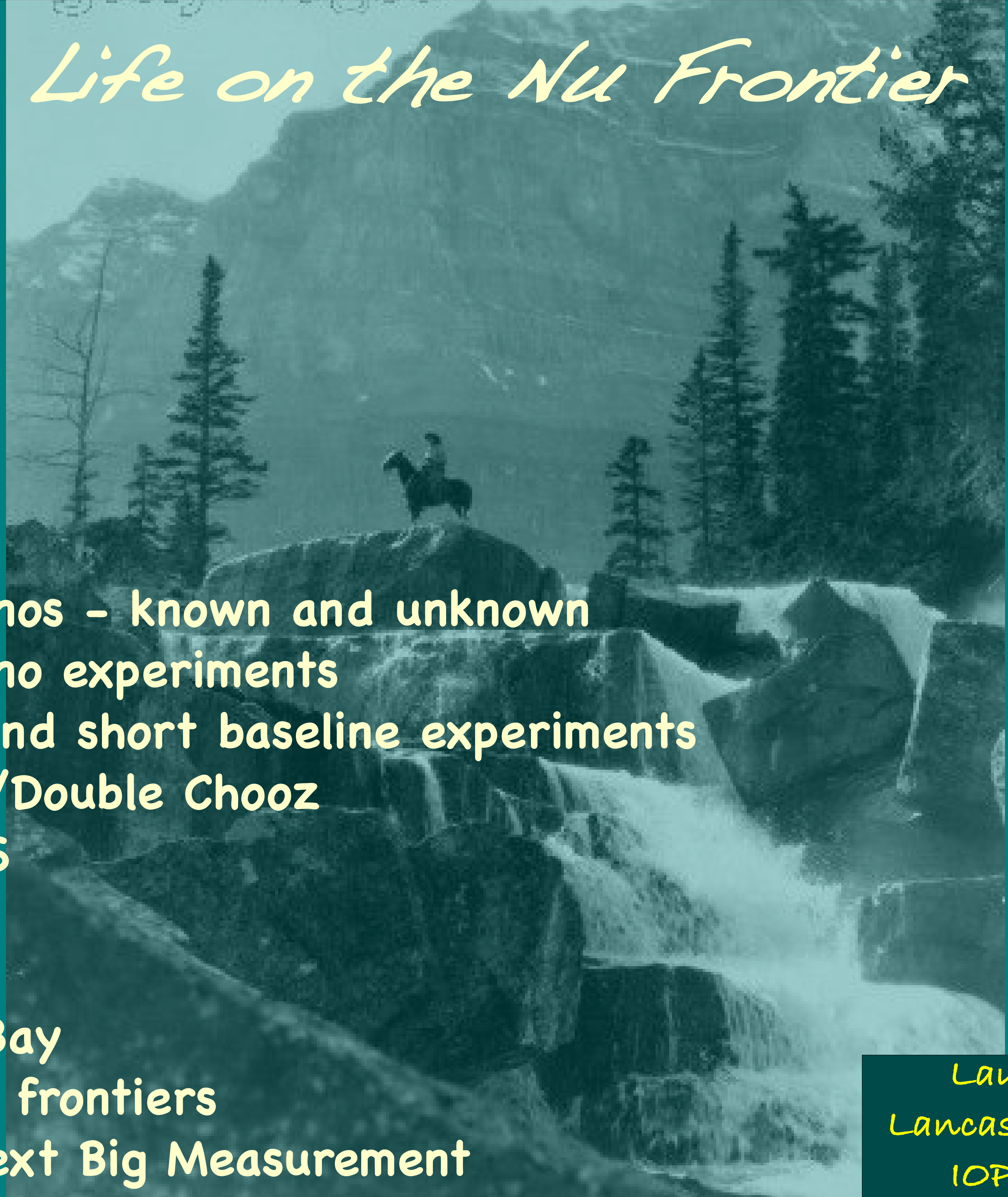
Life on the Nu Frontier



- Neutrinos - known and unknown
- Neutrino experiments
- Long and short baseline experiments
- Chooz/Double Chooz
- MINOS
- T2K
- Nova
- Daya Bay
- Future frontiers
- The Next Big Measurement

Laura Kormos
Lancaster University
IOP HEP 2010

Neutrino mixing can be described by a set of linear equations ⇨ matrix.

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

weak eigenstates

mass eigenstates

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

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

Parameters describing flavour change and matter/antimatter asymmetry.

- **Neutrinos - known and unknown**
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weak eigenstates

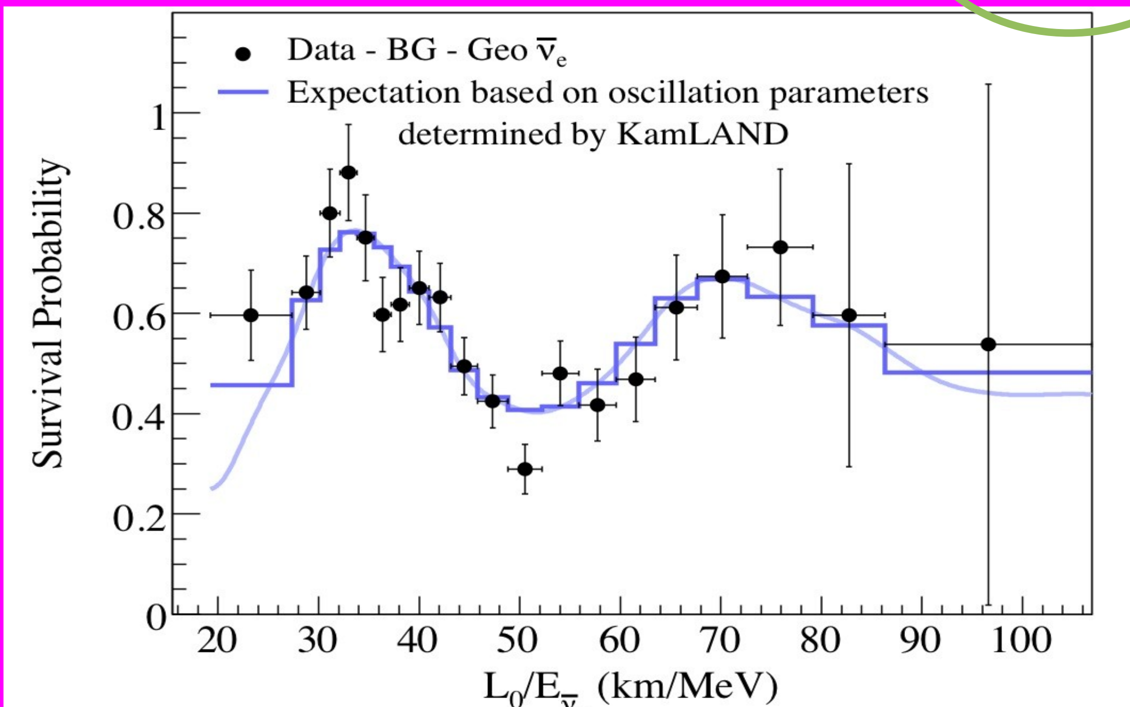
mass eigenstates

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

atmospheric

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

solar



For some combinations of L, E, Δm_{ij}^2, mixing between 2 states dominates other mixings.

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2[1.27\Delta m^2 L/E_\nu]$$

Neutrino mixing can be described by a set of linear equations ⇒ matrix.

mass eigenstates

weak eigenstates

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

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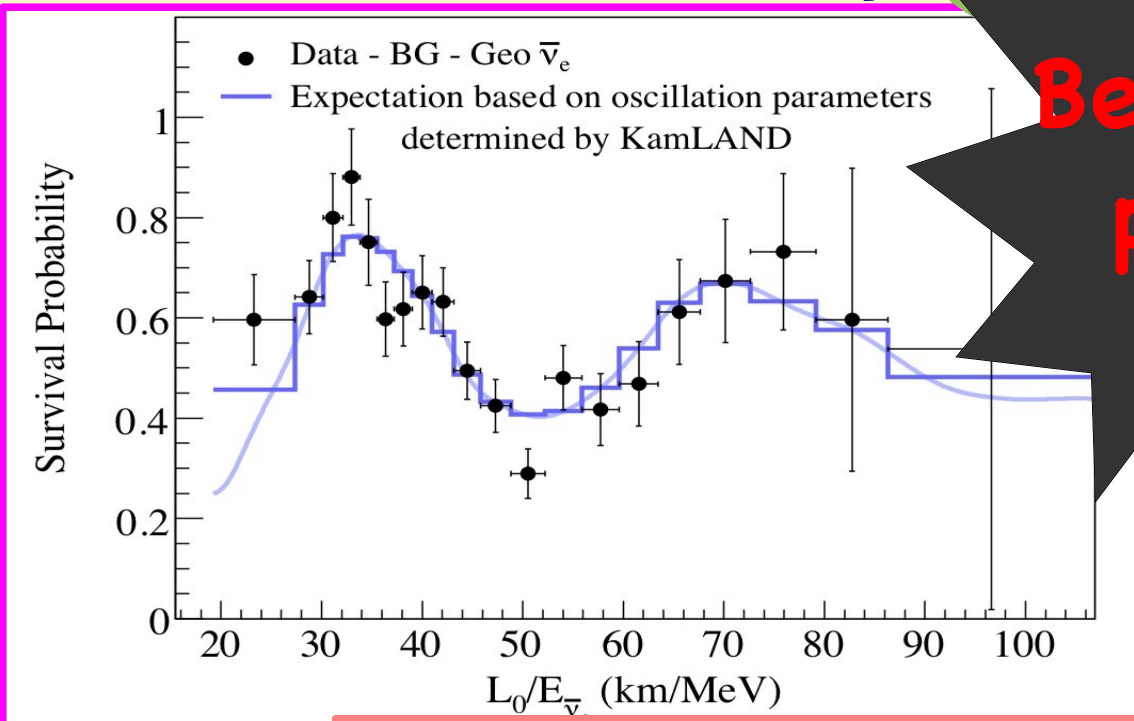
$$U=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

solar

1st Beyond SM physics!

…ome combinations of L, E, Δm_{ij}^2, mixing between 2 states dominates other mixings.



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \, \sin^2[1.27\Delta m^2 L/E_\nu]$$

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Neutrinos - known and unknown

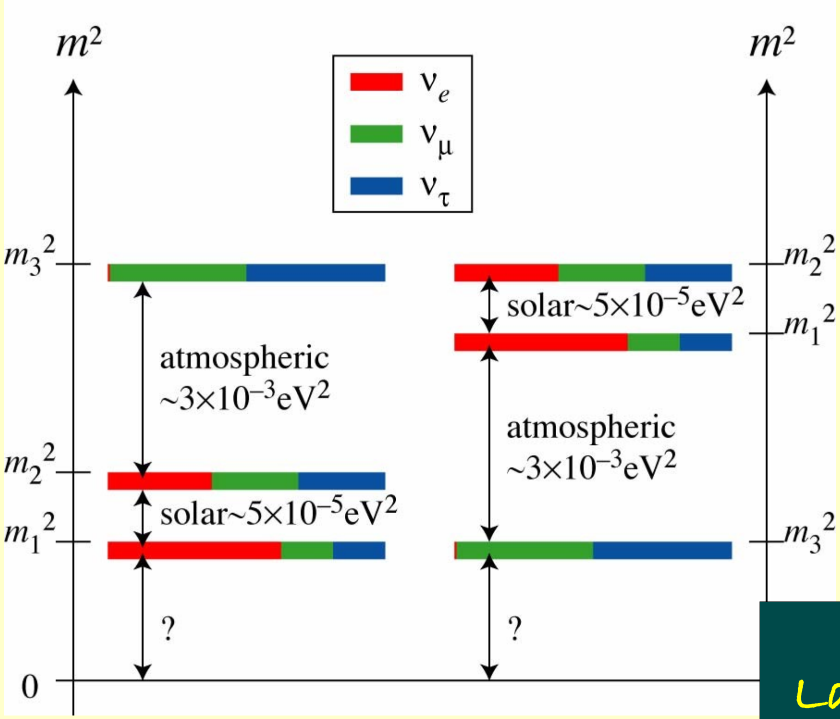
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \sim \begin{pmatrix} 0.8 & 0.5 & s_{13} e^{-i\delta} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

We know:

- ν's have mass.
- ν's change flavour.
- Flavour change is consistent with oscillation.
- $\theta_{12} \sim 35^\circ$.
- $\theta_{23} \sim 37\text{–}53^\circ$.
- $\theta_{13} < 12^\circ$.
- Δm^2_{23}, Δm^2_{12}.

We don't know:

(1) Value of θ_{13}.
(2) Sign of the mass ordering.
(3) Deviation of θ_{23} from maximal.
(4) Value of δ.
(5) Number of ν types.
(6) Majorana or Dirac?
(7) Absolute ν masses.



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We know:

- ν's have mass.
- ν's change flavour.
- Flavour change is consistent with oscillation.
- θ_{12} ~ 35°.
- θ_{23} ~ 37–53°.
- θ_{13} < 12°.
- Δm^2_{23}, Δm^2_{12}.

Measure me!

We don't know:

(1) Value of θ_{13}.

(2) Sign of the mass ordering.

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(5) Number of ν types.

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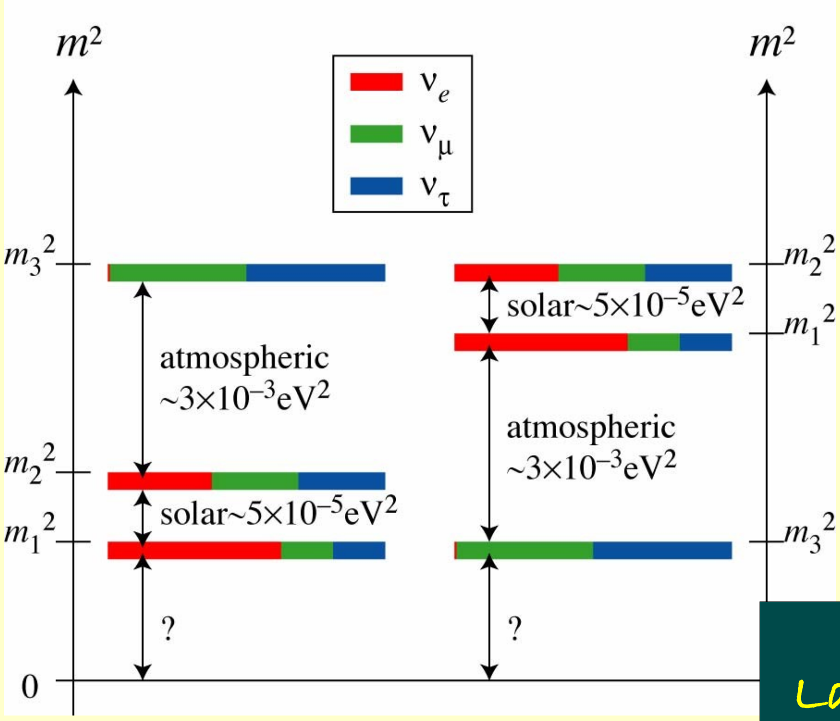

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Neutrinos - known and unknown

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} \sim \begin{pmatrix}0.8 & 0.5 & s_{13}e^{-i\delta}\\ 0.4 & 0.6 & 0.7\\ 0.4 & 0.6 & 0.7\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Measure me!

We don't know:

Long- and short-baseline expts:

(1) Value of θ_{13}.

(2) Sign of the mass ordering.

(3) Deviation of θ_{23} from maximal.

(4) Value of δ.

MiniBooNE:

(5) Number of ν types.

$0\nu\beta\beta$ expts:

(6) Majorana or Dirac?

(7) Absolute ν masses. → Tritium decay expts

We know:

- ν's have mass.
- ν's change flavour.
- Flavour change is consistent with oscillation.
- θ_{12} ~ 35°.
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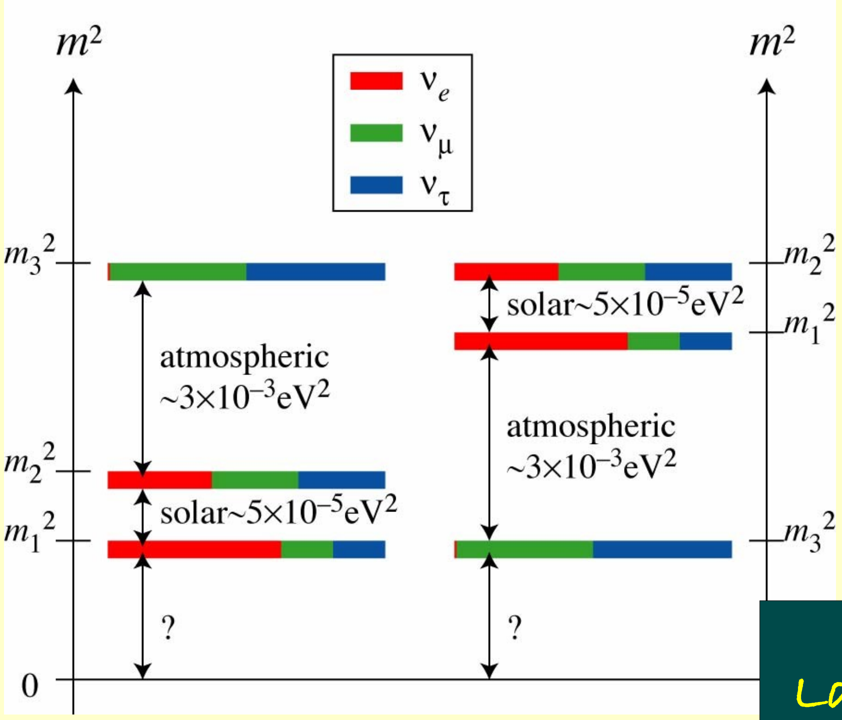
- θ_{13} < 12°.
- Δm^2_{23}, Δm^2_{12}.



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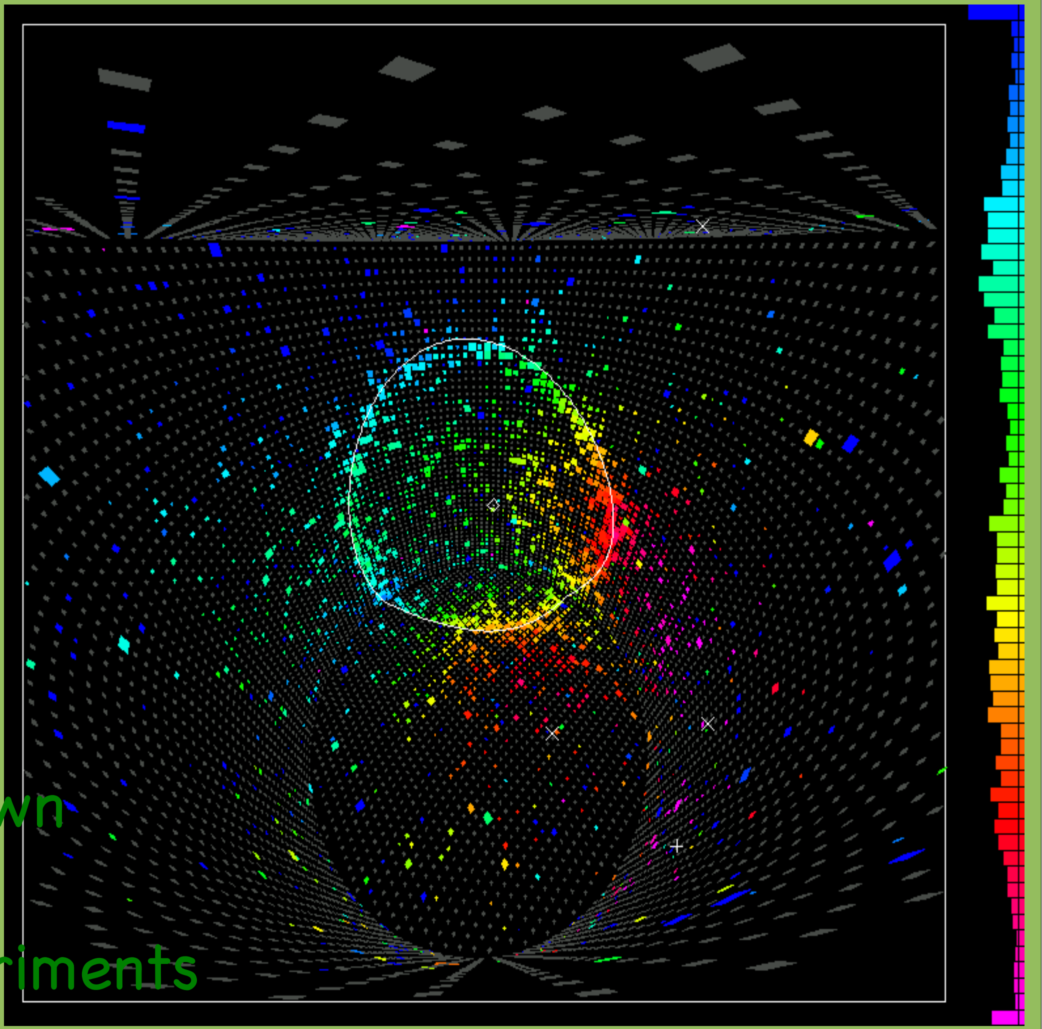
ν are produced by:

- the sun,
- cosmic rays in the atmosphere,
- or we make them ourselves in
  - reactors,
  - dedicated beams.



A muon in Super Kamiokande

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Solar/Atmospheric	Short-baseline/ reactor	Long-baseline/ accelerator
θ_{12}/θ_{23}	θ_{23}, θ_{13}	θ_{23}, θ_{13}, MSW effects, δ
SNO (ended 2006) Borexino Super Kamiokande	Chooz (ended 1998) KamLAND DoubleChooz Daya Bay Reno	K2K (ended 2005) MINOS MiniBooNE Icarus and Opera T2K Nova

Not an exhaustive list!

Short-baseline/ reactor

$\theta_{23,}\theta_{13}$

Chooz (ended 1998)

KamLAND

DoubleChooz

Daya Bay

Reno

Long-baseline/ accelerator

$\theta_{23,}\theta_{13}$,

MSW effects, δ

K2K (ended 2005)

MINOS

MiniBooNE

Icarus and Opera

T2K

Nova

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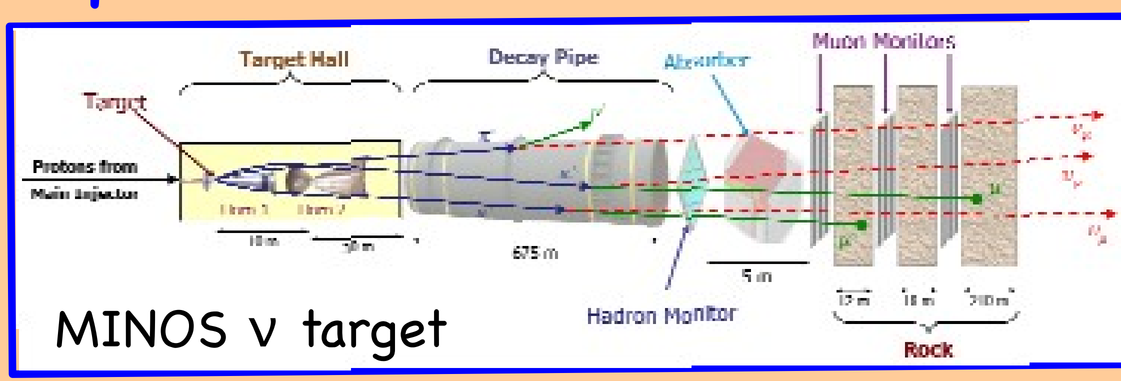

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Short-baseline/ reactor

$\theta_{23,} \theta_{13}$

Chooz (ended 1998)
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Long-baseline/ accelerator

$\theta_{23,} \theta_{13},$
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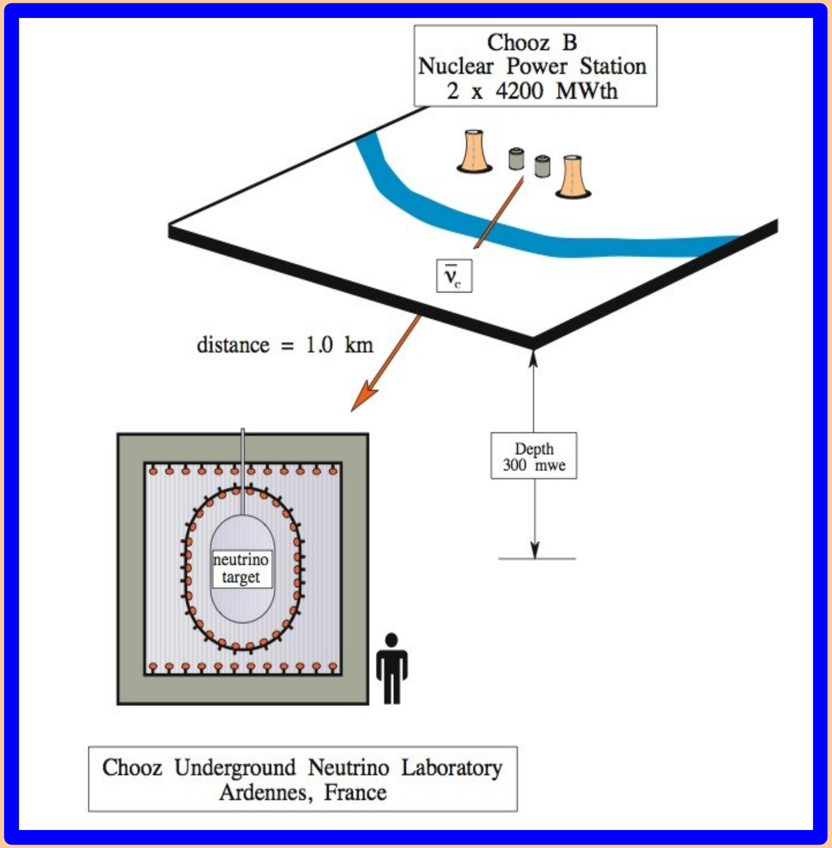
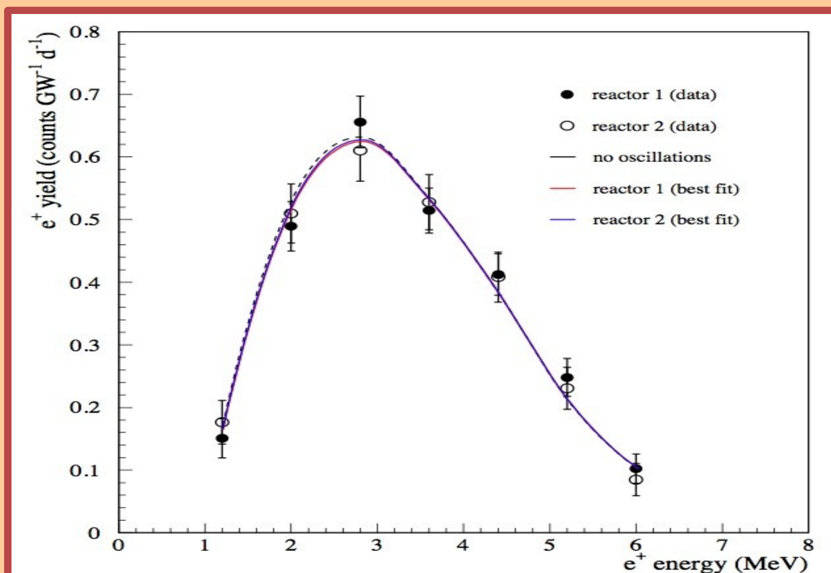


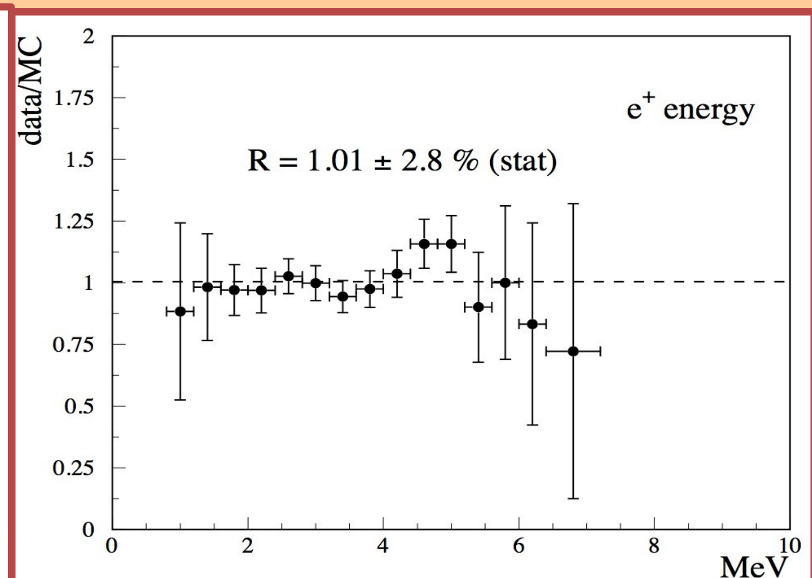
Chooz: Reactor anti-ν_e

Looking for anti-ν_e disappearance.

- Detected via $\bar{\nu}_e + p \rightarrow e^+ + n$
- Baseline: 1.0 and 1.1 km
- Target: 5 ton 0.09% Gd in LS
- Data: Apr '97 - Jul '98

No evidence of disappearance but best limit to date on θ_{13}.





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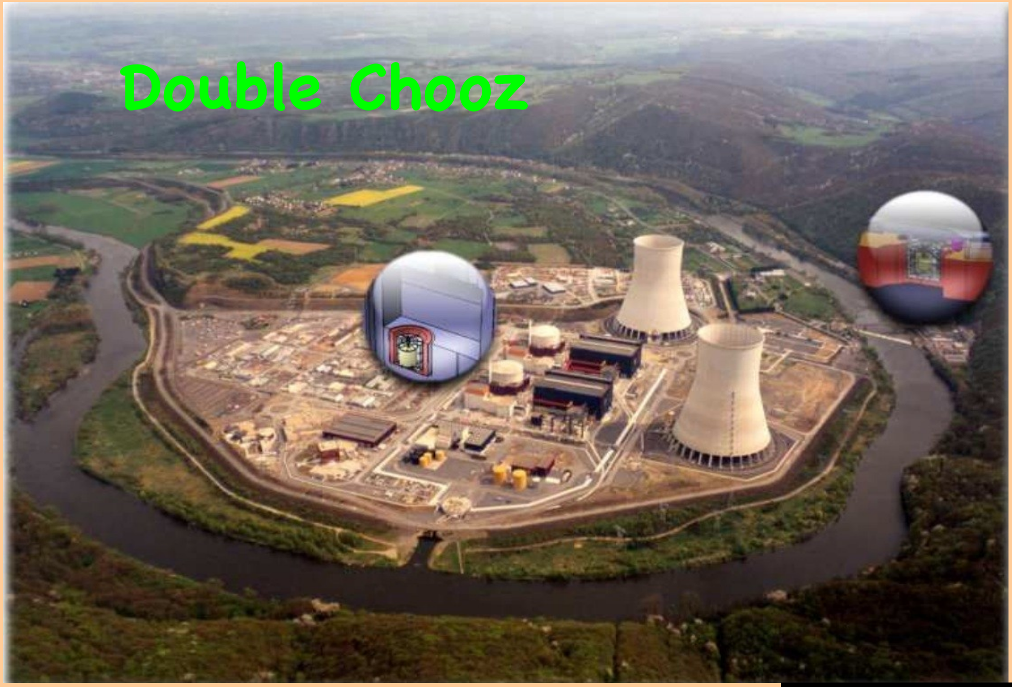
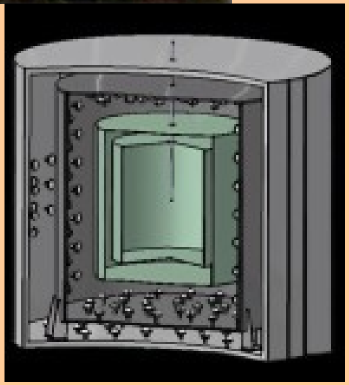
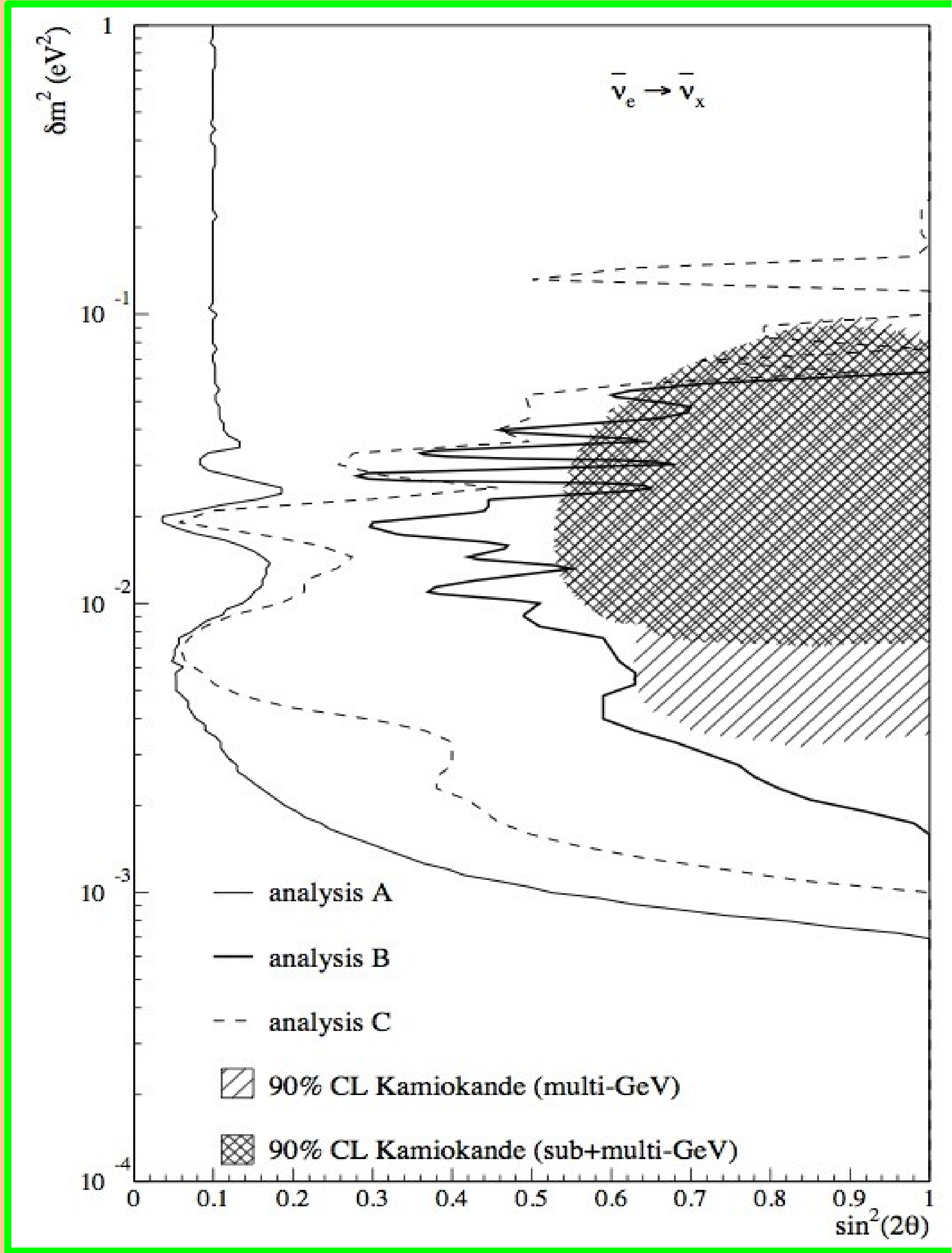
Chooz: $\sin^2 2\theta_{13} < 0.10$ ($\theta < 9.2^o$)







Double Chooz

- 2 identical detectors
- Near: 400m; Far: 1.05 km

Expected limits:

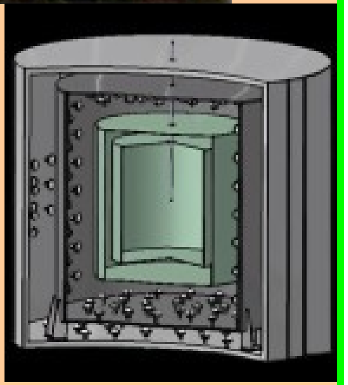
Phase 1 2010

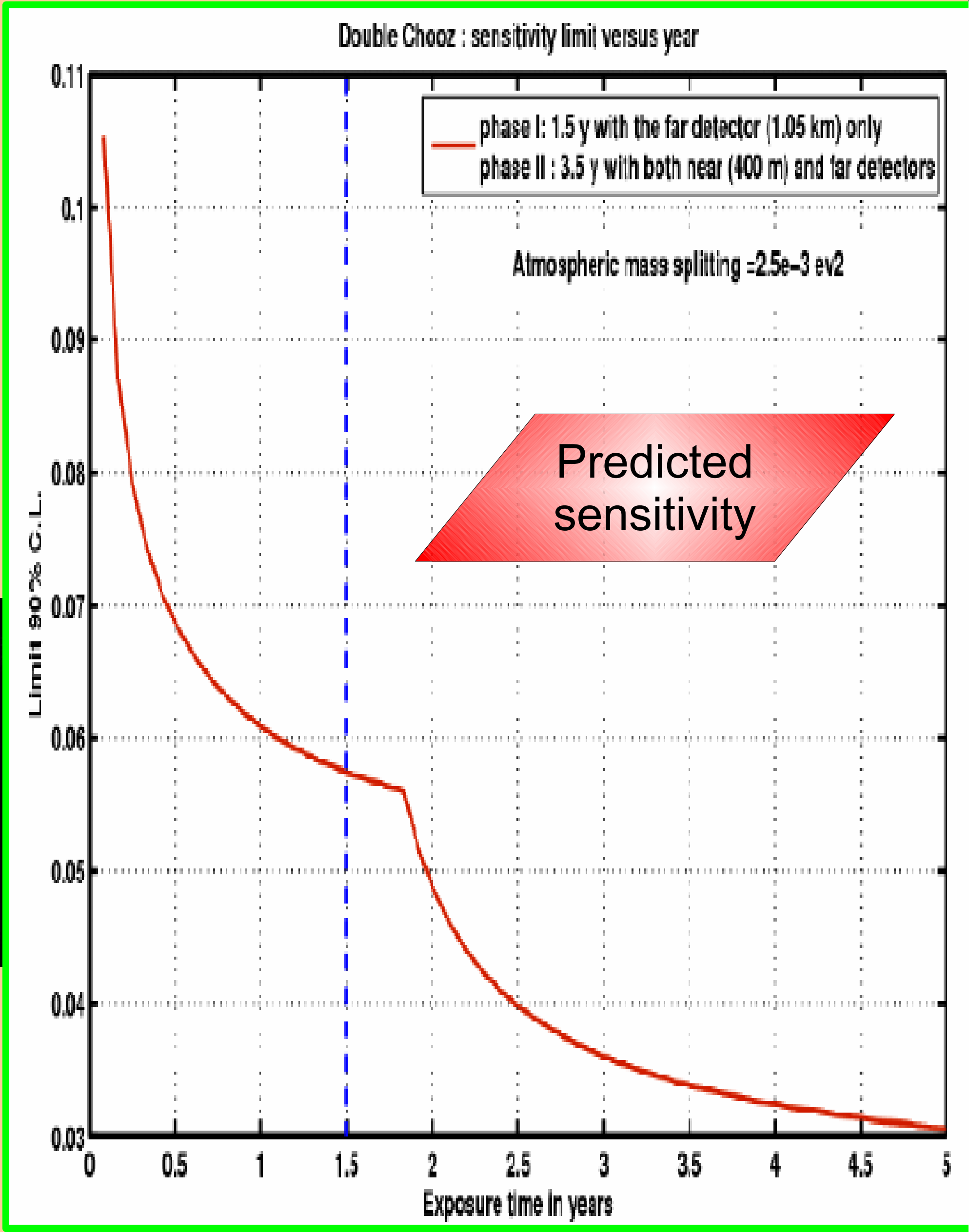
FD 1.5 yrs $\sin^2 2\theta_{13} < 0.08$.

Phase 2 2012

ND+FD, 3 yrs $\sin^2 2\theta_{13} < 0.03$.

DoubleChooz: $\sin^2 2\theta_{13} < 0.03$





Double Chooz

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Phase 1 2010

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ND+FD, 3 yrs $\sin^2 2\theta_{13} < 0.03$.

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MINOS: Accelerator ν_μ. Looking for ν_e appearance, ν_μ disappearance, sterile ν

Detect $\nu_e + Fe \rightarrow e + X$ (CC)

- NuMI beam from FNAL
- Baseline: 735 km
- Far detector in Soudan Mine
- Near detector at 1 km.

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MINOS detectors

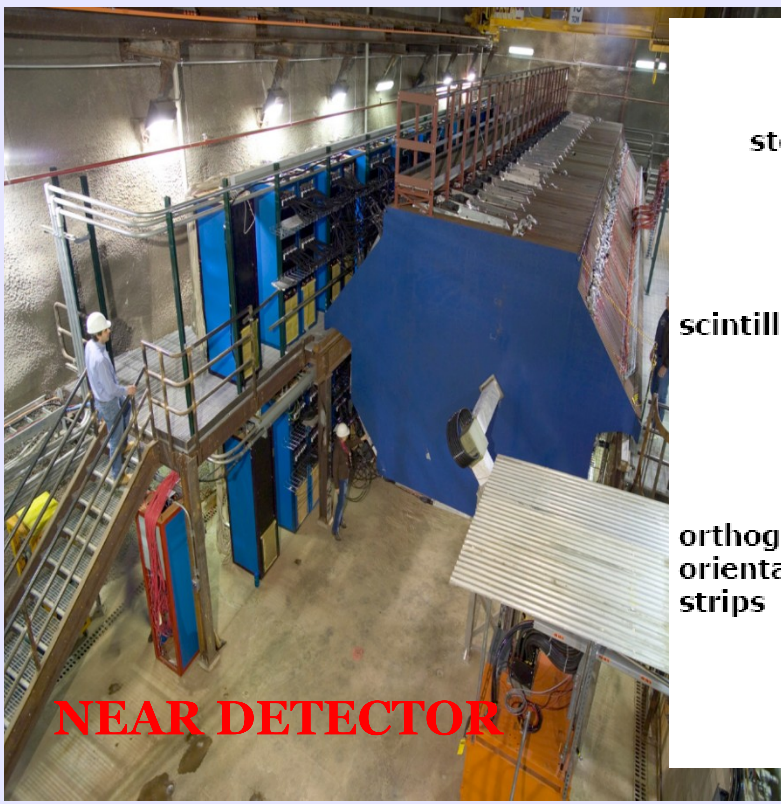
Steel/scintillator sampling calorimeters, magnetised ~1.3T

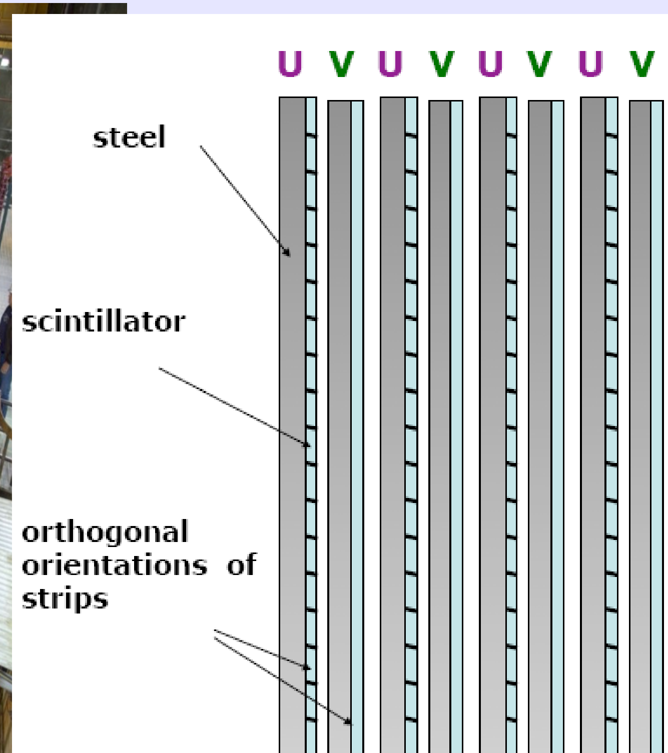
Near Detector:

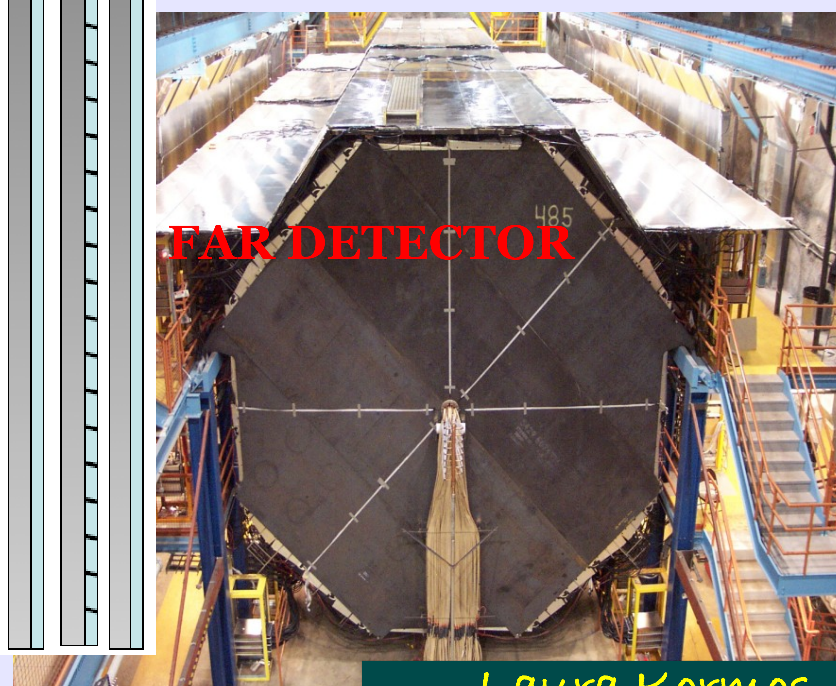
1km downstream of target, ~1kT total mass, shaped as squashed octagon $4.8x3.8x15m^3$, partially instrumented (282 steel, 153 scintillator planes)

Far Detector:

735km downstream of target, 5.4kT with 2 supermodules shaped as octagonal prism $8x8x30m^3$, 486 steel, 484 scintillator planes)







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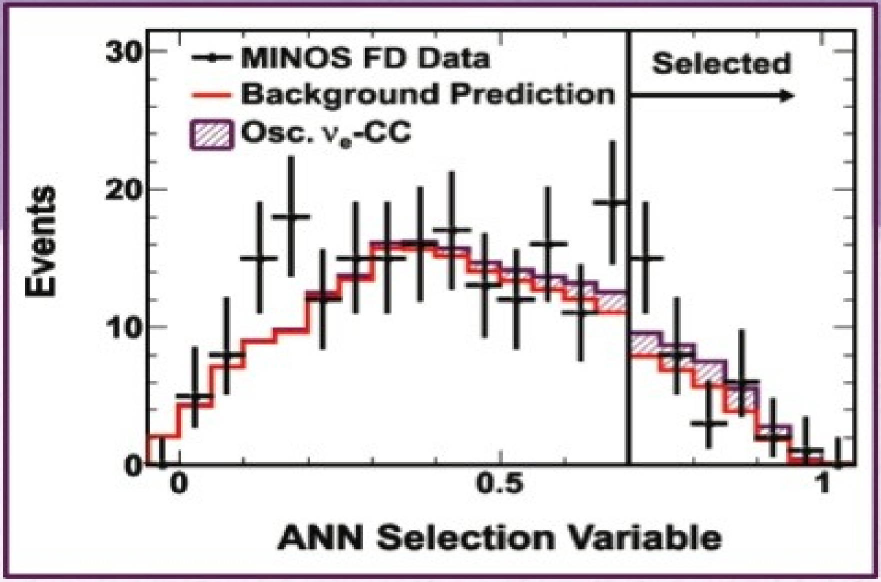
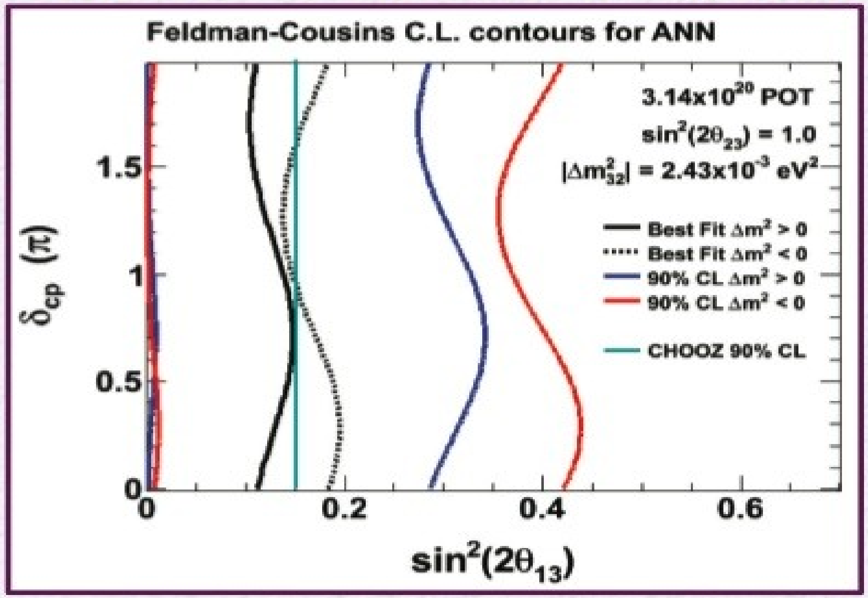
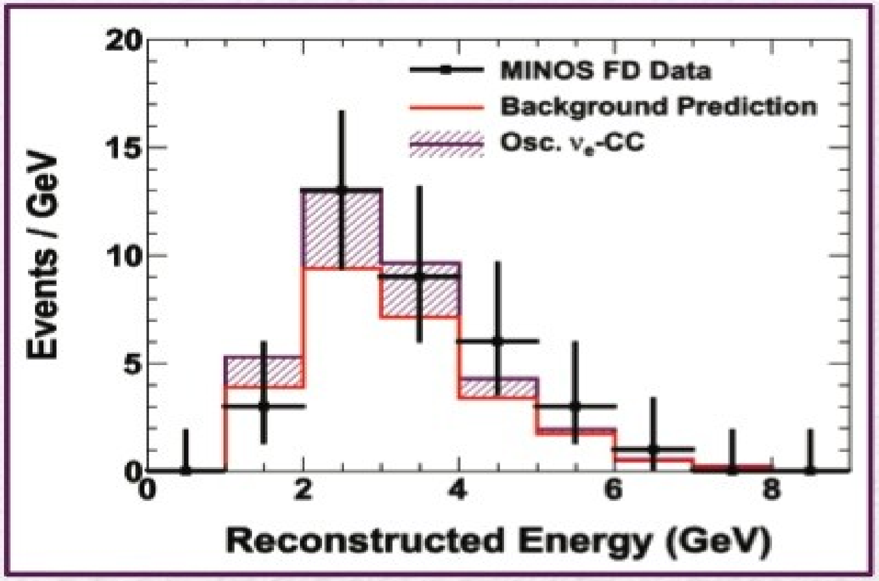
MINOS $\nu_\mu \rightarrow \nu_e$ Search



With an exposure of 3.14×10^{20} POT
BG Expectation: 27±5(stat.)±2(syst.) events
FD Observation: 35 events
1.5σ excess of events over background





Analysis with double the exposure, coming soon!

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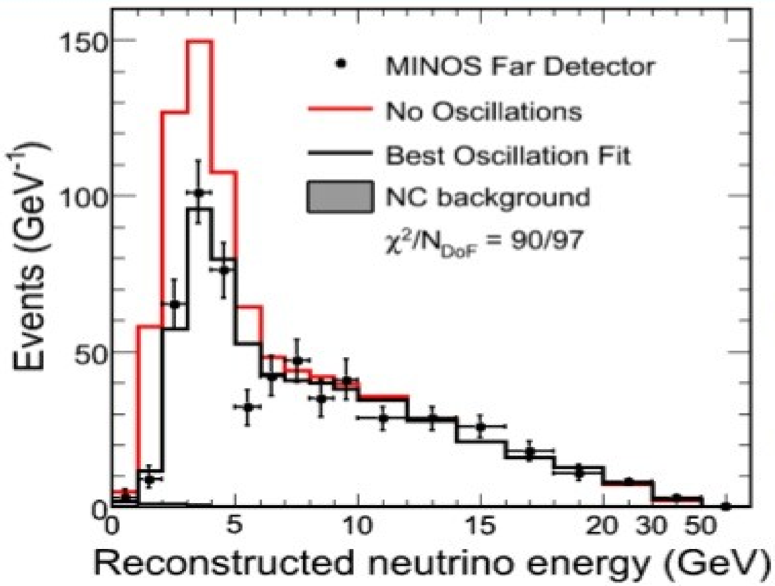
MINOS disappearance highlights



Unconstrained fit:

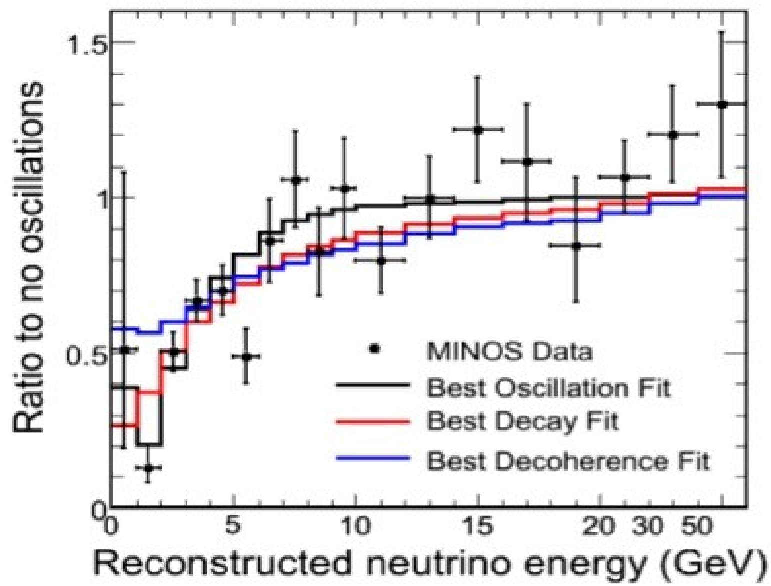
$|\Delta m|^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2

$\sin^2(2\theta) > 0.95$ [χ^2/ndof = 90/97, 68% C.L.]

Constrained ($\sin^2(2\theta)$=1.) fit:

$|\Delta m|^2 = 2.33 \times 10^{-3}$ eV^2

$\sin^2(2\theta)$=1.07 [$\Delta\chi^2$=-0.6]



Decay

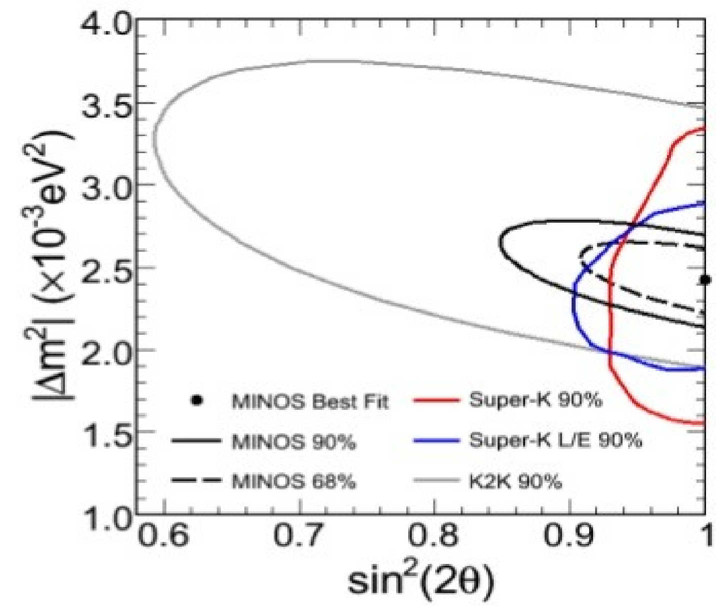
$\Delta\chi^2 = 14$

disfavored at 3.7σ

Decoherence

$\Delta\chi^2 = 33$

disfavored at 5.7σ



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MINOS search for active neutrino disappearance

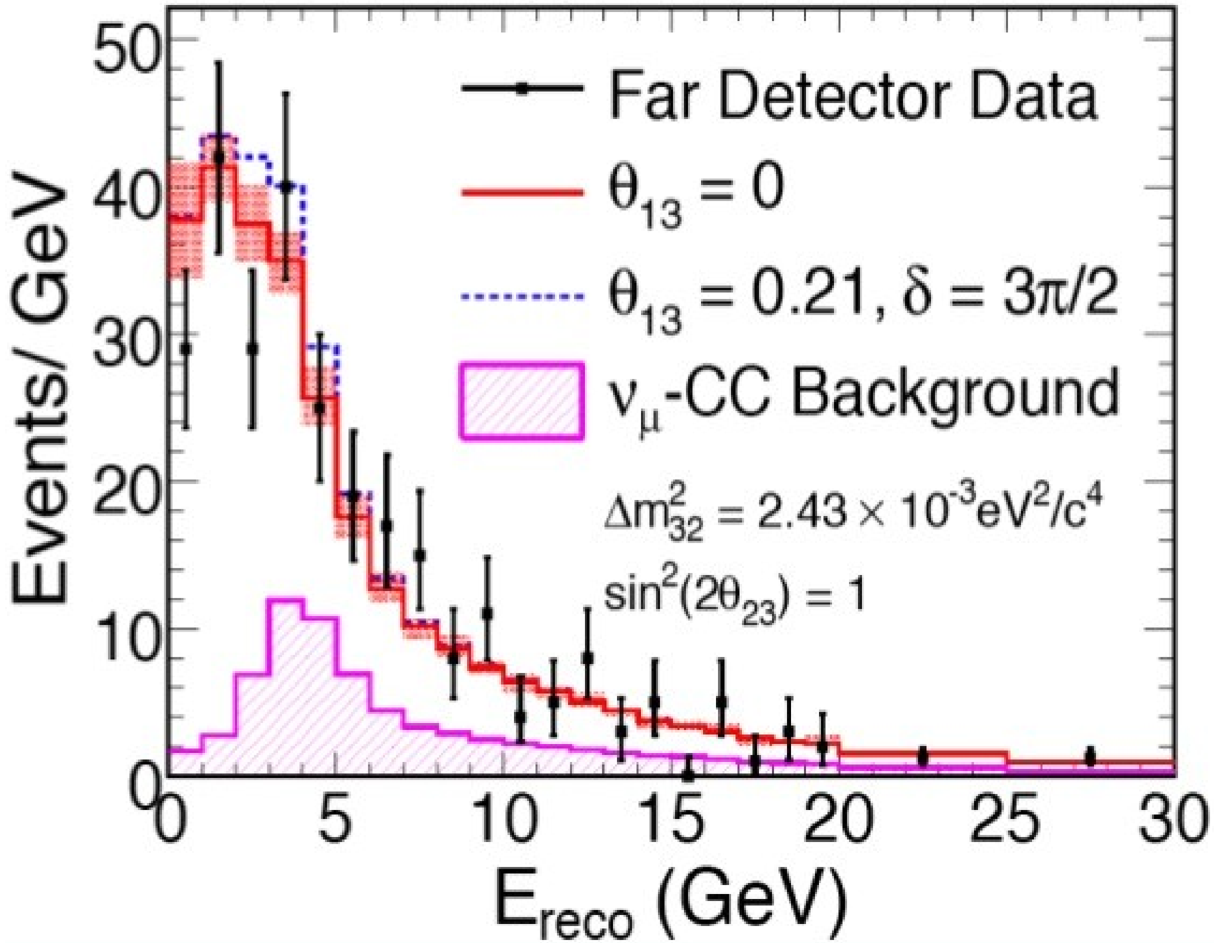
Z-decay width → 3 active ν flavours.

Sterile ν do not interact via weak force.

Sterile ν → deficit of NC events in MINOS.

f = fraction of disappearing ν_μ that could convert to ν_s.

PRL 101, 221804 (2008)



$$f_s \equiv \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.68 \text{ (90\% CL)}$$

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MINOS upcoming!

April 9th!

New ν_e result with 2x statistics.

2010

ν_{μ}, $\bar{\nu}_{\mu}$, sterile ν.

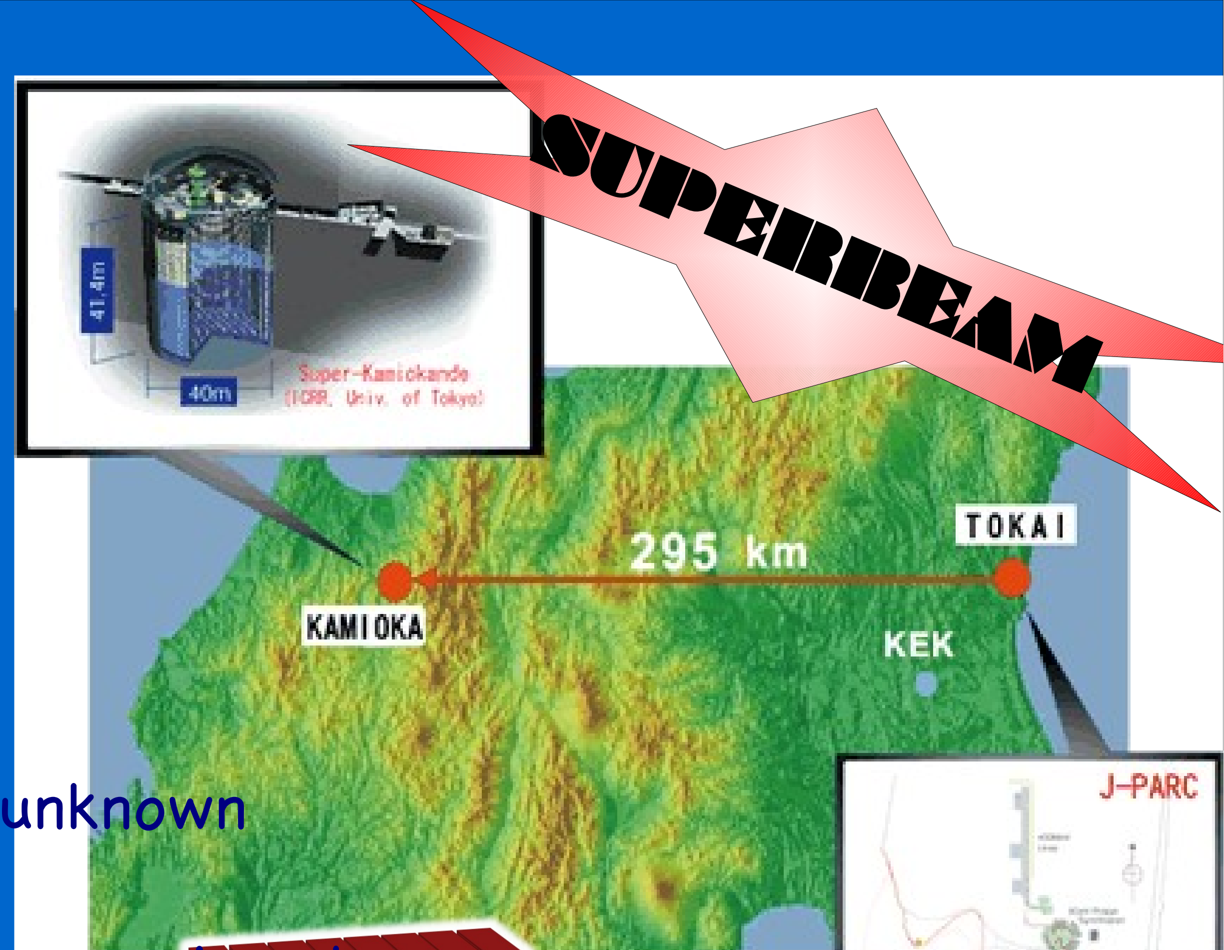
Just finished $\bar{\nu}_{\mu}$ run with 1.8×10^{20} POT.

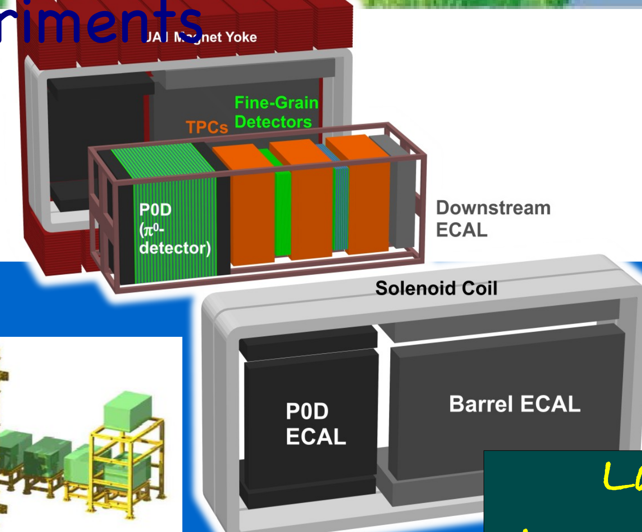
Switching back to ν_{μ}.

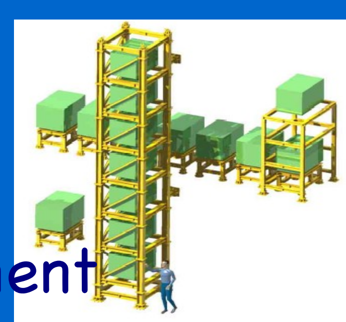
Plan to run until Oct 2011

T2K: Accelerator ν_μ.
Looking for ν_e appearance, ν_μ disappearance, δ

- 2 near detectors at 280 m
  - INGRID (on-axis)
  - ND280 (off-axis)
- Far detector at 295 km
  - SuperKamiokande







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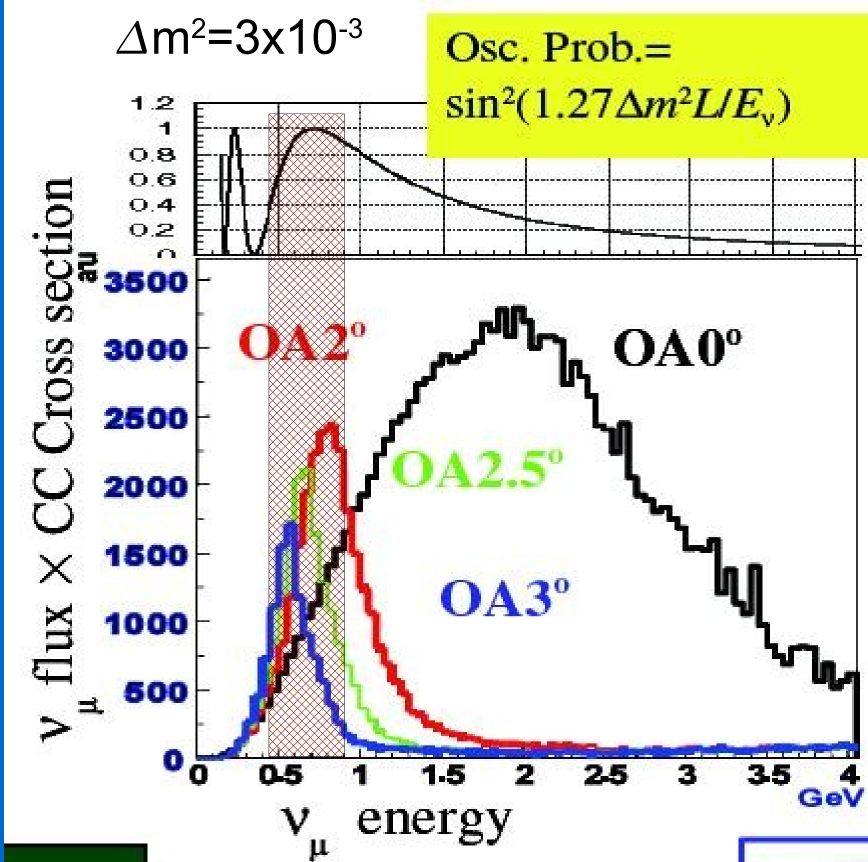
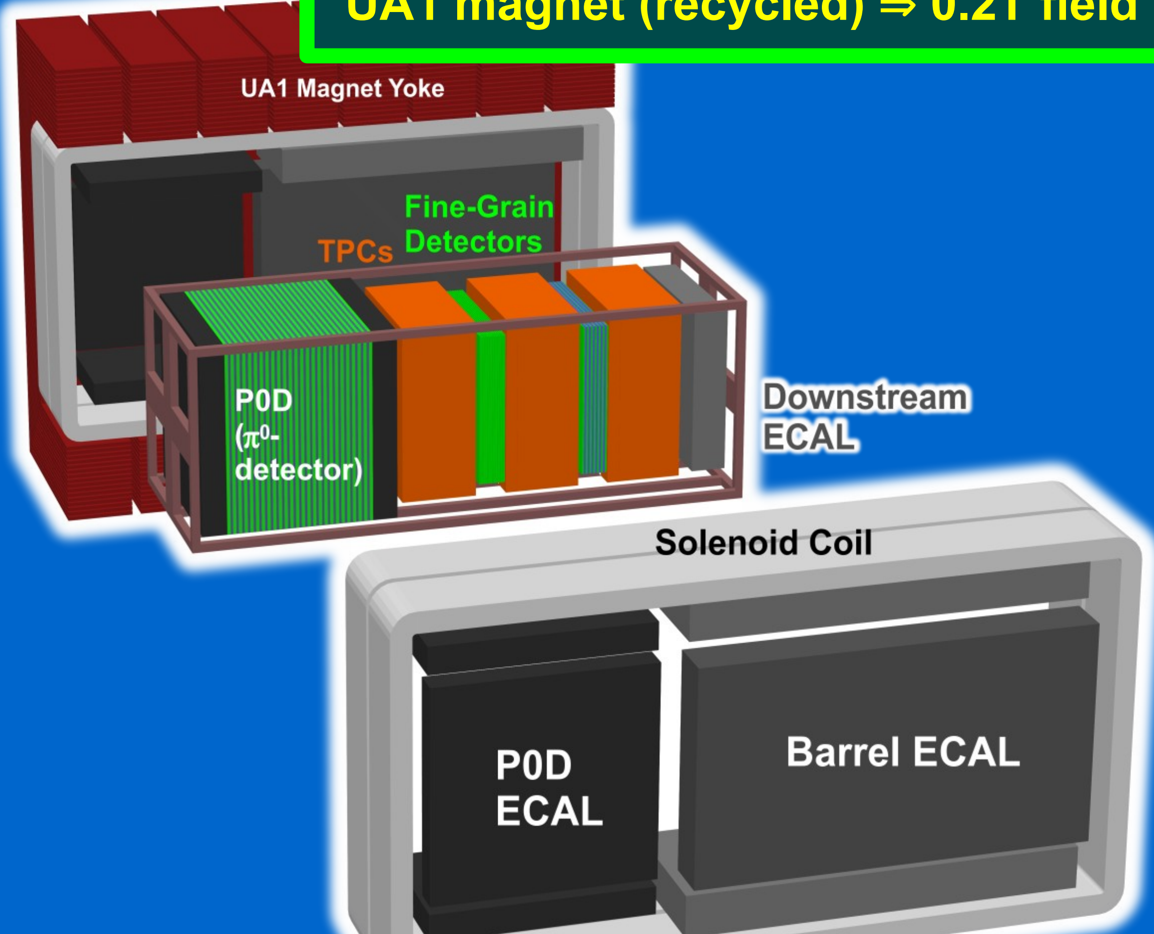
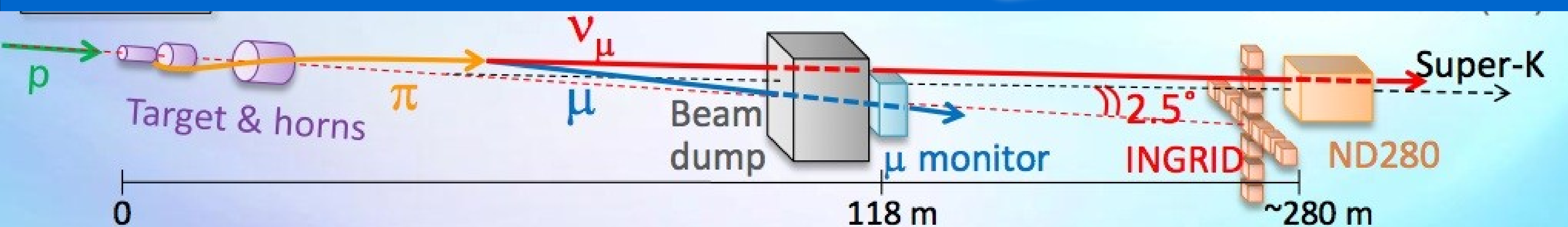


UA1 magnet (recycled) ⇒ 0.2T field



Off axis-beam ⇒ narrow band, just the ν we want.

Detect ν_μ + O,C → μ + X (CC)



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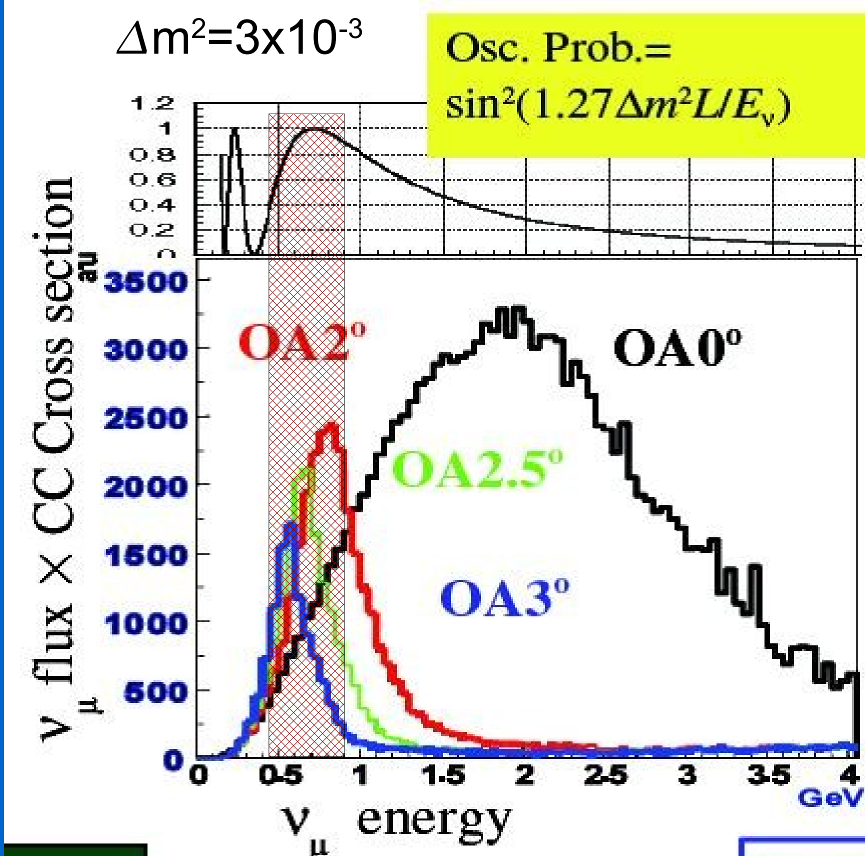

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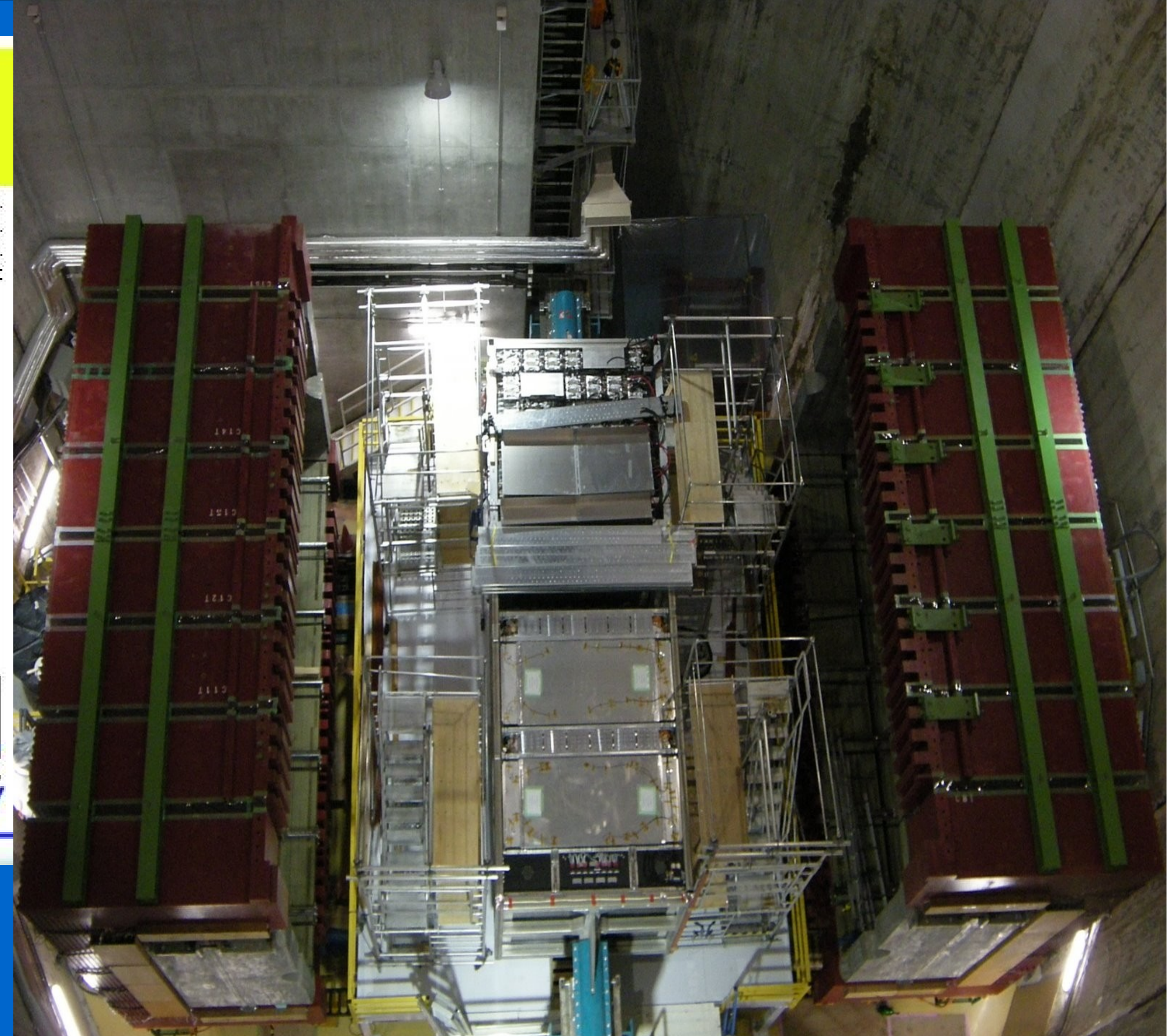

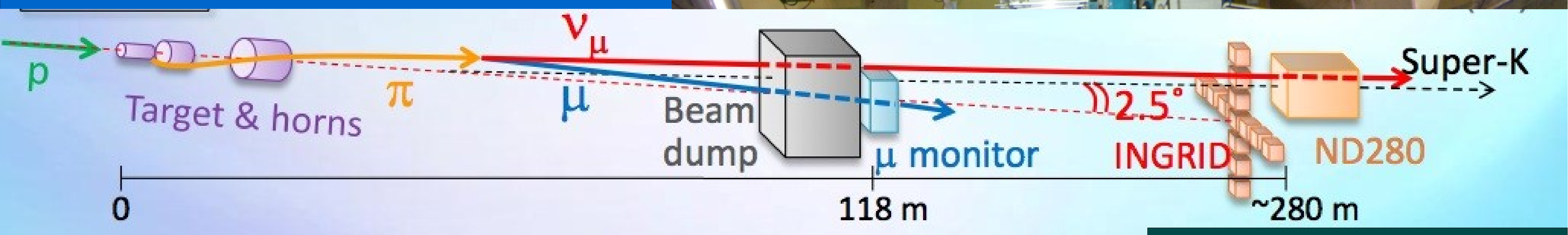

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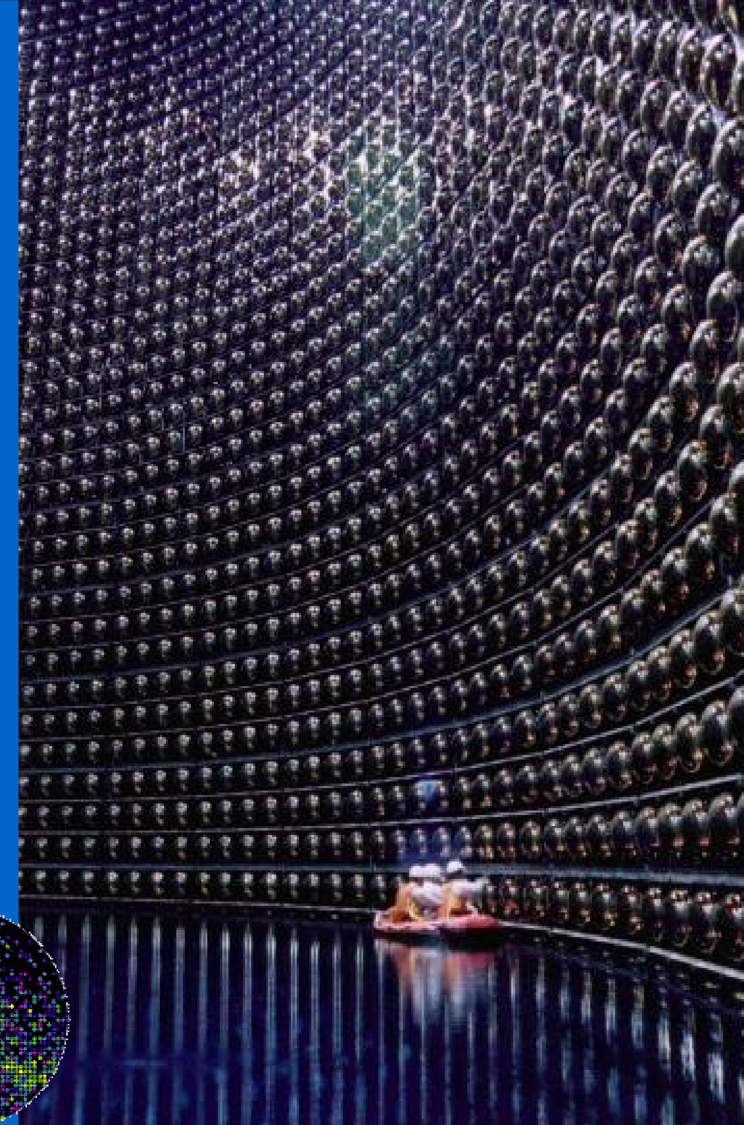
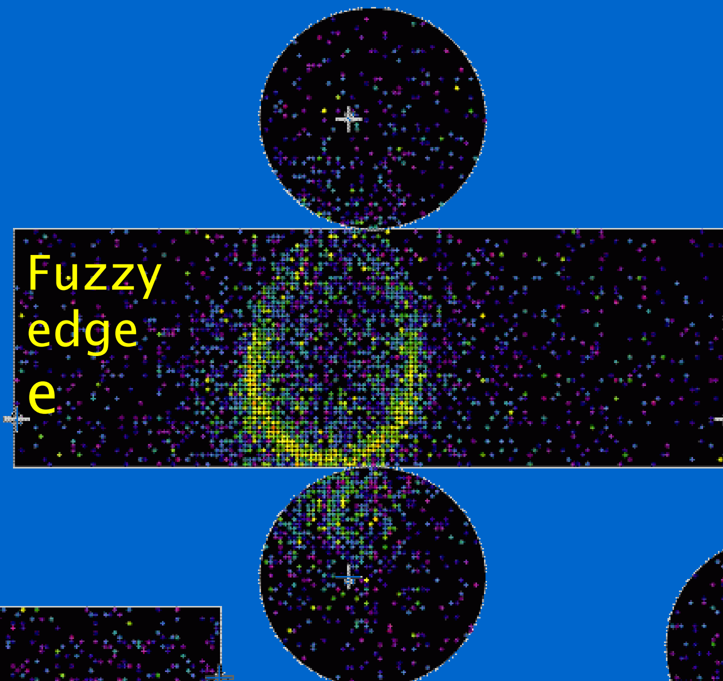
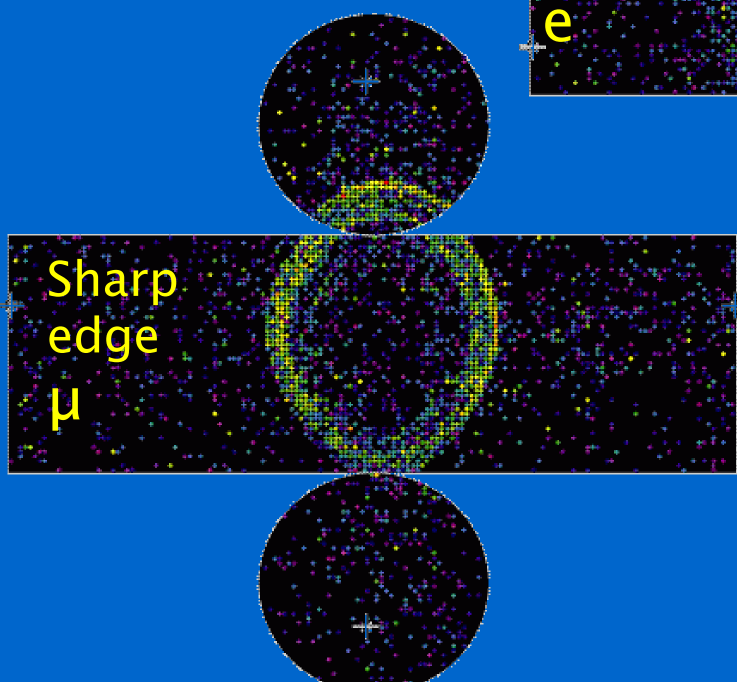
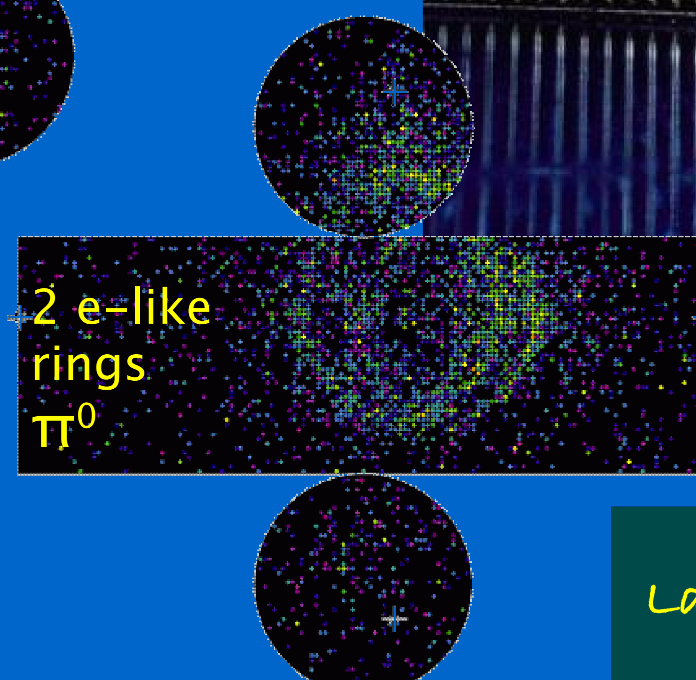
SK: 50,000 tons
water-Cherenkov
cylindrical detector
in the Kamioka mountains.









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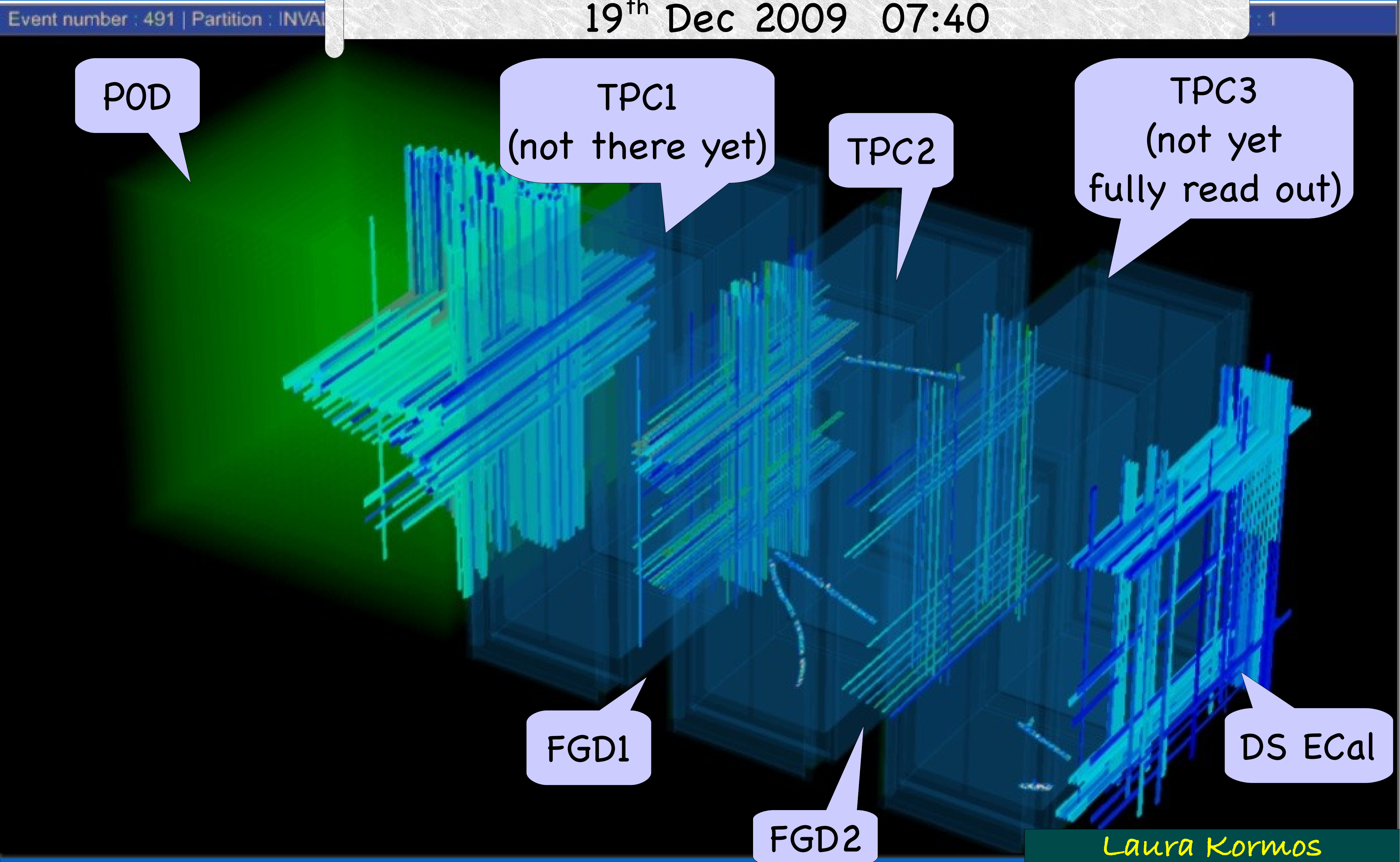
Lancaster University
IOP HEP 2010

First ND280 Neutrino Event

19th Dec 2009 07:40



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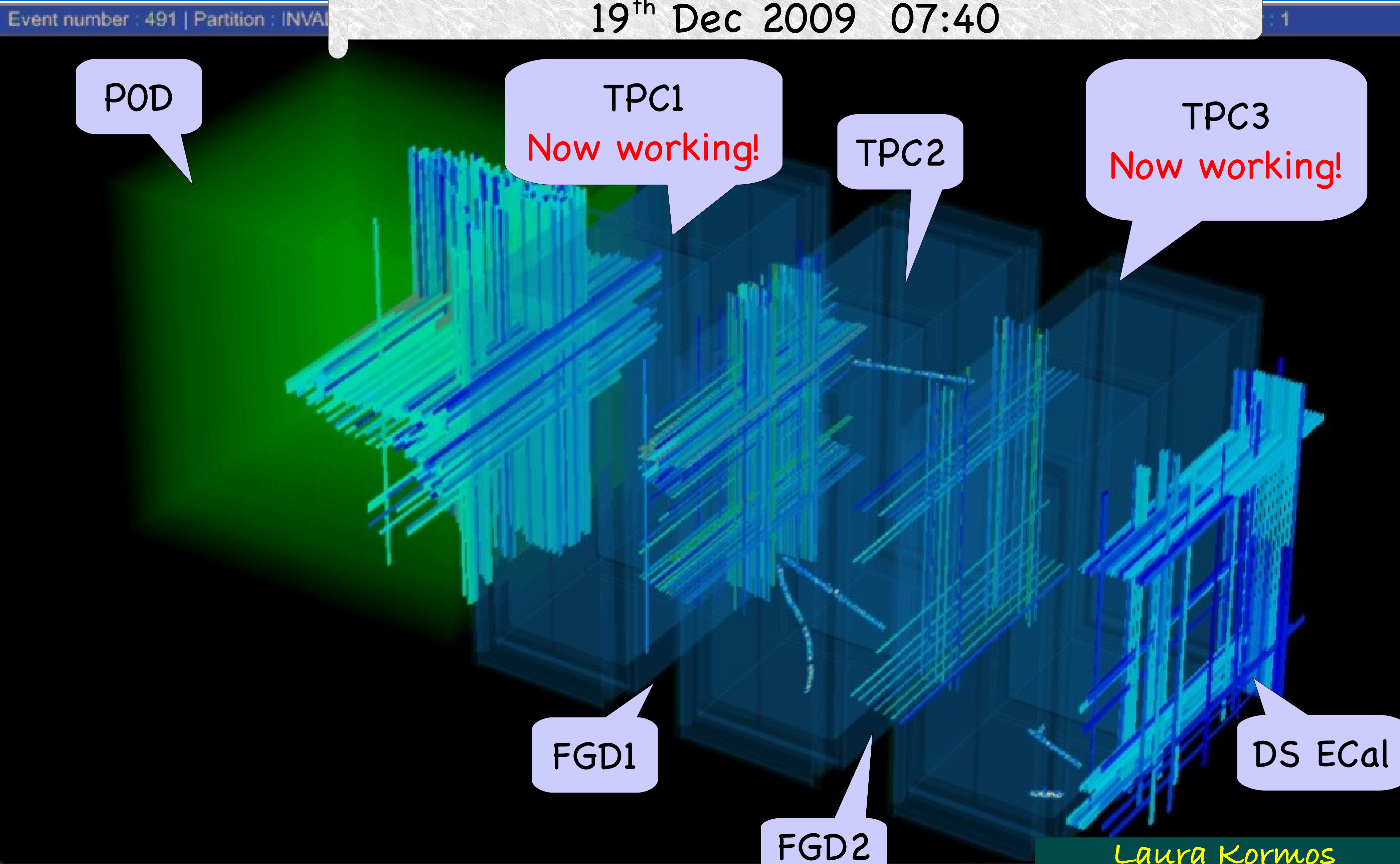

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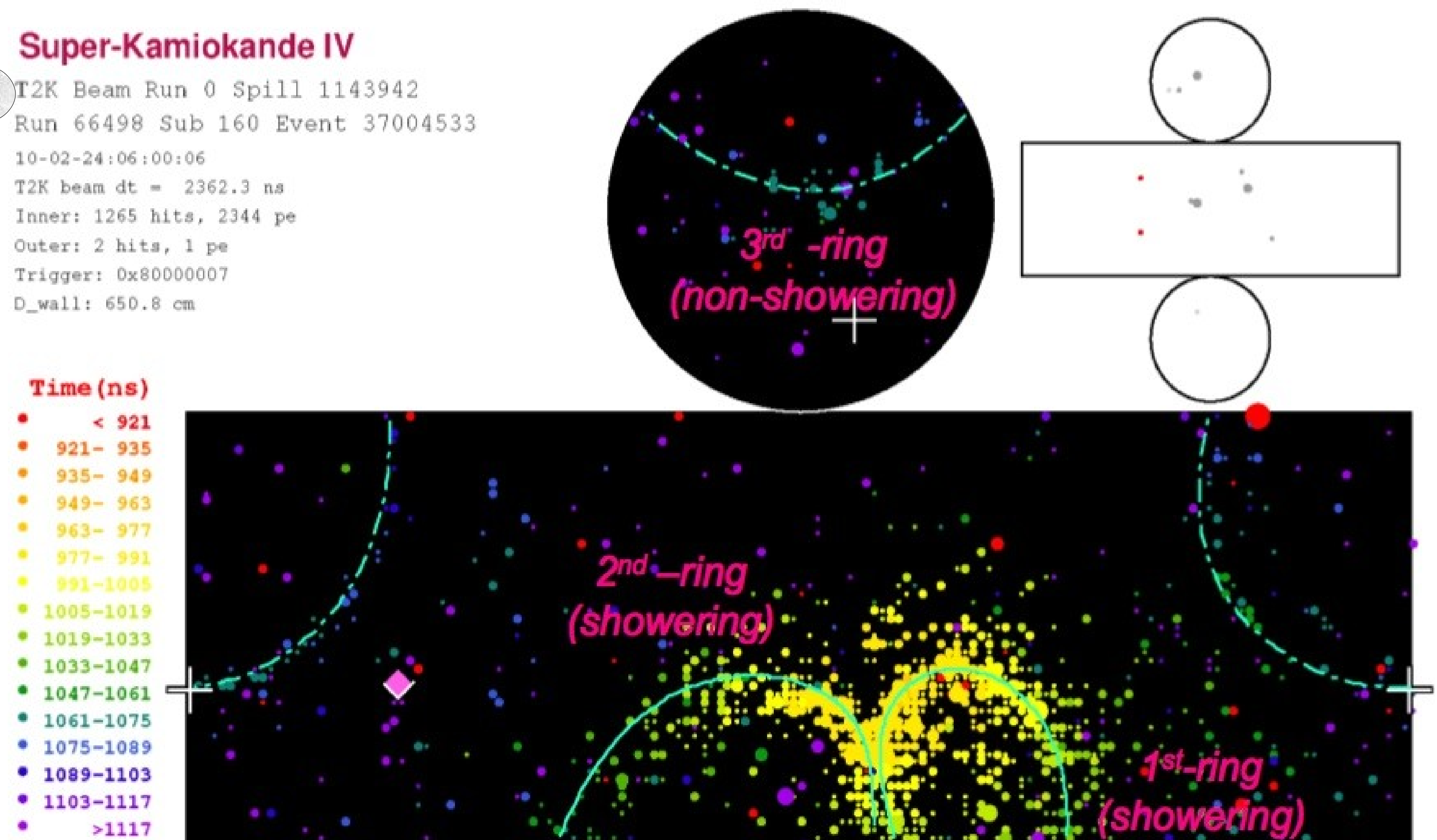
First T2K Event at SK

24th Feb 2010 06:00

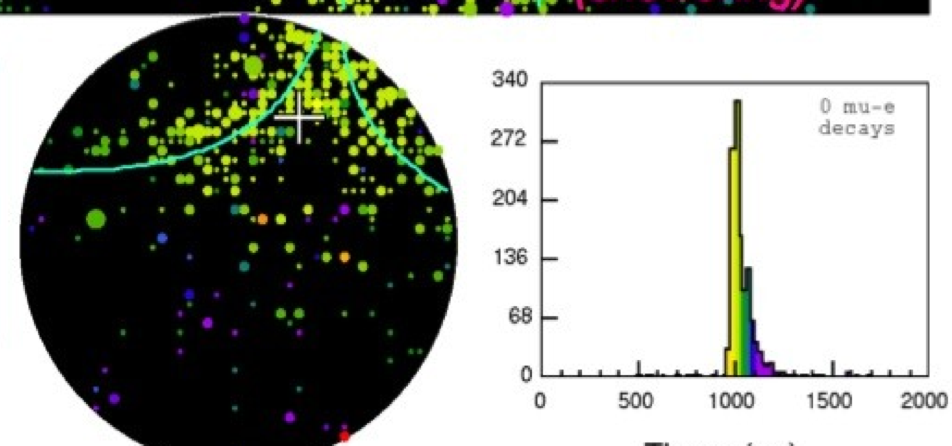


1st ring + 2nd ring

Invariant mass : 133 MeV/c²

(close to π^0 mass)

momentum : 148 MeV/c



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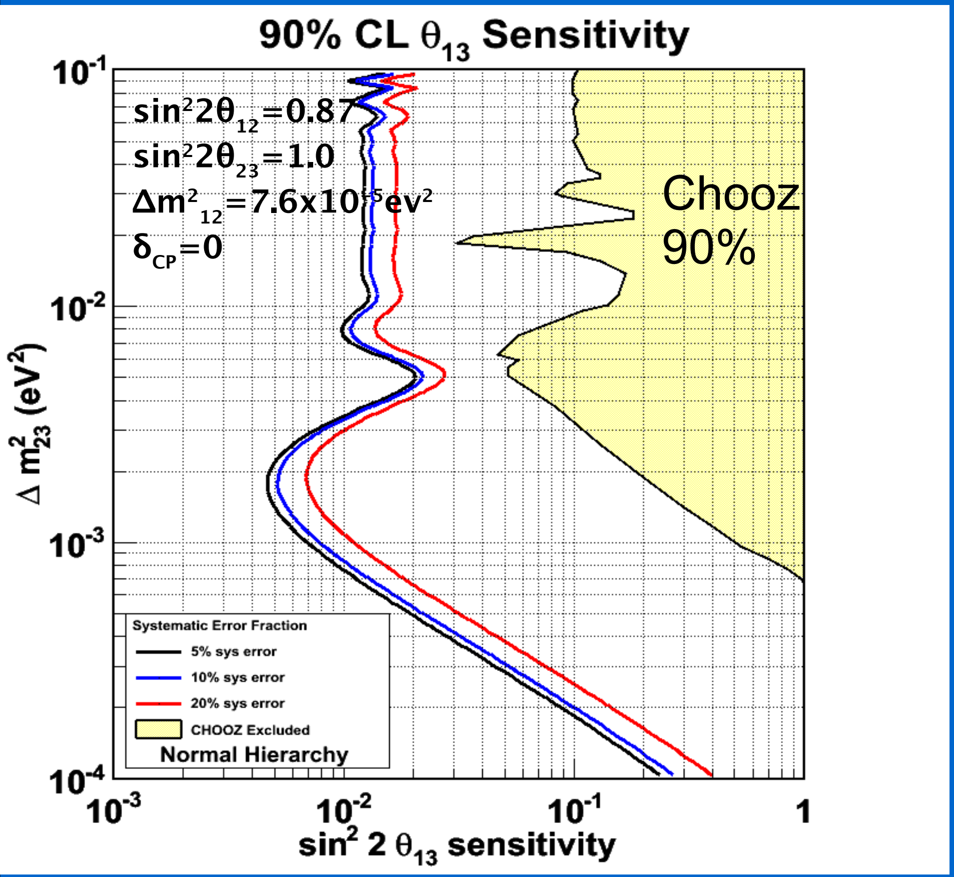
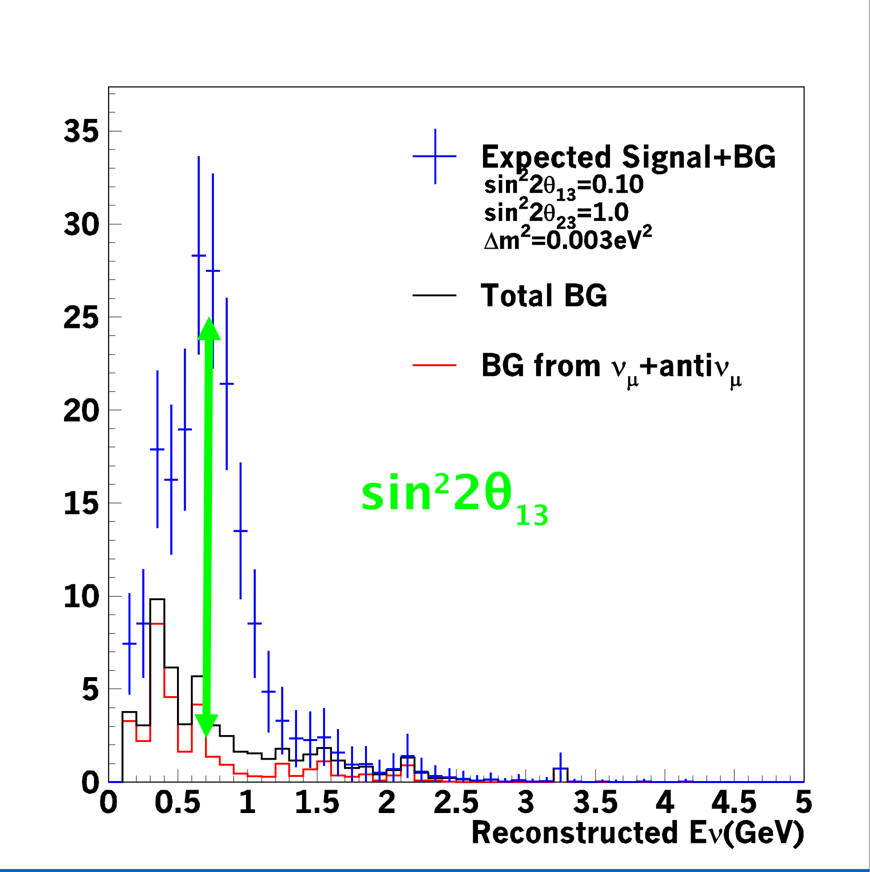
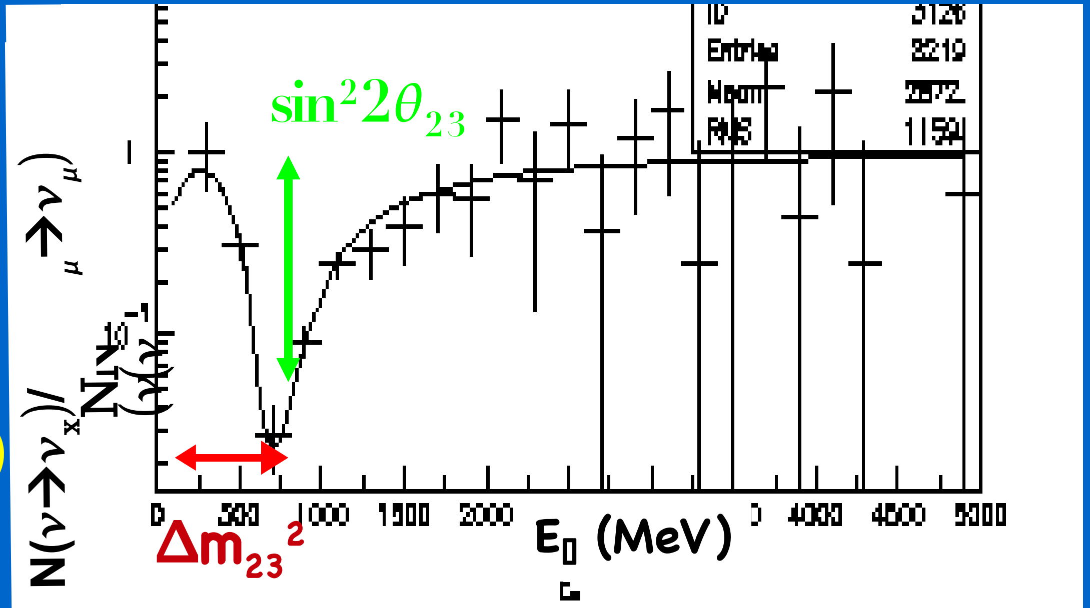
ν_e appearance





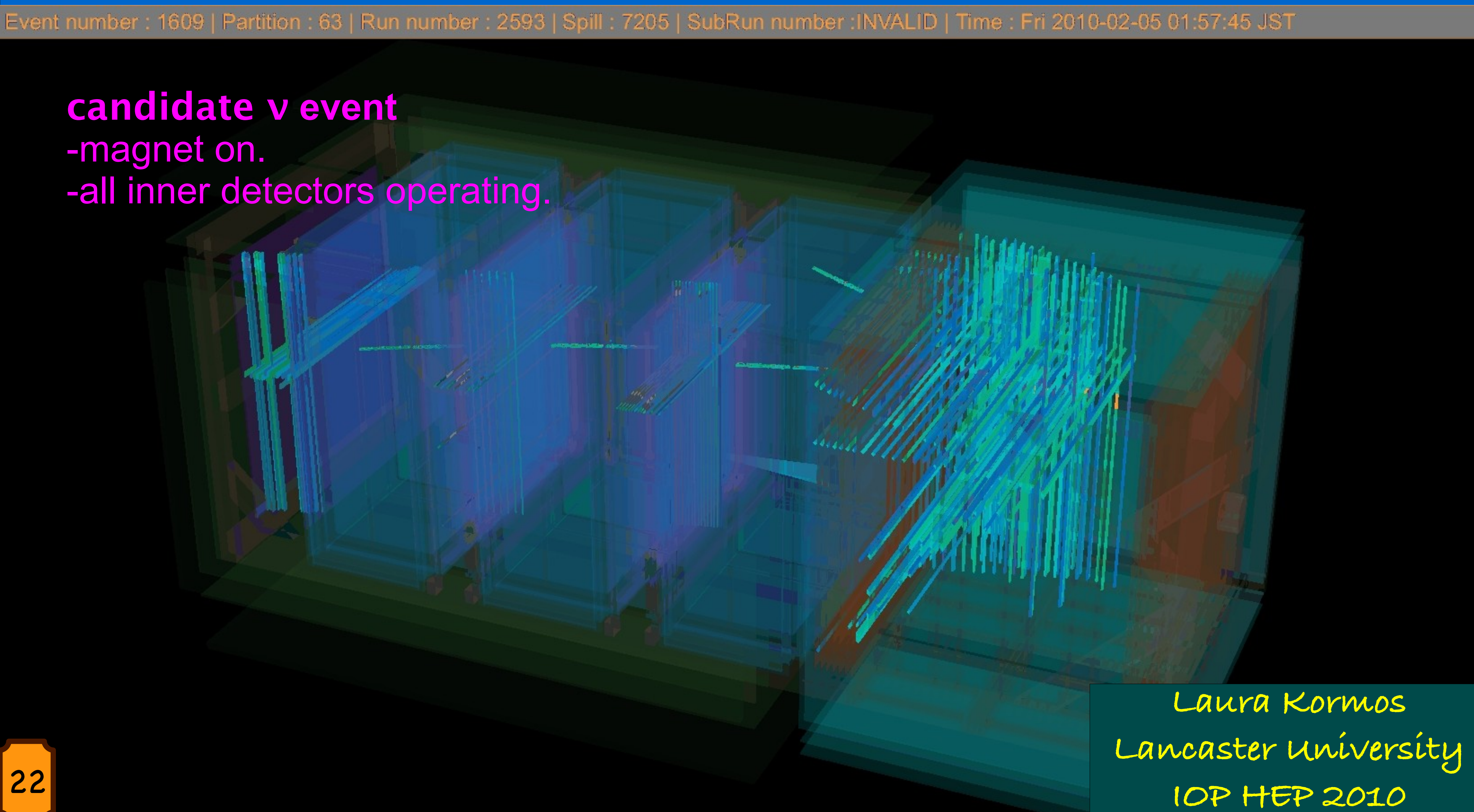
ν_μ disappearance



Predicted sensitivity to θ_{13} ($\nu_e$appearance) and θ_{23} (ν_μ disappearance) after 5 years (750 kW)of beam (end 2014)

Current status:

- taking ν data until summer shutdown (Jul-Sep).
- beam group working to improve intensity/stability.
- everyone working to develop/refine analyses.
- finishing initial detector calibrations.



candidate ν event
-magnet on.
-all inner detectors operating.

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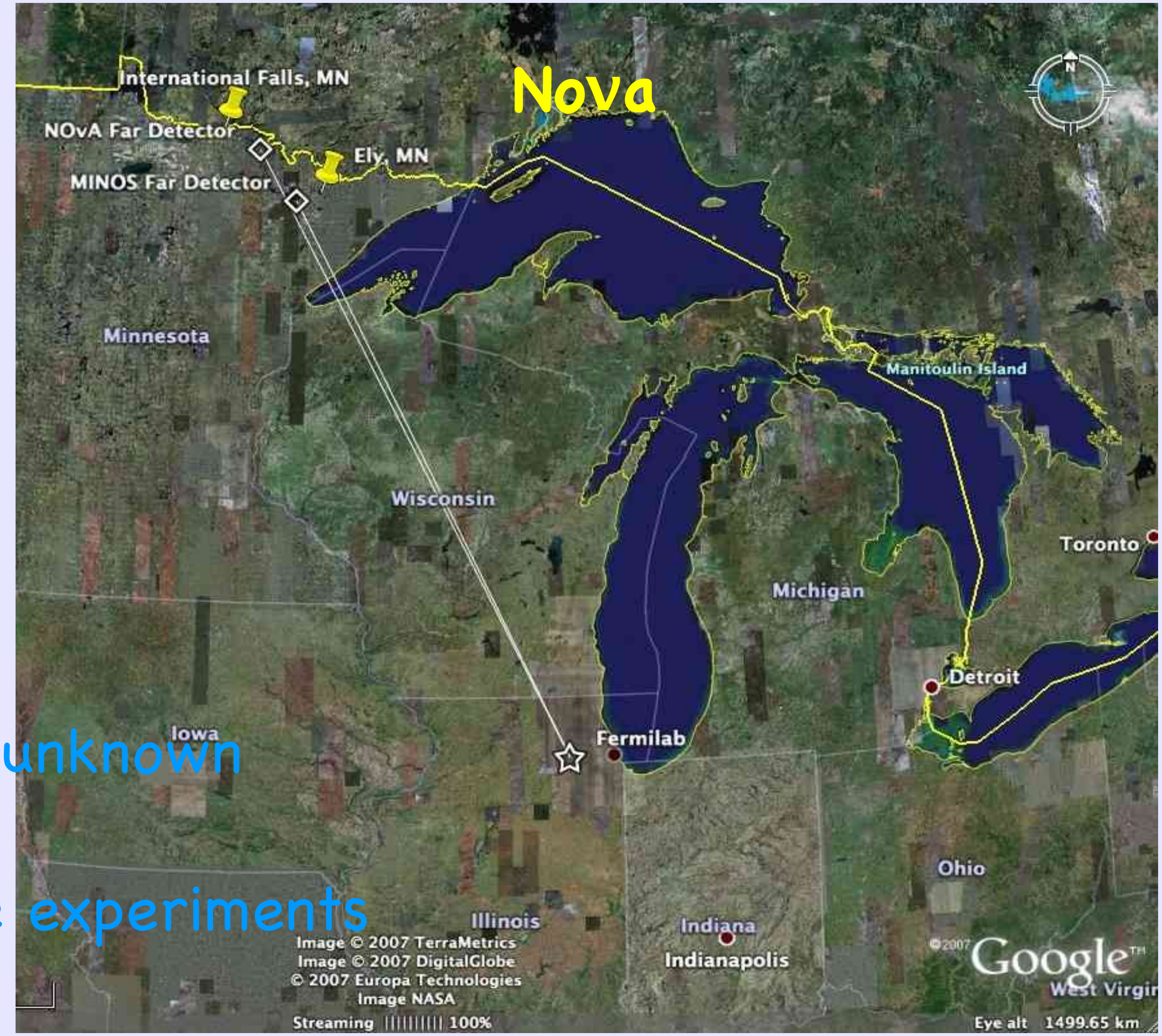
Nova: Accelerator ν_μ. Looking for ν_e appearance, ν_μ disappearance, δ, mass hierarchy.

Detect $\nu_\mu + N \rightarrow \mu + N'$ (CC)

- NuMI beam from FNAL
- Baseline: 810 km
  - off-axis 0.8°, 2 GeV



- Neutrinos - known and unknown
- Neutrino experiments
- Long and short baseline experiments
- Chooz/Double Chooz
- MINOS
- T2K
- **Nova**
- Daya Bay
- Future frontiers
- The Next Big Measurement

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Detect $\nu_\mu + N \rightarrow \mu + N'$ (CC)

- NuMI beam from FNAL
- Baseline: 810 km
  - off-axis 0.8°, 2 GeV
- Far detector 15 kT
  - Ash River MN
- Identical Near detector
  - 215 T at 1 km.
- 3 years ν_μ, 3 years anti-ν_μ.

ND taking data *on surface* spring 2010. Move UG autumn 2011.
FD construction 2011-2013. Modular → data after 1st few kT.
Sensitivity ~ T2K, reactor experiments.

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Daya Bay - Reactor anti-ν_e search for θ_{13}.

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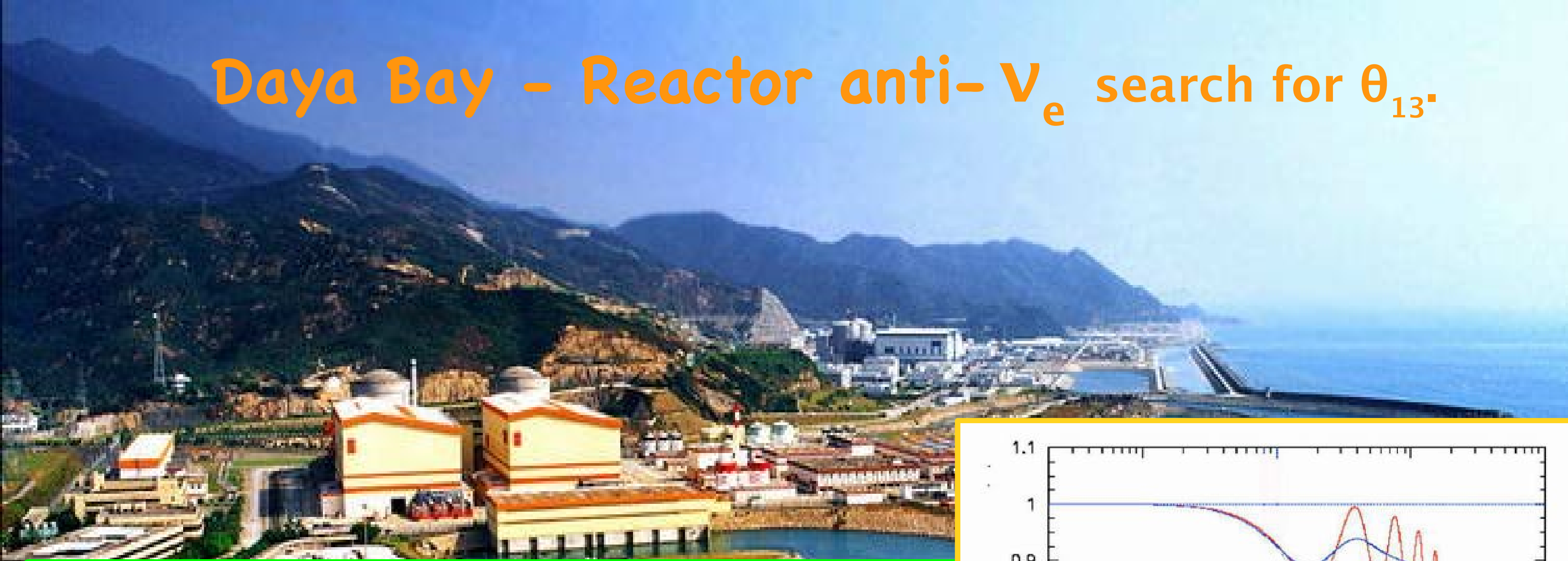
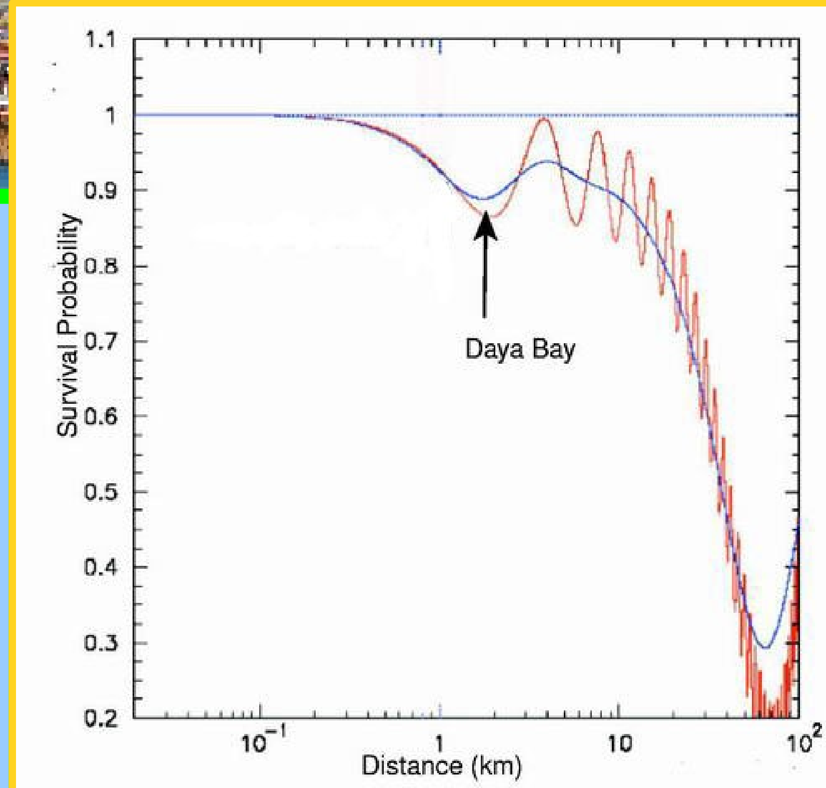
- 70 km NE of Hong Kong airport.
- Detectors underground in the hills.

Daya Bay - Reactor anti-ν_e search for θ_{13}.



- 2 power plants, 2 ND, 1 FD.
- 8 moveable, identical, interchangeable 20 T, anti-nu detector (AD) modules.
- Each ND has 2 modules.
- FD has 4 modules.
- Expect 1% sensitivity.
- Peak E_ν = 4 MeV.
- $\bar{\nu}_e + p \rightarrow n + e^+$



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Daya Bay - Reactor anti-ν_e search for θ_{13}.

Baselines in meters

reactors \ sites	DYB	LA	far
Daya Bay	363	1347	1985
Ling Ao I	857	481	1618
Ling Ao II	1307	526	1613

Expected number of IBD events, hall depth, expected muon and background rates.

	DYB	LA	far
IBD Event/AD/day	840	760	90
Hall depth (m)	98	112	350
Muon Rate/AD (Hz)	36	22	1.2
Accidental B/S (%)	< 0.2	< 0.2	< 0.1
Fast neutron B/S (%)	0.1	0.1	0.1
$^8He/^9Li$ B/S (%)	0.3	0.2	0.2

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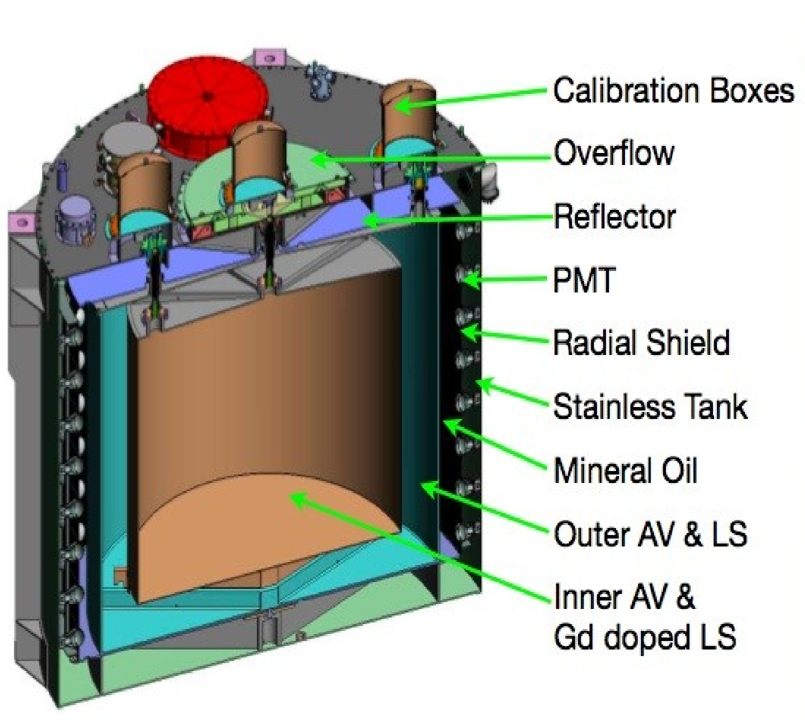

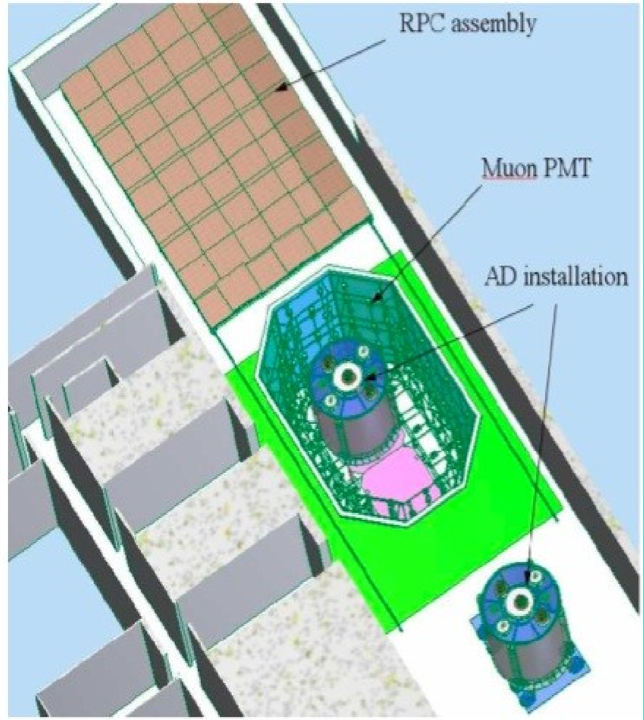

- Civil construction started 2007.
- First pair of ADs
  to Daya Bay 2009.
- Data 2010.
- 3 years to reach sensitivity goal.

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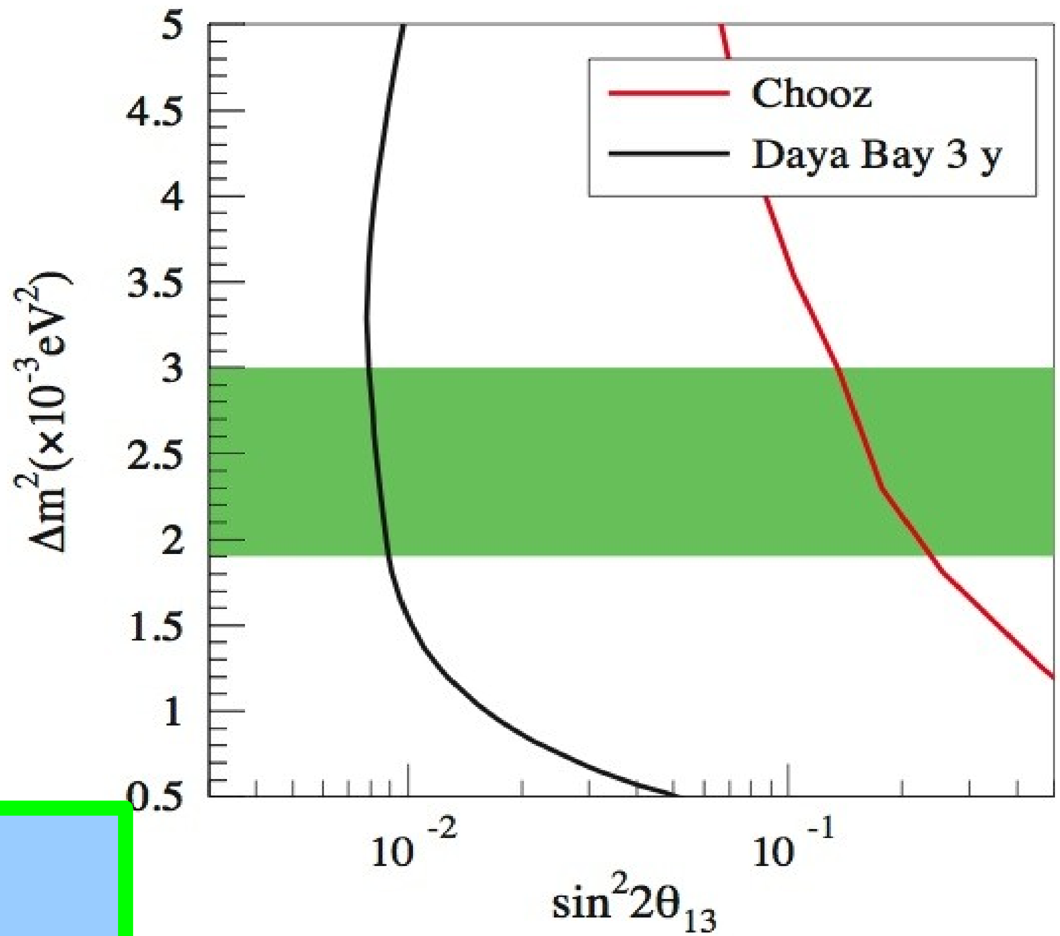
3 years 90% CL.
Green band is 90% Confidence region on Δm^2_{13} .



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What does the future hold?

* Many new experiments coming online now or in the next 5 years.
* Possible upgrades (depending on what we find)
  * T2HK, T2HKK,
  * DUSEL
  * β-beams, ν-factories
  * All-purpose neutrino/DM/0νββ sites.

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θ_{13}

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θ_{13} constrains existing models
(GUT, tribimaximal mixing, flavour models).
If large enough, we next measure δ.
(It could be why we're all here....)
See next talks for more details!

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