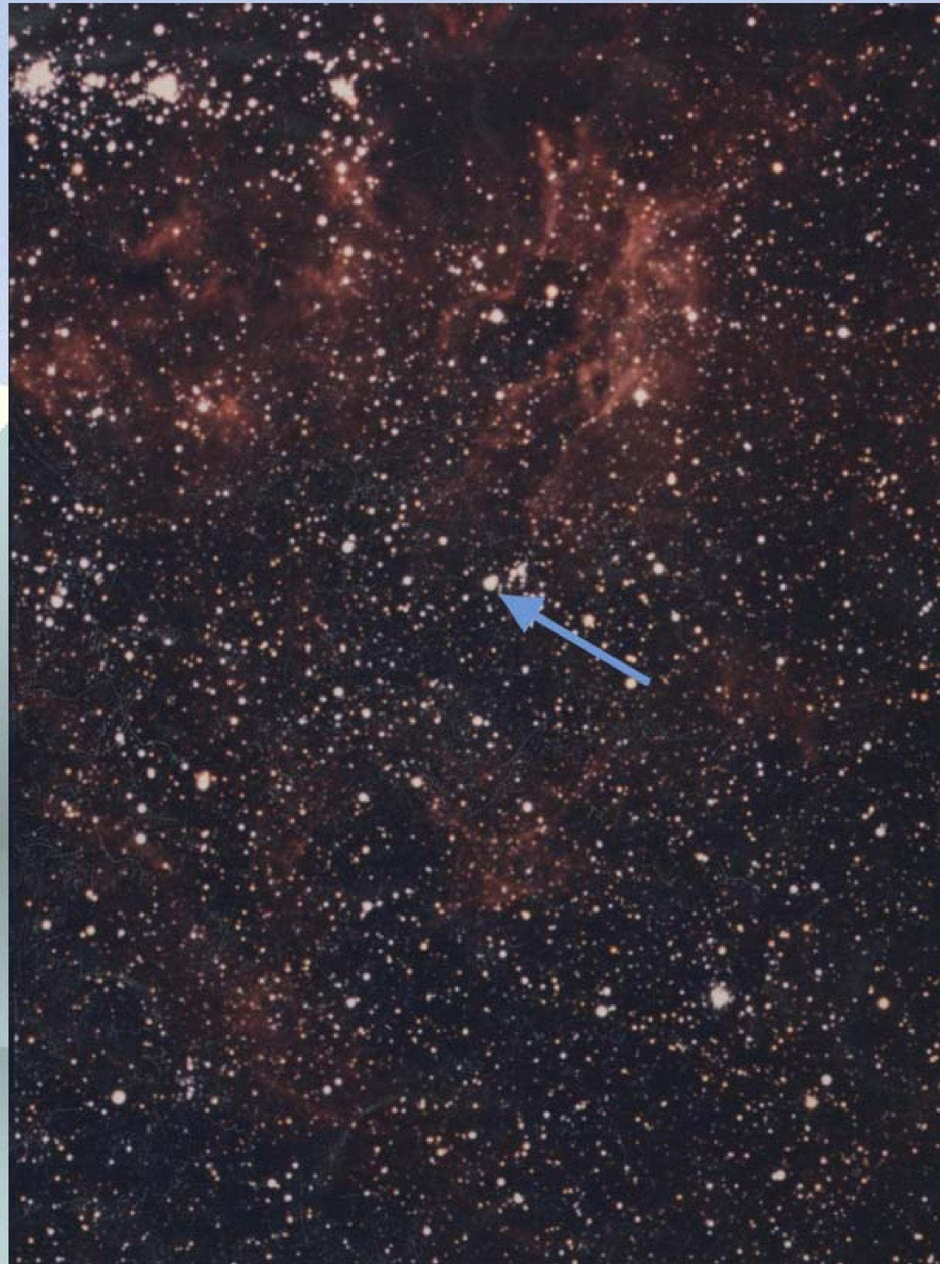
Neutrino Physics

Takashi Kobayashi
Institute for Particle & Nuclear Studies
High Energy Accelerator Research Organization (KEK)

20 yrs ago

- **1987 Feb 23 16:35:35** (+170,000yr)



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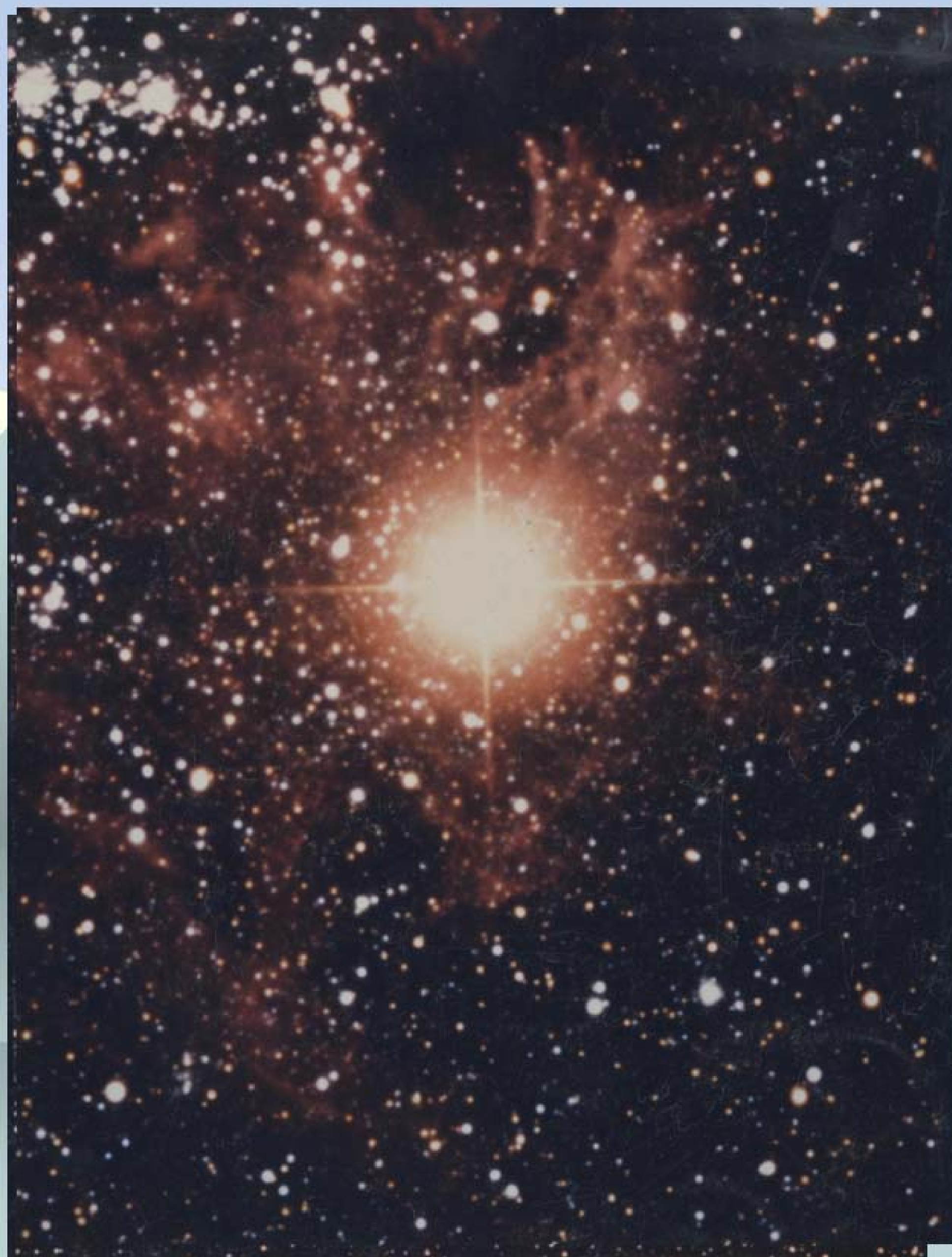
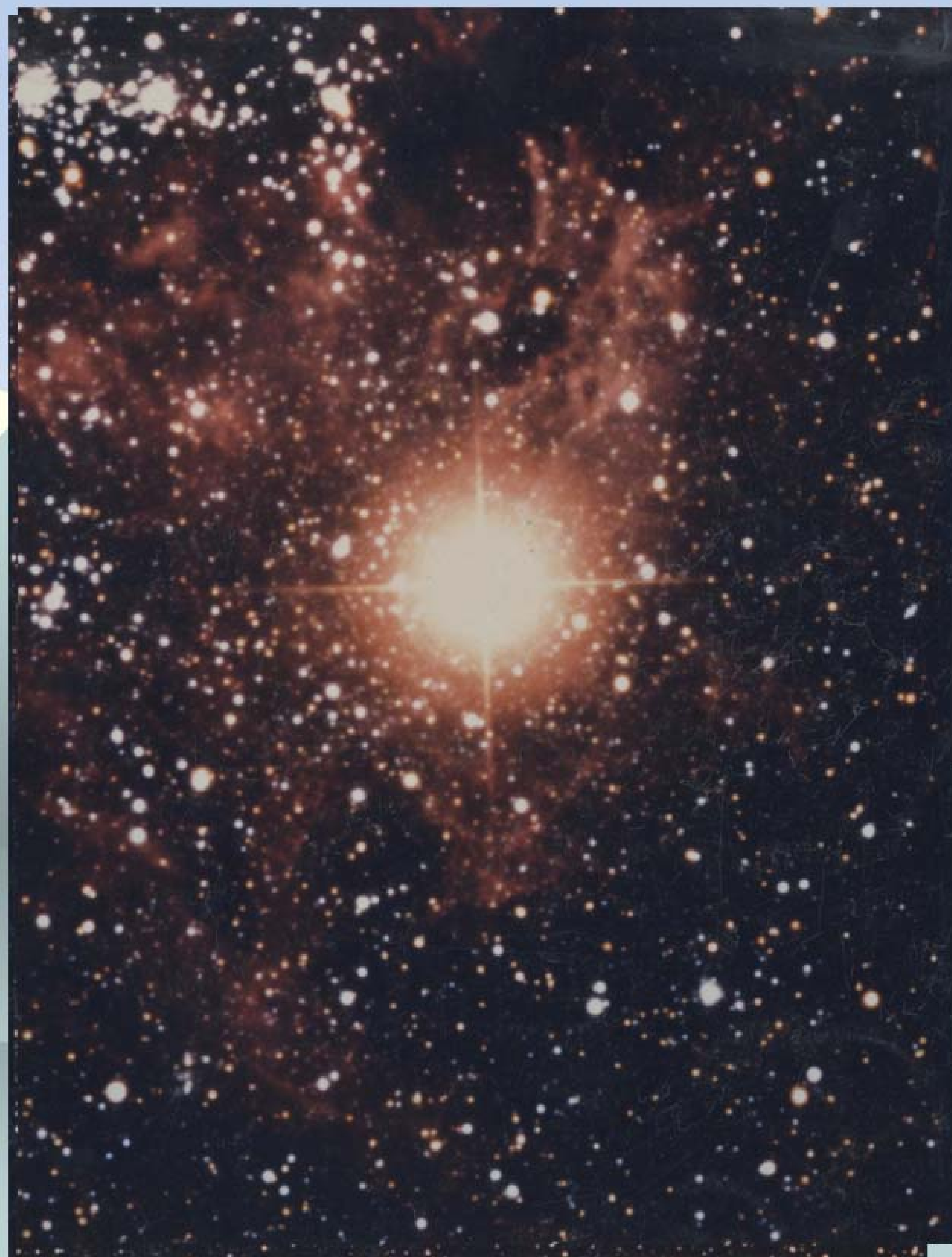


- Supernova

20 yrs ago

- **1987 Feb 23 16:35:35** (+170,000yr)
- Supernova exploded
  - Large Magellanic Cloud



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- **1987 Feb 23 16:35:35** (+170,000yr)
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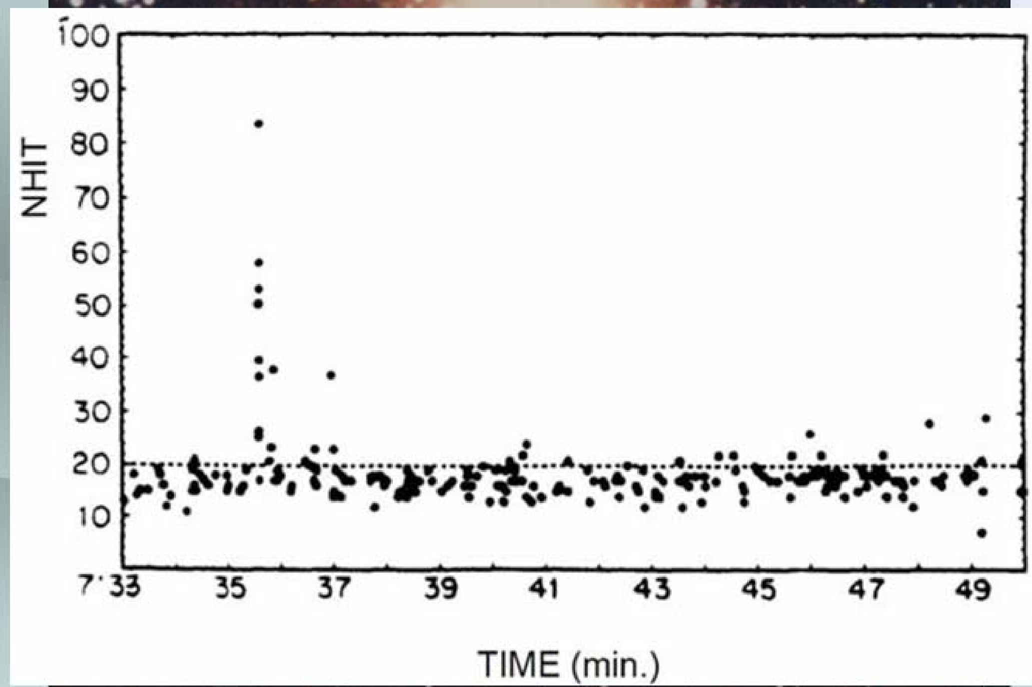
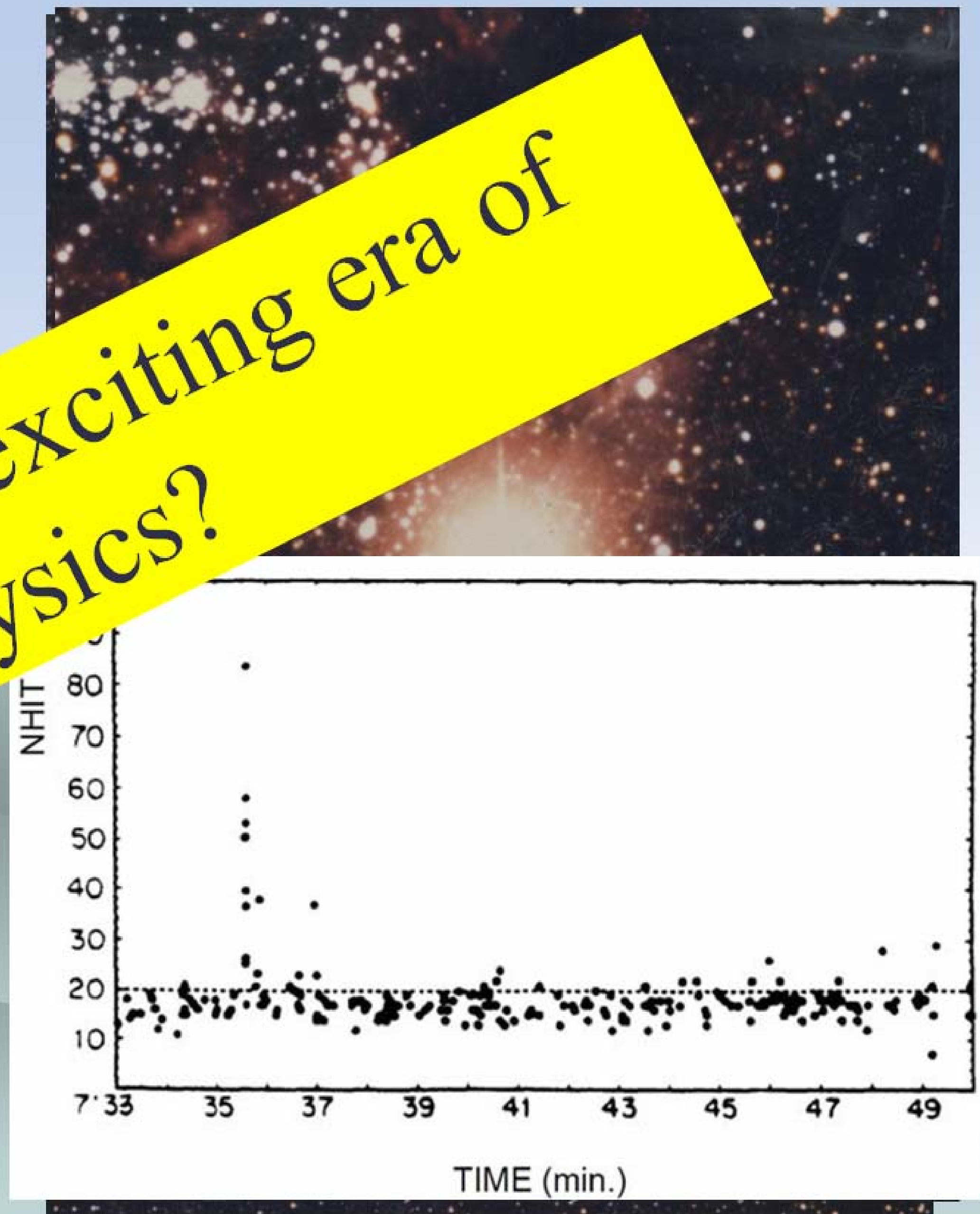
  - Large Magellanic Cloud
- Neutrino detected by Kamiokande

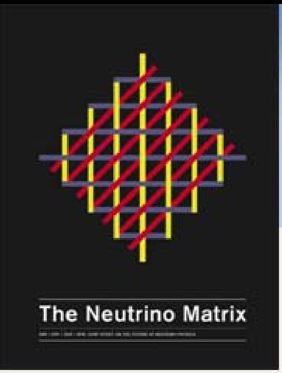


20 yrs ago

- **1987 Feb 23 16:35:35** (+170,000yr)
- Supernova explode[…]
  - La[…] Clo[…]
- Neutri[…] detected by Kamiokande

Start of new exciting era of neutrino physics?





Introduction

The Growing Excitement of Neutrino Physics

Pauli predicts the Neutrino

Fermi's theory of weak interactions

Reines & Cowan discover (anti)neutrinos

2 distinct flavors identified

Davis discovers the solar deficit

Kamioka II confirms solar deficit

LEP shows 3 active flavors

SAGE and Gallex see the solar deficit

Kamioka II and IMB see atmospheric neutrino anomaly

Kamioka II and IMB see supernova neutrinos

Nobel Prize for discovery of distinct flavors!

LSND sees possible indication of oscillation signal

Nobel Prize for ν discovery!

Super K sees evidence of atmospheric neutrino oscillations

Super K confirms solar deficit and "images" sun

SNO shows solar oscillation to active flavor

Nobel Prize for neutrino astroparticle physics!

KamLAND confirms solar oscillations

K2K confirms atmospheric oscillations

1930 | 1955 | 1980 | 2005

The Neutrino Matrix

Introduction

The Growing Excitement of Neutrino Physics

- Neutrino was least known matter particle 20yrs ago
  - Standard model **ASSUMES**: mass=0, No flavor mixing
- **Great progress since then**
- Still neutrino is least known particle now in 2007
  - Many unanswered fundamental questions
- New era of "Neutrino Flavor Physics" just opened
  - Many new projects
- This talk
  - Progress made in last ~20yrs (masses&mixings)
    - Solar ν/Atm ν/Acc/Reactor
  - unanswered questions
  - (not all) future projects

K2K confirms atmospheric oscillations

KamLAND confirms solar oscillations

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1930 1955 1980 2005

Neutrino Oscillation (in 2flavor approx.)

➢ Neutrino Mixing

$$\begin{pmatrix} |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$

Weak eigenstates — Mass eigenstates

mass: m_1, m_2

$$\Delta m^2 \equiv \left| m_1^2 - m_2^2 \right|$$

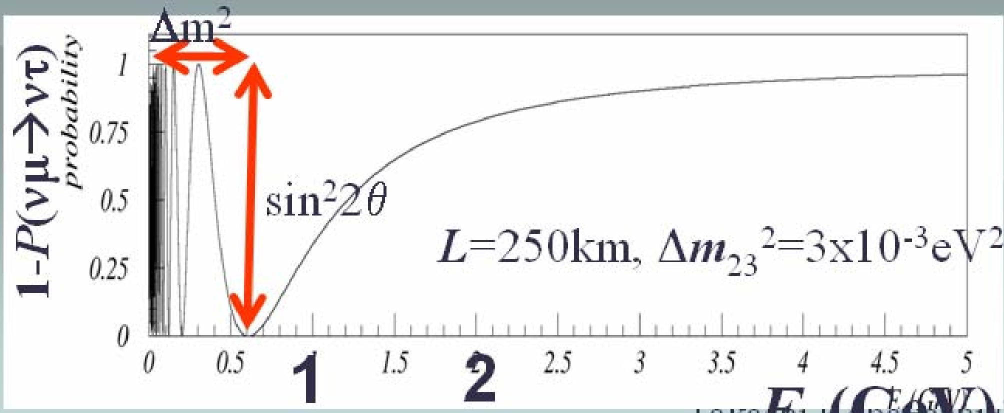
$$|\nu_\mu(0)\rangle = |\nu_1\rangle\cos\theta - |\nu_2\rangle\sin\theta$$

$$|\nu_\mu(t)\rangle = |\nu_1\rangle e^{-i\frac{m_1^2}{2E}L}\cos\theta - |\nu_2\rangle e^{-i\frac{m_2^2}{2E}L}\sin\theta$$

➢ Probability to change flavor

L:flight dist、E_ν:neutrino energy

$$P(\nu_\mu \to \nu_\tau) = \left|\langle\nu_\tau|\nu_\mu(t)\rangle\right|^2 = \sin^2 2\theta \cdot \sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]\cdot L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$



Signature

- Decrease of orig flavor ("Disappearance")
- Appearance of diff flavor ("Appearance")
- Characteristic energy (or L/E) distortion

3 flavor mixing

$$\left|\nu_l\right\rangle = \Sigma U_{li}\left|\nu_i\right\rangle$$

m_i: 3 masses,

Weak　　　　Mass eigenstates

Maki-**N**akagawa-**S**akata **Matrix** $s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

LBL acc. experiments

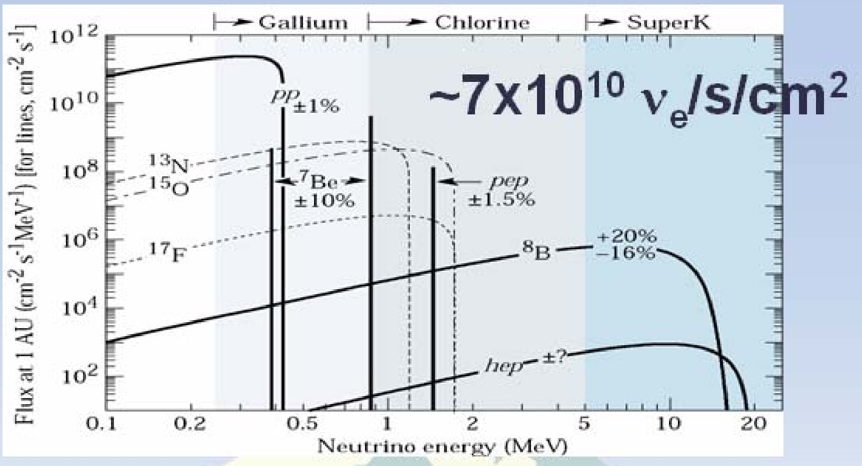
$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 &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

(Solar
LBL reactor)　　(Atm ν)　　Reactor

Δm_{ij}: 2 independent differences

3 mixing angles and 1 CPV phase

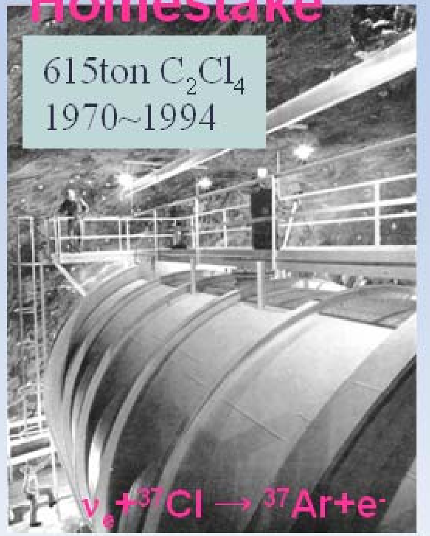
Solar Neutrino Problem ('70~'90)

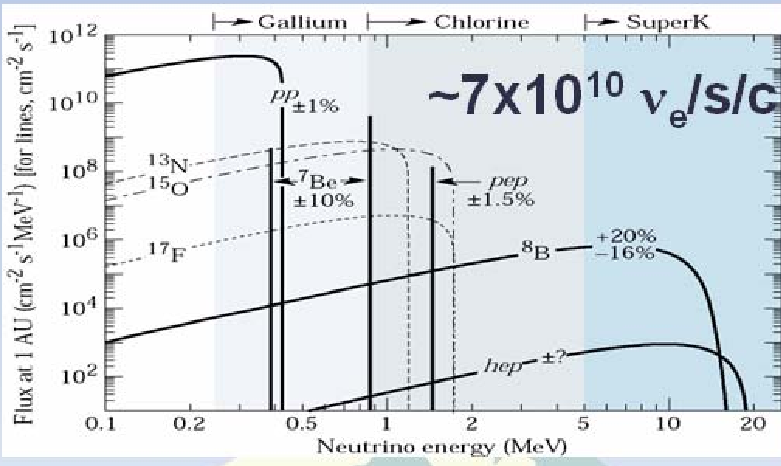


Solar Neutrino Problem ('70~'90)

"Radio-Chemical"

Homestake





Galium exp's
Gallex+SAGE
(1991~2003) (1990~)

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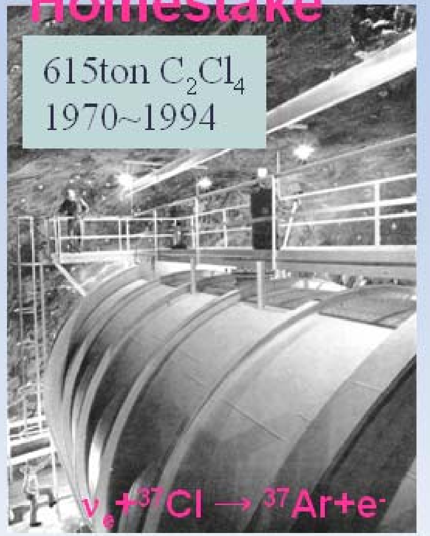
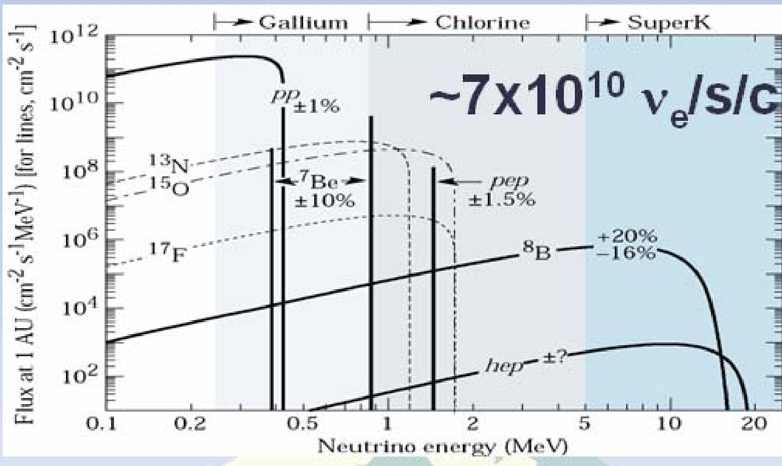


615ton C_2Cl_4
1970~1994

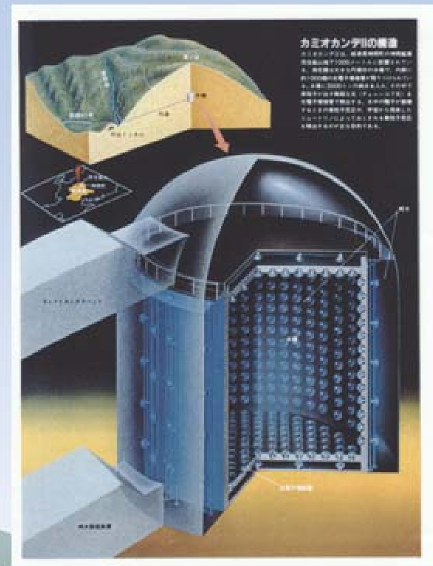
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$



~7×10^{10} ν_e/s/cm^2

Kamiokande

(1983~1996)



$\nu_e + e^- \rightarrow \nu_e + e^-$

Real time, Energy
Dir. Info.

Galium exp's
Gallex+SAGE

(1991~2003) (1990~)

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

Solar Neutrino Problem ('70~'90)

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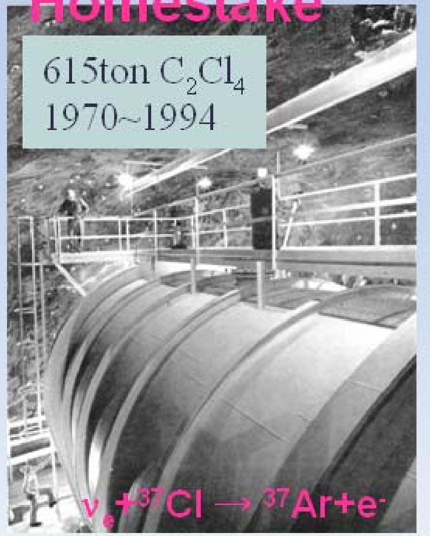

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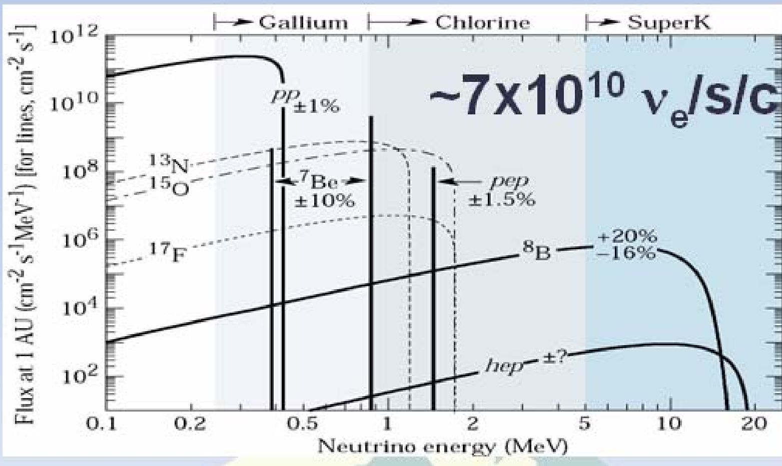
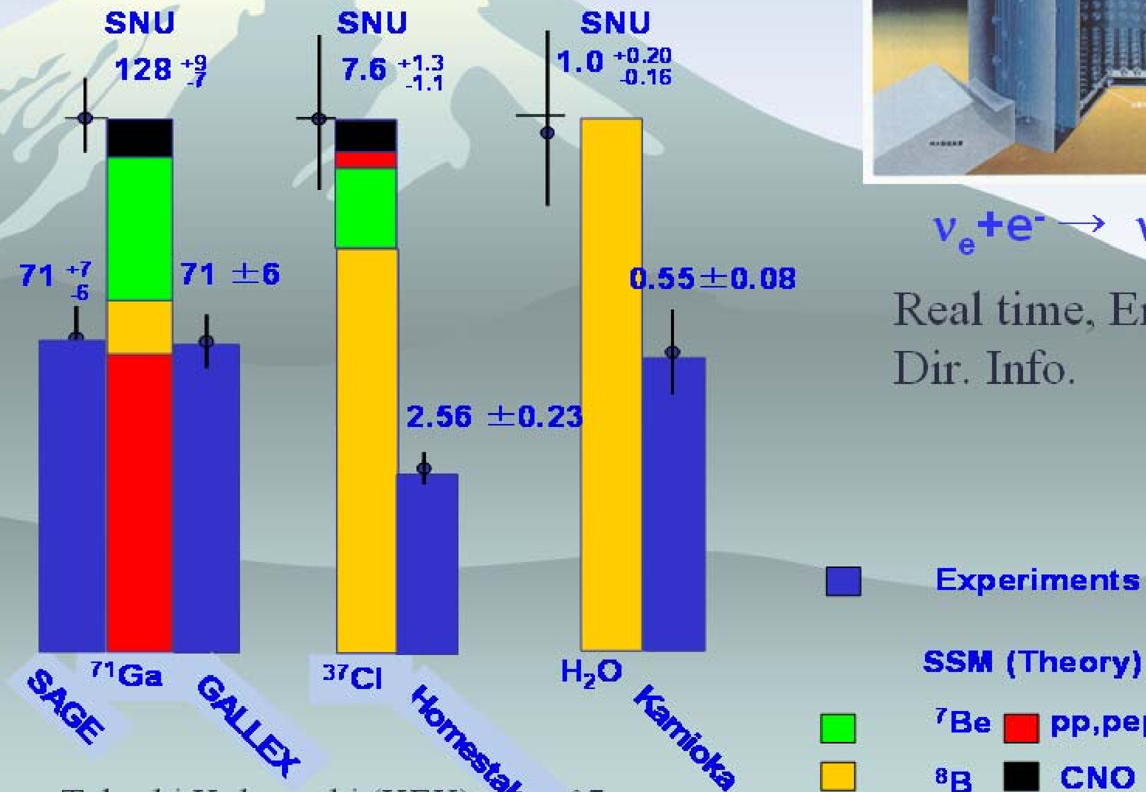
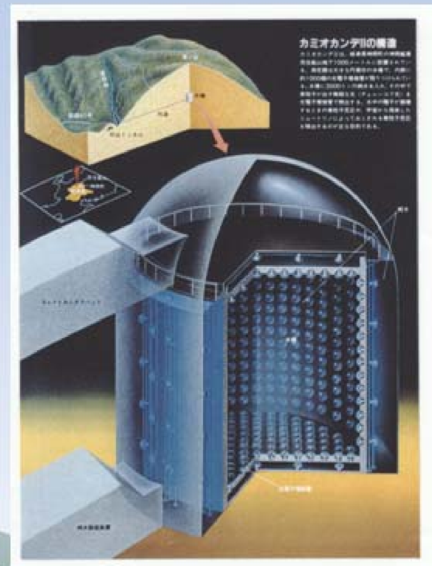


~$7 \times 10^{10}\ \nu_e$/s/cm^2



Kamiokande
(1983~1996)



$\nu_e + e^- \rightarrow \nu_e + e^-$

Real time, Energy
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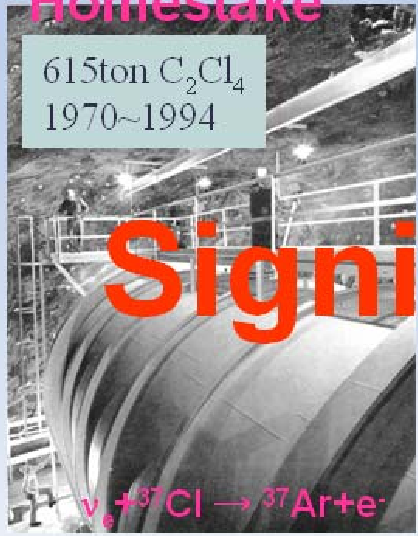
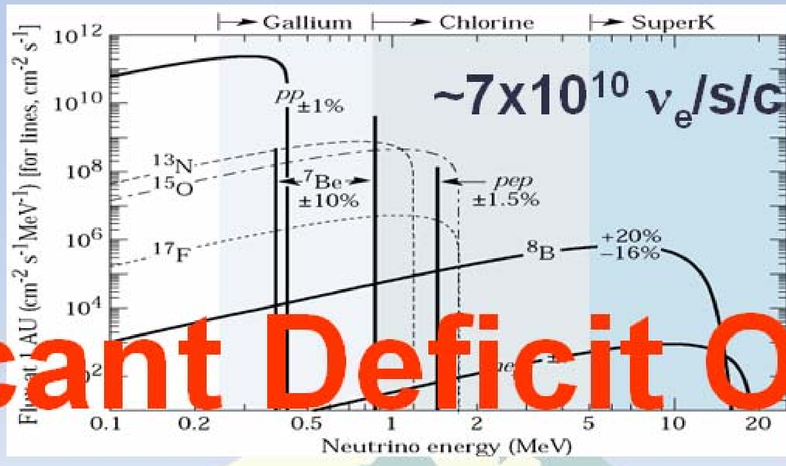




Significant Deficit Observed!!

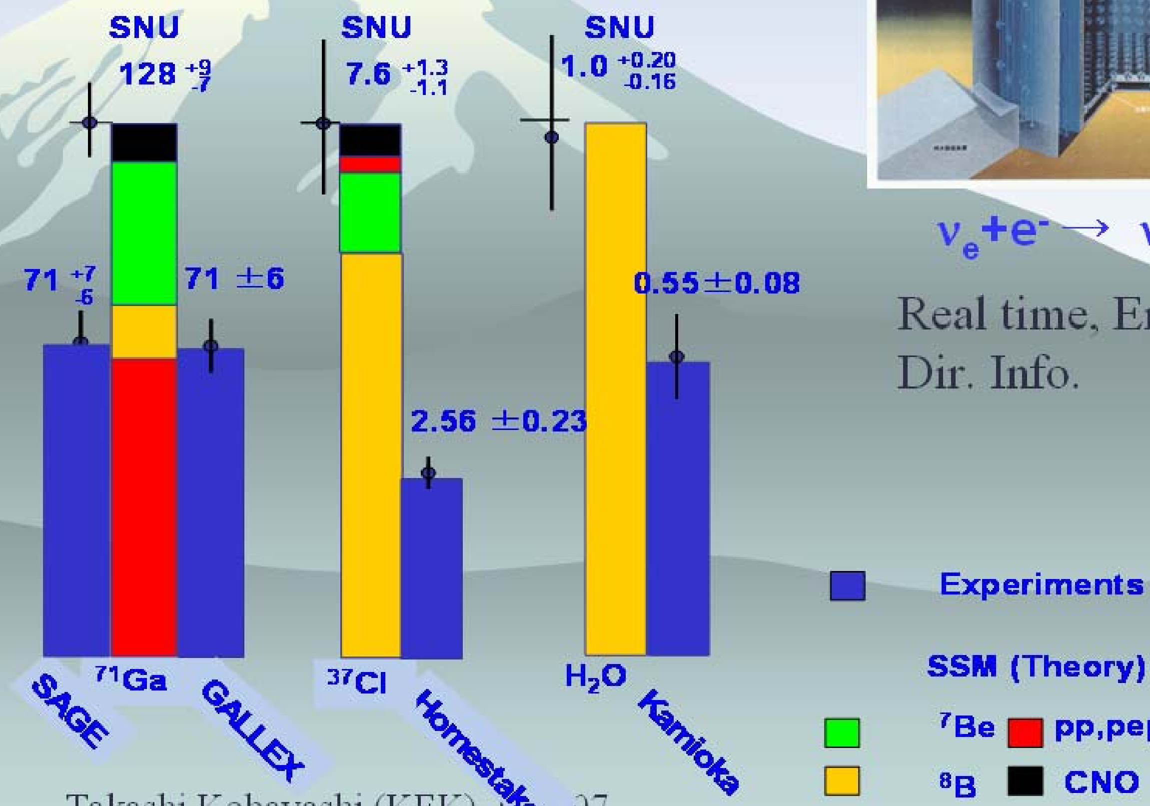
Kamiokande

(1983~1996)

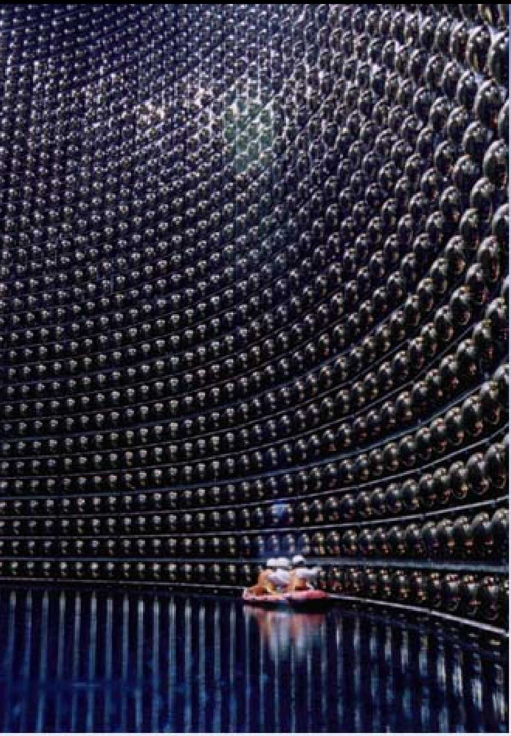
$\nu_e + e^- \rightarrow \nu_e + e^-$

Real time, Energy
Dir. Info.

Galium exp's
Gallex+SAGE
(1991~2003) (1990~)

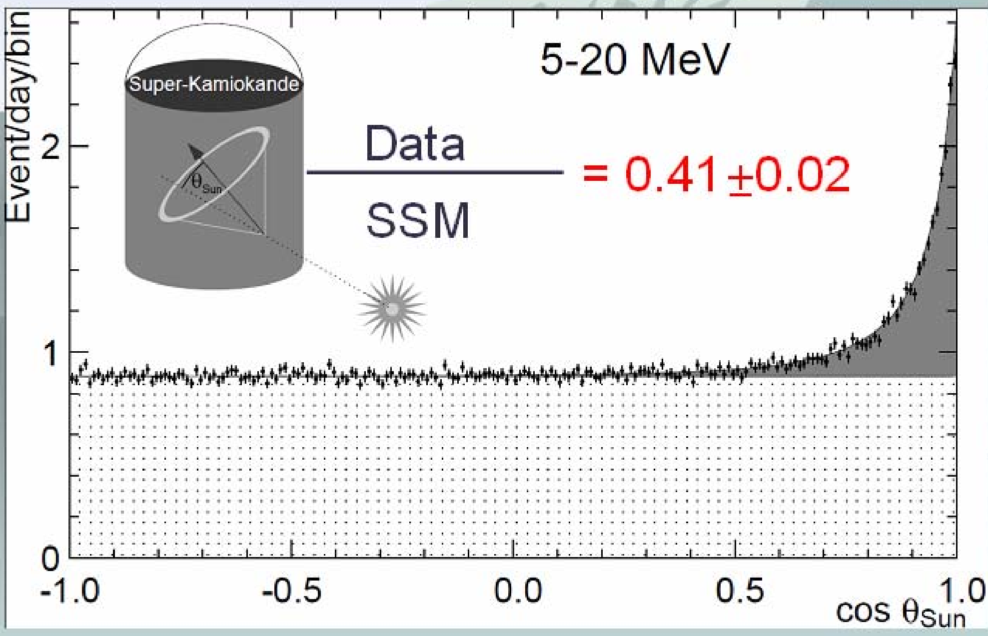


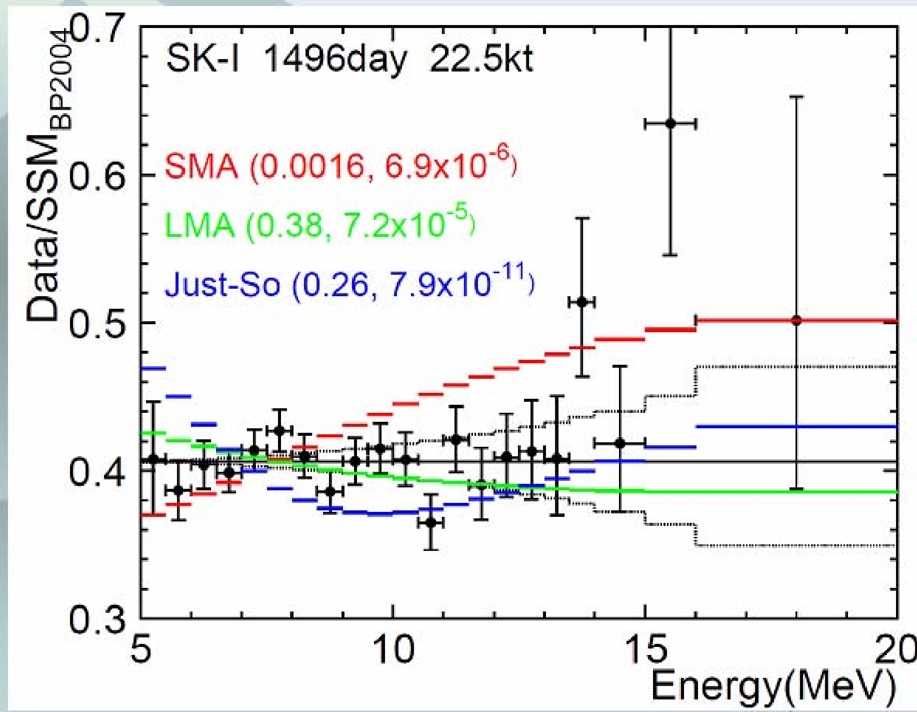
Super-Kamiokande (1996~)



- 50,000ton Water Cherenkov
  - >10x(all solar ν experiments)!
- Elastic Scatt (ES): $\nu_X + e^- \rightarrow \nu_X + e^-$
  - $\nu_e + 0.15\,(\nu_\mu + \nu_\tau)$
- Observed deficit, spectrum, etc

SK-I (1996~2001)

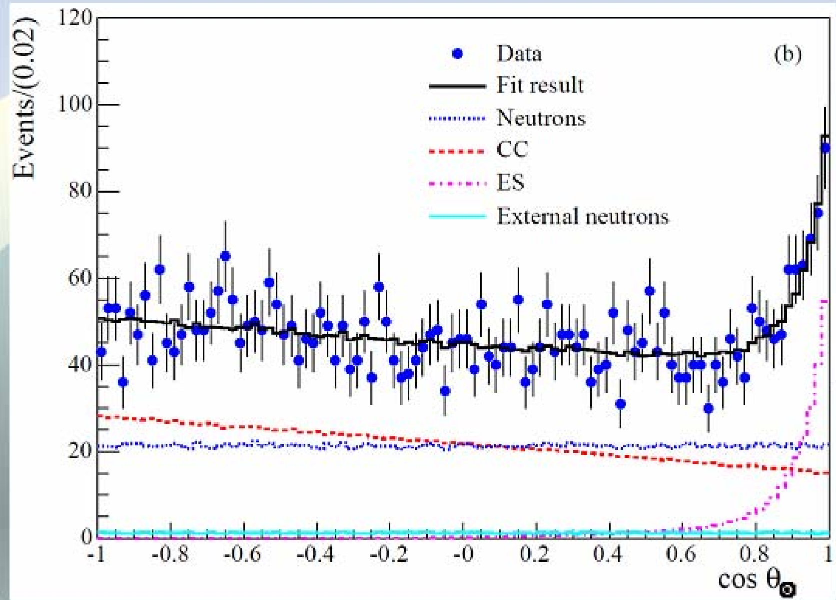




SNO @Ontario, Canada (1999~2006)

- 1000ton D_2O Cherenkov
- 6000m w.e. UG
- 12mϕ Acrylic Vessel
- 9,500 20cm-PMTs (60% coverage)

Sensitive to	# of evts
NC: $\nu_x + d \rightarrow p + n + \nu_x$	$\propto \Phi_{e+\mu+\tau}$
ES: $\nu_x + e^- \rightarrow \nu_x + e^-$	$\propto \Phi_e + 0.15\Phi_{\mu+\tau}$
CC: $\nu_e + d \rightarrow p + p + e^-$	$\propto \Phi_e$



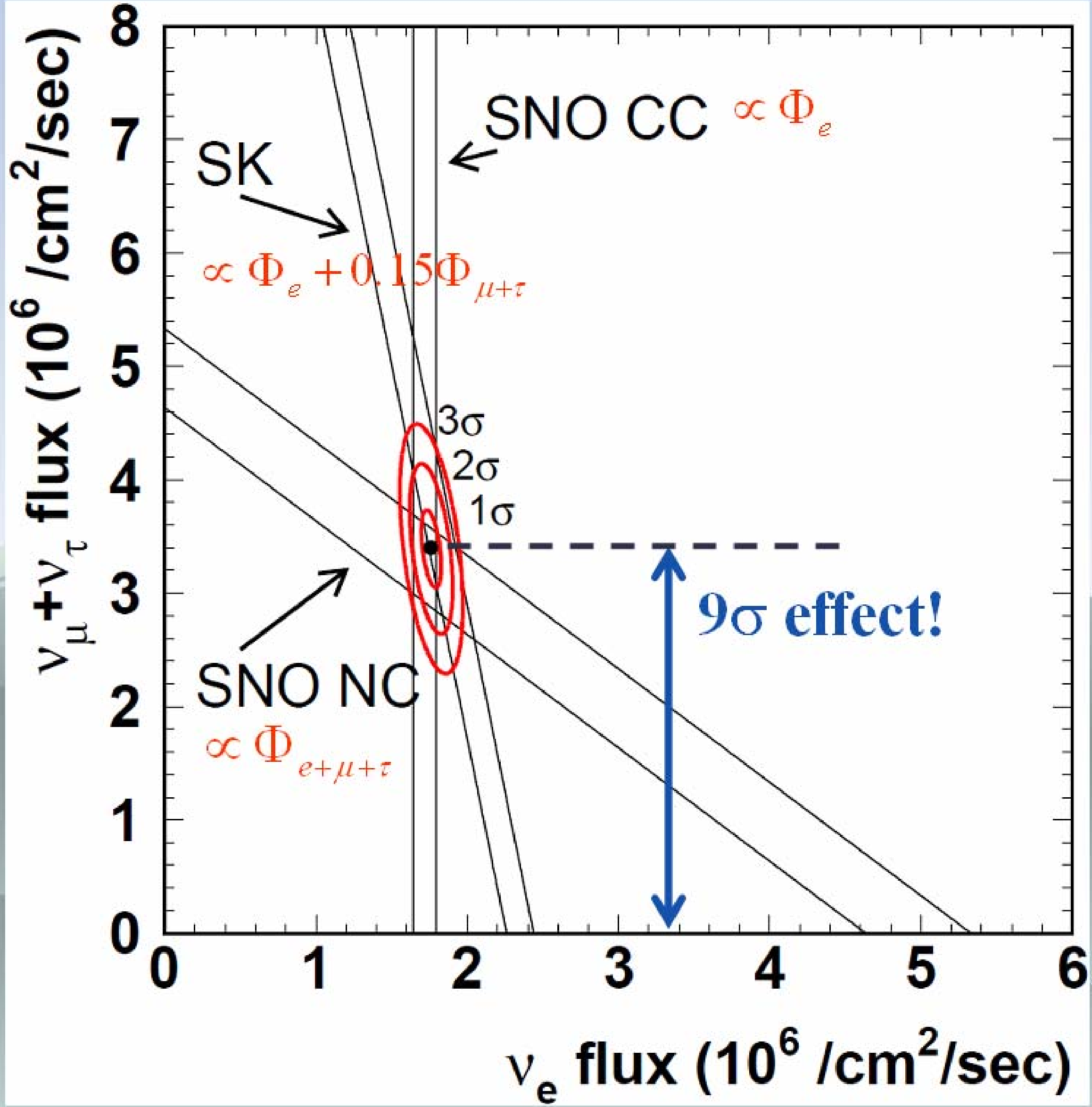
$$\Phi_{e+\mu+\tau} = 4.94 \pm 0.21(stat)^{+0.38}_{-0.34}(syst)$$

$$\Phi_e + 0.15\Phi_{\mu+\tau} = 2.35 \pm 0.22(stat) \pm 0.15(syst)$$

$$\Phi_e = 1.68 \pm 0.06(stat)^{+0.08}_{-0.09}(syst) \quad (\times 10^6 / cm^2 / sec)$$

PhysRevC72,055502(2005)

Evidence of non-ν_e components



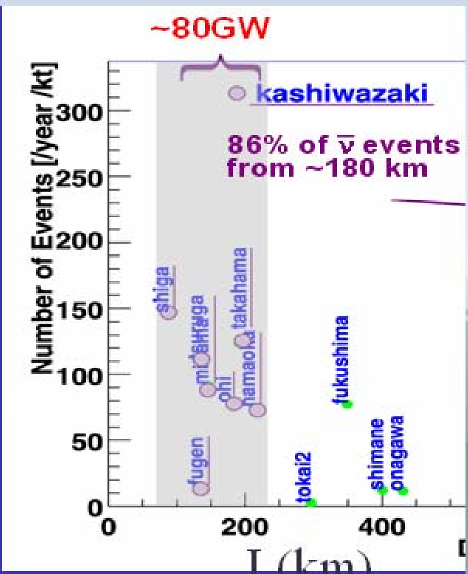
KamLAND reactor neutrino exp.(2002~)

- 1000ton liq. Scint.
  - In spherical balloon 13 m dia., 135μ thick
- 1325 17inch PMT
- <L>~180km, <E_ν>~few MeV
  - Attack Sol. ν of $\Delta m^2 > 10^{-5}$eV

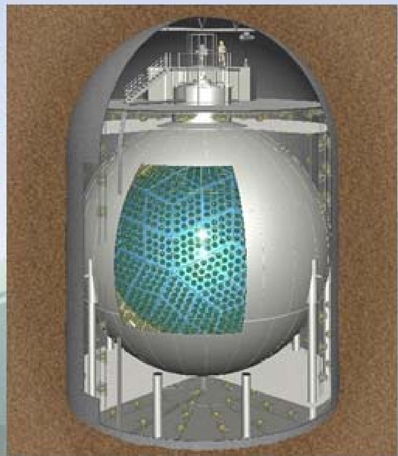
Detect $\bar{\nu}_e$ from reactor

$$\bar{\nu}_e + p \rightarrow e^+ + n, \quad e^+ + e^- \rightarrow 2\gamma \text{ (prompt)}$$

$$n + p \rightarrow d + \gamma \text{ (2.2 MeV) (delayed)}$$



L(km)



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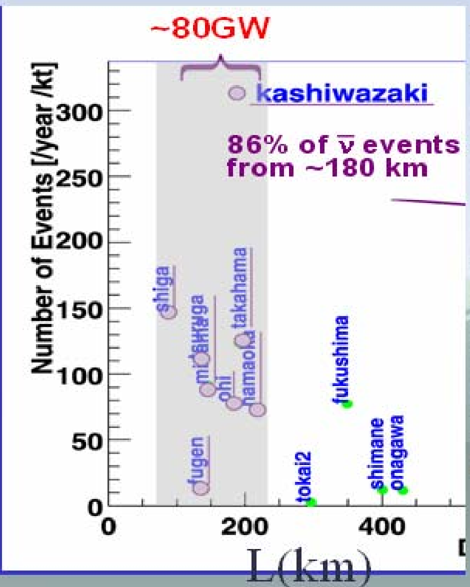
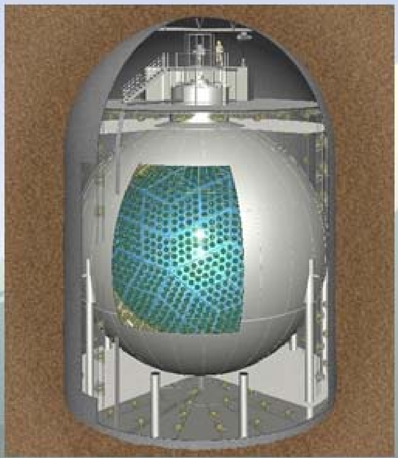
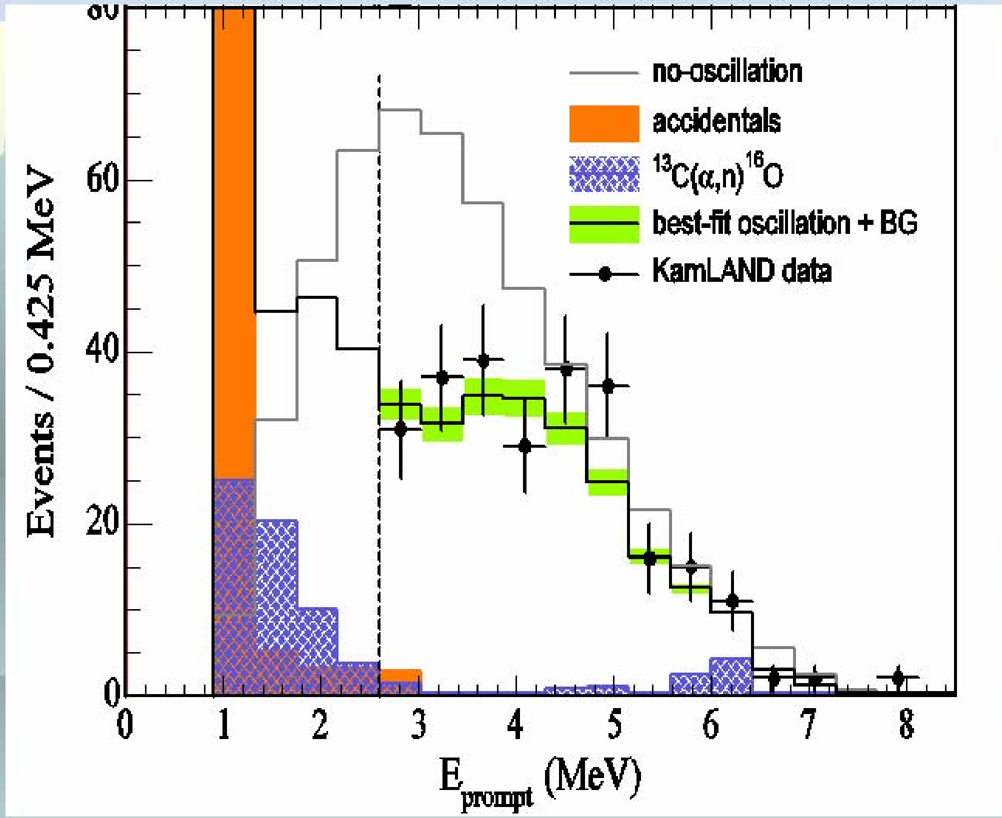
Significant deficit & Distortion Observed!







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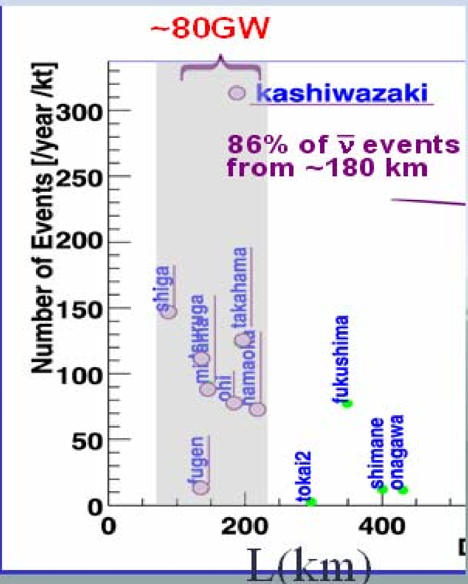
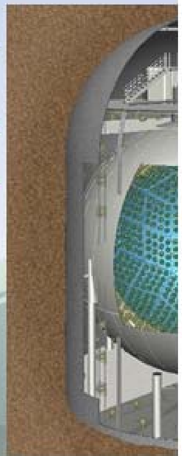
$\overline{\nu}_e$ + p → e^+ + n, $e^+ + e^- \rightarrow 2\gamma$ (prompt)

n + p → d + γ (2.2 MeV) (delayed)

Oscillatory Behavior Observed!

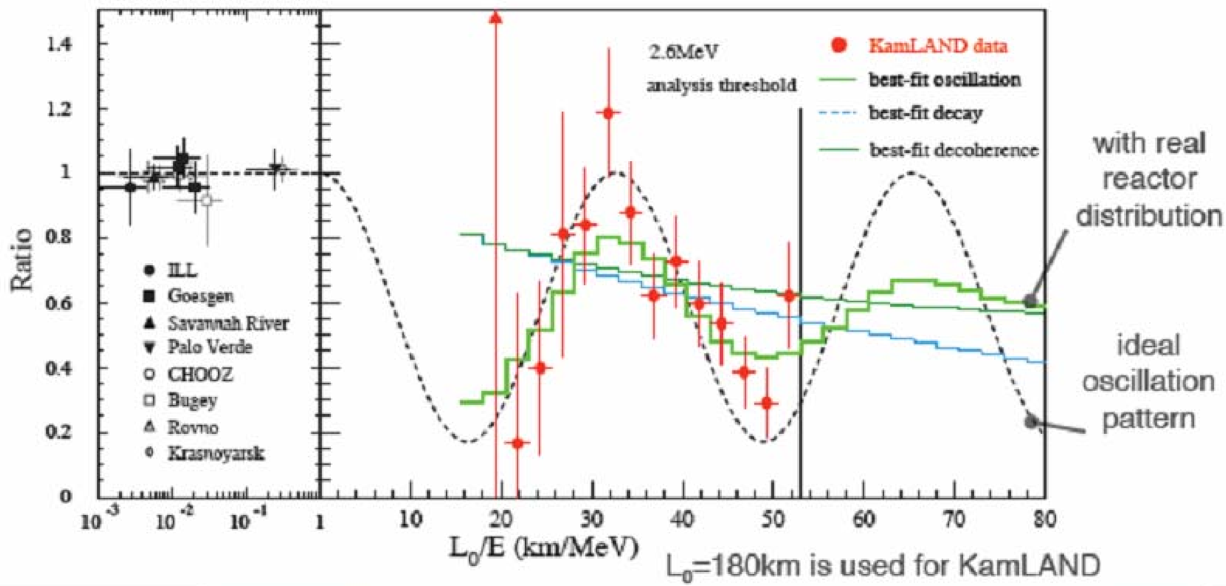




oscillation $P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4}\frac{L}{E})$

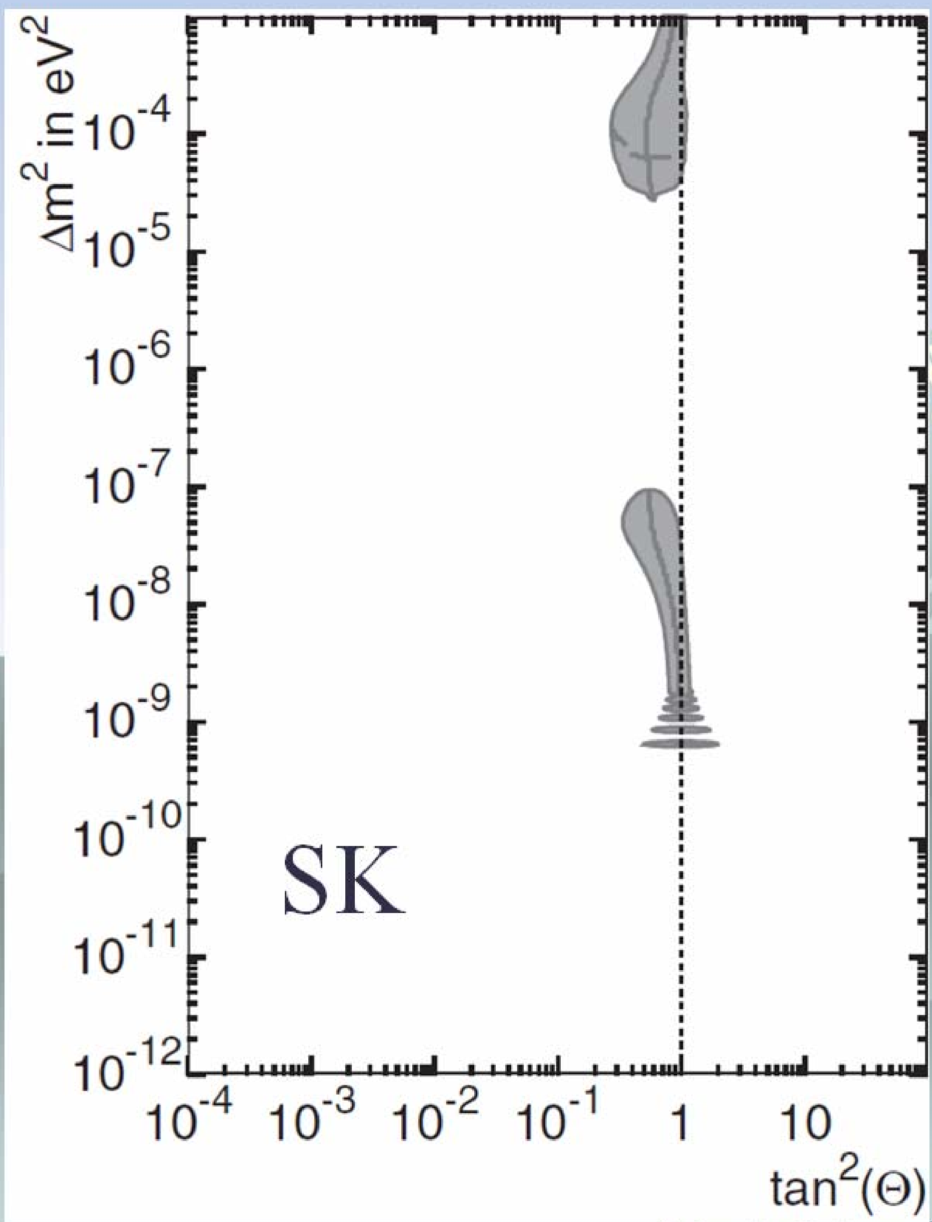
decay $P_{ee} = (\cos^2\theta + \sin^2\theta \exp(-\frac{m_2}{2\tau}\frac{L}{E}))^2$

decoherence $P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta(1 - \exp(-\gamma\frac{L}{E}))$



No osc. excluded @ 99.999995%

Constraints on Δm_{12}^2, θ_{12}



$$P = \sin^2 2\theta_{12} \cdot \sin^2\left(1.27 \frac{\Delta m_{12}^2[\mathrm{eV}^2] \cdot L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

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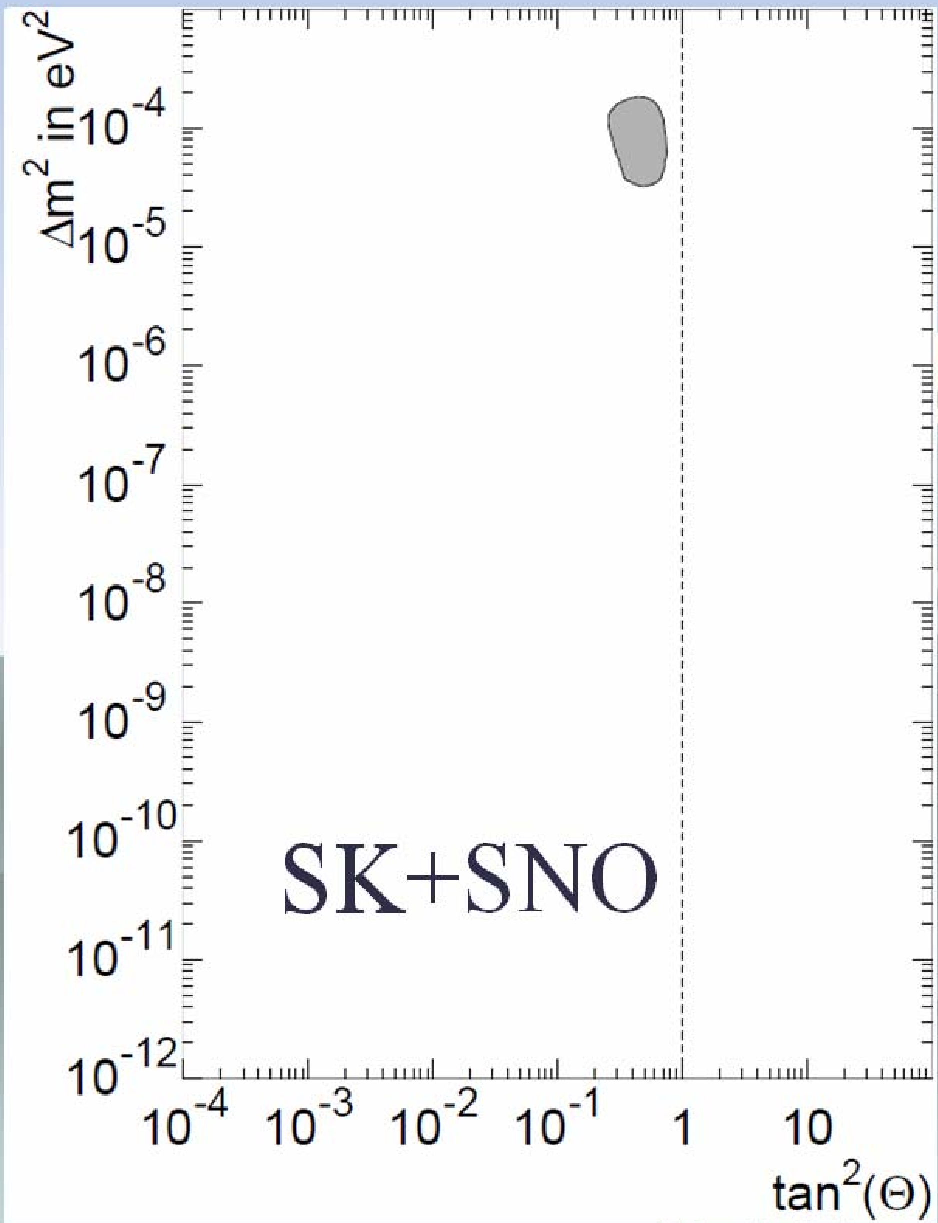

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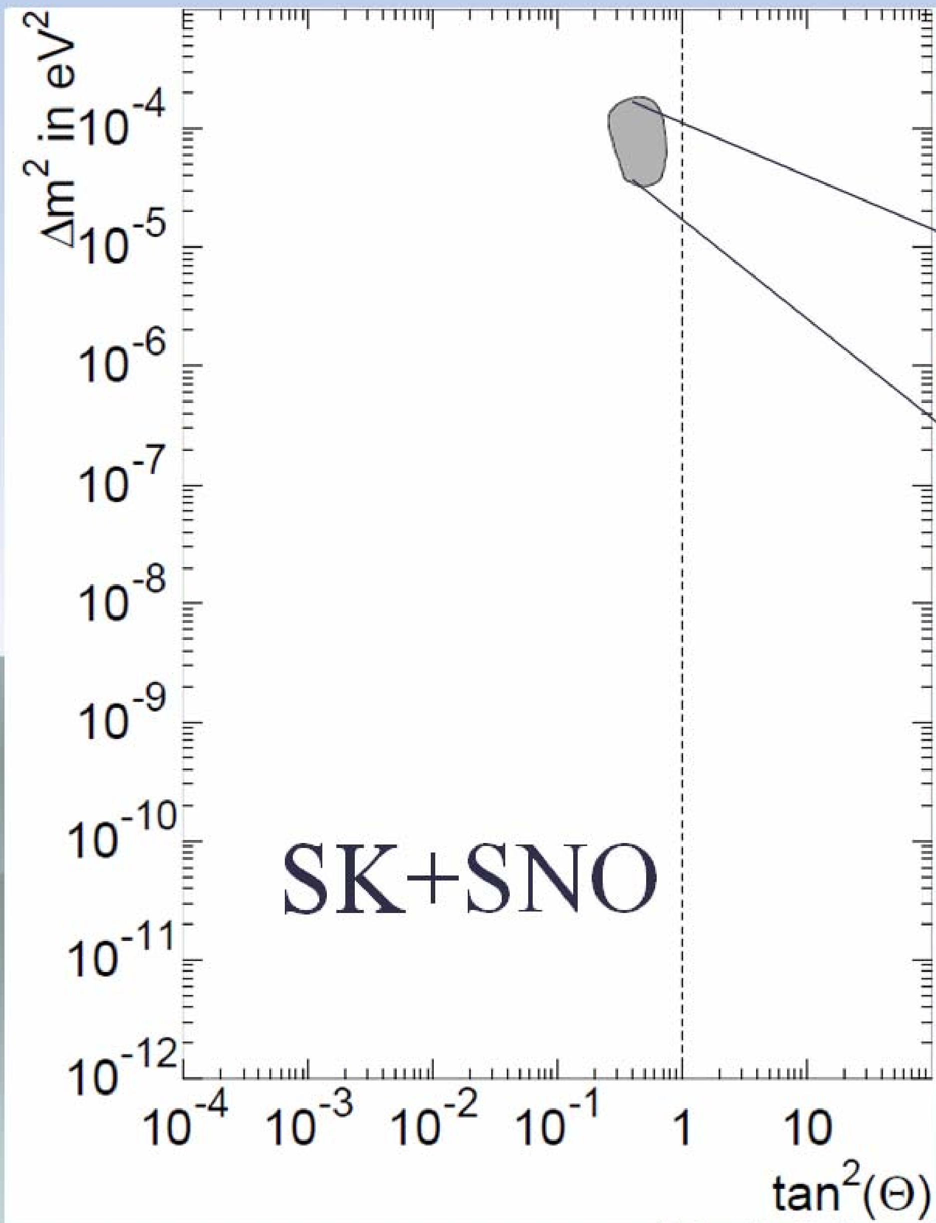

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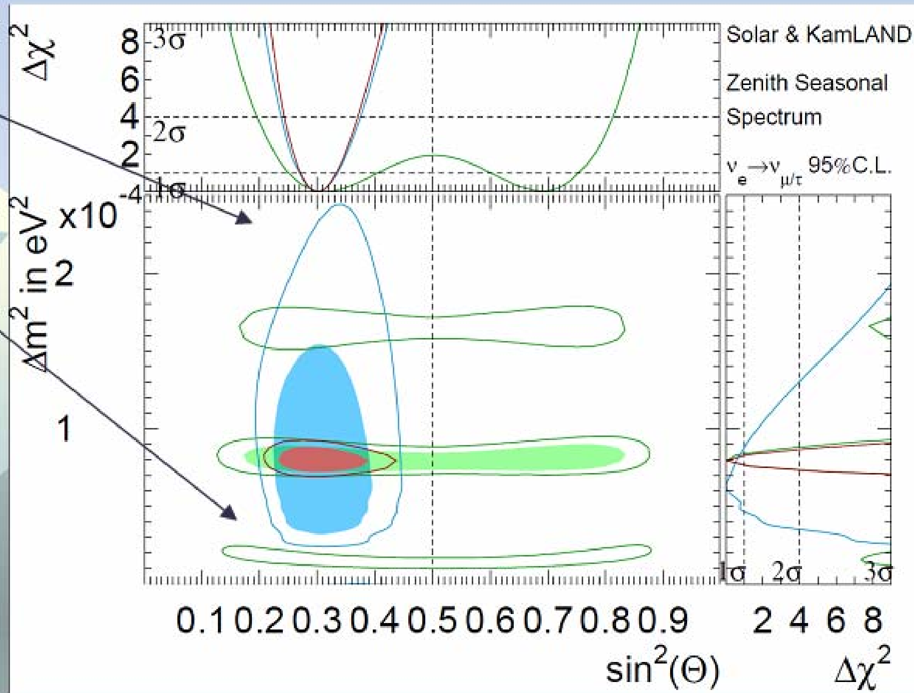

All Solar + KamLAND

Constraints on Δm_{12}^2, θ_{12}

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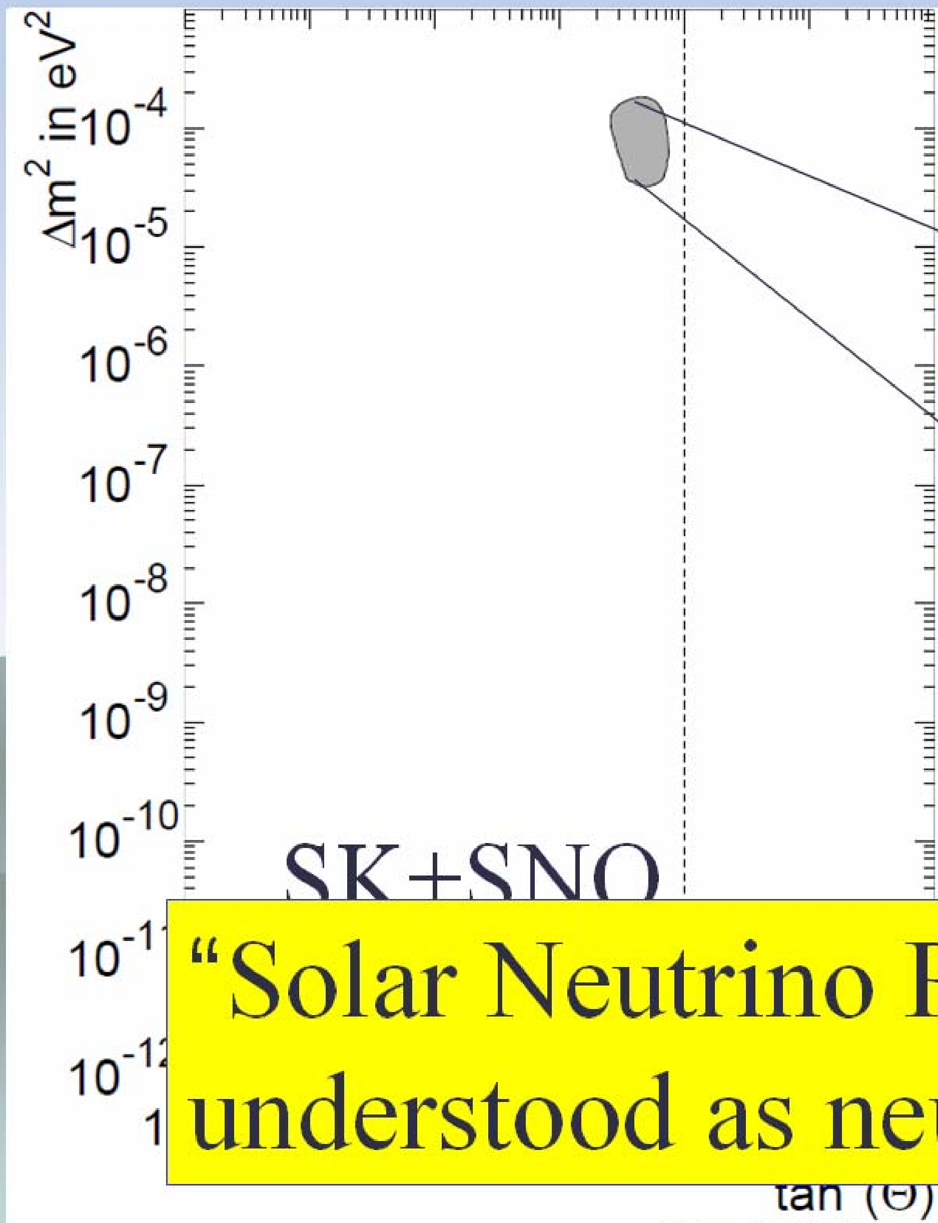
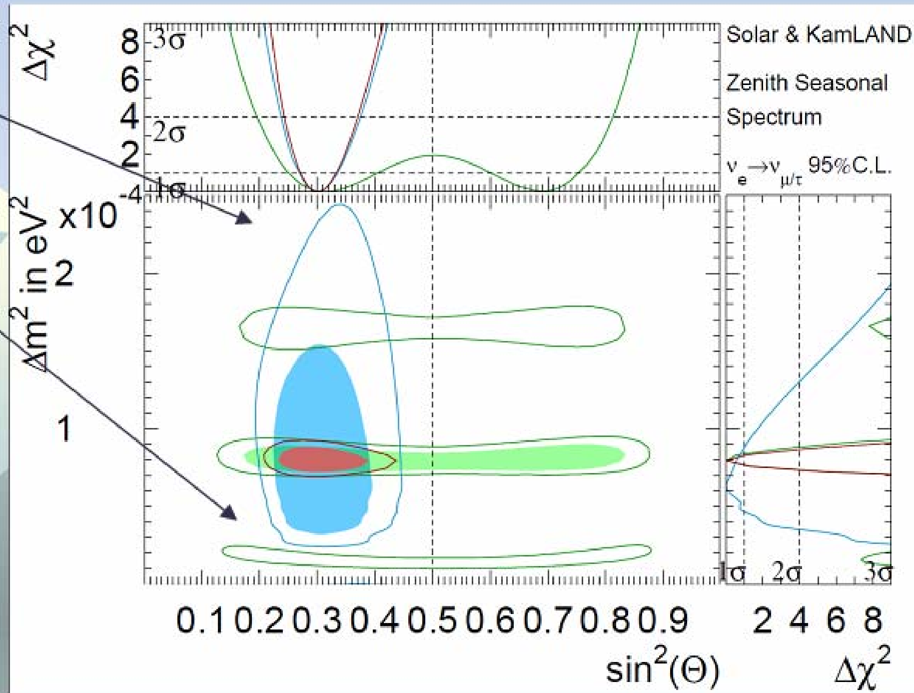




"Solar Neutrino Problem" is now understood as neutrino oscillation

Cosmic ray(proton, He)

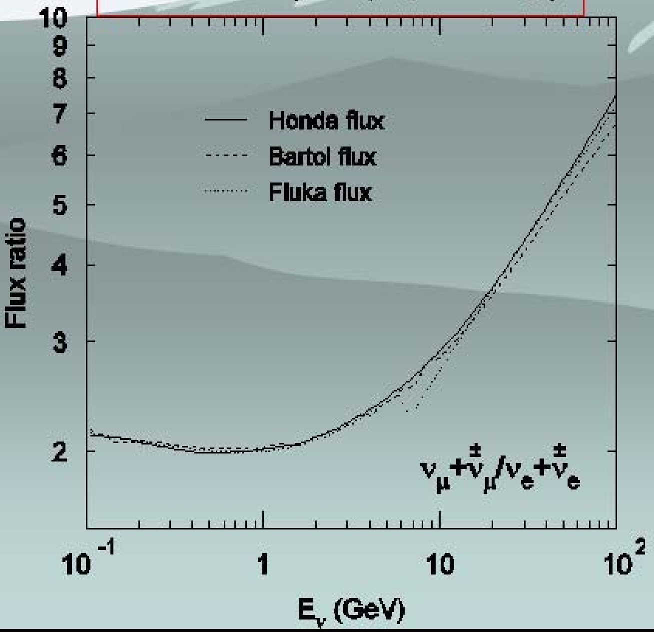
p, He

Altitude10-20 km

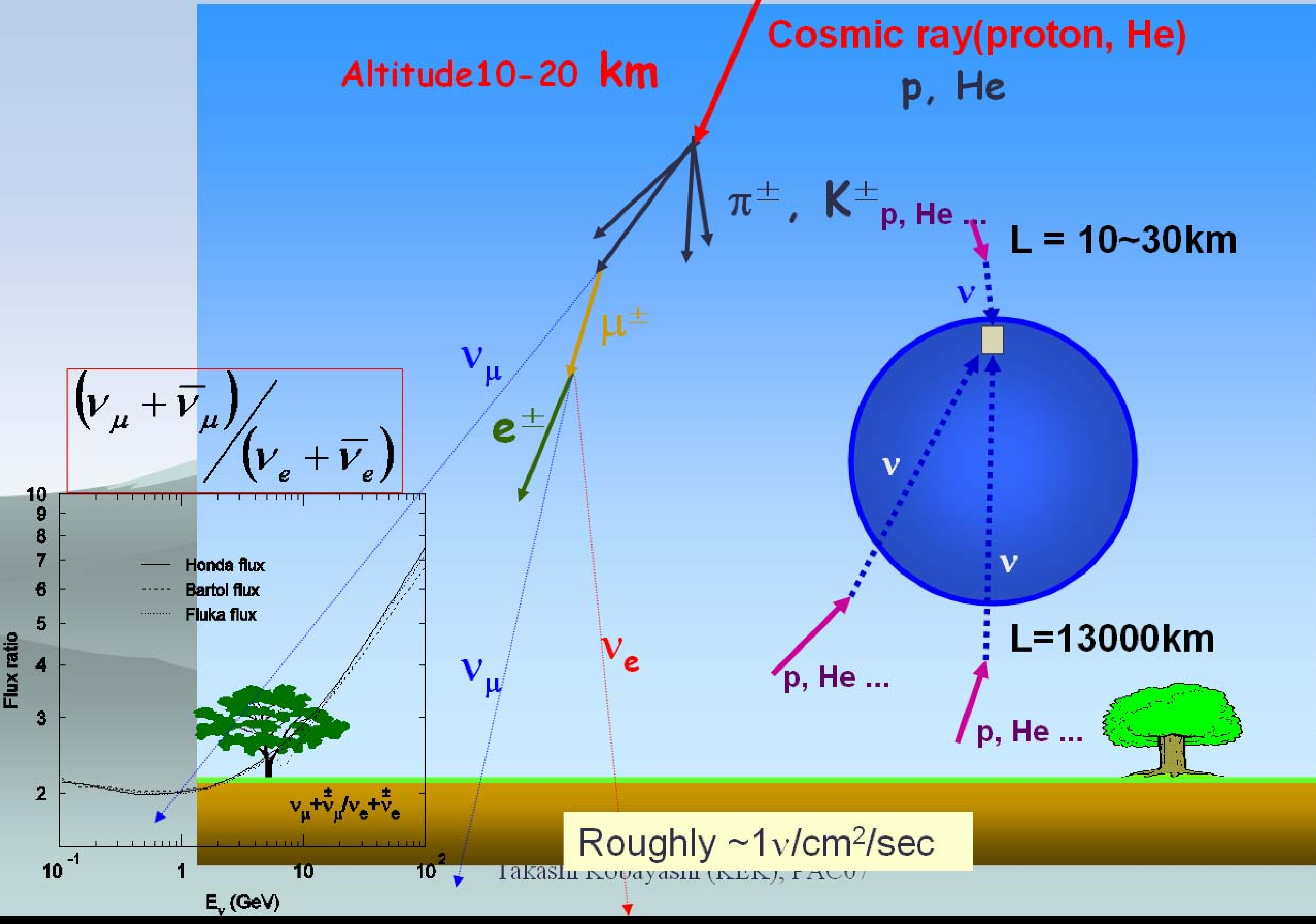
$\mu^{\pm}$

ν_{μ}

$$\left(\nu_{\mu}+\overline{\nu}_{\mu}\right) \Big/ \left(\nu_{e}+\overline{\nu}_{e}\right)$$



Atmospheric neutrino

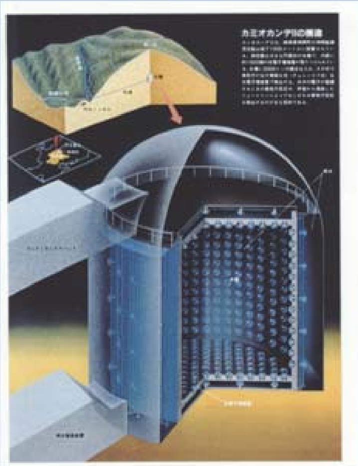


$$\left(\nu_\mu + \bar{\nu}_\mu\right) \Big/ \left(\nu_e + \bar{\nu}_e\right)$$

Roughly ~1ν/cm²/sec

"Atmospheric neutrino anomaly" before SK

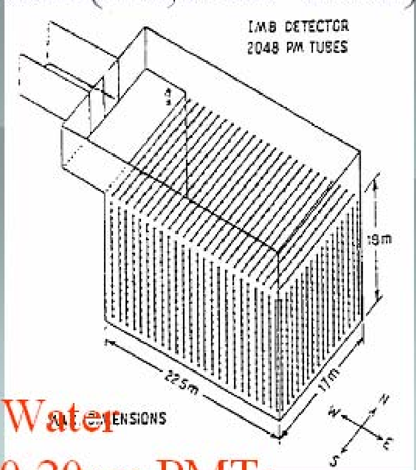
Kamiokande



3kt Water,
1000 50cm PMTs

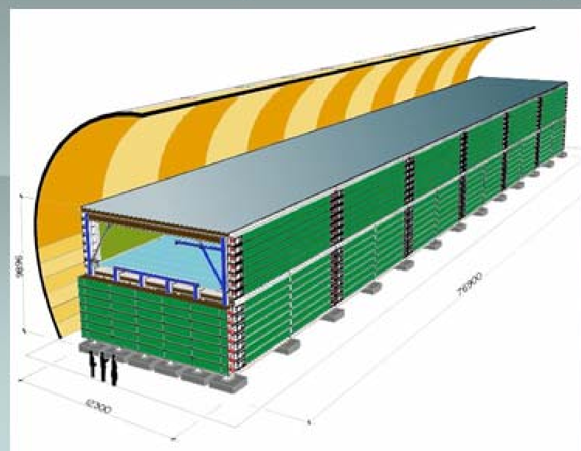
Soudan-2 (US, 1989-1991)

IMB(US,1982~1991)



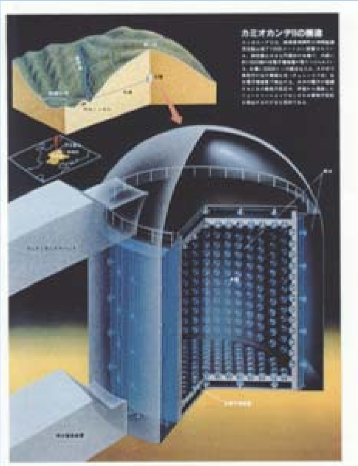
8kt Water
2000 20cm PMTs

MACRO (Gran Sasso)



"Atmospheric neutrino anomaly" before SK

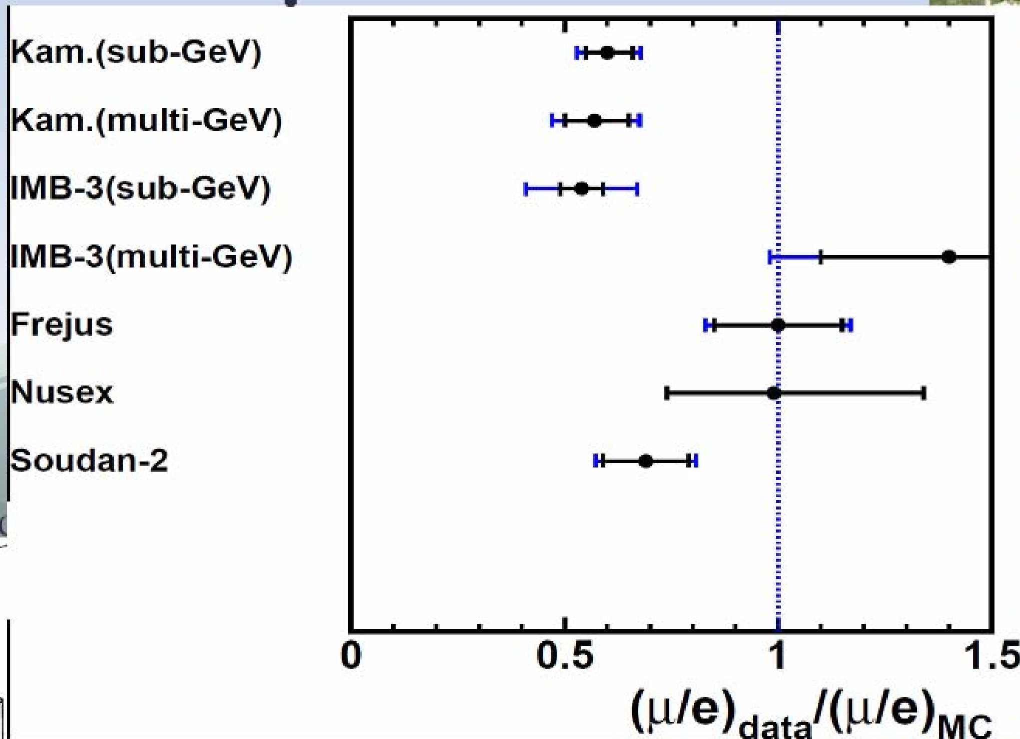
Kamiokande



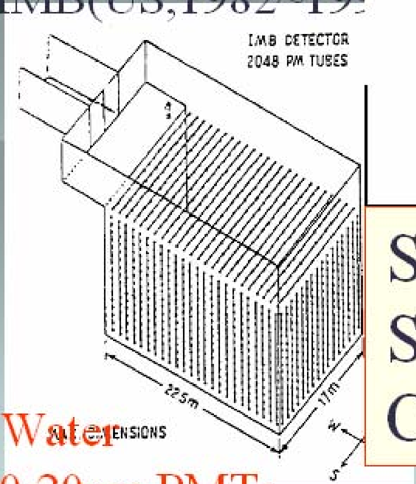
3kt Water,
1000 50cm PMTs

Soudan-2 (US, 1989-1991)

μ/e ratio

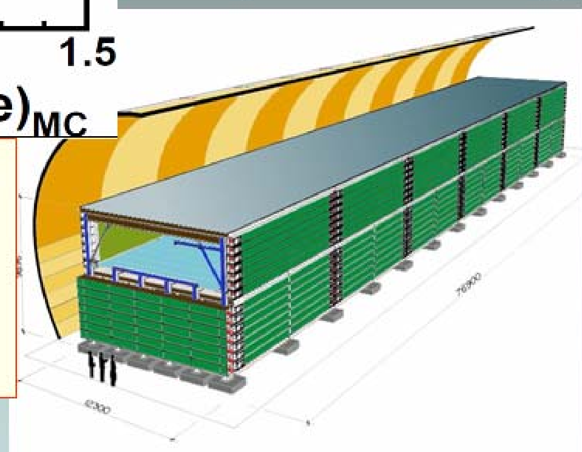


IMB(US,1982~19



8kt Water
2000 20cm PMTs

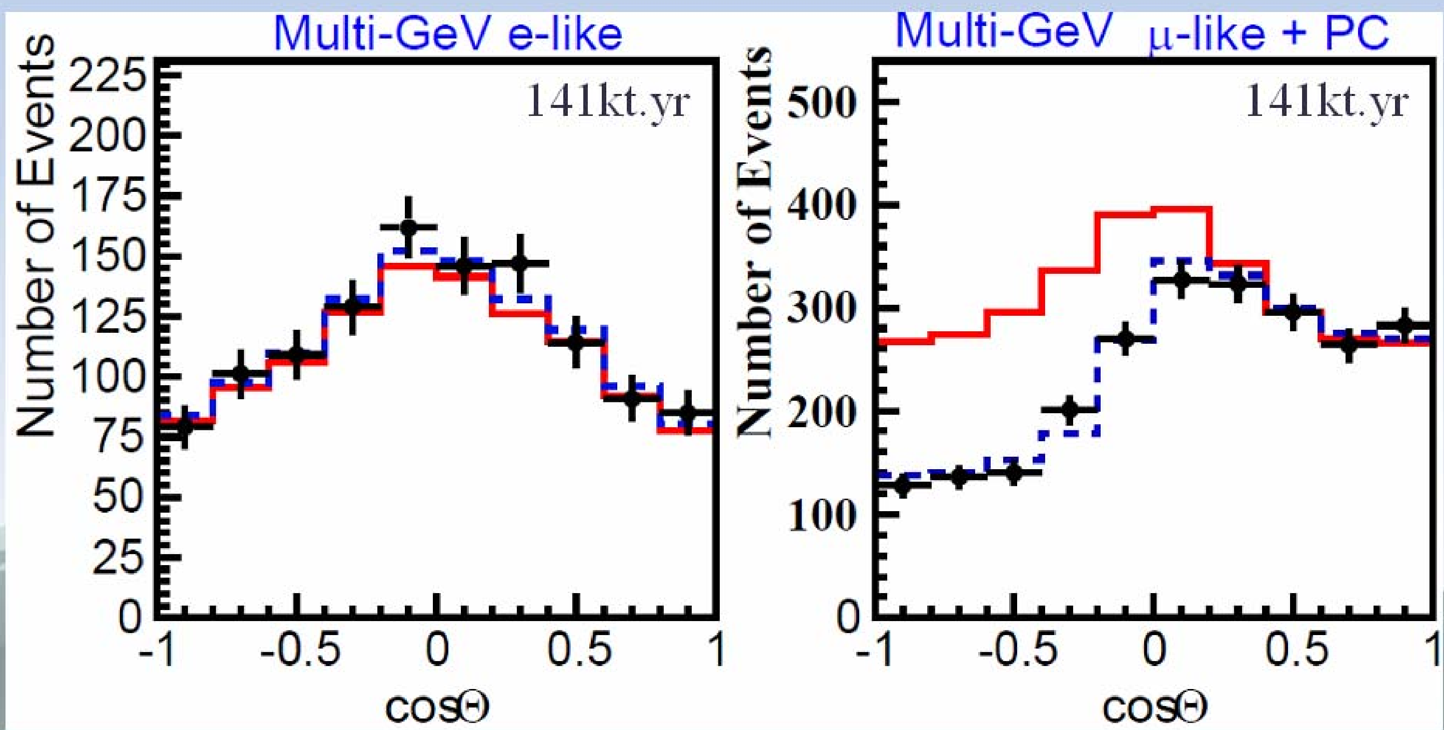
CRO (Gran Sasso)

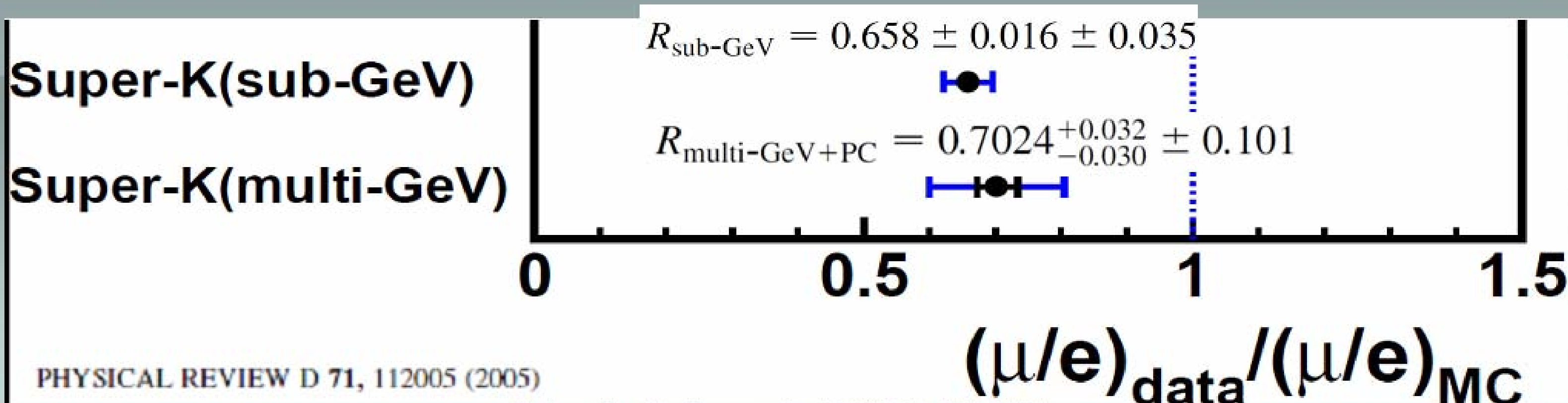


Smaller than exp'ed significantly
Some agree w/ exp'ed
Clarification was desired

Super-Kamiokande Observations (1996~)

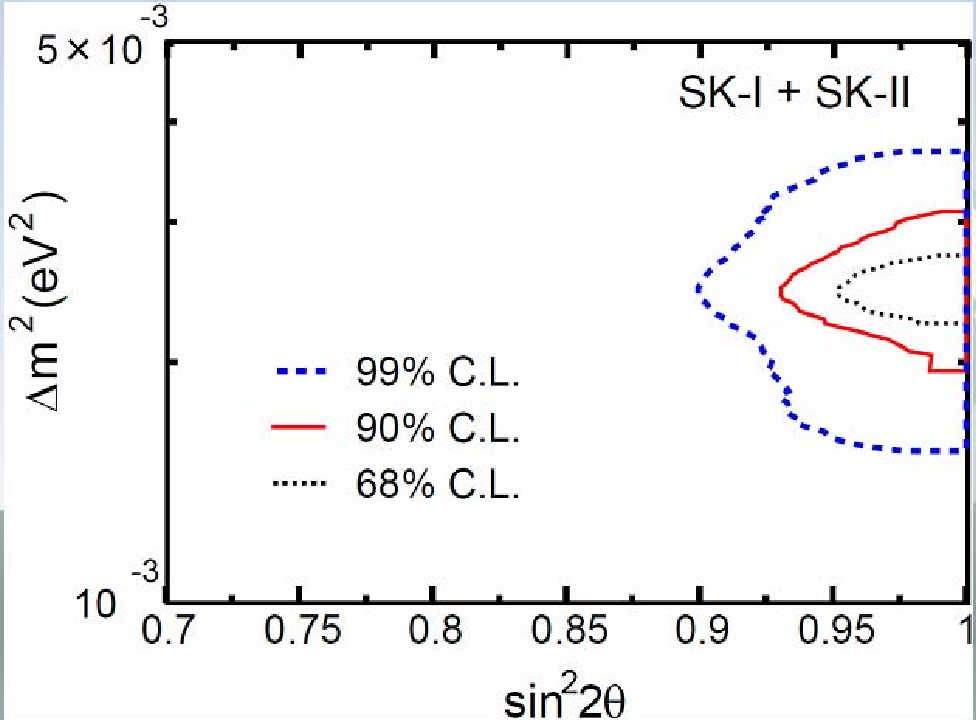
- "Evidence of neutrino oscillation"



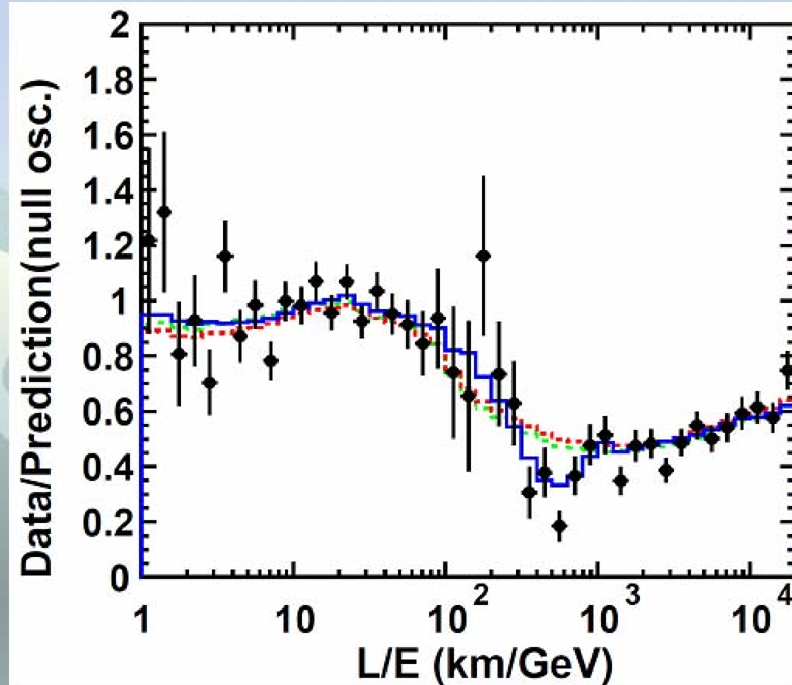


Constraint on Δm_{23}^2, θ_{23} from SK

Allowed parameter region



L/E analysis



90% CL allowed region:

$\sin^2 2\theta_{23} > 0.93$

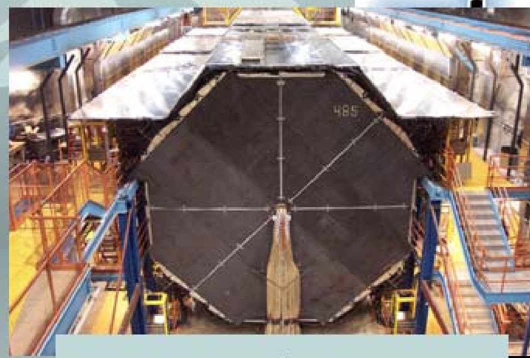
$1.9 < \Delta m_{23}^2 < 3.1\times10^{-3} eV^2$

Clear oscillatory behavior

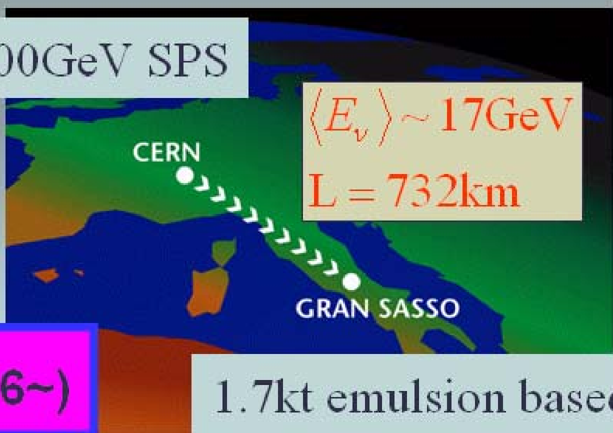
$$P \approx \sin^2 2\theta_{23} \cdot \sin^2\left(1.27\frac{\Delta m_{23}^2[\mathrm{eV}^2]\cdot L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

Confirmation by accel. long baseline (LBL) experiments

- p+X→π^+→$\nu\mu$+μ
  - Pure (~99%) $\nu\mu$, ~1% ν_e
- Confirm SK atm ν w/ different, well-controled systematics
  - L, dir. Known
  - Eν can be measured
  - → Spectrum distortion
  - Initial spec/flavor contents measured
- K2K(1999~2004) FINISHED!
  - $\nu\mu$ disapp/ νe app
- MINOS (2005~) ON-GOING
  - $\nu\mu$ disapp/(νe app)
- OPERA(2006~) Commissioning
  - $\nu\tau$ appearance
  - Beam: 1st comm:Aug2006, 2nd :Sep2007
  - 60~70k /154k emulsion bricks when 2nd comm.



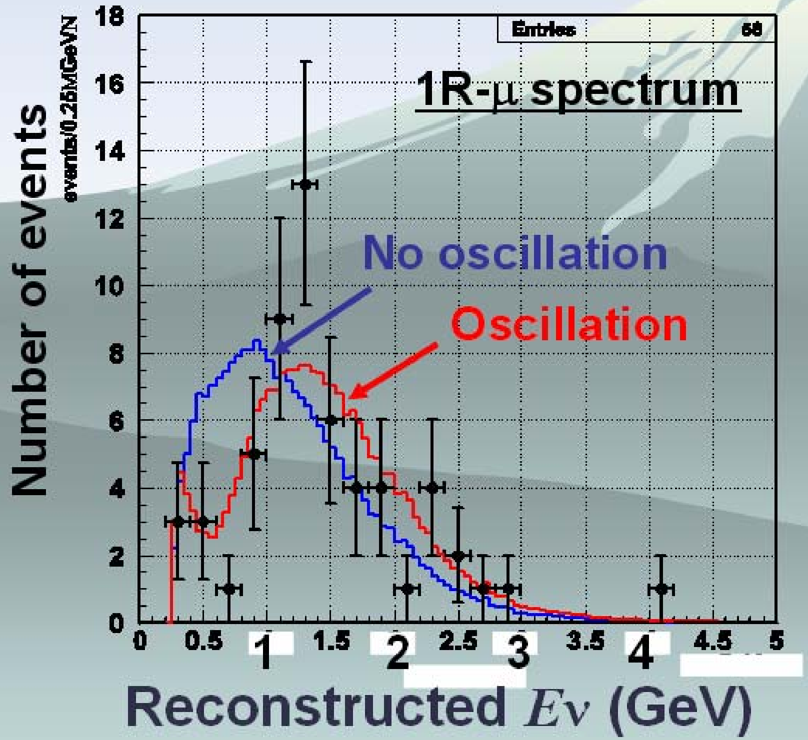
5.4kt Mag'ed Iron-scinti. Sandwich trk.



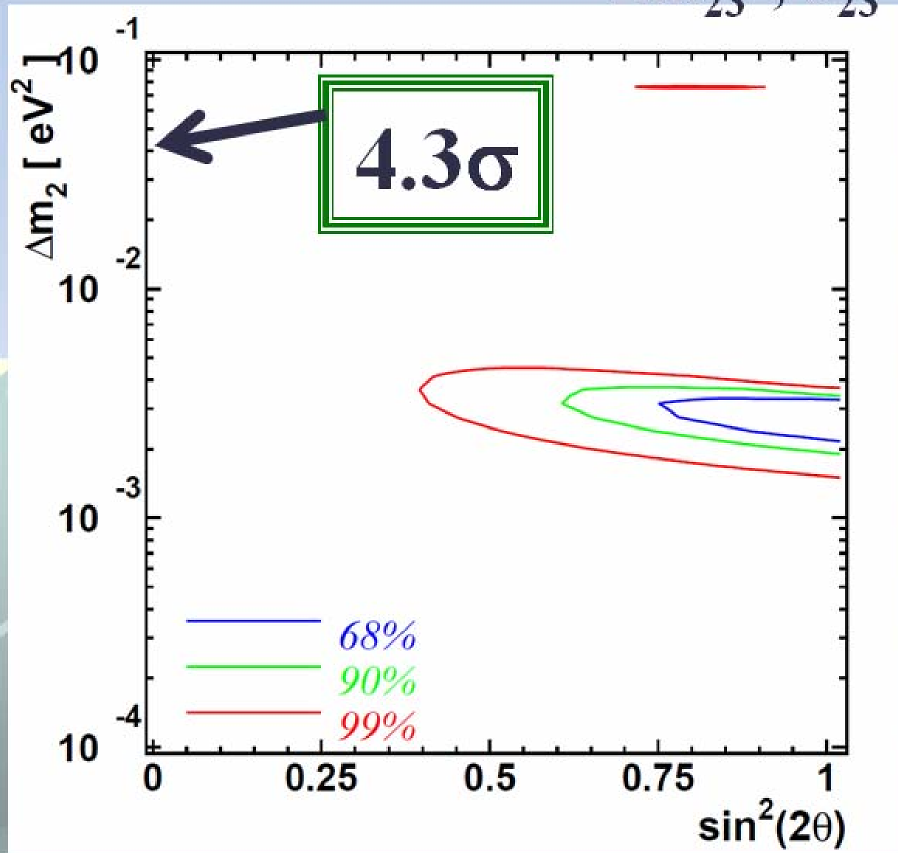
1.7kt emulsion based

K2K final results (2006)

- # of events
  - Exp'ed: $158.1^{+9.2}_{-8.6}$
  - Obs'ed: **112**
- Spectrum shape
  - 2.8σ distortion



$\Delta m_{23}^2, \theta_{23}$

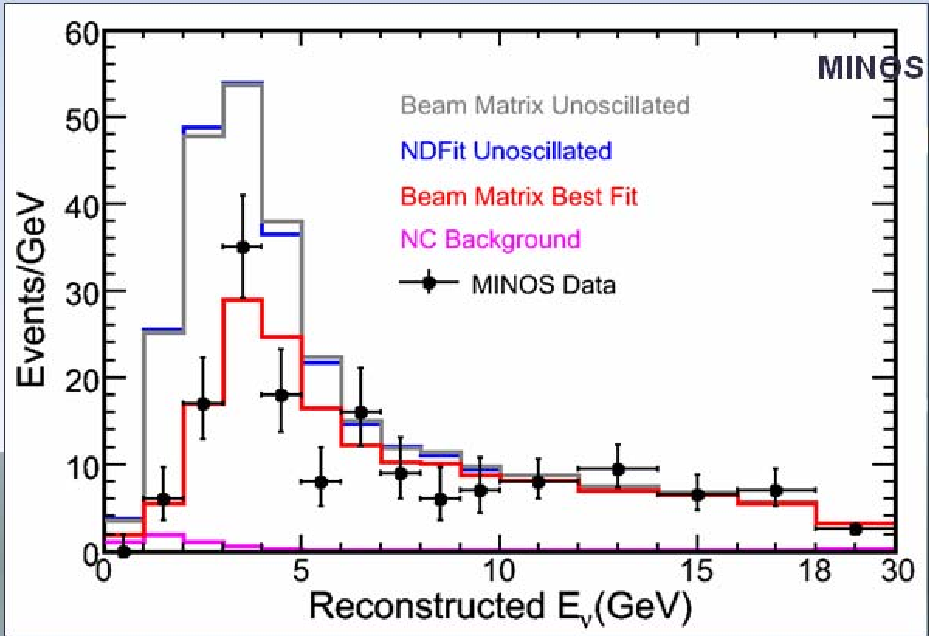


Consistent w/ SK

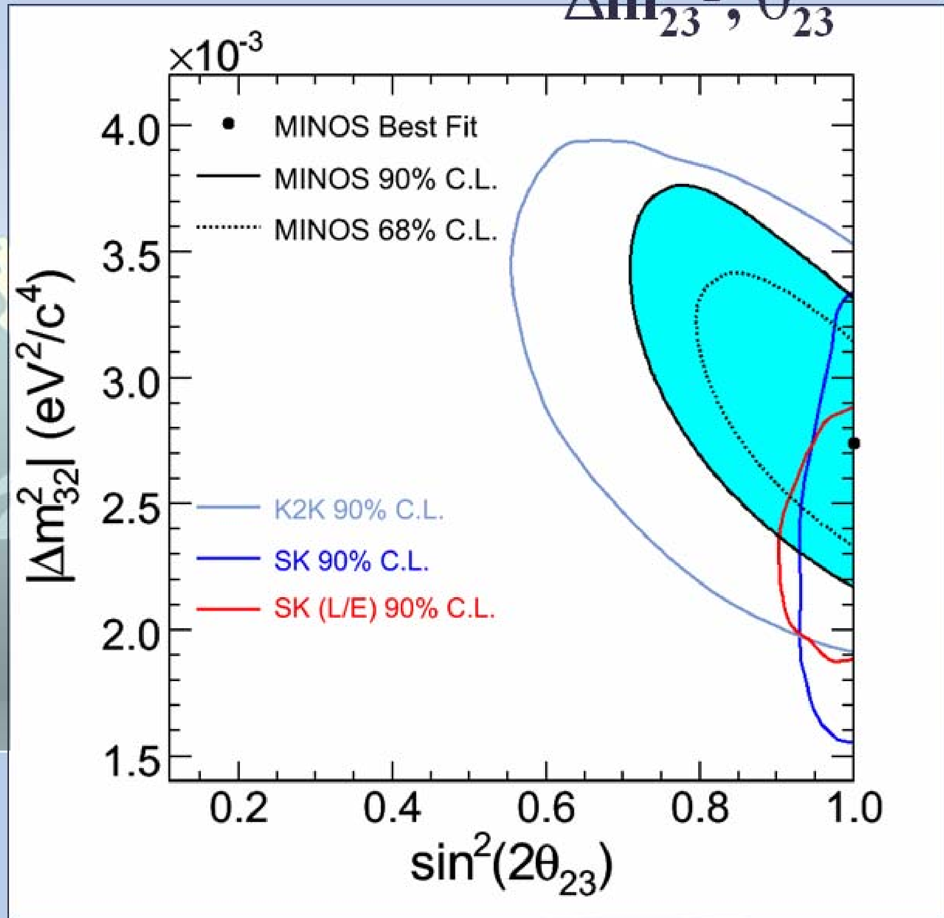
Definitely confirmed SK atm ν results!

MINOS 1st yr results

- May 2005~Mar. 2006
- Best-fit spectrum for 1.27x10^{20} POT



$\Delta m_{23}{}^2$, θ_{23}



$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\text{stat} + \text{syst}) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}\ (\text{stat} + \text{syst})$$

$$\text{Normalizat ion} = 0.98$$

MINOS 1st yr results

- May 2005~Mar. 2006
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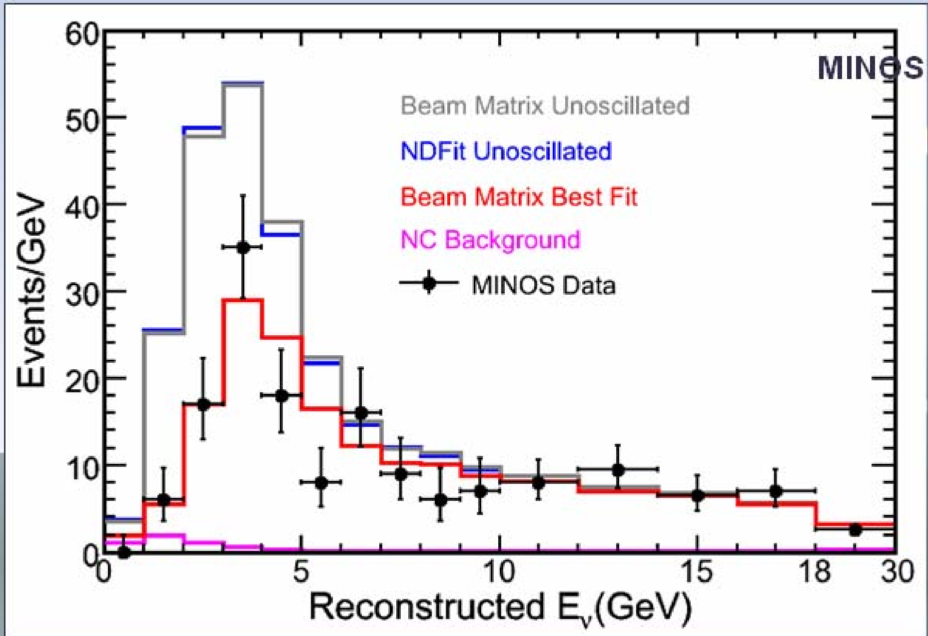
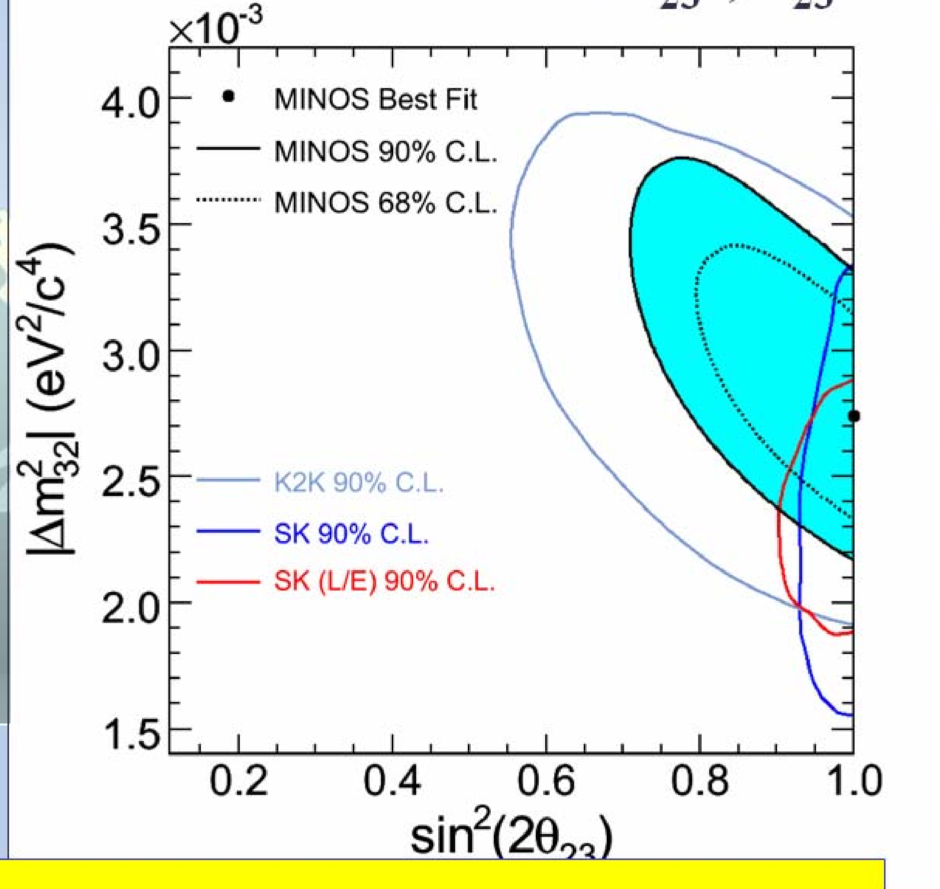


Δm_{23}^2, θ_{23}

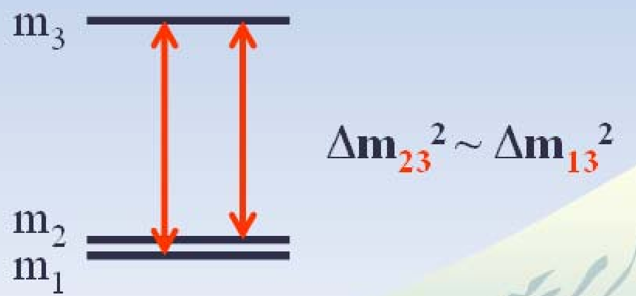


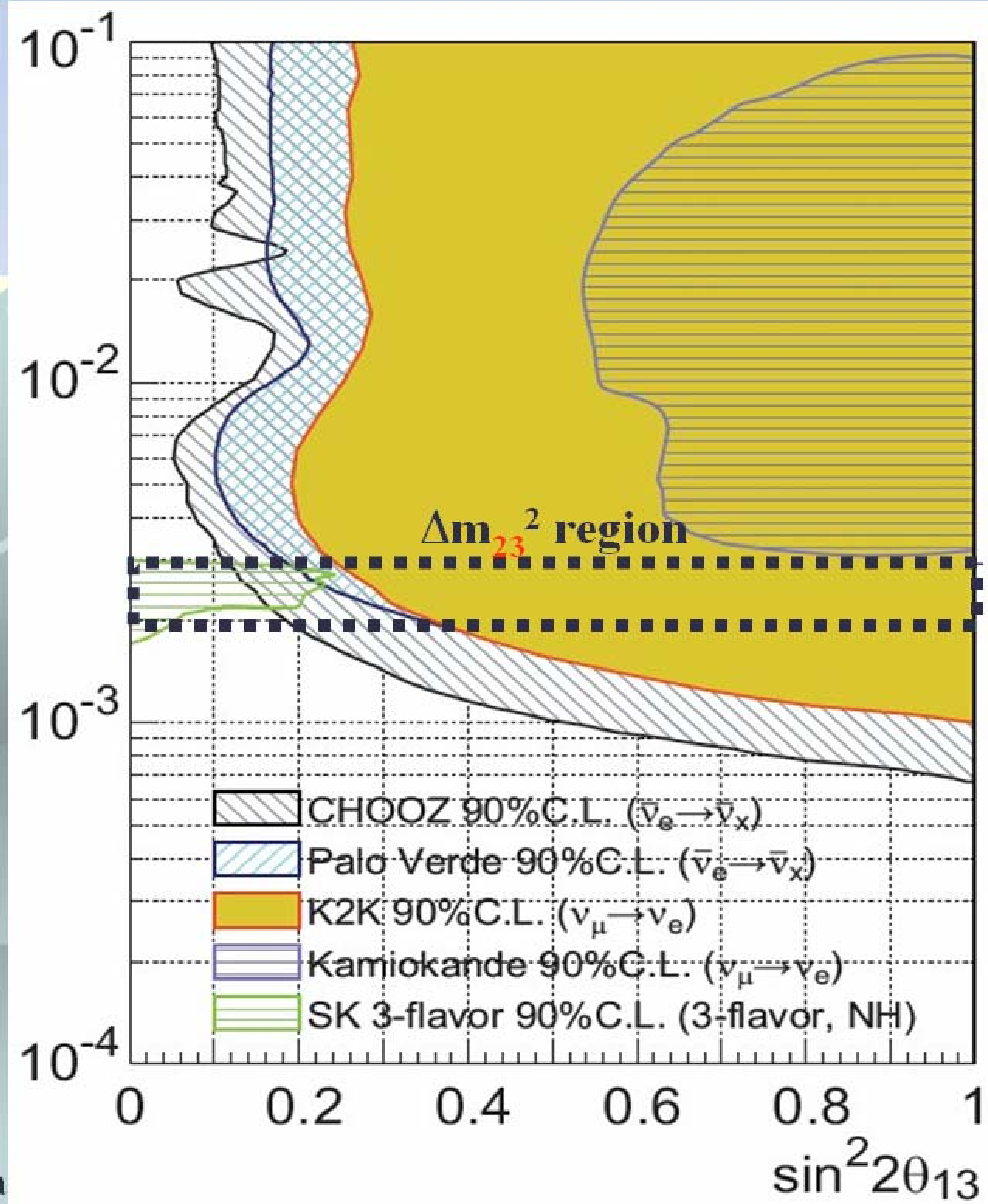
$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\text{stat} + \text{syst}) \times 10^{-3}\,\text{eV}^2$$

"Atmospheric Neutrino Anomaly" is now understood as neutrino oscillation

ν_μ<->ν_e osc. Search around atm ν Δm^2: Constraint on Δm_{13}^2, θ_{13}

$$P \approx \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\frac{\Delta m_{13}^2[\mathrm{eV}^2]\cdot L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$



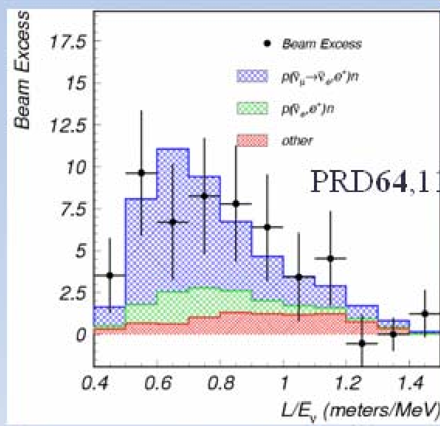


- $\nu_\mu \to \nu_e$ appearance search
  - Atm ν
  - K2K
- $\bar{\nu}_e$ disappearance search in reactor
  - Eν~MeV, L~km
- No evidence so far
- $\sin^2 2\theta_{13} < 0.15$ at $\Delta m^2 = 2.5\times 10^{-3}$ eV^2
  - From Chooz reactor exp

LSND Issue

New! (Apr.2007)

- **LSND observe ν_e excess in ν_μ beam (2001)**
  - ~30MeV $\nu\mu$ from μ^+ decay at rest det'ed ~30m
  - If oscillation: Δm^2~1eV^2, $\sin^2 2\theta$~$10^{-(2\sim3)}$
- If true
  - 3 mass diff. (sol~10^{-4}/atm~2.5×10^{-3}/LSND~1)
    - ➔ **>3 ν's?,** Sterile? (LEP says # of active vs .le. 3)
  - **CPTV?**
- Definite confirmation necessary
  - w/ **different systematics**
  - ➔ **MiniBooNE**
- MiniBooNE Experiment (2002~)
  - ~GeV wideband $\nu\mu$ beam from 8GeV Booster @ FNAL
  - 800ton pure mineral oil, R=6m Cherenkov det @ 500m, 1280 PMT
  - Search for ν_e events

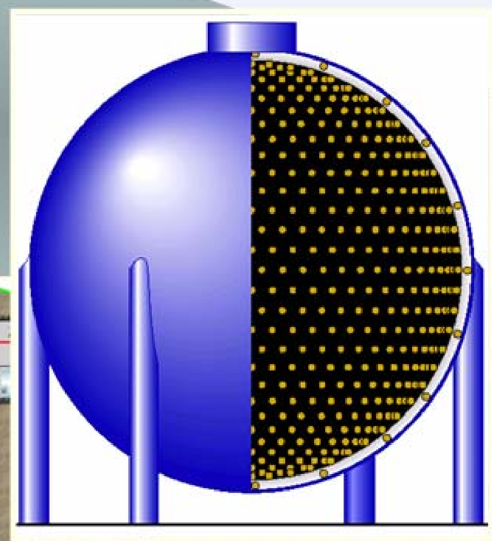


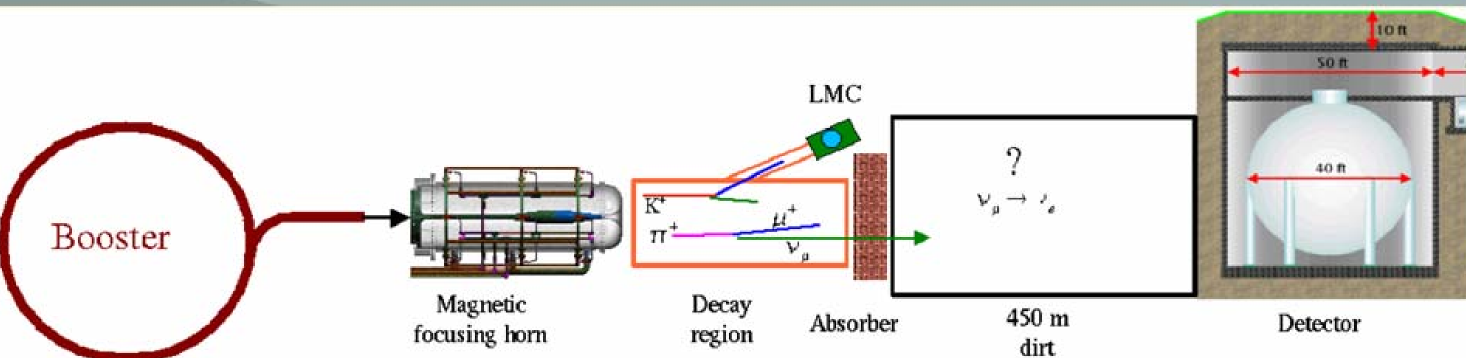
PRD**64**,112007(2001)

Excess of candidate $\bar{\nu}_e$ events

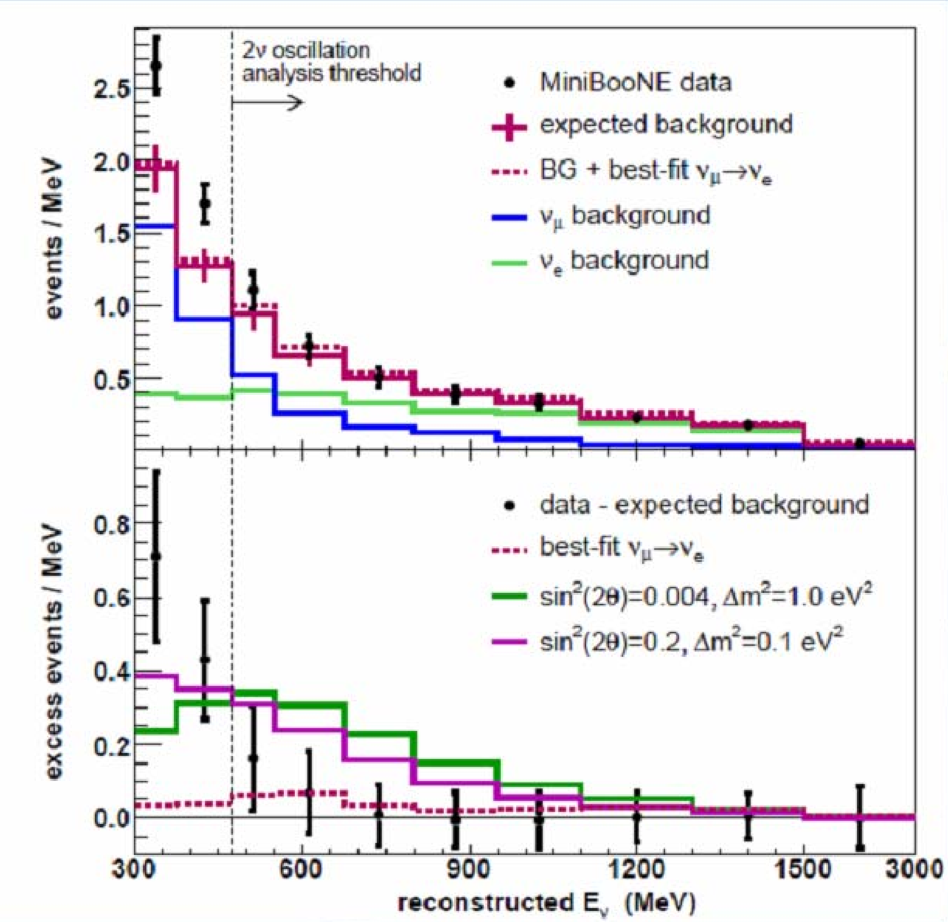
87.9 ± 22.4 ± 6.0 events (3.8σ)

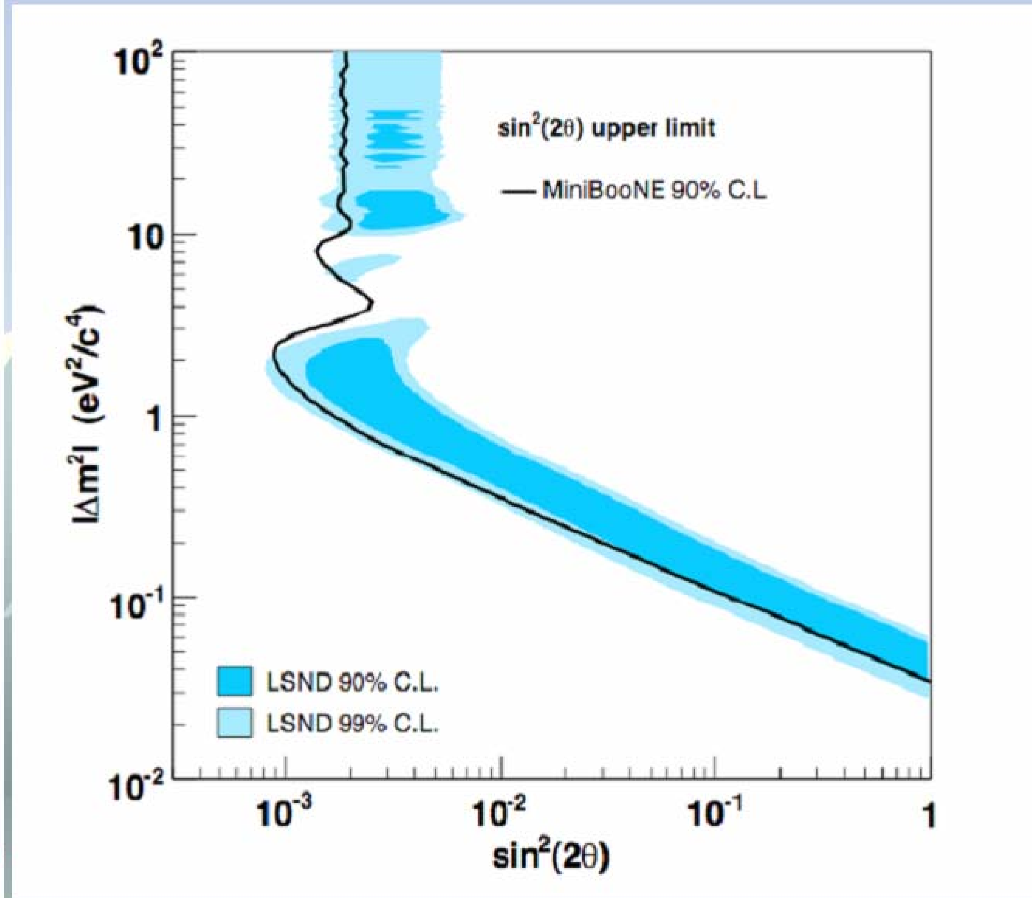
P($\bar{\nu}_\mu \to \bar{\nu}_e$) = 0.264 ± 0.081 %





MiniBooNE First Result (Apr.2007)



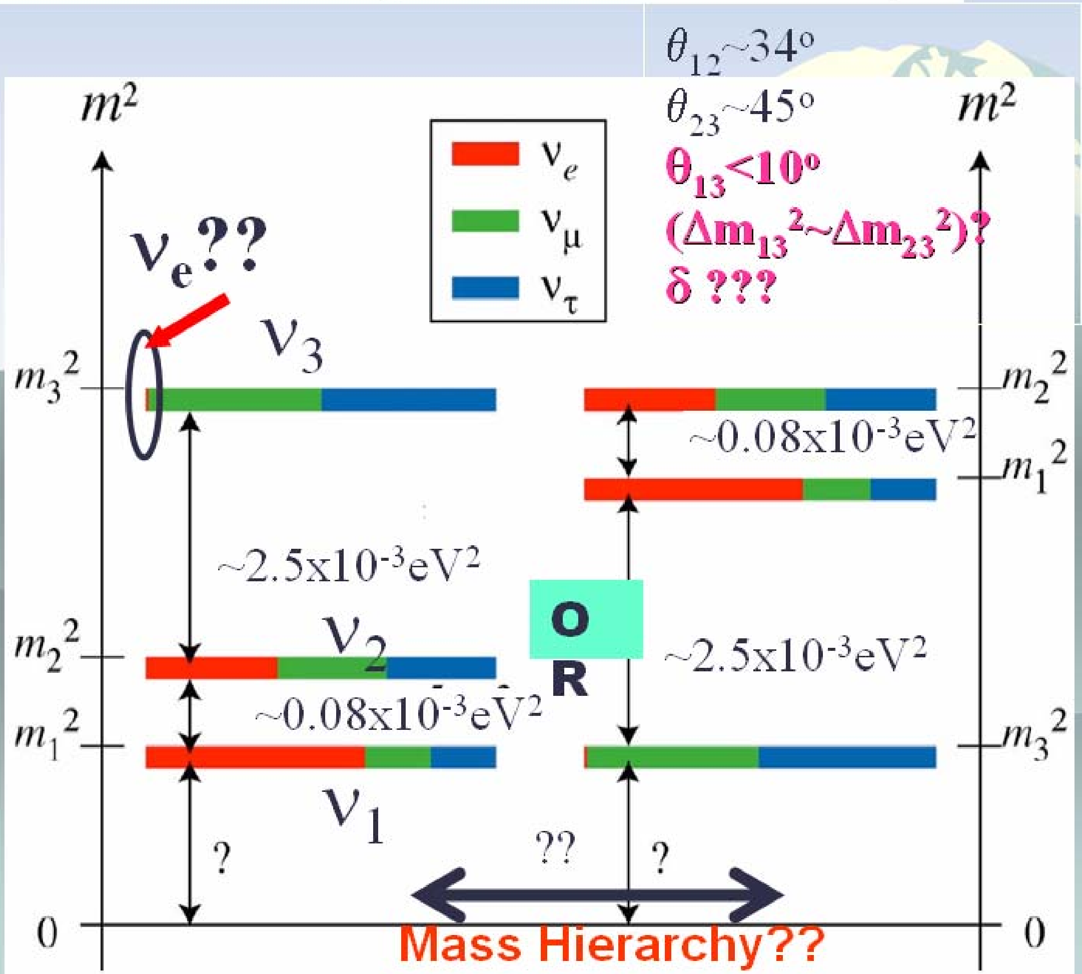


- Observed NO excess beyond background
- LSND allowed region mostly excluded (90%CL)

What are known and unknown

NEUTRINOS

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & \boxed{?} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$



Unknowns (not all)

- Mixing angle θ_{13}
- Mass Hierarchy (sign(Δm_{23}^2)
- CP violation
  - Baryon asymmetry in universe?
- Absolute Neutrino Mass
- Dirac or Majorana?
- New physics??

Whole understanding

→Hint of Phys Beyond SM

What are known and unknown

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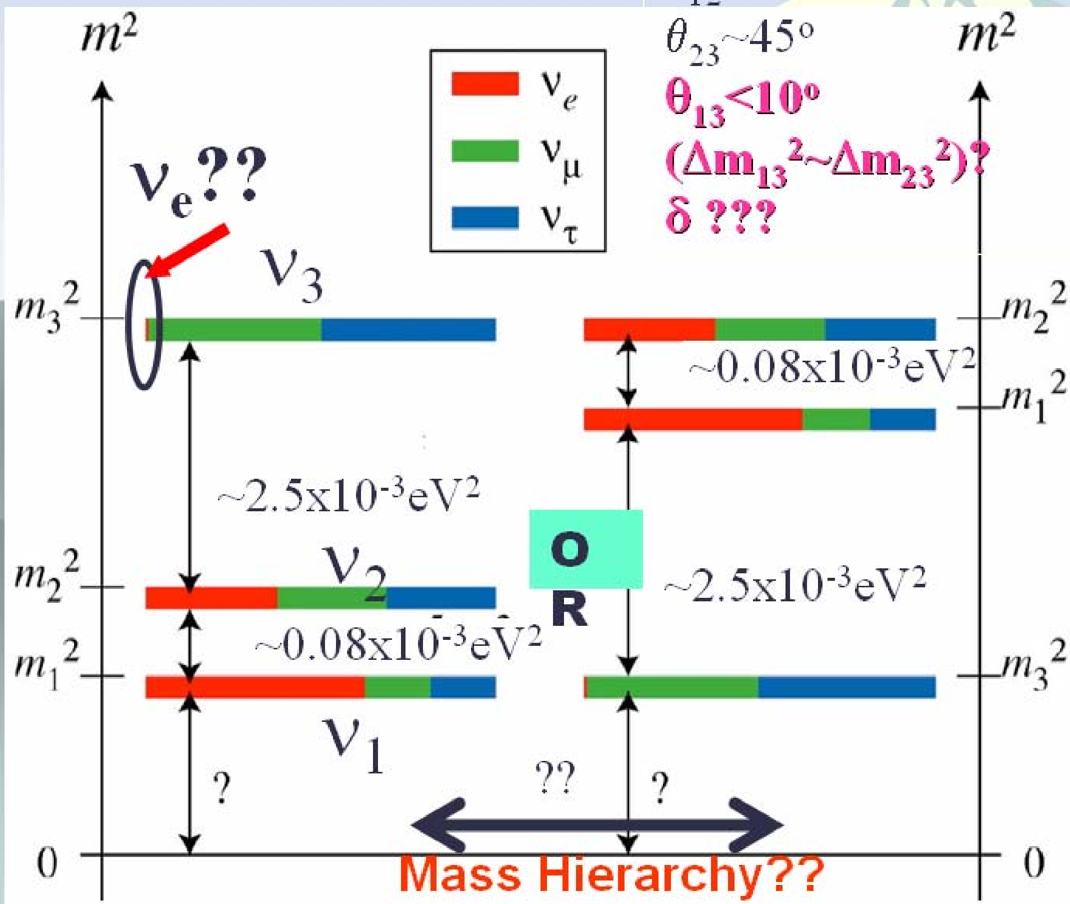
$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & \boxed{?} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$\theta_{12} \sim 34^\circ$
$\theta_{23} \sim 45^\circ$
$\theta_{13} < 10^\circ$
$(\Delta m_{13}^2 \sim \Delta m_{23}^2)$?
δ ???



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  - **0n2β/β decay spec**
  - **Cosmology**
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Whole understanding

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What are known and unknown

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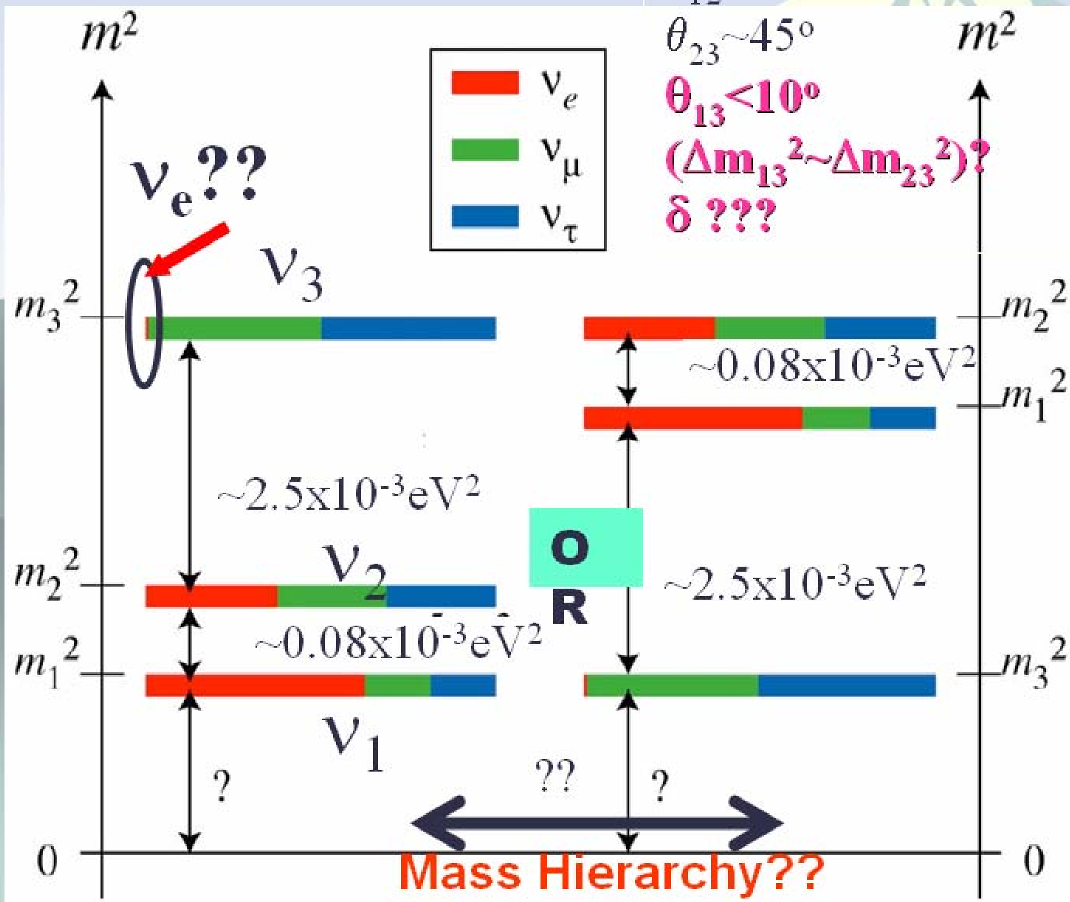
$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & \boxed{?} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$\theta_{12} \sim 34^o$



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- Absolute Neutrino Mass
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  - 0ν2β
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Whole understanding

➔Hint of Phys Beyond SM

Next most important step: θ_{13}. Why?

CPV & sign(Δm^2) will be probed thru ν_e appearance in accel LBL

$$P(\nu_\mu \to \nu_e) = \boxed{4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \ (1 - 2S_{13}^2)\right)}$$

Leading

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$$

$$\boxed{-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}}$$

CP-odd

+ other terms..

$\delta \to -\delta$, $a \to -a$ for $\overline{\nu}_\mu \to \overline{\nu}_e$

Matter eff.: $a = 7.56 \times 10^{-5} [\mathrm{eV}^2] \cdot \left(\frac{\rho}{[\mathrm{g/cm}^3]}\right) \cdot \left(\frac{E}{[\mathrm{GeV}]}\right)$

CP-odd term $\propto \sin\delta \cdot s_{12} \cdot s_{23} \cdot s_{13}$

(where $\sin\theta_{12} \sim 0.5$, $\sin\theta_{23} \sim 0.7$, $\sin\theta_{13} < 0.2$)

- If θ_{13} is large ($\sin^2 2\theta_{13} > 0.01$)
  - νe app. seen in next gen acc exp
  - CPV may be seen in (upgraded) next gen exp's
- If θ_{13} is too small ($\sin^2 2\theta_{13} << 0.01$)
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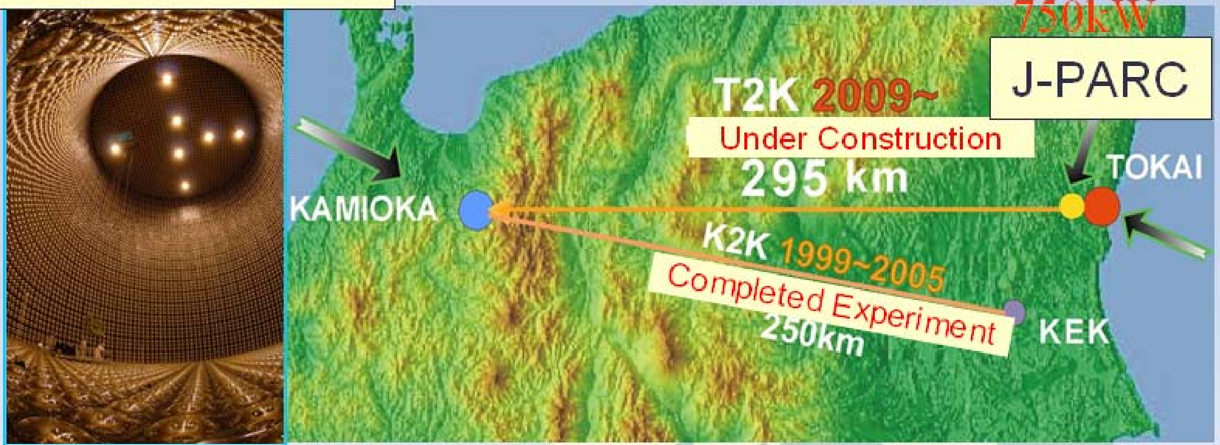
  - may need to wait νFact to see CPV

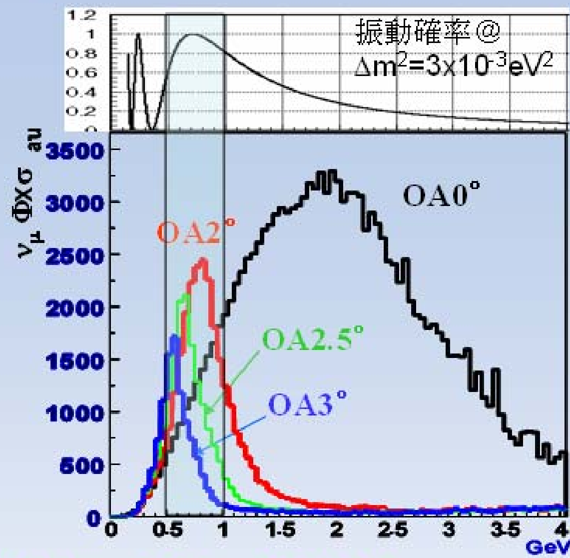
The size of θ_{13}
Decide future dir.!

Tokai-to-Kamioka (T2K) experiment

Super-Kamiokande

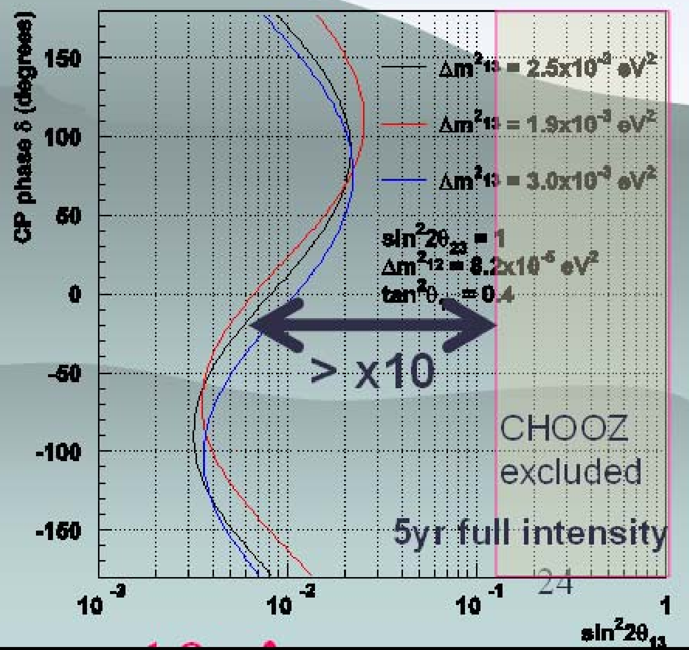
(See TUXKI03 Ishida's talk)



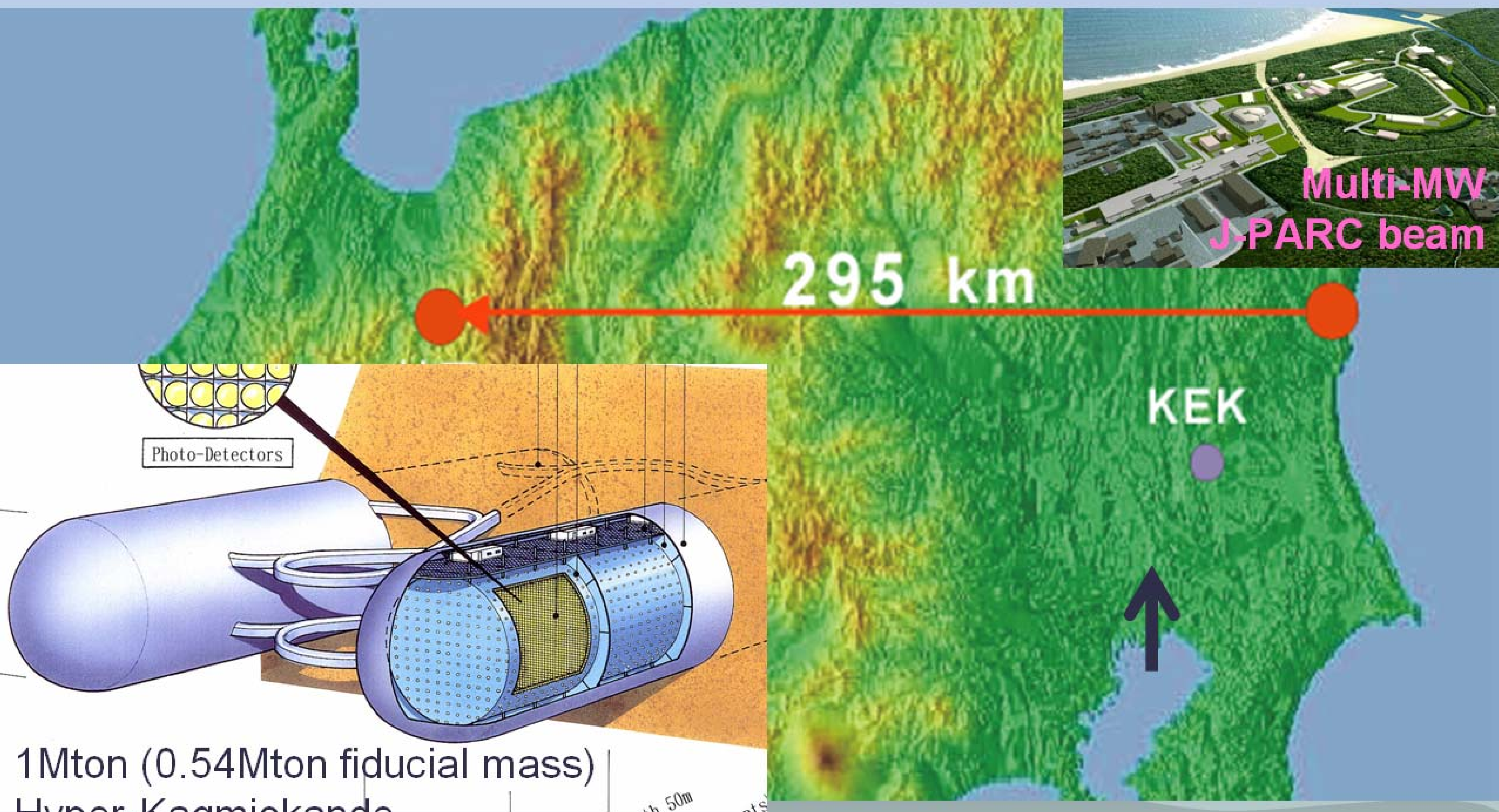


1600ν_μCC/yr/22.5kt (2.5deg)

- **Main goals**
  - **Discovery of νe appearance**
  - Precise measurements on νμ disapp.
- Highest intensity J-PARC PS (750kW)
  - Commissioning: May2008~
- ν beamline in J-PARC
  - **Off-axis narrow band beam** tuned at osc. max
  - Construction 2004~2008
  - **Commissioning : Apr.2009~**
- SK full recovery done in 2006

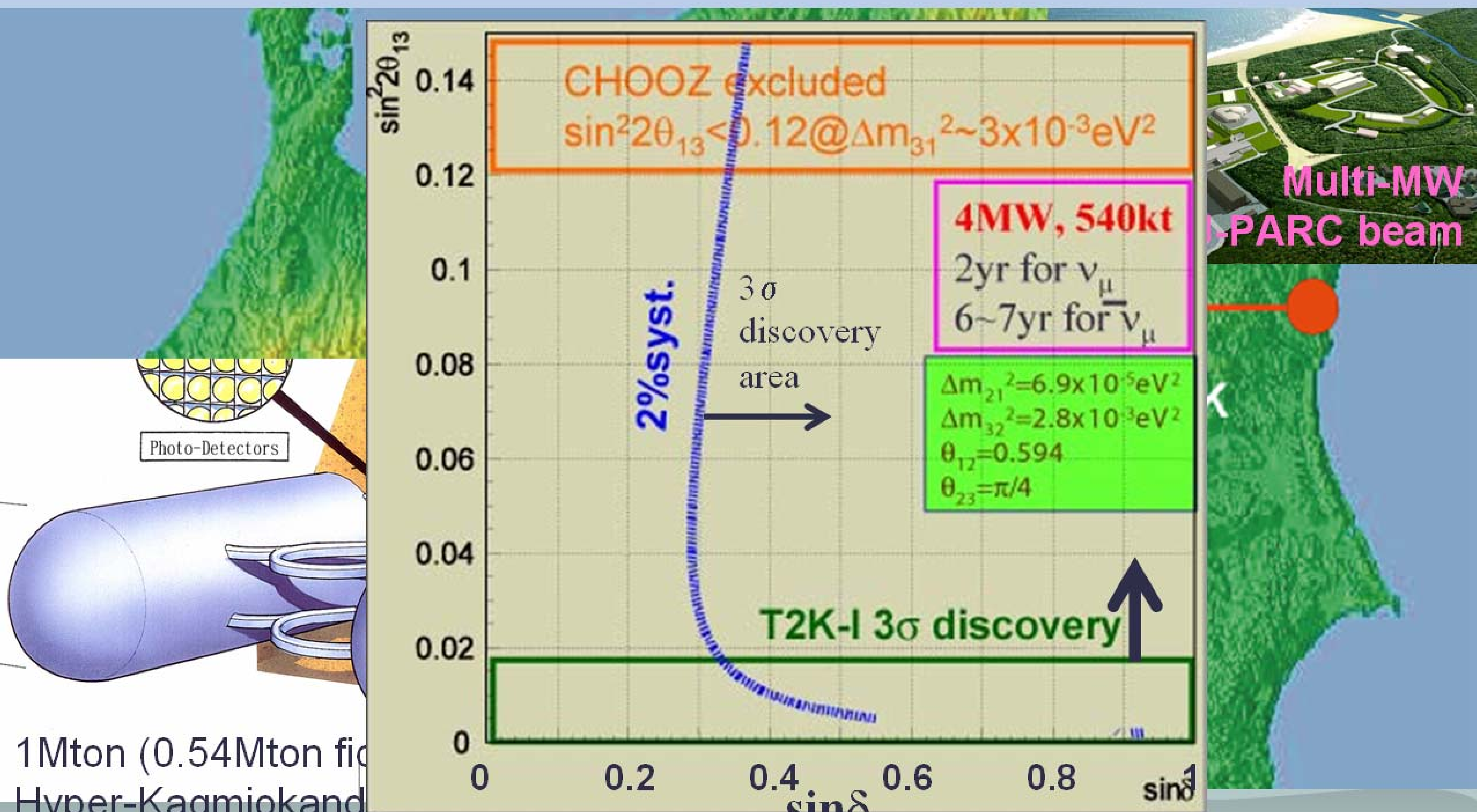


T2K possible extension: CPV search



2years of ν run + 7 years of anti-ν run ➔ O(10^6) events for both runs

T2K possible extension: CPV search



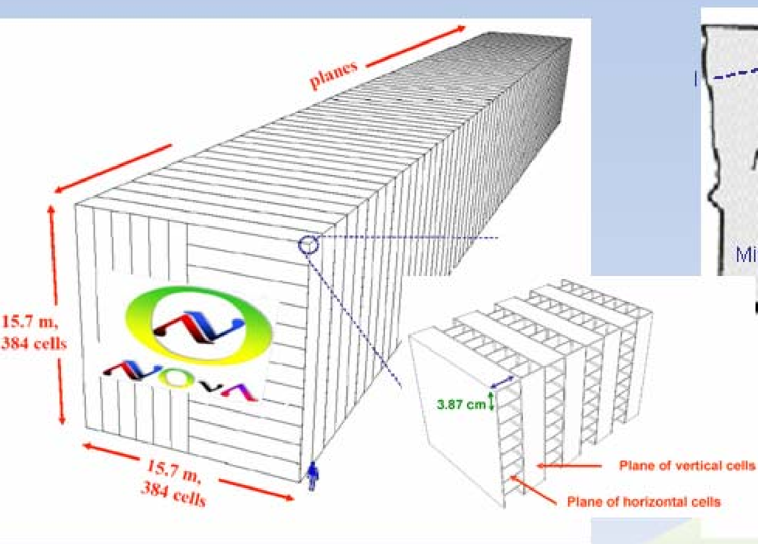
1Mton (0.54Mton fid
Hyper-Kaqmiokand

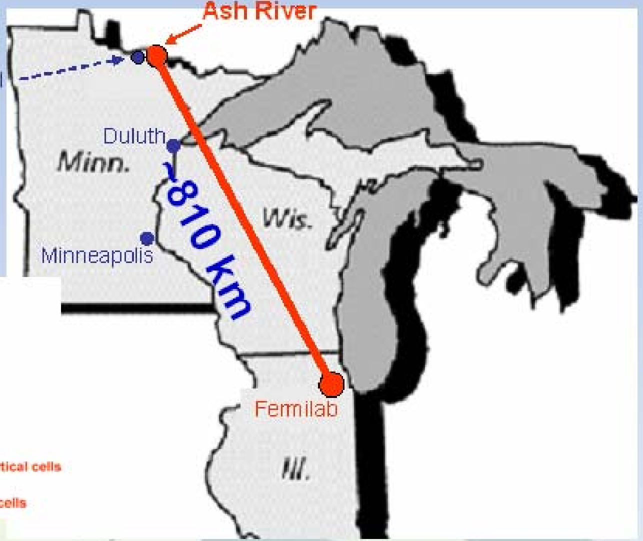
$\sin\delta$

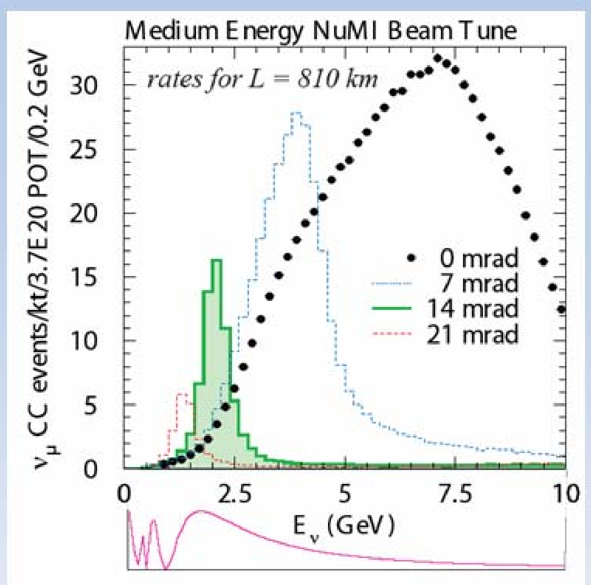
2years of ν run + 7 years of anti-ν run ➔ O(10^6) events for both runs

3σ CP sensitivity : $|\delta| > 20^\circ$ for $\sin^2 2\theta_{13} > 0.01$

NOνA (2011?~)

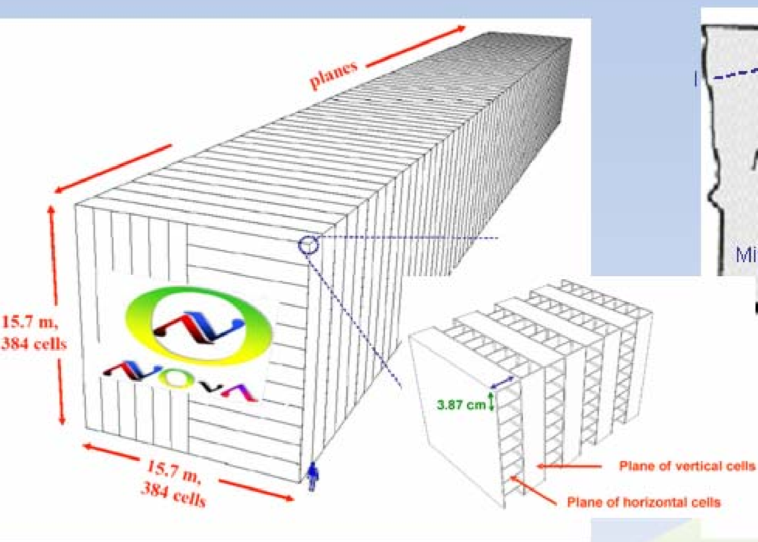


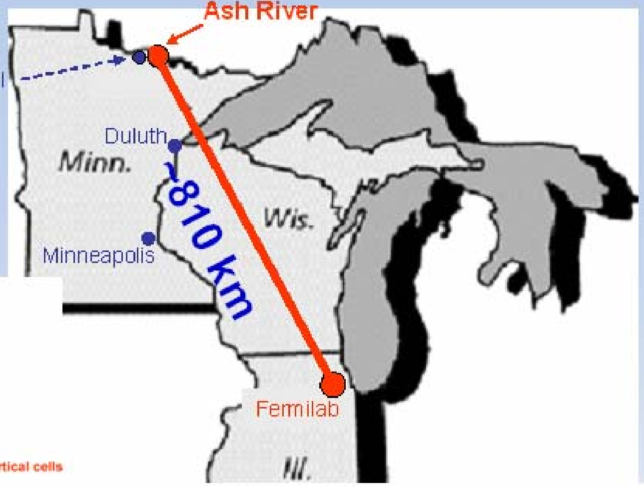


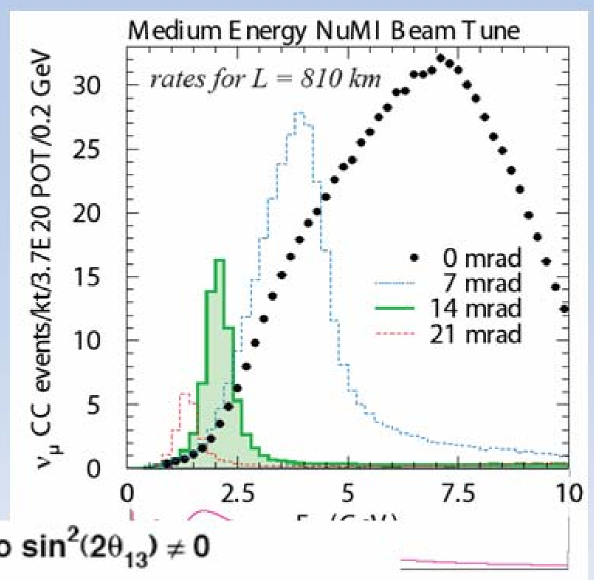


- Existing NuMI Off-axis beam
  - 200kW (→ 320 → 700 → 1200kW upgrade plan)
- New Full active liq. Scint fine grained
  - 15kton
  - @~810km, ~15mr-off

NOvA (2011?~)







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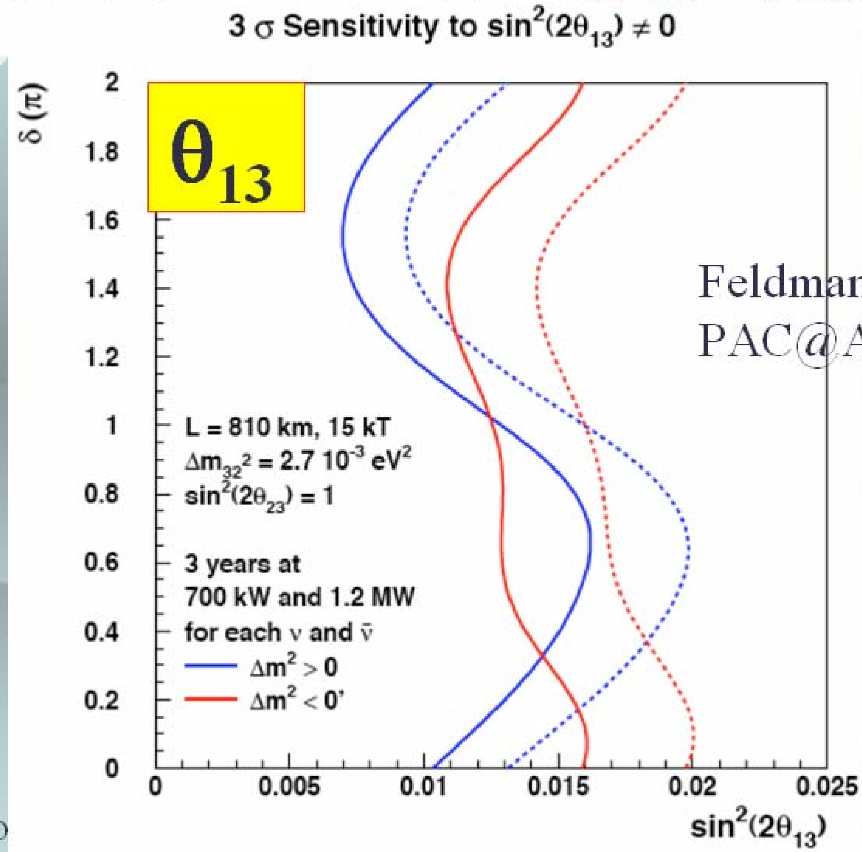
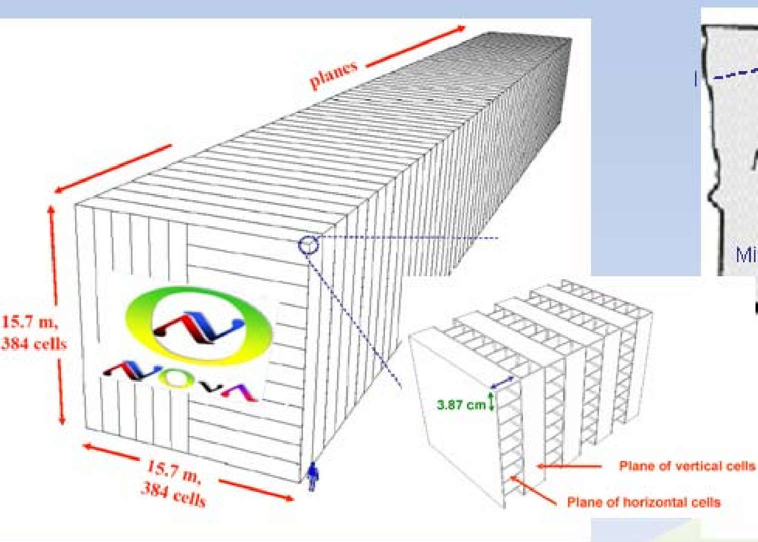
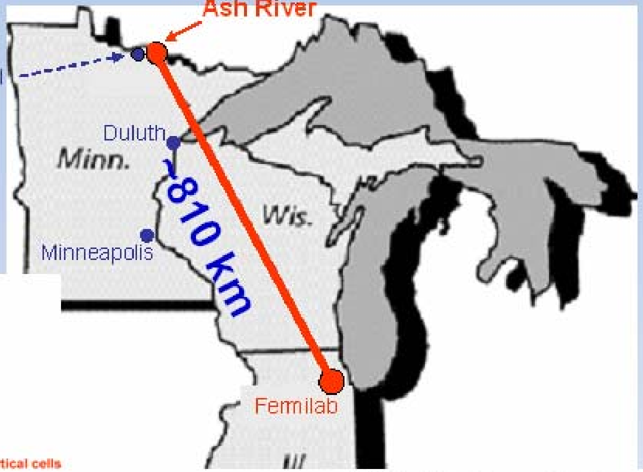
  - 200kW (→ 320 → 700 → 1200kW upgrade plan)
- New Full active liq. Scint fine grained
  - 15kton
  - @~810km, ~15mr-off
- ν_e **appearance**
  - Comparable to T2K

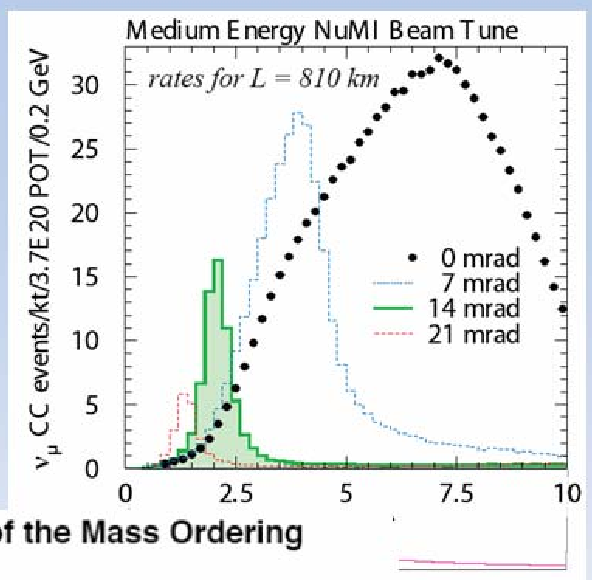


Feldman
PAC@Aspen,07

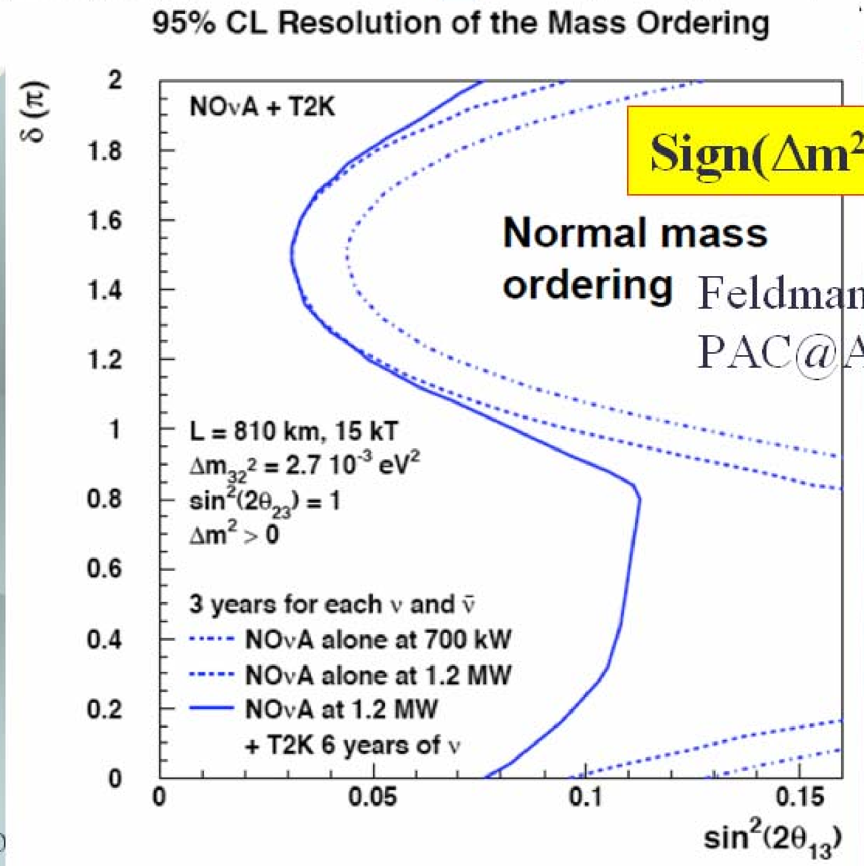
NOvA (2011?~)







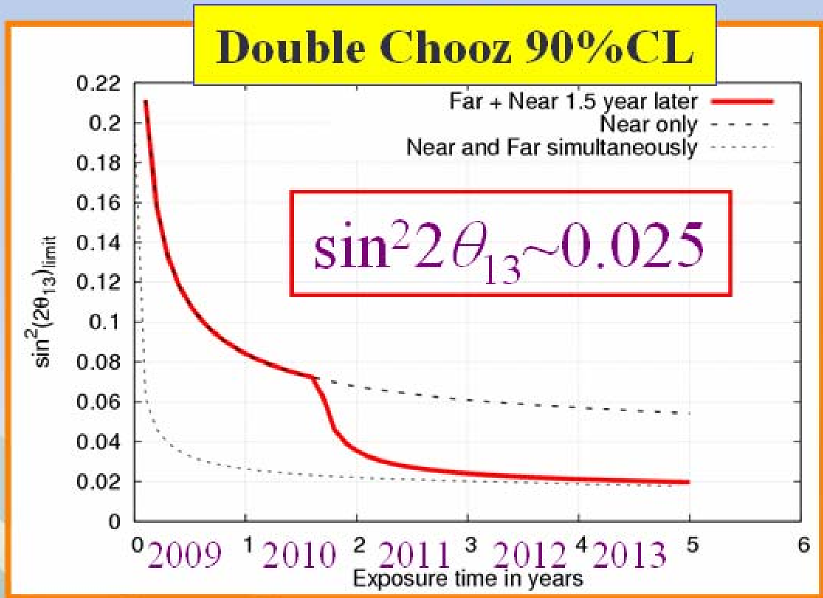
- Existing NuMI Off-axis beam
  - 200kW (→ 320 → 700 → 1200kW upgrade plan)
- New Full active liq. Scint fine grained
  - 15kton
  - @~810km, ~15mr-off
- **ν_e appearance**
  - Comparable to T2K
- **Sign(Δm^2_{13})** thru matt. eff.
  - Unique feature of NOvA
  - cf longer dist/higher E than T2K



Feldman PAC@Aspen,07

Reactor Experiments for θ_{13}

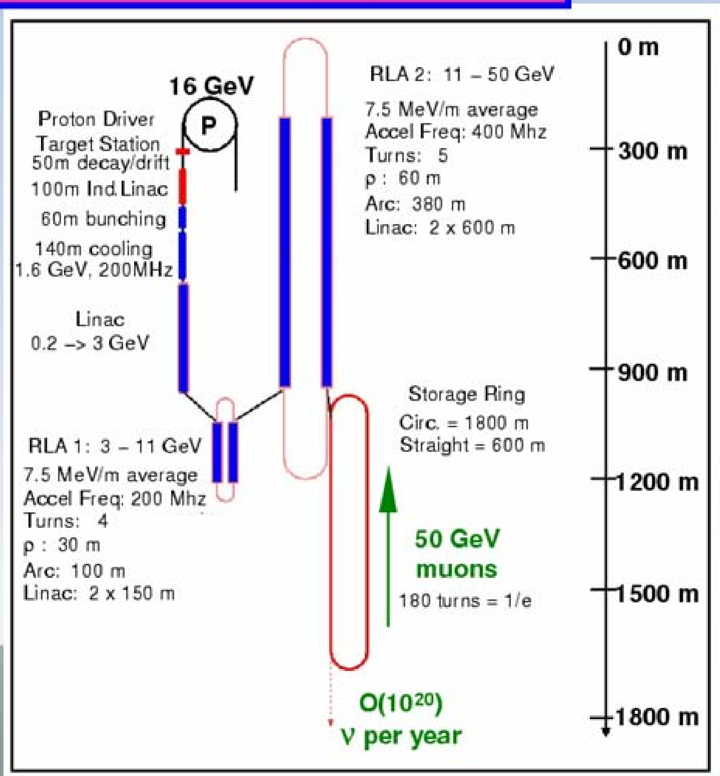
- Disapp. of ~3MeV ν_e bar at ~ km
- Purely sensitive to θ_{13}
  - No sensitivity on CPV & matter effect (signΔm^2)
  - Complementary to acc. LBL exp's
- Small signal → syst limited
  - Identical near/far det

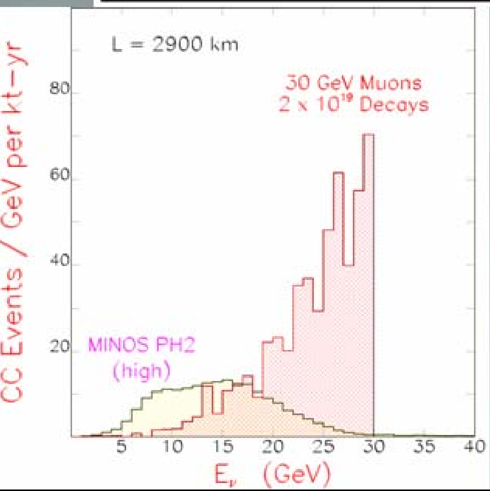


Reactor	Optimistic start date	Detectors ton@km	GW-t-yr (yr)	90% CL $\mathrm{Sin}^2 2\theta_{13}$ sensitivity	Far event rate	
Double Chooz	2009?	10.2@0.15 10.2@1.067	80(4)	0.025	15,000/yr	Partially funded
RENO	Late 09	20@0.15 20@1.5	340(1)	0.03	18,000/yr	Funded
Daya Bay	08(fast) 09(full)	40@0.36 40@0.5 40x2@1.75	3700(3)	0.008	70,000/yr 110,000/yr (before/after 2010)	Proposed
ANGRA	2013(full)	1@0.05 50@0.3 500@1.5	15000(5)	0.0055	350,000/yr	Proposed

If θ_{13} is (unfortunately) very small?

Neutrino Factory



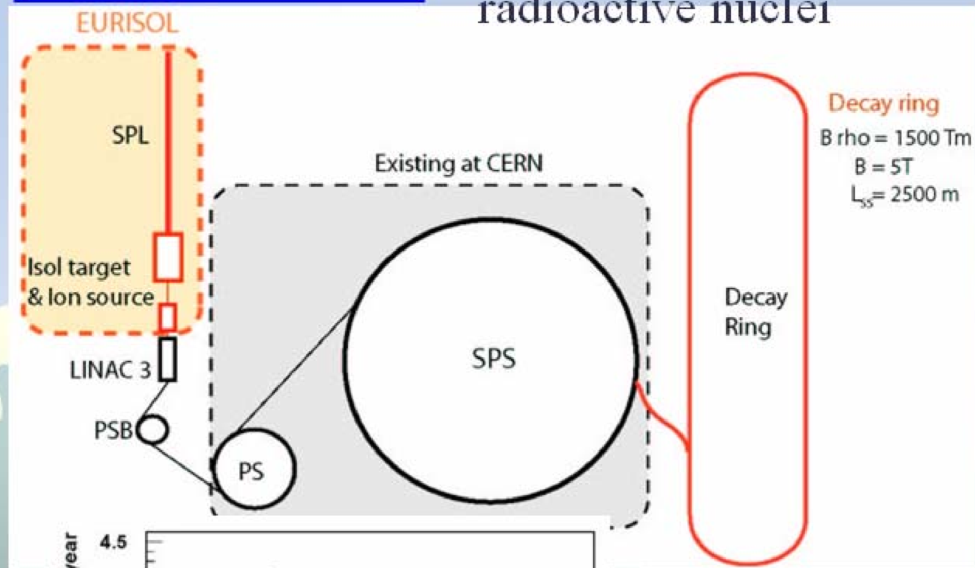


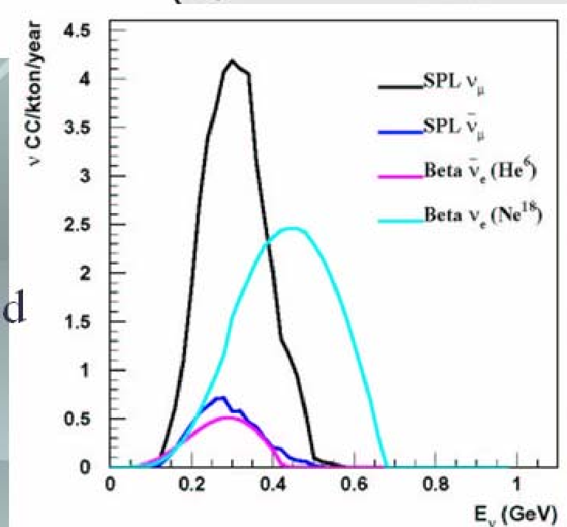
$\nu_\mu/\overline{\nu}_e$ from accelerated muons

- No ambiguity in flux
- High intensity
  $\nu e \rightarrow \nu\mu$
- Need magnetized det.

Beta Beam

ν_e from accelerated radioactive nuclei



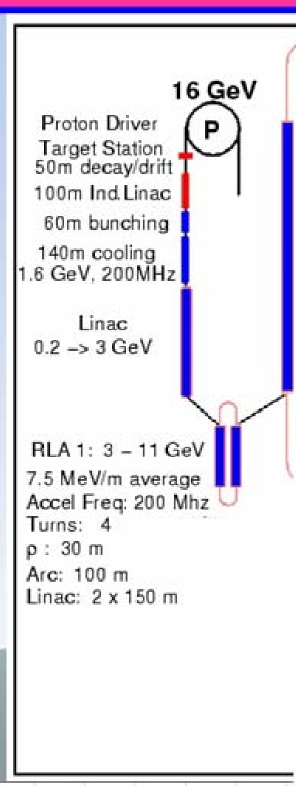


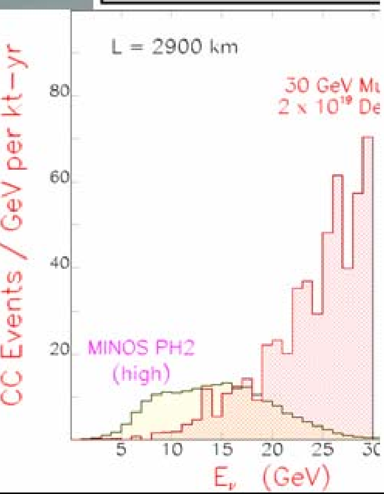
Pure ν_e
No ambiguity in flux

Need to establish basic technologies

If θ_{13} is (unfortunately) very small?

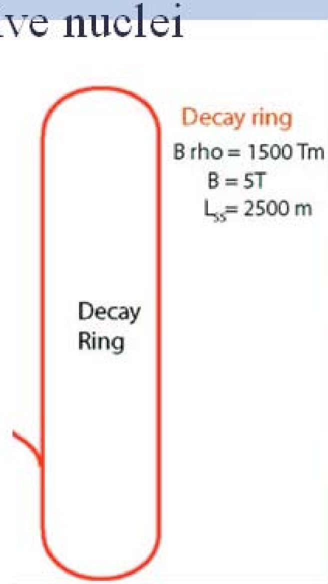
Neutrino Factory

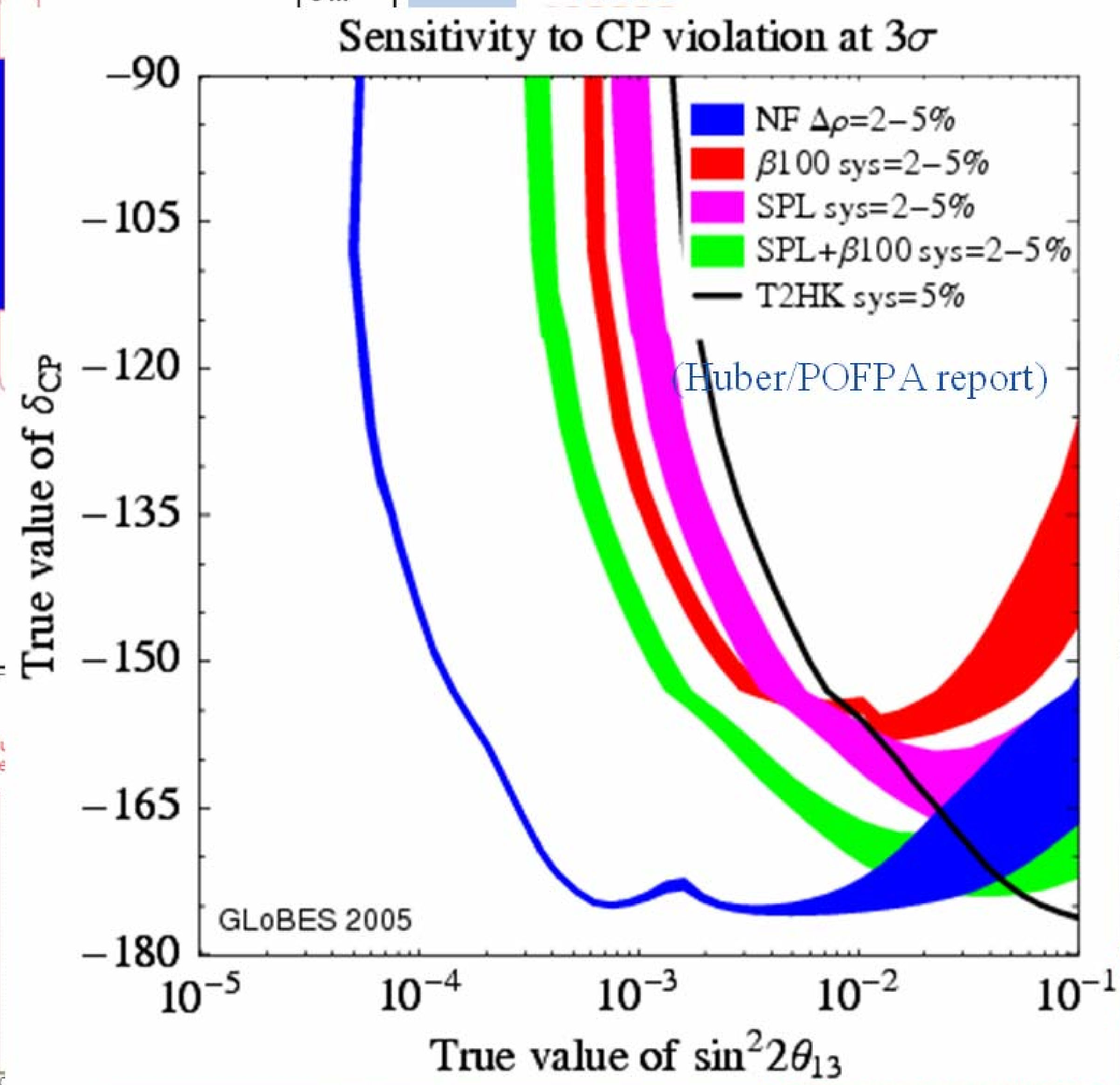




Beta Beam

ν_e from accelerated radioactive nuclei

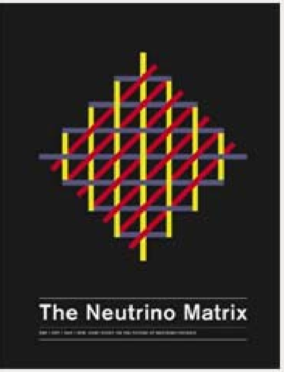




Pure ν_e
No ambiguity in flux

...lish basic ...

Summary



The Growing Excitement of Neutrino Physics

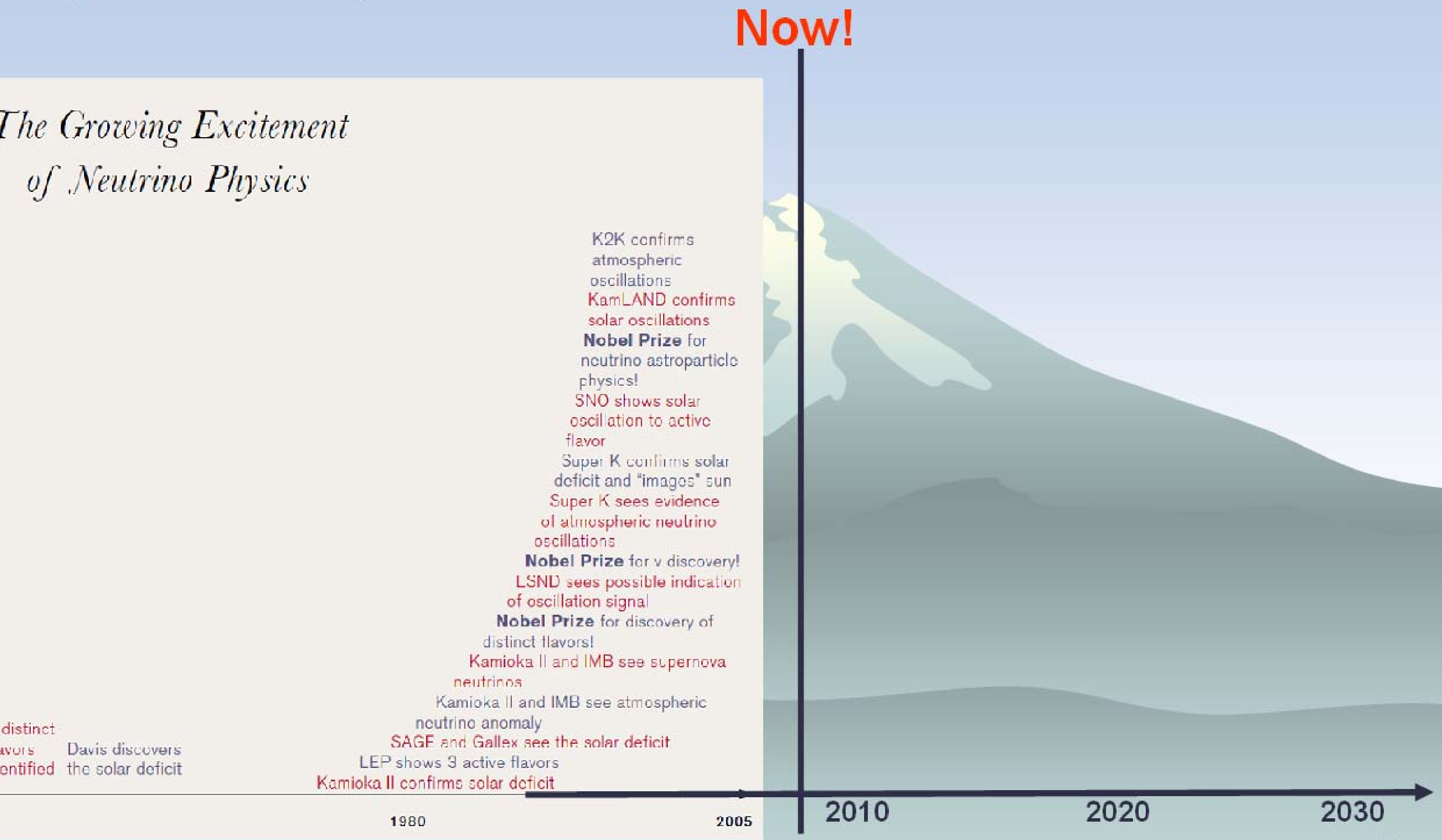
K2K confirms atmospheric oscillations
KamLAND confirms solar oscillations
Nobel Prize for neutrino astroparticle physics!
SNO shows solar oscillation to active flavor
Super K confirms solar deficit and “images” sun
Super K sees evidence of atmospheric neutrino oscillations
Nobel Prize for ν discovery!
LSND sees possible indication of oscillation signal
Nobel Prize for discovery of distinct flavors!
Kamioka II and IMB see supernova neutrinos
Kamioka II and IMB see atmospheric neutrino anomaly
SAGE and Gallex see the solar deficit
LEP shows 3 active flavors
Kamioka II confirms solar deficit

Pauli predicts the Neutrino
Fermi's theory of weak interactions
Reines & Cowan discover (anti)neutrinos
2 distinct flavors identified
Davis discovers the solar deficit

1930 1955 1980 2005

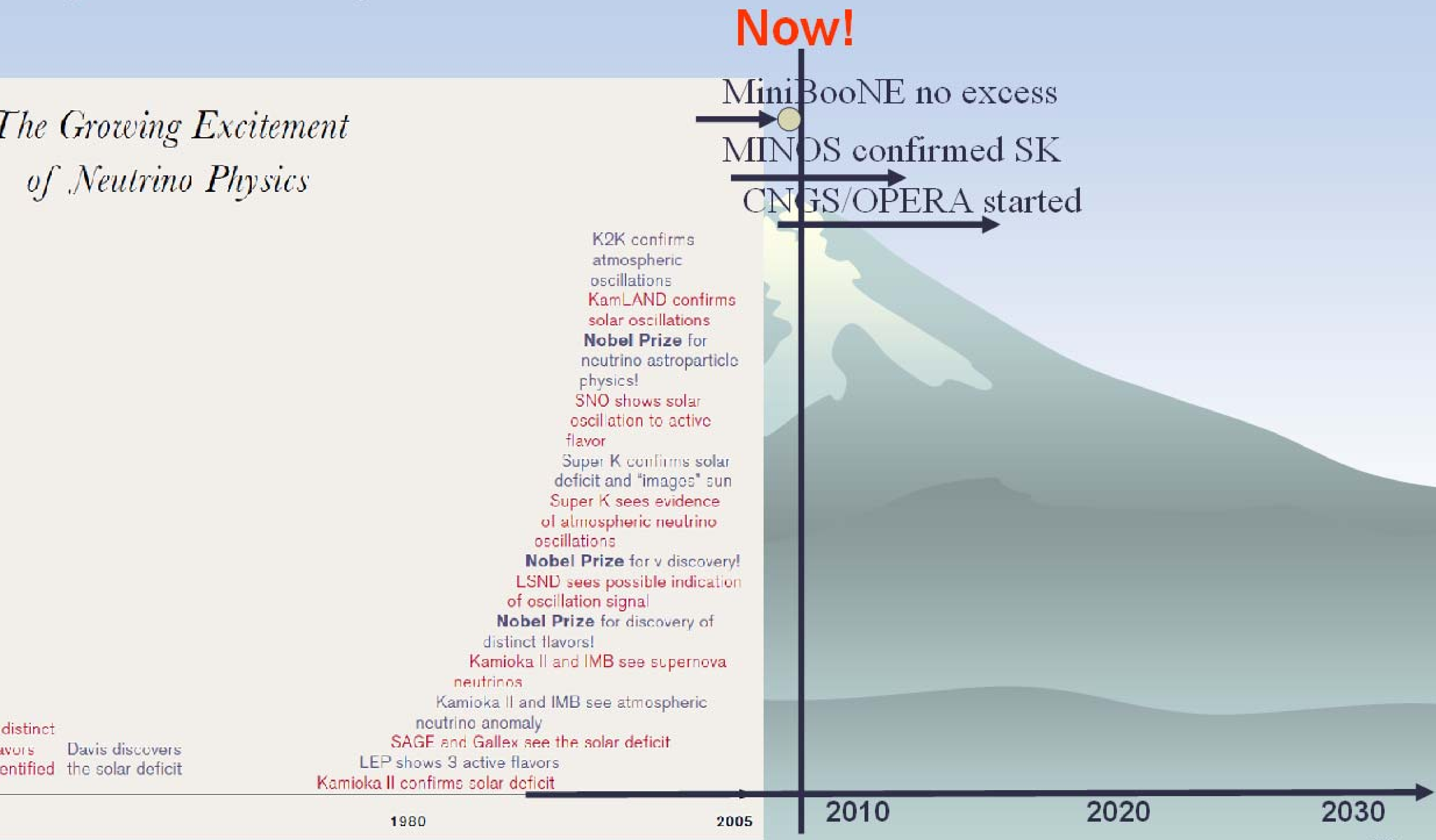
Summary

Continuing Excitement of Neutrino Physics



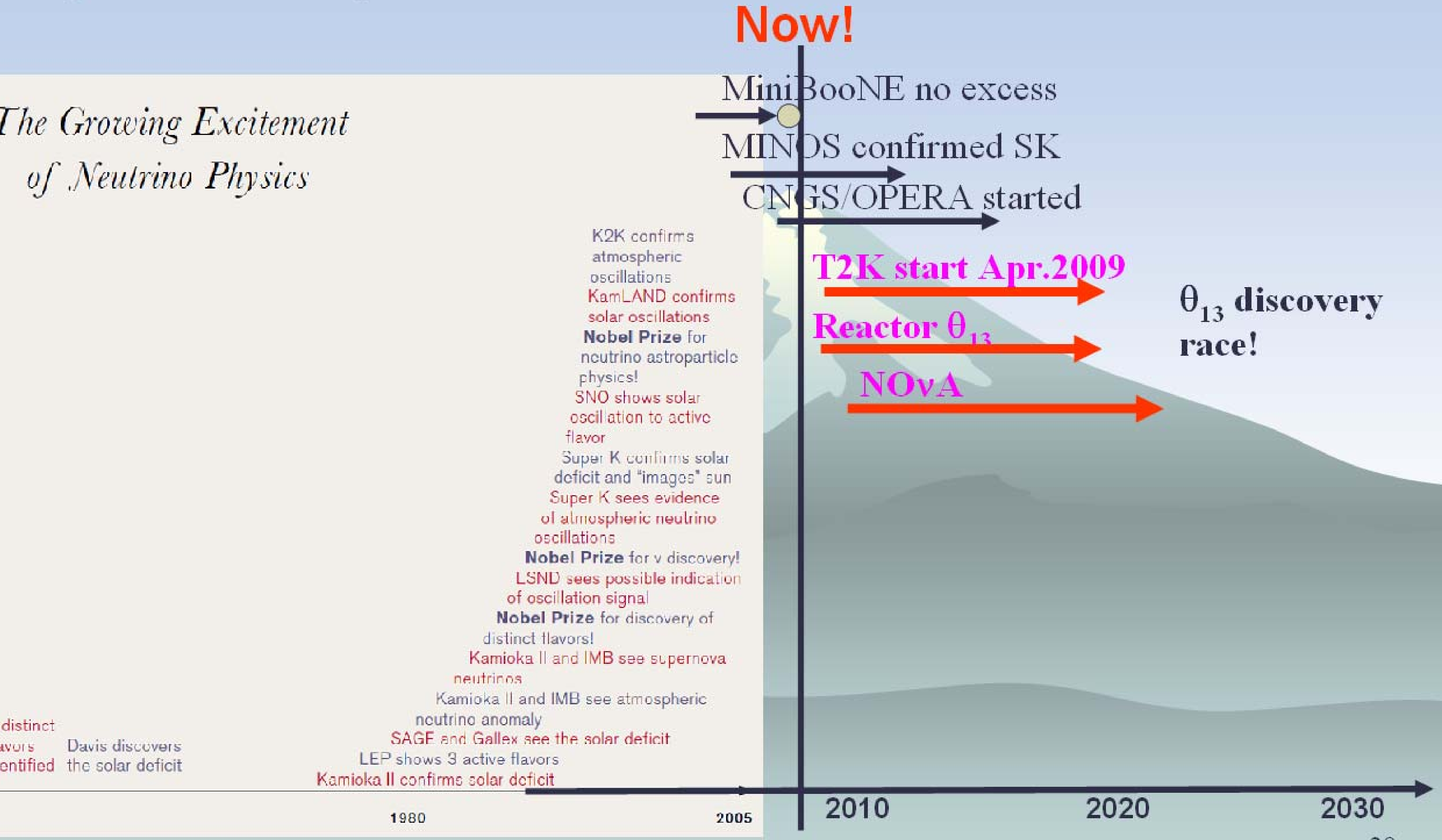
Summary

Continuing Excitement of Neutrino Physics



Summary

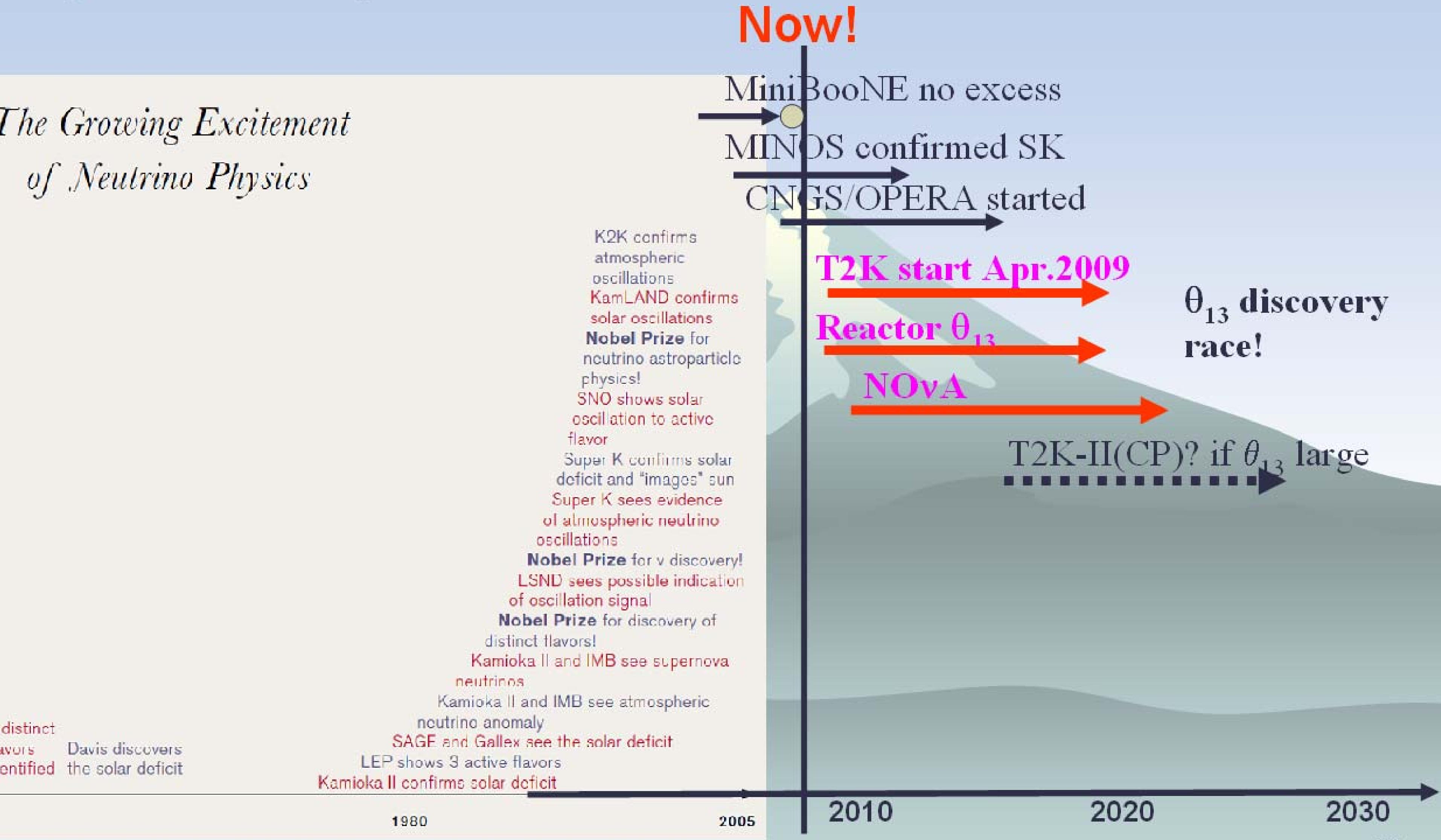
Continuing Excitement of Neutrino Physics



Takashi Kobayashi (KEK), PAC07

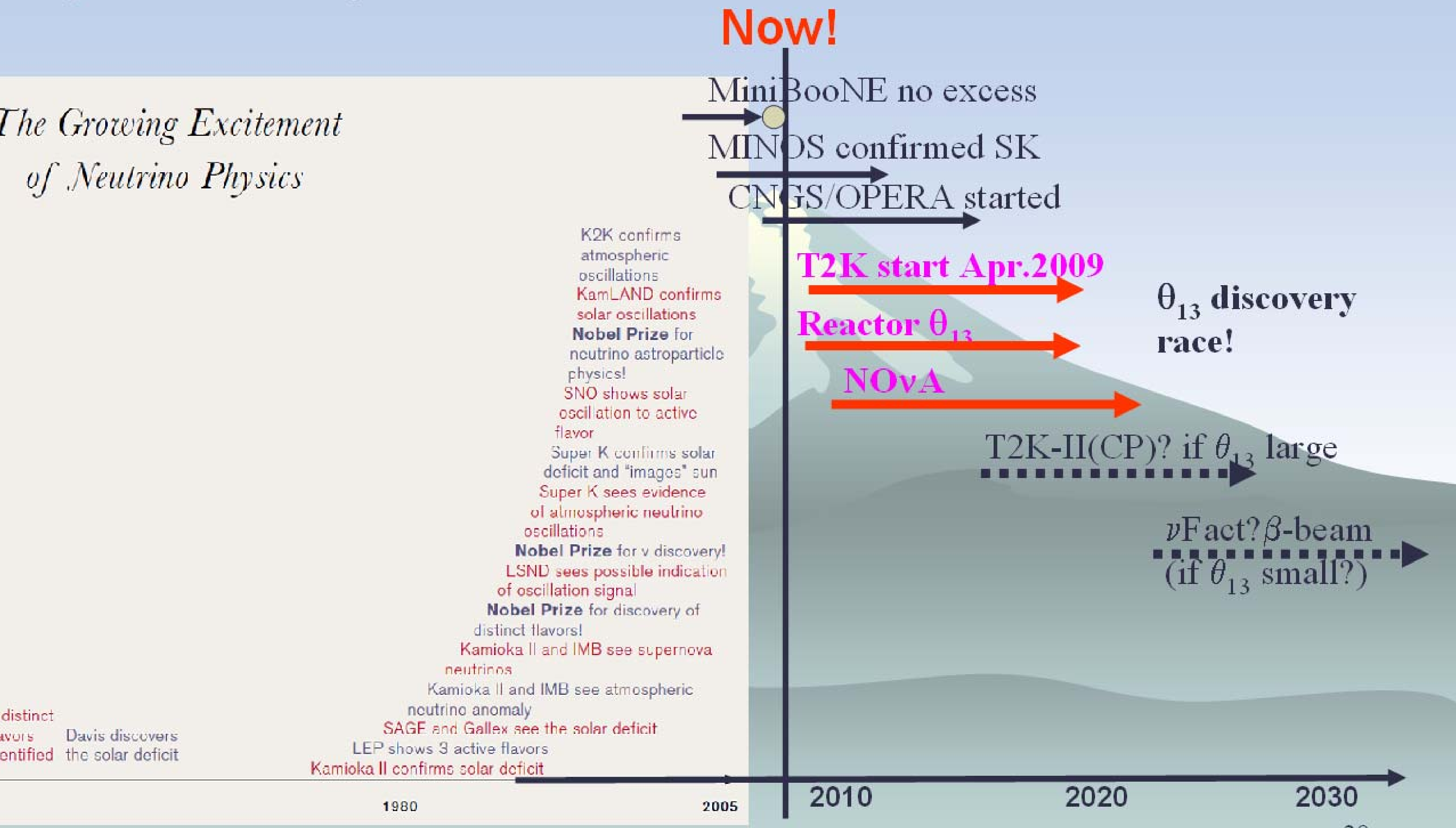
Summary

Continuing Excitement of Neutrino Physics



Summary

Continuing Excitement of Neutrino Physics



Summary

Continuing Excitement of Neutrino Physics

Takashi Kobayashi (KEK), PAC07

Summary

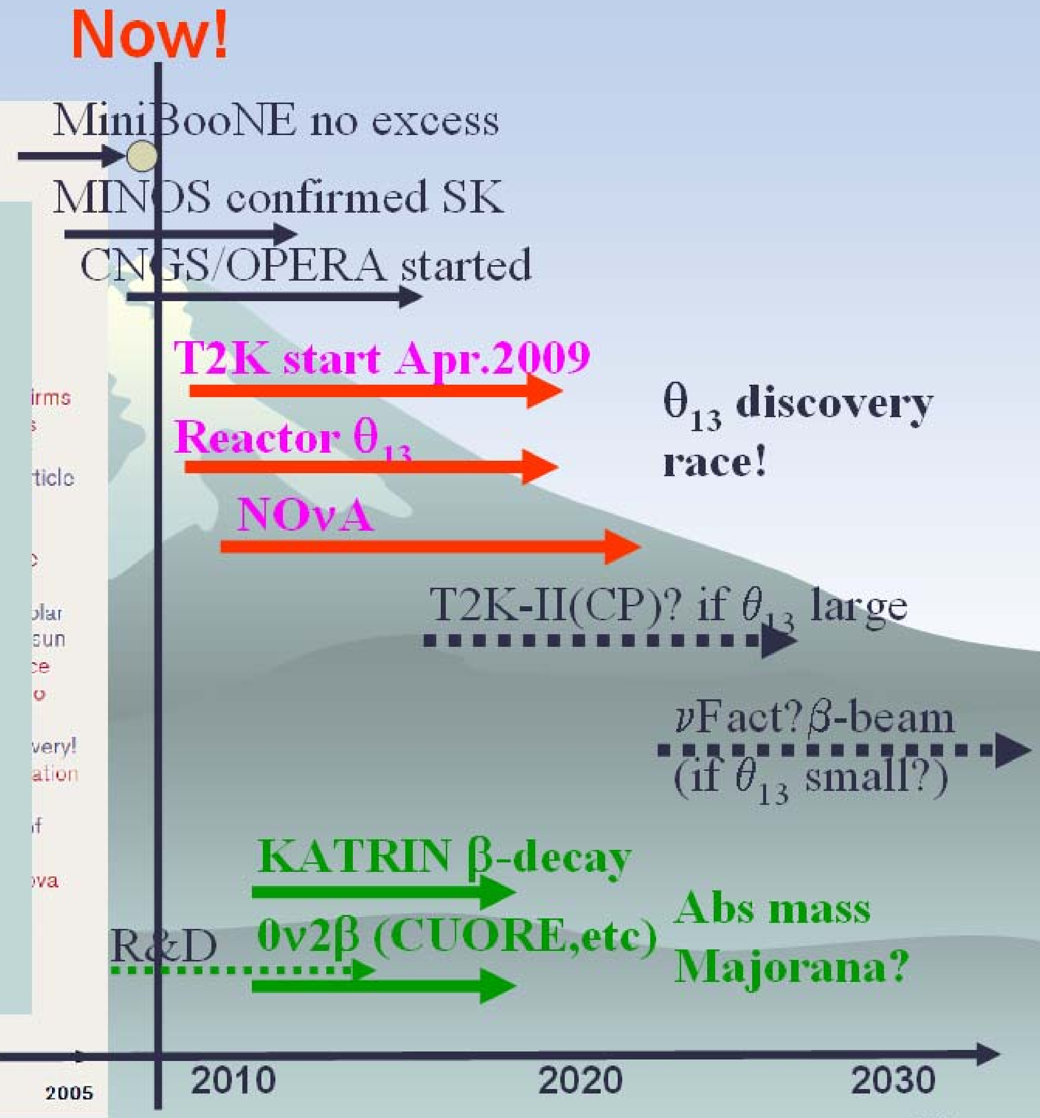
Continuing Excitement of Neutrino Physics

Summary

Continuing Excitement of Neutrino Physics

The Growing Excitement of

- **Neutrino has now**
  - **Finite mass!!**
  - **Large mixing!!**

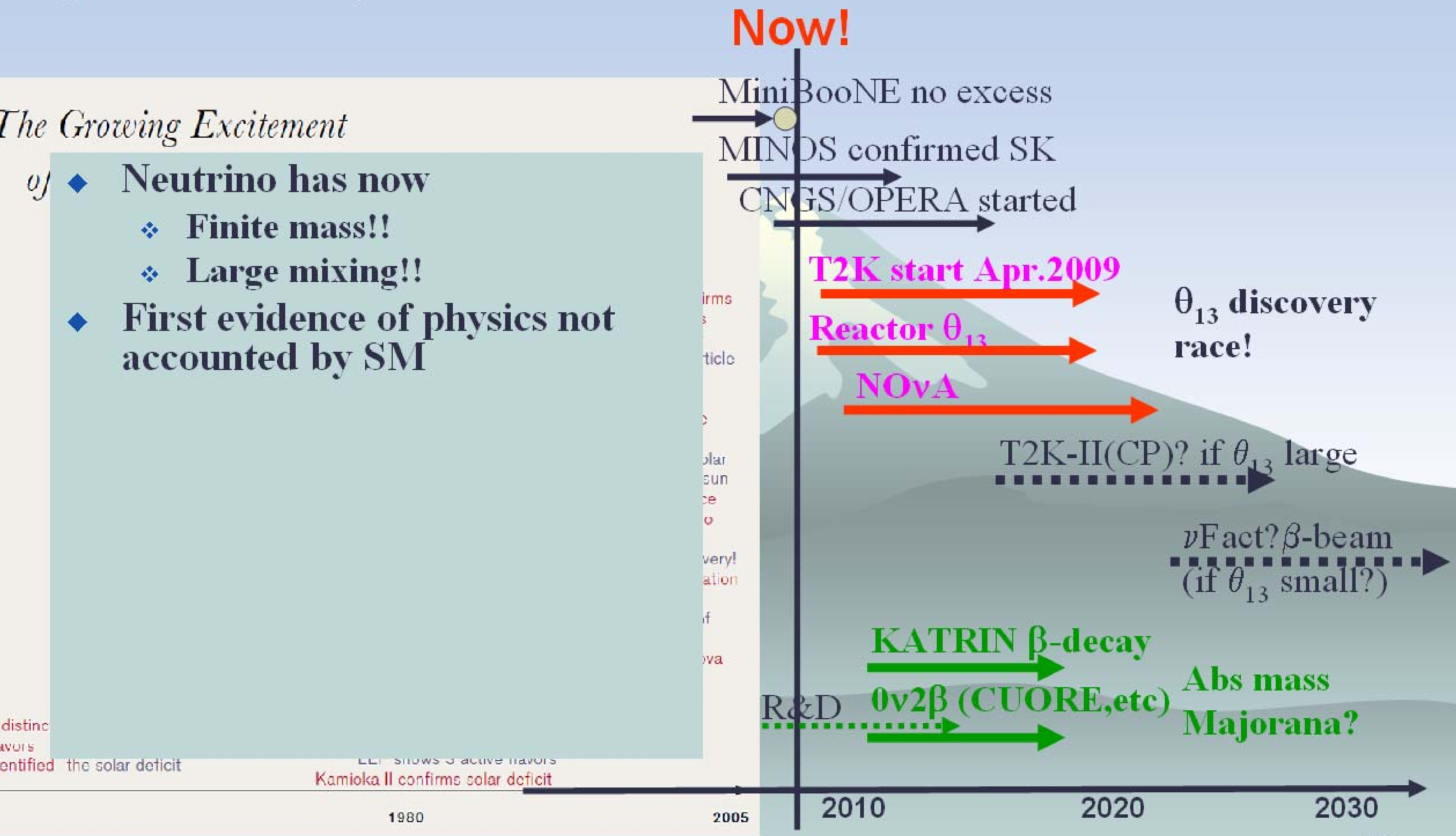


Summary

Continuing Excitement of Neutrino Physics

The Growing Excitement of

- **Neutrino has now**
  - **Finite mass!!**
  - **Large mixing!!**
- **First evidence of physics not accounted by SM**



Takashi Kobayashi (KEK), PAC07

Summary

Continuing Excitement of Neutrino Physics

The Growing Excitement of

- **Neutrino has now**
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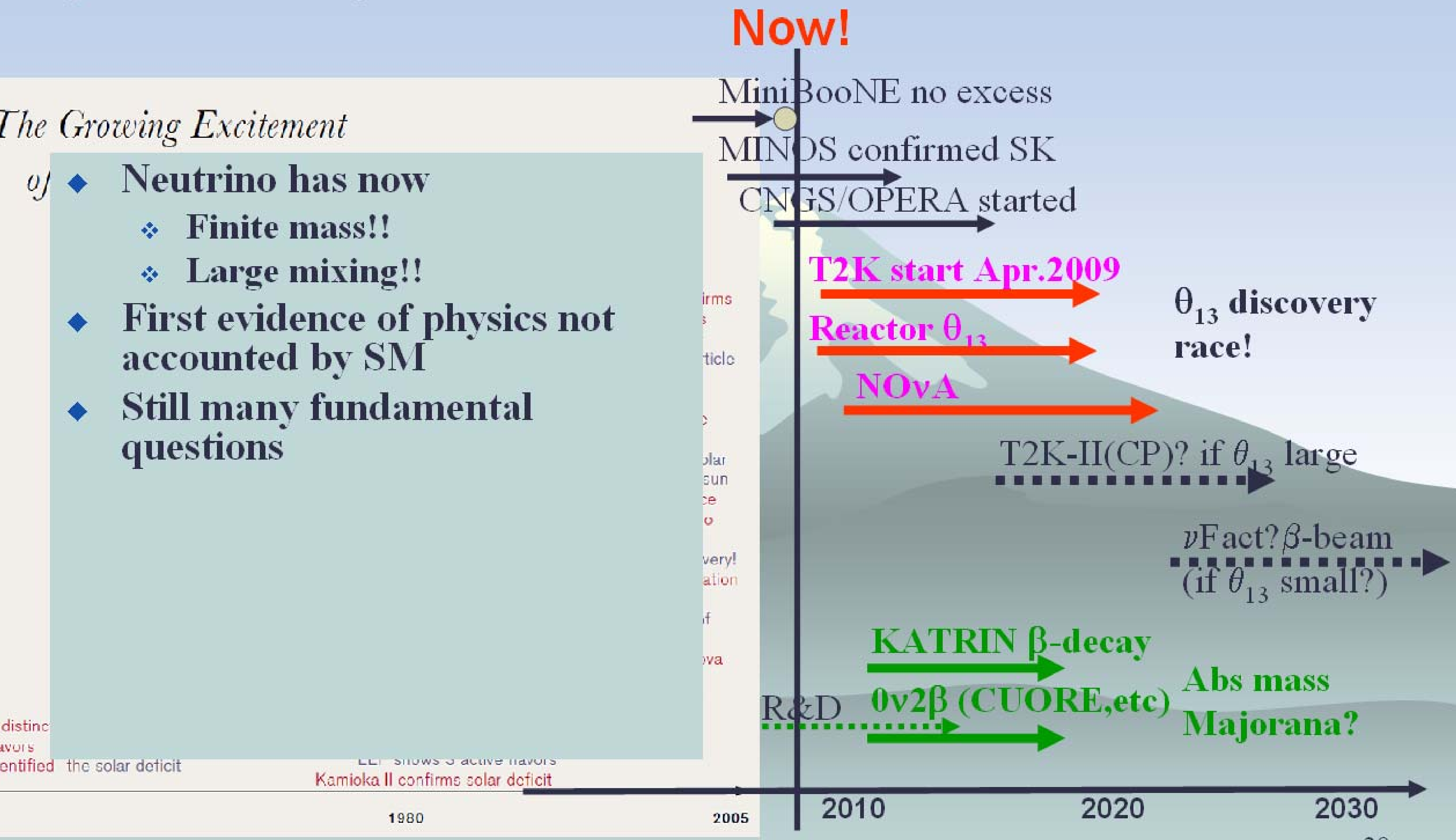
  - **Large mixing!!**
- **First evidence of physics not accounted by SM**
- **Still many fundamental questions**



Summary

Continuing Excitement of Neutrino Physics

The Growing Excitement of

- Neutrino has now
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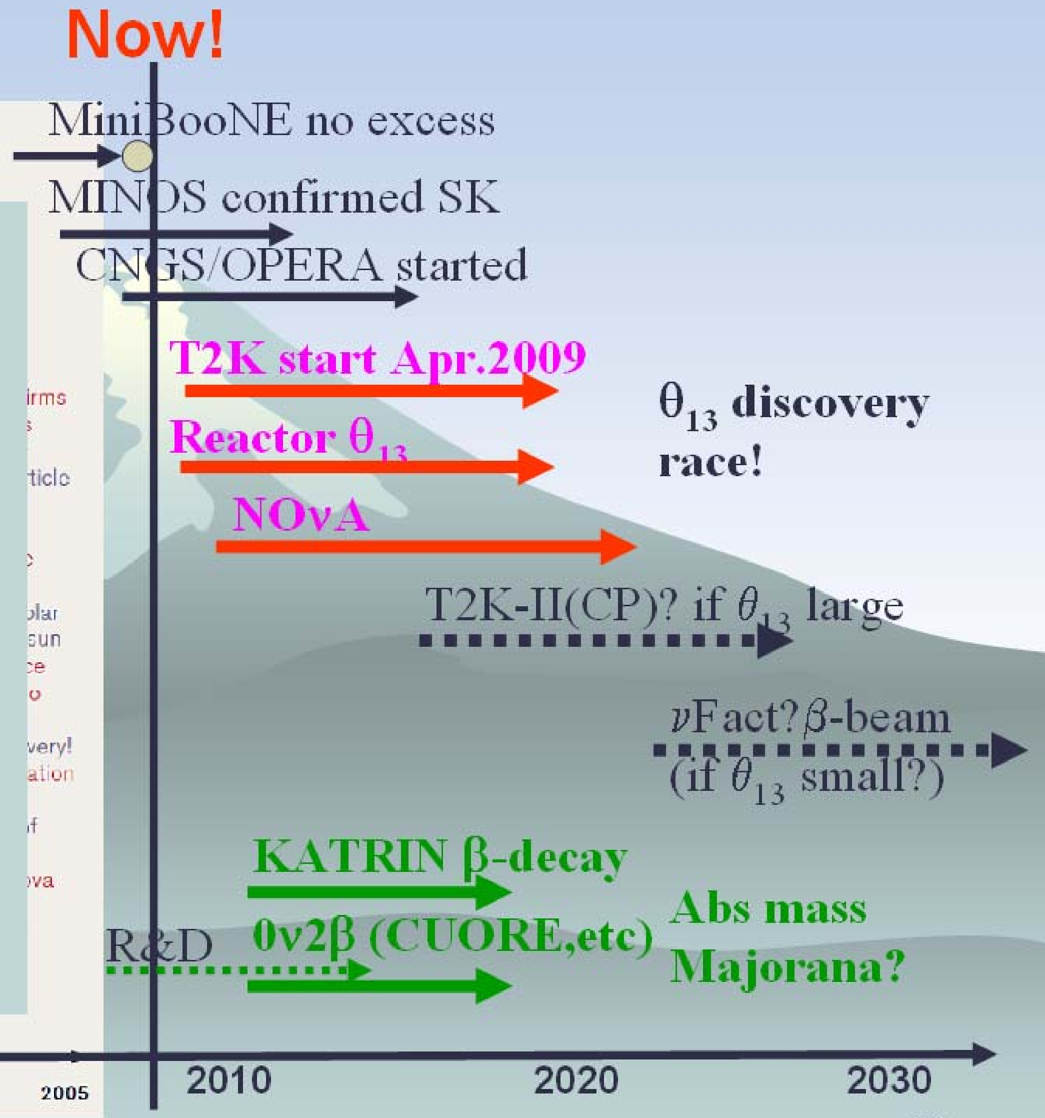
- First evidence of physics not accounted by SM
- Still many fundamental questions
- Could be clue to Physic Beyond SM

Summary

Continuing Excitement of Neutrino Physics

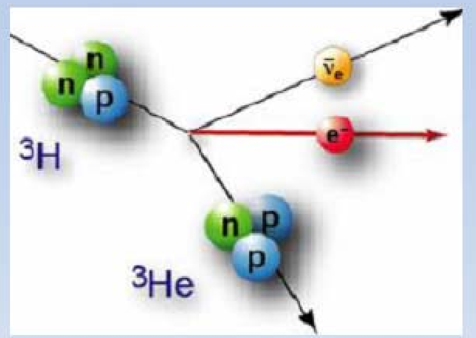
The Growing Excitement of

- Neutrino has now
  - Finite mass!!
  - Large mixing!!
- First evidence of physics not accounted by SM
- Still many fundamental questions
- Could be clue to Physic Beyond SM
- Neutrino Physics will continue to be exciting for > several 10yrs
  - (like last 40yrs of quarks)

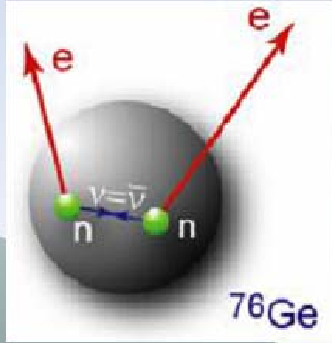


Abs. mass & Majorana?

- Tritium β-decay experiments
  - Shift of end-point of β-ray spectrum
  - ➔ $m_{\nu e}^2 = \sum_i |U_{ei}|^2 m_i^2$
  - Present: m_ν<2.2eV (Mainz, Troitk
  - Potential: m_ν<0.3eV (KATRIN, 2010~)



- 0ν2β decay experiments
  - Only if Majorana ($\nu=\bar{\nu}$) & massive
  - Peak in energy spec at Q-value
  - Present: <~0.35eV
  - Potential: 0.03eV (CUORE, Gerda, Majorana, EXO..)



- Cosmology
  - Large scale structure, CMB
  - $\Sigma = m_1 + m_2 + m_3$
  - Present: 0.7eV

Backup

MW Proton Facility : J-PARC

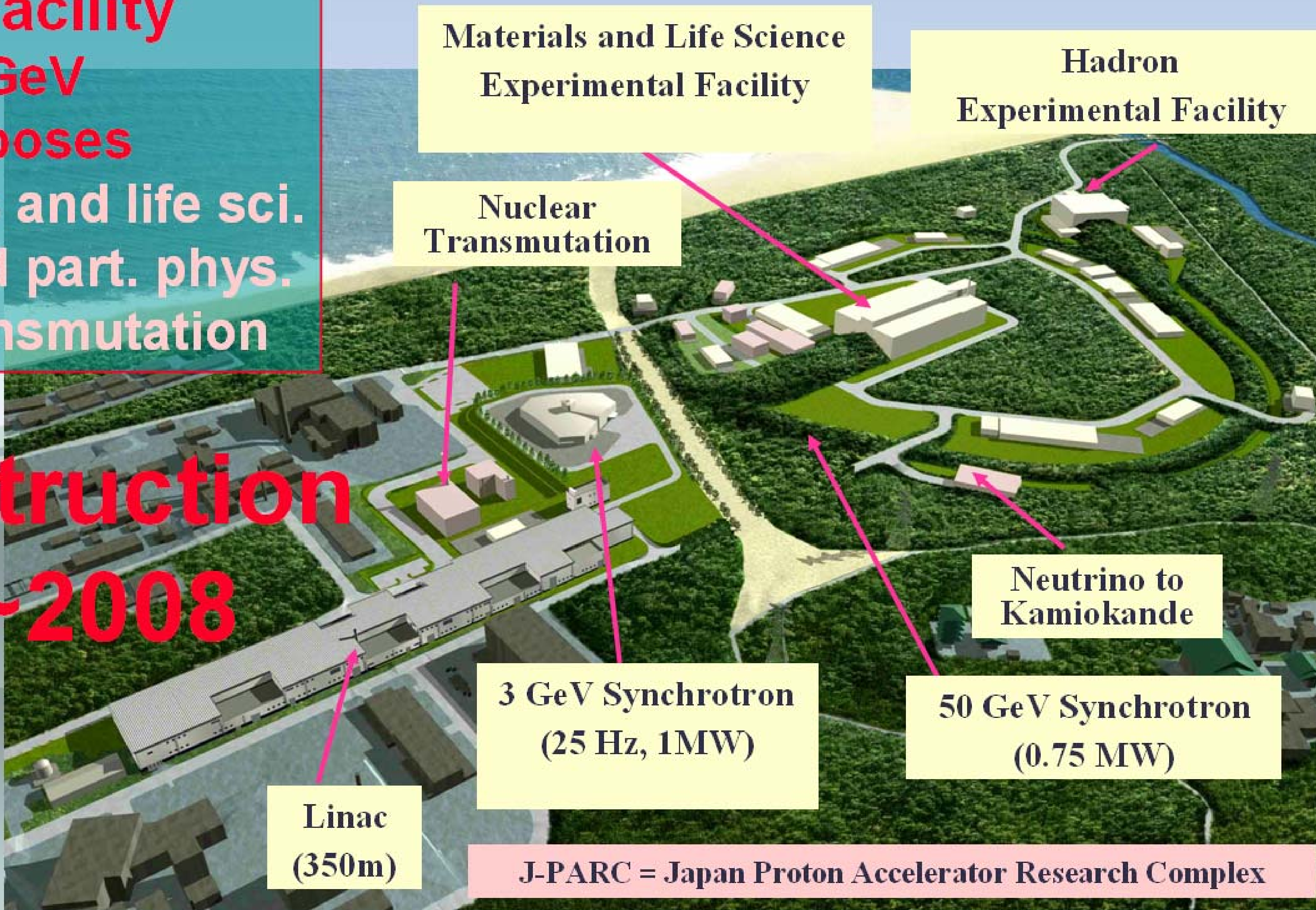
Unique facility

3GeV+50GeV

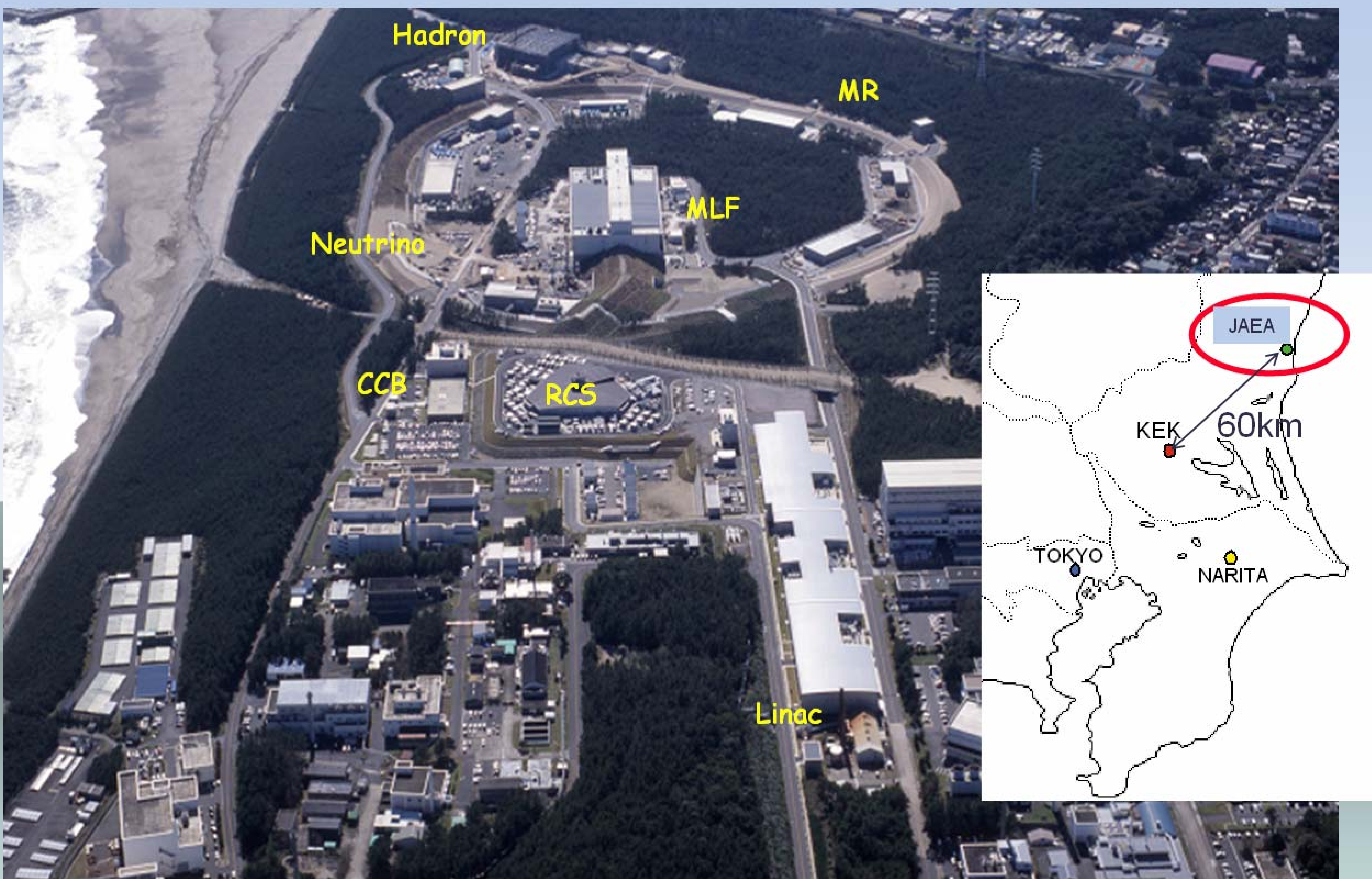
Multi-purposes

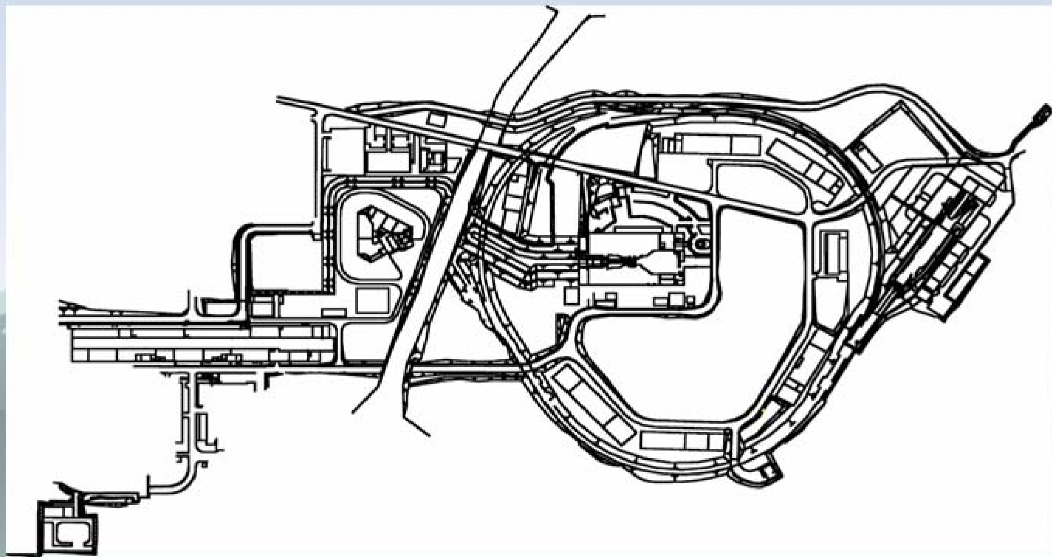
- Materials and life sci.
- Nucl. and part. phys.
- Nucl. transmutation

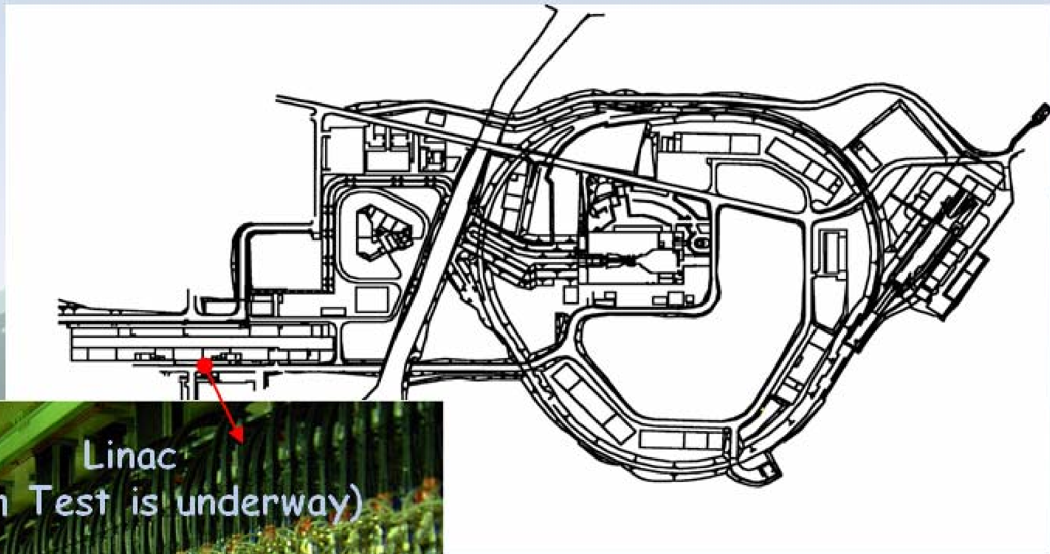
Construction 2001~2008



Bird View Photograph, Nov. 2006

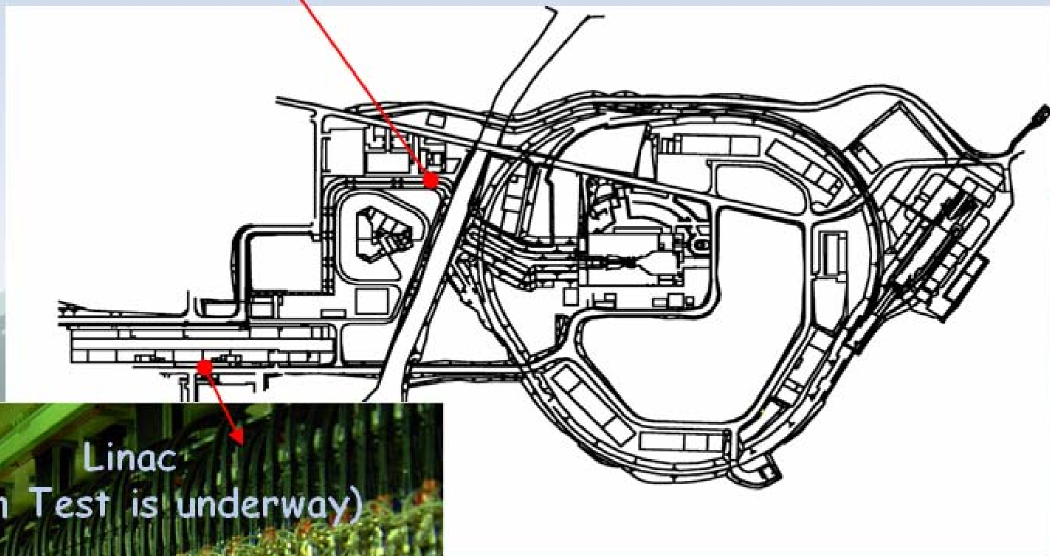







Linac
(Beam Test is underway)


3 GeV Tunnel
(Beam injection in the fall of 2007)

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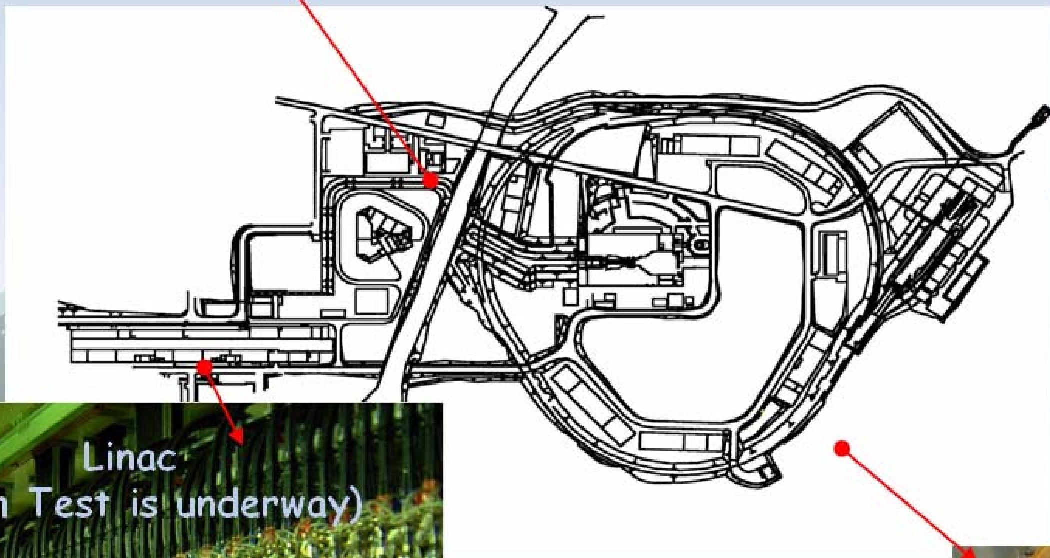


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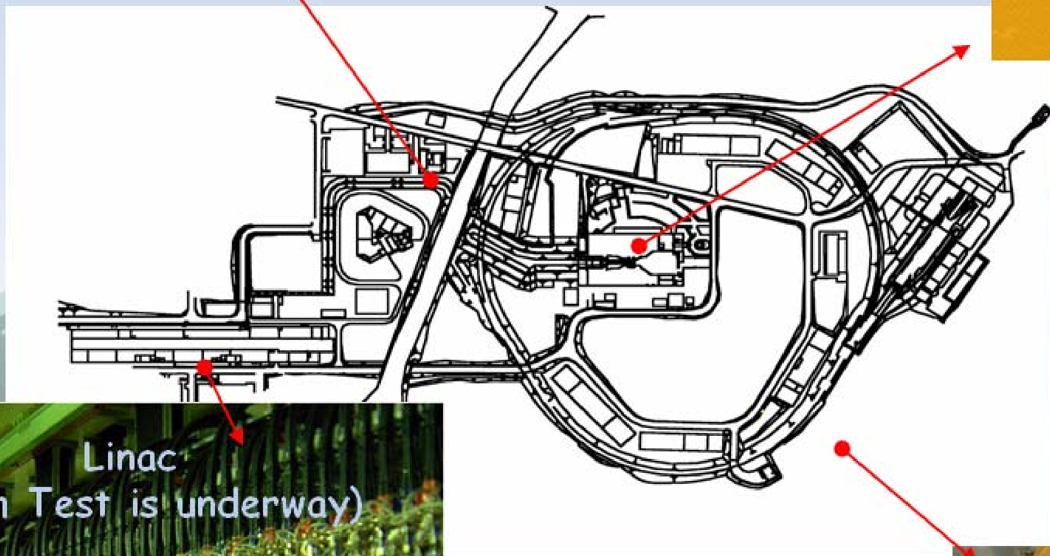
Neutron Source
(Beams in the
Spring of 2008)

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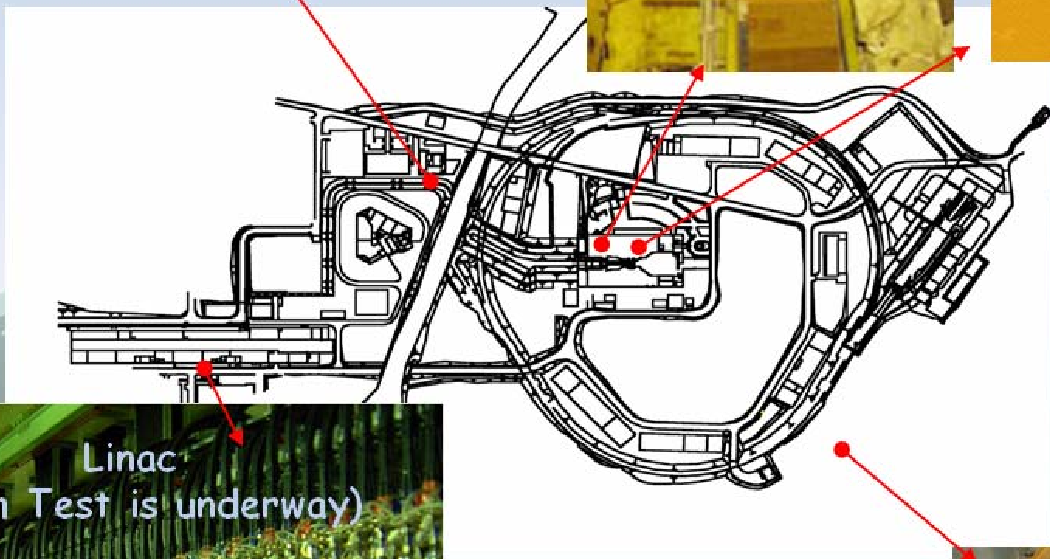
Muon area
(Beams in the
Spring of 2008)


Neutron Source
(Beams in the
Spring of 2008)

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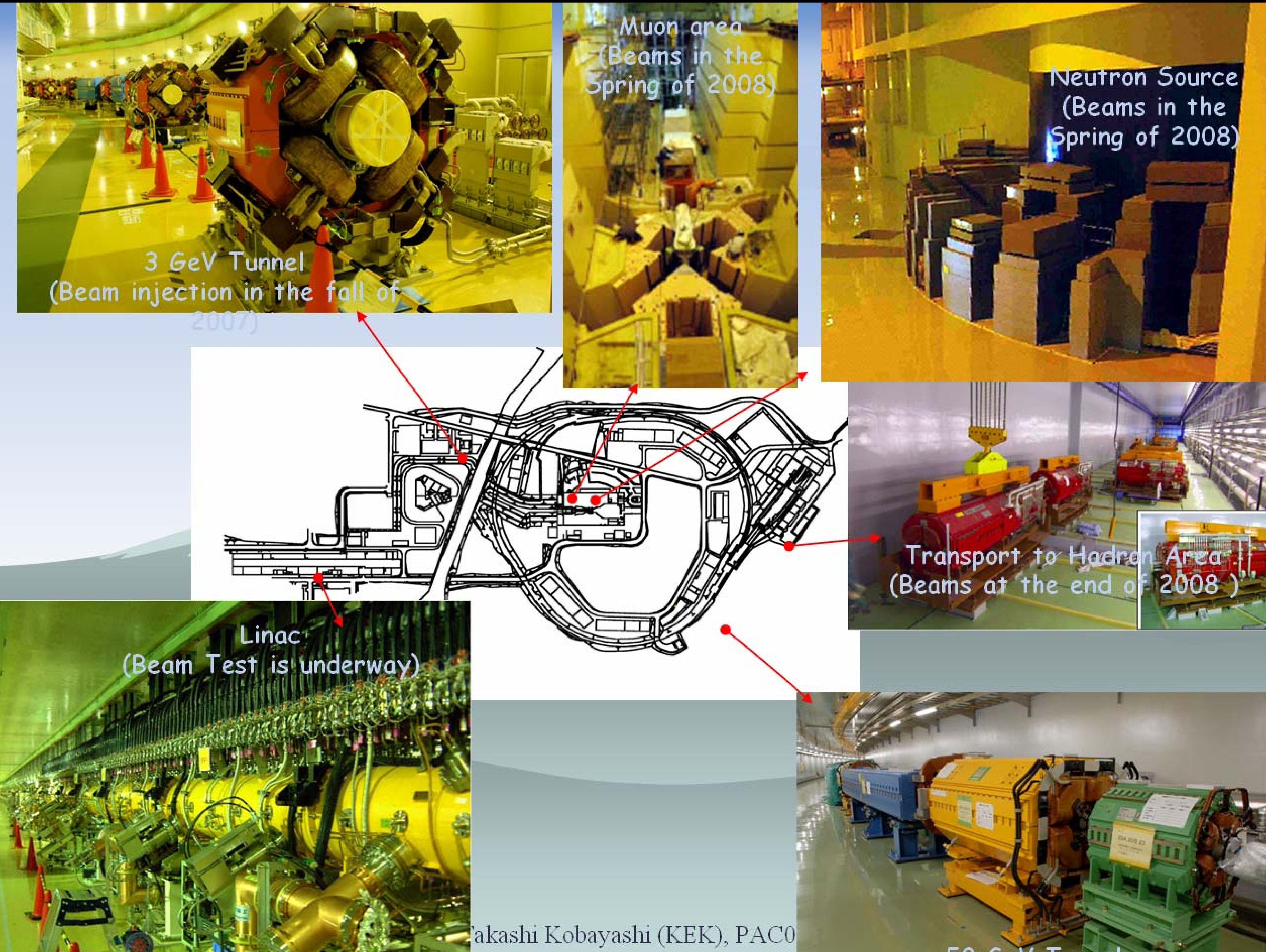
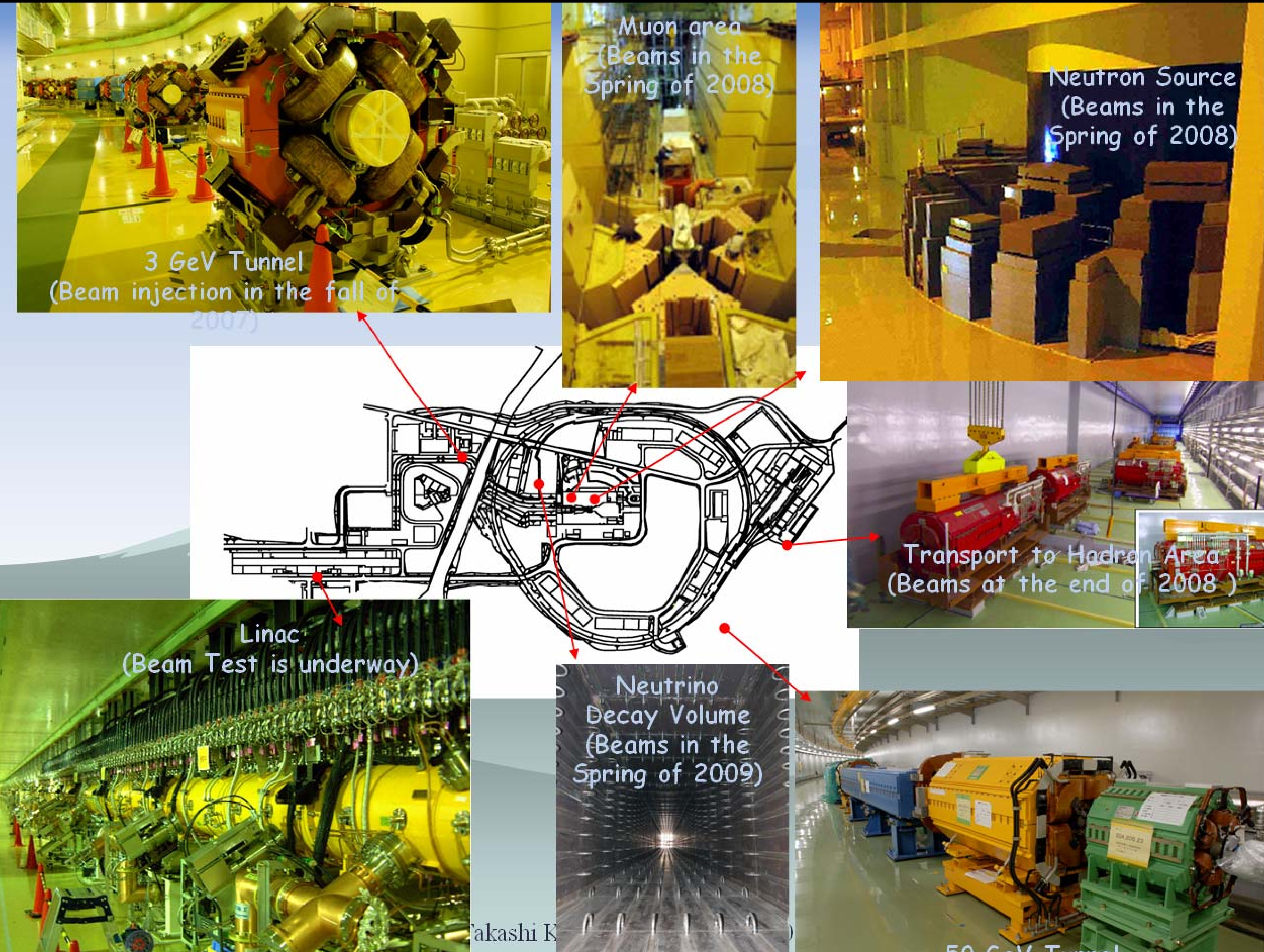

3 GeV Tunnel
(Beam injection in the fall of 2007)
Muon area
(Beams in the Spring of 2008)
Neutron Source
(Beams in the Spring of 2008)
Transport to Hadron Area
(Beams at the end of 2008)
Linac
(Beam Test is underway)


3 GeV Tunnel
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Spring of 2008)
Transport to Hadron Area
(Beams at the end of 2008)
Linac
(Beam Test is underway)
Neutrino
Decay Volume
(Beams in the
Spring of 2009)

Linac beam on Jan. 24, 2007

Accelerated up to design energy of 181MeV

Linac beam on Jan. 24, 2007

Accelerated up to design energy of 181MeV

T2K status (photo album)

Primary line tunnel

April, 2007

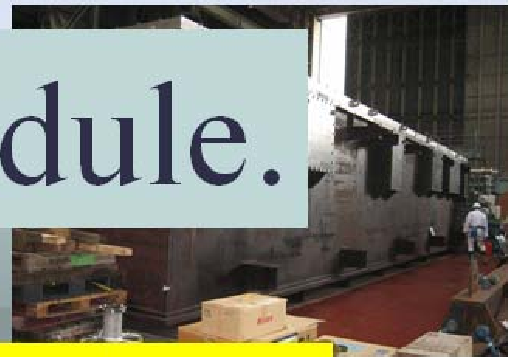
Target station

TS Helium vessel

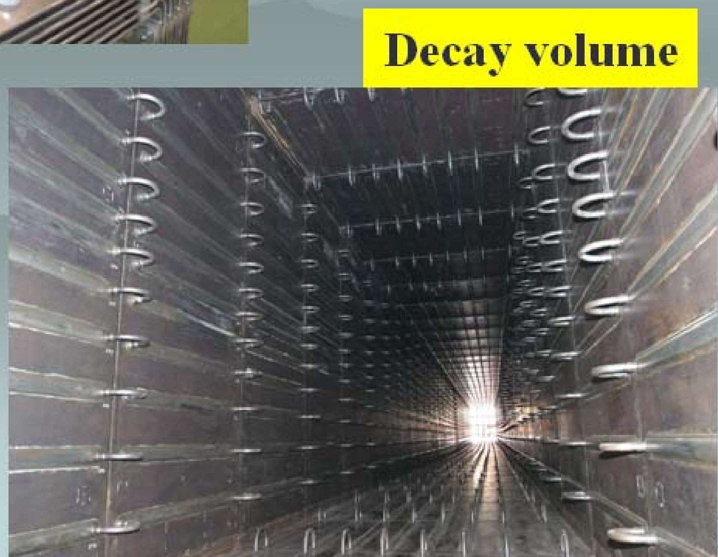
Decay volume

Beam dump core

T2K status (photo album)

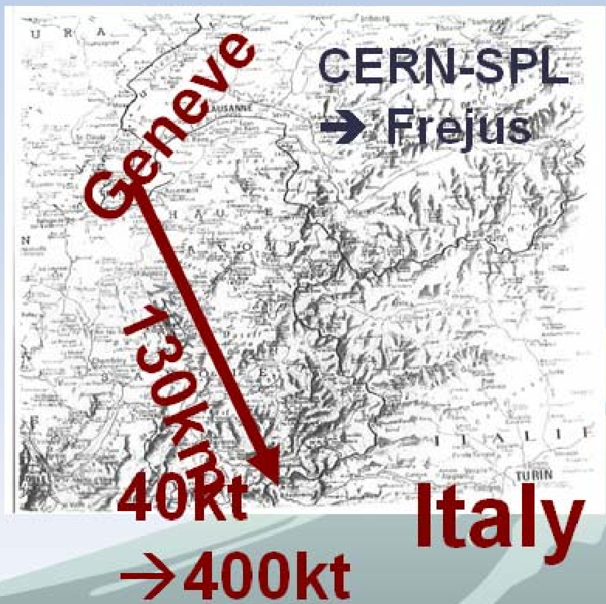


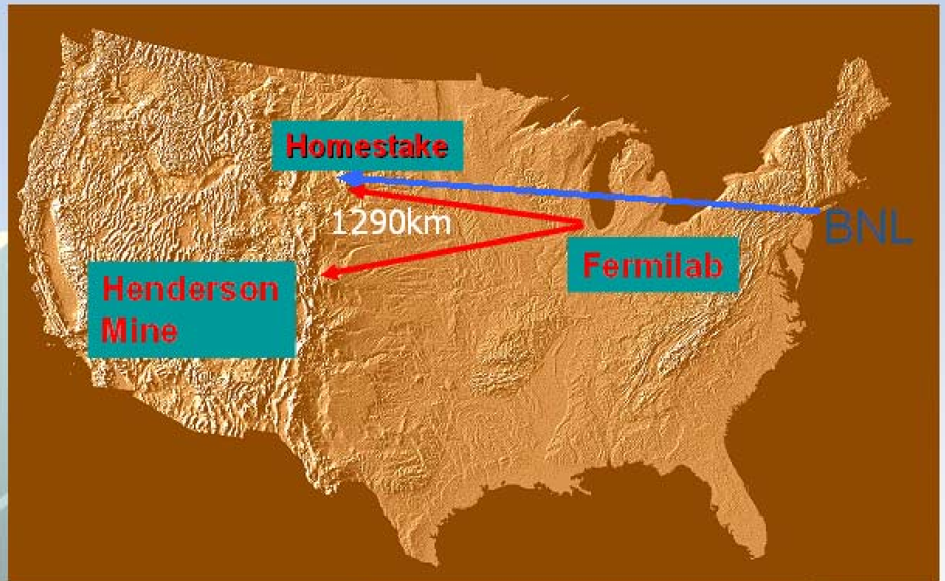
In short, on schdule.



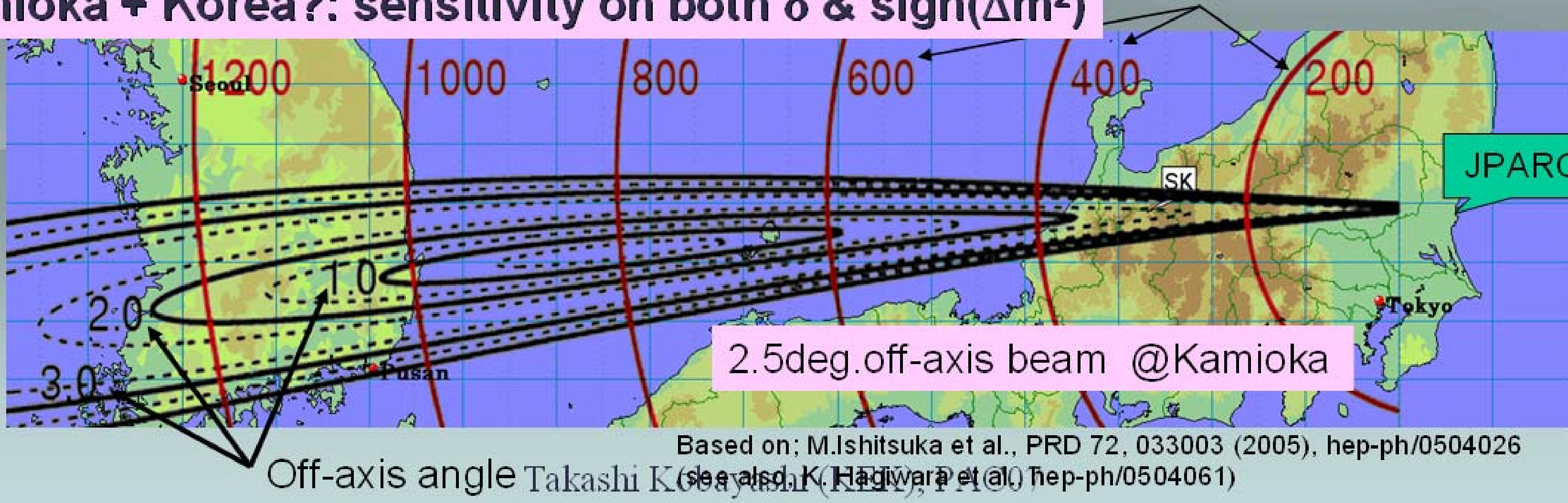
Other ideas of future acc. experiments

- CPV and matter effect
- All needs multi-MW + ~Mton detector





T2Kamioka + Korea?: sensitivity on both δ & sign(Δm^2)



Based on; M.Ishitsuka et al., PRD 72, 033003 (2005), hep-ph/0504026
(see also, K.Hagiwara et al, hep-ph/0504061)