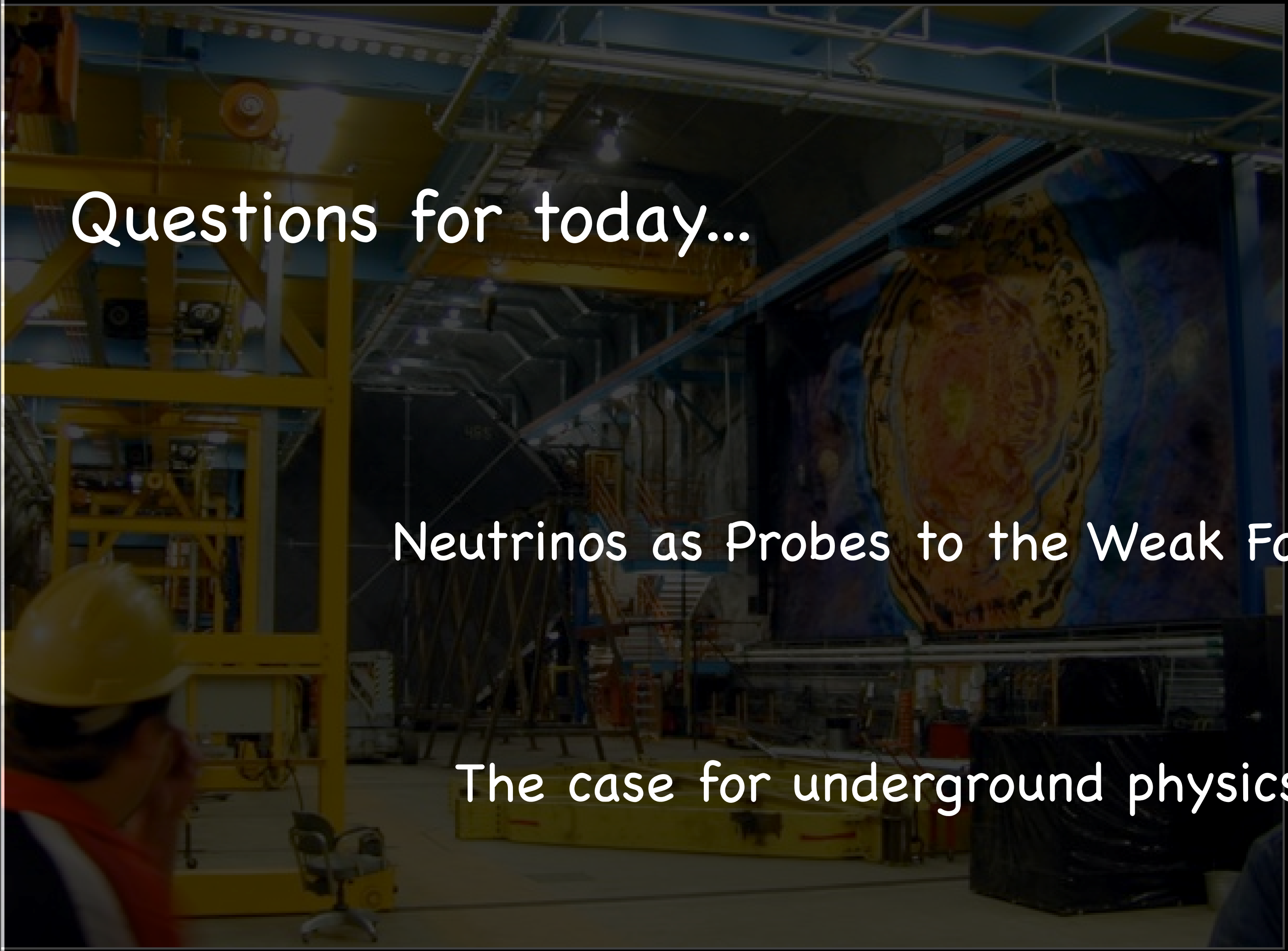
The Neutrino World

Topics in Nuclear Physics
8.712

Lecture 2 : Neutrino detection techniques

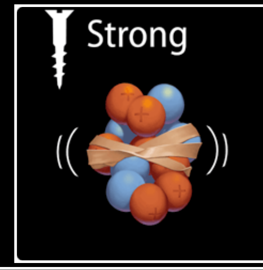


Questions for today...

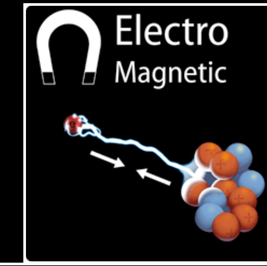
Neutrinos as Probes to the Weak Force

The case for underground physics.

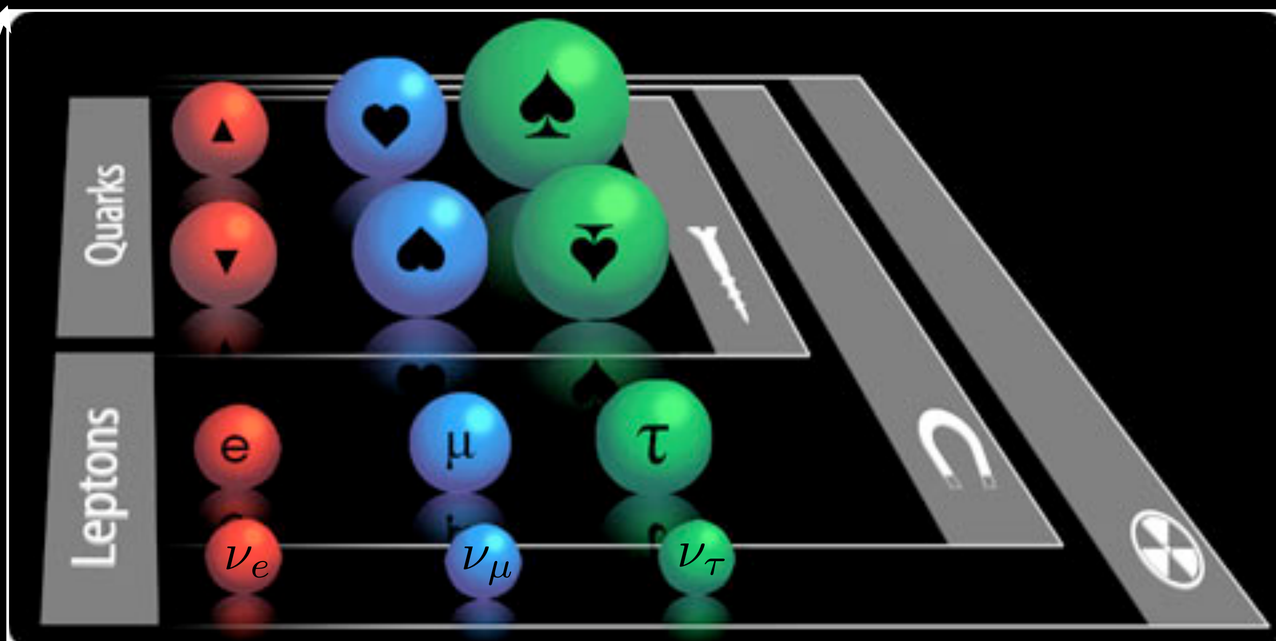
Within the Framework



Binds nucleii;
mediated by gluons;
only couples to quarks



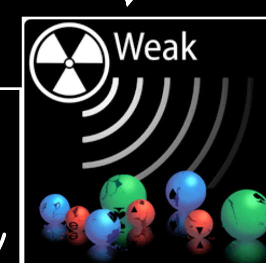
Couples to charge;
mediated by photons;
felt by quarks and leptons



Spin 1

Spin 1/2

Common to all particles;
mediated by the $W^{\pm}/Z^0$ bosons;
Neutrinos can only interact weakly



The Weak Force

- Fermi got it almost right, describing the weak force as a 4-point interaction.

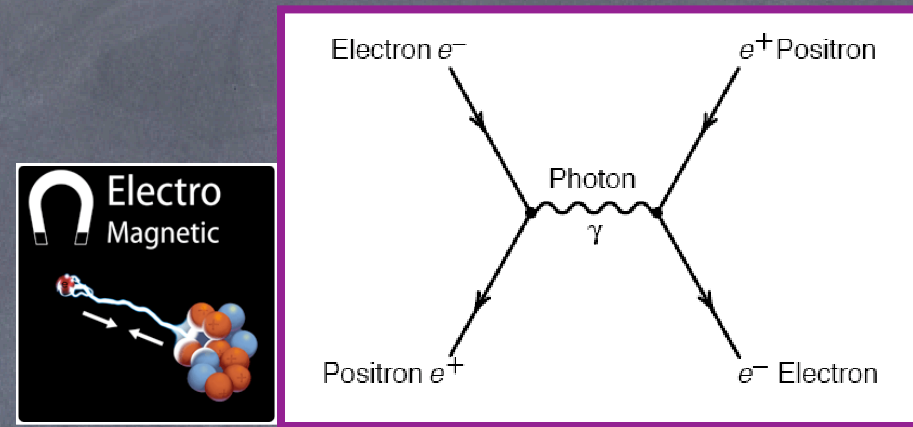
- Mediated through a heavy spin-1 boson ($W^{\pm}$,Z^0)

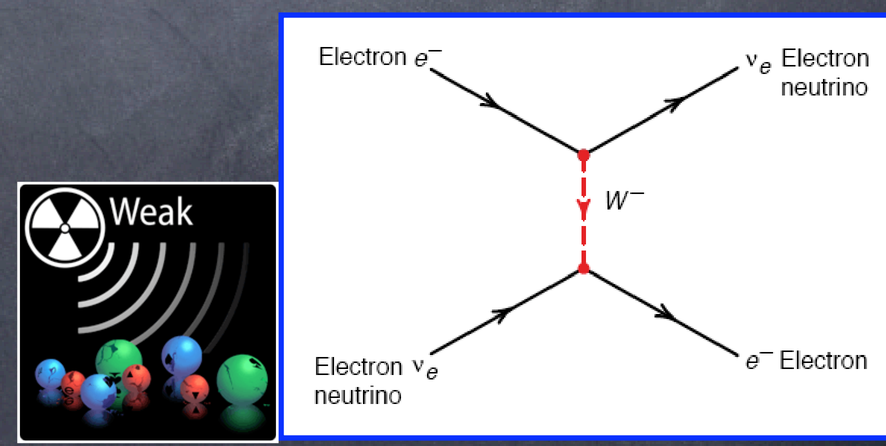
  Mass of $W^{\pm}$: 80.425 GeV/c^2

  Mass of Z^0: 91.188 GeV/c^2

- The boson mass is so large that it acts like a point-like exchange.

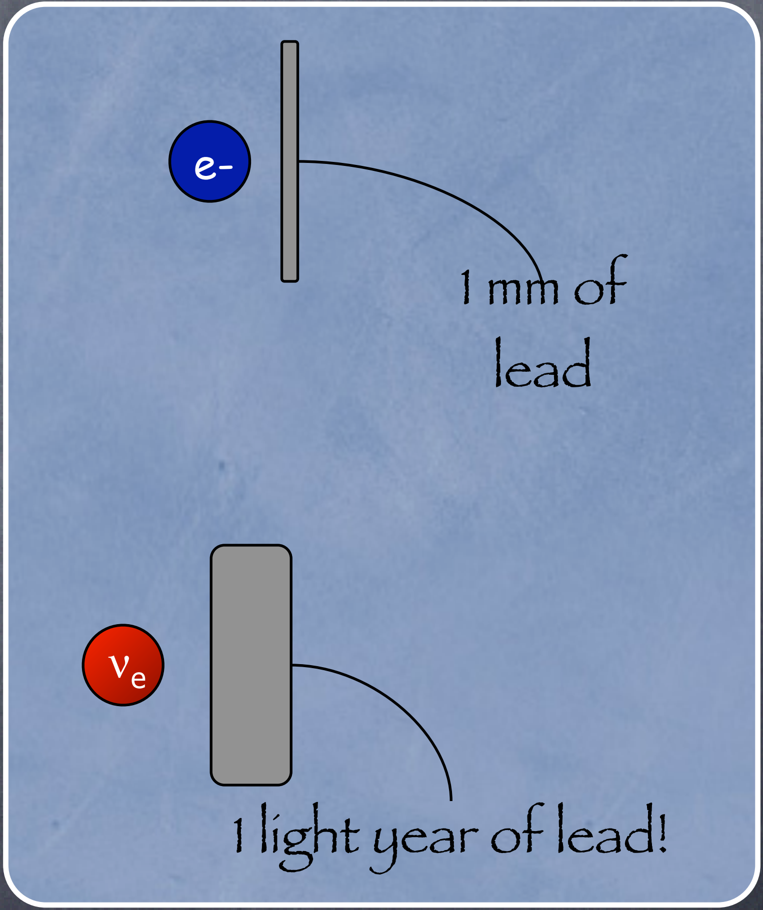
- Responsible for most of the radioactivity around our world.





They are not very social...

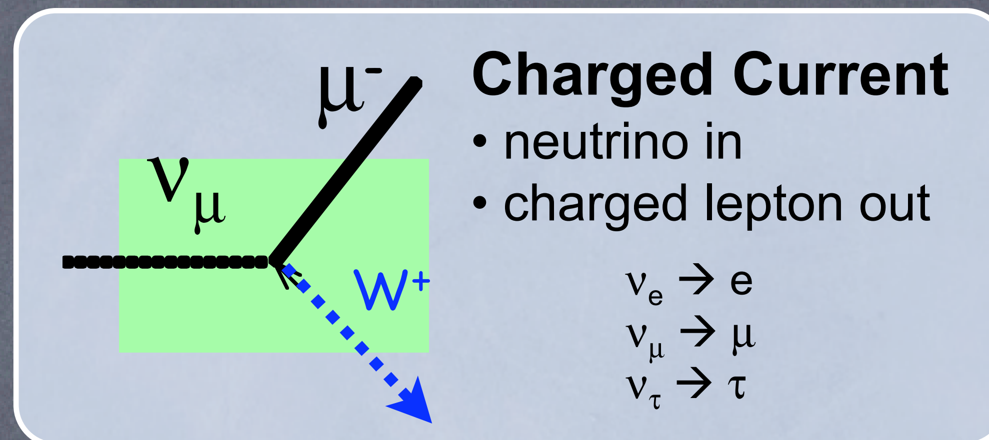
- They have no charge...
- They do not interact with quarks (because they are leptons)...
- In fact, they don't interact with much of anything (there are about ~1 million going through you every second, and they just pass by!)



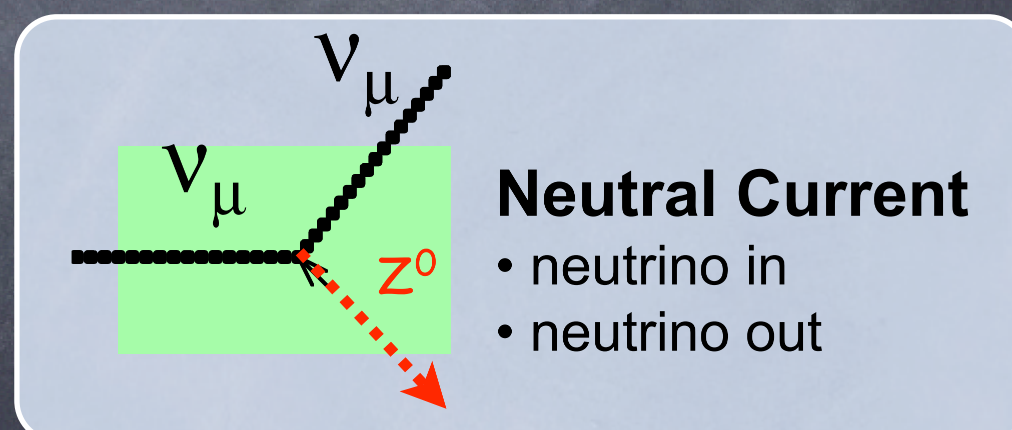
Note: Picture not to scale!

Two ways to interact...

- Charged current interactions allow us to tag the associated lepton.
- Neutral current interactions only leave a neutrino, but also deposit energy on their target.



Example of bubble chamber picture of neutral current event

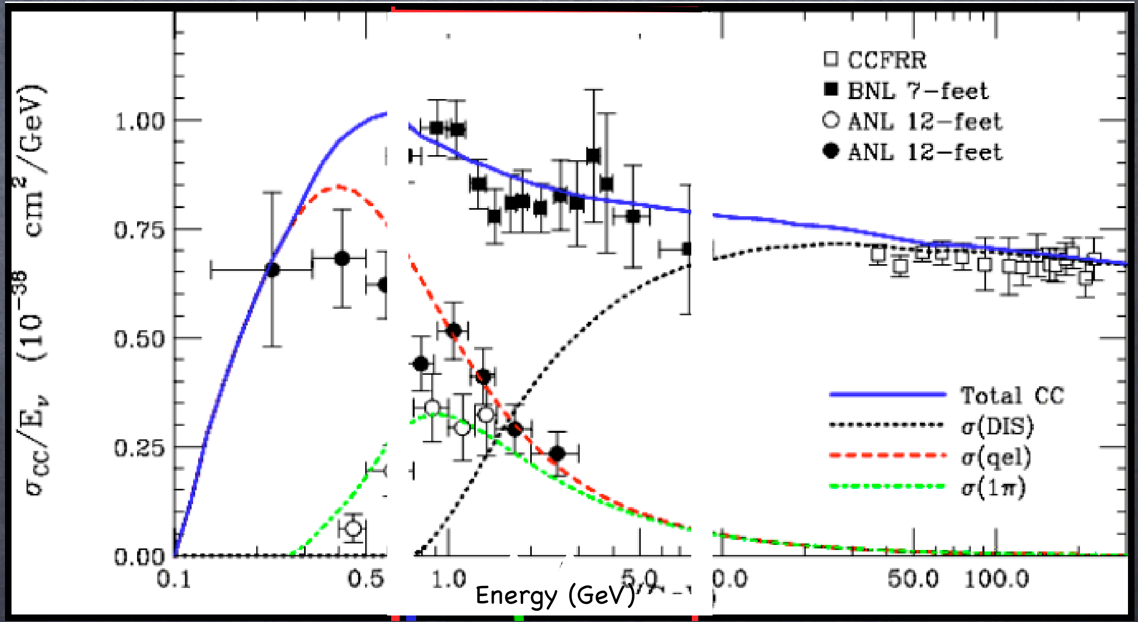


So, what happens when a neutrino does interact?

Elastic Scattering

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

- Experimental tag is single energetic electron.
- Reaction involves both charged current and neutral exchanges.
- Excellent probe into the nature of the weak current.



Neutrino cross-section as a function of energy.

So, what happens when a neutrino does interact?

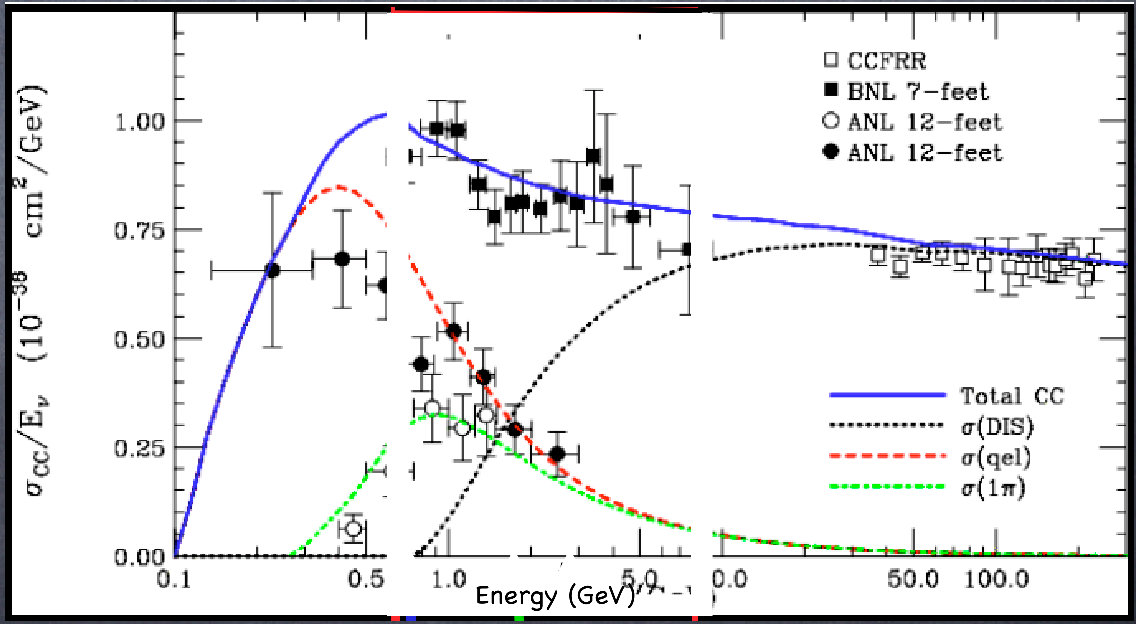
Quasi-Elastic Scattering

$$\nu_l + N \rightarrow l + N'$$

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 M_p^2}{8\pi E_\nu^2}\{A(Q^2) \mp B(Q^2)\frac{(s-u)}{M_p^2} + C(Q^2)\frac{(s-u)^2}{M_p^4}\}$$

$$(s-u) = 4M_pE_\nu - Q^2$$

- Experimental tag is lepton + proton or neutron.
- Reaction changes protons into neutrons (and vice versa).
- Dominates below 1 GeV



Neutrino cross-section as a function of energy.

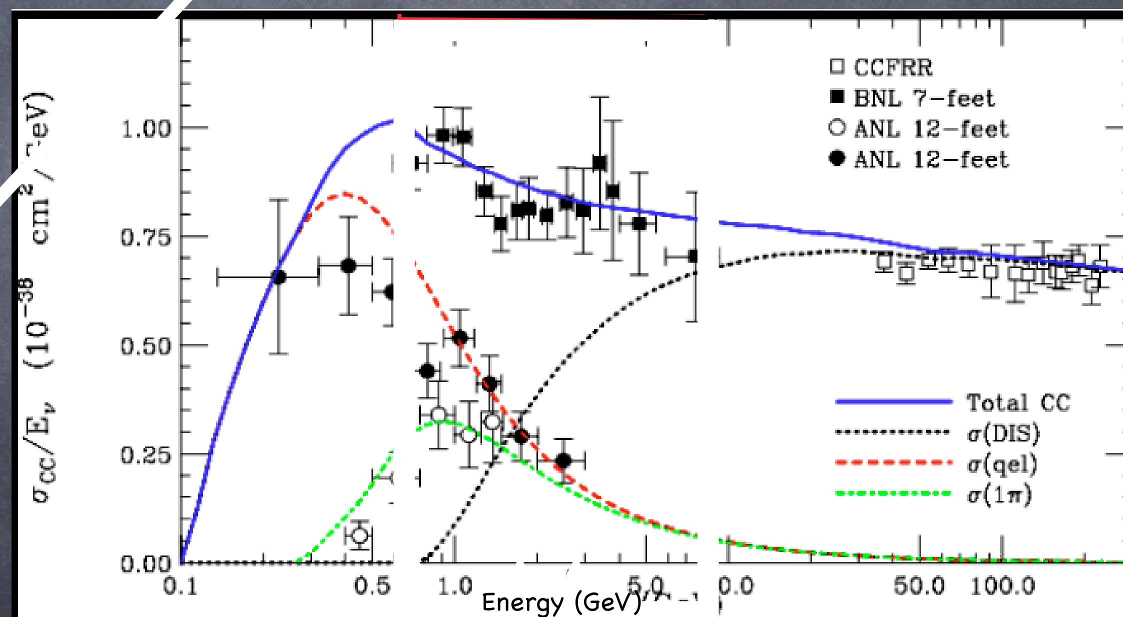
So, what happens when a neutrino does interact?

Pion Resonance

$$\nu_l + N \rightarrow l + N' + \pi$$

$$\nu_l + N \rightarrow \Delta^* + l \rightarrow l + N' + \pi$$

- Energetic enough to produce a delta resonance
- Reaction changes protons into neutrons (and vice versa).
- Dominates around 1 GeV; often a background for experiments



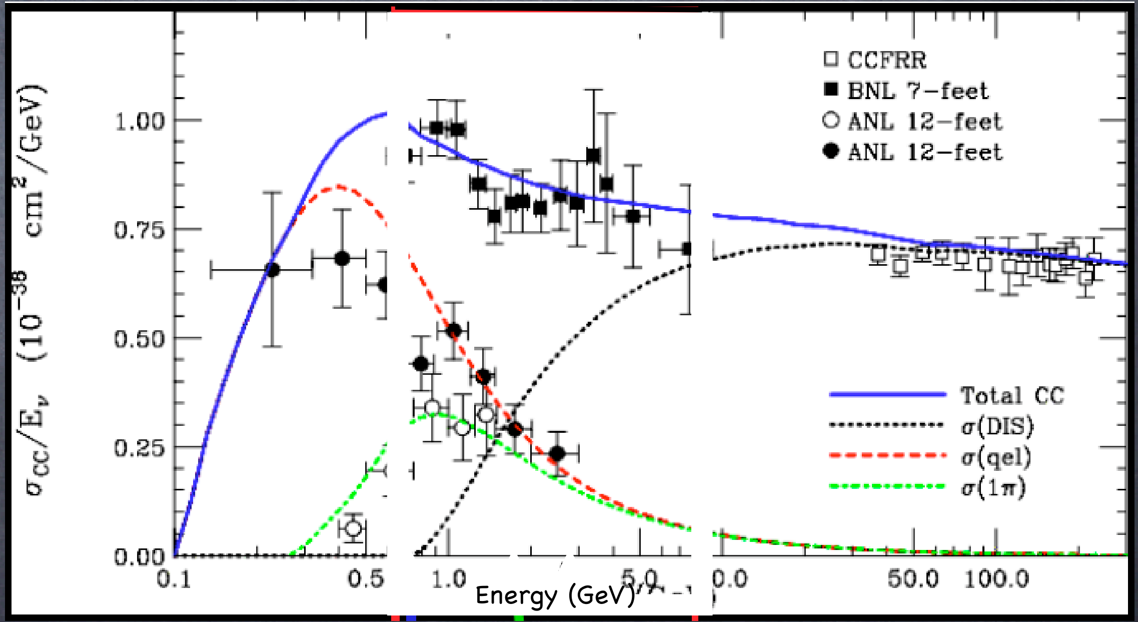
Neutrino cross-section as a function of energy.

So, what happens when a neutrino does interact?

Deep Inelastic (DIS)

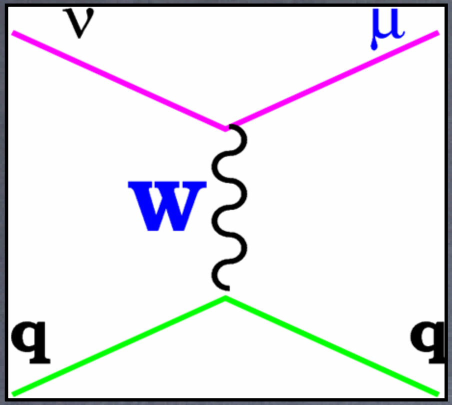
$$\nu_l + N \to l + X$$

- After a few GeV, the nucleus begins to break apart as the neutrino strikes it and many, many final states are produced.
- This is known as deep inelastic scattering (DIS).
- Probes the interior of the nucleus.

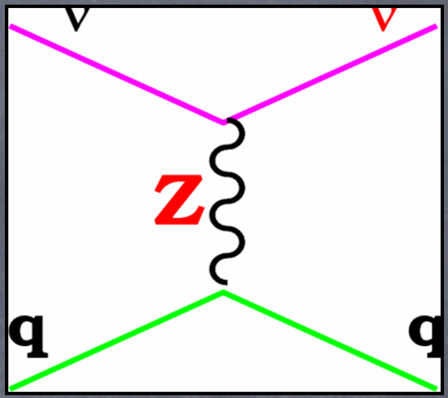


Neutrino cross-section as a function of energy.

Neutrinos as Weak Probes



Charged Current

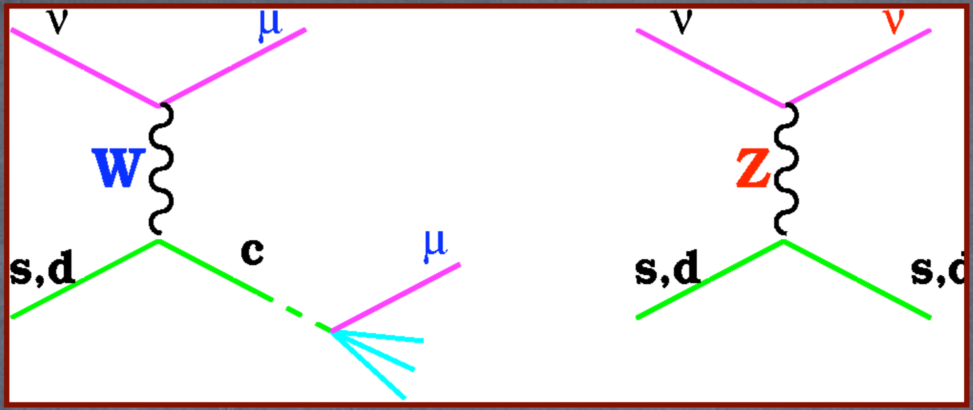


Neutral Current

Tests of the M_W/M_Z relation

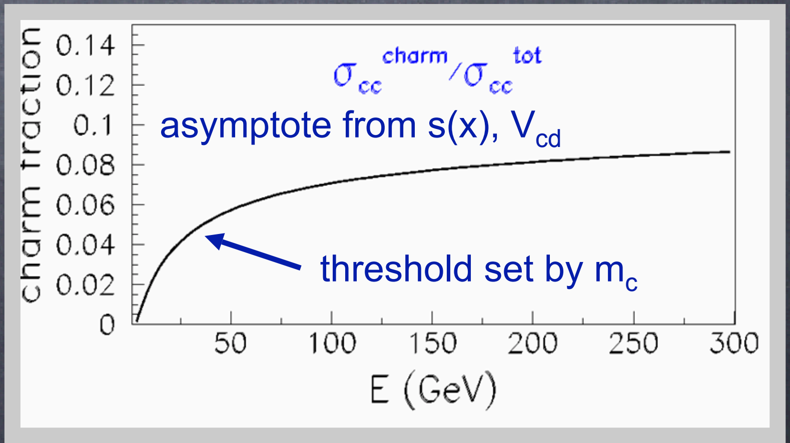
- It is possible to use neutrinos as direct probes of the predictions of the Standard Model (beyond questions of mass)
- Often looking at the difference between charged current and neutral current reactions.

The Effects of Charm

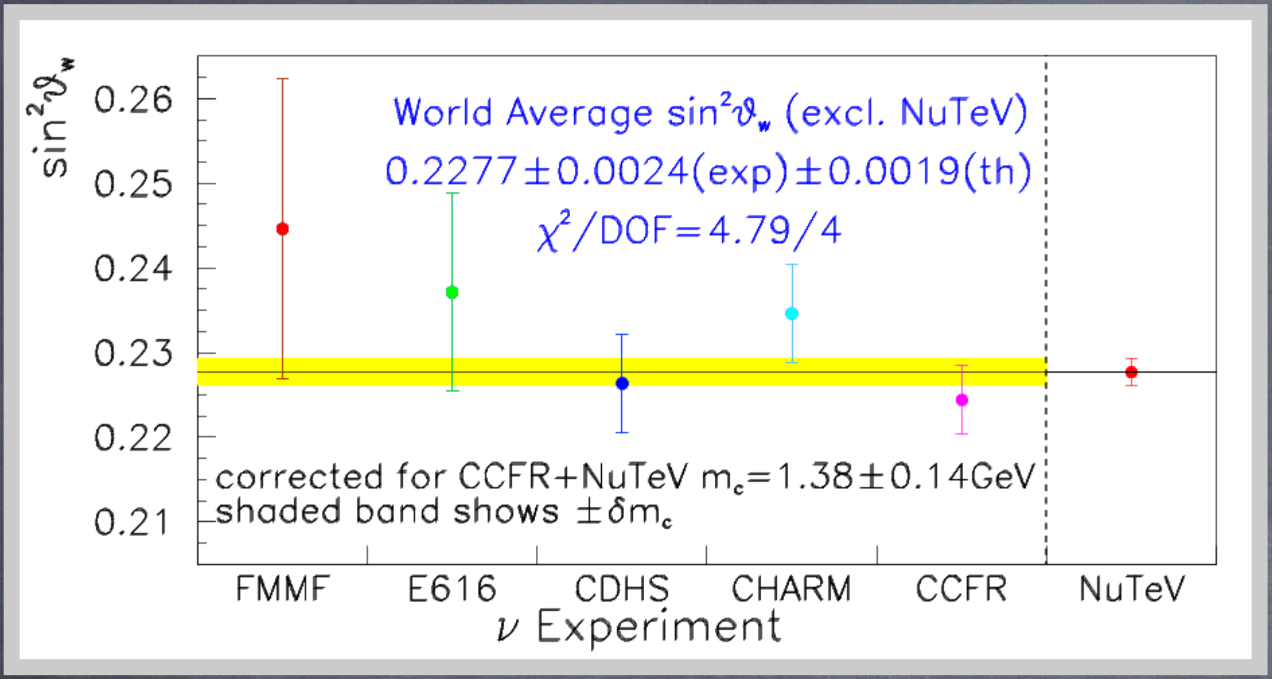


Depends on m_c and strange-sea portion of nucleus.

- The charm threshold has an energy dependence that influences the CC/NC ratio.
- Need something that gets away from this dependence

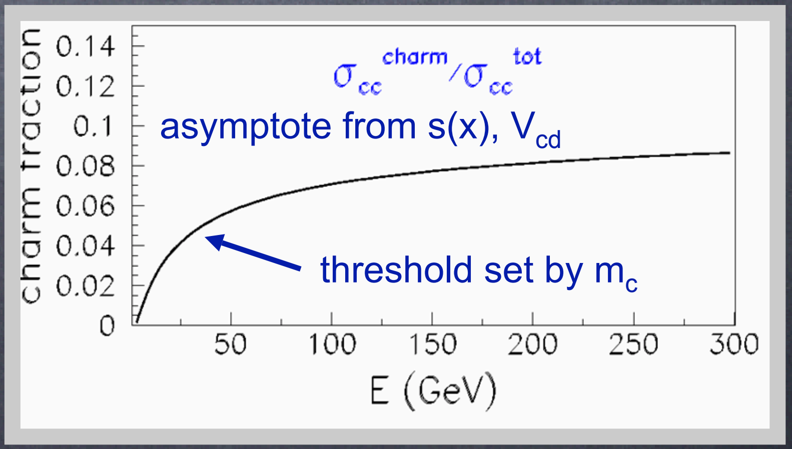


The Effects of Charm



$$\sin^2\theta_W^{on-shell} = 1 - \frac{M_W^2}{M_Z^2} = 0.2277 \pm 0.0036$$
$$\Rightarrow M_W = 80.14 \pm 0.19\ GeV$$

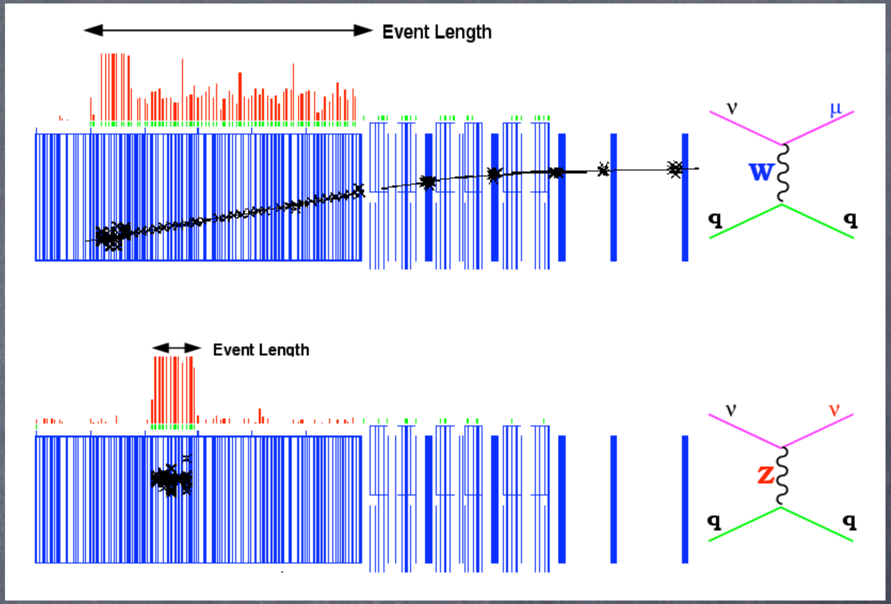
- The charm threshold has an energy dependence that influences the CC/NC ratio.
- Need something that gets away from this dependence



An Alternate Method

Paschos - Wolfenstein Relation

$$R^{-} = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}} = \rho^2 \left(\tfrac{1}{2} - \sin^2\theta_W\right) = g_L^2 - g_R^2$$



NuTeV CC/NC Separation

- By using a subtraction method, it is possible to remove all dependencies against strange-sea contributions (hence of the charm quark as well).
- The catch? You need a neutrino and an anti-neutrino beam.

$$\sigma\left(\nu_\mu\, d_{sea}\right) - \sigma\left(\bar{\nu}_\mu\, \bar{d}_{sea}\right) = 0 \quad \Rightarrow \quad \text{Only } d_{valence} \text{ contribute}$$

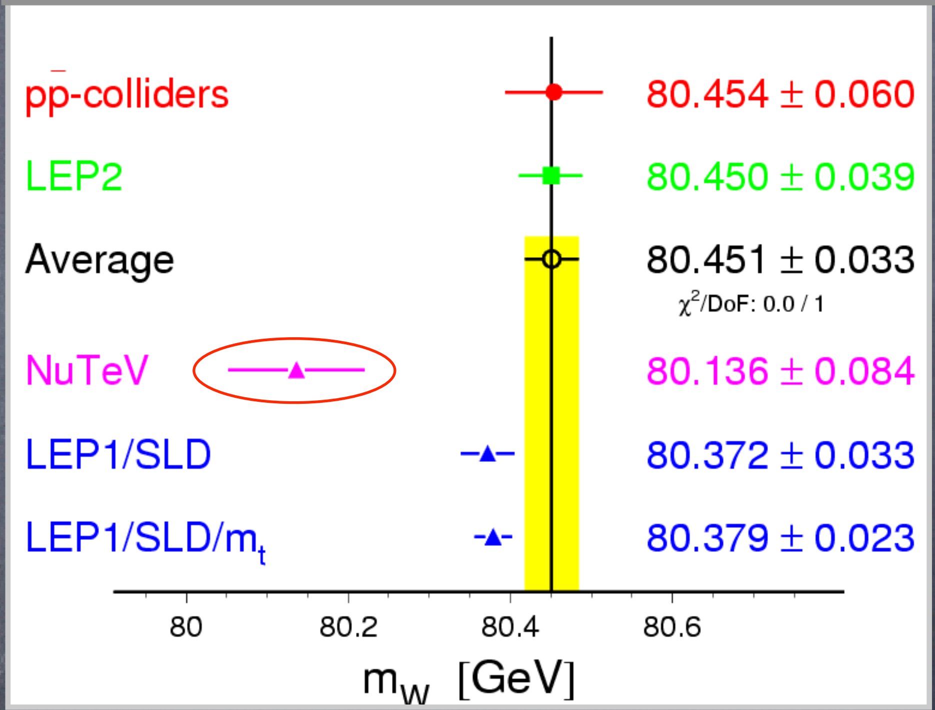
$$\sigma\left(\nu_\mu\, \bar{u}_{sea}\right) - \sigma\left(\bar{\nu}_\mu\, u_{sea}\right) = 0 \quad \Rightarrow \quad \text{Only } u_{valence} \text{ contribute}$$

$$\sigma\left(\nu_\mu\, s_{sea}\right) - \sigma\left(\bar{\nu}_\mu\, \bar{s}_{sea}\right) = 0 \quad \Rightarrow \quad \text{No } strange-sea \text{ contribution}$$

Precision Measurements Can Surprise You!

- NuTeV's measurement of the CC/NC ratio from neutrinos shows a 3-sigma shift from Standard Model predictions.
- Either a failure to understand the subtleties of the nucleus (strange-sea) or new physics.

Weak mixing angle measurement converted to M_W value "on-shell"



$$M_W = 80.136 \pm 0.084\ GeV$$

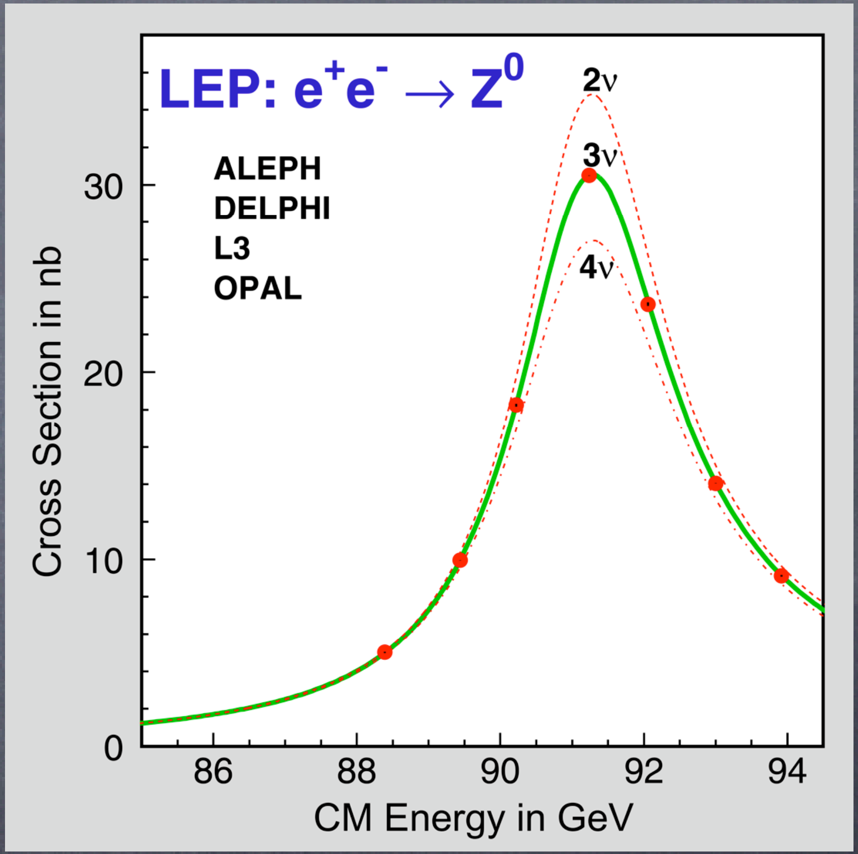
$$\textit{from} \quad \sin^2\theta_W^{(on-shell)} \equiv 1 - \frac{M_W^2}{M_Z^2}$$

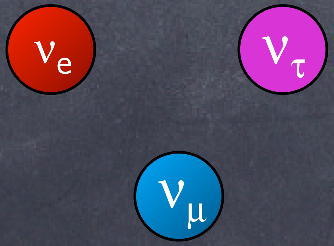
Other Standard Model Precision Tests

- Can look at "invisible" decays of Z^0 to determine the total number of ordinary, light neutrinos.

- Data from LEP experiments constrain number of neutrinos to...

$N = 2.984 \pm 0.008$





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?

And now for something completely different...

Questions still out there...

(orange)	Involves underground physics
(magenta)	Involves neutrinos & underground physics

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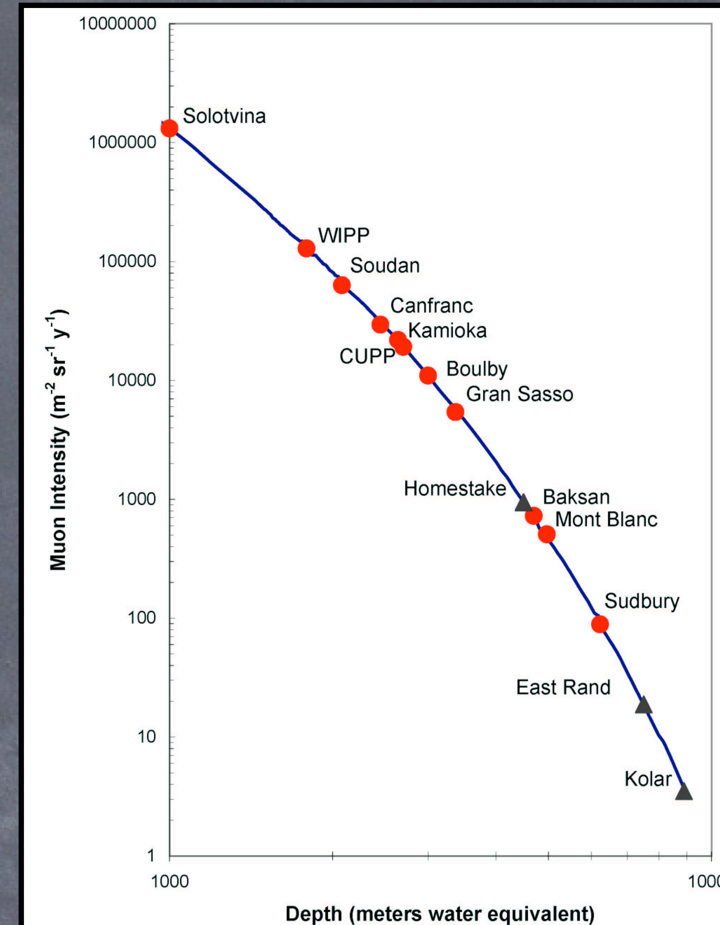
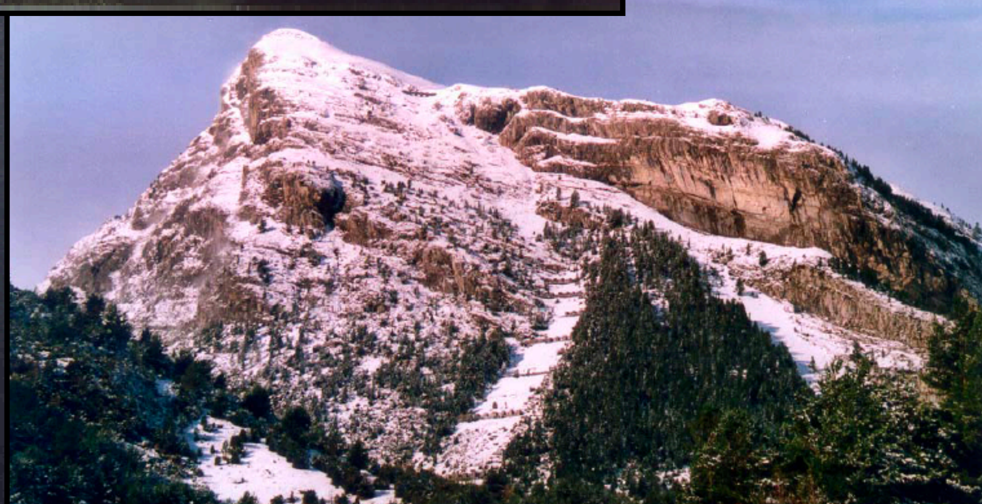
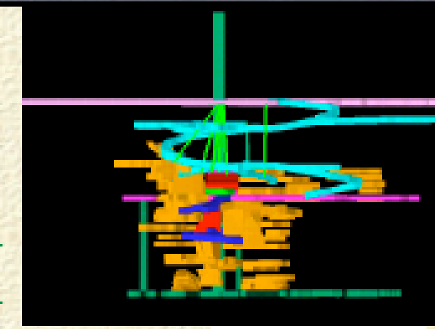


Vertical muon flux as function of depth.



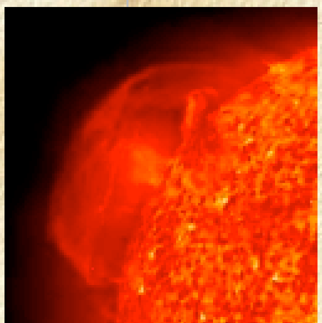
Underground Physics



Education & Outreach

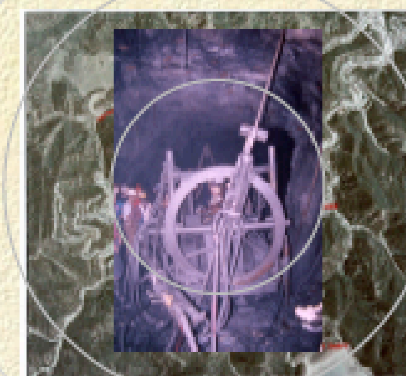
Dark Matter
Cosmology
Astrophysics
Neutron Oscillation

Geo-Database
Geo Modeling
Geophysics
Seismology
Fracture Study

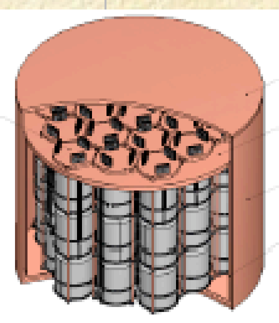


Solar Neutrinos
Geoneutrinos
Underground
Accelerator for
Astrophysics
Gravity Waves

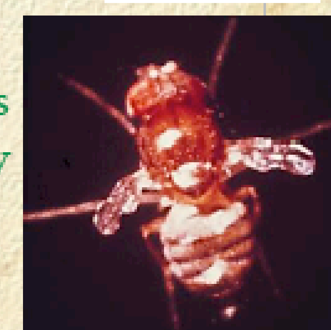
Cloud Formation
Lightning Physics
Thermal History



Coupled Processes
Rock Mechanics
Hydrology
Mineral Studies
Economic Geology



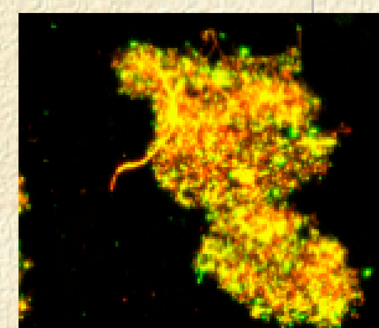
Neutrinoless ββ Decay
U/G Manufacturing
Low Background Counting



Geomicrobiology
Bioprospecting
Life at Extreme
Conditions

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

Underground
Engineering



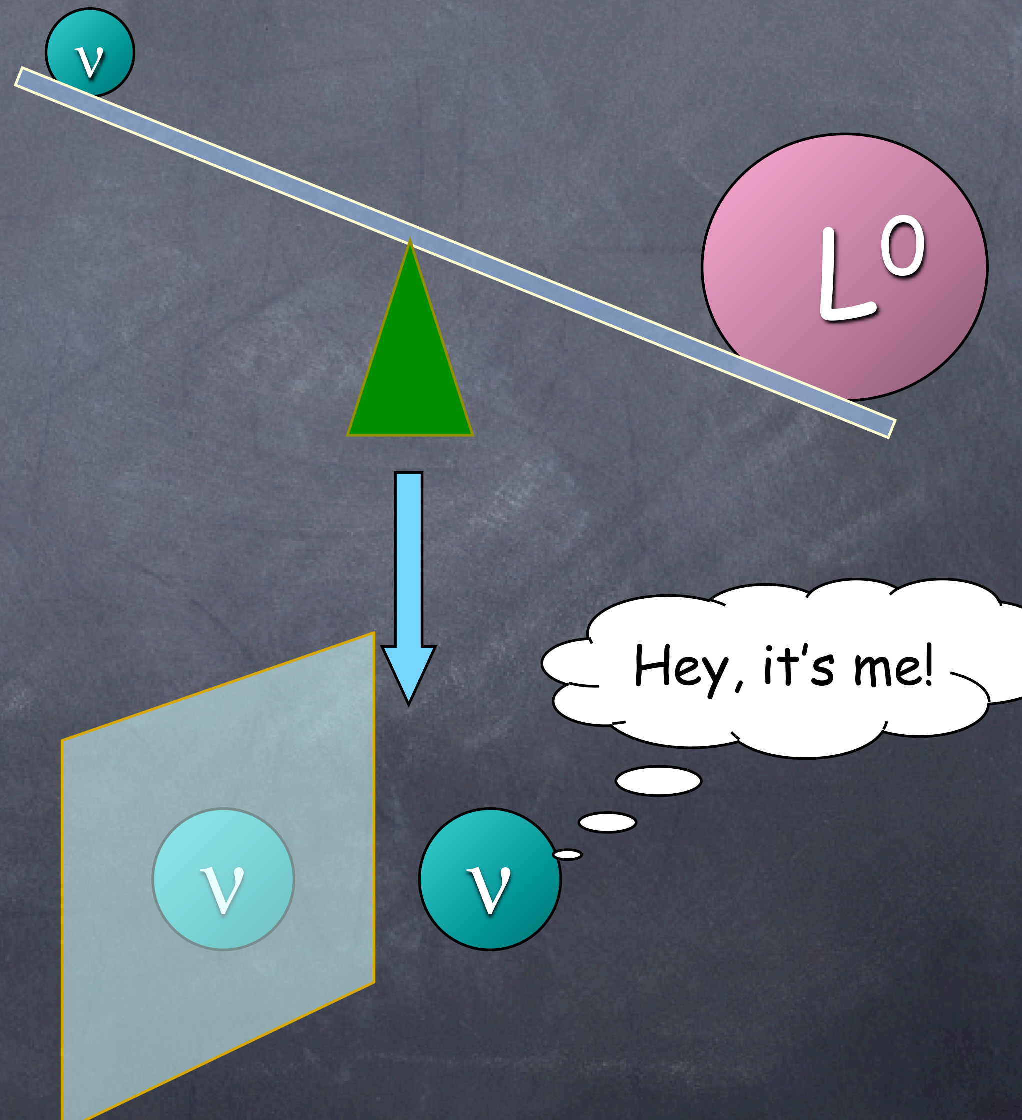
Geochemistry
Ecology
Environmental
Studies

Homeland Security

(Coutersy, Kevin Lesko)

The Nature of Neutrino Mass

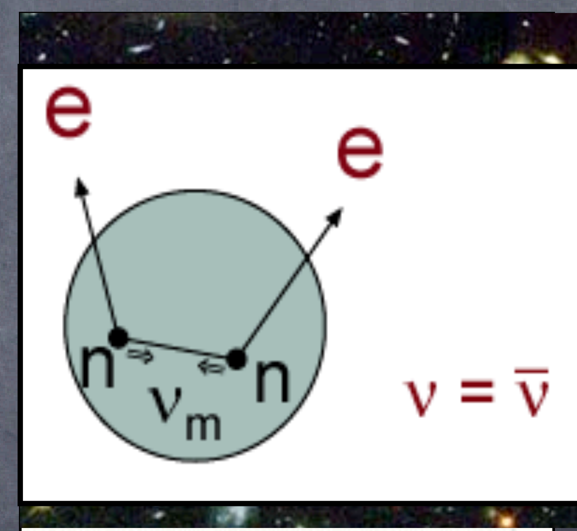
- Beyond the Mass Spectrum
  - One outstanding question is the mechanism behind the smallness of the neutrino mass
  - Possible incorporate the neutrino mass within theories beyond the Standard Model
- Implications → the neutrino & anti-neutrino are the same particle!
- Neutrinos would then be known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

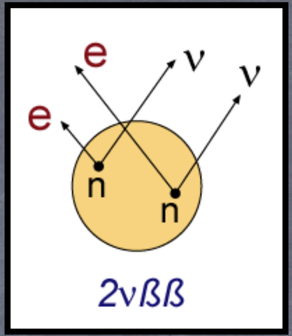
How rare is it?

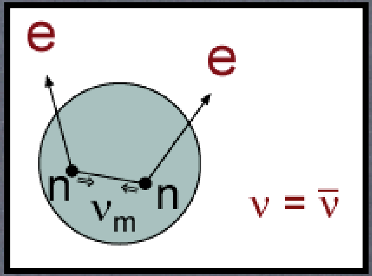


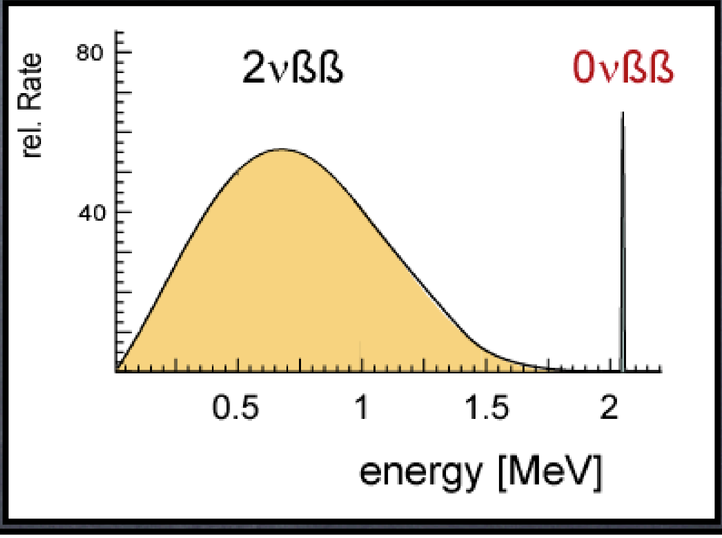
Neutrinoless Double Beta Decay...
$\sim 10^{25}$ years

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.







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

Decay Rates and Majorana Masses

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_\nu \rangle^2 \qquad \langle \mathrm{m}_\nu \rangle^2 = \left| \sum_{\mathrm{i}} \eta \mathrm{U}_{\mathrm{ei}}^2 \mathrm{m}_{\mathrm{i}} \right|^2$$

CP phase

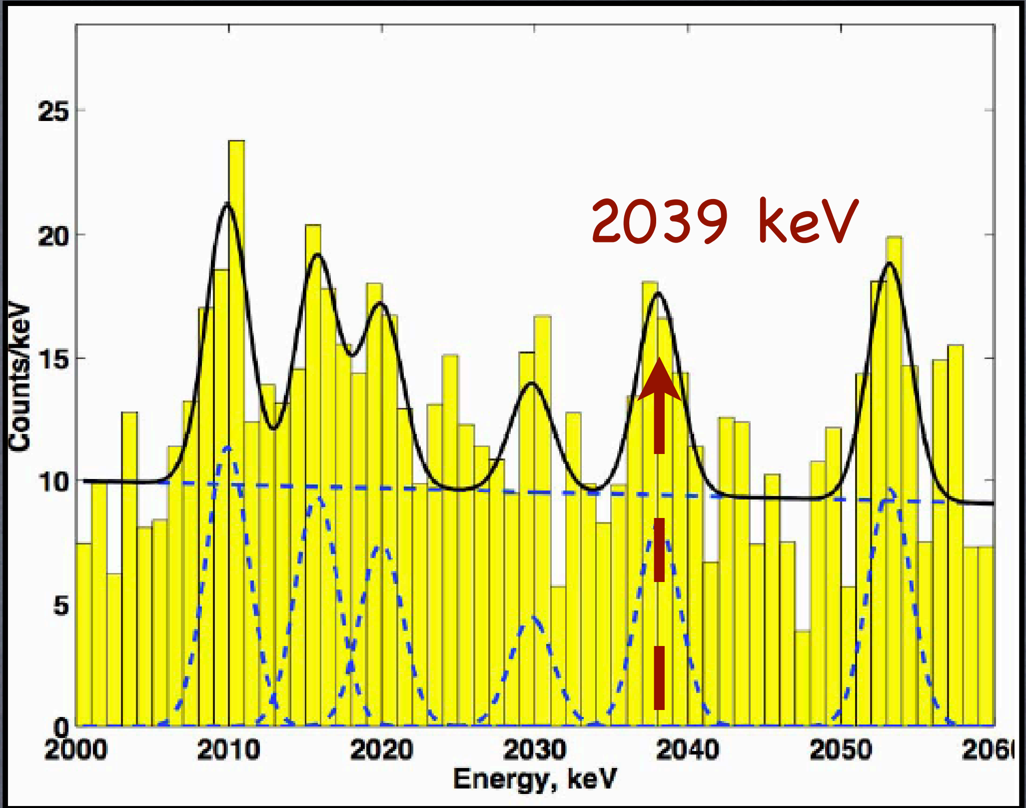
Mixing Matrix

Mass Eigenstates

- The neutrinoless-double beta decay mode is directly proportional to the mass eigenstates.
- The CP-phase elements do play a role in the observed mass. In principle, they can destructively interfere.
- Can use oscillation experiments to help discern what outcomes are possible.

Possible Signal?

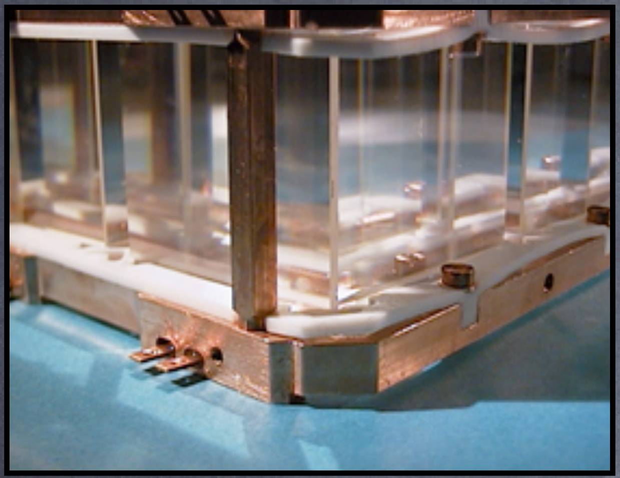
- Possible (4.2 sigma) signal claimed by the Heidelberg-Moscow Germanium experiment.
- Highly controversial:
  - Unknown lines
  - Rejected by part of the collaboration
  - No other measurement to verify it.
- If true, it does imply a neutrino Majorana mass that can be measured in the near future.

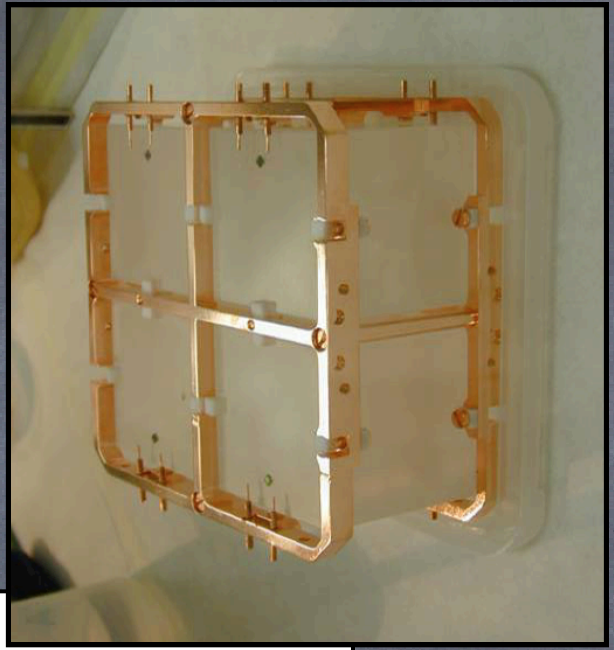


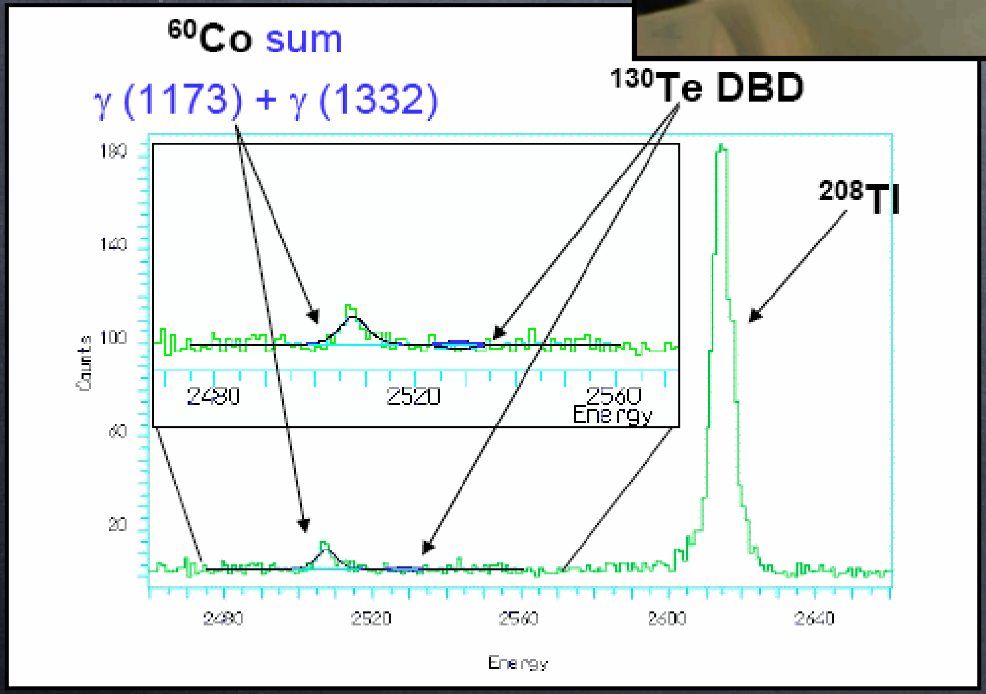
Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

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

Experiments on the Horizon

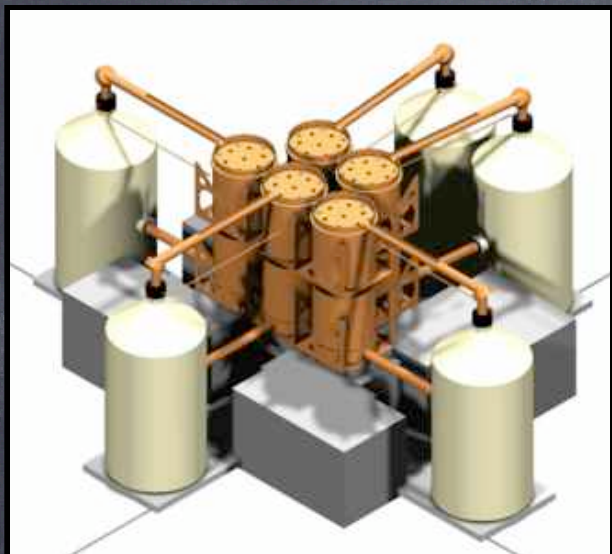




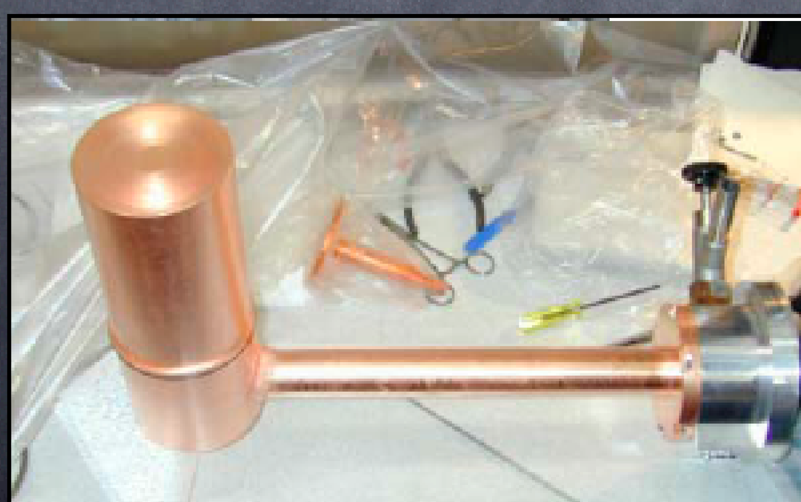


- CUORE
  - Use 750 kg of natural tellurium (^{130}Te). They already have 200 kg of it.
  - Cryogenic detectors to determine energy deposited by the two electrons.

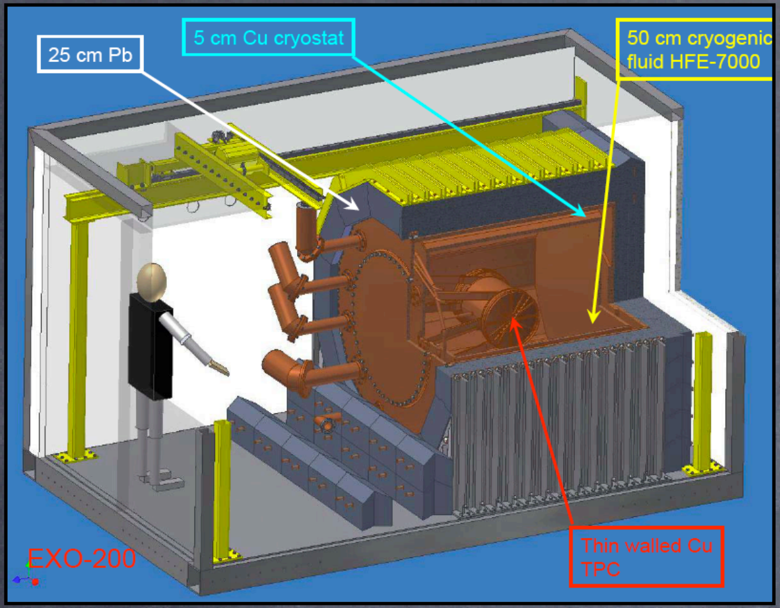
Experiments on the Horizon

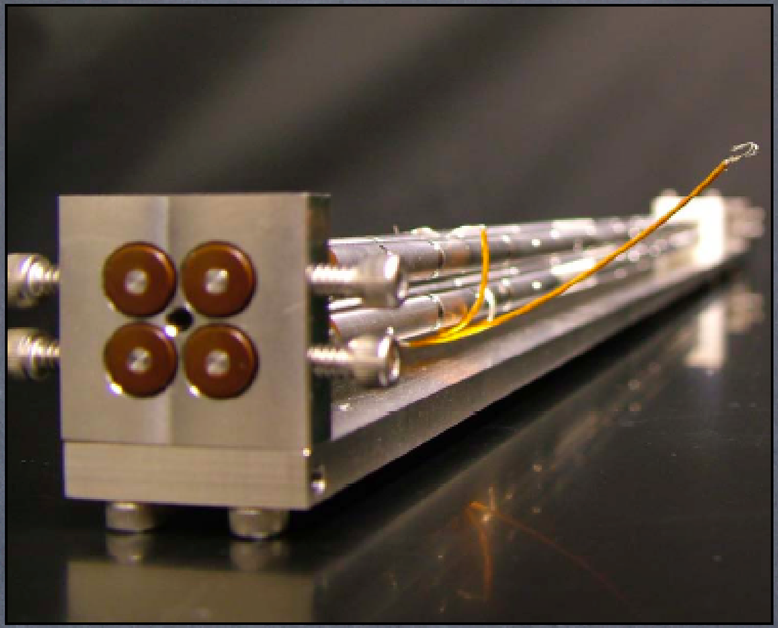


- Majorana & GERDA
  - Use enriched ^{76}Ge germanium (very well-tested technique).
  - Extremely precise energy measurement of all particles that interact in the medium.



Experiments on the Horizon





- EXO
  - Use enriched ^{136}Xe, which is a liquid noble gas
  - Liquid nobles can be made extremely clean, are self-shielding, and produce ionization and scintillation light.
  - Can use the residual nucleus (^{136}Ba) as a tag against backgrounds !

Common Problems & Solutions

- "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.

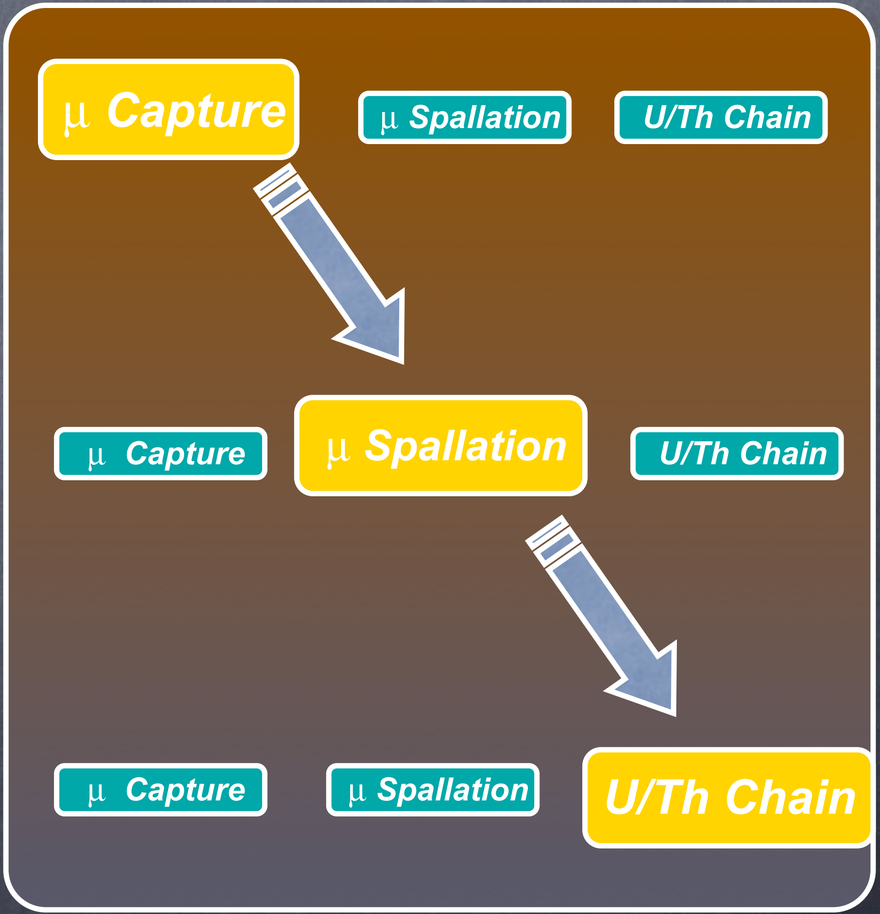
"(Come in under the shadow of this red rock),
And I will show you something different from either
Your shadow at morning striding behind you
Or your shadow at evening rising to meet you;
I will show you fear in a handful of dust."

--T.S. Eliot, The WasteLand

Worrying about Backgrounds...

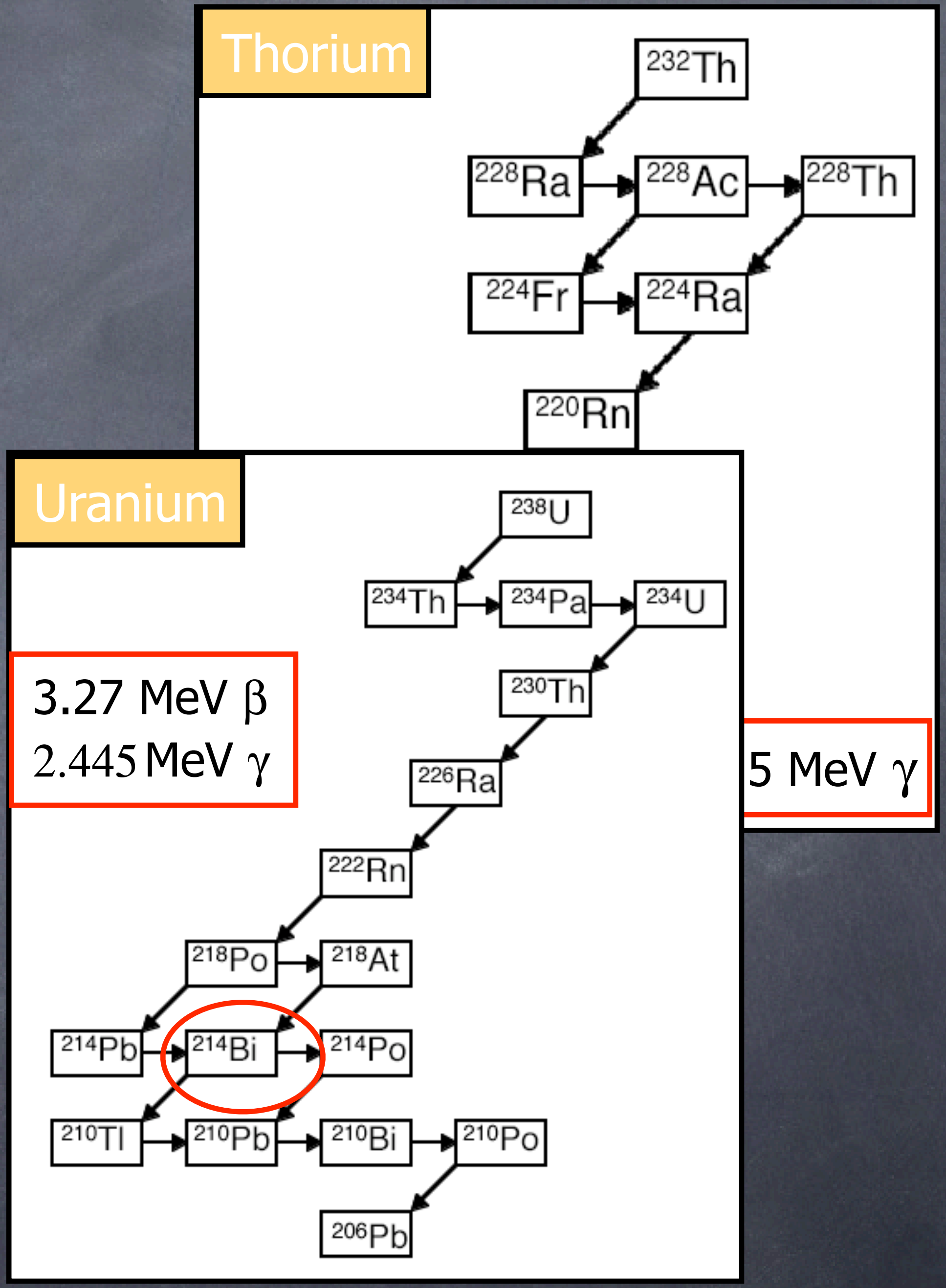
- Typically, shallow depth enables you to escape the nucleonic background from cosmic rays.
- Beyond 350 meters water equivalent (mwe), the background that dominates depends on the depth of the experiment.
- If we take neutrons, for example (important for dark matter) muon capture dominates at shallow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

What Dominates?



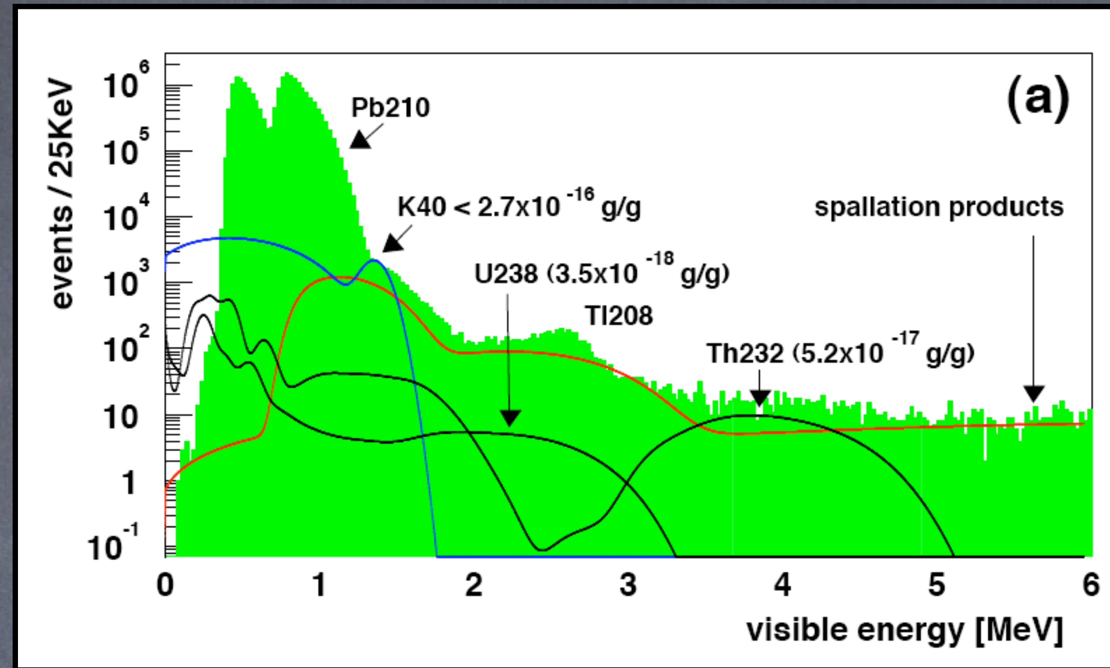
Radioactive Backgrounds

- 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.



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.



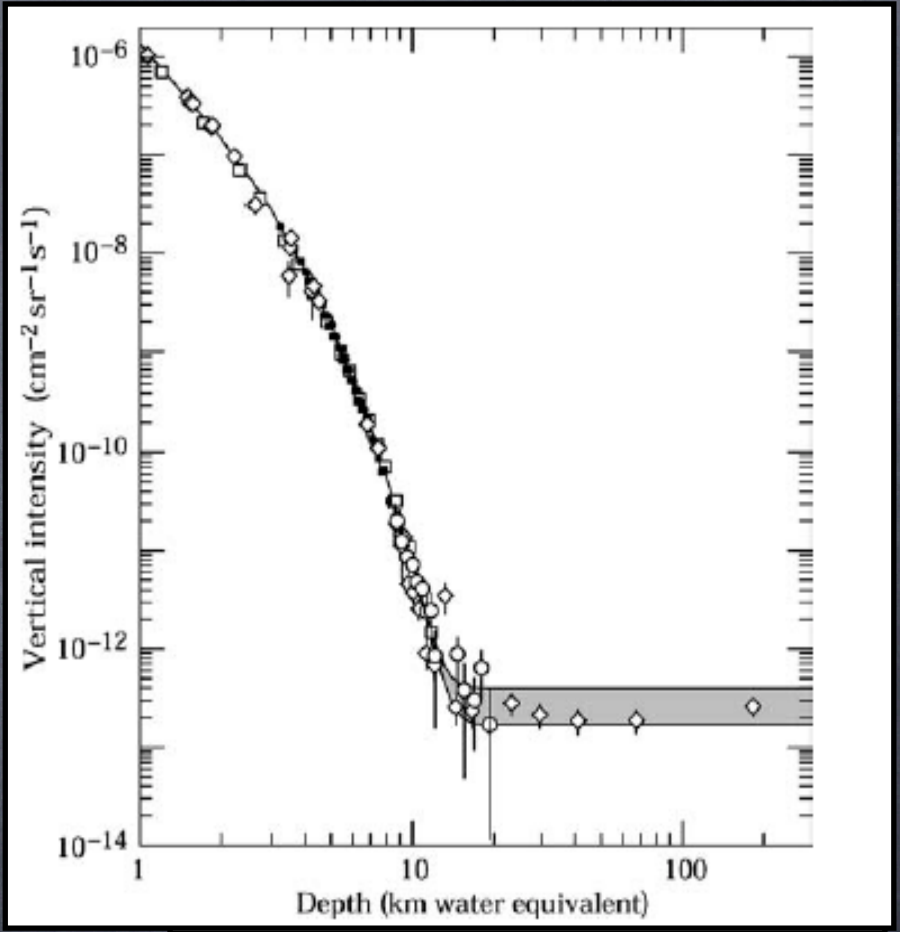
U/Th from Scintillator (KamLAND)

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)

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

Muon Capture

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

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

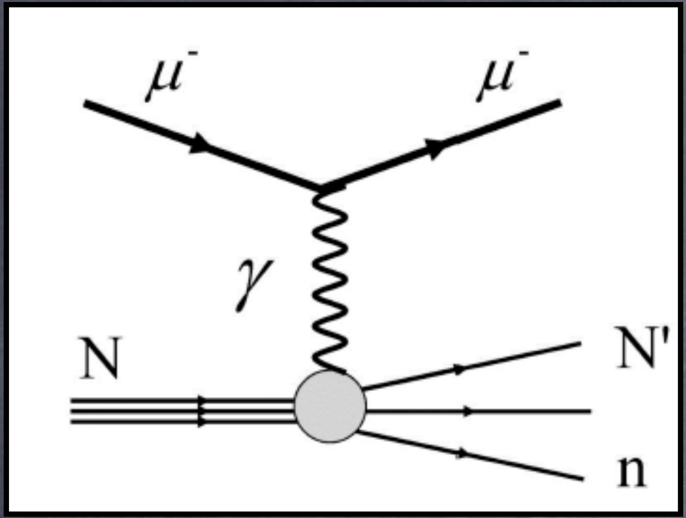
- One or more neutrons typically produced, depending on target material.

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

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

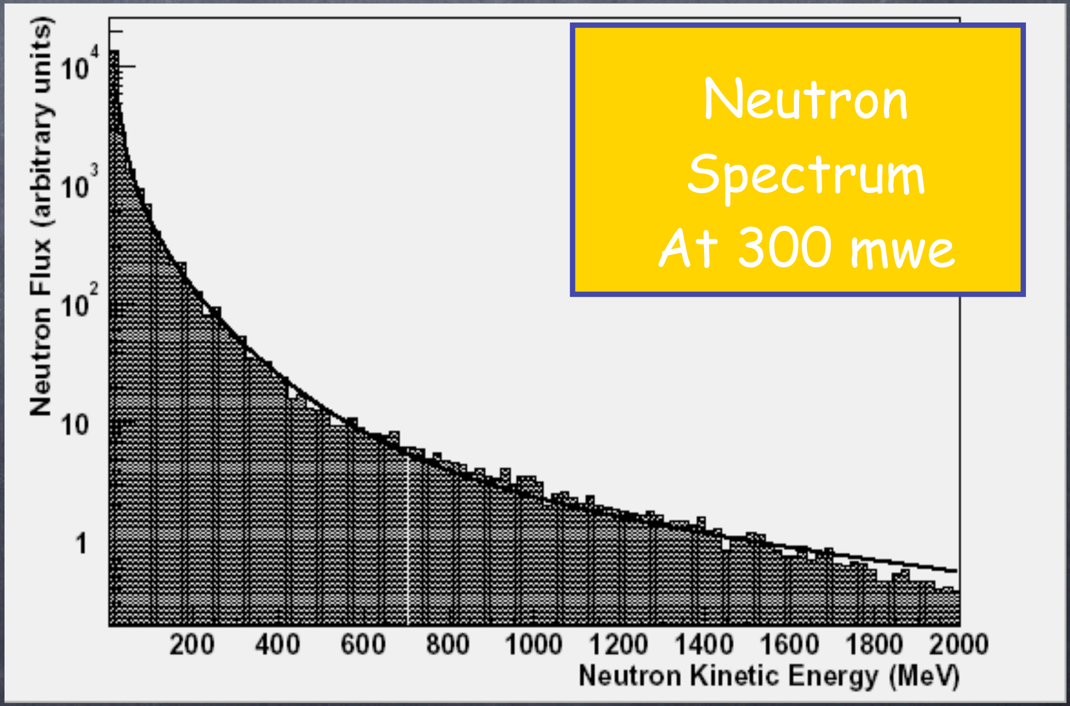
Suzuki T, et al.
Phys. Rev. C 35: 2212 (1989)

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.



Questions still out there...

(orange)	Involves underground physics
(magenta)	Involves neutrinos & underground physics

- 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?

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.