NEUTRINOS IN NUCLEAR PHYSICS

Ben Jones, University of Texas at Arlington

UNIVERSITY OF TEXAS ARLINGTON

ON THE MENU

- I have been asked to cover all of neutrino physics in 4 lectures, which is **clearly impossible.**
- Instead, you get a mix of:
  - Historical things
  - Pedagogical things
  - Breaking news
  - My own opinions about things

Menu

L1:
- Neutrinos in β decay
- Reactor neutrinos
- Endpoint ν mass searches

L2:
- Solar neutrinos
- Neutrino oscillations
- MSW effect

L3:
- Majorana v. Dirac
- Double beta decay

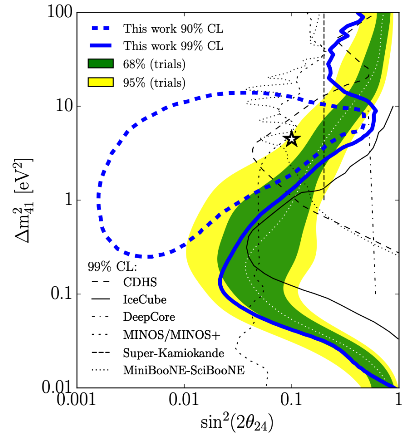
L4:
- Atmospheric neutrinos
- Accelerator neutrinos
- Gallium anomaly
- Sterile neutrinos, etc

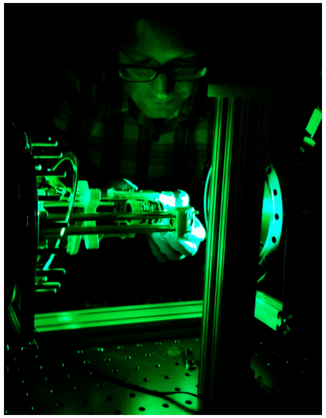
ABOUT ME…

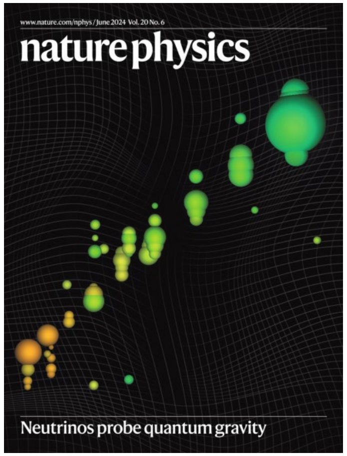
UNIVERSITY OF TEXAS ARLINGTON

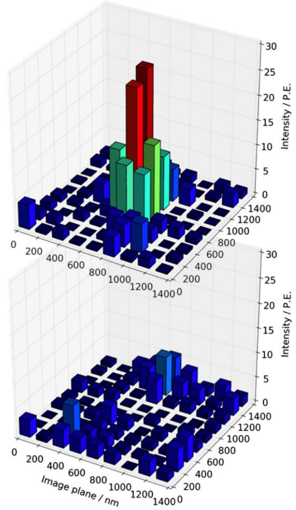
- **Career path:**
  - BA M.Sci at Cambridge
  - PhD at MIT 2009-2015
  - Postdoc at UTA 2015-2016
  - Prof at UTA 2016-present.

- **Main things I have worked on:**
  - **MicroBooNE (2009-2015)**
    - *SBN Accelerator ν; worked on liquid argon TPC technology focused on optical systems and properties.*
  - **IceCube (2013-2023)**
    - *Atmospheric and Astro ν; led high energy oscillation analyses including worlds best limits on sterile ν, quantum gravity & NSI.*
  - **NEXT (2016-present)**
    - *0nubb search in xenon gas; developed single Ba^{2+} tagging techniques and led US contributions to NEXT-White and NEXT-100.*
  - **Project 8 (2023-present)**
    - *Direct ν mass search; working on magnetic evaporative cooling beamline for atomic tritium source.*
  - **Creative bits and pieces**
    - *I also like to explore new ideas in neutrino pheno and experiment concepts – its fun to be creative!*



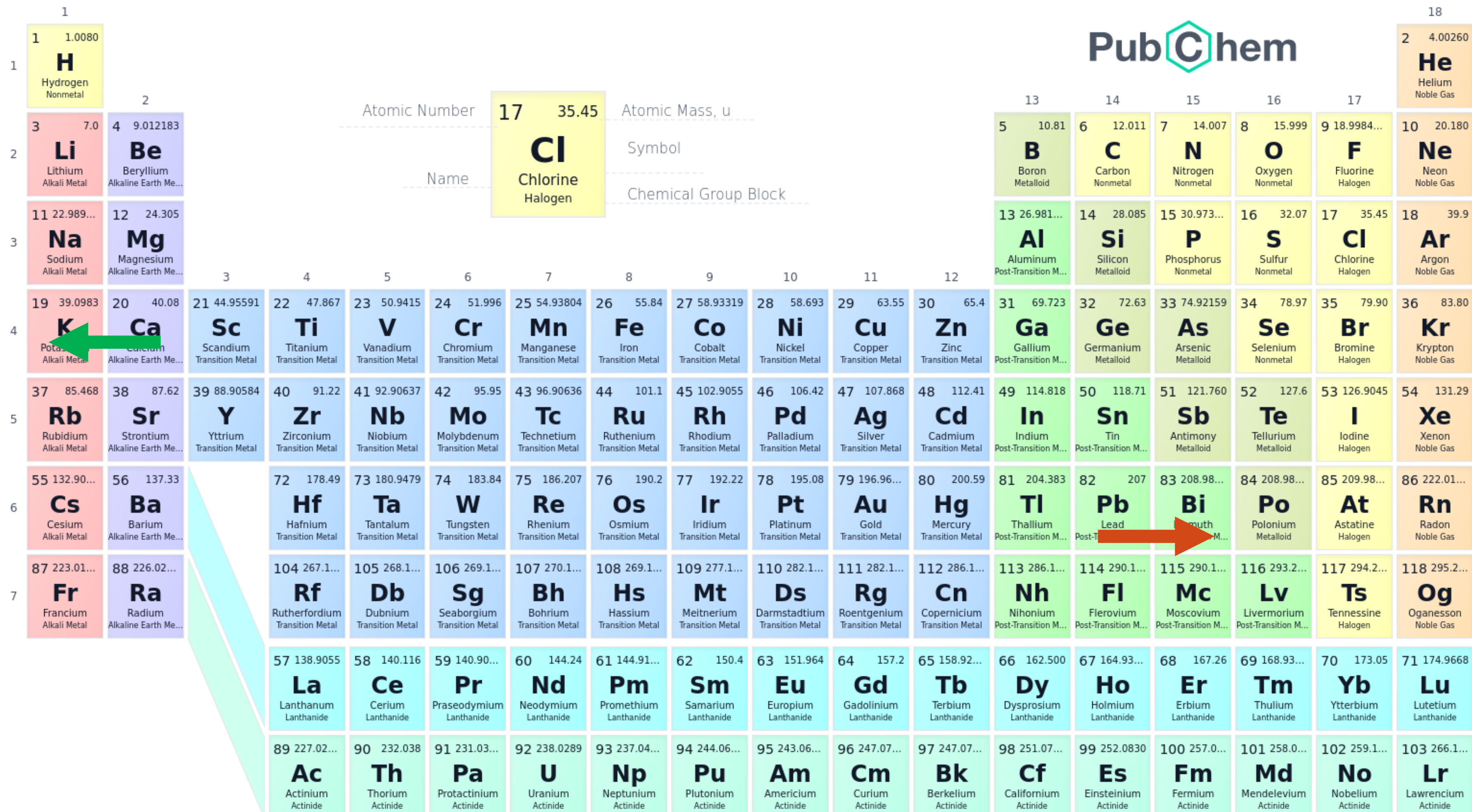






My Group Website: https://nures.uta.edu/

BETA DECAY AS ALCHEMY:

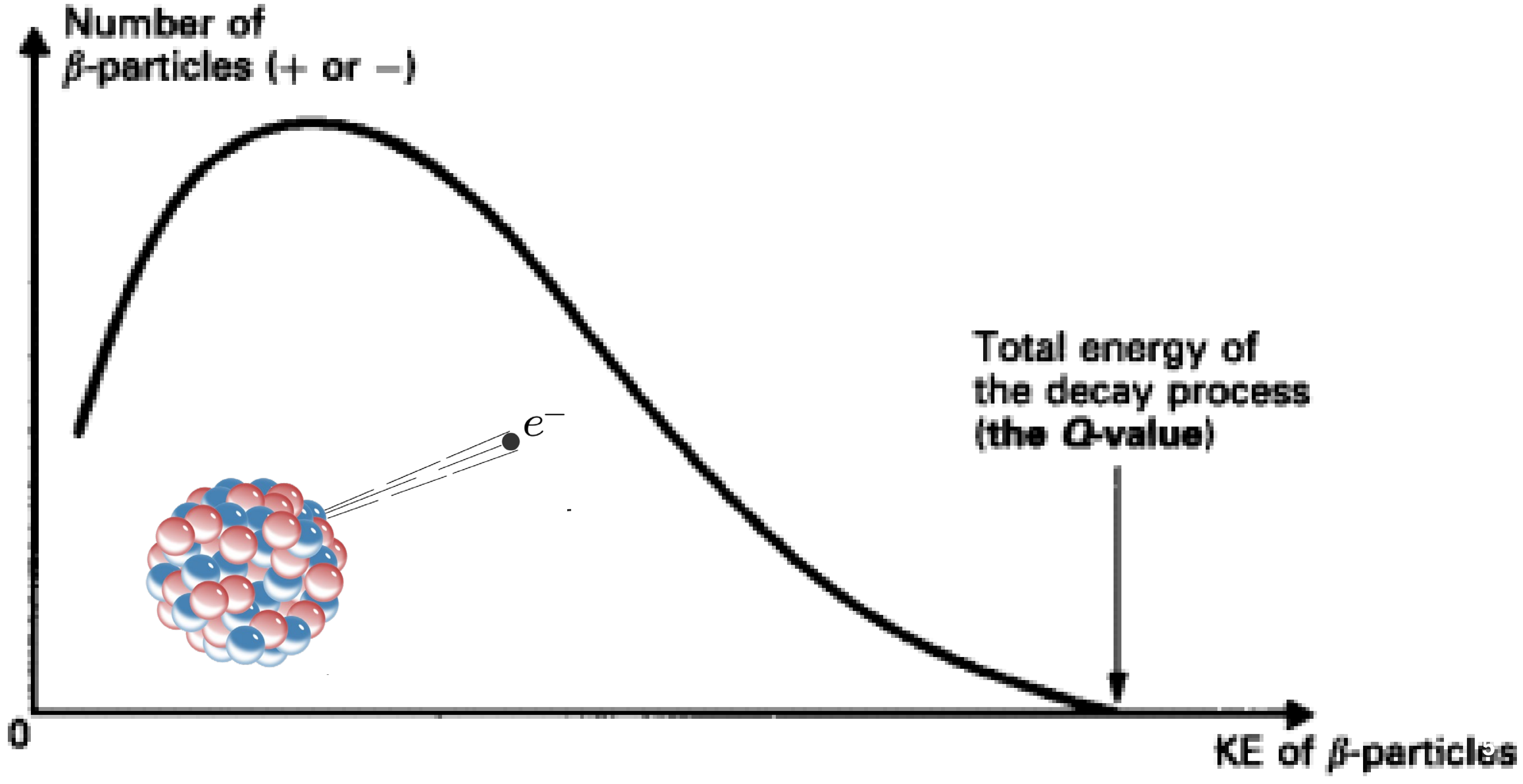


$p \rightarrow n + e^+$ (β^+ decay)

$n \rightarrow p + e^-$ (β^- decay)

Energy available in the decay is the mass difference between initial and final nuclei (n.b., final one may be in excited state)

If you measure the energy of the electron in beta decay you get a continuous energy distribution.



A BOLD IDEA...

- Apparent momentum non-conservation in beta decay led Pauli to propose the existence of an “undetectable” particle in a now famous letter:

Wolfgang Pauli, 1930

Original - Photocopie of PLC 0393
Abschrift/15.12.56 FM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. **Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light.**

The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. **The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than e • (10-13cm).**

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

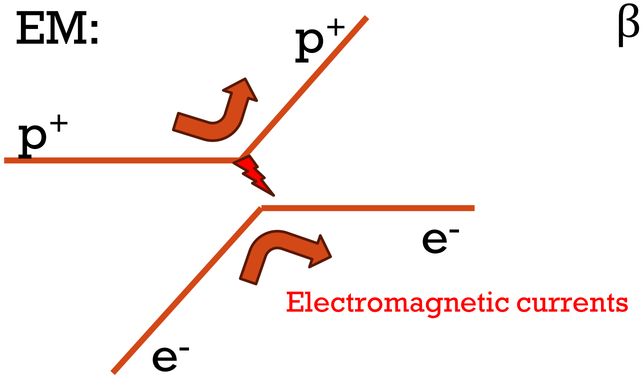
I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue.

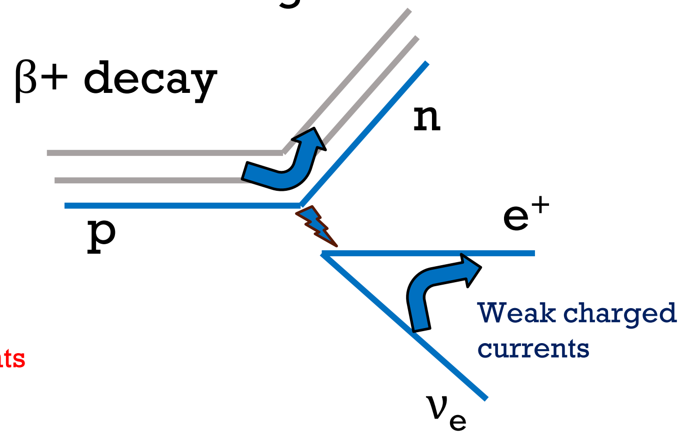
Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

signed W. Pauli

FERMI THEORY

Fundamental theory of beta decays was developed by Fermi, through analogy with electromagnetism:





Enrico Fermi

(nb this is an era before Feynman diagrams… think instead about interacting currents)

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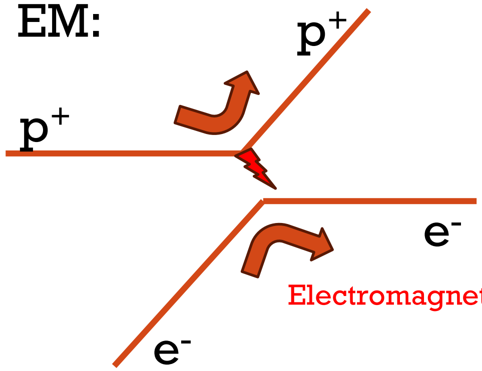
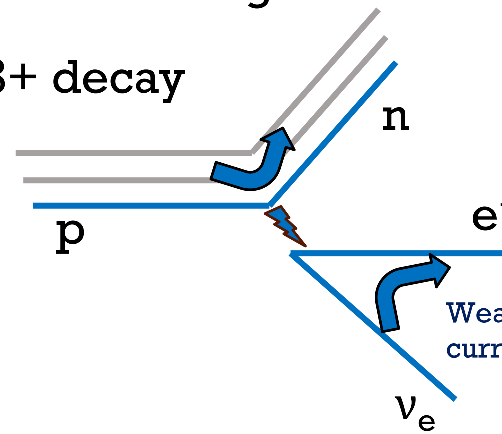
EM:



β+ decay



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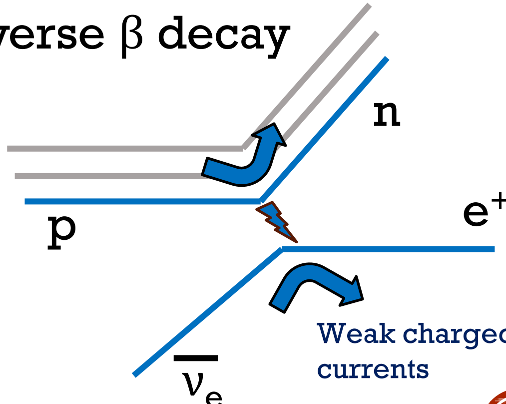
→ A corollary: if you know the rate of **beta decay**, you can know what the cross section for neutrinos to interact through **inverse beta decay**.

Inverse β decay



Hans Bethe and Rudolf Pierls did the calculation and found a crazy small cross section, concluding: **"there is no practically possible way of detecting the neutrino."**

FIRST ATTEMPT TO DISCOVER THE NEUTRINO

- Bruno Pontecorvo suggested using neutrino capture on chlorine from a nuclear reactor, an experiment first attempted by Ray Davis:

Ray Davis

Savannah river nuclear reactor – a copious source of neutrinos

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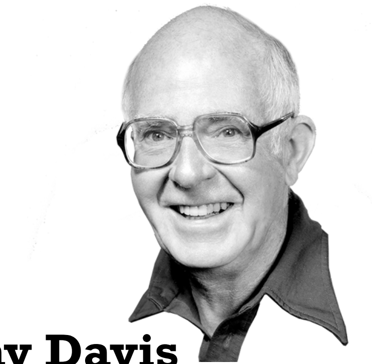
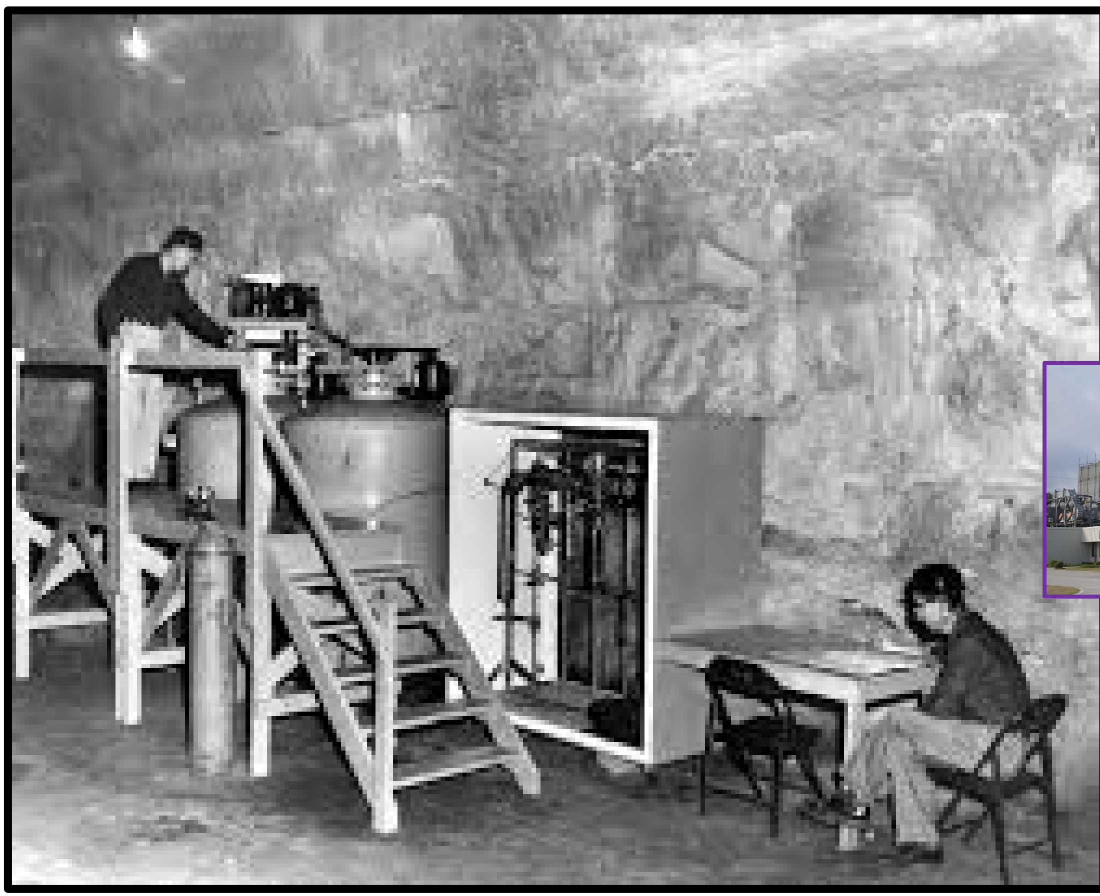
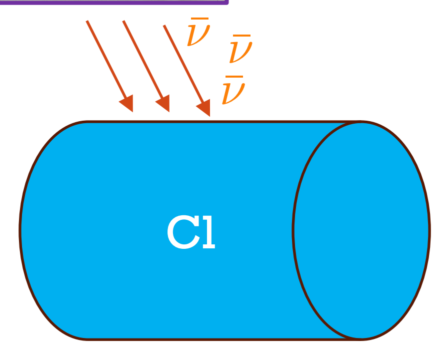


Ray Davis



Proposed process:

$$\bar{\nu} + {}^{37}Cl \rightarrow e^{-} + {}^{37}Ar$$



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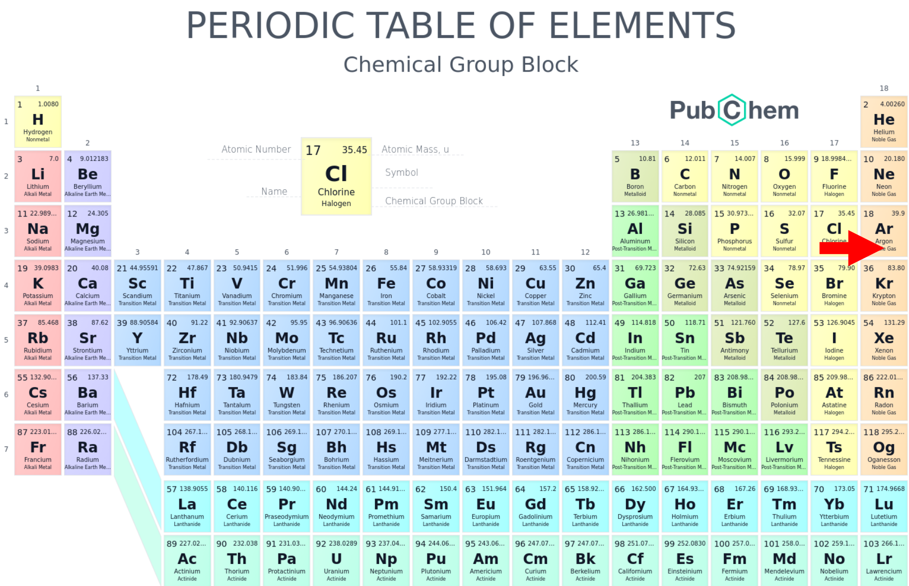
Proposed process:

$$\bar{\nu} + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

But it didn't work…

Why not?

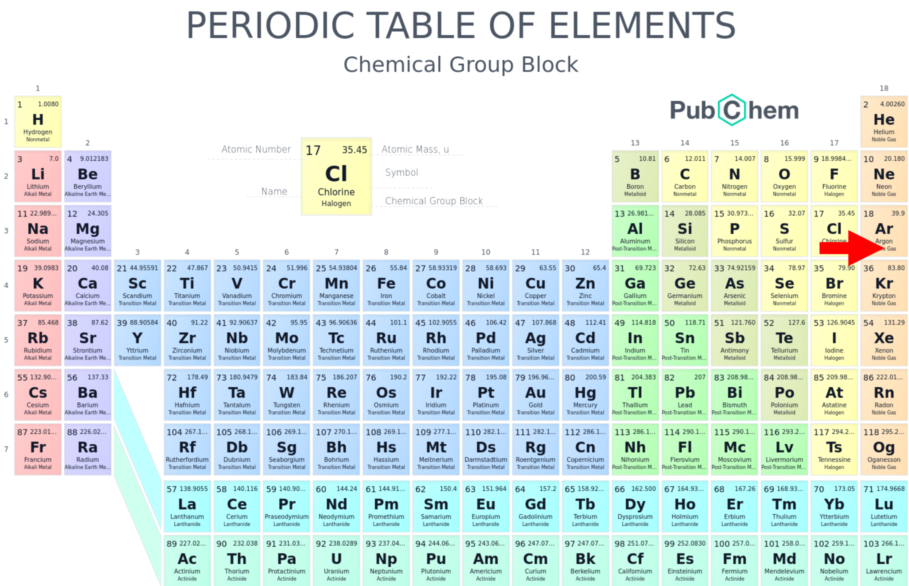


Go this way,
- Means adding more + to the nucleus
- Means making an e- to conserve charge
- Means absorbing a neutrino to conserve L

- This process is only sensitive to **neutrinos!**

Chlorine neutrino reaction as a path to neutrino detection

- And reactors only make **antineutrinos!**



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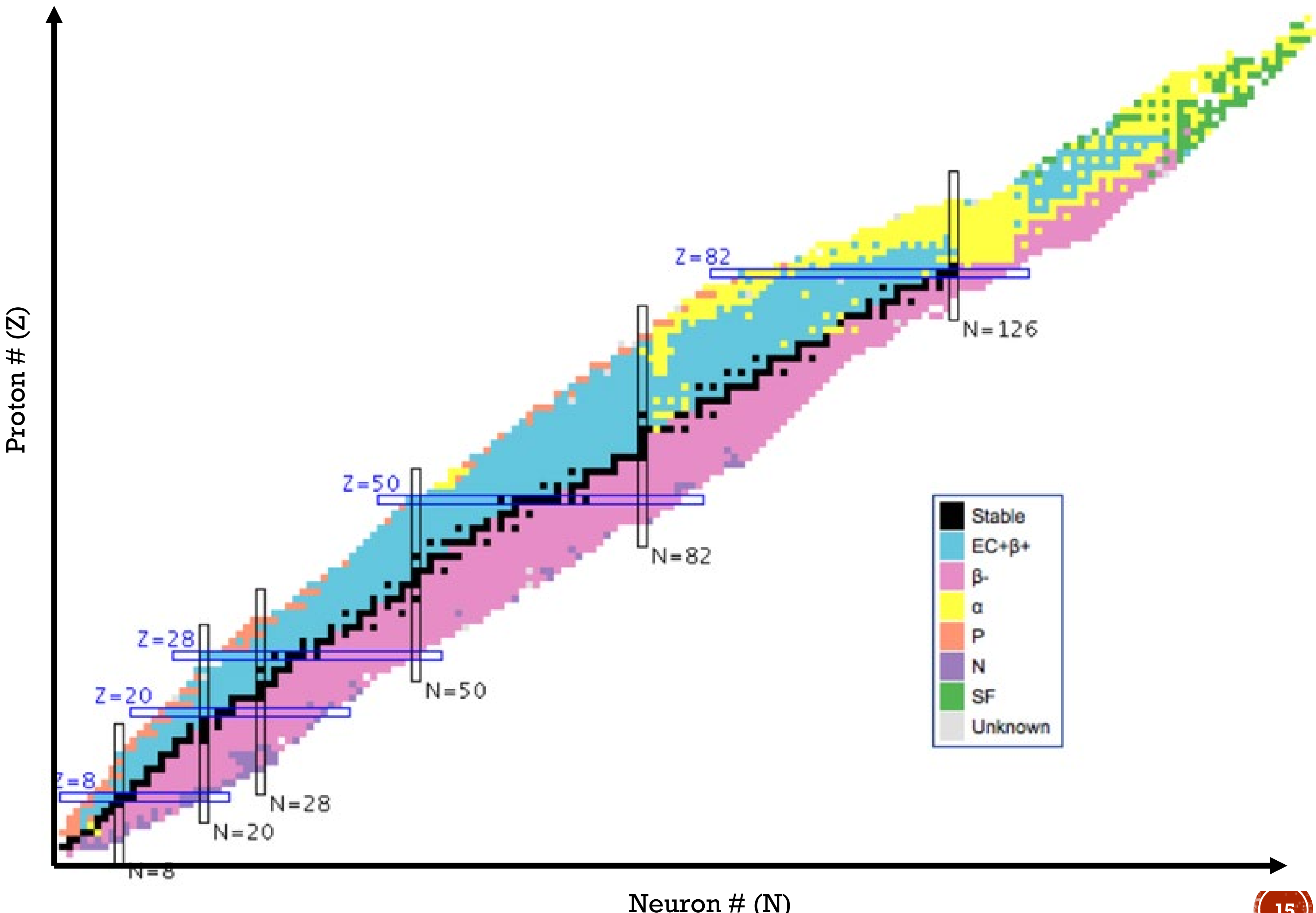
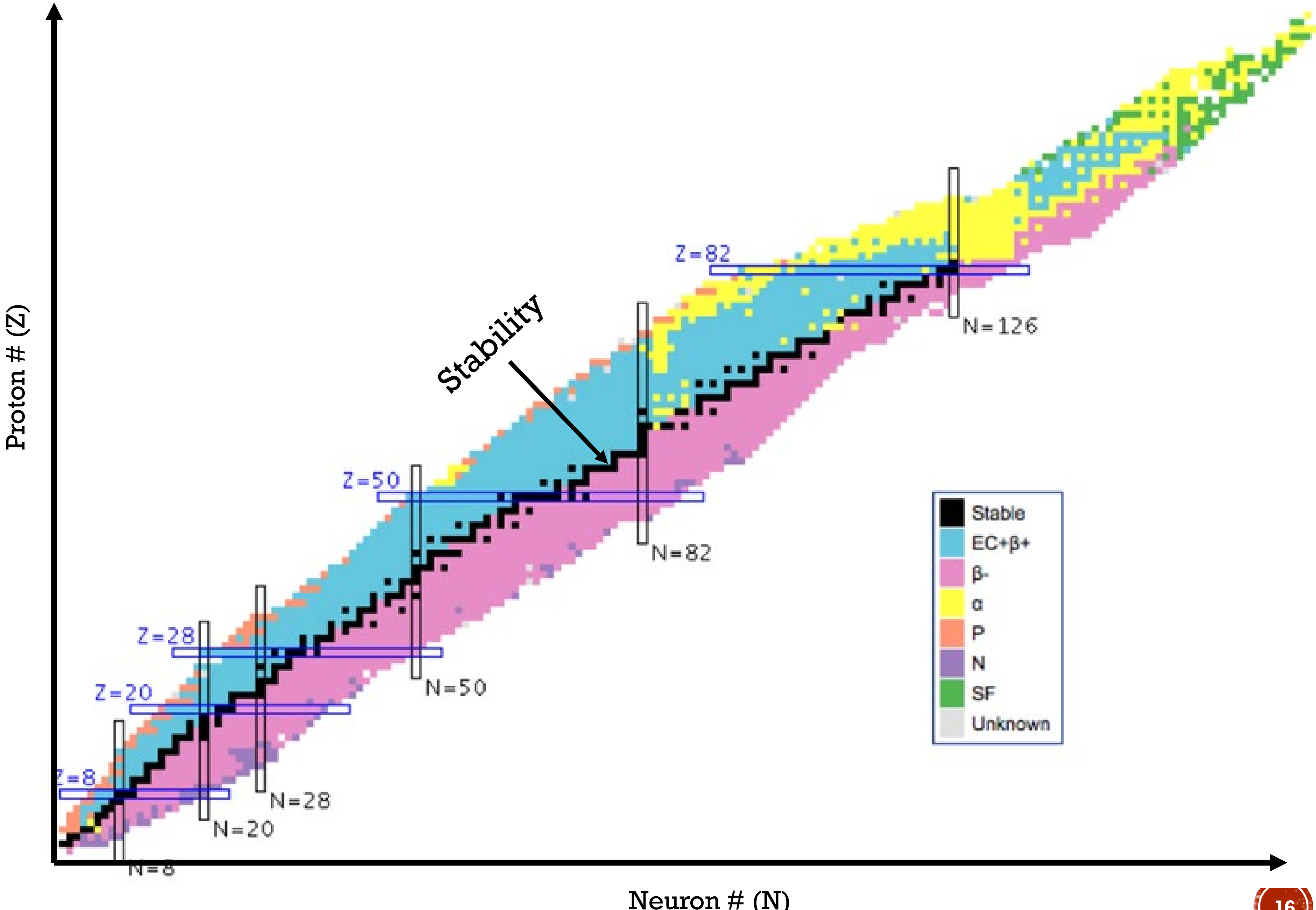


Proton # (Z)
Neuron # (N)
Z=8
Z=20
Z=28
Z=50
Z=82
N=8
N=20
N=28
N=50
N=82
N=126
Stable
EC+β+
β-
α
P
N
SF
Unknown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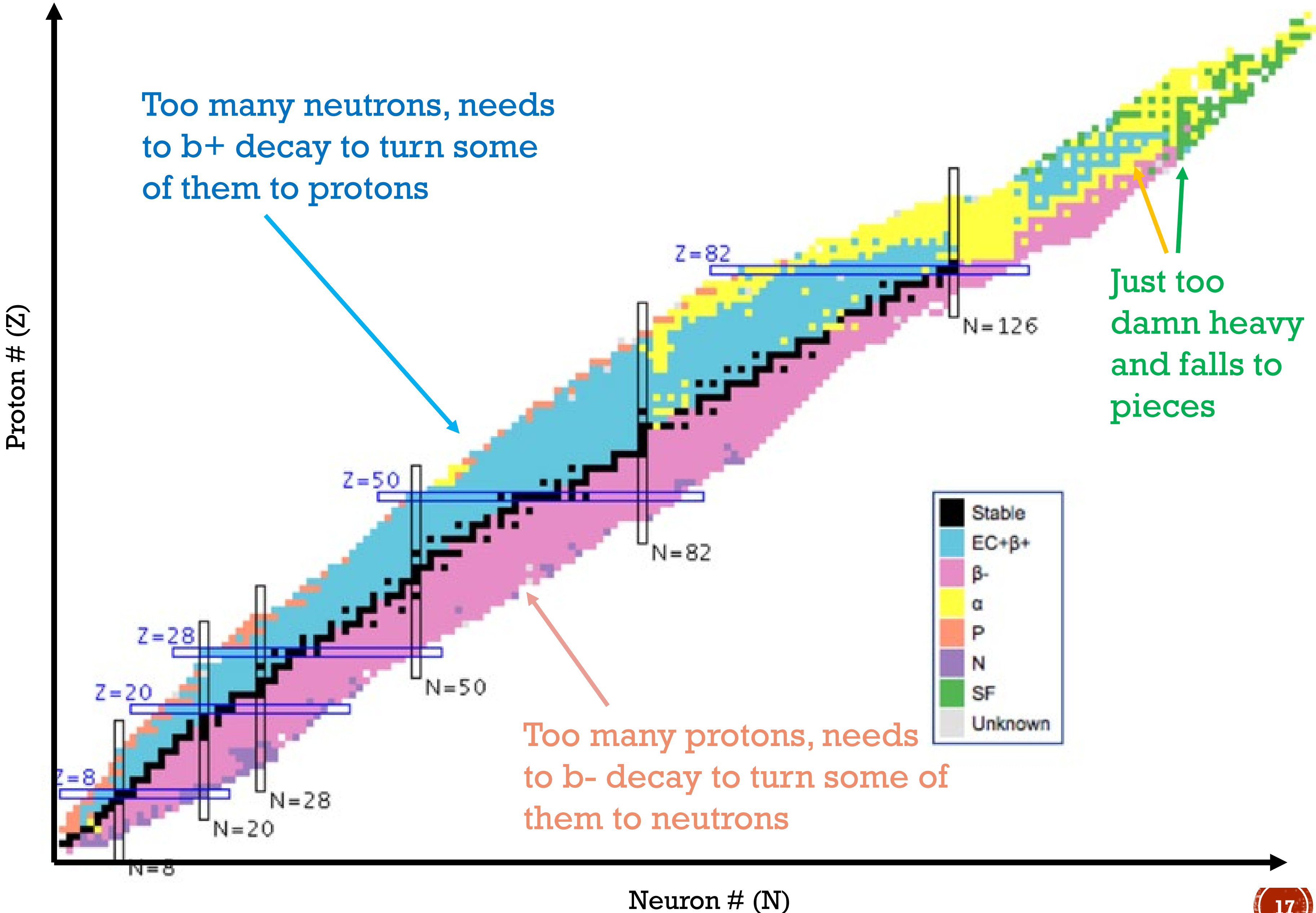
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N=8
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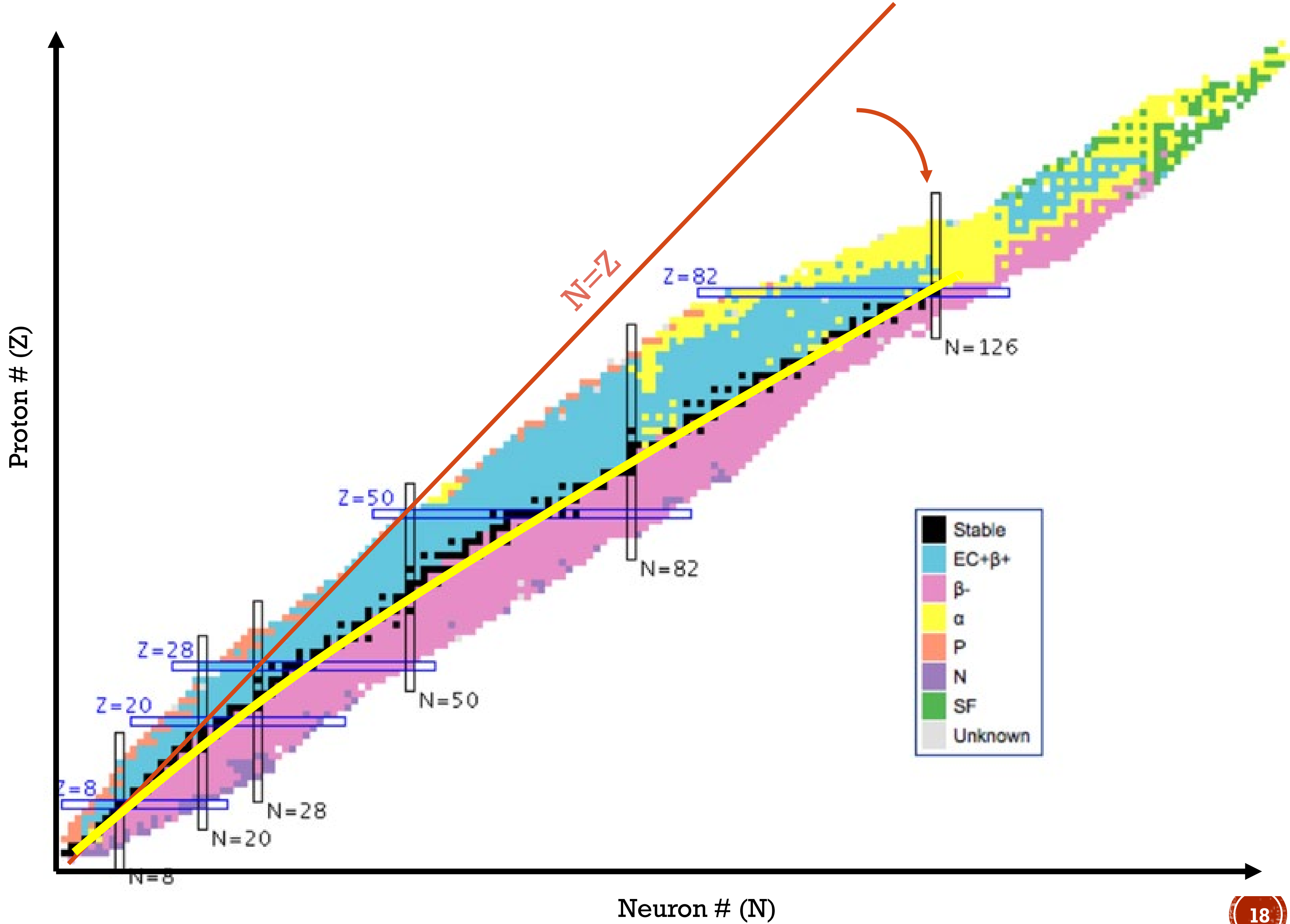
N=28
N=50
N=82
N=126
Stable
EC+β+
β-
α
P
N
SF
Unknown
Too many neutrons, needs to b+ decay to turn some of them to protons
Too many protons, needs to b- decay to turn some of them to neutrons
Just too damn heavy and falls to pieces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Z=8
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N=8
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N=50
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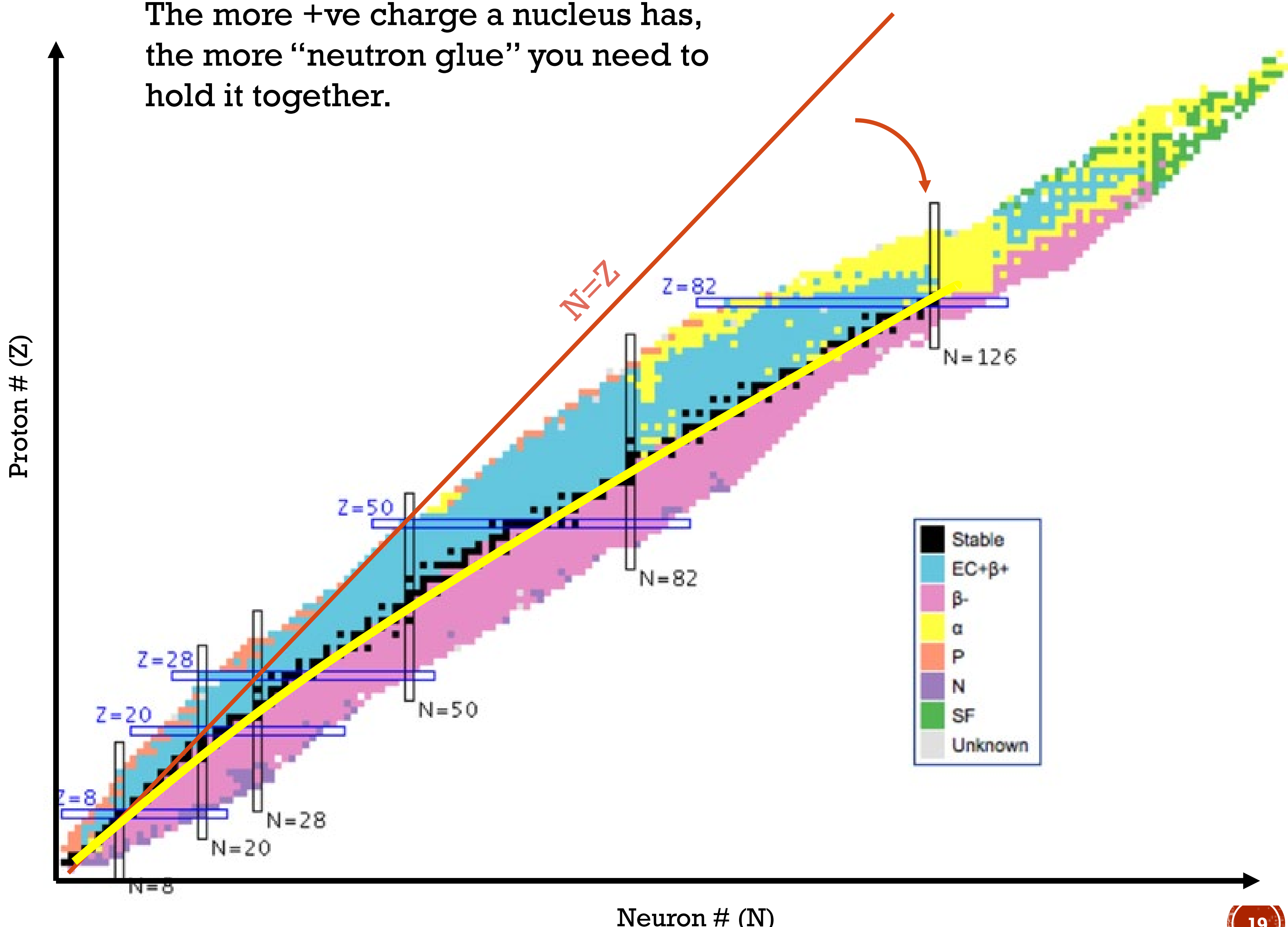
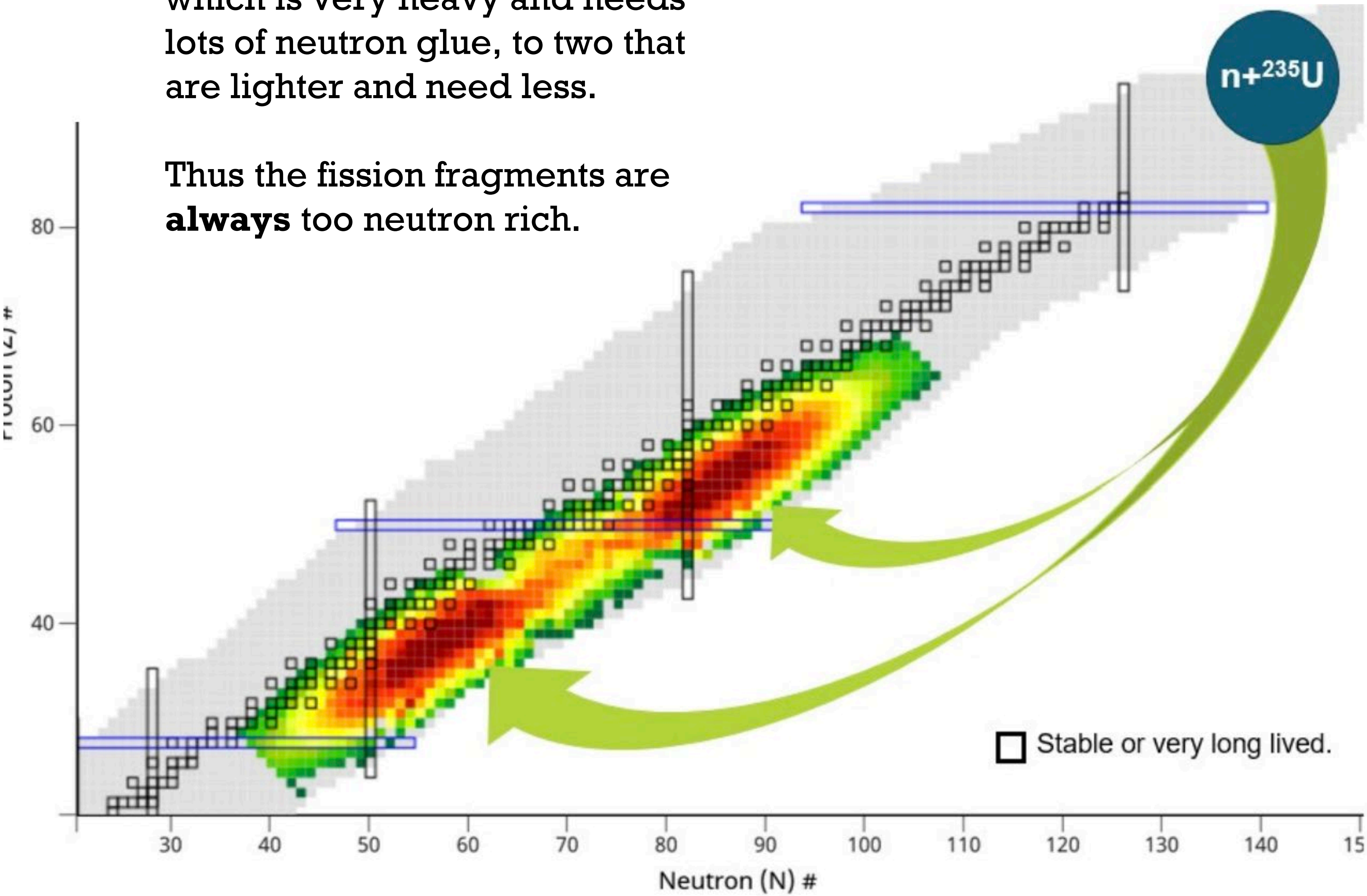
Stable
EC+β+
β-
α
P
N
SF
Unknown

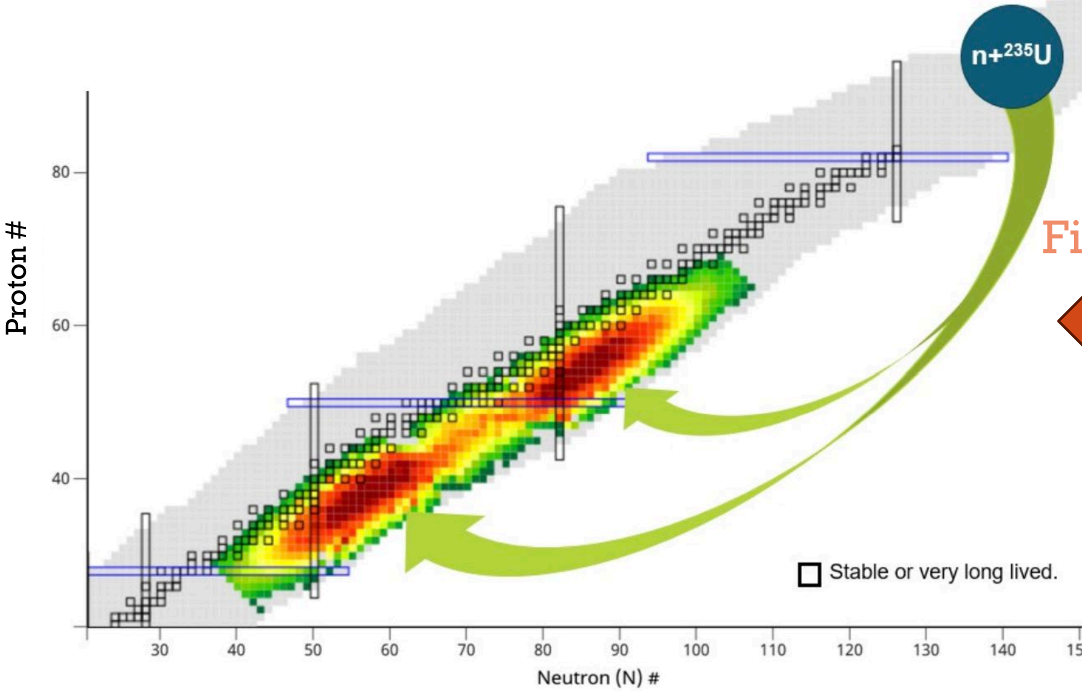
The more +ve charge a nucleus has, the more "neutron glue" you need to hold it together.



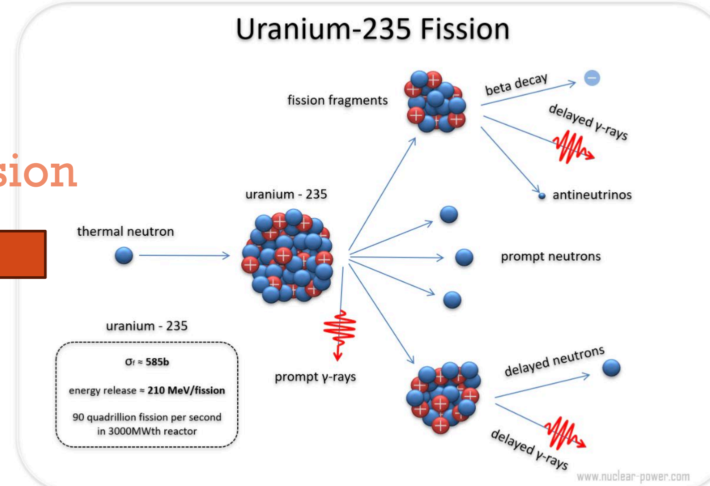
Nuclear Fission takes a nucleus which is very heavy and needs lots of neutron glue, to two that are lighter and need less.

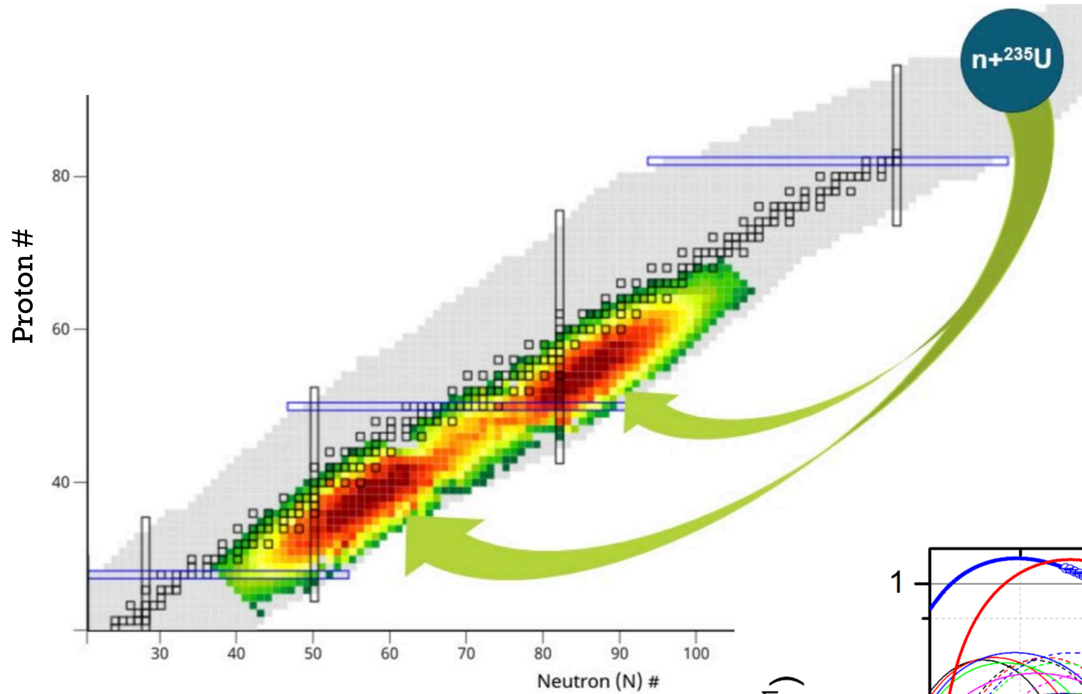
Thus the fission fragments are **always** too neutron rich.




n+^{235}U
Proton #
Neutron (N) #
80
60
40
30
40
50
60
70
80
90
100
110
120
130
140
15
Stable or very long lived.

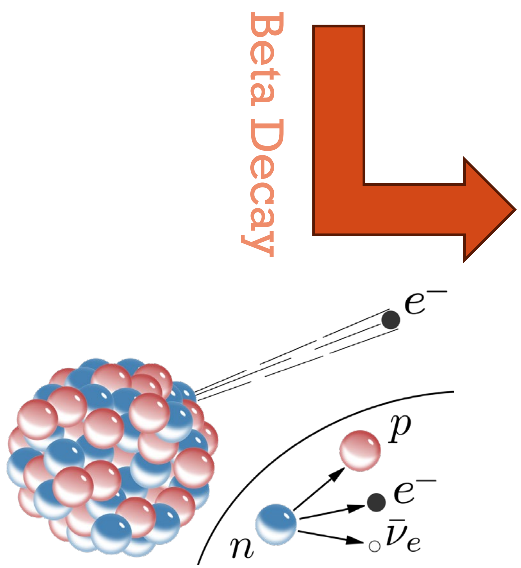
Fission

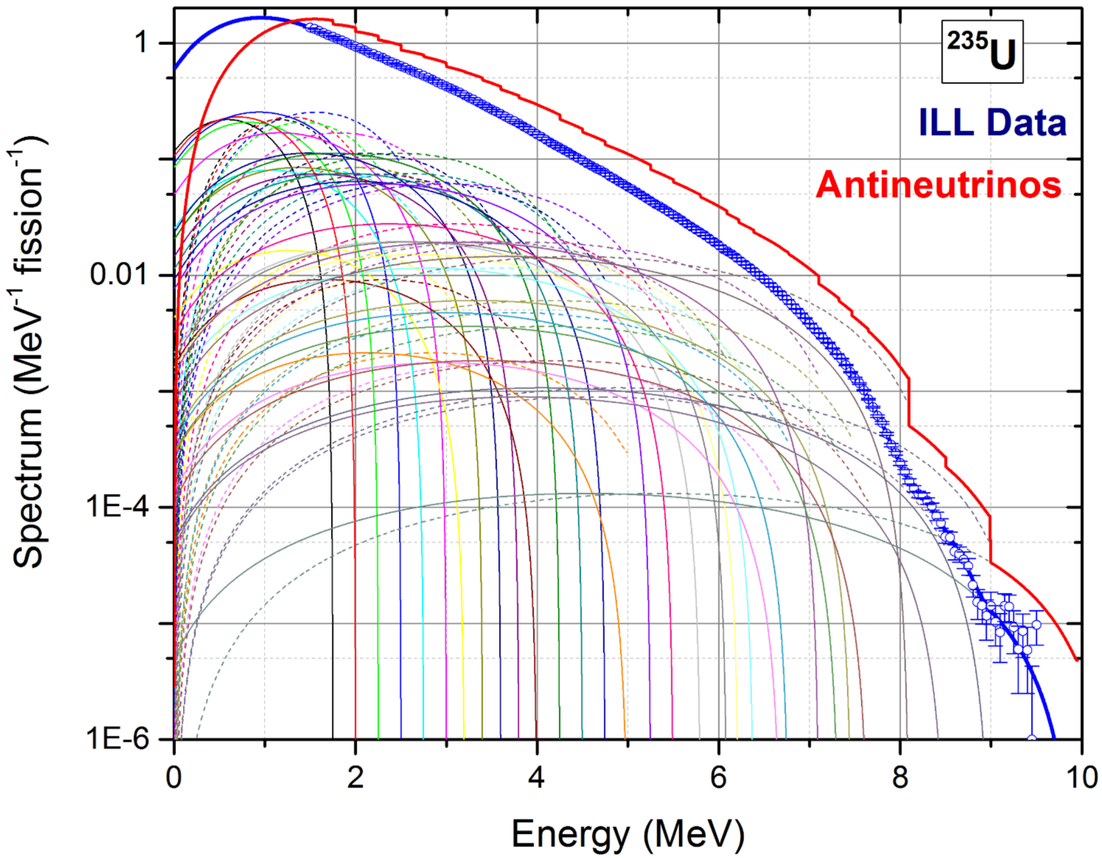

Uranium-235 Fission
fission fragments
beta decay
delayed γ-rays
antineutrinos
uranium - 235
thermal neutron
prompt neutrons
prompt γ-rays
delayed neutrons
delayed γ-rays
uranium - 235
σ_f ≈ 585b
energy release ≈ 210 MeV/fission
90 quadrillion fission per second in 3000MWth reactor
www.nuclear-power.com



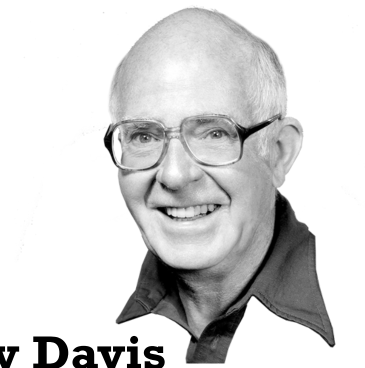
Those products then need to β- decay to get back to stability.

And that makes **antineutrinos**.





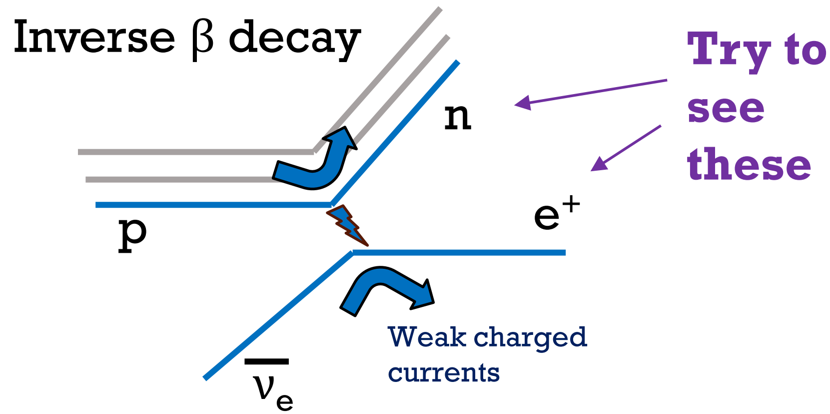
HE'LL BE BACK SOON →



Ray Davis

IN THE MEAN TIME…
HOW ABOUT WE USE A DETECTOR THAT CAN SEE ANTINEUTRINOS?

Neutrinos can be detected via ***Inverse beta decay*** *in liquid scintillator*



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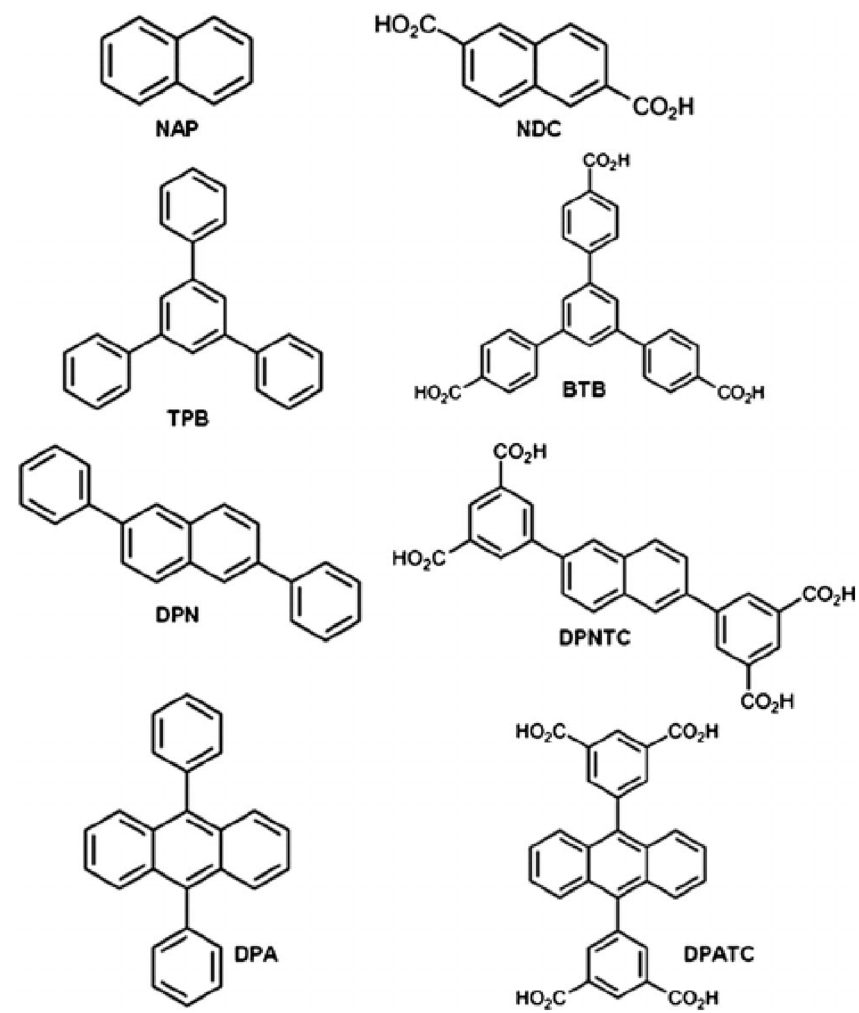
Liquid scintillator is a bunch of this kind of crap that emits light when charged particles go through it →



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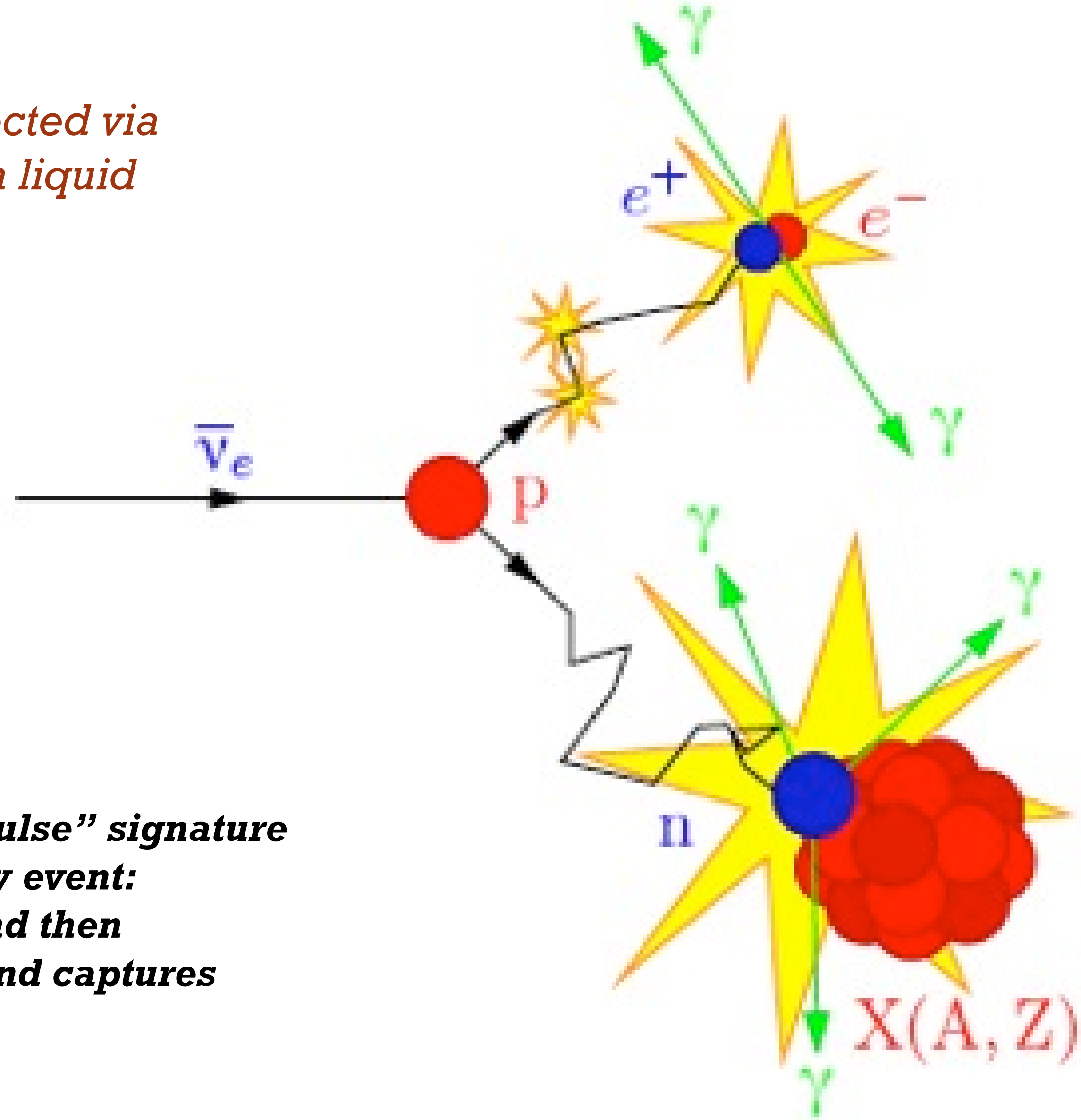
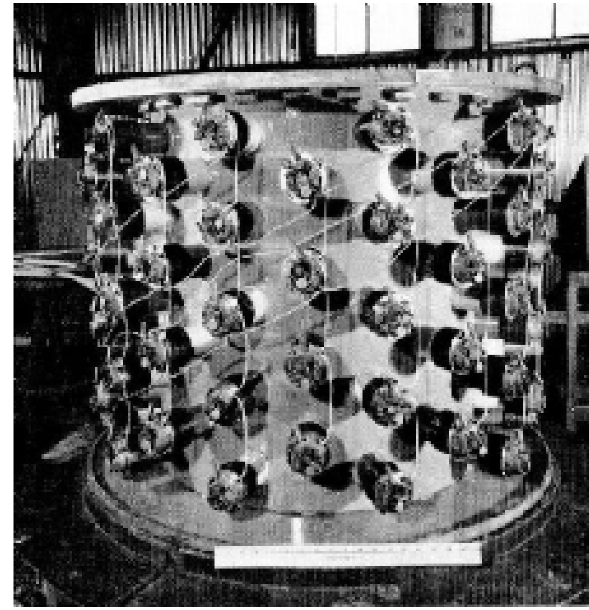


You get a handy "double pulse" signature from an inverse beta decay event:

1. ***Positron scintillates and then***
2. ***Neutron thermalizes and captures***

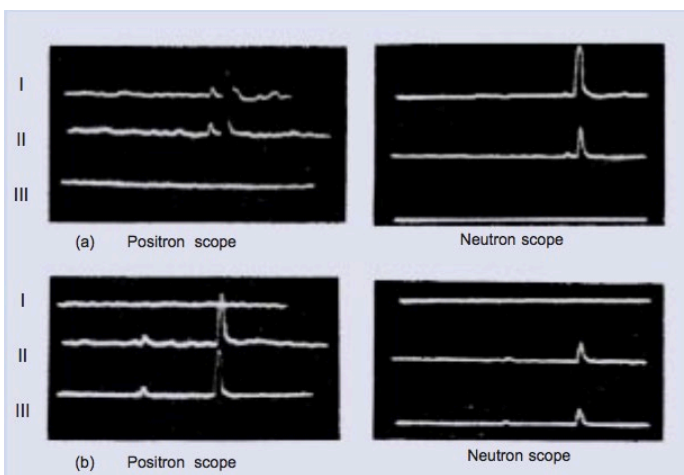
THE NEUTRINO DISCOVERED BY PROJECT POLTERGEIST

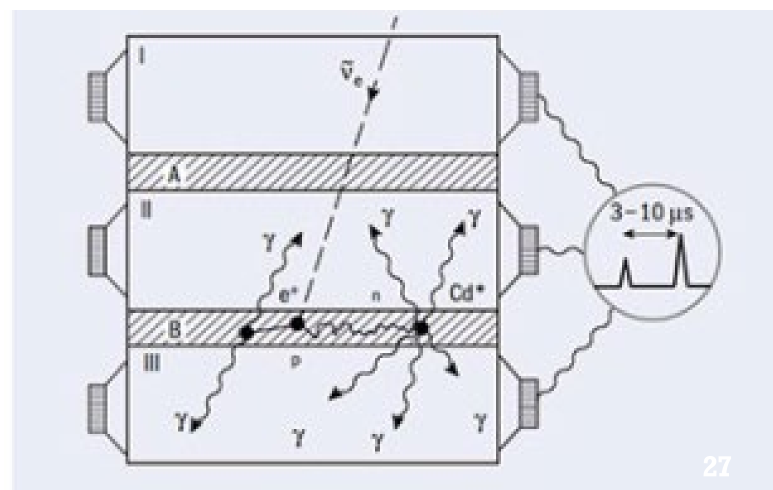
Detected 1955 with reactor antineutrinos and organic scintillator.



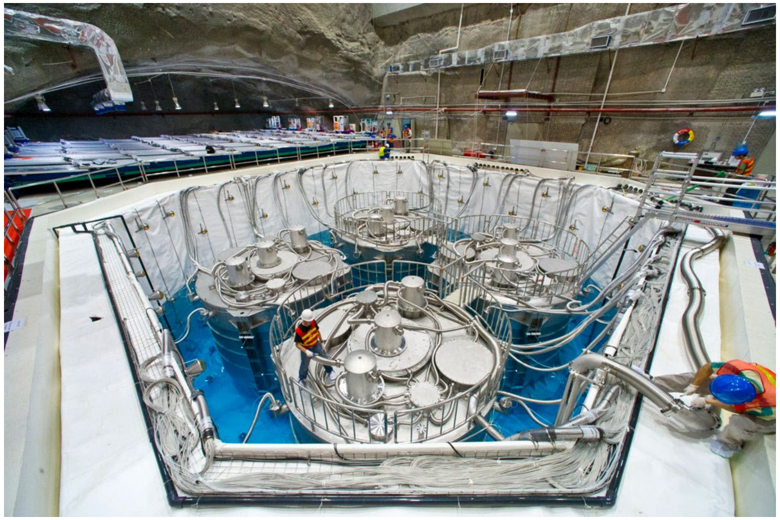
Plus cameras that took photos of oscilloscopes.

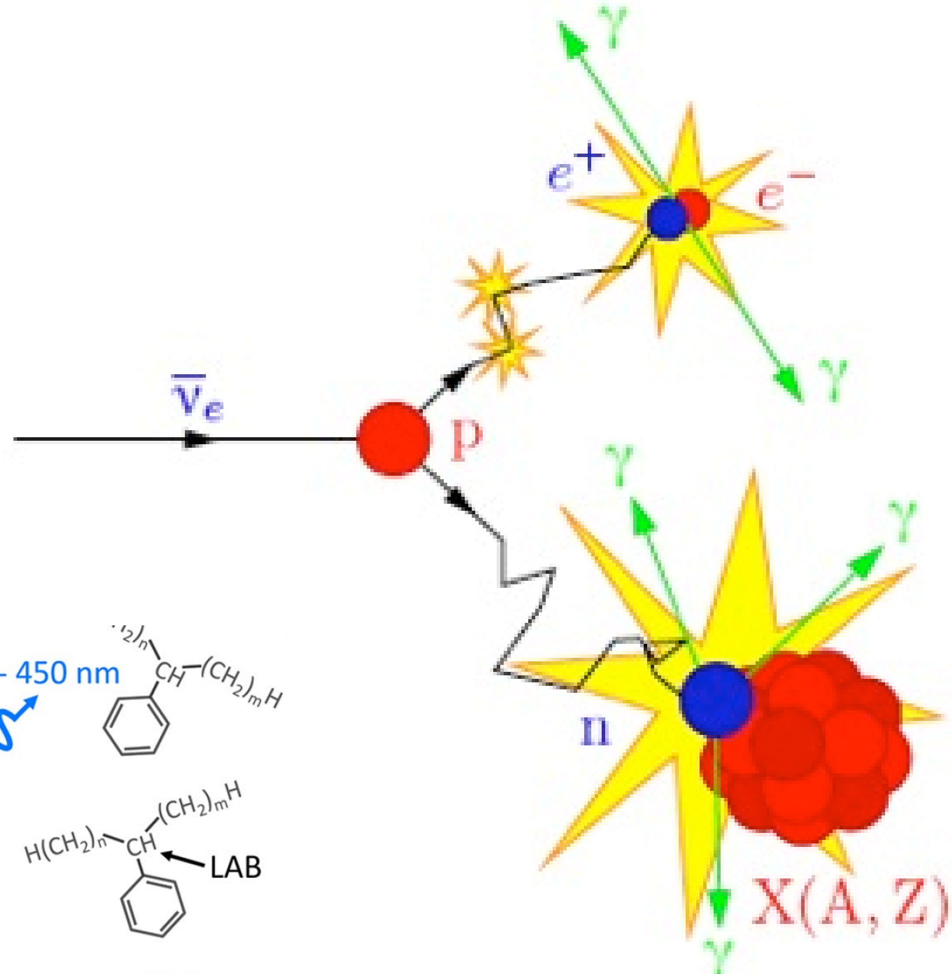
Boom boom, there it is →

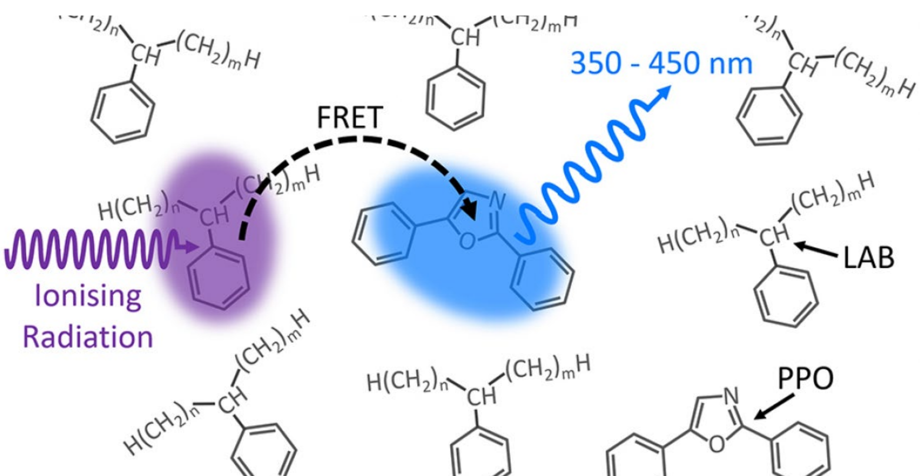




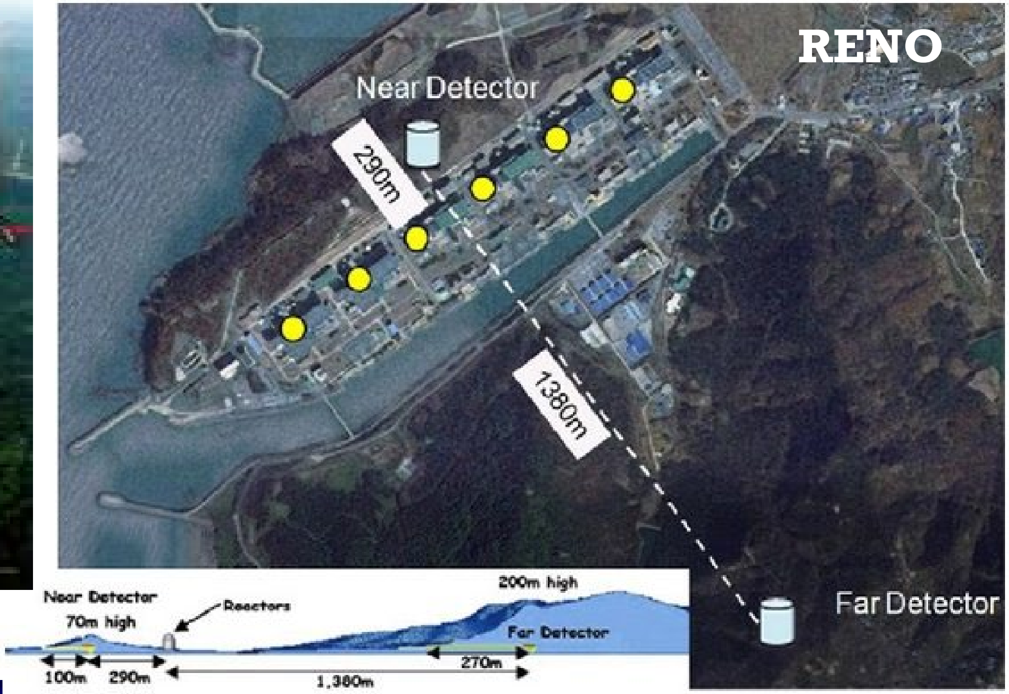
Apart from using more complex mixtures of scintillating stuff, this is still basically exactly how all reactor neutrino experiments in all of history have worked…







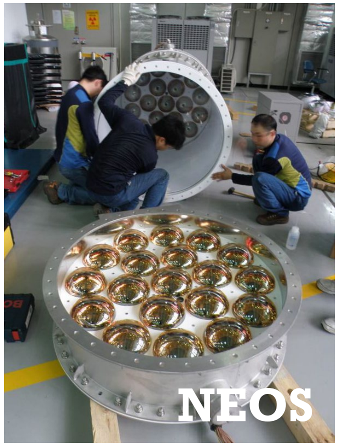

Double CHOOZ

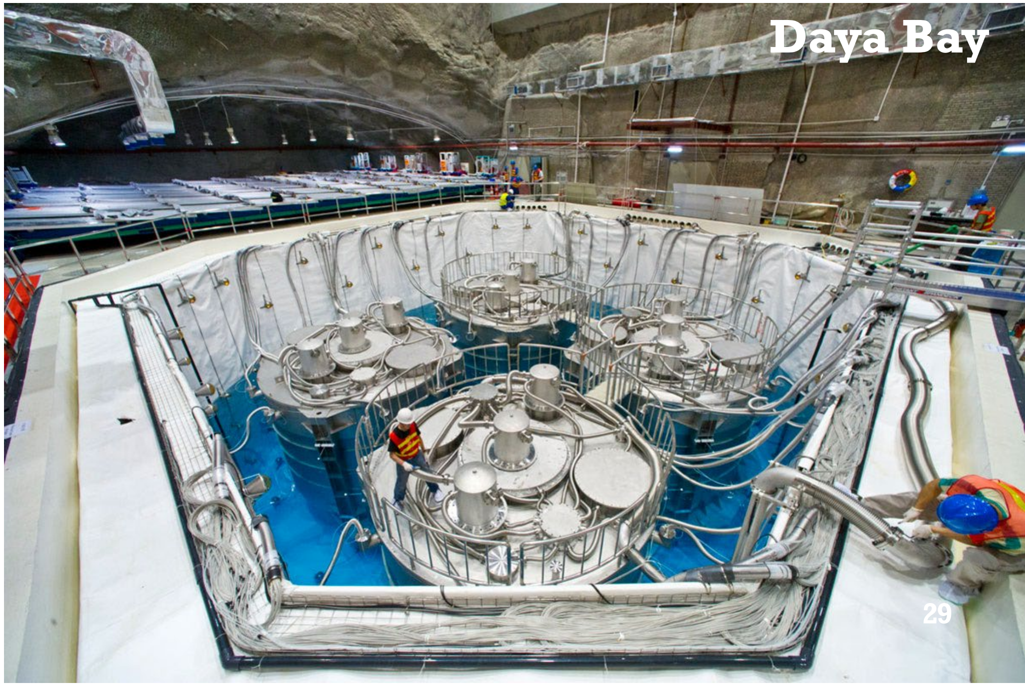

RENO
Near Detector
290m
1380m
Far Detector
Near Detector
70m high
Reactors
200m high
Far Detector
270m
100m
290m
1,380m


PROSPECT
PROSPECT


STEREO


New results
from the DANSS experiment
Nataliya Skrobova (ITEP, LPI, MIPT)
on behalf of the DANSS collaboration
(ITEP, JINR)
DANSS
August 26, ICNFP-2019, Kolymbari


NEOS

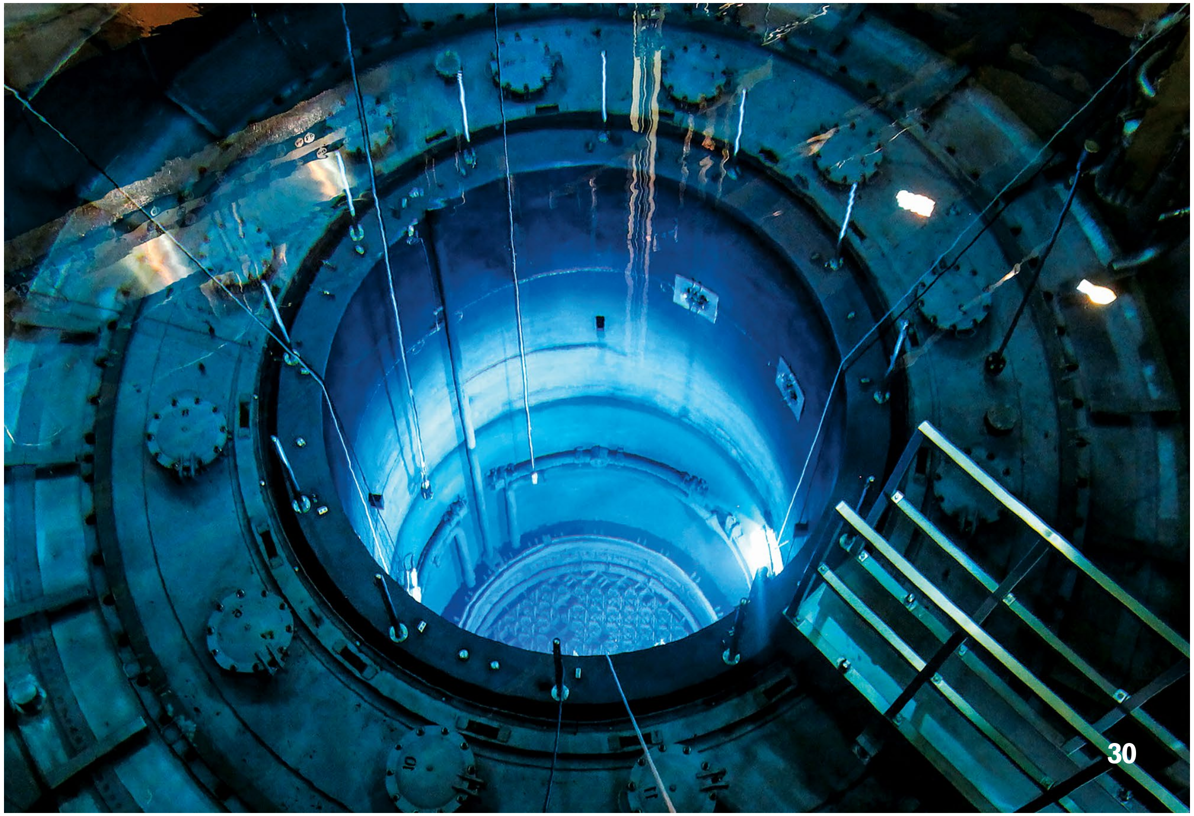

Daya Bay

WE HAVE BEEN DETECTING

ANTINEUTRINOS FROM BETA DECAYS IN NUCLEAR REACTORS

FOR 65 YEARS.

We must be basically perfect at it by now, right?

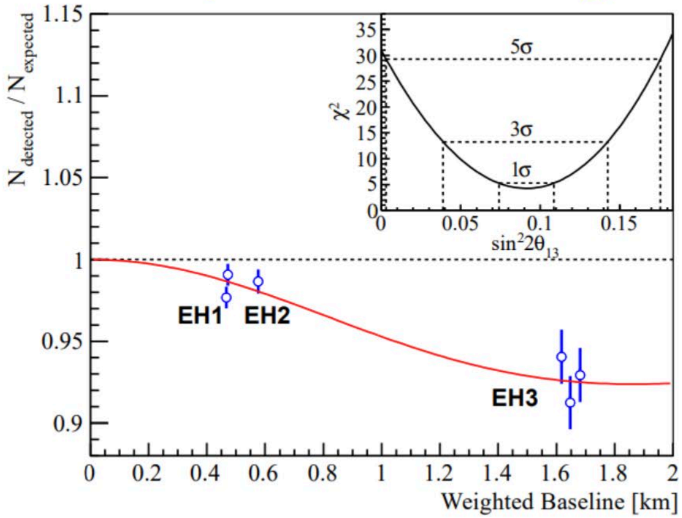


BEST OSCILLATION MEASUREMENT EVER:

We have used reactor antineutrinos to measure oscillation parameter θ_{13}

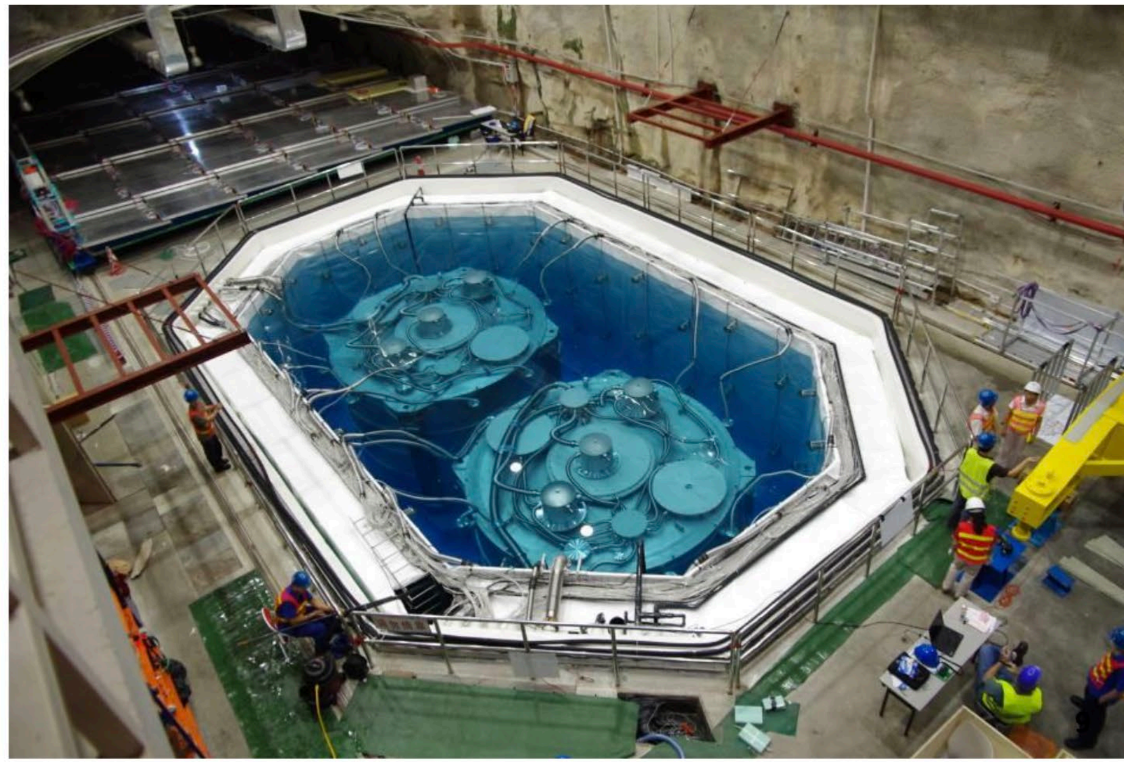
$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

March 2012, 5.2σ for non-zero $\sin^2 2\theta_{13}$



Daya Bay

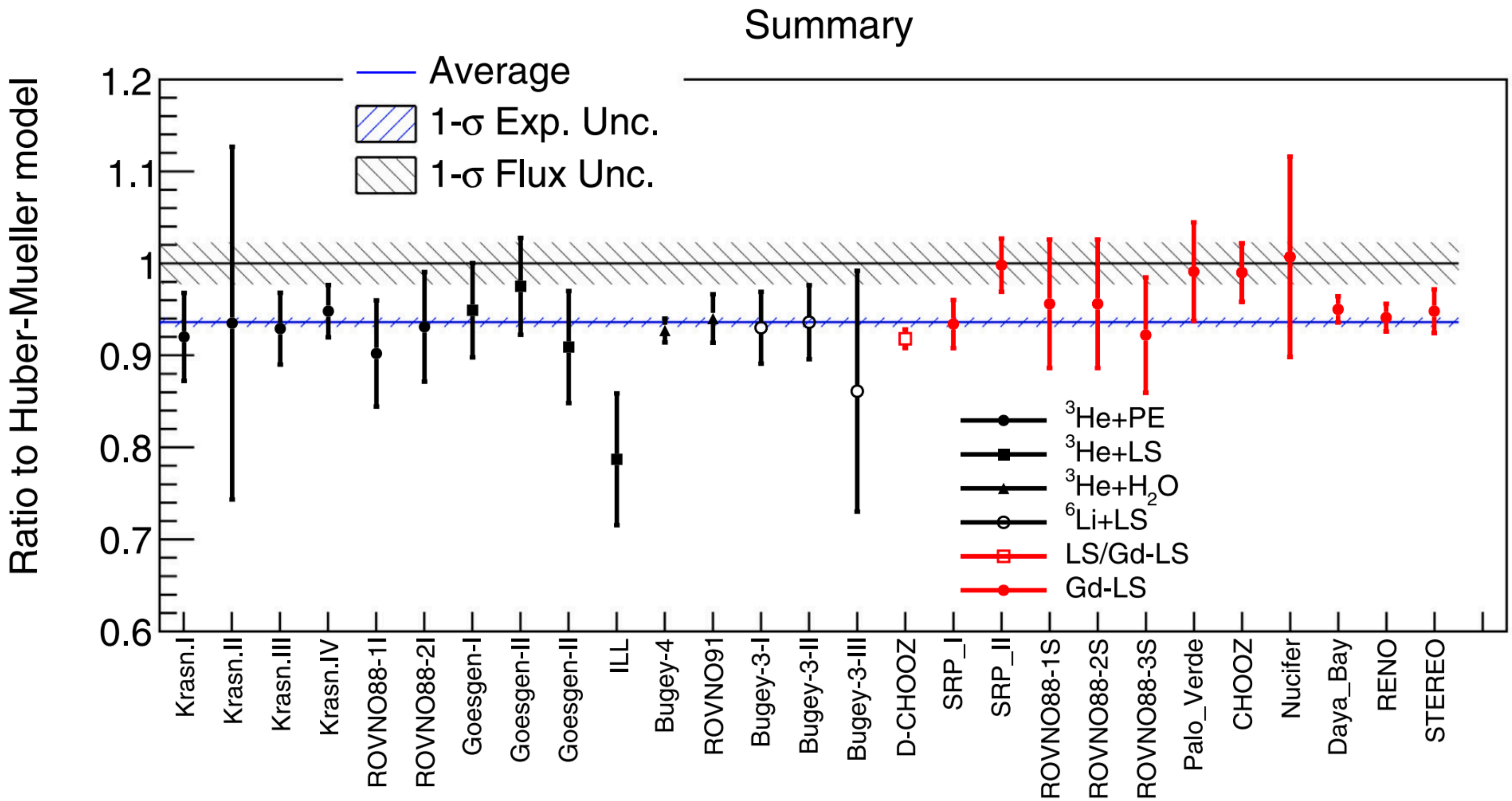
Phys.Rev.Lett. 108 (2012) 171803



And is the best measured neutrino oscillation parameter ever.

(more on this when we talk about neutrino oscillations later)

ALL IS NOT WELL IF WE MEASURE THE FLUXES

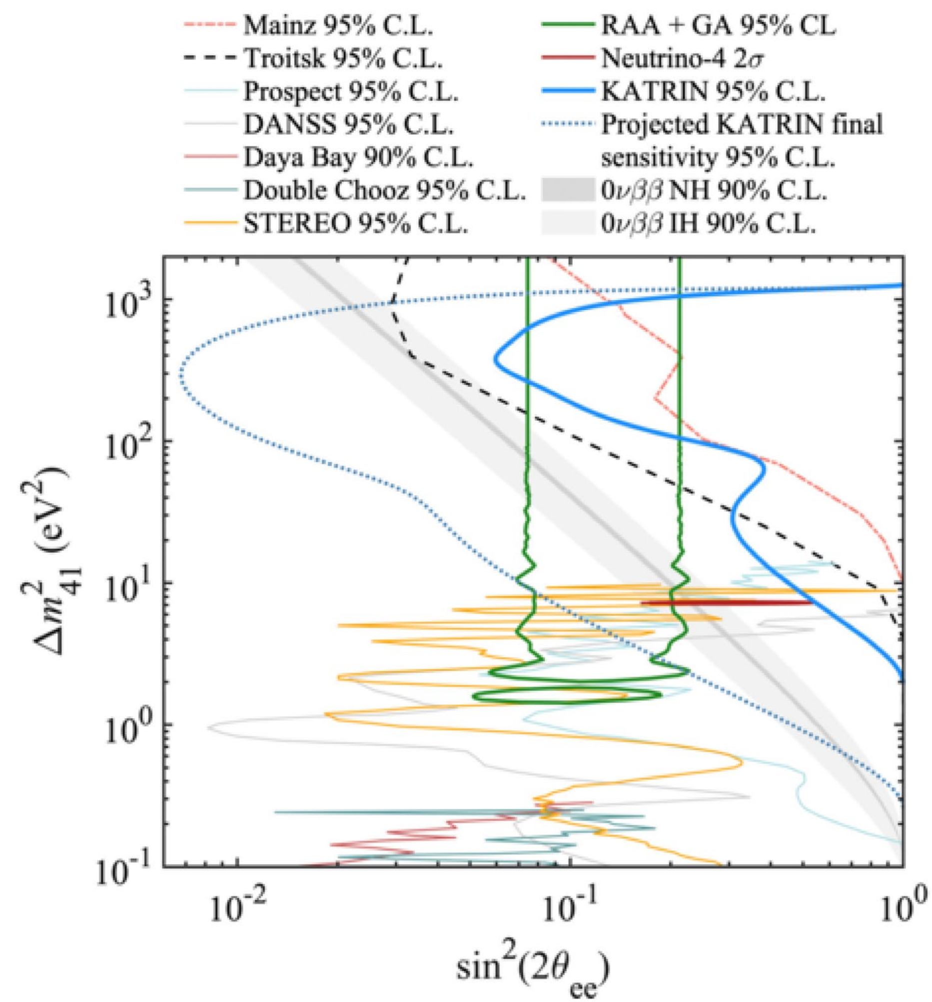


- There is a general tendency for world data on neutrino rates to be low compared to flux predictions.
- A tangled story, mostly related to evolving theory: Used to be fine, then it was much worse, now its still an significant disagreement but less than before...
- This discrepancy is called the **Reactor Antineutrino Anomaly (RAA)**

NEW PHYSICS AT REACTORS

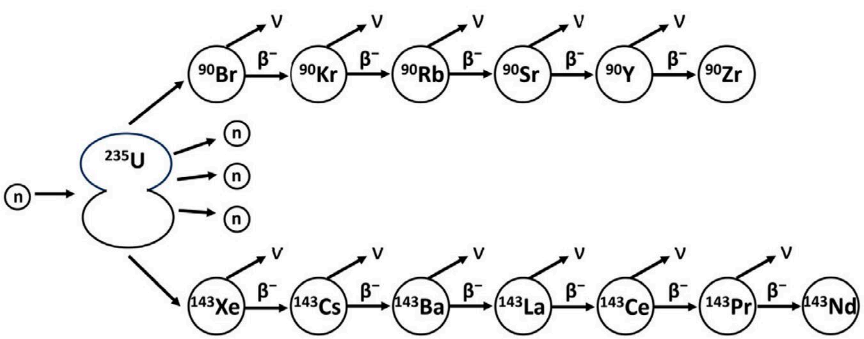
- Some have interpreted the RAA as evidence for new physics in neutrino oscillations.

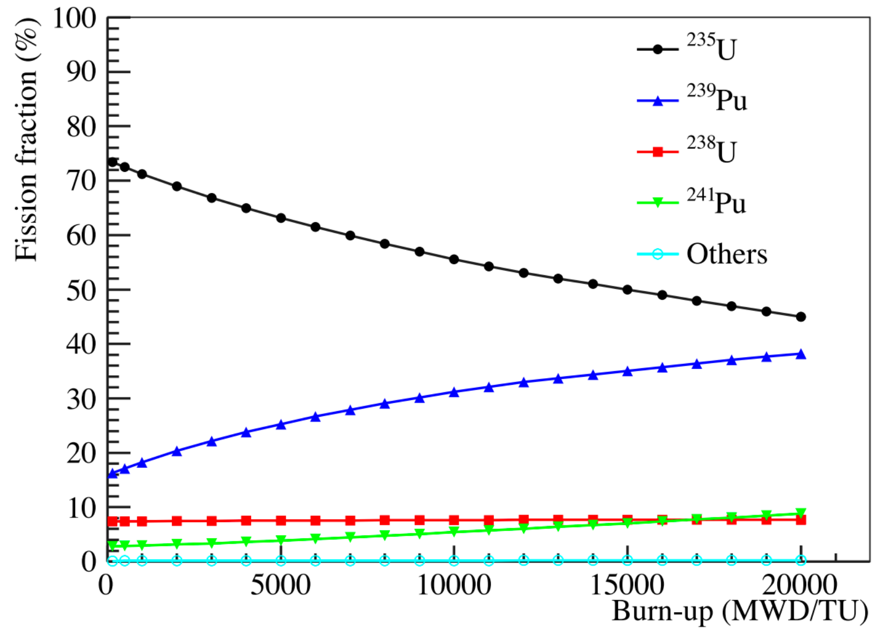
- The RAA has generally been among the weaker of the neutrino anomalies, since the calculations of the fluxes are both:
- 1. very involved
  and
- 2. have a history of significantly changes between iterations.



Isotope	Origin	σ_{fis} (barn)	Fission fraction	Energy per fission (MeV/fission)	IBD yield (10^{-43} cm^2/fission)
^{235}U	Enrichment	531	0.58	202.36	6.69
^{238}U	Natural abundance	–	0.08	205.99	10.10
^{239}Pu	$^{238}U(n,\gamma)^{239}U(\beta^-)^{239}Np(\beta^-)^{239}Pu$	750	0.29	211.12	4.36
^{241}Pu	$^{239}Pu(n,\gamma)^{240}Pu(n,\gamma)^{241}Pu$	1010	0.05	214.26	6.05

- Neutrino flux depends on state of the reactor fuel.
- ^{235}U is the main fissile isotope.
- As reactor operates, other fissile materials build up, with their own fission patterns →
- Each fission creates ~200MeV of energy and a chain of decays yielding approx. 6 antineutrinos.



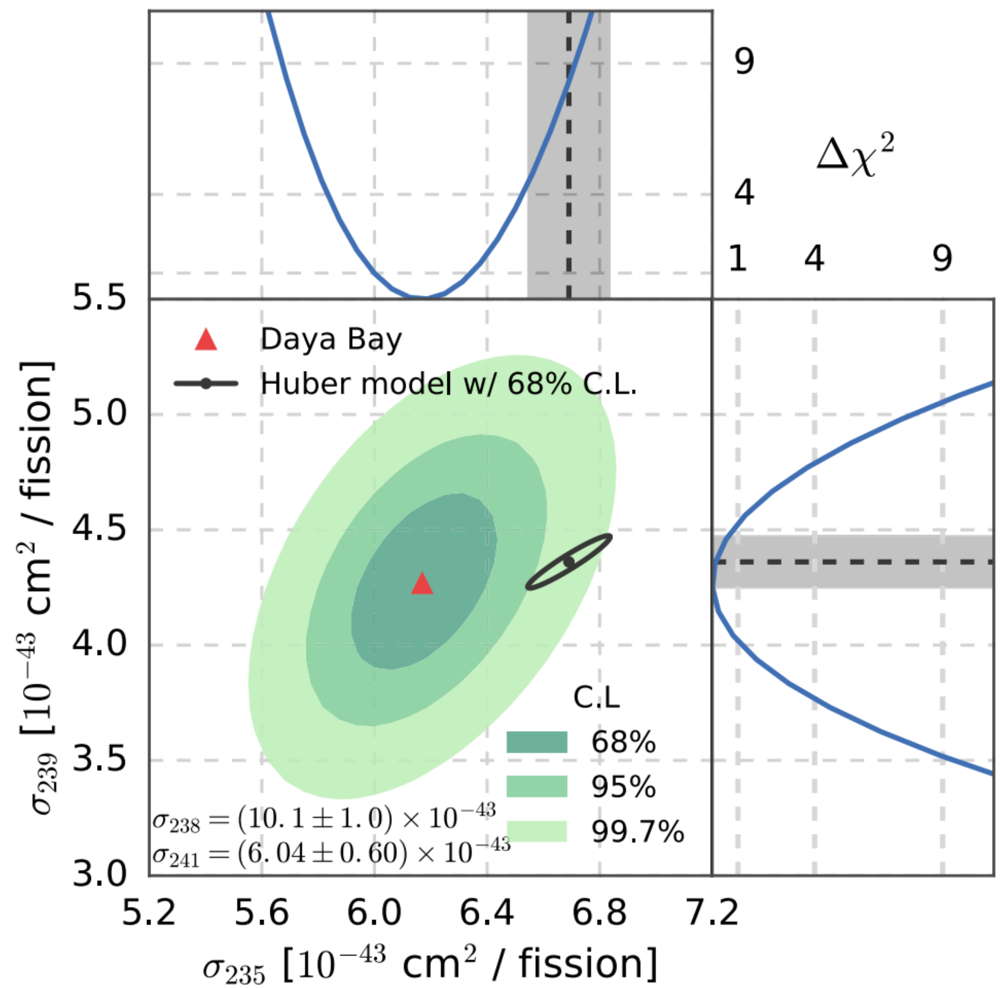


RESOLVING THE RAA?

Daya Bay has observed that the strength of the RAA depends on the ratio of fissile isotopes during burnup.

- Consistent with ^{235}U neutrinos being underpredicted

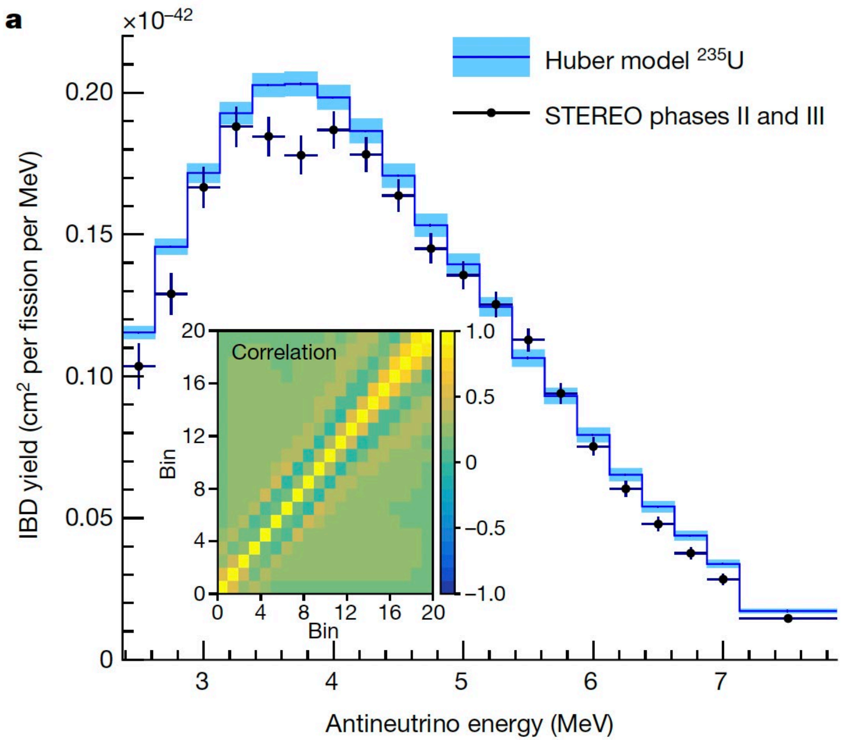
- Not consistent with new neutrino oscillation physics.



RESEARCH REACTORS

Research reactors are mostly ^{235}U, vs commercial power reactors which mix up the isotopes.

STEREO confirms underprediction in the ^{235}U neutrino yields.

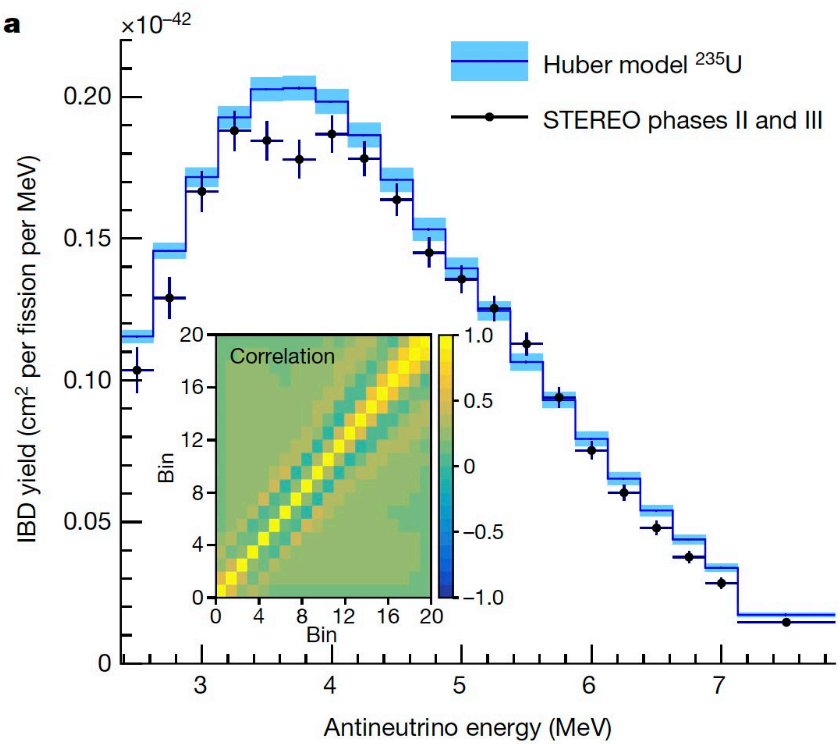


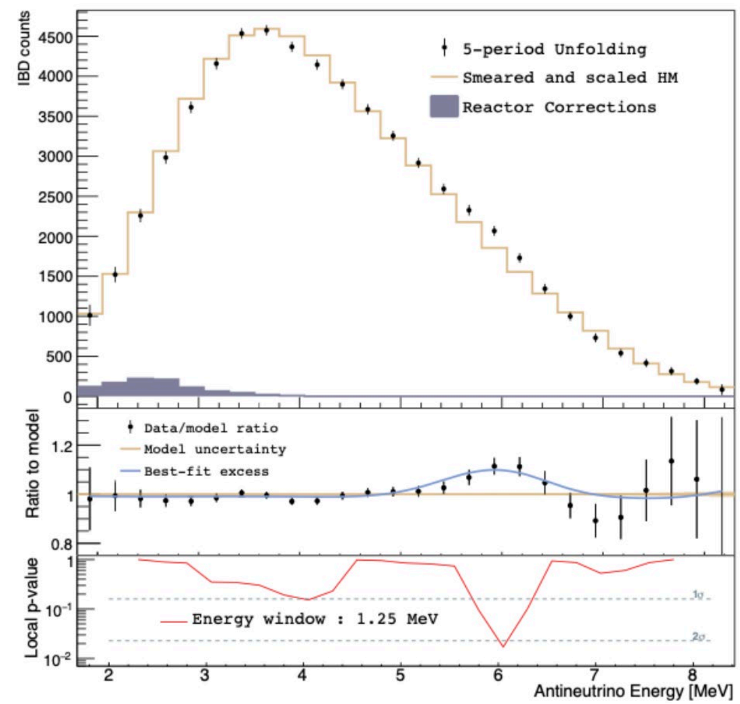
RESEARCH REACTORS

Research reactors are mostly ^{235}U, vs commercial power reactors which mix up the isotopes.

STEREO confirms underprediction in the ^{235}U neutrino yields.

Prospect data seem to be low but maybe not quite low enough…

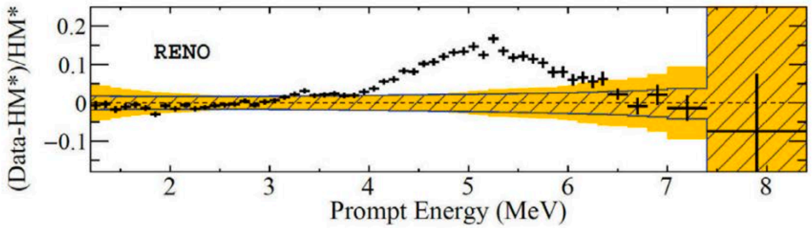


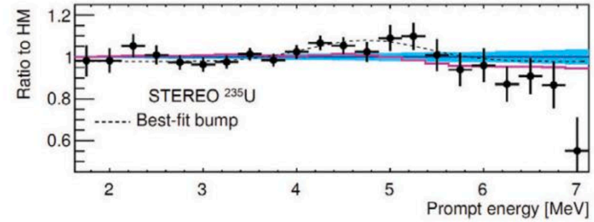


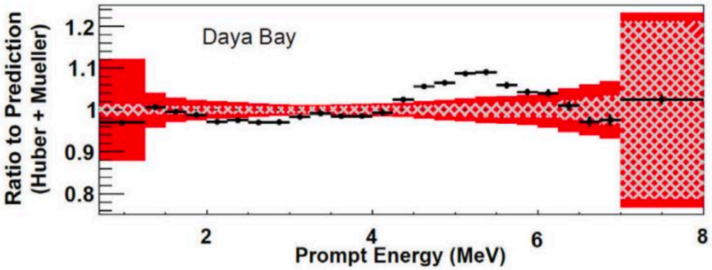
→ Seems rather likely that ^{235}U neutrino flux model is the issue.

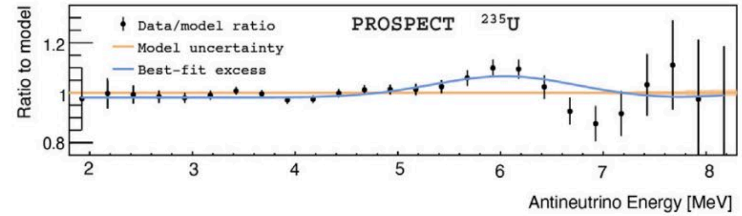
Oh yeah, also this weird bump at 5 MeV…

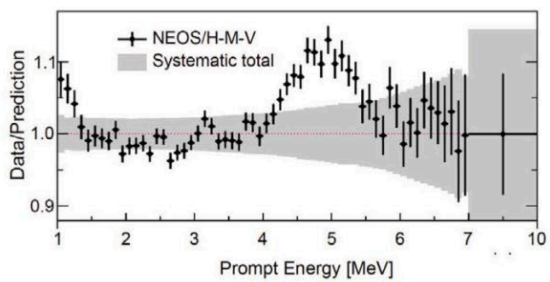
That basically every reactor experiment sees.

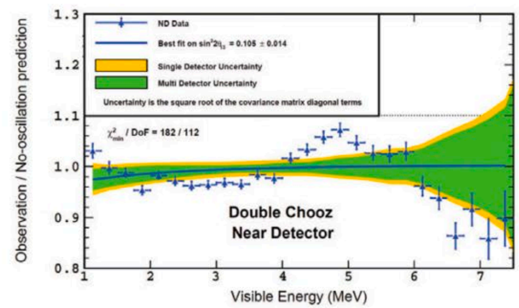


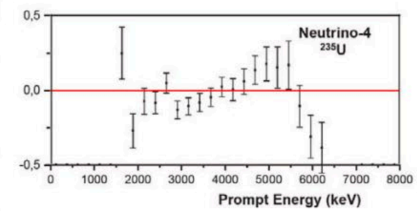


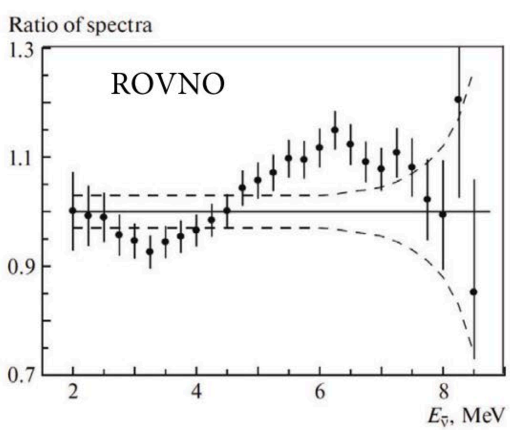


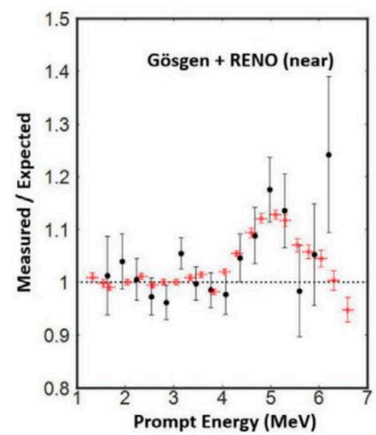


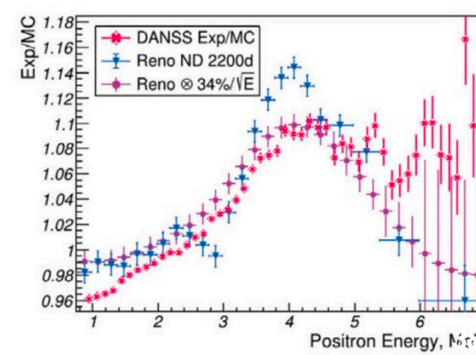












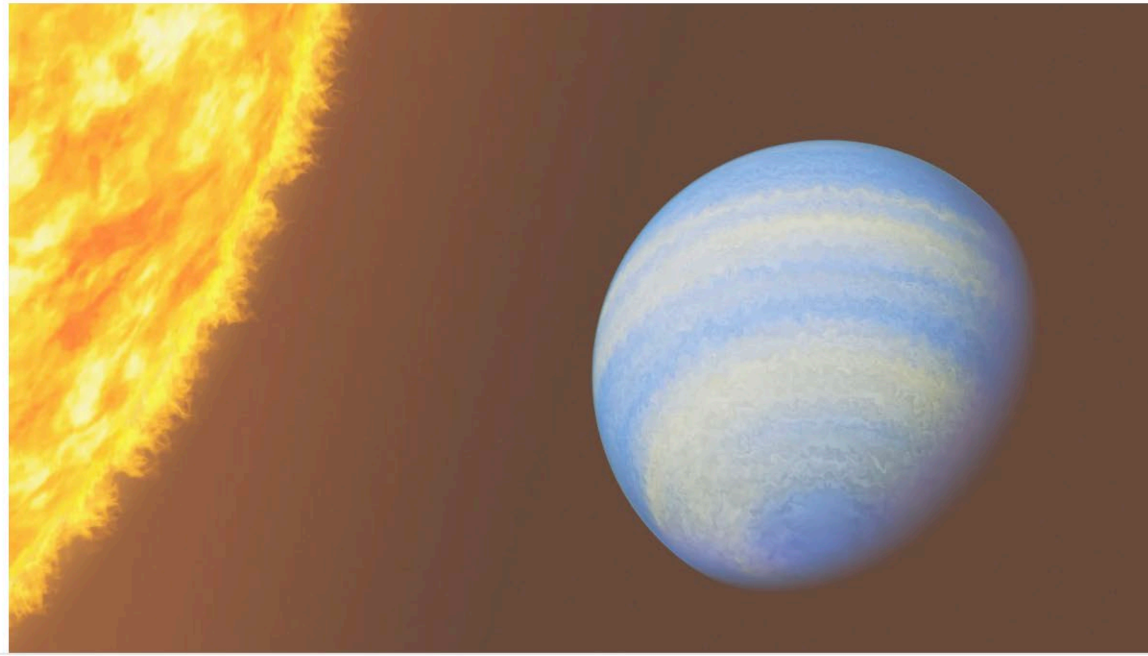
If you wanted your PhD to be easy, you should have worked on exoplanets.

BBC

Smelly planet 'reeks of rotten eggs'

Most of HD 189733 b's atmosphere is hydrogen sulphide, which is also emitted during farts.

14 hrs ago | Science & Environment



nature

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Article | Published: 08 July 2024

Hydrogen sulfide and metal-enriched atmosphere for a Jupiter-mass exoplanet

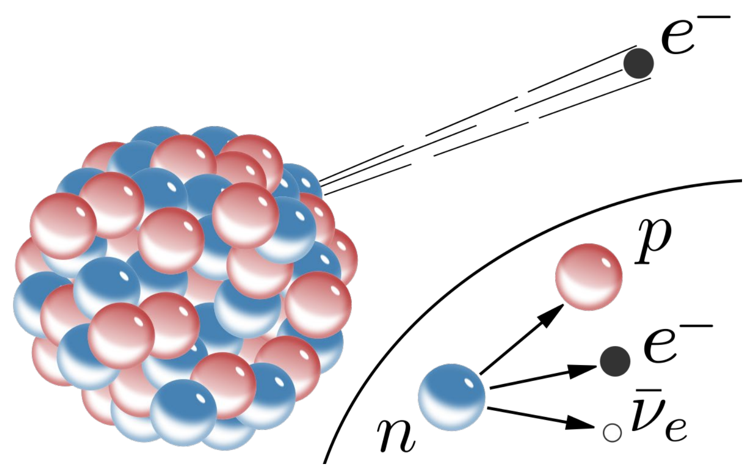
Guangwei Fu, Luis Welbanks, Drake Deming, Julie Inglis, Michael Zhang, Joshua Lothringer, Jegug Ih, Julianne I. Moses, Everett Schlawin, Heather A. Knutson, Gregory Henry, Thomas Greene, David K. Sing, Arjun B. Savel, Eliza M.-R. Kempton, Dana R. Louie, Michael Line & Matt Nixon

Nature (2024) | Cite this article

(BBC news and Nature, literally last week)

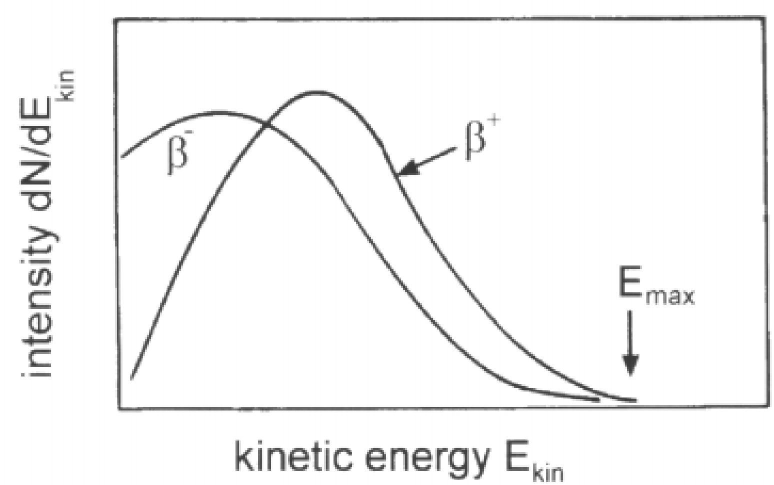
EXPERIMENTS WITH A SINGLE ISOTOPE

- The reason reactor spectra are so hard to predict is that they derive from an enormously complex chain of nuclear reactions.



- Those reactions stem from fission to nearly every possible element and decay chains ~6 deep from there.

- If we do experiments with just a single beta emitting isotope, that should be easy, right?



EXPERIMENTS WITH A SINGLE ISOTOPE

High precision measurement of the ^{99}Tc β spectrum

M. Paulsen,[1,2,*] P. C.-O. Ranitzsch,[3,†] M. Loidl,[4] M. Rodrigues,[4] K. Kossert,[3] X. Mougeot,[4,‡] A. Singh,[4,§] S. Leblond,[4] J. Beyer,[1] L. Bockhorn,[3,¶] C. Enss,[2] M. Wegner,[5,6] S. Kempf,[6,5] and O. Nähle[3]

Well… maybe…

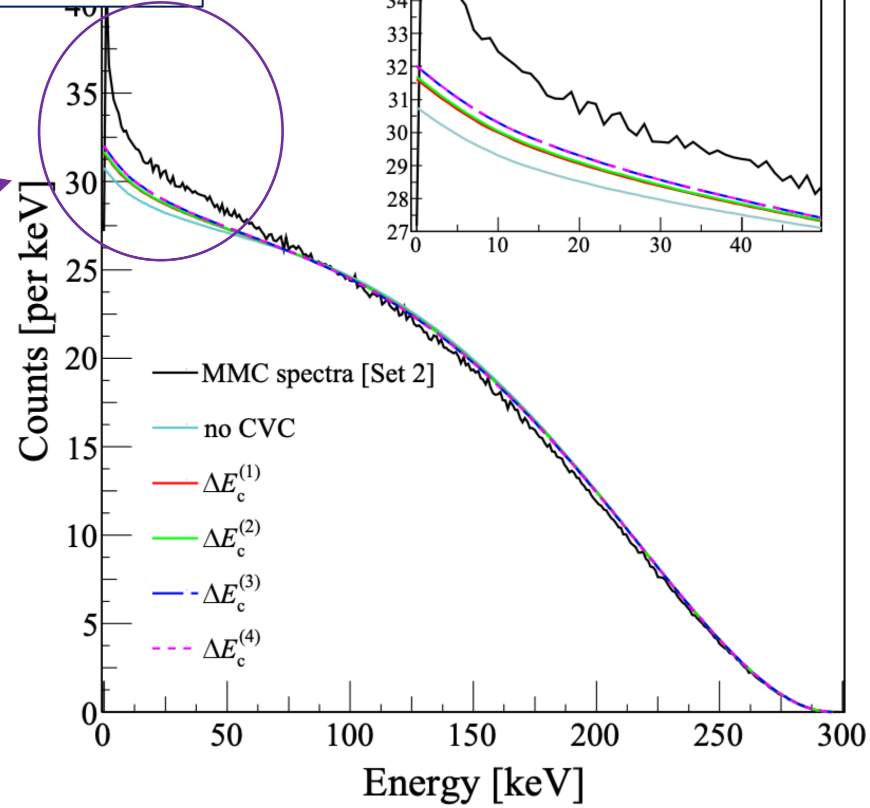


FIG. 6: Comparison of the measured ^{99}Tc spectrum with different theoretical curves. CVC is either ignored or included for different estimates of the Coulomb displacement energy ΔE_C. An inset shows the low-energy part of the spectrum.

Nuclear modelling very complex in this part of the spectrum, especially for heavy isotopes.

We'll return to these difficulties when we talk about double beta decay…

EXPERIMENTS WITH A SINGLE ISOTOPE

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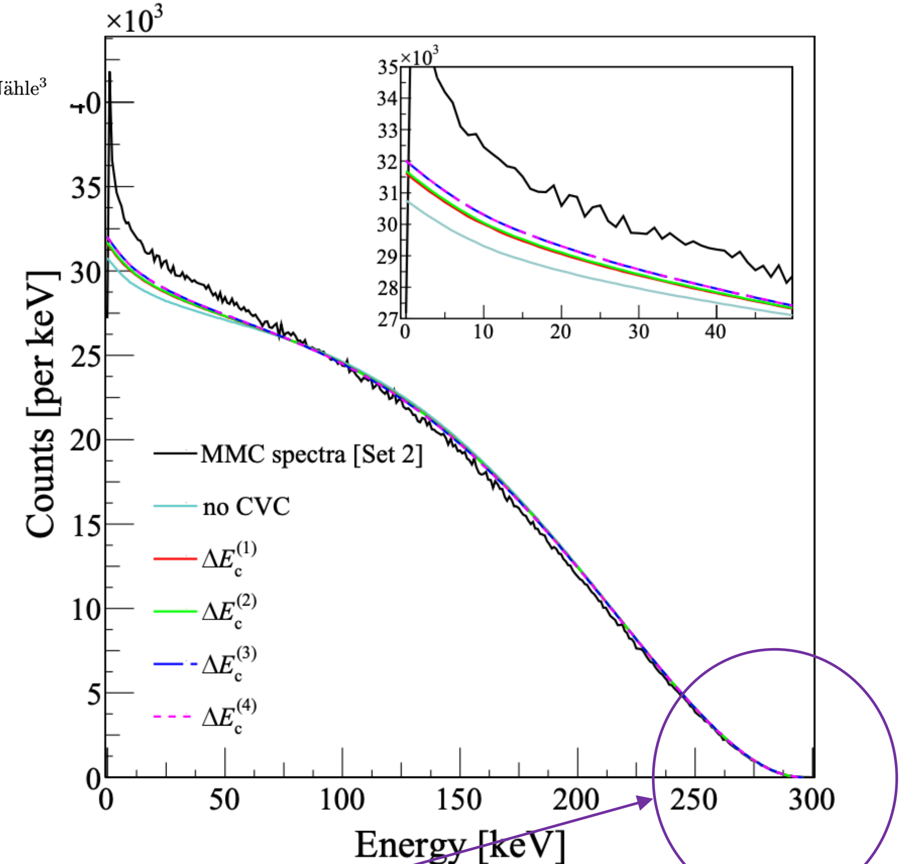
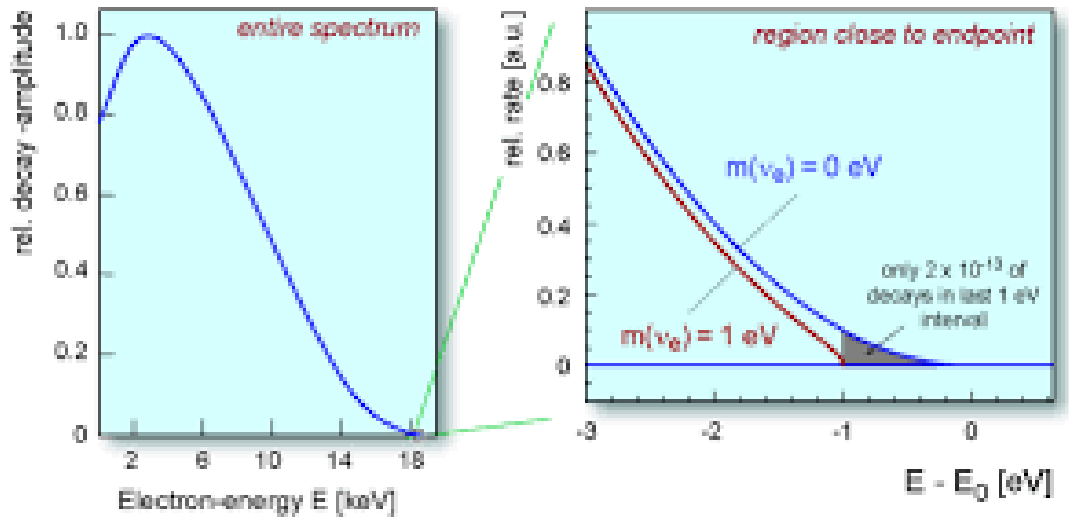


FIG. 6: Comparison of the measured ^{99}Tc spectrum with different theoretical curves. CVC is either ignored or included for different estimates of the Coulomb displacement energy ΔE_C. An inset shows the low-energy part of the spectrum.

At least down here it looks ok…

THE BETA ENDPOINT

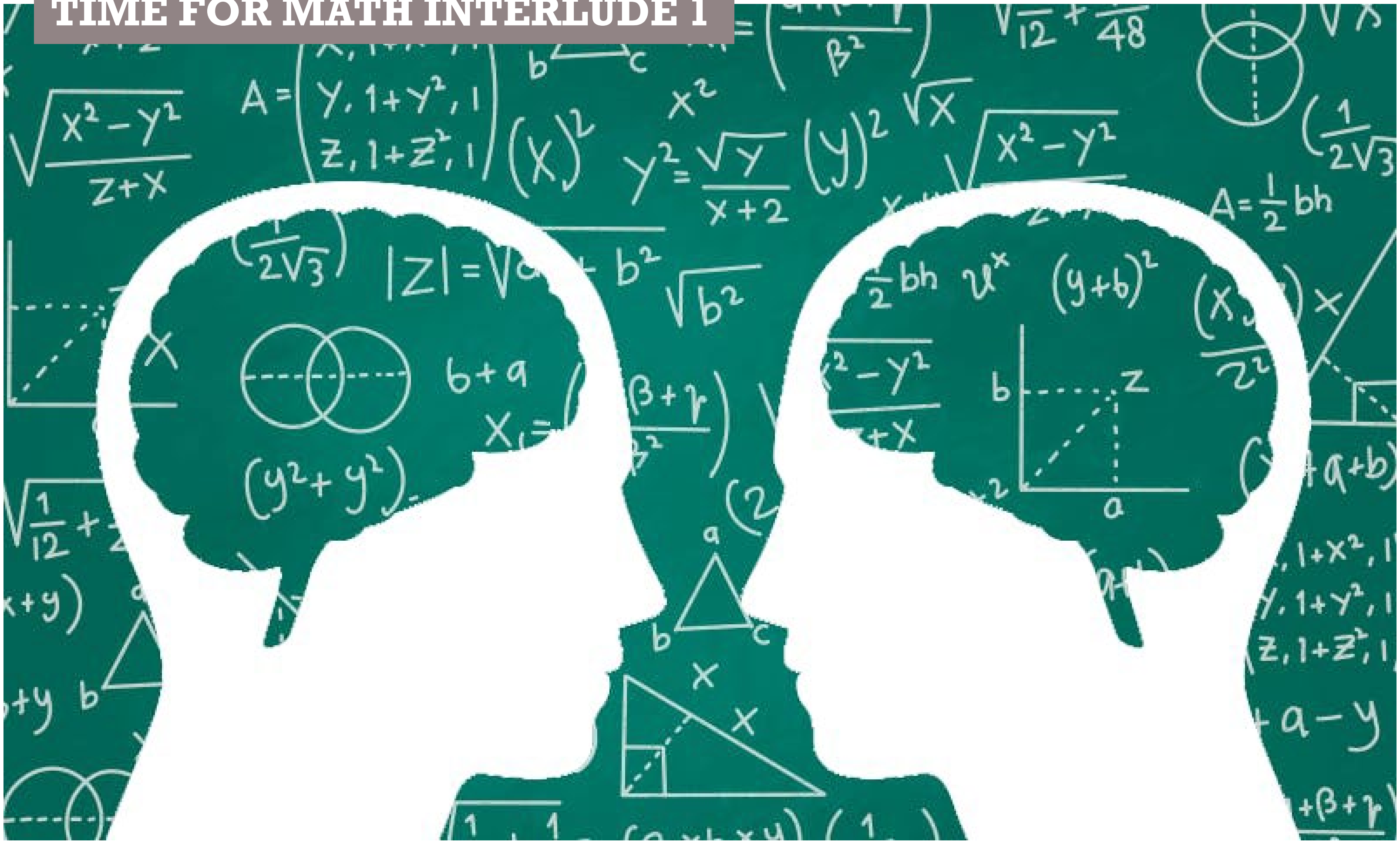
- The the end-point, shape is dictated primarily by phase space arguments, *not* by nasty nuclear physics.
- And it is a particularly interesting part of the beta spectrum for neutrino physics…
- The size of the mass of the neutrino changes the shape and position of the endpoint, in measurable way.
- **LETS DERIVE IT!**



The size of the deviation is governed by this effective parameter

$$m^2_{\nu,eff} = \sum_i^3 |U_{ei}|^2 m_i^2$$

TIME FOR MATH INTERLUDE 1



MEASURING THE BETA END POINT

- Experimentally, we need to measure a shape deviation that occurs in the last ~1eV of the spectrum.

- The lower the Q value we use, the larger the fraction of decay events that will be.

- To have any hope at all, use a very low Q value isotope:

Tritium
- E_0 = 18.6 keV, $T_{1/2}$ = 12.3 a

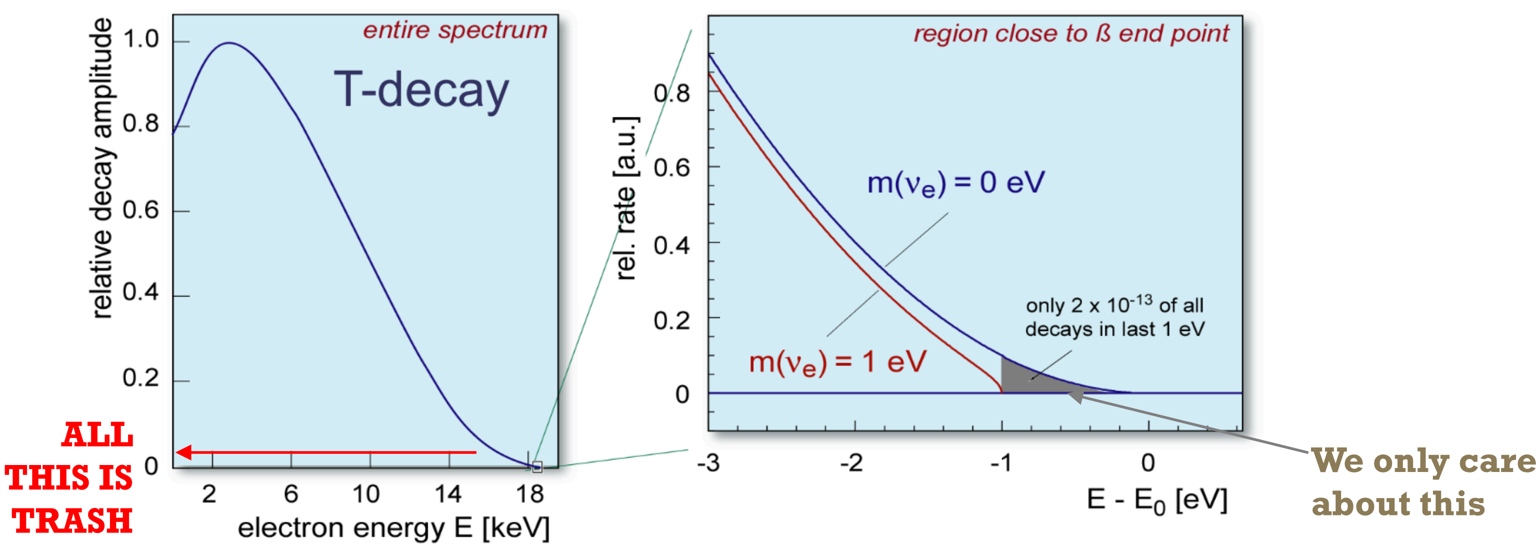
Rhenium
- E_0 = 2.47 keV, $T_{1/2}$ = 43.2 Gy

Holmium (EC decay)
- $Q_{EC} \approx 2.5$ keV, $T_{1/2}$ = 4570 y

HOW TO BUILD AN EXPERIMENT…

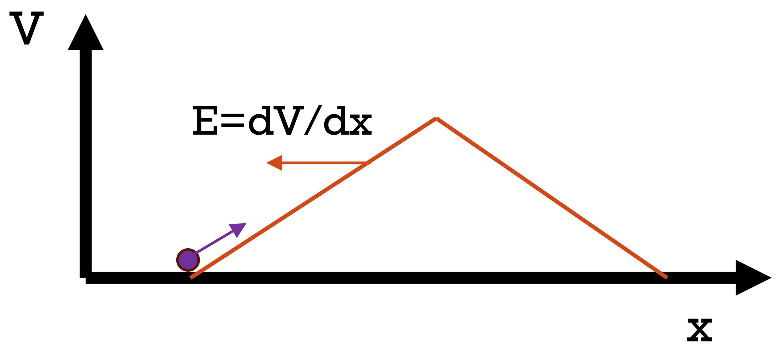
- Still need to reject all except 10^{-12} of the beta electrons to look at the ones we care about…

- Use some kind of "**filter**" to only accept the high energy electrons, perhaps?



HOW TO CATCH ONLY THE FAST ONES…

- Apply an electric field against the electrons to sap their energy away… then only the higher energy ones can pass?



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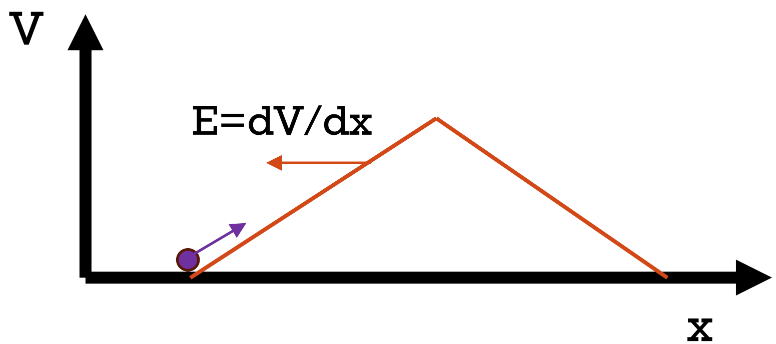
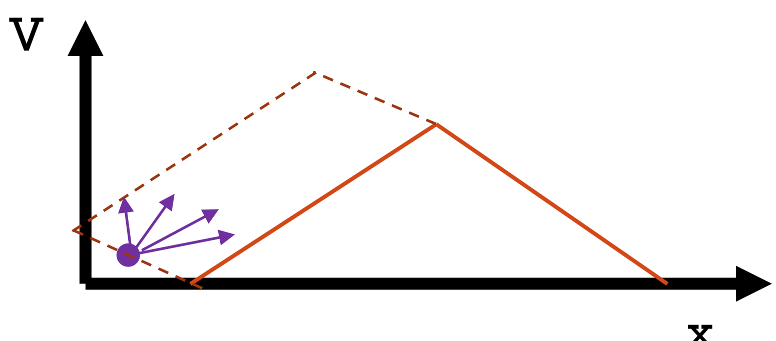


- The problem is they come out in all directions… need to turn them all to face the same way first, somehow.

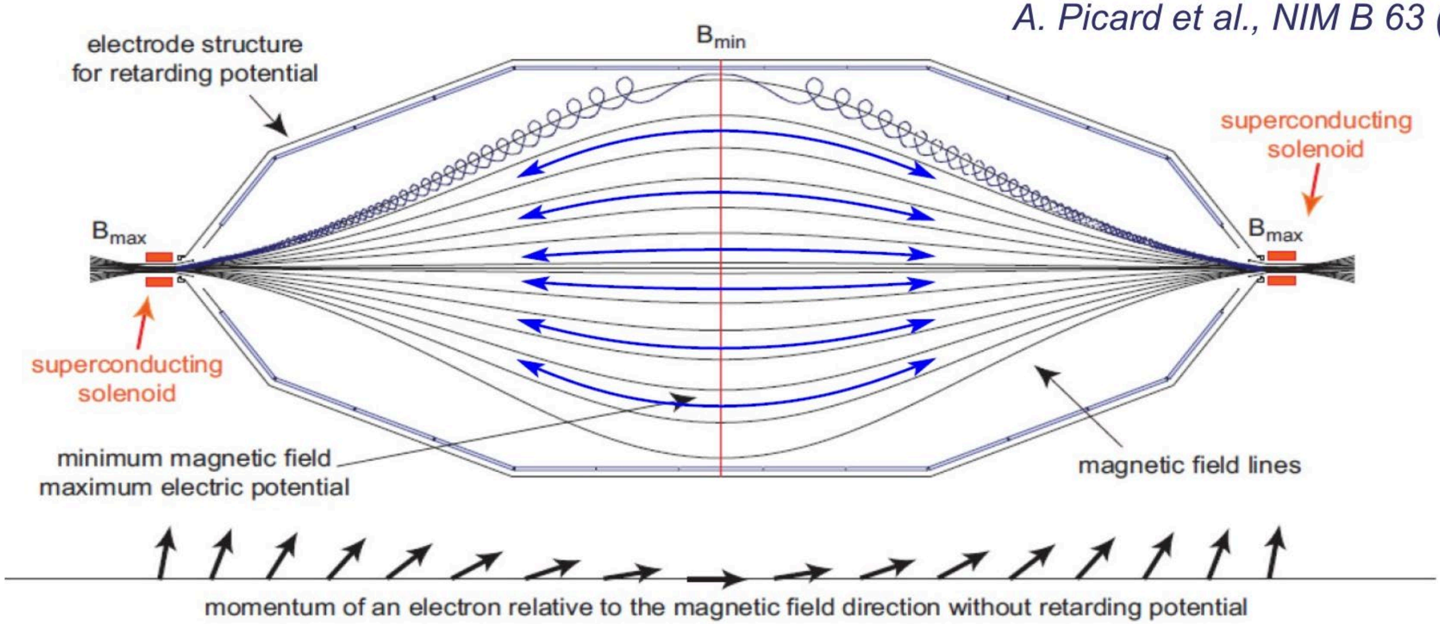


How can you turn them all to face the same way without giving or taking any energy?

MAC-E FILTERING

<u>M</u>agnetic <u>A</u>diabatic <u>C</u>ollimation combined with an <u>E</u>lectrostatic Filter

A. Picard et al., NIM B 63 (1992)



$$\mu = \frac{E_\perp}{B} = \text{const}$$

$$\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}}$$

A MAC-E filter adiabatically rotates the electron momentum directions and then applies the potential filter.

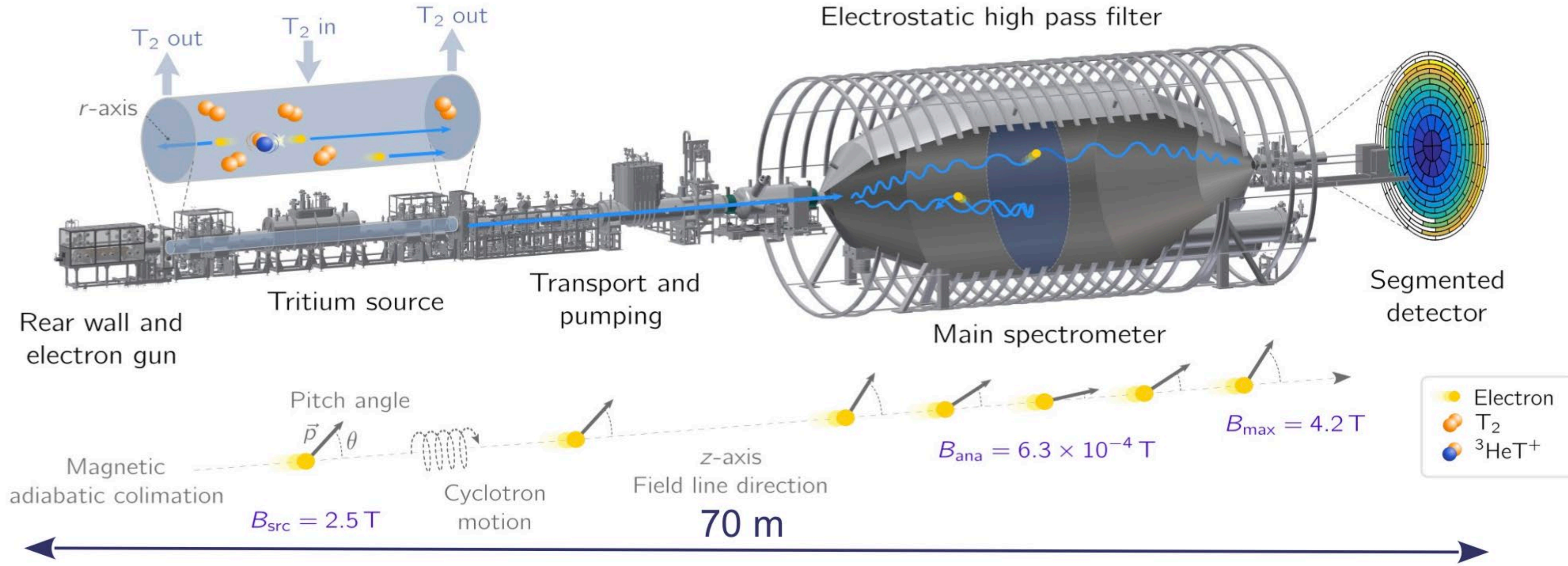
A frightfully clever way of adiabatically rotating all the electrons to face the same way using E and B fields

KATRIN MAC-E FILTER

Leopoldshafen, Germany (near Karlsruhe) November 2006

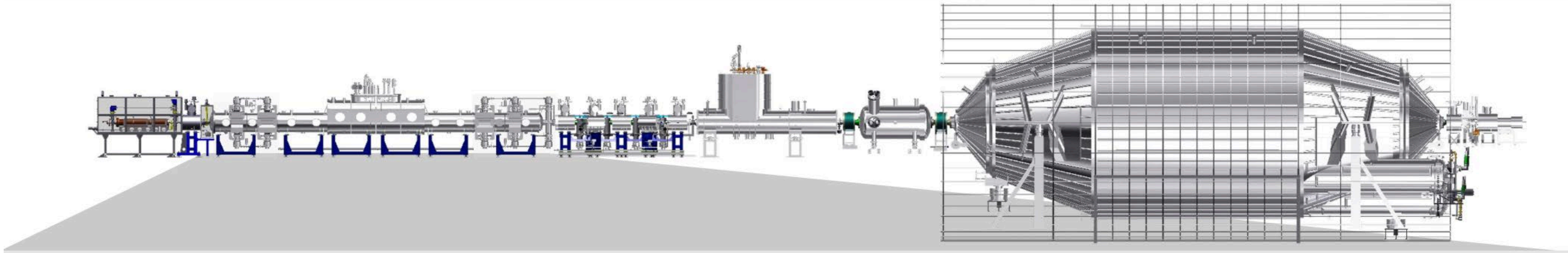
- 10^{11} tritium decays/s
- B-field range 3 - 60000 G
- $\Delta E = 0.93$ eV
- Design sensitivity: 0.2 eV @ 90% CL

KATRIN experiment at KIT

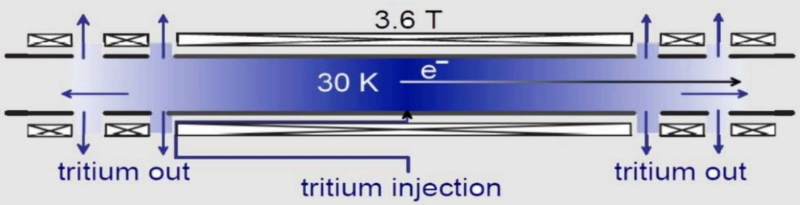


Windowless Gaseous Tritium Source

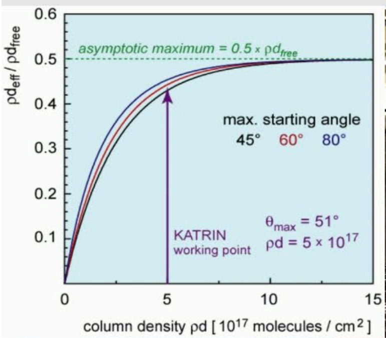
Universität Münster



- beam tube — Ø = 9 cm , L = 10 m
- guiding field — 2.5 T
- Temperature — 80 K ± 0.01 K
- T_2 purity — 95% ± 0.1 %
- column density — $5 \cdot 10^{17}$ T_2/cm^2
- luminosity — $1.7 \cdot 10^{11}$ Bq

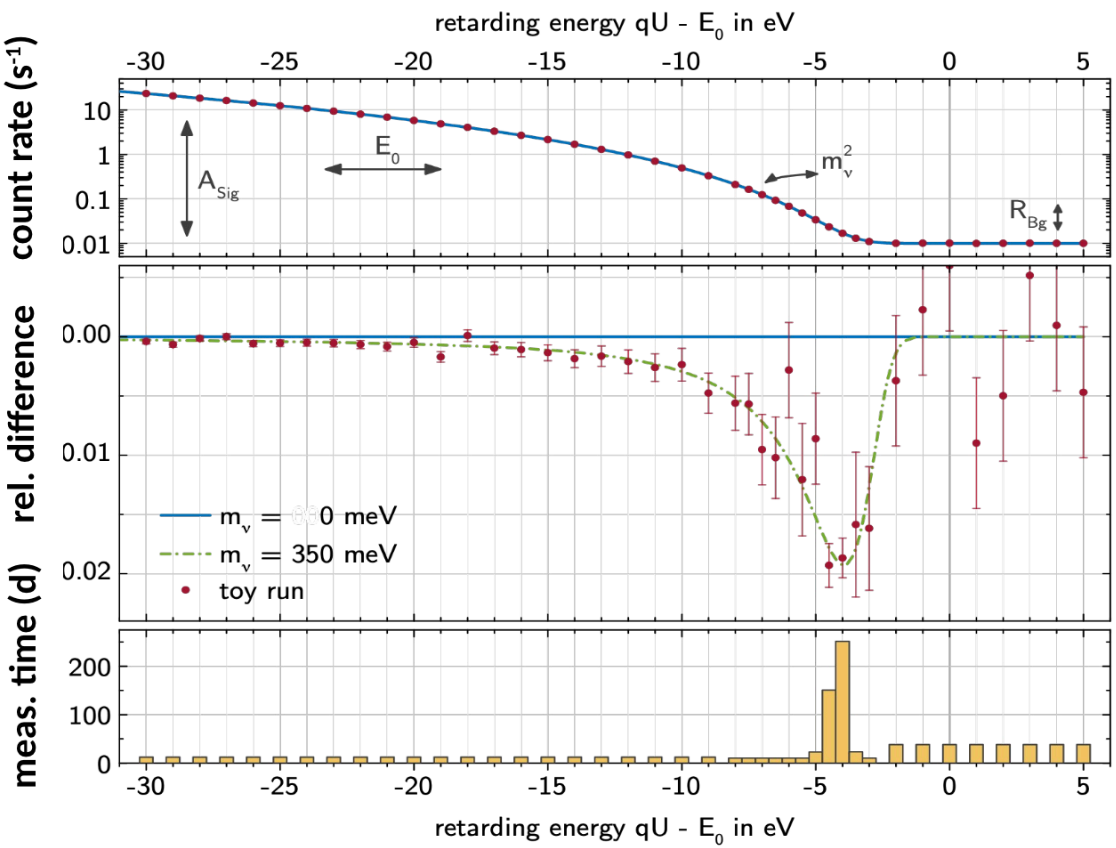


- T_2 flow rate — $5 \cdot 10^{19}$ molecules/s (40 g of T_2 / day)



Measurement principle

- Direct **shape** measurement of **integrated β spectrum**



Four fit parameters:

spectrum ampl. $\mathbf{A_{sig}}$	spectrum endpoint $\mathbf{E_0}$
background rate $\mathbf{R_{bg}}$	squared mass $\mathbf{m^2_\nu}$

~10^{-8} of all β-decays in scan region ~40 eV below endpoint

Eur. Phys. J. C 79 (2019) 204

KATRIN new limit as of Neutrino2024:

Preprint →
https://www.katrin.kit.edu/130.php#Anker0

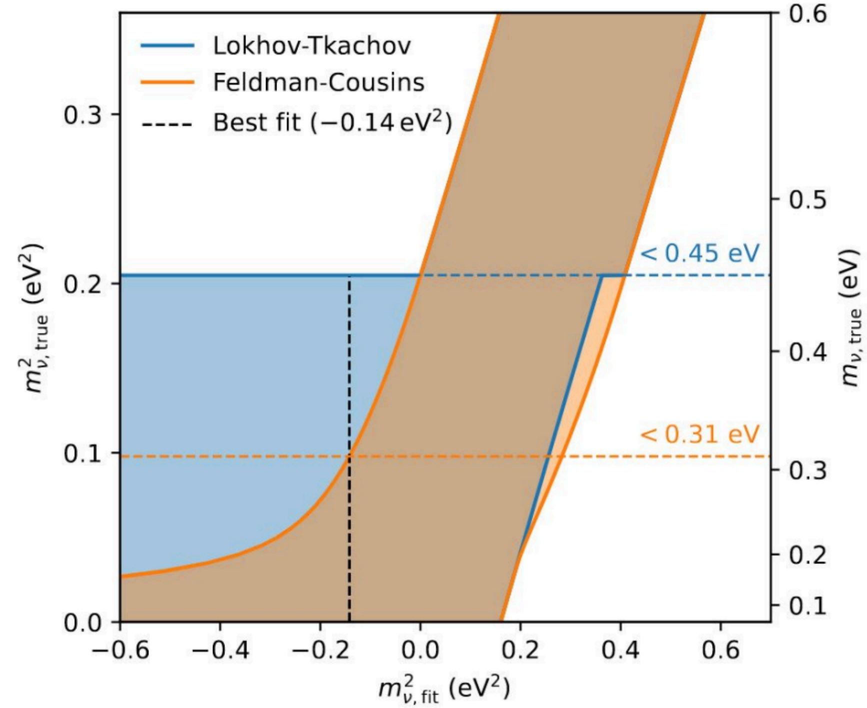
Confidence interval

- KATRIN's **new** upper limit

$$\boxed{m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})}$$

  using **Lokhov-Tkachov** construction
- Feldman-Cousins limit:
  - $m_\nu < 0.31$ eV at 90 % CL
  - Shrinking upper limit for negative m_ν^2
- Bayesian analysis in preparation

Poster by W. Xu



Lokhov, Tkachov, Phys. Part. Nucl. 46 (2015) 3, 347-365
Feldman, Cousins, Phys. Rev. D 57 (1998) 3873-3889

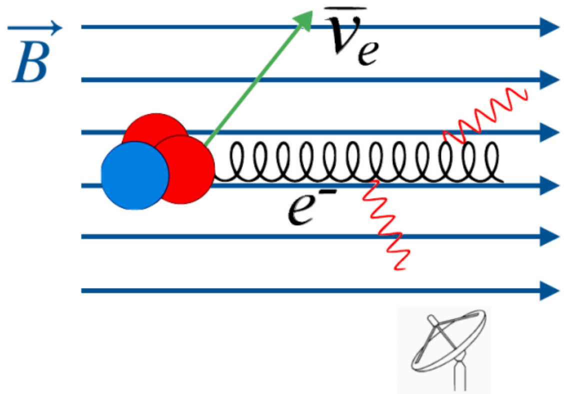
19

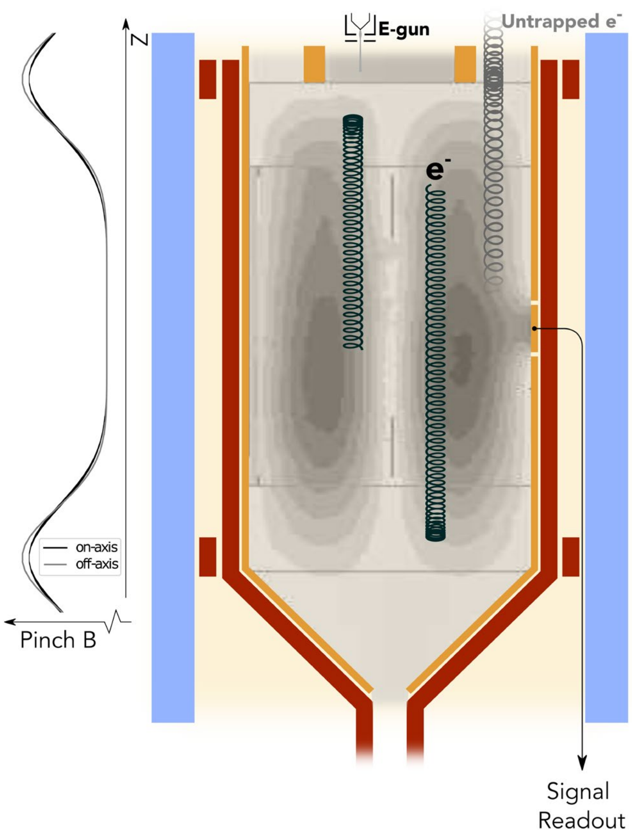
NEXT GEN: DO ANOTHER ONE 10X AS BIG?

- 10^{11} tritium decays/s
- B-field range 3 - 60000 G
- $\Delta E = 0.93$ eV
- Design sensitivity: 0.2 eV @ 90% CL

ANOTHER WAY TO FILTER…

PROJECT 8

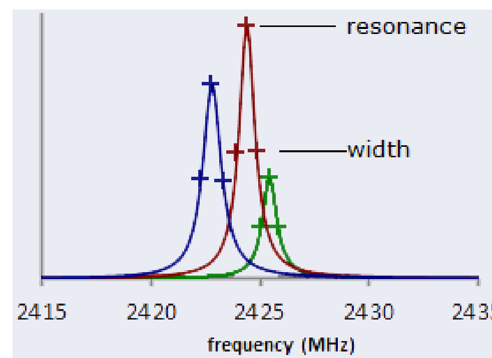




1) An electron in a magnetic field will radiate at

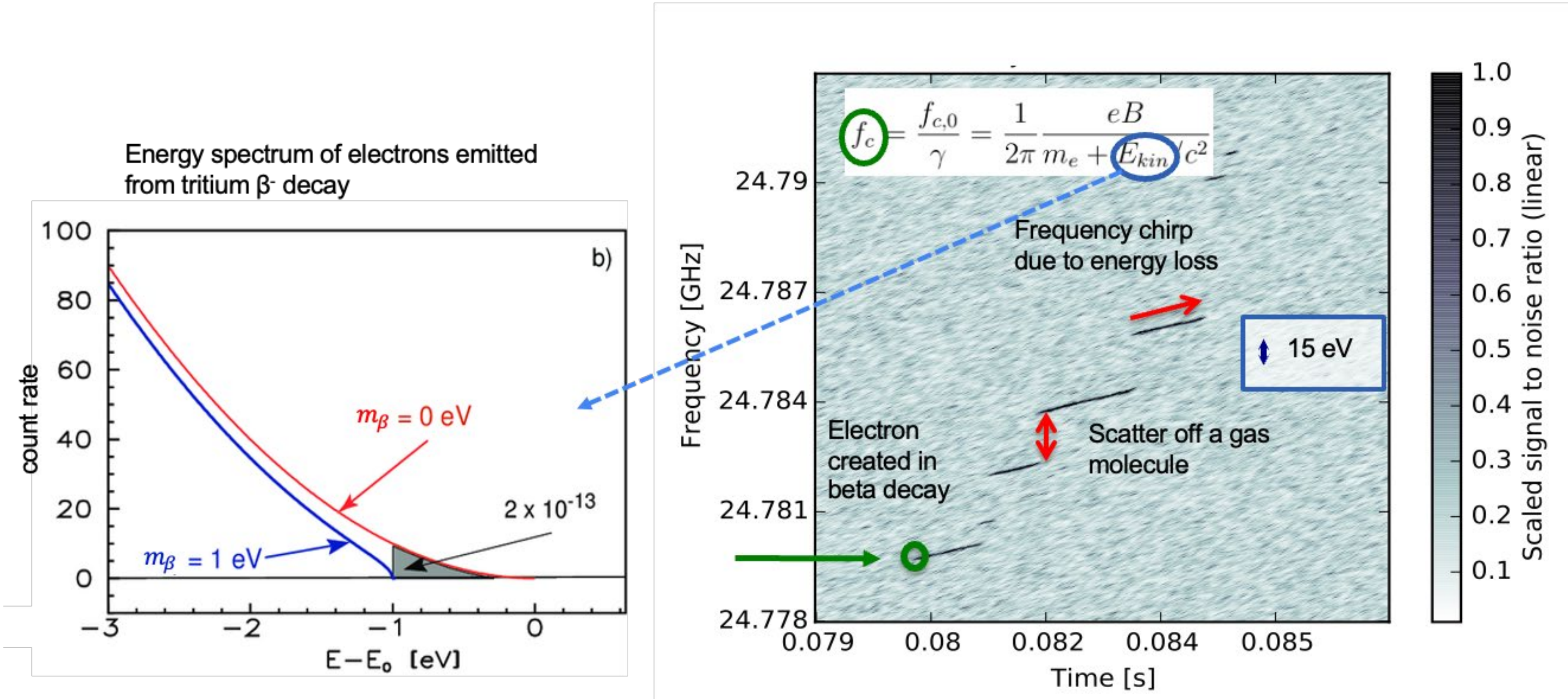
$$f_\gamma = \frac{f_c}{\gamma} = \frac{eB}{2\pi} \frac{1}{m_e + \frac{1}{c^2} E_\beta}$$

2) And a radiofrequency cavity naturally filters out a band around the resonant frequency…



Cyclotron radiation emission spectroscopy in an RF cavity → Project 8

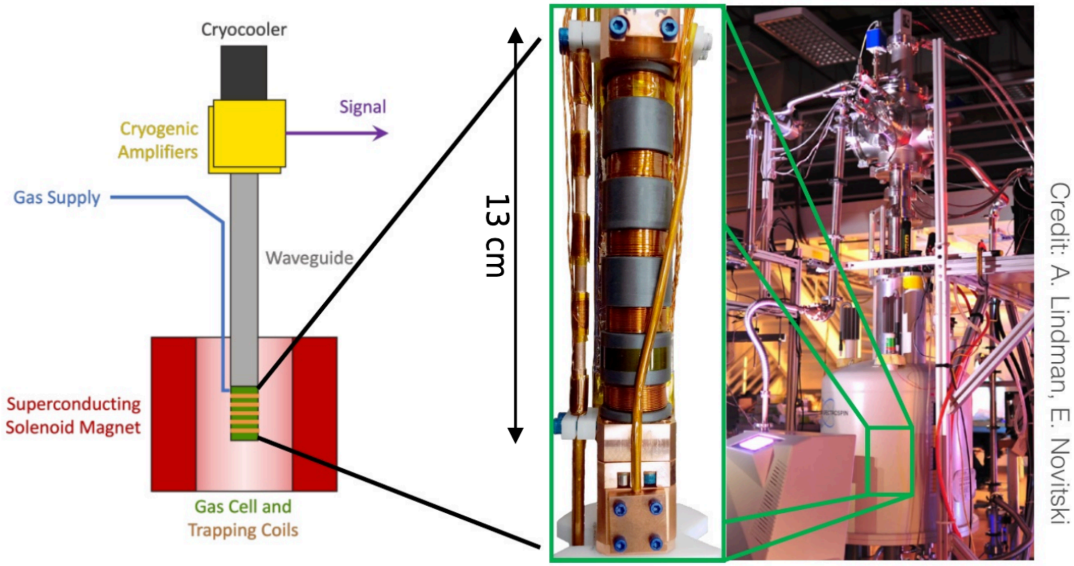
ELECTRON TRACKS IN PROJECT 8

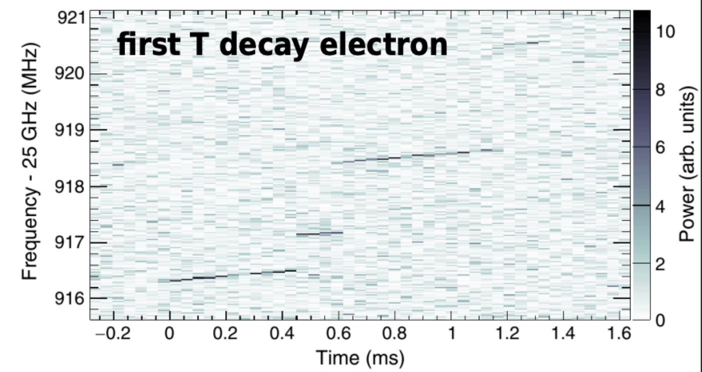


- Trap tritium inside the cavity and let it decay there.
- Measure response in frequency space near the end point.
- Electron tracks slope up because of cyclotron losses
- And they step because of random inelastic scatters.

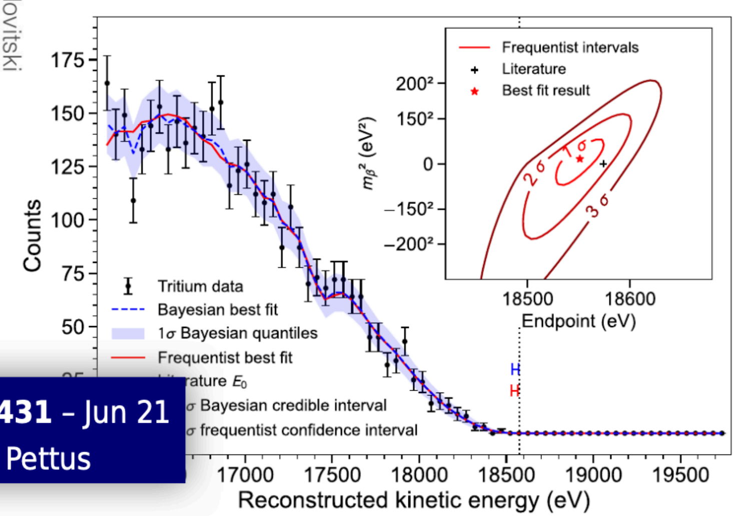
From Neutrino2024:

Project8: phase II results





A. Ashtari Esfahani et al. Phys. Rev. C 109, 035503



4 different experimental phases since 2009

long term sensitivity goal: 40 meV 90% CL (phase IV)

phase II with T_2 adsorbed in getter

- demonstrated T decay spectroscopy with **0 background**
- ΔE_{FWHM}=54 eV (deep trap configuration)
- 3770 T decays within wave guide in 82 days
- → $\boldsymbol{m_\nu}$ **< 152 eV** 90% CL *Project 8 Collaboration, PRL 131 (2023) 102502*

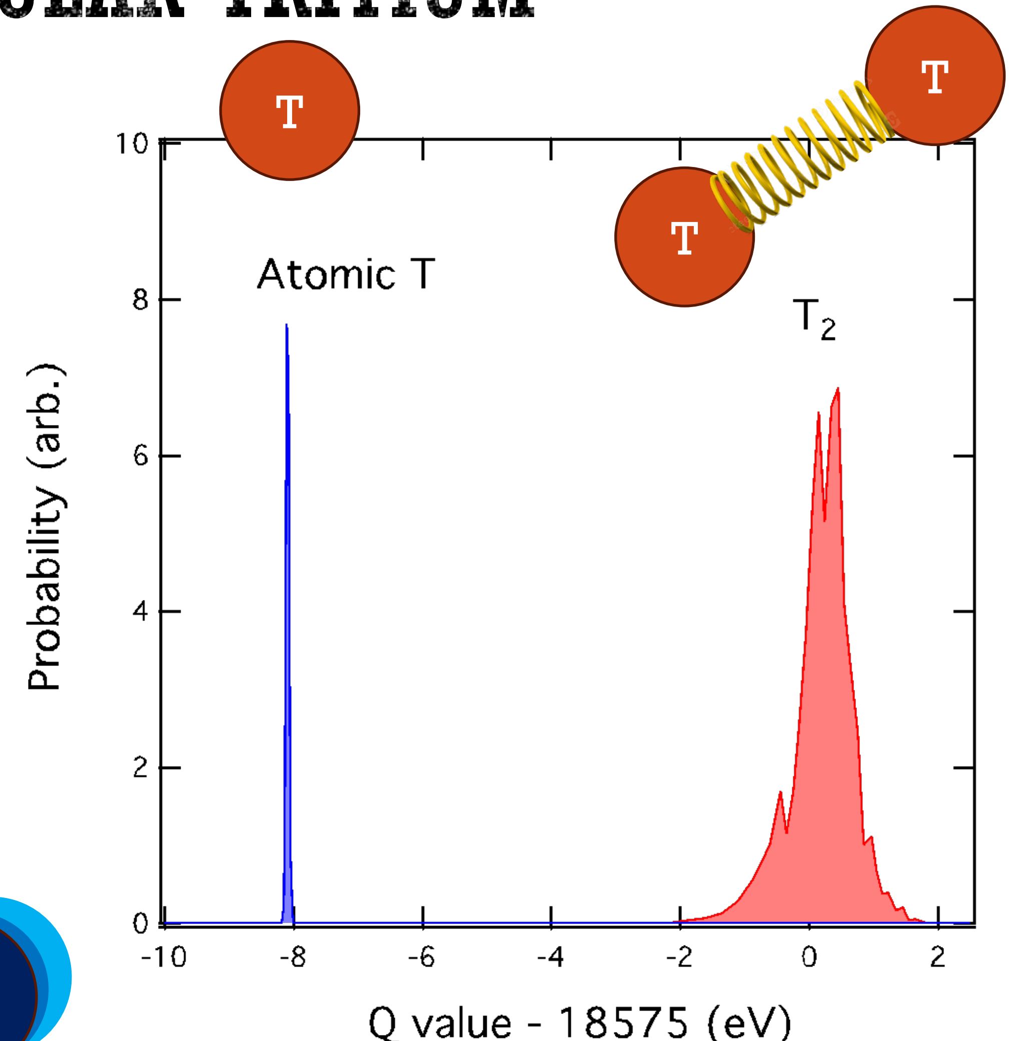
poster 431 – Jun 21
W. Pettus

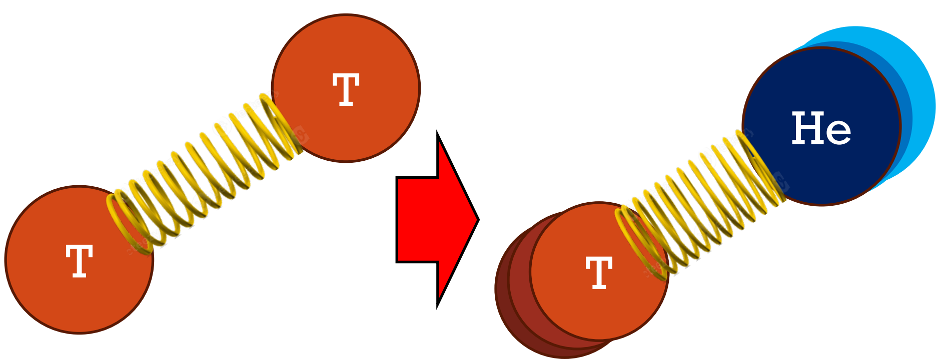
ATOMIC AND MOLECULAR TRITIUM

To extend further in sensitivity, another challenge faces tritium experiments.

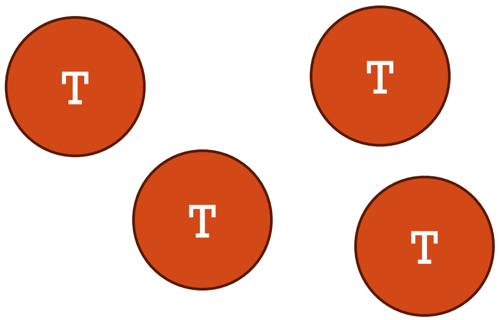
When T2 molecule decays, it makes a THe molecule, which has vibrational excited states.

The excitation absorbs a random amount of energy, effectively smearing the end-point.

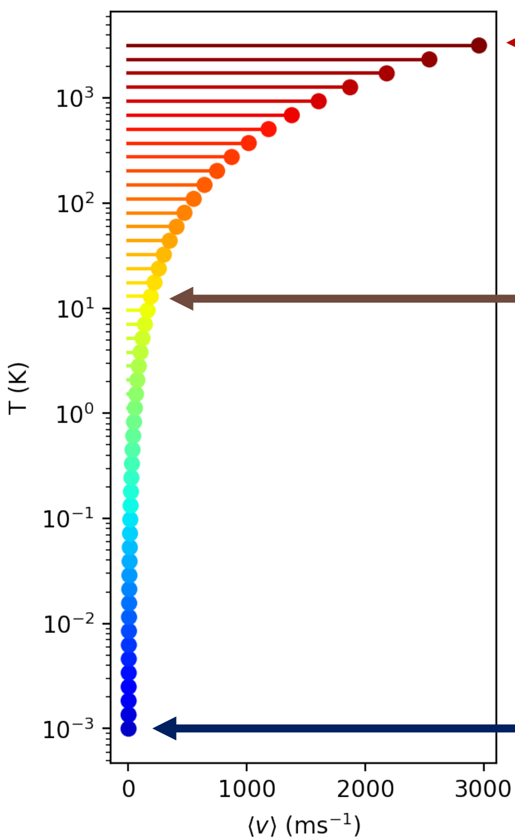




ATOMIC TRITIUM



- Its easy to make T from T2 – just heat it up and it cracks!
- But if you let it touch any surfaces, it will recombine back to T2…
- Need to cool to 1 mK (somehow) and store in a magnetic bottle.



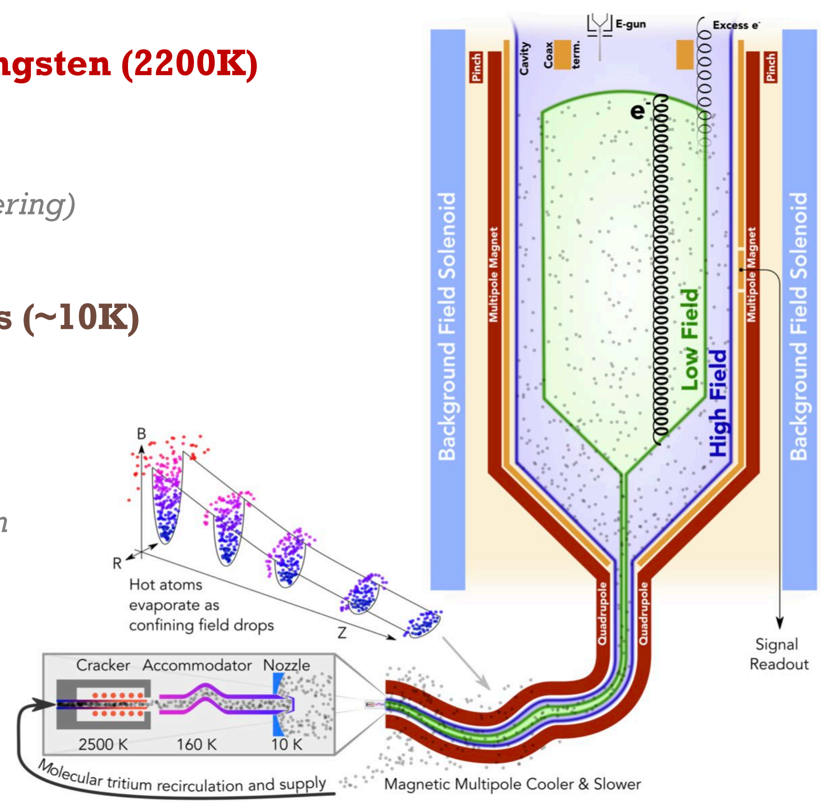
T2 to T cracks on hot tungsten (2200K)

Accommodator (cool by scattering)

T binds to solid surfaces (~10K)

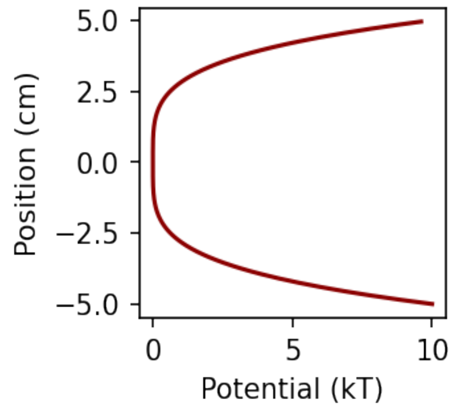
MECB (cool by evaporation

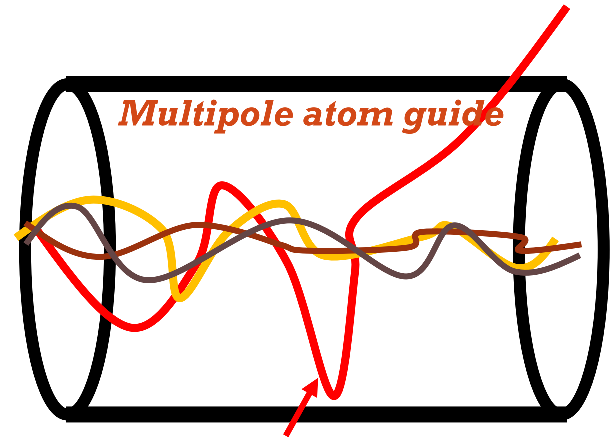
T gravitationally storable in 3m trap (~1mK)



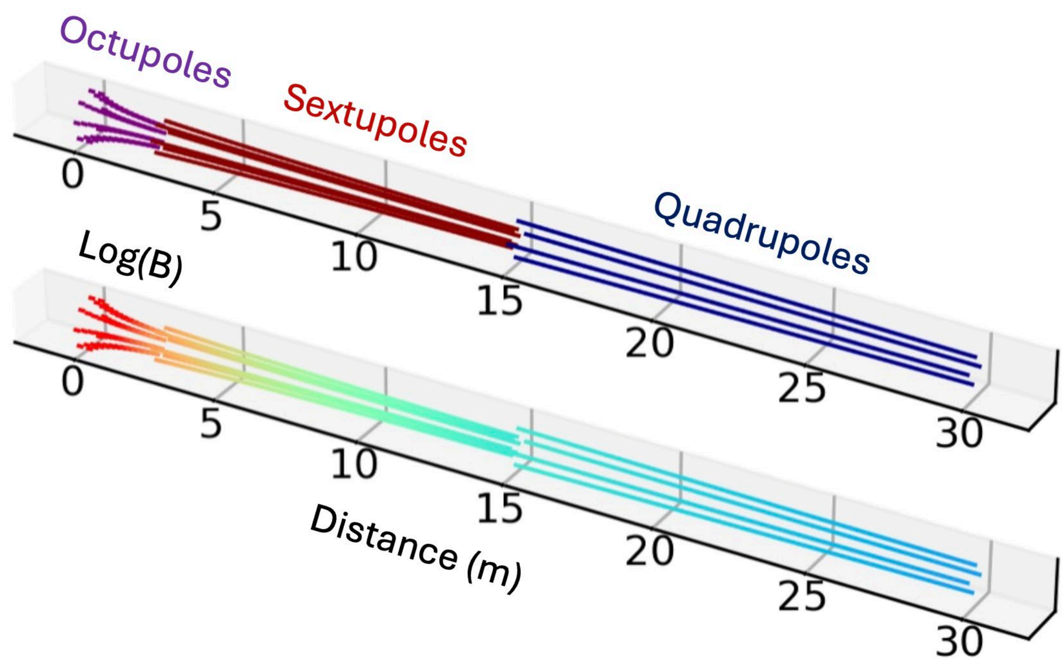
COOLING T

- A major ongoing research area in Project 8 (including in my own group, and at IU!)
- Can’t access any tritium lines with powerful enough lasers for laser cooling.
- Also can’t let it touch any surfaces or it will recombine to T2.
- Proposed solution is magnetic evaporative cooling from multipole magnetic guides →



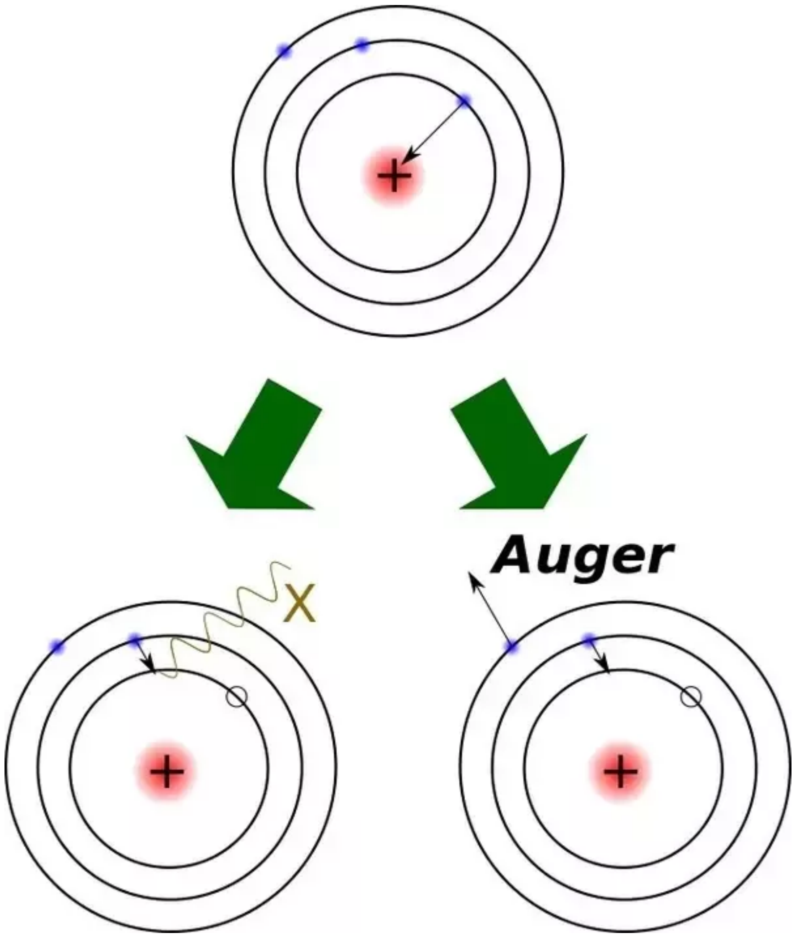


Only the highest energy atoms escape magnetic potential.



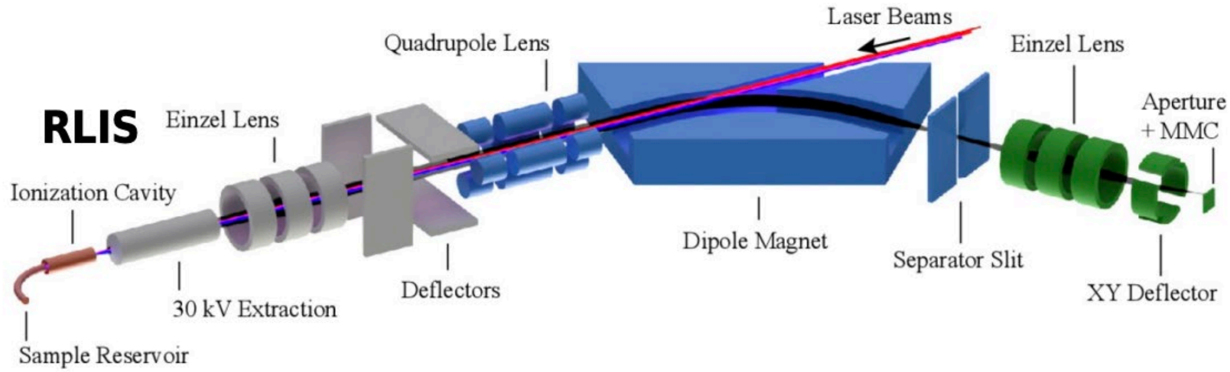
HOLMIUM ELECTRON CAPTURE

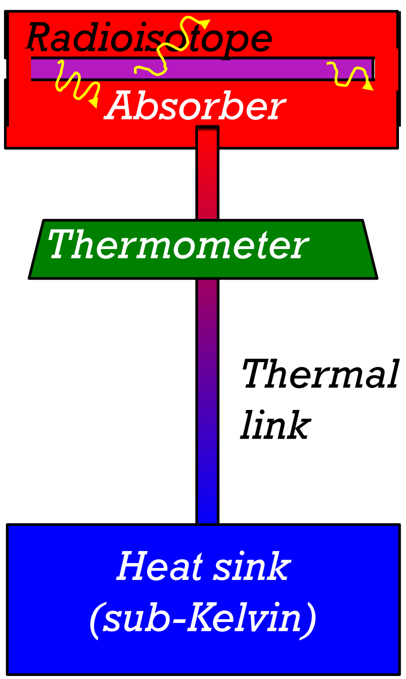
- ^{163}Ho undergoes electron capture decay with a very low Q-value (2.5 keV).
- The neutrino leaves, and the rest of the energy comes out through various de-excitation processes.
- For holmium electron capture decay, the neutrino mass can in principle be measured through **calorimetry.**

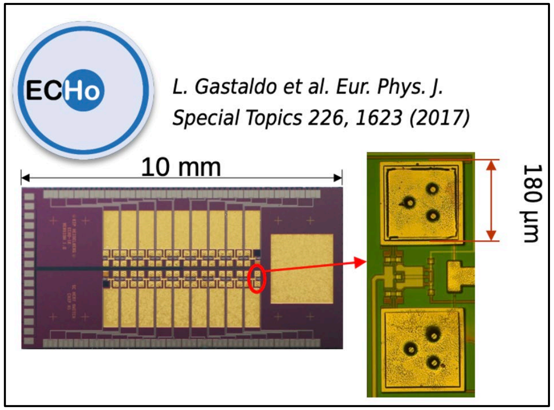


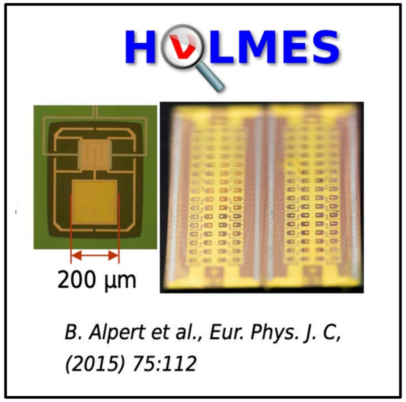
MICROCALORIMETRY

^{163}Ho accelerated and implanted into absorber →









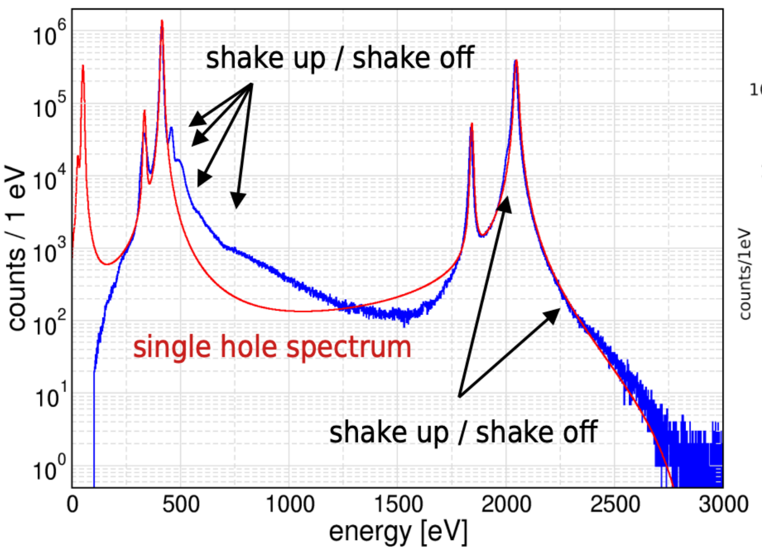
← Then heat depositions read out via precise thermometry:

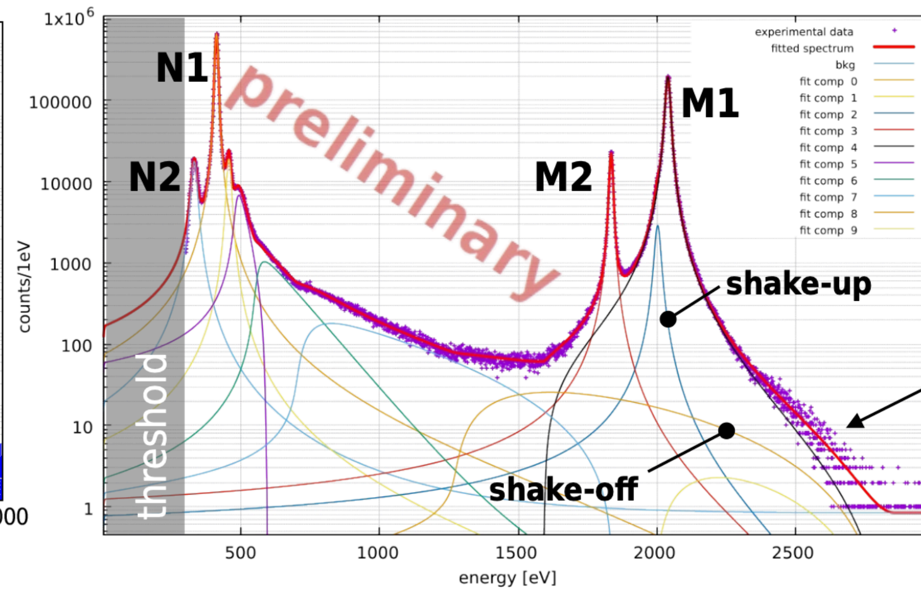
Holmes: Transition Edge Sensors

Echo: Magnetic Micro-calorimeters

From Neutrino2024:

HOLMES high statistics measurement: spectral shape





signal rate higher than single-hole

impact on m_β sensitivity?

experimental EC spectrum deviates from all theoretical predictions

→ **phenomenological description** of the EC spectrum

- shake-up peaks and shake-off spectra
- strongly asymmetric Lorentzians (Fano-like interference?)

needed for assessing sensitivity of future ^{163}Ho experiments

end-point region is smooth and featureless

A. De Rújula et al., J. High Energ. Phys., 2016 (2016) 15
A. Faessler et al., Phys. Rev. C, 95 (2017) 045502
M. Brass et al.t, New J. Phys., 22 (2020) 093018
R. G. H. Robertson, Phys. Rev. C, 91 (2015) 035504

SUMMARY

- Neutrinos were invented as a "desperate remedy" to understand the energy spectrum of beta decay.

- They were then detected via beta decays from fission products in reactors.

- The end-point of beta decay is a powerful tool to try to measure the absolute value of the neutrino mass.

- We have much work to do, both experimentally and theoretically, to understand the ~130 year old beta decay process.