Underground…

The Next Frontier

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National Nuclear Physics
Summer School

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"(Come in under the shadow of this red rock),
And I will show you something different from either
Your shadow at morning striding behind you
Or your shadow at evening rising to meet you;
I will show you fear in a handful of dust."

--T.S. Eliot, The WasteLand

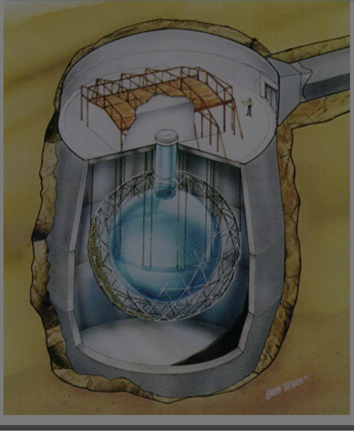
Lesson #4

m_ν is finite*

*and thus can be measured...

Neutrino mass continued...

Neutrino Oscillations



Probe mass differences

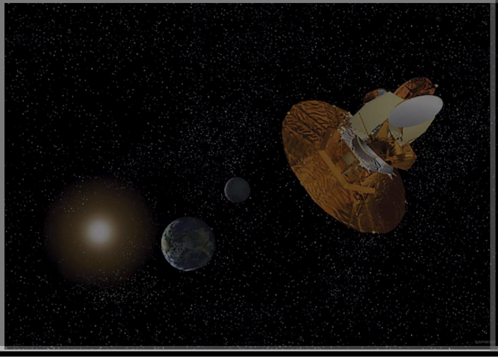
Use quantum mechanical effects

Sources: Reactor, solar, atmospheric, beams

Cosmology

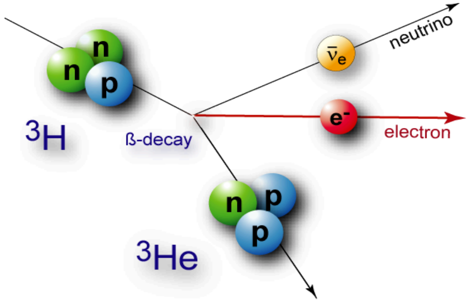
Probe total neutrino mass
Use Gen. relativity

Satellites & ground observatories



ν

Single Beta Decay



Probe absolute mass scale

Use conservation of energy

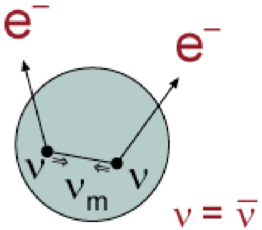
Model-independent

0ν Double Beta Decay

Probe Majorana masses

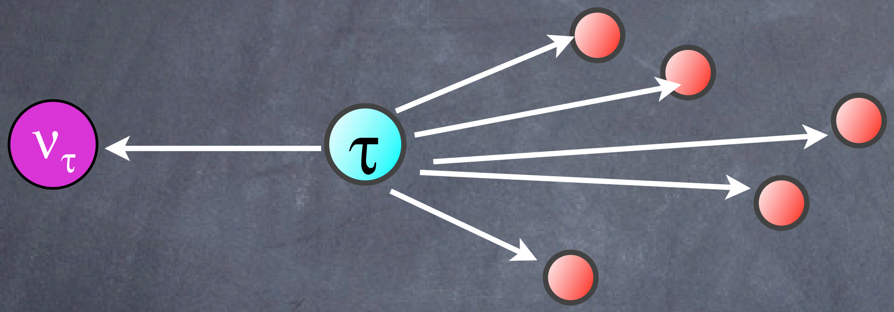
Use rarest decays on Earth

Probe identity of neutrinos

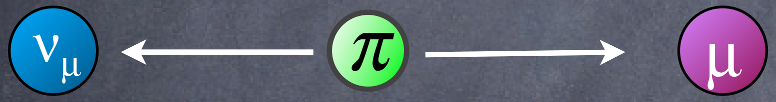


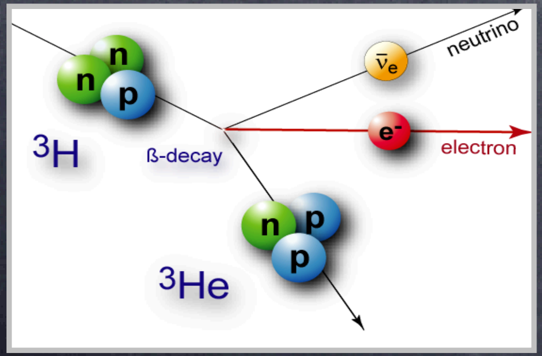
0νßß

Direct Measurements



5π





$m_{\nu_\tau} < 18.2$ MeV (95% CL)

(ALEPH 1998)

$m_{\nu_\mu} < 170$ keV (90%CL)

(PSI 1996)

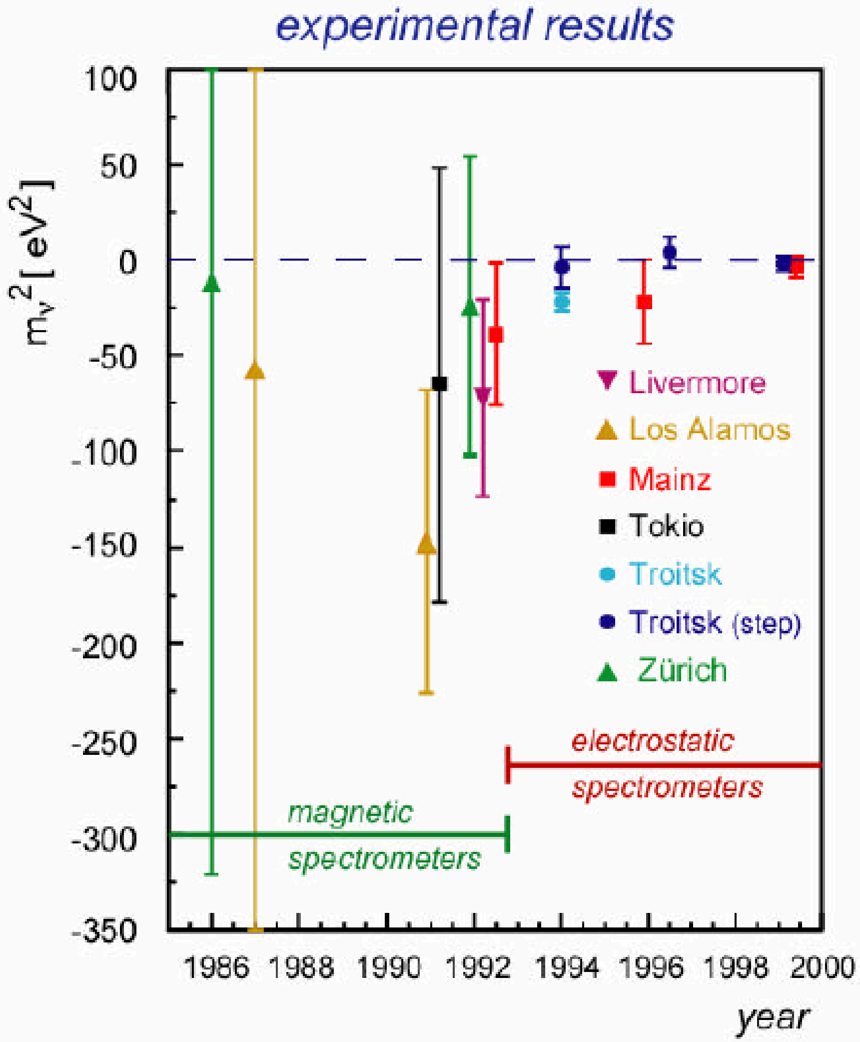
$m_{\nu_e} < 2.2$ eV (95% CL)

(Mainz 2000)

Oscillation results tell us probing ν_e probes all neutrinos at once !

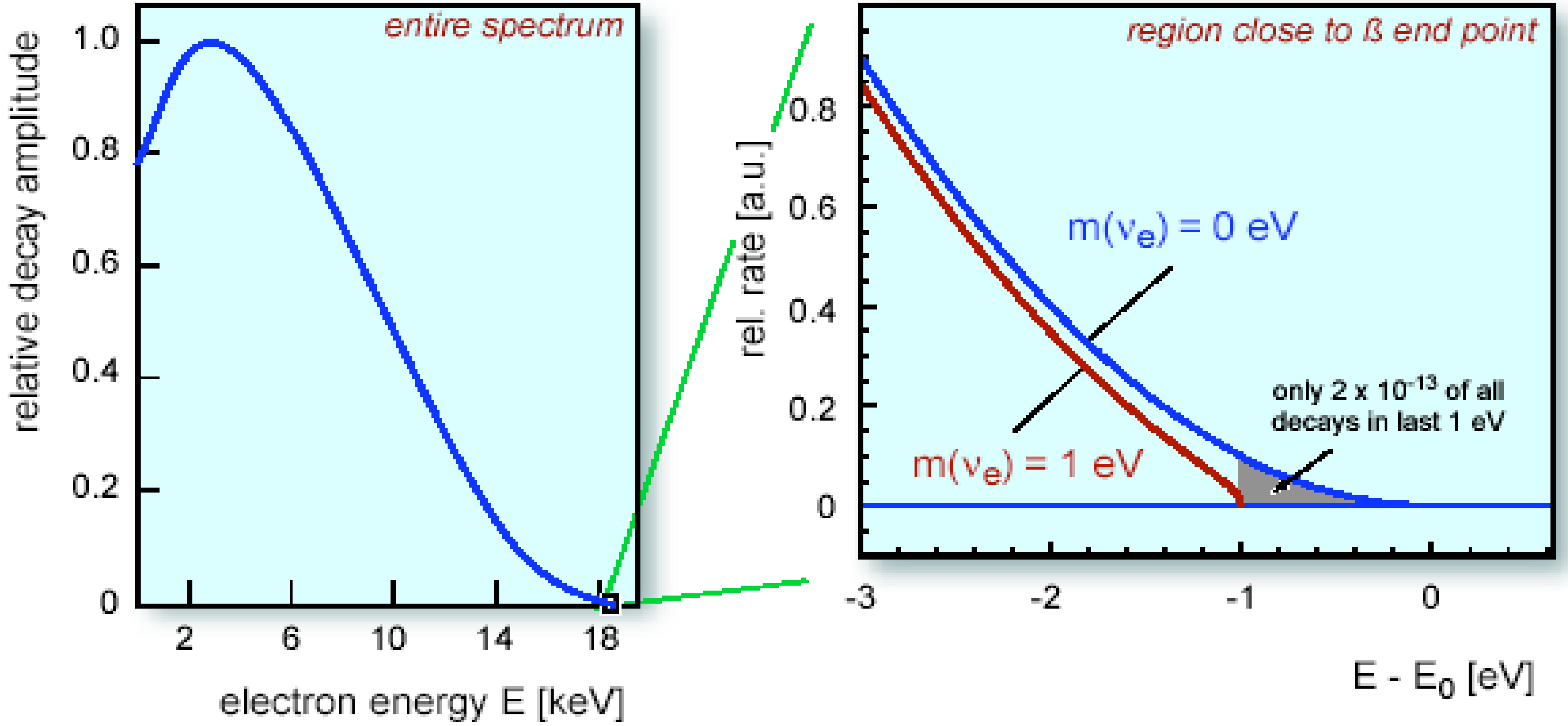
The Past....

	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	< 2.2 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.2 eV



β-decay Endpoint Measurement

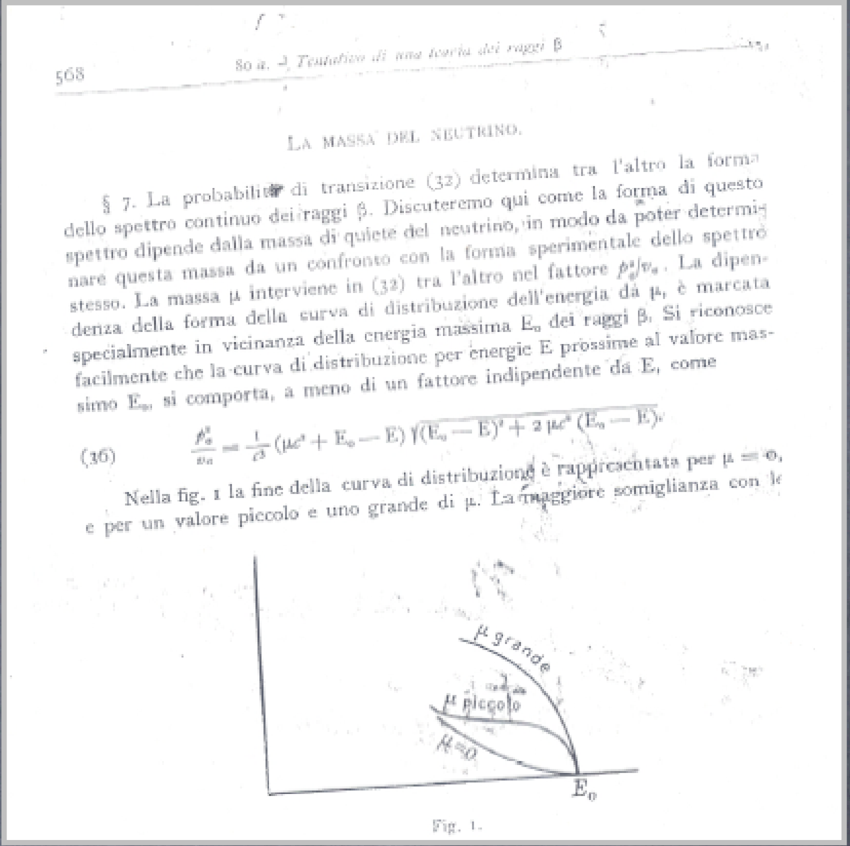
$$\frac{dN}{dE} = C \times F(Z,E)p_e(E+m_e^2)(E_0-E)\sum_i |U_{ei}|^2\sqrt{(E_0-E)^2+m_i^2}$$



Tritium β-decay allows precise measurement of the absolute neutrino mass scale.

Essentially a search for a distortion in the shape of the β-spectrum in the endpoint energy region.

Beta Decay from Tritium



568 80 a. – Tentativo di una teoria dei raggi β

LA MASSA DEL NEUTRINO.

§ 7. La probabilità di transizione (32) determina tra l'altro la forma dello spettro continuo dei raggi β. Discuteremo qui come la forma di questo spettro dipende dalla massa di quiete del neutrino, in modo da poter determinare questa massa da un confronto con la forma sperimentale dello spettro stesso. La massa μ interviene in (32) tra l'altro nel fattore p_σ^2/v_σ. La dipendenza della forma della curva di distribuzione dell'energia da μ, è marcata specialmente in vicinanza della energia massima E_0 dei raggi β. Si riconosce facilmente che la curva di distribuzione per energie E prossime al valore massimo E_0, si comporta, a meno di un fattore indipendente da E, come

$$\frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}. \tag{36}$$

Nella fig. 1 la fine della curva di distribuzione è rappresentata per μ = 0, e per un valore piccolo e uno grande di μ. La maggiore somiglianza con l

Fig. 1.

- Matrix element independent of neutrino mass.
- Mass term comes from kinetic (energy conservation) term.
- Final states need to be understood or avoided.

$$F(Z,E) = \frac{x}{1 - exp{-x}}(a_0 a_1 \cdot \beta);$$

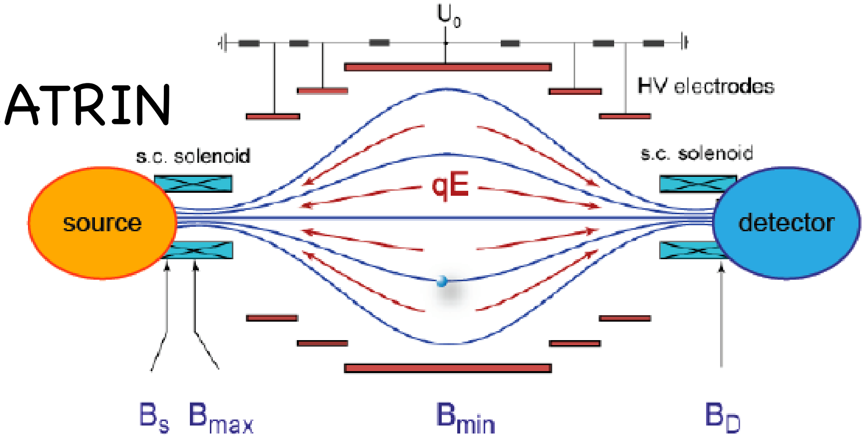
$$a_0 = 1.002037, a_1 = -0.001427, x = \frac{2\pi Z \cdot \alpha}{\beta}$$

$$\frac{dN}{dE} = C \times F(Z,E) p_e (E + m_e^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 + m_i^2}$$

Two Techniques

Spectroscopy

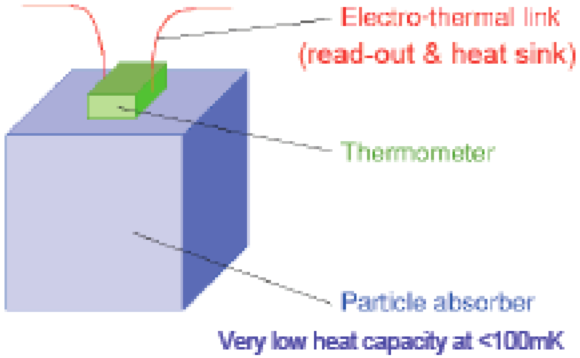
KATRIN



$$^{3}\mathrm{He} \rightarrow {}^{3}\mathrm{H} + e^{-} + \bar{\nu}_e$$

Bolometry

MIBETA
&
MARE



$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^{-} + \bar{\nu}_e$$

Examines only region of interest.

Excellent statistics.

Excellent resolution (1 eV).

Disadvantages: final states, scattering

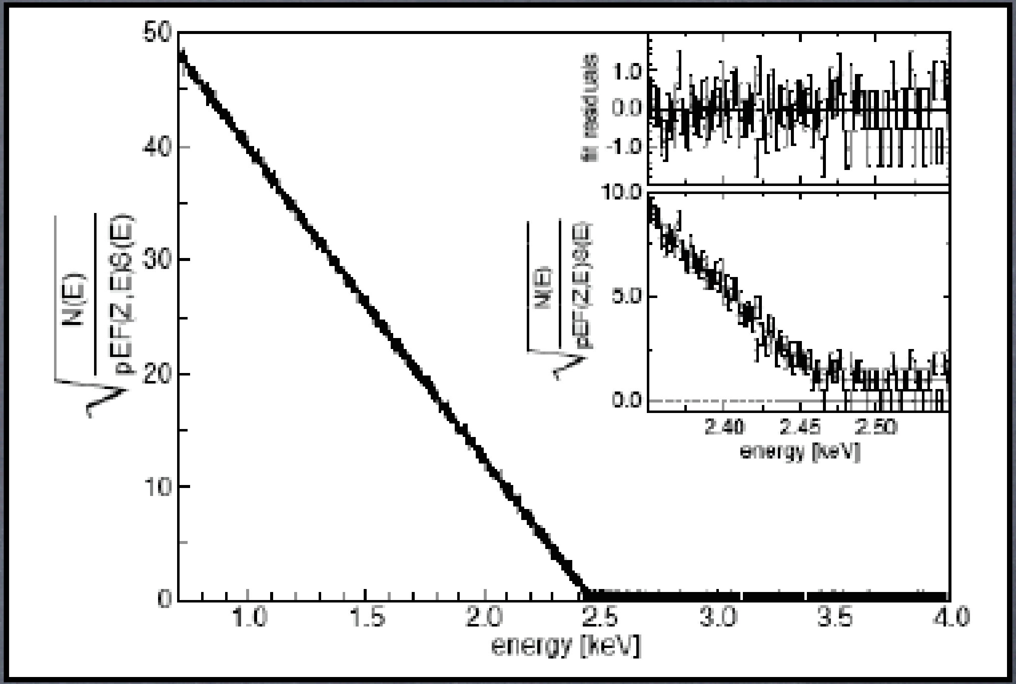
Detection of all energy, including final states.

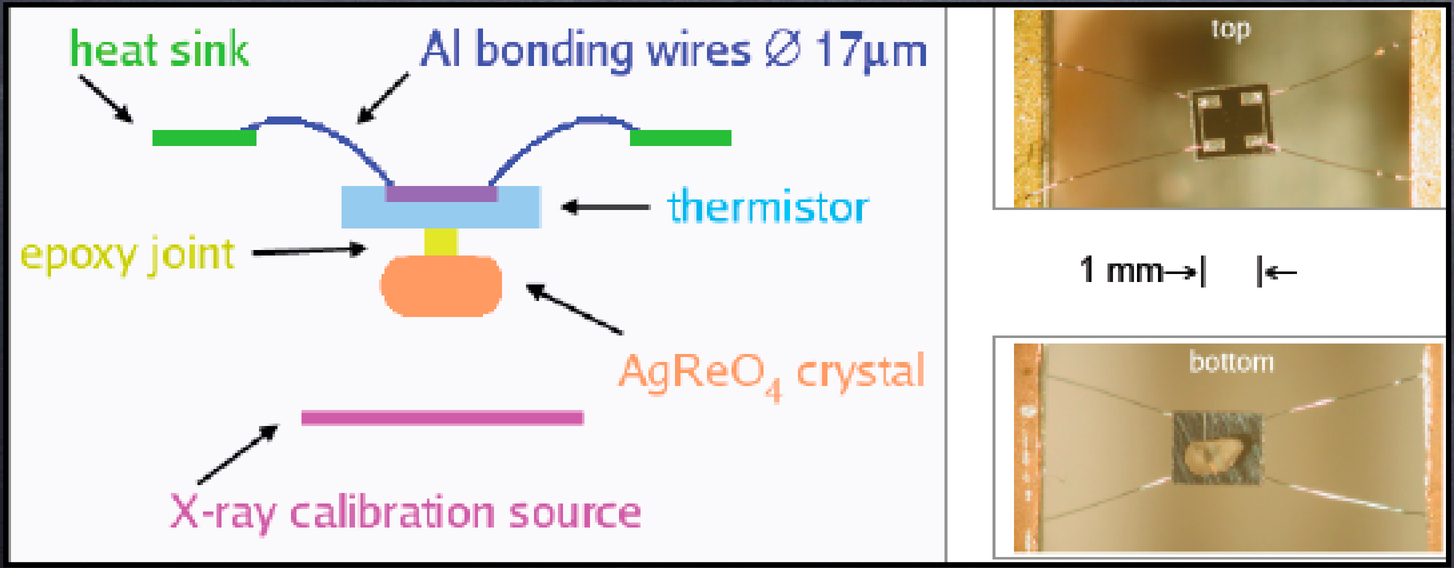
Potential next-next-generation.

Disadvantages: measures all spectrum (pile-up); multiple detectors

Bolometry

- Bolometry uses instrument both as source and as detector.
- Measures all energy from the decay (except neutrino). No issues with final state losses.
- Small units (necessary, if one wants to avoid pile-up from multiple decays.

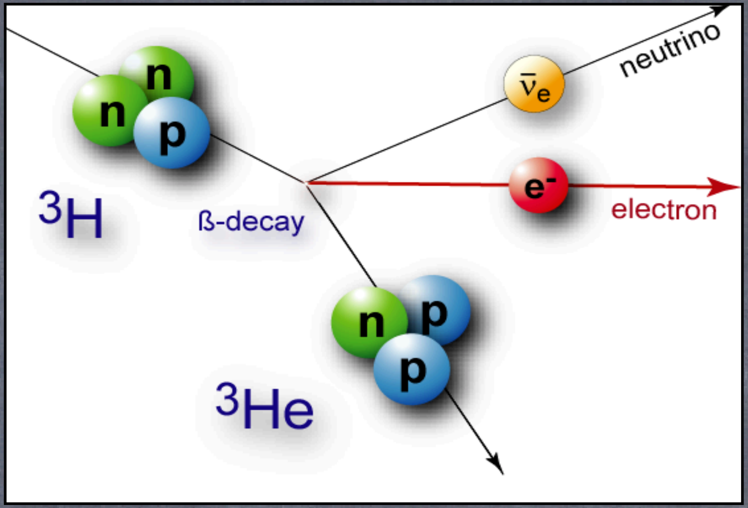




Current sensitivity:

m < 15 eV (90% C.L.)

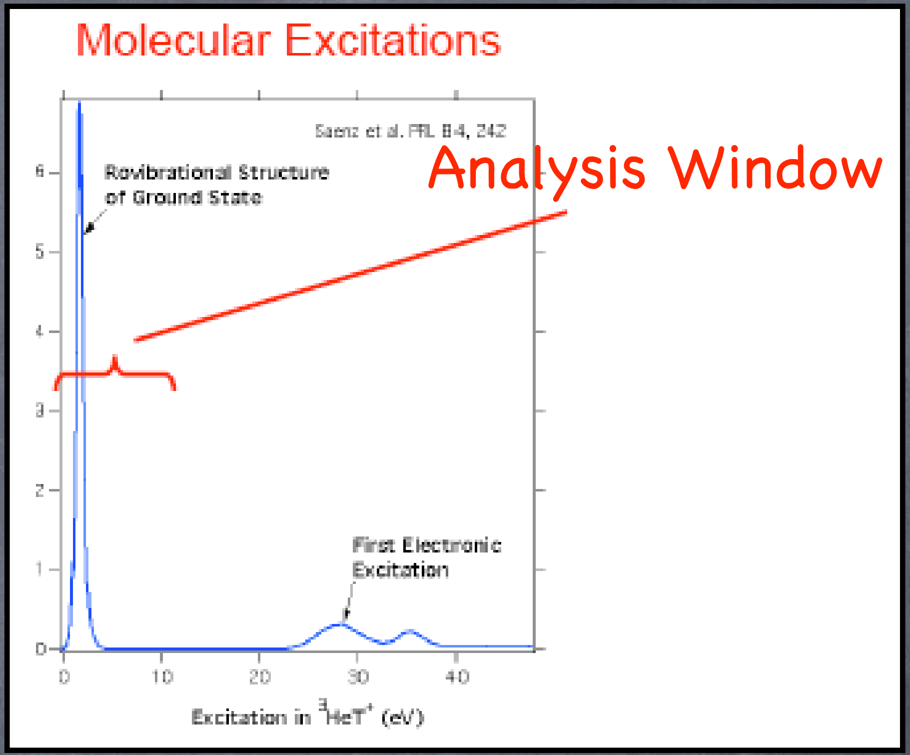
Advantages of Tritium



- Tritium is an almost ideal β-emitter for neutrino mass investigations:
  - Low endpoint energy of 18.7 keV.
  - Modest half-life (12.3 years)
  - Tritium beta decay is a super-allowed nuclear transition.
  - Tritium and its daughter ($^3He^+$) have a simple electron shell configuration.

Beta Decay from Tritium

- Matrix element independent of neutrino mass.
- Mass term comes from kinetic (energy conservation) term.
- Final states need to be understood or avoided.

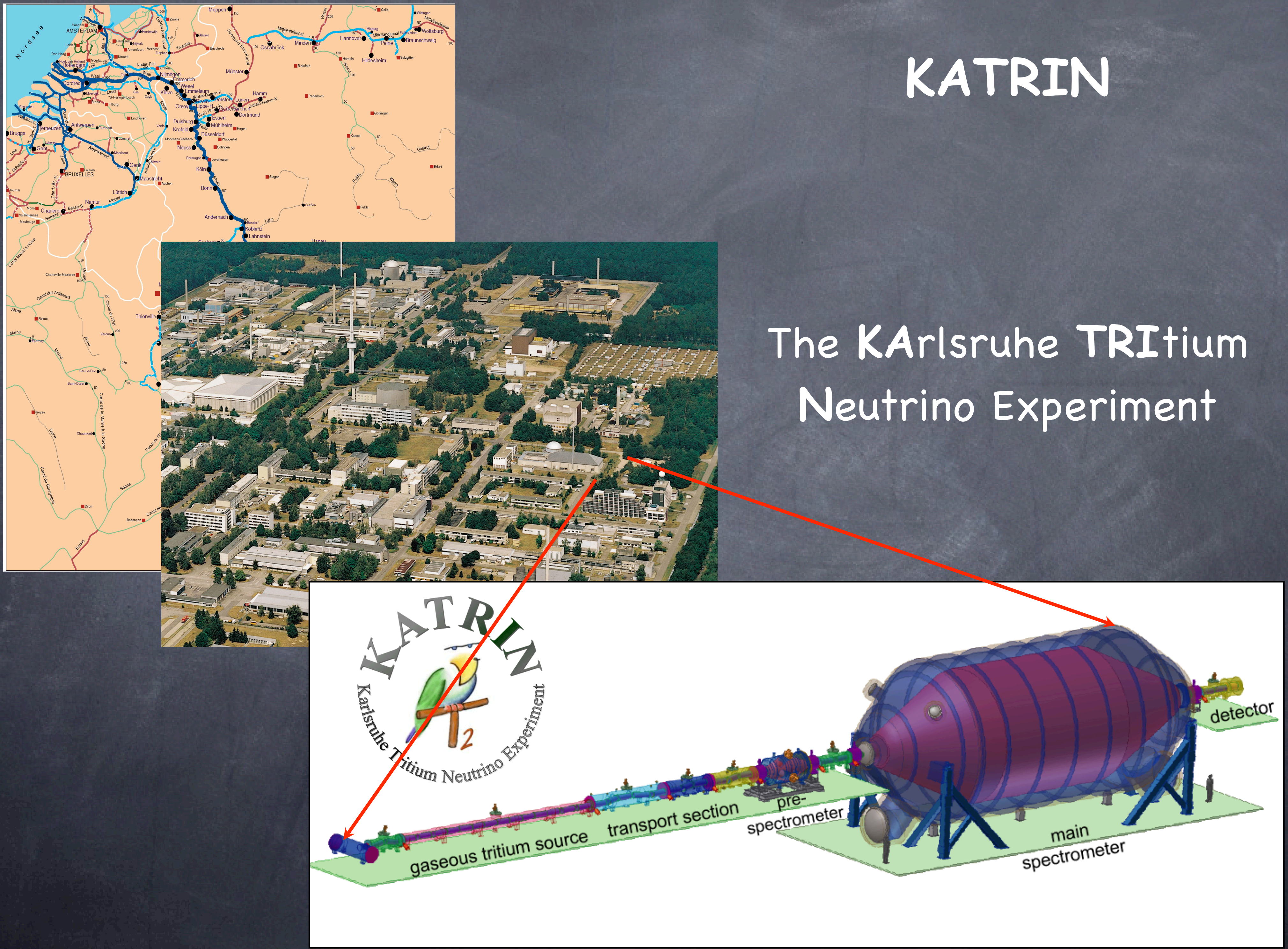


decay process (with $\bar{\nu}_e$)	$\tilde{Q} = E_0 - \Delta M(^3\mathrm{He}, ^3\mathrm{H})$	comment
$^3\mathrm{H} \rightarrow\ ^3\mathrm{He}^+ + e^-$	-24.6 eV	atomic decays
$^3\mathrm{H}^- \rightarrow\ ^3\mathrm{He} + e^-$	-0.75 eV	
$^3\mathrm{H}^+ + e^- \rightarrow\ ^3\mathrm{He}^{++} + 2e^-$	-65.4 eV	
$^3\mathrm{H}_2 \rightarrow (^3\mathrm{He}^3\mathrm{H})^+ + e^-$	-16.5 eV	molecular decays
$^3\mathrm{H}_2^+ + e^- \rightarrow (^3\mathrm{He}^3\mathrm{H})^{++} + 2e^-$	-48.9 eV	
$^3\mathrm{H}_3^+ +\ ^3\mathrm{H} + e^- \rightarrow (^3\mathrm{He}^3\mathrm{H}_2)^{++} + 2e^-$	-35.1 eV[31]	

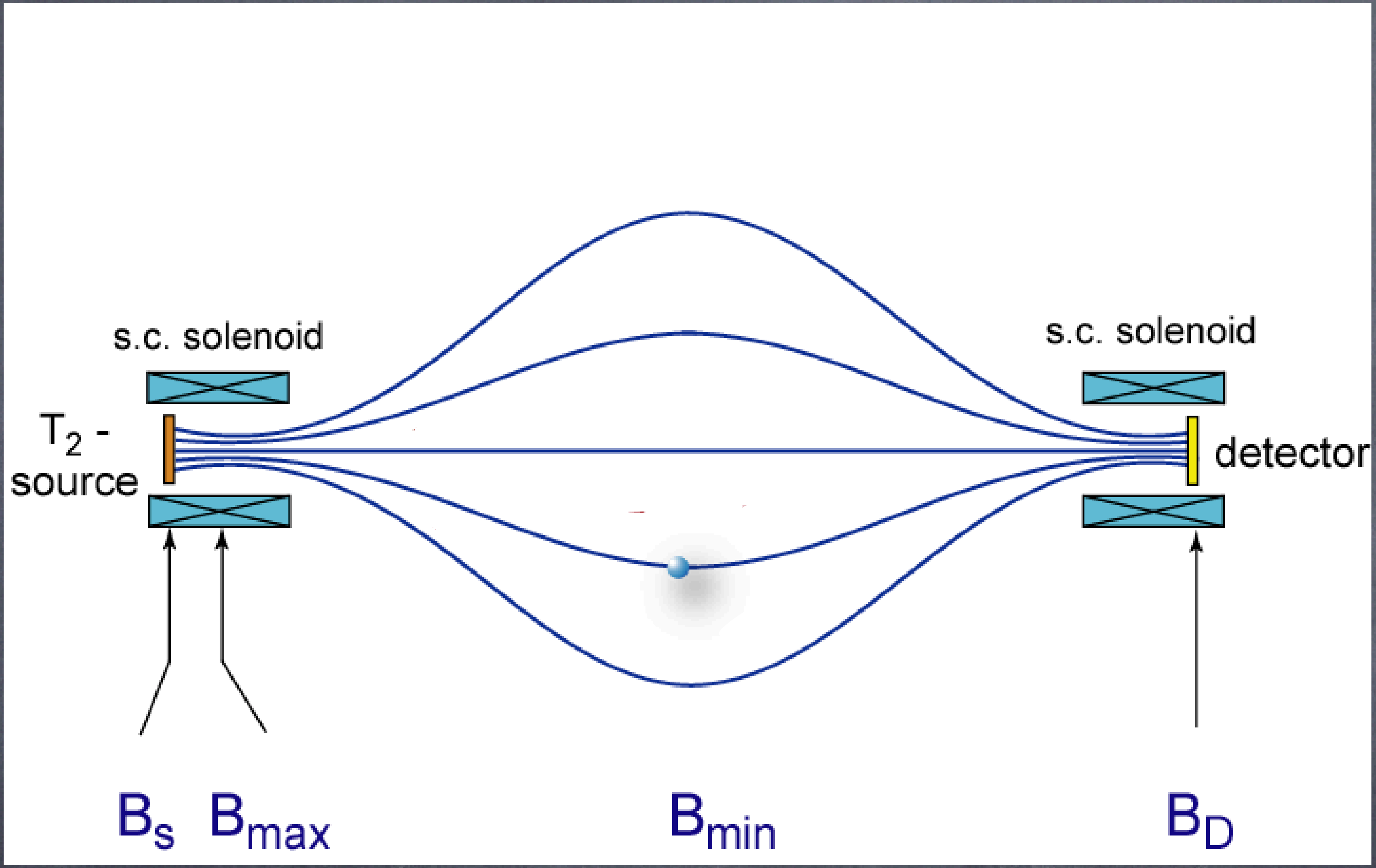
$$\frac{dN}{dE} = C \times F(Z,E)p_e(E + m_e^2)(E_0 - E)\sum_i |U_{ei}|^2\sqrt{(E_0 - E)^2 + m_i^2}$$

KATRIN

The **KA**rlsruhe **TRI**tium **N**eutrino Experiment



MAC-E Filter Technique



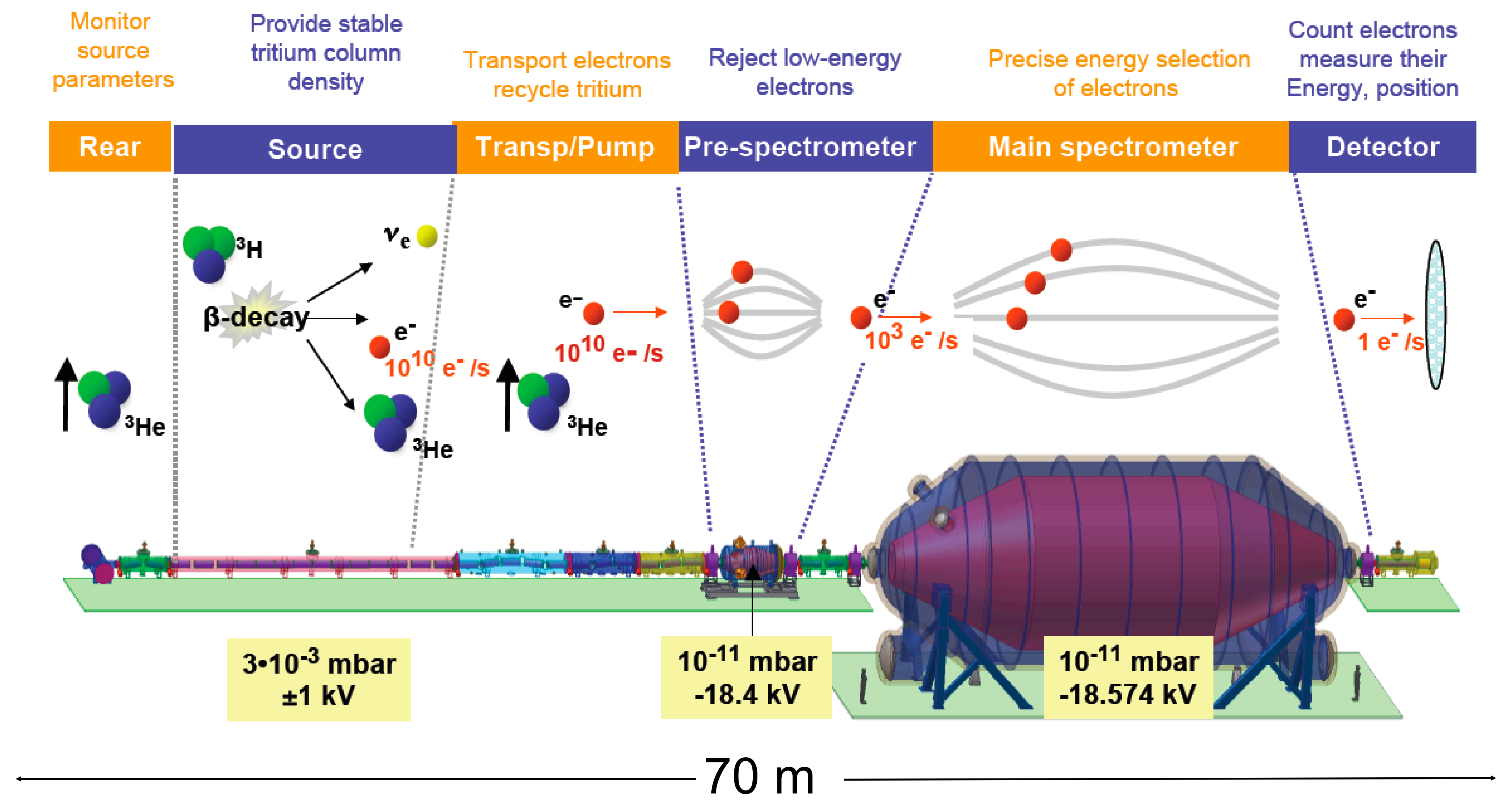
Magnetic Adiabatic Collimation:

- Use adiabatic guiding to move β^- particles along B-field lines.
- Field constrained by 2 s.c magnets.

Electrostatic Filter:

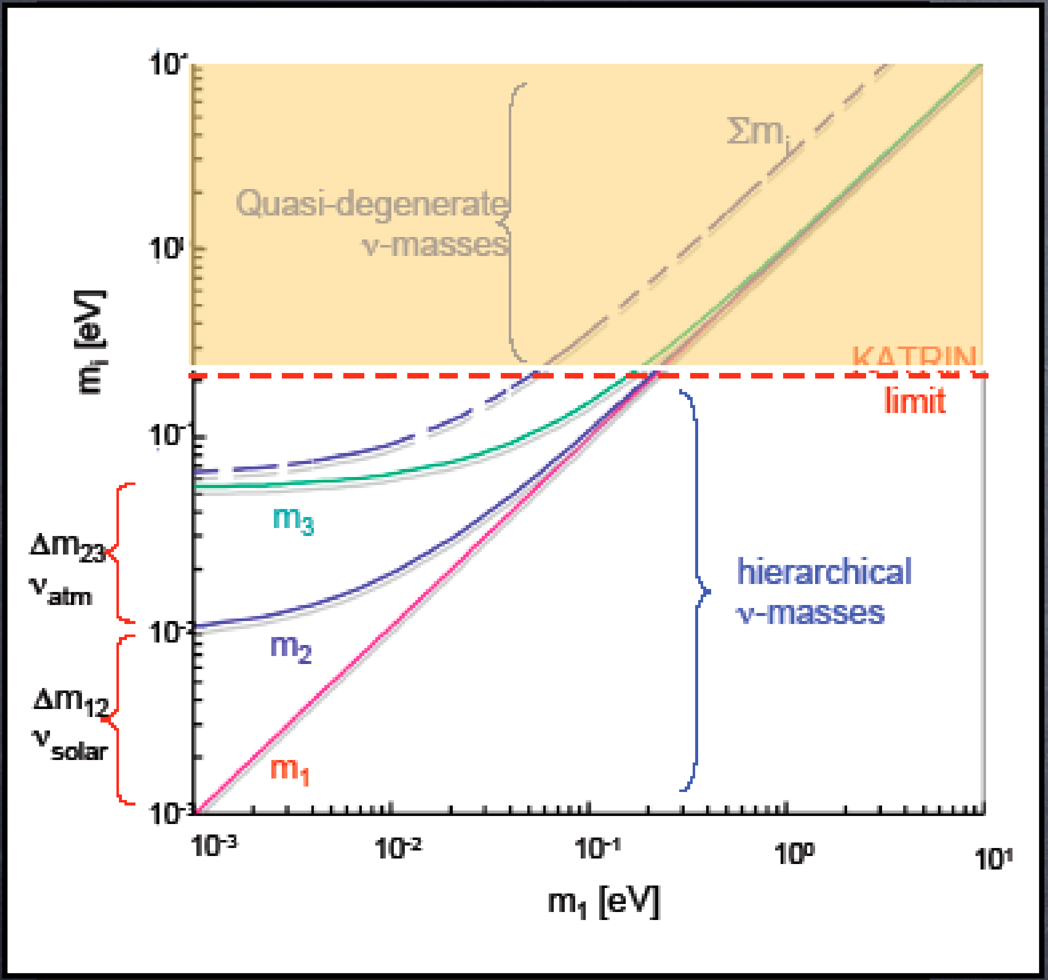
- Use retarding potential to remove β^- particle below threshold.
- High pass filter (variable potential)

KATRIN Layout



Rear	Source	Transp/Pump	Pre-spectrometer	Main spectrometer	Detector
Monitor source parameters	Provide stable tritium column density	Transport electrons recycle tritium	Reject low-energy electrons	Precise energy selection of electrons	Count electrons measure their Energy, position

Final Sensitivity



- Concentrating on last 10 eV allows better handle on theoretical systematics

- Maximum sensitivity achieved in 3 years of running.

$m_\nu < 0.25$ eV (90 % C.L.)

- If $m_\nu > 0.39$ eV, it will correspond to a 5 sigma signal.

- Solve whether masses are degenerate or hierarchical.

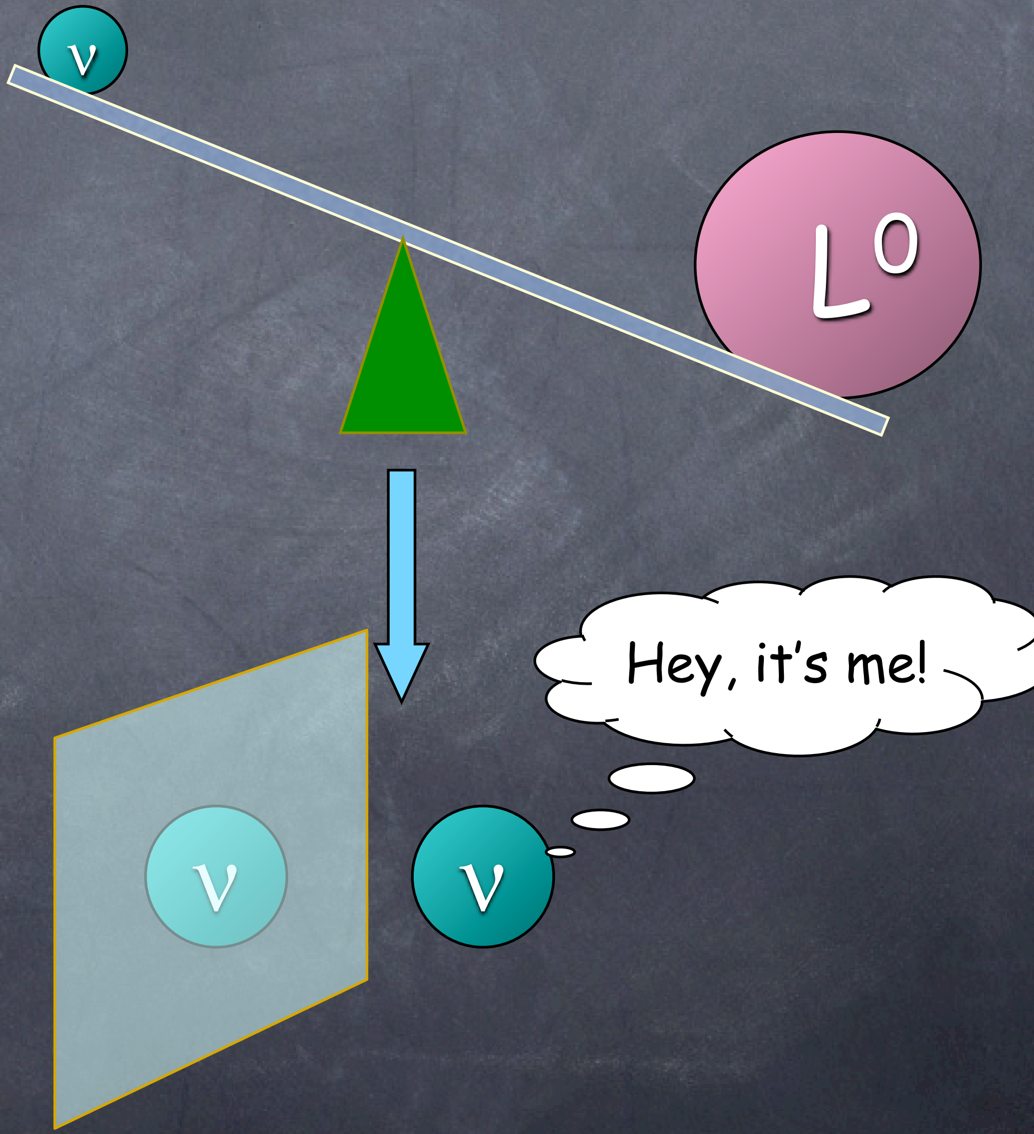
Lesson #4

Is m_ν unique?

(The search for Majorana mass)

The Nature of Neutrino Mass

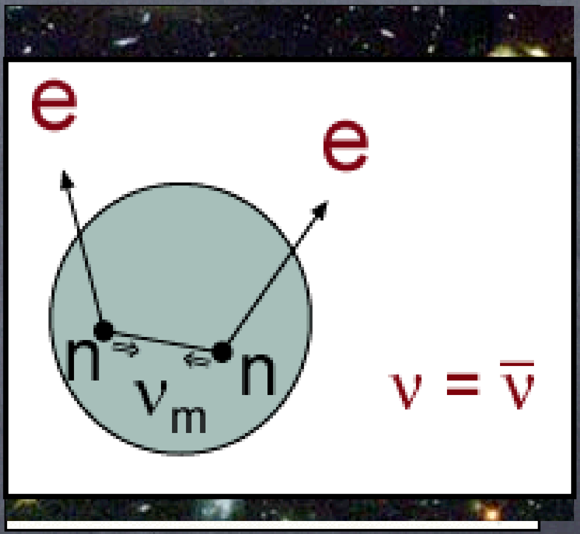
- Beyond the Mass Spectrum
  - One outstanding question is the mechanism behind the smallness of the neutrino mass
  - Possible incorporate the neutrino mass within theories beyond the Standard Model
- Implications → the neutrino & anti-neutrino are the same particle!
- Neutrinos would then be known as Majorana particles.



How to measure Majorana mass?

- For us to distinguish neutrinos as their own anti-particles, the neutrinos must possess a finite mass.
- To measure it, we need to measure what is probably the rarest decay known to exist (double beta decay).
- Only certain select nuclei can participate in this process.

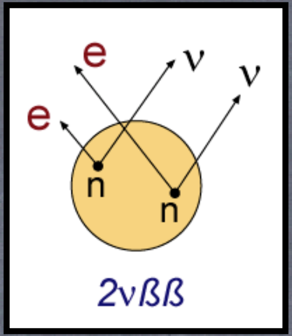
How rare is it?

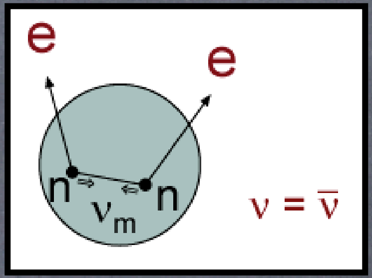


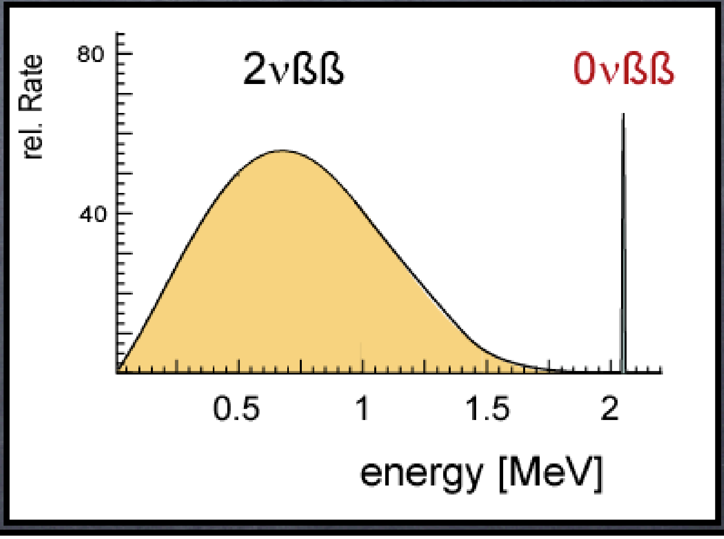
Neutrinoless
[illegible]
Double Beta Decay...
[illegible]
$\sim 10^{25}$ years

Majorana Masses

- Prohibited by lepton number conservation.
- Depends only on matrix elements and the Majorana mass.
- Though other exotic processes can mediate process, still implies neutrino Majorana mass.



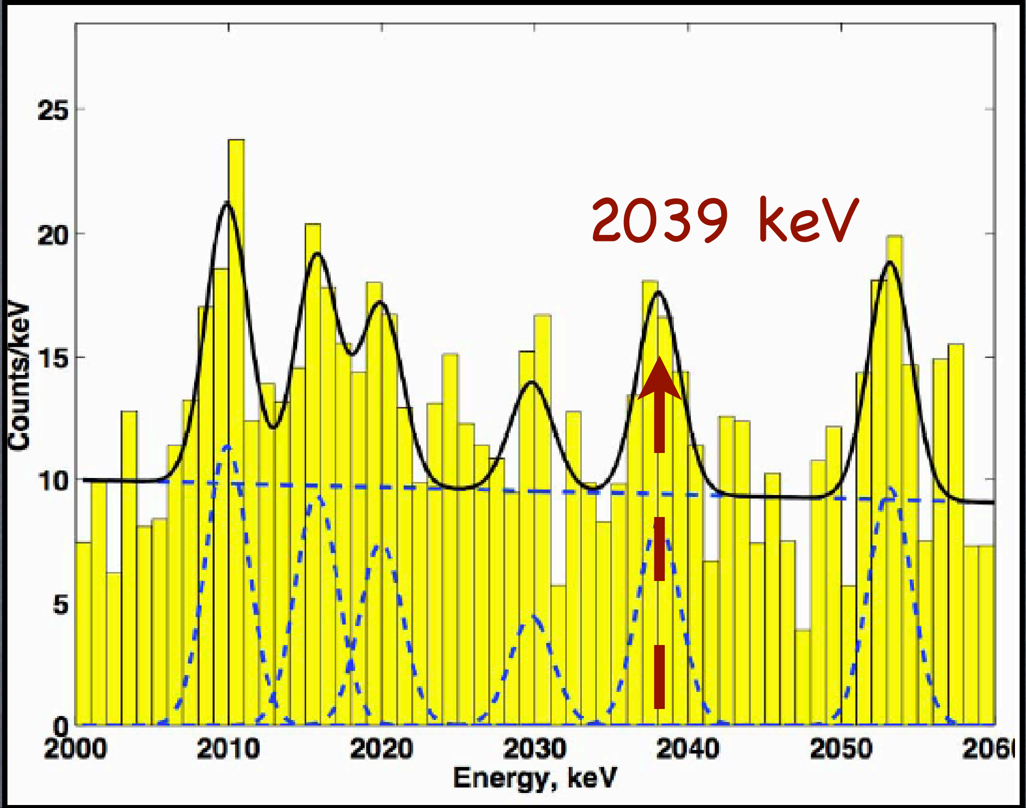




$$[\, T^{0\nu}_{1/2}\,(0^+ \rightarrow 0^+)\,]^{-1} = |\, M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2}\, M^{0\nu}_F \,|^2 \times \left(\frac{\langle m_\nu \rangle}{m_e} \right)^2 \times G^{0\nu}_1$$

Possible Signal?

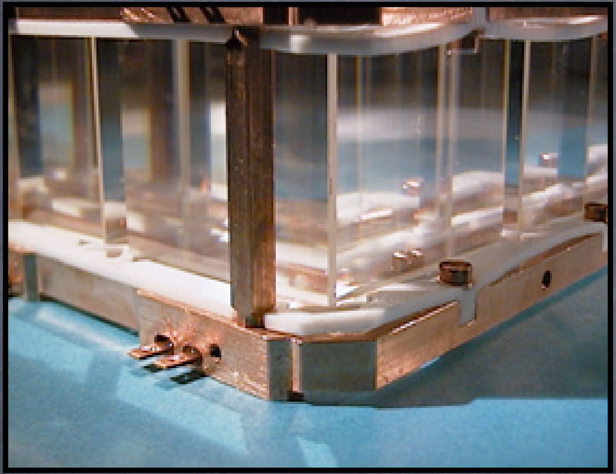
- Possible (4.2 sigma) signal claimed by the Heidelberg-Moscow Germanium experiment.
- Highly controversial:
  - Unknown lines
  - Rejected by part of the collaboration
  - No other measurement to verify it.
- If true, it does imply a neutrino Majorana mass that can be measured in the near future.

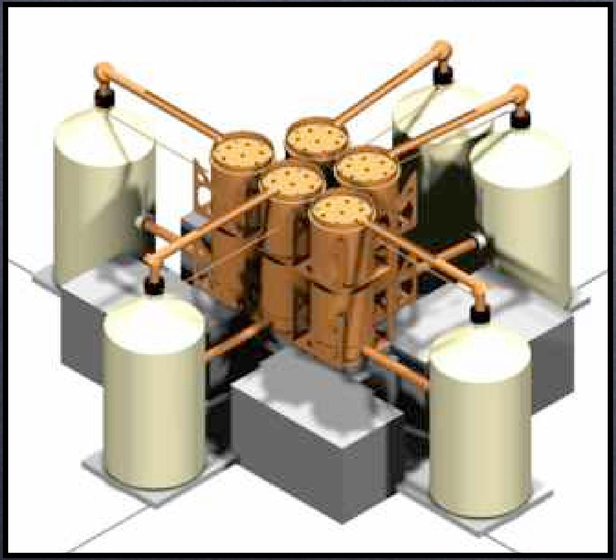


Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

$$0.24 < m_\nu < 0.58 \ (\pm\, 3\ \sigma)$$

Experiments on the Horizon





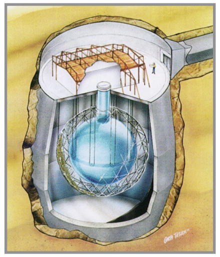
- CUORE
  - Use 750 kg of natural tellurium (^{130}Te). They already have 200 kg of it.
  - Cryogenic detectors
- Majorana
  - Use enriched ^{76}Ge germanium (very well-tested technique).
  - Extremely precise energy measurement of all particles that interact in the medium.

Complementarity

Neutrino Oscillations

Sets lowest mass

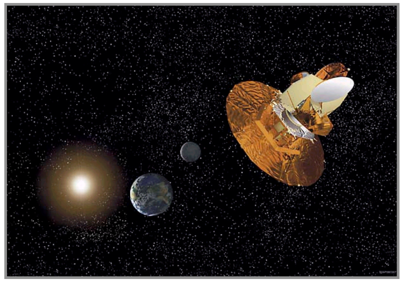
$m_\nu > 50$ meV



Cosmology

Look at the sky to determine mass

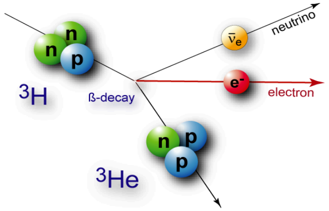
$\sum m_\nu < 200 - 700$ meV --> $m_\nu < 50$ meV



Tritium Beta Decay

Look at kinematics to find mass

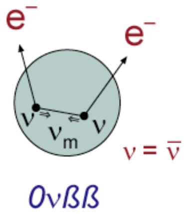
$m_\nu < 2.2$ eV --> $m_\nu < 200$ meV



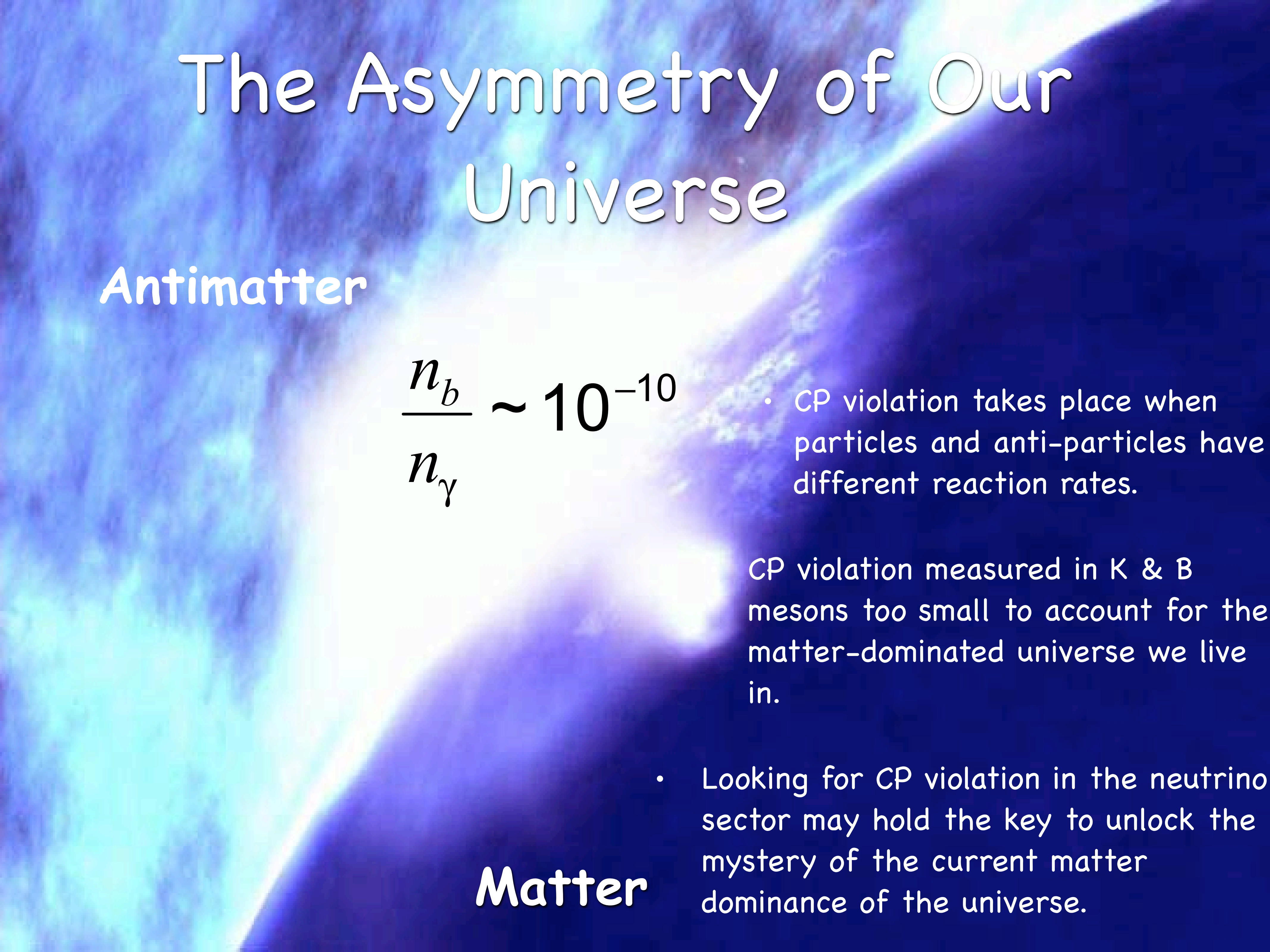
Double Beta Decay

Nature of neutrino mass measured

$\sum m_\nu < 200 - 700$ meV --> $m_\nu < 50$ meV



The Asymmetry of Our Universe



$$\frac{n_b}{n_\gamma} \sim 10^{-10}$$

- CP violation takes place when particles and anti-particles have different reaction rates.

CP violation measured in K & B mesons too small to account for the matter-dominated universe we live in.

- Looking for CP violation in the neutrino sector may hold the key to unlock the mystery of the current matter dominance of the universe.

The Asymmetry of Our Universe

- CP violation takes place when particles and anti-particles have different reaction rates.
- CP violation measured in K & B mesons too small to account for the matter-dominated universe we live in.
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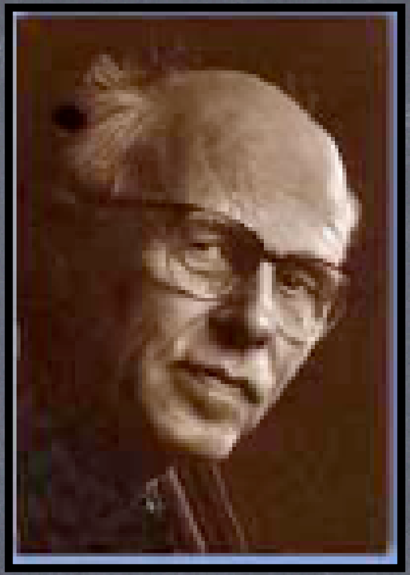
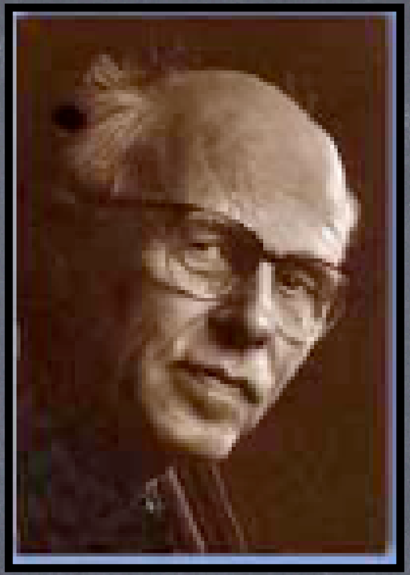
Matter

Sahkarov's Three Conditions:



1. Violation of baryon number
2. Violation of discrete symmetry C and CP
3. Departure from thermal equilibrium

Sahkarov's Three Conditions:



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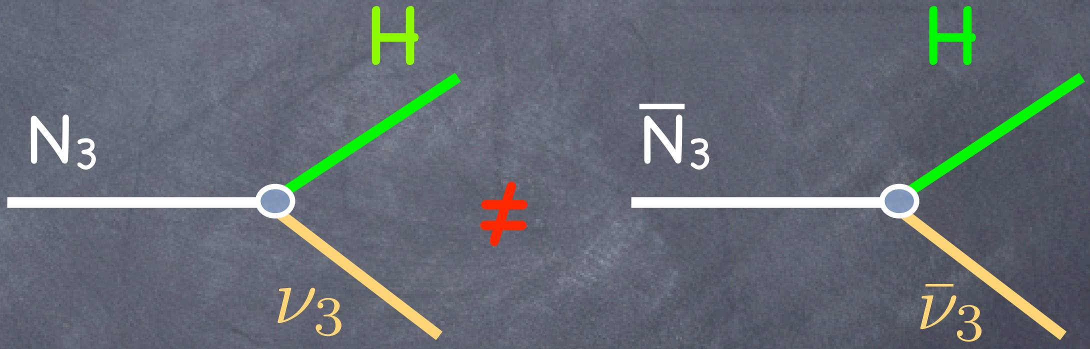
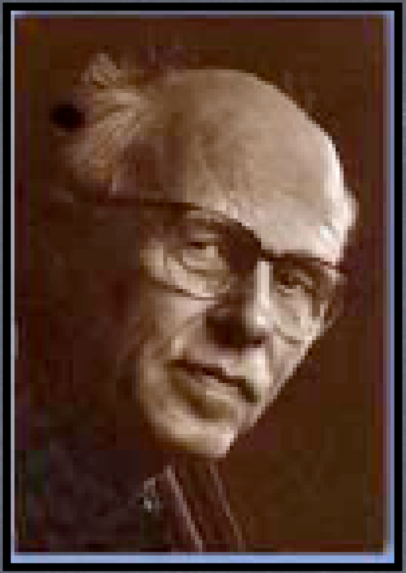


Anomolous decay of heavy Majorana neutrino;

Violates (B,L) but not B-L

Baryon number asymmetry

Sahkarov's Three Conditions:

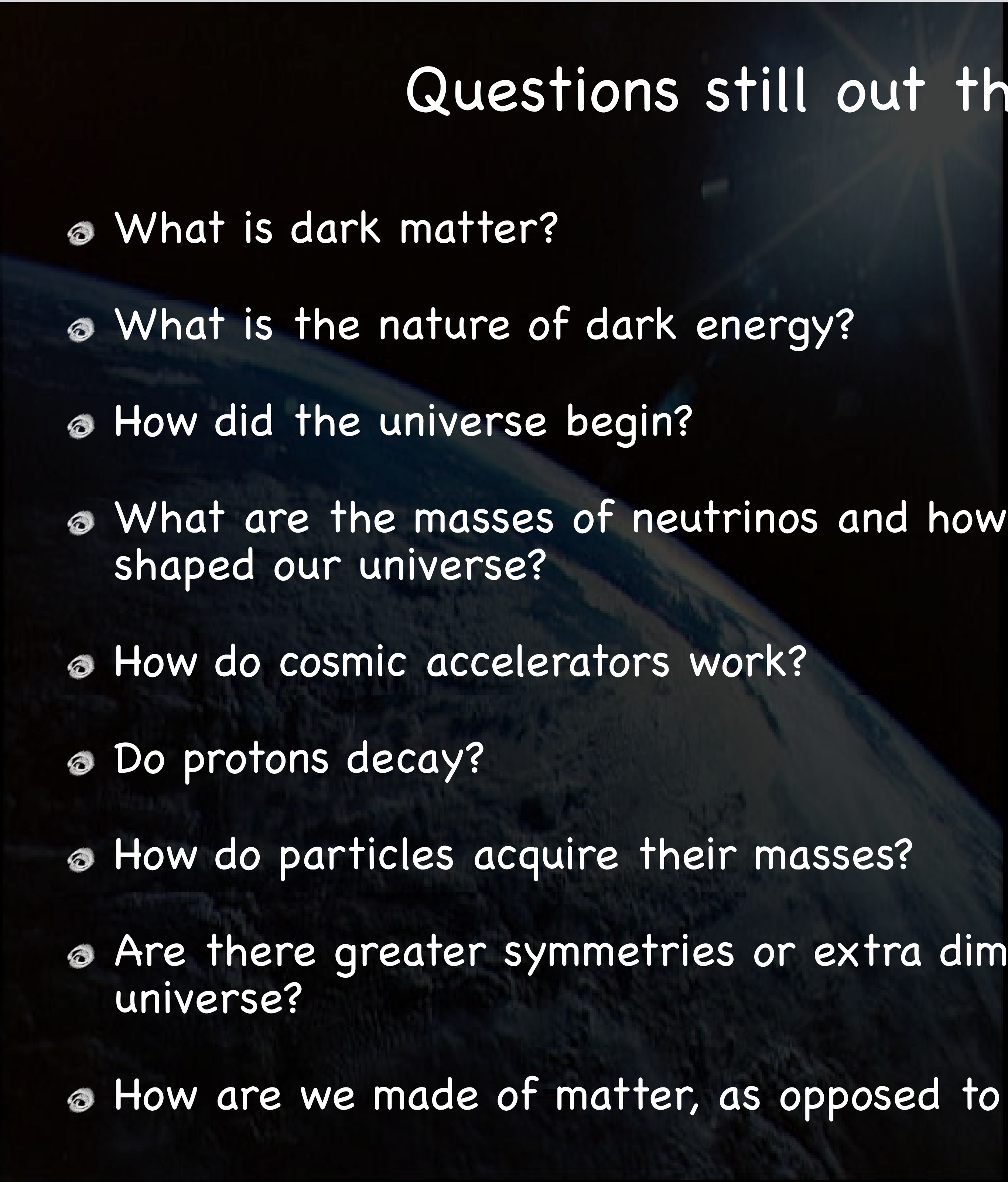


1. Violation of baryon number
2. Violation of discrete symmetry C and CP
3. Departure from thermal equilibrium

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

CP violation seen in baryon sector, but insufficient;
Neutrinos can also violate CP;
Need q_{13} to be non-zero.

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$



Questions still out there...

- What is dark matter?
- What is the nature of dark energy?
- How did the universe begin?
- What are the masses of neutrinos and how have they shaped our universe?
- How do cosmic accelerators work?
- Do protons decay?
- How do particles acquire their masses?
- Are there greater symmetries or extra dimensions in our universe?
- How are we made of matter, as opposed to anti-matter?

Questions still out there...

🟨	Involves underground physics
🟪	Involves neutrinos & underground physics

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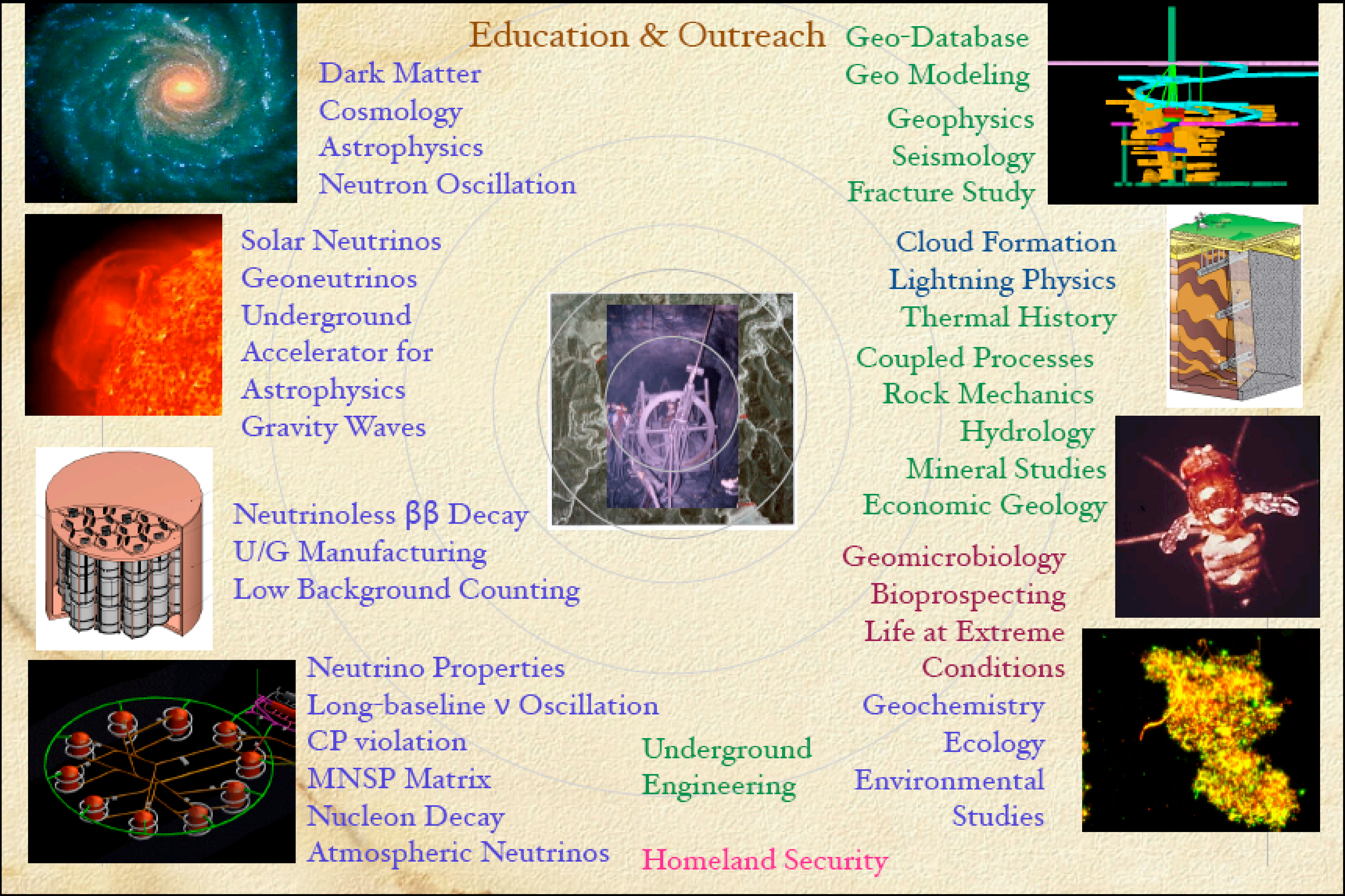
Underground Physics



Education & Outreach

Dark Matter
Cosmology
Astrophysics
Neutron Oscillation

Geo-Database
Geo Modeling
Geophysics
Seismology
Fracture Study

Solar Neutrinos
Geoneutrinos
Underground
Accelerator for
Astrophysics
Gravity Waves

Cloud Formation
Lightning Physics
Thermal History
Coupled Processes
Rock Mechanics
Hydrology
Mineral Studies
Economic Geology

Neutrinoless ββ Decay
U/G Manufacturing
Low Background Counting

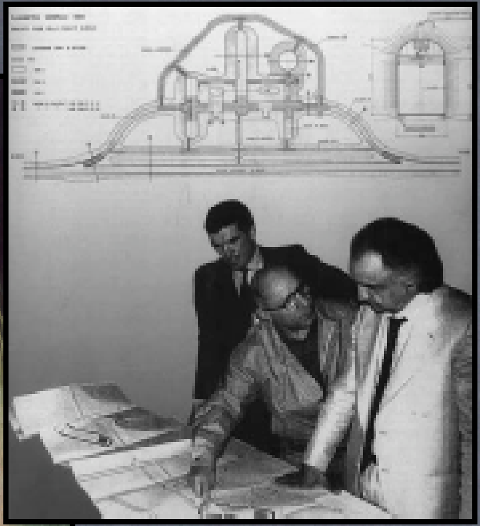
Geomicrobiology
Bioprospecting
Life at Extreme
Conditions
Geochemistry
Ecology
Environmental
Studies

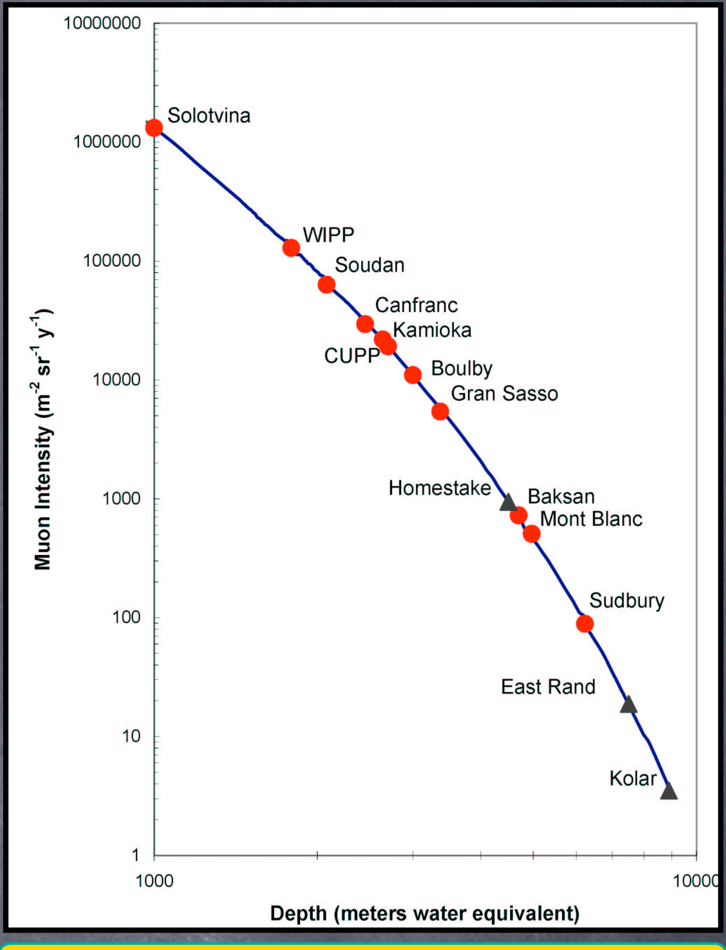
Neutrino Properties
Long-baseline ν Oscillation
CP violation
MNSP Matrix
Nucleon Decay
Atmospheric Neutrinos

Underground
Engineering

Homeland Security

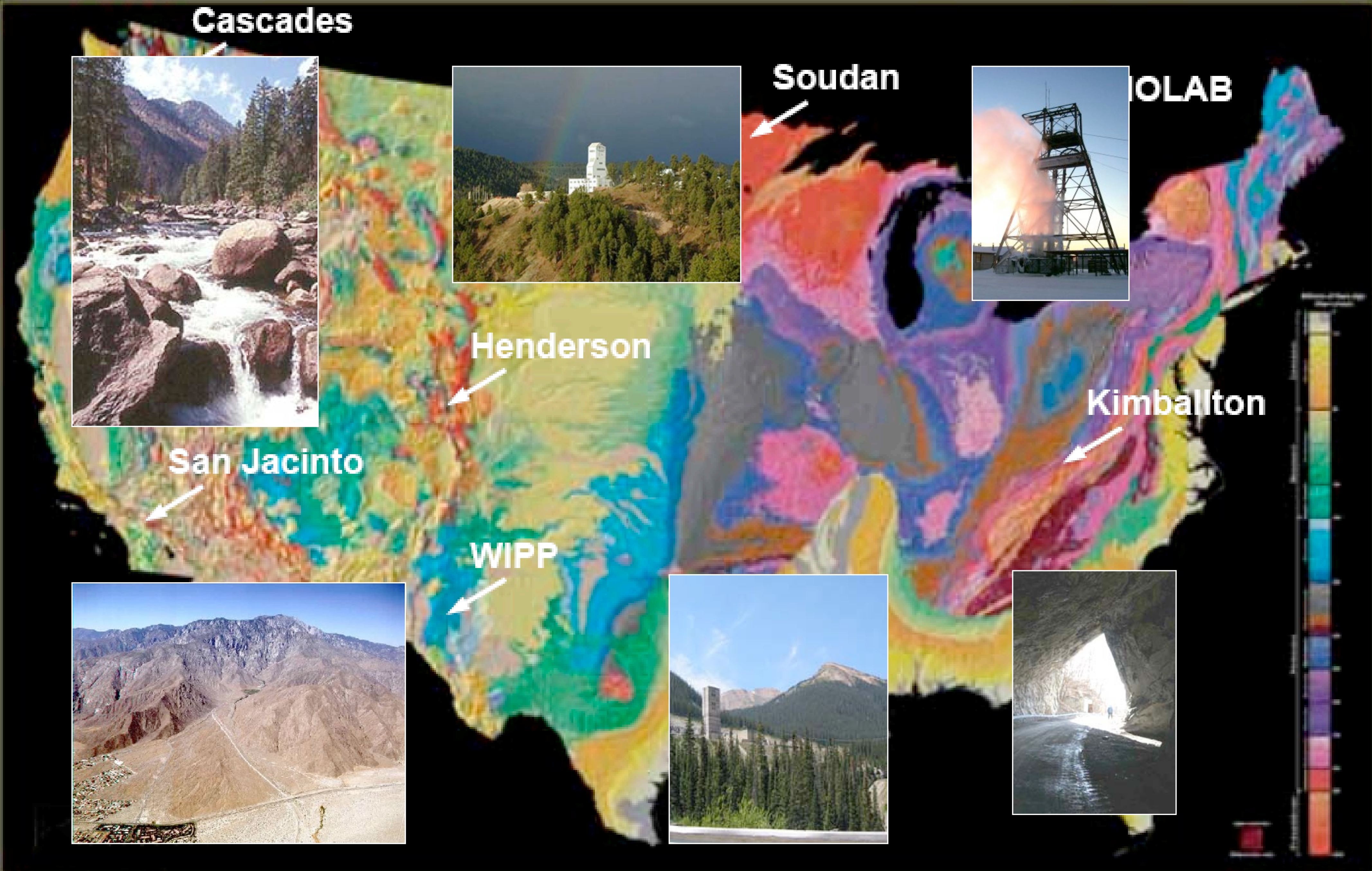
(Coutersy, Kevin Lesko)





Vertical muon flux as function of depth.

…The Future


Cascades
Soudan
OLAB
Henderson
Kimballton
San Jacinto
WIPP

Strategy for Future Experiments

- “Bigger is better…”
  - More massive targets, enriched materials”
- “Keep it clean…”
  - Extremely clean materials and environments
- “Keep it deep…”
  - Filter out cosmic rays as much as possible
- “Redundancy is key…”
  - Using different techniques and target materials to ensure a true signal.

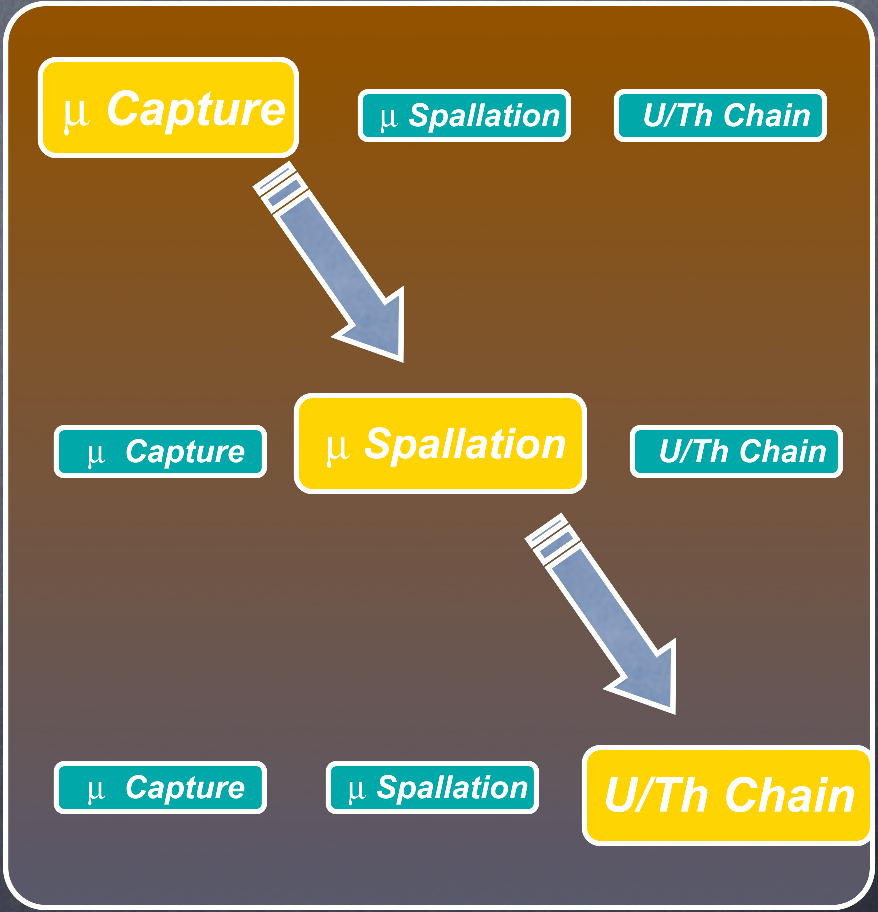
“(Come in under the shadow of this red rock),
And I will show you something different from either
Your shadow at morning striding behind you
Or your shadow at evening rising to meet you;
I will show you fear in a handful of dust.”

--T.S. Eliot, The WasteLand

Worrying about Backgrounds...

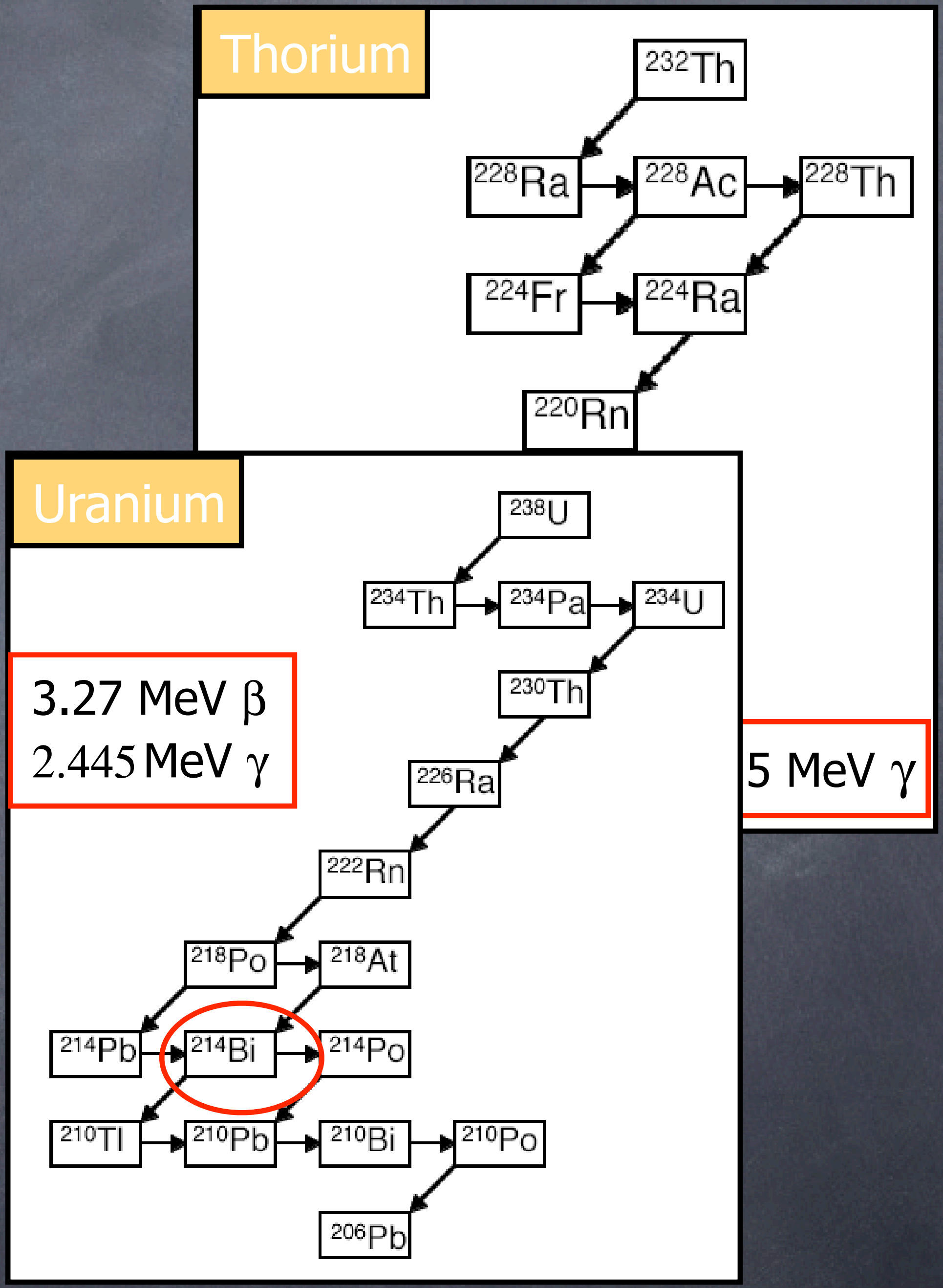
- Typically, shallow depth enables you to escape the nucleonic background from cosmic rays.
- Beyond 350 meters water equivalent (mwe), the background that dominates depends on the depth of the experiment.
- If we take neutrons, for example (important for dark matter) muon capture dominates at shallow depths, then muon spallation, then U/Th.
- Bottom line: choose your depth wisely (usually, deeper is better)

What Dominates?



Radioactive Backgrounds

- Most abundant radio-elements to worry about are ^{238}U, ^{232}Th, and ^{40}K.
- For deep underground facilities, often the main source of background for experiments.
- Contributes to both photon and the alpha/neutron background in the detector.
- Natural concentrations in surrounding environment, as well as detector materials.
- A problem for all experiments, regardless of depth.



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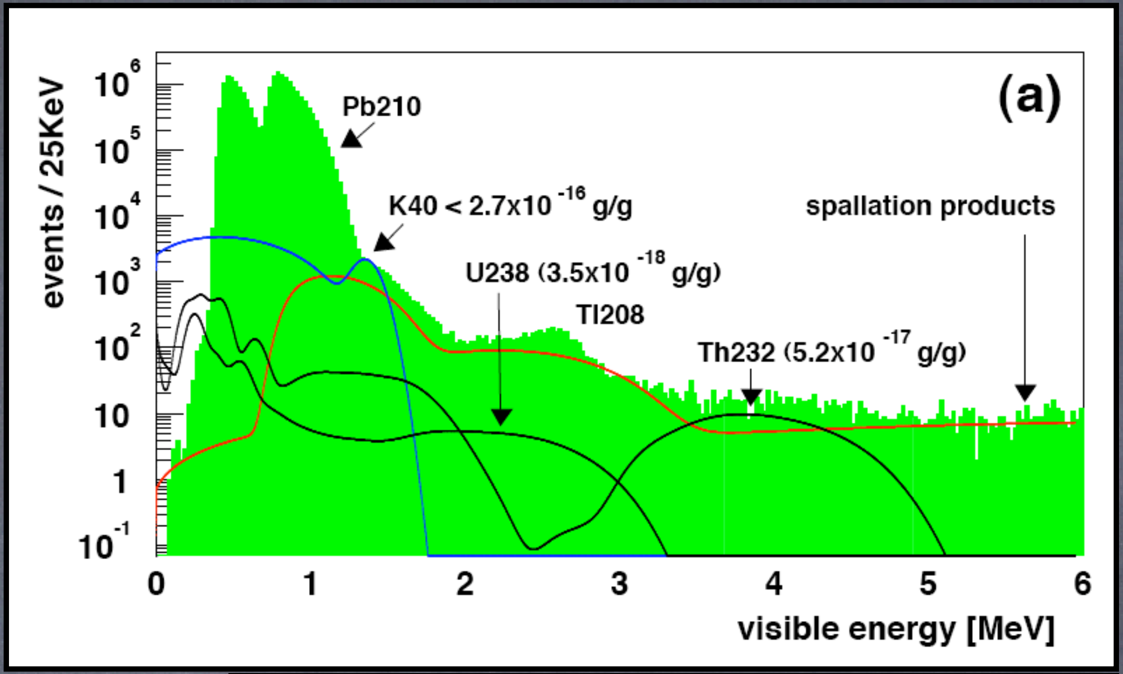
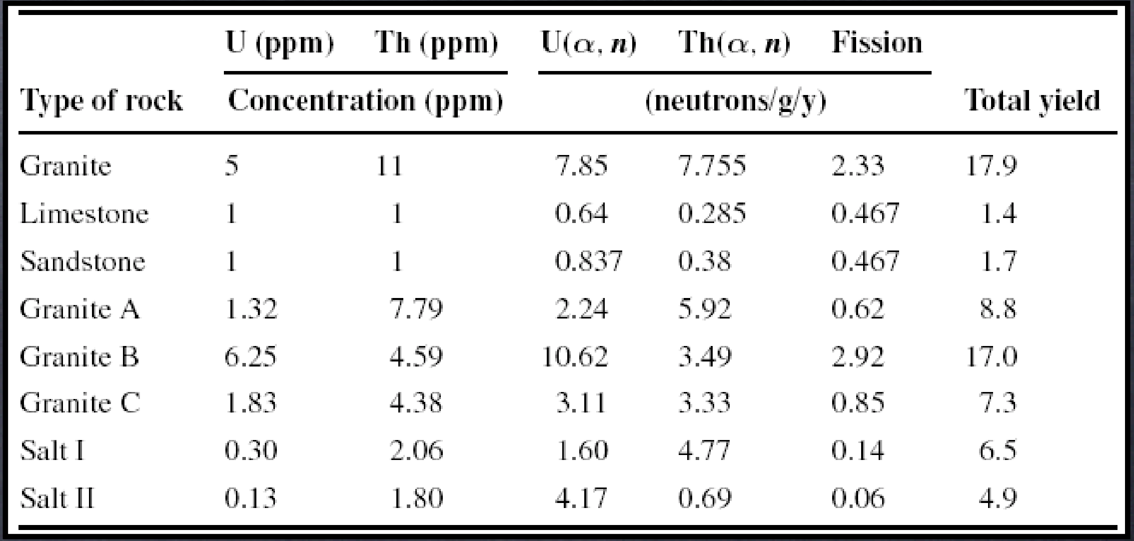


U/Th from Scintillator (KamLAND)

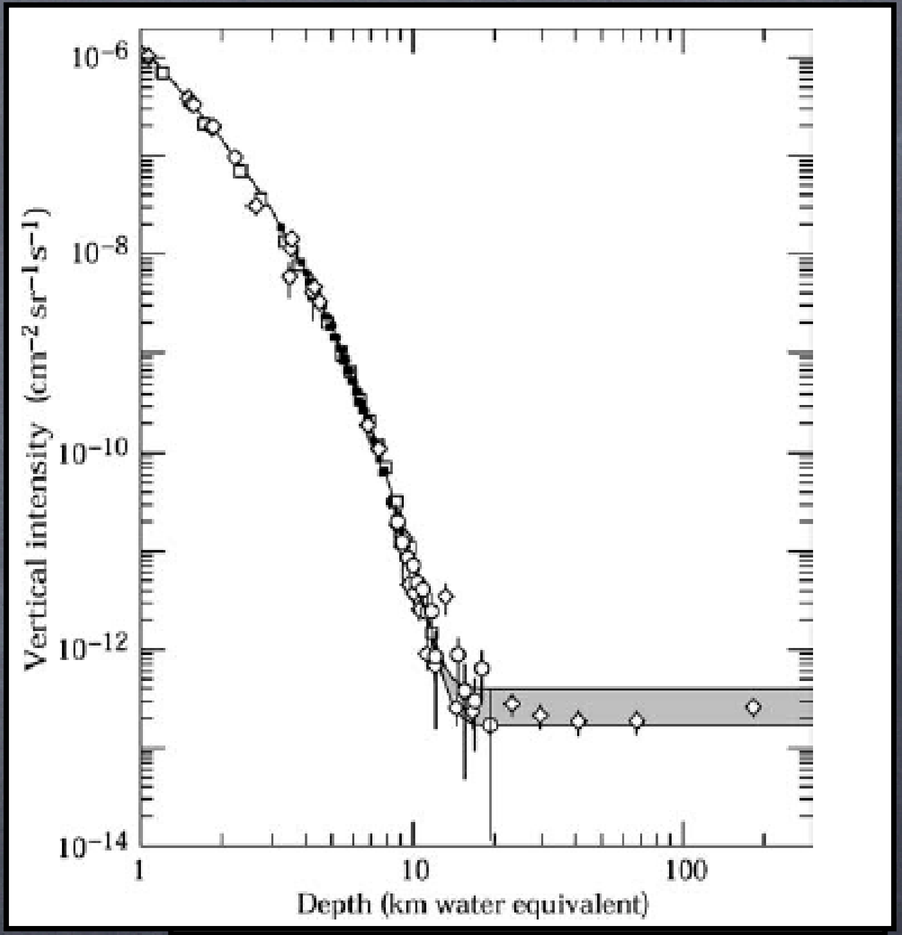
U/Th from Rock



Type of rock	U (ppm)	Th (ppm)	U(α, n)	Th(α, n)	Fission	Total yield
	Concentration (ppm)		(neutrons/g/y)			
Granite	5	11	7.85	7.755	2.33	17.9
Limestone	1	1	0.64	0.285	0.467	1.4
Sandstone	1	1	0.837	0.38	0.467	1.7
Granite A	1.32	7.79	2.24	5.92	0.62	8.8
Granite B	6.25	4.59	10.62	3.49	2.92	17.0
Granite C	1.83	4.38	3.11	3.33	0.85	7.3
Salt I	0.30	2.06	1.60	4.77	0.14	6.5
Salt II	0.13	1.80	4.17	0.69	0.06	4.9

Cosmic Ray Flux

- Once below ~30 mwe, cosmic ray flux is dominated primarily by muons.
- For muons that reach deep sites, the LVD parameterization works well to determine incoming rate and spectrum.
- Well measured by existing underground experiments.



Hagiwara K, et al. Phys. Rev.D66:010001(2002)

$$\frac{dN_\mu}{dE_\mu d\Omega} \cong 0.14 E_\mu^{-(\gamma-1)} \left\{ \left(1 + \frac{1.1 E_\mu \cos(\theta)}{115\mathrm{GeV}} \right)^{-1} + 0.054 \left(1 + \frac{1.1 E_\mu \cos(\theta)}{850\mathrm{GeV}} \right)^{-1} \right\} cm^{-2} s^{-1} sr^{-1} \mathrm{GeV}^{-1}$$

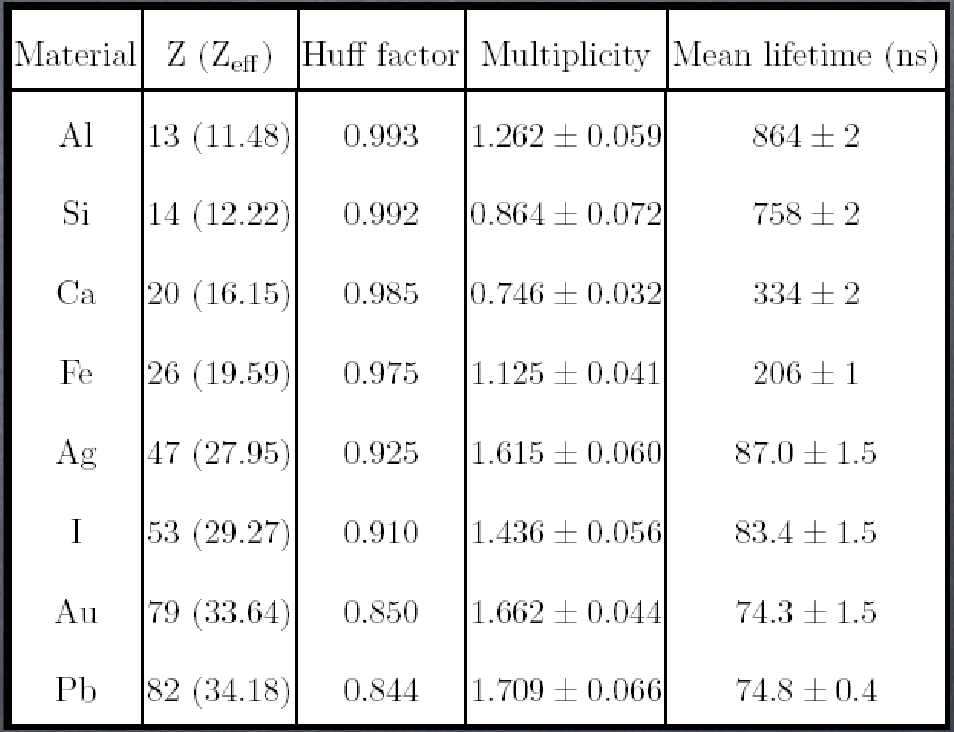
Muon Capture

- Source of neutron production, typically dominant at shallow depths.

$\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z-1, N+1)$

- One or more neutrons typically produced, depending on target material.

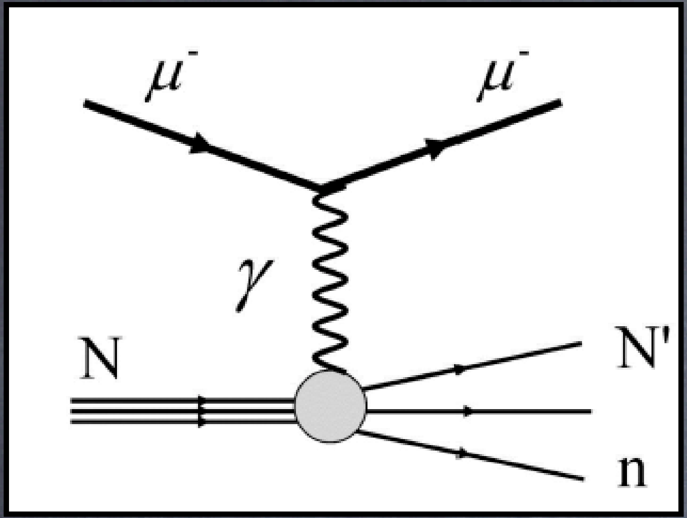
$$\Gamma_c(A,Z) = Z_{\text{eff}}^4 X_1 \left(1 - X_2 \frac{A-Z}{2A}\right)$$



Material	Z (Z_{eff})	Huff factor	Multiplicity	Mean lifetime (ns)
Al	13 (11.48)	0.993	1.262 ± 0.059	864 ± 2
Si	14 (12.22)	0.992	0.864 ± 0.072	758 ± 2
Ca	20 (16.15)	0.985	0.746 ± 0.032	334 ± 2
Fe	26 (19.59)	0.975	1.125 ± 0.041	206 ± 1
Ag	47 (27.95)	0.925	1.615 ± 0.060	87.0 ± 1.5
I	53 (29.27)	0.910	1.436 ± 0.056	83.4 ± 1.5
Au	79 (33.64)	0.850	1.662 ± 0.044	74.3 ± 1.5
Pb	82 (34.18)	0.844	1.709 ± 0.066	74.8 ± 0.4

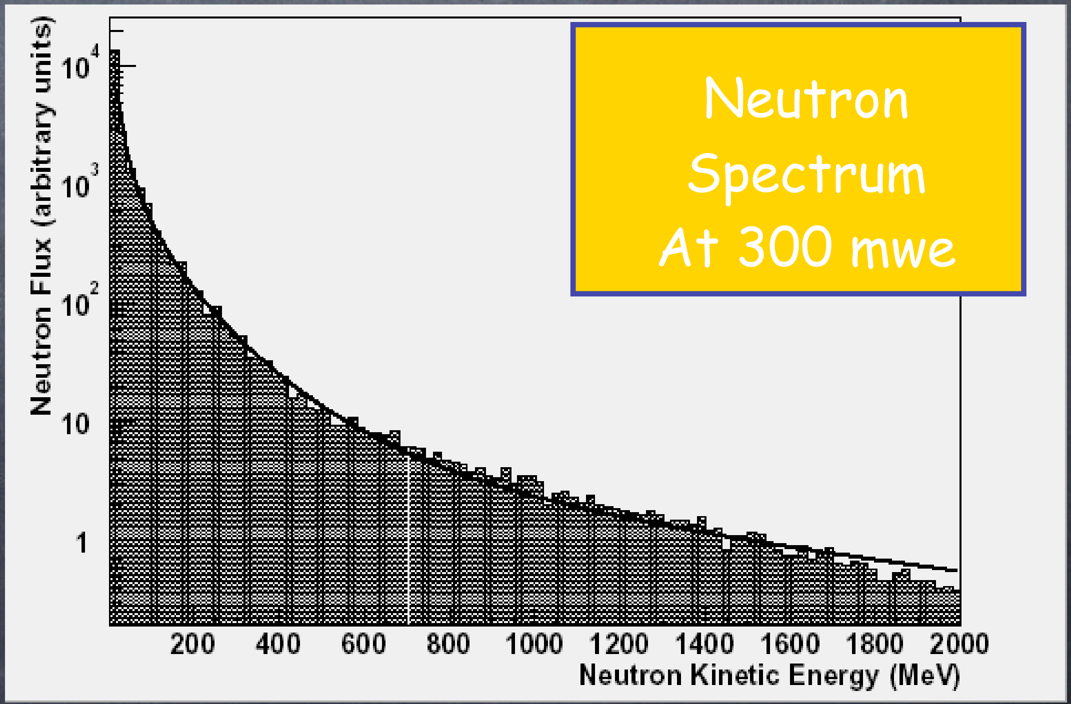
Suzuki T, et al.
Phys. Rev. C 35: 2212 (1989)

Muon Spallation



$$\sigma_{\mu N} = \int \frac{n_\gamma(\nu)\sigma_{\gamma N}(\nu)}{\nu} d\nu.$$

- Actually, a complex process, since a number of physics processes are at play:
  - Virtual photon exchange.
  - Secondary production from particle showers.
  - Electromagnetic interactions.



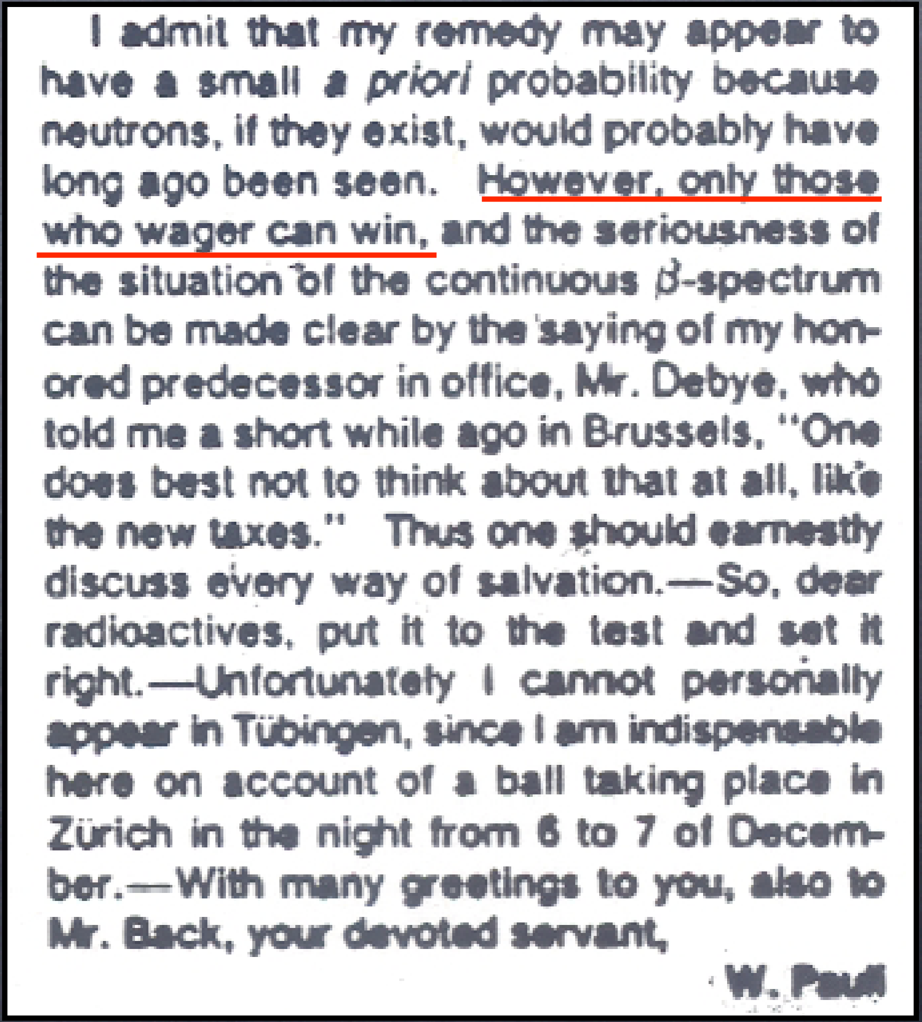
Neutron Spectrum At 300 mwe

Books of Note:

- For Neutrino Physics and Neutrino Mass:
  - “Particle Physics and Cosmology”, by P.D.B. Collins, A.D. Martin, and E.J. Squires.
  - “The Physics of Massive Neutrinos,” (two books by the same title, B. Kayser and P. Vogel,F. Boehm
  - “Los Alamos Science: Celebrating the Neutrino”, a good 1st year into into neutrinos, albeit a bit outdated now.
  - “Massive Neutrinos in Physics and Astrophysics,” Mohapatra and Pal.
- For Underground Science:
  - G. Heusser, “Low-Radioactivity Background Techniques”, Ann. Rev. Nucl. Part. Sci. 1995, 45, 543-590.
  - J. Formaggio and C. J. Martoff, “Backgrounds to Sensitive Experiments Underground”, Ann. Rev. Nucl. Part. Sci. 1995, 54, 361 (2004).
  - “Measurements of Weak Radioactivity”, by Pall Theodorsson.

Parting Words...

Wolfgang Pauli



I admit that my remedy may appear to have a small *a priori* probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous β-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, who told me a short while ago in Brussels, "One does best not to think about that at all, like the new taxes." Thus one should earnestly discuss every way of salvation.—So, dear radioactives, put it to the test and set it right.—Unfortunately I cannot personally appear in Tübingen, since I am indispensable here on account of a ball taking place in Zürich in the night from 6 to 7 of December.—With many greetings to you, also to Mr. Back, your devoted servant,

W. Pauli

Wolfgang Pauli

Wager... Win.