Test 1

- Test 2

Test III

Two OLD methods to measure the electron-neutrino MASS

$$Z[i] \to (Z+1)[f] + e^- + \bar{\nu}_e$$

$$Q \equiv M_i - M_f$$

$$\frac{d\Gamma}{dE_e} = \frac{1}{2} |\mathcal{M}|^2 F(E_e)\, \Phi,$$

$$|\mathcal{M}|^2 \approx 32\, G_F^2 \cos^2\theta_C\, M_i\, M_f |\mathcal{M}_N|^2 E_e\, E_{\bar{\nu}}$$

$$n : \Uparrow\ 1 + 3\, g_A^2$$

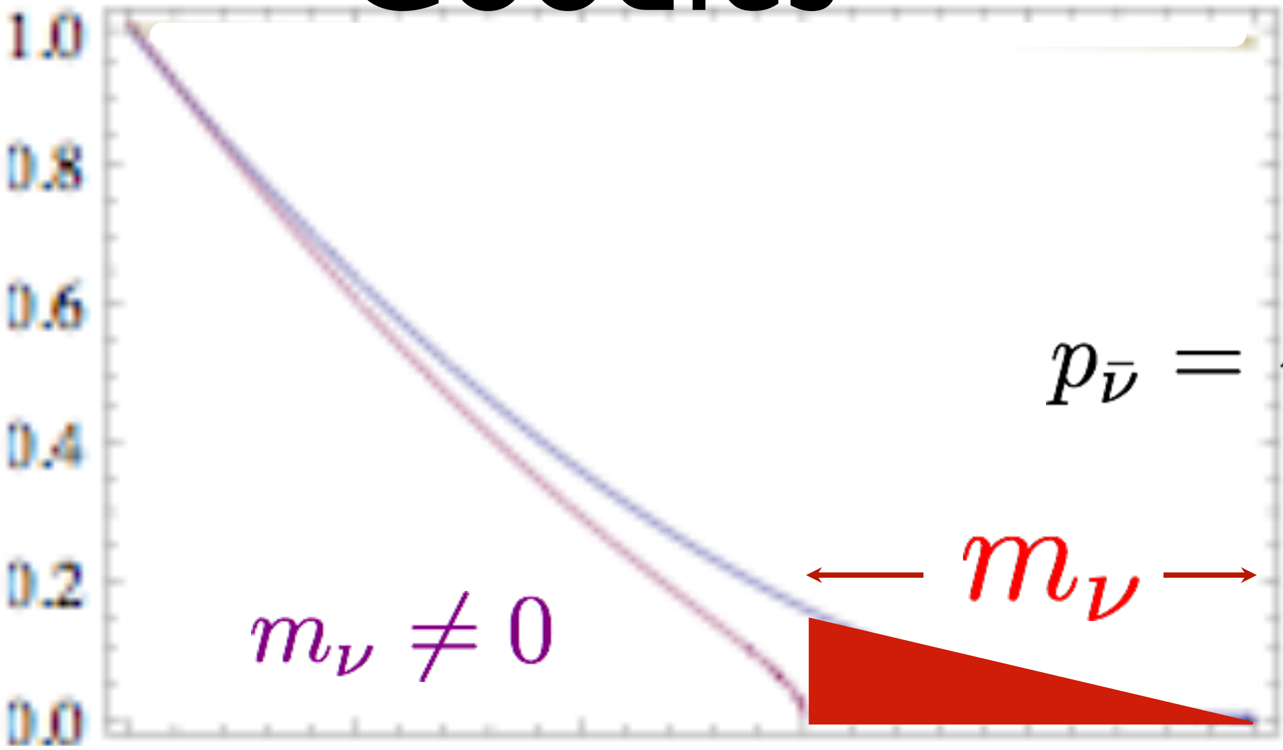
$F(E_e)$: Fermi function

$$\Phi_3 = \frac{1}{8\pi^3} \frac{p_e\, p_{\bar{\nu}}}{M_i\, M_f},$$

$$p_{\bar{\nu}} = \sqrt{E_{\bar{\nu}}^2 - m_{\bar{\nu}}^2}, \qquad E_{\bar{\nu}} = Q - E_e$$

Fraction f of "Goodies"

$$\frac{d\Gamma}{dE_e}$$



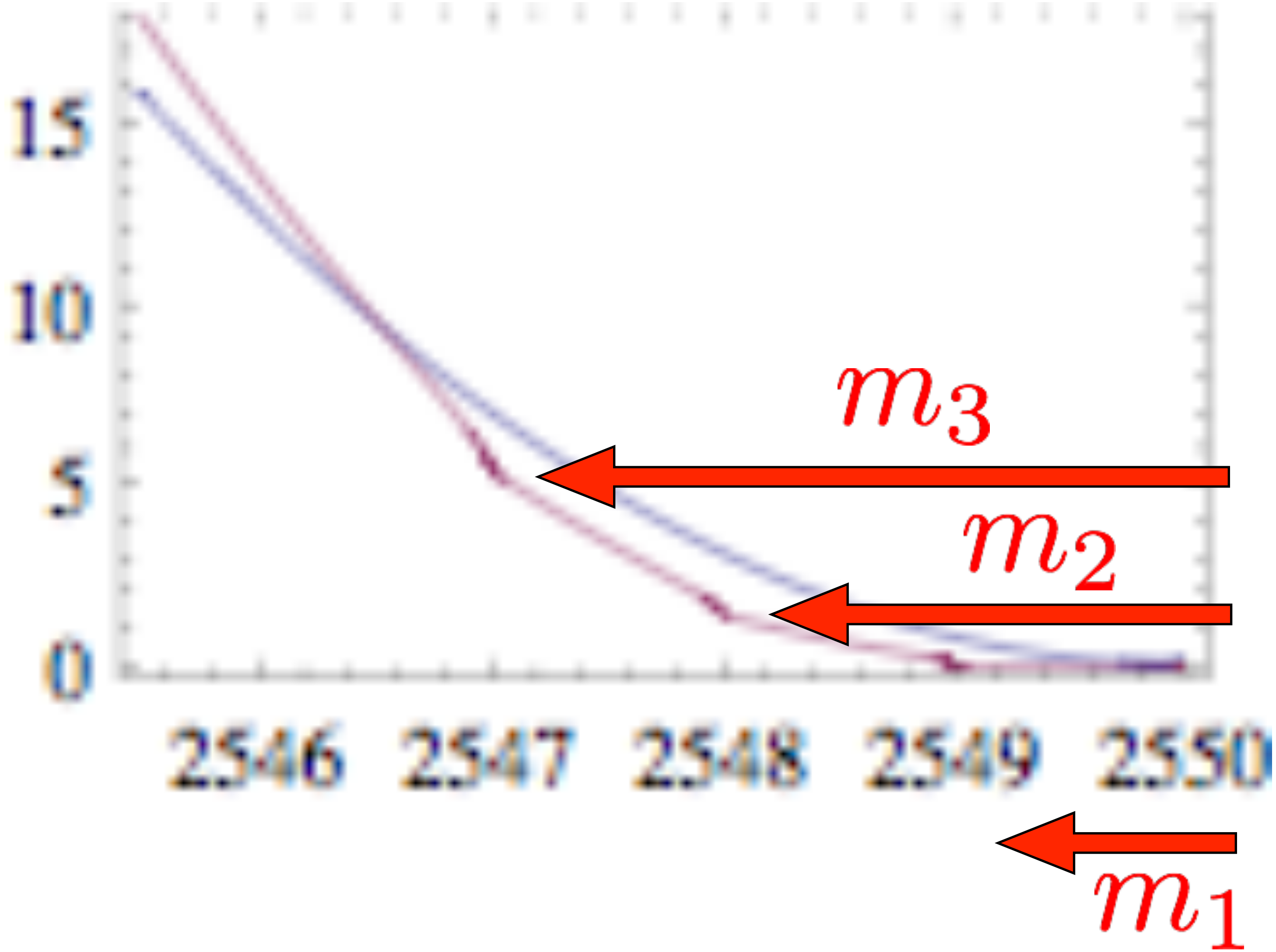
$$p_{\bar\nu} = \sqrt{E_{\bar\nu}^2 - m_{\bar\nu}^2}$$

Q

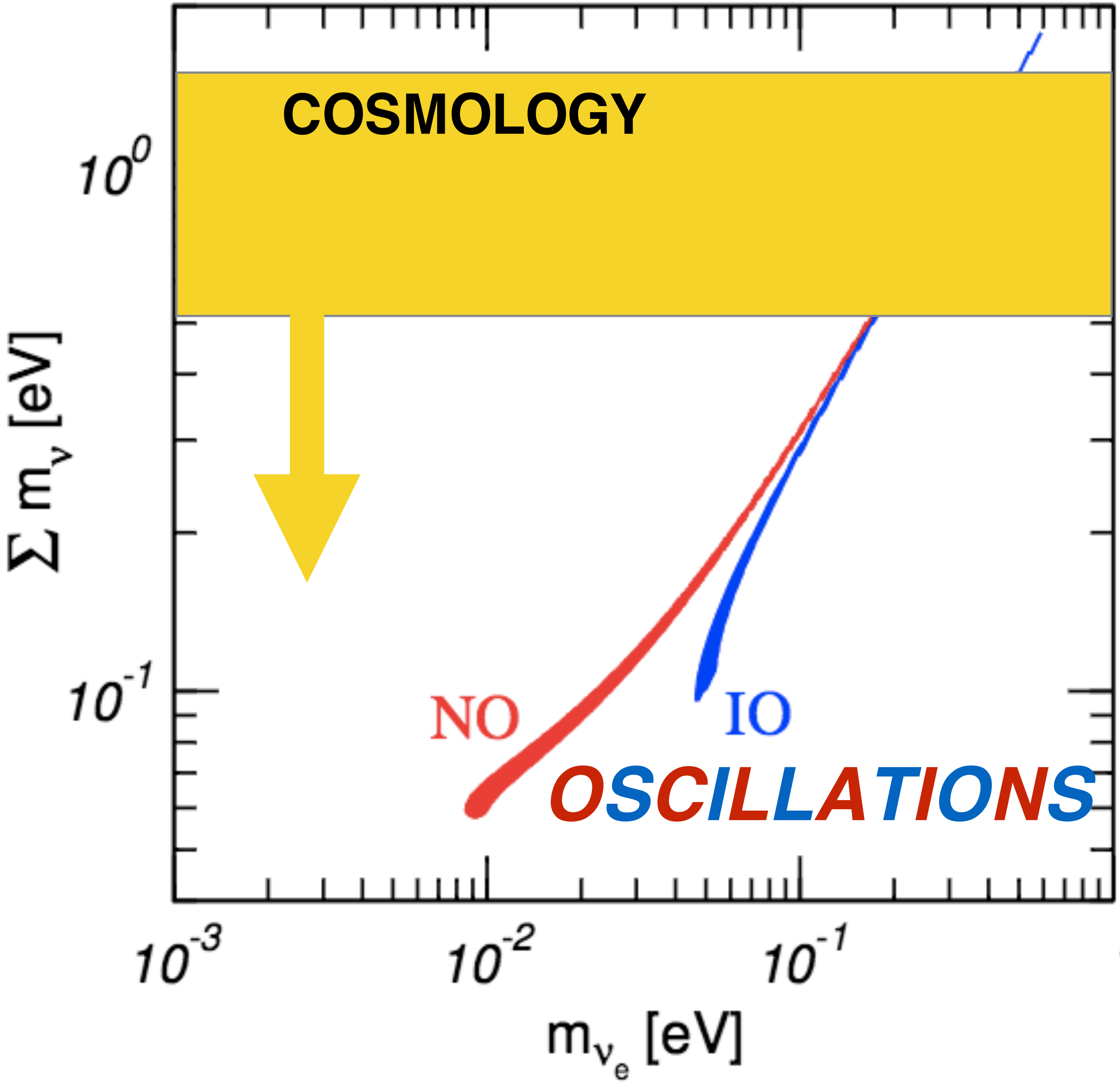
$$f = \int_{Q-m_\nu}^{Q} \frac{d\Gamma}{dE}\, dE \,/\, \int_0^Q \frac{d\Gamma}{dE}\, dE \propto \left[\frac{m_\nu}{Q}\right]^3$$

"Difficulty" $\propto 1/\mathrm{m}_\nu^3$

	^{3}H	^{187}Re
Q in keV	18.6	2.47



$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i}$$ ***if unresolved***

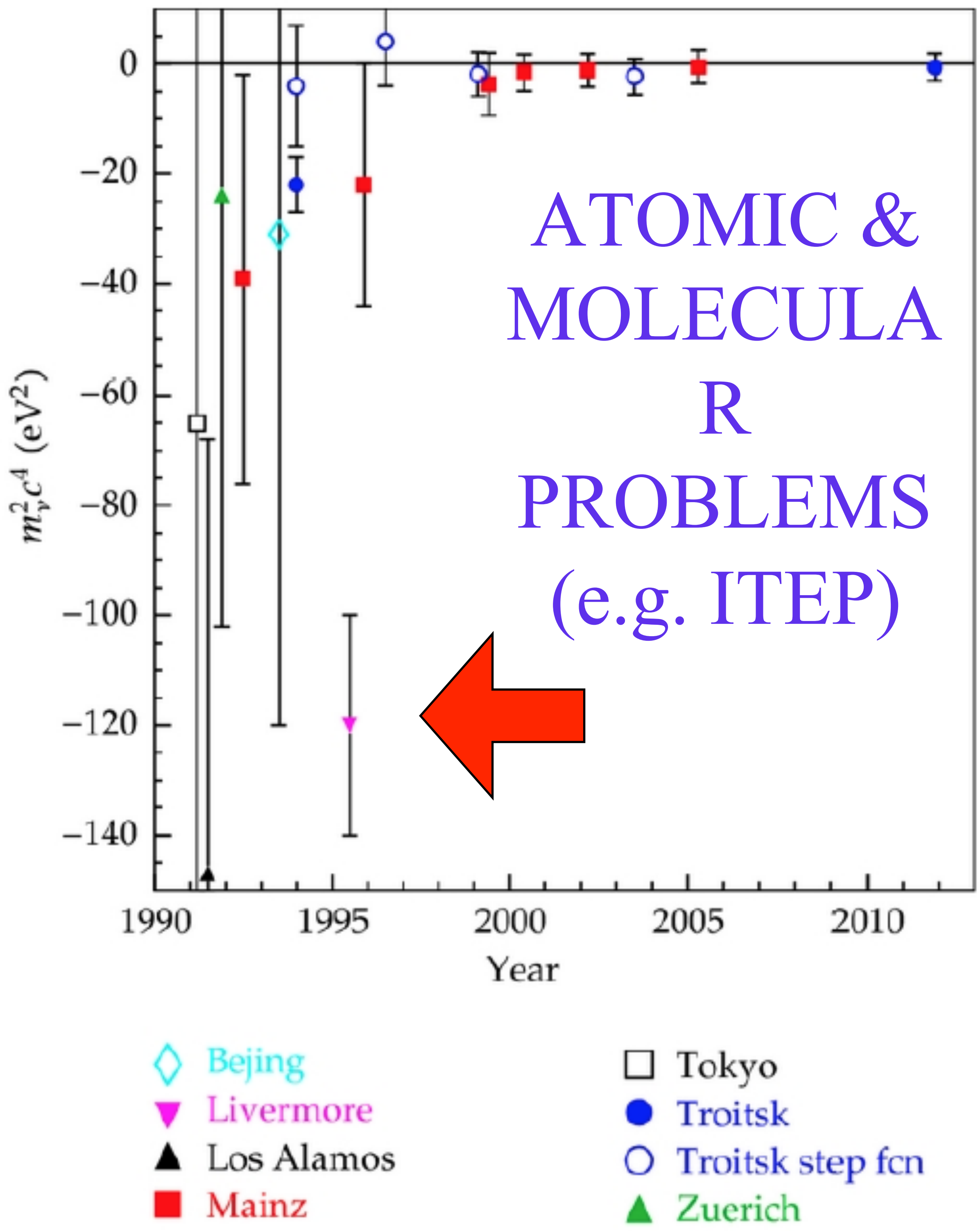


M.C. Gonzalez-Garcia, Michele Maltoni, Thomas Schwetz

arXiv:1512.06856

< 1 eV

EC or β decay effective mass



$$m_{\bar{\nu}} < 2.3\,\mathrm{eV}$$
$$(95\%\ C.L.)$$

(Mainz)

$$m_{\bar{\nu}} < 2.05\,\mathrm{eV}$$
$$(95\%\ C.L.)$$

(Troitsk)

ATOMIC & MOLECULAR PROBLEMS

??

ITEP experiment

$$[^3\mathrm{H}]\mathrm{Valine} \rightarrow \mathrm{e}^- + \overline{\nu}_\mathrm{e} + [^3\mathrm{He}]\mathrm{Valine}^{\star\star}$$

$$E_\nu + E_e = Q = \Delta M^{\star\star}$$

Spectrum = Sum of spectra with different endpoints

KATRIN, Project 8

Gaseous $^3H_2$

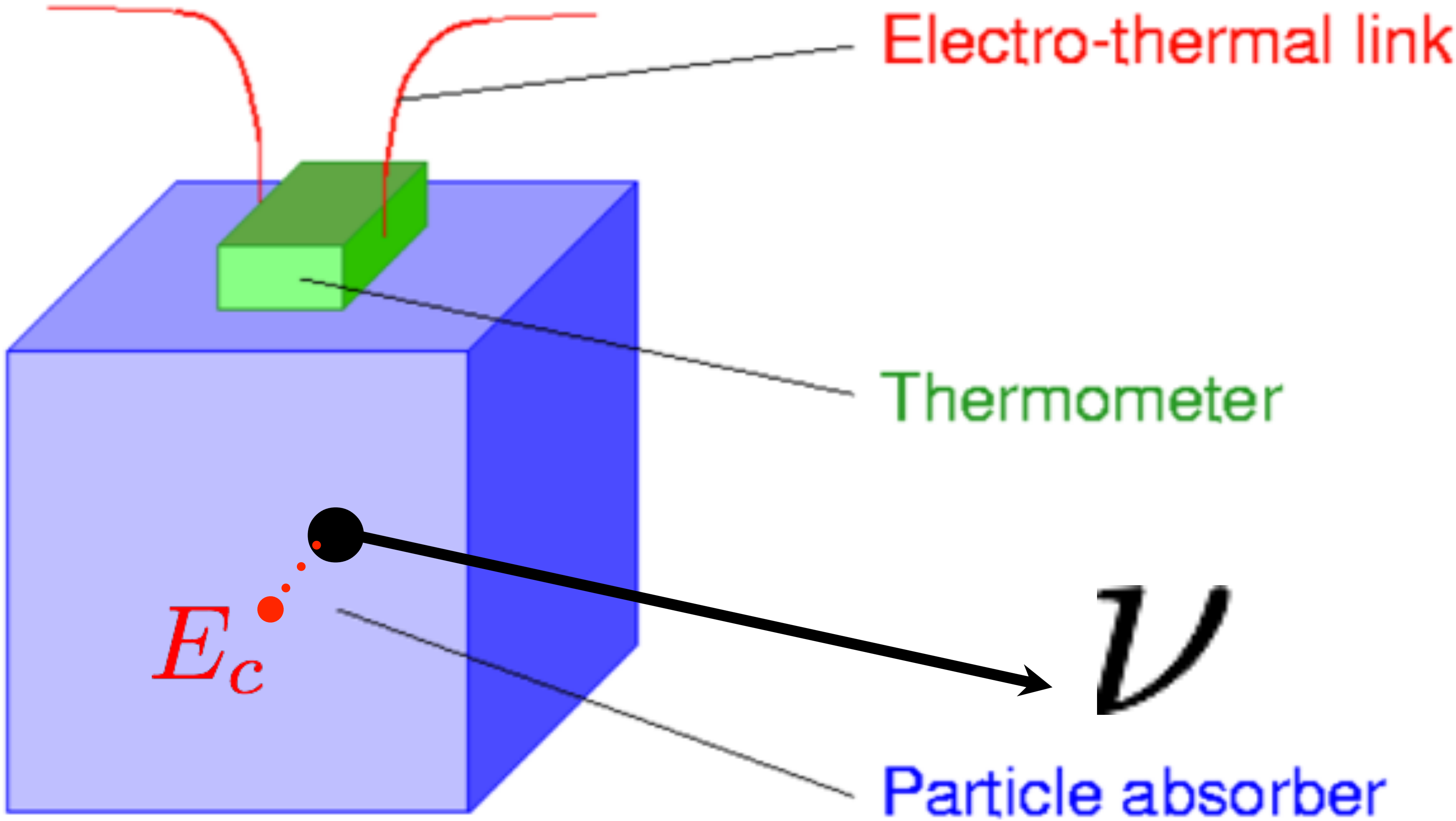
KATRIN on her way

A UNIQUE Q UNIQUE Q

for ALL DECAYS ?

⇒

CALORIMETRY



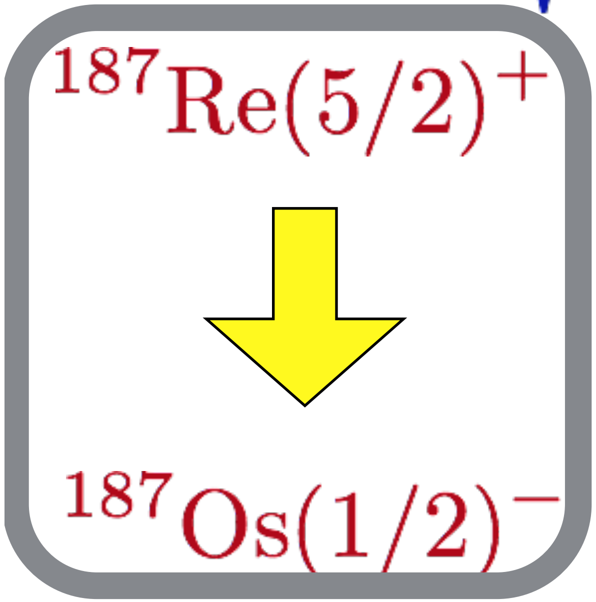
$$D[\text{before}] \rightarrow D[\text{after}] + E_c + \nu$$

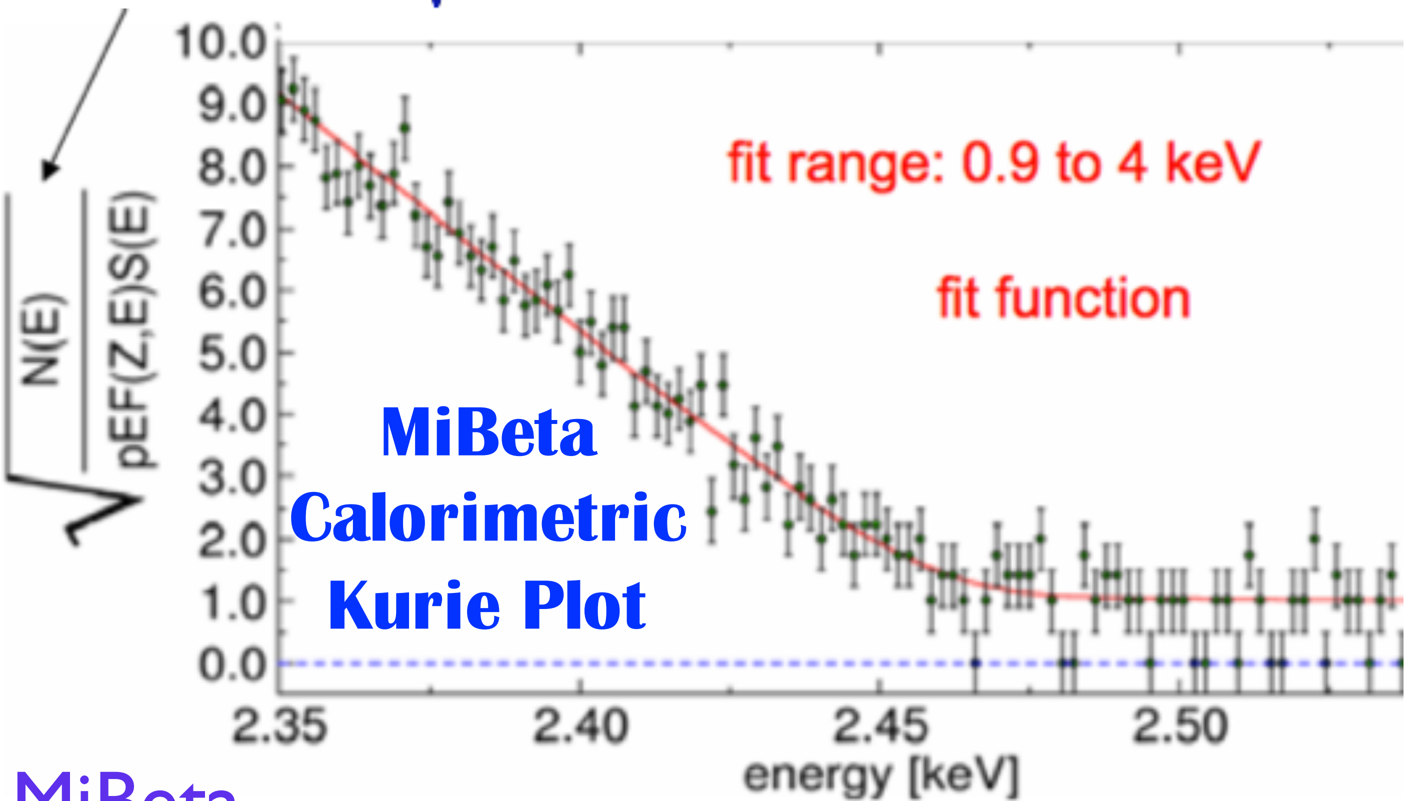
3-body phase space, as in beta decay

Q = MD[before] - MD[after] ***Indep. of decay chain***

$$K(E_e) \equiv \sqrt{\frac{d\Gamma}{F(E_e)\, p_e\, E_e\, dE_e}} \propto \sqrt{E_{\bar{\nu}}\, p_{\bar{\nu}}}$$

$$= \sqrt{(Q - E_e)\sqrt{(Q - E_e)^2 - m_{\bar{\nu}}^2}}$$





MaNu (Genova)

MiBeta (Milano/Como)

$m_\nu < 15.6\,\text{eV}\ (90\%\text{C.L.})$

Atomic beta decay by electron capture

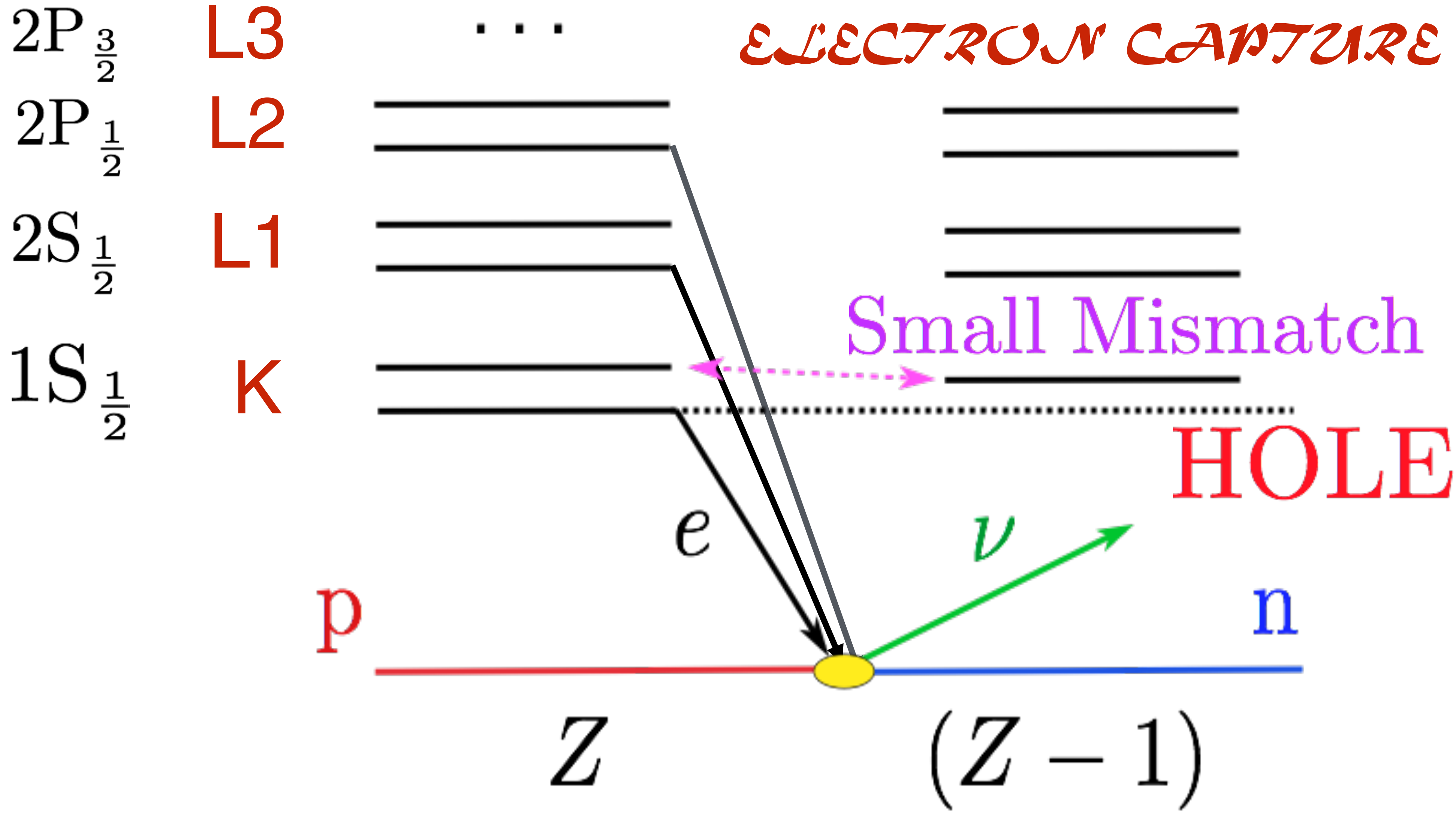
The e-neutrino mass(es)

Calorimetric measurements

Maurizio Lusignoli

ADR, Maurizio Lusignoli 1982

Experimental Progress, e.g.: Galeazzi et al., Ranitsch et al., Gastaldi et al., Sisti et al., Nuccioti et al., Eliseev et al...



Requires $\varphi_{\mathrm{H}}(0) \neq 0$ $\quad n\, l_j = n\, S_{1/2}$

Small-component $\mathcal{O}(\alpha\, Z)$ mixing $\quad n\, l_j = n\, P_{1/2} \leftrightarrow n\, S_{1/2}$

$$Z \to (Z-1)^H + \nu$$

$$M_Z = M_{Z-1} + E_H + E_\nu$$

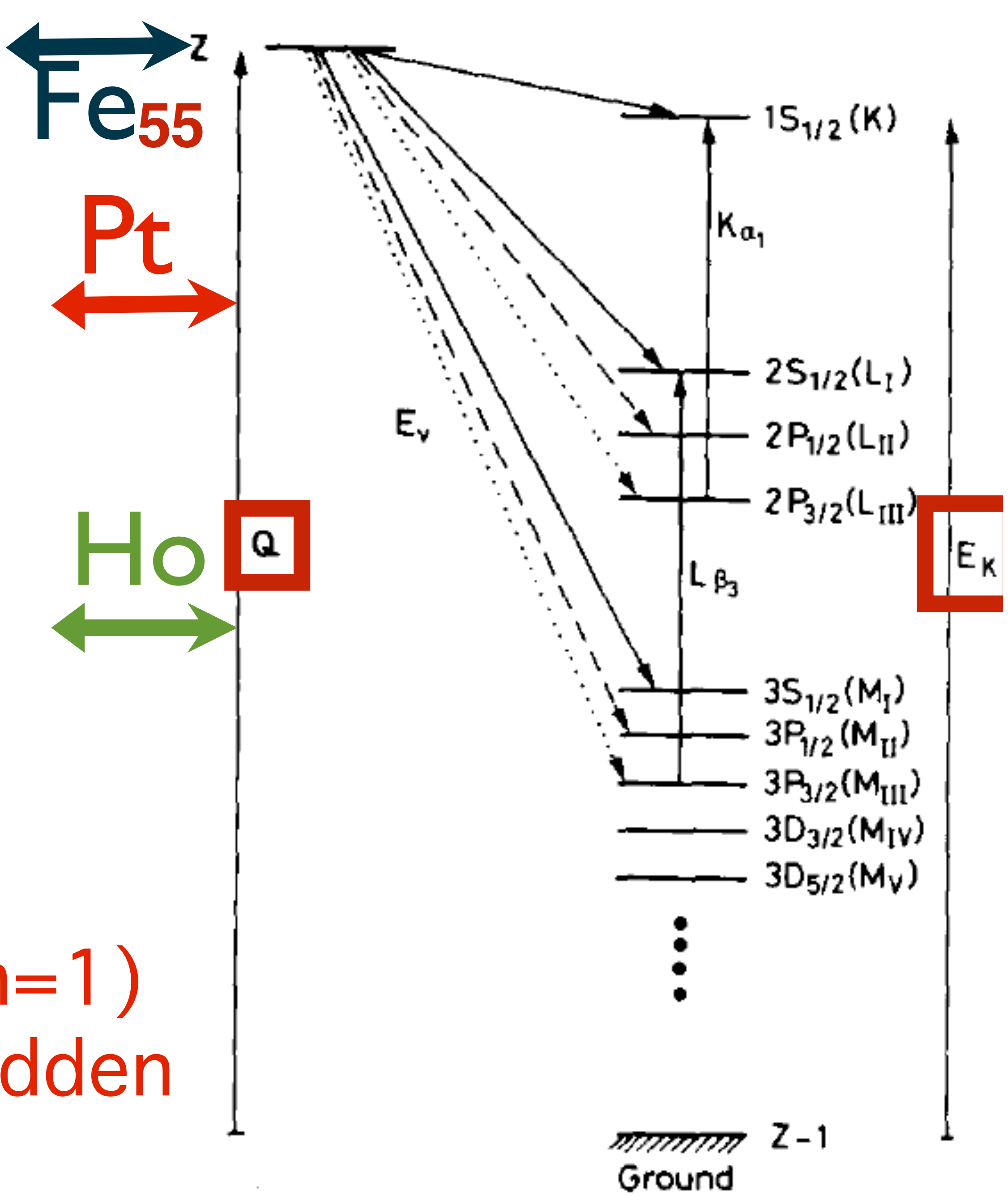
$$> 0$$

$$Q \equiv M_Z - M_{Z-1}$$

$$= E_H + E_\nu$$

$$E_H \pm i\Gamma_H \to E_c$$

$$\sum \text{Holes}$$



$^{193}_{78}\text{Pt}$ K (n=1) forbidden

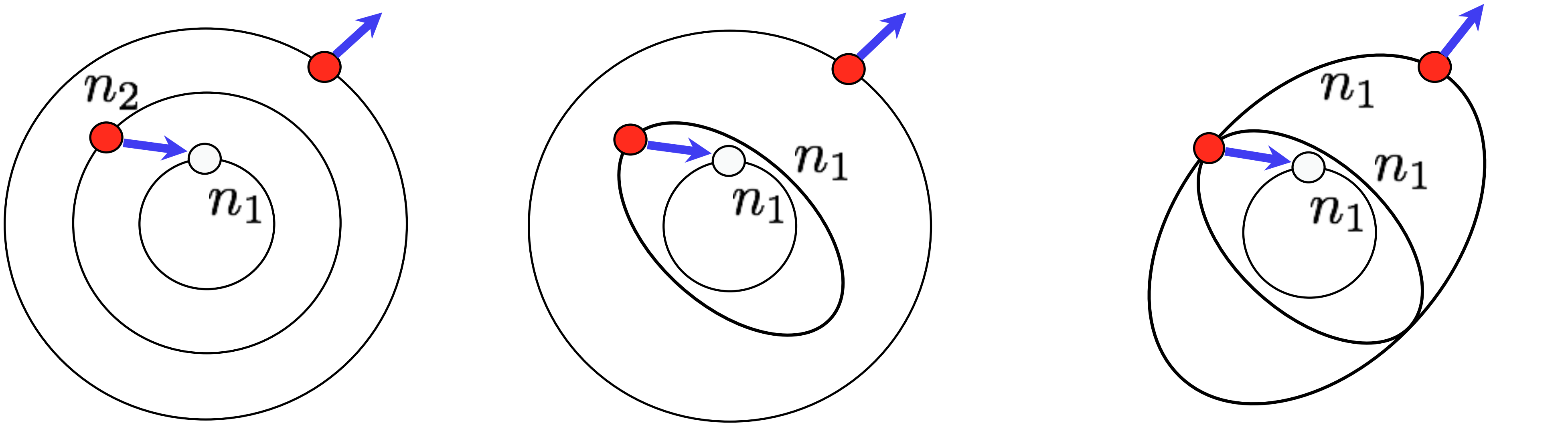
$^{163}_{67}\text{Ho}$ K, L (n=1,2) forbidden

$$Z \to (Z-1)^H + \nu$$

H decay ?

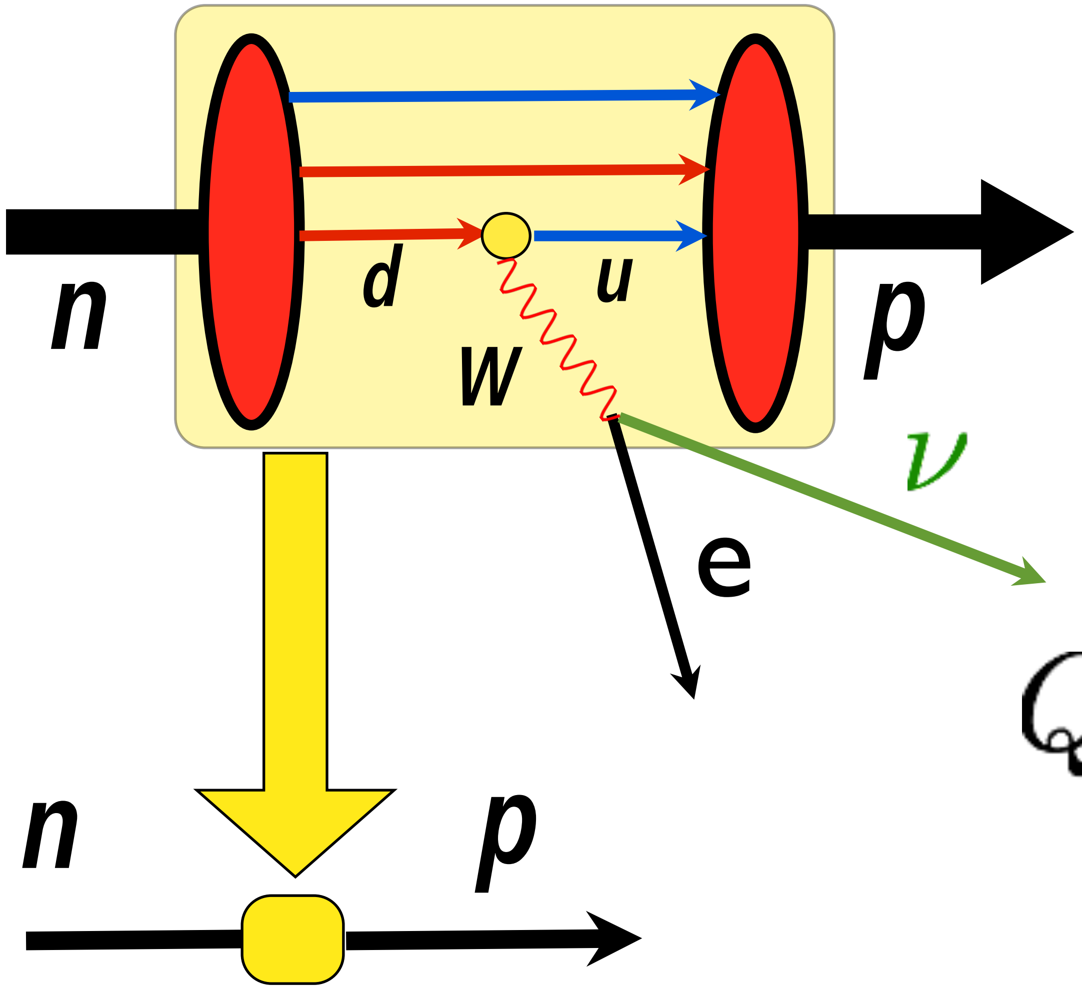
In a [clean] calorimetric measurement all endpoints of all decay channels coincide at E_c = Q = MD[before]-MD[after] $- m_\nu$

This includes all photon- or electron-emission atomic de-excitations



Auger   Coster-Kronig   Super-Coster-Kronig

“Effective” neutron-decay theory



High spacial resolution totally UNNECESSARY

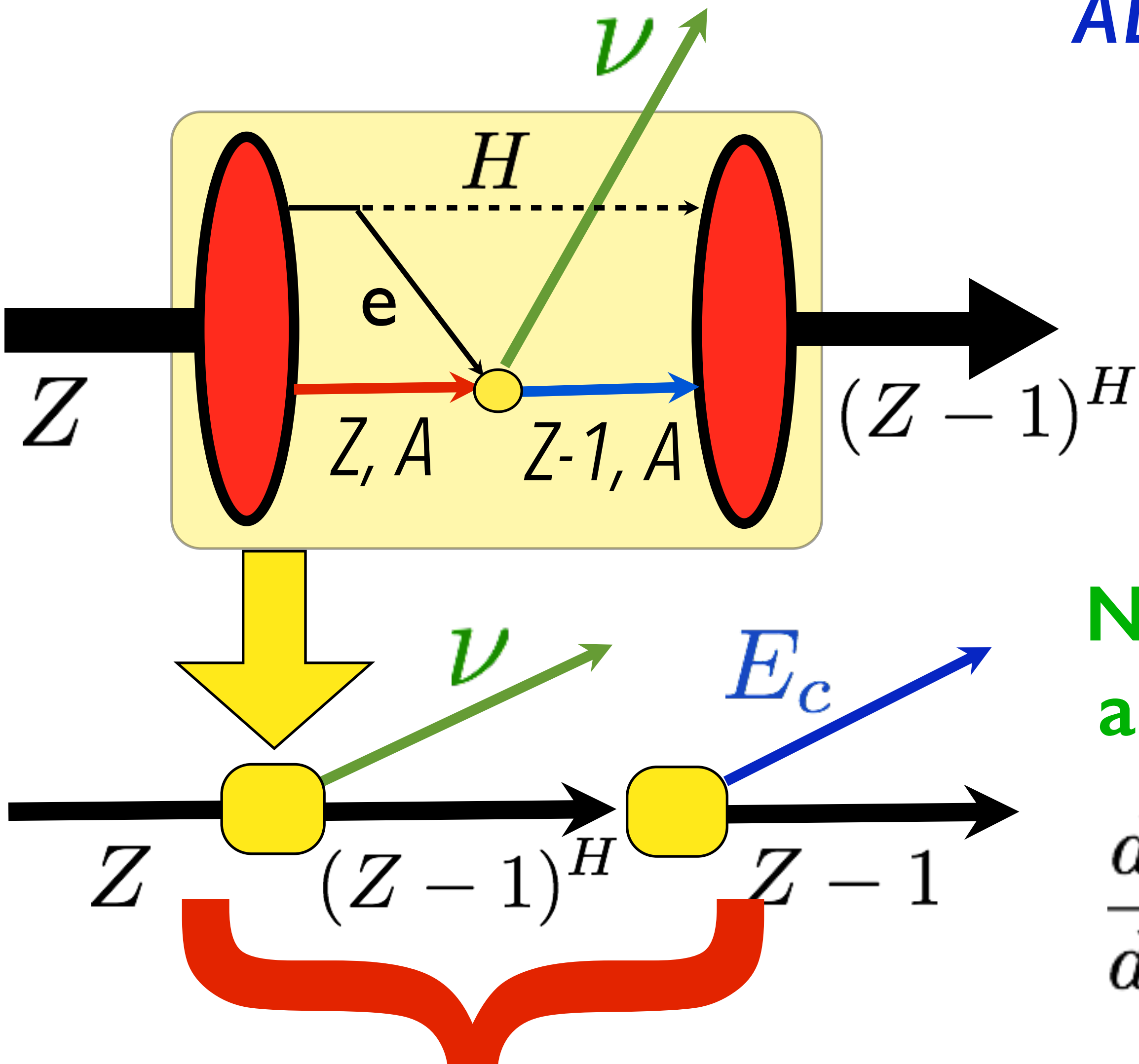
$$Q = m_n - m_p$$

PROCEED

$$\gamma_\mu \left(1 + g_A \gamma_5\right) \quad E_e \sim Q \quad \frac{d\Gamma}{dE_e} \propto E_\nu \, p_\nu$$

"Effective" calorimetric theory,

ADR & Lusignoli (1982)



Q = M[det.,before] - M[det.,after]

(Chem. pure detector)

$$Q = E_\nu + E_c$$

No matter what H was and how it deexcited !

$$\frac{dW}{dE_c} = -\frac{dW}{dE_\nu}\Big|_{E_\nu = Q - E_c}$$

$$\frac{dW}{dE_c} \propto \underbrace{(Q - E_c)}_{E_\nu}\underbrace{\sqrt{(Q - E_c)^2 - m_\nu^2}}_{p_\nu}\sum_H \frac{\varphi_H^2(0)\ \Gamma_H}{(E_c - E_H)^2 + \Gamma_H^2/4}$$

In EC, the Holes are RESONANCES that, if close to the endpoint, enormously enhance the matrix element

$^{163}\mathrm{Ho}$ Q-value ?

- To be consistently measured in each e-capture experiment itself, but …

$$Q[\mathrm{recommended}] = 2555 \pm 16\,\mathrm{eV}$$

$$Q[\mathrm{Penning\,trap}] = 2833(30)_{\mathrm{stat}}(15_{\mathrm{sys}})\,\mathrm{eV}$$

Eliseev et al. PRL 115 (2015) 062501

“Wrong Direction”

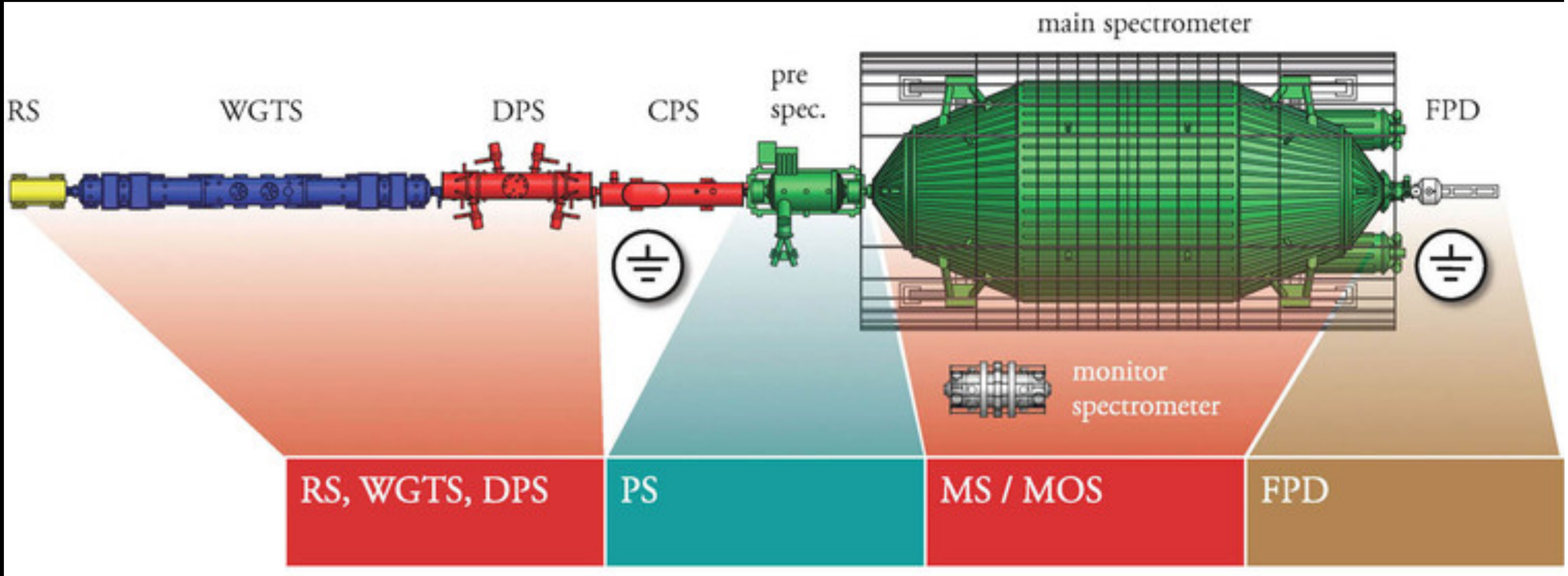
3 current $^{163}Ho \rightarrow ^{163}Dy^{H} + \nu_e$ e-capture EXPERIMENTS

ECHo
https://www.kip.uni-heidelberg.de/echo/

HOLMES
http://artico.mib.infn.it/nucriomib/

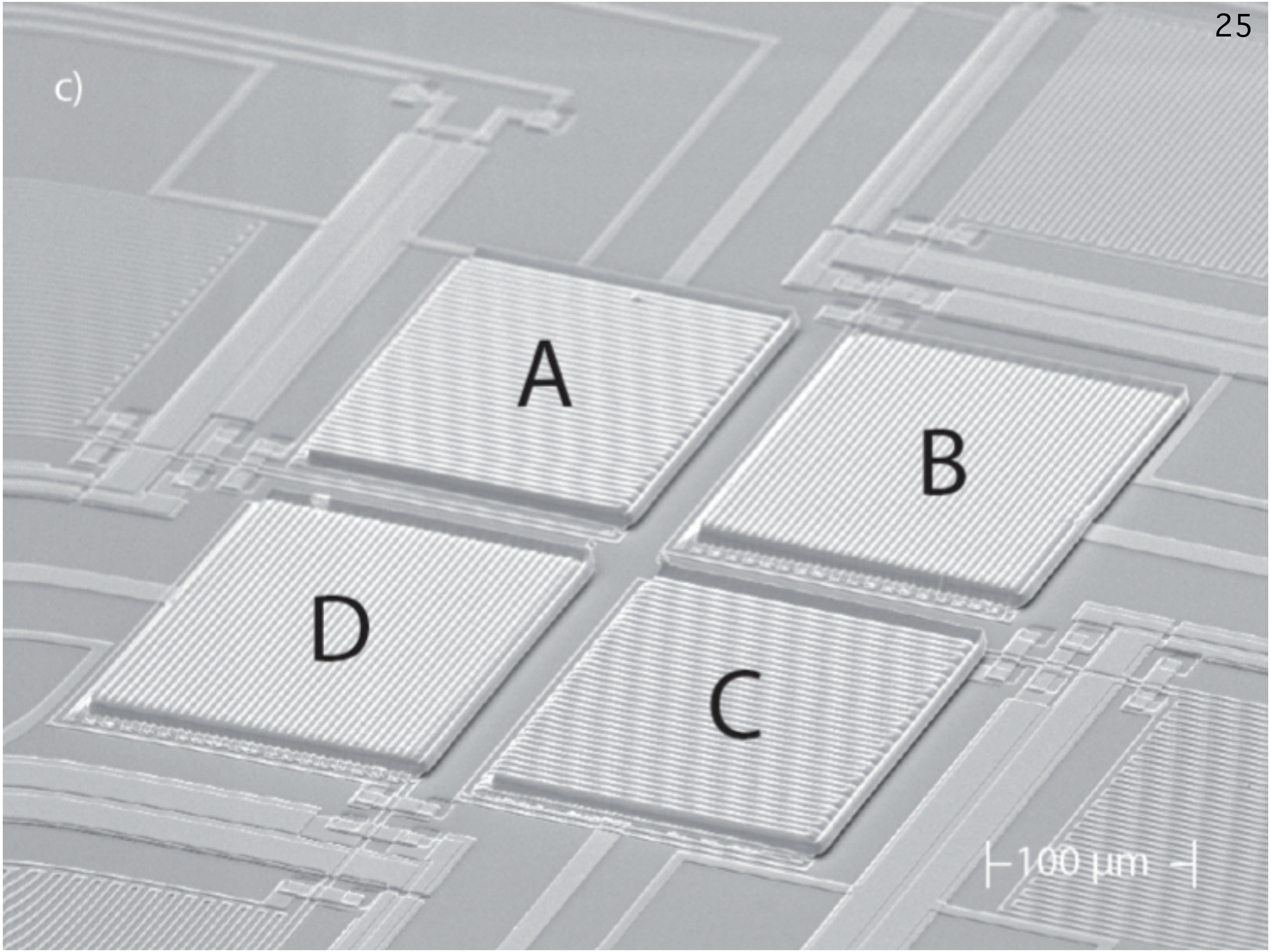
NuMECS
http://p25ext.lanl.gov/~kunde/NuMECS/

β decay KATRIN

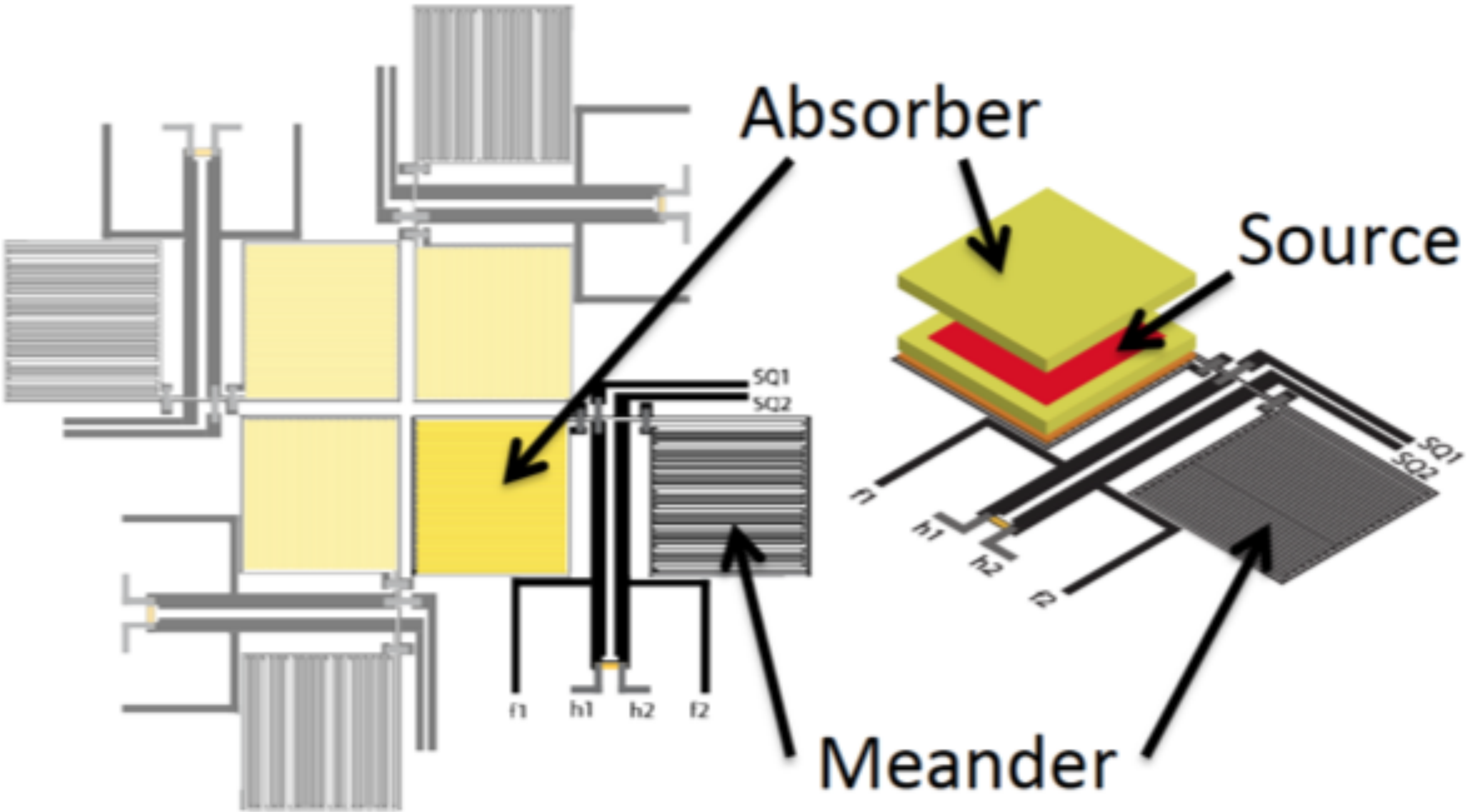


70 m

SHOW AND TELL


c)
A
B
C
D
100 µm

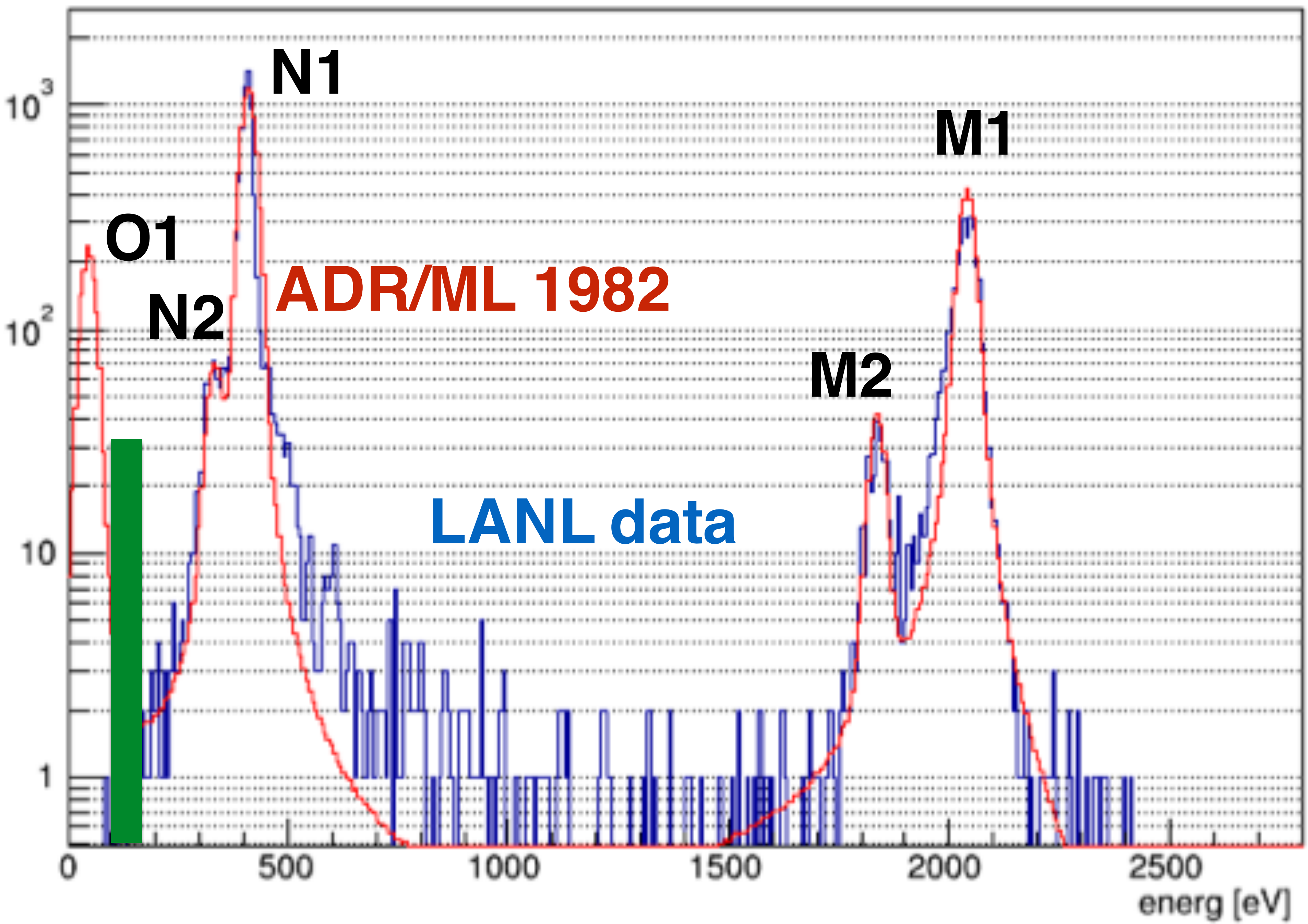
ECHo



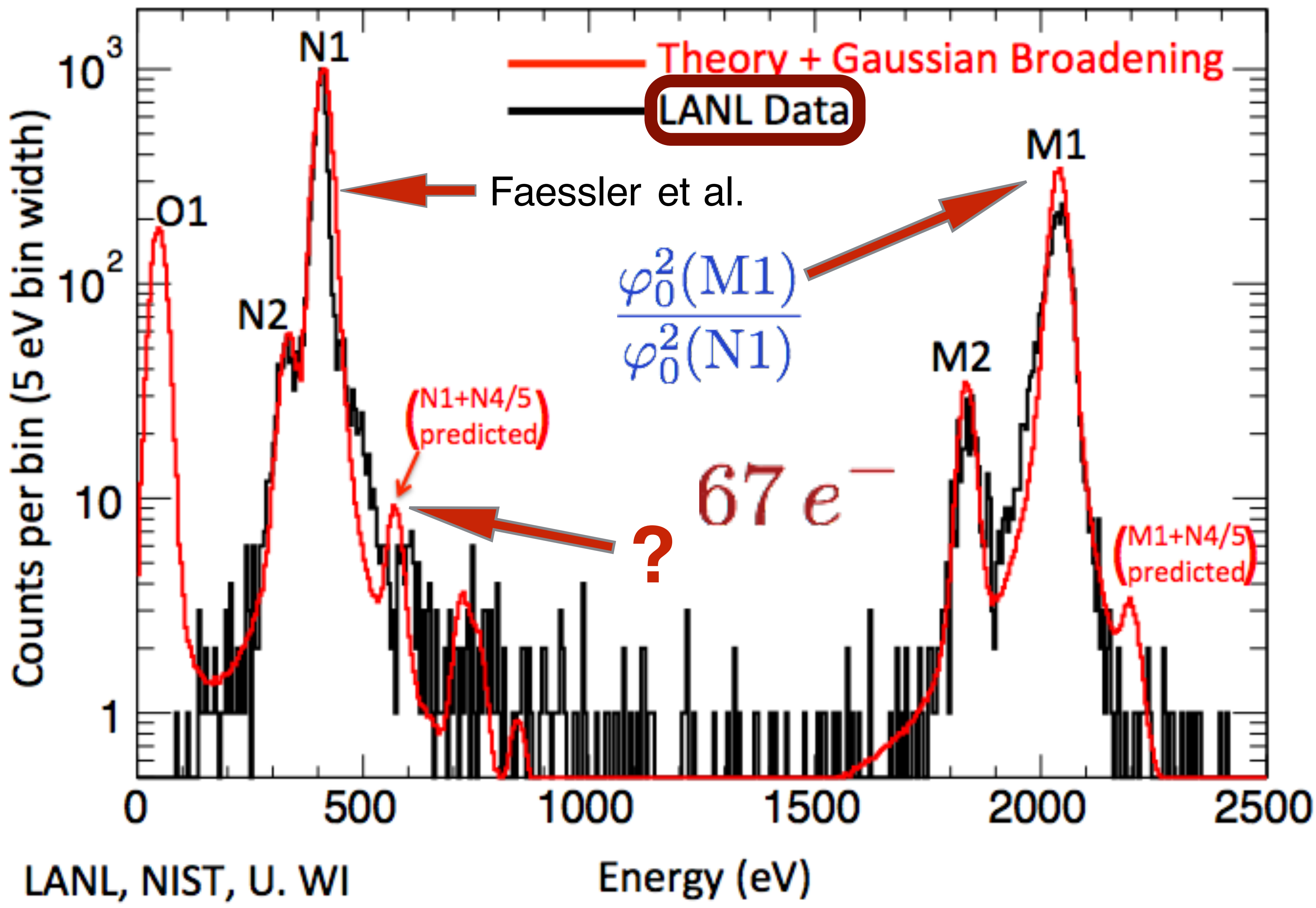
Is the TH

good

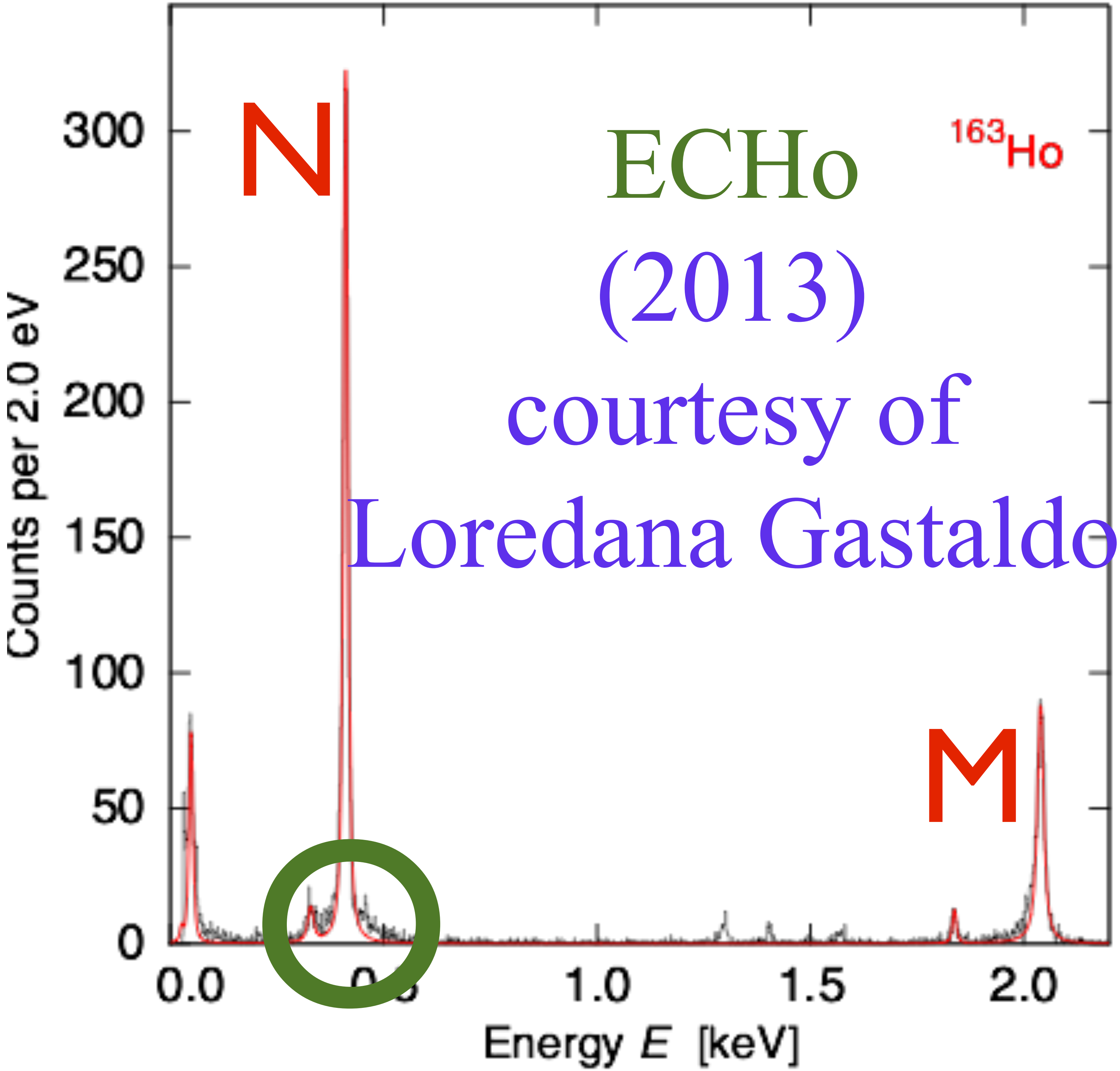
enough ?

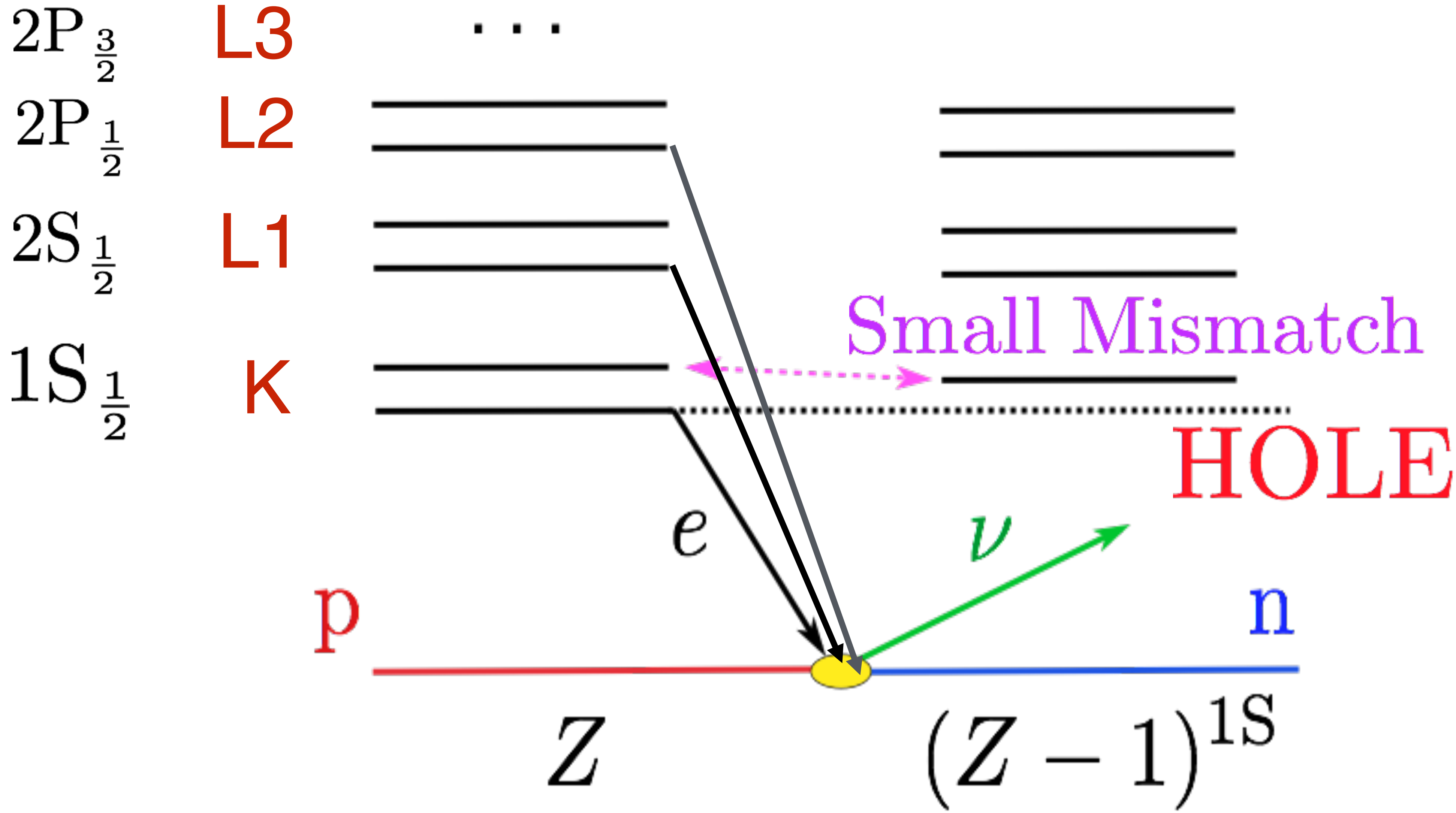


N1
M1
O1
N2
ADR/ML 1982
M2
LANL data
10^3
10^2
10
1
0
500
1000
1500
2000
2500
energ [eV]



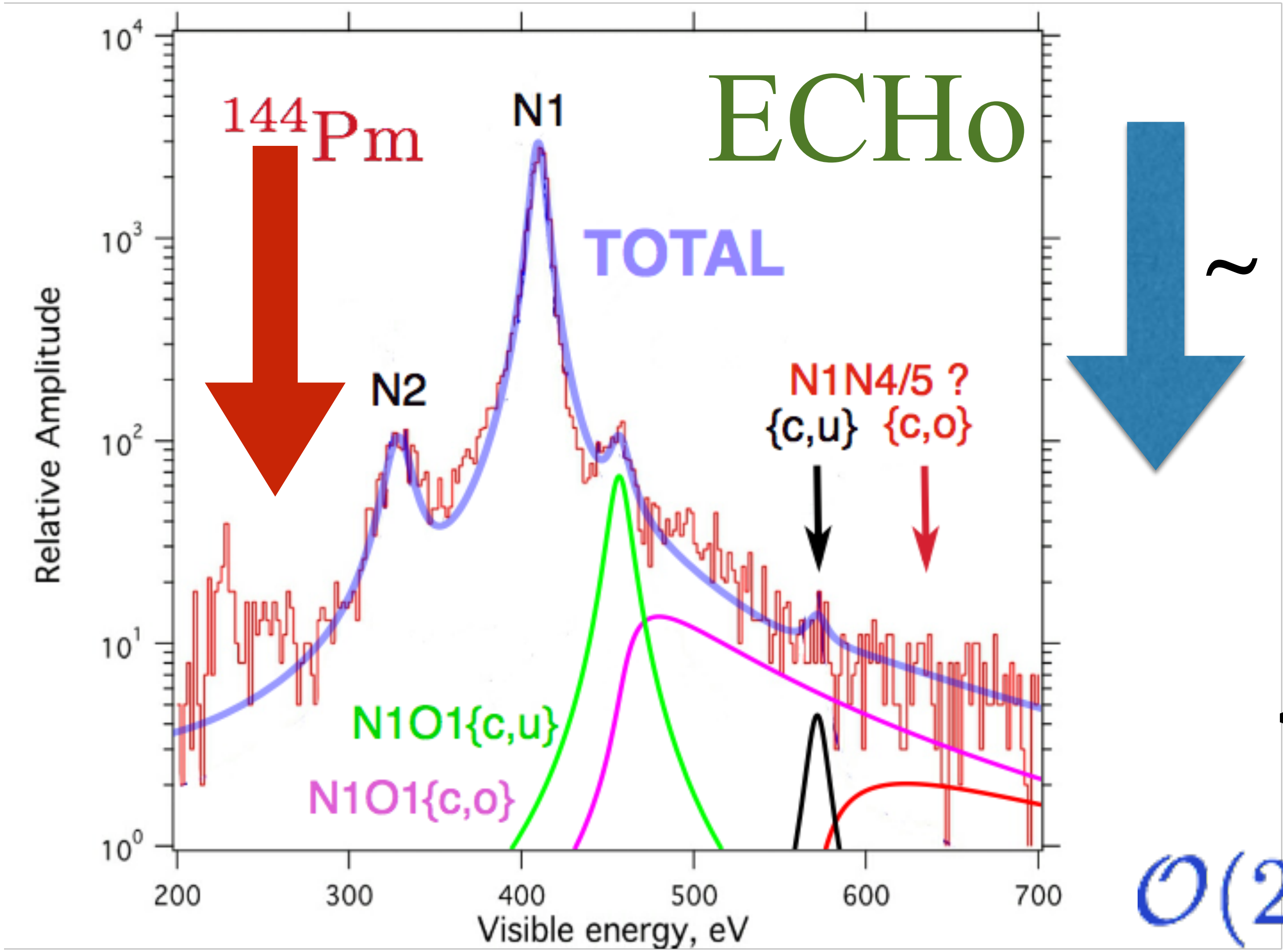
Theory + Gaussian Broadening
LANL Data
N1
O1
N2
Faessler et al.
M1
M2
$\frac{\varphi_0^2(\mathrm{M1})}{\varphi_0^2(\mathrm{N1})}$
(N1+N4/5 predicted)
$67\,e^-$
?
(M1+N4/5 predicted)
Counts per bin (5 eV bin width)
Energy (eV)
1
10
10^2
10^3
0
500
1000
1500
2000
2500
LANL, NIST, U. WI


N
M
ECHo
(2013)
courtesy of
Loredana Gastaldo
^{163}Ho
Counts per 2.0 eV
Energy E [keV]
0
50
100
150
200
250
300
0.0
1.0
1.5
2.0



Requires $\varphi_{\rm H}(0) \neq 0$ $\quad n\,l_j = n\,S_{1/2}$

Small-component $\mathcal{O}(\alpha\,Z)$ mixing $\quad n\,l_j = n\,P_{1/2} \leftrightarrow n\,S_{1/2}$



~ %

Maurizio Lusignoli + ADR

(à la 1967 Intemann & Pollock)

{ , }

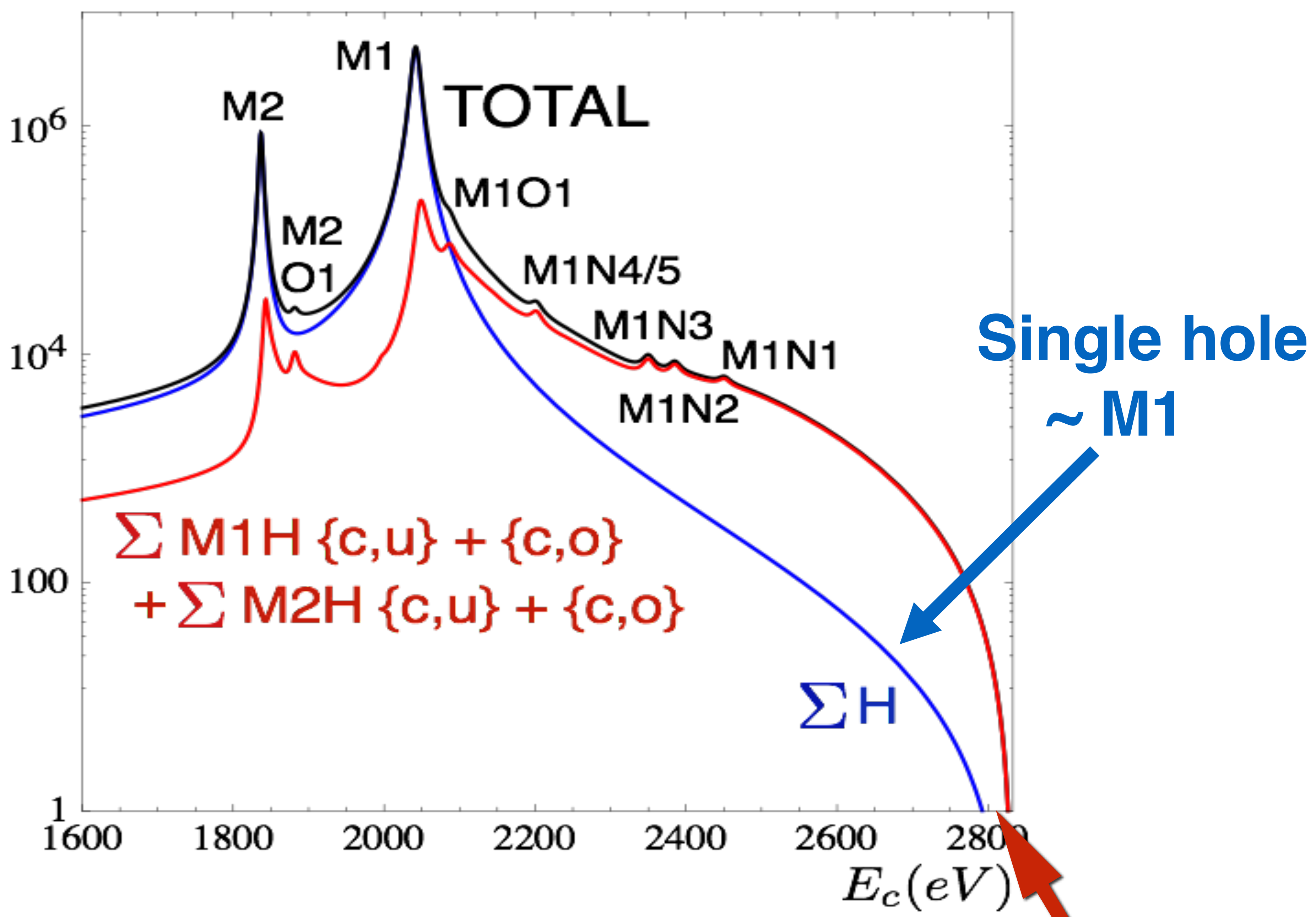
$\mathcal{O}(2)$ Massage

{c,u} **1 e captured; 1 e up to unoccupied level**

{c,o} **1 e captured; 1 e off to the continuum**

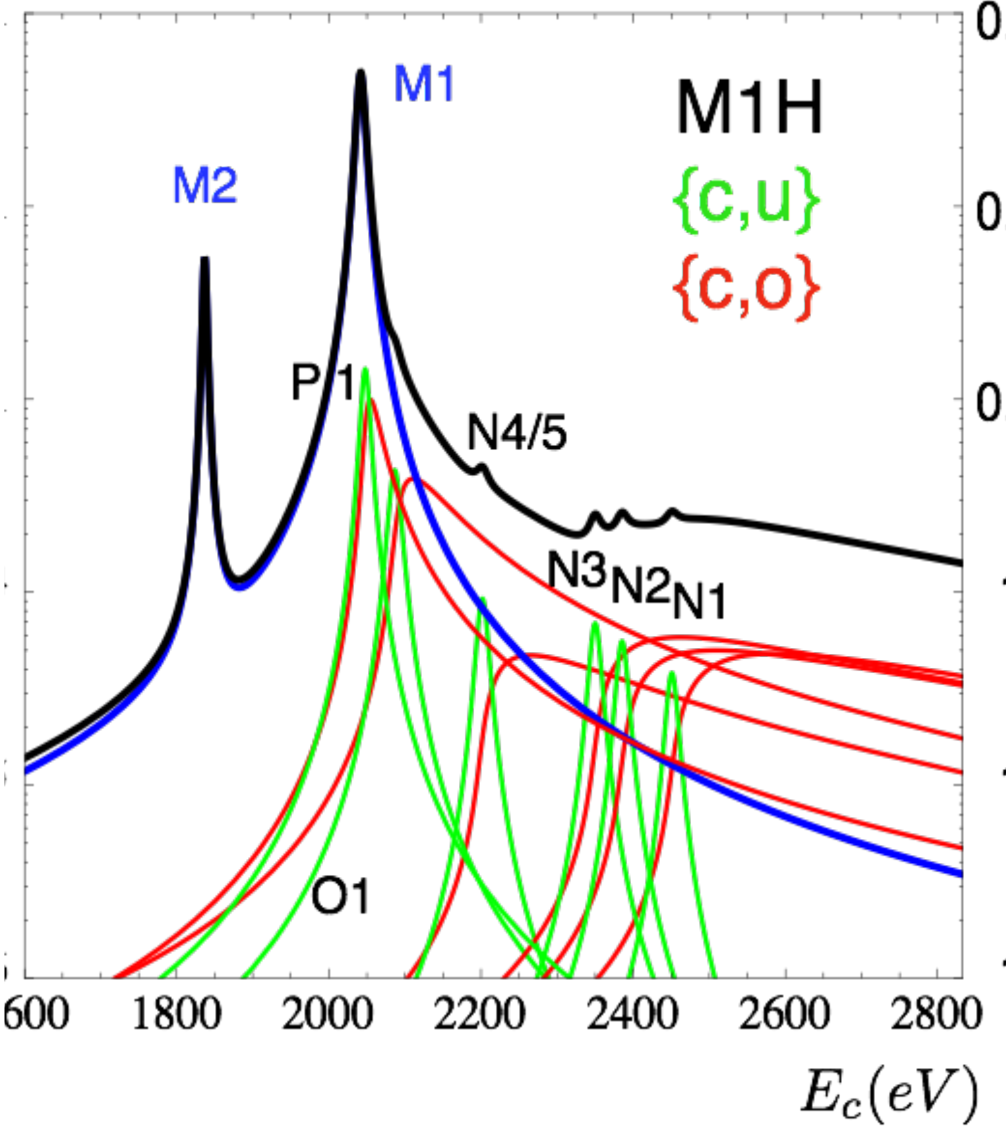
Electron ShakeOff previously FORGOTTEN!!

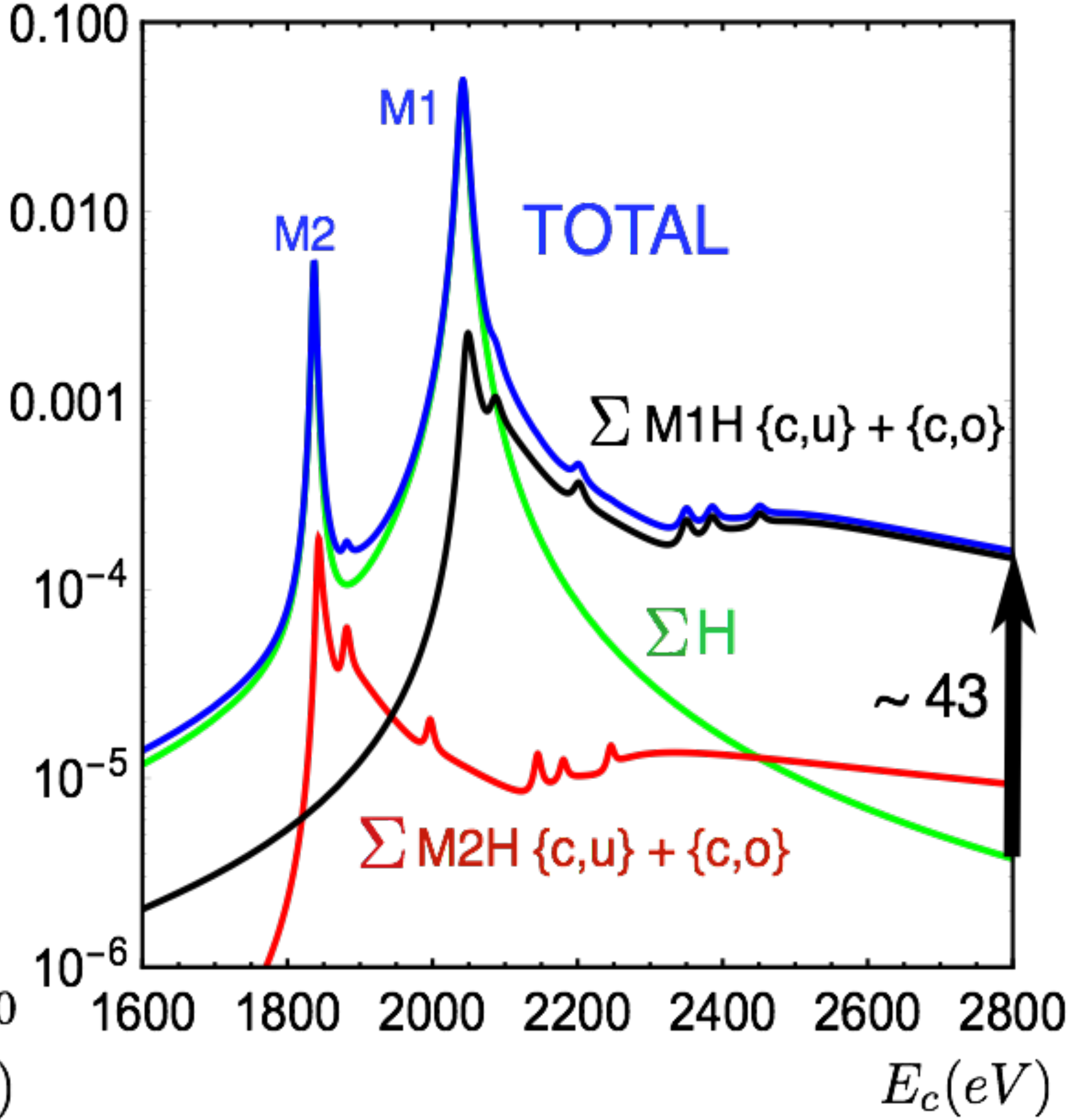
Are double holes an endpoint's nightmare ?

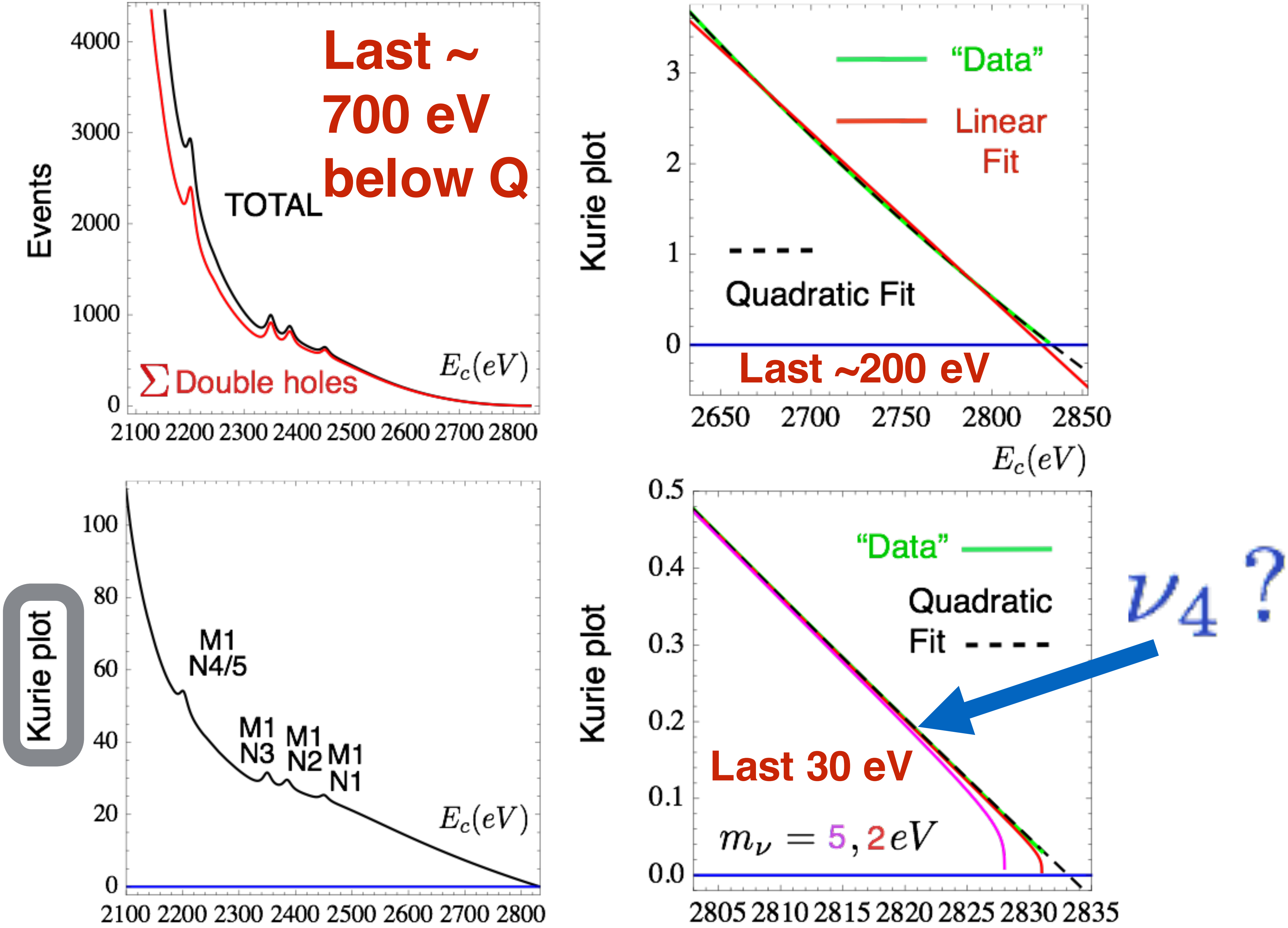


$$E_\nu\, p_\nu = (Q - E_c)\sqrt{(Q - E_c)^2 - m_\nu^2}$$

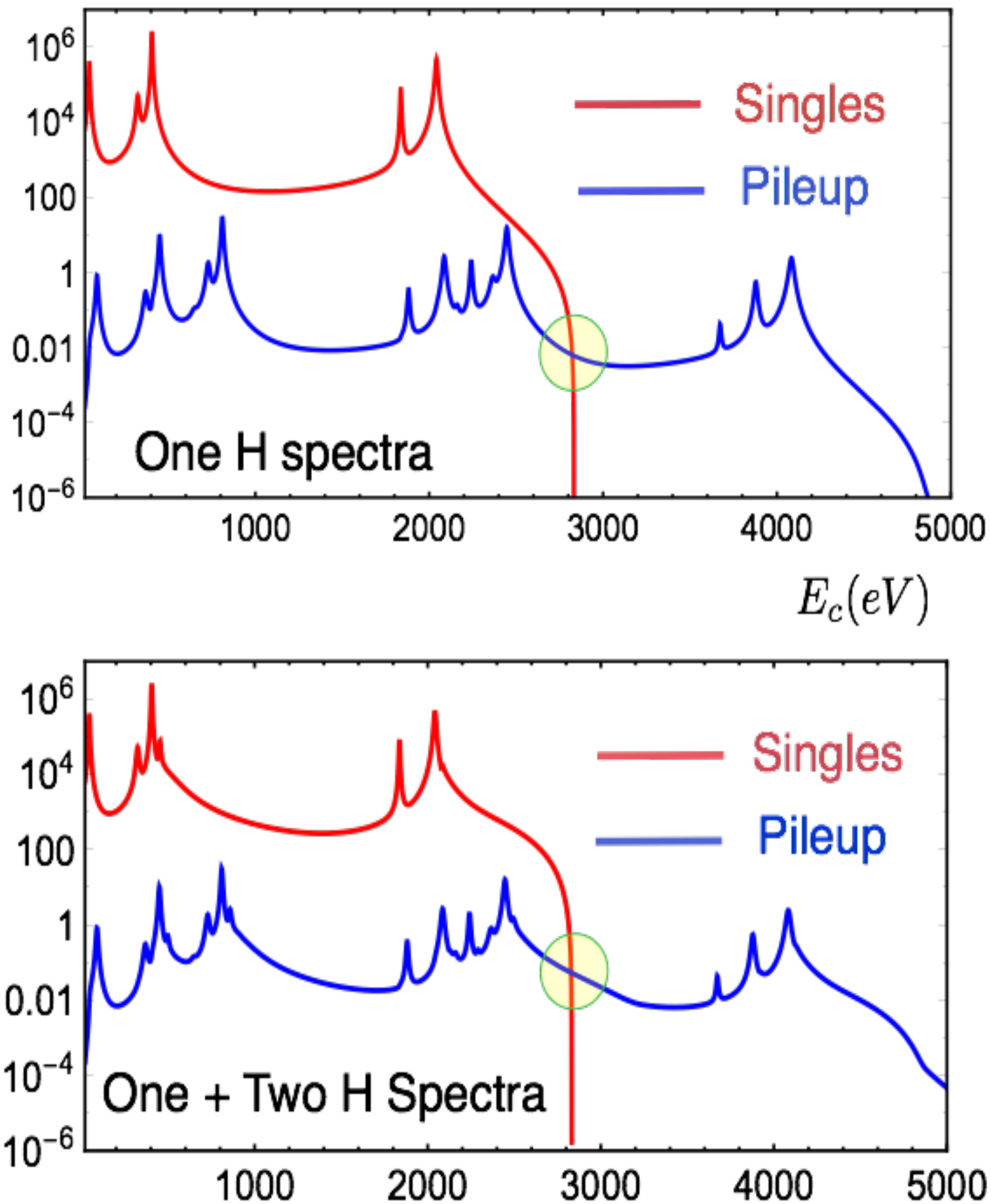
Take out E_ν p_ν factor

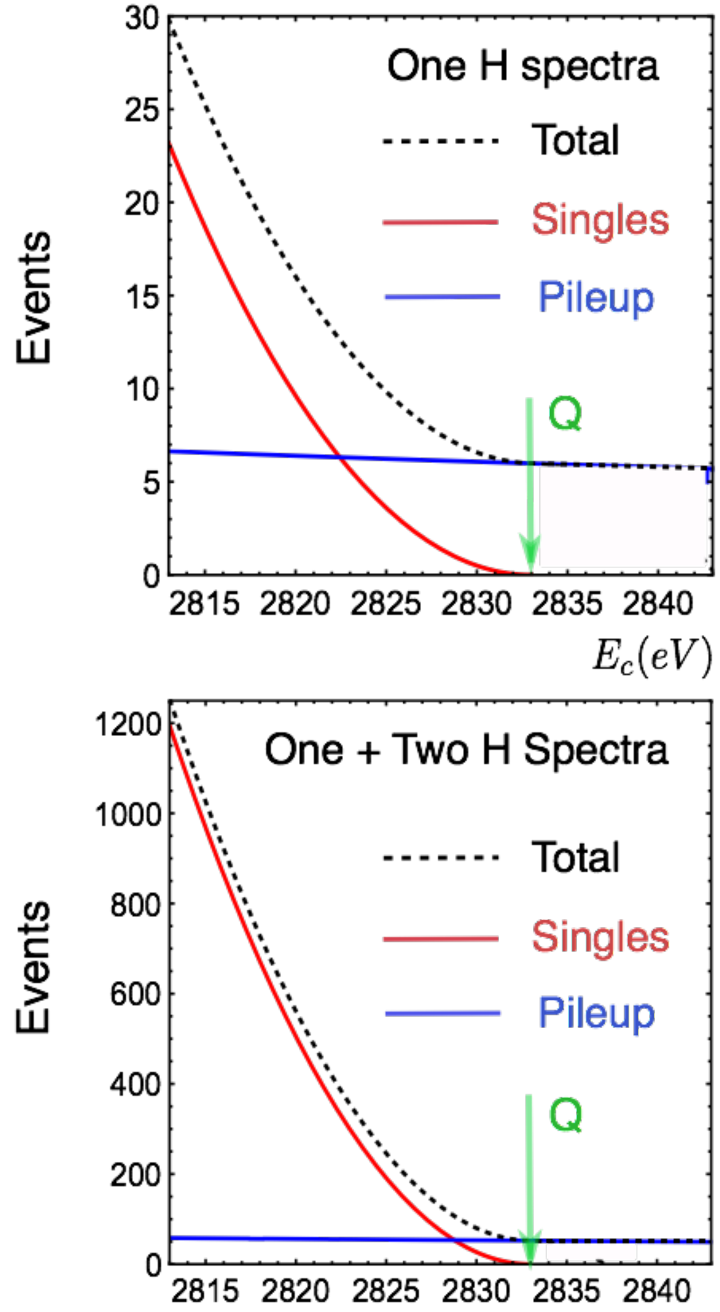






Last ~
700 eV
below Q
TOTAL
Events
∑Double holes
$E_c(eV)$
4000
3000
2000
1000
0
2100 2200 2300 2400 2500 2600 2700 2800
"Data"
Linear
Fit
Quadratic Fit
Kurie plot
Last ~200 eV
3
2
1
0
2650 2700 2750 2800 2850
$E_c(eV)$
Kurie plot
M1
N4/5
M1
N3
M1
N2
M1
N1
$E_c(eV)$
100
80
60
40
20
0
2100 2200 2300 2400 2500 2600 2700 2800
Kurie plot
"Data"
Quadratic
Fit
ν_4 ?
Last 30 eV
$m_\nu = 5, 2 eV$
0.5
0.4
0.3
0.2
0.1
0.0
2805 2810 2815 2820 2825 2830 2835





x ~ 6 IMPROVEMENT

CONCLUSIONS

Double Holes not a problem but possibly... a BLESSING:

~ 40 statistics, ~ 1/6 pileup

Theory PRELIMINARY!

Experiments will improve.

With their help, so should TH

Parameters of our universe chosen
$\ni$ ν Physics ♣♣♣

$\Delta m^2_{ij},\ \theta ij,\ \delta?$

$E(CRs),\ h(atms);\ \rho(atms),\ \tau(\mu),\ \tau(\pi^{\pm})$

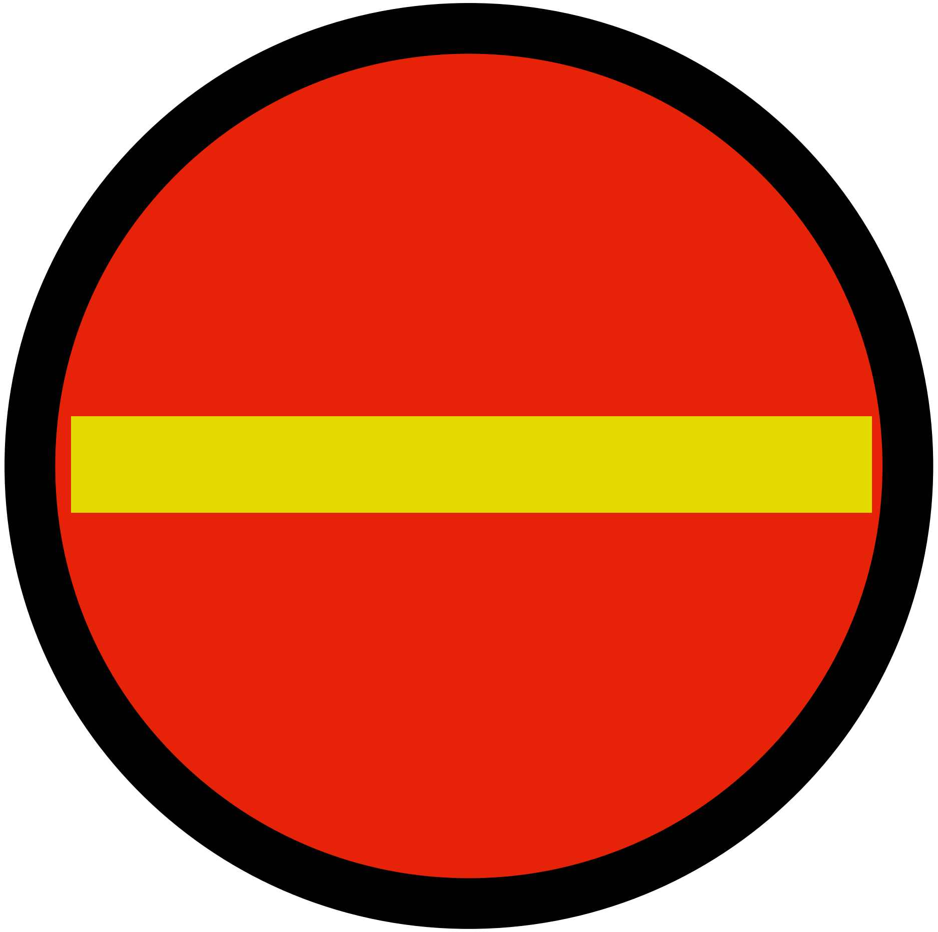
$R_{\odot},\ \rho_{\odot},\ R_{\otimes},\ \rho_{\otimes}\ \ \exists\ Reactors$ ♣♣♣

EC measurements of e-neutrino "mass" ??

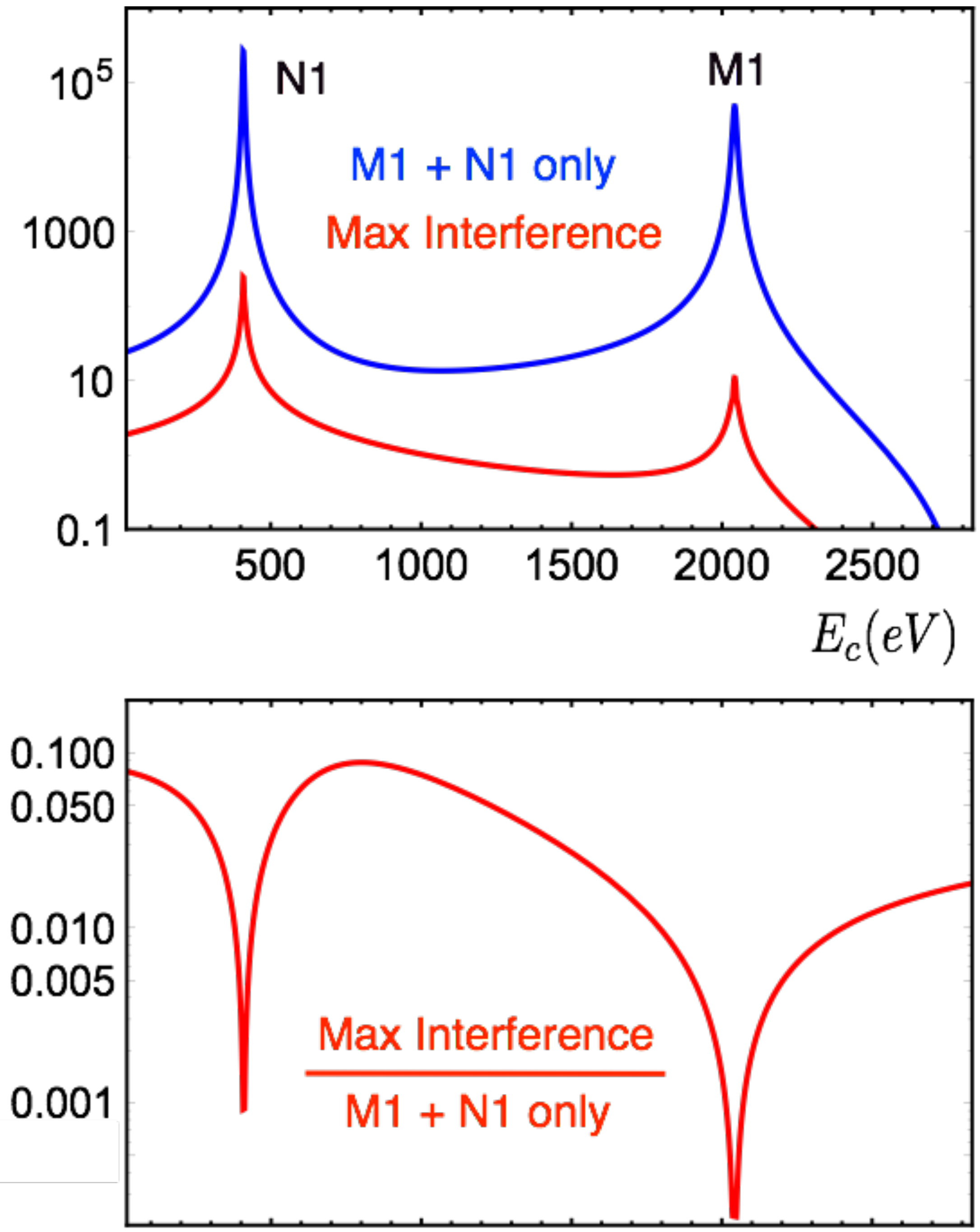
Microcalorimeters, etc !!

$\exists\ Hope\ for\ m(\nu_e)\ experiments$

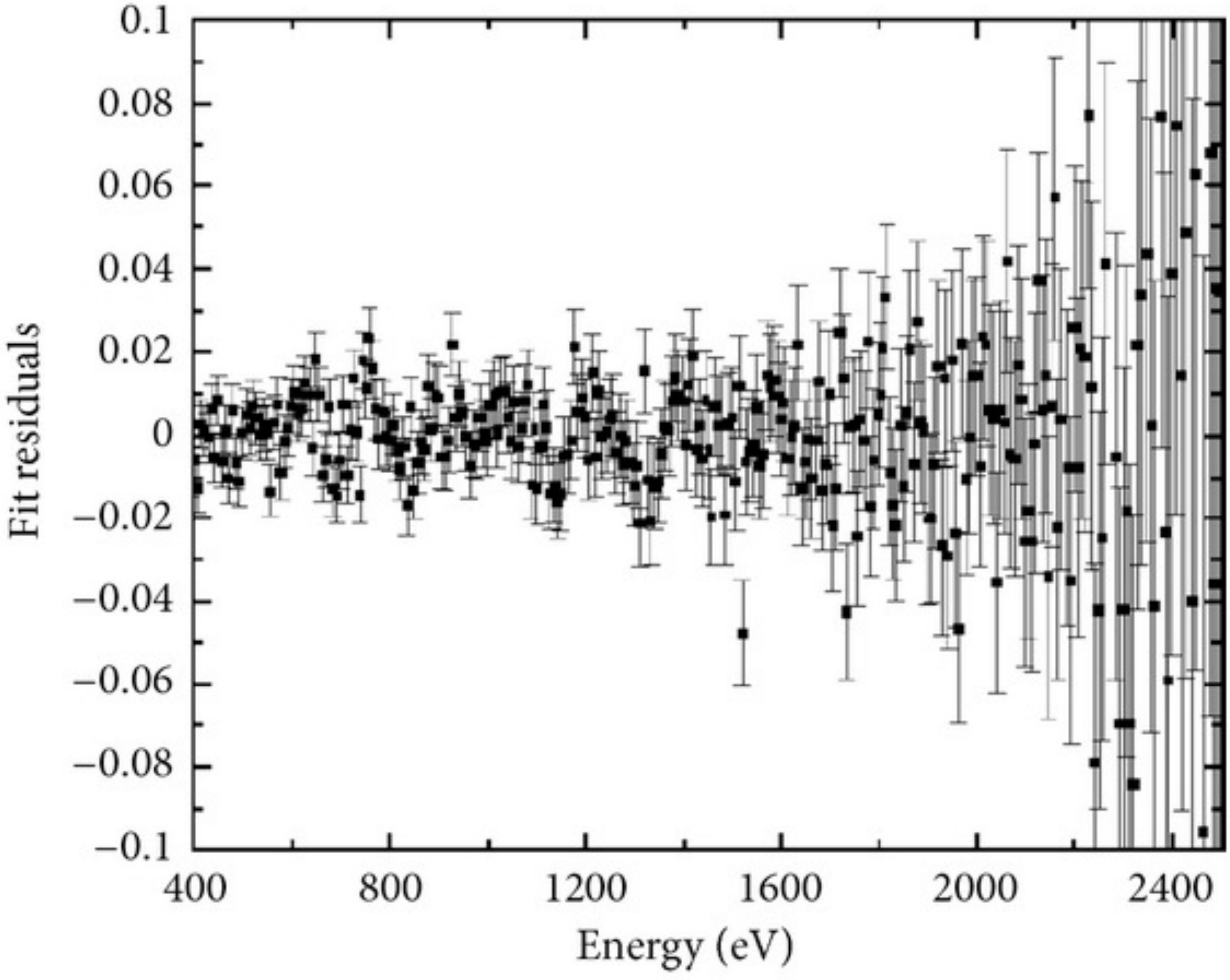
Holmium From Latin "Holmia": Stockholm.



ELECTRO-
THERMAL LINK

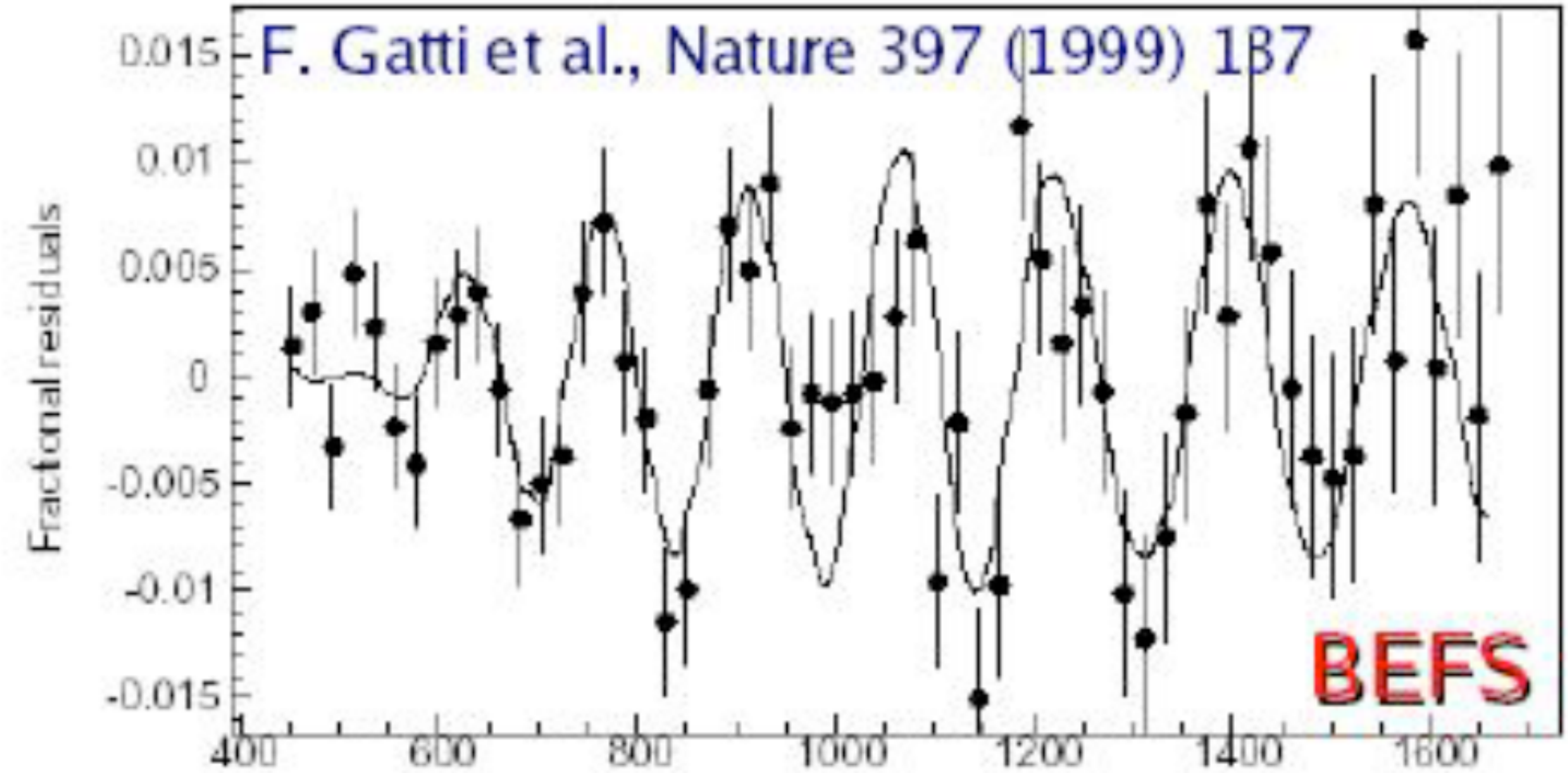


N1
M1
M1 + N1 only
Max Interference
10^5
1000
10
0.1
500
1000
1500
2000
2500
$E_c(eV)$
0.100
0.050
0.010
0.005
0.001
Max Interference
M1 + N1 only

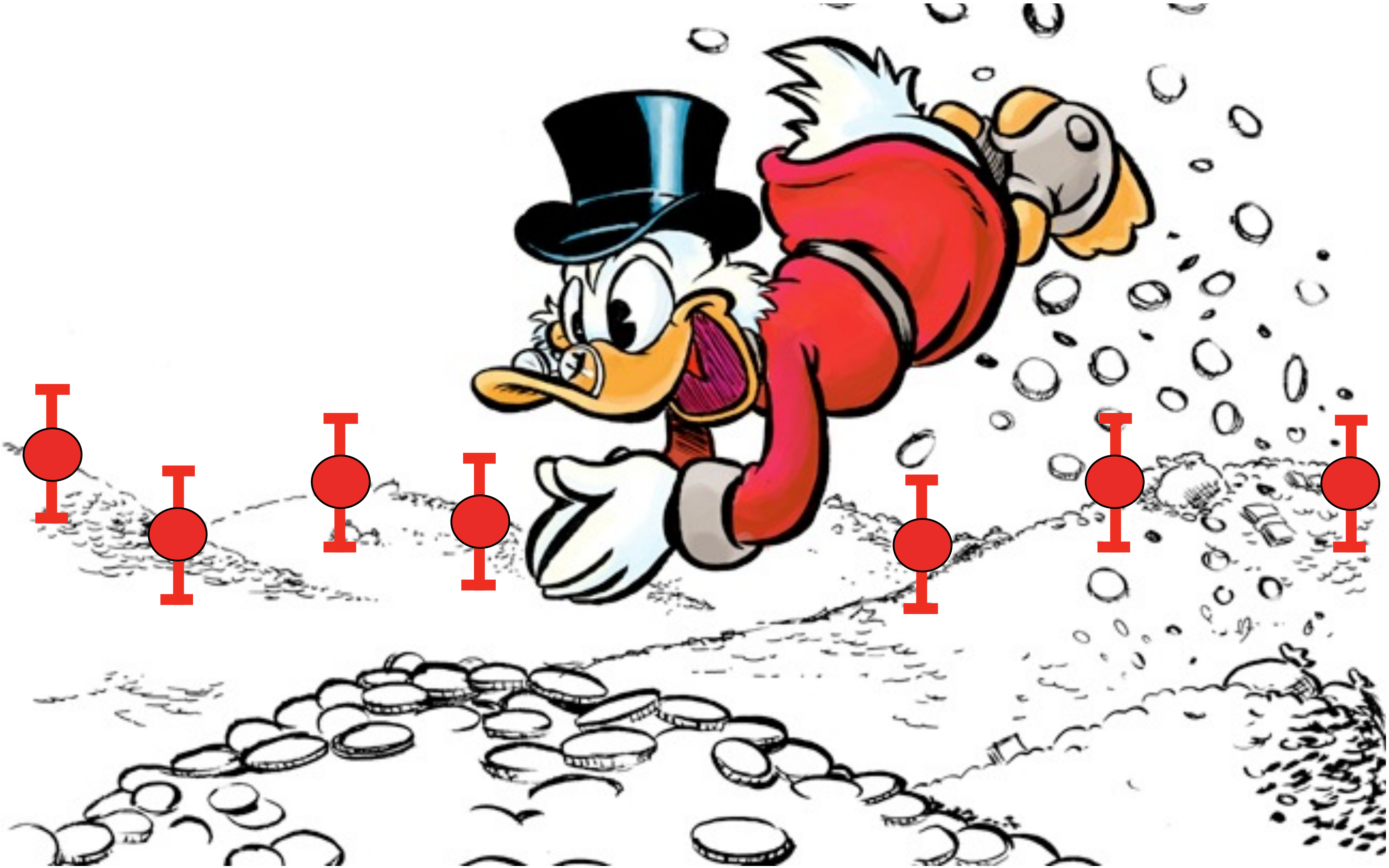


0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
Fit residuals
400
800
1200
1600
2000
2400
Energy (eV)

Enlarged bins



??????????????????????



Beta-Environmental Fine Structure (BEFS)

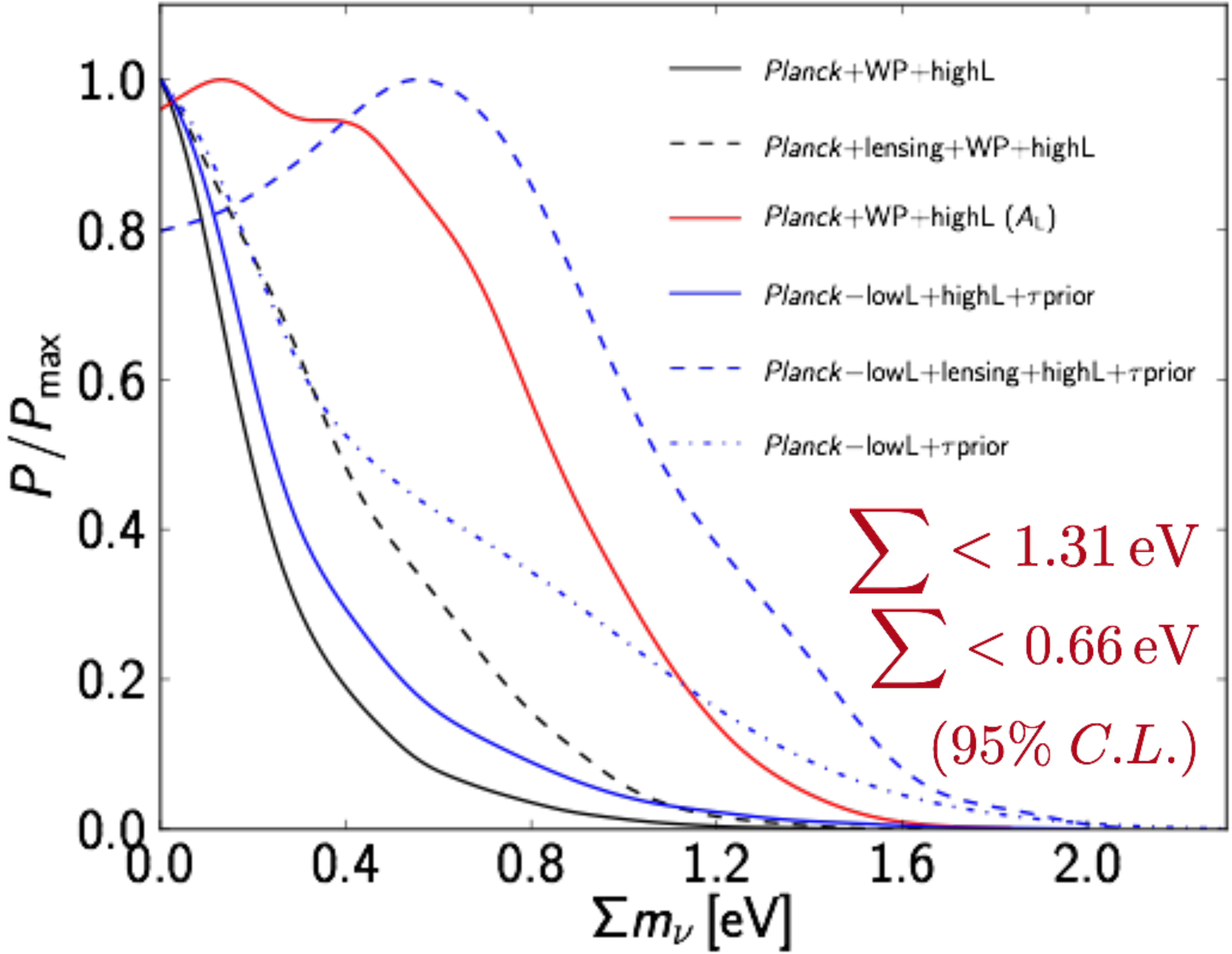
OSCILLATIONS

$\sum m$ limits depend on M-Hierarchy

$$\sum_i m_{\nu_i} > 0.06 \text{ eV},$$ "NORMAL"

$$\sum_i m_{\nu_i} > 0.1 \text{ eV},$$ "INVERTED"

e.g. Gonzalez-García et al.



Planck+WP+highL
Planck+lensing+WP+highL
Planck+WP+highL (A_L)
Planck−lowL+highL+τprior
Planck−lowL+lensing+highL+τprior
Planck−lowL+τprior
$\sum < 1.31\,\mathrm{eV}$
$\sum < 0.66\,\mathrm{eV}$
(95% C.L.)
P/P_{max}
Σm_ν [eV]
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.4
0.8
1.2
1.6
2.0

In EC, the X-rays are

RESONANCES

that enormously

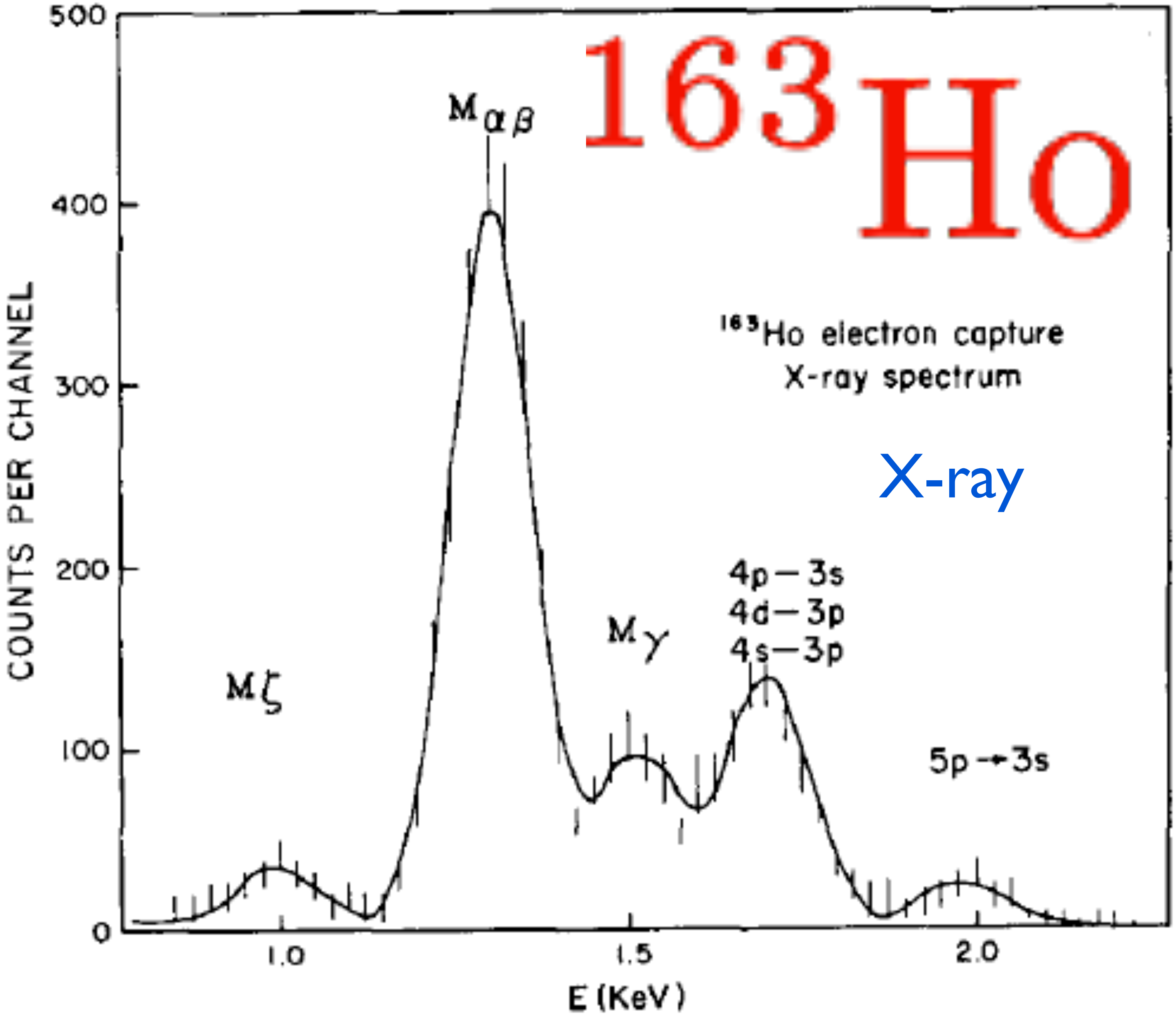
enhance the

matrix element

Φ is 3 body as in β decay

in all useful cases

Bennett et al. 1981



...
NOT ATO MIC PHY CISI STS

$^{163}_{67}\mathrm{Ho}$

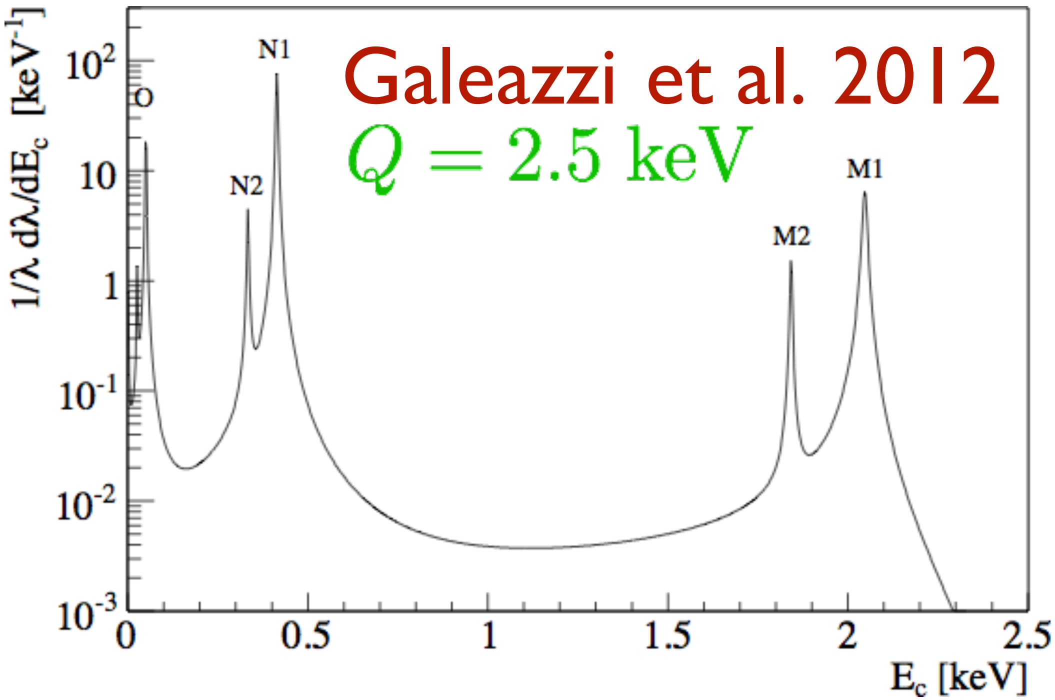
$$Q = 2.3 \text{ to } 2.8\,\mathrm{keV}$$

$$Q = 2.58 \pm 0.10\,\mathrm{keV};\ \mathrm{T}_{1/2} = (7 \pm 2)\ 10^3\ \mathrm{y}$$

Anderson et al. 1982

$$Q = 2.30 \pm 0.15\,\mathrm{keV};\ \mathrm{T}_{1/2} = 900\ {}^{+500}_{-200}\ \mathrm{y}$$

Yasumi et al. 1982



$K(n = 1),\ L(n = 2)$

Capture forbidden

$M_1\,(3S_{1/2}),\ M_2\,(3P_{1/2})$

$N_1\,(4S_{1/2}),\ N_2\,(4P_{1/2})$

etc allowed

Bennett et al. 1981

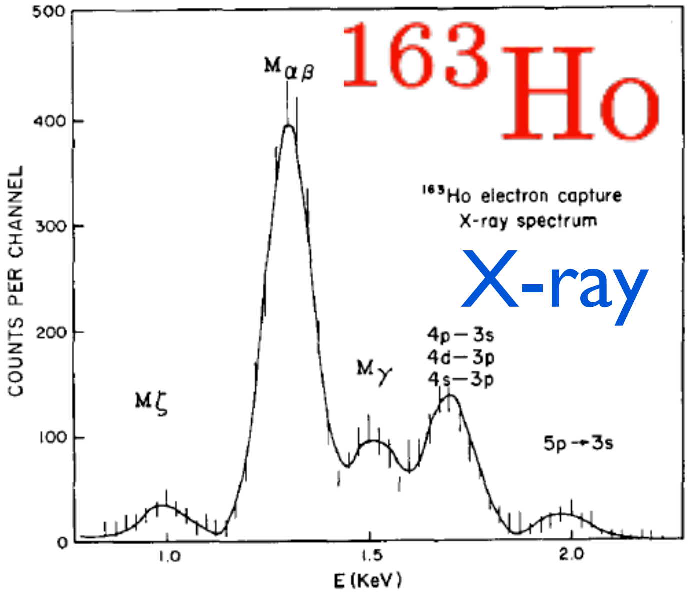
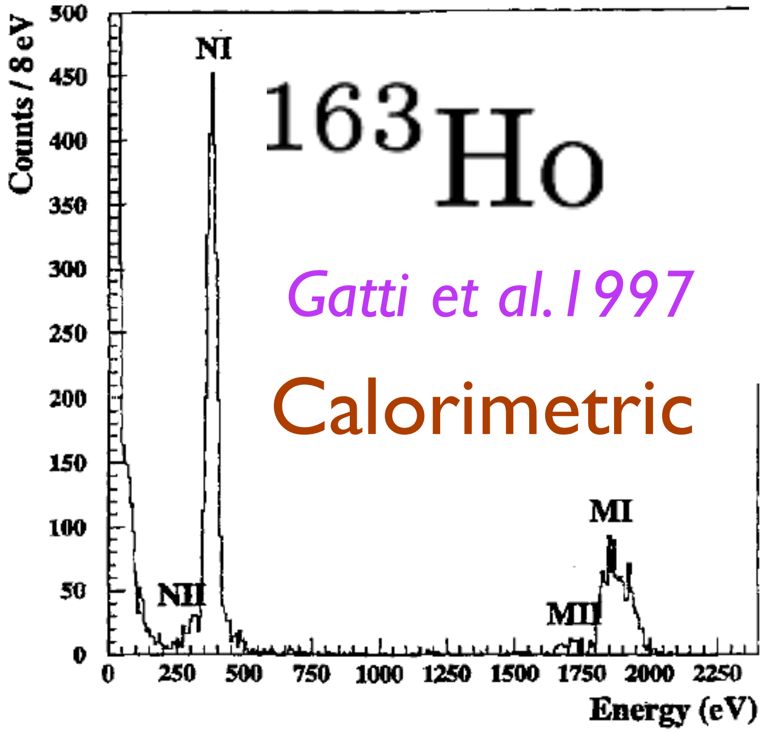
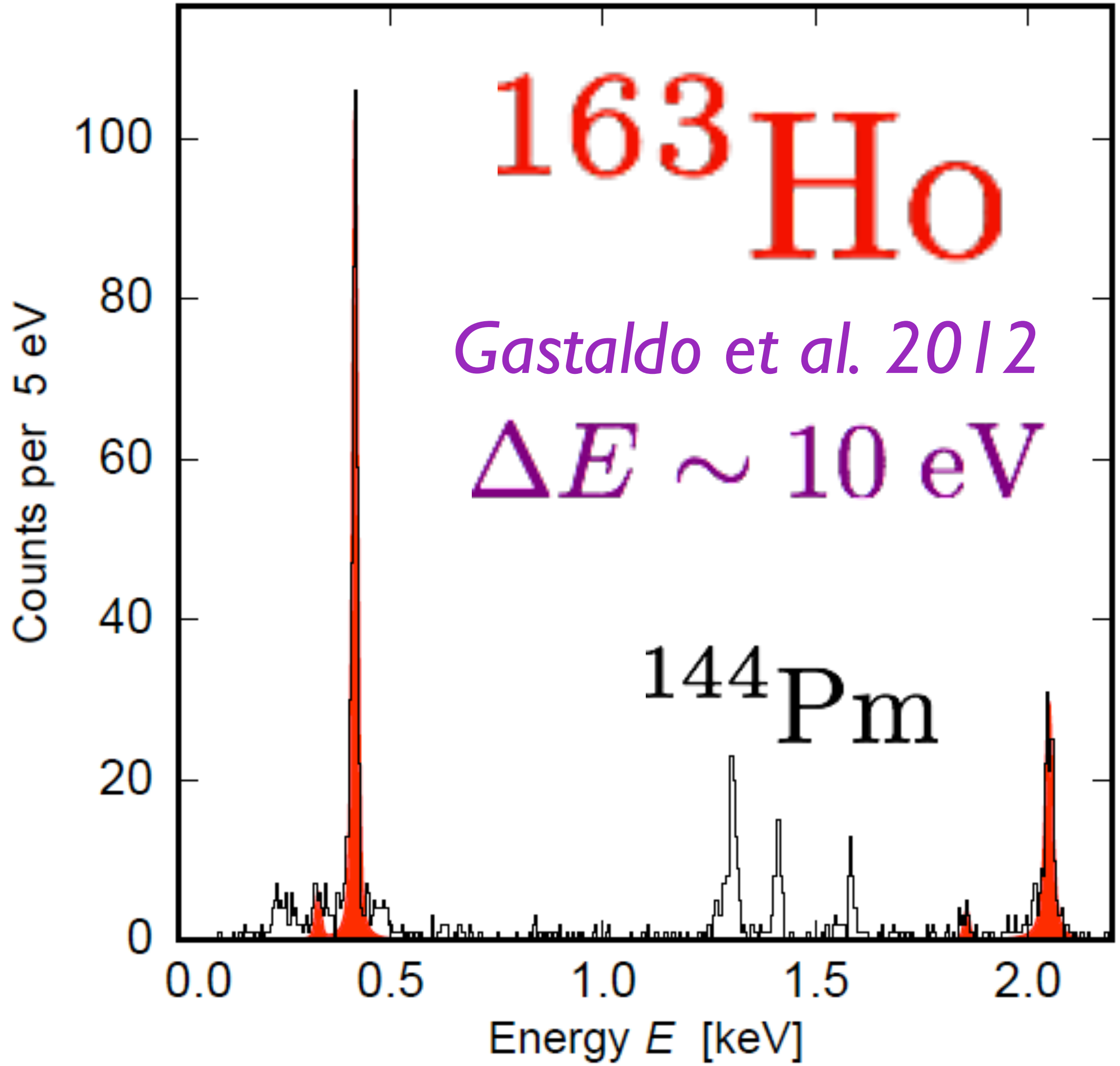


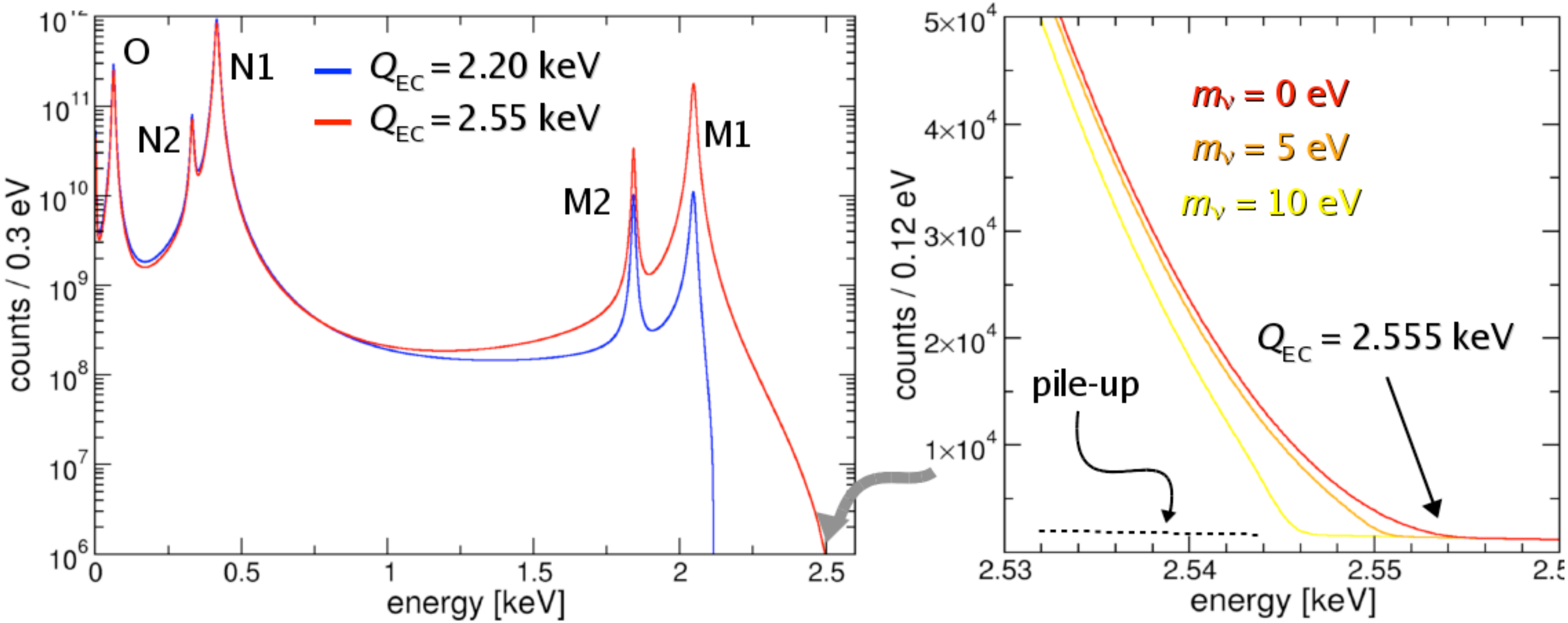
Fig. 1. The X-ray spectrum observed following decay of ^{163}Ho. Lines are labeled by either Siegbahn notation or the transition involved.



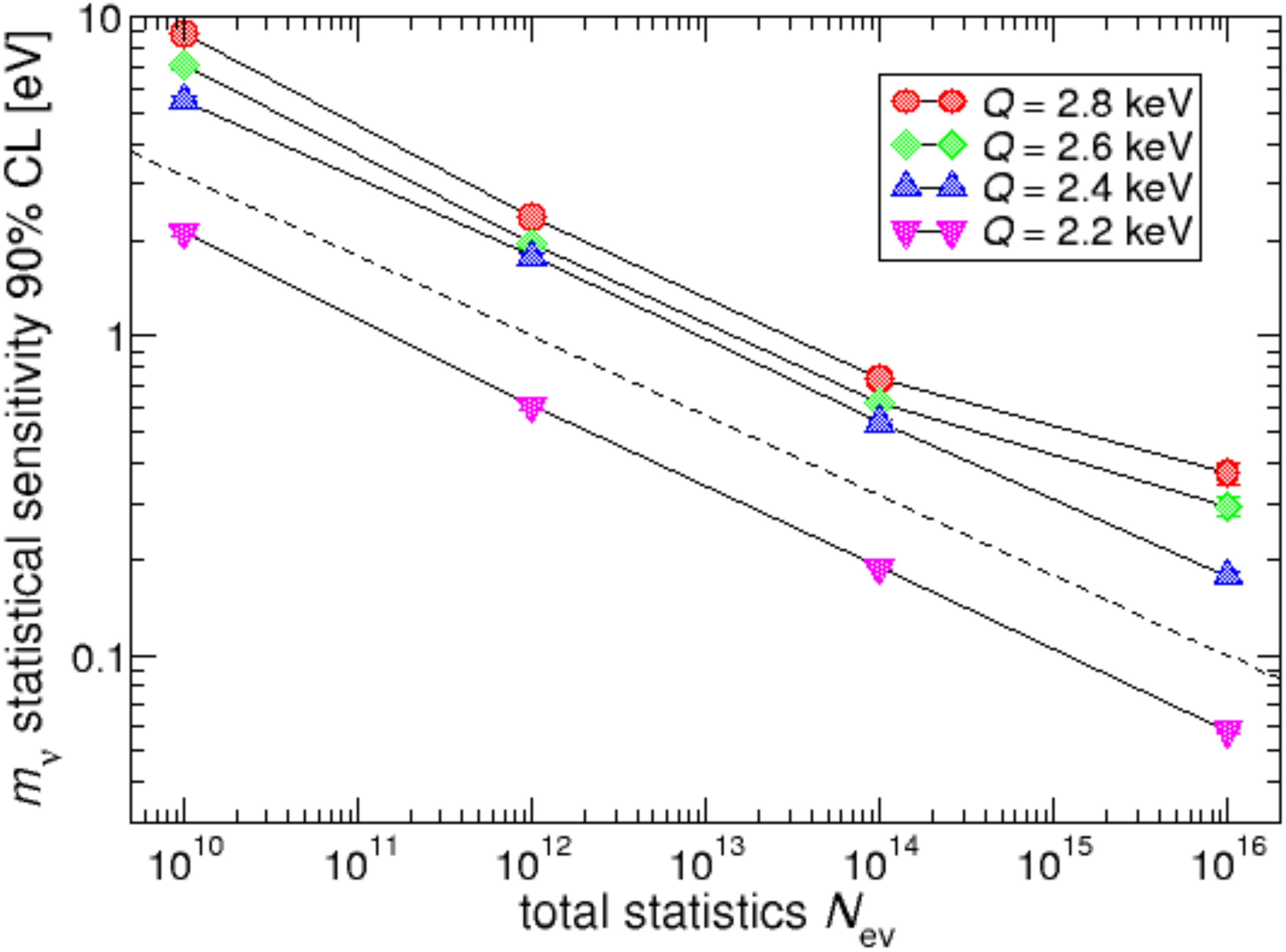


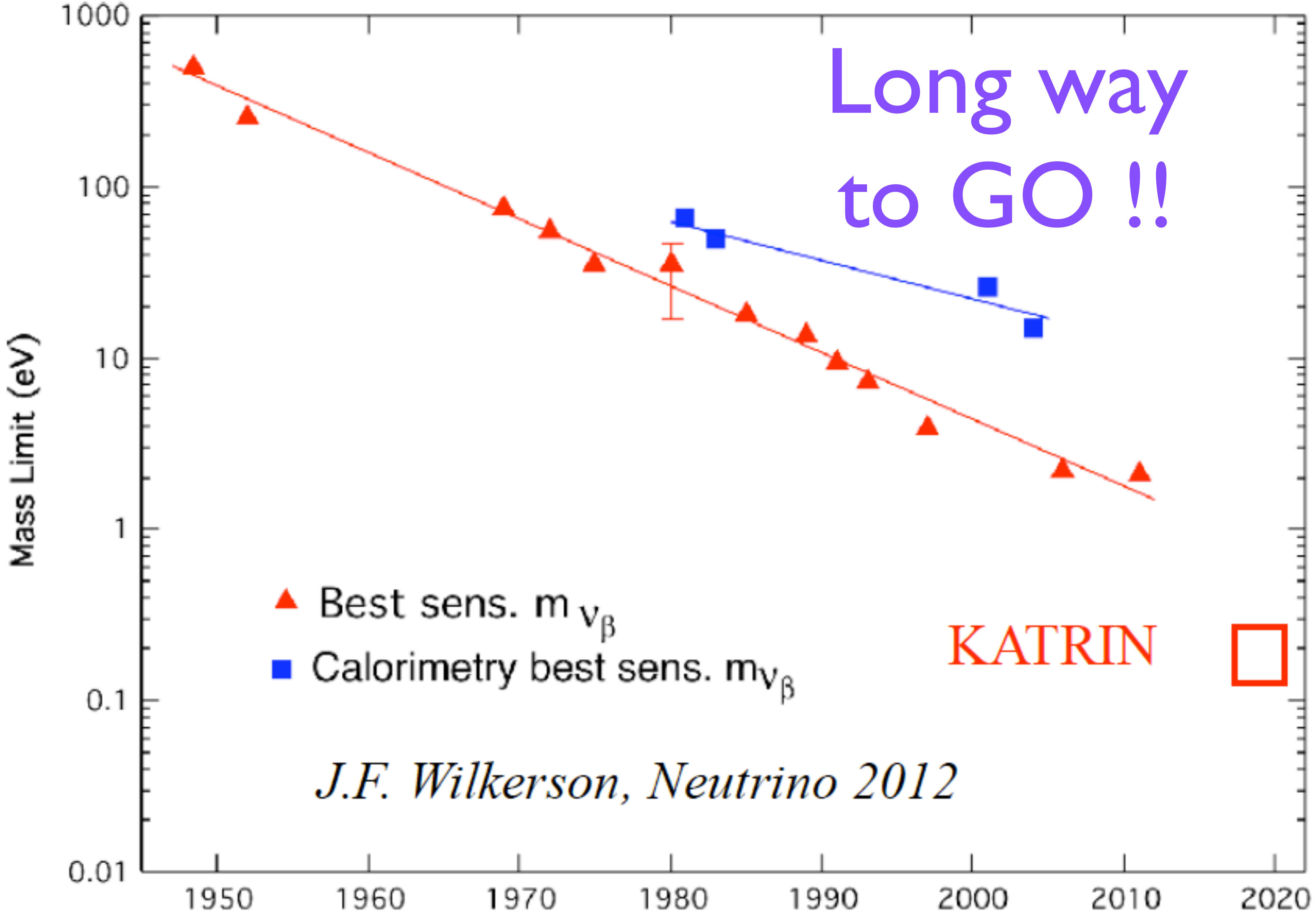
ECHo Calorimetry, source from ISOLDE

HOLMES


O
N1
N2
M2
M1
Q_{EC} = 2.20 keV
Q_{EC} = 2.55 keV
counts / 0.3 eV
energy [keV]
m_ν = 0 eV
m_ν = 5 eV
m_ν = 10 eV
Q_{EC} = 2.555 keV
pile-up
counts / 0.12 eV
energy [keV]

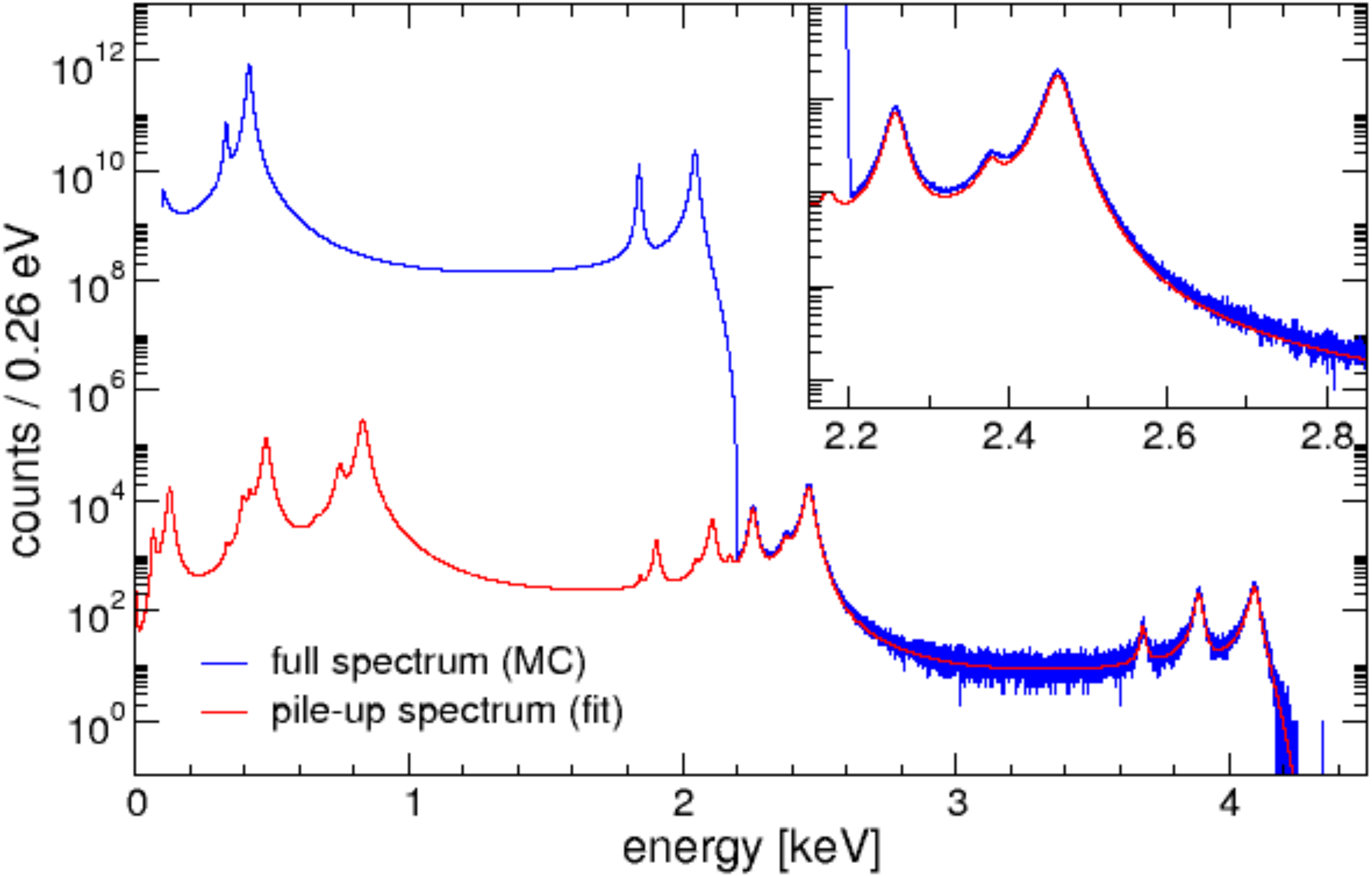
HOLMES


10
1
0.1
m_ν statistical sensitivity 90% CL [eV]
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
total statistics N_{ev}
Q = 2.8 keV
Q = 2.6 keV
Q = 2.4 keV
Q = 2.2 keV

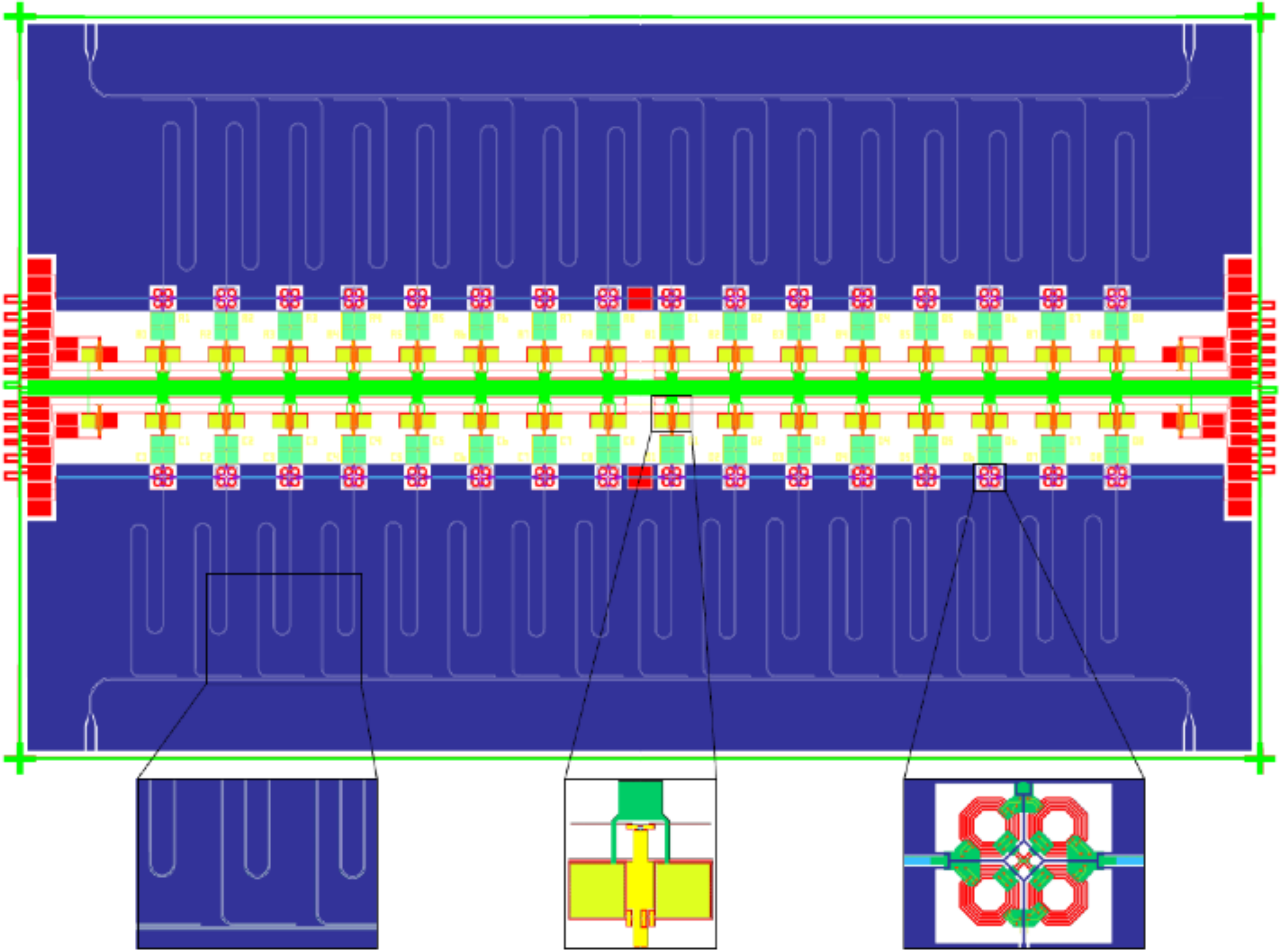


Long way to GO !!
Mass Limit (eV)
1000
100
10
1
0.1
0.01
1950
1960
1970
1980
1990
2000
2010
2020
Best sens. m_{ν_β}
Calorimetry best sens. m_{ν_β}
KATRIN
J.F. Wilkerson, Neutrino 2012

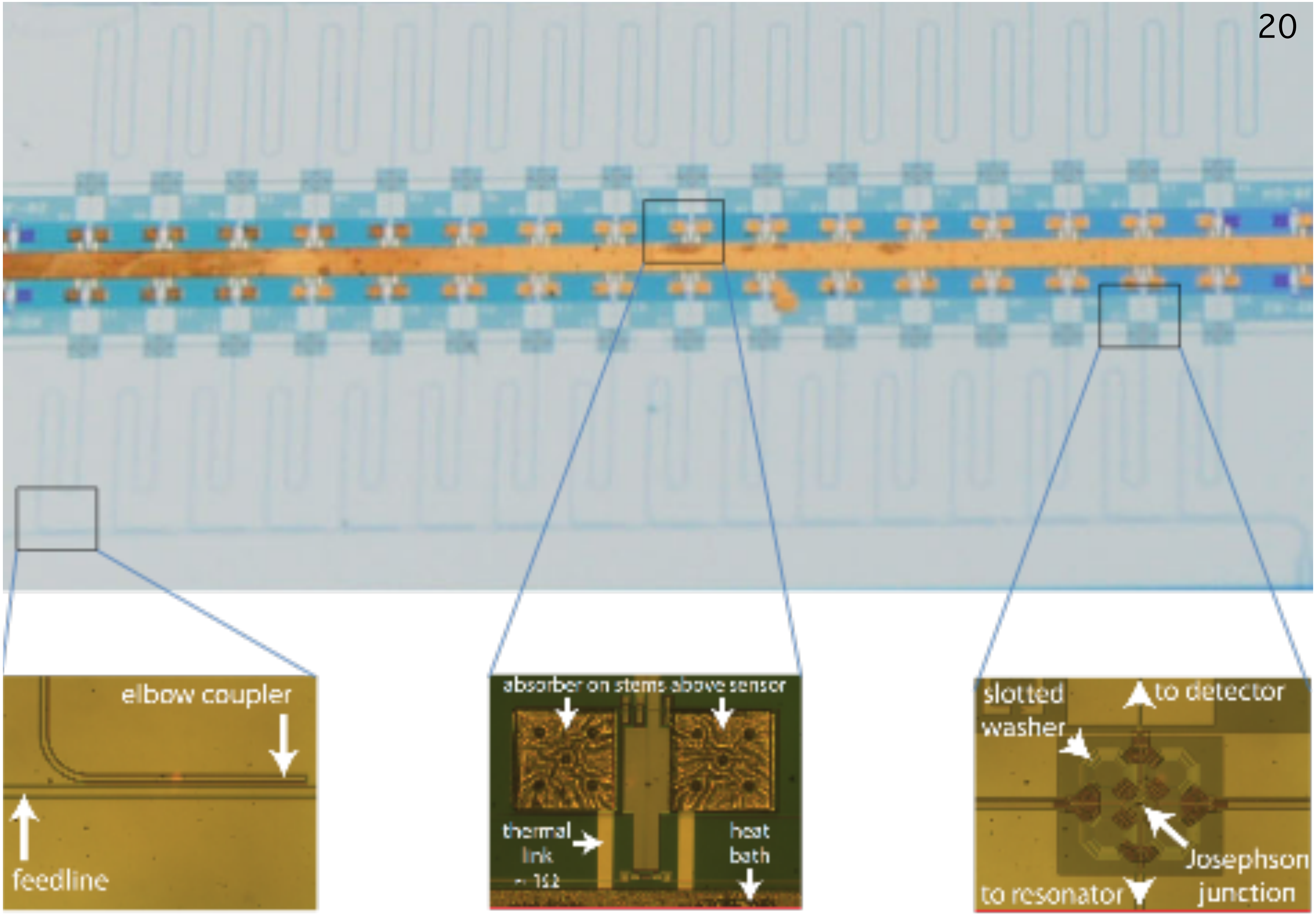
HOLMES



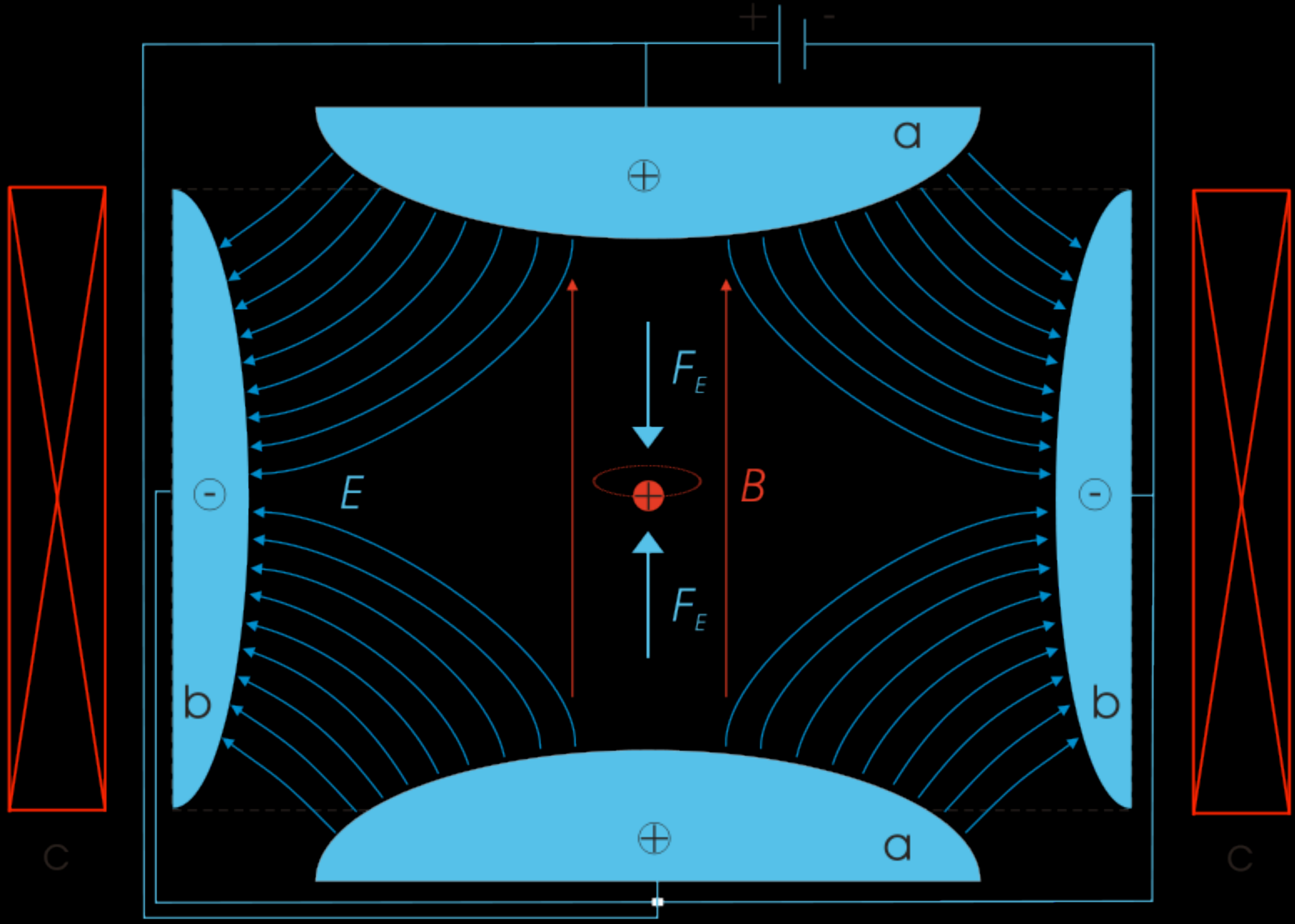
counts / 0.26 eV
energy [keV]
full spectrum (MC)
pile-up spectrum (fit)



ECHo, courtesy of Loredana Gastaldo


elbow coupler
feedline
absorber on stems above sensor
thermal link
heat bath
slotted washer
to detector
to resonator
Josephson junction

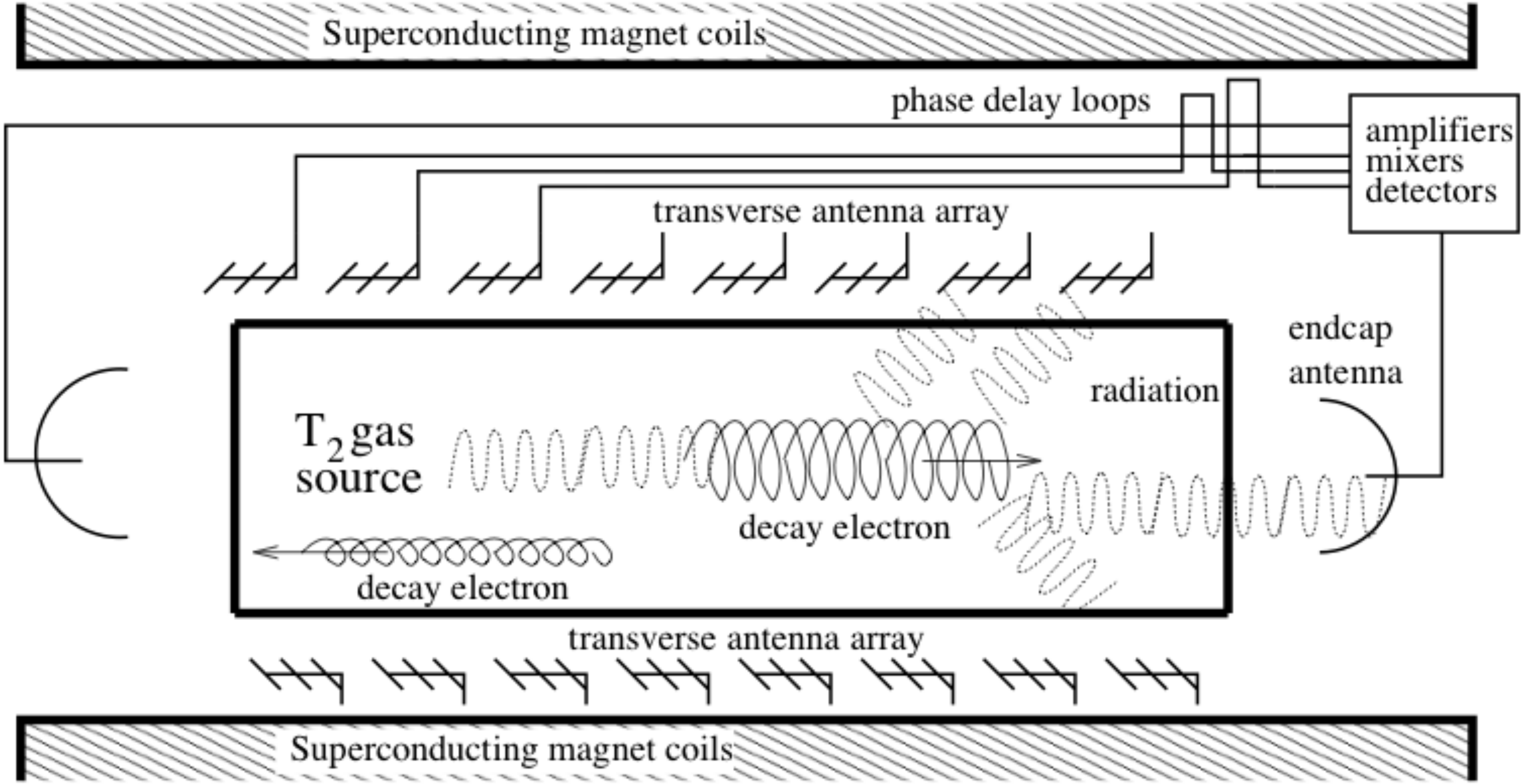
Penning Traps: accurate Q-values



OTHER AMBITIOUS PROJECTS

-1

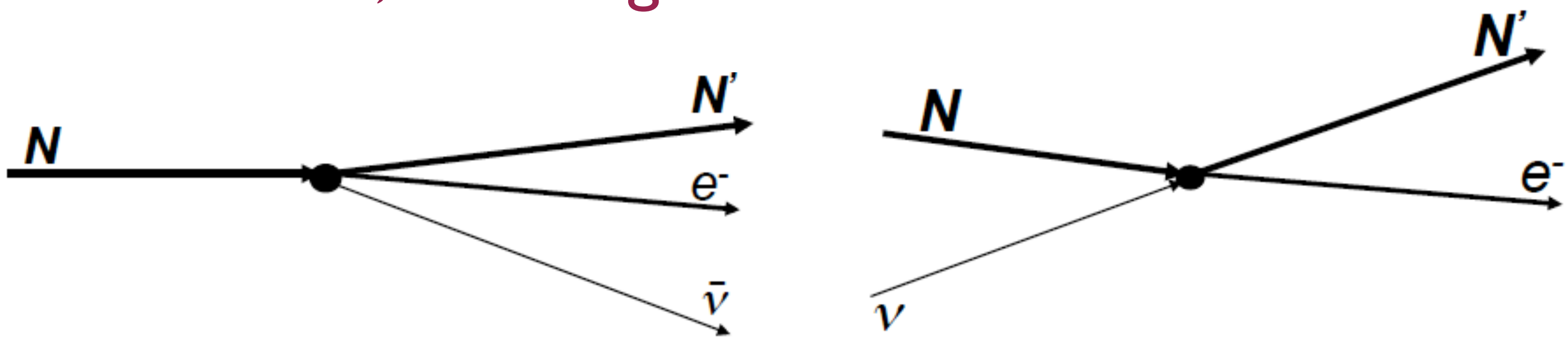
Project 8, B. Monreal & J. Formaggio

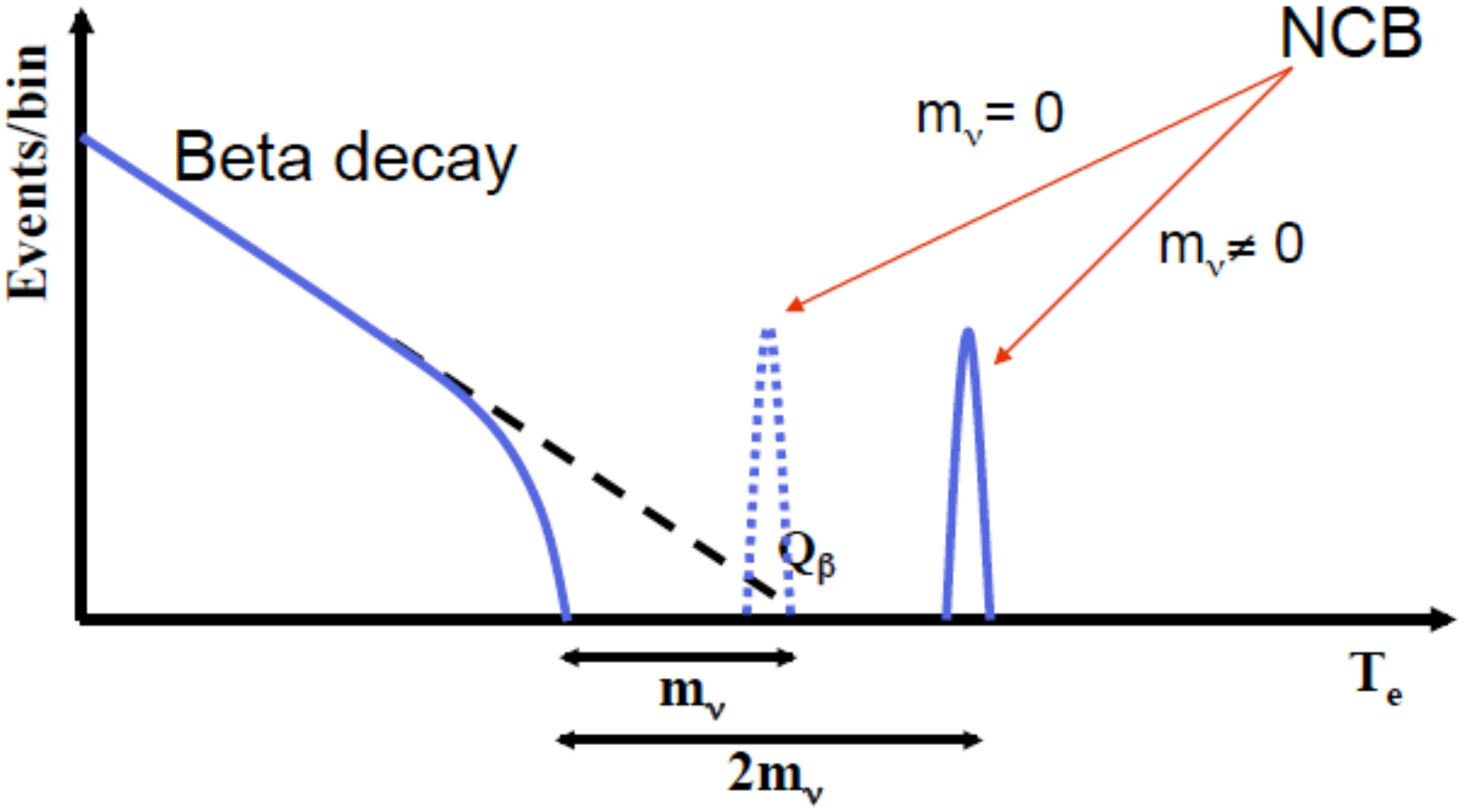


Electron E in Tritium decay measured via synchrotron radiation. At B=1T, E=Q: 26 GHz

GOAL: 0.05 eV sensitivity in Phase III

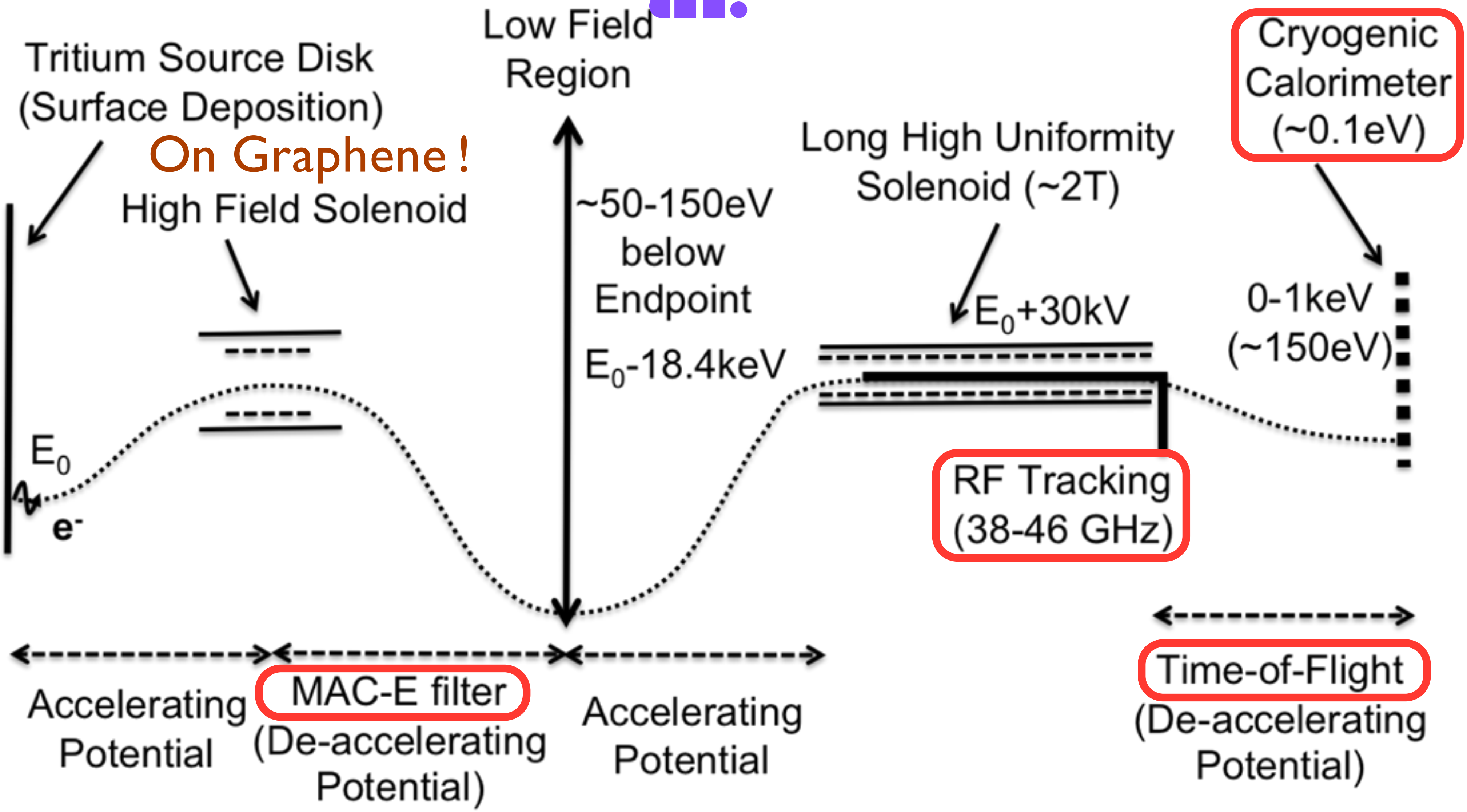
Neutrino Cosmic Background (Weinberg 1962 !!! A.G. Cocco, G. Mangano & M. Messina. 2007)





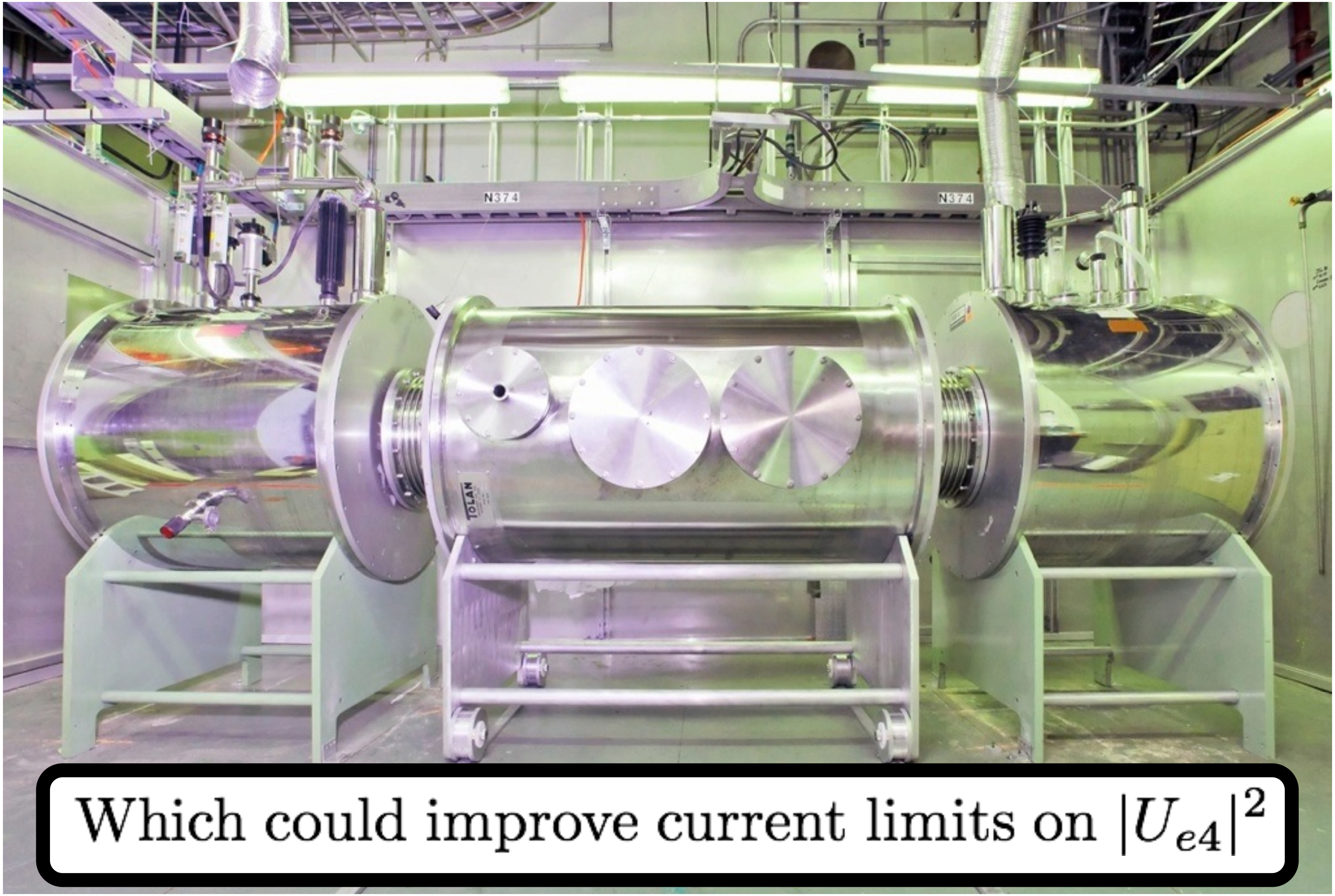
After C/2 no longer considered a joke!!

PTOLEMY; Chris Tully et al.



GOAL: > 9 events/y with 100 gr of T

WORKING PROTOTYPE



Which could improve current limits on $|U_{e4}|^2$

Holmium From Latin "Holmia": Stockholm.

Dysprosium from Greek "δυσπρόσιτος", "hard to get at".

Rhenium From Latin *Rhenus*, the river Rhine.

Osmium From Greek ὀσμή "a smell".
Gadolinium in honor of Johan Gadolin, one of the founders of Nordic chemistry, discovered Yttrium, and pioneered laboratory exercise teaching.

Samarium after "Samarskite", the mineral named after "Colonel Vasili Samarsky-Bykhovets", a Russian mine official

$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0.178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$