XIX International Workshop on Neutrino Telescopes

Neutrino Masses and Mixing

- Mixing, squared mass differences and CPV
- $0\nu\ \beta\beta$ searches
- Direct (kinematic) measurement of m_β

Stefano Ragazzi

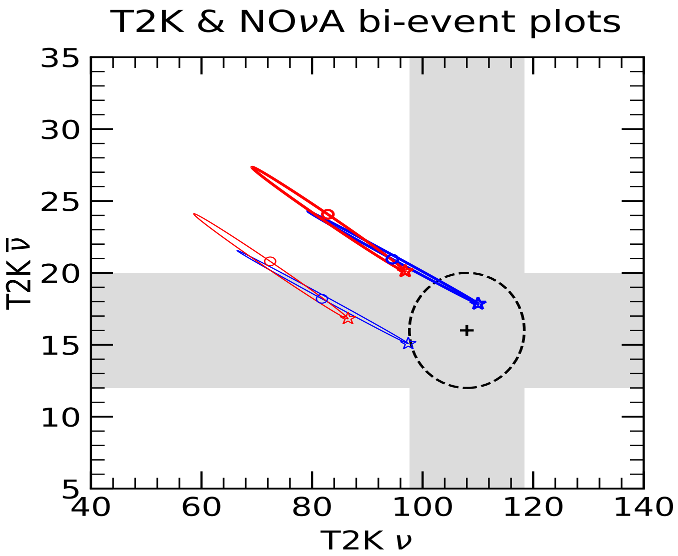
Neutel 2021

Mixing, squared mass differences and CPV

A superb update by Antonio Marrone at this Workshop

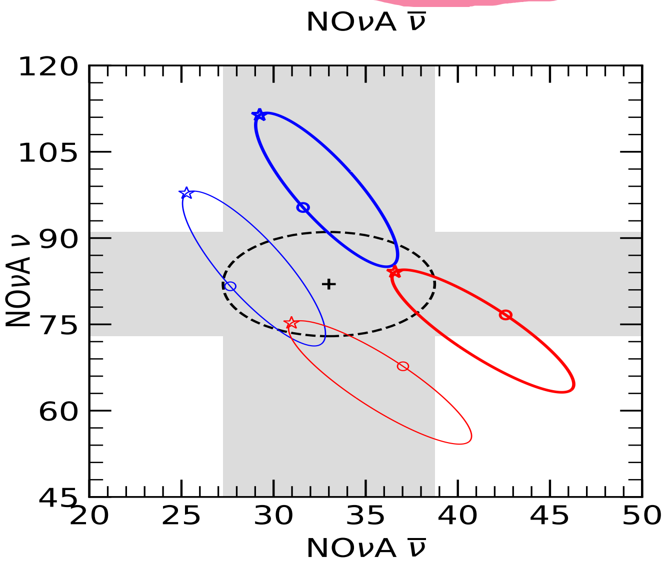
- Let me highlight ***tensions*** between results of T2K and NOνA and their consequences: weaker hints on δ **and on NO**

Integrated info on ν and $\bar{\nu}$, stat errors only (but analysis uses spectral data)



$s^2_{23} = \begin{matrix} 0.57 \\ 0.45 \end{matrix}$ NO IO $\delta = \begin{matrix} \pi & \circ \\ 3\pi/2 & \star \end{matrix}$

T2K alone prefers:
NO
$\delta \sim 3\pi/2$
2nd octant of θ_{23}

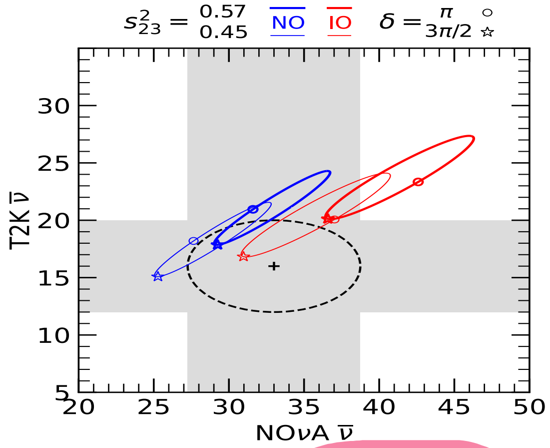


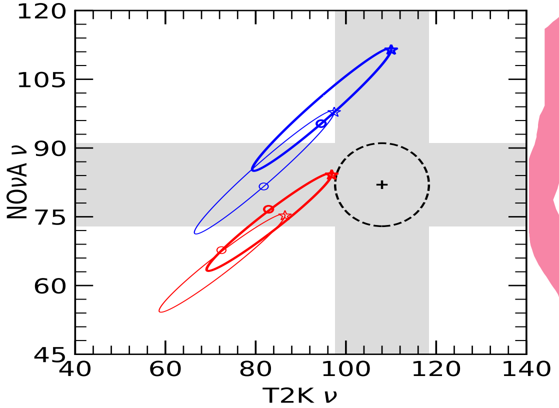
NOνA alone prefers:
NO
CP conservation
(~octant degenerate)

Integrated info on ν and $\bar{\nu}$, stat errors only
(but analysis uses spectral data)

T2K & NOνA bi-event plots

T2K + NOνA ($\bar{\nu}$) prefer:
IO
$\delta \sim 3\pi/2$
1st octant of θ_{23}





T2K + NOνA (ν) prefer:
IO
$\delta \sim 3\pi/2$
2nd octant of θ_{23}

-> T2K and NOνA alone:
NO preferred

-> T2K and NOνA combined:
IO preferred

-> In IO:
CP violation preferred

2

Mixing and CPV what next

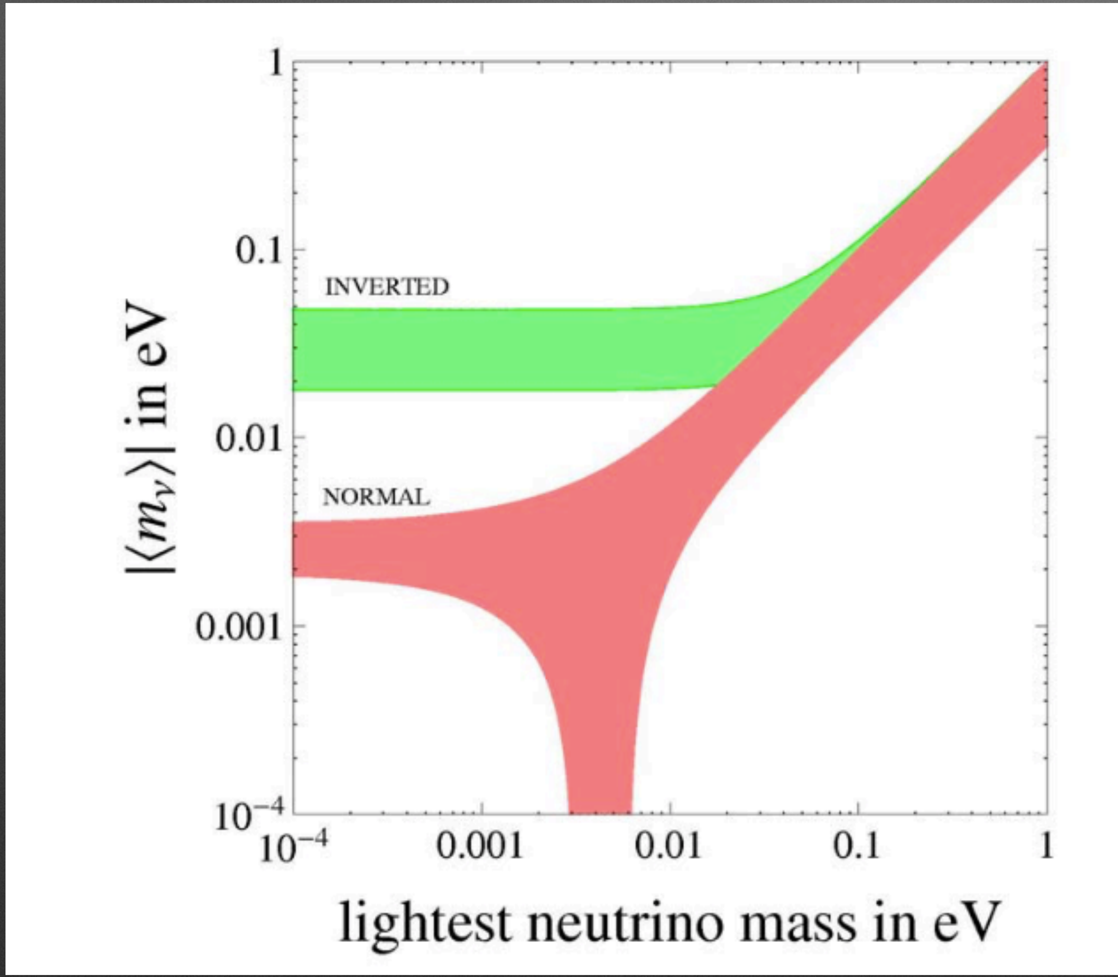
- Two *privileged* players in the future
  - T2K + beam upgrade + HK
  - DUNE
- Wide, long-lasting physics program for both of them

- *Privileged* = fully supported by reference laboratories

$0\nu\ \beta\beta$ searches

The evolution of the universe of $0\nu\ \beta\beta$ searches

- Please look at the full presentation by Nando Ferroni in the opening session: I'm going to show 3 slides out of 57



realistic predictions say:

20 meV for IH

2 meV for NH

now you can design your new generation experiment !

The lifetime sensitivity to chase

- For **next to next** generation experiments
- $\tau_{1/2} \sim 10^{29}$y
- ~ 100 t of isotope
- Forget about isotopic enrichment (this technology is not very popular… thus do not expect that it will be cheaper)

The menu

The problem at 10^{29} is rather the signal than the background !!!!

Probing Majorana neutrinos in the regime of the normal mass hierarchy

Steven D. Biller
Department of Physics, University of Oxford, Oxford OX1 3RH, UK

Isotope	Q (MeV)	percent natural abund.	element cost [5] ($/kg)	$G^{0\nu}$ (10^{-14}/yr) [6]	$M^{0\nu}$ (avg) [7]	$T^{0\nu}_{1/2}$ for 2.5meV (10^{29}yrs)	tons of isotope for 1 ev/yr	equivalent natural tons	annual world production [5] (tons/yr)	natural elem. cost ($M)	enriched at $20/g ($M)	$0\nu/2\nu$ rate [2][8] (10^{-8})
^{48}Ca	4.27	0.19	0.16	6.06	1.6	2.70	31.1	16380	2.4×10^{8}	2.6	622	0.016
^{76}Ge	2.04	7.8	1650	0.57	4.8	3.18	58.2	746	118	1221	1164	0.55
^{82}Se	3.00	9.2	174	2.48	4.0	1.05	20.8	225	2000	39	416	0.092
^{96}Zr	3.35	2.8	36	5.02	3.0	0.93	21.4	763	1.4×10^{6}	27	427	0.025
^{100}Mo	3.04	9.6	35	3.89	4.6	0.51	12.2	127	2.5×10^{5}	4.4	244	0.014
^{110}Pd	2.00	11.8	23000	1.18	6.0	0.98	26.0	221	207	5078	521	0.16
^{116}Cd	2.81	7.6	2.8	4.08	3.6	0.79	22.1	290	2.2×10^{4}	0.81	441	0.035
^{124}Sn	2.29	5.6	30	2.21	3.7	1.38	41.2	736	2.5×10^{5}	22	825	0.072
^{130}Te	2.53	34.5	360	3.47	4.0	0.75	23.6	68	$\sim$150	24	471	0.92
^{136}Xe	2.46	8.9	1000	3.56	2.9	1.40	45.7	513	50	513	914	1.51
^{150}Nd	3.37	5.6	42	15.4	2.7	0.37	13.4	240	$\sim10^{4}$	11	269	0.024

The only choice that does not call for an impossible cost for the enrichment points to natTe

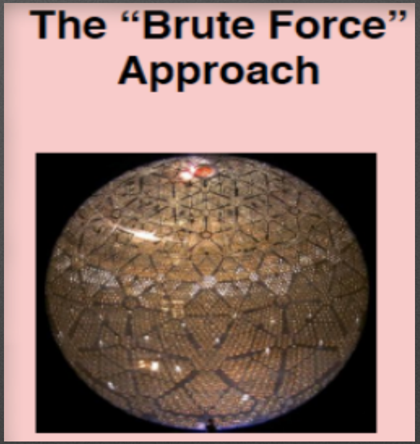
- N.B. forget about the second in the shortlist: ^{100}Mo has a horrible 2ν rate

The (poisonous) Tellurium soup

Te might strikes back

Dissolve a huge quantity of natural Te (few hundred tons) at the highest concentration allowed by the transmission of the light in a scintillator

(Juno -20000 tons)
(SuperK -50000tons)



Two backgrounds are serious: $2\nu\beta\beta$ and ^{8}B from the Sun

The neutrinos from the Sun might be tagged if some directionality could be implemented (Cherenkov !)

No life in the far future for the "peak squeezing" approach?

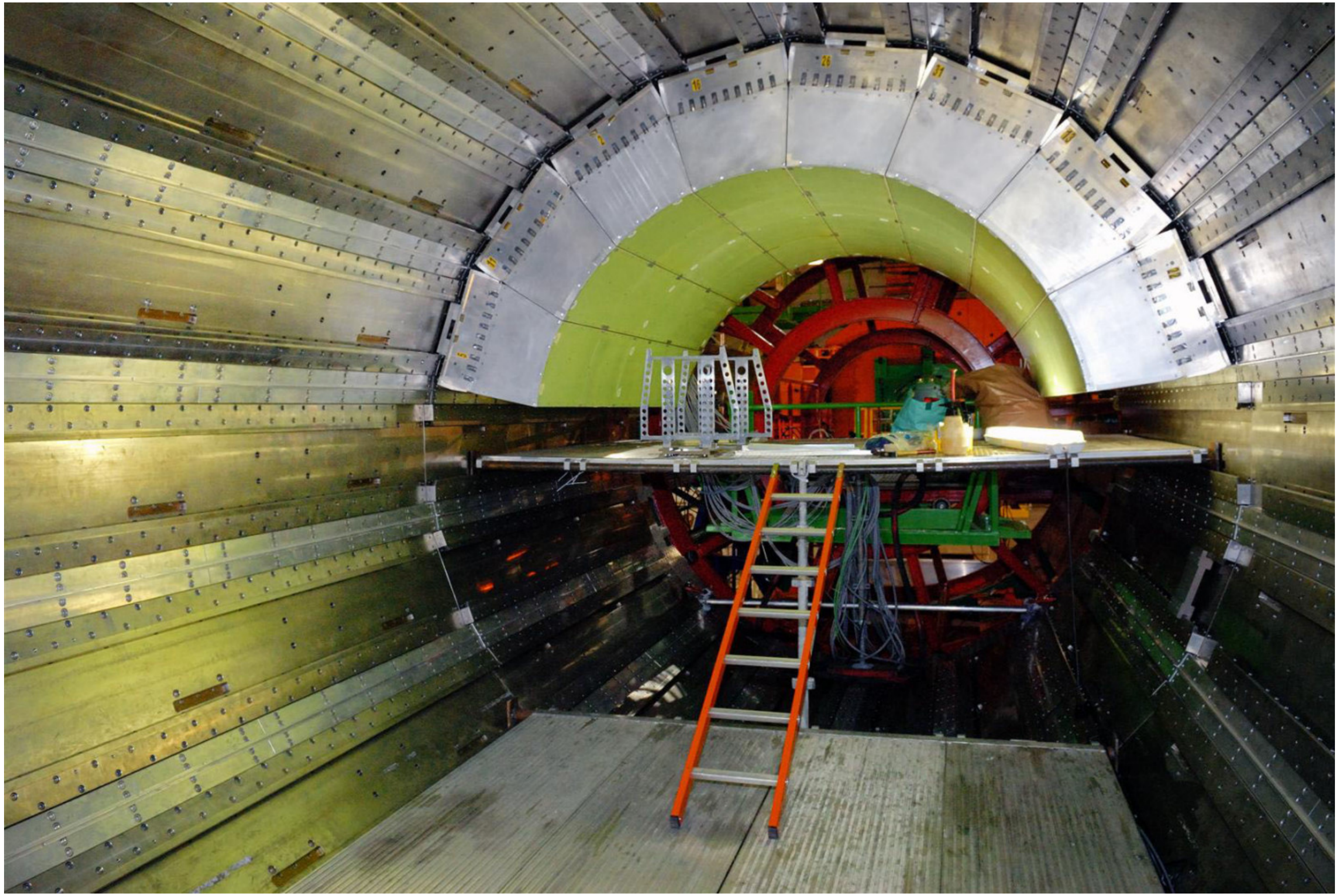
- Keep natural Te => 100 x CUORE

  1. ~ 100k Crystals calorimeter
  2. At 10 mK
  3. 1/100 bkg

- **Impossible or challenging?**

100k Crystal calorimeter

- It is run at 291 K, quite higher than 10 mK



100 x CUORE Cryostat

- CUORE cryostat has been a very challenging project
  - btw: congratulations to CUORE for the impressive duty cycle attained, 2 years ago I could not believe that the cryostat would be useful for CUPID
- Commercial mK cryogenics is ramping up
- What the impact of QC based on superconducting qbits is going to be on cryogenics?
- *Keep calm and carry on*

Background reduction

- At the beginning it had to be an extreme peak-squeezing approach
- What went wrong?
- Where is energy escaping or trapped?
- If we seek extreme performance we should better understand our detectors
- Keep in mind the long path of bkg reduction of Ge based experiments

Nuclear Instruments and Methods in Physics Research 224 (1984) 83–88
North-Holland, Amsterdam 83

LOW-TEMPERATURE CALORIMETRY FOR RARE DECAYS

E. FIORINI
Dipartimento di Fisica dell'Università and INFN, Milano, Italy

T.O. NIINIKOSKI
CERN, Geneva, Switzerland

Received 27 December 1983

The recent developments in underground low-counting experiments give limits to rare decays which are hard to improve since scaling the size and the resolution of the combined source–detector is difficult with the existing techniques. We explore here the possibility of low-temperature calorimetry to improve the limits on processes such as neutrinoless double-beta decay and electron decay.

N.B. Θ_D for Te reported by Fiorini-Niinikoski is ~2x lower than Θ_D of TeO_2 crystals

…and things may be different

- Just add one sterile neutrino
- The end of the game may be far away even for IO

Sebastian Böser[1], Christian Buck[2], Carlo Giunti[3], Julien Lesgourgues[4], Livia Ludhova[5,6], Susanne Mertens[7,8], Anne Schukraft[9], Michael Wurm[1,*]

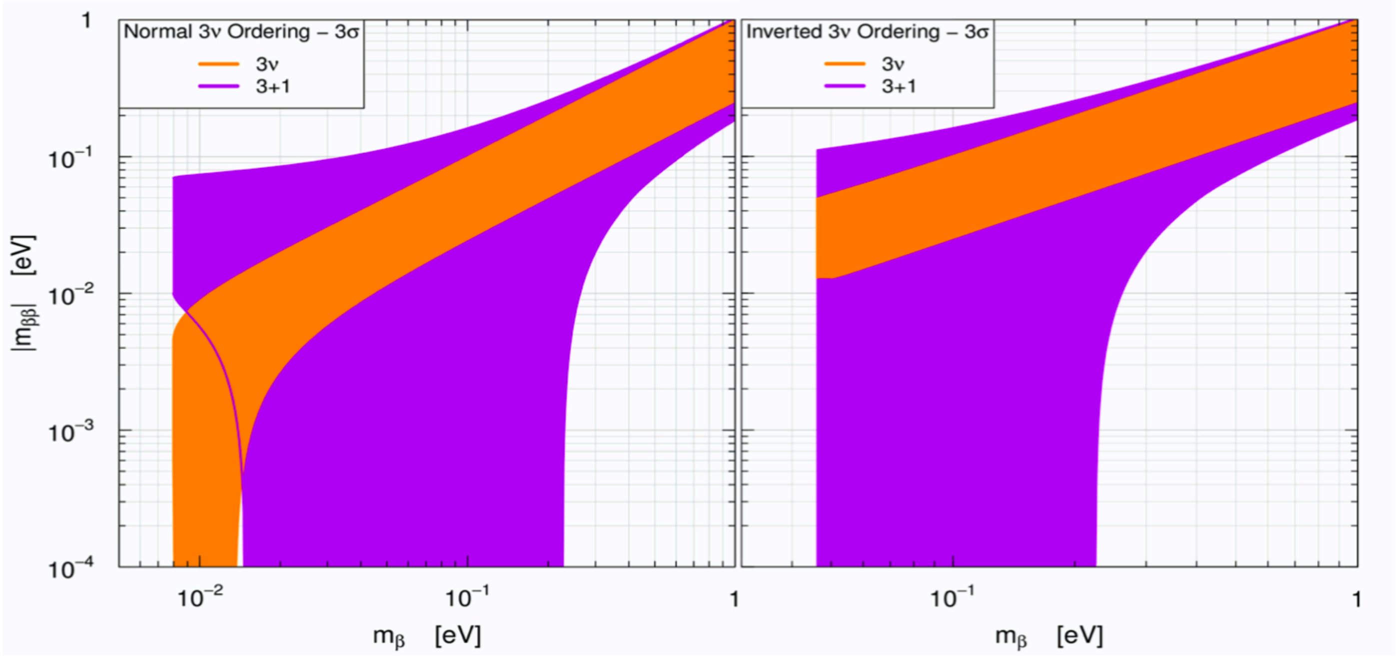
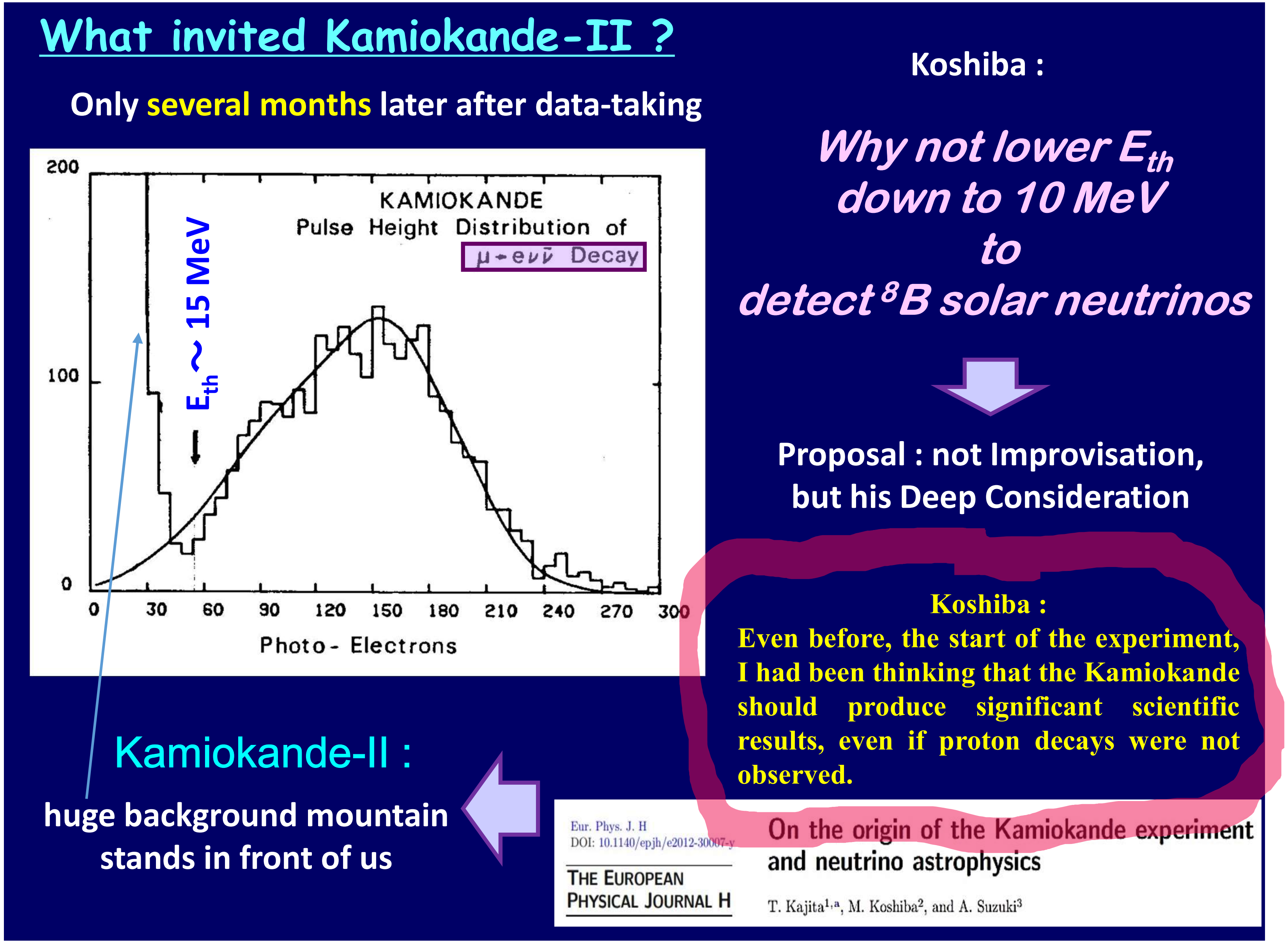


Figure 7: Predicted ranges for the Majorana neutrino mass $|m_{\beta\beta}|$ as a function of the effective electron neutrino mass m_β: While left and right panels distinguish normal and inverted neutrino mass ordering, the different-color bands illustrate the different allowed ranges in case of 3-flavor and (3+1) scenarios [69].

A dangerous killer

- From Atsuto Suzuki retrospective on Dr. Masatoshi Koshiba



Direct (kinematic) measurement of m_β

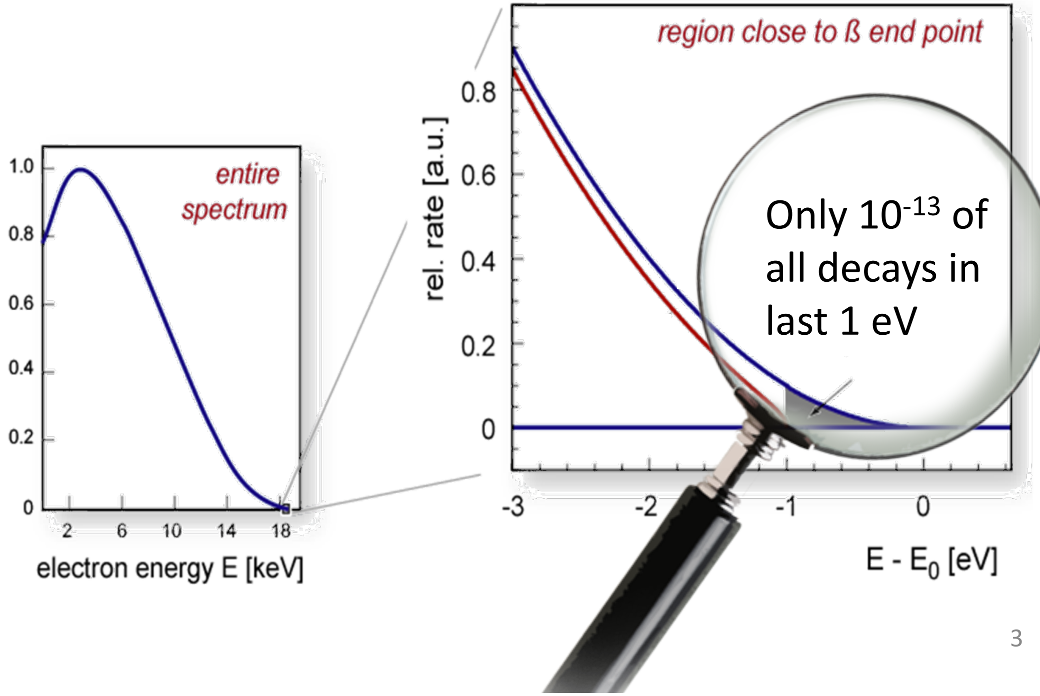
A single BIG player today: KATRIN

Katrin

- Slide by Susanne Mertens @Neutrino 2020

The challenge

- Ultra-strong β-source: 10^{11} decays/s
- Low background level < 0.1 cps
- Excellent energy resolution ~ 1 eV
- Precise understanding of spectrum



3

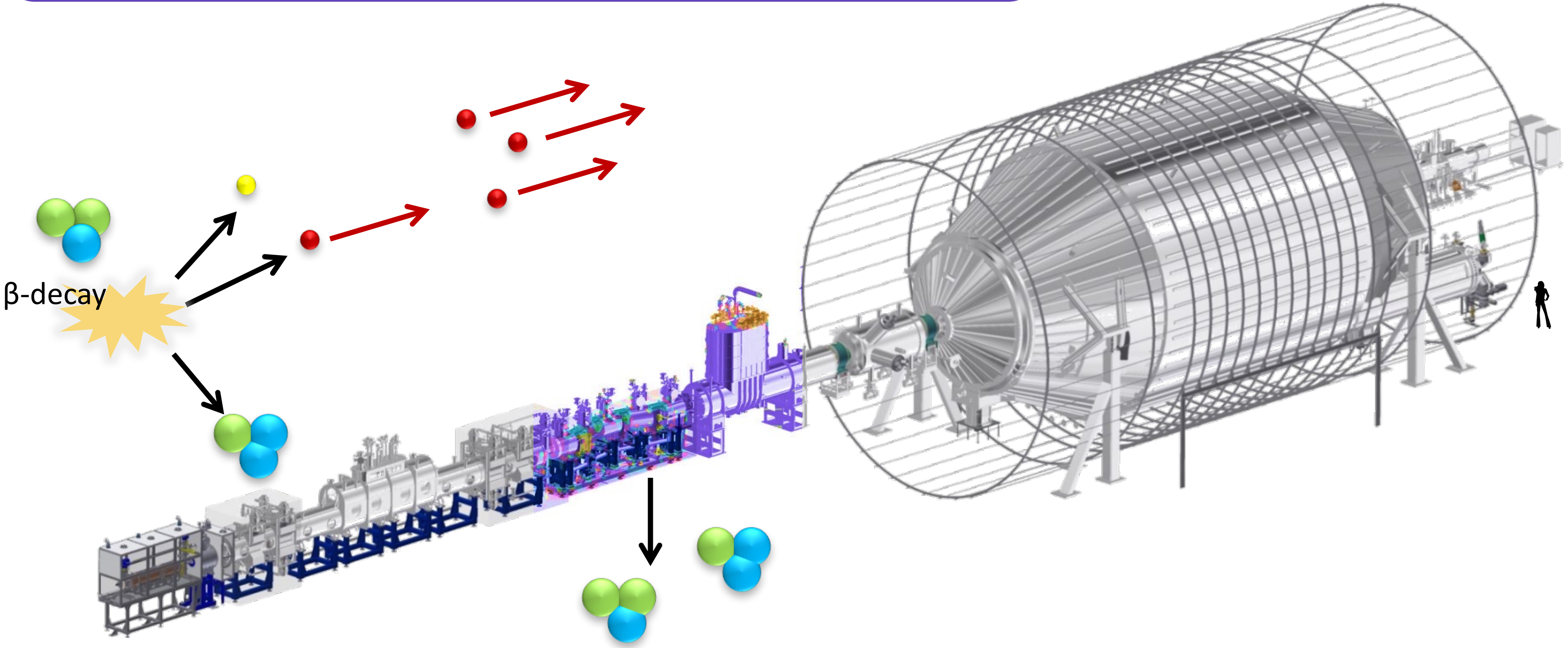
Susanne Mertens (MPP, TUM)

KATRIN Working Principle

Katrin

- Slide by Susanne Mertens @Neutrino 2020

Transport section
- magnetic guidance of electrons (@ 4 T)
- tritium flow reduction by > 10^{14} + tritium ion removal



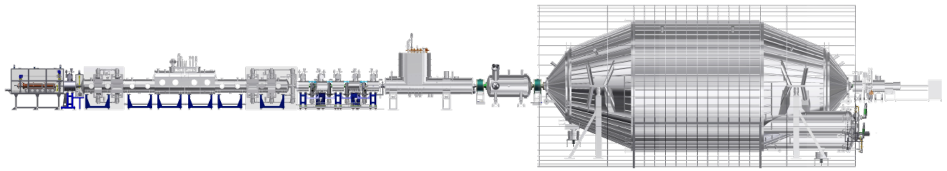
Susanne Mertens

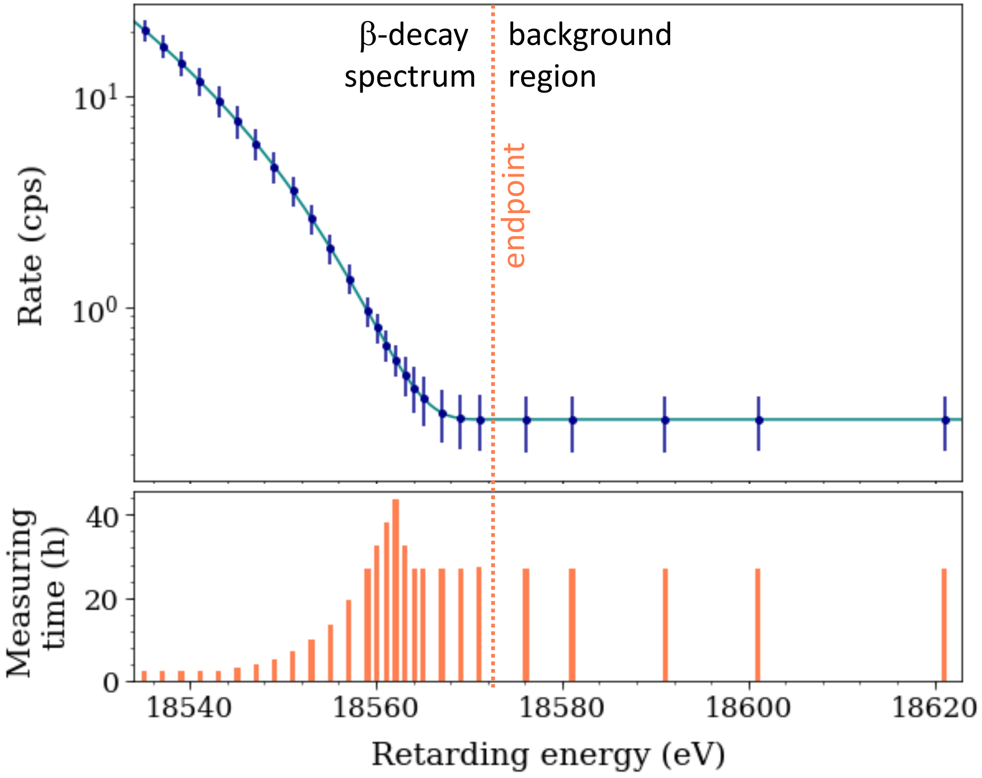
Katrin

- Slide by Susanne Mertens @Neutrino 2020

Measurement strategy

- # HV set points: **27**
- interval: **E_0 – 40 eV , E_0 + 50 eV**
- scanning time: **2 hours**
- # scans: **274**
- HV stability: **20 mV (ppm-level)**





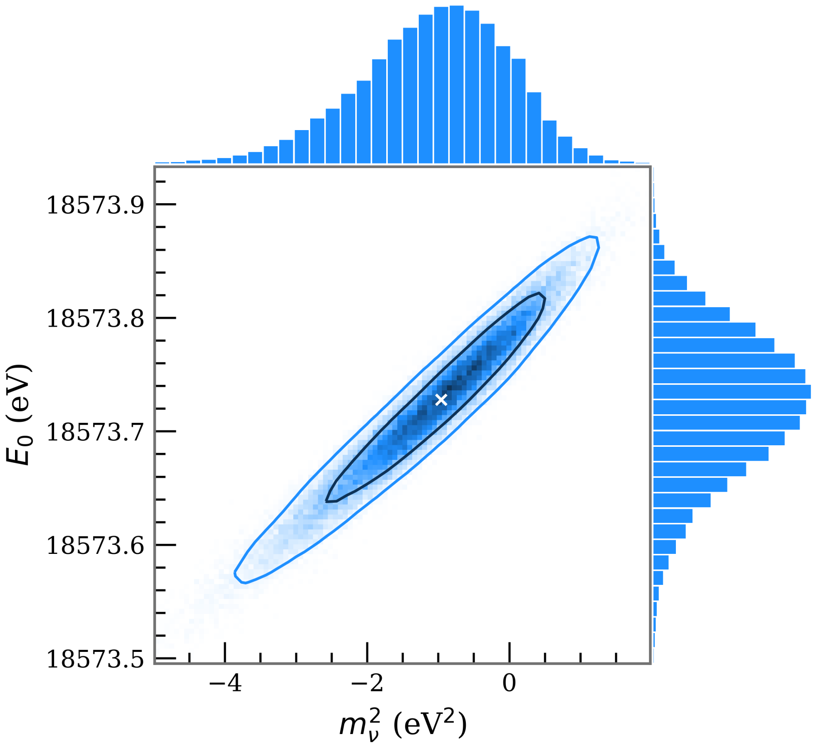
15

Susanne Mertens

Katrin

- Slide by Susanne Mertens @Neutrino 2020

Final fit result



Best fit results:

$$m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)\ \text{eV}^2$$

→ compatible with zero

→ probability of 16%, if true m_ν = 0 eV

$$E_0 = 18573.7 \pm 0.1\ \text{eV}$$

→ Q-value : 18575.2 ± 0.5 eV

→ good agreement with literature (Q = 18575.72 ± 0.07 eV)

E. Myers et al. Phys. Rev. Lett. 114, 013003 (2015)

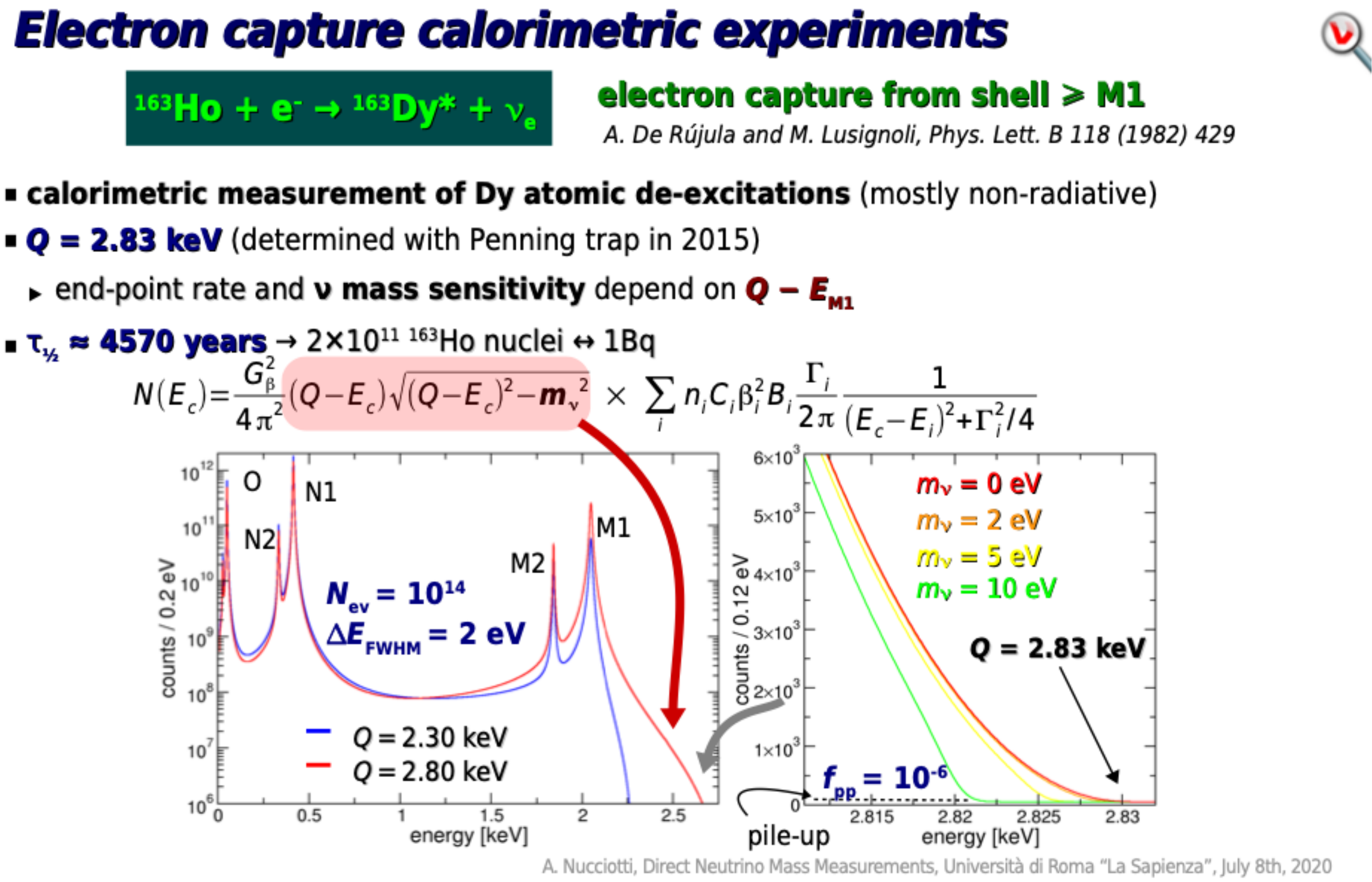
Susanne Mertens

Katrin – what next

- Search for signatures of m_4 mixing: distortions in beta spectrum
  1. eV scale sterile neutrino -> same data as for standard m_β
  2. keV scale neutrino mass: needs segmented final detector -> TRISTAN
- Further upgrades? Katrin deserves to be fully exploited

m_β from electron capture

- ECHO and HOLMES
- **Milestone**: demonstrate 1 eV capability
- No general consensus on the costs for a sub-eV detector
  - It depends on number of channels, which depends on maximum tolerable rate per channel
- Be optimistic on major costs reduction from commercial technologies



Slide by A. Nucciotti

m_β novel concepts

- Project 8
  - Novel approach to e^- spectrometry: measure frequency, not E
    - In progress

- PTOLEMY
  - Very ambitious: initially proposed as a *Telescope for Relic Neutrinos* – m_β as a by-product
  - Novel concepts for
    - Source: ^3H embedded in a graphene layer, ~ x10^3 Katrin source intensity
    - Spectrometer: differential high-res spectrometry
    - Detector: low-energy high-resolution detector
  - Every item has to be developed and demonstrated
  - Please refrain from calling it a Neutrino Telescope at least until LIX Neutel
  - Remarkable anyway

Final remarks

- Mixing, phases, squared mass difference experiments are in a *privileged* position
  - Supported by reference laboratories
  - Making measurements
  - Wide physics menu
- Majorana $m_{\beta\beta}$ searches
  - Healthy competition and variety of approaches – some downselection will occur
  - You pay for $(1/m_{\beta\beta})^2$ at least
  - "Zero background" approach has to go ahead if we don't want to pay for $(1/m_{\beta\beta})^4$ or hit a systematics wall
    - Peak squeezing technique: it is mandatory to take advantage of the time of CUPID construction and run for a better understanding of detectors
  - Beware of single item physics menu! It can be more poisonous than a tellurium soup

Final remarks (continued)

- m_β measurement
  - Measure $(m_\beta)^2$ pay for $1/(m_\beta)^2$
  - The shores of neutrino mass spectroscopy are at 50 meV or nearer: a tiny effect for NO a major shoulder for IO
  - A single big operating experiment: Katrin
    - It was a tremendous effort: congratulations to Katrin
    - Fully exploit Katrin + Upgrades (Tristan …)
  - The shores of neutrino mass spectroscopy are at 50 meV or nearer: a tiny effect for NO a major shoulder for IO

Final remarks - m_β measurement (continued)

- EC (Holmium) experiments
  - Costs would be unsustainable **today** for a sub-eV experiment, but they will tremendously benefit of development of commercial technologies
  - There still is a long way to go along the path followed by Mac-E Spectrometers: important milestone at 1 eV
- New spectrometers
  - Project-8 - measure frequency not energy
  - Ptolemy - very ambitious fininal goal: detect relic neutrinos (m_β as a by-product): novel concept for source, spectrometer, detector
    - It needs a supporting laboratory (at least)

Thanks

- Many thanks to NeuTel organizers for invinting me

- Many thanks to O. Cremonesi, A. Nucciotti, S. Pirro, F. Terranova for enlightening discussion