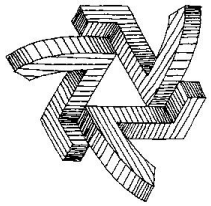
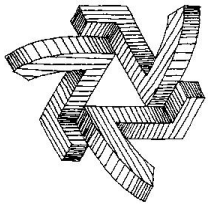


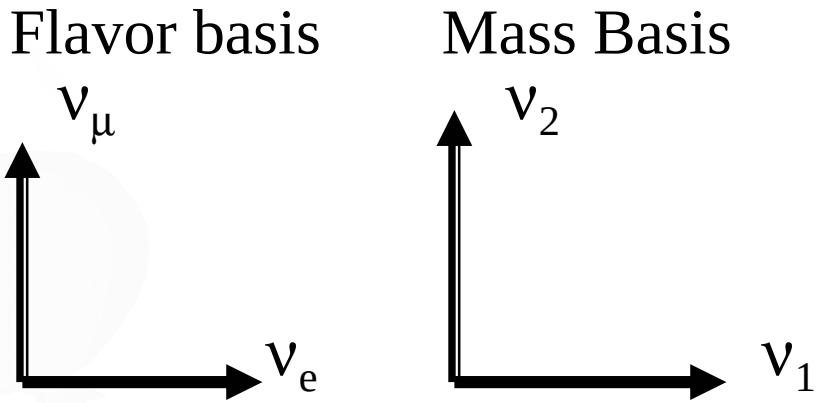
An Update on Long-Baseline ν Experiments (MINOS and Beyond)

- Another Review of Neutrinos
- MINOS & CNGS
- Future "off-axis" ν proposals/ideas
- Using Reactors to Search for θ_{13}
- Underground Labs
- UNO



(Another) ν review

Mixing



$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$

$$\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

$$\nu(t) = e^{-\imath E t}\nu(0)$$

$$P(\nu_e \rightarrow \nu_\mu) = \langle \nu_e(t) | \nu_\mu(0) \rangle = \sin^2\theta\cos^2\theta |e^{-\imath E_2 t} - e^{-\imath E_1 t}|^2$$

$$= \sin^2(2\theta)\, \sin^2(1.27\, \Delta m^2 L/E)$$

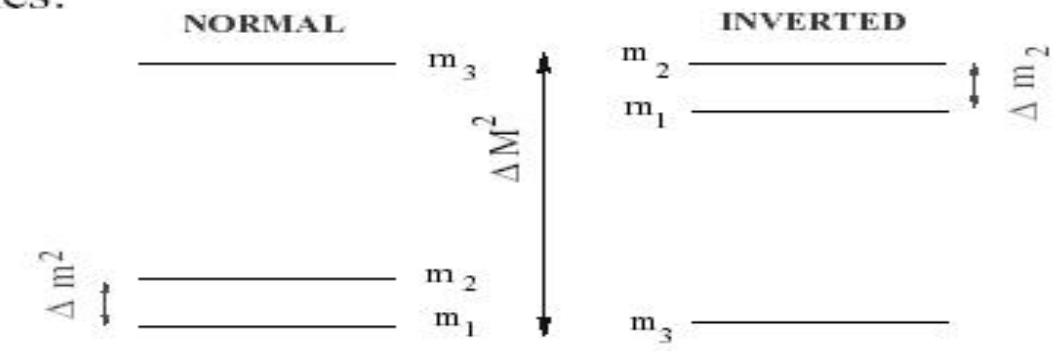
MNS matrix

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

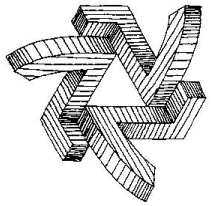
– U: 3 angles, 1 CP-phase + (2 Majorana phases)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

– Two schemes:



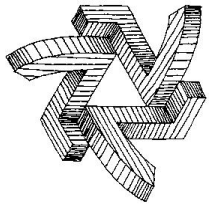
3 ν Equations



- Based on θ_{12}, θ_{13}, θ_{23}
- $P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\,\theta_{13})\sin^2(\theta_{23})\sin^2(\Delta m^2 L/4E)$
- $P(\nu_e \rightarrow \nu_\tau) = \sin^2(2\,\theta_{13})\cos^2(\theta_{23})\sin^2(\Delta m^2 L/4E)$
- $P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\,\theta_{23})\cos^4(\theta_{13})\sin^2(\Delta m^2 L/4E)$
- $P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\,\theta_{13})\sin^2(\theta_{23})\sin^2(\Delta m^2 L/4E)$

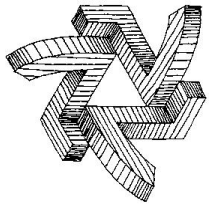
Ignoring the small Δm^2 scale and CP violation and matter effects.

Why we still see 2n analyses



- For atmospheric ν's,
  - we can ignore m_2 compared to m_3
  - $\cos^4\theta_{13} \sim 1$
- For solar ν's,
  - the high Δm^2 term (i.e. $\propto m_3^2$) are multiplied by $\sin^2\theta_{13}$
  - For $P(\nu_e \rightarrow \nu_e)$, θ_{23} drops out because $\cos^2(\theta_{23})+\sin^2(\theta_{23})=1$

The truth about ν's



What we know:

- $\theta_{23} \sim 45^o$;
- $\Delta m^2_{23} \sim .002\text{-}.005\ eV^2$
- $\theta_{12} \sim 30^o$ LMA,
- Δm^2_{12} , $\sim 7 \times 10^{-5}\ eV^2$
- $\sin^2 2\theta_{13} < 0.05$
- Everything except LSND fits 3 ν framework

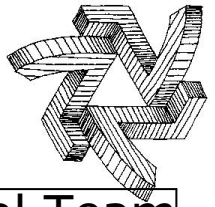
What we'd like to know

- See the dip in atmo ν L/E distribution
- Measure the whole solar ν energy spectrum.
- Determine U_{e3} (θ_{13})
- Are CP violation effects Large?
  - If so, what is the CP phase δ?
- Can we see τ's in $\nu_\mu \rightarrow \nu_\tau$?
- Can we settle the LSND question?
- Measure the absolute ν masses?
- Is the neutrino Majorana or Dirac?
- Is the mass hierarchy normal?
- Astrophysical sources of >TeV ν's?

The Theorist

by Rodin

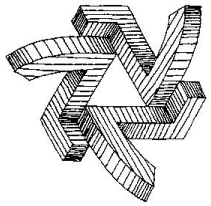
What new neutrino experiments will tell us.



The Experimental Team
by Rodin

- See atmospheric L/E dip.
- Measure whole solar E_ν spectrum
- Determine U_{e3} (θ_{13})
- Is CP violation large?
  - → If so, what is the CP phase δ?
- See τ's in $\nu_\mu \rightarrow \nu_\tau$.
- Settle LSND.
- Measure absolute ν masses.
- Is the neutrino Majorana or Dirac?
- Is the mass hierarchy normal or inverse?
- Astrophysical sources of >TeV ν's?

What we'll know



MINOS/UNO

Borexino/Lens

JPARC/reactor

Off-axis

OPERA

Mini-BooNE

KATRIN

ββ

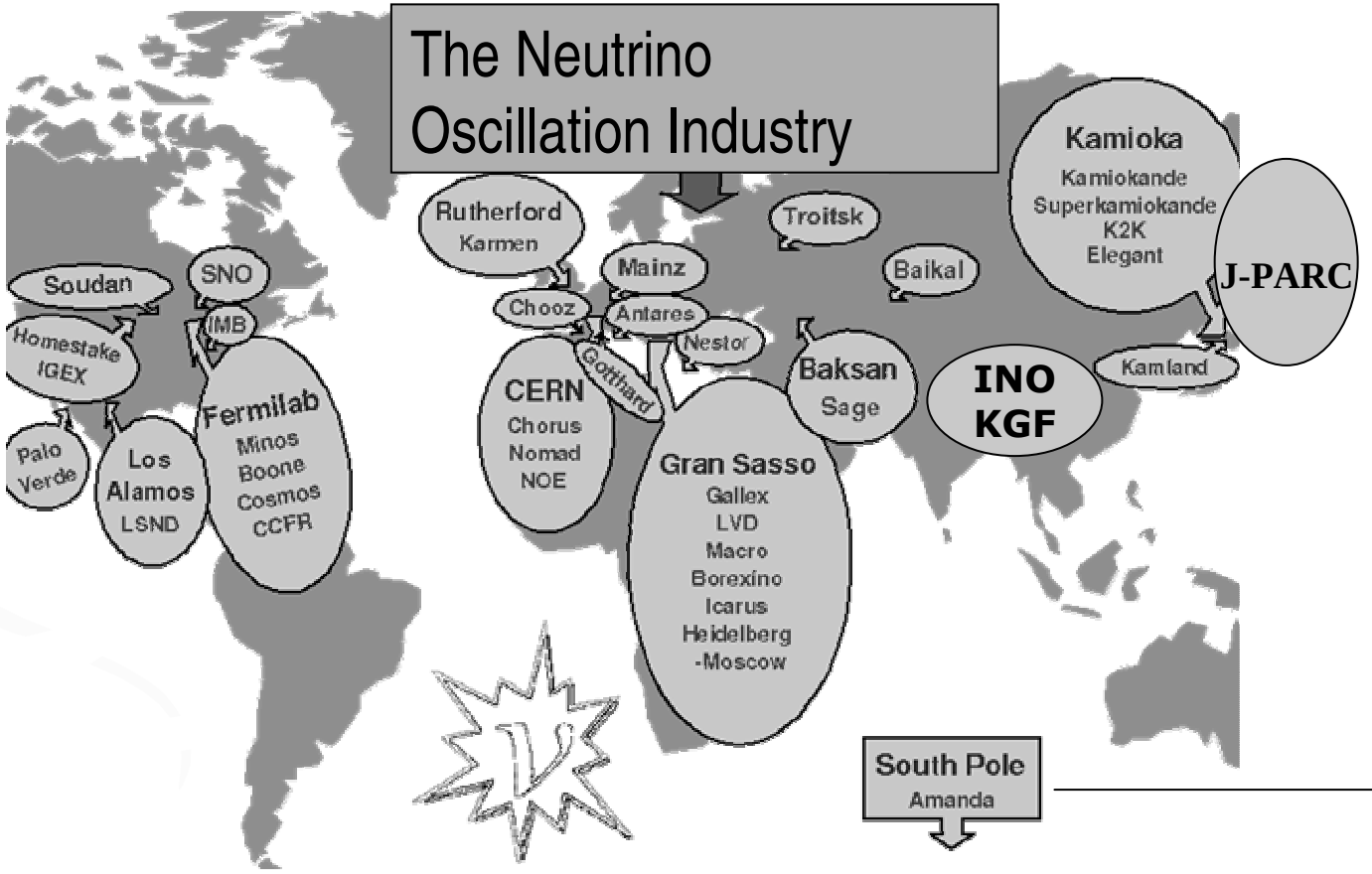
ν-Factory

ν-Telescopes

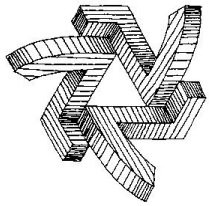
- ✓ See dip in atmospheric ν L/E distribution
- ✓ Measure the Energy Spectrum of Solar ν's.
- ✓ Determine U_{e3} (θ_{13})
- ✓ Are CP violation effects Large?
  - ✓ If so, what is the CP phase δ?
- ✓ Can we see τ's in $\nu_\mu \rightarrow \nu_\tau$?
- ✓ Can we settle the LSND question?
- ✓ Measure the absolute ν masses?
- ✓ Is the neutrino Majorana or Dirac?
- ✓ Is the mass hierarchy normal or inverse?
- ✓ Are there astrophysical sources of >TeV ν's?

Neutrino World

http://www.neutrinooscillation.org/



New Accelerator Experiments



Short-Baseline

♪ Mini-BooNE

Non-oscillation

♪ NuMI on/off-axis

♪ Booster

Particle Production

♪ HARP

♪ MIPP

New Long-Baseline

❁ From FNAL/BNL/CERN & KEK/J-PARC

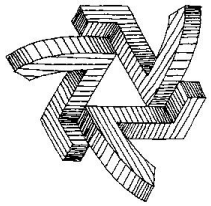
❁ Conventional

❁ Super-beam

❁ Neutrino Factory

❁ β-beams

How Long is Long?



Definitions of "Long-Baseline"

(my use is for accelerator based experiments)

- Webster - *(long - measuring much, or more than usual, from end-to-end in space or time)*
- Practical - Off site
- Useful (Beam) - The distance from the ν source to the detector is much greater than the length of the decay pipe.

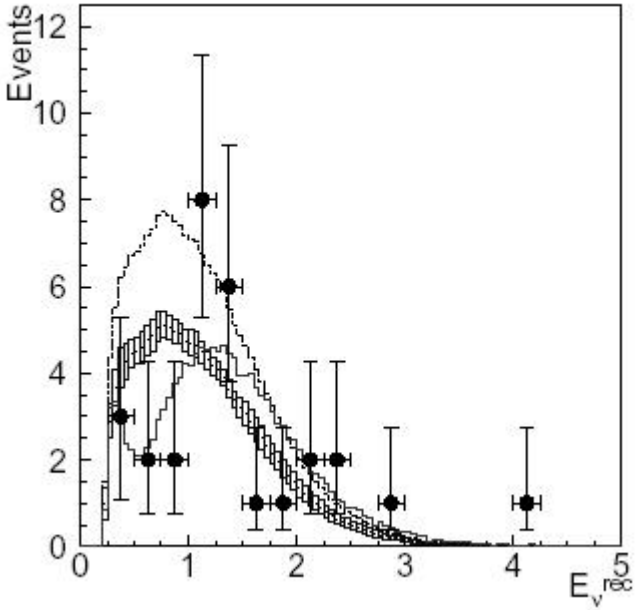
  $\therefore$ **beam is a point source**
- Useful (Physics) - $L >> E_\nu/\Delta m^2$

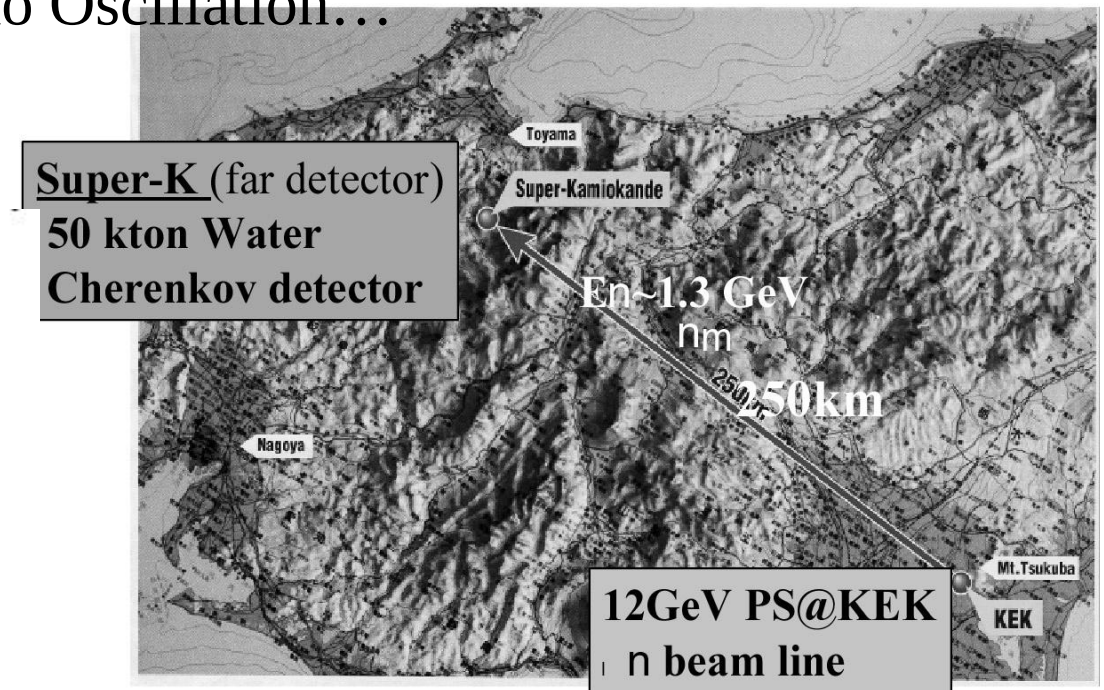
  $\therefore$ **neutrinos have fully oscillated**

K2K

Indications of Neutrino Oscillation…

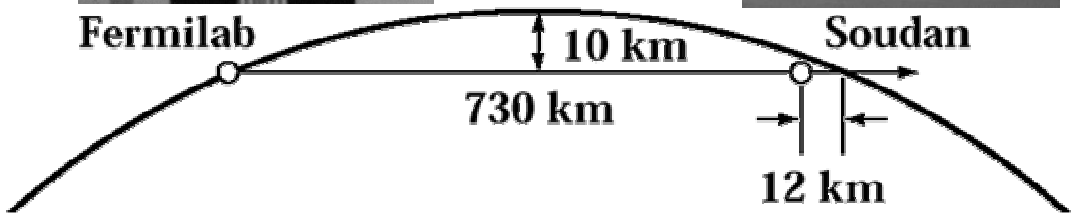
hep-ex/0212007



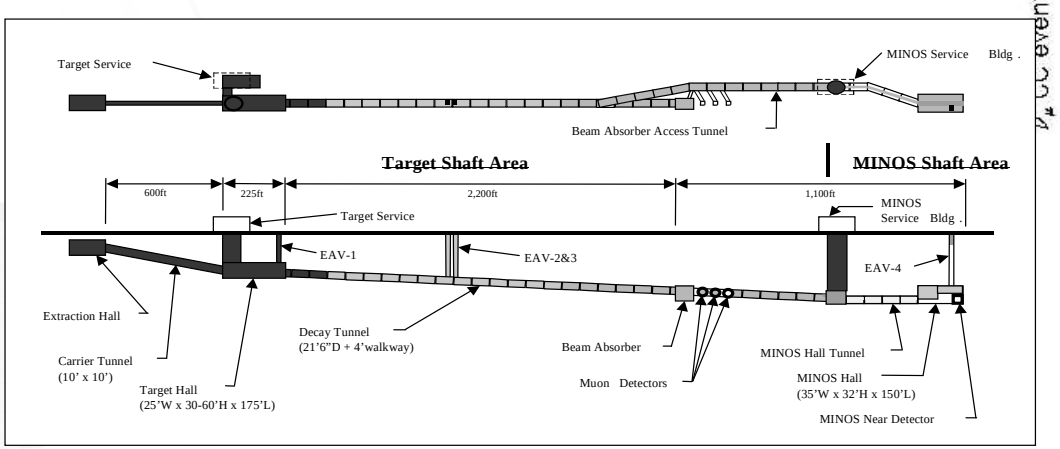


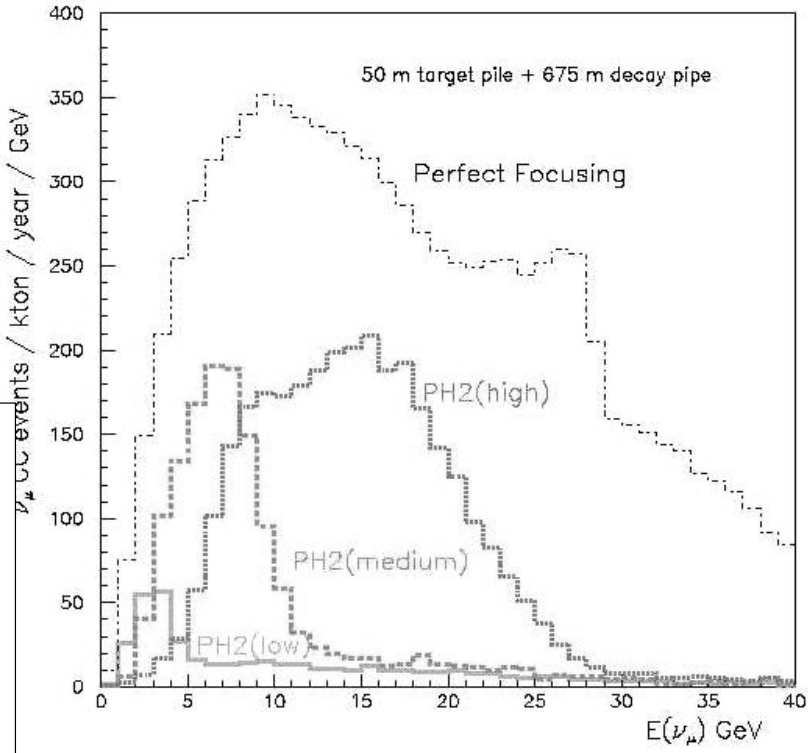
MINOS

A neutrino beam from Illinois to Minnesota

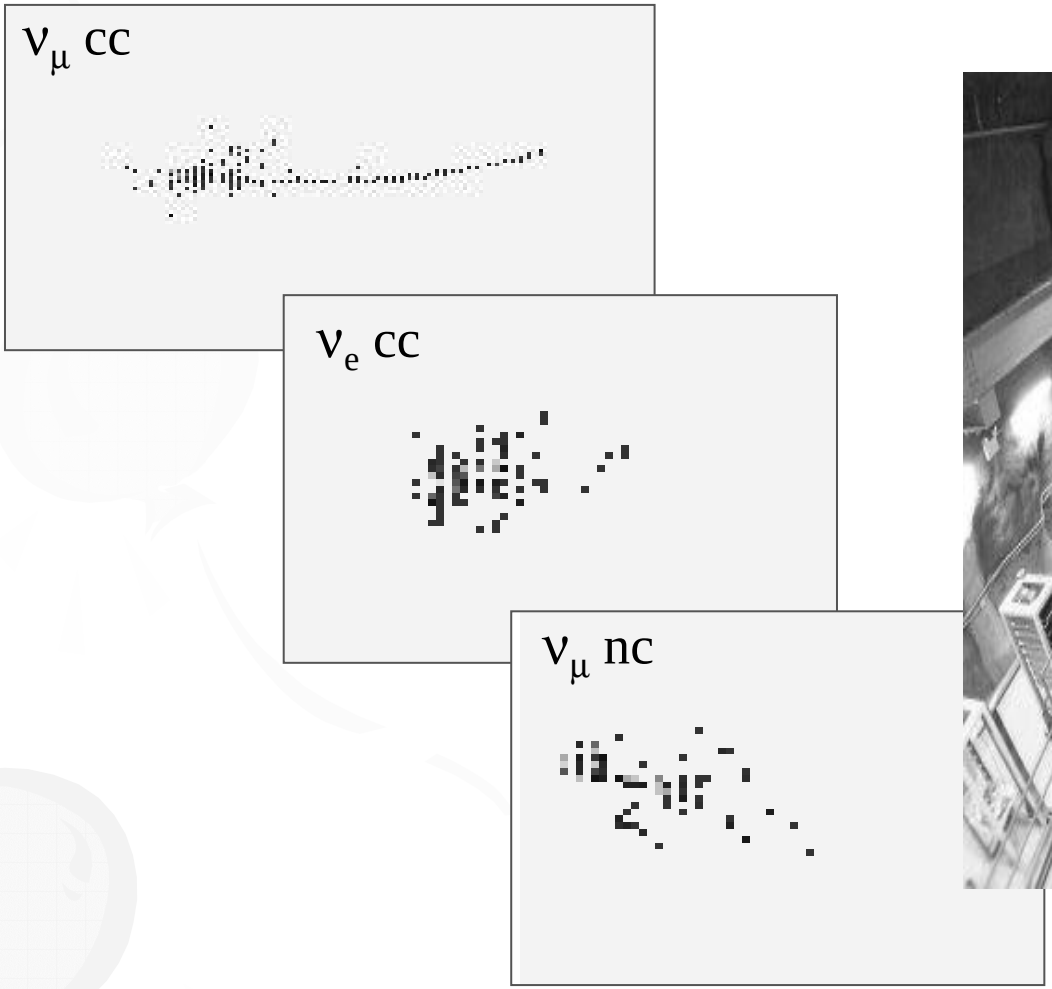


NuMI Beamline



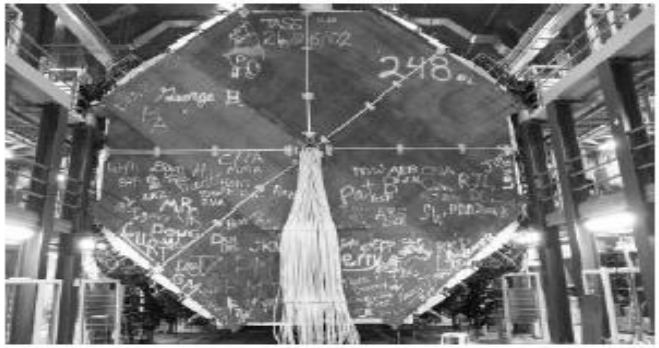


MINOS far detector

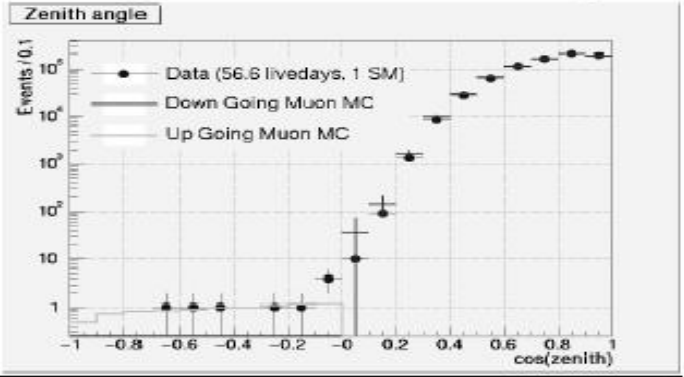


NuMI Status (Witherell@P5)

Status of the NuMI Project



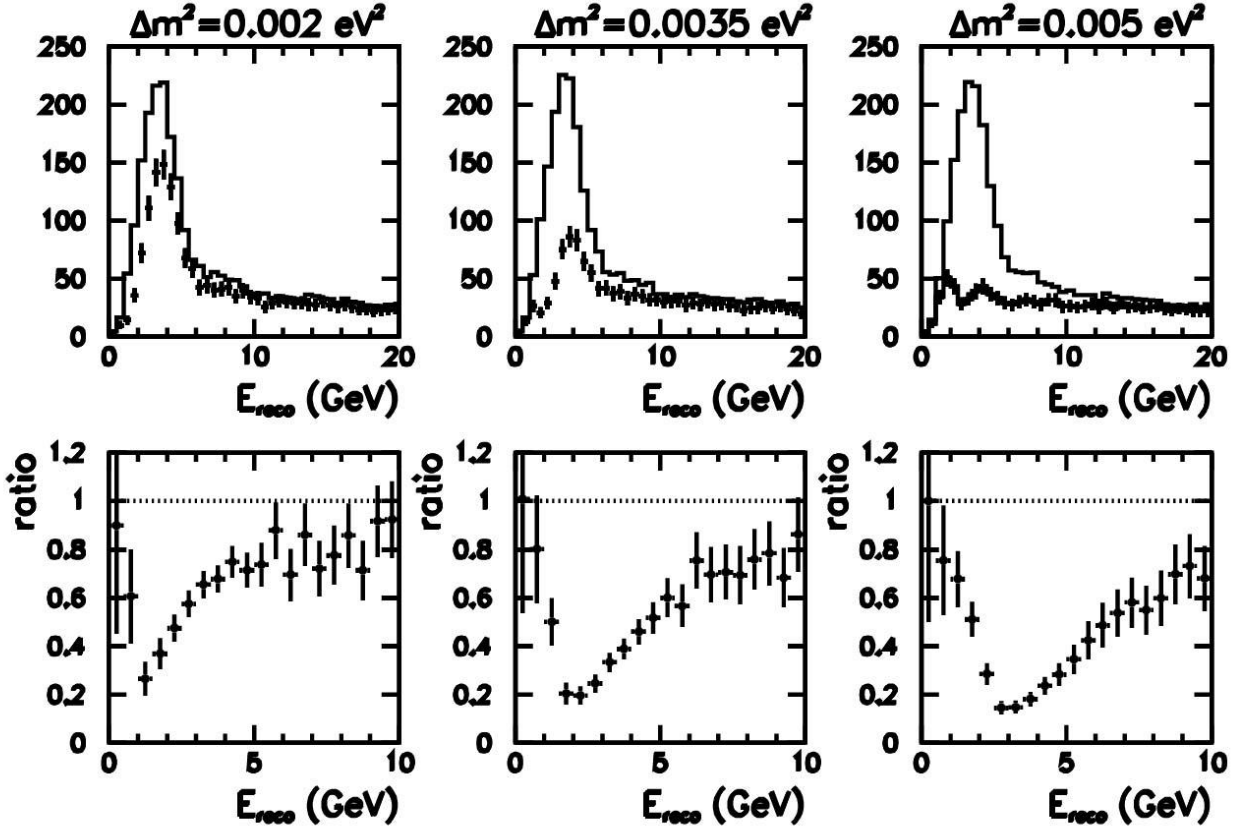
- Good progress on construction
  - Tunnels and Halls contract complete 11/22/02
  - Surface Buildings and Outfitting contract work started 11/1/02
- 432/484 planes of MINOS far detector installed and operating
  - Cosmic ray studies underway
- Heading toward beam in early 2005

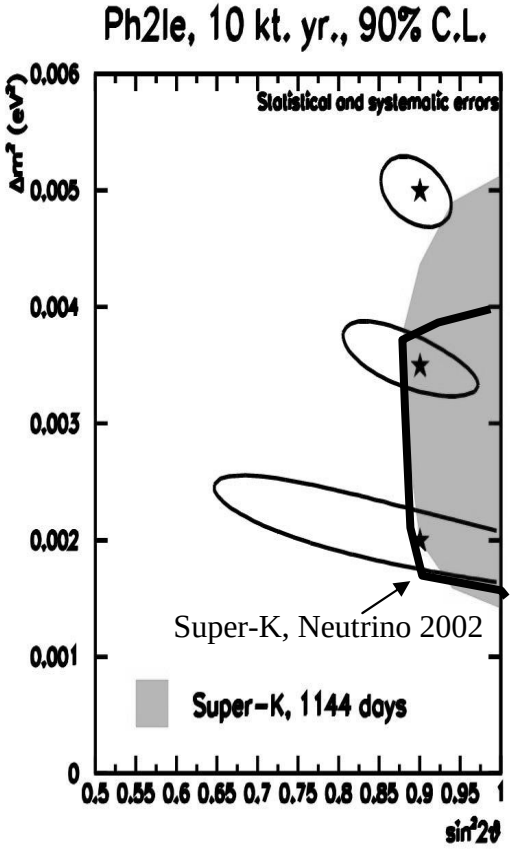


MARCH 26, 2003 P5 10

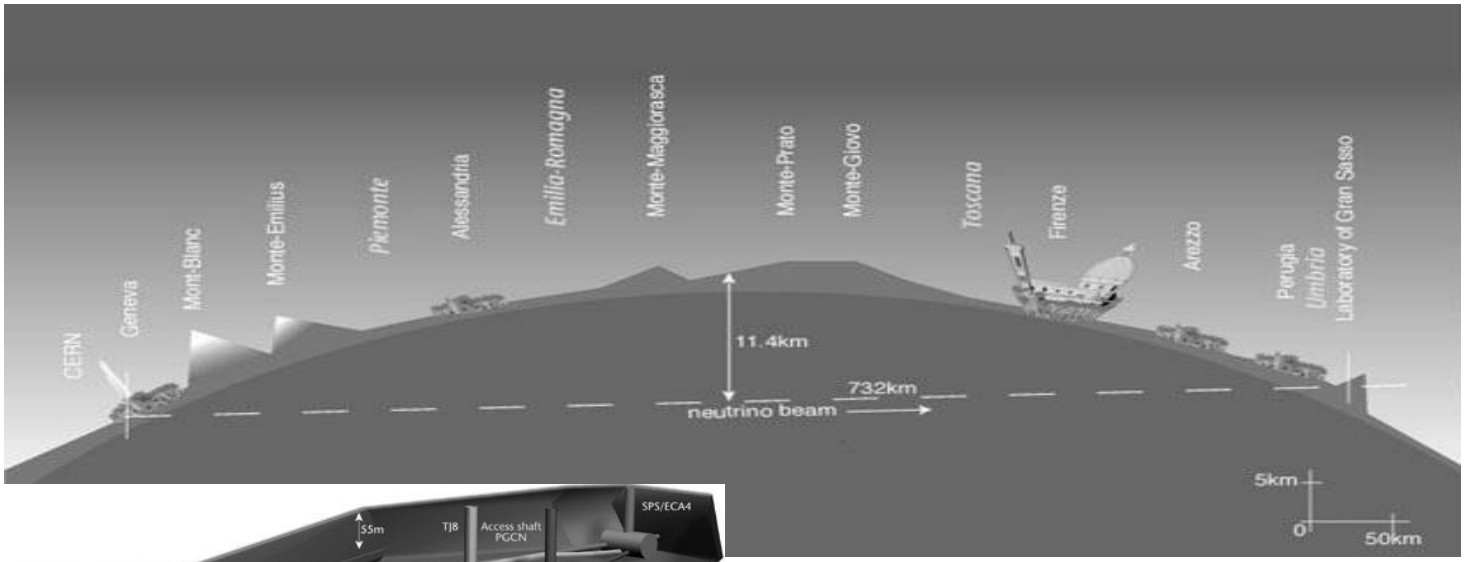
Measurements in MINOS

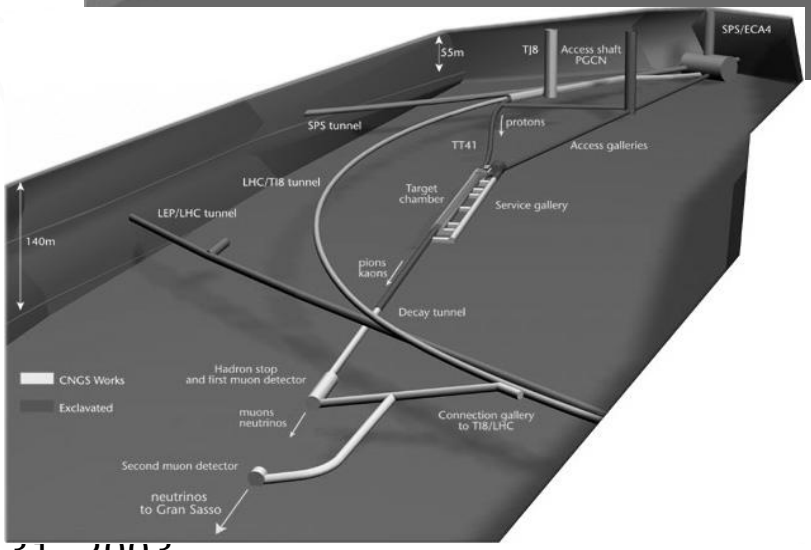
CC energy distributions – Ph2le, 10 kt.yr., $\sin^2(2\vartheta)=0.9$





CNGS

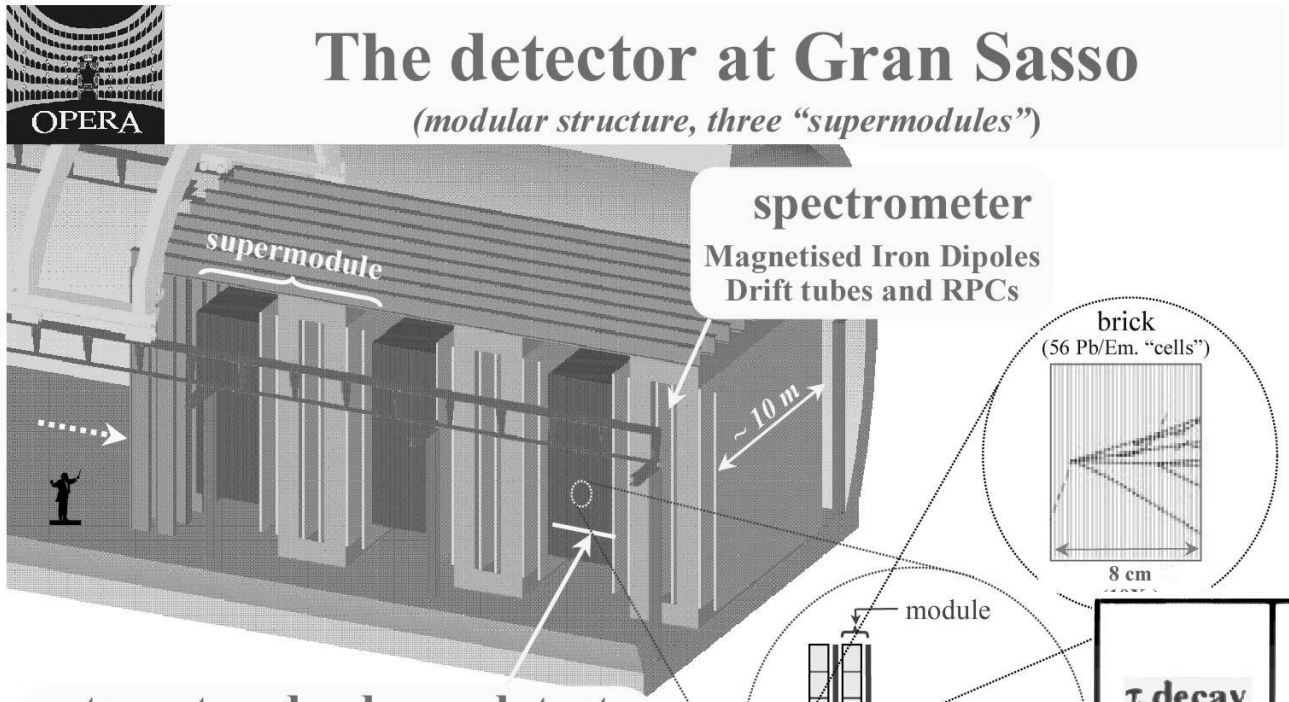




CERN SPS to the Italian Gran Sasso Laboratory

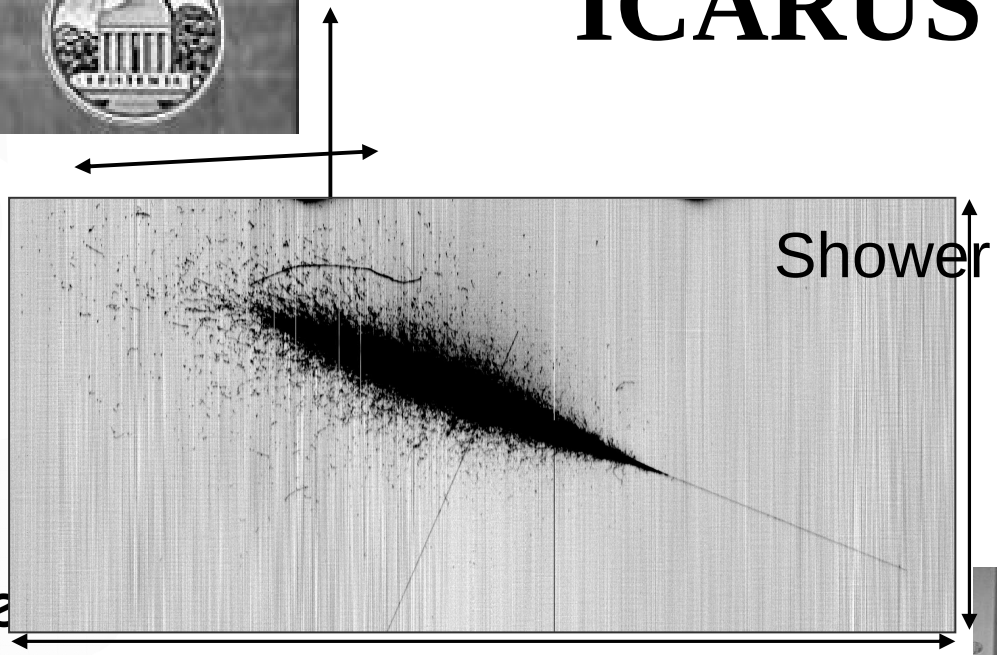
732 km

OPERA

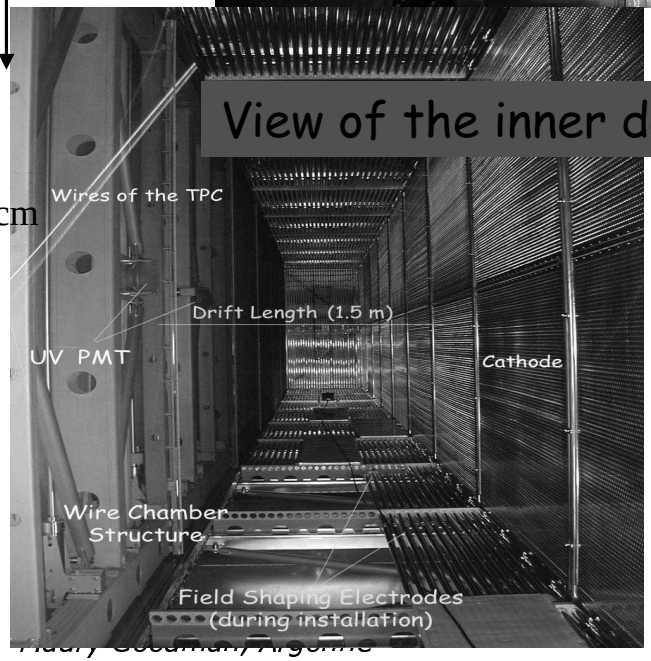


τ decay	ν_τ events Δm^2 (10^{-3} eV^2) 1.5	3.2	5.0	b.g.
e	1.7	7.7	18.5	0.19
μ	1.3	5.7	13.8	0.13
h	1.1	4.9	11.8	0.25
Total	**4.1**	**18.3**	**44.1**	0.57

ICARUS



View of the inner detector

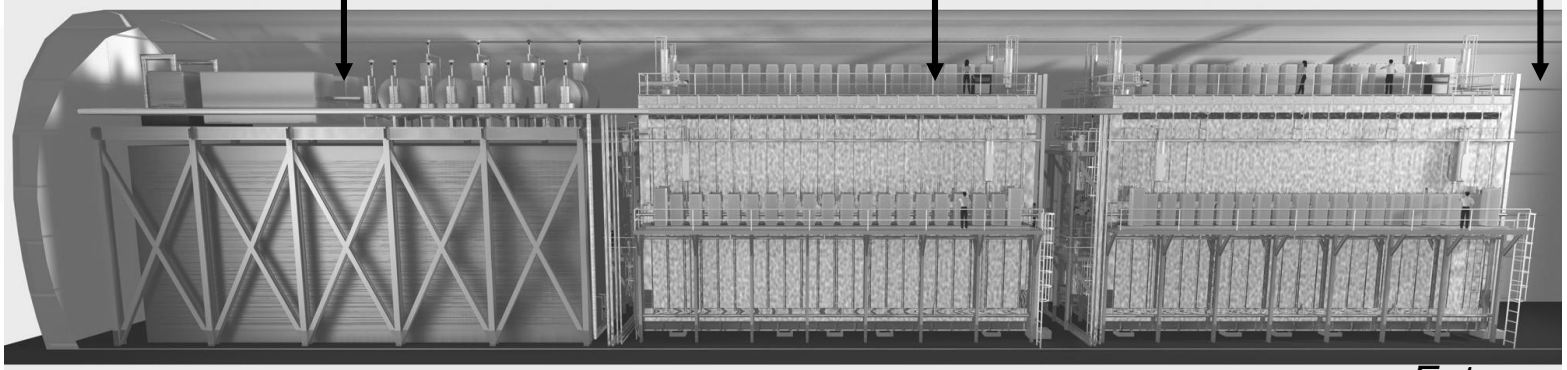


3 kiloton ICARUS

First Unit T600 + Auxiliary Equipment

T1200 Unit (two T600 superimposed)

T1200 Unit (two T600 superimposed)



Improved statistics for:

≈ 70 Metres

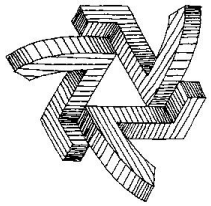
Future extension to additional modules

1. **Solar neutrinos**
2. **Atmospheric neutrinos**
3. **Supernova neutrinos**
4. **CERN-NGS neutrinos**
5. **Proton decay**

T600: installed in LNGS in 2003

T3000: operational by summer 2006

Measuring θ_{13} (1)



- $P(\nu_\mu \rightarrow \nu_\tau) = \underline{\sin^2(2\,\theta_{23})\cos^4(\theta_{13})}\sin^2(\Delta m^2 L/4E)$

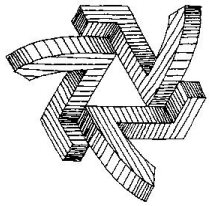
  ~ 1.0

- $P(\nu_\mu \rightarrow \nu_e) = \underline{\sin^2(2\,\theta_{13})\sin^2(\theta_{23})}\sin^2(\Delta m^2 L/4E)$

  < 0.05

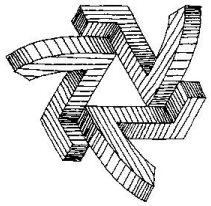
Ignoring matter effects, the small Δm^2 scale and CP violation

Measuring θ_{13} (2)



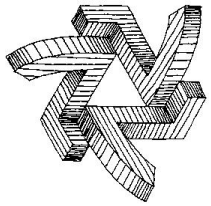
- Measure $\nu_\mu \rightarrow \nu_e$ at the "atmospheric" L/E
- Signature, electron appearance
- Backgrounds
  - ν_e in the beam, (~1%, from μ, $K^{\pm}_{e3}$, K^0_{e3})
  - e from ν_τ, $\tau \rightarrow$ e, (at high energy)
  - showers which look like e's, particularly $\nu N \rightarrow \nu N \pi^0$, $\pi^0 \rightarrow \gamma\gamma$

Measuring θ_{13} (3)



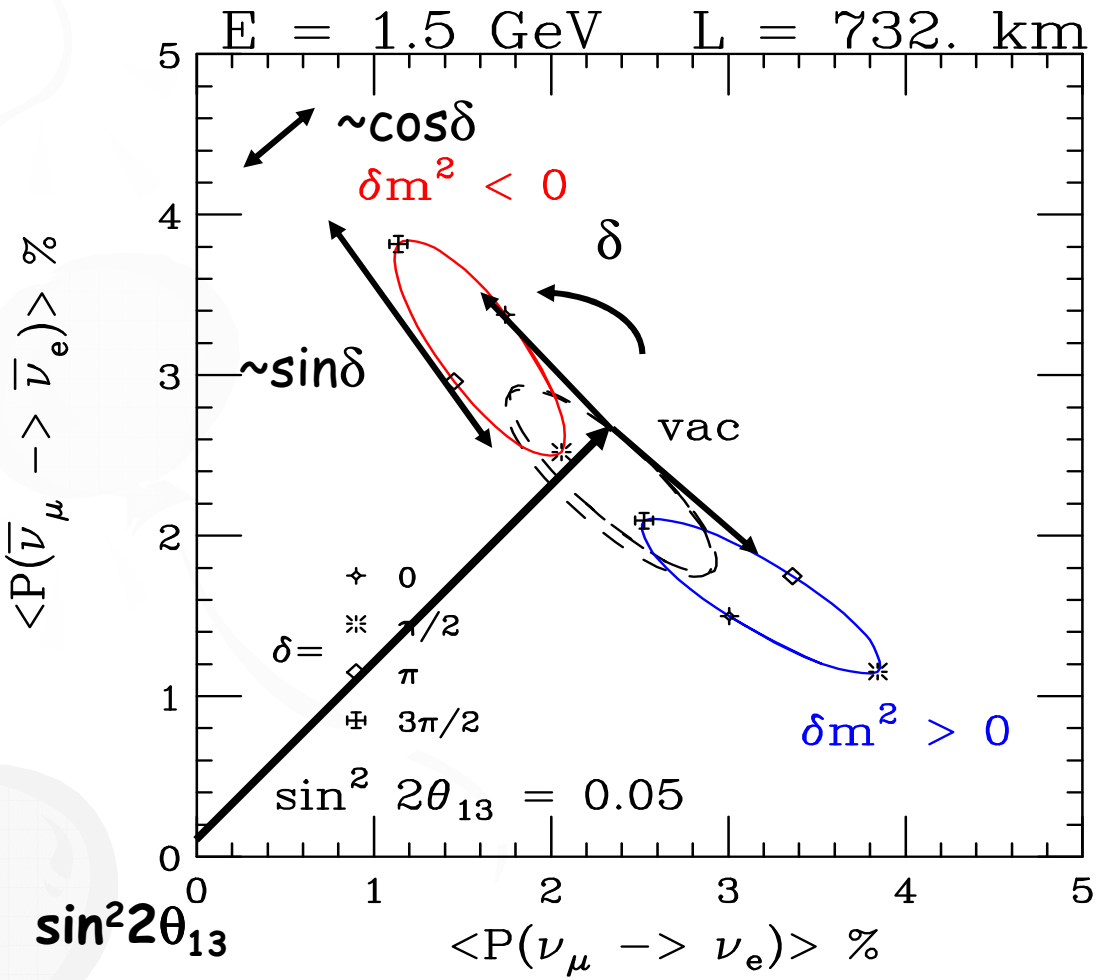
- It would be nice to have a high energy ν_e beam.
- $\nu_e \rightarrow \nu_\mu$ would be a fairly background free signature for θ_{13}.
- A Neutrino Factory or a Beta Beam would be a way to do this, but they are "futuristic".

Degeneracies



- Experiment measures oscillation probability. It is not unambiguously related to <u>fundamental</u> parameters, θ_{13} or δ.
- There are degeneracies with respect to matter effects (sign of Δm_{12}^2), δ, and uncertainties in Δm_{12}^2, θ_{23} and θ_{12}
- At low values of $\sin^2 2\theta_{13}$ (~0.01), the uncertainty could be as much as a factor of 4.
- Optimize by a judicious choice of running time between ν and $\bar{\nu}$, and choice of L and E_ν.

Bi-probability ellipses



Minakata and Nunokawa, hep-ph/0108085

Observables are:

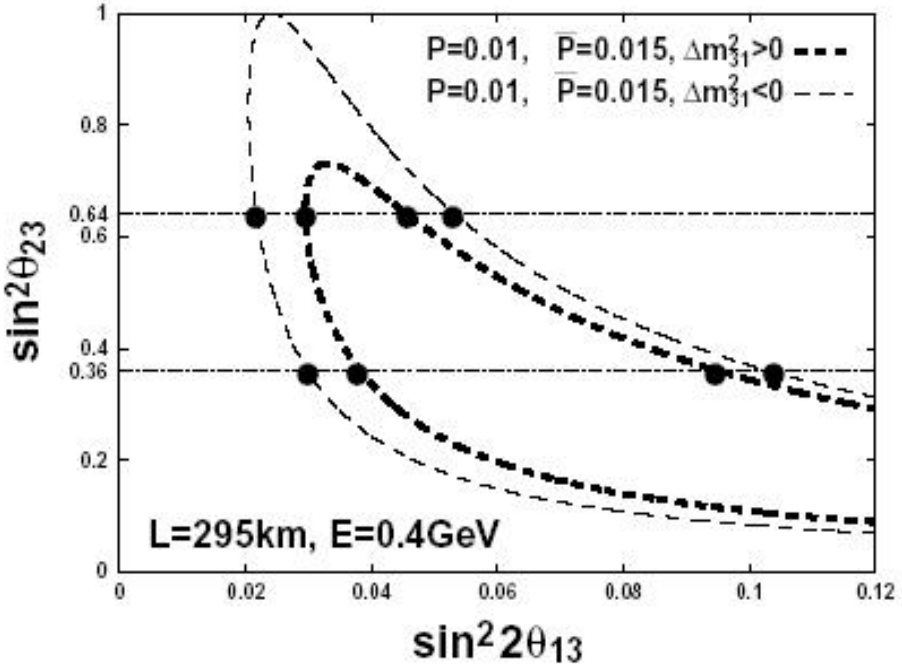
- P
- $\bar{P}$

Interpretation in terms of $\sin^2 2\theta_{13}$, δ and sign of Δm^2_{23} depends on the value of these parameters and on the conditions of the experiment: L and E

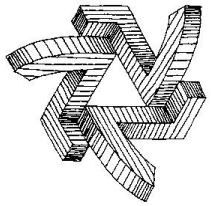
Consequence of degeneracies

One set of measurements at some L,E

$\rightarrow$ eight values of θ_{13}



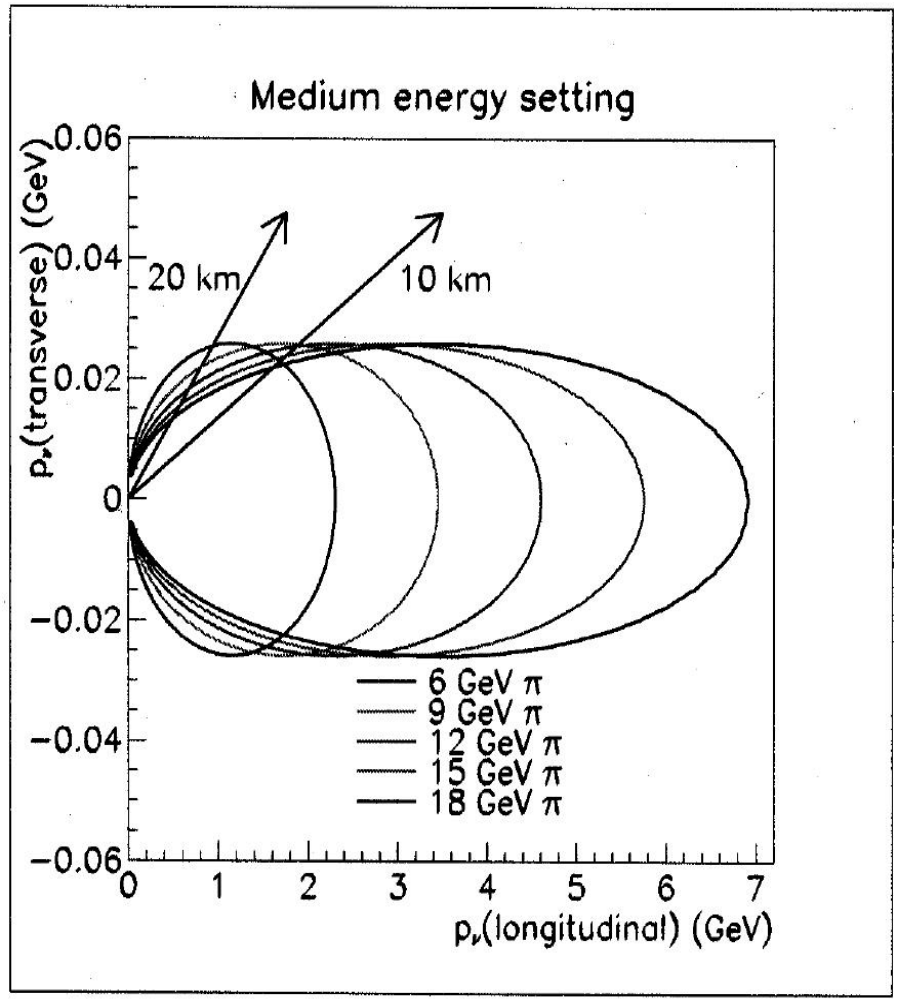
Solutions



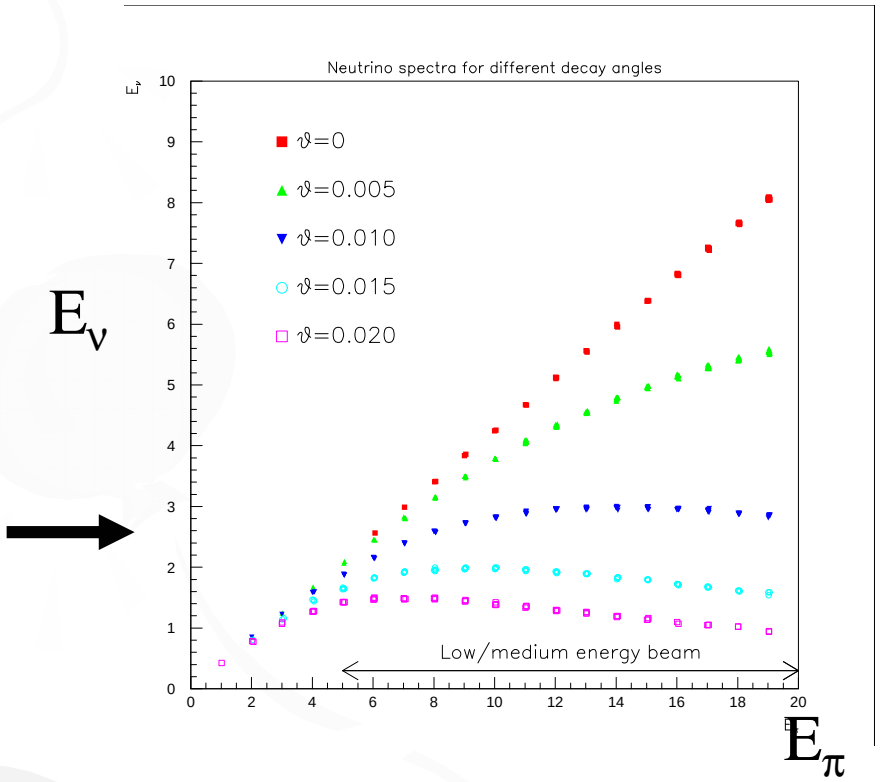
- J-PARC ⇨Super-Kamiokande, Hyper-Kamiokande
- BNL (Brookhaven) ⇨ SOUDAN/NUSEL/WIPP
- Fermilab (NuMI) Off-axis

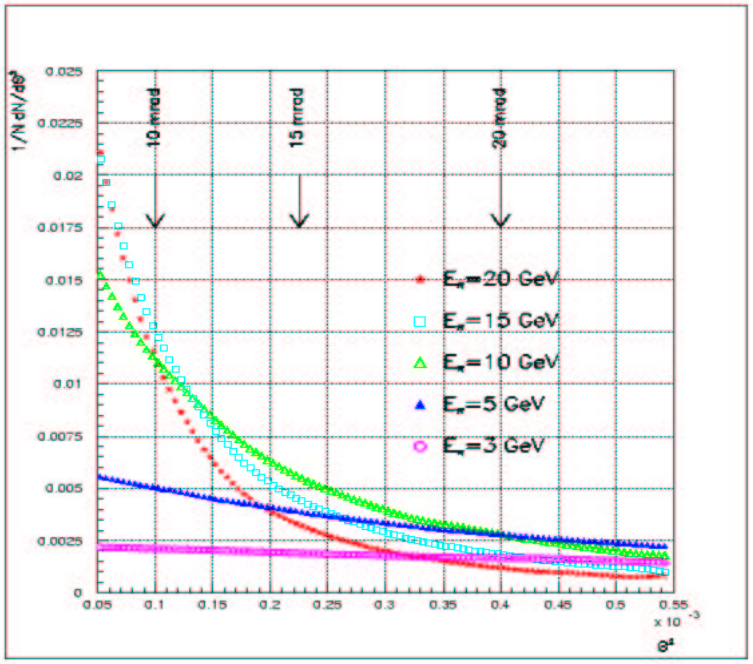
NuMI Off-axis Physics

- Off axis is lower flux, reduced event rate
- Narrow(er) band beam, so lower nc background from "high energy tail"
- Lower intrinisic ν_e's at the interesting energy
- Good sites near Soudan are available
- Letter-of-intent submitted to FNAL



Off-axis



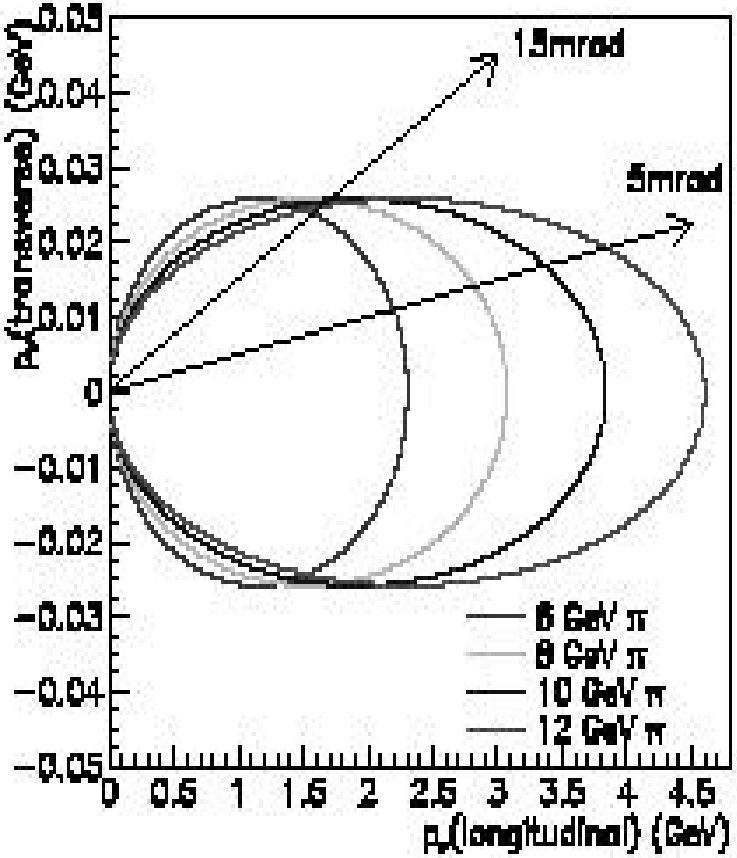


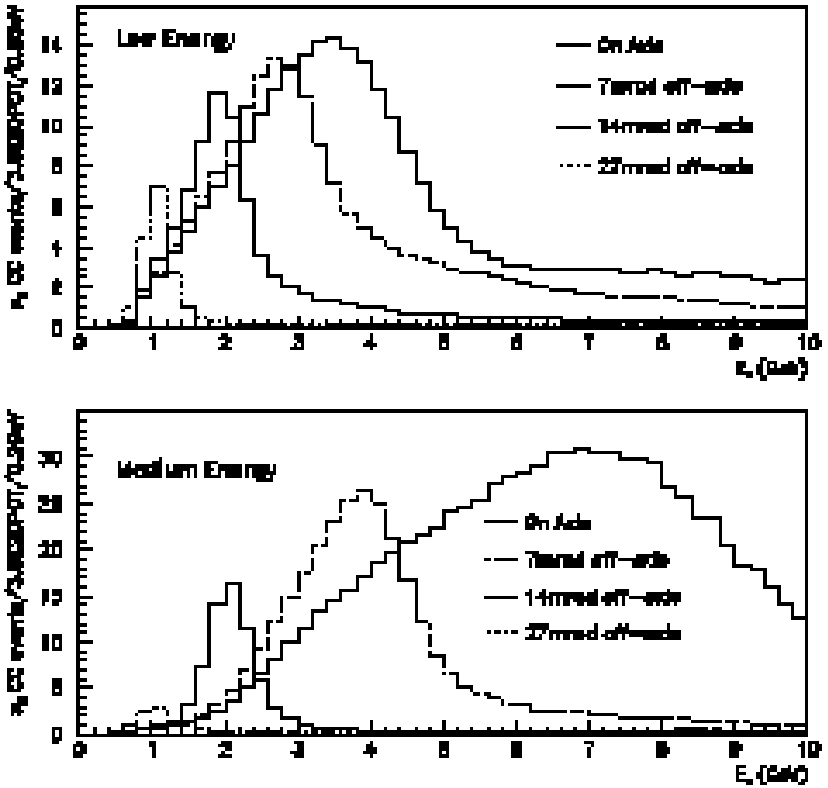
1-3 GeV intense beams with well defined energy in a cone around the nominal beam direction

$$Flux = \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \frac{A}{4\pi z^2}$$

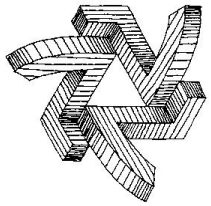
Off-Axis ν

leads to a narrow band beam





-/+ off axis



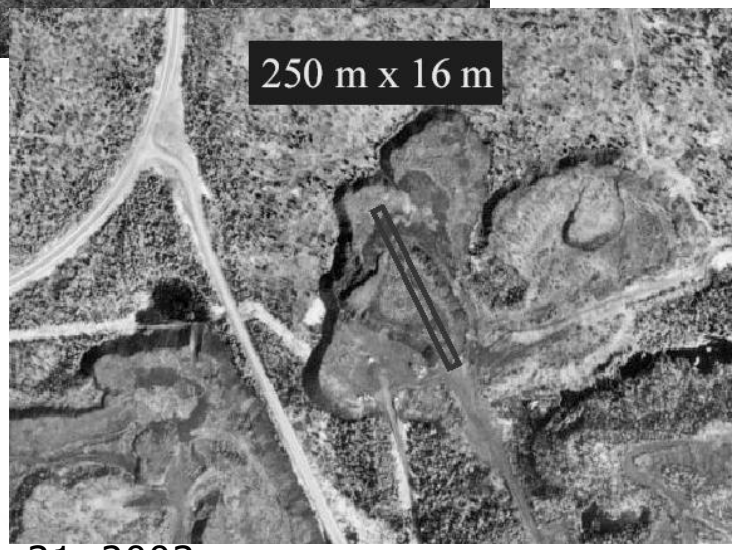
- Rates way down (already an obvious significant issue in long-baseline ν)
- + Backgrounds reduced
  - 0 ν_e in the beam mostly at higher energy
  - 0 e from ν_τ, No ν_τ interactions below 4 GeV
  - 0 NC background not eliminated, but since there is no high energy tail, it is reduced.

NuMI Off-axis Sites

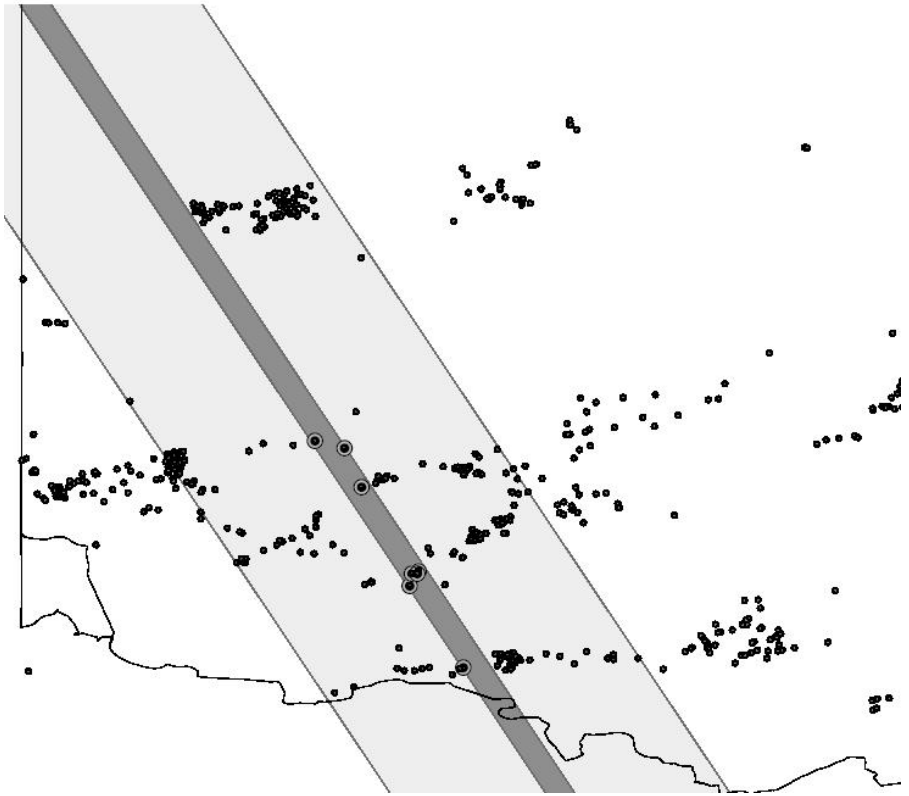
LTV mine

Minn.

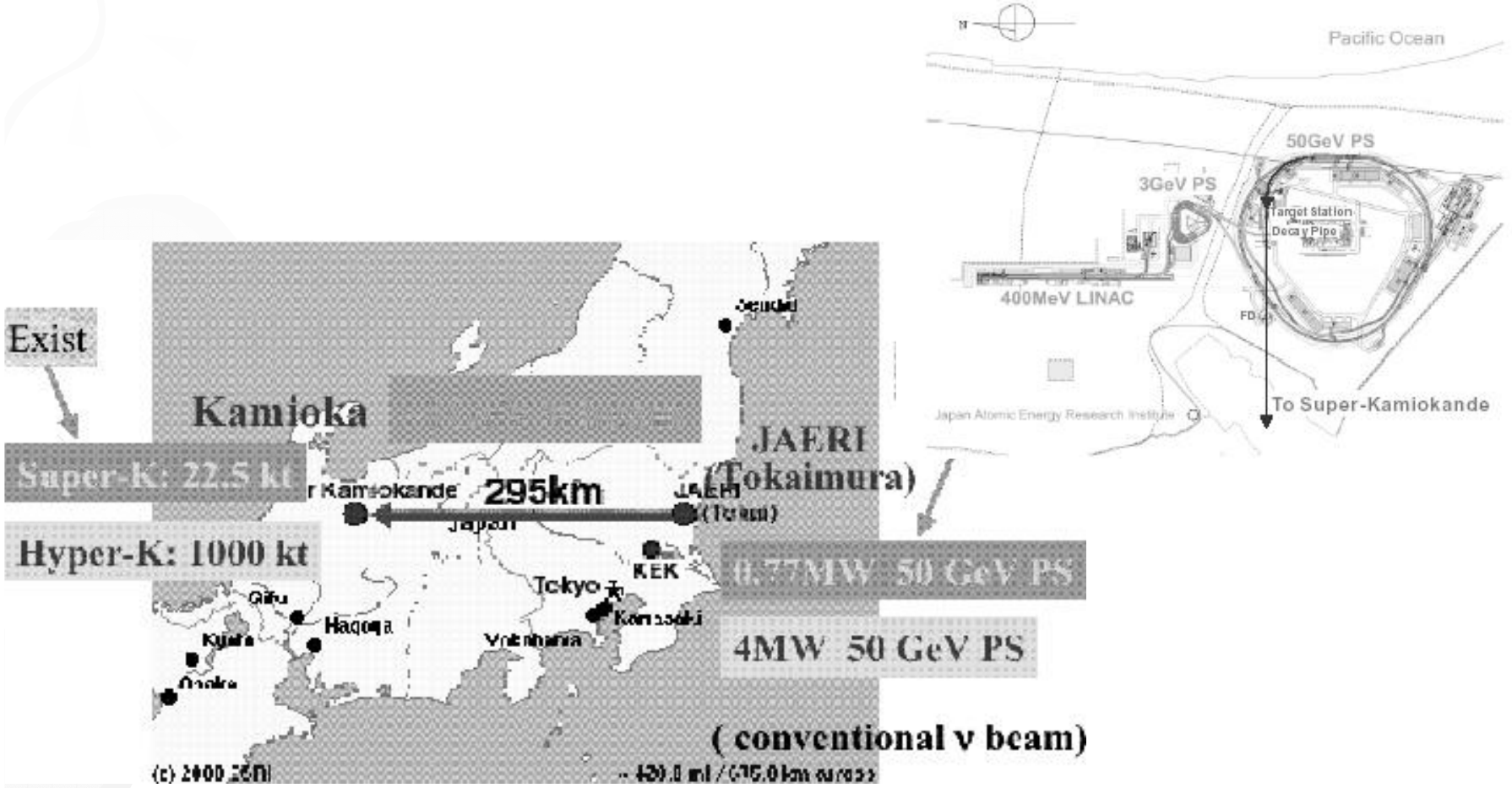
10km off



Sites in Canada

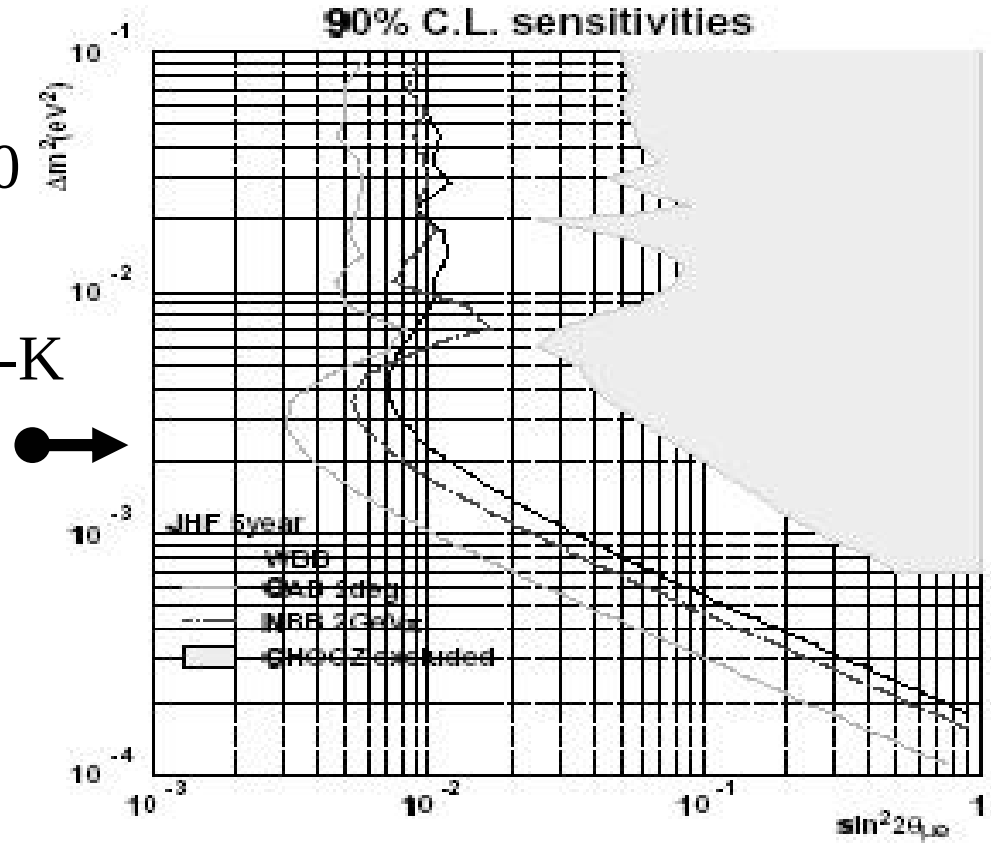


J-PARC(nu)2K

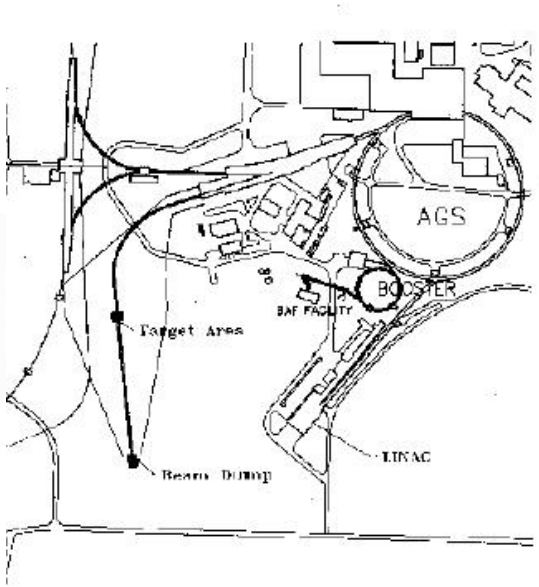

Pacific Ocean
50GeV PS
3GeV PS
Target Station
Decay Pipe
400MeV LINAC
FD
Japan Atomic Energy Research Institute
To Super-Kamiokande
Exist
Kamioka
Super-K: 22.5 kt
Hyper-K: 1000 kt
295km
Japan
JAERI
(Tokaimura)
KEK
Tokyo
4MW 50 GeV PS
(conventional ν beam)

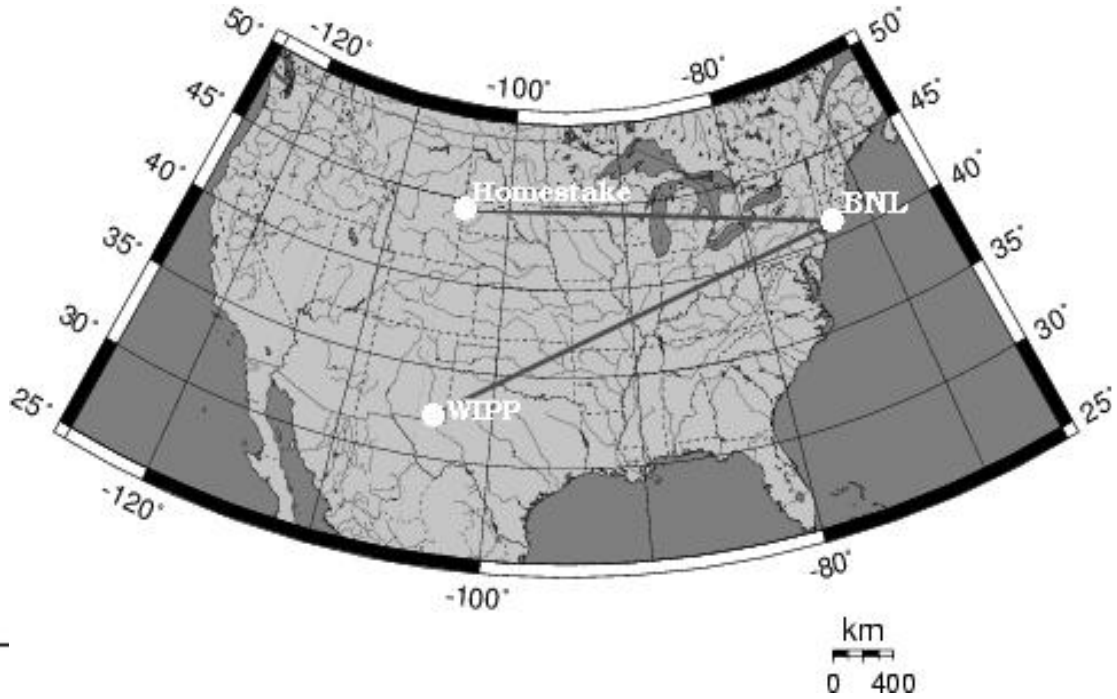
θ_{13} in J-PARCν

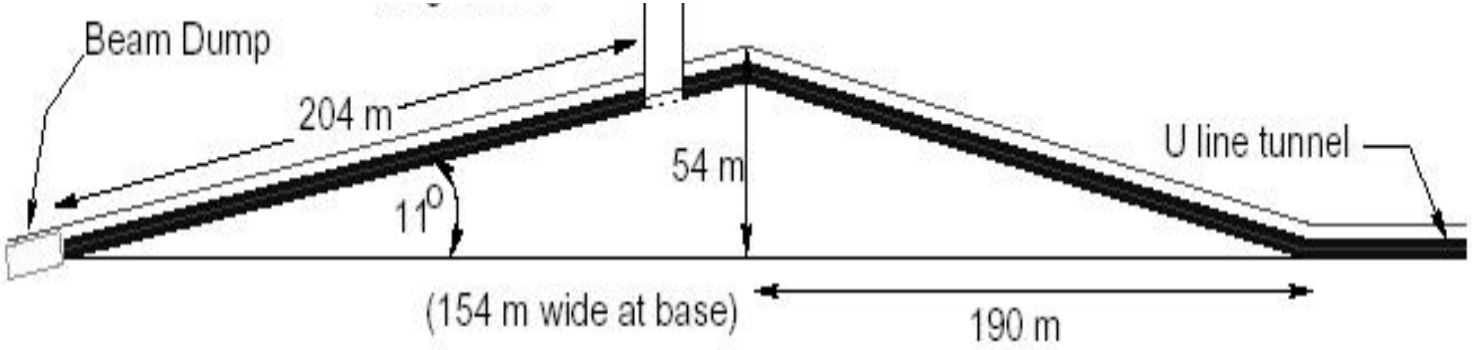
- Also called JHF2K, JHFν
- Start in 2008?
- Can push θ_{13} reach by 10
- Can expand its reach when/if Super-K⇨Hyper-K



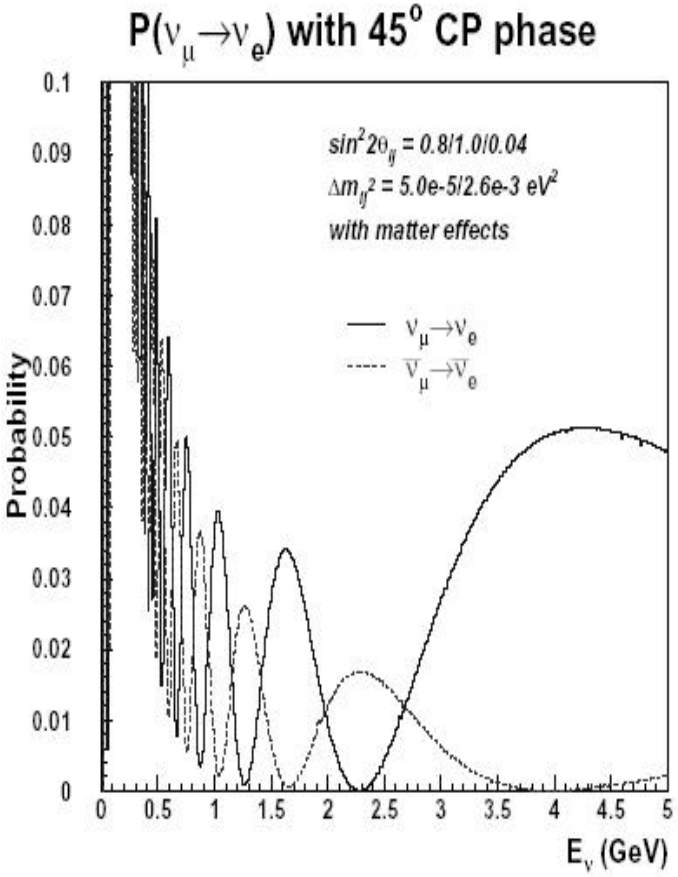
Brookhaven

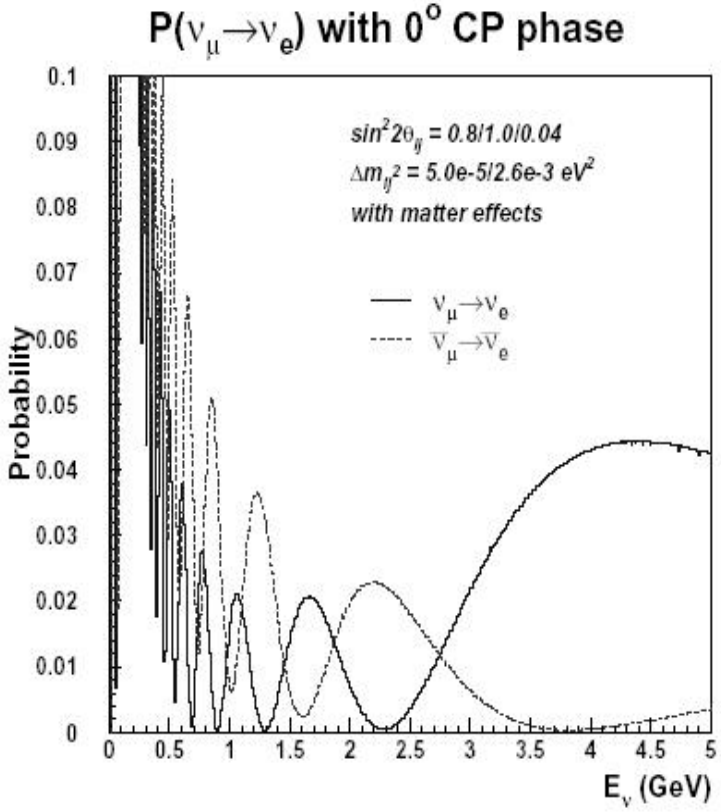

AGS
BOOSTER
Target Area
LINAC
Beam Dump


Homestake
BNL
WIPP
km
0 400

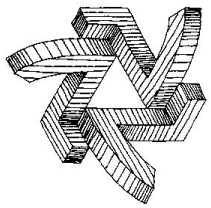

Beam Dump
204 m
11°
54 m
U line tunnel
(154 m wide at base)
190 m

CP-2540 km


P(ν_μ→ν_e) with 45° CP phase
sin²2θ_ij = 0.8/1.0/0.04
Δm_ij² = 5.0e-5/2.6e-3 eV²
with matter effects
ν_μ→ν_e
ν̄_μ→ν̄_e
Probability
E_ν (GeV)


P(ν_μ→ν_e) with 0° CP phase
sin²2θ_ij = 0.8/1.0/0.04
Δm_ij² = 5.0e-5/2.6e-3 eV²
with matter effects
ν_μ→ν_e
ν̄_μ→ν̄_e
Probability
E_ν (GeV)

Is the surface ok for off-axis?



- ✓ Consider NuMI off-axis ($100x20x20m^3$)

During the 1.2 μs beam spill there are

- ❖ 1.1 10^8 μ/year
- ❖ 3.6 10^6 n/year
- ❖ 2-20 2 GeV e signal events per year

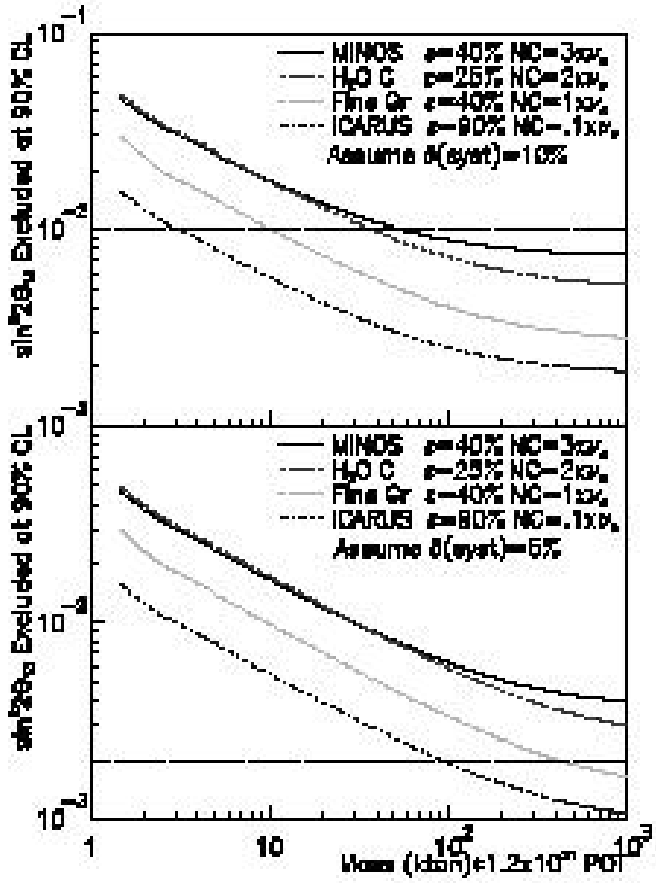
Reduce background with

- ❖ Fiducial cuts
- ❖ Pattern recognition
- ❖ Overburden
- ❖ Active Veto
- ❖ Better Timing During Spill (bunch timing)

Detector choices

- Detector possibilities
  - Water Cerenkov
  - Steel/Scintillator
  - Liquid Argon
  - Plastic/RPC

  n.b. 20 kilotons of anything is likely to be expensive.



Possible Detector

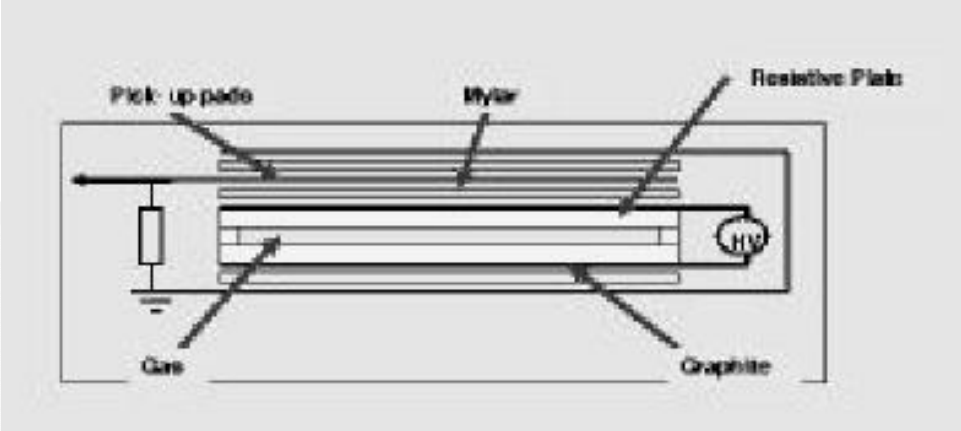
20 kiloton

containerized detector

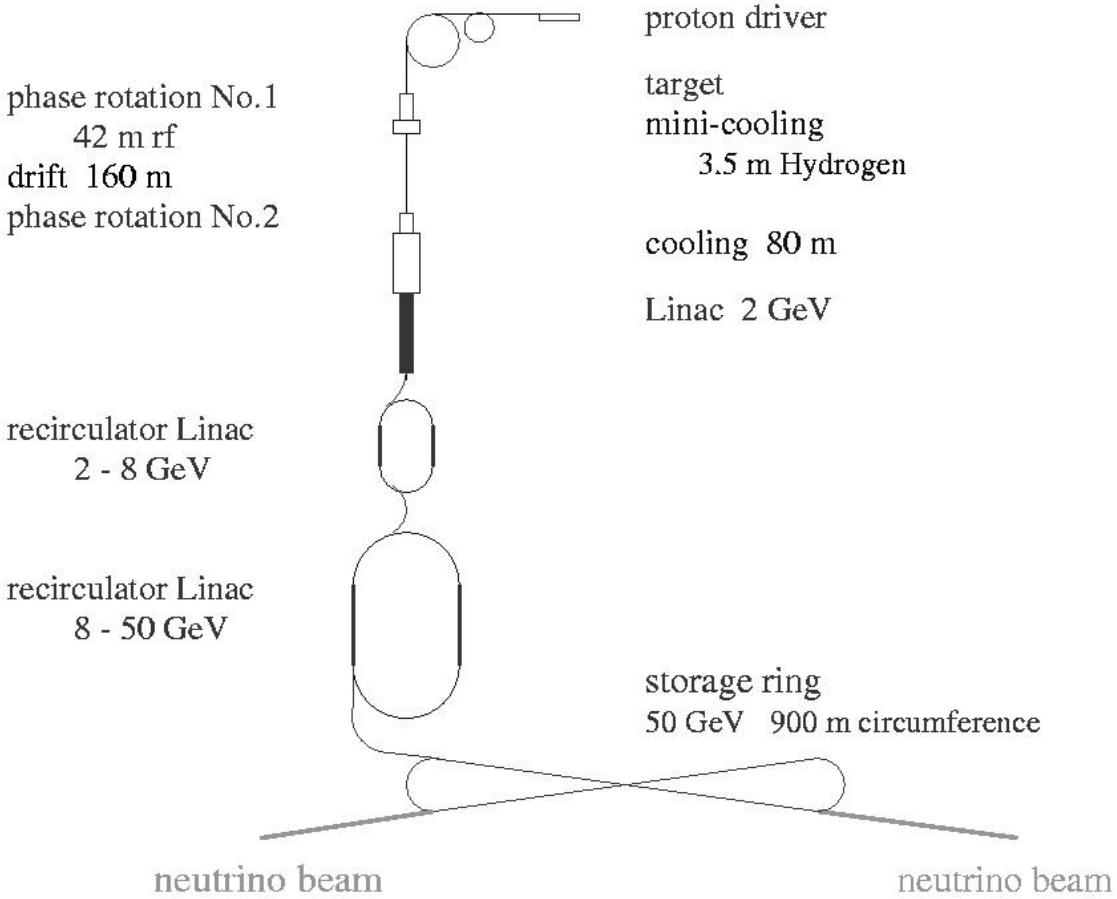
RPC's &

steel/plastic/H_2O

$30M-$250M

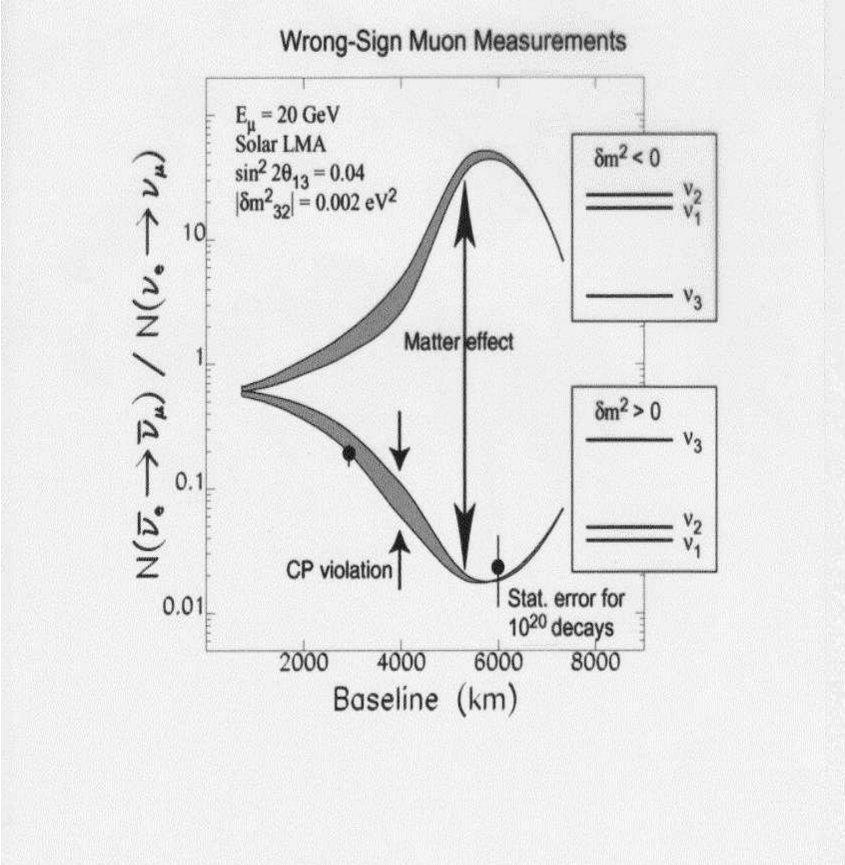


ν factory


proton driver
target
mini-cooling
3.5 m Hydrogen
cooling 80 m
Linac 2 GeV
phase rotation No.1
42 m rf
drift 160 m
phase rotation No.2
recirculator Linac
2 - 8 GeV
recirculator Linac
8 - 50 GeV
storage ring
50 GeV 900 m circumference
neutrino beam
neutrino beam

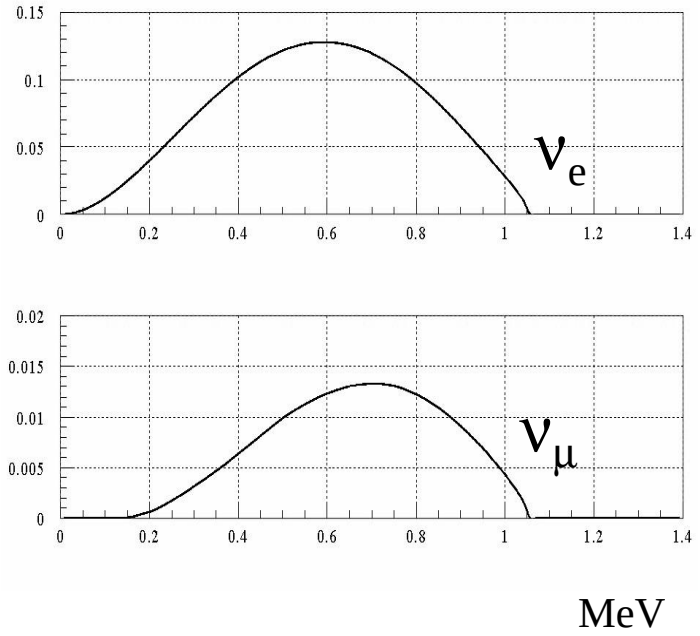
θ_{13} at a ν factory

- Easier signature (wrong sign muon)
- Can run with μ^+ or μ^-
- Push $\sin^2\theta_{13}$ to 10^{-4}

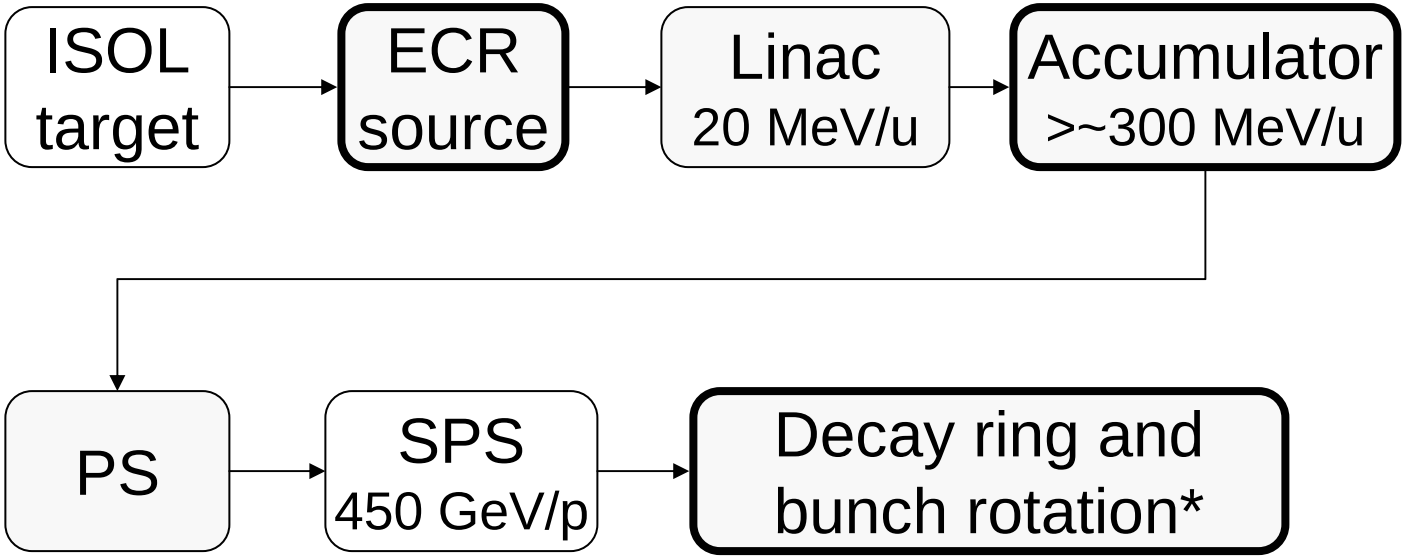


Beta Beams

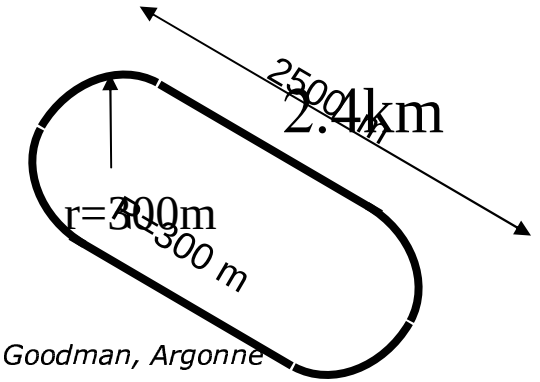
- Accelerate Heavy ions which β decay
- ^{6}He for ν, ^{18}Ne for $\bar{\nu}$
- Might use CERN-ISOLDE heavy ion accelerator, PS, SPS, +storage ring



β Acceleration



* CRUCIAL aspect for atmospheric background rejection.

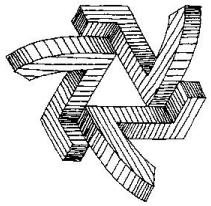


Physics reference numbers:

65%Transmittance into the decay ring

Γ=150 for ^{6}He

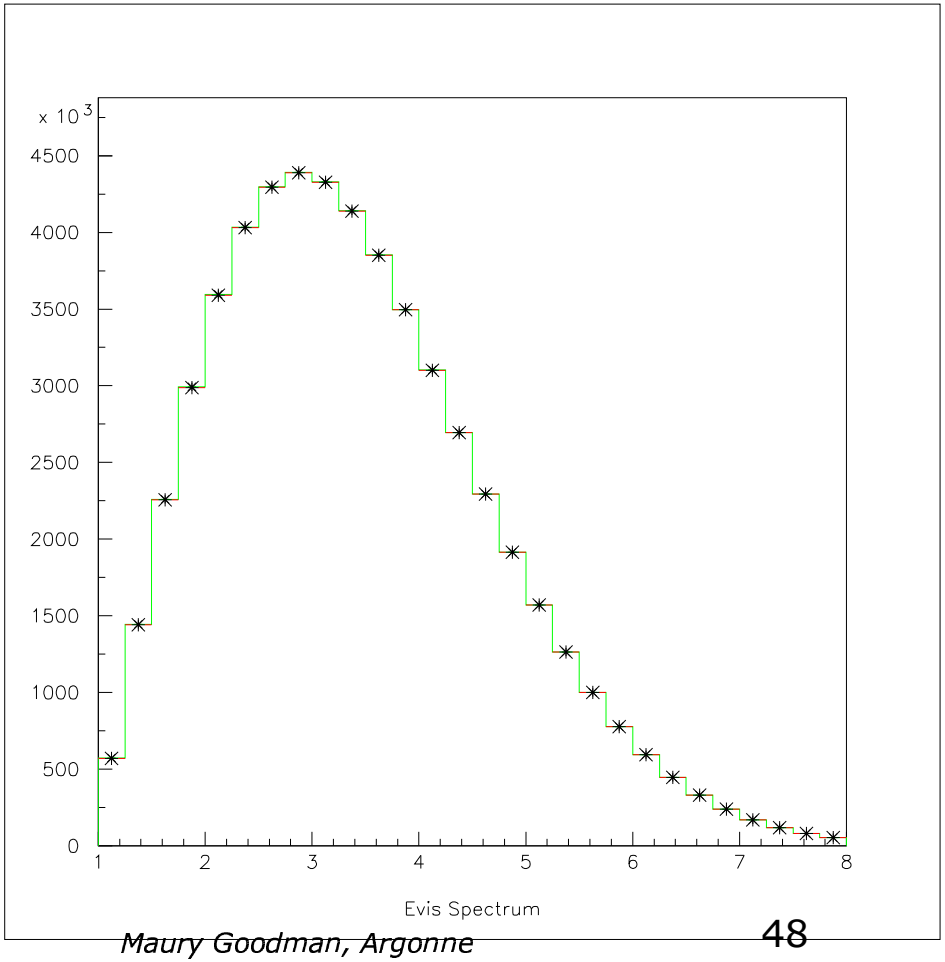
Acceleration cycle into the storage ring: 8s



Using Reactors for θ_{13}

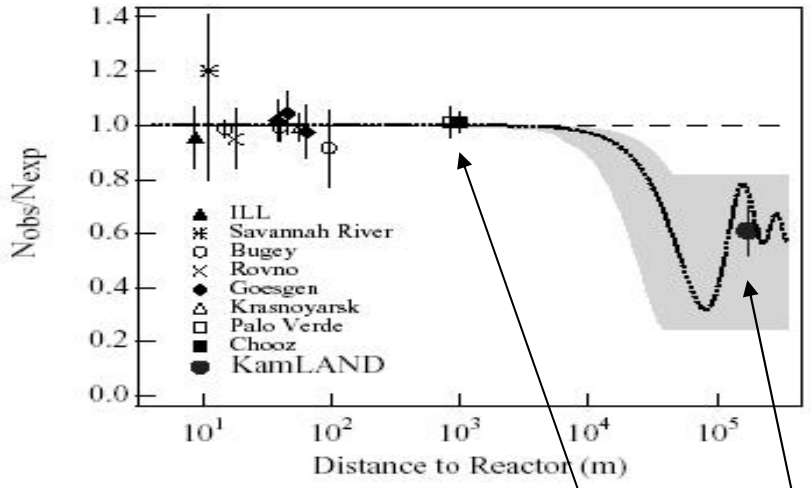
Reactor ν

- Reactors provide a fairly steady flux of 1-10 MeV ν's
- Signal $\propto 1/L^2$
- Background Reduced by overburden
- Experiments L>1km underground



Reactor search for θ_{13}??

- Previous experiments limited by 3% uncertainty in reactor power.
- All measure the same energy spectrum.
- Further detectors need more overburden to reduce backgrounds
- Need 10-100 tons (not kilotons)
- Use 2 or 3 similar detectors
- Need careful control of systematics!!!



KamLAND sees a 40% deficit/shape at 200km

related to Δm^2_{12}

Search for a 1-5% deficit/shape at ~1 km

related to Δm^2_{23}

Θ_{13} from reactors?

$P(\nu_e \rightarrow \nu_e) = 1$

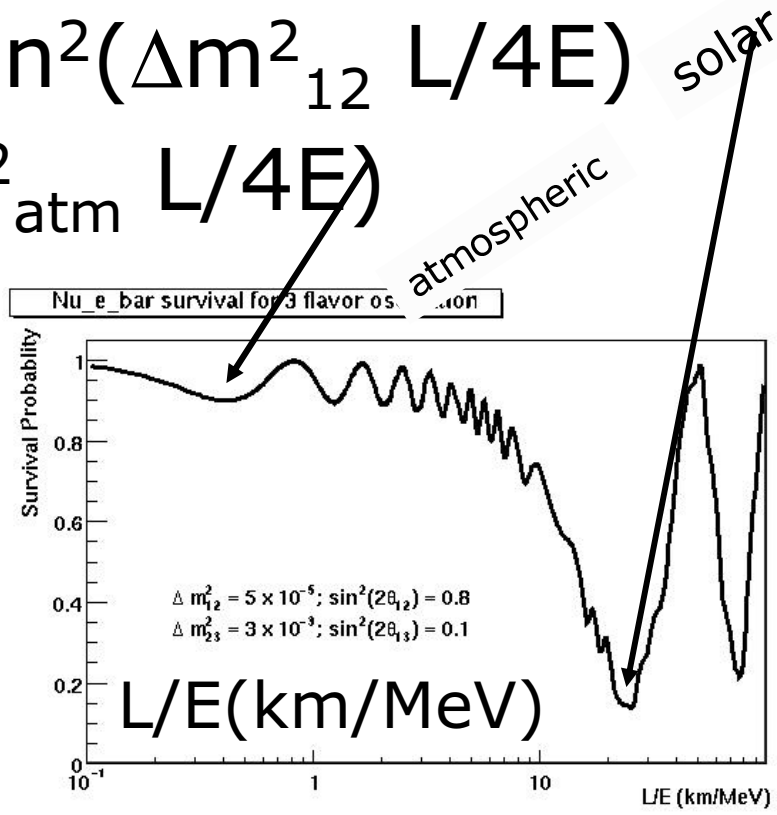
$- \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m^2_{12} L/4E)$

$- \sin^2 2\theta_{13} \sin2 (\Delta m^2_{atm} L/4E)$

(Ignores CP)

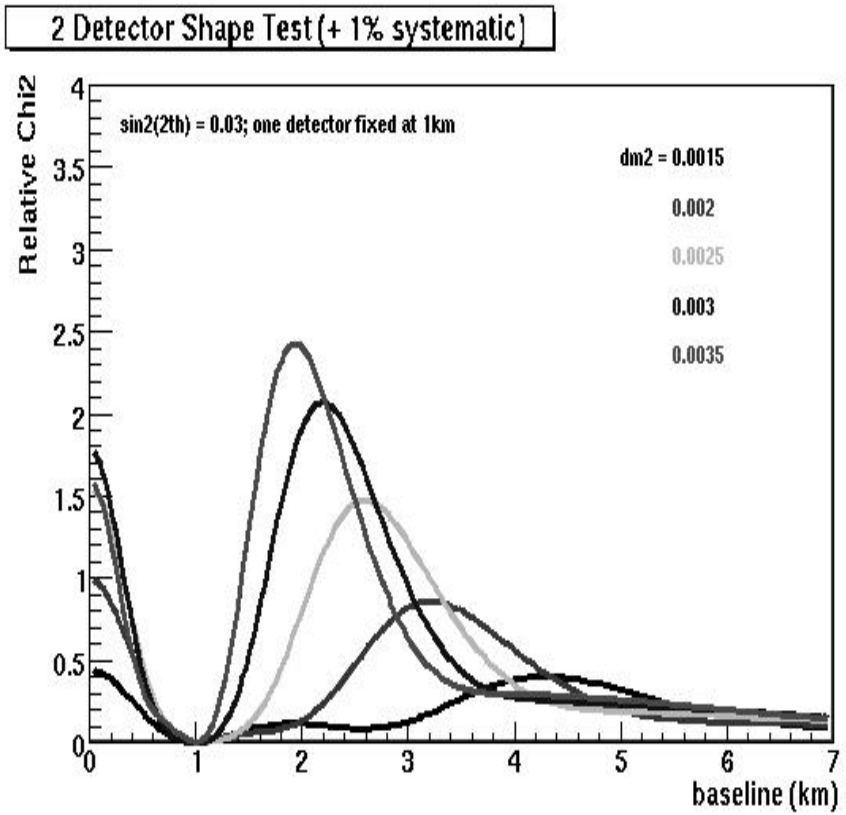
(Ignores matter)

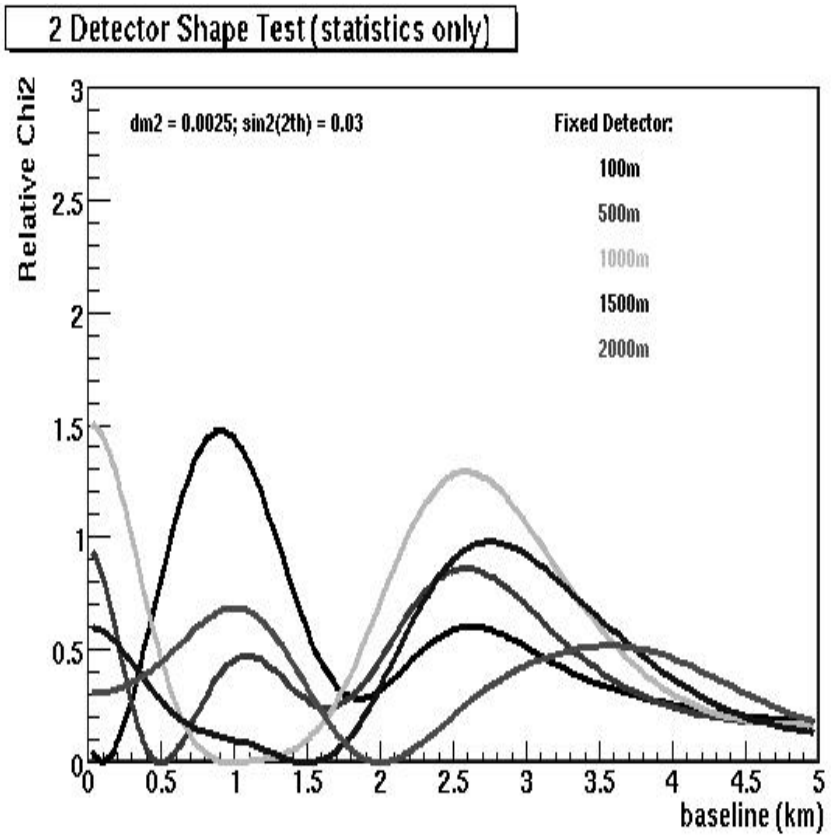
P



Detector Location

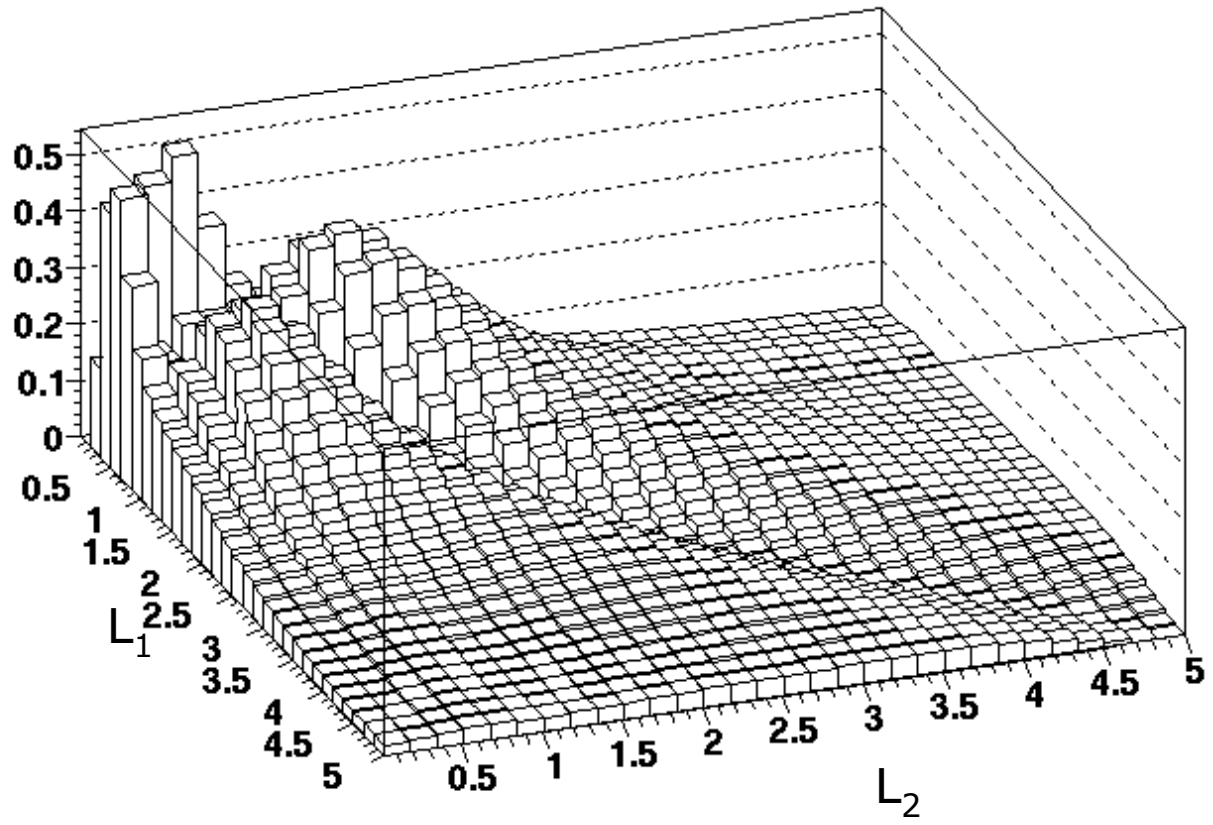
- Compare Shape test vs location; Δm^2_{atmo}



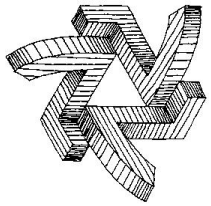


L_1, L_2 optimization

Statistics only



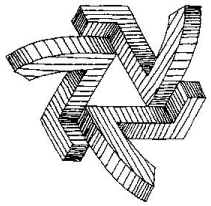
Possible Sites?



Previous Reactor Experiments and new sites under consideration

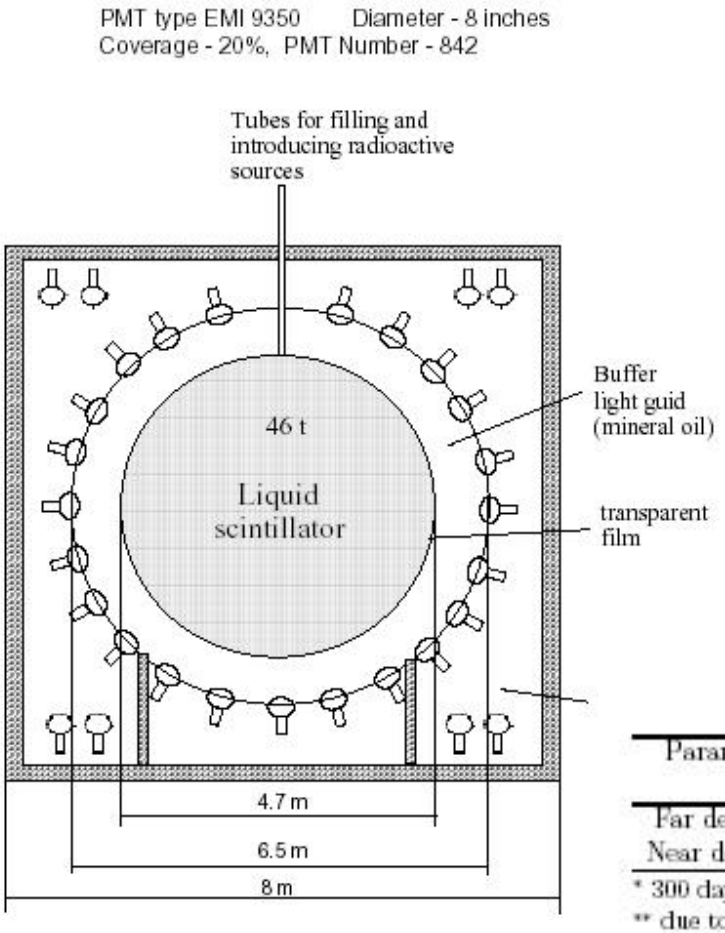
Chooz	France	1100 m	8.5 Gw	300 MWE	5 ton
Bugey	France	40/95 m	5.6 Gw	16 MWE	1/0.5 ton
Palo Verde	US	890 m	11.6 Gw	32 MWE	11.3 ton
KamLAND	Japan	180 km	200 GW(26)	2700 MWE	1000 ton
Krasnoyarsk	Russia	115/1000 m	~1 GW	600 MWE	46t
Chooz-2	France	450/1100 m	8.5 GW	?/300 MWE	
Diablo Canon	US (Cal)	(~1 km?)	6.1	600 MWE	
Wolf Creek	US (KS)	(~1 km?)	3.2 GW		
Boulby	UK	25 km	3.1 GW	2860 MWE	
Heilbronn	Germany	19.5 km	6.4 GW	480 MWE	
Kashiwasaki	Japan	1.7 km	24.3 GW		20 ton
Texono	Taiwan	(~2 km?)	4.1 GW(NP4)		
IMB/Perry	US(Ohio)	10 km	1.2 GW	1570 MWE	
Reactor	Location	Detector L	Power	Overburden	Detector M

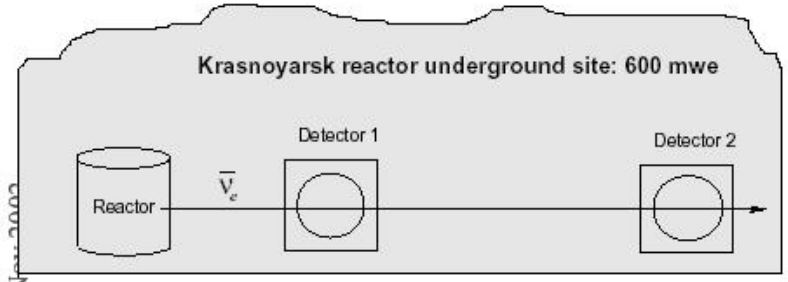
Kr2DET



- Two 46 ton detectors at 115m, 1000m near Krasnoyarsk
- 900 8” pmts for 20% coverage
- 4200 events/day (near); 55/day (far)
- Much of the city is at depth 600 MWE → low backgrounds
- Reactor fuel cycle well understood

KR2DET (2)





x/0211070 v1 28 Nov 2002

	115 m	1000 m
Target:	46 t	46 t
Rate:	4200/day	55 /day
S:B	>>1	~ 10:1

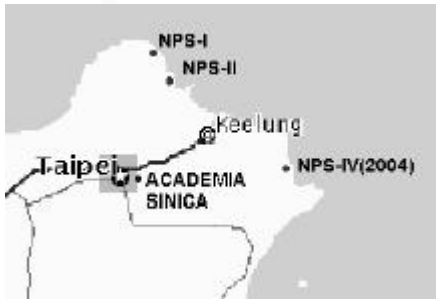
Table 1:

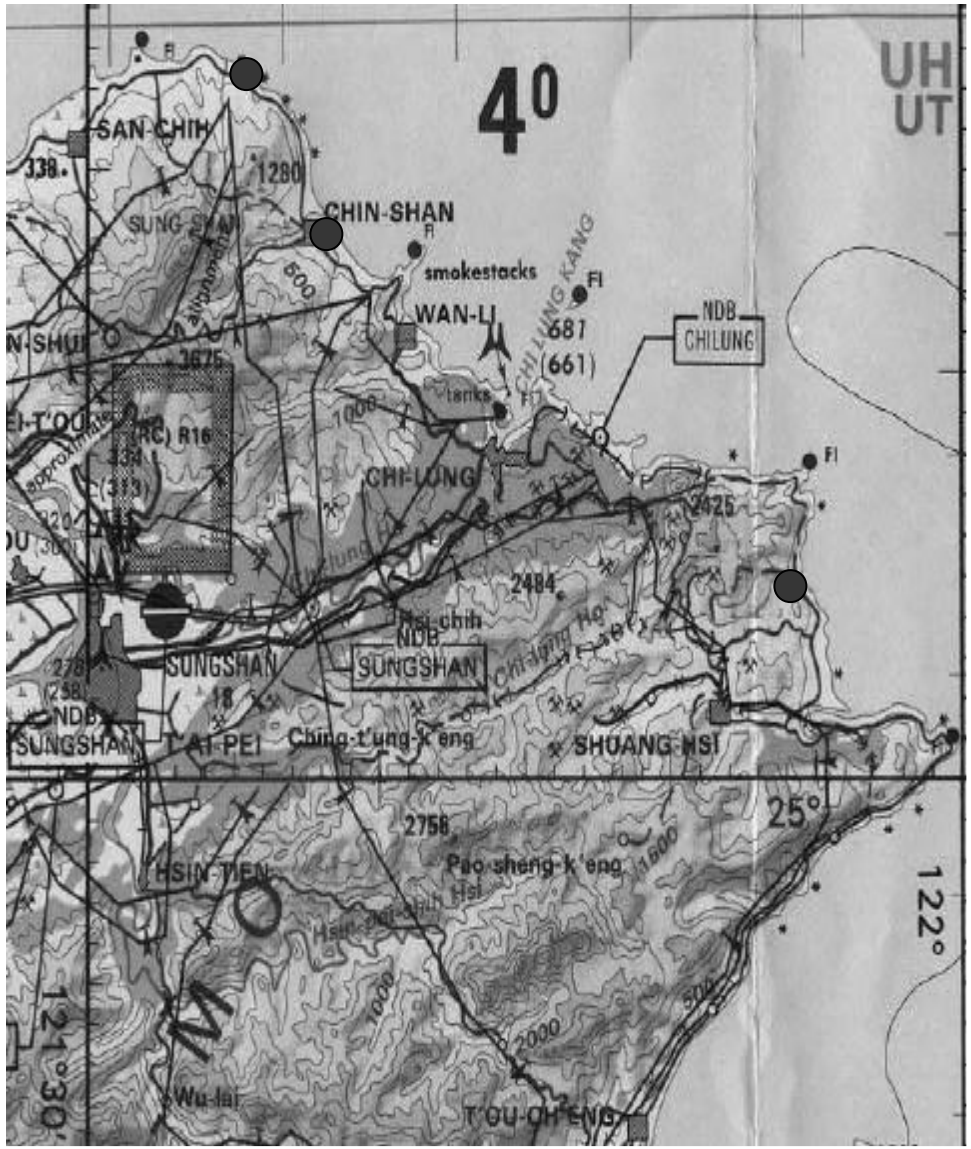
Parameter	Distance, m	Target, mass, ton	$N(e^+,n)$, day^{-1}	$N(e^+,n)$, year^{-1}*	Backgr., day^{-1}	
					correl.	accid.**
Far detector	1000	46	55	$16.5 \cdot 10^3$	5	~0.3
Near detector	115	46	4200	$12.5 \cdot 10^5$	5	~0.3

* 300 days/year at full power.
** due to internal radioactivity of the detector materials only.

Texono sites

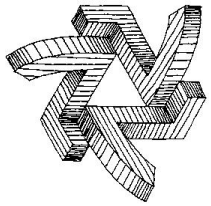
- Small experiment for ν magnetic moment at NPS-2
- I(1.78 Gw); II(2.90Gw); IV(4.1Gw) now 2006
- Road tunnels and mines in area





March 31, 2003
University of Michigan Seminar

Costs (from M. Shaevitz)



Comparison of Possible Scenarios

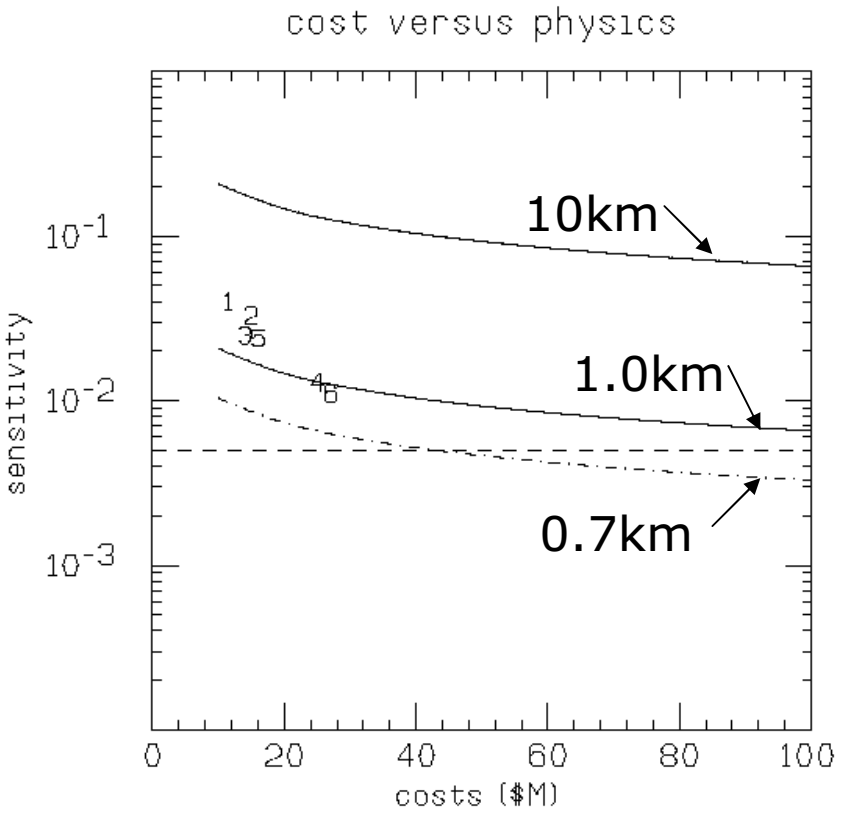
- Example scenarios with 3 year data runs
  - 50 ton far (near) detector at 1200m (150m)
  - One (or two) 3 GW reactors
- Costs
  - Detector based on similar MiniBooNE detector
  - Tunnel/hall cost estimates from NuMI engineer
  - Should add +50% contingency to cost

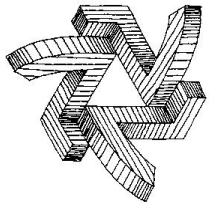
Unit	Cost ($M)
Detector	5
Hall at 32ft	1
Hall at 300ft	2
Hall at 600ft	3
Tunnel&Halls at 32ft	5
Tunnel& Halls at 300ft	15
Tunnel&Halls at 600ft	17

Source	Depth (mwe)	Detector	Events Far	Background	Rel Norm Err	Cost ($M)	$\sin^2 2\theta_{13}$ @ $\Delta m^2 = 2.5\times10^{-3}$ 90% CL	$\sin^2 2\theta_{13}$ @ $\Delta m^2 = 2.5\times10^{-3}$ 3 σ
One	32	Fixed	64,000	101,000	0.008	12	0.056	0.132
Reactor		Moveable	57,000	91,000	0.0023	15	0.052	0.122
	300	Fixed	64,000	10,1000	0.008	14	0.024	0.057
		Moveable	57,000	9100	0.0023	25	0.012	0.029
	600	Fixed	64,000	5100	0.008	16	0.024	0.055
		Moveable	57,000	4600	0.0023	27	0.011	0.027
Two	32	Fixed	128,000	110,000	0.008	12	0.040	0.093
Reactors		Moveable	115,000	99,000	0.0016	15	0.033	0.077
	300	Fixed	128,000	10,900	0.008	14	0.025	0.059
		Moveable	115,000	9900	0.0016	25	0.013	0.031
	600	Fixed	128,000	5500	0.008	16	0.024	0.056
		Moveable	115,000	4900	0.0016	27	0.011	0.025

Physics vs costs

- Scale cost of Chooz ($10M) vs detector size
- 10km, 1.0km, 0.7km
- Stats only
- Comparable to [1-6] Shaevitz estimates
- Looks promising





Labs for Underground Neutrino Research

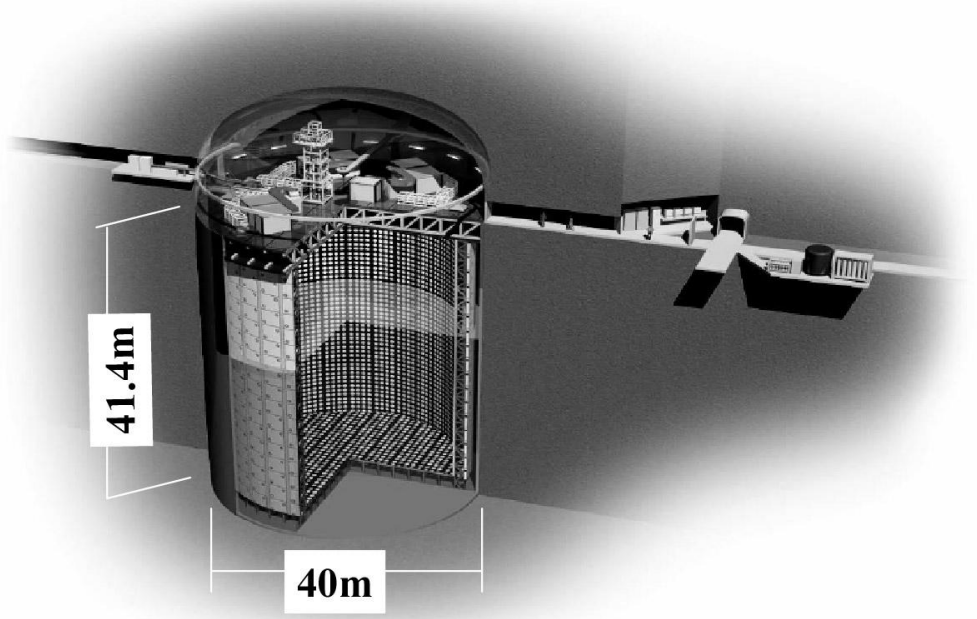
Gran Sasso

- Borexino — solar
- GNO — solar
- Heidelberg-Moscow — $0\nu-\beta\beta$
- LVD — supernova
- OPERA — long-baseline
- ICARUS — long-baseline
- MACRO — atmospheric

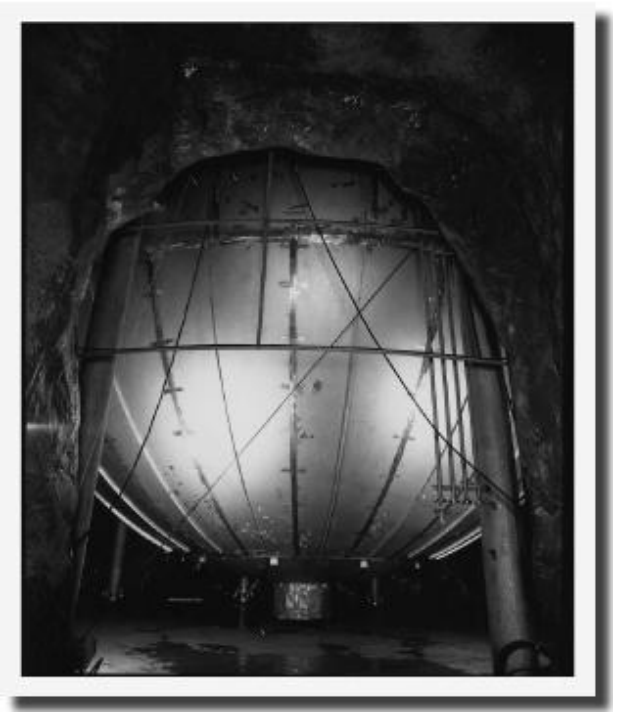
Kamioka Lab

50,000 ton water Cherenkov detector (22.5 kton fiducial volume)

Optically separated INNER and OUTER detector

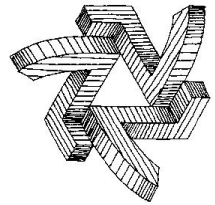


Super-Kamiokande/K2K

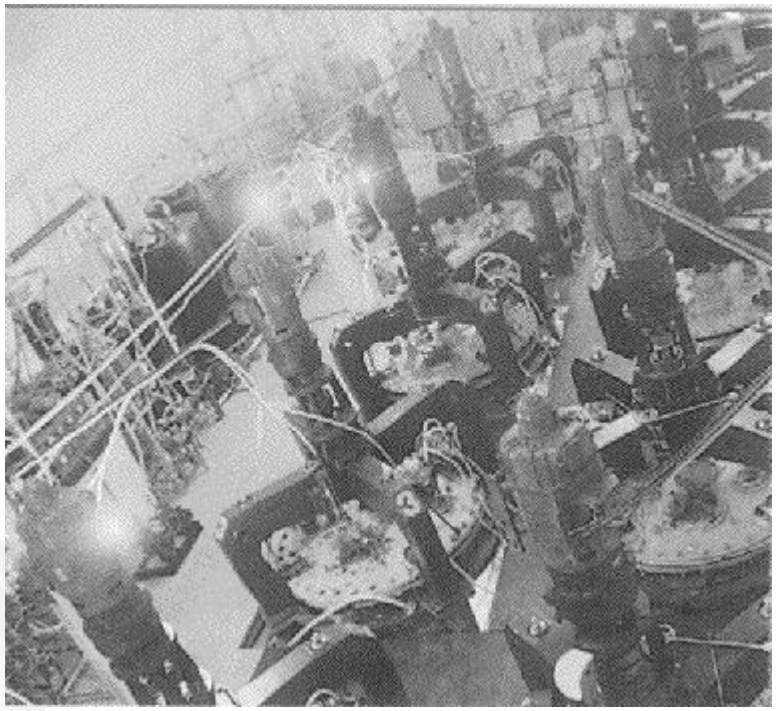


Kamland

Baksan

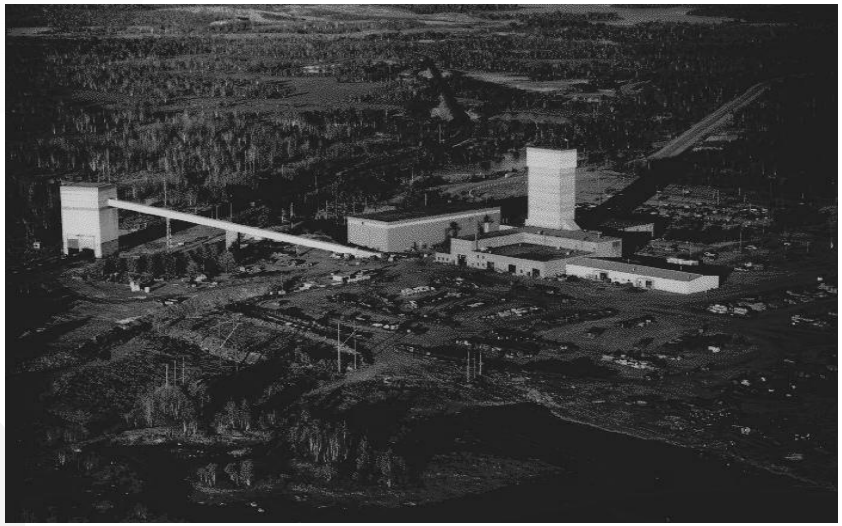


- Located in Caucausus Mountains
- Home to SAGE (Solar) and BUST (Atmospheric) experiments

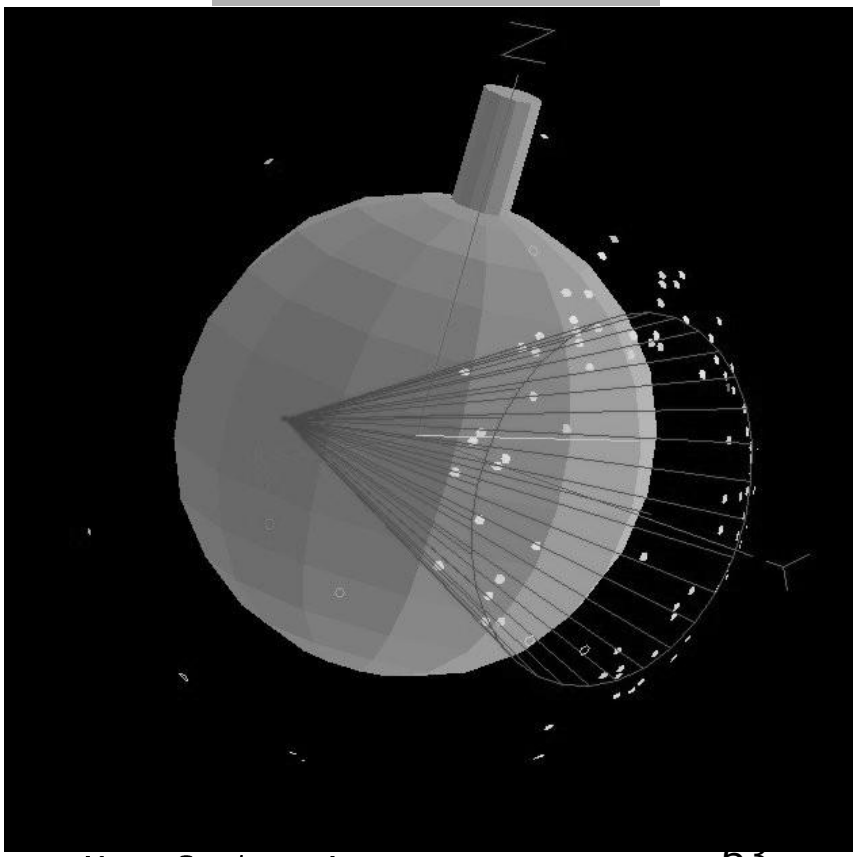


Sudbury

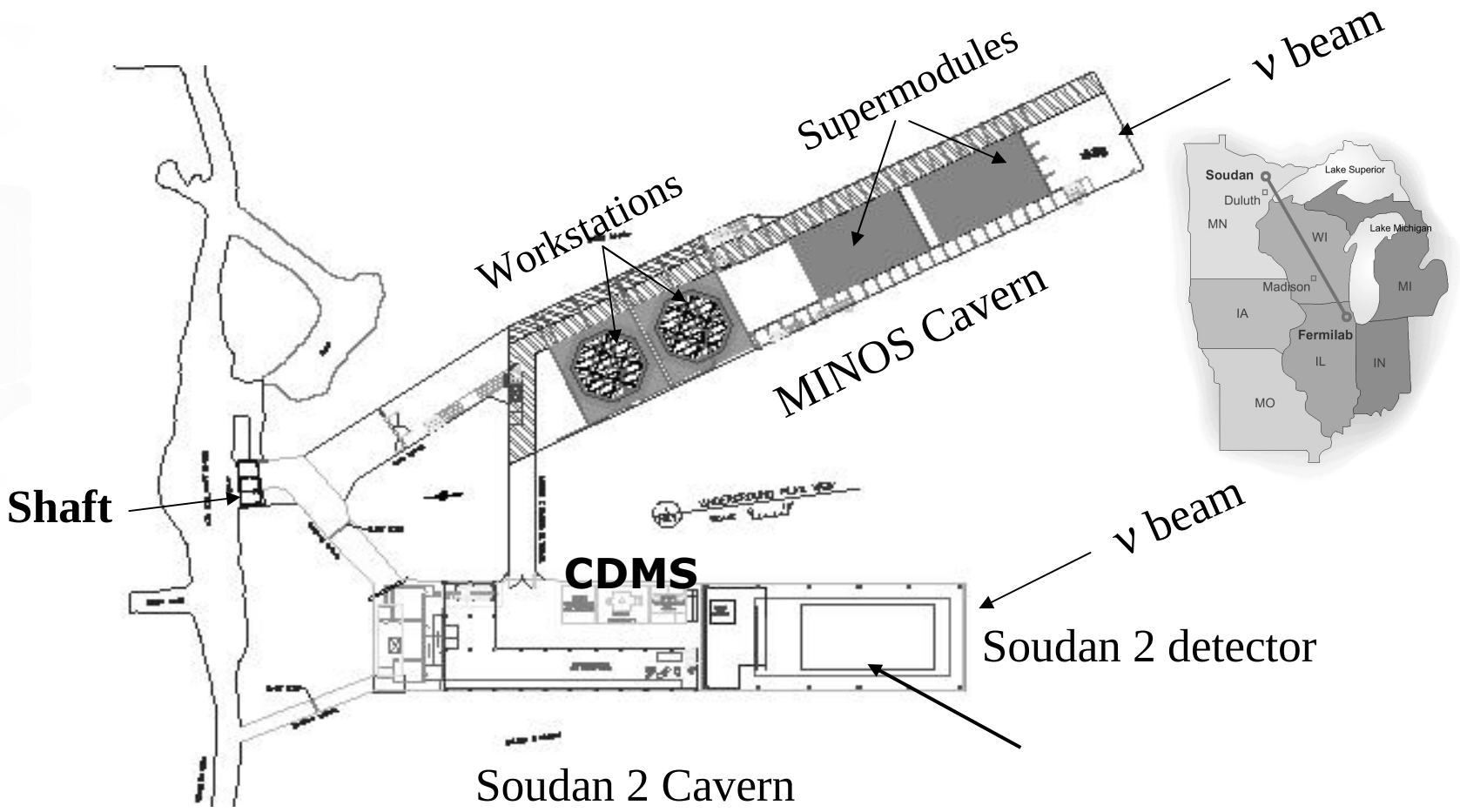
- Sudbury Ontario Canada
- SNO will measure NC again
- New International Facility for Underground Science



SNO ν event



Soudan Underground Physics Laboratory

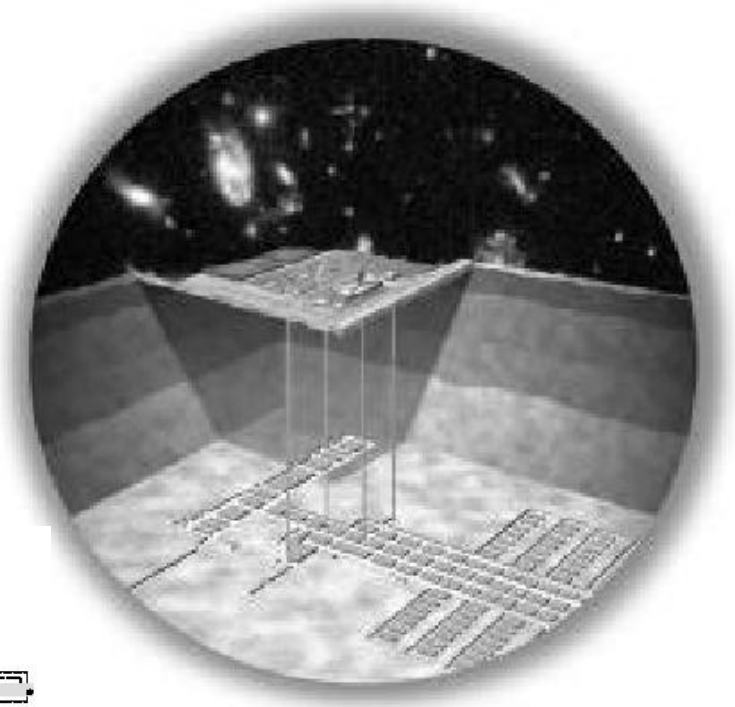


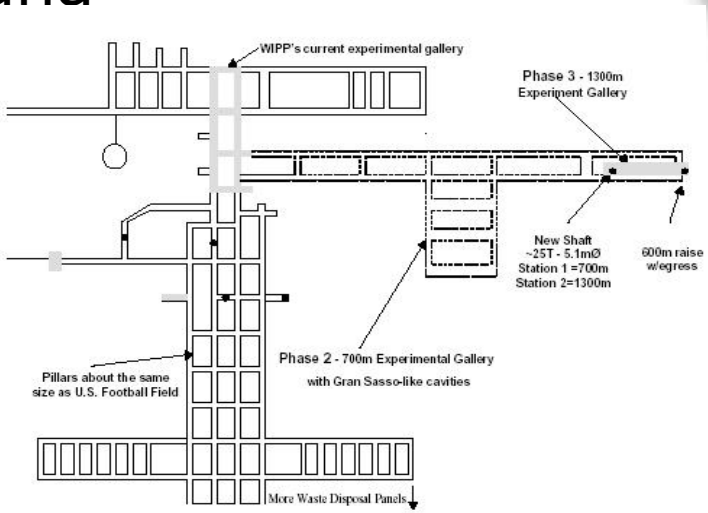
Frejus

- Site of previous large p-decay detector
- New tunnel motivated by Mt. Blanc accident
- Possible site for ν superbeam from CERN SPL or β-beam from ISOLDE/SPL

WIPP
Waste Isolation Pilot Plant

- Carlsbad New Mexico
- Possible site for
  - OMNIS
  - EXO
  - Majorana
  - UNO





NUSEL

National Underground
Science and Engineering Lab

A NUSEL collaboration has submitted a proposal to NSF

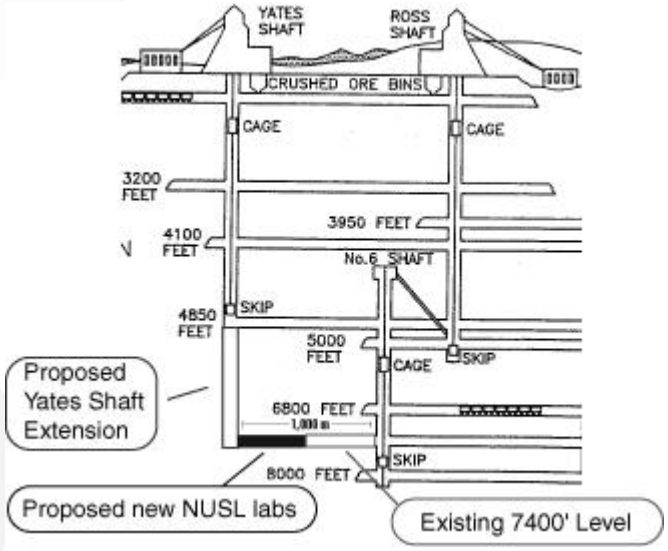
Areas of science focus (e.g., Bahcall Report*):

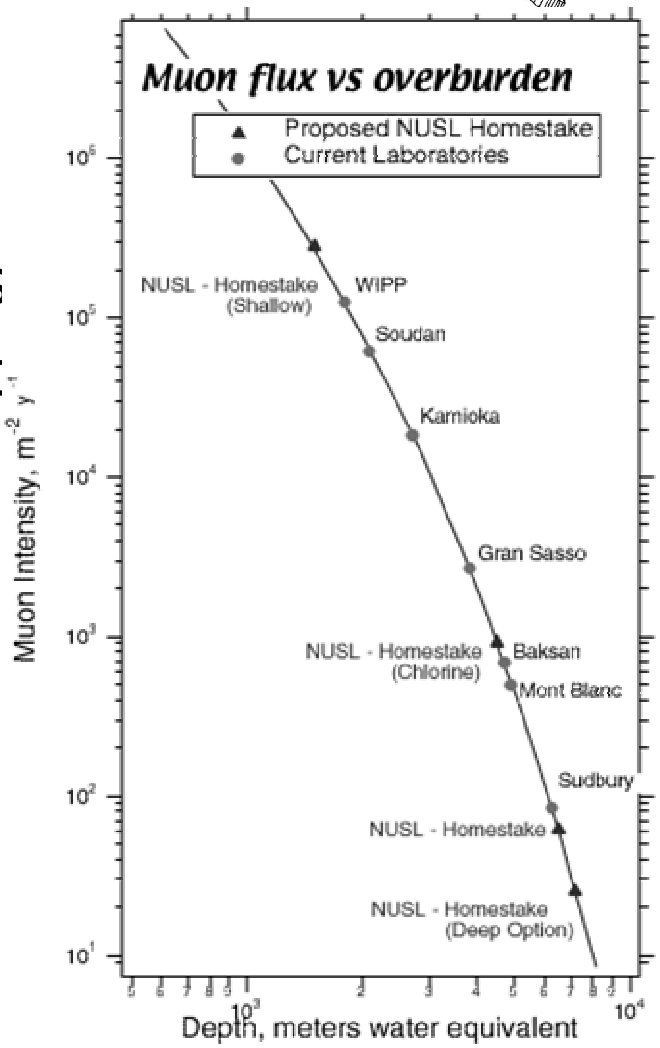
1. Solar νs	2. $\beta\beta$ decay
3. Dark matter	4. Nucleon decay
5. Atmospheric νs	6. Long baseline νs
7. Supernova νs	8. Nuclear astrophysics
9. Geoscience	10. Materials development
11. Nonproliferation	12. Geomicrobiology

*http://int.phys.washington.edu/NUSL/

NUSEL

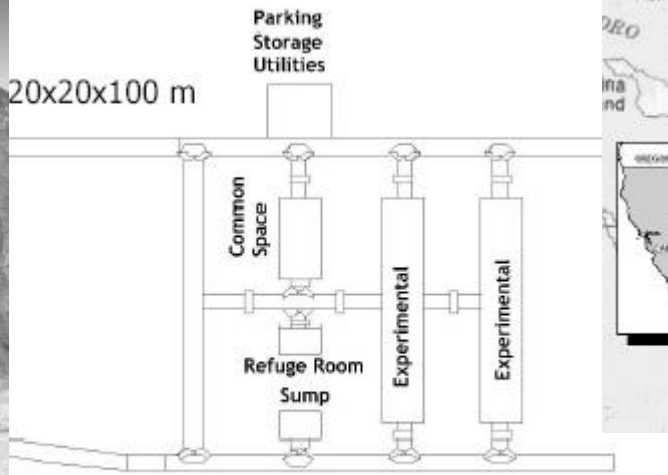
- Homestake South Dakota
- Mine recently closed
- Political & scientific endorsements
- 12/02 NUFAC report "time is right"



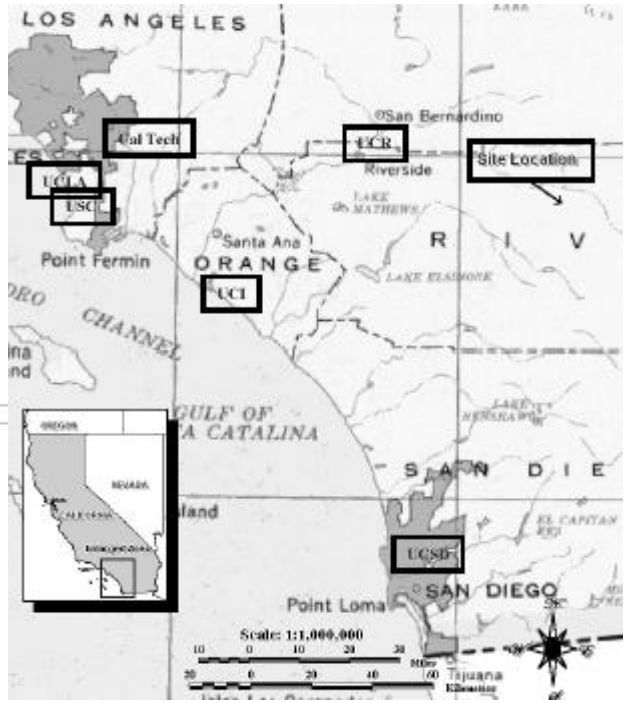


San Jacinto

- Proposal for new laboratory with horizontal access
- Near Palm Springs California/Chino Canyon
- Submitted to NSF & DOE
- About $200M to construct

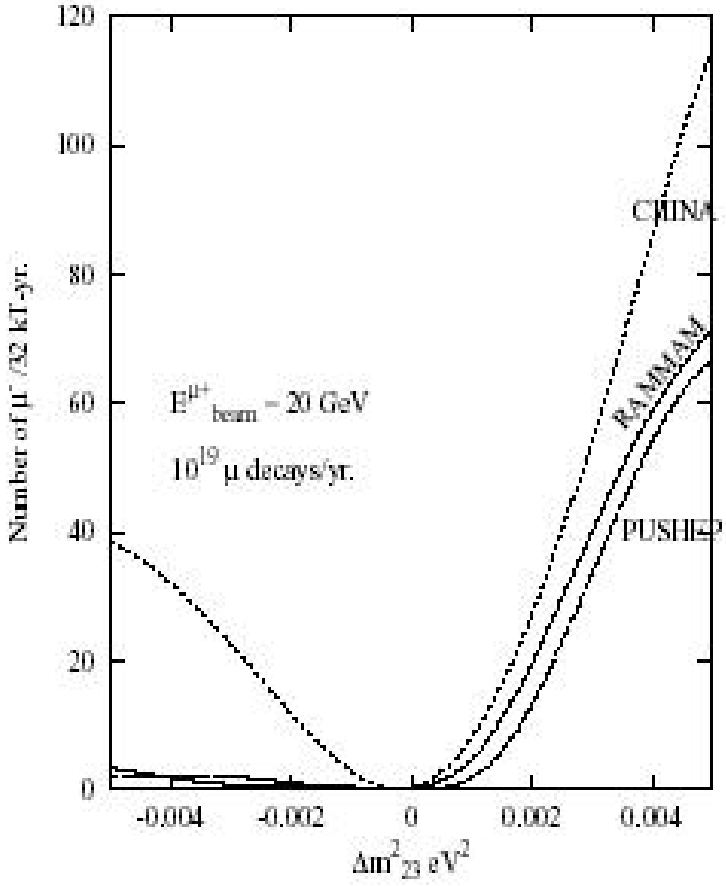


San Jacinto Underground Labratory Complex



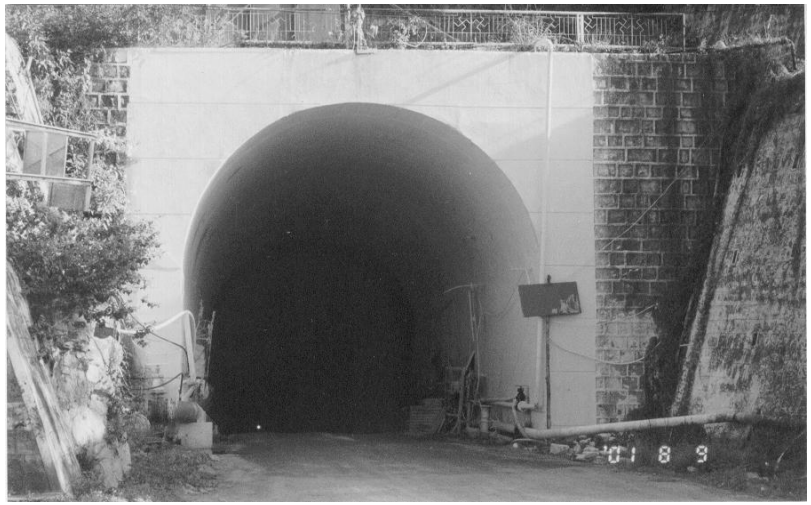
Indian Neutrino Observatory (INO)

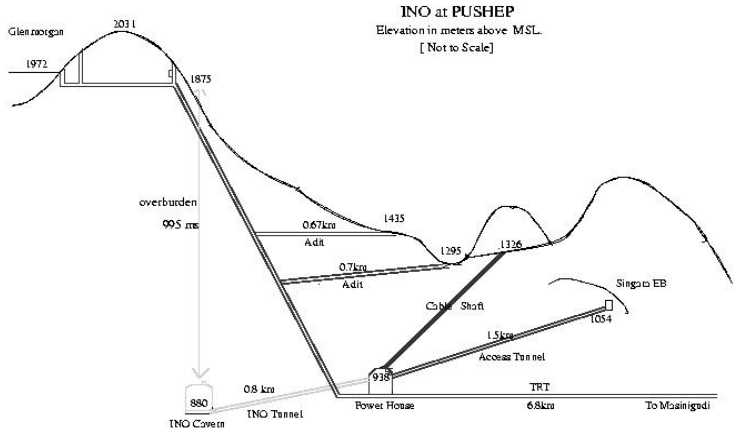
- ~40 physicist from 12 institutions
- 2 sites being considered
  - PUSHEP (Pykara Ultimate Stage Hydro Electric Project)
  - RAMMAM Hydro Electric Project Site
- ICAL; 30 kiloton Iron/RPC calorimeter
- Start with atmospheric, then long-baseline (wrong sign muons)



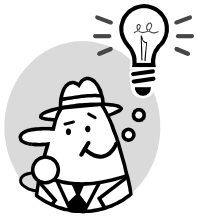
INO PUSHEP

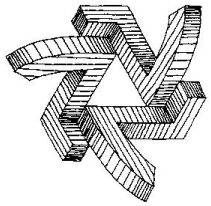
- Near Ooty Cosmic Ray experiments in Tamil Nadu
- PUSHEP better rock
- RAMMAM (Himalayas near Darjeling) deeper
- Physics & site proposals for both sites being developed (2003)





A thought



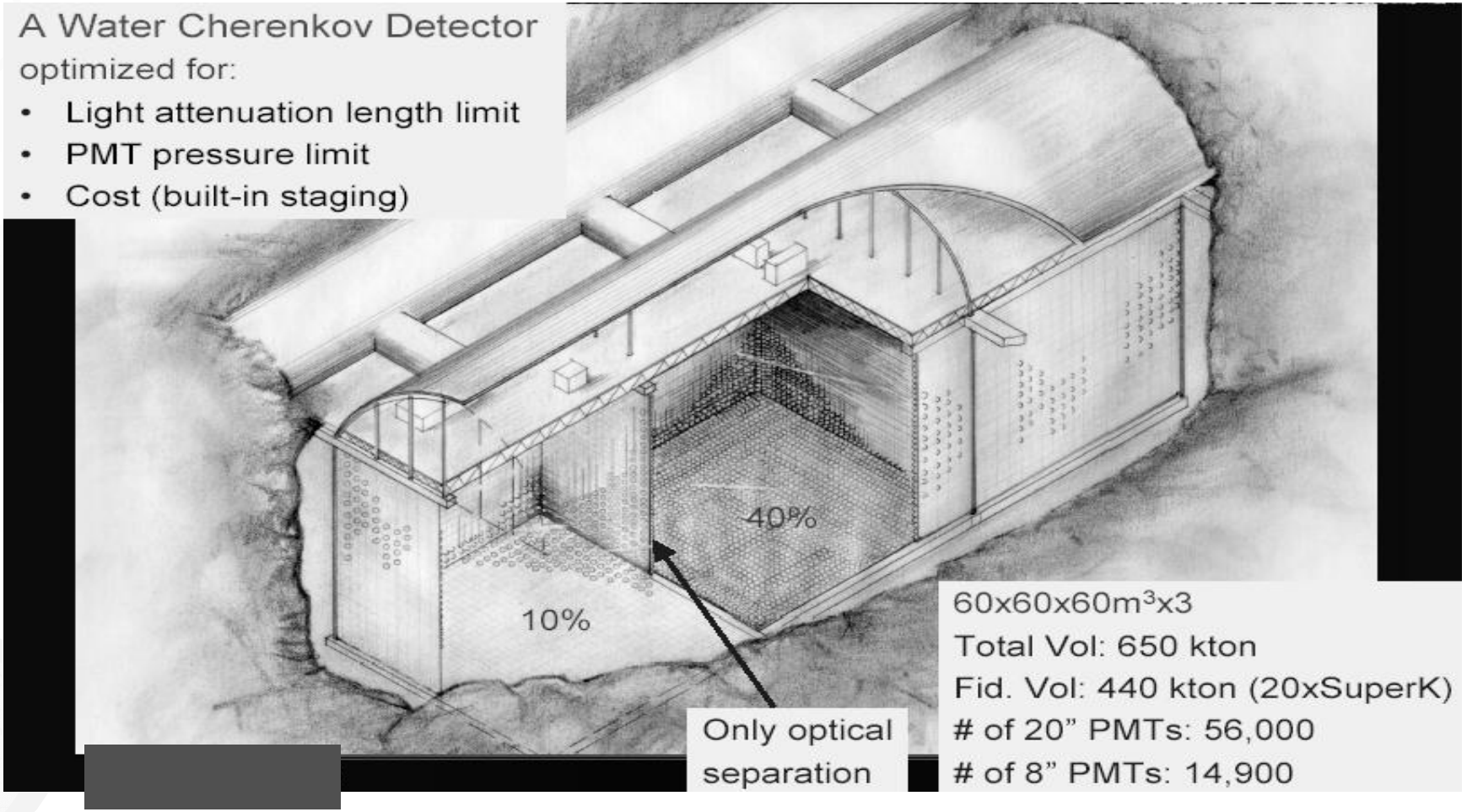


- The best way to find out more about neutrinos may be to continue to pursue proton decay.

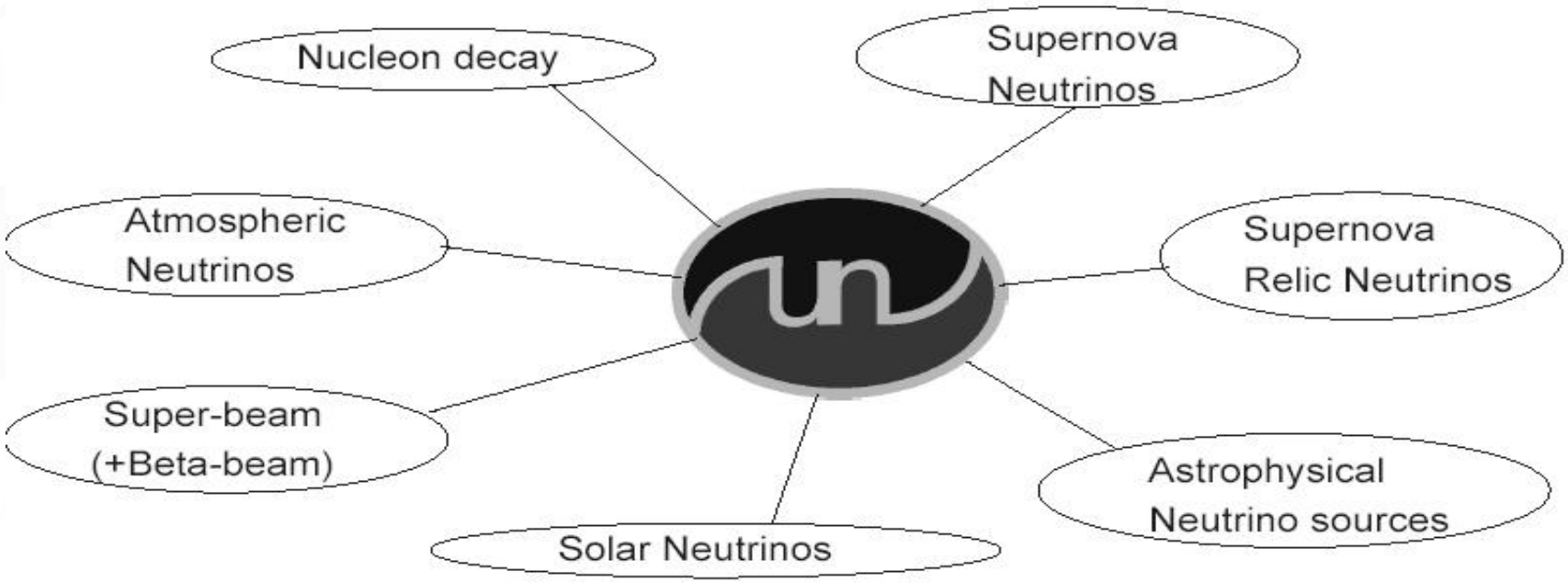
- Maybe we'll also find that the proton decays!

UNO

UNO Conceptual Design



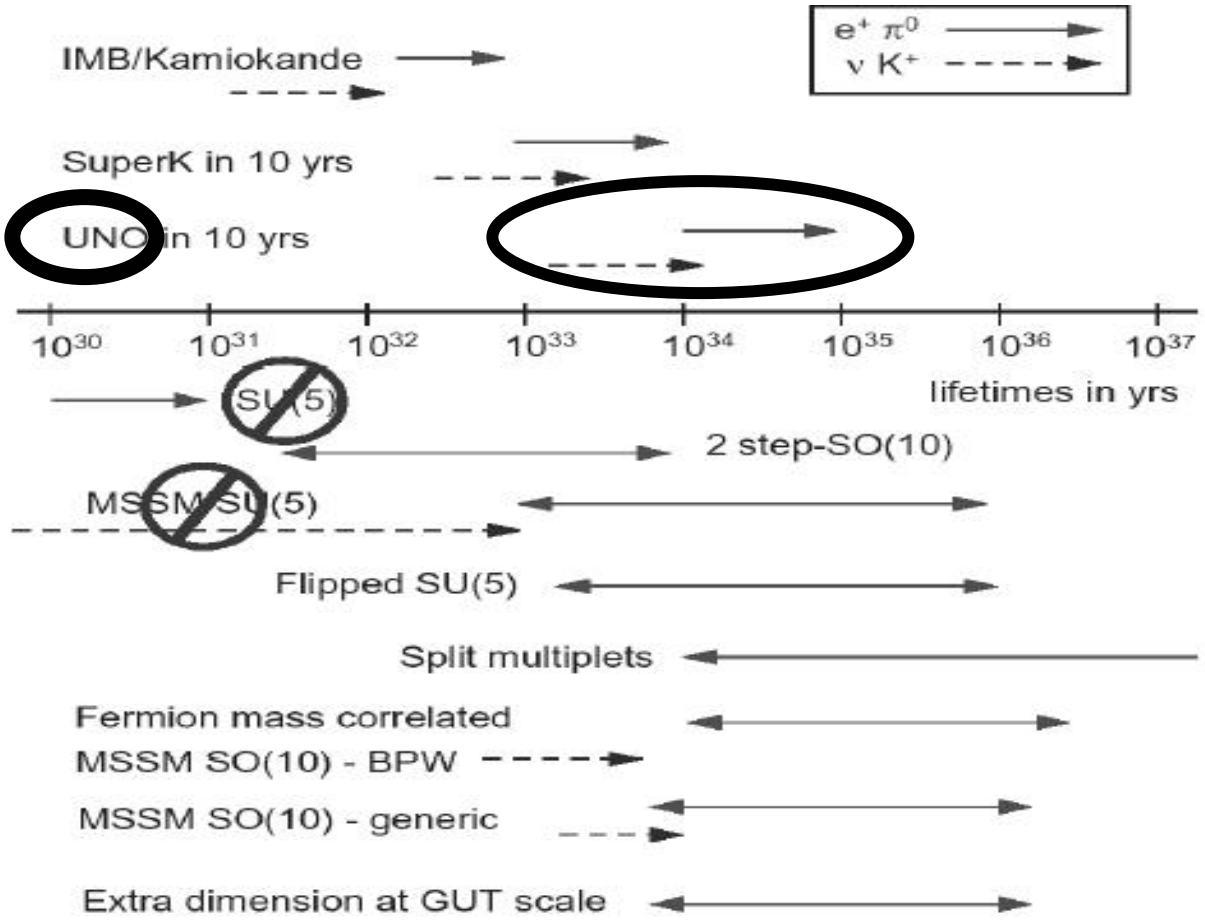
UNO physics goals



⇒ Multi-purpose detector with comprehensive physics programs for astrophysics, nuclear physics and particle physics

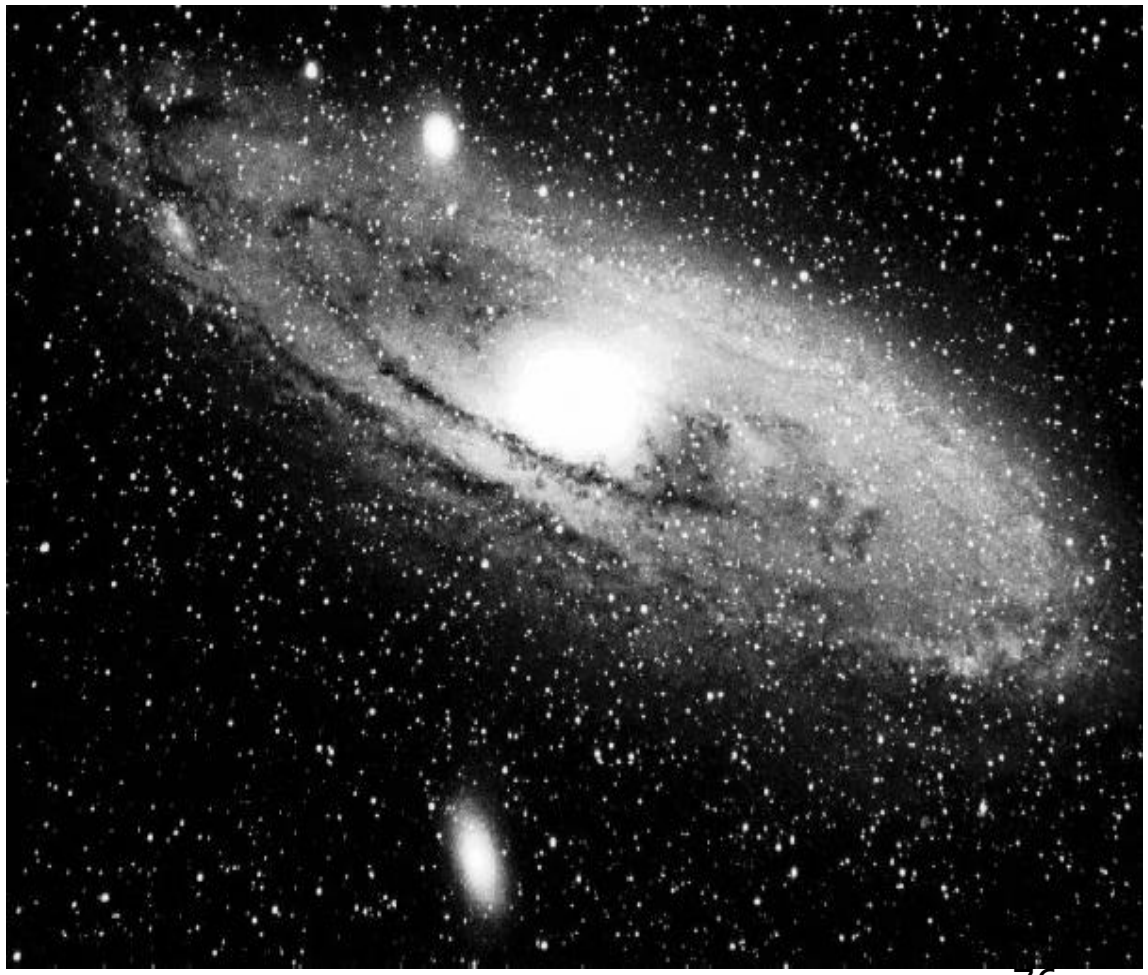
⇒ Synergy between accelerator physics and non-accelerator physics

UNO p-decay sensitivity



Andromeda

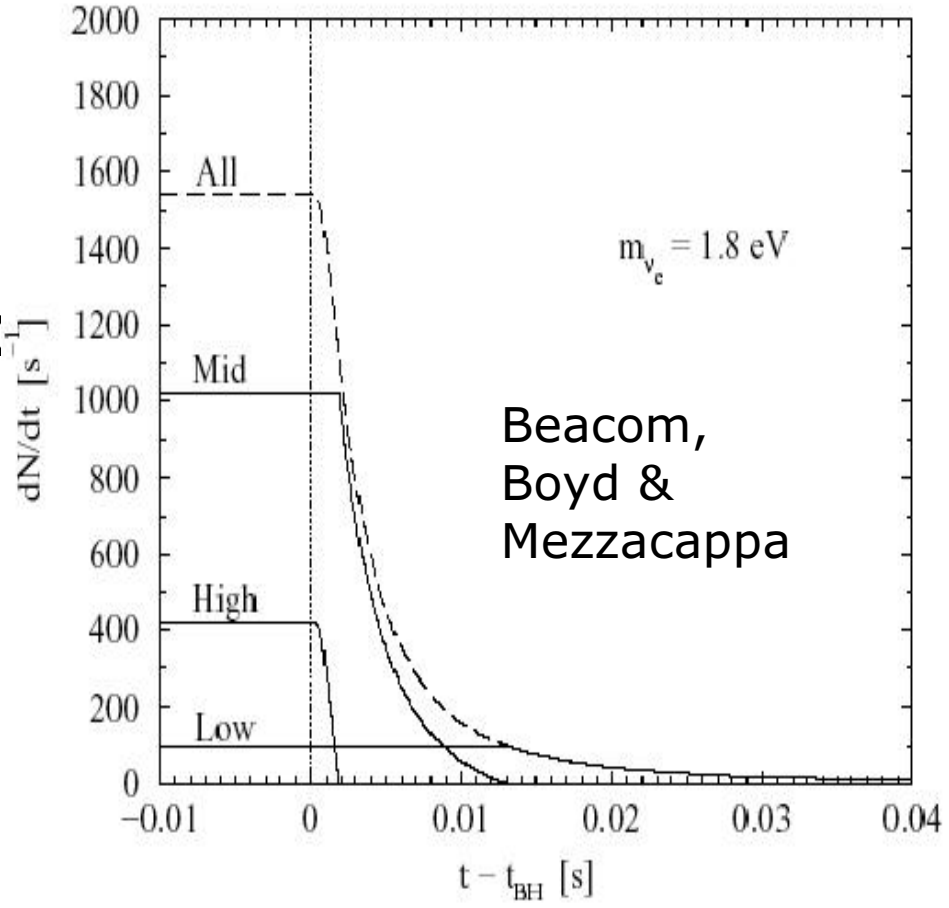
- Supernova Reach 1 Mpc (local group of galaxies)
- Rate 1/15 per year?



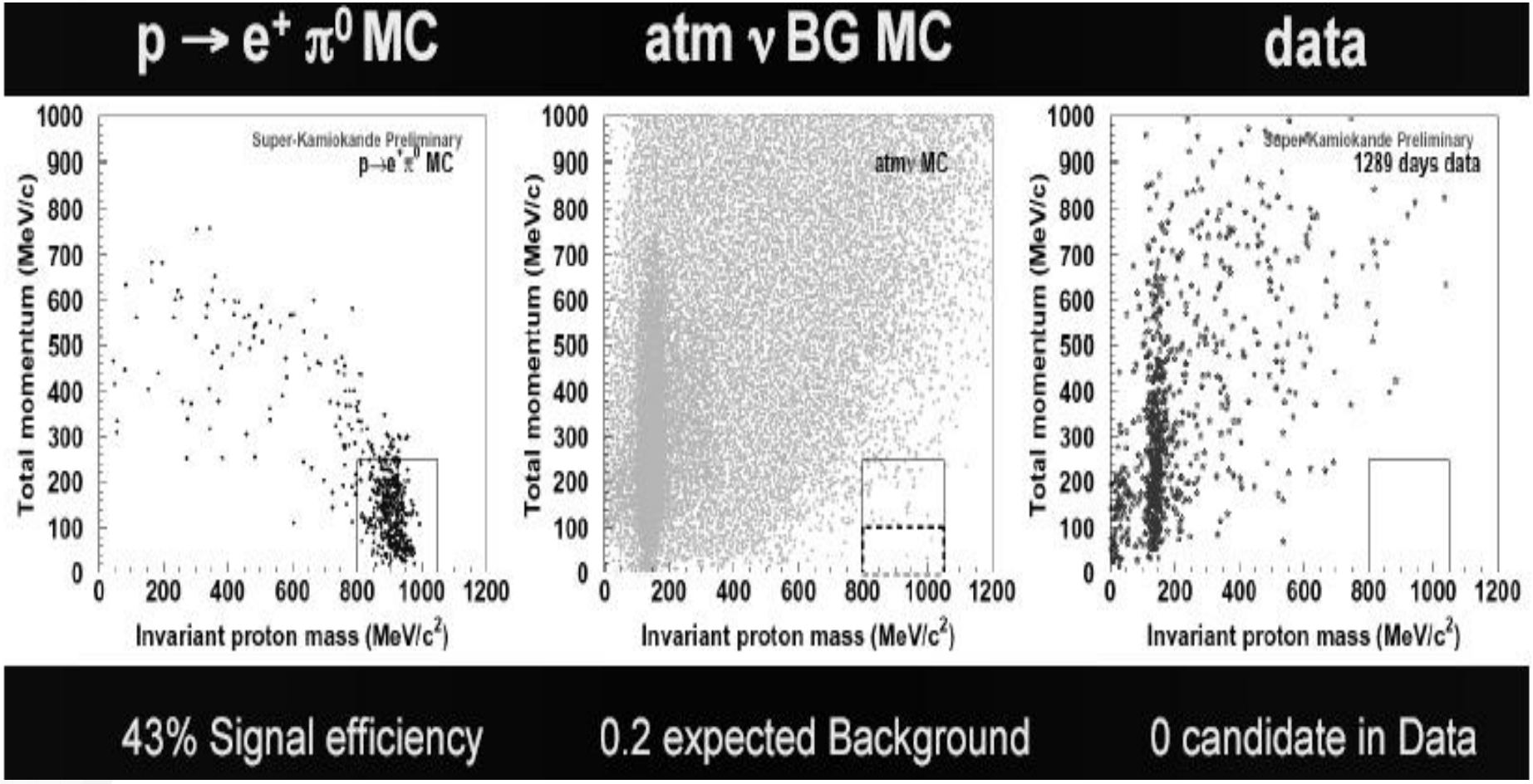
Maury Goodman, Argonne

Galactic Supernova

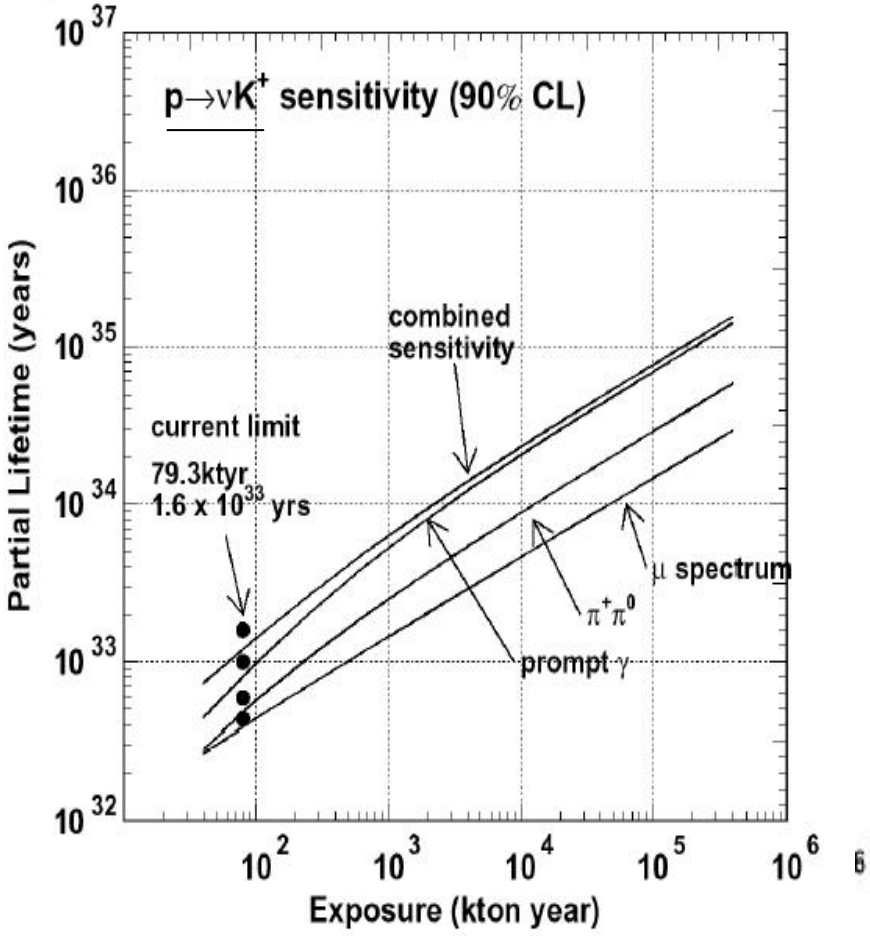
- 140,000 events (UNO)
- msec timing structure of the flux >>>core collapse mechanism
- Observe birth of Black hole

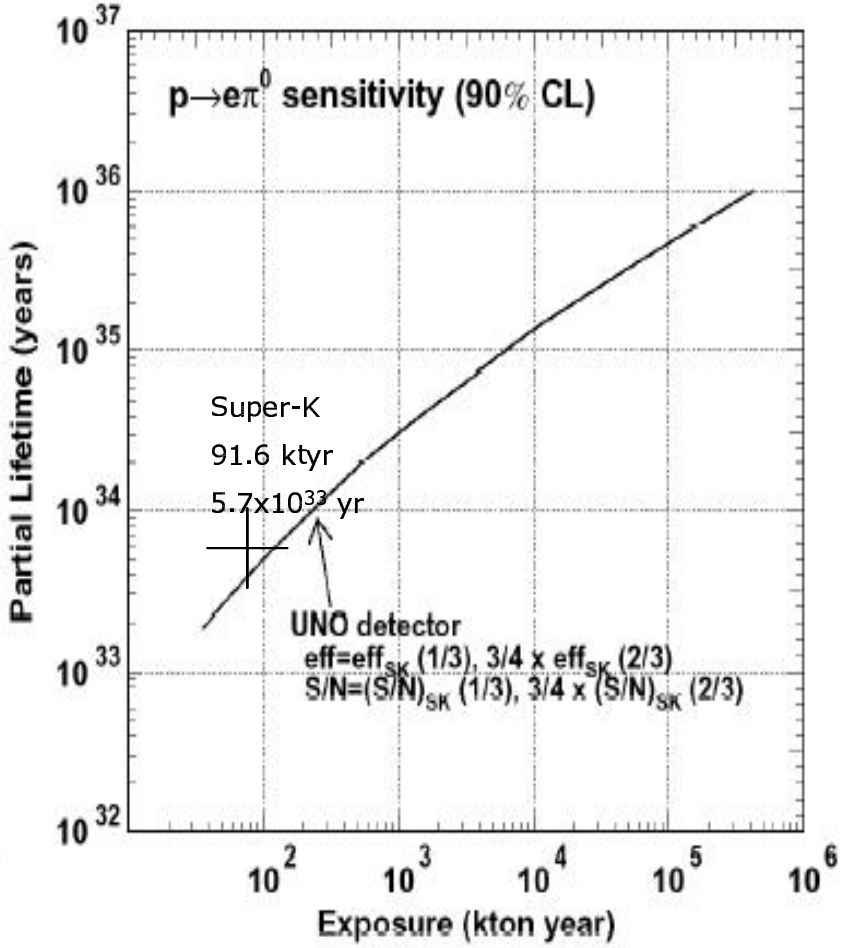


$p \rightarrow e^+ \pi^0$ search (Super-Kamiokande)



UNO sensitivity

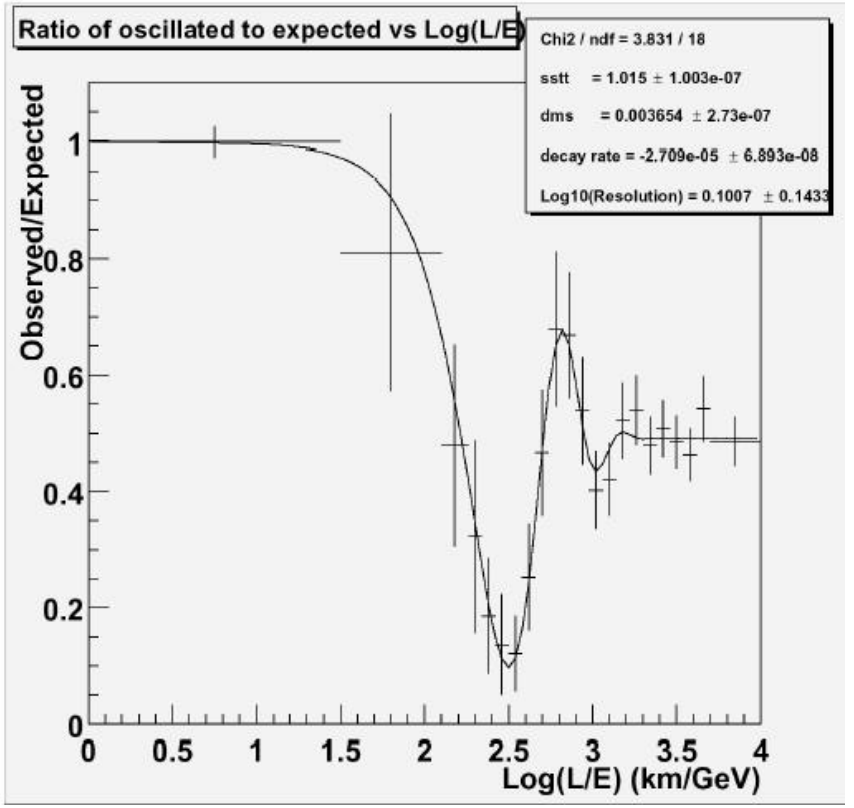




Oscillations in Atmospheric L/E

<u>Proposal Status</u>

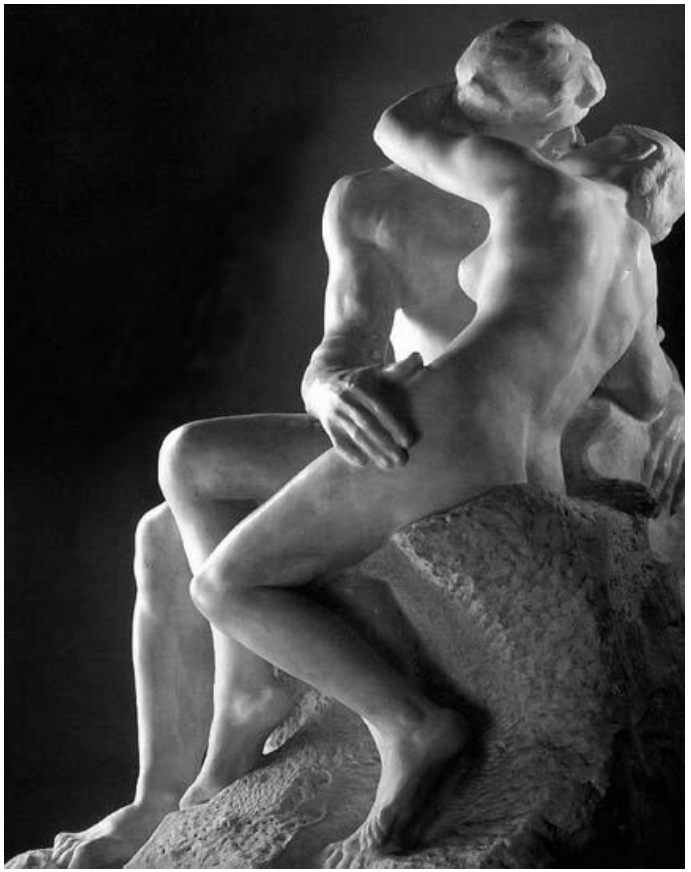
- o 2001 White Paper
- o 2003 HEPAP/Orbach list ($500M-$1B)



7 years of UNO,

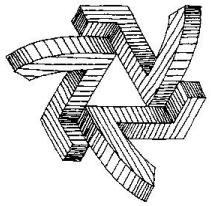
Conclusion

- New underground ν experiments will answer more questions
- Pursuing θ_{13} will be challenging and rewarding
- Proton decay too!
- Neutrino physicists are getting more passionate in their pursuits.



"The Experimentalist and the Theorist" *by Rodin*

Advertisement(s)



- Free monthly neutrino rumor newsletter -- ~100 lines,
- send "subscribe" to maury.goodman@anl.gov or see http://www.hep.anl.gov/ndk/longbnews/
- Neutrino Oscillation Industry Web Page http://www.neutrinooscillation.org/