Neutrino Astrophysics (neutrino astronomy?)

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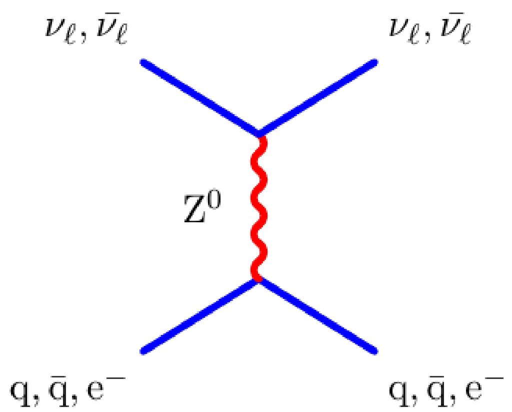
Lecture outline

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

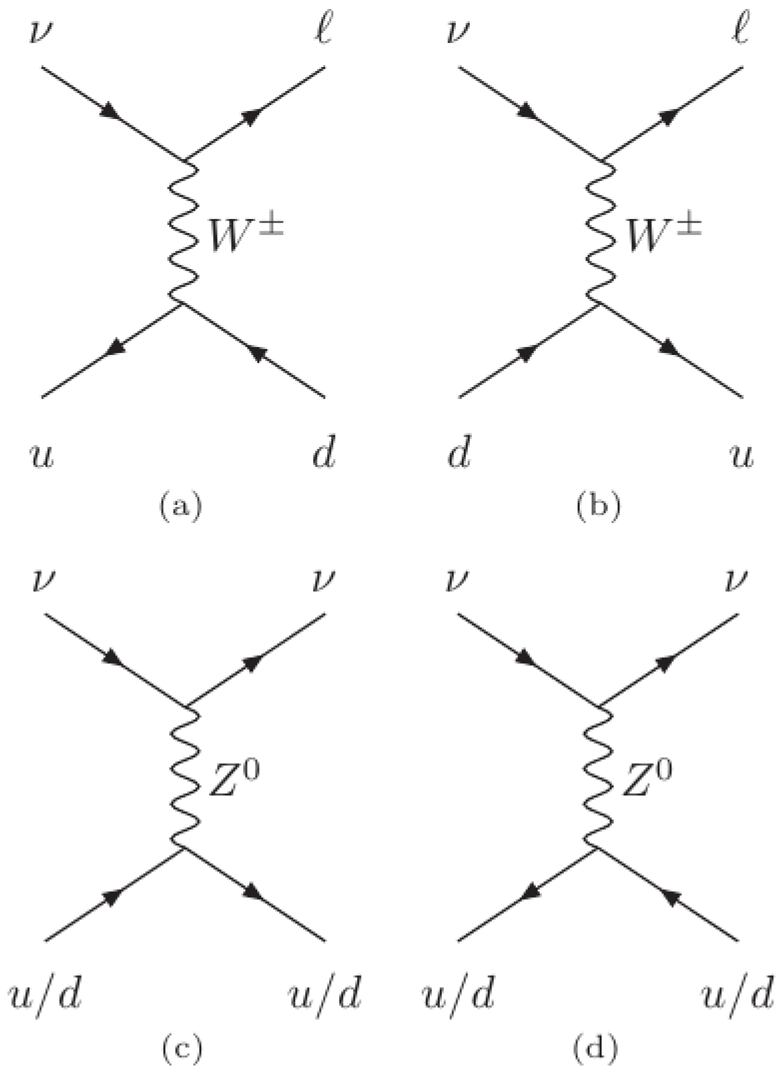
Neutrinos

- Very small mass (at lest 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



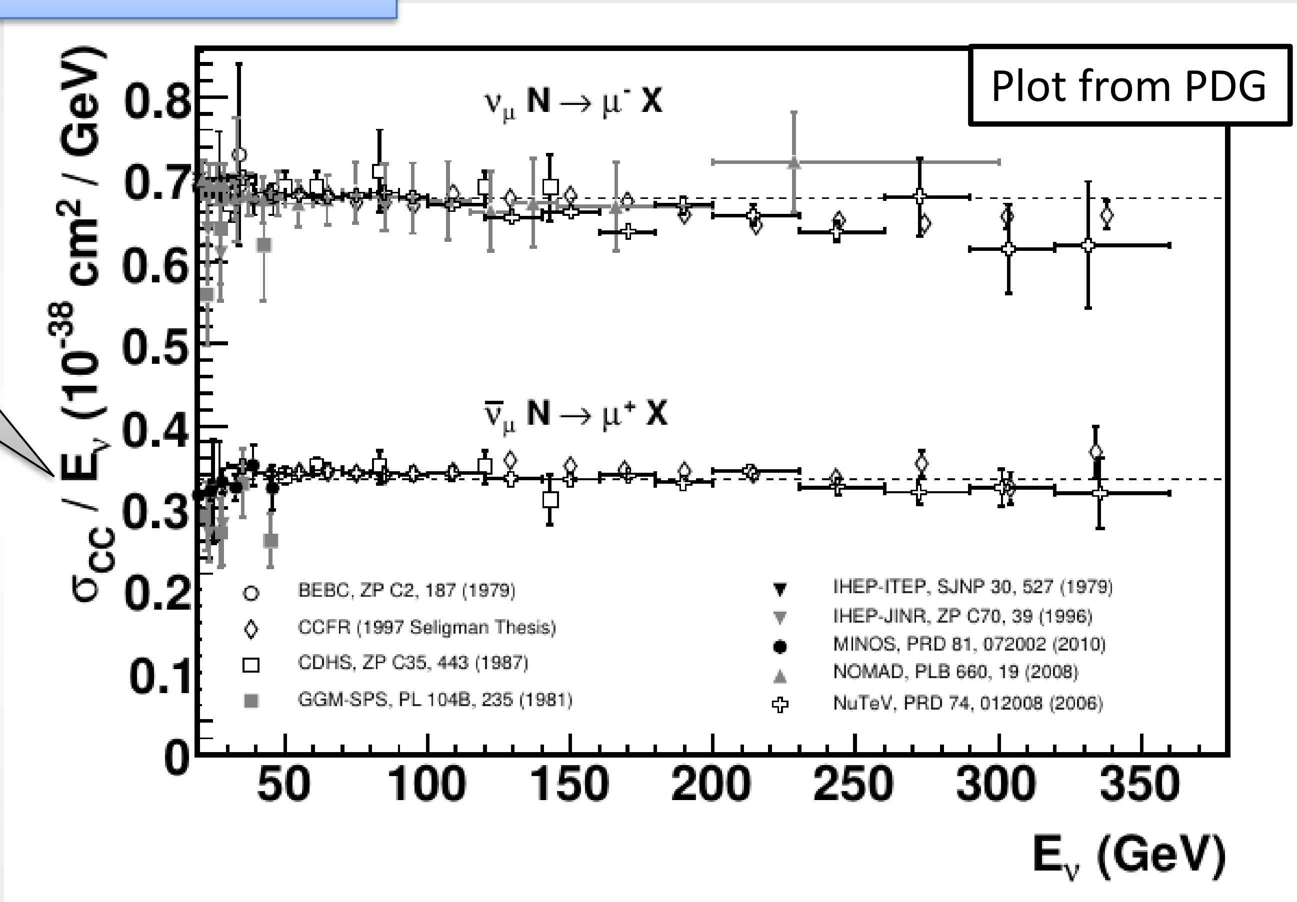
Feynman diagrams for neutral current (NC) neutrino interactions.



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

Neutrino cross-sections

CC interaction on nuclei



Plot from PDG

Notice the scaling!

For comparison
300 GeV muons:

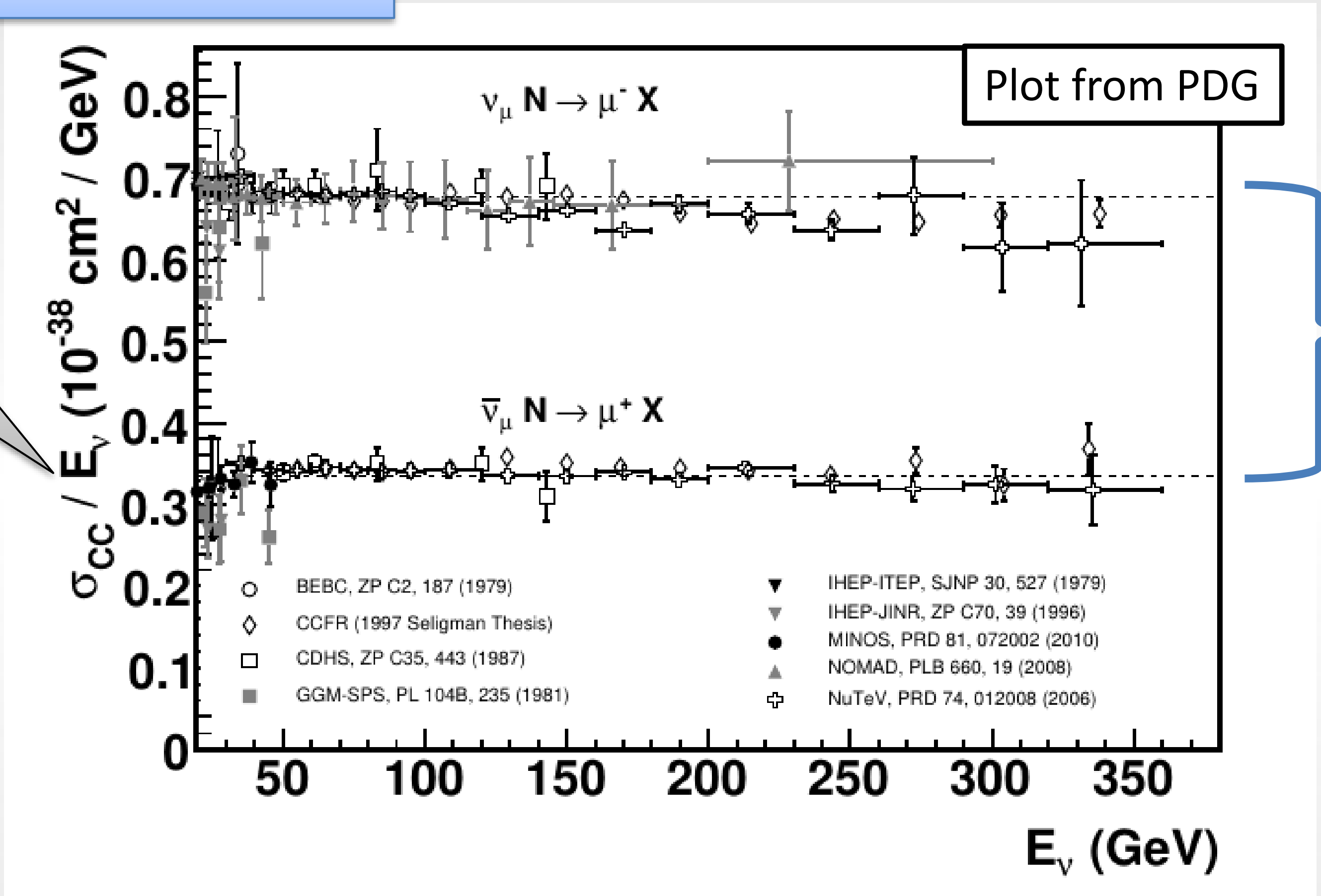
$$\sigma_{\mu N}^{\text{total}} \approx (1-2) \times 10^{-29}\,\text{cm}^2$$

Neutrinos:
$0.5\text{x}10^{-38}$ cm^2 GeV^{-1} * 300 GeV = $1.5\text{x}10^{-36}$ cm^2

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

Neutrino cross-sections

CC interaction on nuclei



Plot from PDG

Notice the scaling!

Why the difference?
BTW: why $\pi^\pm$ decays to $\mu^\pm$ and not $e^\pm$?

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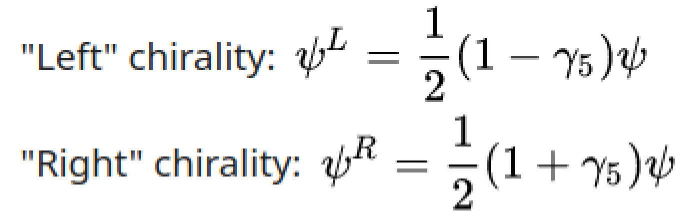
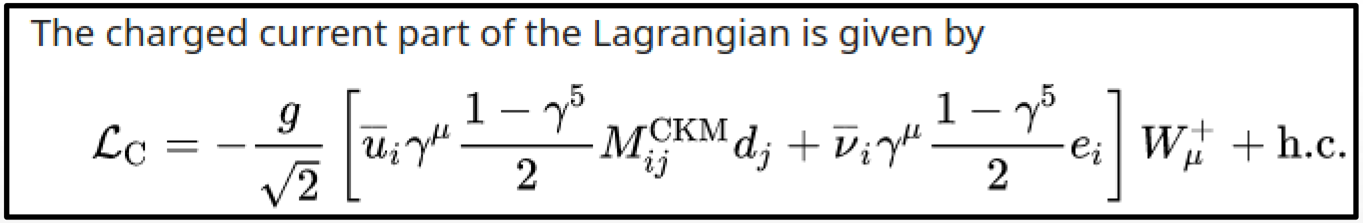
BTW: why $\pi^{\pm}$ decays to $\mu^{\pm}$ and not $e^{\pm}$?

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

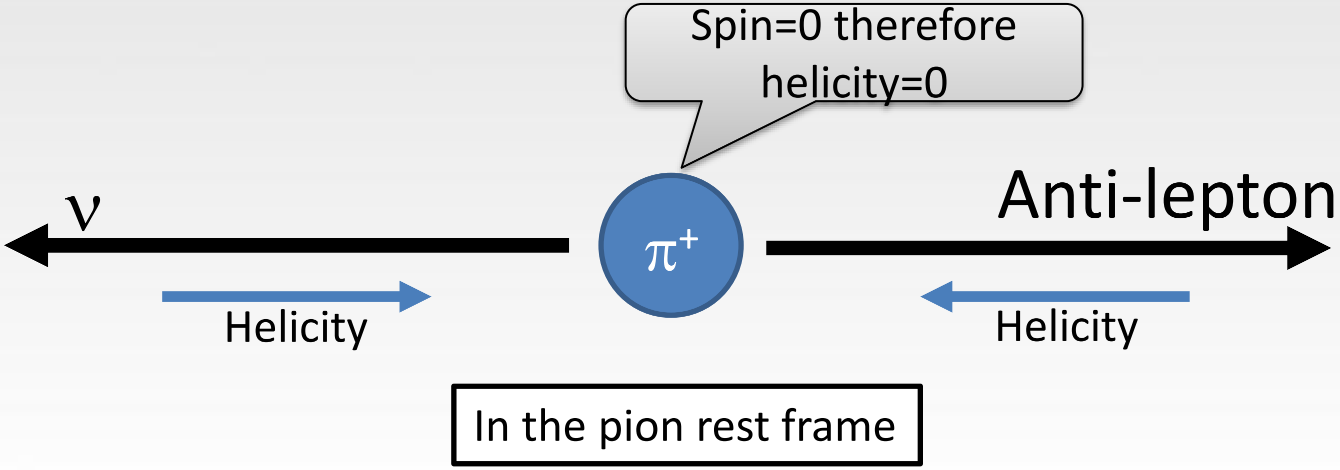


The charged current part of the Lagrangian is given by

$$\mathcal{L}_{\mathrm{C}} = -\frac{g}{\sqrt{2}}\left[\overline{u}_i\gamma^\mu\frac{1-\gamma^5}{2}M^{\mathrm{CKM}}_{ij}d_j + \overline{\nu}_i\gamma^\mu\frac{1-\gamma^5}{2}e_i\right]W^+_\mu + \mathrm{h.c.}$$

- 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 $\pi^\pm$ decays to $\mu^\pm$ and not $e^\pm$?



Spin=0 therefore helicity=0

ν

π^+

Anti-lepton

Helicity

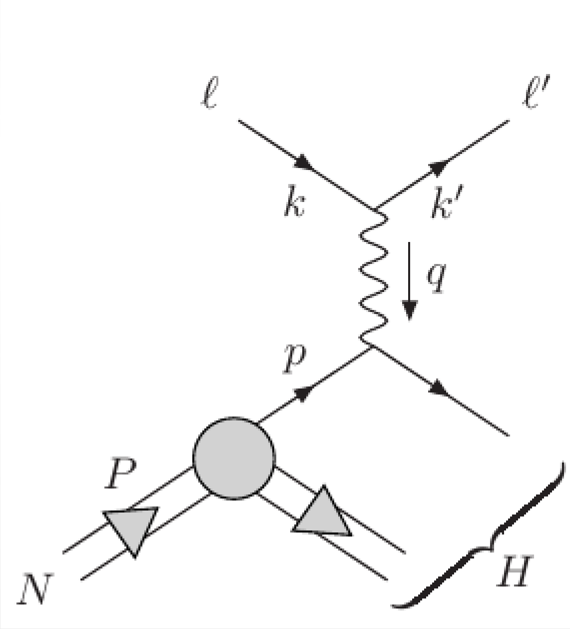
Helicity

In the pion rest frame

- The neutrino is close to massless → travels close to c → 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 → muon is slower → the needed (=left-handed)(=opposite to the particle chirality) component of the helicity is larger → 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.



$$s \equiv (P+k)^2 \qquad t \equiv q^2 \equiv -Q^2$$

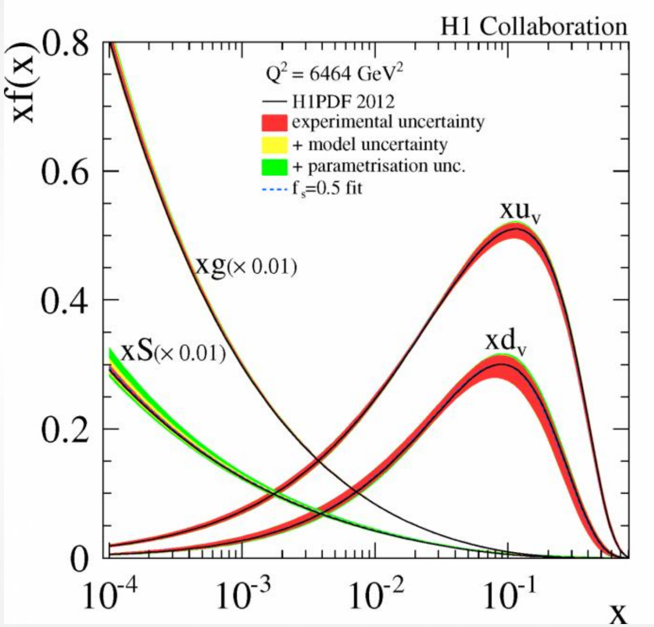
$$M^2 \equiv P^2 \qquad W^2 \equiv (P+q)^2$$

$$x \equiv \frac{Q^2}{2\,q \cdot P} \qquad y \equiv \frac{q \cdot P}{k \cdot P}$$

(Bjorken – x) (inelasticity)

$$Q \gg M \qquad W \gg M$$

(deep) (inelastic)



PDF example - proton

x – fraction of the nucleon momentum carried by the parton
y – fraction of the energy transferred to the target nucleon
Q^2 - square of the momentum transferred

* DIS = deep inelastic scattering

Neutrino DIS* helicity suppression

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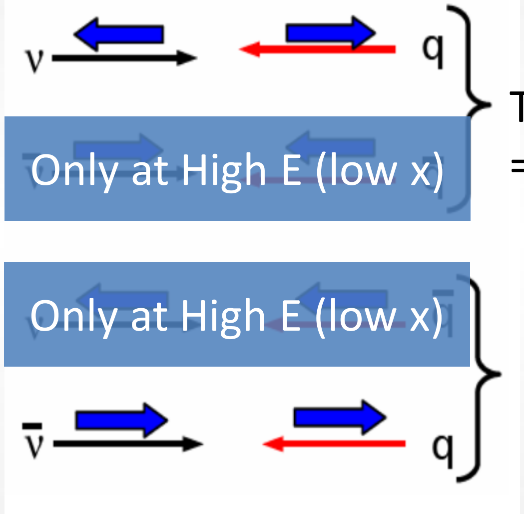
Possible helicity (spin) configurations:



Total spin = 0

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

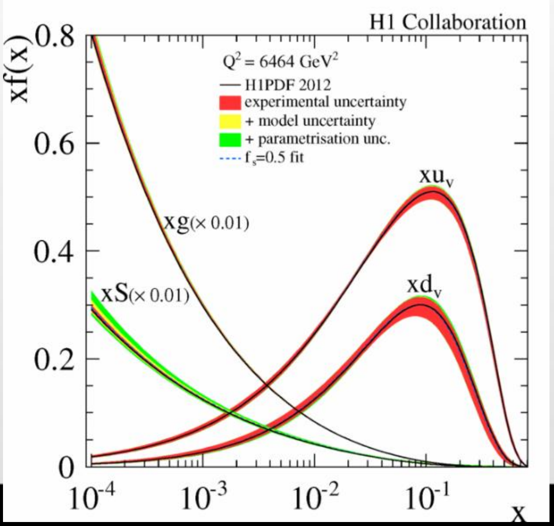
Total spin = 1

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

All Particles have their “preferred” helicities

ν + quarks → tot spin 0 mode

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



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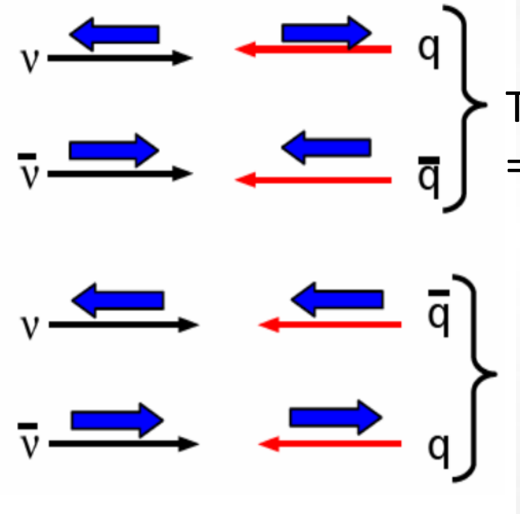

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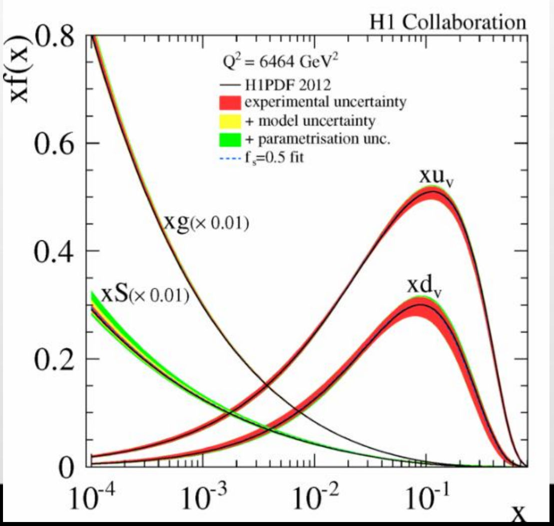
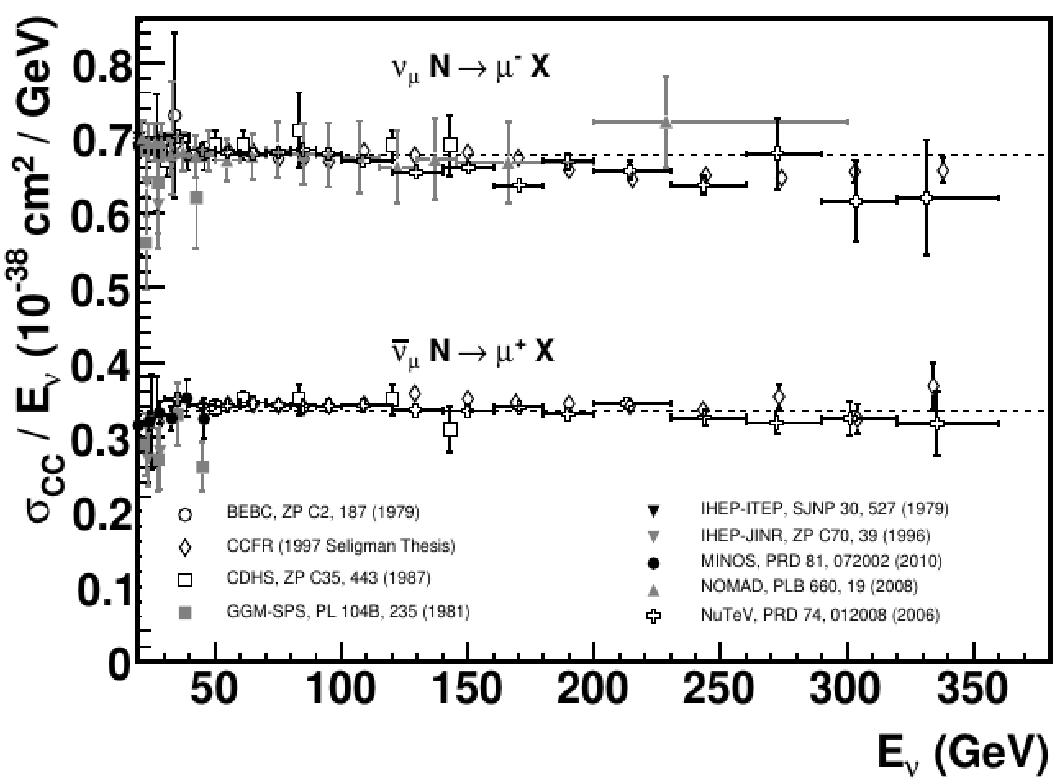
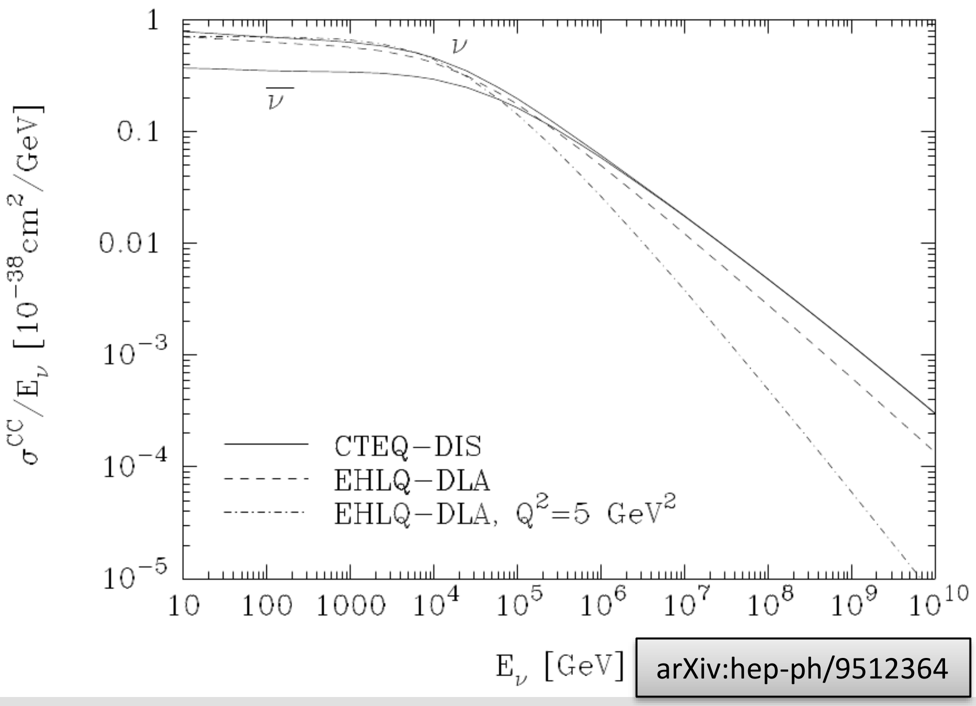


At higher energies

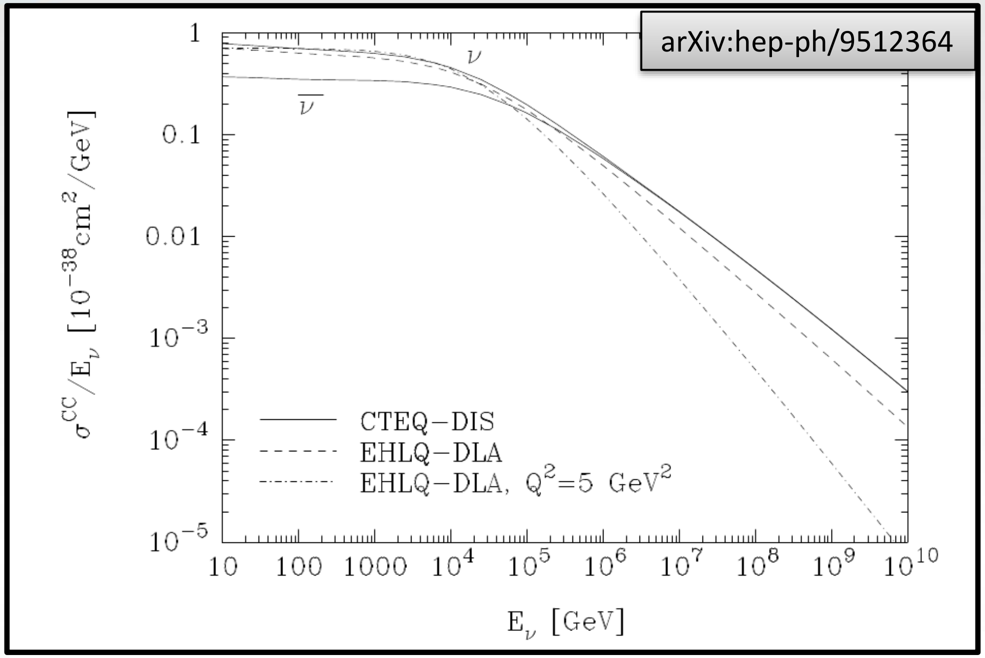


- As the ν energy grows it probes the "quark see"
- Same number of quarks and anti-quarks
- Difference in cross-section vanishes



arXiv:hep-ph/9512364

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

CC differential cross-section

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

Propagator term

No factor for spin 0

The factor for spin 1

Small energies: M^2_W dominates – propagator is energy independent → E_ν 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

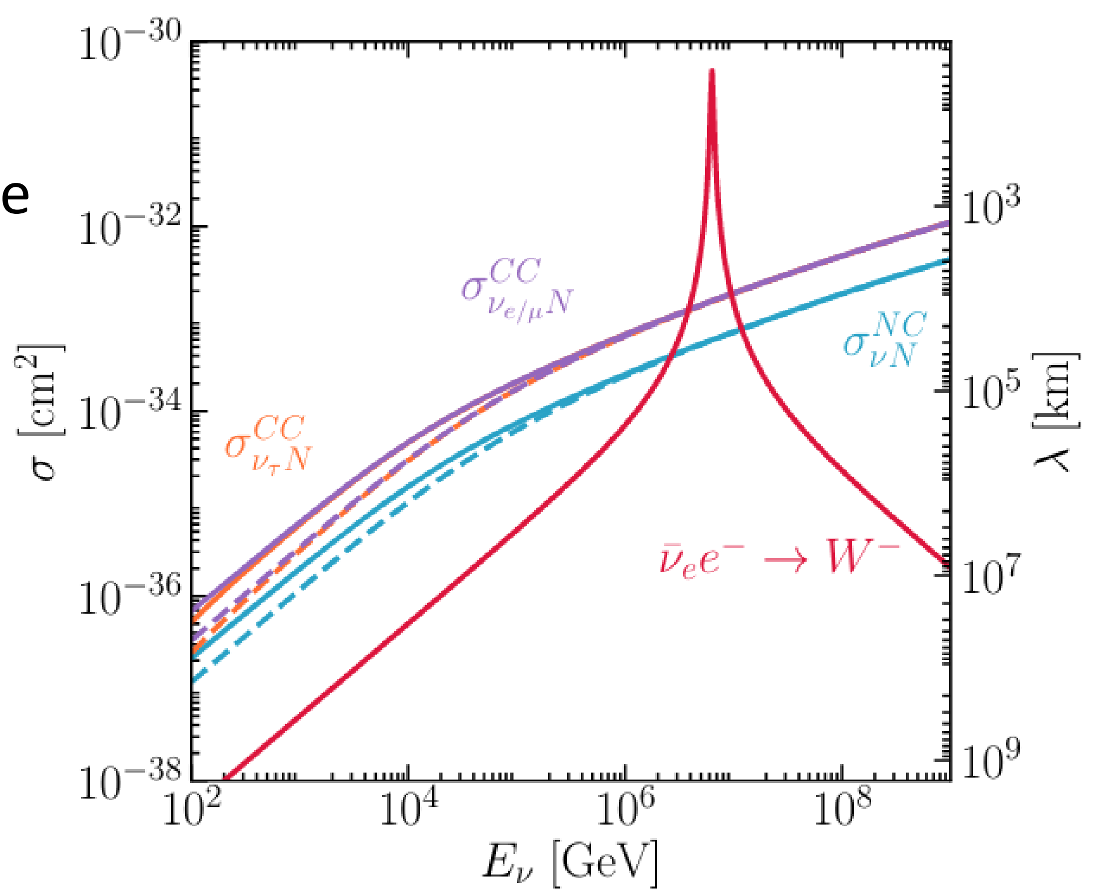

FIG. 1. Cross sections of neutrino scattering on a nucleon or electron. The red curve signifies the case of the GR. The deep inelastic scattering processes include the neutral-current interaction for all neutrino flavors (blue curves), and the charged-current interactions for ν_μ/ν_e (purple curves) 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$^-$

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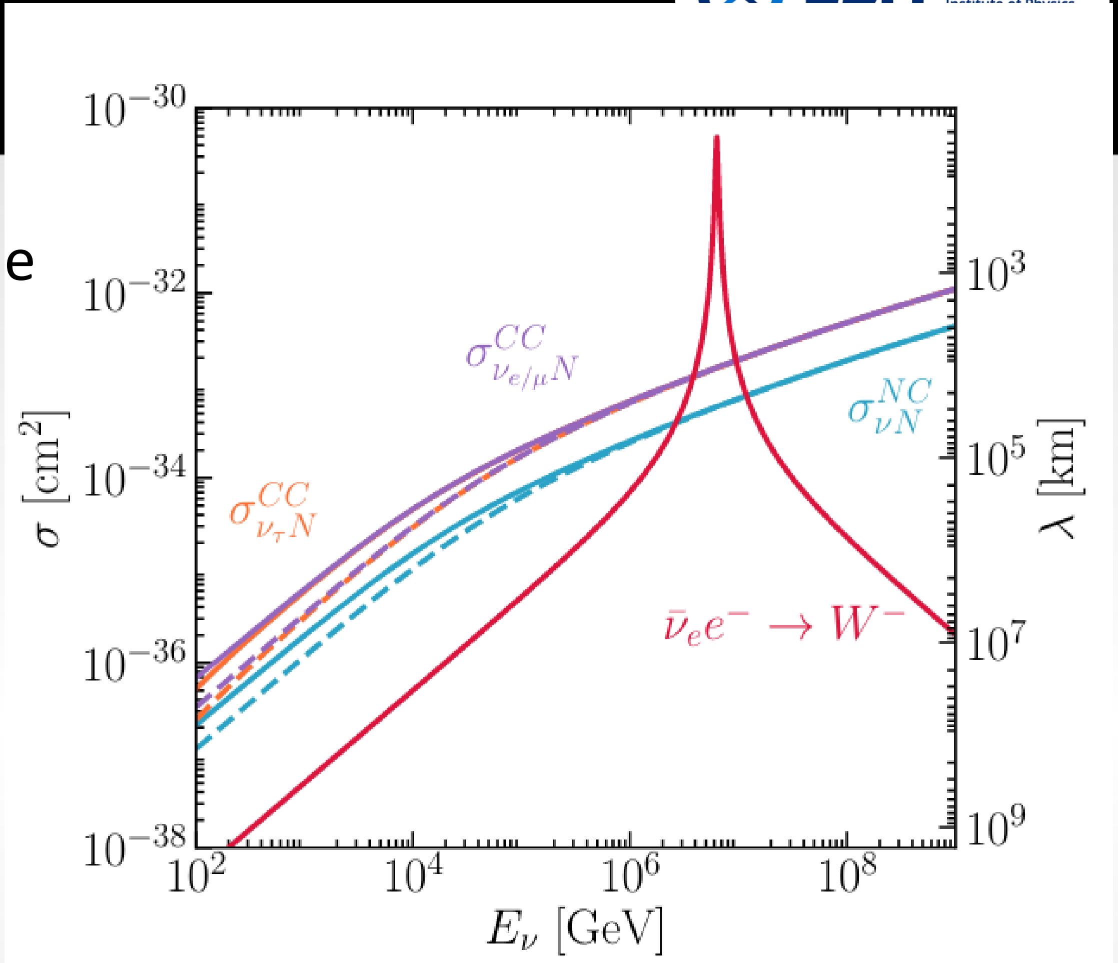

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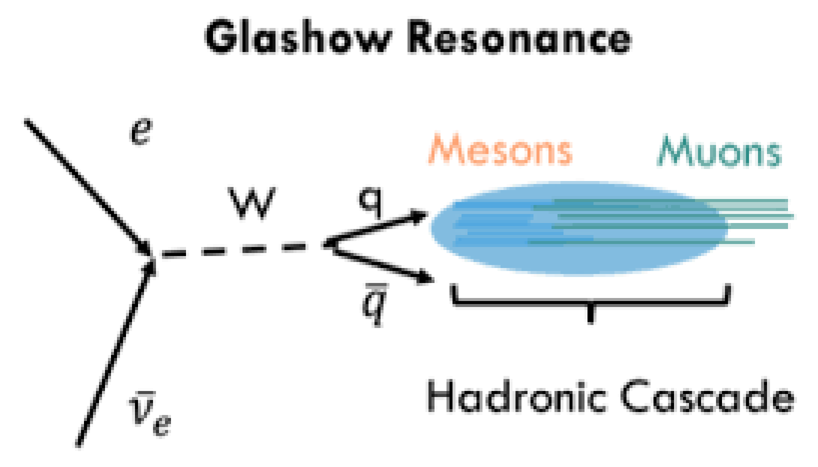
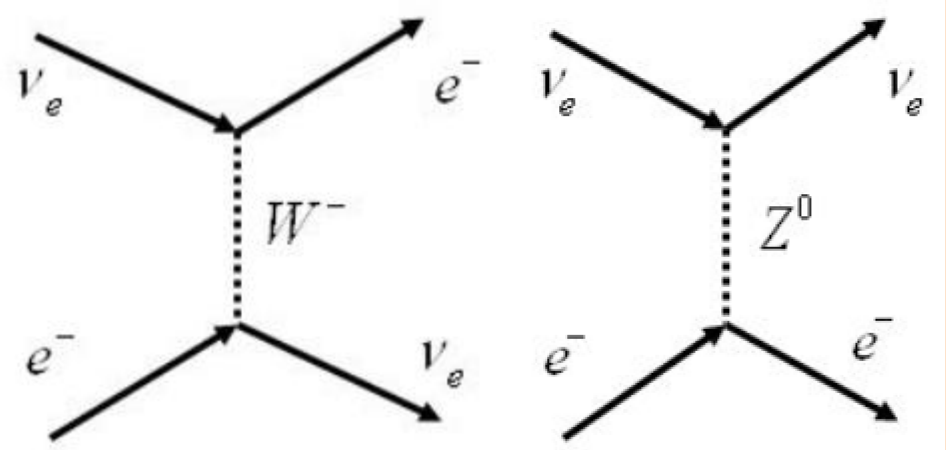
Mean free path = interaction length
Assume water as medium

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



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

- ν scatters away and takes away some momentum



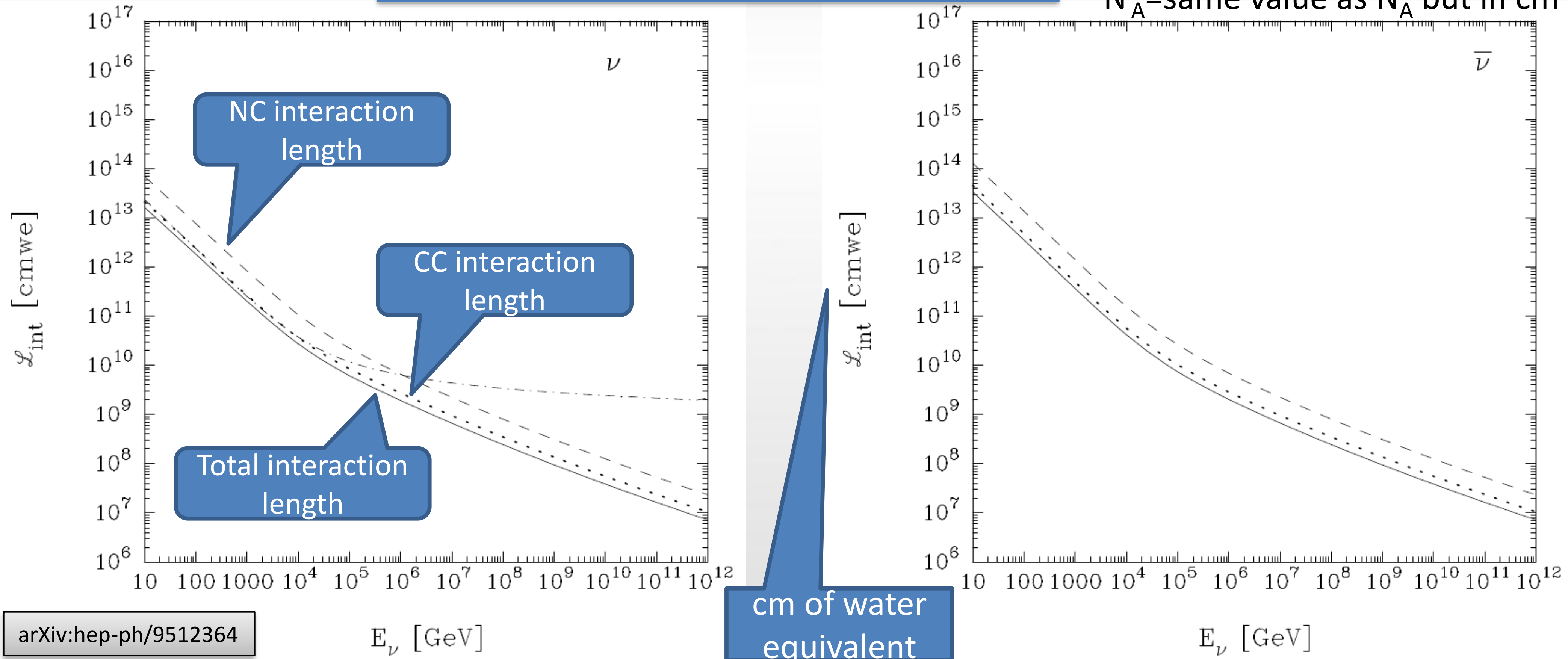
Consequences of ν cross-sections

- 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



NC interaction length

CC interaction length

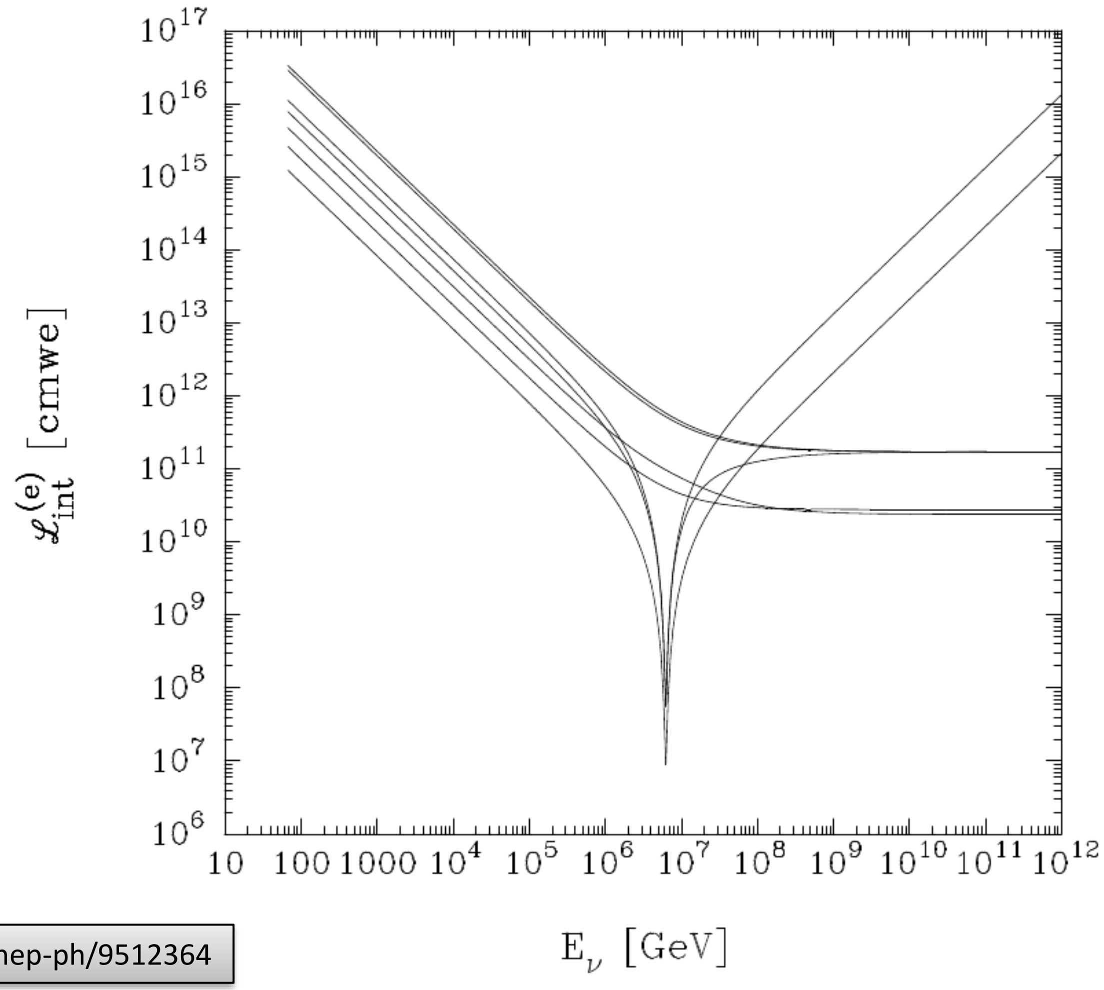
Total interaction length

cm of water equivalent

arXiv:hep-ph/9512364

Consequences of ν cross-sections

For interactions on electrons



arXiv:hep-ph/9512364

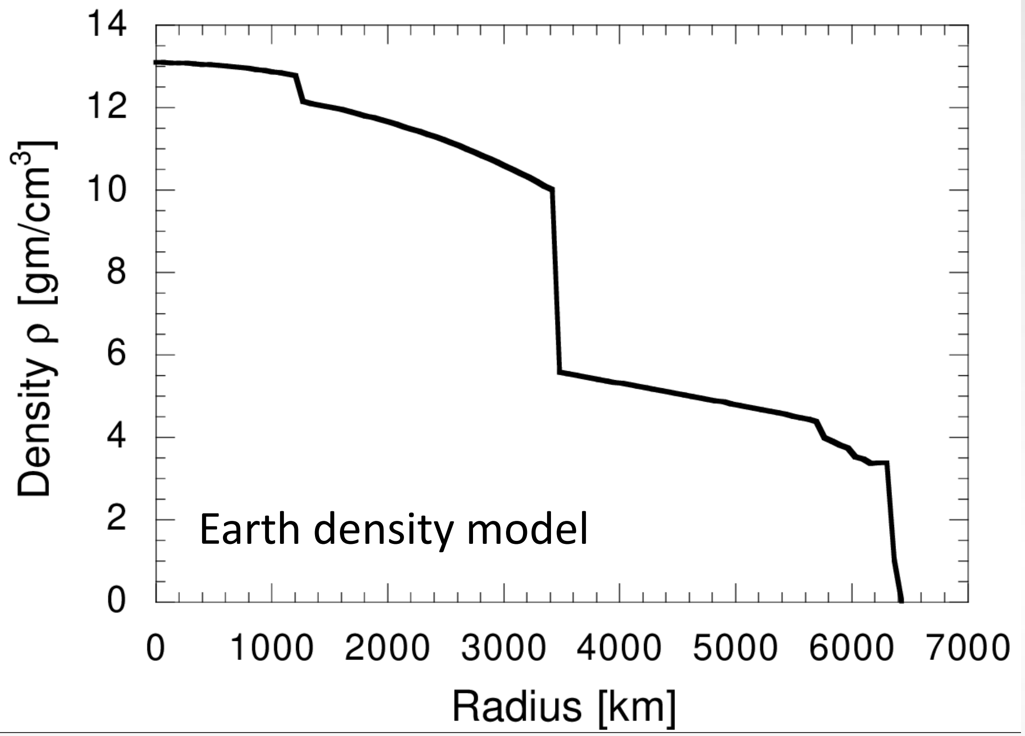
Fig. 13. Interaction lengths for neutrino interactions on electron targets. At low energies, from smallest to largest interaction length, the processes are (i) $\bar{\nu}_e e \rightarrow$ hadrons, (ii) $\nu_\mu e \rightarrow \mu \nu_e$, (iii) $\nu_e e \rightarrow \nu_e e$, (iv) $\bar{\nu}_e e \rightarrow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

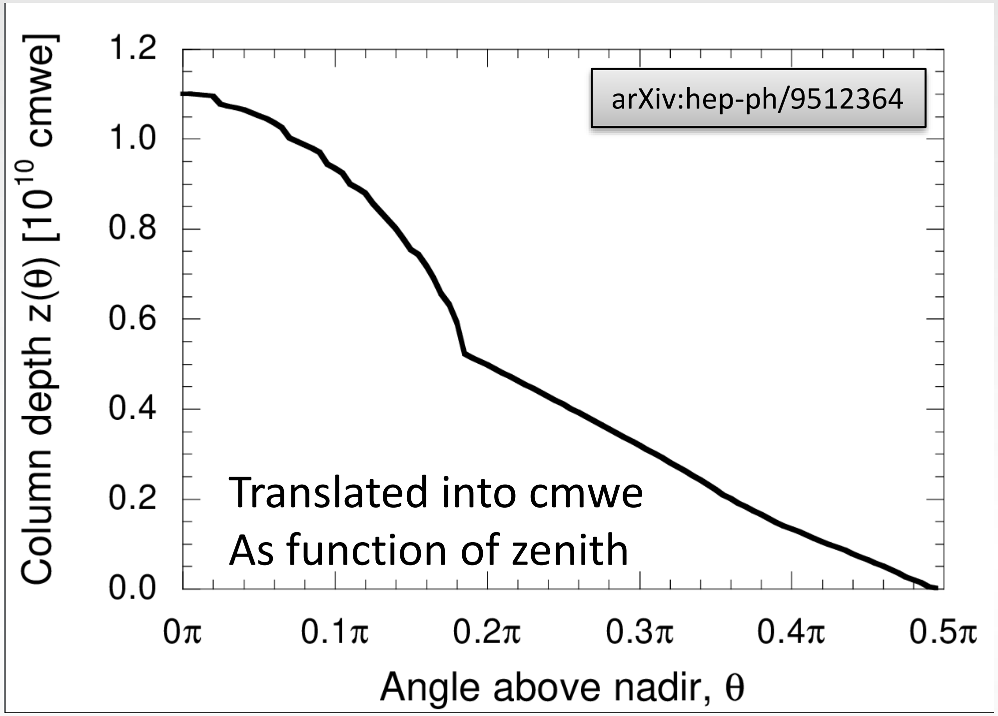
$$\mathcal{L}^{(e)}_{\rm int} = \frac{1}{\sigma_{\nu e}(E_\nu)(10/18)N_{\rm A}} \,,$$

Electrons nucleons ratio for water

Neutrinos passing trough Earth?



Earth density model



arXiv:hep-ph/9512364

Translated into cmwe
As function of zenith

Rough estimate example:

1 TeV neutrino, vertical:

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

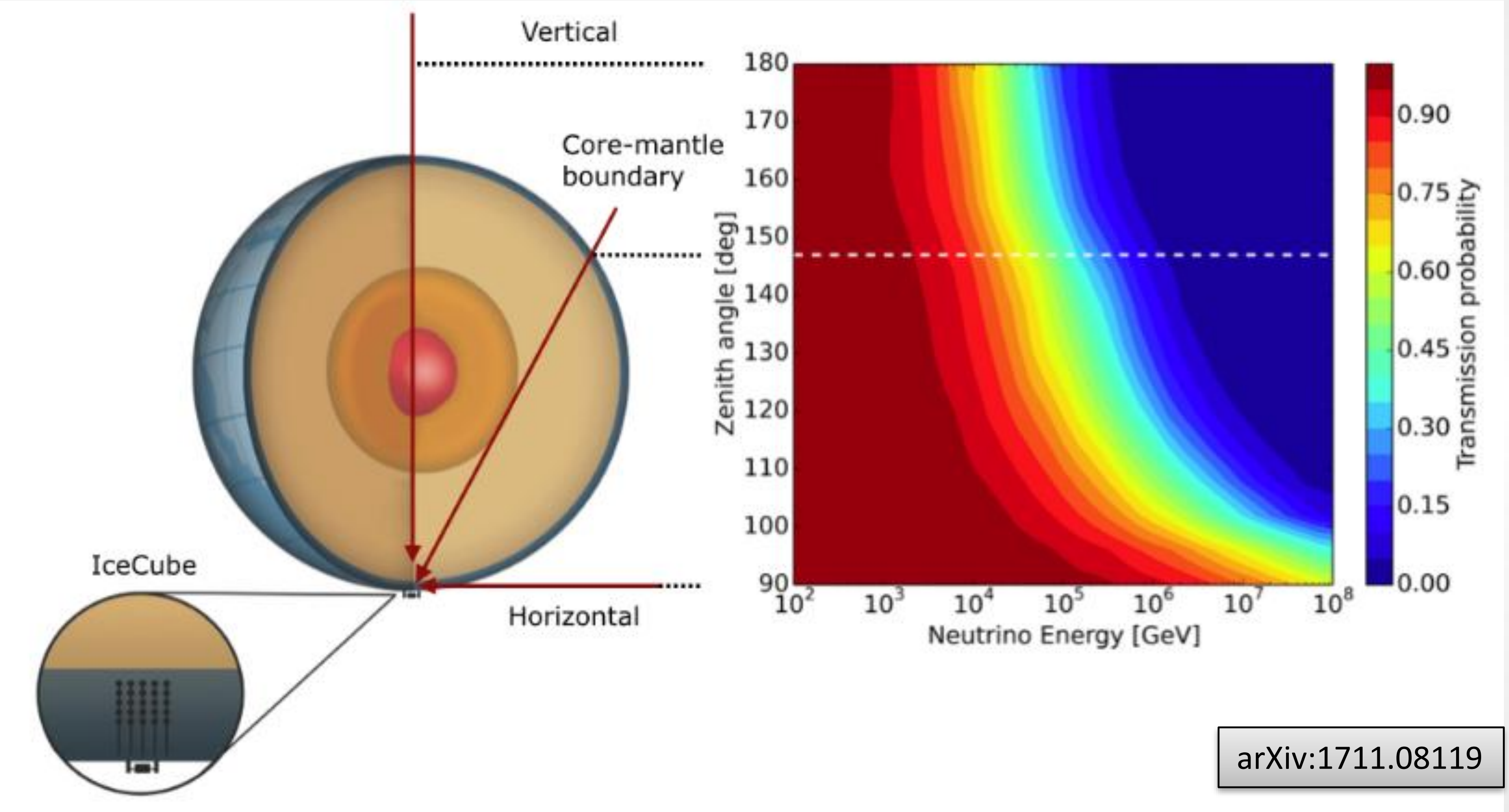
100 TeV neutrino, vertical:

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

ν_e near G resonance, vertical:

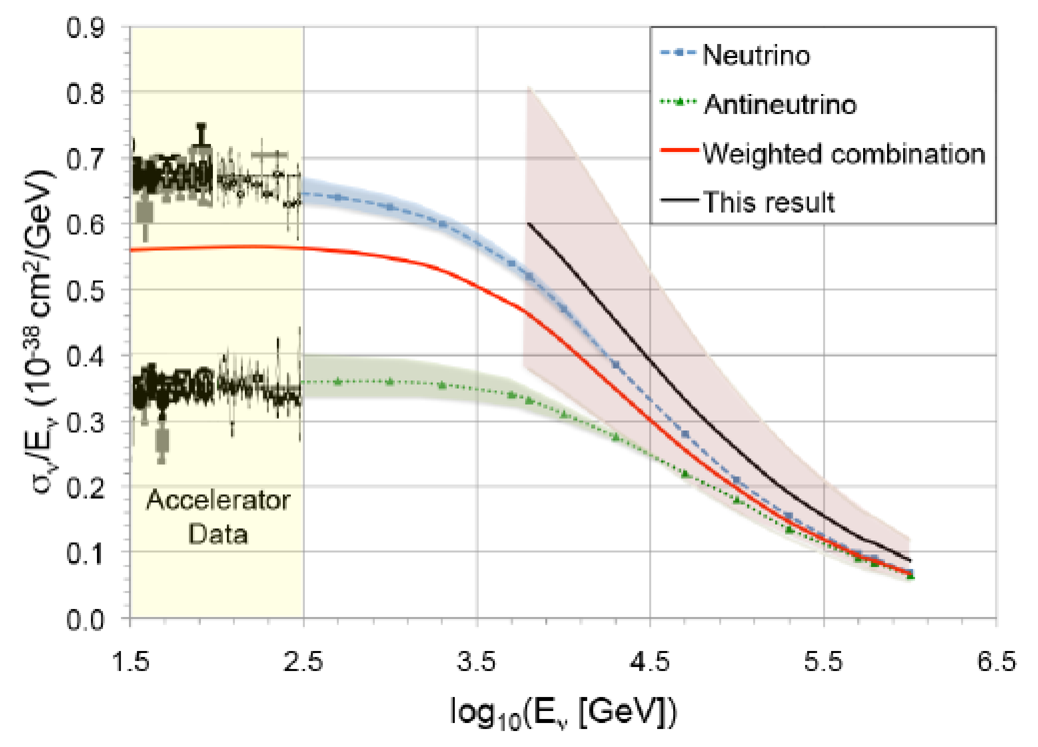
- $L_{int} = 10^8$ cmwe,
- $I/I_0=\exp(-10^{10}/10^8)$=practically 0

Neutrinos passing trough Earth?



arXiv:1711.08119

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:

- $L_{int} = 10^{13}$ 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:

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

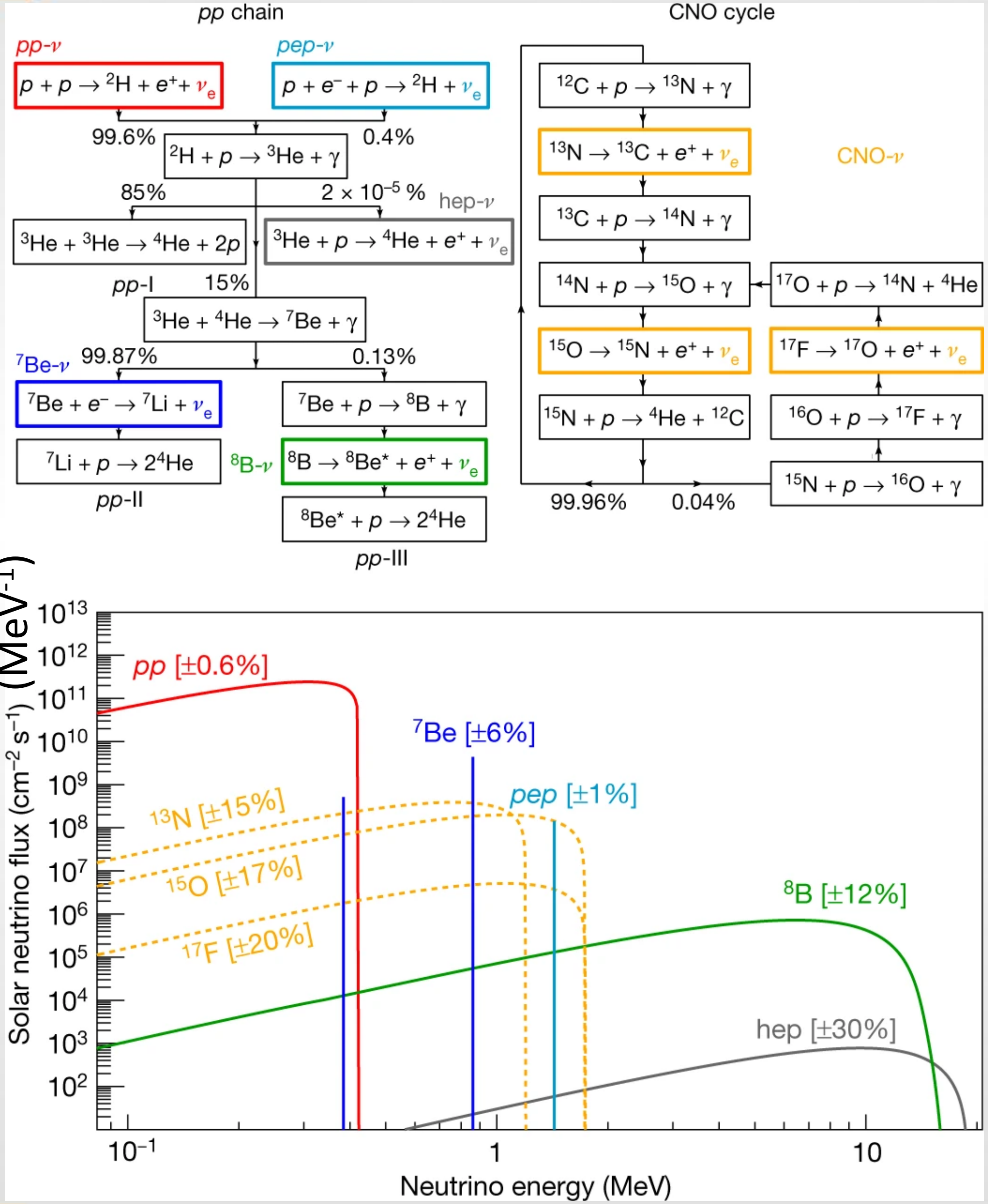
Everything you ever wanted to know about neutrino cross-sections:
From eV to EeV: Neutrino Cross Sections Across Energy Scales
J.A. Formaggio, G.P. Zeller, arXiv:1305.7513

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 νs is very large.

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

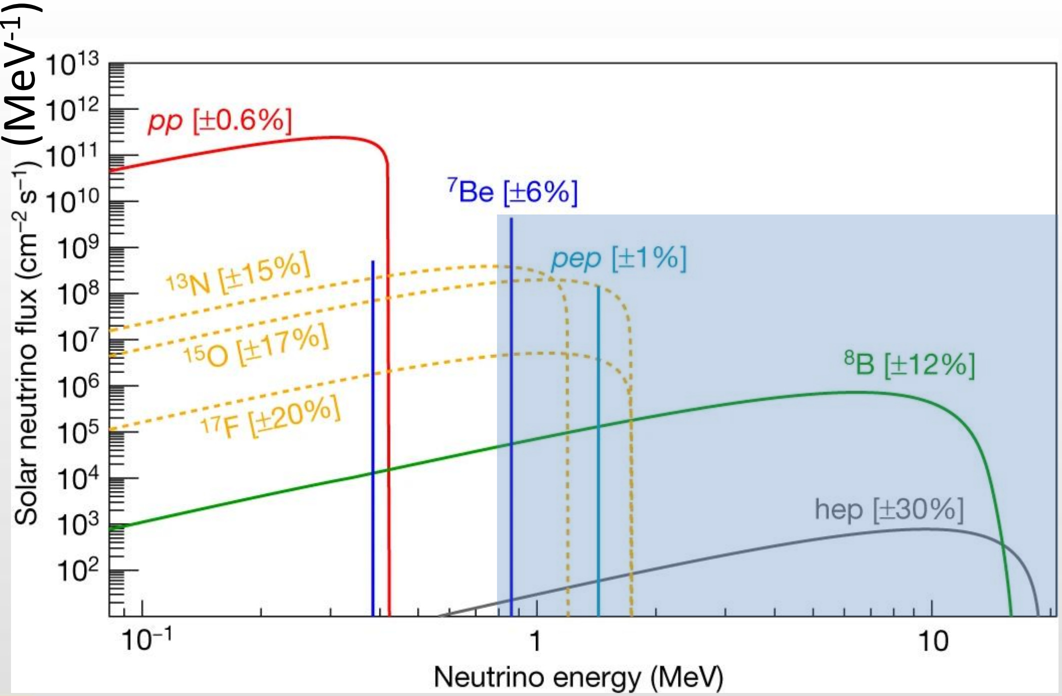
The standard solar model



- 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: $\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar}^+ + e^-$
- Energy threshold: 0.814 MeV
- The main contributors are ^{8}B and ^{7}Be νs



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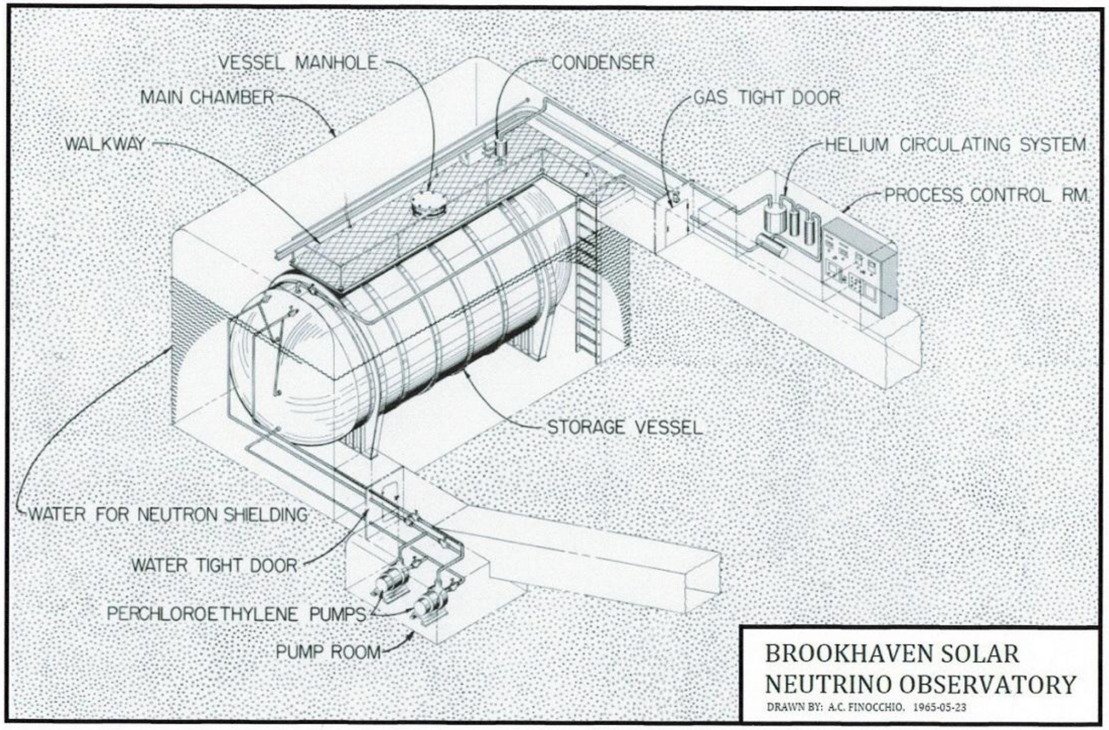
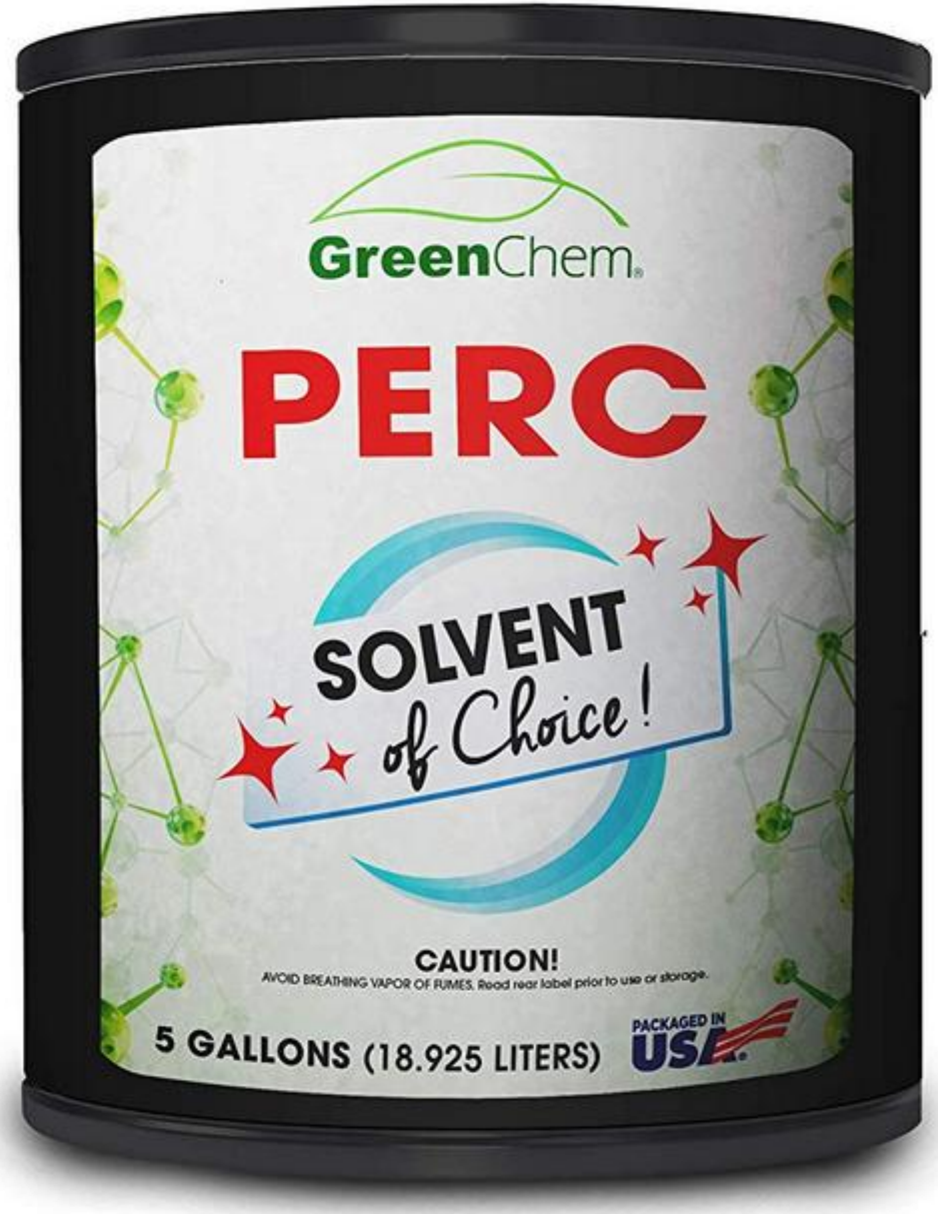


THE HOMESTAKE EXPERIMENT

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

The Homestake experiment



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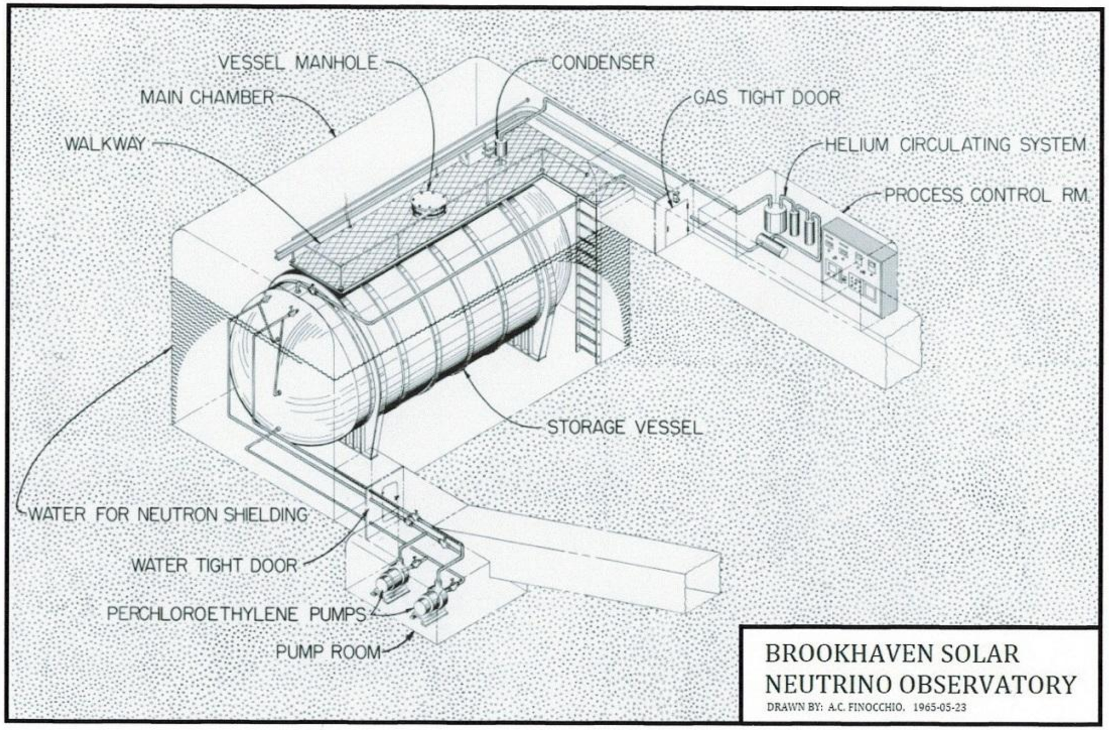

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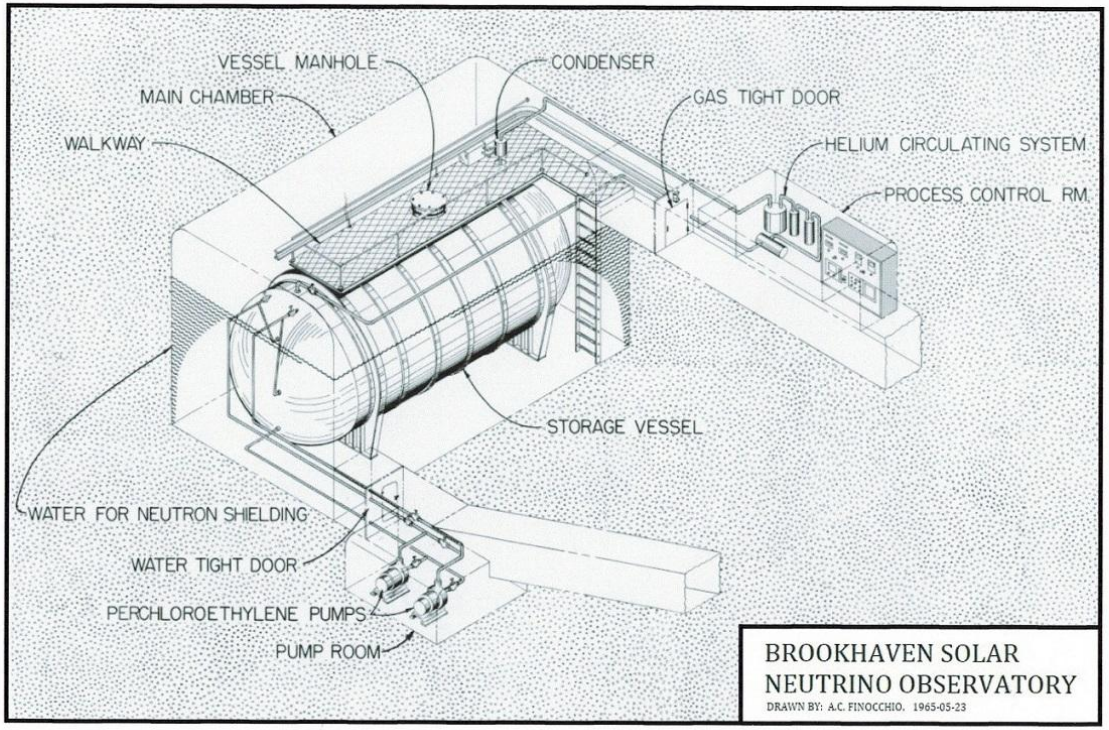
The Homestake experiment

Raymond Davis, Jr.

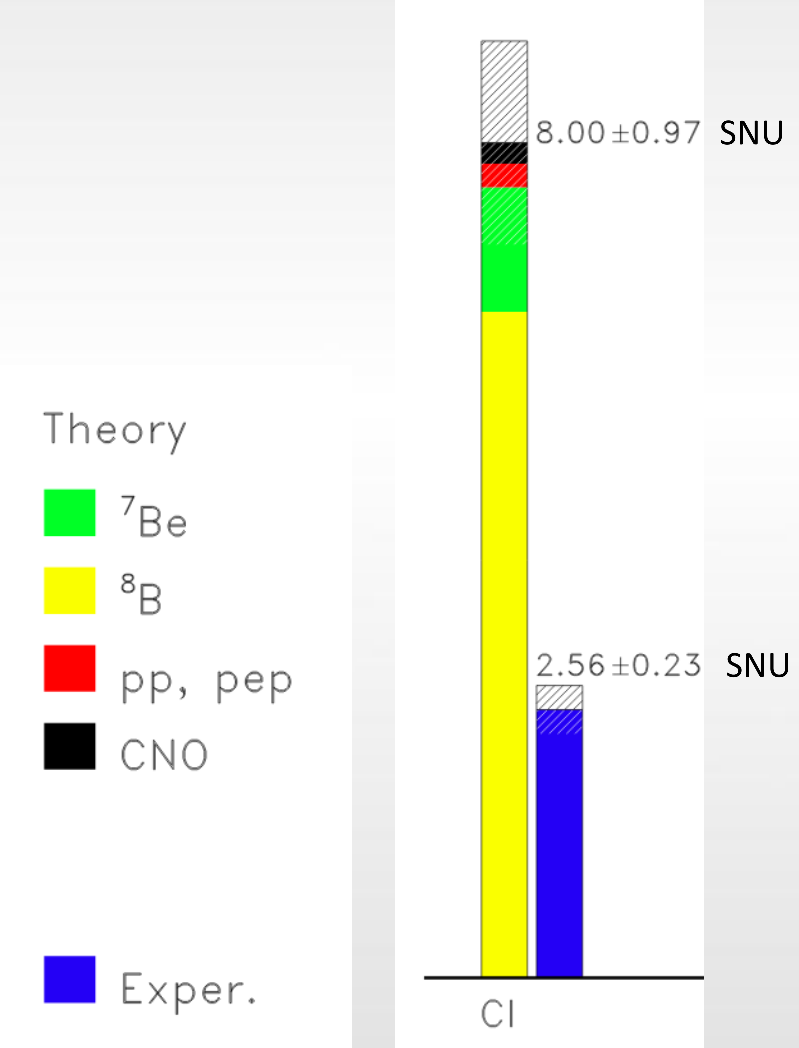
The Homestake experiment



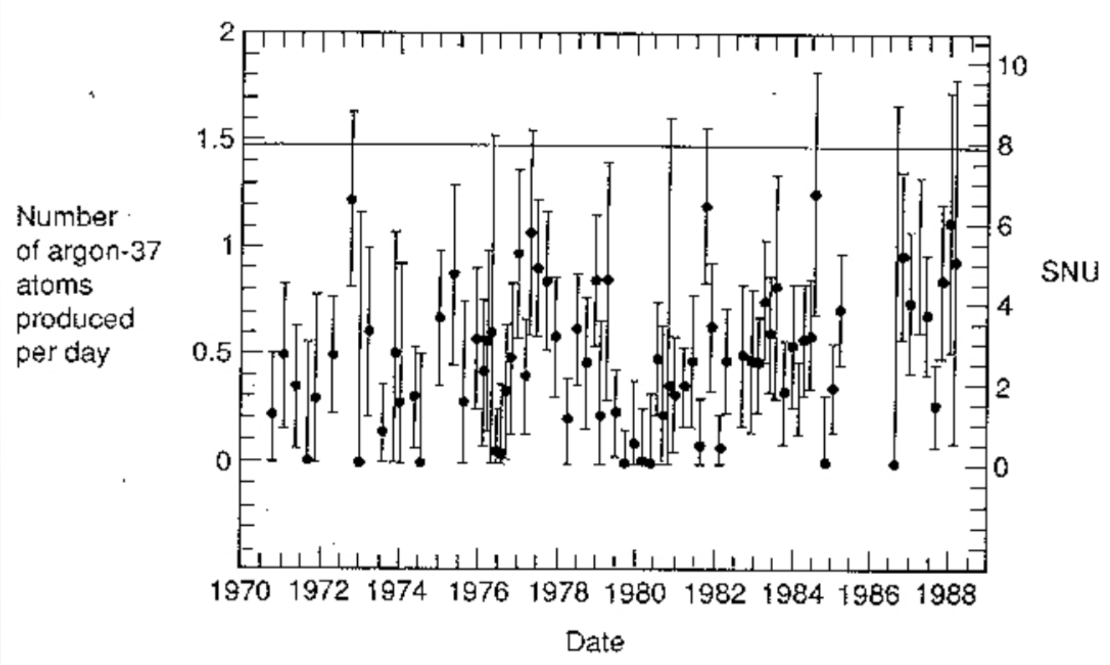
THE HOMESTAKE EXPERIMENT

- 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



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



What's SNU ?

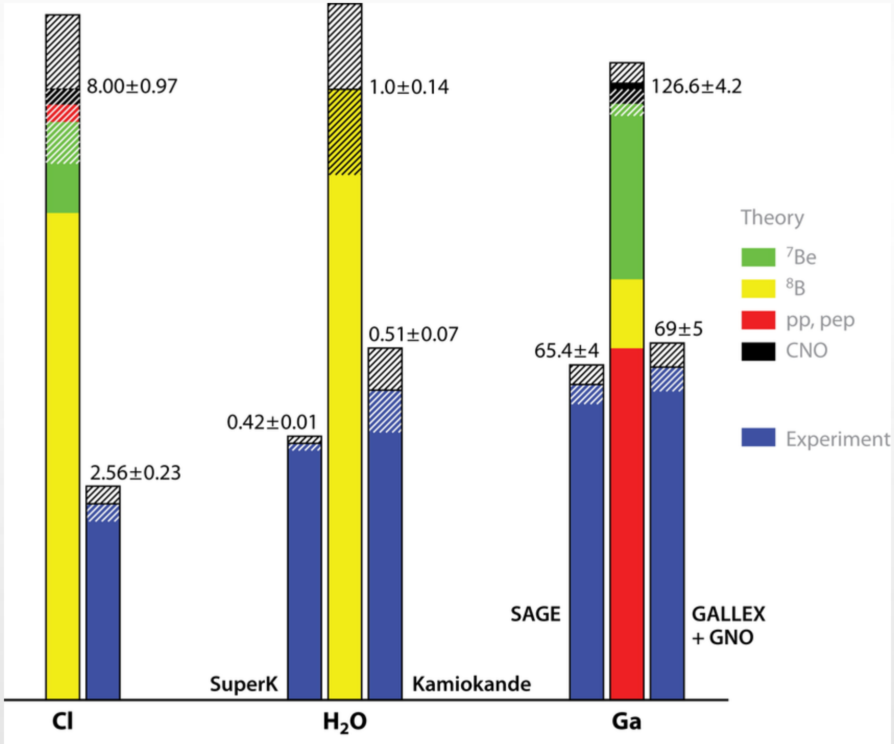
1 SNU = 10^{-36} captures per second per target nucleus

Solar Neutrino Unit

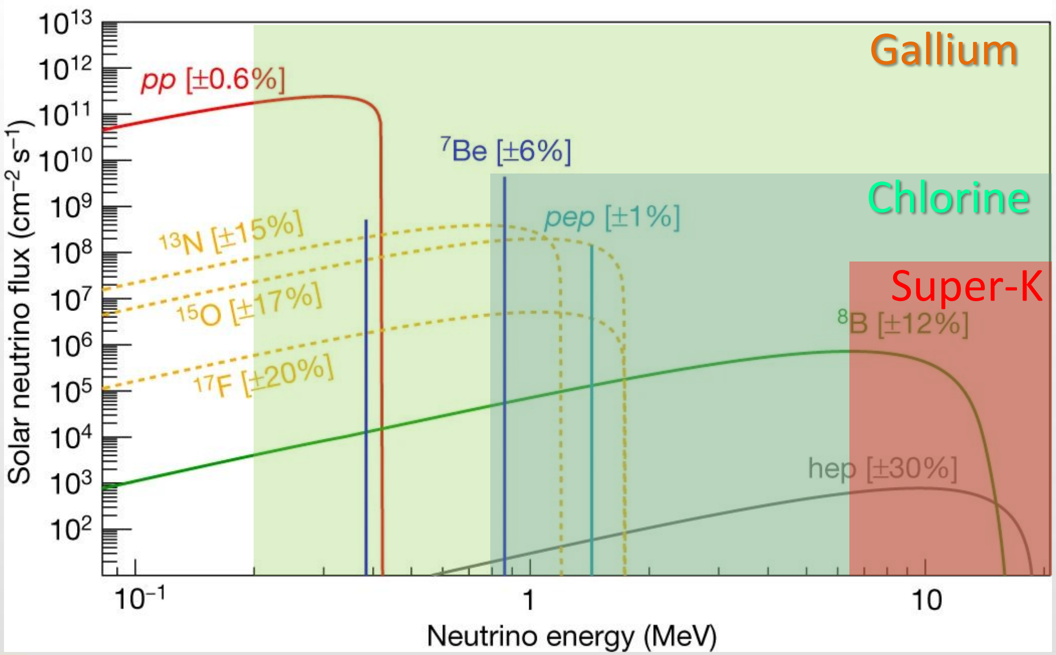
Other Experiments confirmed missing ν_e

- SAGE- Soviet-American Gallium Experiment and GALLEX (Italy):
  Measured: $\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$
- 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 νs 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 νs massive they can change flavour – in todays 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:

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

Propagation: $\nu_1(t) = \nu_1(0)e^{-iE_1 t}$ $\nu_2(t) = \nu_2(0)e^{-iE_2 t}$

- 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 $m_{1,2}$ <<E , p≈E: $E_i = p + \frac{m_i}{2p^2}$ $\Delta E = \frac{\Delta m_{12}^2}{E}$

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

$$\nu_e(t) = \nu_e(0)\left[1 - \sin\theta_{12}\cos\theta_{12}(-e^{-iE_1 t} + e^{-iE_2 t})\right]$$

and the probability of observing an oscillation to ν_μ is:

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

Neutrino oscillations will not be explained here ;-)

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

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

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

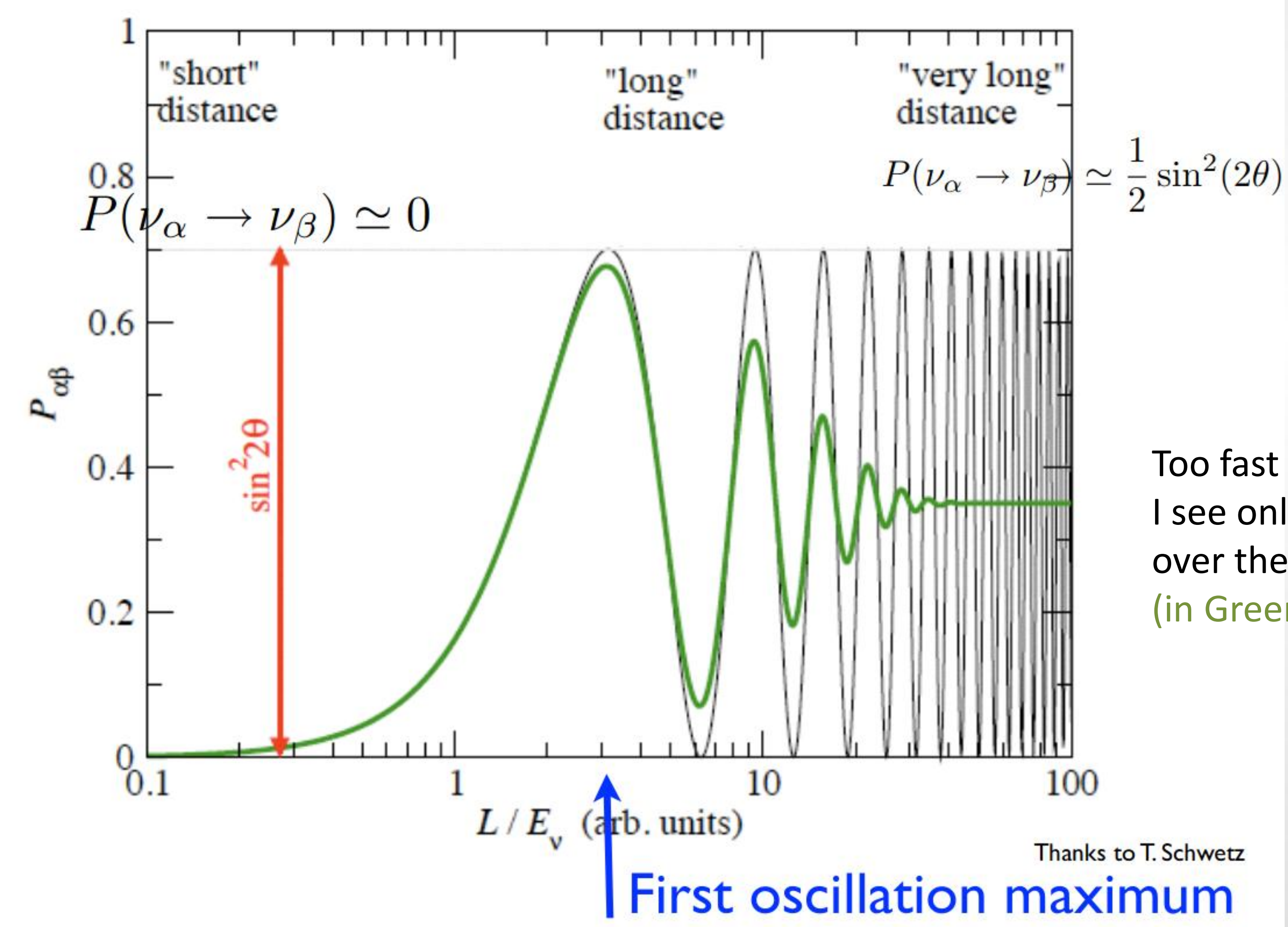
- We have a new parameter θ_{12}
- $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} \\ -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$

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

Neutrino oscillations will not be explained here ;-)

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

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



Thanks to T. Schwetz

First oscillation maximum

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

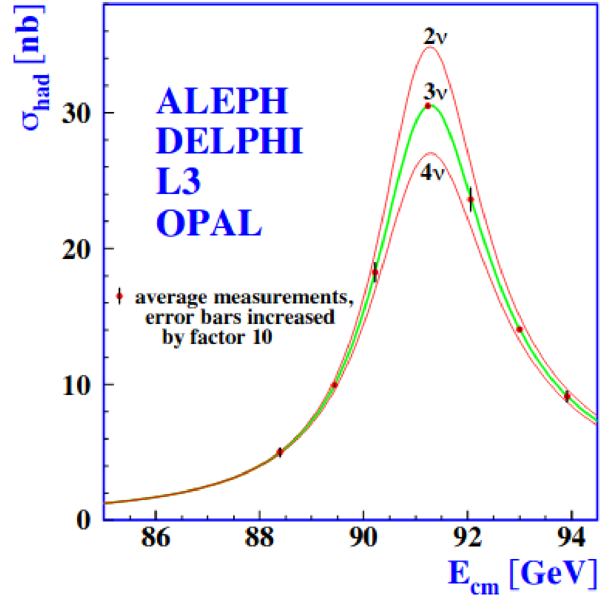
reactor disapp + LBL appearance searches

solar + KamLAND measurements

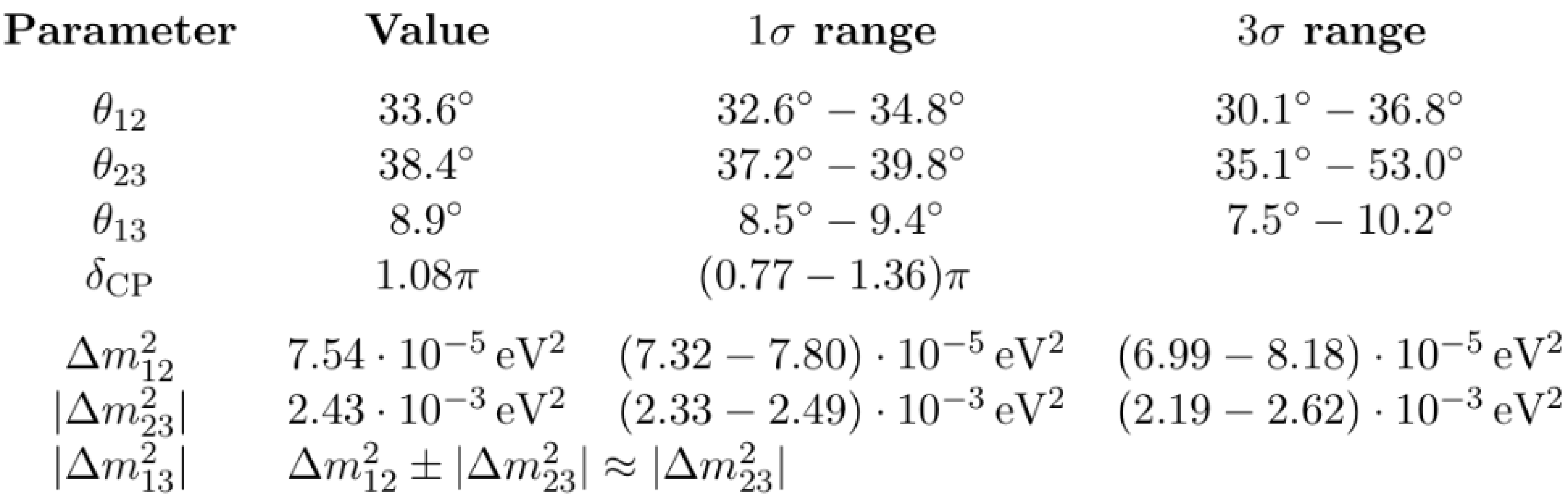
$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$$

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^2_{12}	$7.54 \cdot 10^{-5}\,\mathrm{eV}^2$	$(7.32 - 7.80) \cdot 10^{-5}\,\mathrm{eV}^2$	$(6.99 - 8.18) \cdot 10^{-5}\,\mathrm{eV}^2$
$\lvert\Delta m^2_{23}\rvert$	$2.43 \cdot 10^{-3}\,\mathrm{eV}^2$	$(2.33 - 2.49) \cdot 10^{-3}\,\mathrm{eV}^2$	$(2.19 - 2.62) \cdot 10^{-3}\,\mathrm{eV}^2$
$\lvert\Delta m^2_{13}\rvert$	$\Delta m^2_{12} \pm \lvert\Delta m^2_{23}\rvert \approx \lvert\Delta m^2_{23}\rvert$		

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

Matter Effects

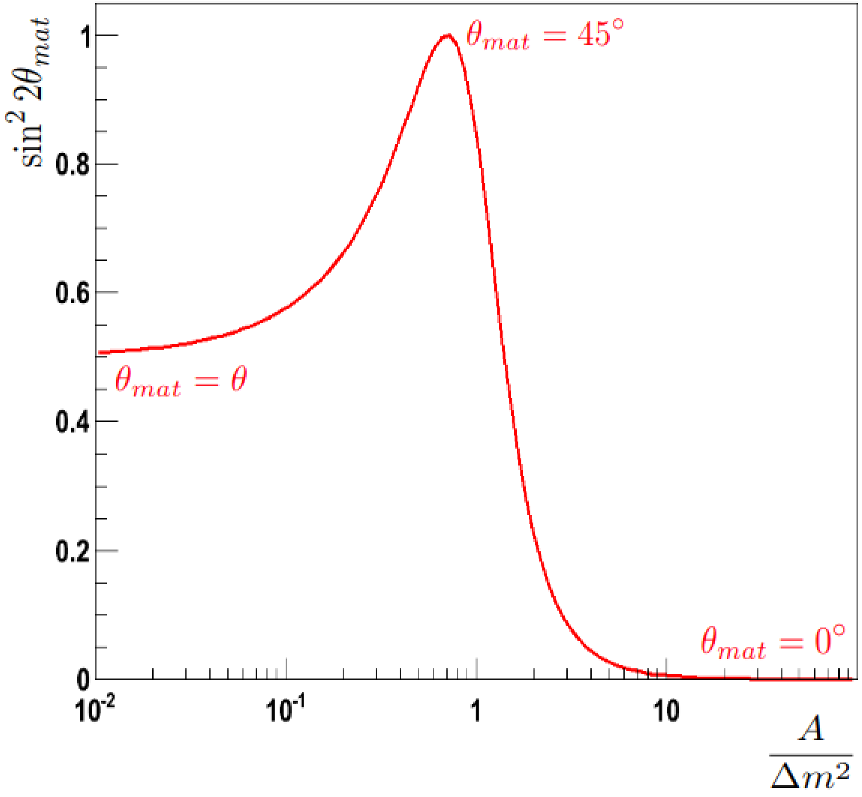
- As neutrinos propagate and oscillate
- Different flavour have different cross-section for interaction with matter:
  - Z – all flavours
  - W – only ν_e
- Important as they pass trough the Sun and Earth
- Mikheyev-Smirnov-Wolfenstein effect

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

Mikheyev-Smirnov-Wolfenstein effect

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

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



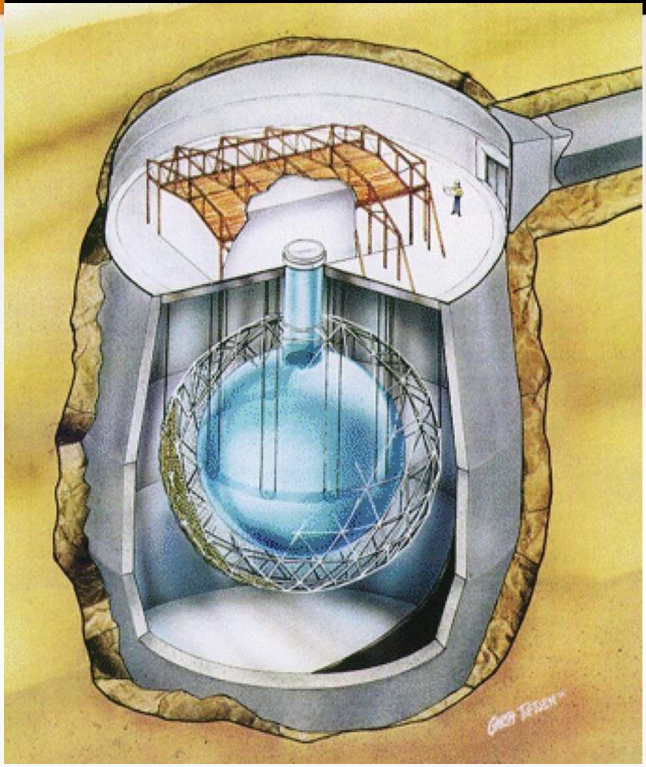
→ $\sin^2 2\theta_{\text{mat}}$ has the shape of a Breit-Wigner resonance as a function of $A/\Delta m^2$

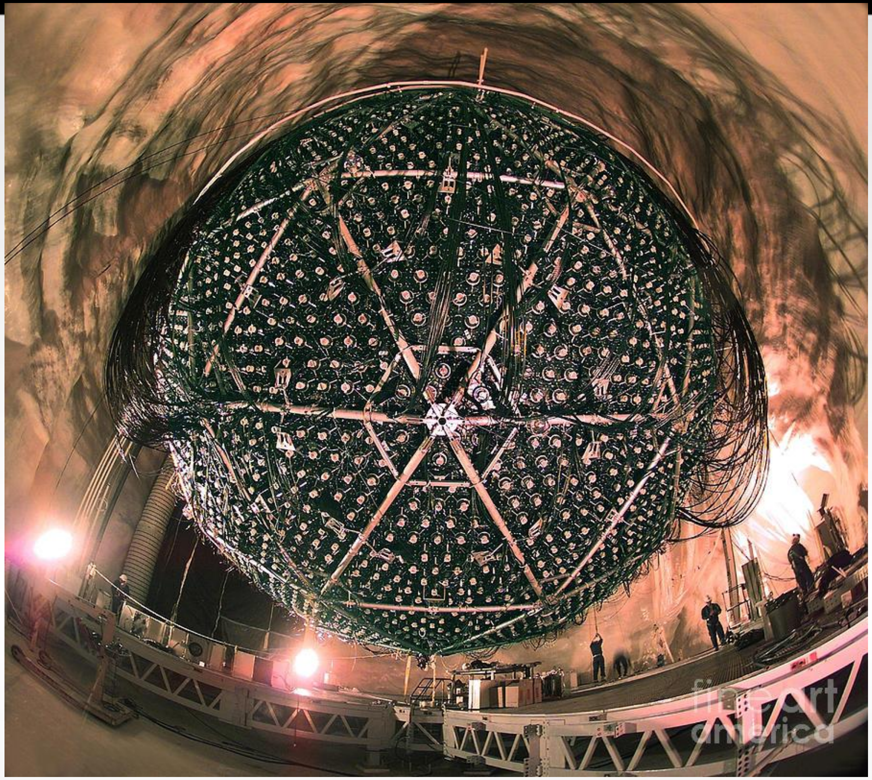
$$\frac{A}{\Delta m^2} = \underbrace{\frac{2\sqrt{2}G_F}{\Delta m^2}}_{\text{natural const.}} \cdot N_e \cdot p$$

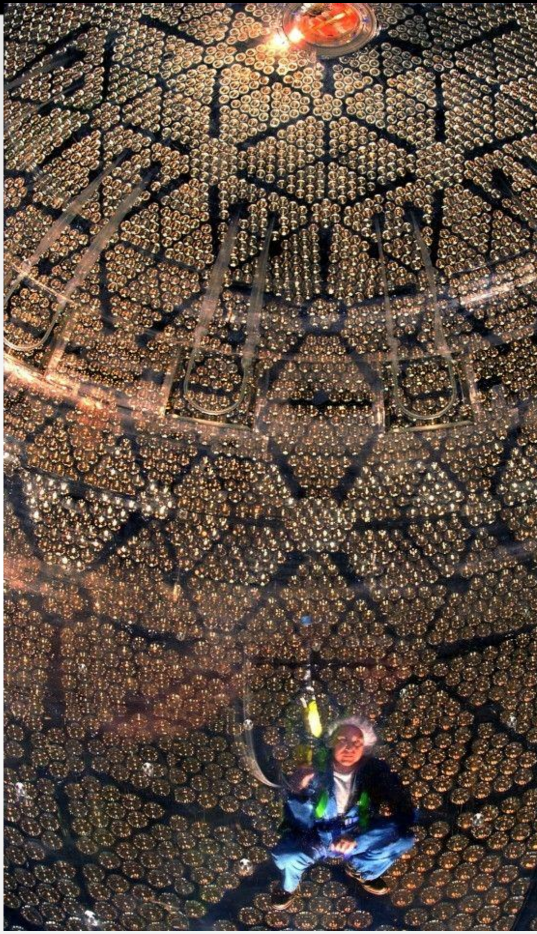
- Maximum mixing $\sin^2 2\theta = 1$ for resonance condition:

$$N_e E = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F}$$

Sudbury Neutrino Observatory (SNO)

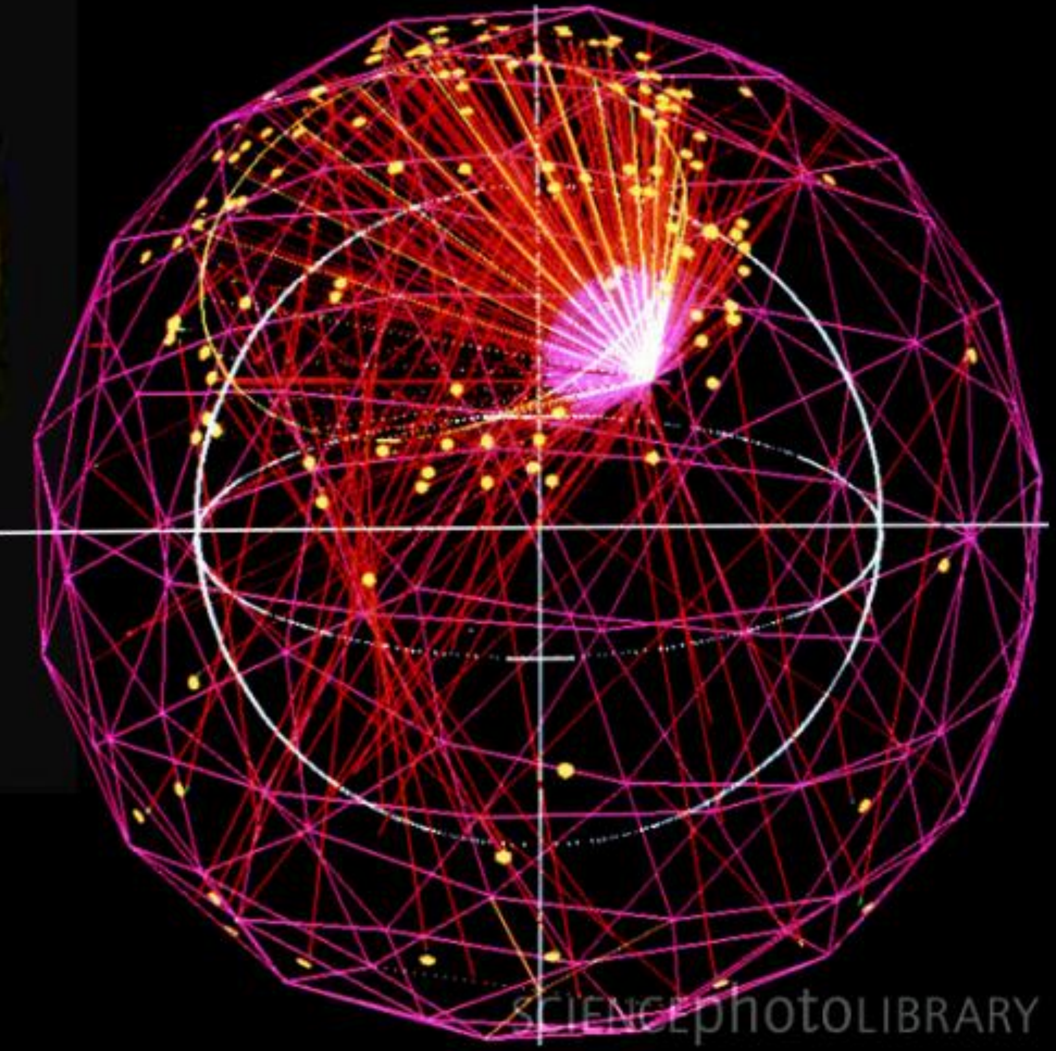




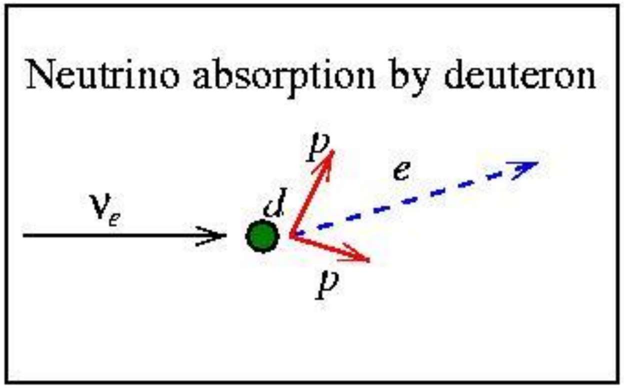


- 2100 m underground in Vale's Creighton Mine in Sudbury, Ontario, Canada
- Operational from 1999 to 2006
- 6-metre-radius acrylic (transparent) vessel
- 1000t of heavy water
- 9600 photomultiplier tubes (PMTs)

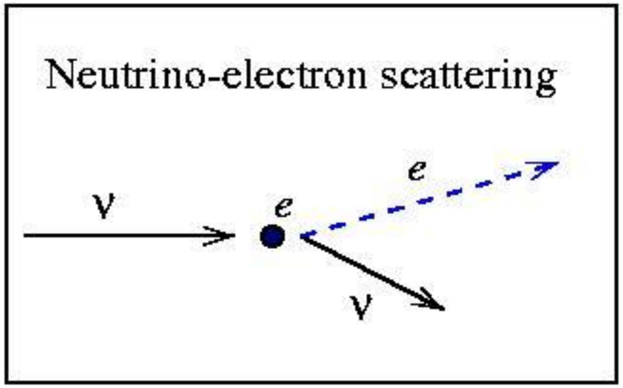
SNO Event Display



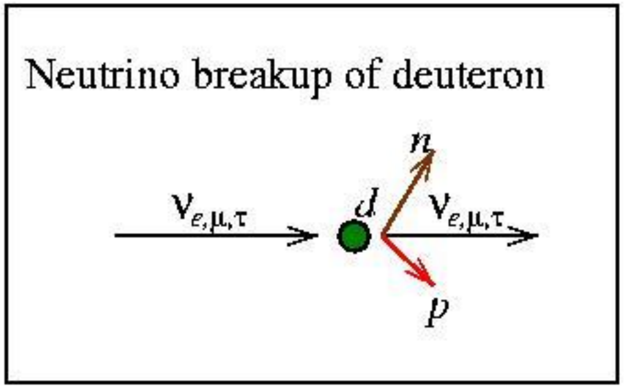
Sudbury Neutrino Observatory (SNO)



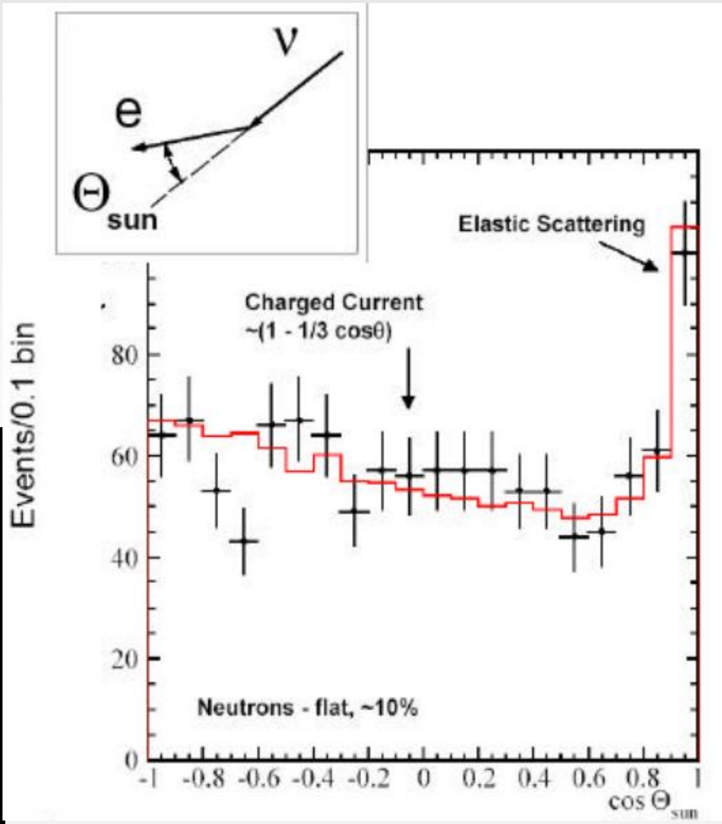
CC process
- Only ν_e
- Protons undetected
- e^- Cherenkov light
- Amost isotropic



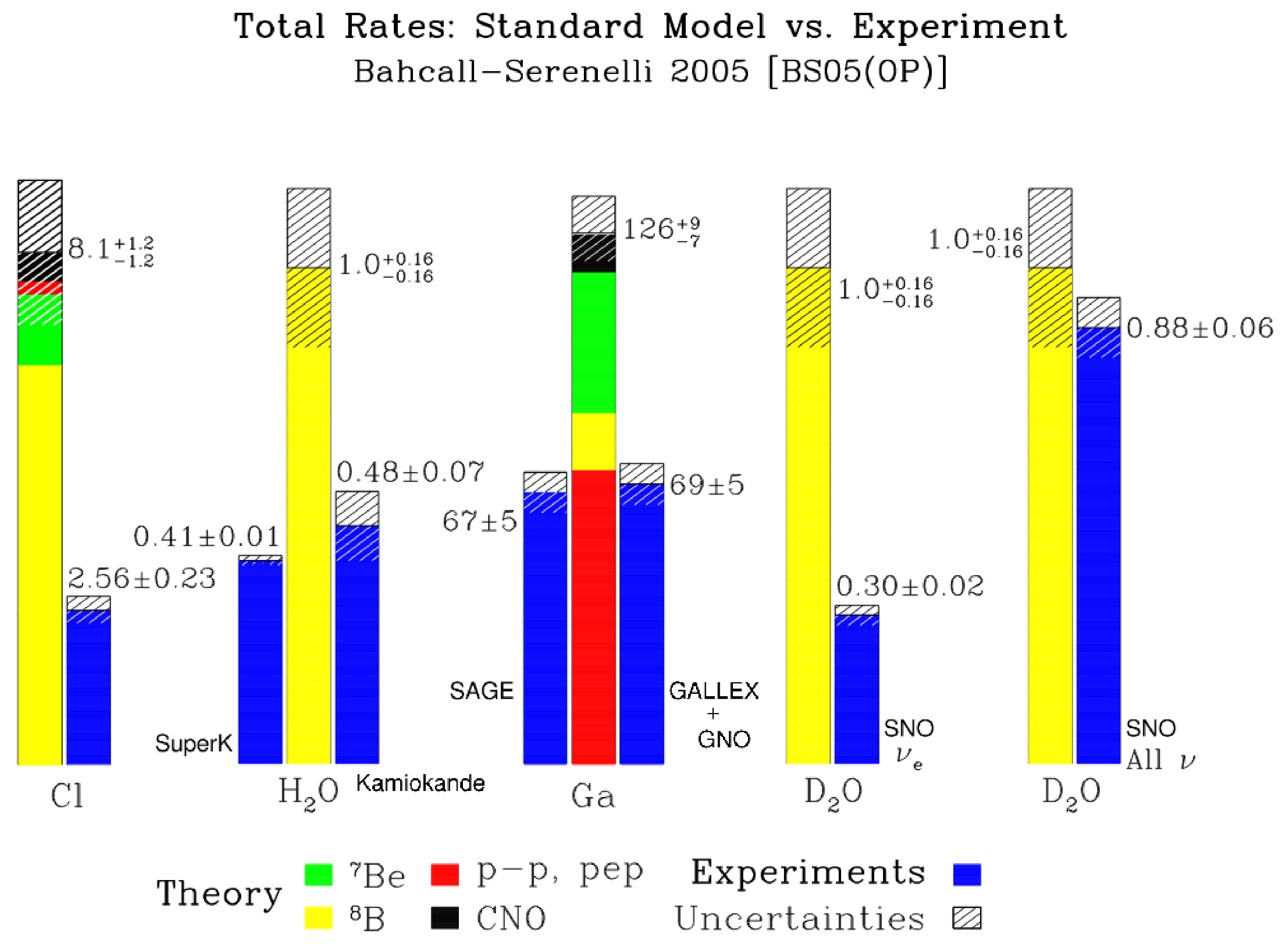
Electron scattering
- Mainly ν_e (via W and Z)
- Other flavours only Z
- e^- Cherenkov light
- (how Super-K observes solar ν)
- Points in the direction of ν



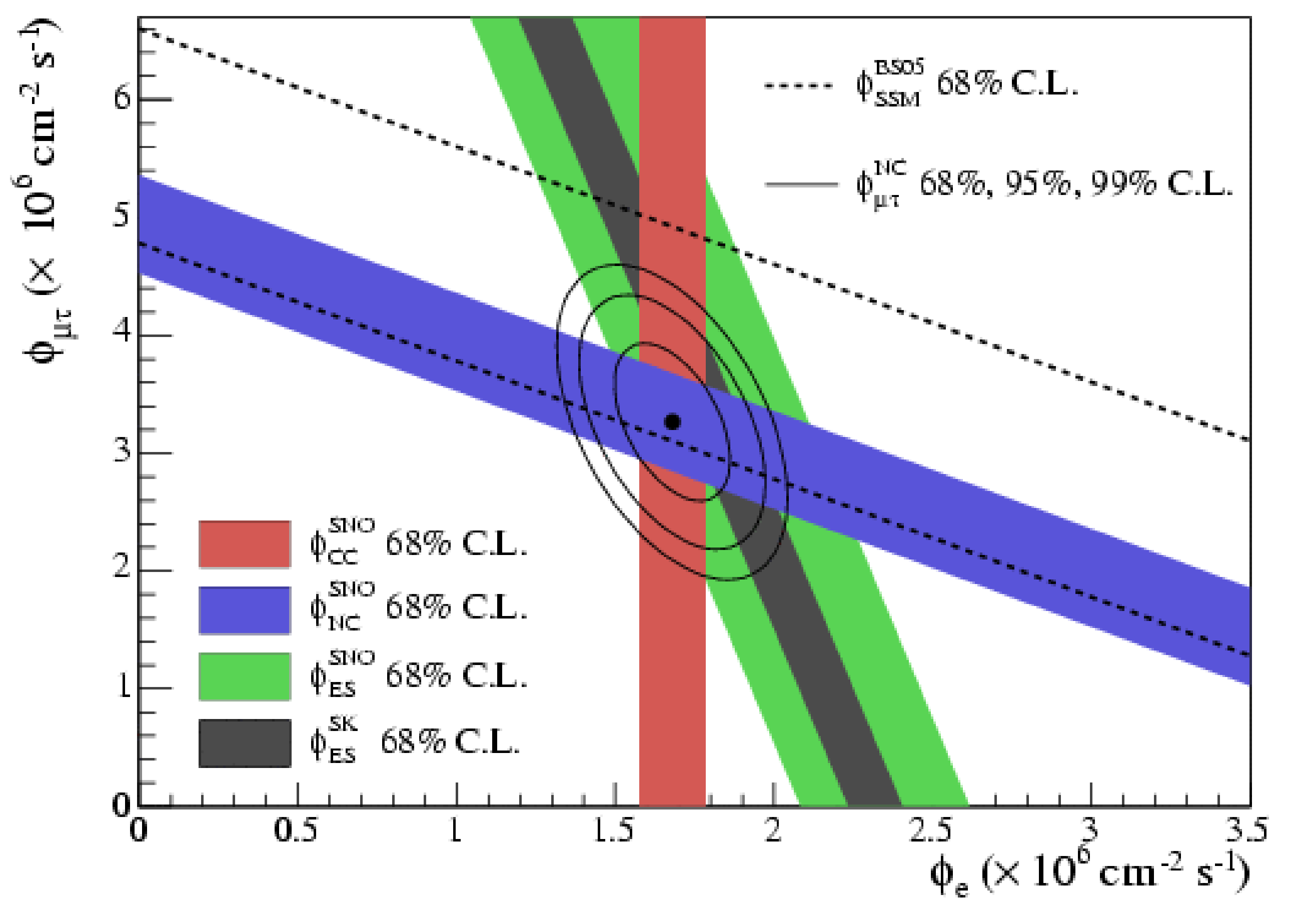
NC process
- All ν same cross-section
- Protons undetected
- Neutron capture-> γs -> e^- scattering -> e^- Cherenkov light
- NaCl and ^{3}He upgrade
- isotropic



Solar neutrino not a problem



SNO results

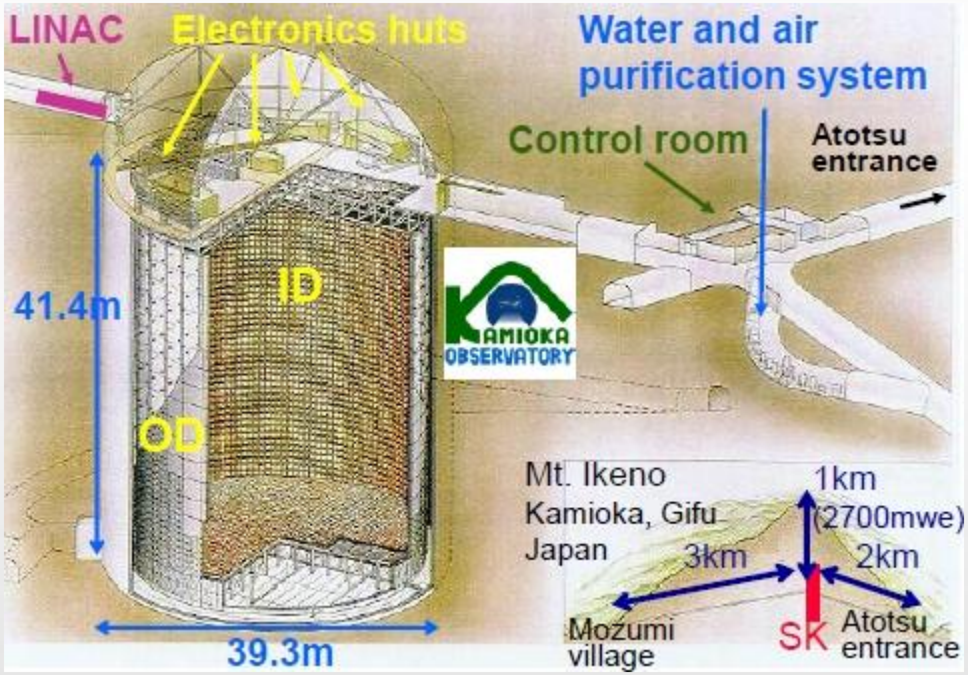


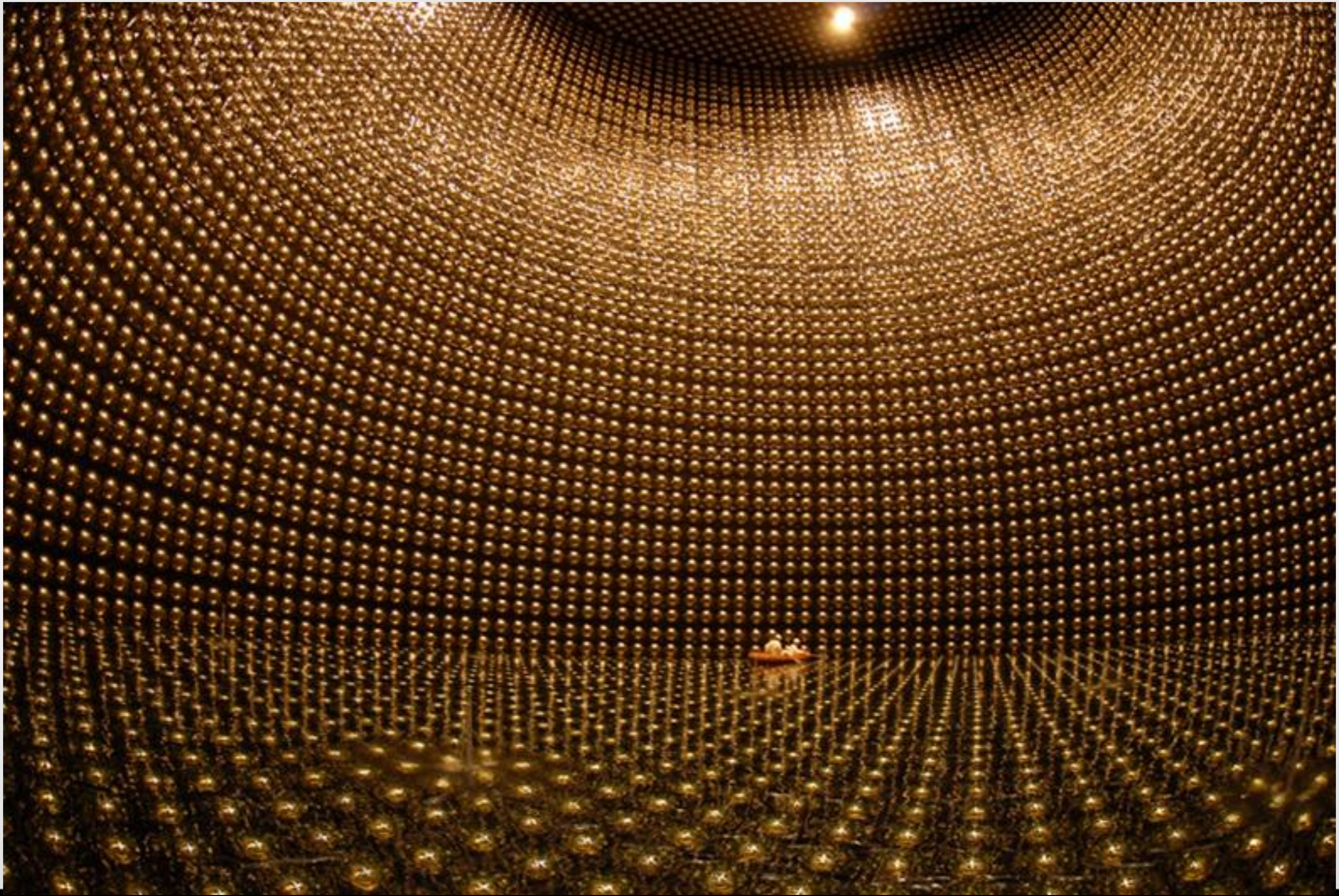
- The fluxes of ν_e and $\nu_{\mu+\tau}$ can be determined
- Super-K contribution

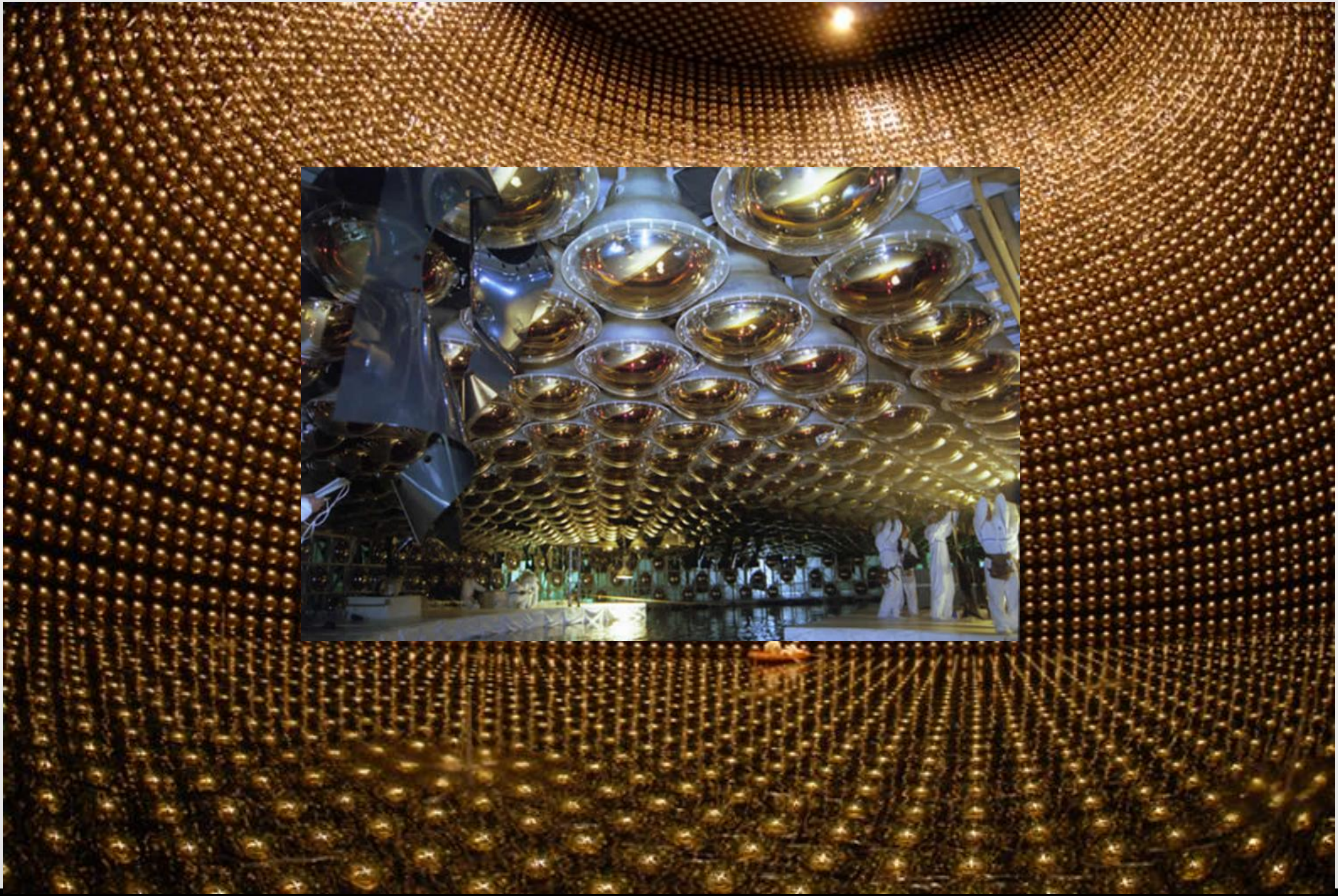
Super KamiokaNDE

- Successor of KamiokaNDE (Kamioka Nucleon Decay Experiment)

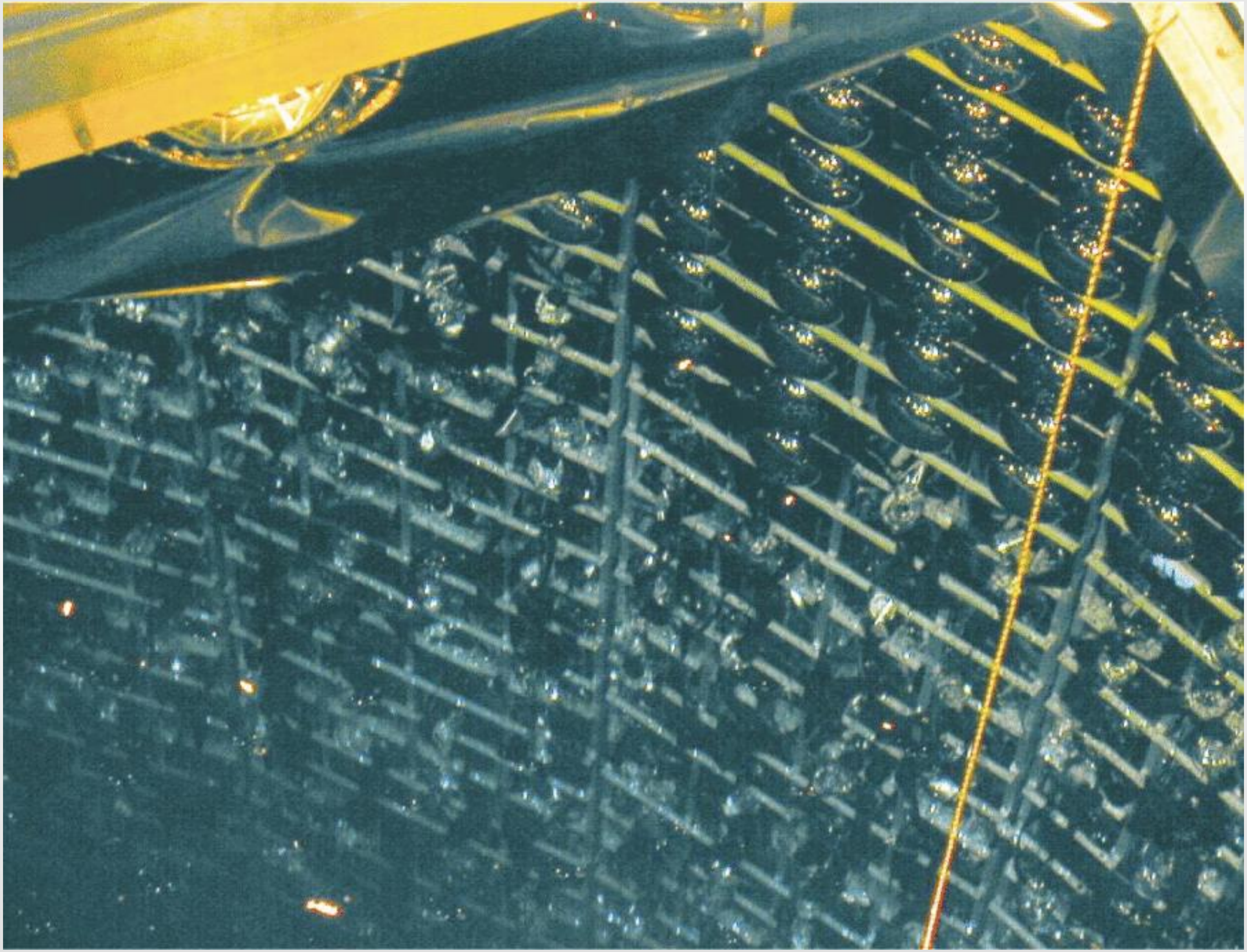
- 1000 m underground in the Mozumi Mine
- 50000 t of ultrapure water
- ID: 11146 PMTs 50 cm
- OD: 1885 20 cm







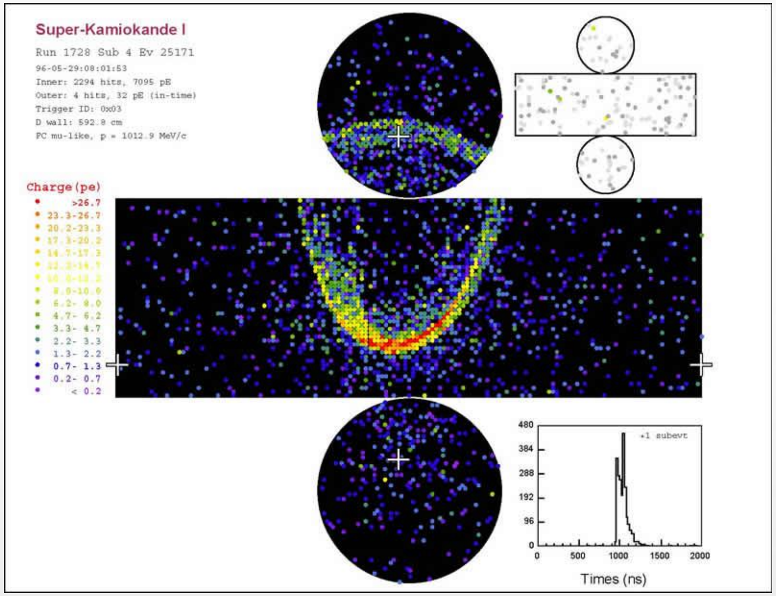
Famous accident 2001

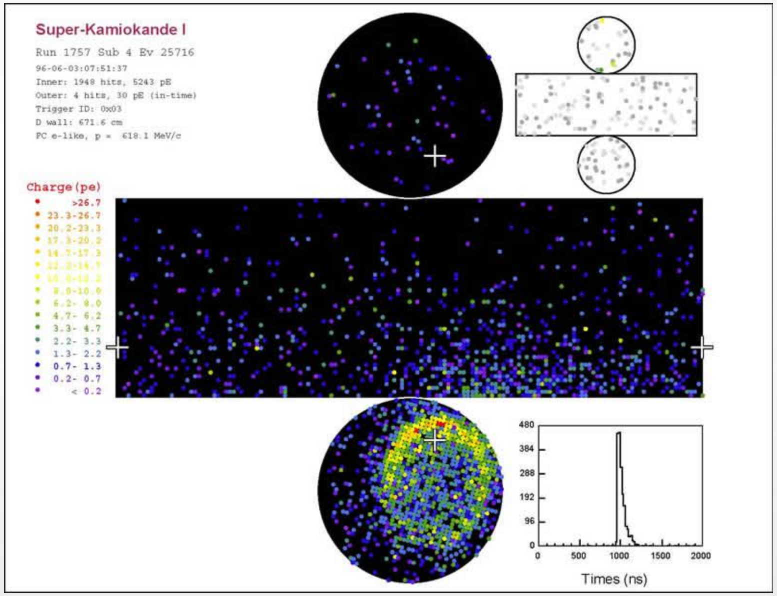


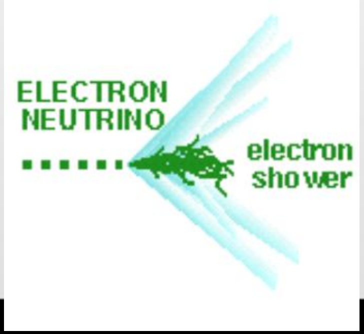
Super K events

Cherenkov ring by a muon from neutrino
1GeV moun

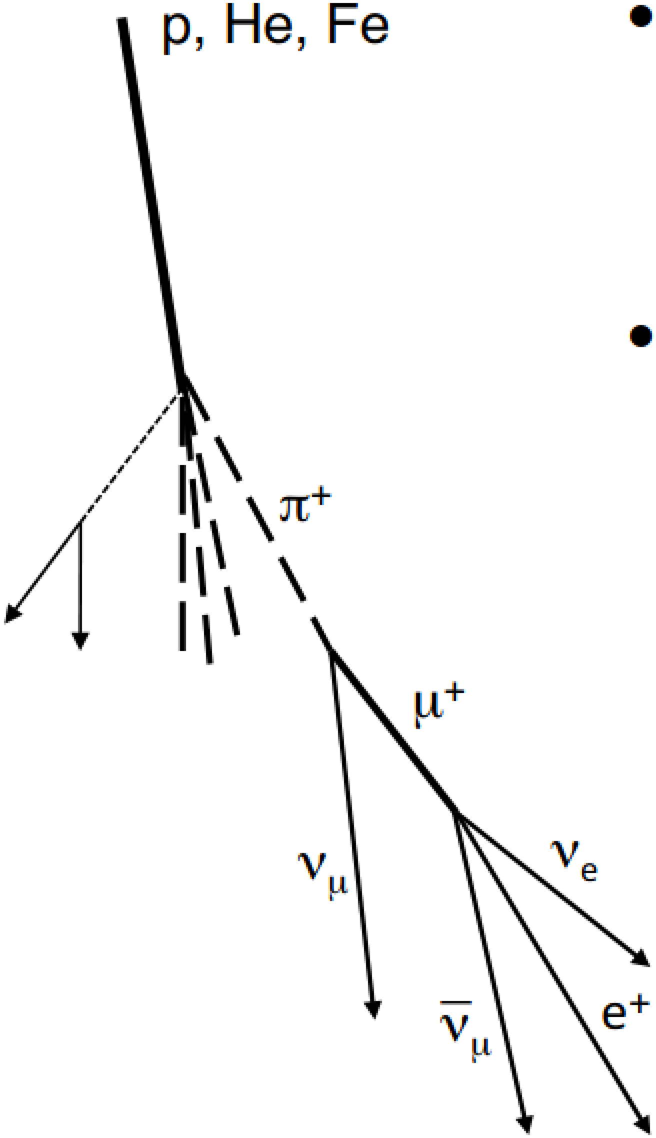
Electron neutrino event. 0.6 GeV
An electron neutrino scatters an electron in water. The emitted electron generates an electromagnetic shower, leading to the fuzzy edge of the Cherenkov ring







Atmospheric neutrino production



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

$$p + N \rightarrow p + N' + \pi, K\ldots$$

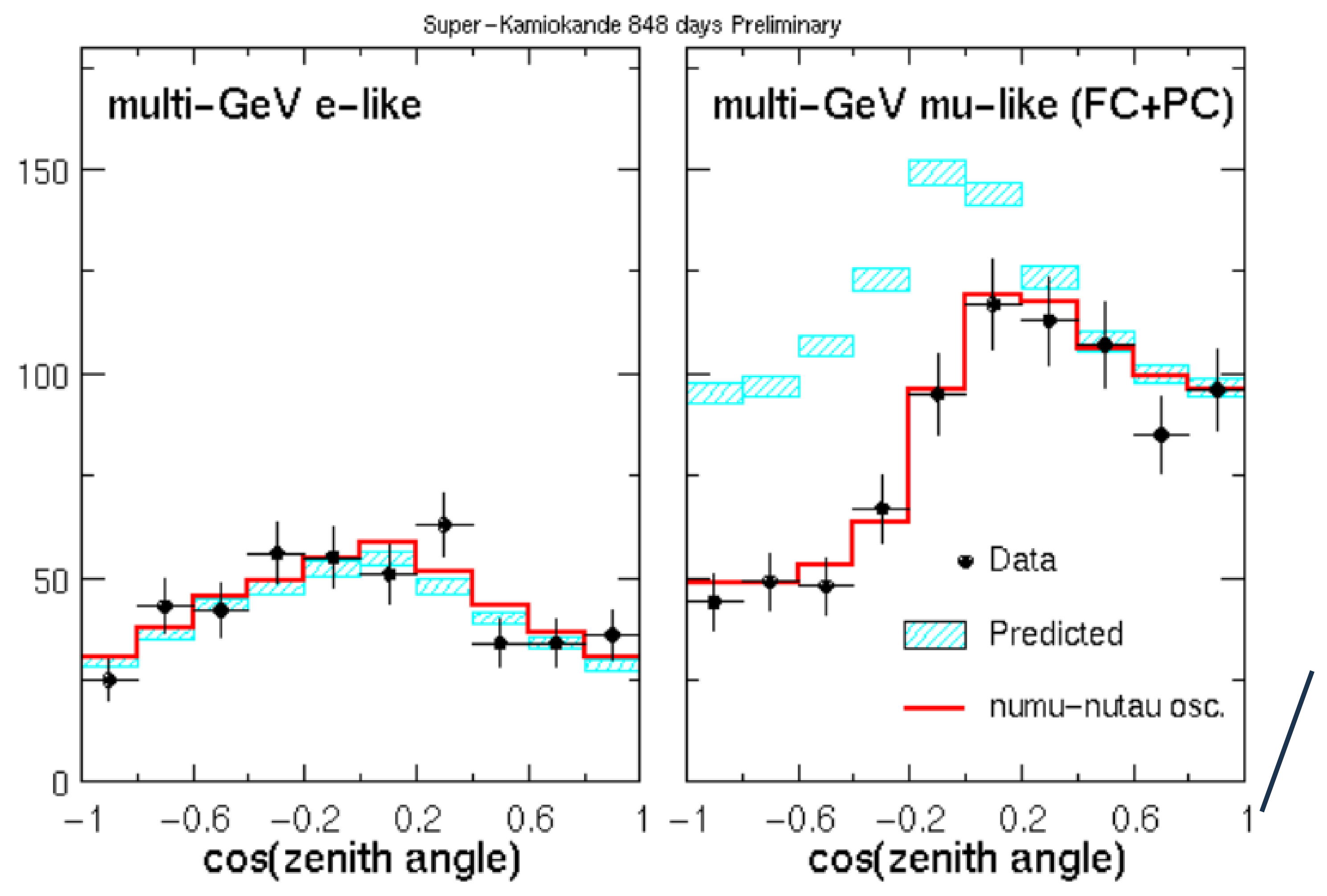
- Charged mesons decay into neutrinos:

$$\begin{aligned} \pi^+, K^+ &\rightarrow \mu^+ \nu_\mu \\ & \quad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \end{aligned}$$

$$\begin{aligned} \pi^-, K^- &\rightarrow \mu^- \bar{\nu}_\mu \\ & \quad \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \end{aligned}$$

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

Observed angular distributions



Down-going cos(0)=1

ν_e as expected

ν_μ something is going on here

Travel distance of Atmospheric νs

- This does fit the expectation for ν oscillations!
- For current best values, oscillation lengths are

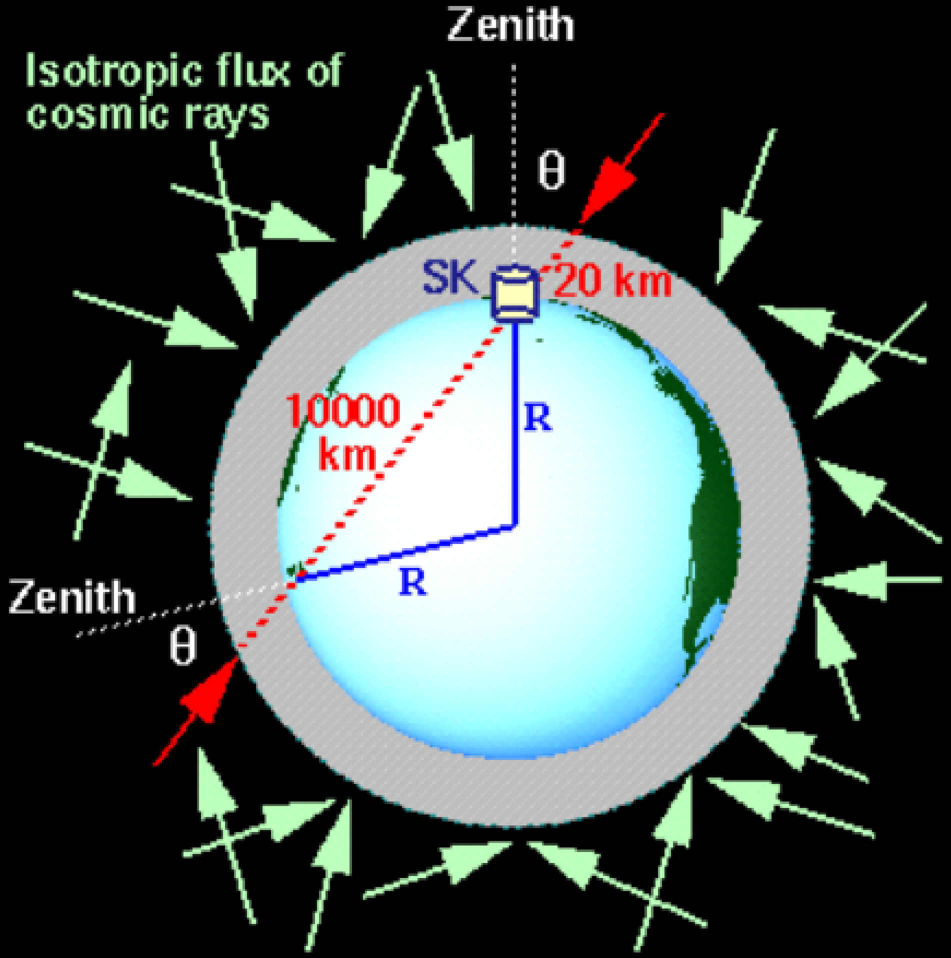
  $L_{23} \approx 10^3$ km @ 1 GeV
  $L_{12} \approx 3\mathrm{x}10^4$ km

- For ν_μ **from above**, baseline < L_{12}, L_{23}

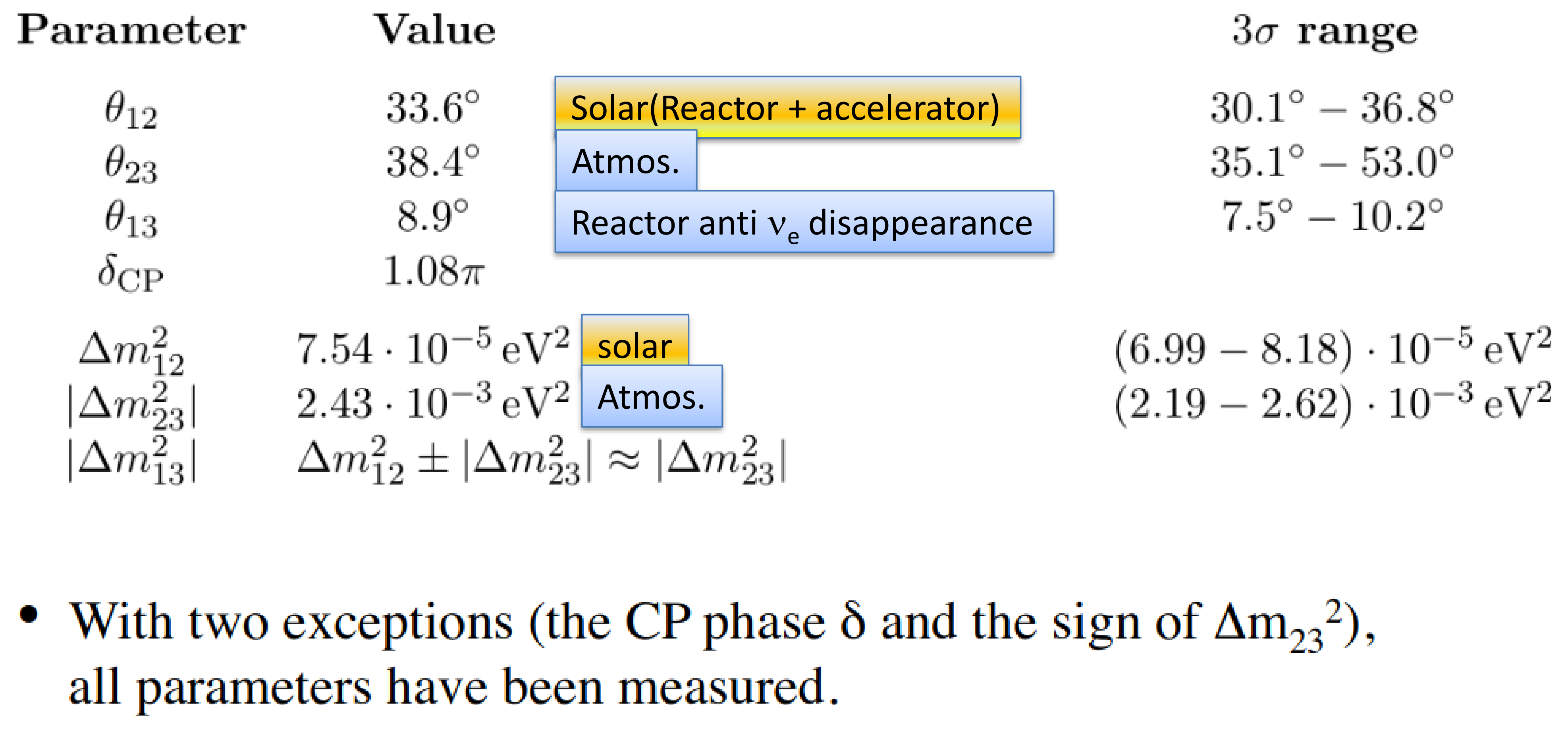
  → **no oscillation**

- For ν_μ **from below**, L_{23} < baseline < L_{12}

  → no $\nu_\mu \rightarrow \nu_e$ oscillations,
  but $\boldsymbol{\nu_\mu \rightarrow \nu_\tau}$!



Current best-fit values



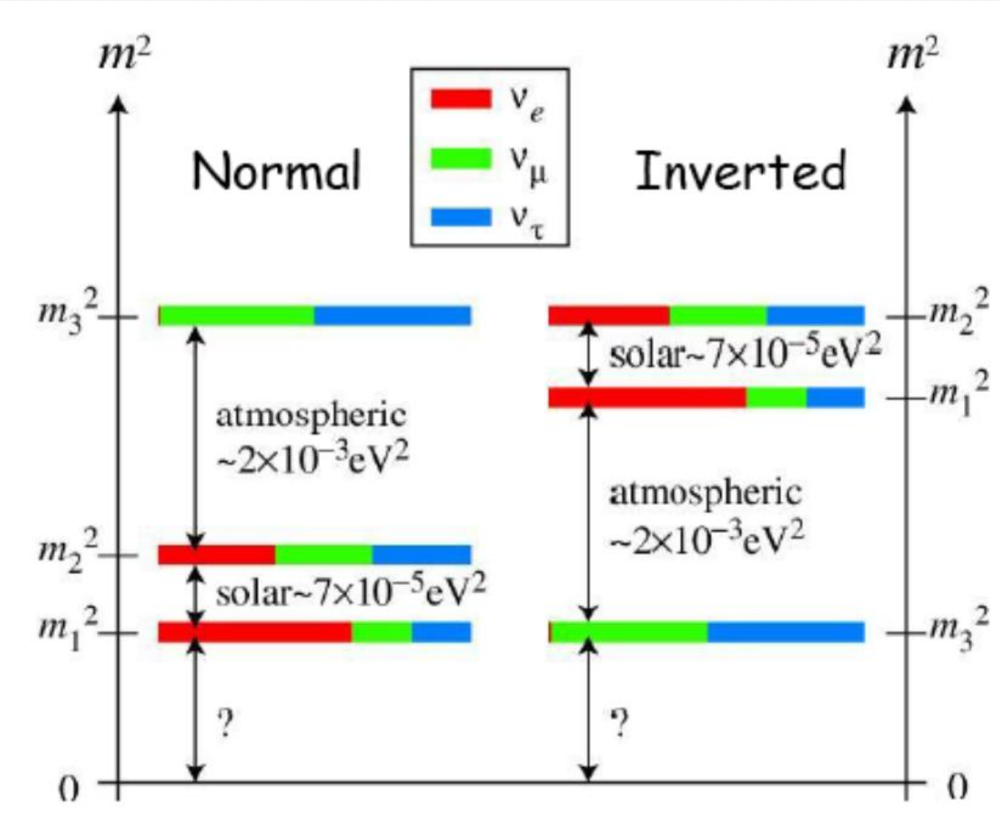
Parameter	Value		3σ range
θ_{12}	33.6°	Solar(Reactor + accelerator)	$30.1^\circ - 36.8^\circ$
θ_{23}	38.4°	Atmos.	$35.1^\circ - 53.0^\circ$
θ_{13}	8.9°	Reactor anti ν_e disappearance	$7.5^\circ - 10.2^\circ$
δ_{CP}	1.08π		
Δm^2_{12}	$7.54 \cdot 10^{-5}\,\mathrm{eV}^2$	solar	$(6.99 - 8.18) \cdot 10^{-5}\,\mathrm{eV}^2$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

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

Unknowns: Neutrino mass, hierarchy, δ_{CP}

- Upper limit (KATRIN) 0.45 eV (90% C.L.)
- We know the m_1 (the one with largest νe fraction) is below m_2 (2^{nd} largest νe fraction) (from the effects of matter on oscillations in the sun)
- We know $\Delta m^2_{21} \ll |\Delta m^2_{31}| \simeq |\Delta m^2_{32}|$

- To determine Δm^2_{31} matter effects when passing trough Earth could be used



CP violation can only take place in *appearance* experiments

Look for $P(\nu_\mu \rightarrow \nu_e) \neq P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$

Next time - Part 2

- Astrophysical neutrinos and experiments.