Neutrino oscillations: the state of the subject

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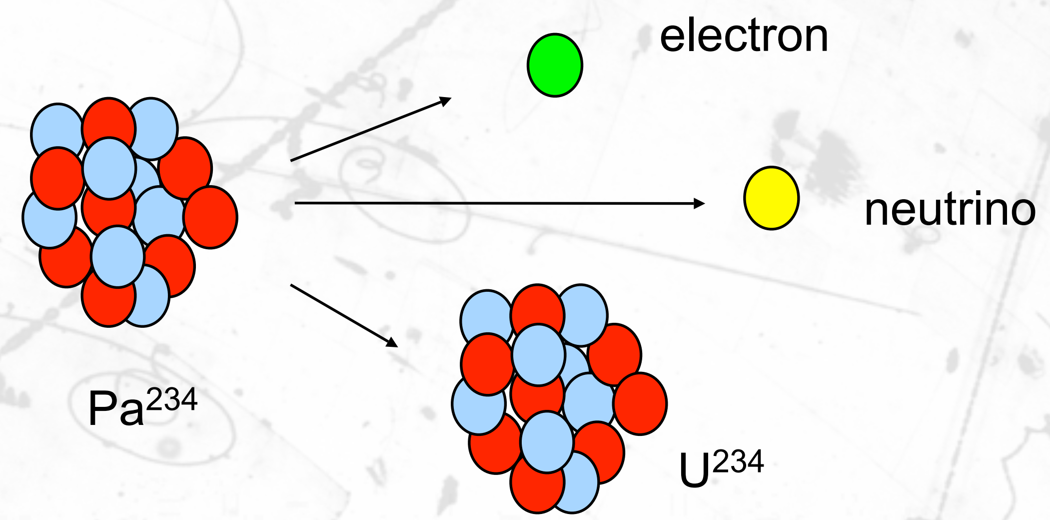
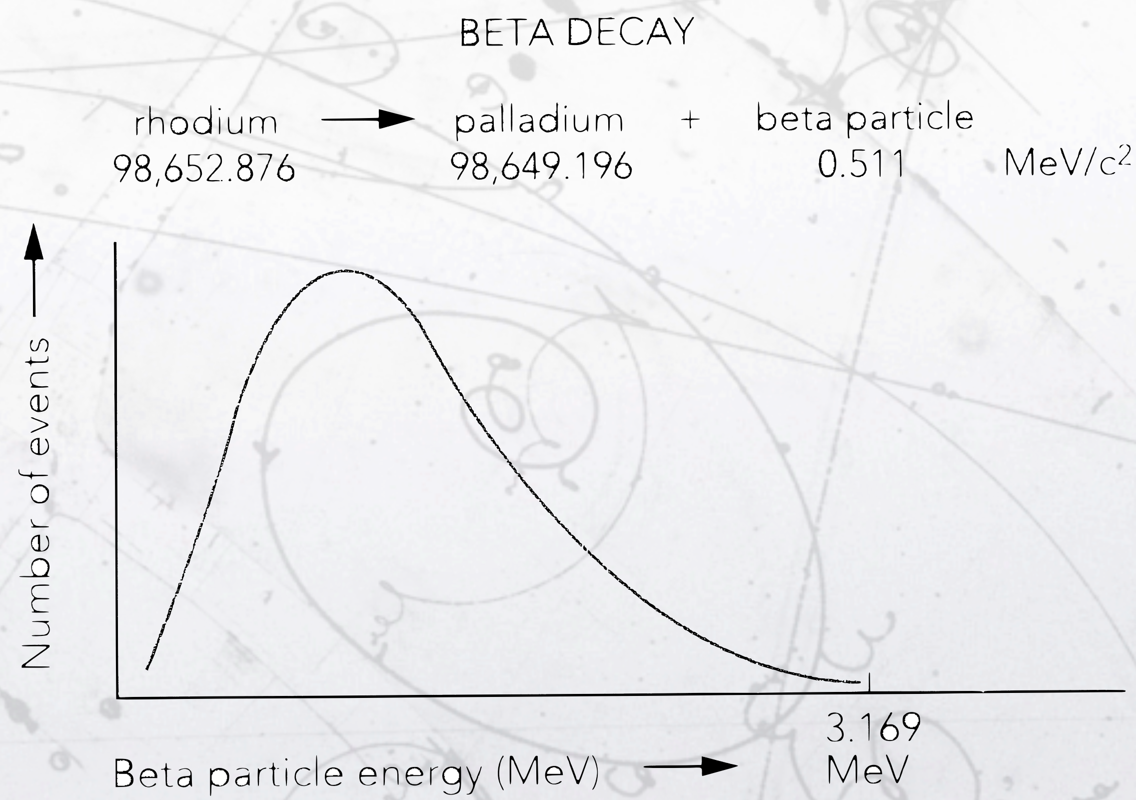
Outlook

- Neutrinos: discovery and early ideas.
- Oscillation phenomenology:
  - Solar neutrinos + Kamland
  - Atmospheric neutrinos + Long Base line experiments.
  - θ_{13} & CP violation.
- Closing remarks

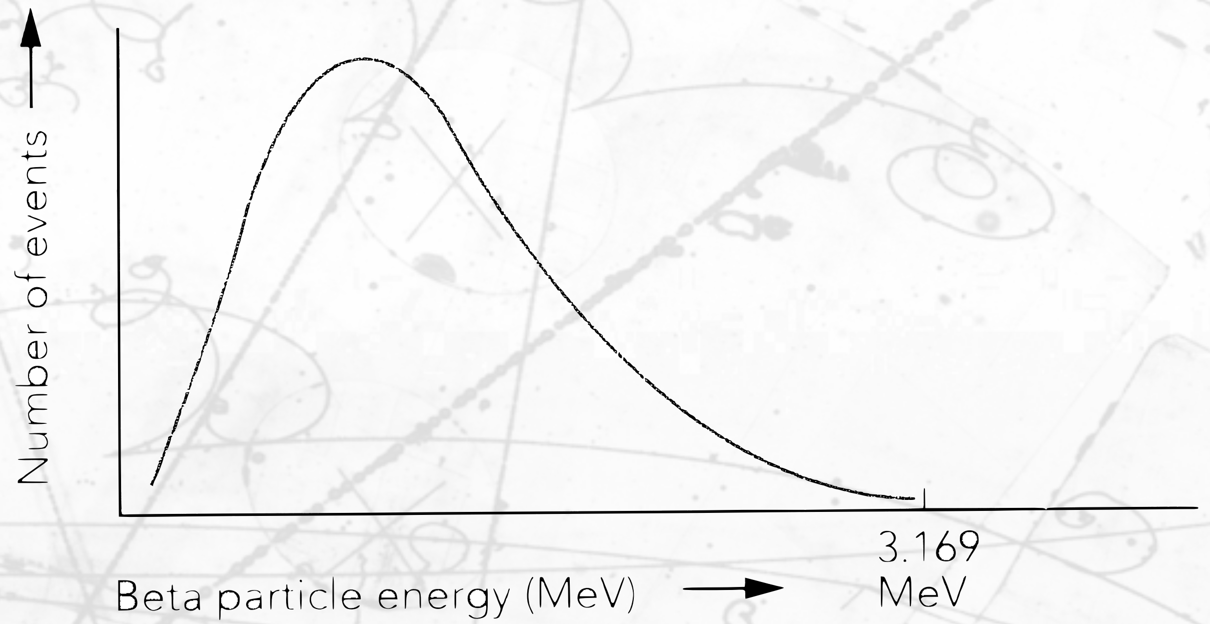
Neutrinos

- Neutrinos were proposed in 1931 by Pauli in a desperate attempt to understand the β spectrum.
- The particle (first called neutron) had the following properties:
  - Neutral
  - weakly interacting
  - low mass (<< m_e)
  - Spin 1/2





Neutrino mass



In the 30's, it was already known that m_ν<100MeV

- Mass of the neutrino can be measured by the end point of the β decay spectrum:

$$m_\nu = M_{Rhodium} - M_{Palladium} - E_{e^-}^{max}$$

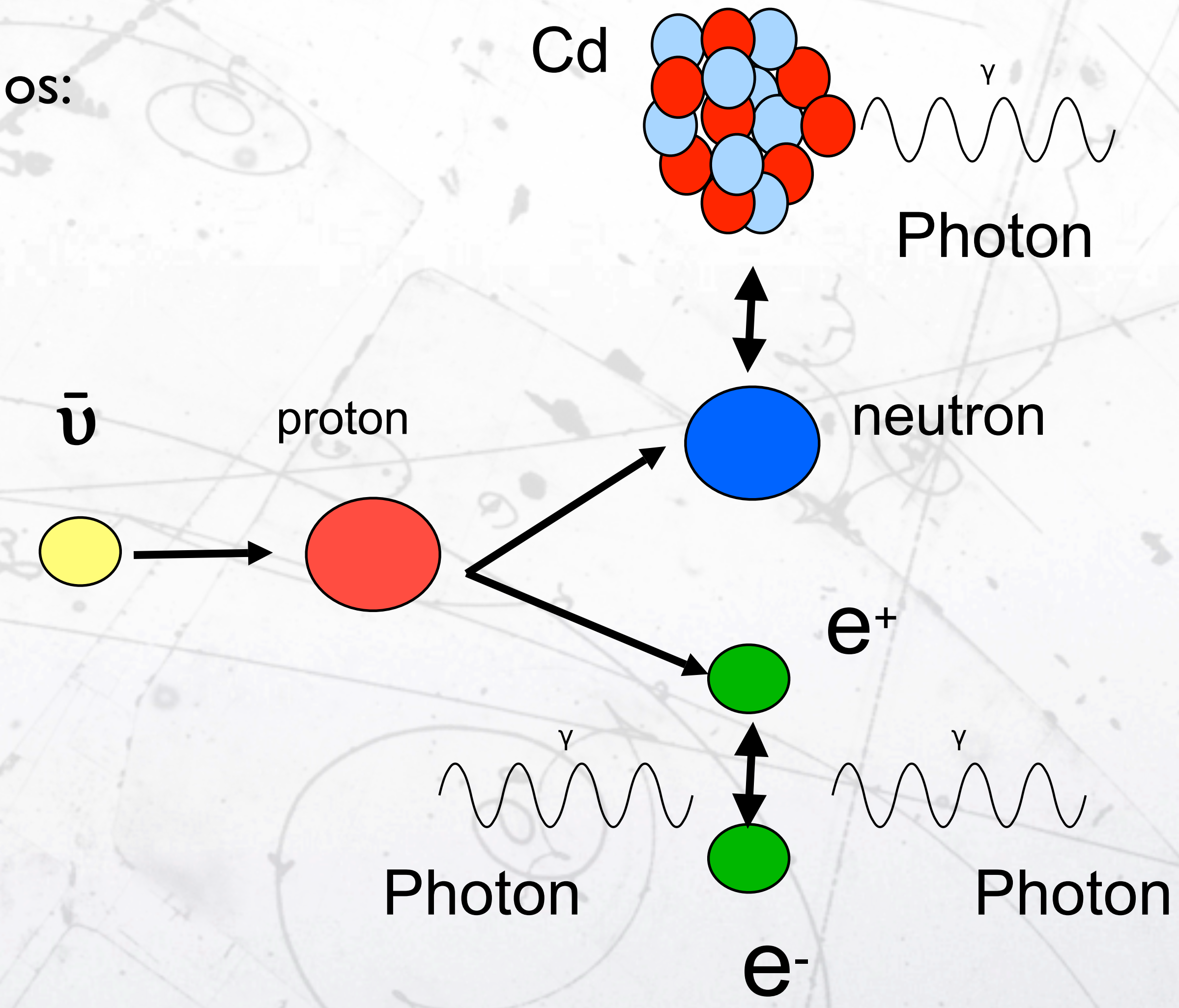
The m_ν precision is limited by the resolution of masses and electron energy.

Nowadays we still use the same technique in Katrine

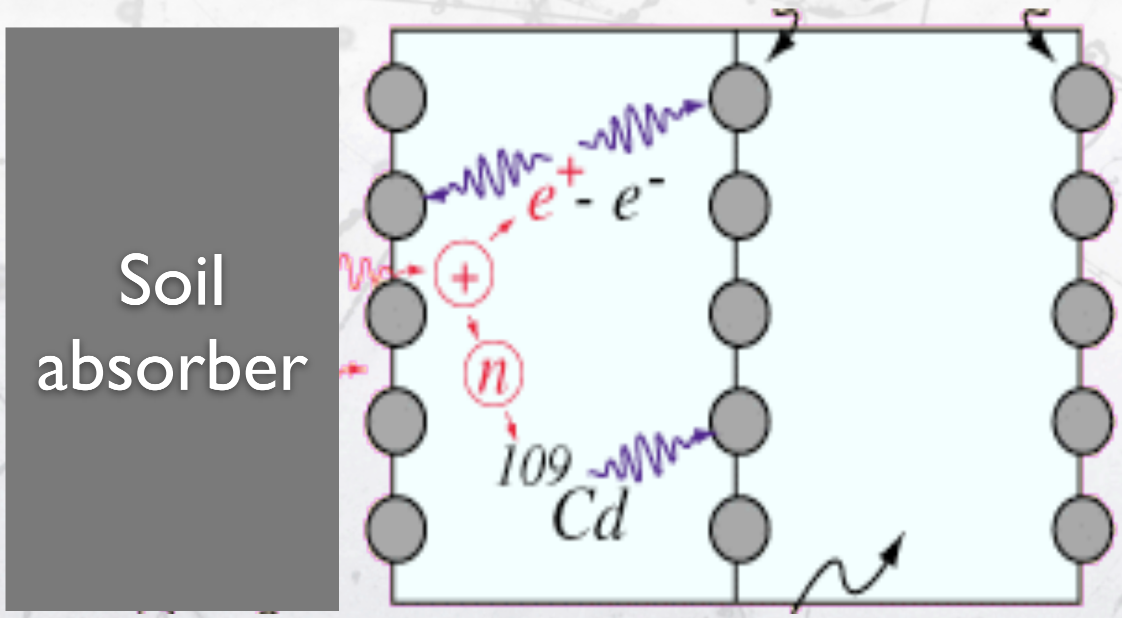
Neutrino discovery

- The first neutrino detection was done by Reines & Cowan in 1956.

- Neutrinos from the Savannah River (USA) experimental nuclear power plant: very intense source of neutrinos!
- A retarded coincidence signal was used to detect neutrinos:
  - Prompt positron (measures neutrino energy)
  - electron-positron annihilation
  - neutron absorption in Cd.



10^{13} ν/cm²/s

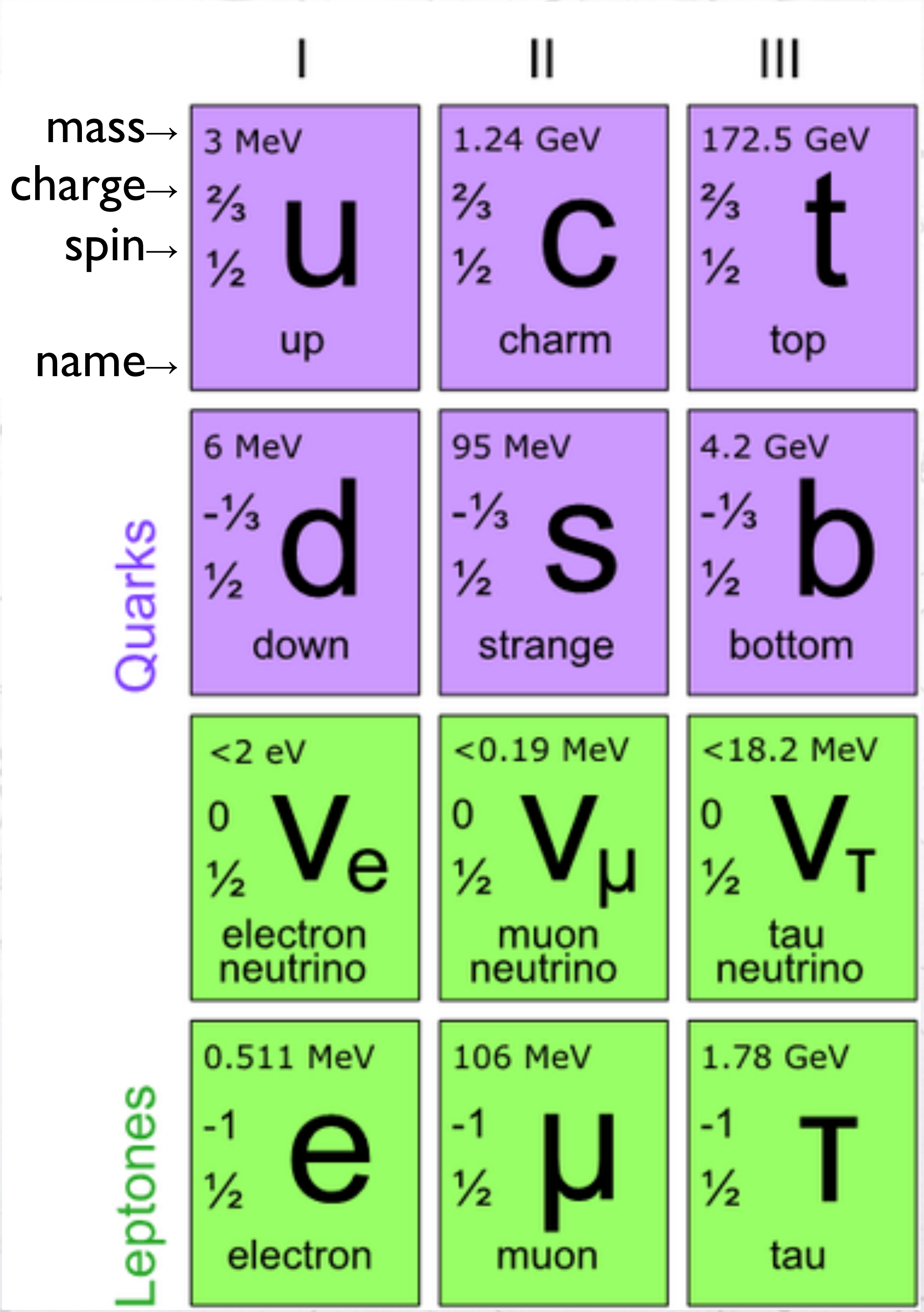


How many neutrinos ?

		I	II	III
	mass→ charge→ spin→ name→	3 MeV ⅔ ½ u up	1.24 GeV ⅔ ½ c charm	172.5 GeV ⅔ ½ t top
Quarks		6 MeV -⅓ ½ d down	95 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom
		<2 eV 0 ½ ν_e electron neutrino	<0.19 MeV 0 ½ ν_μ muon neutrino	<18.2 MeV 0 ½ ν_τ tau neutrino
Leptones		0.511 MeV -1 ½ e electron	106 MeV -1 ½ μ muon	1.78 GeV -1 ½ τ tau

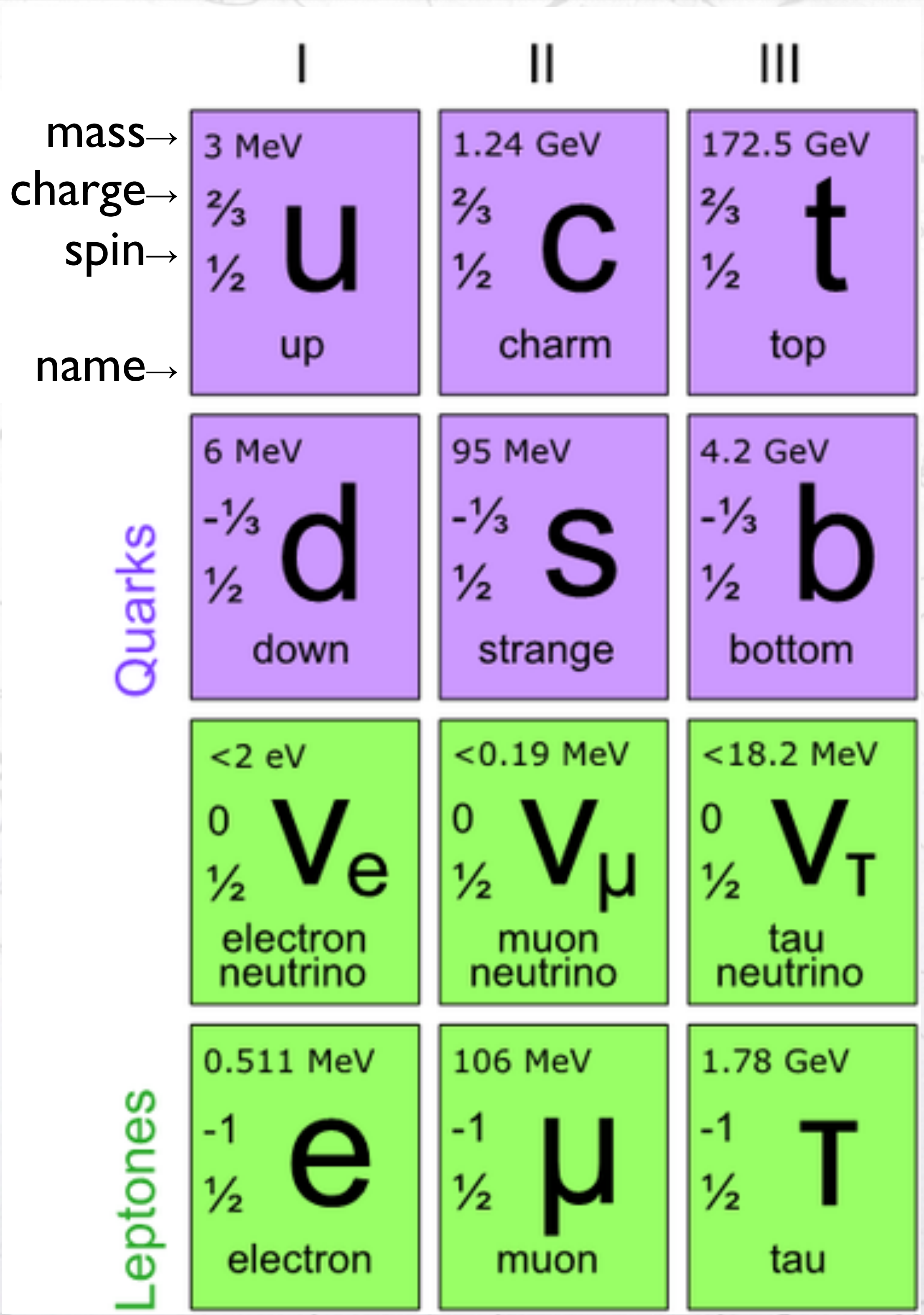
How many neutrinos ?

- Elementary particles are grouped in 3 generations.



How many neutrinos ?

- Elementary particles are grouped in 3 generations.
- Each generation is like the previous but with larger masses.



How many neutrinos ?

- Elementary particles are grouped in 3 generations.
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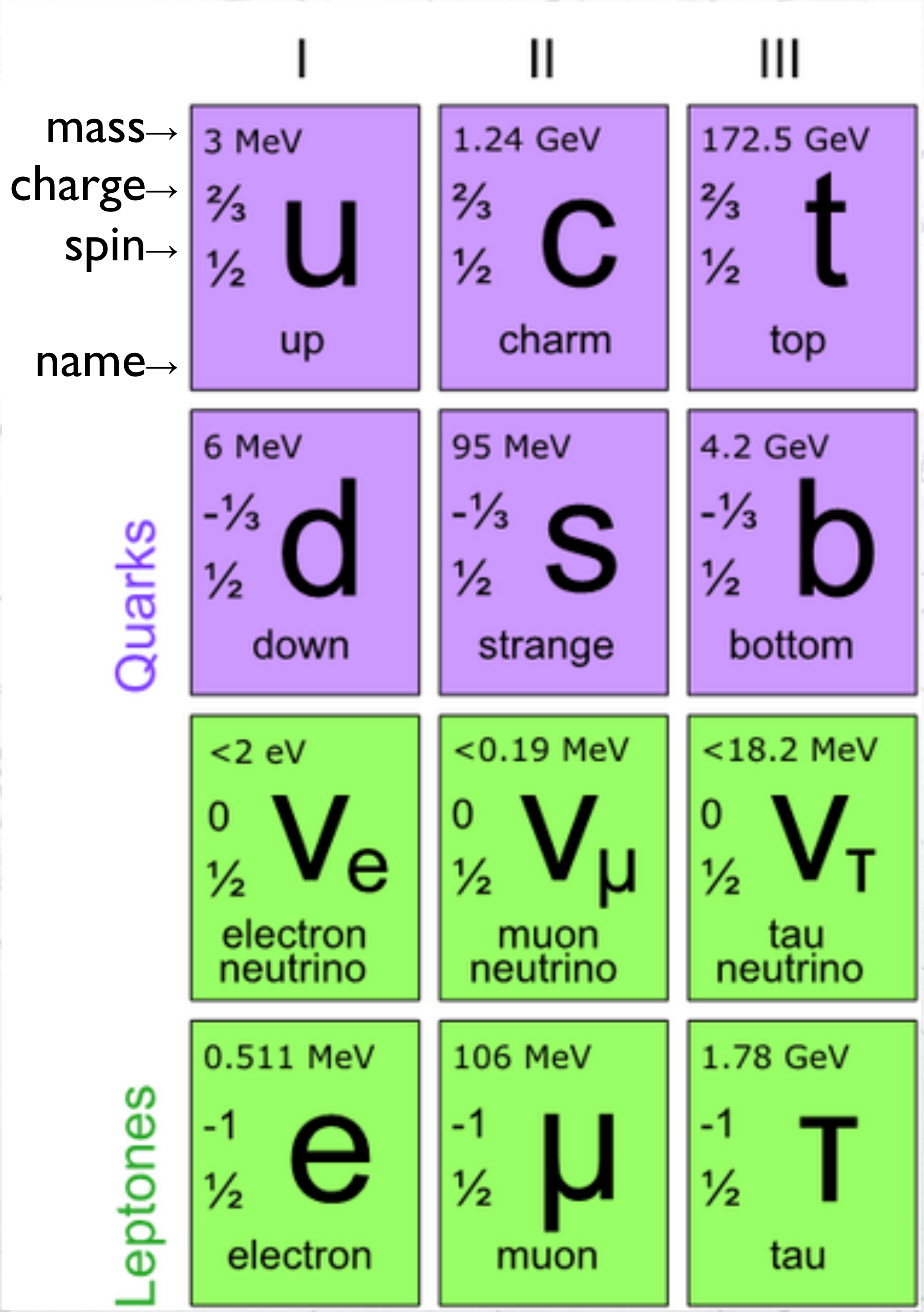
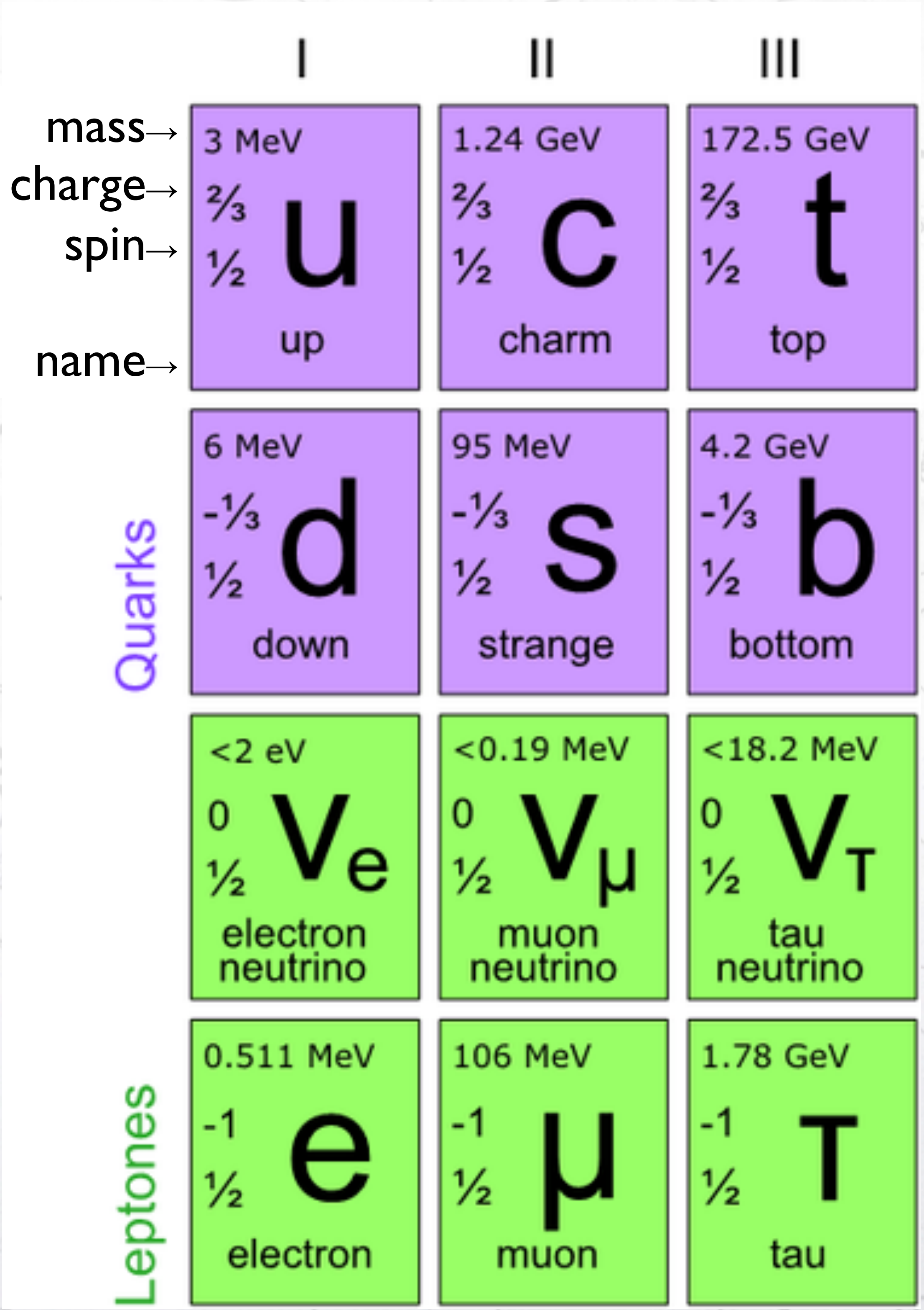
- Ordinary matter is made of the lightest generation (protons, neutrons and electrons).



How many neutrinos ?

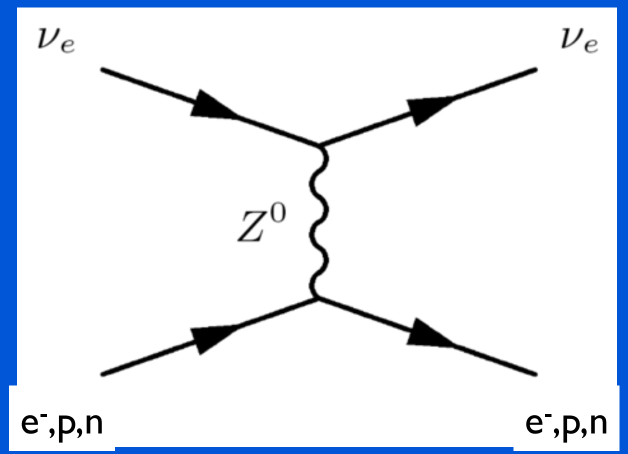
- Elementary particles are grouped in 3 generations.
- Each generation is like the previous but with larger masses.
- Ordinary matter is made of the lightest generation (protons, neutrons and electrons).
- There is one neutrino associated to each family: 3 neutrinos!.



Neutrino interactions

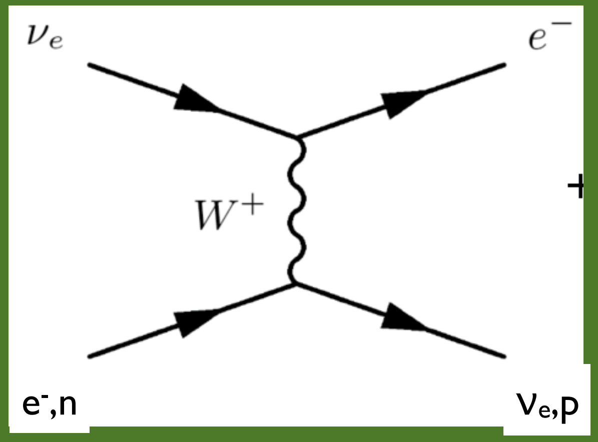
Neutrinos suffer only weak interactions

Neutral Current



Neutrinos in the final state.
It does not distinguish neutrino flavour

Charged Current



Massive lepton in the final state.
It does distinguish neutrino flavour

Neutrinos has no electric charge. Neutrinos has to (weakly) interact to be detected.

At distances of around 3×10^{-17} m, the weak interaction is 10,000 times weaker than the electromagnetic

Neutrino interactions

- Neutrinos suffer only weak interactions.
- Weak interactions couple only to left-handed chiral (~helicity in the massless limit) particles.
- The usual Dirac Lagrangian term for the mass is given by:

$$\mathcal{L}_D = -m_D \bar{\nu}_L \nu_R + h.c.$$

- This implies that, if the neutrino has mass there should be both right handed and left handed neutrinos.
- Right handed neutrinos are "sterile":
  - this was the main argument to believe that the neutrinos were massless.

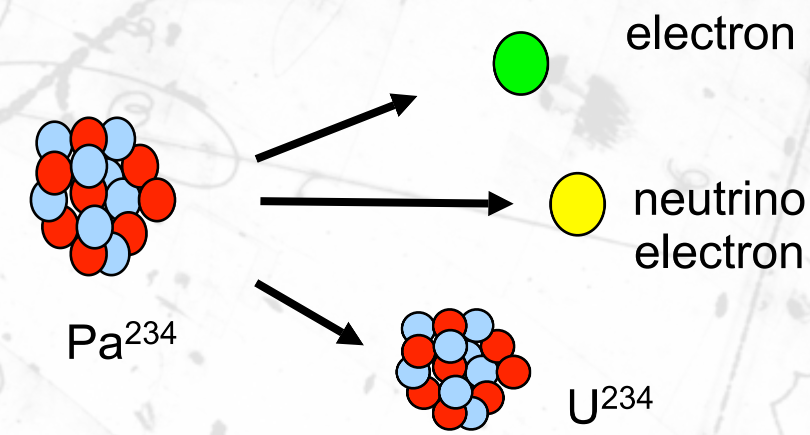
There are models were neutrino = antineutrinos avoiding the "sterile" component.

Neutrino flavour ?

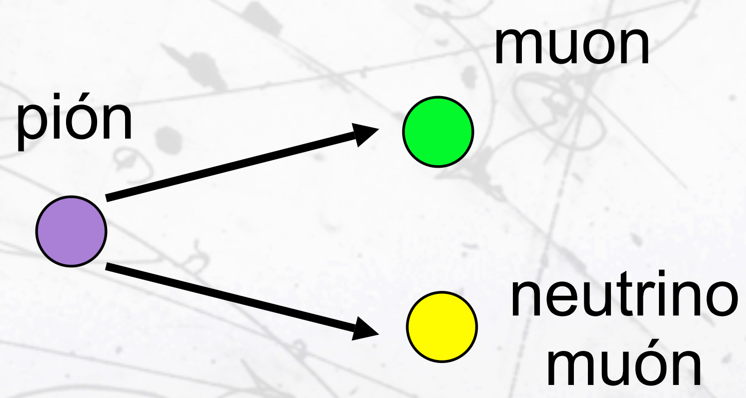
Neutrino flavour depends on the way it interacts

- When a neutrino interacts (produced o disappeared) it is associated to :
  - electron, muon (μ) or tau (τ)
- Depending on the associated particle (leptón) neutrinos are classified as:
  - neutrino electron (ν_e)
  - neutrino muon (ν_μ)
  - neutrino tau (ν_τ)

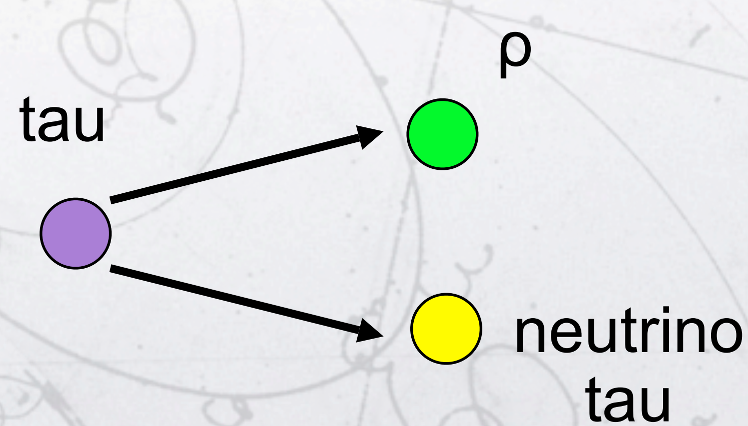
Neutrino electron



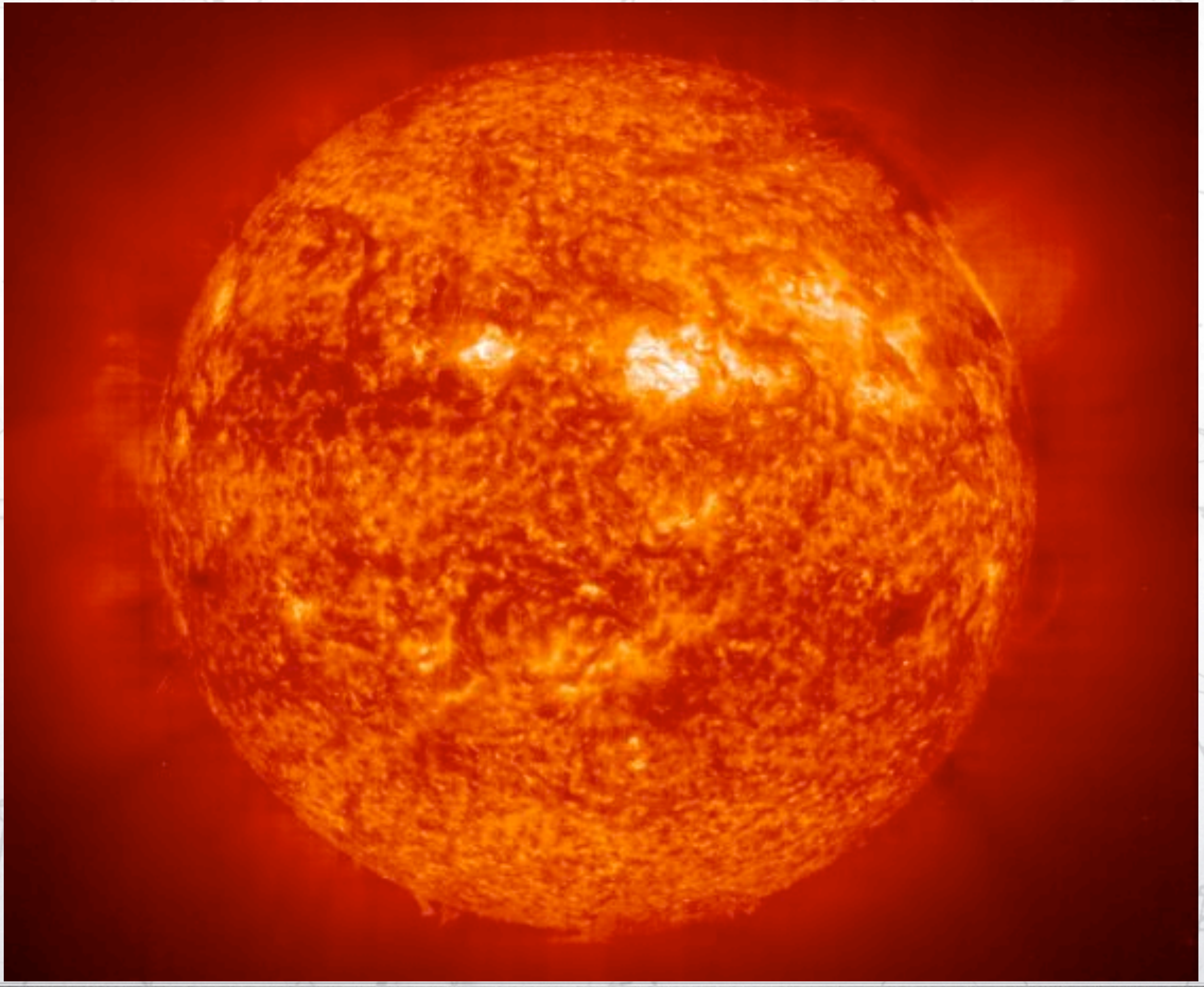
Neutrino muon



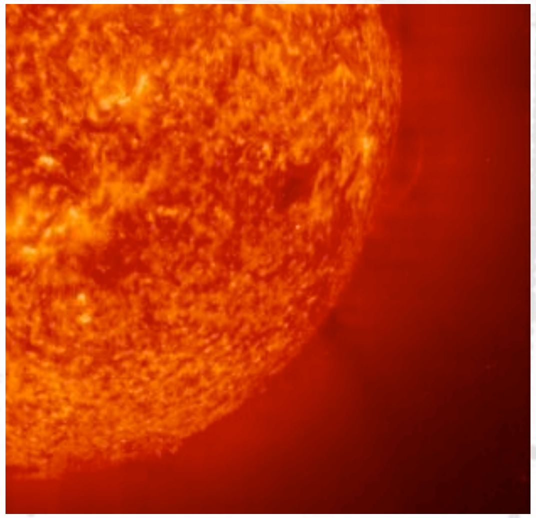
Neutrino tau



The sun



Solar neutrinos



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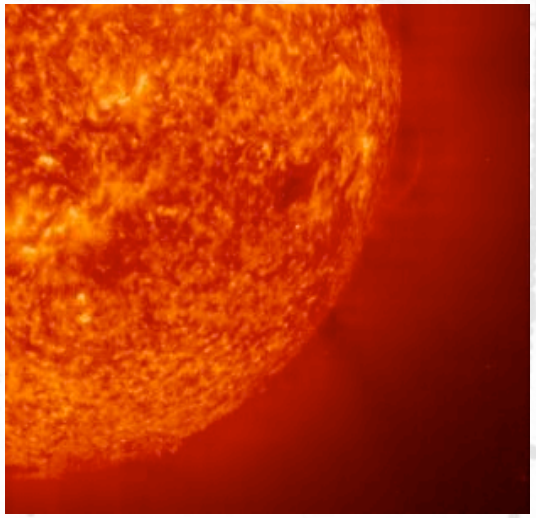
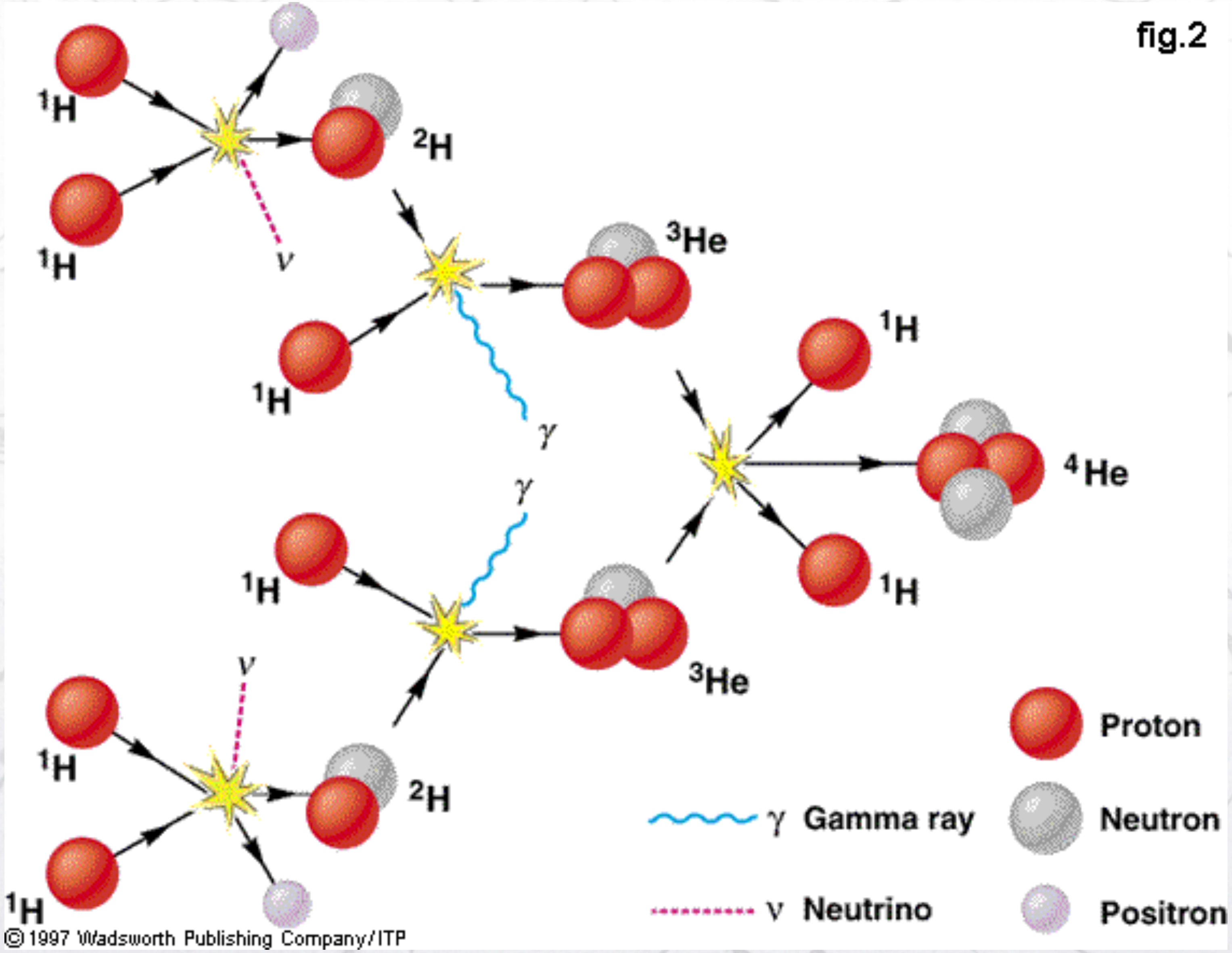


- 4 protons fuse producing a Helium 2 positrones and 2 neutrinos.



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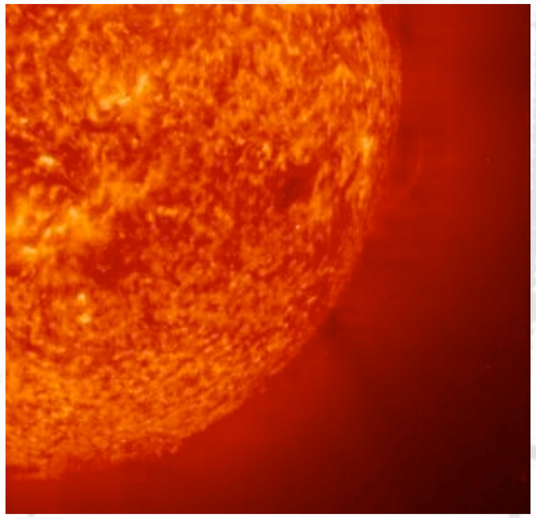

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Solar neutrinos

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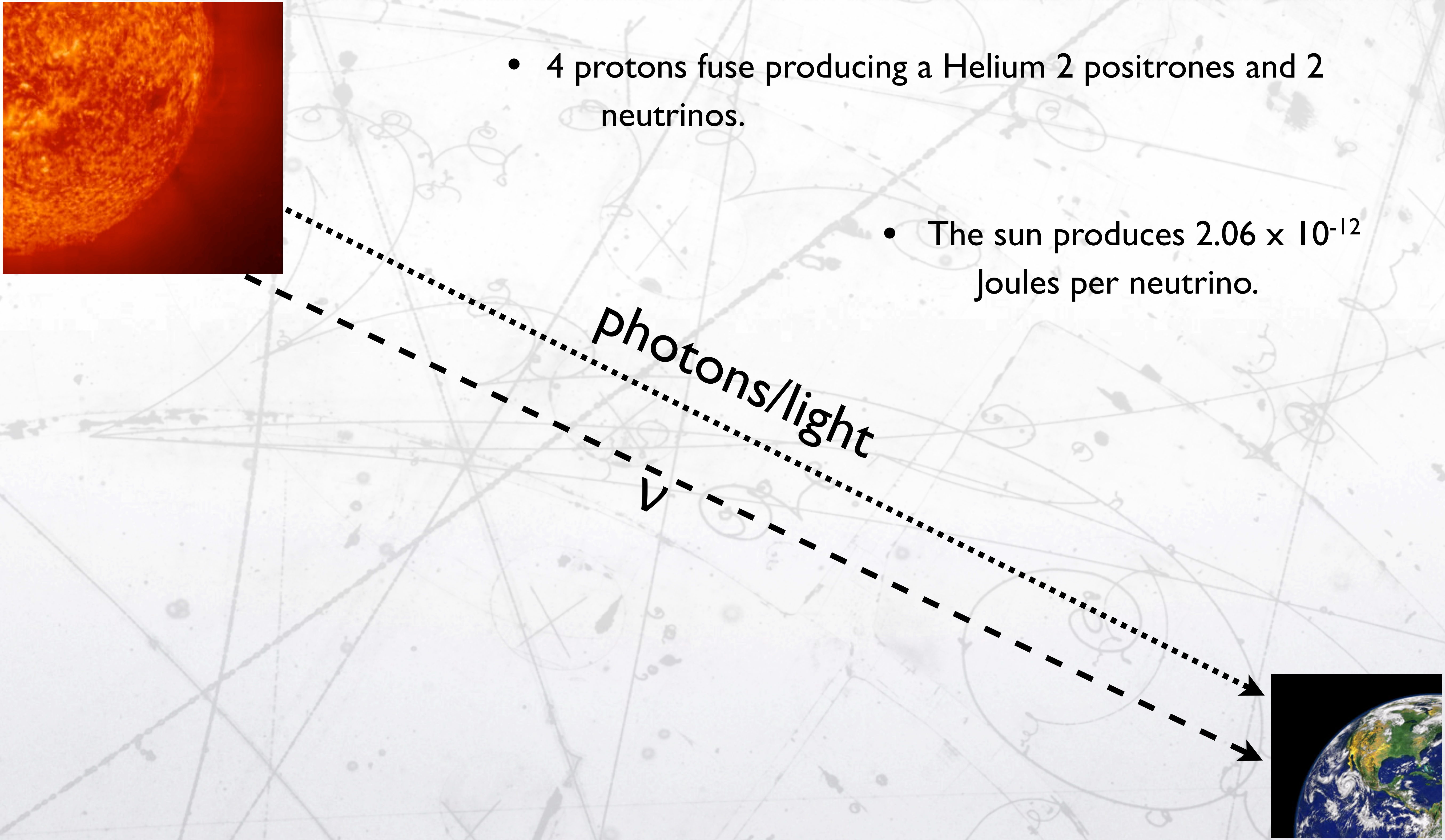
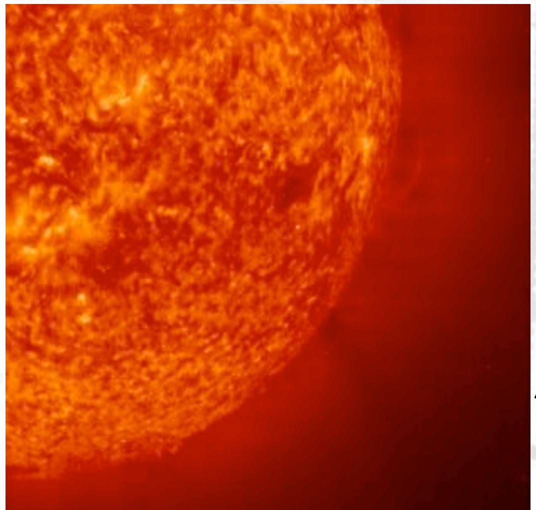
- The sun produces 2.06 x 10^{-12} Joules per neutrino.



Solar neutrinos



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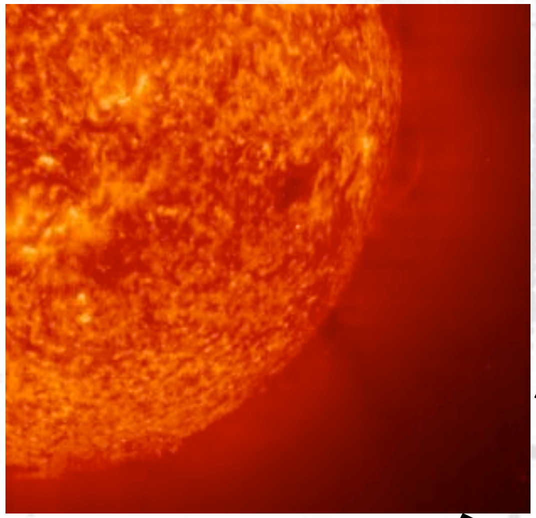
photons/light

ν

- The solar irradiation at the earth superface is 1370 Watts/m^2

Solar neutrinos



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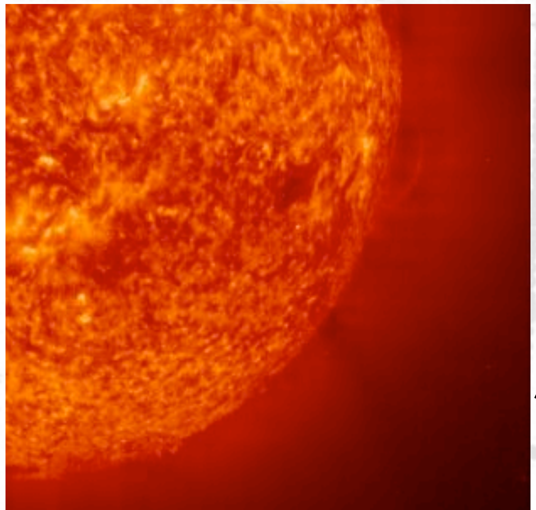
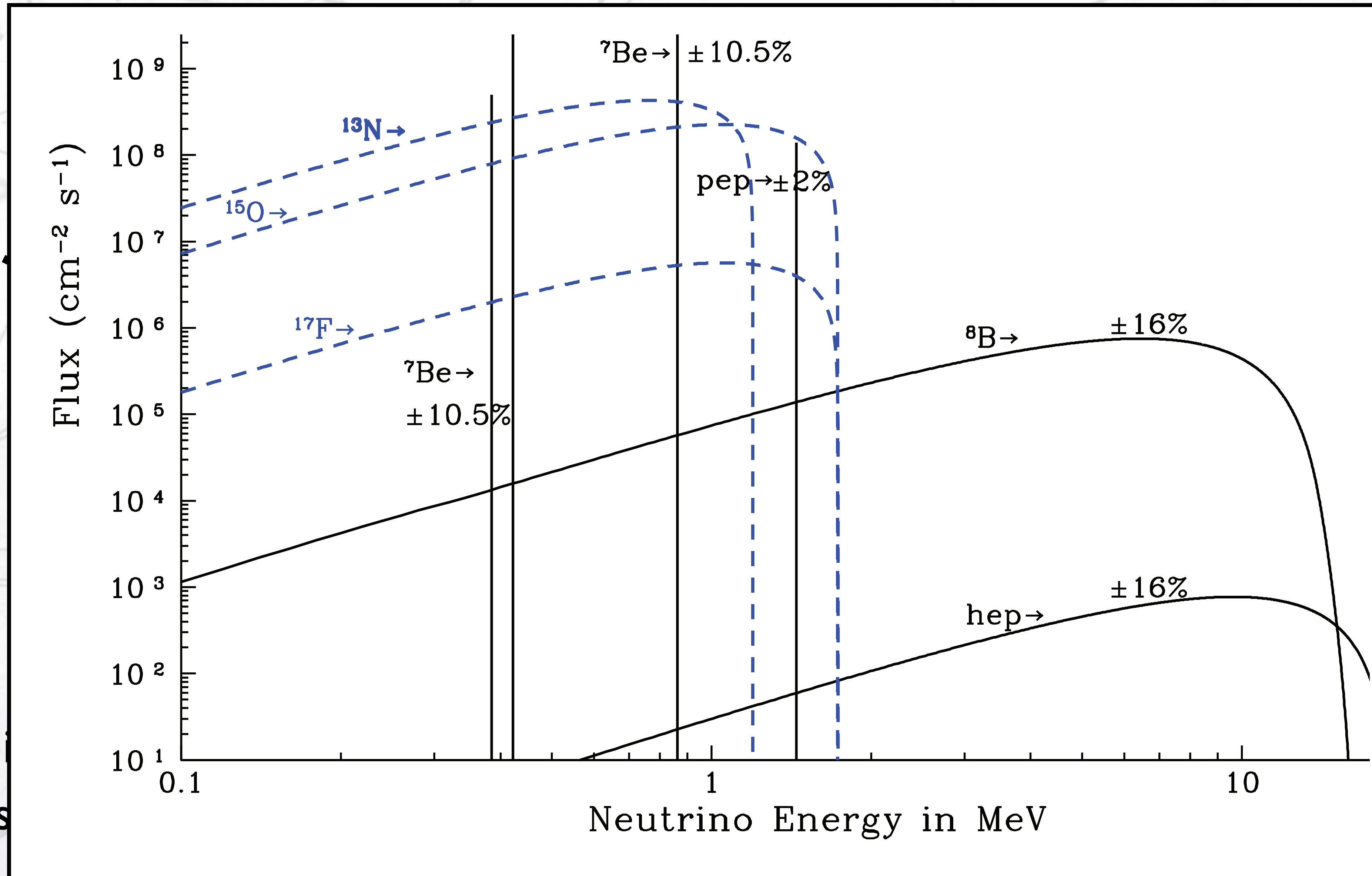
- Neutrino flux is:
  - 1370/(2.06 x 10^{-12})/m^2/sec = 6.65x10^{10}/cm^2/sec.

Solar neutrinos





2

10^{-12}

- The solar irradi
  superface is

The spectrum is known with 10% error

- Neutrino flux is:
  - $1370/(2.06 \times 10^{-12})/m^2/sec = 6.65 \times 10^{10}/cm^2/sec.$

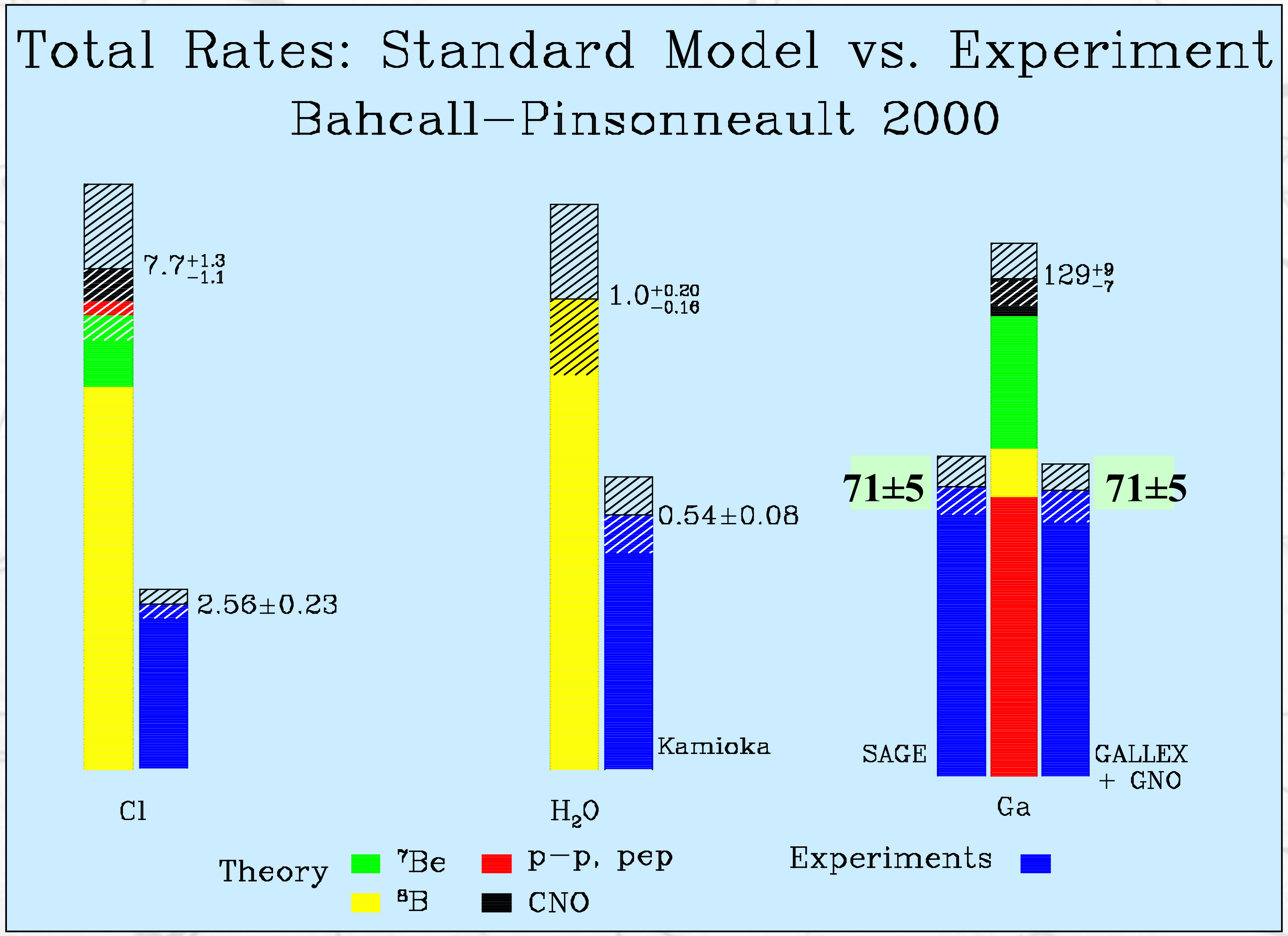
Solar Neutrinos

The experiments

- The first experiments were based on radiochemical detection:
  - Chlorine: $\nu_e {}^{37}Cl \rightarrow {}^{37}Ar\ e^-$ (E_ν> 0.8 MeV)
  - SAGE/Gallex/GNO: $\nu_e {}^{71}Ga \rightarrow {}^{71}Ge\ e^-$ (E_ν> 0.2 MeV)
- Later the water Cherenkov detector Kamiokande was added to the list with a threshold of ~6 MeV.
  - Water Cherenkov added the possibility of online event recording and the determination of neutrino direction:
    - Reduced background, Day/Night and seasonal effects...

Solar neutrinos

The experiments



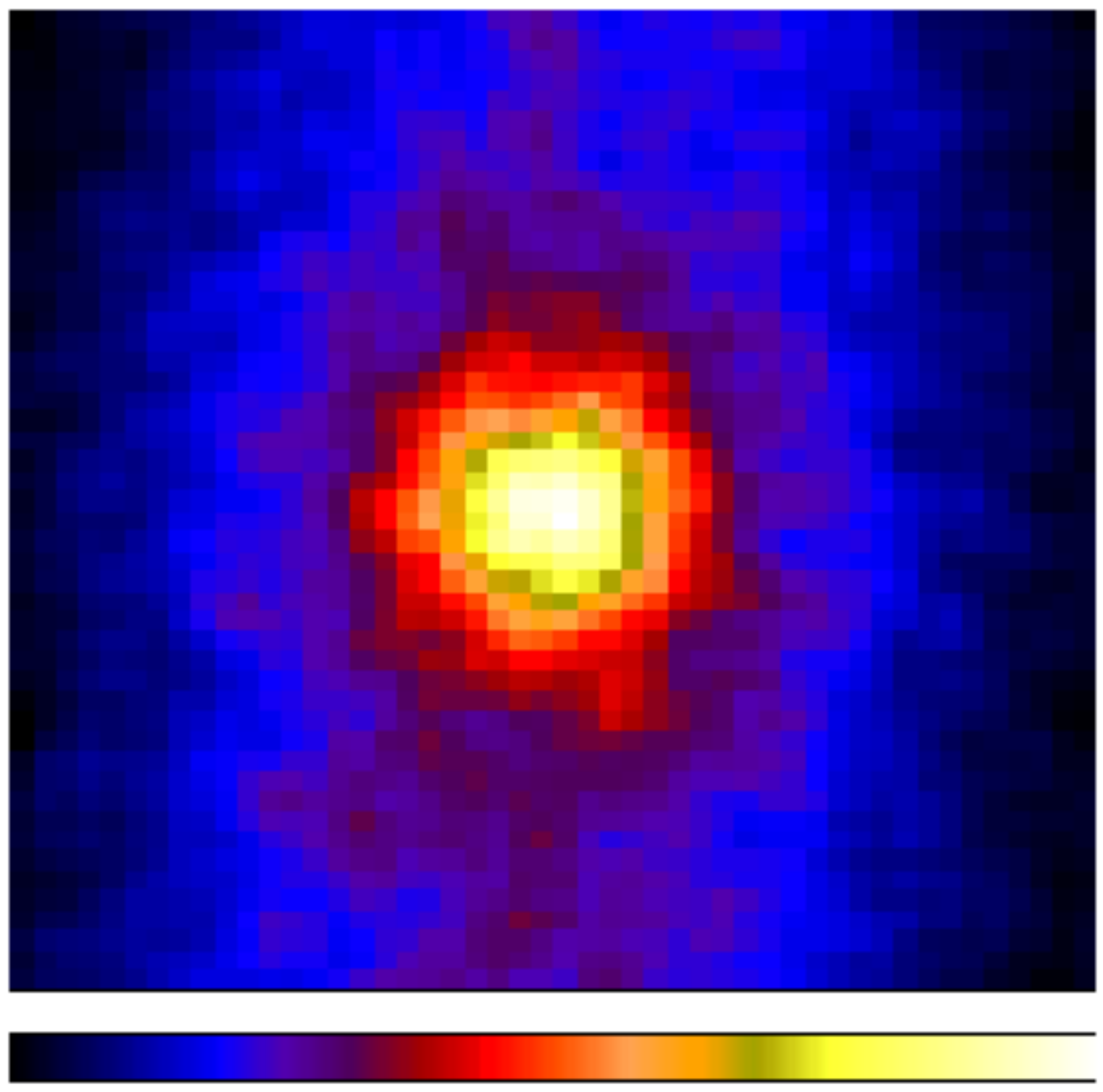
- All of them detected neutrinos, but at a different rate than expected: solar model?, detector efficiencies?, neutrino deficit through oscillations?,…
- This disagreement was called for years “the solar neutrino problem”.

Solar neutrino problem

The paradigm

- Pontecorvo: "Unfortunately, the weight of the various thermonuclear reactions in the sun, and the central temperature of the sun are insufficiently well known in order to allow a useful comparison of expected and observed solar neutrinos..."
- Georgi & Luke: "Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of ^{8}B neutrinos to within a factor of 2 or 3..."
- Yang: "I did not believe in neutrino oscillations even after Davis' painstaking work and Bahcall's careful analysis. The oscillations were, I believed, uncalled for."
- Drell: "… the success of the Standard Model was too dear to give up."

Picture of the sun taken with neutrinos by Super-Kamiokande.



Early ideas

- Bruno Pontecorvo proposed, back in 1957, that the lepton sector might show oscillation phenomena similar to that of the K^0 meson. Neutrinos were neutral particles, and the lepton-hadron analogy was assumed.
- At that time Davis was doing experiments with anti-neutrinos from a reactor looking for the reaction:

$$\bar{\nu}_e \ {}^{37}Cl \rightarrow e^- \ {}^{37}Ar$$

  - And observed some events !!!!!

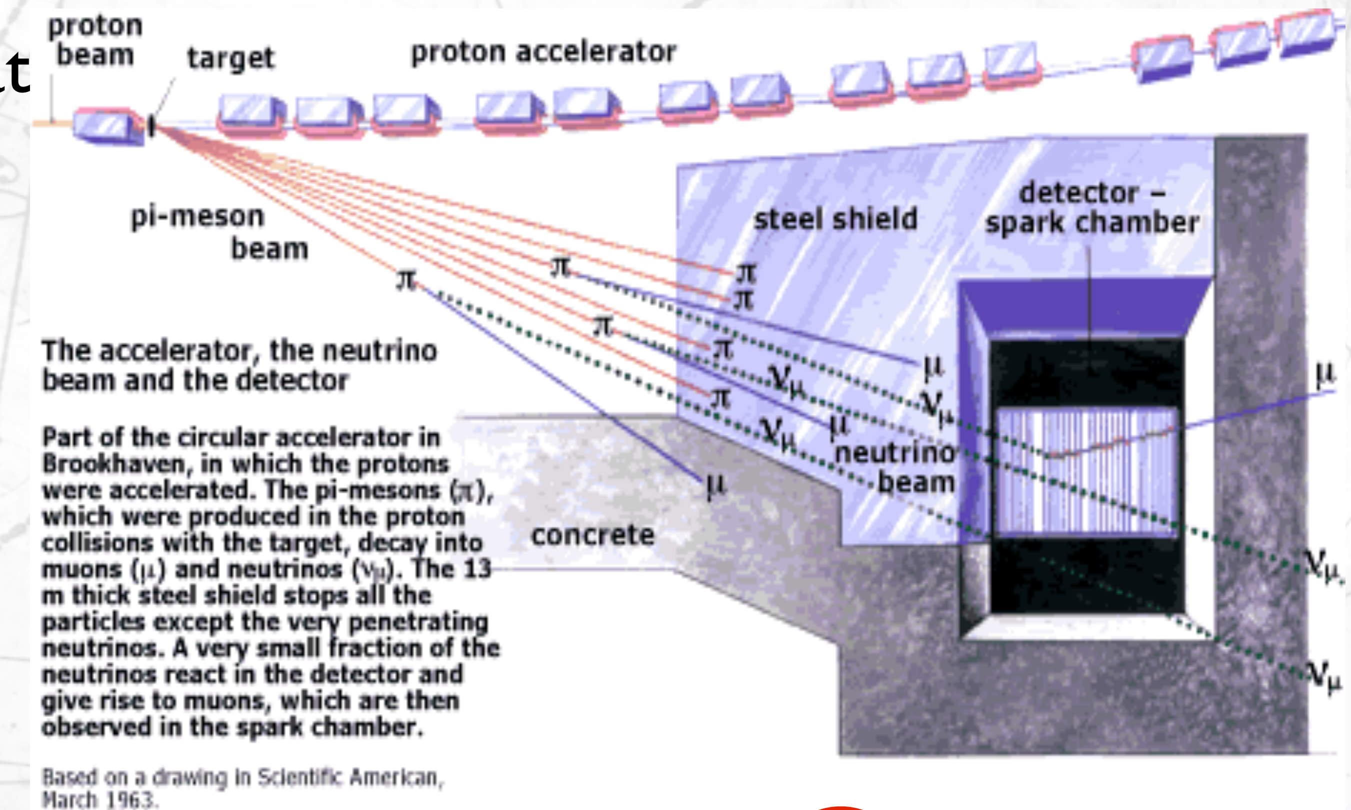
As many other times the hints finally vanished.

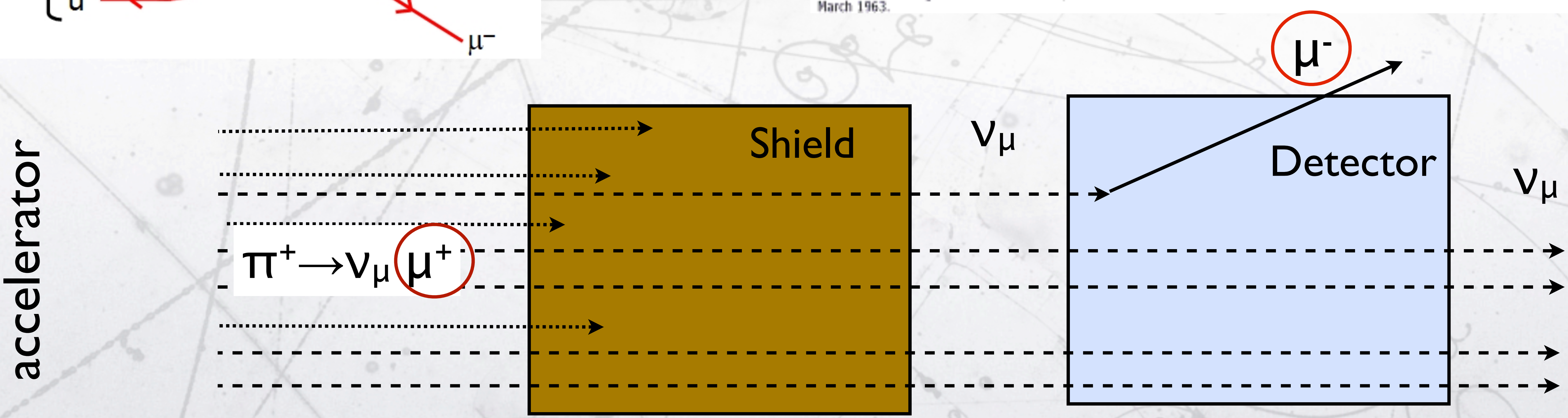
- At that time only one neutrino especie was known and then the only option was to have oscillations (also similar to K^0 system) was:

$$\nu \rightleftharpoons \bar{\nu}$$

This is the valid reaction: $\bar{\nu}_e^{37}Cl \rightarrow e^{+\,37}S$

- Muon neutrino was discovered in 1962 at Brookhaven using the new technology to accelerate protons to high energies.
- This is the same technology use today in neutrino experiments!

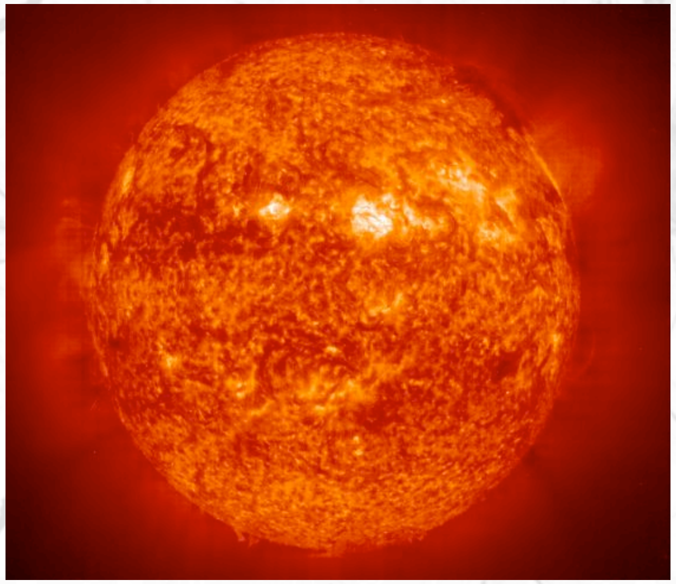




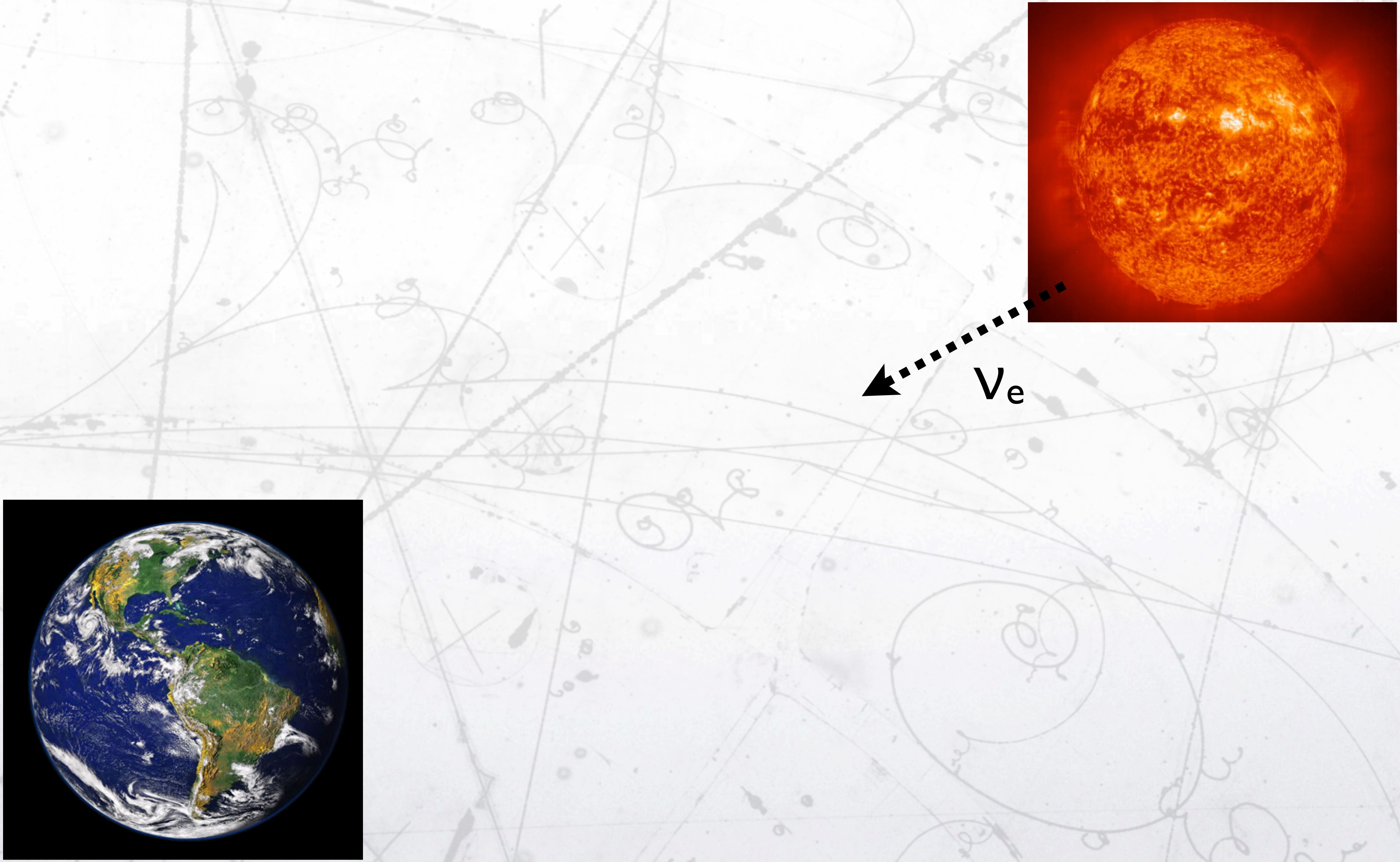
Neutrino oscillation

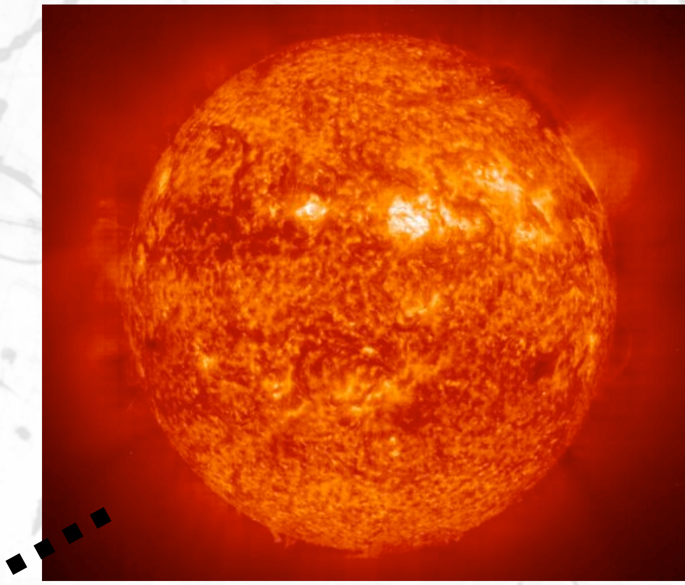
- After the ν_μ discovery at Brookhaven, Bruno Pontecorvo proposed the alternative model based on $\nu_\mu \leftrightharpoons \nu_e$ oscillations.
- The model "only" required:
  - that neutrinos were massive.
  - mass eigenstates are different from flavour eigenstate.
- But, neutrinos were thought to be massless:
  - this was a mainly to avoid the need for "sterile" right handed neutrinos needed to form the Dirac mass term.

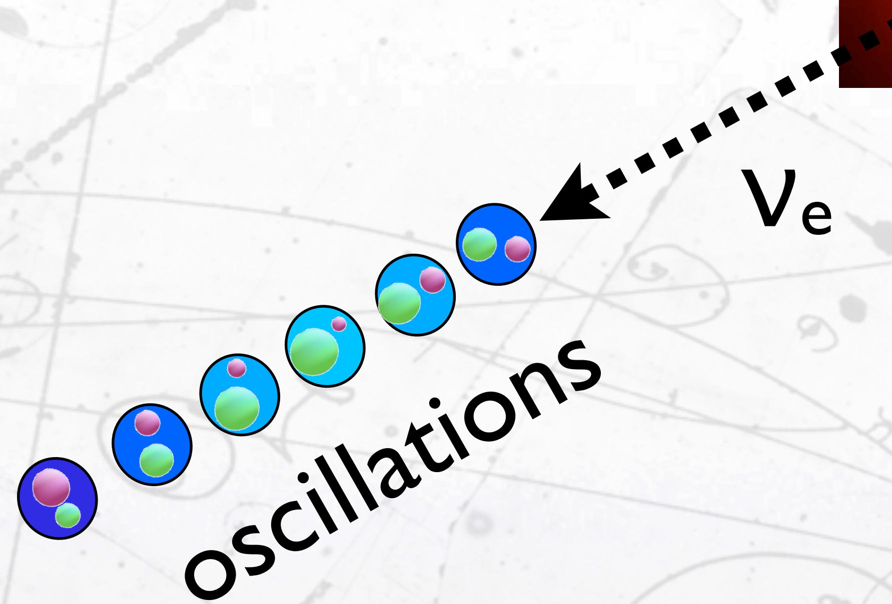
Theoretical prejudicies!



Solar neutrinos & oscillations

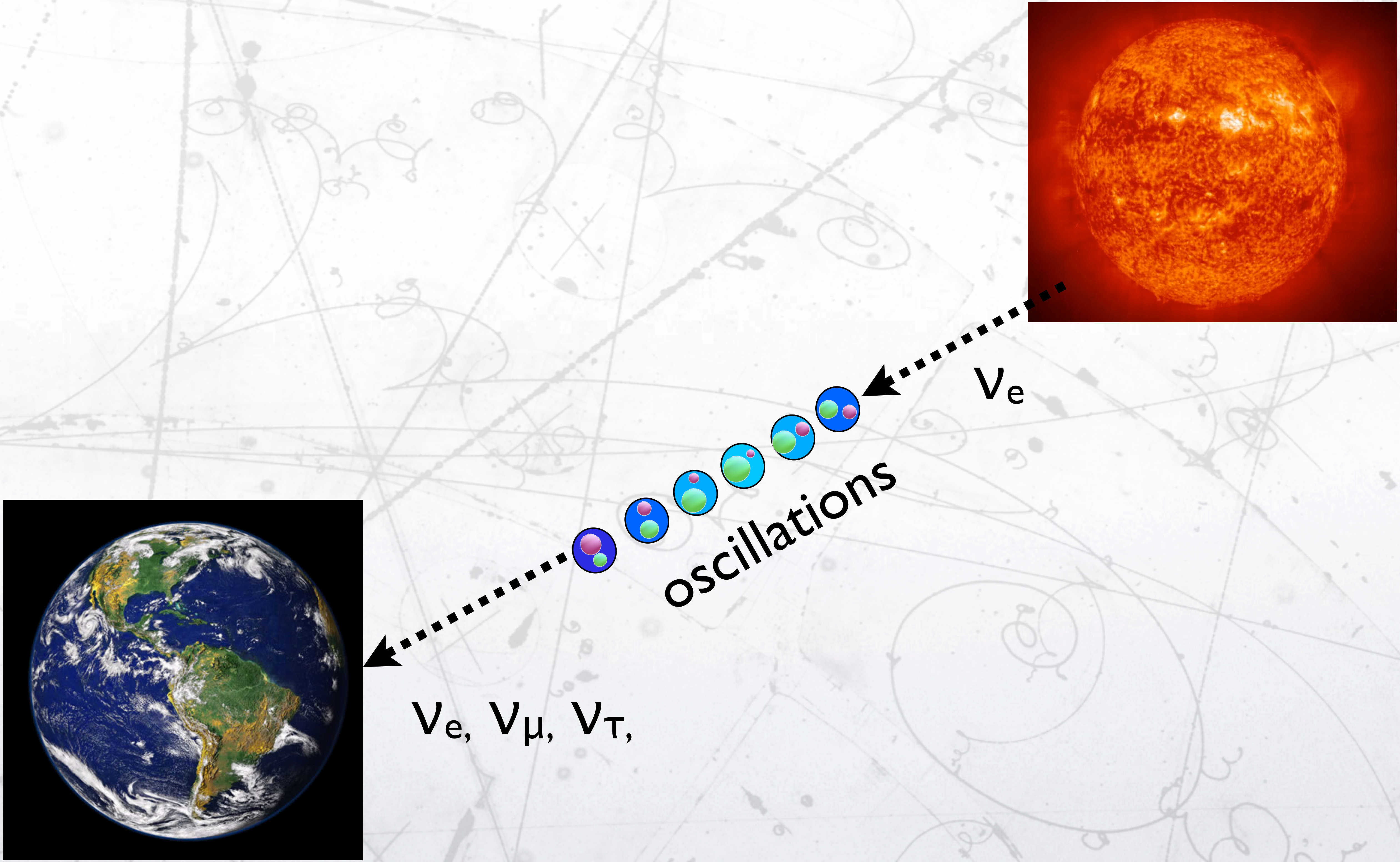






ν_e
oscillations

Solar neutrinos & oscillations

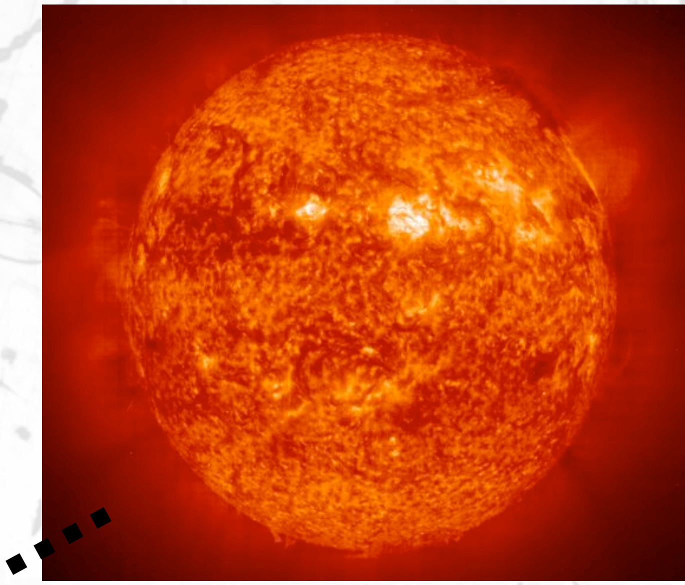


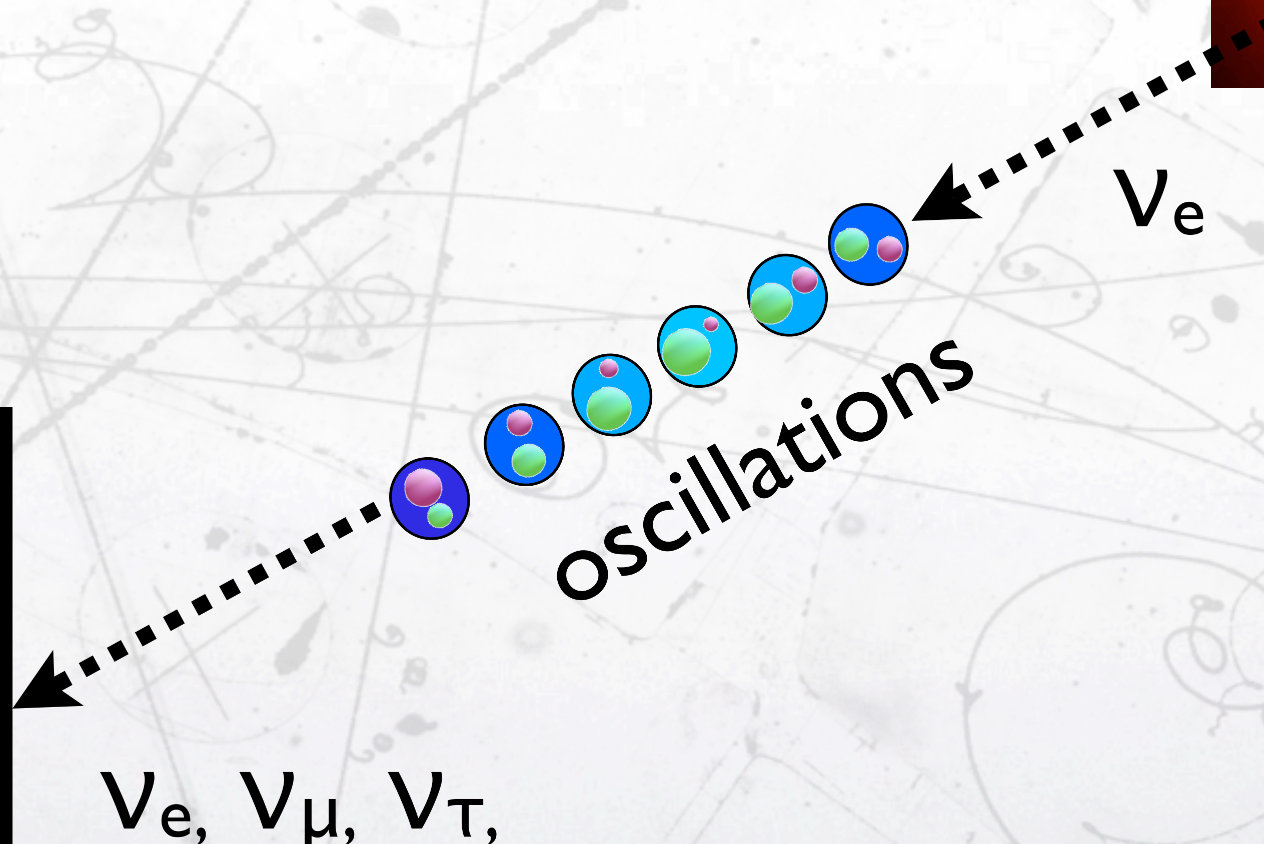
Solar neutrinos & oscillations

The oscillations do not change the number of neutrinos:

$$N_{\nu e} + (N_{\nu\mu} + N_{\nu\tau}) = N^{sol}_{\nu e}$$

But, not all of them are electron neutrinos.





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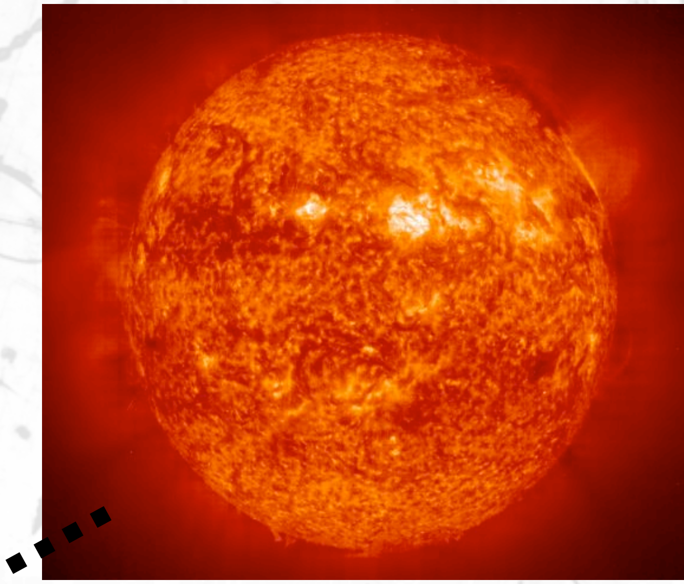
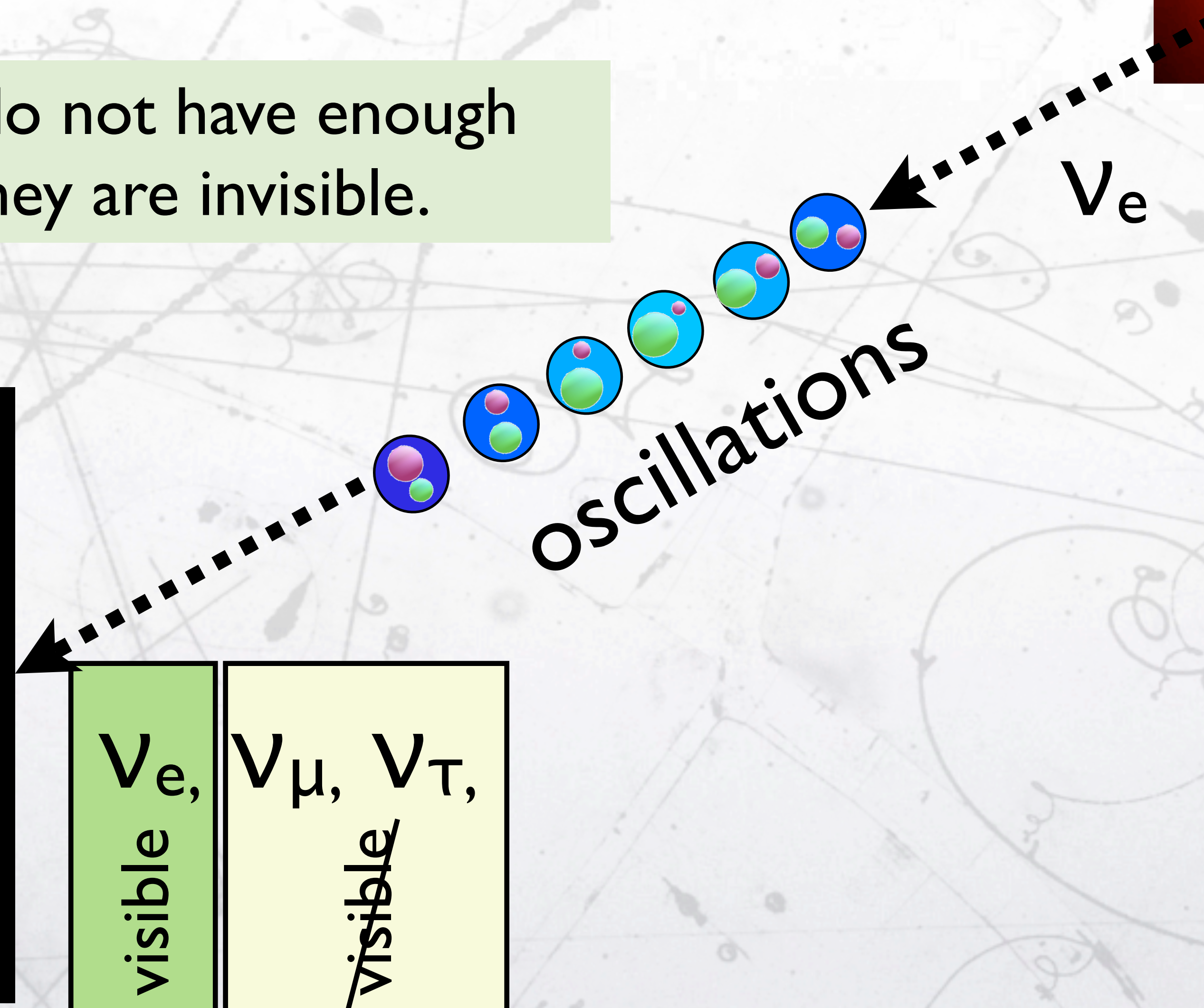
Muon and tau neutrinos do not have enough mass to be detected → they are invisible.





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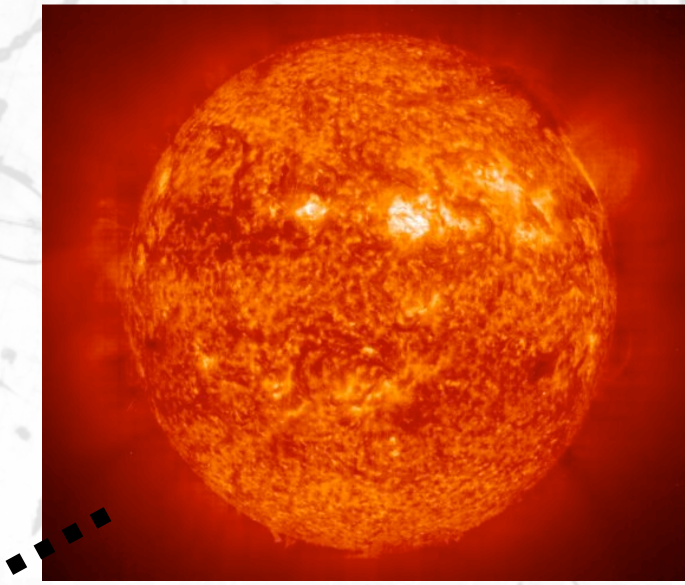

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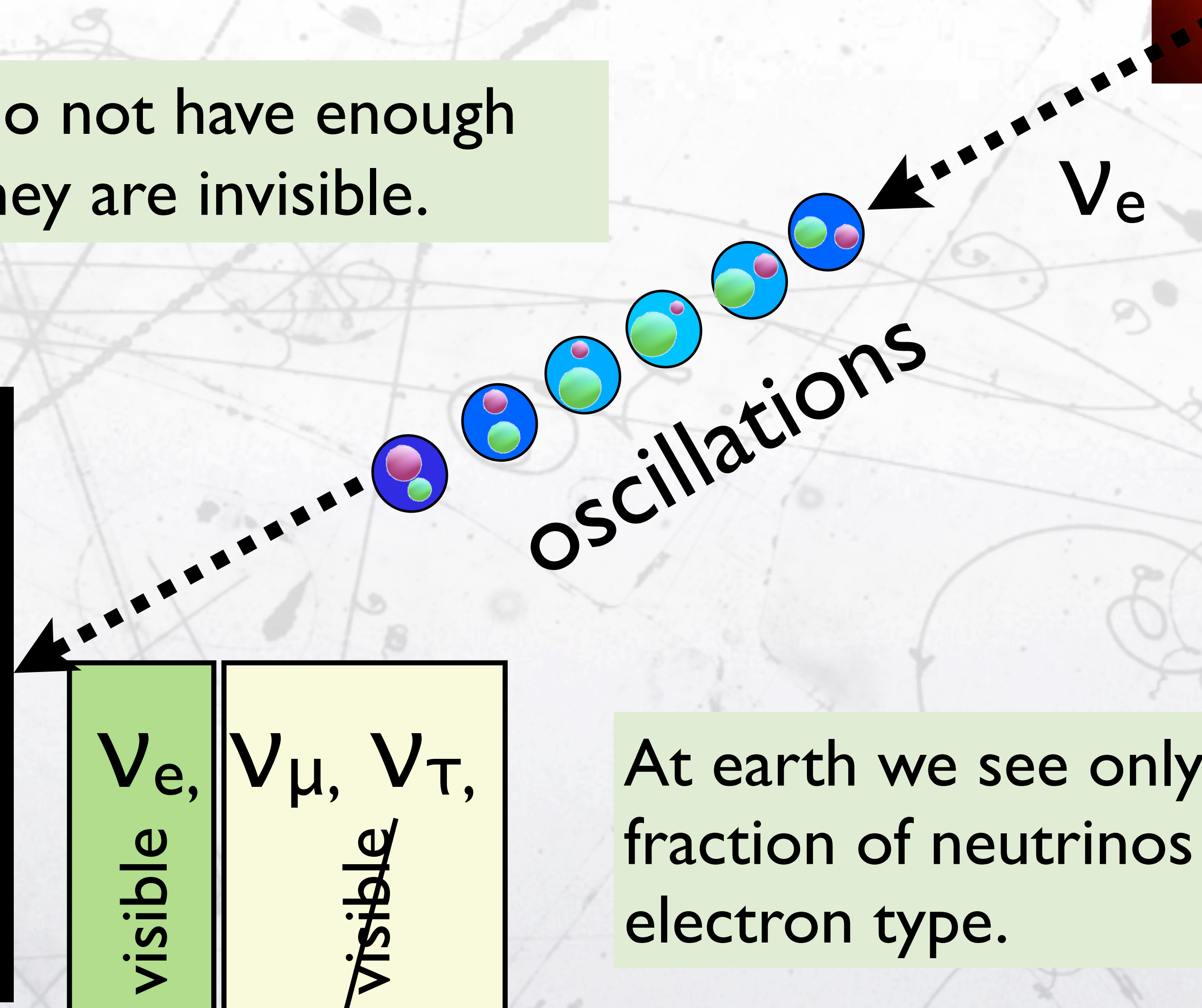


At earth we see only the remaining fraction of neutrinos that are still electron type.

Neutrino oscillation

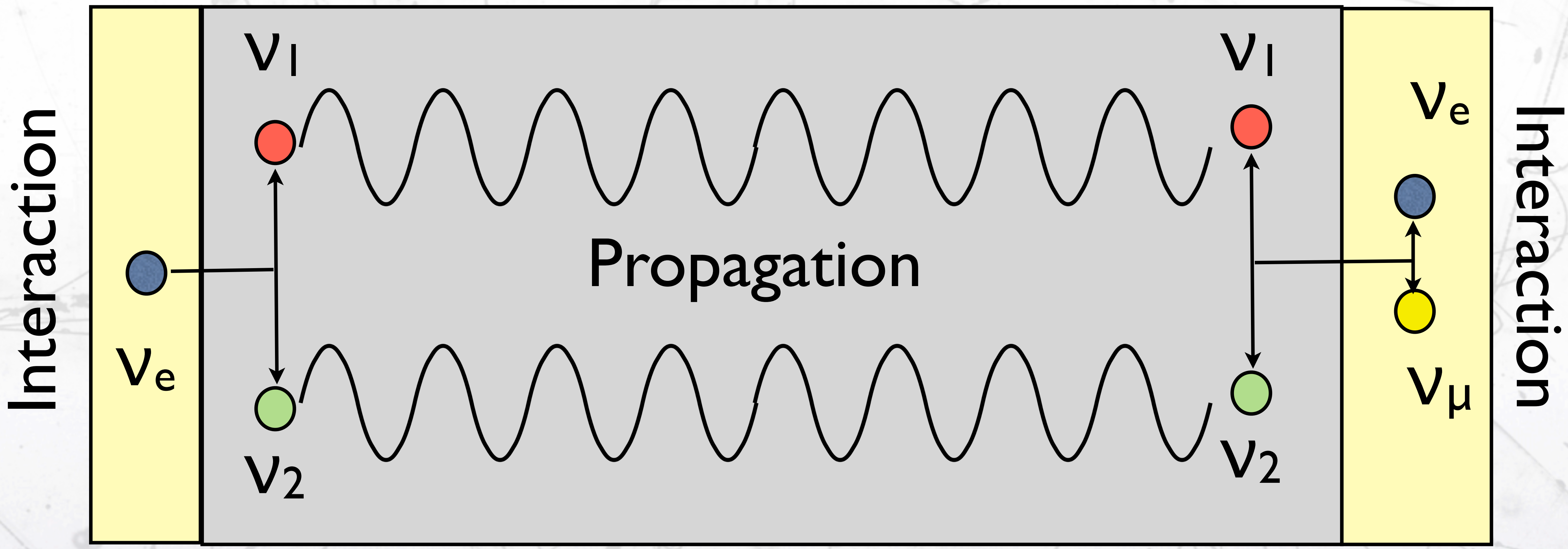
The theory

- The first phenomenological neutrino oscillation model was elaborated by Gribov and Pontecorvo in 1969.
- The model assumed that:
  - neutrinos have mass, albeit a very small one.
  - neutrinos interacts as ν_e or ν_μ (neutrino flavour).
  - the eigenstates of flavour and mass(Lorentz) are not the same. They can be related via a linear combination or rotation between the two bases.

$$
\begin{aligned}
|\nu_e> &= \cos\theta|\nu_1> + \sin\theta|\nu_2> \\
|\nu_\mu> &= -\sin\theta|\nu_1> + \cos\theta|\nu_2>
\end{aligned}
$$

Neutrino oscillation

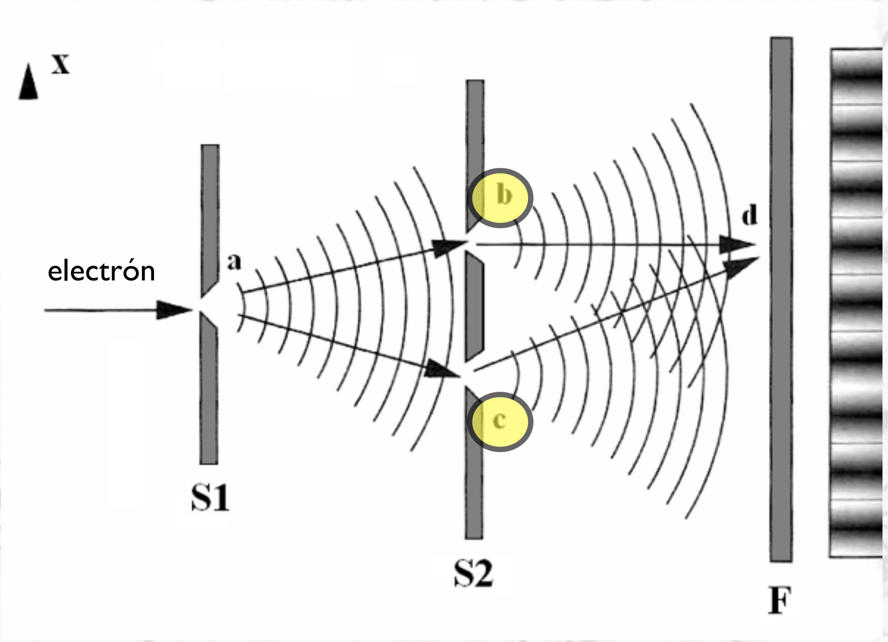
- Neutrinos are produced always as a flavour neutrino but they propagate in vacuum as mass eigenstates.



- If neutrinos 1 & 2 propagate at different speeds (mass) and they keep the coherence at the interaction point the proportions are changed and it might appear other neutrino flavour.

Neutrino oscillation

Neutrino oscillations is similar to the double slit experiment.



Each slit is equivalent to a mass state in the neutrino case. It is a different path to go from emission to detection.

Particles go from source to detector through both slits.

Neutrinos fly through both mass states at the same time.

Every slit gives a different path length → interference

Every mass state gives a different path length (phase) → interference

Neutrino Oscillation

The theory

- When we produce electron neutrino:

$$|\nu_e> \quad = \quad \cos\theta|\nu_1> + \sin\theta|\nu_2>$$

- Neutrinos are transported in vacuum following the Schrödinger equation in vacuum:

$$i\hbar\frac{\partial\nu}{\partial t} = H\,\nu = E\,\nu = \sqrt{m_\nu^2 + p^2}\,\nu$$

- $m_\nu << p$:

$$i\hbar\frac{\partial\nu}{\partial t} = (p + \frac{m_\nu^2}{2p})\nu$$

$$\nu(t) = e^{i(p+\frac{m_\nu^2}{2p\hbar})t}\nu(0)$$

Neutrino Oscillation

- If we produce a ν_e, after some time the state is:

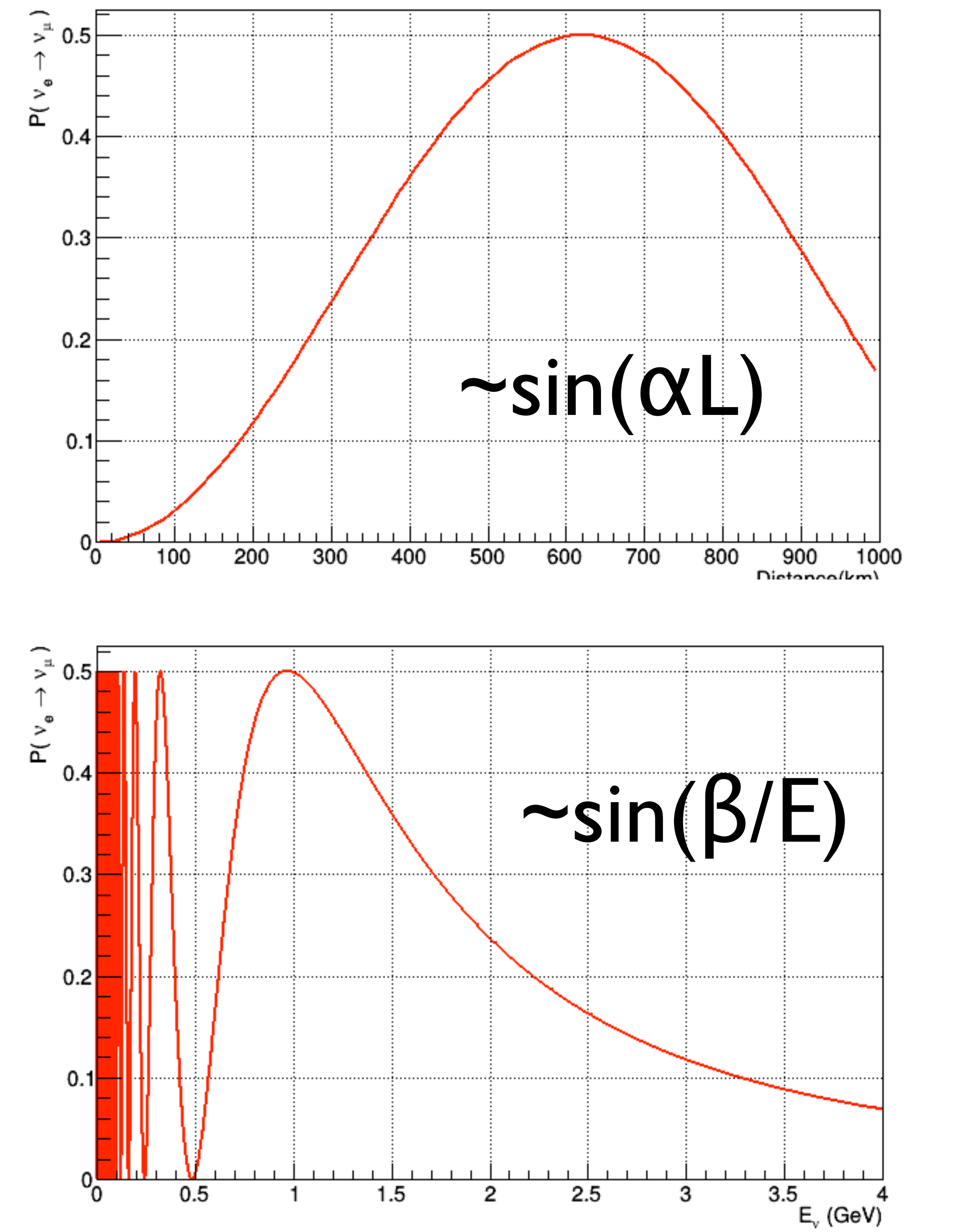
$$|\nu_e;t>=\cos\theta e^{i(p+\frac{m_1^2}{2p})\frac{t}{\hbar}}|\nu_1;0>+\sin\theta e^{i(p+\frac{m_2^2}{2p})\frac{t}{\hbar}}|\nu_2;0>=$$
$$e^{i(p+\frac{m_1^2}{2p})}(\cos\theta|\nu_1;0>+\sin\theta e^{i\frac{m_2^2-m_1^2}{2p}\frac{t}{\hbar}}|\nu_2;0>)$$

- The probability of getting a ν_μ at the interaction is then:

$$|<\nu_\mu|\nu_e;t>|^2 = |-\cos\theta\sin\theta<\nu_1|\nu_1;0>+\sin\theta\cos\theta e^{i\frac{m_2^2-m_1^2}{2p}\frac{t}{\hbar}}<\nu_2|\nu_2;0>|^2$$
$$= \sin^2\frac{\theta}{2}\sin^2\frac{m_2^2-m_1^2}{4p}\frac{t}{\hbar}=\sin^2\frac{\theta}{2}\sin^2 1.267\frac{\Delta m^2 L}{E}\frac{GeV}{eV^2 km}$$

- Flavour-lepton number is not conserved!. Opens the possibility for flavour violation in lepton decay & production.

Neutrino Oscillation



θ = π/2

$\Delta m^2 = 2.\times 10^{-3}\ eV^2$

$$|<\nu_\mu|\nu_e;t>|^2 = \sin^2\frac{\theta}{2}\sin^2 1.267\frac{\Delta m^2 L}{E}\frac{GeV}{eV^2 km}$$

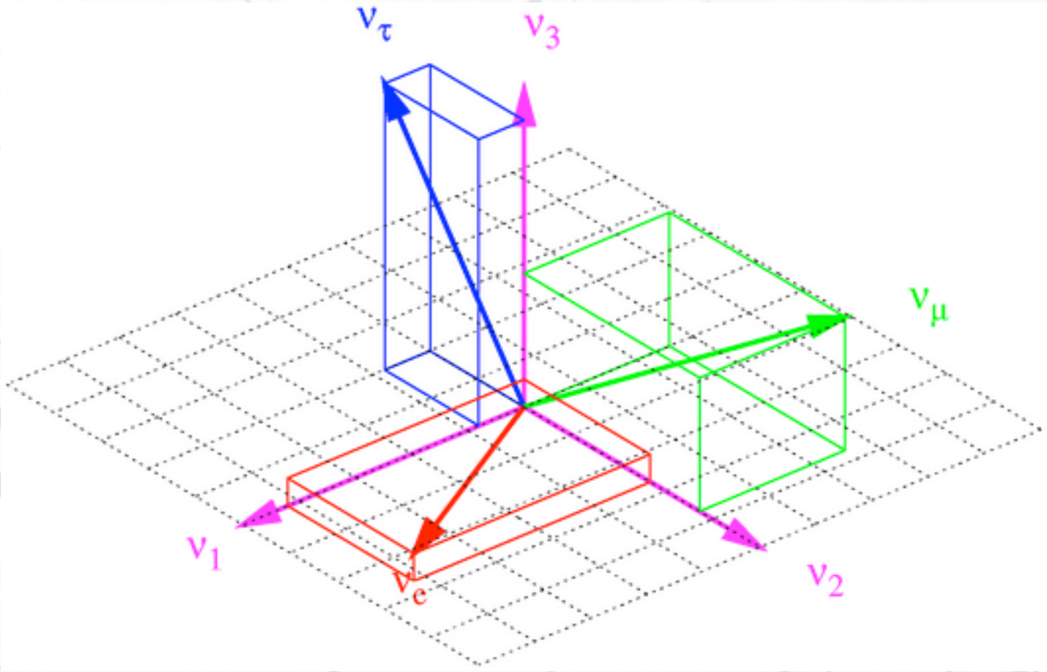
Oscillations are seen as change of ν flavour composition as function of:

Energy

Distance

The theory

$$\begin{pmatrix}\nu_e & \nu_\mu & \nu_\tau\end{pmatrix} = U_{PNMS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



$$U_{PNMS} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{21} & \sin\theta_{21} & -\sin\theta_{21}\\ 0 & \cos\theta_{21} & 0\\ 0 & 0 & 1\end{pmatrix}$$

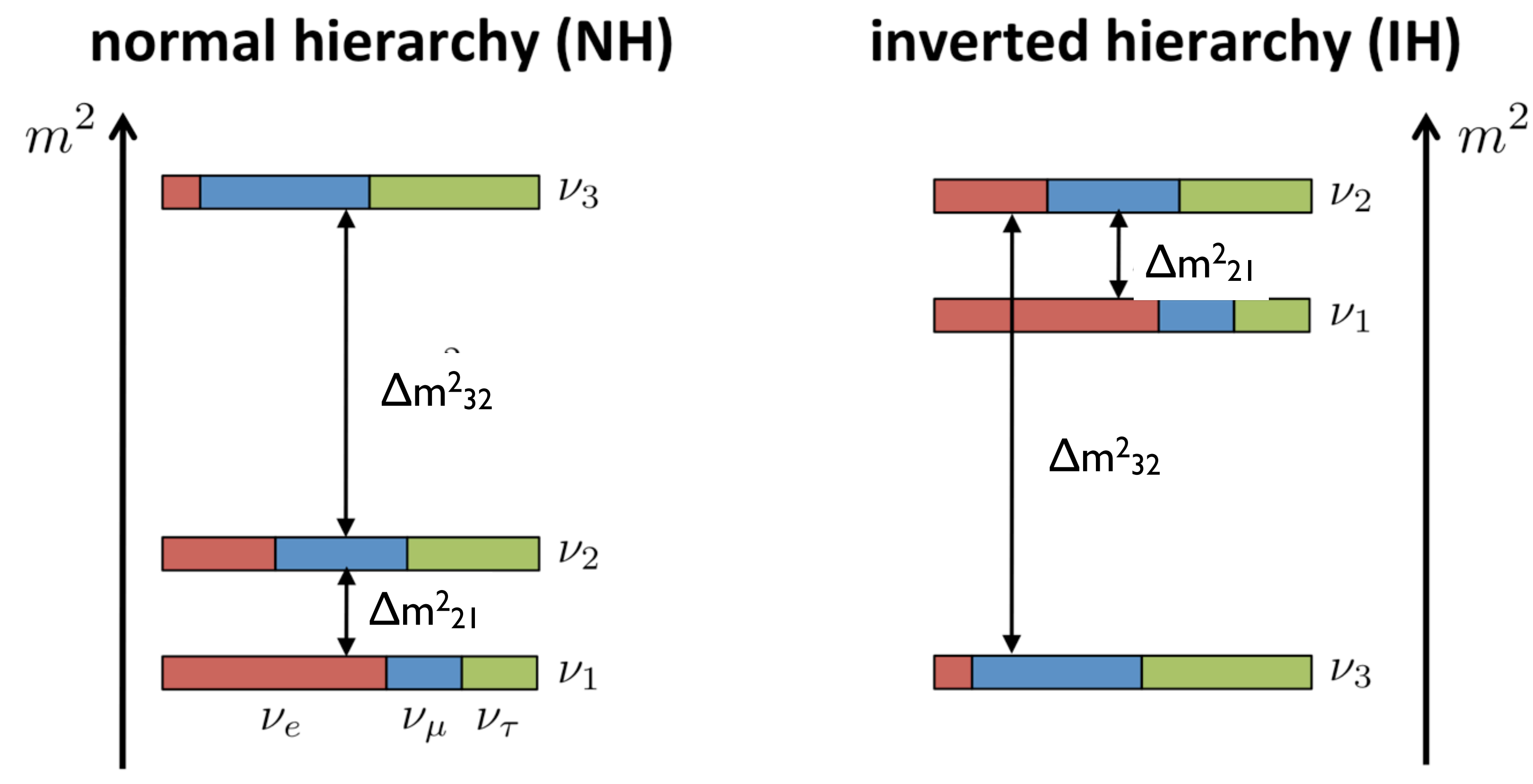
- With 3ν, there are 3 angles and 1 imaginary phase:
- The phase allows for CP violation similar to the quark sector.
- There are also 2 values of Δm^2, traditionally $\Delta m^2{}_{12}$ &$\Delta m^2{}_{31}$.

Oscillations & mass

- ν oscillation is an interference phenomenon:
  - We can't measure the absolute neutrino mass, only differences.
- ν mass levels do not need to follow the ones of the "heavy" leptons.

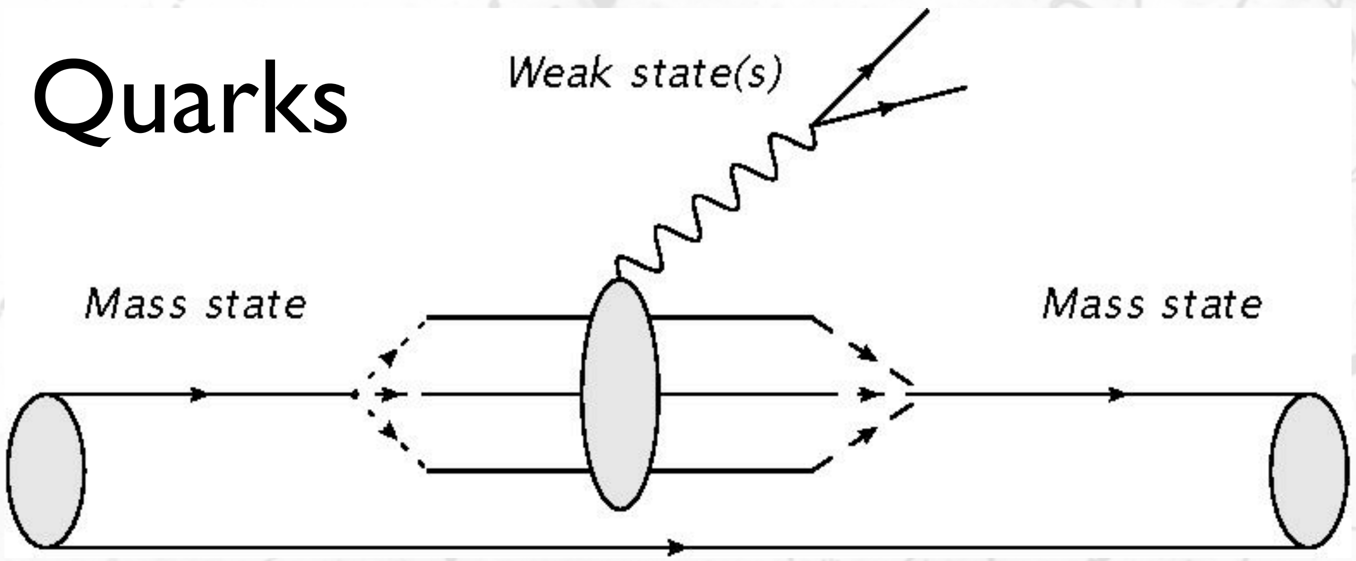
<u>Definition</u>

ν_1 is the largest component of ν_e
ν_2 is the largest component of ν_μ
ν_3 is the largest component of ν_τ

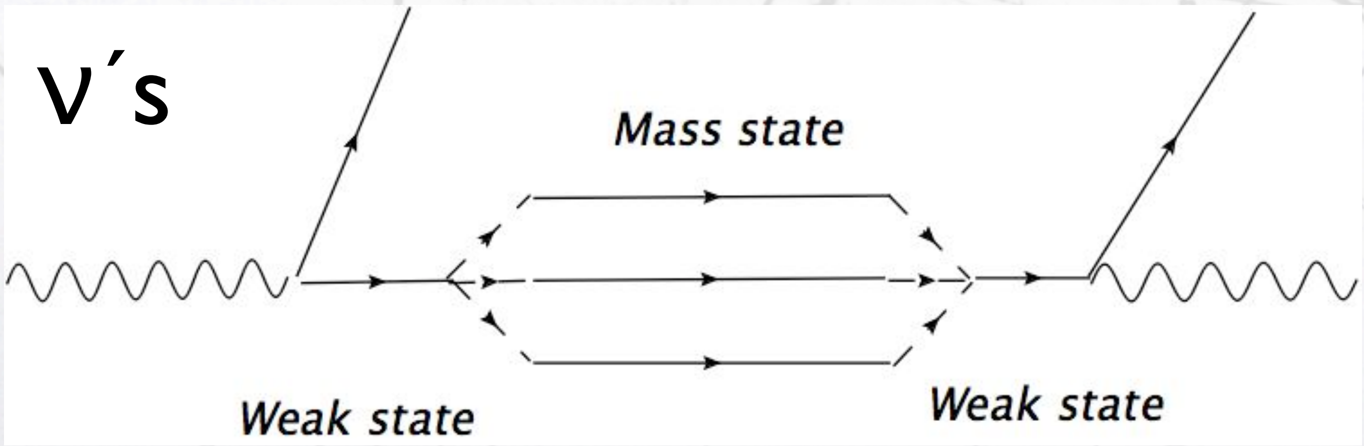


Lepton vs. quark mixing

Quarks



ν´s



Quark and neutrino mixing are the same phenomena!

- Quarks & neutrinos exist in matter and vacuum as mass states.
- In quark mixing, the quark is at the mass state at the initial and final state.
- In neutrino oscillations, the mass state are intermediate states, initial and final ar flavour states.
- There are cases where the neutrino behaves "as the quarks do": i.e. lepton flavour violation in decays.

Back to experiments

- How to unveil the "solar neutrino" problem?
  - It was not statistics or systematics, repeating experiments won't help.
  - measure the total neutrino flux (3 flavours) from the Sun (SNO).
  - produce a neutrino flux that is calculable. (Kamland).
- In parallel, search in the ν_μ sector for equivalent phenomena (atmospheric neutrinos & SuperKamikande).

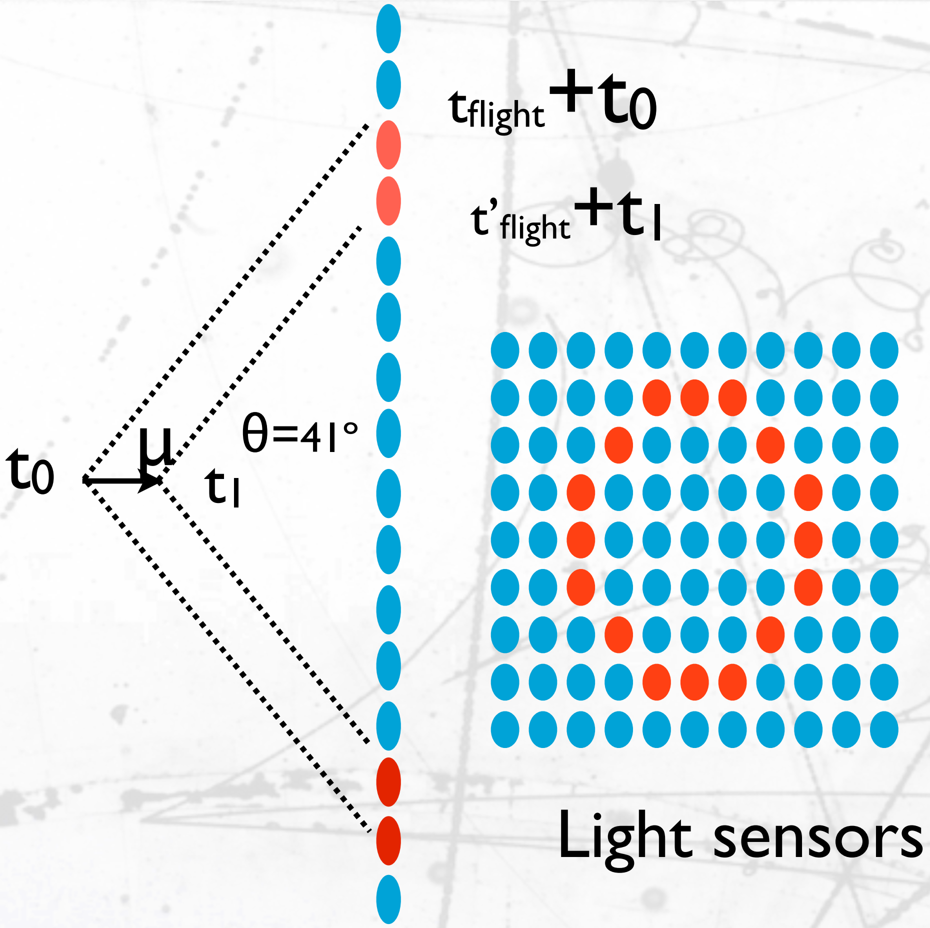
Detecting neutrinos

- Neutrinos have a very low probability (weak force) to interact with matter.
  - neutrinos of 1 GeV can cross 10^9 earth diameters without interaction.

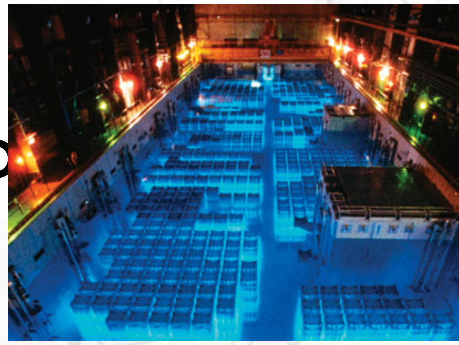
10^9 earth diameters.

- We need very large neutrino fluxed (~10^{20}) and detectors (hundreds of Tons) to detect a handful of neutrinos.

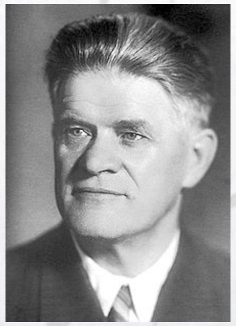
Cerenkov & big detectors



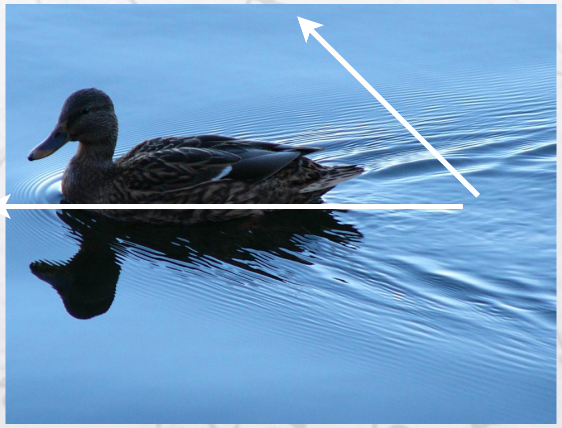
- When charged particles travels in a material faster than the speed of light in this material emits ultraviolet and blue light.



- This light forms a shock wave, so it remembers the particle direction.
- In water the light is emitted in a 45° code around the particle. dirección.



- Shock waves are visible in other areas of physics.

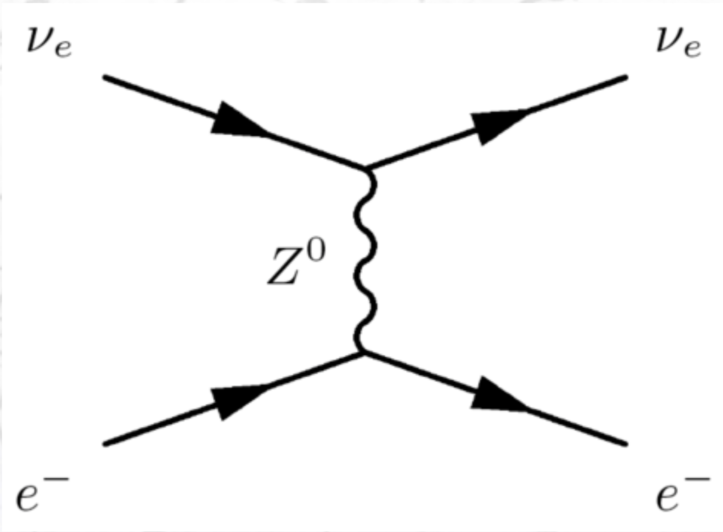


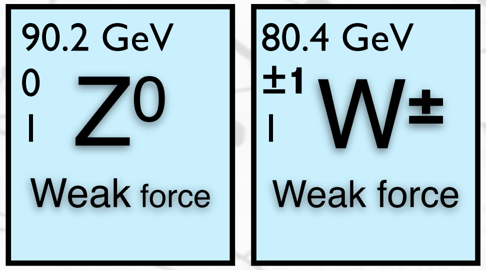
SNO
The solution to the solar neutrino problem

Θ_{12} & Δm^2_{12}

SNO experimental concept.

- SNO tried to measure the total flux of solar neutrinos.
- Neutral currents do not produce heavy leptons, only neutrinos. There is no energy limit in the reaction:



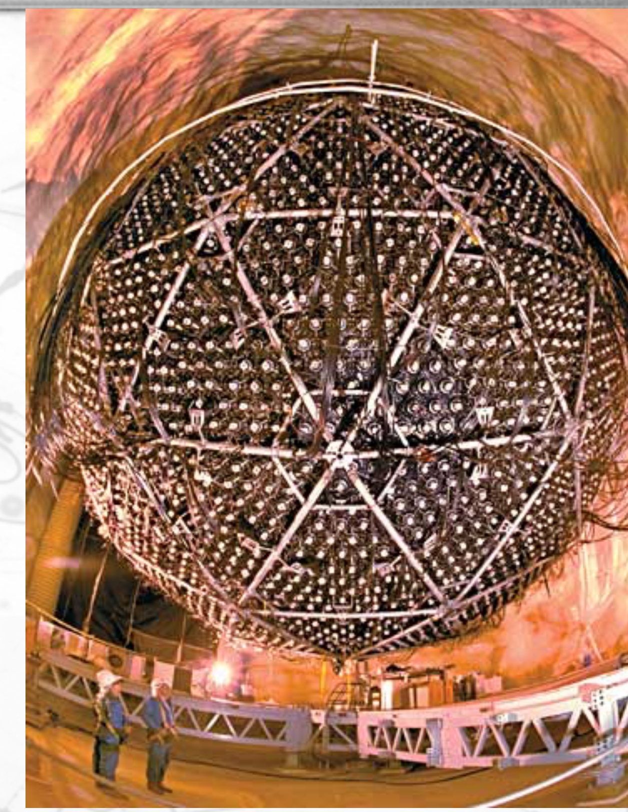


- Neutral currents do not distinguish the flavour of the neutrino, but the integrated flux:

$$N_{\nu}^{neutral\,current} \approx N_{\nu_e} + N_{\nu_\mu} + N_{\nu_\tau} = N_{\nu_e}^{sun}$$

SNO

SNO = Sudbury Neutrino Observatory



Filled with heavy water.
In heavy water the hydrogen is replaced by deuterium: 1 proton and 1 neutron.

Deuterium is a neutron moderator.
Canadian strategic reserve.

Cerenkov light detection

SNO

- SNO made 3 measurements each with a different neutrino interaction reaction

$\nu_x\ e^- \rightarrow \nu_x\ e^-$	$\nu_e\ d \rightarrow p\ p\ e^-$	$\nu_x\ d \rightarrow \nu_x\ n\ p$

~5 events/day

SNO

- SNO made 3 measurements each with a different neutrino interaction reaction

$\nu_x\, e^- \rightarrow \nu_x\, e^-$	$\nu_e\, d \rightarrow p\, p\, e^-$	$\nu_x\, d \rightarrow \nu_x\, n\, p$
Electron neutrinos bring 9 times more events.	*It is only sensitive to electron neutrinos.*	*The three neutrinos give the same signature.*

~5 events/day

SNO

- SNO made 3 measurements each with a different neutrino interaction reaction

ν_x e$^-$ → ν_x e$^-$	ν_e d → p p e$^-$	ν_x d → ν_x n p
Electron neutrinos bring 9 times more events.	*It is only sensitive to electron neutrinos.*	*The three neutrinos give the same signature.*
$N_{meas.} = 9\,N_{electron}+N_\mu+N_\tau$	$N_{meas.} = N_{electron}$	$N_{meas} = N_{electron}+N_\mu+N_\tau$

~5 events/day

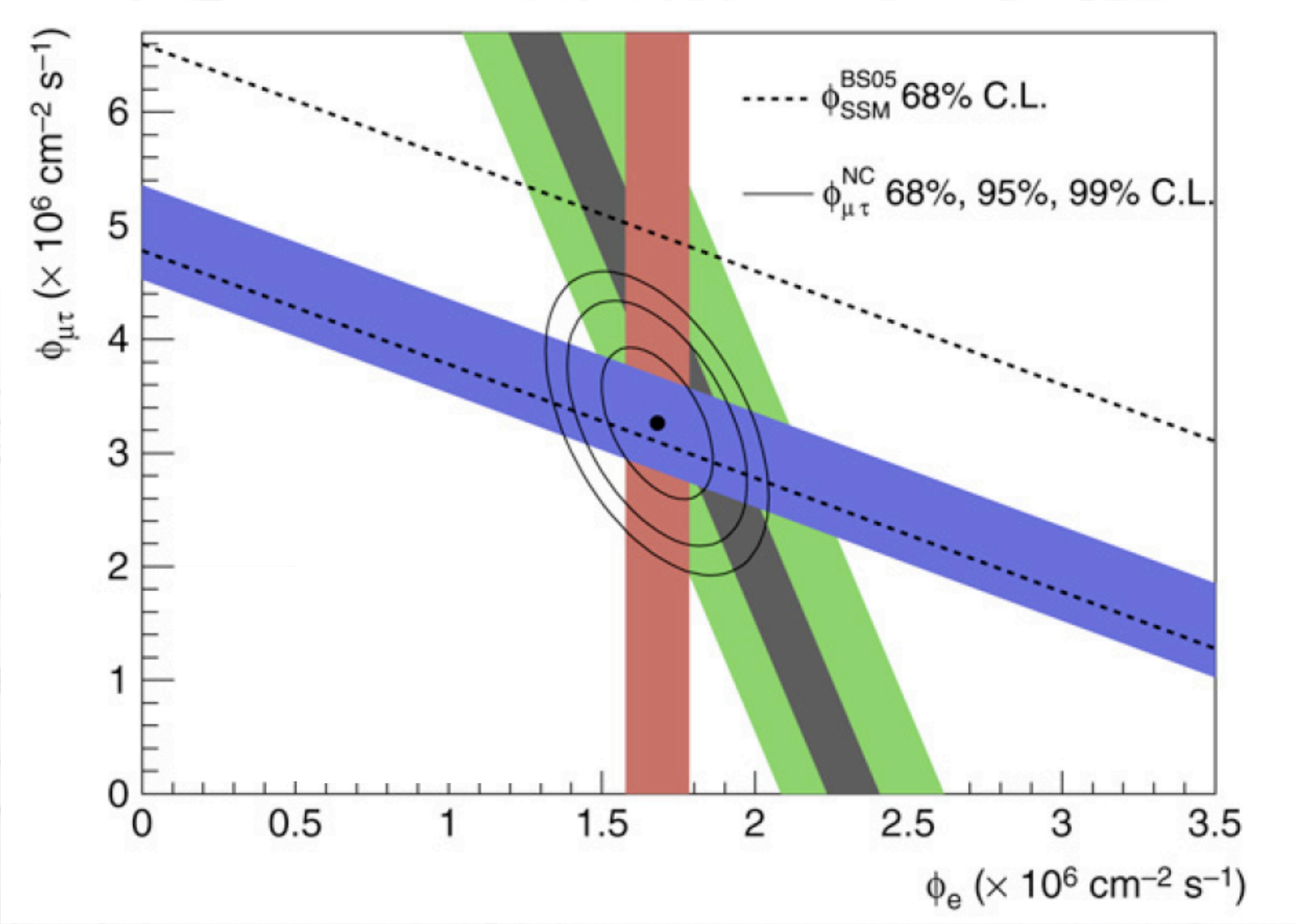
SNO

- SNO made 3 measurements each with a different neutrino interaction reaction

$\nu_x\ e^- \rightarrow \nu_x\ e^-$	$\nu_e\ d \rightarrow p\ p\ e^-$	$\nu_x\ d \rightarrow \nu_x\ n\ p$
Electron neutrinos bring 9 times more events.	*It is only sensitive to electron neutrinos.*	*The three neutrinos give the same signature.*
$N_{meas.} = 9\ N_{electron}+N_\mu+N_\tau$	$N_{meas.} = N_{electron}$	$N_{meas} = N_{electron}+N_\mu+N_\tau$
Signal: 1 electron pointing back to the sun.	*Signal: 1 electron not pointing to the sun.*	*Signal: 1 neutron*

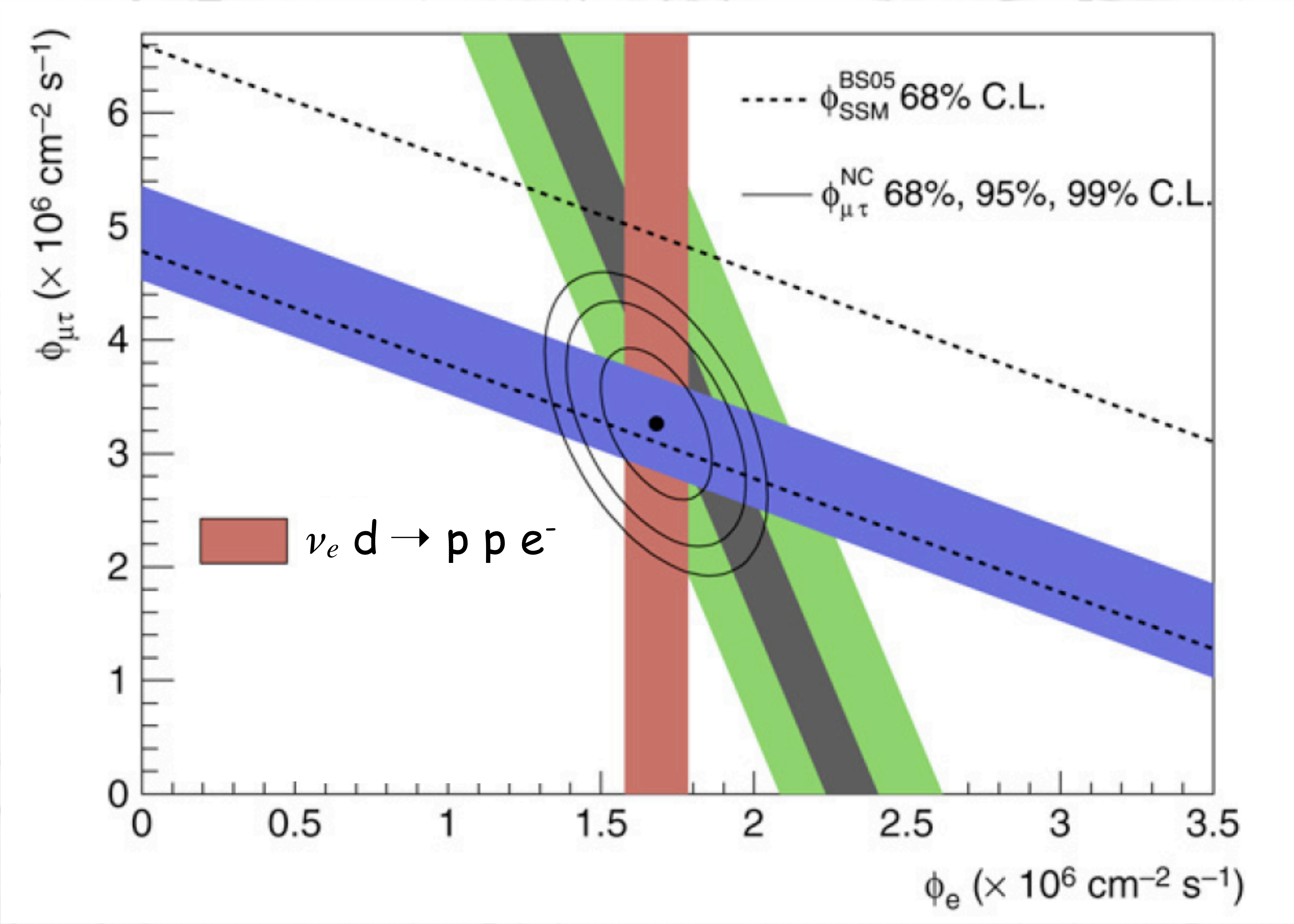
~5 events/day

SNO



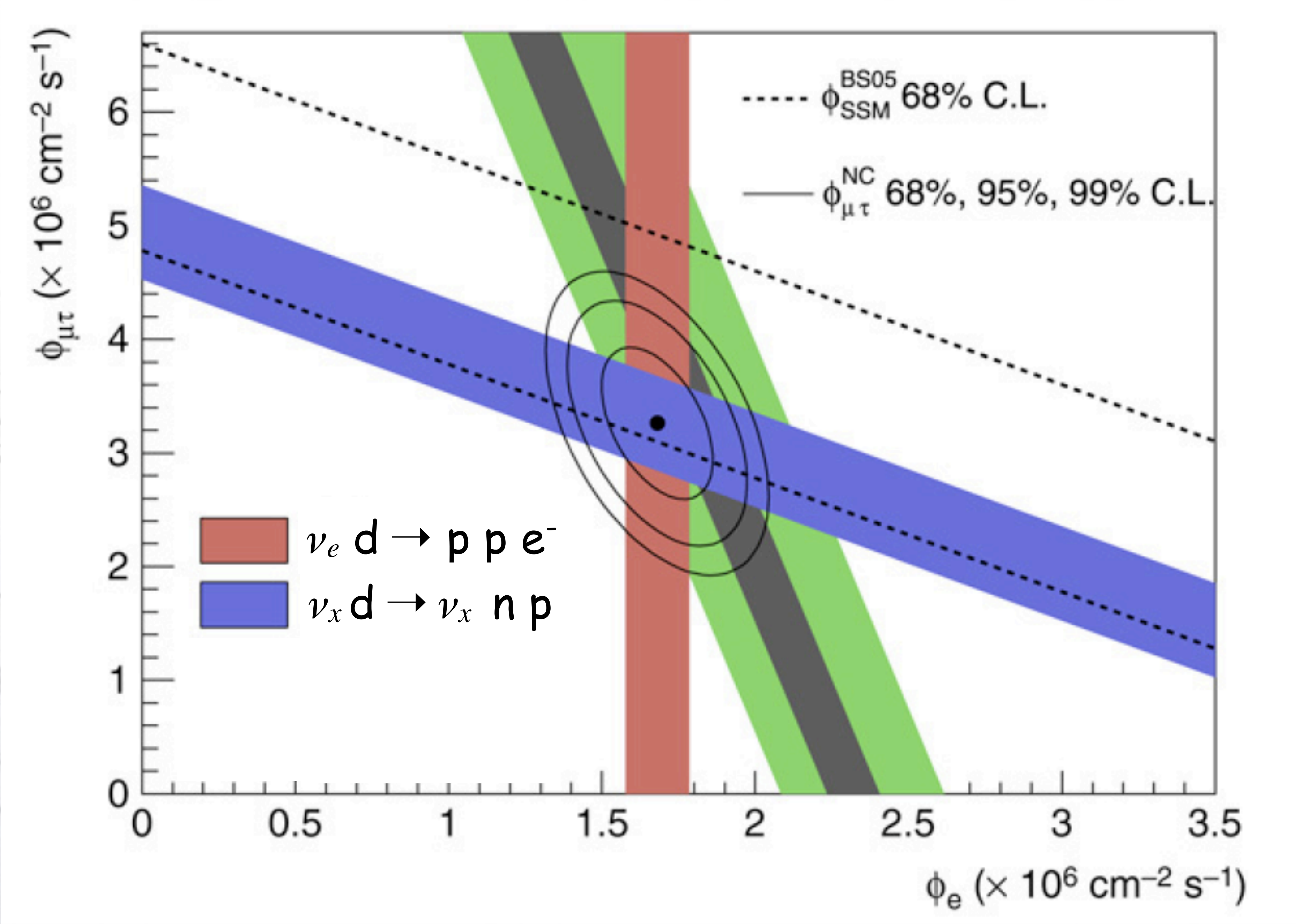
ϕ_{SSM}^{BS05} 68% C.L.
$\phi_{\mu\tau}^{NC}$ 68%, 95%, 99% C.L.
$\phi_{\mu\tau}$ ($\times 10^6$ cm^{-2} s^{-1})
ϕ_e ($\times 10^6$ cm^{-2} s^{-1})
0
1
2
3
4
5
6
0
0.5
1
1.5
2
2.5
3
3.5

SNO



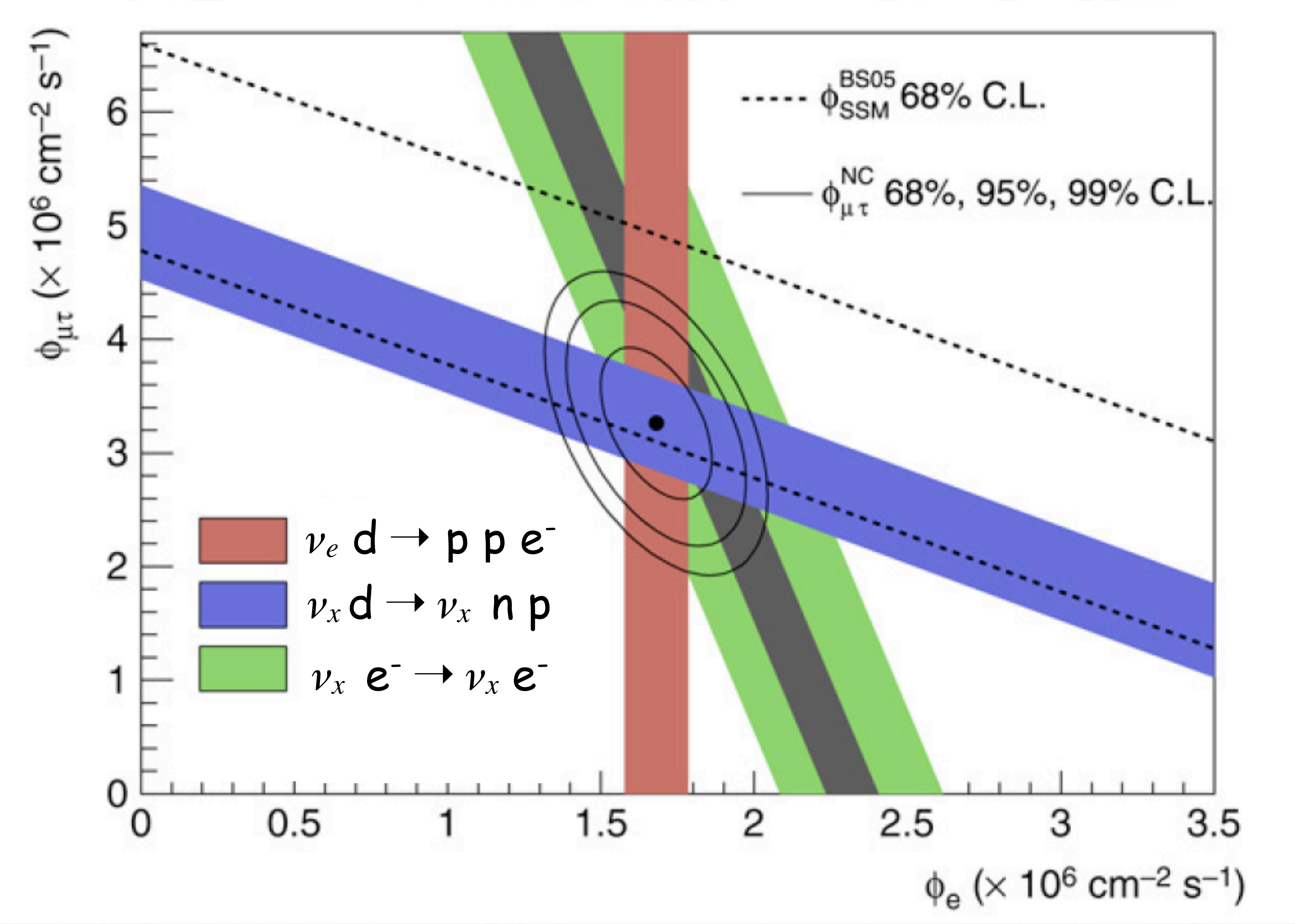
ϕ_{SSM}^{BS05} 68% C.L.
$\phi_{\mu\tau}^{NC}$ 68%, 95%, 99% C.L.
ν_e d → p p e⁻
$\phi_{\mu\tau}$ (× 10⁶ cm⁻² s⁻¹)
ϕ_e (× 10⁶ cm⁻² s⁻¹)
0
1
2
3
4
5
6
0
0.5
1
1.5
2
2.5
3
3.5

SNO



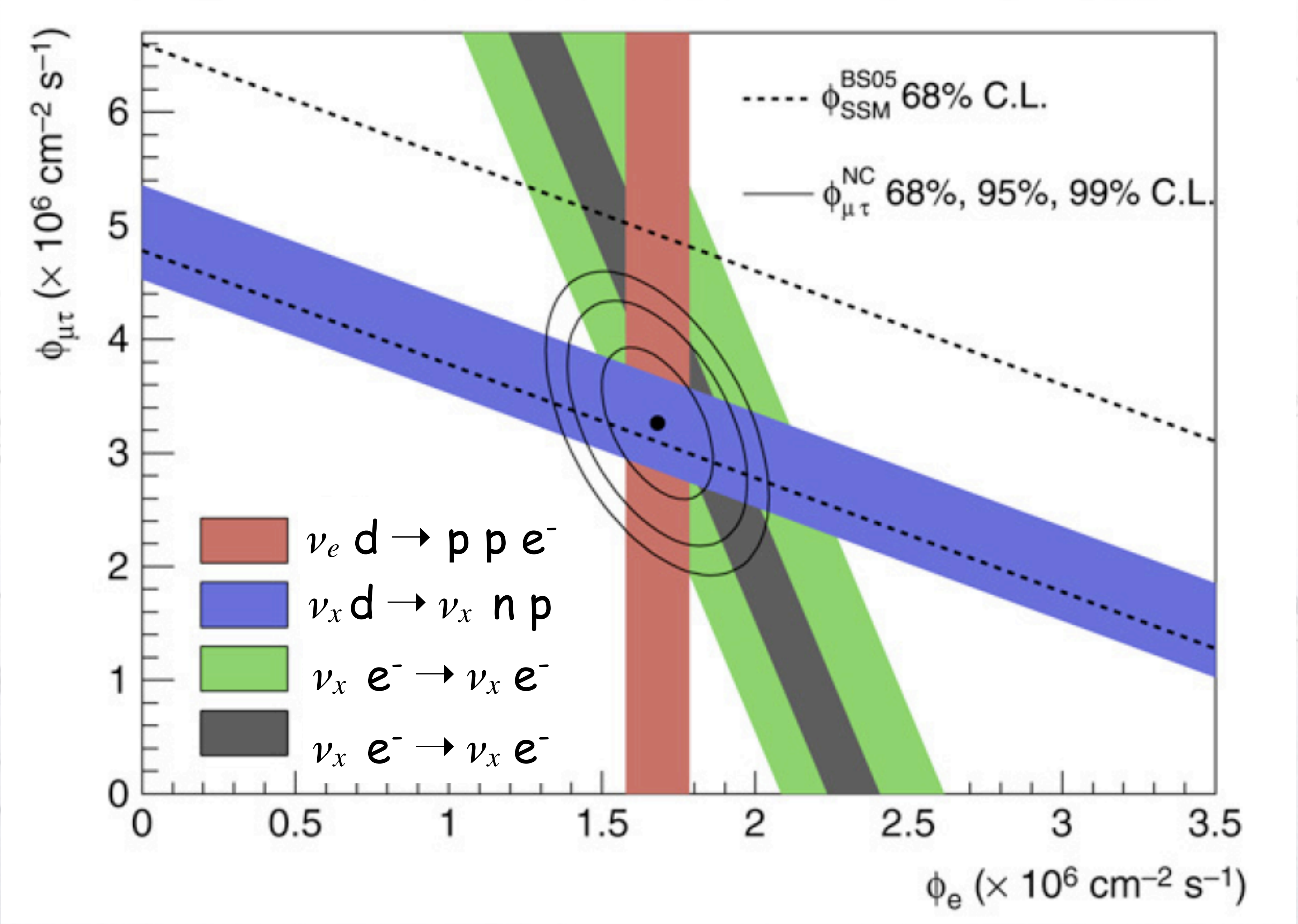
ϕ_{SSM}^{BS05} 68% C.L.
$\phi_{\mu\tau}^{NC}$ 68%, 95%, 99% C.L.
ν_e d → p p e⁻
ν_x d → ν_x n p
$\phi_{\mu\tau}$ (× 10⁶ cm⁻² s⁻¹)
ϕ_e (× 10⁶ cm⁻² s⁻¹)

SNO

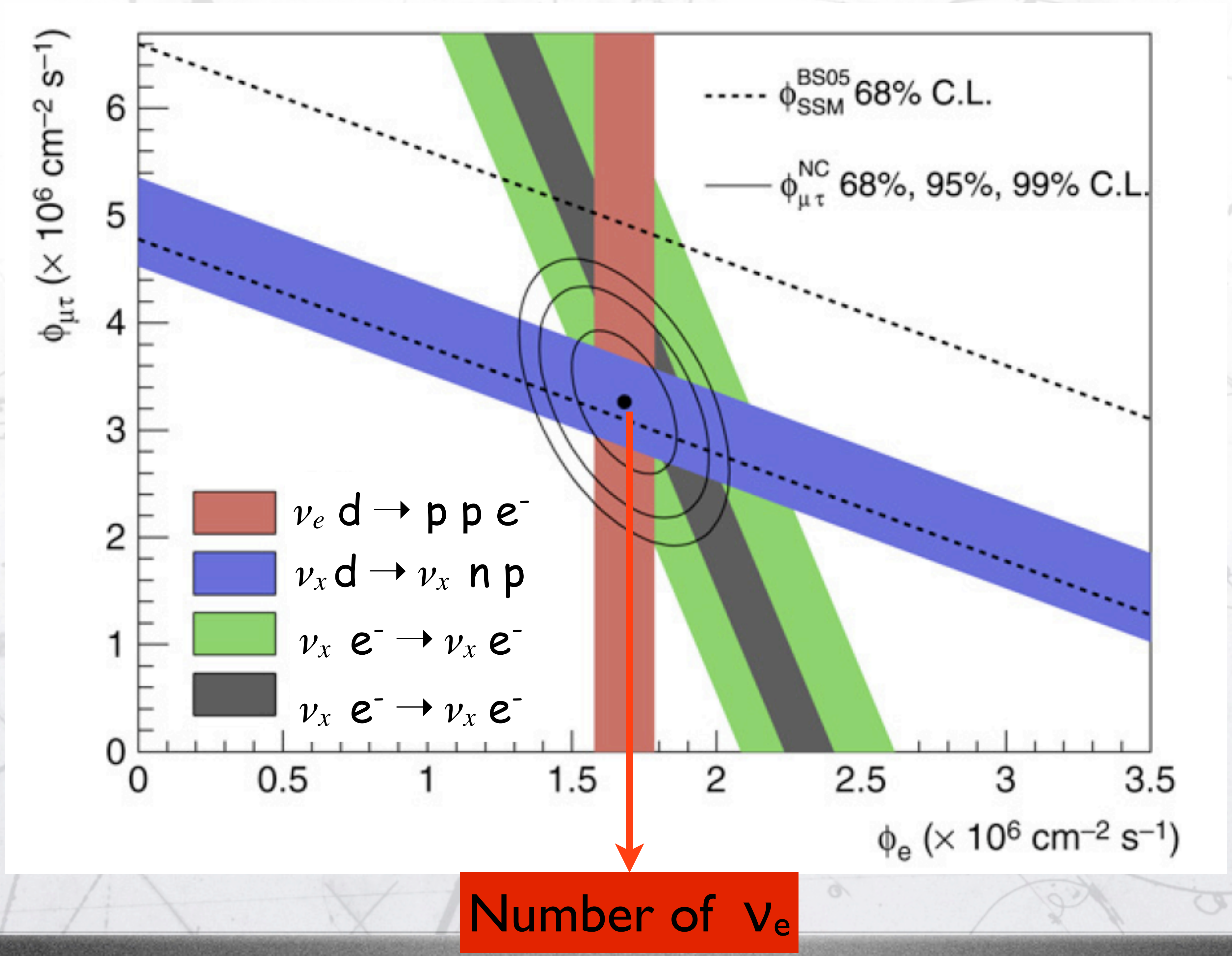


ϕ_{SSM}^{BS05} 68% C.L.
$\phi_{\mu\tau}^{NC}$ 68%, 95%, 99% C.L.
ν_e d → p p e$^-$
ν_x d → ν_x n p
ν_x e$^-$ → ν_x e$^-$
$\phi_{\mu\tau}$ (× 10^6 cm^{-2} s^{-1})
ϕ_e (× 10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
0
0.5
1
1.5
2
2.5
3
3.5

SNO



ϕ^{BS05}_{SSM} 68% C.L.
$\phi^{NC}_{\mu\tau}$ 68%, 95%, 99% C.L.
ν_e d → p p e⁻
ν_x d → ν_x n p
ν_x e⁻ → ν_x e⁻
ν_x e⁻ → ν_x e⁻
$\phi_{\mu\tau}$ (× 10⁶ cm⁻² s⁻¹)
ϕ_e (× 10⁶ cm⁻² s⁻¹)
0
1
2
3
4
5
6
0
0.5
1
1.5
2
2.5
3
3.5


ϕ_{SSM}^{BS05} 68% C.L.
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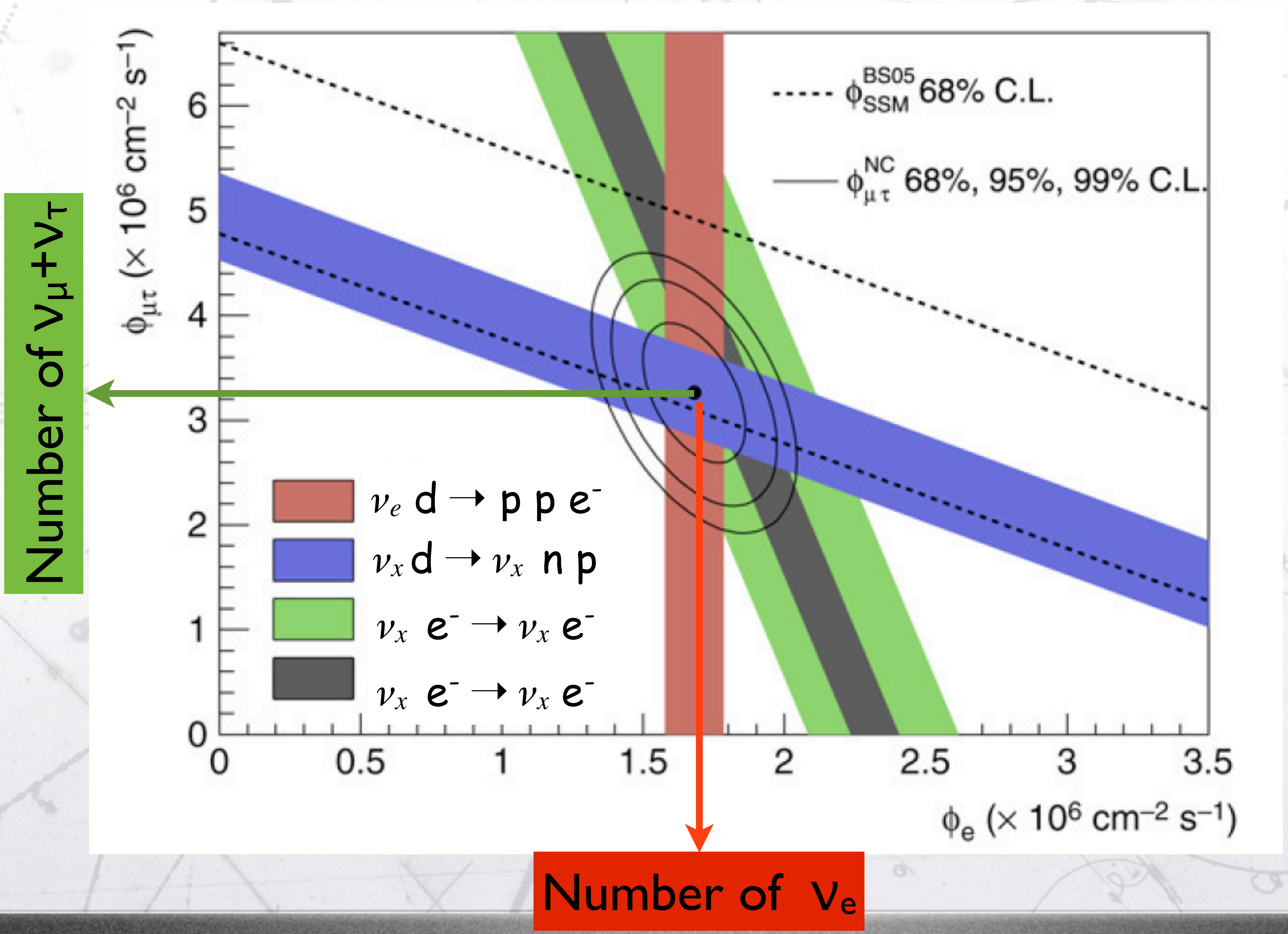
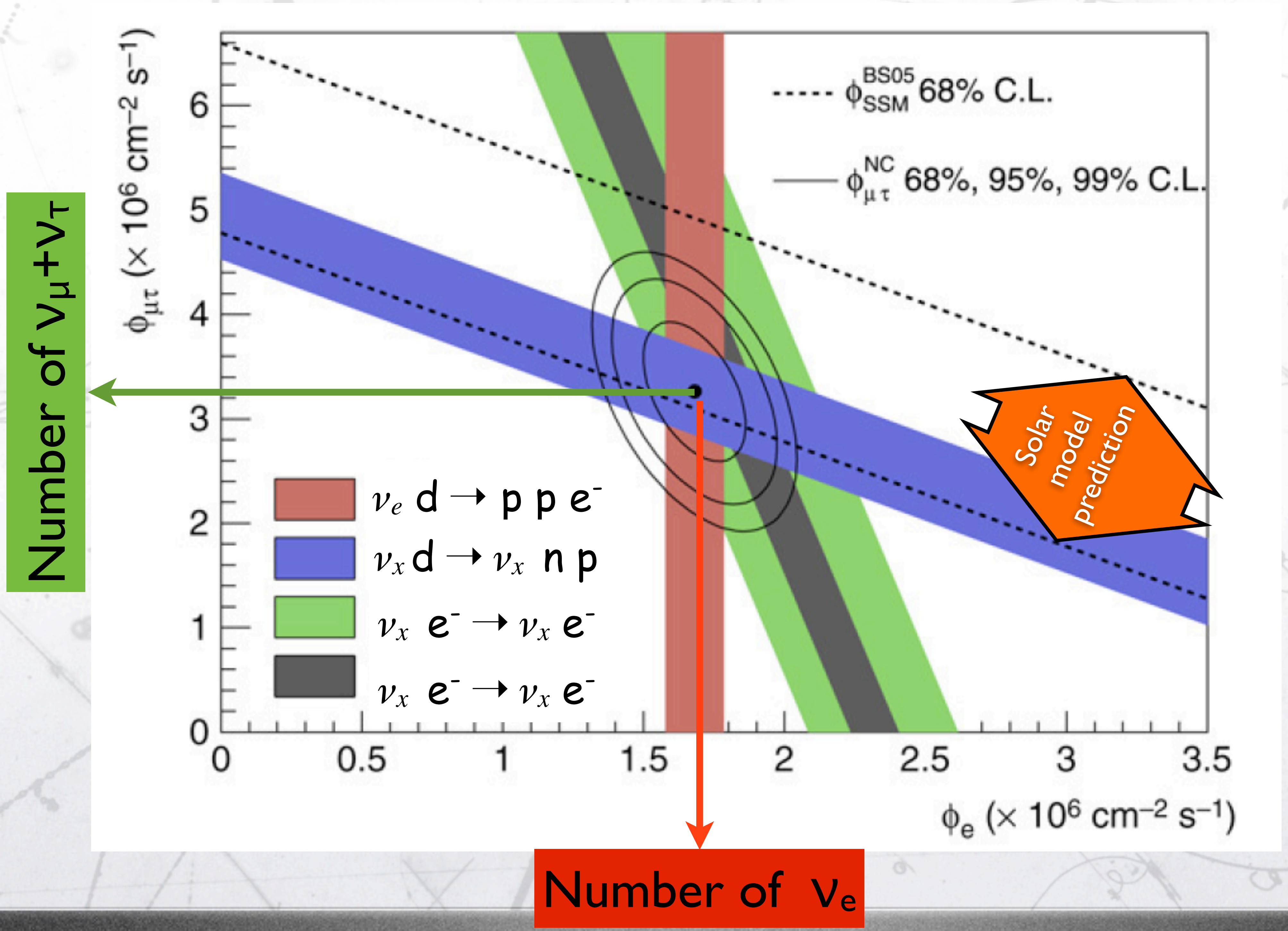
ν_e d → p p e$^-$
ν_x d → ν_x n p
ν_x e$^-$ → ν_x e$^-$
ν_x e$^-$ → ν_x e$^-$
$\phi_{\mu\tau}$ ($\times 10^6$ cm^{-2} s^{-1})
ϕ_e ($\times 10^6$ cm^{-2} s^{-1})
0
0.5
1
1.5
2
2.5
3
3.5
1
2
3
4
5
6
Number of ν_e

SNO

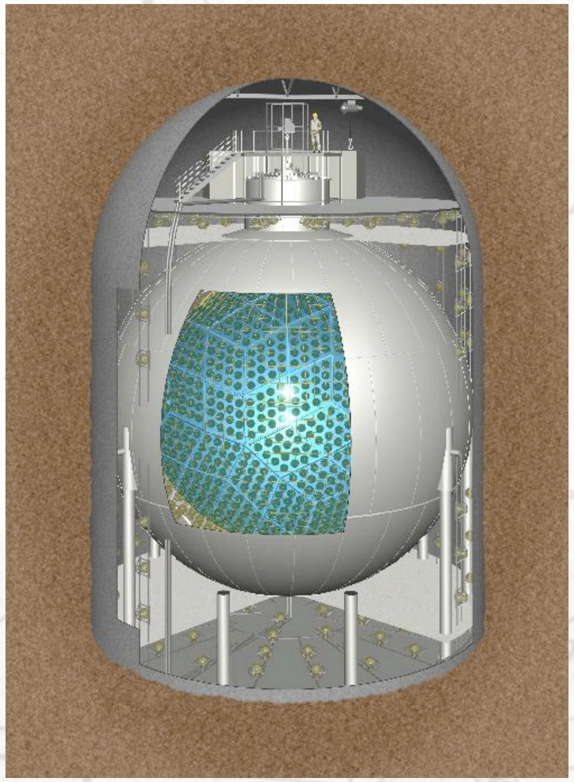


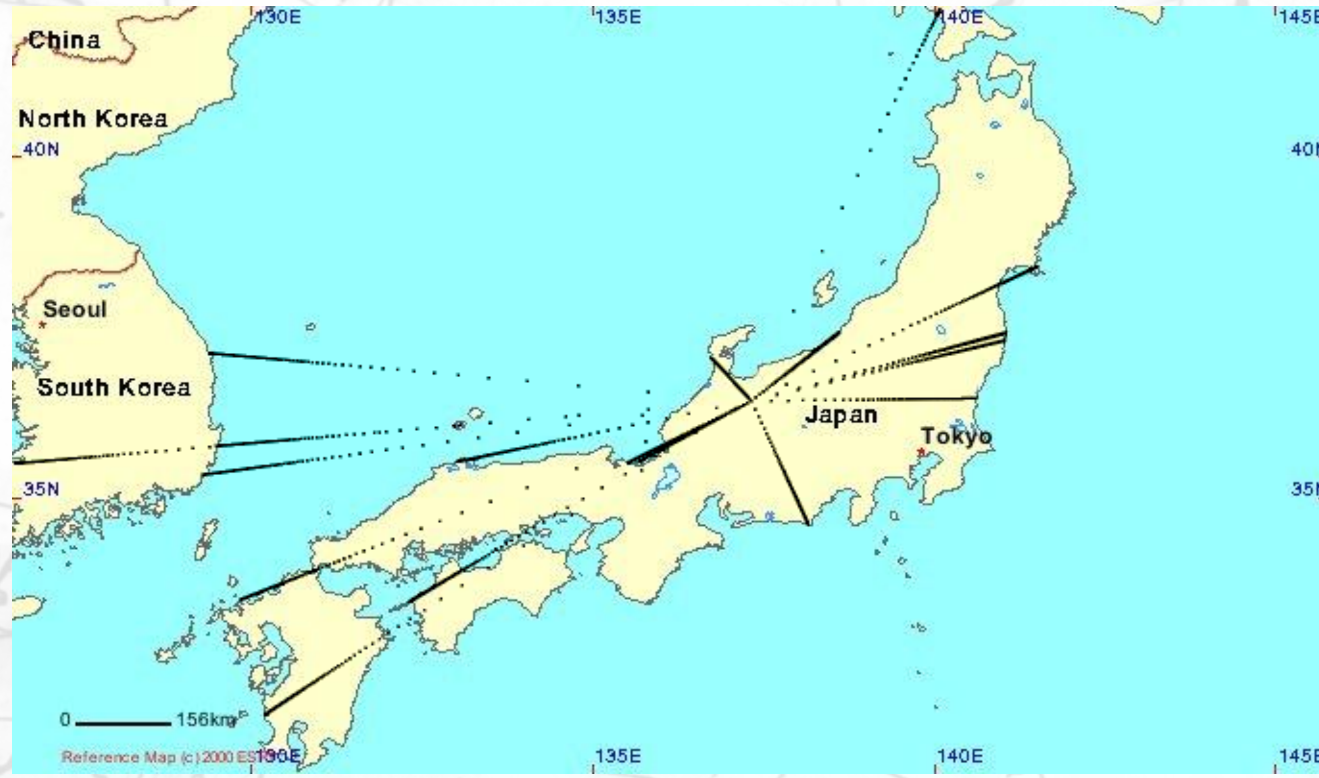
ϕ^{BS05}_{SSM} 68% C.L.
$\phi^{NC}_{\mu\tau}$ 68%, 95%, 99% C.L.
$\nu_e\, d \rightarrow p\, p\, e^-$
$\nu_x\, d \rightarrow \nu_x\, n\, p$
$\nu_x\, e^- \rightarrow \nu_x\, e^-$
$\nu_x\, e^- \rightarrow \nu_x\, e^-$
$\phi_{\mu\tau}$ ($\times 10^6$ cm^{-2} s^{-1})
ϕ_e ($\times 10^6$ cm^{-2} s^{-1})
Number of $\nu_\mu+\nu_\tau$
Number of ν_e


Number of $\nu_\mu+\nu_\tau$
$\phi_{\mu\tau}$ ($\times 10^6$ cm^{-2} s^{-1})
ϕ_{SSM}^{BS05} 68% C.L.
$\phi_{\mu\tau}^{NC}$ 68%, 95%, 99% C.L.
ν_e d → p p e$^-$
ν_x d → ν_x n p
ν_x e$^-$ → ν_x e$^-$
ν_x e$^-$ → ν_x e$^-$
Solar model prediction
ϕ_e ($\times 10^6$ cm^{-2} s^{-1})
Number of ν_e

Kamland

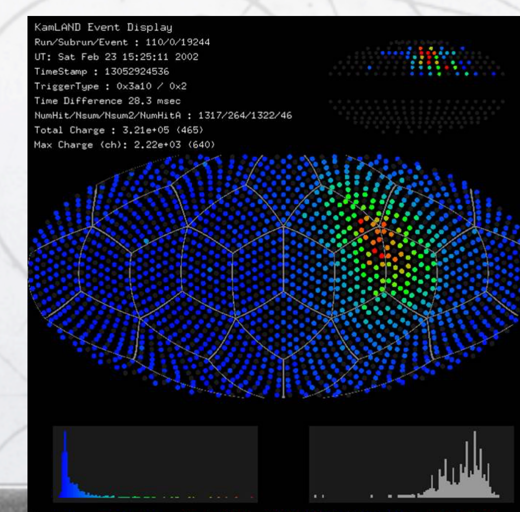
The experiments





- Search for $\bar{\nu}_e$ oscillations from nuclear reactors.
- Average distance: ~180km.
- Average Energy: ~4 MeV.
- Sensitive to $\Delta m^2 \sim 10^{-4}\ eV^2$

- Liquid scintillator detector.

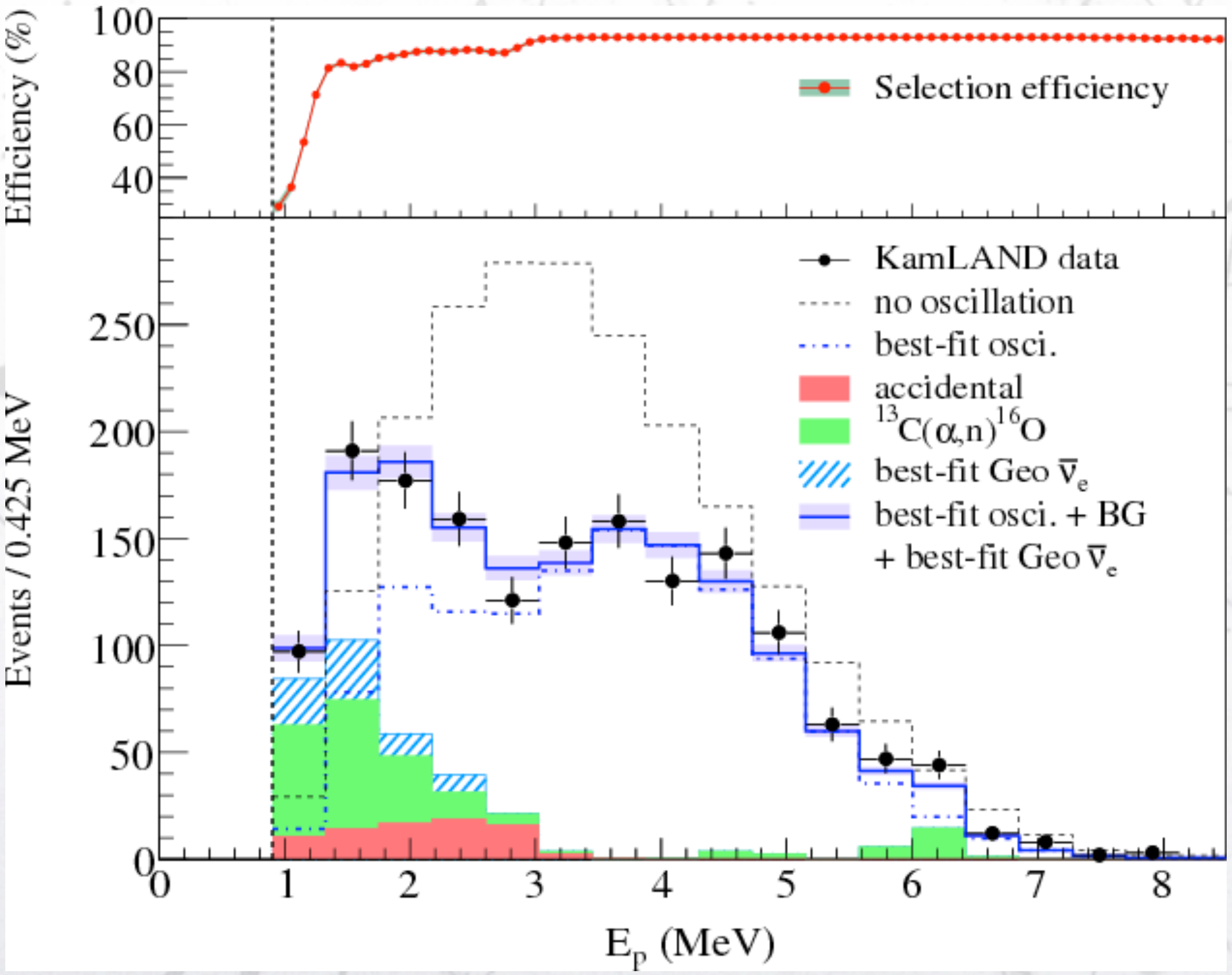


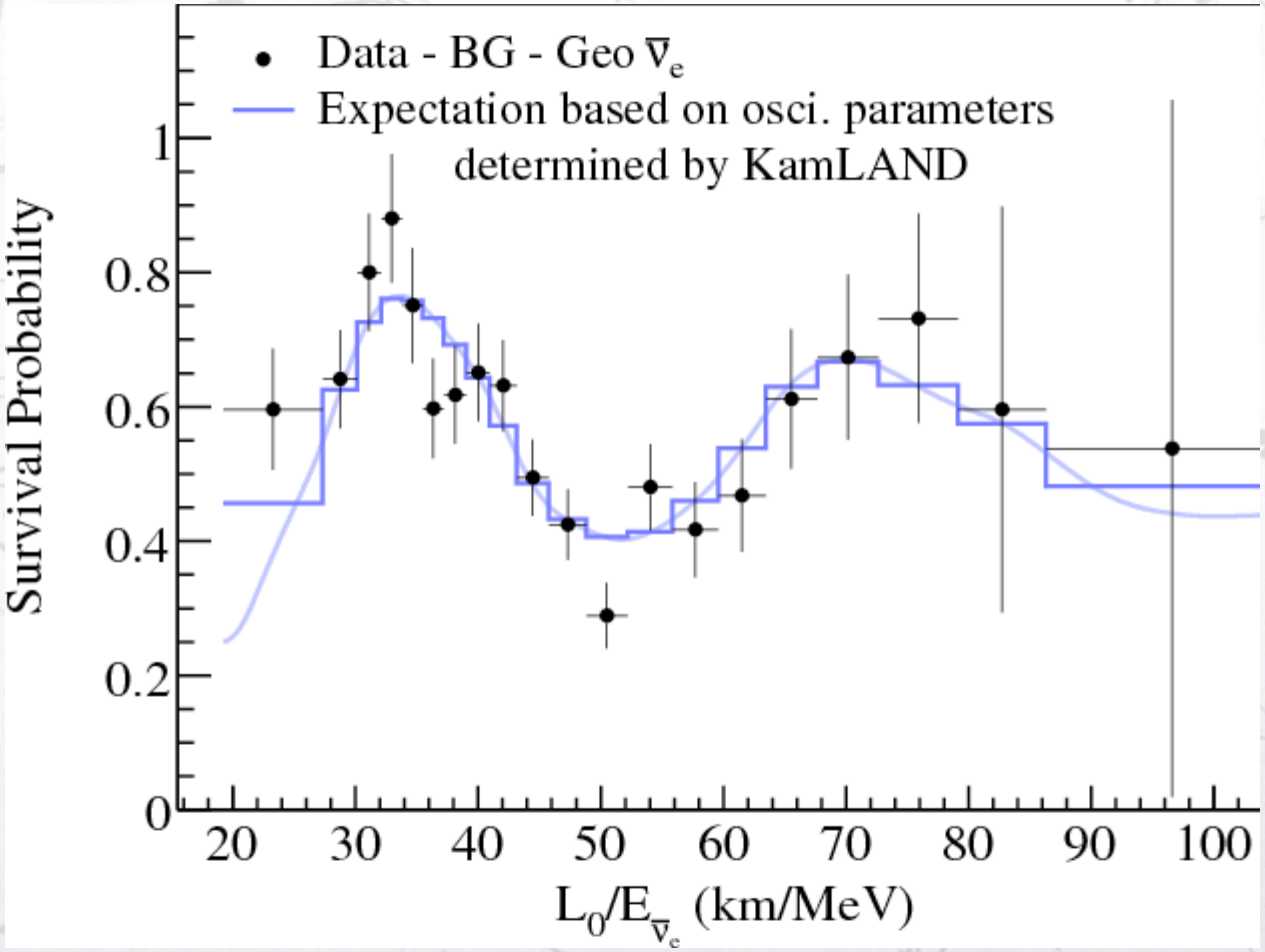
Kamland

$\nu_e \rightarrow \nu_\tau\ \nu_\mu$ not enough energy to see τ or μ

~sin(β/E)

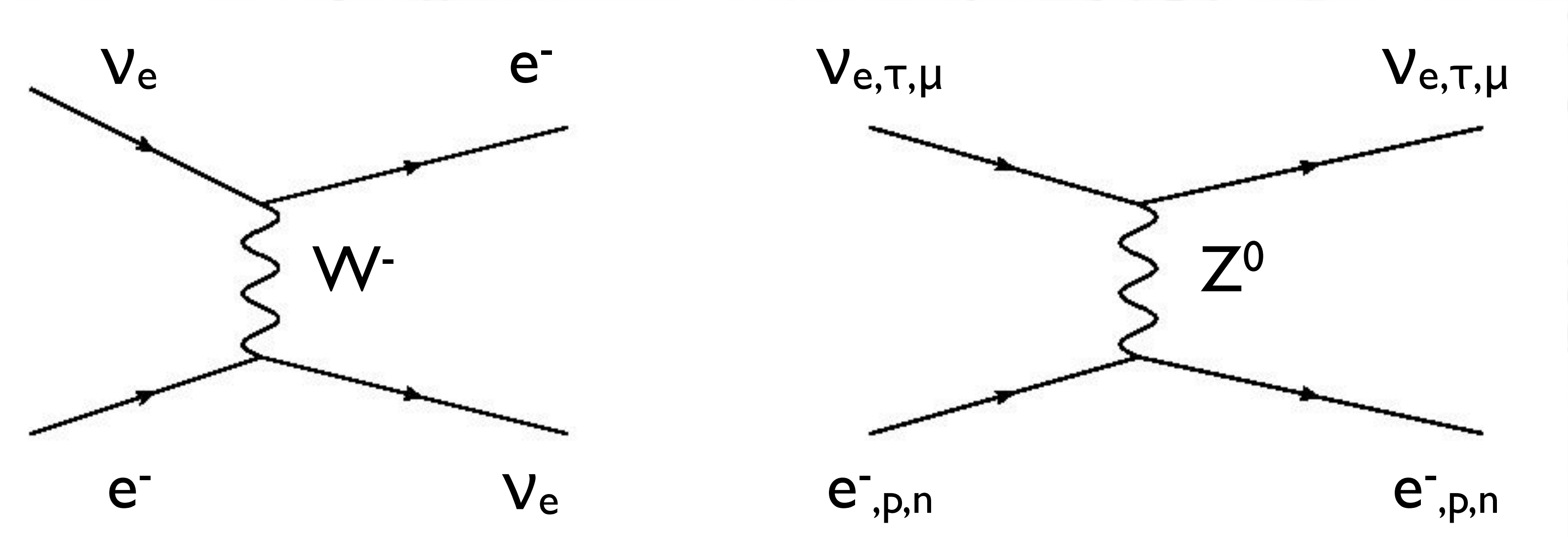
~sin(α L/E)





Neutrinos in matter

- Neutrinos in matter react differently depending on the flavour:

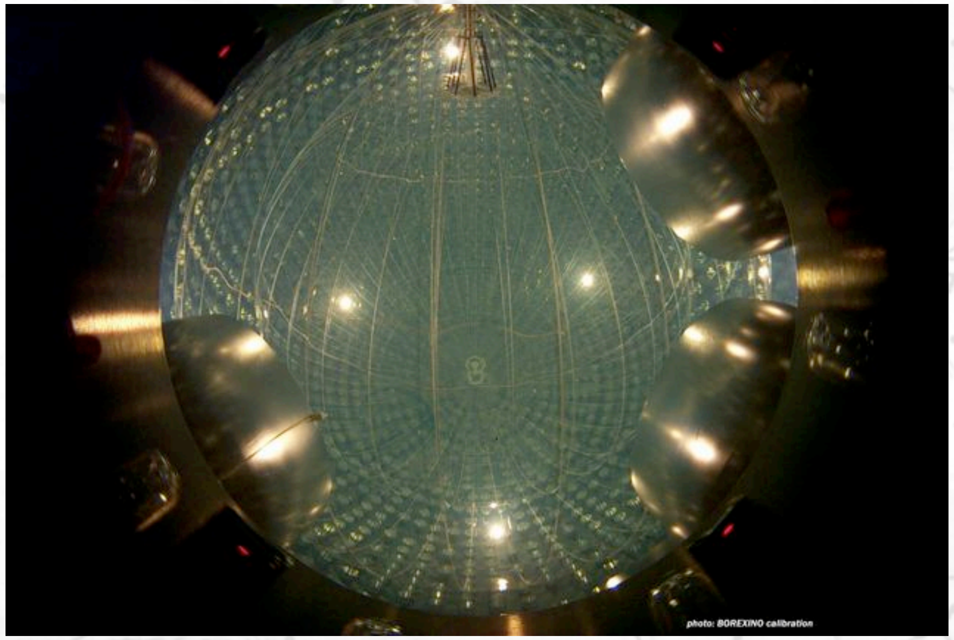


Coherent scattering, only phase is change!

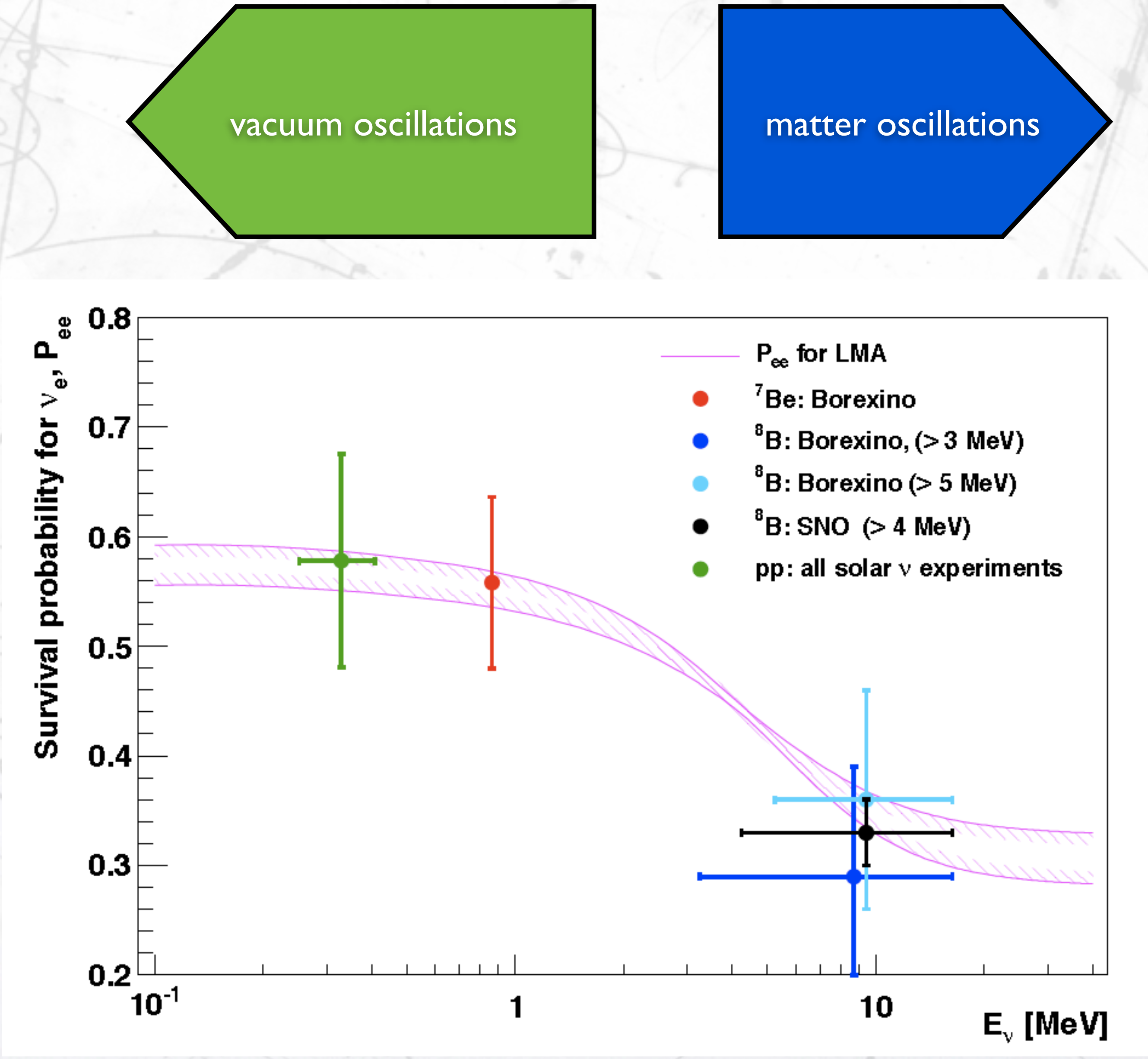
- Electron neutrinos behave differently in matter than the tau and muon neutrinos.
  - This is like having a different effective mass ("index of refraction")
- This is more relevant for higher neutrino energies and high electron density (THE SUN!!!).
- The effect is a "modified" oscillation pattern (matter effects).
- Neutrinos are emitted from the sun in the state with largest mass (ν_2)

Borexino & Matter effects

- Liquid scintillator detector.



- Borexino, low energy solar neutrino experiment, was able to check the matter effects.
- The matter resonant effect depends on the neutrino energy.
  - So, we should expect a transition when this happens.

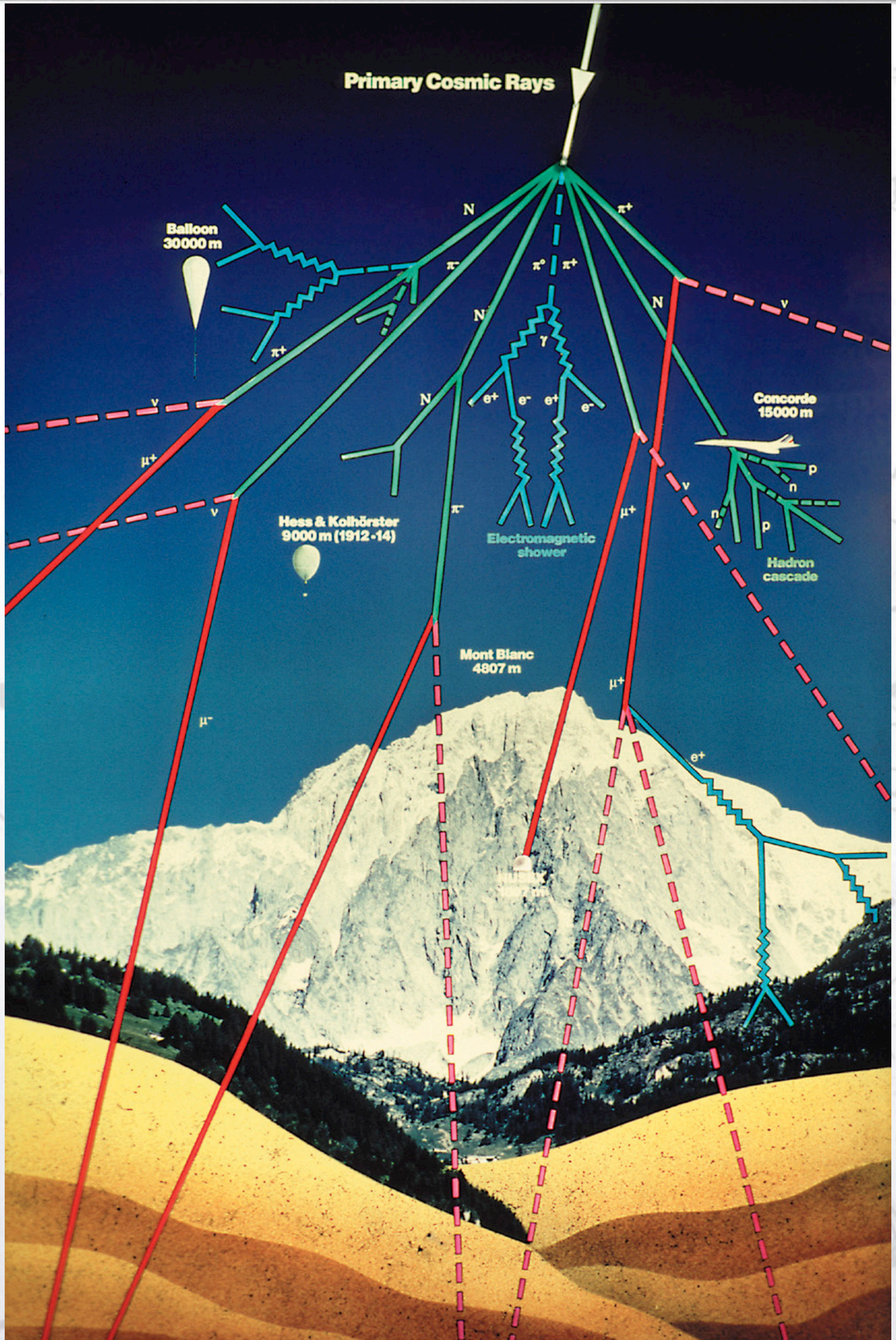


SuperKamiokande & the universality of neutrino oscillations.

Θ_{23} & Δm^2_{23}

Atmospheric ν

- Up to now we have been looking at ν_e disappearance:
  - Is the ν_e oscillating to ν_μ or ν_τ ?
  - What about the ν_μ and ν_τ ?
- Some trivialities:
  - Solar neutrinos (~MeV) do not have energy to produce μ (106MeV) or τ(1777MeV). So, we can't distinguish them. Only NC are possible (SNO).
  - We need another "abundant" source of higher energy neutrinos:
    - the atmosphere!!.



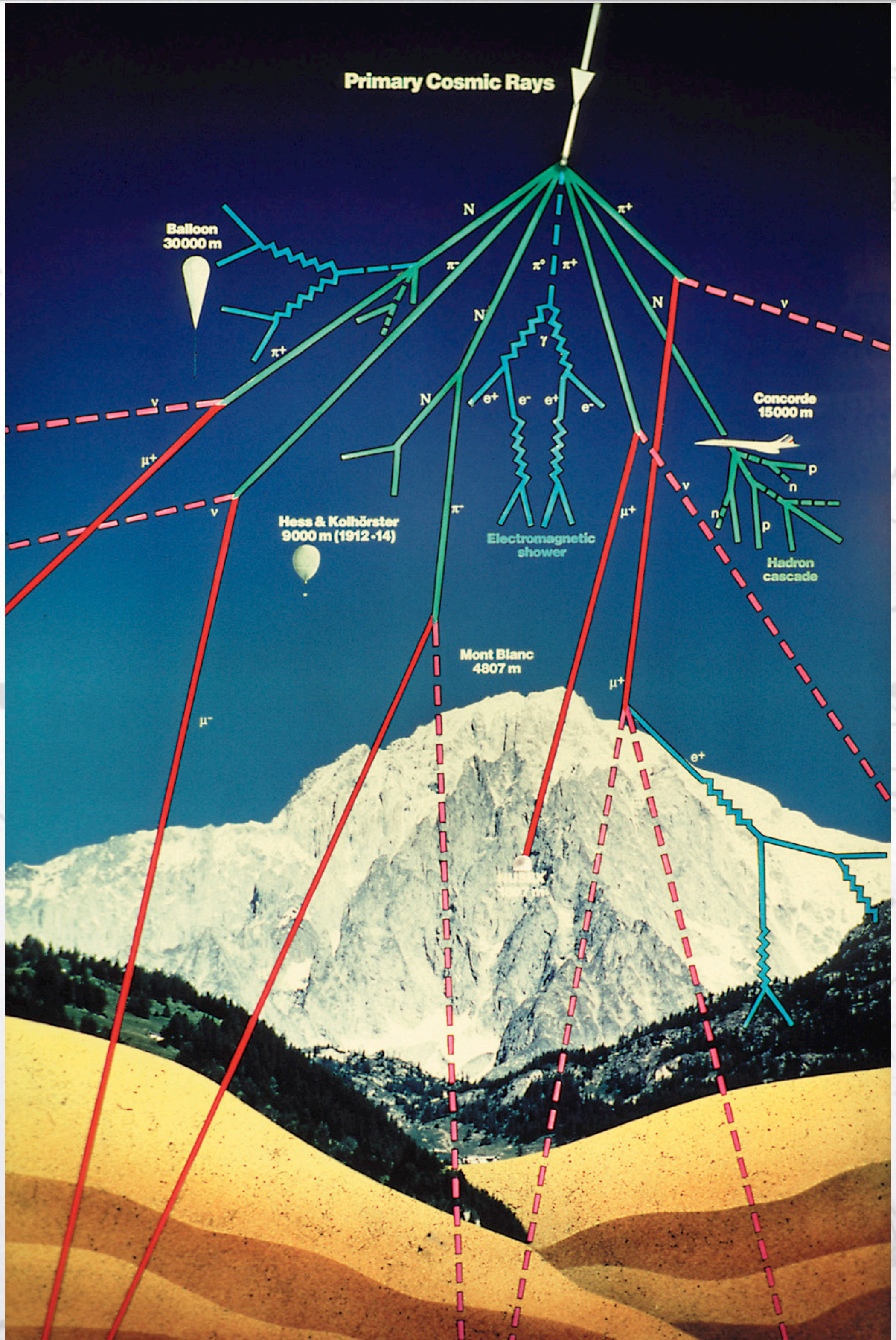
Atmospheric neutrinos

Extraterrestrial high energy protons collide with the atmosphere and produce a “shower” of particles.

Many of the particles are pions that decay into muons and muon neutrinos. $1\ \nu_\mu$

Muons decay into electrons, muon neutrinos and electron neutrinos. $1\ \nu_\mu + 1\ \nu_e$

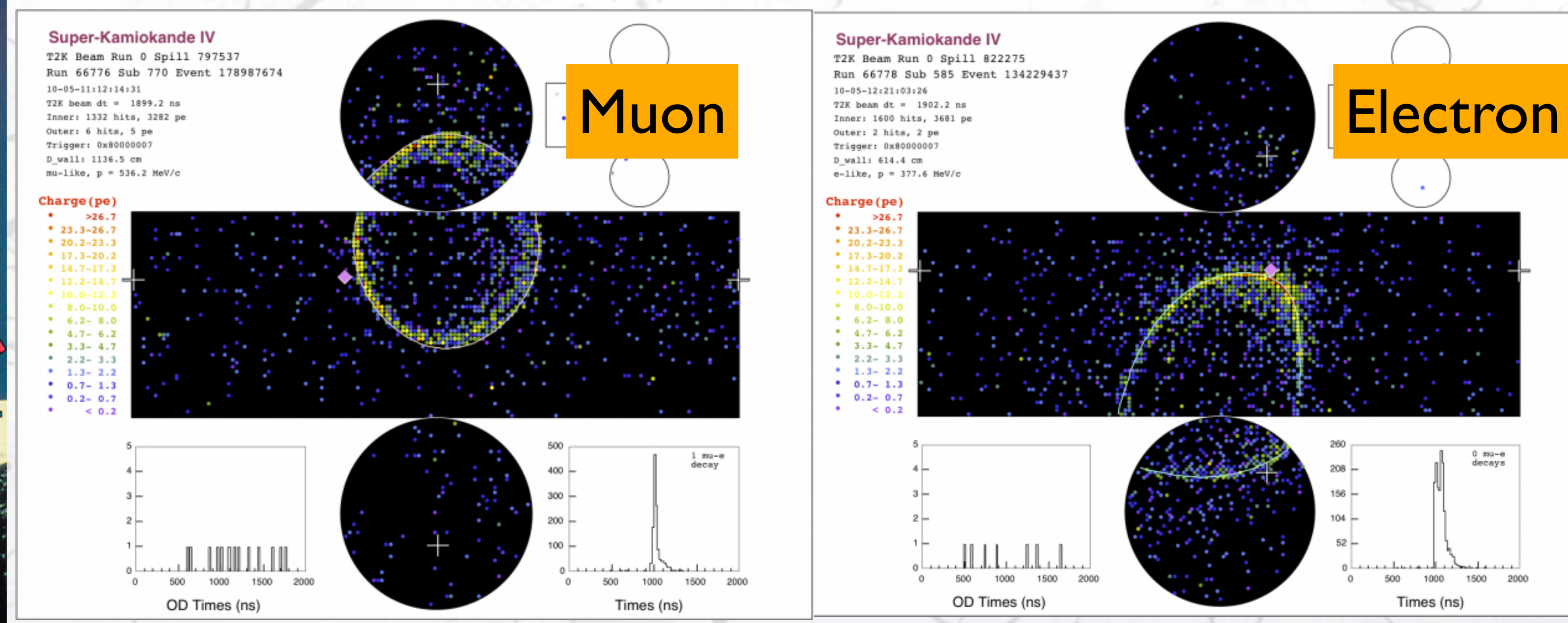
In atmospheric showers, ~2 muon neutrinos are produced per electron neutrino.



Atmospheric neutrinos

SK uses the ~2 ν_μ/ν_e ratio

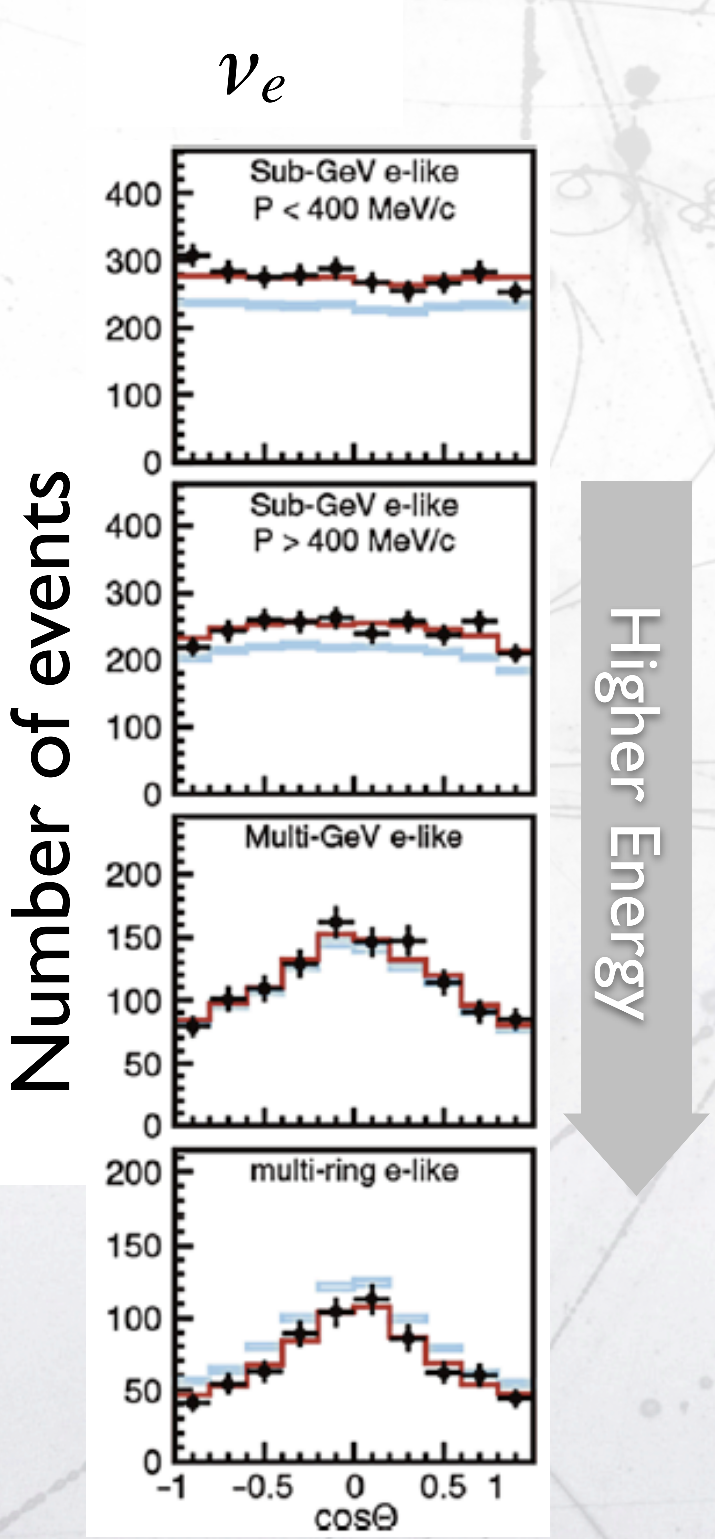
Super-Kamiokande distinguish between electrons and muons.



Super-Kamiokande also detect the direction of the lepton. (directionality of Cerenkov light)

SuperKamiokande

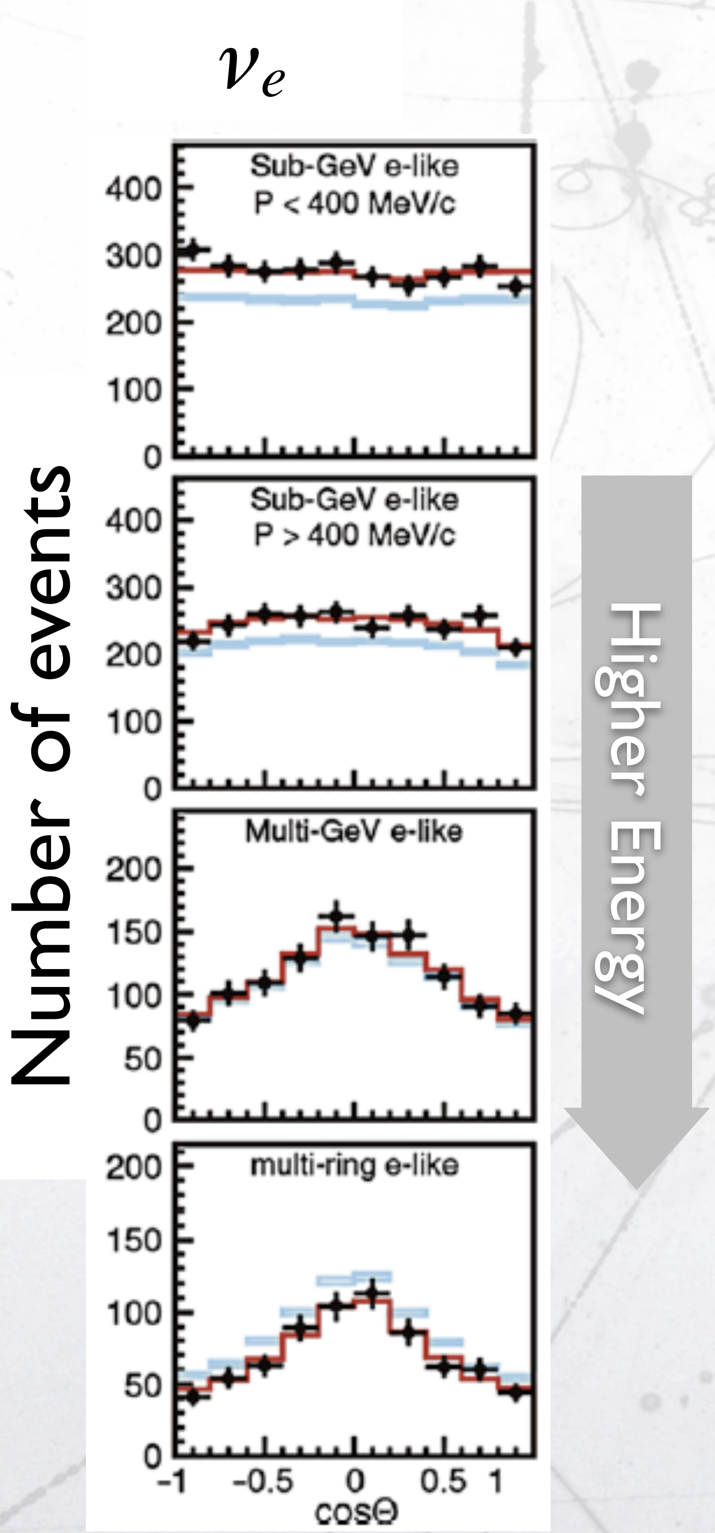
1. Electron sample is similar to expected

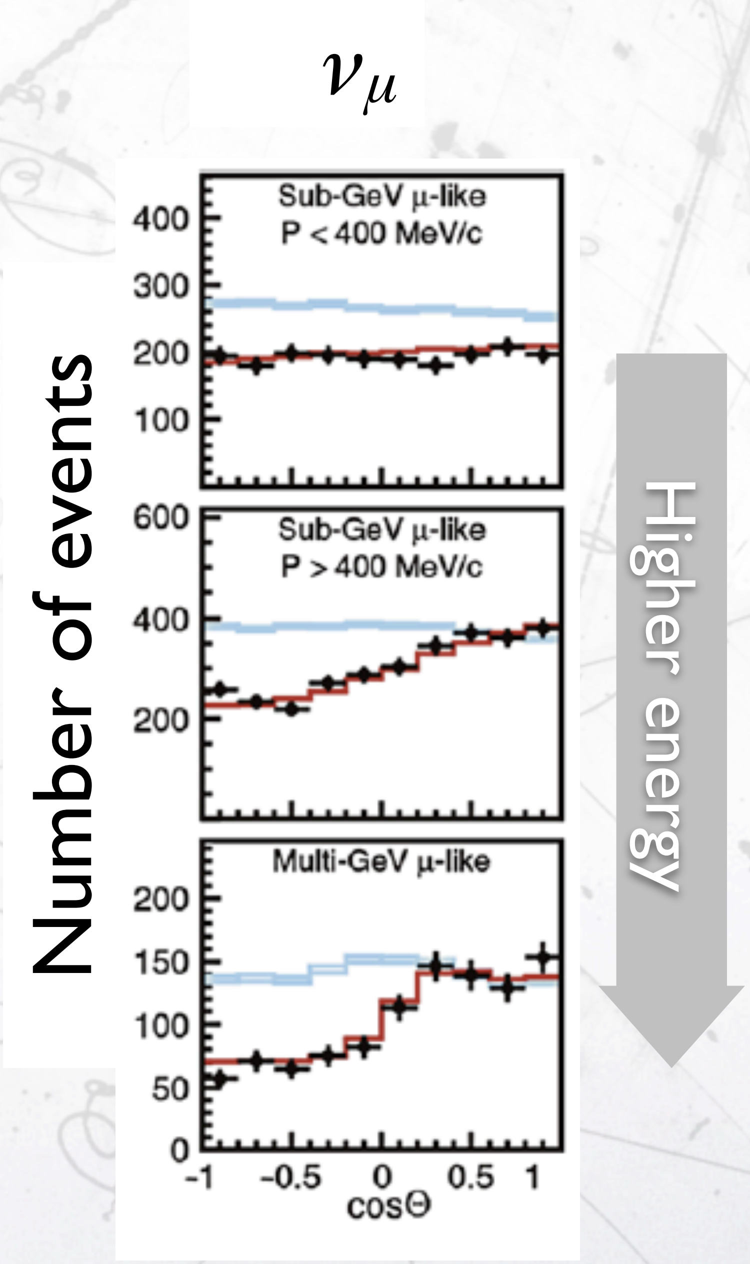


SuperKamiokande

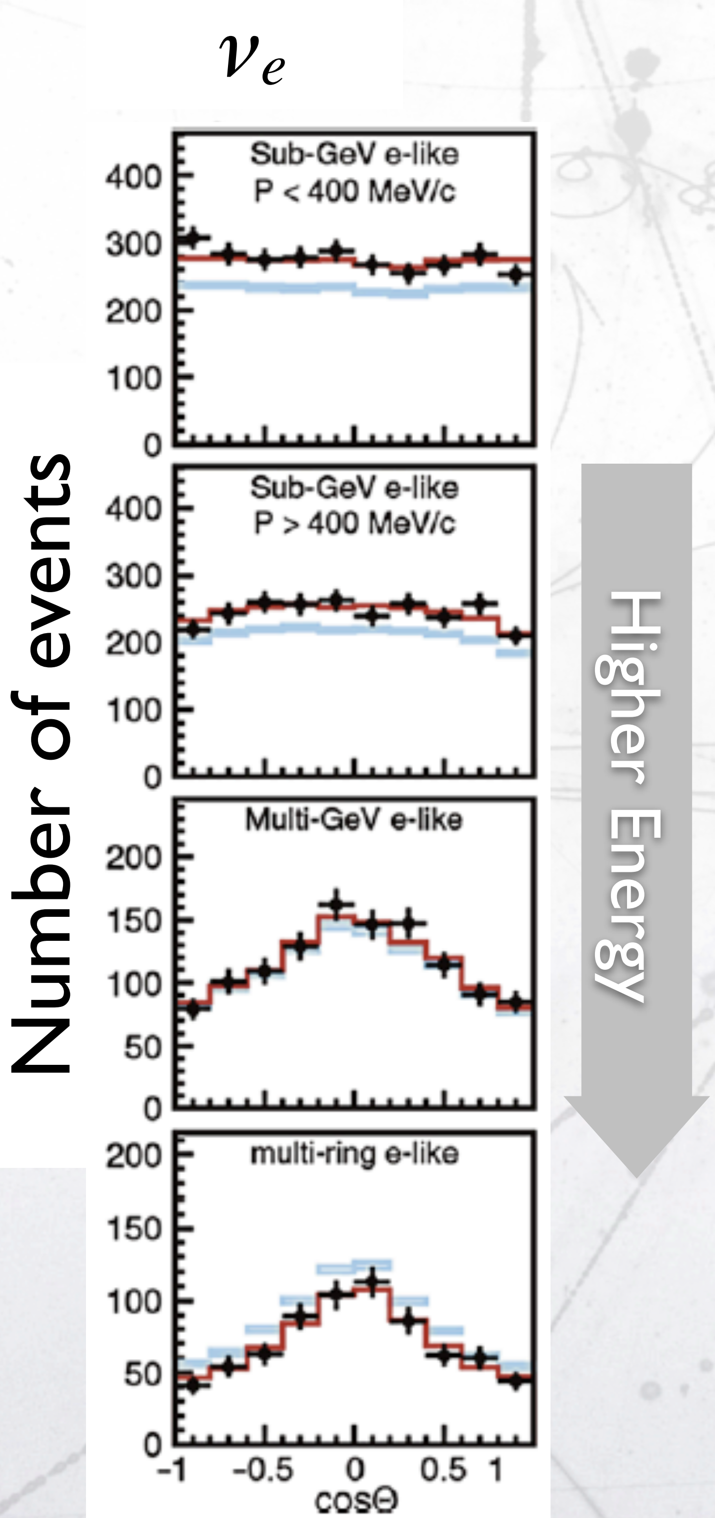
1. Electron sample is similar to expected

2. There is a deficit of muon neutrinos crossing the earth.





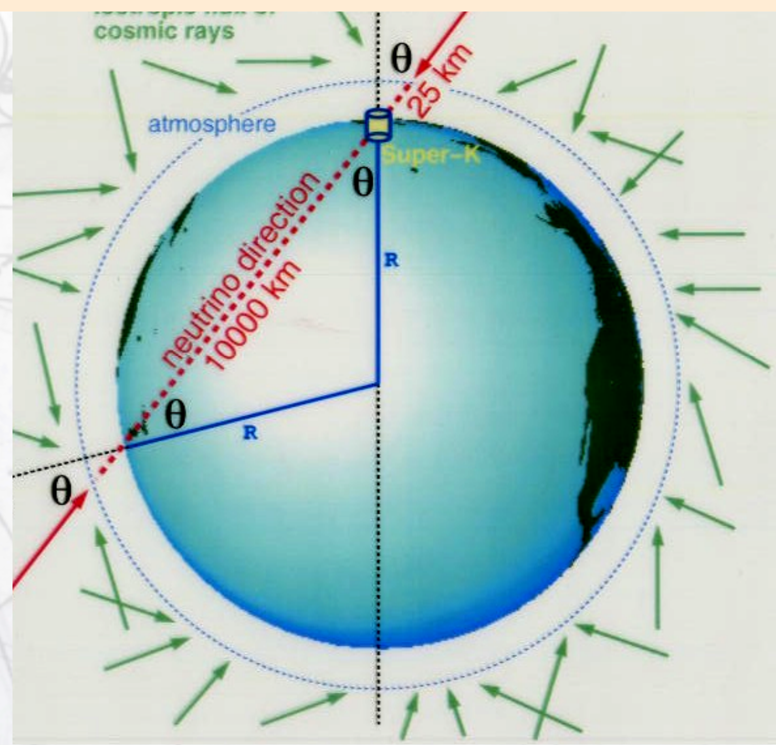
SuperKamiokande

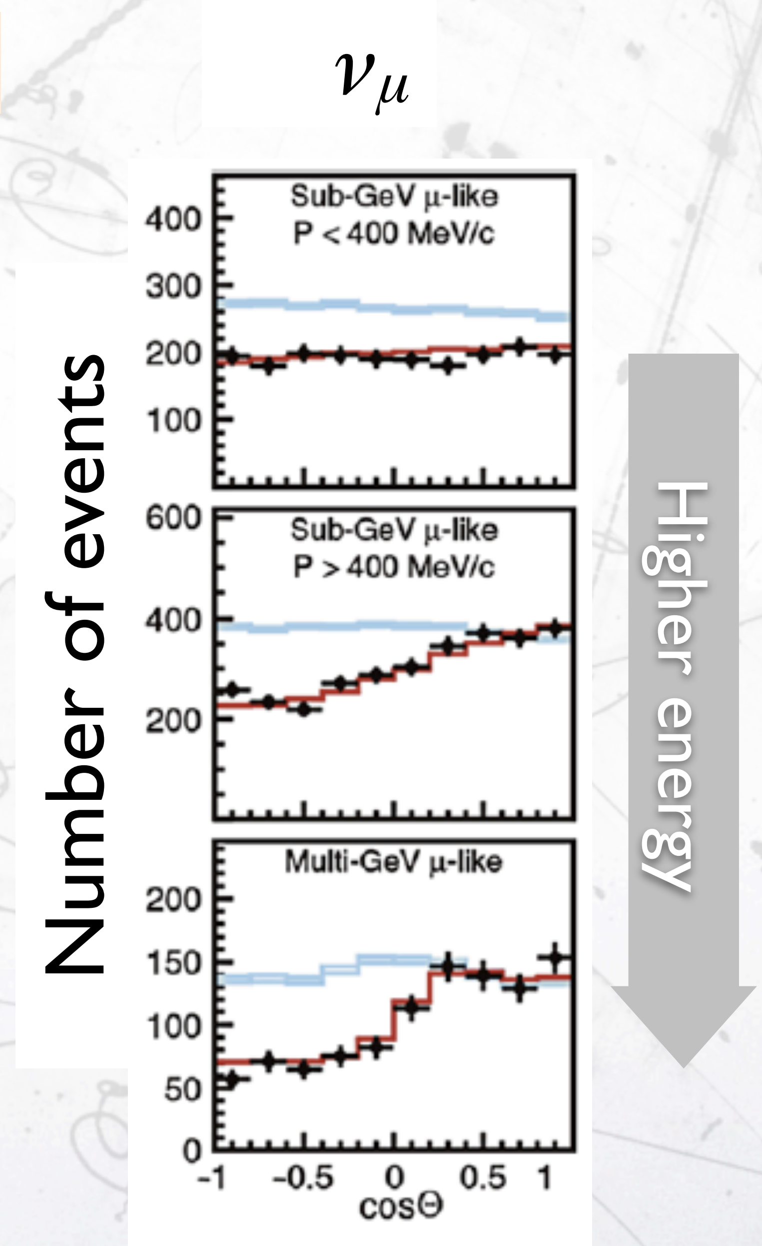


1. Electron sample is similar to expected

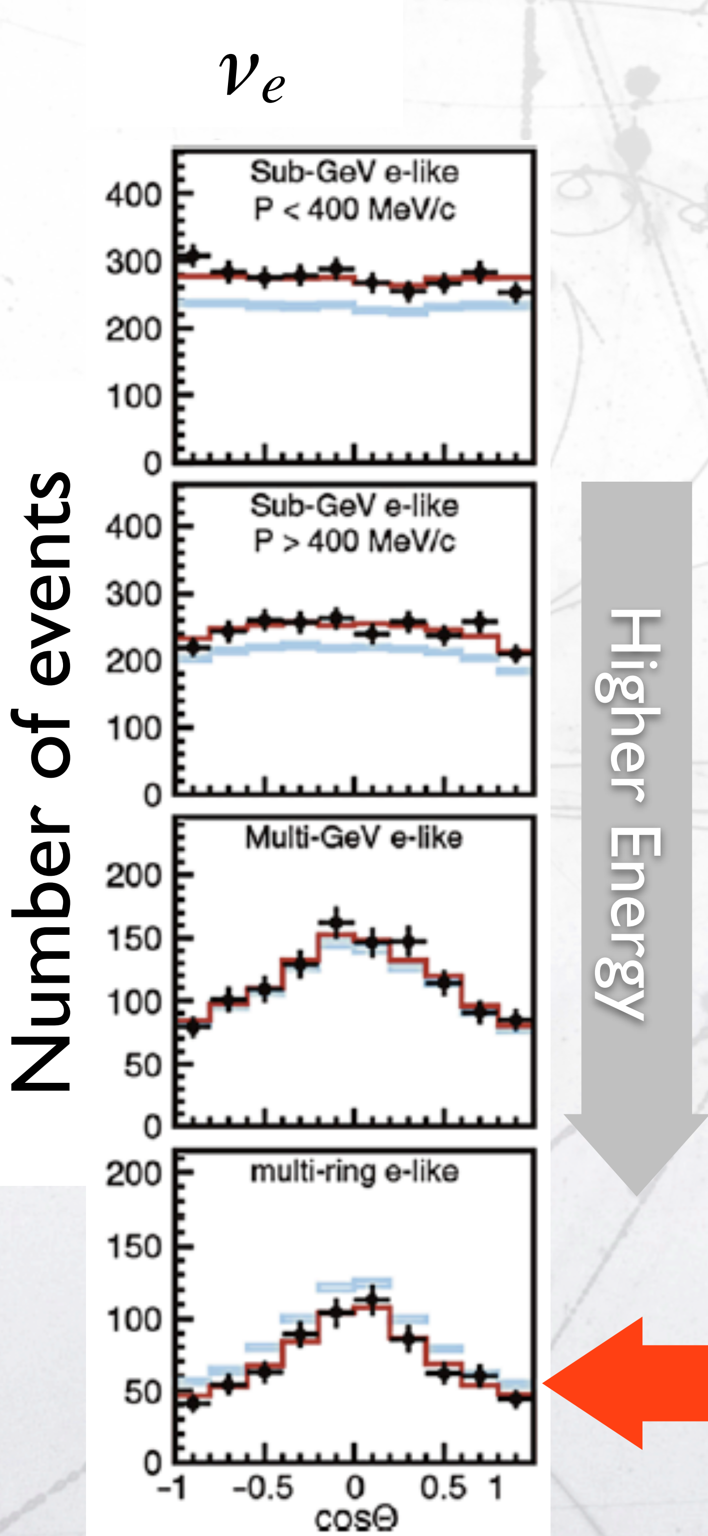
2. There is a deficit of muon neutrinos crossing the earth.

3. The angle provides the ν travel, and mixing, distance.





SuperKamiokande



1. Electron sample is similar to expected

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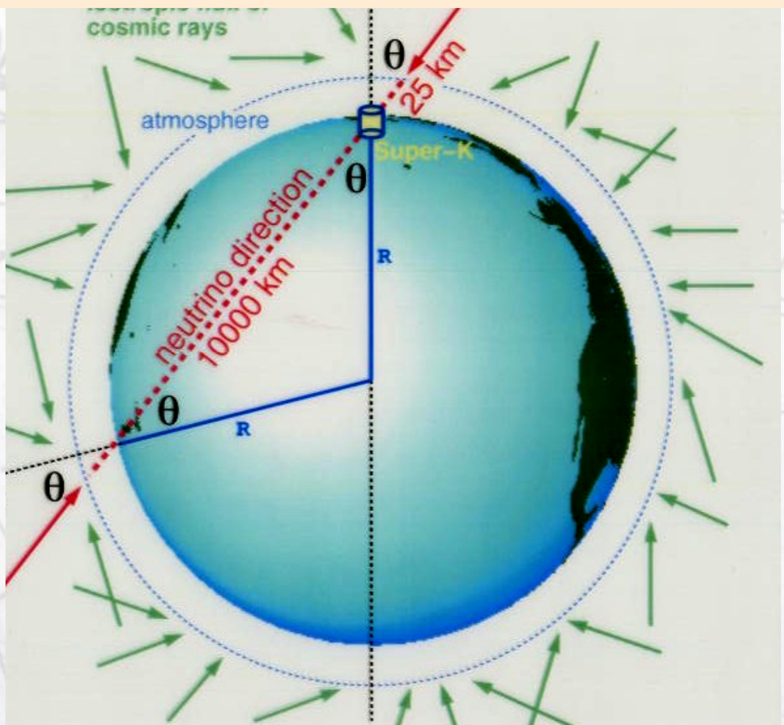
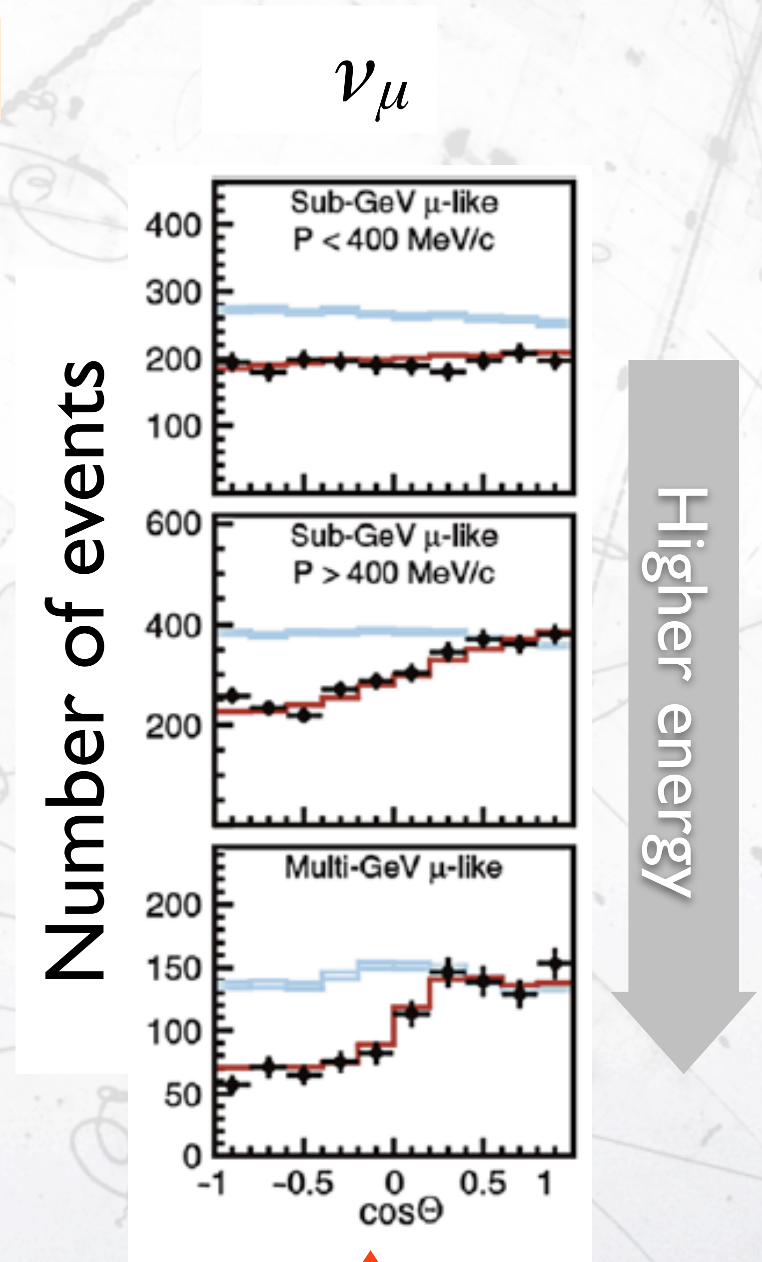


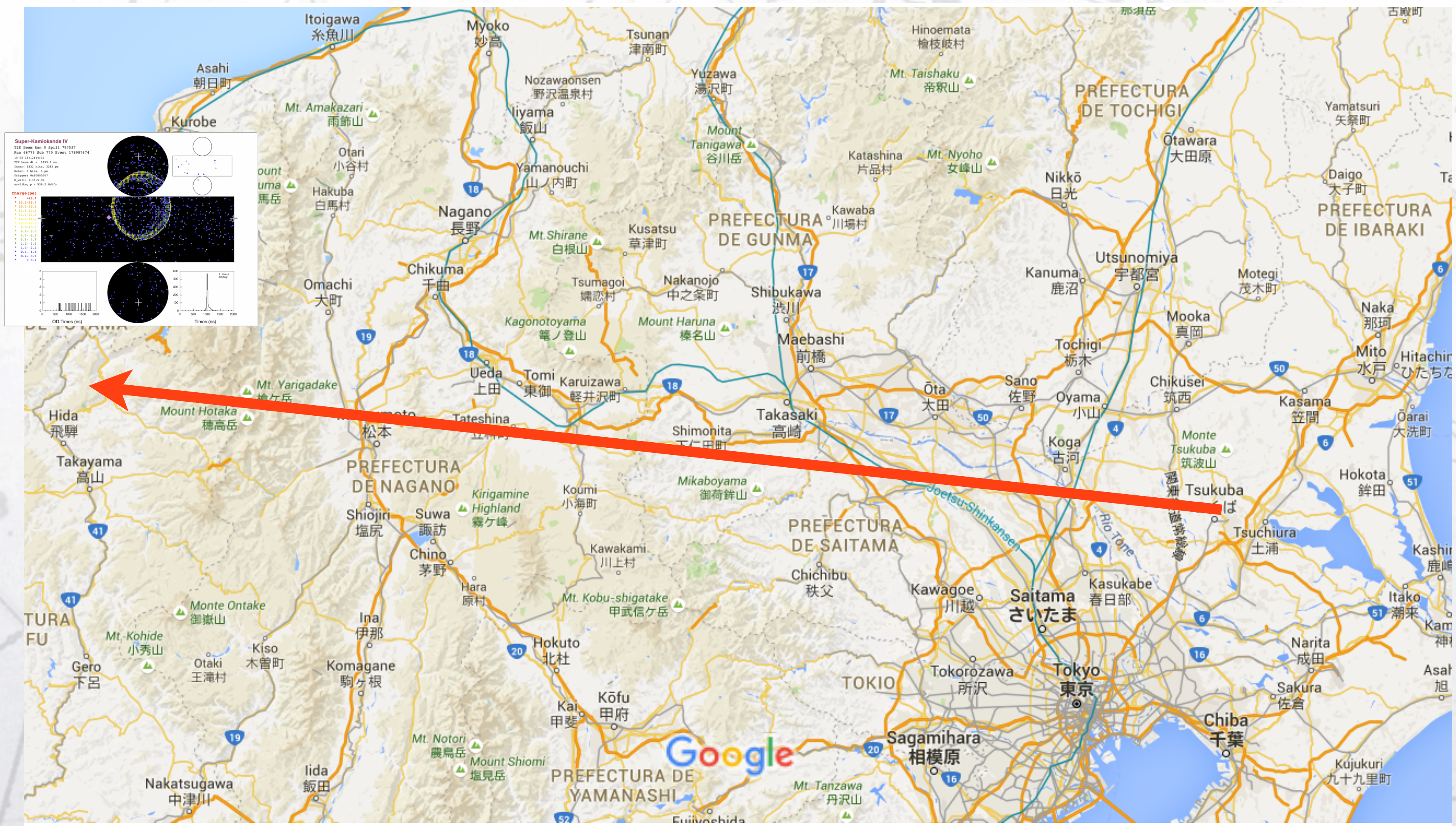


Hypothesis:
electron neutrinos did not oscillate.
Muon neutrinos oscillate to tau neutrinos.

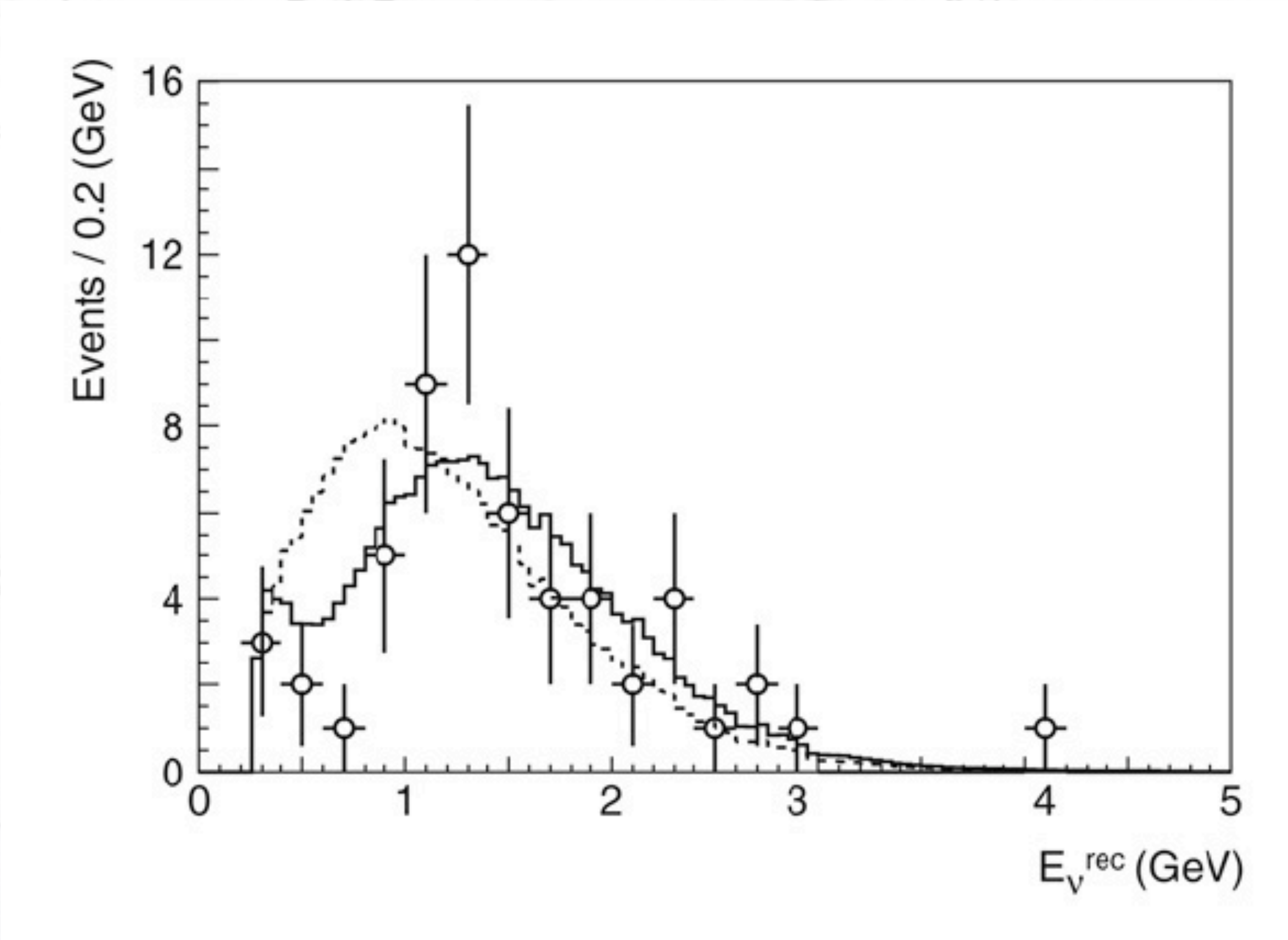
K2K: the confirmation

The experiments

- Artificial neutrinos of ~1.6 GeV are produced in the east coast of Japan.
- Neutrino flux and spectrum is measured at a near detector to reduce uncertainties ("a priori" large)
- Neutrinos were detected at 250 km at Superkamiokande.



K2K, the confirmation



- 1[st] long base line experiment: prove of principle and technology.
- Deficit and spectrum distortion compatible with SK results.
- man-made beam confirming oscillations.

Minos came later to improve these results!

Decoupled Solar & atmospheric

- The observed oscillations are:
  - $\nu_e \rightarrow \nu_{\mu,\tau}$ (SOLAR) θ_{12}
  - $\nu_\mu \rightarrow \nu_\tau$ (ATMOSPHERIC) θ_{32}

Solar & atmospheric appear to us like two decoupled oscillations

- To observe $\nu_\mu \rightarrow \nu_e$ from solar parameters (θ_{12} , Δm^2_{12})
  - the energy should be similar to solar neutrinos or the distance should be very large.

$$\frac{\Delta m^2_{23}}{\Delta m^2_{12}} \approx 30.$$

Selecting E and/or distance we can chose one or the other

  - We need energies 30x smaller (~30MeV where ν_μ production & detection is difficult) or distances 30x larger (tough, we can't make earth 30 times larger!) than standard atmospheric experiments.

The most recent results:

Θ_{13} angle

Measuring θ_{13}

The theory

- There are two possibilities:
  - $\nu_\mu \longrightarrow \nu_e$ with atmospheric Δm^2 (long base line: T2K, Nova)

$$\begin{aligned} P_{\nu_\mu,\nu_e} \approx & \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\ \pm & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \frac{\Delta m^2_{31} L}{4E} \\ - & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \frac{\Delta m^2_{31} L}{4E} \sin \frac{2\Delta m^2_{31} L}{4E} \\ + & (\frac{\Delta m^2_{12}}{\Delta m^2_{31}})^2 \cos^2\theta_{23} \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} \end{aligned}$$

  - Sensitive to violation of Charge Parity symmetry.

  - $\nu_e \longrightarrow \nu_e$ with "atmospheric" Δm^2

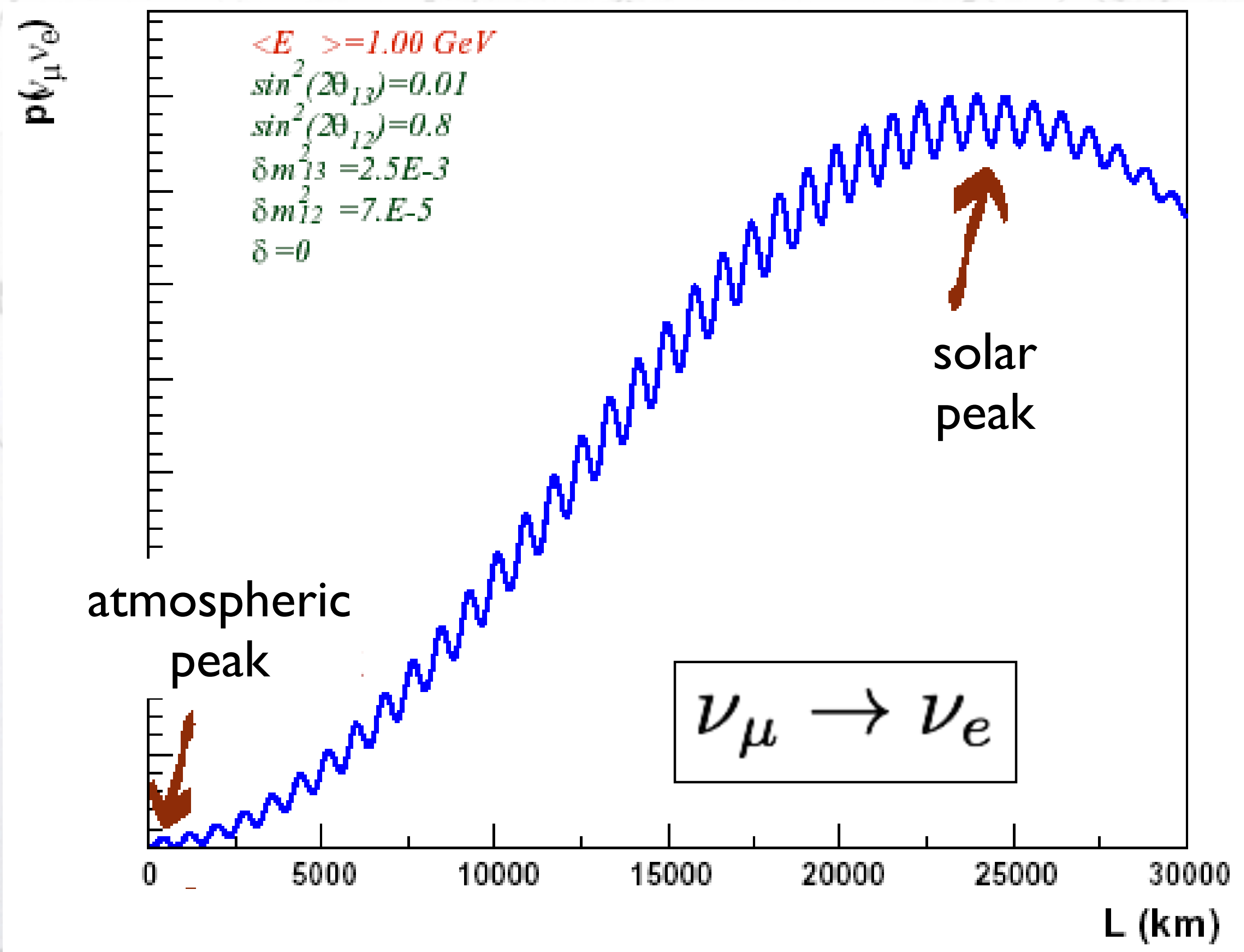
$$P_{\nu_e,\nu_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

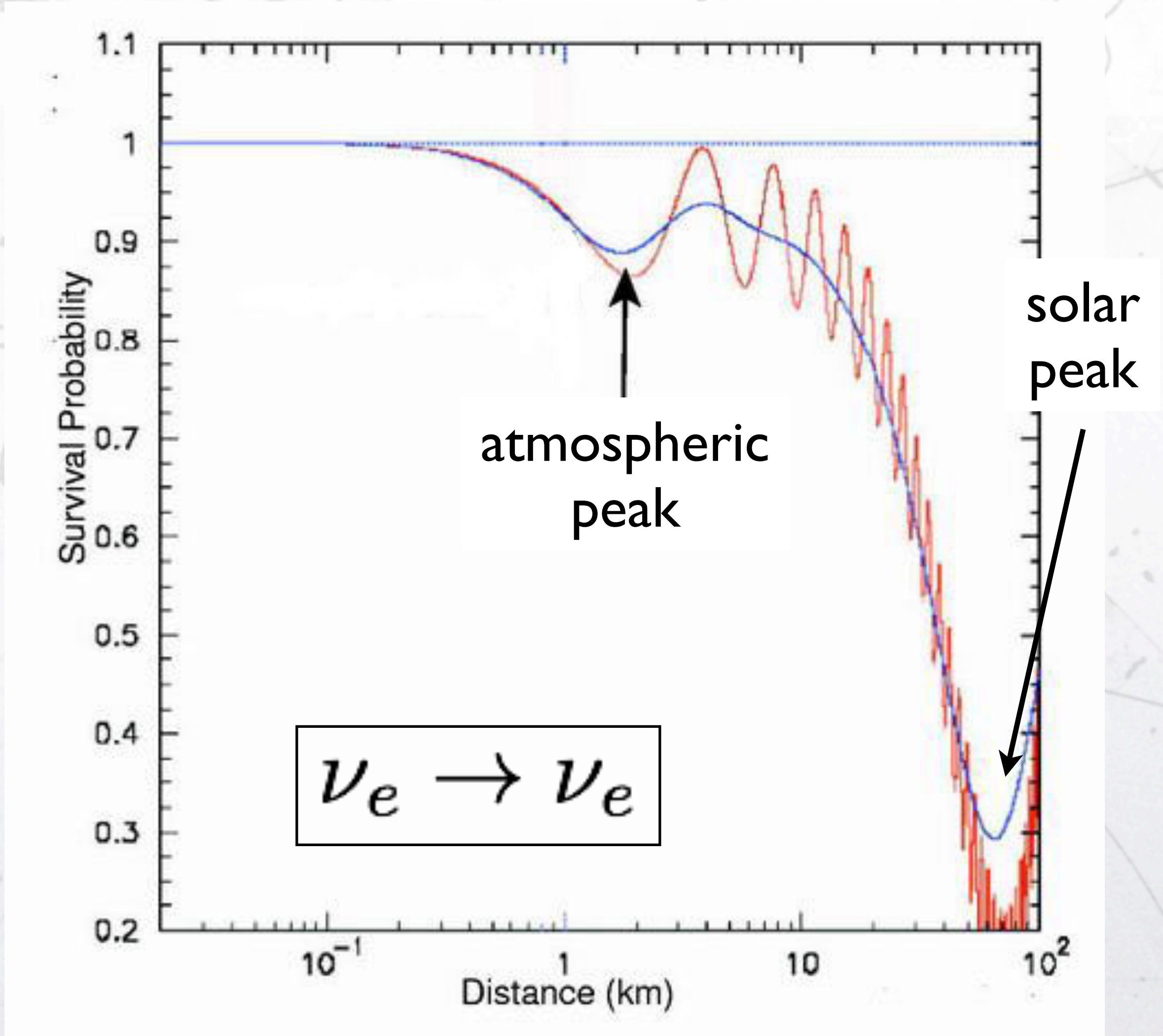
  - Insensitive to CP phase.

Measuring θ_{13}

Look for ν_e appearance from ν_μ at atmospheric neutrino oscillations distances.

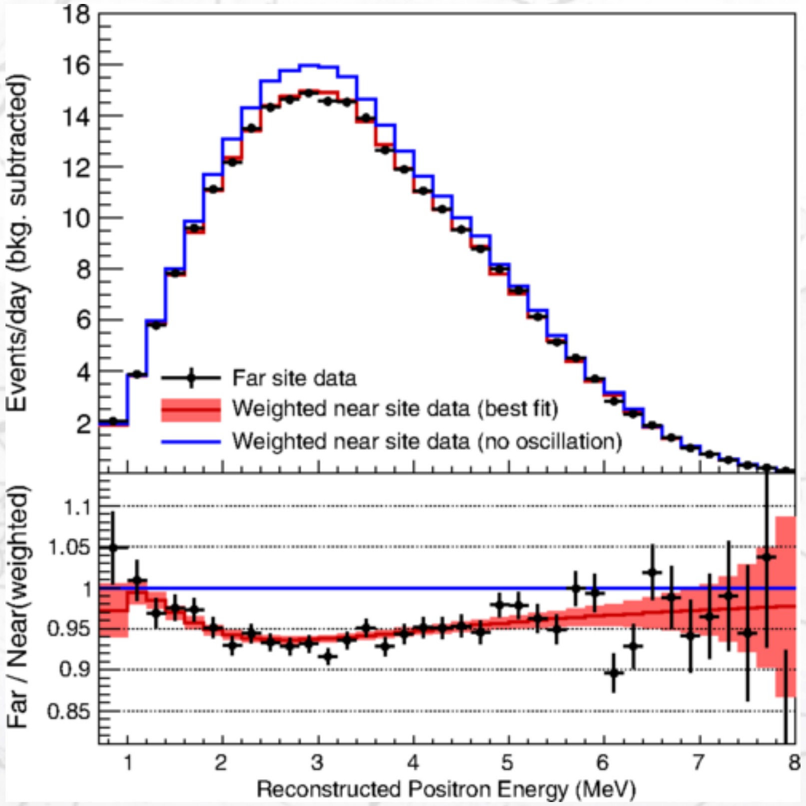
Look for ν_e disappearance (like solar oscillations) at atmospheric neutrino oscillations distances.

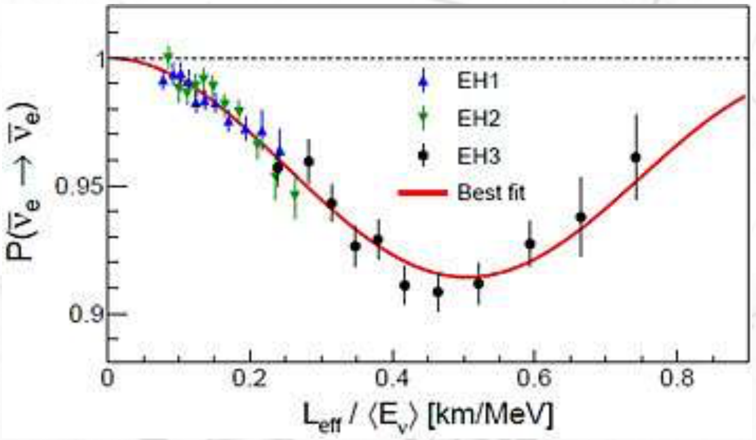




Daya Bay

- Electron anti-neutrinos from a powerful nuclear power plant.
- Several sites & detectors (near and far)



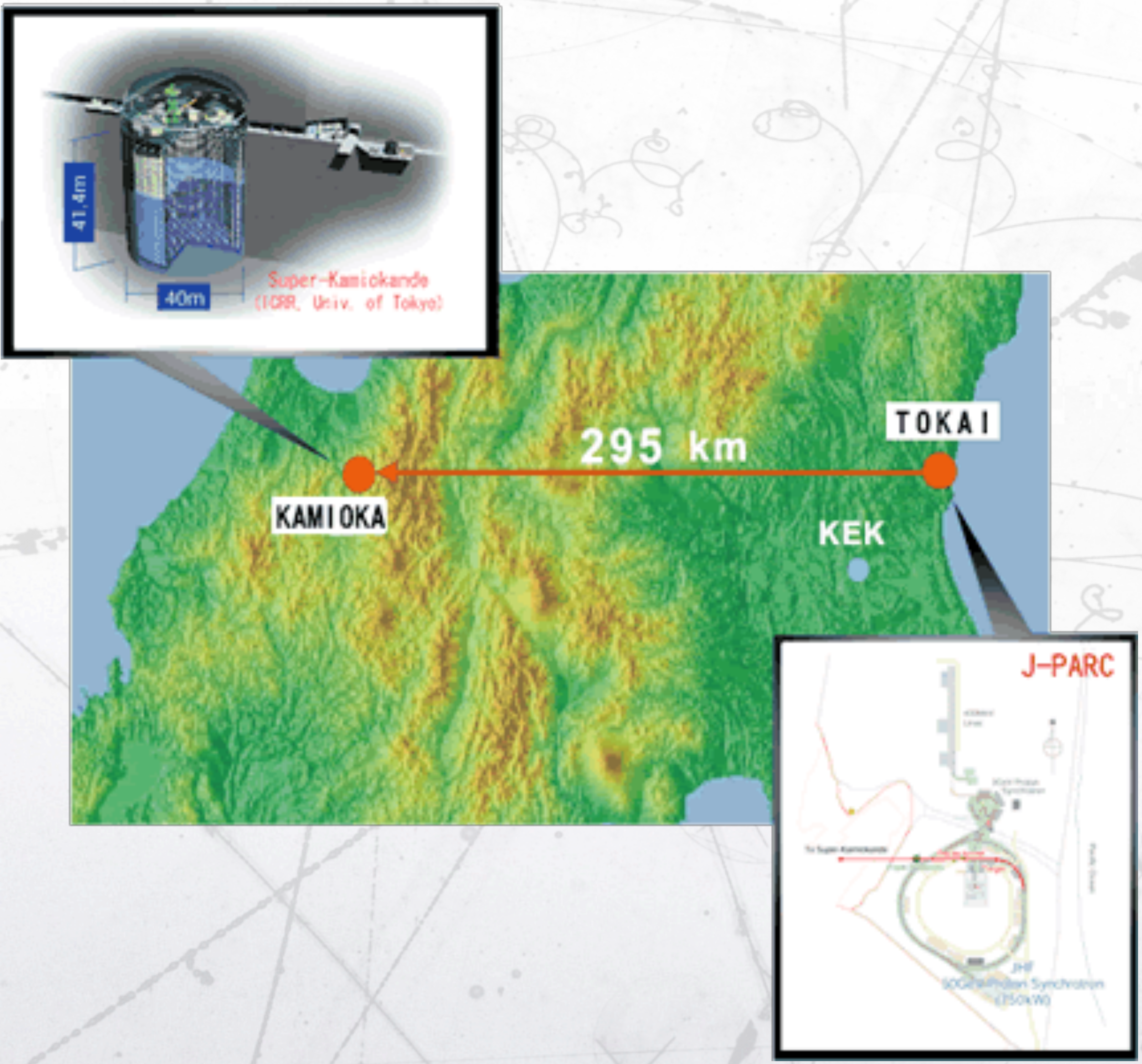


$\sin^2 2\theta_{13} = 0.084 \pm 0.005$

The most precise mixing angle measured so far.

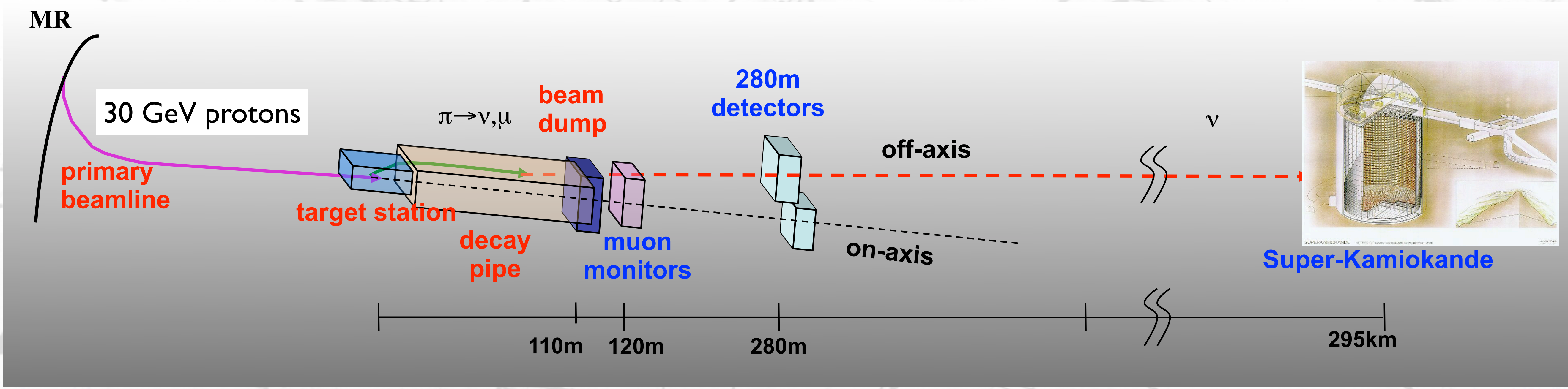
Detection technique (inverse β decay) similar to the original Davis experiment.

T2K



- High intensity ν_μ beam is produced at high intensity (400 kW) JPARC accelerator complex in Tokai.
- Neutrino flux measured at the near detector site prior to oscillations.
- Neutrinos are detected at the Super-Kamiokande detector at the west coast.

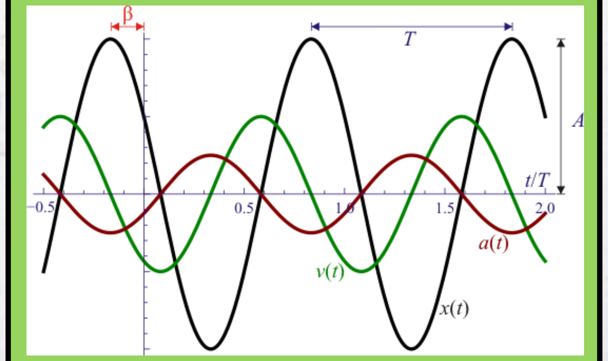
T2K



Neutrinos are produced in an accelerator:
1. Protons produce pions that decay into muon neutrinos.
2. Pions are focused with a magnetic horn.

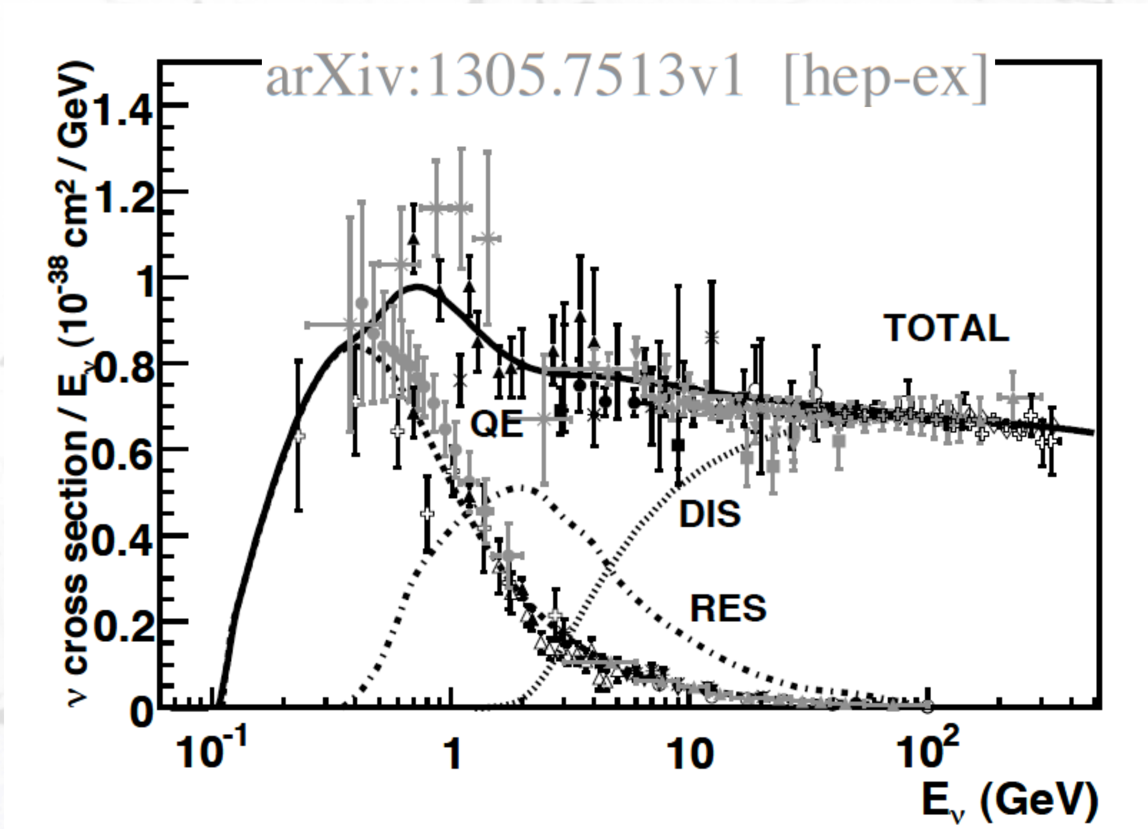
The flux is measured to reduce errors.

Oscillations



Measurement of oscillated flux.

$\sigma_{\nu N}$



Charge current	
CC-QuasiElastic	$\nu_\mu n \rightarrow \mu^- p$
CC-Resonance	$\nu_\mu N \rightarrow \mu^- \pi^{+,0} N$
CC-Deep Inelastic	$\nu_\mu N \rightarrow \mu^- X$

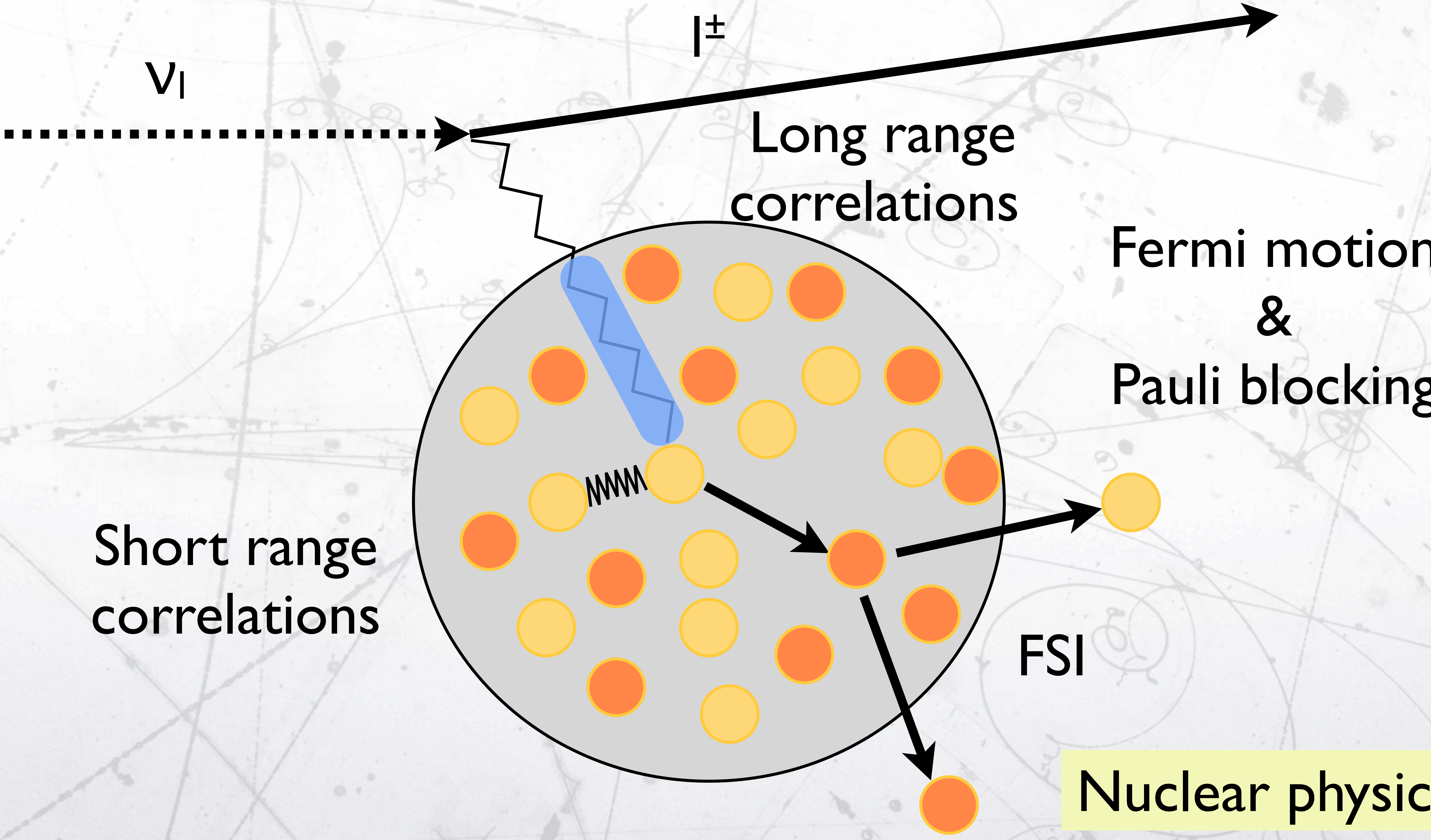
Neutrino spectrum is always broad (we do not know how to make it mono-energetic)

We relay on the interaction to reconstruct the neutrino energy.

E_ν>100MeV the ν-Nucleus cross-section dominates.

Modelling of ν-Nucleus is not trivial.

Cross-sections!



Nuclear physics!

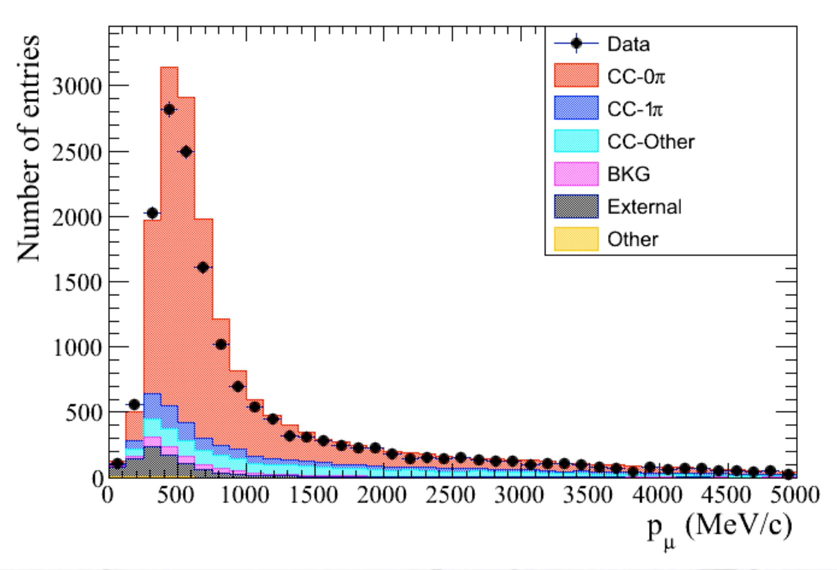
T2K measurement

Measurements

Predictions

T2K measurement

Measurement at the near detector



Measurements

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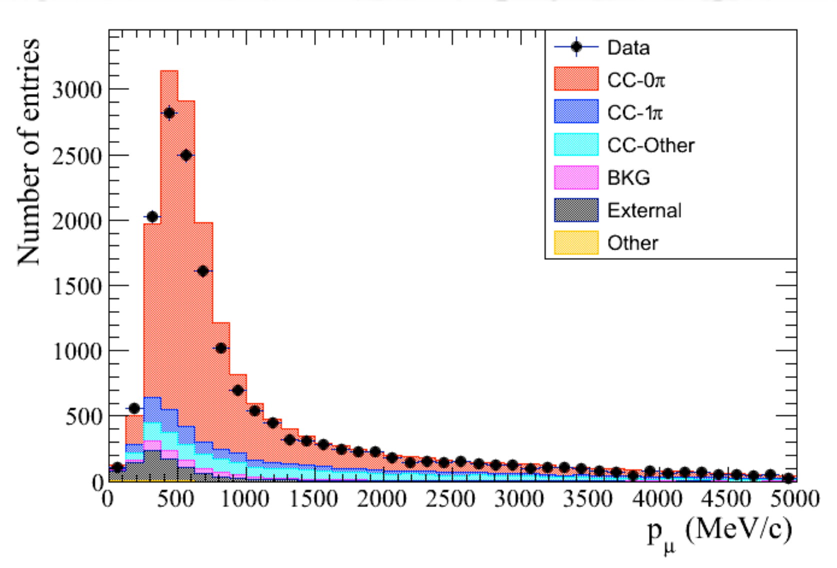
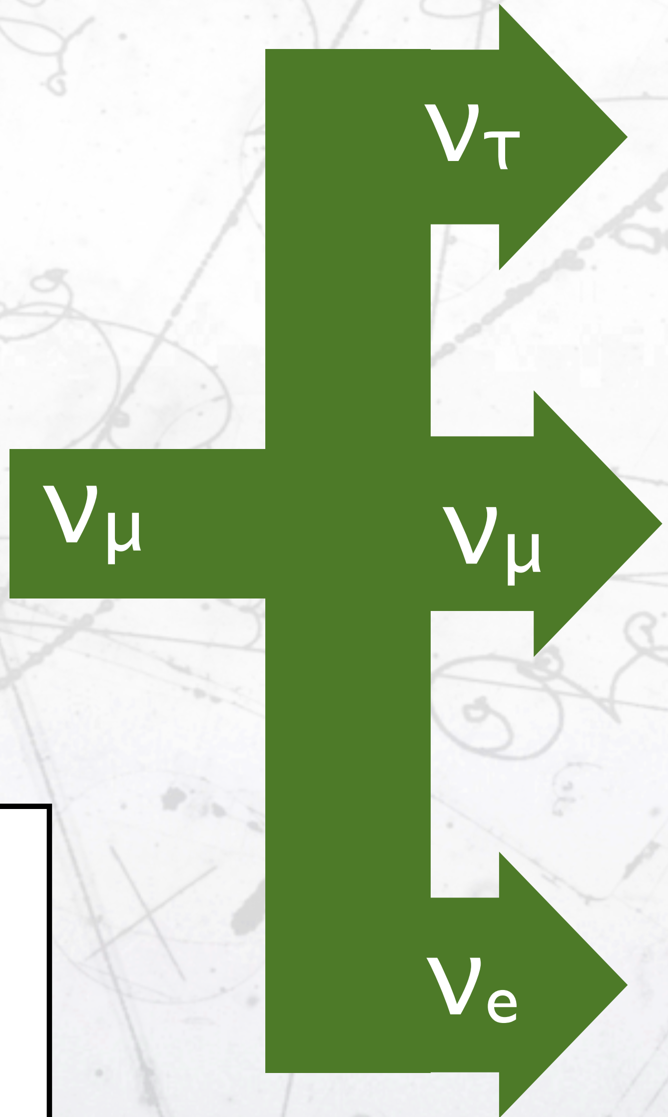


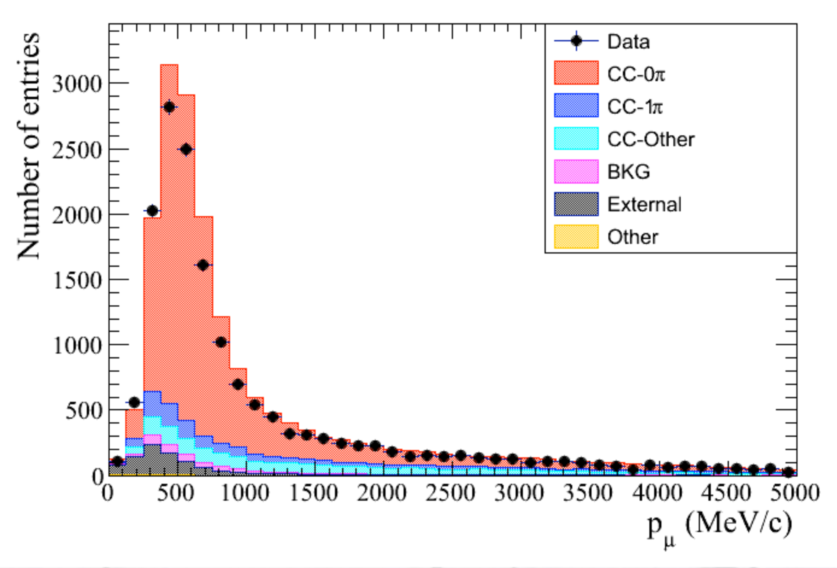
Measurements

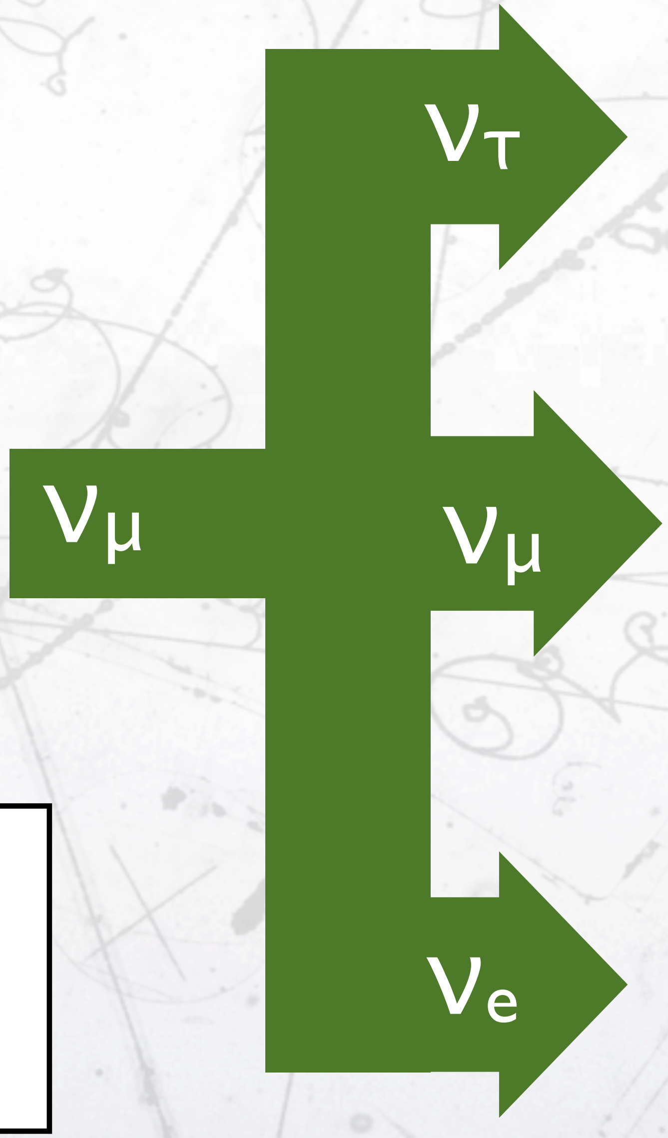
Predictions



Measurement at the near detector

Super-Kamiokande

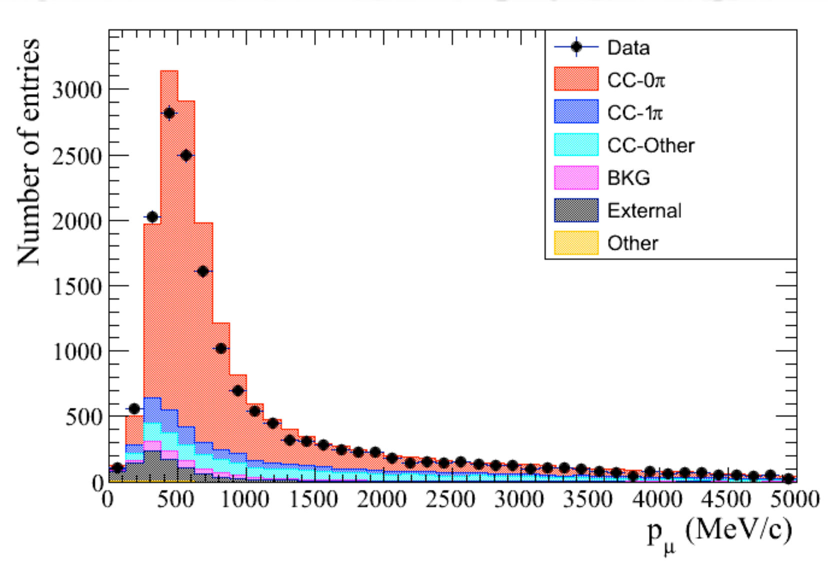




●	Measurements
⎍	Predictions

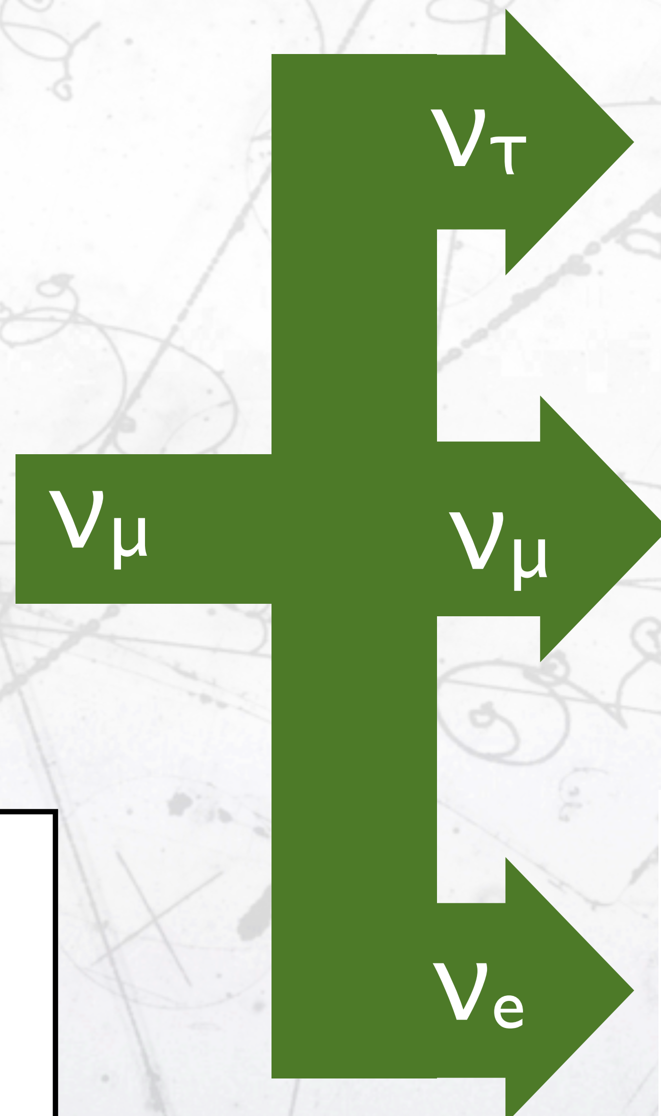
T2K measurement

Measurement at the near detector

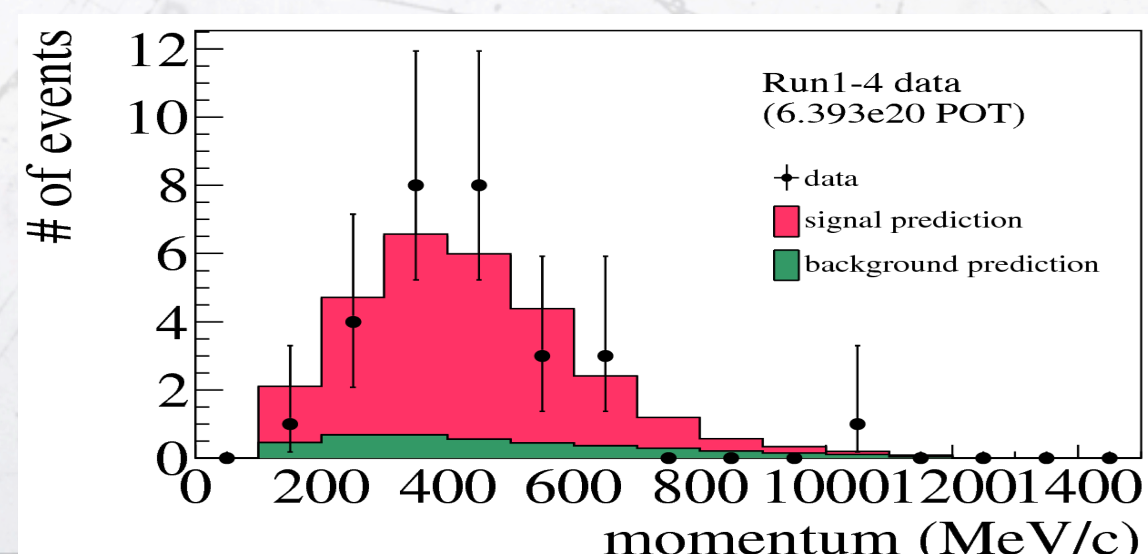


Measurements

Predictions

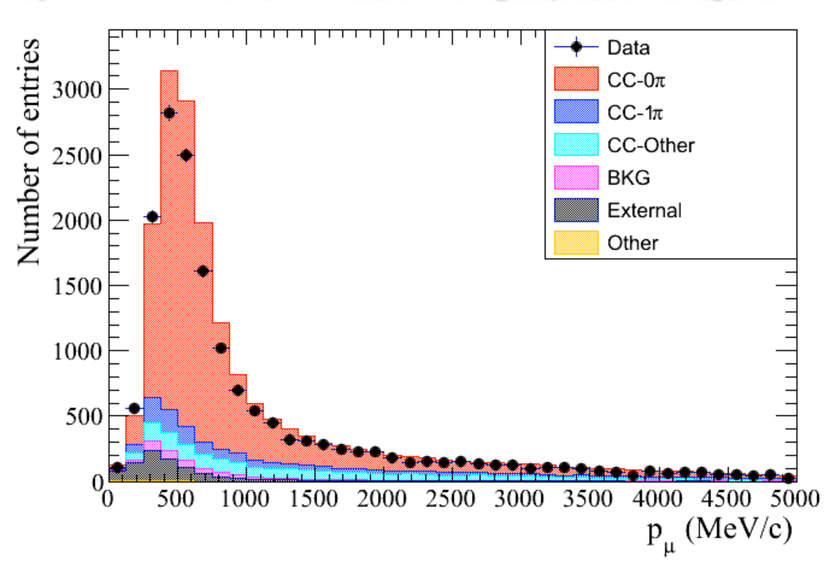


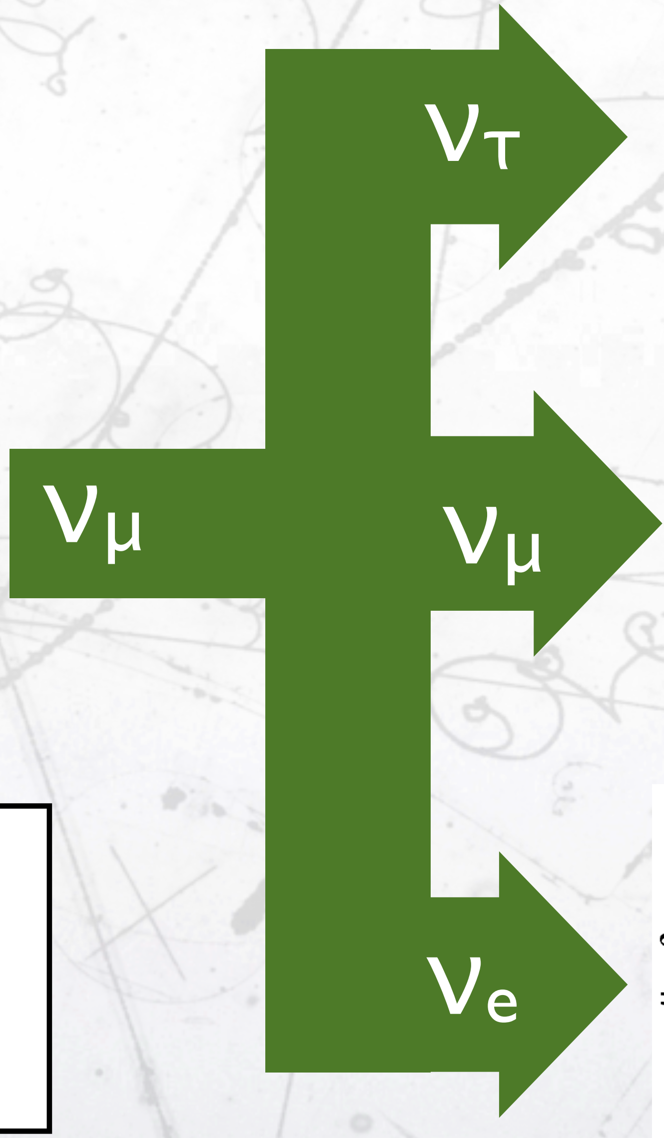
Super-Kamiokande



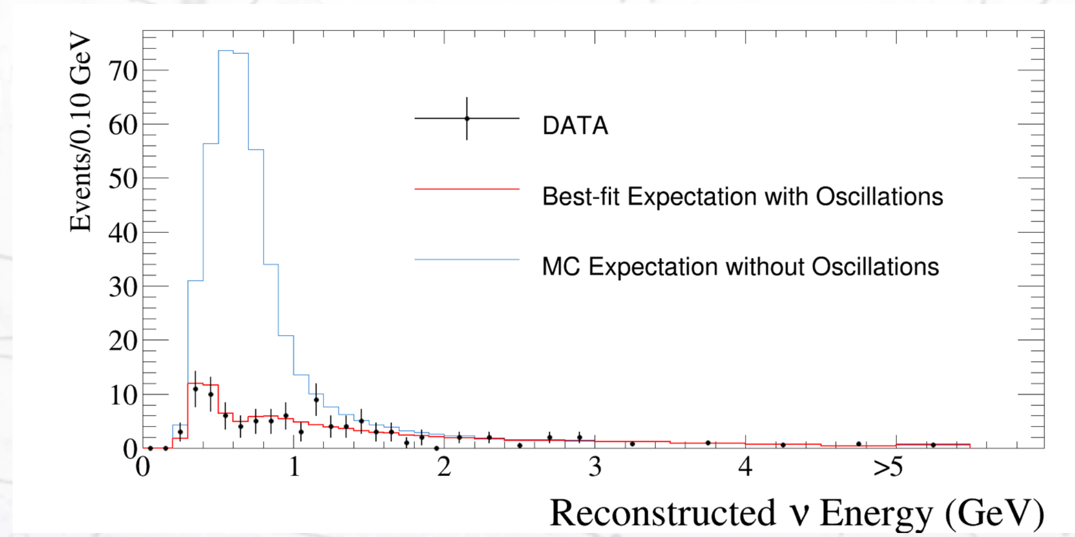
T2K measurement

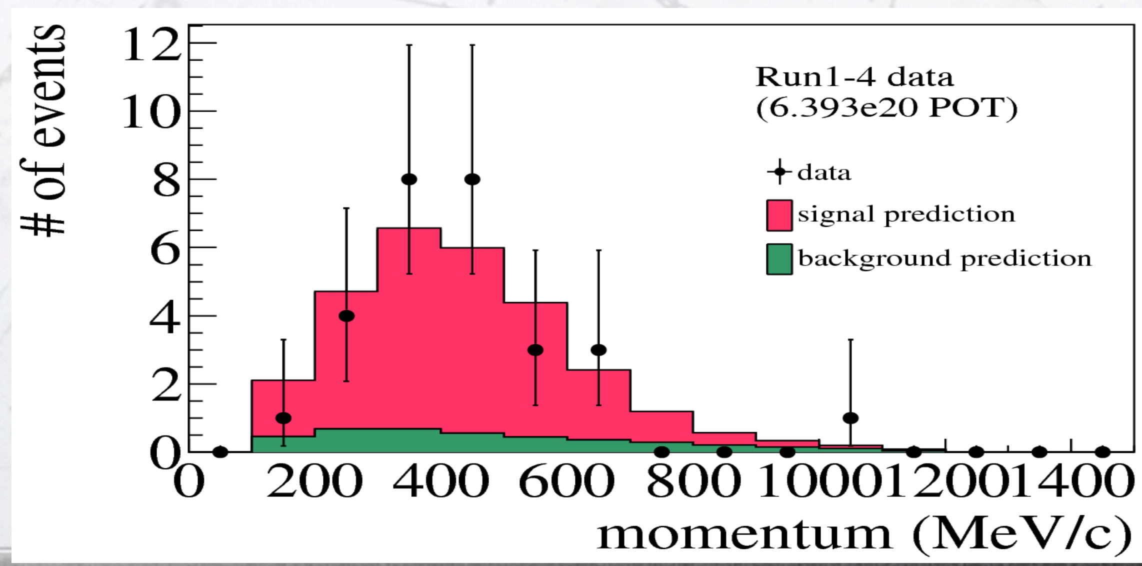
Measurement at the near detector





Super-Kamiokande



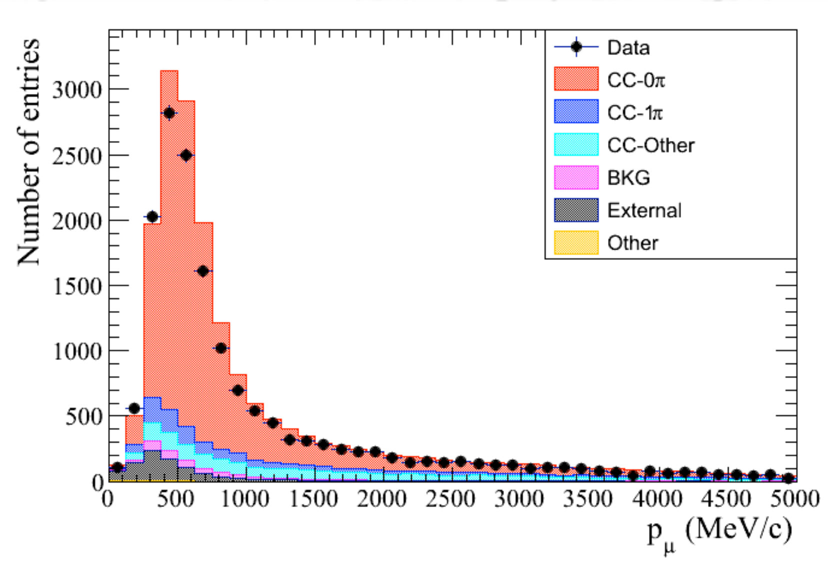


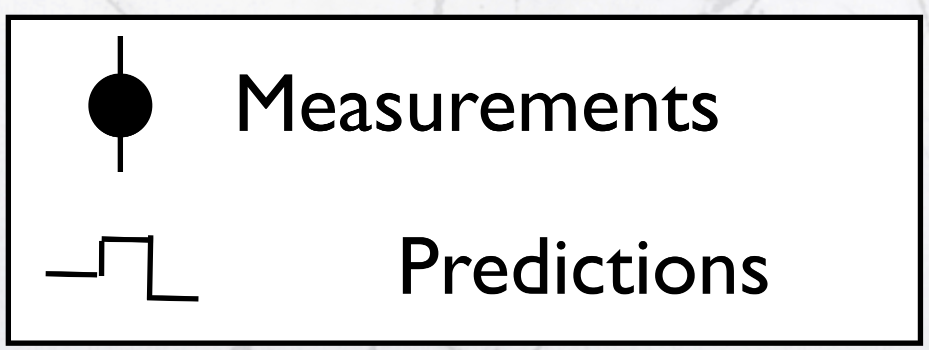
Measurements

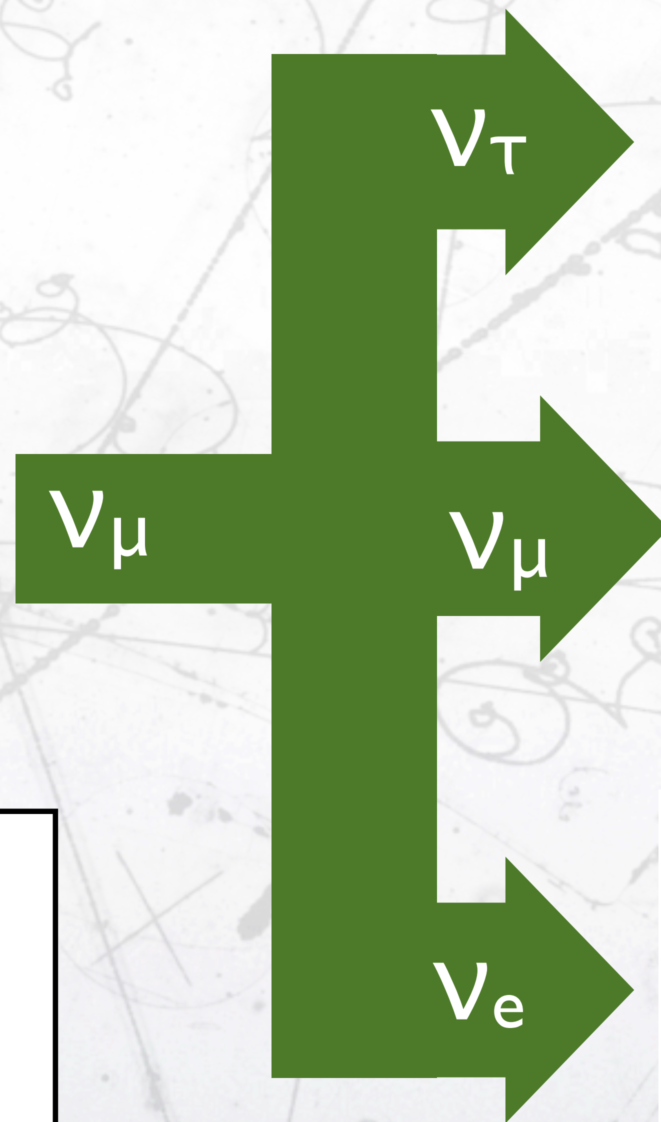
Predictions

T2K measurement

Measurement at the near detector

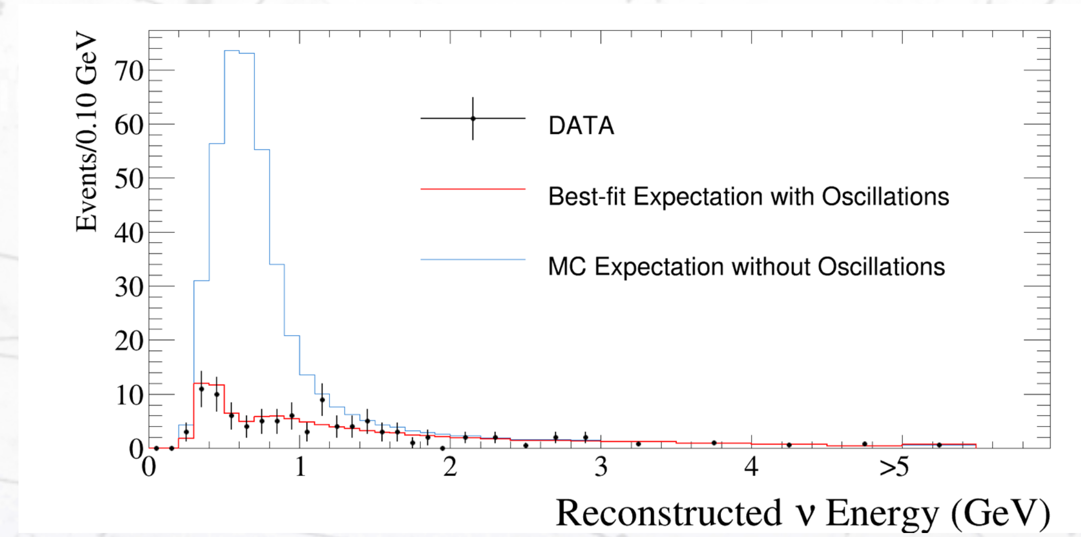


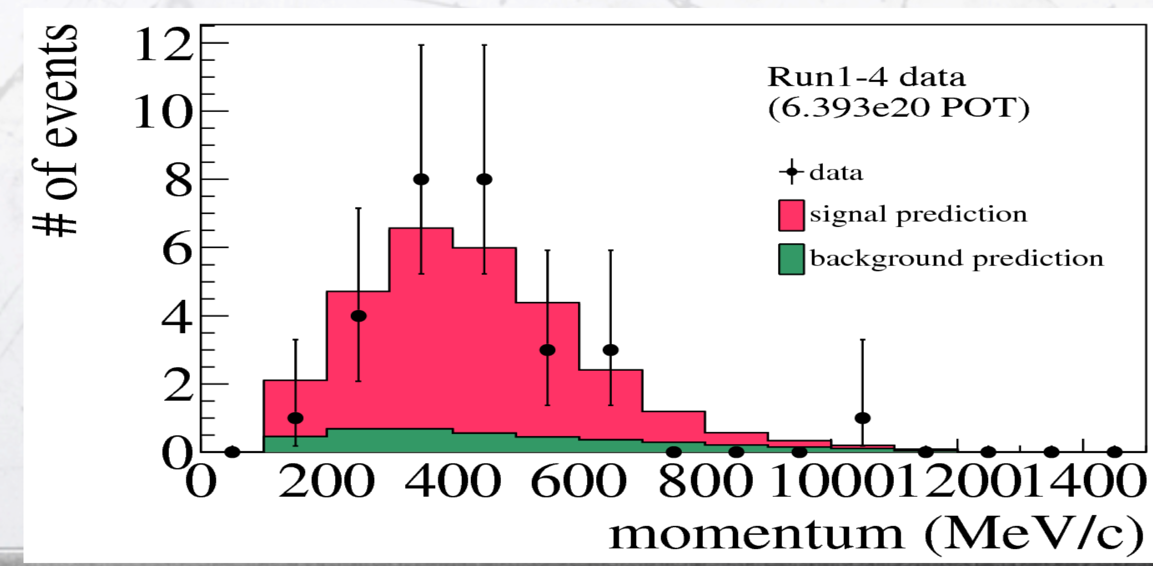




Super-Kamiokande

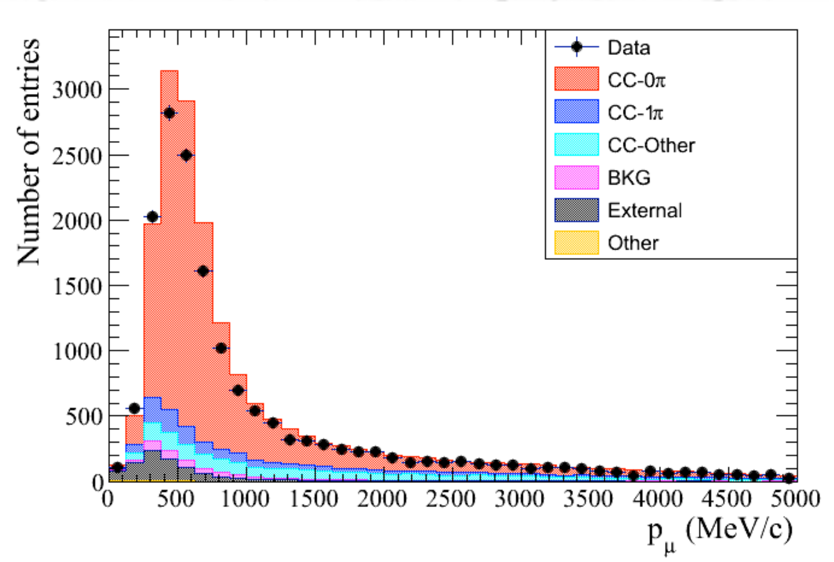
Invisible @ T2K
Not enough energy.

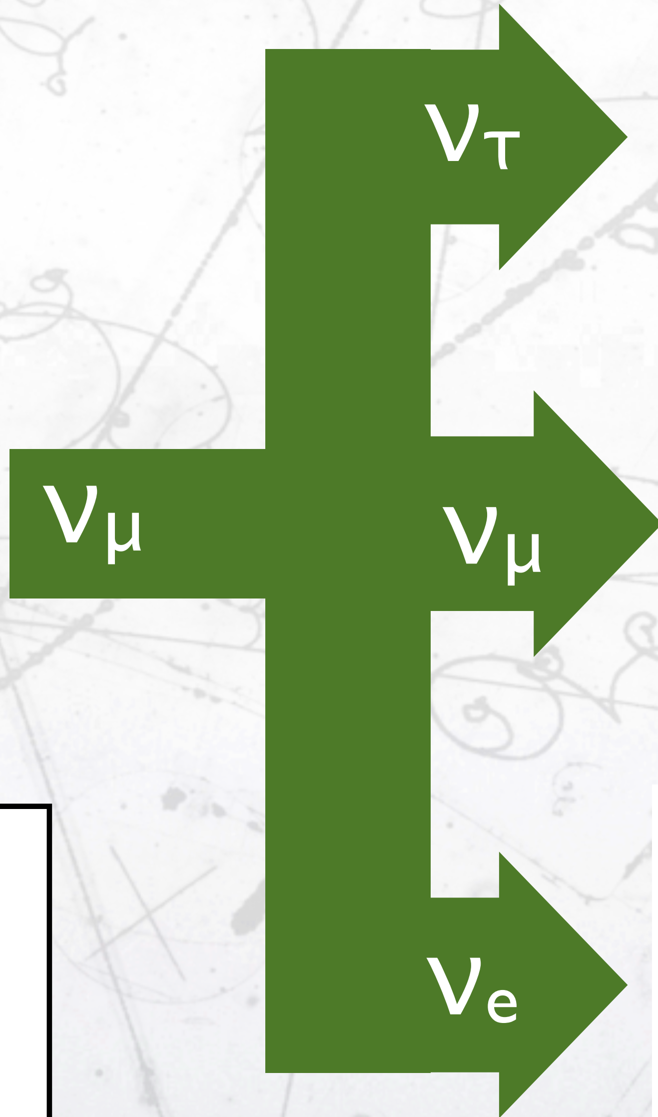




T2K measurement

Measurement at the near detector





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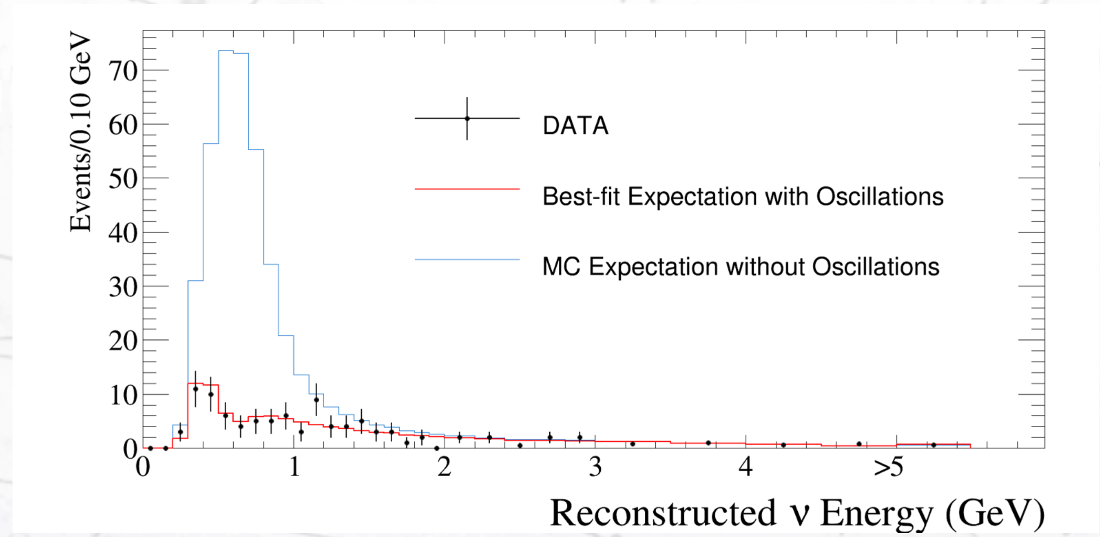
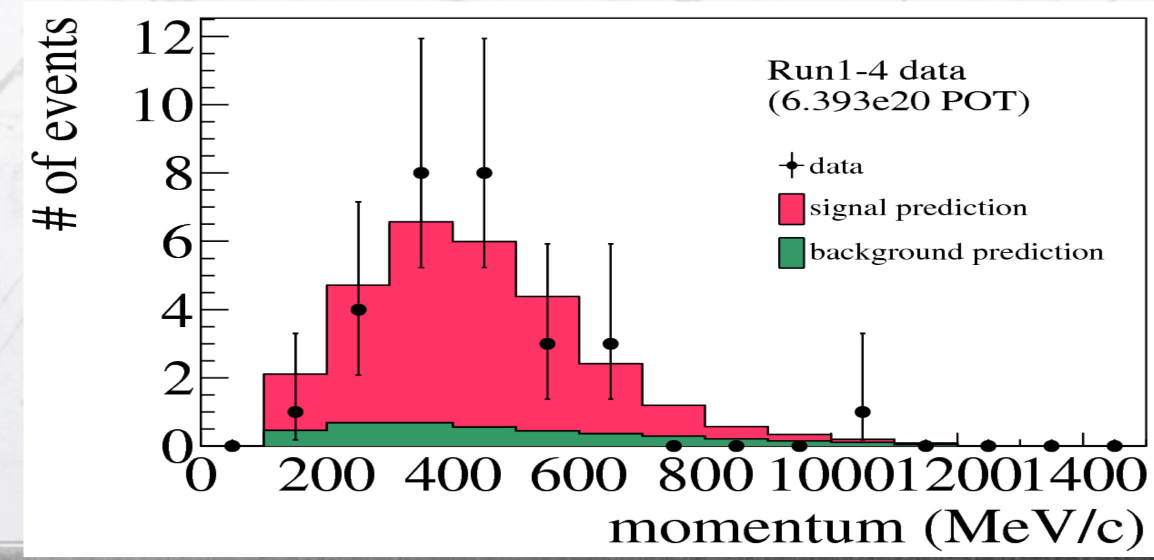


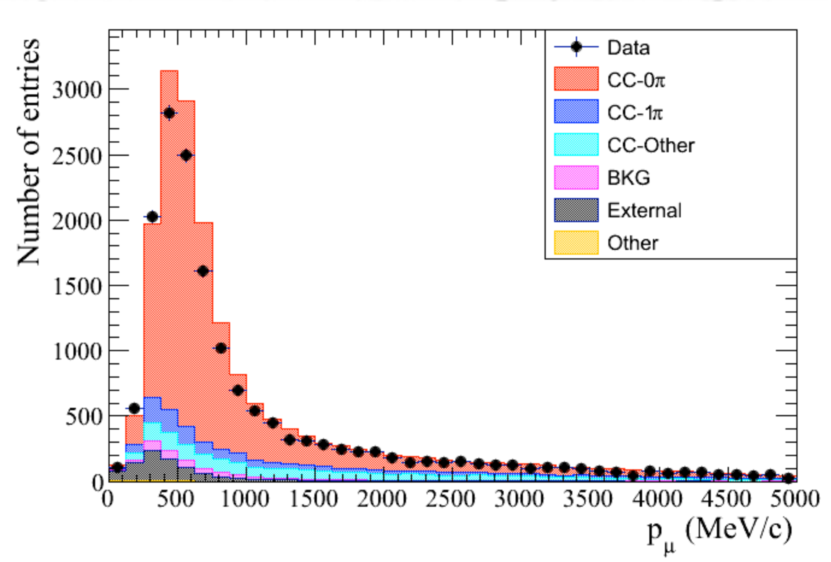


Measurements

Predictions

T2K measurement

Measurement at the near detector



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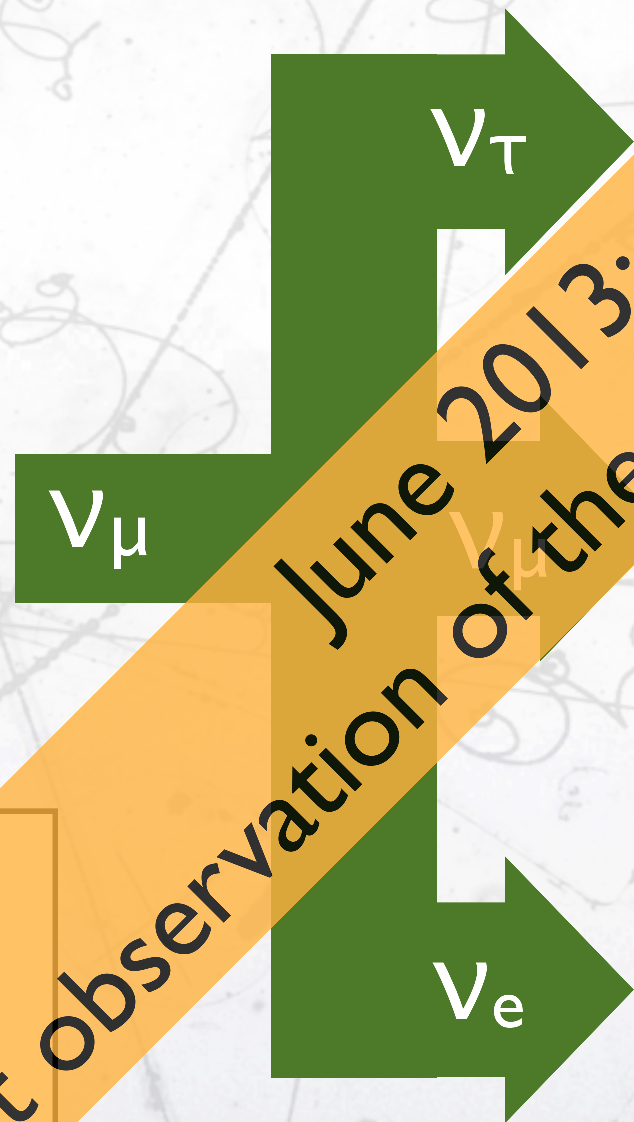

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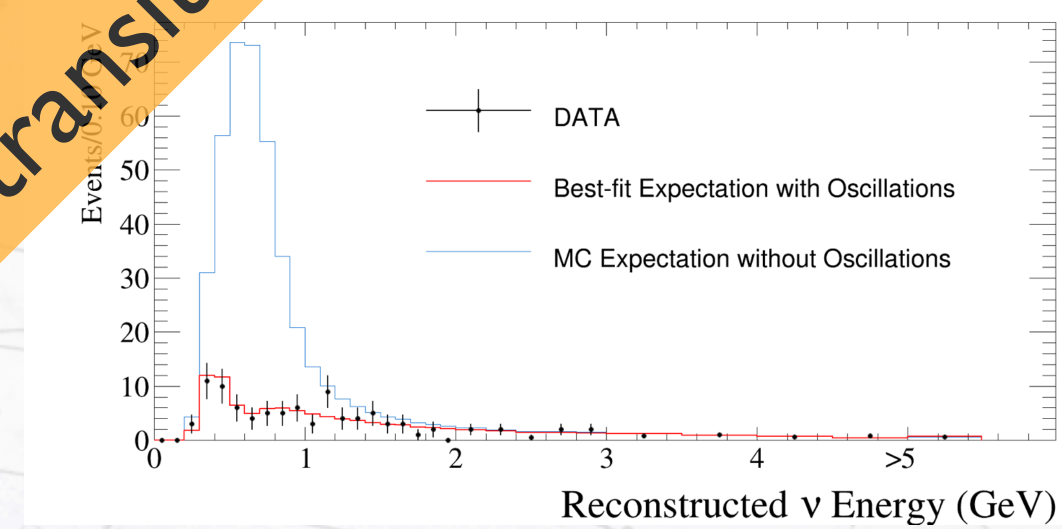
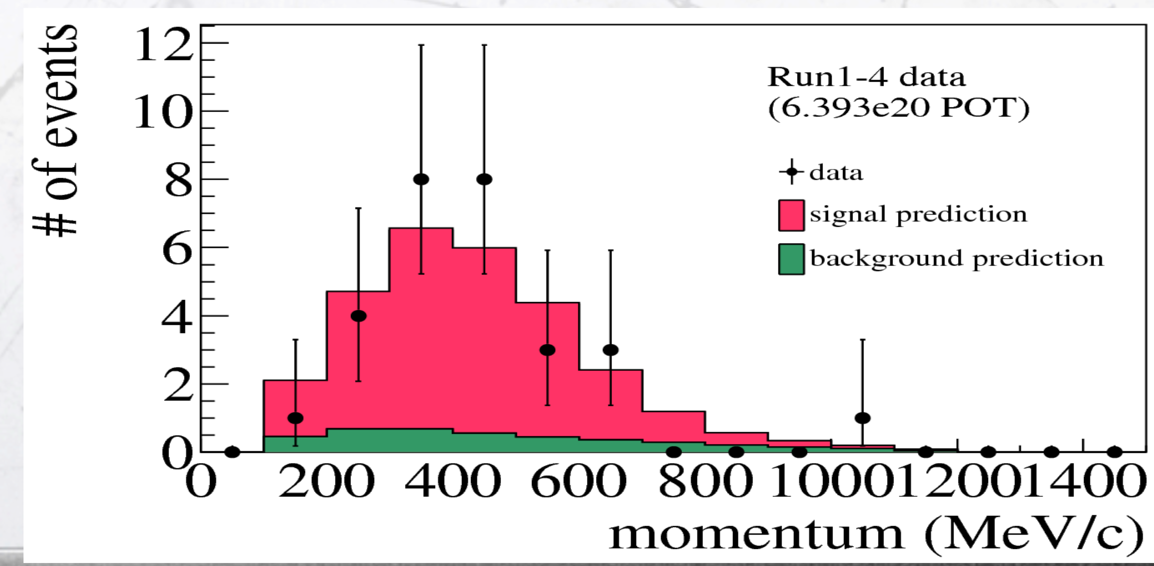
Invisible @ T2K

Not enough energy.

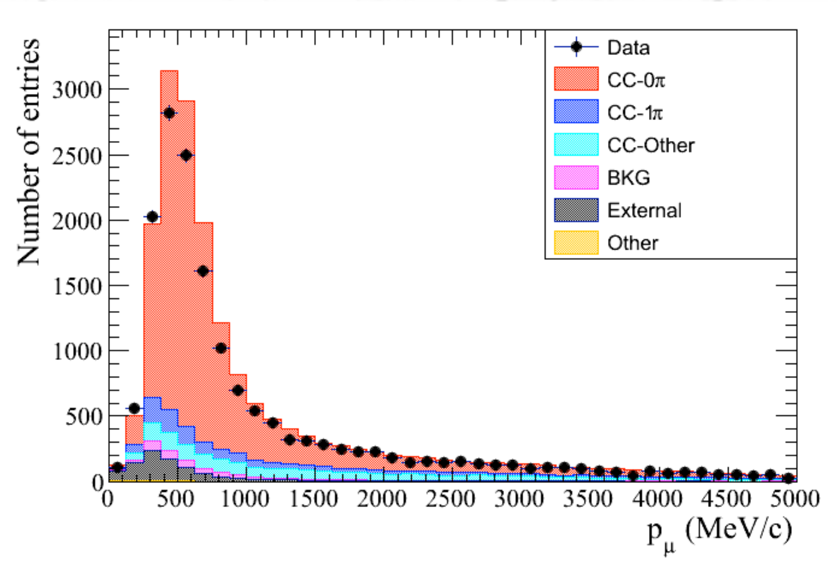




June 2013:

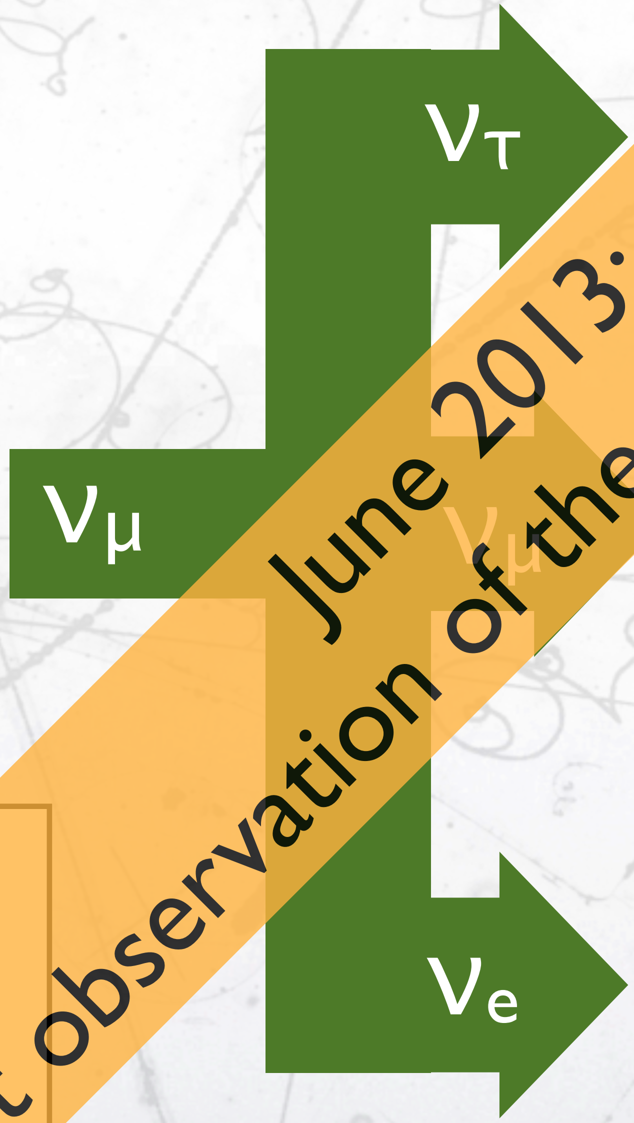
First observation of the transition $\nu_\mu \rightarrow \nu_e$

Measurement at the near detector



Measurements

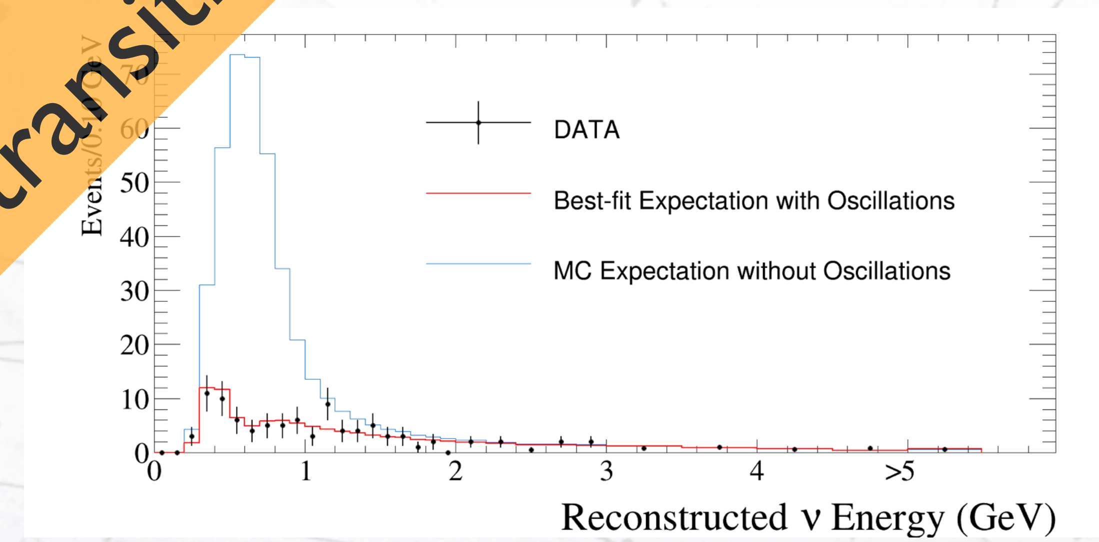
Predictions

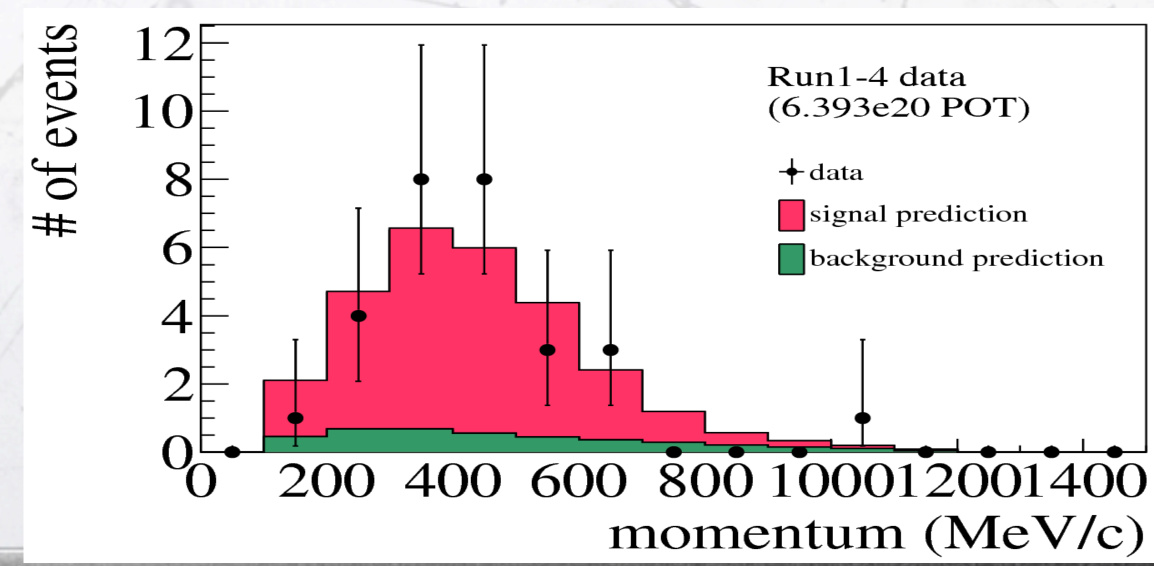


Super-Kamiokande

Invisible @ T2K

Not enough energy.





June 2013: First observation of the transition $\nu_\mu \rightarrow \nu_e$

Results confirmed by Nova Collab.

Measuring δ_{CP}

To measure CP we need $\theta_{13} \neq 0$. 👌

Direct CP violation determination

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

✓ Model independent.

✗ Inefficient to produce and detect anti-neutrinos.

Indirect CP violation determination

Compare $P(\nu_\mu \rightarrow \nu_e)$ with $P(\nu_e \rightarrow \nu_e)$

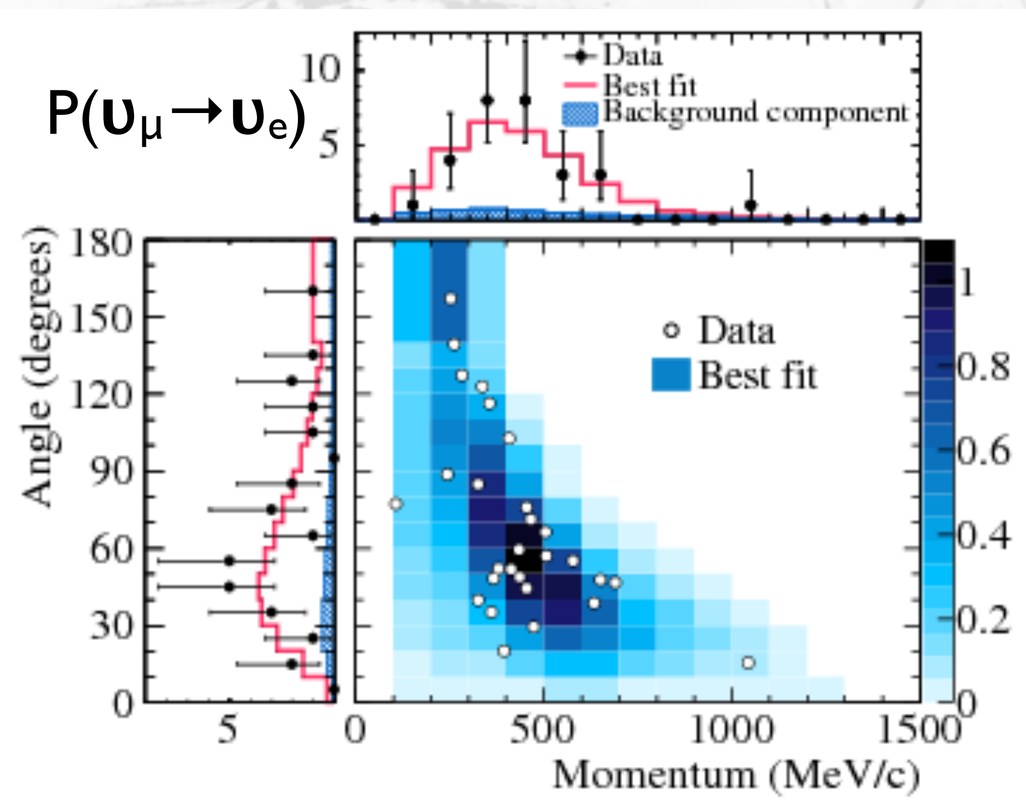
✗ Model dependent

✓ $\#\nu_\mu$/€ >> $\#\bar{\nu}_\mu$/€

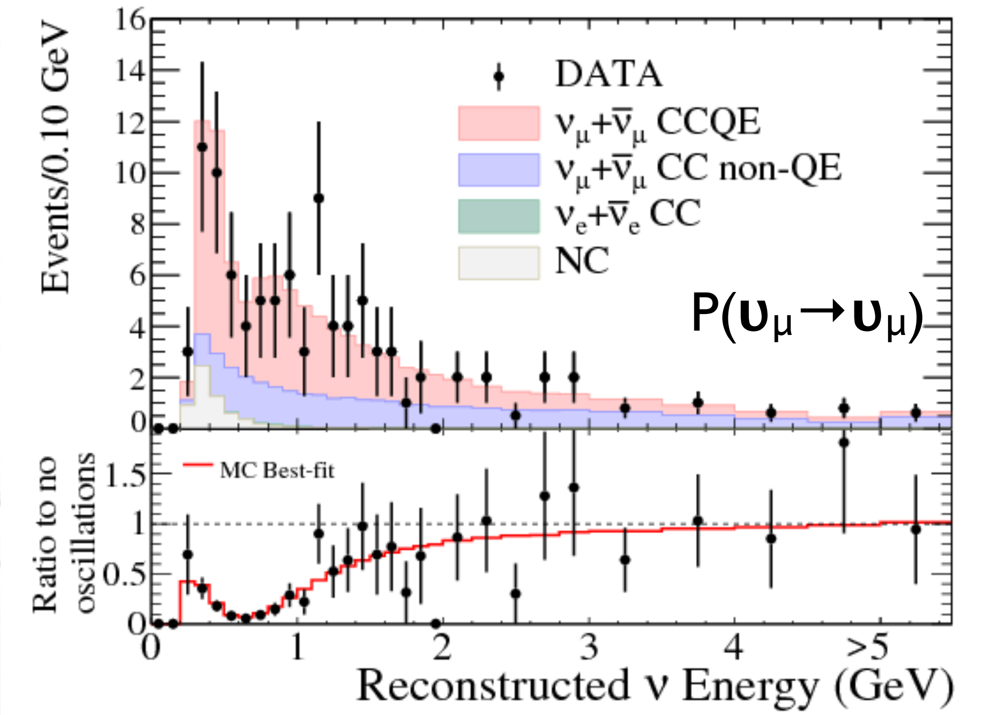
Matter effects also alter the results differently for neutrinos and antineutrinos (matter is made of matter!) and for the sign of Δm^2 (is $m_3 > m_1$? hierarchy)

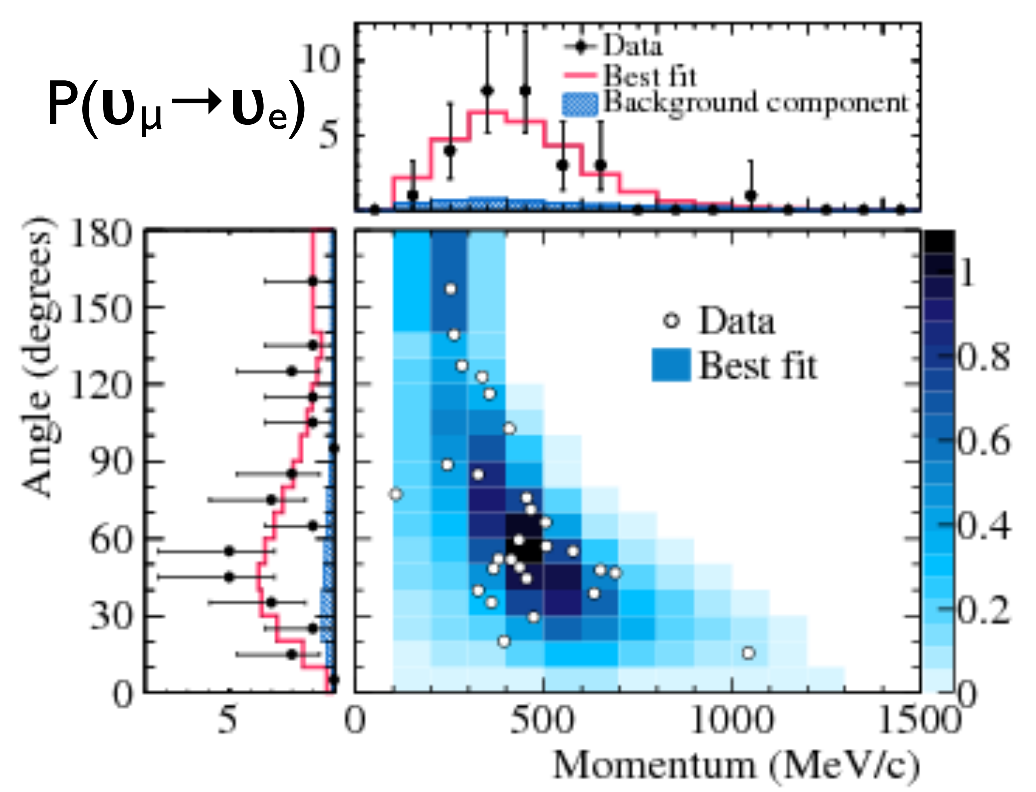
CP violation

CP violation

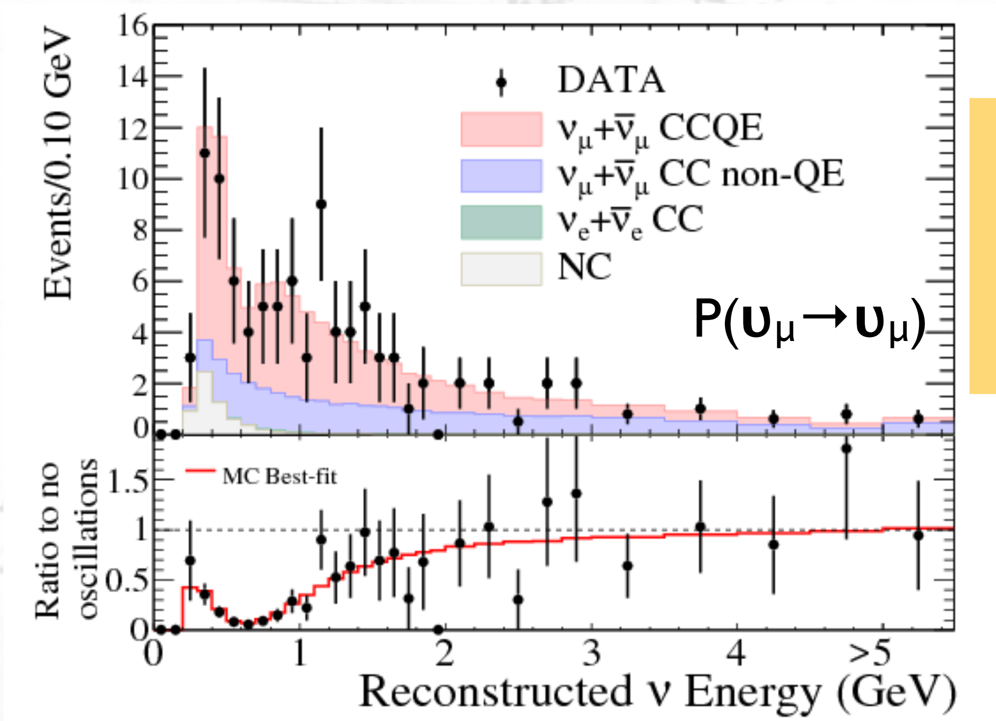


CP violation

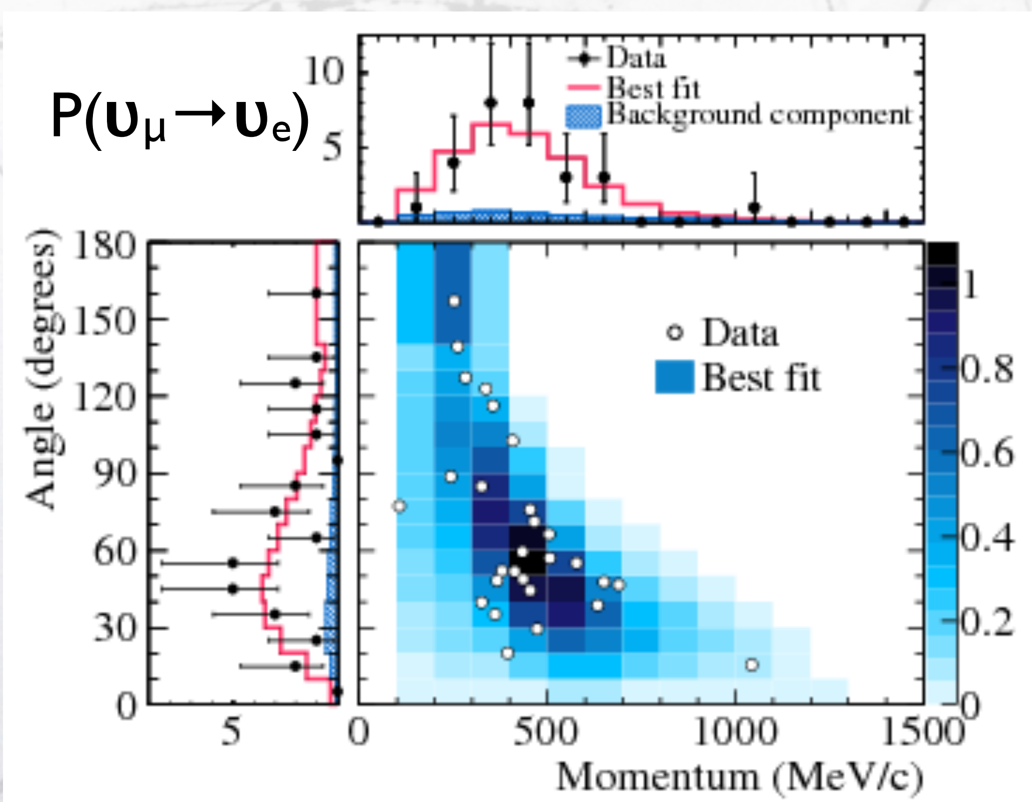




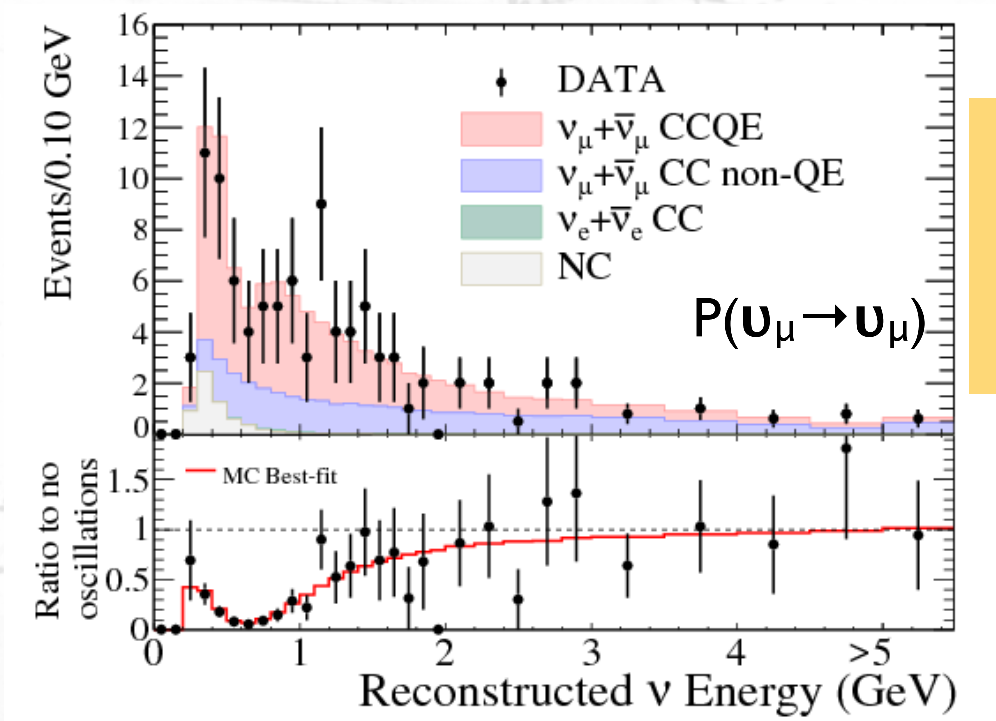
CP violation



atmospheric Θ_{23}

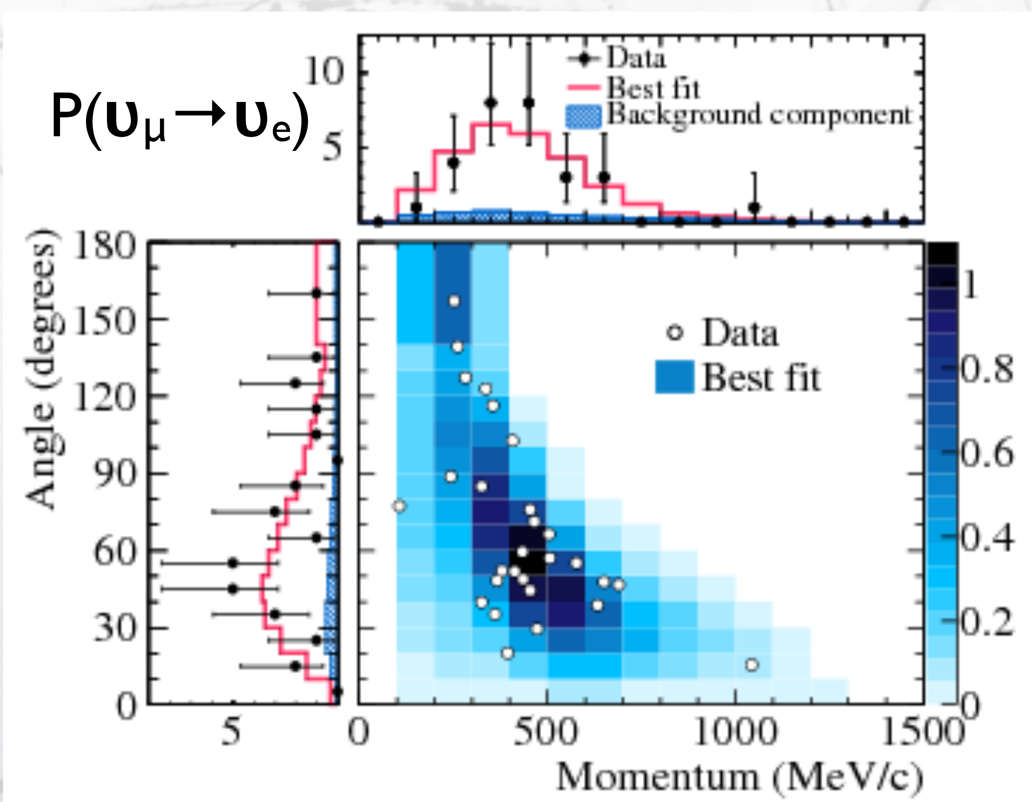


CP violation

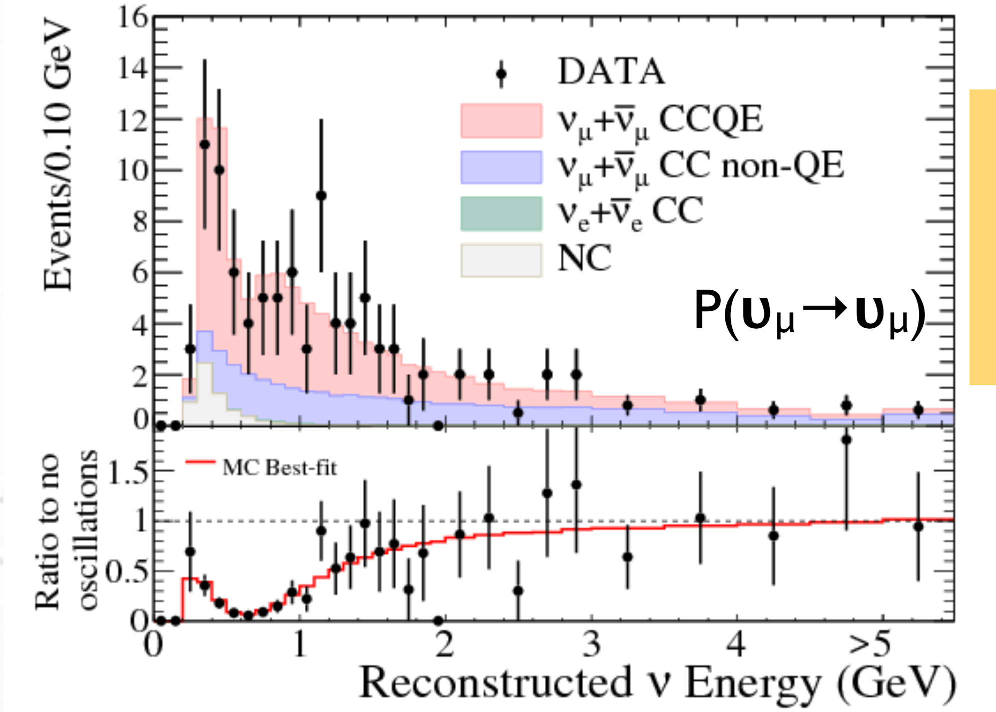


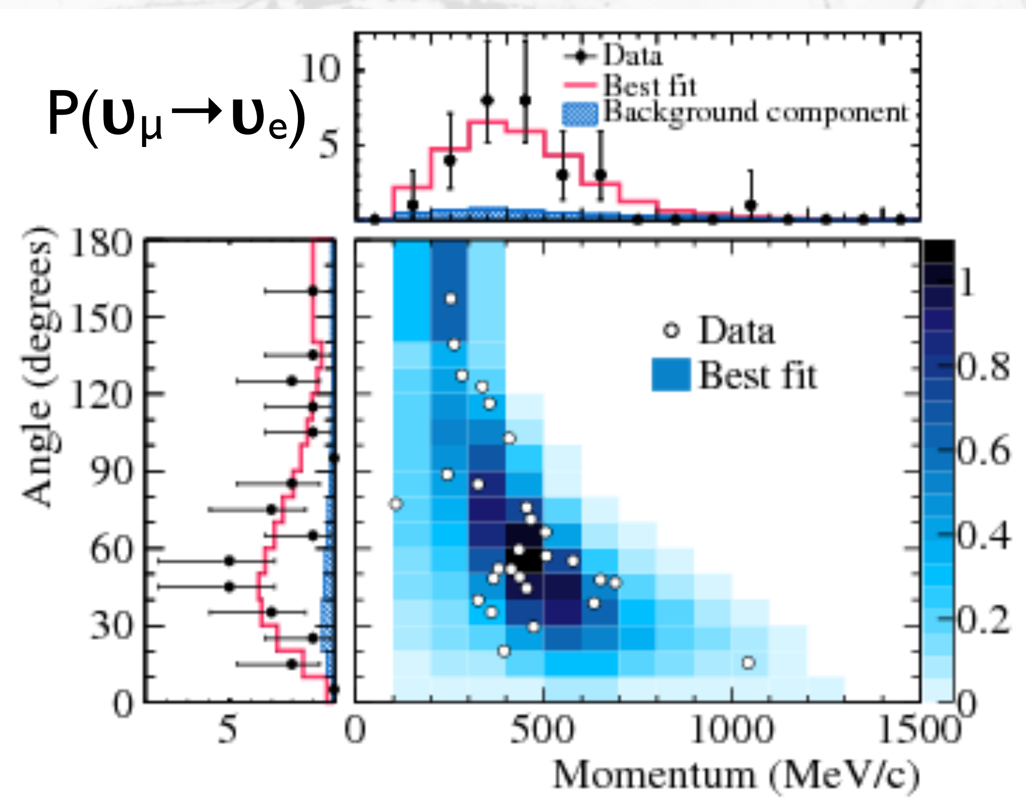
atmospheric Θ_{23}

Solar Θ_{12}



CP violation



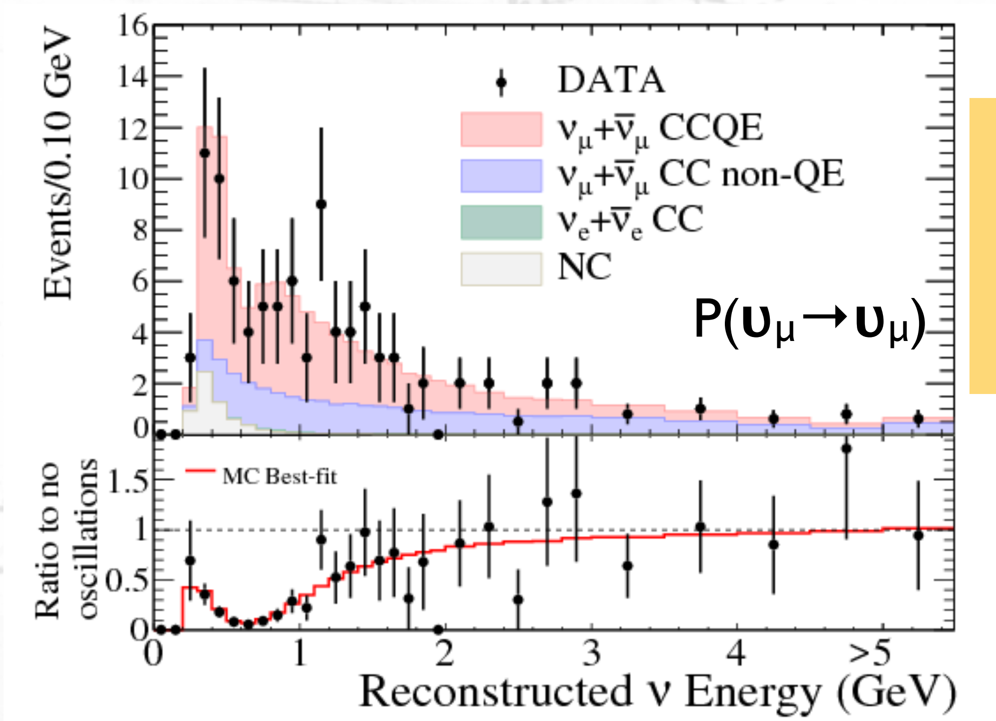


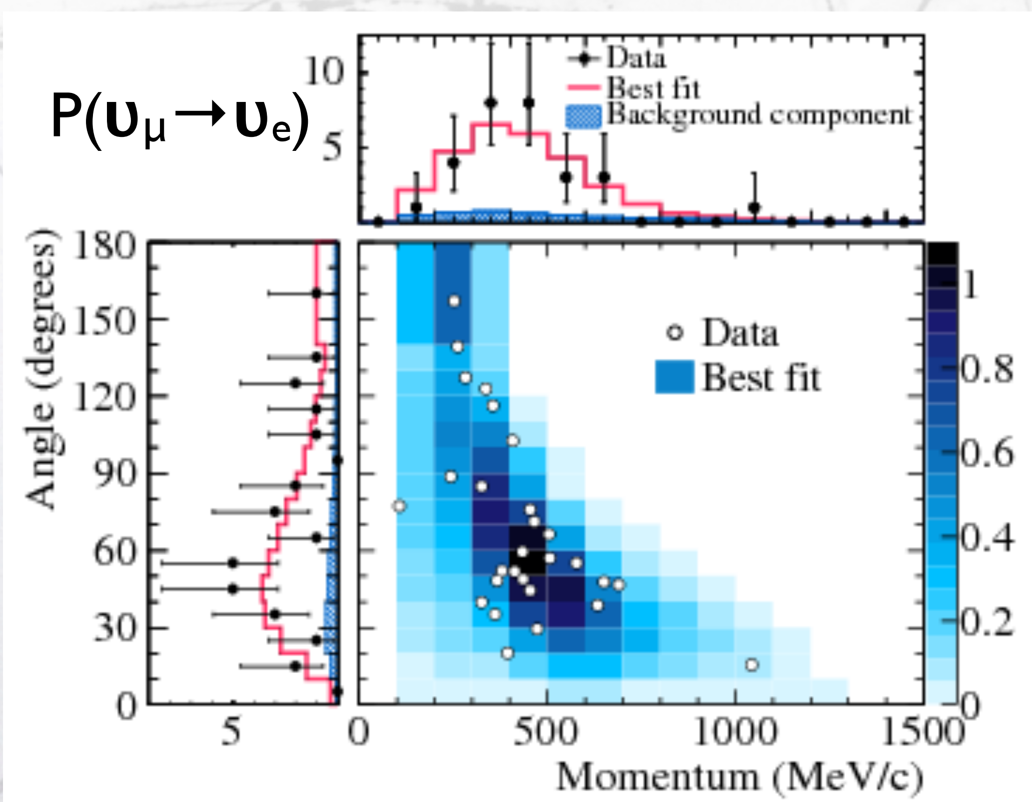
atmospheric Θ_{23}

Solar Θ_{12}

$$P_{\nu_\mu,\nu_e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$
$$\pm \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \frac{\Delta m^2_{31} L}{4E}$$
$$- \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \frac{\Delta m^2_{31} L}{4E} \sin \frac{2\Delta m^2_{31} L}{4E}$$
$$+ \left(\frac{\Delta m^2_{12}}{\Delta m^2_{31}}\right)^2 \cos^2\theta_{23} \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

CP violation

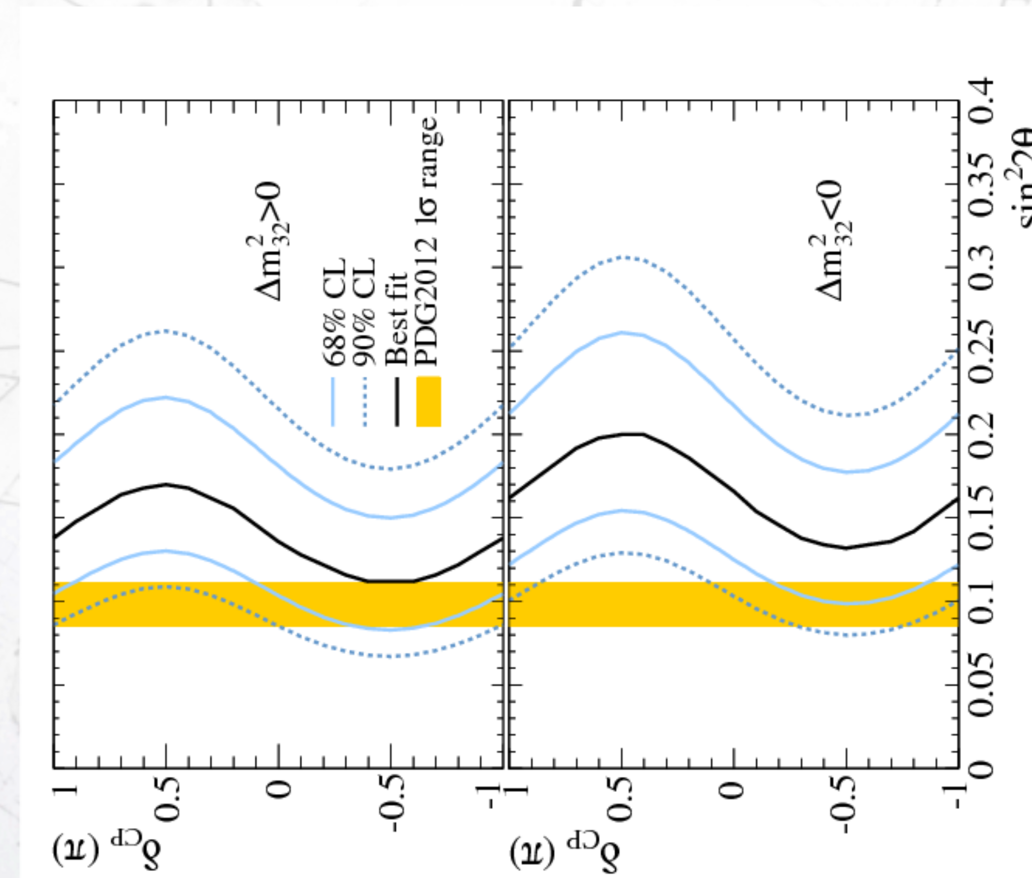




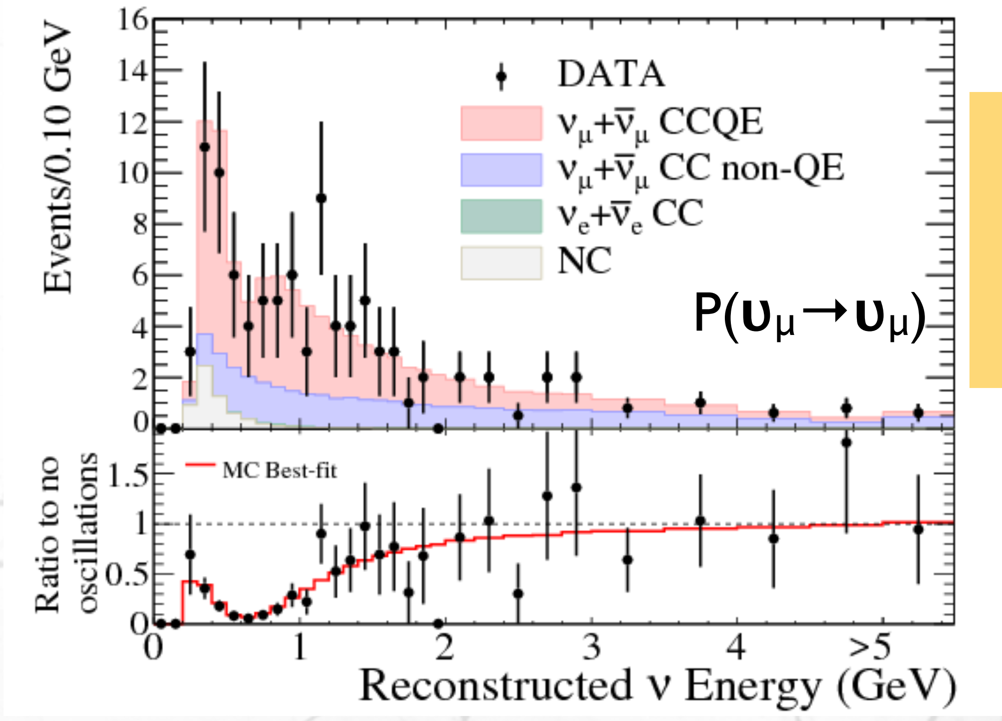
atmospheric Θ_{23}

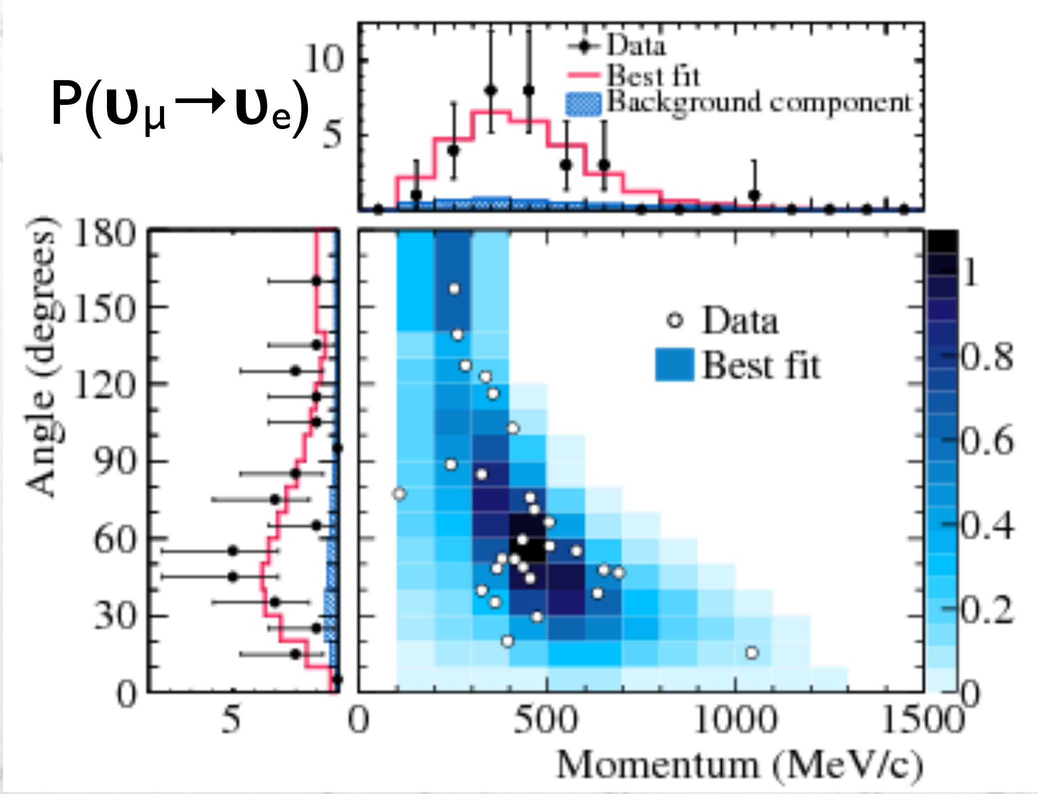
Solar Θ_{12}

$$
\begin{aligned}
P_{\nu_\mu,\nu_e} \approx\ & \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
\pm\ & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \frac{\Delta m^2_{31} L}{4E} \\
-\ & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \frac{\Delta m^2_{31} L}{4E} \sin \frac{2\Delta m^2_{31} L}{4E} \\
+\ & \left(\frac{\Delta m^2_{12}}{\Delta m^2_{31}}\right)^2 \cos^2\theta_{23} \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E}
\end{aligned}
$$



CP violation



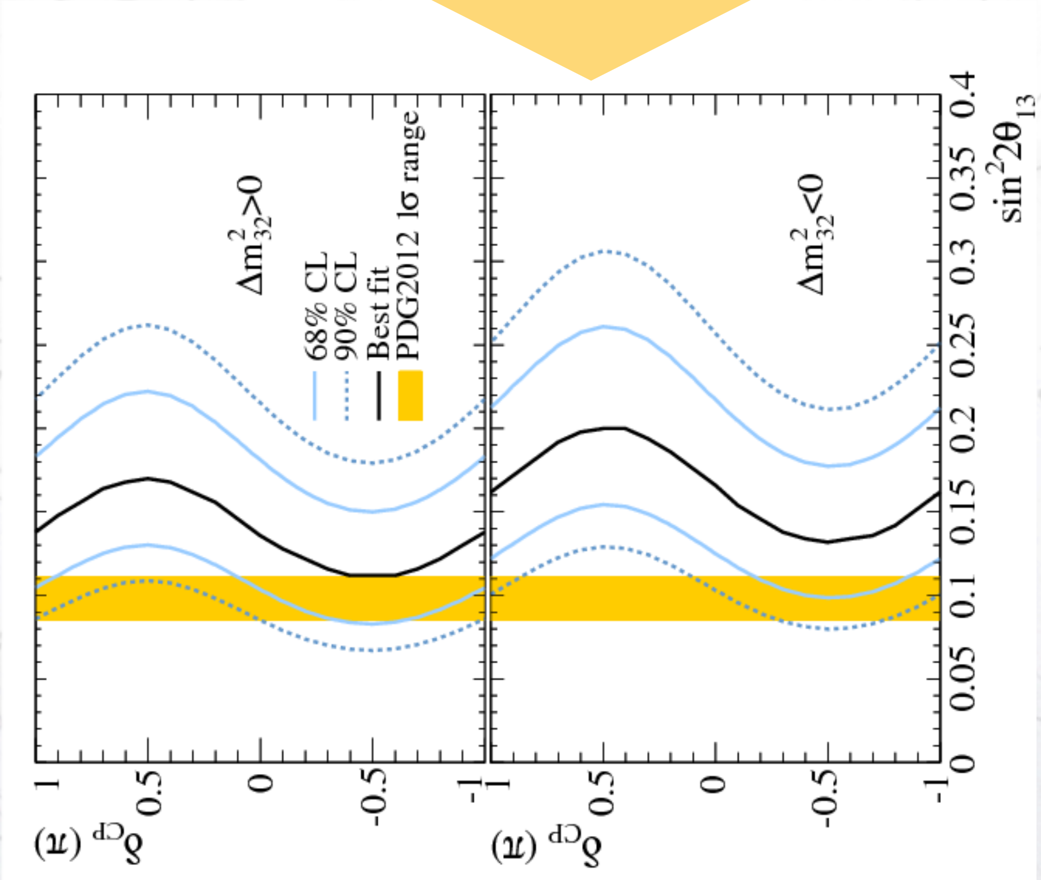


atmospheric Θ_{23}

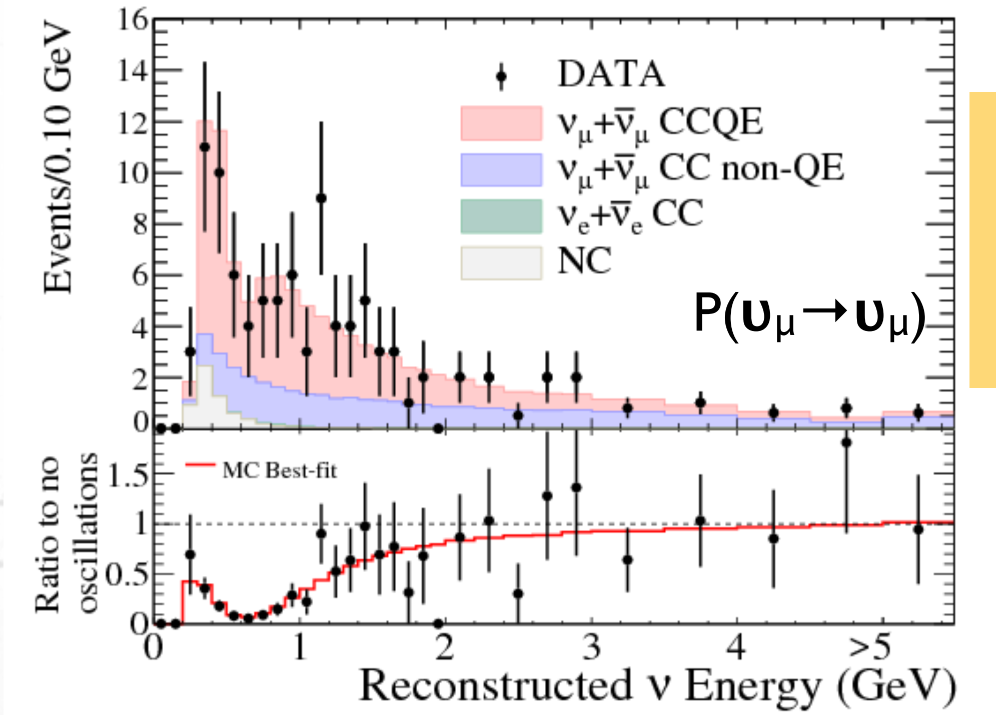
Solar Θ_{12}

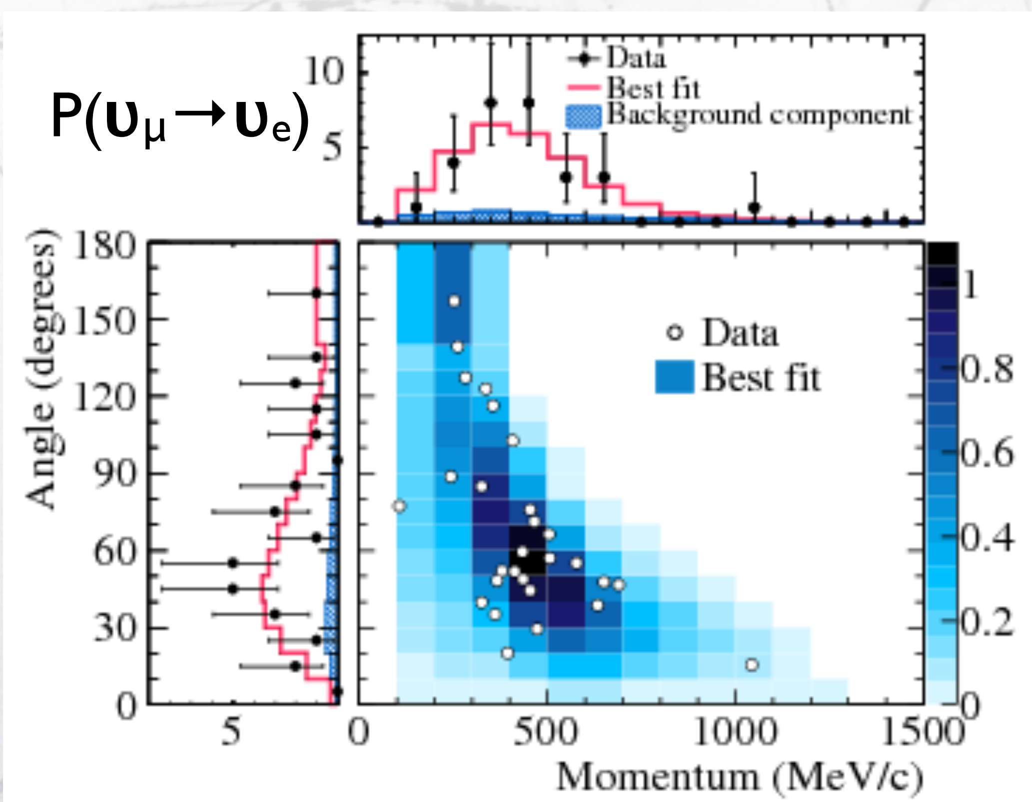
P($\upsilon_e \rightarrow \upsilon_e$) Θ_{13}

$$
\begin{aligned}
P_{\nu_\mu,\nu_e} \approx\ & \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
\pm\ & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \frac{\Delta m^2_{31} L}{4E} \\
-\ & \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \frac{\Delta m^2_{31} L}{4E} \sin \frac{2\Delta m^2_{31} L}{4E} \\
+\ & \left(\frac{\Delta m^2_{12}}{\Delta m^2_{31}}\right)^2 \cos^2\theta_{23} \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E}
\end{aligned}
$$



CP violation



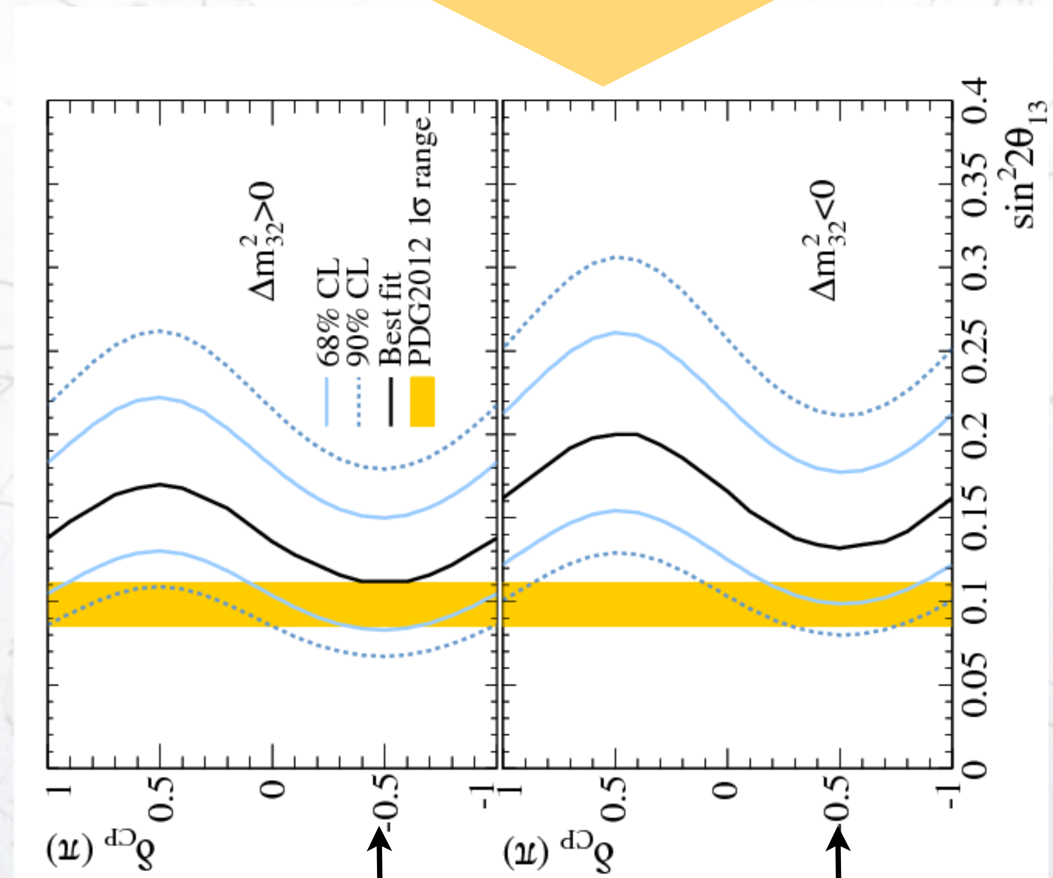


atmospheric Θ_{23}

Solar Θ_{12}

$P(\nu_e \rightarrow \nu_e)$ Θ_{13}

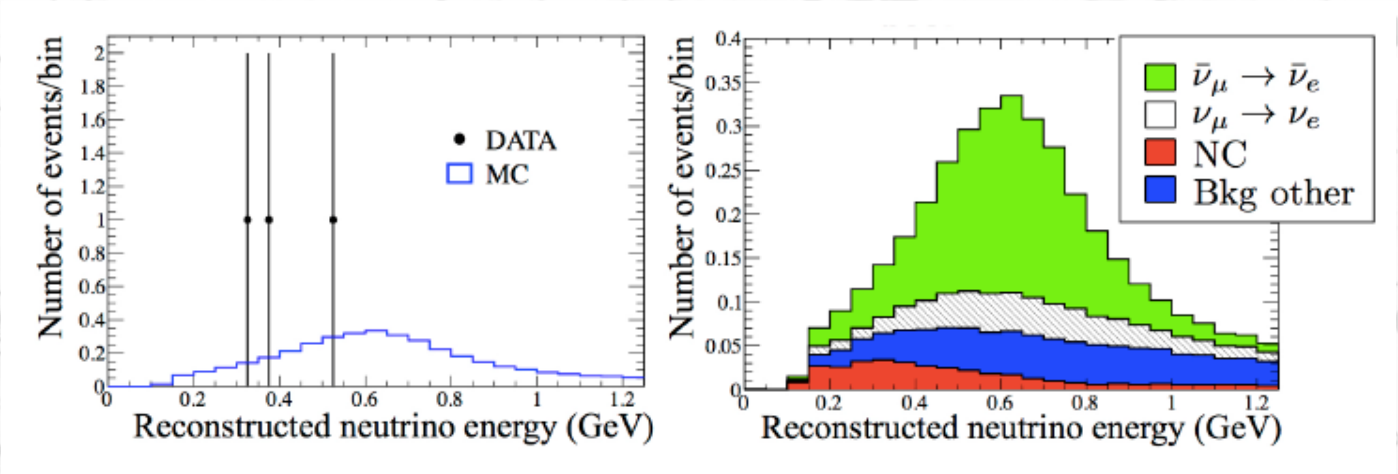
$$P_{\nu_\mu,\nu_e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$
$$+ \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \frac{\Delta m^2_{31} L}{4E}$$
$$- \frac{\Delta m^2_{12}}{\Delta m^2_{31}} \sin 2\theta_{13} \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \frac{\Delta m^2_{31} L}{4E} \sin \frac{2\Delta m^2_{31} L}{4E}$$
$$+ \left(\frac{\Delta m^2_{12}}{\Delta m^2_{31}}\right)^2 \cos^2\theta_{23} \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$



Preferred solution is not 0!

CP violation

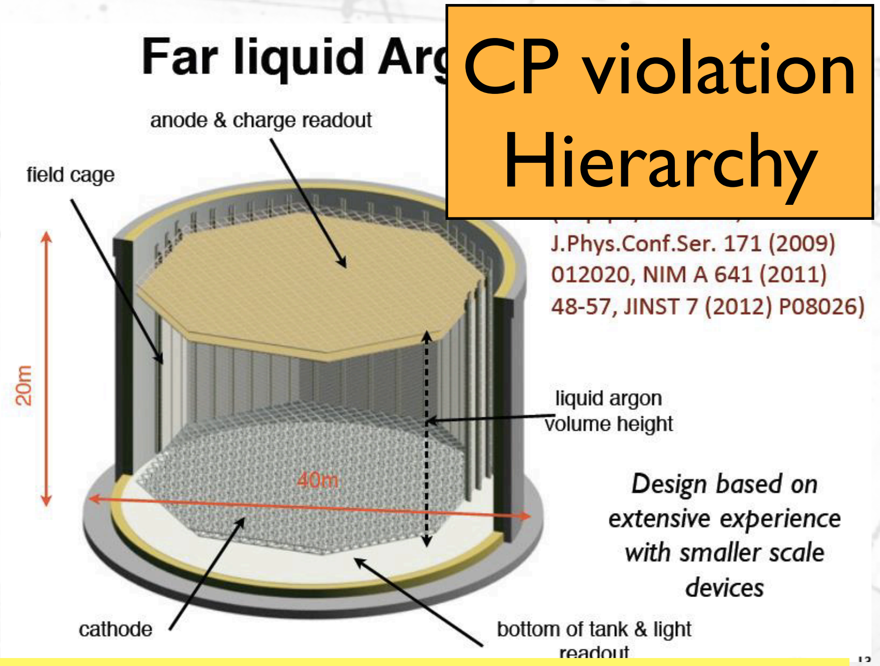
- T2K has been looking for anti-neutrino electrons in an anti-neutrino muon beam since 2014.
- Statistics (3 events) is very low! (T2K got ~15 neutrinos for the same number of protons on target).



- Statistics is the key !
  - Next generation of experiments aimed at larger neutrino fluxes (x2 or 3) and/or larger detector masses (factors 2 to 10)
    - HyperKamiokande, Dune, etc...

The future

Dune



CP violation
Hierarchy

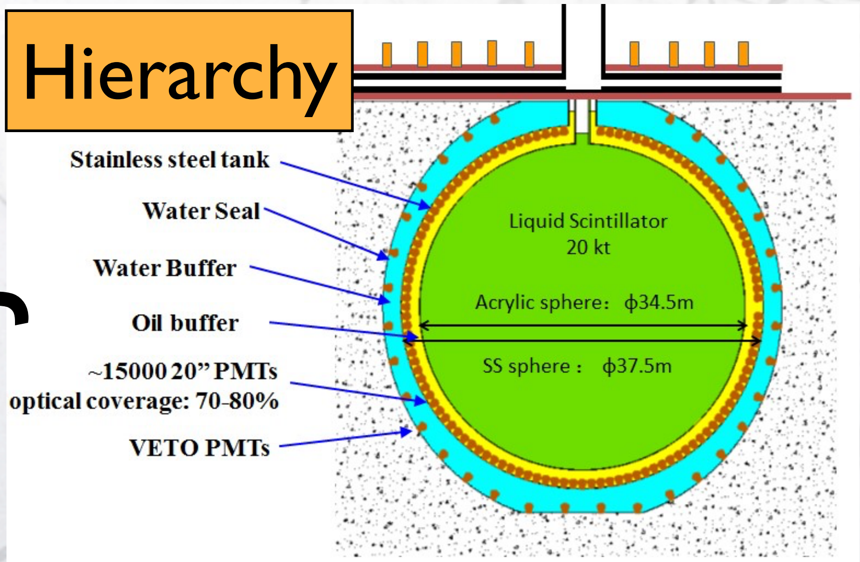
40 Ktons of Liquid Argon
TPC in 4 tanks!

HyperKamiokande

CP violaton

500 Ktons of pure water
Cerenkov detector in 2 tanks!

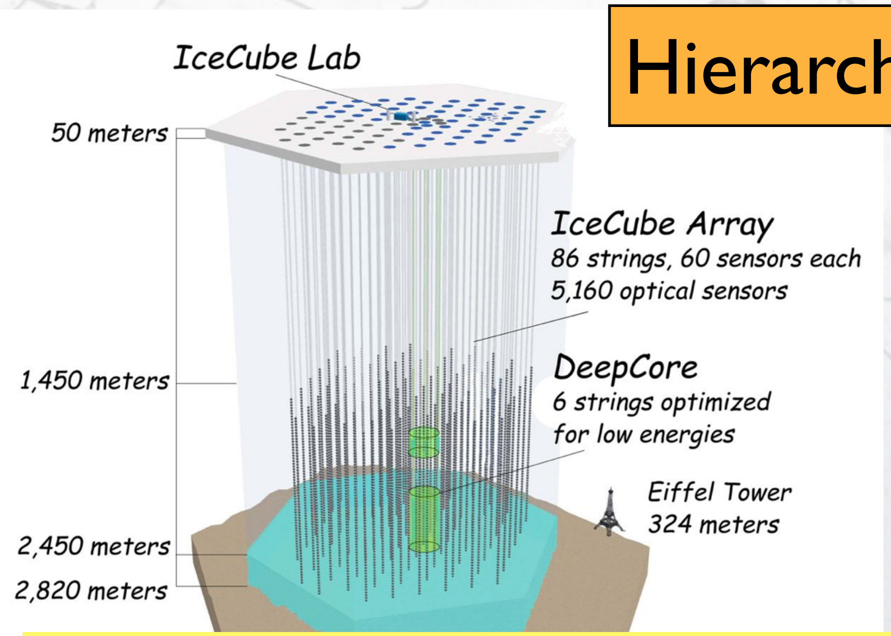
Juno



Hierarchy

20 Ktons of liquid scintillator

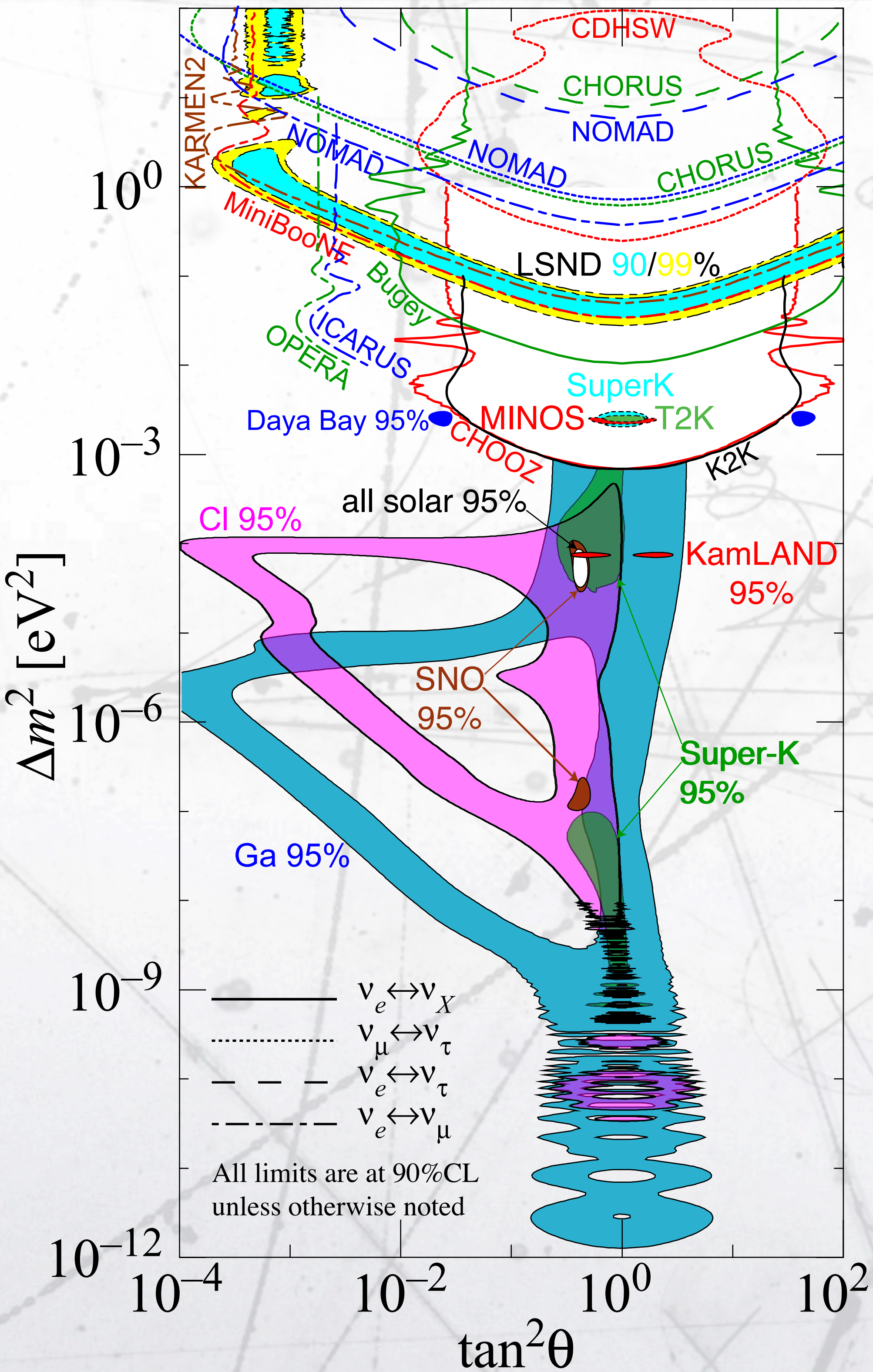
IceCube/Pingu



Hierarchy

1 km^3 of ice

As conclusions



- Fast development in the last 20 years:
  - mixing parameters (for $\bar{\nu}$ & ν)
    - over ~13 orders of magnitude.
  - mass differences and hierarchies (for $\bar{\nu}$ & ν):
    - over ~6 orders of magnitude.
  - solar and atmospheric models tested at several experiments with natural and artificial sources.

Parameter	best-fit ($\pm1\sigma$)	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$	6.99 – 8.18
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.43 ± 0.06 (2.38 ± 0.06)	2.23 – 2.61 (2.19 – 2.56)
$\sin^2\theta_{12}$	0.308 ± 0.017	0.259 – 0.359
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$	0.374 – 0.628
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$	0.380 – 0.641
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$	0.0176 – 0.0295
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$	0.0178 – 0.0298
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ ($1.31^{+0.29}_{-0.33}$)	$(0.00 - 0.16) \oplus (0.86 - 2.00)$ $((0.00 - 0.02) \oplus (0.70 - 2.00))$

As conclusions

- But, we still miss few more measurements:
  - Precision, precision, precision !!!!
    - How close is θ_{23} to $\pi/2$? (sort of magic number → theoretical implications)
  - Hierarchy ($m_3 > m_1$?)
  - CP violation ?
  - What is the absolute mass of the neutrinos ?
- And, a theory capable to describe massive neutrinos inside the Standard Model in a coherent way:
  - Why are the masses so low?
  - Right handed neutrinos are "sterile" but they are needed to provide mass to the neutrino in the Dirac model. (Is this correct?)
  - What is the relation between quark and neutrino mixing ?

Cosmic Gall

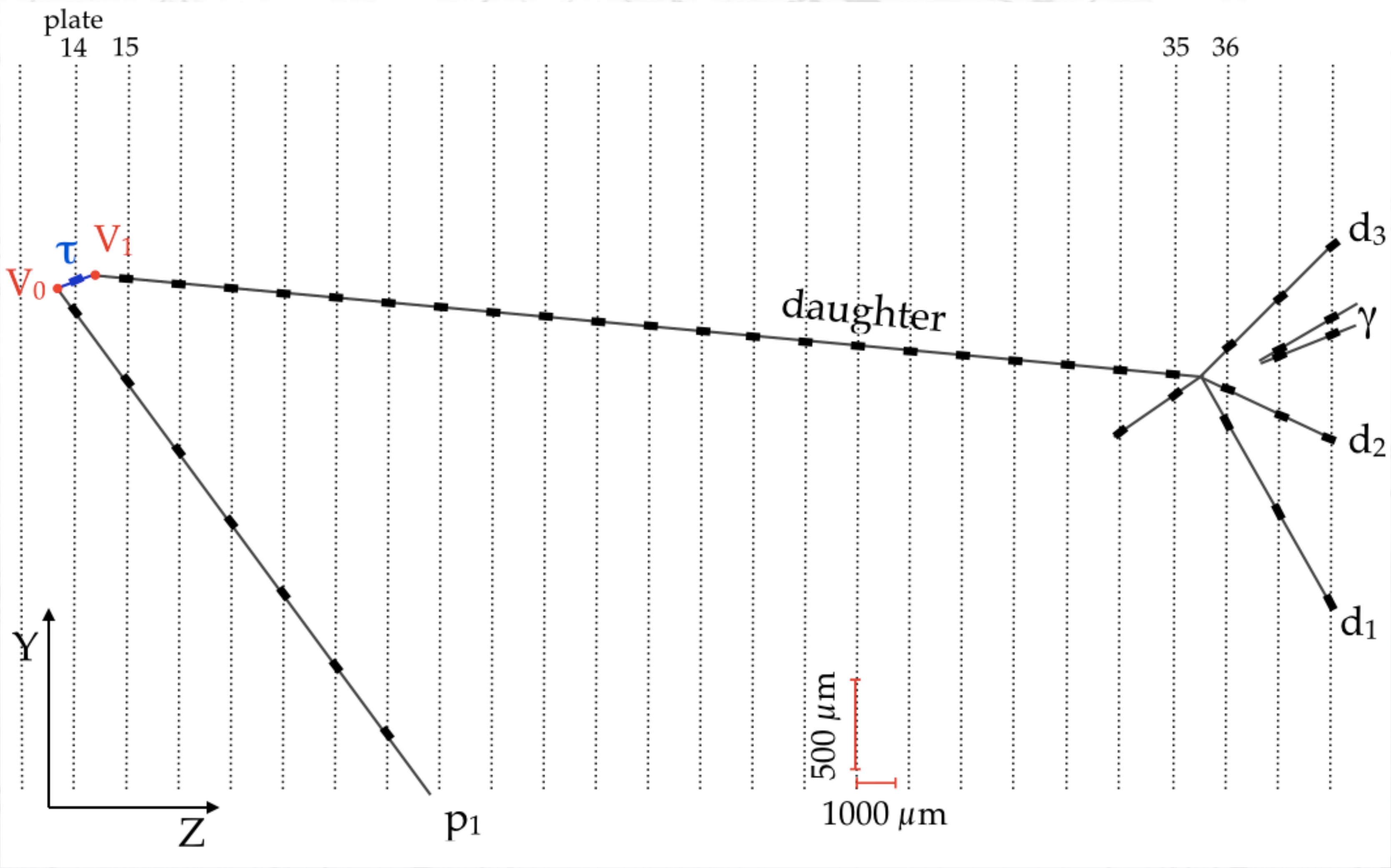
NEUTRINOS, they are very small.
They have no charge and have no mass
And do not interact at all
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
and painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
From underneath the bed-you call
It wonderful; I call it crass.

- *Telephone Poles and Other Poems*, John Updike, Knopf, 1960

Support slides

Tau neutrinos

- Transition: $\nu_\mu \rightarrow \nu_\tau$ detected at the CNGS/OPERA experiment.
- 5 events with kink detected in the detector emulsion.



Neutrinos in matter

The theory

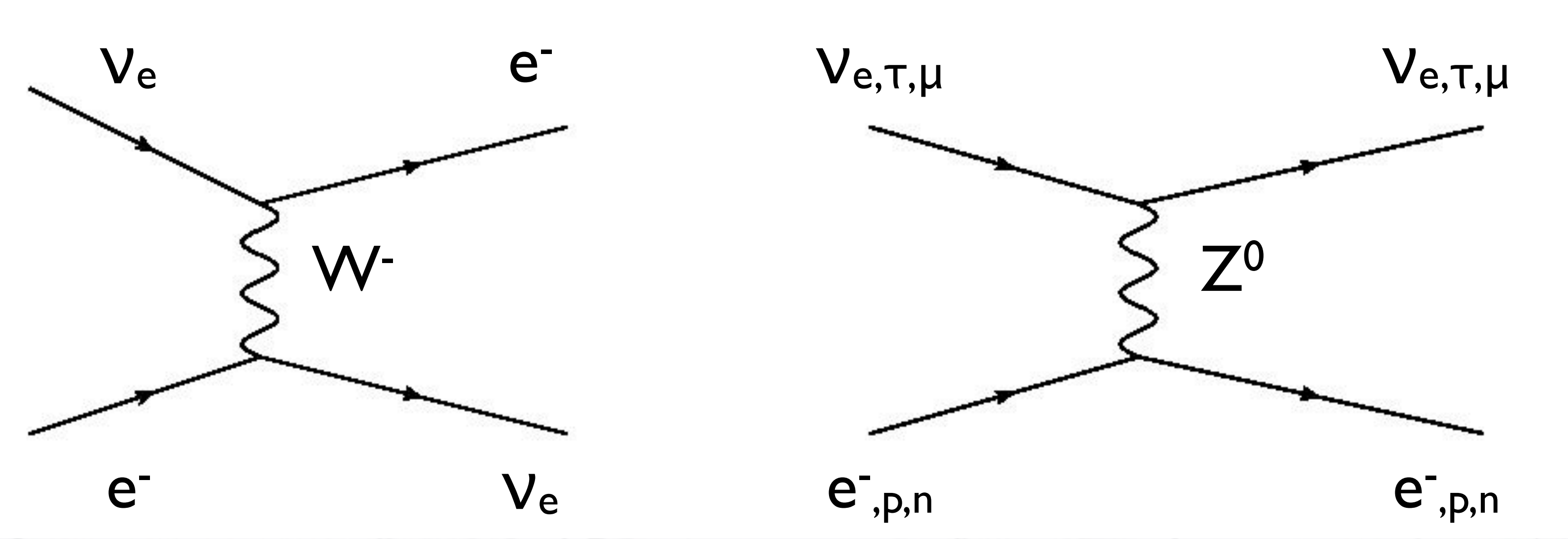
- Neutrinos can have two types of interaction with matter:
  - Incoherent inelastic: $\sigma \sim 10^{-43}\,(E/MeV)^2$
  - Coherent. The medium is unchanged and the scattered and un-scattered waves interfere enhancing the effect.
    - It introduces a phase in the propagation, that can be invisible… except for the fact that matter is made of electrons.

Neutrinos in matter

- The Schrödinger equation of ν in matter:

$$i\hbar\frac{\partial\nu_i}{\partial t} = (\frac{m_i^2}{2E} + V_C^i)\nu_i$$

- V_C introduces the coherent interaction (phase) depending on the neutrinos flavour:



- The NC phase is common and factorizes. The CC remains:

$$V_C = diag(\pm\sqrt{2}G_F n_e, 0, 0)$$

Neutrinos in matter

- The mass effect can be interpret as a change in the mass eigenstate and eigenvalue. It changes interference pattern & effective mixing angle. Both depend on the neutrino energy and local electron density.

$$\mu^2_{1,2}(x) = \frac{m_1^2+m_2^2}{2} + E_\nu(V_\alpha + V_\beta) \mp \frac{1}{2}\sqrt{[\Delta m^2\cos 2\theta - A]^2 + [\Delta m^2 \sin 2\theta]^2}$$

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A}$$

$$A = 2E_\nu(V_\alpha - V_\beta)$$

- As we have seen, $V_\alpha = \pm\sqrt{2}\, G_F\, n_e$, $V_\beta=0$
- When crossing $A\sim\Delta m^2\cos(2\theta)$, the $\tan(2\theta_m)$ changes sign -> The proportions of 1&2 invert for α&β states ("level crossing").

- The first experiments to determine the mass of neutrinos were proposed in 1933 by Perrin and Fermi. The idea was to investigate the endpoint of the β spectrum.
    - This is still the method used for direct search in Katrin!!!!
    - At that time, upper limits of 100 eV were achieved.
- After the parity violation in β-decays were discovered, the two-component neutrino theory (Landau , Lee and Yang and Salam, 1957) was the first theoretical idea about neutrino masses.
    - The idea was simple, two neutrinos (Left-Right), one of them is "sterile" (do not interact) so it is not "needed".

Neutrinos

- If we consider that the neutrino field has two components (L,R) the Dirac equations can be written as:

$$i\gamma^\alpha \partial_\alpha \nu_L(x) - m_\nu \nu_R(x) = 0$$
$$i\gamma^\alpha \partial_\alpha \nu_R(x) - m_\nu \nu_L(x) = 0$$

- Taking into account the boundaries and the fact that only one field was needed (L or R) to describe the weak interactions, it was accepted that $m_\nu = 0$.
- The "other" helicity was a "sterile": no mass & no interaction.
- The neutrino helicity was measured in 1958 in a spectacular experiment by M. Goldhaber: neutrinos were left-handed.

Neutrinos

- From this point of view the parity violation in weak interactions was due to the fact that the neutrino mass was zero and only one neutrino helicity existed.
- This idea was changed after the Feynman, Gell-Mann, Marshak and Sudarshan proposed the V-A theory in 1958. The two component theory was not needed because the interaction was governed by the propagator and not the neutrino helicity.
- But, the simplicity of the $m_\nu = 0$ theory prevailed for years... and it was "assumed" that neutrinos were massless.

Majorana masses

- If neutrinos have mass, then the right-handed neutrino "has to exists". After 60 years, we go back to the problem that there is a type of neutrino (Right helicity) that is sterile (does not interact).
- Theory proposed an alternative: Majorana mass. In this case the neutrino is the same as its antiparticle, so the right handed neutrino is just the anti-particle.
- This is only possible for neutrinos because it is the only neutral fundamental lepton in the SM.
- We can write the mass term (Lorentz invariant) in two ways (or both):

Dirac $\mathcal{L}_D = -m_D \bar{\nu}_L \nu_R + h.c.$

Majorana $\mathcal{L}_M = -m_M \bar{\nu^c_R} \nu_R + h.c.$

Majorana masses

- Majorana mass implies two new properties:
  - The neutrino is equal to its antiparticle.
  - There is no right handed, it is just the anti-particle.
- Turning the argument around!. We need an additional symmetry to forbid the Majorana term in the Lagrangian. Whatever we discover will be very relevant to the SM.
- How to detect them:
  - We can boost back a neutrino and find an antineutrino.
  - We can look for a process where the neutrino-antineutrino cancels in a loop or propagator: neutrino-less double beta decay, or any $\Delta L=2$ process.

Majorana & Seesaw

- Consider that we have both Majorana (m^M) and Dirac (m^D) mass terms.

$$\mathcal{L} = -\frac{1}{2}\left(\bar{\nu}_L \bar{\nu}_R^c\right)\begin{pmatrix} m_L^M & m^D \\ m^D & m_R^M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$$

- When we diagonalize the matrix we obtain the following eigenvalues:

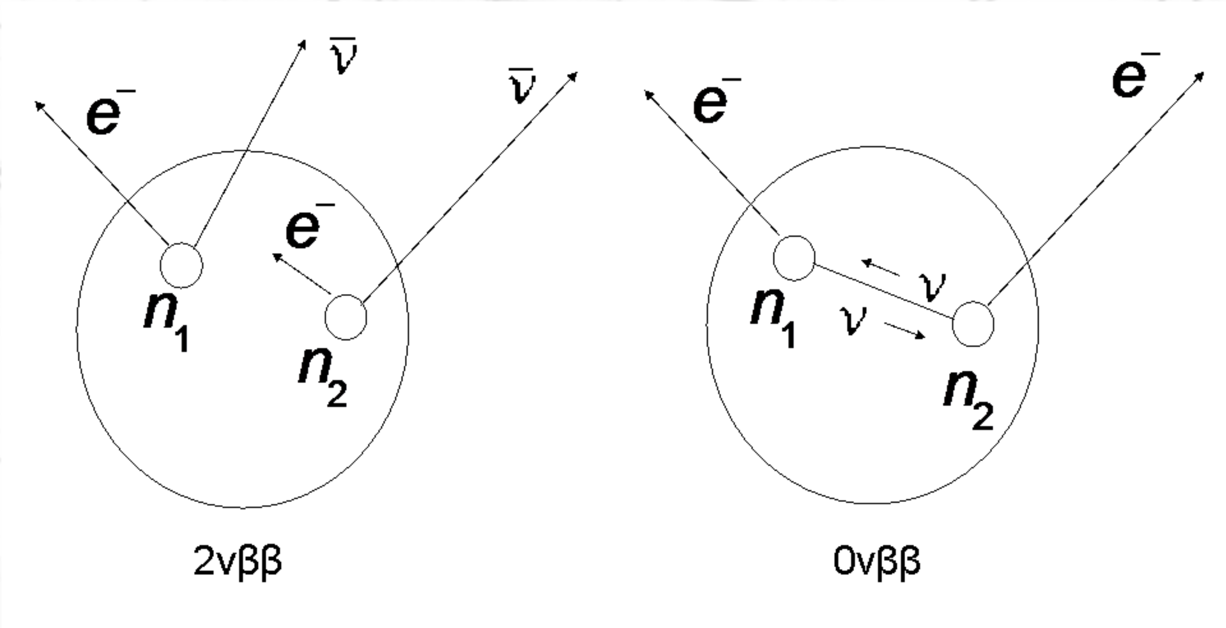
$$\lambda_\pm = \frac{1}{2}(m_L^M + m_R^M) \pm \frac{1}{2}\sqrt{(m_L^M + m_R^M)^2 - 4(m_L^M m_R^M - m^D m^D)}$$

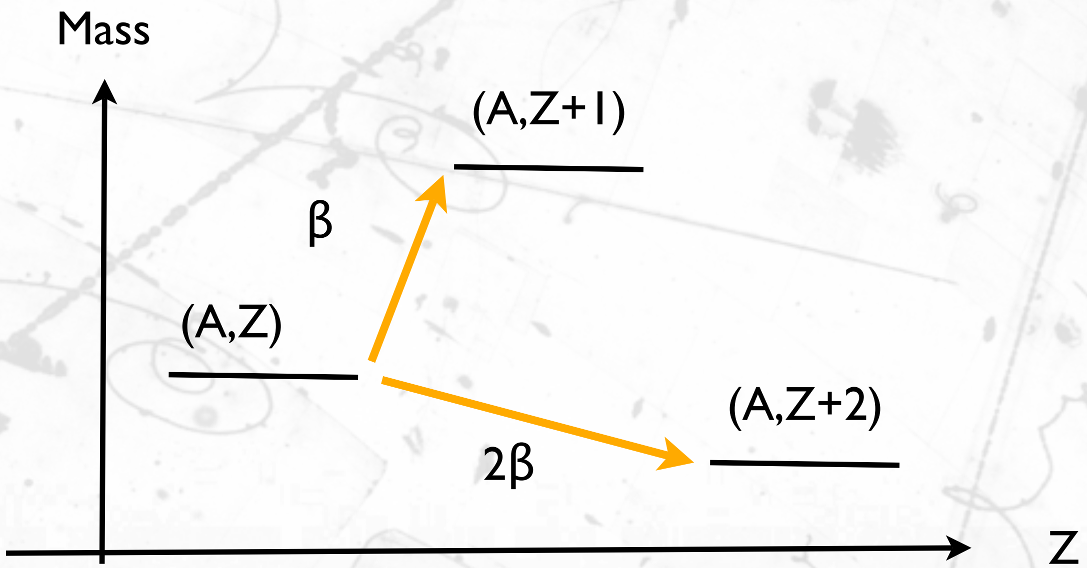
- If we assume $(m_L^M m_R^M - m^D m^D) << (m_L^M + m_R^M)^2$, then:

$$\lambda_+ = m_L^M + m_R^M$$
$$\lambda_- = \frac{(m_L^M m_R^M - m^D m^D)}{m_L^M + m_R^M}$$

- And, $\lambda_+ >> \lambda_-$. Tunning the values of m_R^M we can generate the λ_- as small as needed since m_R^M is basically a free parameter.

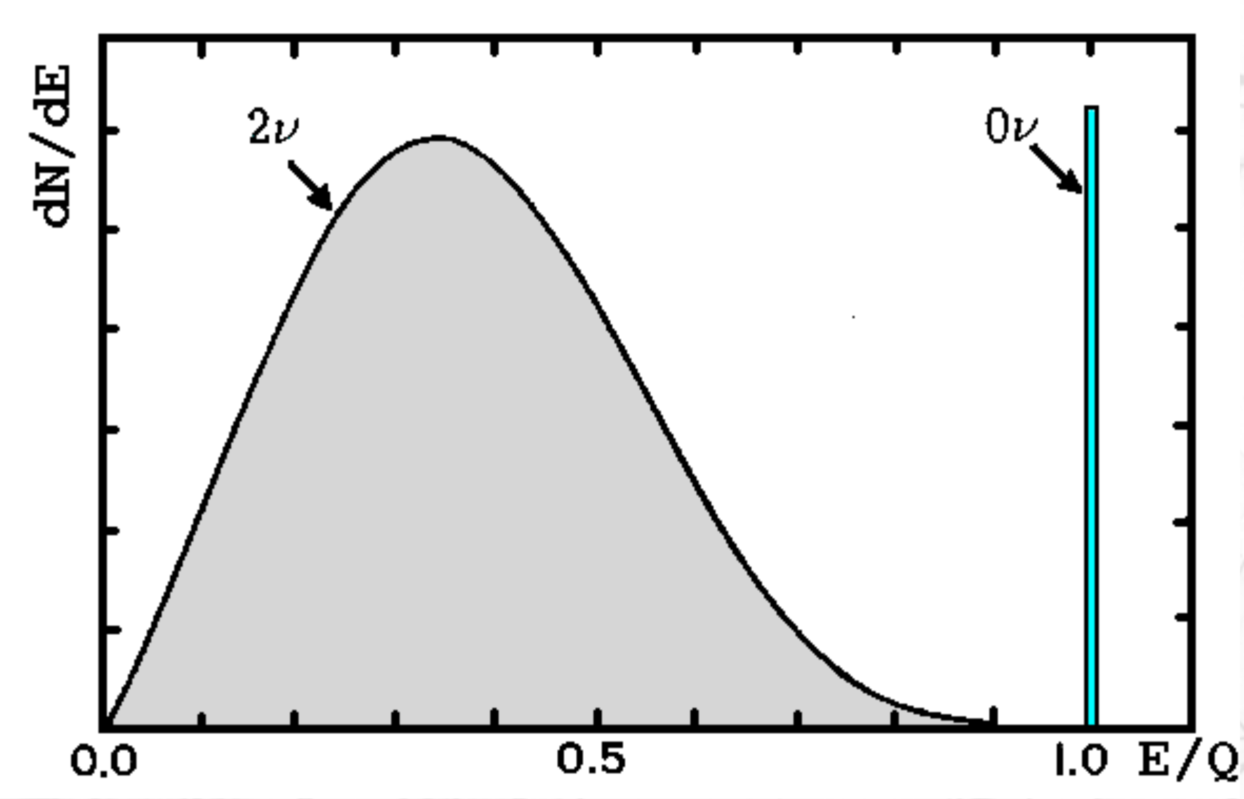
0ν2β process





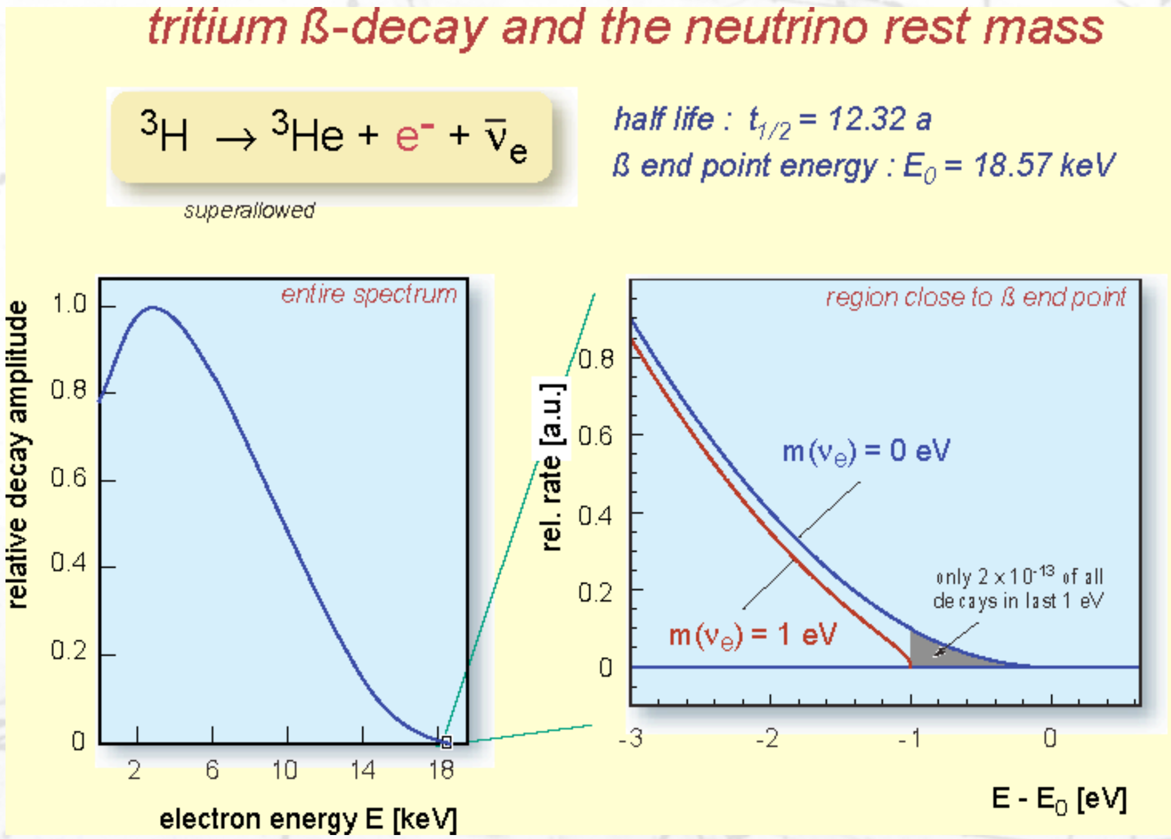
- The 2ν2β has been measured for several isotopes.
- The 0ν2β has been search in many of them ("almost") without success.
- Experimentally is complex, both processes are rare: $T_{1/2} >> 10^{20}$ s
- The rate of 0ν2βis proportional to a ν effective mass: kind of ν mass scale.

0ν2β process



- The 0ν2β is characterized by a monochromatic 2e emission.
- The experiments are mainly low background underground high resolution calorimeters (ΔE/E ~ 0.2 %)
- New experiments try to get the advantage of the 2 electrons to reduce non 2β background from natural radioactivity: NEMO, NEXT,...

Katrin



- Absolute neutrino mass experiment:
  - ^3H β-decay end point.
  - MAC-E filter threshold spectrometer.
  - High resolution: ~0.2eV