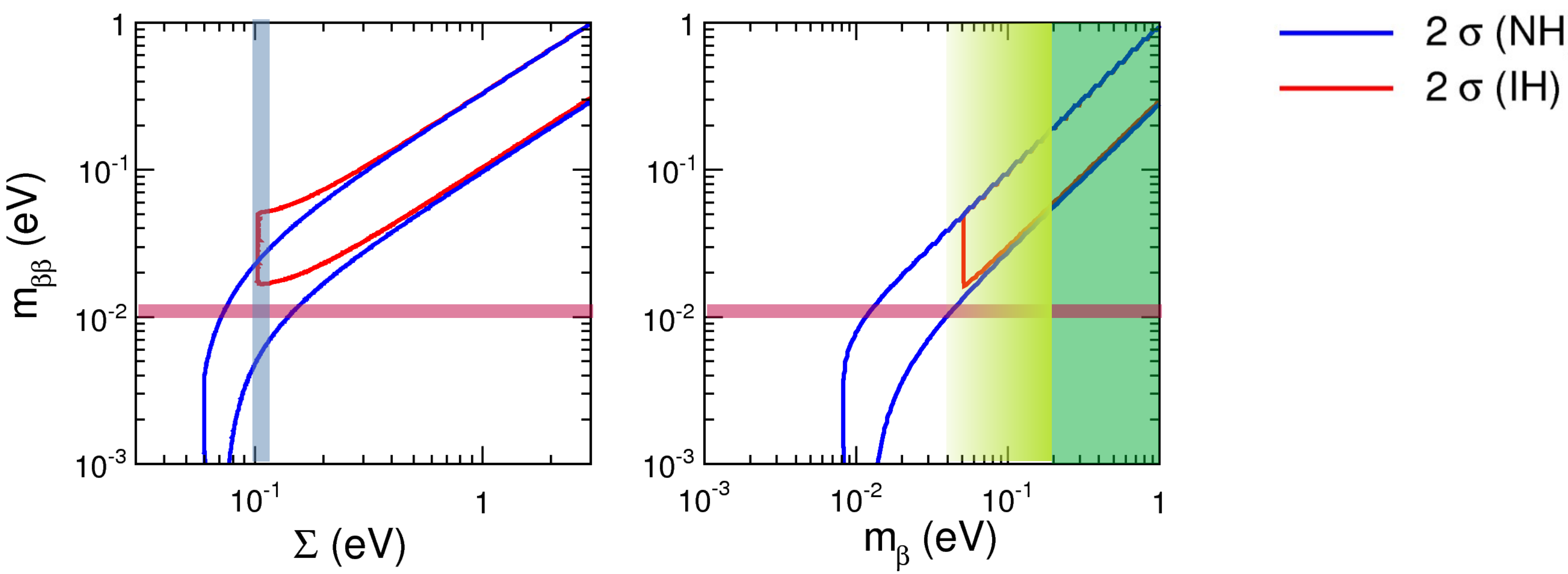


NH and **IH** 2σ bands from oscillation parameters

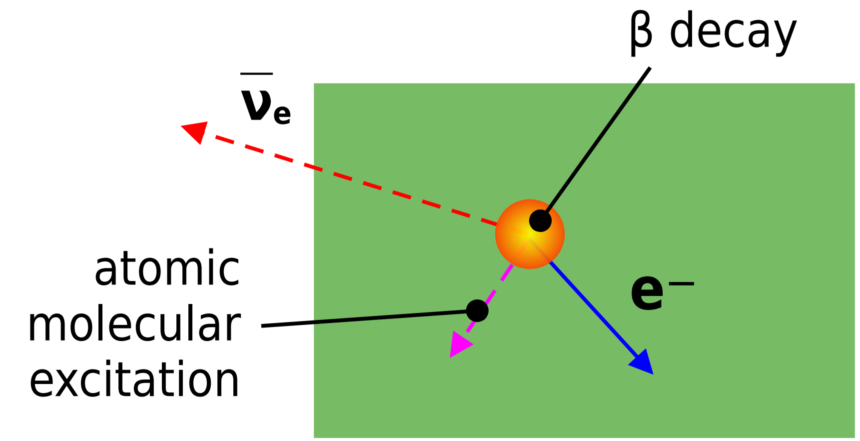
G.Fogli et al., Phys. Rev. D 86 (2012) 013012 (only minor updates in 2022)

m_β KATRIN goal

m_β $m_{\beta\beta}$ **Σ** next generation experiments



Calorimetric experiments



ideal calorimetric experiment

- radioactive source embedded in the detector(s)
- only the neutrino energy escapes detection

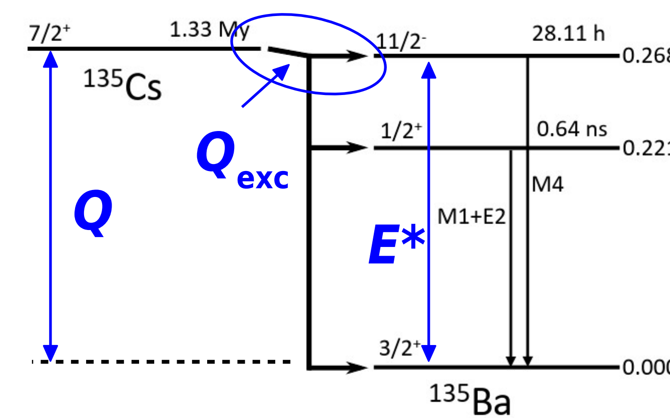
→ $\boldsymbol{E_c = Q - E_\nu}$

▲ no backscattering
▲ no energy losses in source
▲ no decay final state effects
▲ no solid state excitation
▼ low activity → limited statistics
▼ pile-up background

ideal isotope has

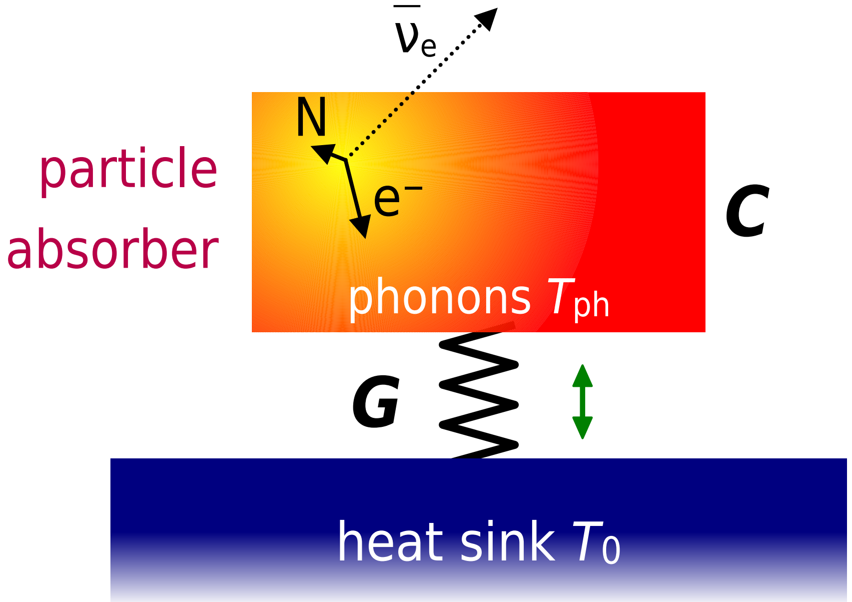
- low *Q*
  - → larger fraction of decays in ROI
  - → easier calorimetry
- for EC: capture peak close to end-point
- short decay time

isotope	*Q* [eV]	$\tau_{½}$ [y]	decay	B.R.	experiments
^{3}H	18592.01(7)	12	β⁻	1	Simpsons's
^{187}Re	2470.9(13)	4.3×10^{10}	β⁻	1	MANU, MIBETA
^{163}Ho	2833(30)	4570	EC	1	Holmes, ECHo
^{135}Cs	440	8.0×10^{11}	β⁻	1.6×10^{-6}	-
^{115}In	155	4.3×10^{20}	β⁻	1.1×10^{-6}	-



A. de Roubin et al. PRL. 124, 222503 (2020)

Low temperature detector principles



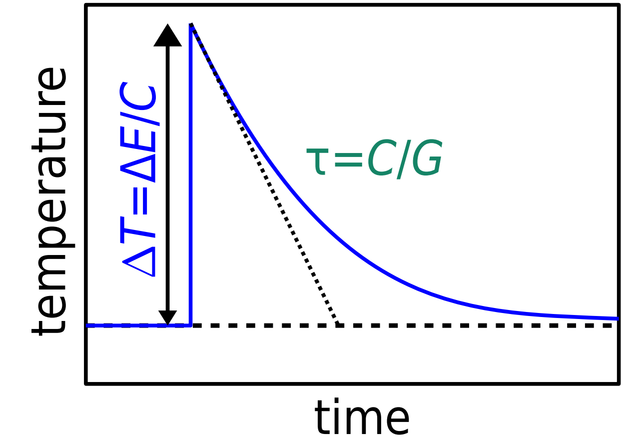
E → $\Delta T \approx \Delta E/C$ → $\Delta X(T)$

e.g: $R=R(T)$, $M=M(T)$

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

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

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



energy resolution limited by thermodynamic fluctuation noise TFN

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

$$\sigma_E=\Delta U_{rms}=\sqrt{N_{ph}}\langle E_{ph}\rangle=\sqrt{k_B T^2 C}$$

- detectors used for calorimetric neutrino mass experiments are more complex
- in metallic calorimeters energy is transferred to electronic system with T_e
- thermodinamycs and statistical mechanics still provide for TFN $\sigma_E=\sqrt{k_B T^2 C}$

200×200×2 μm³ (1.5 μg)

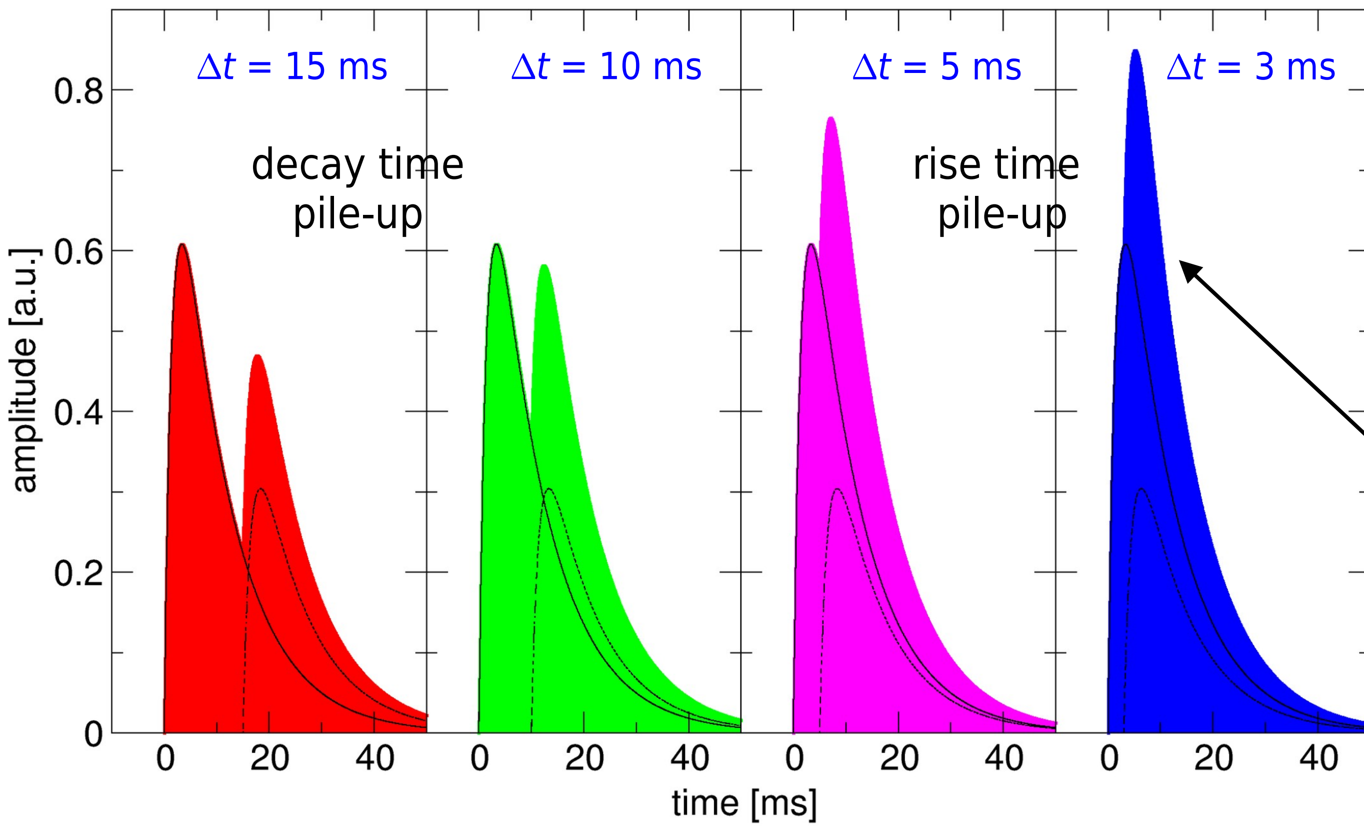
Au absorber @ 100 mK

$C \approx C_e \propto T_e \rightarrow C \approx 5\times10^{-13}$ J/K

$\sigma_E \approx 3.4$ eV (better estimate for TES detectors gives **$\sigma_E \approx 0.4$ eV**)

Pile-up in low temperature detectors

- calorimeters detect all β source decays
- low temperature detectors are *slow* devices
- simple pulse model $A(t) = A(e^{-t/\tau_{decay}} - e^{-t/\tau_{rise}})$
  - for microcalorimeters: $\tau_{rise} \approx$ 0.1-10 μs and $\tau_{decay} \approx$ 0.1-10 ms



2 pulses with:

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

first approximation for rise time p-up
resolving time $\boldsymbol{\tau_R} \approx$ rise time $\boldsymbol{\tau_{rise}}$

for $\Delta t < \tau_R$

→ accidental coincidence

→ $E_{meas} = E_1 + E_2$

- $\Delta t \gg \tau_{rise}$ → pile-up on the decay time → dead time
- $\Delta t \lesssim \tau_{rise}$ → pile-up on the rise time → spectral distortions and background

Calorimetry of beta decays: statistical sensitivity

rise time pile-up resolving time $\boldsymbol{\tau_R}$

ROI $\boldsymbol{\Delta E}$

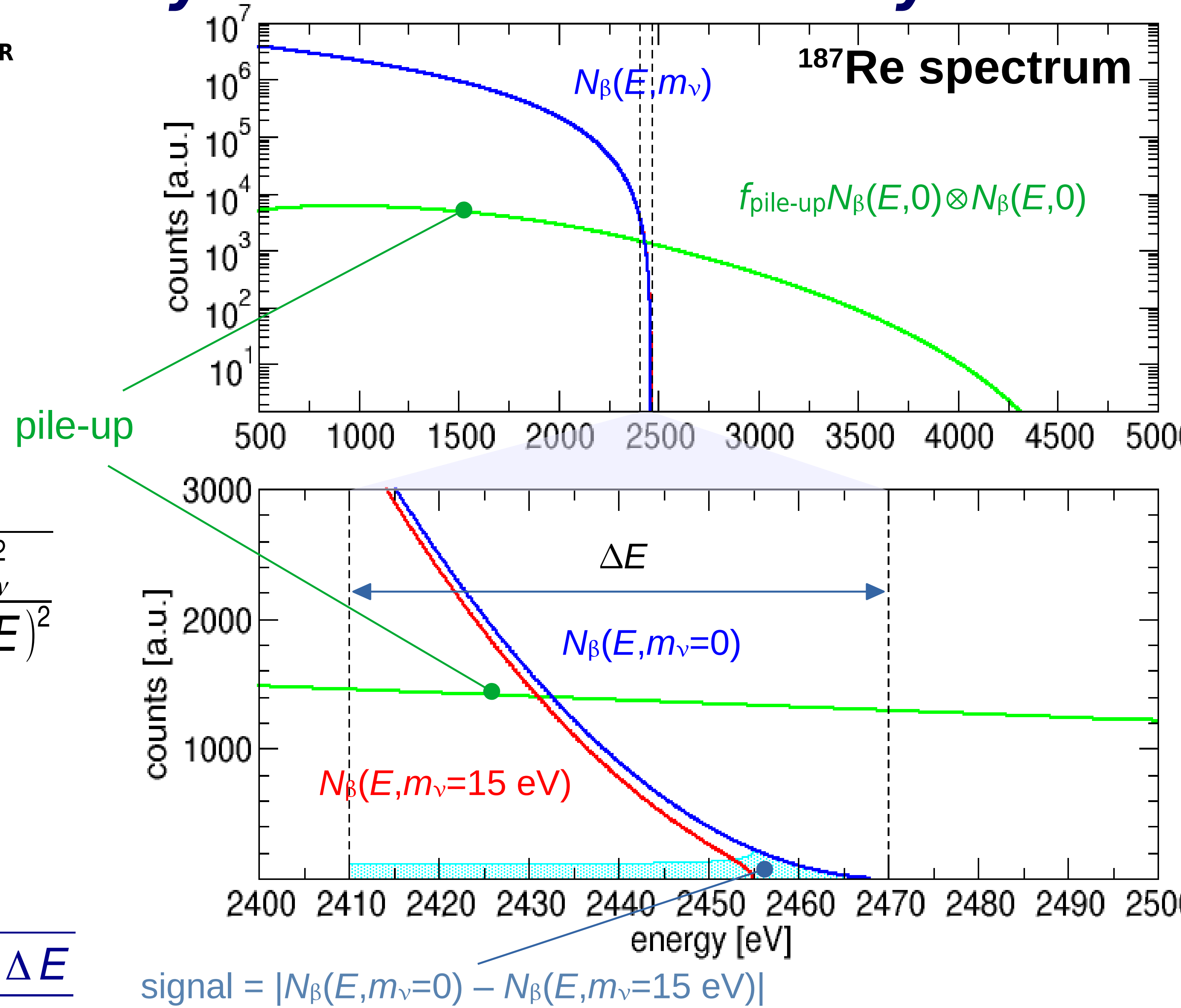
source activity $\boldsymbol{A_\beta}$

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

measuring time $\boldsymbol{T_M}$

number of detectors $\boldsymbol{N_{det}}$

exposure $\boldsymbol{t_M = T_M \times N_{det}}$



^{187}Re example:

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

$\Delta E \approx \Delta E_{FWHM}$

pile-up is negligible when

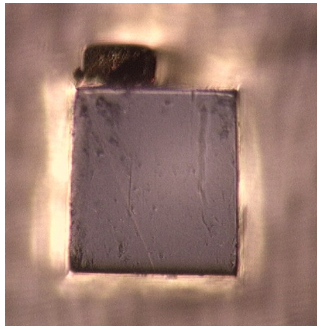
$$f_{pile-up} = \tau_R A_\beta \ll \frac{\Delta E^2}{Q^2}$$

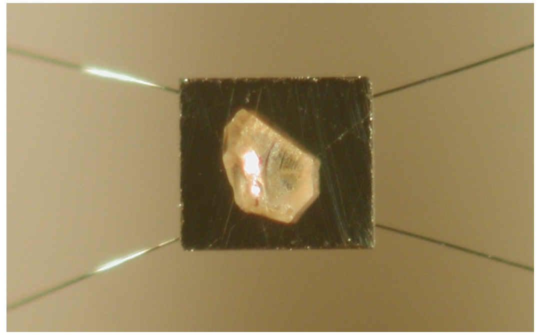
then

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

A. Nucciotti et al., Astropart. Phys. 34, 80 (2010).

Rhenium-187 experiments





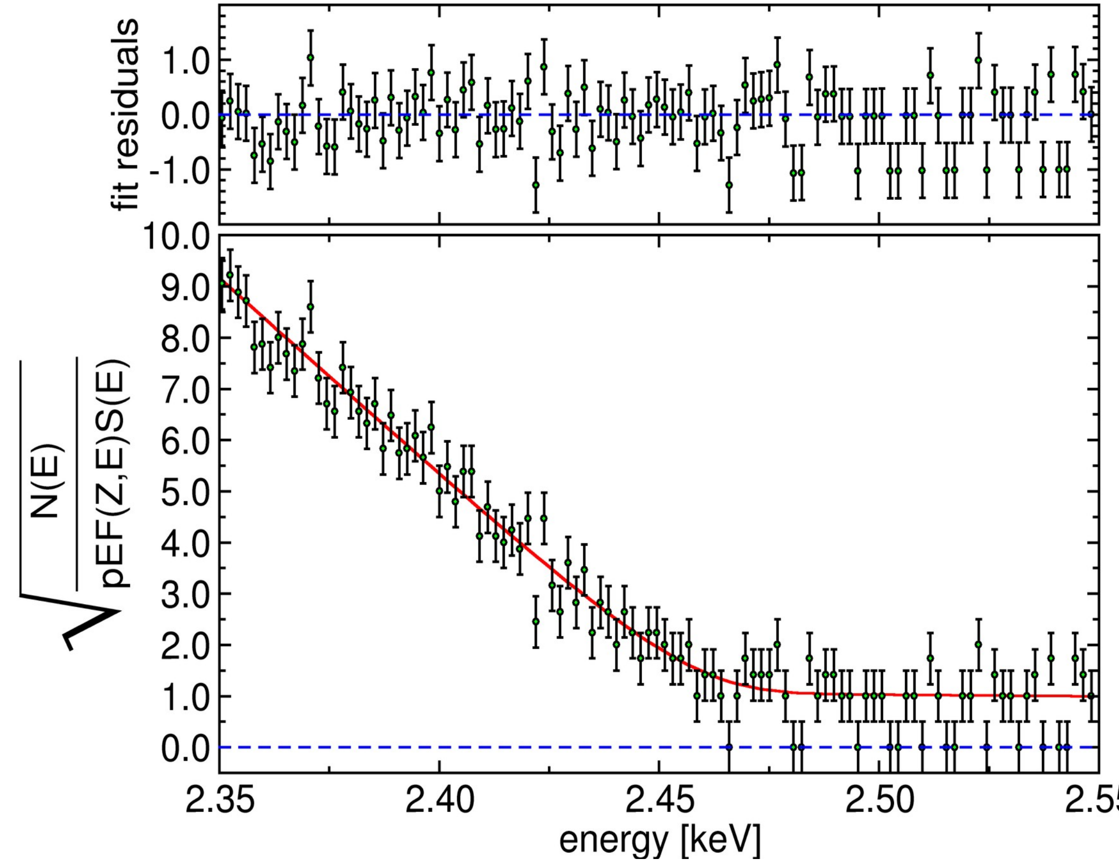
first ^{187}Re experiments: $N_{ev}\approx 10^7$ events

MIBETA @ Milano with $AgReO_4$

→ m_ν< 15 eV 90% C.L. M.Sisti et al., NIM A 520 (2004) 125

- MANU @ Genova with metallic Re

→ m_ν< 26 eV 95% C.L. F.Gatti et al., Nucl. Phys. B91 (2001) 293



1990 → 2006 MIBETA (Milano/MilanoBicocca) + MANU (Genova)

^{187}Re → m_ν<15 eV (+ BEFS...)

2006 MARE (Microcalorimeter Array for a Rhenium Experiment) int'l project for **m_ν<0.1 eV**

2007 → 2013 MARE R&D for phase 1→ Re+TES/MMC / $AgReO_4$+Si-Impl

2013 MARE project with ^{187}Re abandoned due to insurmountable technical obstacles

A. Nucciotti, Adv. High Energy Phys. 2016, 9153024 (2016)

Electron capture calorimetric experiments

$^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy[H]} + \nu_e$

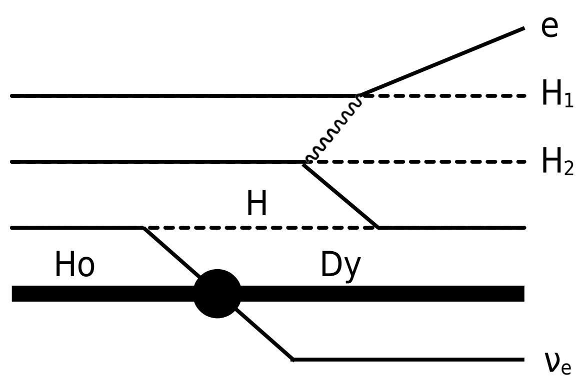
$^{163}\mathrm{Dy[H]} \rightarrow {}^{163}\mathrm{Dy} + E_c$

shell binding energy: $E_b(\mathrm{M1})=2.05$ keV

→ electron capture from shell ⩾M1

→ H=M1, M2, N1, N2, O1, O2, P1

$\Gamma_{M1}\approx 13$ eV

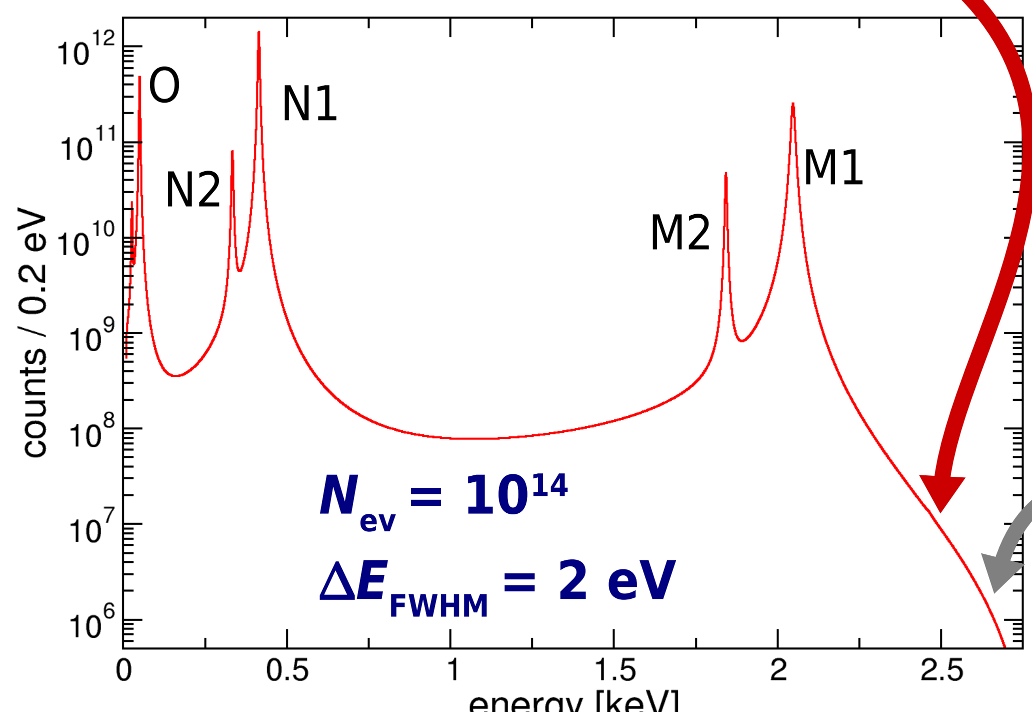


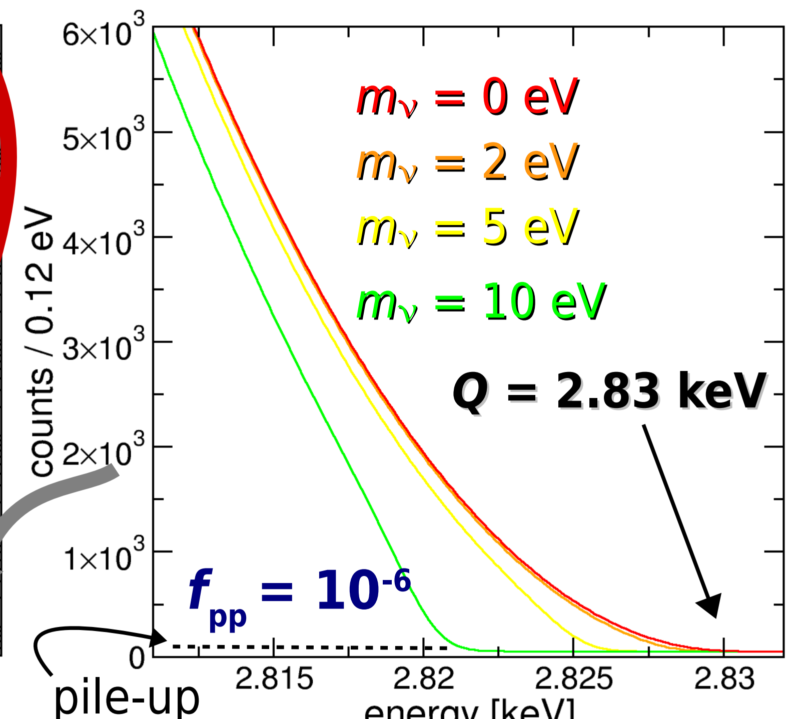
A. De Rújula and M. Lusignoli, Phys. Lett. B 118 (1982) 429

- calorimetric measurement of Dy atomic de-excitations (E_c)
  - ▹ mostly Auger and Coster-Kronig ($\omega_{M1,2}\approx 10^{-3}$, $\omega_{N1,2}\approx 10^{-5}$)
- $Q=2.833\pm 0.030^{stat}\pm 0.015^{sys}$ keV

  S. Eliseev et al., Phys. Rev. Lett. 115 (2015) 062501
  - ▸ end-point rate and ν mass sensitivity depend on $Q-E_{M1}$
- $\tau_{1/2}\approx 4570$ years → 2×10^{11} ^{163}Ho nuclei ↔ 1 Bq

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

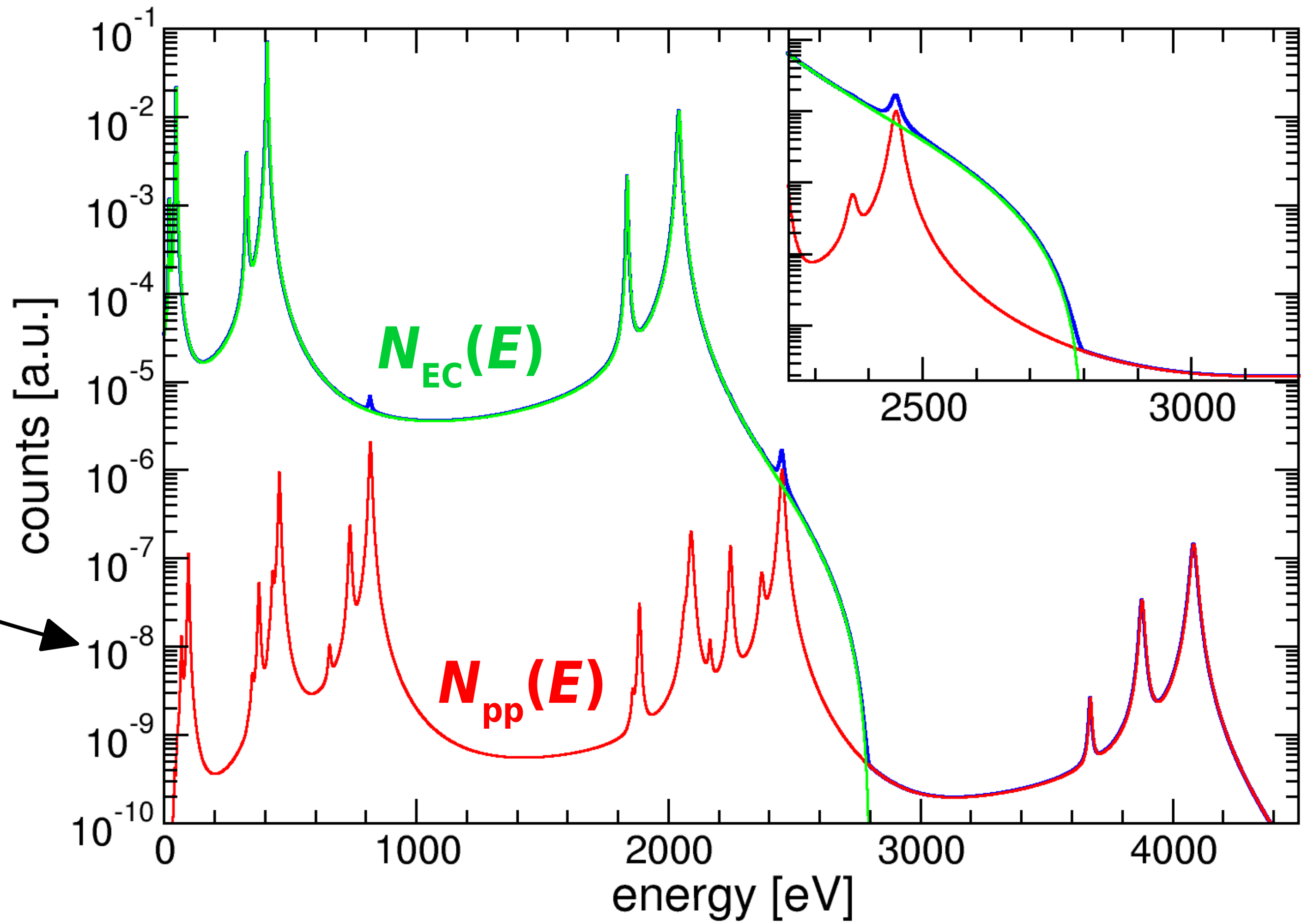




Pile-up in ^{163}Ho EC calorimetric experiments / 2

- accidental coincidences → complex pile-up spectrum
- calorimetric measurement → **detector speed is critical**
  - $N_{pp}(E) = f_{pp}\, N_{EC}(E) \otimes N_{EC}(E)$ with $f_{pp} \approx A_{EC}\, \tau_R$

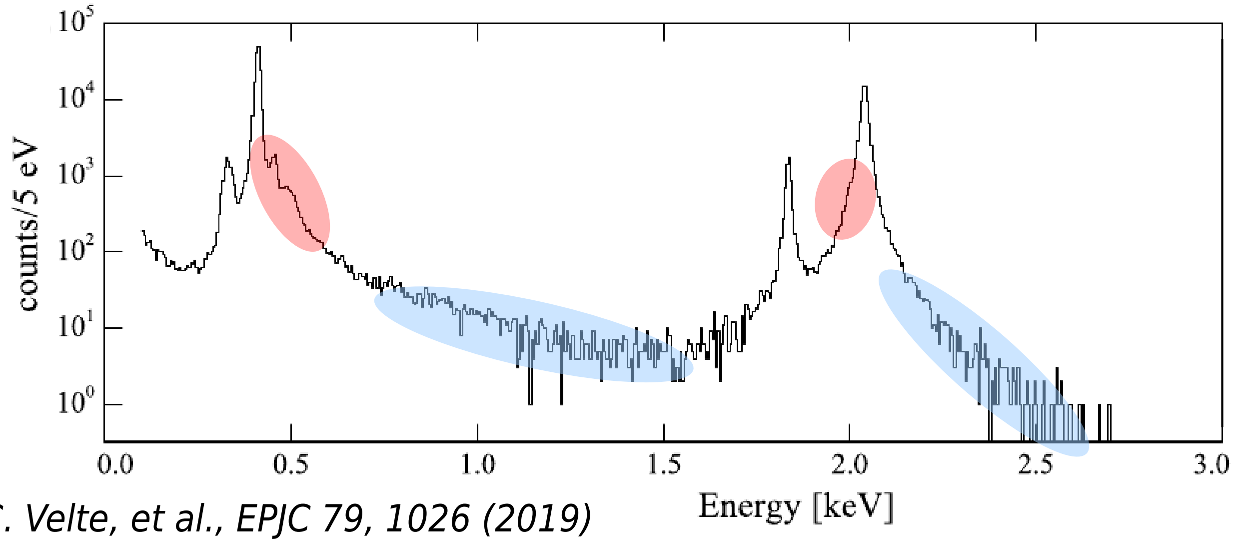
A_{EC} EC activity per detector
τ_R time resolution (≈rise time)



Q = 2800 eV

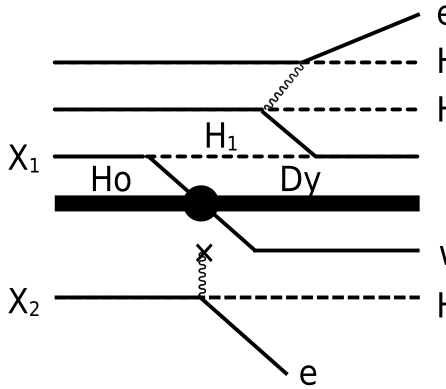
$f_{pp} = 10^{-4}$

Double hole processes / 1



C. Velte, et al., EPJC 79, 1026 (2019)

- high-statistic low background **ECHo** spectrum shows extra features
  - extra peaks close to N1 and M1
  - N/M peak asymmetries / high energy tails



Single hole: the Dy atom is left by EC with one hole in the shell (M, N, O…)

→ for H_1 in shell X_1 with binding energy $E_b(X_1)$ → resonance for E_c=$E_b(X_1)$

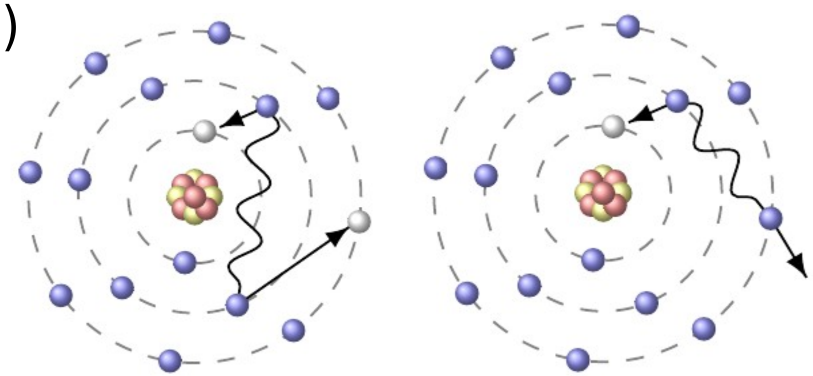
Double hole processes

the perturbation due to the nuclues charge change (Ho→Dy) "shakens" one or more additional atomic electron to an upper bound state (shake-up) or to the continuum (shake-off or Auger)

→ shake up: additional hole H_2 in X_2 → resonance for E_c=$E_b(X_1)$+$E_b(X_2)$

→ shake off: additional hole H_2 in X_2

→ tail to peaks from E_c=$E_b(X_1)$+$E_b(X_2)$ up to E_c=Q



Double hole processes / 2

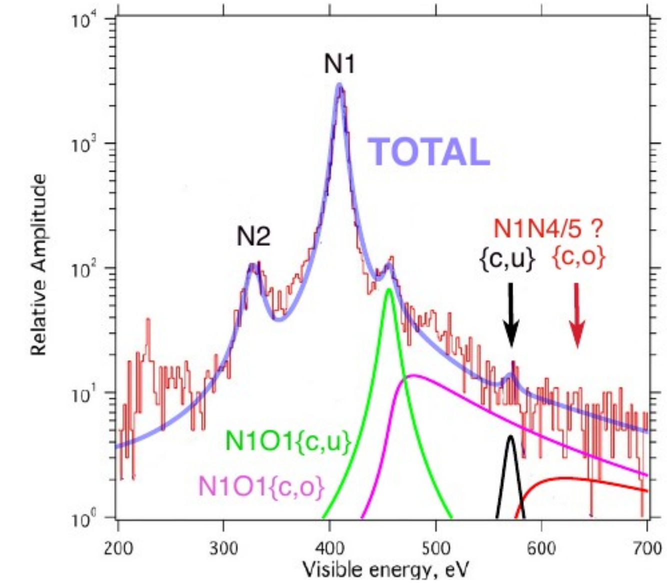
- several attempts to include double hole processes

  H. Robertson et al., A. Faessler et al., A. De Rújula and M. Lusignoli, ...

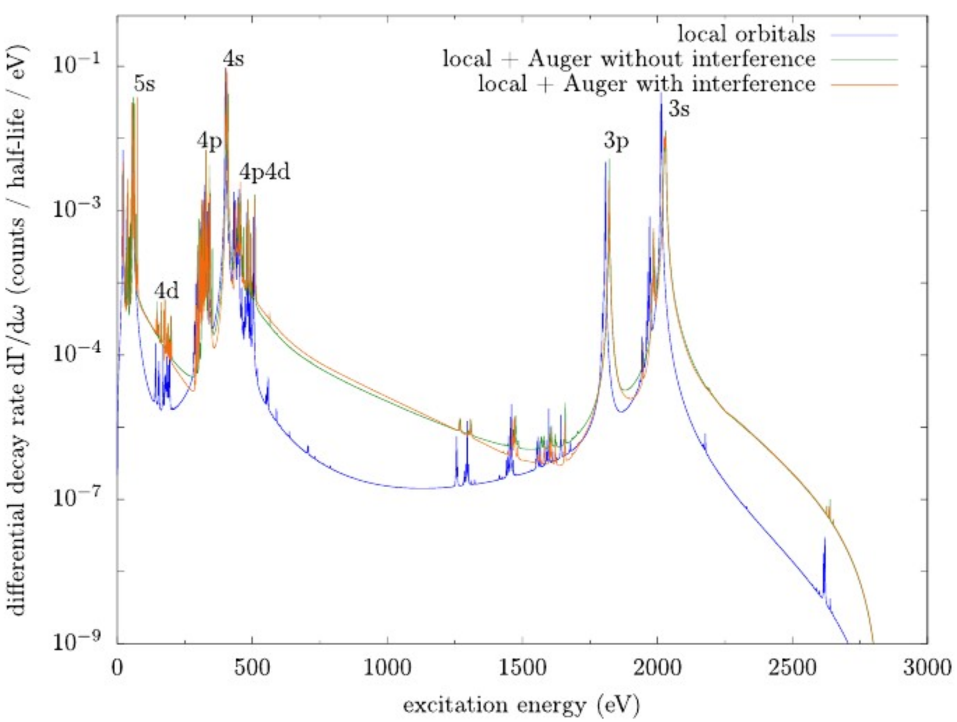
- recent work from M. Haverkort and collaborators:

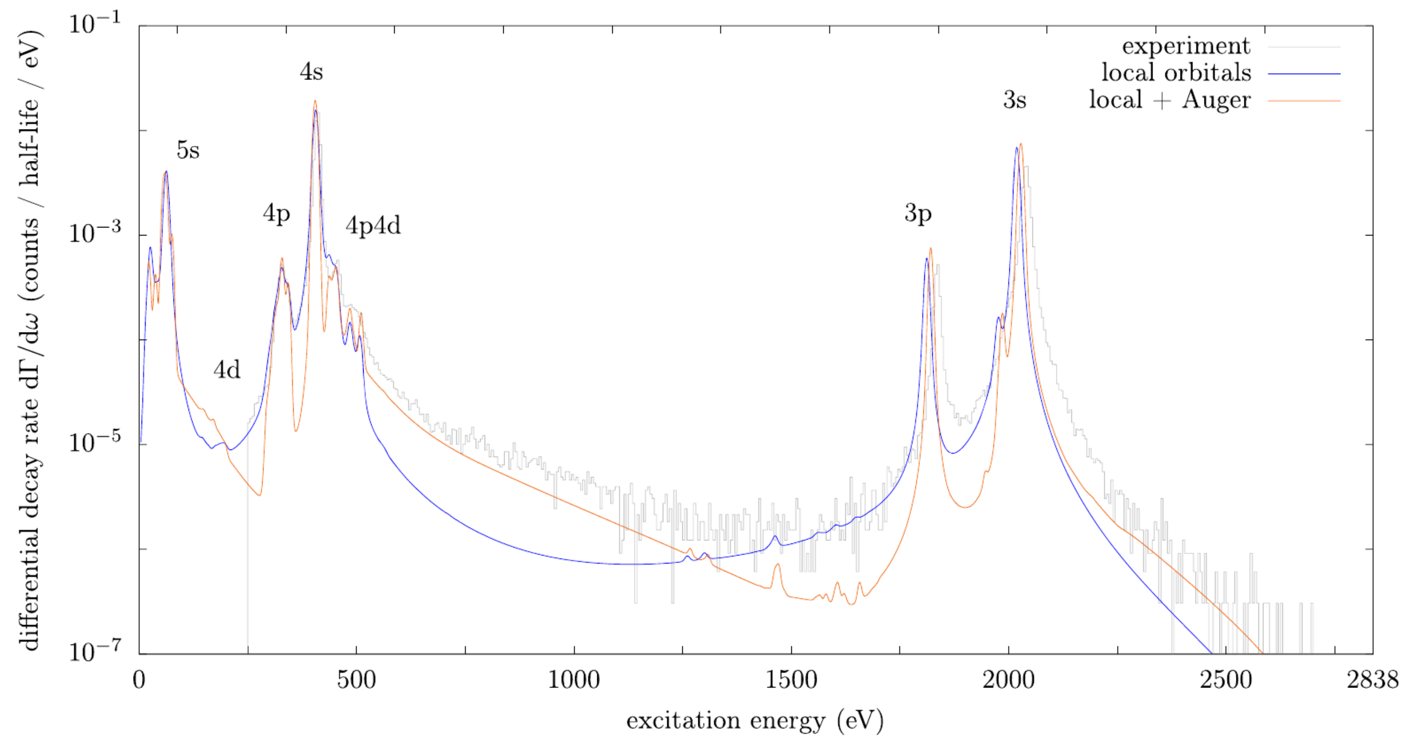
  ab-initio calculations including Coulomb interactions between multi core bound and unbound states (work in progress)

  - missing because of computational limits: intrinsic resonance linewidths, full shake-off contributions, radiative transitions, ...



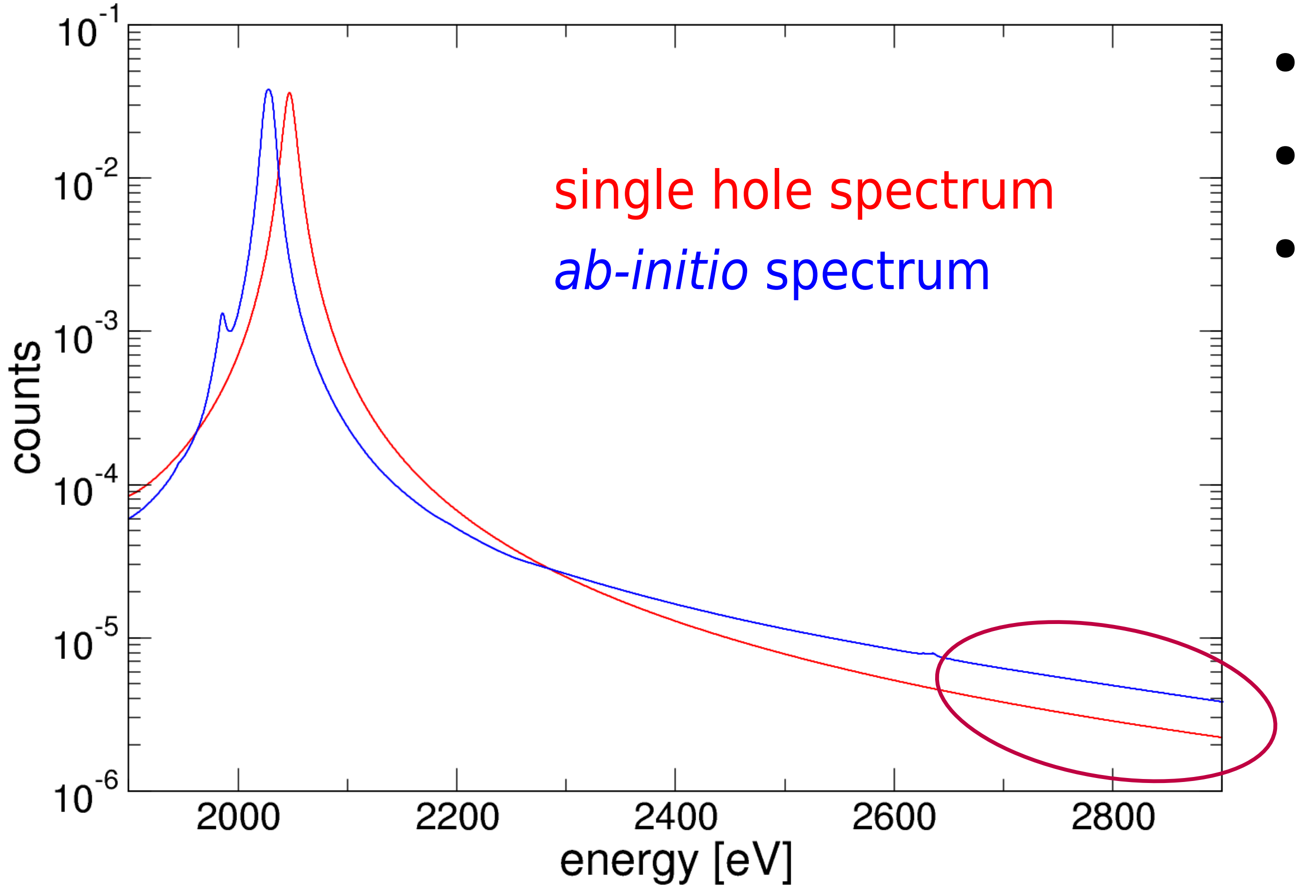
A.De Rújula & M. Lusignoli, J. High Energ. Phys. (2016) 2016: 15





M. Brass and M. W. Haverkort, New J. Phys. 22 (2020) 093018

End-point spectral shape



- “bare” spectra (without phase space)
- *ab-initio* with additional Lorentzian broadening
- spectra are normalized to unity
  - end-point region is smooth and featureless
  - phase space factor leaves unmistakable imprint

  → possibly small systematic uncertainties

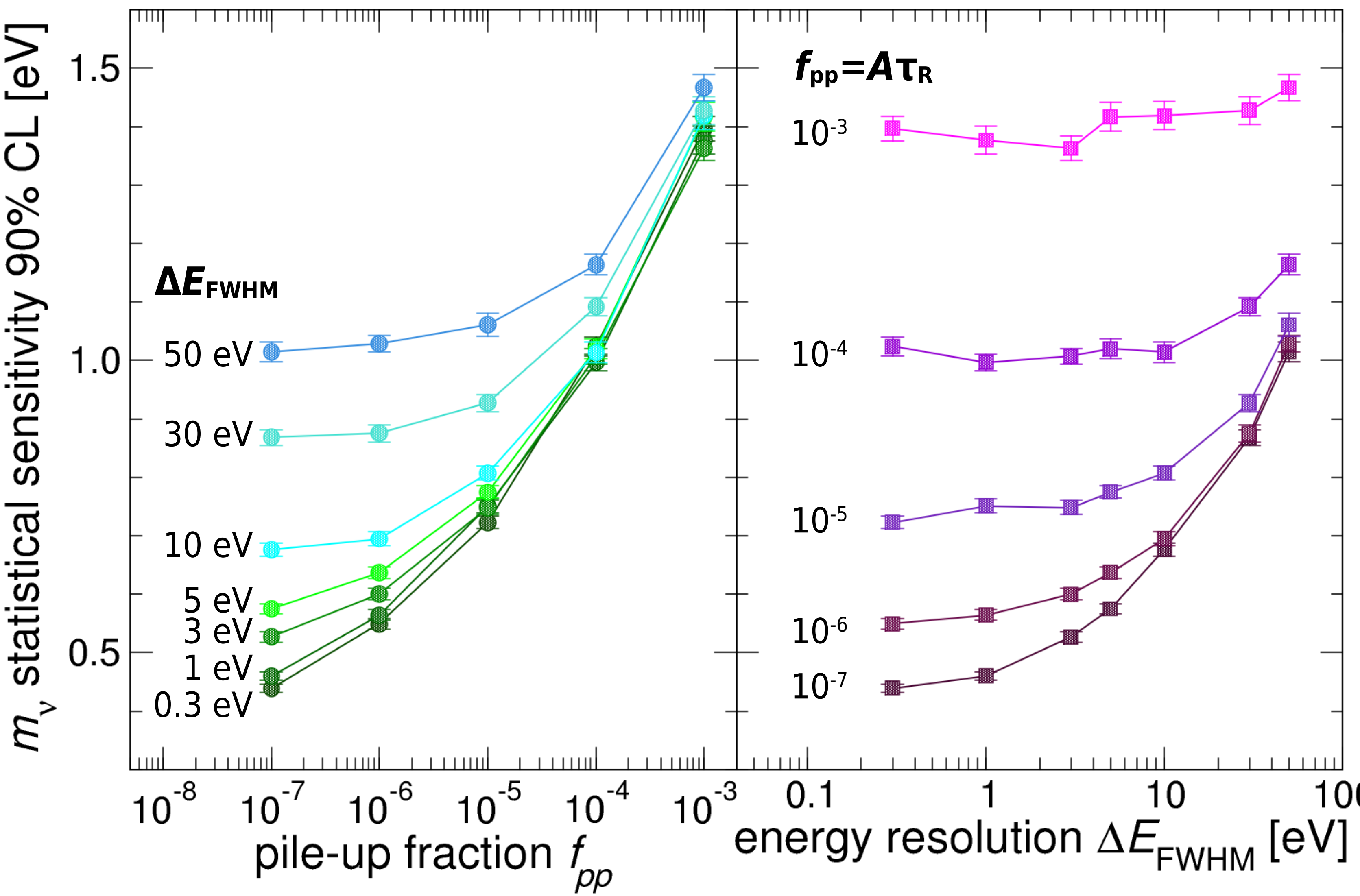
  → to be proved

- apparently *ab-initio* spectrum has higher rate at endpoint
- also pup spectrum is higher

  → small gain on statistical sensitivity

Statistical sensitivity: pile-up and energy resolution

- Montecarlo simulations for statistical sensitivity with **single-hole spectrum**
- simulations confirm that sensitivity Σ scales as $1/(N_{ev})^{0.25}$



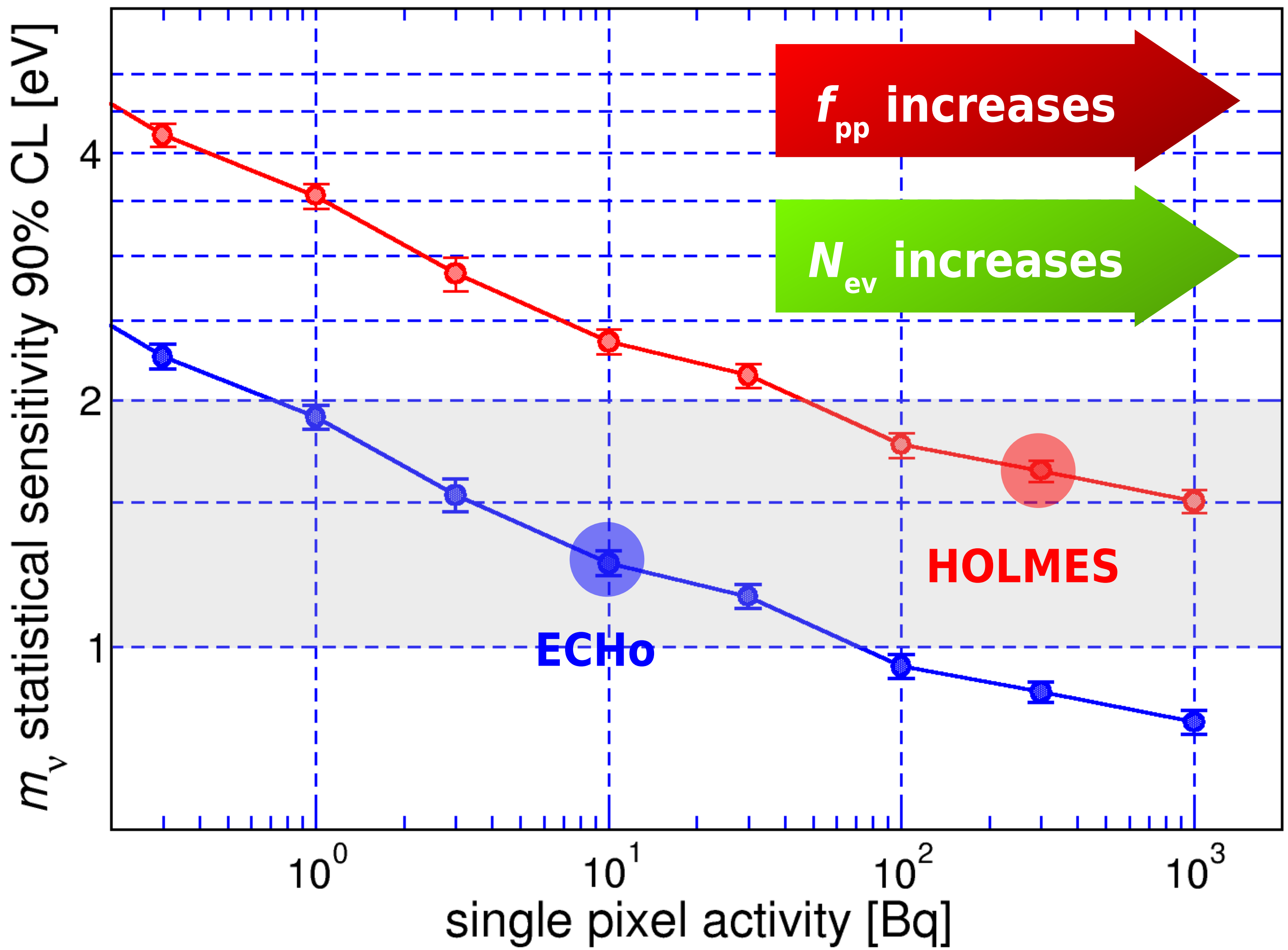
$N_{ev}=10^{14}$

$$\Sigma(m_\nu) \propto \sqrt[4]{1/N_{ev}}$$

$$N_{ev} = A\, t_M\, N_{ch}$$

A. Nucciotti, Eur. Phys. J. C 74.11 (2014)

Neutrino mass statistical sensitivity



MC simulations

A. Nucciotti, Eur. Phys. J. C 74.11 (2014)

single-hole spectrum

ΔE =1 eV

τ_R = 1 μs

$N_{det}t_M$ = 1000 det × 3 years

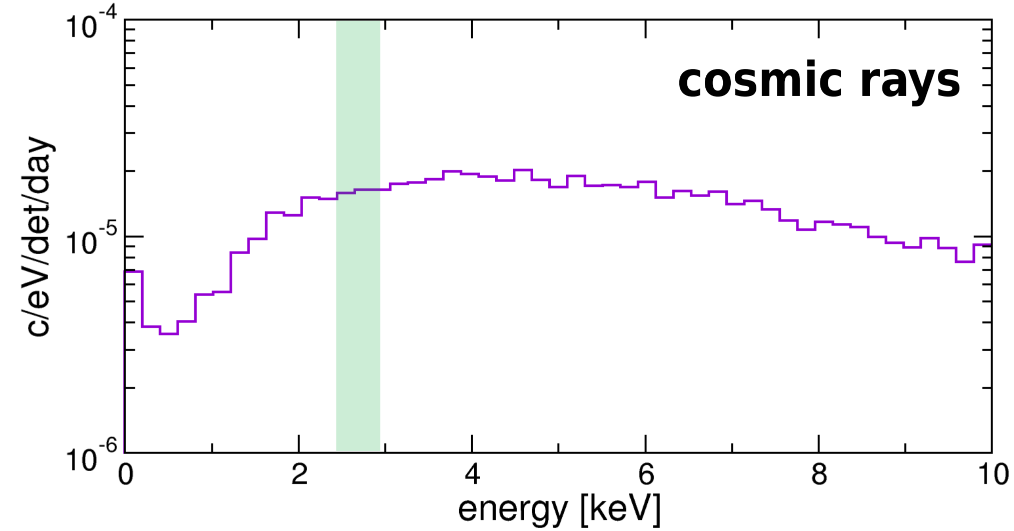
$N_{det}t_M$ = 12000 det × 3 years

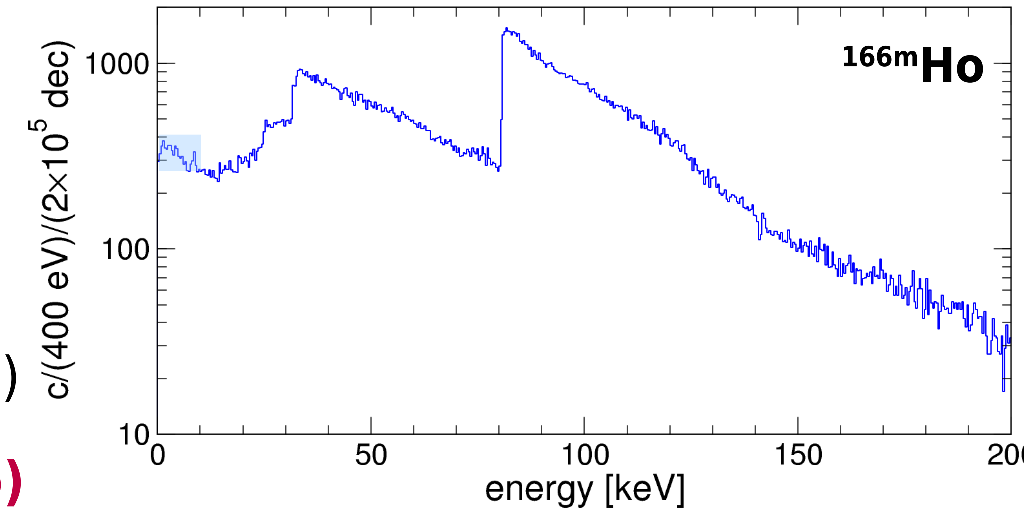
high activity → robustness against (flat) background

A_{EC}=300 Bq → b<≈0.1 counts/eV/day/det

Low energy background

- pile-up in ROI (single-hole) $\boldsymbol{b_{pp}\approx 0.35\, f_{pp} A}$ **c/eV/day**
- environmental γ radiation
- γ, X and β from close surroundings
- cosmic rays
  - ▷ GEANT4 (HOLMES) → $\boldsymbol{b_{CR}\approx 10^{-5}}$ **c/eV/day/det** (0 - 4 keV)
- internal radionuclides
  - ▷ ^{166m}**Ho** (β⁻, Q=1.8 MeV, $\tau_{1/2}$=1200 y)
  - ▷ co-produced with ^{163}Ho: $A(^{163}\mathrm{Ho})/A(^{166m}\mathrm{Ho})>500$ (HOLMES)
  - ▷ GEANT4 (HOLMES) → $\boldsymbol{b_{166m}\approx 0.3}$ **c/eV/day/det/Bq(^{166m}Ho)**

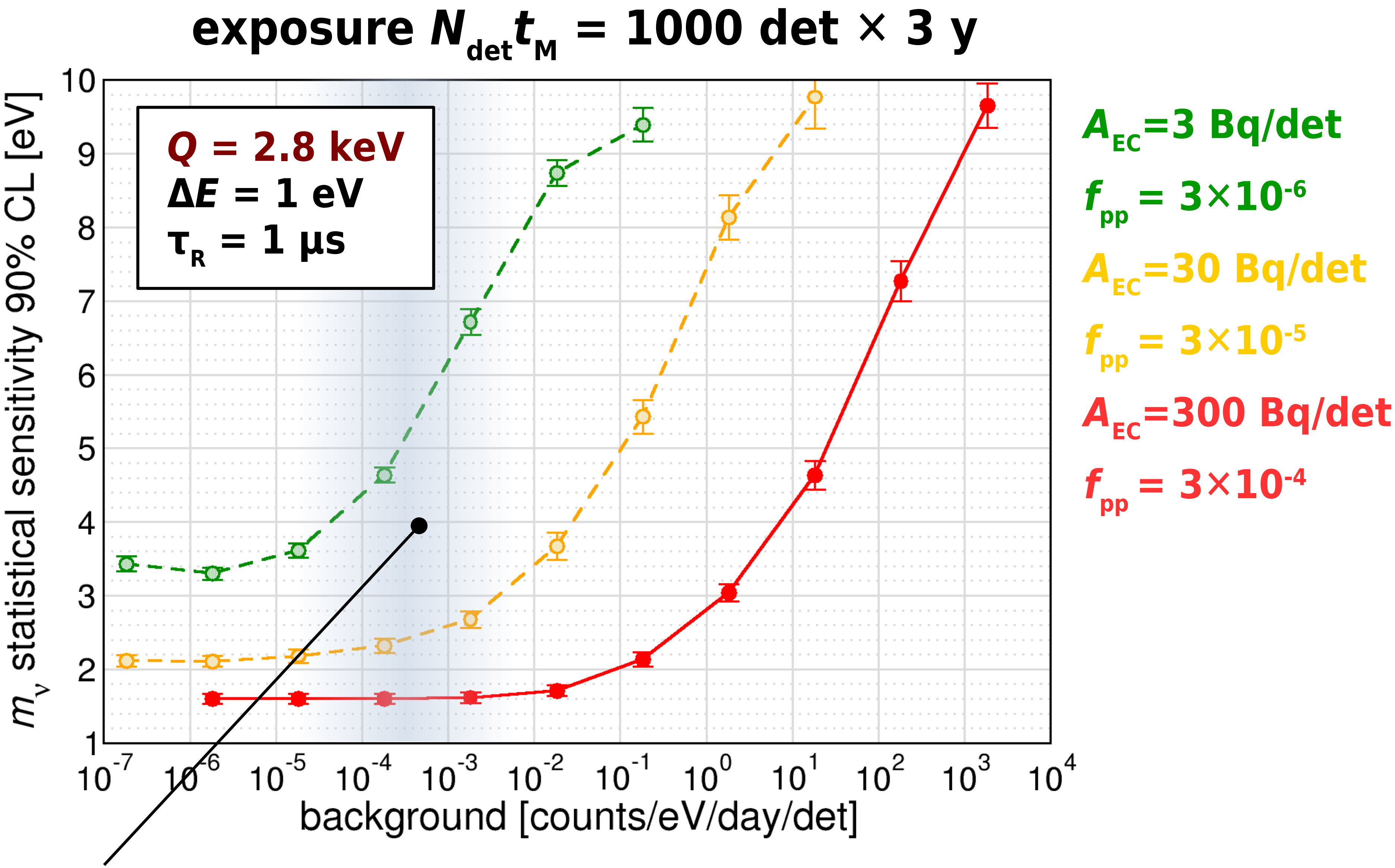




$A(^{163}\mathrm{Ho})$ [Bq]	f_{pp}	b_{pp} [c/eV/day]	max b ‡ [c/eV/day]	max $A(^{166m}\mathrm{Ho})$	$A(^{163}\mathrm{Ho})/A(^{166m}\mathrm{Ho})$	$N(^{163}\mathrm{Ho})/N(^{166m}\mathrm{Ho})$
3	3×10^{-6}	3.2×10^{-6}	10^{-5}	3×10^{-5}	10^{5}	4×10^{5}
300	3×10^{-4}	3.2×10^{-2}	10^{-1}	0.3	1000	4000

‡ from MC simulations

Effect of flat background on sensitivity



expected from simulations and preliminary HOLMES and ECHo measurements

A. Goeggelmann et al., EPJ.C 81 (2021) 363

A. Goeggelmann et al., EPJ.C 82 (2022) 139

The ECHo experiment

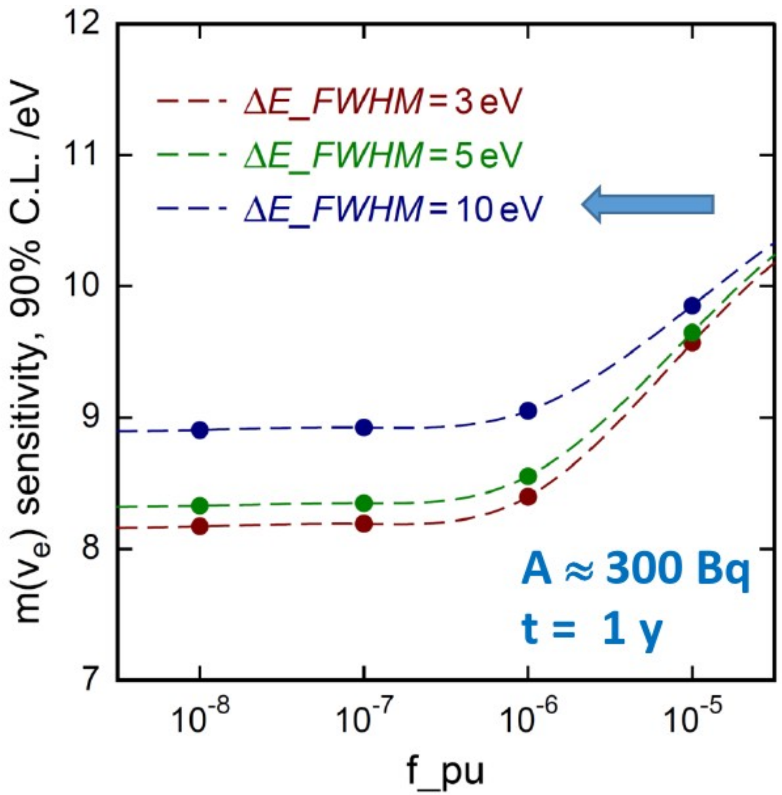
Arrays of Magnetic Metallic Calorimeters with ion-implanted ^{163}Ho

L. Gastaldo et al. Eur. Phys. J. Special Topics 226, 1623 (2017)

ECHo-1k

- number of detectors: 60~100 pixels
- activity: 1~5 Bq/pixel
- read-out: two-stage dc-SQUID
- energy resolution: ΔE_{FWHM}<10 eV

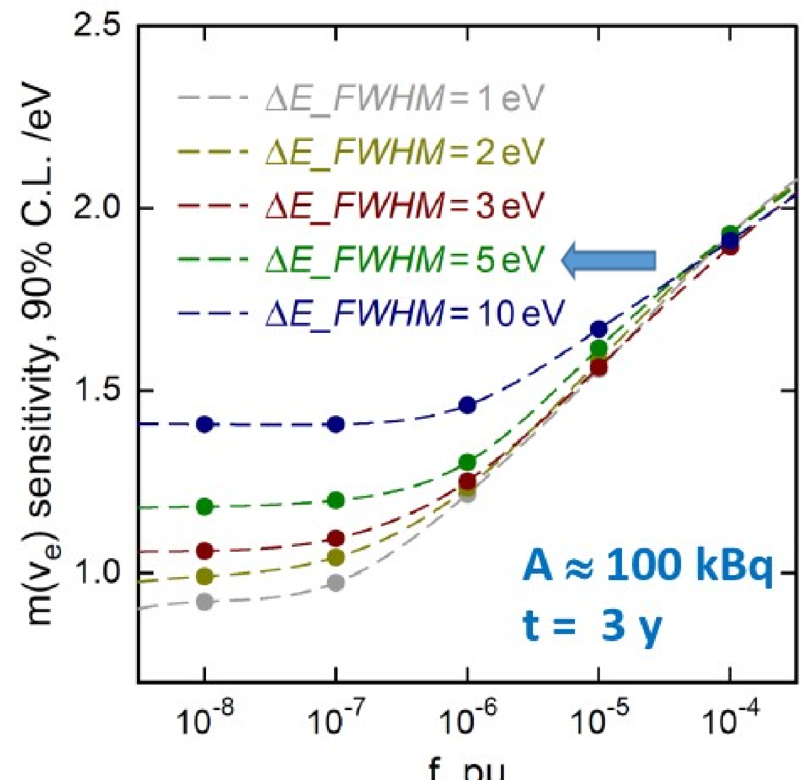
→ ***m*$_\nu$ statistical sensitivity <20 eV**



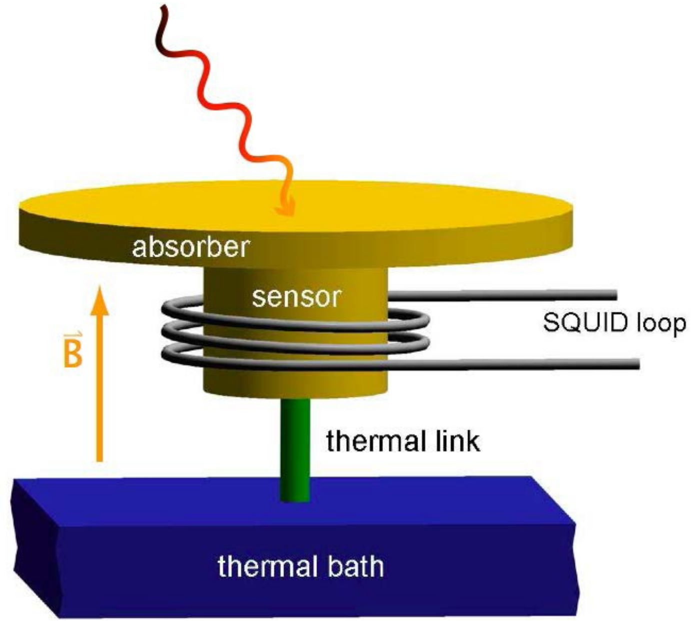
ECHo-100k

- number of detectors: 12000 pixels
- activity: 10 Bq/pixel
- read-out: microwave multiplexing
- energy resolution: ΔE_{FWHM}<5 eV

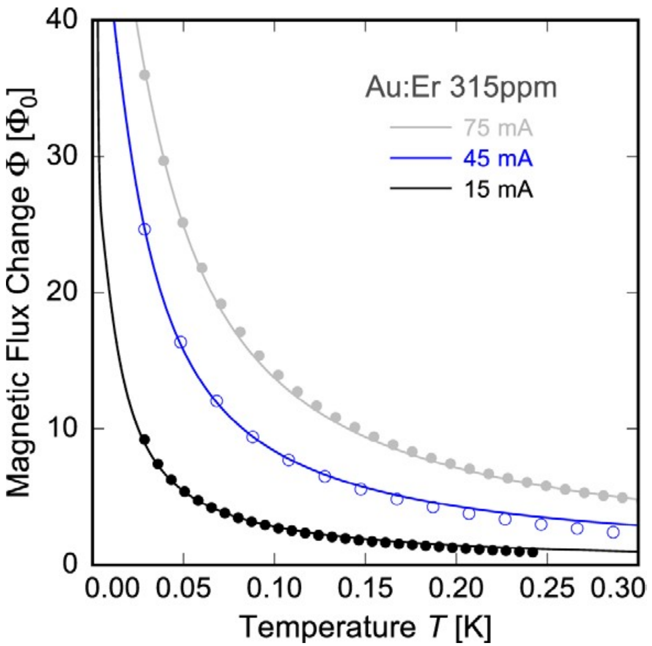
→ ***m*$_\nu$ statistical sensitivity <1.5 eV**



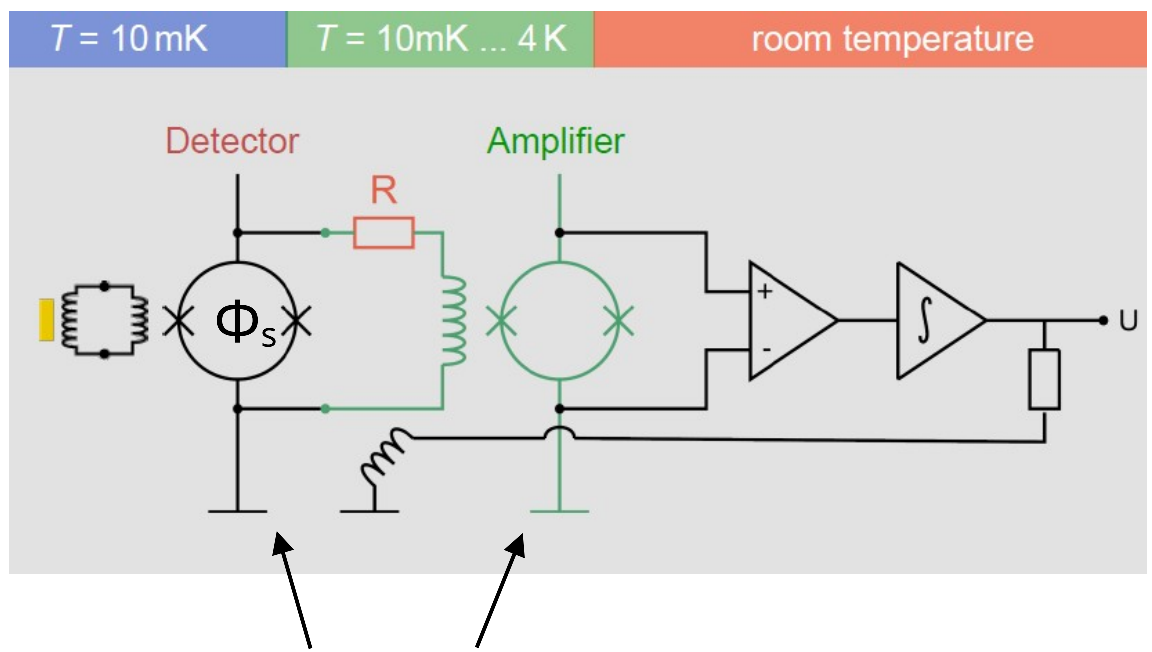
Metallic Magnetic sensors



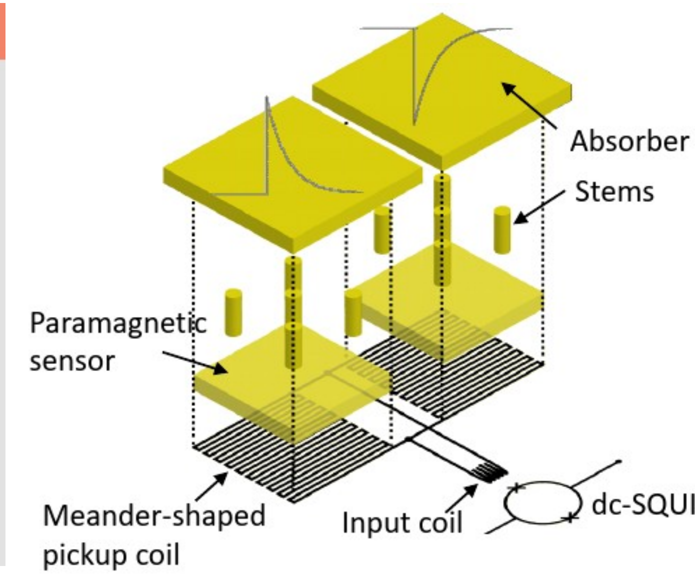
- paramagnetic temperature sensor
- **Ag:Er**, Au:Er …
- no power dissipation in the sensor no Johnson noise
- SQUID read-out → multiplexing for arrays
- large operating temperature range 10 - 100 mK
  - ECHo operates at $T \approx 30$ mK
- strong spin-electron coupling → fast rise time (≈100 ns)



$\Delta T \rightarrow \Delta M \rightarrow \Delta \Phi_s$



dc-SQUIDs

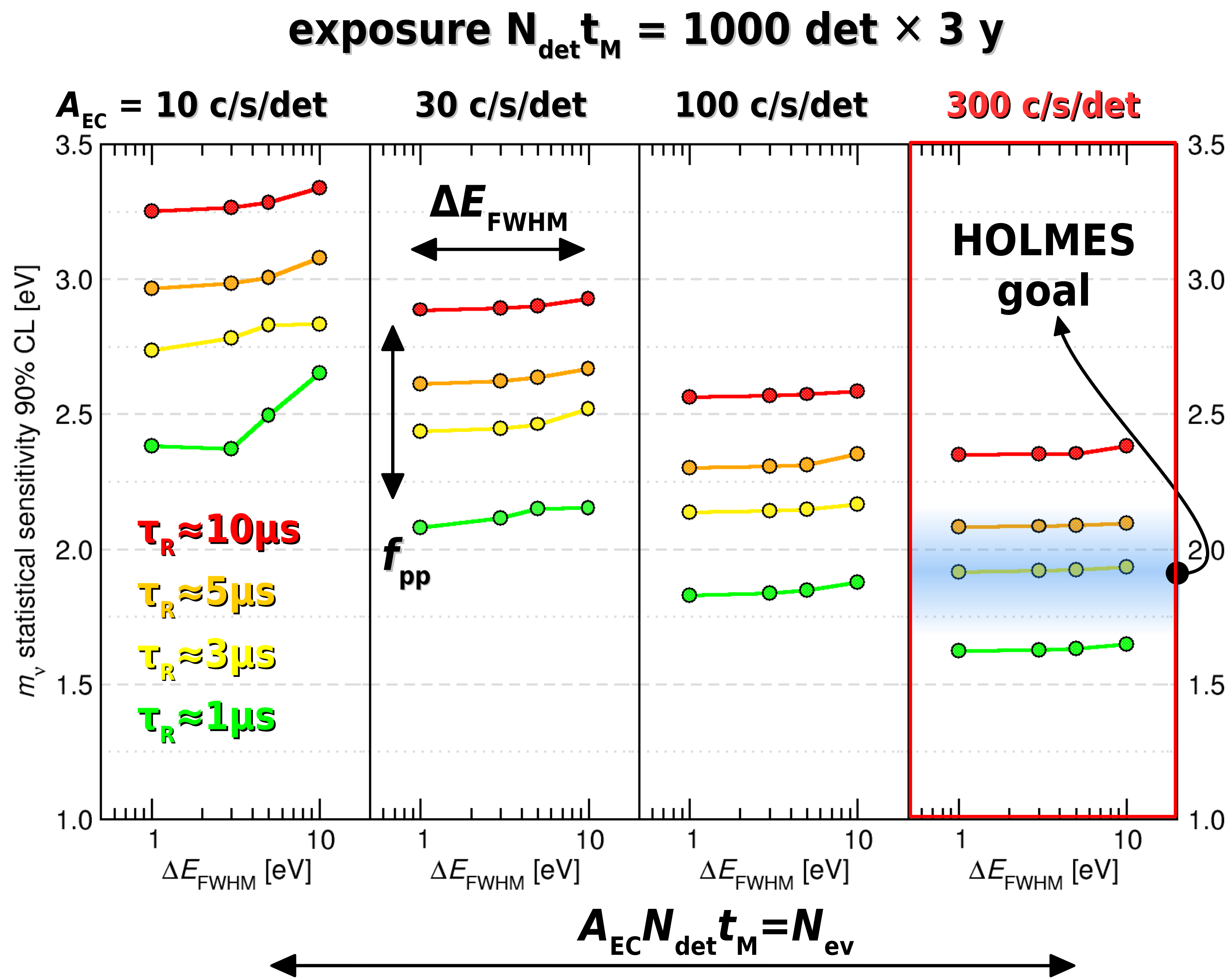


gradiometric configuration
2 MMC pixels on 1 SQUID channel

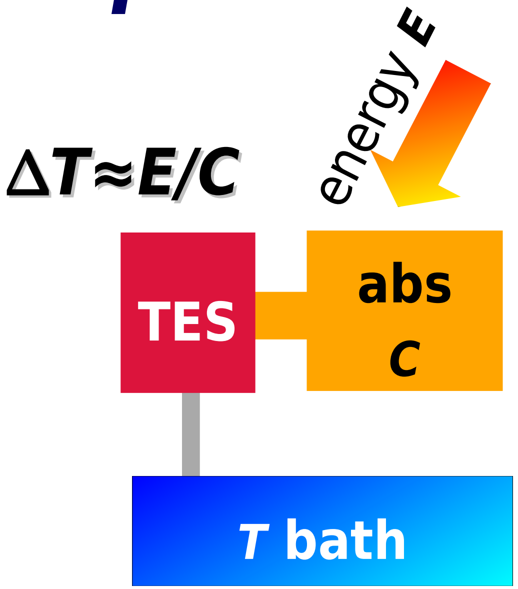
The HOLMES experiment

- Transitione Edge Sensors (TES) microcalorimeters with ion-implanted ^{163}Ho
- 6.5×10^{13} atom/det → A_{EC}=300 c/s/det
- $\Delta E \approx 1$ eV and $\tau_R \approx 1$ µs
- 1000 TES microcalorimeters
- 16 × 64-pixel arrays with microwave multiplexed read-out
- 6.5×10^{16} ^{163}Ho nuclei → ≈18 µg
  → 3×10^{13} events in 3 years
  → **m_ν statistical sensitivity ≈1 eV**

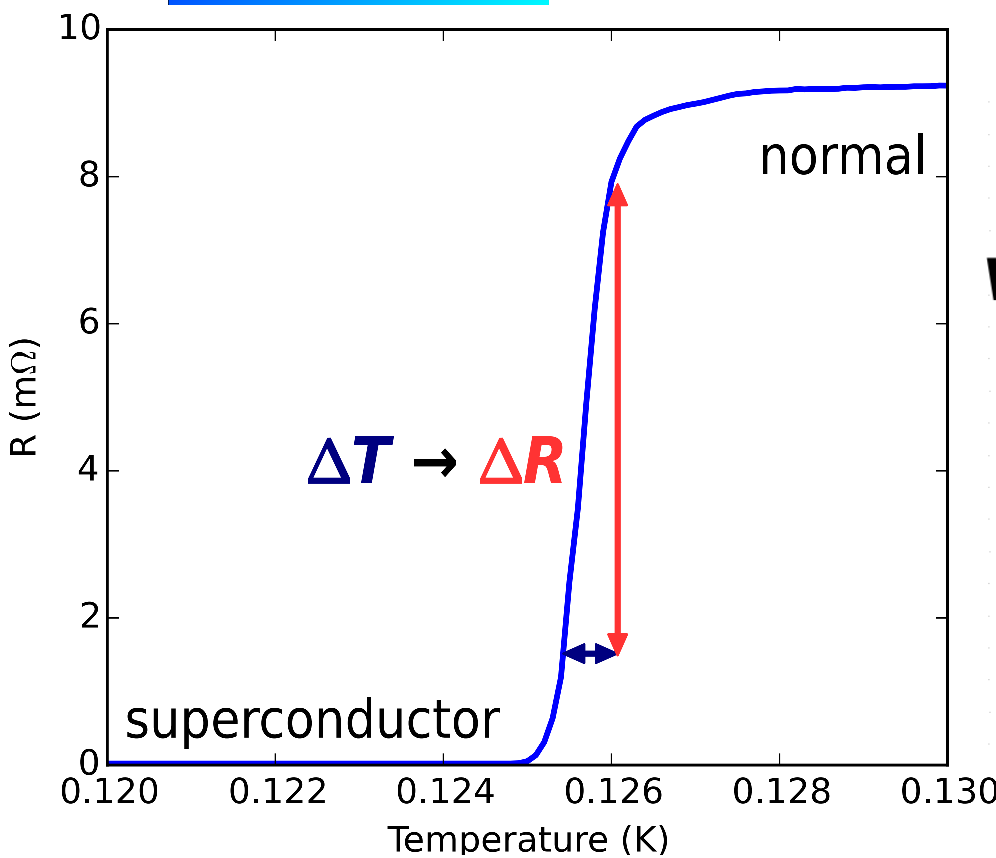
B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

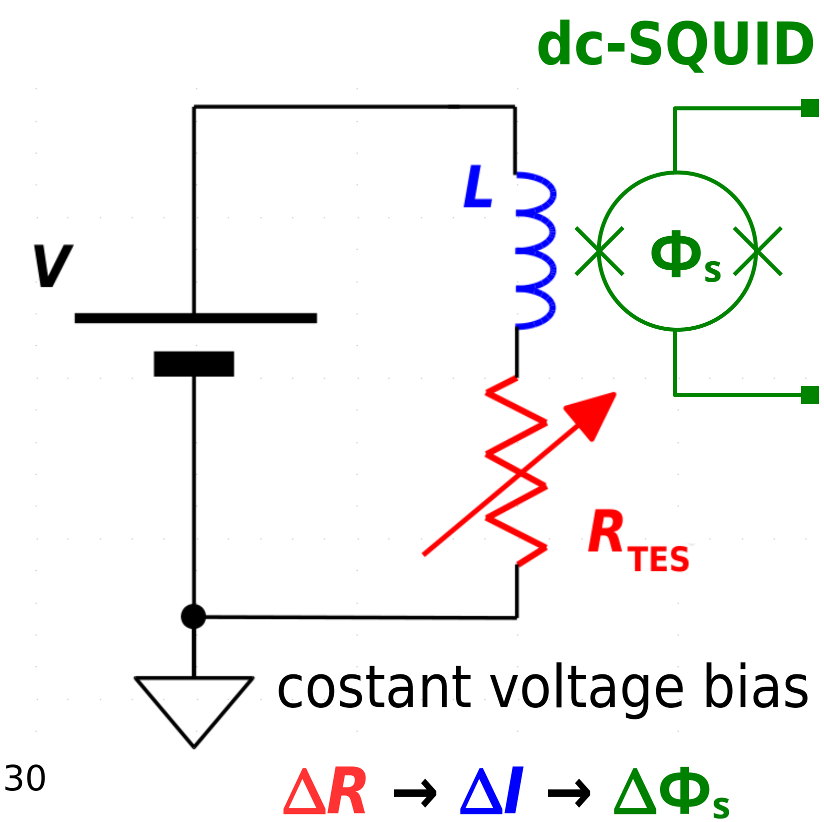


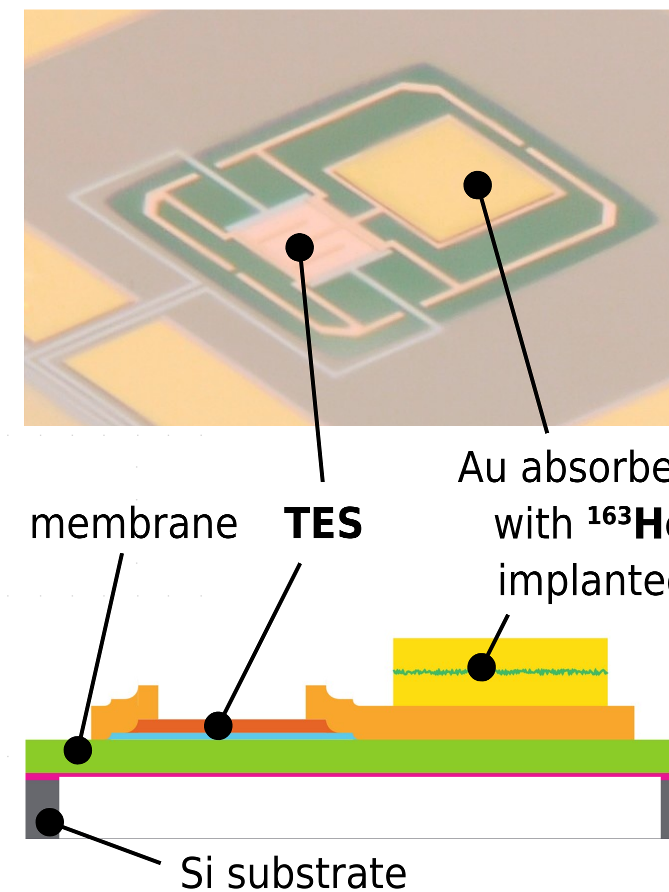
Superconducting transition edge sensors (TES)



- superconducting thin films operated inside the phase transition at T_C
  - HOLMES: Mo/Cu bilayer tuned for $T_c \approx 100$ mK
- high sensitivity $TdR/(RdT) \approx 100$ → high energy resolution $\sigma_E^2 \approx \xi^2 k_B T^2 C$
- strong internal coupling → high intrinsic speed
- low impedance (mΩ → Ω) → SQUID read-out → multiplexing for arrays

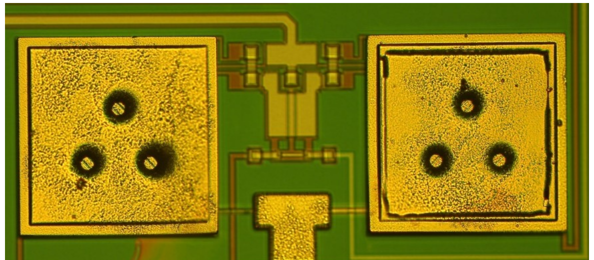


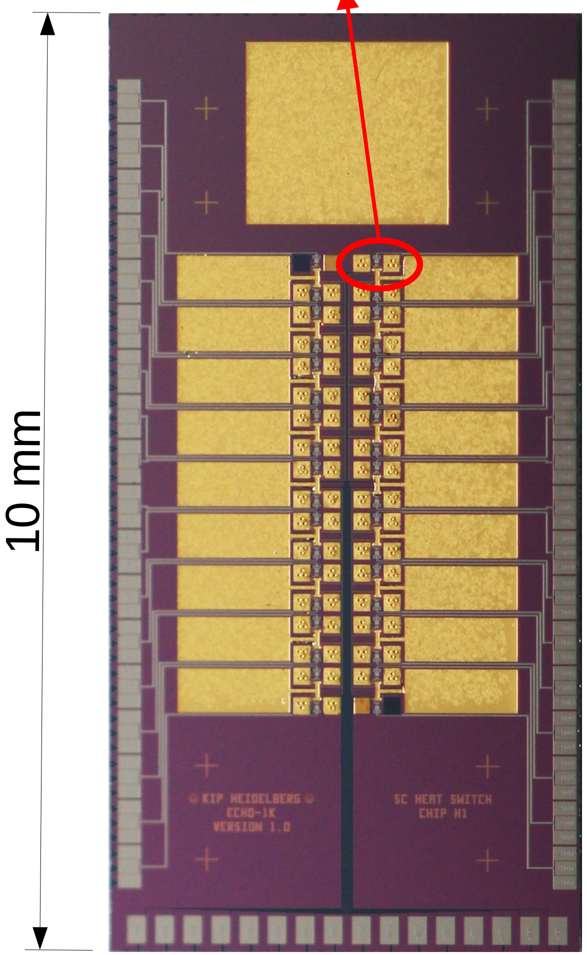




Microcalorimeters arrays

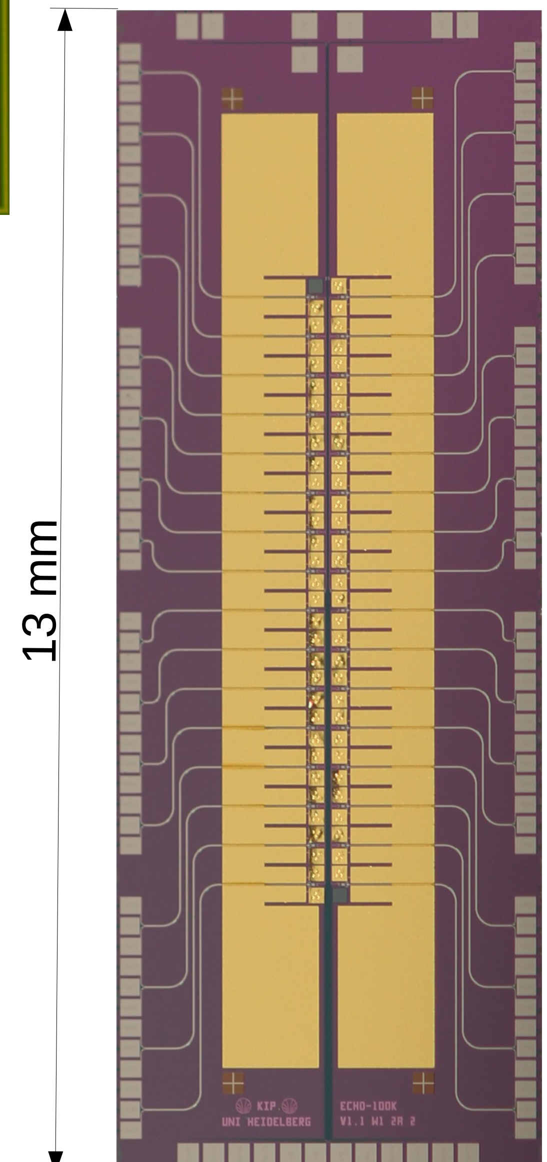
ECHo-1k





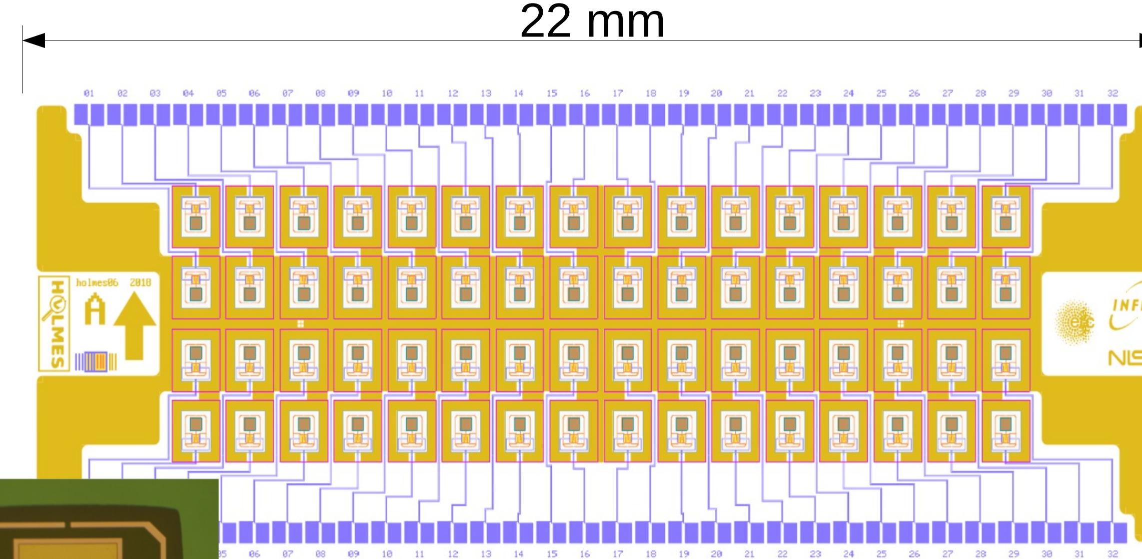
72 pixels

ECHo-100k

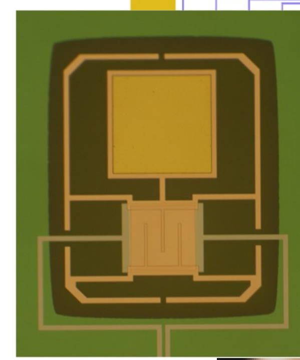


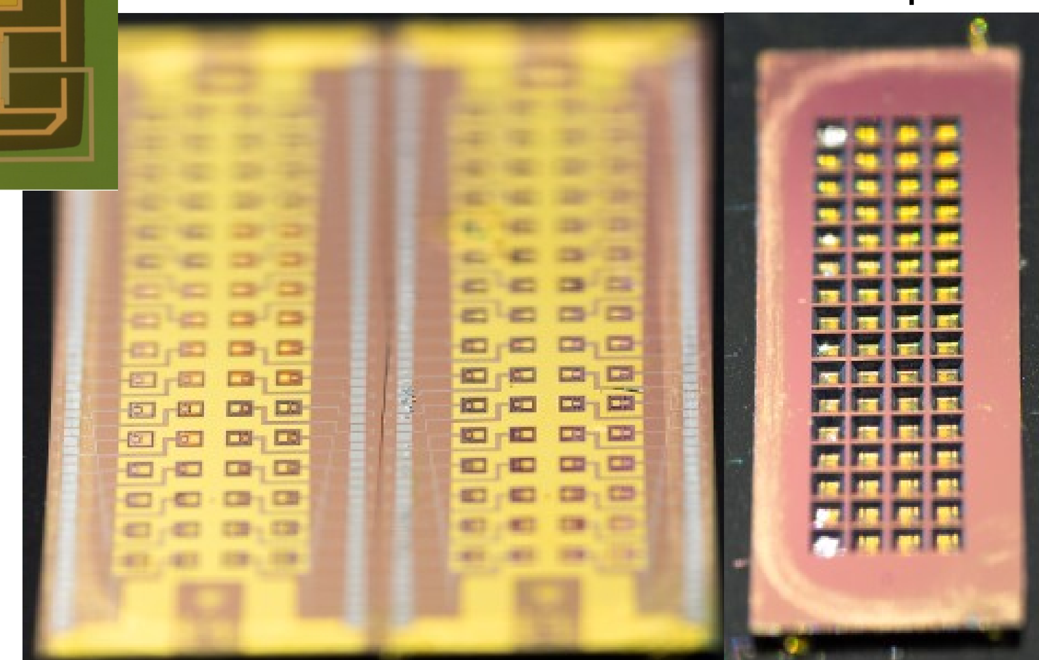
64 pixels

HOLMES



64 pixels



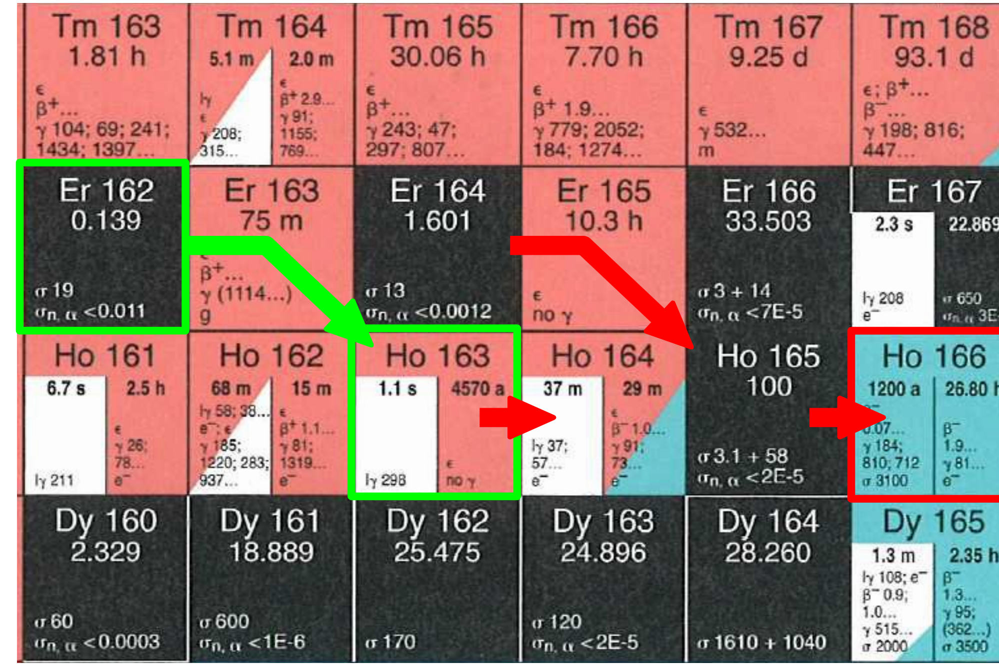


KOH micromachining

Isotope production

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

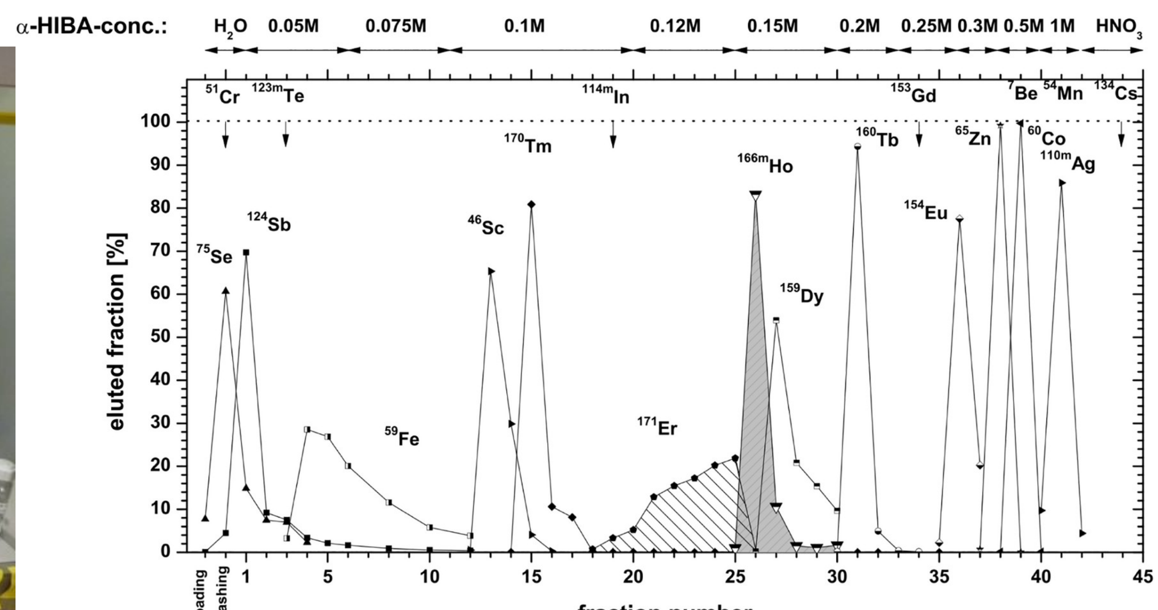
$^{163}\mathbf{Er} \rightarrow\ ^{163}\mathbf{Ho} + \nu_e \quad \tau_{1/2}^{EC} \approx 75$ min

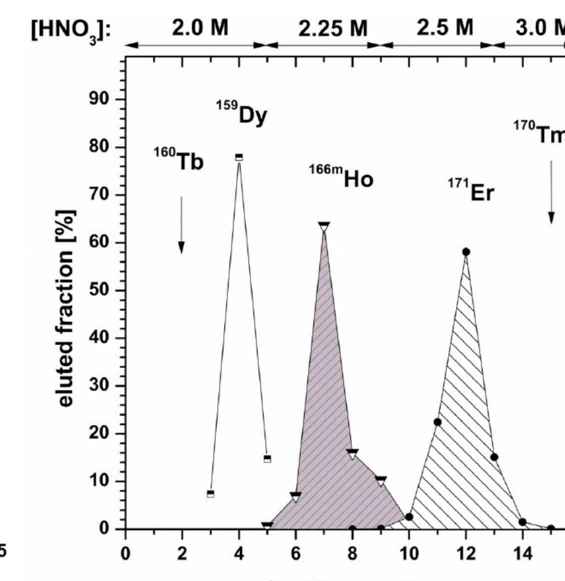


- ^{162}Er irradiation at **ILL nuclear reactor** (Grenoble, France)
  - thermal neutron flux 1.3×10^{15} n/cm^2/s
- Ho chemical separation with ion-exchange resins in hot-cell to remove Er matrix and and radioactive products
- separation efficiency >90 %
- HOLMES has collected ≈200 MBq of ^{163}Ho (+ ≈400 kBq of ^{166m}Ho)

H. Dorrer et al., Radiochim. Acta, 106 (2018) 535

S. Heinitz et al., PLoS ONE 13(8): e0200910

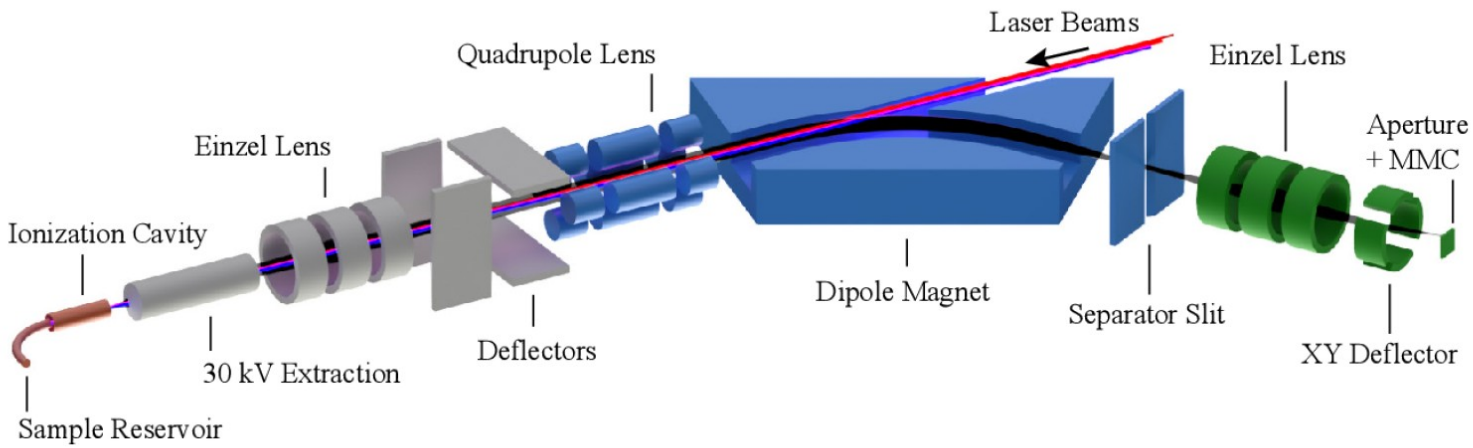




Mass separation and isotope embedding

^{166m}Ho must be separated by magnetic mass spectrometer

requires high current, high source and geometrical efficiency



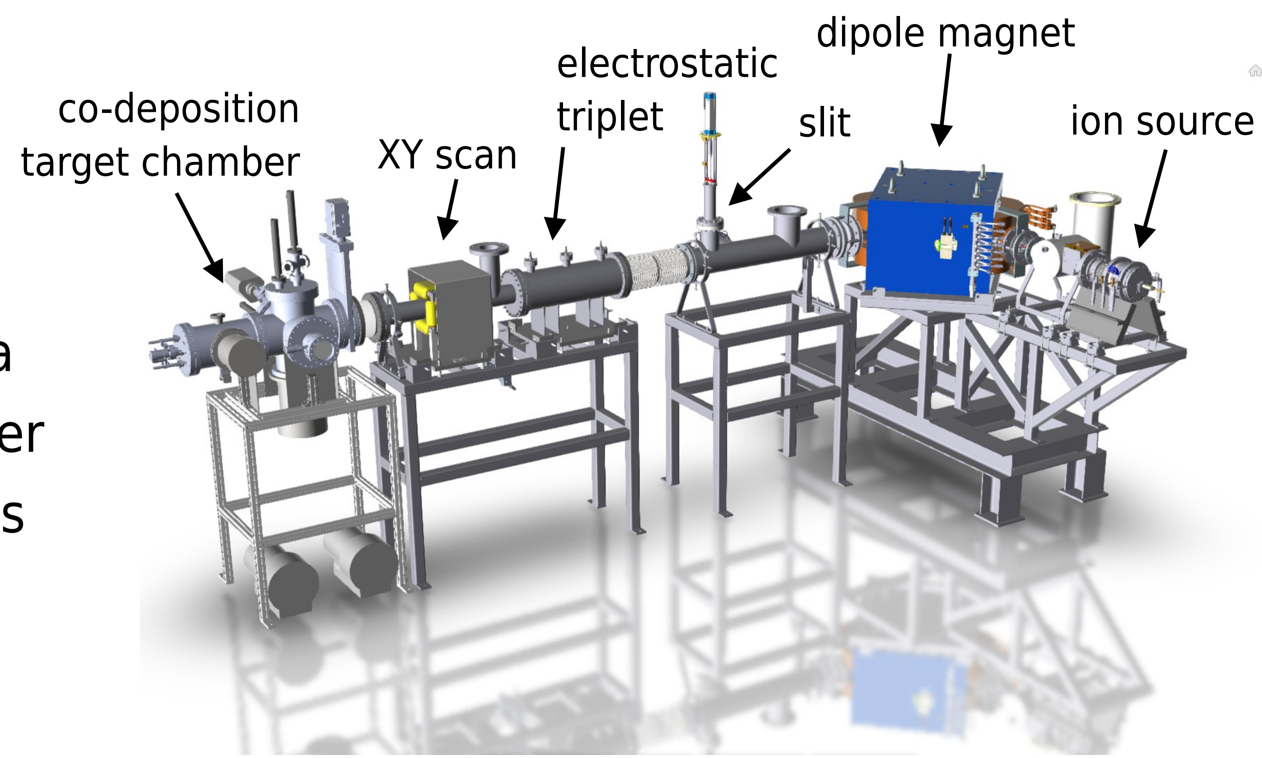
ECHo: resonant ionization laser ion source (RILIS)

- RISIKO at Mainz University
- efficiency: (69 ± 5stat ± 4syst) %
- ^{166m}Ho/^{163}Ho < 4(2)10^{-9}

T. Kieck et al., NIM A, 945, 2019, 162602.

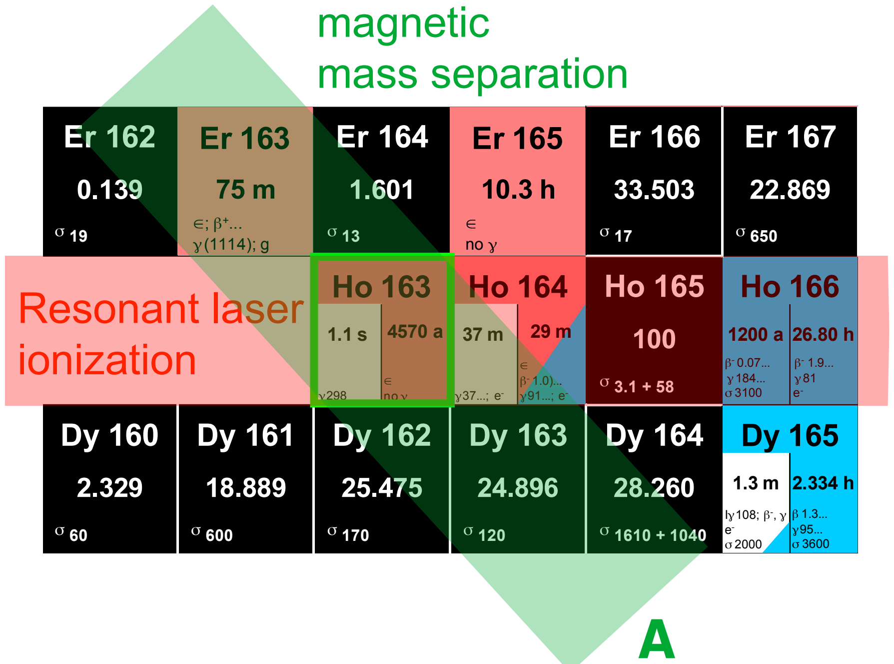
HOLMES: Ar plasma sputter ion source

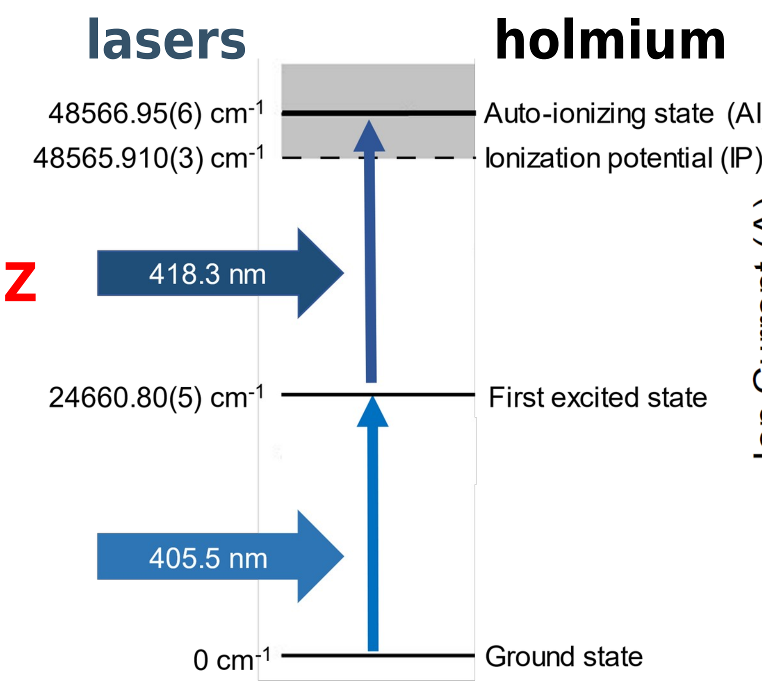
- all components ready for installation in Genova
- now testing without triplet/XY-scan and chamber
- high current ion source optimization in progress



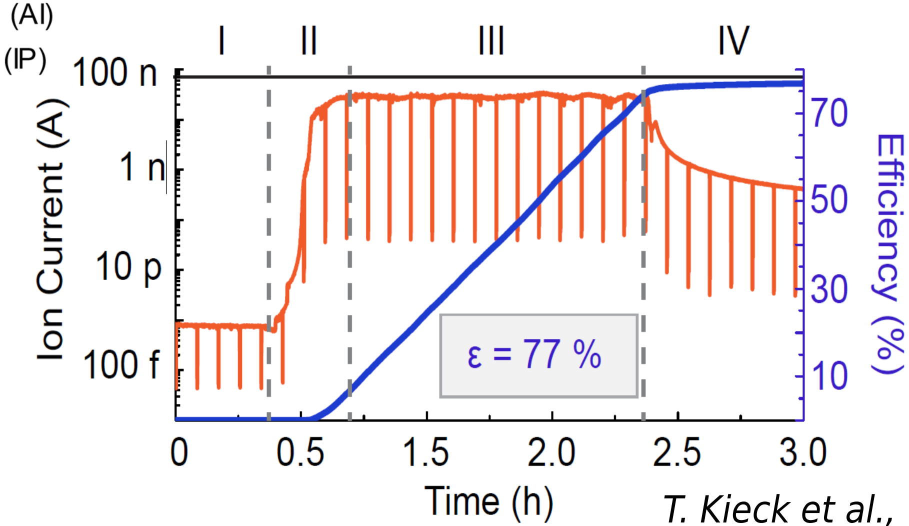
RISIKO for ECHo

- Resonant laser ionization
  → 2 lasers tuned to selectively ionize Ho
  → high ionization efficiency ion source





ε=(69 ± 5stat ± 4syst)%



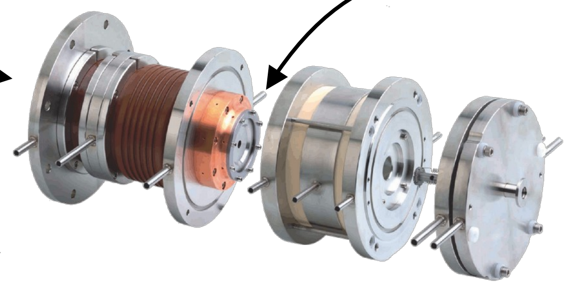
T. Kieck et al., NIM A, 945, 2019, 162602.

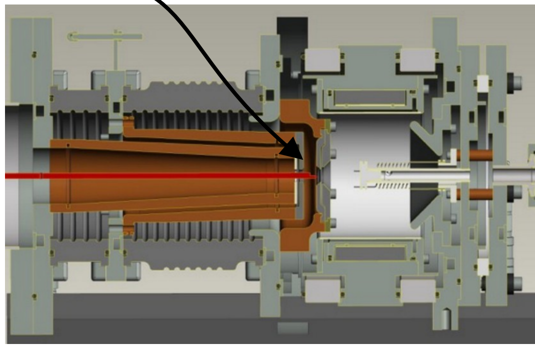
Ion Source **30 keV Acceleration** **Magnet** **Slits** **Focalization** **Implantation**

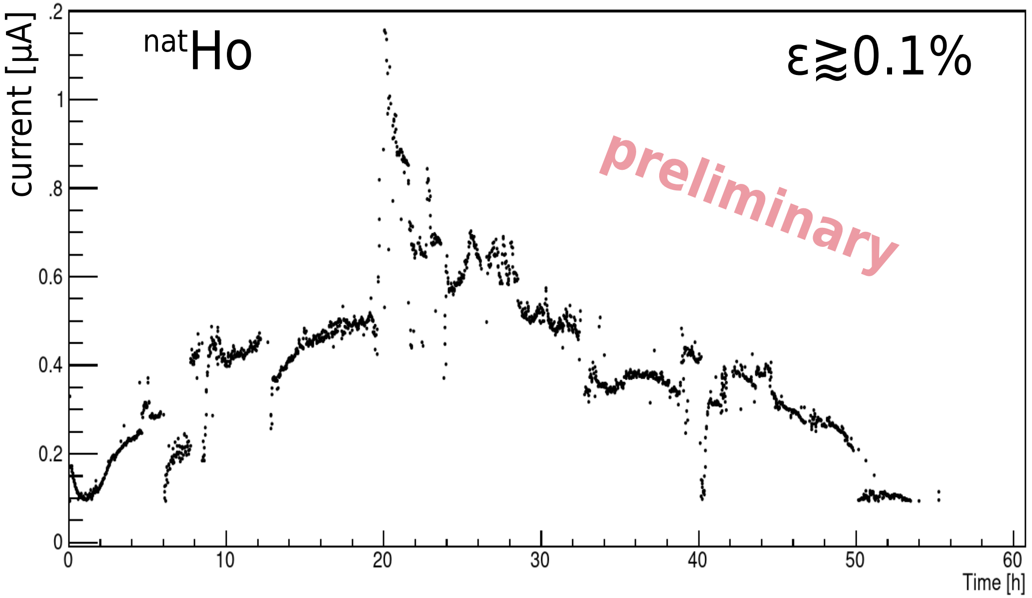
HOLMES ion implanter progresses

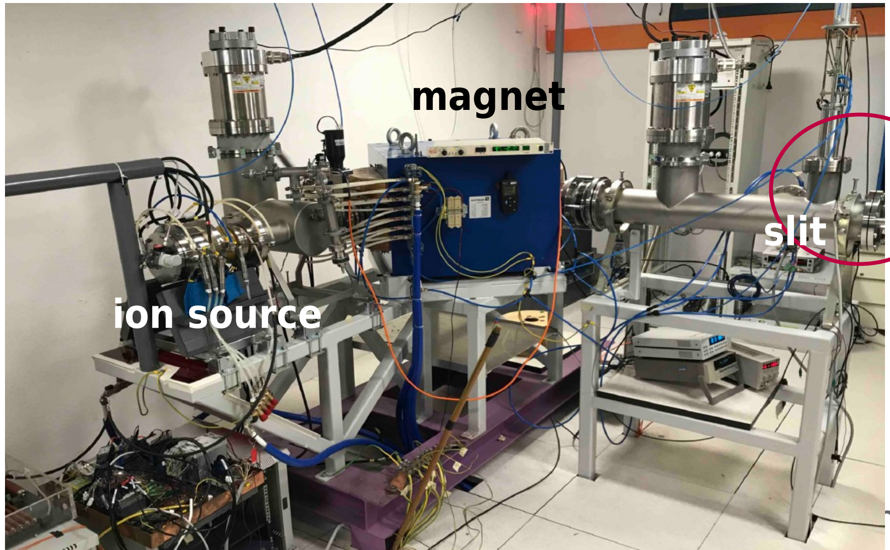
- high current sputter source
- several sputter targets tested
- sintered Zr-Y-Al-Ho$(NO_3)_3$

→ highest effieciency, current and stability



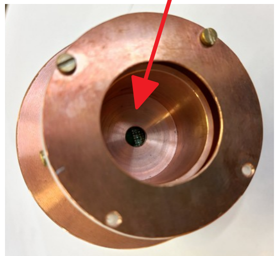


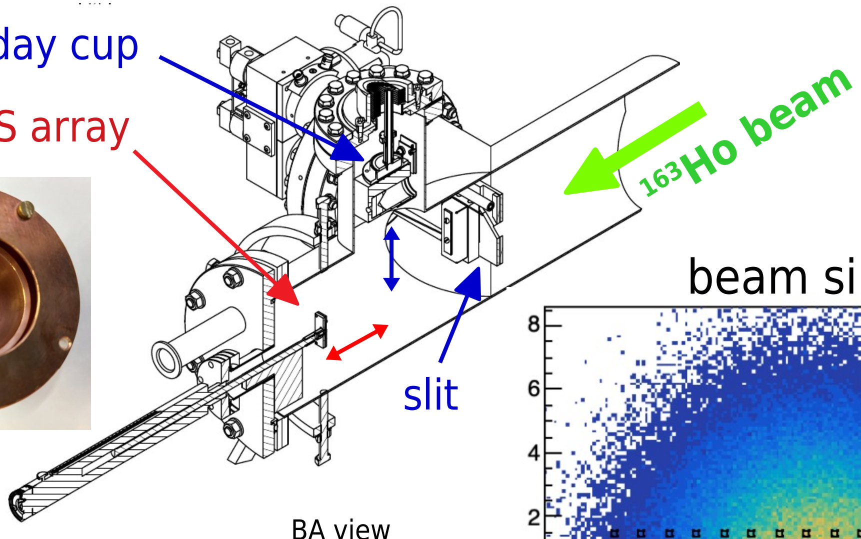




configuration without focussing

for first low activity implants





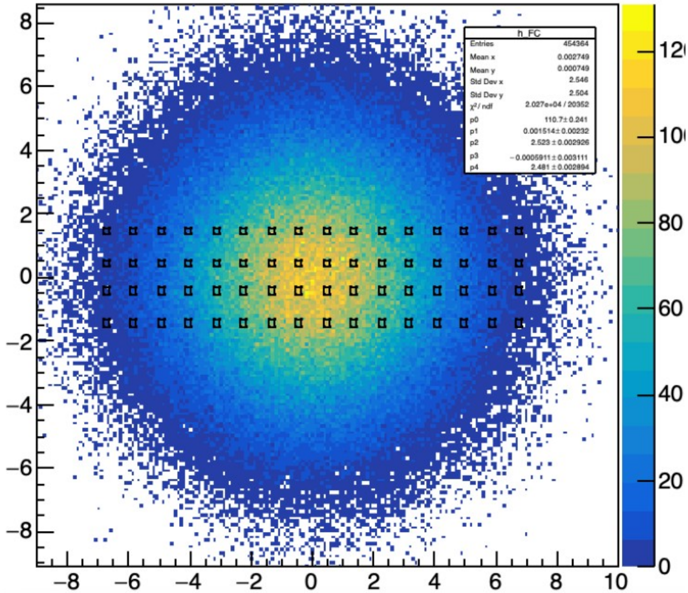
8 MBq of ^{163}Ho in ^{nat}Ho (0.35%)

$I(^{nat}\mathrm{Ho})$=0.2 μA for 24 h

→ peak pixel activity ≈1 Bq

uniform activity with 3 shots

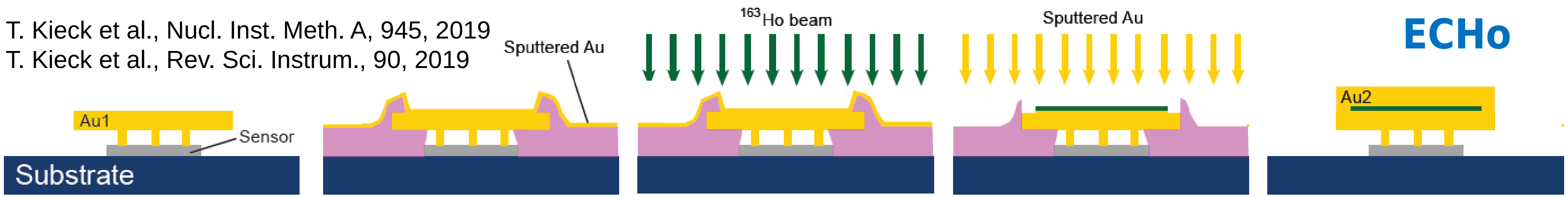
beam simulation

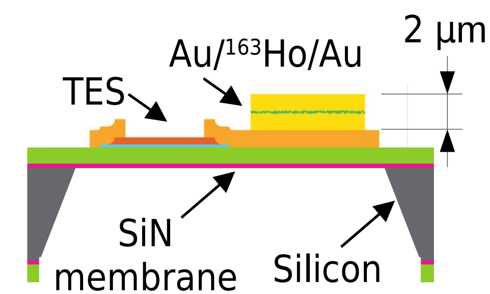


Detector absorbers for calorimetry

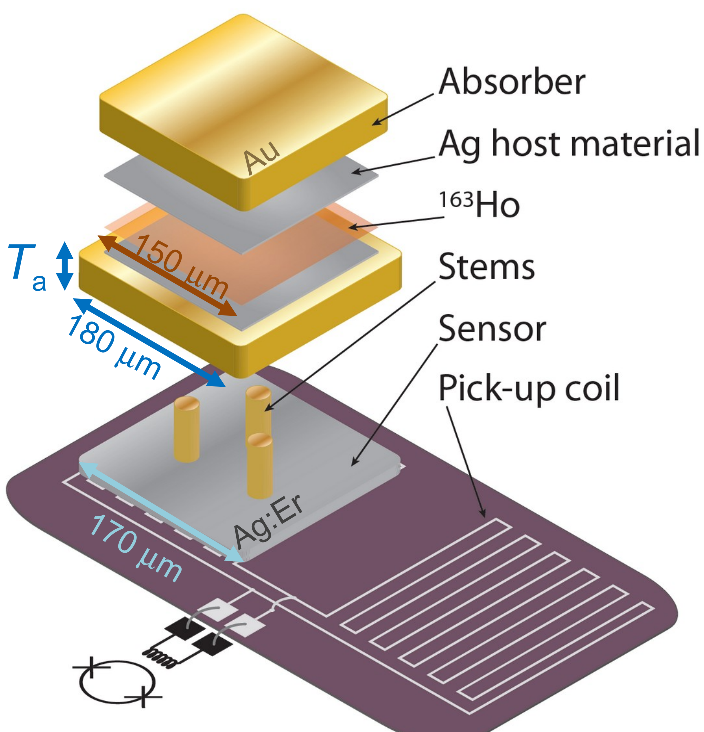
- Au absorber must stop all radiation from atomic de-excitations with $E_c \approx Q$
  - for H=M1 → 3-4 Auger/C-K electrons carry most of E_c (the most energetic with $\langle E_e \rangle \approx 2$ keV)
  - for H=M1 → rarely ($\omega_M \approx 10^{-3}$) one X with $\langle E_X \rangle \approx 2.5$ keV and low energy electrons
  - shake-off electrons have energies mostly ≲800 eV

T. Kieck et al., Nucl. Inst. Meth. A, 945, 2019
T. Kieck et al., Rev. Sci. Instrum., 90, 2019





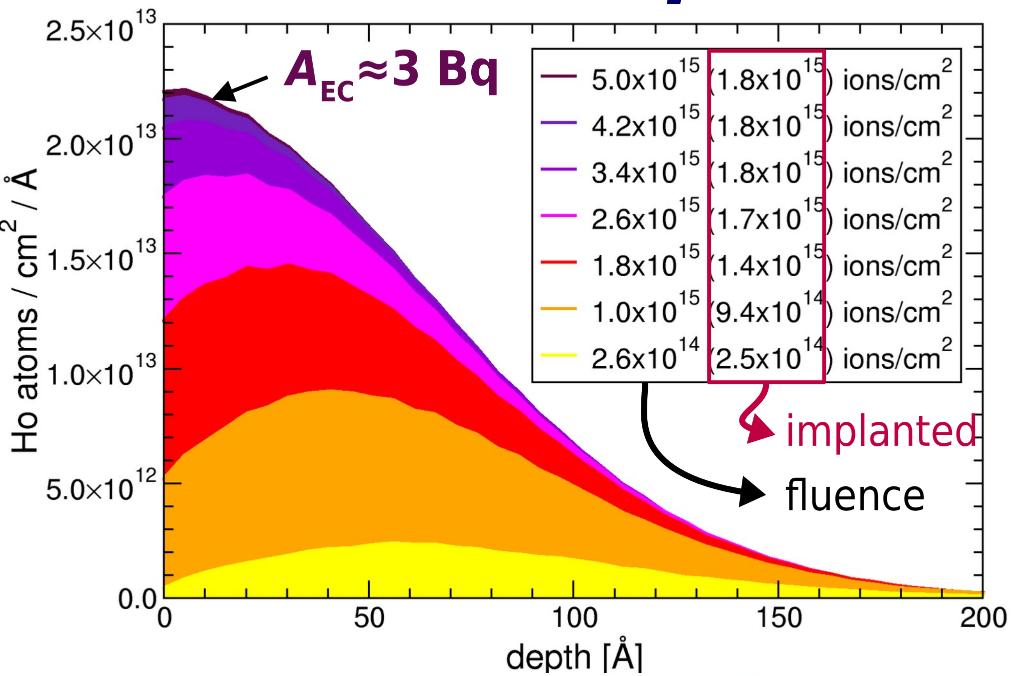
HOLMES



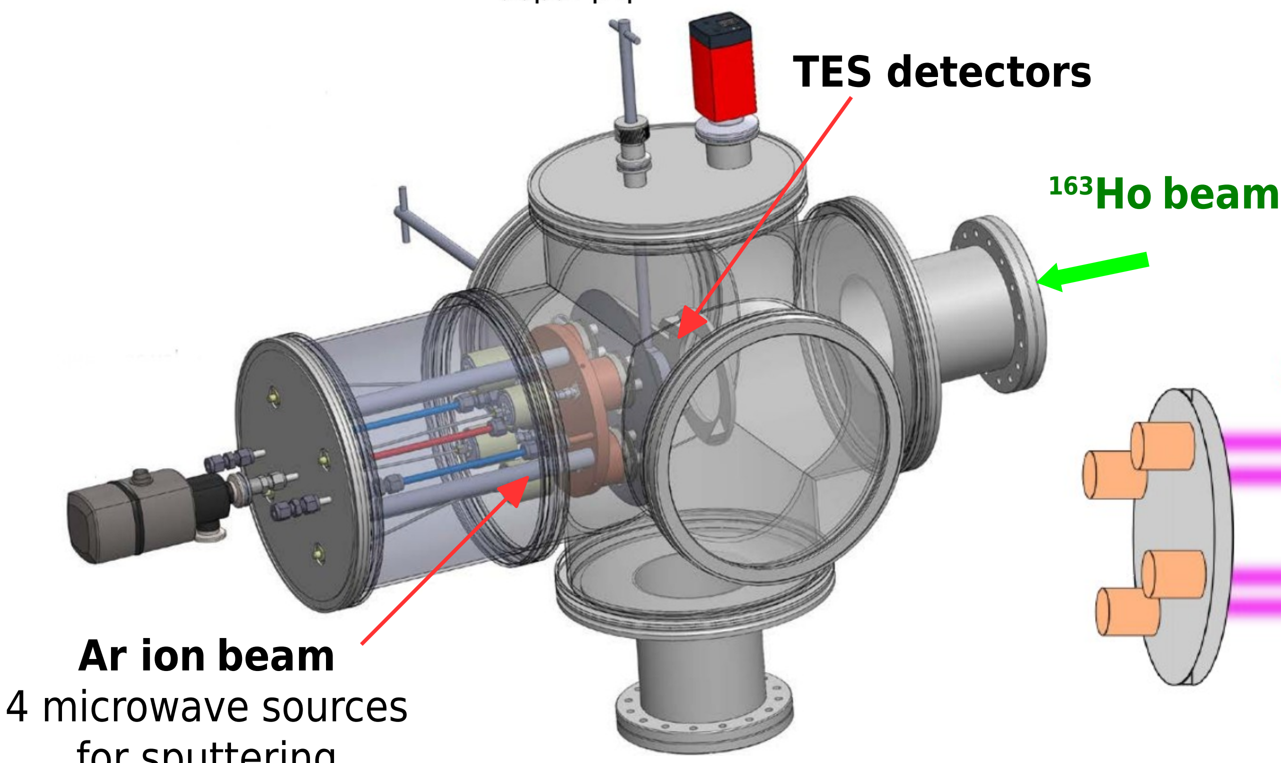
ECHo design

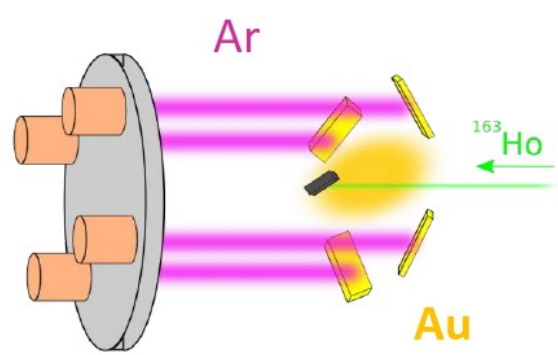
- **ECHo**: T_a=3 µm
  - electrons: fully contained (no simulation)
  - X-rays (2.6 keV<E_X<Q): 1.5×10^{-5} escaping ("raytracing" sim)
- **HOLMES**: T_a=1 µm (Geant4 MC simulations for $E_{X,e}$=Q)
  - fully implanted surface (no containement border)
  - electrons: 1.5×10^{-4} escaping (→ tail with same intensity)
  - X-rays: 4×10^{-3} escaping (→ tail with intensity 1.3×10^{-3})

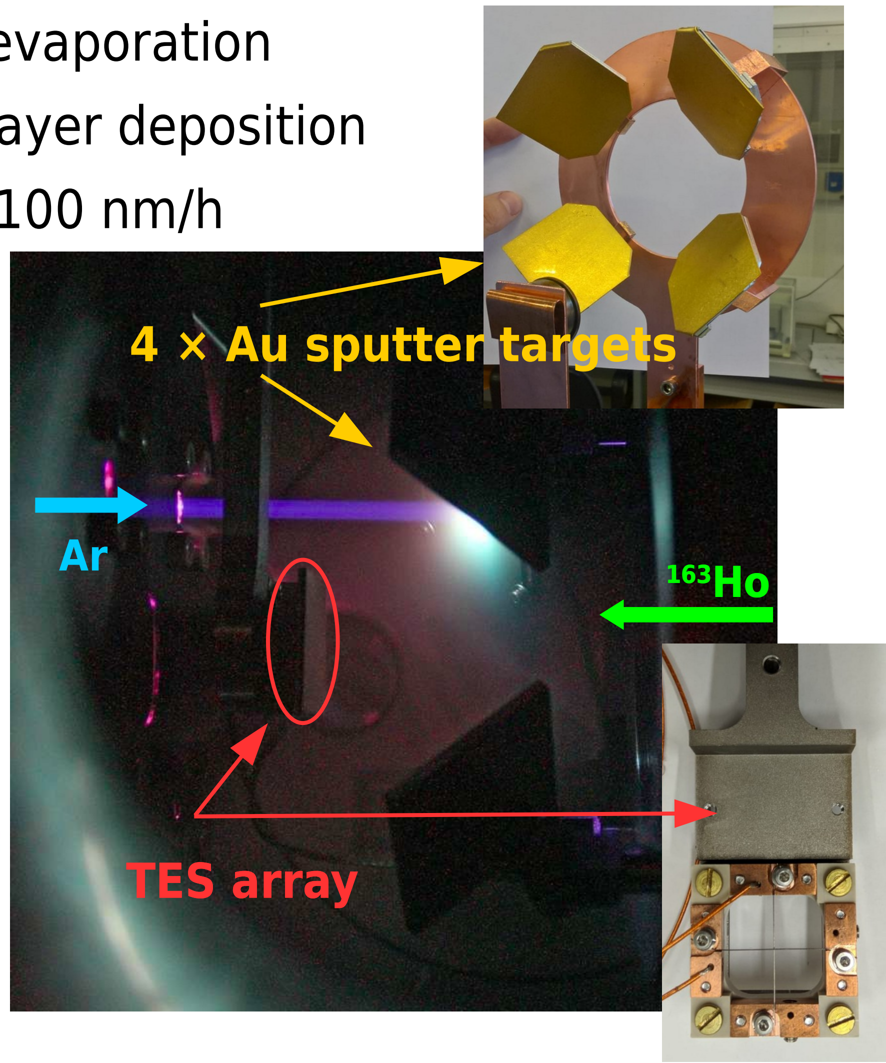
HOLMES co-deposition system



- ion implant simulation with SRIM2013
- **^{163}Ho ions on Au (E_{ion} = 50 keV)**
- ^{163}Ho ion beam sputters off Au from absorber (≈26 Au/Ho)
  - implanted ^{163}Ho saturates at A_{EC}≈3 Bq (HOLMES design)
  - compensate by Au co-evaporation
  - in situ upper 1 µm Au layer deposition
    → with 4 ion sources >100 nm/h







Implanted Ho heat capacity

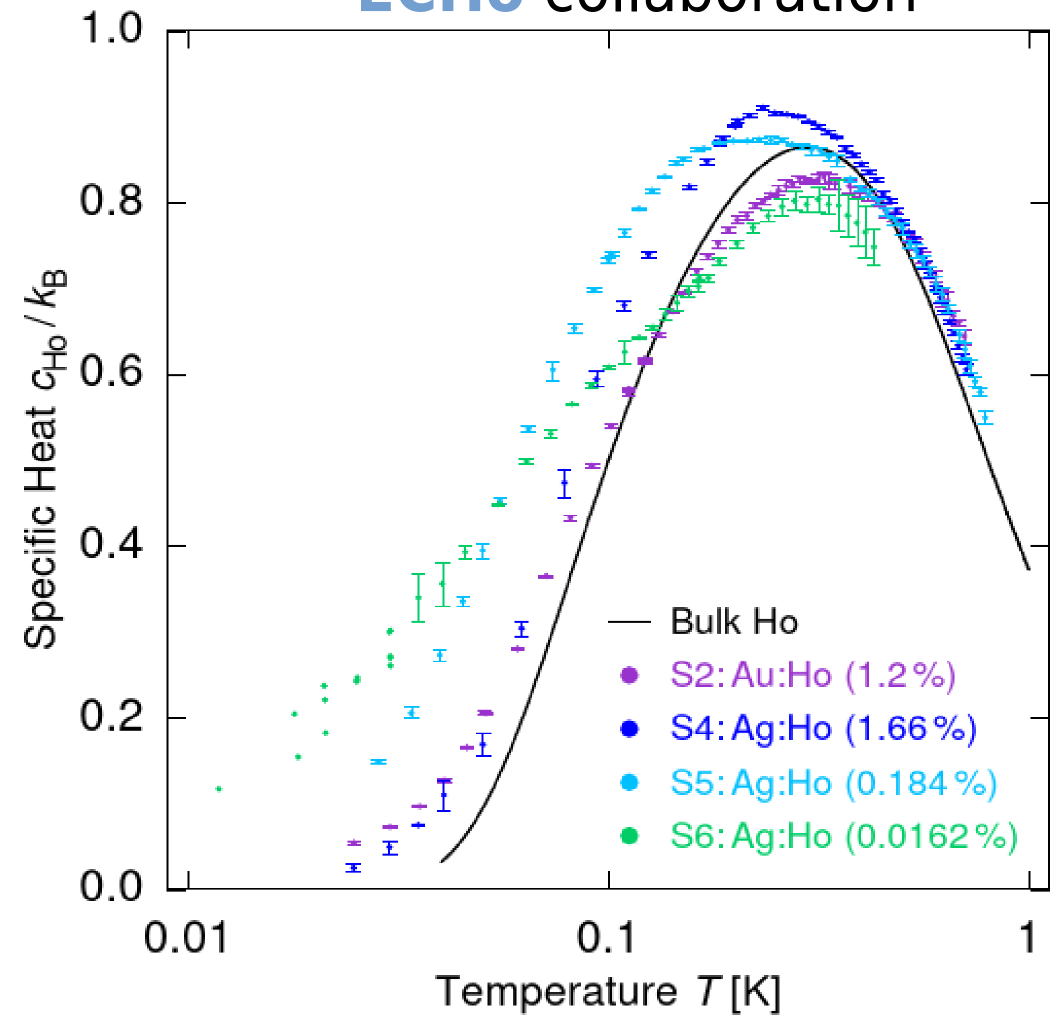
- optimal ΔE depends on C and T

$$\Delta E \propto T\sqrt{C}$$

$$C = C_a + C_{\mathrm{Ho}}$$

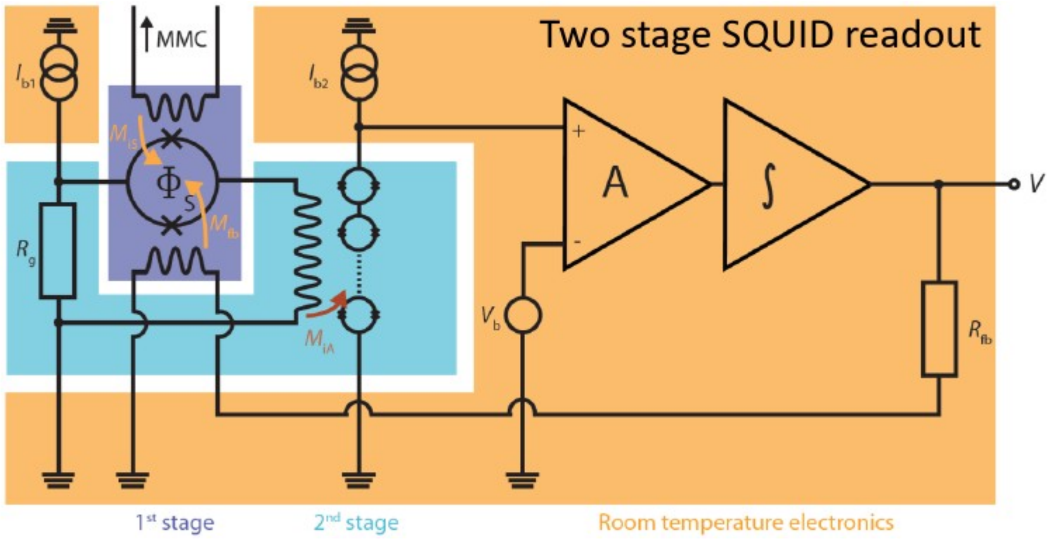
- Ho heat capacity C_{Ho} dominated by a Schottky anomaly at ≈300 mK
  - ***J***=8 and ***I***=7/2 → hyperfine and crystal field splittings
- contradictory C measurements for Ag:Ho
  - still under investigation
- high activities could be manageable
  - operating at 30 mK or below
  - A=300 Bq → x_{Ho}>10 % → closer to bulk C
  - to be explored by HOLMES

ECHo collaboration



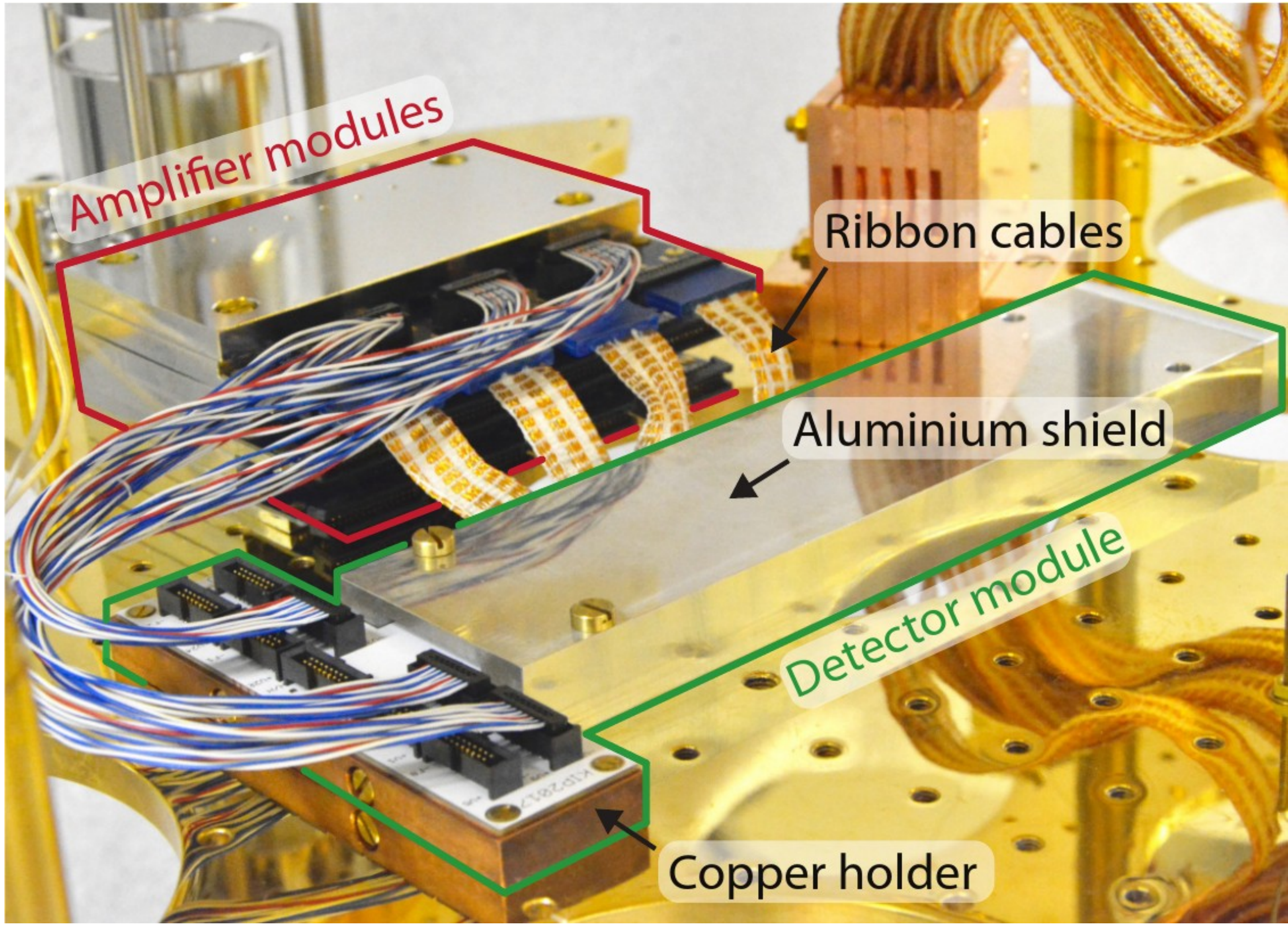
Herbst, M. et al., J Low Temp Phys 202, 106–120 (2021)

ECHo-1k read-out



parallel SQUID read-out
1 SQUID channel for 2 pixels

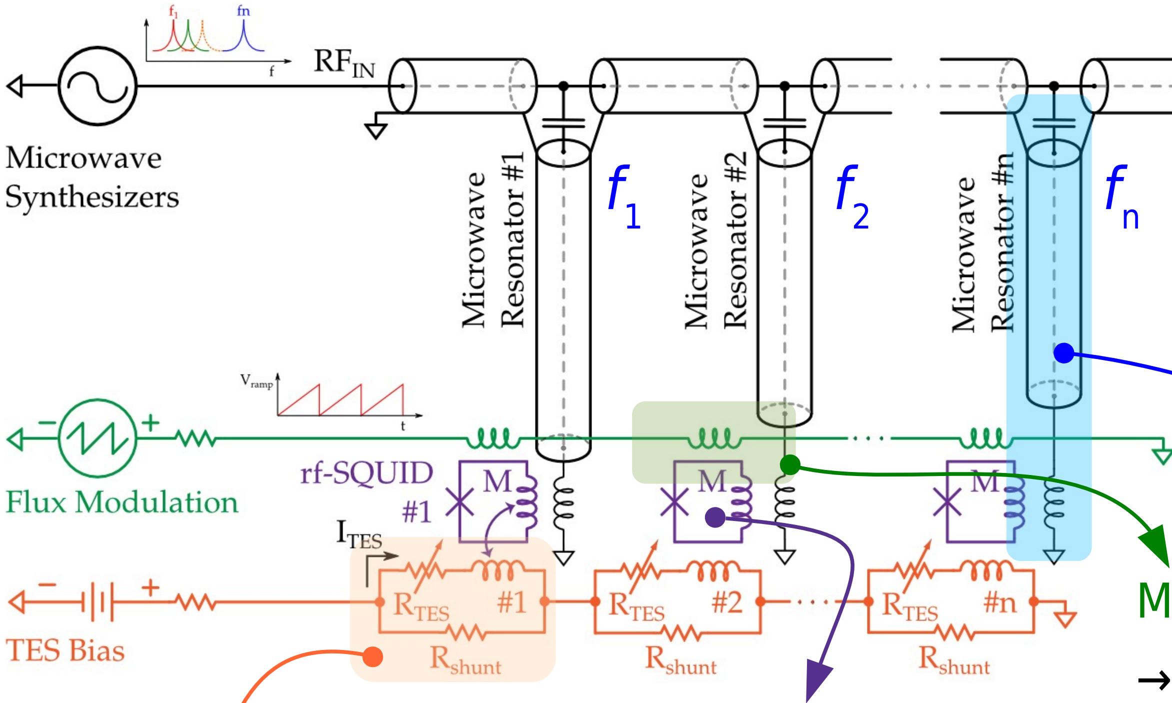
72 read-out channels for ECHo-1k
10 wires/channel to room temperature
→ **720** wires from low to room temperature
→ not viable for ⩾1000 channels ...



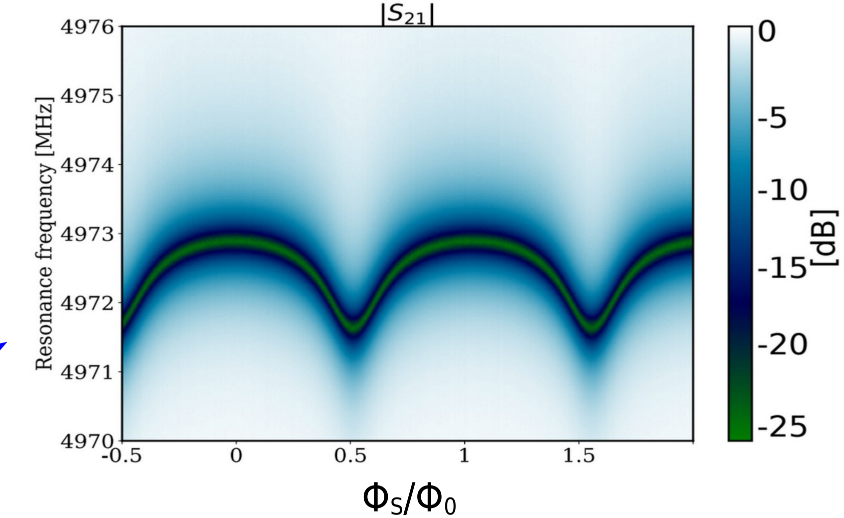
F. Mantegazzini et al. JINST16 (2021) P08003

Microwave multiplexing for array read-out

microwave multiplexing to read-out many detectors with one single RF line and HEMT amplifier



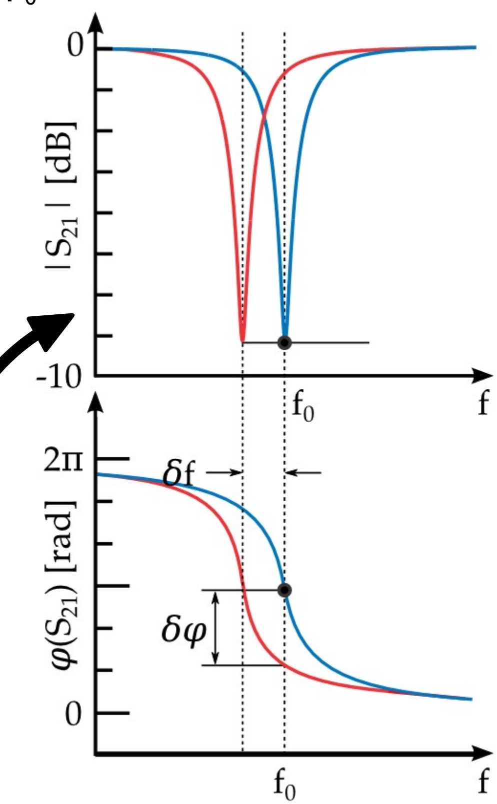
GHz LC resonator f_i



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

→ linearizes flux-inductance relation

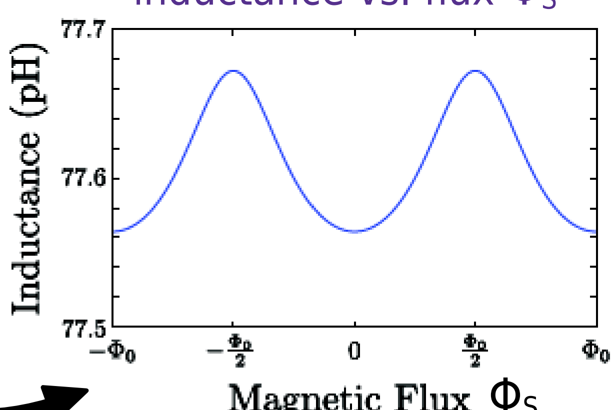
→ converts flux $\Delta\Phi_S$ to phase shift ϕ

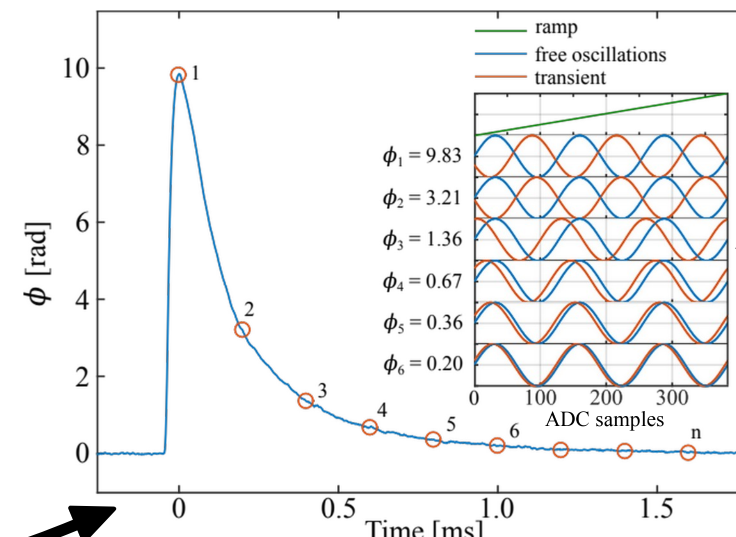


dc-biased TES

$\Delta T \rightarrow \Delta I \rightarrow \Delta\Phi_S$

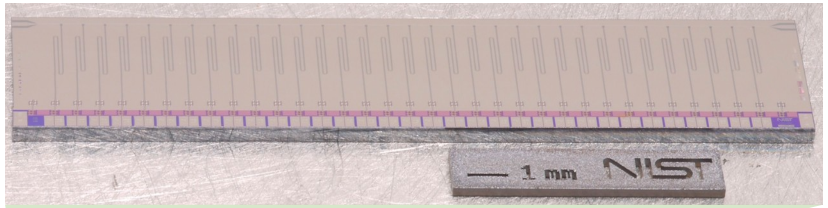
non-hysteretic rf-SQUID inductance vs. flux Φ_S





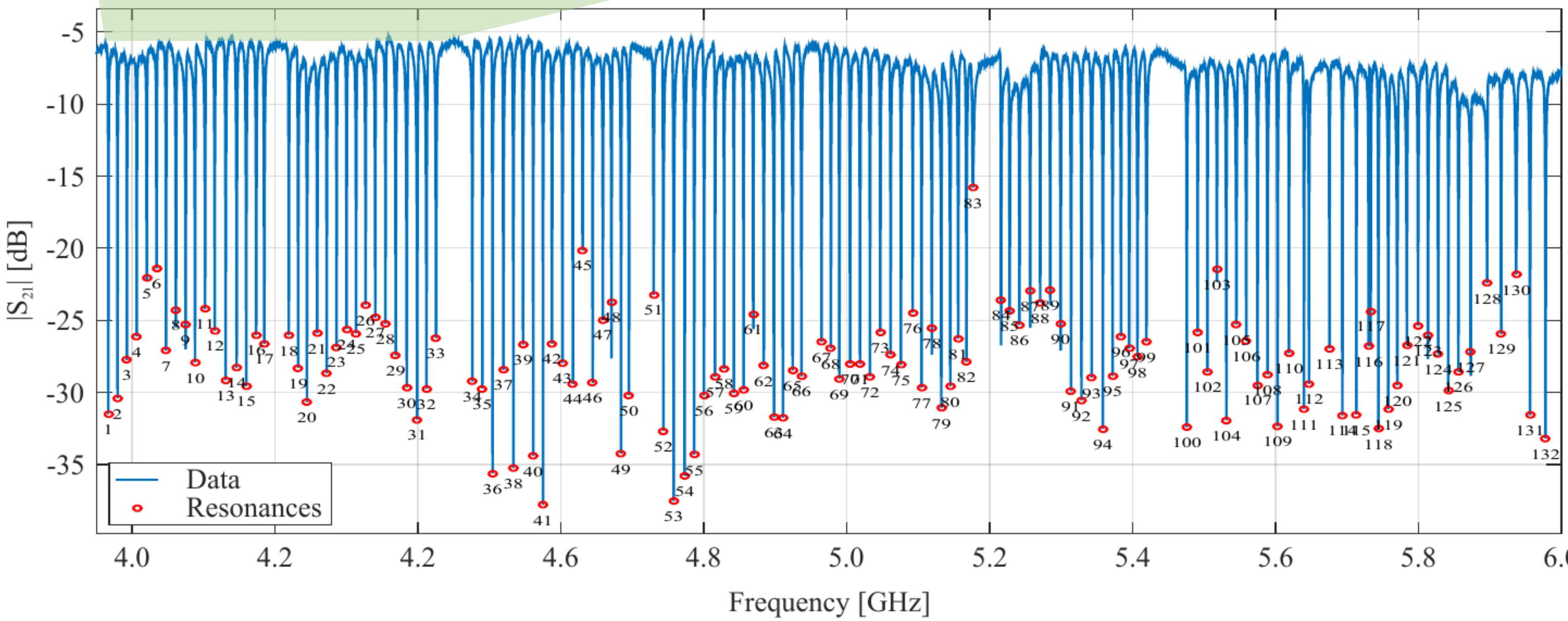
D.T. Becker et al 2019 JINST 14 P10035

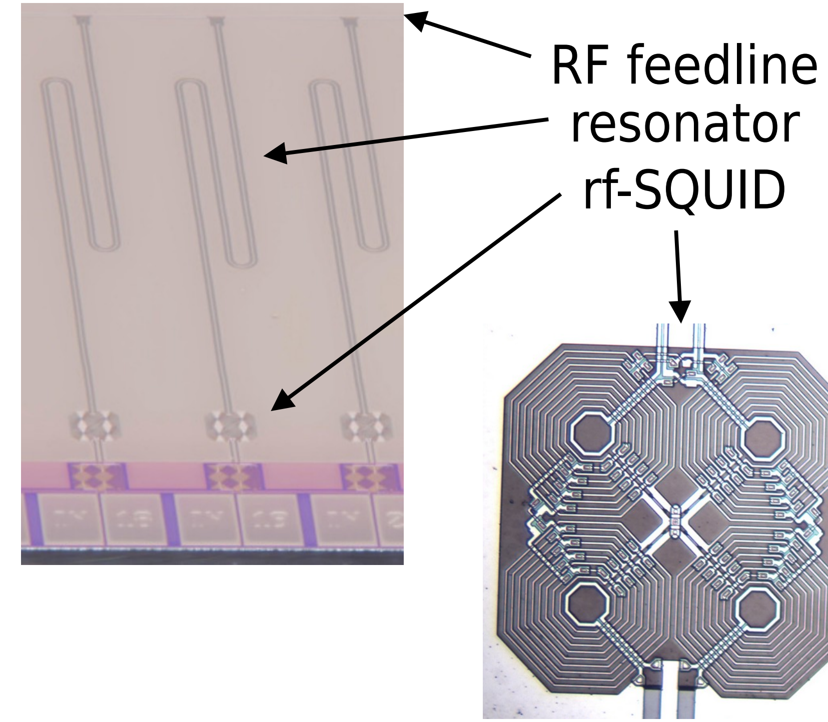
Microwave mux results: HOLMES



4 µmux chips in series

→ 132 resonances in 2 GHz





		required	measured
Resonator bandwidth	Δf_{BW} [MHz]	2	2±1
Resonator spacing	Δf [MHz]	14	14±1
Resonator depth	ΔS [dB]	>10	29±6

multiplexing factor n_{TES}

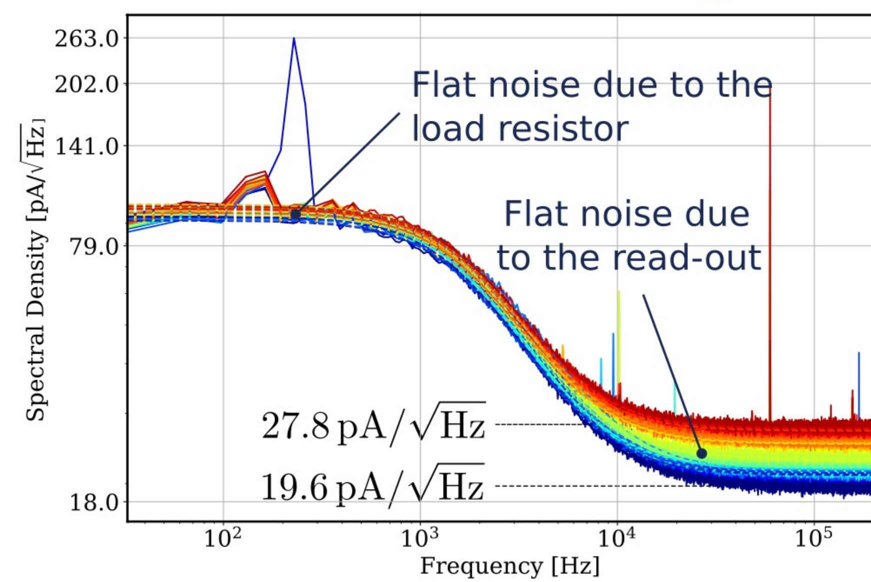
$$\frac{n_{TES}}{f_{ADC}} \approx \frac{\tau_{rise}[\mu s]}{140} \frac{1}{MS/s}$$

for f_{ADC}=512 MS/s and τ_{rise}≈10 µs

→ n_{TES}≈32

Read out noise

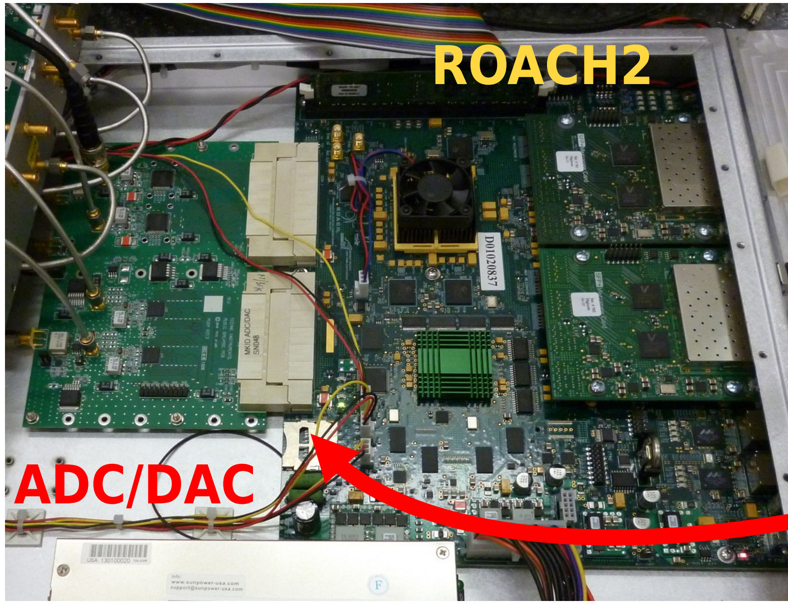
32 Channels, no TES bias applied



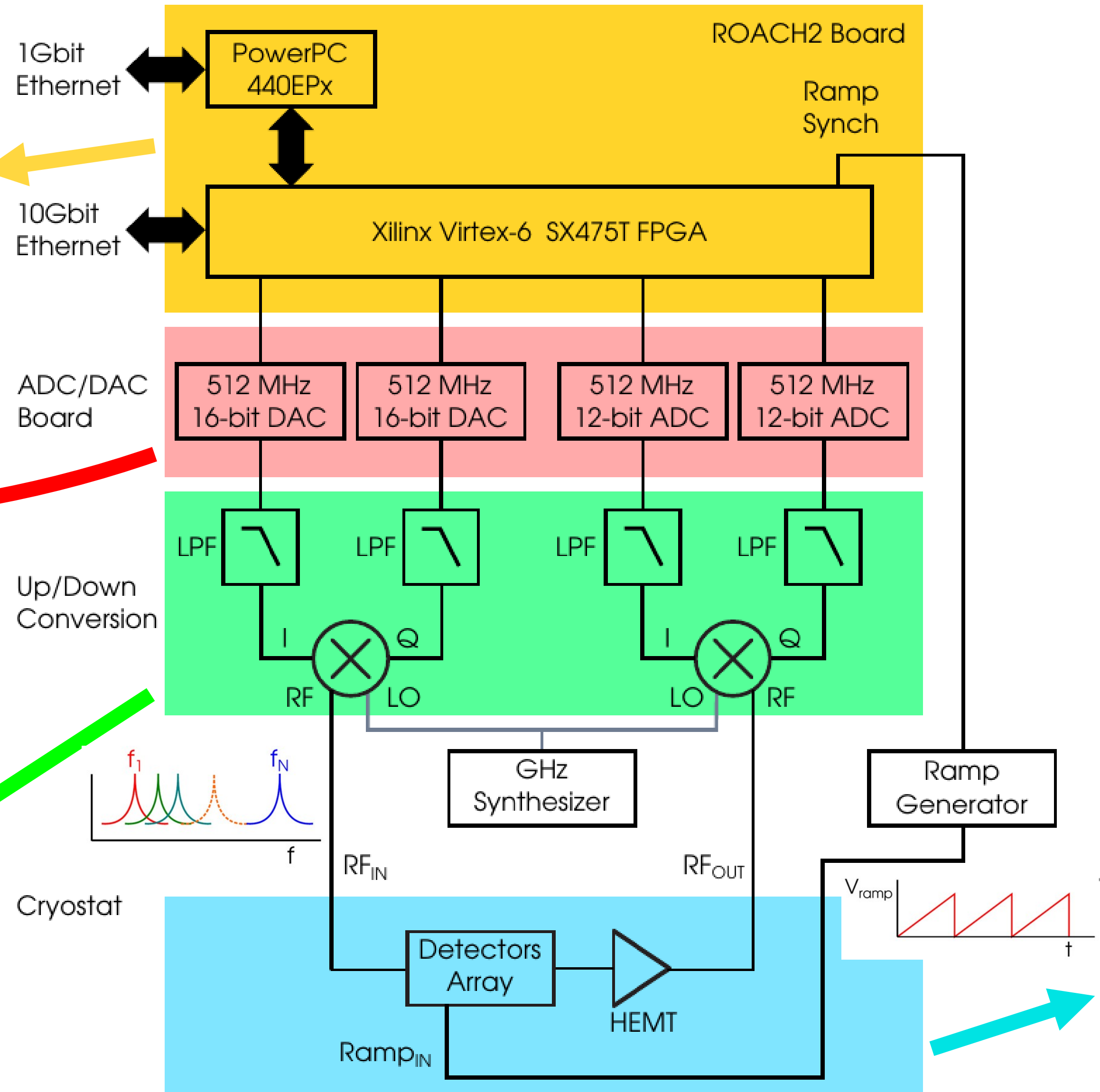
D.T. Becker et al 2019 JINST 14 P10035

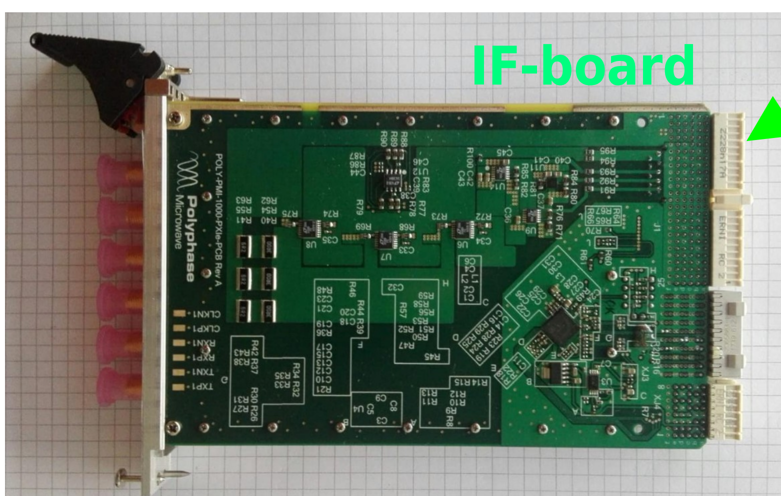
HOLMES heterodyne readout

Software Defined Radio generates RF tones and demodulates output RFsignals



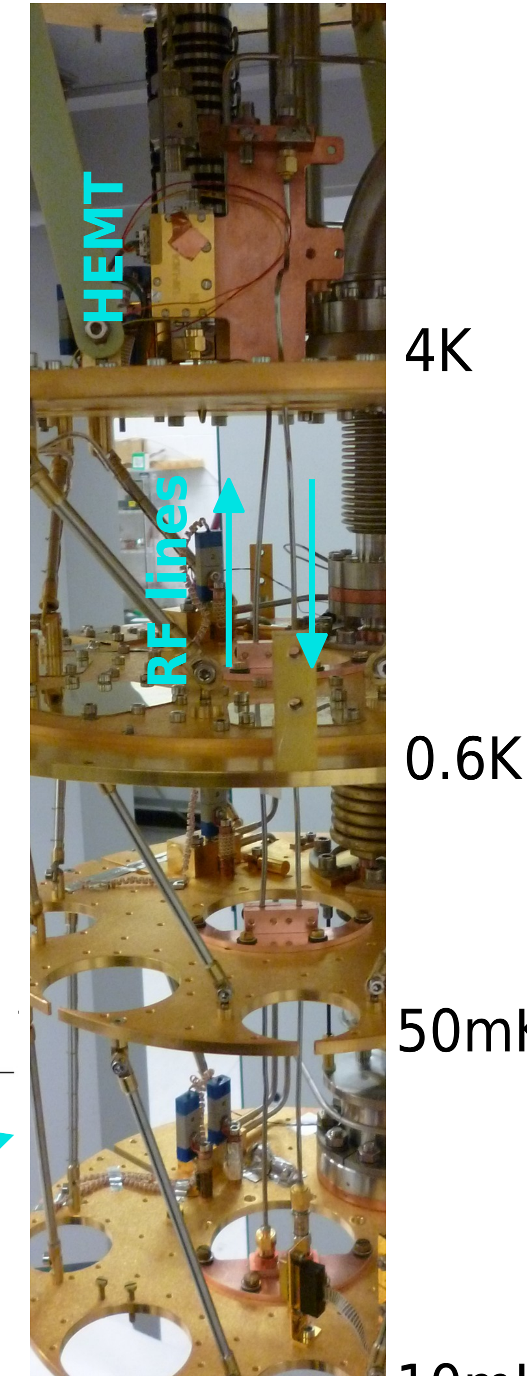
1 ROACH2 (f_{ADC}=512 MS/s)
for 32 detectors





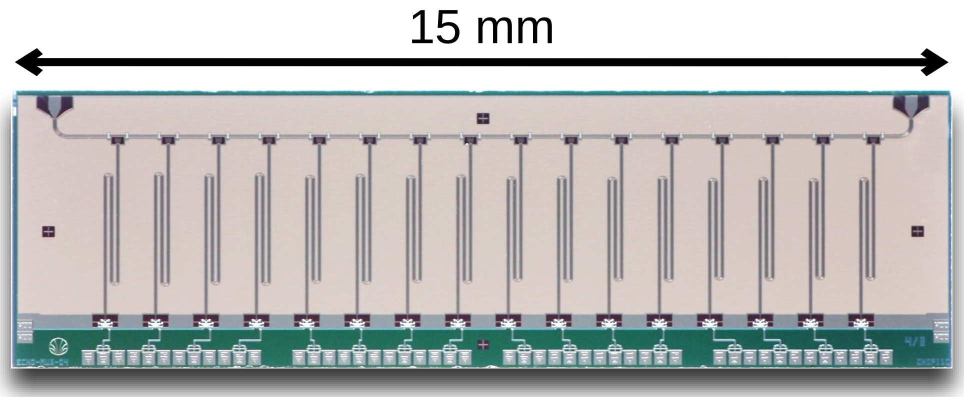
1 IF-board for 32 detectors

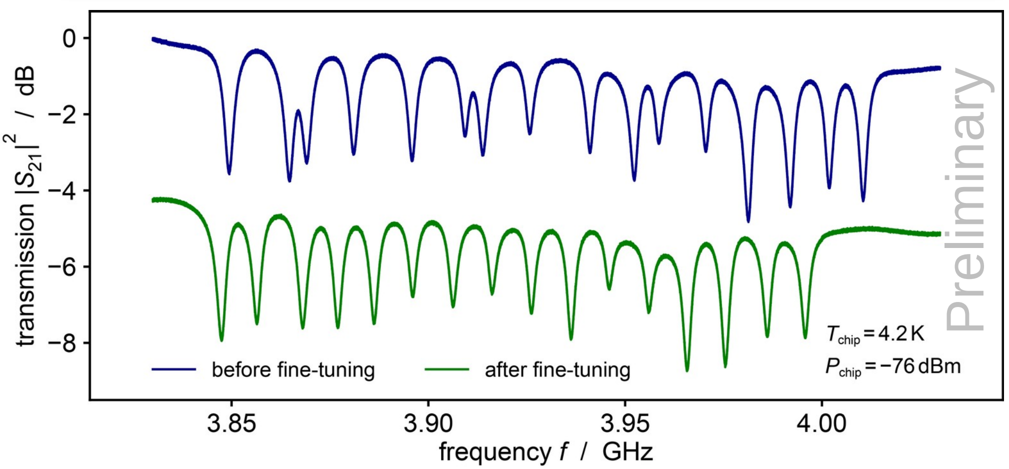
1 HEMT (BW 4-8 GHz)
for 256 detectors



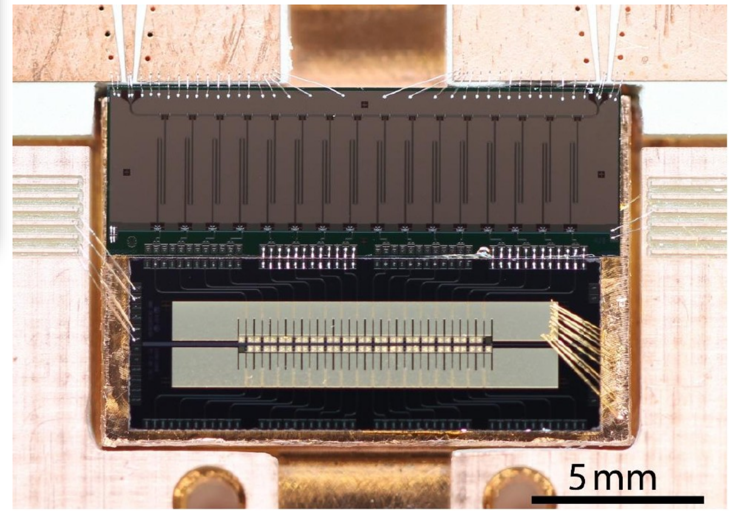
ECHo-100k

ECHo-100k will implement microwave multiplexing to readout 12000 MMCs

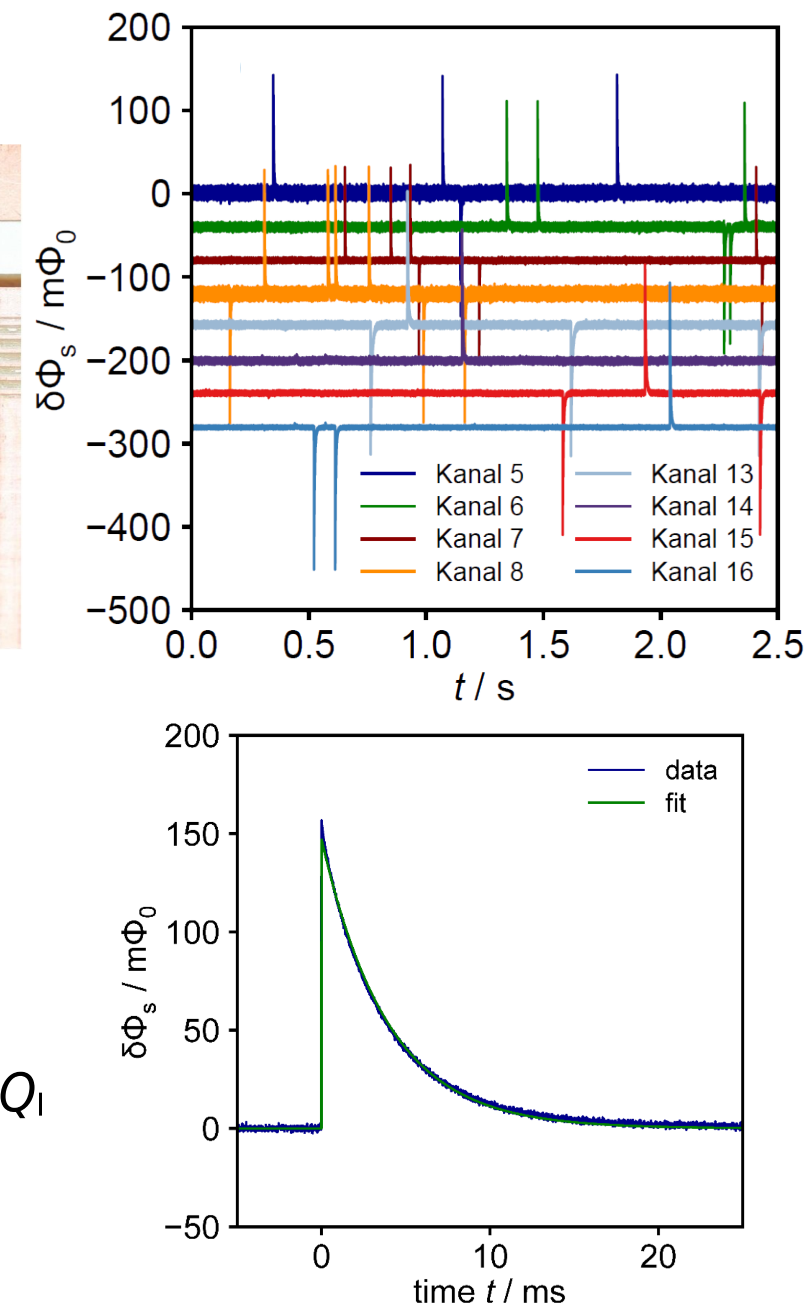




16 channel µmux chip



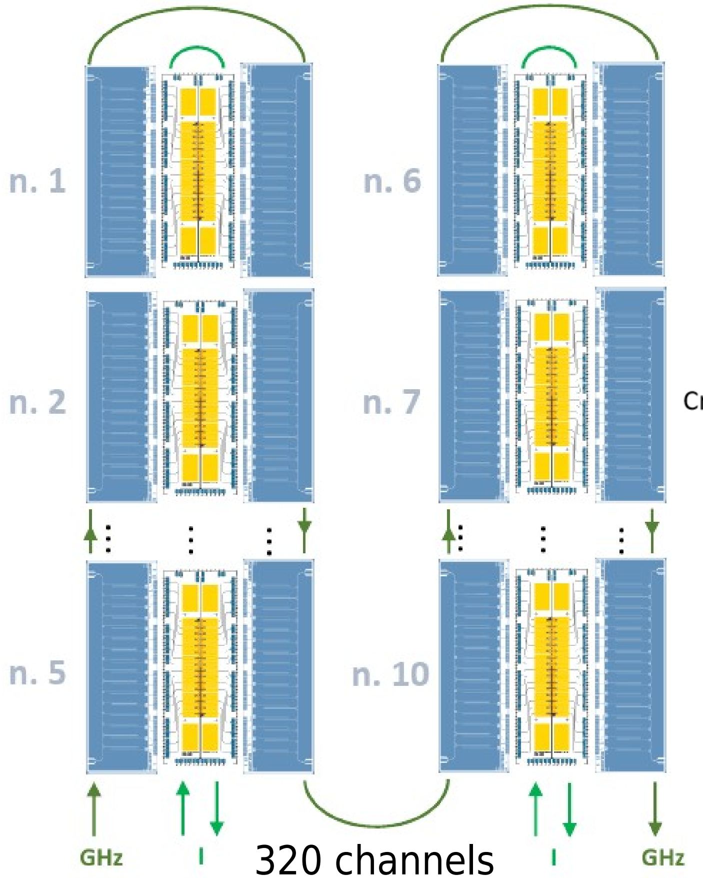
ECHo-100k
16+16 channels array
(32+32 pixels)



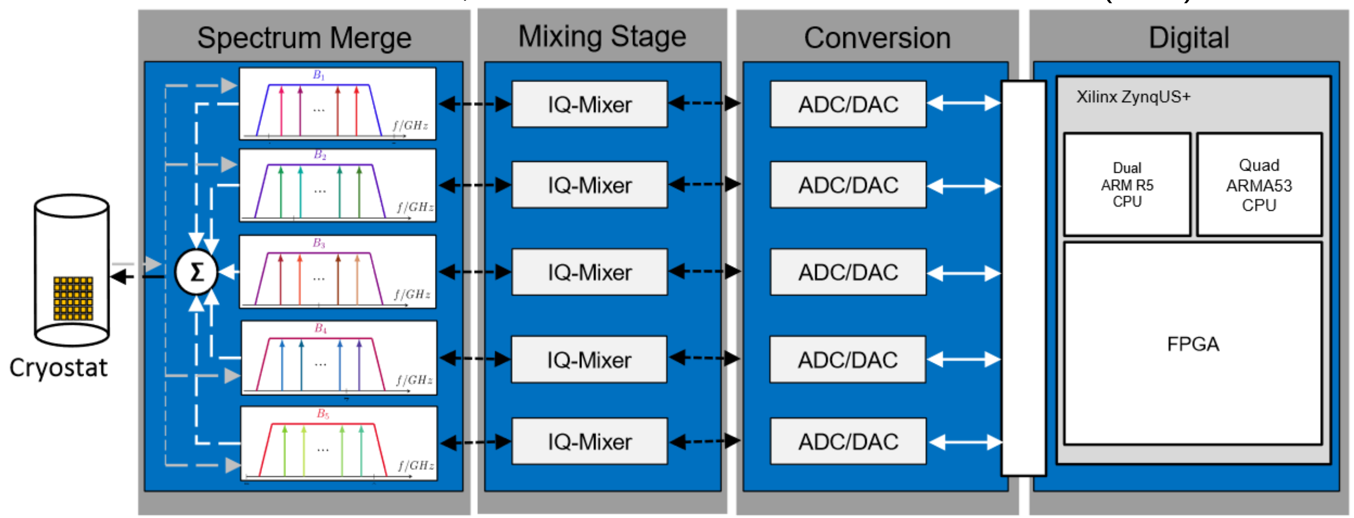
- successful read-out of 8 channels (16 pixels)
- noise limited by low available RF power
  → $\Delta E_{FWHM} \approx$ 10-30 eV (low power) depending on Q_l
- with high power read-out of 2 channels
  → $\Delta E_{FWHM} \approx$ 9 eV

F. Ahrens, PhD,
Heidelberg University, 2022

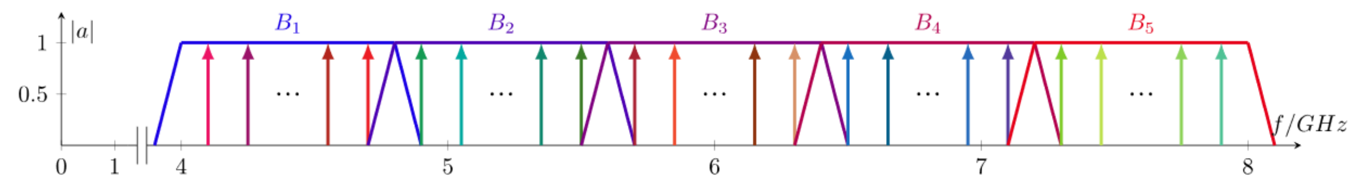
ECHO-100k: SDR for heterodyne readout development



O. Sander *et al.*, *IEEE Transactions on Nuclear Science* 66.7 (2019)



Software-defined Radio (SDR) system architecture



Spectrum of one single transmitter/receiver-pair

ECHo-100k

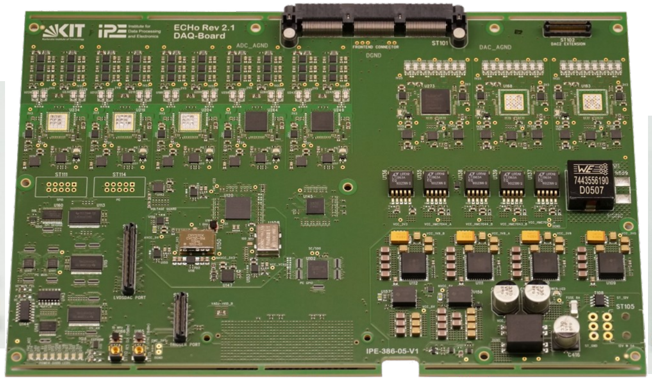
12000 MMC pixels =

400 MMC channels ×

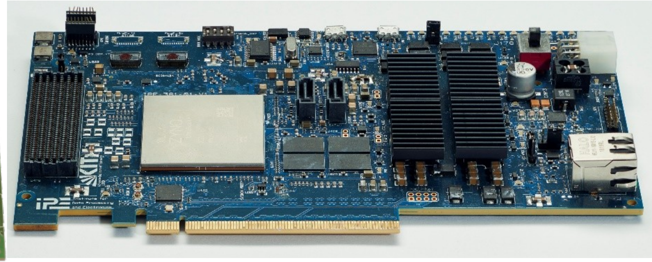
15 SDR systems / HEMT

Mixing stage

1GS/s ADC / 500MS/s DAC Board

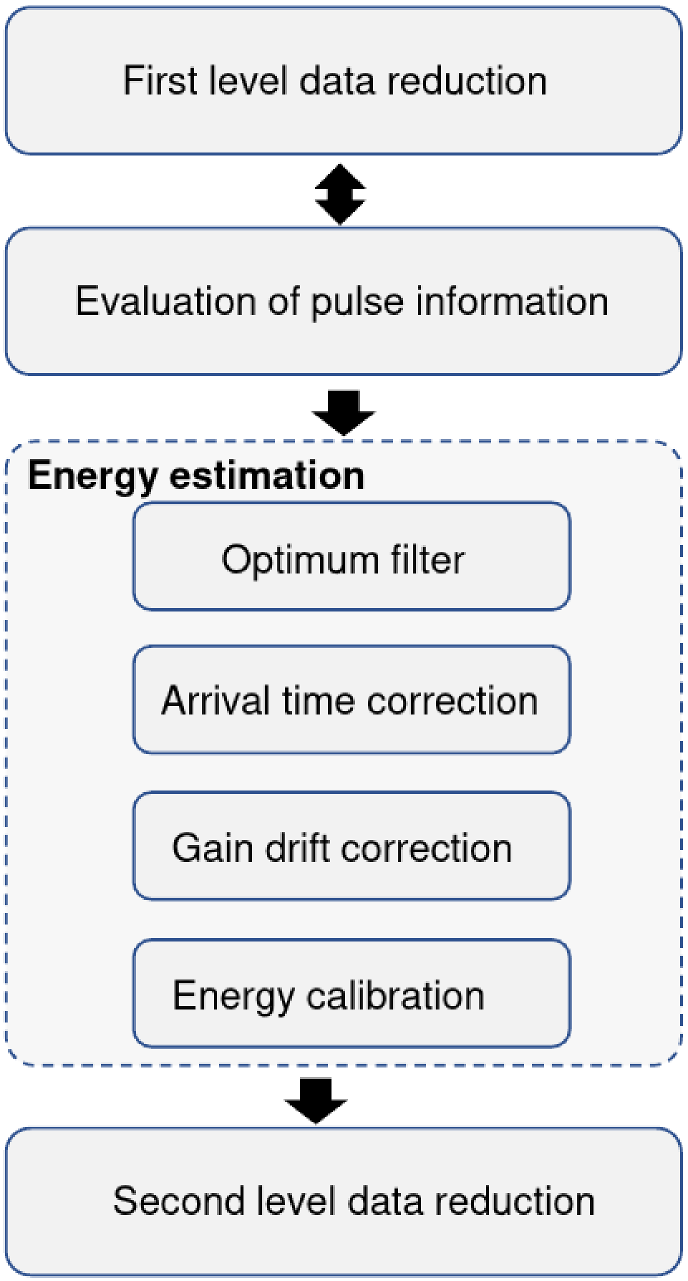


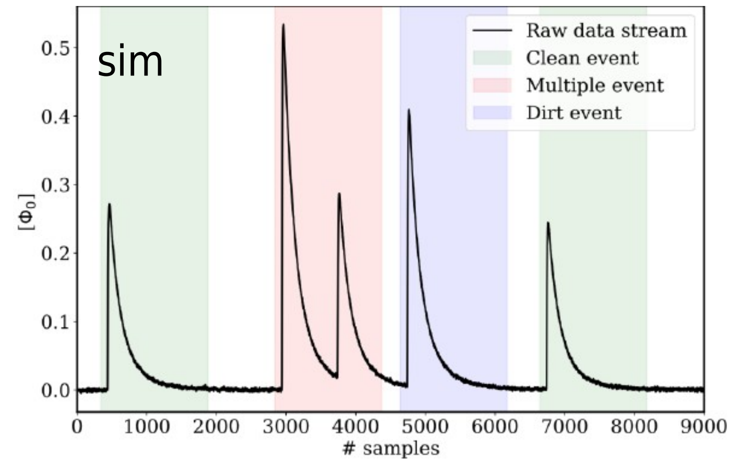
FPGA-Board



HEMT 4-8 GHz band covered by 5×800 MHz bands → 80 channel/band → 400 total channels

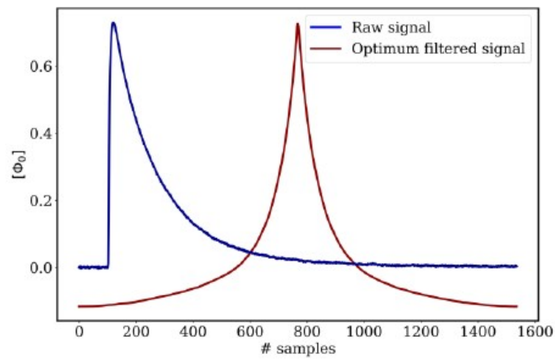
Data analysis

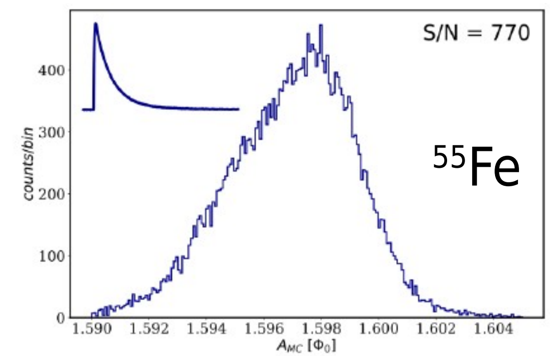


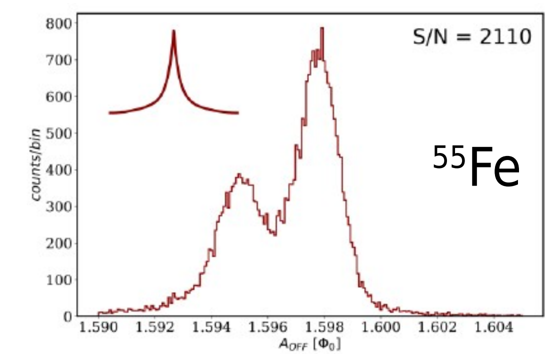


- classify events
- discard bad ones
- estimate time contants, arrival time, pretrigger level (baseline), and other parameters

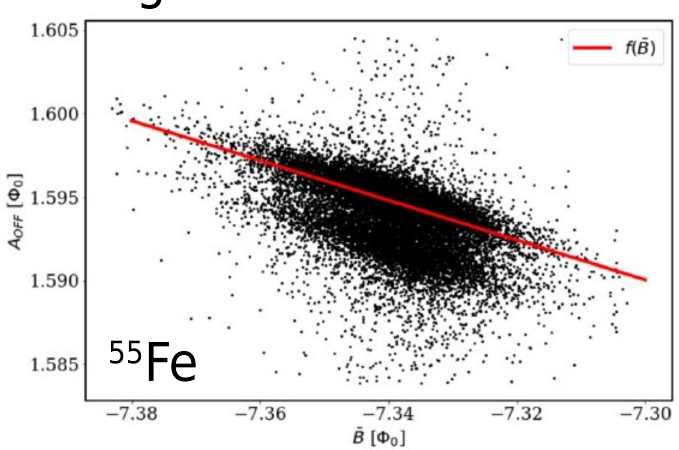
energy estimator based on optimal filter in various implementations





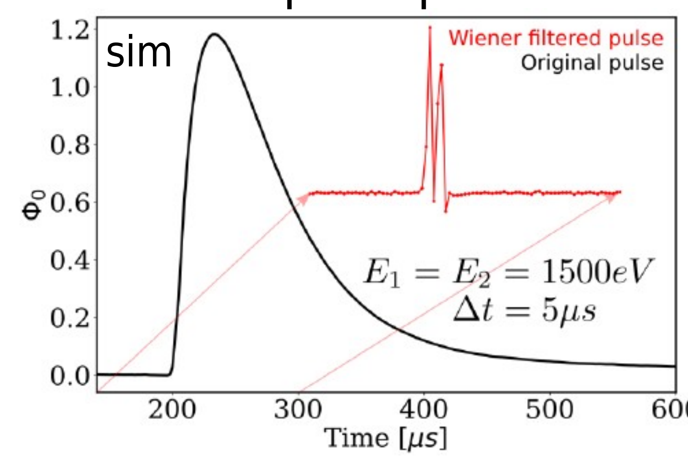


gain drift correction



amplitude vs. baseline ($\propto T_{op}$) correlation

rise time pile-up detection



M. Borghesi, PhD, U. Milano-Bicocca, 2022

Hammann, R. et al. EPJ C 81, 963 (2021)

Pile-up discrimination

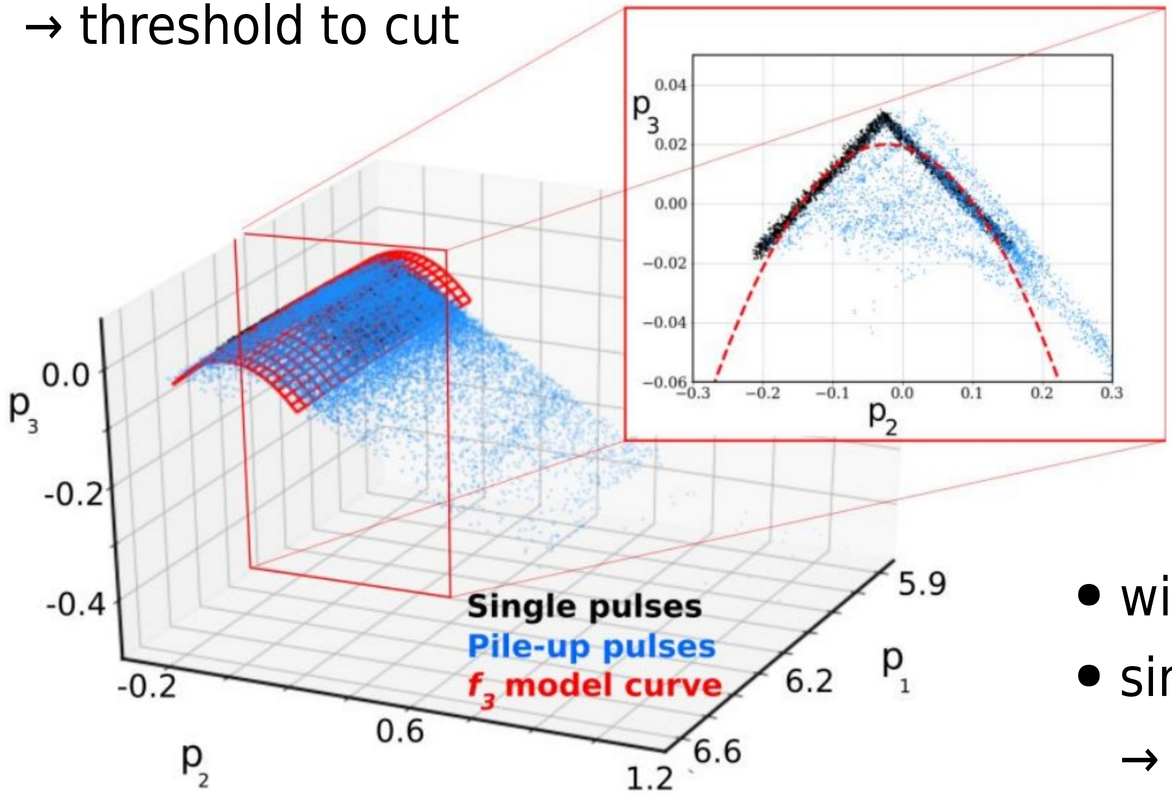
- advanced discrimination technique to identify pile-up events
  - Discrimination through Singular Vector Projections (DSVP)
  - “unsupervised learning” technique, based on singular value decomposition, PCA and multiple linear regression

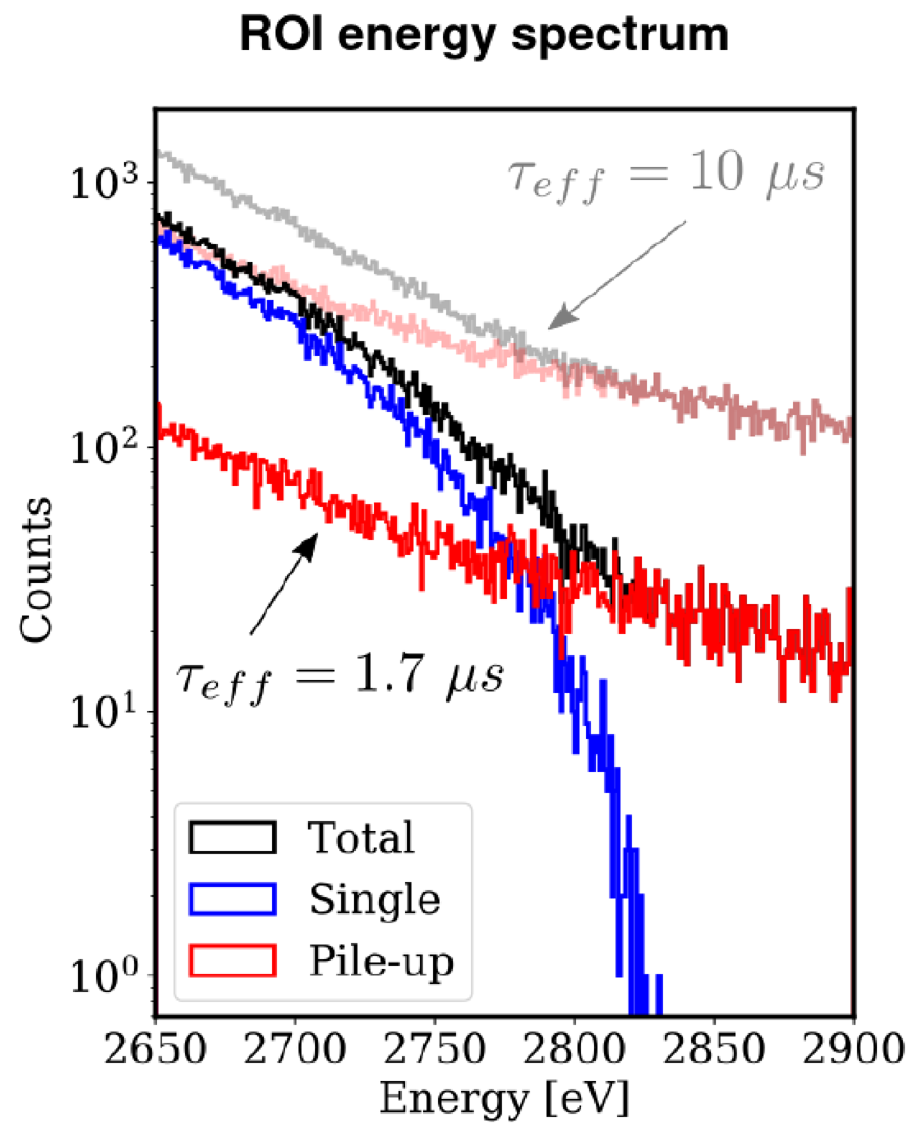
→ SVP decomposition

→ raw dataset cleaning (PCA)

→ model point distribution in singular vector projection space

→ threshold to cut





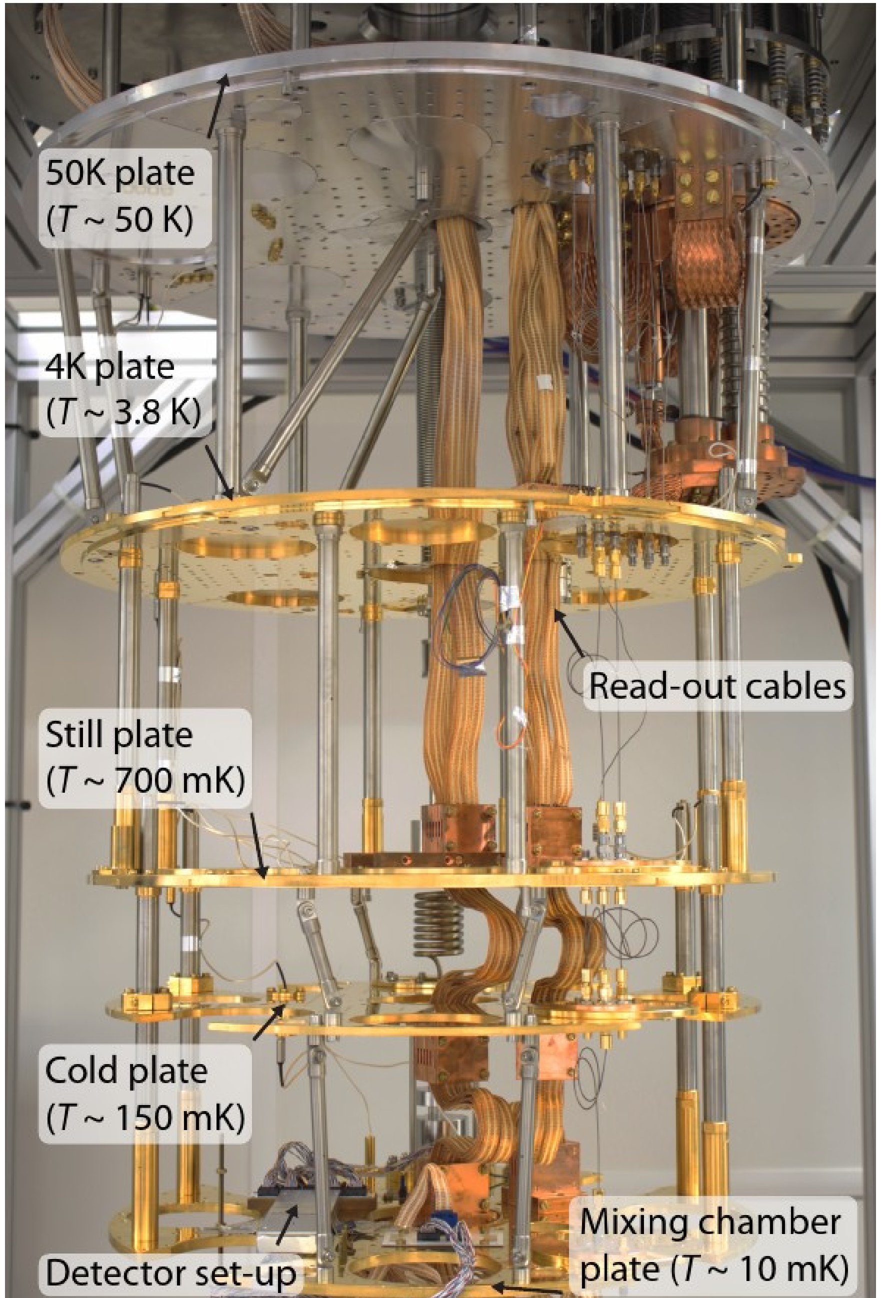
- with DSVP τ_R is limited by the pulse sampling time $1/f_{ramp}$
- simulations for HOLMES pulses

  → $\tau_R \approx 1\text{-}2\ \mu s$ for $\tau_{rise} \approx 10\text{-}20\ \mu s$ and $f_{ramp} = 500$ kHz

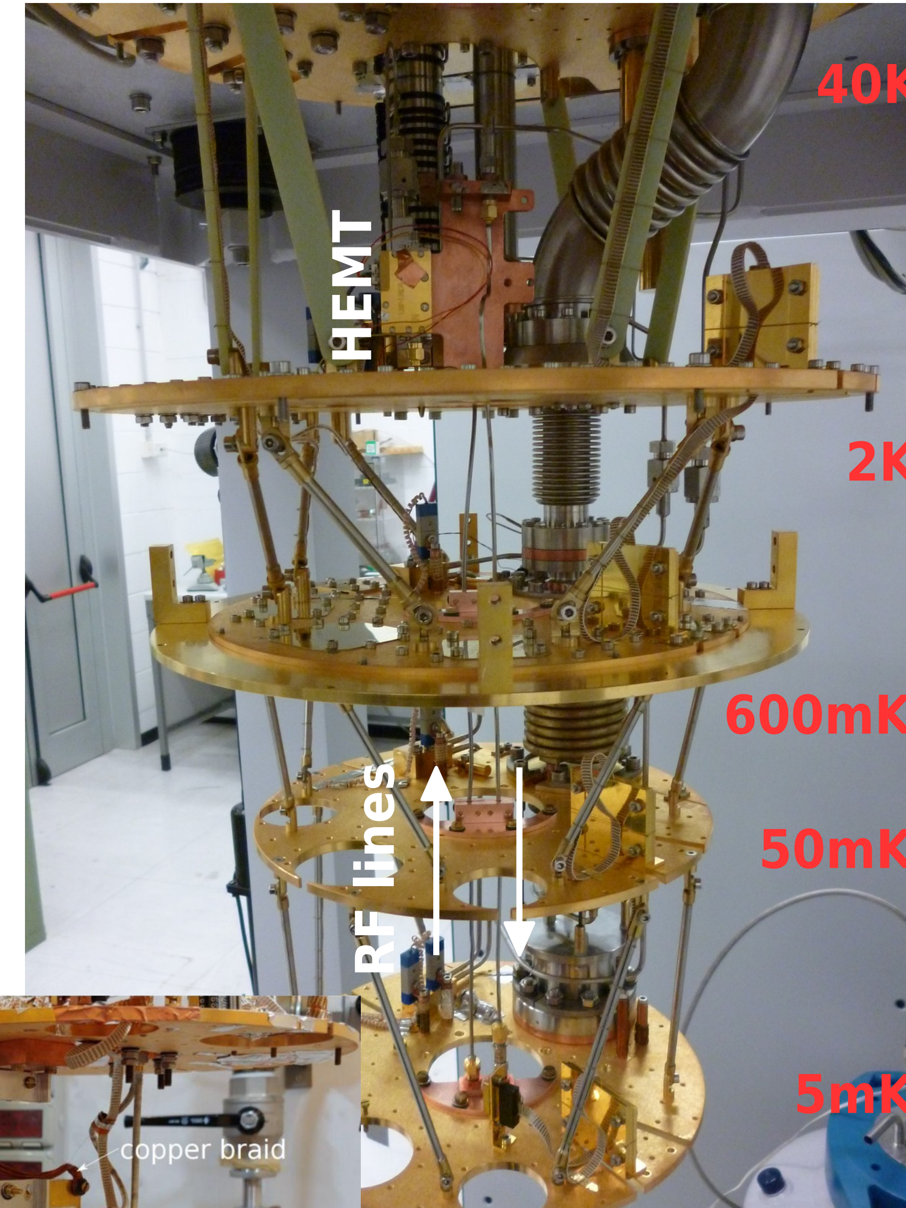
Borghesi, M. et al. EPJ C 81, 385 (2021)

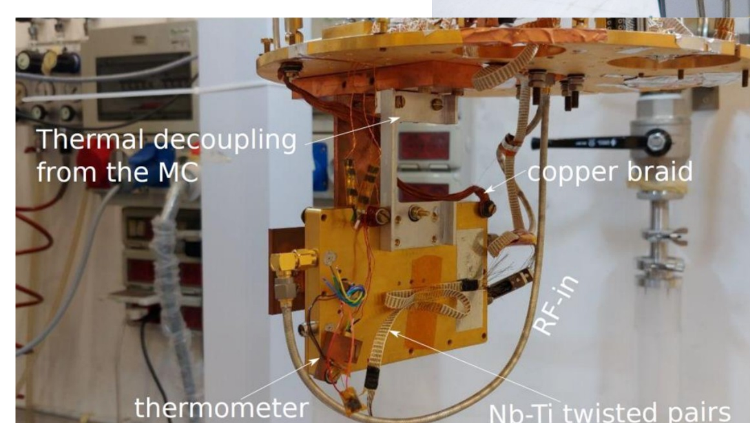
Cryogenic set-ups

ECHo-1k



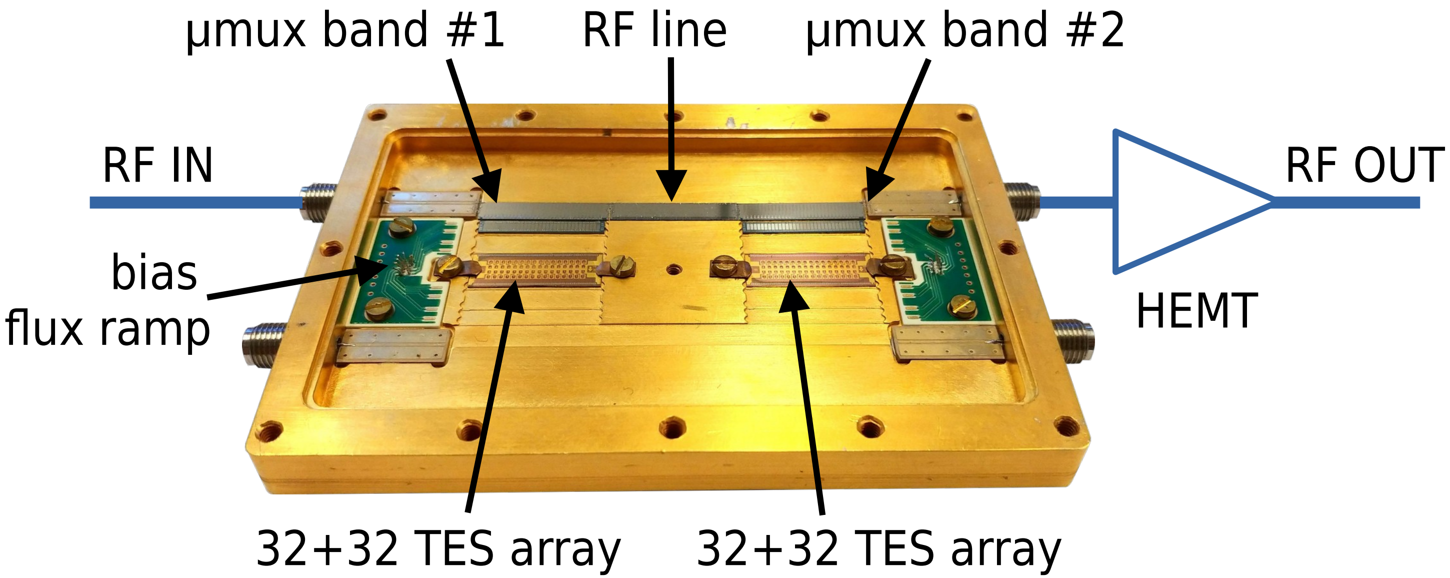
HOLMES (for 256 pixels)





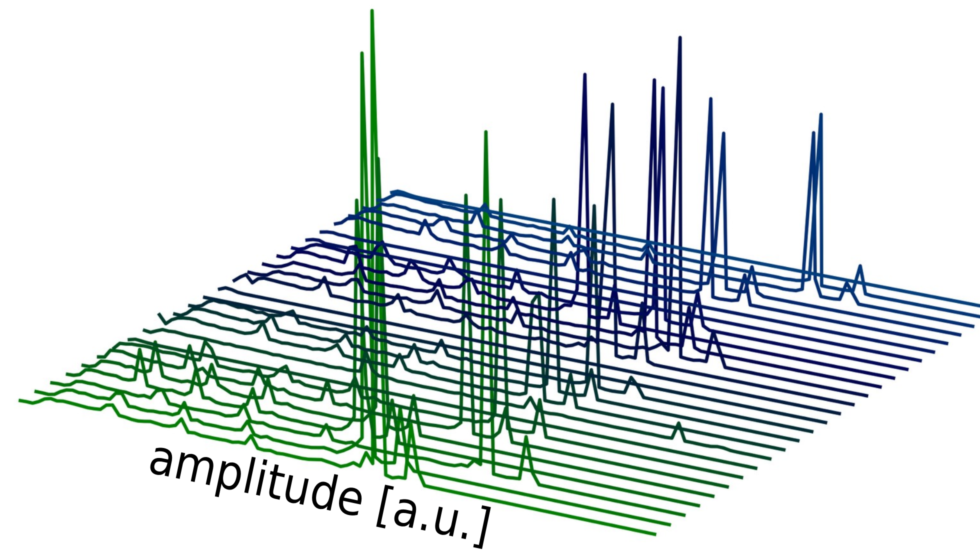
HOLMES status: detectors, readout, analysis

64 multiplexed detectors



raw data from 26 multiplexed detectors

^{55}Fe X-rays + Al, Cl, Ca X-ray fluorescence

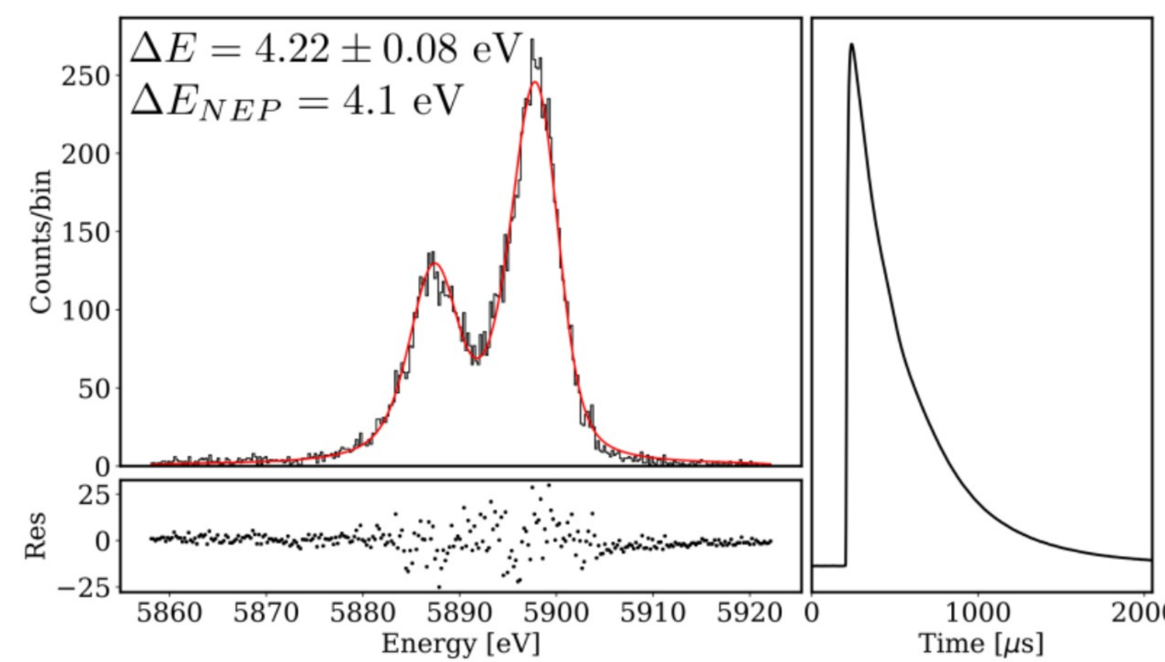


- fully processed TES arrays without ^{163}Ho implant
- set-up for 126 multiplexed pixels
- 2 μmux chips but only 32 bonded pixels
- 16 channel firmware version (stable) for ROACH2
- at 5.9 keV:

→ $\Delta E_{FWHM} \approx$ 4-6 eV

→ $\tau_{rise} \approx$ 15 μs (R/L limited to match DAQ) → $\tau_R \approx$ 1.5 μs

→ $\tau_{decay} \approx$ 300 μs



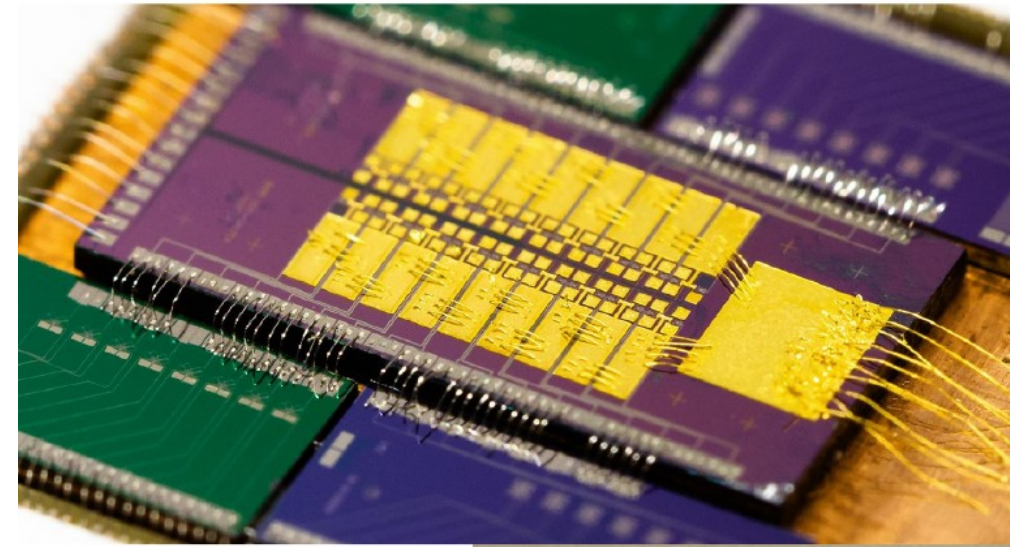
M. Borghesi et al., EPJ. C 81.5 (2021)

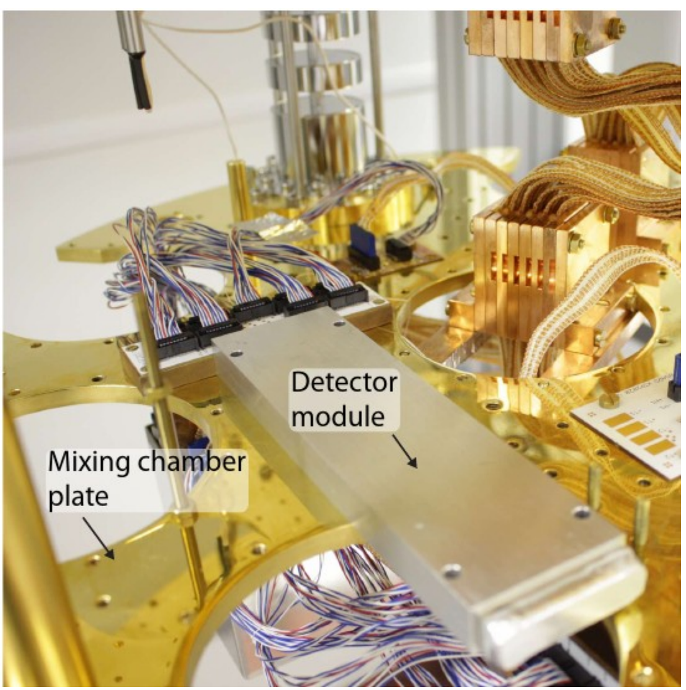
ECHo-1k status: detectors

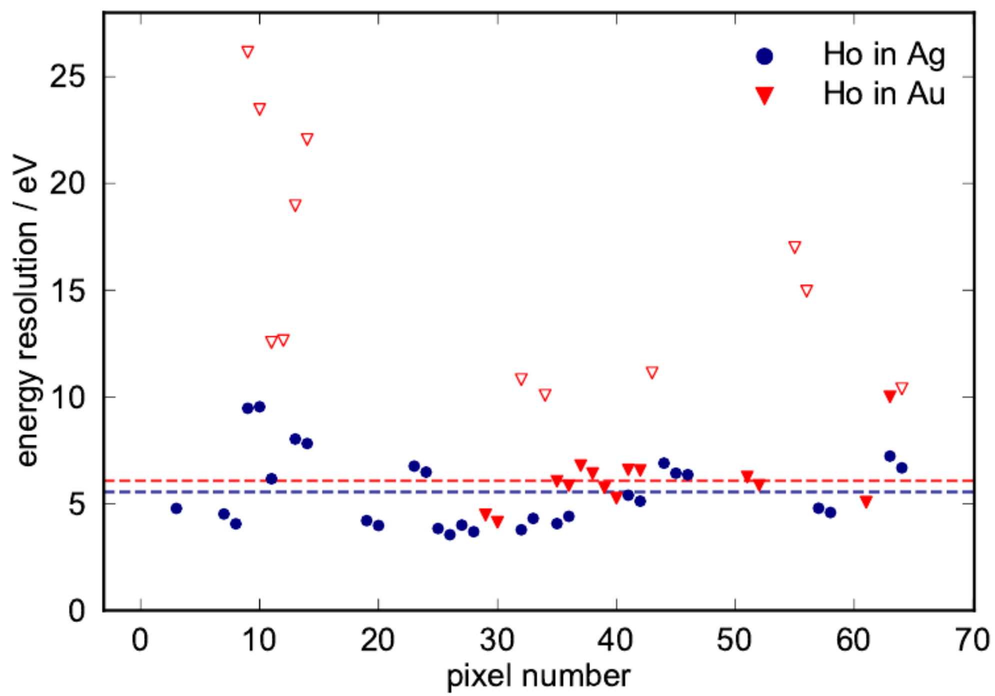
2 detector modules with ^{163}Ho in Au and Ag host material

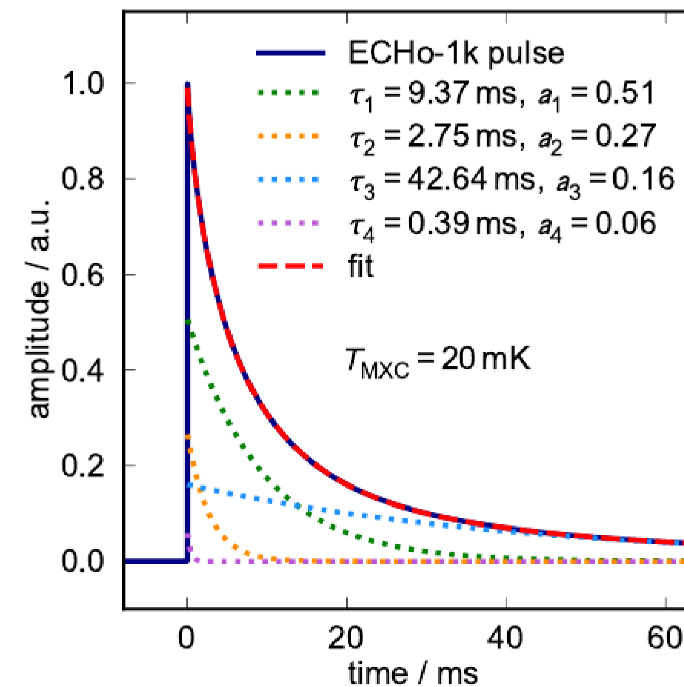
parallel dc-SQUID readout

host	^{163}Ho pixels	bkg pixels	⟨A⟩ [Bq]	A_{tot} [Bq]
Au	23	3	0.94	28.1
Ag	34	6	0.71	25.9







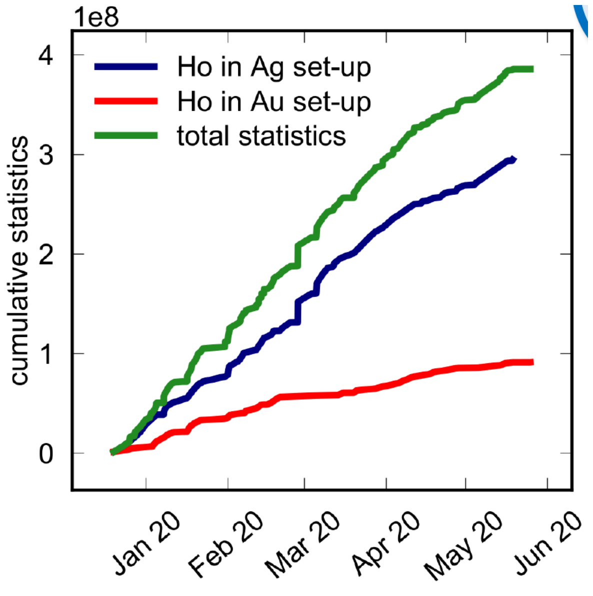


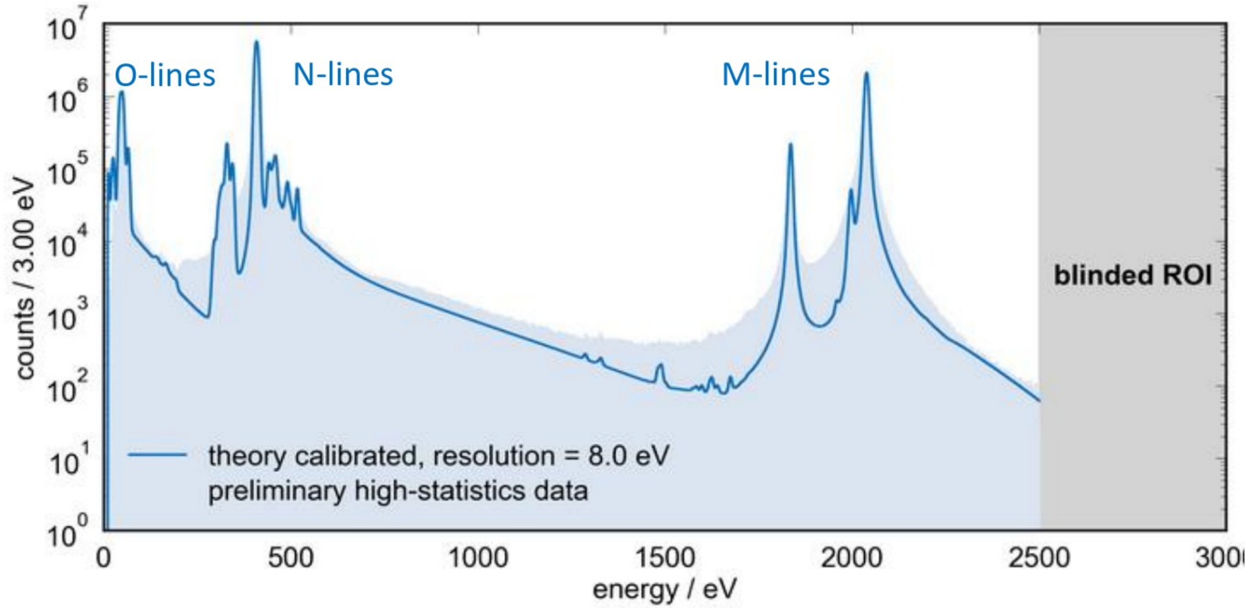
F. Mantegazzini et al, NIM A 1030 (2022) 166406

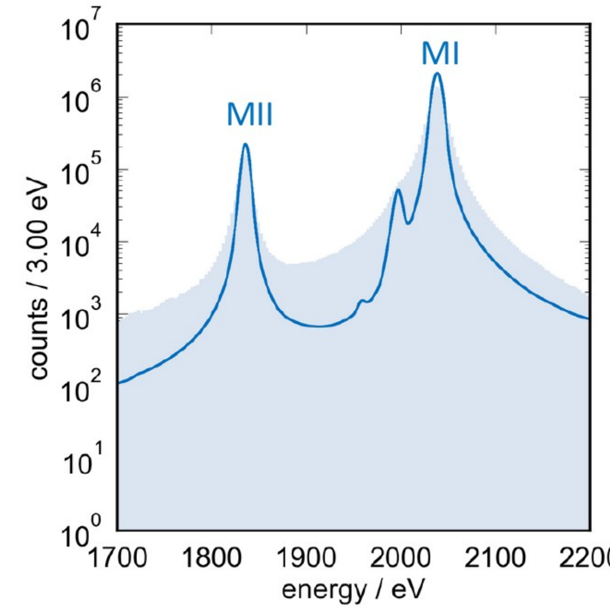
- $\tau_{rise} \approx 1$ µs limited by SQUID bandwidth
- complex decays time: mostly $\tau_1 \approx 10$ ms

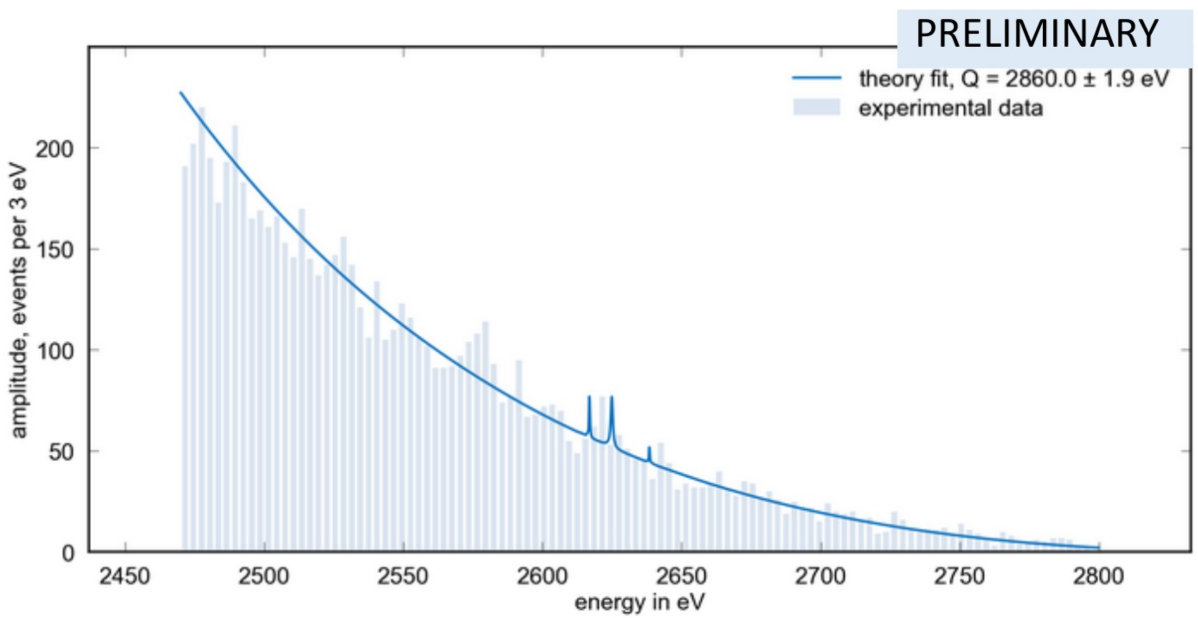
ECHo-1k status: 10^7 events spectrum

6×10^7 events acquired with detectors having ^{163}Ho in Ag host material







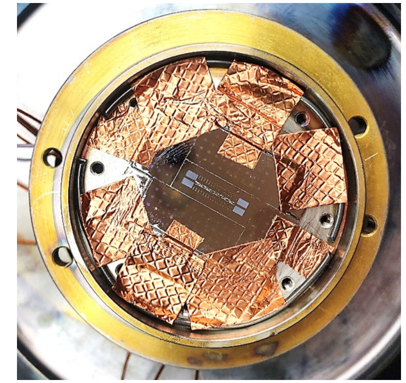


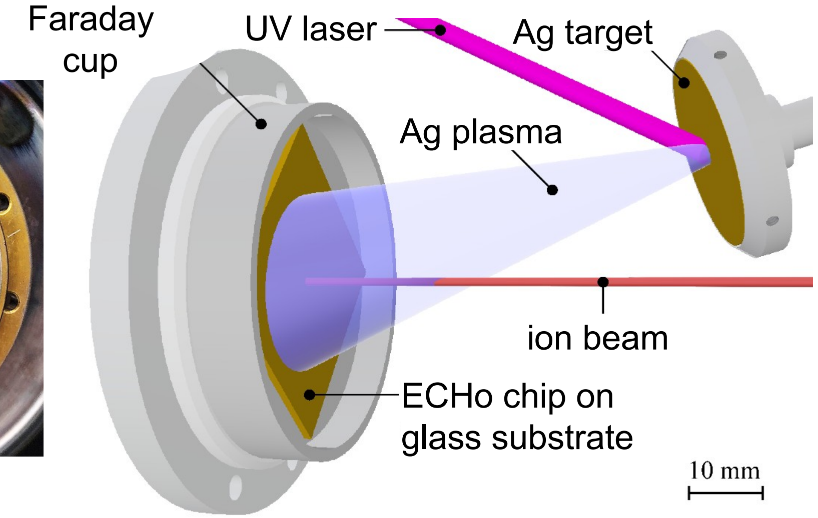
- end-point analysis in progress
- from preliminary end-point analysis
  - EC Brass & Haverkort theory
  - Flat background

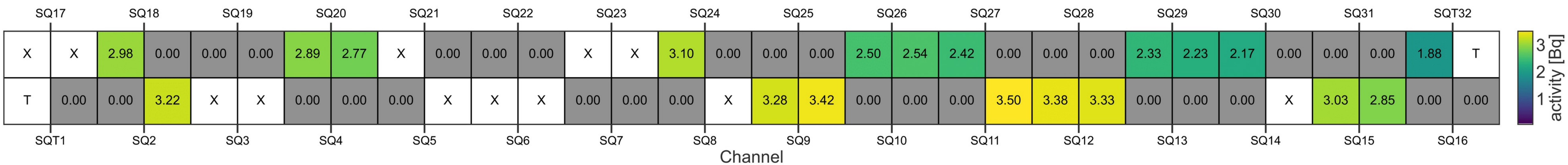
  → Q_{EC}=(2860 ± 2stat ± 5syst) eV

ECHo-100k progresses

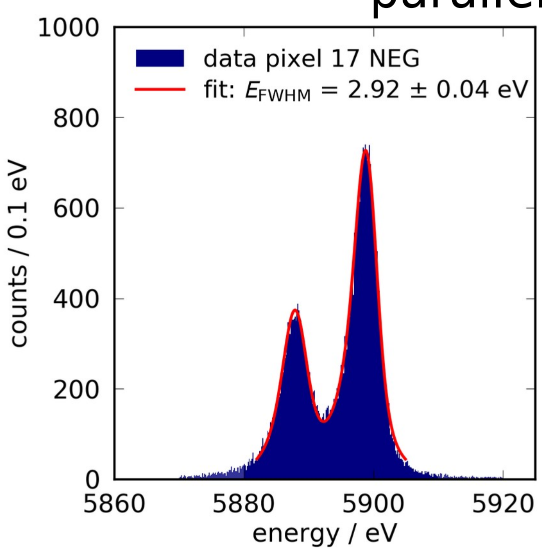
- 30 MBq of pure ^{163}Ho available
- implant system improvements for 10 Bq
  - beam positioning on ECHo-100k wafer
  - co-deposition through PLD in progress
- pixel design optimization to minimize C
- µmux read-out system development in progress

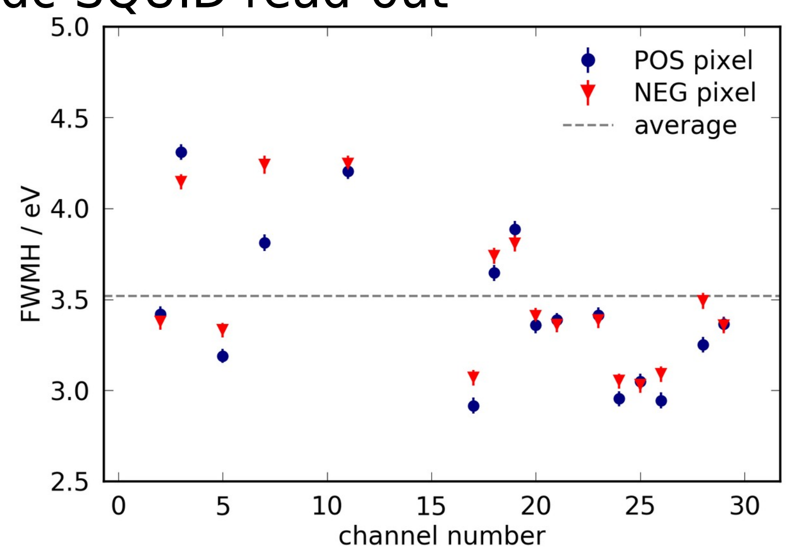




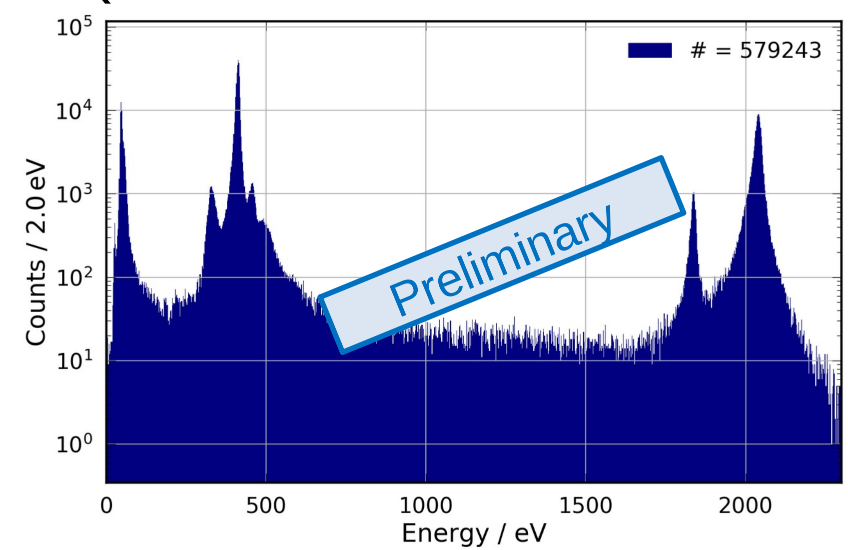


pixel characterization before ion implant
parallel dc-SQUID read-out



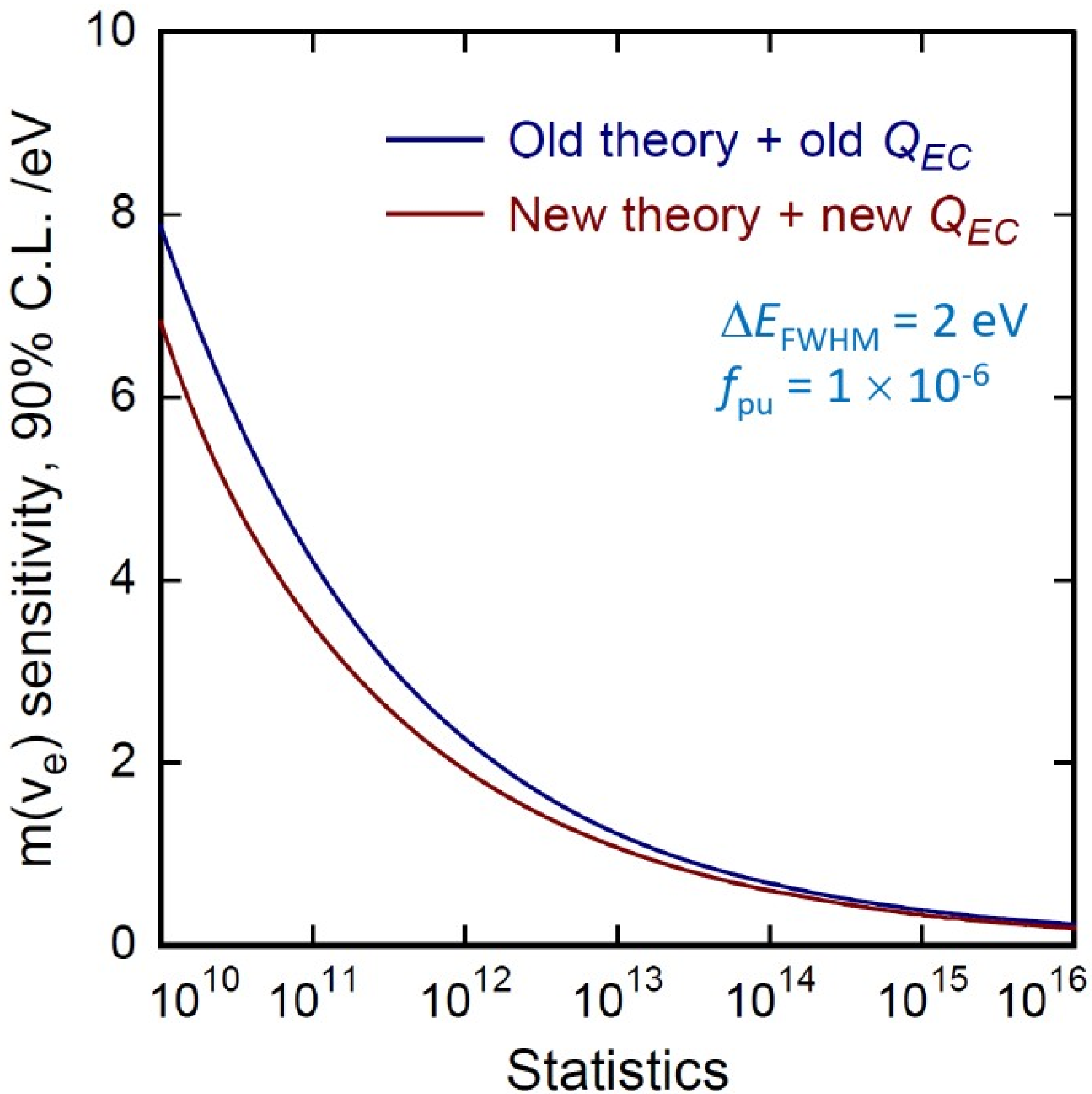


after ion implant without second Au layer
dc-SQUID read-out → ΔE≈3.4 eV at N1 line

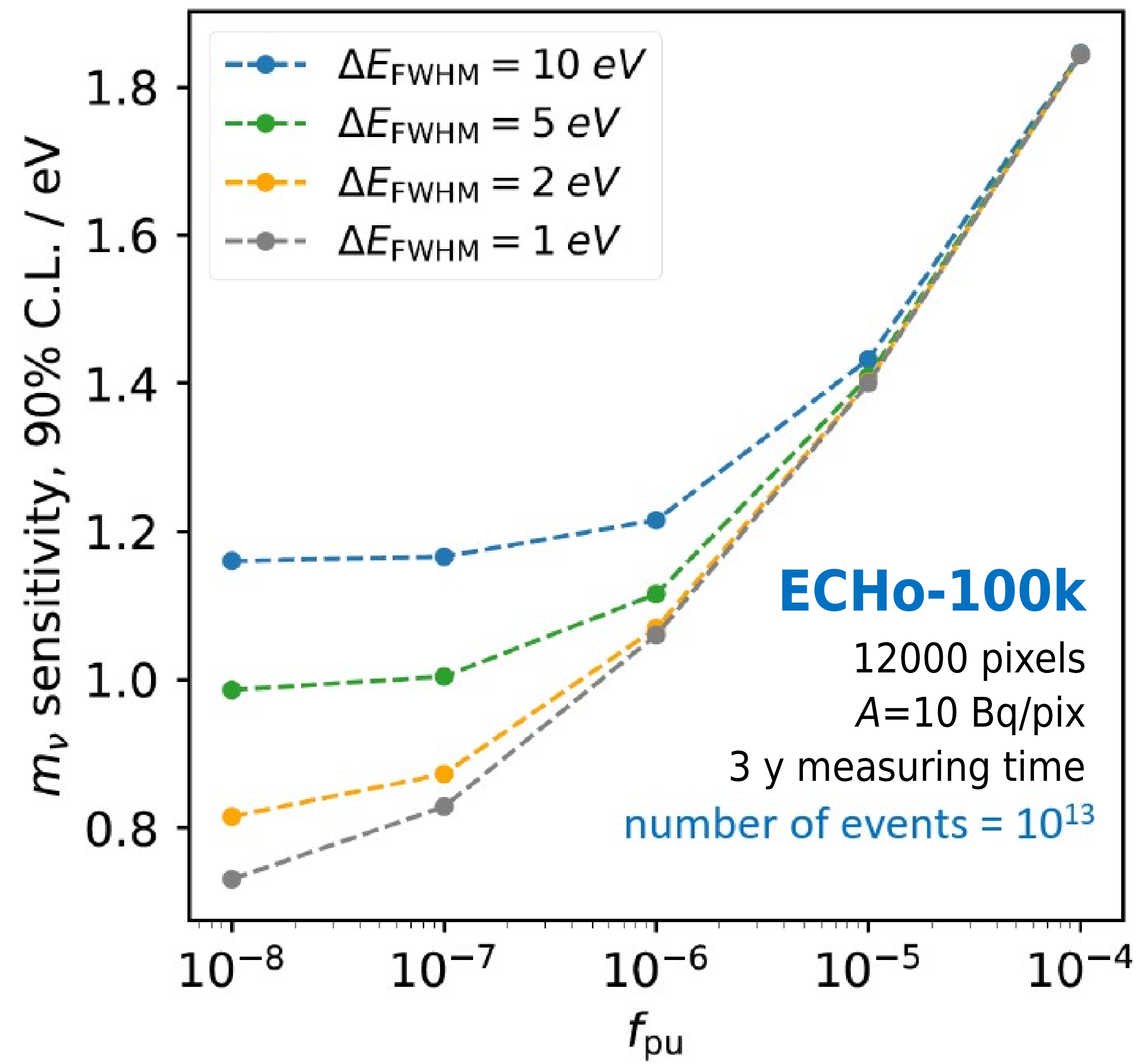


ECHo-100k updated expected sensitivity

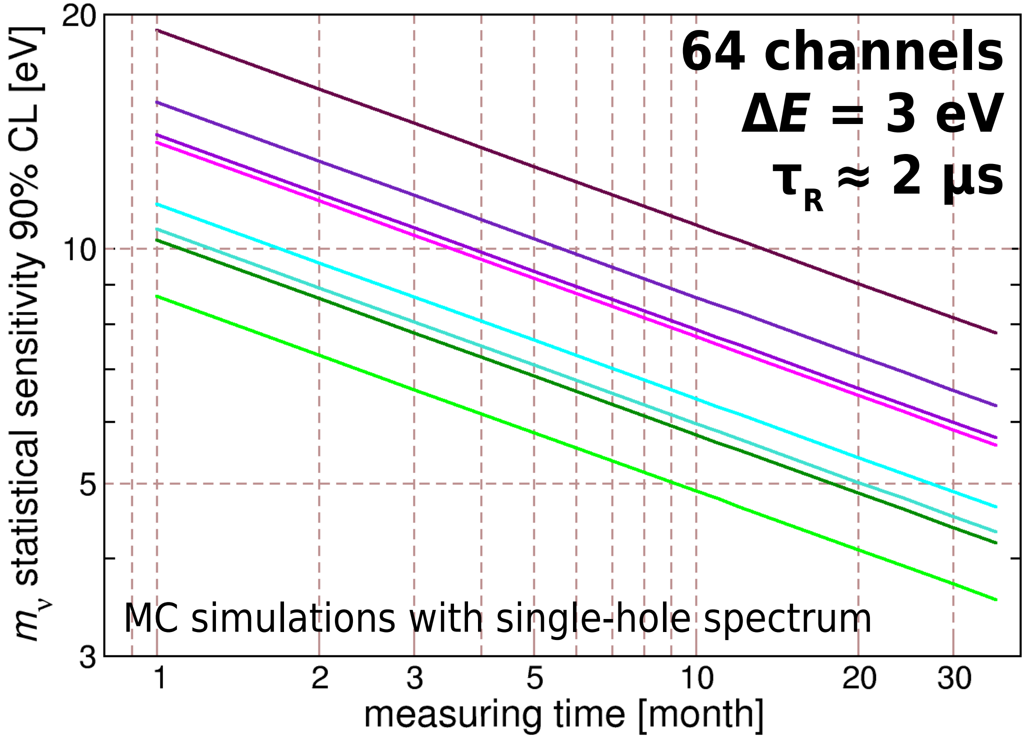
Brass & Haverkort theoretical model + new Q_{EC}-value

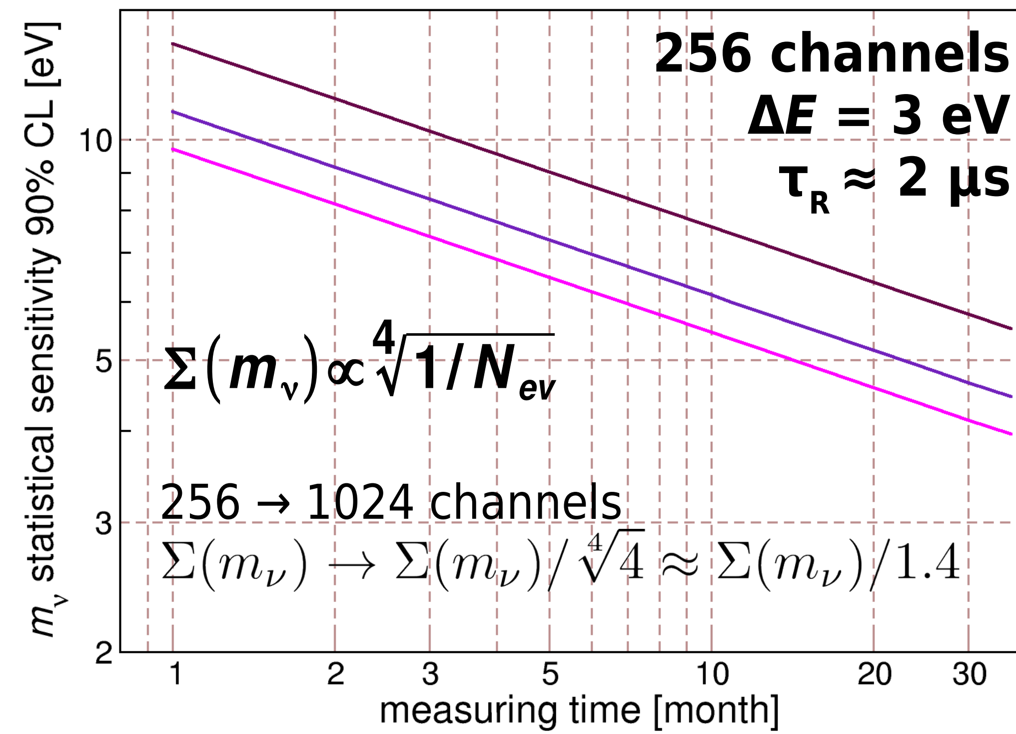


Sensitivity for the coming phase of ECHo



HOLMES sensitivity evolution vs. pixel activity





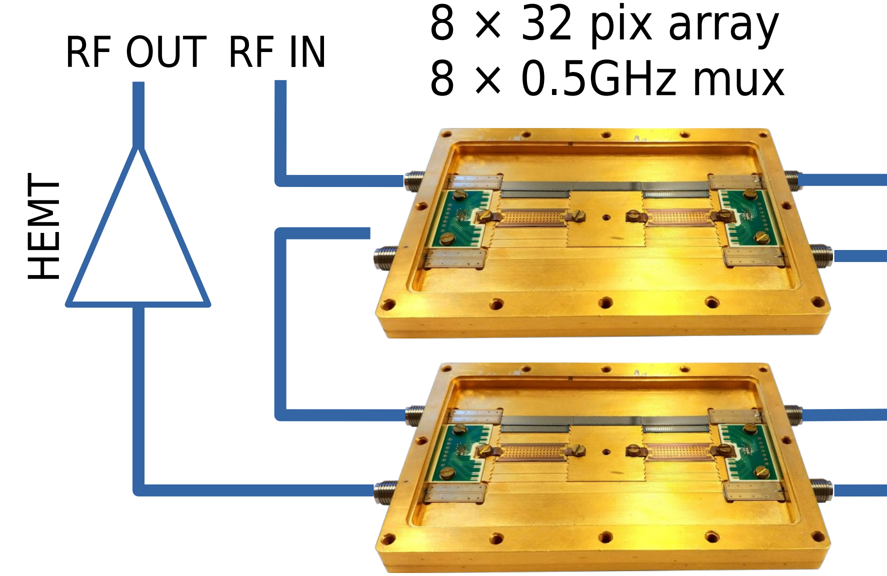
***A* = 1 Hz/det**
***A* = 3 Hz/det**
low dose

***A* = 5 Hz/det**
***A* = 10 Hz/det**
***A* = 30 Hz/det**
***A* = 50 Hz/det**
***A* = 100 Hz/det**
***A* = 300 Hz/det**

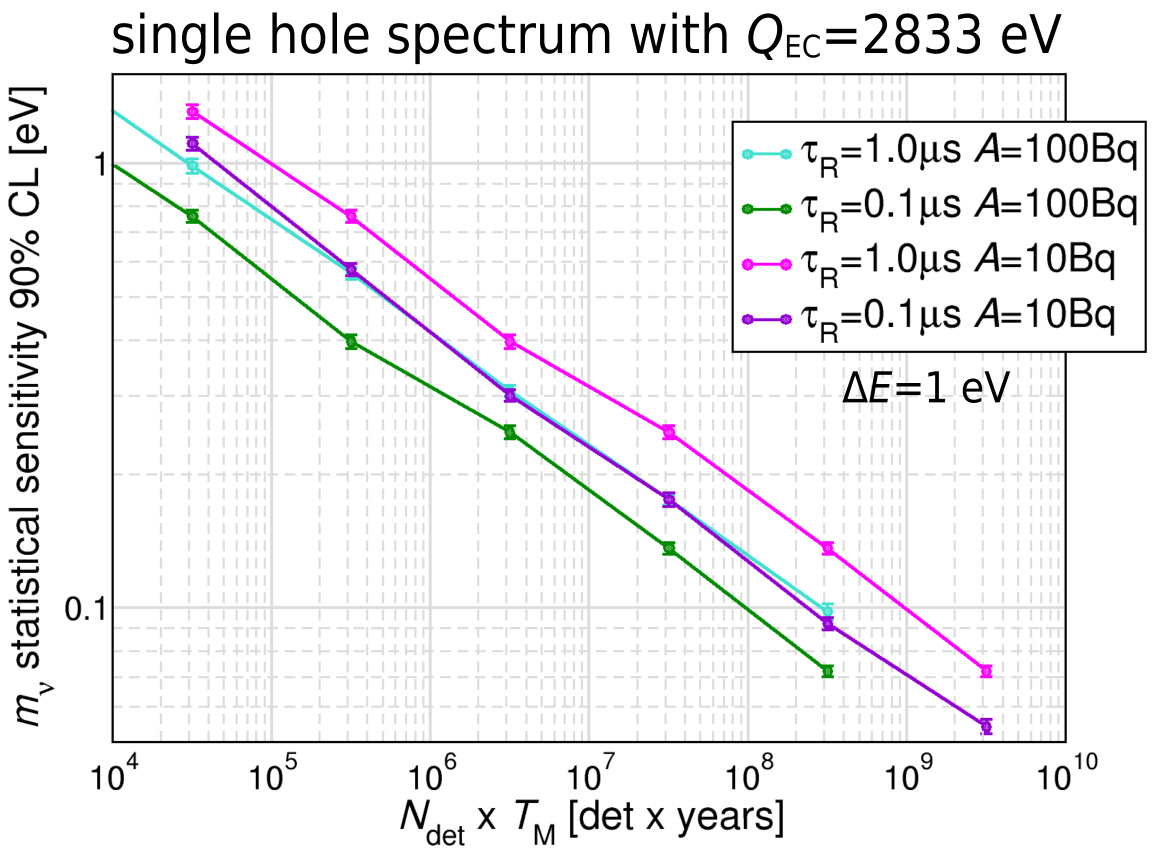
with focusing

?

8 × ROACH2+IF boards



Beyond ECHo and HOLMES: a 0.1eV experiment



10 years measuring time

***A*/det [Bq]**	10	10	100	100	1000	1000
τ_R [us]	0.1	1	0.1	1	0.1	1
f_{pp}	1.0E-06	1.0E-05	1.0E-05	1.0E-04	1.0E-04	1.0E-03
N_{det}	3.0E+07	9.8E+07	9.8E+06	3.0E+07	3.0E+06	1.3E+07
***A* total [Bq]**	3.0E+08	9.8E+08	9.8E+08	3.0E+09	3.0E+09	1.3E+10
^{162}Er [mg] *	2274	7429	7429	22742	22742	98548

* ^{162}Er/A(^{163}Ho) = 3790 mg/GBq + 50% usage efficiency

- pixel activity ≥100Bq/det ↔ ^{163}Ho heat capacity
- time resolution below 0.1μs ↔ multiplexing and DAQ bandwidth
- about 10M pixels ↔ multiplexing and DAQ bandwidth

Conclusions

- **ECHo and HOLMES are reaching a statistical sensitivity of order of 1 eV in few years**
  - many technical challenges faced successfully (also separately by ECHo and HOLMES)
    - production of large amounts of clean 163Ho samples
    - efficient ion implantation
    - high resolution detectors with multiplexed read-out
    - sophisticated analysis tools
  - some activities are still required to fully assess the potential of holmium experiments
    - understanding the holmium decay spectrum
    - effect of high activities on detector performances
    - investigating systematic effects
- **longer term plans: next generation experiments for sub-eV sensitivities require**
  - larger international collaboration
  - increased single pixel activity
  - cost reduction (isotope production and efficient usage, readout electronics)

Collaborations

HOLMES

Università di Milano-Bicocca, Italy

INFN Milano-Bicocca, Italy

INFN Genova, Italy

INFN Roma, Italy

INFN LNGS, Italy

NIST, Boulder, USA

PSI, Villigen, Switzerland

ILL, Grenoble, France

ECHo

Heidelberg University, Germany

Johannes Gutenberg University, Mainz, Germany

GSI. Darmstadt, Germany

Helmholtz Institute Mainz, Mainz, Germany

University of Tübingen, Tübingen, Germany

MPI für Kernphysik,, Heidelberg, Germany

KIT, Karlsruhe, Germany

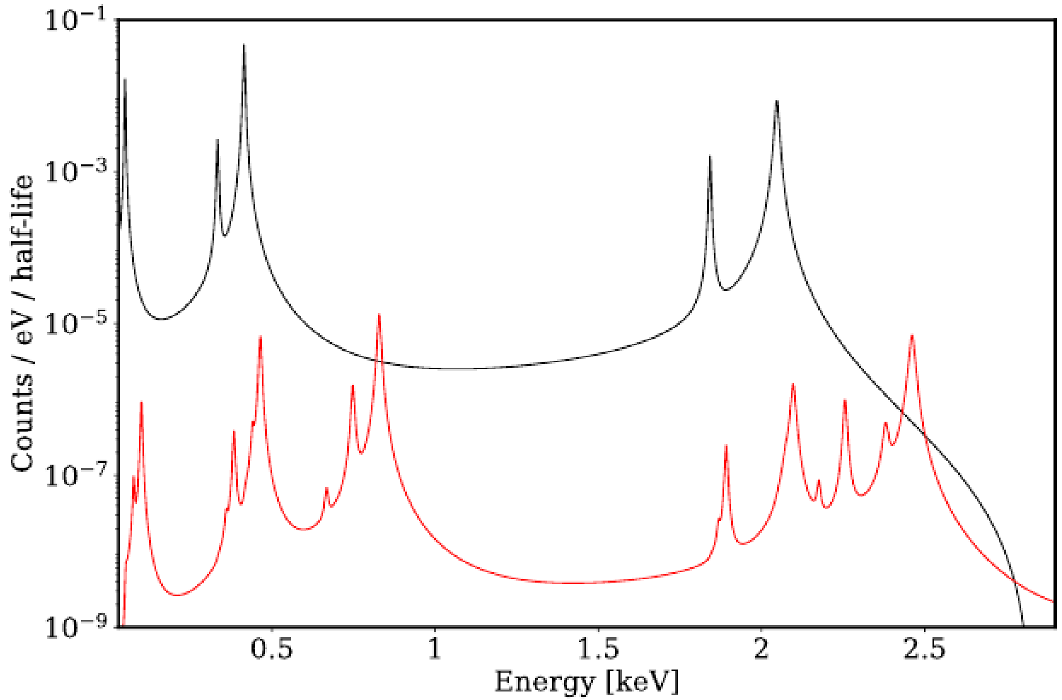
Petersburg Nuclear Physics Institute, Gatchina, Russia

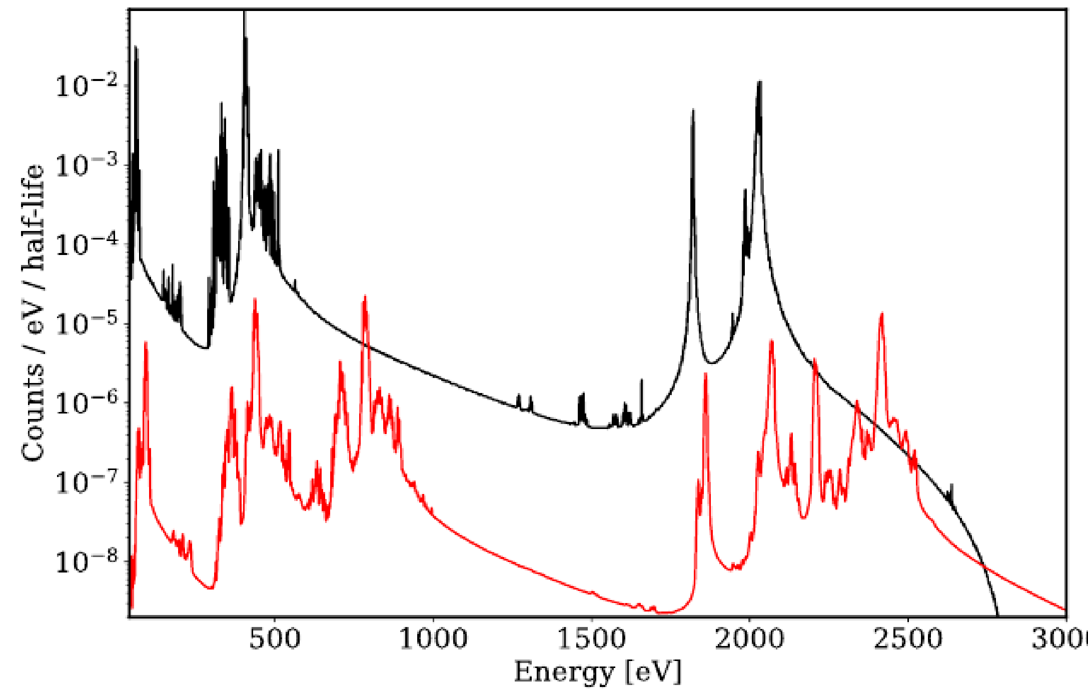
Laboratoire Souterrain de Modane, Modane, France

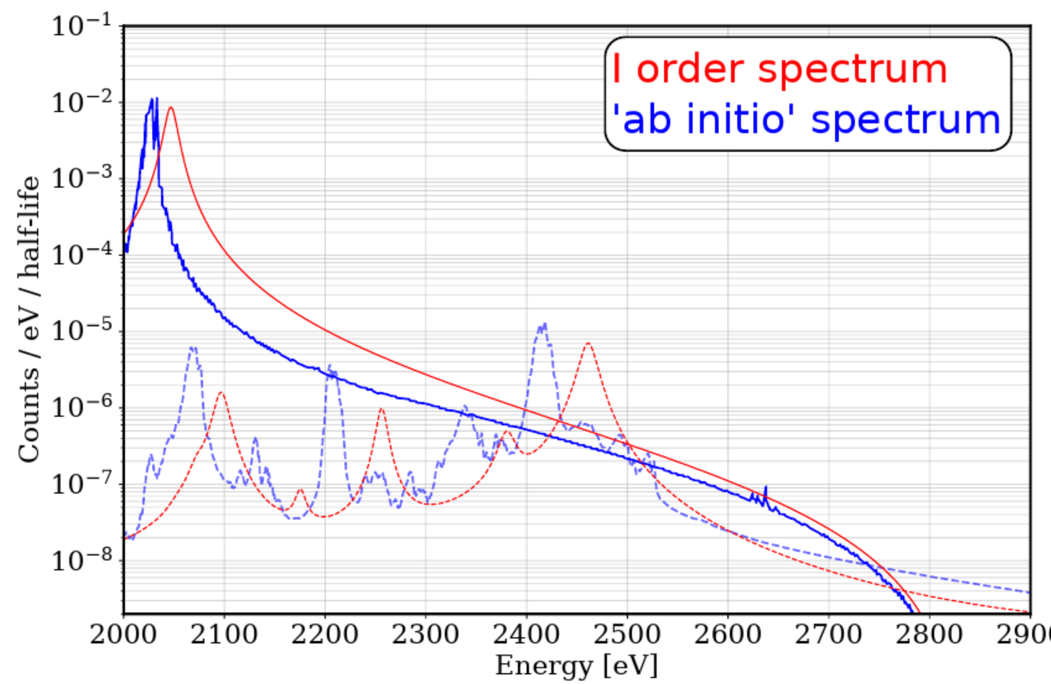
CERN, Geneva, Switzerland

ILL, Grenoble, France

backup slides...


Counts / eV / half-life
Energy [keV]

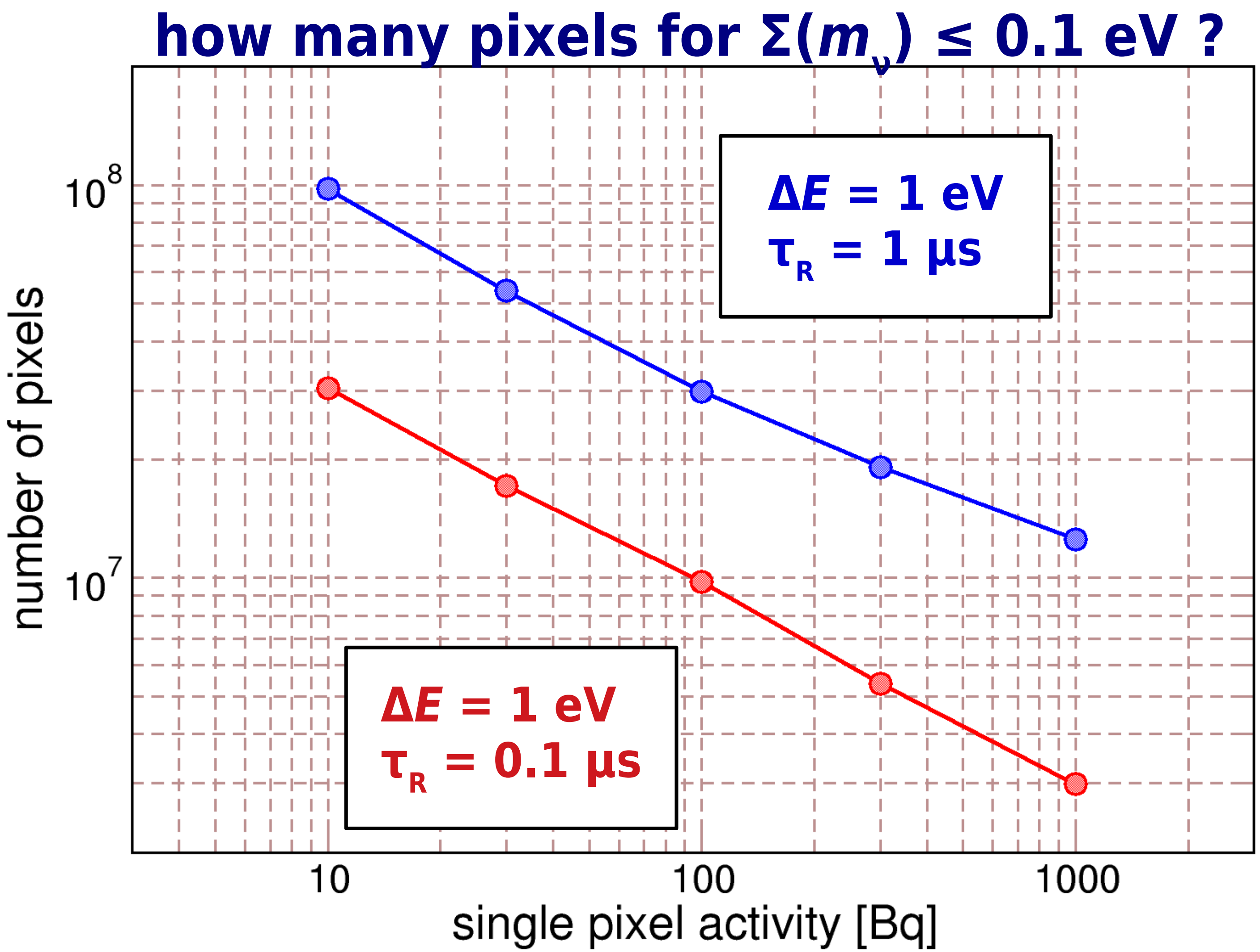

Counts / eV / half-life
Energy [eV]


I order spectrum
'ab initio' spectrum
Counts / eV / half-life
Energy [eV]

Beyond HOLMES (and ECHo...)

- requires ≥100Bq/det
- international collaboration starting with
  - cross-check and align sensitivity estimates
  - share theoretical spectrum
  - unified effort for isotope production
  - joint development of a dedicated ion implant facility
  - joint development of DAQ HW and FW
  - joint development of software tools
- keep detector development lines separated at the beginning
- consider a shared facility for underground measurements

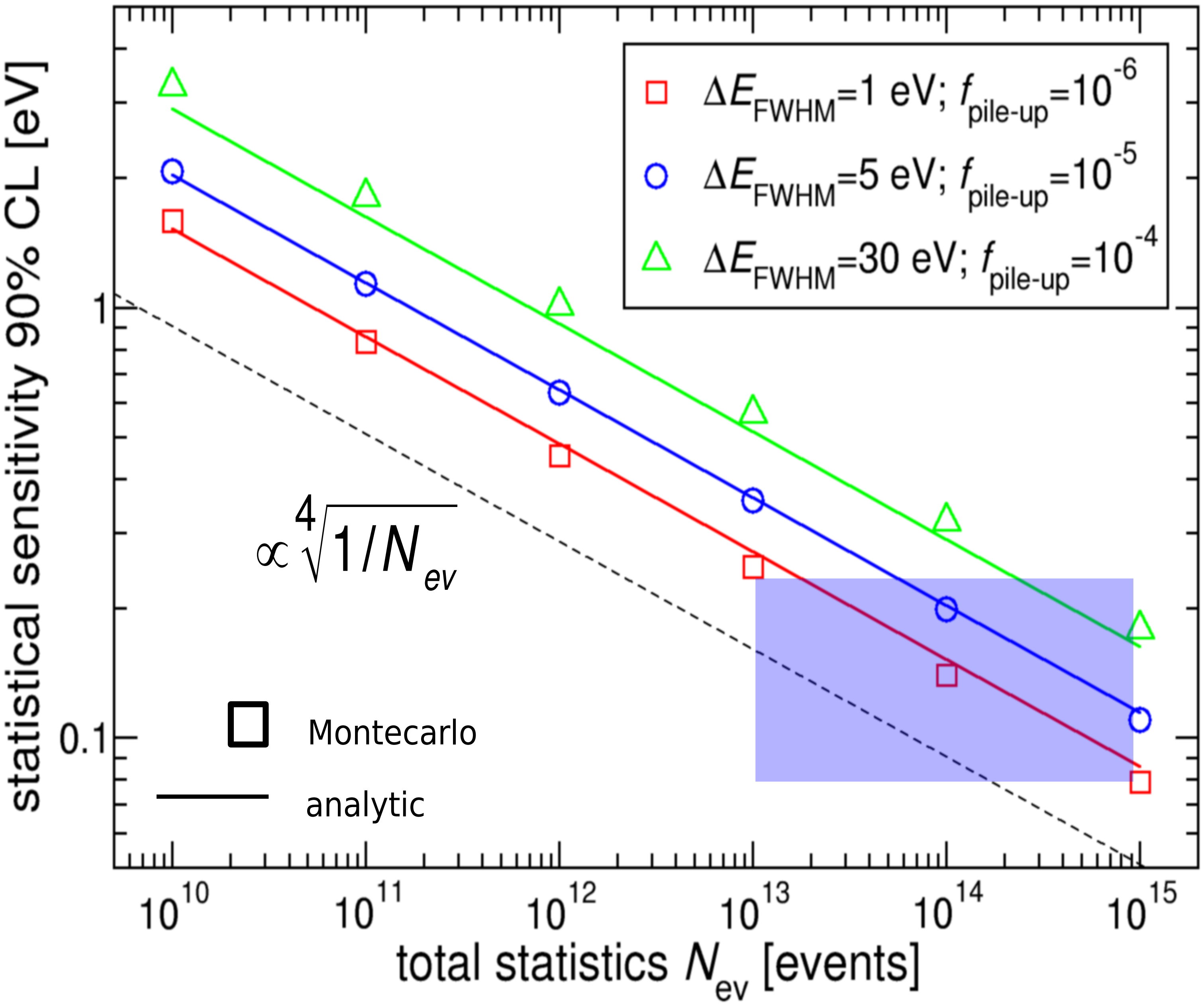
Beyond HOLMES: a 0.1eV experiment



t_M = 10 years

- multi-site experiment
- cost per channel dominated by electronics
- how to increase pixel activity?

Rhenium-187: MARE project



MARE

Microcalorimeter Array for a Rhenium Experiment

ITALY:

INFN / Univ. di Genova / Univ. di Milano-Bicocca / Univ. dell'Insubria / Univ. di Roma “La Sapienza / FBK, Trento / SISSA, Trieste

GERMANY:

Universität Heidelberg / PTB, Berlin / GSI, Darmstad

USA:

University of Miami / Wisconsin University, Madison / GSFC/NASA / NIST, Boulder Co / JPL/Caltech

PORTUGAL:

Universidade de Lisboa and ITN

FRANCE:

CNRS, Grenoble

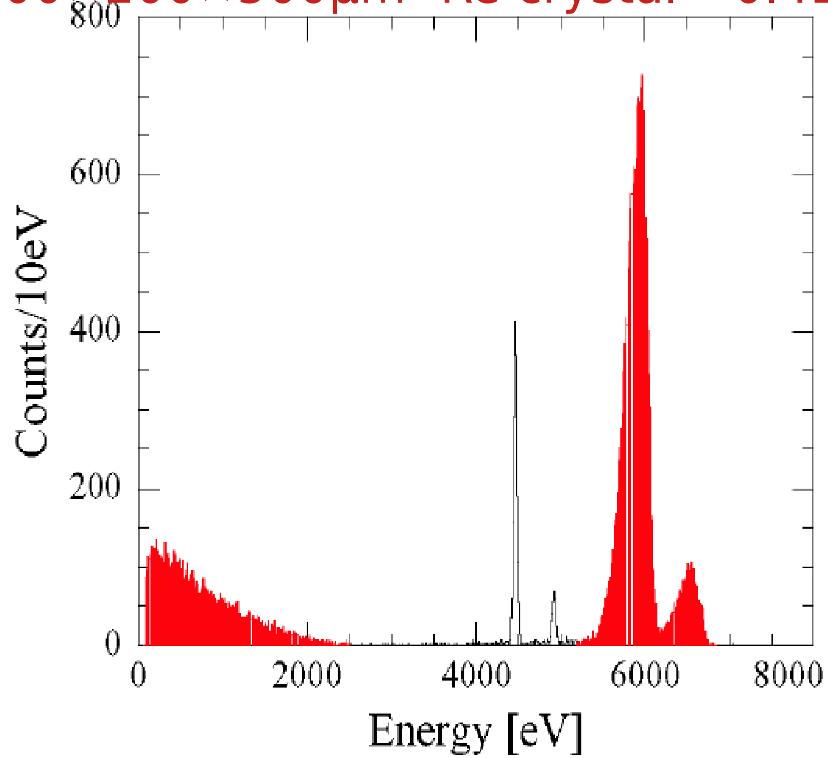
A. Nucciotti et al., Astropart. Phys. 34, 80 (2010). https://doi.org/10.1016/j.astropartphys.2010.05.004

http://crio.mib.infn.it/wig/silicini/proposal/proposal_MARE_v2.6.pdf

Rhenium-187: MARE project

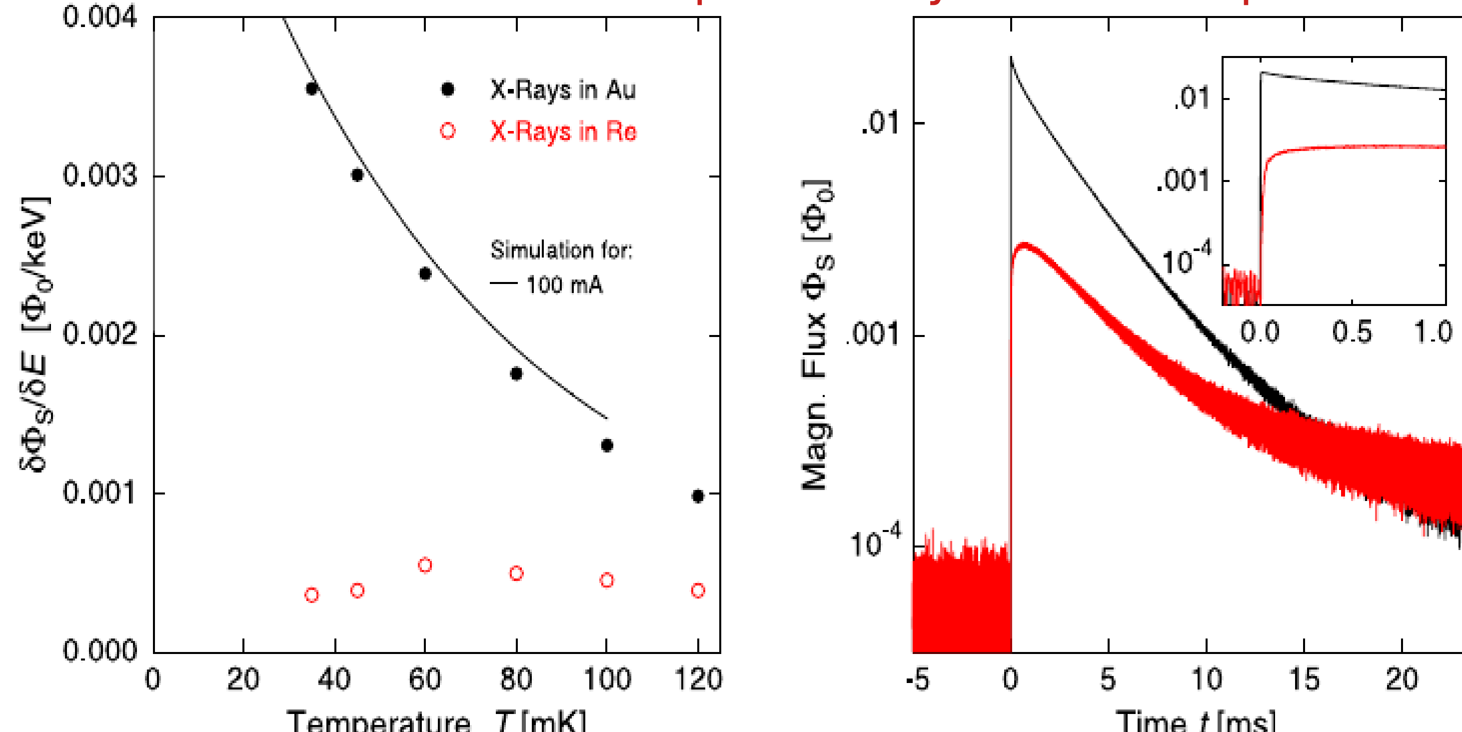
- **metallic Re + MMC** studies @ Heidelberg University (2007-2012)
- poor energy thermalization in superconducting Re
  - 95% of the energy missing
  - small pulses → poor energy resolution
  - long decay time constants

200×200×500µm³ Re crystal→ 0.4Bq



L. Gastaldo et al. AIP Conf. Proc. 1185, 607 (2009);
https://doi.org/10.1063/1.3292415

240×240×500µm³ Re crystal → 0.6Bq



P. C.-O. Ranitzsch et al., J. of Low Temp. Phys, 167(5-6) (2012) 1004.

Rhenium-187: conclusions

- Re detector development → no satisfactory results with Si/Ge thermistors, TES, MMCs... in about **20 years** of testing (1990-2010) at Standford, Genova, Milano, Heidelberg
  - no clear understanding of Re absorber physics
  - purity and superconductivity?
  - extra *C* due to nuclear quadrupole moment?
- low specific activity → “large” masses → fabrication issues
- possibly large systematics
  - Beta Environmental Fine Structure (BEFS)
  - detector response function
- MARE project shifted to **^{163}Ho** → ECHo and HOLMES

A. Nucciotti, Adv. High Energy Phys. 2016, 9153024 (2016).
https://doi.org/10.1155/2016/9153024

Other beta isotopes for calorimetry

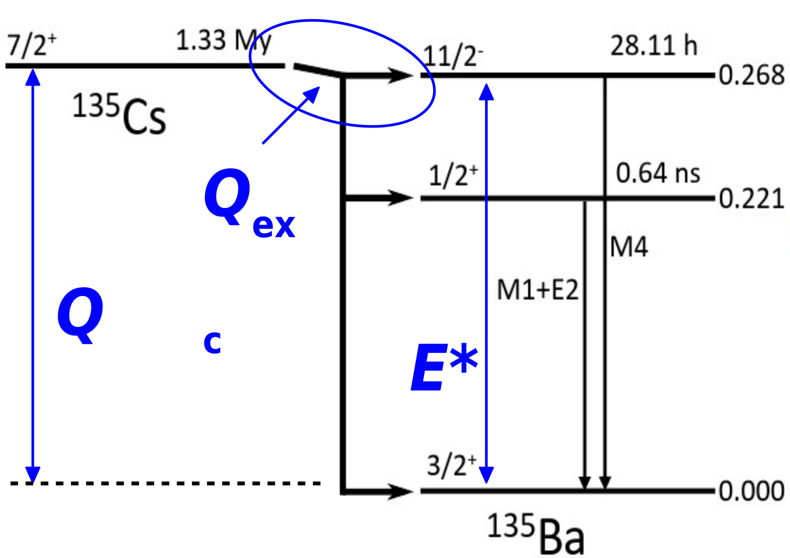
*** hypothesis**
- ^{187}Re shape
- negligible pile-up
- no background
- 100% enrichment

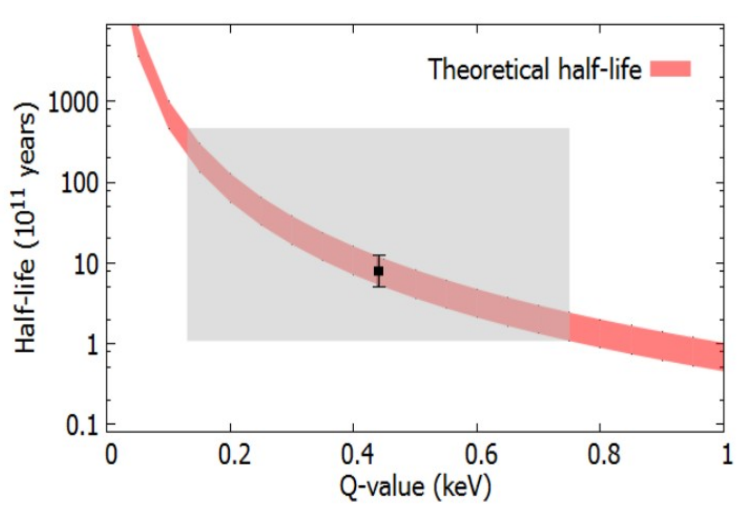
good isotope requires low Q_{exc} ($\rightarrow Q \approx E^*$), "long" half life and favorable B.R.

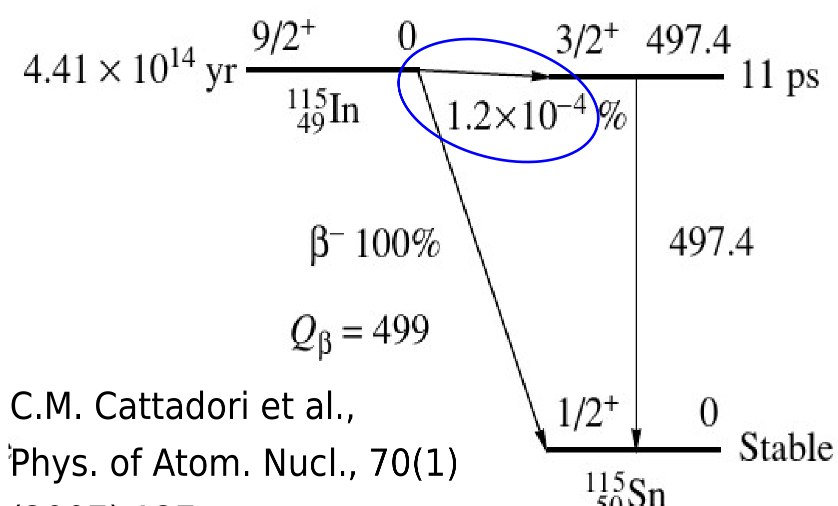
Q (and Q_{exc}) have errors (O(keV) or more), B.R. not known ...

Q → systematic measurements with traps, B.R. → theory/measurements

	a.i. [%]	half-life [y]	Q [keV]	B.R. (→ E^*)	Q_{exc} [eV]	half-life (→ E^*) [y]	N_{ev} for **$\Sigma(m_\nu)$=0.1eV ***	Mass for **T_M=10y *** [g]	Activity (→ E^*) [1/s]	Activity main [1/s]
^{187}Re	63	4.3E+10	2.47	1	2470	4.3E+10	9.5E+13	182	298258	0
^{115}In	96	4.0E+14	499	1.1E-06	155	3.7E+20	2.3E+10	2.38E+08	74	6.8E+07
^{135}Cs	0	1.3E+06	270	1.6E-06	440	8.0E+11	5.3E+11	14	1686	1.0E+09
^{135}Cs	*0*	*1.3E+06*	*270*	*1.3E-05* *4.3E-08*	*750* *130*	*1.0E+11* *3.0E+13*	*2.6E+12 1.4E+10*	*9 – 13*	*8350 – 43*	*1.0E+09*







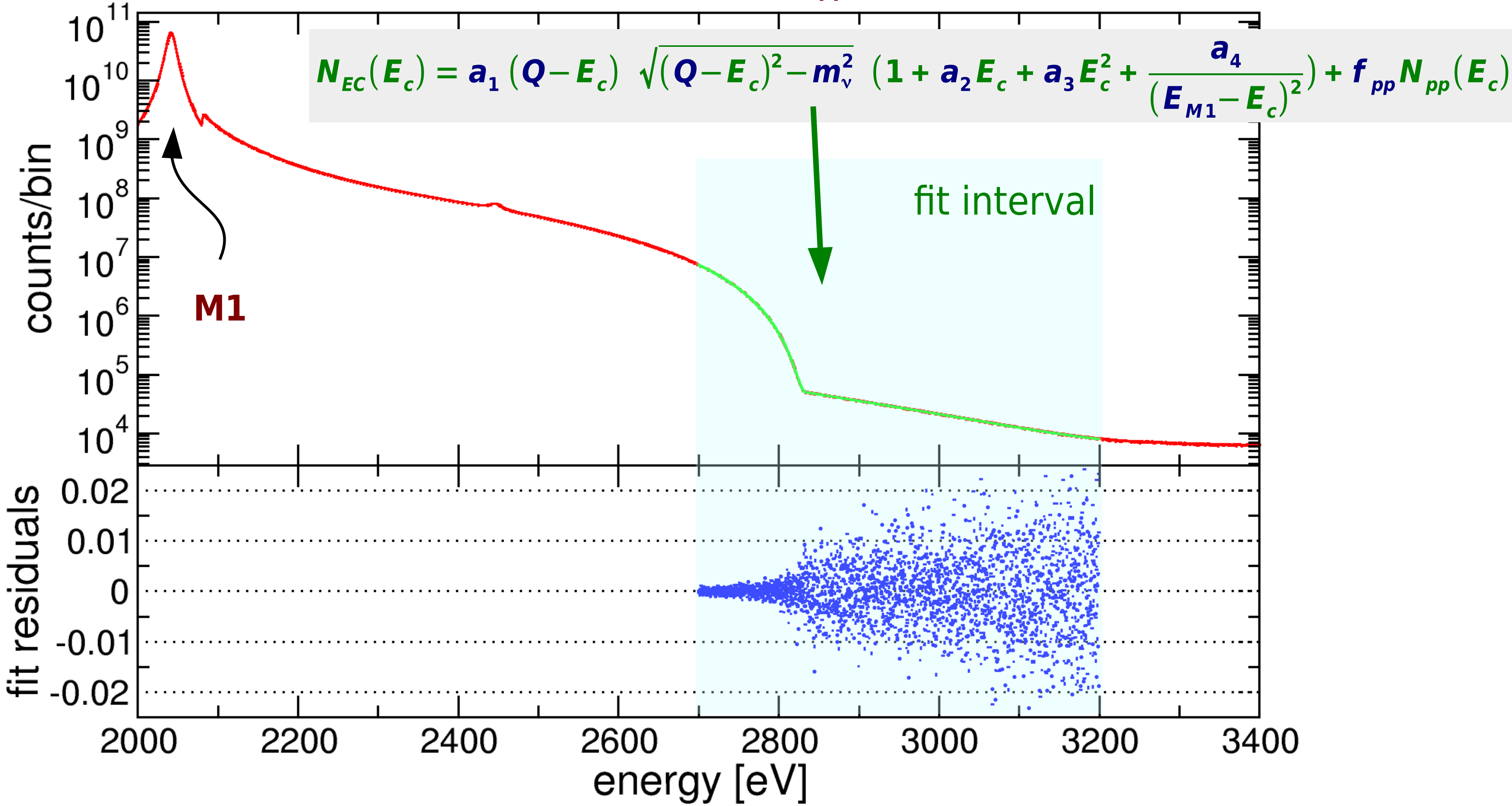
C.M. Cattadori et al.,
Phys. of Atom. Nucl., 70(1) (2007) 127

A. de Roubin et al. Phys. Rev. Lett. 124, 222503 (2020)

Statistical sensitivity: shake-off processes

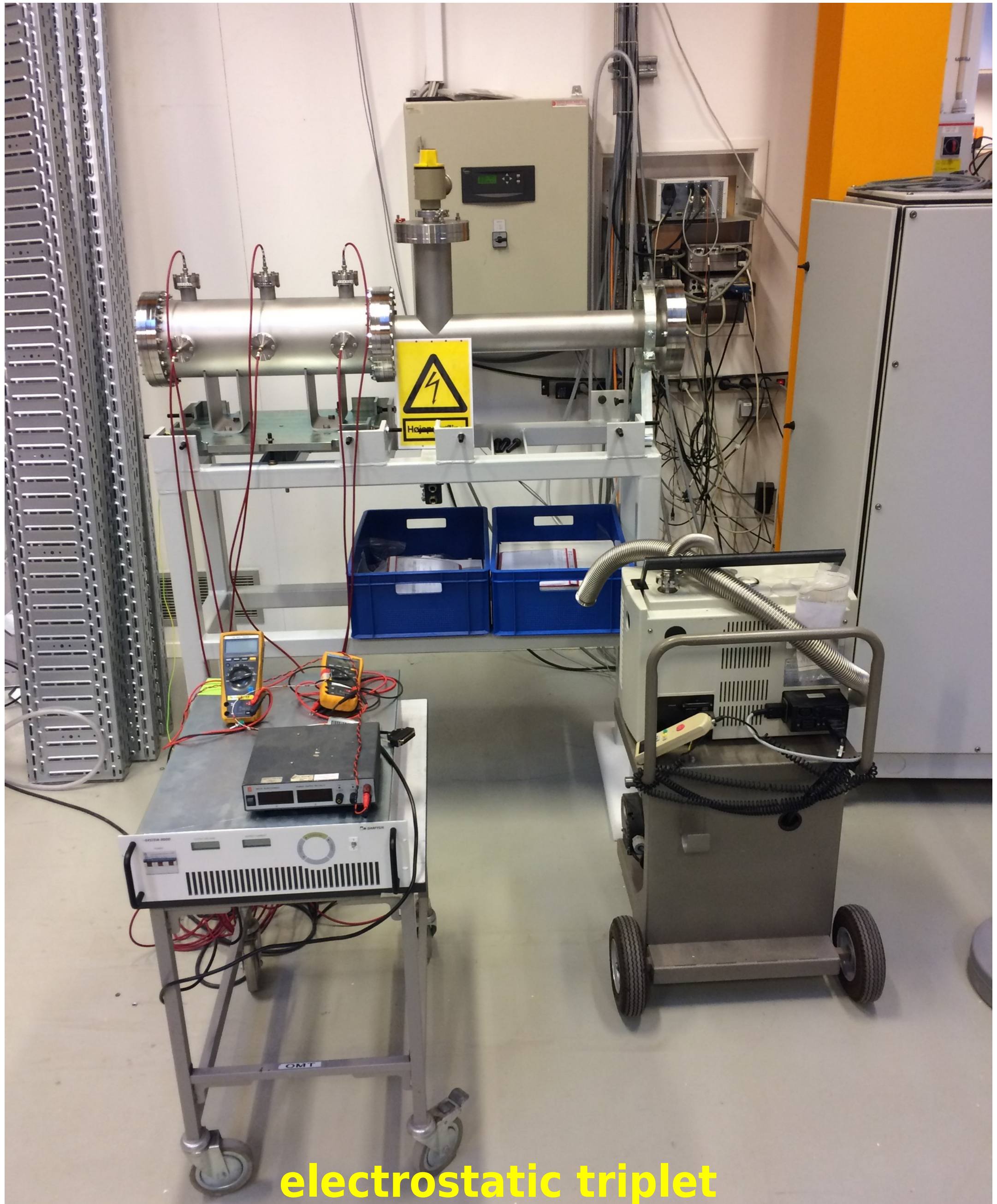
HOLMES simulation with the *optimistic* spectrum from A.De Rújula & M. Lusignoli

$Q = 2833$ eV, $N_{ev} = 3\times10^{13}$, $f_{pp} = 3.0\times10^{-4}$, $\Delta E = 1.0$ eV

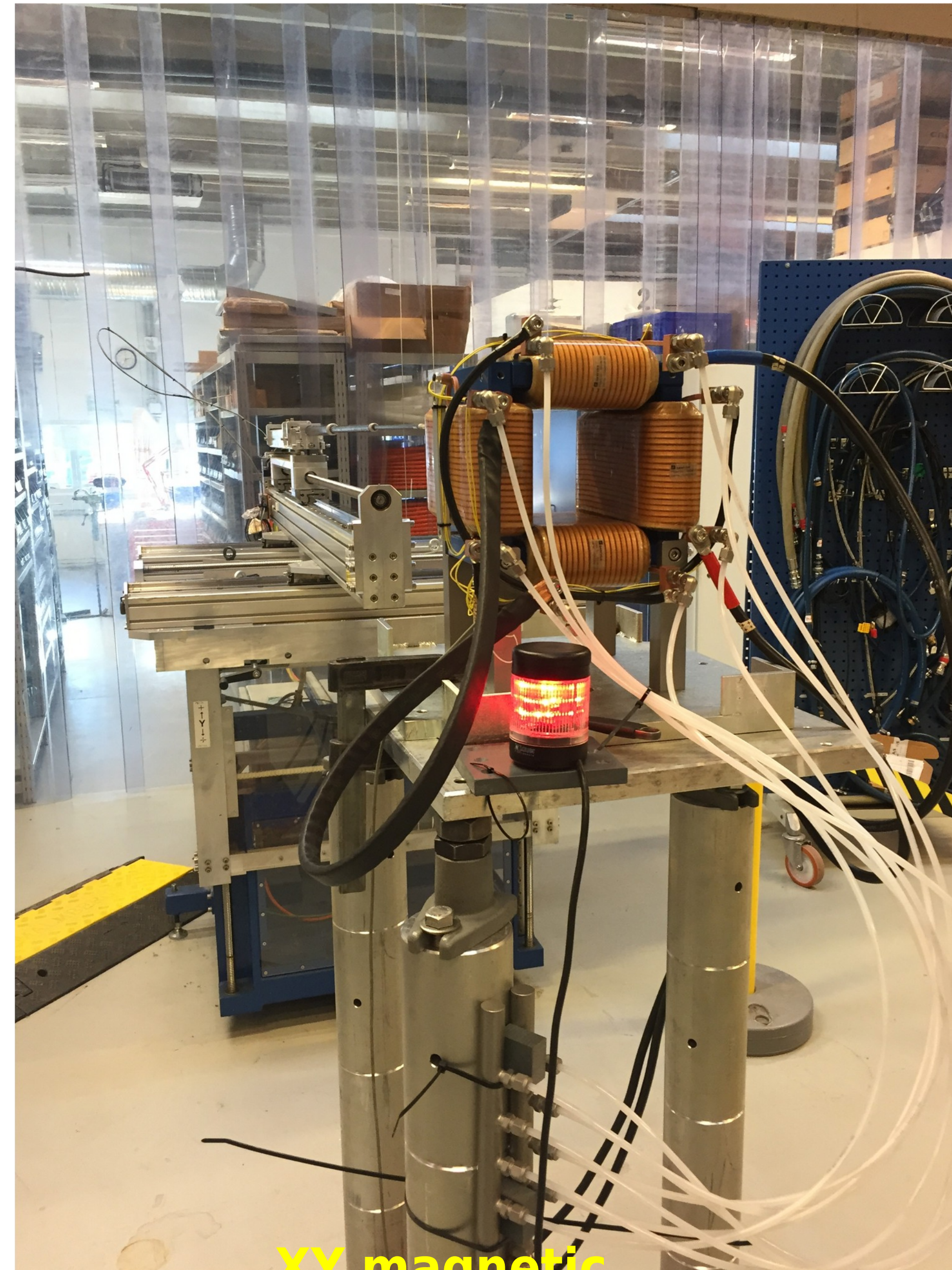


statistical sensitivity $\Sigma(m_\nu) \approx 0.64 \pm 0.03$ eV

HOLMES ion implantation system extension



electrostatic triplet



XY magnetic scan

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 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 Δf_{BW}

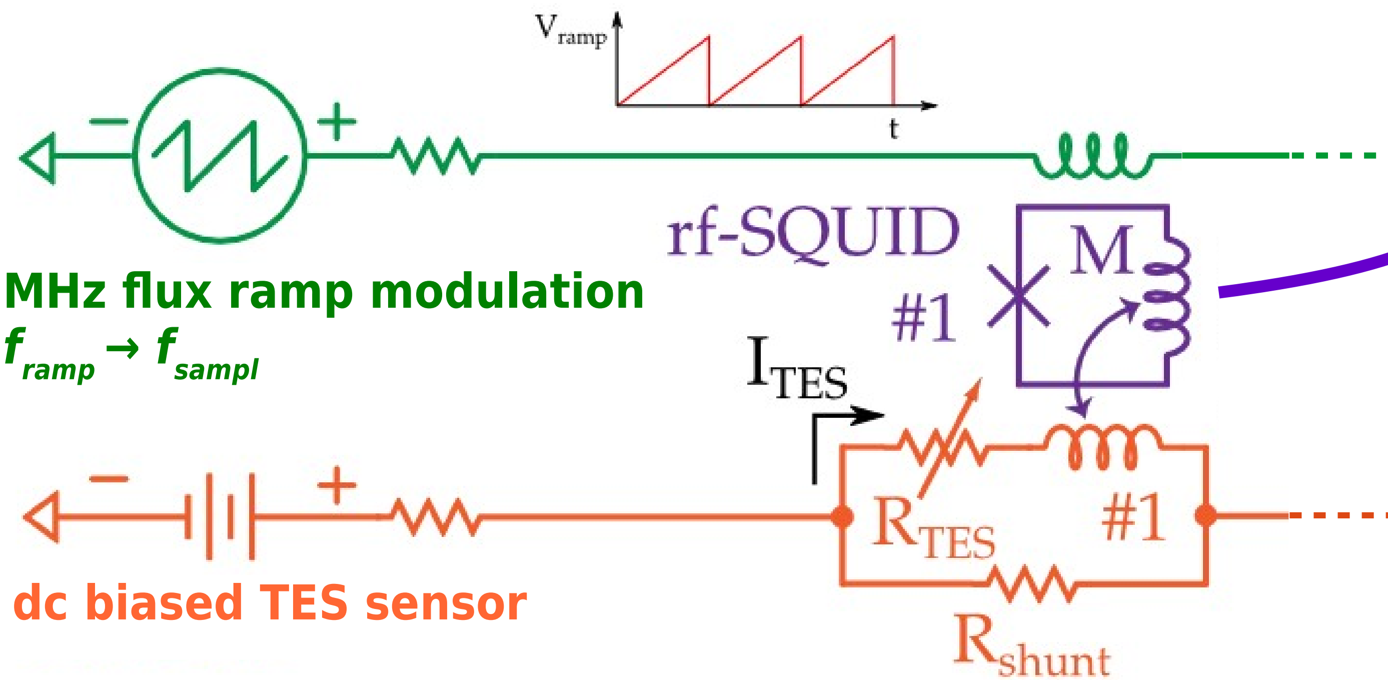
$$\Delta f \geq g_f f_{res} = \frac{2 R_d g_f n_{\Phi_0}}{\tau_{rise}}$$ microwave tones separation against crosstalk ($g_f \gtrsim 7$)

multiplexing factor → $$n_{TES} = \frac{f_{ADC}}{\Delta f} \leq \frac{f_{ADC} \tau_{rise}}{2 R_d g_f n_{\Phi_0}} \approx \frac{f_{ADC} \tau_{rise}}{140}$$

for fixed f_{ADC}**=512MHz** and n_{TES}**=32** ↔ τ_{rise}**≈10μs** with f_{samp}**=0.5MHz**

→ check for slew rate, τ_R and ΔE...

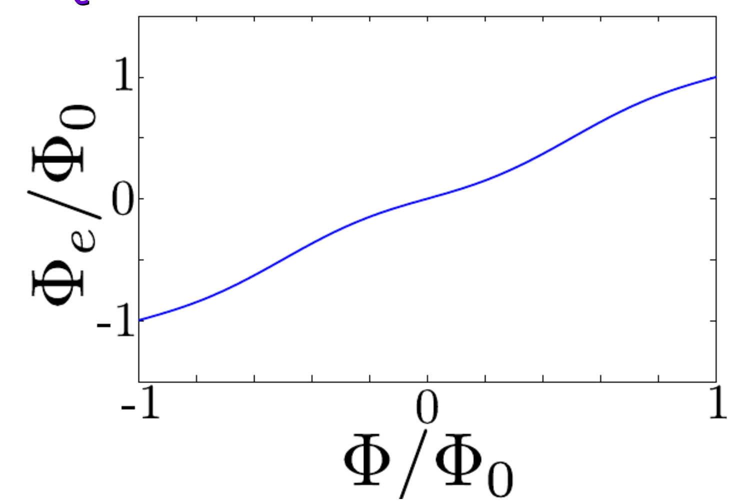
HOLMES array read-out: rf-SQUID

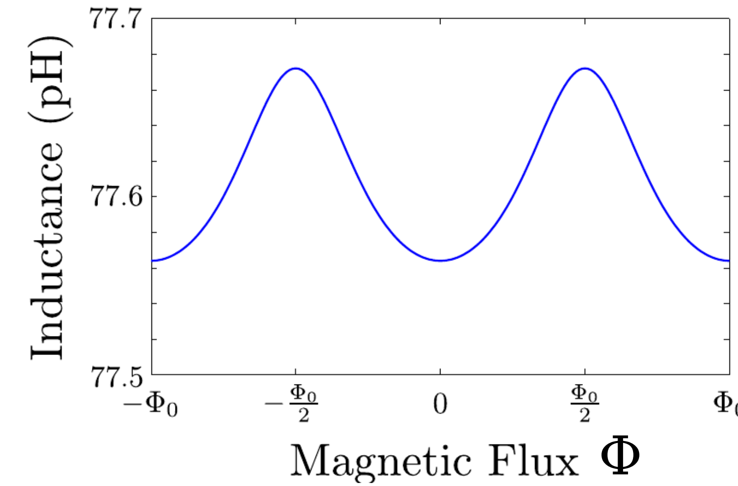


MHz flux ramp modulation
$f_{ramp} \rightarrow f_{sampl}$

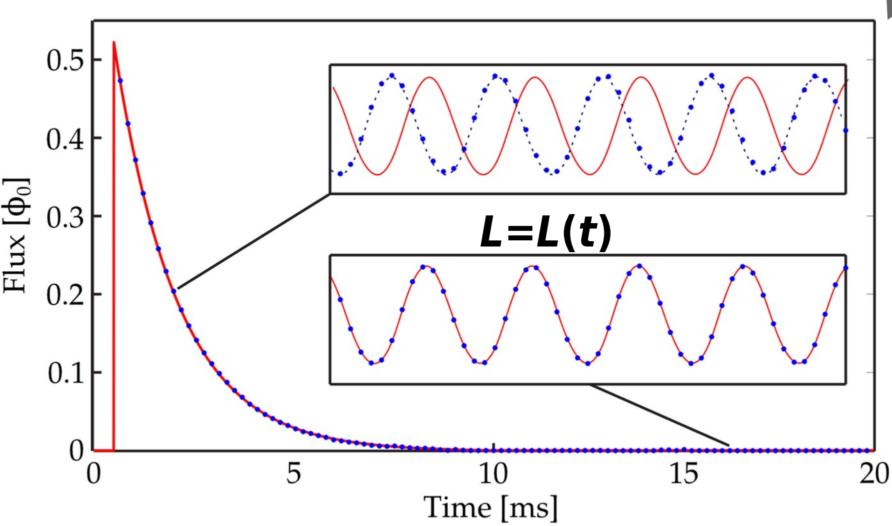
dc biased TES sensor

non-hysteretic rf-SQUID
Φ_e vs. Φ and L vs. Φ responses





$$\Delta T \rightarrow \Delta R_{TES} \rightarrow \Delta I_{TES} \rightarrow \Delta \Phi_e \rightarrow \Delta \Phi \rightarrow \Delta L$$



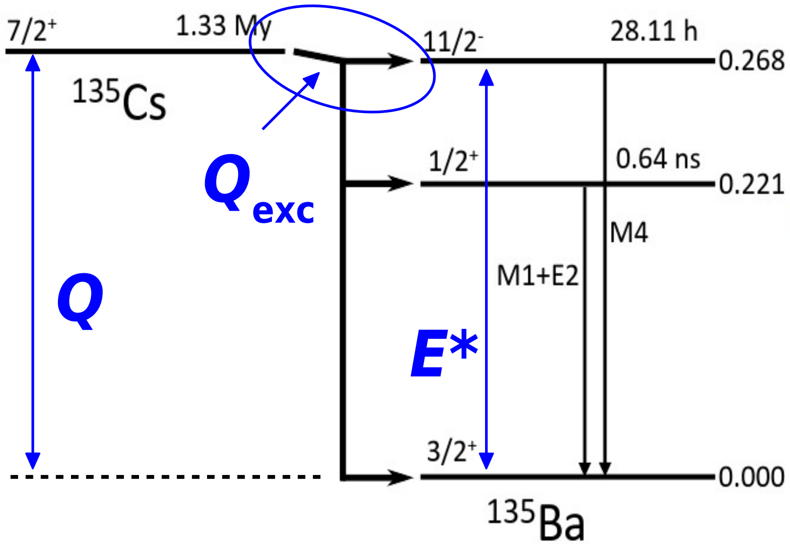
- **$\Phi_e = \Phi_{TES} + \Phi_{ramp}$**
- **flux-ramp modulation**
  - phase modulated MHz signal $L(t)$
  - linearized non-hysteretic rf-SQUID response
  - avoid low frequency noise sources

Other beta isotopes for calorimetry

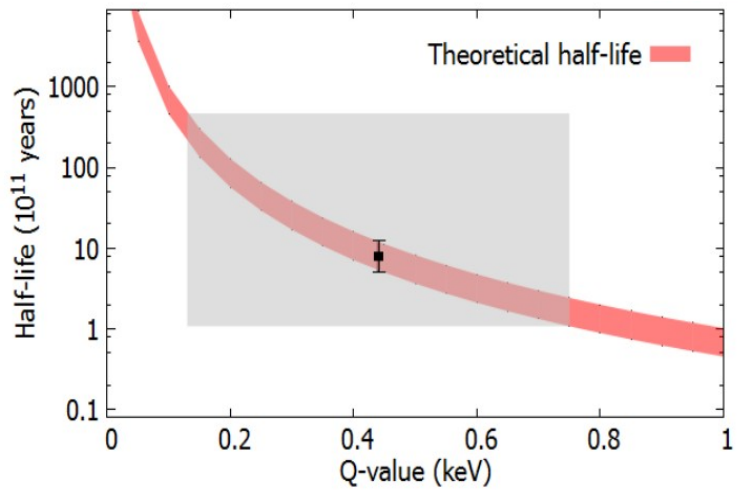
good isotope requires low Q_{exc} ($\rightarrow Q \approx E^*$), "long" half life and favorable B.R.

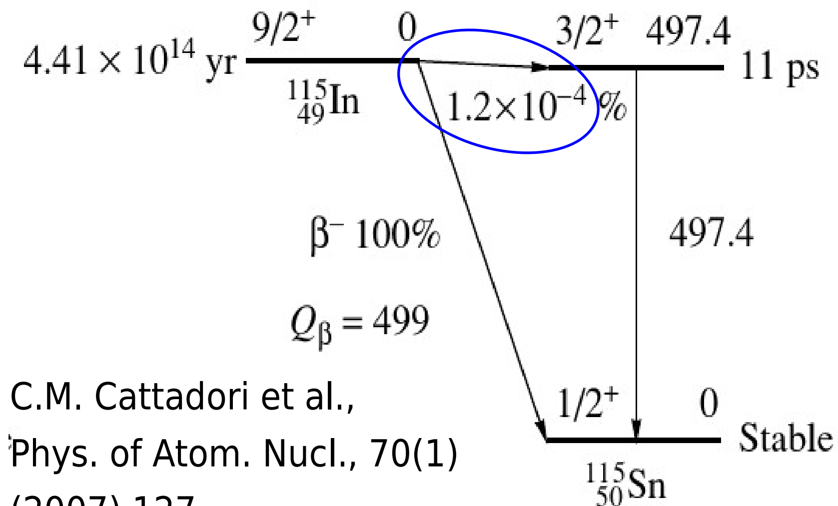
Q (and Q_{exc}) have errors (O(keV) or more), B.R. not known ...

Q → systematic measurements with traps, B.R. → theory/measurements



A. de Roubin et al. Phys. Rev. Lett. 124, 222503 (2020)





C.M. Cattadori et al., Phys. of Atom. Nucl., 70(1) (2007) 127

$$\Sigma_{90}(m_\nu) \propto \sqrt[4]{\frac{Q^3}{N_{ev}}}$$

for given T_M
$$\Sigma_{90}(m_\nu) \propto \sqrt[4]{\frac{Q^3}{A_\beta N_{det}}}$$

$$A_\beta N_{det} = \lambda N_{nuclei} = \lambda \frac{M}{A} N_{Av}$$

for a target $\boldsymbol{\Sigma_{90}(m_\nu)}$

$$M \propto \frac{Q^3}{\lambda(Z,Q,S(Q))} \propto \approx \frac{1}{Q^2}$$

for LTDs calorimeters

$$\Delta E_{FWHM} \propto \sqrt{\frac{M}{N_{det}} T^2}$$

HOLMES background measurements