Dec. 15, 2006
宇宙線研共同利用
研究成果発表研究会

スーパーカミオカンデ

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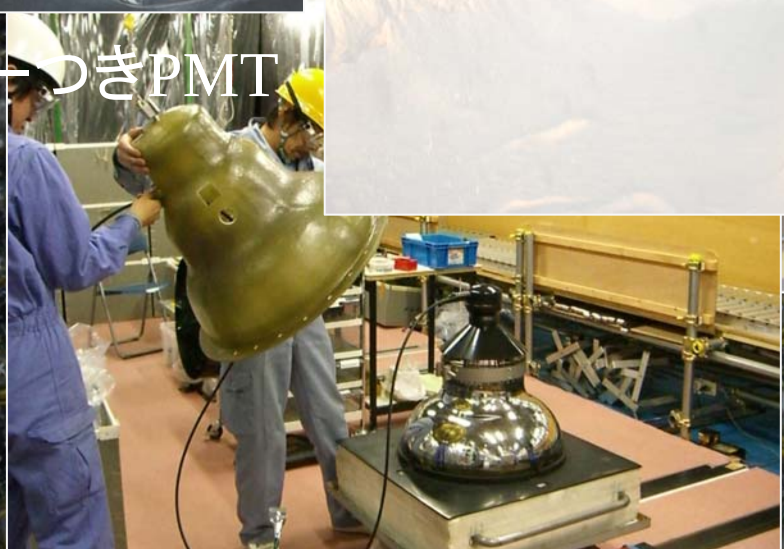
宇宙線研 神岡宇宙素粒子研究施設

2005年10月~2006年4月 SK完全再建

- 全てのPMTに衝撃波防止カバーを取り付けた。

平成18年豪雪

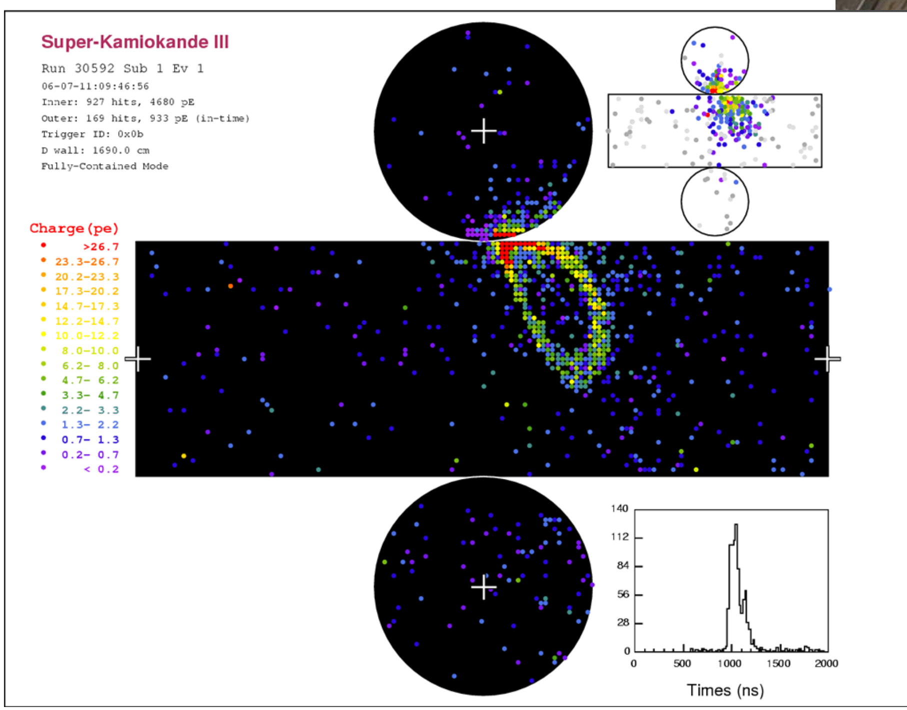


カバーつきPMT

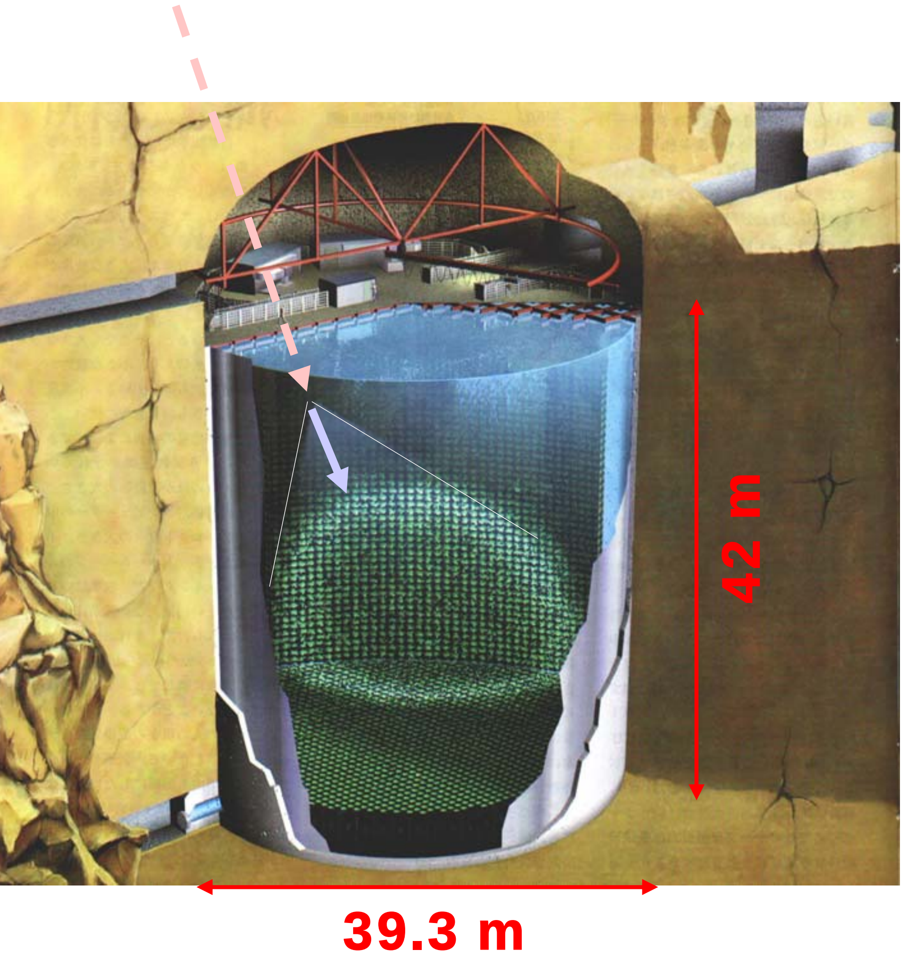
再建作業へはトロッコで…

2006/7/11 観測再開

- 2006年7月、最後のPMTを取り付け、満水にし、観測再開した。



Super-Kamiokande



- 50kton pure water (22.5kt fid.vol.)
- 11200 (Inner detector) + 1800 (Outer detector) PMTs
- 1000m underground → 2700m wat. eq.

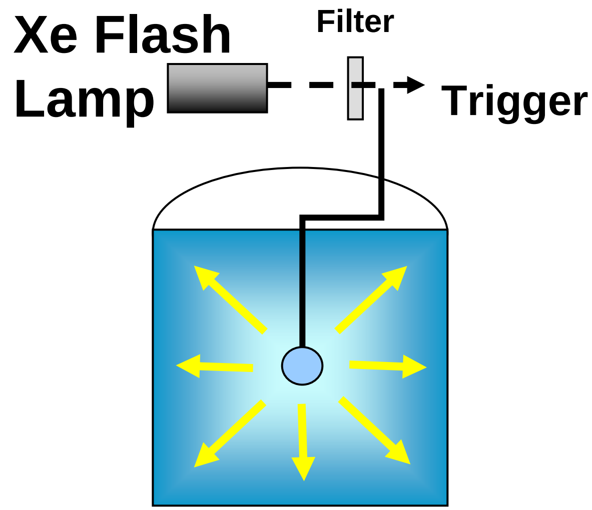
History

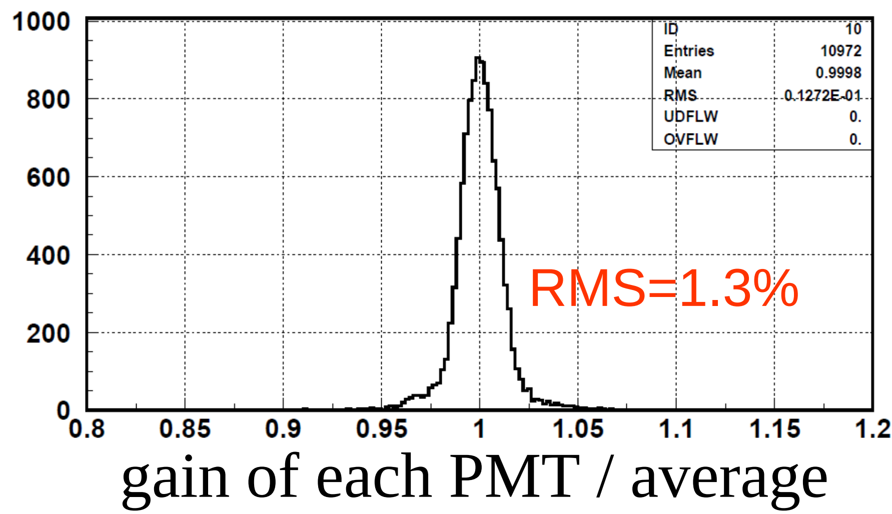
Year	Phase	# of PMT (Photo Coverage)	Energy Threshold (Solar ν)	Major Physics Outputs
1996	Start			
1997–2001	SK-I	11,146 (40%)	5 MeV	Atm. ν Oscilaltion Phys. Rev. Lett. 81,1562(1998) Solar ν Oscilaltion Phys. Rev. Lett. 86,5651(2001)
2001	事故			
2002	部分再建			
2003–2005	SK-II	5,182 (19%)	7 MeV	Atm. ν L/E Phys. Rev. Lett. 93, 101801(2004) K2K Final Result Phys.Rev.D74:072003, (2006)
2006	完全再建			
2006–2008	SK-III	11,129 (40%)	4 MeV(plan)	

SK-III Startup Calibrations

Gain adjustment of PMT

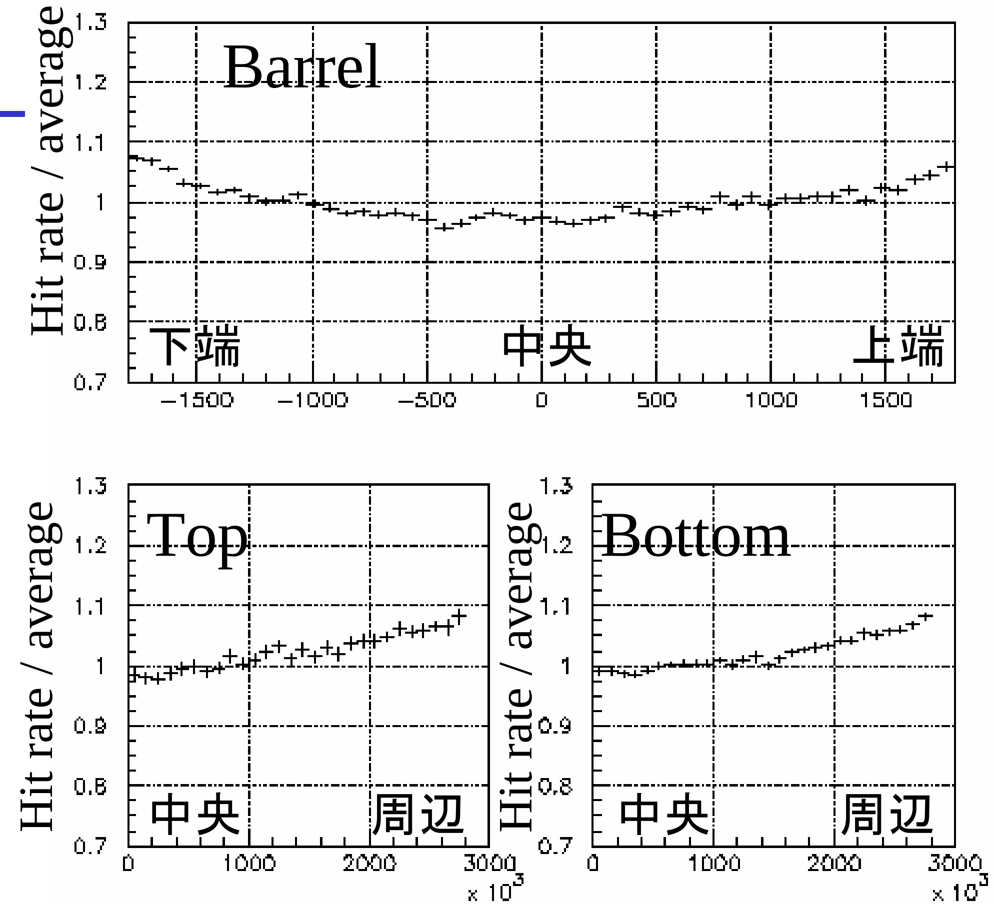
- タンク外で一部のPMTを同じ gain (= QE * Amplification) になるように適正HV値を求めておく。(Pre-Calibration)
- SKに全PMTを取付、注水後、タンク内のシンチレータをXenon ランプで光らせ、取り付けた全てのPMTについて近傍のpre-calibrated PMT と同じ gain になるようHV値を調整
- HV最終調整後、最終的な gain のばらつきを測定した。
→ RMS=1.3%





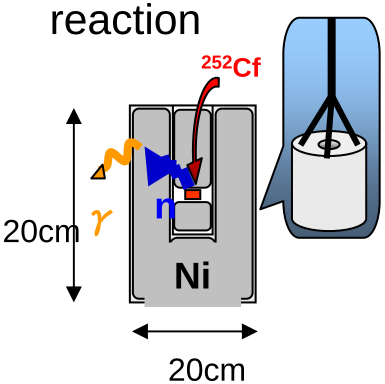
Quantum Efficiency Measurement

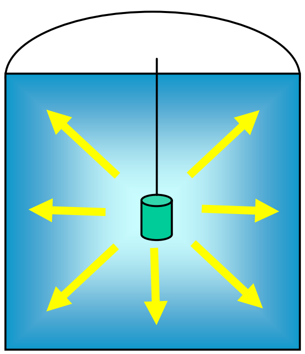
- タンク内に$^{58}\mathrm{Ni}(n,\gamma)^{59}\mathrm{Ni}$ ソースを入れる（1 photon level の光源）
- 各PMTのHit Rateを求める。 (r^2, acceptance correction)



Light Source

→ 9MeV γ-rays emitted from $^{58}\mathrm{Ni}(n,\gamma)^{59}\mathrm{Ni}$ reaction





Top-Bottom asymmetry = +0.3%

top-bottom asymmetry = (<top> - <bottom>) / <barrel>

Energy calibration for Low E

- "N50" = Num. of hits in 50ns timing window
- SK-III:

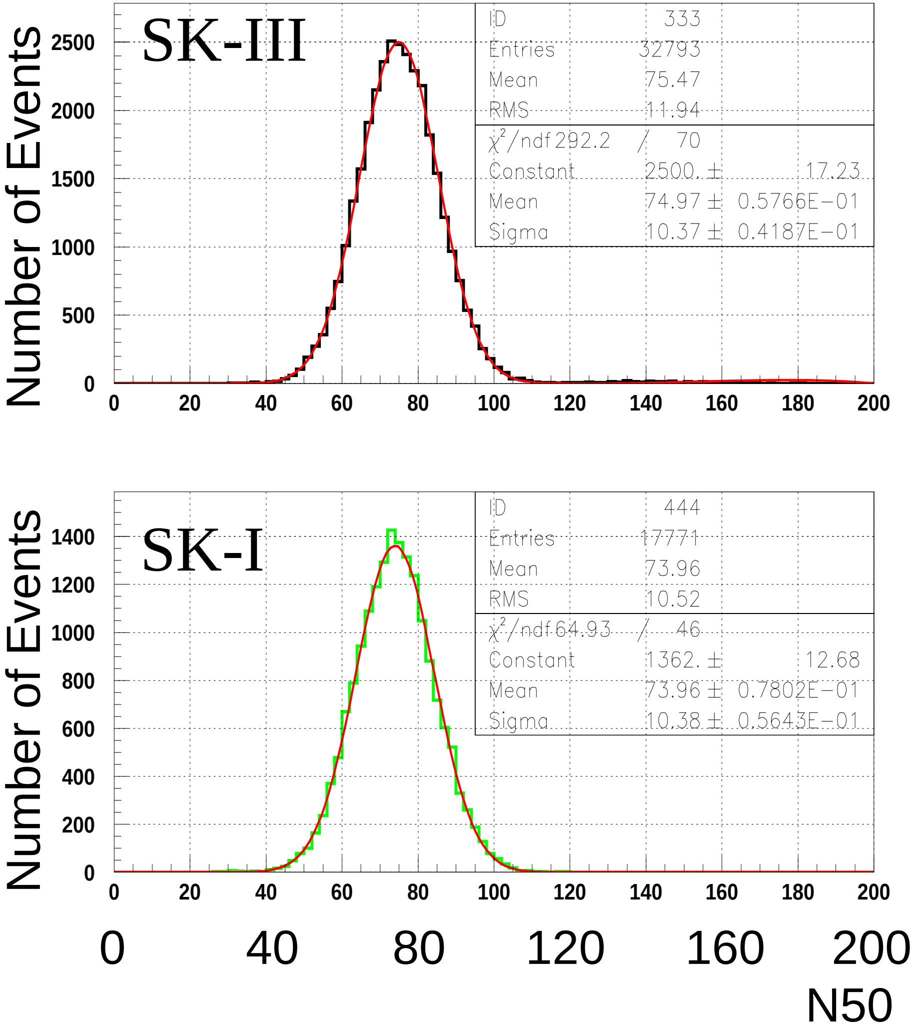
  N50 = 74.97±0.06

  σ = 10.37±0.05
- SK-I:

  N50 = 73.98±0.08

  σ = 10.38±0.06
- Performance is Comparable.

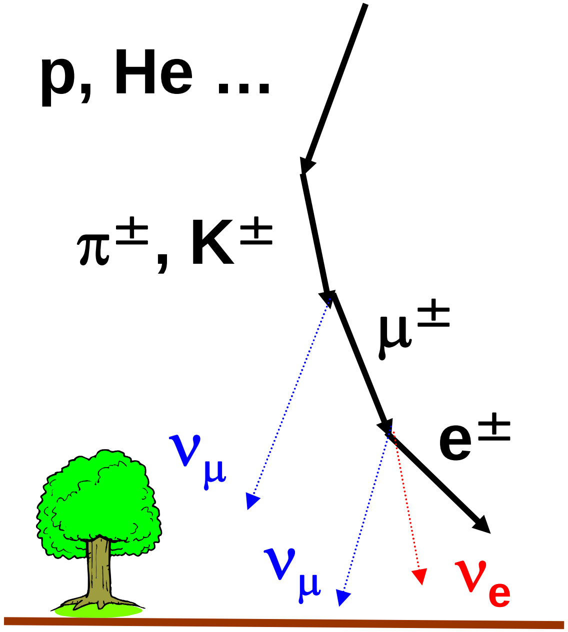
LINAC 13.6 MeV/c Mode



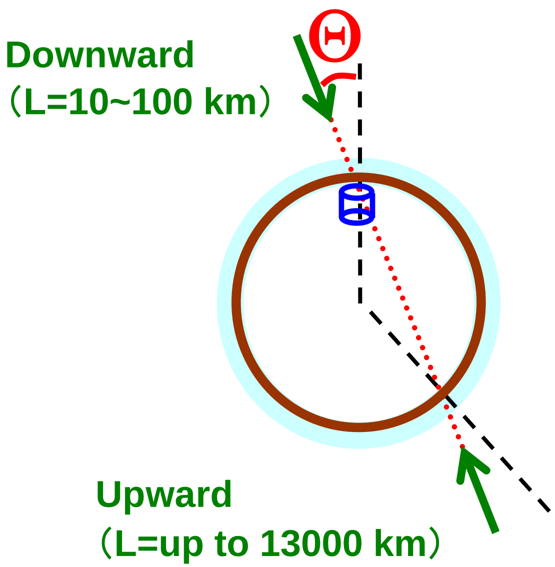
Physics Results

- Atmospheric Neutrinos
  - $\nu\mu$ disappearance analysis
  - $\nu\mu \rightarrow \nu\tau$ or other modes?
- Solar Neutrinos
  - SK-I + SK-II results
  - Improvement for SK-III
- Supernovae Neutrinos
- Proton Decay Search

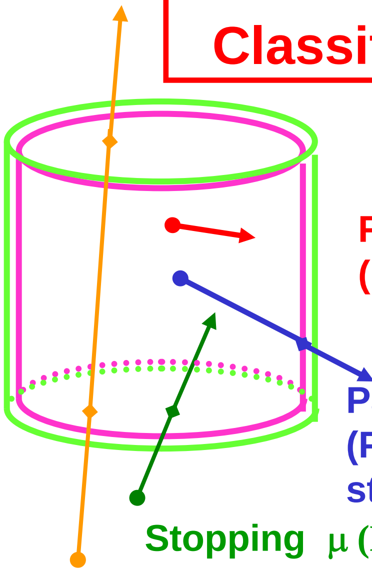
Atmospheric Neutrinos



Zenith angle



Event Classification



Fully Contained (FC) (E_ν ~1GeV)

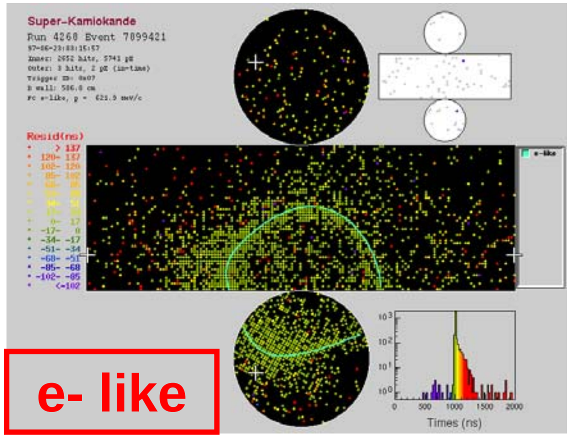
Partially Contained (PC) (E_ν ~10GeV) stop/through OD

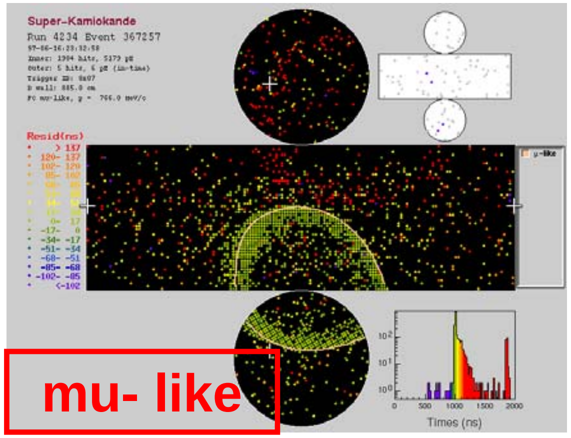
Stopping μ (E_ν ~10GeV)

Through-going μ (E_ν ~100GeV)
Showering/ Non-Showering

Particle ID

(Fully Contained)



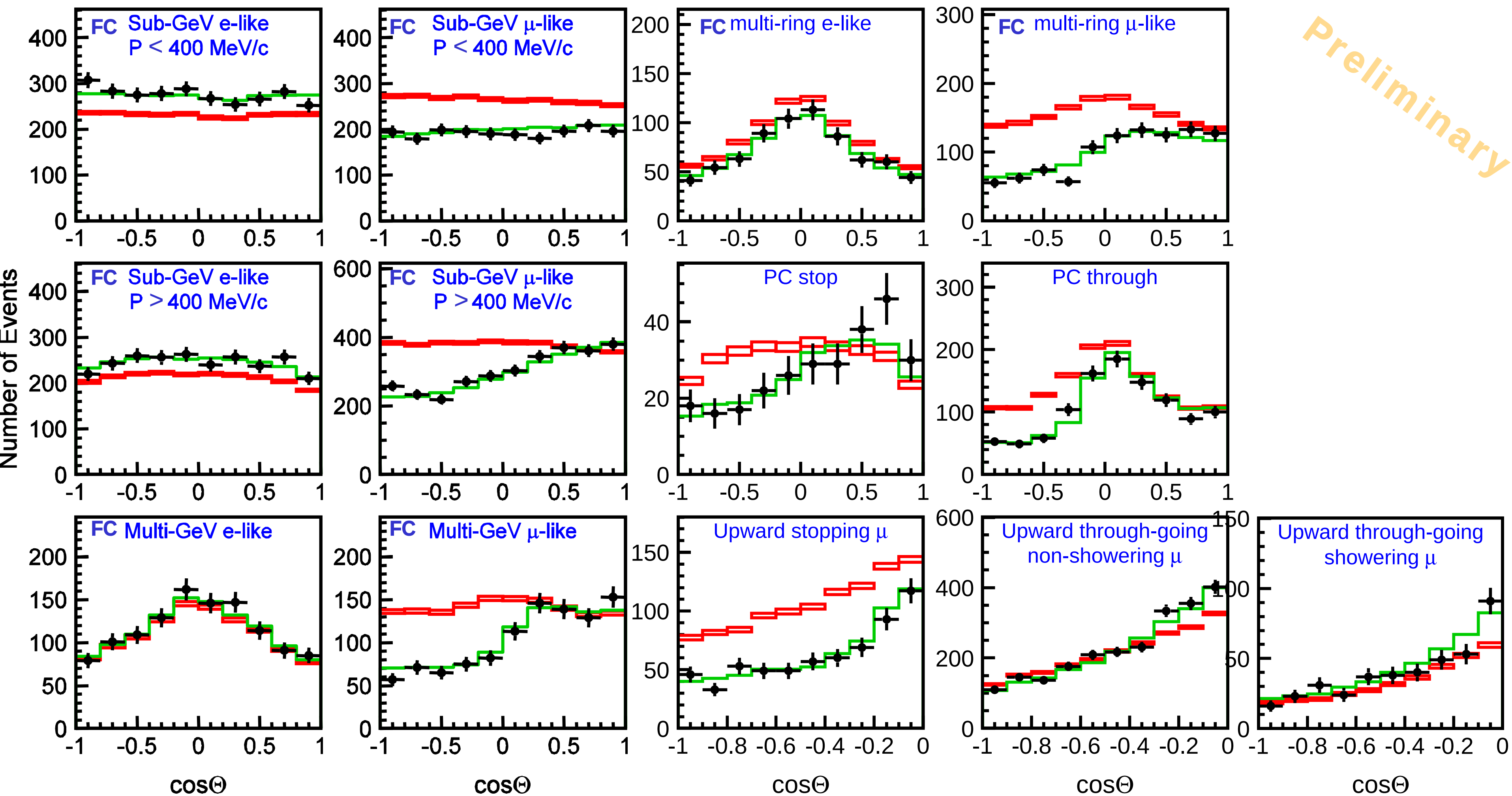


Zenith Angle Distribution

SK-I : 1489 days
SK-II : 804 days

$\nu_\mu - \nu_\tau$ oscillation (best fit)
null oscillation

SK-I + SK-II



Oscillation Analysis

μ/e double ratio

Sub-GeV

SK-II : $\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.656 \pm 0.022 \pm 0.033$

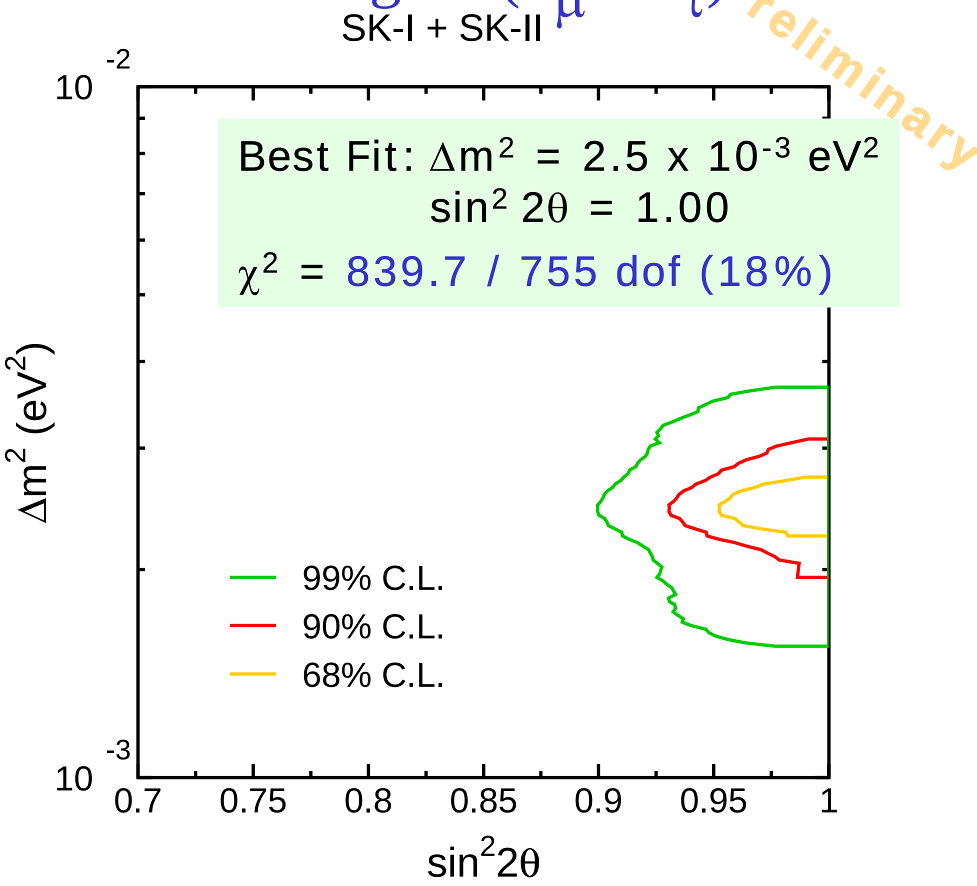
SK-I : $0.658 \pm 0.016 \pm 0.035$

Multi-GeV (FC+PC)

SK-II : $\frac{(\mu/e)_{DATA}}{(\mu/e)_{MC}} = 0.746^{+0.047}_{-0.044} \pm 0.055$

SK-I : $0.702^{+0.032}_{-0.030} \pm 0.101$

allowed region ($\nu_\mu \to \nu_\tau$)



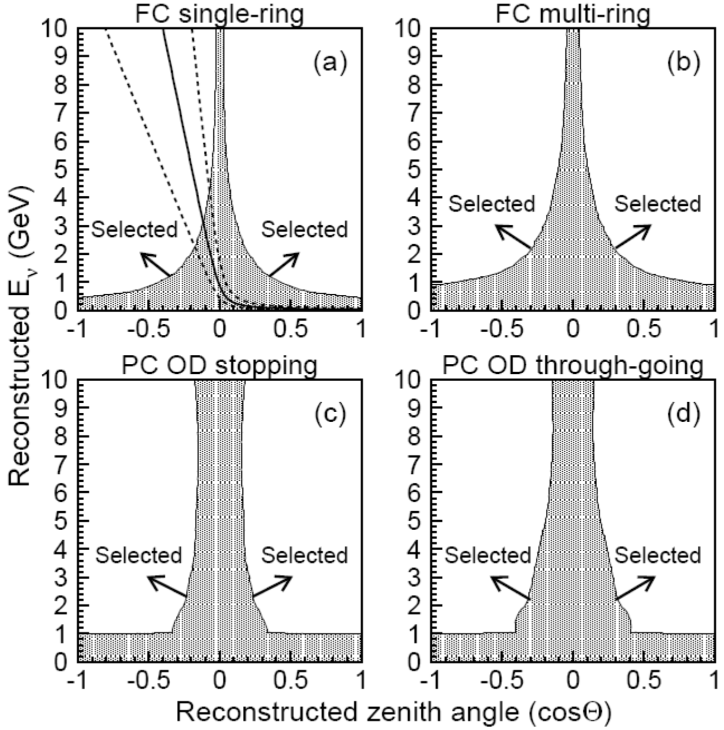
$1.9 \times 10^{-3}\ \mathrm{eV}^2 < \Delta m^2 < 3.1 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2 2\theta > 0.93$ at 90% CL

L/E analysis

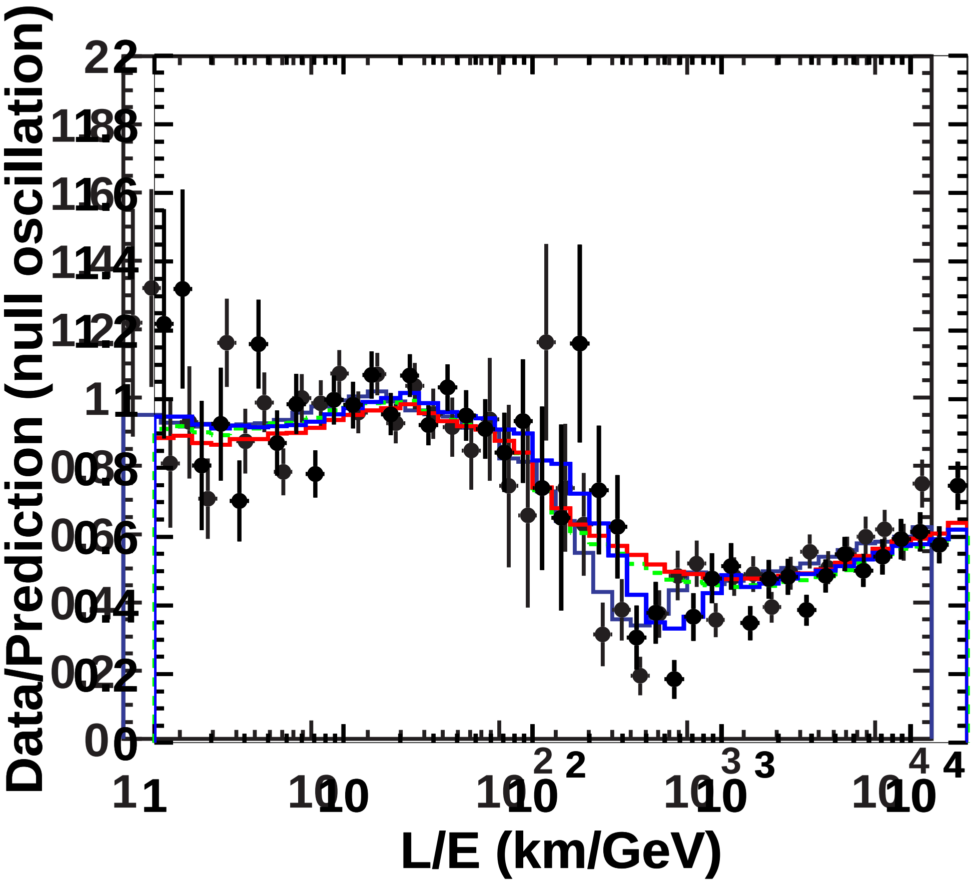
- $P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 (\mathrm{eV}^2) L(\mathrm{km})}{E(\mathrm{GeV})} \right)$

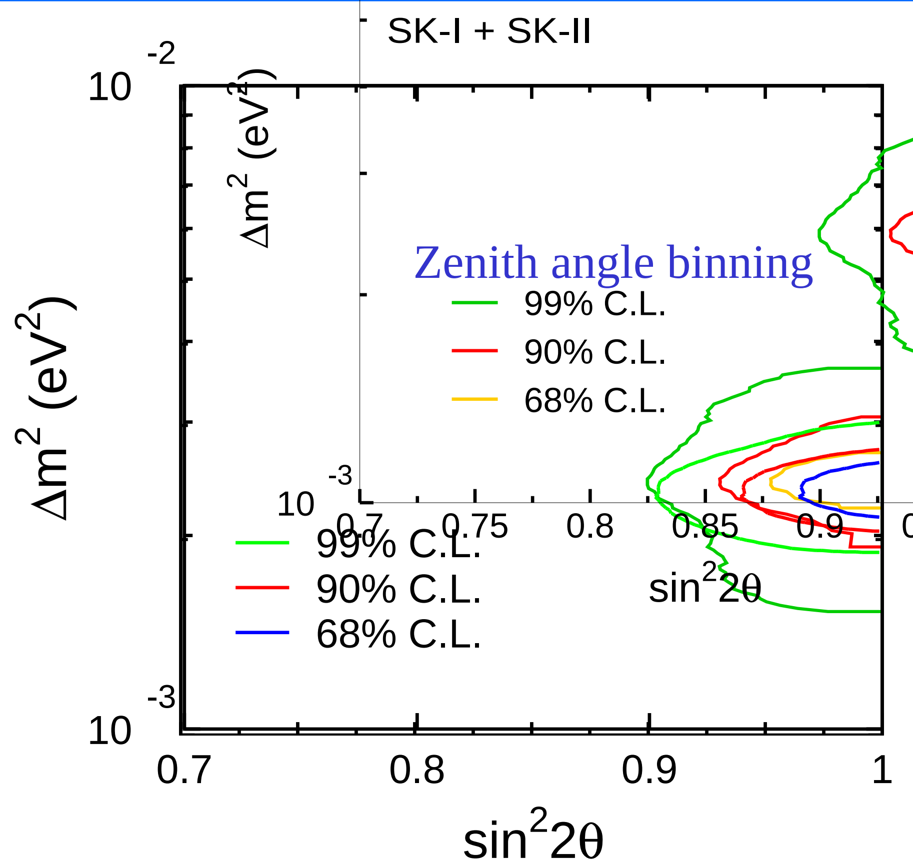
- Select good L/E resolution (<70%) events
- Perform oscillation analysis with L/E binning



L/E Analysis result

Update from
Phys. Rev. Lett. 93,101801(2004)





Oscillation best fit χ^2_{osc} = 83.9/d.o.f

at $(\sin^2 2\theta, \Delta m^2) = (1.00, 2.3 \times 10^{-3} eV^2)$

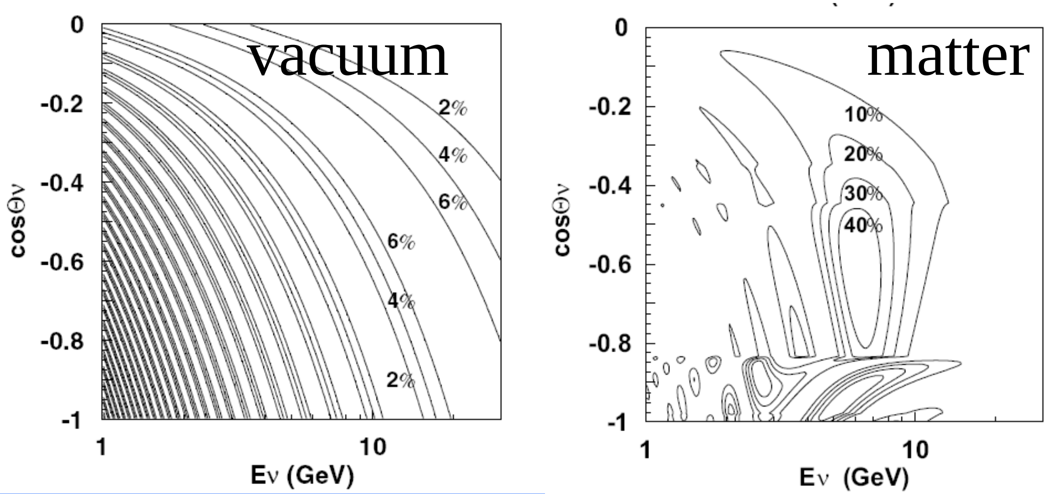
3 Flavor Oscillation

- In the case $\theta_{13} \neq 0$:

$$
\begin{aligned}
\mathrm{P}(\nu_e \to \nu_e) &= 1 - \sin^2 2\theta_{13} \sin^2(\frac{1.27\Delta m^2 L}{E}) \\
\mathrm{P}(\nu_\mu \to \nu_e) &= \mathrm{P}(\nu_e \to \nu_\mu) \\
&= \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(\frac{1.27\Delta m^2 L}{E}) \\
\mathrm{P}(\nu_\mu \to \nu_\mu) &= 1 \\
&\quad -4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23}) \\
&\quad \times \sin^2(\frac{1.27\Delta m^2 L}{E})
\end{aligned}
$$

νe excess may be seen

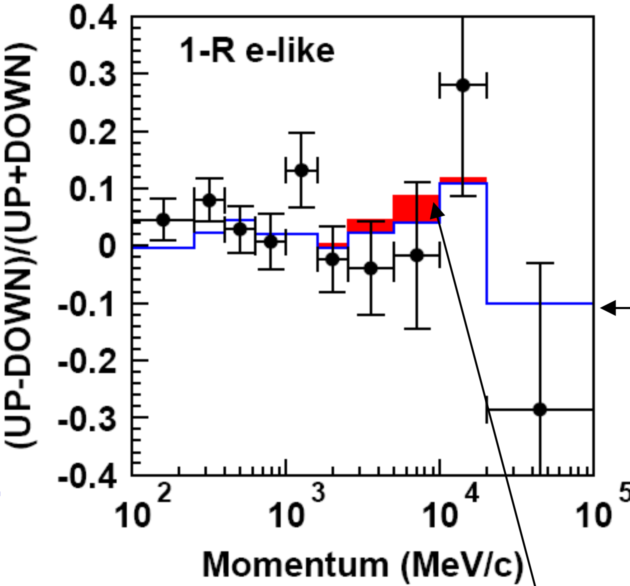
- Matter effect enhance ν_e appearance



$\nu\mu \to \nu e$ oscillation probability,
$\Delta m^2 = 2.5\times10^{-3}\mathrm{eV}^2$,
$\sin^2\theta_{23} = 0.5$,
$\sin^2\theta_{13} = 0.04$

3 Flavor Analysis Result

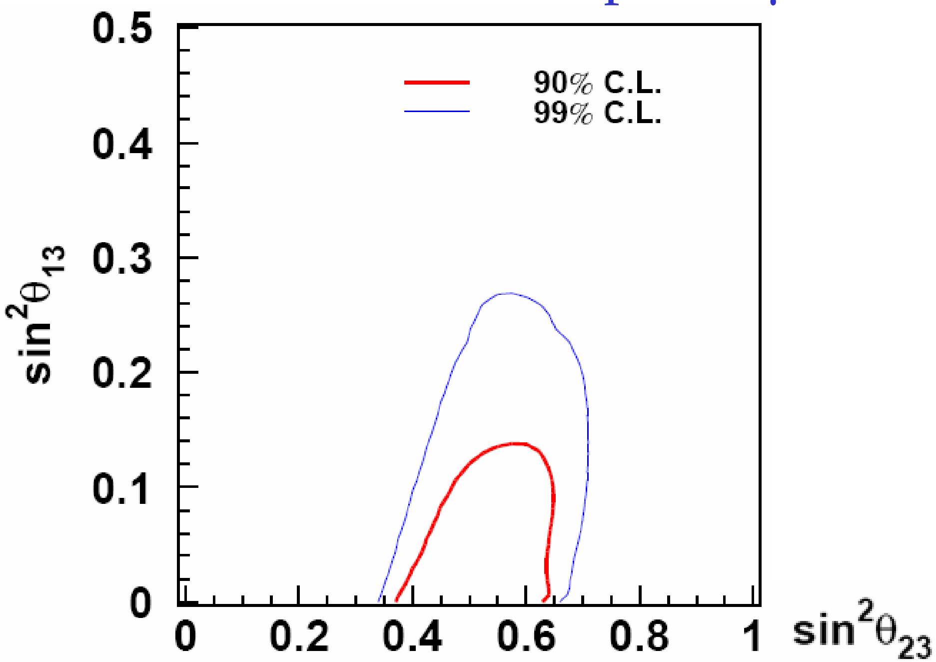
- Excess of up-going νe?
  - SK data shows no excess (yet)
- Allowed region
  - Consistent with pure νμ→ντ



SK-I
1489days

Best fit
(Δm^2=2.5 x10^{-3}eV^2, $\sin^2\theta_{23}$=0.5, $\sin^2\theta_{13}$=0.0)

Expected excess
(Δm^2=2.5x10^{-3}eV^2, $\sin^2\theta_{23}$=0.5, $\sin^2\theta_{13}$=0.04)

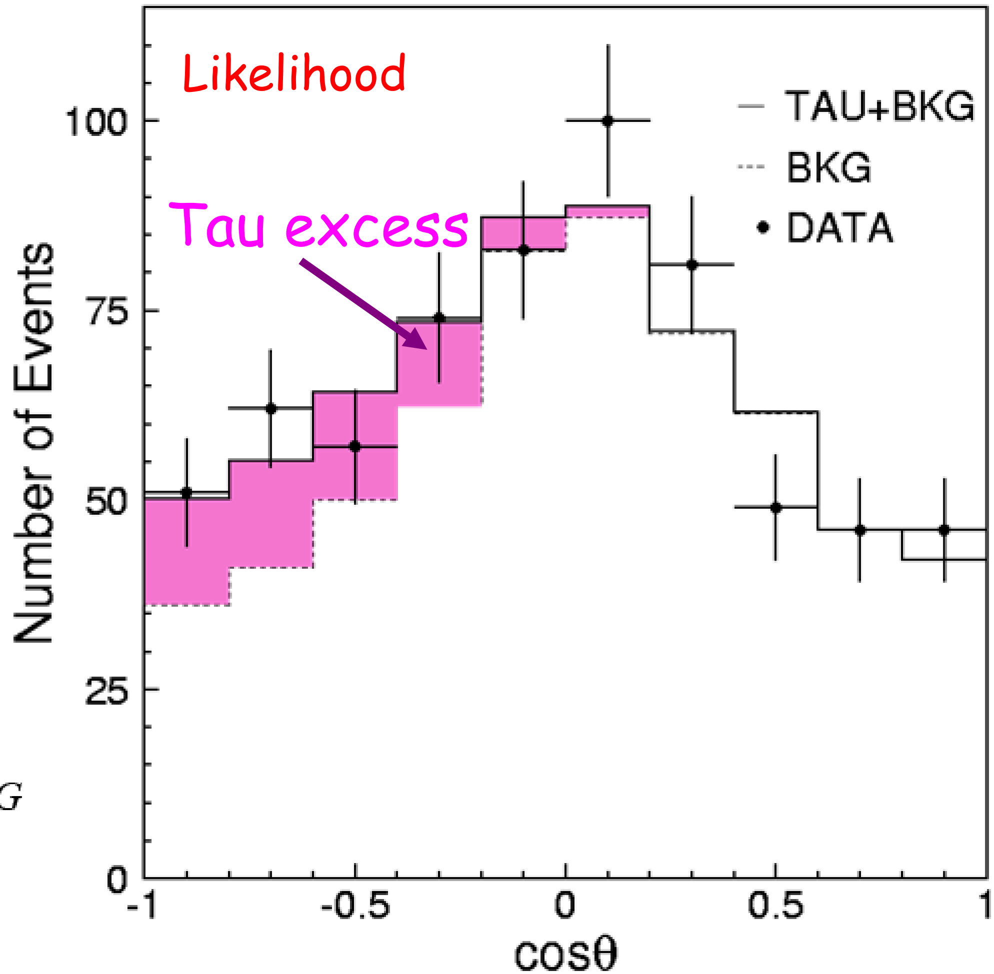


Phys. Rev. Lett. 97, 171801 (2006)

Tau Appearance Search

- Tau Enrich Sample:
  - Evis>1.33GeV (Multi-GeV)
  - Most energetic ring is e-like
  - Likelihood selection
    - Visible Energy
    - Sphericity
    - Distance between ν interaction and decay-e
- Zenith angle fit with tau signal and background

$$N_{total}\left(cos\left(\theta\right)\right)=\alpha\, N_{Tau}+\beta\, N_{BKG}$$



- χ^2/DOF = 7.6/8
  (χ^2/DOF = 16.3/9 assuming no tau appearance)

- Total τ excess: 138 ± 48(stat.)
  (signal efficiency: 43.1%)

Exotic Modes?

$\nu_\mu \rightarrow \nu_s$?

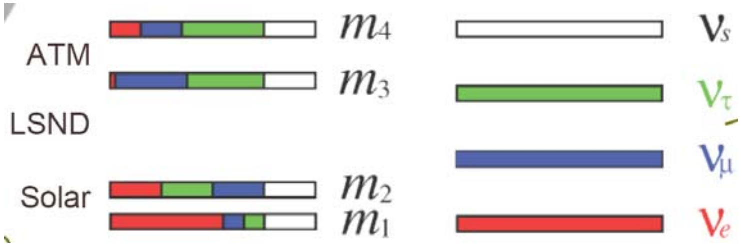
Neutrino Decay?

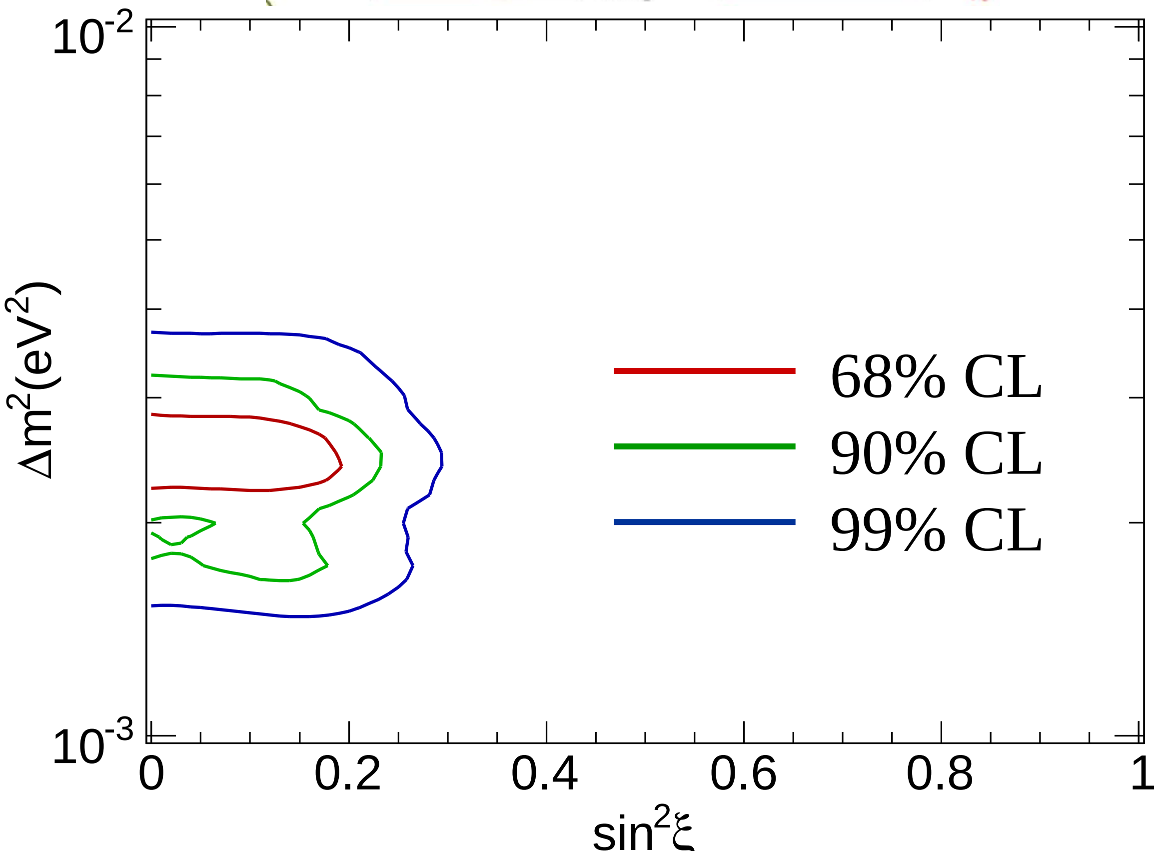
Decoherence?

$\nu_\mu \rightarrow \nu_s$?

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \nu_s \end{pmatrix}$$

- Admixture of $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$
- Based on Fogli et al, PRD 63(053008), 2001
- $\nu_\mu \rightarrow \nu_s$ case:
  - deficit of NC interaction
  - matter effect
- Zenith angle distribution are used in the analysis

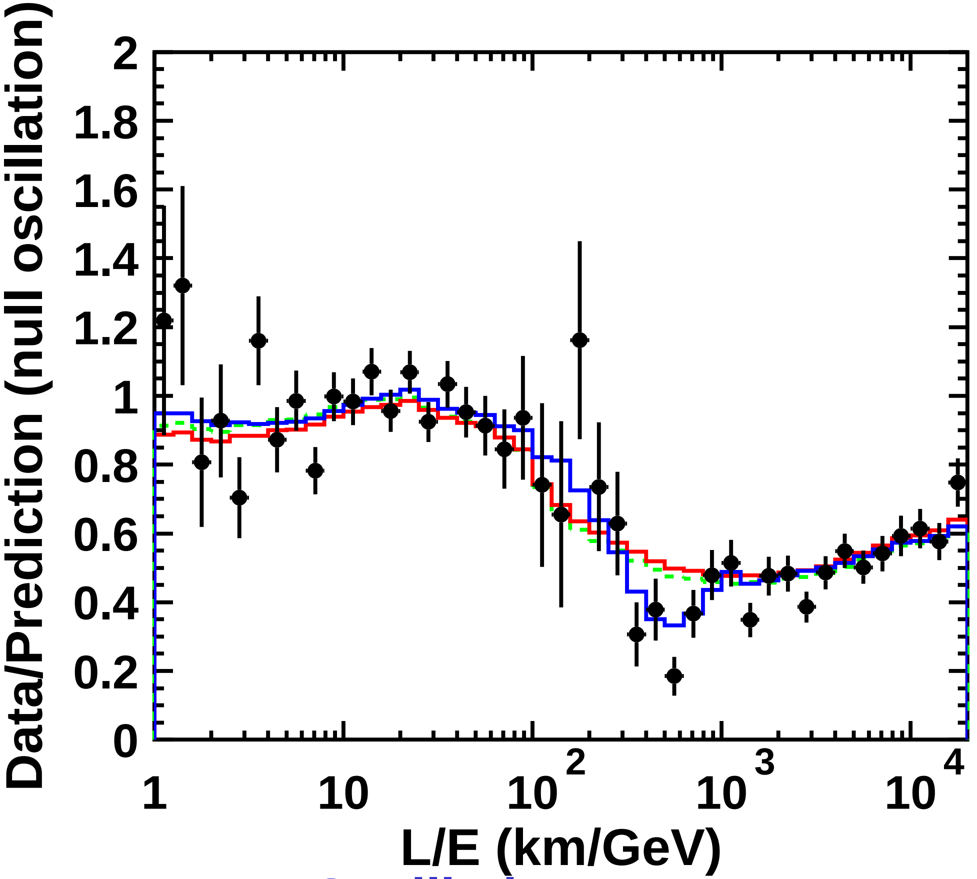




$$\sin^2\xi < 23\% @ 90\% CL$$

L/E Analysis with exotic modes

Update from
Phys. Rev. Lett. 93,101801(2004)



Decay

$$P(\nu_\mu \rightarrow \nu_\mu) = \left[\sin^2\theta + \cos^2\theta \exp\left(-m/2\tau \cdot L/E\right)\right]^2$$

Decoherence

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \frac{1}{2}\sin^2 2\theta \left[1 - \exp\left(-\gamma_0 L/E\right)\right]$$

Oscillation χ^2_{osc} = 83.9/d.o.f

Decay χ^2_{dcy} = 107.1/d.o.f, $\Delta\chi^2$ = 23.2(**4.8** σ)

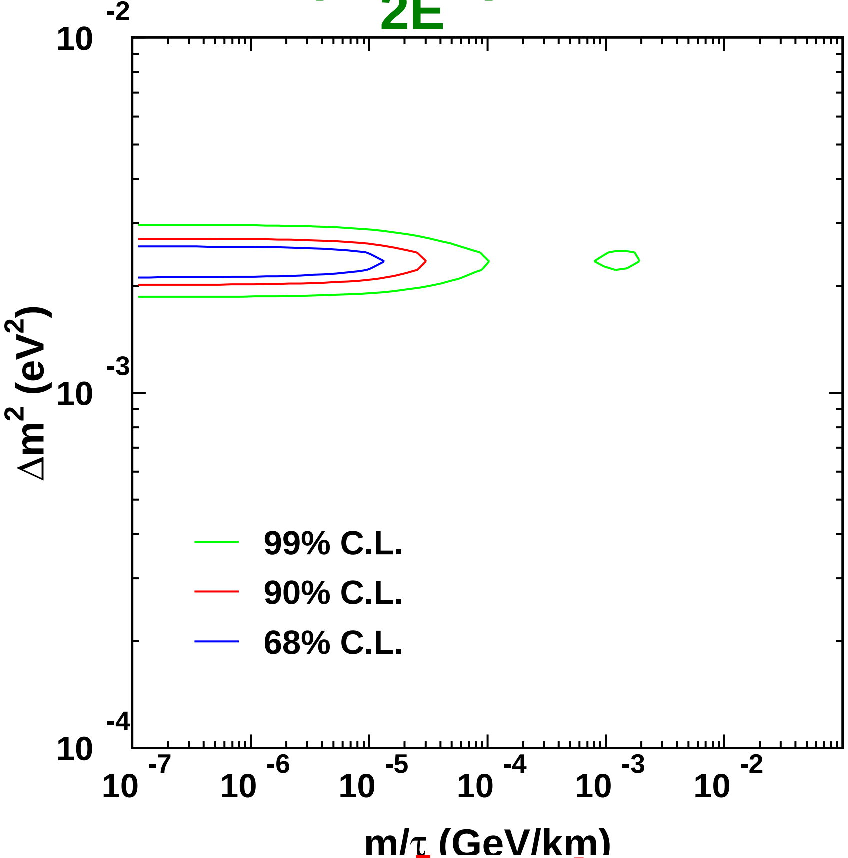
Decoherence χ^2_{dec} = 112.5/d.o.f, $\Delta\chi^2$ = 27.6(**5.3** σ)

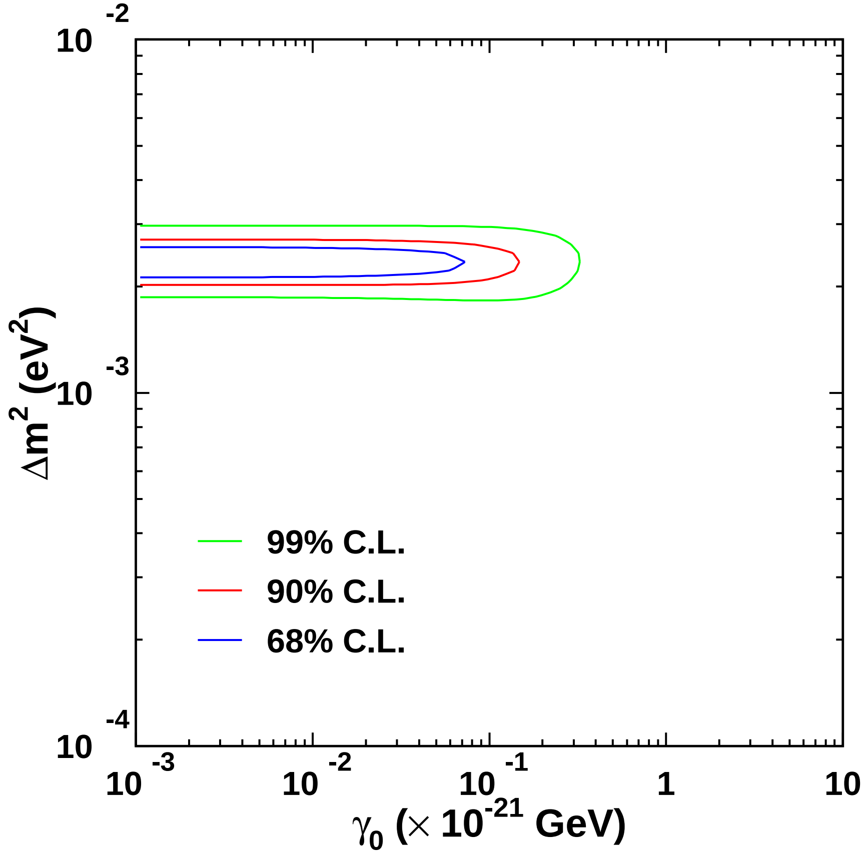
Oscillation + Decay/Decoherence?

(Full mixing)

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta \times \exp\left(-\frac{m}{\tau}\frac{L}{E}\right) + 2\sin^2\theta\cos^2\theta \times \exp\left(-\frac{m}{2\tau}\frac{L}{E}\right) \times \cos\left(\frac{\Delta m^2 L}{2E}\right)$$

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \times \left\{1 - \exp\left(-\gamma_0\frac{L}{E}\right) \times \cos\left(\frac{\Delta m^2 L}{2E}\right)\right\}$$



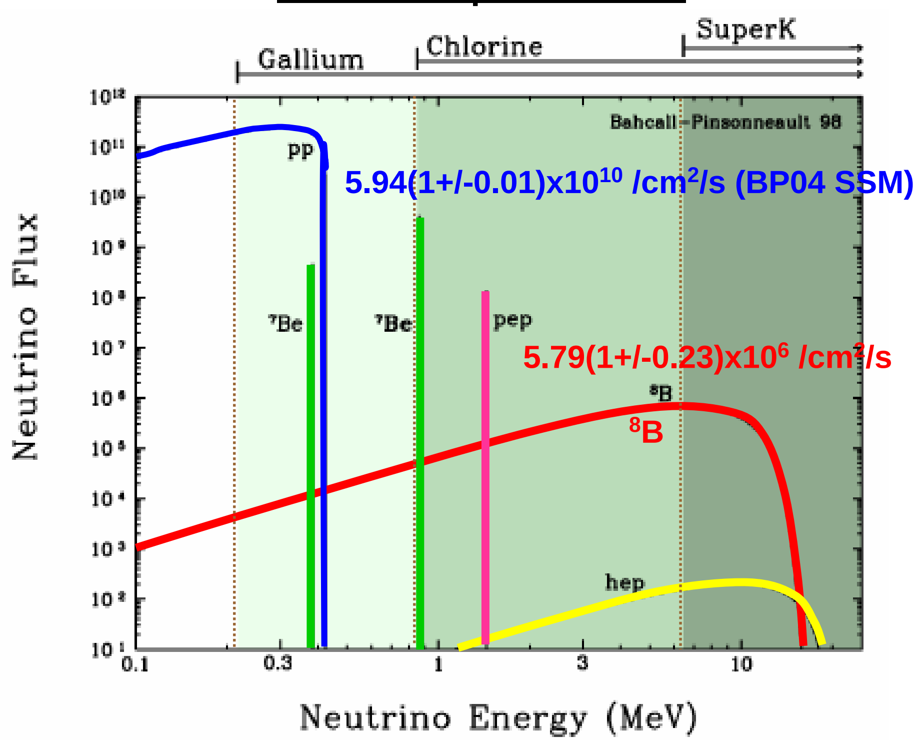


$m/\tau < 3.2 \times 10^{-5}$ GeV/km@90%CL

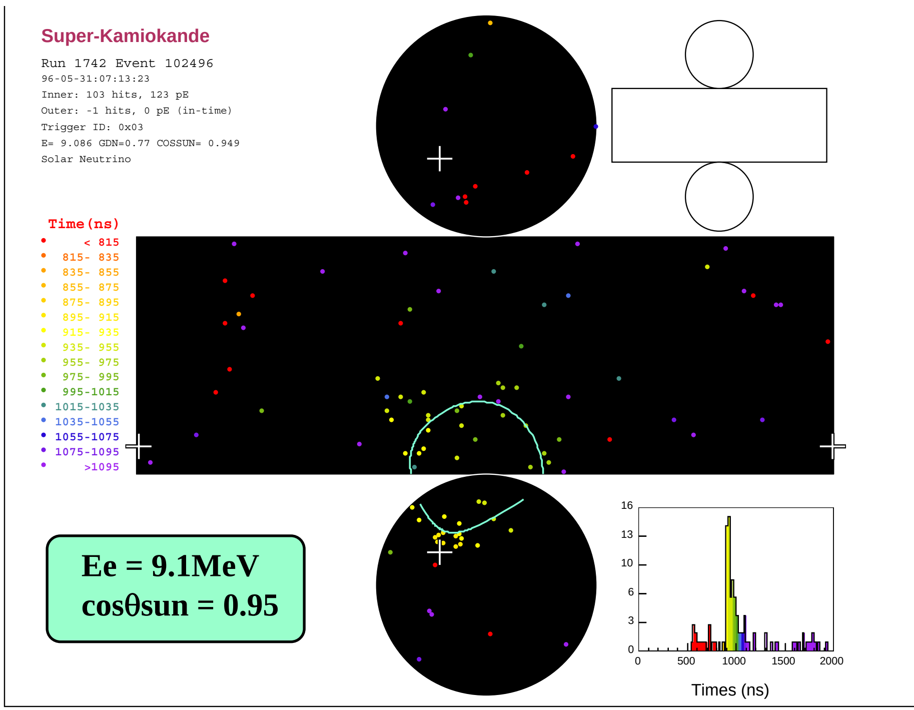
$\gamma_0 < 1.4 \times 10^{-22}$@90%CL

- ^{8}B neutrino – electron scattering $\nu + e^- \rightarrow \nu + e^-$

SSM Expectation

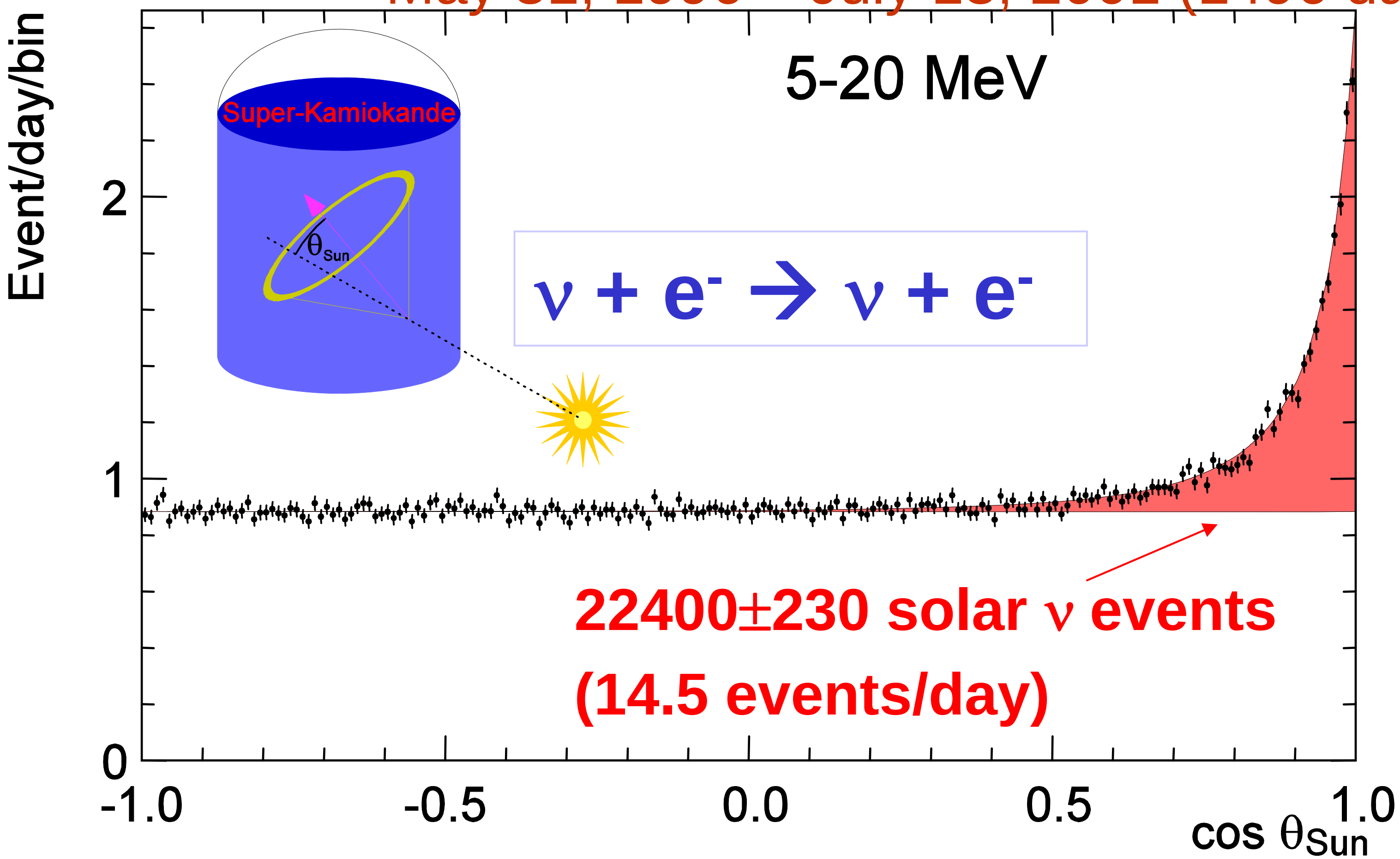


Typical Solar ν event



Solar ν Data of SK-I

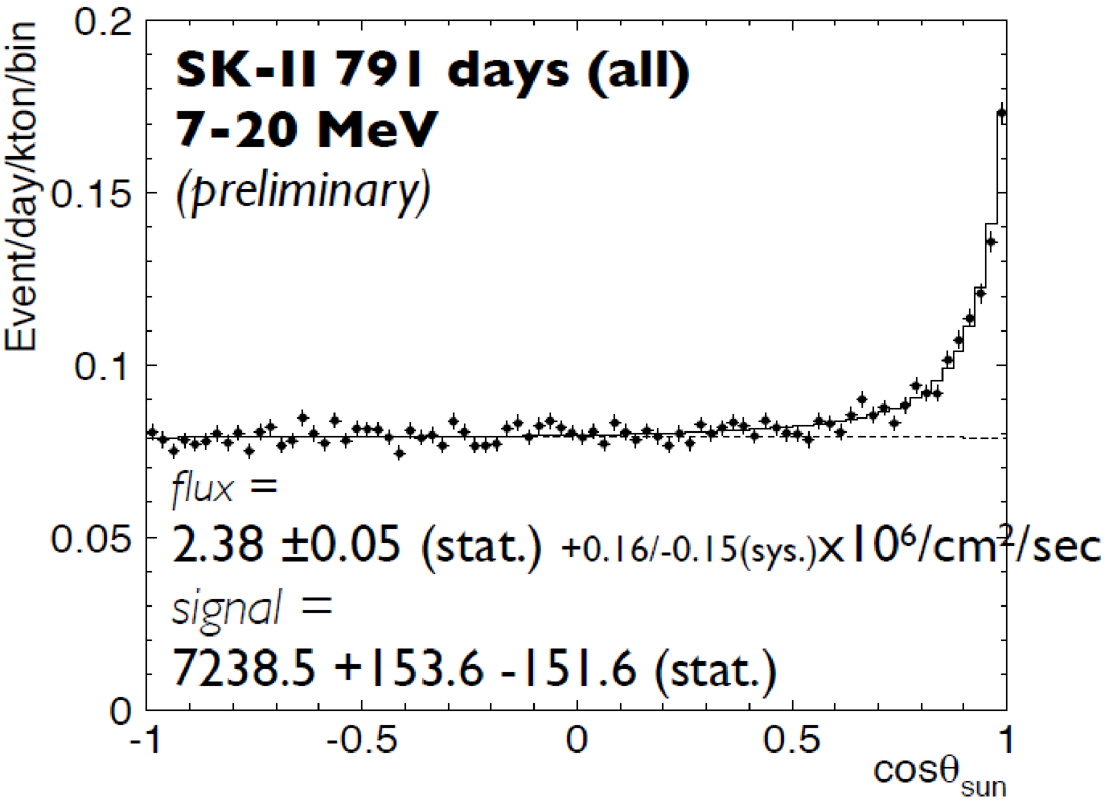
May 31, 1996 – July 13, 2001 (1496 days)



^{8}B flux : 2.35 ± 0.02 ± 0.08 [x 10^6 /cm^2/sec]

$$\frac{\text{Data}}{\text{SSM(BP2004)}} = 0.406 \pm 0.004 \, {}^{+0.014}_{-0.013}$$

Solar ν data of SK-II



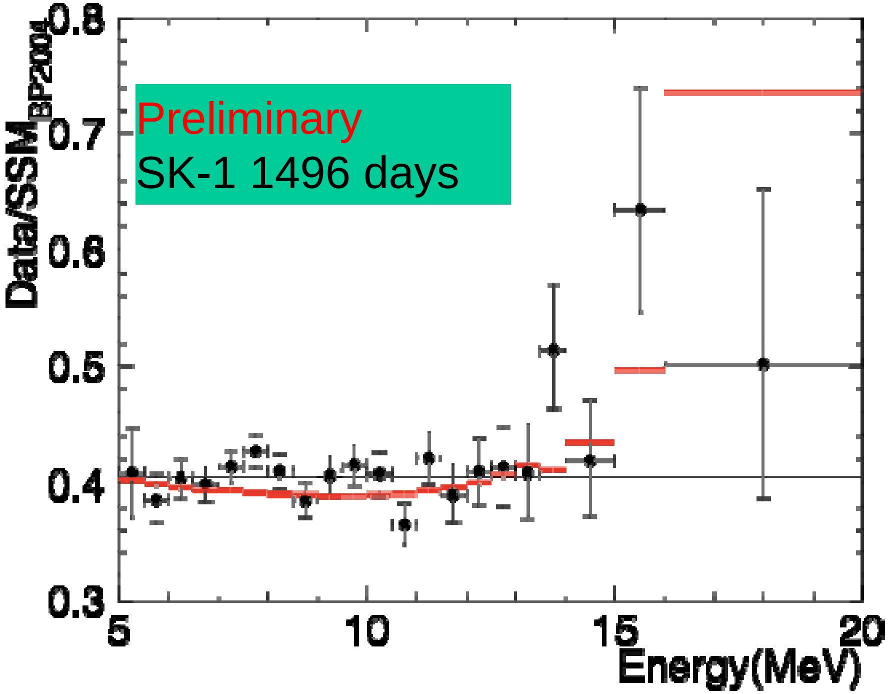
$$A_{DN} = 2\times\frac{\text{Day} - \text{Night}}{\text{Day} + \text{Night}} = -0.063 \pm 0.042\ (\text{stat.})$$

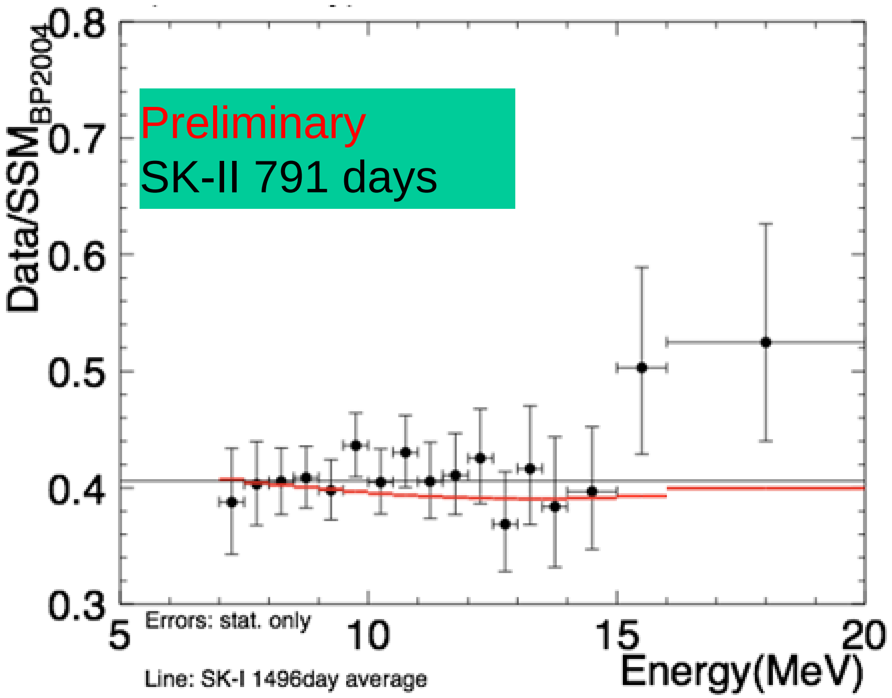
(Preliminary)

SK-I $A_{DN} = -0.021 \pm 0.020 +0.013 -0.012$

SK Spectra @ global best fit

$\tan^2\theta = 0.40 \quad \Delta m^2 = 6.03\times10^{-5}$

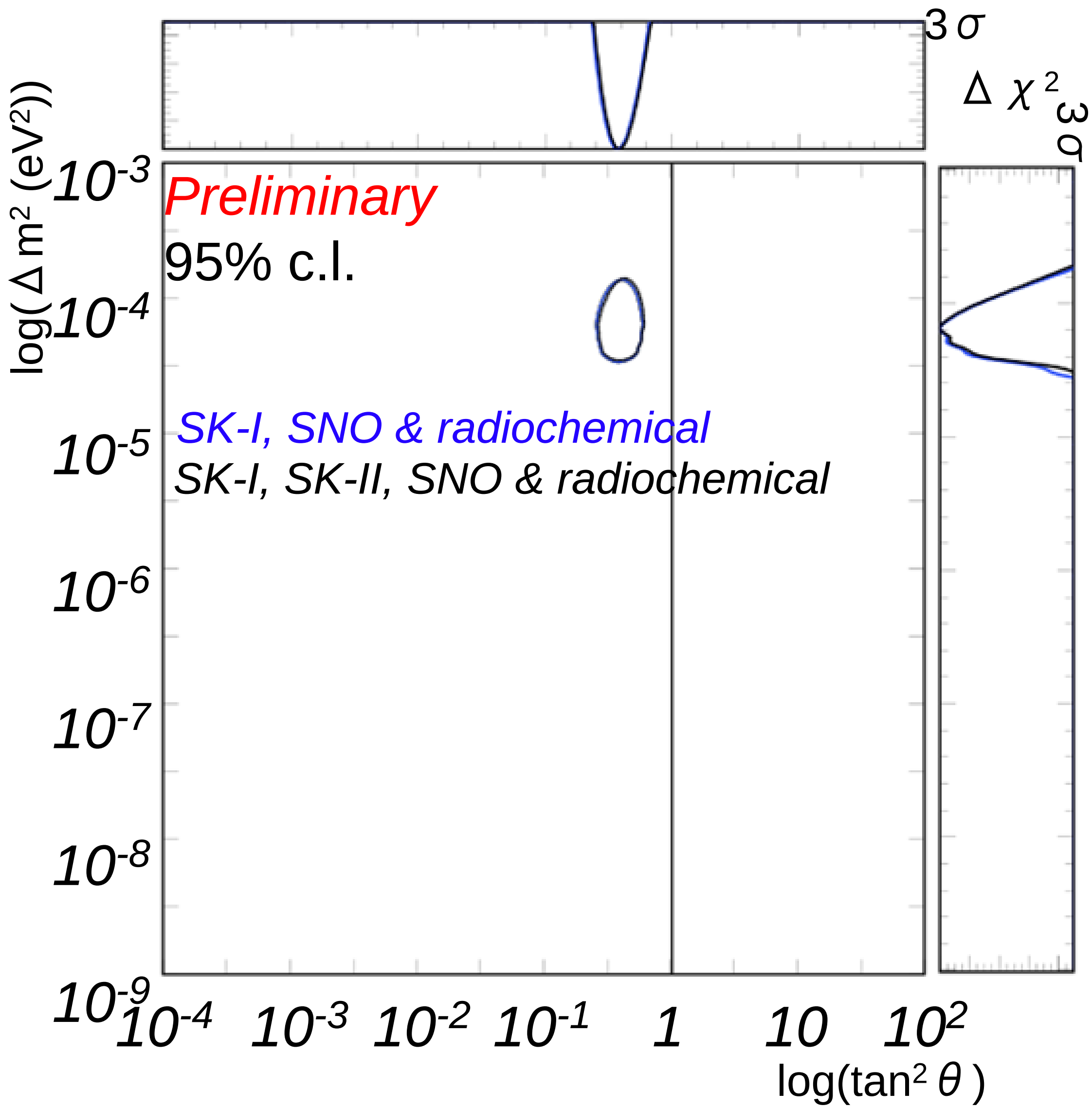




^{8}B *flux = 0.90 x SSM* = **5.21x10^{6}** cm^{-2}s^{-1}

hep flux = 8.62 x SSM = **6.79x10^{4}** cm^{-2}s^{-1}

SK Global Oscillation Analysis



SK-1 & SNO

Minimum at LMA

$tan^2\theta = 0.38$

$\Delta m^2 = 6.03\text{x}10^{-5}\ eV^2$

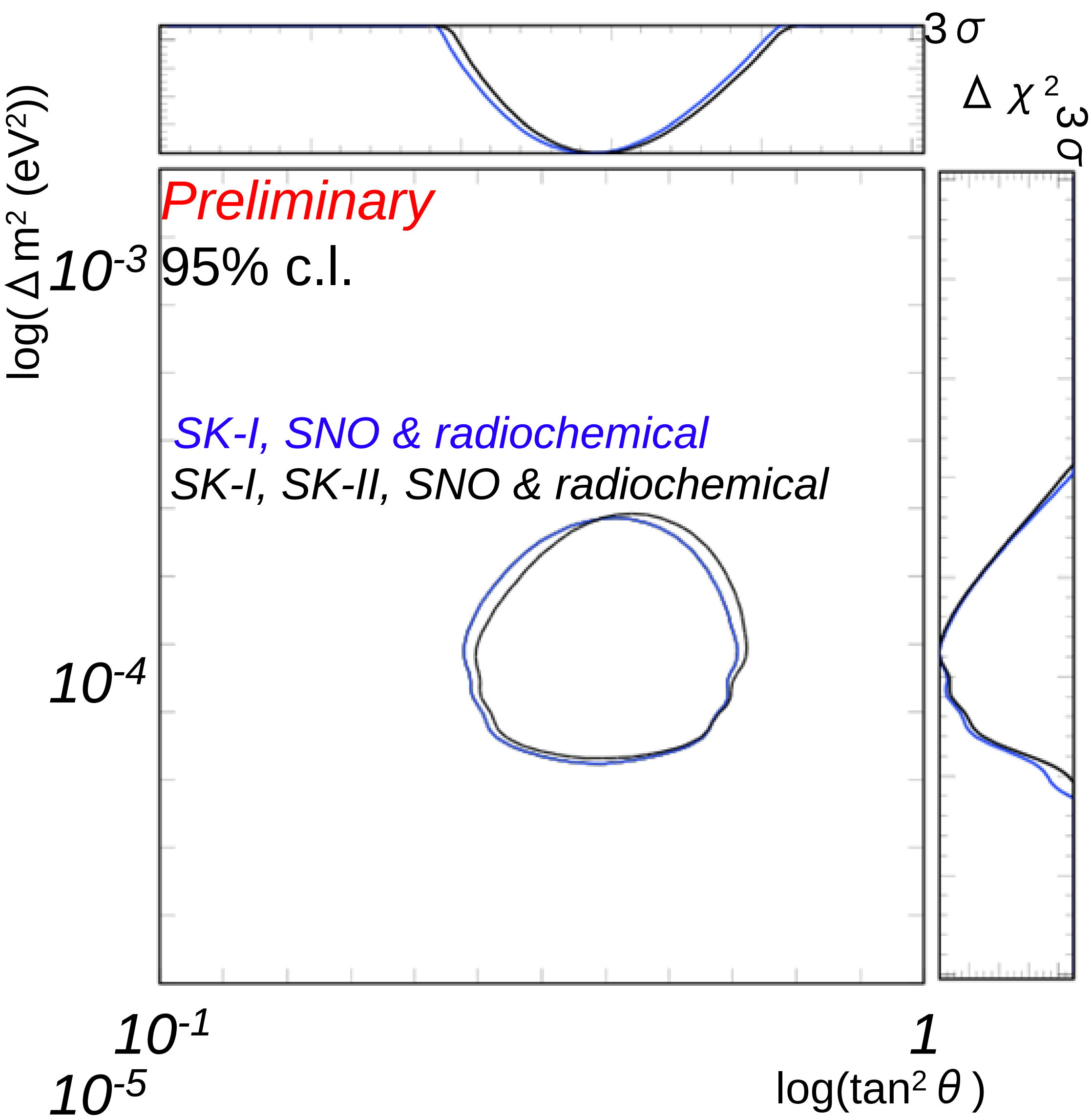
SK-1, SK-II & SNO

Minimum at LMA

$tan^2\theta = 0.40$

$\Delta m^2 = 6.03\text{x}10^{-5}\ eV^2$

SK Global Oscillation Analysis



SK-1 & SNO

Minimum at LMA

$tan^2\ \theta = 0.38$

$\Delta m^2 = 6.03x10^{-5}\ eV^2$

SK-1, SK-II & SNO

Minimum at LMA

$tan^2\ \theta = 0.40$

$\Delta m^2 = 6.03x10^{-5}\ eV^2$

Supernova Neutrino Bursts

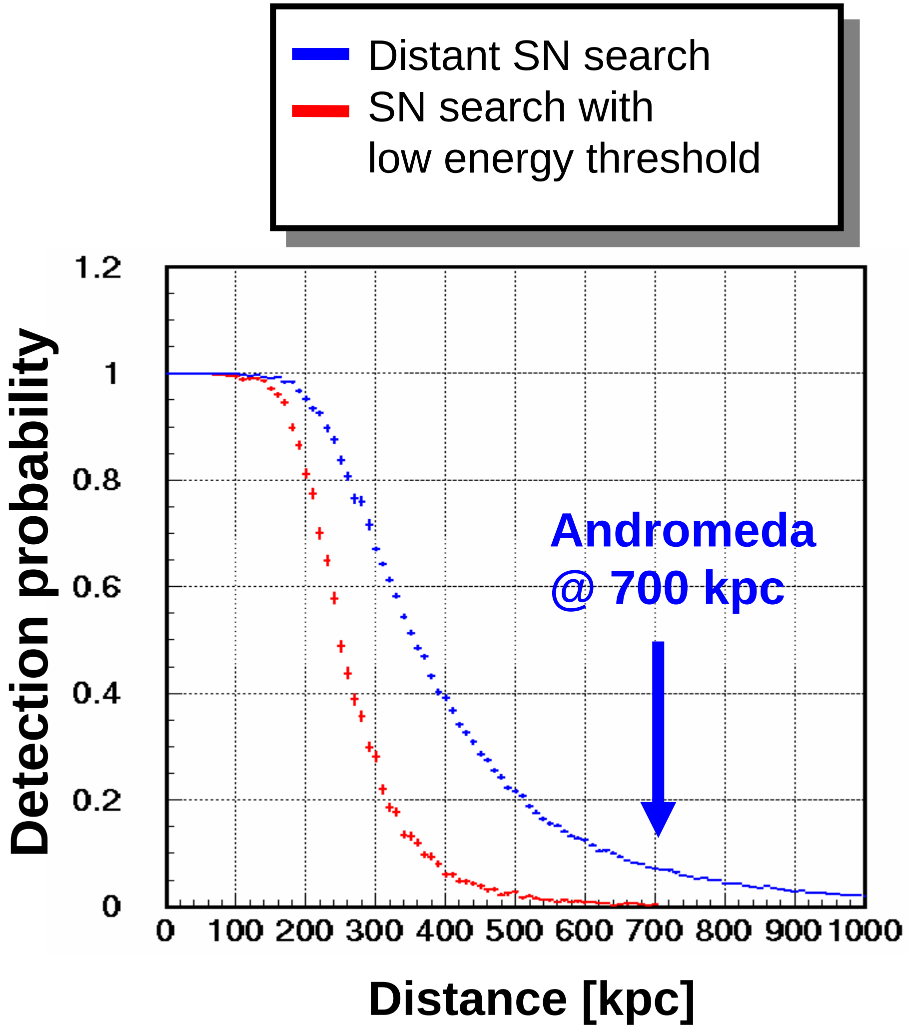
- No supernova signal during SK-I and SK-II (total livetime =2589.2 day)
- Supernova rate limit in our galaxy is obtained as

  0.32 SN/yr @ 90% C.L

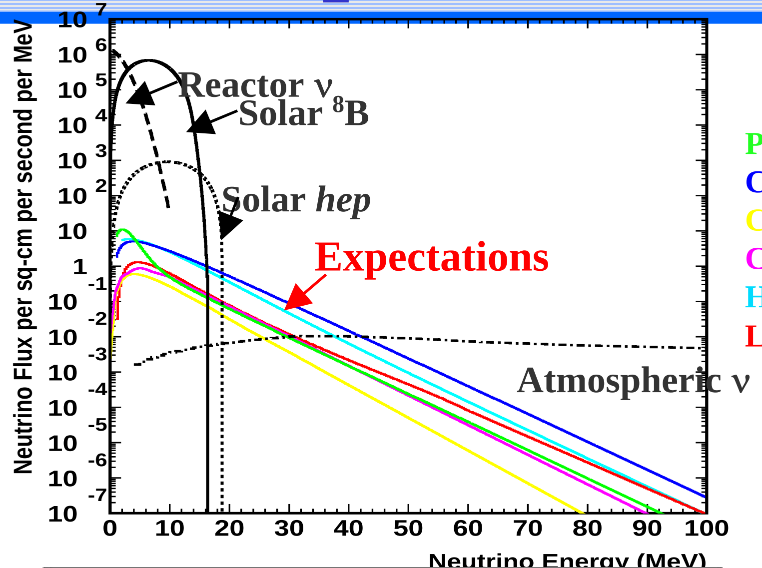
- After combine SK-I ,SK-II, and Kamiokande results

  0.20 SN/yr @ 90% C.L

Efficiency vs. Distance

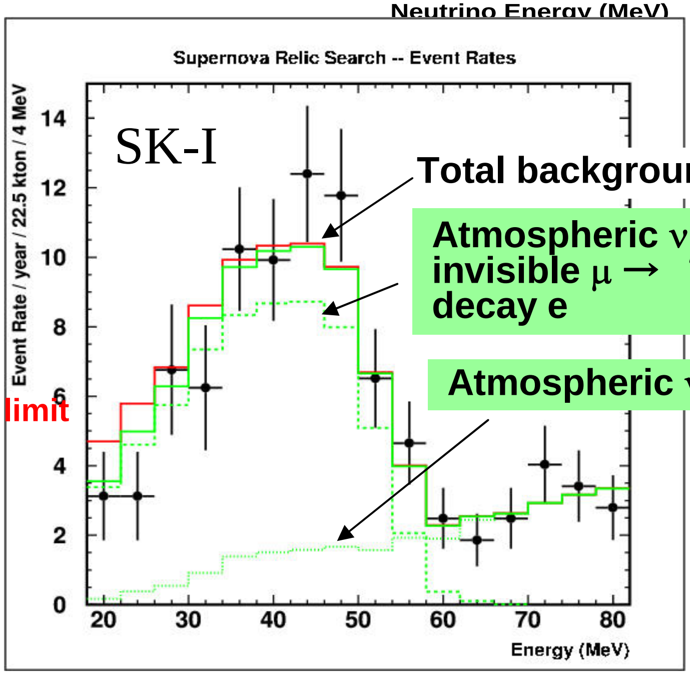


Supernovae Relic Neutrinos



Population synthesis (Totani *et al.*, 1996)
Constant SN rate (Totani *et al.*, 1996)
Cosmic gas infall (Malaney, 1997)
Cosmic chemical evolution (Hartmann *et al.*, 1997)
Heavy metal abundance (Kaplinghat *et al.*, 2000)
LMA ν oscillation (Ando *et al.*, 2002)

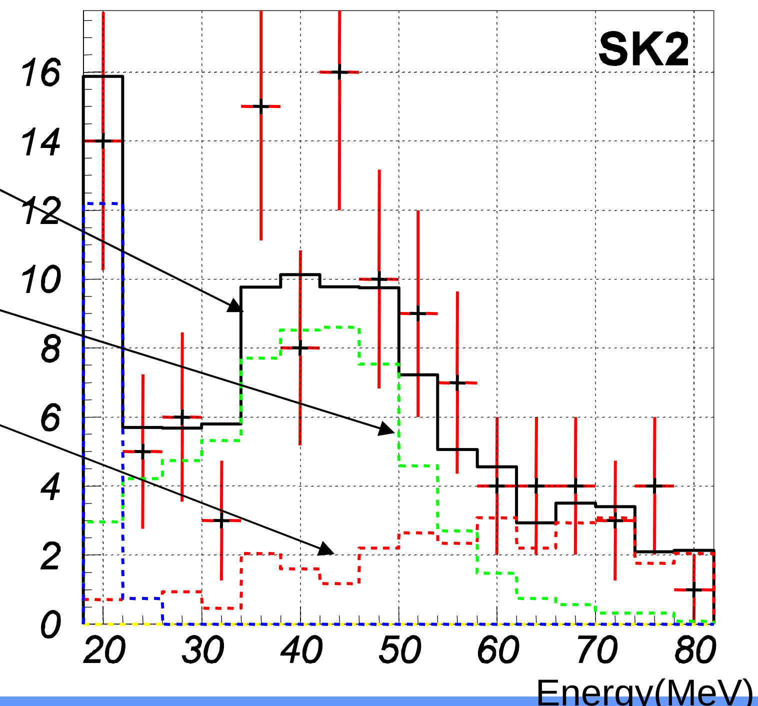
90% CL limit of SRN



Total background

Atmospheric $\nu_\mu \rightarrow$ invisible $\mu \rightarrow$ decay e

Atmospheric ν_e

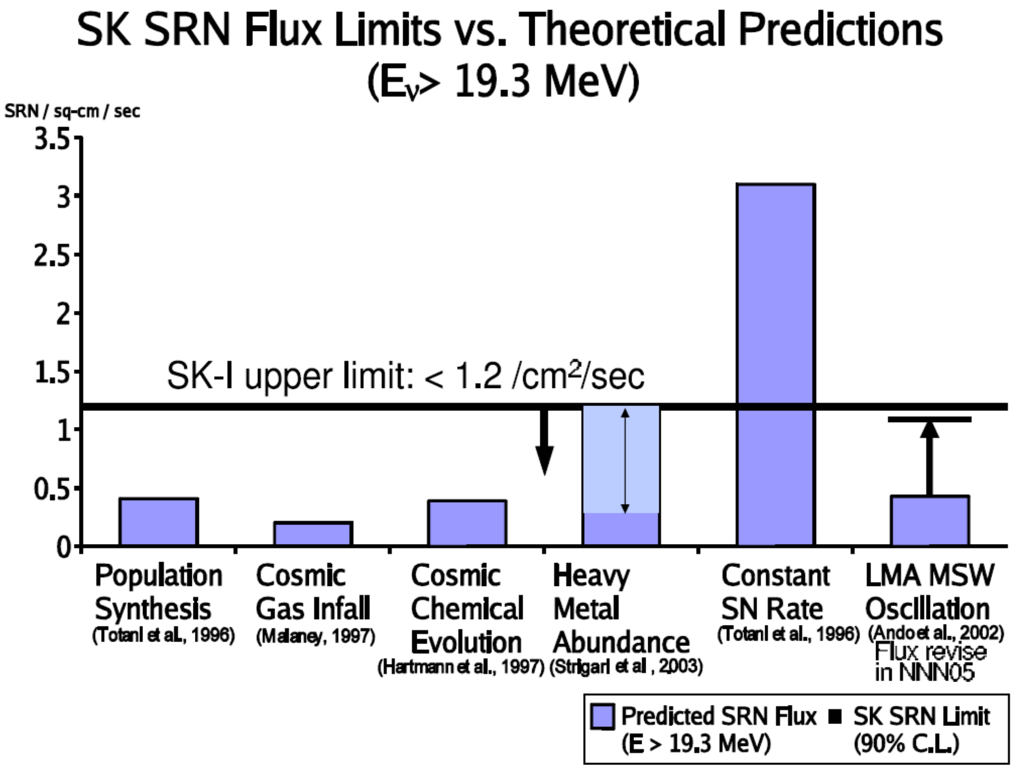


SRN Flux Limit

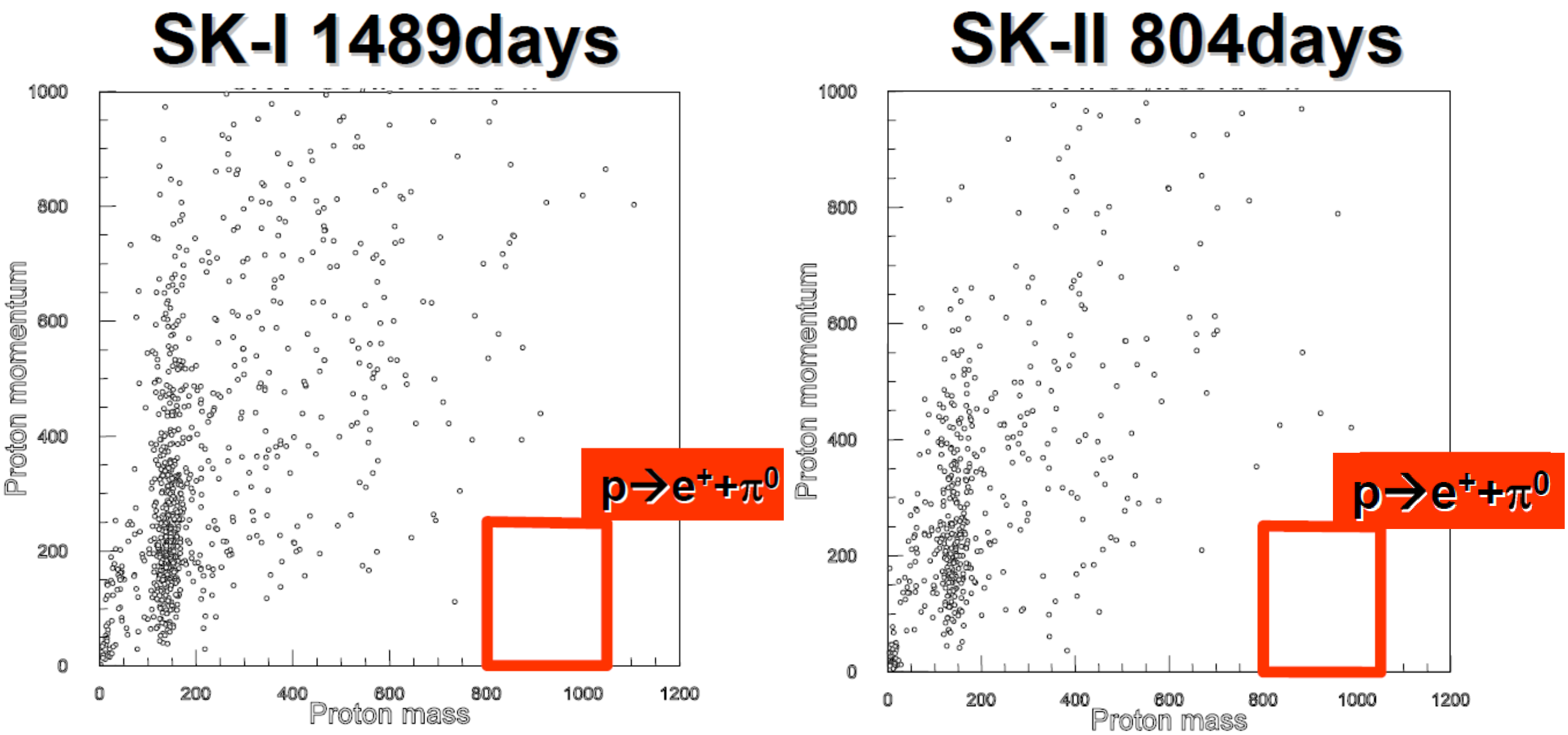
Flux limit

SK-II < 3.8 [/cm^2/sec]

SK-I < 1.2 [/cm^2/sec] Phys. Rev. Lett. 90, 061101(2003)

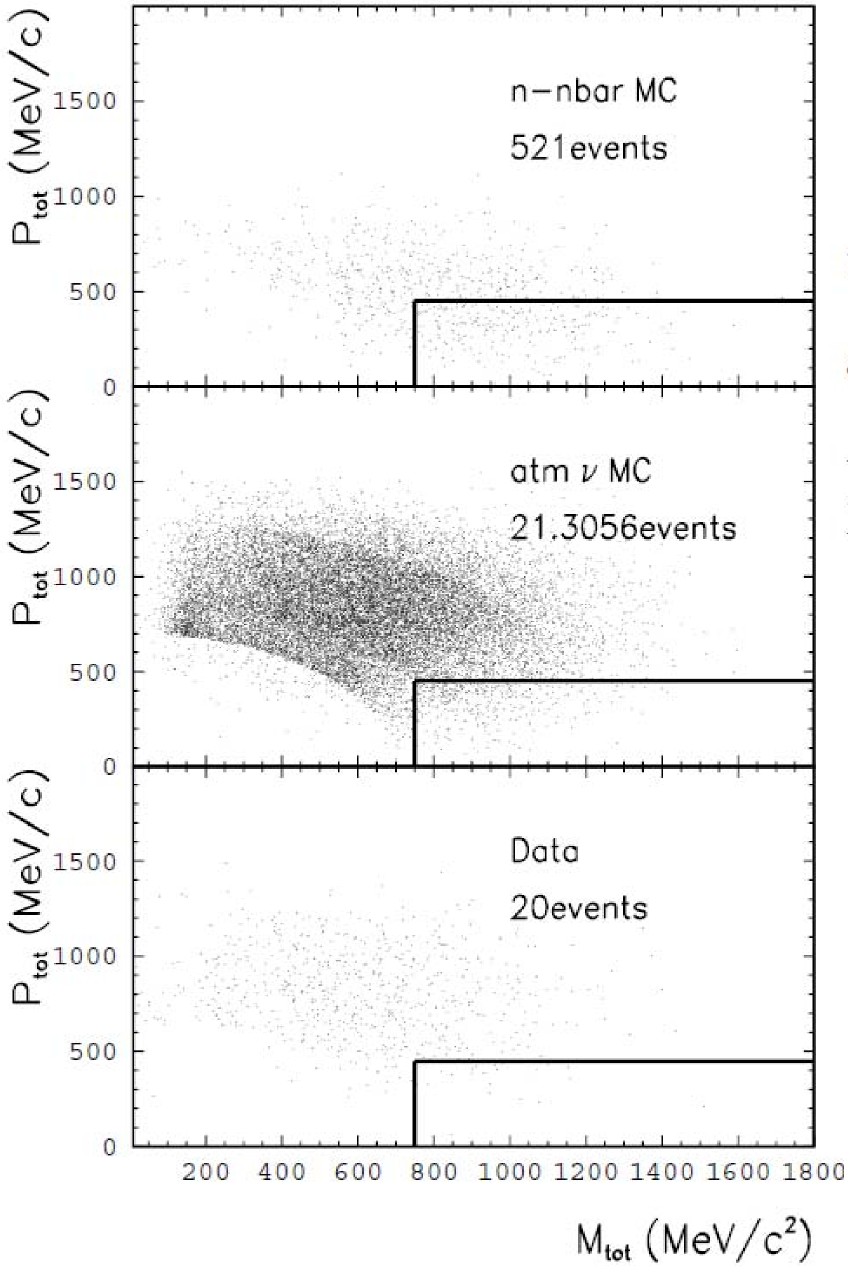


Proton Decay Search ($p \rightarrow e^+\pi^0$)



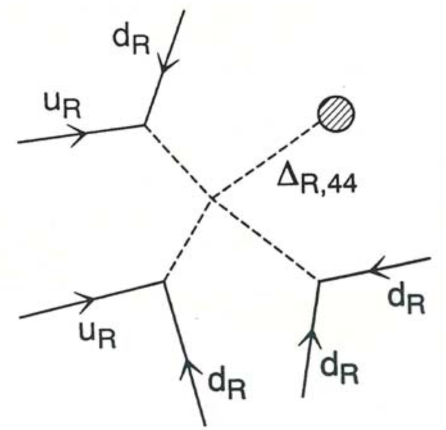
- τ_p/Branch > 8.4 x 10^{33}years (90% CL)

$n - \bar{n}$ oscillation



n↔*nbar* transitions in SO(10)

→ $SU(2)_L \times SU(2)_R \times SU(4)_C$



$$m_{\Delta R,44} \sim 10^5 GeV$$

Efficiency=10.4%

Livetime for SK-I=4.077yrs

N_{obs}=20, μ_B(expected BG)=21.31

Syst for the ε = 15.2%

Syst for the BG = 32%

$$\tau / B = 1.77 \times 10^{32} \text{ yrs (90\% CL)}$$

Future Plan

Computers and Electronics Upgrade

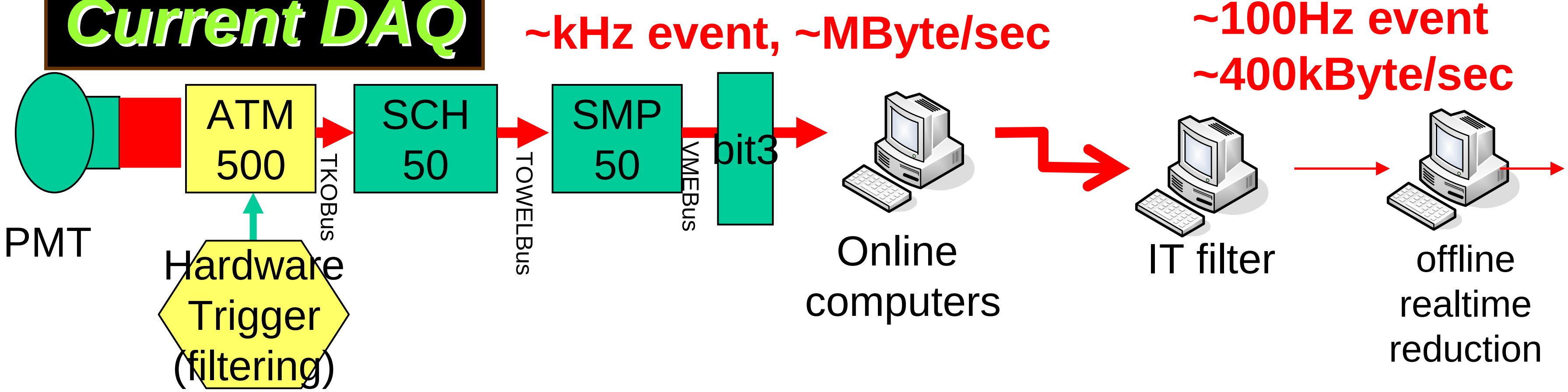
T2K Long Baseline Experiment

Computer Upgrade (2007/3~)

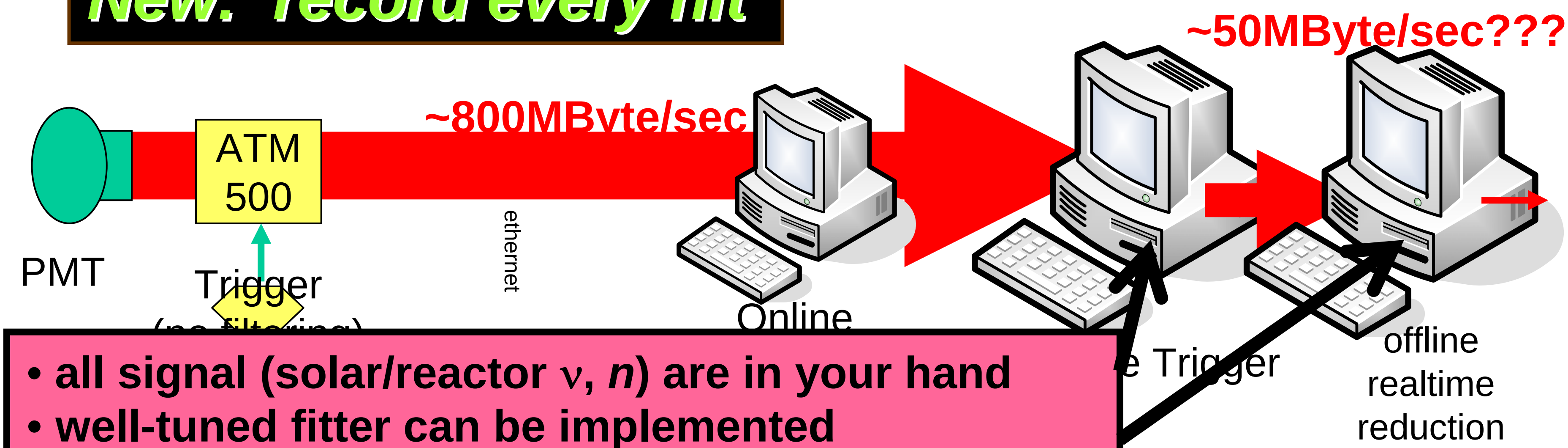
- Computation
  - Sparc Solaris → Intel Linux
  - Offline computation power:
    - Sparc 200CPU → Xeon 1128core (33840 SPECint_rate_base2000)
- Storage
  - HPSS (Tape strage) ~700TBytes
  - → DISK 700TB + Tape 400TB
- Network
  - Full GbE (Partially 10GbE)

New Electronics (2008~)

Current DAQ



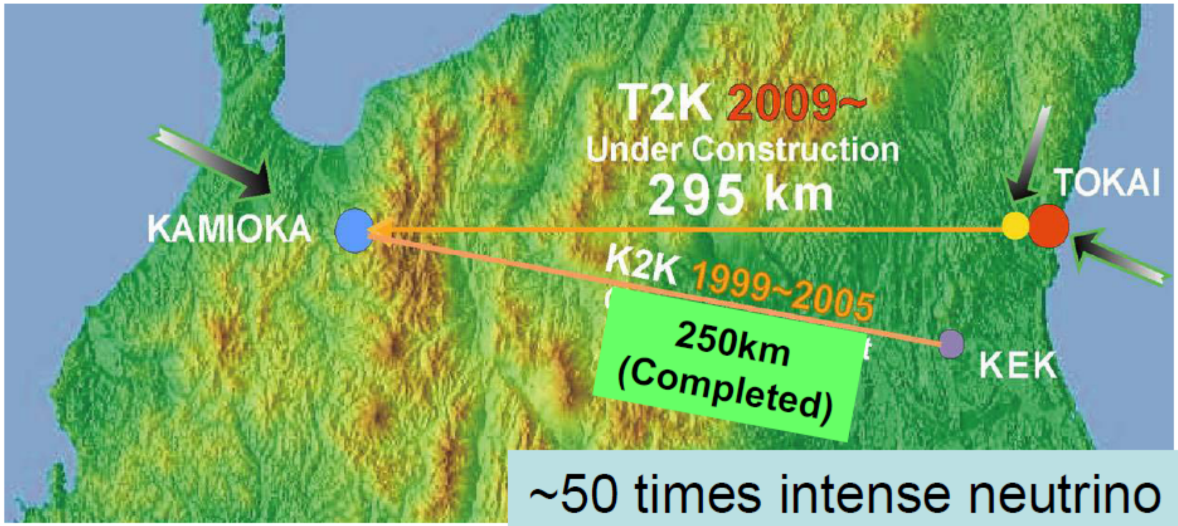
New: 'record every hit'



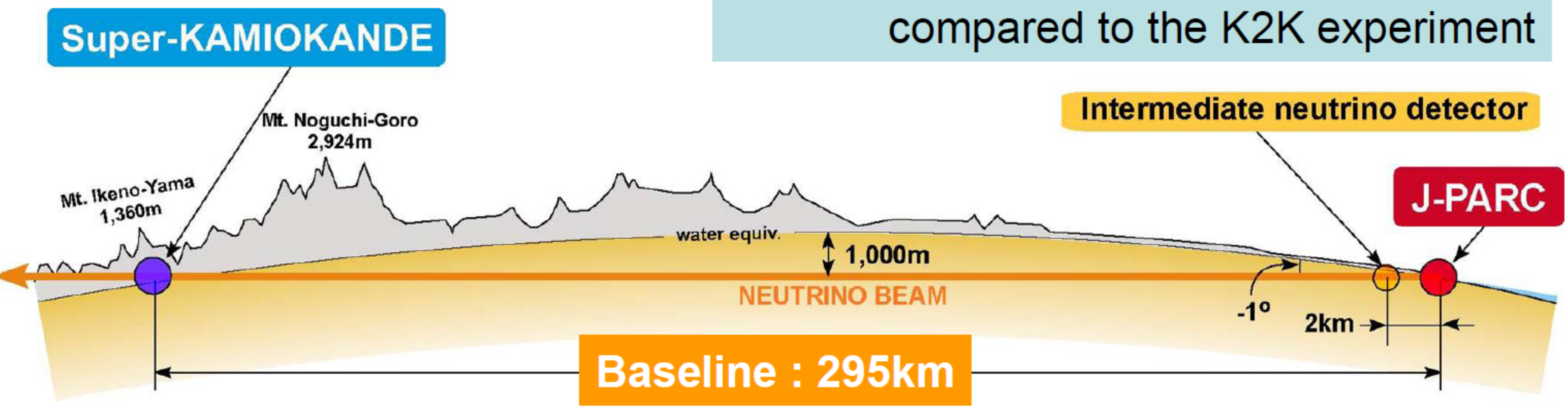
- all signal (solar/reactor ν, *n*) are in your hand
- well-tuned fitter can be implemented
- best filtering algorithms at that time

T2K実験(2009~)

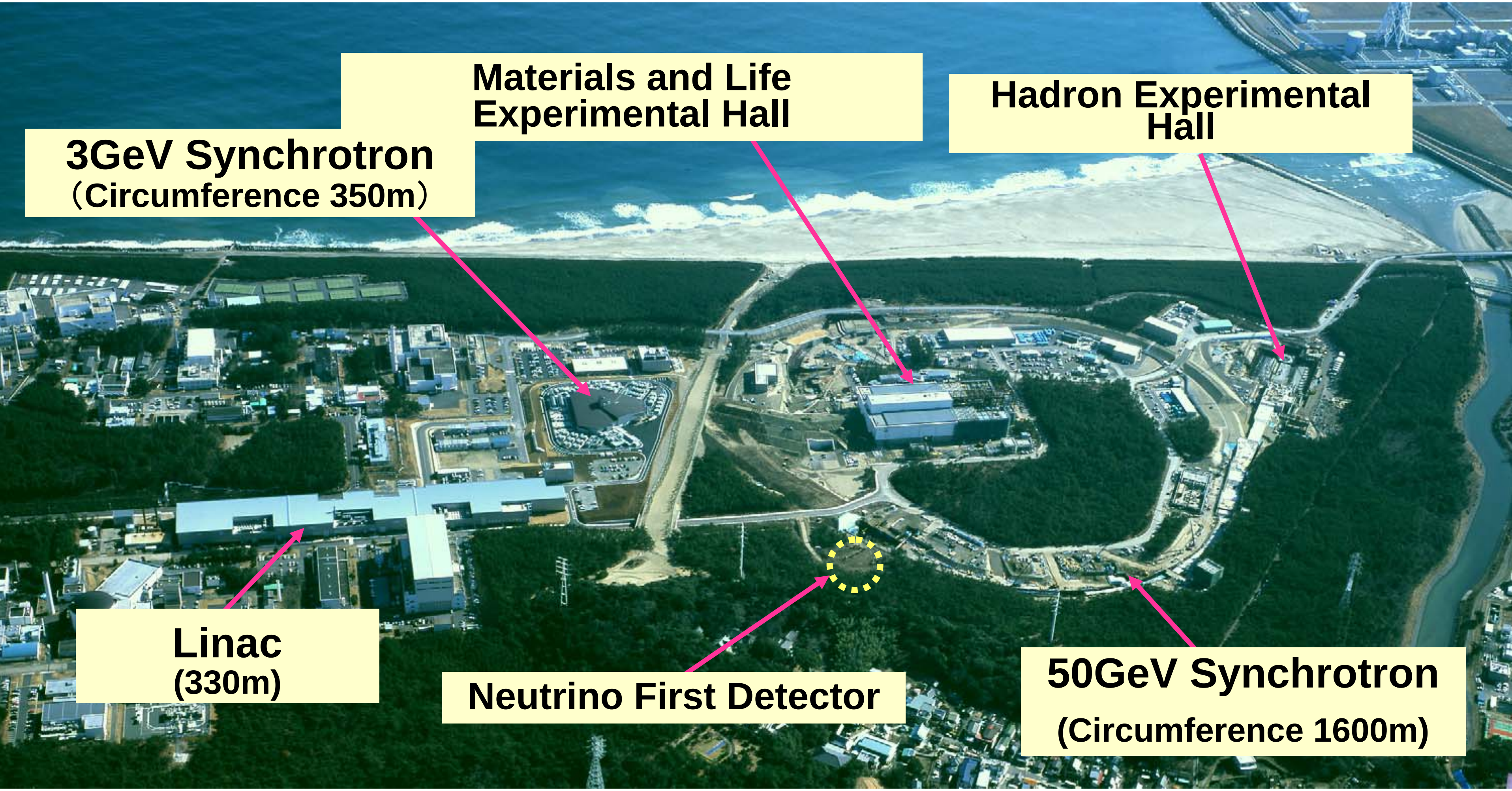
(0.75MW 50GeV PS , 30GeV @ T=0)



~50 times intense neutrino beam
compared to the K2K experiment

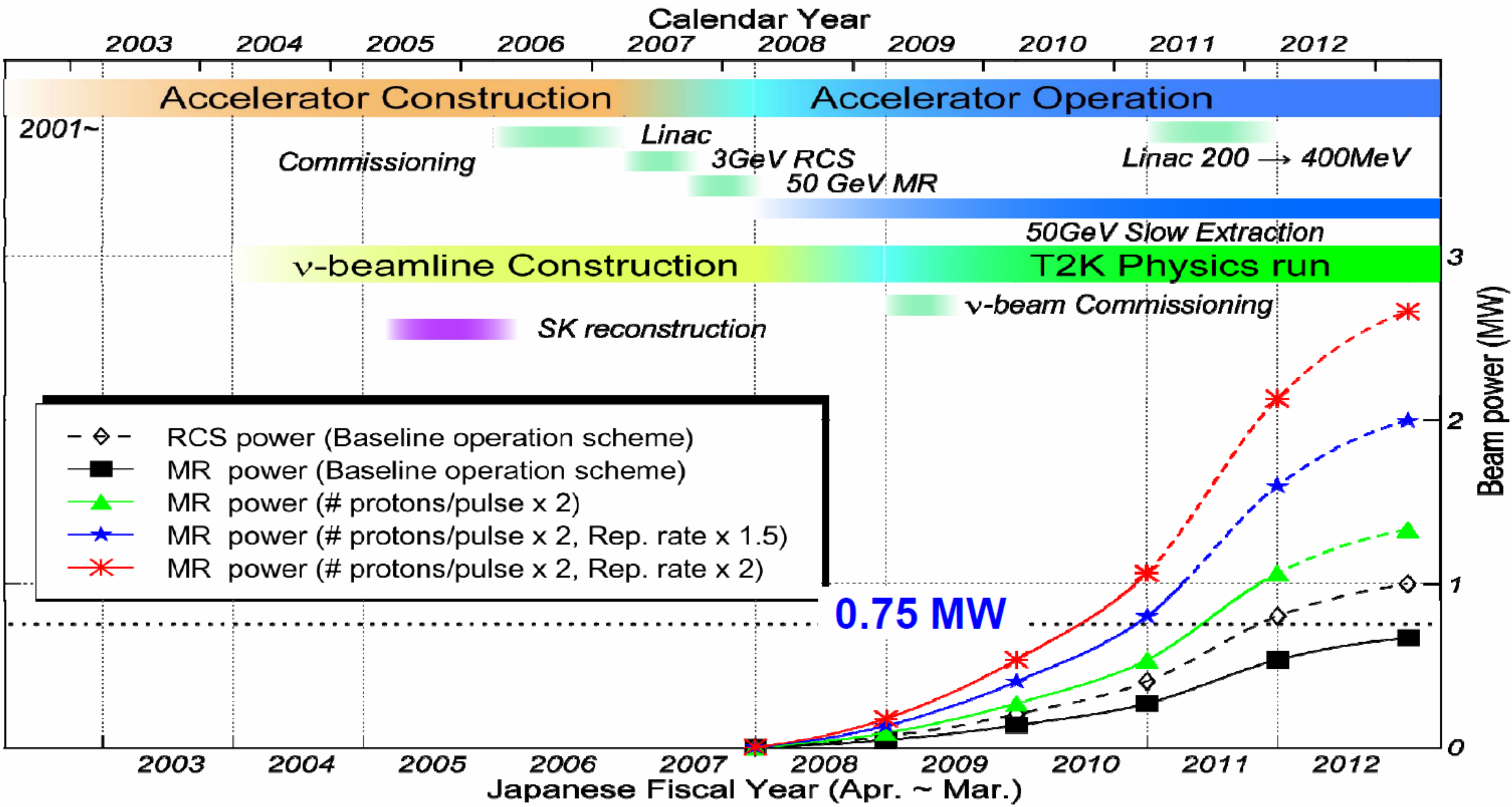


Construction Status of J-PARC



平成１８年２月航空写真

T2K Beam Power Estimation



Summary

- Full reconstruction is finished, SK-III started
- Atmospheric neutrinos
  - Oscillation analysis results based on SK-I + SK-II are presented
  - Consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillation.
  - Some non-tau modes are tested → unlikely
- Solar Neutrinos
  - Oscillation analysis based on SK-I + SK-II are presented though energy threshold of SK-II is 7Mev
- Supernova Neutrinos
  - Upper limits for SN and SRN rate are obtained
- Proton decay
- Future Plan:
  - SK upgrade
  - T2K experiments