Do-it-yourself Neutrinos: Beams, stars, and other weekend projects

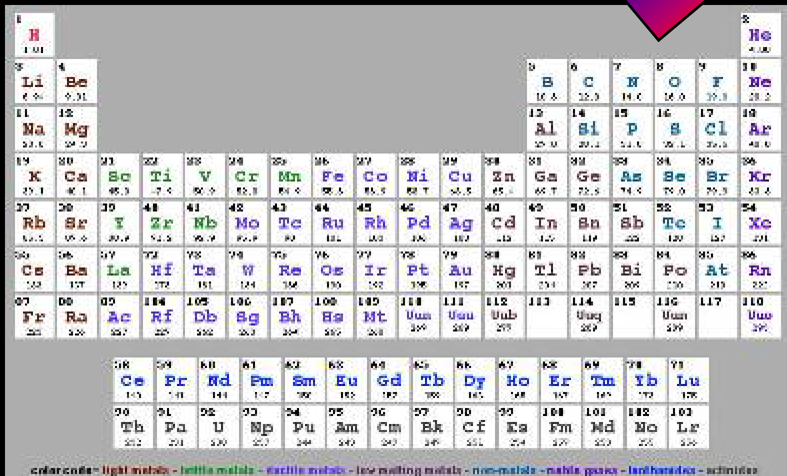
Many Early Slides stolen shamelessly from
Joe Formaggio's
2009 INSS lecture on sources
http://vmsstreamer1.fnal.gov/VMS_Site_03/Lectures/NuSS/090706Formaggio/index.htm

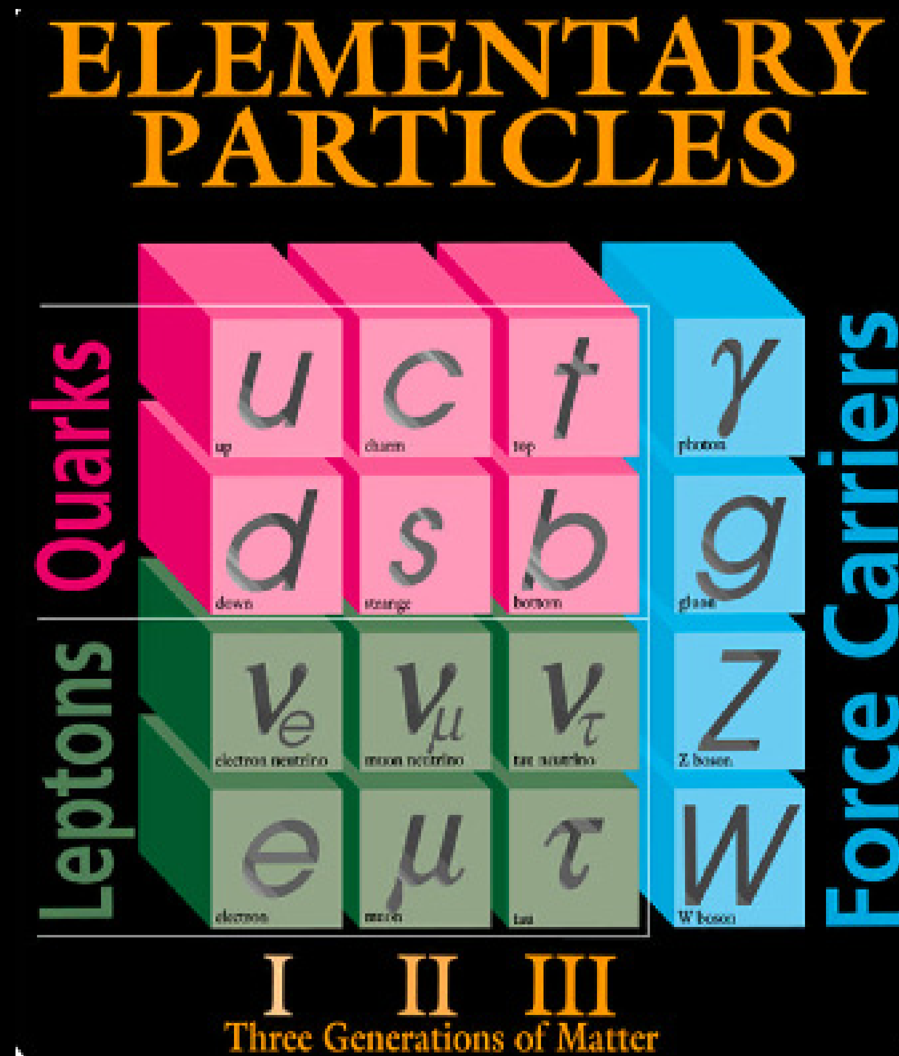
Deborah Harris

June 24, 2010

How do neutrinos fit in?

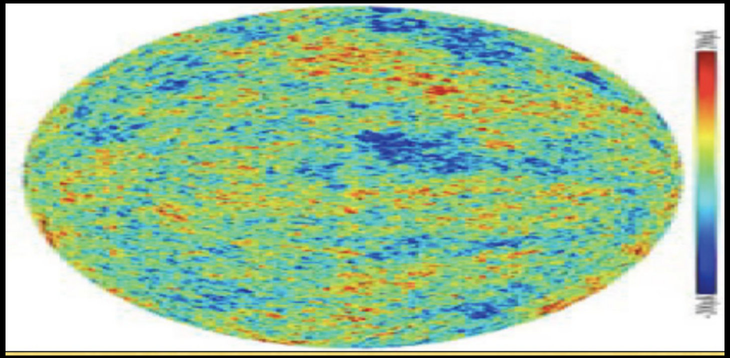
- What is the world made of?
- Molecules
- Atoms
  - Protons
  - Neutrons
  - Electrons





In the beginning…

- Remember the Big Bang?
  - Lots of particles produced all at once, including neutrinos and antineutrinos
  - They can annihilate with eachother…
  - High density of neutrinos and electrons, they interact with each-other easily and "cool together" as universe cools down
  - As universe expands, neutrinos transition from when they are in thermal equilibrium with electrons to one where they are decoupled
  - Infer from how many photons left over from the big bang: these neutrinos are:

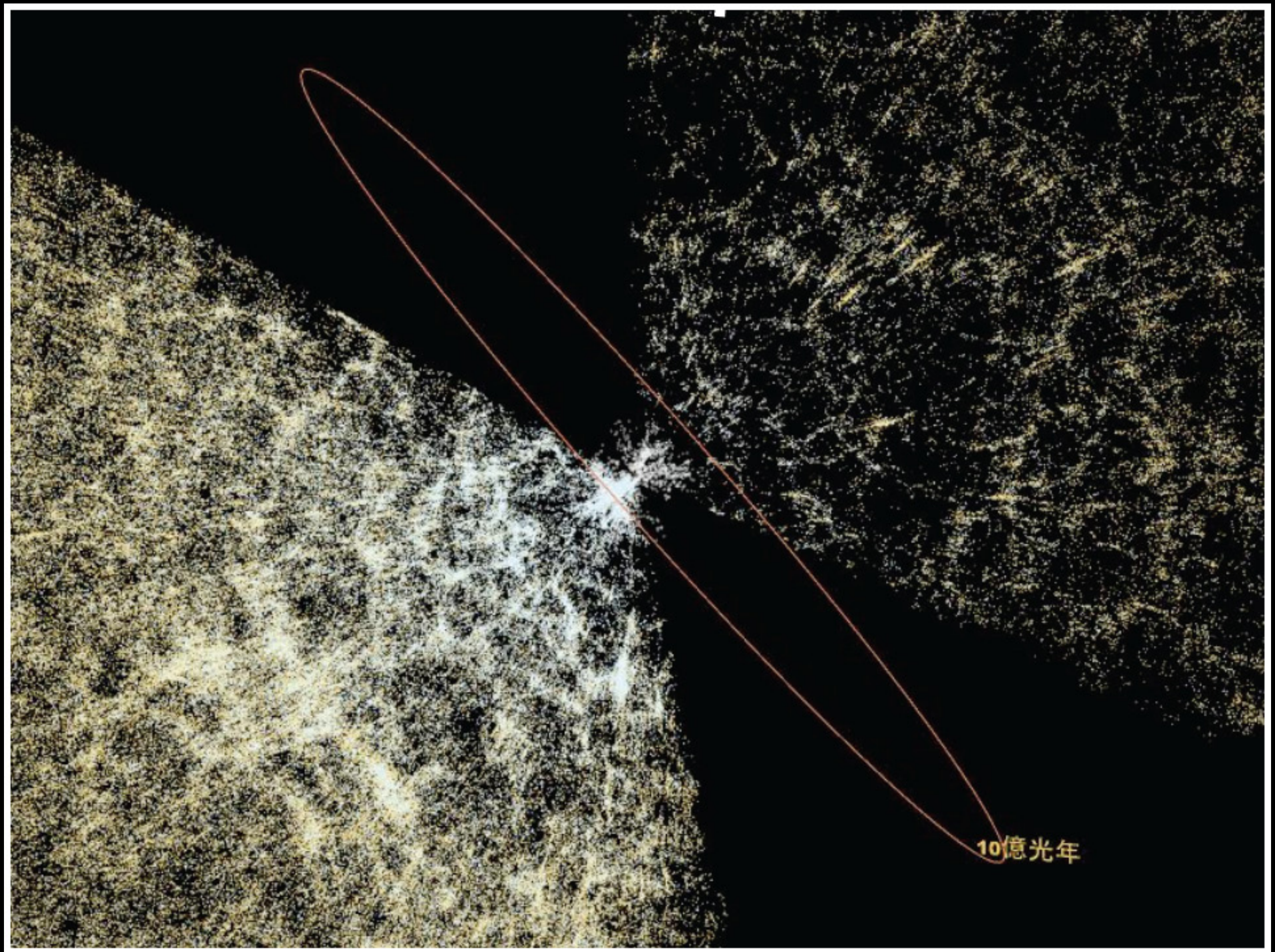


Temperature of decoupling…

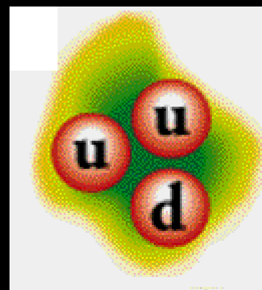
$$T_D(\nu_e) \simeq 2.4 \text{ MeV}$$
$$T_D(\nu_{\mu,\tau}) \simeq 3.7 \text{ MeV}$$

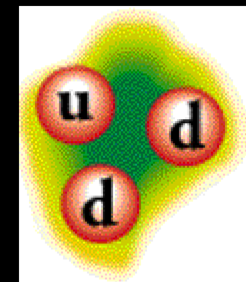
Why do we care about such low energy neutrinos?

- They affected how galaxies clustered and give us the (night) sky we see…

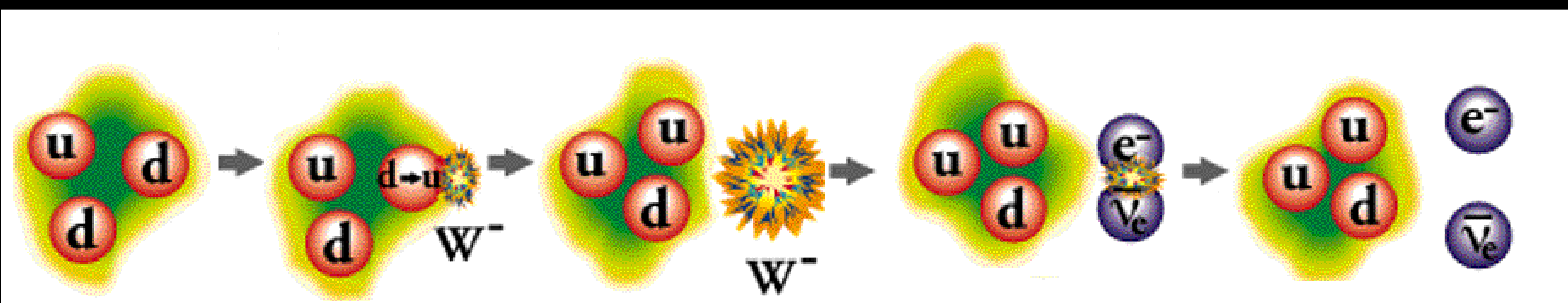


From neutrons to protons

- Proton 

- Neutron 

Neutrinos get you from neutron to proton, or from down to up



$$n \rightarrow p\ e^- \ \bar{\nu}_e$$

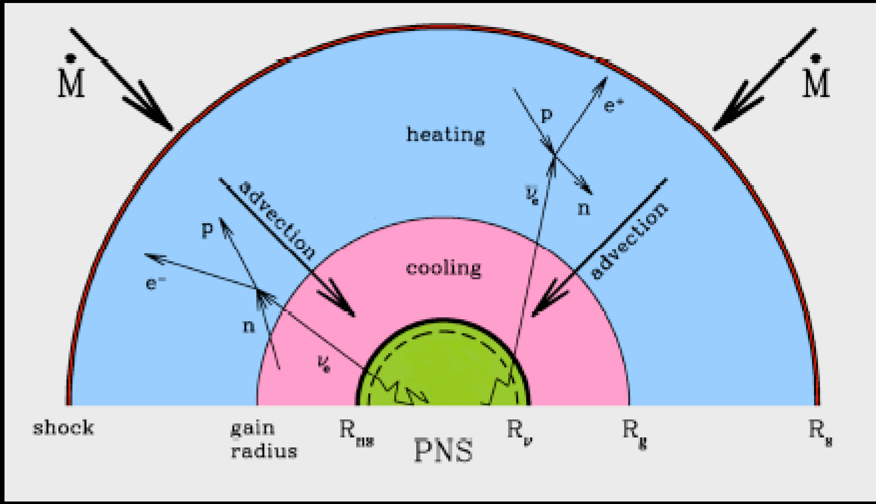
See www.Particleadventure.org

Neutrino Sources

- Any time you have protons turning into neutrons or vice versa, you make neutrinos
  – (fission, fusion, you get the idea)
- Any time you have particles undergoing a weak decay, you make neutrinos
- The energy from each source depends on the energy of the other particles involved

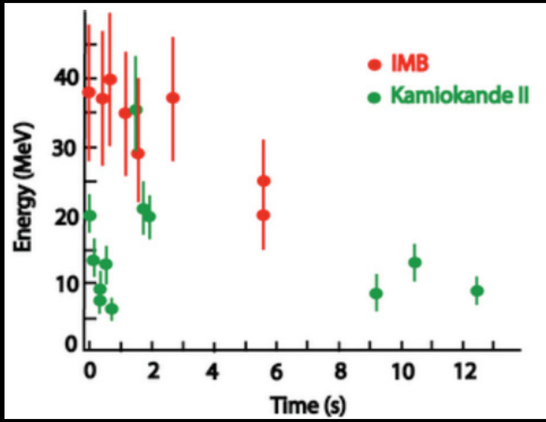
Death of a Star

- When a star undergoes core collapse, it's another situation with a lot of neutrinos in a small volume
- Lots of energy, you can produce all flavors of neutrinos
- Almost all gravitational energy gets radiated away as neutrinos
- Intense enough to be seen on Earth…



Supernovae 1987A

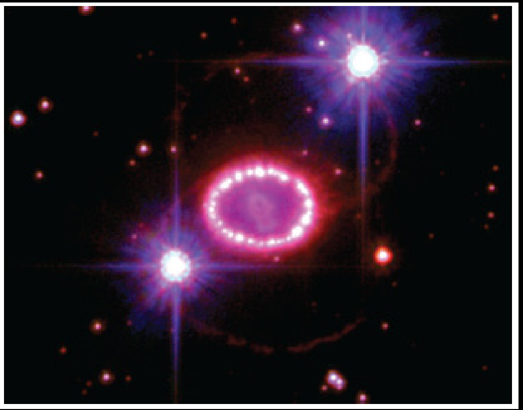
- SN1987A was seen by making use of the short time scale over which the neutrinos arrived at the earth
- Seen first optically
- Neutrino detectors were alive and taking data looking for other things…(proton decay)



Before

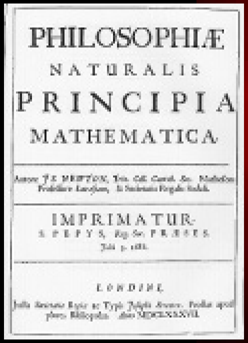
During (few days later)

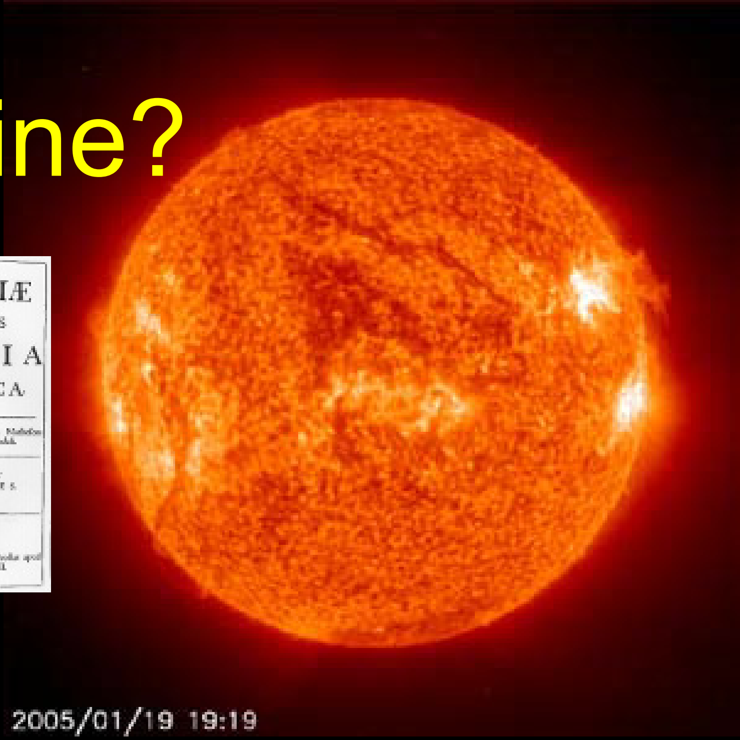
After



What makes the sun shine?

- Newton (1700's): sun weighs 2 million trillion trillion kilograms ($2x10^{30}$kg)



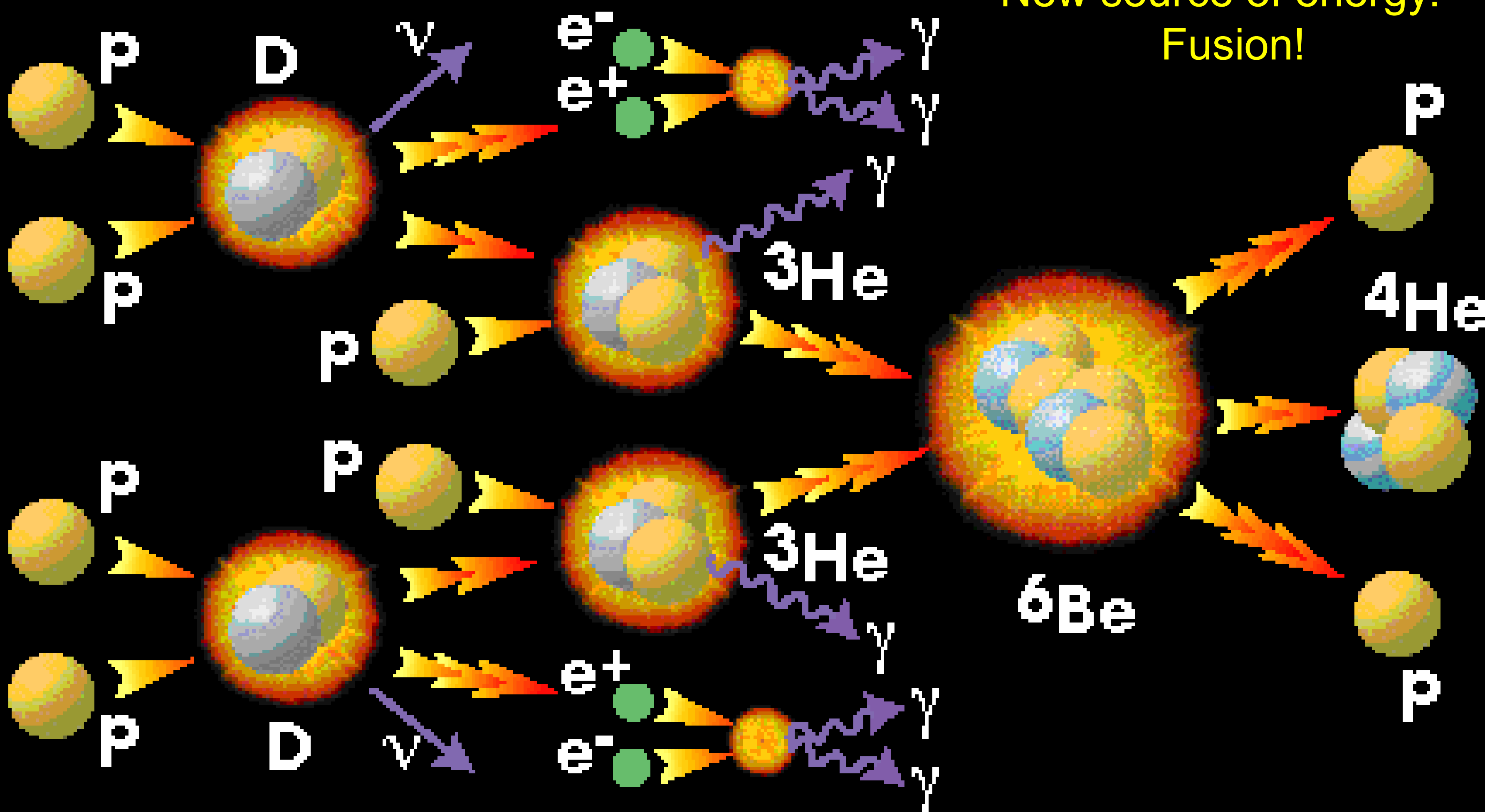


- We get about a million Joules for a kg of fuel

- We know how bright the sun is ($4x10^{26}$ Joules/second)
- Calculation: the sun will only burn 2 centuries…
- There are buildings older than that…how can this be?

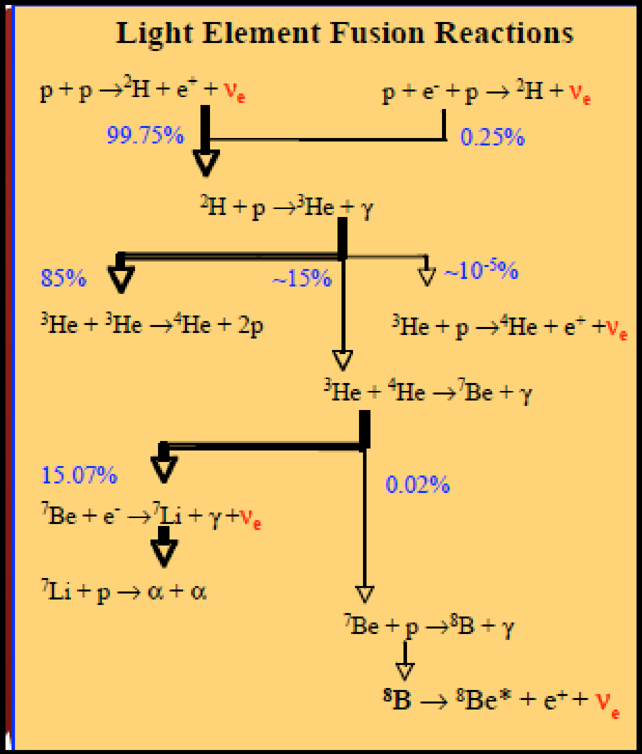
You guessed it: Neutrinos

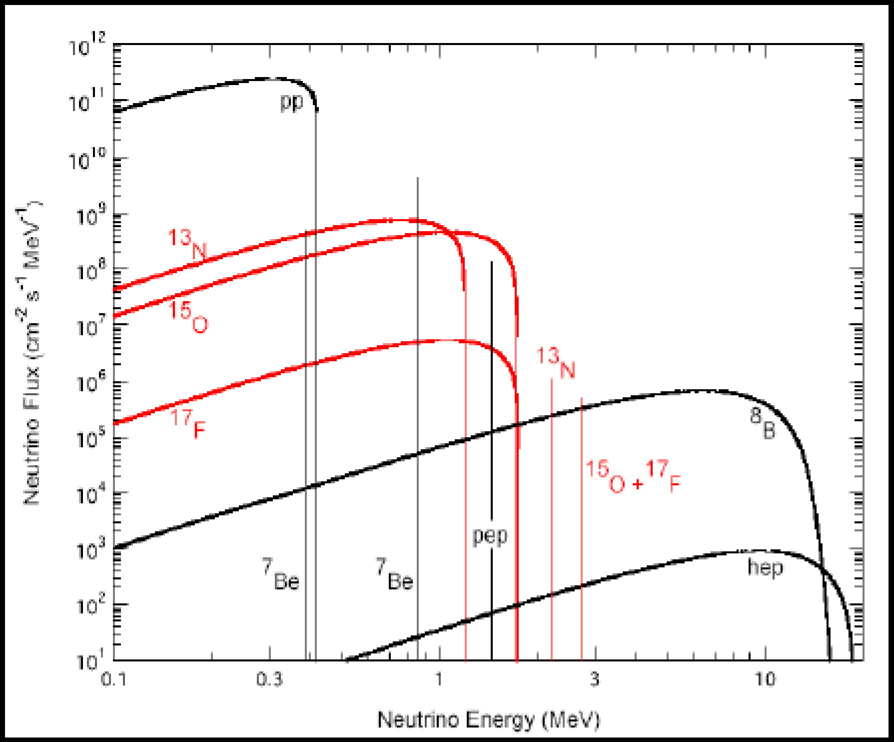
New source of energy:
Fusion!



Energies of Solar Neutrinos

- Several different chains of reactions that take place
- This leads to several different energy neutrinos…





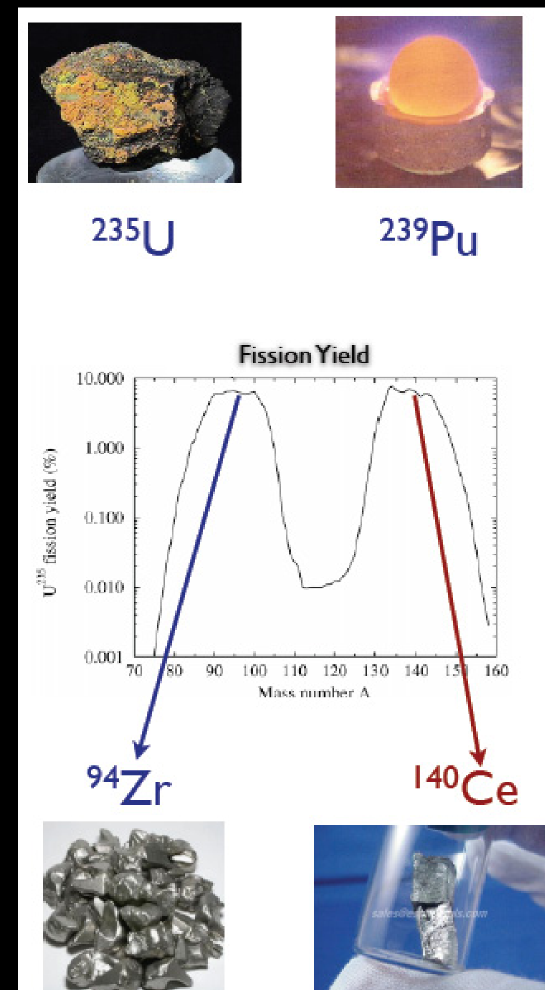
Neutrinos from Fission

- Example reaction…

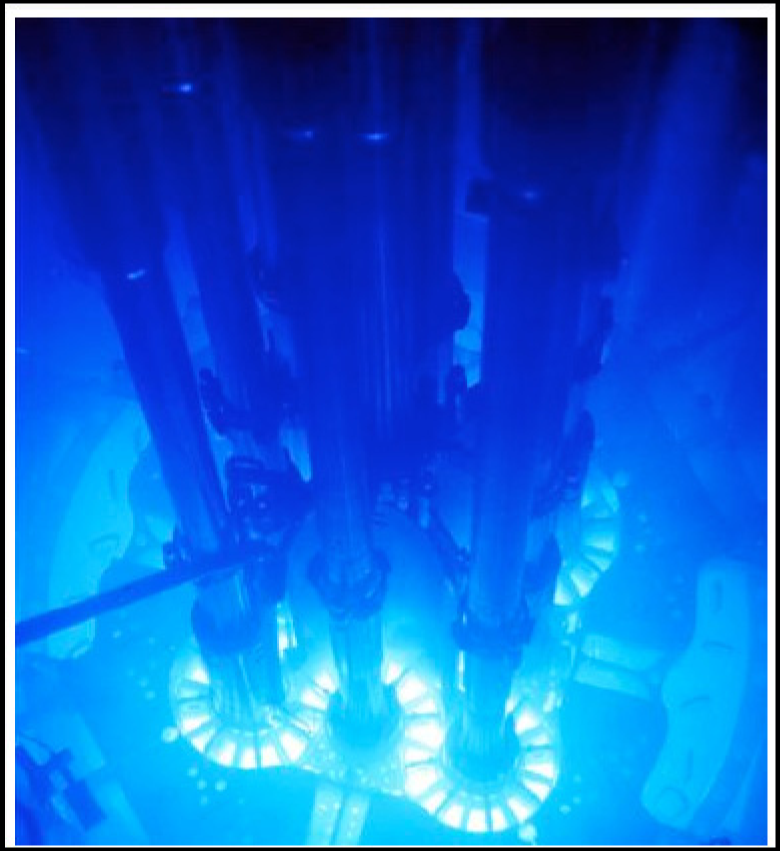
$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n \rightarrow$$

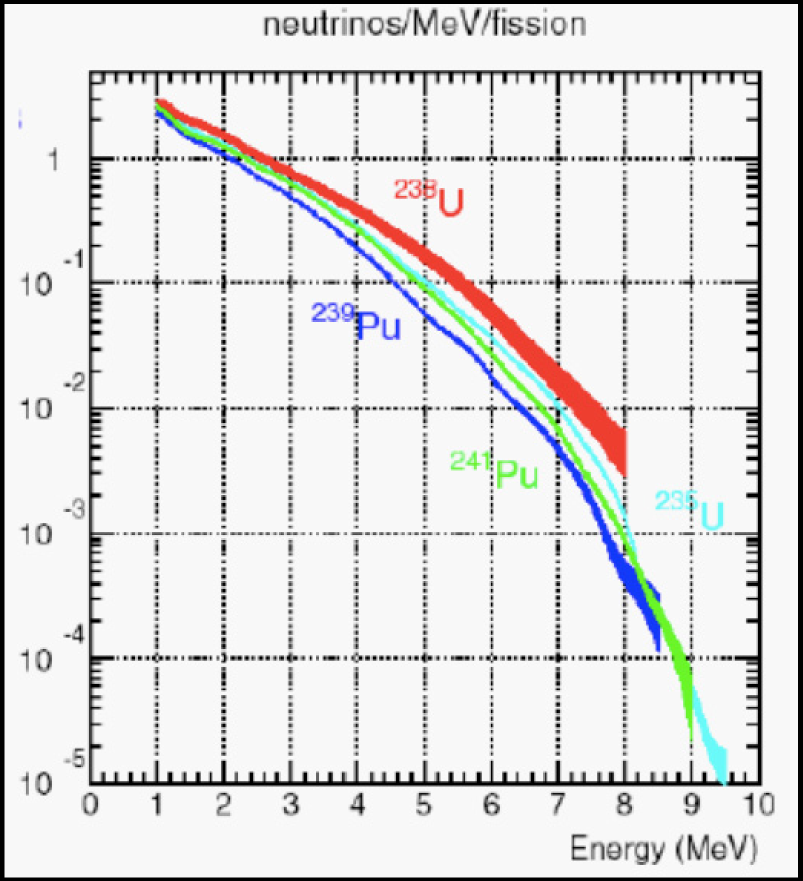
$$\ldots ^{94}_{40}Zr + ^{140}_{58}Ce$$

Sample Fission: ^{235}U



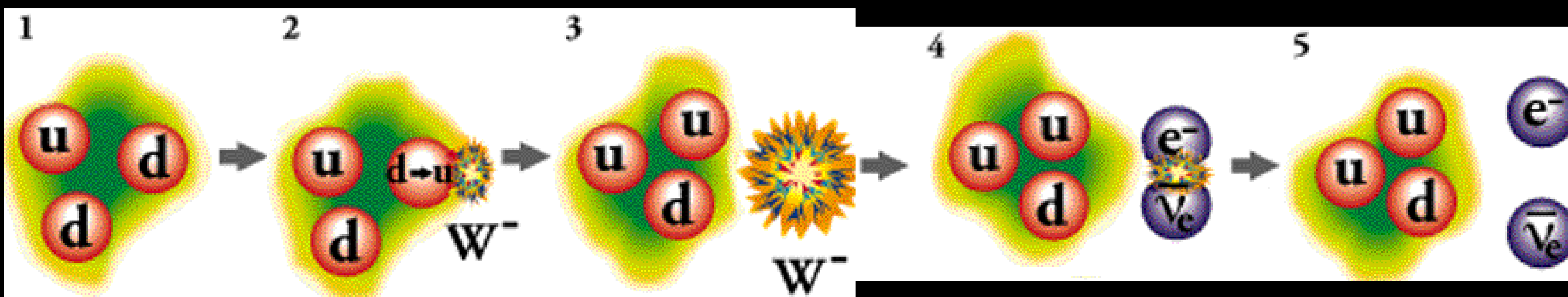
Neutrinos from Fission



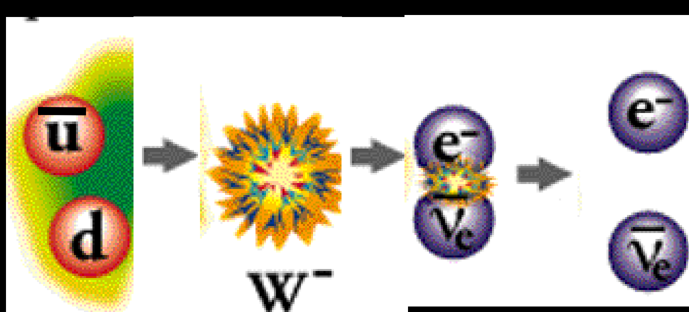


Neutrinos from Pions

Remember neutron decay?...subtract one quark, turn the other to an antiquark…



If d →u + W⁻ then d+anti-u → W⁻ and u+anti-d → W⁺



$\pi^- \rightarrow W^- \rightarrow e^- + \overline{\nu_e}$

$\pi^- \rightarrow W^- \rightarrow \mu^- + \overline{\nu_\mu}$

But not $\pi^- \rightarrow W^- \rightarrow \tau^- + \overline{\nu_\tau}$ why?

Neutrinos from Pions

$$\pi^- \rightarrow W^- \rightarrow e^- + \bar{\nu}_e$$
$$\pi^- \rightarrow W^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Change particles to antiparticles…

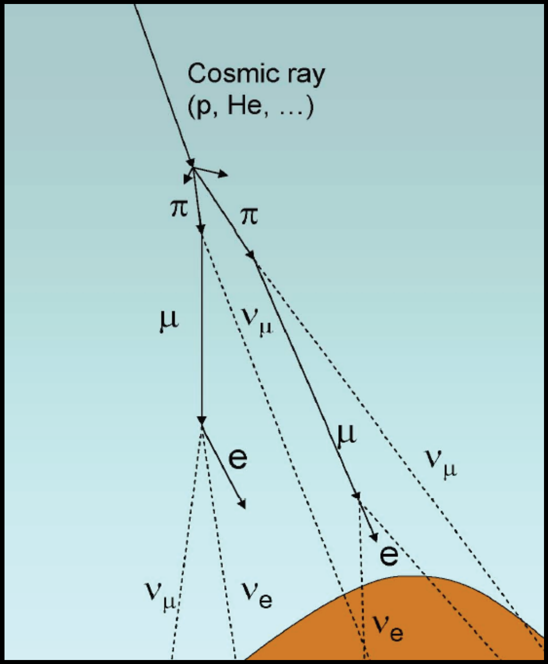
$$\pi^+ \rightarrow W^+ \rightarrow e^+ + \nu_e$$
$$\pi^+ \rightarrow W^+ \rightarrow \mu^+ + \nu_\mu$$

- Because of spin and pion and muon masses, pions decay to muons much more than they decay to electrons

But don't forget… $\mu^- \rightarrow W^- + \nu_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

Neutrinos from the Atmosphere

- Lots of high energy protons bombarding the atmosphere, making pions…guess what happens

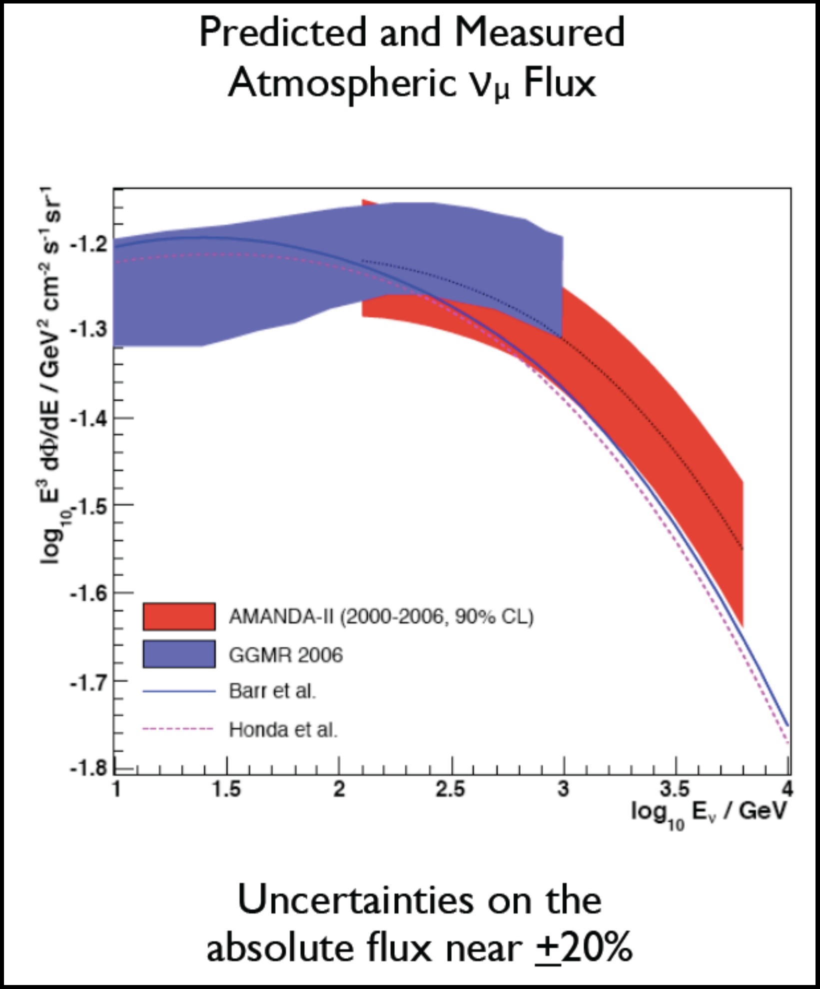


$$p +^{16} N \rightarrow \pi^+, K^+, D^+, \text{etc.}$$

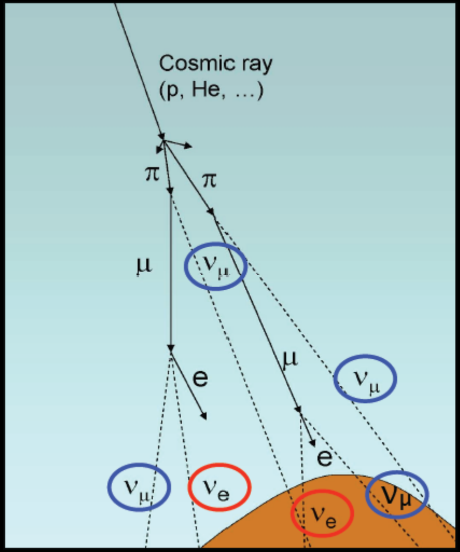
$$\pi^+ \rightarrow \nu_\mu + \mu^+$$

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

Neutrinos from the Atmosphere

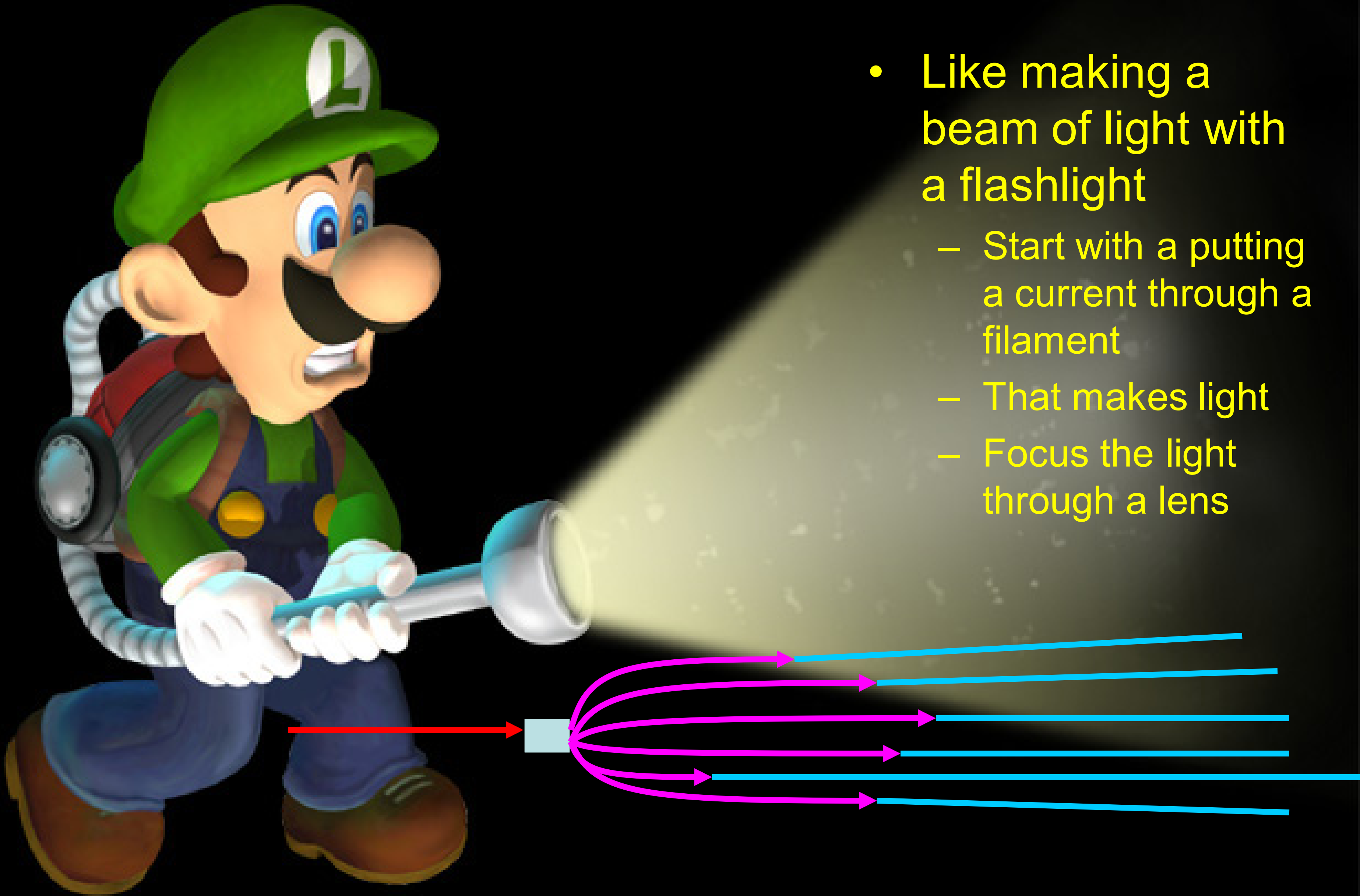


- Absolute Fluxes of muon neutrinos from atmosphere not so well known…
- But ratio of electron neutrinos to muon neutrinos pretty well-under-stood
- (2:1)



Neutrino Beams from accelerators…

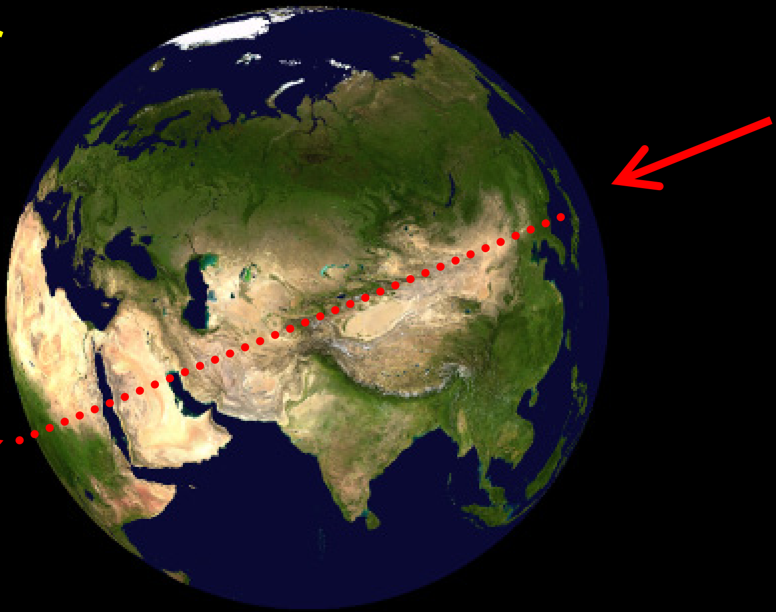
- Like making a beam of light with a flashlight
  - Start with a putting a current through a filament
  - That makes light
  - Focus the light through a lens

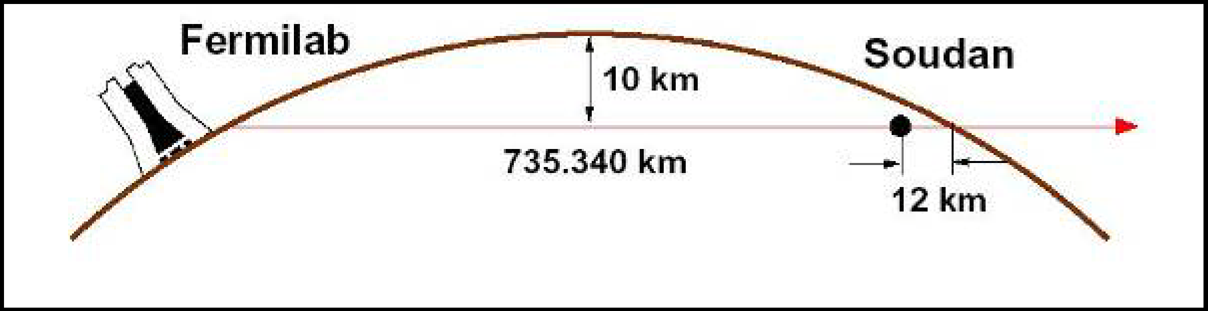


protons→target→unstable particles→neutrinos

Why are we sending a neutrino beam to Minnesota?

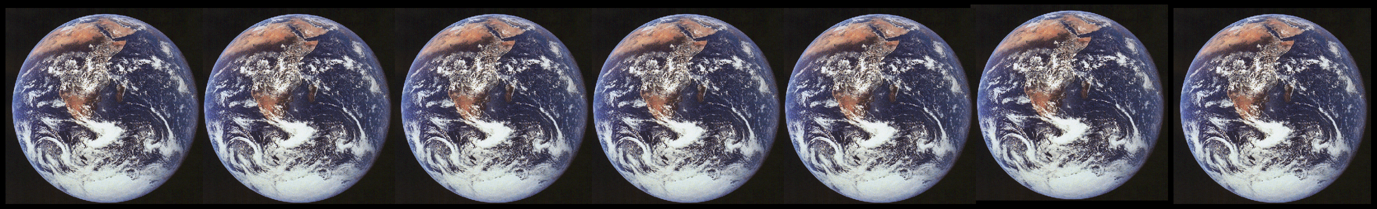
- The state with the most saunas per capita in the US
- They have the best iron mines
- Measurements of neutrinos from atmosphere:
  - Neutrinos from above don't change flavors
  - Neutrinos from below change a lot
  - Neutrinos have to go at least a few hundred miles to change at all
  - So we have to send a beam of neutrinos far enough through the earth so that they will have had at least that much time to change…



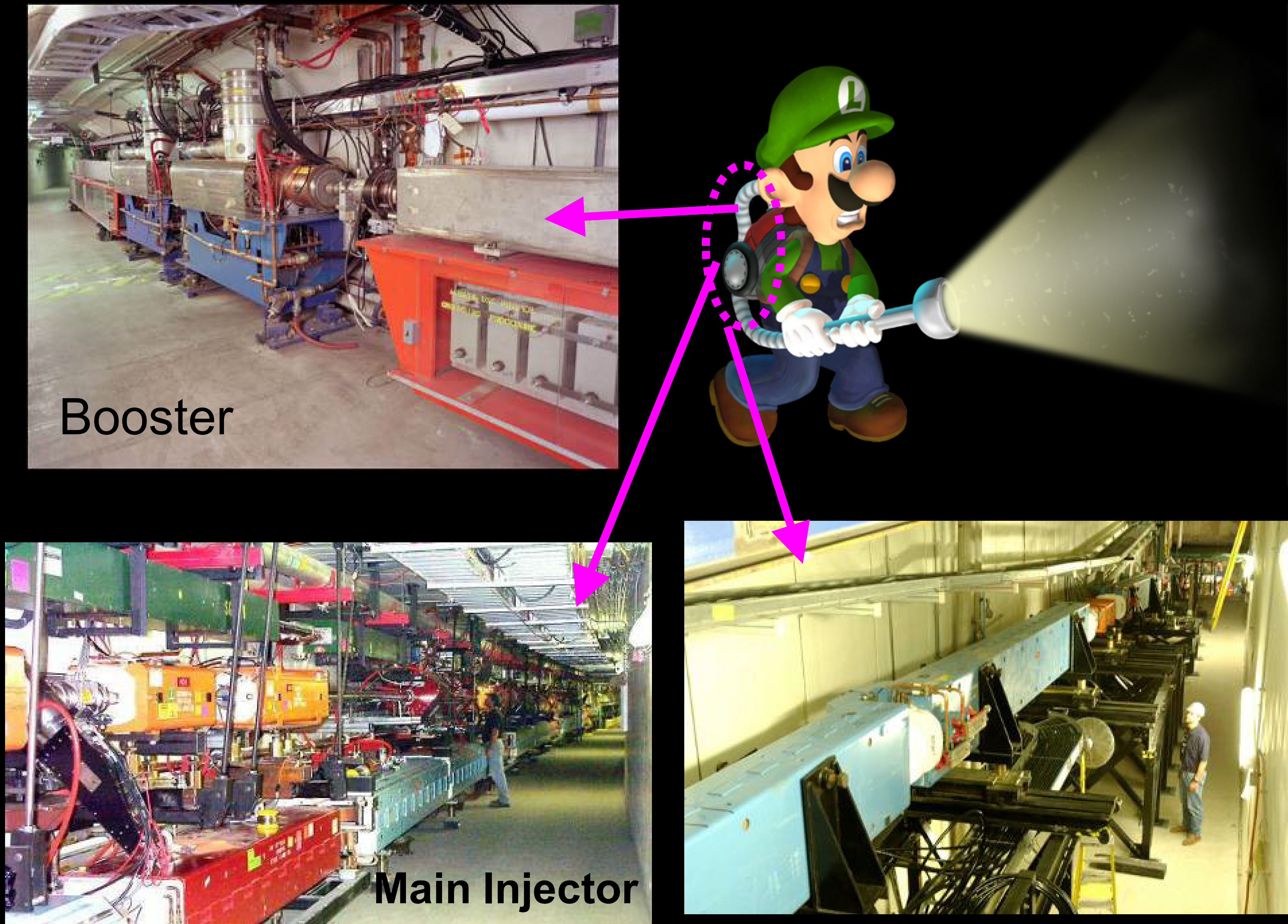


How do you get neutrinos from here to Minnesota?

- Just shoot them!
- Don't need a tunnel all the way there

$\nu \longrightarrow$  ……

- The catch:
  - Need lots of neutrinos
  - Need lots of detector

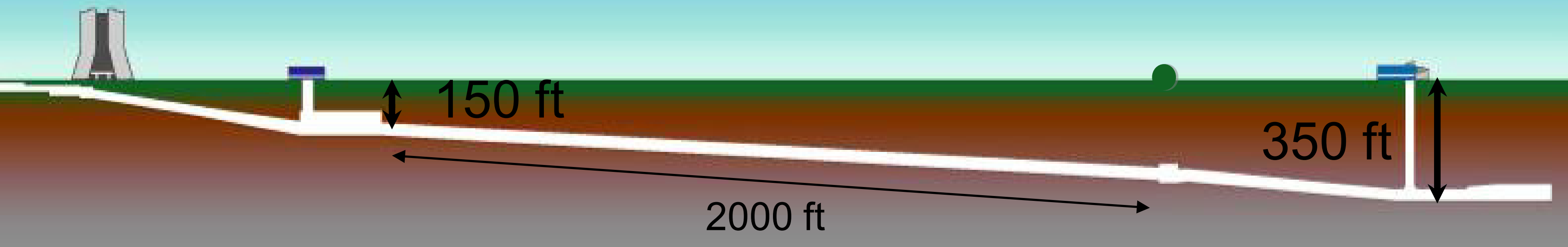

Booster
Main Injector

These targets see 10's' of trillions of
Particles:
How can you keep something cool when you keep pumping energy into it?

MiniBooNE power: 50 kWatts
MINOS power: 200kWatts
Hair Dryer: 1500Watts

- MiniBooNE Horn:
  - Has pulsed >100 million times
  - 5 times a second!
- MINOS Horns
  - 10 million pulses
  - Once every 2 seconds
- Horn Currents: ~200,000 Amps
- 200,000 toasters!

Beamline for MINERνA



- Miners excavated a mile of underground tunnels
- Inserted 6’ tall pipe
- Filled the rest back up with concrete: 3000 cement trucks’ worth of cement
- Two large halls
  - Target hall: filled with target, horns shielding blocks
  - Near Detector Hall: 150ft long, filled with MINOS Near detector
- 3½ year construction just to remove the rock…



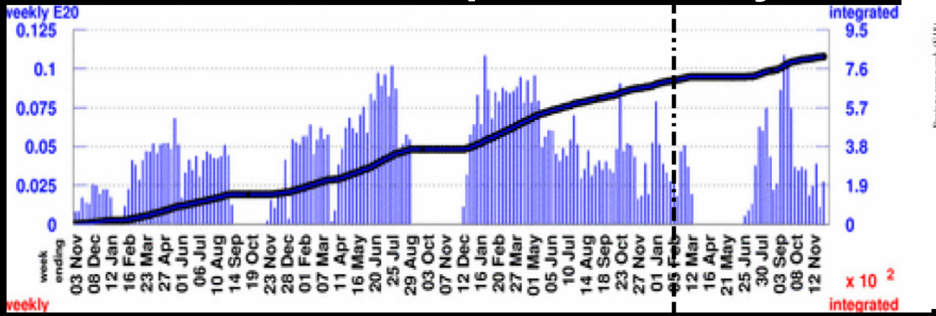


APR 17 2002

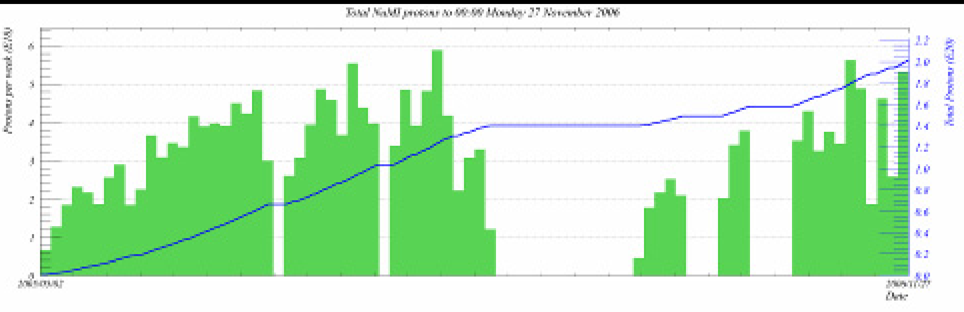
Ode to those who put the protons right on target

- In order to make neutrinos, someone has to accelerate protons
- Direct them through the beamline
- Hit the target
- And never miss!
- Like walking a mile with a glass full of milk that you cannot spill…
  - Over and over and over again for years…
- And what thanks do they get?

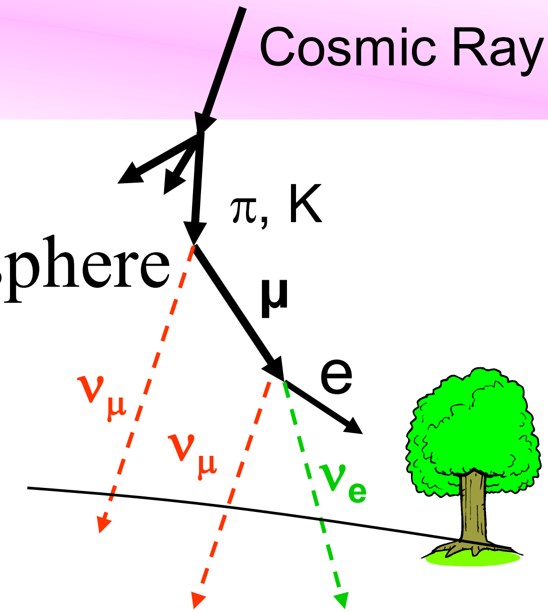
MiniBooNE: 9×10^{20} protons in 4 years!!!



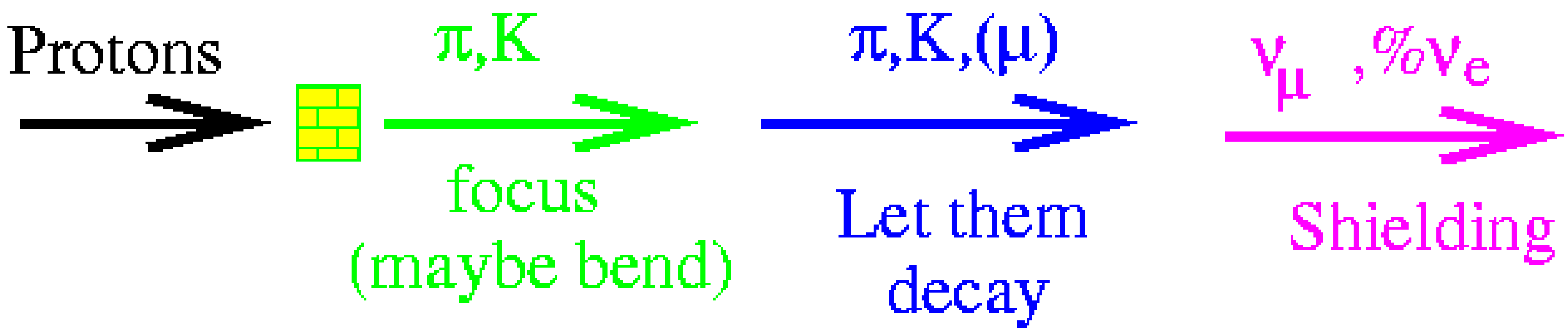
MINOS: 2×10^{20} protons in 1½ years!!!



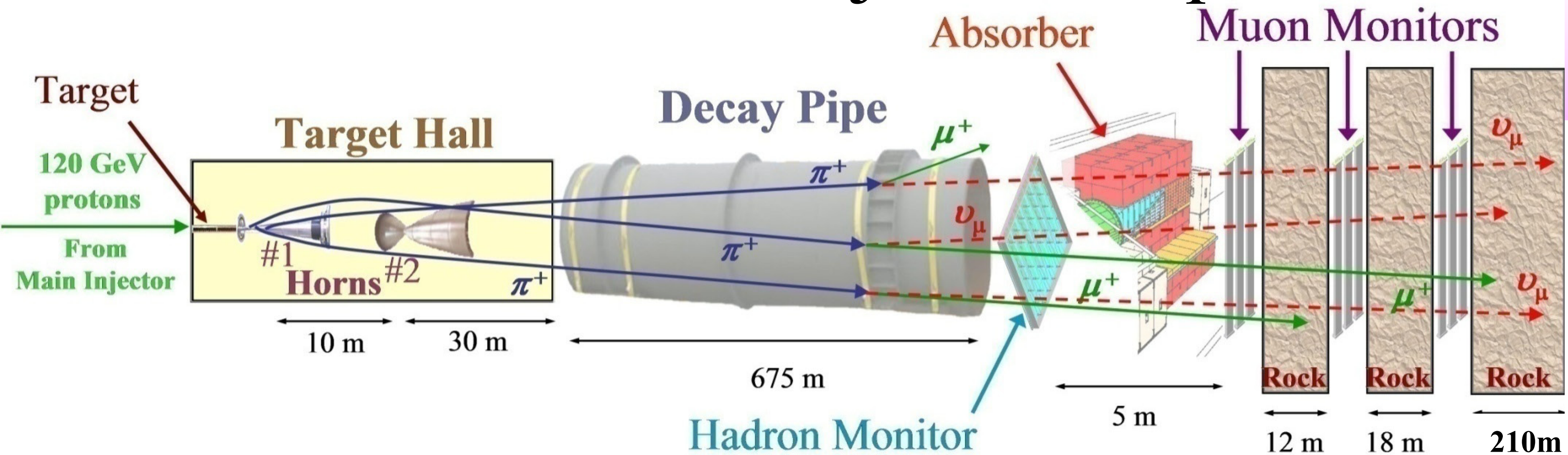
Neutrino Beam Fundamentals



- 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!



But we do more than just make pions…



Major Components:

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

Most ν_μ's from 2-body decays:

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

ν energy is only function of $\nu\pi$ angle and π energy

Most ν_e's from 3-body decays:

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

Proton Beam

- 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 protons you need…

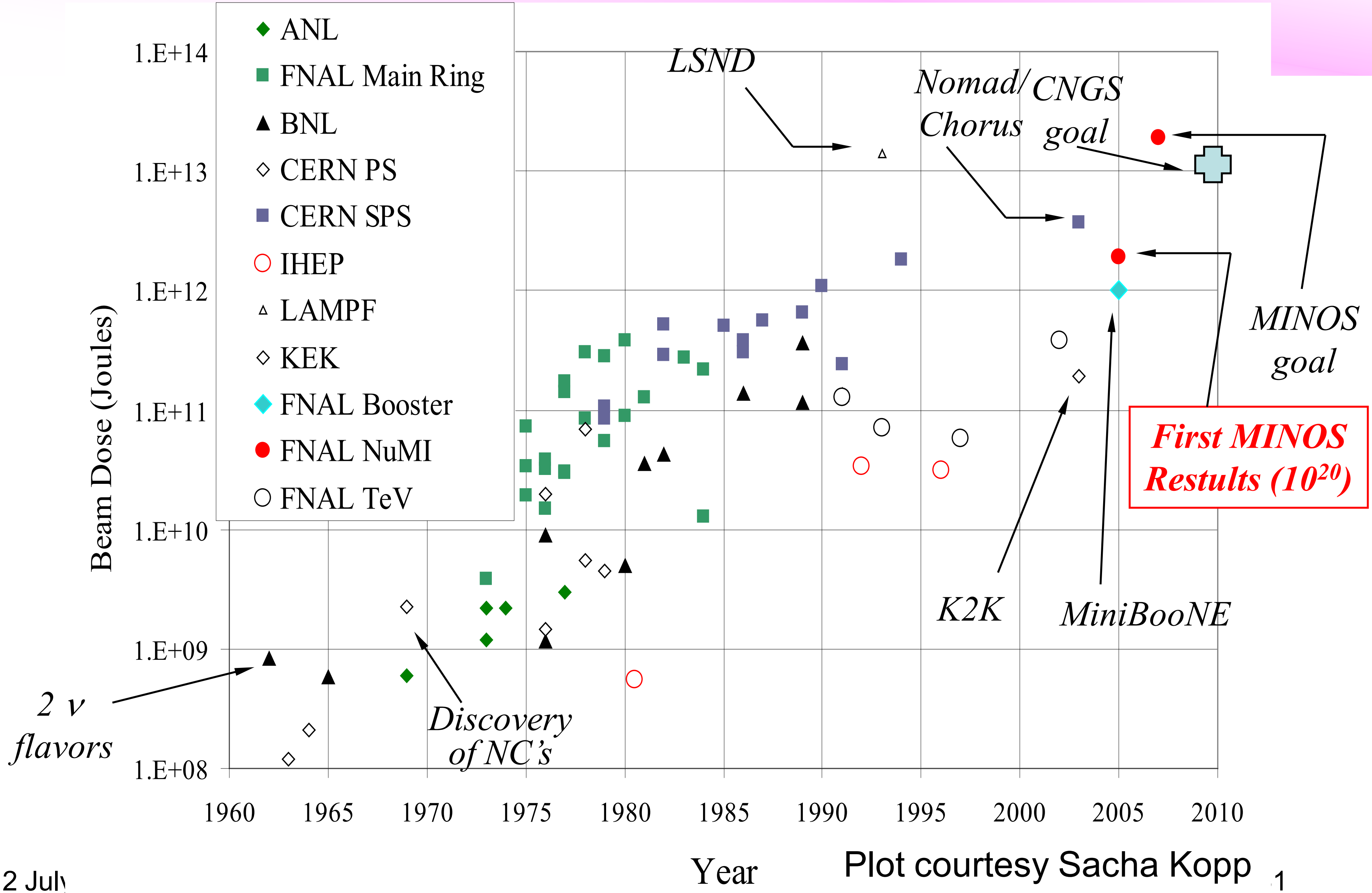
Proton Source	Experiment	Proton Energy (GeV)	p/yr	Power (MW)	Neutrino Energy (GeV)
KEK	K2K	12	$1\times10^{20}/4$	0.0052	1.4
FNAL Booster	MiniBooNE	8	5×10^{20}	0.05	1
FNAL Main Injector	MINOS and NOvA	120	2.5×10^{20}	0.25	3-17
CNGS	OPERA	400	0.45×10^{20}	0.12	25
J-PARC	T2K	40-50	11×10^{20}	0.75	0.77

Directing Protons is not trivial…

- Example from NuMI: extract beam from between two other beamlines, then make it point down at 3.5^{o} so it comes through the earth in Soudan Minnestota, 735km away:

- Example from T2K: Proton source on prime real estate, direction to K2K determined, need to bend HE protons in small space: "combined function" magnets (D and Q)

Integrated proton power vs time…



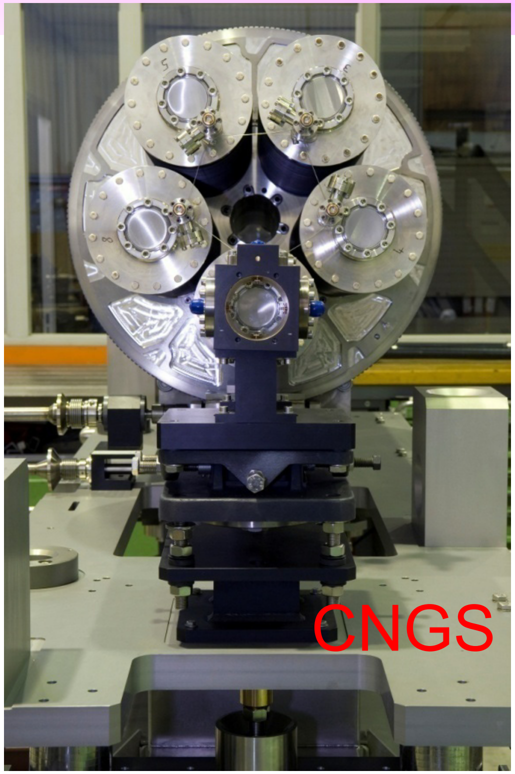
Plot courtesy Sacha Kopp

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

	Target Material	Shape	Size (mm)	Length (cm)
Mini-BooNE	Be	cylinder	10	70
K2K	Al	cylinder	30	66
MINOS	graphite	ruler	6.4x20	90
NOvA	graphite	ruler	>6.4	90
CNGS	carbon	ruler	4mm wide	200
J-PARC	graphite	cylinder	12-15 mm	90

Target Photo Album



Shapes are similar, but cooling methods vary…some water cooled, some air cooled

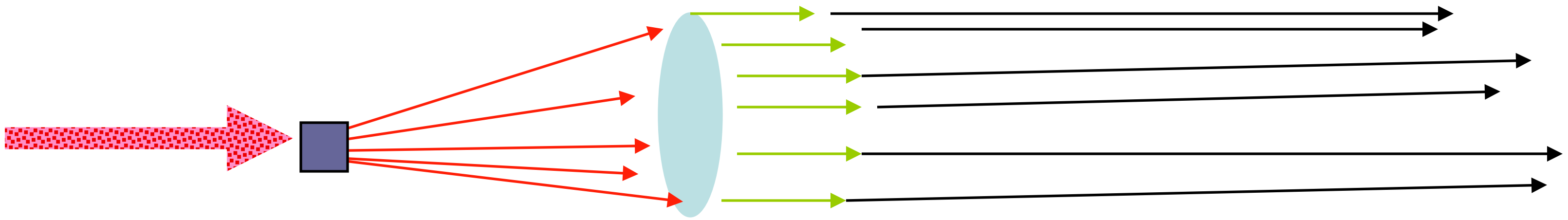
Focusing Systems

- 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 would work best?

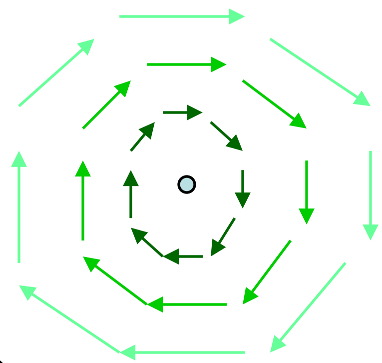
- Imagine particles flying out from a target:
  - When particle gets to front face of horn, it has transverse momentum proportional to radius at which it gets to horn



B Field from line source of current is

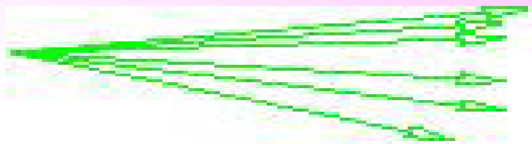
in the Φ direction

but has a size proportional to 1/r



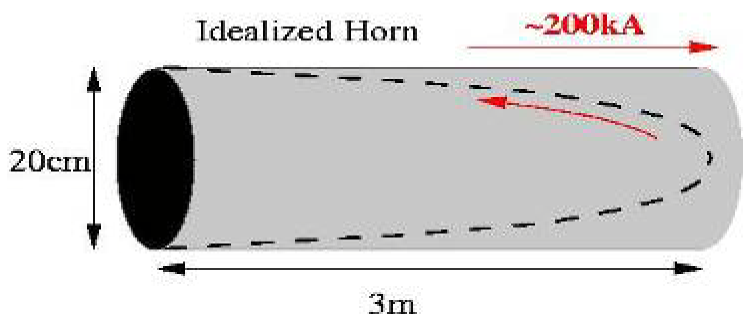
How do you get around this? (hint: $\partial pt \propto B \times \partial l$)

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

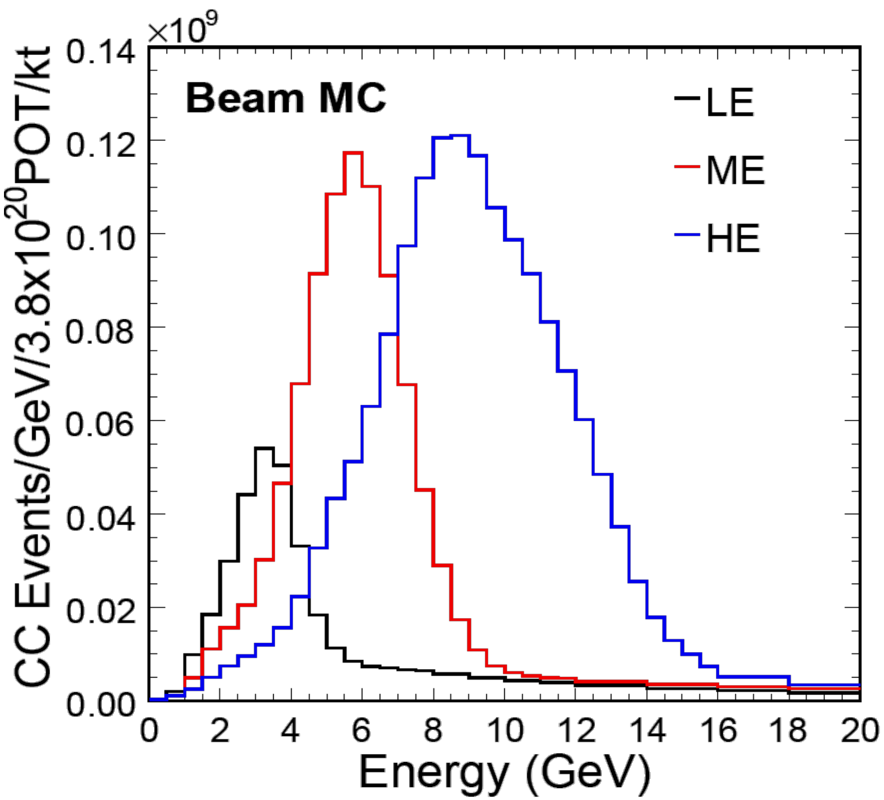
$$\delta p_t \approx \frac{e\mu_0 I}{2\pi c r} \times \frac{r^2 l}{r_{outer}^2} \approx p_{tune}\theta$$



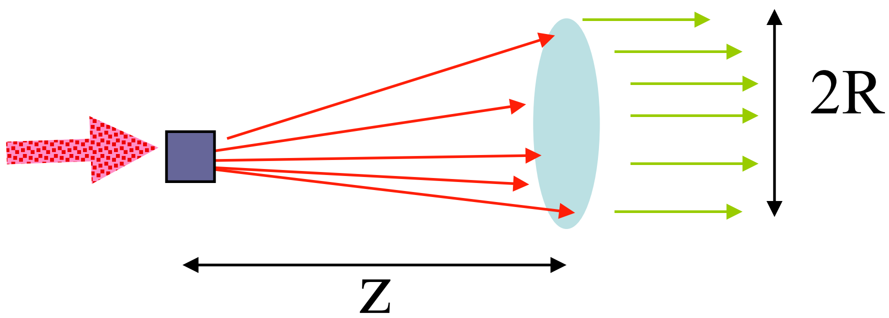
- There are also conical horns—what effect would conical horns have?

Tuning the Neutrino Beam Energy

- The farther upstream the target is, the higher momentum pions the horns can "perfectly focus"..see this by considering



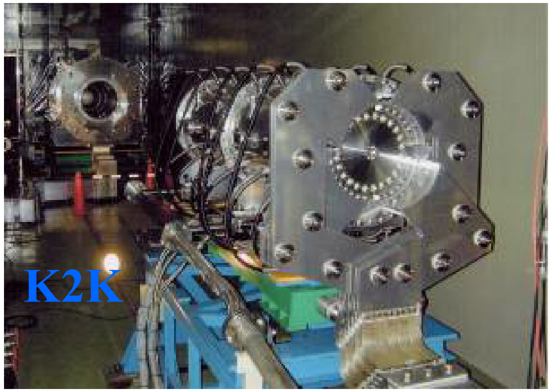
$$\delta p_t \approx \frac{e\mu_0 I}{2\pi c r} \times \frac{r^2 l}{r_{outer}^2} \approx p_{tune}\theta = p_{tune}\frac{R}{Z}$$

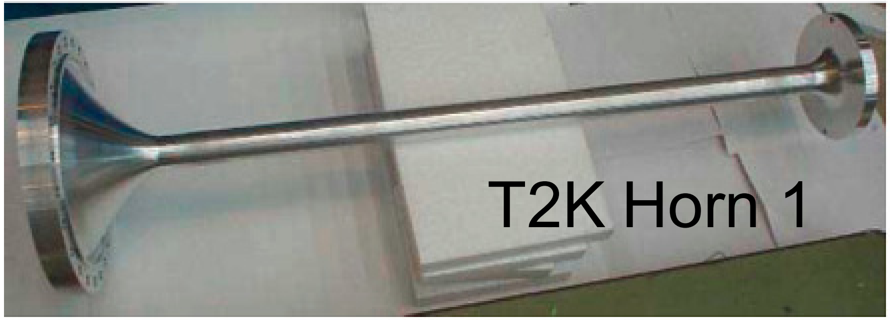


As z gets larger, then p_{tune} gets higher for the same R

	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

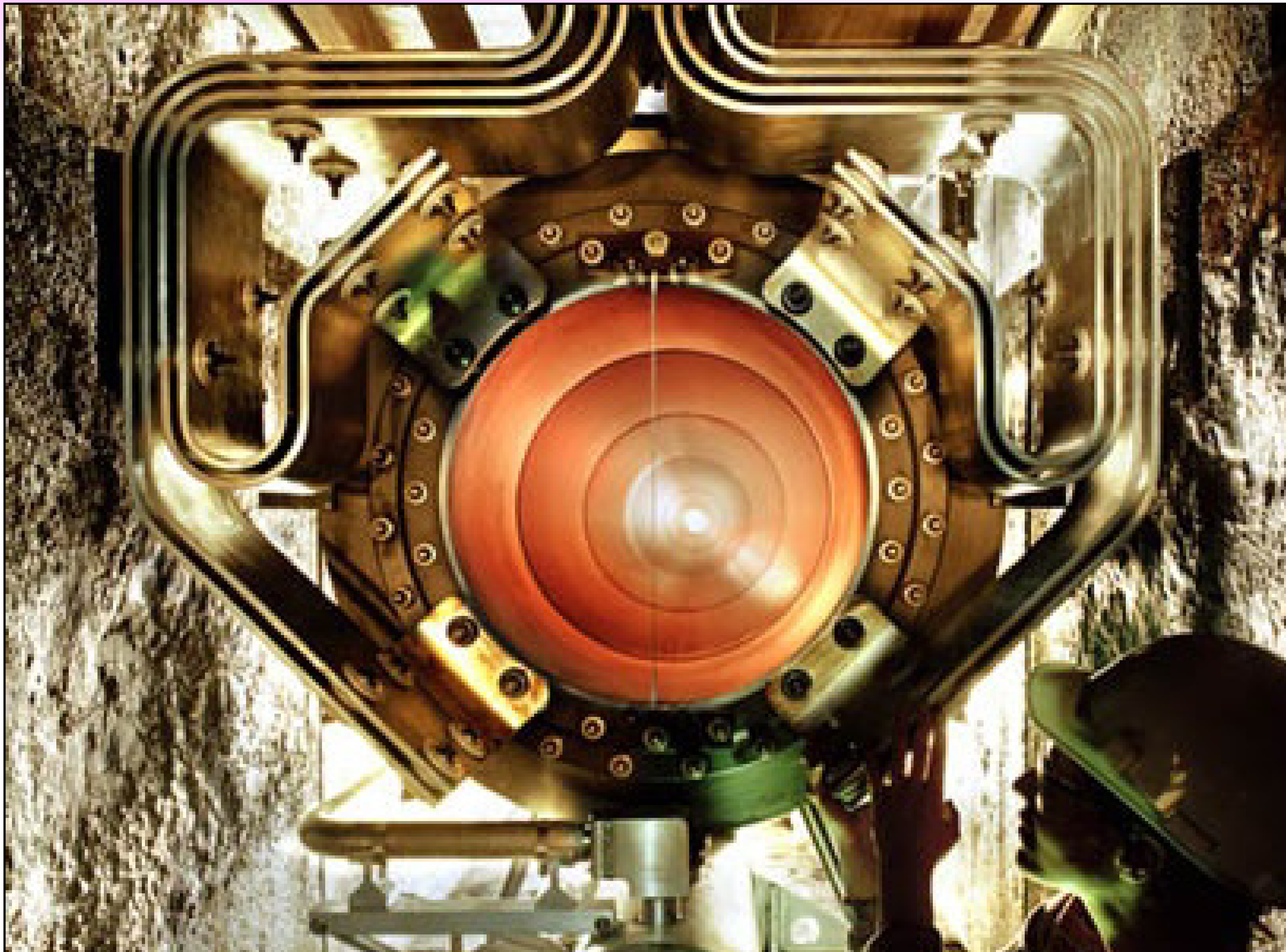
Horn Photo Album





Horn World Record (so far):
MiniBooNE horn pulsed for
100M pulses before failing

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

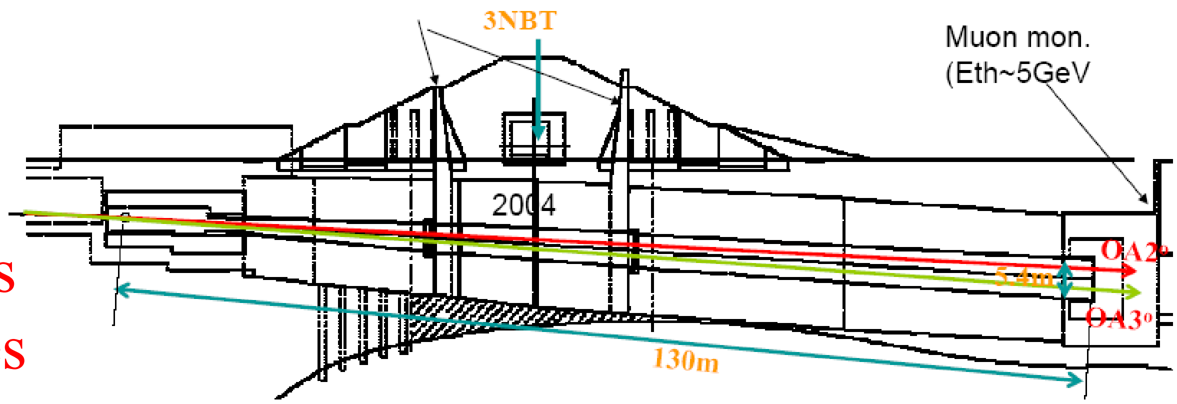


Decay Regions

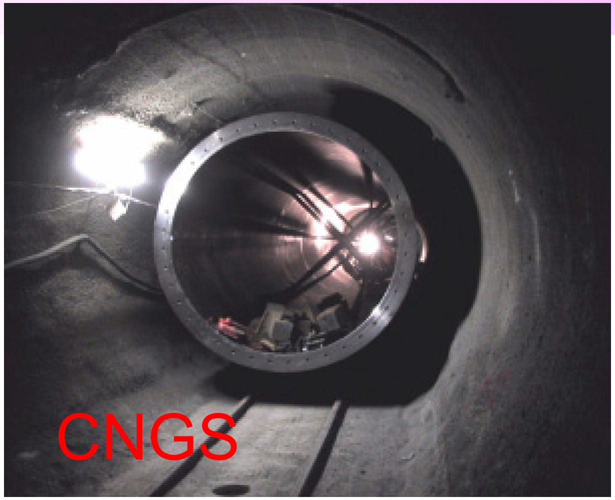
- How long a decay region you need (and how wide) depends on what the energy of the pions you're trying to focus.
- The longer the decay region, the more muon decays you'll get (per pion decay) and the larger ν_e contamination you'll have
- Again, tradeoffs between evacuating the decay volume and needing thicker vacuum windows to hold the vacuum versus filling the decay volume with Helium and thin windows, or with air and no windows…

	Length	Diameter
MBoone	50m	1.8m
K2K	200m	Up to 3m
MINOS	675m	2m
CNGS	1000m	2.45m
T2K	130m	Up to 5.4m

T2K Decay Region:
Can accommodate off axis
Angles from 2 to 3 degrees



Decay Pipe Photo Album



Beamline Decay Pipe Comparison

You can all show that neglecting things hitting the side of the decay pipe…

$$\frac{\Phi(\nu_e)}{\Phi(\nu_\mu)} = \frac{Lm_\mu c}{E_\pi \tau_\mu}\left(\frac{1}{e^{y_\pi}-1}+1-\frac{1}{y_\pi}\right)$$

y_π=the number of pion lifetimes in one decay pipe… $y_\pi = \frac{Lm_\pi c^2}{E_\pi c \tau_\pi}$

	Length	E_π (GeV)	y_π	y_μ	$\Phi(\nu_e)/\Phi(\nu_\mu)$ (theoretical)
MiniBooNE	50m	2.5	0.36	0.3%	0.15%
K2K	200m	3.5	1.0	0.9%	0.5%
MINOS	675m	9	1.3	1.2%	0.8%
CNGS	1000m	50	0.36	0.3%	0.15%
T2K	130m	9	0.47	0.2%	0.10%