

Neutrino Astrophysics (neutrino astronomy?)

Asen Christov

20.2.2023

Lecture outline

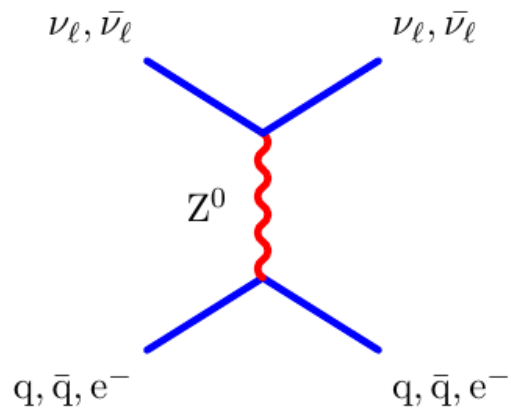
1. (Some) neutrino properties
2. Solar neutrinos
3. Supernova neutrinos
4. Astrophysical neutrinos (+ Atmospheric neutrinos)

Neutrinos

- Very small mass (at least two have to be massive – we will get to this)
- Only weak interactions → small cross-sections

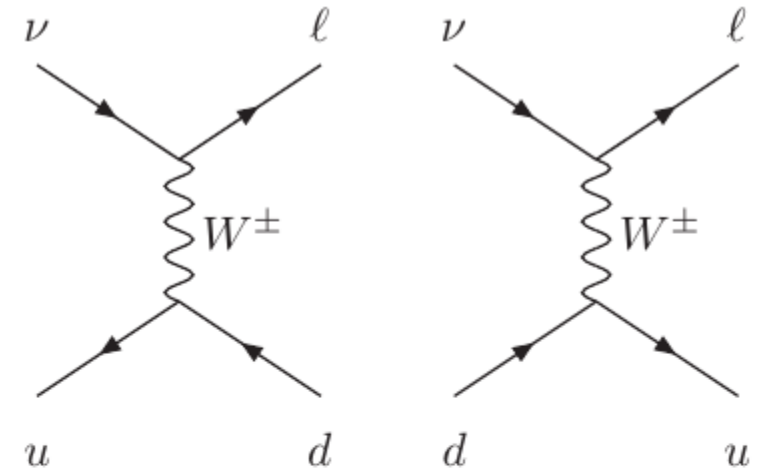
- OK, what does “small” mean?

Neutrino interactions in matter



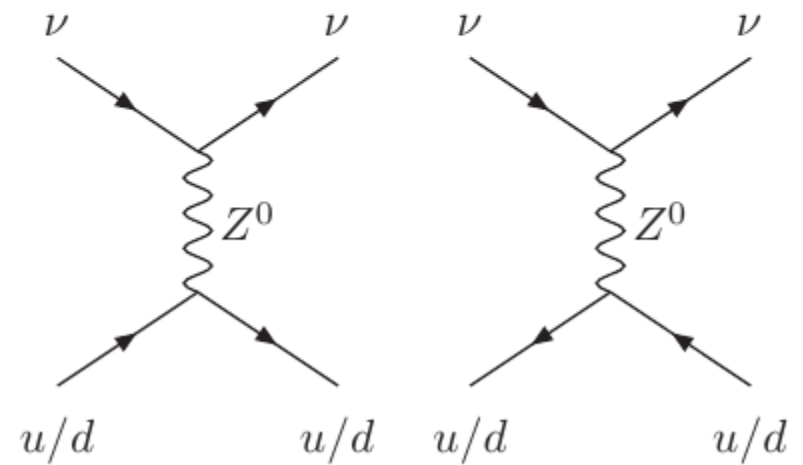
Feynman diagrams for neutral current (NC) neutrino interactions.

Since neutrinos are detected via their interactions with matter, only the target particles present in normal matter are included in the listed Feynman diagrams.



(a)

(b)

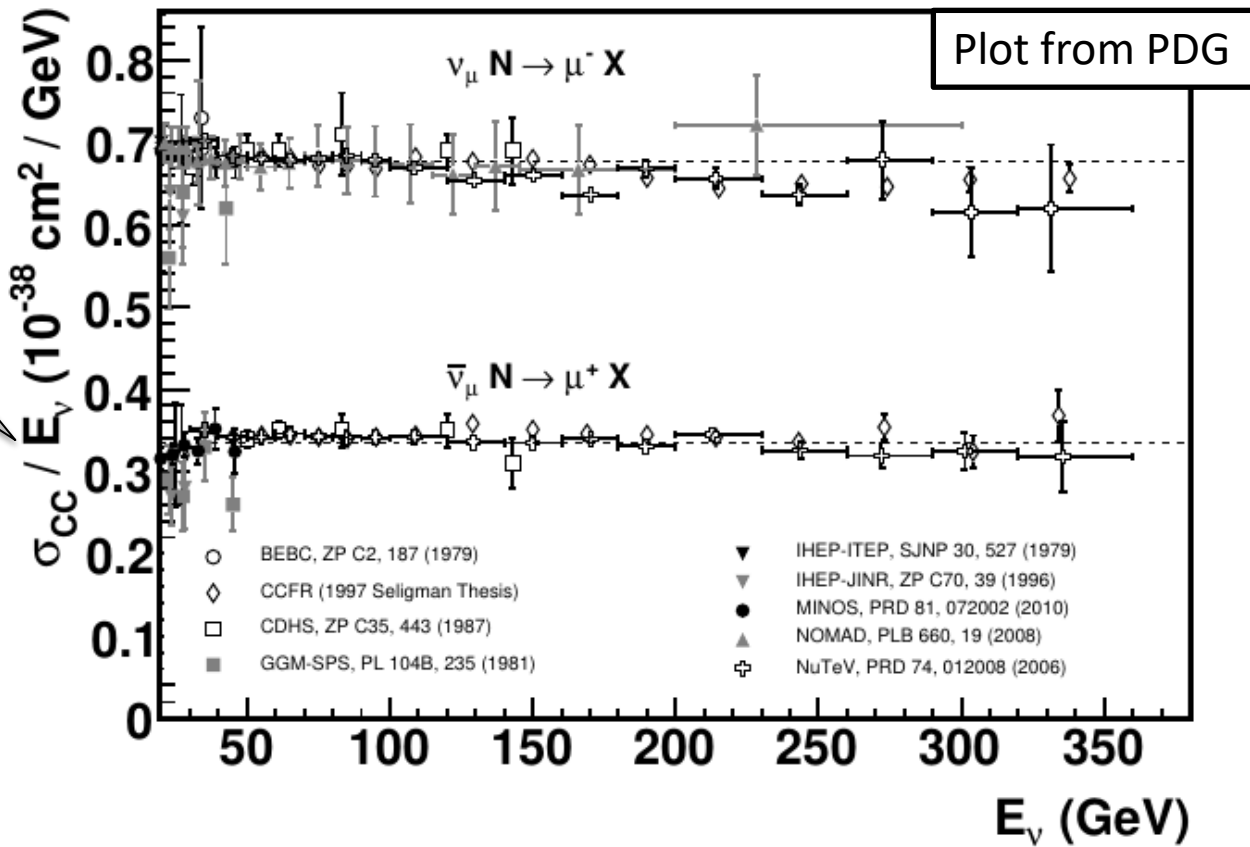


(c)

(d)

Neutrino cross-sections

CC interaction on nuclei

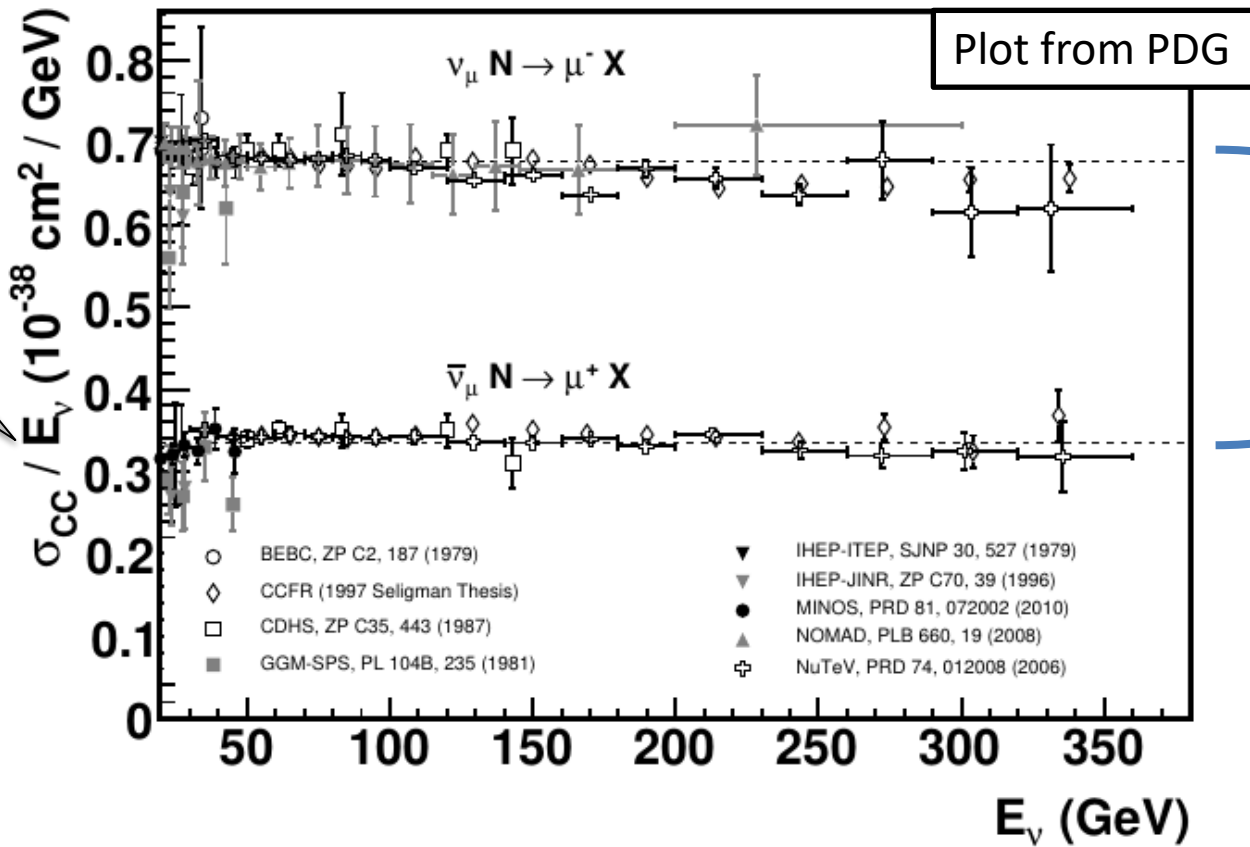


Notice the scaling!

Cross-section grows linearly with energy (up to ~5 TeV)

Neutrino cross-sections

CC interaction on nuclei



Notice the scaling!

Why the difference? BTW: why π^{\pm} decays to μ^{\pm} and not e^{\pm} ?

Why the difference?

BTW: why π^\pm decays to μ^\pm and not e^\pm ?

- Over-simplified version, for more details look up your SM lectures
- Chirality – particle property, Only left-handed fermions (and right-handed anti-fermions) participate in the weak interactions.

"Left" chirality: $\psi^L = \frac{1}{2}(1 - \gamma_5)\psi$

"Right" chirality: $\psi^R = \frac{1}{2}(1 + \gamma_5)\psi$

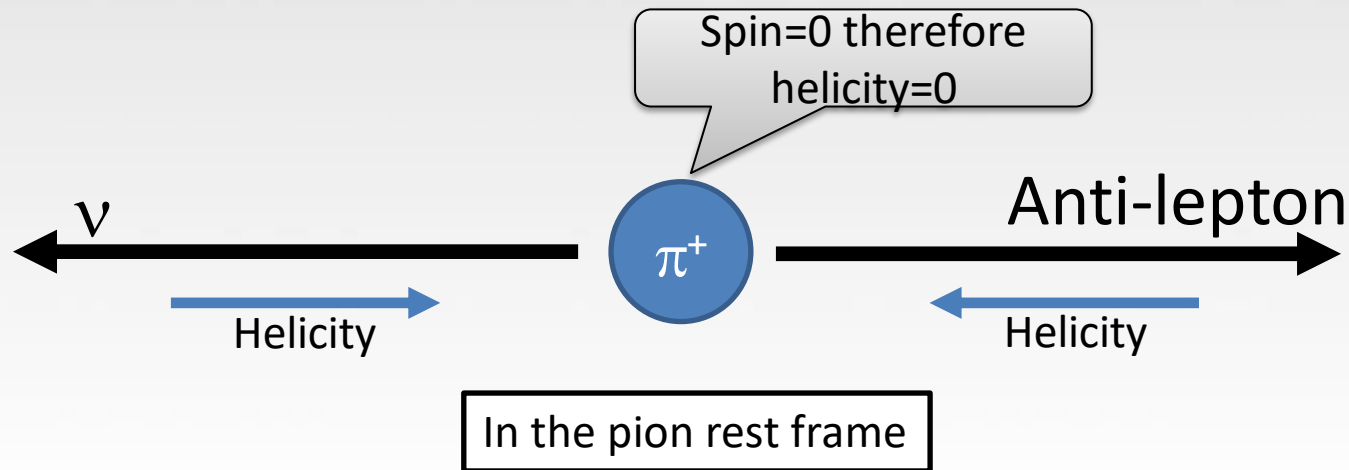
The charged current part of the Lagrangian is given by

$$\mathcal{L}_C = -\frac{g}{\sqrt{2}} \left[\bar{u}_i \gamma^\mu \frac{1 - \gamma^5}{2} M_{ij}^{\text{CKM}} d_j + \bar{\nu}_i \gamma^\mu \frac{1 - \gamma^5}{2} e_i \right] W_\mu^+ + \text{h.c.}$$

- Helicity – projection of the spin in the momentum direction.
 - For massless particles (traveling at c) helicity=chirality
 - For massive particles depends on the ref. frame
 - For given chirality of a massive particle, depending on the ref. frame, the helicity will be mixture of neg. and positive state, the closer to c the closer is helicity to chirality.

Why the difference?

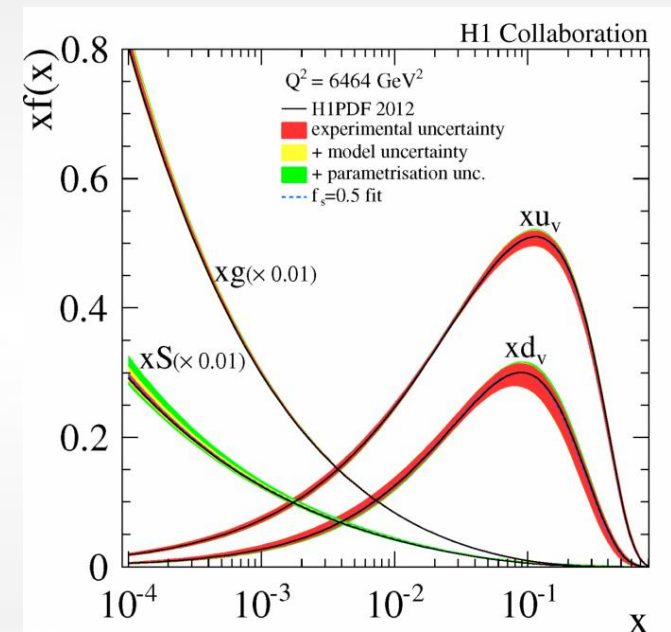
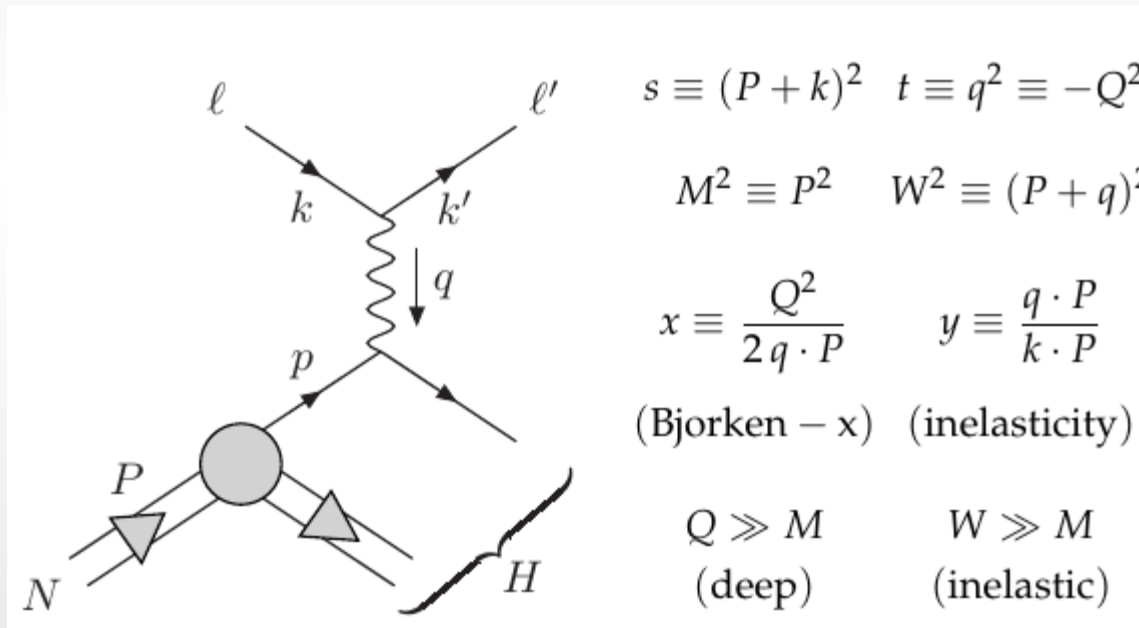
BTW: why π^\pm decays to μ^\pm and not e^\pm ?



- The neutrino is close to massless \rightarrow travels close to c \rightarrow helicity left-handed
- This requires the anti-lepton to be helicity left-handed too.
- But the anti-lepton is **chirality** right-handed
- The closer the anti-lepton to c , the smaller is the opposite component of the helicity.
- Muon heavier than e \rightarrow muon is slower \rightarrow the needed (=left-handed)(=opposite to the particle chirality) component of the helicity is larger \rightarrow preferred decay mode (despite the larger kinematic phase space for e).

Neutrino DIS* helicity suppression

- At lower ν energies (larger x) the nucleon PDFs (parton distribution functions) are dominated by the valence quarks.



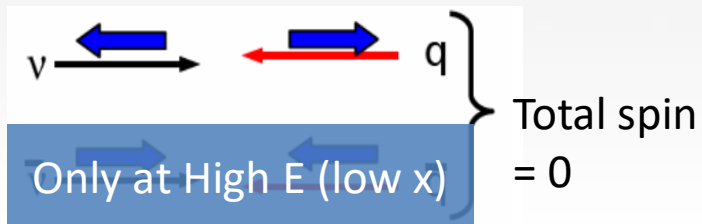
PDF example - proton

* DIS = deep inelastic scattering

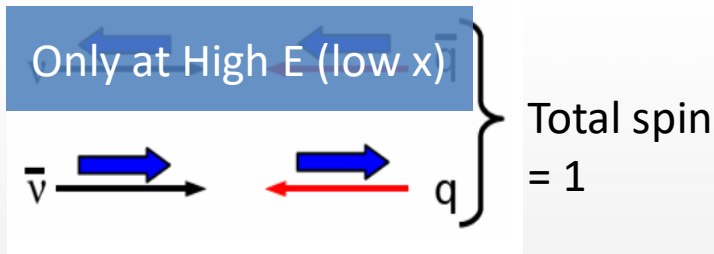
Neutrino DIS* helicity suppression

- At lower ν energies (larger x) the nucleon PDFs (parton distribution functions) are dominated by the valence quarks.

Possible helicity (spin) configurations:



$$\frac{d\sigma_{CC}(\nu_{\mu}q)}{dy} = \frac{d\sigma_{CC}(\bar{\nu}_{\mu}\bar{q})}{dy} = \frac{2G_F^2 m_q E}{\pi}$$

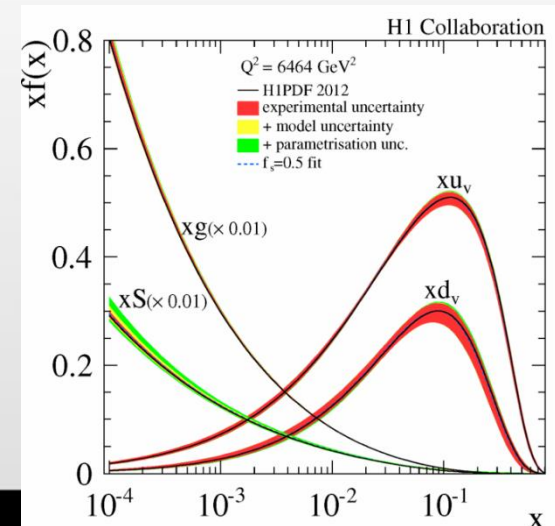


$$\frac{d\sigma_{CC}(\nu_{\mu}\bar{q})}{dy} = \frac{d\sigma_{CC}(\bar{\nu}_{\mu}q)}{dy} = \frac{2G_F^2 m_q E}{\pi} (1-y)^2$$

All Particles have their “preferred” helicities

ν + quarks \rightarrow tot spin 0 mode

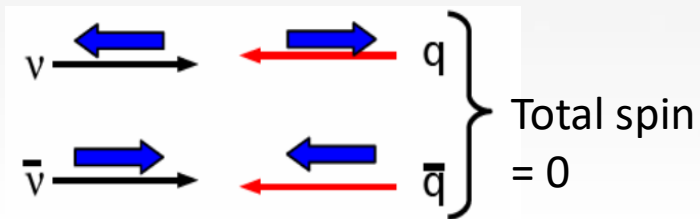
Anti ν + quarks \rightarrow tot spin 1 \rightarrow $(1-y)^2$ suppression



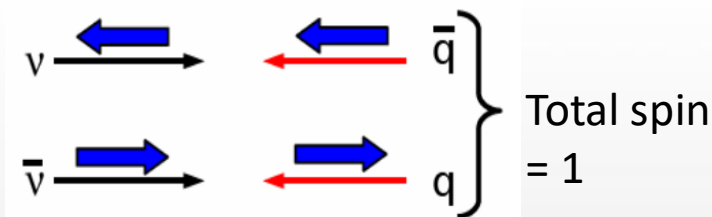
Neutrino DIS* helicity suppression

- At lower ν energies (larger x) the nucleon PDFs (parton distribution functions) are dominated by the valence quarks.

Possible helicity (spin) configurations:

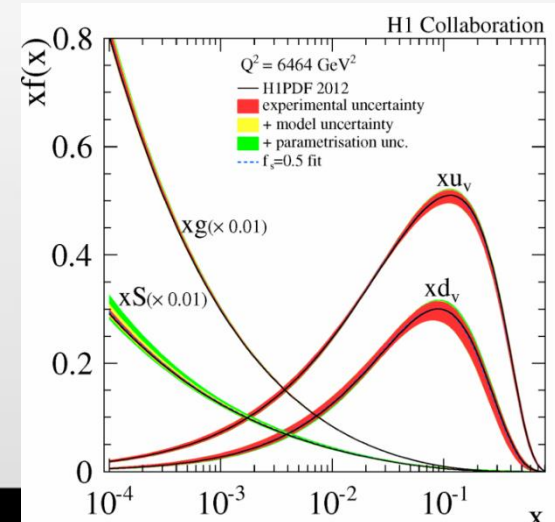


$$\frac{d\sigma_{CC}(\nu_{\mu}q)}{dy} = \frac{d\sigma_{CC}(\bar{\nu}_{\mu}\bar{q})}{dy} = \frac{2G_F^2 m_q E}{\pi}$$

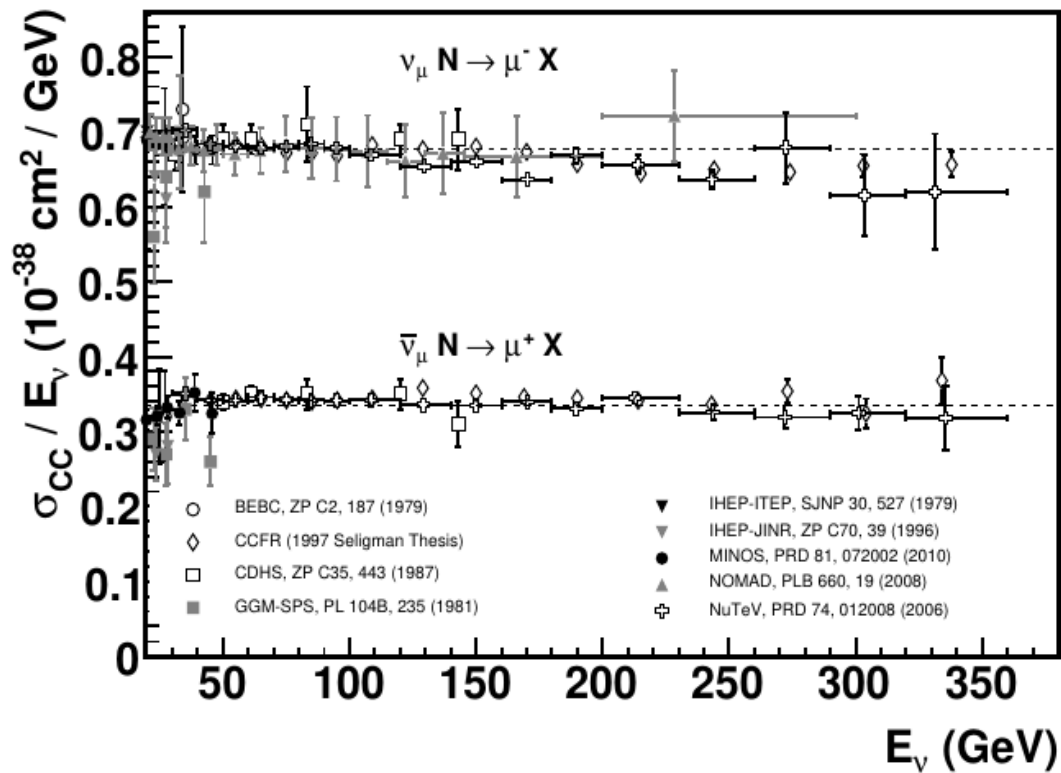


$$\frac{d\sigma_{CC}(\nu_{\mu}\bar{q})}{dy} = \frac{d\sigma_{CC}(\bar{\nu}_{\mu}q)}{dy} = \frac{2G_F^2 m_q E}{\pi} (1-y)^2$$

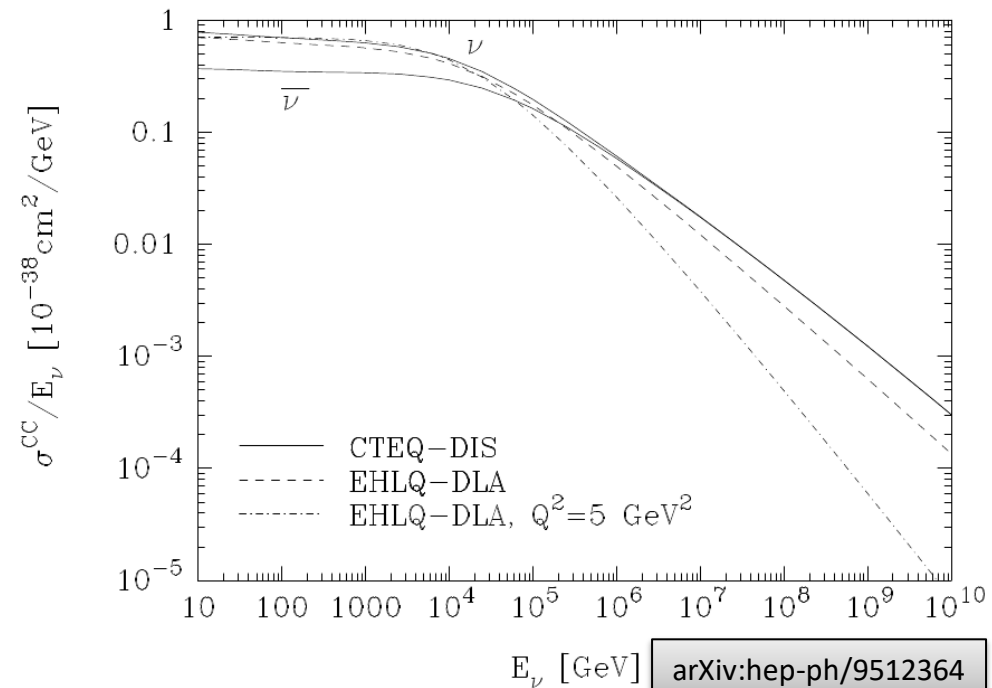
All Particles have their “preferred” helicities



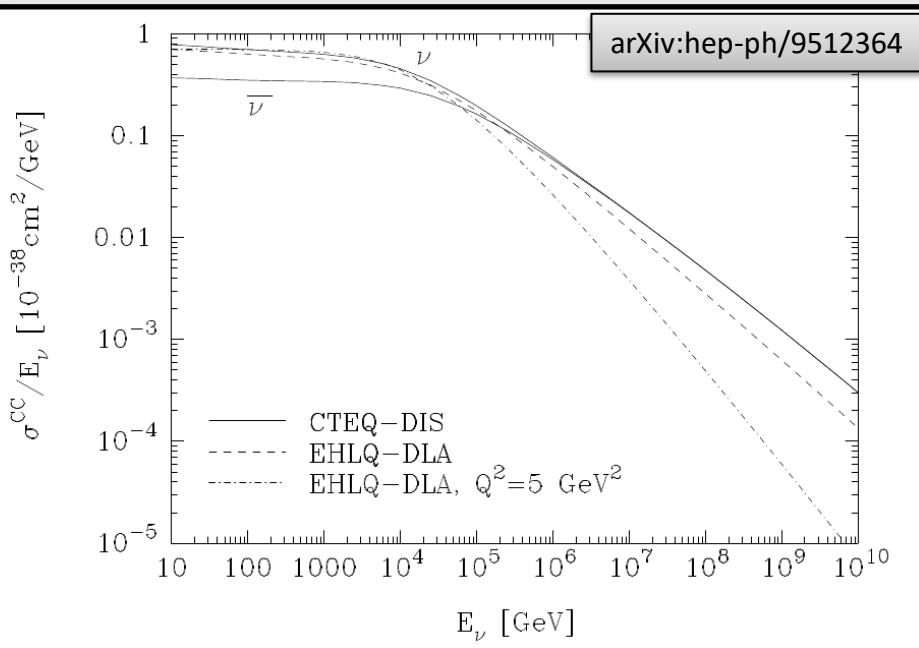
At higher energies



- As the ν energy grows it probes the “quark sea”
- Same number of quarks and anti-quarks
- Difference in cross-section vanishes



At higher energies



Why the linear growth stops?
(remember the $1/E$ factor for the
vertical scale!!!)

CC differential cross-section

$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi} \left(\frac{M_W^2}{Q^2 + M_W^2} \right)^2 \left[xq(x, Q^2) + x\bar{q}(x, Q^2)(1-y)^2 \right]$$

Propagator
term

No factor for
spin 0

The factor
for spin 1

Small energies: M_W^2 dominates – propagator is energy independent $\rightarrow E_\nu$ dominates
Larger energies: Q^2 dominates in the propagator, growth slows down

* Similar arguments for NC

Interactions with e^-

- In matter only interactions with e^- , there are no other leptons available
- Suppressed due to low mass, exception: Glashow resonance @ 6.3 PeV

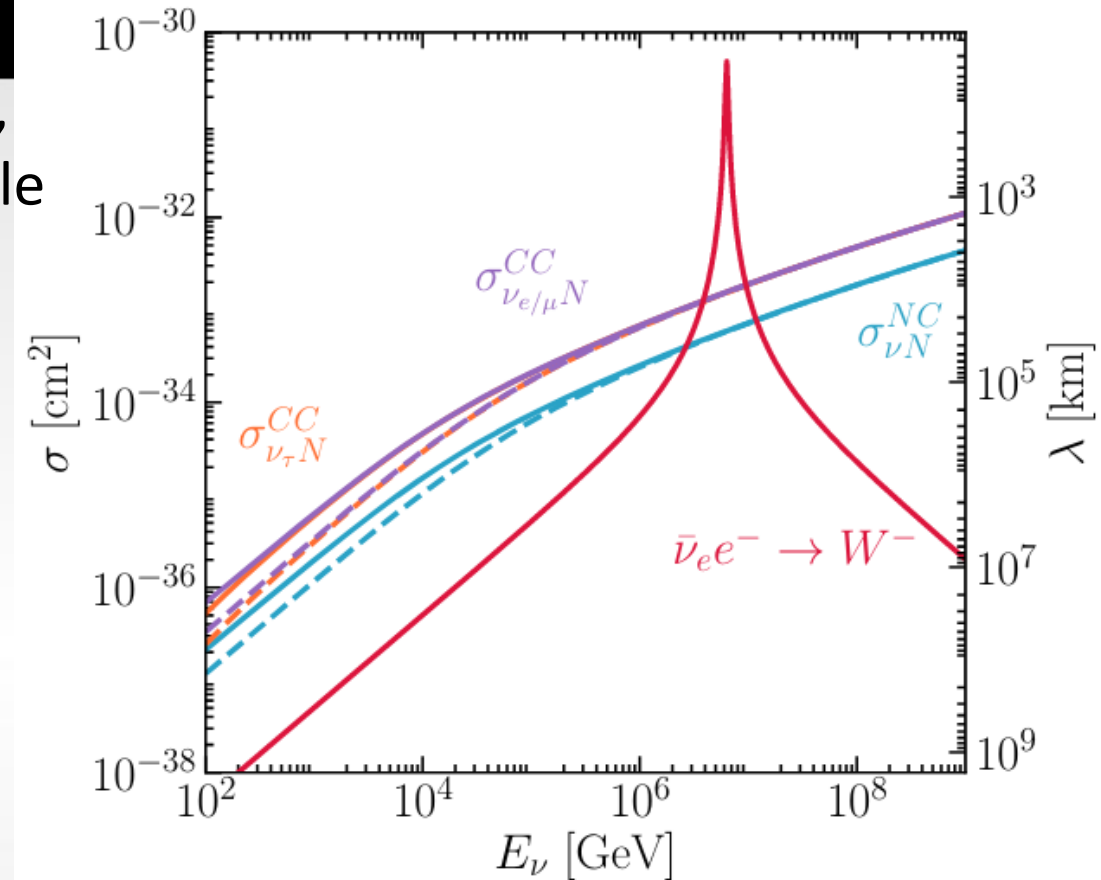


FIG. 1. Cross sections of neutrino scattering on a nucleon or electron. The red curve signifies the case of the GR. The deep inelastic scattering processes include the neutral-current interaction for all neutrino flavors (blue curves), and the charged-current interactions for ν_μ/ν_e (purple curves) and for ν_τ (orange curves). Solid curves stand for neutrinos and dashed ones for antineutrinos. The y-axis on the right represents the water equivalent MFP of these interactions.

Interactions with e^-

- In matter only interactions with e^- , there are no other leptons available
- Suppressed due to low mass, exception: Glashow resonance @ 6.3 PeV

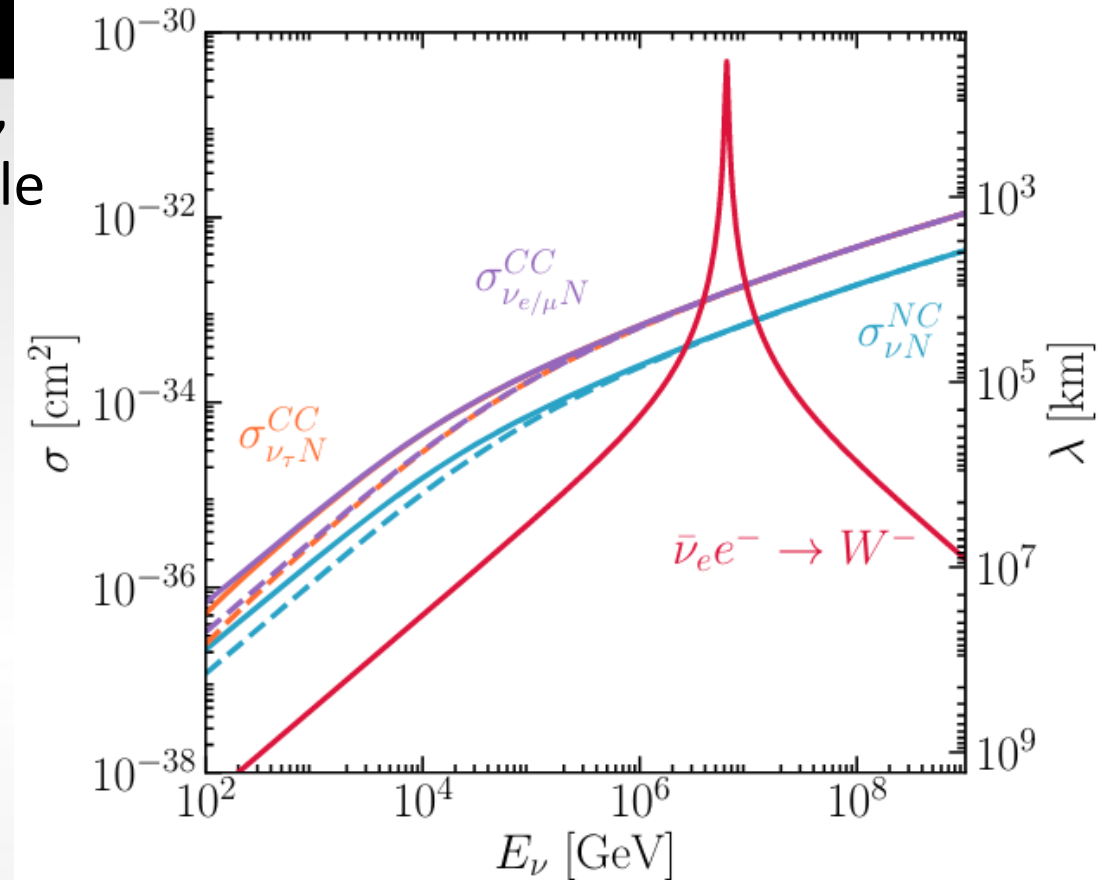
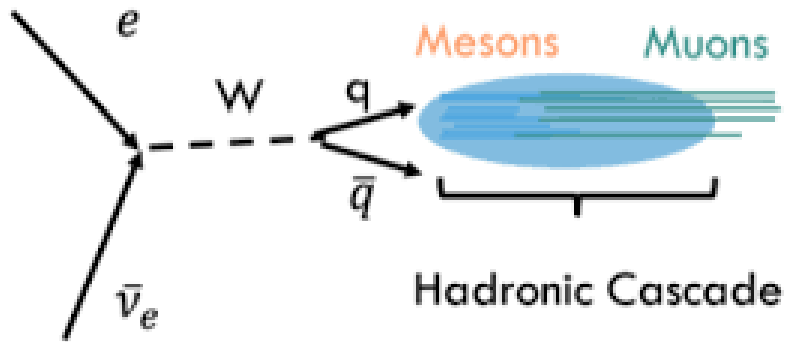


FIG. 1. Cross sections of neutrino scattering on a nucleon or electron. The red curve signifies the case of the GR. The deep inelastic scattering processes include the neutral-current interaction for all neutrino flavors (blue curves), and the charged-current interactions for ν_μ/ν_e (purple curves) and for ν_τ (orange curves). Solid curves stand for neutrinos and dashed curves for antineutrinos. The y-axis on the right represents the water equivalent MFP of these interactions.

Mean free path = interaction length
Assume water as medium

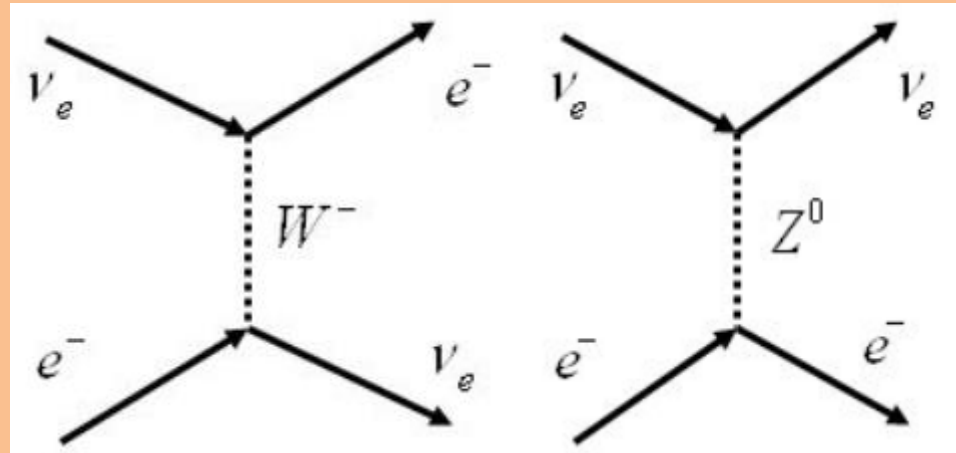
Why there is no “ Z^0 Glashow resonance”?

Glashow Resonance



- Simple kinematics
- e^- and anti ν_e interact and only W leaves

- ν scatters away and takes away some momentum



Consequences of ν cross-sections

- Before diving into neutrino studies we need to answer two questions:

1. Can the neutrinos reach my detector?
2. Can I detect them? (or how big should be my detector?)

$$\mathcal{L}_{int} = \frac{1}{n\sigma} = \frac{M}{N_A \rho A \sigma} = \frac{1}{N'_A \sigma}$$

M =molar mass=18 g mol⁻¹

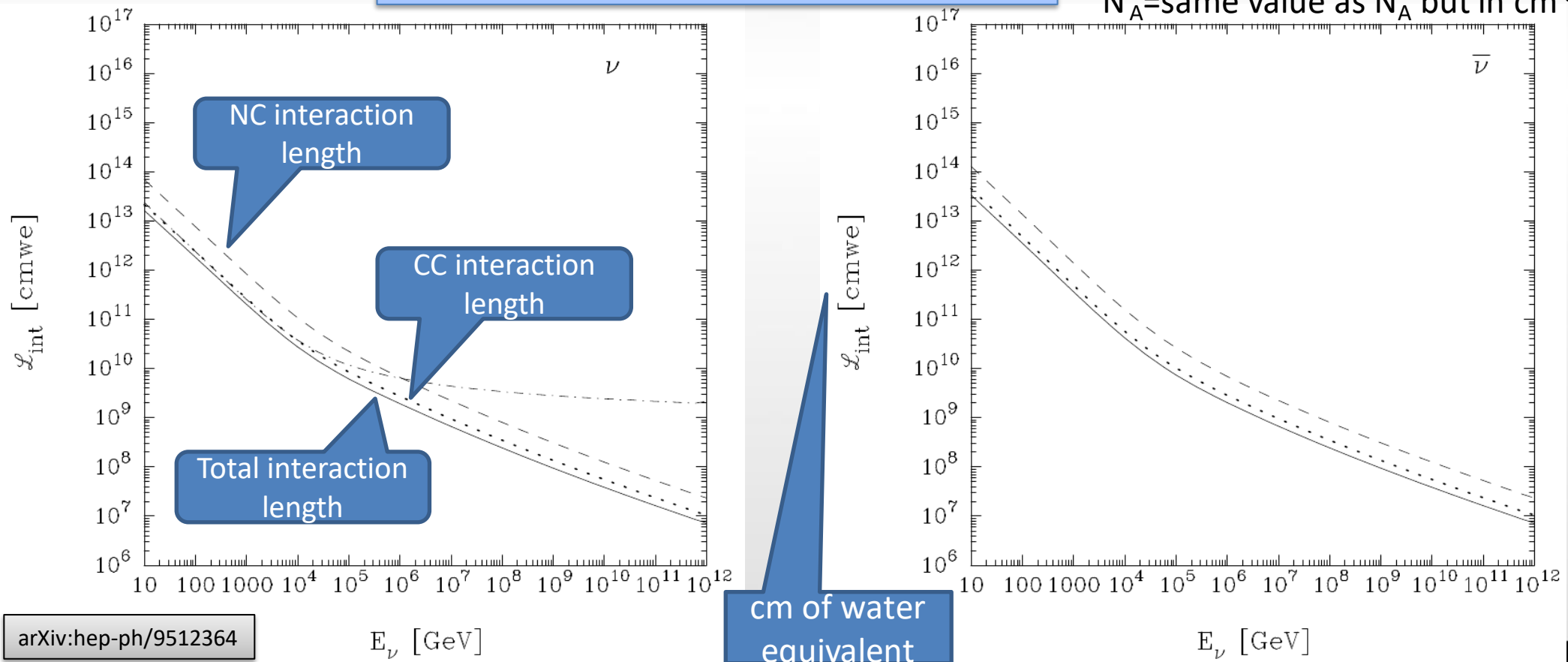
N_A =Avogadro n. (mol⁻¹)

ρ = 1 g cm⁻³

A = 18 (number of nucleons)

N'_A =same value as N_A but in cm⁻³

For interactions on nucleons



arXiv:hep-ph/9512364

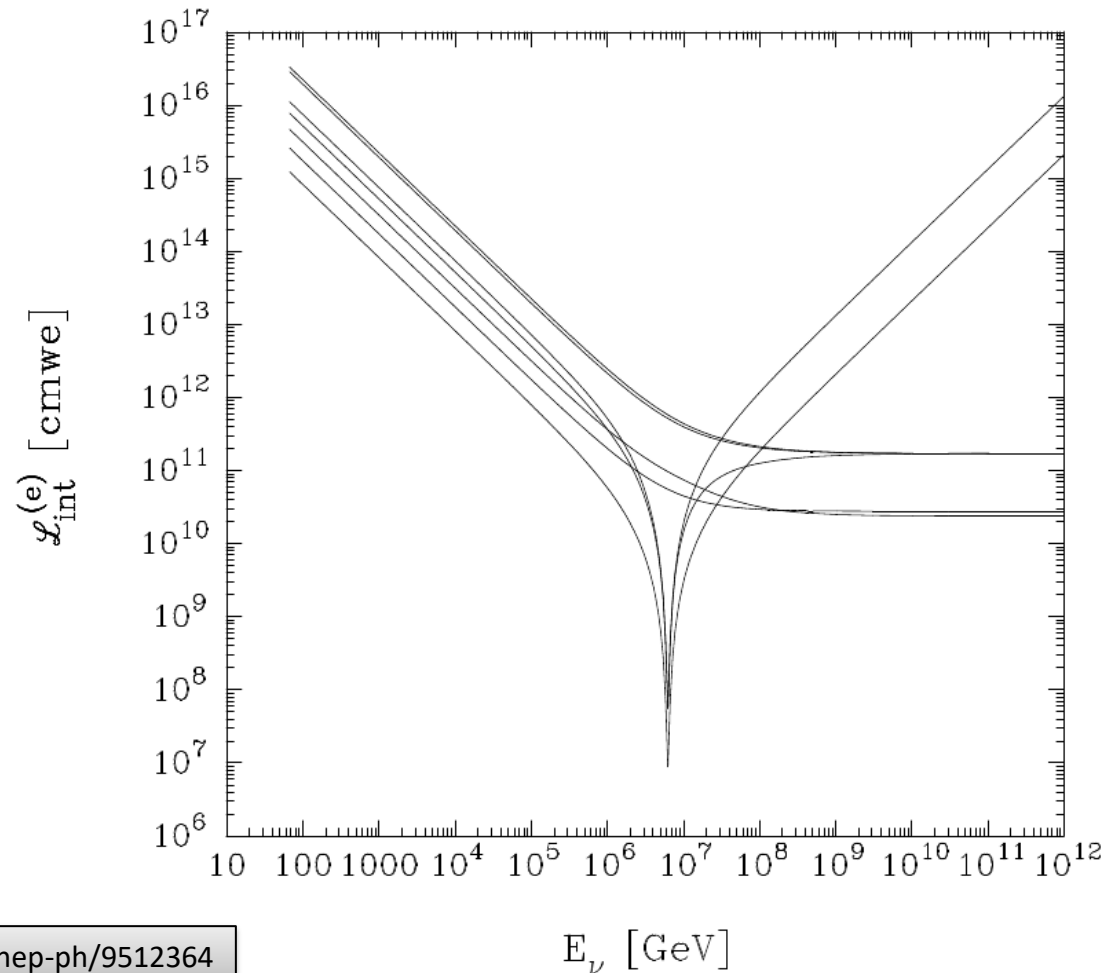
E_ν [GeV]

cm of water
equivalent

E_ν [GeV]

Consequences of ν cross-sections

For interactions on electrons



arXiv:hep-ph/9512364

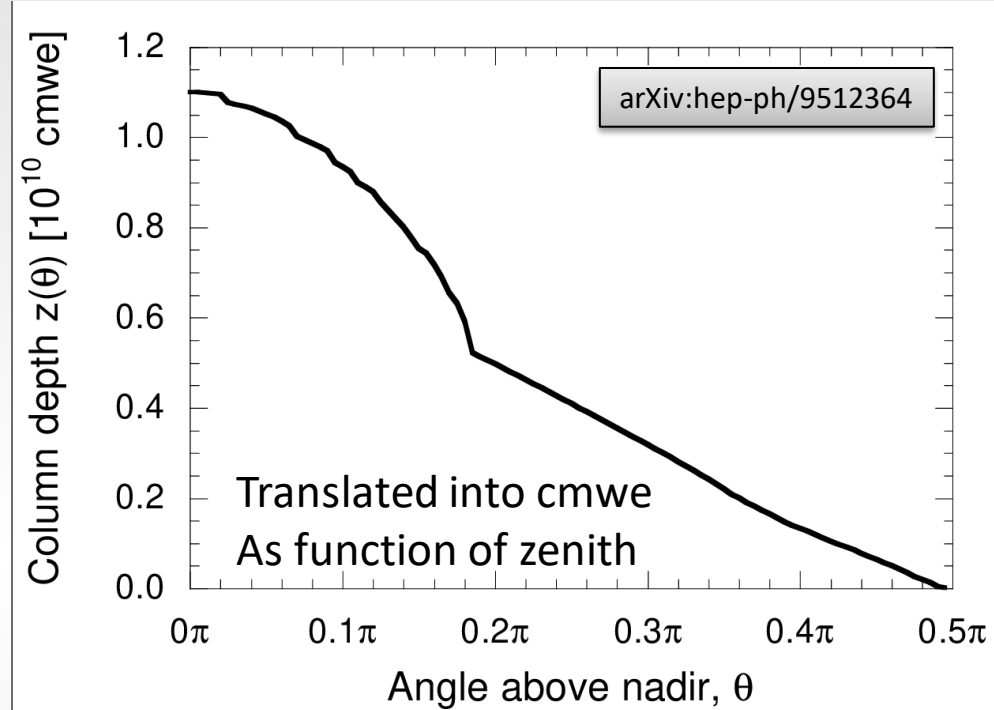
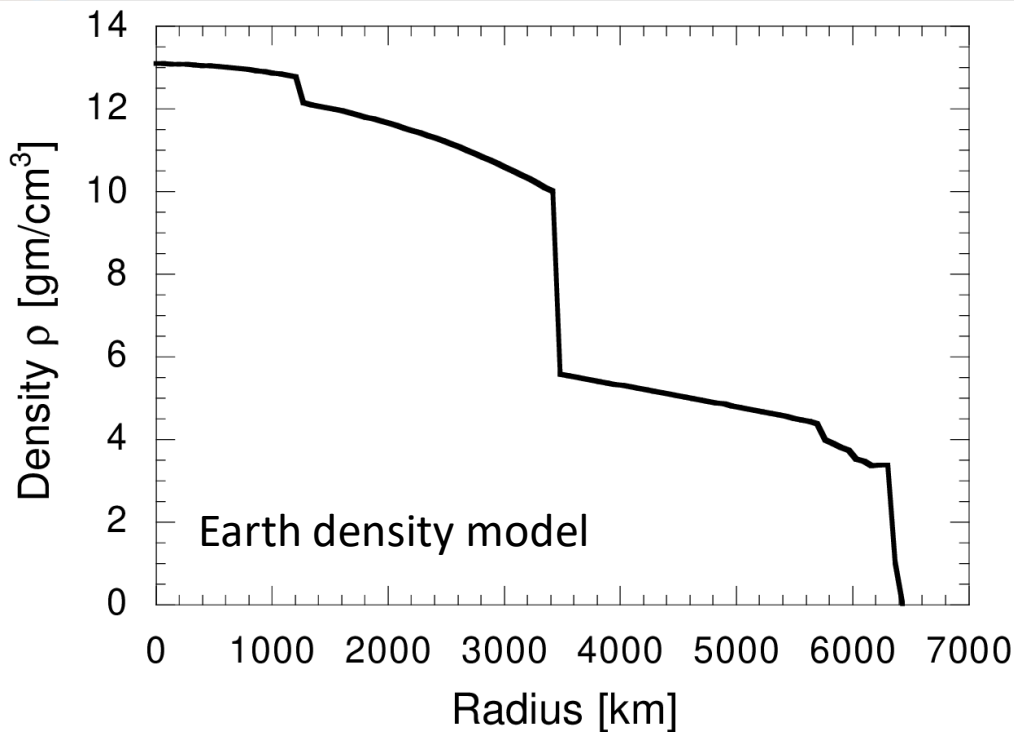
Fig. 13. Interaction lengths for neutrino interactions on electron targets. At low energies, from smallest to largest interaction length, the processes are (i) $\bar{\nu}_e e \rightarrow$ hadrons, (ii) $\nu_\mu e \rightarrow \mu \nu_e$, (iii) $\nu_e e \rightarrow \nu_e e$, (iv) $\bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu$, (v) $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$, (vi) $\nu_\mu e \rightarrow \nu_\mu e$, (vii) $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$.

Notice the int. length is larger then for interactions on nucleons due to the lower cross-section

$$\mathcal{L}_{\text{int}}^{(e)} = \frac{1}{\sigma_{\nu e}(E_\nu)(10/18)N_A},$$

Electrons nucleons
ratio for water

Neutrinos passing through Earth?



Rough estimate example:

1 TeV neutrino, vertical:

- $L_{\text{int}} = 10^{11}$ cmwe,
- $I/I_0 = \exp(-10^{10}/10^{11}) = 0.9$

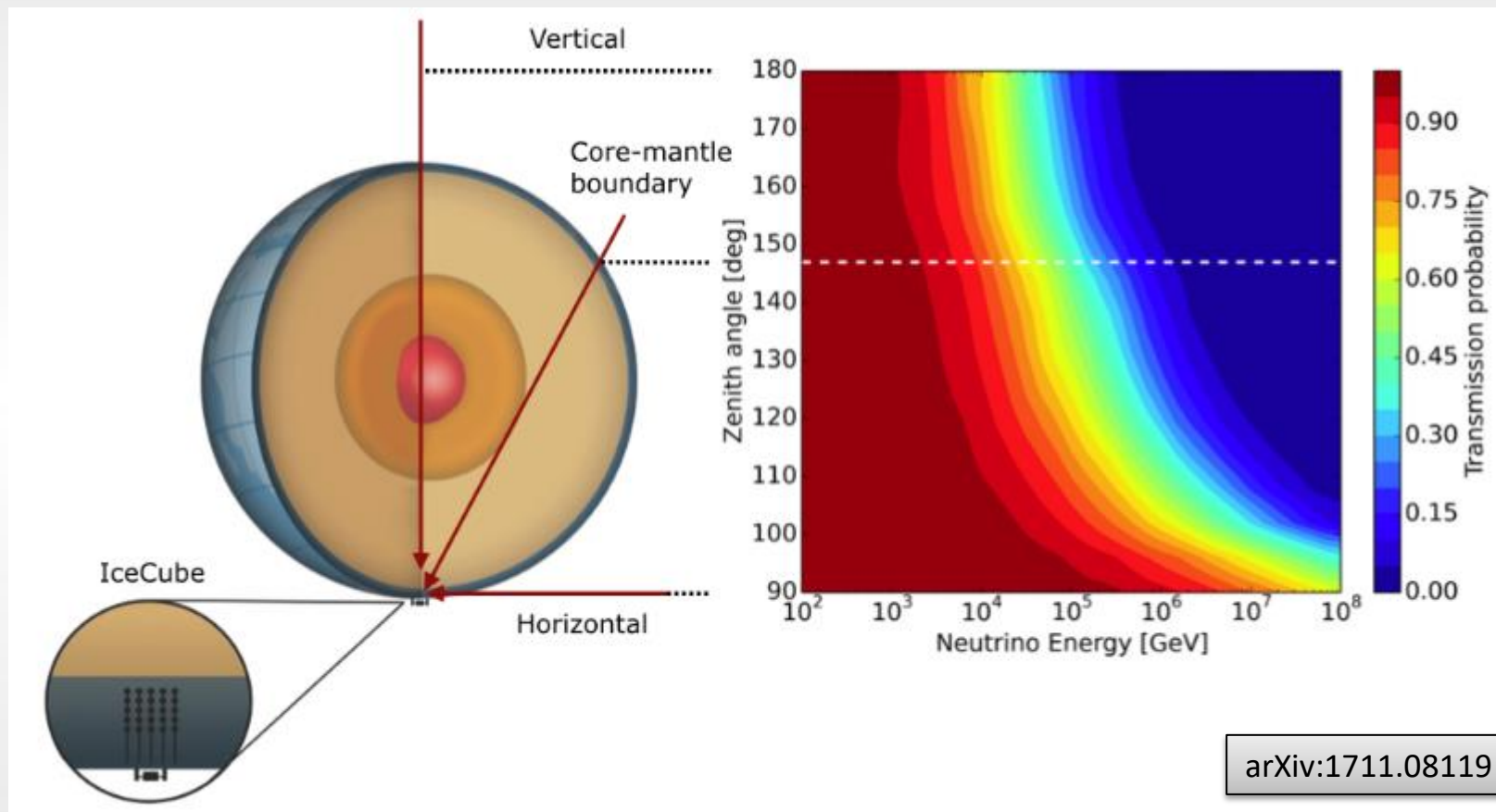
100 TeV neutrino, vertical:

- $L_{\text{int}} = 6E9$ cmwe,
- $I/I_0 = \exp(-10^{10}/6 \cdot 10^9) = 0.18$

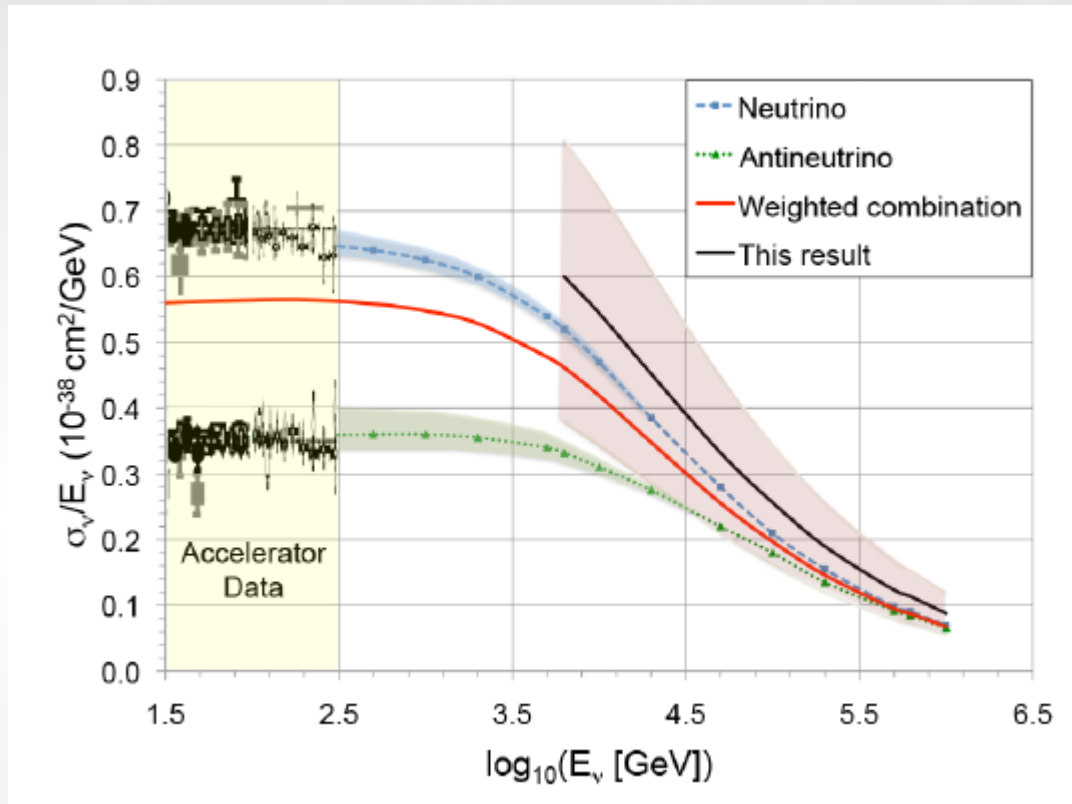
ν_e near G resonance, vertical:

- $L_{\text{int}} = 10^8$ cmwe,
- $I/I_0 = \exp(-10^{10}/10^8) = \text{practically } 0$

Neutrinos passing through Earth?



Turn the problem around



IceCube measurements

arXiv:1711.08119

- Measure ν cross-section by using Earth as a target (absorption medium)
- OK within the error bars

Detector size?

Note: previously we calculated “survival rates” now we need interaction probability: $1-I/I_0$

1km (1E5 cm) of water (IceCube od KM3net)

10 GeV neutrino, vertical:

- $L_{\text{int}} = 10^{13}$ cmwe,
- $1-I/I_0 = 1 - \exp(-10^5/10^{13}) = 1E-8$

- Even for a 1 km detector the interaction probabilities are very small
- Need large detectors

1 TeV neutrino, vertical:

- $L_{\text{int}} = 10^{11}$ cmwe,
- $I/I_0 = 1 - \exp(-10^5/10^{11}) = 1E-6$

Everything you ever wanted to know about neutrino cross-sections:

[From eV to EeV: Neutrino Cross Sections Across Energy Scales](#)

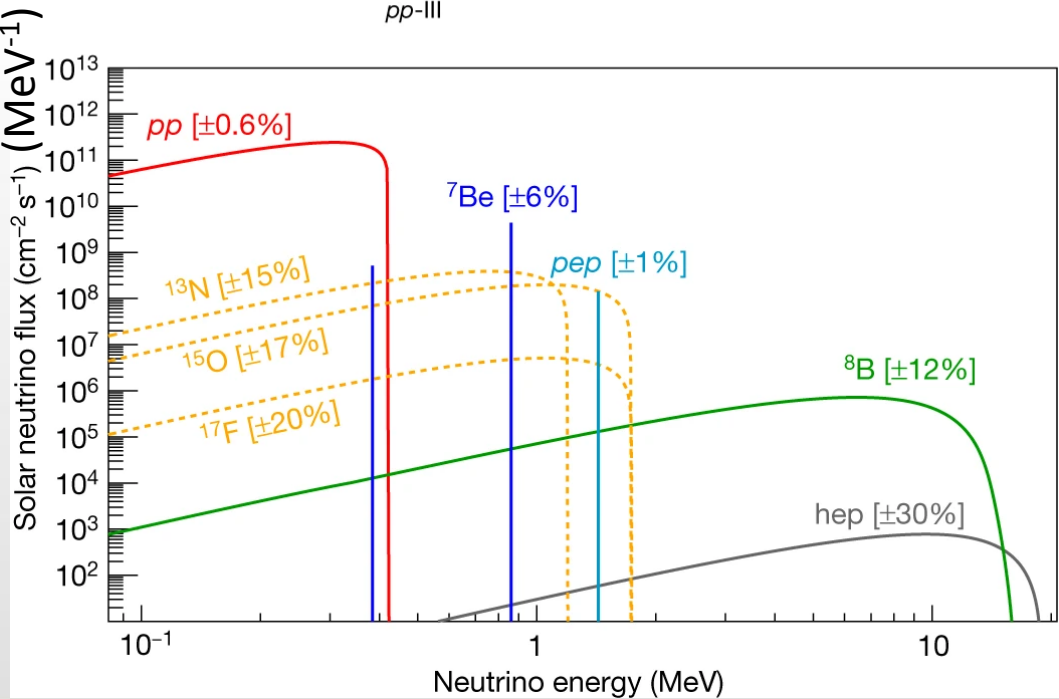
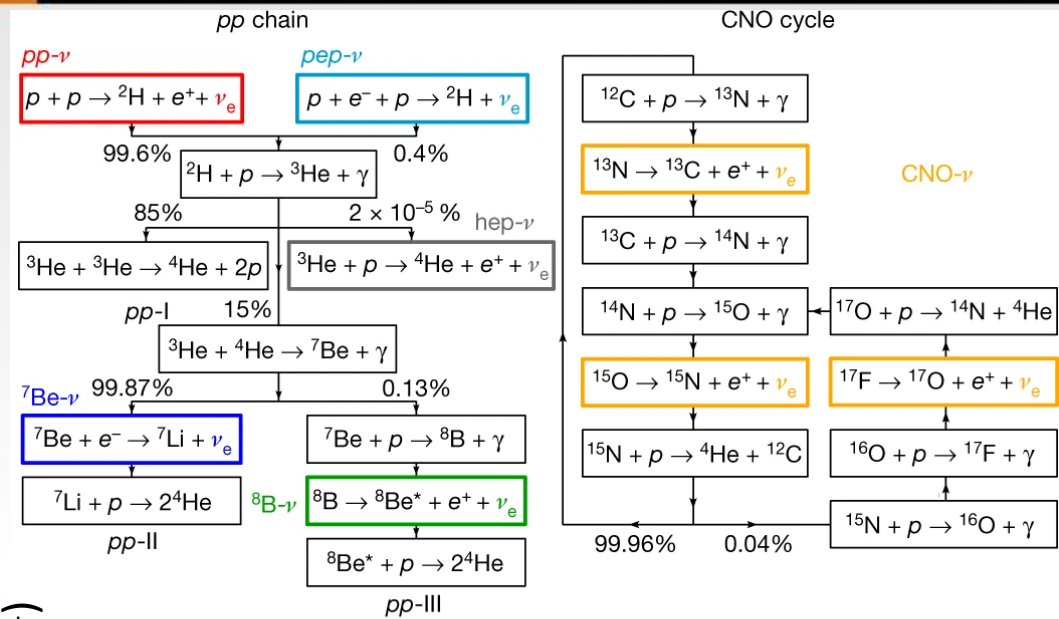
J.A. Formaggio, G.P. Zeller, arXiv:1305.7513

Solar neutrinos

- Nuclear reactions in the Sun produce neutrinos
- In mid-60's theoretical models could predict the spectra
- From the energy output of the sun it was clear that the flux of ν_s is very large.

- Large enough to overcome the low cross-section and make it possible detect solar neutrinos?

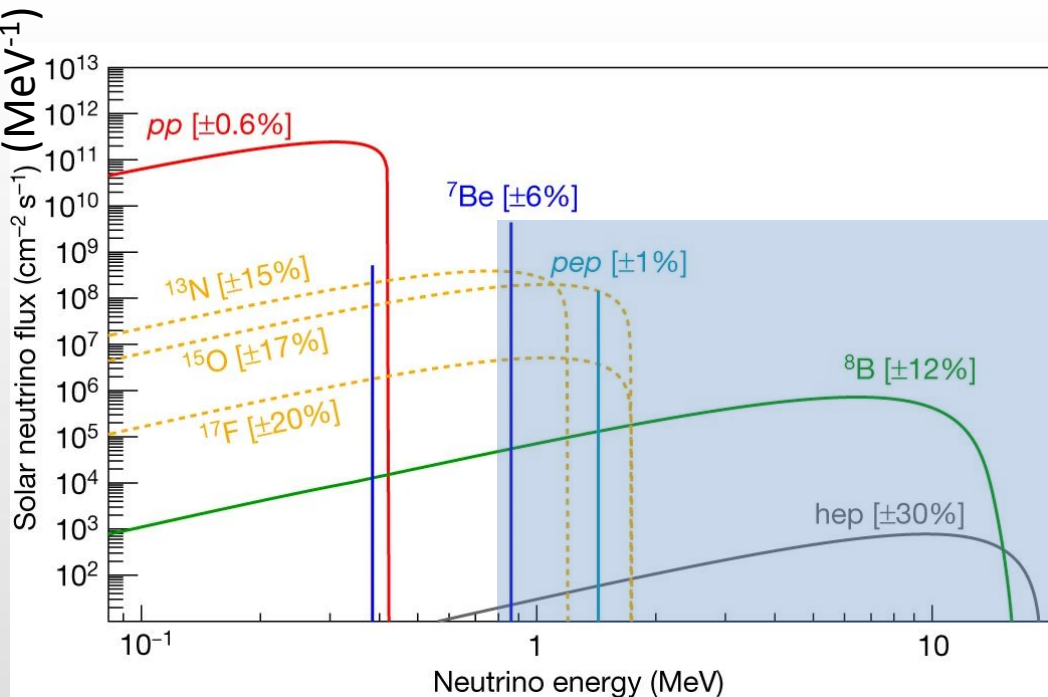
The standard solar model



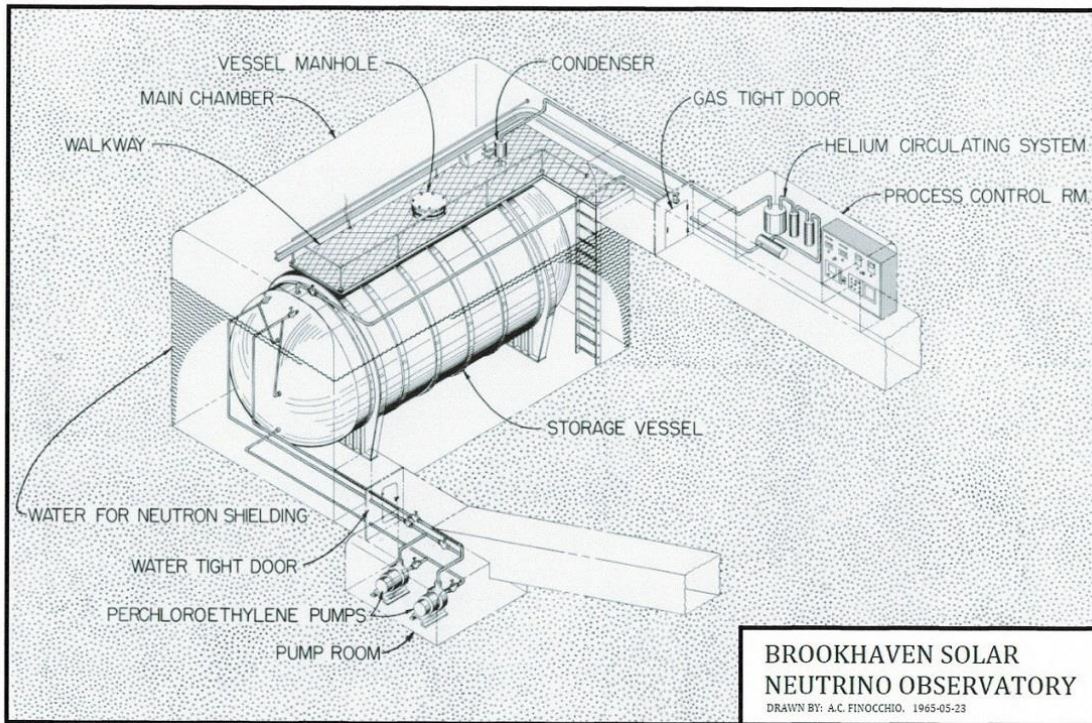
- Modern solar neutrino spectrum.
- In brackets are the uncertainties
- Are the units clear? (just checking...)
- Notice that all the neutrinos are produced as ν_e

The Homestake experiment

- Raymond Davis, Jr. and John N. Bahcall proposed to use the reaction: $\nu_e + {}^{37}\text{Cl} \longrightarrow {}^{37}\text{Ar} + e^-$.
- Energy threshold: 0.814 MeV
- The main contributors are ${}^8\text{B}$ and ${}^7\text{Be}$ vs



The Homestake experiment



THE HOMESTAKE EXPERIMENT

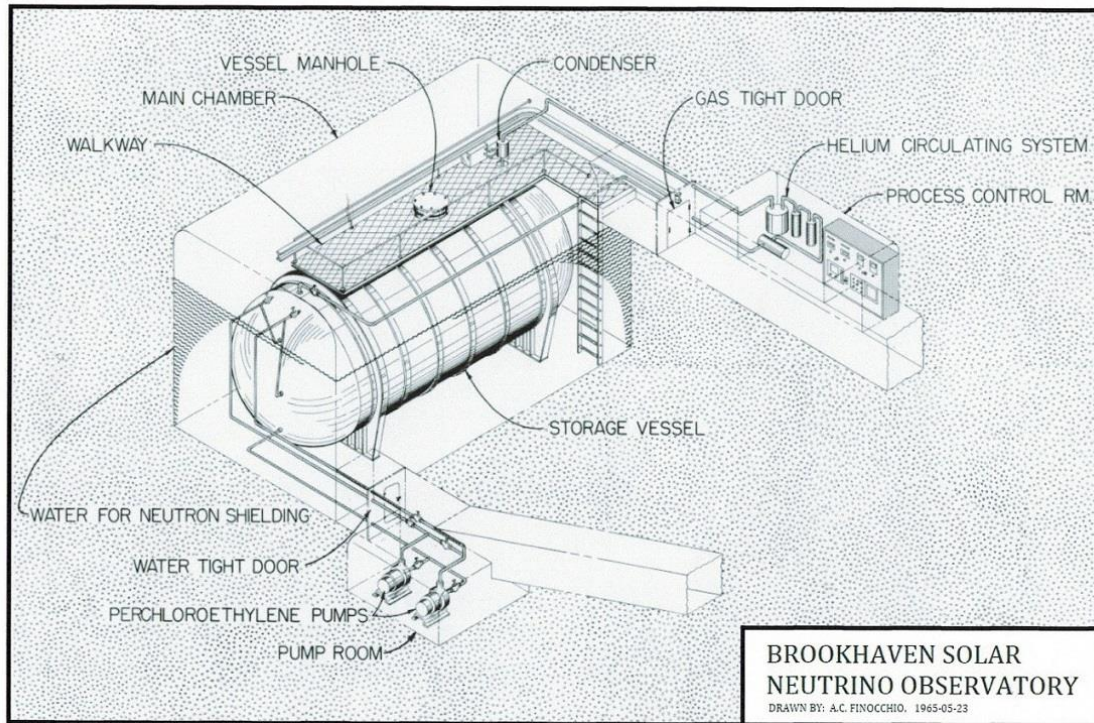
- 1478 meters underground (Homestake Gold Mine)
- 380 cubic meter tank of perchloroethylene

The Homestake experiment

- 1478 meters underground (Homestake Gold Mine)
- 380 cubic meter tank of perchloroethylene



The Homestake experiment



THE HOMESTAKE EXPERIMENT

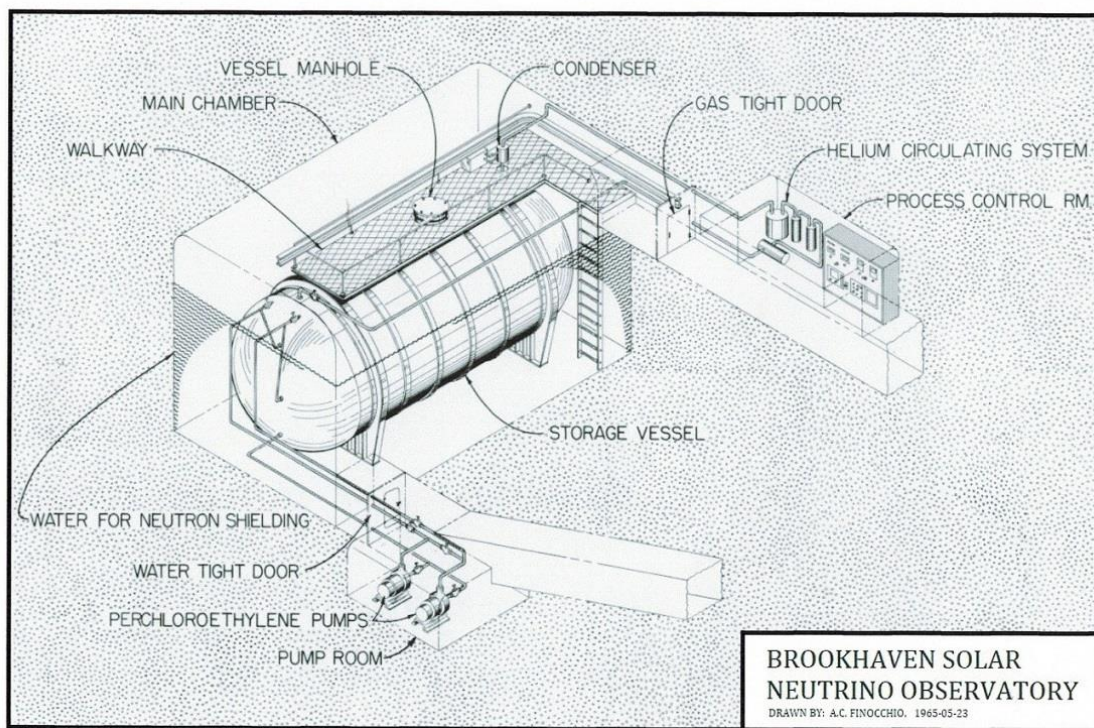
- 1478 meters underground (Homestake Gold Mine)
- 380 cubic meter tank of perchloroethylene
- Submerged in water for neutron shielding

The Homestake experiment



Raymond Davis, Jr.

The Homestake experiment

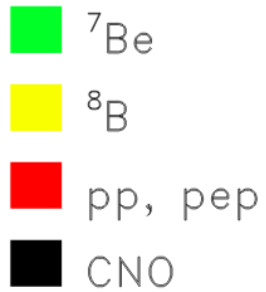


THE HOMESTAKE EXPERIMENT

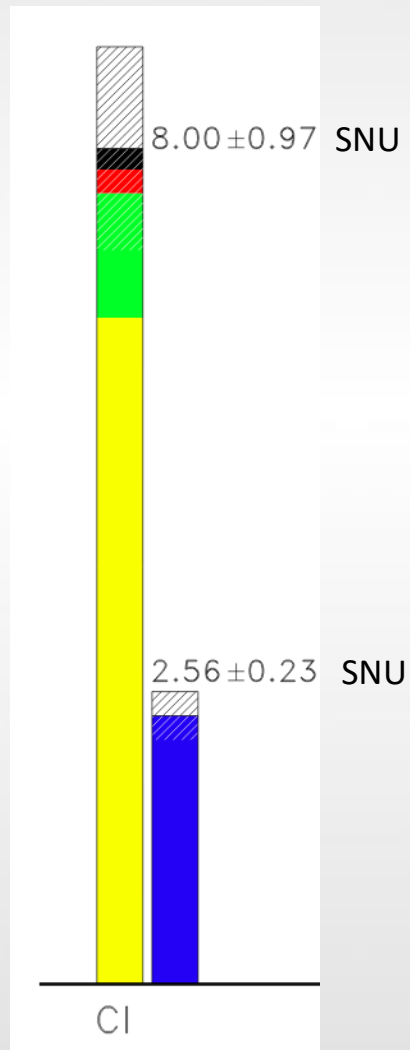
- 1478 meters underground (Homestake Gold Mine)
- 380 cubic meter tank of perchloroethylene
- Submerged in water for neutron shielding
- Careful extraction of ^{37}Ar
<https://iopscience.iop.org/article/10.1086/305343/fulltext/34468.text.html>

The Mystery of the Missing Neutrinos

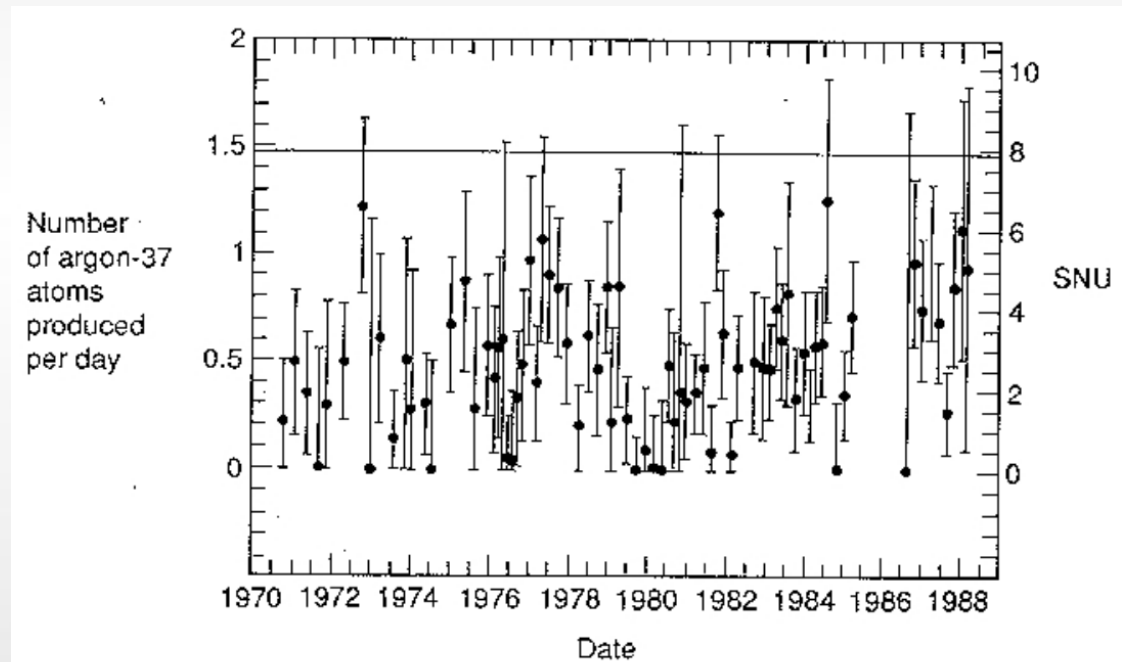
Theory



■ Exper.



- Predicted 1.5 ${}^{37}\text{Ar}$ atoms(!) per day.
- Measured only ~1/3 of that



What's SNU ?

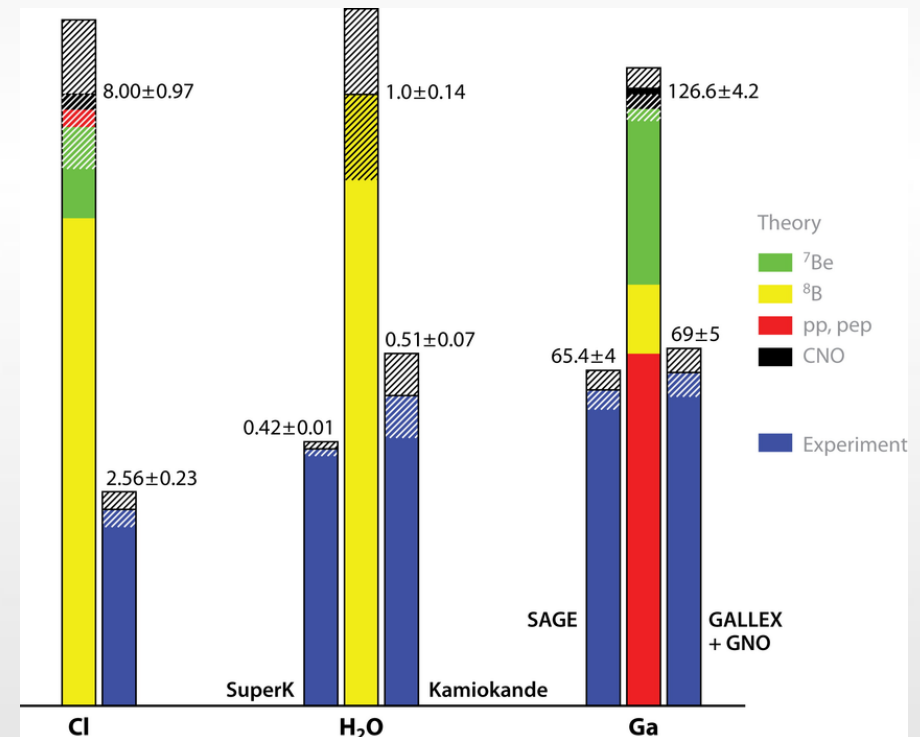
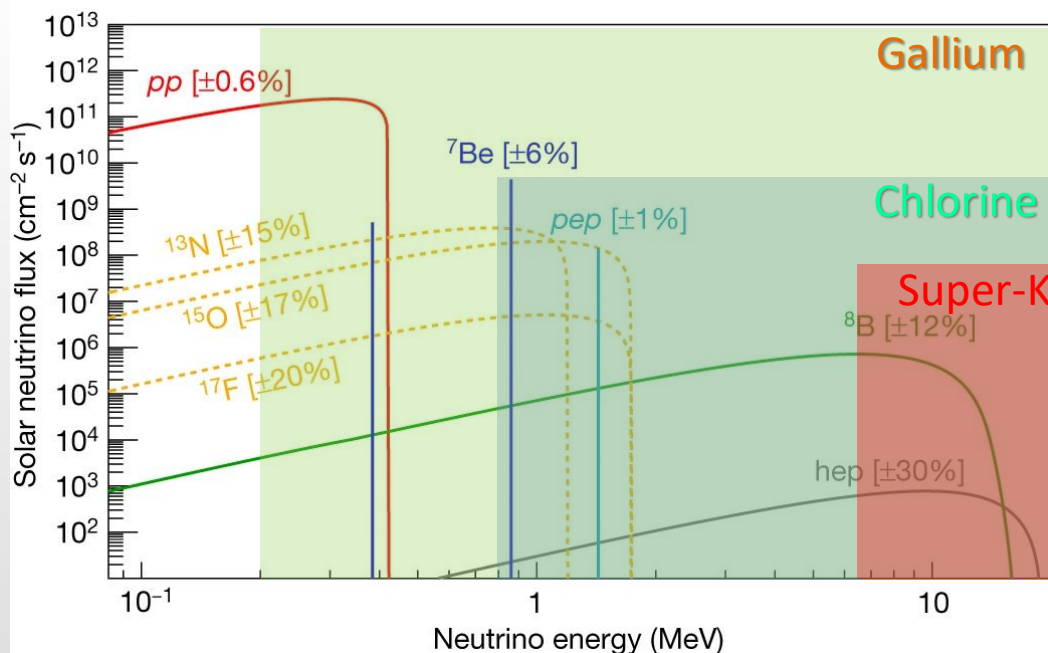
1 SNU = 10^{-36} captures per second per target nucleus


Solar Neutrino Unit

Other Experiments confirmed missing ν_e

- SAGE- Soviet-American Gallium Experiment, GALLEX (Italy):
Measured: $\nu_e + {}^{71}\text{Ga} \rightarrow e^- + {}^{71}\text{Ge}$
- Super Kamiokande
 - $\nu_e + e^- \rightarrow \nu_e + e^-$
 - Can confirm direction

Depending on the energy threshold
a different fraction of ν missing



 Haxton WC, et al. 2013.
Annu. Rev. Astron. Astrophys. 51:21–61

Take-away message

- Sensitive only to ν_e
- Flux measurement – some of the ν s missing
- Energy measurement – only Kamiokande, Super-K
- Directional measurement – only Kamiokande, Super-K
- Possible solutions:
 - Wrong solar model – verified repeatedly, no major flaw
 - Experimental mistake – all looked fine
 - New physics in the ν sector
 - Gribov & Pontecorvo suggested that if ν s massive they can change flavour – in today's terms “neutrino oscillations”

Neutrino oscillations

are not going to be explained here ;-)

- Two flavours example:
- At the moment of production – weak eigenstates – i.e. pure ν_e or ν_μ
- Weak ν_e or ν_μ are not mass eigenstates, instead a linear combination:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} \\ -\sin \theta_{12} & \cos \theta_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad \text{Propagation: } \nu_1(t) = \nu_1(0)e^{-iE_1t} \quad \nu_2(t) = \nu_2(0)e^{-iE_2t}$$

- If m_1 and m_2 are different (i.e. at least one must be non-zero) then E_1 and E_2 are different, assuming $m_{1,2} \ll E$, $p \approx E$: $E_i = p + \frac{m_i^2}{2p}$ $\Delta E = \frac{\Delta m_{12}^2}{2E}$

If we start off with a pure ν_e beam, the amplitude for ν_e at a later time t is:

$$\nu_e(t) = \nu_e(0) \left[\cos^2 \theta_{12} e^{-iE_1t} + \sin^2 \theta_{12} e^{-iE_2t} - \sin \theta_{12} \cos \theta_{12} (e^{-iE_1t} - e^{-iE_2t}) \right]$$

and the probability of observing an oscillation to ν_μ is:

$$P(\nu_e \rightarrow \nu_\mu) = |\nu_\mu(t)|^2 = 1 - |\nu_e(t)|^2 = \sin^2 2\theta_{12} \sin^2 \frac{(E_2 - E_1)t}{2}$$

Neutrino oscillations will not be explained here ;-)

$$P(\nu_e \rightarrow \nu_\mu) = |\nu_\mu(t)|^2 = 1 - |\nu_e(t)|^2 = \sin^2 2\theta_{12} \sin^2 \frac{(E_2 - E_1)t}{2}$$

$$= \sin^2(2\theta_{12}) \sin^2 \left(\frac{\Delta m_{12}^2}{4E} L \right)$$

$$\frac{\Delta m_{21}^2}{4E} L = 1.27 \frac{\Delta m_{21}^2 [\text{eV}^2]}{4 E [\text{GeV}]} L [\text{km}]$$

- We have a new parameter θ_{12}

- Unitary matrix

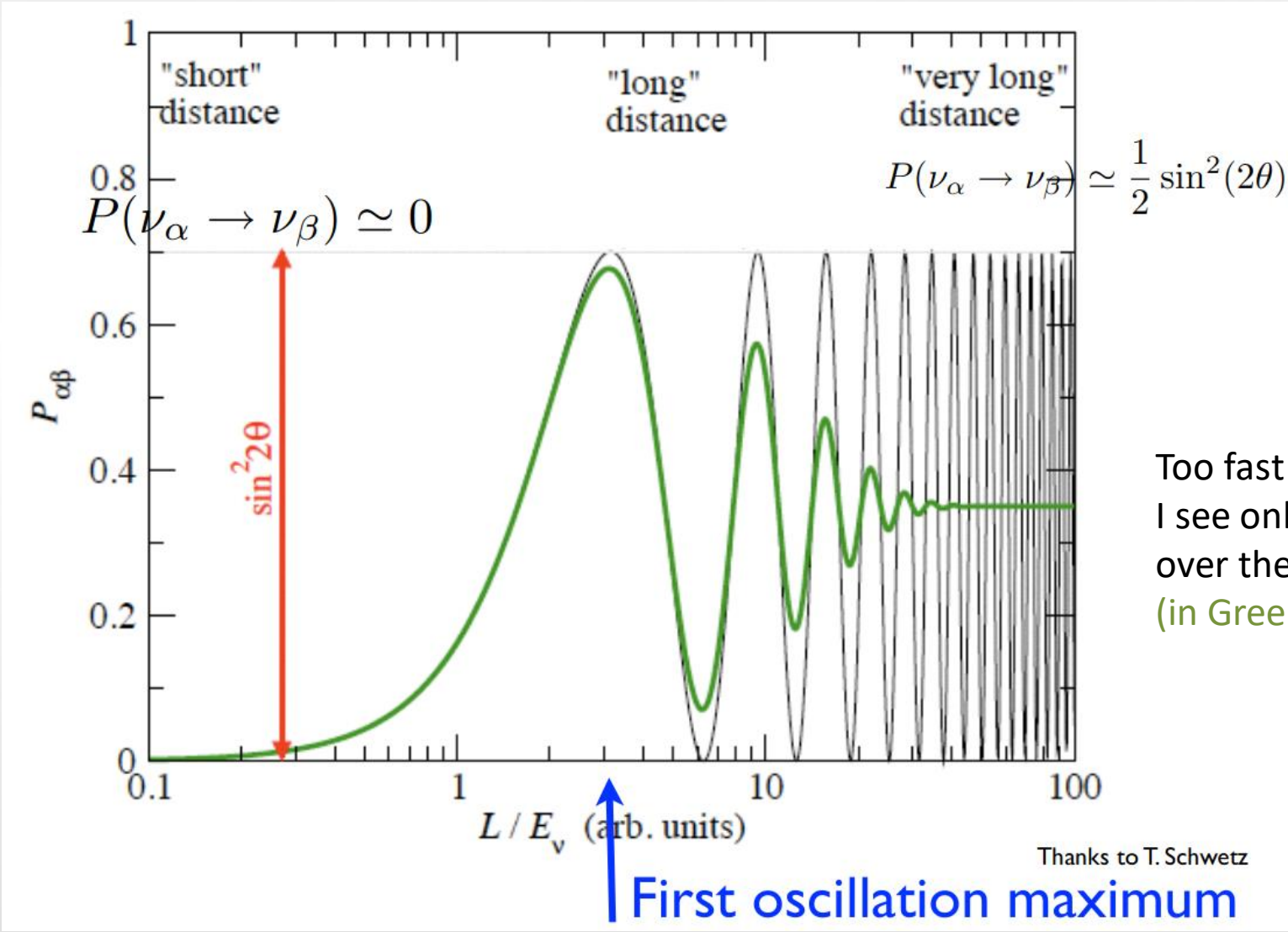
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} \\ -\sin \theta_{12} & \cos \theta_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- Neutrino changes flavour depending on combination of:
 - Mass difference
 - Energy
 - Distance

Neutrino oscillations will not be explained here ;-)

$$P = \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)$$

We care for the ratio of L/E , lower energy closer will be the same as higher energy further away



Too fast oscillations
I see only the average
over the precision range
(in Green)

Neutrino oscillations will not be explained here ;-)

In case of three flavours:

PMNS: Pontecorvo,
Maki, Nakagawa, Sakata

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$V_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric + LBL
measurements

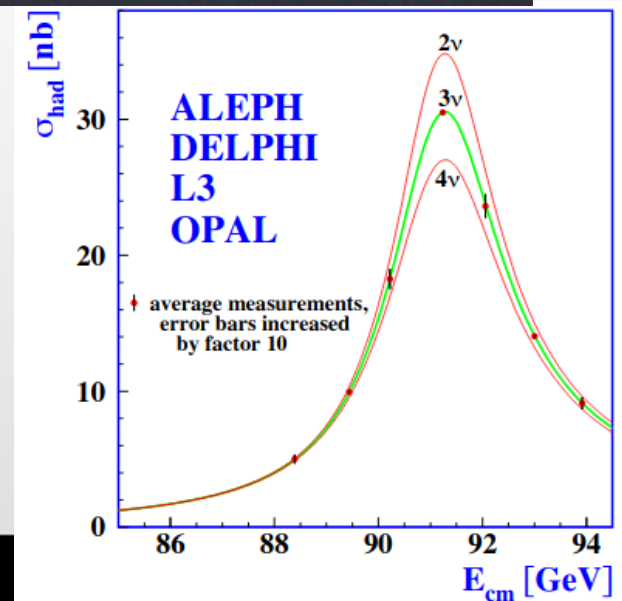
reactor disapp + LBL
appearance searches

solar + KamLAND
measurements

$$s_{ij} = \sin \theta_{ij}, c_{ij} = \cos \theta_{ij}$$

So we have:

- Three angles θ_{ij}
- Complex phase δ
- Two mass differences Δm_{12} and Δm_{23}
- And everything is way more complicated than for two flavours
- PMNS Unitary (?) how do we know there are 3 nu flavours?



Current best-fit values

Parameter	Value	1σ range	3σ range
θ_{12}	33.6°	$32.6^\circ - 34.8^\circ$	$30.1^\circ - 36.8^\circ$
θ_{23}	38.4°	$37.2^\circ - 39.8^\circ$	$35.1^\circ - 53.0^\circ$
θ_{13}	8.9°	$8.5^\circ - 9.4^\circ$	$7.5^\circ - 10.2^\circ$
δ_{CP}	1.08π	$(0.77 - 1.36)\pi$	
Δm_{12}^2	$7.54 \cdot 10^{-5} \text{ eV}^2$	$(7.32 - 7.80) \cdot 10^{-5} \text{ eV}^2$	$(6.99 - 8.18) \cdot 10^{-5} \text{ eV}^2$
$ \Delta m_{23}^2 $	$2.43 \cdot 10^{-3} \text{ eV}^2$	$(2.33 - 2.49) \cdot 10^{-3} \text{ eV}^2$	$(2.19 - 2.62) \cdot 10^{-3} \text{ eV}^2$
$ \Delta m_{13}^2 $	$\Delta m_{12}^2 \pm \Delta m_{23}^2 \approx \Delta m_{23}^2 $		

- With two exceptions (the CP phase δ and the sign of Δm_{23}^2), all parameters have been measured.

Matter Effects

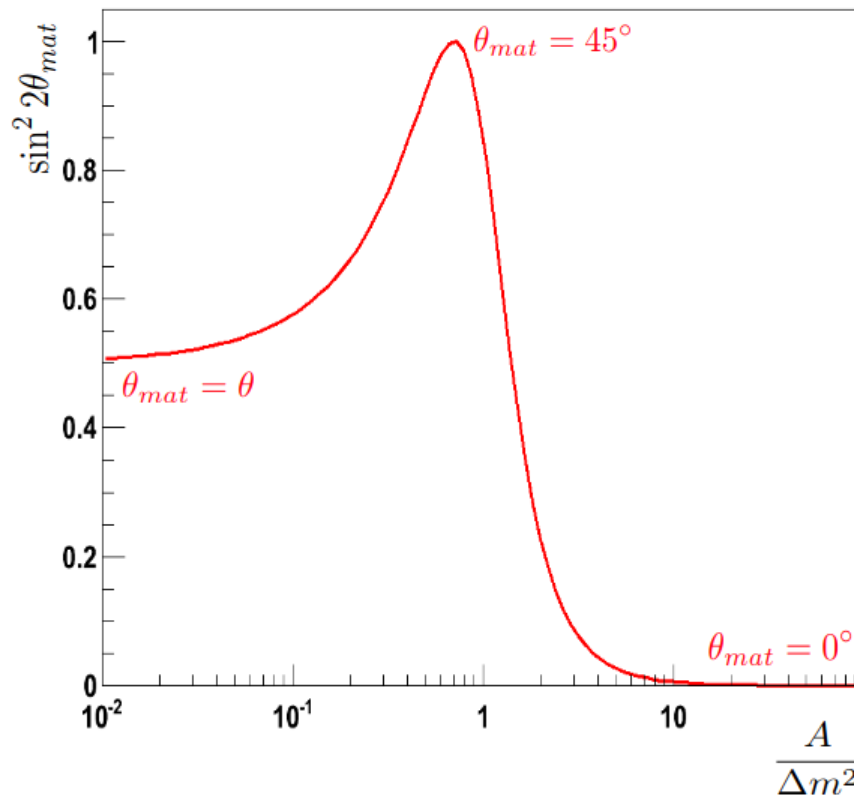
- As neutrinos propagate and oscillate
- Different flavour have different cross-section for interaction with matter:
 - Z – all flavours
 - W – only ν_e
- Important as they pass through the Sun and Earth
- Mikheyev-Smirnov-Wolfenstein effect

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)$$

Mikheyev-Smirnov-Wolfenstein effect

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right)$$

$$\sin^2(2\theta_{\text{mat}}) = \frac{\sin^2 2\theta}{\left(\frac{A}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$



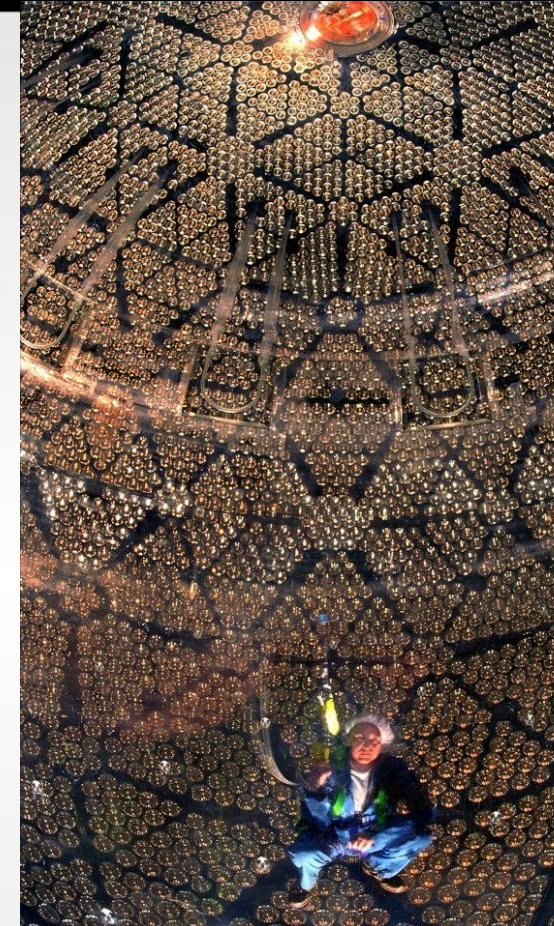
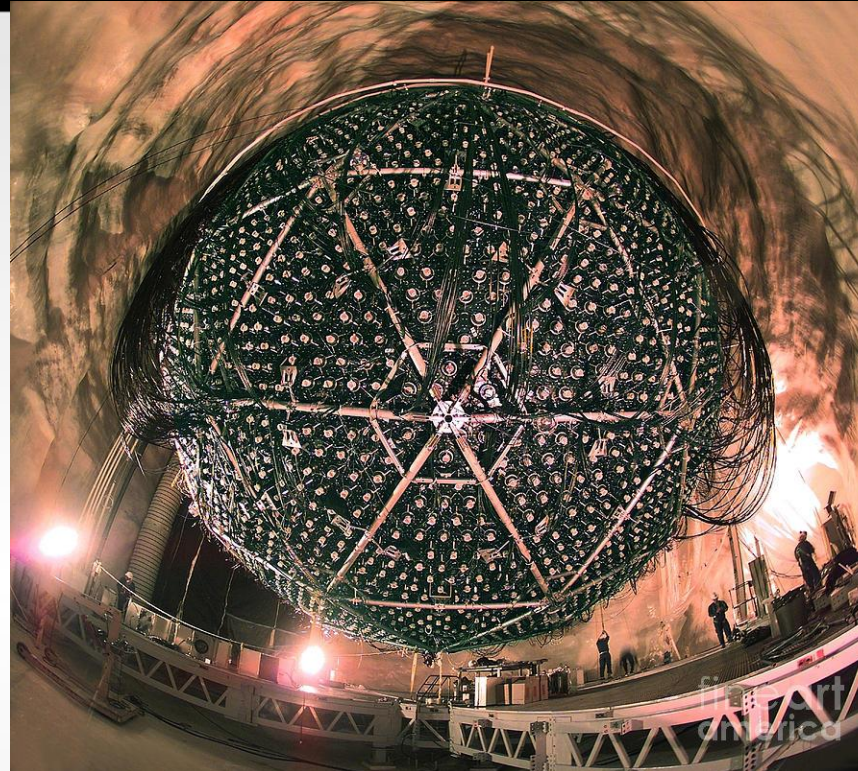
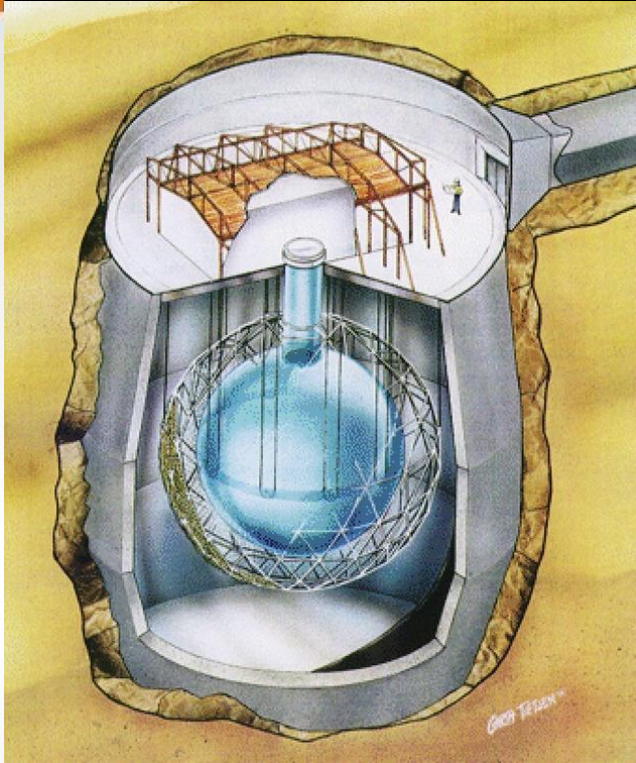
→ $\sin^2 2\theta_{\text{mat}}$ has the shape of a Breit-Wigner resonance as a function of $A/\Delta m^2$

$$\frac{A}{\Delta m^2} = \underbrace{\frac{2\sqrt{2}G_{\text{F}}}{\Delta m^2}}_{\text{natural const.}} \cdot N_e \cdot p$$

- Maximum mixing $\sin^2 2\theta = 1$ for resonance condition:

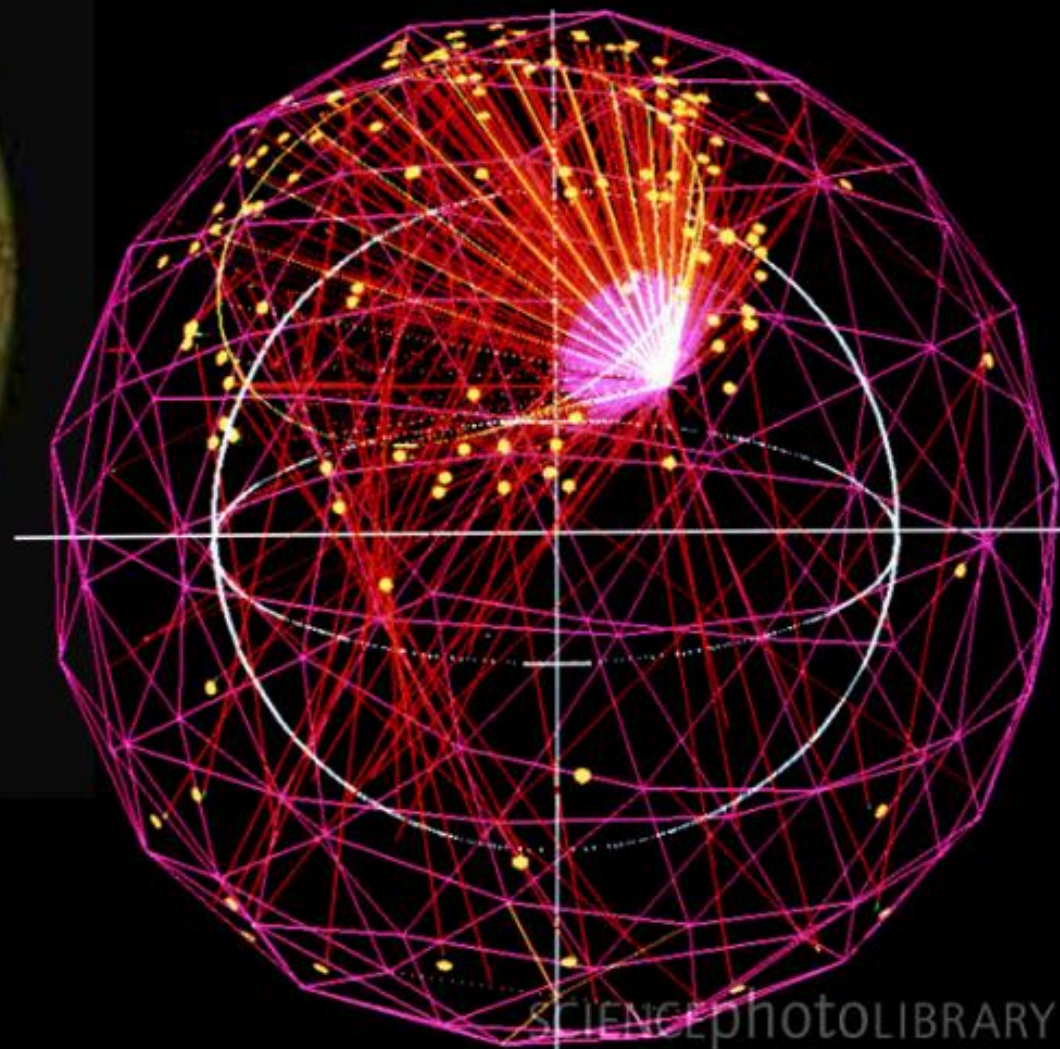
$$N_e E = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_{\text{F}}}$$

Sudbury Neutrino Observatory (SNO)



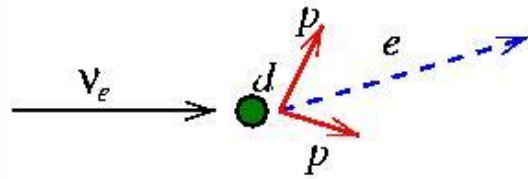
- 2100 m underground in Vale's Creighton Mine in Sudbury, Ontario, Canada
- Operational from 1999 to 2006
- 6-metre-radius acrylic (transparent) vessel
- 1000t of heavy water
- 9600 photomultiplier tubes (PMTs)

SNO Event Display



Sudbury Neutrino Observatory (SNO)

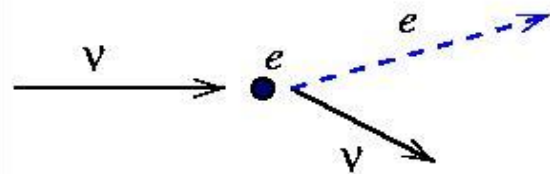
Neutrino absorption by deuteron



CC process

- Only ν_e
- Protons undetected
- e^- Cherenkov light

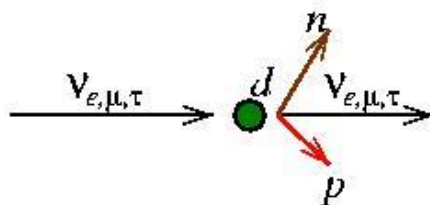
Neutrino-electron scattering



Electron scattering

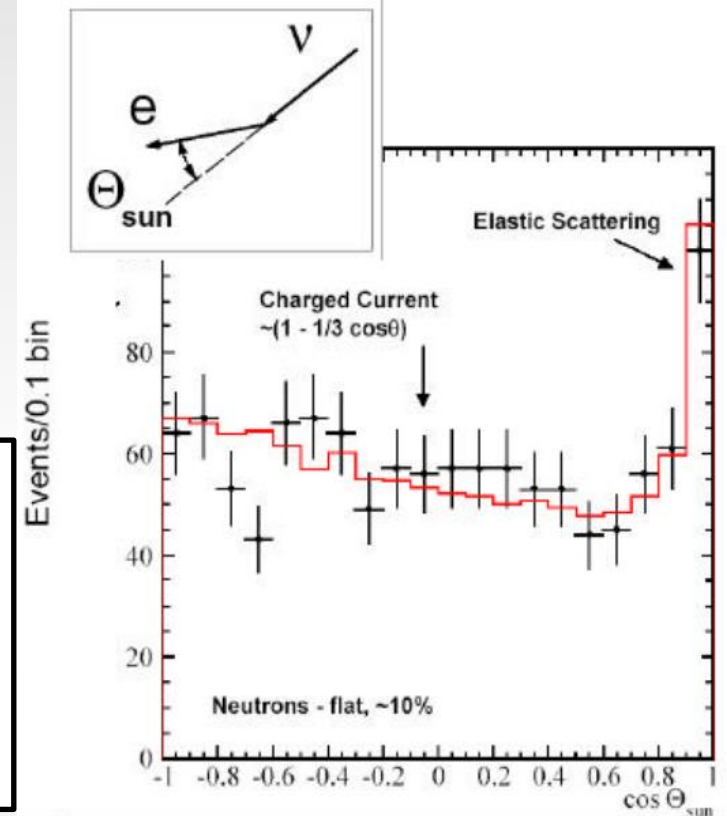
- Mainly ν_e (via W and Z)
- Other flavours only Z
- e^- Cherenkov light
- (how Super-K observes solar ν)

Neutrino breakup of deuteron



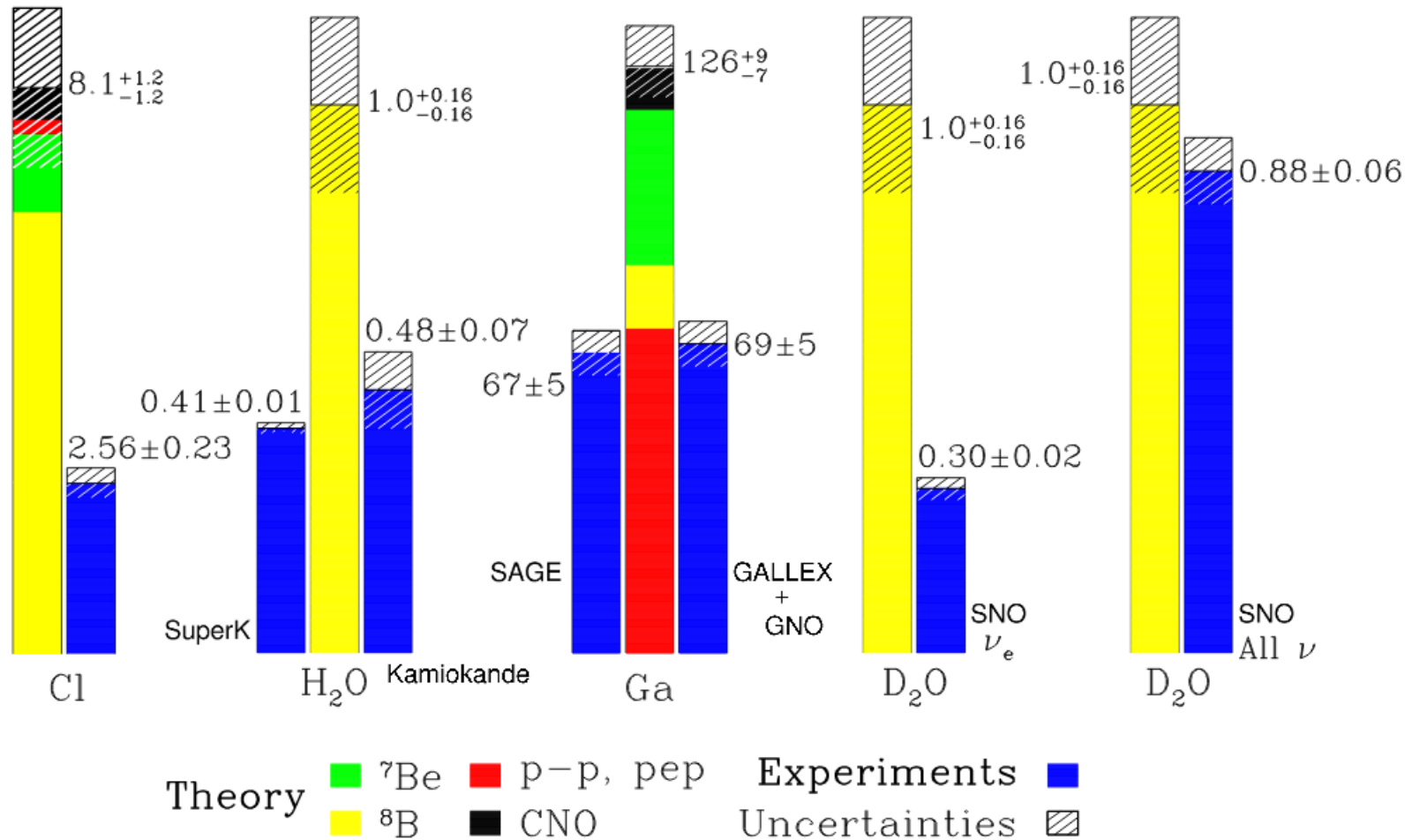
NC process

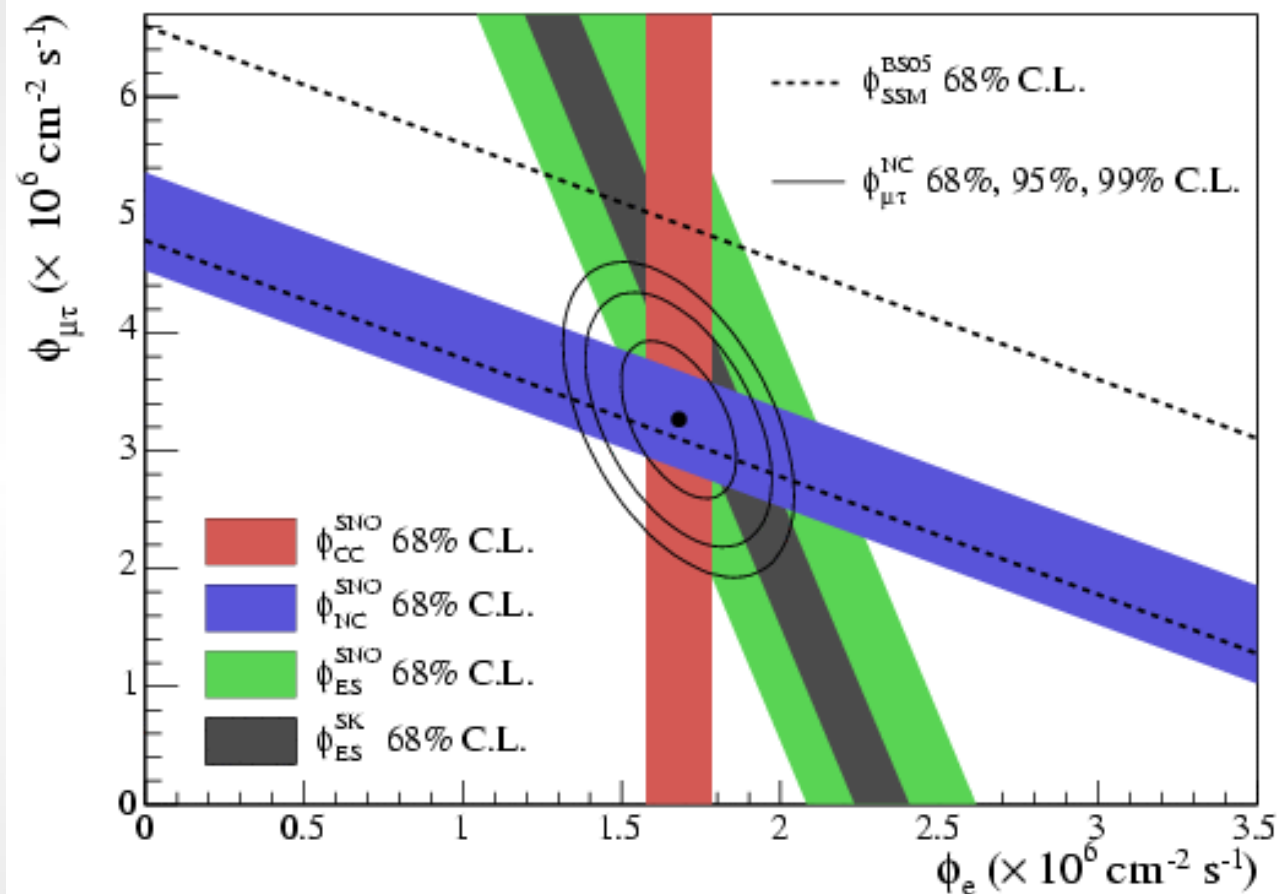
- All ν same cross-section
- Protons undetected
- Neutron capture $\rightarrow \gamma$ s $\rightarrow e^-$ scattering $\rightarrow e^-$ Cherenkov light
- NaCl and ^3He upgrade



Solar neutrino not a problem

Total Rates: Standard Model vs. Experiment
Bahcall-Serenelli 2005 [BS05(OP)]

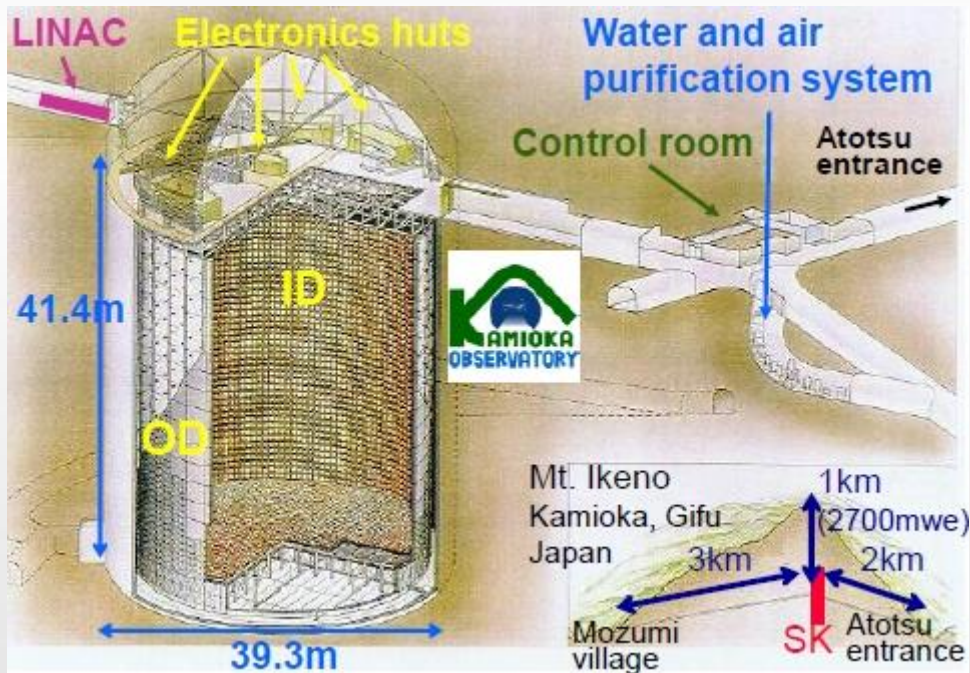


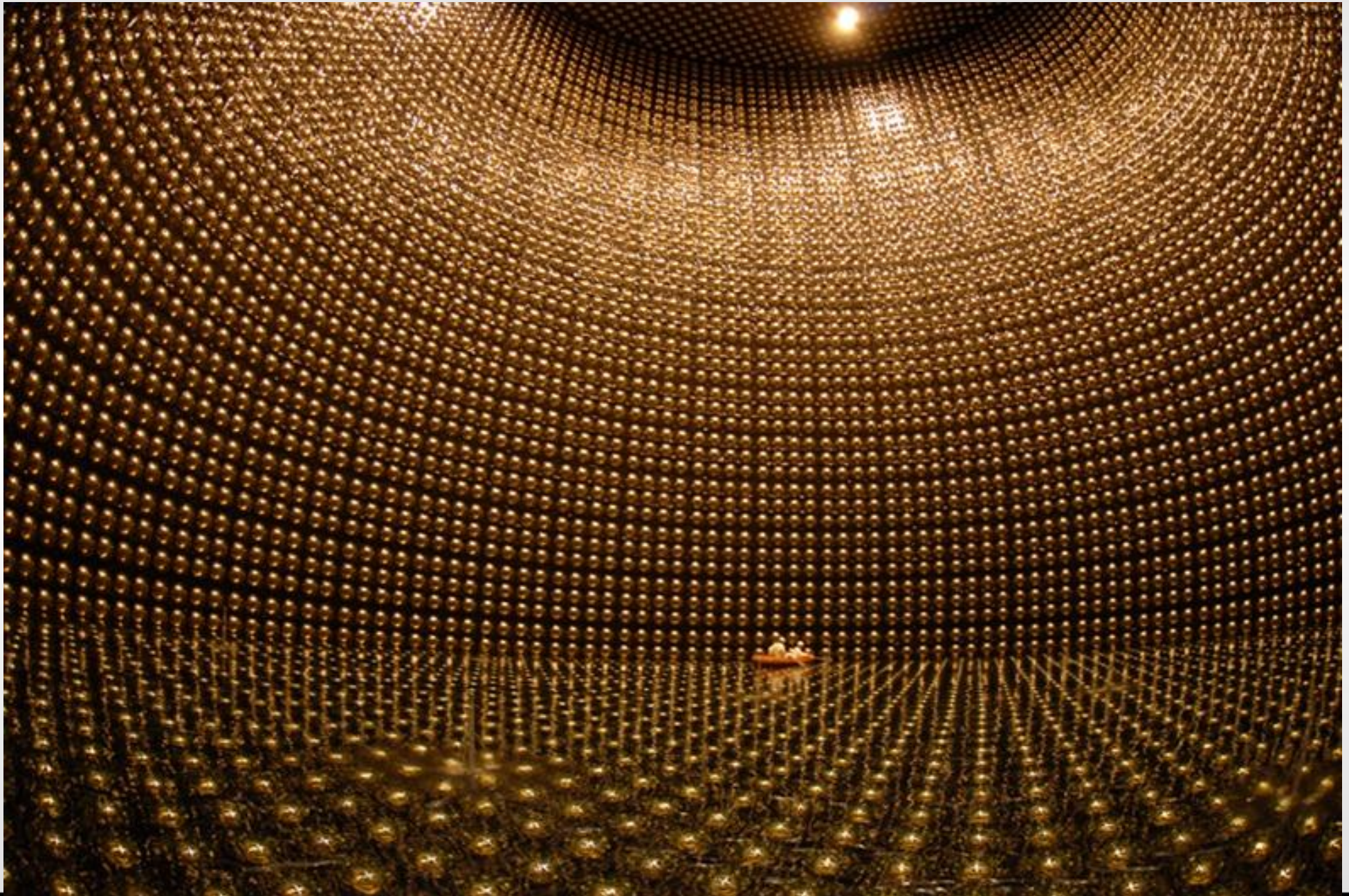


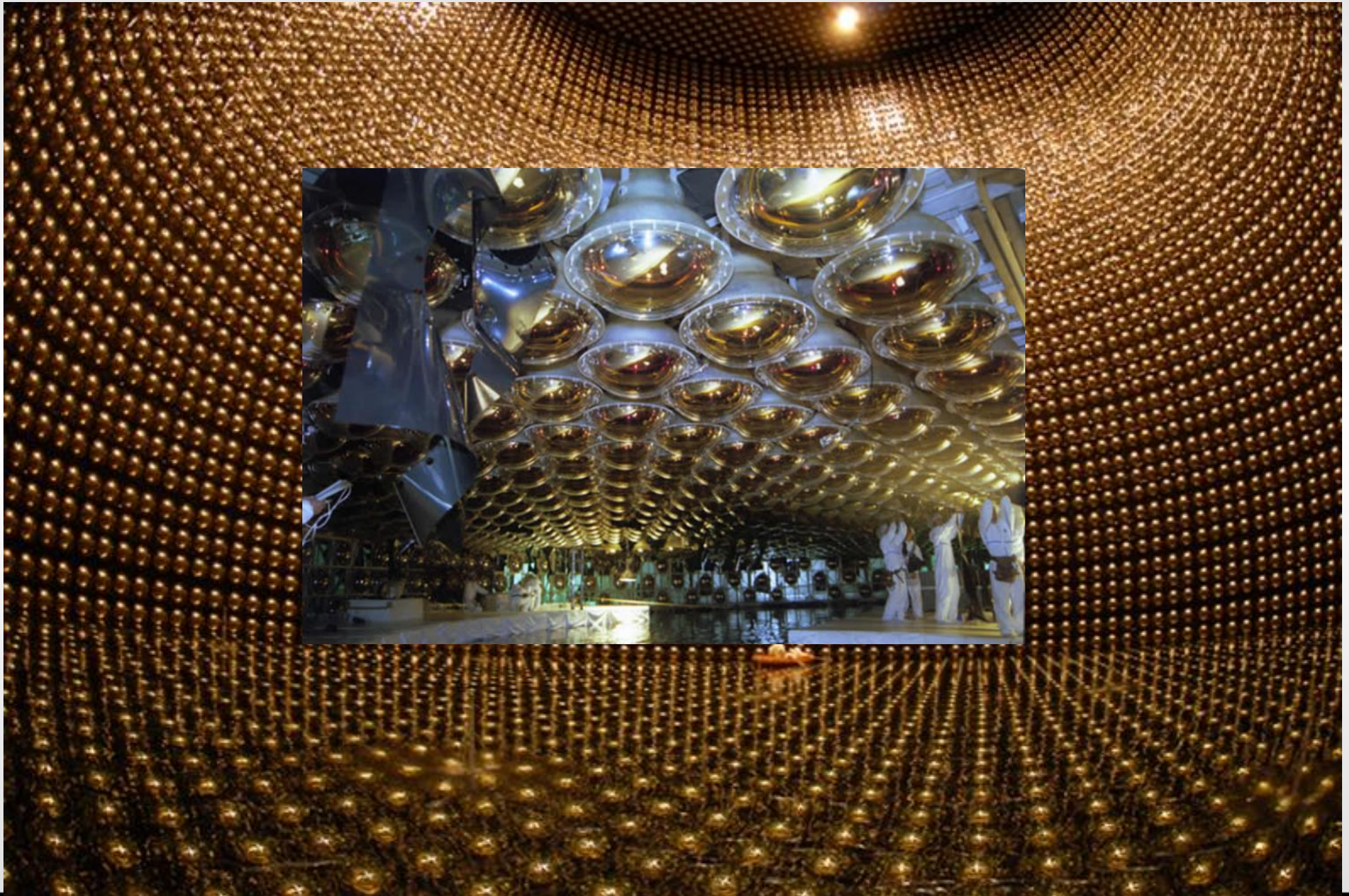
- The fluxes of ν_e and $\nu_{\mu+\tau}$ can be determined
- Super-K contribution

Super KamiokaNDE

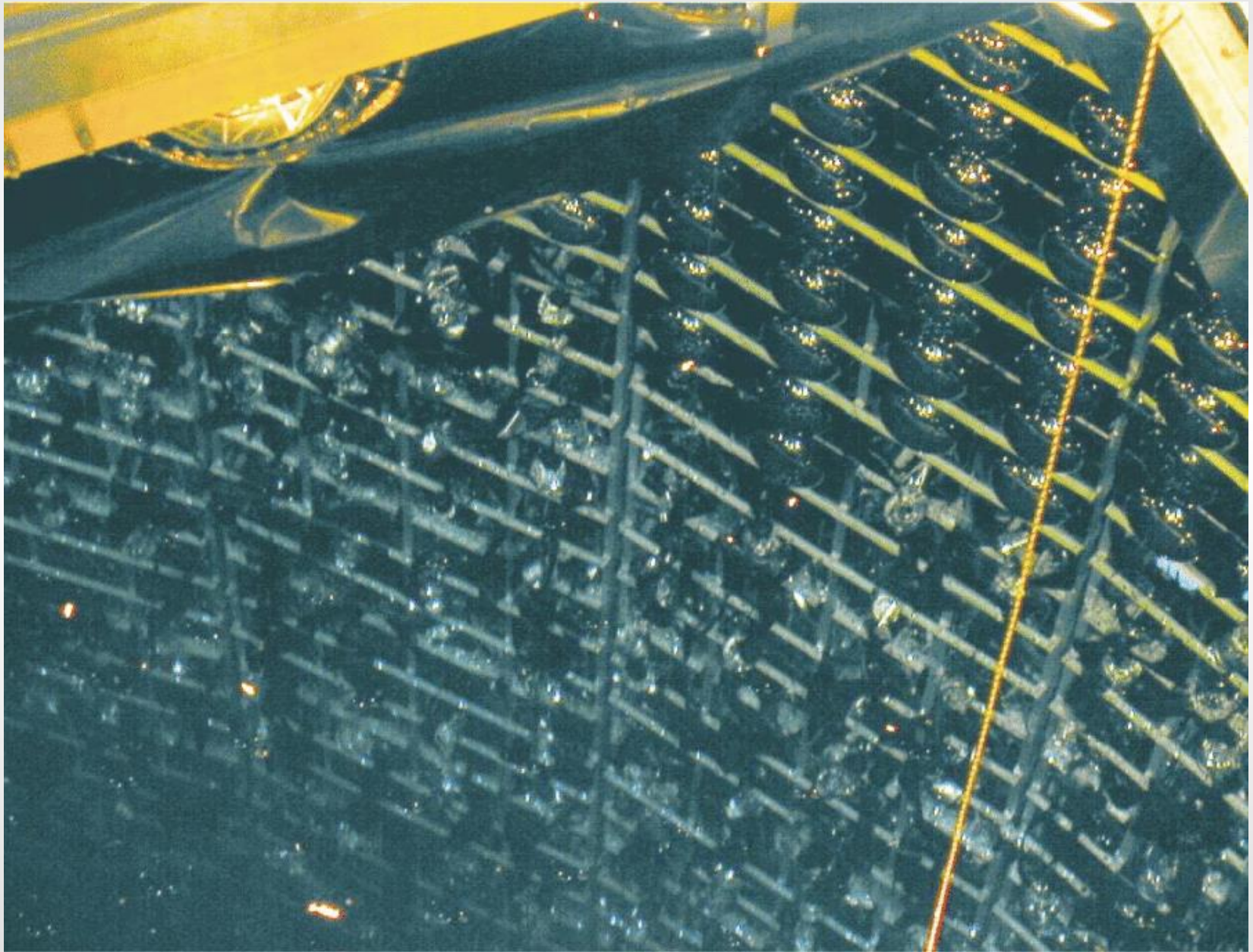
- Successor of KamiokaNDE (Kamioka Neutron Decay Experiment)
 - 1000 m underground in the Mozumi Mine
 - 50000 t of ultrapure water
 - ID: 11146 PMTs 50 cm
 - OD: 1885 20 cm





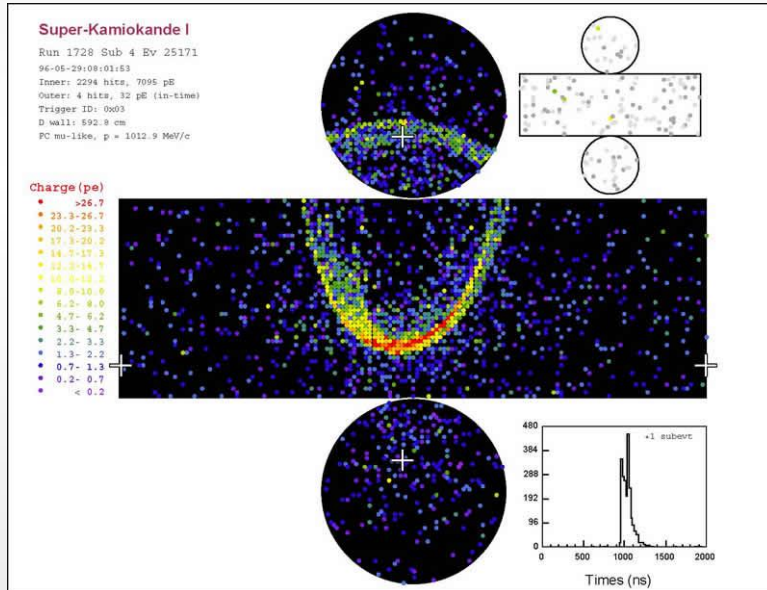


Famous accident 2001

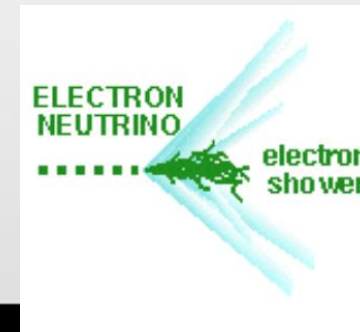
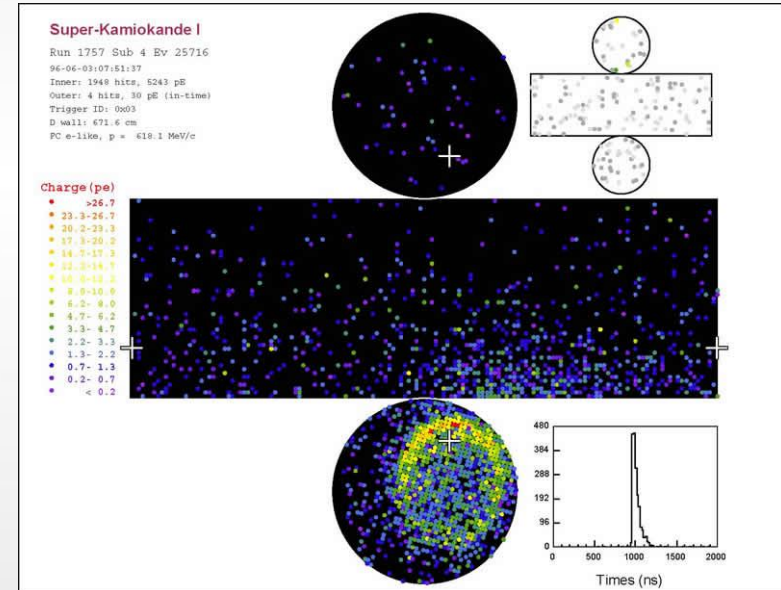


Super K events

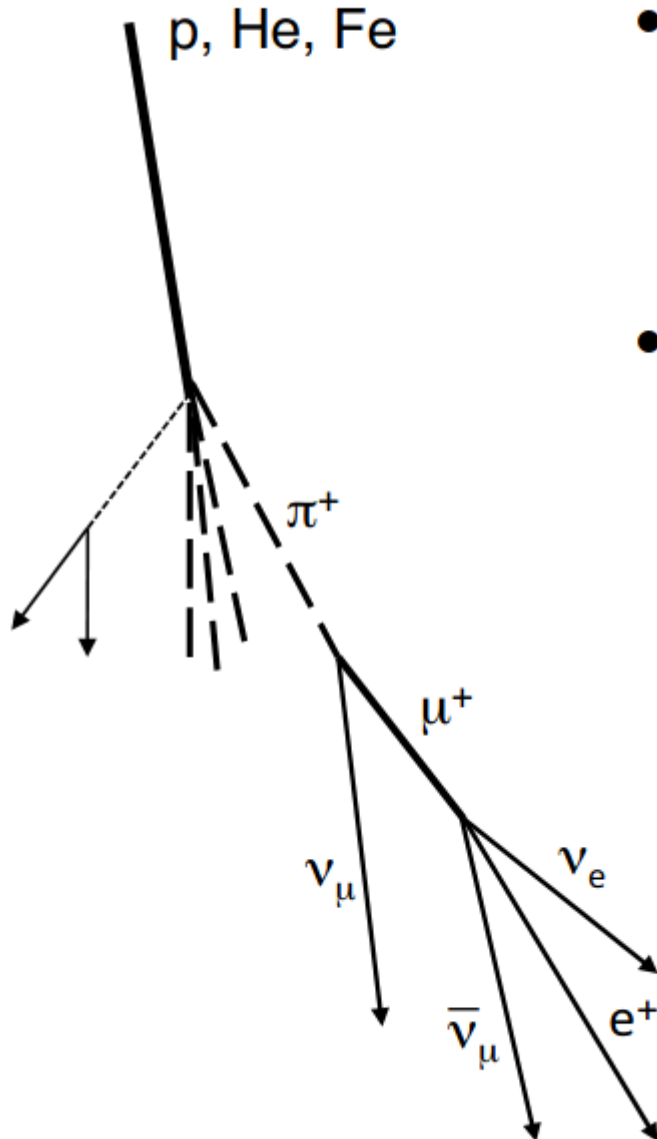
Cherenkov ring by a muon from neutrino
1GeV moun



Electron neutrino event. 0.6 GeV
An electron neutrino scatters an electron in water. The emitted electron generates a electromagnetic shower, leading to the fuzzy edge of the Cherenkov ring



Atmospheric neutrino production



- High-energy cosmic rays collide with nitrogen in the Earth's atmosphere

$$p + N \rightarrow p + N' + \pi, K \dots$$
- Charged mesons decay into neutrinos:

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

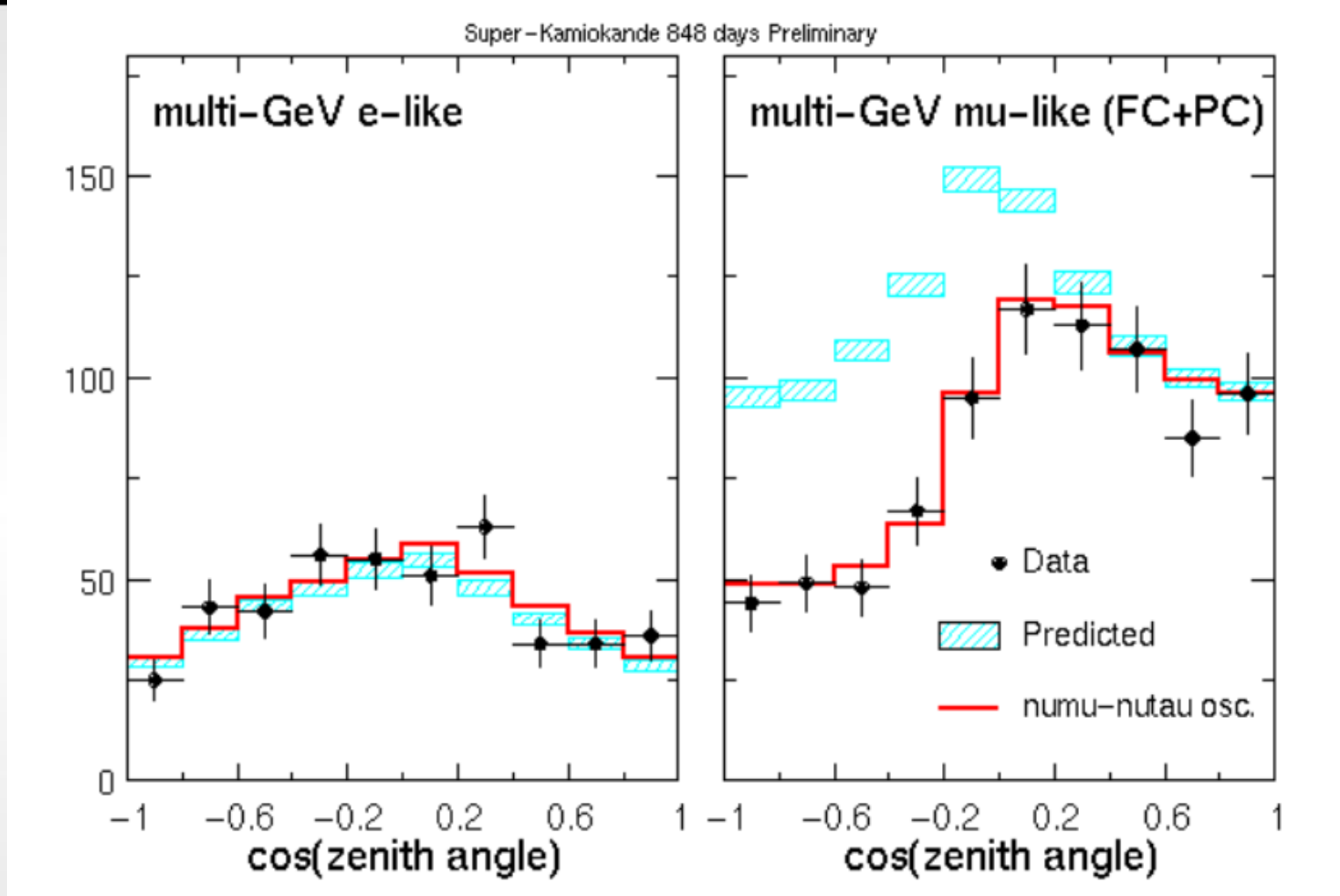
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\pi^-, K^- \rightarrow \mu^- \bar{\nu}_\mu$$

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

→ At GeV energies, the expected ratio of ν_μ to ν_e is $R_{\text{th}} = 2$.

Observed angular distributions

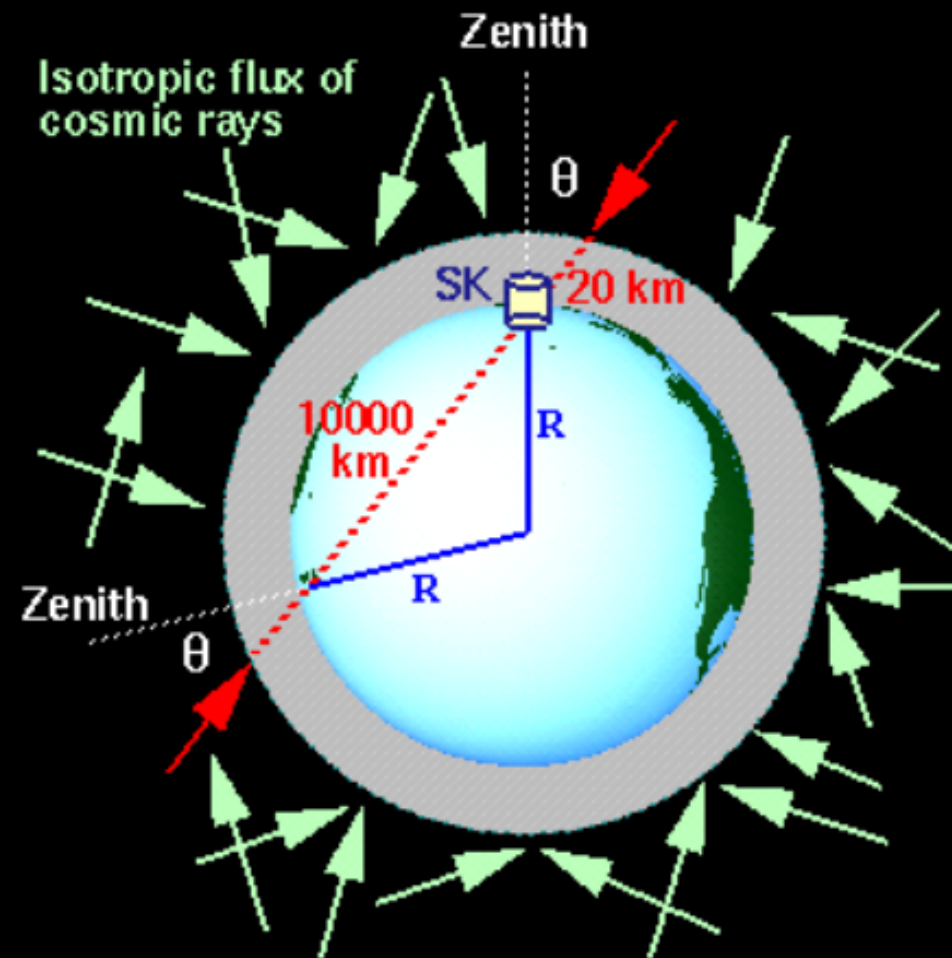


ν_e as expected

ν_μ something is going on here

Travel distance of Atmospheric ν s

- This does fit the expectation for ν oscillations!
- For current best values, oscillation lengths are
 $L_{23} \approx 10^3 \text{ km @ } 1 \text{ GeV}$
 $L_{12} \approx 3 \times 10^4 \text{ km}$
- For ν_μ **from above**,
baseline $< L_{12}, L_{23}$
 \rightarrow no oscillation
- For ν_μ **from below**,
 $L_{23} < \text{baseline} < L_{12}$
 **\rightarrow no $\nu_\mu \rightarrow \nu_e$ oscillations,
but $\nu_\mu \rightarrow \nu_\tau$!**



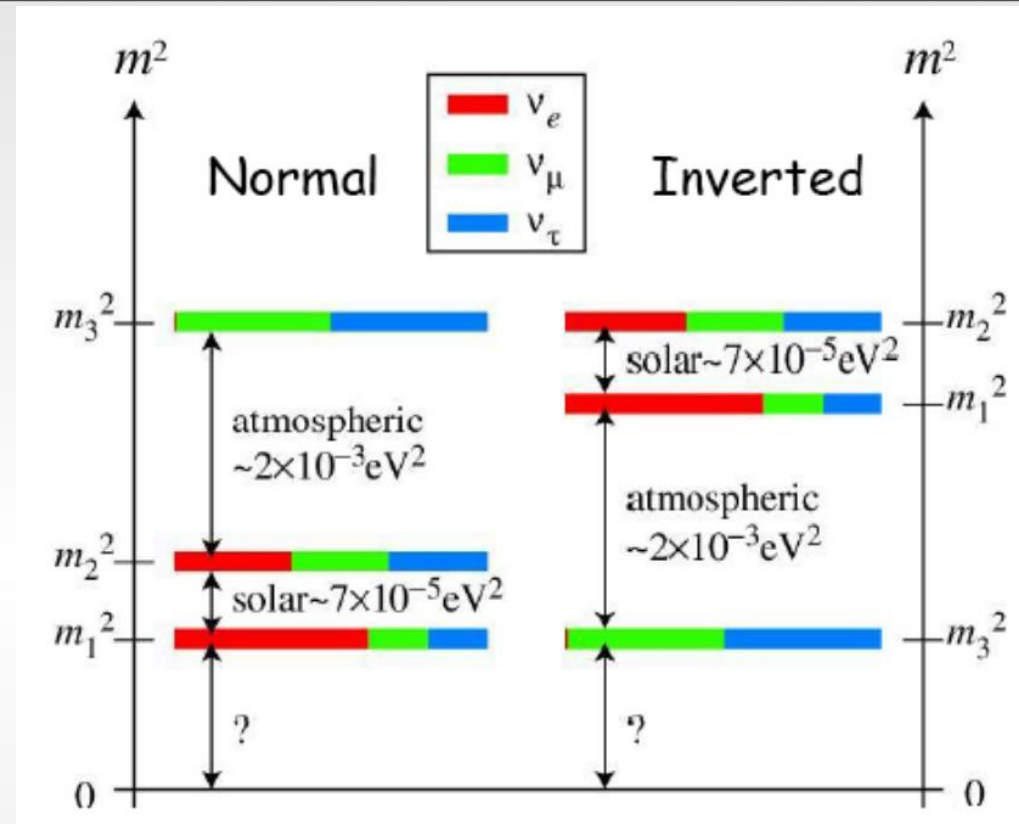
Current best-fit values

Parameter	Value		3σ range
θ_{12}	33.6°	Solar(Reactor + accelerator)	$30.1^\circ - 36.8^\circ$
θ_{23}	38.4°	Atmos.	$35.1^\circ - 53.0^\circ$
θ_{13}	8.9°	Reactor anti ν_e disappearance	$7.5^\circ - 10.2^\circ$
δ_{CP}	1.08π		
Δm_{12}^2	$7.54 \cdot 10^{-5} \text{ eV}^2$	solar	$(6.99 - 8.18) \cdot 10^{-5} \text{ eV}^2$
$ \Delta m_{23}^2 $	$2.43 \cdot 10^{-3} \text{ eV}^2$	Atmos.	$(2.19 - 2.62) \cdot 10^{-3} \text{ eV}^2$
$ \Delta m_{13}^2 $	$\Delta m_{12}^2 \pm \Delta m_{23}^2 \approx \Delta m_{23}^2 $		

- With two exceptions (the CP phase δ and the sign of Δm_{23}^2), all parameters have been measured.

Unknowns: Neutrino mass, hierarchy, δ_{CP}

- Upper limit (KATRIN) 1.1 eV (90% C.L.)
- We know the m_1 (the one with largest ν_e fraction) is below m_2 (2nd largest ν_e fraction) (from the effects of matter on oscillations in the sun)
- We know $\Delta m_{21}^2 \ll |\Delta m_{31}^2| \simeq |\Delta m_{32}^2|$
- To determine Δm_{31}^2 matter effects when passing through Earth could be used



CP violation can only take place in *appearance* experiments

Look for $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Next time - Part 2

- Astrophysical neutrinos and experiments.