Applications of Nuclear Data

Libby McCutchan

National Nuclear Data Center

Nuclear Data Program

Link between basic science and applications

Nuclear Science Community

- experiments
- theory

Application Community

needs data:

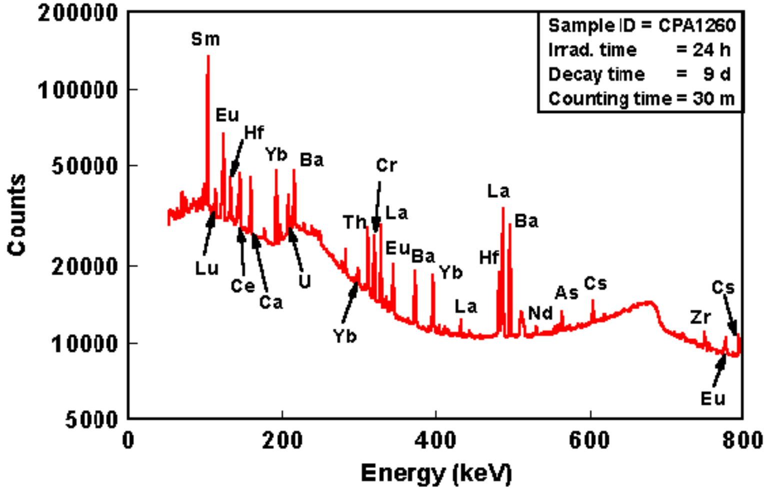
✦ complete
✦ organized
✦ traceable
✦ readable

Nuclear Data Community

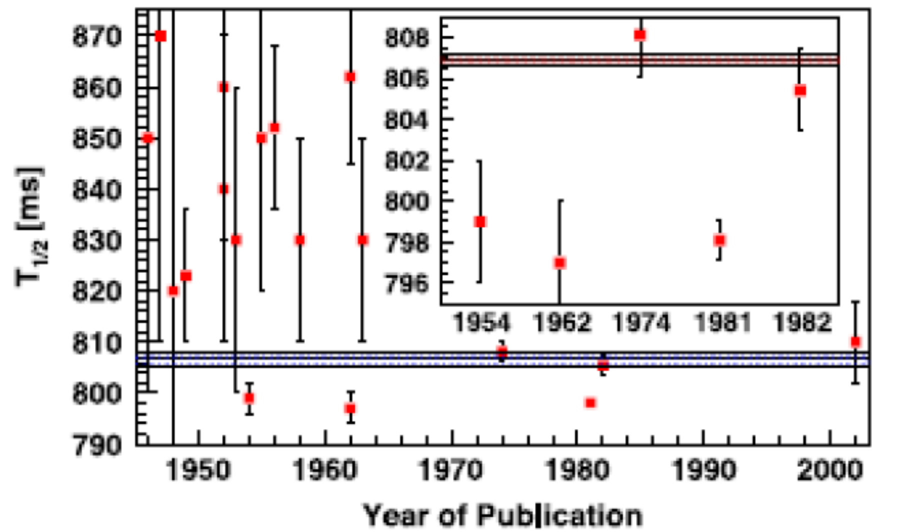
✦ compilation
✦ evaluation
✦ dissemination
✦ archival

Why do we need ENDSF?

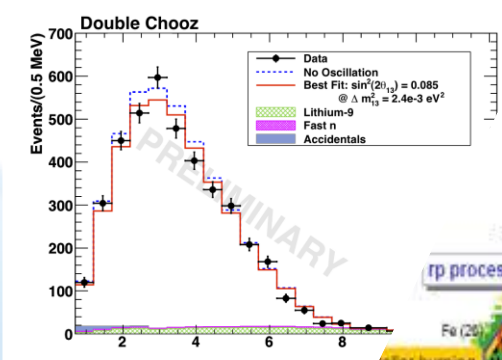
Used in all aspects of gamma-ray spectroscopy

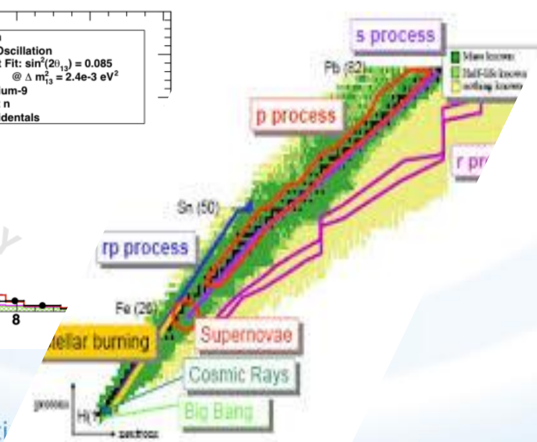


Facilitates comparison to theory

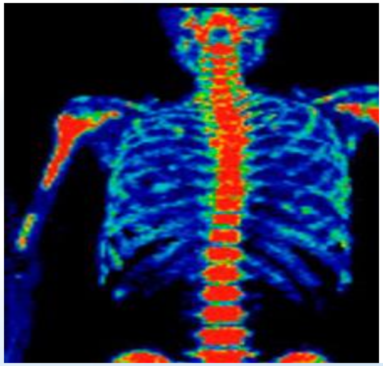


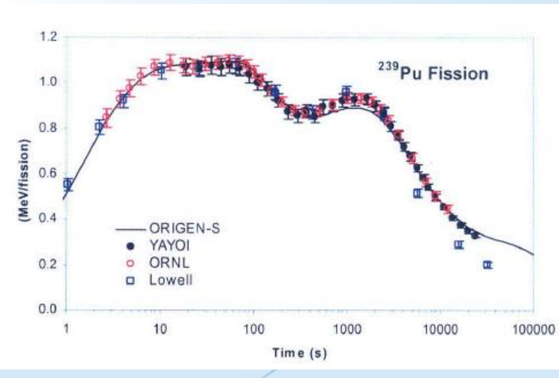
Input for other basic science fields



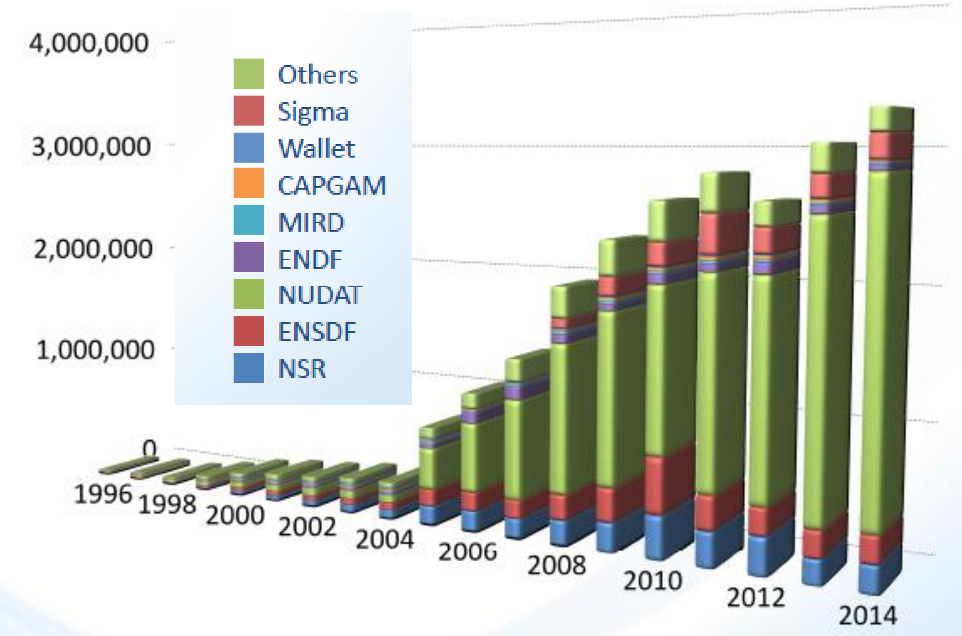


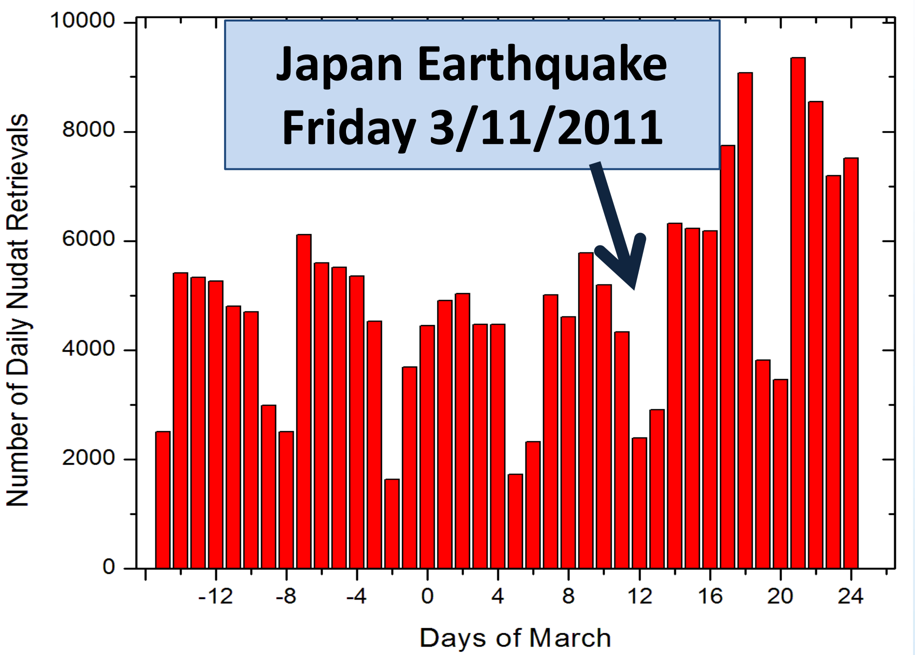
Wide range of applications require nuclear structure data





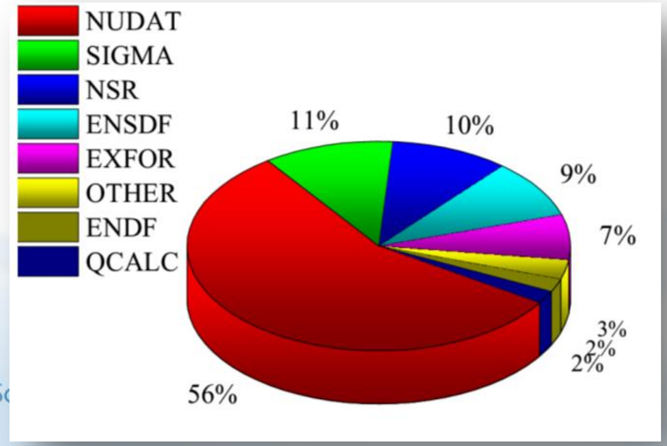
Users of Nuclear Data





> 3 million retrievals / year

Relevance to society



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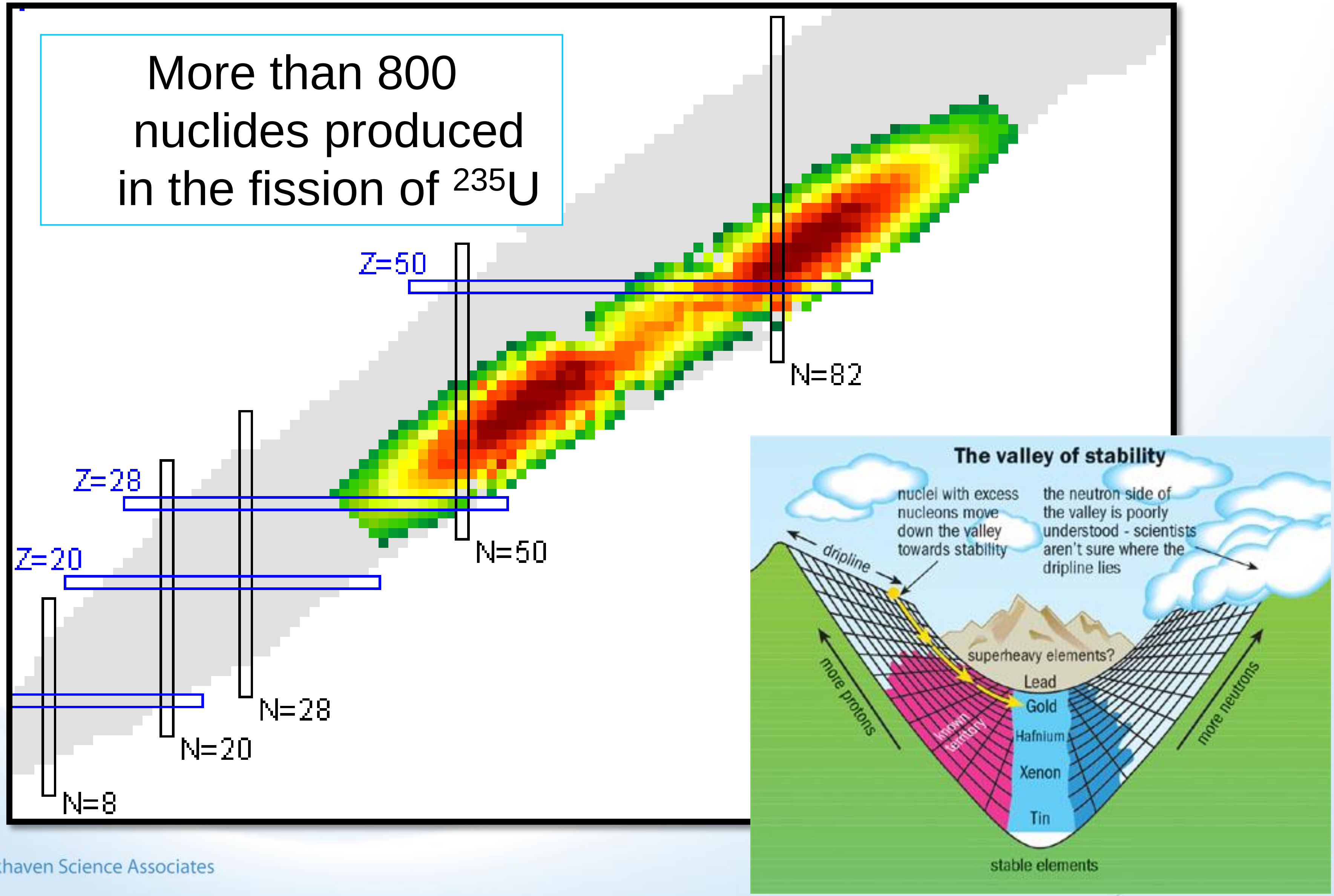
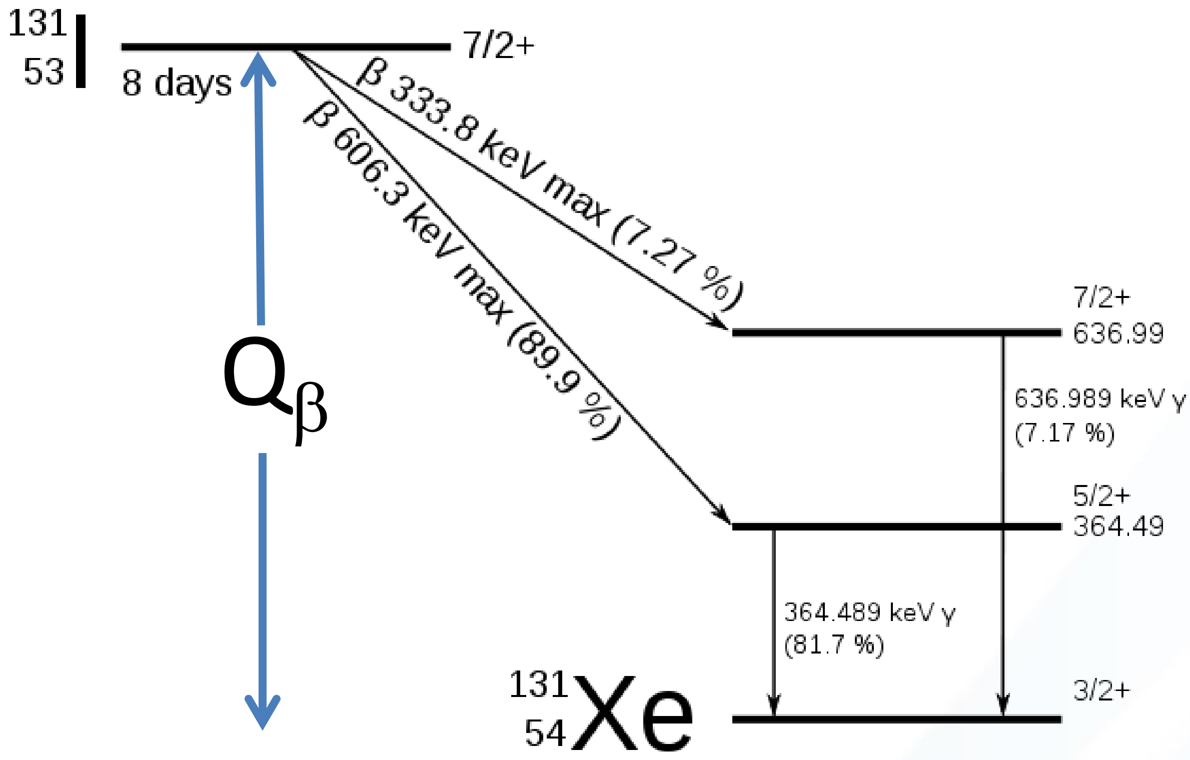
Using the Databases

Many applications involve fission



Energy released in beta decay

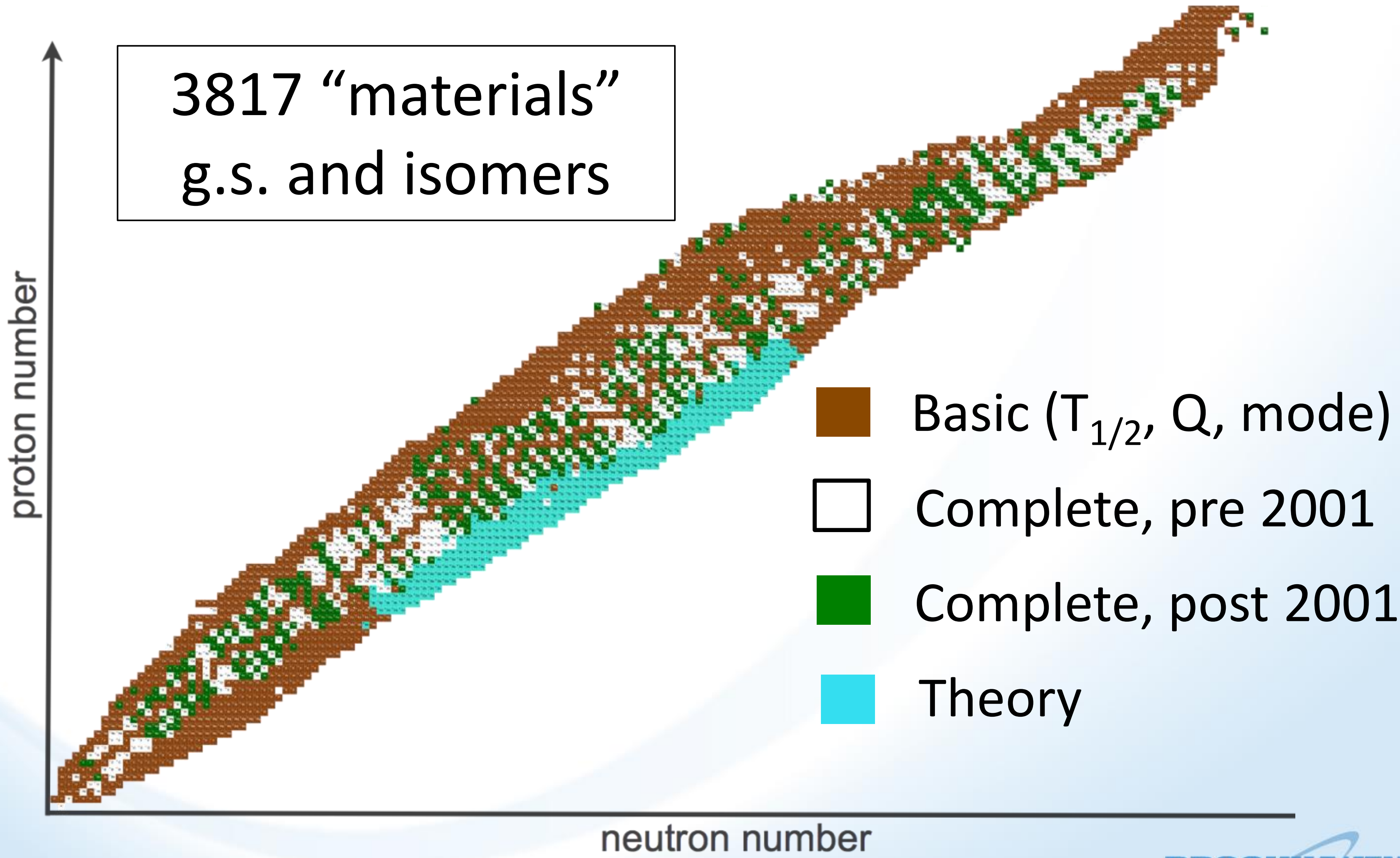


$$\text{Electromagnetic (EM)} = \Sigma I_\gamma E_\gamma + \Sigma I_{x\text{-}ray} E_{x\text{-}ray}$$

$$\text{Light Particle (LP)} = \Sigma I_{\beta\text{-}} E_{\beta\text{-}} + \Sigma I_{ce} E_{ce} + \Sigma I_{Auger} E_{Auger}$$

$$\text{Total Energy} = EM + LP + E_{neutrino} = Q(\beta\text{-})$$

The beta-decay database



M. Chadwick *et al.,* Nucl. Data Sheets **112**, 2887 (2011).

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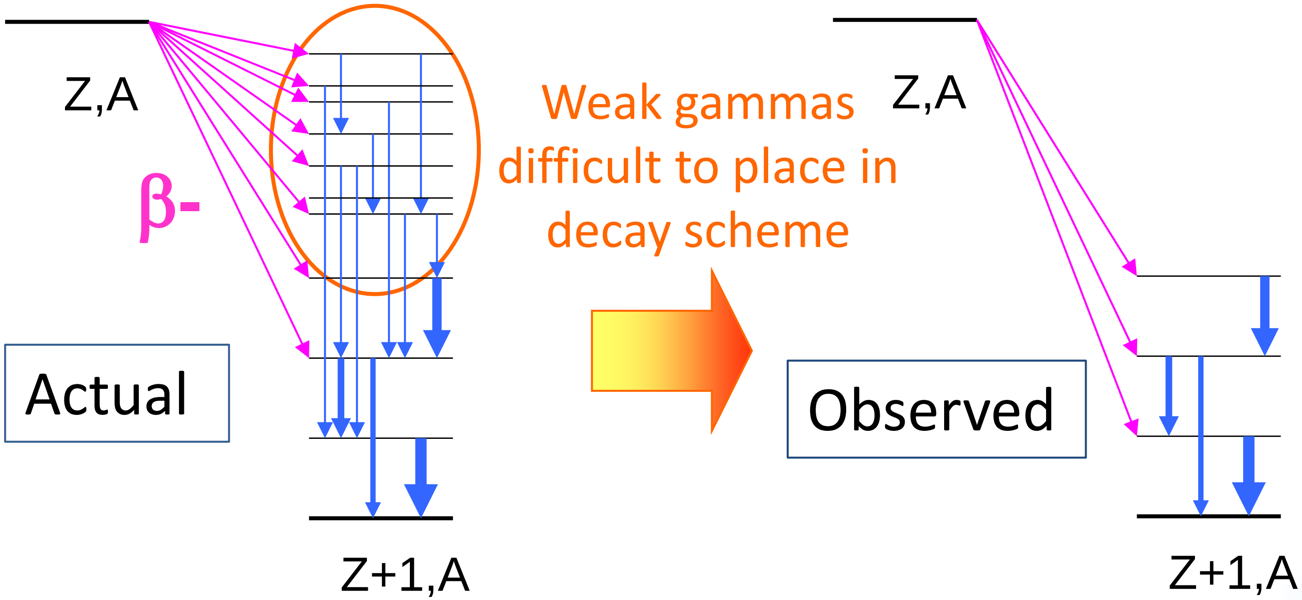
But most things aren’t simple



Incomplete decay schemes:

- Smaller gamma-ray energies
- Larger beta energies
- 1st realized by Hardy in 1970’s
- Termed Pandemonium effect

New RIB facilities + New Total Absorption Gamma-ray Spectrometers (TAGS) :
Will soon address these issues

What's it good for …

- Decay heat
- Antineutrino spectra
- Delayed nu-bars (reactor operation)
- Astrophysics
- ????

Decay heat from a reactor

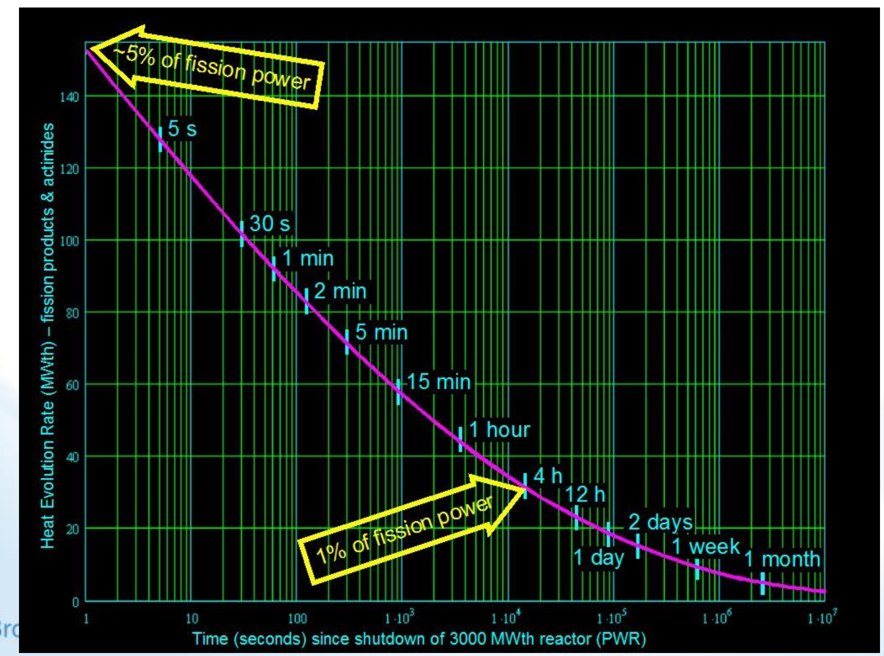
$$DH(t) = \sum_i E_i \lambda_i N_i(t)$$

E_i = Decay energy (β,γ or both)

λ_i = decay constant

$N_i(t)$= number of nuclei *i* at cooling time t

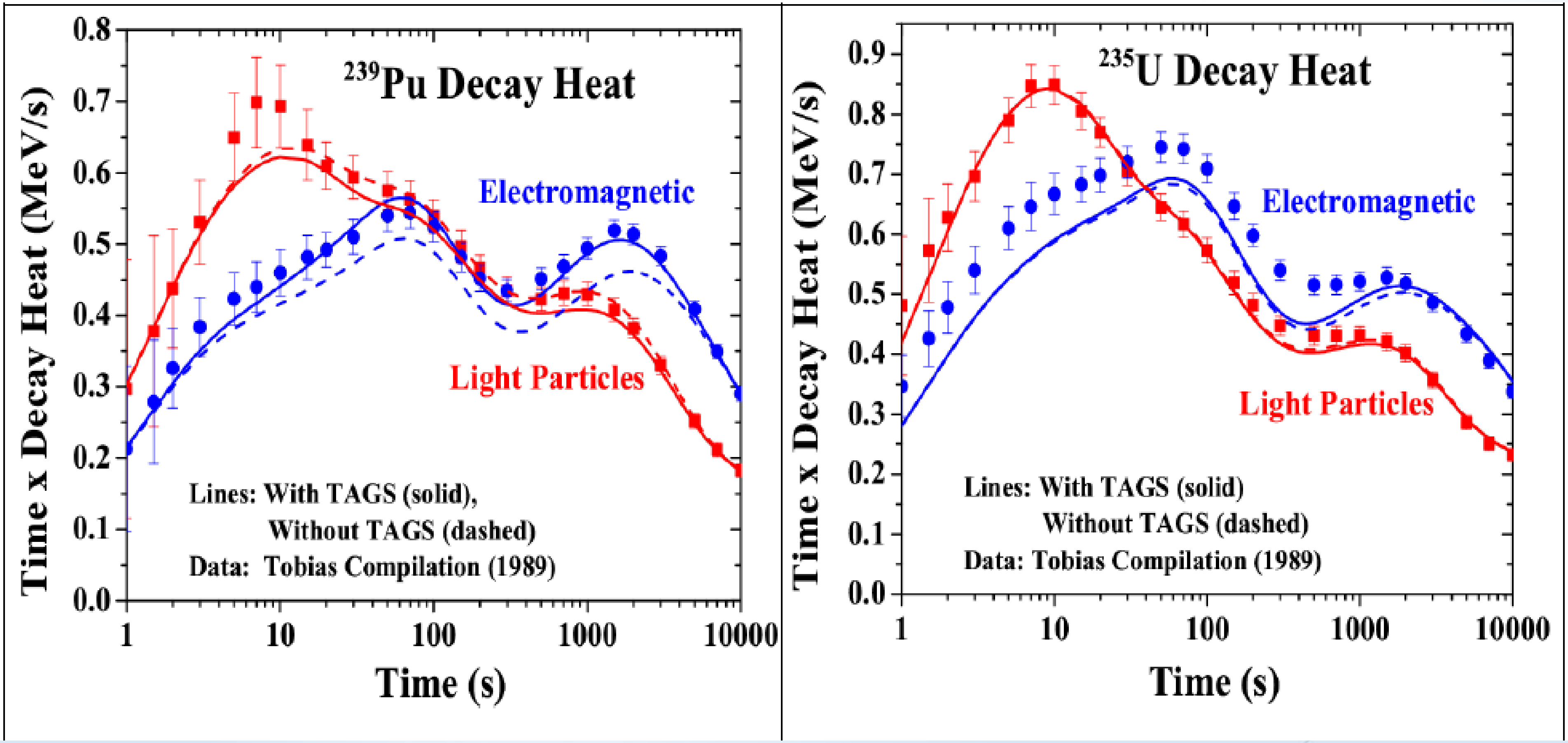
Essential for
- Reactor control
- Shut down
- Post processing of fuel



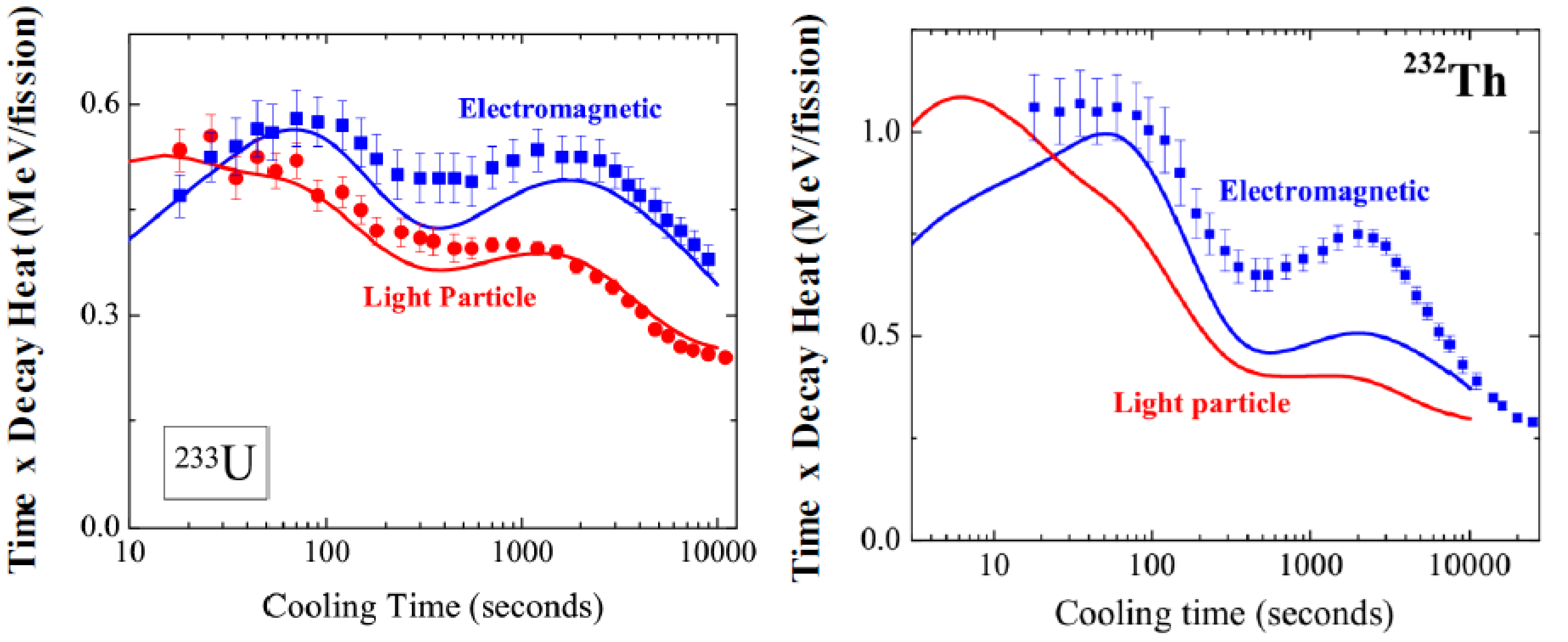
Incorporating TAGS data

- IAEA project (2006) identified 22 "high priority" nuclei
- New TAGS data on 7 nuclei from Valencia collaboration

Algora *et al.,* Phys. Rev. Lett. **105**, 202501 (2010).



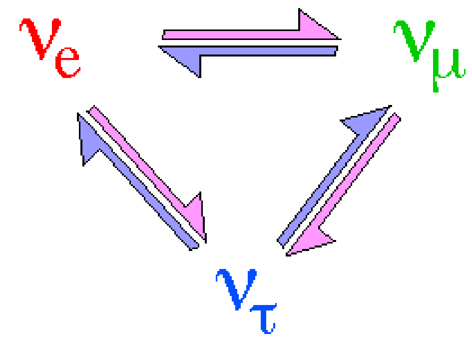
Decay Heat for Advanced Fuel Cycles



Lots of room for improvement !!

And now for something completely different …

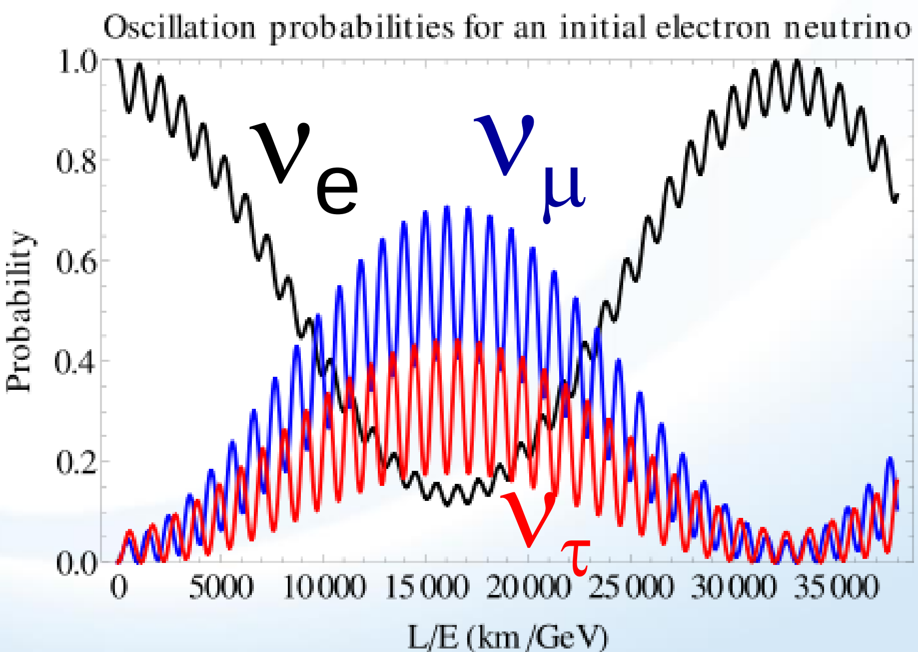
Neutrino Oscillations



$$|\nu_\alpha\rangle = \sum U_{\alpha i}^{*} |\nu_i\rangle$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

$\theta_{23} = 40.4^{\circ}{}^{+0.8^{\circ}}_{-1.8^{\circ}}$ $\theta_{13} = ??$ $\theta_{12} = 32.4^{\circ} \pm 0.8^{\circ}$



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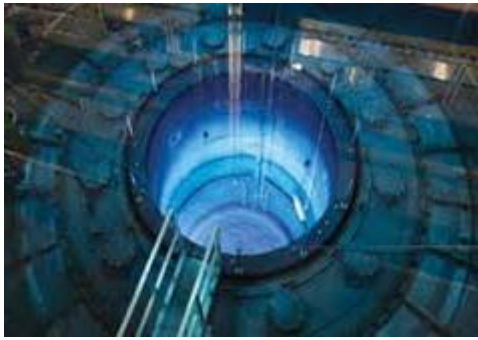
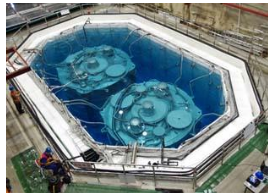
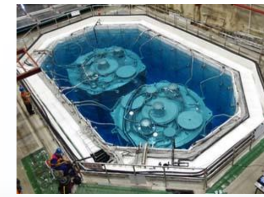
The race to measure the final mixing angle

Intense source of $\bar{\nu}_e$ → Distance from reactor





100 ton detectors



θ_{13}

Daya Bay θ_{13}

Selected for a Viewpoint in *Physics*
PRL 108, 171803 (2012) PHYSICAL REVIEW LETTERS week ending 27 APRIL 2012

Observation of Electron-Antineutrino Disappearance at Daya Bay

F. P. An,[1] J. Z. Bai,[1] A. B. Balantekin,[2] H. R. Band,[2] D. Beavis,[3] W. Beriguete,[3] M. Bishai,[3] S. Blyth,[4] K. Boddy,[5] R. L. Brown,[3] B. Cai,[5] G. F. Cao,[1] J. Cao,[1] R. Carr,[5] W. T. Chan,[3] J. F. Chang,[1] Y. Chang,[4] C. Chasman,[3] H. S. Chen,[1]

PRL 108, 131801 (2012) PHYSICAL REVIEW LETTERS week endi 30 MARCH

Indication of Reactor $\bar{\nu}_e$ Disappearance in the Double Chooz Experiment

Y. Abe,[28] C. Aberle,[21] T. Akiri,[4,15] J. C. dos Anjos,[5] F. Ardellier,[15] A. F. Barbosa,[5,*] A. Baxter,[26] M. Bergevin, A. Bernstein,[16] T. J. C. Bezerra,[30] L. Bezrukhov,[14] E. Blucher,[6] M. Bongrand,[15,30] N. S. Bowden,[16] C. Buck,[21] J. Busenitz,[2]

DOUBLE CHOOZ

RENO θ_{13}

PRL 108, 191802 (2012) PHYSICAL REVIEW LETTERS week ending 11 MAY 2012

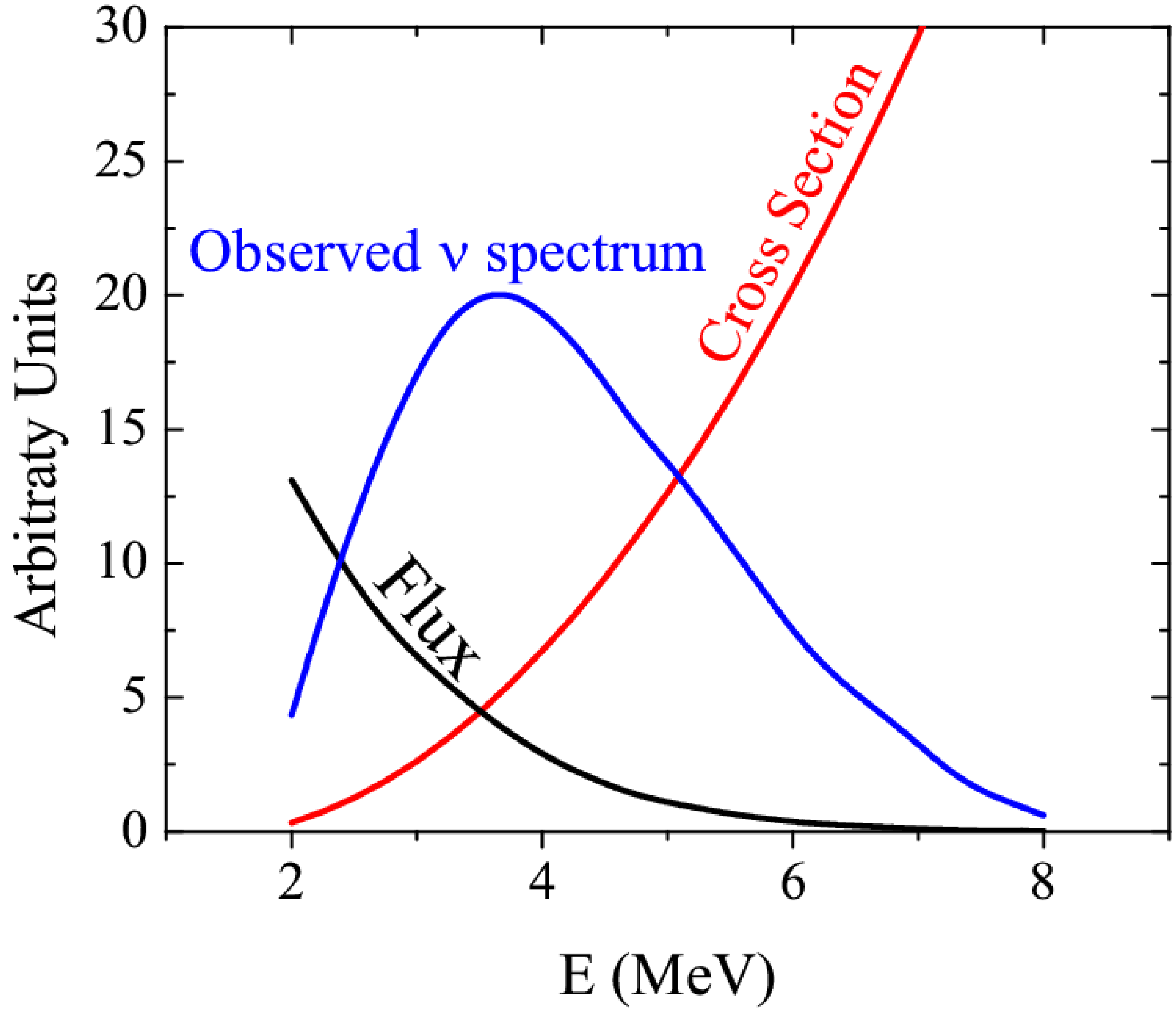
Observation of Reactor Electron Antineutrinos Disappearance in the RENO Experiment

J. K. Ahn,[7] S. Chebotaryov,[6] J. H. Choi,[4] S. Choi,[10] W. Choi,[10] Y. Choi,[12] H. I. Jang,[11] J. S. Jang,[2] E. J. Jeon,[8] I. S. Jeong,[2] K. K. Joo,[2] B. R. Kim,[2] B. C. Kim,[2] H. S. Kim,[1] J. Y. Kim,[2] S. B. Kim,[10] S. H. Kim,[7] S. Y. Kim,[7] W. Kim,[6] Y. D. Kim,[8]

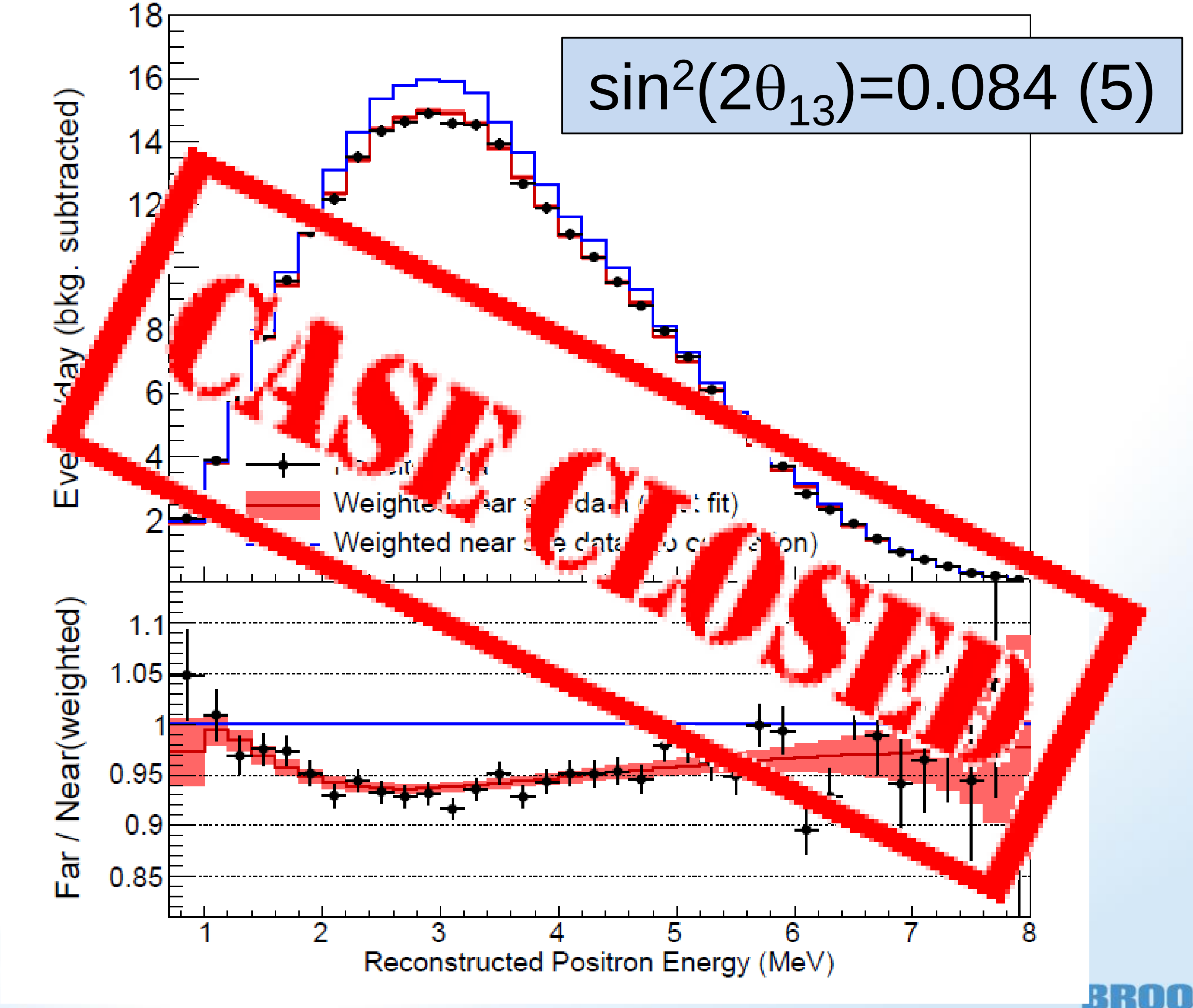
Antineutrino Spectrum

Detection through inverse β decay on proton

$$\bar{\nu}_e + p \rightarrow n + e^+$$



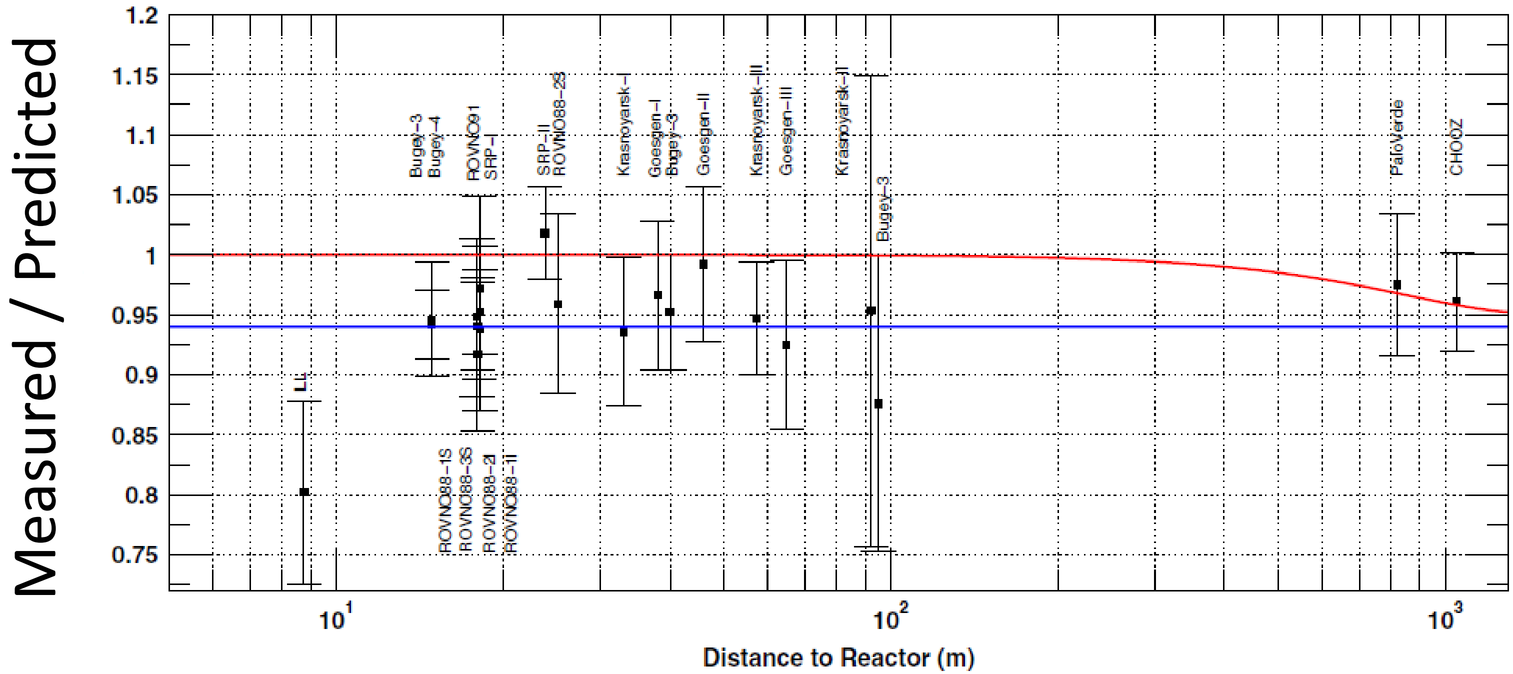
Daya Bay Results



F.P. An *et al*, Phys. Rev. Lett. **115**, 111802 (2015)

And then the story got more interesting

Analysis of all experiments close to reactors



Deficit in antineutrinos in all short baseline experiments

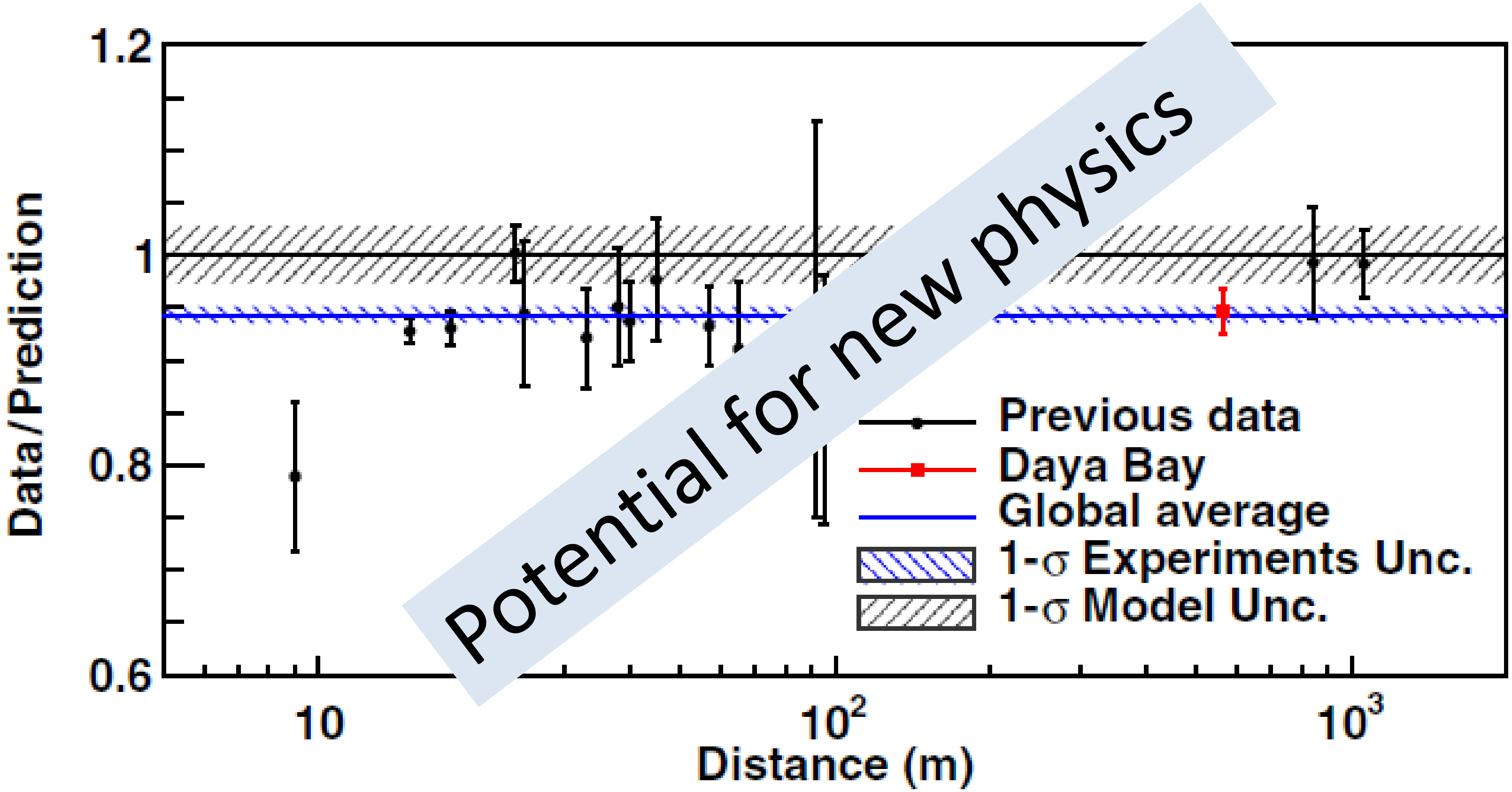
PHYSICAL REVIEW D 83, 073006 (2011)

Reactor antineutrino anomaly

G. Mention,[1] M. Fechner,[1] Th. Lasserre,[1,2,*] Th. A. Mueller,[3] D. Lhuillier,[3] M. Cribier,[1,2] and A. Letourneau[3]

And then the story got more interesting

Re-analysis + New Daya Bay results



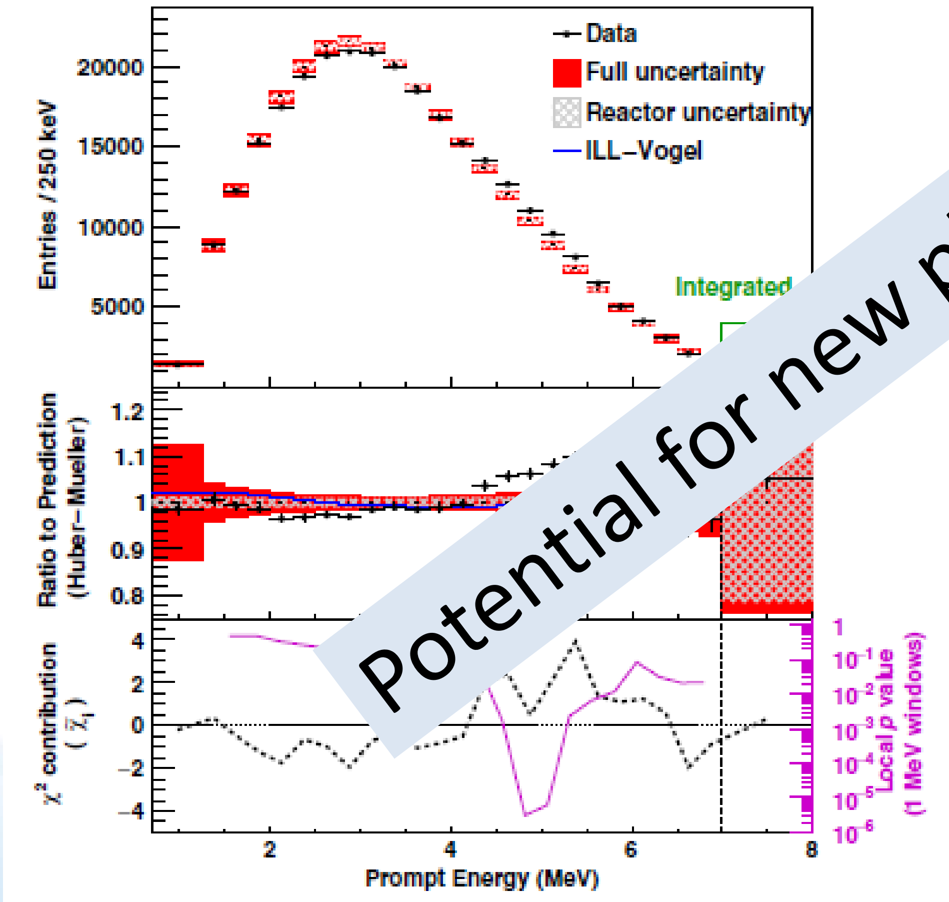
PRL 116, 061801 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay

And more interesting

The **"bump"** :

An excess of measured antineutrinos relative to predictions



Potential for new physics

Observed in Daya Bay, Reno and Double Chooz

F.P. An *et al*, Phys. Rev. Lett. **116**, 061801 (2016)

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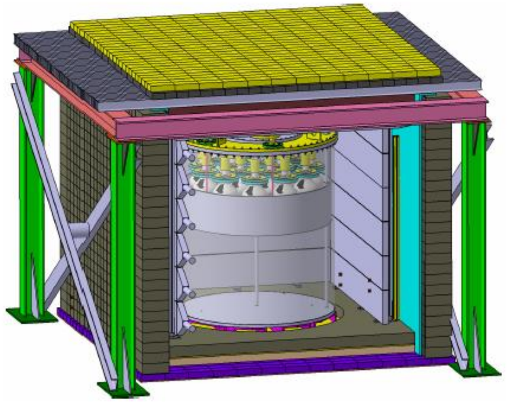
What are the implications?

Many possible explanations

- Predicted Antineutrino spectrum is incorrect
- Experimental bias in all 19 experiments
- New physics at short baselines
  - Existence of a 4th sterile neutrino
  - Would impact θ_{13} results

Efforts by the Neutrino Community

Numerous Very Short Baseline Experiments ranging from operating to planning stages

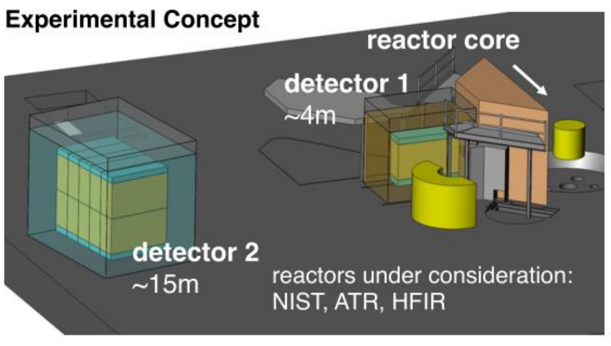


Nucifer, France

Operational, D=7m

Neutrino-4, Russia

Nearly Operational, D=6-13m



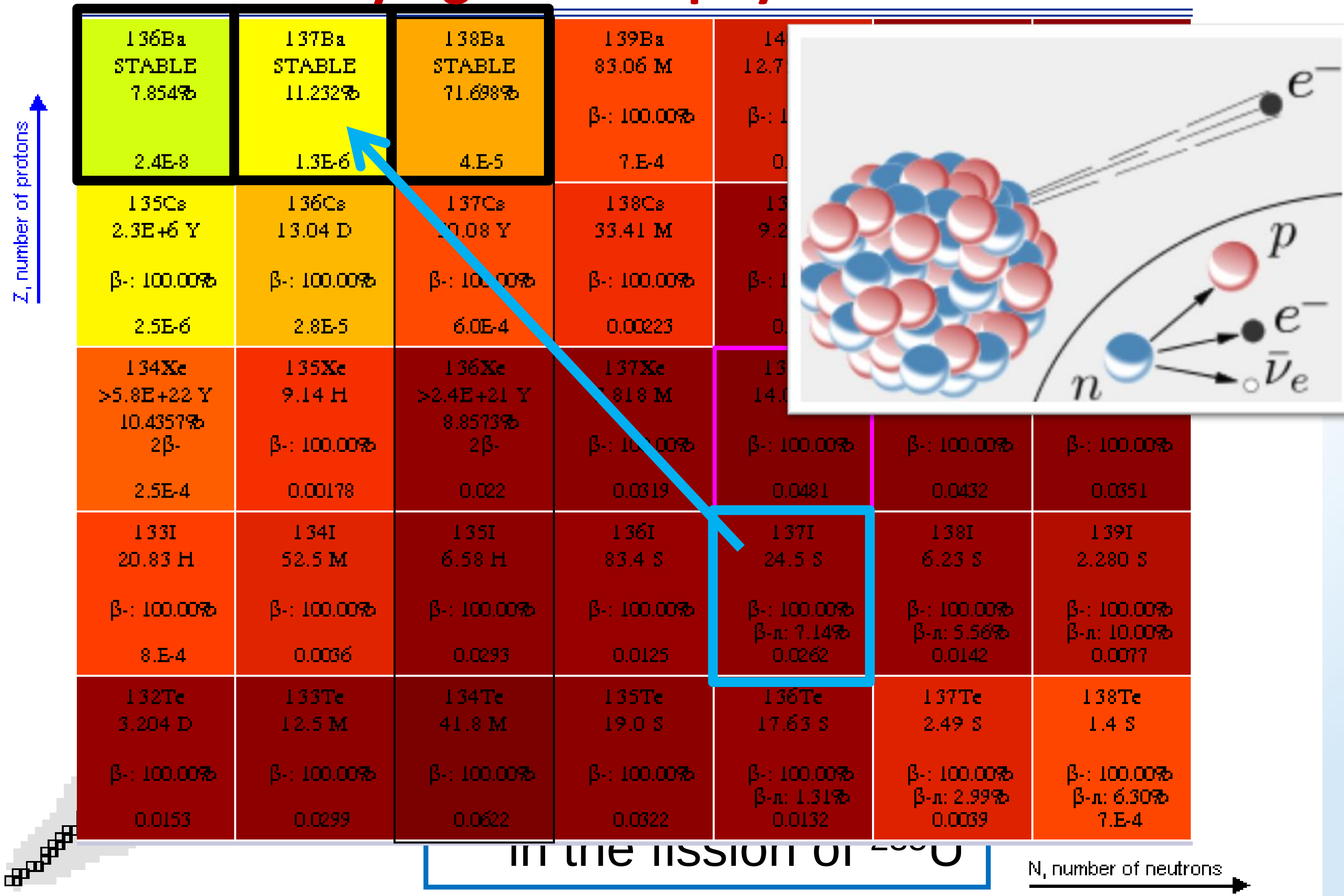
PROSPECT, USA

Under Construction, ORNL

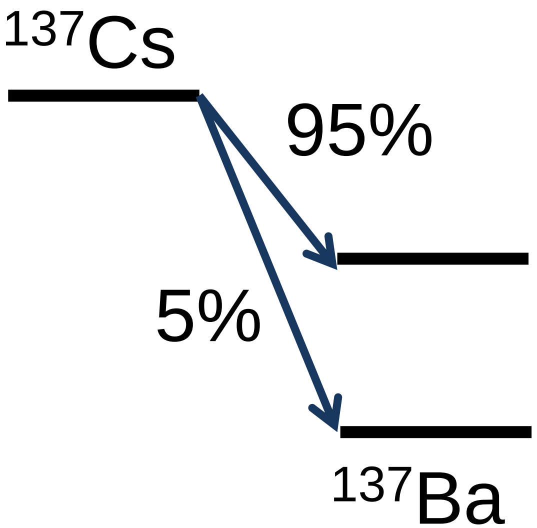
CORMORAD – Italy, PANDA – Japan, SOLiD - France

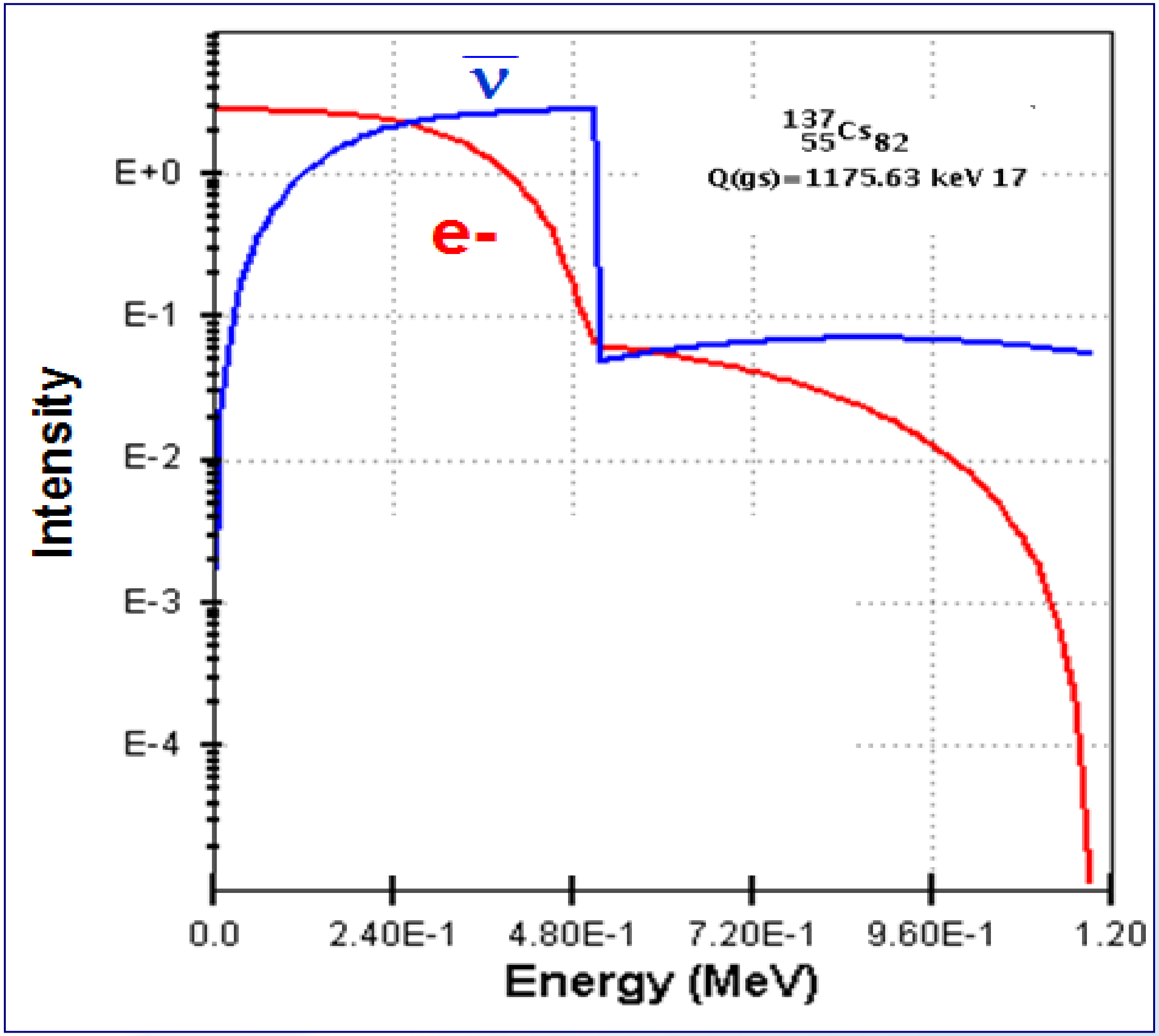
Method to calculate the spectrum

Relies on underlying nuclear physics in a reactor



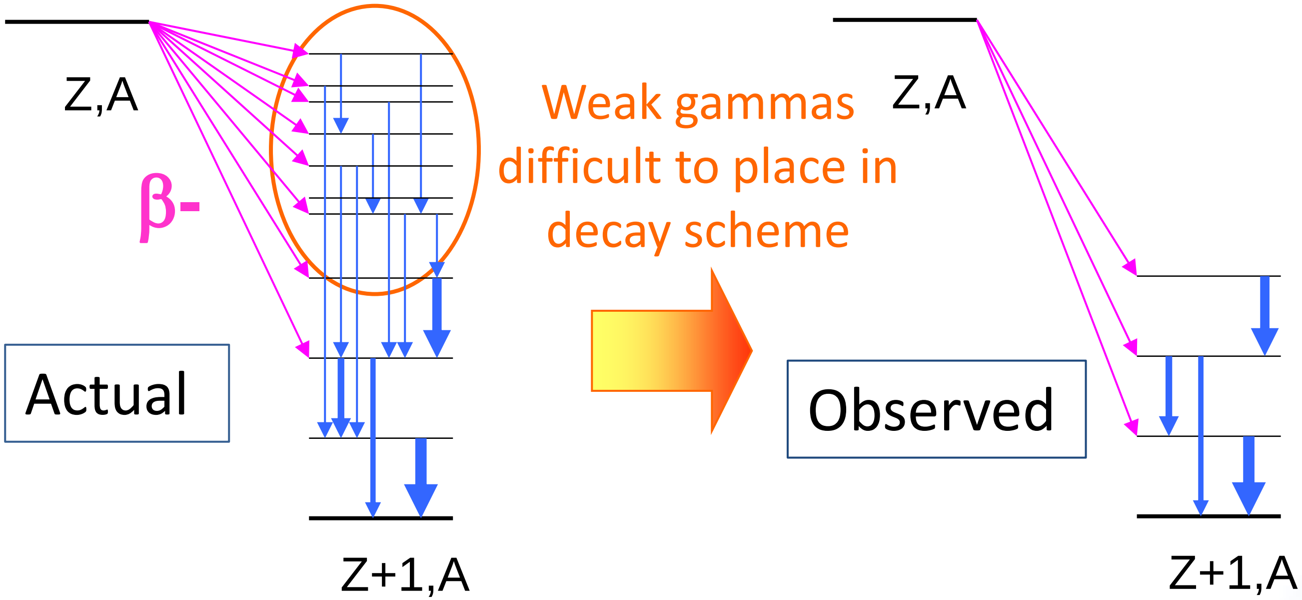
Simple Example : ^{137}Cs





$$I(E)=N\,W\,(W^2-1)^{1/2}(W-W_0)^2\,F(Z,W)\,C_{exp}\,C_L\,C_{screen}\,C_{rad}\,C_{wm}$$

But most things aren't simple



Incomplete decay schemes:

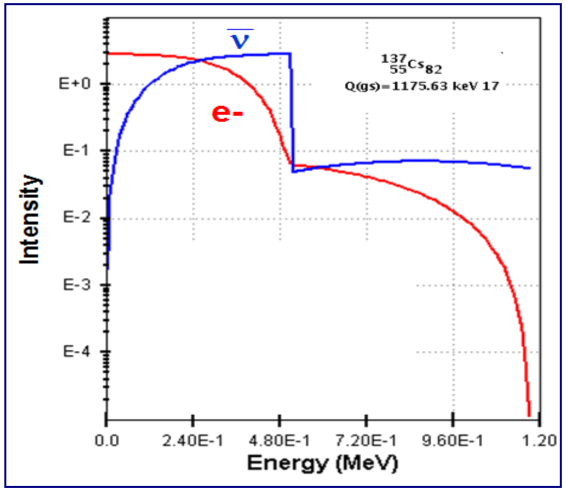
- Smaller gamma-ray energies
- Larger beta energies
- 1st realized by Hardy in 1970's
- Termed Pandemonium effect

New RIB facilities + New Total Absorption Gamma-ray Spectrometers (TAGS): Will soon address these issues

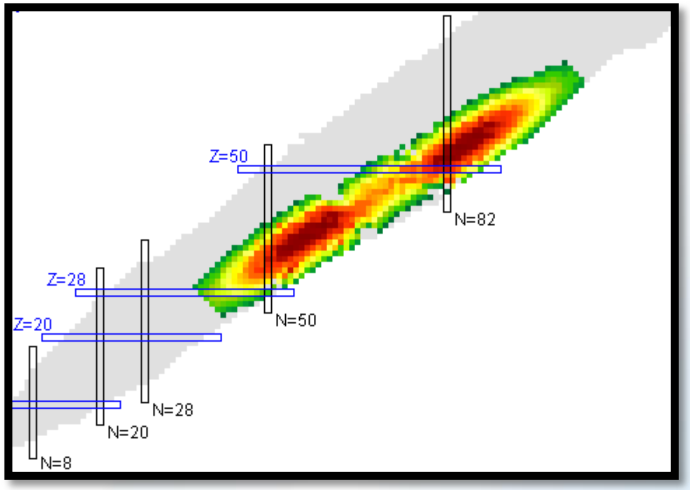
Alternative Method = Summation

Two main ingredients

Beta spectra



Fission Yields



Low precision (~10 % uncertainty) but …

- Can calculate for any fissioning isotope
- Has direct link to underlying physics
- Doesn’t rely on a single measurement

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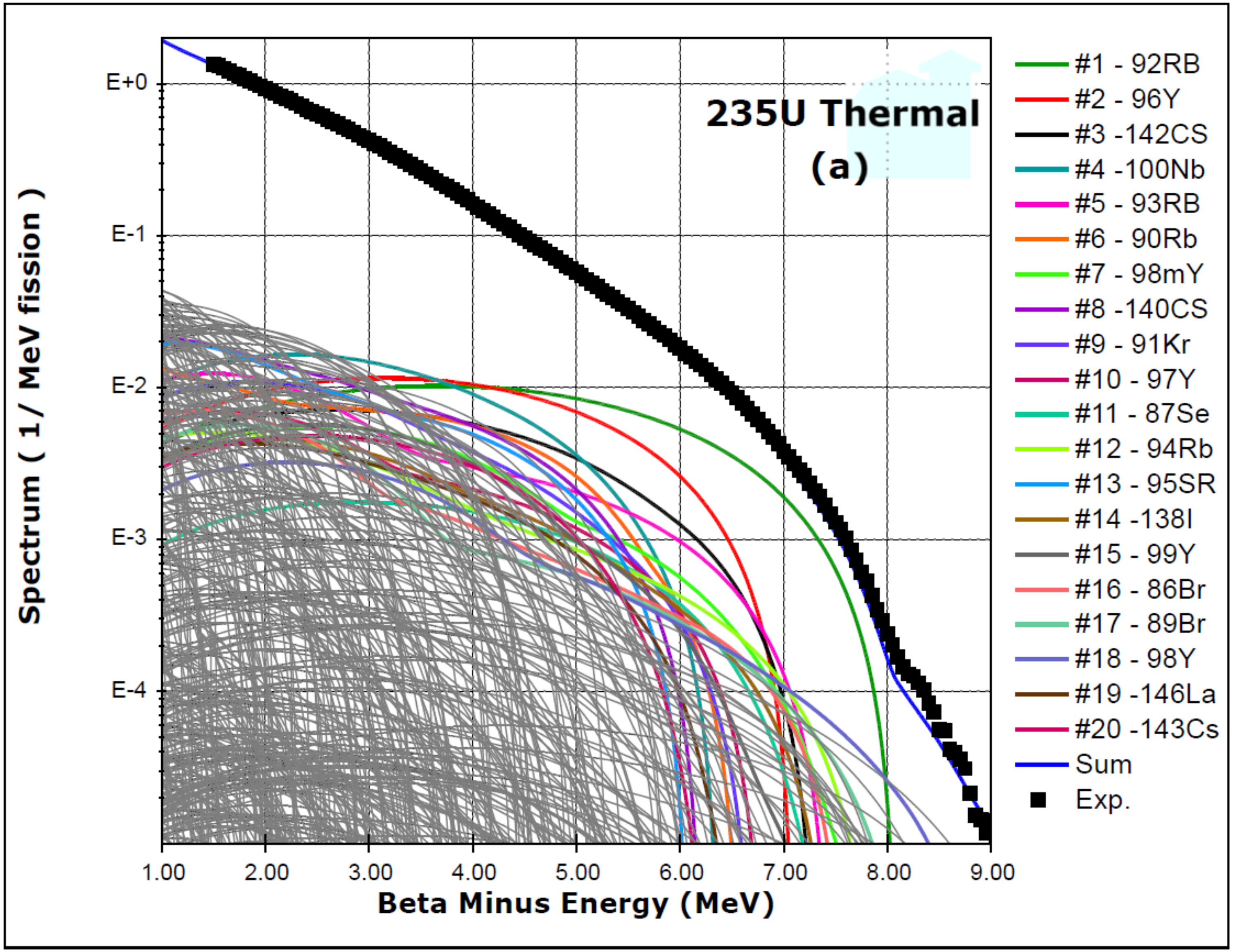
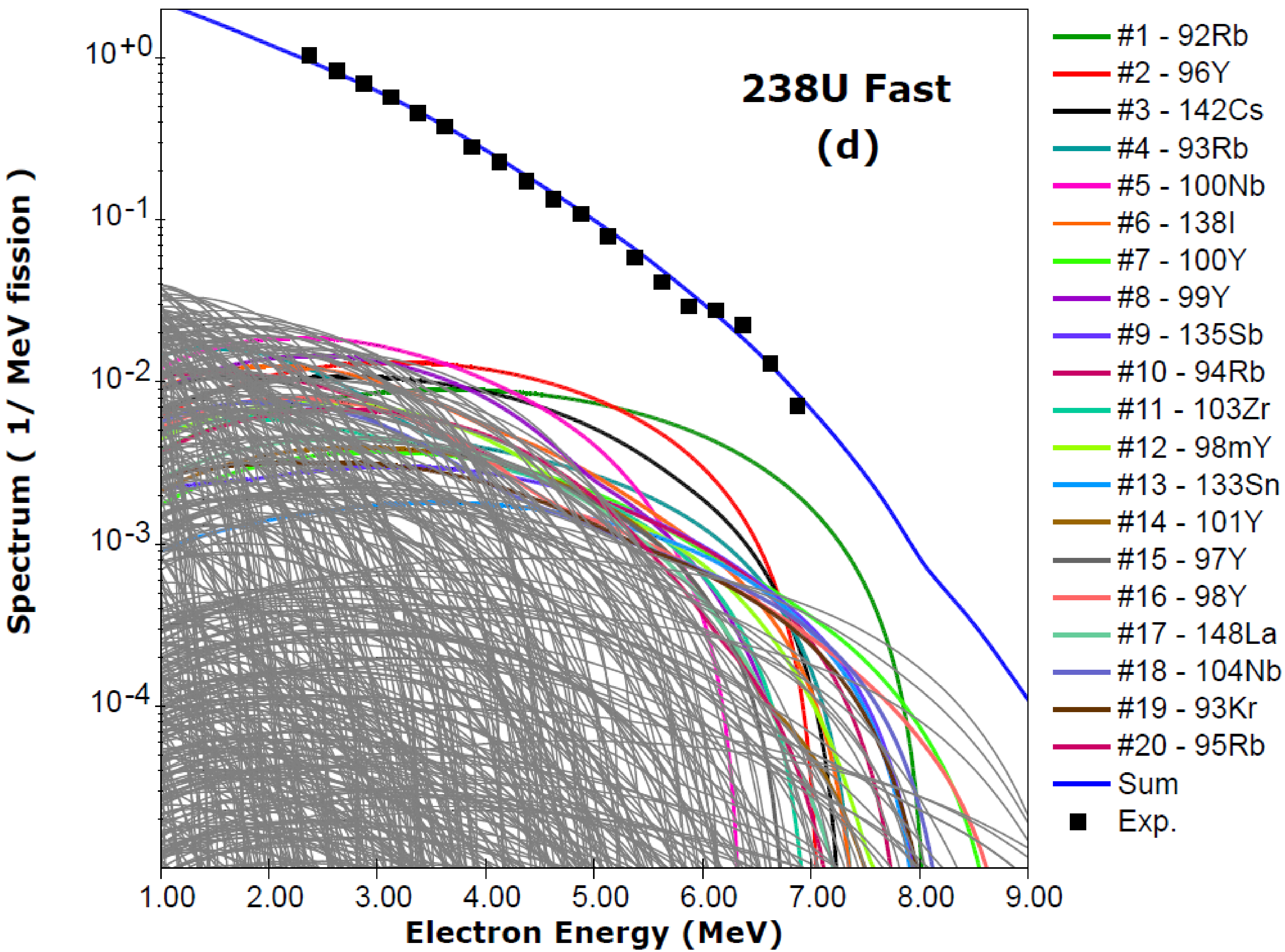
NNDC Calculations for ^{235}U

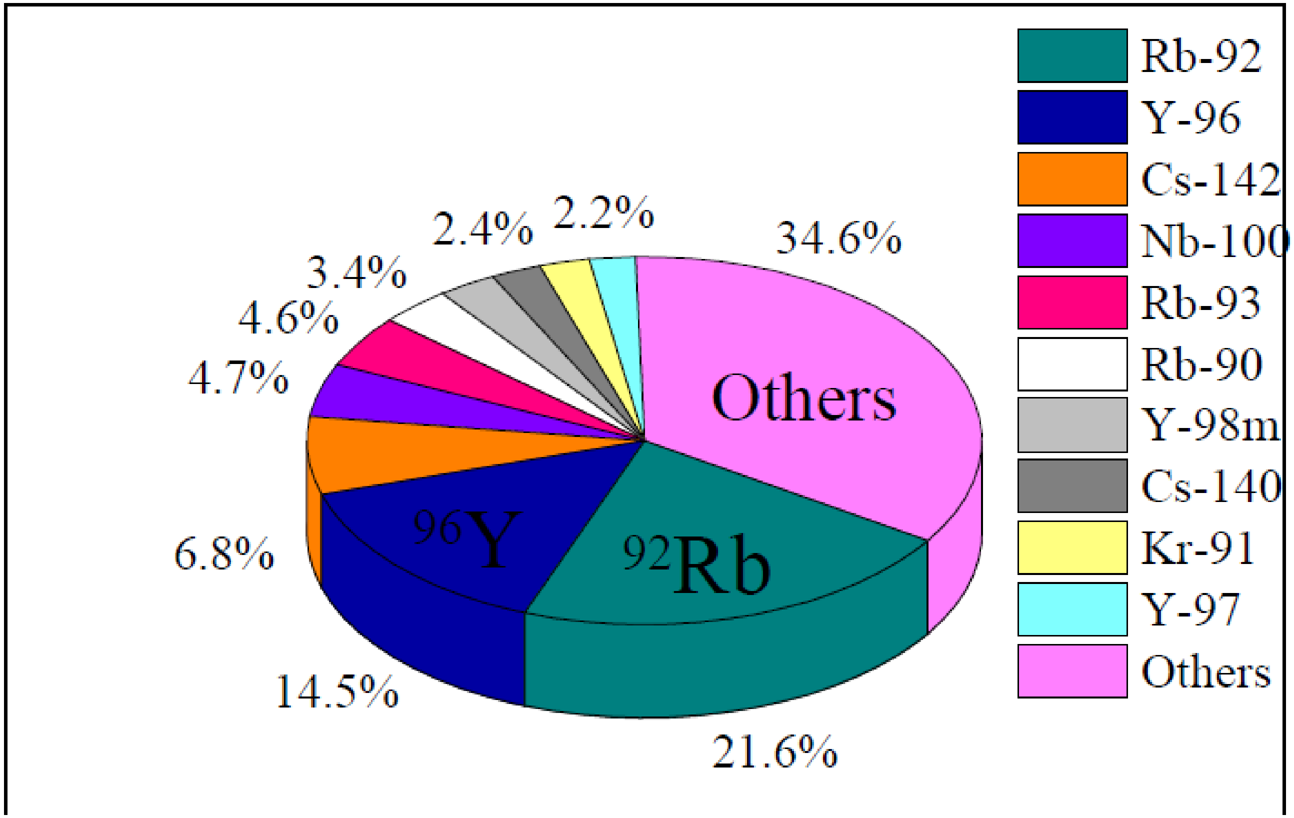


A.A. Sonzogni, T.D. Johnson, E.A. McCutchan, Phys. Rev. C 91, 011301(R) (2015).

NNDC Calculations for ^{238}U



Main Contributors at ~5 MeV



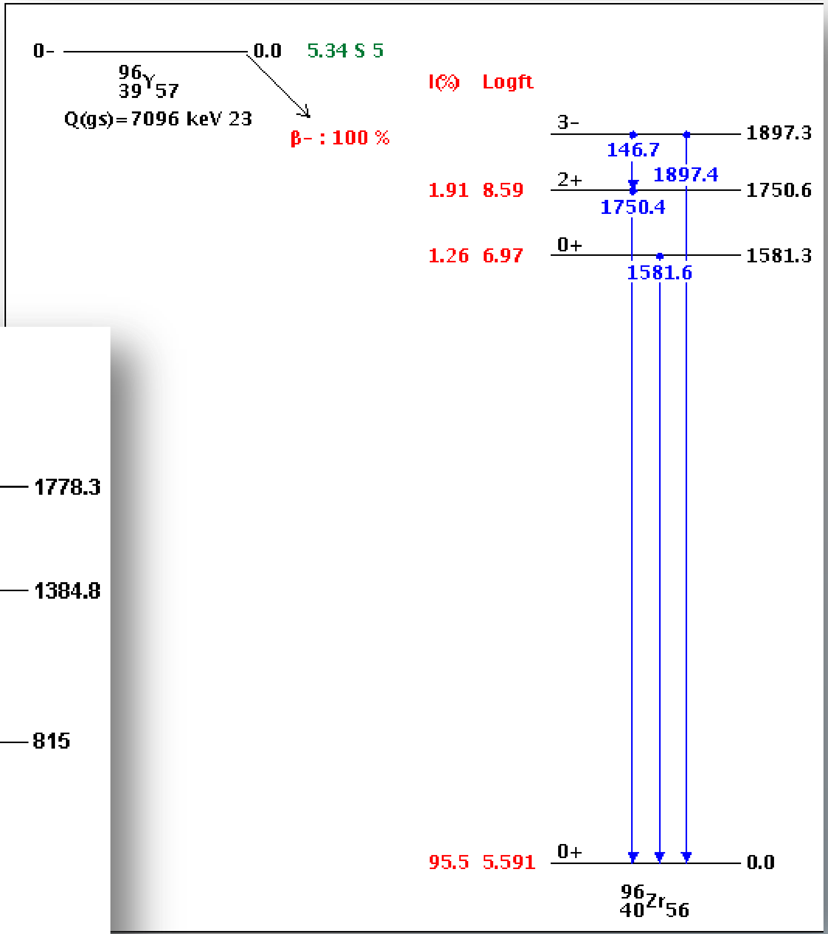
Top 10 contribute more than 60% to the overall spectrum

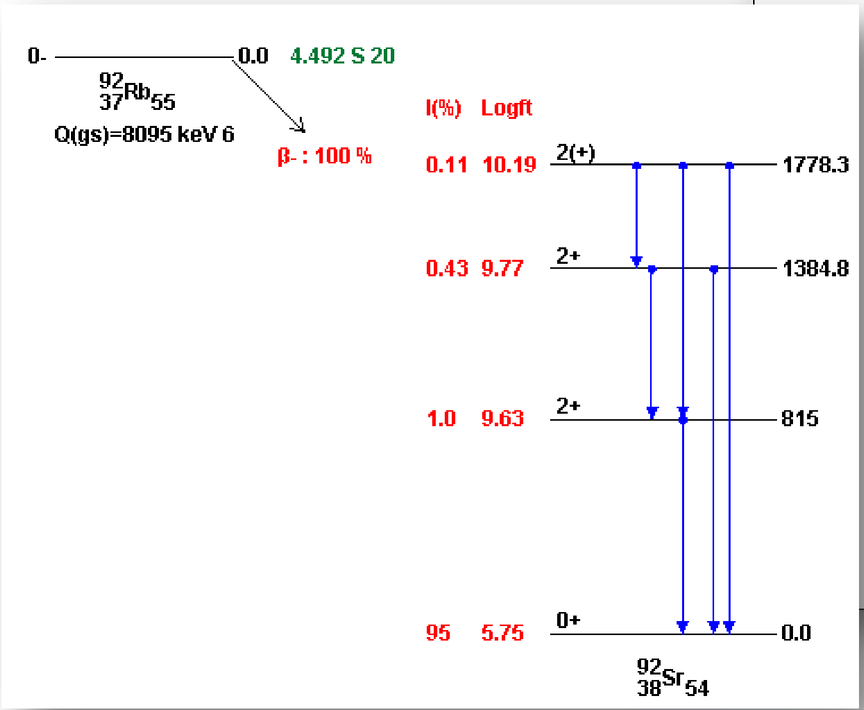
New measurements underway based on these sensitivity studies

D.A. Dwyer and T.D. Langford, Phys. Rev. Lett. 114, 012502 (2015).
A.-A. Zakari-Issoufou et al., Phys Rev. Lett. 115 102503 (2015).

What do these have in common?

First forbidden non-unique, ground-state to ground-state transition accounting for 95% of beta intensity





Need precise measurements of g.s. to g.s. (or g.s. to low-lying states) β intensity

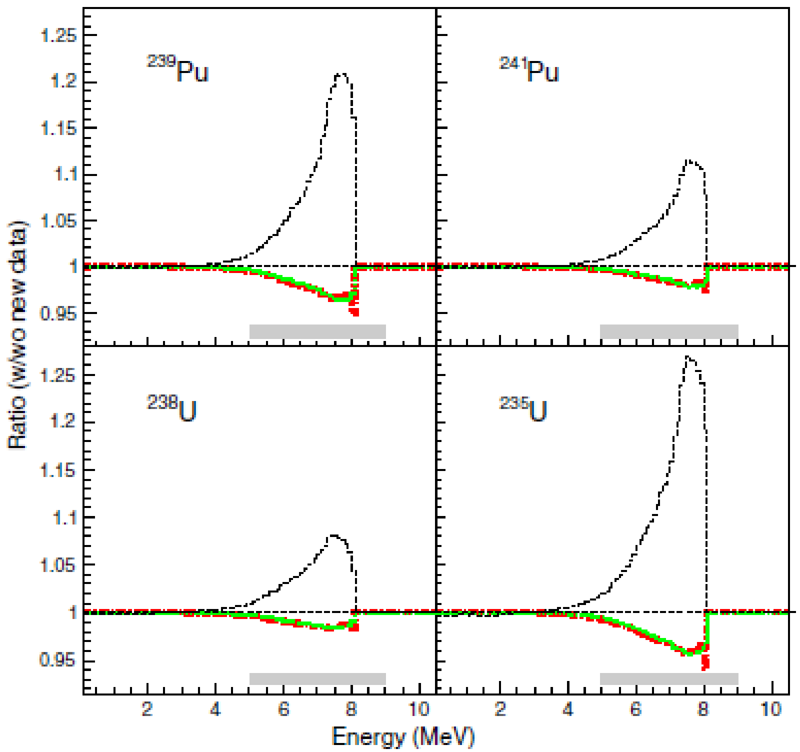
The ^{92}Rb race is on

PRL 115, 102503 (2015) PHYSICAL REVIEW LETTERS week ending 4 SEPTEMBER 2015

Total Absorption Spectroscopy Study of ^{92}Rb Decay: A Major Contributor to Reactor Antineutrino Spectrum Shape

A.-A. Zakari-Issoufou,[1] M. Fallot,[1] A. Porta,[1,*] A. Algora,[2,3] J. L. Tain,[2] E. Valencia,[2] S. Rice,[4] V. M Bui,[1] S. Cormon,[1] M. Estienne,[1] J. Agramunt,[2] J. Äystö,[5] M. Bowry,[4] J. A. Briz,[1] R. Caballero-Folch,[6] D. Cano-Ott,[7] A. Cucoanes,[1] V.-V. Elomaa,[8] T. Eronen,[8] E. Estévez,[2] G. F. Farrelly,[4] A. R. Garcia,[7] W. Gelletly,[2,4] M. B. Gomez-Hornillos,[6] V. Gorlychev,[6] J. Hakala,[8] A. Jokinen,[8] M. D. Jordan,[2] A. Kankainen,[8] P. Karvonen,[8] V. S. Kolhinen,[8] F. G. Kondev,[9] T. Martinez,[7] E. Mendoza,[7] F. Molina,[2,†] I. Moore,[8] A. B. Perez-Cerdán,[2] Zs. Podolyák,[4] H. Penttilä,[8] P. H. Regan,[4,10] M. Reponen,[8,‡] J. Rissanen,[8] B. Rubio,[2] T. Shiba,[1] A. A. Sonzogni,[11] C. Weber,[8,§] and IGISOL collaboration[8]

G.S. Branch from
95 % to 87.2 (25)%

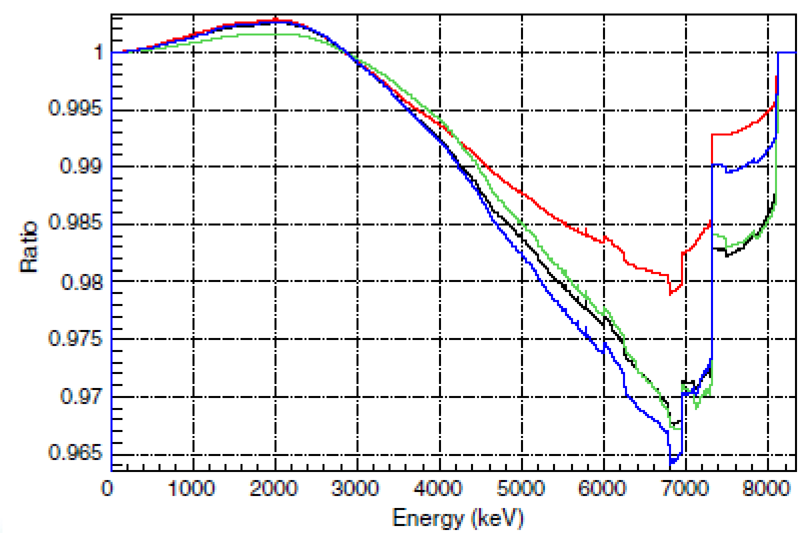


PRL 117, 092501 (2016) PHYSICAL REVIEW LETTERS week ending 26 AUGUST 2016

Decays of the Three Top Contributors to the Reactor $\bar{\nu}_e$ High-Energy Spectrum, ^{92}Rb, ^{96gs}Y, and ^{142}Cs, Studied with Total Absorption Spectroscopy

B. C. Rasco,[1,2,3,4,*] M. Wolińska-Cichocka,[5,2,1] A. Fijałkowska,[6,3] K. P. Rykaczewski,[2] M. Karny,[6,2,1] R. K. Grzywacz,[3,2,1] K. C. Goetz,[7,3] C. J. Gross,[2] D. W. Stracener,[2] E. F. Zganjar,[4] J. C. Batchelder,[8,1] J. C. Blackmon,[4] N. T. Brewer,[1,2,3] S. Go,[3] B. Heffron,[3,2] T. King,[3] J. T. Matta,[2] K. Miernik,[6,1] C. D. Nesaraja,[2] S. V. Paulauskas,[3] M. M. Rajabali,[9] E. H. Wang,[10] J. A. Winger,[11] Y. Xiao,[3] and C. J. Zachary[10]

G.S. Branch 91 (3) %



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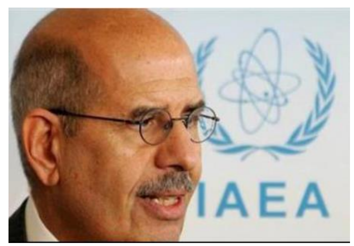
Real “applied” uses for antineutrinos ?

Outside-the-box thinking

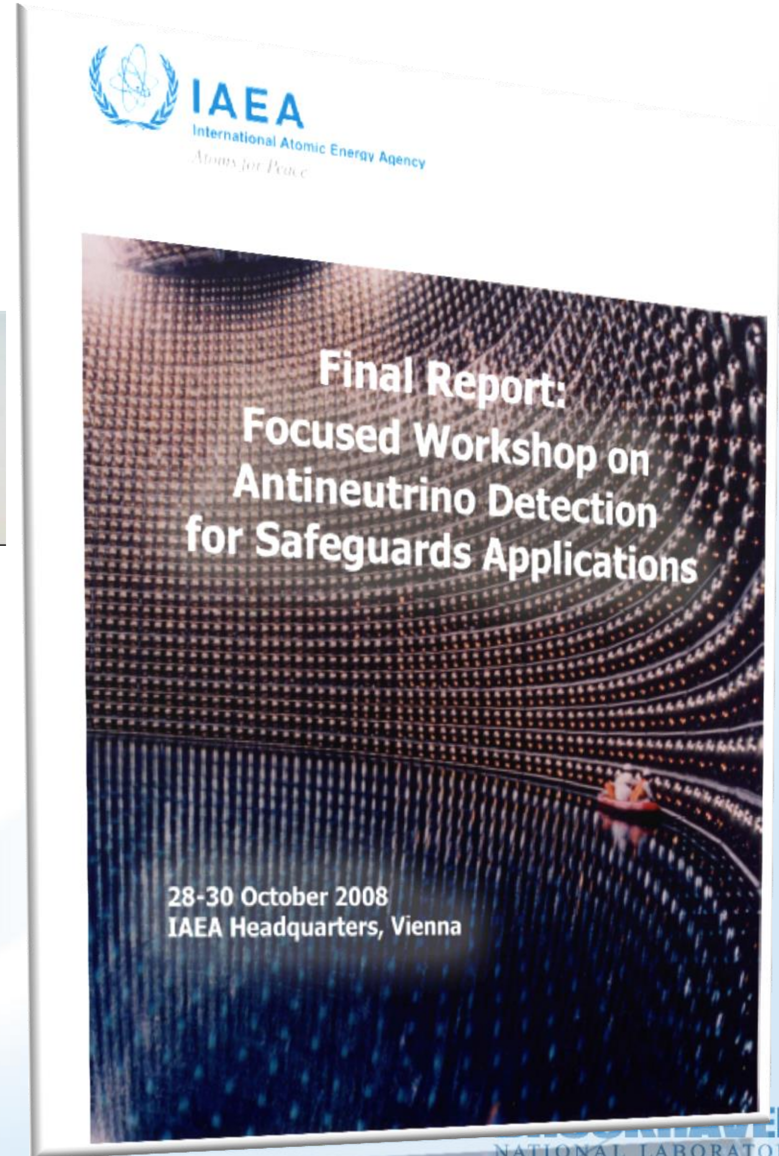
"In regard to nuclear proliferation and arms control, the fundamental problem is clear: Either we begin finding creative, outside-the-box solutions or the international nuclear safeguards regime will become obsolete."

-

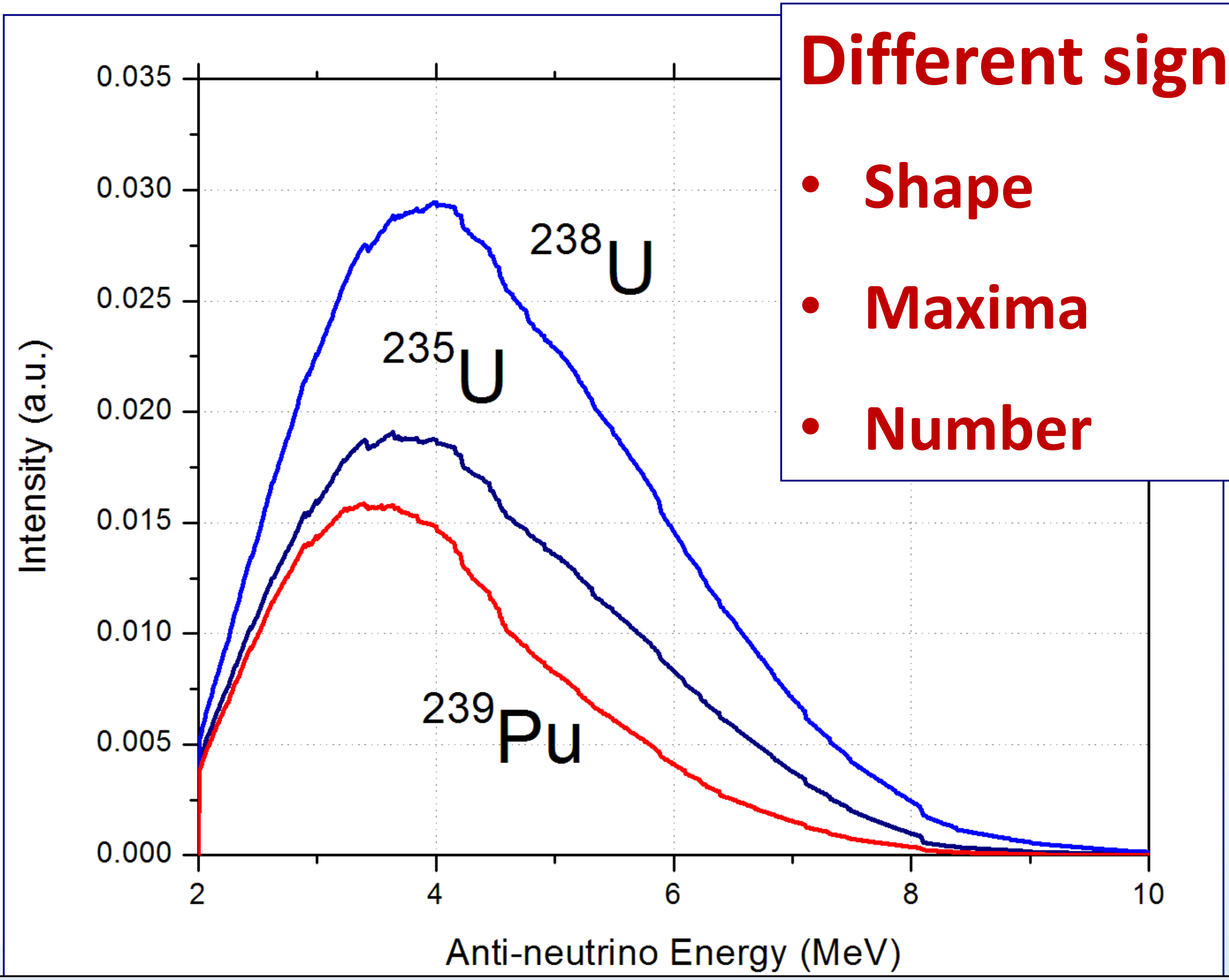
M. ElBaradei,
then Director General of the IAEA
Washington Post, June 14, 2006



- Neutrinos go through everything
- Large investments in neutrino detection technology
- Understand neutrino flux from reactors



Exploit differences in signal

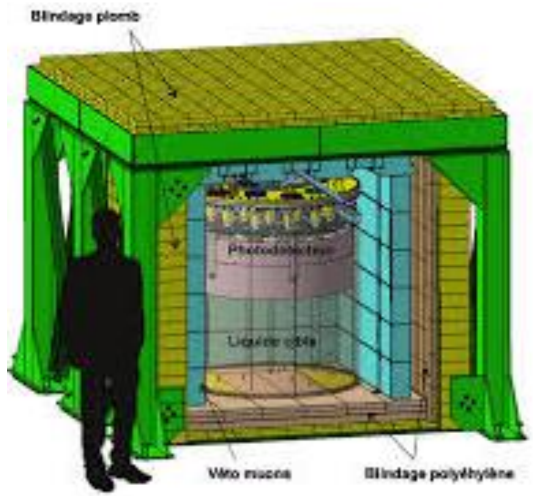


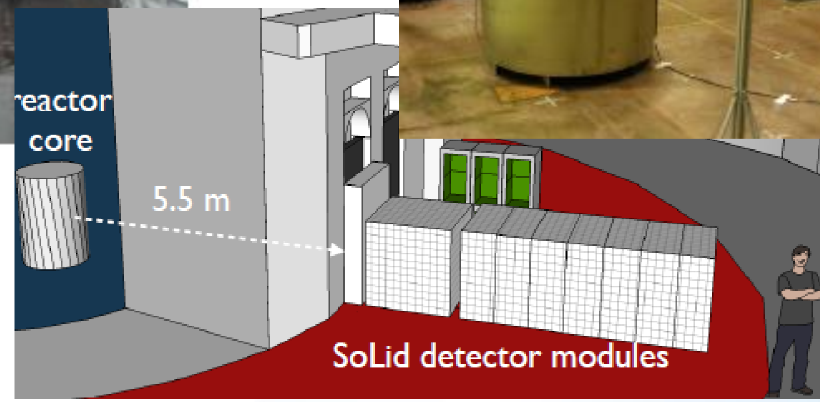
Different signal in

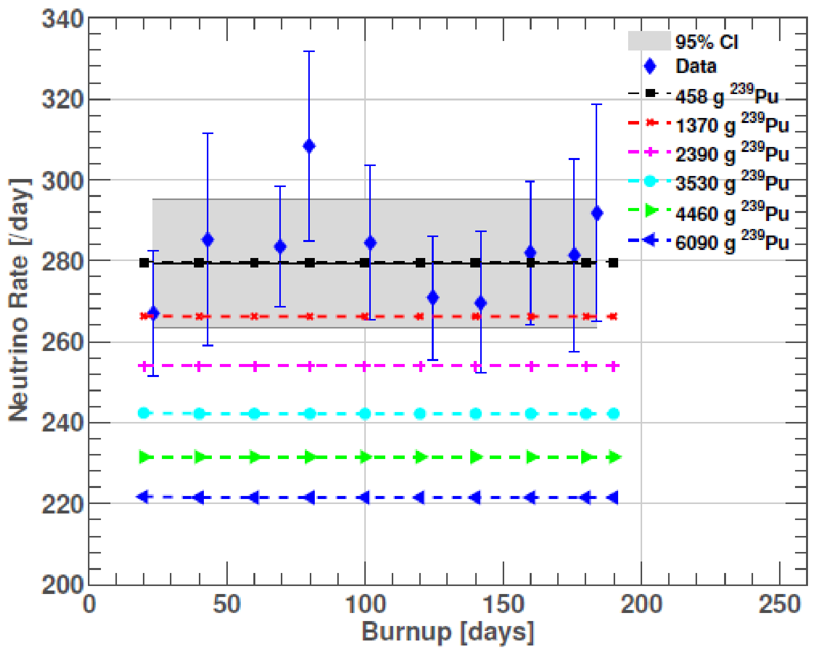
- **Shape**
- **Maxima**
- **Number**

Can be used in non-proliferation and reactor monitoring
Advantages : Non-intrusive, "real-time" measurements

This sounds crazy… but its not







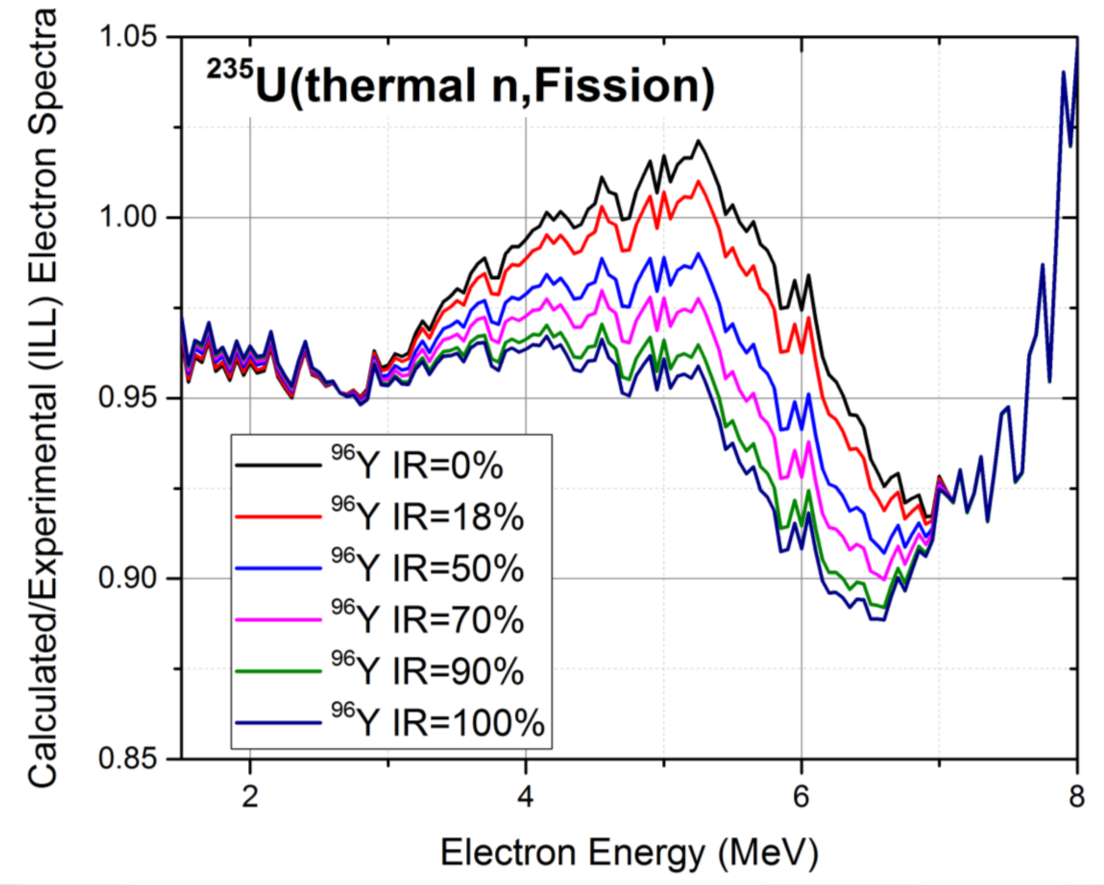
Many efforts

- USA
- Canada
- Japan
- France
- Brazil
- Italy
- UK
- Korea

BROOKHAVEN NATIONAL LABORATORY

And will stay open

^{96}Y Isomeric Yield Effect



$$IR = \frac{IFY(^{96m}Y)}{IFY(^{96m}Y) + IFY(^{96gs}Y)}$$

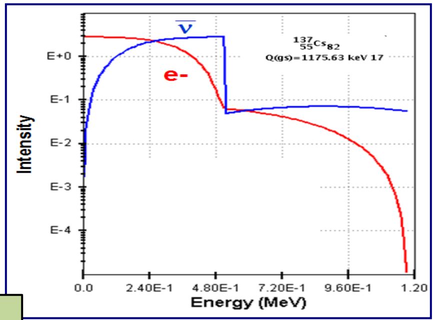
Estimates of IR vary from 18% to 70%

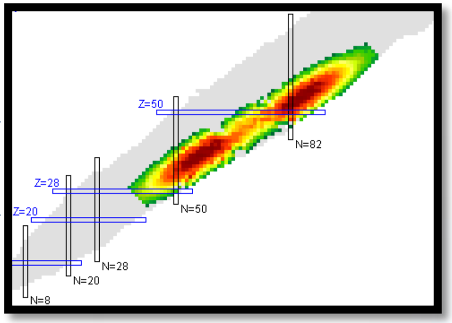
Changes predicted spectrum by up to 7%

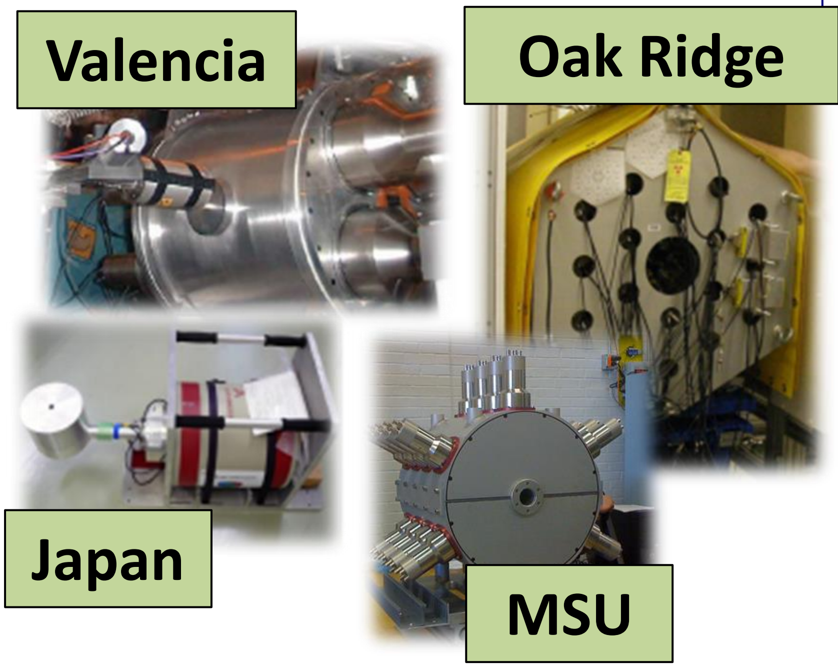
NNDC,ILL,Mainz approved experiment to measure at ILL soon

But not for long

Beta Spectrum







Fission Yields

RIB facilities making new measurements every day

SPIDER: A new instrument for fission fragment research at the Los Alamos Neutron Science Center

Fredrik Tovesson[1,a], Charles Arnold[1], Rick Blakeley[2], Adam Hecht[2], Alexander Laptev[1], Drew Mader[2], Krista Meierbachtol[1], Lucas Snyder[3], and Morgan White[1]

- High precision
- Range of neutron energies