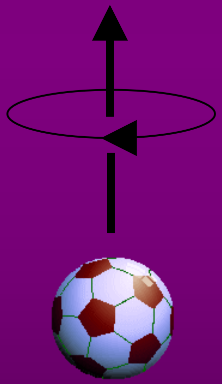
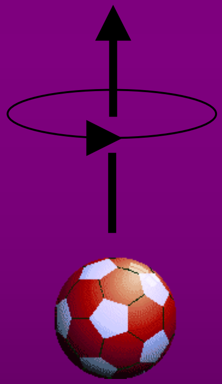
Plans and prospects in neutrino physics

E. Rondio
Workshop, 2.11.2005



Neutrino



Anti Neutrino

program

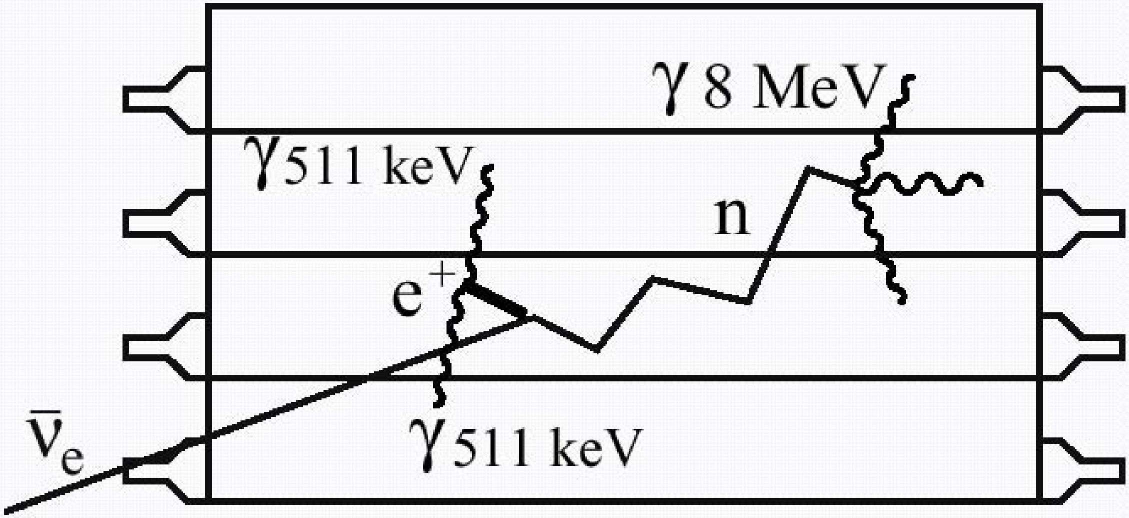
- Neutrino sources
- Evidence for oscillation and knowledge about parameters
- Open questions
- Next generation experiments and their needs for beam
- How parameters can be determined (solving ambiguities in mixing angle and CP phase)

how (anti)neutrinos can be seen

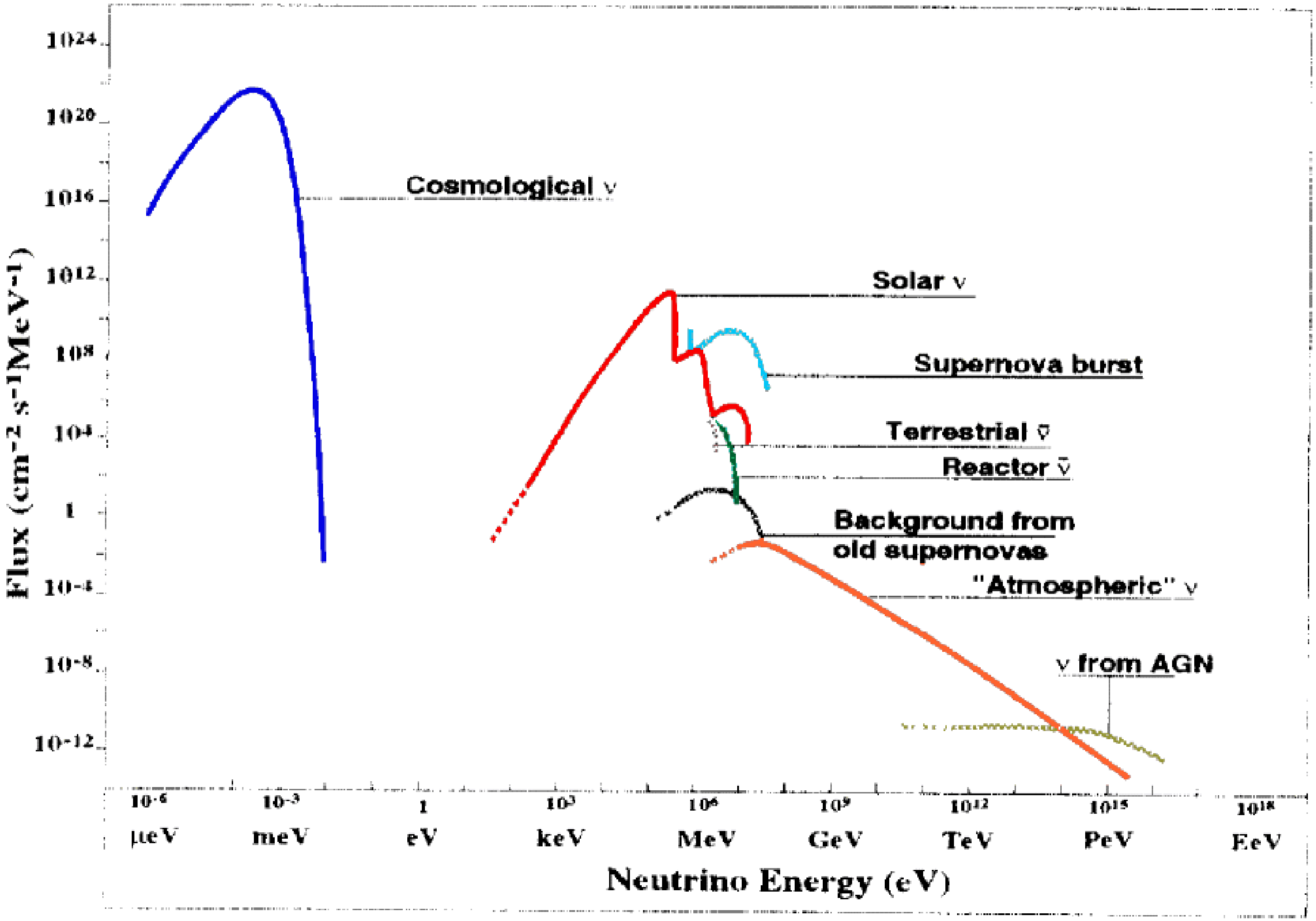
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Large(r) cross-section
- Specific signature

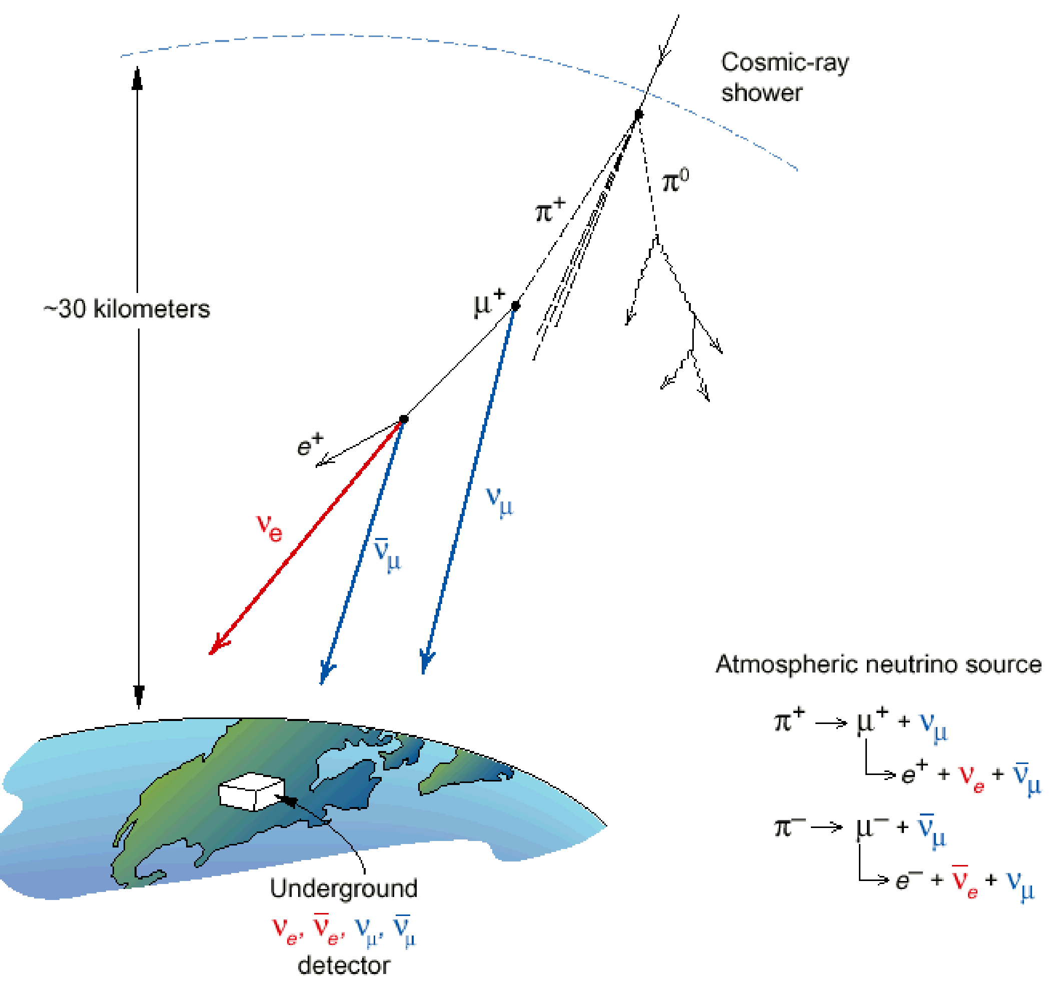
- e^+ kinetic energy (<8 MeV)
- 2 annihilation γs (0.5 MeV)
- neutron capture (2 to 8 MeV)



Natural sources of neutrinos

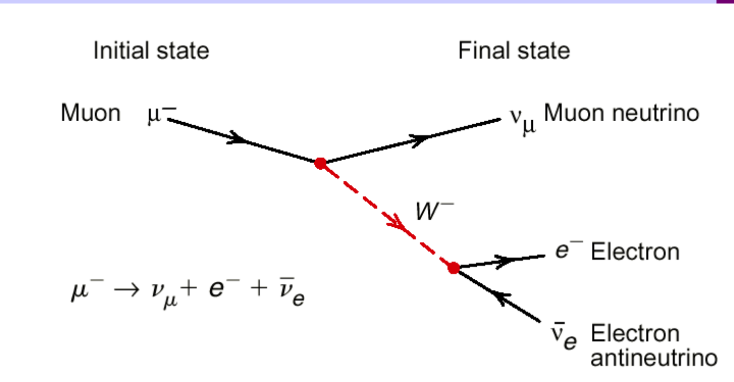


Atmospheric Neutrinos



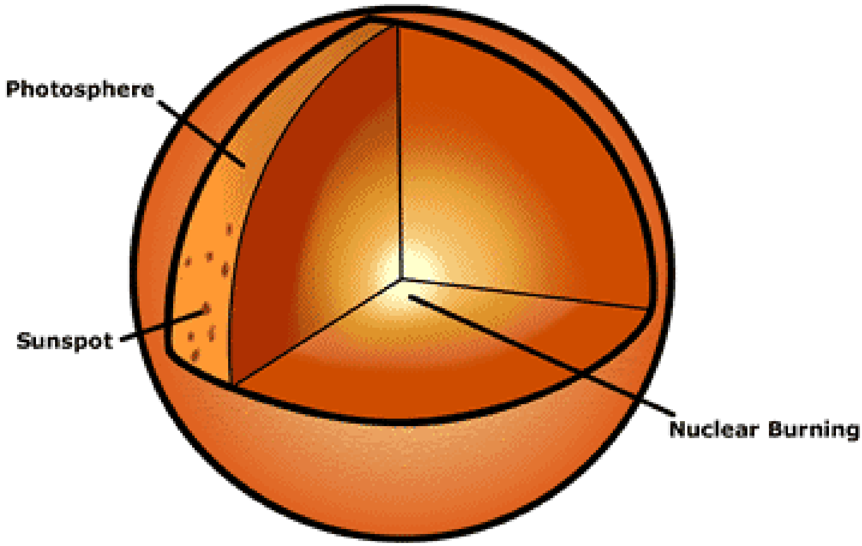
Weak decays are sources of neutrinos:

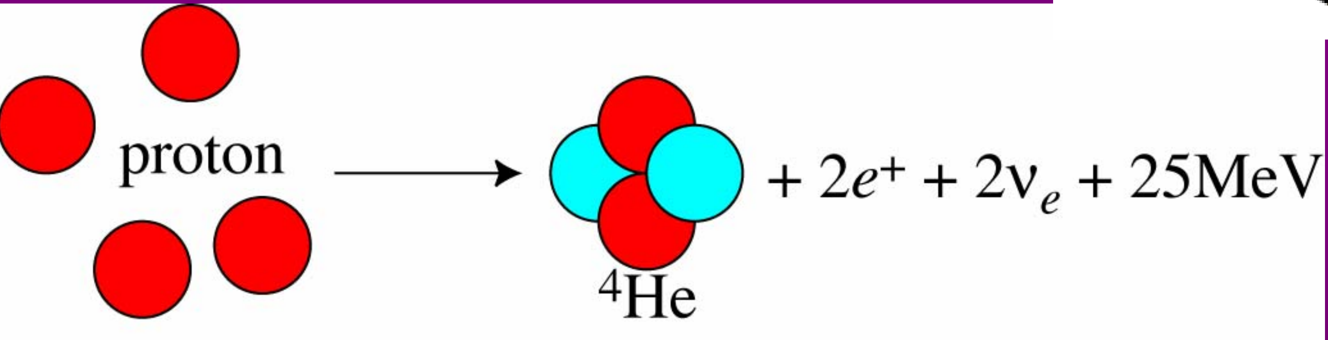
- p, K mesons decay on the way to Earth
- some muons (μ) also decay but many reach the surface (exercise: calculate the path of a muon of 20 GeV with lifetime 2×10^{-6} s)



How the Sun burns

The Sun emits light because nuclear fusion produces a lot of energy





$+ 2e^+ + 2\nu_e + 25\text{MeV}$

$$\Phi_\nu = \frac{2L_{\text{sun}}}{25\text{MeV}} \frac{1}{4\pi(1\text{AU})^2} = 7\cdot 10^{10}\ \text{sec}^{-1}\ \text{cm}^{-2}$$

where L_{sun} is the Sun luminosity
1AU is the distance from Sun to Earth

Thermonuclear fusion reactions

$p+p \longrightarrow \nu_e+e^++d$

0.42MeV max

$p+e^-+p \longrightarrow \nu_e+d$

1.44 MeV

$d+p \longrightarrow \gamma+{}^3He$

${}^3He+{}^3He \longrightarrow {}^4He+p+p$

ppI (85%)

${}^3He+{}^4He \longrightarrow {}^7Be+\gamma$

${}^7Be+e^- \longrightarrow \nu_e+{}^7Li$

.86 MeV

${}^7Li+p \longrightarrow {}^4He+{}^4He$

ppII (15%)

${}^7Be+p \longrightarrow {}^8B+\gamma$

${}^8B \longrightarrow e^-+\nu_e+{}^8Be$

rare but easier

15 MeV max

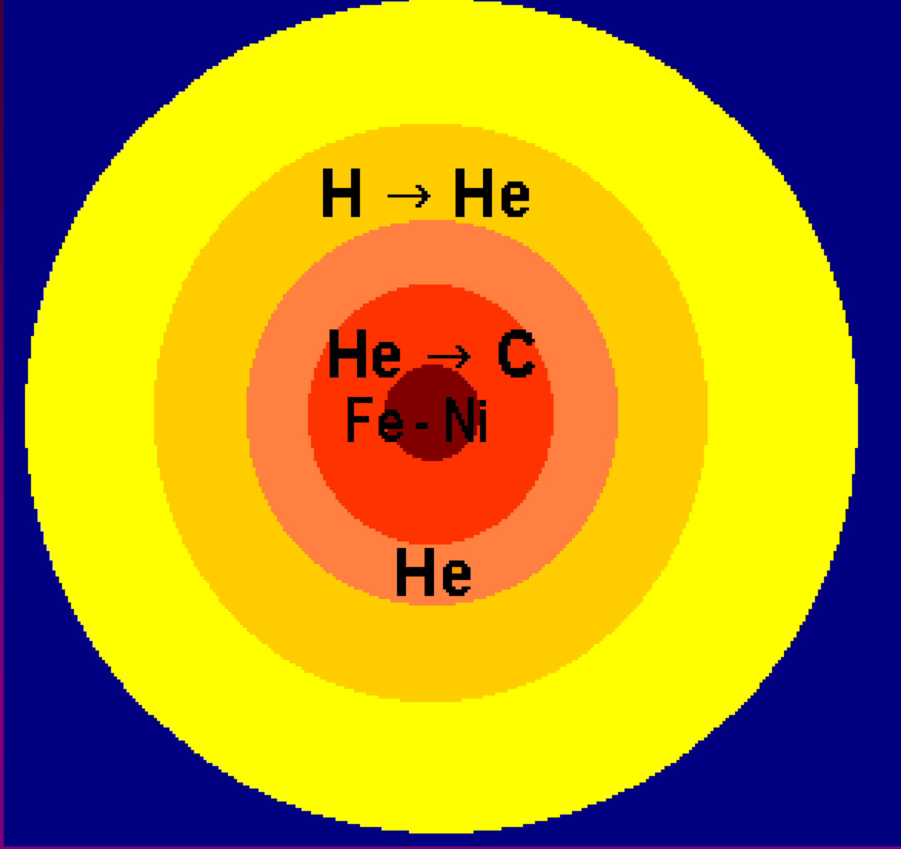
${}^8Be \longrightarrow {}^4He+{}^4He$

ppIII (0.01%)

Origins of Supernovae

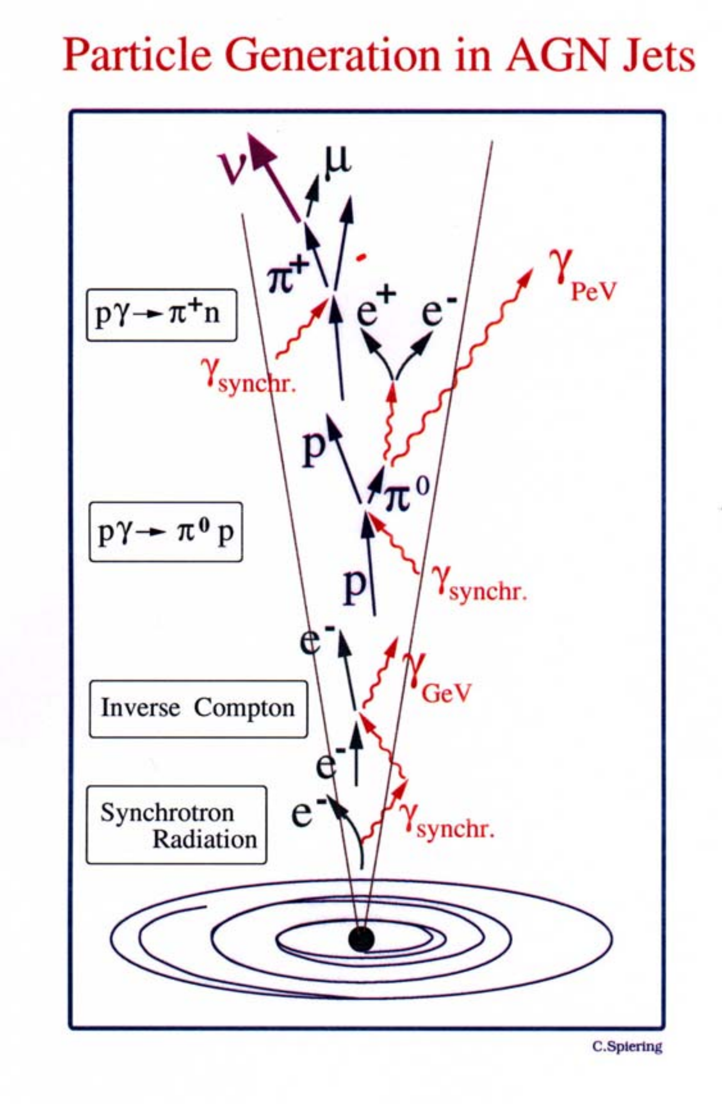
Major thermonuclear reactions:

Reaction	Ignition temperature (in millions of deg K)
4 ^{1}H --> ^{4}He	10
3 ^{4}He --> ^{8}Be + ^{4}He-> ^{12}C	100
^{12}C + ^{4}He --> ^{16}O	
2 ^{12}C --> ^{4}He + ^{20}Ne	600
^{20}Ne + ^{4}He --> n + ^{23}Mg	
2 ^{16}O --> ^{4}He + ^{28}Si	1500
2 ^{16}O --> 2 ^{4}He + ^{24}Mg	4000
2 ^{28}Si --> ^{56}Fe	6000

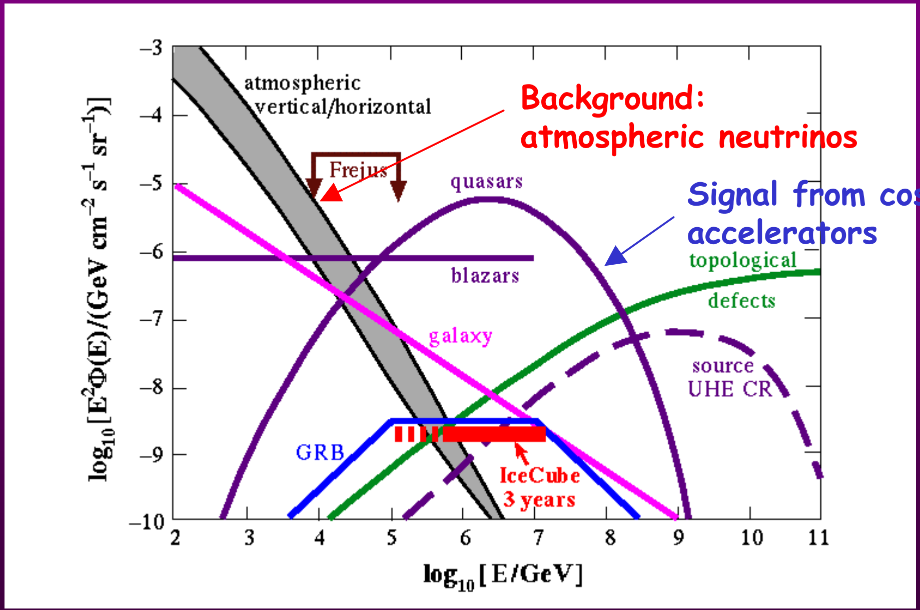


Fe-Ni core

High-Energy Neutrino Astrophysics



- Proton accelerators generate roughly equal numbers of gamma rays and neutrinos !
- Neutrinos are not absorbed in the sources because they interact only weakly during propagation
- Many gammas are absorbed or their energy decreased during propagation



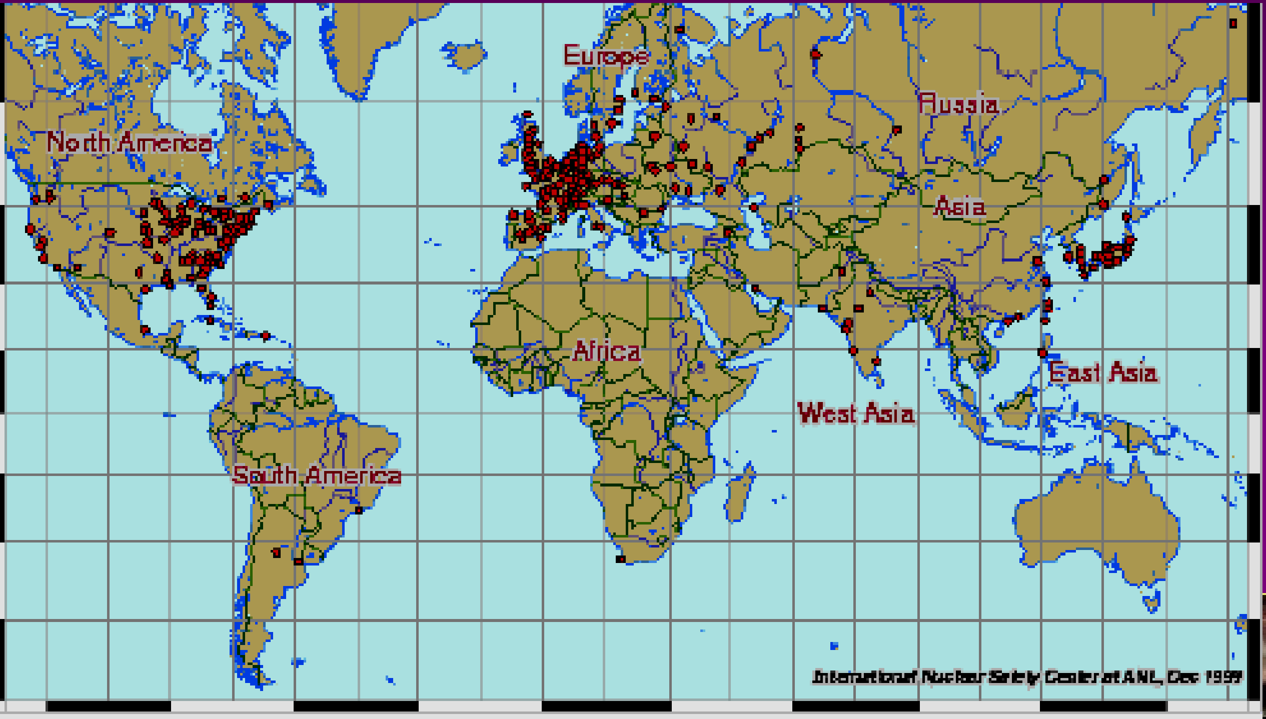
Background: atmospheric neutrinos

Signal from cosmic accelerators

Neutrino telescopes
search for dark matter and cosmic ν sources

Detector	Location		Detection method
Amanda	South pole		Cherenkov light in ice
Ice Cube	„	$1 km^3$	„
Baikal	Russia		Cherenkov light, water
Antares	Mediteranian Sea		„
Nestor	„		„

nuclear reactors produce neutrinos



Large power plant gives:

6×10^{20} anty-ν/sek

and 3 GW heatting power

Can be used for neutrino eksperiment

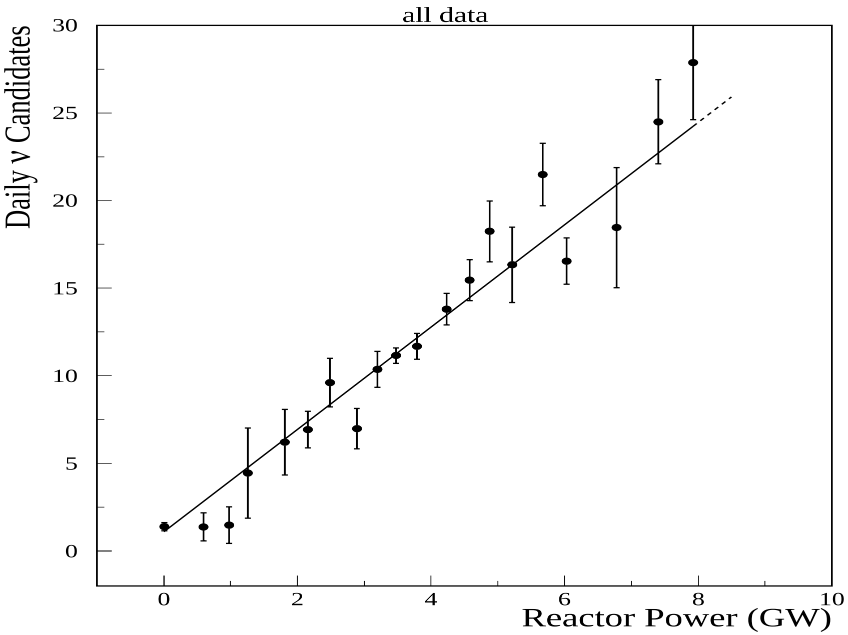
for example: Palo Verde

Reactor Power vs. Neutrino Flux

- Reactor neutrino rate is proportional to its power!

- Anyineutrino emission is isotropic and therefore its flux decreases with square of distance from reactor!

Chooz



Neutrinos produced in accelerators

In order to have high energy neutrinos one needs to:

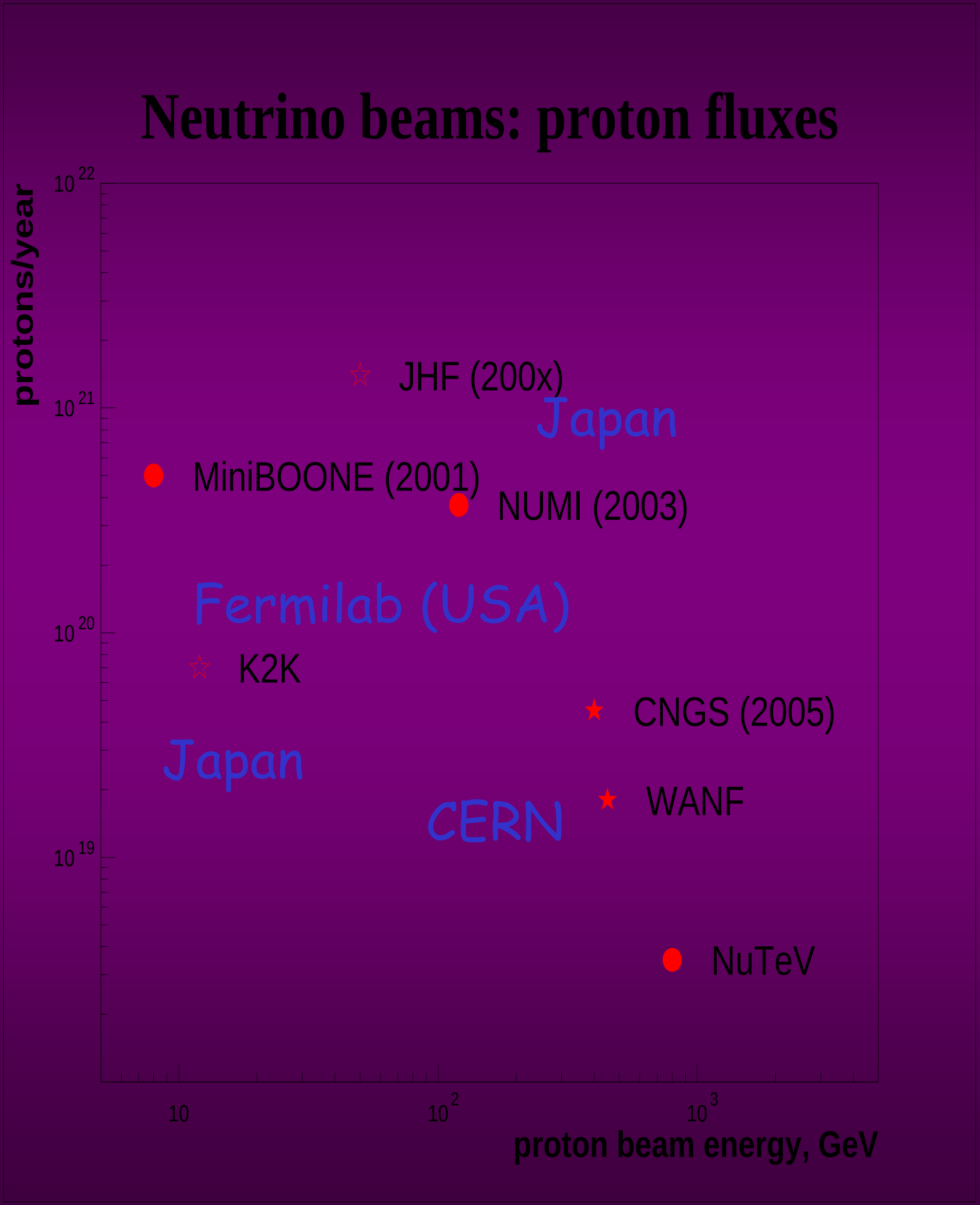
- Accelerate protons
- Make those protons interact in a target to produce many mesons

$$p + p \rightarrow p + n + \pi + \pi + K + ...$$

- Allow pions to decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- Collimate pions to form a beam
- Absorb remaining charged particles at the end of the beam line
- To avoid admixtures try to reduce decays:

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu \qquad K^\pm \rightarrow \pi^0 + e^\pm + \nu_e(\overline{\nu}_e)$$

Neutrino production starts with acceleration of protons



Quark mixing in Standard Model

States partcipating in strong interactions with well defined masses (mass matrix eigenstates):

$$\begin{matrix} u & c & t \\ d & s & b \end{matrix}$$

Staes participating in weak interactions:

$$\begin{matrix} u & c & t \\ d` & s` & b` \end{matrix}$$

Quark mixing:

$$\begin{bmatrix} d' & s' & b' \end{bmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Neutrino mixing NOT in Standard Model

IF neutrinos are massive:

States with well defined masses (mass matrix eigenstates):

$$\begin{array}{ccc} e^- & \mu^- & \tau^- \\ \nu_1 & \nu_2 & \nu_3 \end{array}$$

Staes participating in weak interactions:

$$\begin{array}{ccc} e^- & \mu^- & \tau^- \\ \nu_e & \nu_\mu & \nu_\tau \end{array}$$

$W^\pm$

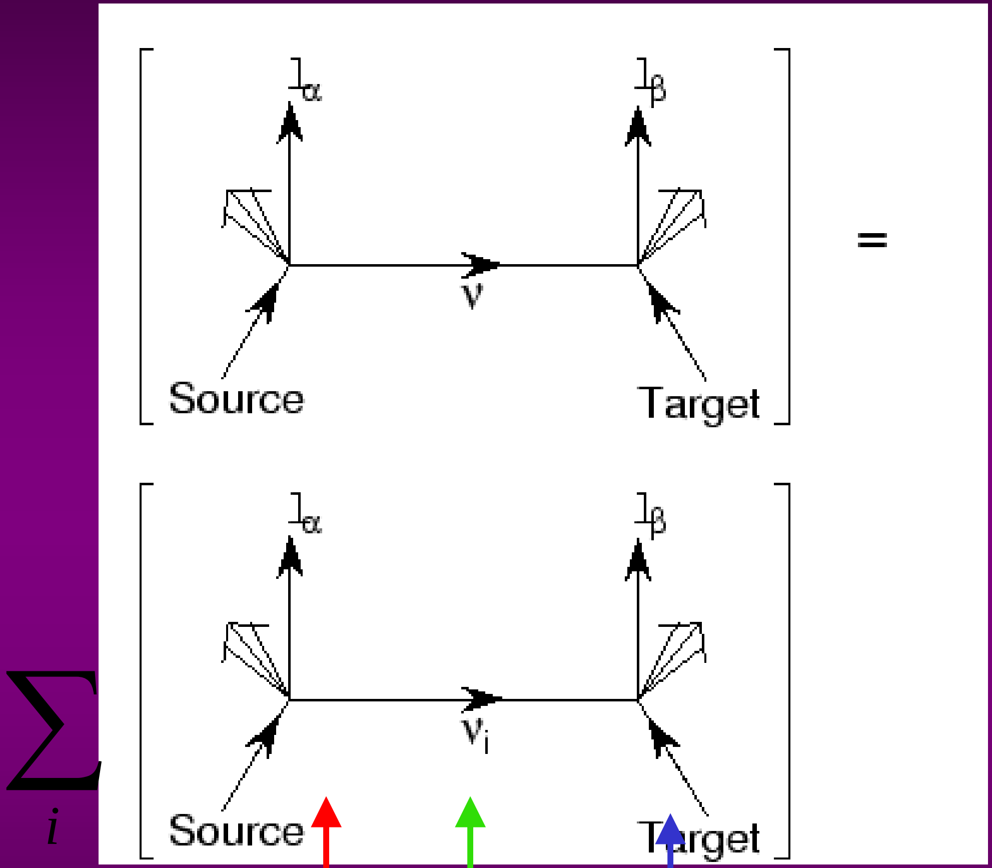
Lepton mixing:

$$\begin{bmatrix} \nu_e & \nu_\mu & \nu_\tau \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Describing ν propagation

Amplitude

Amplitude



$$A = \sum_i {\color{red}U^*_{\alpha i}}\, {\color{green}e^{-i\frac{m_i^2}{2E}L}}\, {\color{blue}U_{\beta i}}$$

Evidence of oscillations in atmospheric neutrinos

- Missing ν_μ,

  Effect observed in different event samples

  and also by other experiments

  Significance above 10 sigmas
- Angular distributions

  probability of ν_μ disappearance depends on its path-lenght and energy in a way consistent with oscillation
- ν_μ survival dependnce on L/E

  only oscillations can produce a dip

$$\nu_\mu \leftrightarrow \nu_\tau$$

- Oscillation parameters from comparison between data and MC simulations

$$0.0019 < \Delta m^2 < 0.0030 \text{ eV}^2$$

$$\sin^2 2\vartheta > 0.90 \quad \text{at 90\% c.l.}$$

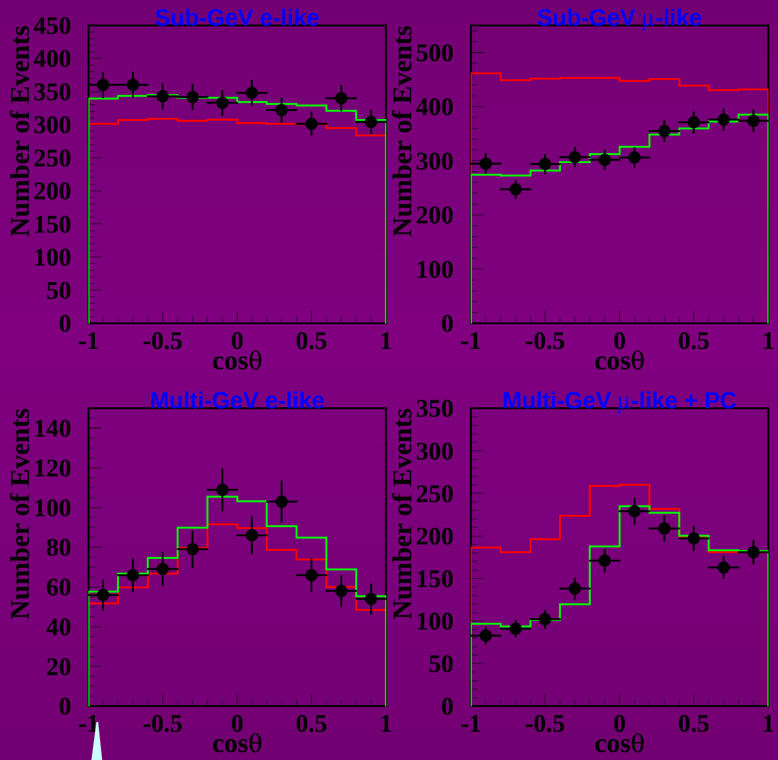
Zenith angle distributions

e-like
1 ring

μ-like
1 ring

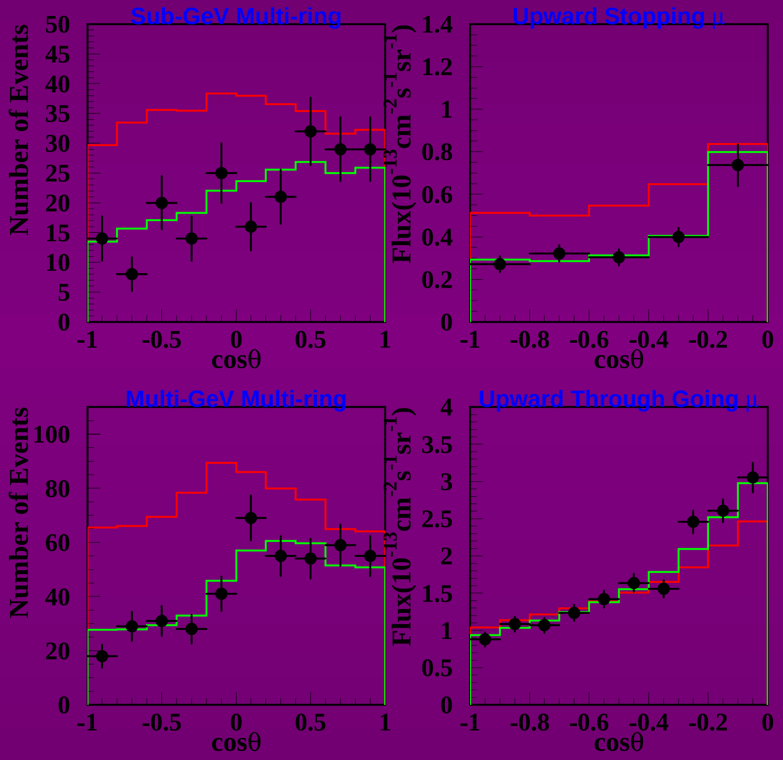
μ-like
multi- ring

upward going μ



Sub-GeV

Multi-GeV



up

down

1489 days – updated Nov 2003

Oscillation probability – 2 flavors

Probability of transition from a state α to a state β:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

where $\Delta m^2 = m_1^2 - m_2^2$

oscillation parameters

m – mass (in eV)
θ – mixing angle

experimental conditions:

E $_\nu$ – neutrino energy (in GeV)
L – distance from a neutrino source to detector (km)

Oscillation length:

$$\sin\left(\frac{1.27\Delta m^2 L}{E_\nu}\right) = \sin\left(\pi \frac{L}{L_{osc}}\right)$$

$$L_{osc} = \frac{2.5E_\nu}{\Delta m^2}$$

Appearance and disappearance experiments

$$\Delta m^2 = m_1^2 - m_2^2$$

In an appearance experiment one searches for neutrinos ν_β in an initial beam of ν_α :

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \, \sin^2\left(\frac{1.27 \Delta m^2 L}{E_\nu}\right)$$

In a disappearance experiment one counts how many of the initial neutrinos ν_α are left after passing a distance *L*:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{1.27 \Delta m^2 L}{E_\nu}\right)$$

Note: Neutrino oscillate only if masses are non-zero and not the same

$$\Delta m_{ij}^2 = 0 \Longrightarrow P(\nu_\alpha \to \nu_\beta) = 0$$

Sensitivity to oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

	E_ν (MeV)	L (m)	Δm^2
Supernovae	<100	$>10^{19}$	10^{-19} - 10^{-20}
Solar	<14	10^{11}	10^{-10}
Atmospheric	>100	10^4 - 10^7	10^{-4}
Reactor	<10	$<10^6$	10^{-5}
Accelerator with short baseline	>100	10^3	10^{-1}
Accelerator with long baseline	>100	$<10^6$	10^{-3}

Rough estimate of Δm^2

Oscillation length: $L_{osc} = \frac{2.5E_\nu}{\Delta m^2}$

E_ν – neutrino energy (inGeV)
L – distance (km)

Max probability of oscillation for $L=L_{osc}/2$
Find corresponding Δm^2

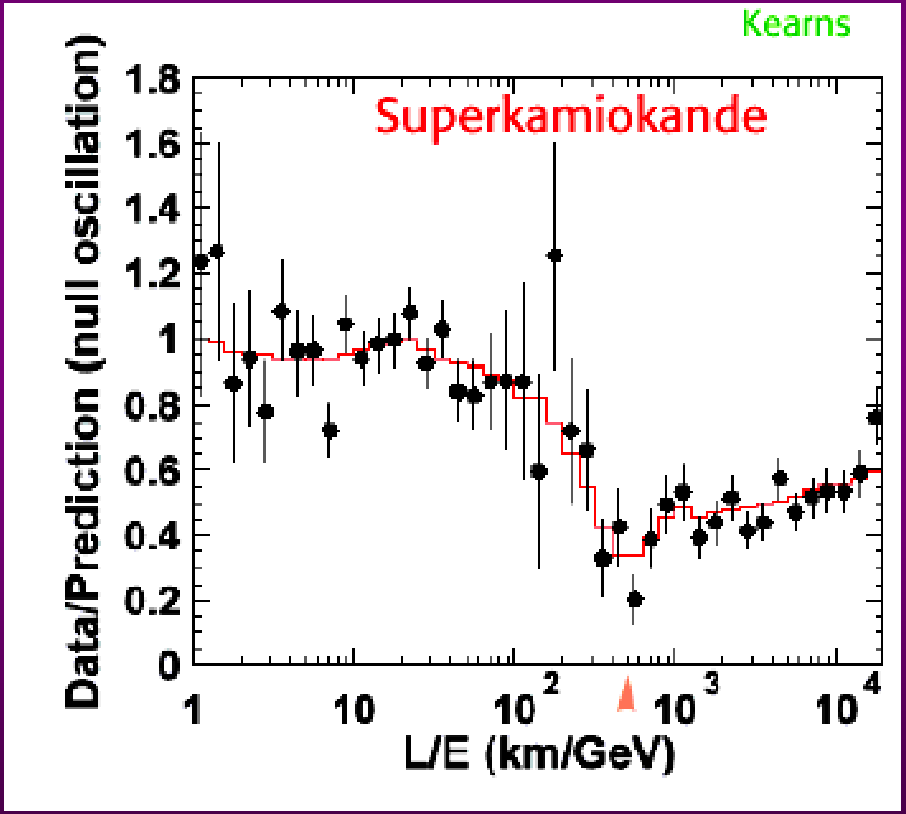
	Down, L=15 km	Up, L=12000 km
For E_ν=1 GeV	0.08 eV^2	$\approx 0.0001\ eV^2$
For E_ν=10 GeV	0.8 eV^2	$\approx 0.001\ eV^2$
For E_ν=100 GeV	8 eV^2	$\approx 0.01\ eV^2$

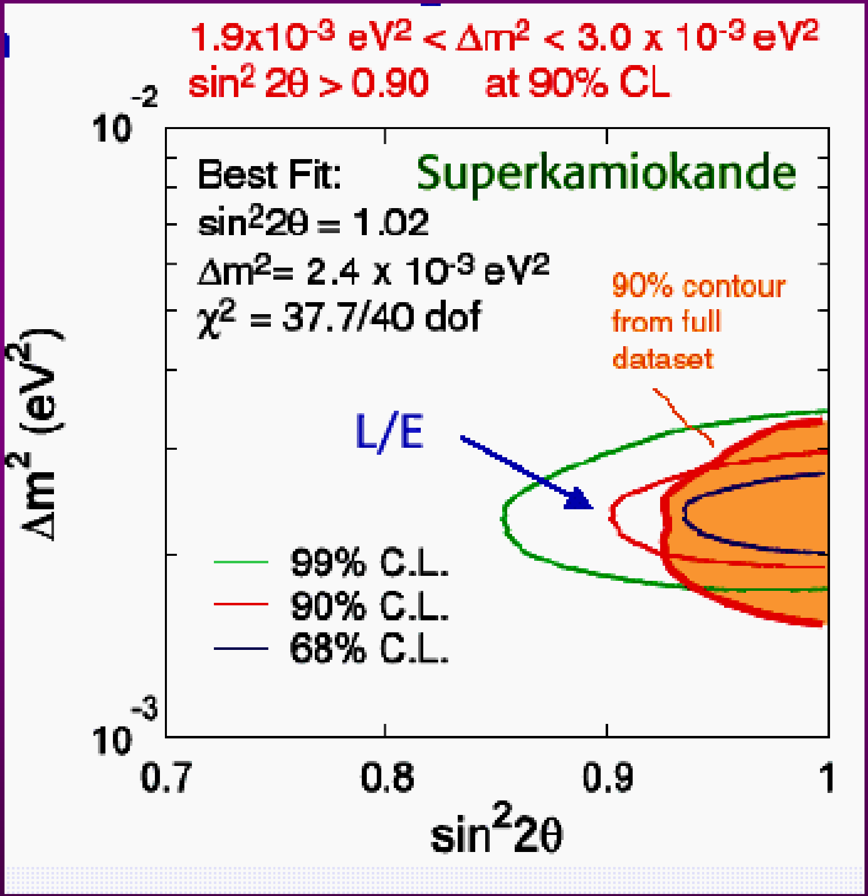
The trouble is - we don't know precisely E_ν

Atmospheric Neutrinos: SuperKamiokande –

(Neutrino04)

L/E distribution – direct oscillation signal

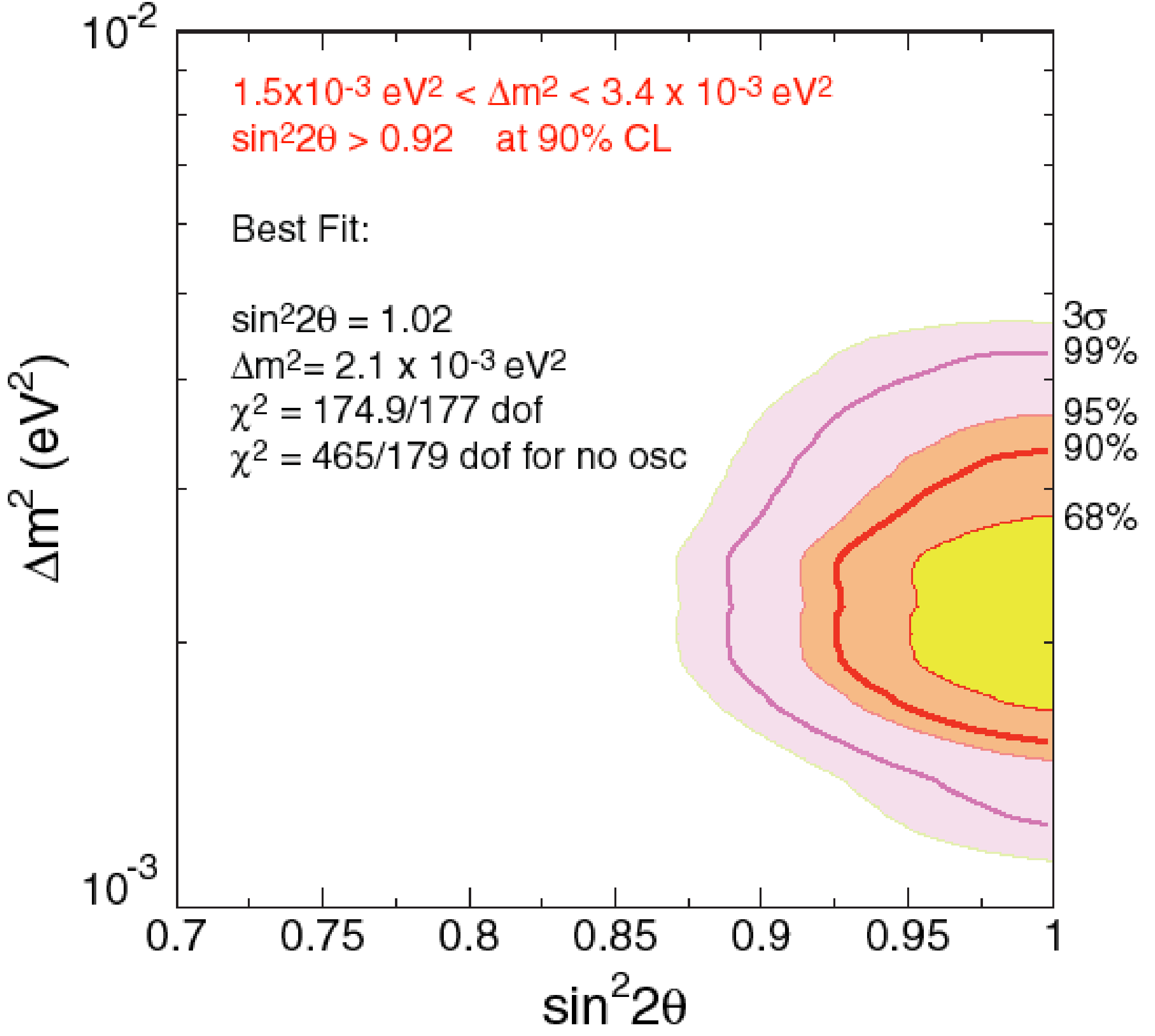




1.9×10^{-3} eV^2 < Δm^2 < 3.0×10^{-3} eV^2
$\sin^2 2\theta > 0.90$ at 90% CL

Best Fit:
$\sin^2 2\theta = 1.02$
$\Delta m^2 = 2.4\times10^{-3}$ eV^2
$\chi^2 = 37.7/40$ dof

Results of combined fit $\nu_\mu \leftrightarrow \nu_\tau$


$1.5\times10^{-3}\ \mathrm{eV}^2 < \Delta m^2 < 3.4\times10^{-3}\ \mathrm{eV}^2$

$\sin^2 2\theta > 0.92$ at 90% CL

Best Fit:

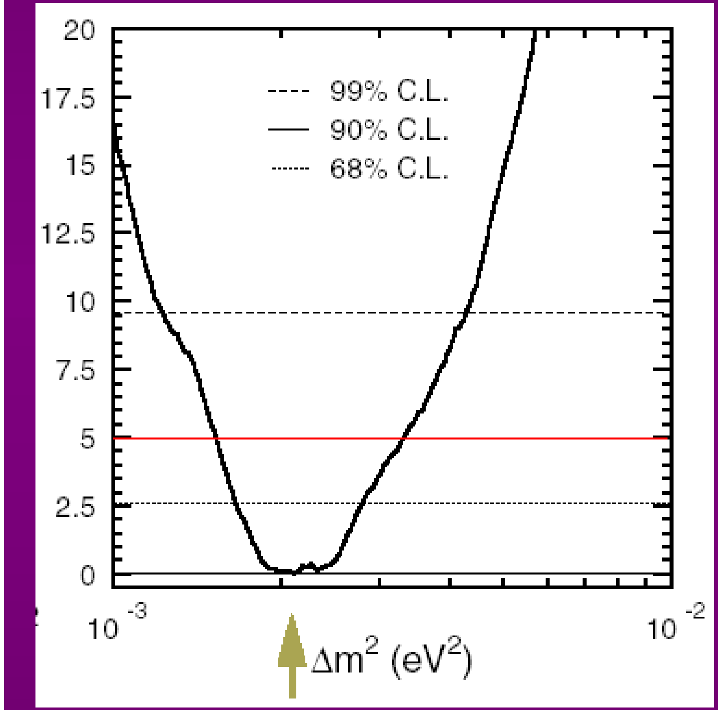
$\sin^2 2\theta = 1.02$

$\Delta m^2 = 2.1\times10^{-3}\ \mathrm{eV}^2$

$\chi^2 = 174.9/177$ dof

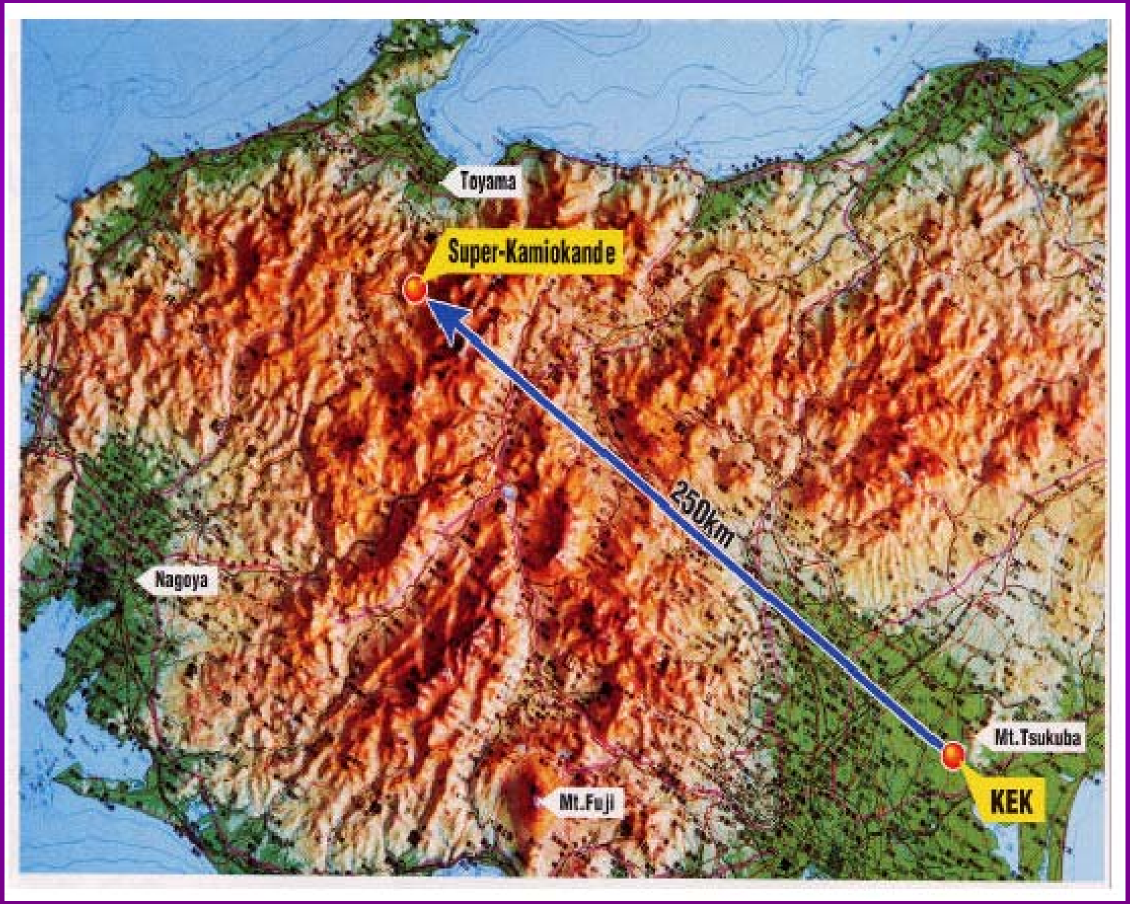
$\chi^2 = 465/179$ dof for no osc

χ^2 vs Δm^2



flat between
0.0019 and 0.0025

K2K - KEK to Kamioka Neutrino Oscillation Experiment



- ν_μ (99%) beam
- $<E_\nu> \sim$ **1.3GeV**
- **Near detector**

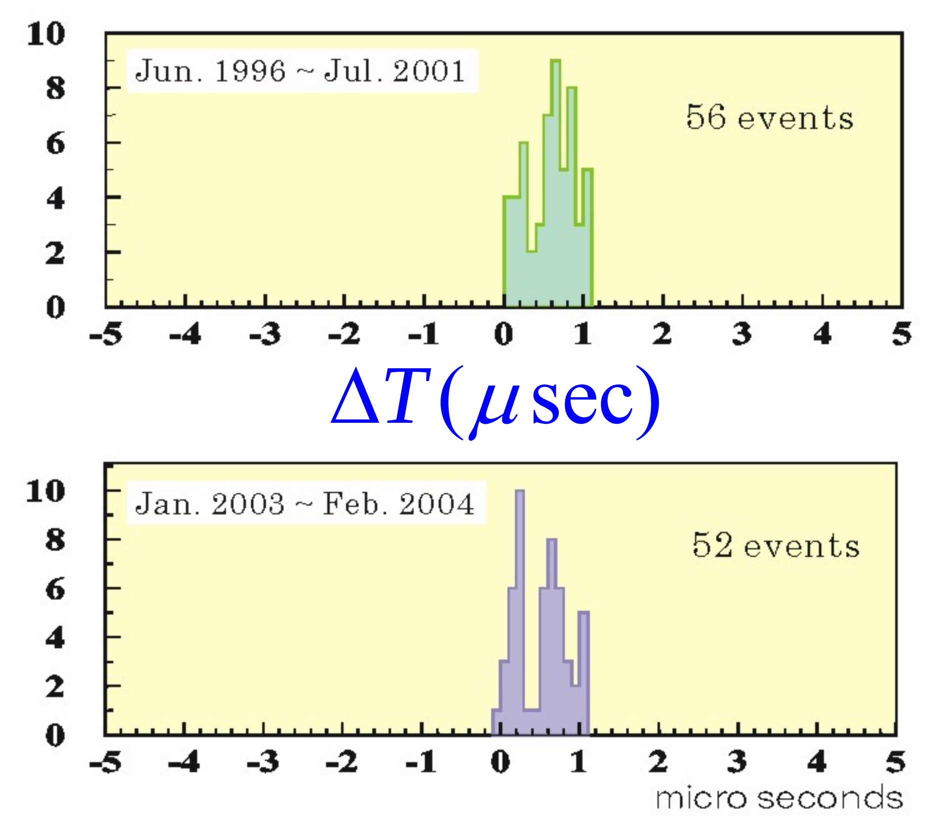
  @300m
- **Far detector**:

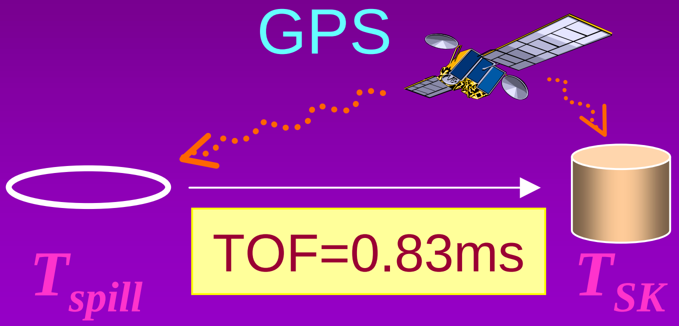
  Super Kamiokande(SK)

  @**250km**
- Sensitive for

  $\Delta m^2 > 2x10^{-3}$ eV^2

Event selection at Super-Kamiokande




GPS

T_{spill}

TOF=0.83ms

T_{SK}

$$\Delta T \equiv T_{SK} - T_{spill} - \mathrm{TOF}$$

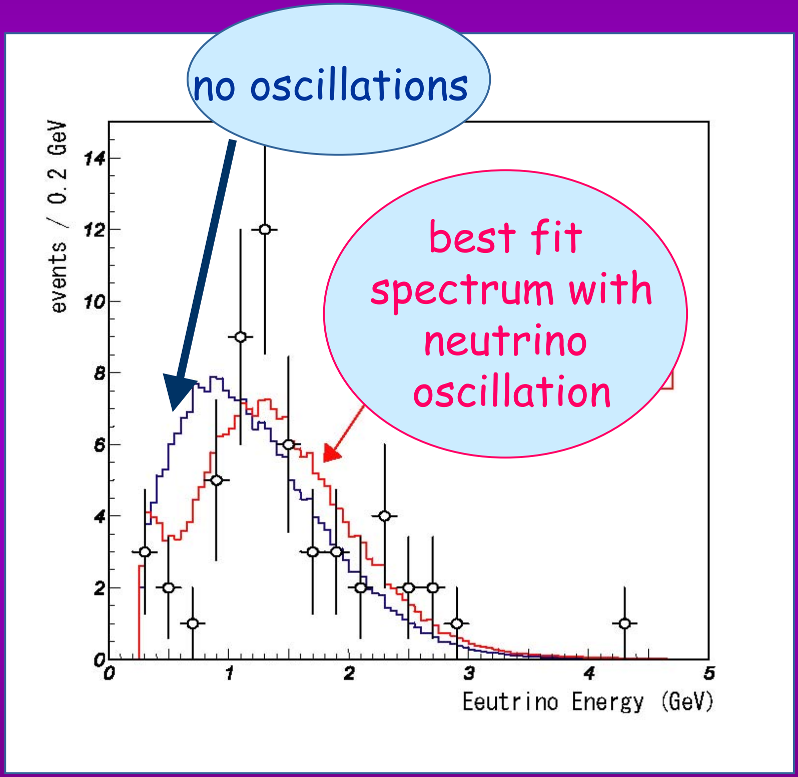
requiring

$$-0.2 \le \Delta T \le 1.3\mu s$$

Expected number of atmospheric ν BG:

$<10^{-3}$ events

Observation of ν_μ oscillation in K2K
b) energy spectrum modulation

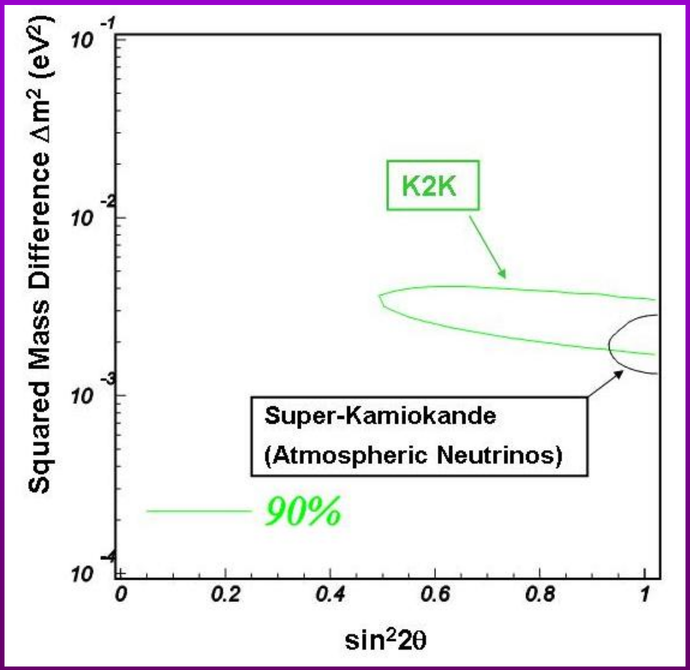


no oscillations

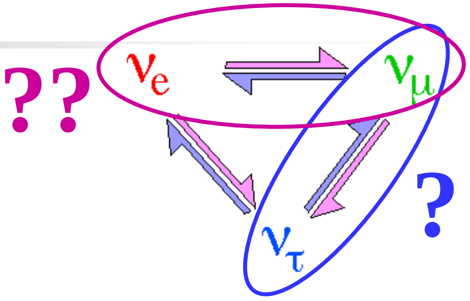
best fit spectrum with neutrino oscillation

A combination of oberved:
- event deficit
- spectrum

→ 4σ effect



Discover the source of the atmospheric ν_μ "deficit"



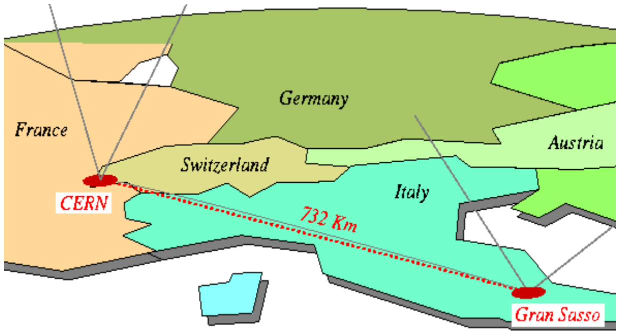
$\nu_\mu \rightarrow \nu_\tau$ oscillations?

The proof: "appearance" of ν_τ in a ν_μ beam

ν_μ ………….. ν_τ

High energy, **long** baseline ν beam

($E_{CM} >> m_\tau$ $L \sim 1000$ km)



Detection of τ leptons

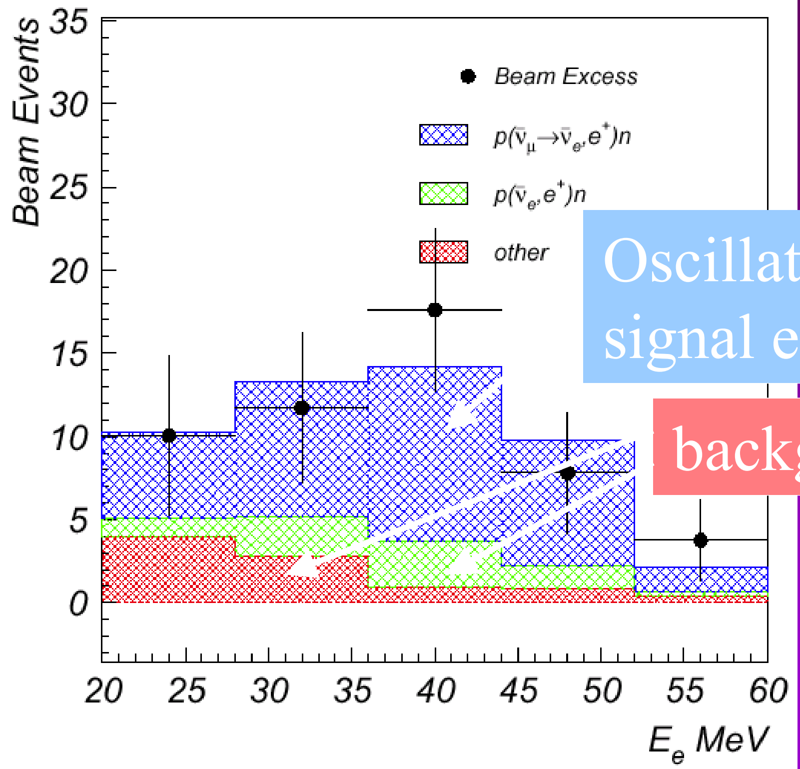
Sensitivity to $\Delta m^2 = 1.9–3.0 \times 10^{-3}$ eV^2

High background rejection and $M_{target} = O(1 \text{ kton})$

As by product sensitivity to $\nu_\mu \rightarrow \nu_e$ is also there

(limited by statistics and ν_e beam contamination)

LSND and KARMEN search for $\overline{\nu}_\mu \to \overline{\nu}_e$



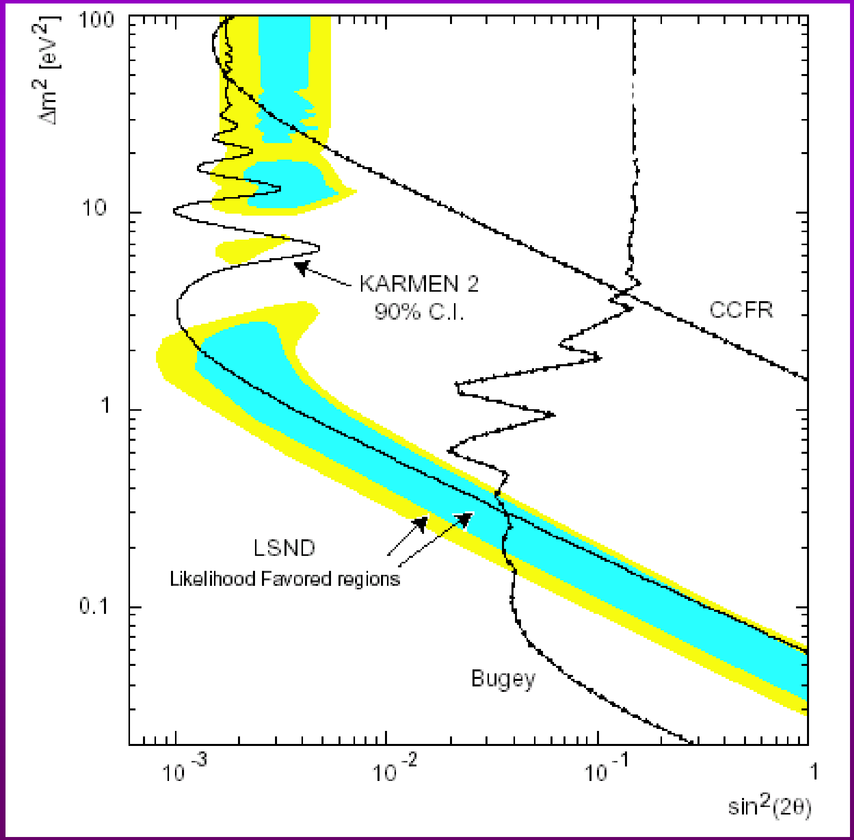
Oscillation signal expectation

backgrounds

Source is μ^+ decay at rest
endpoint energy 53 MeV

LSND
Signal above background:
87.9±22.4±6.0 events
Oscillation Probability:
(0.264±0.067±0.045)%

KARMEN 2
Excludes part of LSND region
Observes signal consistent with
Expected background



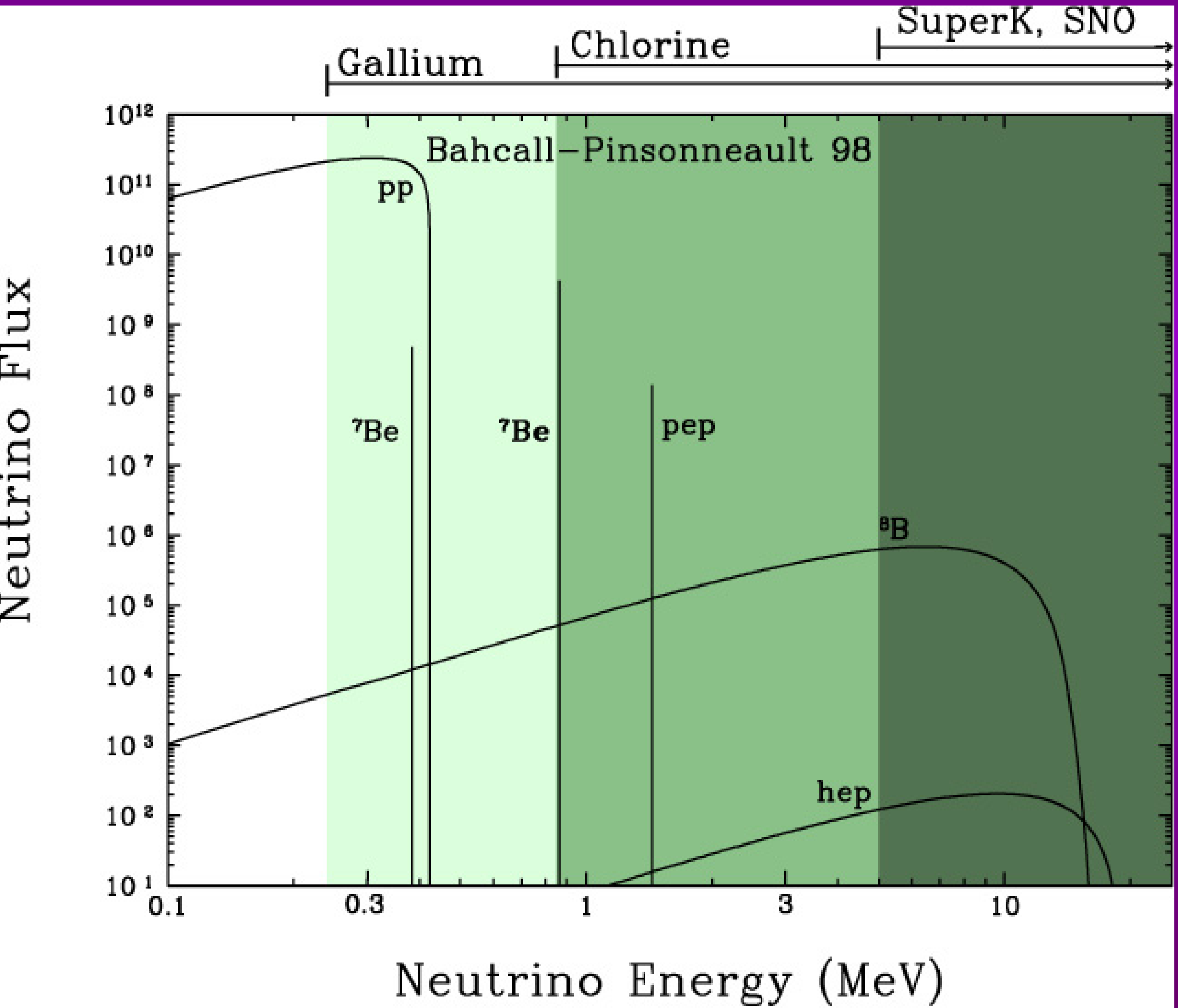
Experiments with ν from accelerators

name	accelerator	det. technique	distance	mass
K2K	KEK	water Cherenkov	250 km	50kt
MiniBoone	Fermilab	liquid scintillator	0.5 km	
MINOS	Fermilab (NuMi)	iron/scintillator	750 km	4.5kt
Icarus	CERN	liquid argon TPC	730 km	3 kt
Opera	CERN	lead/emulsion	730 km	2 kt

longer term future:

JHF to SuperKamiokande			300 km	500kTon

Spectrum of solar neutrinos



<u>radiochemical (Gallium & Chlorine):</u>

- low energy threshold
- only events are counted

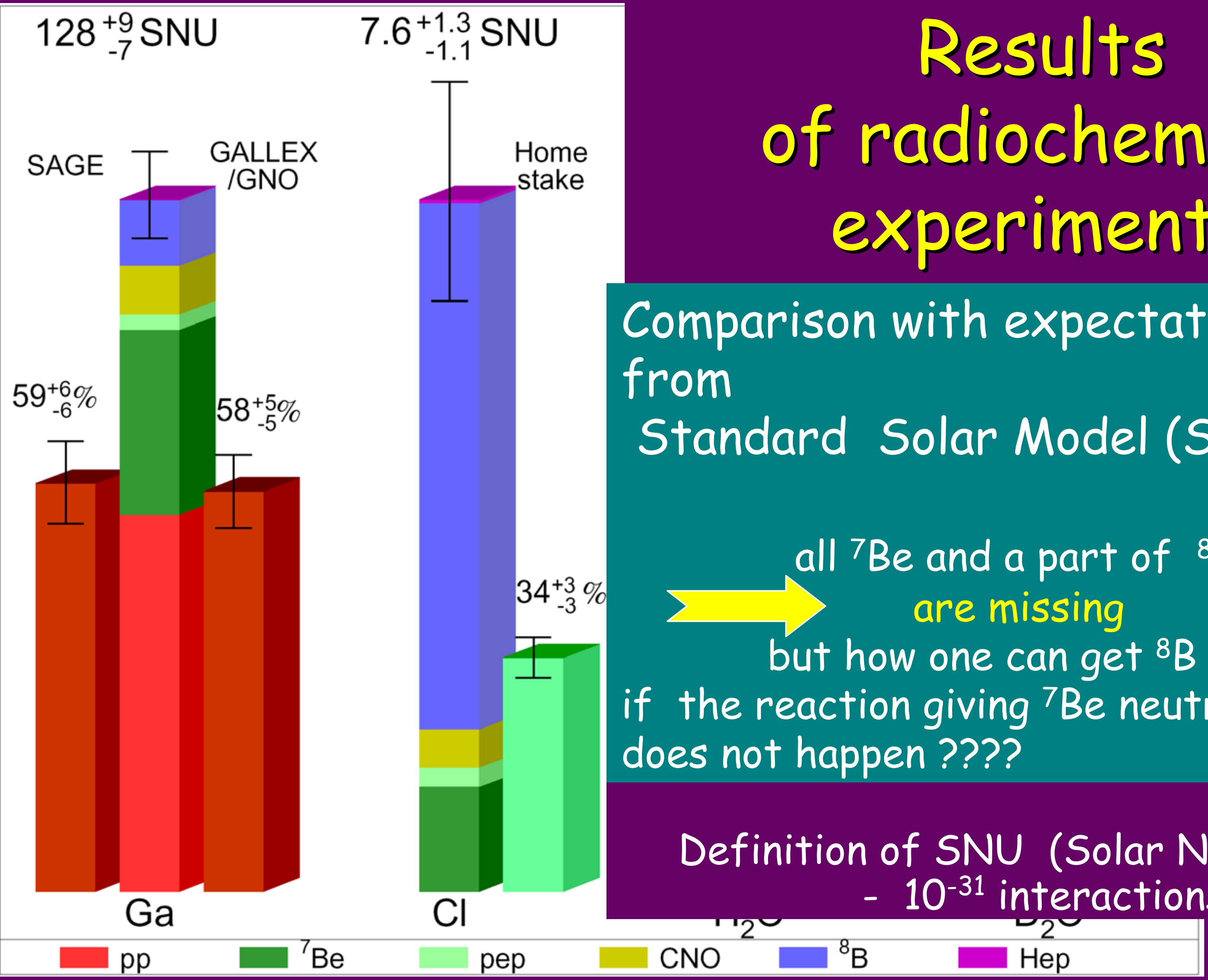
<u>Cherenkov detectors (SuperKamiokande, SNO)</u>

- higher energy threshold
- for every event:
  time, direction, energy

Solar neutrino detectors

name	location	mass	reaction	start
Homestake	S.Dakota USA	615	$^{37}Cl(\nu_e,e^-)^{37}Ar$	1968
SAGE	Baksan, Russia	50	$^{71}Ga\ (\nu_e,e^-)^{71}Ge$	1990
Galex/GNO	Gran Sasso, Italy	30	$^{71}Ga\ (\nu_e,e^-)^{71}Ge$	1992
Kamiokande	Kamioka, Japan	2000	$\nu_x e^- \rightarrow \nu_x e^-$	1986
Super Kamiokande	Kamioka, Japan	50000	$\nu_x e^- \rightarrow \nu_x e^-$	1996
SNO	Sudbury, Canada	8000	$\nu_e d \rightarrow e^-\ pp$	1999
			$\nu_x d \rightarrow \nu_x\ np$	2001
			$\nu_x e^- \rightarrow \nu_x e^-$	1999

Results of radiochemical experiments



Comparison with expectatations from Standard Solar Model (SSM):

all ^{7}Be and a part of ^{8}B neutrinos are missing

but how one can get ^{8}B neutrinos if the reaction giving ^{7}Be neutrinos does not happen ????

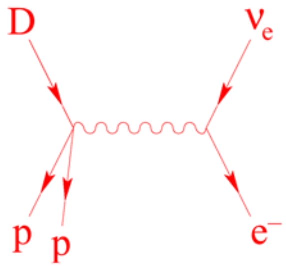
Definition of SNU (Solar Neutrino Unit) - 10^{-31} interactions/atom/sec

Solar ν Interactions in SNO

Elastic Scattering (ES) $\quad \boldsymbol{\nu_x + e^- \rightarrow \nu_x + e^-}$

- Directional sensitivity (e^- forward peaked)
- Cross-section for ν_e is $6.5\times$ larger than for $\nu_{\mu\tau}$

Charged Current (CC) $\quad \boldsymbol{\nu_e + d \rightarrow p + p + e^-}$



- Some directional information $(1 - \frac{1}{3}\cos\theta_{e\nu})$
- good E_ν sensitivity (ν_e spectrum)

Neutral Current (NC) $\quad \boldsymbol{\nu_x + d \rightarrow n + p + \nu_x}$

- Total flux of active neutrinos above 2.2 MeV
- Detect neutrons by $n + d \rightarrow t + 6.25$ MeV γ

Solar neutrino flux measured in SNO

(phase 1)

SNO ϕ_{CC} = 1.76±0.11

SK ϕ_{ES} = 2.32±0.09

[x10⁶/cm²/s]

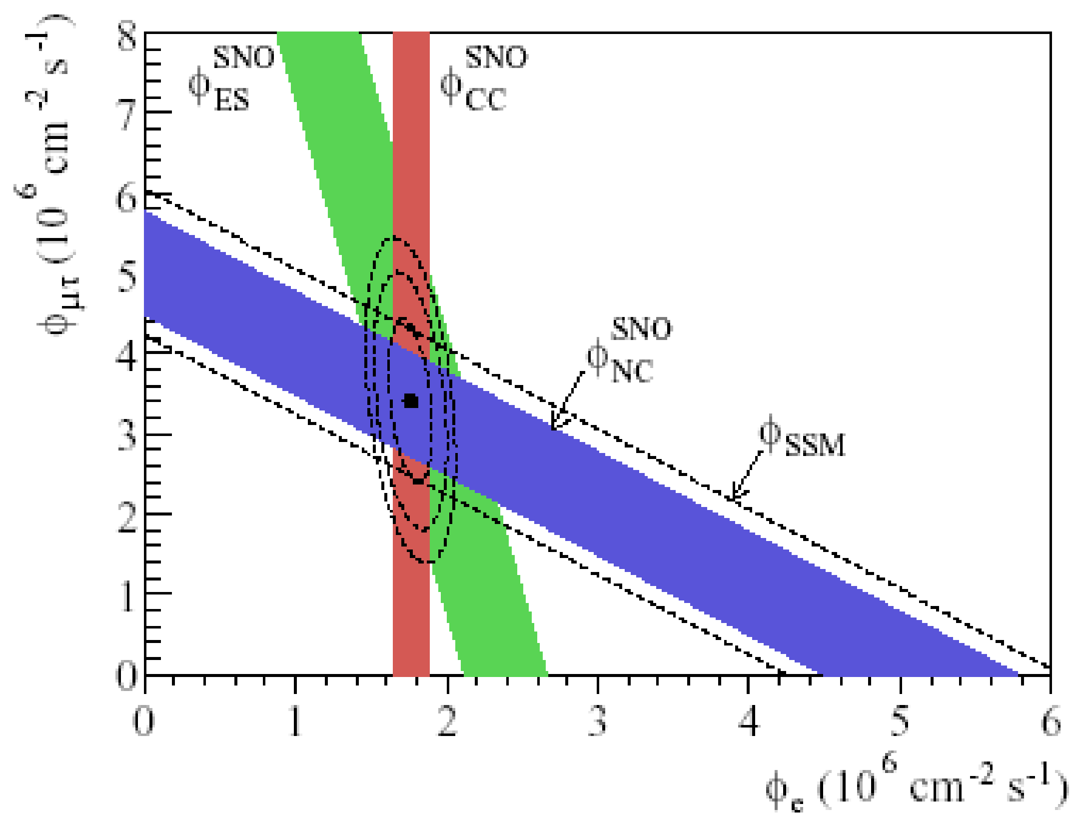
$\phi_{CC} = \phi_e$

$\phi_{ES} = \phi_e + 0.154\,\phi_{\mu,\tau}$

$\phi_{\mu,\tau}$ = 3.45±0.65

$\phi_X = \phi_{NC}$ = 5.21±0.66 (total flux of ^{8}B neutrinos)

(ϕ_{SSM} = 5.05+1.01/-0.81)

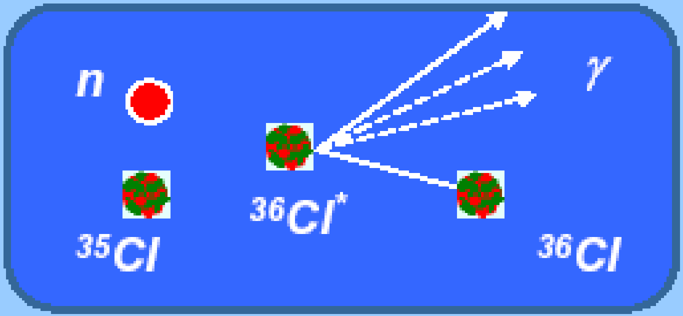


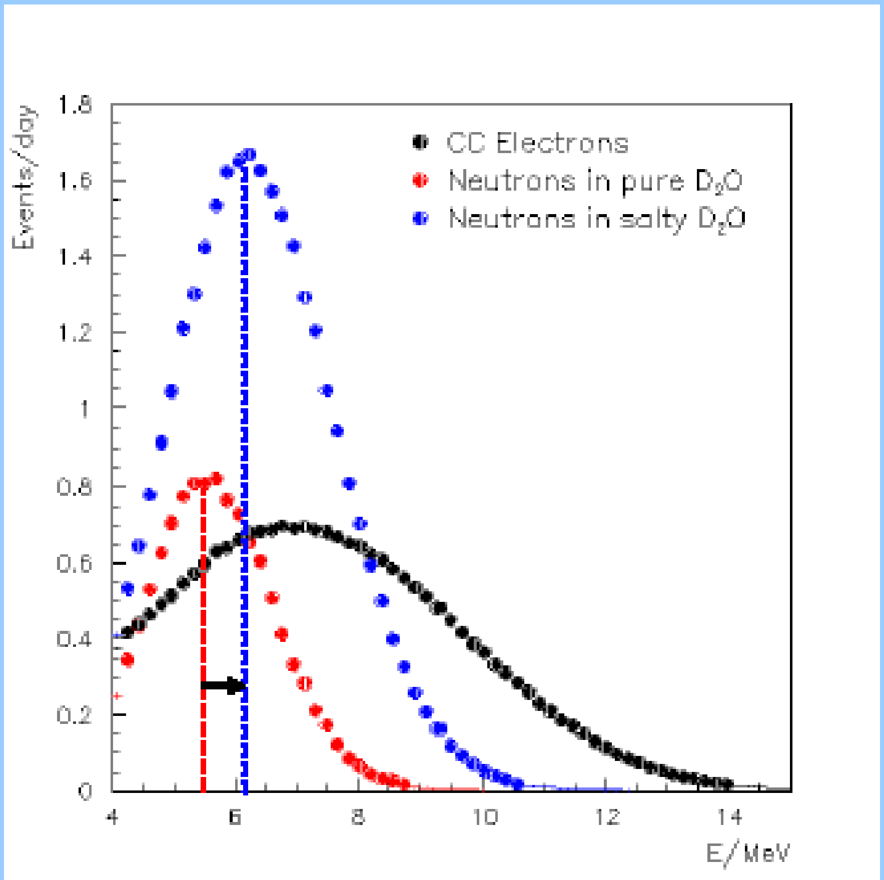
Proof, that the neutrinos oscillate:

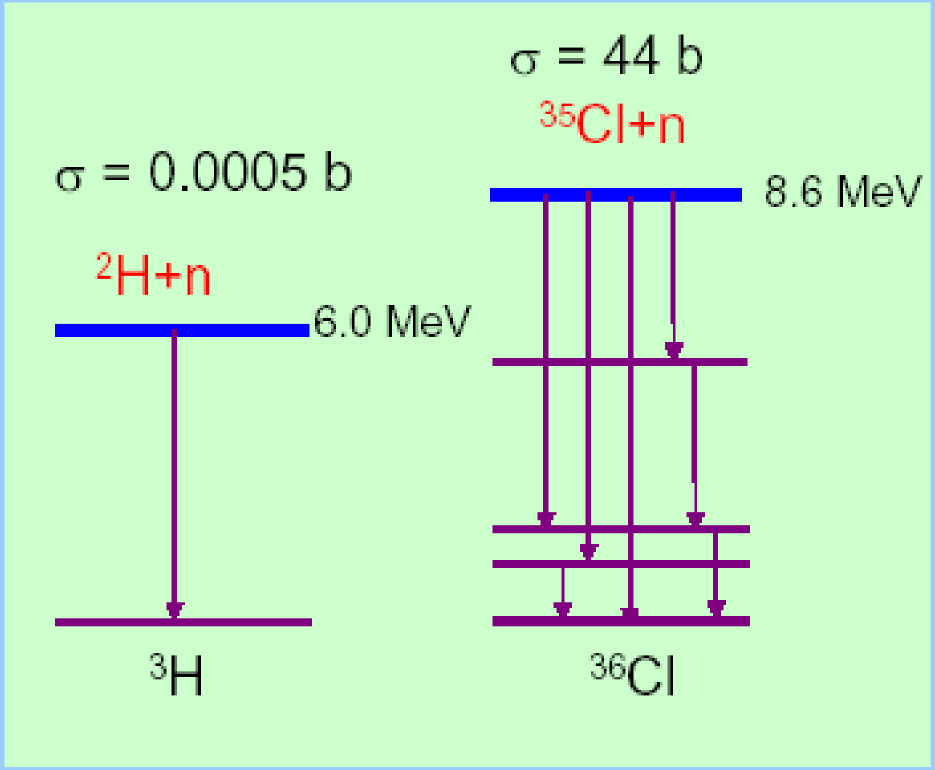
$$\nu_e \rightarrow \nu_{\mu/\tau}$$

Neutrons in Salt → NaCl Capture

- Higher capture cross section
- Higher energy release
- Many gammas







Comparison with phase I

3055 candidate events
254 live days

⇨

#EVENTS

CC	$1339.6^{+63.8}_{+61.5}$
ES	$170.3^{+23.9}_{+20.1}$
NC	$1344.2^{+69.8}_{+69.0}$

84 external-source neutrons

$$\Phi_{SSM} = 5.05^{+1.01}_{-0.81}$$

^{8}B shape constrained

Pure D_2O (phase I)

$$\Phi_{CC}^{I-cons.} = 1.76^{+0.06}_{-0.05}(stat.)^{+0.09}_{-0.09}(syst.)$$

$$\Phi_{ES}^{I-cons.} = 2.39^{+0.24}_{-0.23}(stat.)^{+0.12}_{-0.12}(syst.)$$

$$\Phi_{NC}^{I-cons.} = 5.09^{+0.44}_{-0.43}(stat.)^{+0.46}_{-0.43}(syst.)$$

Salt (phase II)

$$\Phi_{CC}^{II-cons.} = 1.70 \pm 0.07(stat.)^{+0.09}_{-0.10}(syst.)$$

$$\Phi_{ES}^{II-cons.} = 2.13^{+0.29}_{-0.28}(stat.)^{+0.15}_{-0.08}(syst.)$$

$$\Phi_{NC}^{II-cons.} = 4.90 \pm 0.24(stat.)^{+0.29}_{-0.27}(syst.)$$

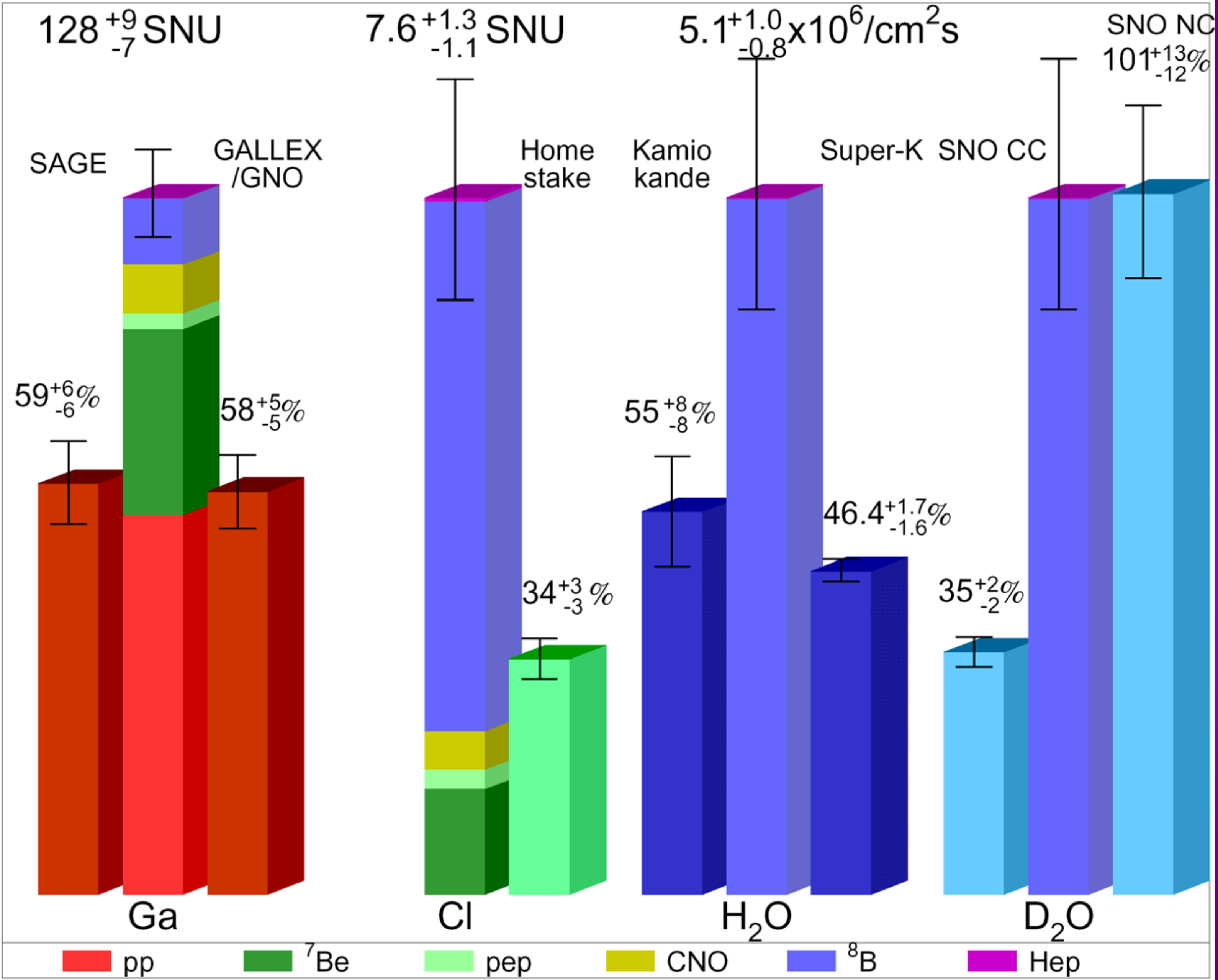
The measurement from phase I
were confirmed with better precisi

- evidence for $\nu_{\mu/\tau}$ appearance in their flightfrom the Sun
- the total neutrino flux (all flavor

Φ_{NC} agrees with SSM

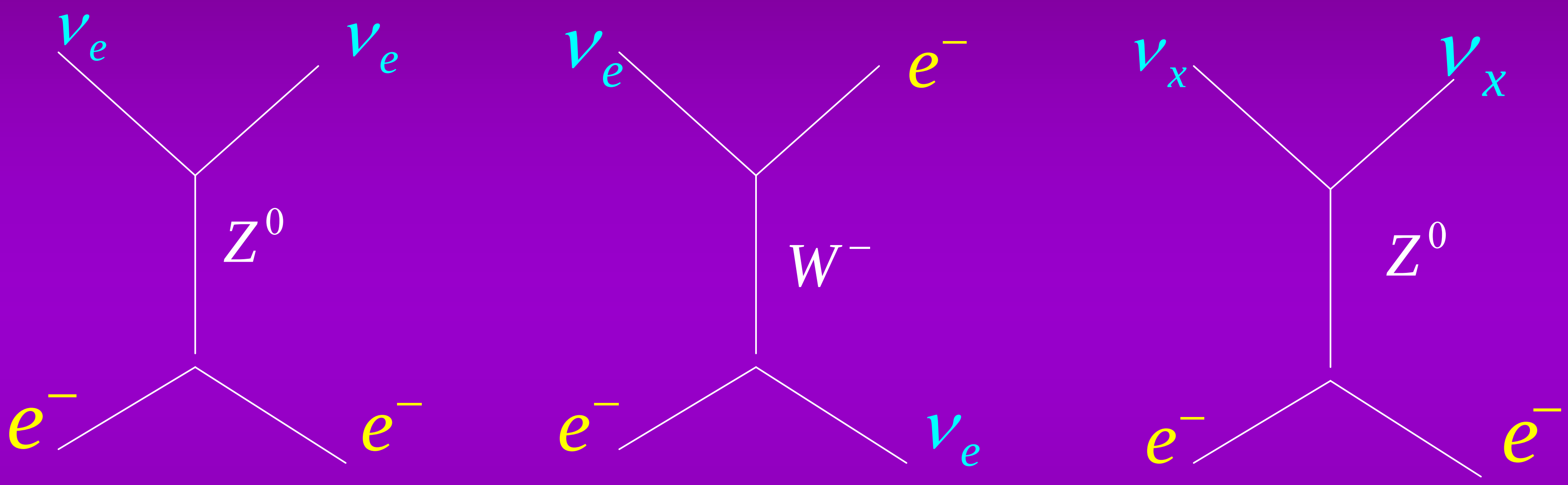
$$\Phi_{NC}^{II-unc.} = 5.21 \pm 0.27(stat.) \pm 0.38(syst.)$$

Results of all the solar experiments



MSW Effect

If ν_e and ν_x have different interactions:



$$\Delta V = \sqrt{2}\, G_F\, \rho(x)$$

weak coupling constant

local electron density

MSW effect

One can define effective (matter) mixing angle and mass difference :

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\underbrace{\left(\frac{2\sqrt{2}G_F \rho E_\nu}{\delta m^2} - \cos 2\theta\right)}_{\text{resonant condition if =0}}^2 + \sin^2 2\theta}$$

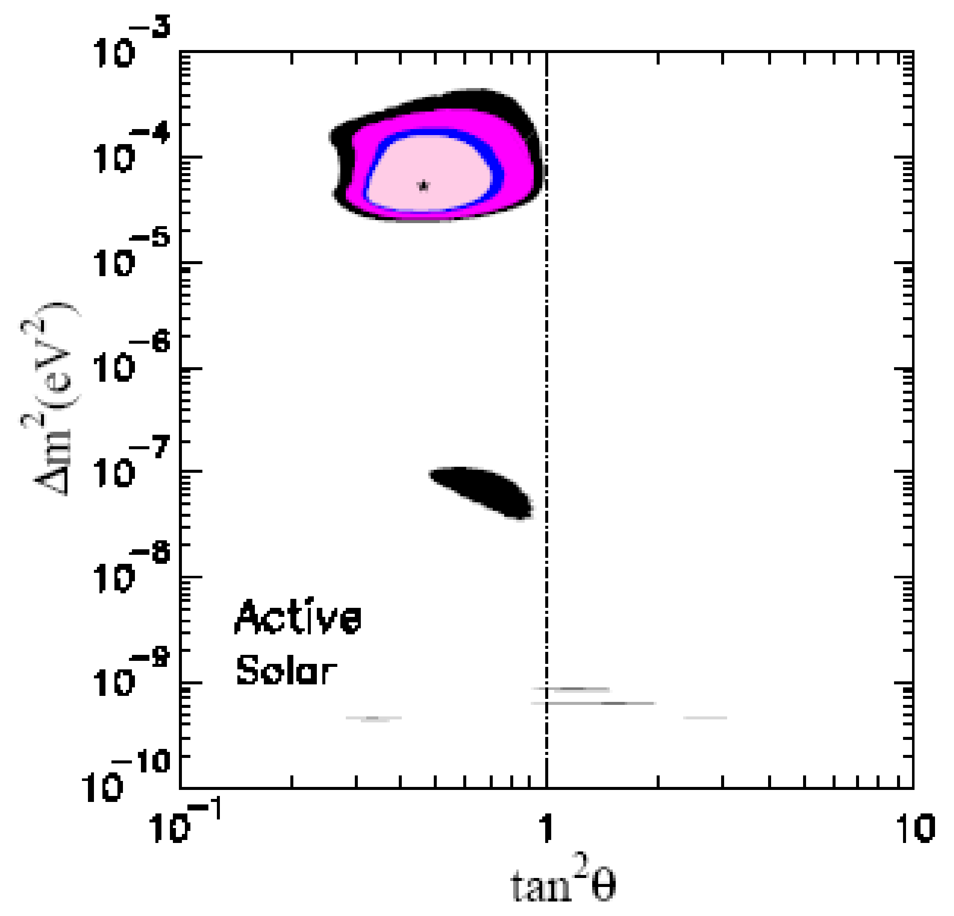
$$\Delta M^2 = \delta m^2 \sqrt{\left(\frac{2\sqrt{2}G_F \rho E_\nu}{\delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$

- Effective mixing θ_m may be large even if θ small
- At resonance effective ΔM much smaller than δm
- A neutrino passing through various local densities ρ can easily get into a resonant condition

Note that matter effects are sensitive to:

$$\vartheta' \to \frac{\pi}{2} - \vartheta$$

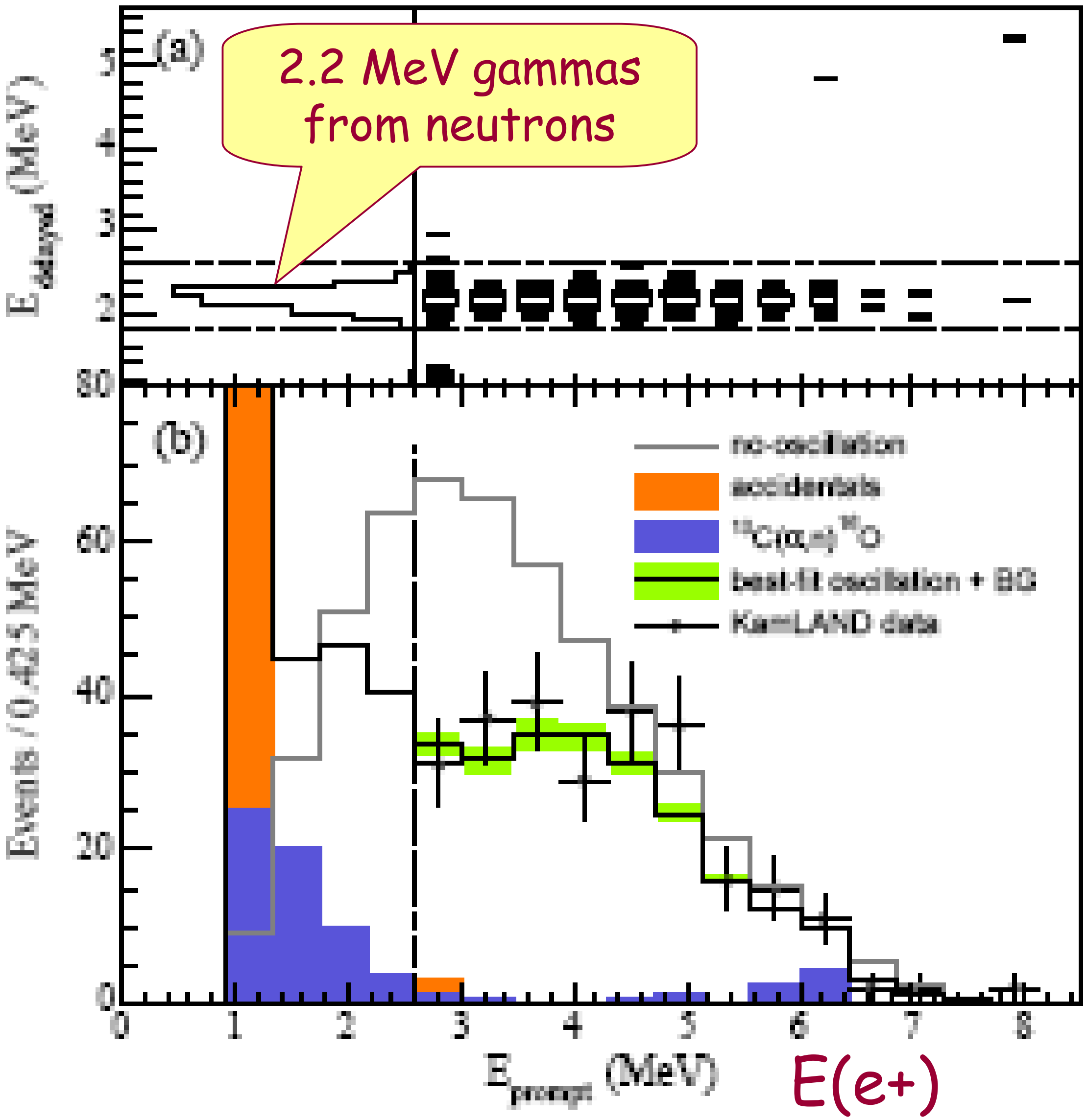
Oscillation parameters of solar ν with SNO results



Only so called
LMA
(large mixing angle)
solution remained
with SNO results

Bahcall, Gonzales-Garcia and Pena-Garay, hep-ph/0212147

KamLAND - results



2.2 MeV gammas from neutrons

E(e+)

hep-ex/0406035

E_{prompt}>2.6 MeV:

Data: 258

Expected: 365.2+-23.7

Background: 17.8+-7.3

mainly:

$^{13}C(\alpha,n)^{16}O^*$

α from ^{210}Po (from Rn)

Deficit of events and spectrum modification:

99.998%

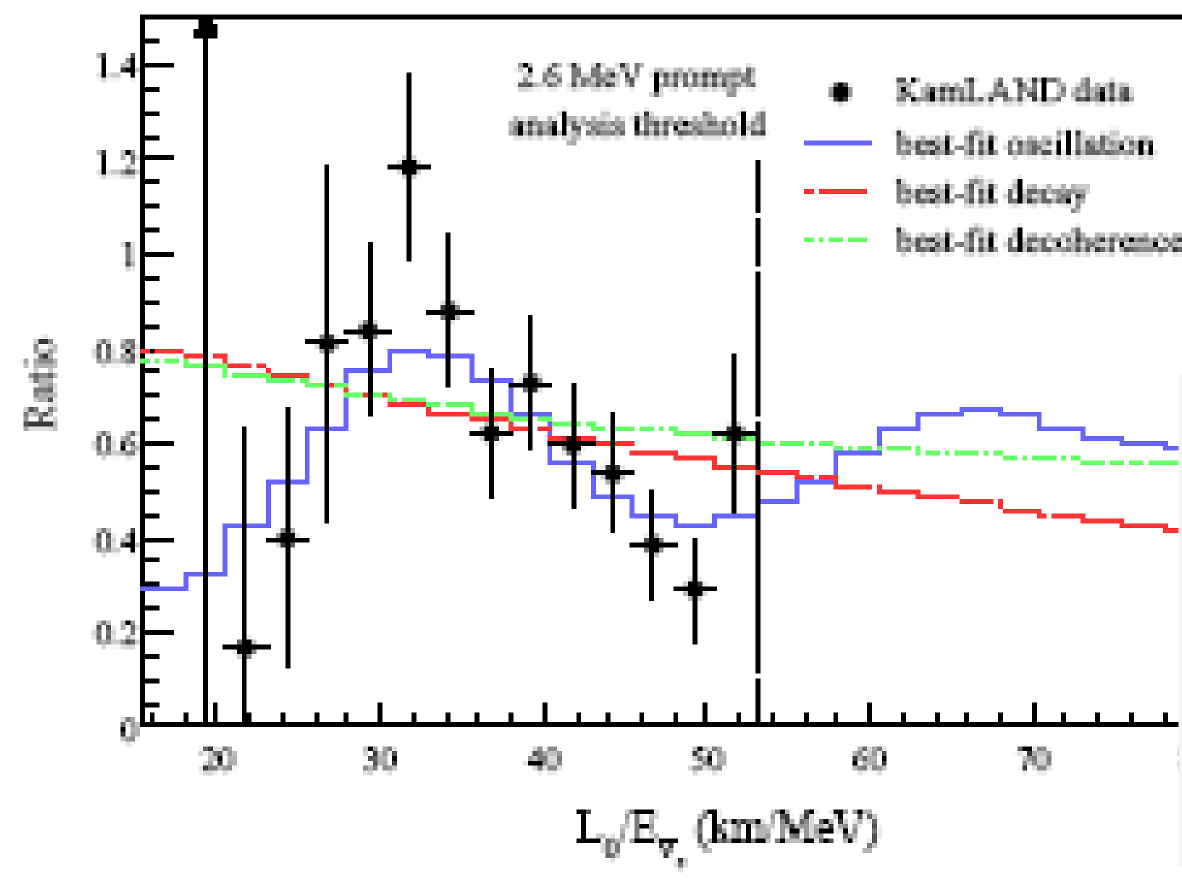
disappearance of $\bar{\nu}_e$

KamLAND – evidence of spectral distortion

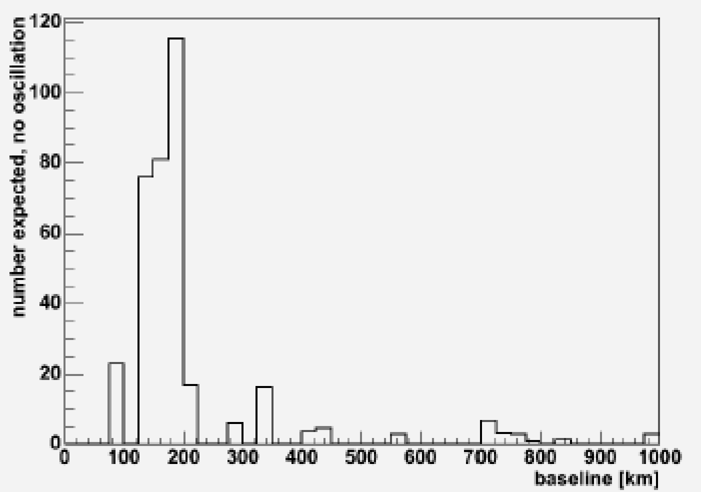
hep-ex/0406035

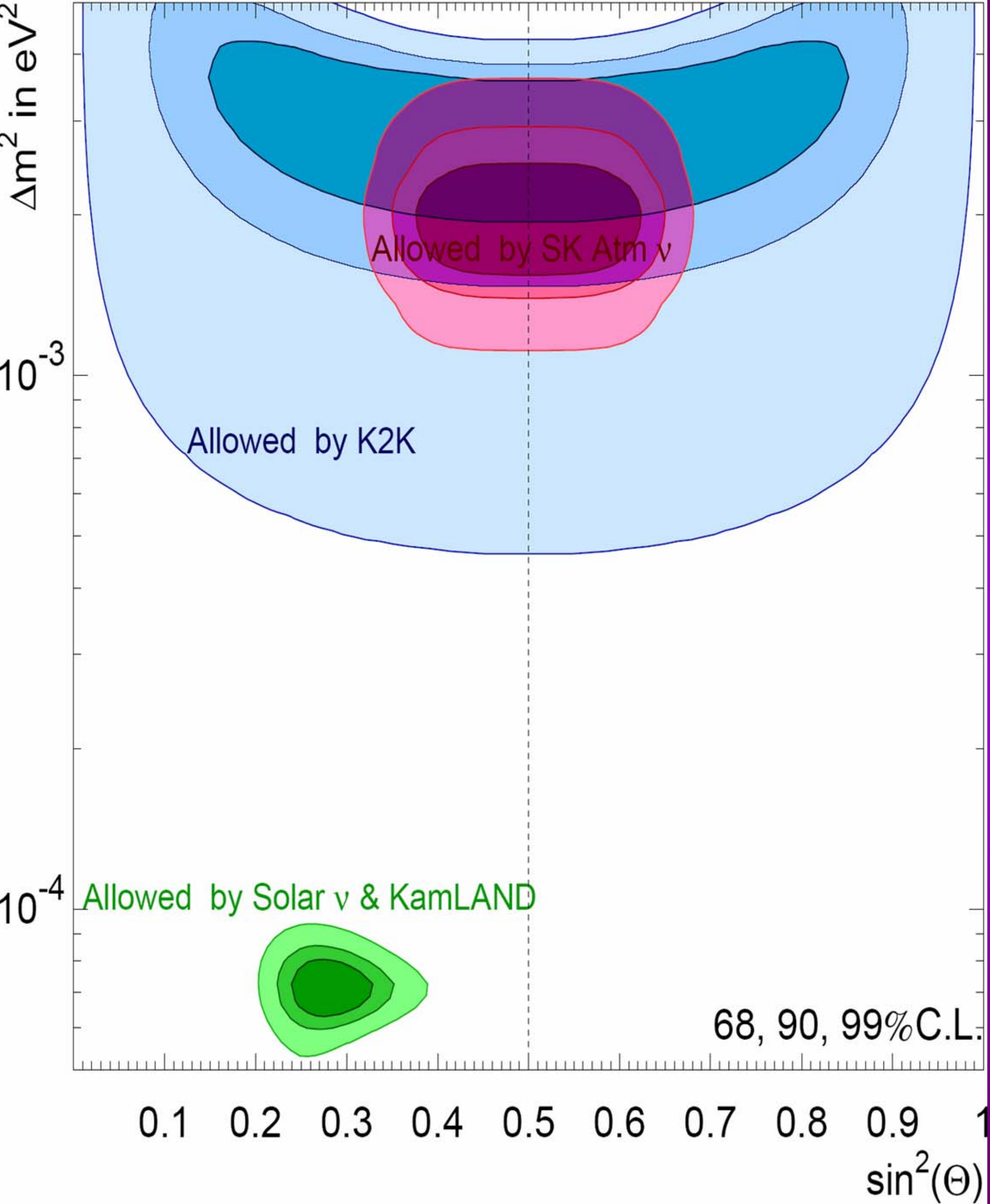
ratio= observed/expected

assuming a single reactor at L_o= 180km



Distances
reactor – Kamioka mine





Atmospheric neutrinos

$$0.0019\,\mathrm{eV}^2 < \Delta m^2_{atm} < 0.003\,\mathrm{eV}^2$$

maximal mixing

Solar neutrinos and Kamland

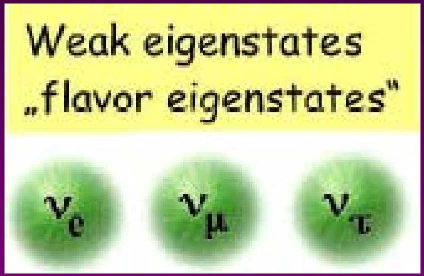
$$0.00005\,\mathrm{eV}^2 < \delta m^2_{solar} < 0.00008\,\mathrm{eV}^2$$

but max mixing (1,2) excluded

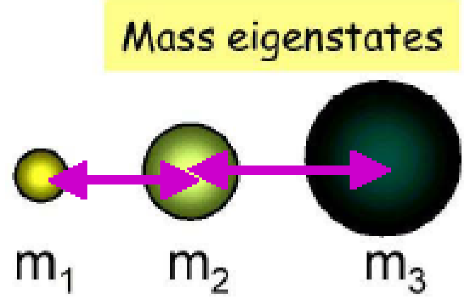
On plots like that the mixing angle means:

ϑ_{12}	for solar neutrinos
ϑ_{23}	for atmosph. neutrinos

Mixing matrix



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



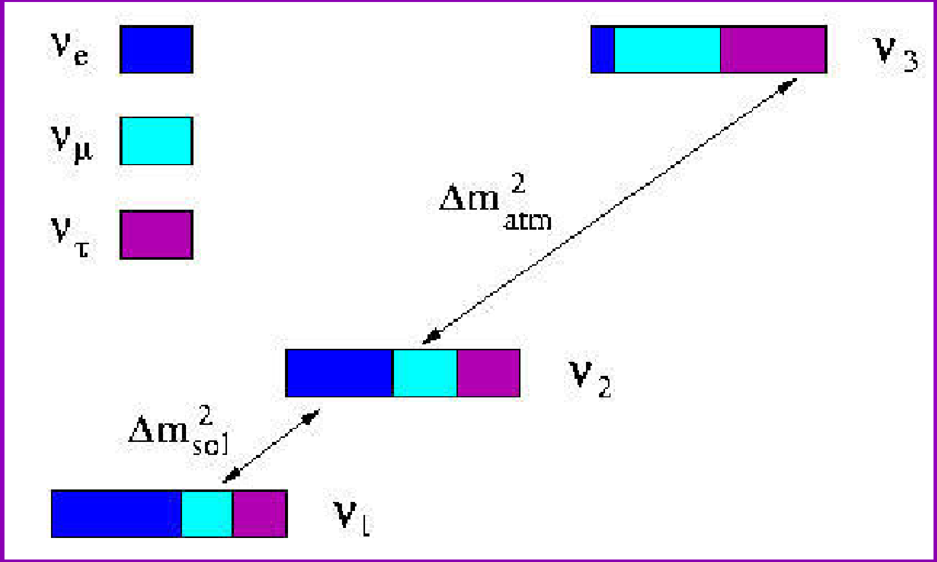
$$\underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}\underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}}$$

mixing angle	**$\theta_{12} \sim 45^o$ large**	**$\theta_{23} \sim 45^o$ large**	**θ_{13} ~ small**
Oscil. frequency	**$1.27\Delta m_{12}^2 L/E$**	**$1.27\Delta m_{23}^2 L/E$**	**$1.27\Delta m_{13}^2 L/E$**
	Solar neutrinos	**Atm. neutrinos**	

+ unknown phase (or two)

Summary – Evidence for neutrino oscillations

- Neutrino eigenstates with definite flavor are mixtures of states of definite mass.



- This results in neutrino oscillations measured in 2 sectors:
  - ❖ atmospheric

$$\nu_\mu \to \nu_\tau \qquad \Delta m^2_{23} \approx 0.002\, eV^2$$

  - ❖ solar

$$\nu_e \to \nu_{\mu/\tau} \qquad \Delta m^2_{12} \approx 0.00006\, eV^2$$

Sources of neutrinos for future studies:

- Beta beams
- Super beams
- Neutrino factories

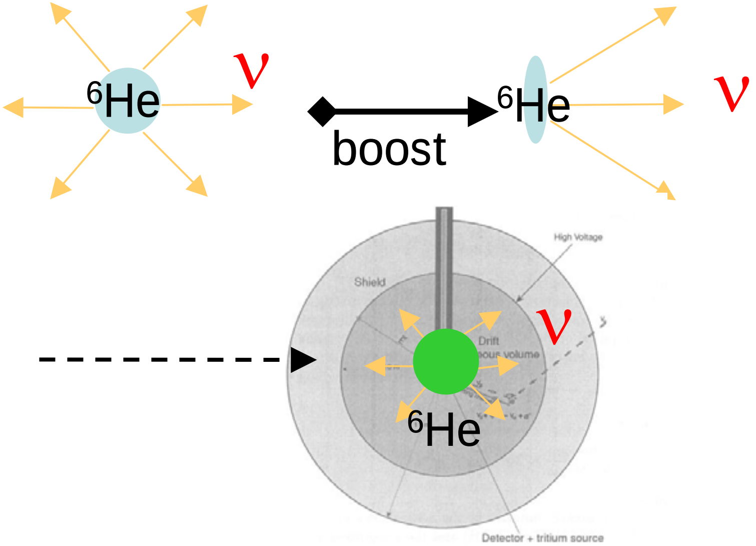
Beta-beams - concept

THE PROPOSAL

To exploit the beta-beam concept to produce intense and pure low energy (10-100 MeV) neutrino beams.

PHYSICS POTENTIAL

- Neutrino-nucleus interaction studies.
- Neutrino properties,
  like the ν magnetic moment.
- . . .

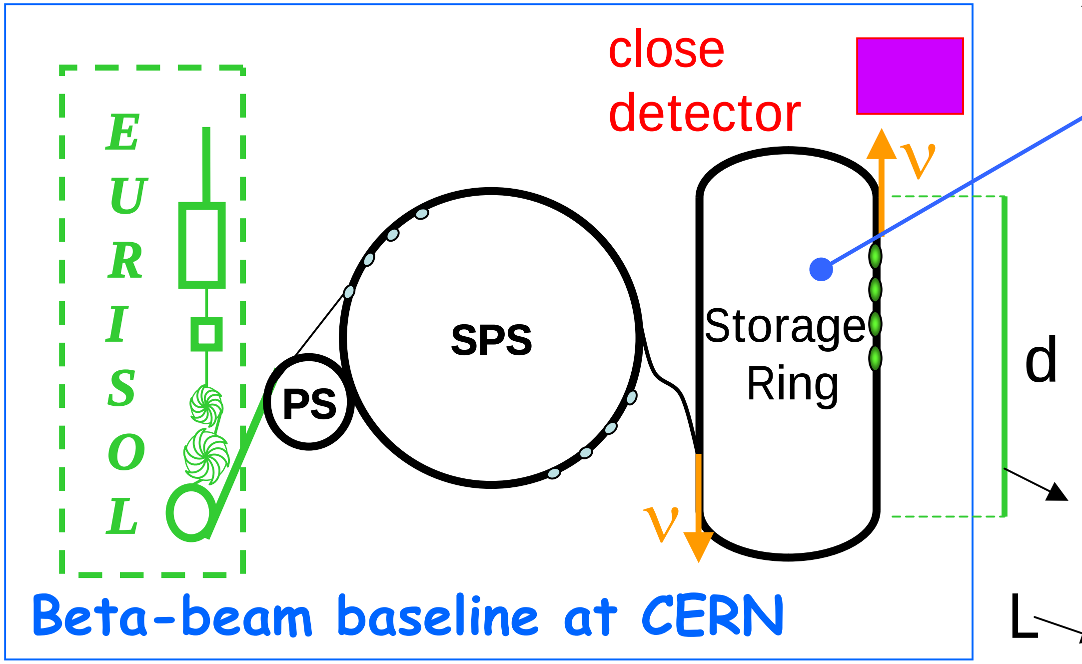


A BETA-BEAM FACILITY FOR LOW ENERGY NEUTRINOS.

SITES

Neutrino-nucleus measurements

Serreau and Volpe,
hep-ph/0403293,
PRC70 (2004).



Beta-beam baseline at CERN

Two options studied :
- Large ring
  (standard β-beam)
- Small Ring
  (ex. GSI future ring)

d → length of the straight sections

L → total length

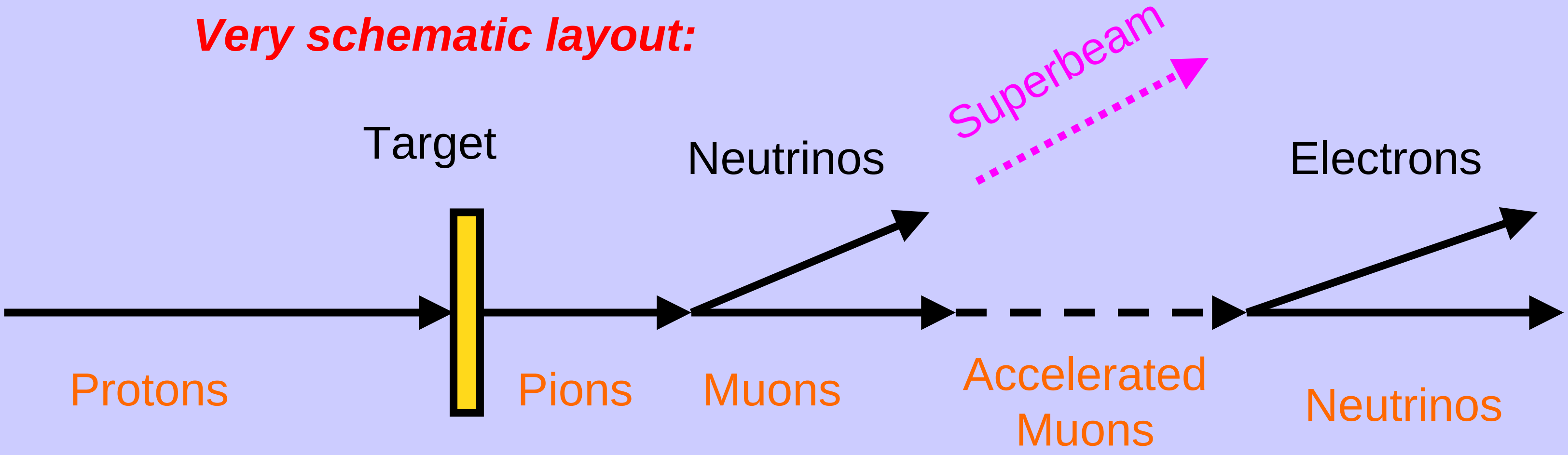
What is a Superbeam?

A Superbeam is a “conventional” ν-beam where the νs are produced by π (and K) decay but at a much higher intensities

What is a Neutrino Factory?

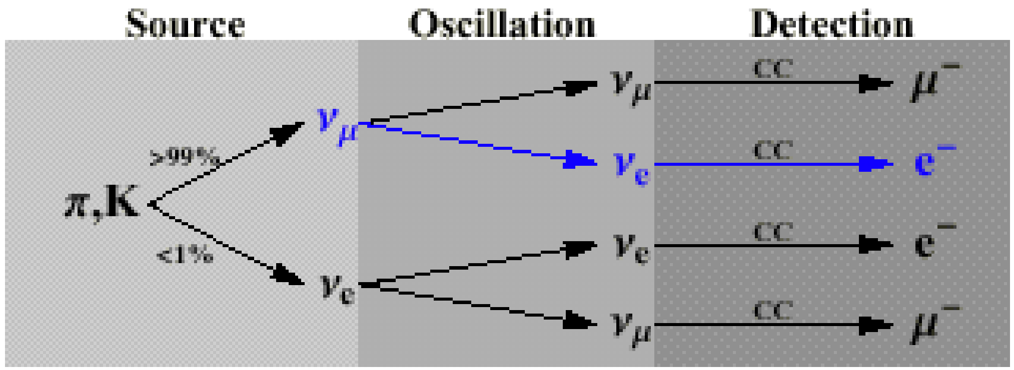
A Neutrino Factory is a machine where the ν-beam is produced by μ decay, which are in turn produced by the decay of πs. The μ beam is of good quality and may open the way to μ colliders (the ultimate high energy for lepton colliders)

Very schematic layout:

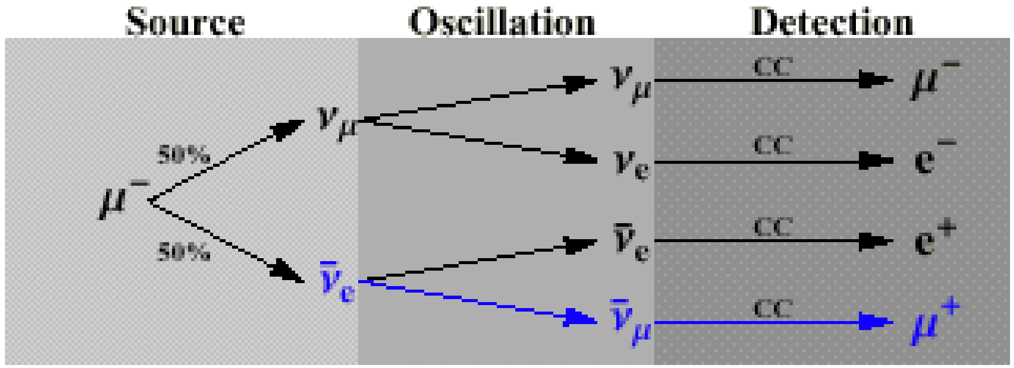


Future plans for neutrino beams

Superbeams



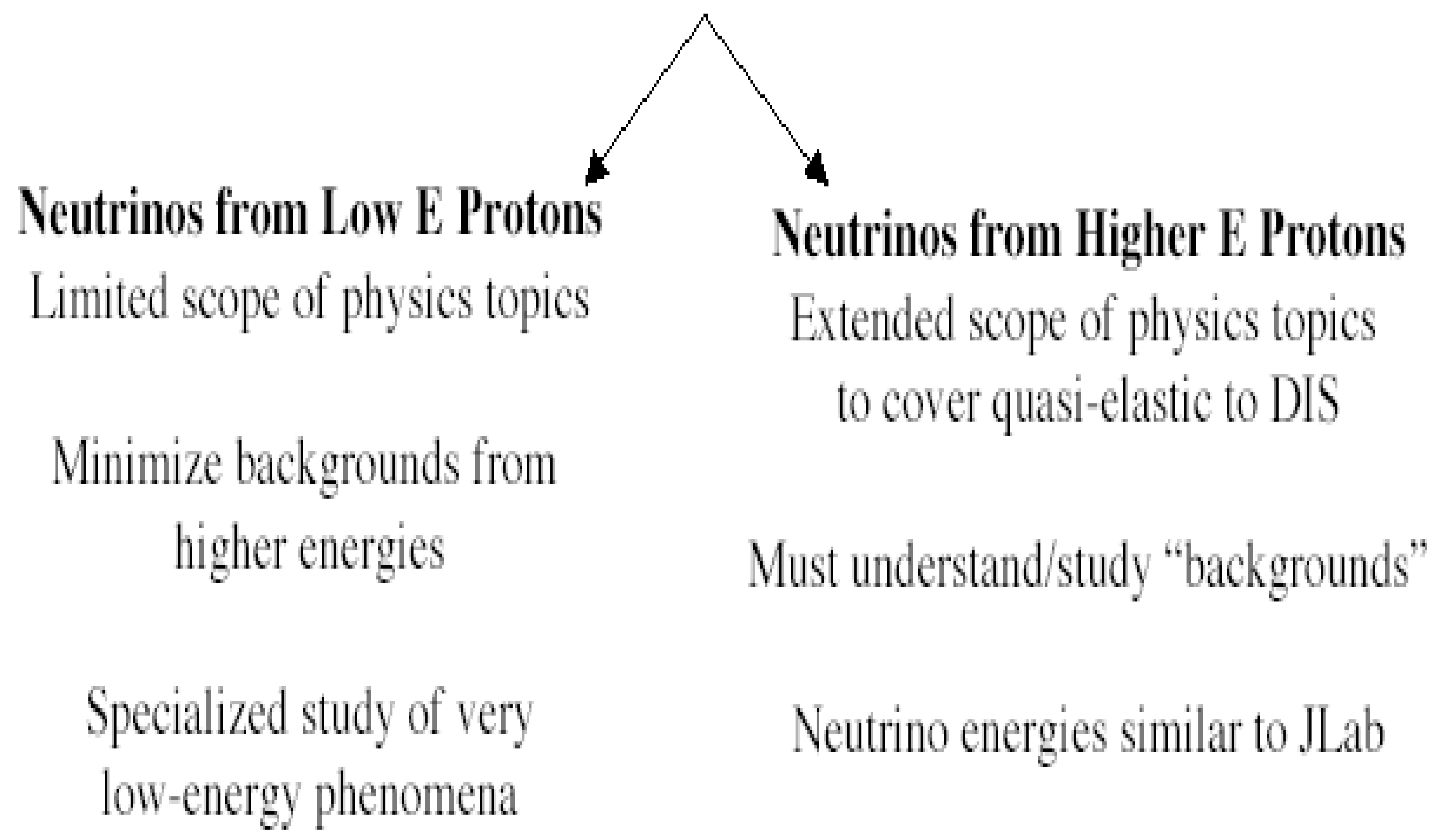
Neutrino Factories



Superbeams
-convenctional beams
with high intensity

neutrino factories
- new type of
accelerator

Plans for future neutrino beams



Neutrinos from Low E Protons

Limited scope of physics topics

Minimize backgrounds from
higher energies

Specialized study of very
low-energy phenomena

Neutrinos from Higher E Protons

Extended scope of physics topics
to cover quasi-elastic to DIS

Must understand/study "backgrounds"

Neutrino energies similar to JLab

MINOS Long-Baseline Experiment: Physics Goals

★ **Demonstrate oscillation behaviour**

- confirm flavour oscillations describe data
- provide high statistics discrimination against alternative models:
  decoherence, ν decay, extra dimensions, etc.

★ **Precise Measurement of Δm^2_{23}**

- ~10 %

★ **Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations**

- first measurements of θ_{13} ?

\+ **MINOS is the 1st large deep underground detector with a B-field**

- first direct measurements of ν vs $\bar{\nu}$ oscillations from atmospheric neutrino events

Next generation LBL experiments in Japan
“J-PARC - Kamioka neutrino project”
First superbeam

Baseline ~295km

Conventional ν_μ beam

Beam Energy ~1GeV

→ Will be adjusted to the oscillation maximum

	Beam power	Far detector	Physics
1st phase	0.75MW	Super Kamiokande(50kt)	disappearance $\nu_\mu \to \nu_X$ appearance $\nu_\mu \to \nu_e$ NC measurements
2nd phase	~4MW	Hyper Kamiokande(1Mt)	CP violation Proton decay

Neutrino factories

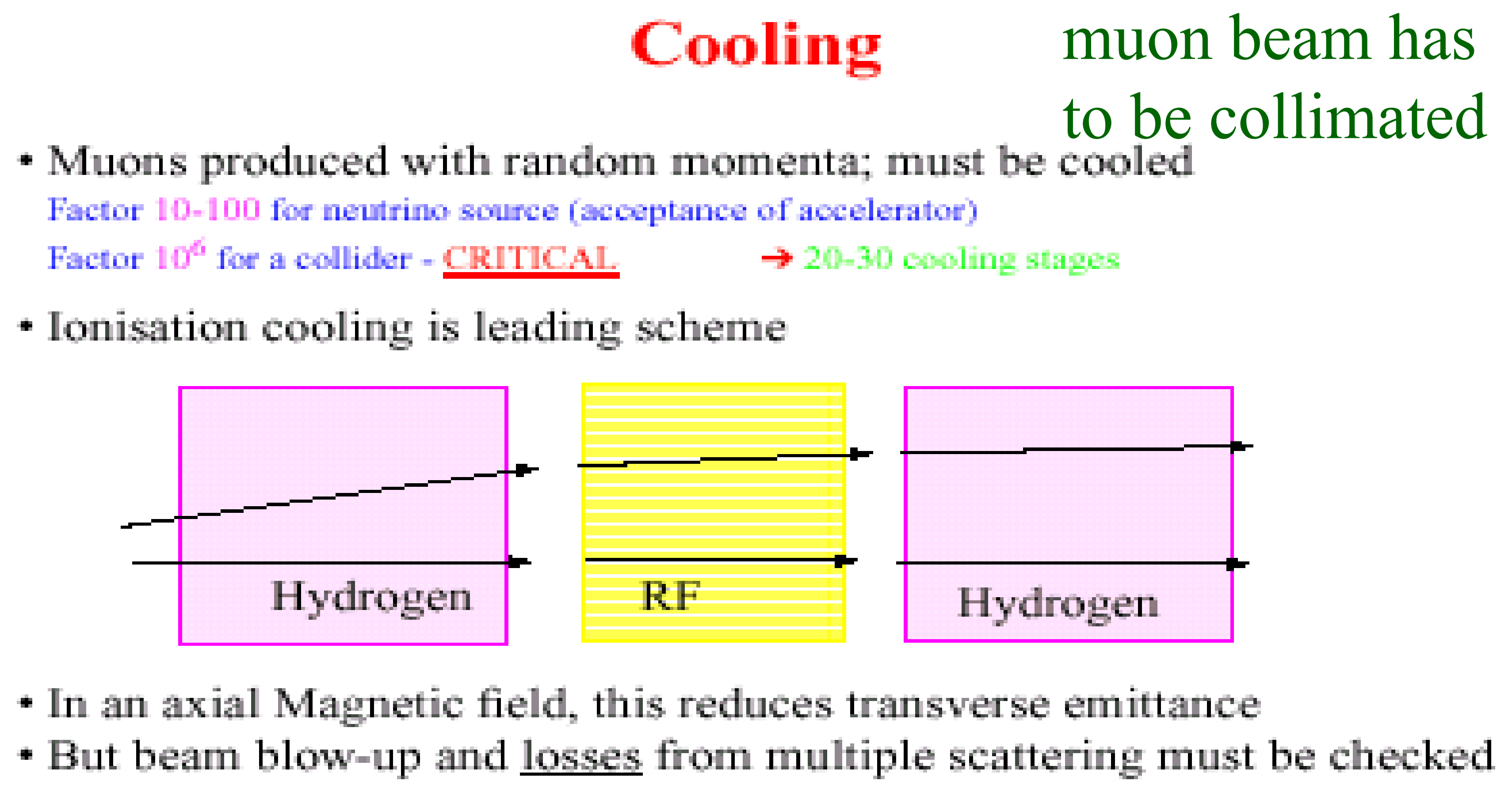
- high flux
- how? wait longer to allow μ decays

⇒ this requires a muon storage ring

- beam can be very clean

$\nu_e\bar{\nu}_\mu$ or $\bar{\nu}_e\nu_\mu$ with μ^+ or μ^- stored in the ring

needed for rare events and CP violation searches



Cooling

- Muons produced with random momenta; must be cooled

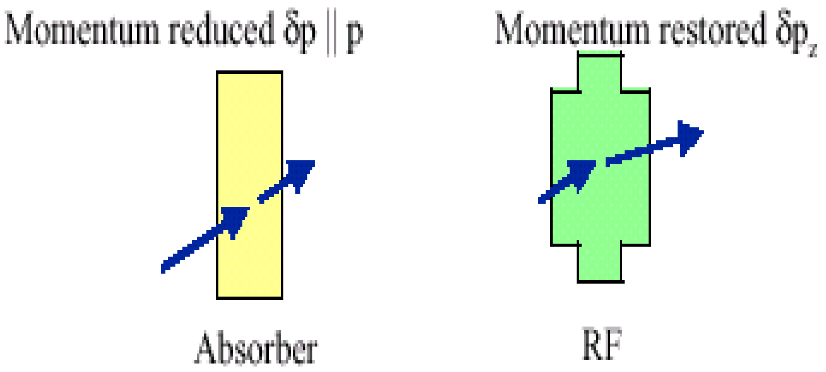
  Factor 10-100 for neutrino source (acceptance of accelerator)

  Factor 10^6 for a collider - CRITICAL → 20-30 cooling stages

- Ionisation cooling is leading scheme

- In an axial Magnetic field, this reduces transverse emittance
- But beam blow-up and losses from multiple scattering must be checked

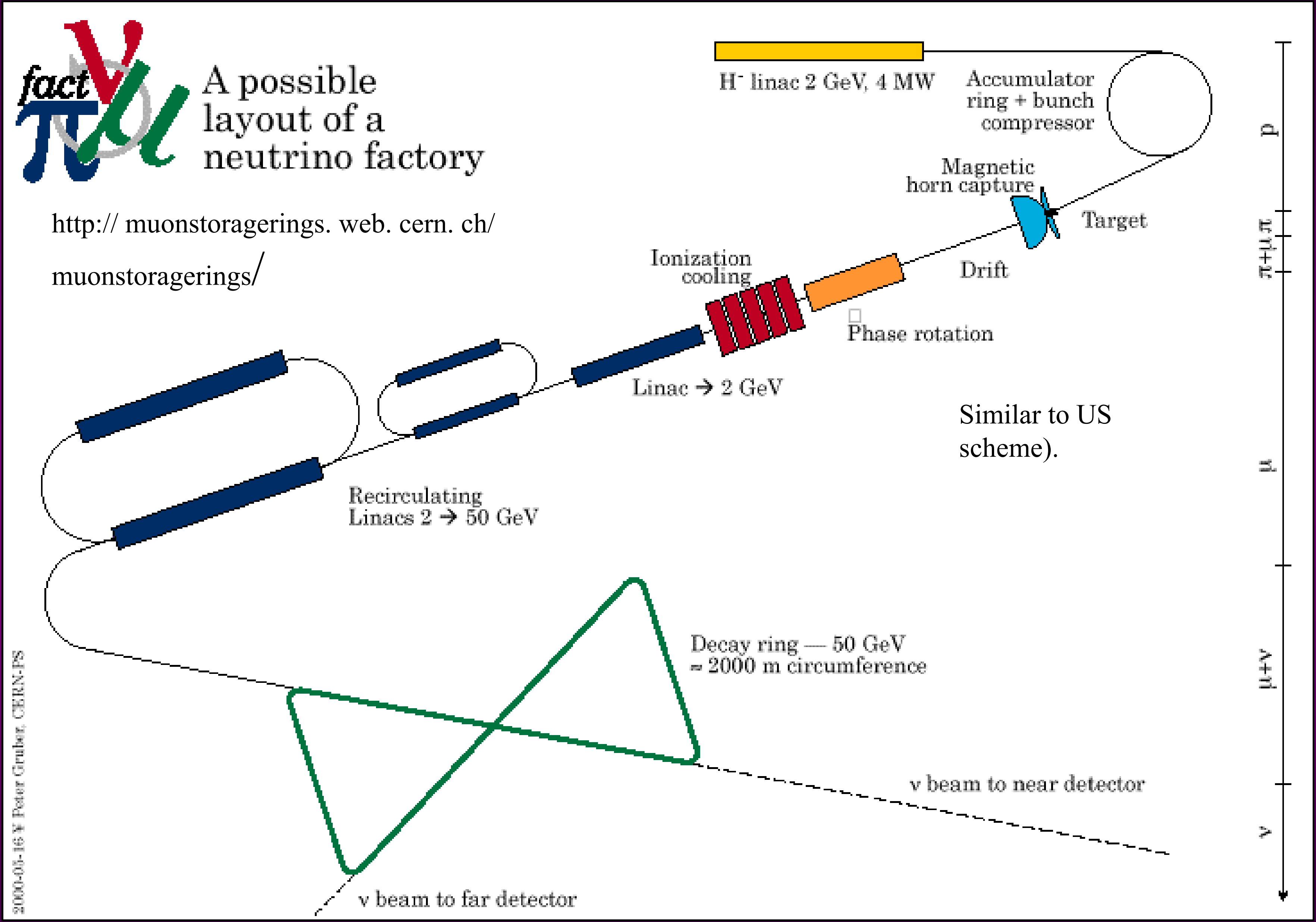
muon beam has to be collimated



concept of ionization cooling:

- energy loss in longitudinal and transverse direction,
- acceleration in RF cavity (only in required direction)

Full scale project: ν factory and μ collider



http:// muonstoragerings. web. cern. ch/ muonstoragerings/

Similar to US scheme).

What are the Open Questions in Neutrino Physics

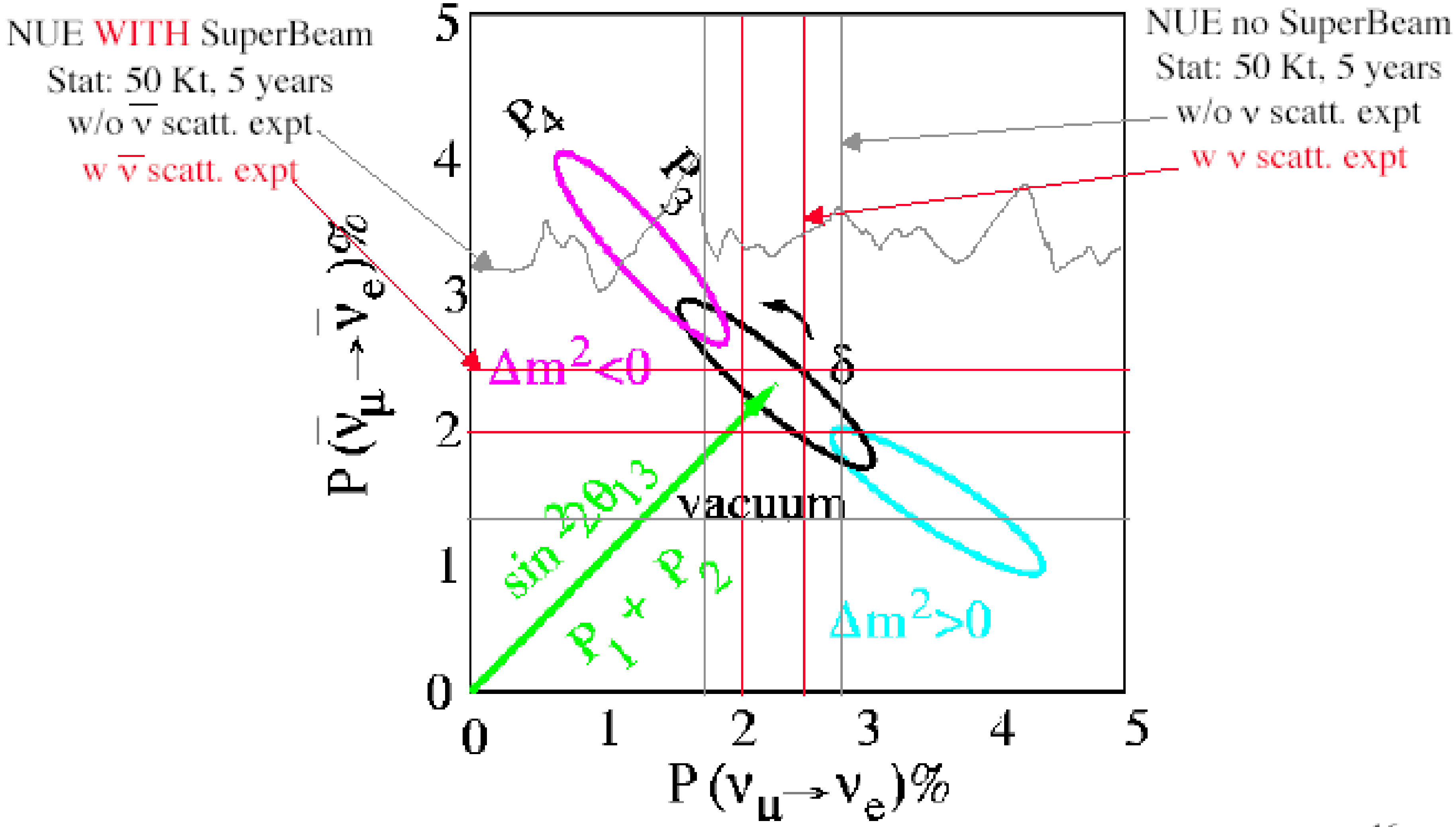
From the APS Multi-Divisional Study on the Physics of Neutrinos

- What are the masses of the neutrinos?
- What is the pattern of mixing among the different types of neutrinos?
- Are neutrinos their own antiparticles?
- Do neutrinos violate the symmetry CP?
- Are there "sterile" neutrinos?
- Do neutrinos have unexpected or exotic properties?
- What can neutrinos tell us about the models of new physics beyond the Standard Model?

The answer to almost every one of these questions involves understanding how neutrinos interact with matter!

Why do we need an $\bar{\nu}$ Beam?

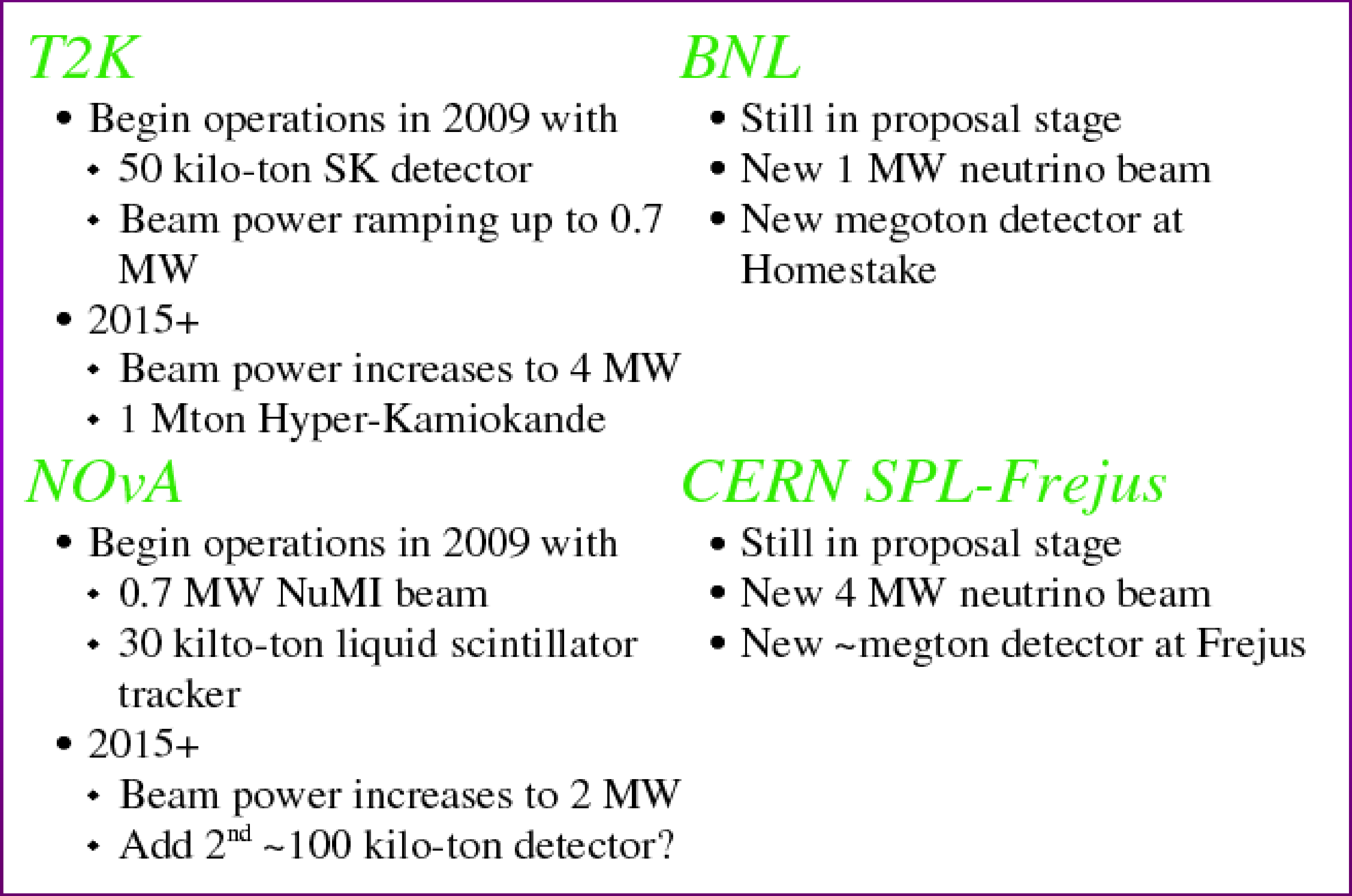
Control ν / $\bar{\nu}$ systematics at the 1 percent level for mass hierarchy and CP studies.



NUE WITH SuperBeam
Stat: 50 Kt, 5 years
w/o $\bar{\nu}$ scatt. expt
w $\bar{\nu}$ scatt. expt

NUE no SuperBeam
Stat: 50 Kt, 5 years
w/o ν scatt. expt
w ν scatt. expt

Super-beams programs



T2K

- Begin operations in 2009 with
  - 50 kilo-ton SK detector
  - Beam power ramping up to 0.7 MW
- 2015+
  - Beam power increases to 4 MW
  - 1 Mton Hyper-Kamiokande

BNL

- Still in proposal stage
- New 1 MW neutrino beam
- New megoton detector at Homestake

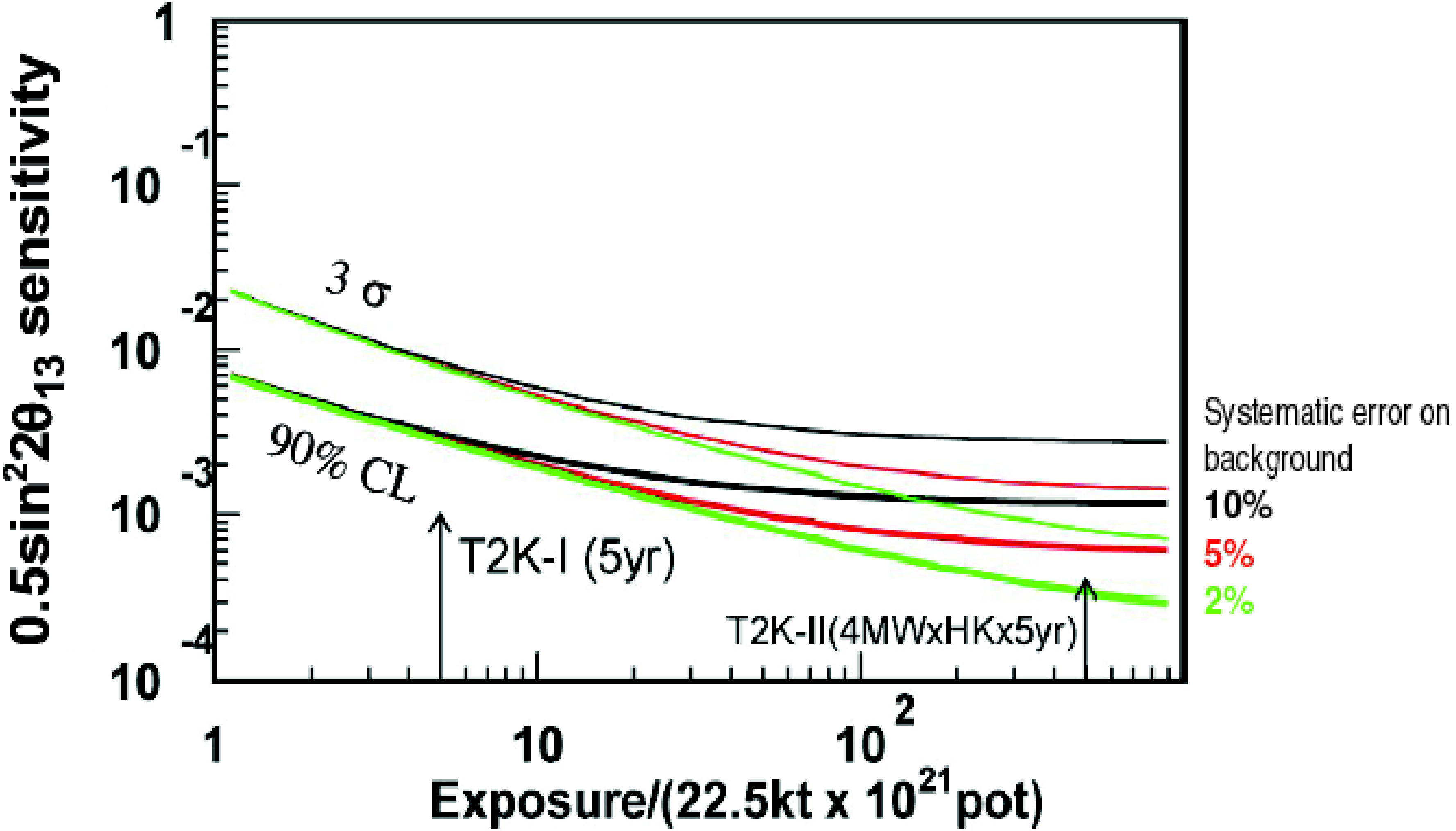
NOνA

- Begin operations in 2009 with
  - 0.7 MW NuMI beam
  - 30 kilto-ton liquid scintillator tracker
- 2015+
  - Beam power increases to 2 MW
  - Add 2nd ~100 kilo-ton detector?

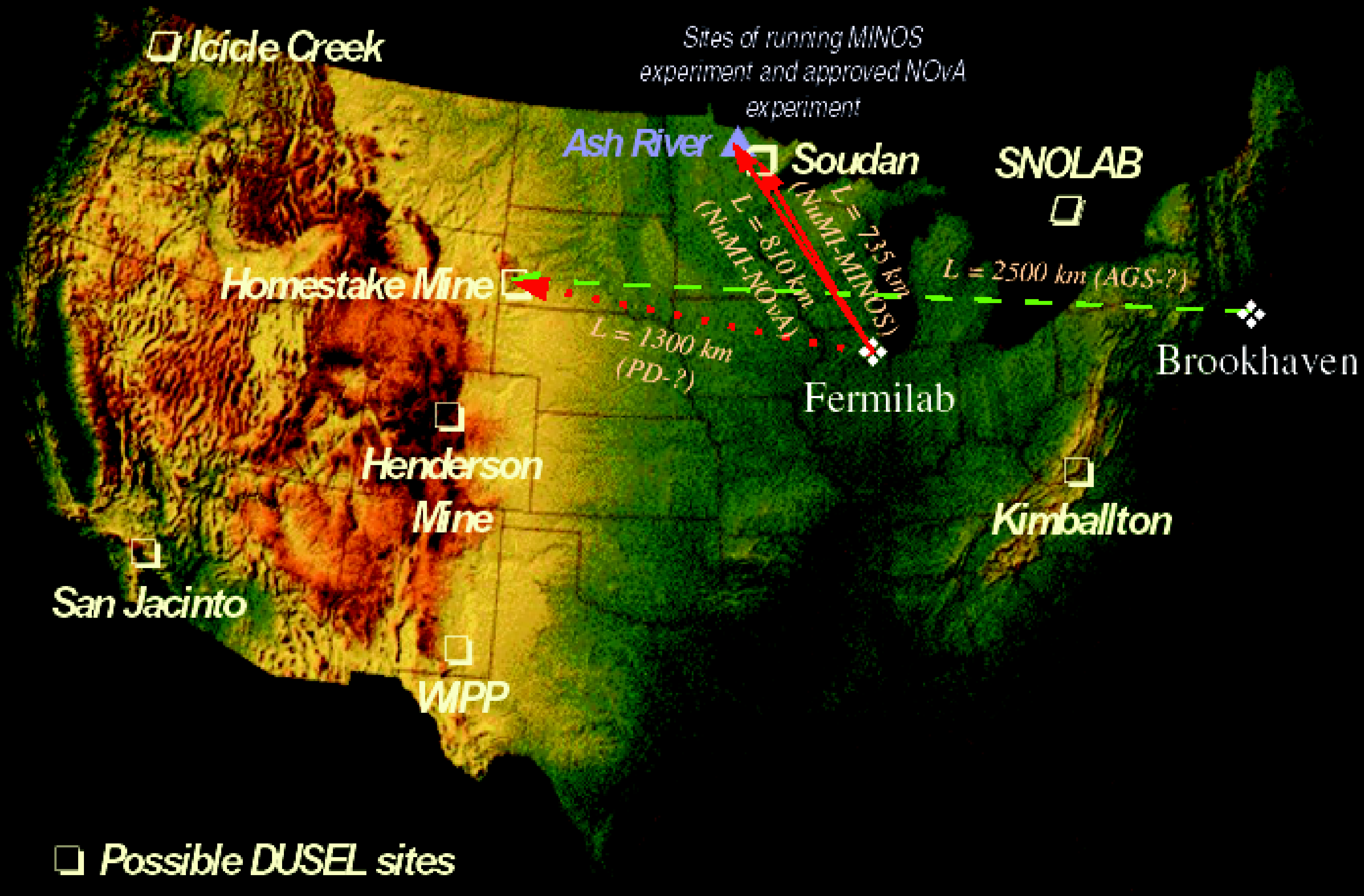
CERN SPL-Frejus

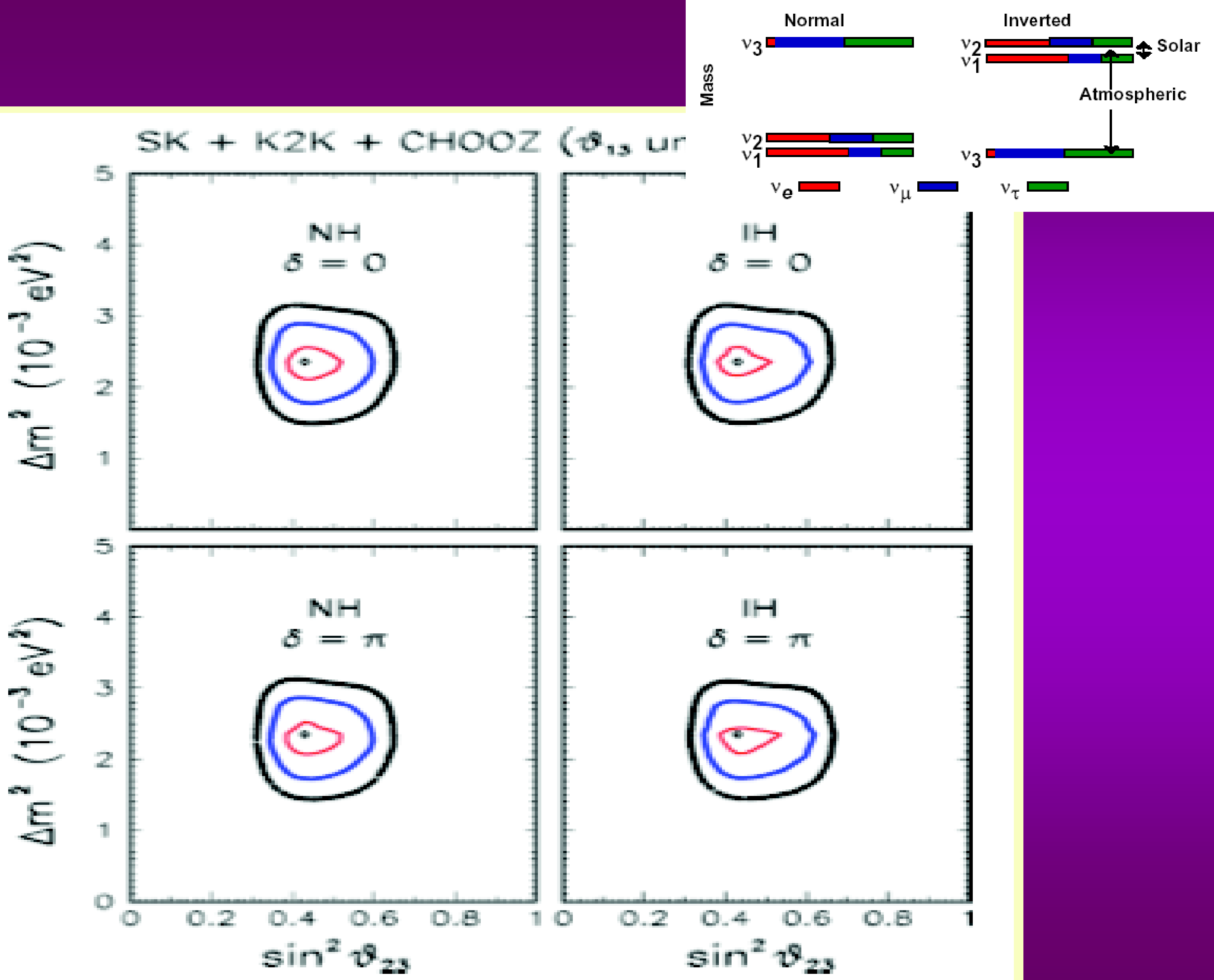
- Still in proposal stage
- New 4 MW neutrino beam
- New ~megton detector at Frejus

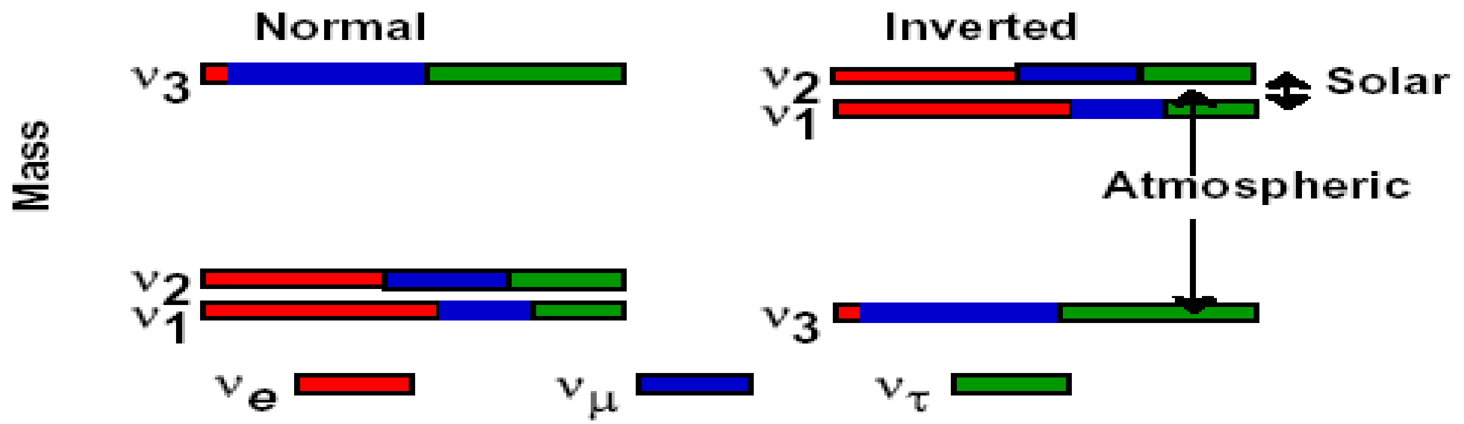
T2K Phase 2 Sensitivity



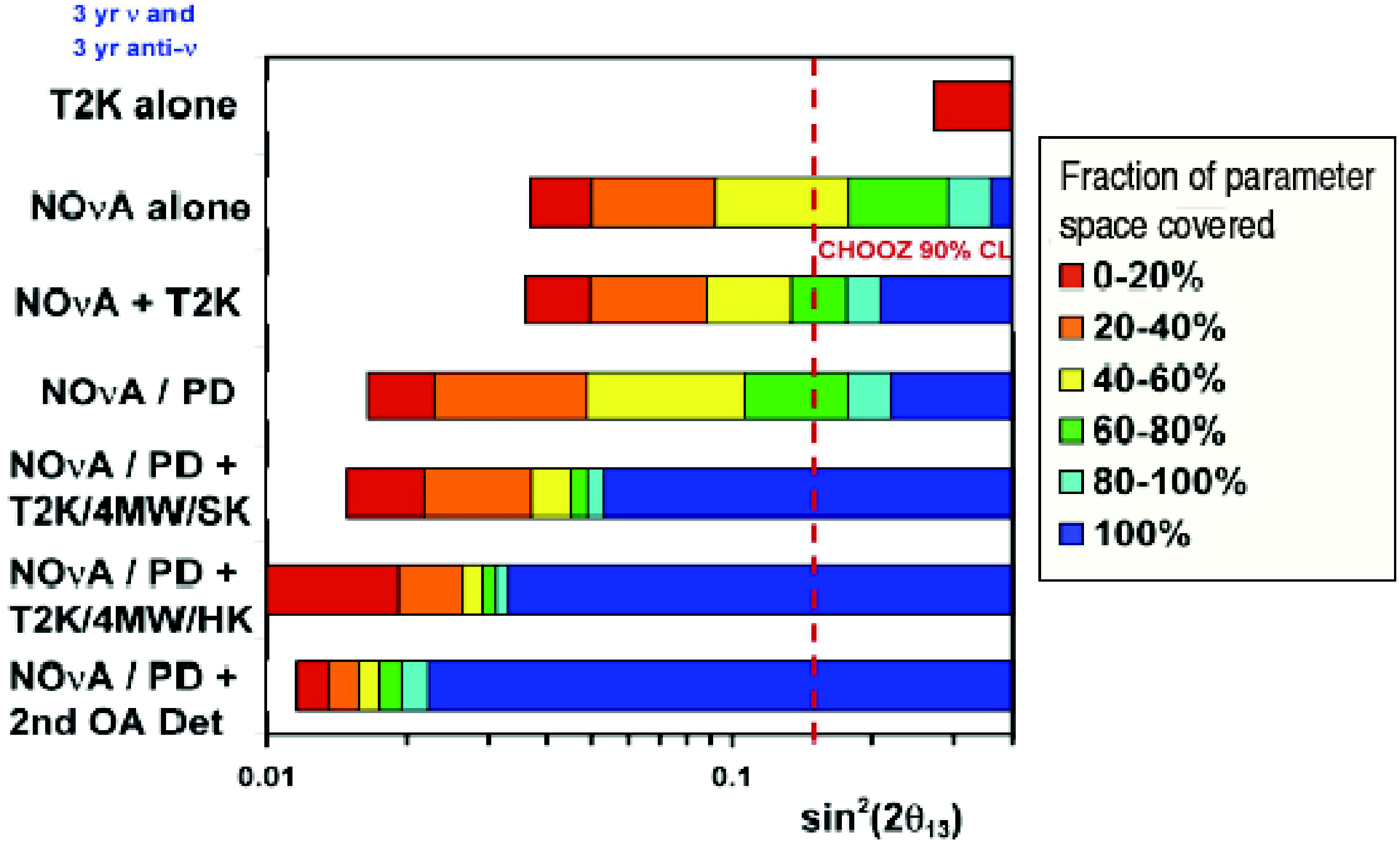
Superbeams in the United States

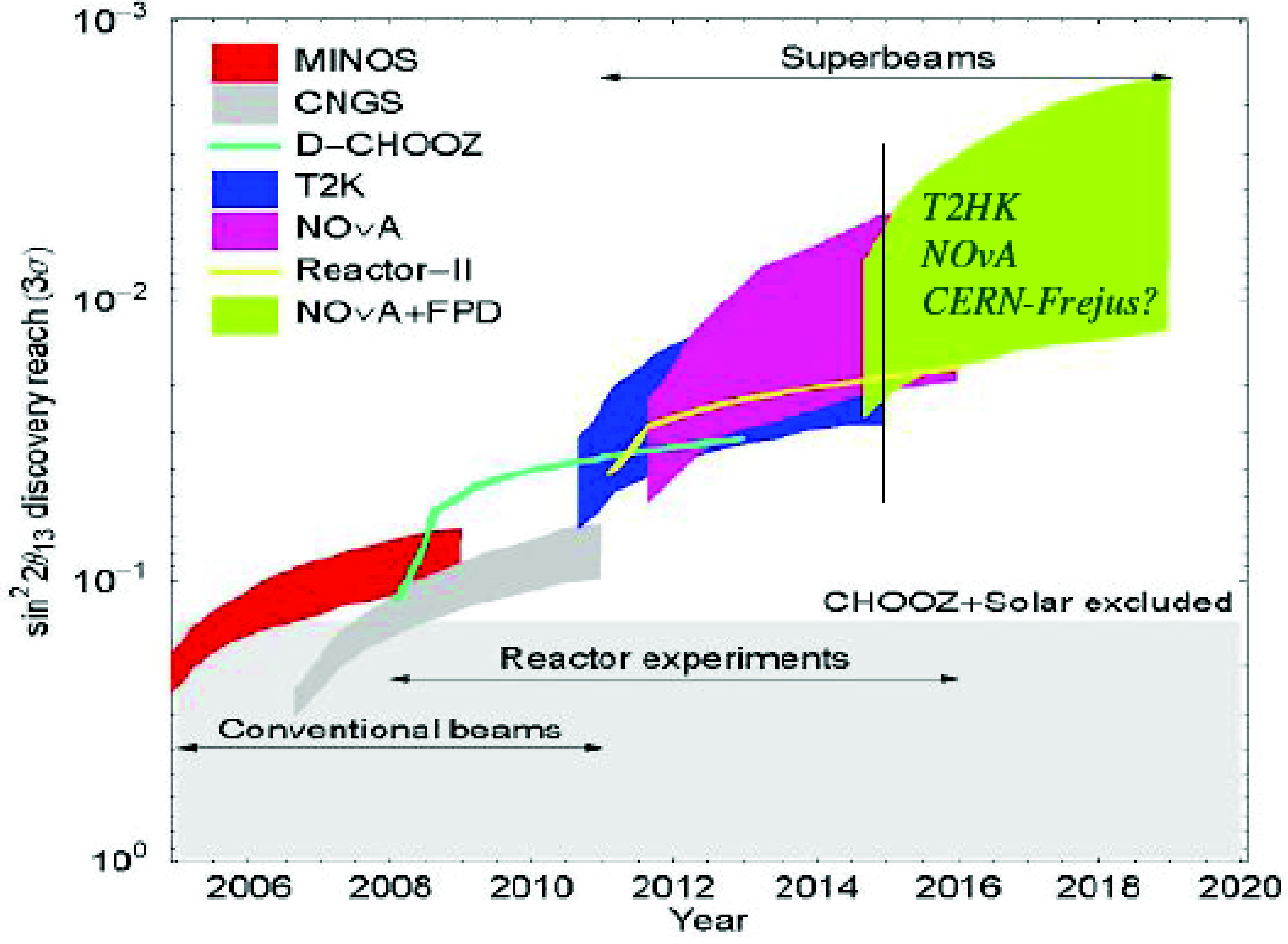


SK + K2K + CHOOZ (ϑ_{13} ur
NH
$\delta = 0$
IH
$\delta = 0$
NH
$\delta = \pi$
IH
$\delta = \pi$
Δm^2 (10^{-3} eV^2)
0
1
2
3
4
5
0
0.2
0.4
0.6
0.8
1
$\sin^2 \vartheta_{23}$
Normal
Inverted
Mass
ν_3
ν_2
ν_1
Solar
Atmospheric
ν_e
ν_μ
ν_τ



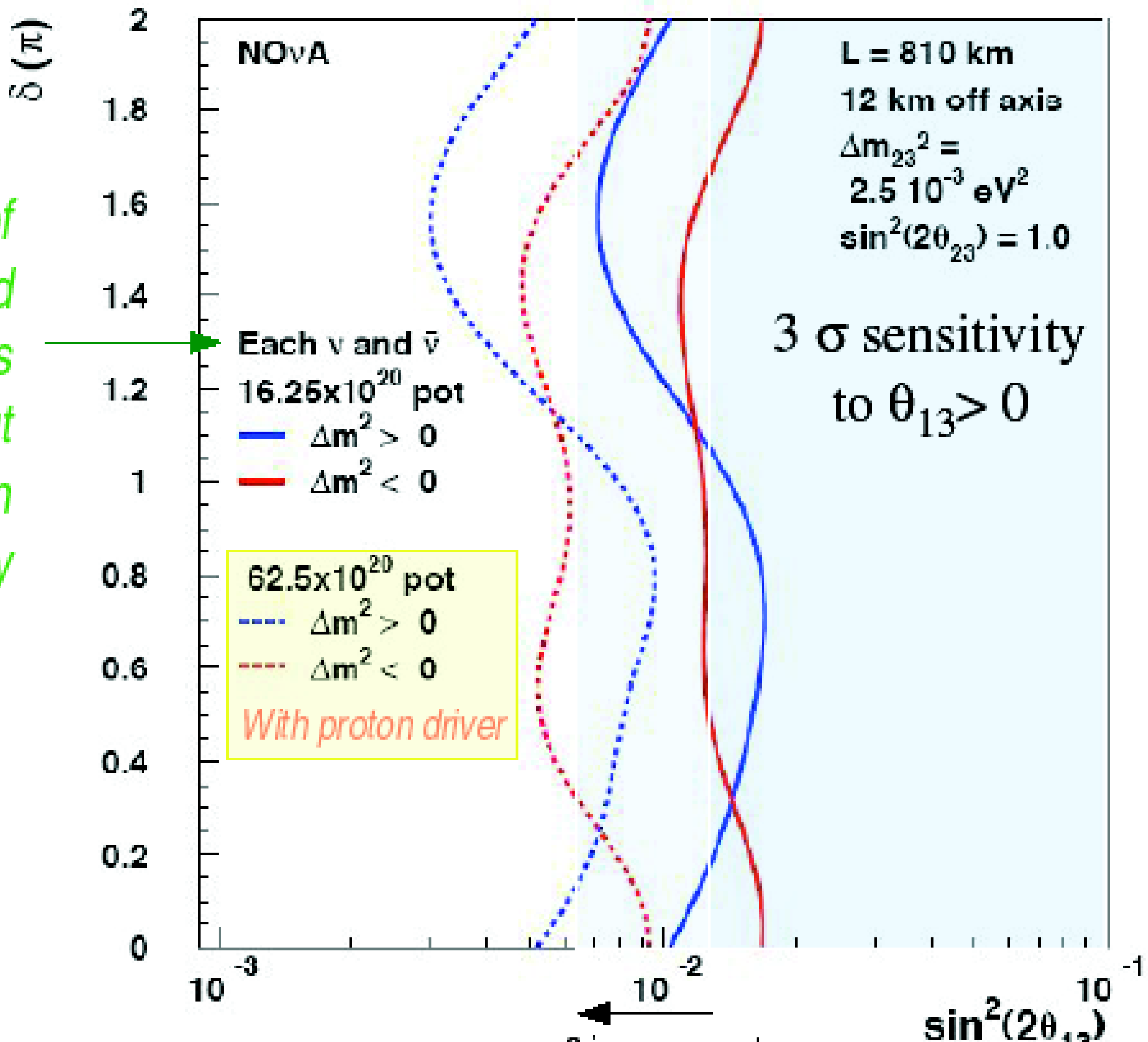
95% CL Determination of the Mass Ordering




MINOS
CNGS
D−CHOOZ
T2K
NOνA
Reactor−II
NOνA+FPD
Superbeams
T2HK
NOνA
CERN-Frejus?
CHOOZ+Solar excluded
Reactor experiments
Conventional beams
10^{-3}
10^{-2}
10^{-1}
10^{0}
$\sin^2 2\theta_{13}$ discovery reach (3σ)
2006
2008
2010
2012
2014
2016
2018
2020
Year

NOνA sensitivity with proton driver

Mixture of neutrinos and anti-neutrinos evens out variations in sensitivity



x2 improvement in sensitivity

Gary Feldman WIN'05

Towards precision neutrino physics ....

LEP EW Working Group, 2005

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02770
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.390
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.4

Solar neutrinos (Bari group), 2005