Neutrino Helicity at 50:
A Celebration of the Goldhaber-Grodzins-Sunyar Experiment

Looking forward

Super-Kamiokande

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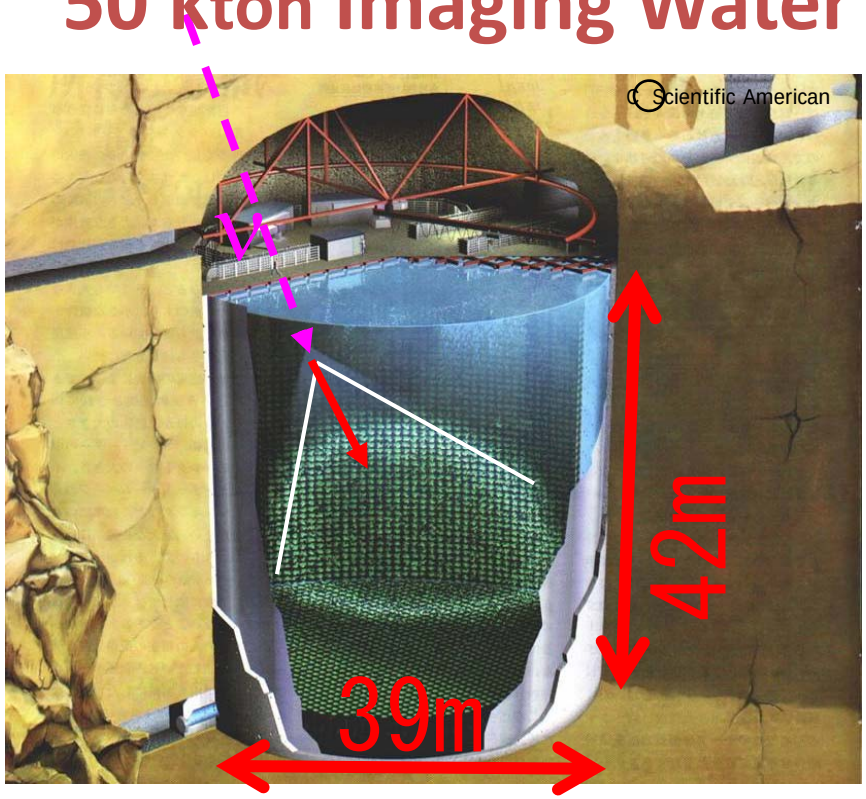
May-2, 2008 @ Brookhaven National Laboratory

Super-Kamiokande

50 kton Imaging Water Cherenkov Detector



- **Inner: 32,000 tons**

  (Outer Vol. : ~2.5 m thick)

  Fid. Vol. : 22.5 kt
- **11,146 PMTs (ID)**

  50 cm in diameter

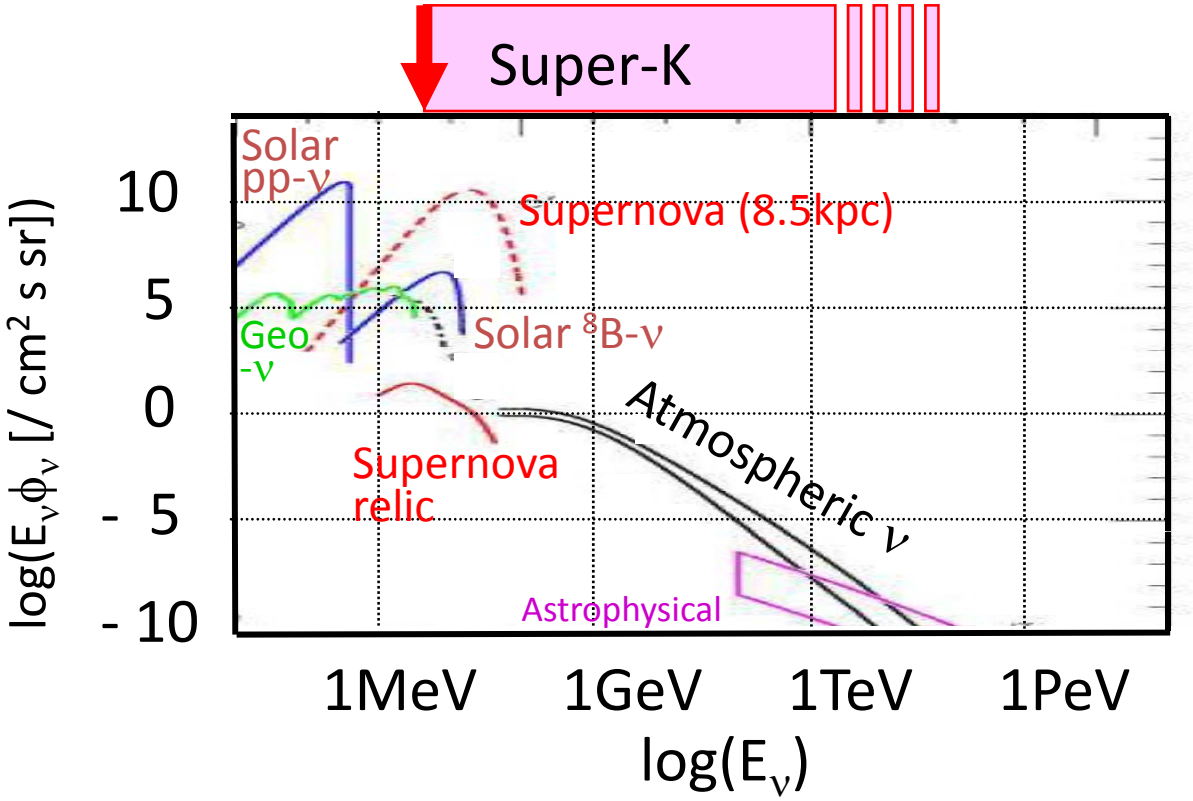
  40% coverage
- **1,885 PMTs (OD)**

  20 cm in diameter
- **1,000 m underground**

- ***~15 solar neutrino events per day***
- ***~10 atmospheric neutrino events per day***

Energy Range (data from SK-I)

- Trigger: 100% eff. for E_{obs} > **4.5 MeV**
  (50% efficiency @ 3.7MeV)
- Trigger Rate: 1,700Hz → 15 Hz (recorded)



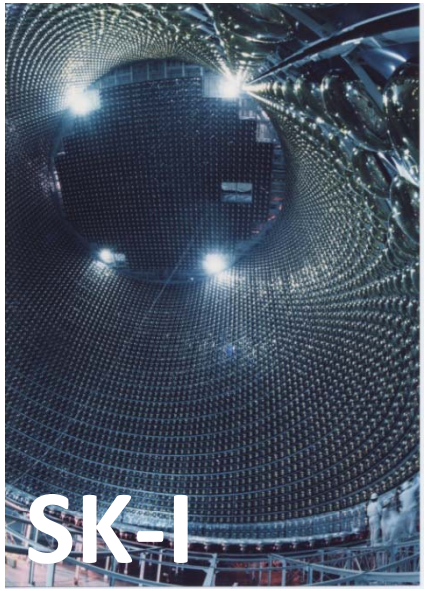
- 6 p.e. / MeV
- Resolution

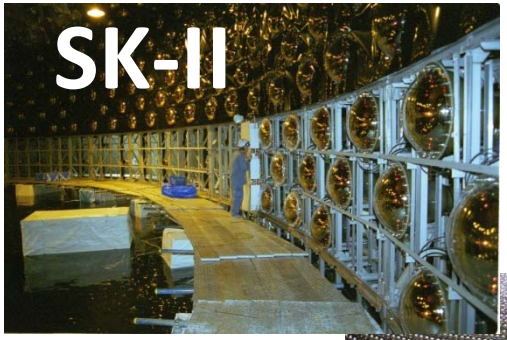
(solar/supernova ν)
14.2% @10MeV

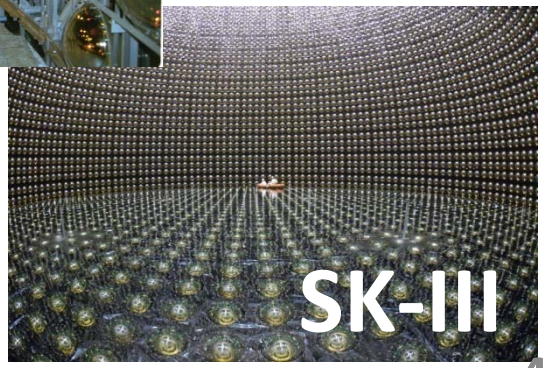
(atmospheric ν)
$1.7+0.7/\sqrt{E(\mathrm{GeV})}$ %
(single ring μ)

Brief history (looking back)

1991-1996	Super-Kamiokande Construction
1996	Super-Kamiokande (SK-I) started
1998	➔ Discovery of the Atmospheric Neutrino Oscillation
1999	K2K started
2001	➔ Evidence of the Solar Neutrino Oscillation (SNO+SK)
2001	Accident (lost 6777 PMTs)
2002	SK-II started (w/ ~50% PMT)
2004	➔ Confirmation of Atmospheric ν oscillation (K2K/SK)
2006	SK-III started (full recovery)







The Super-Kamiokande Collaboration

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31 Tokai University, Japan
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33 University of Tokyo, Japan
34 Tsinghua University, China
35 Warsaw University, Poland
36 University of Washington, USA

- **~ 130 collaborators**
- **36 institutions**
- **5 countries**
- **most from Japan and US**

Maurice Goldhaber in 1995

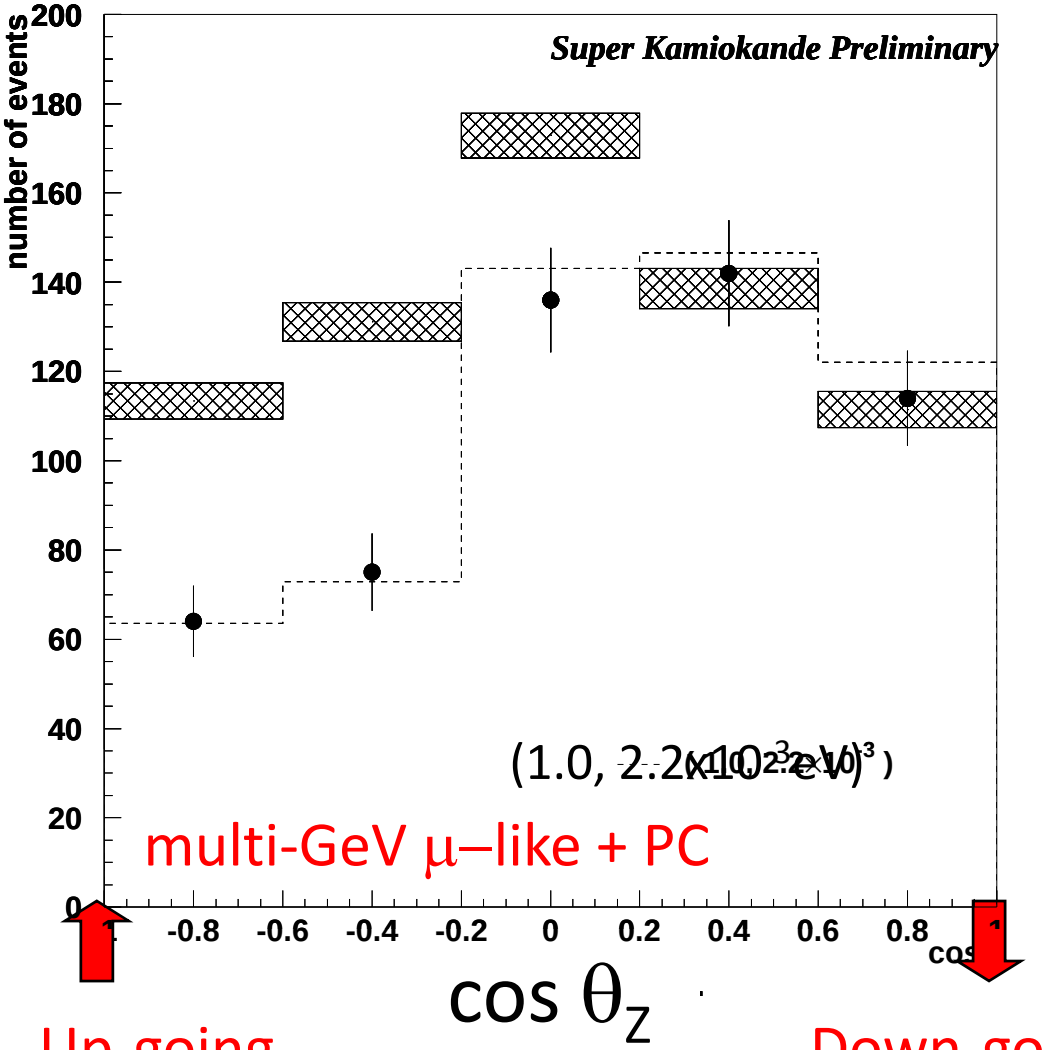
1995, 11.11.

Celebration for completion of the construction of Super-K

2008: 10th anniversary of

Discovery of Atmospheric Neutrino Oscillation by Super-Kamiokande

ν_μ - ν_τ

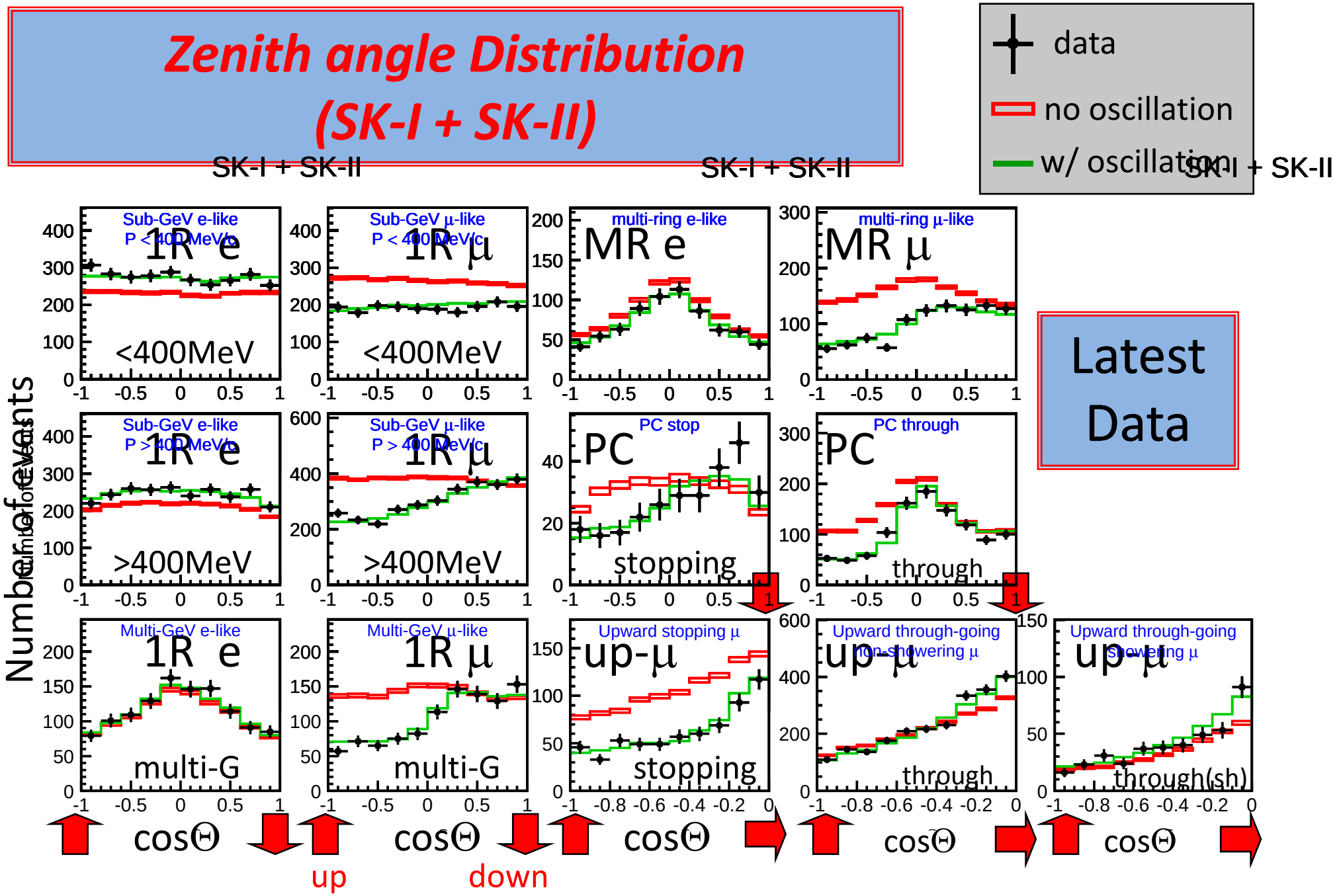


In 1998 @Neutrino98

SK has shown definitive evidence of neutrino oscillation:

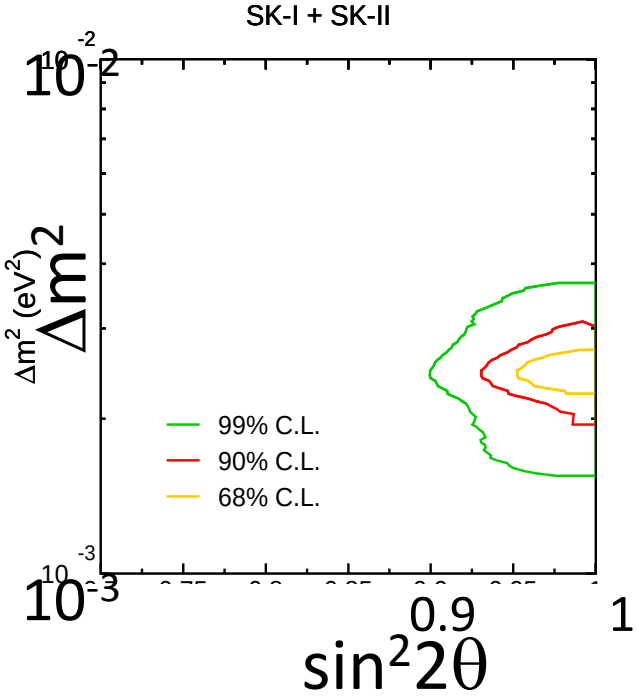
- **Asymmetry of the zenith angle distributions consistent with neutrino oscillation**
- **independent of the flux calculations.**

Zenith angle Distribution (SK-I + SK-II)

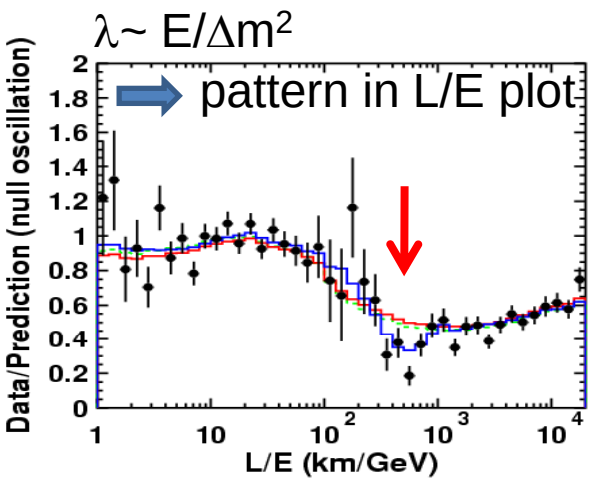


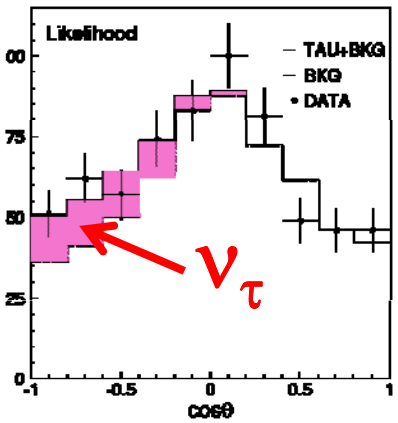
Oscillation Parameters

- Best fit (Physical Region)
  $\sin^2 2\theta = 1.00$
  ($\sin^2 2\theta > 0.93$ (@90%C.L.))
  $\Delta m^2 = 2.5\times10^{-3}\ eV^2$
  ($1.9\times10^{-3} eV^2 < \Delta m^2 < 3.1\times10^{-3}\ eV^2$)



- More Evidence for the oscillation
  - Oscillatory Behavior
  - ν_τ appearance (stat. method)
  - Confirmation (K2K)
- Confirmation: MINOS



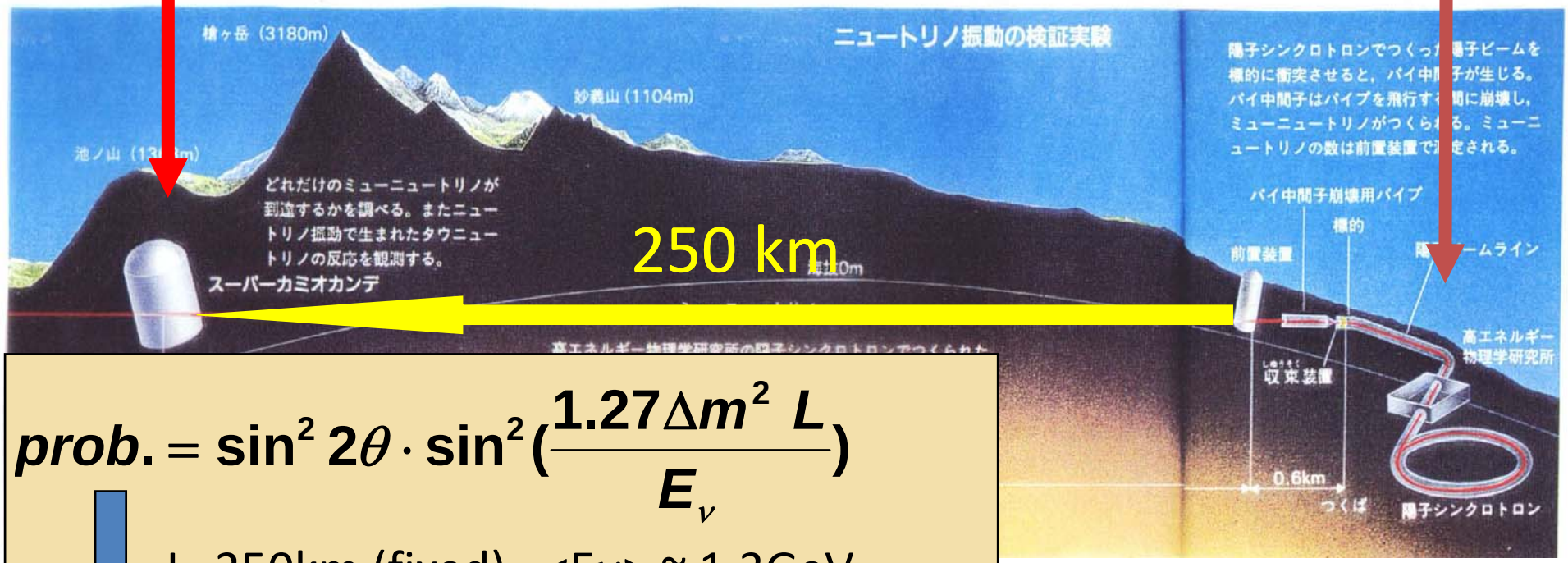


K2K (KEK to Kamioka)

Experiment started in March, 1999
Completed in November, 2004

Super-K

KEK
12GeV
PS



$$prob. = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

L=250km (fixed), <Eν> ~ 1.3GeV

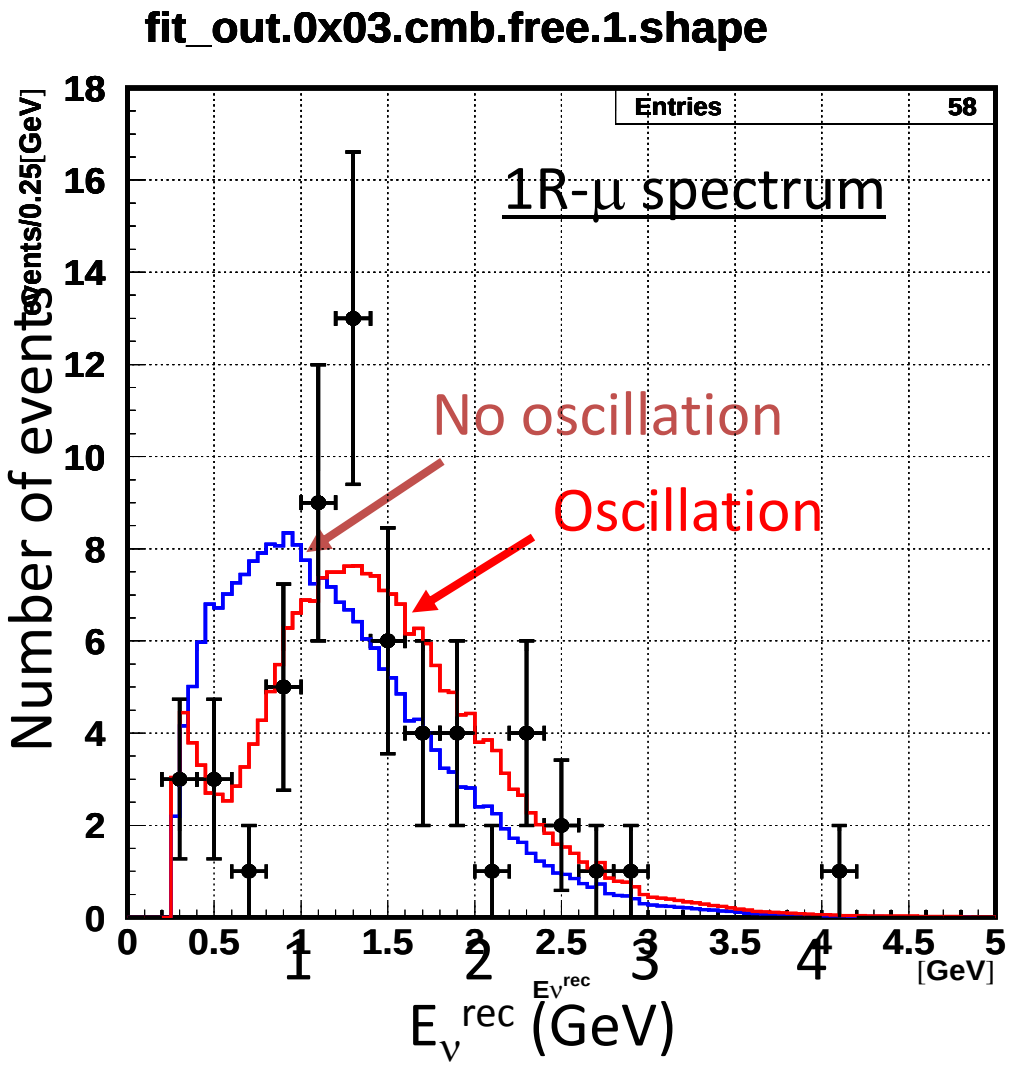
$\Delta m^2 = 2.5\times 10^{-3}\ eV^2$, $\sin^2 2\theta = 1$

~ 0.3

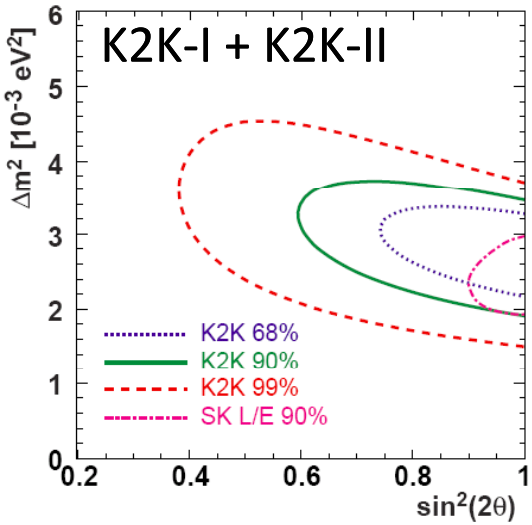
Expect ~70% survival

Total POT used
Jun.1999 – Nov.2004
0.9×10^{20} POT

K2K_SK event summary



	N_{sk}^{obs}	N_{sk}^{pred}
All	**112**	155.9
1 ring	**67**	99.0
μ-like	58	90.8
e-like	9	8.2
multi-ring	**45**	56.8

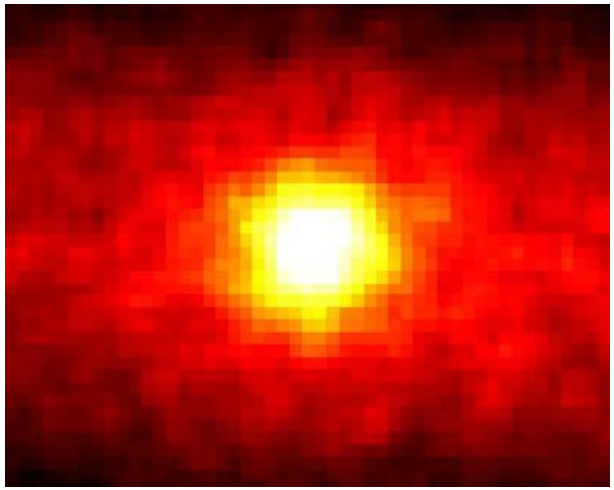


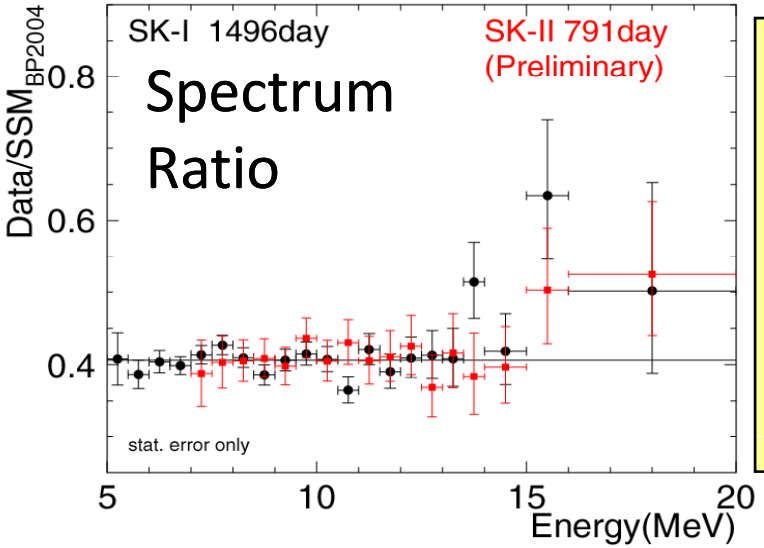
Solar Neutrinos
(Brief summary)

- (ES: electron scattering): $\nu + e \rightarrow \nu + e$

  Energy, time and direction can be measured

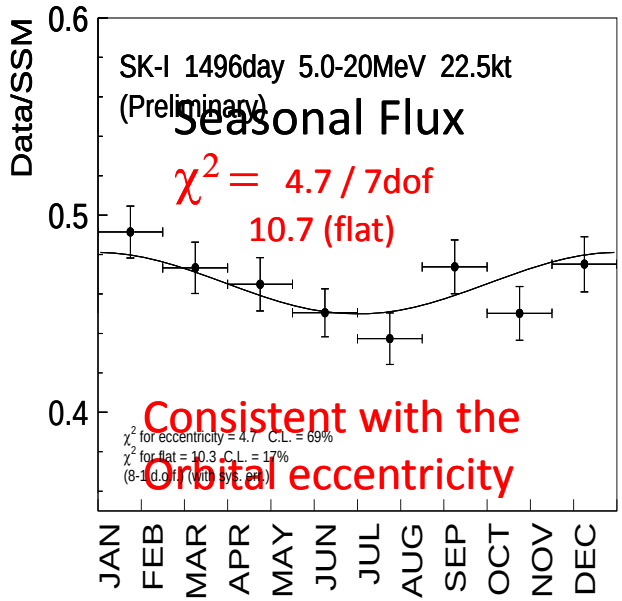
  Sensitive to ν_e, ν_μ, ν_τ: $\sigma(\nu_{\mu,\tau} e) \sim 0.15 \times \sigma(\nu_e e)$
- Original Aim (flux independent eff.)
  - Spectrum distortion
  - Time Variation (Day/Night, Seasonal)
- LMA solution ➔ small such effects





$$\frac{\text{Day} - \text{Night}}{(\text{Day} + \text{Night})/2} = -0.021 \pm 0.020 \pm {}^{0.013}_{0.012}$$

~0.01~0.02 expected from LMA



Precise measurement

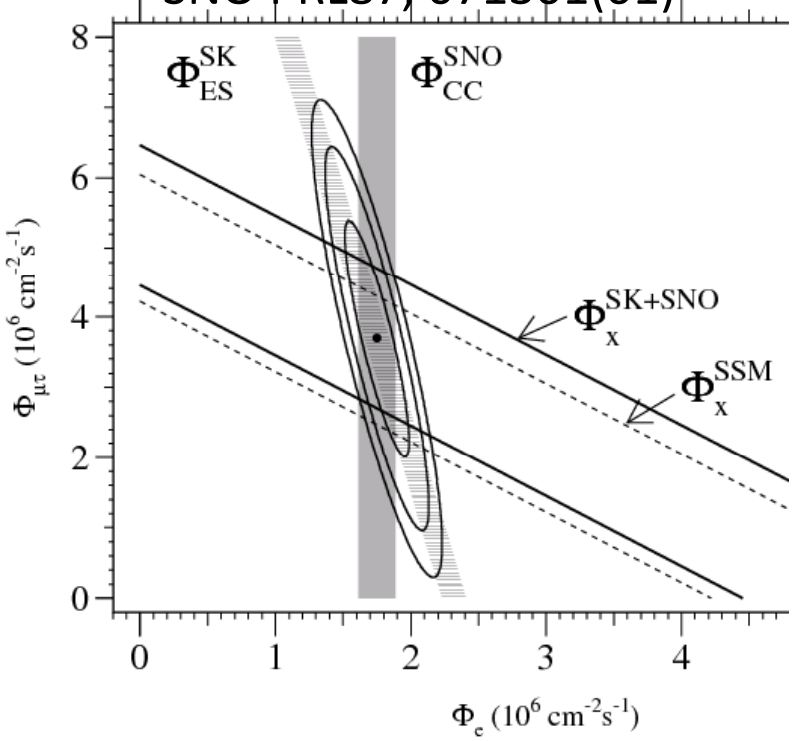
- SK 1258 days ES flux: PRL86 in June 18, 2001 issue
  - $\nu + e \rightarrow \nu + e$ **$2.35 \pm 0.02 \pm 0.08 \times 10^6\ cm^{-2}s^{-1}$**
- SNO CC results: announcement in June 18, 2001
  - $\nu_e + d \rightarrow p + p + e^-$ **$1.76 \pm 0.06 \pm 0.09 \times 10^6\ cm^{-2}s^{-1}$**

- **SNO+SK (in 2001)**

  ➔ **4.3 σ effect of the existence of non-electron neutrino components in solar neutrinos on the earth**

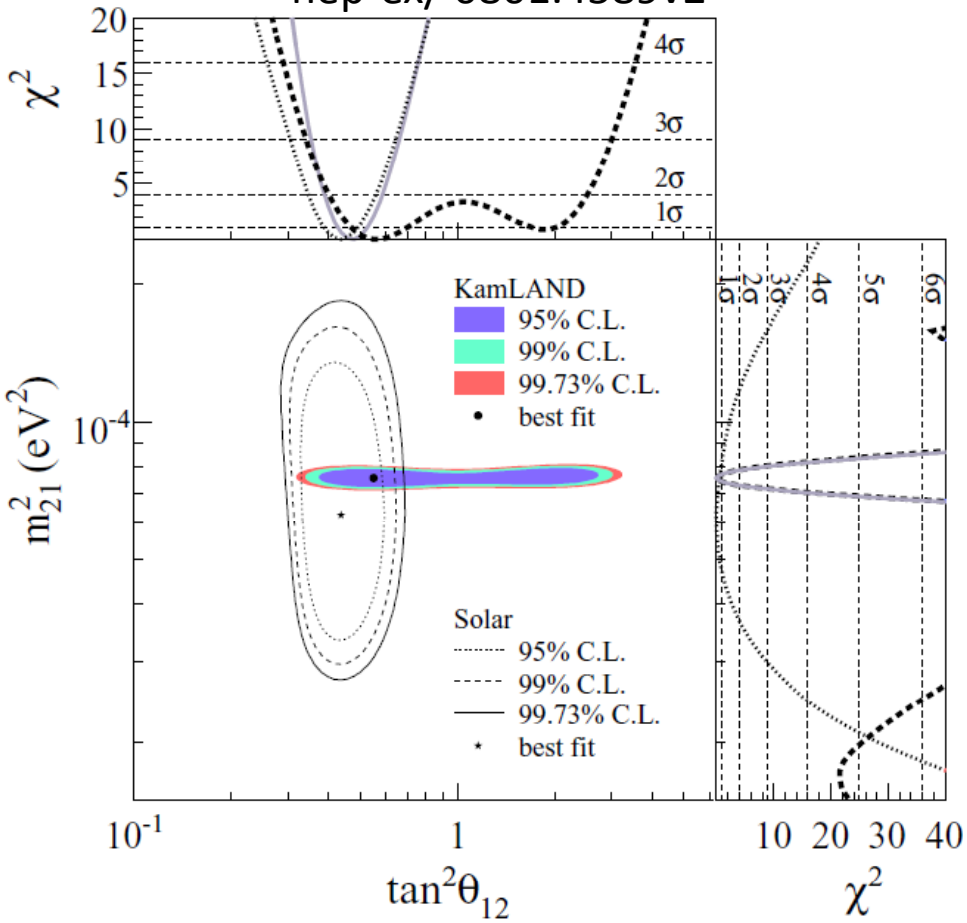
  ➔ **Evidence for Solar Neutrino Oscillation**

SNO PRL87, 071301(01)



Solar + KamLAND results
in 2008 (KamLAND paper)

hep-ex/ 0801.4589v2



Solar: SK + SNO + Cl + Ga

Best-fit (solar+KL):

$\tan^2\theta_{12}$=0.47+0.06/-0.05

Δm_{12}^2

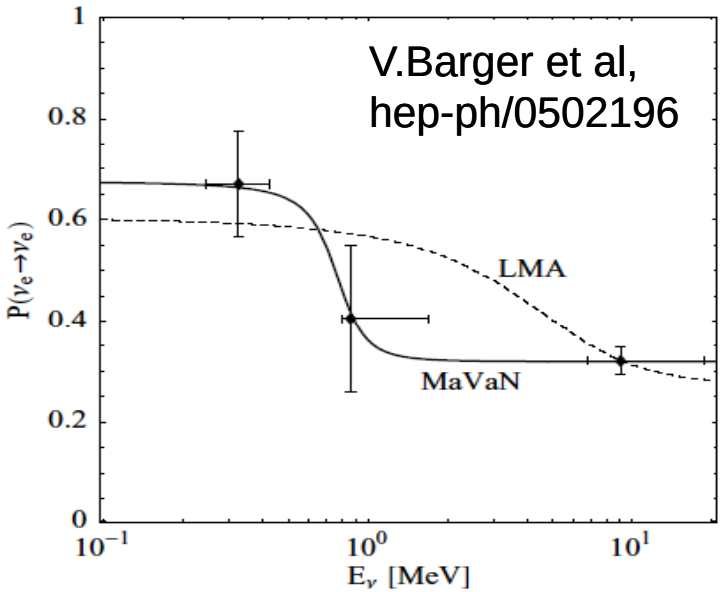
=7.59+/-0.21x10^{-5}eV^2

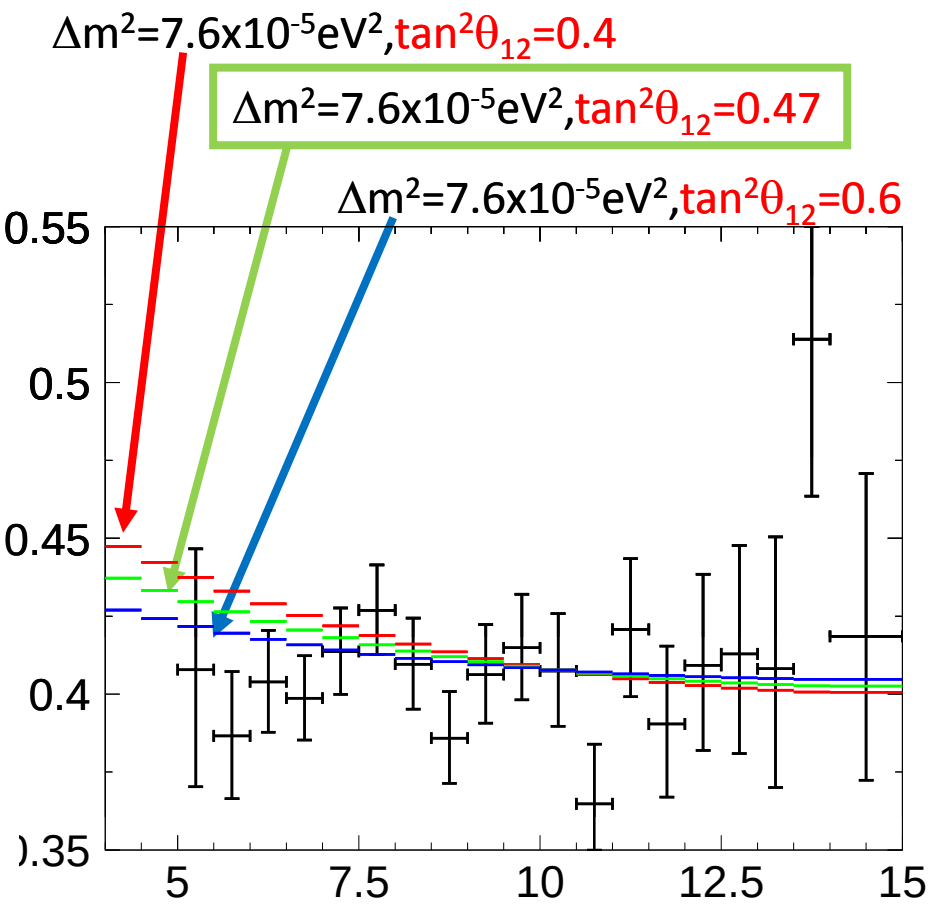
Looking Forward
Super-K

Precise solar-ν measurement in future

What can SK do in future?

- Precise spectrum measurement down to 4 MeV:
  - → Strong test of LMA
    - → Precise determination of oscillation parameters(θ_{12})
  - → sub-dominant effects? or exotics?





A future option - Gd loaded Super-K

Beacom & Vagins, PRL93 (2004)171101

- Identify neutrons in Super-K

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

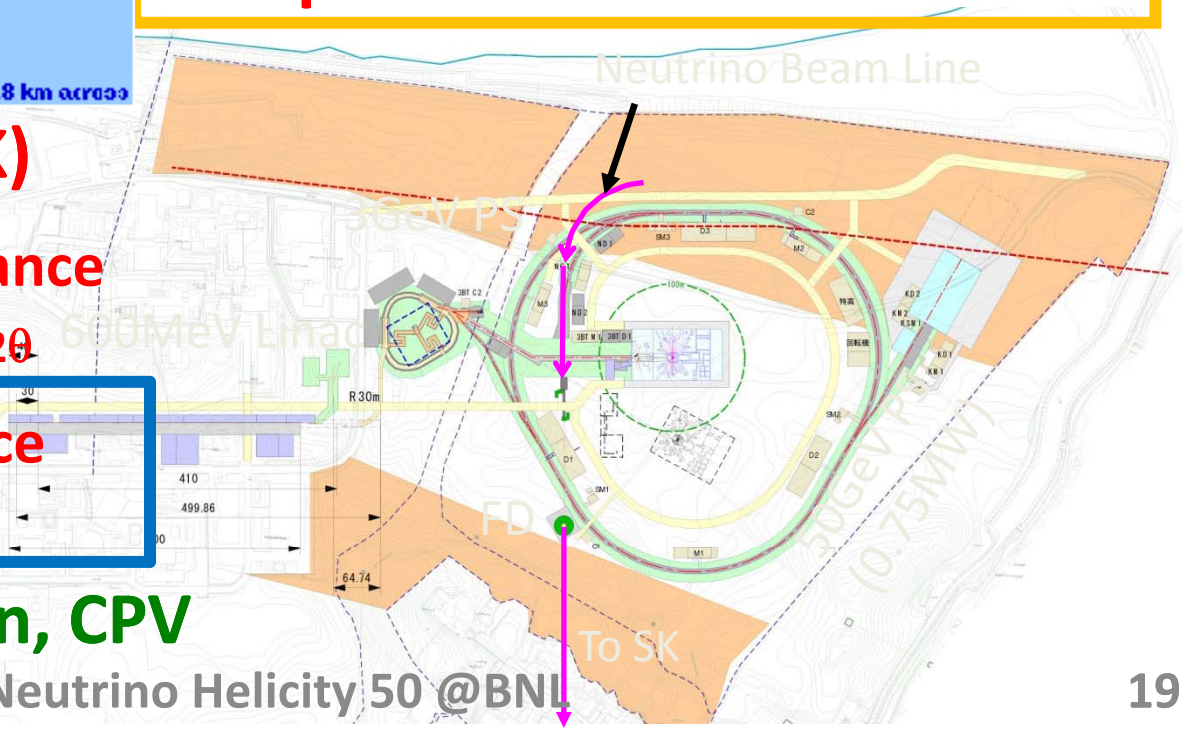
tag this neutron

load 0.2% Gd → 90% of neutrons to be captured on Gd emitts γs, total $E\gamma \sim$ 8MeV

- Physics Aims: SN relic neutrinos, reactor anti-neutrinos, SN neutrino bursts, proton decay BG reduction, …
- R&Ds are on going (transparency, safety, …)

Tokai to Kamioka （T2K）

- **Long baseline oscillation experiment from JPARC-PS@Tokai to SK**
- **Beam Intensity: ~50 x K2K**
- **Baseline: 295km**
- **Experiment: 2009 ~**

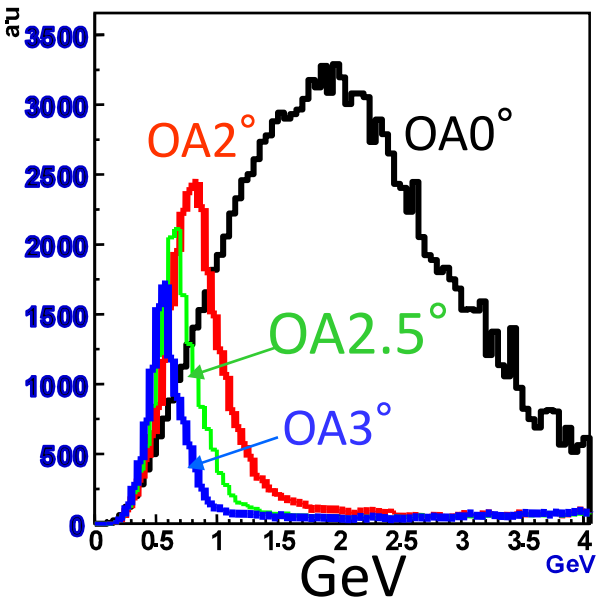


Phase 1 (0.75MW + SK)

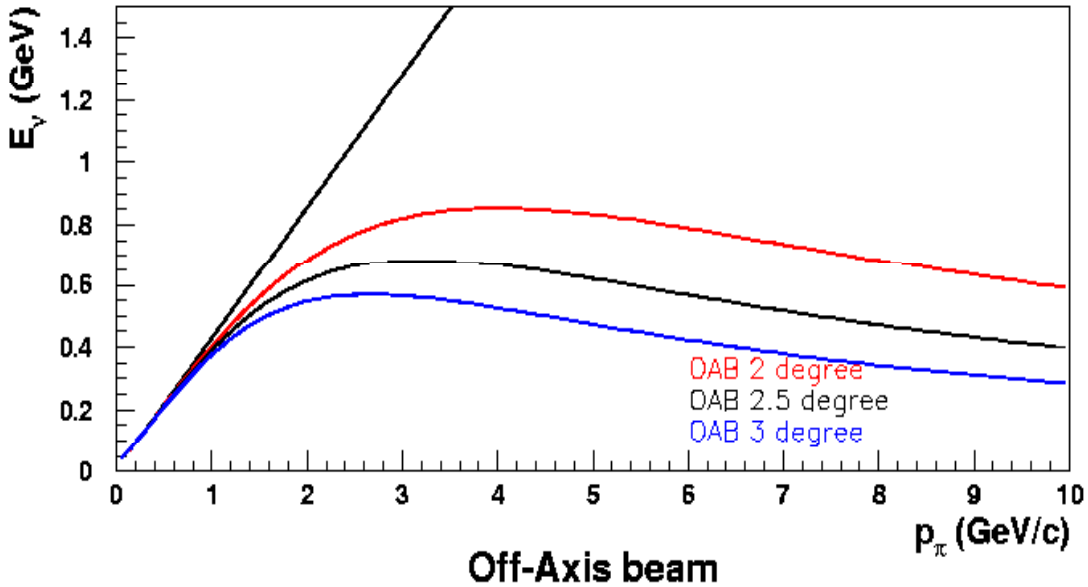
- $\nu_\mu \rightarrow \nu_x$ disappearance
  - Precise Δm^2, $\sin^2 2\theta$
- $\nu_\mu \rightarrow \nu_e$ appearance
  - Finite θ_{13} ?

Phase 2 → 4MW, Mton, CPV

Beam and Event rate

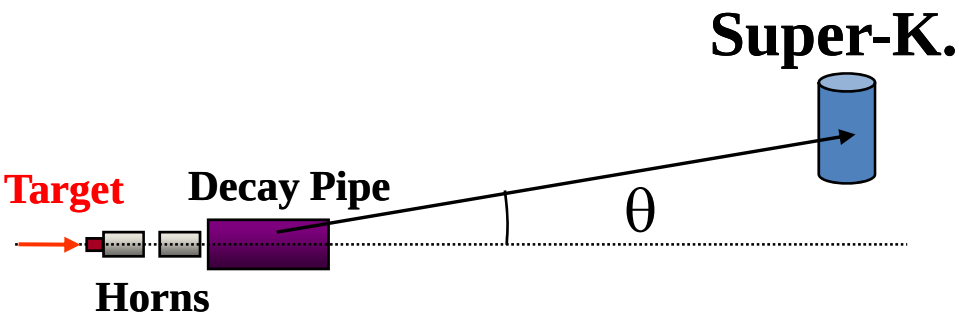


Off Axis ν Beam



→Quasi Monochromatic
→2~3 times intense than NBB
→Can be tuned at oscill. max.

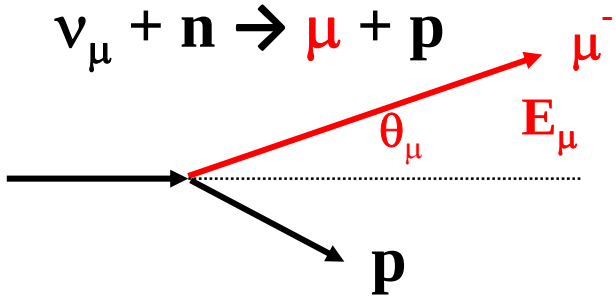
Statistics at SK (OAB 2.5 deg, 5 yr)
ν_μ total ~ 11,000
ν_μ CC ~ 8,000
ν_e ~ 0.4% at ν_μ peak



Determination of θ_{23} , Δm_{23}^2

1 ring μ-like events

$\nu_\mu + n \rightarrow \mu + p$



Current accuracy

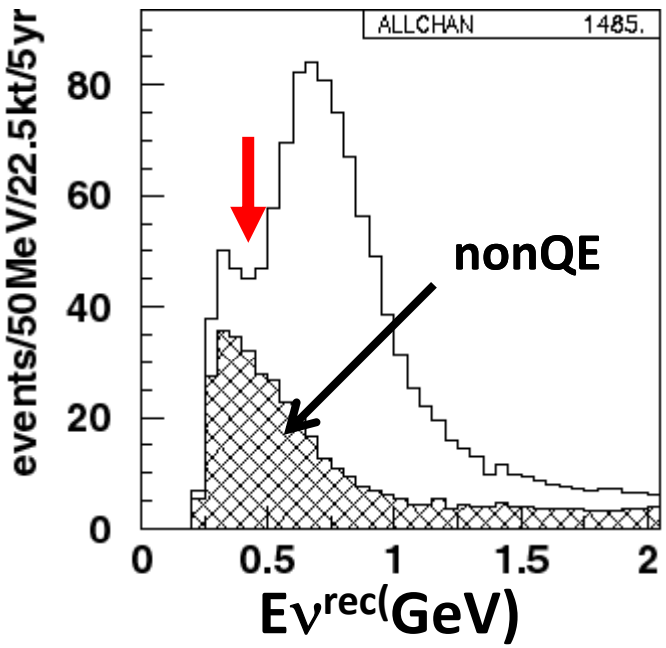
$\delta(\Delta m^2_{23})$~1×10^{-3} eV^2

$\delta(\sin^2 2\theta_{23})$~0.1

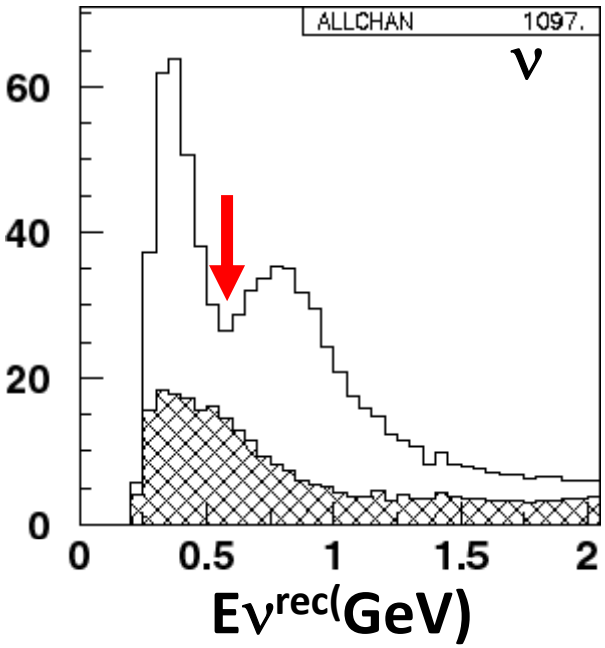
$\delta(\Delta m^2_{23}) < 1\times10^{-4}$ eV^2

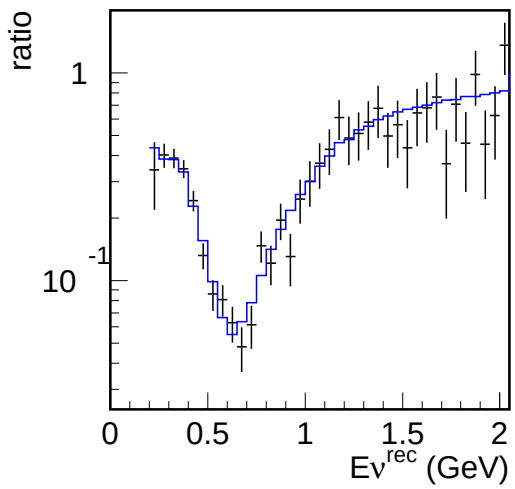
$\delta(\sin^2 2\theta_{23})$~0.01

$\Delta m^2 = 2.0\times10^{-3}$ eV^2



$\Delta m^2 = 2.5\times10^{-3}$ eV^2





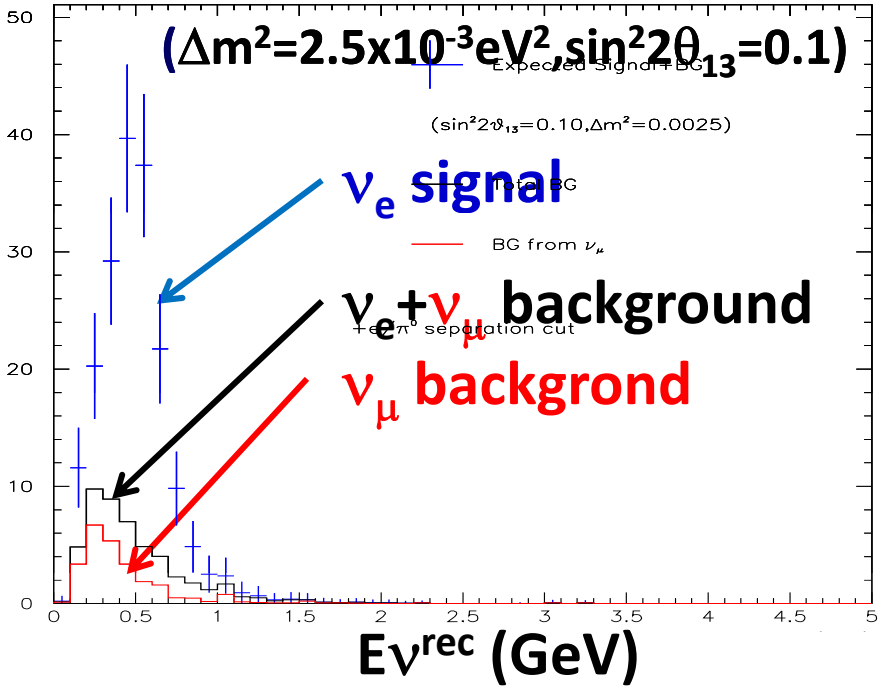
θ_{13}: look for ν_e appearance search

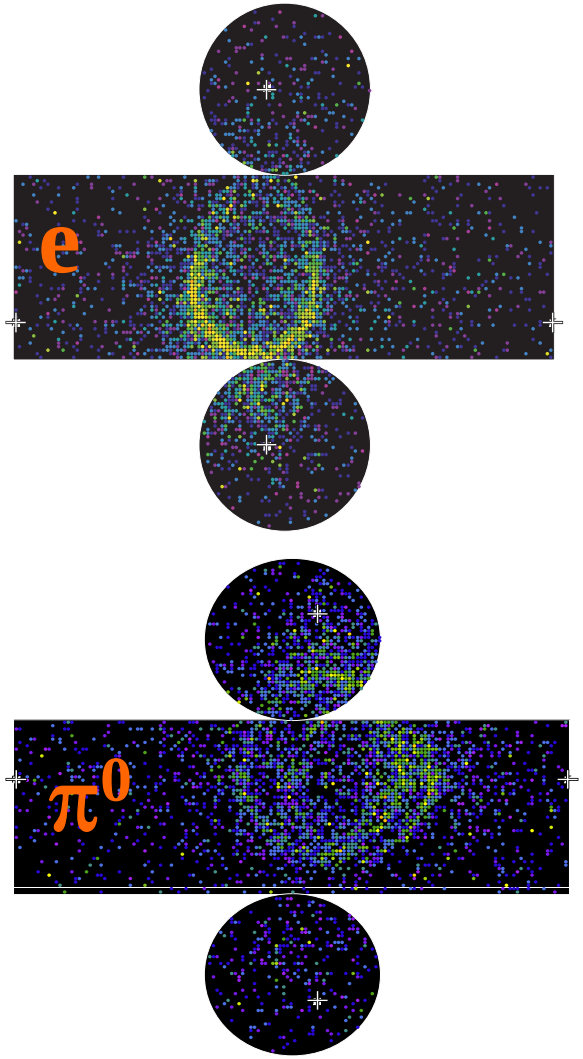
Signal (ν_e) :

- 1ring e-like event (CC QE sample)

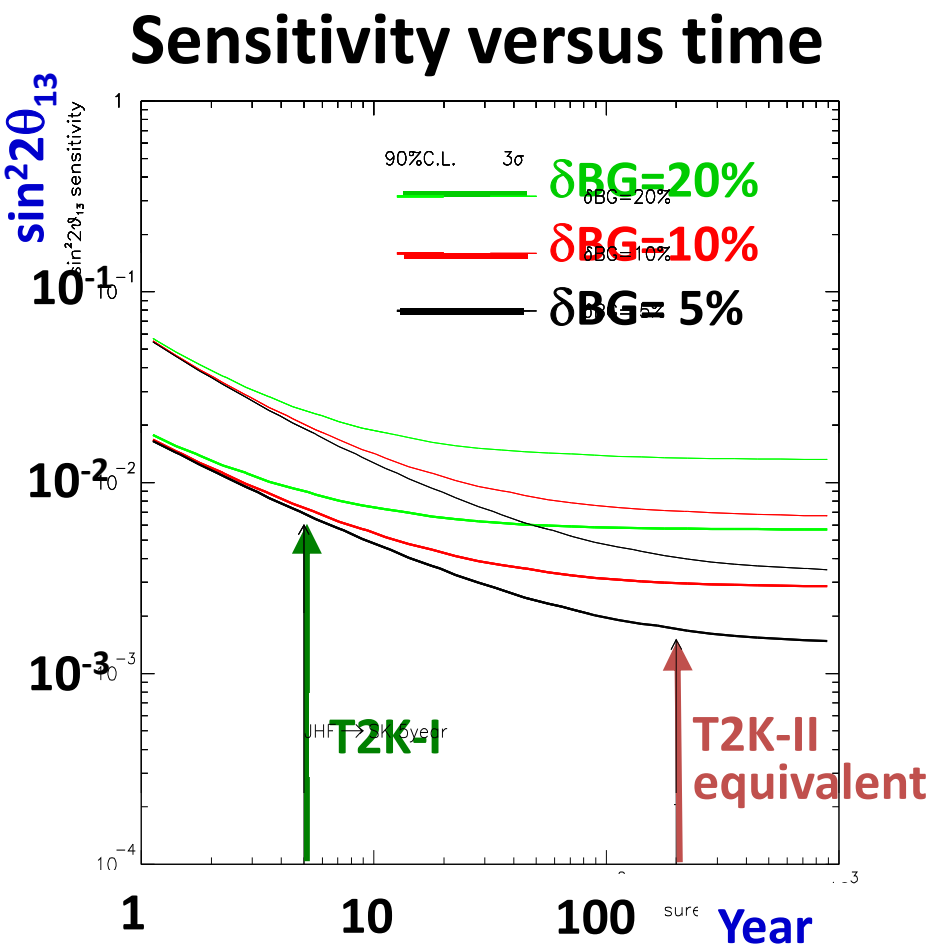
Background:

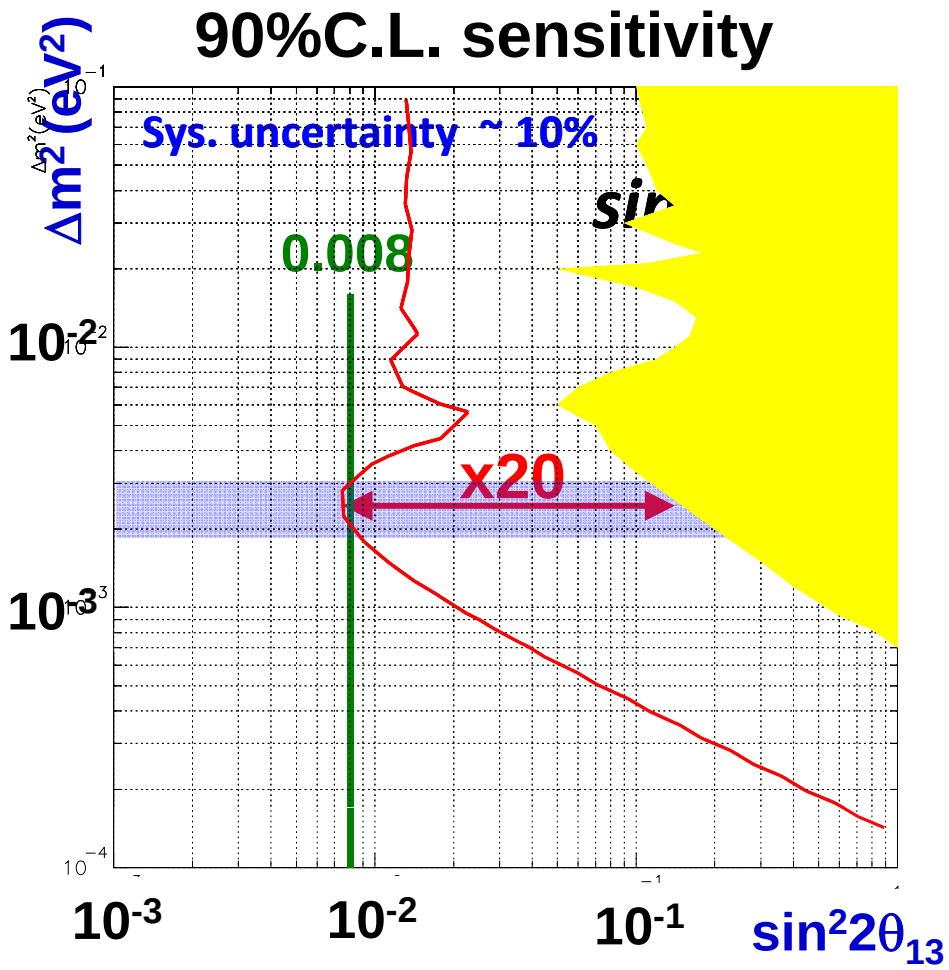
- ν_e contamination in beam (0.4% of ν_μ)
- mis-reconstructed π^0 event (ν_μ origin)

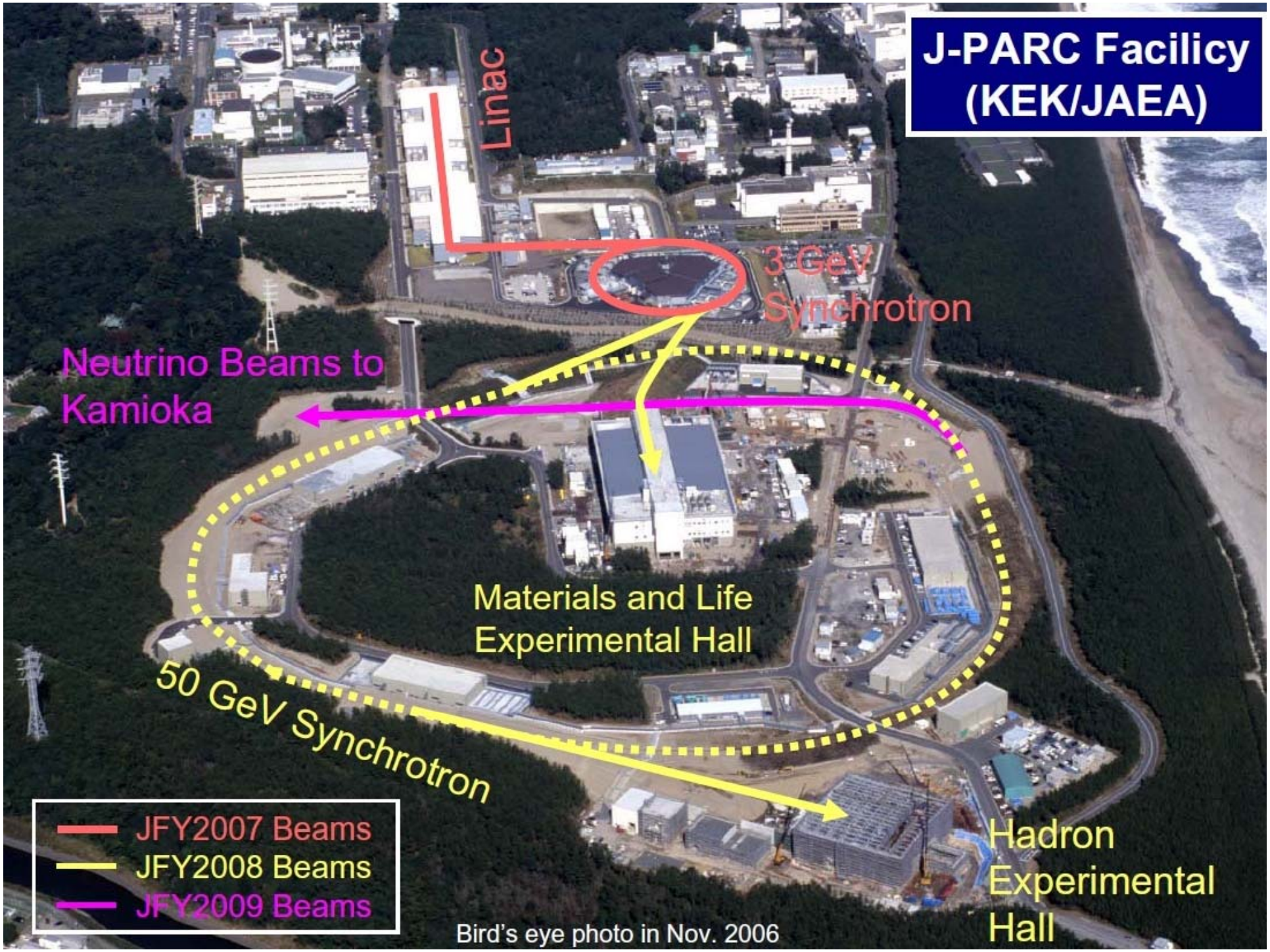




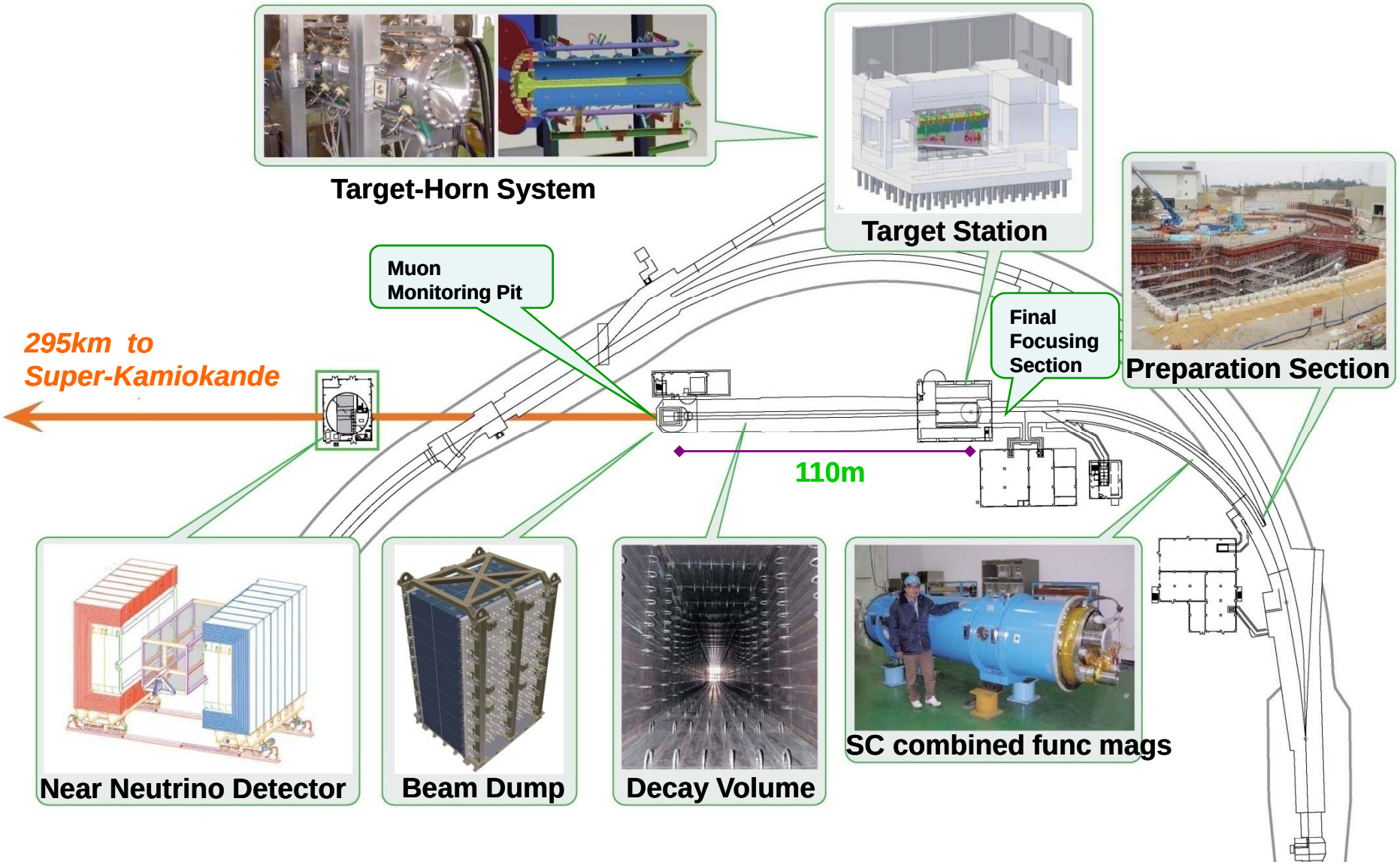
Sensitivity






J-PARC Facilicy
(KEK/JAEA)
Linac
3 GeV
Synchrotron
Neutrino Beams to
Kamioka
Materials and Life
Experimental Hall
50 GeV Synchrotron
Hadron
Experimental
Hall
JFY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in Nov. 2006

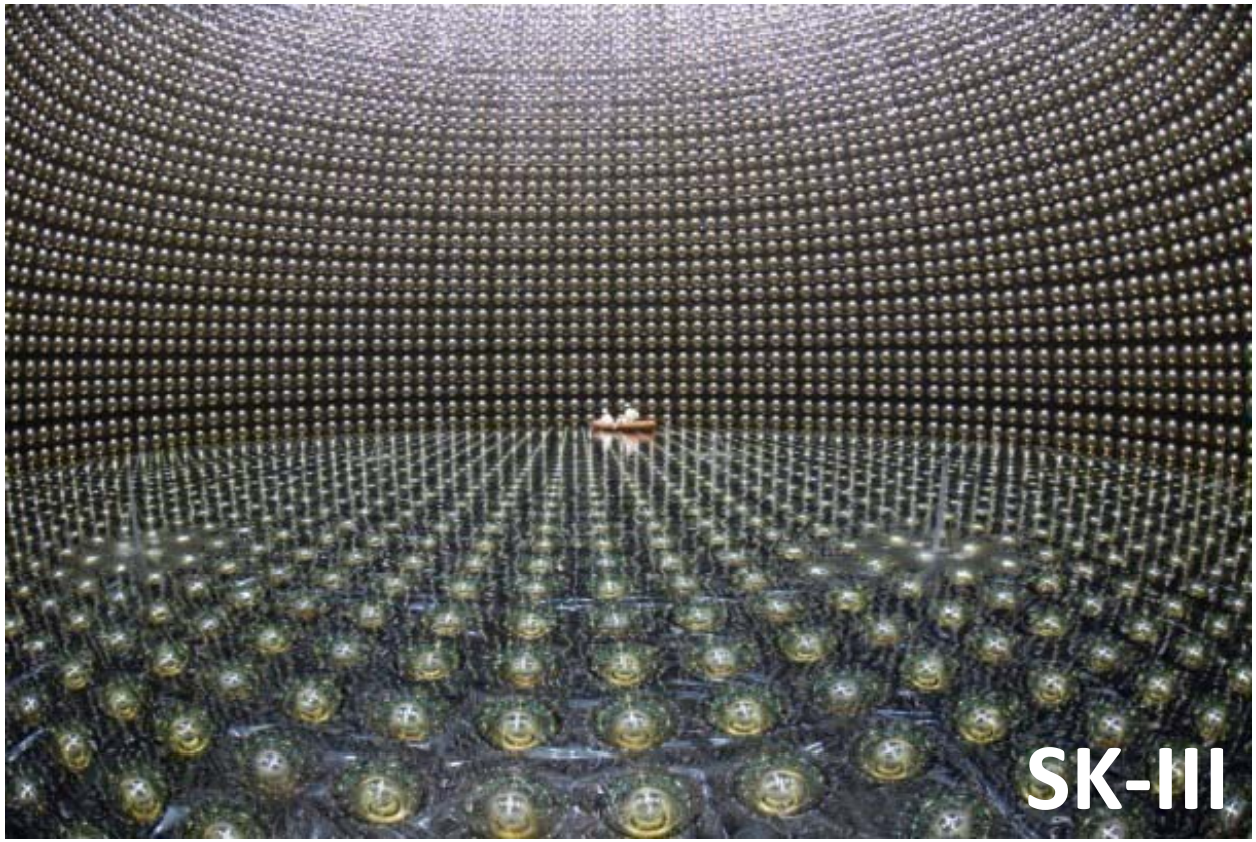
The Neutrino Facility in J-PARC



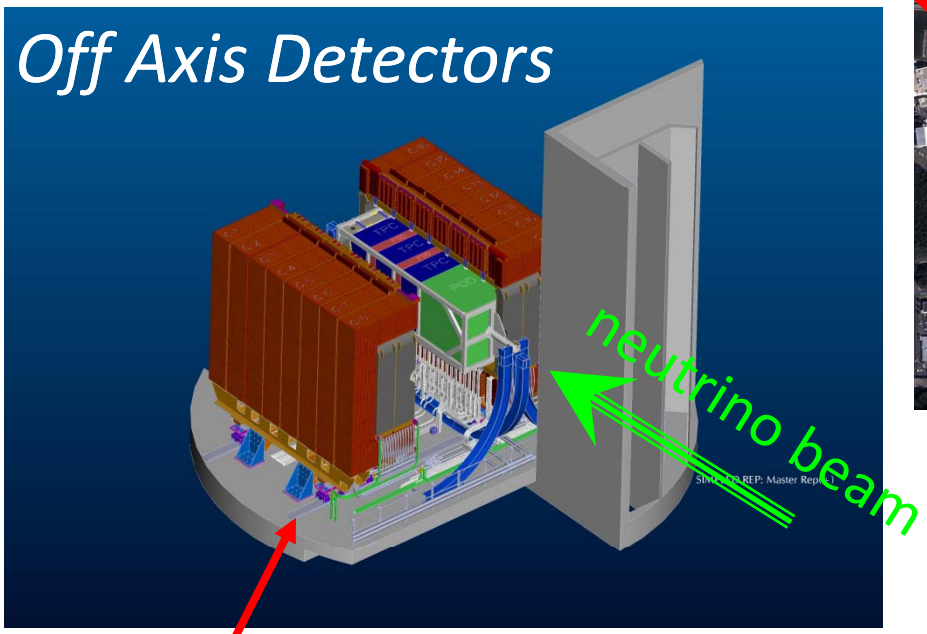
Construction: Apr. 2004 ~ Mar. 2009 (5yrs)

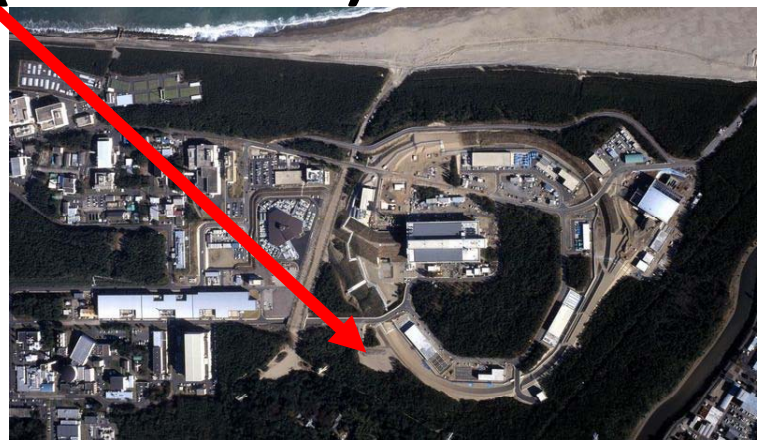
Far Detector

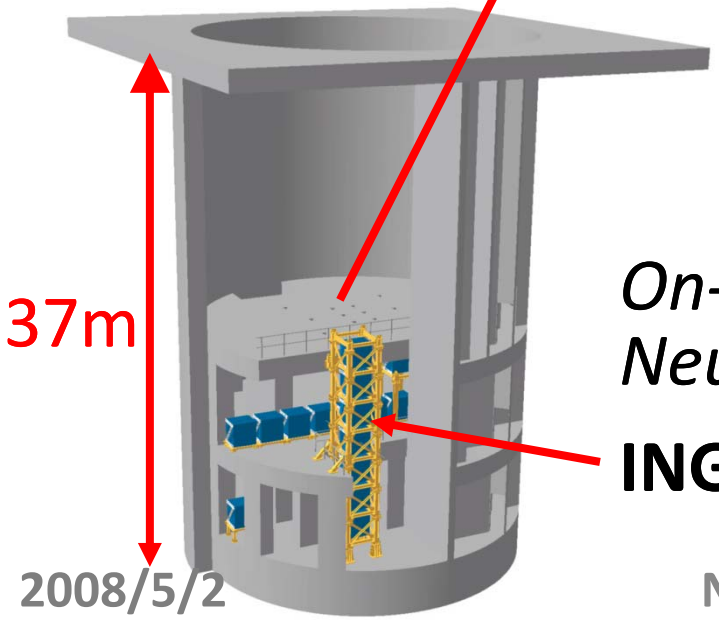
- ***Super-Kamiokande***
  - **Detector is ready**
  - **New electronics (replacement: summer, 2008)**



Near Detectors (ND280)



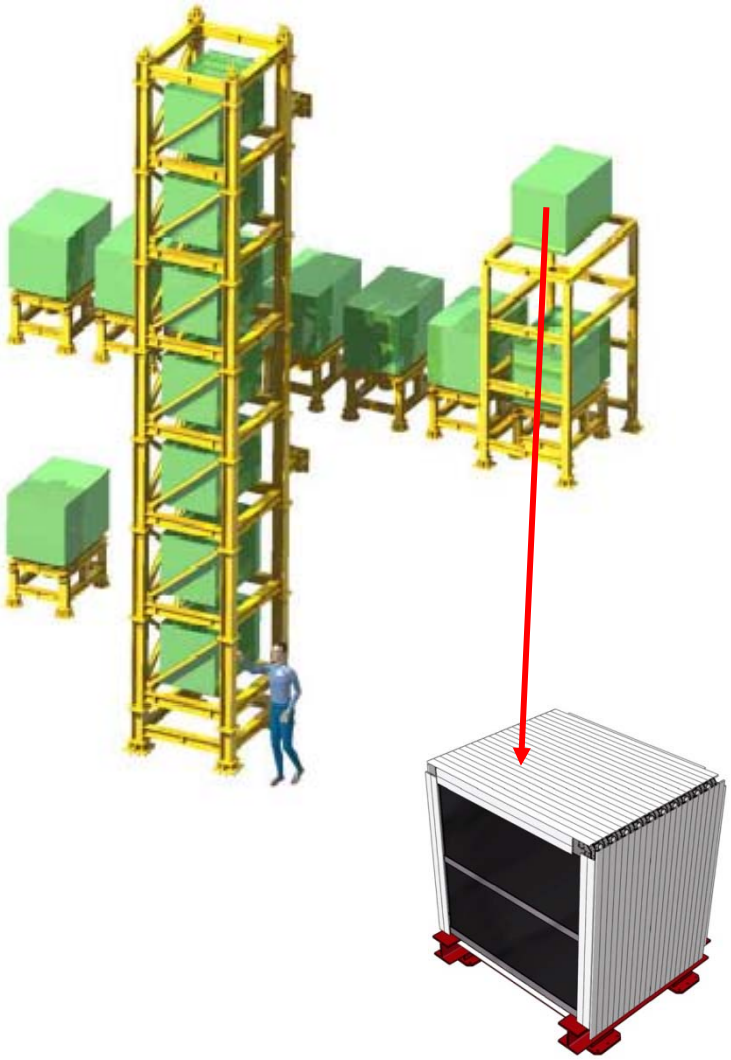




On-Axis
Neutrino Monitor :

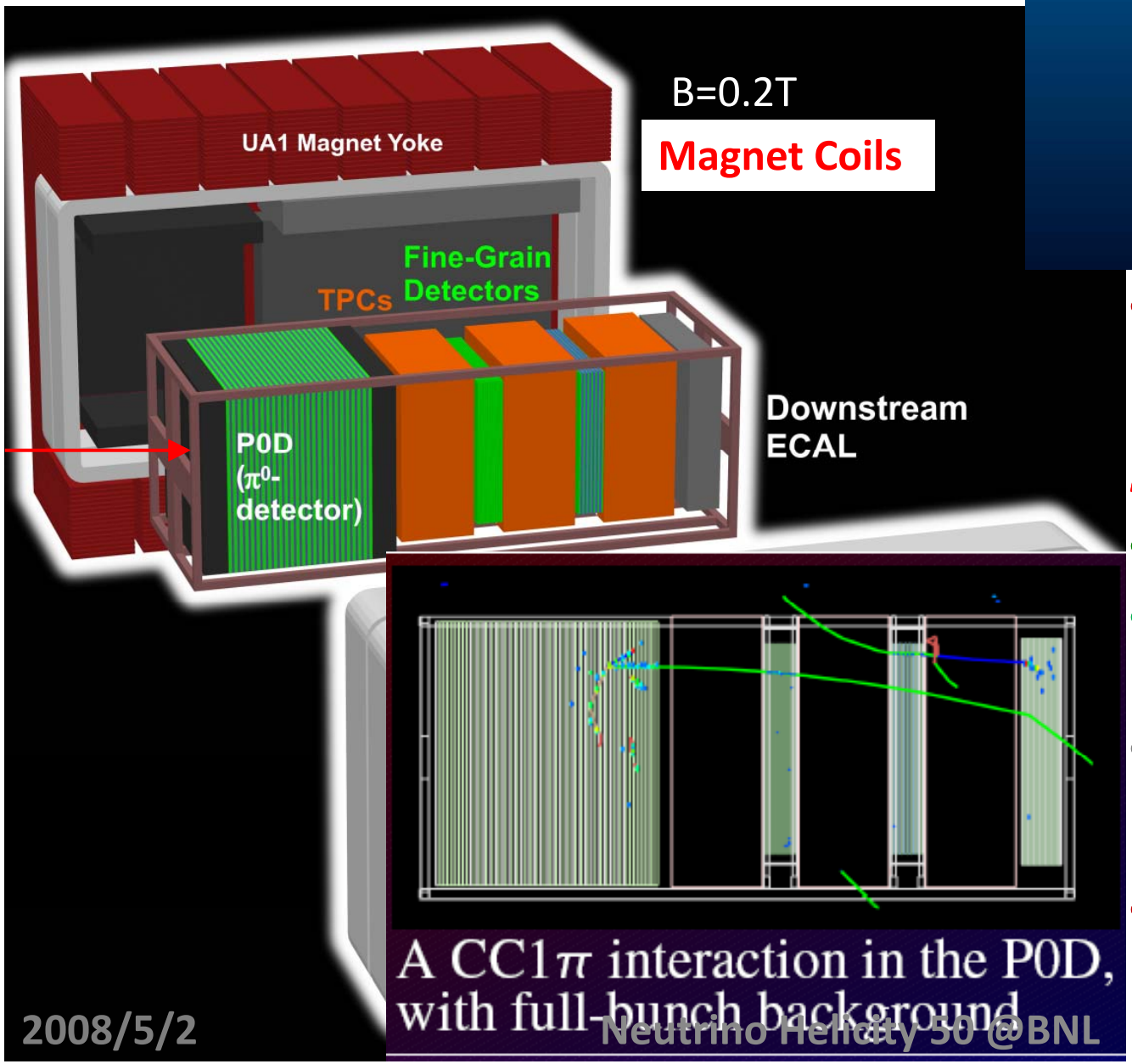
INGRID

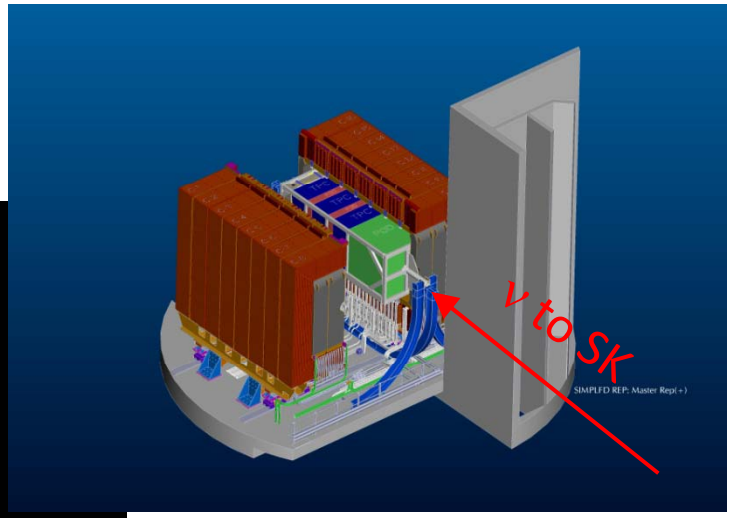
INGRID: Neutrino Beam Monitor



- 7+7+2 modules
  - 10,000 events/mod/day
  - Intensity, direction, spectrum, stability
- $120\times5\times1cm^3$ scintillator
  - ~ 10,000 pieces
  - read by wave length shifter fiber & MPPC
  - ～15p.e./cm
- Ready by April, 2009

Off Axis Detectors





- **Volume:**
  - **3.5×3.5×7.0m^3**

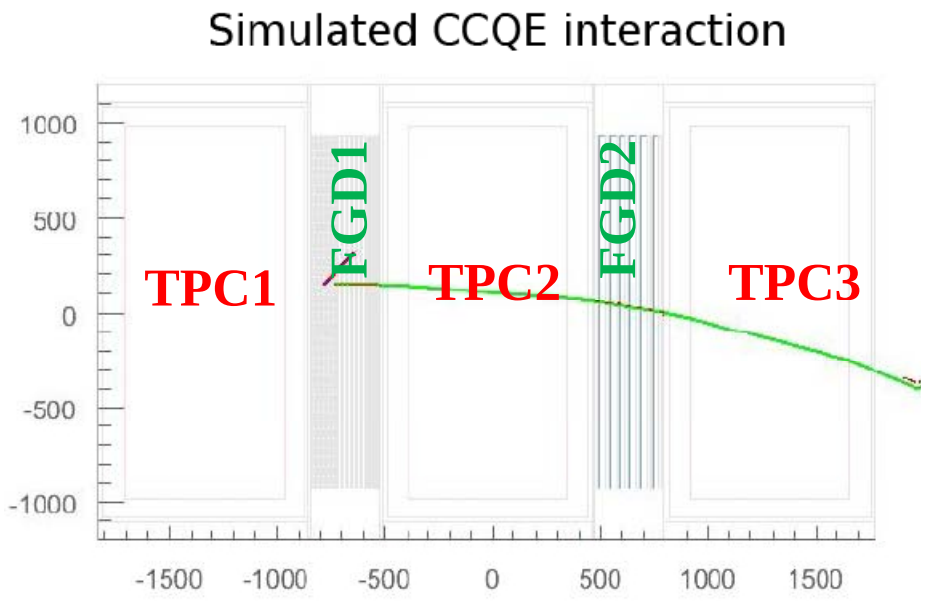
From Upstream

- **P0D π^0 detector**
- **FGD+TPC:**
  - **Detect Charged P.**
- **Electro Magnetic Calorimeter**
- **Side μon Detector**

FGD + TPC

Fine Grain Detector

- **Vertex Detector for neutrino interactions**
- **1cm x 1cm scintillator, Wave length Shifter Fiber＋MPPC**
- **Install in summer, 2009.**



Tracker volume

3TPC

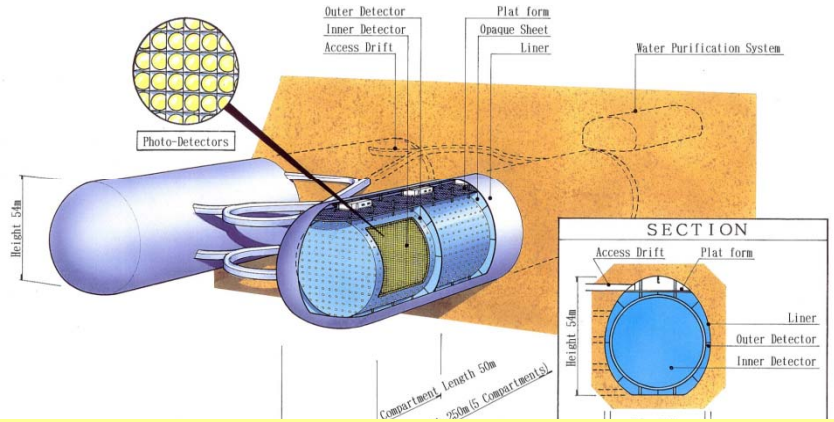
- **MicroMegas (8mm × 8mm pad size)**
- **Momentum resolution**
  ~10% (p<1GeV/c)
  ~10% dE/dx resolution
- **2 TPCs to be installed in 2009.**

Beyond

- *Mission of T2K (2009~): Phase I*
  ➔ Discovery of ν_e appearance!

- **Next step: Phase II**
  - **Discovery of CP violation in neutrino sector.**
  - **Discovery of proton decays.**
  - **Others**

Hyper-Kamiokande OR ??



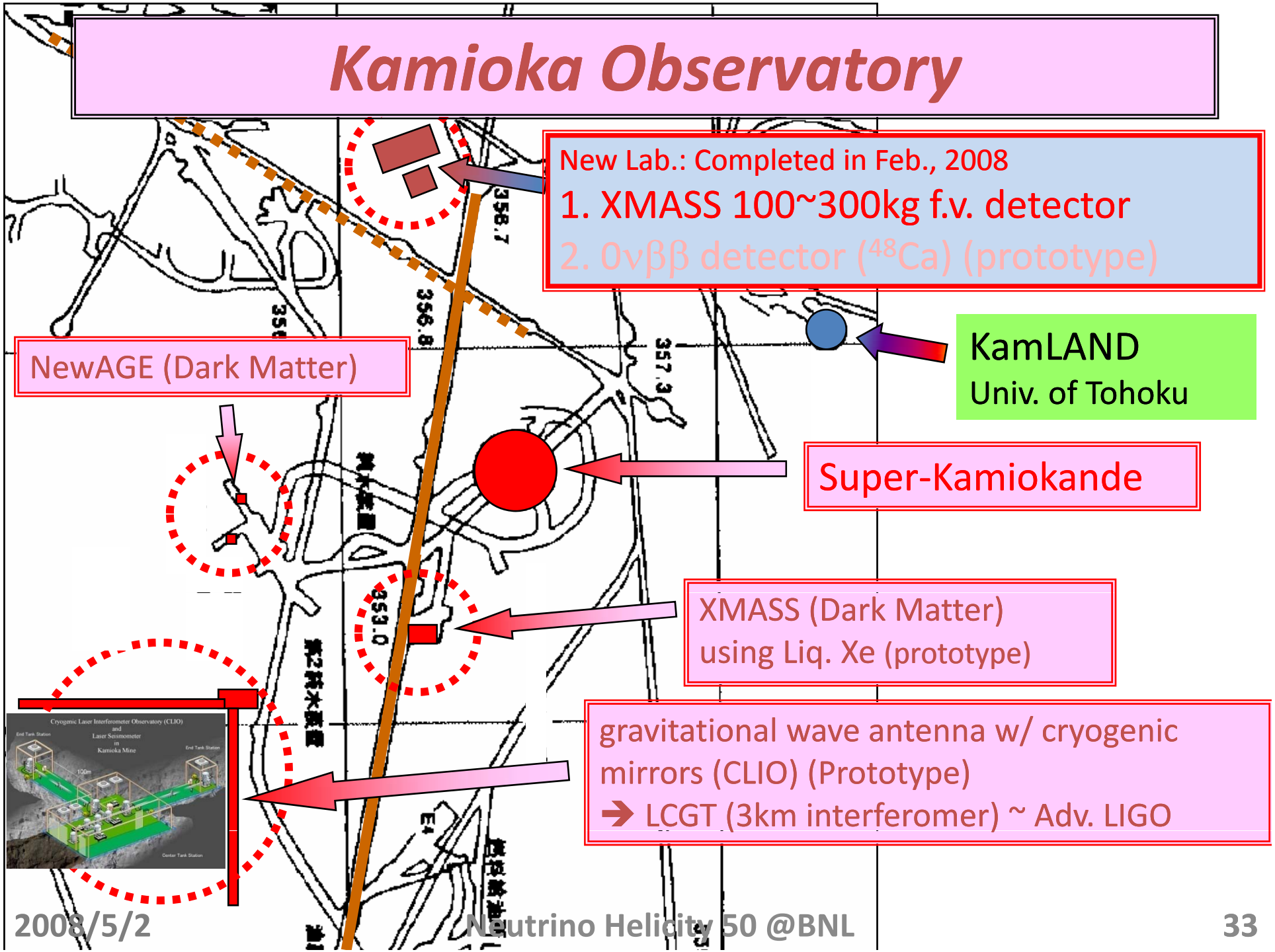
~0.5Megaton fid vol. (0.27Mton x 2 detectors)
Needs ~200,000PMTs (assume 40% coverage)

Under Discussion

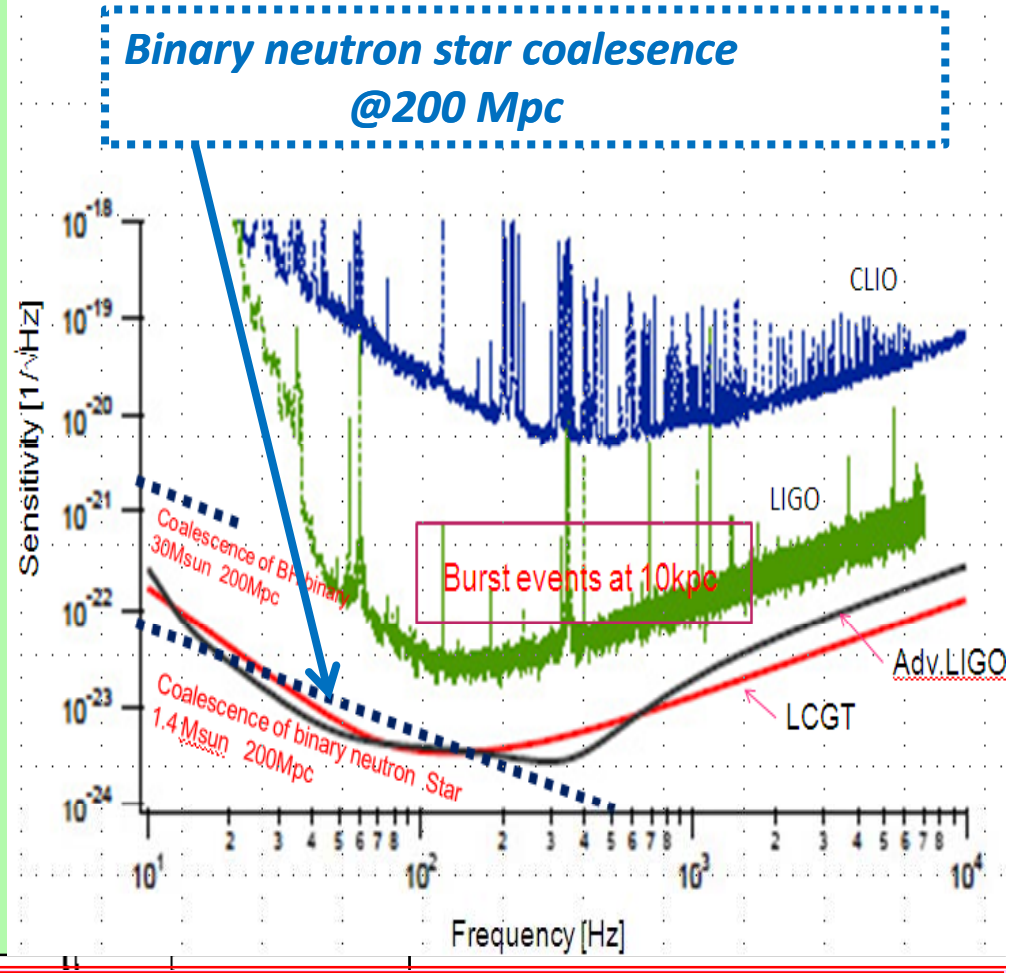
END

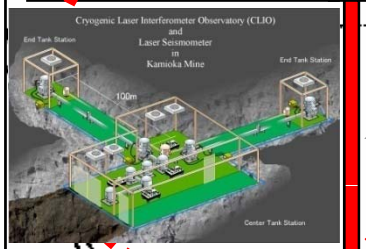
Activity at Kamioka Observatory

Kamioka Observatory



- **Large Cryogenic Gravitational Wave Telescope (LCGT)**
  - Baseline ~ 3km
  - 150W laser
  - Underground
    - ➔ Small Seismic Noise
  - Cryogenic mirror
    - ➔ 30kg Sapphire mirrors
    - ➔ Reduce thermal Noise
  - Budget request
  - Prototype CLIO
    - 100m interferometer





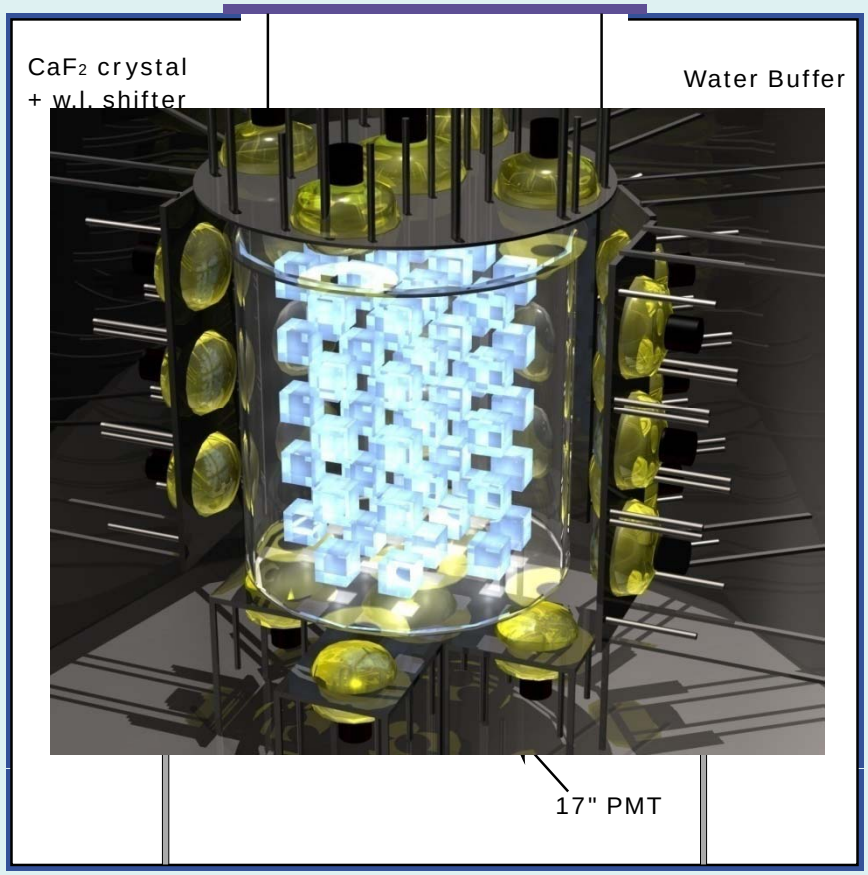
gravitational wave antenna w/ cryogenic mirrors (CLIO) (Prototype)
➔ LCGT (3km interferomer) ~ Adv. LIGO

Kamioka Observatory

New Lab.: Completed in Feb., 2008

1. XMASS 100~300kg f.v. detector
2. 0νββ detector (^{48}Ca) (prototype)

CANDLES



- undoped **CaF_2** (CaF_2(pure))
  - **^{48}Ca (0.187%) Q=4.27 MeV**
  - 305 kg (III-chika) 10^3cmx96

    ⇩

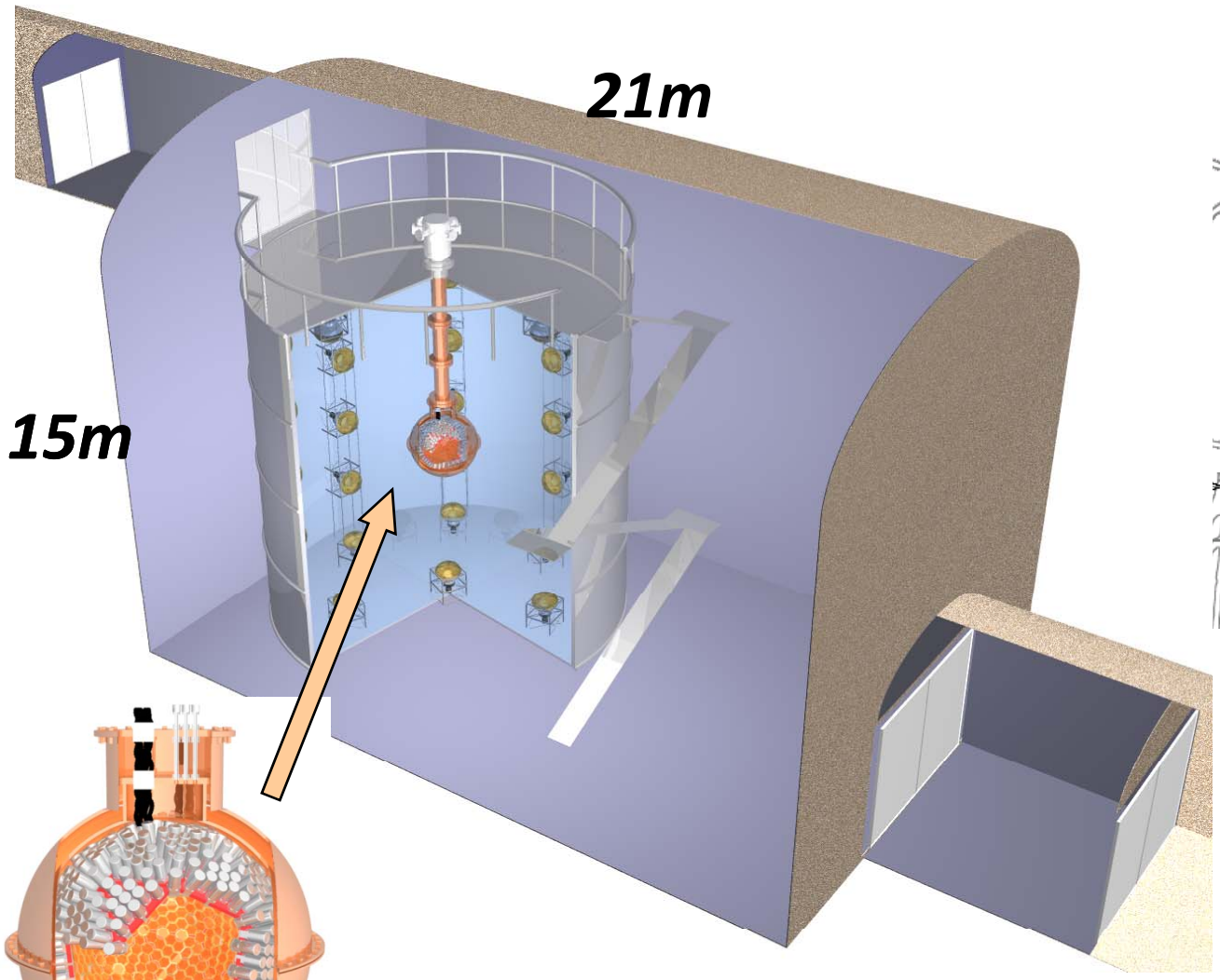
    3.4 t (IV) ~0.1 eV

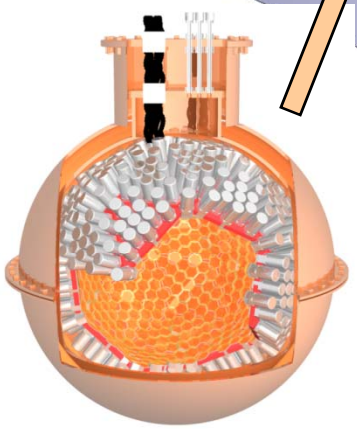
    ⇩

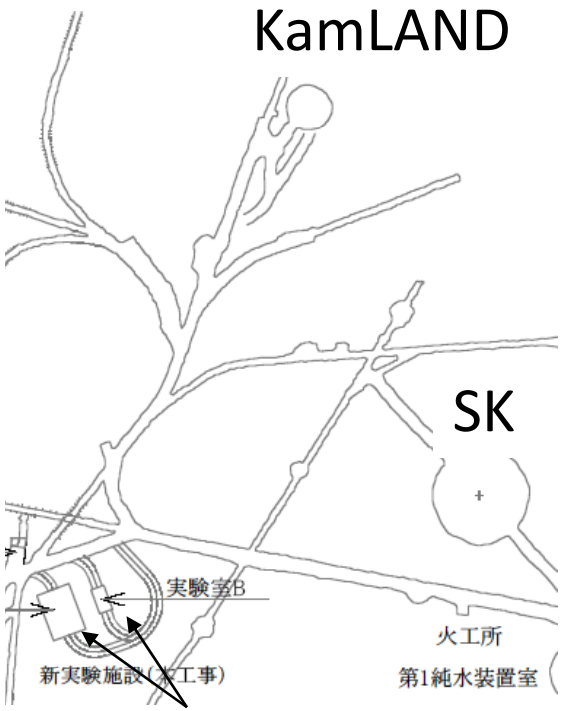
    30 t, 2% enriched (V)

    ~30 meV (best NME)
- Liquid Scintillator (LS)
  - 4π active shield
- Photomultiplier
  - large photo-coverage
- Water buffer→Passive shield

XMASS experimental hall





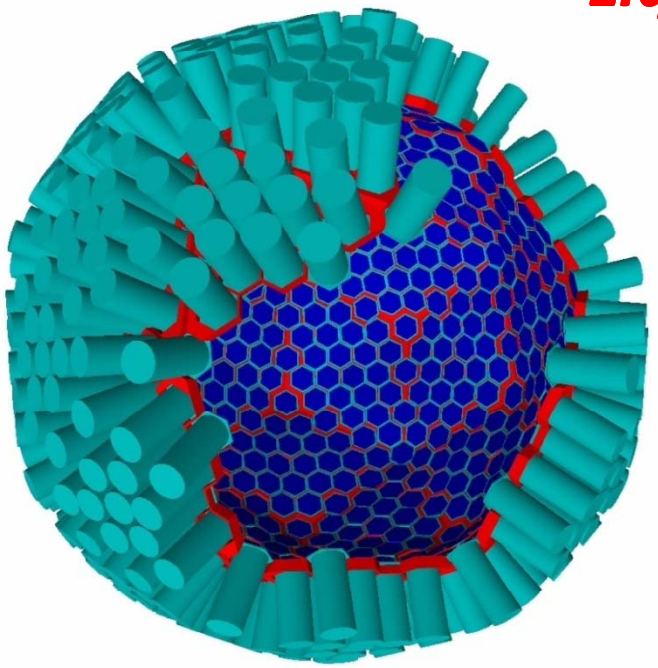


New Halls

Cavity is completed in Feb., 2008.

XMASS

~1ton liquid xenon detector



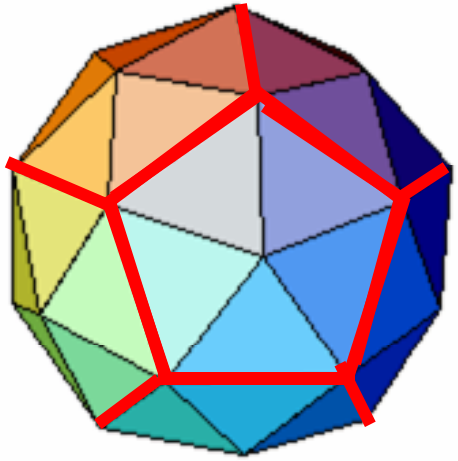
Liquid Xenon

- **Large photon yield (~42 photons/keV ~NaI(Tl))**
  - ➔ **Low threshold**
- **High density (~3 g/cm^3)**
  - ➔ **Compact detector** (80cm in diameter)
- **Large Z =54**
  - ➔ **Shielding effect of itself is large: Ext. BG**
- Purification is easy (distillation) : ^{85}Kr
- No long life radioactive isotope in Xe
- Scintillation wavelength is 175 nm,
  - ➔ detected directly by PMT

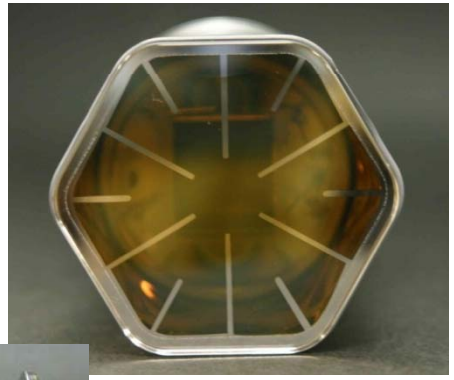
XMASS: uses 812 PMTs providing ~70% photo-cathode coverage and also give fiducial volume of ~200kg (20 cm self-shielding layer)

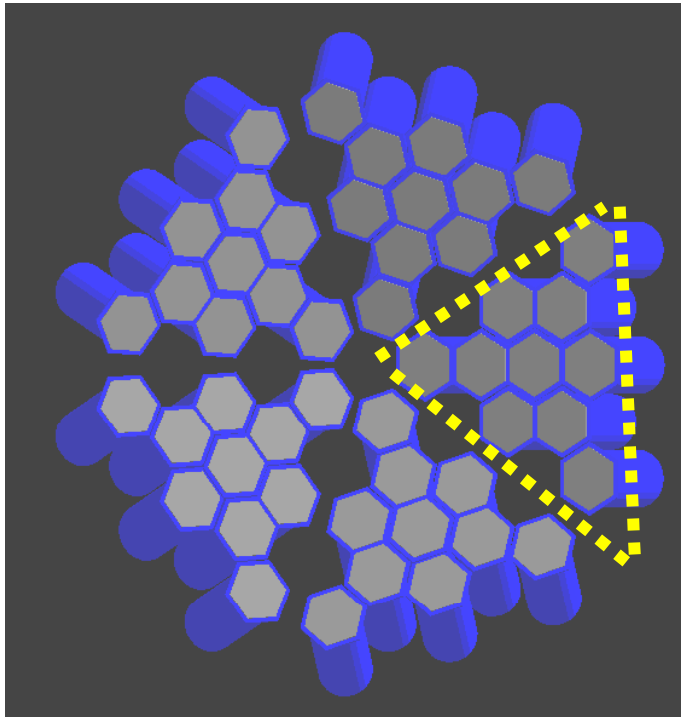
We can achieve low energy threshold and low background (aim 10^{-4} /keV/kg/day)

Structure of the detector



Pentakis-dodecahedron
12 pyramids ➔



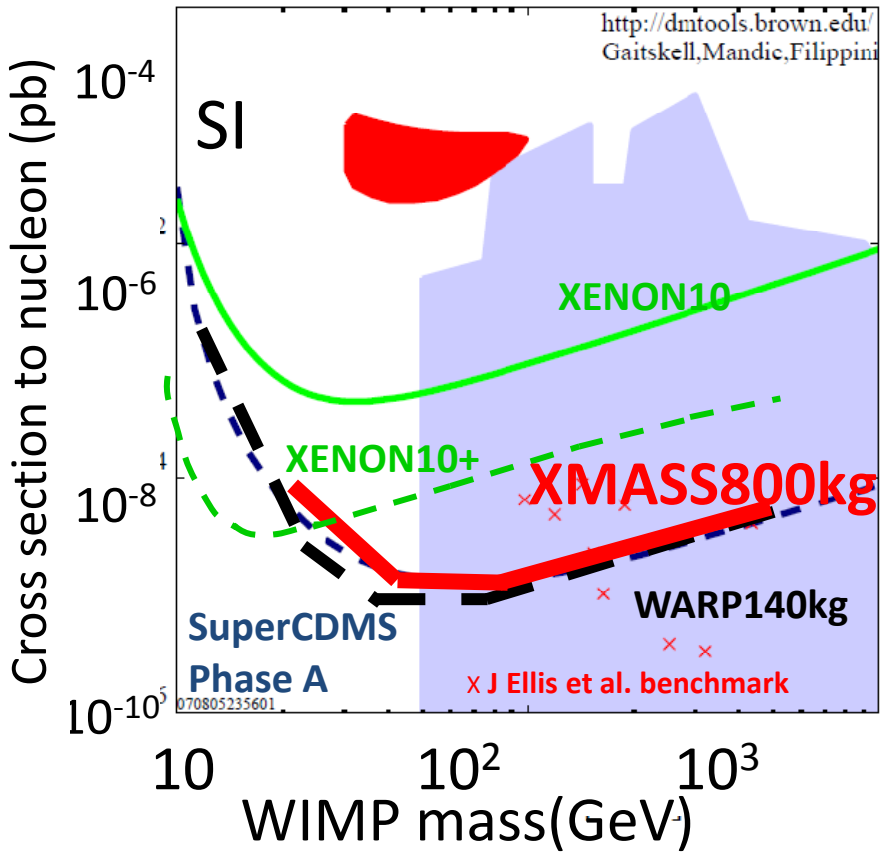


5 triangles make pentagonal pyramid

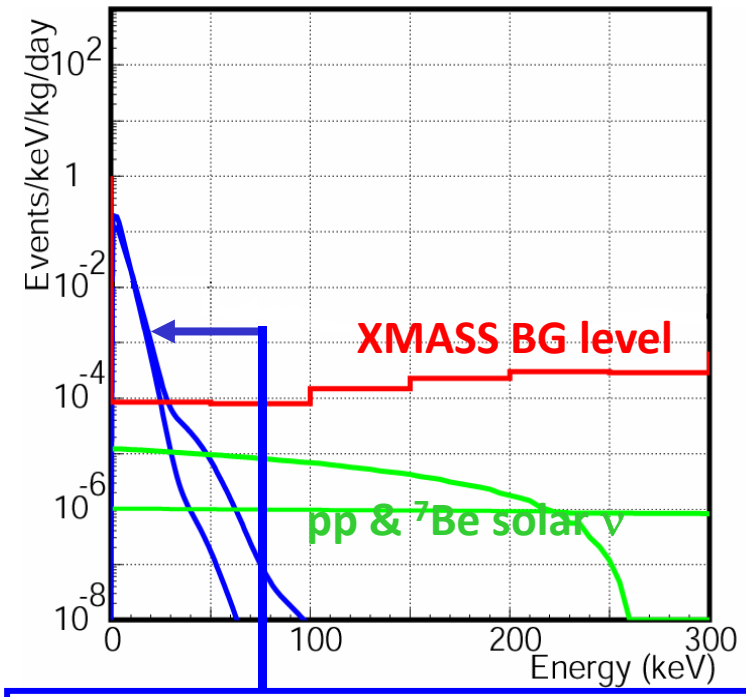
- **Center to inner surface (photocathode) ~45cm**

Sensitivity of the 800kg detector

Plots exept for XMASS
From http://dmtools.berkeley.edu
Gaitskell & Mandic



XMASS 100kg, 5yr
3σ discovery



Expected dark matter signal for 50 GeV and 100 GeV (assuming 10^{-42} cm^2, Q.F.=0.2)

Conclusions

- **50yrs after the measurement of neutrino helicity, we know that neutrino has a tiny mass and oscillates. The smallness of the neutrino mass is a clue to the physics beyond the standard model and gives us a hit for origin of matter.**
- **Neutrino physics has made a remarkable development for the last 50 years and we, experimentalists, are now studying many interesting scientific objects by making use of neutrinos.**