Neutrino Sources

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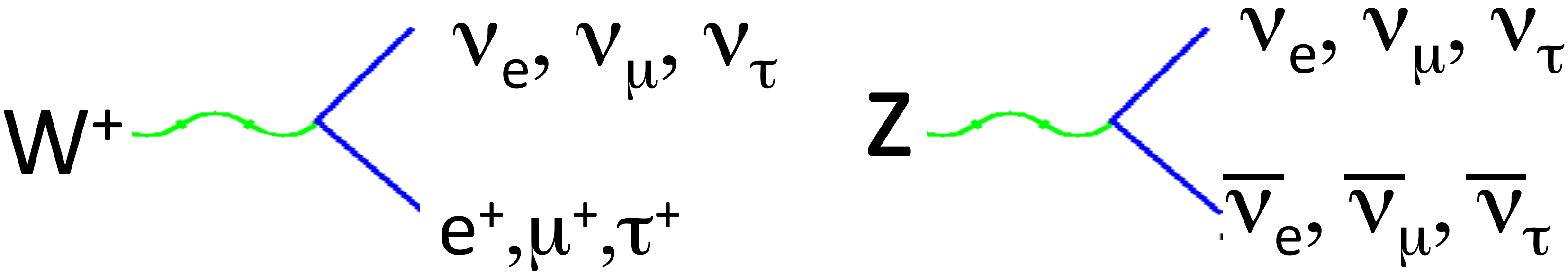
SLAC Summer Institute

Neutrino Sources, Simplified

- Charged and Neutral Current Interactions



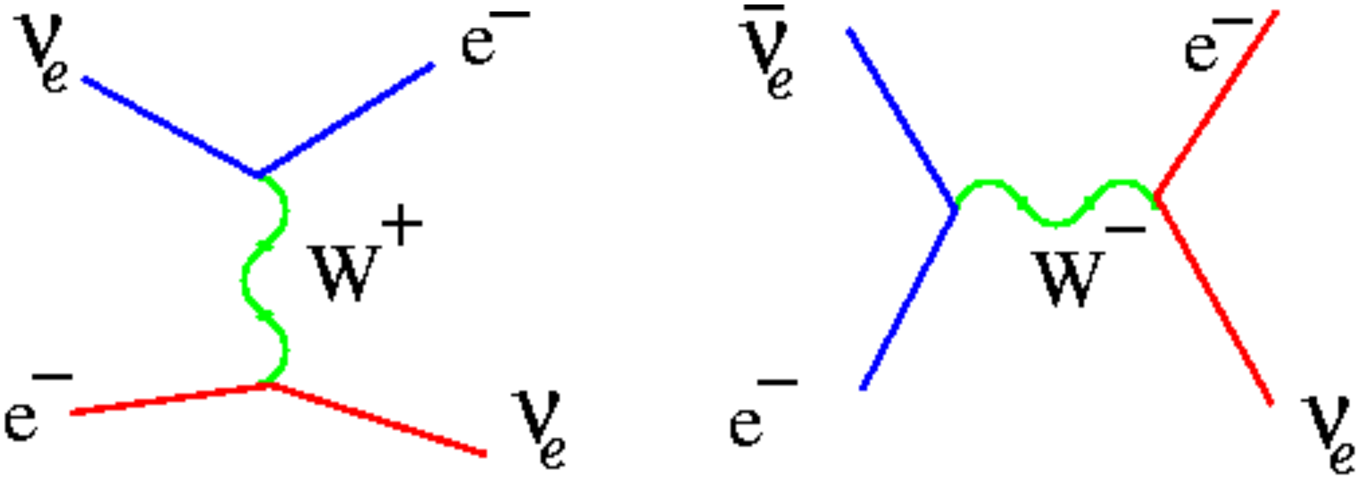
- Neutral Current neutrino production:
  - All neutrino flavors produced in equal amounts
  - Neutrino and Antineutrinos produced equally
- Charged Current neutrino production:
  - W needs enough energy to produce associated charged lepton
    - Electron: 511keV, Muon: 106MeV, Tau: 1.8GeV

Neutrino Sources

- Key Parameters:
  - Energy Spectrum
  - Rate (Flux)
  - Flavor and Helicity Composition
    - This is complicated by oscillations: so 2 more factors become important
  - Baseline (where might we see the neutrinos from the source of interest)
  - "Source Environment": do neutrinos have to propagate through a lot of material?

Matter Effects

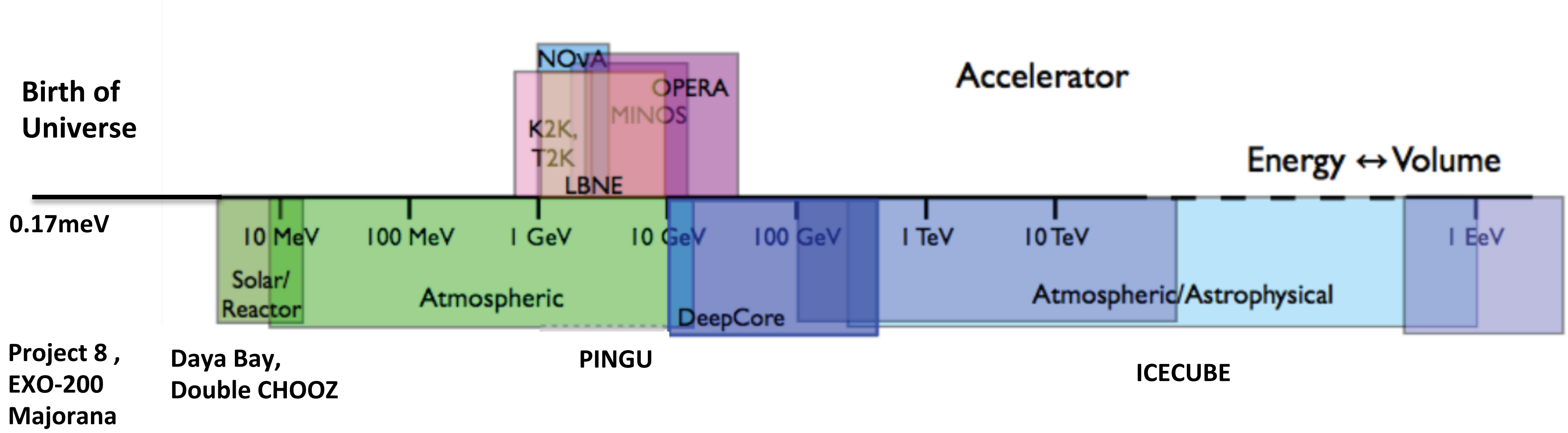
- As electron neutrinos or antineutrinos propagate through matter, they develop equal and opposite potentials because of the electrons in matter



Wolfenstein, PRD (1978)

- Can't treat neutrinos propagating through sun, supernova core, or even earth simply as mass eigenstates, have to take into account electron flavor

Neutrino Source Energy Span



Birth of Universe

0.17meV

Project 8 ,
EXO-200
Majorana

Daya Bay,
Double CHOOZ

PINGU

ICECUBE

- At low end of spectrum (10^{-4}eV):
  - We expect those neutrinos to be there but haven't measured them directly yet
- At high end of spectrum (10^{14}eV)
  - We have seen direct evidence of ~100TeV neutrinos but don't have easy picture of how they have been created

Graphic adapted from D.Williams

The rest of this lecture:

- Big Bang
- Stars
- Sun
- Reactors
- Atmosphere
- Accelerators

Note: only one of these sources is truly
under our own control, and
able to access CP violation…
so I will describe that source in the most detail

Earliest Source of Neutrinos: Big Bang

- In the beginning, energy density was high, neutrinos and photons were coupled through electrons

$$e^+ + e^- \leftrightarrow \bar{\nu} + \nu$$
$$\bar{\nu} + \nu \leftrightarrow \bar{\nu} + \nu$$
$$\nu + e^\pm \leftrightarrow \nu + e^\pm$$

- As the universe expanded and cooled, eventually the expansion rate was larger than the interaction rate, and neutrinos decoupled

$$\Gamma = <\sigma\, n\, v> \simeq \frac{16 G_F^2}{\pi^3}\left(g_L^2 + g_R^2\right) T^5$$

Annihilation Rate

$$H(t) = 1.66 g_*^{1/2} \frac{T^2}{m_{\mathrm{Planck}}}$$

Expansion Rate

$T_D(\nu_{\mu,\tau}) \cong 3.7\mathrm{MeV}$

$T_D(\nu_e) \cong 2.4\mathrm{MeV}$

“Relic Neutrinos”

- Once they decouple, neutrinos are unlikely to interact as they travel through the universe
- Thermal distributions are red-shifted as universe expands, just like photons
- So neutrinos and photons from the Big Bang are intrinsically related to eachother and

Jenni Adams, INSS 2014

$$n_{\nu\bar{\nu}}(1\text{ flavor}) = \frac{4}{11} \times \frac{3}{4} \times n_\gamma = \frac{3}{11} n_\gamma \approx 112\text{ cm}^{-3}$$

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.95\text{ K} \quad \text{for massless neutrinos}$$

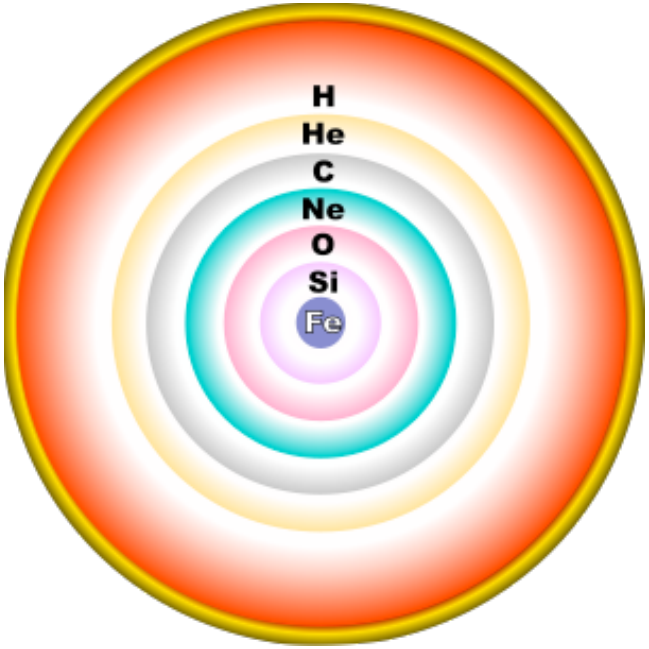
1.95K = 0.17meV

Big Bang as a neutrino source

- High flux: These relic neutrinos are more abundant than protons by ~700 million
- The number of these neutrinos influenced the abundances of different elements in the universe
- If these neutrinos have mass then they influence the large scale structure of matter in the universe
- Already the measurements of large scale structure imply limits on total neutrino mass
- Seeing these neutrinos at all would be stunning success of our understanding of cosmology
- Experimental Challenge how do you design a detector that is sensitive to 0.17meV?

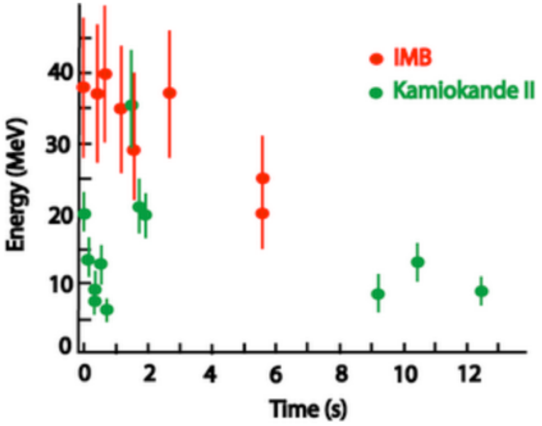
Neutrinos from Stars

- Stars provide a huge energy density
  - 10^{11}-10^{15} g/cm^3
  - Very high temperature: 1-50MeV
  - $10^{51\text{-}53}$ ergs
  - All three neutrino species are present
- When the star eventually collapses, the energy escapes through neutrinos (and photons)
- Experimental Challenge: Patience to wait for the next Supernovae
  - 1/30 years in our galaxy



Content courtesy Joe Formaggio

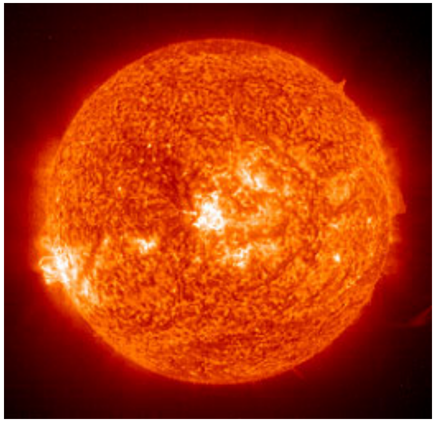
$$e^+\ e^- \leftrightarrow \nu_i\bar{\nu}_i$$
$$\nu_e\ n \leftrightarrow p\ e^-$$
$$\bar{\nu}_e\ p \leftrightarrow n\ e^+$$



What about our own star?

A Helium nucleus is produced by the fusion of 4 Hydrogen nuclei;

$$4p \rightarrow He + 2e^{+} + 2\nu_e$$



This reaction produces about 27 MeV energy.
Then, the total neutrino flux on the Earth is;

$$flux = \frac{1}{4\pi R^2} \times \frac{L_{sun}}{27\,MeV} \times 2\nu_e$$

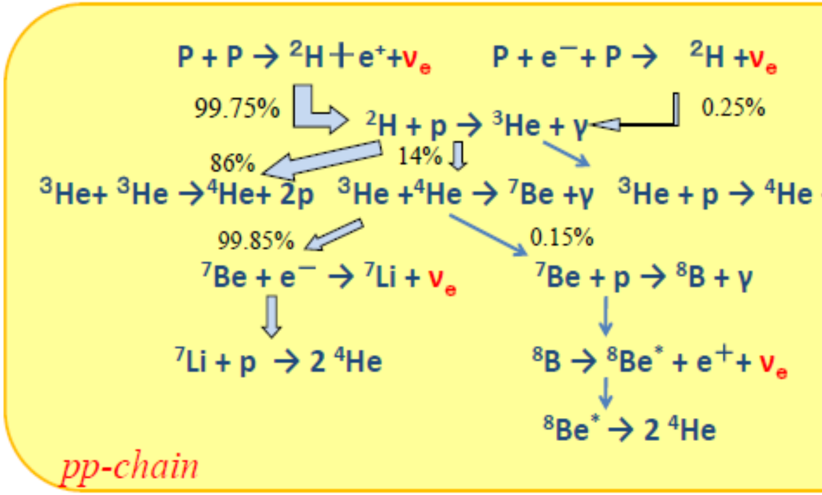
$$(L_{sun} = 3.86 \times 10^{33}\, erg/\sec)$$

$$= 6 \times 10^{10}\, \nu_e / cm^2 / \sec$$

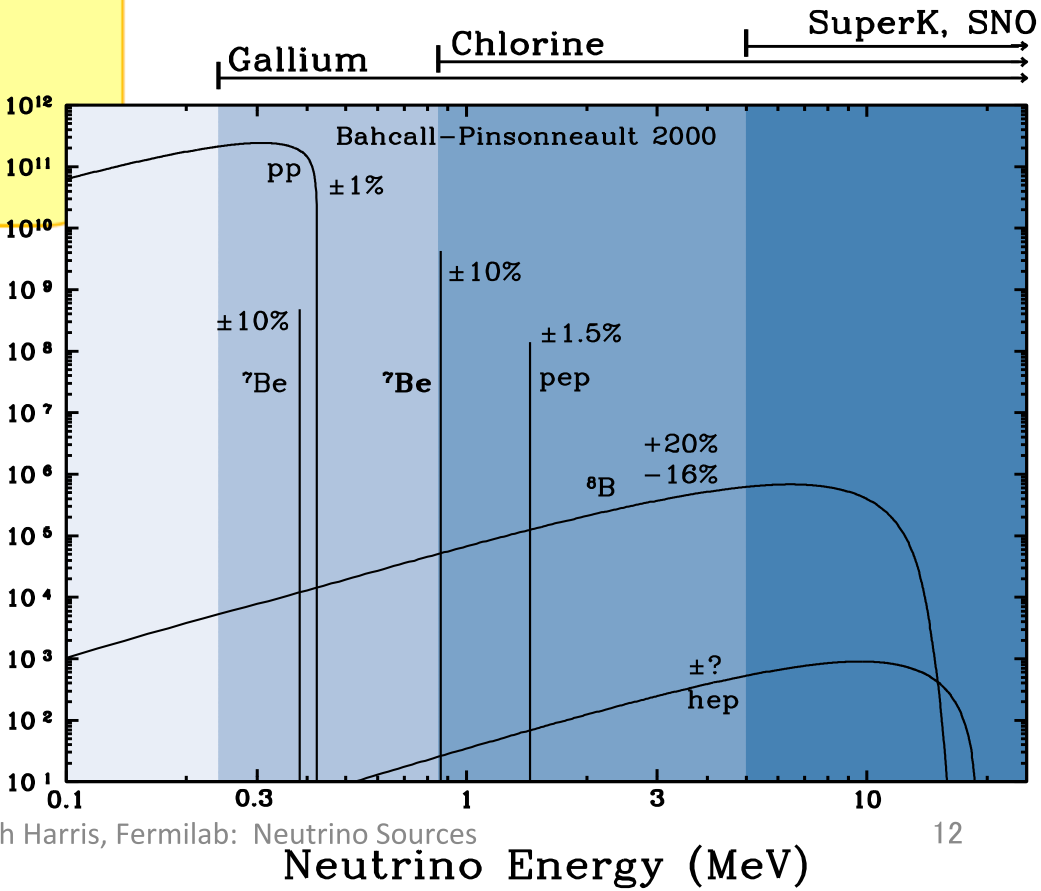
Observing neutrinos from the sun is direct proof that the generation of the energy in the Sun is due to nuclear fusion.

T. Kajita, INSS 2013

Solar Neutrino Energy Spectrum



However, in reality, 4 protons cannot make a Helium nucleus at a time…



T. Kajita, INSS 2013

Vital Statistics of Solar Neutrinos

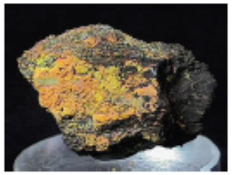
- Baseline: 10^8km
  - Distance to sun changes based on the season
  - Day/night asymmetry changes whether or not ν's went through the earth before detection
- Solar Neutrinos all start as ν_e
- Matter effects
  - ^{8}B ν's feel matter effects from sun
  - Resonance is set up such that by the time neutrinos leave the sun, they are all ν_2's

Experimental Challenges with Solar Neutrino Measurements

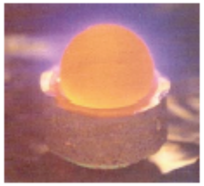
- Neutrinos are very low in energy
  - Very few interactions are accessible
  - Cannot make final state muons or taus, so only neutral current or ν_e charged current interactions are available
  - Different detectors have different energy thresholds, most neutrinos from sun not visible by most techniques
  - Cannot turn off the sun to measure backgrounds in the detector
  - “Standard Solar Model” had many tunable parameters…flux predictions suspect for a long time.

Neutrinos from a Reactor

- Like the sun, but fission instead of fusion
- n → p e^- anti-ν_e but buried in a nucleus



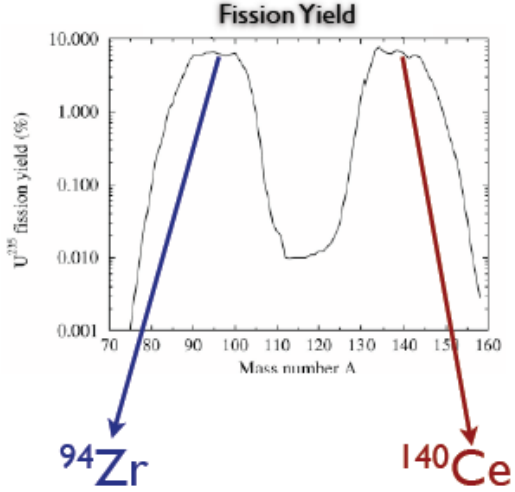
^{235}U

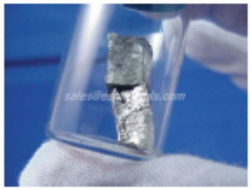


^{239}Pu

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n \rightarrow$$
$$\ldots^{94}_{40}Zr + ^{140}_{58}Ce$$

Sample Fission: ^{235}U

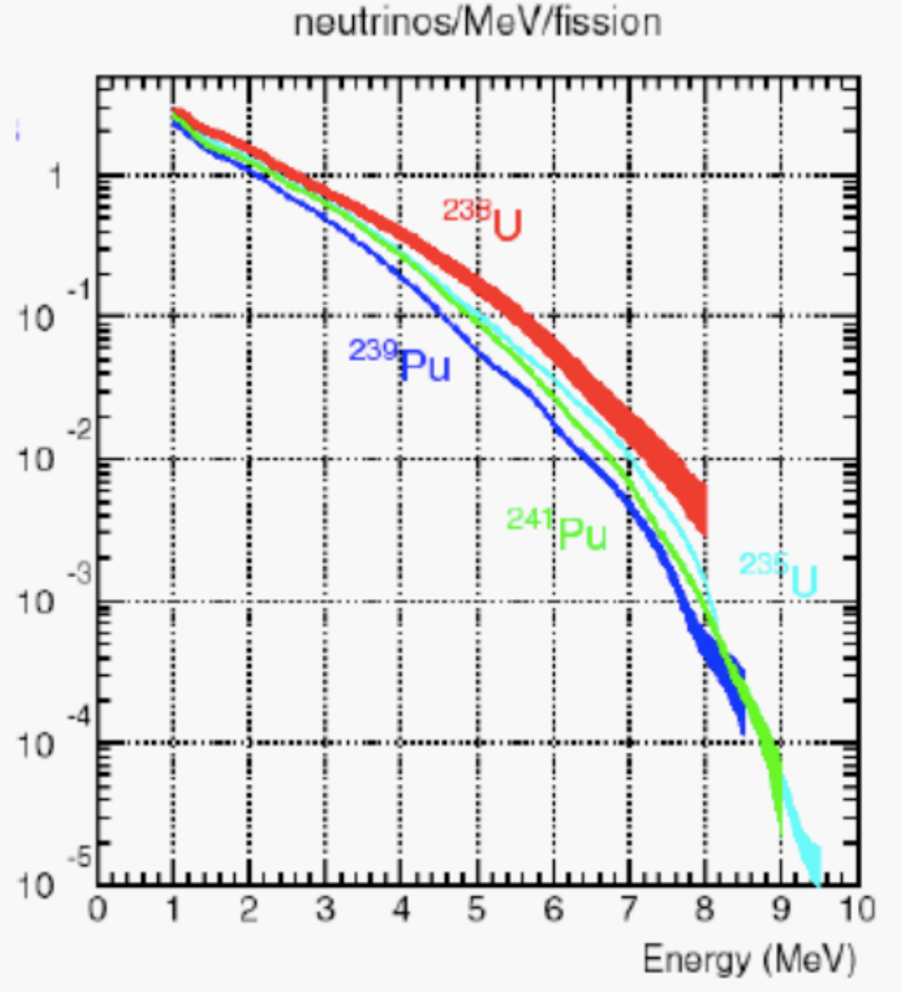




Content courtesy Joe Formaggio

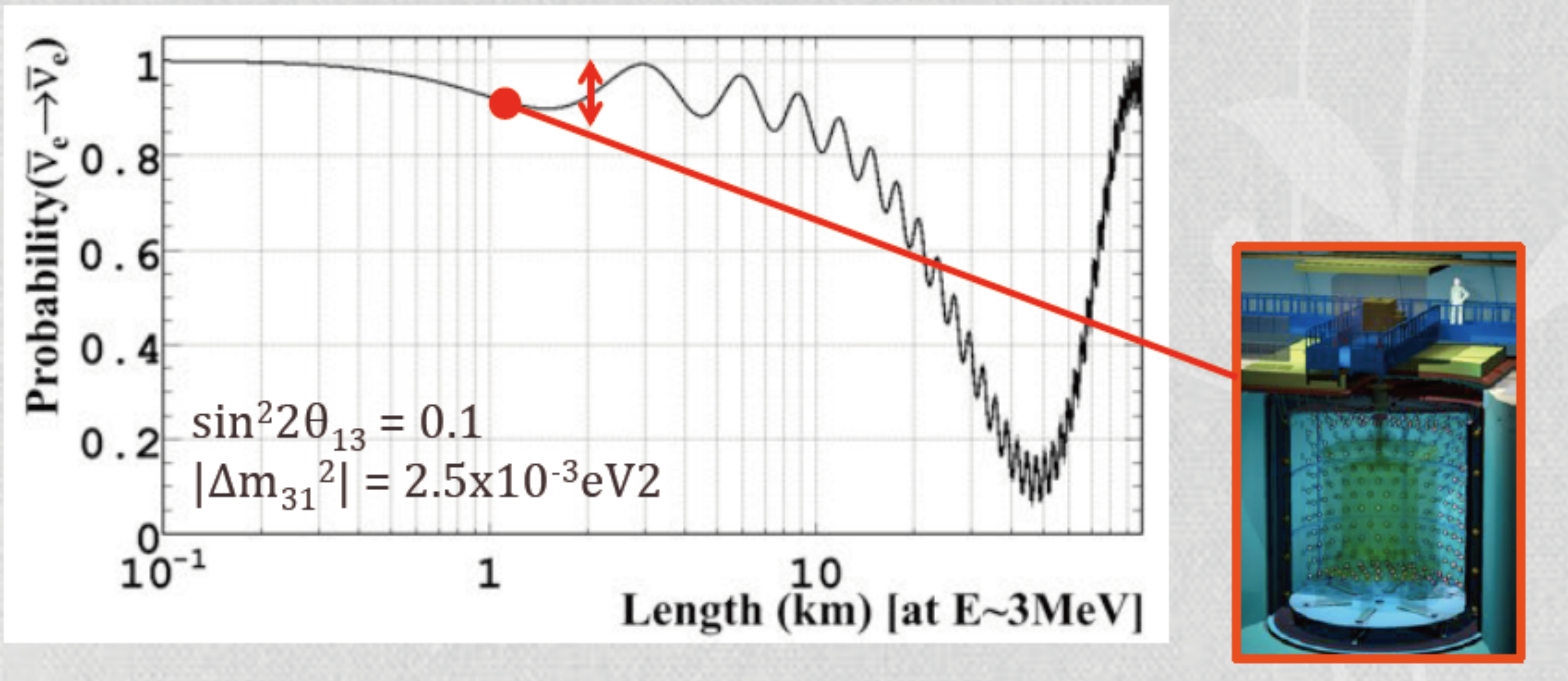
Energy Spectrum from Reactors

- Several processes occurring during the fuel cycle of a reactor, with different yields and energy spectra



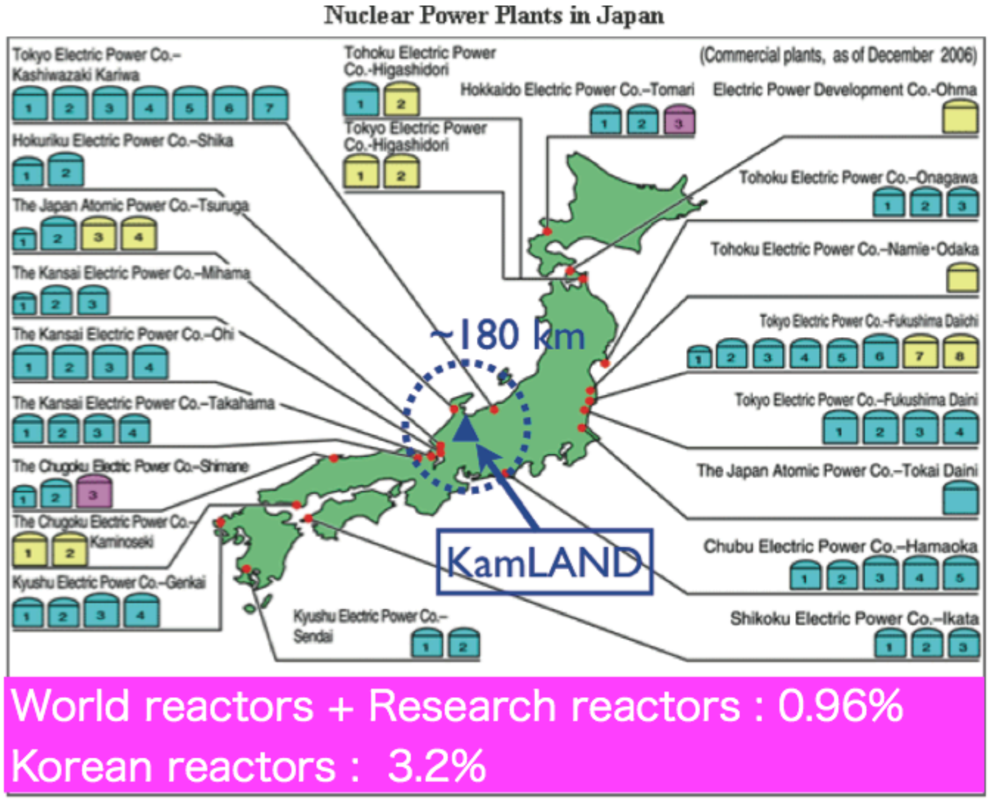
Baselines available

- Reactors send out neutrinos in all directions, so you could put detectors at any baseline you chose
- Different physics can be reached at different baselines



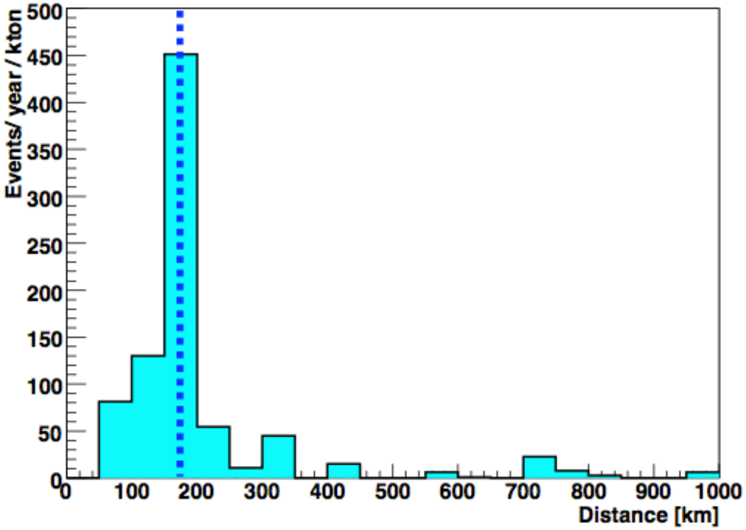
Extreme Example of Long baseline

- Kamland experiment: saw neutrinos from large array of reactors in Japan



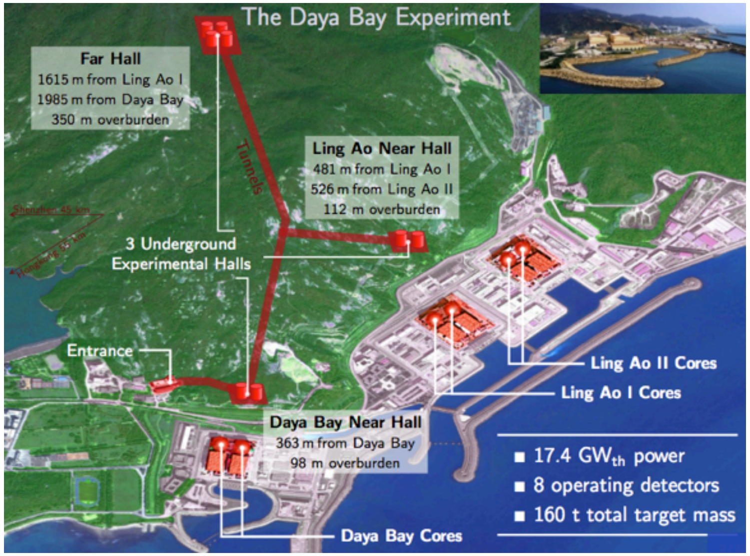
World reactors + Research reactors : 0.96%
Korean reactors : 3.2%

Effective baseline ~180 km



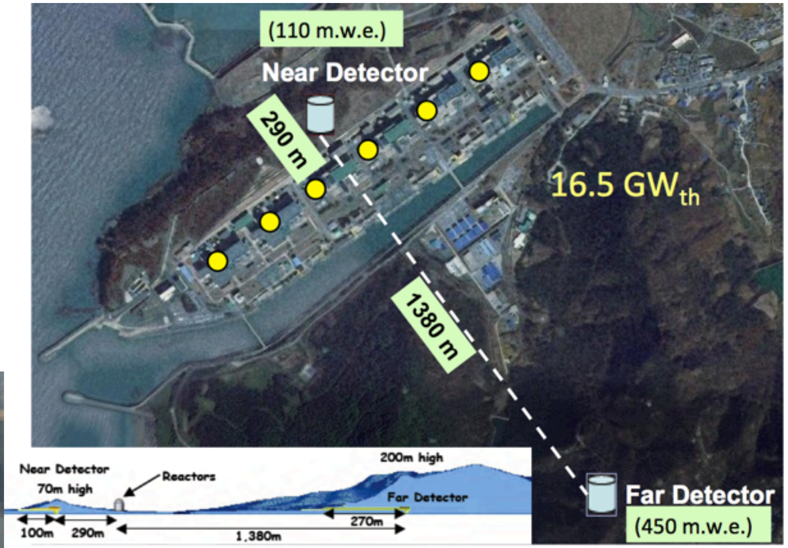
Ichimura, ν2008

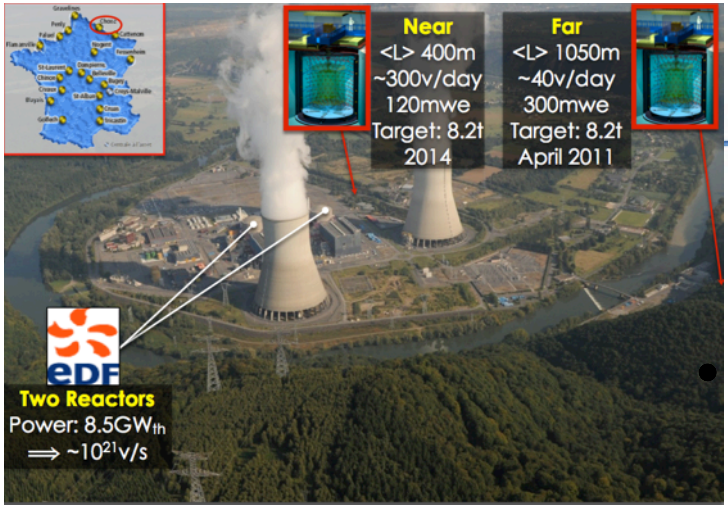
Shorter Baselines used



Daya Bay: 3 cores, 3 halls, baselines of 1.6-2.0km

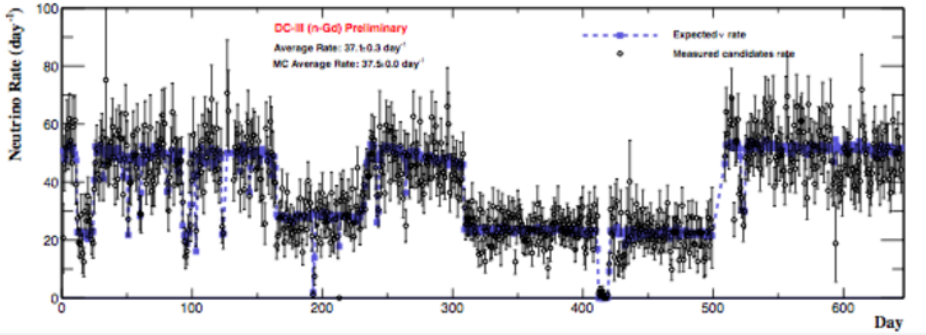
Reno: 6 reactor cores, 2 halls, baseline(s) ~1.3km





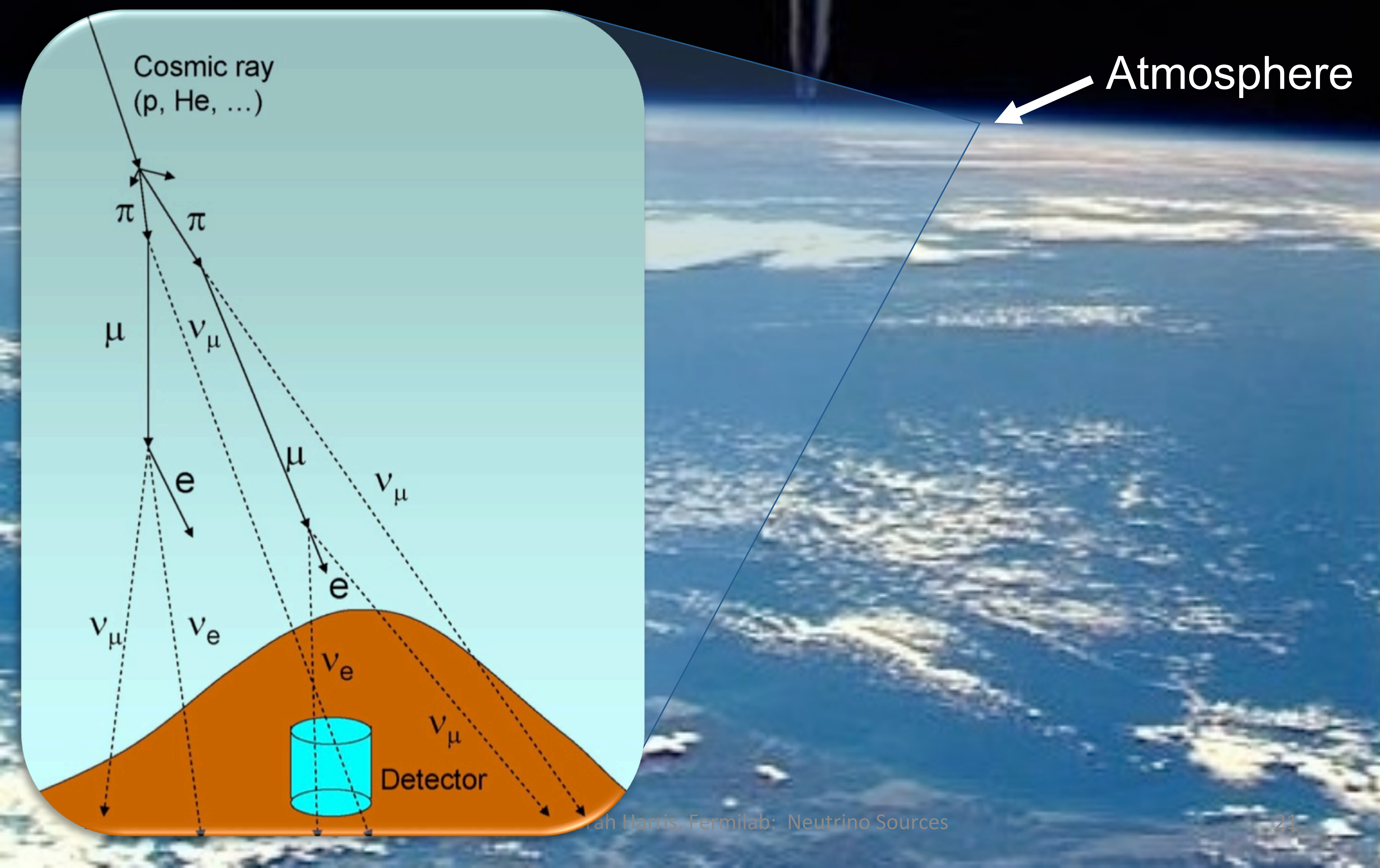
- Double Chooz: 2 cores, 2 halls at 0.4 and 1.0km

Experimental Challenges with Reactor Fluxes

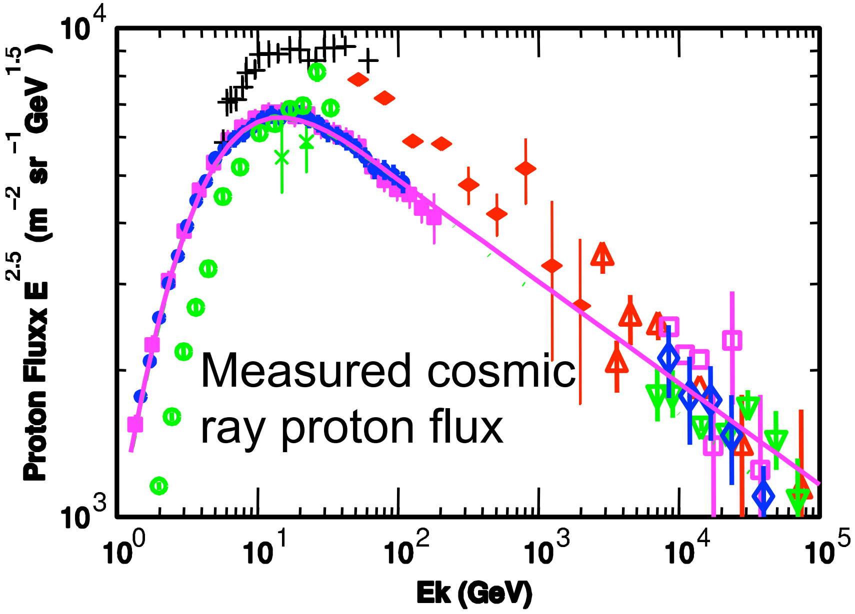


- Flux changes over time because of fuel cycle
  - Double Chooz(ν2014) at right
- Have several cores, not all at the same distance from the detector
- Energy deposited in detector is so low you can't possibly figure out original direction of neutrino
- Hard to determine backgrounds since reactors are always on (usually), signal rates very different between near and far detectors

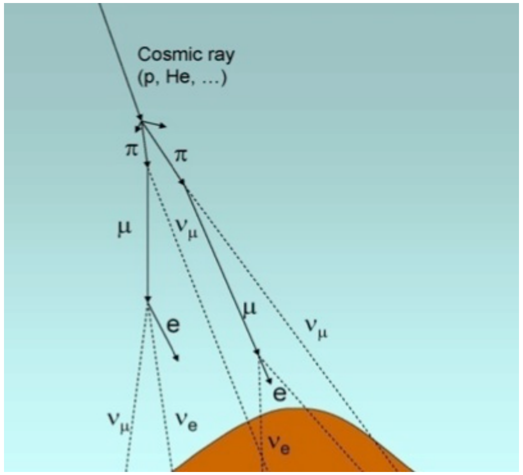
Atmospheric Neutrinos



From Cosmic Rays to Neutrinos

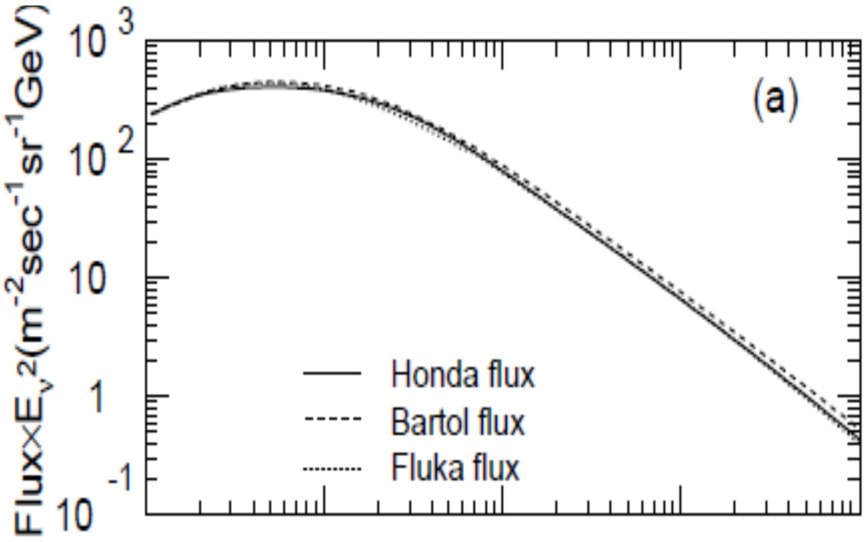


Measured cosmic ray proton flux



Carrying out the calculation all over the Earth

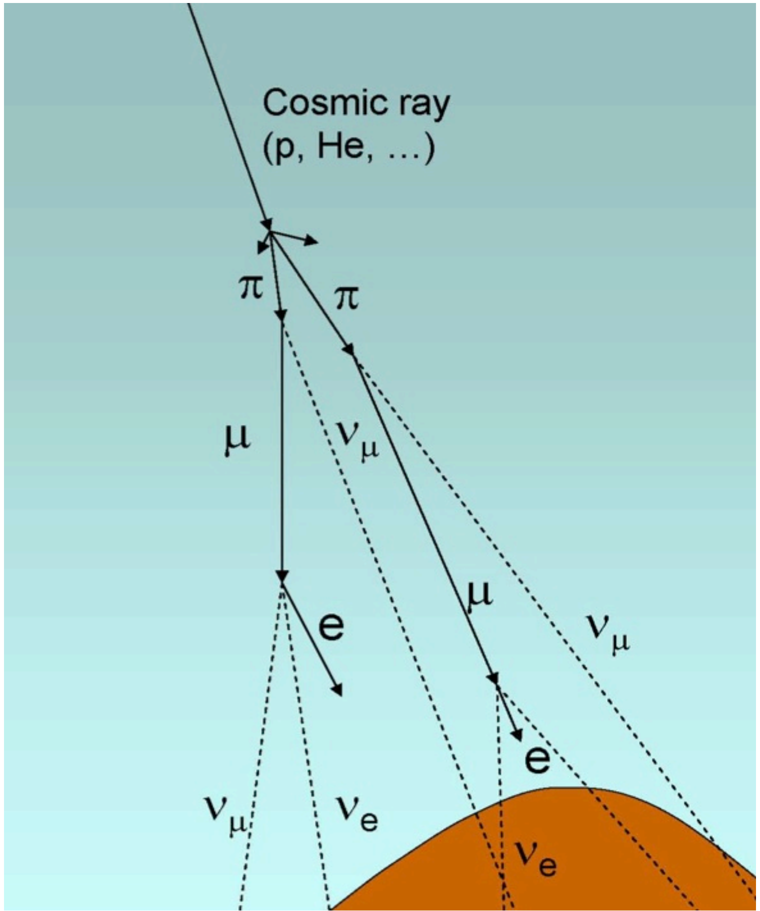
+ solar activity
+ geomagnetic field
+ (p+Nucleon) int.
+ decay of π or K

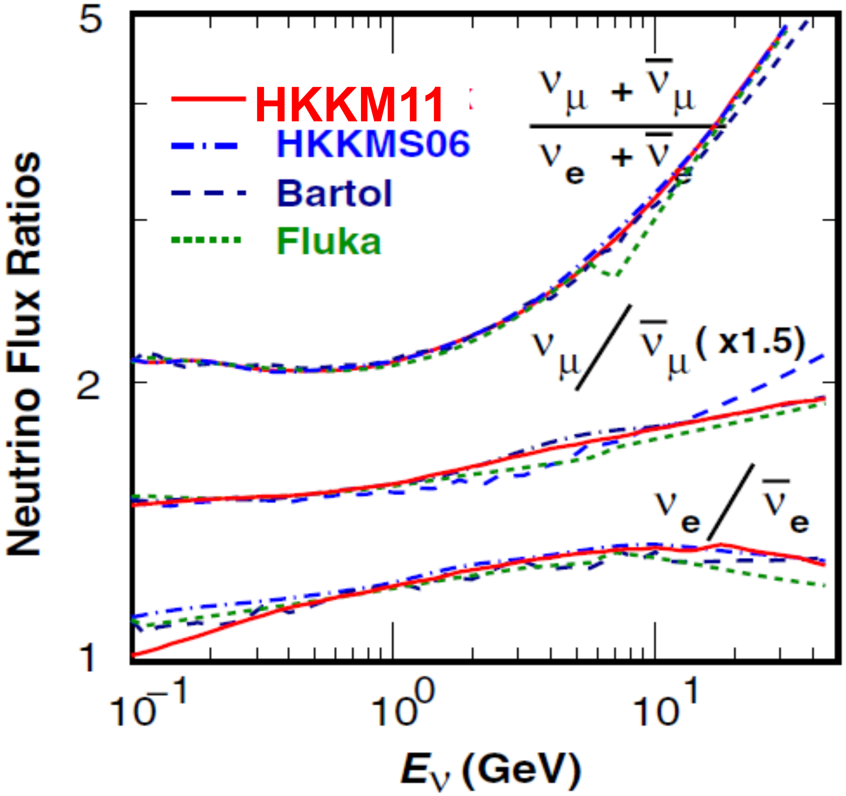


T.Kajita, INSS 2013

What is known well

$(\nu_\mu+\bar{\nu}_\mu)/(\nu_e+\bar{\nu}_e)$





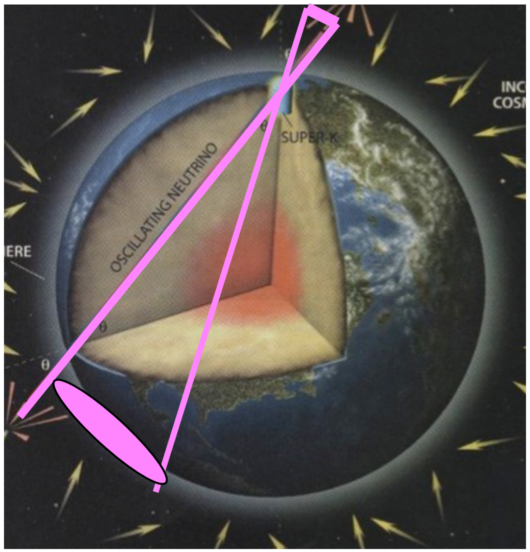
M. Honda et al., PRD 83, 123001 (2011)

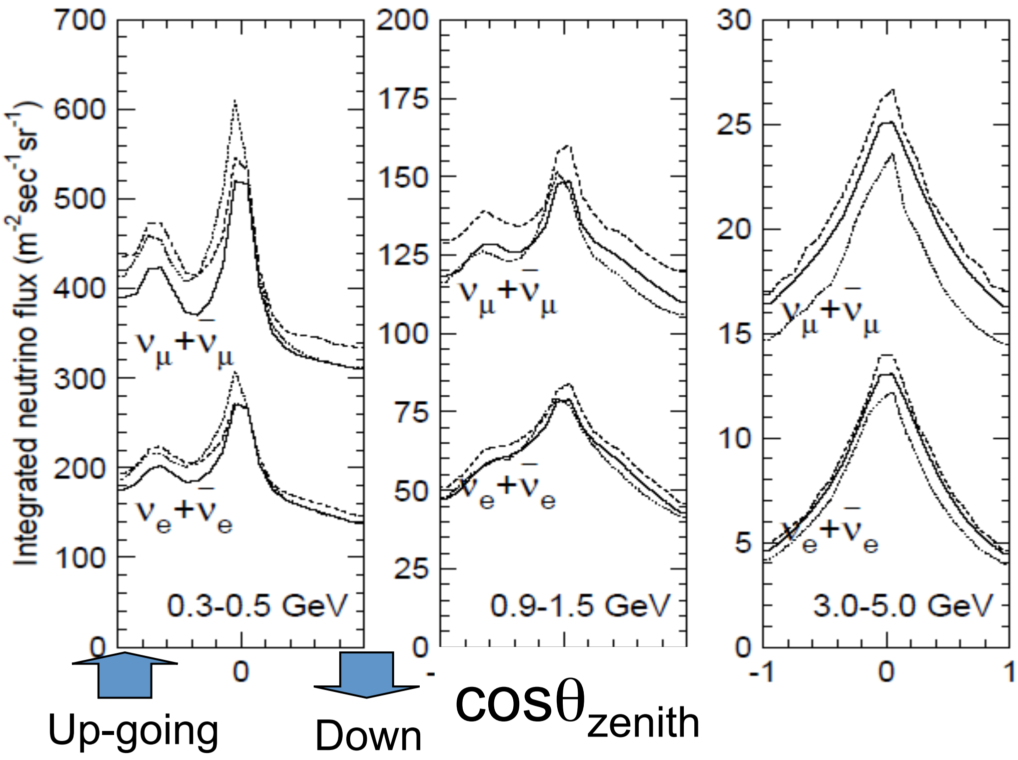
- ✓ ν_μ/ν_e ratio is calculated to an accuracy of about 2% below ∼5GeV.
- ✓ ν and anti−ν ratios also accurately calculated.

T.Kajita, INSS 2013

What else is known well: up/down

Zenith angle





@Kamioka (Japan)

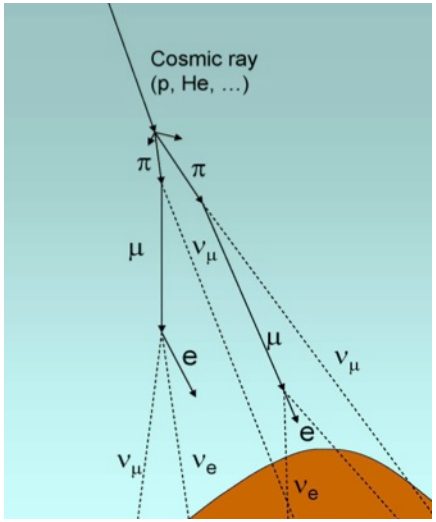
Up/down ratio very close to 1.0 and accurately calculated (1% or better) above a few GeV.

Experimental Challenges with Atmospheric Fluxes

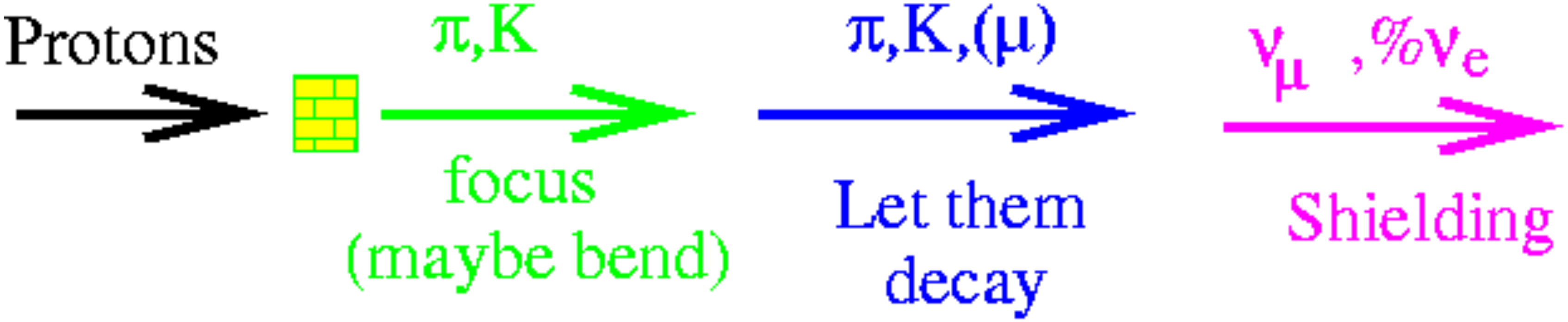
- Absolute rates are hard to predict
- Overall rates are low and steeply falling in energy
- Near equal mix of neutrino and antineutrino means CP violation measurement is near impossible
- *Homework question: how might you be able to see matter effects using atmospheric neutrinos? Do you NEED a magnetic field in your detector?*

Neutrinos from Accelerators

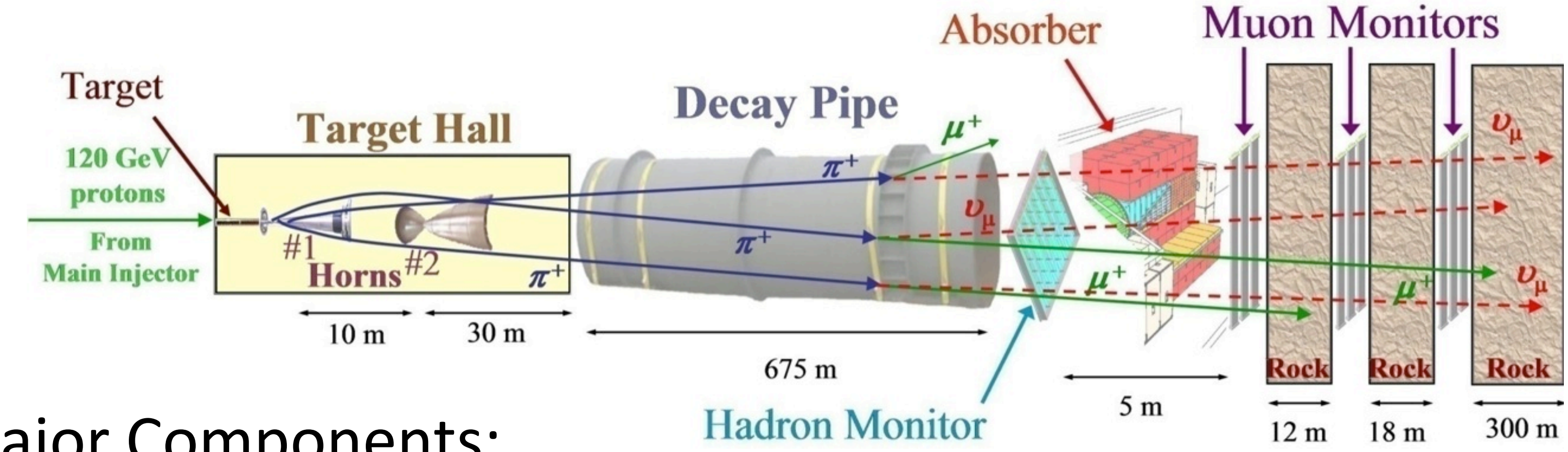
- Atmospheric Neutrino Beam:
  - High energy protons strike atmosphere
  - Pions and kaons are produced
  - Pions decay before they interact
  - Muons also decay



- Conventional Neutrino Beam: very similar!



Example: NuMI beamline at Fermilab



Major Components:

- Proton Beam
- Pion Production Target
- Focusing System
- Decay Region
- Absorber
- Shielding…

Most ν_μ's from 2-body decays:

$\pi^+ \rightarrow \mu^+ \nu_\mu$

$K^+ \rightarrow \mu^+ \nu_\mu$

Most ν_e's from 3-body decays:

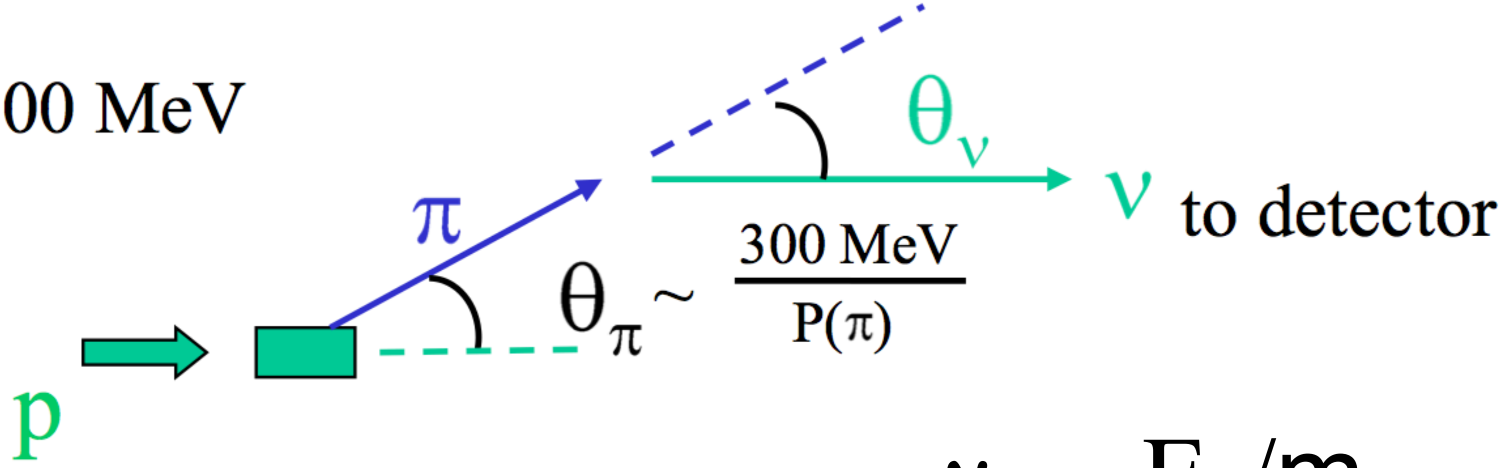
$\mu^+ \rightarrow e^+ \nu_e \nu_\mu$

$K^+ \rightarrow \pi^0 e^+ \nu_e$

2-body Decay Kinematics

- Energy of neutrino uniquely determined here…

$P_t(\pi) \sim 300$ MeV



$$\theta_\pi \sim \frac{300 \text{ MeV}}{P(\pi)}$$

$$\gamma_\pi = E_\pi / m_\pi$$

$$E_\nu \sim \frac{0.43\, E_\pi}{1 + \gamma_\pi^2 \theta_\nu^2} \qquad \text{Flux} \sim \frac{\gamma_\pi^2}{(1 + \gamma_\pi^2 \theta_\nu^2)^2}$$

3-body kinematics

- The story is not as simple with 3-body decays

2-body decays:

$\pi^+ \rightarrow \mu^+ \nu_\mu$

$K^+ \rightarrow \mu^+ \nu_\mu$

3-body decays:

$\mu^+ \rightarrow e^+ \nu_e$ anti-ν_μ

$K^+ \rightarrow \pi^0 e^+ \nu_e$

  - Energy not uniquely determined
  - Average neutrino energy still proportional to parent energy

“Wrong Sign” Neutrinos

- Why are there antineutrinos in a neutrino beam?

$\pi^+ \rightarrow \mu^+ \nu_\mu$
$K^+ \rightarrow \mu^+ \nu_\mu$

$\mu^+ \rightarrow e^+ \nu_e$ anti-ν_μ
$K^+ \rightarrow \pi^0 e^+ \nu_e$

$\pi^- \rightarrow \mu^-$ anti-ν_μ
$K^- \rightarrow \mu^-$ anti-ν_μ

$\mu^- \rightarrow e^-$ anti-ν_e ν_μ
$K^- \rightarrow \pi^0 e^-$ anti-ν_e

2 components: “wrong sign” mesons that decay, or muon decay

Proton beam Basics

- Rules of Thumb
  - number of pions produced is roughly a function of "proton power" (or total number of protons on target x proton energy)
  - The higher energy ν beam you want, the higher energy p you need

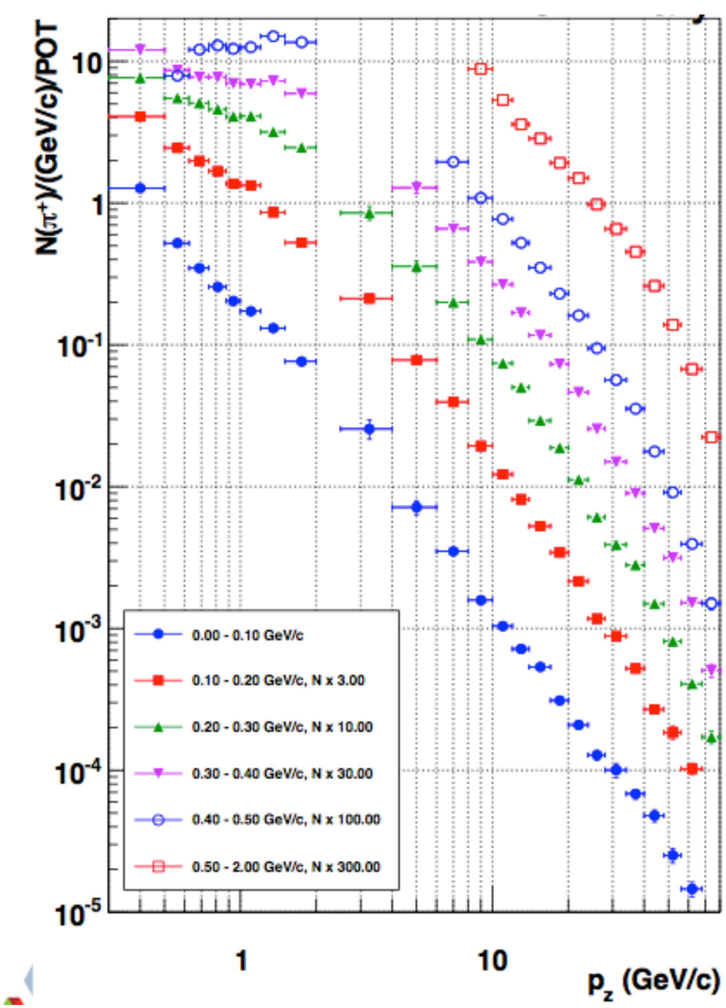
Proton Source	Experiment (current)	Proton Energy (GeV)	p/yr	Power (MW)	Neutrino Energy (GeV)
FNAL Booster	MicroBooNE	8	5×10^{20}	0.05	1
FNAL Main Injector	MINOS+, MINERvA, NOvA	120	$3\text{-}6\times 10^{20}$	0.3 to 0.7	3-17
CNGS	OPERA,ICARUS	400	0.45×10^{20}	0.48	25
J-PARC	T2K	40-50	11×10^{20}	0.25 to 0.75	0.77

Neutrino Production Targets

- Have to balance many competing needs:
  - The longer the target, the higher the probability the protons will interact
  - The longer the target, the more the produced particles will scatter
  - The more the protons interact, the hotter the target will get—targeting above ~1MW not easy!
  - Rule of thumb: want target to be 3 times wider than +- 1 sigma of proton beam size

Hadron Production

- This is tricky stuff, hard to predict with theory alone
- Copious thin target measurements available, but neutrino targets are usually long
- NA61 data from CERN: thin and thick target data used for T2K analysis
- New: MIPP hadron production results (Fermilab), using same target as used for MINOS, and 120GeV protons (at right)



Ref: J.M.Paley, et al, Phys.Rev. D90 (2014) 3, 032001

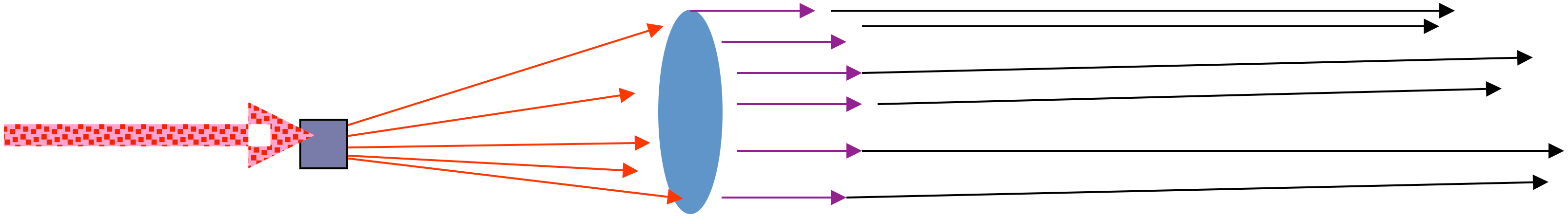
Focusing Systems

- Want to focus as many particles as possible for highest neutrino flux
- Typical transverse momentum of secondaries:

  approximately Λ_{QCD}, or about 200MeV
- Minimize material in the way of the pions you've just produced
- What kinds of magnets are there?
  - Dipoles—no, they won't focus
  - Quadrupoles
    - done with High Energy neutrino beams
    - focus in vertical or horizontal, need pairs of them
    - they will focus negative and positive pions simultaneously

What focusing works best?

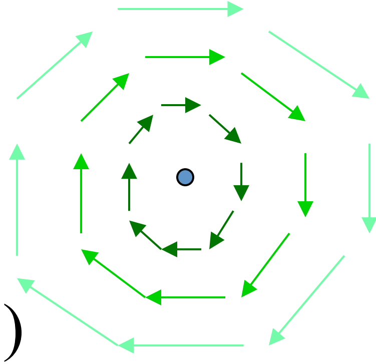
- Imagine particles flying out from a target:
  - When particle gets to front face of horn, it has transverse momentum proportional to radius at which it gets to horn



B Field from line source of current is

in the Φ direction

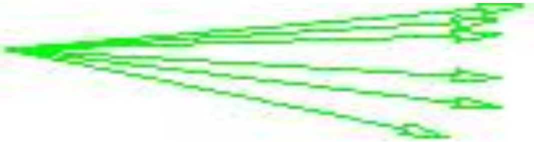
but has a size proportional to 1/r



How do you get around this? (hint: $\partial p_t \propto B \times \partial l$)

What should the B field be?

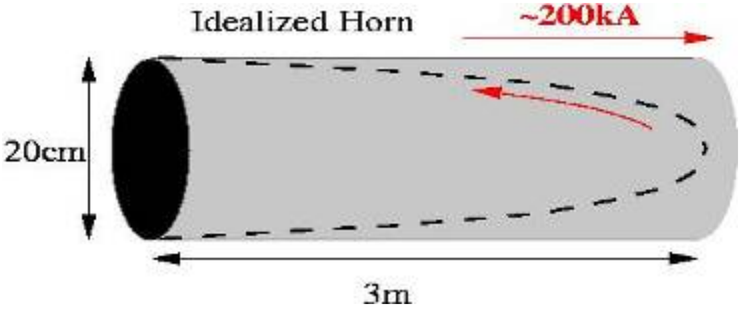
FROM



TO

- Make the particles at high radius go through a field for longer than the particles at low radius. ($B \propto 1/r$, but make $dl \propto r^2$)
- Horn: a 2-layered sheet conductor
- No current inside inner conductor, no current outside outer conductor
- Between conductors, toroidal field proportional to 1/r

$$\delta p_t \approx \frac{e\mu_0 I}{2\pi c r} \times \frac{r^2 l}{r_{outer}^2} \approx p_{tune}\theta$$



Horn Photo Album

	Length (m)	Diameter (m)	# in beam
K2K	2.4,2.7	0.6,1.5	2
MBooNE	~1.7	~0.5	1
NuMI	3,3	0.3,0.7	2
CNGS	6.5m	0.7	2
T2K	1.4,2,2.5	.47,.9,1.4	3

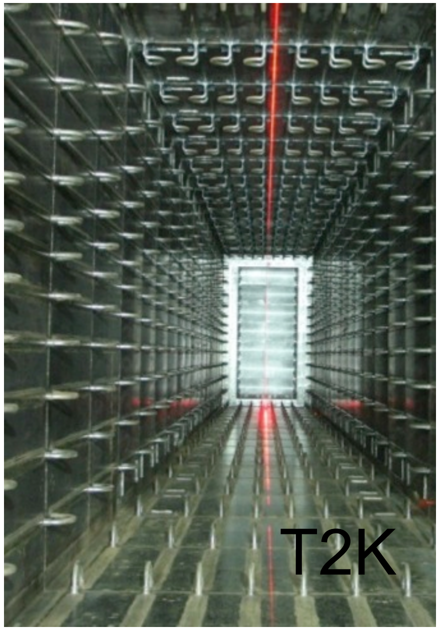
Designing what provides the 180kA is almost as important as designing the horn itself!

Decay Regions

- How long a decay region you need (and how wide) depends on what the energy of the pions you're trying to focus.
- The longer the decay region, the more muon decays you'll get (per pion decay) and the larger ν_e contamination you'll have
- *What is better: air, vacuum window, or He-filled decay pipe? Does it depend on energy?*

	Length	Diameter
BNB	50m	1.8m
NuMI	675m	2m
CNGS	1000m	2.45m
T2K	130m	Up to 5.4m

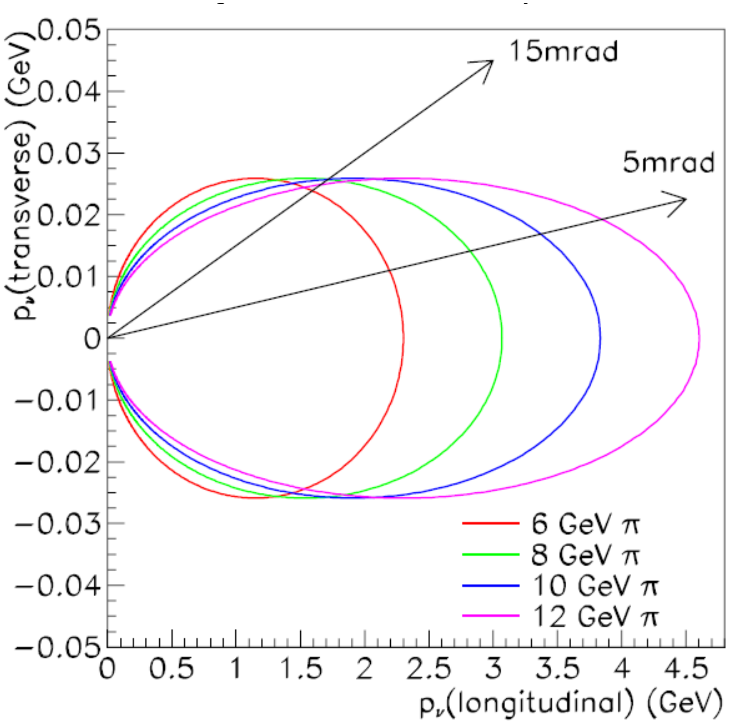

NUMI

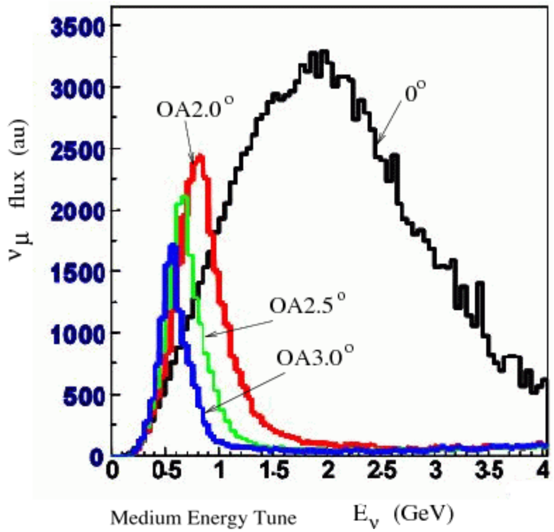

T2K


CNGS

Off-Axis Technique

- 1-1 relationship between neutrino energy and pion energy+angle between neutrino and pion
- Off axis neutrino beams: aim pions and kaons AWAY from detector





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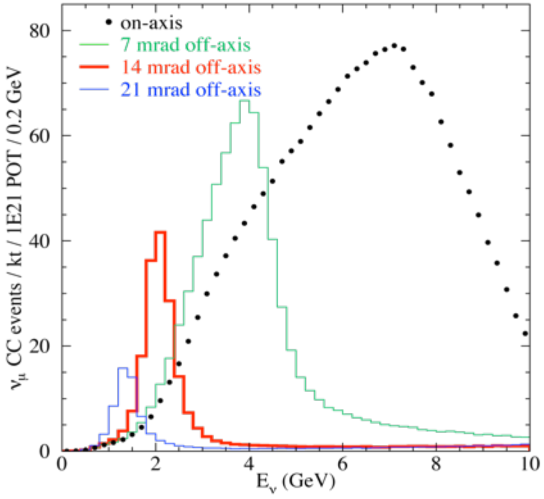


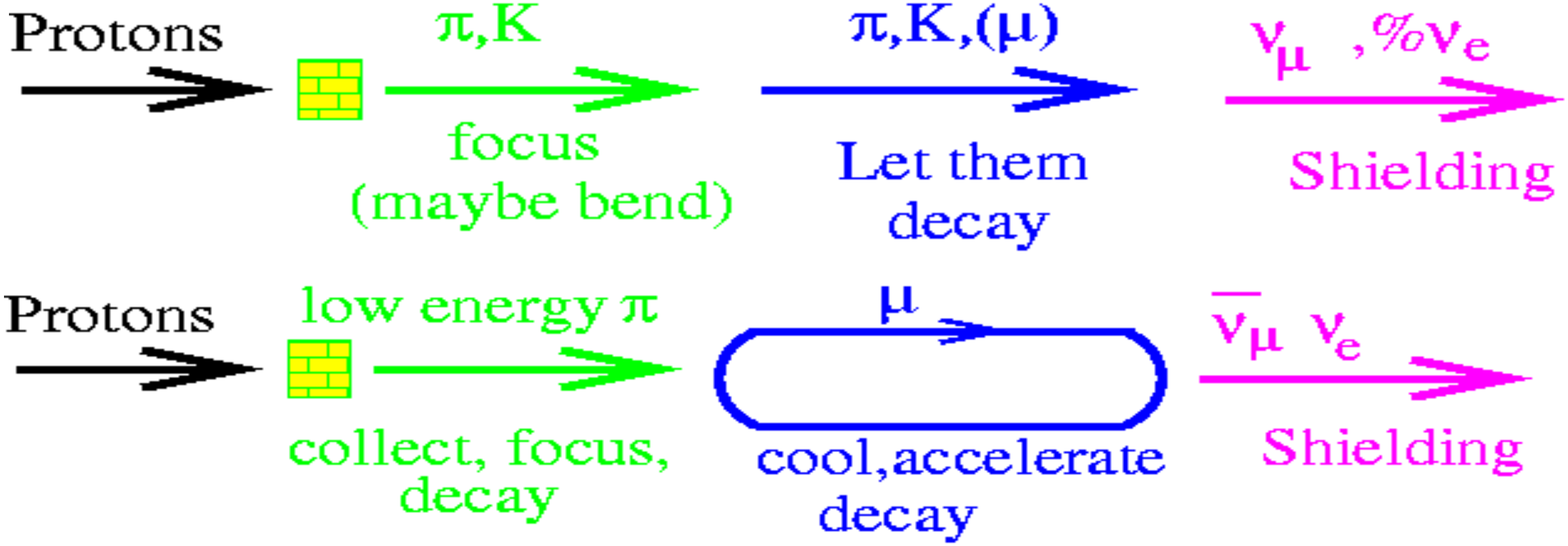
NOvA

Experimental Challenges with Accelerator-based Neutrinos

- Operations
  - Target and horns must be robust
  - Still working on a target that can survive 1MW beam power
- Composition
  - Can never make pure beam, always some contamination of anti-neutrinos or ν_e's in what you designed as ν_μ beam
- Flux Predictions
  - Hadron production uncertainties still at the 5% level even with new data
  - Using different hadron shower models to predict flux gives even higher differences
  - Beamline optics can also introduce uncertainties

Other Neutrino Source: "Neutrino Factory"

- Neutrino Factory: what if you could collect and accelerate large numbers of muons?



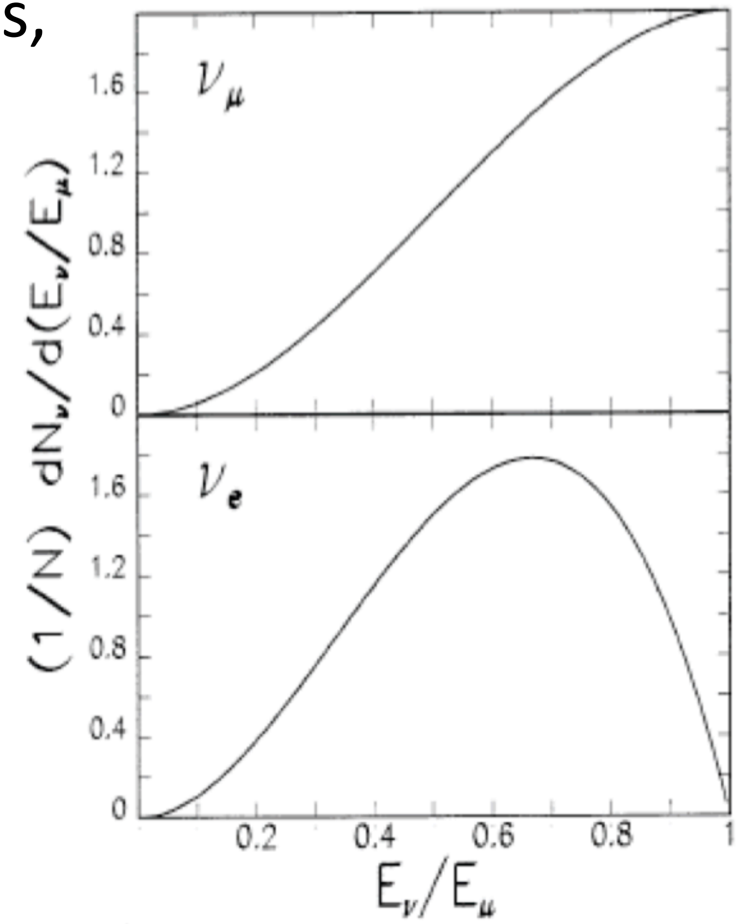
- Good news: fluxes per proton on target can be much higher than conventional beams (γ^3)
- Bad news: oscillation experiments way low γ

Neutrino Factory Fluxes

- Neutrino Spectrum precisely determined
- To measure ν_μ to ν_e oscillations, only need to know charge of final state muon in detector
- Back when ν_μ to ν_e oscillations were assumed to be tiny, this looked like an absolutely critical necessity

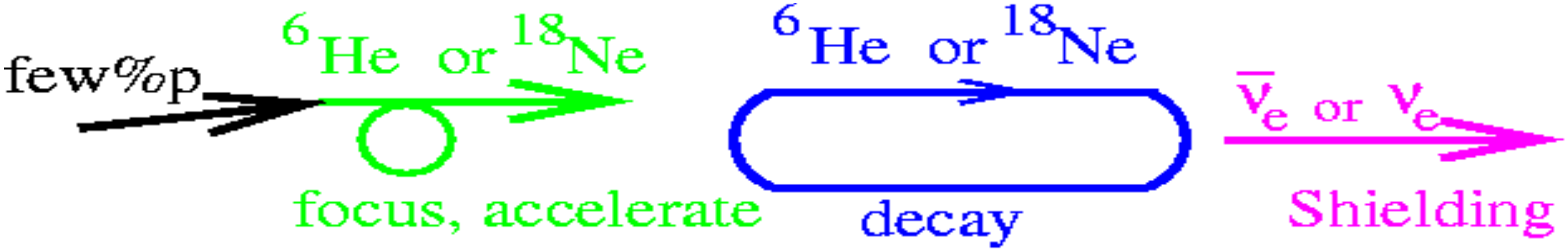
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



Still another idea: "Beta Beam"

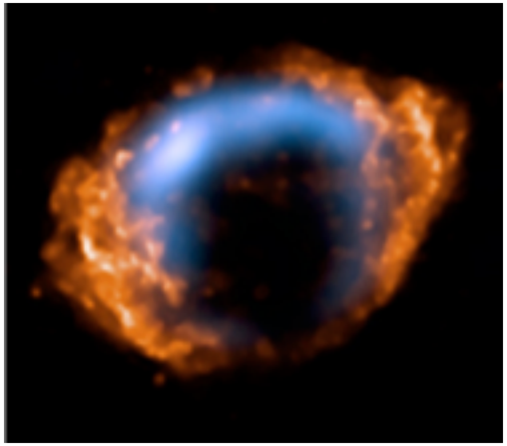
- What if you could accelerate a huge number of a radioactive isotope?



- This would give you a very pure beam of electron neutrinos (or anti-neutrinos)
- Accelerator challenges are even larger here
- Need to make ν_e's energetic enough so that if they oscillate to ν_μ's they can produce a muon in a charged current interaction

Ultra-High Energy Neutrinos

- Same mechanism we've seen before: pion decay
- Question is: where do those high energy pions come from?
  high energy protons



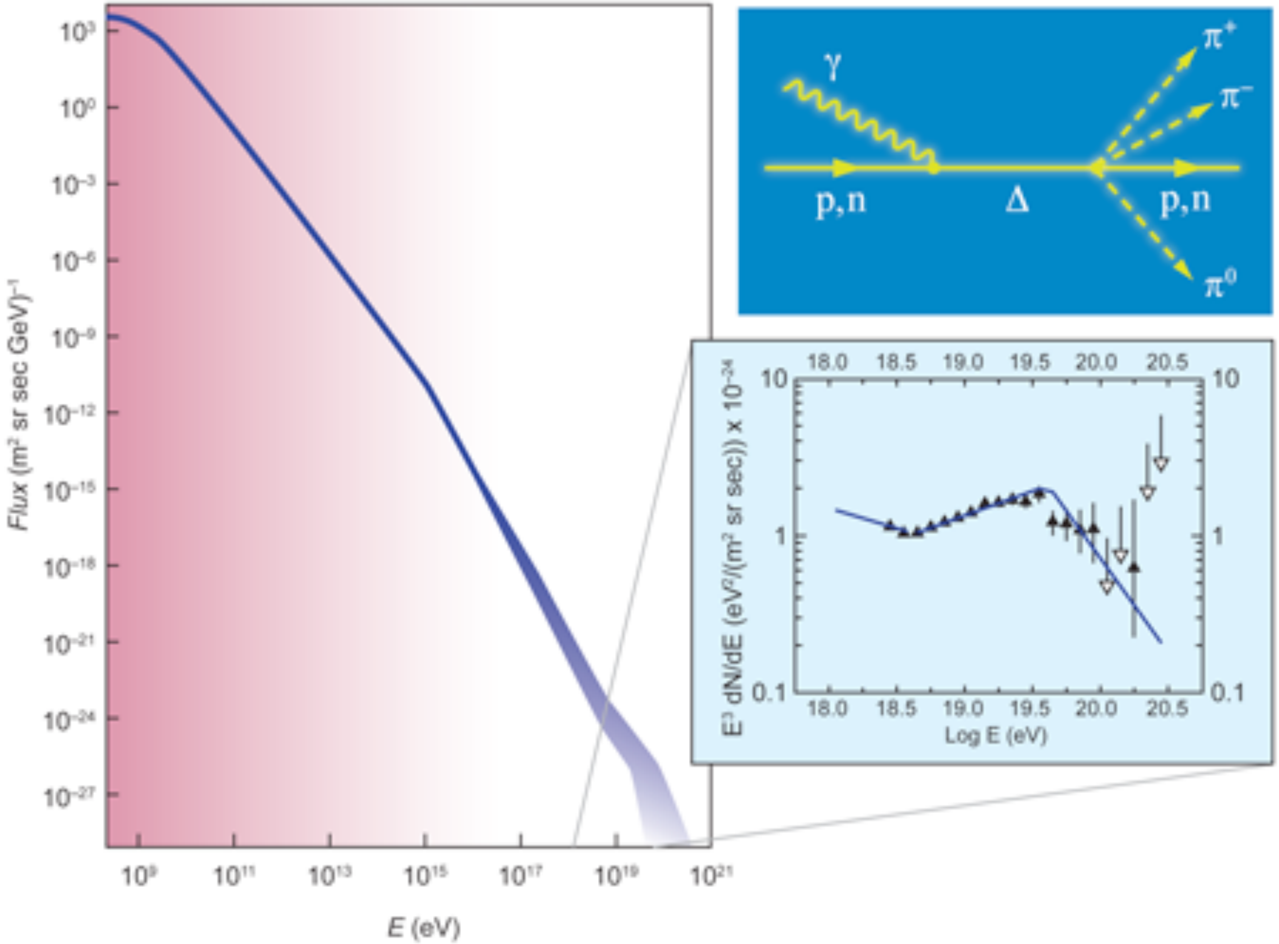
$$pp \to NN + \text{pions}; \qquad p\gamma \to \mathrm{p}\pi^0,\ n\pi^+$$

$$\pi^+ \to \nu_\mu + \underset{\substack{\downarrow \\ \bar{\nu}_\mu + e^+ + \nu_e}}{\mu^+}$$

- Seeing ultra-high energy neutrinos can provide input into models for proton acceleration mechanisms (GRB's, AGN's?)

Other High Energy Mechanisms

- "GZK neutrinos" : What happens if a proton is so high in energy that it can interact with a CMB photon to make a delta?
- What about other massive particles (not in standard model) anihilating in outer space and making neutrinos?
- Your idea here…



Graphics courtesy Joe Formaggio

Neutrino Source Summary

Source	Flux	ν Energy	Composition	Baseline	Matter Effects?
Big Bang	110/cm^3	0.17meV	All flavors	n/a	no
Supernovae	variable	~50MeV	All flavors	depends	yes
Sun	6x10^{10} ν/cm^2/sec	0.1-10MeV	ν_e (ν_2)	10^{8}km	yes
Reactor	10^{20} ν/sec/GW	1-10MeV	Anti-ν_e	1-180km	Not yet…
Atmosphere	1 ν/cm^2/sec	0.1-10^{4}GeV	ν_e+ν_μ and anti-	80-10^{4}km	yes
Accelerator	6x10^5 ν/cm^2/sec @1km*	0.1-100GeV	ν_μ+%ν_e or anti-ν_μ+%ν_e	1-1000km	yes

* NuMI beamline “low energy tune”, on axis, currently x3 higher!

What to remember from this lecture

- Neutrinos come from only two interactions, but span a great energy range 0.2meV to PeV
- Most sources produce broad range of energies
- Neutrinos are messengers from many places
  - First seconds after birth of universe
  - Inside of a star
  - Our own sun
  - Reactor cores
  - Highest energy accelerators ever found in nature
- We have ways to make custom neutrino beams so we can study neutrinos precisely

Sources

- Sources
  - Joe Formaggio, 2009 International Neutrino Summer School
  - Takaaki Kajita, 2013 International Neutrino Summer School
  - Jenni Adams, 2014 International Neutrino Summer School
- Conventional Neutrino Beam Reference:
  - S. E. Kopp, Phys.Rept. 439 (2007) 101-159