Neutrinos

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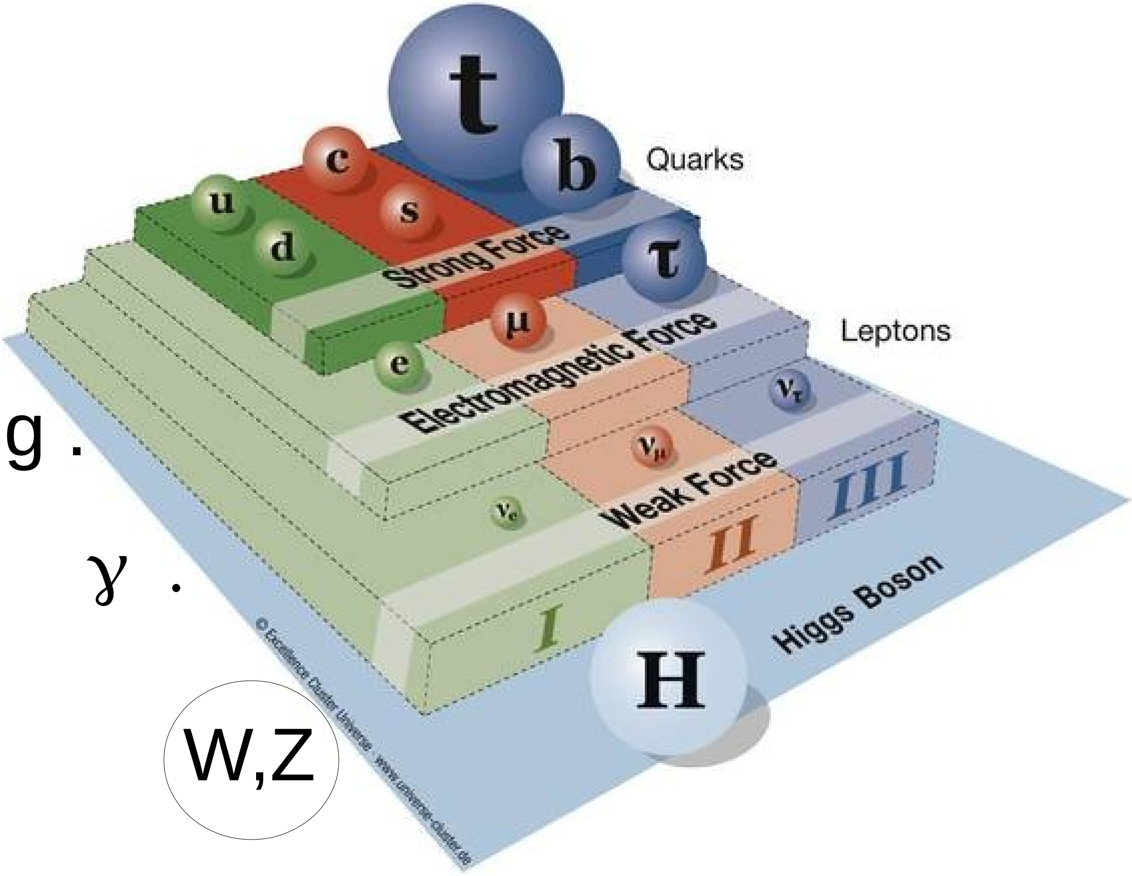
July 2019, LIP

Neutrinos, in the Standard Model



No charge

… or color charge
… only weak interaction

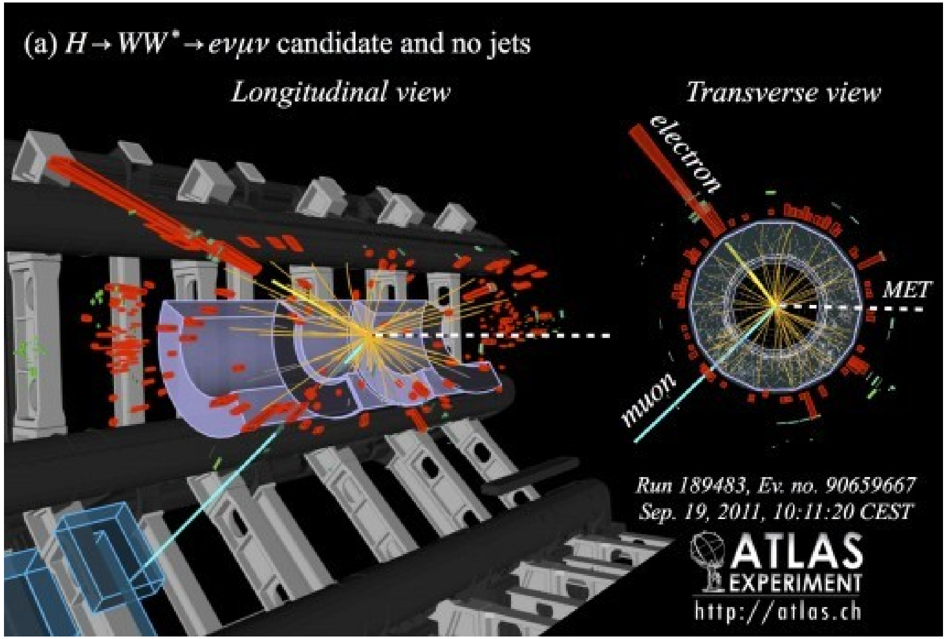
Undetectable in most experiments,
interesting messengers and probes

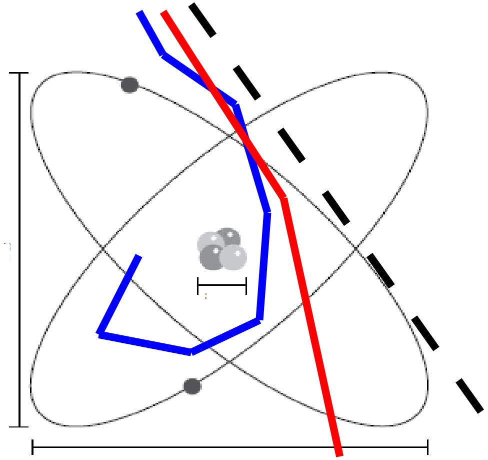
Little mass

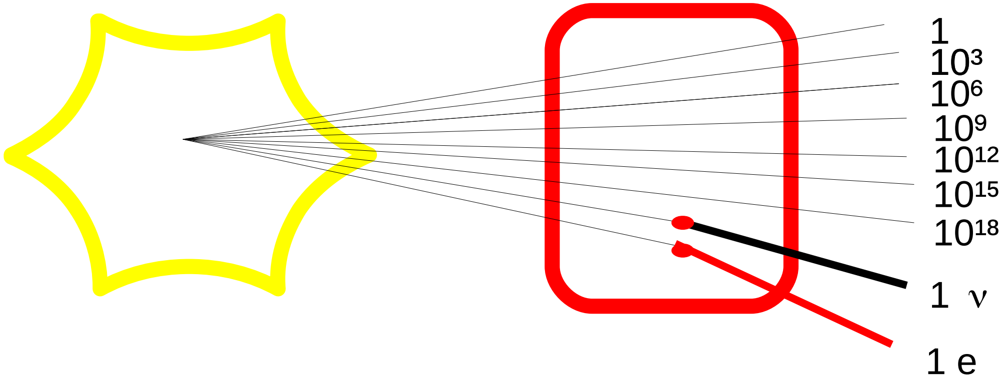
… almost zero
… much smaller than others

No mass in original SM,
maybe not (only) the Higgs mechanism

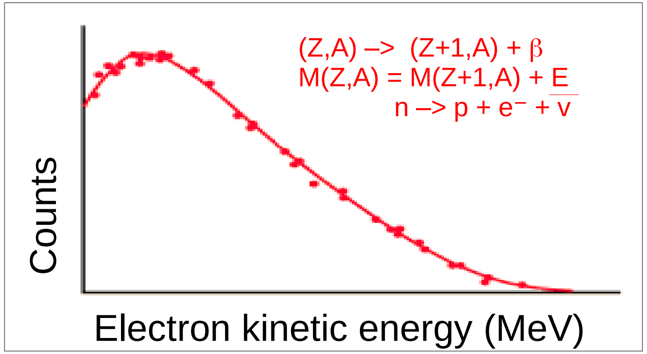
Neutrinos as “missing energy”



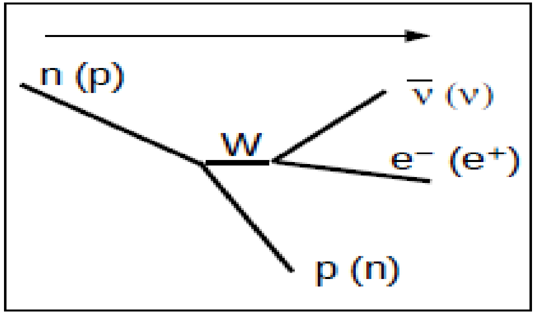




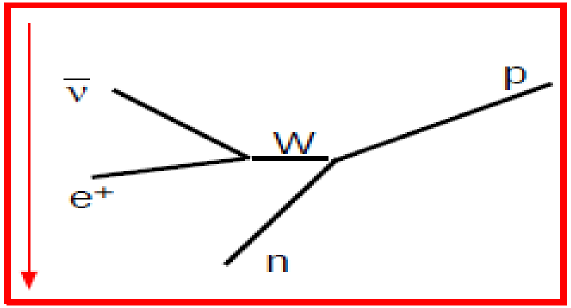
weakly interactive particles



Proposed by Pauli in 1930
Detected 25 years later



nuclear bomb
or nuclear reactor



large detector
sensitive to e^+ / n

Conservation of energy, momentum, charge, leptonic number
Cross-section calculable from neutron lifetime ~ 6×10^{-48} m^2

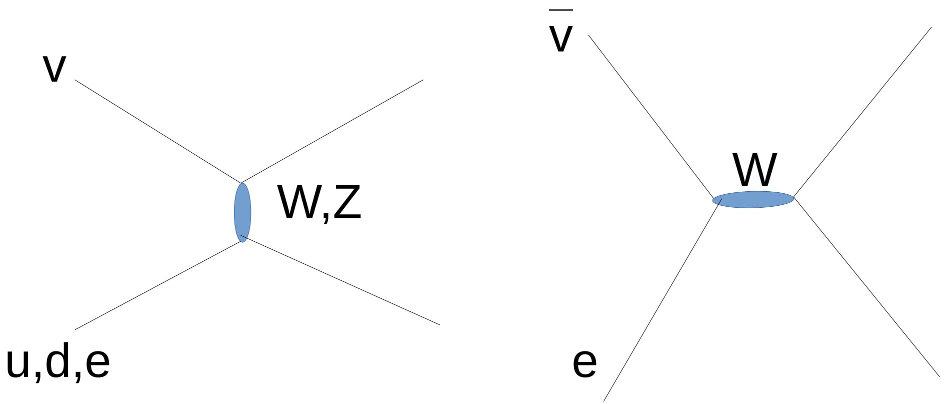
$\lambda = 1 / N_{int} = N_p / \sigma.\rho \sim 10^{17}$ m ~ 10 light-years of water !!!
~ million x Earth diameter !

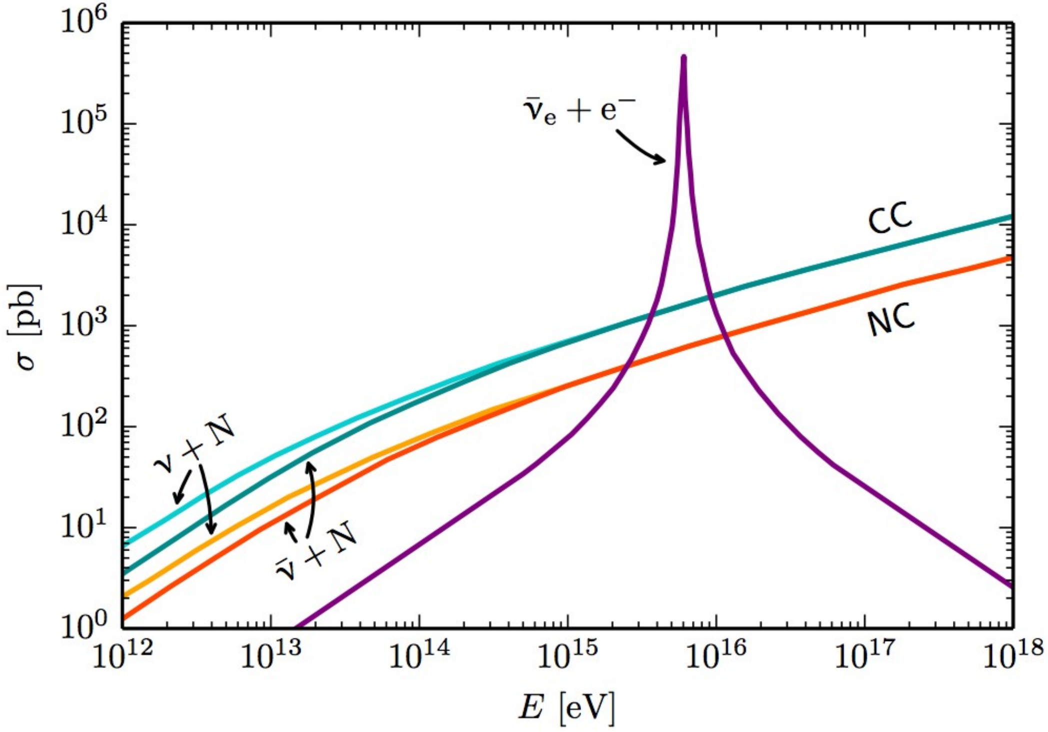
interactions

$\sigma = 2\, G_F{}^2\, M\, (hc)^2/(3\pi)\, E$

Interaction with electrons / nucleon scaled by

$m_e / M_N \sim 0.5$ MeV / 1 GeV $\sim 0.5 \times 10^{-3}$



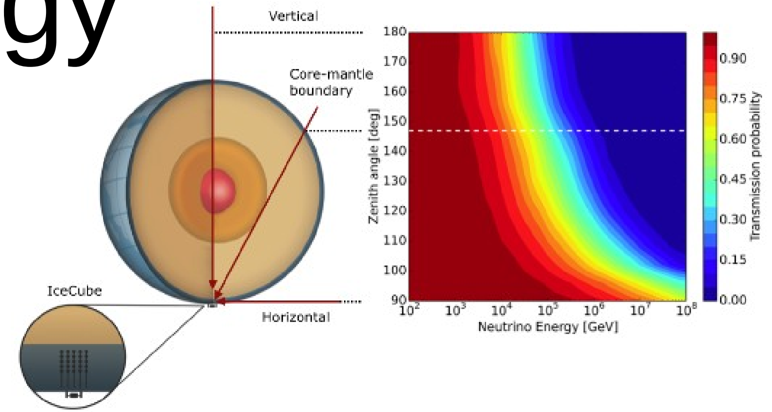


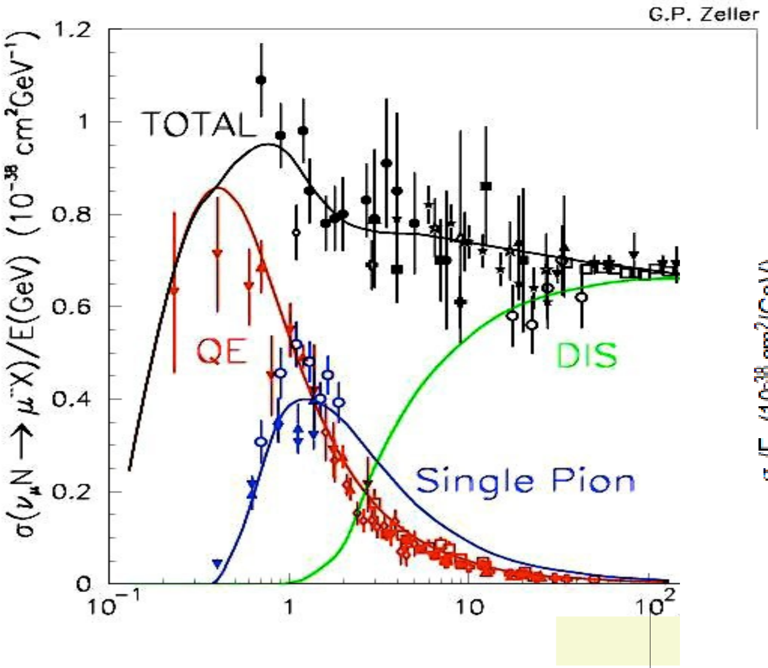
Special interaction for electron anti-neutrino!

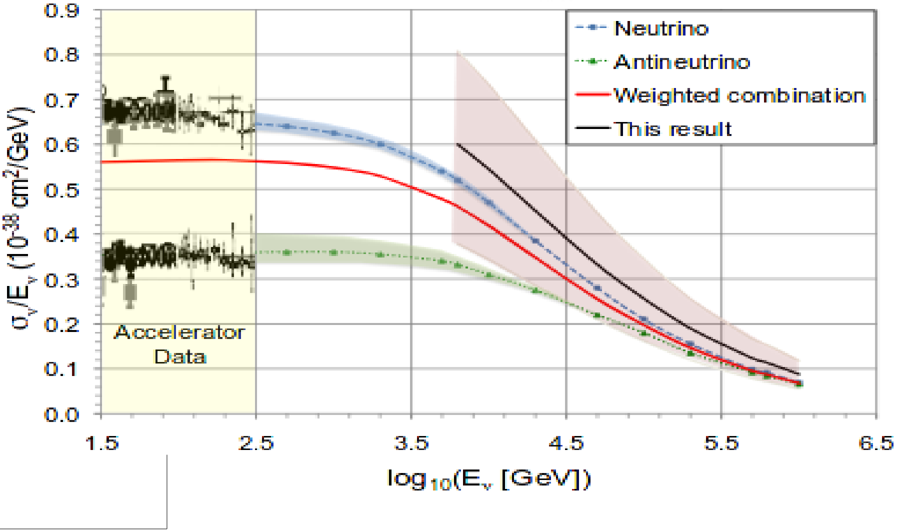
Resonance W production with electron at rest, for very high energy (10 PeV) !

low energy to high energy

Neutrinos (E<TeVs) can cross the Earth, and also their sources!
Above TeV, full Earth can be used as a neutrino absorber ...

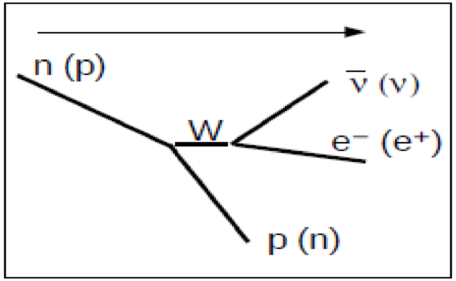


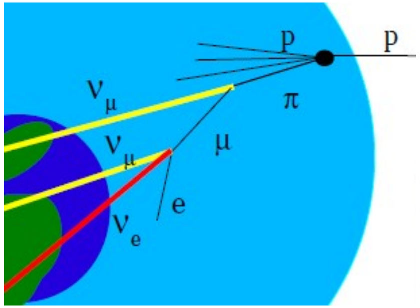


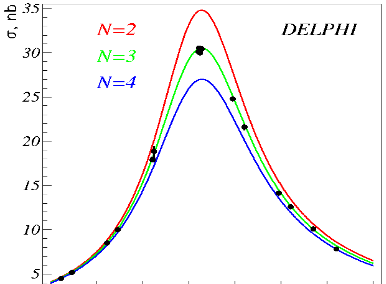


3 neutrinos & oscillations

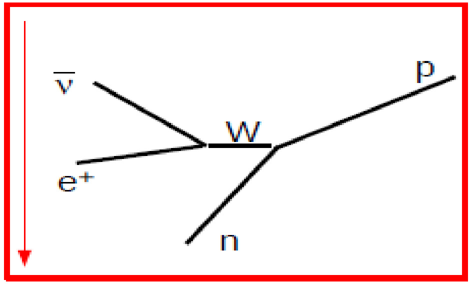
production







discovery



1990: 3 neutrinos
($e^+e^- \rightarrow Z \rightarrow$ invisible)

2000: 1st tau neutrino
(not yet anti-neutrinos)

neutrino Id

Reactors: @ MeV
electron anti-neutrinos

Sun: @ MeV
electron neutrinos

Accelerators / cosmic rays:

@ GeV muon neutrinos (or anti-neutrinos)

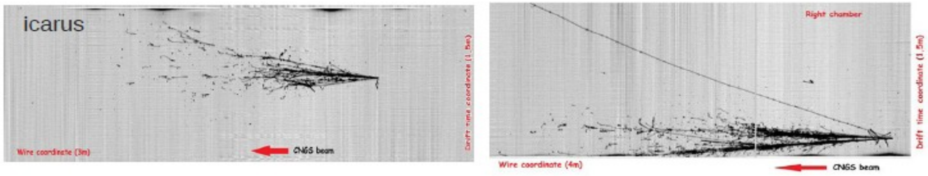
large distance

Solar rates lower than expected...

(30%? 50%?)

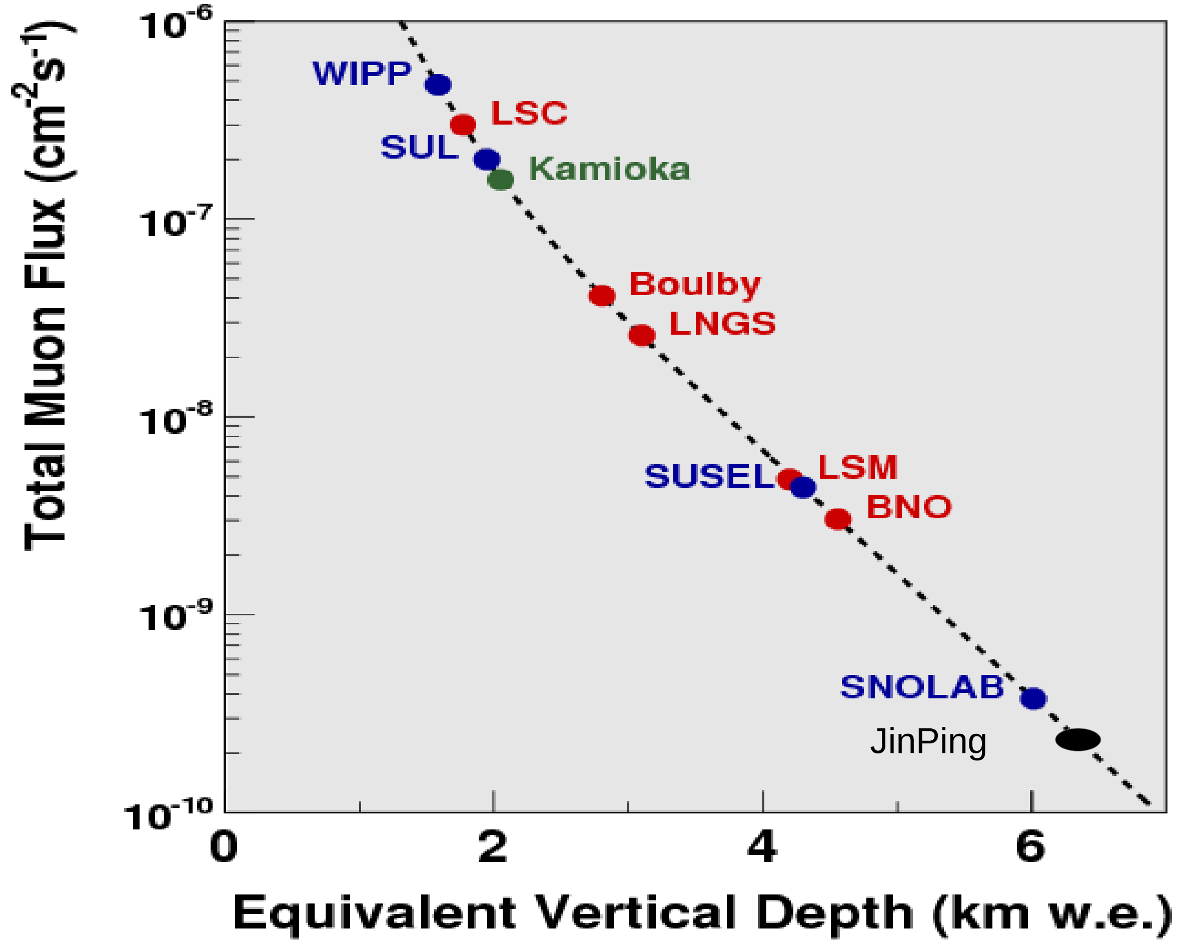
Rates of muons depend on L & E

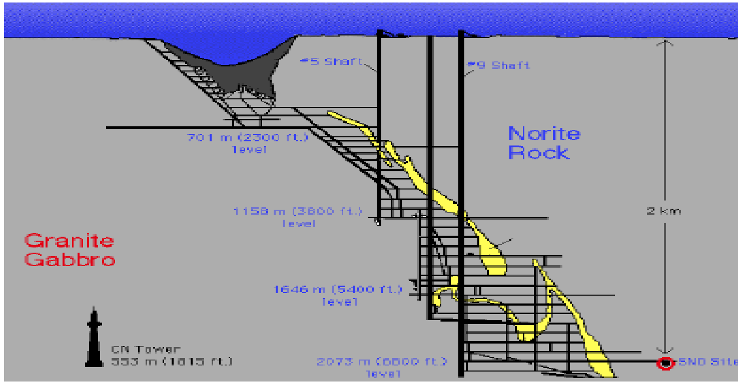
(electrons ~ok)

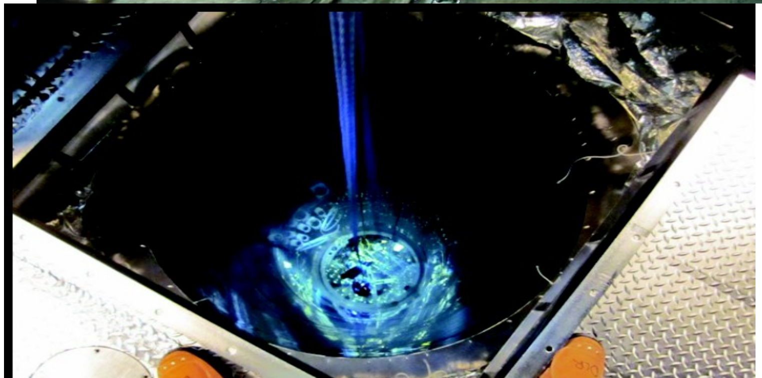


3 neutrino same "neutral current" interaction with Z

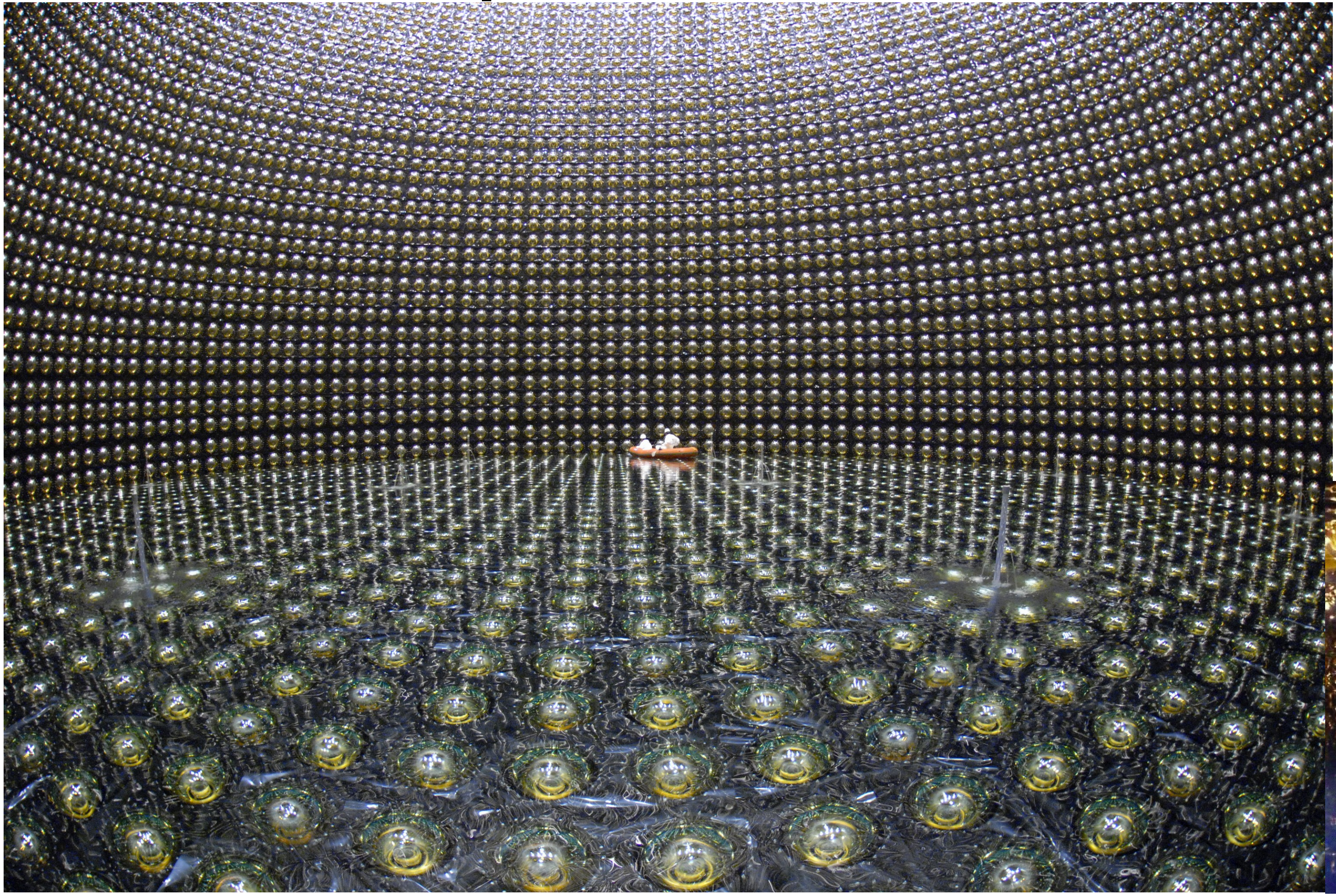
underground telescopes





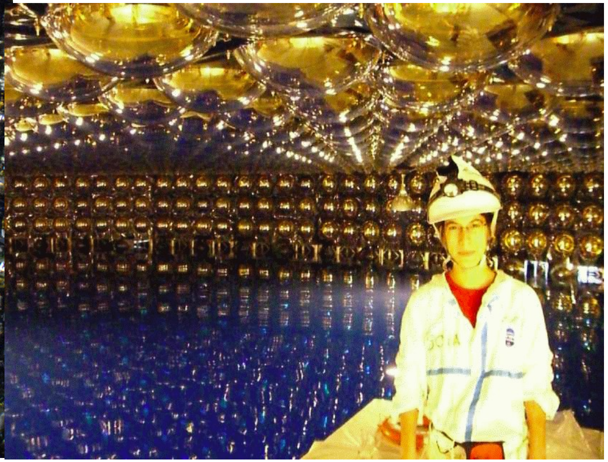


the Super Kamiokande detector



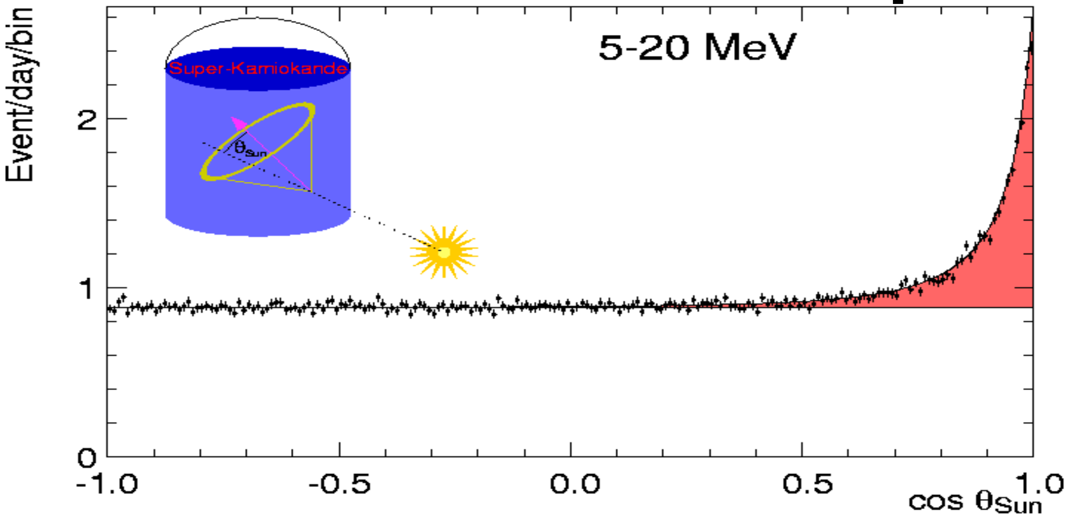
50 kTon of water,
working since 1996

Atmospheric+Solar+ Acc.
Succeeds Kamioka, now
HyperK programmed :-)

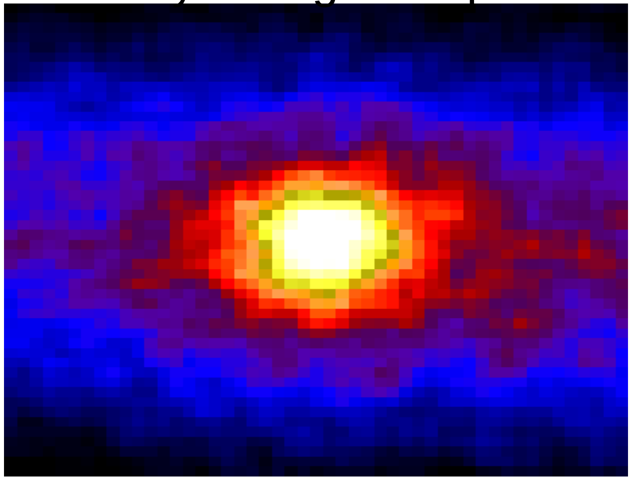


ν from Nature @ Super Kamiokande

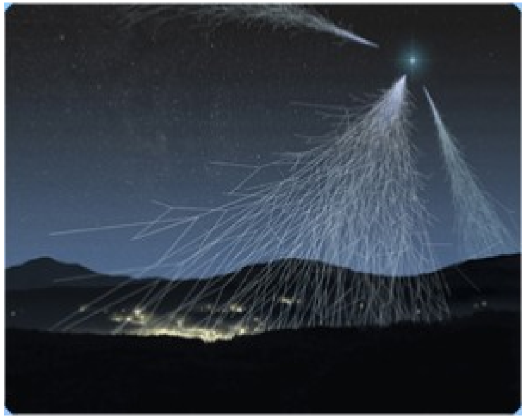
Solar
@ MeV

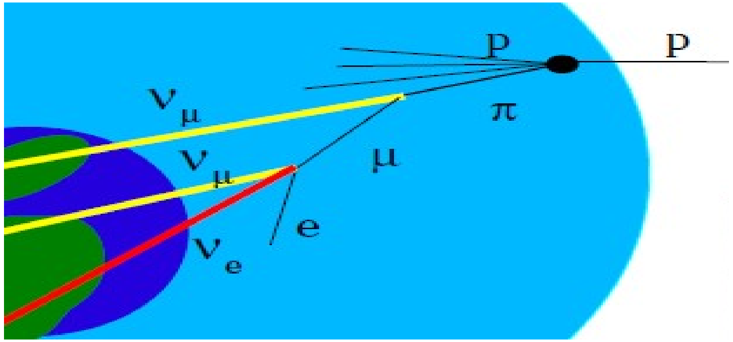


500 days + nights exposure



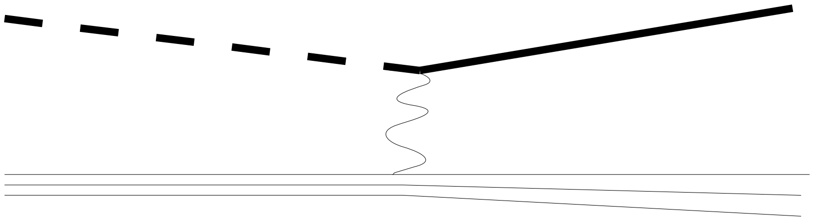
Atmospheric
@ GeV





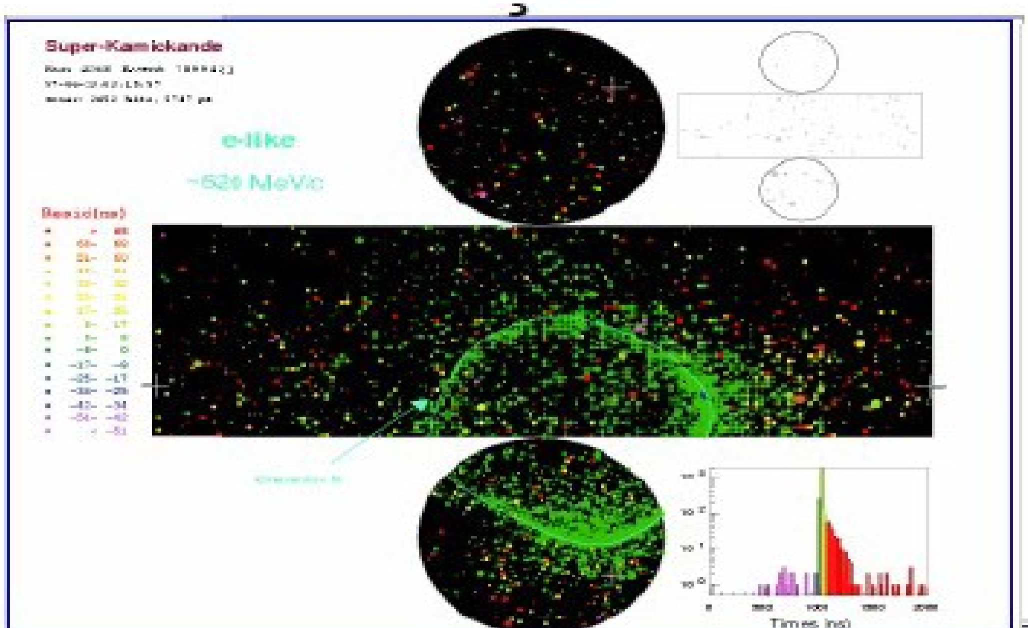
higher energy but lower flux

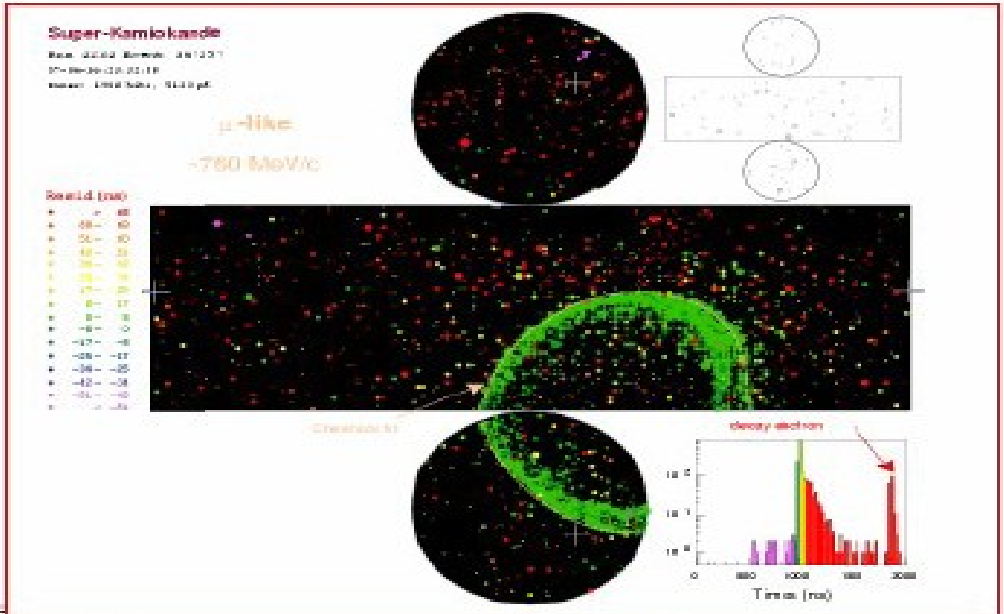
identifying electrons and muons



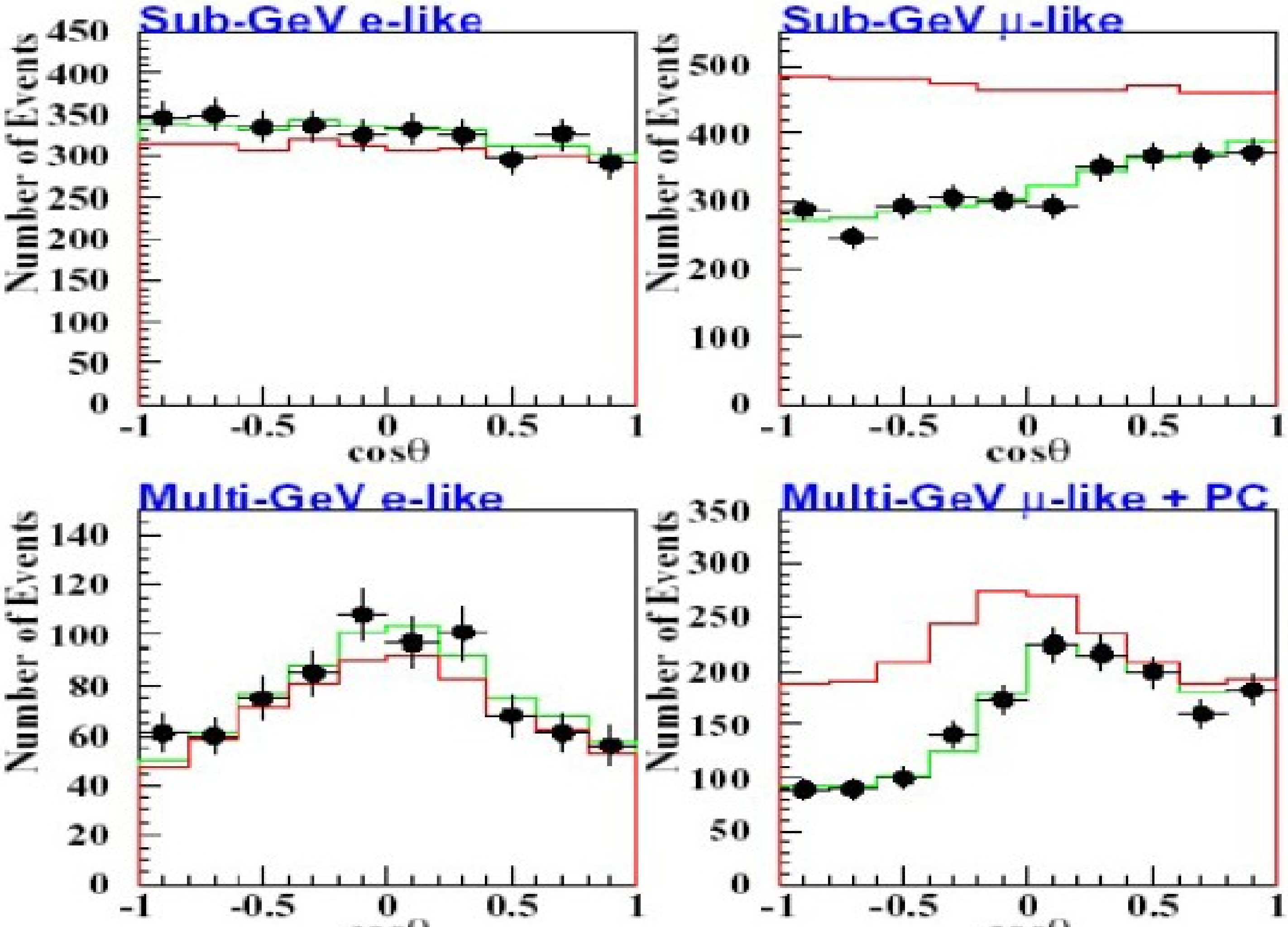
Kinematics of lepton =>
energy and direction

no charge measurement





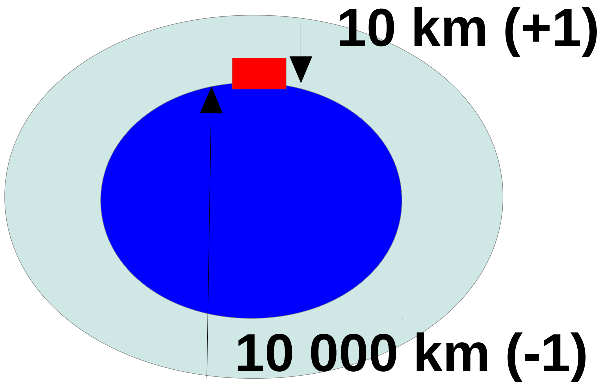
muon neutrino disappearence



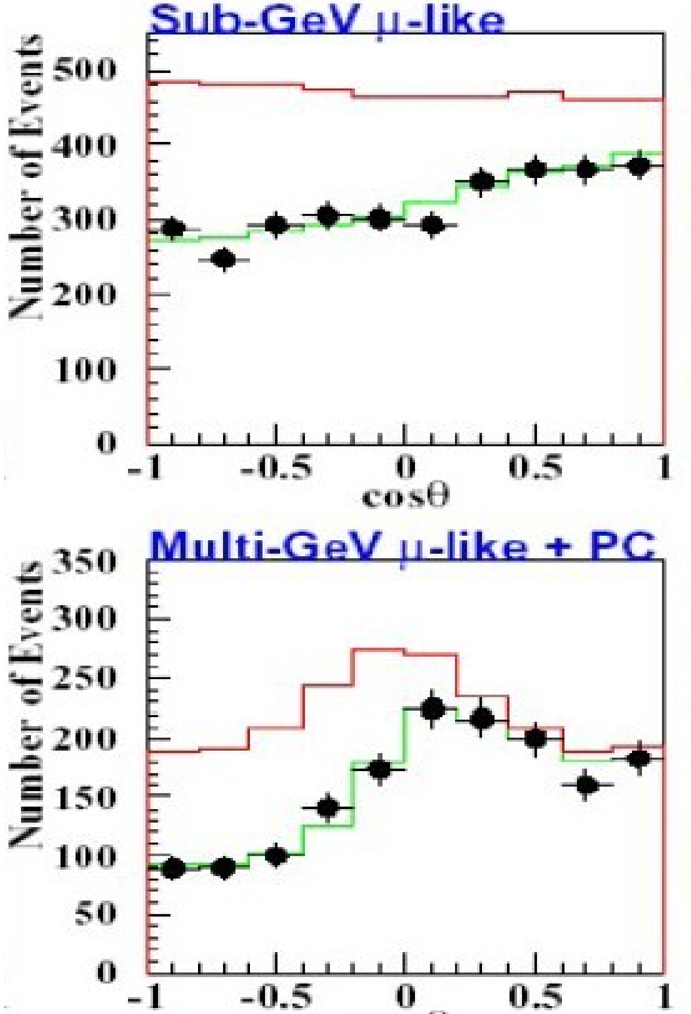
$\pi \rightarrow \mu\ \nu \rightarrow e\ \nu\ \nu\ \nu$

Confirm electron prediction
=> cosmic ray calculation

Muon deficit depends on
distance (and also energy)

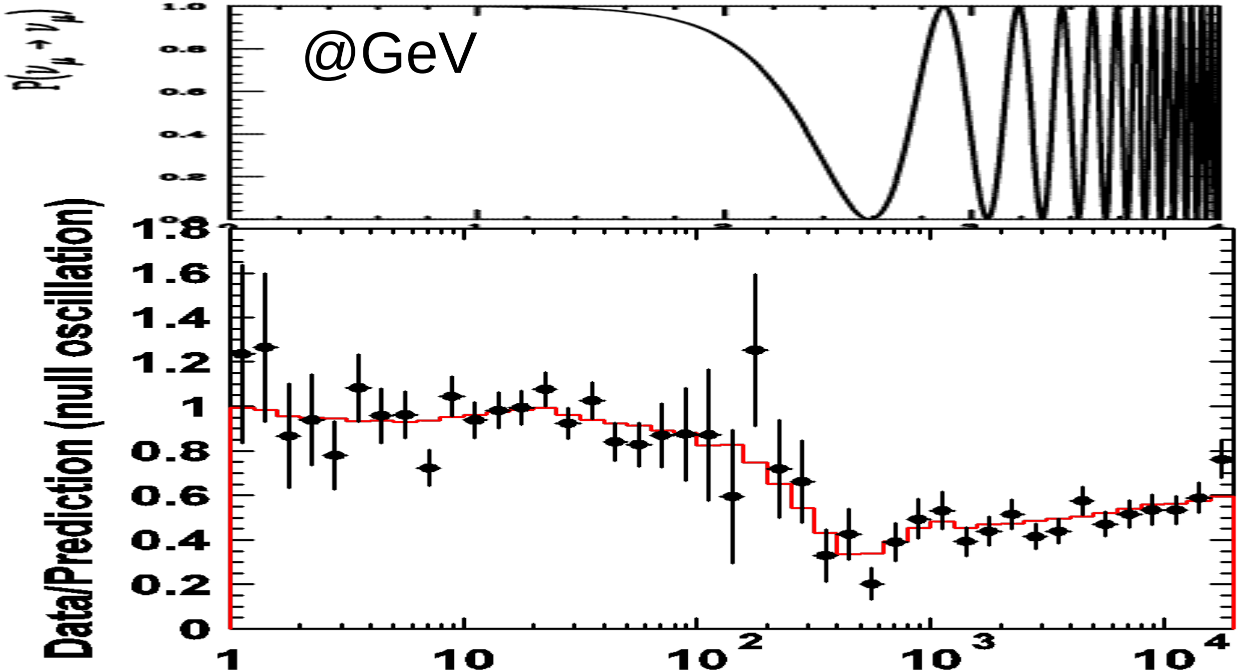


first measurement of ν oscillations

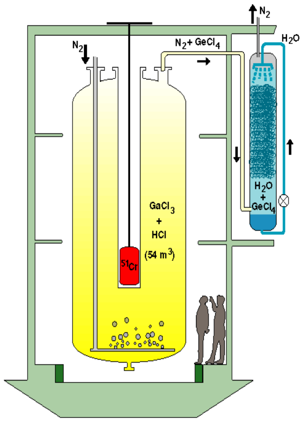


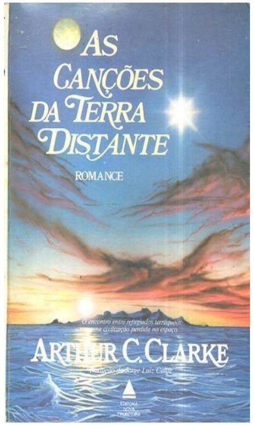
expected from cosmic ray fluxes confirmed by electron measurements

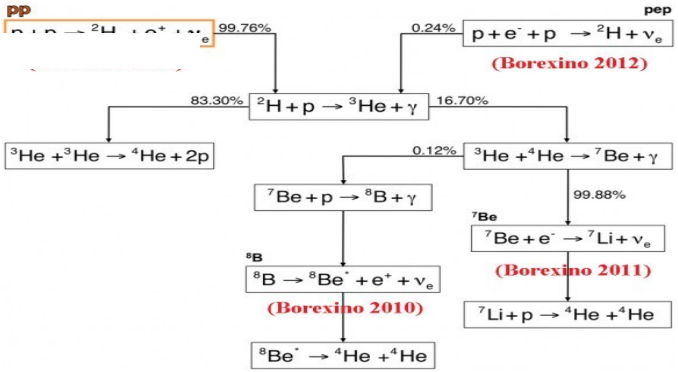
fit with 1 – A sin²(f L/E)

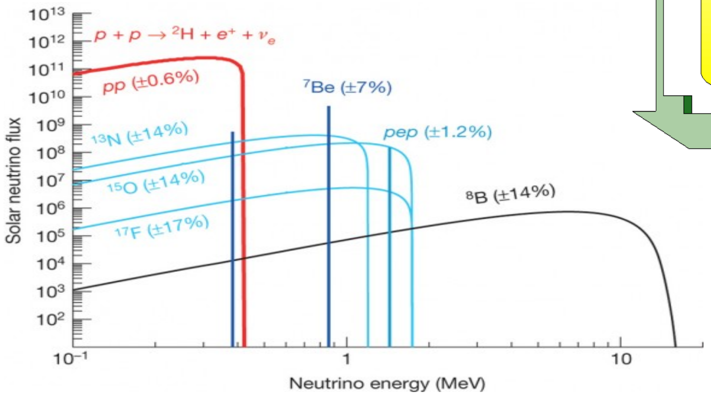


the solar neutrino problem

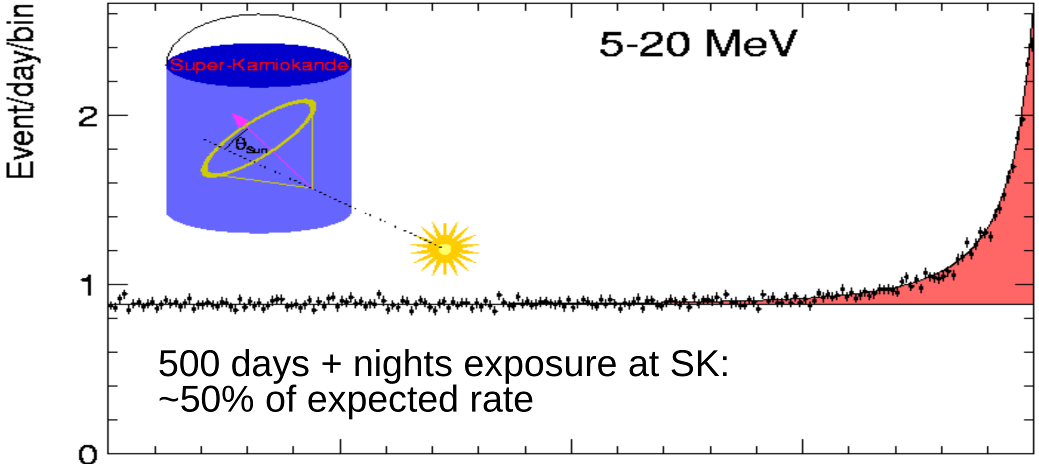


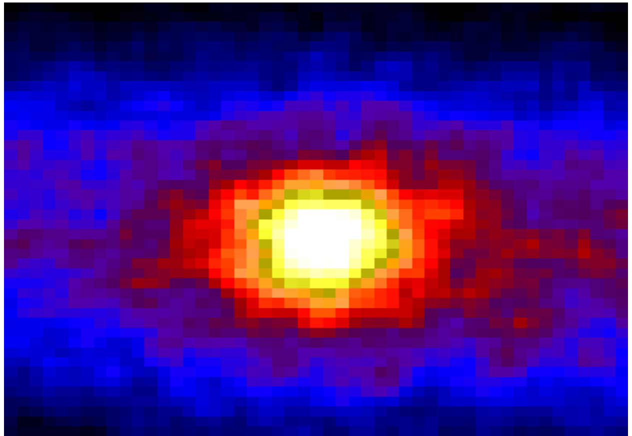




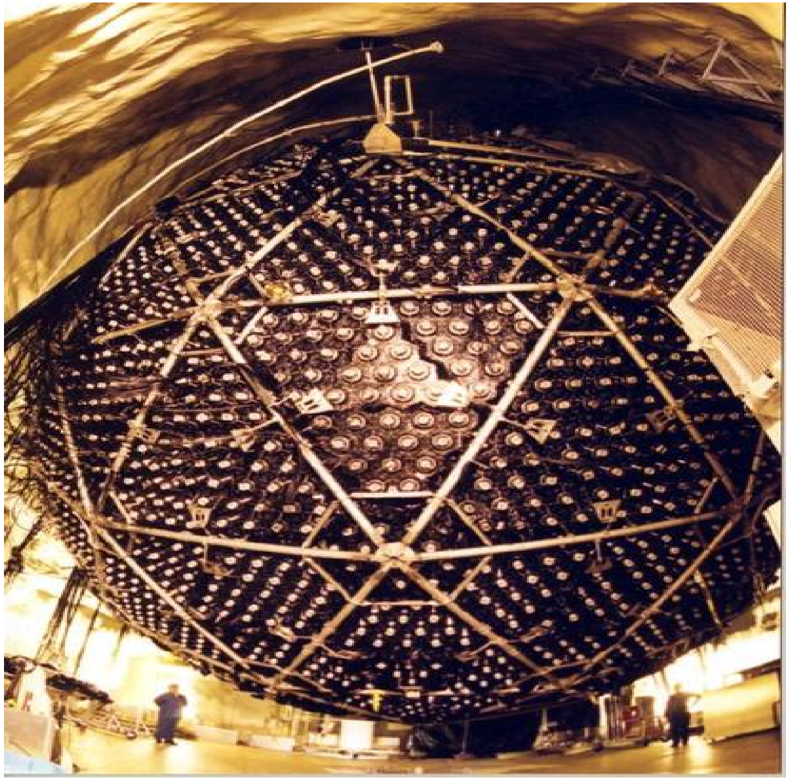


Solar luminosity
=> 60 billion/cm²/s





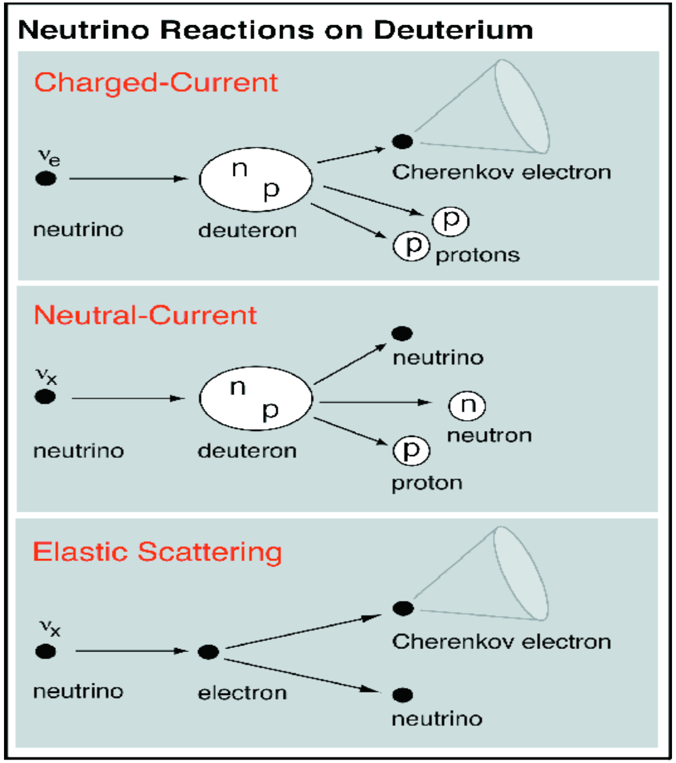
Sudbury Neutrino Observatory



ν + D --> p + p + l
(electron neutrinos)
Energy sensitivity

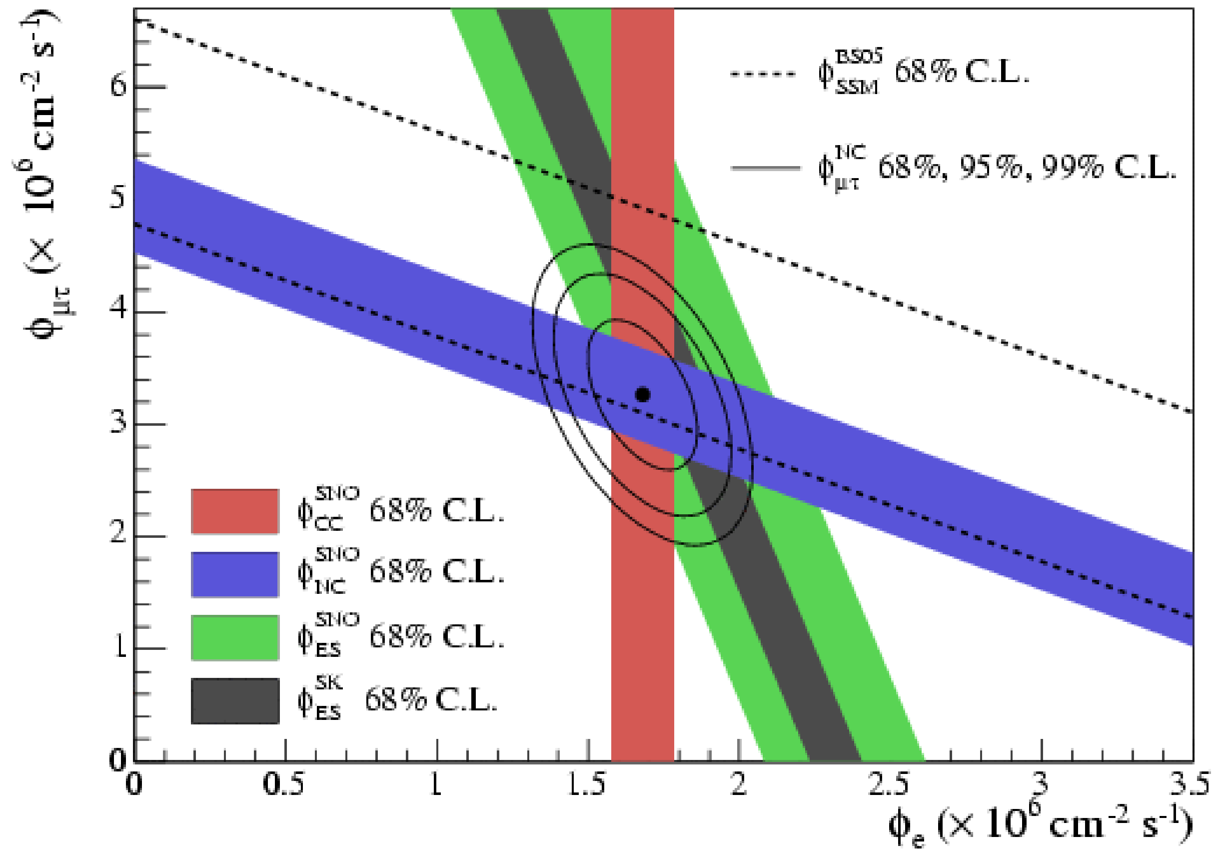
ν + D --> p + n + ν
(equally all neutrinos)
N + Cl ---> Cl + γγ

ν + e --> ν + e
(5x more for electron)
Direction sensitivity



Sudbury Neutrino Observatory was a (Salted) Heavy Water Detector:
CC measure electron neutrinos; NC measure all neutrino types

Sun is OK, neutrinos change flavor



NC: sensitive to all neutrino types
Confirms prediction of Solar Model

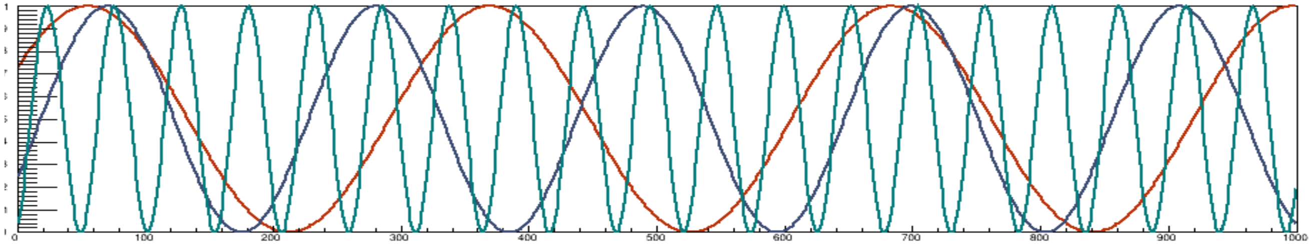
CC: sensitive to electron neutrino only
Confirms neutrino oscillations

Only 1/3 of solar neutrinos
arrive to Earth as electron neutrinos!

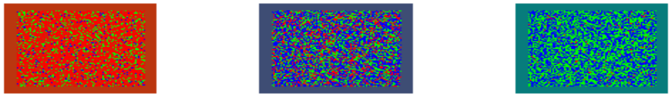
ES: (only process allowed in water)
mixes CC electron-neutrino
and NC for all others –> 50% effect

Also explained by oscillations!
But with different amplitude and frequency!

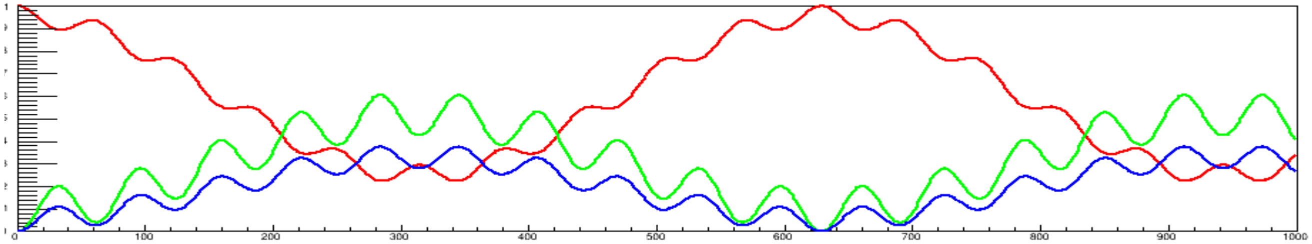
neutrino oscillations and mass



If neutrino masses were equal there would be no oscillation
=> it is the only indication that **neutrinos have non-zero mass**



Each neutrino is created as a sum of 3 waves, that propagate differently (only mass matters)



The lepton that can be detected, is given by the sum of the waves at that time

(Neutral Current interaction does not depend on flavor)

Oscillations

$$\begin{bmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{bmatrix} = \begin{bmatrix} c & s \\ -s & c \end{bmatrix} \begin{bmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{bmatrix}$$

orthogonal states with same mass eigenstates

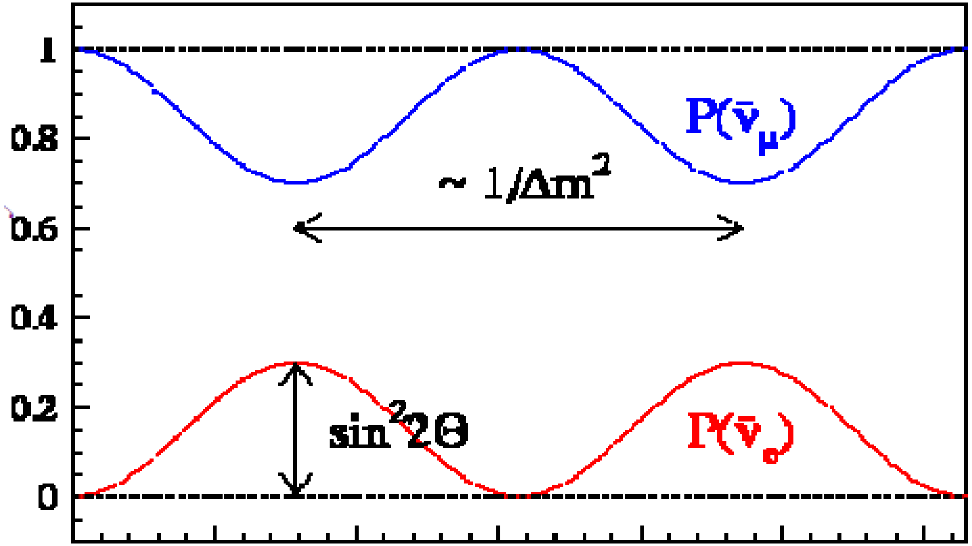
$$|\nu(t=0)\rangle = |\nu_e\rangle = c|\nu_1\rangle + s|\nu_2\rangle.$$

initial state is composition of the two eigenstates

$$|\nu(t)\rangle = c\, e^{-iE_1 t}|\nu_1\rangle + s\, e^{-iE_2 t}|\nu_2\rangle$$

slightly different evolution $E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p} \simeq E + \frac{m_i^2}{2E}$

$$\begin{aligned} P(\nu_e \to \nu_\mu; t) &= |\langle \nu_\mu | \nu(t) \rangle|^2 \\ &= |\{-s\,\langle \nu_1| + c\,\langle \nu_2|\}|\nu(t)\rangle|^2 \\ &= c^2\, s^2\, \left| e^{-iE_2 t} - e^{-iE_1 t} \right|^2 \\ &= 2\, c^2\, s^2\, \{1 - \cos[(E_2 - E_1)t]\} \\ &= \sin^2 2\theta\, \sin^2 \left[\frac{\Delta m^2}{4E} t \right], \end{aligned}$$

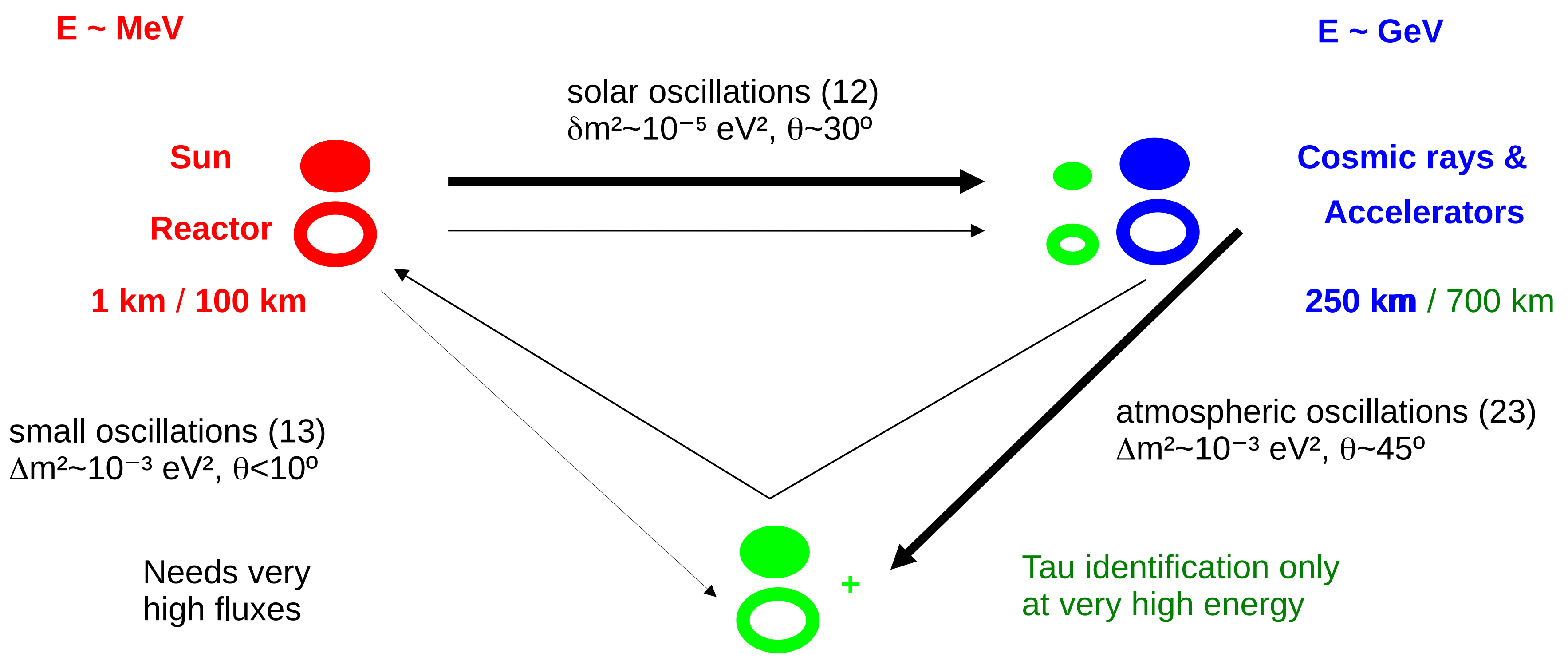


$$P(\nu_e \to \nu_\mu; L) = \sin^2 2\theta\, \sin^2 \left[1.27\, \Delta m^2 \frac{L}{E} \right]$$

closing the circle on 3 neutrinos

$$P = 1 - \sin^2 2\theta \, \sin^2(1.27\, \Delta m^2\, L/E)$$

3 flavors of neutrinos (● & anti-neutrinos ⊙) for 3 mass values

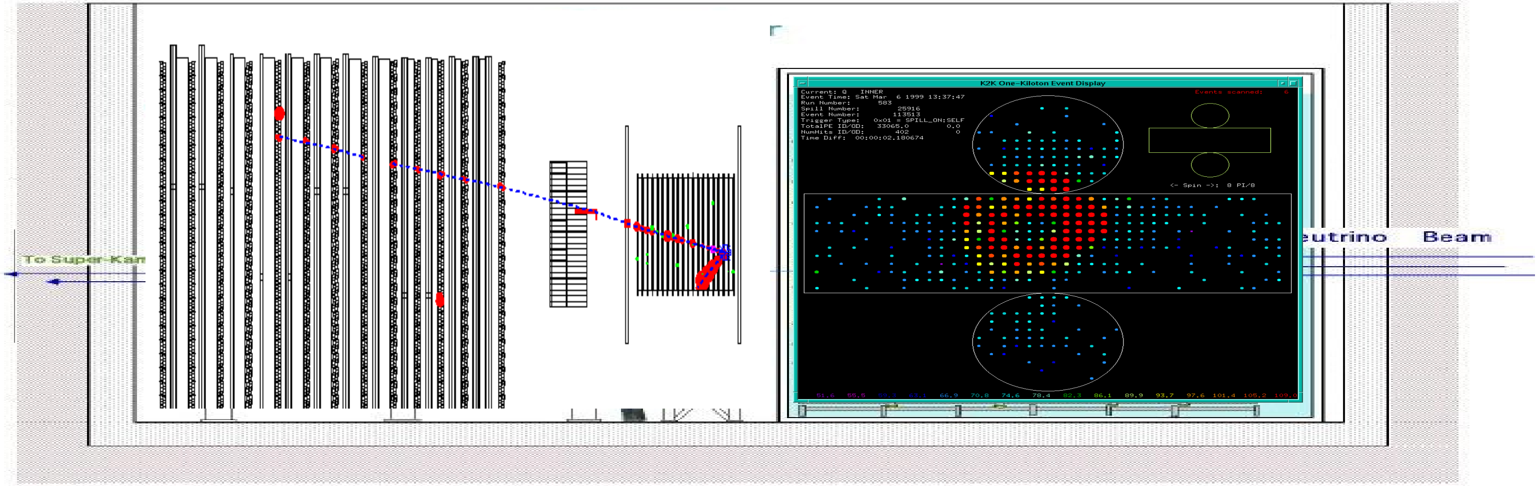


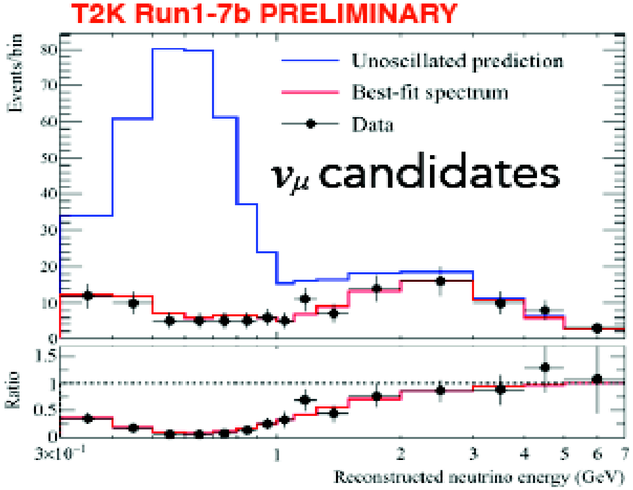
confirmation with accelerators

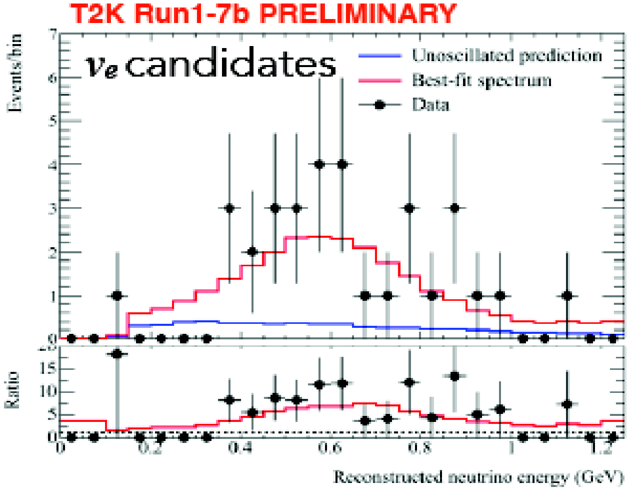
K2K
@ 250 m

◄

SK 250 km







T2K (280 km / 280 m)

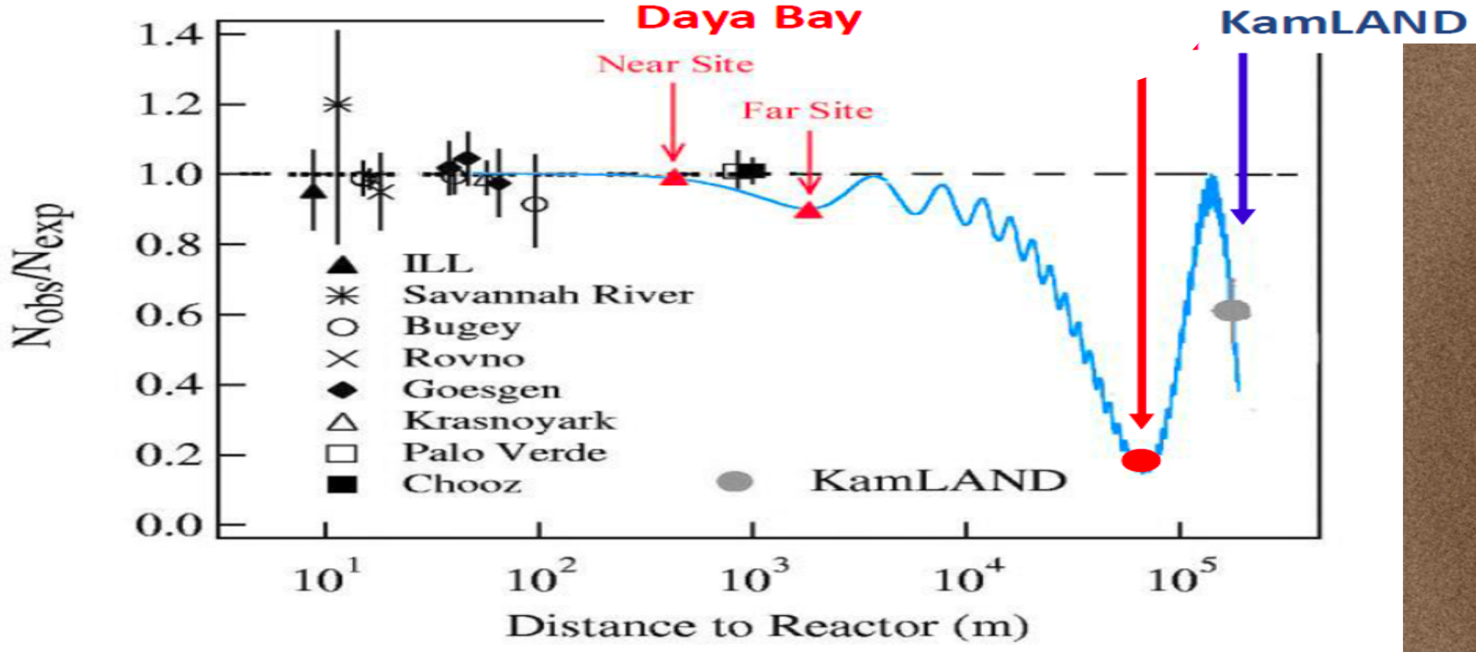
446 ν expected

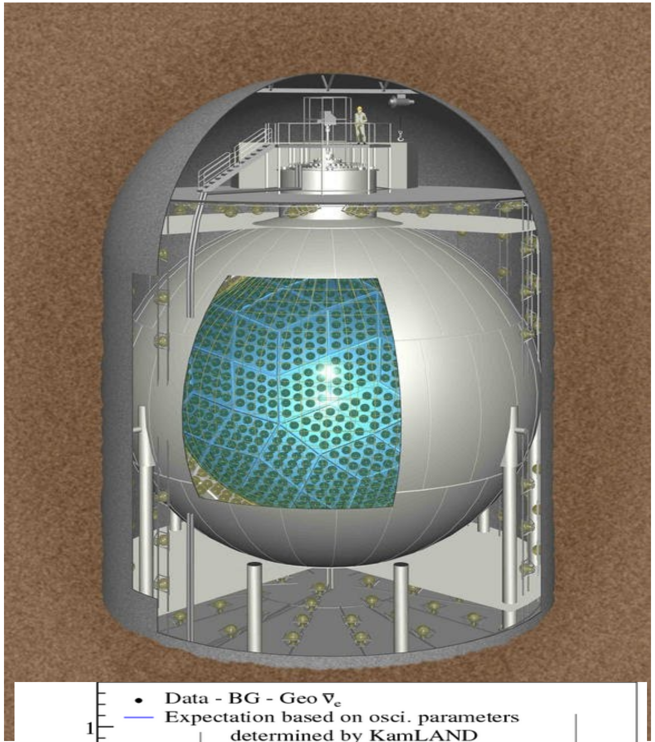
120 ν_μ

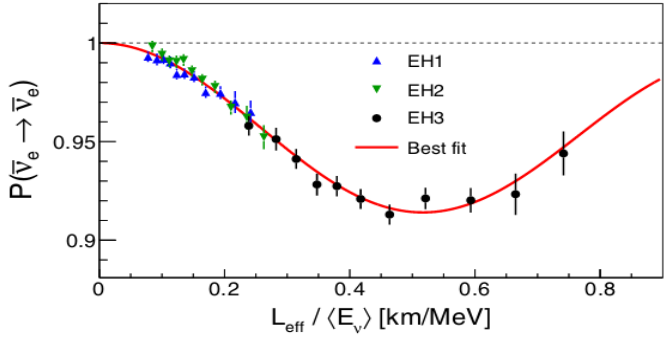
28 ν_e (5 from the beam)

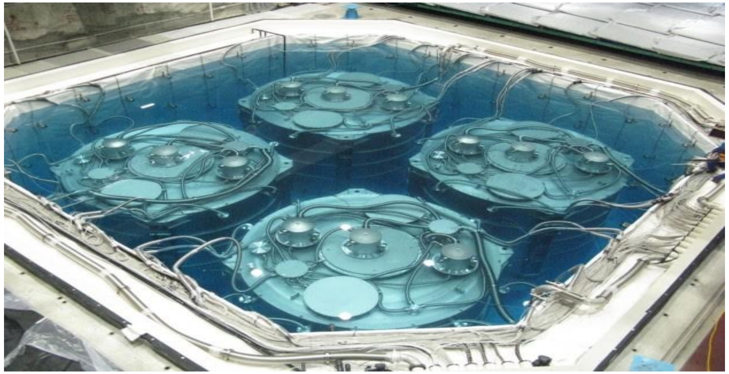
ν_τ invisible

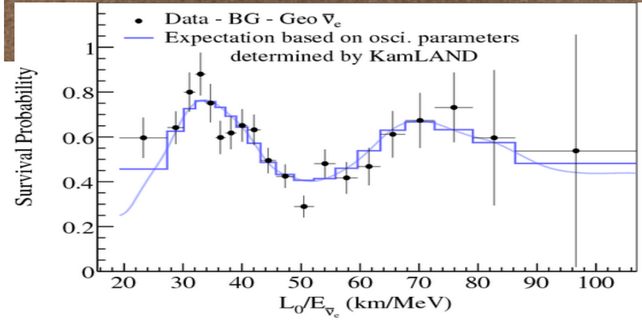
confirmation with reactors







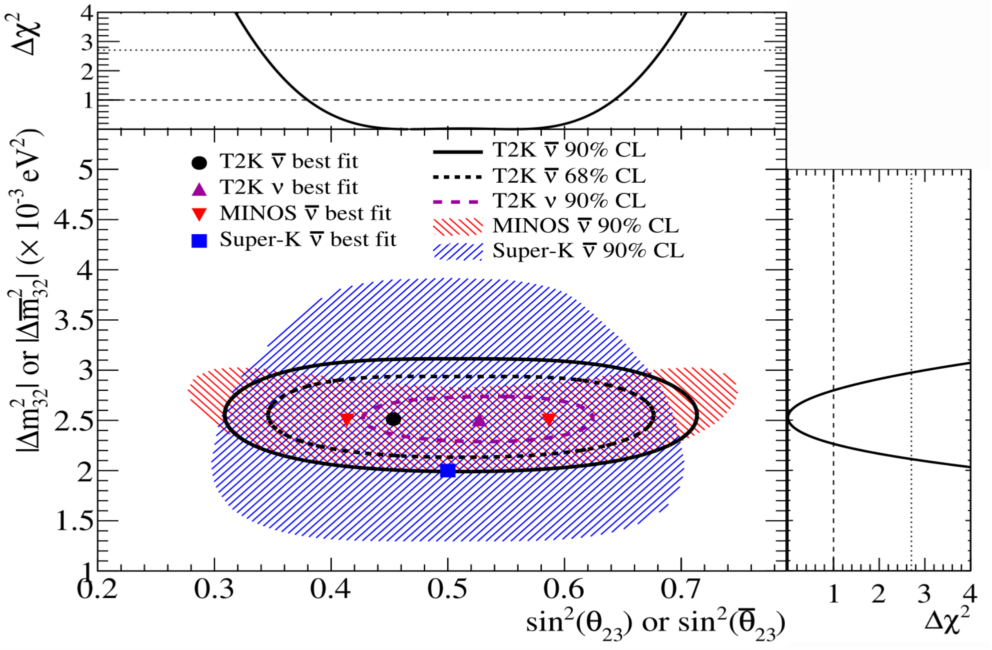


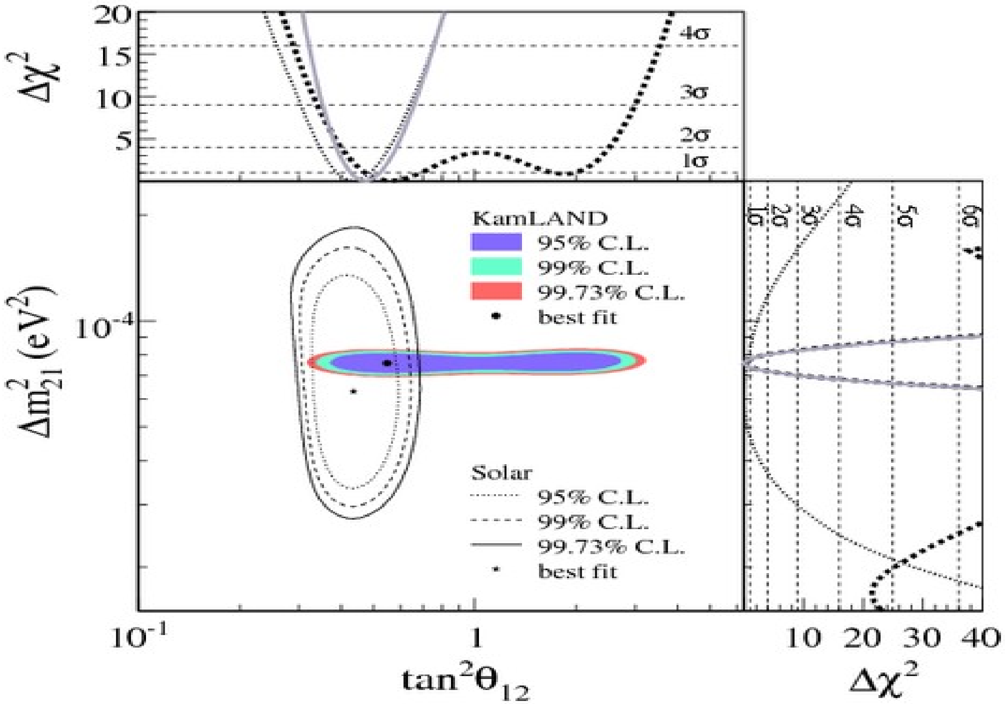


“atmospheric” and “solar” oscillations

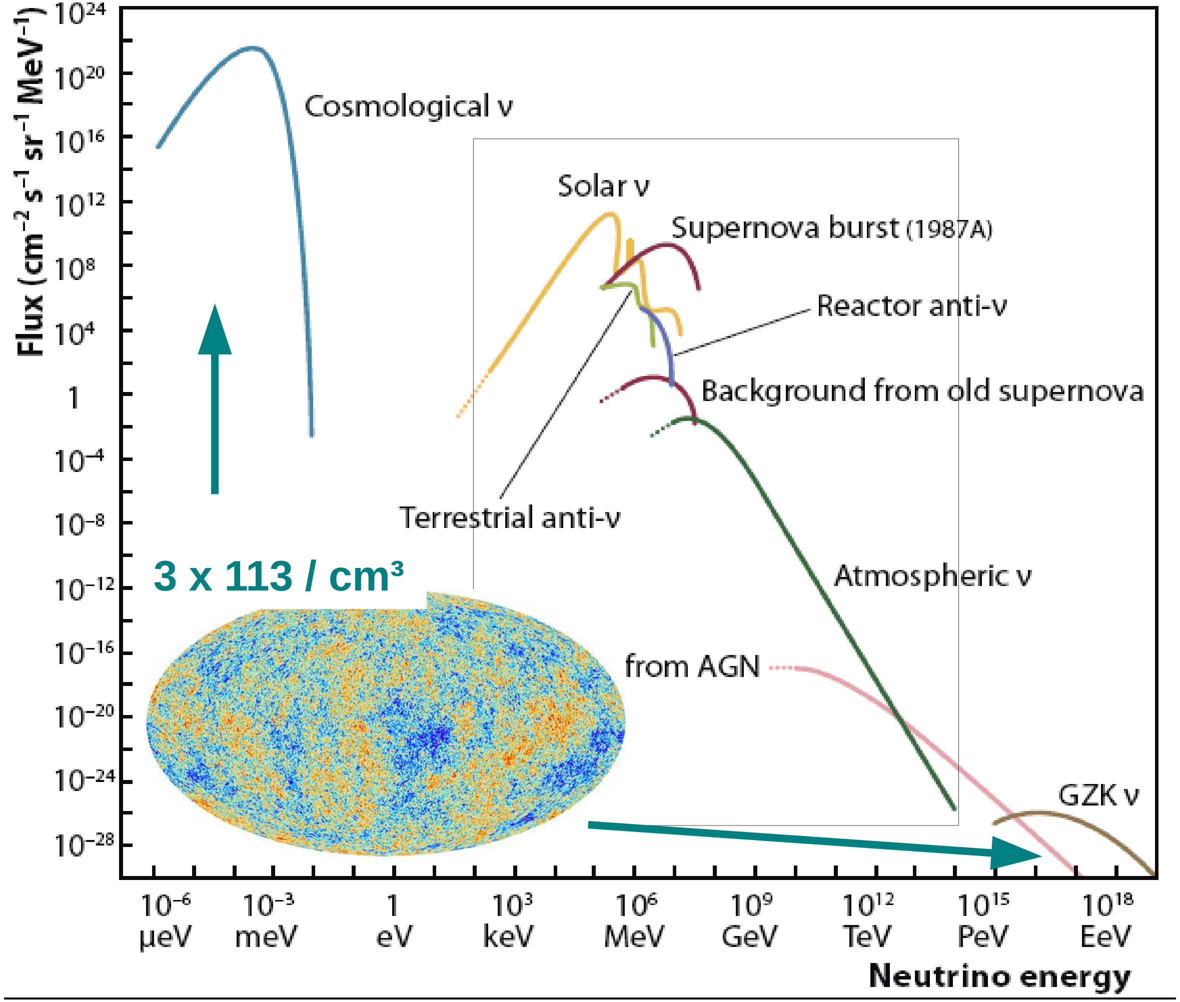
P = 1 - sin²2θ sin²(1.27 Δm² L/E)

compatible in natural and artificial sources,
compatible in neutrinos and anti-neutrinos,
explaining propagation in vacuum and in matter





back to studying sources



1950s: reactors

1960s: the Sun

1960s: Atmospheric (cosmic ray)

1960s: Accelerators

1980s: SuperNova (1987A)

2000s: the Earth

2010s: Galactic sources

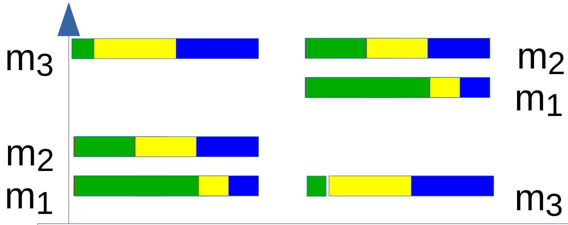
2020s?: GZK

20xxs?: BigBang

Open questions: what is the mass?

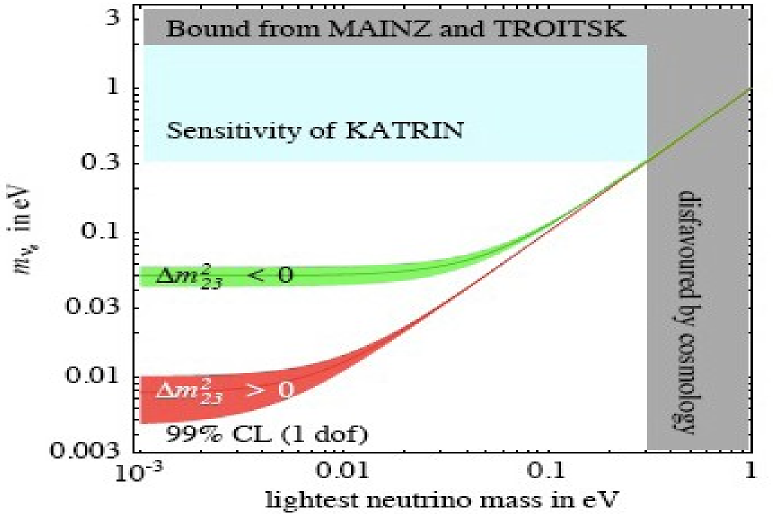
oscillations give the only direct evidence that neutrinos have masses, but not the mass values...

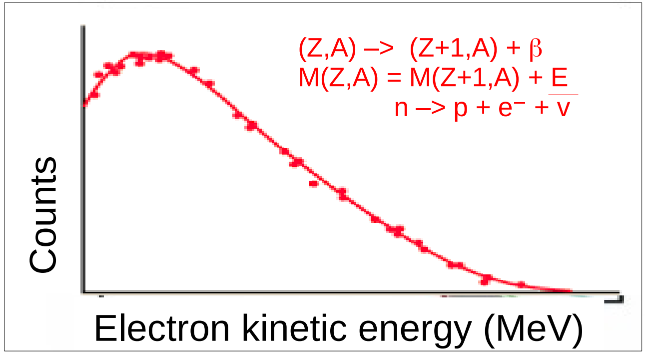
==> what is the mass of the electron anti-neutrino in beta decays??

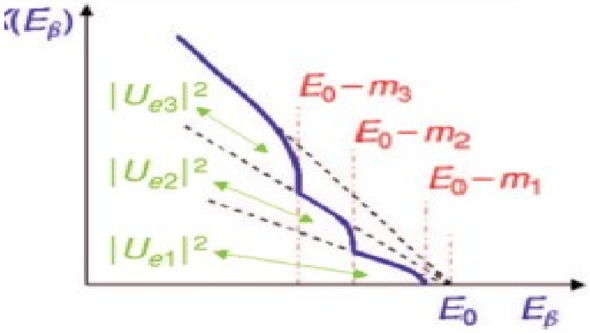


Minimum value is unknown < 2 eV!

$$\langle m_\beta \rangle^2 = \sum_i^{n_\nu} | U_{ei} |^2 \, m_{\nu,i}^2$$



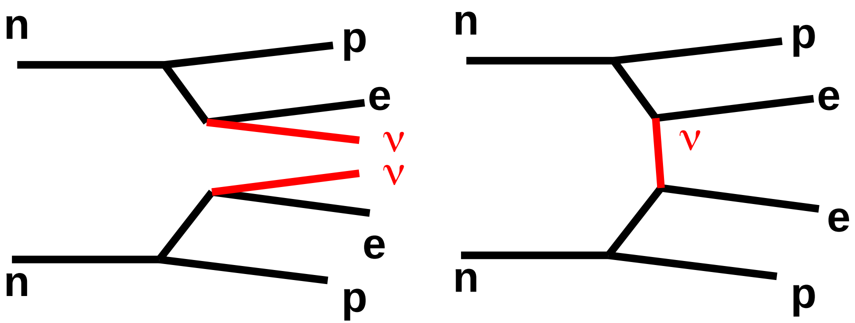


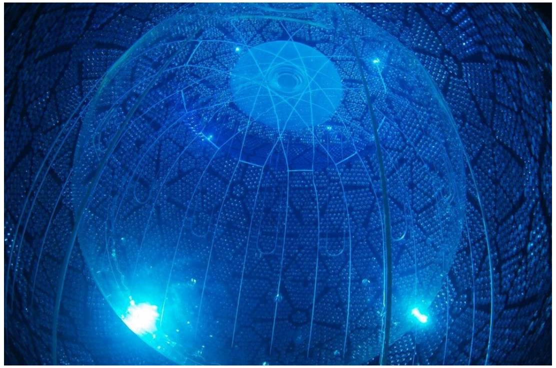


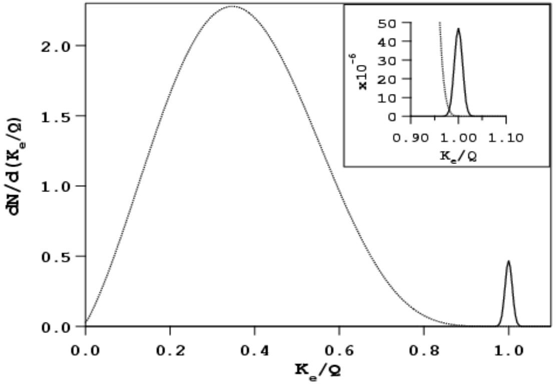
Open questions: what is the mass?

oscillations give the only direct evidence that neutrinos have masses
why are they so much smaller than for other elementary particles?

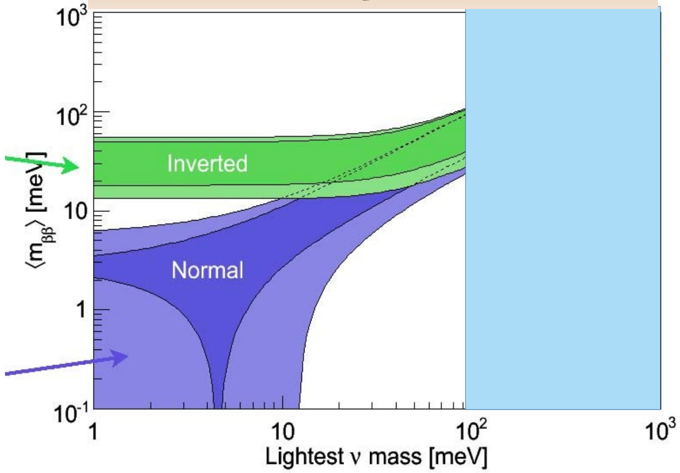
Maybe not only the Higgs mechanism? Others mechanisms possible if particle == anti-particle!







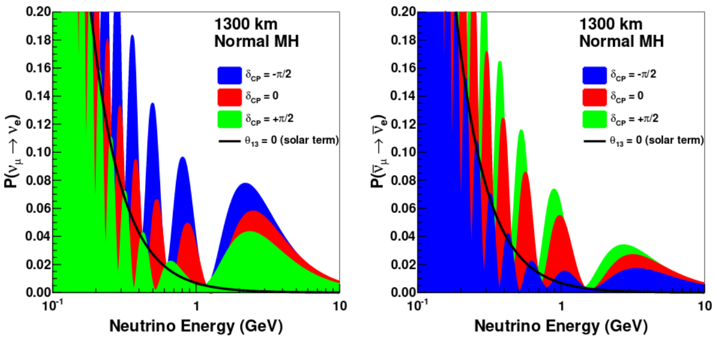
$$\langle m^2_{\beta\beta} \rangle = \left| \sum_i^{n_\nu} U^2_{ei} m_{\nu,i} \right|^2$$

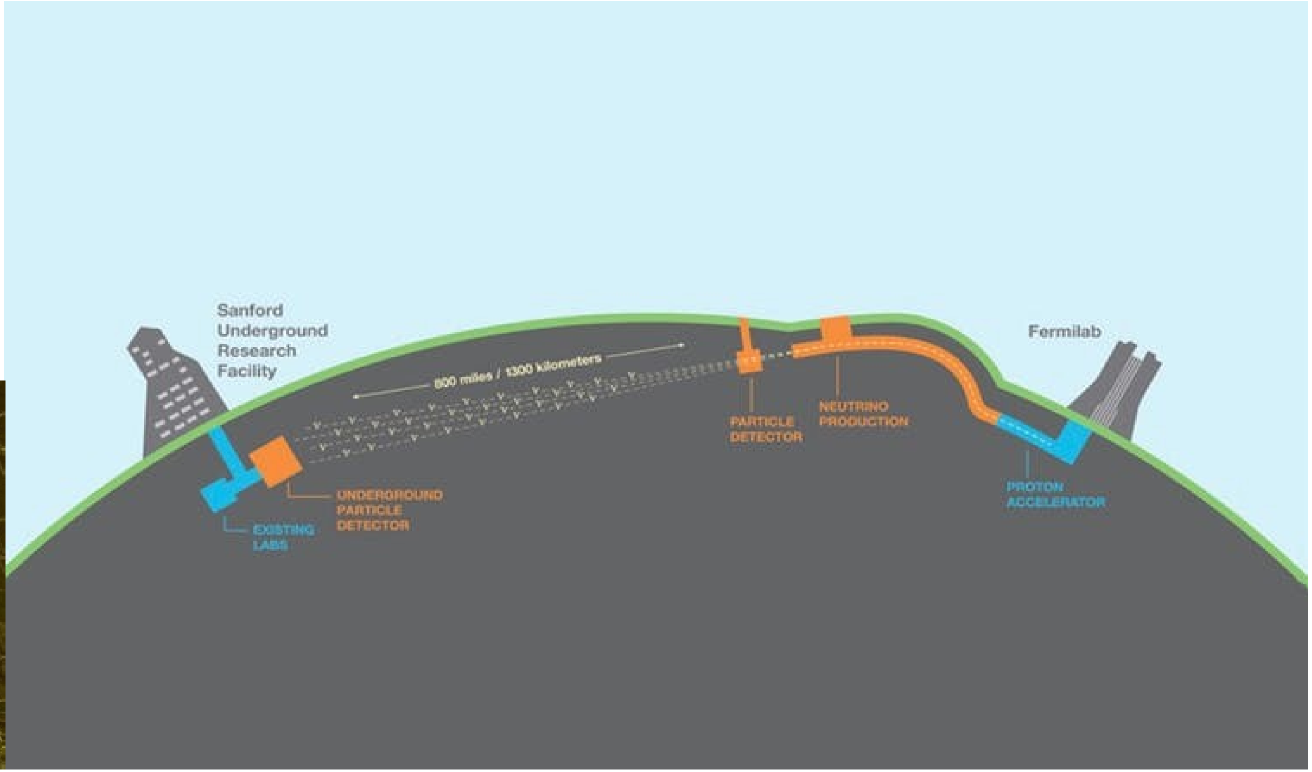


Open questions: matter / anti-matter

Are oscillations exactly reversed for neutrinos and anti-neutrinos?

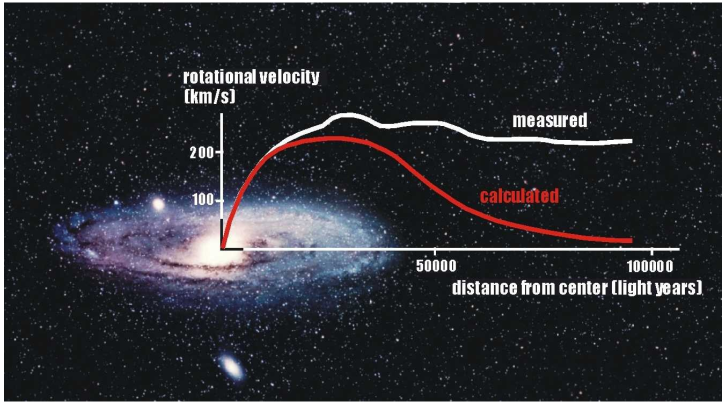
Also mesons/anti-mesons (quarks/anti-quarks) oscillate, with small differences:
but too small to explain why the Universe is made of matter instead of anti-matter

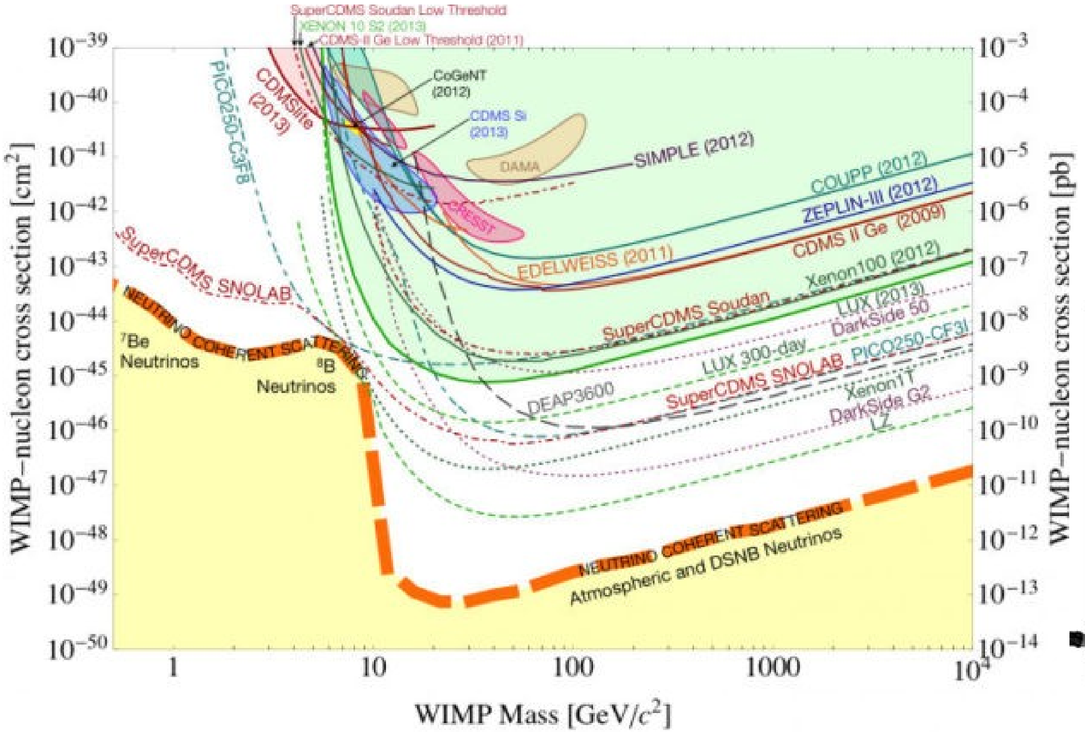


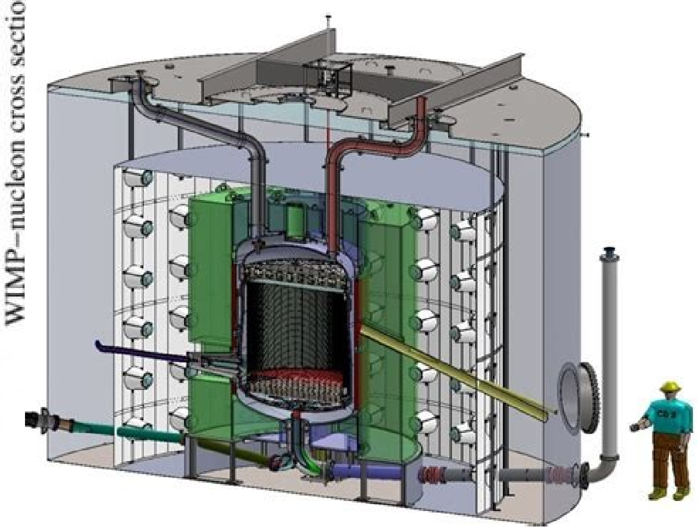


Open questions: and dark matter?

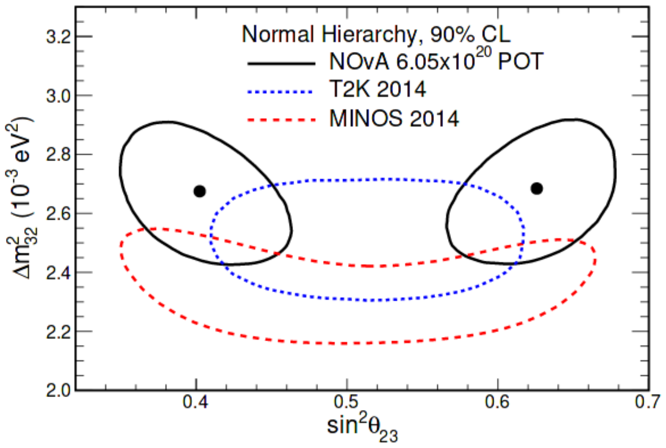
Neutrinos are not Dark Matter: masses too small to create structure!
Could maybe be Heavy (Majorana) neutrinos?
Some other Weakly Interactive Massive Particle?







A surprise from Astroparticles



Neutrinos have non-zero, but very small, masses

Mass combinations select how a neutrino interacts
(ie, the neutrino flavors in the Standard Model)

oscillating over time after neutrino production

With possible implications in cosmology

Mass values still unknown:
why so small? maybe their own anti-particles?

ν may be key to matter/anti-matter asymmetry:
some indications non-conservation of CP

Not dark matter, but maybe related to it?