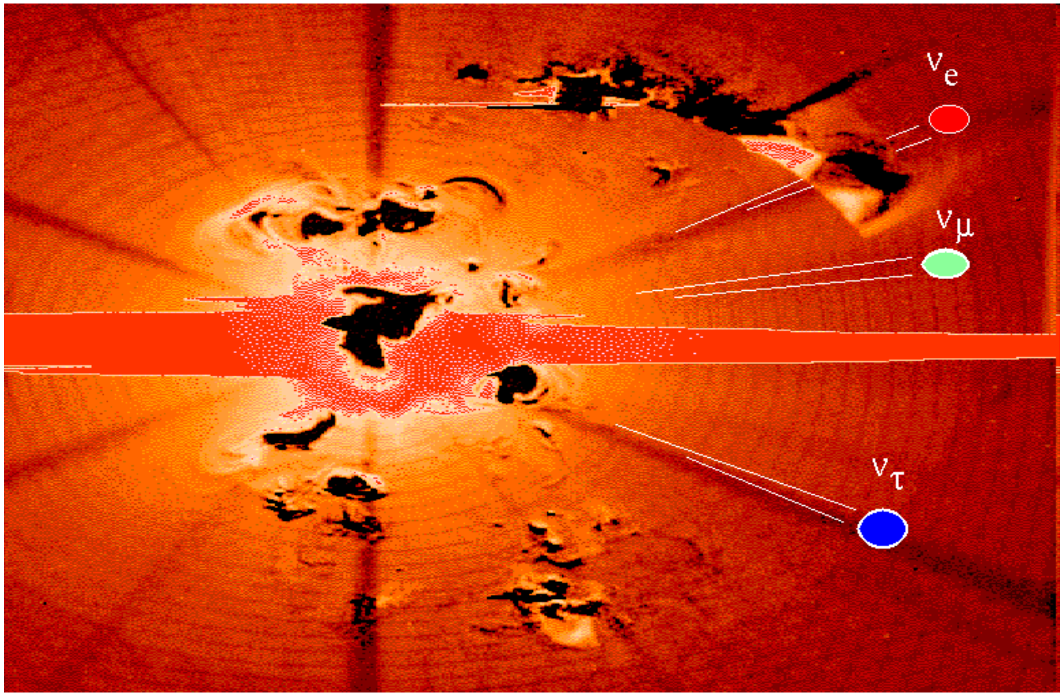
XII MEXICAN WORKSHOP ON PARTICLES AND FIELDS

Introduction to Neutrino Physics: Lecture 1

M. Shaevitz
Columbia University



Neutrinos carry away 99% of the energy in a supernova explosion

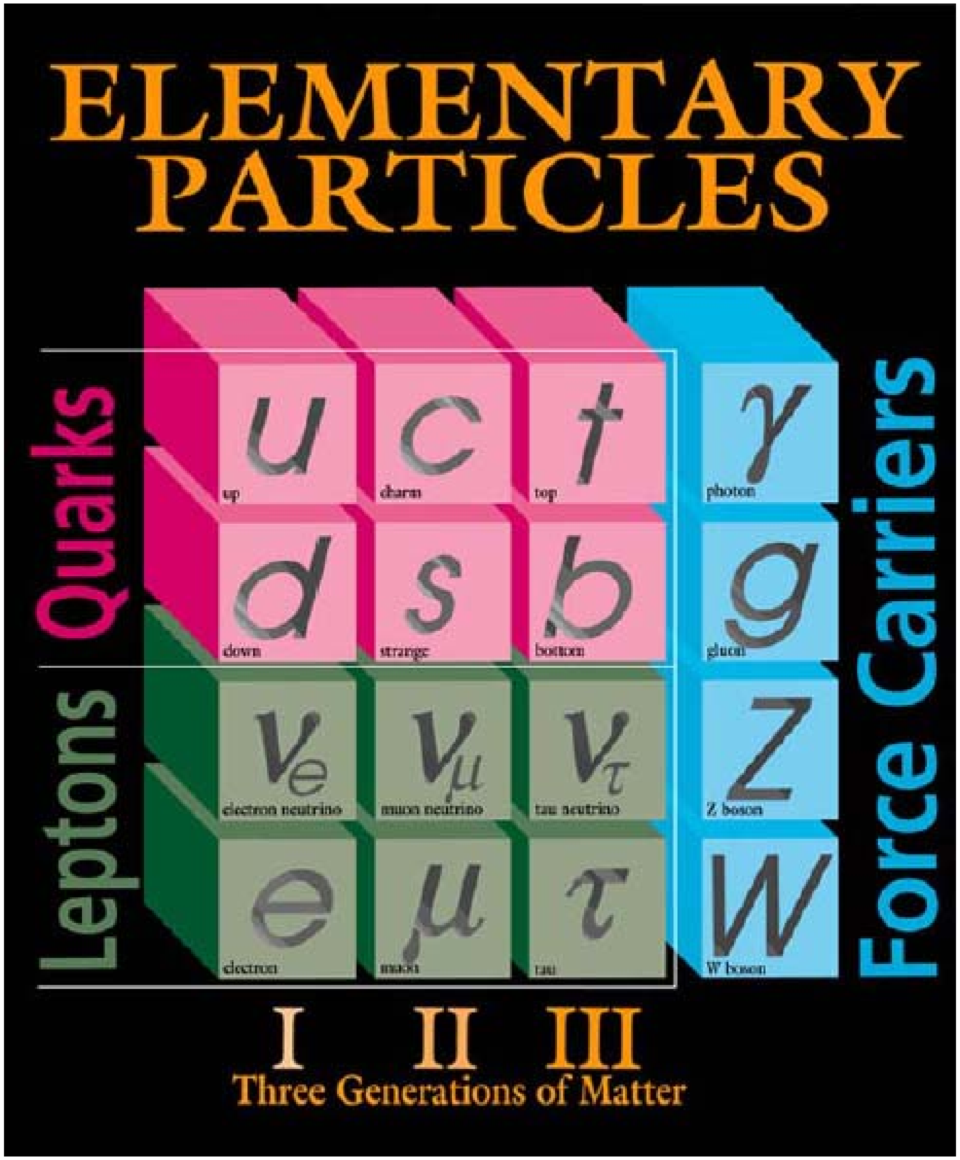
Outline

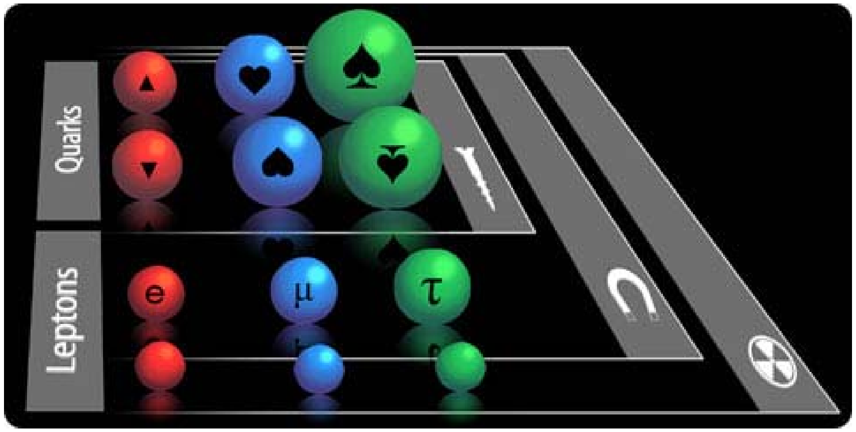
- Lecture 1: Experimental Neutrino Physics
  - Neutrino Physics and Interactions
  - Neutrino Mass Experiments
  - Neutrino Sources/Beams and Detectors for Osc. Exp's

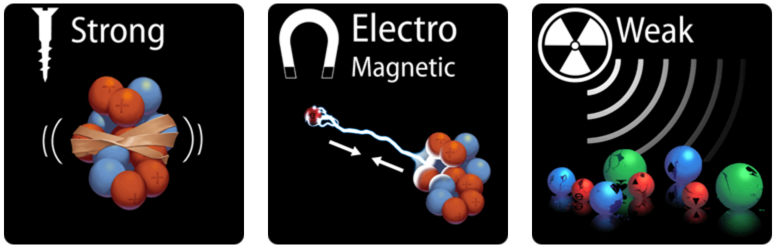
- Lecture 2: The Current Oscillation Results
  - Solar and Kamland Neutrino Results
  - Atmospheric and Accelerator Neutrino Results
  - Global Oscillation Fits

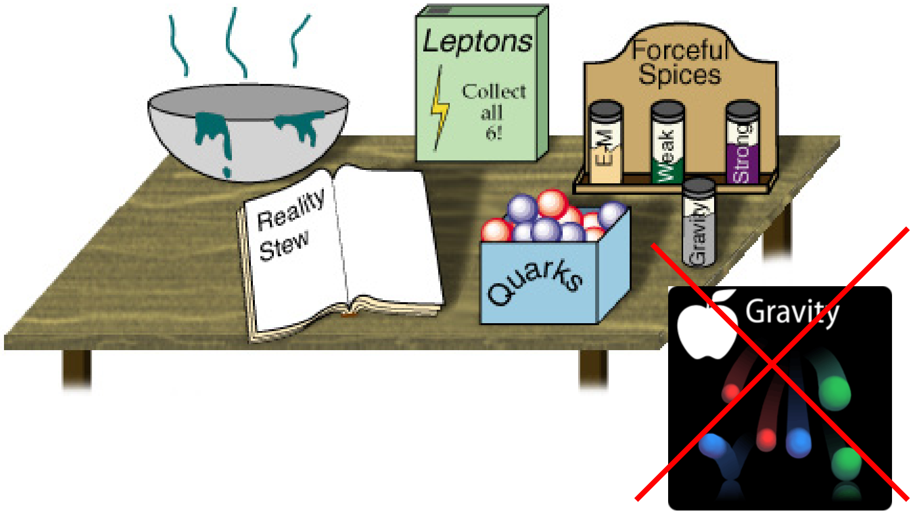
- Lecture 3: Present and Future Oscillation Experiments
  - The Fly in the Ointment: LSND and MiniBooNE
  - Searches for θ_{13} / Mass Hierarchy / CP Violation
    - Current Hints
    - Reactor Experiments
    - Longbaseline experiments
    - Combining Experiments
  - Future Plans for Oscillation Experiments

Standard Model of Particle Physics



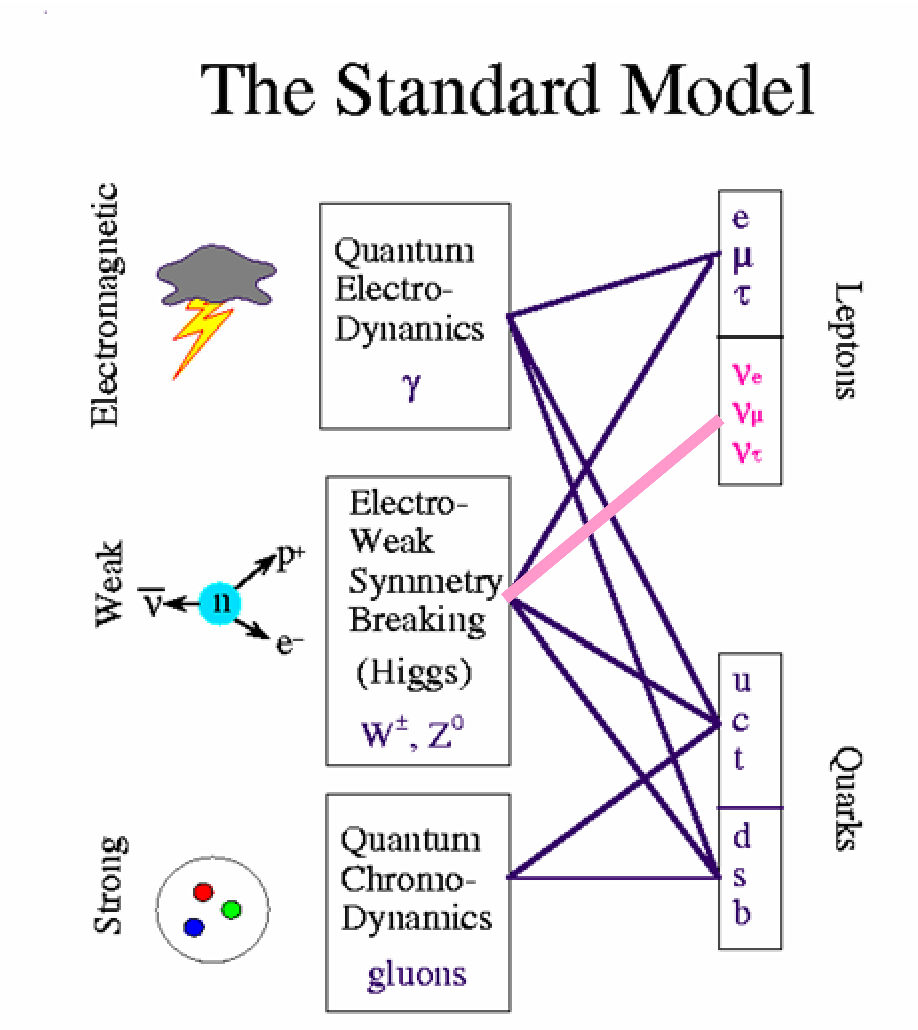






Neutrinos in the Standard Model

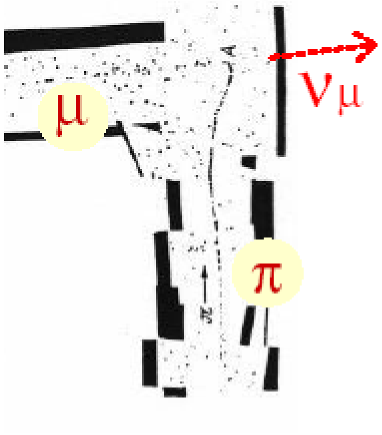
- Neutrinos are the only fundamental fermions with no electric charge
- Neutrinos only interact through the “weak force”
- Neutrino interaction thru W and Z bosons exchange is (V-A)
  - Neutrinos are left-handed (Antineutrinos are right-handed)
- Neutrinos are massless
- Neutrinos have three types
  - Electron $\nu_e \rightarrow e$
  - Muon $\nu_\mu \rightarrow \mu$
  - Tau $\nu_\tau \rightarrow \tau$



Highlights of Neutrino History

1930	Pauli Postulates ν existence	$n \to p + e^{-} + ???$
1953 Nobel 1995	ν Interactions Observed Reines & Cowan	$\bar{\nu} + p \to n + e^{+}$
1957	ν Oscillations Predicted Pontecorvo	$\nu_A \to \nu_B$?
1962 Nobel 1988	ν_μ Observed Lederman, Schwartz, Steinberger	$\nu_\mu + N \to \mu^{-} + X$
1973	Neutral Current ν Interactions Observed Gargamelle	$\nu + N \to \nu + X$
1989	Only 3 light ν families! LEP Experiments	$Z \to \nu\bar{\nu}$
1990's	Oscillations Observed?	$\nu_A \to \nu_B$!

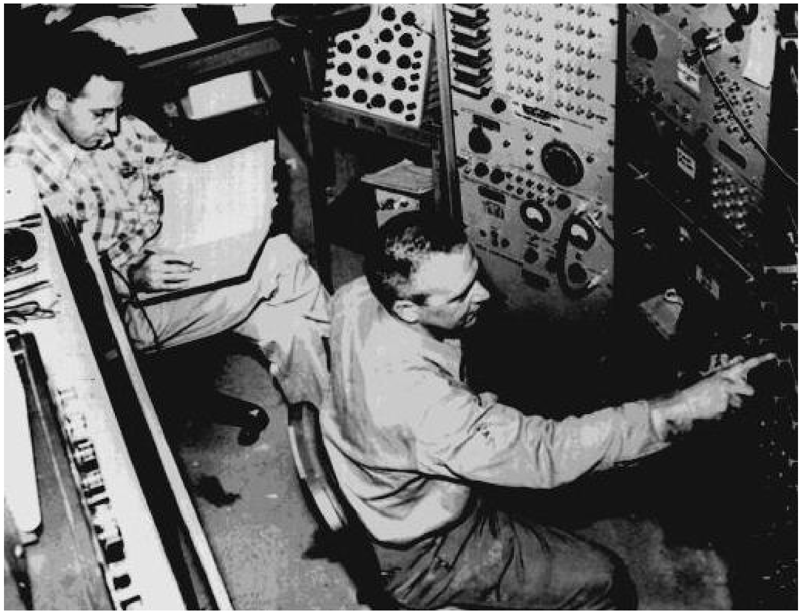
1st Observed
π→μν decay



Nobel 2002 **Observation of neutrinos from the sun and supernovae**
Davis (Solar ν's in 1970) and Koshiba (Supernova ν's 1987)

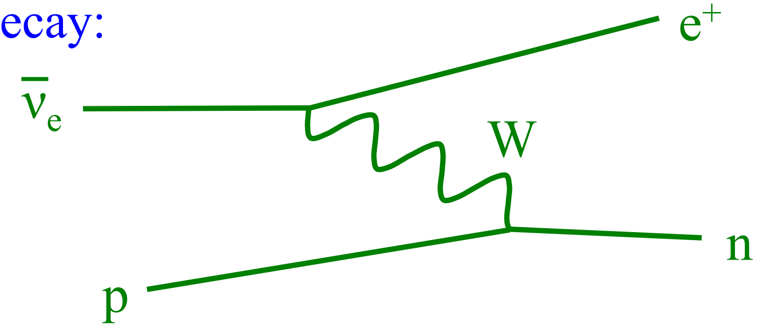
2002 **ν_τ Observed**

The original neutrino discovery experiment, by Reines and Cowan, using reactor $\bar{\nu}_e$ (1953)



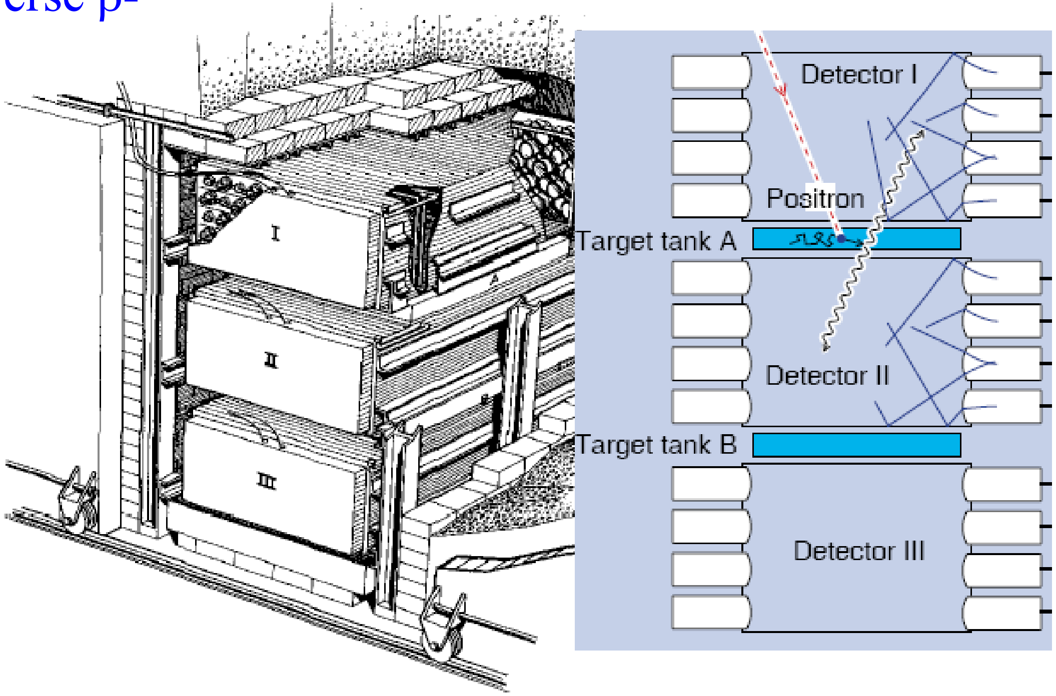
Reines and Cowan at the Savannah River Reactor

The $\bar{\nu}_e$ interacts with a free proton via inverse β-decay:



Later the neutron captures giving a coincidence signal. Reines and Cowan used cadmium to capture the neutrons (modern exp. use Gadolinium)

The first successful neutrino detector



Discovery of Muon Neutrino

1962

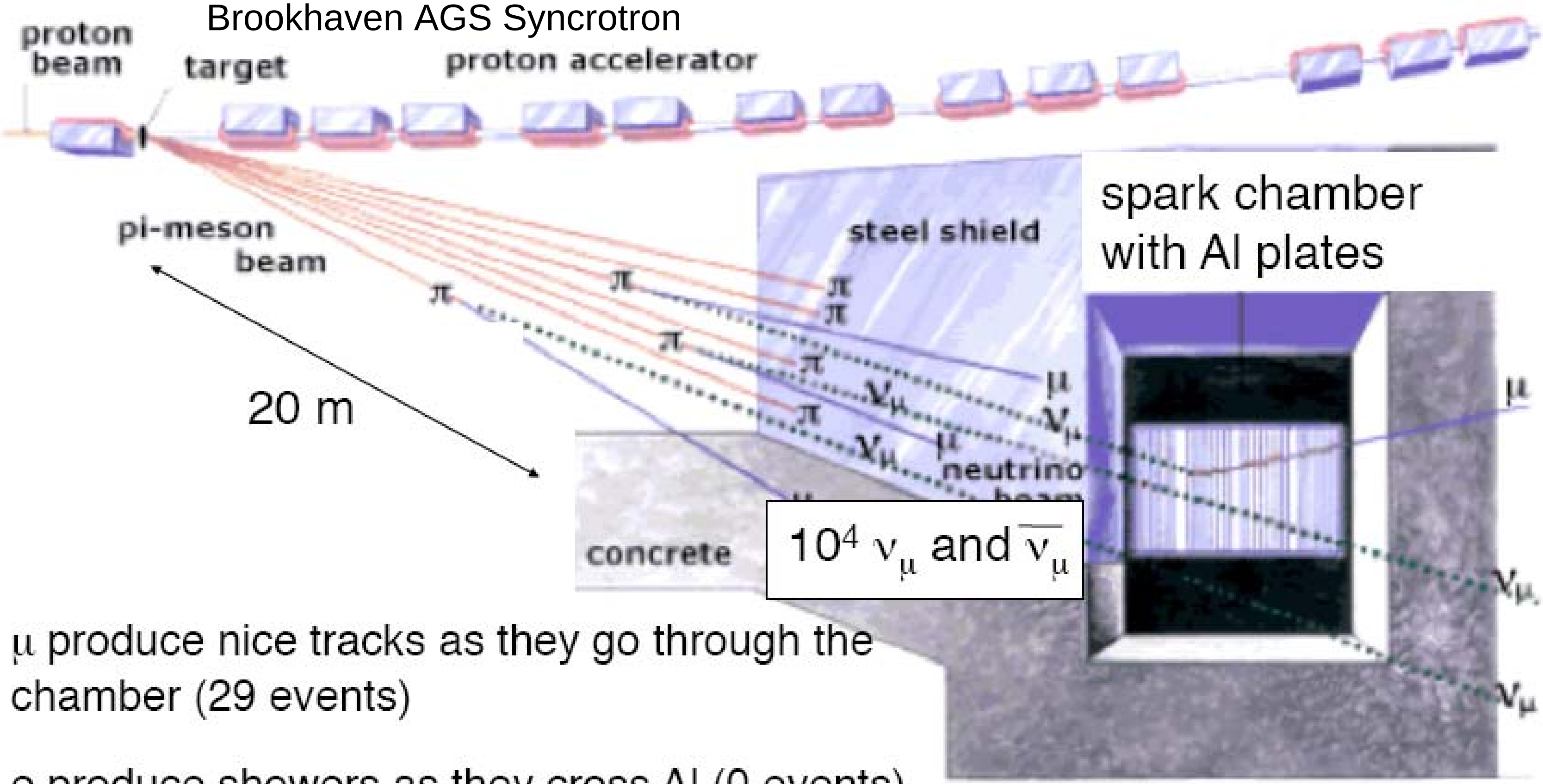
$$\pi \rightarrow \mu + \nu_?$$

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

$$\nu_\mu + n \rightarrow p + \mu^-$$

Lederman, Schwartz, Steinberger

Brookhaven AGS Syncrotron



spark chamber with Al plates

10^4 ν_μ and $\overline{\nu_\mu}$

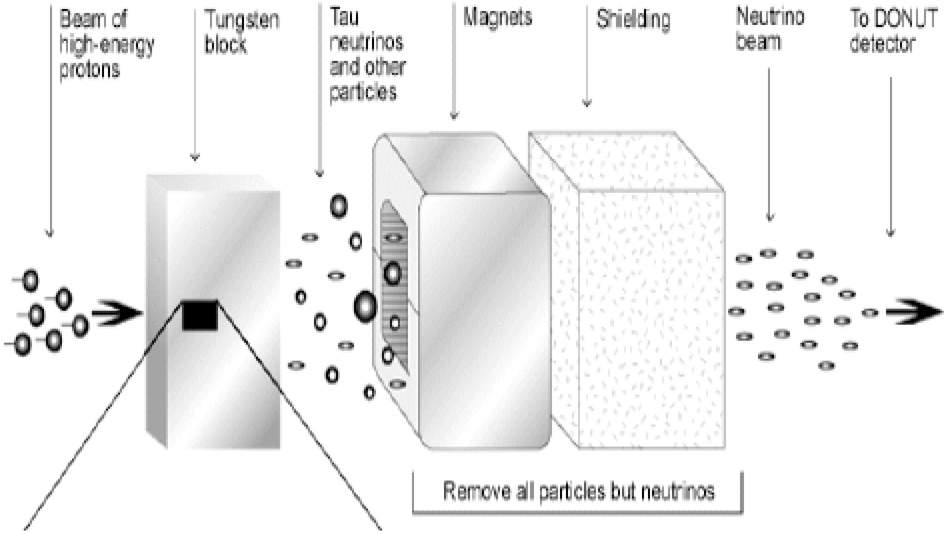
μ produce nice tracks as they go through the chamber (29 events)

e produce showers as they cross Al (0 events)

Discovery of the Tau Neutrino

2000

An 800 GeV beam of protons from the TeVatron collides with a block of tungsten



D_s decay into τ and ν_τ neutrino

$$D_s \to \nu_\tau + \tau$$

$$\tau \to \nu_\tau + X$$

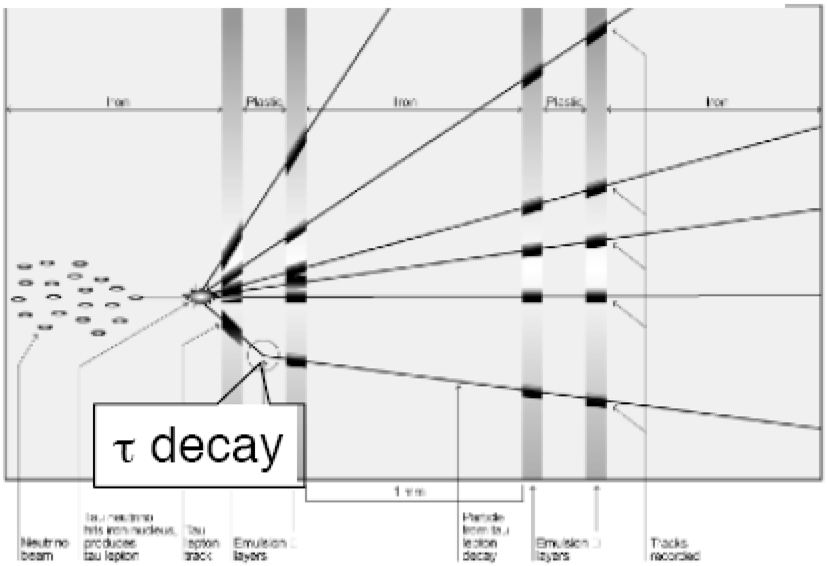
Experimental Challenges:

- Very short lifetime of the τ.
- ν_τ is extremely non-interacting

(detector must have a very fine resolution).

$\Rightarrow$ Use Emulsion Tracker

Detecting a τ Neutrino



6,000,000 candidate events on tape

4 clean tau events

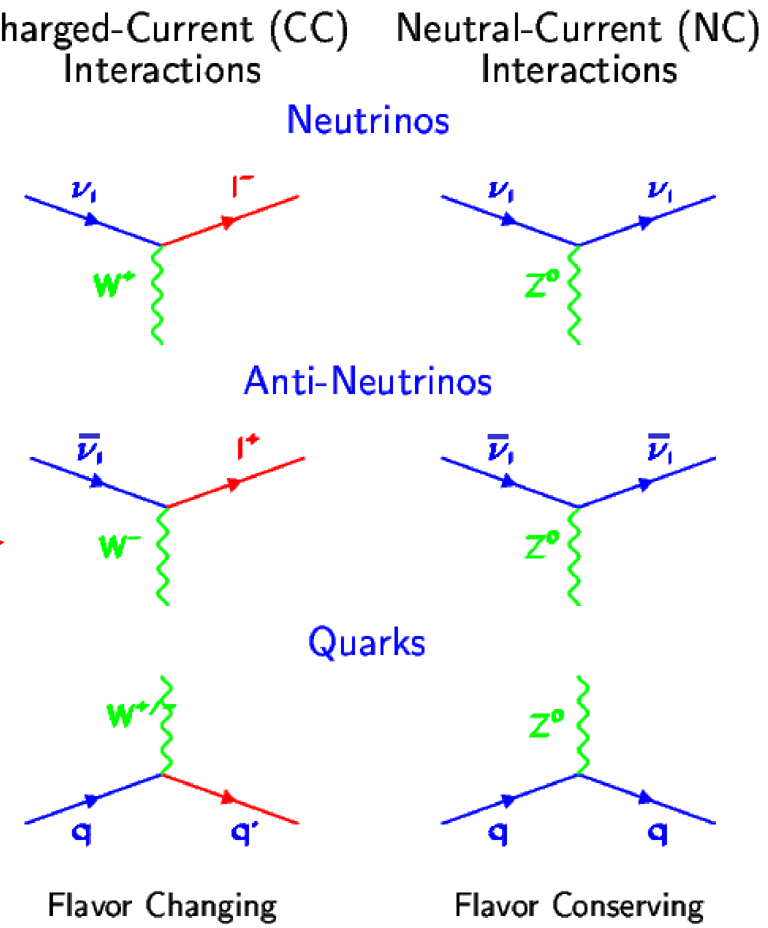
Neutrino Interactions

- W exchange gives Charged-Current (CC) events and
  Z exchange gives Neutral-Current (NC) events
- Discovery of “neutral current” interactions in 1973 was a triumph of the “electroweak” theory
  - Difficult to detect since no outgoing muon or electron so hard to separate from background (neutron or photon interactions)

In CC events the charge of the outgoing lepton determines if neutrino or antineutrino

$$l^- \rightarrow \nu$$

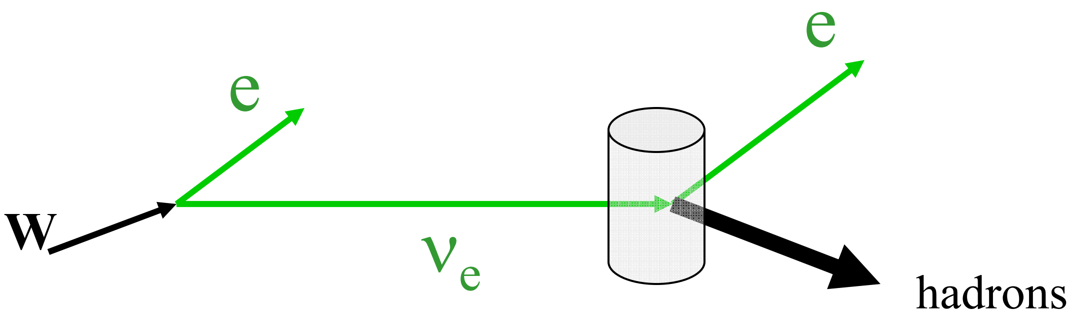
$$l^+ \rightarrow \overline{\nu}$$



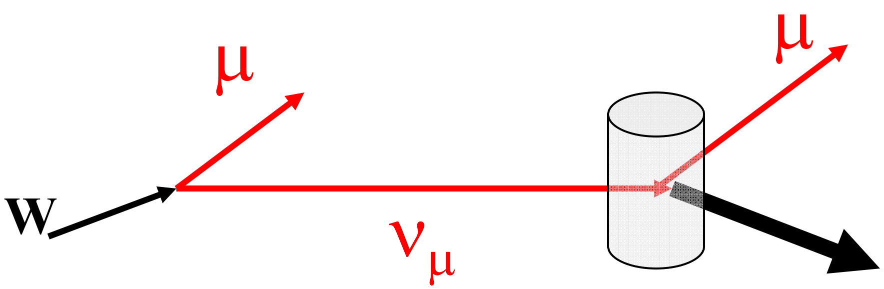
Tagging a Neutrinos Type ⇒ Use Charged Current Interaction

A neutrino produced
together with:

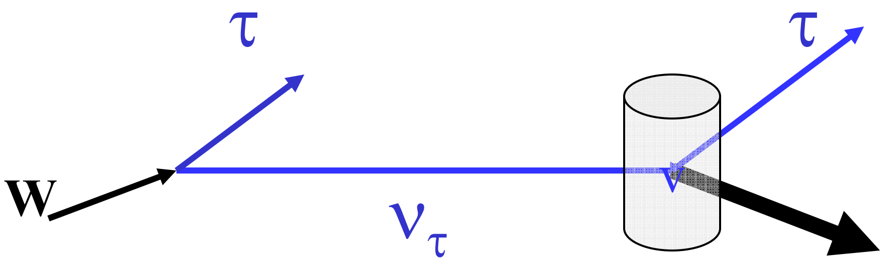
a) An **electron**
Always gives an **electron**
Through a charged current



b) A **muon**
Always gives a **muon**
Through a charged curent

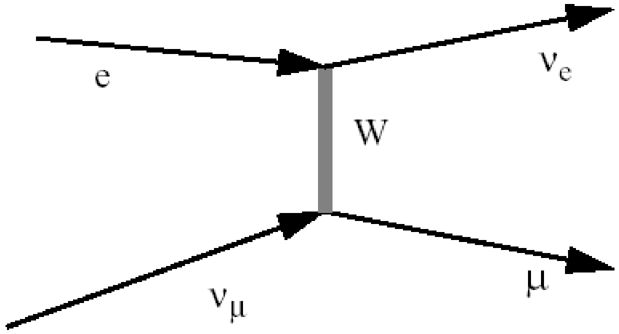


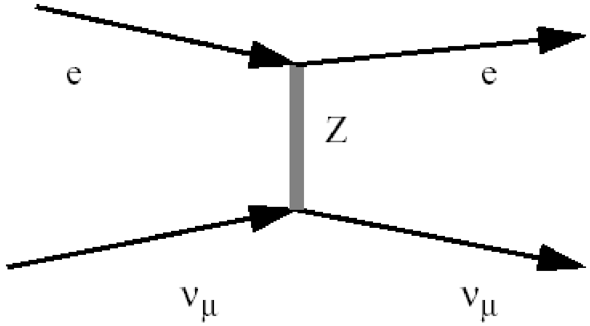
c) A **tau**
Always gives a **tau**
Through a charged current



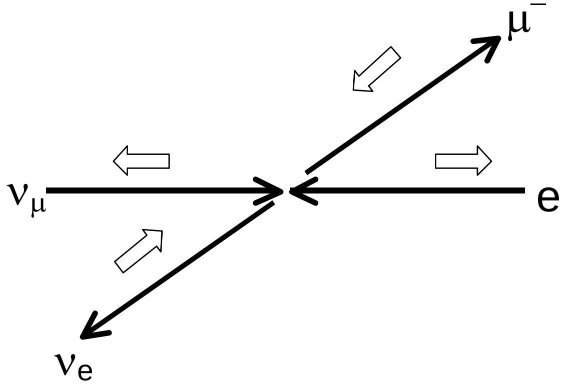
For oscillation experiments, need to identify outgoing lepton

Neutrino-Electron Scattering





- Inverse μ–decay: $\nu_\mu + e^- \to \mu^- + \nu_e$
  - Total spin J=0 (Helicity conserved)



  - Point scattering $\Rightarrow \sigma \propto s = 2m_eE_\nu$

$$\sigma_{TOT} = \frac{G_F^2 s}{\pi} = 17.2 \pm 10^{-42}\, cm^2 / GeV \cdot E_\nu (GeV)$$

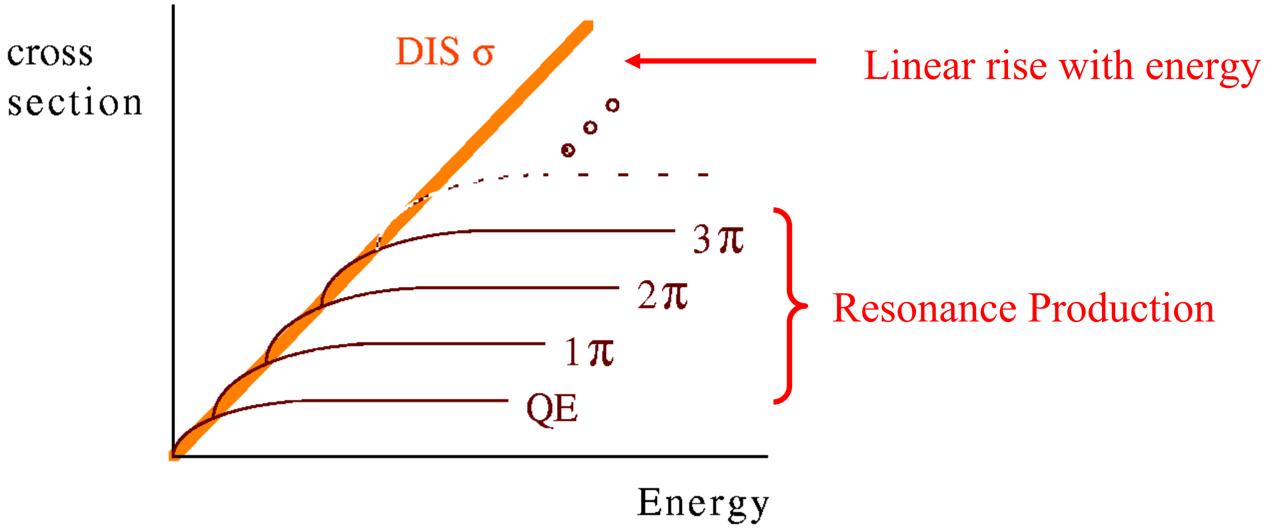
- Elastic Scattering: $\nu_\mu + e^- \to \nu_\mu + e^-$
  - Point scattering $\Rightarrow \sigma \propto s = 2m_eE_\nu$
  - Electron coupling to Z^0
    - (V-A): $-1/2 + \sin^2\theta_W$ J = 0
    - (V+A): $\sin^2\theta_W$ J = 1

$$\sigma_{TOT} = \frac{G_F^2 s}{\pi}\left(\frac{1}{4} - \sin^2\theta_W + \frac{4}{3}\sin^4\theta_W\right)$$

Neutrino-Nucleon Processes

- Charged - Current: $W^\pm$ exchange
  - Quasi-elastic Scattering:
    (Target changes but no break up)
    $\nu_\mu + n \rightarrow \mu^- + p$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + n \rightarrow \mu^- + p + \pi^0$ (N^* or Δ)
    $n + \pi^+$
  - Deep-Inelastic Scattering:
    (Nucleon broken up)
    $\nu_\mu + \text{quark} \rightarrow \mu^- + \text{quark}'$

- Neutral - Current: Z^0 exchange
  - Elastic Scattering:
    (Target doesn't break up or change)
    $\nu_\mu + N \rightarrow \nu_\mu + N$
  - Nuclear Resonance Production:
    (Target goes to excited state)
    $\nu_\mu + N \rightarrow \nu_\mu + N + \pi$ (N^* or Δ)
  - Deep-Inelastic Scattering
    (Nucleon broken up)
    $\nu_\mu + \text{quark} \rightarrow \nu_\mu + \text{quark}$



Neutrino Cross Section is Very Small

- Weak interactions are weak because of the massive W and Z boson exchange $\Rightarrow \sigma^{\text{weak}} \propto (1/M_W)^4$

$$G_F = \frac{\sqrt{2}}{8}\left(\frac{g_W}{M_W}\right)^2 = 1.166\times10^{-5}/GeV^2 \quad (g_W \approx 0.7)$$

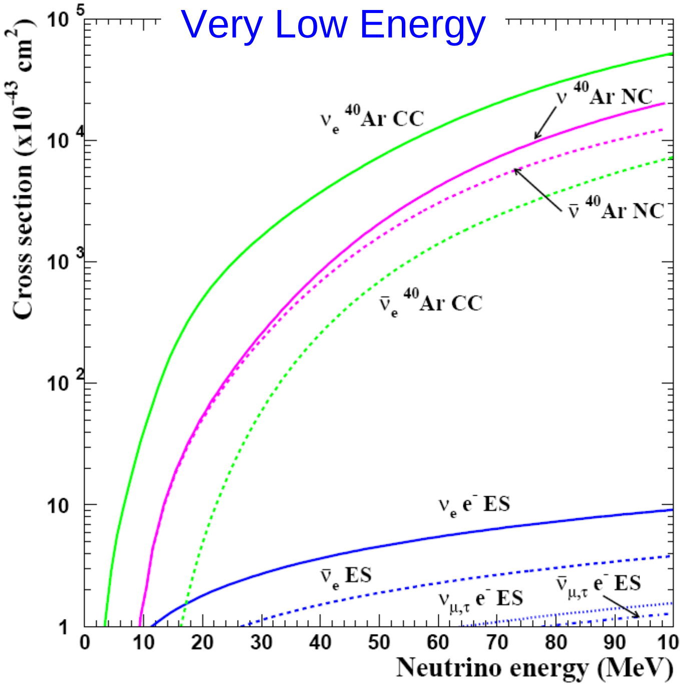
- Examples:
  - 15 MeV Supernova neutrinos interacting in a Liquid Argon detector ($\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$) $\rho_{Ar} = 1.4$ g/cm^3
    - Cross section = 2×10^{-41} cm^2

    $\Rightarrow$ Interaction length = $1/(\rho\ \sigma\ N_{Avg}) = 6 \times 10^{16}$ m

  - MiniBooNE Booster Neutrino Beam from 8 GeV protons in 500 ton mineral oil detector
    - Quasi-elastic CC cross section ($\nu_\mu + n \rightarrow \mu^- + p$) = 1×10^{-38} cm^2 @ 0.7 GeV
    - Flux = 2×10^{11} ν/cm^2 for 5×10^{20} protons on target

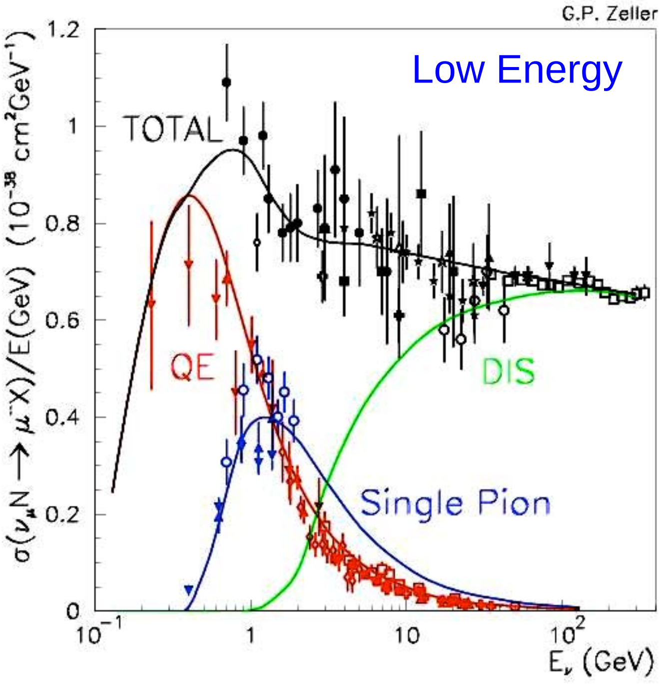
    $\Rightarrow$ ν QE-CC events = mass $\times\ \sigma \times N_{Avg} \times$ Flux
    = 600,000 events

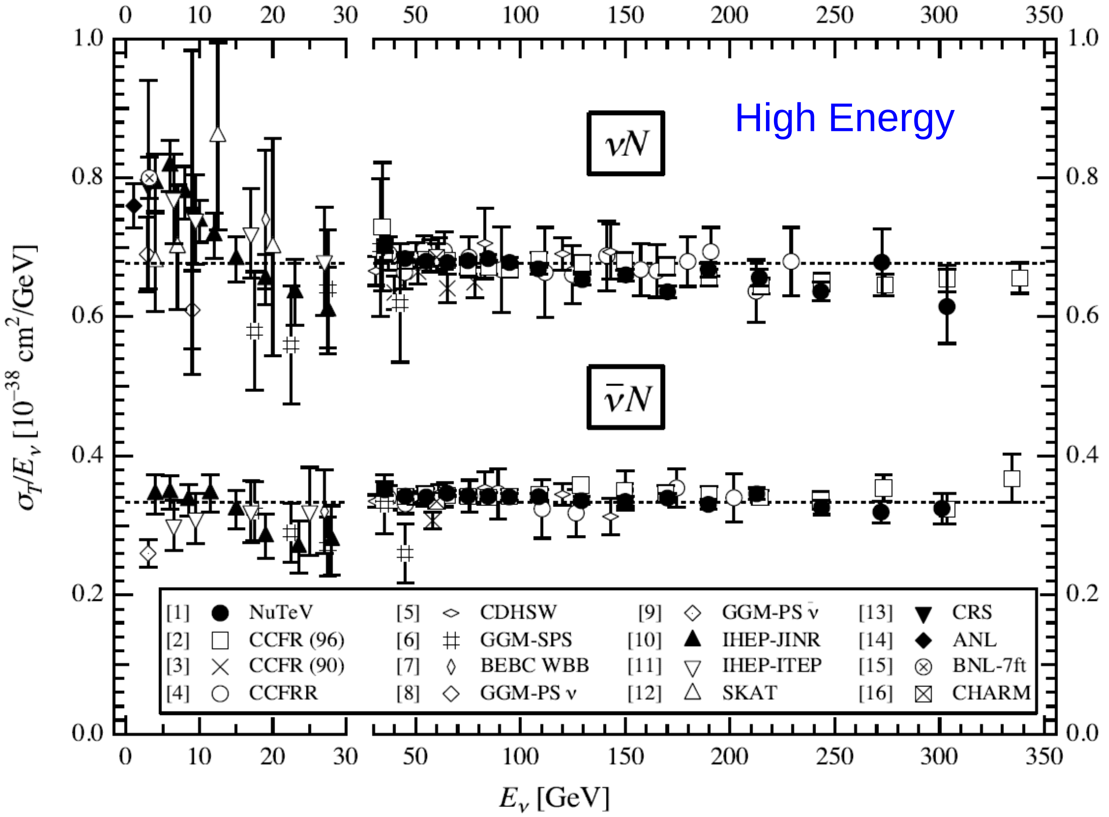
Neutrino Cross Sections


Very Low Energy

Neutrino – electron scattering

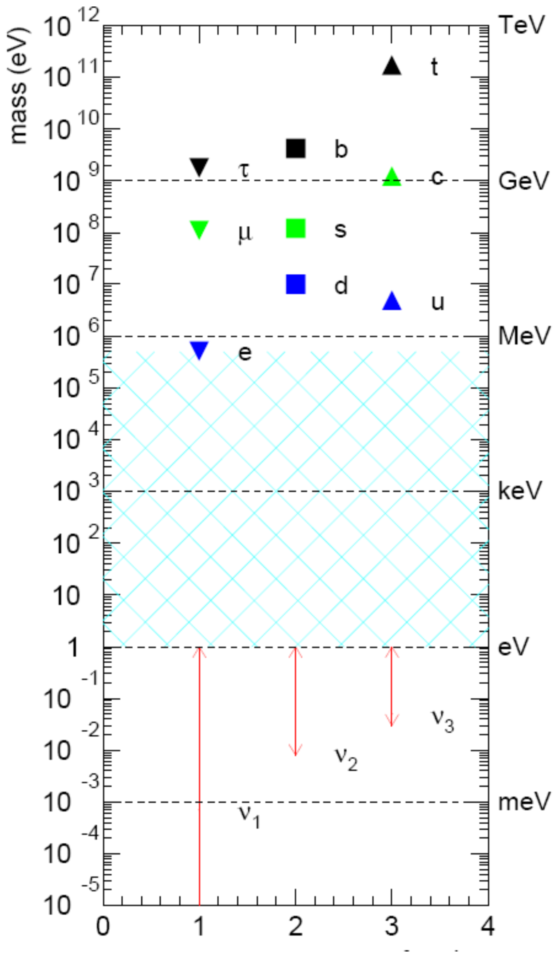
$$\sigma(\nu_e e^- \to \nu_e e^-) = 9.20 \times 10^{-45} E_{\nu_e}(\mathrm{MeV}) \quad \mathrm{cm}^2$$
$$\sigma(\bar{\nu}_e e^- \to \bar{\nu}_e e^-) = 3.83 \times 10^{-45} E_{\bar{\nu}_e}(\mathrm{MeV}) \quad \mathrm{cm}^2$$
$$\sigma(\nu_{\mu,\tau} e^- \to \nu_{\mu,\tau} e^-) = 1.57 \times 10^{-45} E_{\nu_{\mu,\tau}}(\mathrm{MeV}) \quad \mathrm{cm}^2$$
$$\sigma(\bar{\nu}_{\mu,\tau} e^- \to \bar{\nu}_{\mu,\tau} e^-) = 1.29 \times 10^{-45} E_{\bar{\nu}_{\mu,\tau}}(\mathrm{MeV}) \quad \mathrm{cm}^2$$


Low Energy


High Energy

$$\sigma^{\nu\, Iso}/E_\nu = (0.677 \pm 0.014) \times 10^{-38} \mathrm{cm}^2/\mathrm{GeV}$$
$$\sigma^{\bar{\nu}\, Iso}/E_{\bar{\nu}} = (0.334 \pm 0.008) \times 10^{-38} \mathrm{cm}^2/\mathrm{GeV}$$

Neutrino Mass: Theoretical Ideas



- No fundamental reason why neutrinos must be massless
  - – But why are they much lighter than other particles?

➢ **Grand Unified Theories**

- – Dirac and Majorana Mass
  $\Rightarrow$ See-saw Mechanism

➢ **Modified Higgs sector to accommodate neutrino mass**

➢ **Extra Dimensions**

- – Neutrinos live outside of 3 + 1 space

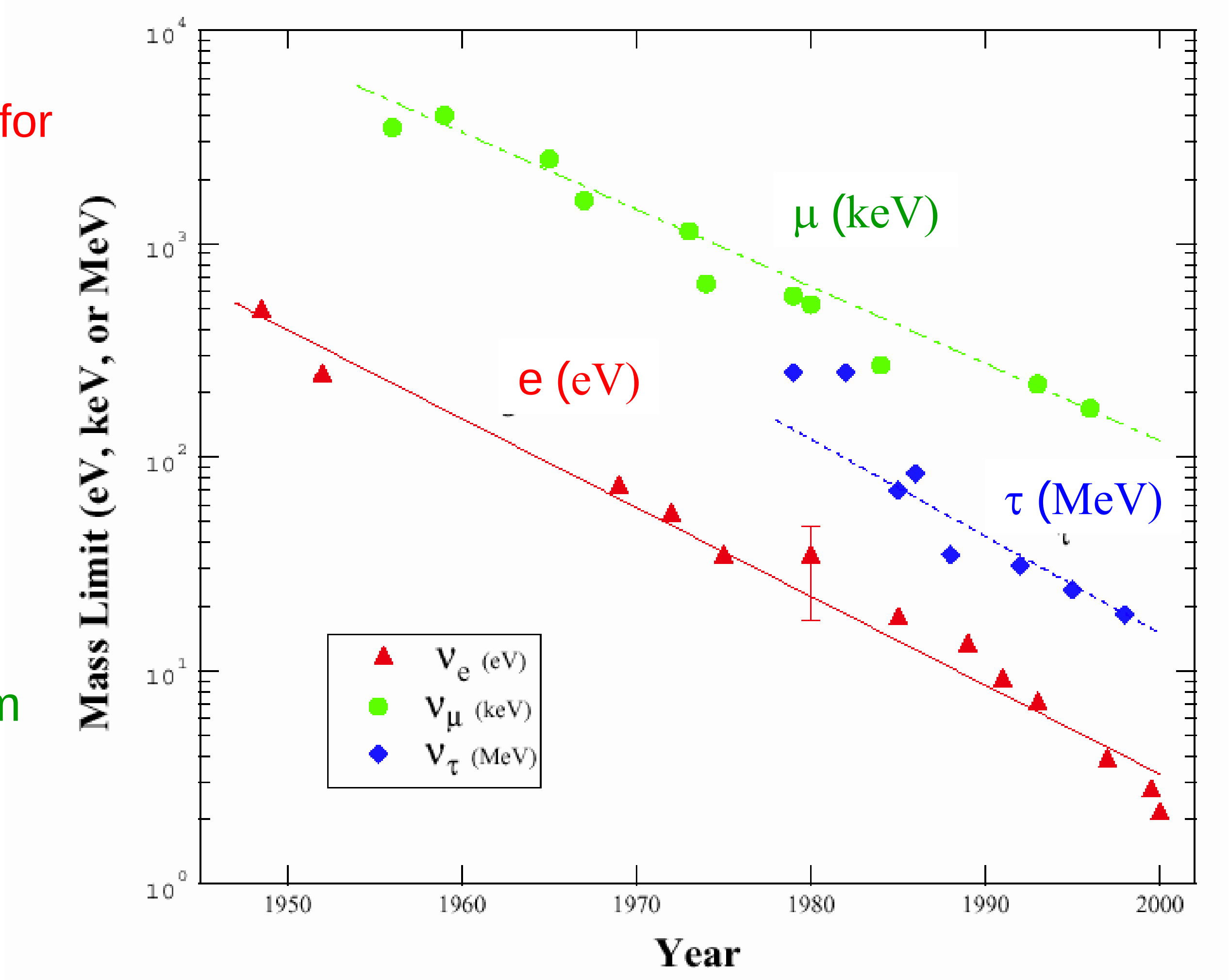
Many of these models have at least one Electroweak isosinglet ν

- – Right-handed partner of the left-handed ν
- – Mass uncertain from light (< 1 eV) to heavy (>10^{16} eV)
- – Would be “sterile” – Doesn’t couple to standard W and Z bosons

How Big are Neutrino Masses?
Direct Neutrino Mass Experiments

- Techniques
  - Electron neutrino:
    - Study E_e end point for $^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \nu_e + e^-$
  - Muon neutrino:
    - Measure P_μ in $\pi \rightarrow \mu \nu_\mu$ decays
  - Tau neutrino:
    - Study $n\pi$ mass in $\tau \rightarrow (n\pi)\, \nu_\tau$ decays

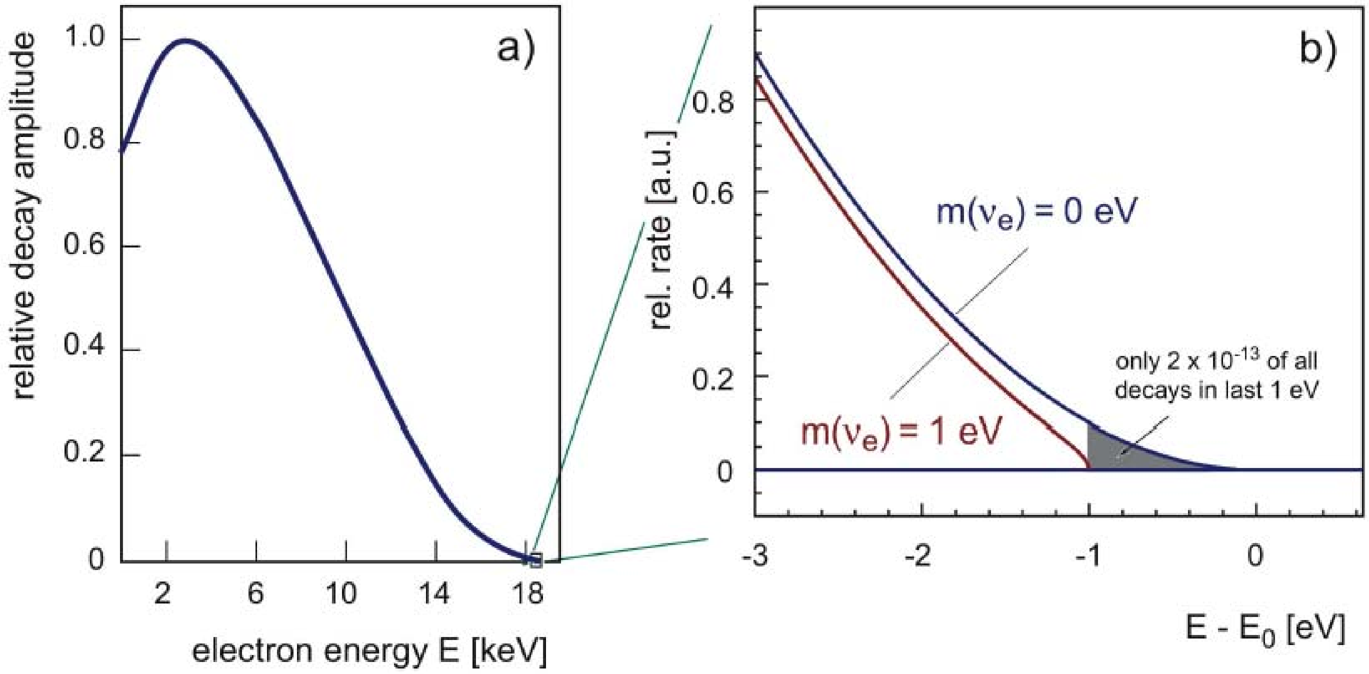
(Also, information from Supernova time-of-flight)



ν_e Mass Measurements (Tritium β-decay Searches)

- Search for a distortion in the shape of the β-decay spectrum in the end-point region.

$$^3H \rightarrow {}^3He + \nu_e + e^-$$



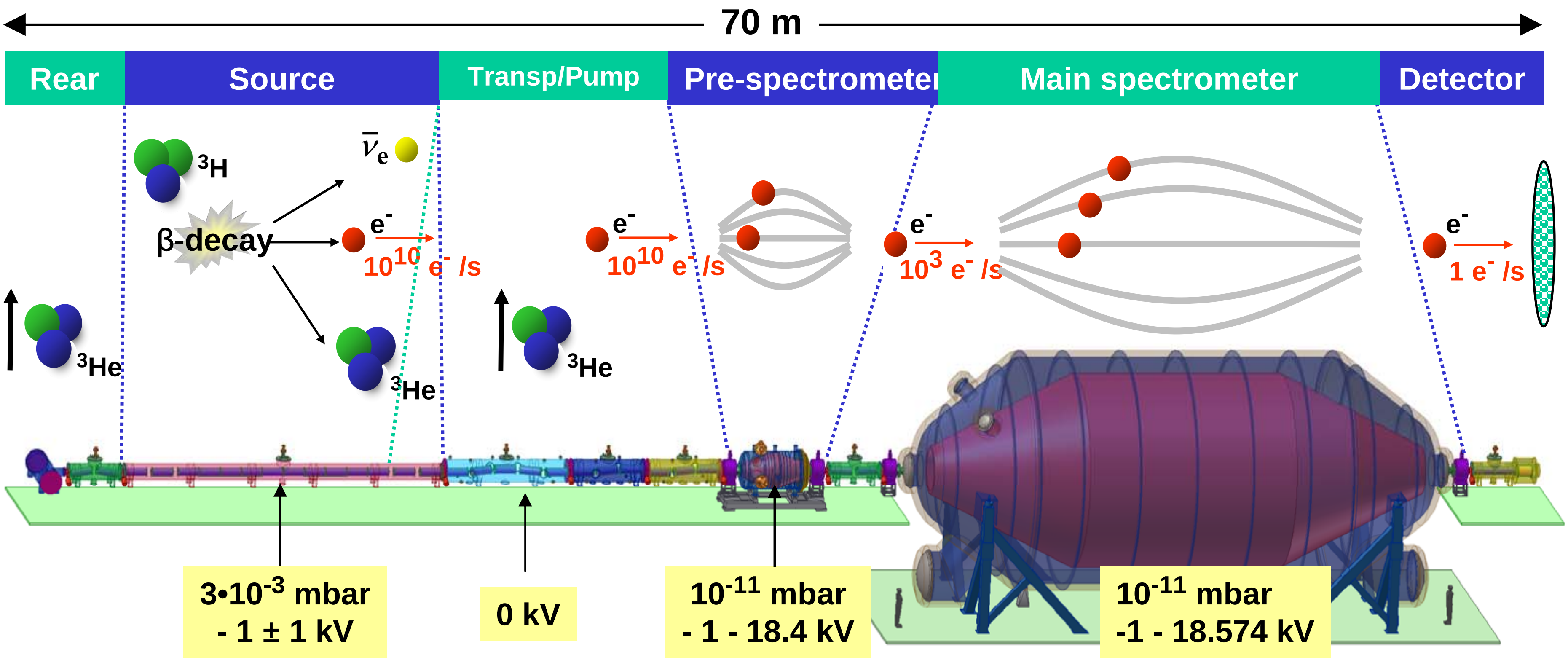
Current limit: $m_\nu < 2.2$ eV @ 95% CL (Mainz group 2000)

Next Generation β-decay Experiment (δm≈0.35 eV)

Karlsruhe Tritium Neutrino Experiment
(KATRIN)

next-generation experiment with sub-eV neutrino mass sensitivity

FH Fulda - FZ & U Karlsruhe - U Mainz - INP Prague - U Seattle - INR Troitsk



Arrival in Leopoldshafen: Nov 24, 2006

discovery potential:

m_ν = 0.35eV (5σ)

m_ν = 0.3eV (3σ)

sensitivity:

$m_\nu < 0.2$eV (90%CL)

Muon Neutrino Mass Studies

- Current best limit from studies of the kinematics of $\pi \rightarrow \mu\ \nu$ decay

$$p_\mu^2 + m_\mu^2 = (m_\pi^2 + m_\mu^2 - m_\nu^2)^2 / 4m_\pi^2$$

- Can use π-decay:
  - **At Rest:**
    Mass of π is dominate uncertainty
  - **In Flight:**
    Resolution on p_π-p_μ limited experimentally
- Best mass limit is from π-decay at rest

< 170 keV at 95% CL

(Assamagan *et al.*, PRD 1996)

Direct ν_τ Mass Limits

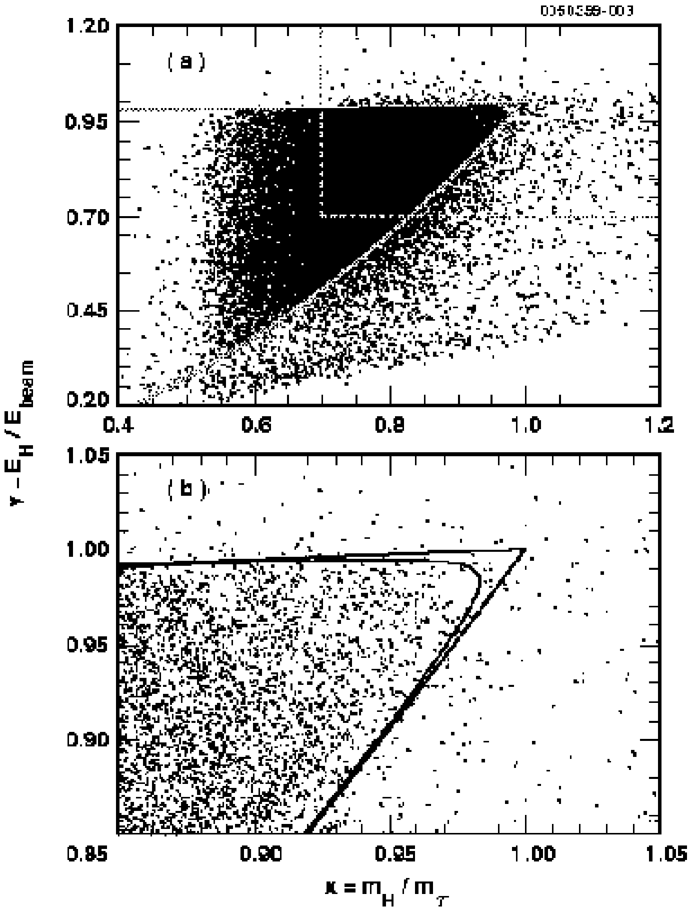
- Look at tau decays near the edge of the allowed kinematic range

  $\tau^- \to 2\pi^- \pi^+ \nu_\tau$ and

  $\tau^- \to 3\pi^-\ 2\pi^+ (\pi^0)\, \nu_\tau$

- Fit to scaled visible energy vs. scaled invariant mass (e.g. hep-ex/9906015, CLEO)

- Best limit is $m(\nu_\tau) < 18.2$ MeV at 95% CL (Aleph, EPJ C2 395 1998)



massive ν_τ
shifts the edge
of the distribution

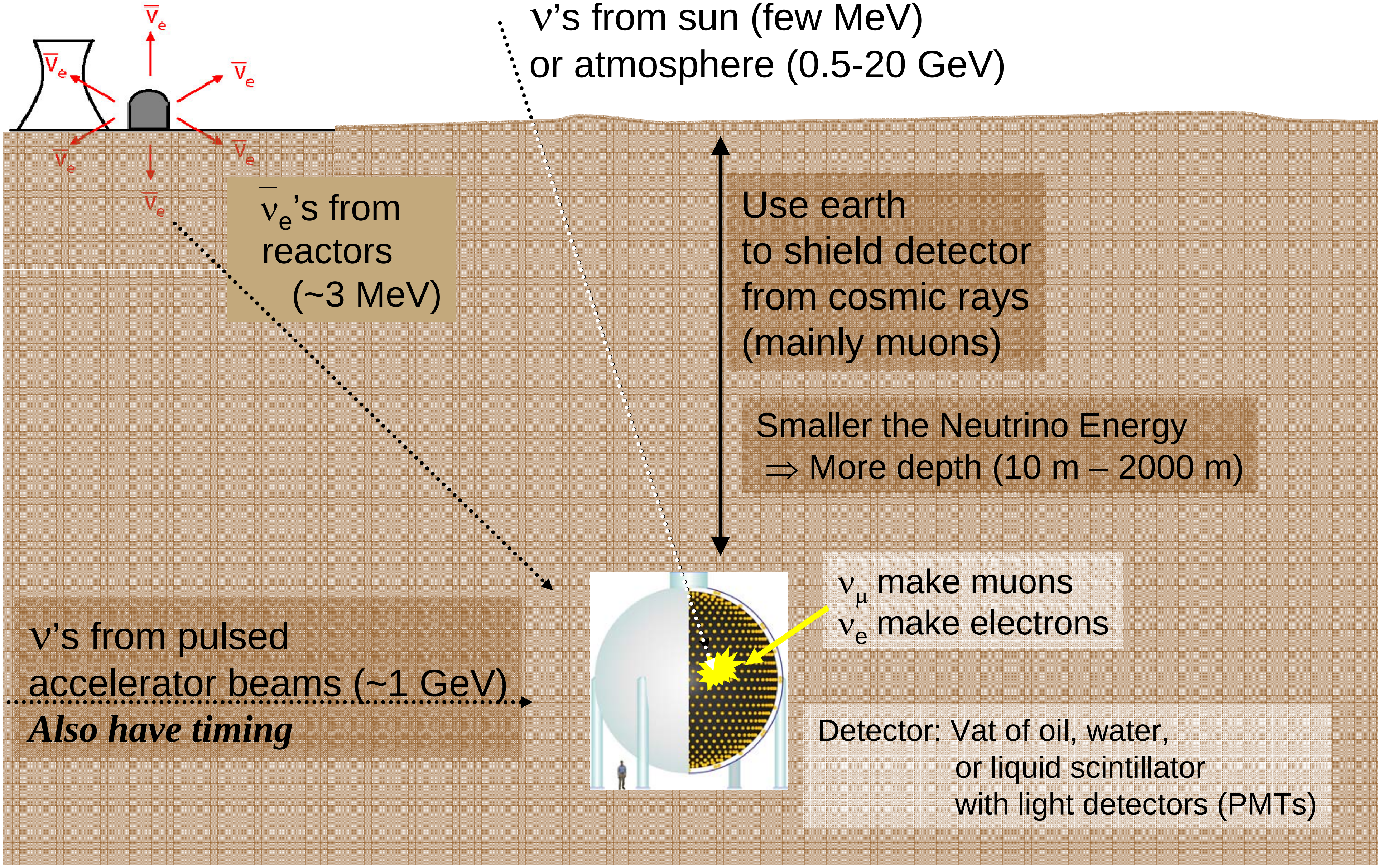
(Outer lines, mass=0;
inner lines, mass=30 MeV)

One can reach very small neutrino masses using "Quantum Interference Effects" ⇒ Neutrino Oscillation Experiments

- Source of Neutrinos
  - Need to understand the rate and type of neutrinos hitting detector
  - Methods: Compare observation to prediction
    - Typically done by calculation knowing the production mechanism
    - For accelerator beams can have ν monitor (ν-detector near location before oscillation.)

- Neutrino detector
  - Measures the energy of outgoing particles ⇒ ~energy of neutrino
  - Determine the type of neutrino from the outgoing lepton in event
  - Since ν cross sections are so low, need to maximize size of detectors within funding constraints.

Sources of Neutrinos for Experiments



ν's from sun (few MeV)
or atmosphere (0.5-20 GeV)

$\bar{\nu}_e$'s from
reactors
(~3 MeV)

Use earth
to shield detector
from cosmic rays
(mainly muons)

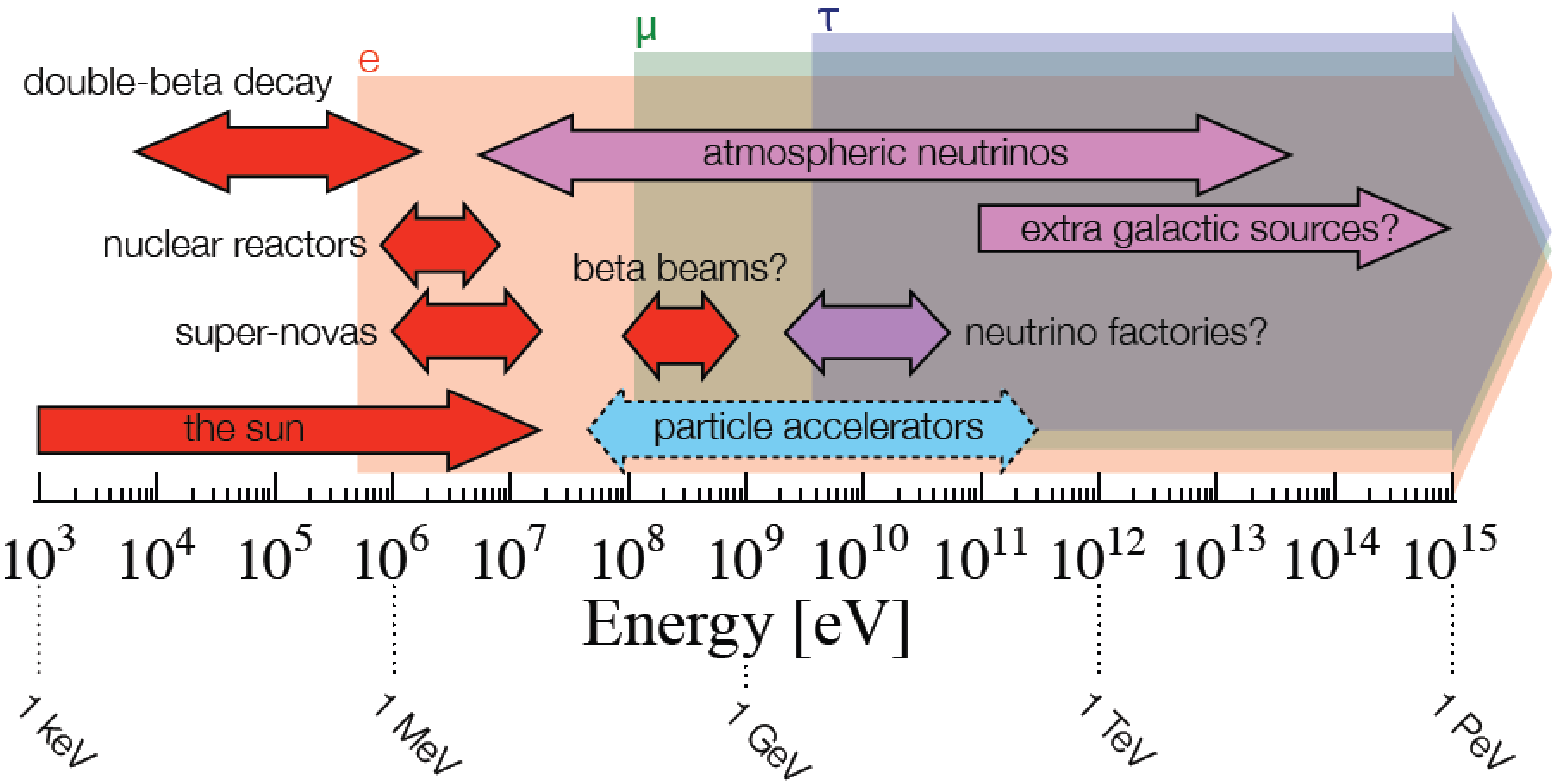
Smaller the Neutrino Energy
⇒ More depth (10 m – 2000 m)

ν_μ make muons
ν_e make electrons

ν's from pulsed
accelerator beams (~1 GeV)
Also have timing

Detector: Vat of oil, water,
or liquid scintillator
with light detectors (PMTs)

Energy Ranges for Neutrinos Sources



But to identify the neutrino type , need to be above threshold to produce the charged lepton

$$l = e \quad m_e = 0.511\ \text{MeV} \quad P_{\text{thresh}} = 0.511\ \text{MeV}$$

$$l = \mu \quad m_\mu = 106\ \text{MeV} \quad P_{\text{thresh}} = 112\ \text{MeV}$$

$$l = \tau \quad m_\tau = 1.78\ \text{GeV} \quad P_{\text{thresh}} = 3.47\ \text{GeV}$$

Big Bang Neutrinos

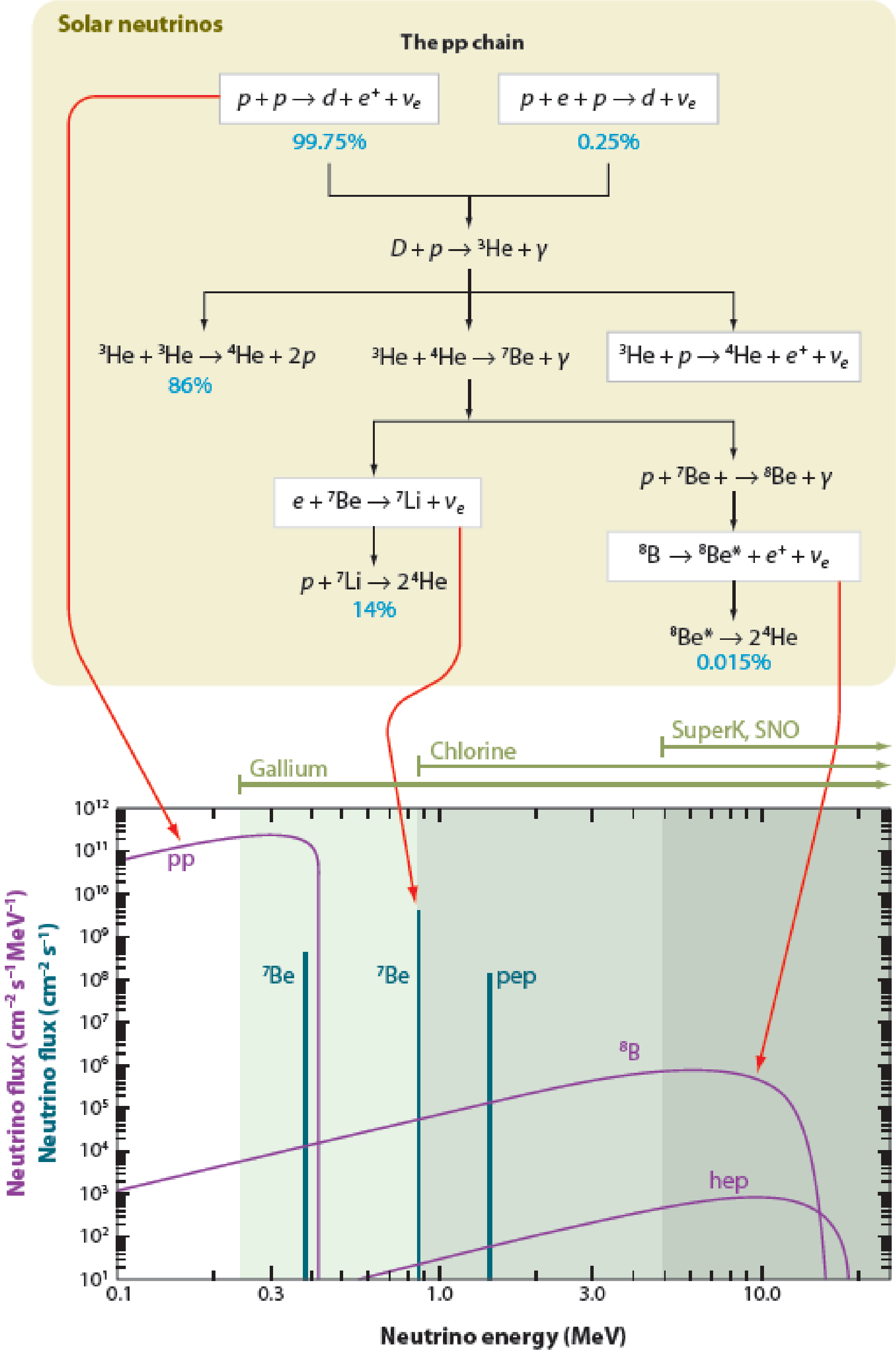
- There are neutrinos all through the universe:
  - Density = 115/cm^3 (ν + $\bar{\nu}$) per neutrino type
  - Temperature = 1.95 ^{0}K = 2×10^{-4} eV
- Originally thought to be a good "Dark Matter" candidate
  - With a mass of 30 eV could explain dark matter and would be non-relativistic
- Many experiments set up to measure neutrino oscillations and electron neutrino mass in the ~30 eV region
  - Now know that neutrino masses are much below this value
- But detecting these neutrinos is still one of the big experimental challenges for us
  - These neutrinos decouple a much earlier times than the CMB so would give new information at the 1 second time scale.

Neutrinos from the Sun

- Standard Solar Model (mainly John Bahcall)
  - Sun is in hydrostatic equilibrium.
  - Main energy transport is by photons.
  - Primary energy generation is nuclear fusion.
  - Elemental abundance determined solely from fusion reactions.

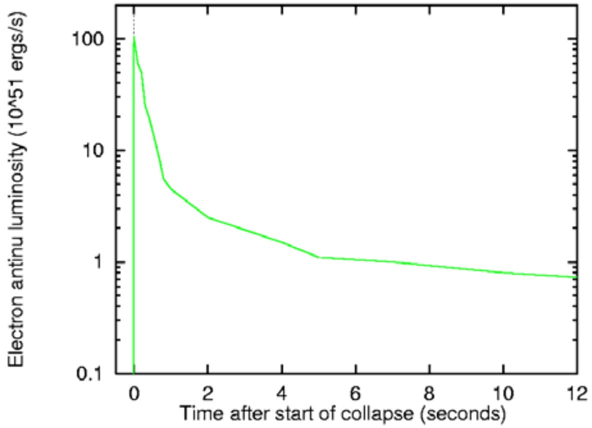
- Only electron neutrinos are produced initially in the sun.
  - Oscillations give other types

- Spectrum dominated by pp fusion chain which only produces low energy neutrinos.

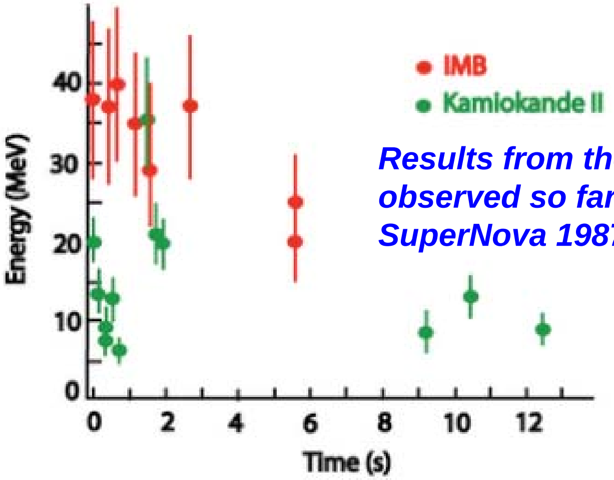


Supernova Neutrinos

- In a super nova explosion
  - Neutrinos escape before the photons
  - Neutrinos carry away ~99% of the energy
  - The rate of escape for ν_e is different from ν_μ and ν_τ (Due extra ν_e CC interactions with electrons)



- Neutrino mass limit can be obtained by the spread in the propagation time
  - t_{obs}-t_{emit} = t_0 $(1 + m^2/2E^2)$
  - Spread in arrival times if $m \neq 0$ due to ΔE
  - For SN1987a assuming emission time is over 4 sec $m_\nu < \sim 30$ eV



Results from the only supernova observed so far: SuperNova 1987a (20 events)

(All arrived within about ~13 s after traveling 180,000 light years with energies that differed by up to a factor of three. The neutrinos arrived about 18 hours before the light was seen)

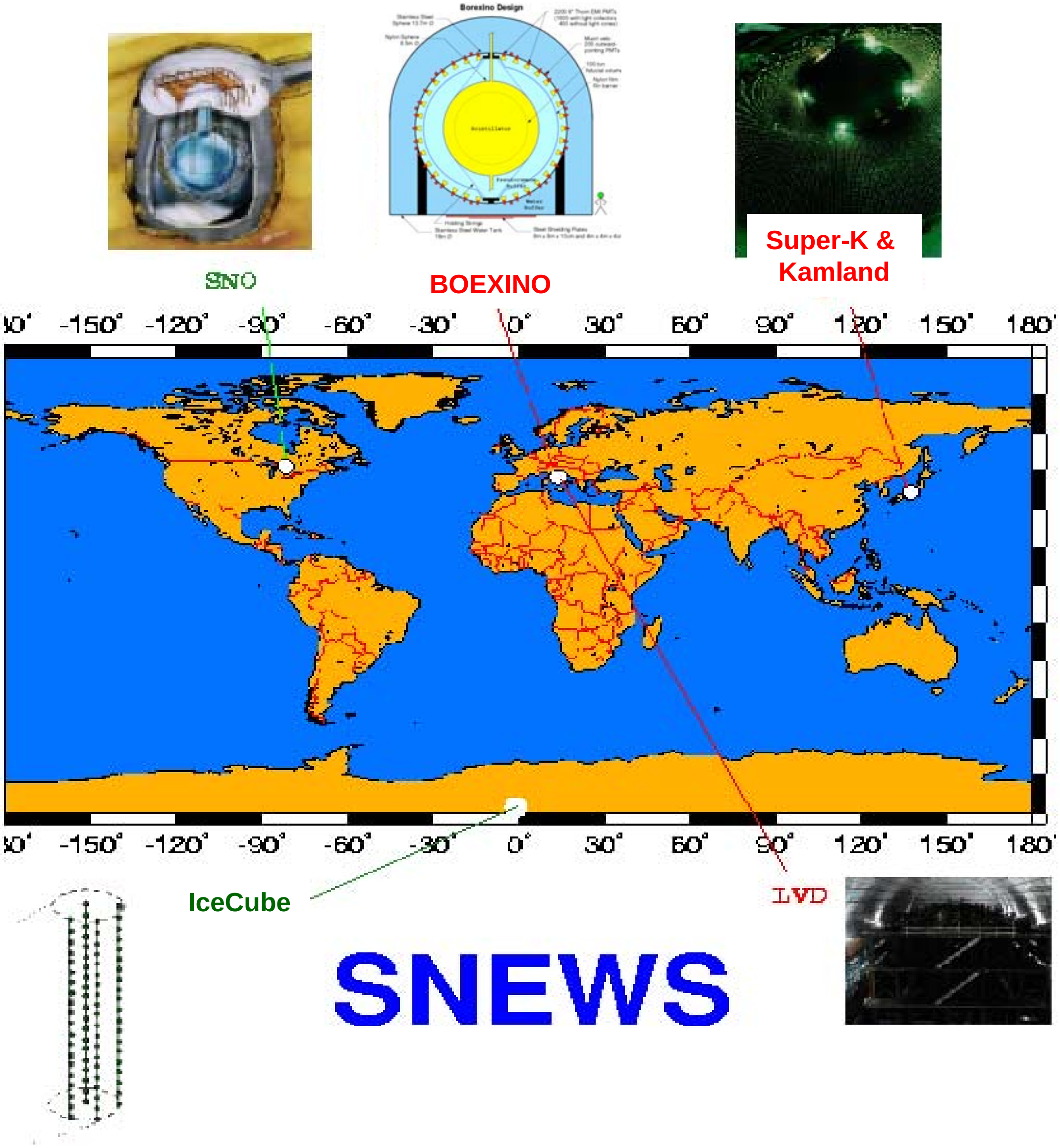
SNEWS
The SuperNova Early Warning Sytem

SNEWS –

- Coincidence trigger between world's ν observatories eliminates instrumental false alarms
- Confidence in such an automated signal allows for FAST enough alarm to beat the photons
- Running in test mode for $\gtrsim 1$ year, will release automated alarms sometime in 2000

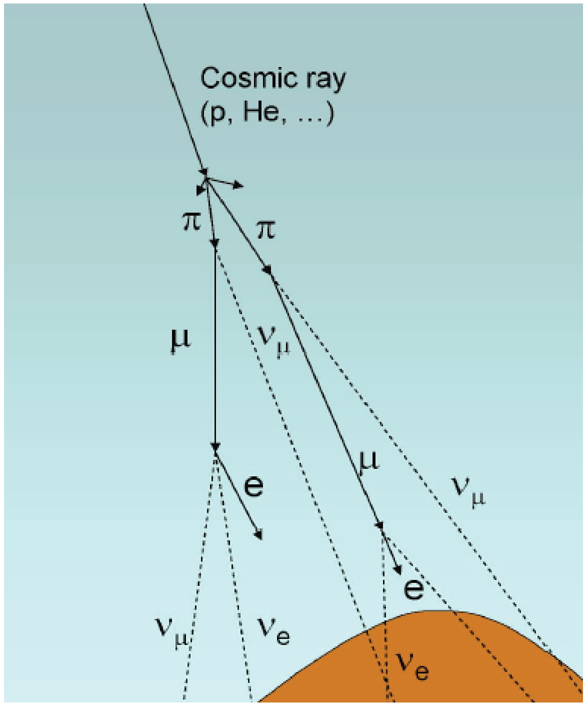
What is to be gained from an early warning?

- UV/soft X-ray flash at shock breakout predicted.
- Environment near progenitor star is probed by the initial stages of the collapse.
- Possible unknown early effects. Who knows what we're missing when observing SN at Mpc distances starting days after the explosion?

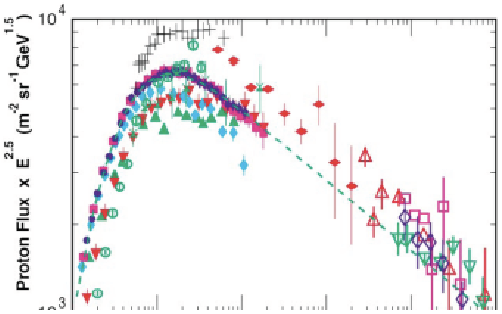


Atmospheric Neutrinos

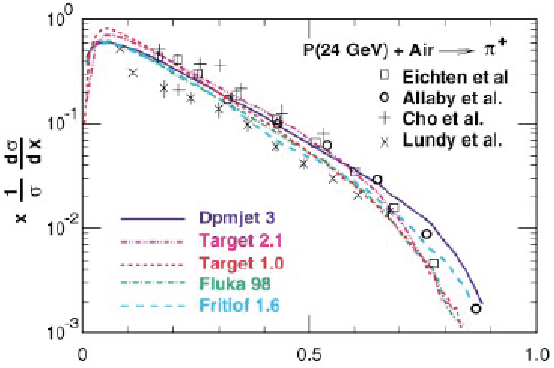
- Produced by high-energy cosmic rays
  - Interact in upper atmosphere to produce pions
  - Pions/muon decay chain gives ν's
- To calculate ν flux
  - Use measured primary CR fluxes combined with hadron production parameterizations



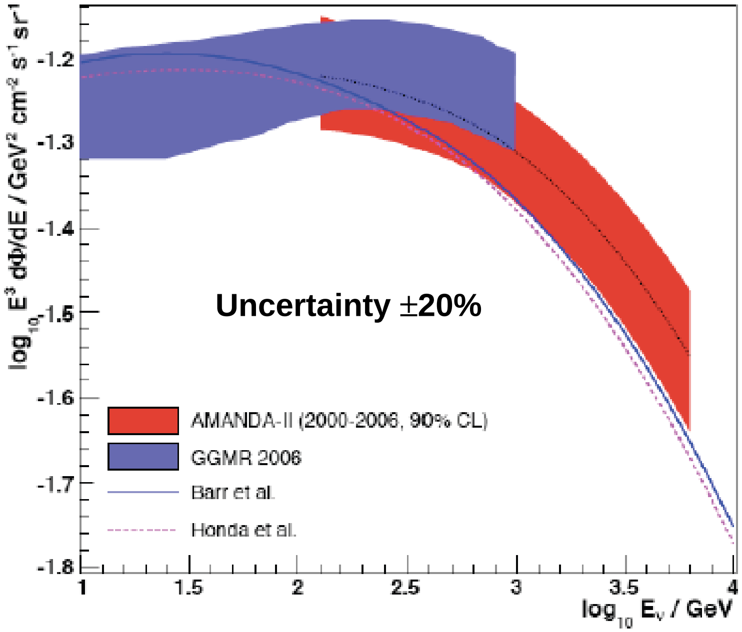
Primary CR flux



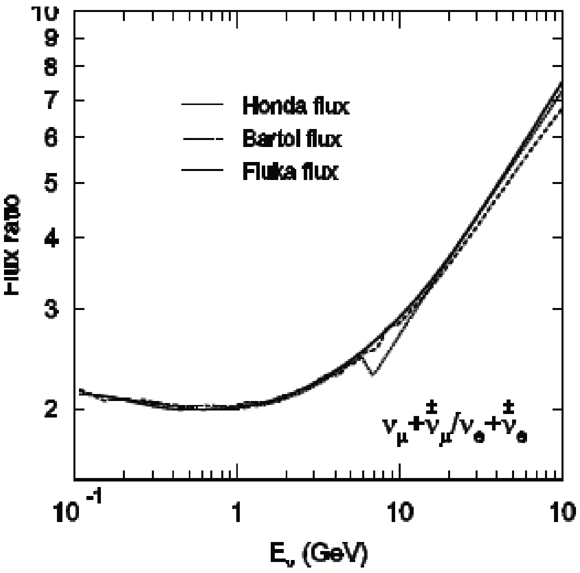
Hadronization



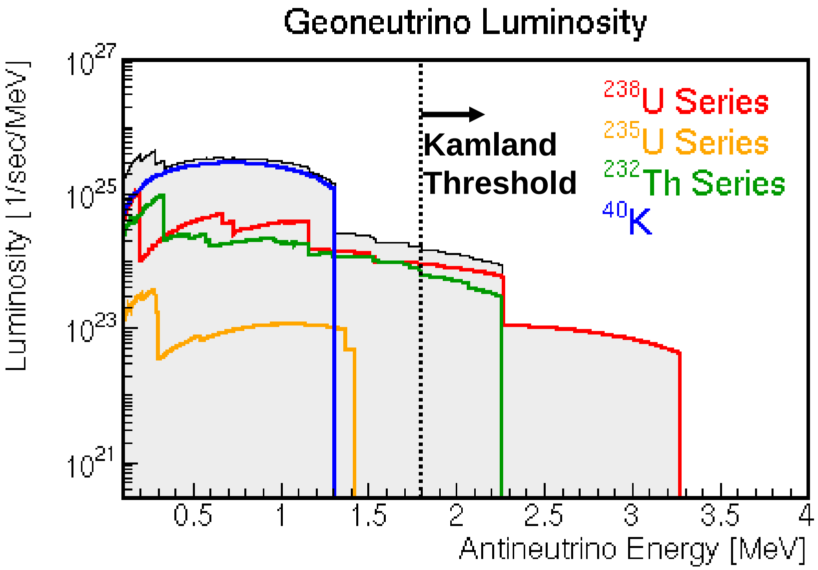
Predicted and Measured Atmospheric ν_μ Flux

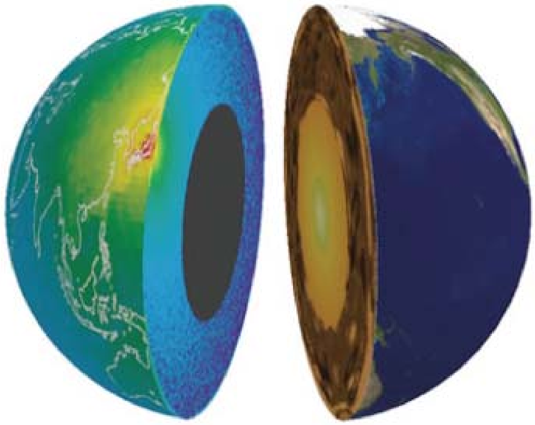


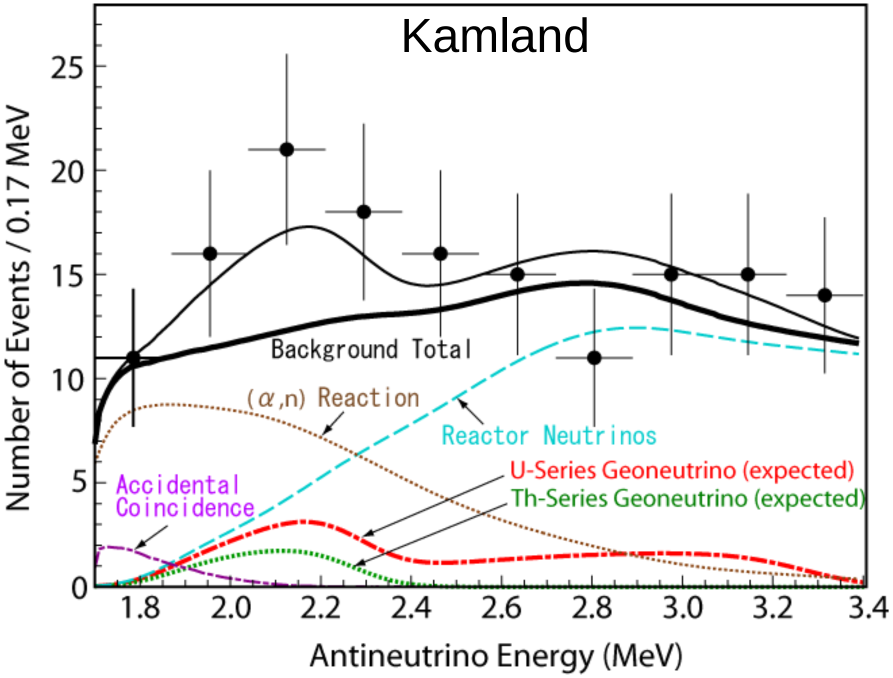
Uncertainty ±20%



Geo-Neutrinos







- Decays of radioactive elements in earth's crust and mantle lead to a flux of low energy neutrinos
- This provides the main portion of the Earth's heating source (~40-60% of 40 TW).
- First hints for geoneutrinos recently from the Kamland experiment.

BG total : 127.4 ± 13.3
Observed : 152
Excess: 25 ± 18
Expect (U & Th): 28.9

Nuclear Reactors as a Source of $\bar{\nu}_e$'s

Where are the reactor $\bar{\nu}_e$'s from?

- Typical modern nuclear power reactor has a thermal power of: P_{therm} = 4 GW
- About e=200 MeV / fission of energy is released in fission of ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu.
- The resulting fission rate, f, is thus: f = 1.2 ×10^{20} fissions/s
- At 6 $\bar{\nu}_e$ / fission the resulting yield is: 7.1 ×10^{20} / s.
- From reactor power, neutrino flux known to ~2% and the spectrum is known to ~1.5%

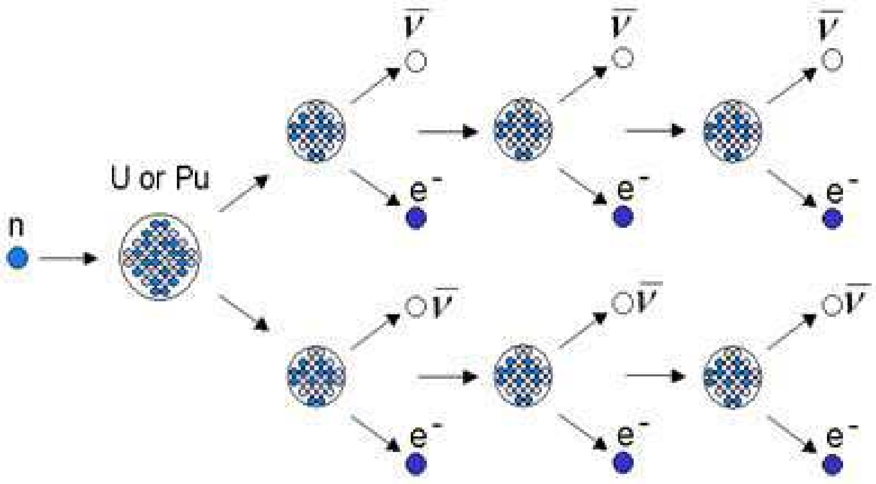
Example: ^{235}U fission

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

nuclei with most likely A from ^{235}U fission $^{94}_{40}Zr$ $^{140}_{58}Ce$

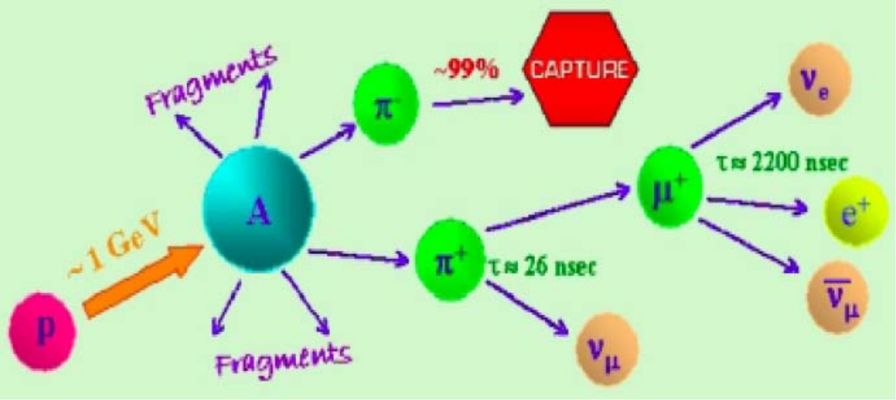
→ on average 6 n have to β-decay to 6 p to reach stable matter.

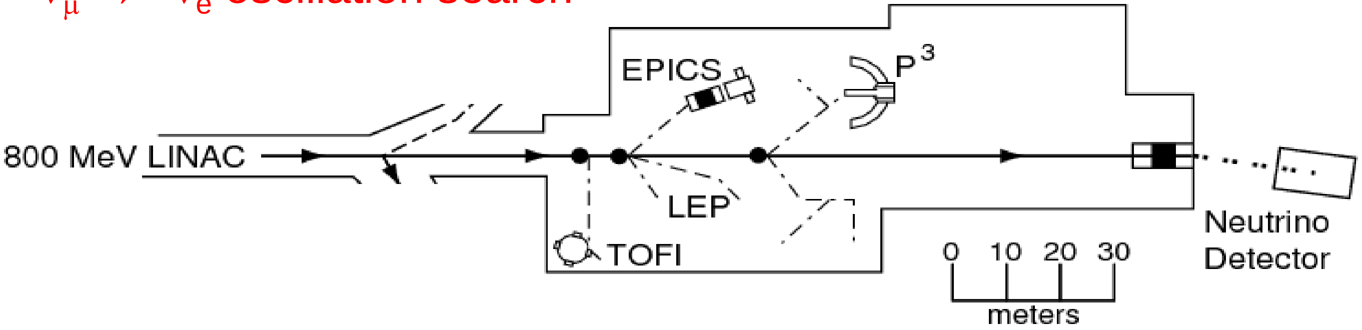
→ on average 1.5 $\bar{\nu}_e$ are emitted with energy > 1.8 MeV



Accelerator “Beam Dump” Neutrino Beams

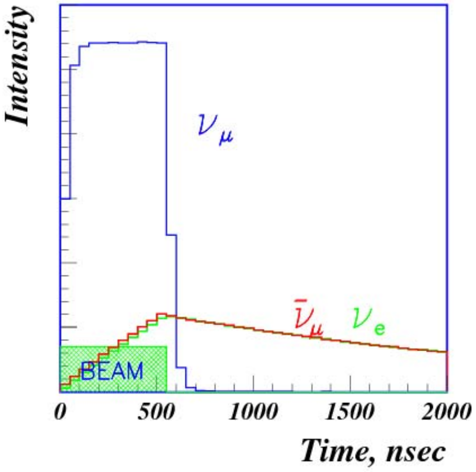
- At Los Alamos, high intensity 800 MeV proton beam goes into water/copper beam dump (also proposed at SNS)
- Protons produce:
  - π^- mesons that are captured in nucleus before decay
  - π^+ mesons that decay into ν_μ, $\bar{\nu}_\mu$ and ν_e
    Very few $\bar{\nu}_e$ in beam ⇒
    Good for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search

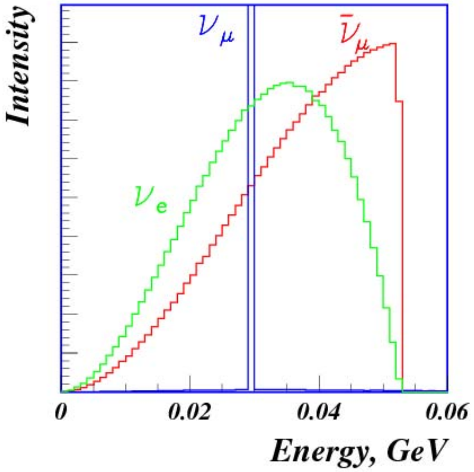




$$\pi^+ \rightarrow \mu^+ \nu_\mu, \qquad \tau = 26\ nsec$$

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e, \qquad \tau = 2.2\ \mu sec.$$





Accelerator Neutrino Beams from π/K decay

- Produce pions and kaons from accelerator protons (8 – 800 GeV)
  - Focus mesons towards detector for higher efficiency
  - Beam is bunched in time so can eliminate many backgrounds recording data only during beam spill
  - Fairly pure beam of ν_μ or $\bar{\nu}_\mu$ neutrinos depending whether you focus π^+ or π^- mesons.

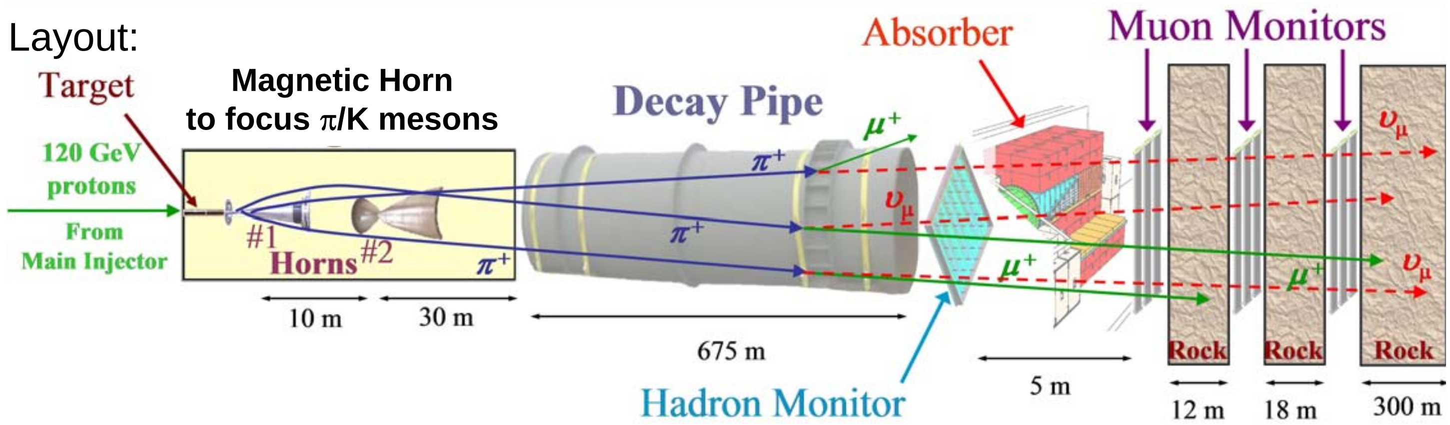
$$\pi^+ \left(\text{or } K^+\right) \to \mu^+ \nu_\mu$$

$$\pi^- \left(\text{or } K^-\right) \to \mu^- \bar{\nu}_\mu$$

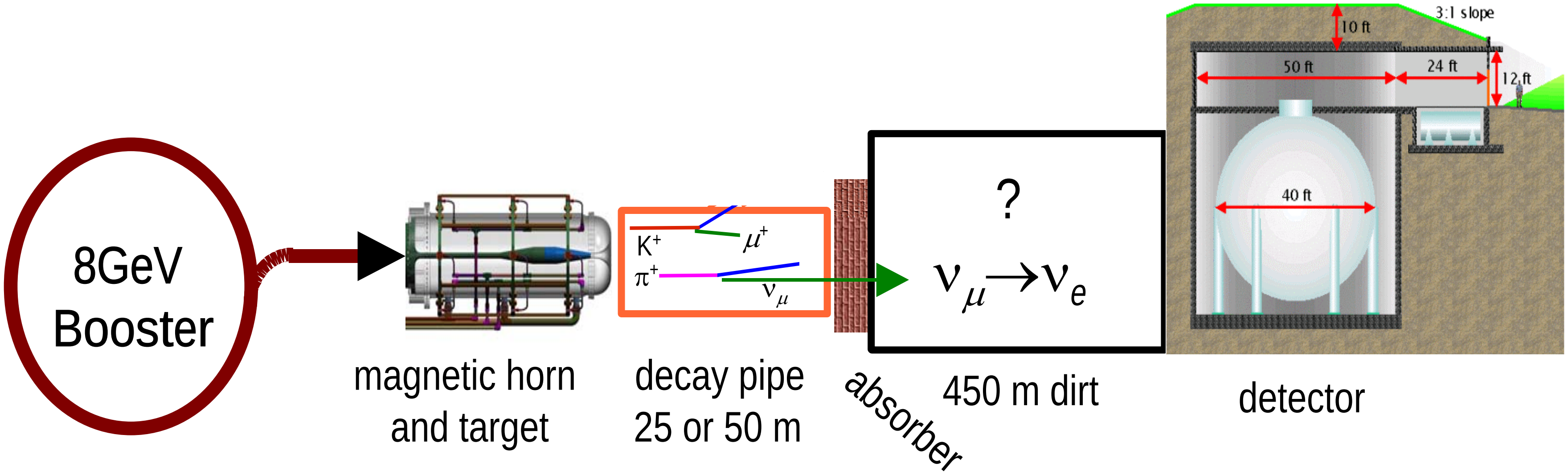
Why little ν_e ?

  - Some contamination (0.5% to 2 %) of ν_e or $\bar{\nu}_e$ from K_{e3} decay ($K \to \pi\, e\, \nu_e$)

NuMI Beam Layout:



Example: MiniBooNE Neutrino Beam



8GeV Booster

magnetic horn and target

decay pipe
25 or 50 m

absorber

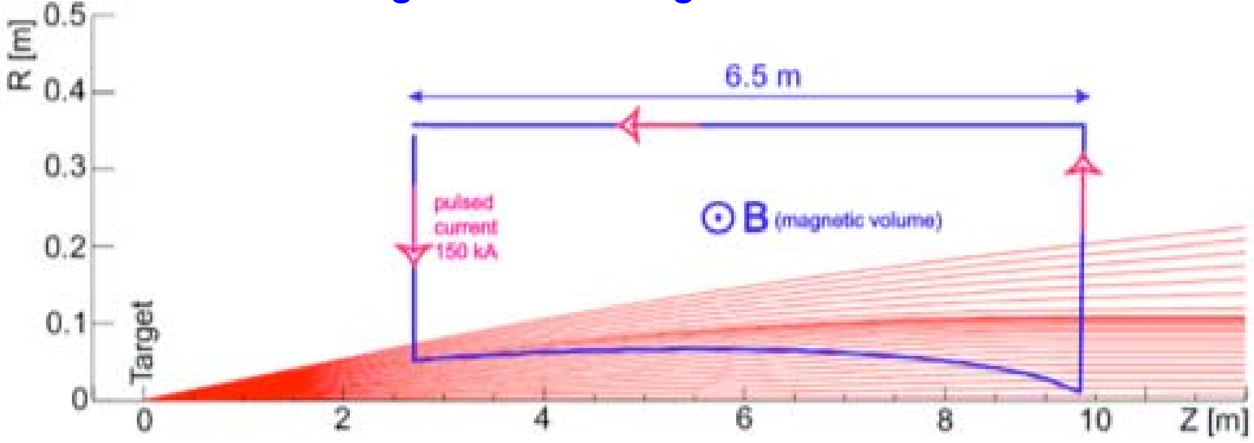
?

$\nu_\mu \rightarrow \nu_e$

450 m dirt

detector

MINOS Magnetic Focusing Horn



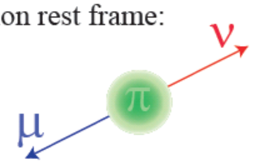
New Wrinkle: Offaxis Beam

- By going offaxis, beam energy is reduced and spectrum becomes very sharp
  - Allows experiment to pick an energy for the maximum oscillation signal
  - Removes the high-energy flux that contributes to background

"Not magic but relativistic kinematics"

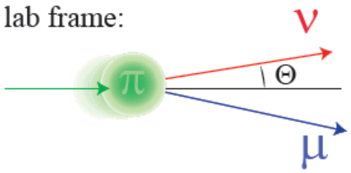
- Problem is reduced rate!
  - need large detectors and high rate proton source

In pion rest frame:

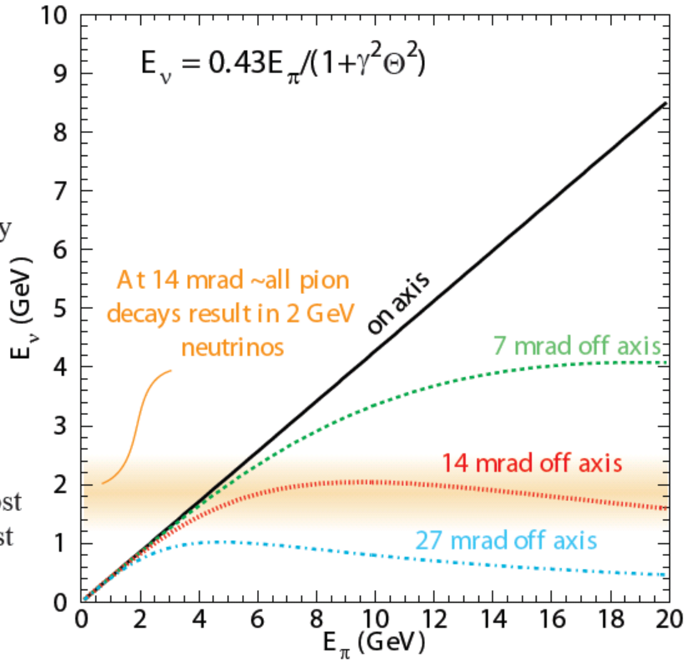


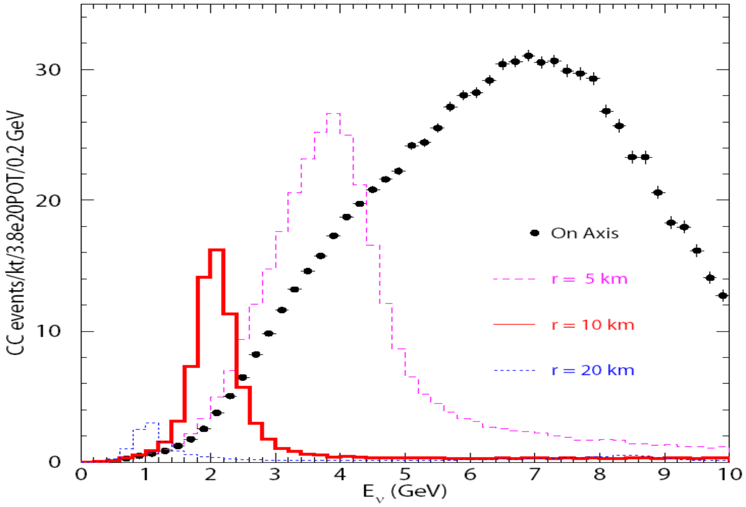
Neutrino and muon energy completely determined by energy conservation

In lab frame:



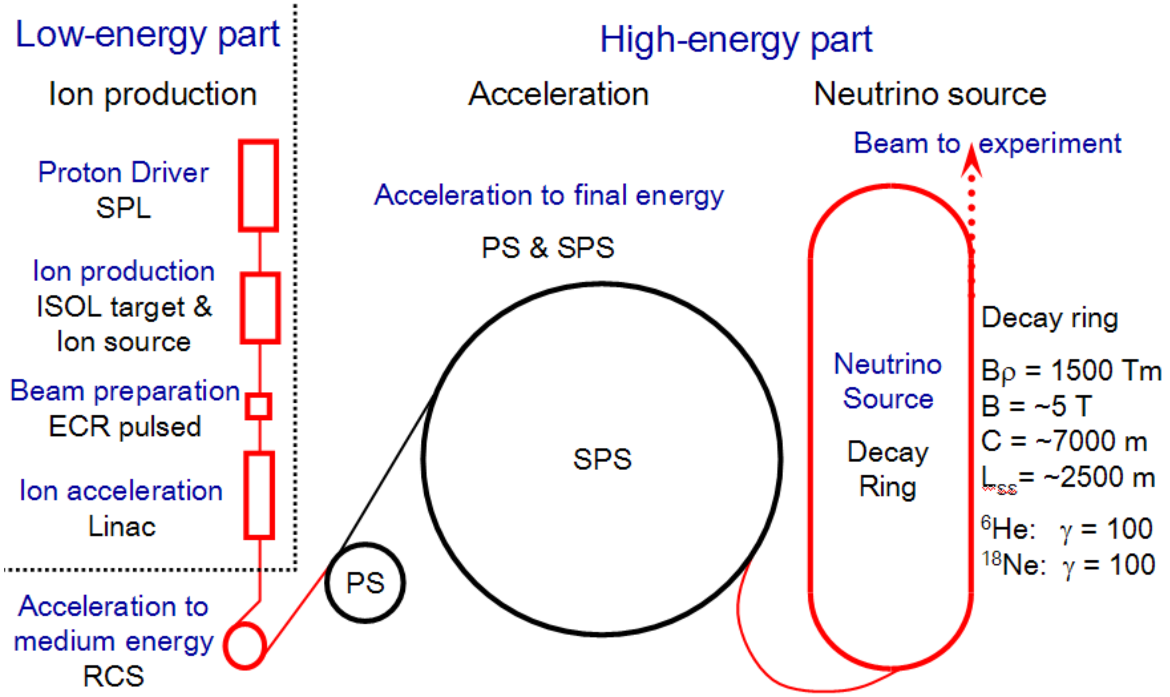
Neutrino energy depends on boost and angle between neutrino boost direction





Beta Beams

- Use accelerator protons to produce radioactive ions that will beta decay
- Capture these ions bunches and accelerate up to high energy (100 to 300 GeV).
- Put this ion beam in a storage ring with long sections where ions can decay giving you a pure ν_e beam.
- Good for $\nu_e \rightarrow \nu_\mu$ oscillation search where detecting an outgoing muon is easier than detecting an outgoing electron.



Low-energy part
Ion production
Proton Driver
SPL
Ion production
ISOL target &
Ion source
Beam preparation
ECR pulsed
Ion acceleration
Linac
Acceleration to
medium energy
RCS

High-energy part
Acceleration
Acceleration to final energy
PS & SPS
PS
SPS

Neutrino source
Beam to experiment
Neutrino
Source
Decay
Ring

Decay ring
$B\rho$ = 1500 Tm
B = ~5 T
C = ~7000 m
L_{ss} = ~2500 m
^{6}He: γ = 100
^{18}Ne: γ = 100

$$^{6}\mathrm{He} \longrightarrow {}^{6}\mathrm{Li}\ e^{-}\ \bar{\nu}_e$$

1/2Life = 0.8 s

Electron Anti-neutrino Source

$$^{18}\mathrm{Ne} \longrightarrow {}^{18}\mathrm{F}\ e^{+}\ \nu_e$$

1/2Life = 1.7 s

Electron Neutrino Source

Possible Future Step: Muon Storage Ring ν–Factory

- Muon storage ring
  - Provides a super intense neutrino beam with a wide range of energies.
  - High intensity, mixed beam allows investigation of all mixings ($\nu_e \rightarrow \nu_{\mu \text{ or } \tau}$)

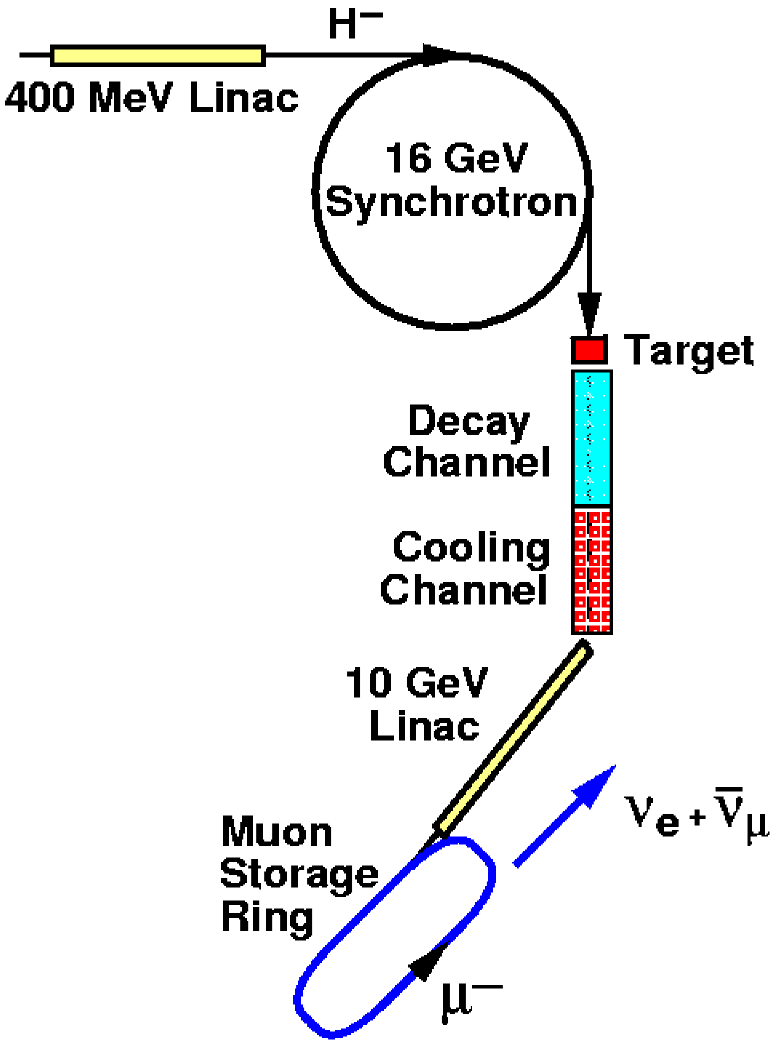
- Flavor composition/energy selectable and well understood:

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e \quad \text{or}$$

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

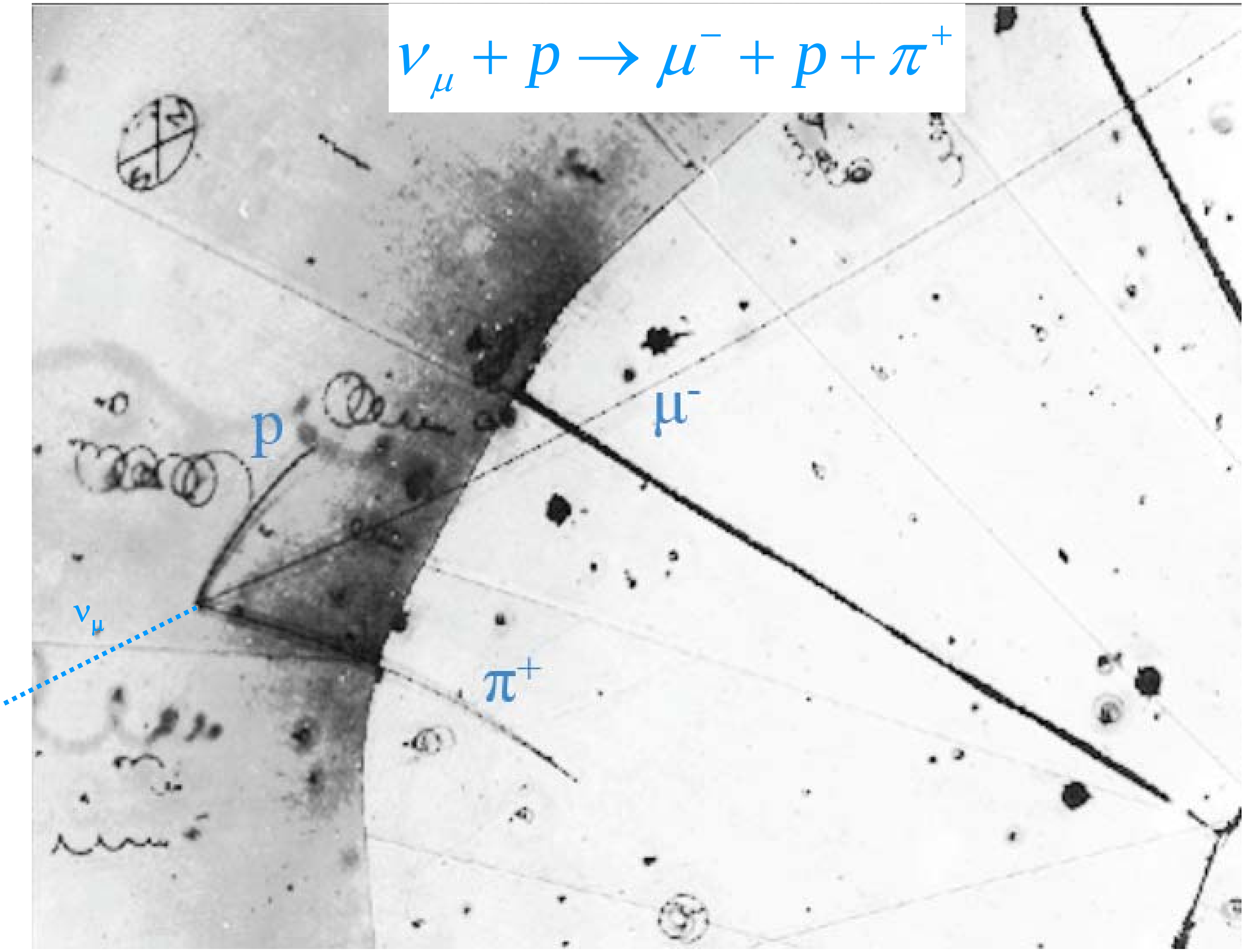
- Highly collimated beam
  - Very long baseline experiments possible

    i.e. Fermilab to California



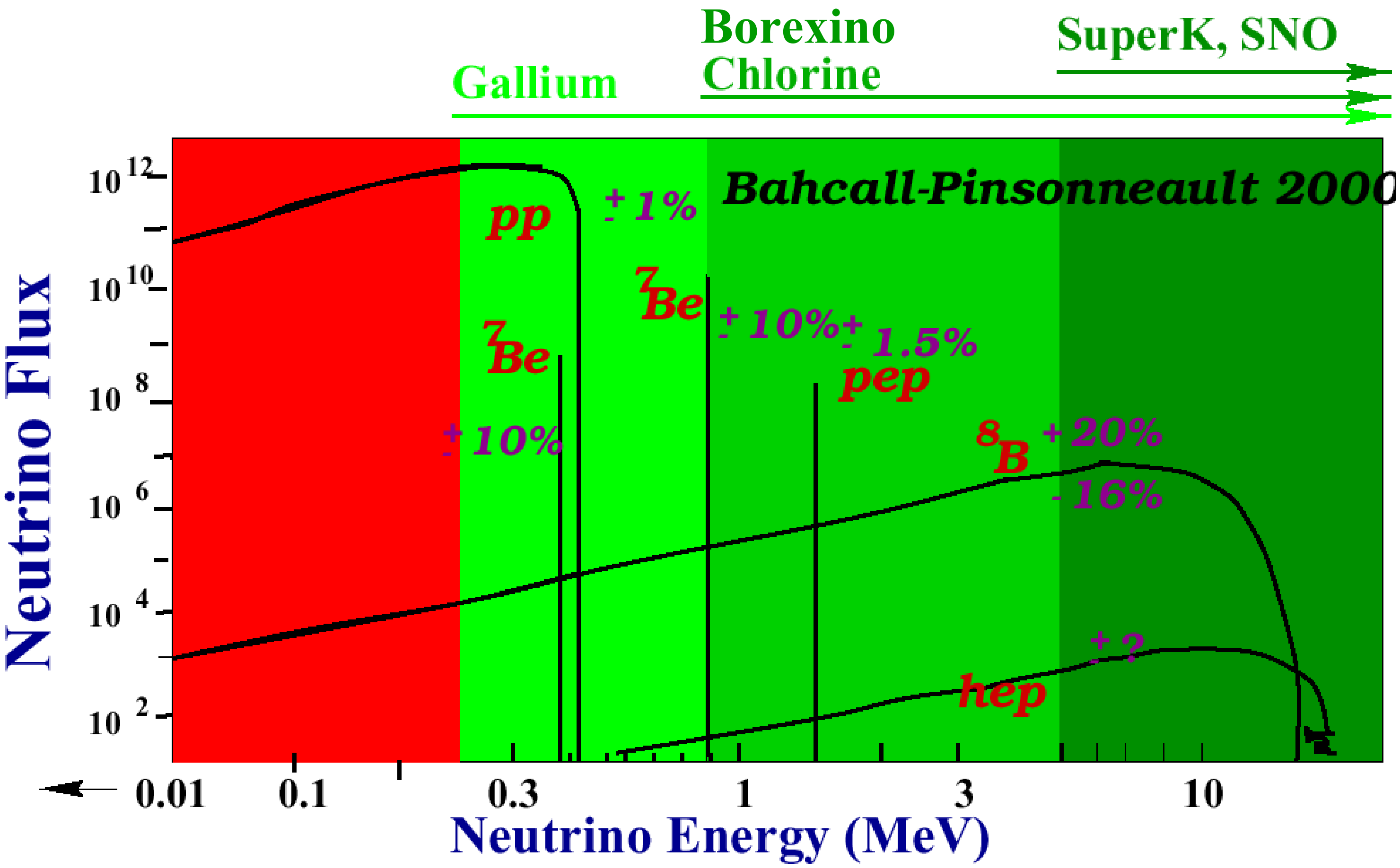
Neutrino Detectors

Early Experiments Used Bubble Chambers



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

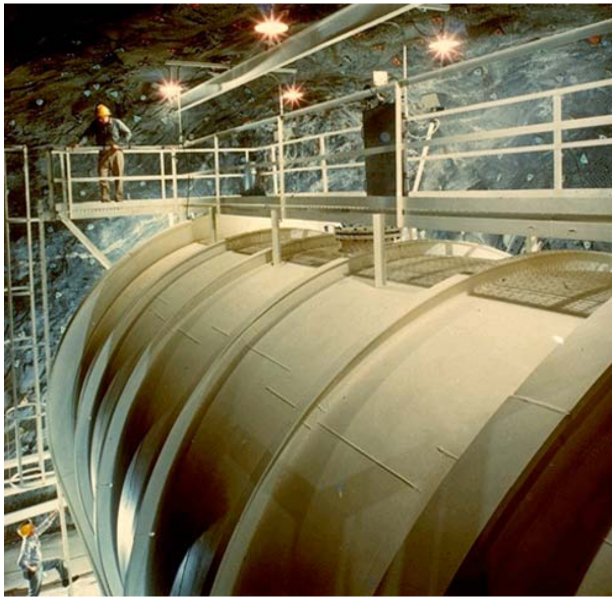
Solar Neutrino Detectors



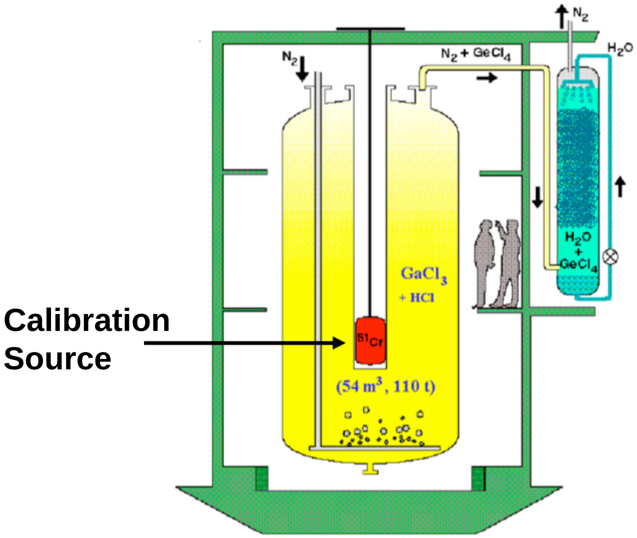
- Two broad categories of detectors:
  - "After the fact" detectors
  - "Real time" detectors

Radio-Chemical Experiments for Solar Neutrinos
"After the Fact Detectors"

- Homestake: $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$
  - Located in Lead, SD
  - 615 tons of C_2Cl_4 (Cleaning fluid)
  - Extraction method:
    - Pump in He that displaces Ar
    - Collect Ar in charcoal traps
    - Count Ar using radioactive decay
  - Never Calibrated with source



- Gallium Exps: $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$
  - GALLEX (Gran Sasso, Italy) uses aqueous gallium chloride (101 tons)
  - SAGE (Baksan,Russia) uses metallic gallium (57 tons)
  - Extraction method:
    - Synthesized into GeH_4
    - Inserted into Xe prop. Counters
    - Detect x-rays and Auger electrons
  - Calibrated with very large Cr source



Neutrino Events and “Real Time” Detectors

Neutrino event topologies

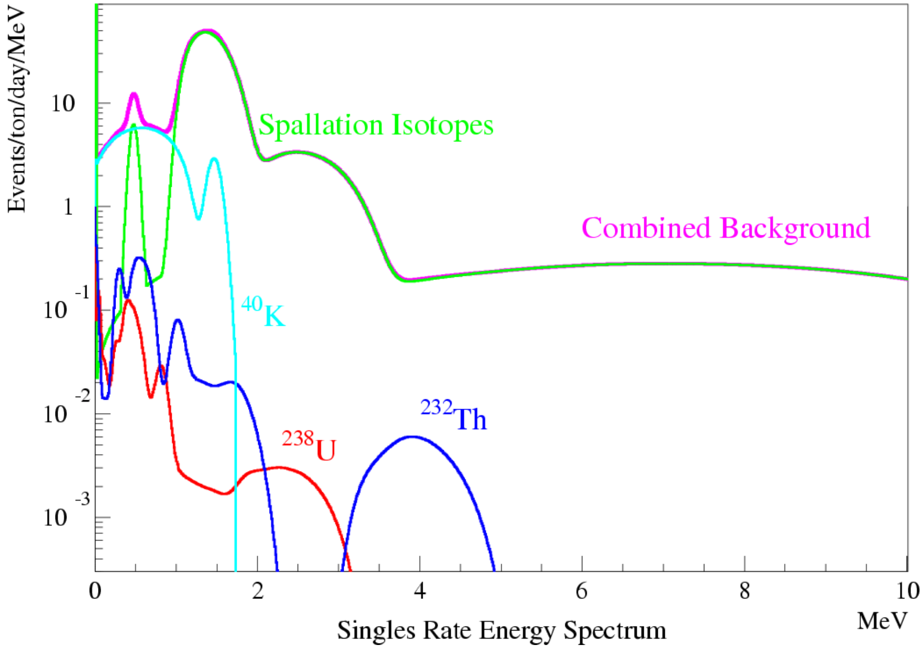
- Muons :
  Long straight, ~constant energy deposit of 2 MeV cm2 / g
- Electrons :
  Create compact showers. Longitudinal size determined by radiation length. Transverse size determined by Moliere radius.
- Photons:
  Create compact showers after a gap of ~1 radiation length.
- Hadrons :
  Create diffuse showers. Scale determined by interaction length

Specific technologies:

- *Cherenkov*:
  Best for low rate, low multiplicity, energies below 1 GeV
- *Tracking calorimeters*:
  Can handle high rate and multiplicities. Best at 1 GeV and above.
- *Unsegmented scintillator calorimeters*:
  Large light yields at MeV energies. Background considerations dominate design.
- Liquid Argon *TPCs*:
  Great potential for large mass with high granularity. Lots of activity to realize potential

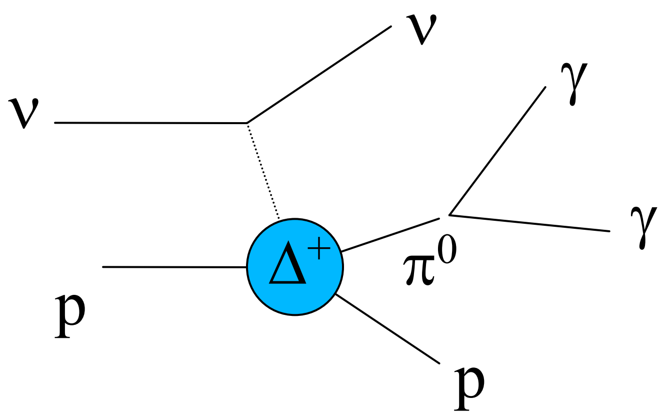
Key Issues for Neutrino Osc Detectors

- Low energy searches (Cerenkov and Scintillation Detectors)
  - Single component signal
    - Background from radioactivity and cosmic-ray spallation
      ⇒ Keep exp clean and shielded
  - Coincidence signals best
    - Electron followed by neutron
    - Muon followed by decay electron signal



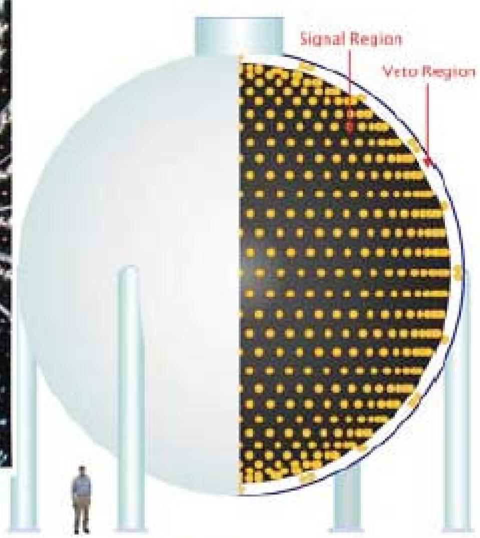
Singles Rate Energy Spectrum

- Appearance Experiments ($\nu_\mu \rightarrow \nu_e$)
  - Major background is NC π^0 prod
    $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0 \rightarrow \gamma\gamma$
    where 1γ is lost
    - Best to be able to separate γ from electron in detector
  - Best to have two detectors – Near/Far
    - Near detector measures unoscillated flux and backgrounds



Cherenkov detectors

MiniBooNE Detector



SNO

6000 mwe overburden

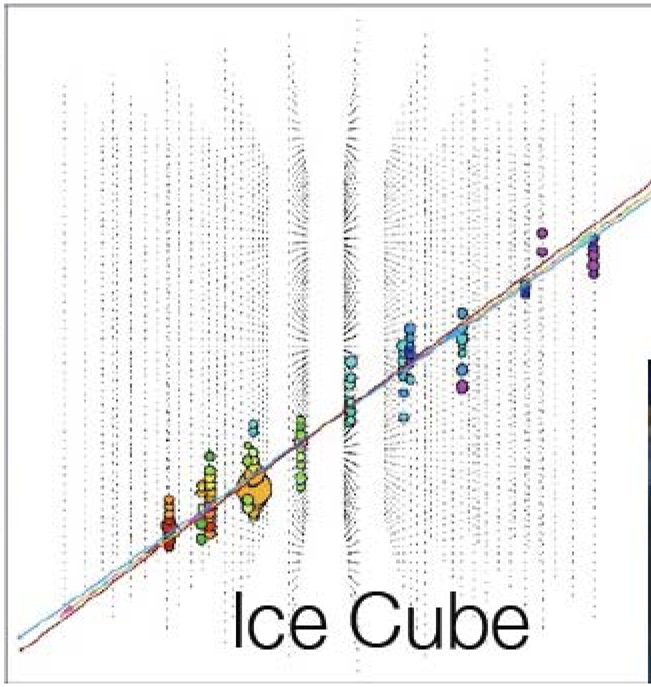
1000 tonnes D_2O

12 m Diameter Acrylic Vessel

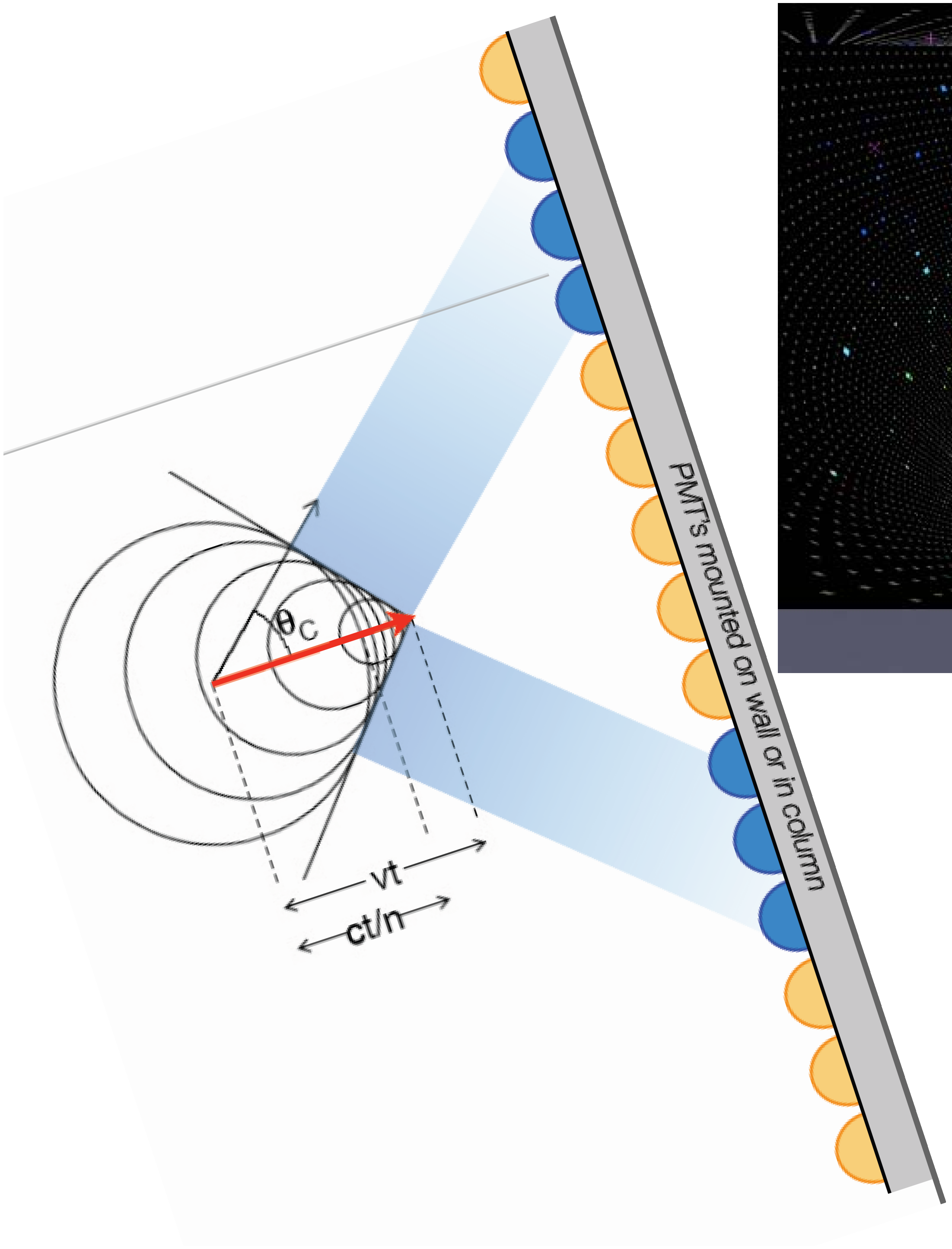
1700 tonnes Inner Shield H_2O

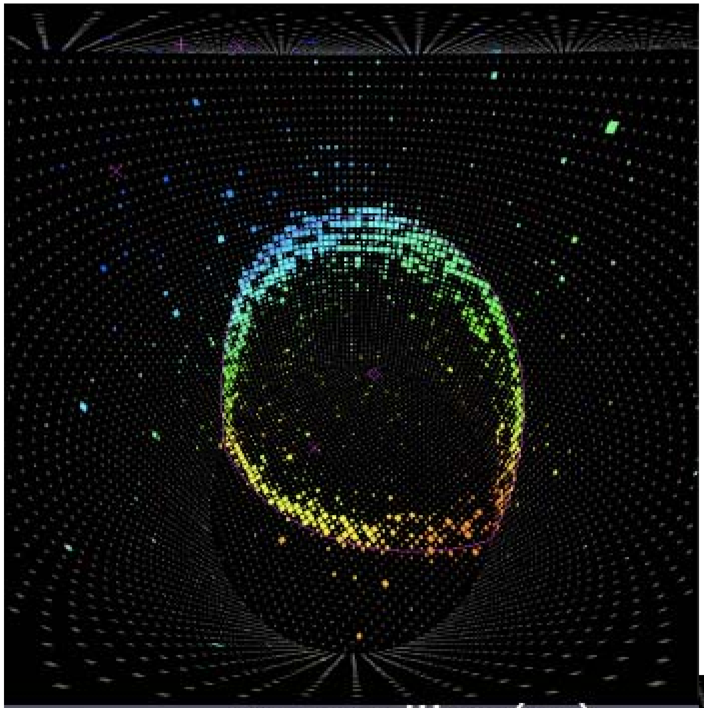
Support Structure for 9500 PMTs, 60% coverage

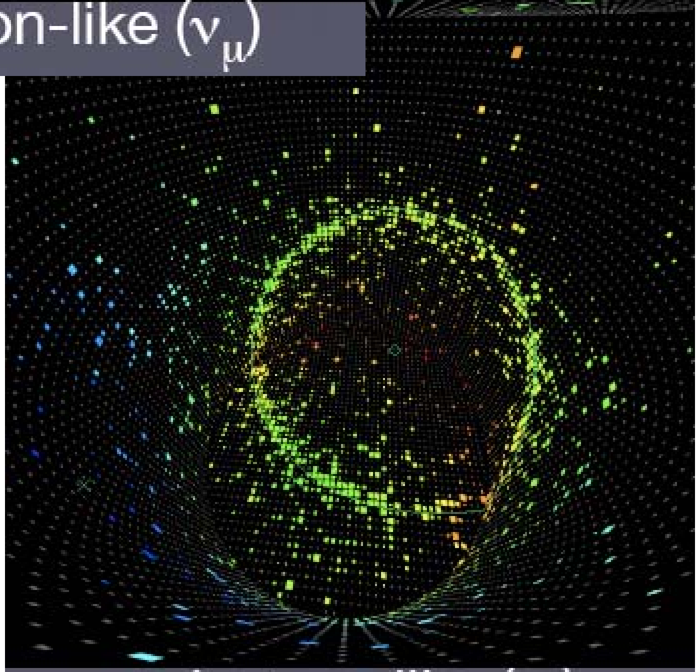
5300 tonnes Outer Shield H_2O



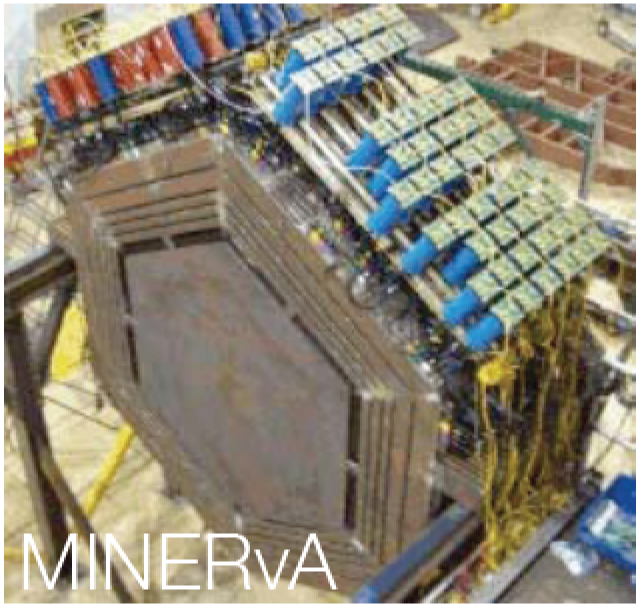
ANTARES

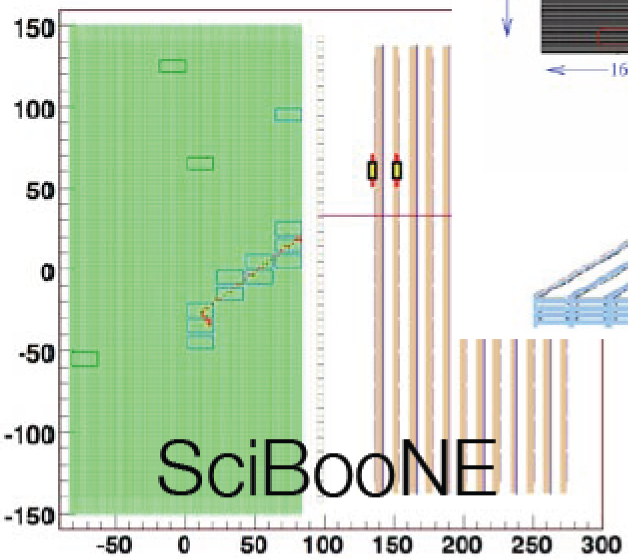


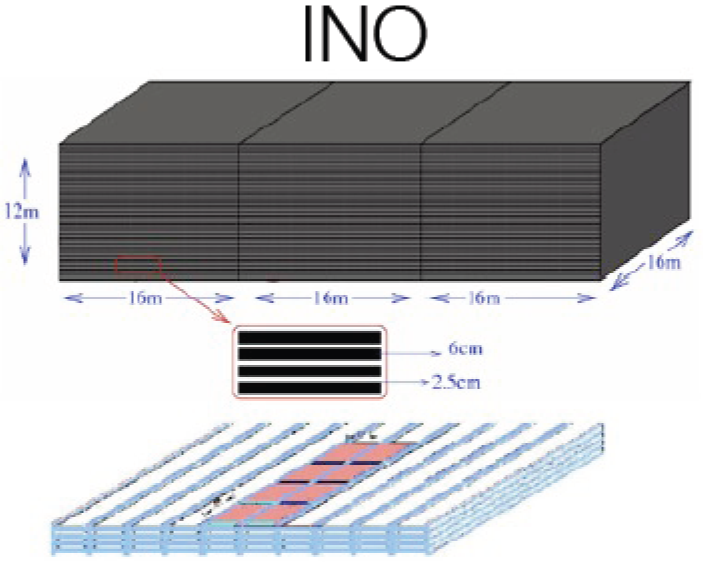

muon-like (ν_μ)

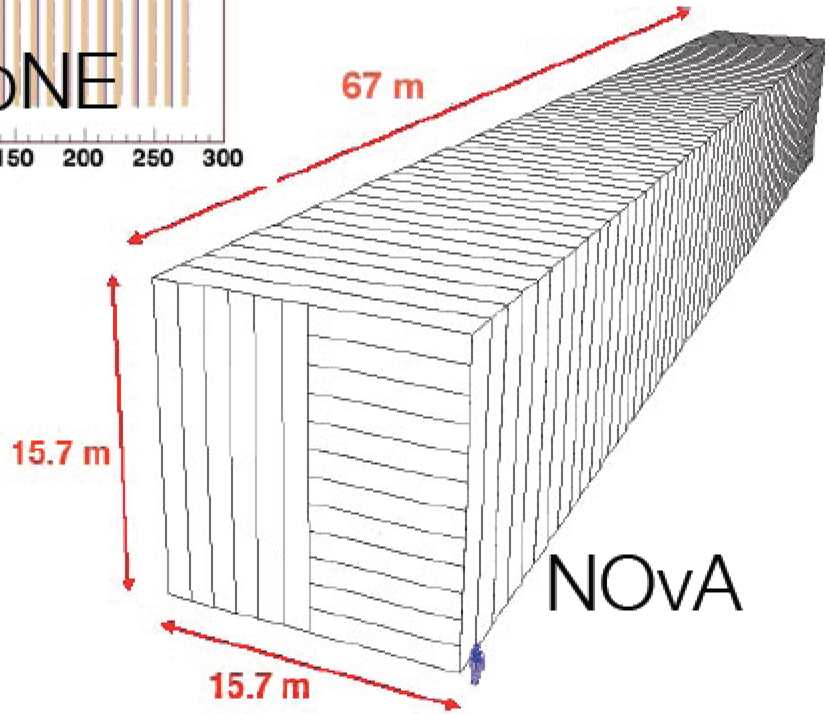

electron-like (ν_e)

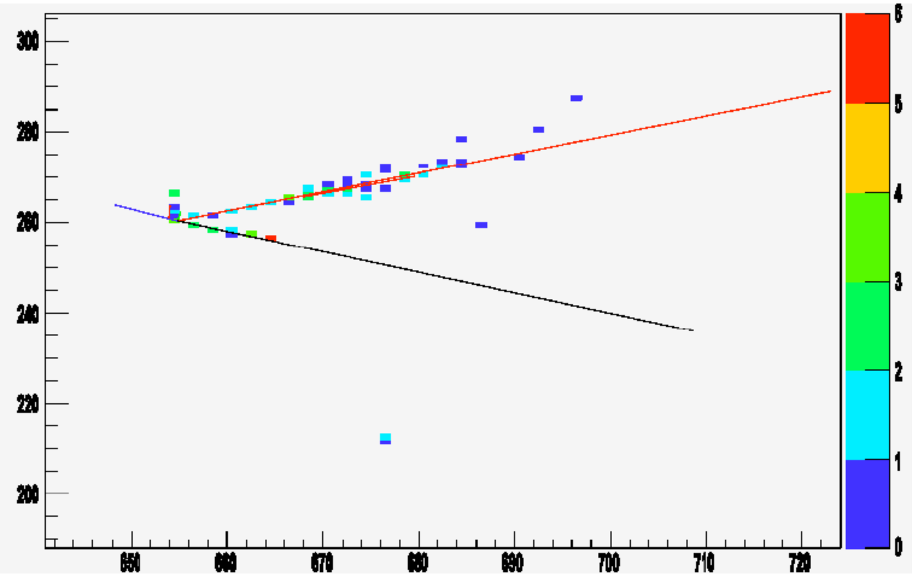
Tracking calorimeters

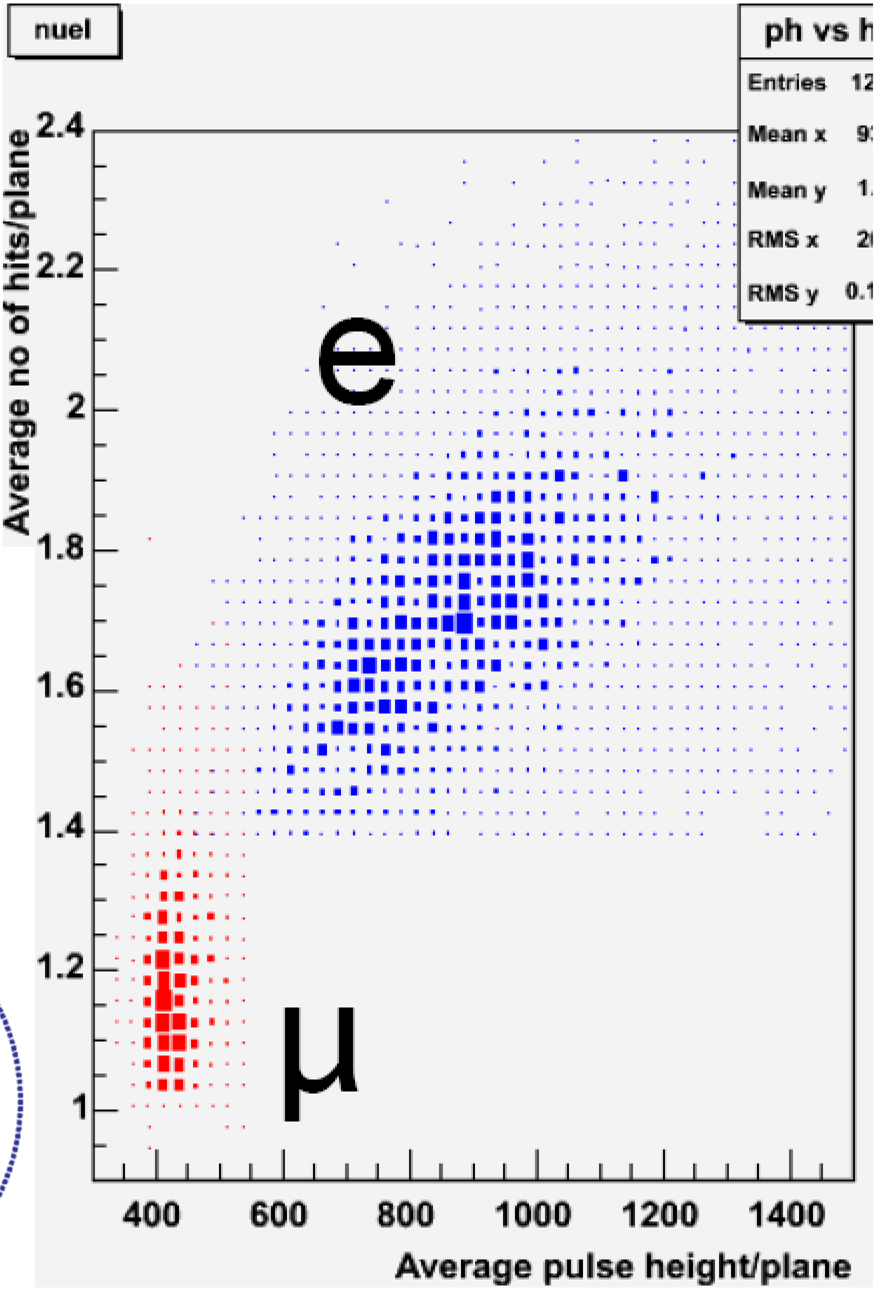


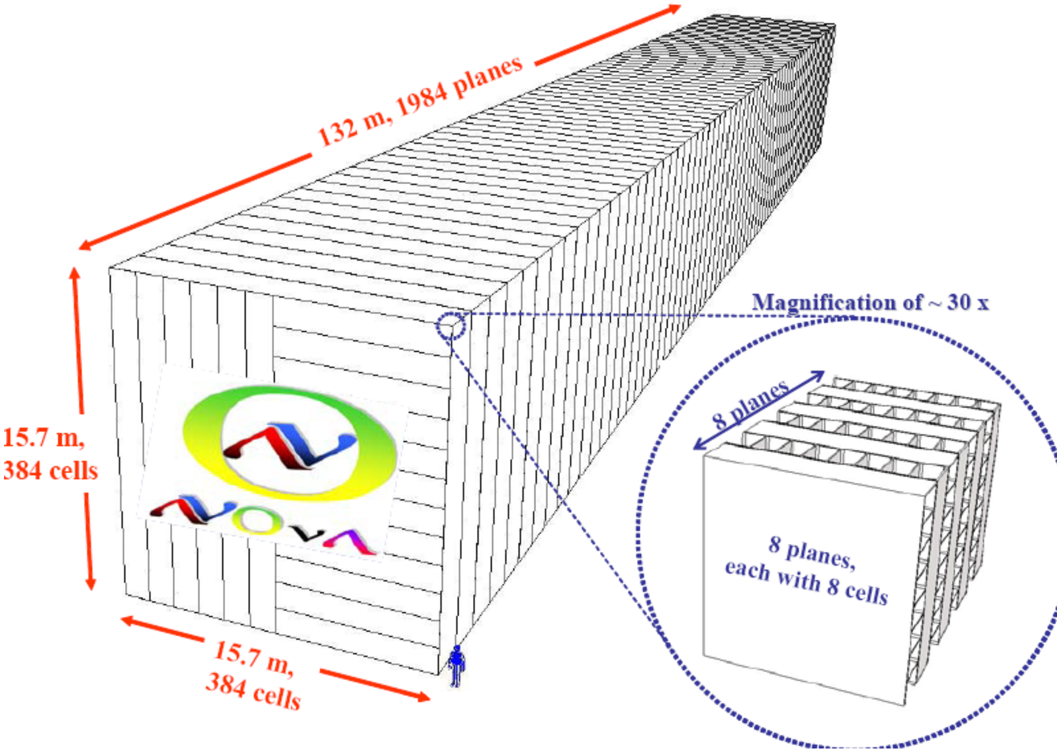






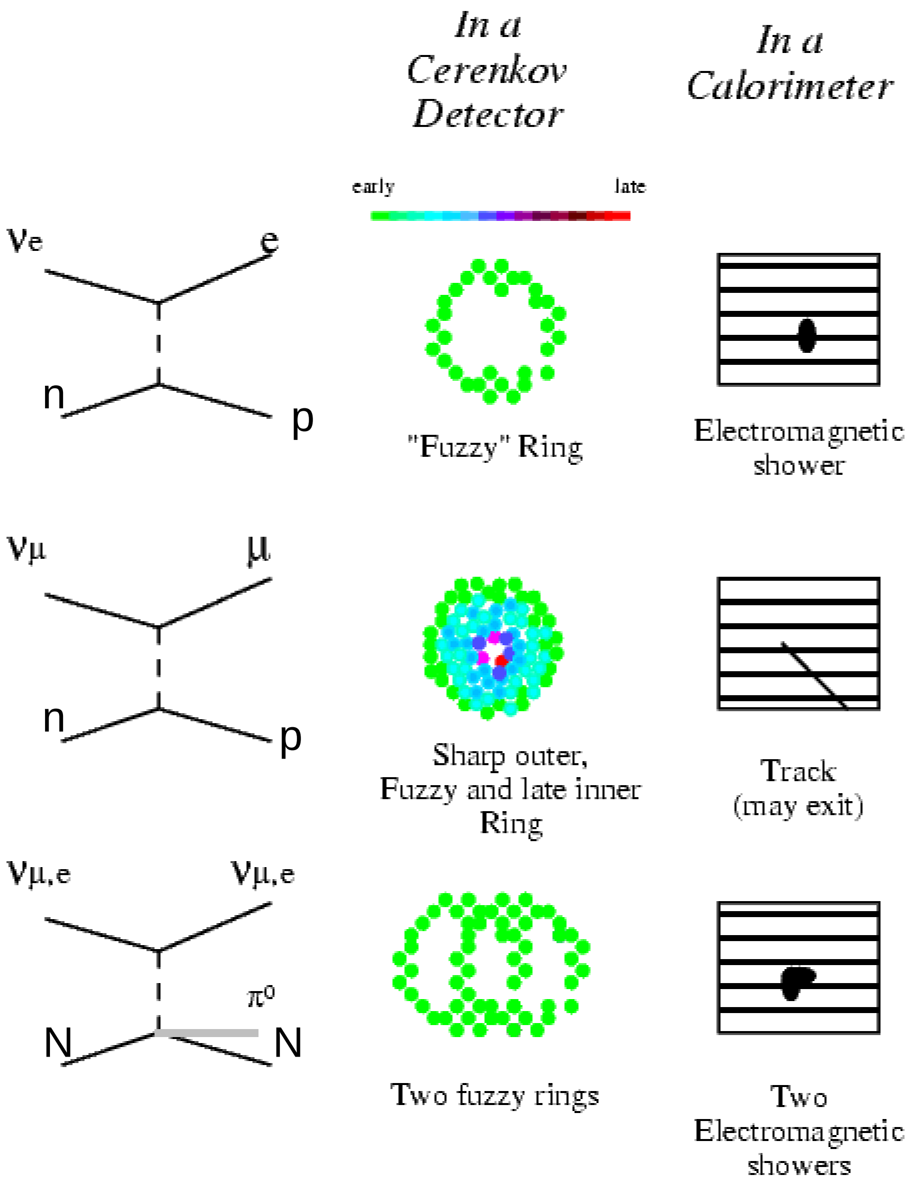

300
280
260
240
220
200
650
660
670
680
690
700
710
720
6
5
4
3
2
1
0


nuel
ph vs h
Entries 12
Mean x 9
Mean y 1.
RMS x 2
RMS y 0.1
Average no of hits/plane
2.4
2.2
2
1.8
1.6
1.4
1.2
1
400
600
800
1000
1200
1400
Average pulse height/plane
e
μ

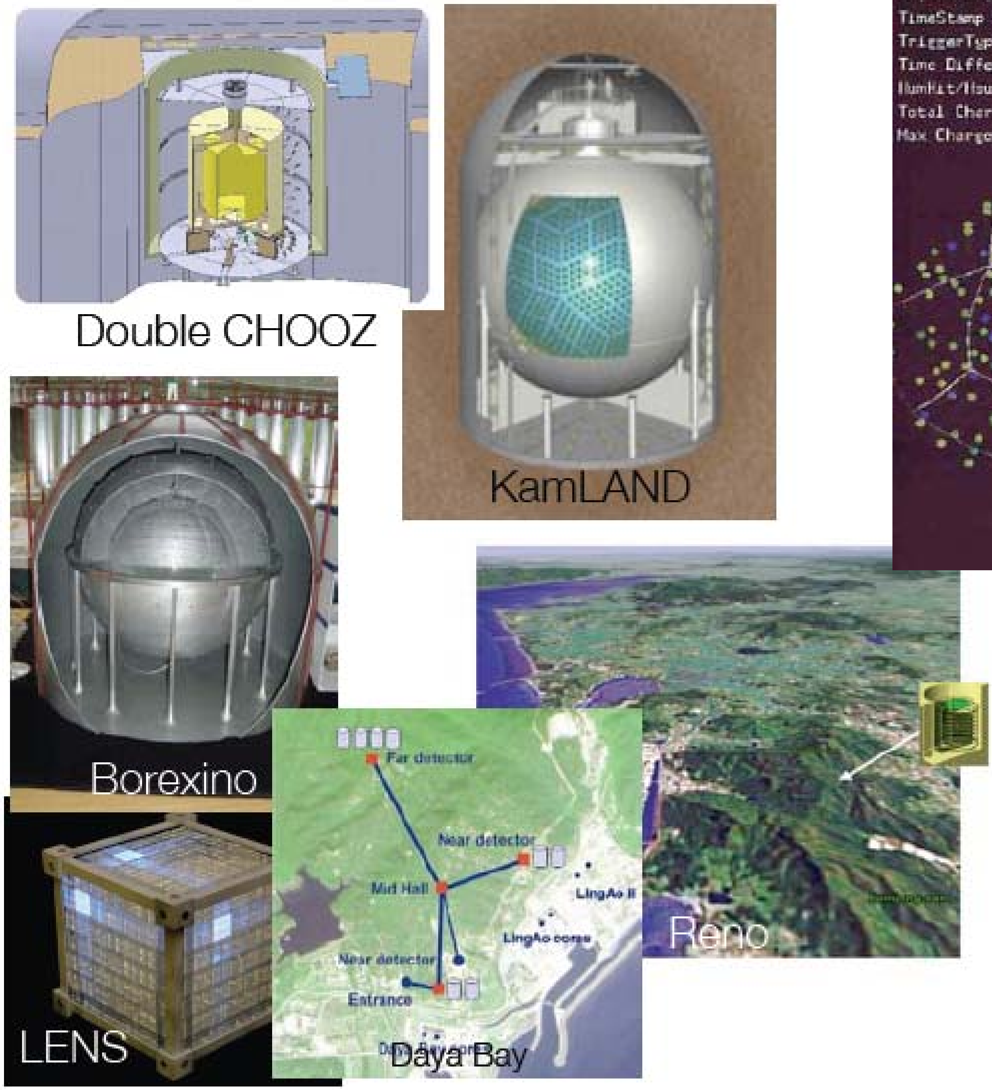

132 m, 1984 planes
15.7 m,
384 cells
15.7 m,
384 cells
Magnification of ~ 30 x
8 planes
8 planes,
each with 8 cells

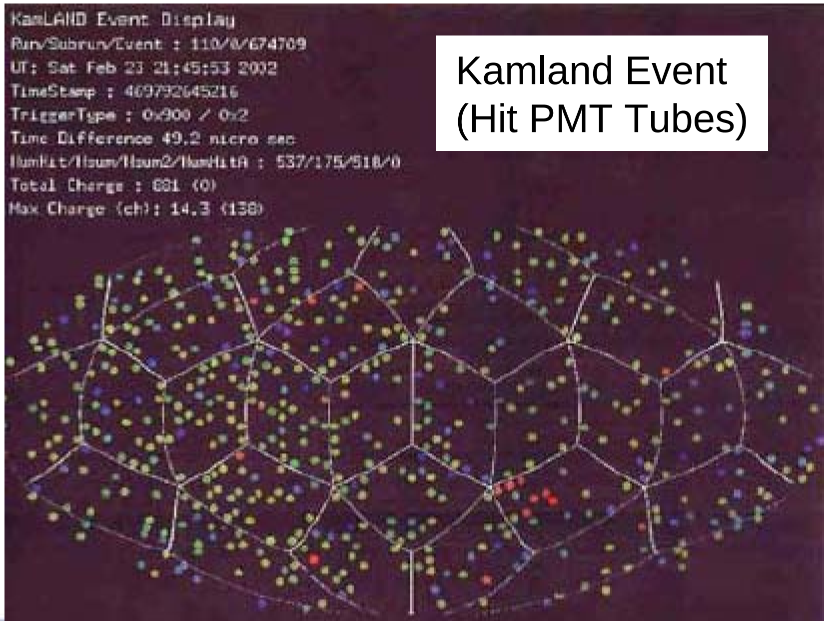
Experimental Techniques

- Water Cerenkov Detectors (Super-K)
  - Identify various event types by the Cerenkov ring configurations (single-ring e's or μ's multi-ring NC and CC)
- Sampling Calorimeters and Trackers (MINOS)
  - Electrons have short showers
  - Muons have penetrating tracks
  - Multi-particle events



Unsegmented liquid scintillator detectors



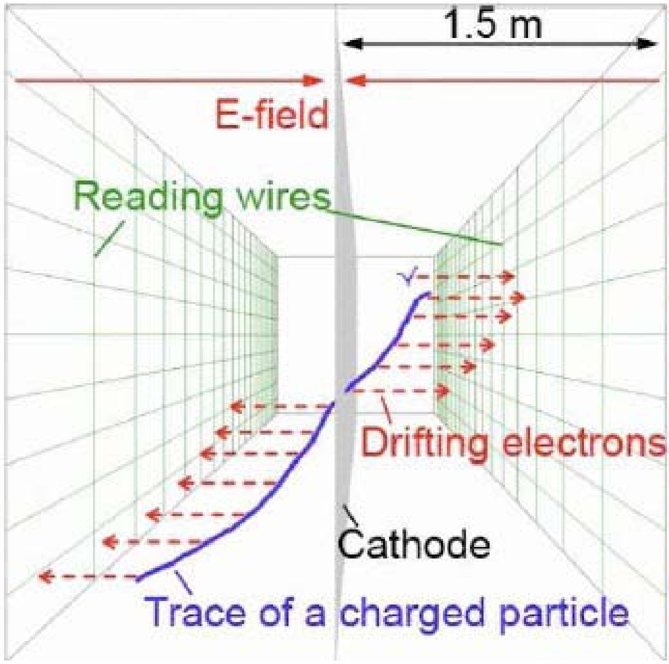


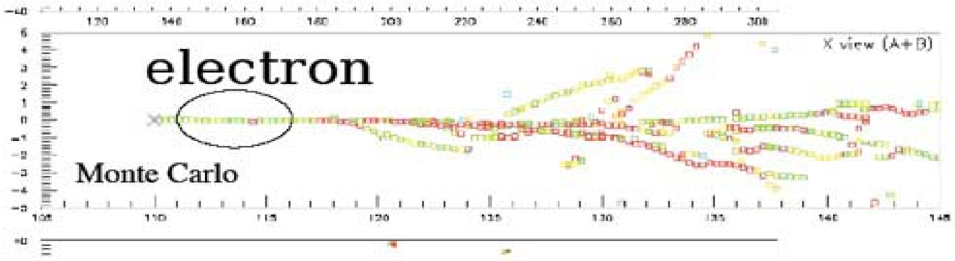
```
KamLAND Event Display
Run/Subrun/Event : 110/0/674709
UT: Sat Feb 23 21:45:53 2002
TimeStamp : 469792645216
TriggerType : 0x900 / 0x2
Time Difference 49.2 micro sec
NumHit/Nsum/Nsum2/NumHitA : 537/175/518/0
Total Charge : 881 (0)
Max Charge (ch): 14.3 (138)
```

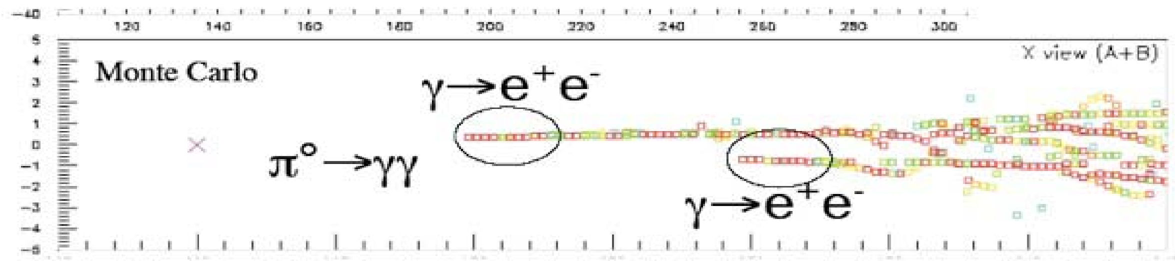
Kamland Event
(Hit PMT Tubes)

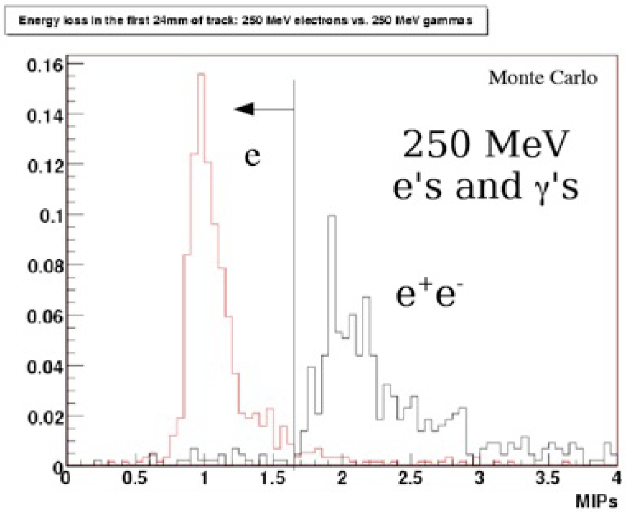
- PMTs around the outside see scintillation light from the particle tracks
  - Time and pulse heights of hits in PMTs can be used to determine the energy and postion of tracks.

Liquid Argon TPC



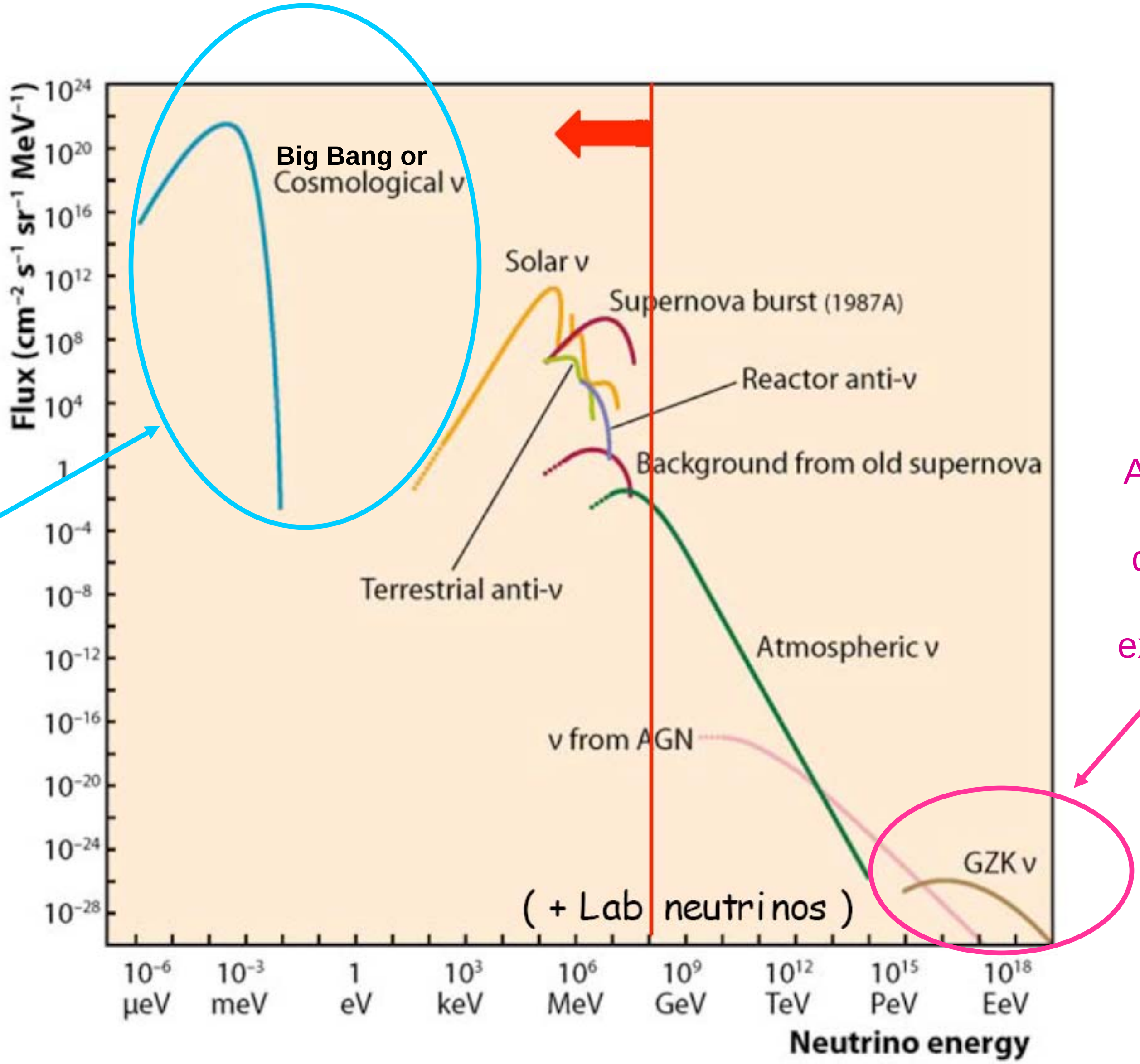






But Very Low Energy and Very High Energy ν Hard to Detect

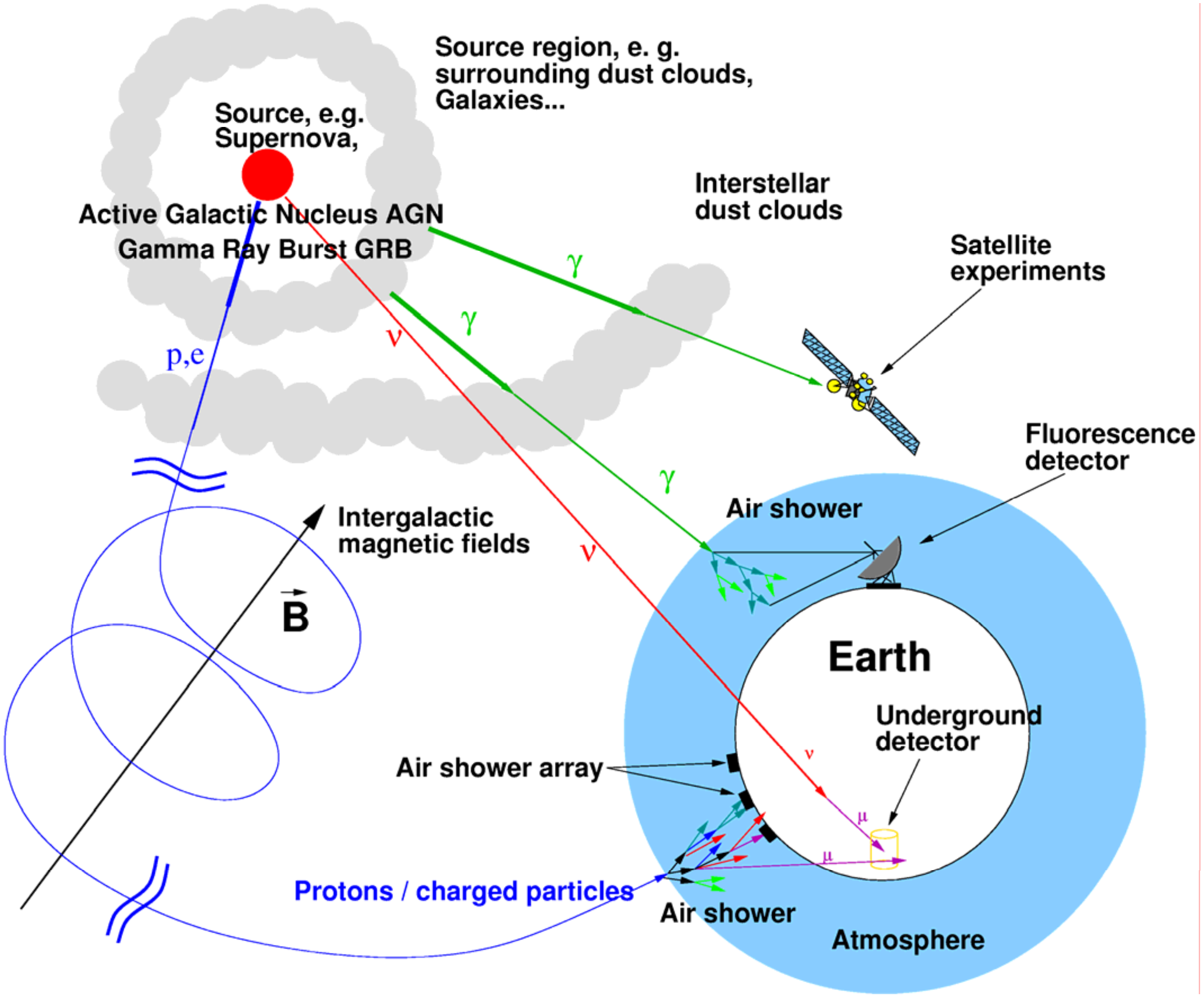
Big Bang ν's hard to detect since cross section is extremely small



A synoptic view of neutrino fluxes. (from ASPERA roadmap)

Astronomical ν's hard to detect since rate is extremely low

Neutrino Astronomy



Neutrinos Needed to Probe Ultra-High Energy Universe

Universe opaque to to high energy (>10 TeV) photons

$\gamma + \gamma_{EBL+CMB} \rightarrow e^+ + e^-$

and protons (>10^{20} eV)

$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$

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

Cosmogenic neutrinos

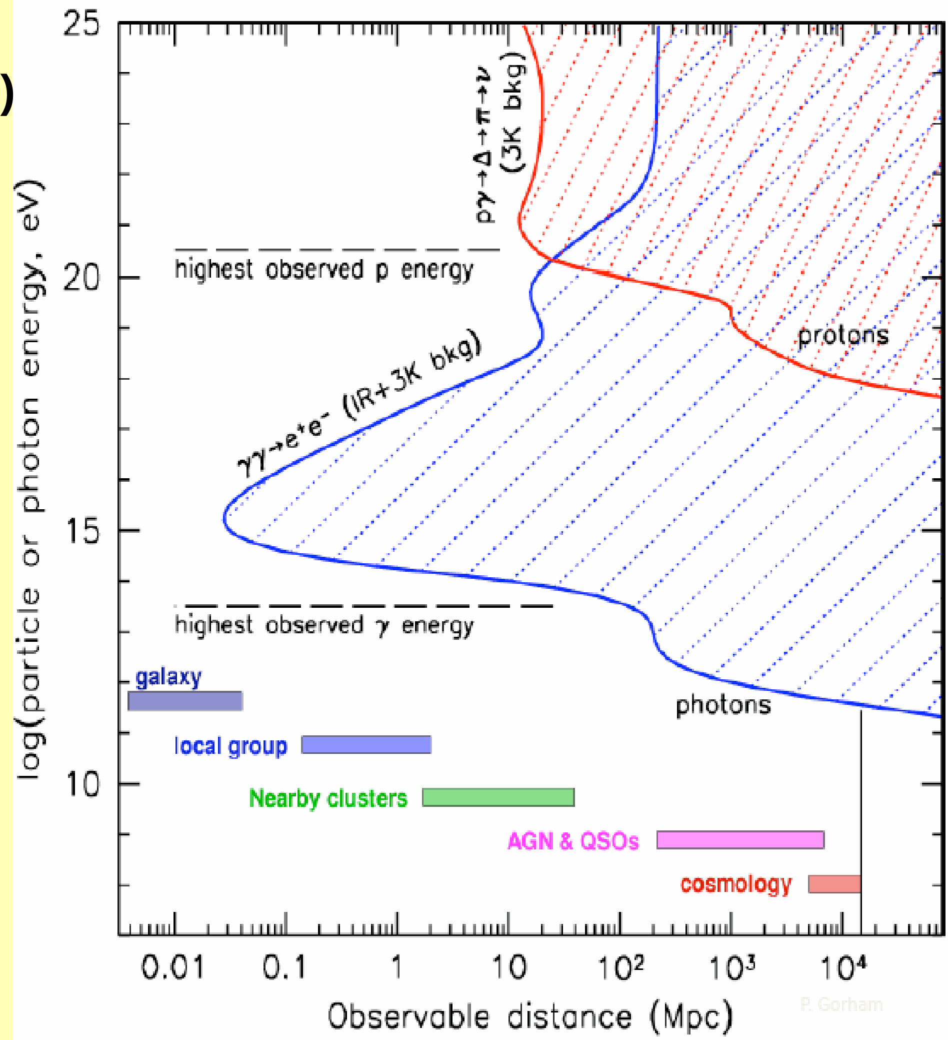
Protons deflected by magnetic field for E < 10^{19} eV!

Not pointing back to the source!

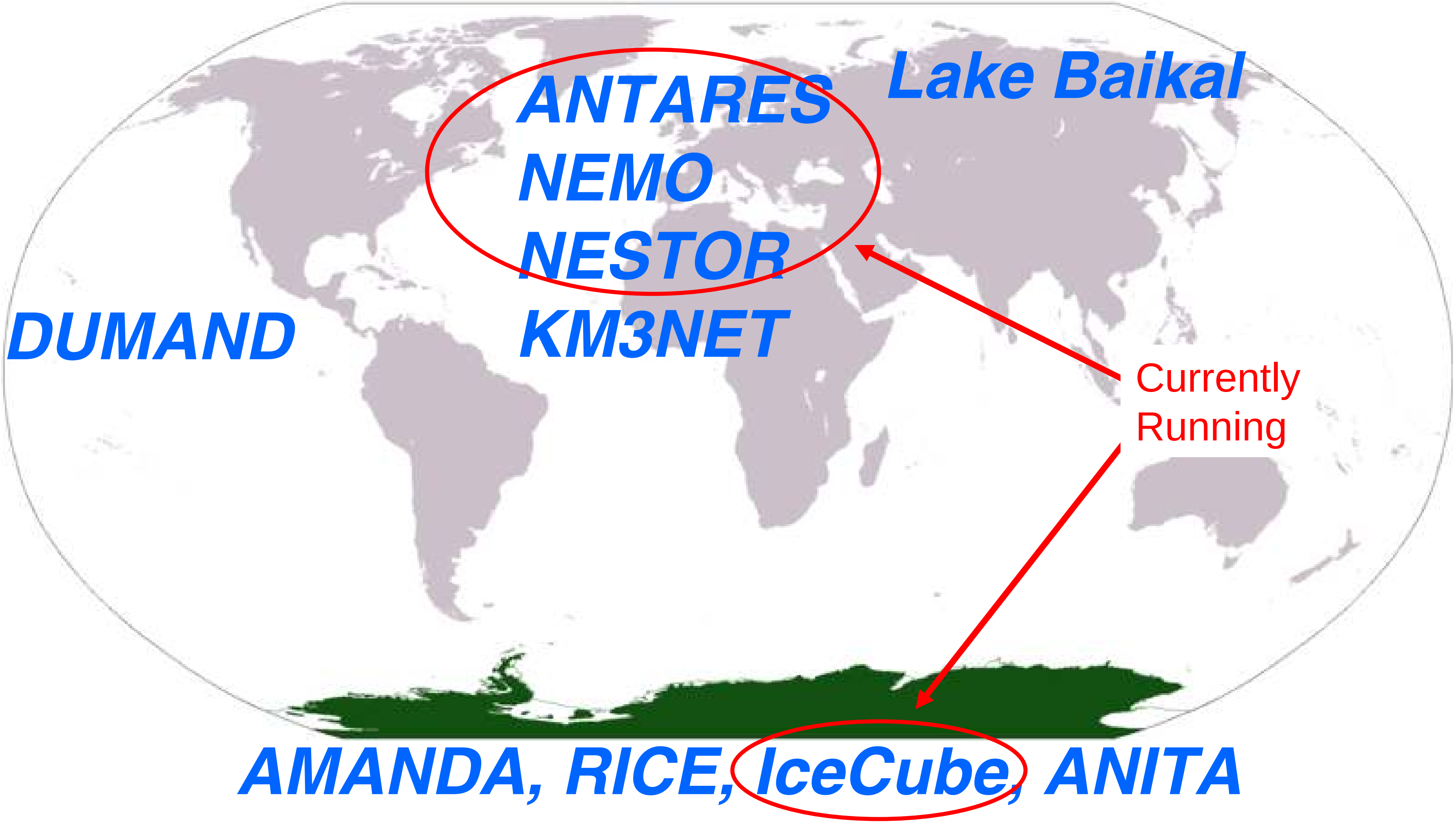
1) Need neutrinos for high energy (>10TeV) cosmic astronomy!

2) Neutrinos provide unambiguous evidence of hadronic acceleration

Possible Sources:
Supernova, AGNs, Gamma Bursts



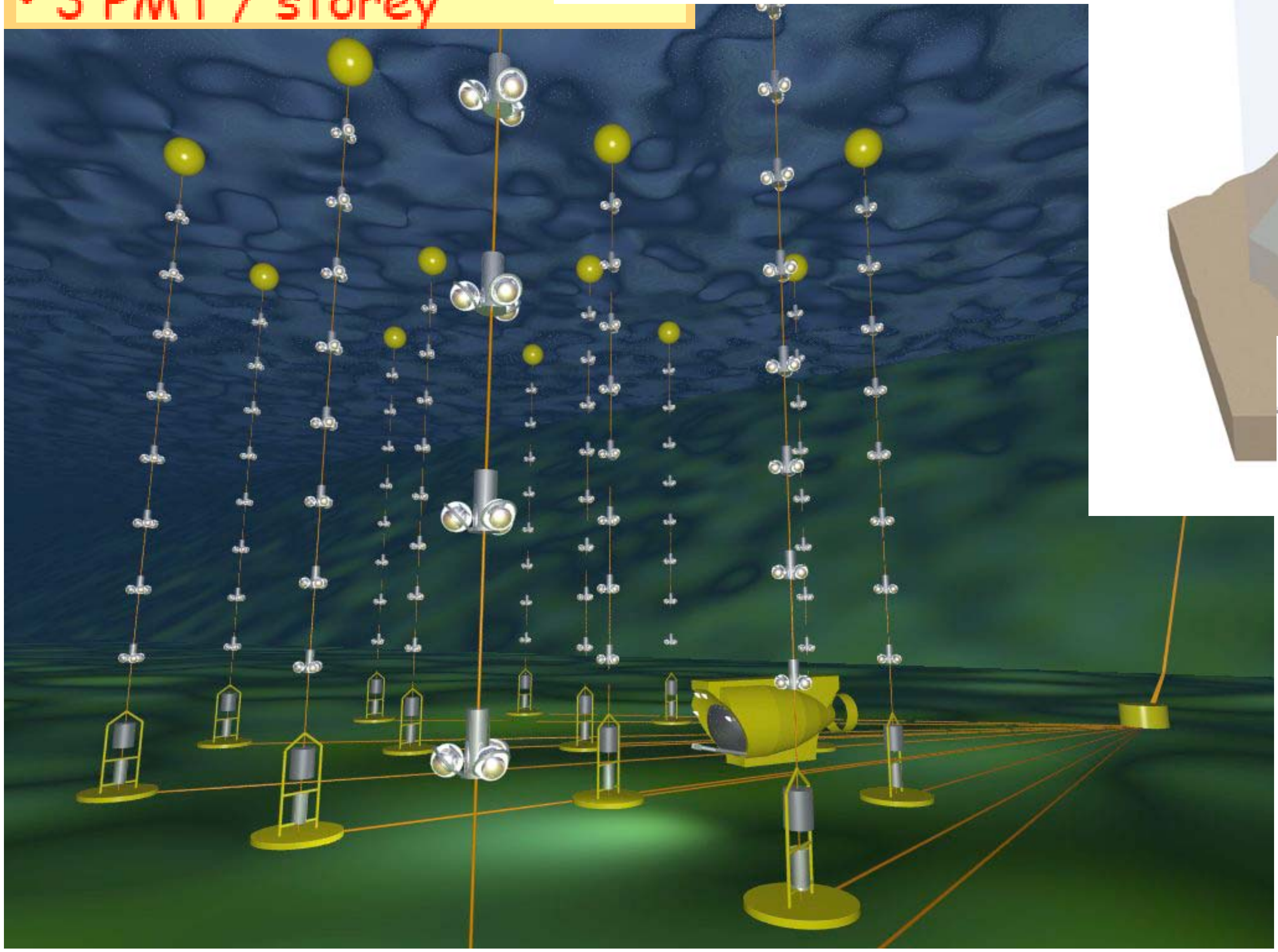
Neutrino Telescopes Old and New

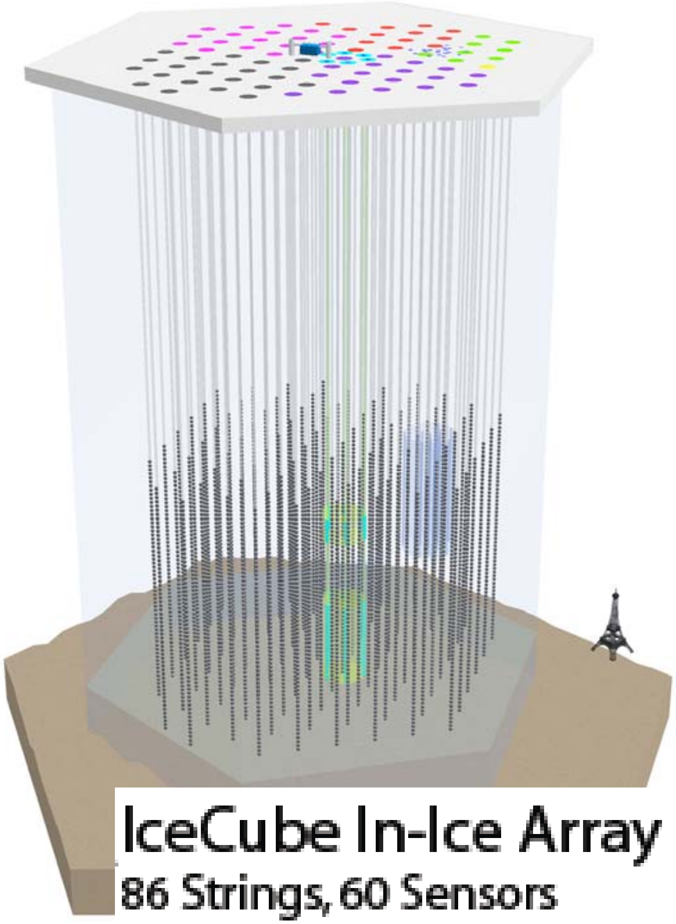


Antares and IceCube Detectors

- 12 lines (900 PMTs)
- 25 storeys / line
- 3 PMT / storey

Antares Experiment
in Mediterranean

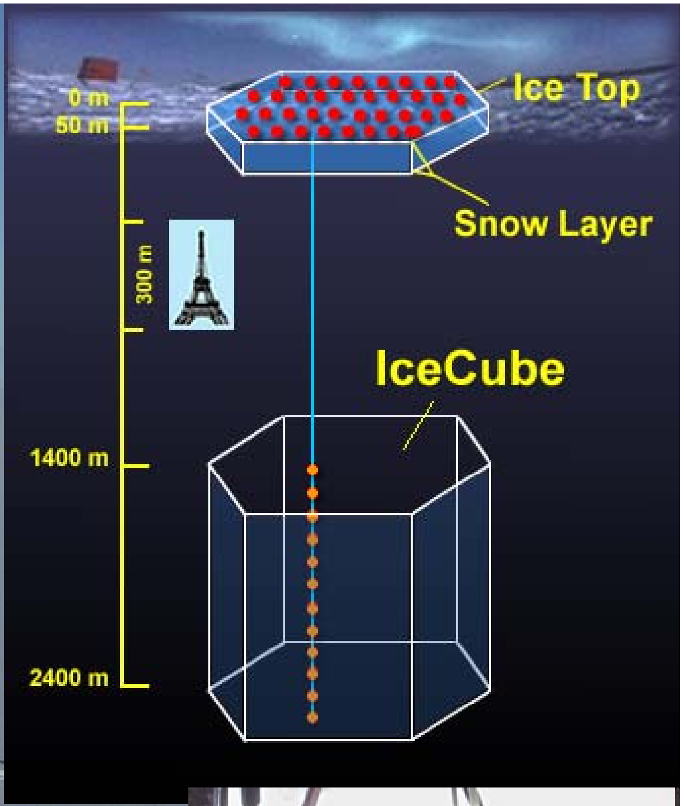




IceCube In-Ice Array
86 Strings, 60 Sensors
5160 Optical Sensors

IceCube at the South Pole

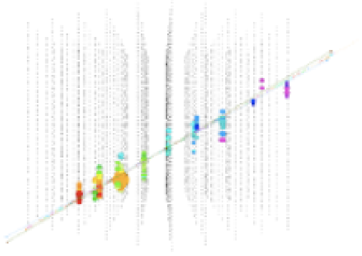
IceCube Location 1 km east
IceCube Instrumented volume:
1 km^3 (1 Gton)



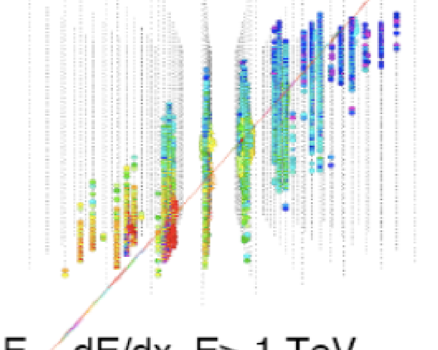
IceCube Detector at South Pole

Muon neutrino

a) E_μ=10 TeV ~ 90 hits



b) E_μ=6 PeV ~1000 hits

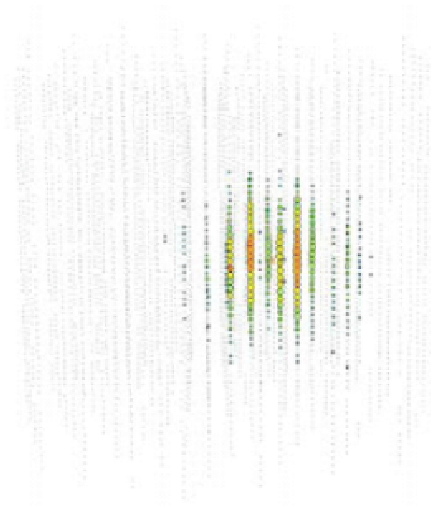


E ~ dE/dx, E> 1 TeV

Energy Res. : log(E)~0.3
Angular Res.: 0.8 -2 deg

Electron neutrino

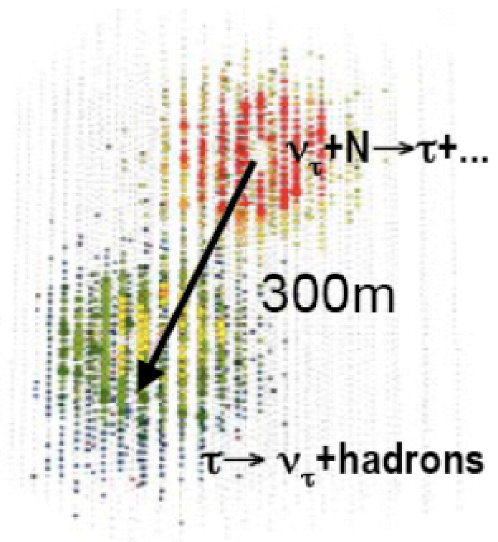
E = 375 TeV



Energy Res. log(E)~0.1-0.2
Poor Angular Resolution

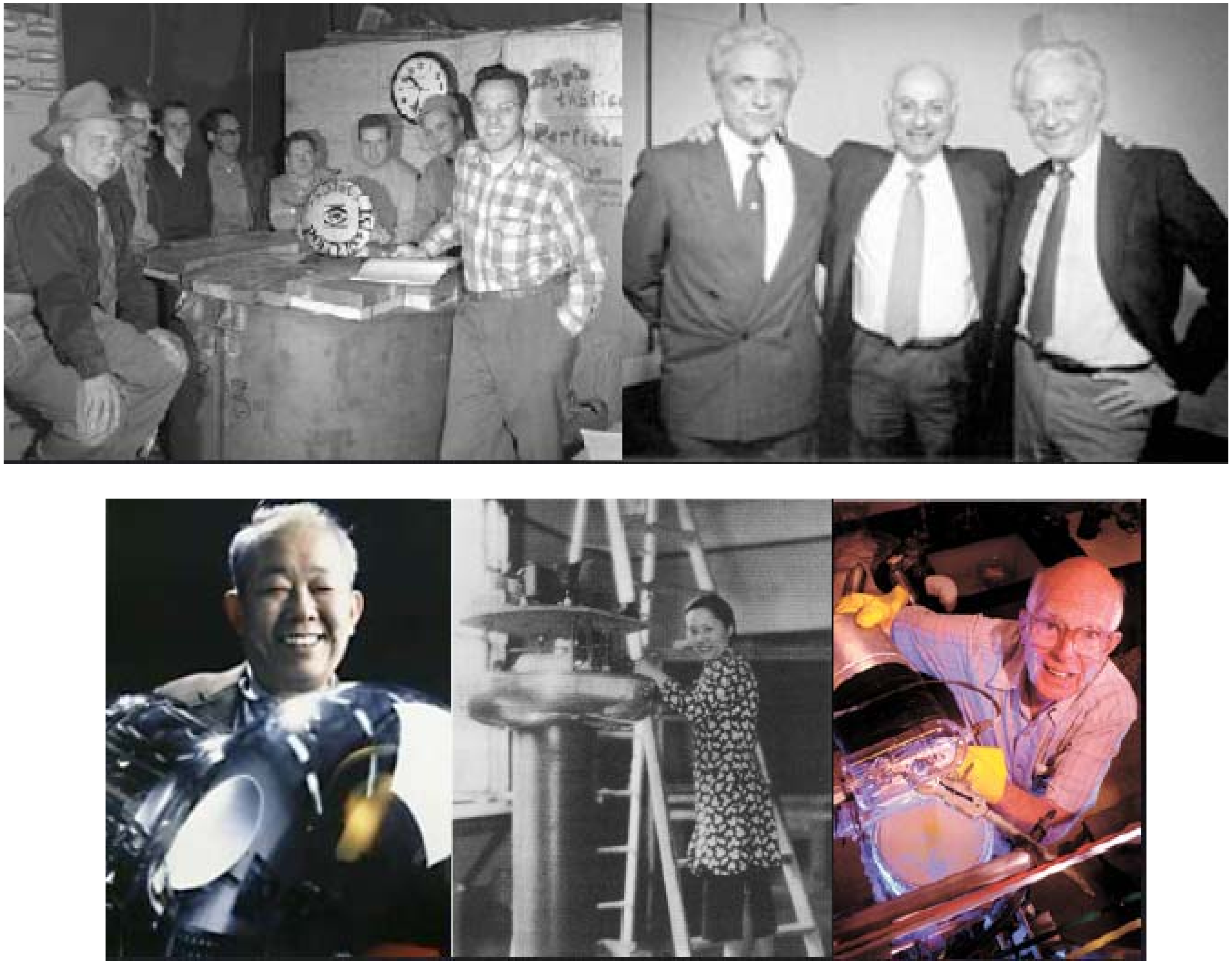
Tau neutrino

E = 10 PeV



Double-bang signature
above ~ 1 PeV
Very low background
Pointing capability
Best energy measurement

Why do these people look so happy?



Answer: They were doing experimental neutrino physics

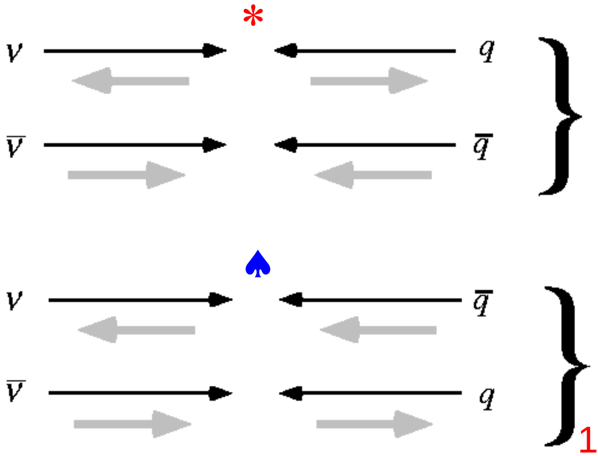
Extras

Neutrinos Probe Quark Structure

(Nucleon Structure Functions)

$$\frac{d\sigma^{\nu p}}{dxdy} = \frac{G_F^2 s}{\pi}\left(\overset{*}{xd^p(x)} + \overset{\spadesuit}{x\bar{u}^p(x)(1-y)^2}\right)$$

$$\frac{d\sigma^{\nu n}}{dxdy} = \frac{G_F^2 s}{\pi}\left(\overset{*}{xd^n(x)} + \overset{\spadesuit}{x\bar{u}^n(x)(1-y)^2}\right)$$



$Total\ Spin = 0$

νq or $\bar{\nu}\bar{q}$

Flat in y

$Total\ Spin = 1$

$\nu\bar{q}$ or $\bar{\nu}q$

1/4(1+cosθ*)^2 = (1-y)^2

Where x = momentum fraction of struck quark
y = energy transferred to struck quark

- For an isoscalar target (# protons = # neutrons):

$$\frac{d^2\sigma^{\nu(\bar{\nu})N}}{dxdy} = \frac{G_F^2 s}{2\pi}\left\{\left(1+(1-y)^2\right)F_2(x) \pm \left(1-(1-y)^2\right)xF_3^{\nu(\bar{\nu})}(x)\right\}$$

$$F_2^{\nu(\bar{\nu})N}(x) = x(u(x)+d(x)+\bar{u}(x)+\bar{d}(x)+s(x)+\bar{s}(x)+c(x)+\bar{c}(x) = xq(x)+x\bar{q}(x)$$

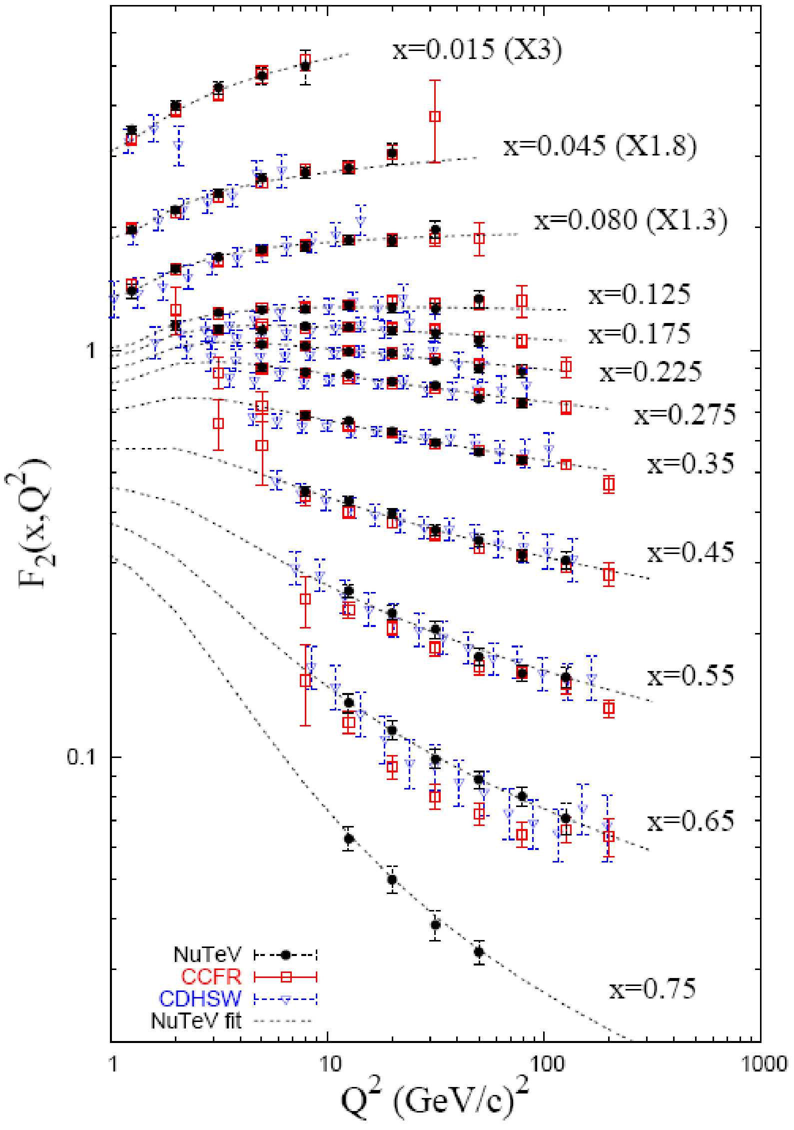
$$xF_3^{\nu(\bar{\nu})N}(x) = xu_{Val}(x)+xd_{Val}(x) \pm 2x(s(x)-c(x))$$

where $u_{Val}(x) = u(x) - \bar{u}(x)$

Neutrino Structure Functions (Quark Distributions)

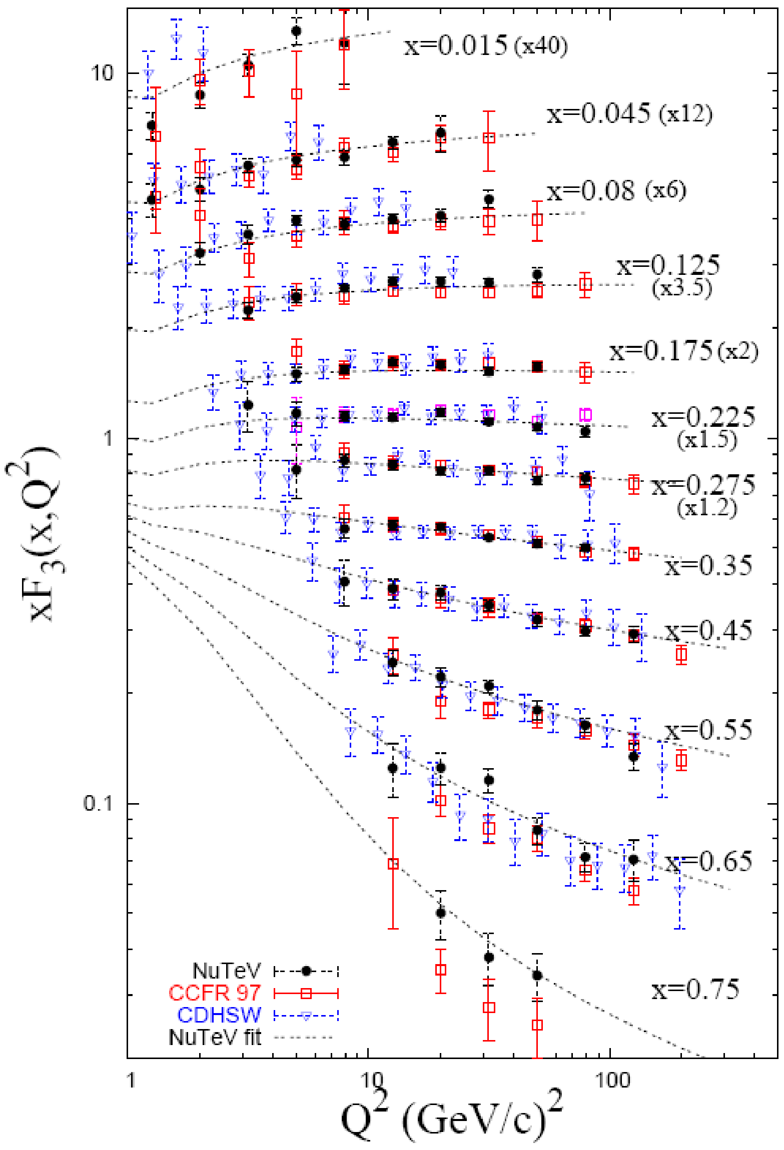
Total Quark Distributions

$F_2(x,Q^2)$



Valence Quark Distribution

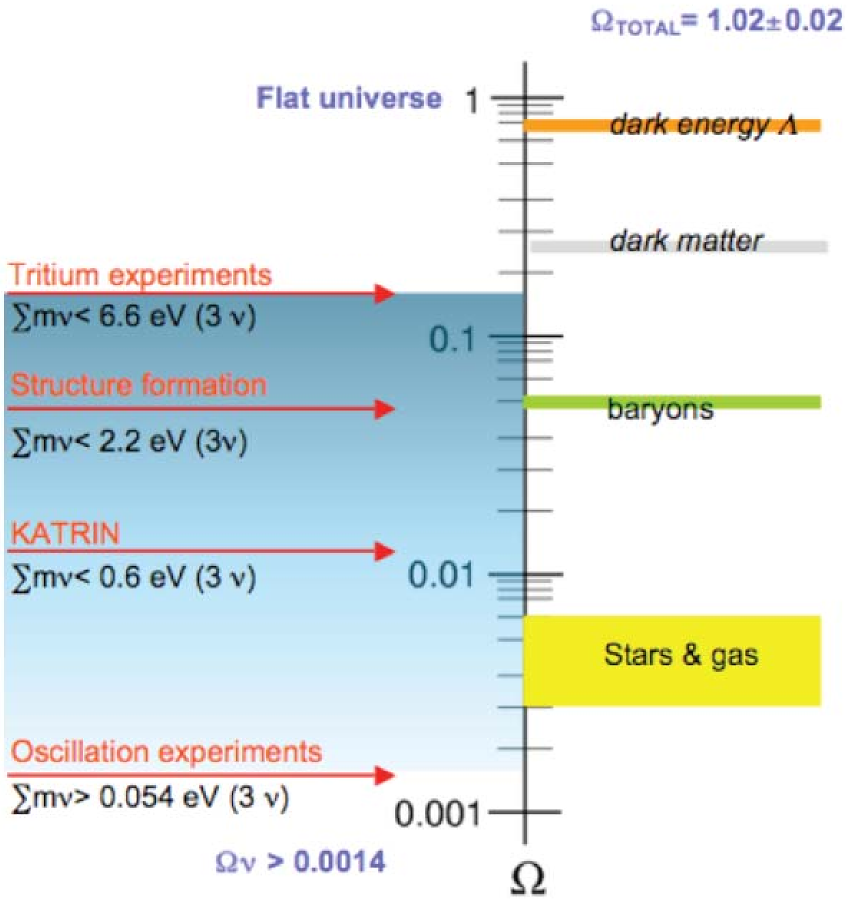
$xF_3(x,Q^2)$ (Unique to ν's)



Why Neutrino Mass Matters?

Cosmological Implications

- Massive neutrinos with osc. important for heavy element production in supernova
- Light neutrinos effect galactic structure formation



Window on Physics at High E Scales

See-Saw Mechanism

Heavy RH neutrino

$$\mathcal{L}^{\mathrm{D+M}} = \mathcal{L}_{\mathrm{L}}^{\mathrm{M}} + \mathcal{L}_{\mathrm{R}}^{\mathrm{M}} + \mathcal{L}^{\mathrm{D}}$$

$$= -\frac{1}{2}\begin{pmatrix}\overline{\nu_L^c} & \overline{\nu_R}\end{pmatrix}\begin{pmatrix} m_L & m_{\mathrm{D}} \\ m_{\mathrm{D}} & m_R \end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix} + \mathrm{h.c.}$$

Typical Dirac Mass

$$m_1 \simeq \frac{(m_{\mathrm{D}})^2}{m_R} \ll m_{\mathrm{D}}\,,$$

Set of very light neutrinos

$$m_2 \simeq m_R\,,$$

Set of heavy sterile neutrinos

$$\tan\vartheta \simeq \frac{m_{\mathrm{D}}}{m_R} \ll 1$$