Nuclear Data in Applications

Libby McCutchan

National Nuclear Data Center
Brookhaven National Laboratory, NY USA

BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

Nuclear Data Program

Link between basic science and applications

Nuclear Science Community

- experiments
- theory

Nuclear Data Community

✦ compilation
✦ evaluation
✦ dissemination
✦ archival

Application Community

needs data:

✦ complete
✦ organized
✦ traceable
✦ readable

Nuclear data as a utility

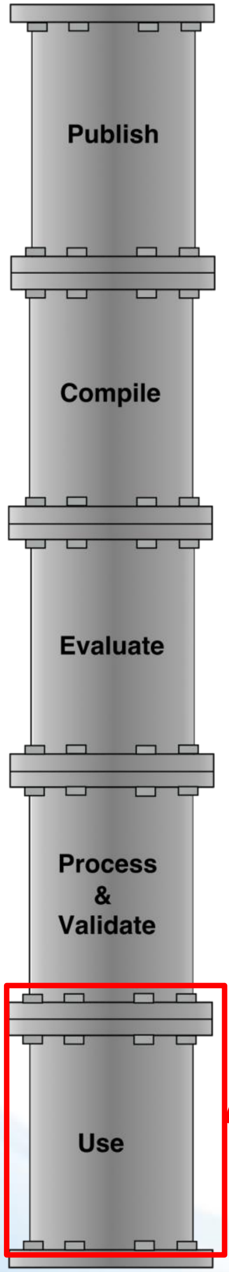
There is a vast source of data

Which is processed, separated and shipped to you

Although not the most exciting part, we can't forget about the infrastructure

In a convenient and usable form

The Nuclear Data Pipeline



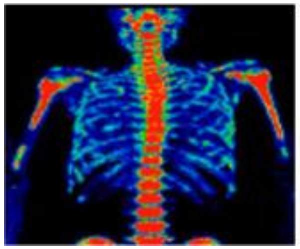
The USNDP's primary goal is to get the highest quality data to users

science

FRIB

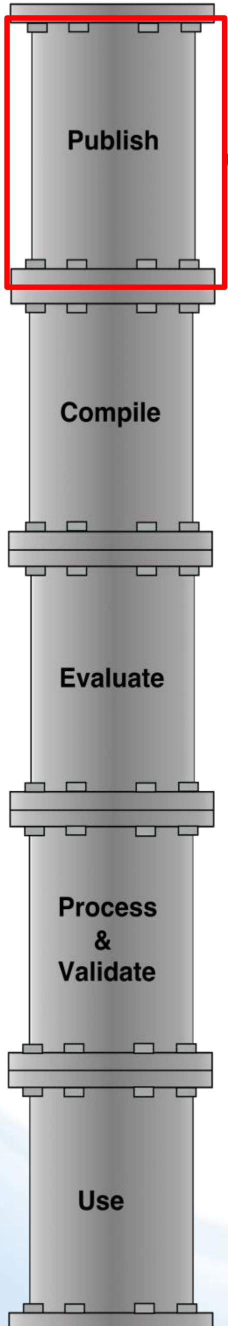
security

isotopes



energy

The Nuclear Data Pipeline

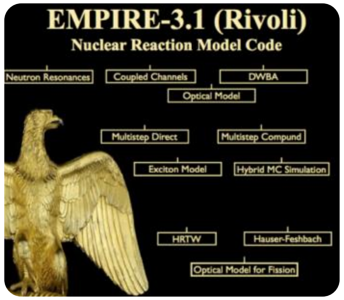


Our work begins when data is (or should be) published

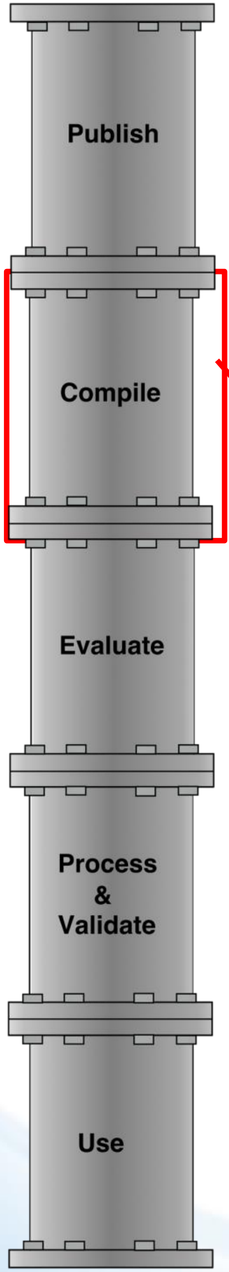
Code development: Actively develop codes that support our work

Archive: Seek “abandoned” data and archive it before it is lost

Address gaps: Perform targeted experiments to address gaps in databases



The Nuclear Data Pipeline



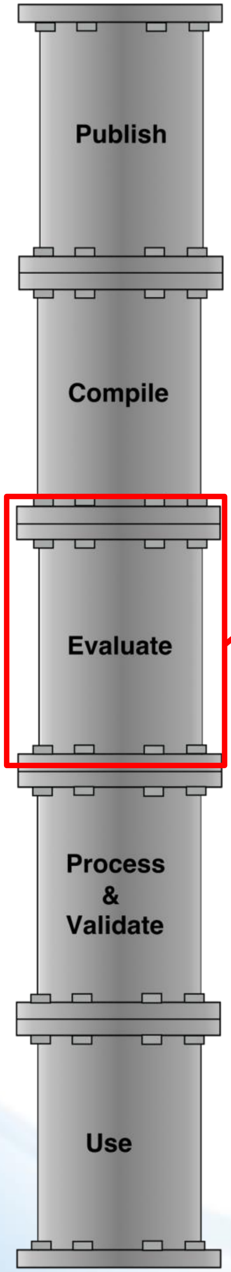
Data is compiled into databases

Nuclear Science References (NSR):
226,000 nuclear physics articles indexed according to content.
3,300 articles added in FY17 from 80 journals.

EXFOR: Compiled nuclear reaction data, originally only for neutron-induced. Data from 100 articles added in FY17.

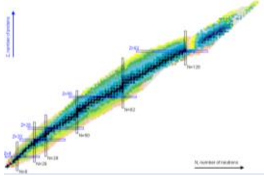
XUNDL: Compiled nuclear structure and decay data.
Data from 325 articles added in FY17.

The Nuclear Data Pipeline



Evaluate data by combining all information into recommended values

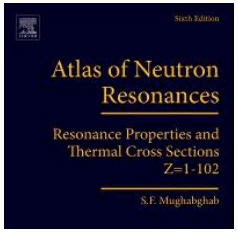
ENSDF: Recommended nuclear structure and decay data for all 3,325 known nuclides.



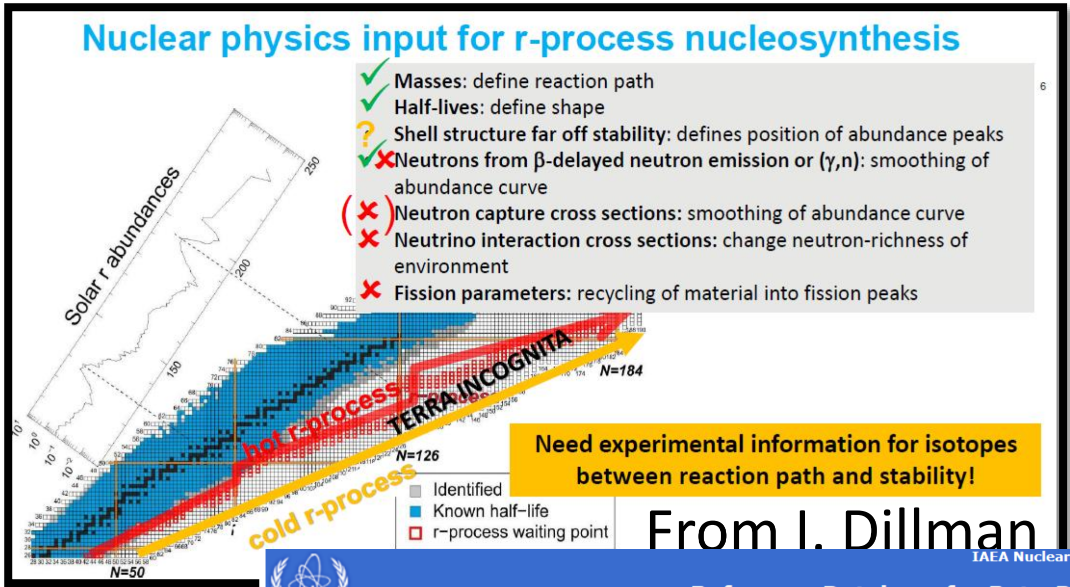
ENDF: Recommended particle transport and decay data, with a strong emphasis on neutron-induced reaction data

ENDF B-VIII.0

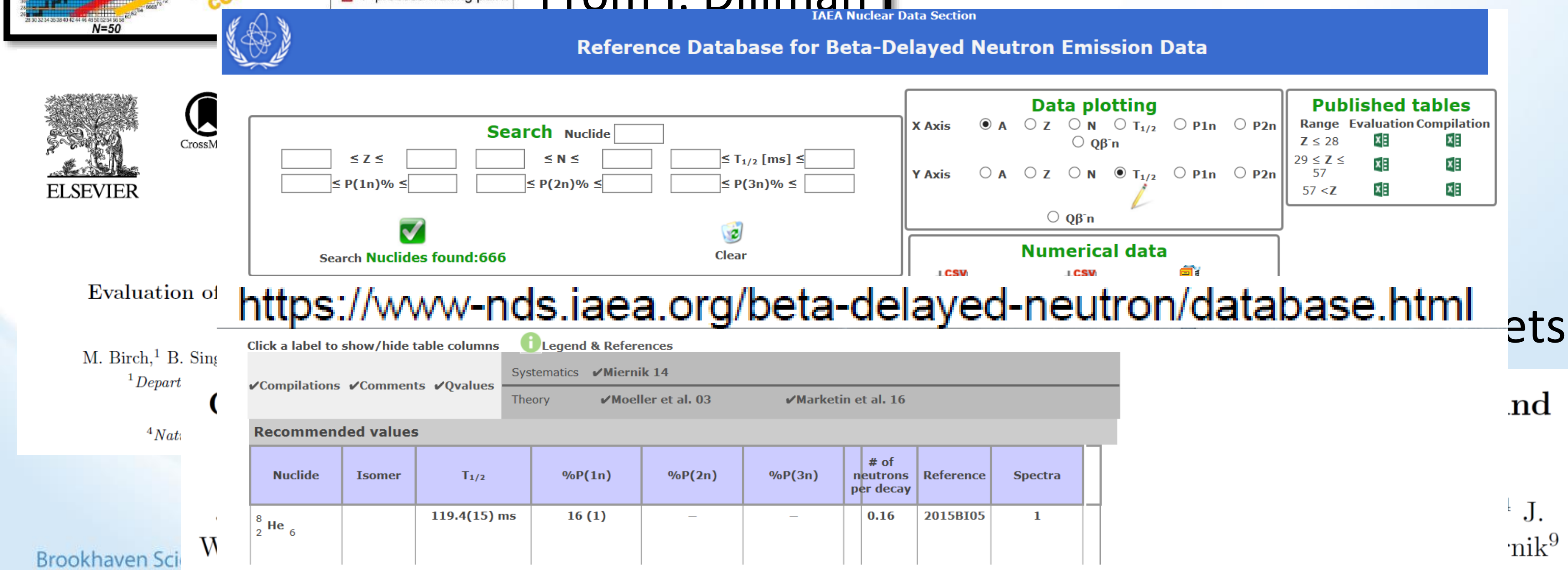
Atlas of Neutron Resonances: 6th edition of the famed successor to BNL-325, contains neutron resonance parameters, thermal cross sections and average resonance parameters.



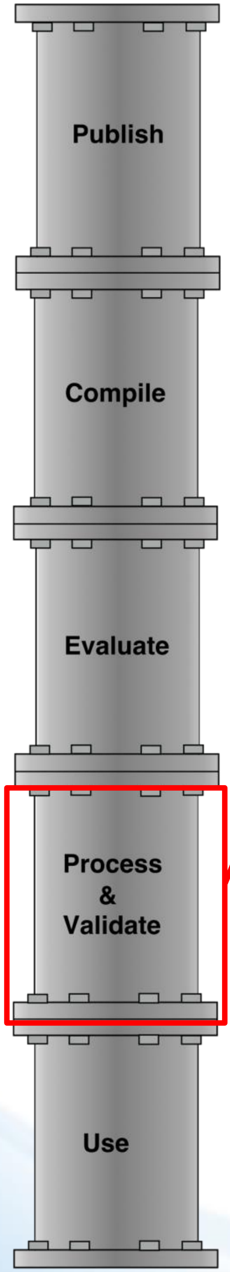
Horizontal Evaluations



- Half-lives and β-delayed neutron emission last compiled by Rudstam 2002
- IAEA coordinated research project, evaluation led by B. Singh



The Nuclear Data Pipeline



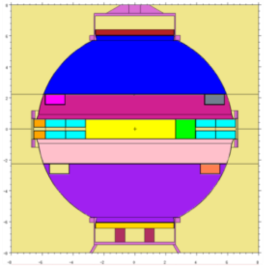
Collaborate with nuclear data community to get data ready for users

Processing: Prepare data for use in application codes.

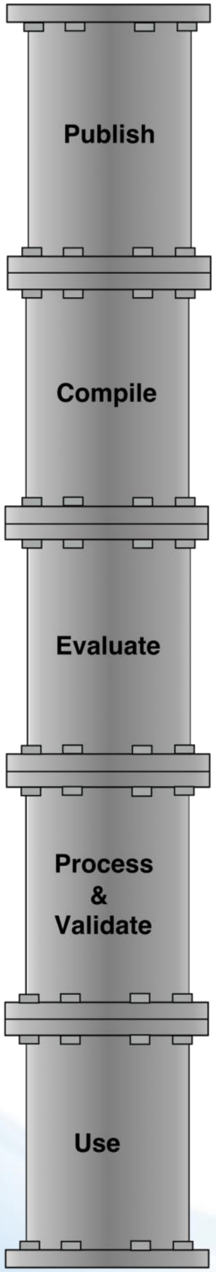
Validation: Test data in simulations of non-trivial, but well understood, nuclear systems.

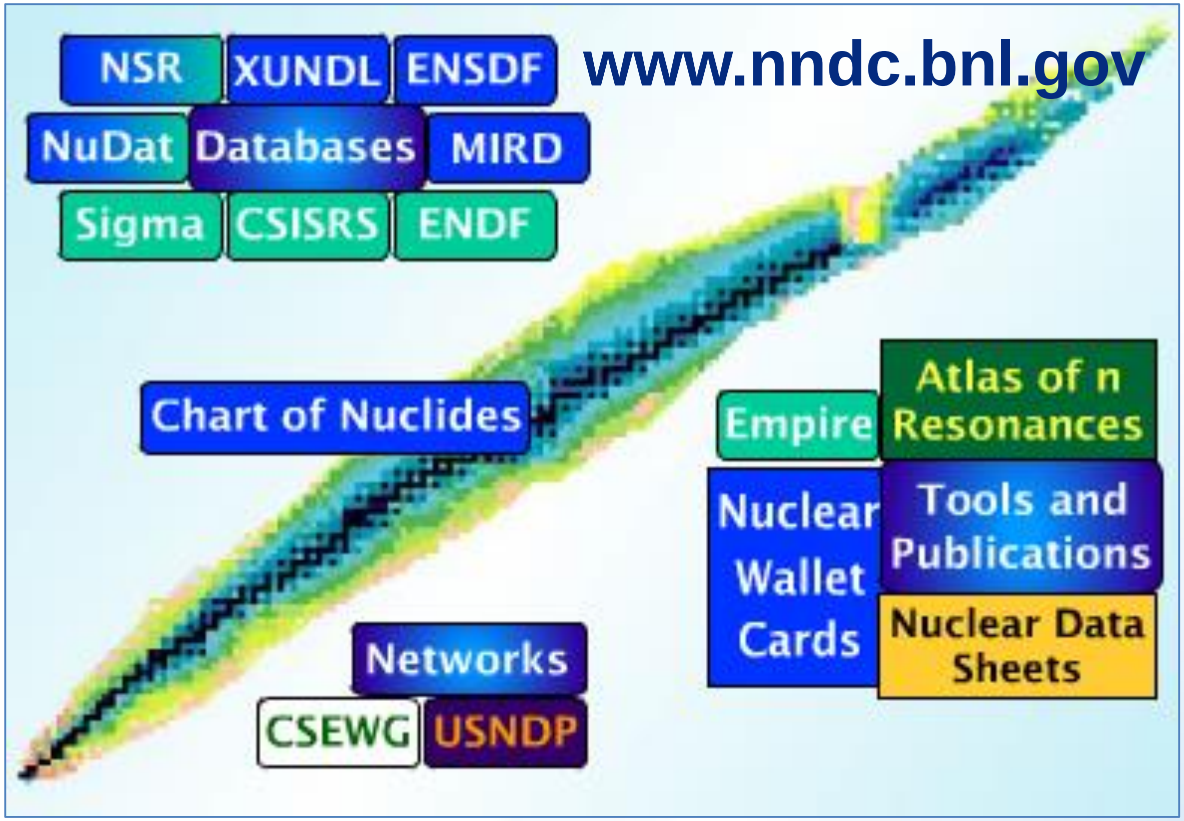
Quality Assurance: The NNDC's ADVANCE nuclear data continuous integration system ensures the quality of data by automatically testing each ENDF evaluation as soon as it is changed.

scale
Nuclear Systems Modeling & Simulation

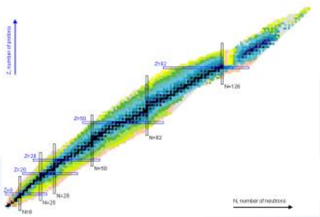


The Nuclear Data Pipeline



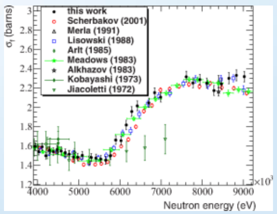


NuDat

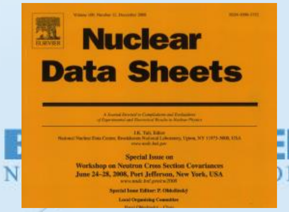


SIGMA

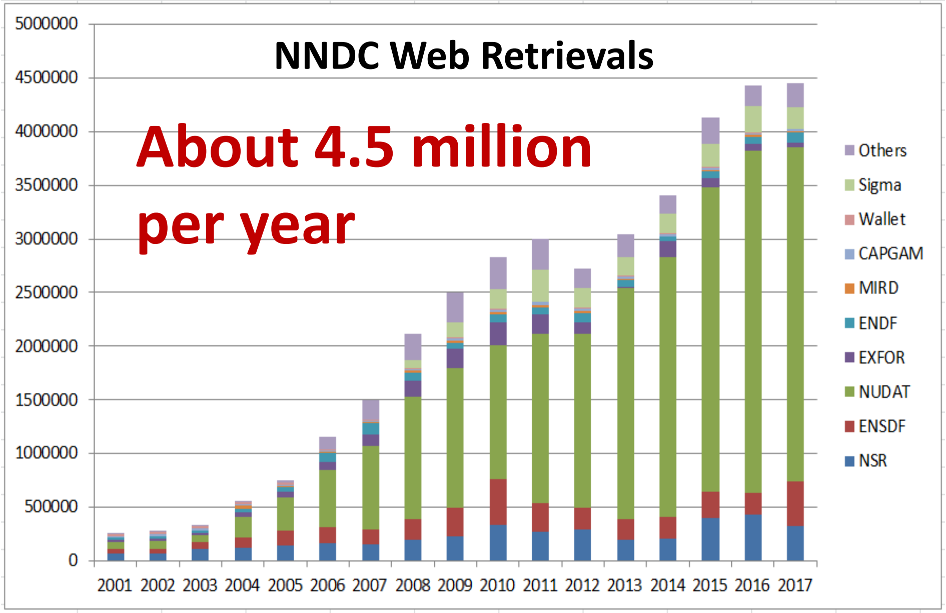
EXFOR searches

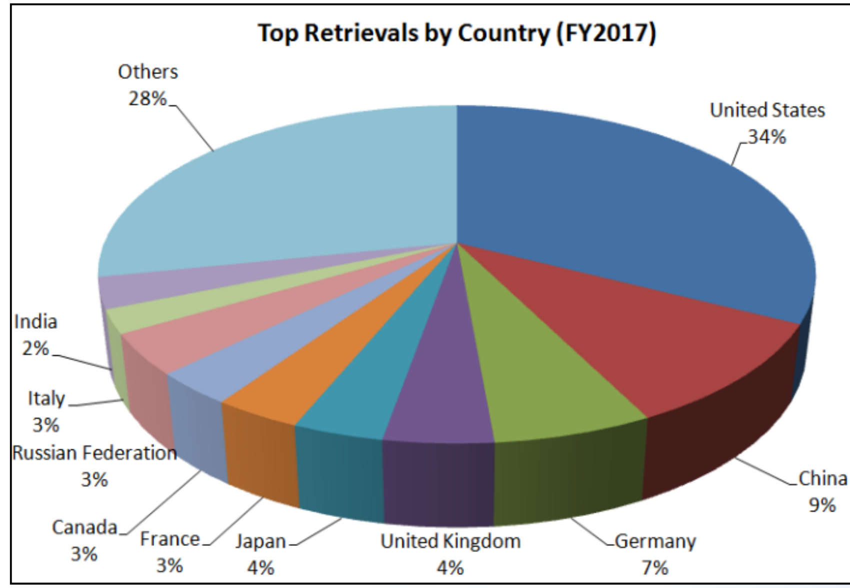


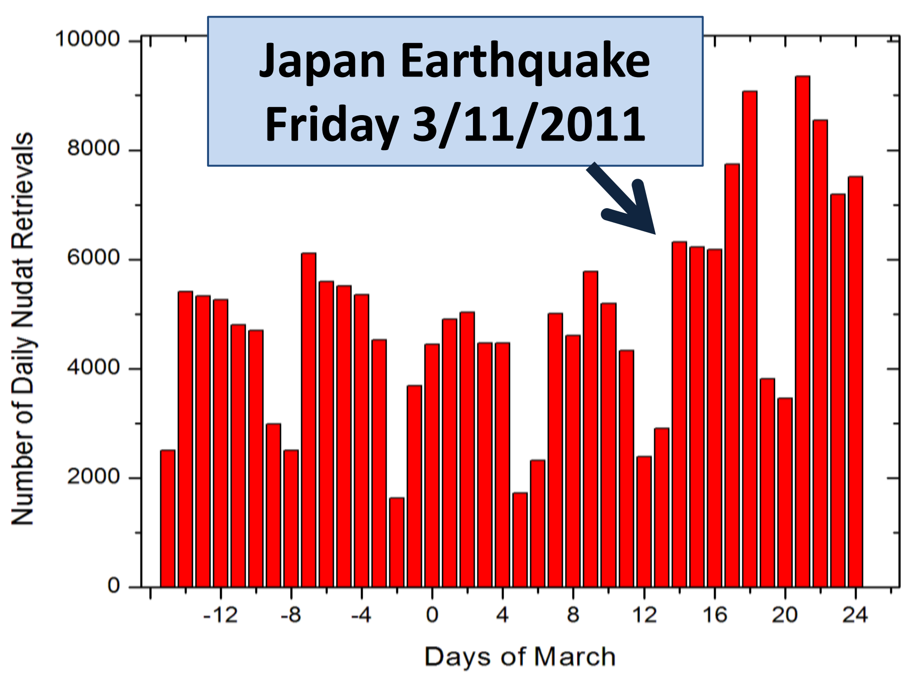
Nuclear Data Sheets

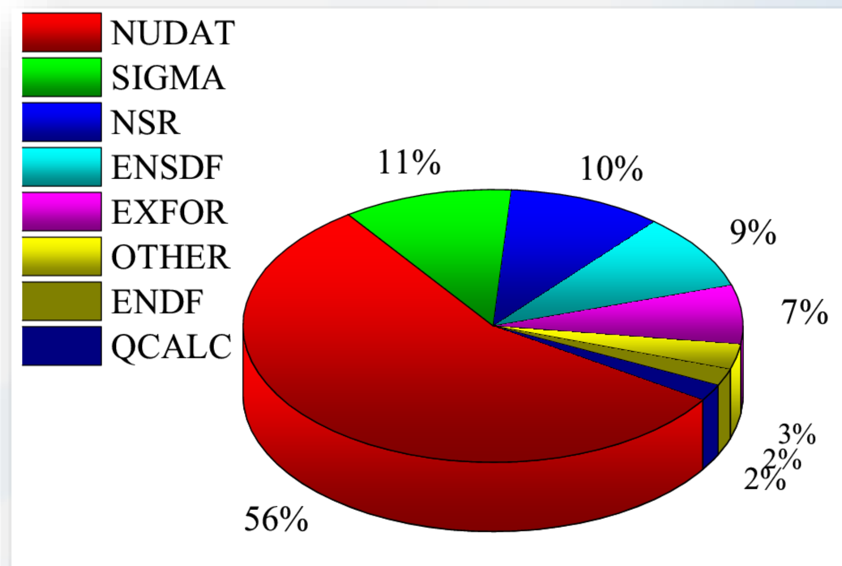


Web Dissemination





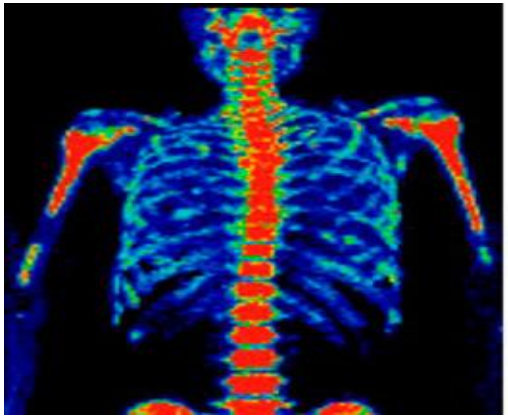




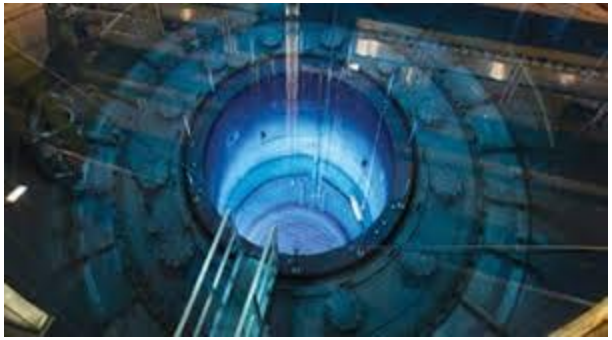
BROOKHAVEN NATIONAL LABORATORY

Users of Nuclear Data

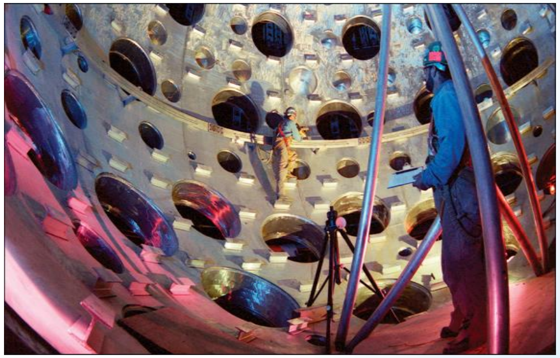
Applications, Applications and More Applications



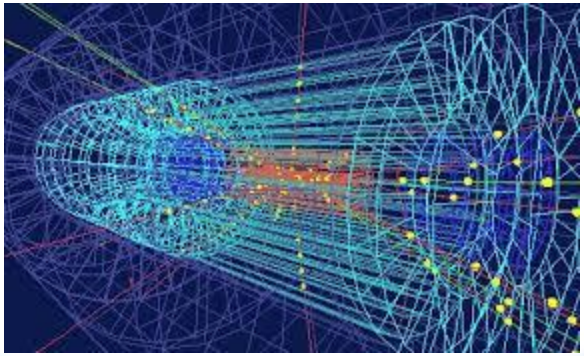
Nuclear Medicine



Nuclear Power



Stockpile Stewardship

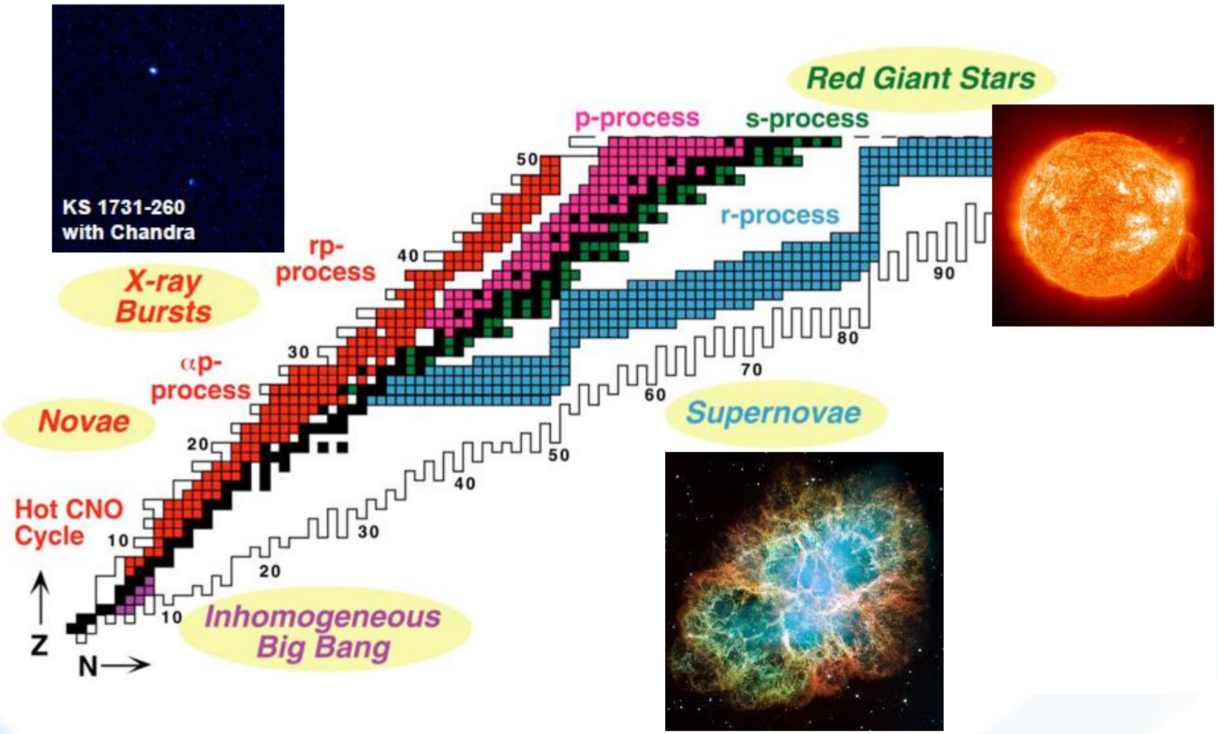


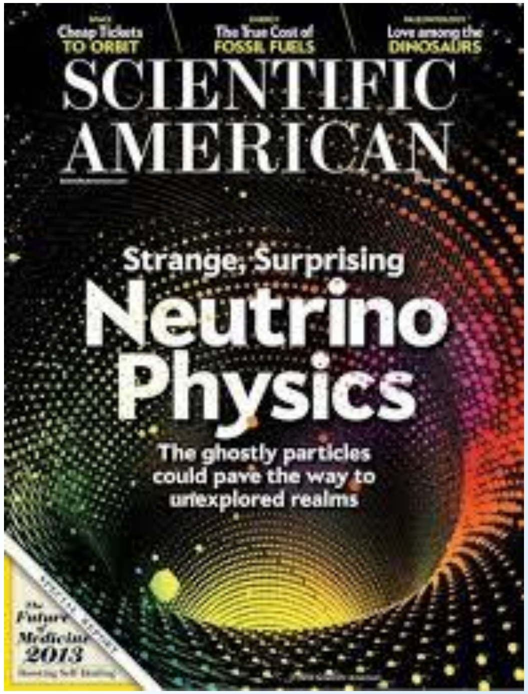
Detector Simulations

Homeland Security

Users of Nuclear Data

Provides essential input for other basic science fields





Astrophysics

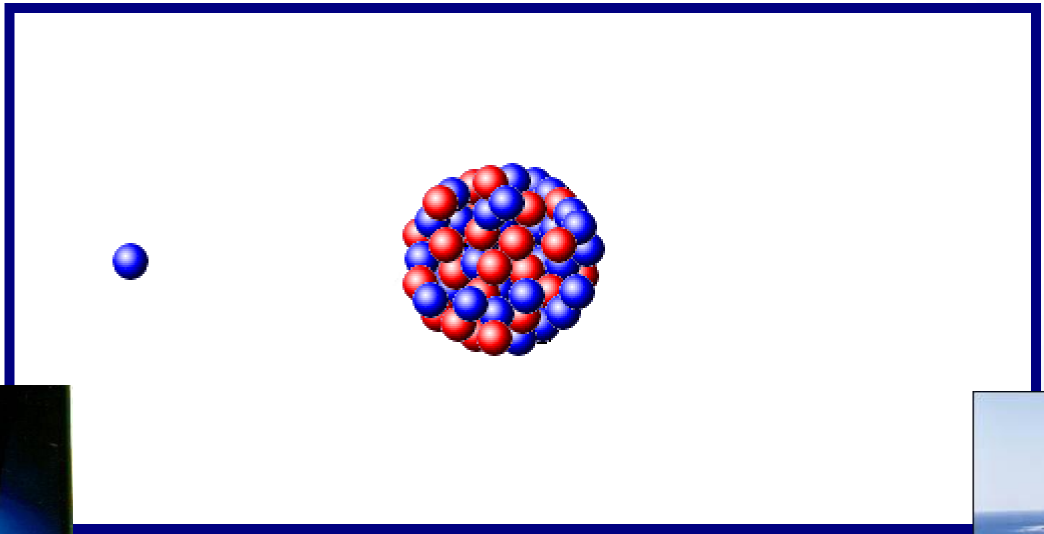
Neutrino Physics

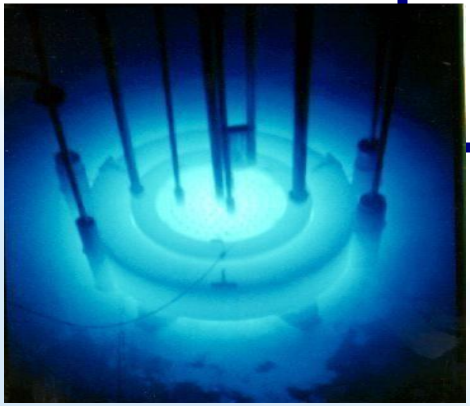
Data are versatile

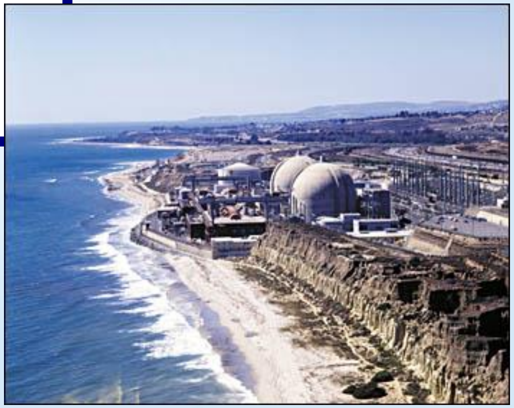
Transforming our vast body of data into something of beauty

Many Applications Involve Fission

- Fissile material, such as uranium or plutonium
- Neutrons are used to induce fission
- Products of fission : 2 lighter nuclei and a few neutrons
- New neutrons carry on, and on, and on the process



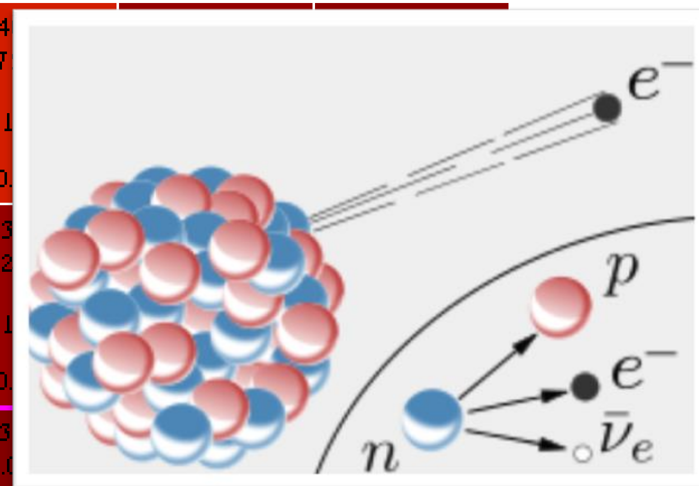




Yields of Fission Fragments

Z, number of protons

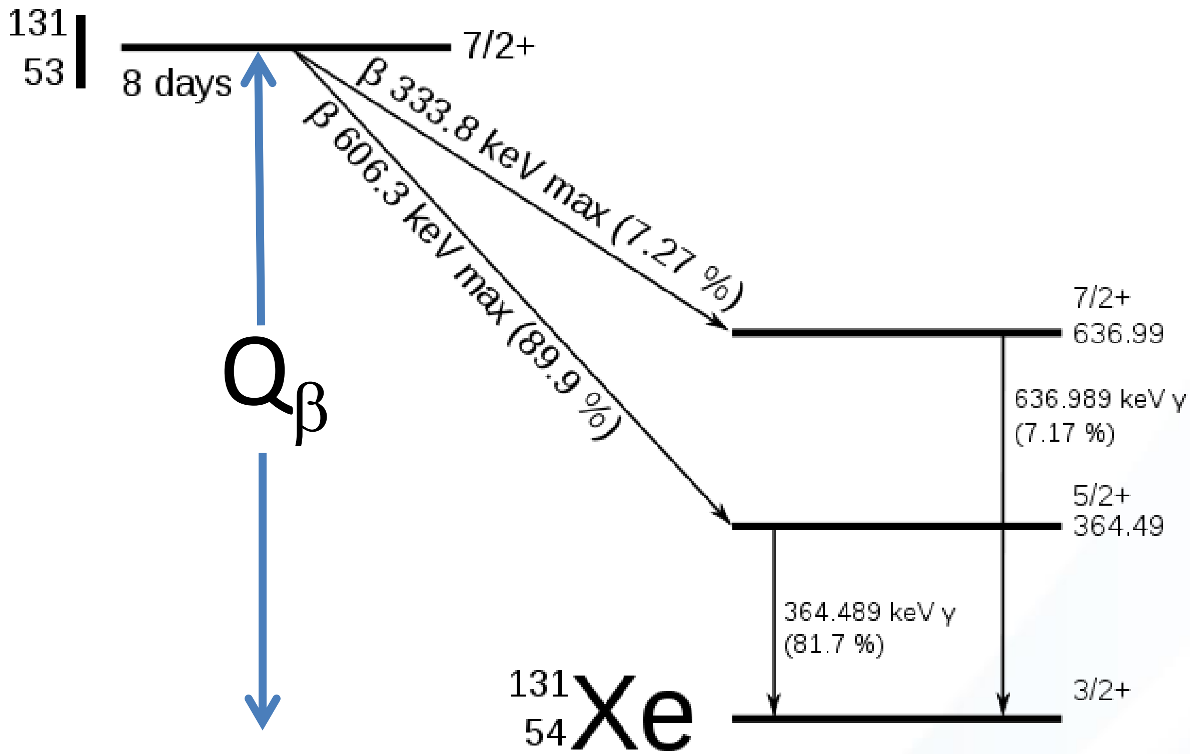
136Ba STABLE 7.854% 2.4E-8	137Ba STABLE 11.232% 1.3E-6	138Ba STABLE 71.698% 4.E-5	139Ba 83.06 M β-: 100.00% 7.E-4	14 12.7 β-: 1 0.		
135Cs 2.3E+6 Y β-: 100.00% 2.5E-6	136Cs 13.04 D β-: 100.00% 2.8E-5	137Cs 0.08 Y β-: 10 00% 6.0E-4	138Cs 33.41 M β-: 100.00% 0.00223	13 9.2 β-: 1 0.		
134Xe >5.8E+22 Y 10.4357% 2β- 2.5E-4	135Xe 9.14 H β-: 100.00% 0.00178	136Xe >2.4E+21 Y 8.8573% 2β- 0.022	137Xe 818 M β-: 10 00% 0.0319	13 14.0 β-: 100.00% 0.0481	β-: 100.00% 0.0432	β-: 100.00% 0.0351
133I 20.83 H β-: 100.00% 8.E-4	134I 52.5 M β-: 100.00% 0.0036	135I 6.58 H β-: 100.00% 0.0293	136I 83.4 S β-: 100.00% 0.0125	137I 24.5 S β-: 100.00% β-n: 7.14% 0.0262	138I 6.23 S β-: 100.00% β-n: 5.56% 0.0142	139I 2.280 S β-: 100.00% β-n: 10.00% 0.0077
132Te 3.204 D β-: 100.00% 0.0153	133Te 12.5 M β-: 100.00% 0.0299	134Te 41.8 M β-: 100.00% 0.0622	135Te 19.0 S β-: 100.00% 0.0322	136Te 17.63 S β-: 100.00% β-n: 1.31% 0.0132	137Te 2.49 S β-: 100.00% β-n: 2.99% 0.0039	138Te 1.4 S β-: 100.00% β-n: 6.30% 7.E-4



N, number of neutrons

BROOKHAVEN NATIONAL LABORATORY

Energy released in beta decay



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

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

Total Energy=EM+LP+$E_{neutrino}$= Q(β-)

Decay heat from a reactor

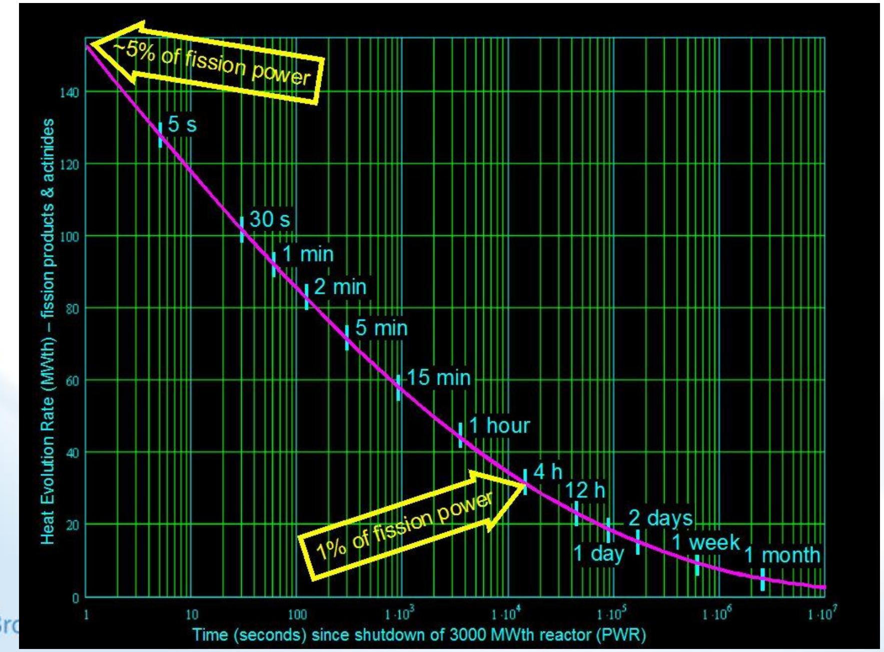
$$DH(t) = \sum_i E_i \lambda_i N_i(t)$$

E_i = Decay energy (β,γ or both)

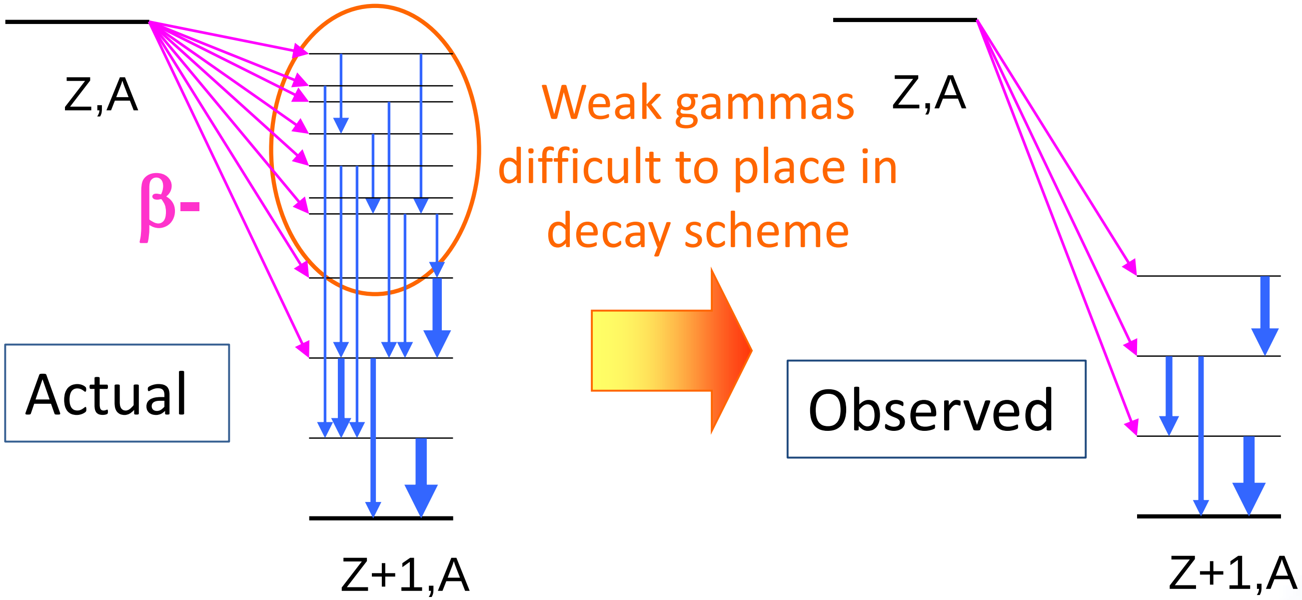
λ_i = decay constant

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

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



But most things aren't simple



Incomplete decay schemes:

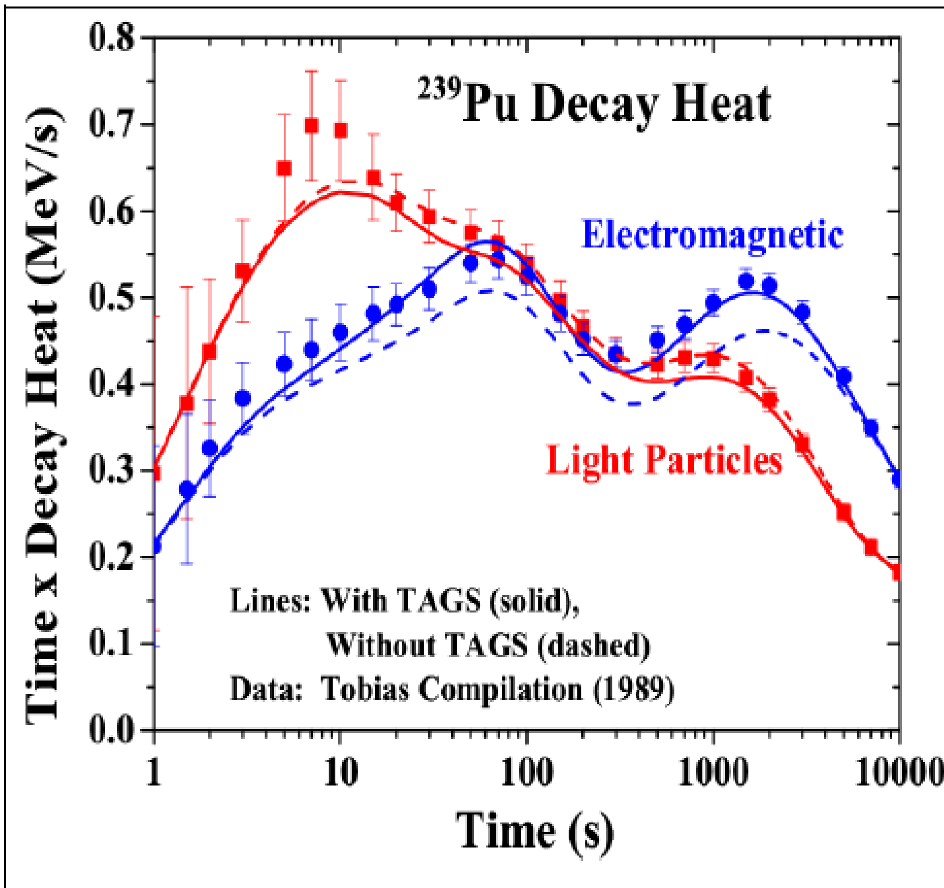
- Smaller gamma-ray energies
- Larger beta energies
- 1st realized by Hardy in 1970's
- Termed Pandemonium effect

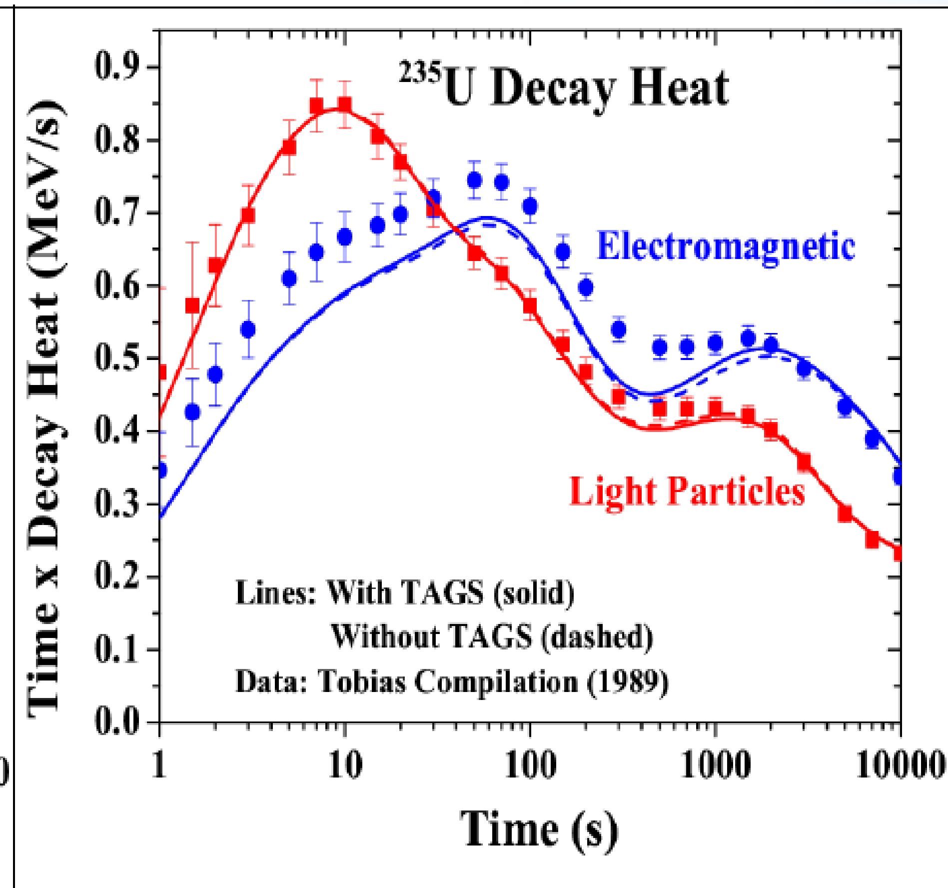
New RIB facilities + New Total Absorption Gamma-ray Spectrometers (TAGS) : Will soon address these issues

Incorporating TAGS data

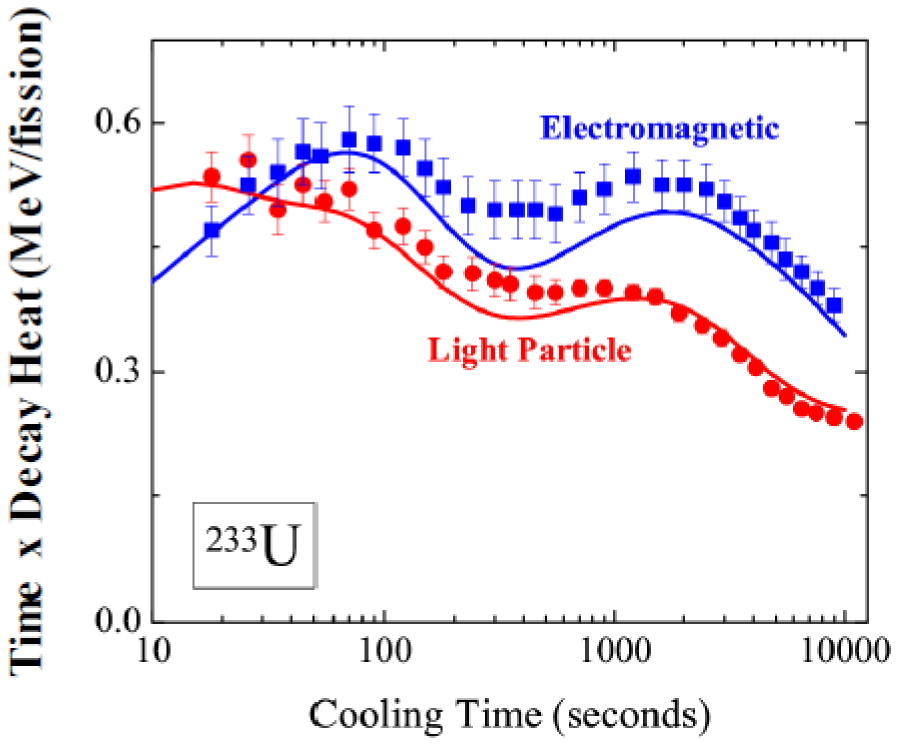
- WPEC-Subgroup (2006) identified 22 “high priority” nuclei
- New TAGS data on 7 nuclei from Valencia collaboration

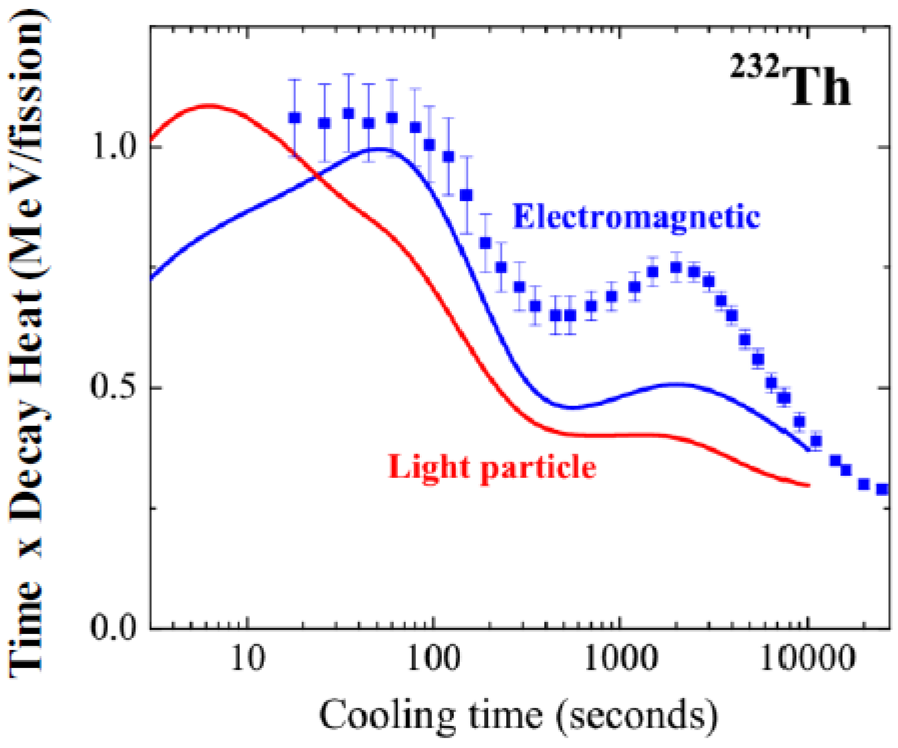
Algora *et al.*, Phys. Rev. Lett. **105**, 202501 (2010).





Decay Heat for Advanced Fuel Cycles

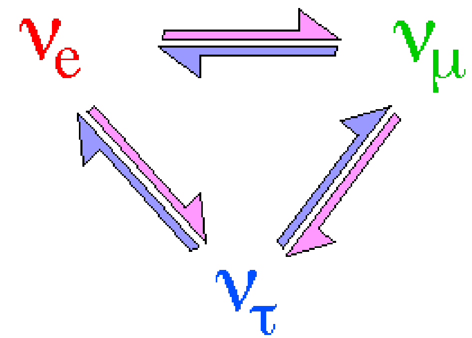




Lots of room for improvement !!

And now for something completely different …

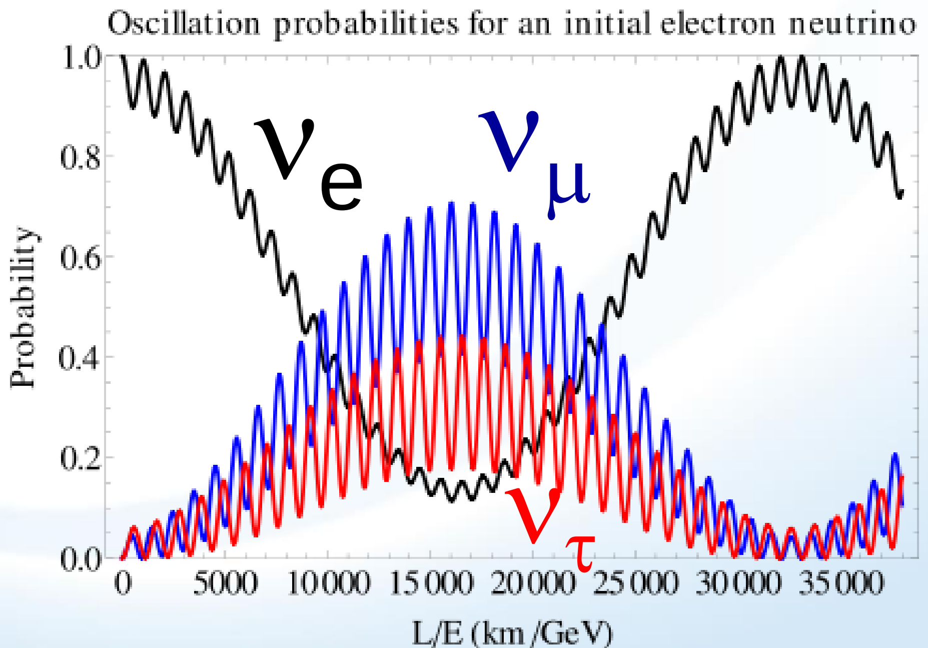
Neutrino Oscillations



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

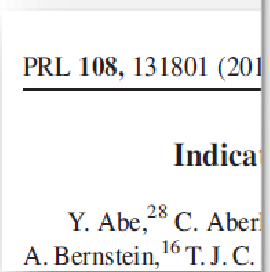
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix}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

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



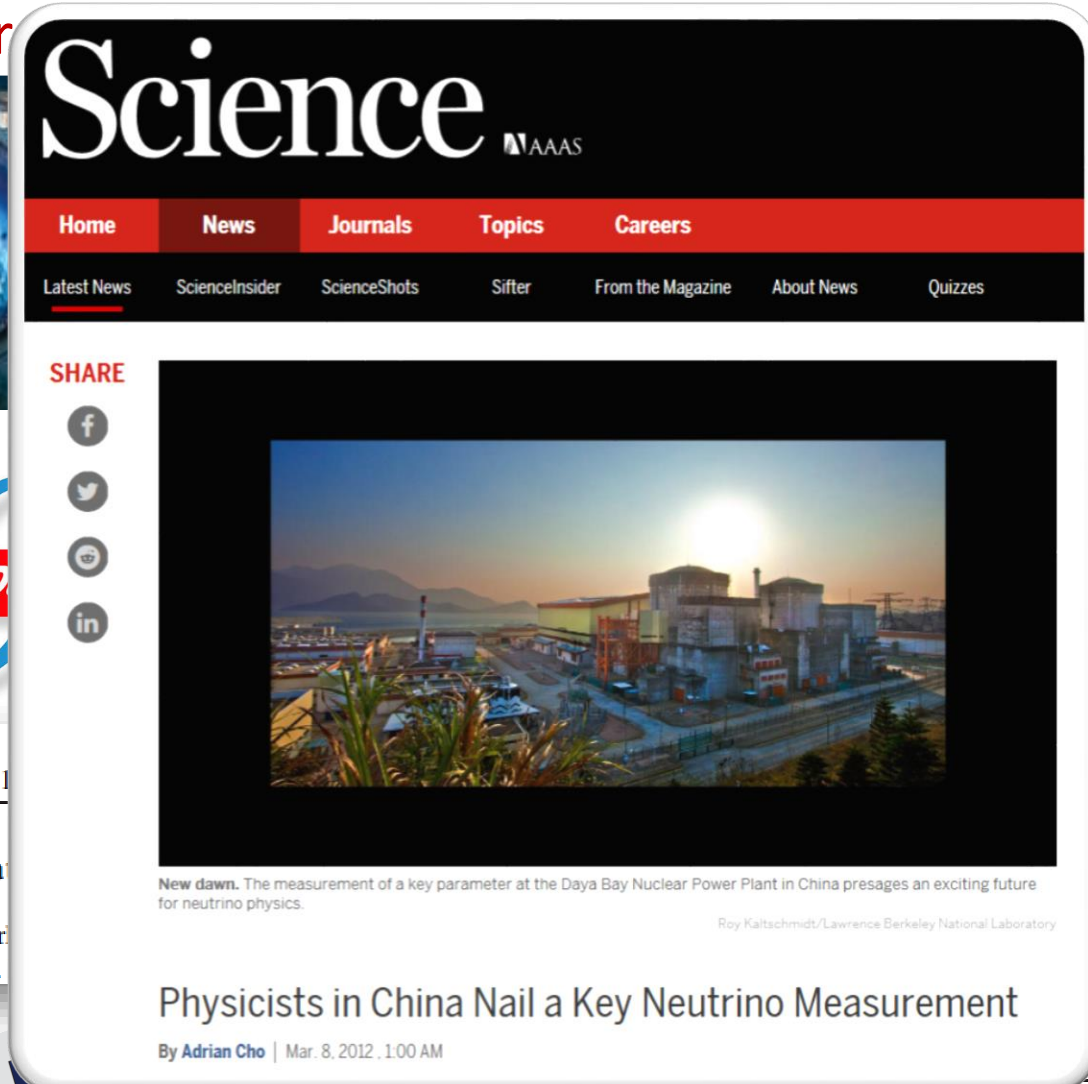
The race to measure the final mixing angle

Intense sour...

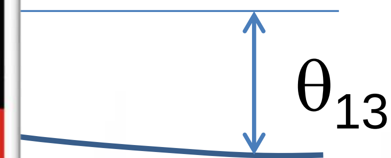

PRL 108, 131801 (201...

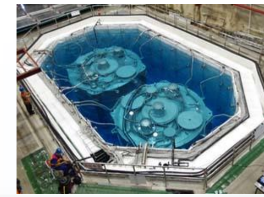
Indica...

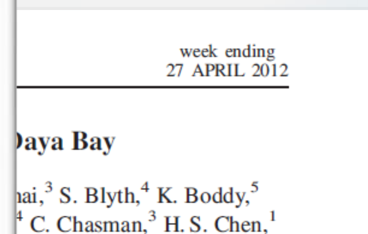
Y. Abe,[28] C. Aber...
A. Bernstein,[16] T. J. C. ...



...tor

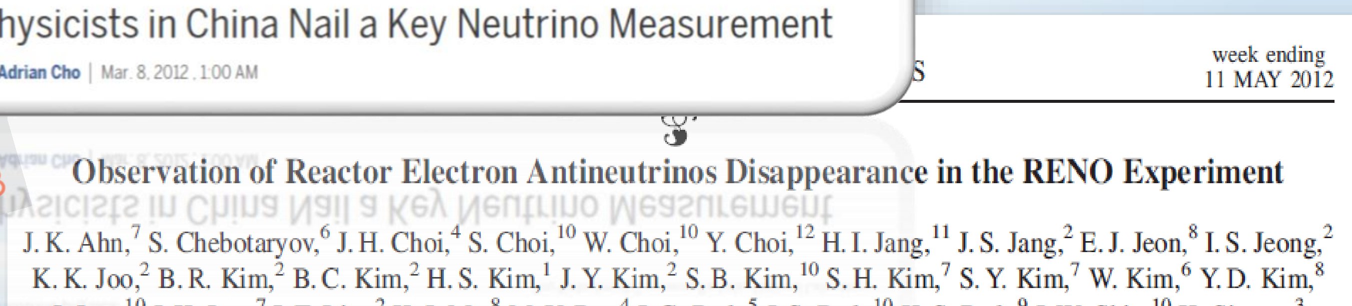





week ending
27 APRIL 2012

...aya Bay

...ai,[3] S. Blyth,[4] K. Boddy,[5]
...[4] C. Chasman,[3] H. S. Chen,[1]

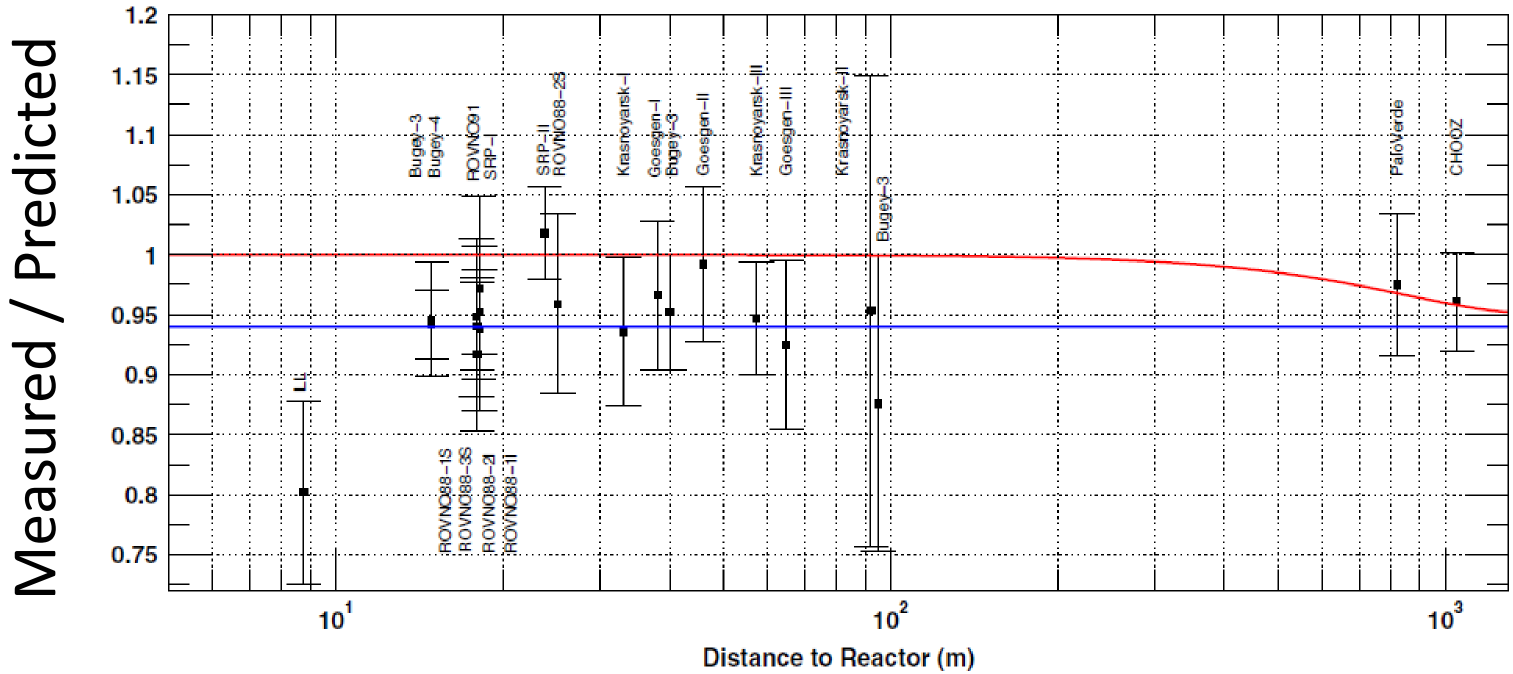

week ending
11 MAY 2012

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]

The story get more interesting

Analysis of all experiments close to reactors



Deficit in antineutrinos in all short baseline experiments

We observe 6% fewer electron antineutrinos from nuclear reactors at short distances, not accounted for the standard 3-flavor oscillation.

PHYSICAL REVIEW D 83, 073006 (2011)

Reactor antineutrino anomaly

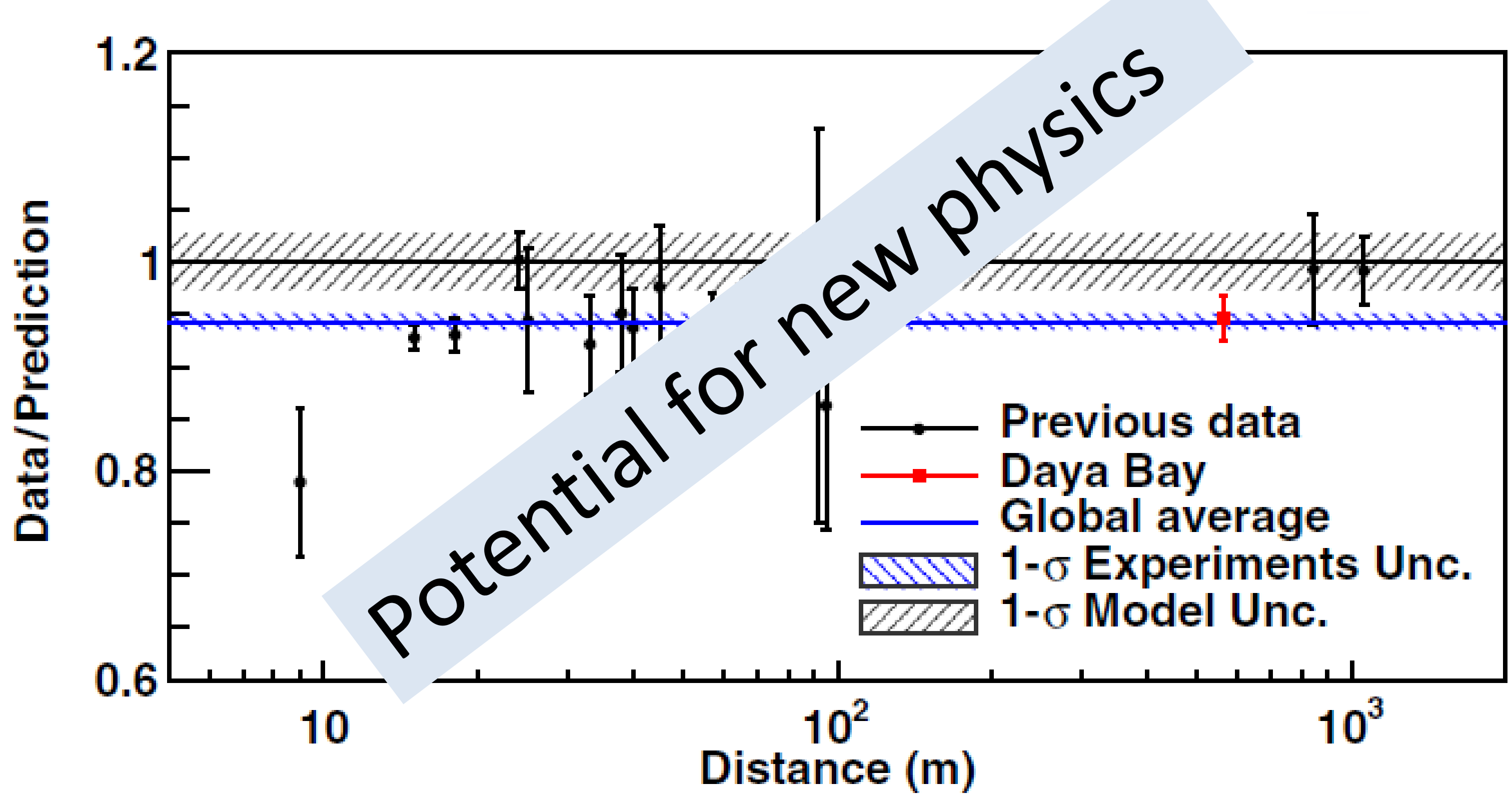
G. Mention,[1] M. Fechner,[1] Th. Lasserre,[1,2,*] Th. A. Mueller,[3] D. Lhuillier,[3] M. Cribier,[1,2] and A. Letourneau[3]

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

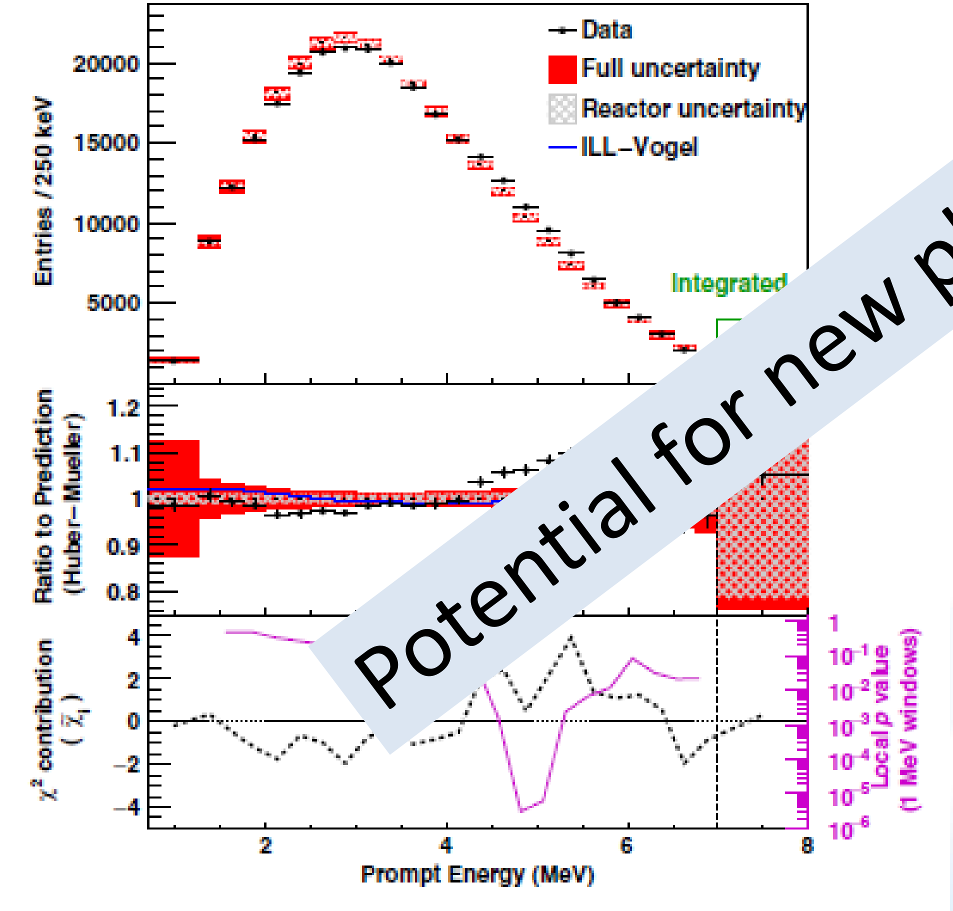


Data/prediction = 0.946+-0.022

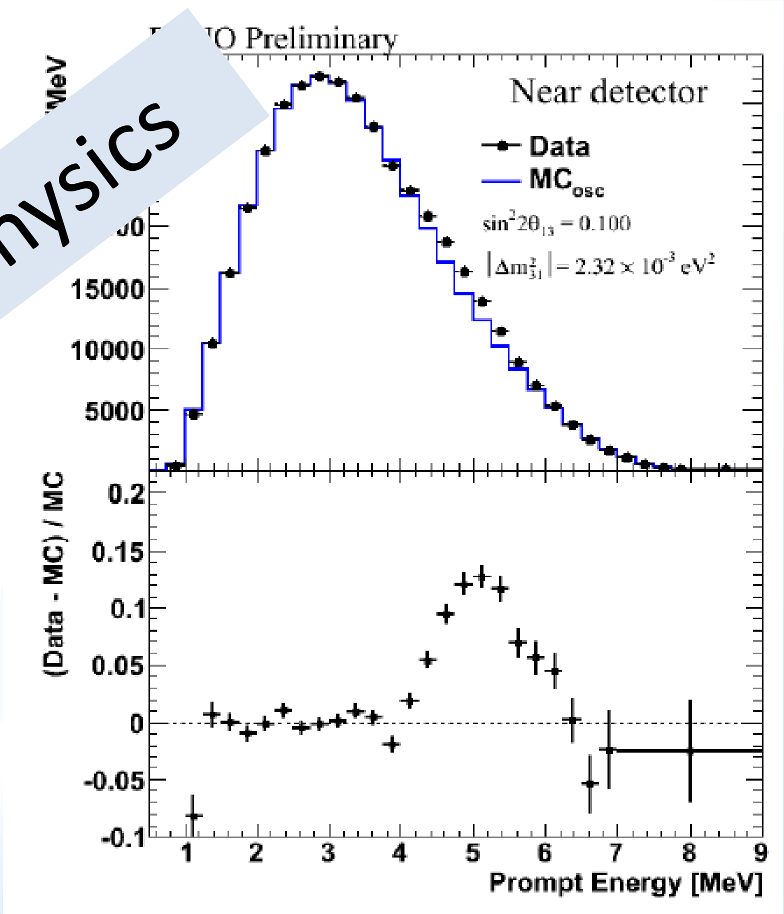
And more interesting

The **“bump”** :

An excess of measured antineutrinos relative to predictions



Potential for new physics



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

NATIONAL LABORATORY

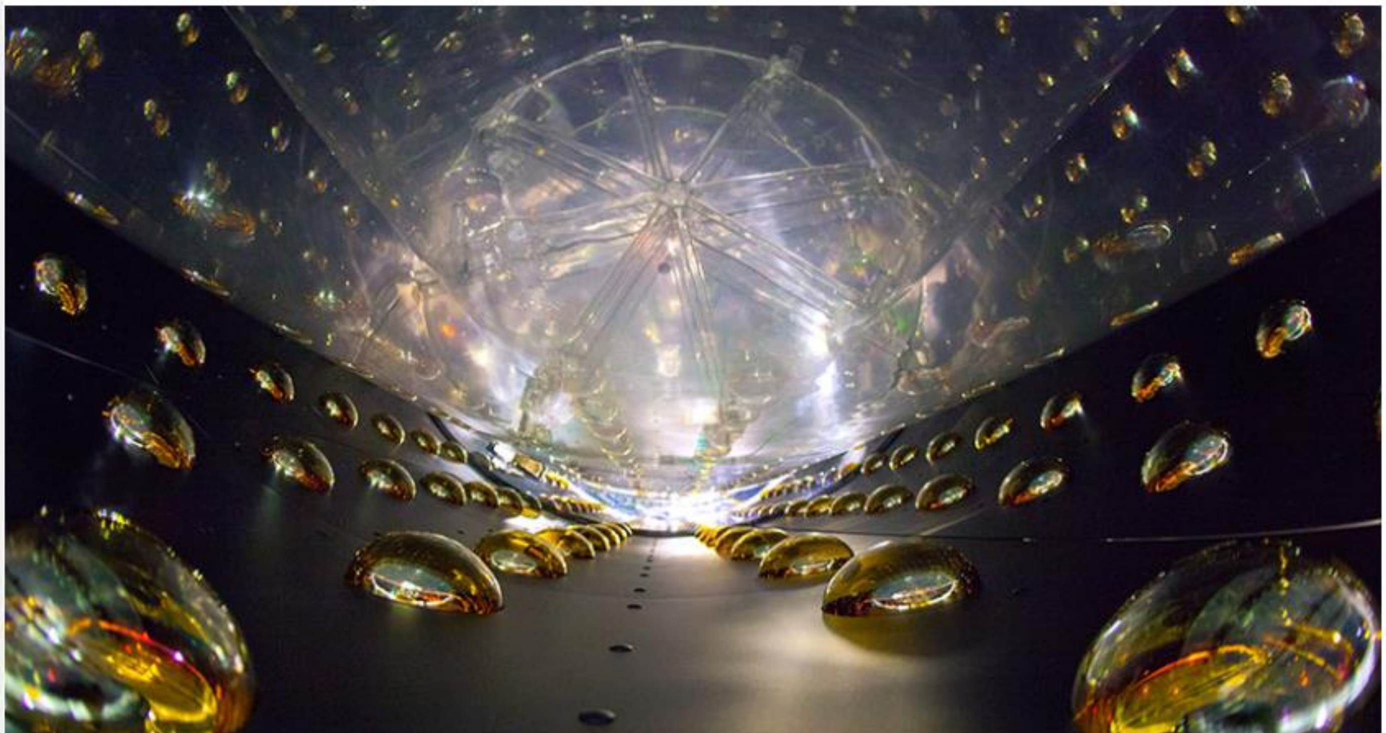
New Physics???

NEWS PARTICLE PHYSICS

Reactor data hint at existence of fourth neutrino

Deficit in antiparticle output exceeds theoretical expectations

BY RON COWEN 1:20PM, FEBRUARY 25, 2016



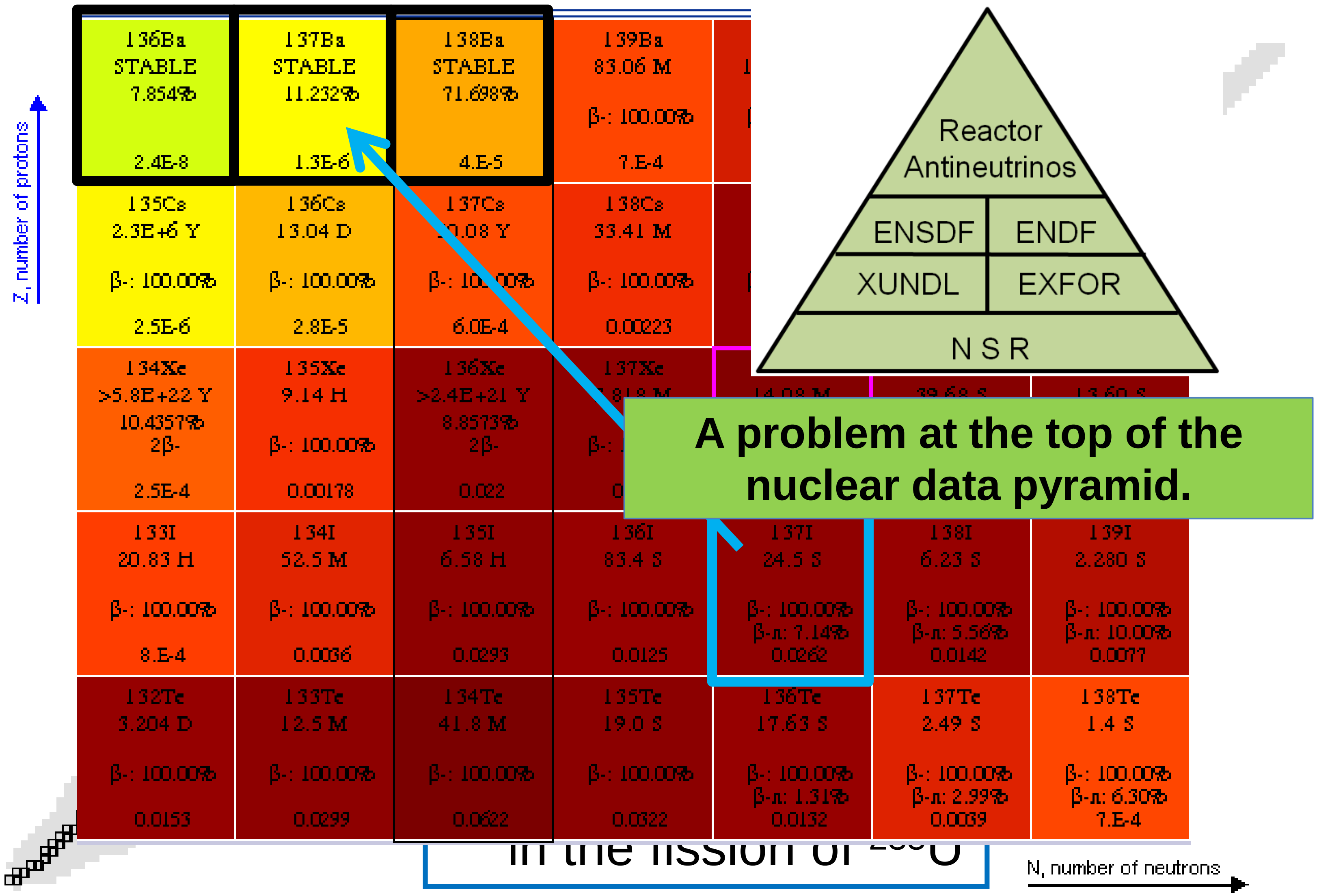
GHOST FINDER New results of experiments at the Daya Bay neutrino detector (walls lined with photomultiplier tubes, shown) hint at the existence of a lightweight sterile neutrino, about one-millionth the mass of an electron.

What are the implications?

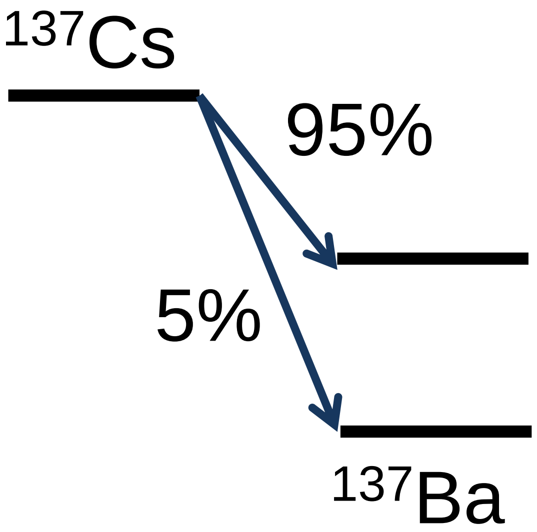
Many possible explanations

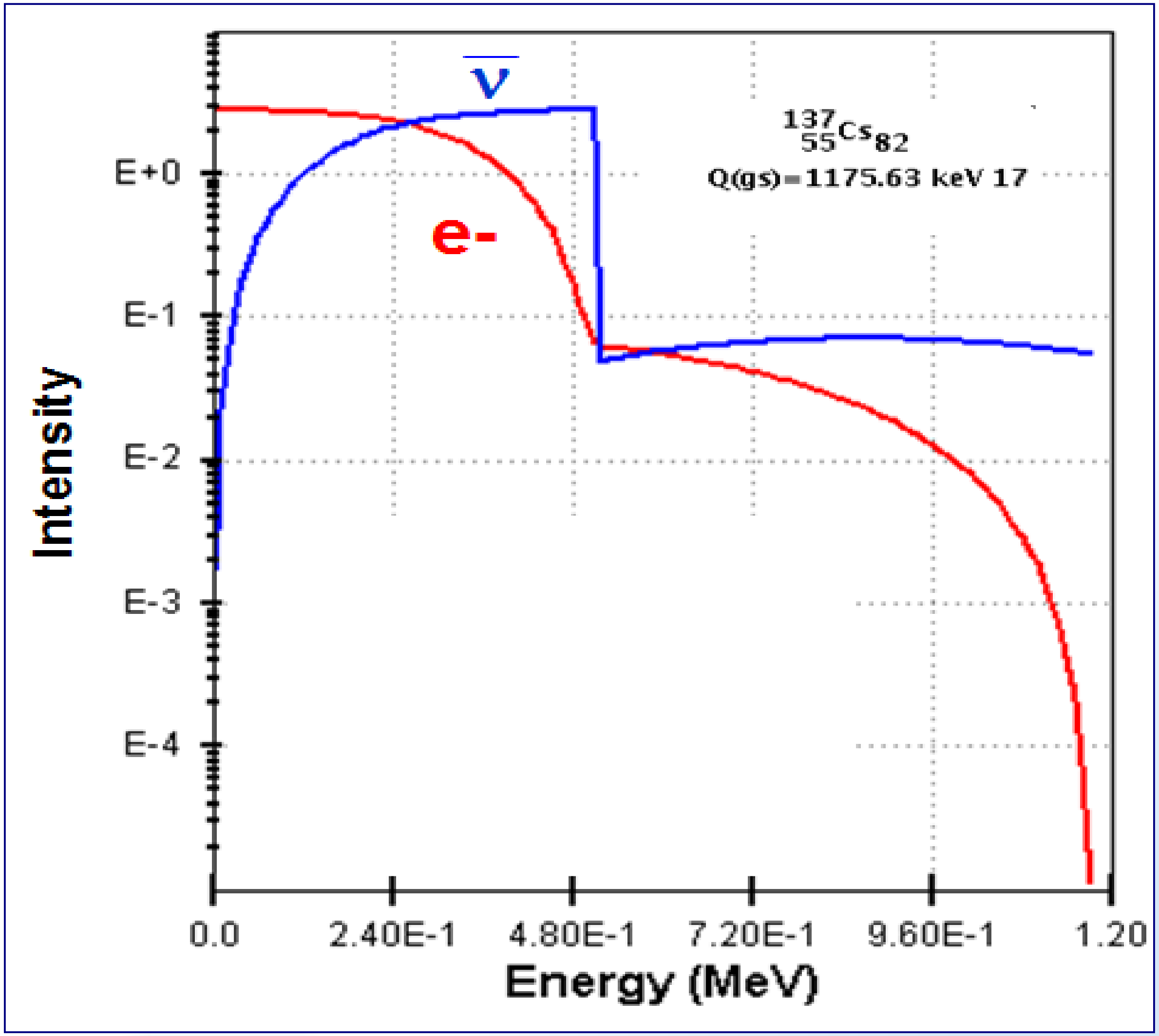
- Predicted Antineutrino spectrum is incorrect
- Experimental bias in all experiments
- New physics at short baselines
    - Existence of one (or more) neutrinos beyond the standard model

Understanding reactor ν_e flux is nuclear physics



Simple Example : ^{137}Cs



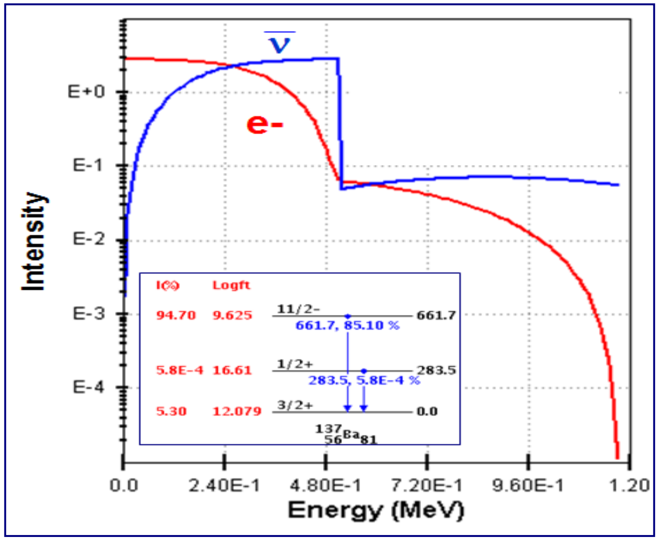


$$I(E)=N\ W\ (W^2-1)^{1/2}(W-W_0)^2\ F(Z,W)\ C(Z,W)(1+\delta)$$

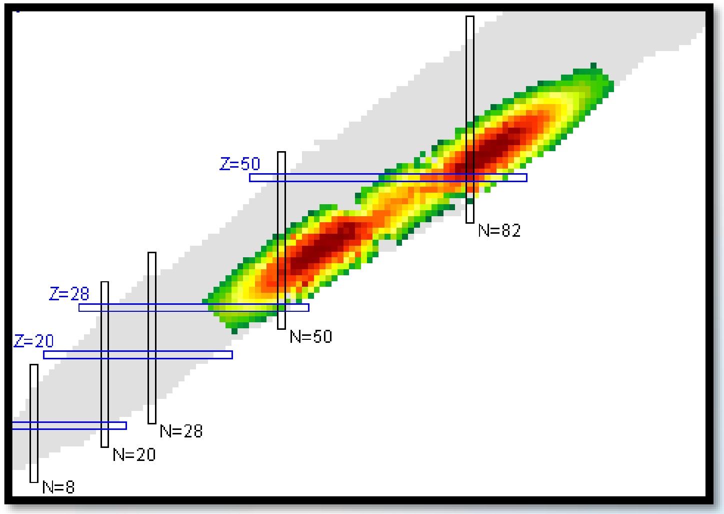
One approach to calculating the ν_e flux

Ab-initio Method or Summation Method

Individual Beta spectra



Fission Yields



Anti-neutrinos from reactors

Detection through inverse β decay on proton

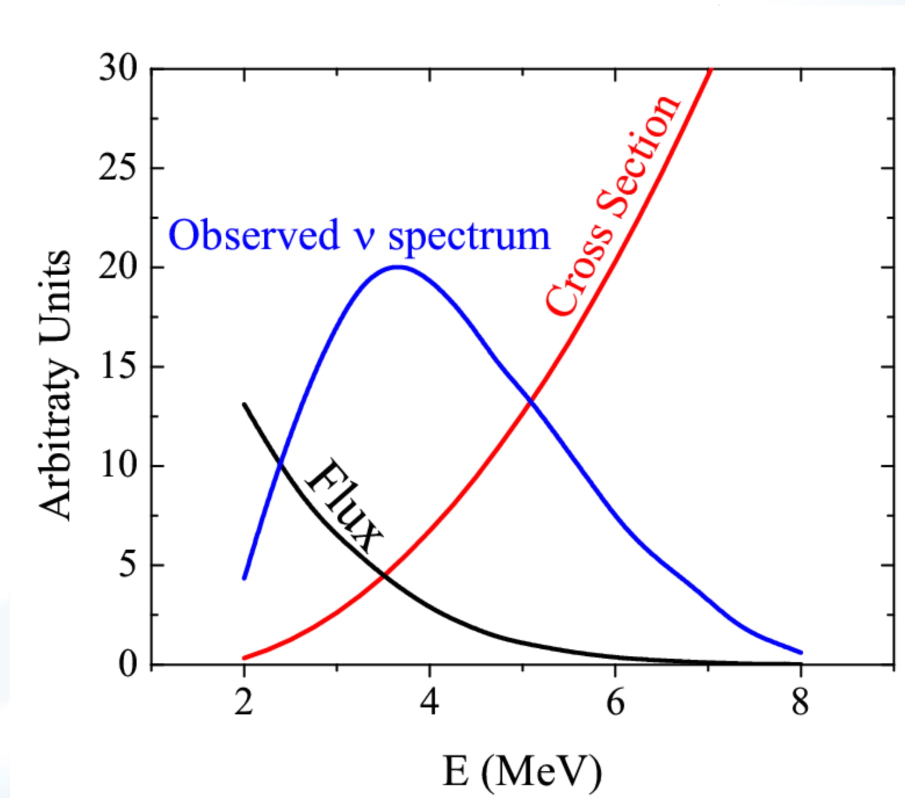
$$\overline{\nu_e} + p \rightarrow e^+ + n$$

But cross section is tiny !!

$$\langle\sigma\rangle \sim 10^{-16}\ mb$$

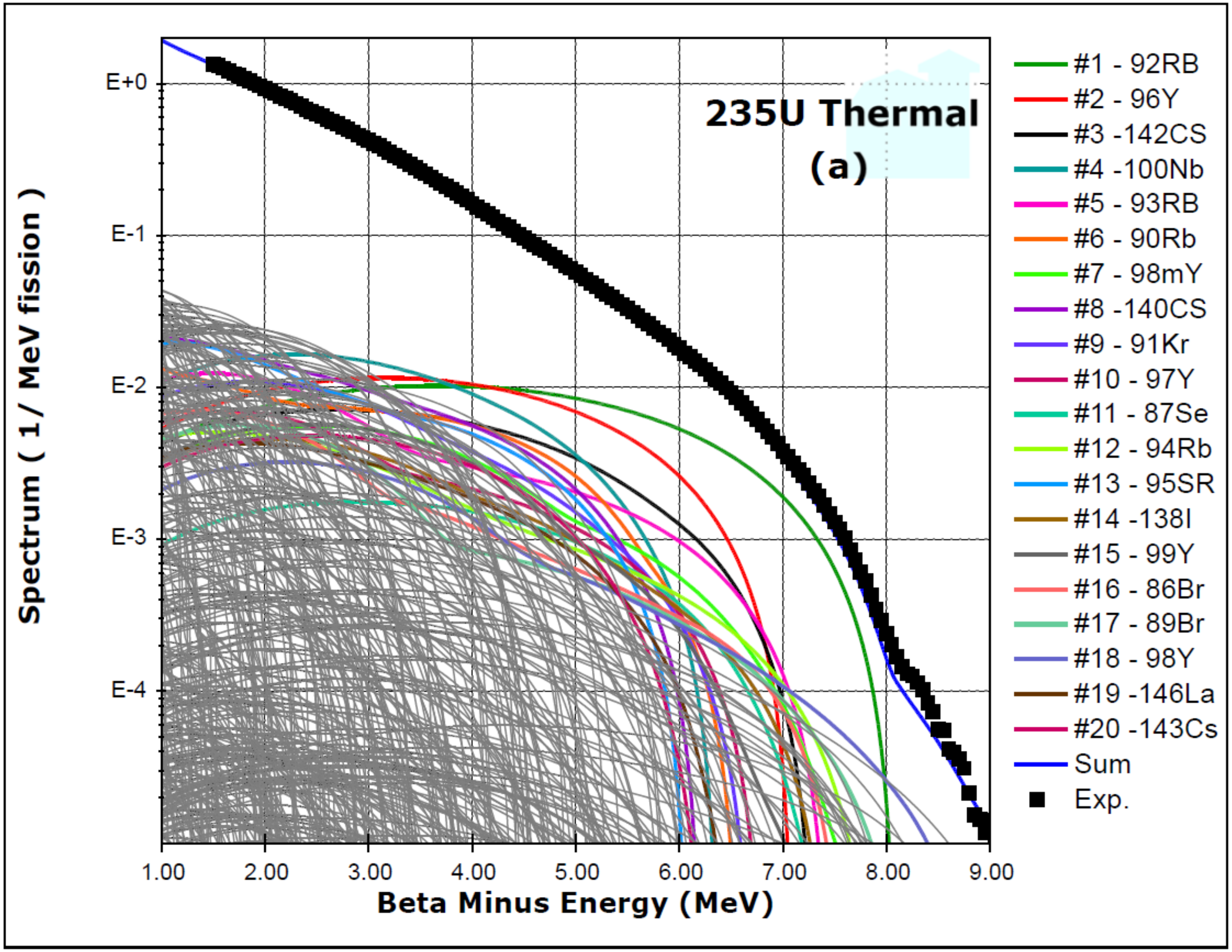
Reactors are copious producers of antineutrinos

$$\sim\ 5 \cdot 10^{20}\ \overline{\nu}_e / s$$



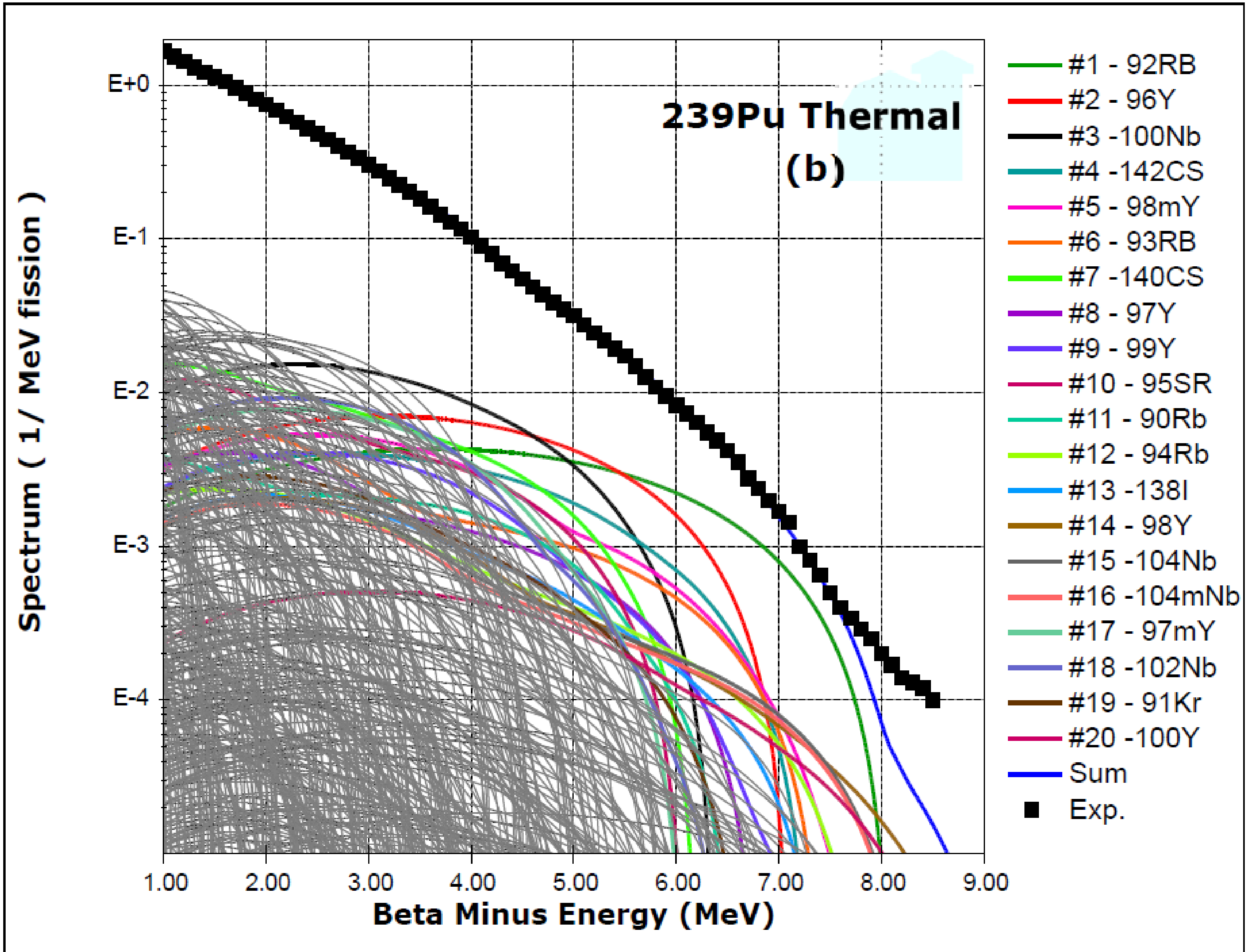
Reaction threshold : ~1.8 MeV

Summation for ^{235}U



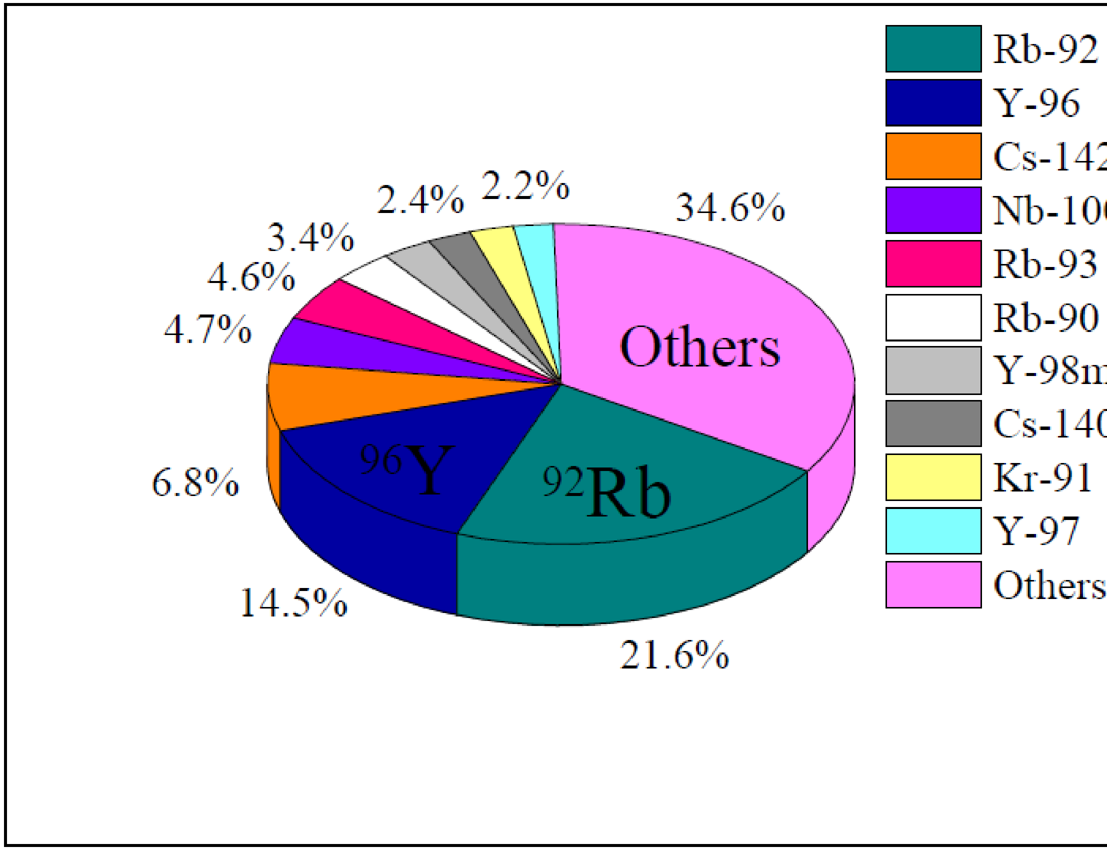
A.A. Sonzogni *et al*., Phys.Rev. C **91**, 011301(R) (2015)

Summation for ^{239}Pu



Main Contributors at ~5 MeV

23
37-Rb-
39-Y-9
41-Nb-
55-Cs-
37-Rb-
55-Cs-
52-Te –
38-Sr-9



238U
-96
b-92
b –100
s-142
e-135
-99
s-143
-138

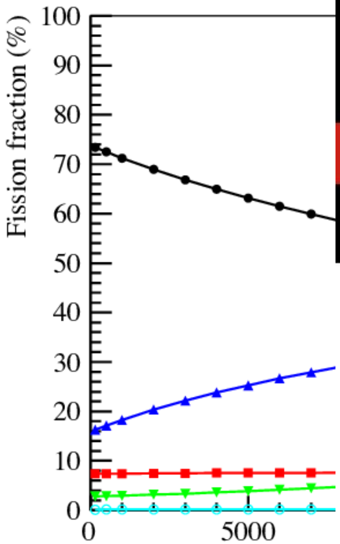
Top 10 contribute ~60% to the overall spectrum

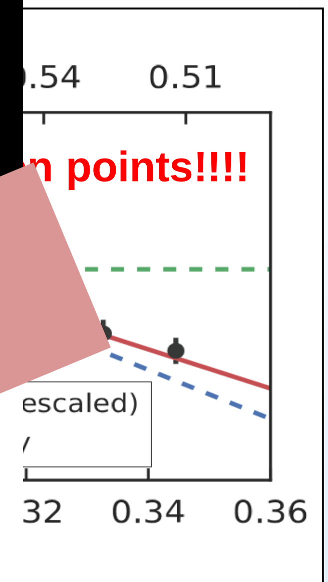
New measurements underway based on these sensitivity studies

The anomaly, or not?

Antineutrino flux versus “time”

Reactor comp





.801 (2017).

- Daya B
- Measur
- Measured
- If anomaly

e reactors

Science AAAS

Home | News | Journals | Topics | Careers

Latest News | ScienceInsider | ScienceShots | Sifter | From the Magazine | About

SHARE

254

The Daya Bay Reactor Neutrino Experiment studies antineutrinos from six reactors near Shenzhen, China.

Photo courtesy of Lawrence Berkeley National Laboratory/Roy Kaltschmidt © 2010 The Regents of the University of California, through the Lawrence Berkeley National Laborator

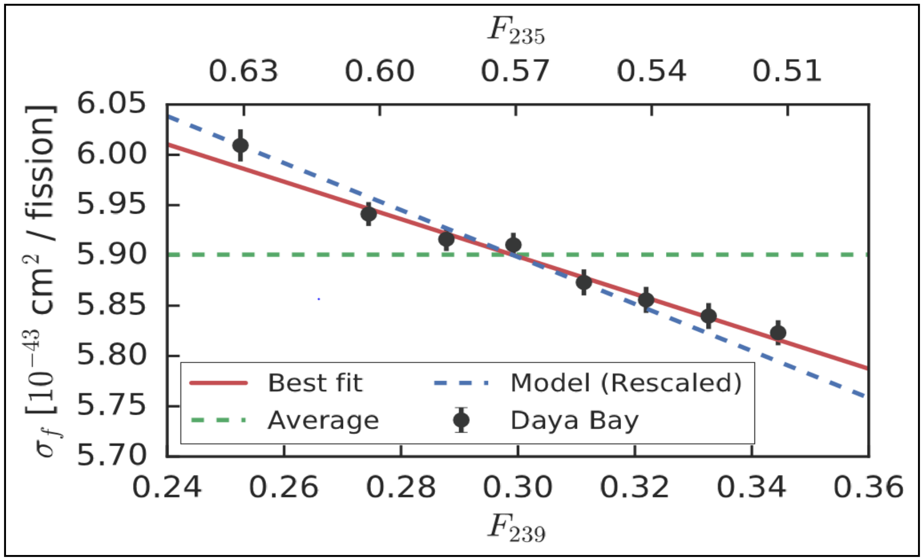
Weird sterile neutrinos may not exist, suggest new data from nuclear reactors

By Adrian Cho | Apr. 6, 2017 , 5:30 PM

This analysis relies on one set of measurements from the 1980’s

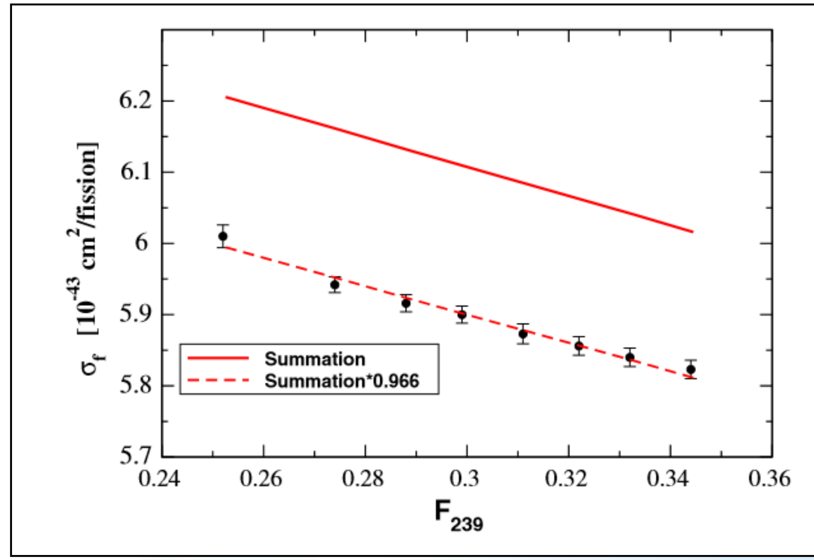
Nuclear data to answer major science question

Daya Bay Analysis
(conversion of ILL data)



Our analysis
(Incorporates vast knowledge of decay data of fission fragments)

NNDC calculations using ENDF decay



Abstract ends with:

'An analysis of the antineutrino spectra that is based on a summation over all fission fragment β decays, using nuclear database input, explains all of the features seen in the Daya Bay evolution data. However, this summation method still allows for an anomaly. We conclude that there is currently not enough information to use the antineutrino flux changes to rule out the possible existence of sterile neutrinos.'

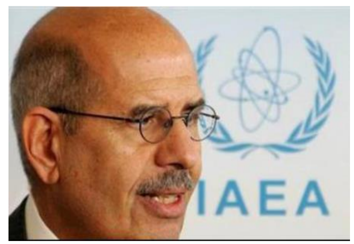
Real "applied" uses for antineutrinos ?

Outside-the-box thinking

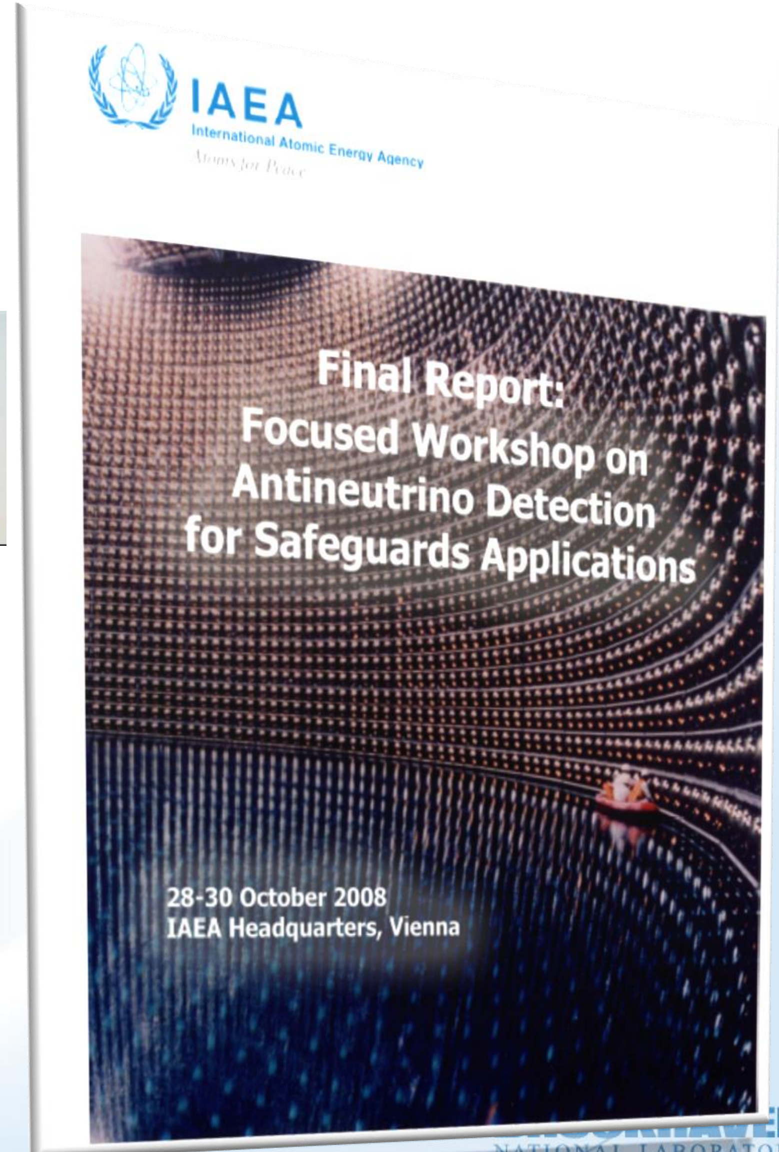
"In regard to nuclear proliferation and arms control, the fundamental problem is clear: Either we begin finding creative, outside-the-box solutions or the international nuclear safeguards regime will become obsolete."

-

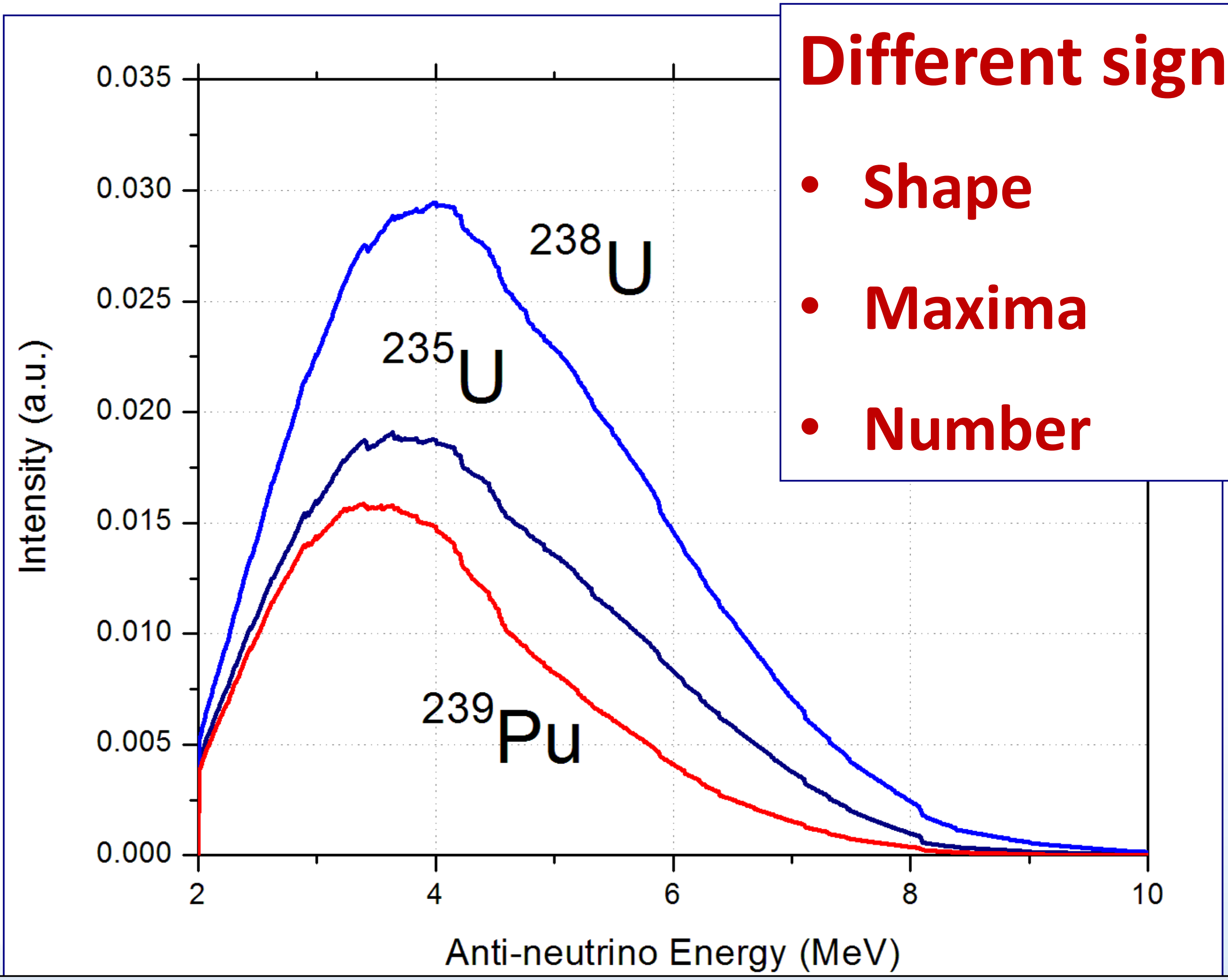
M. ElBaradei,
then Director General of the IAEA
Washington Post, June 14, 2006



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



Exploit differences in signal

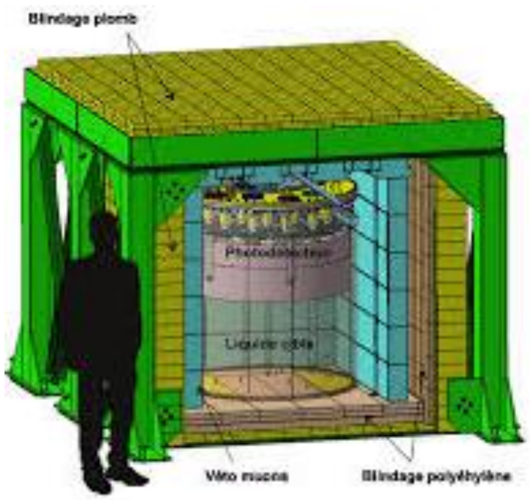


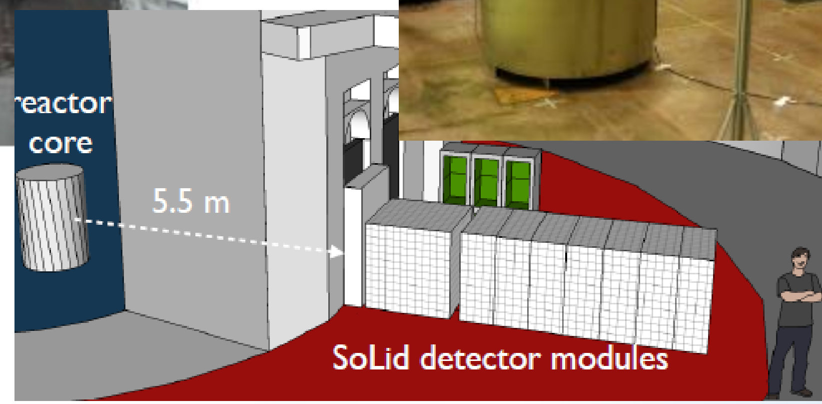
Different signal in

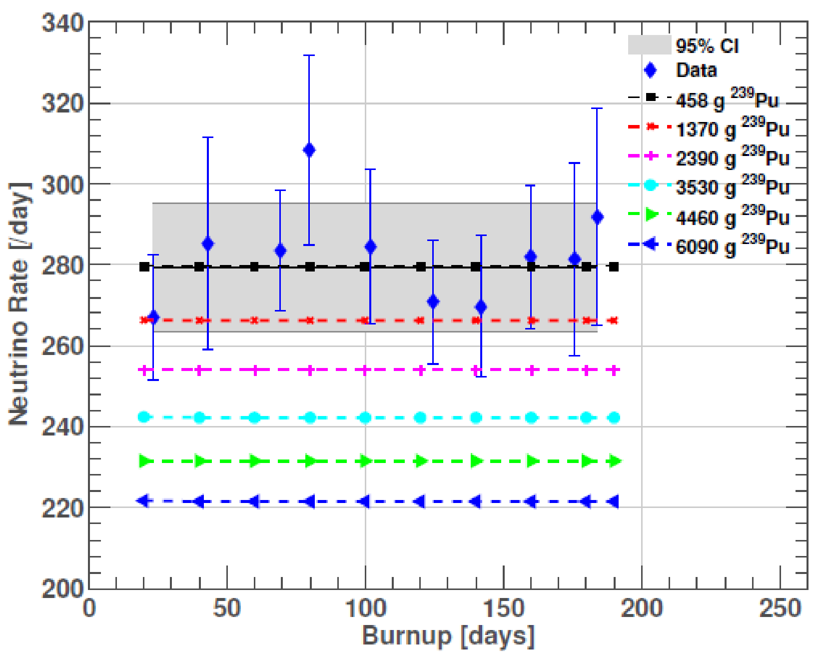
- **Shape**
- **Maxima**
- **Number**

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

Watchman experiment

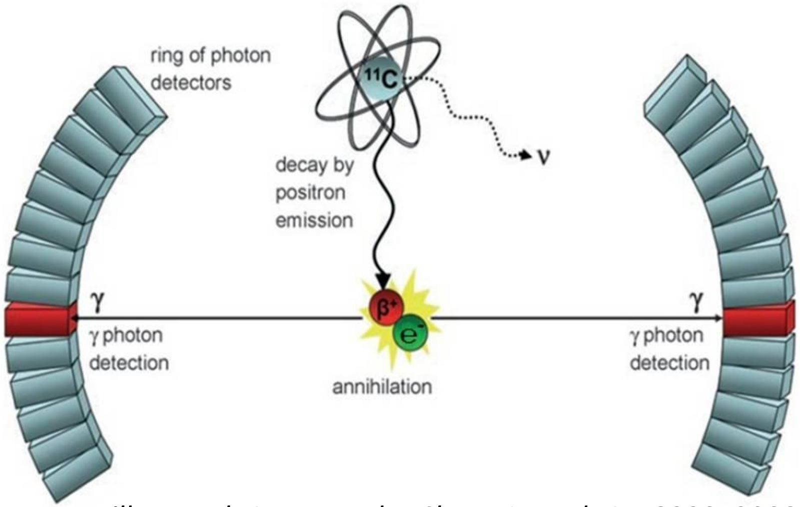
The New York Times

How to Spot a Nuclear Bomb Program? Look for Ghostly Particles

The Boulby mine in northeast England will be home to the Watchman experiment, which aims to

Nuclear Medicine

Positron Emission Tomography (PET)

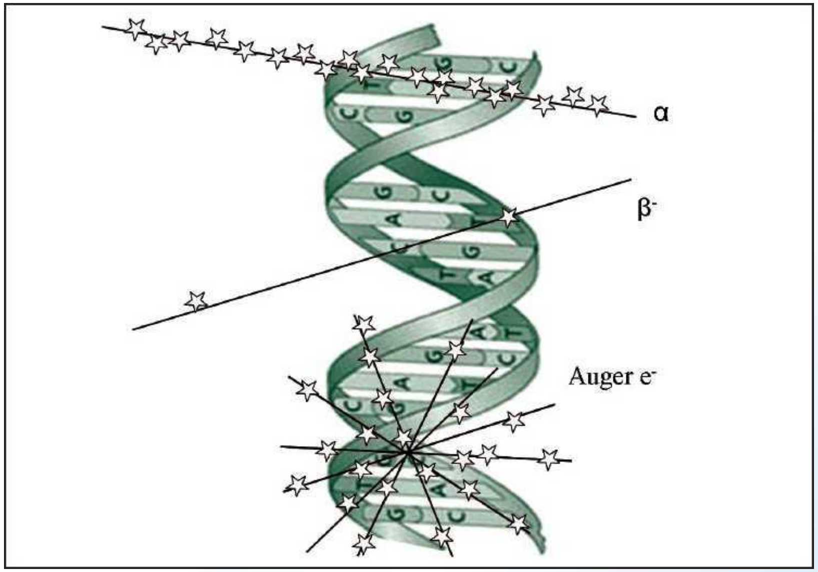


Miller et. al. Angewandte Chem. Int. Ed. 47, 8998, 2008

What is PET?

- PET = positron emission tomography
- Radioactive positron emitters injected into body
- Usually attached to carrier molecule
- Radioactive source accumulates in areas of interest targeted by carrier molecules
- Position sensitive detector "rings" detect back-to-back 511keV annihilation gammas
- More decays from regions of higher concentration

Targeted Radionuclide Therapy

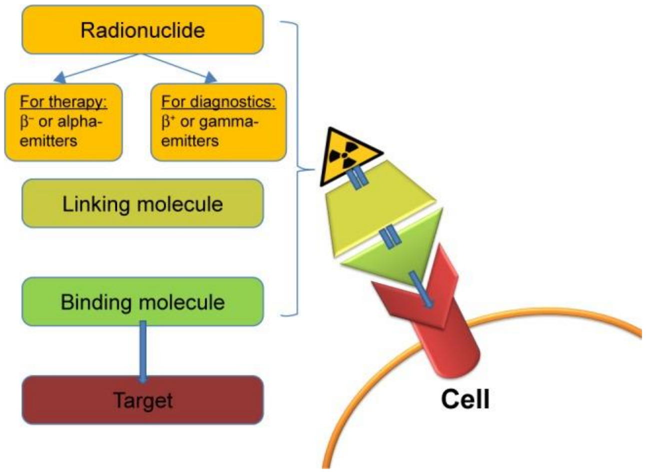


M. Sadeghi et al., J Can Res Ther 2010;6:239

- Ionizing radiation to kill cancer cells and shrink tumors
- Uses molecule labeled with radionuclide
- Beta, alpha or Auger electrons

BROOKHAVEN
NATIONAL LABORATORY

Theranostic Radionuclides



- Simultaneous therapy and imaging
- Visualization of dose and distribution

A. Yordanova et al., Onco Targets Ther. 2017; 10: 4821

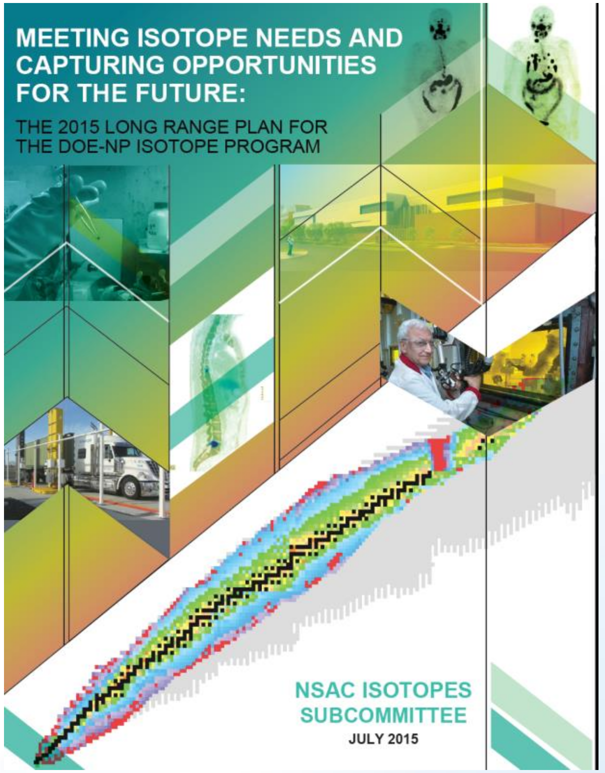


Table 5: Theranostic Isotope P[illegible]t)

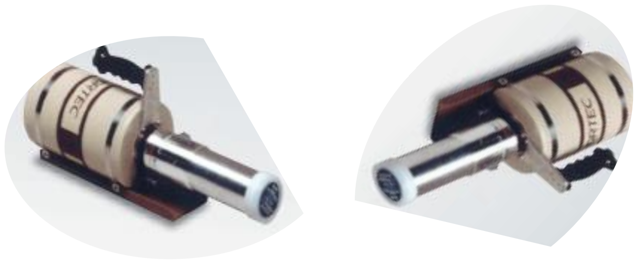
Imaging Isotope (type)	Half-life (hours)	Imaging Emission(s) γ or β + energy in keV (abundance)	Th[illegible] Isotope	[illegible]
^{64}Cu (β +)	12.7	278	^{67}Cu (β -)	61.
^{44}Sc (β +)	4.0	632	^{47}Sc (β -)	80.4
^{86}Y (β +)	14.7	652	^{90}Y (β -)	64.1
^{123}I (γ)	13.2	159 (83%)	^{131}I (β -)	192.5
^{124}I(β +)	100.3	687(12%); 974(11%)	^{131}I (β -)	8.02
^{152}Tb (β +)	17.5	1337(8%); 1186(6%)	^{161}Tb (β -)	165.4
^{72}As (β +)	26.0	1117(64%); 1529(16%)	^{77}As (β -)	38.8
^{155}Tb (γ)	127.7	180(8%); 163(4%)	^{149}Tb (α)	4.12
^{76}Br (β +)	16.2	1532 (26%)	^{77}Br (Auger)	57.0
^{68}Ga (β +)	1.13	836 (88%)	^{67}Ga(Auger)	78.2

Over half were last studied >30 years ago !!

BROOKHAVEN NATIONAL LABORATORY

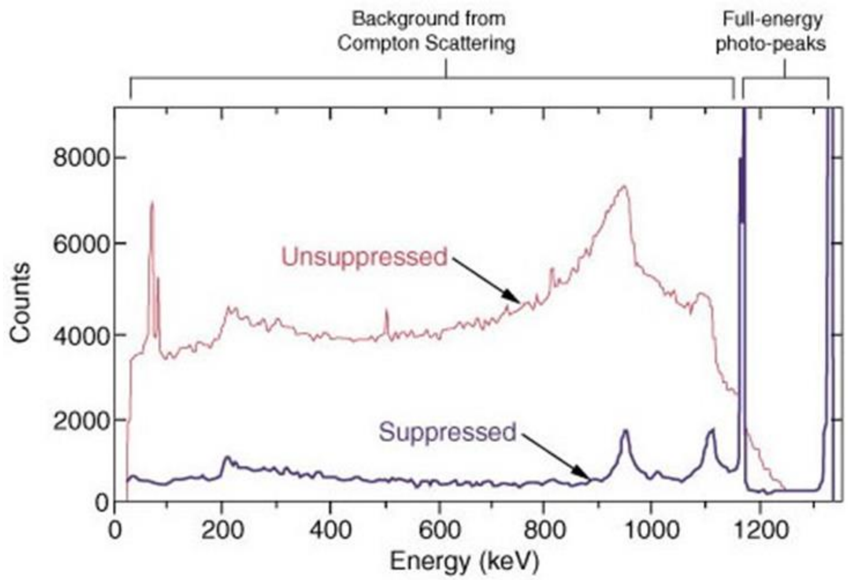
Capitalizing on advances in γ-ray spectroscopy

30 Years ago: 1-2 small detectors

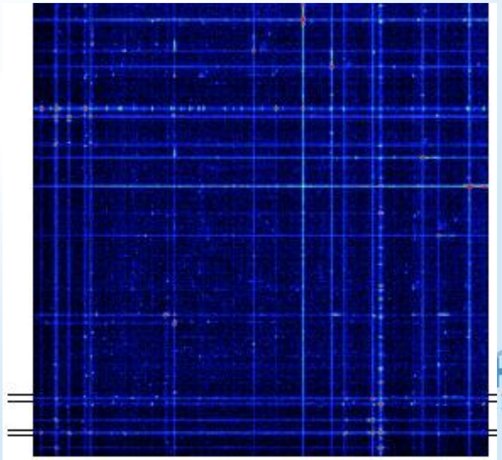


Present: 10-100 detectors

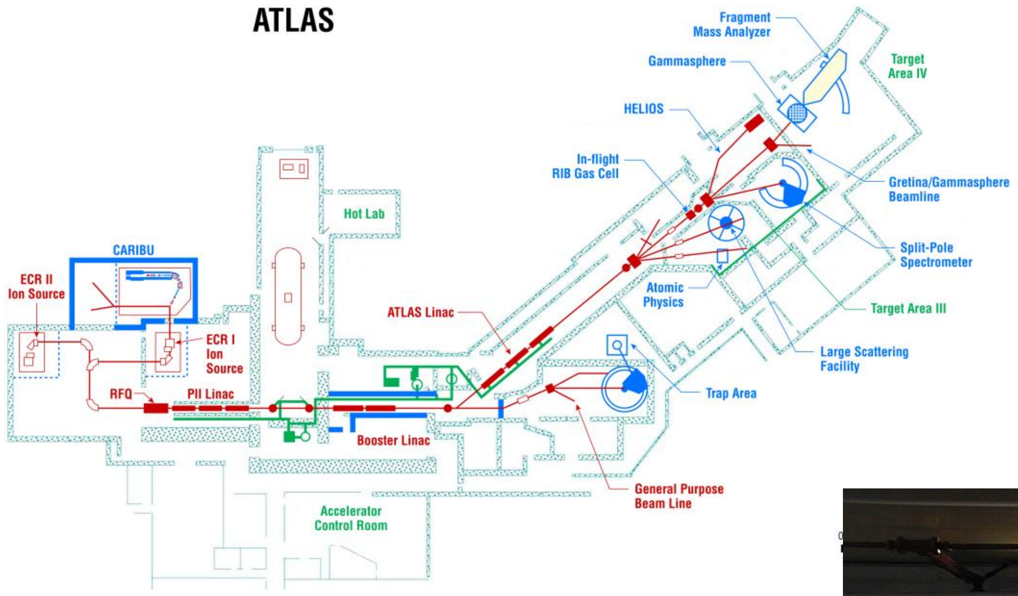
Compton suppression



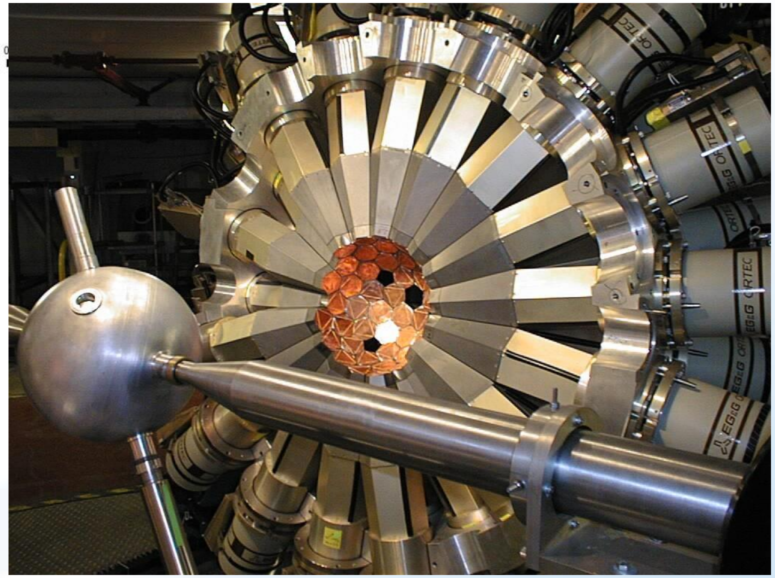
γγ coincidences



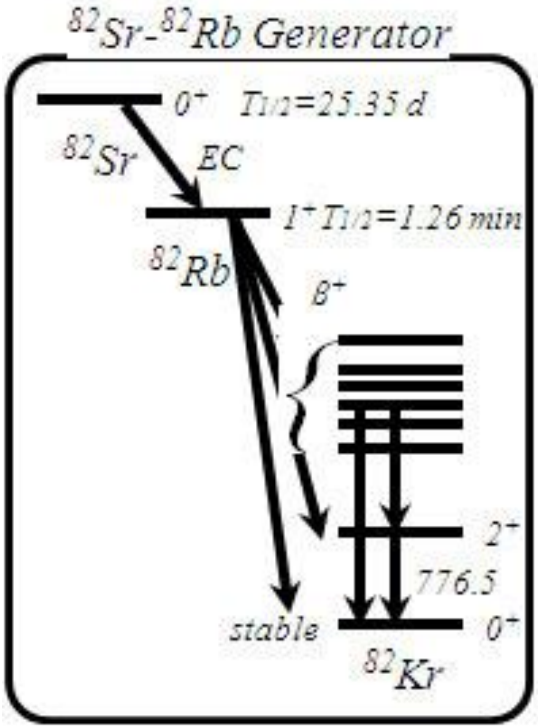
Gammasphere at Argonne National Lab

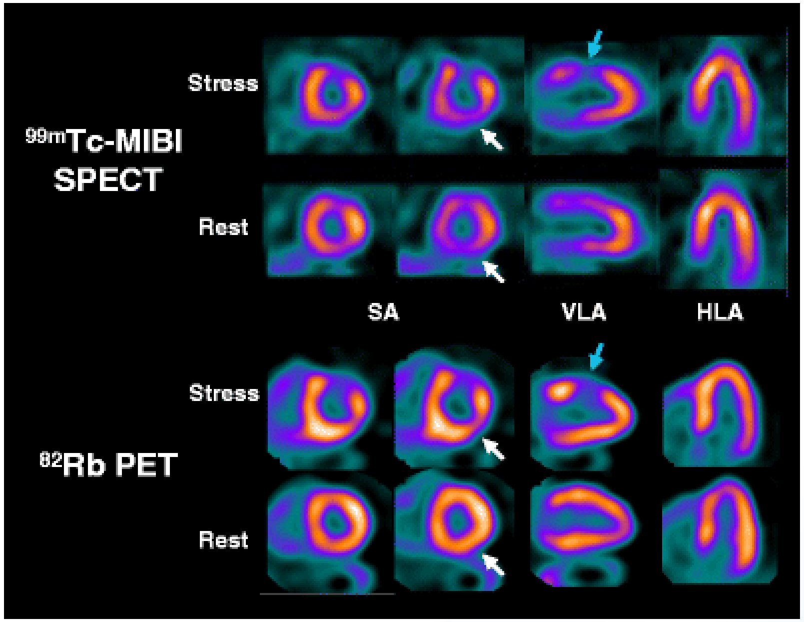


100 HPGe detectors
Compton-suppressed
Digital or analog DAQ

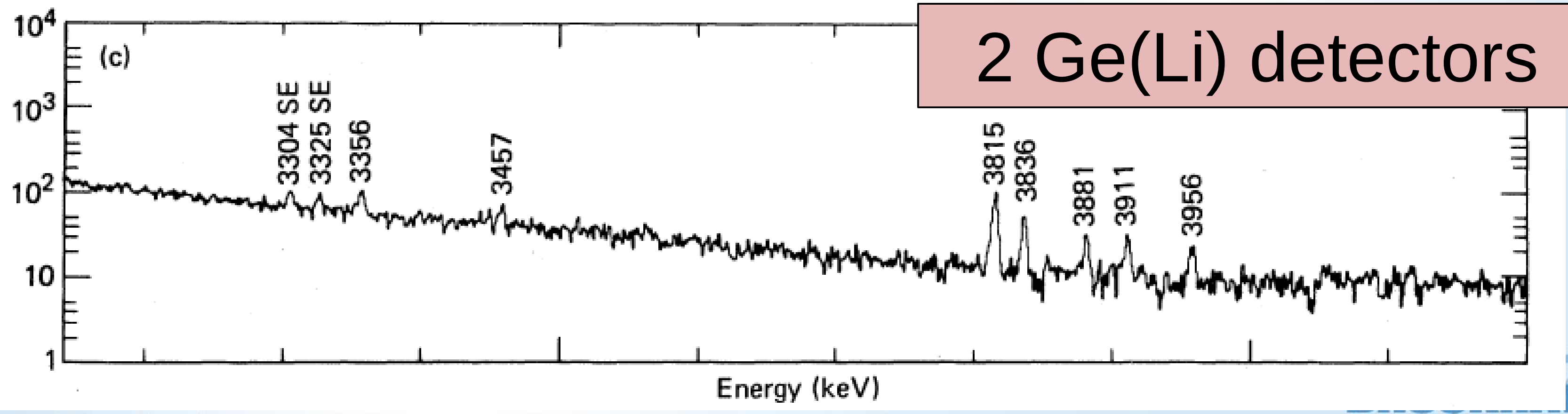


Starting point : ^{82}Rb for Cardiac PET





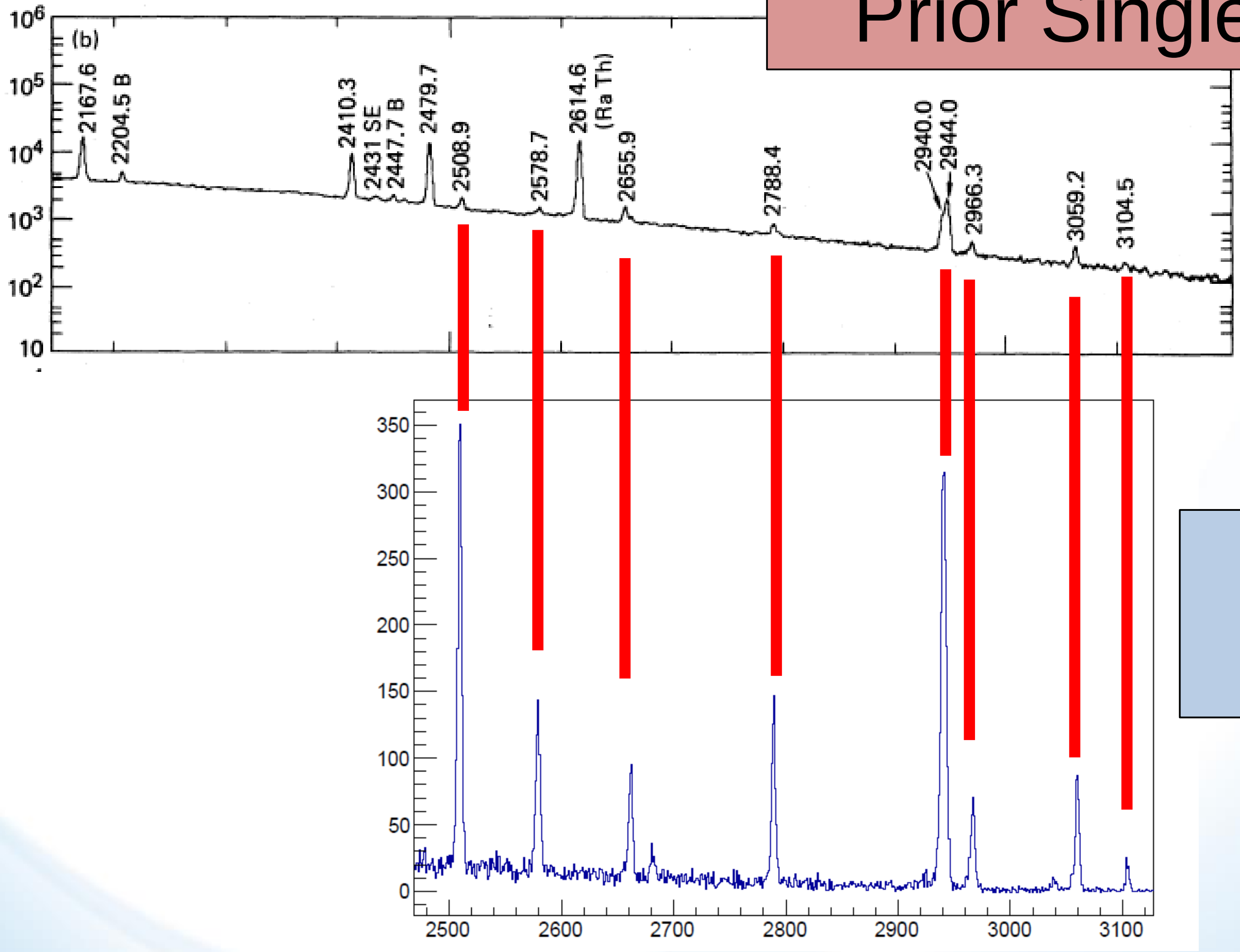
D. Le Guludec *et al.*, Eur. J. Nucl. Med. Mol. Imaging **35**, 1709 (2008).



2 Ge(Li) detectors

R.A. Meyer *et al.*, Phys. Rev. C **27**, 2217 (1983).

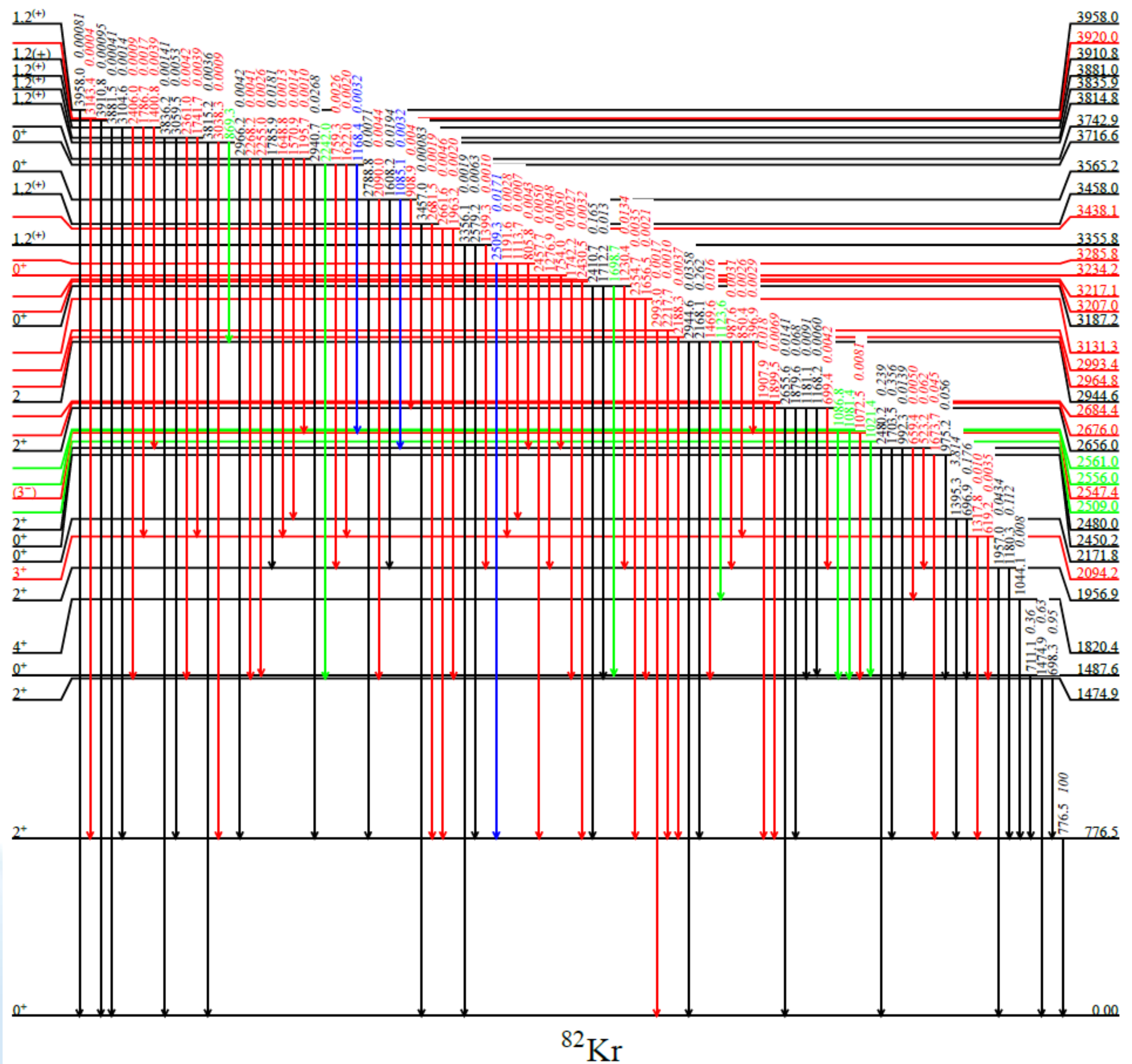
The power of Gammasphere



Prior Singles

Gate on $2^+ \rightarrow 0^+$

Revised decay scheme for ^{82}Rb



New

Confirmed

Removed

Moved

M. Nino *et al*, Phys. Rev. C **93**, 024301 (2016).

BROOKHAVEN NATIONAL LABORATORY

And so much more …

- Stockpile Stewardship
- Isotope Production
- Nuclear Forensics
- Astrophysics
- Oil logging
- Waste disposal and transmutation
- …