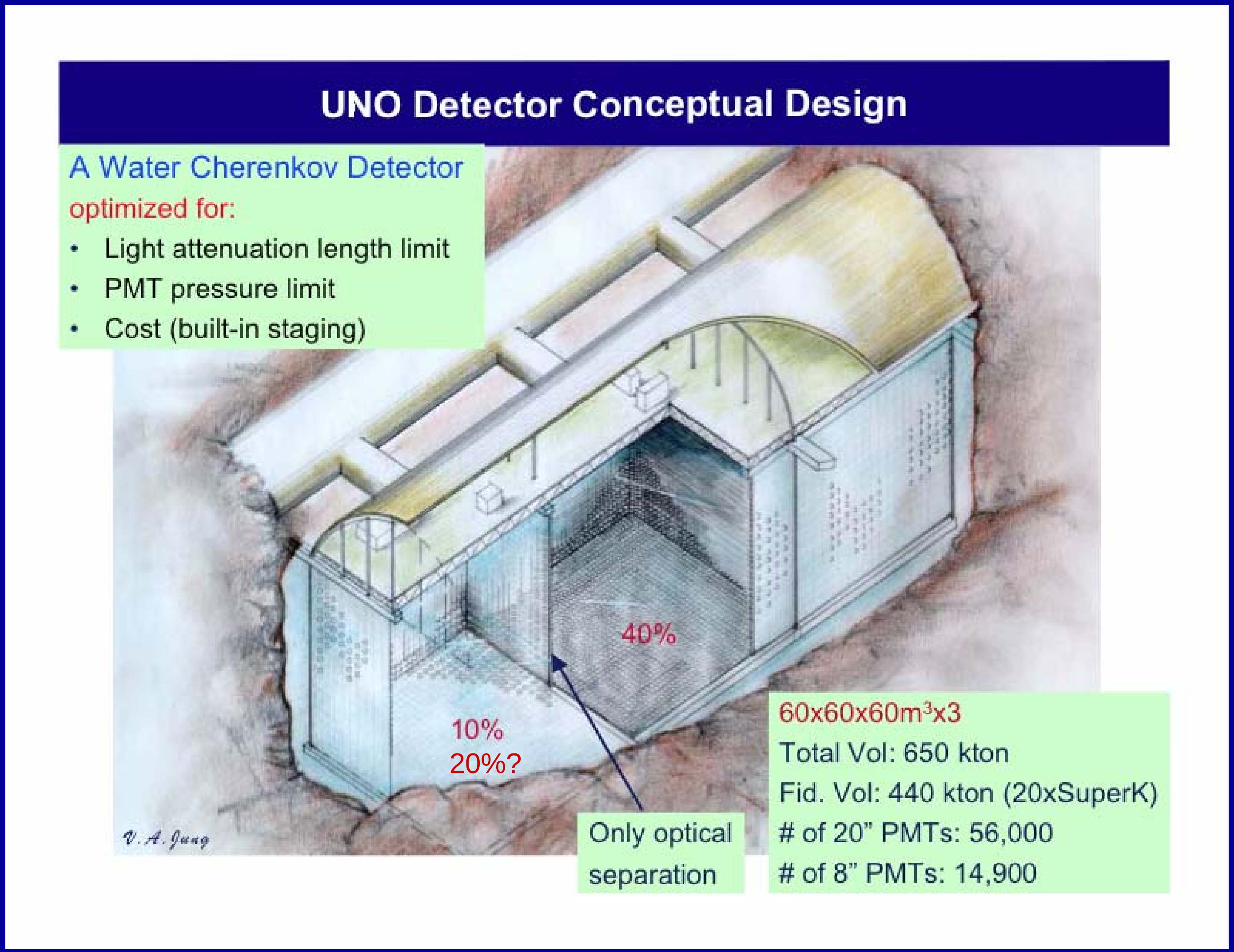
Physics Potential of UNO and Status Update

Chiaki Yanagisawa
Stony Brook University

B-L Workshop at LBNL

September 20, 2007

Conceptual Design of UNO



History of UNO

- Proposed in 1999 at NNN99
- Whitepaper , July 2002 presented at Snowmass, signed by 23 institutions, 49 members: proto-collaborators (22 institutions, 32 members: interest group)
- UNO Narrative for HEPAP 2003 report
- August, 2003: Proto-collaboration evolved to collaboration
- April 2004: The collaboration made up of 40 institutions, 94 members, and 7 countries (has grown since 2002)
- April 6, 2005 UNO meeting in France followed by NNN05
- EOI/R&D proposal 2005

Visit UNO website at http://nngroup.physics.sunysb.edu/uno/

Physics Menu

❑ Lepton number violation = neutrino oscillation

- Very long baseline neutrino oscillation (see Fermilab/BNL study report)
  - Precise measurement of θ_{23} and $|\Delta m^2_{23}|$
  - Measurement of θ_{13} and possibly δ_{CP}
  - Determine the sign of Δm^2_{23} to find out hierarchy
- Atmospheric neutrinos (see Kajita@NOON04, Shiozawa@TAUP2004)
  - Precise measurement of θ_{23} and Δm^2_{23}
  - Possible measurement of θ_{13}

❑ Baryon number violation

- Nucleon decays such as $p \to e^+\pi^0$ and $\bar{\nu}K^+$ (and others in a long list)
- $n - \bar{n}$ oscillation ($|\Delta B|=2$ process)
- B-L violating nucleon decay such as $p \to e^-\pi^+\pi^+$

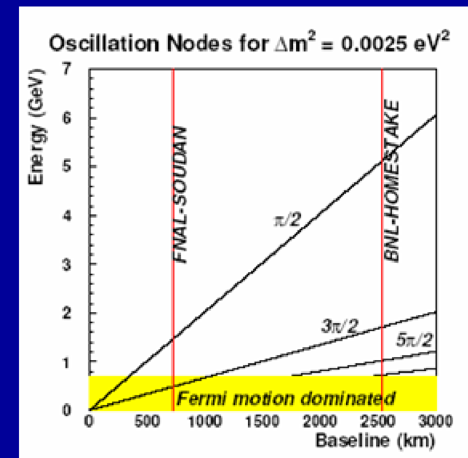
❑ Astrophysics

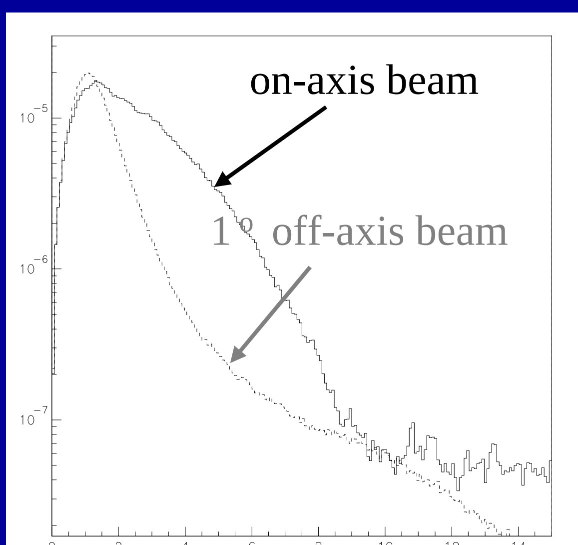
- Neutrinos from supernovae as far as local group galaxies including M31
- Relic neutrinos from past supernovae
- Solar neutrinos

Very Long Baseline Neutrino Oscillation

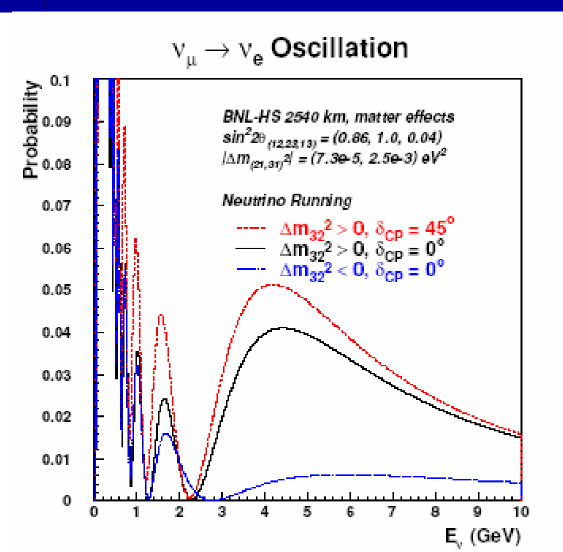
❑ Very long baseline wideband neutrino beam

- Use more than one oscillation nodes
- Avoid energy range where Fermi motion dominates
- Use different behaviors of ν energy spectra at different energy ranges





E_ν (GeV)



E_ν (GeV)

Very Long Baseline Neutrino Oscillation

- First full simulation by Stony Brook group (See NNN06 Proceedings)

  For details also: http://nngroup.physics.sunysb.edu/uno/publications.shtml.

  - Use of SK atmospheric neutrino MC (40% PMT coverage)
    - Standard SK-I analysis package + special π^0 finder (POLfit)
    - Re-weight with the wideband beam spectra
    - Normalize with QE events: 12,000 events for ν_μ , 84 events for beam ν_e for 0.5 Mt F.V. with 5 years of running, 2,540 (1,480) km baseline

BNL to Homestake

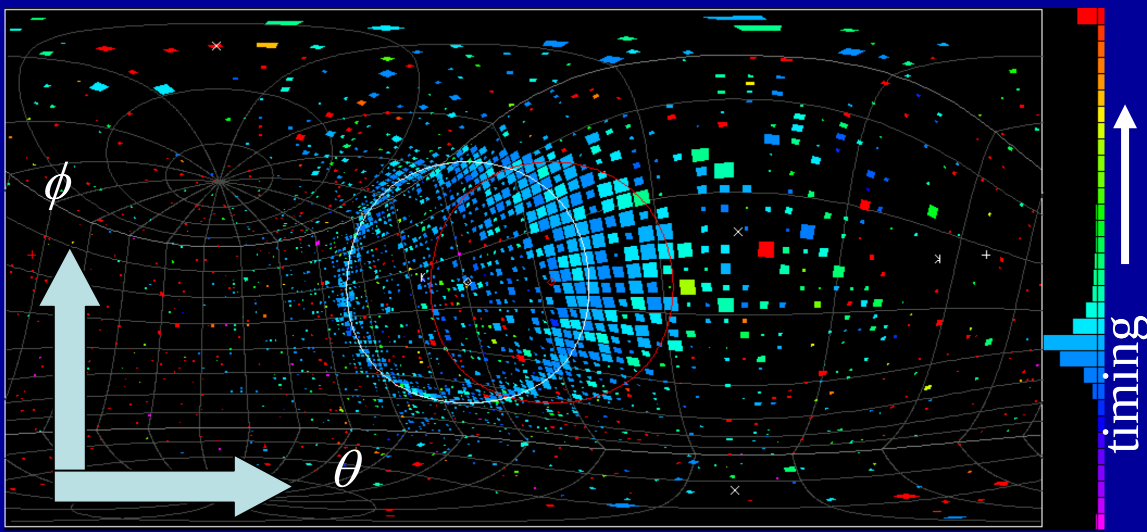
2500 kt •MW•10^7 sec
with BNL 30 GeV AGS

Fermilab to Henderson

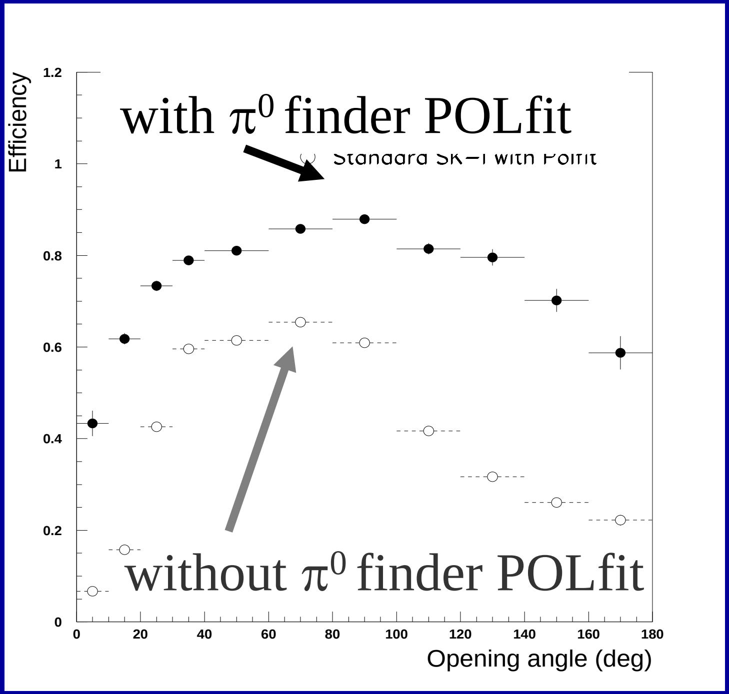
  - Oscillation parameters used:
    - Δm^2_{21} =7.3 x 10^{-5} eV^2, Δm^2_{31}=2.5 x $10^{-3}eV^2$
    - $\sin^2 2\theta_{ij}$(12,23,13)=0.86/1.0/0.04, δ_{CP}=0,+45,+135,-45,-135°
    - Osc. prob. including matter effect (by B.Viren)

Very Long Baseline Neutrino Oscillation

- π^0 detection capability of a water Cherenkov (=SK) with POLfit



A real K2K event detected by SK with two e-like rings identified as a single π^0 using a special π^0 finder



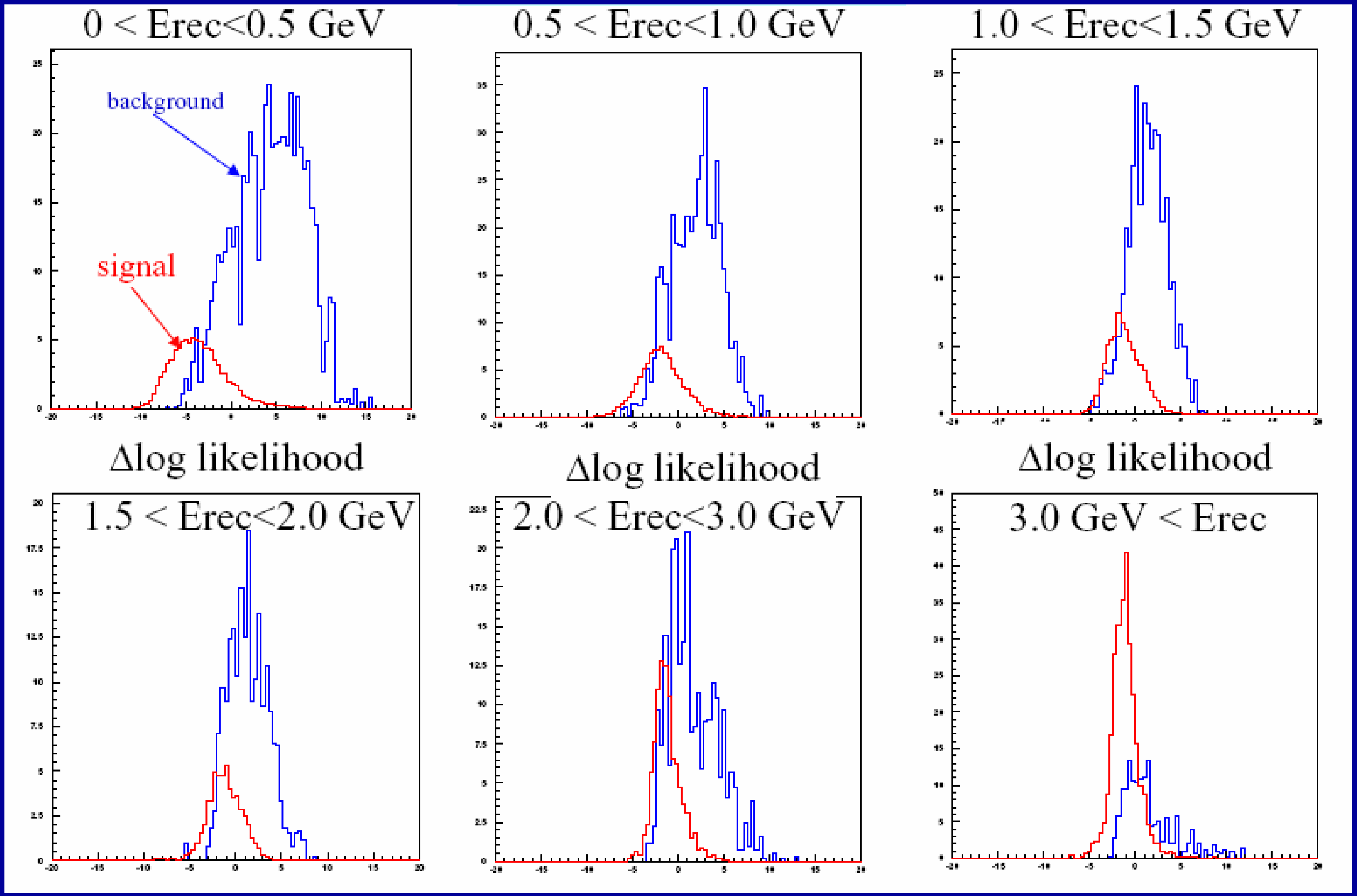
Very Long Baseline Neutrino Oscillation

- $\nu_\mu \to \nu_e$ oscillation
  - $\nu_\mu \to \nu_e$ signal: $\nu_e + N \to e^- + X$ (invisible) Single e-like ring events
  - Major background sources:
    - NC π^0 production, $\nu_x + N \to \nu_x + \pi^0 (\to \gamma\gamma_{missing}) + X$ (invisible)
    - ν_e contamination in the ν_μ beam Single e-like ring events
- Event selection
  - Select single e-like ring events w/o π^0 finder (SK cut)
  - Turn on π^0 finder and use its information to remove π^0 events
- π^0 background removal
  - Using 9 variables that carry information about nature of the e-like ring, charge distribution, and about the event topology, two likelihood functions are calculated for two hypotheses, signal or background.

For details: http://nngroup.physics.sunysb.edu/uno/publications.shtml or NNN06 Proceedings

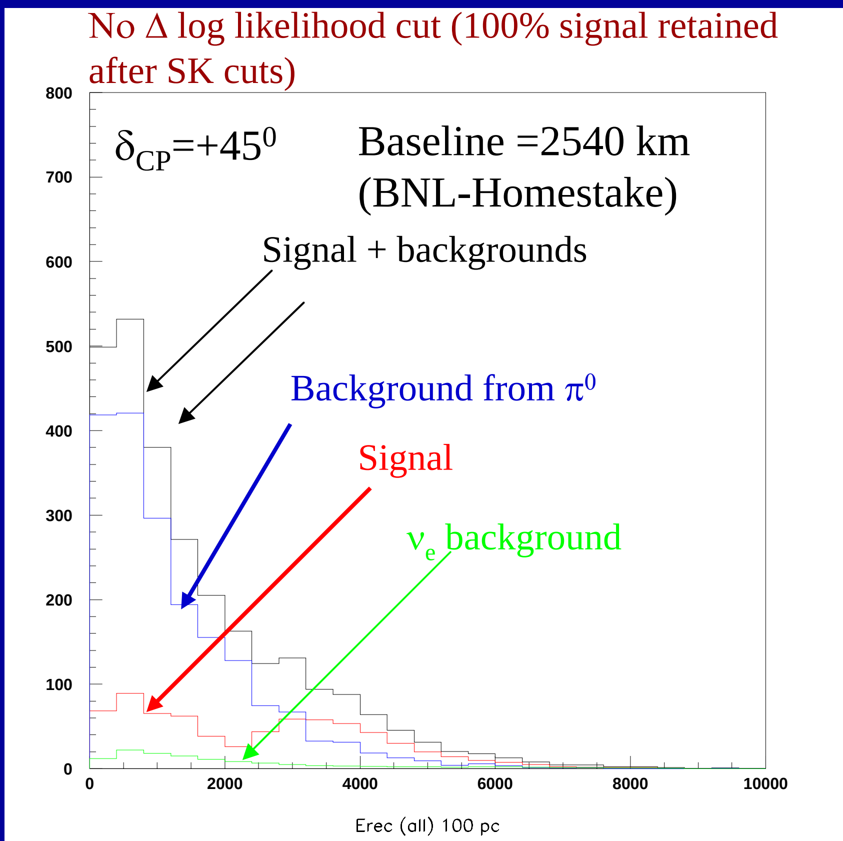
Very Long Baseline Neutrino Oscillation

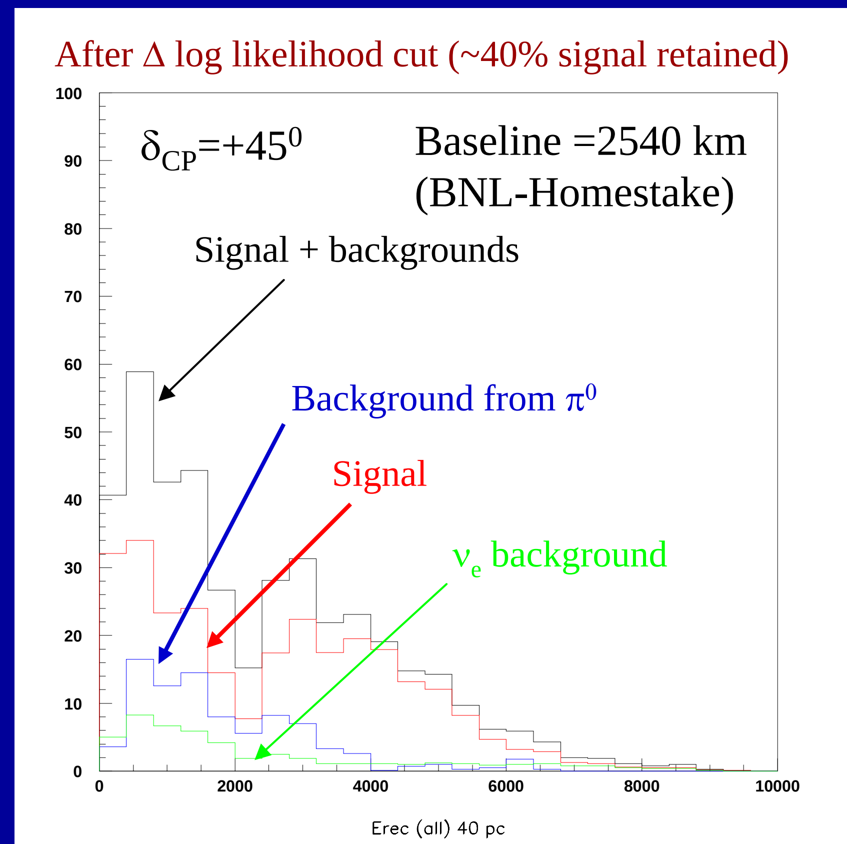
- π^0 background removal: log [lh(bkg)/lh(signal)]=Δ log likelihood
  - Apply a cut on Δ log likelihood to retain 40% of signal after SK cuts



Very Long Baseline Neutrino Oscillation

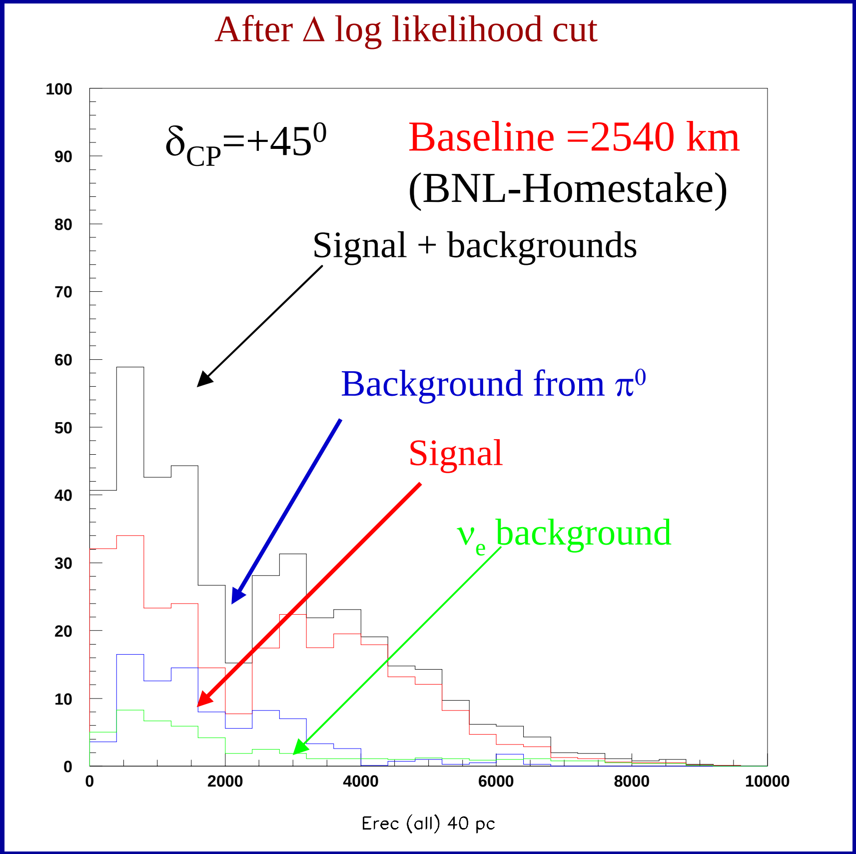
- π^0 background removal: log [lh(bkg)/lh(signal)]=Δ log likelihood
  - Apply a cut on Δ log likelihood to retain 40% of signal after SK cuts

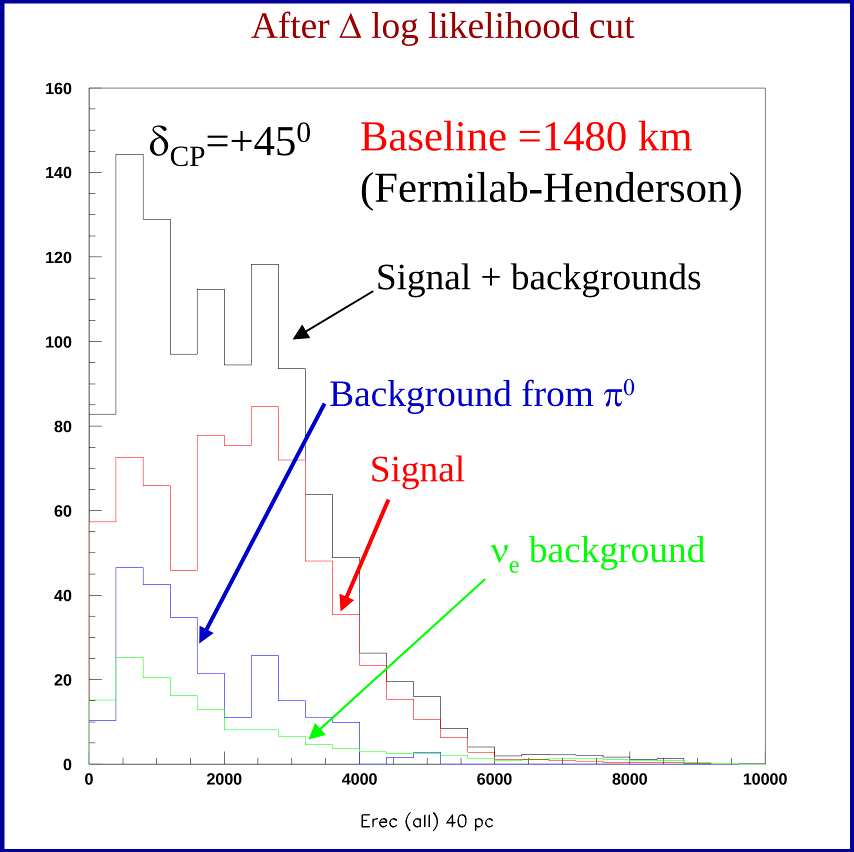




Very Long Baseline Neutrino Oscillation

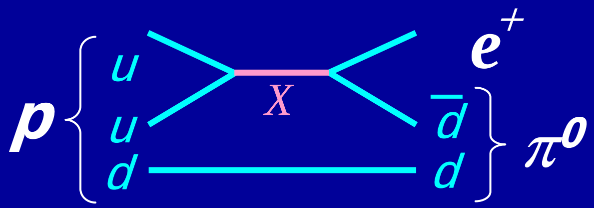
- π^0 background removal: log [lh(bkg)/lh(signal)]=Δ log likelihood
  - Apply a cut on Δ log likelihood to retain 40% of signal after SK cuts

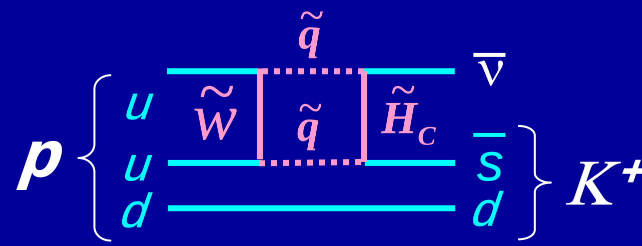


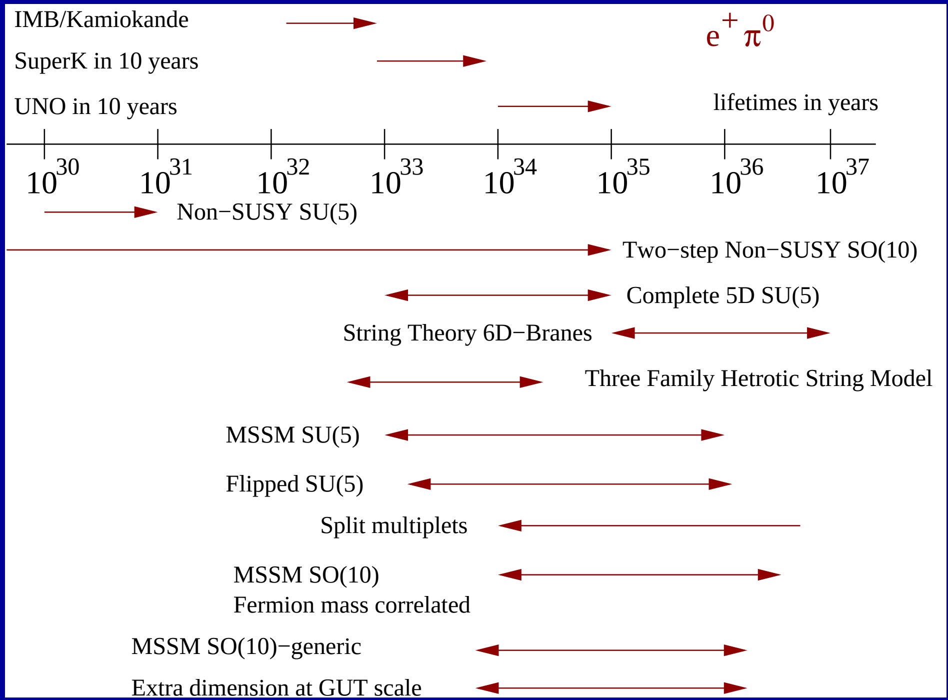


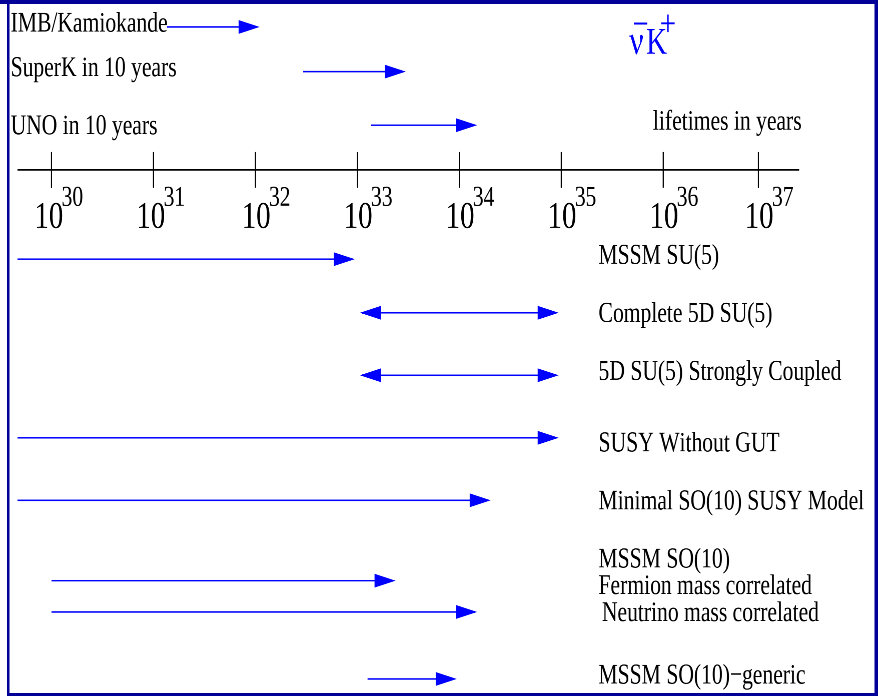
Proton Decays

- Bench mark proton decay modes









Proton Decay p->$e^+\pi^0$

- Event selection (different from SK cuts)
  - 2 or 3 e-like rings with E_{ring}> 30 MeV
  - No decay electron
  - For 3-ring events:
    0.085 < $m_{\gamma\gamma}$ <0.185 MeV/c^2 for SK PMT
    0.010 < <0.220 for ¼ SK PMT
  - 0< $\chi^2 < 6$ from kinematical fit:

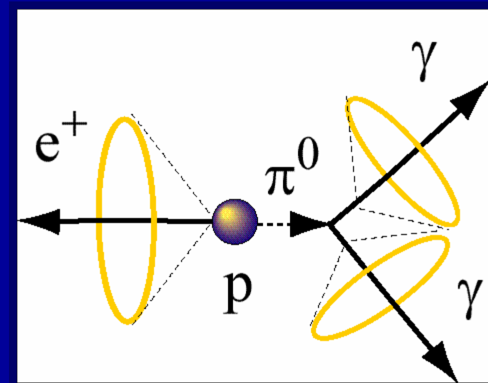
    For 3-ring events with $m_{\gamma\gamma e}=m_p$, $m_{\gamma\gamma}=m_{\pi^0}$

$$\chi^2 = \sum_{i=\gamma_1,\gamma_2,e} \frac{\left(p_i^{mes} - p_i^{fit}\right)^2}{\sigma_{p_i}^2} + \frac{\left(\theta_i^{mes} - \theta_i^{fit}\right)^2}{\sigma_{\theta_i}^2} + \frac{\left(\phi_i^{mes} - \phi_i^{fit}\right)^2}{\sigma_{\phi_i}^2}$$

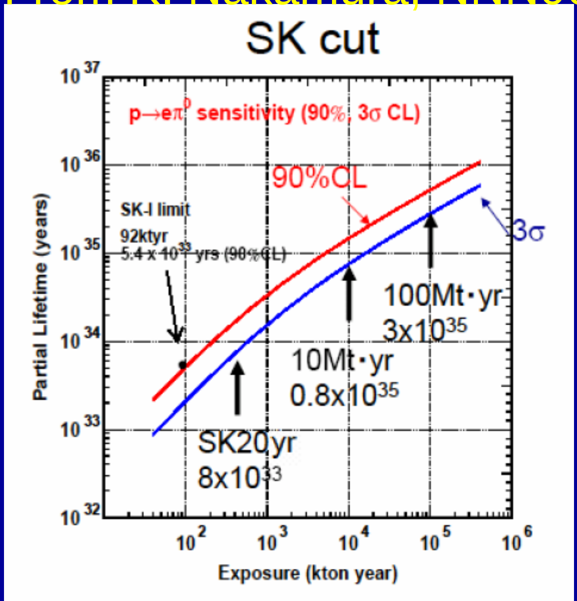
    For 2-ring events with $m_{\gamma e}=m_p$

$$\chi^2 = \sum_{i=\gamma_1,e} \frac{\left(p_i^{mes} - p_i^{fit}\right)^2}{\sigma_{p_i}^2} + \frac{\left(\theta_i^{mes} - \theta_i^{fit}\right)^2}{\sigma_{\theta_i}^2} + \frac{\left(\phi_i^{mes} - \phi_i^{fit}\right)^2}{\sigma_{\phi_i}^2}$$

  - $P_b = |\Sigma \vec{p}_i| < 0.2$ GeV/c after the fit

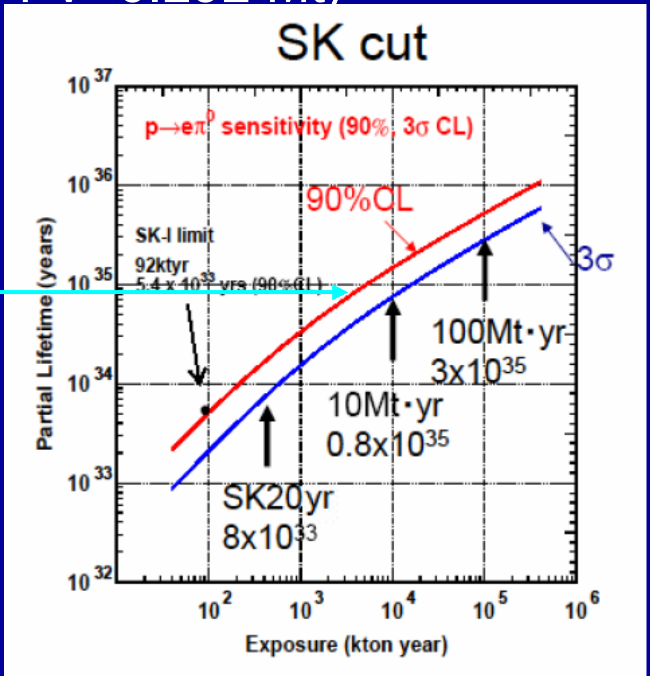


From K. Nakamura, NNN06



Proton Decay $p \to e^+\pi^0$

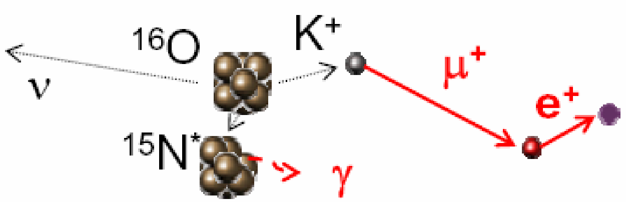
- Sensitivity at 90% C.L.
  - Central compartment (40% PMT coverage, FV=0.151 Mt)
    - -Expected background 0.11 ev/yr
    - - ε_{signal}=0.34
    - - sensitivity 5.4 x 10^{34} yr (10 yrs)
      9.3 x 10^{34} yr (20 yrs)
  - Side compartment (10% PMT coverage, FV=0.292 Mt)
    - -Expected background 0.39 ev/yr
    - - ε_{signal}=0.24
    - - sensitivity 5.0 x 10^{34} yr (10 yrs)
      7.1 x 10^{34} yr (20 yrs)
  - All compartments (FV=0.443 Mt)
    - -Expected background 0.50 ev/yr
    - - ε_{signal}=0.28
    - - sensitivity 8.2 x 10^{34} yr (10 yrs)
      1.2 x 10^{35} yr (20 yrs)



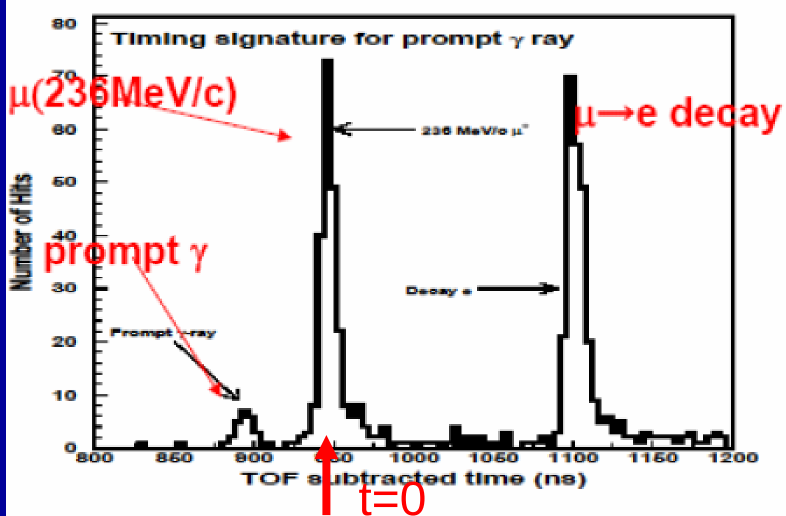
Proton Decay p->νK^+

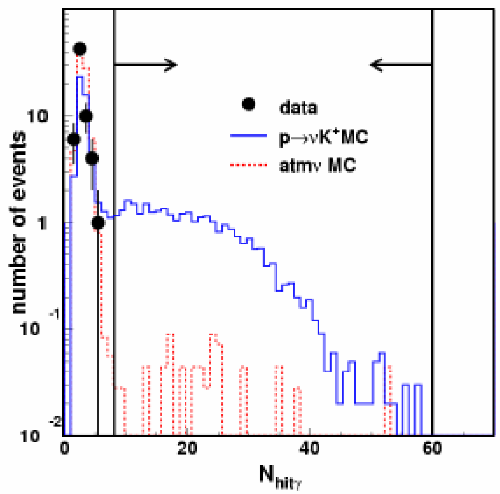
- Most promising among 3 standard Super-K analyses (Nakamura NNN06)

prompt γ tag



- 1 μ and 1 decay electron
- 215 < P_μ < 260 MeV/c
- no proton
- maximize $NHIT_\gamma$ in the 12 ns sliding time window, 7≦ $NHIT_\gamma$ ≦60





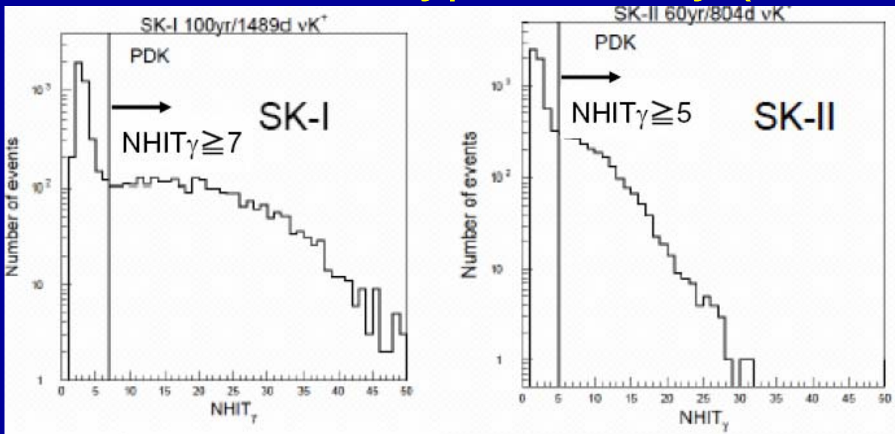
From K. Nakamura, NNN06

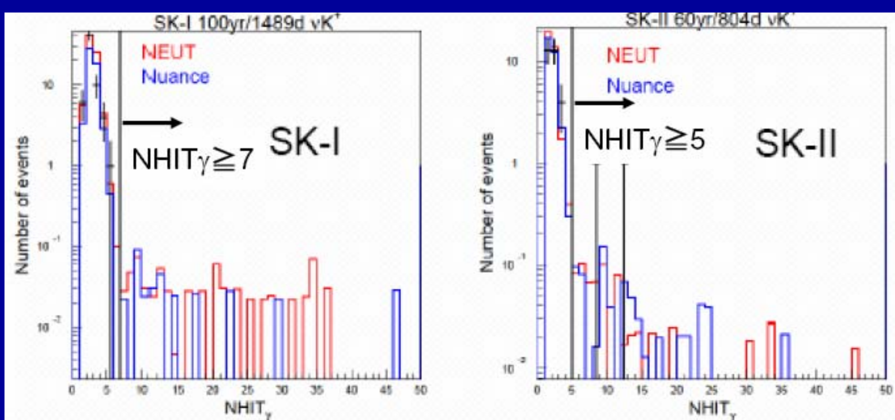
SK-I 1489 days or 92 kton·yr

ε = 8.6 %, 0.7 exp'd BG, 0 candidate

Proton Decay p->νK^+

❑ Results from Hyper-K study (Nakamura NNN06)





	SK-I (40% photocathode coverage)	SK-II (19% photocathode coverage)
Efficiency*	8.6%	4.7%
Background	0.008 ev. /kton/year	0.01 ev. /kton/year

- Photocathode coverage vs. eff.
  40% -> 20% vs. 8.6% ->4.7%
  for the same background level.
- It is not yet known how much the efficiency will be reduced for the PMT coverage of 10% -> for future study.
- A good news is : most of background events come from misfitted vertex position. (Shiozawa NNN02)

Proton Decay $p \to \nu K^+$

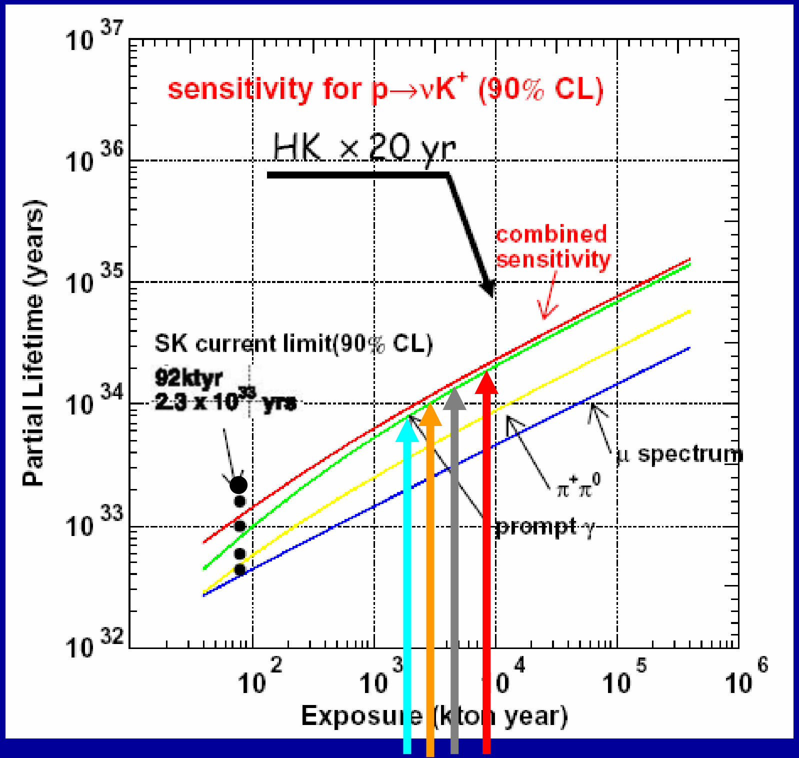
- Case for UNO
  - Keep the same background rejection power and the same efficiency for the SK-I PMT coverage:

SK-I coverage (40%)		$\varepsilon_{I} = 8.6\%$
½ SK-I coverage (20%)		$\varepsilon_{II} \sim 4.7\%$
¼ SK-I coverage (10%)	assume	$\varepsilon_{1/4} \sim 2.1\%$?

→

  - UNO with 40%+40% coverage (UNO40): F.V.=0.44 Mt
  - UNO with 40%+20% coverage (UNO20): F.V.= 0.31 Mt with 40% PMT coverage.
  - UNO with 40%+10% coverage (UNO): F.V.= 0.22 Mt with 40% PMT coverage.

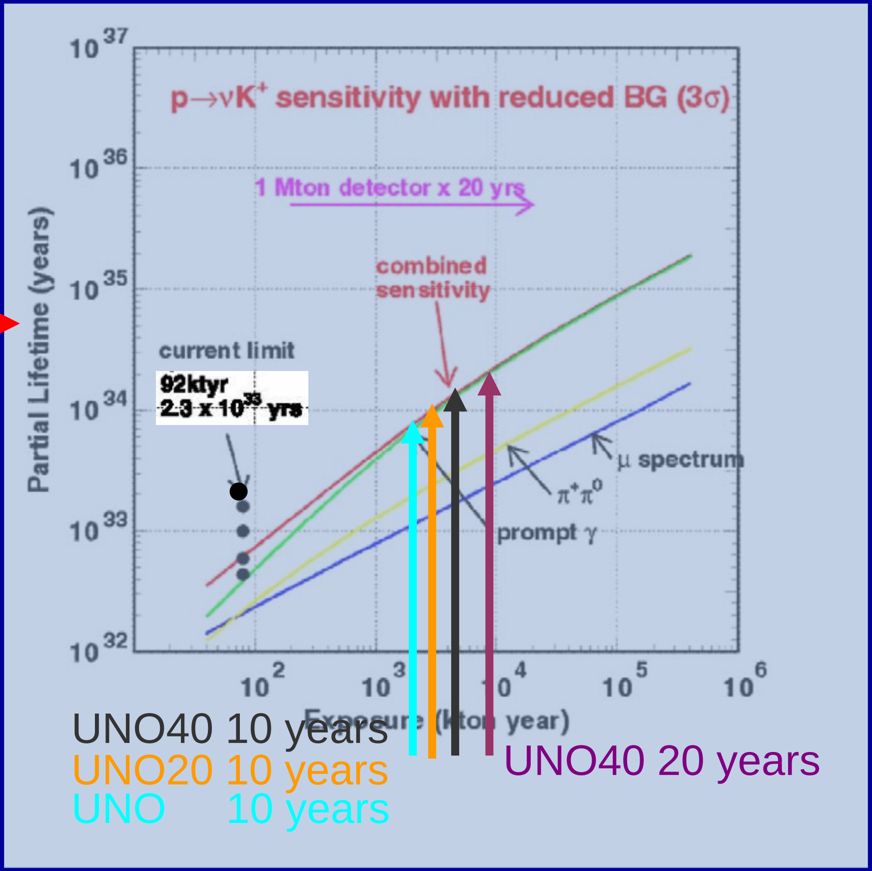
For SK-I PMT coverage (K. Nakamura, NNN06)



Proton Decay p->νK^+ and p->$e^-\pi^+\pi^+$

- **Potential improvement**
  - Major background
    - ~6 events/Mtyr from single-ring μ, π, and p events with misfitted vertex position: Can be improved.
    - If we manage to remove these, then even 3σ sensitivity looks good.

For SK-I PMT coverage (Shiozawa, NNN02)



- **p->$e^-\pi^+\pi^+$ (B-L violating)**
  - Analysis in progress at Stony Brook using SK data but the result is not official
  - Interesting decay channel to look for with UNO too

Conclusions

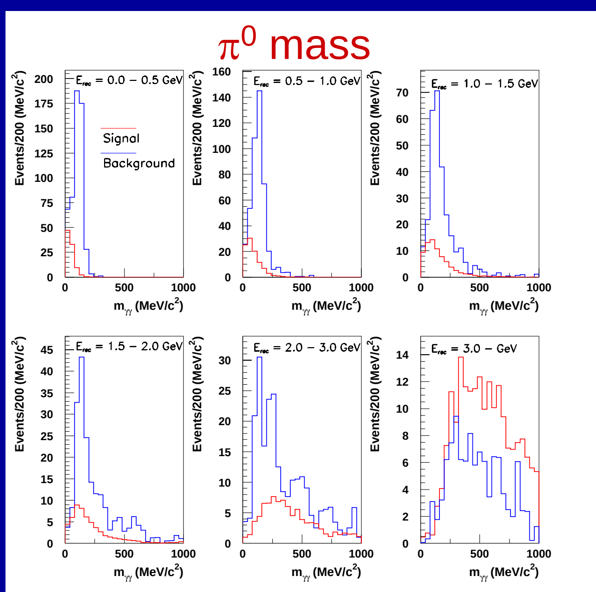
- UNO could be the key to advance our knowledge about neutrino:
  - Precise measurement of θ_{23} and Δm^2_{23}
  - Measurement of θ_{13} and possibly δ_{CP}
  - Determine the sign of Δm^2_{23} to find out hierarchy

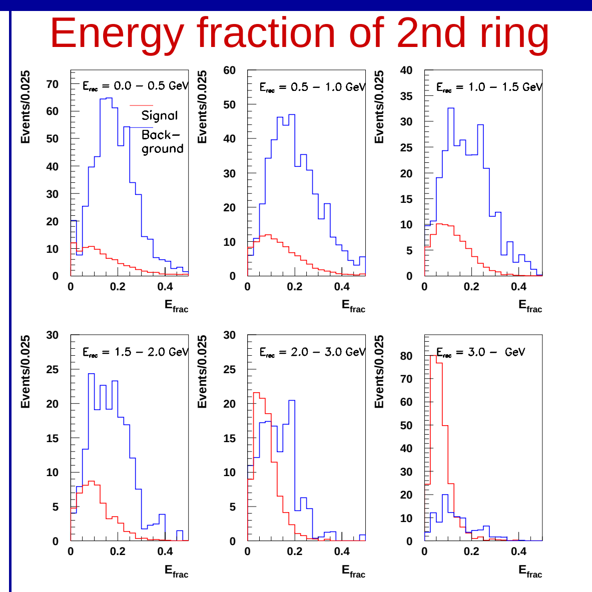
  See Fermilab/BNL study report : arXiv.0705.4396
  Also a detailed study of water Cherenkov at :
  http://nngroup.physics.sunysb.edu/UNO/publications or NNN06 Proceedings
- UNO could be the key to open a door to new era of particle physics if Nature is kind enough to let us detect nucleon decays.
- UNO could be one of the most cost-effective multi-purpose detectors, given the rich list of physics to be done.
- More work needed to optimize the UNO design:
  PMT coverage, granularity, PMT performance, improvement of software

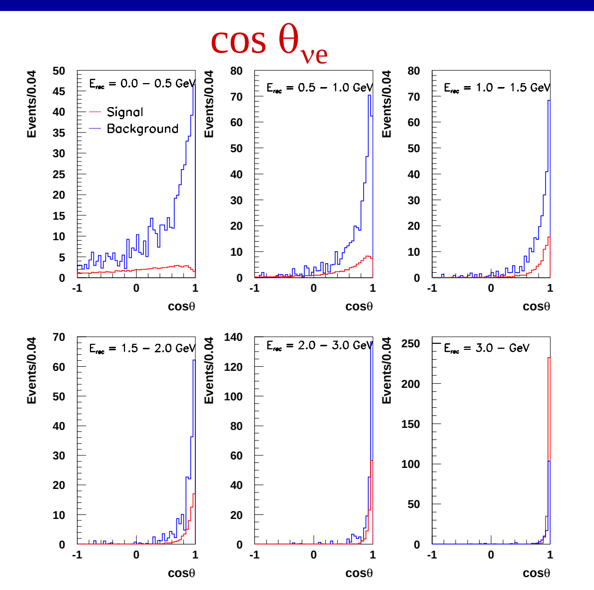
Backup Slides

Very Long Baseline Neutrino Oscillation

- Likelihood analysis using the following 9 variables:
  - π^0 mass (pi0mass)
  - energy fraction (efrac)
  - $\cos\theta_{ve}$
  - π^0-likelihood (pi0-like)
  - e-likelihood (e-like)
  - Δ log π^0-likelihood (Δlog pi0like)
  - single ring-ness (dlfct)
  - total charge/primary ring energy (poa)
  - Cherenkov angle (ange)







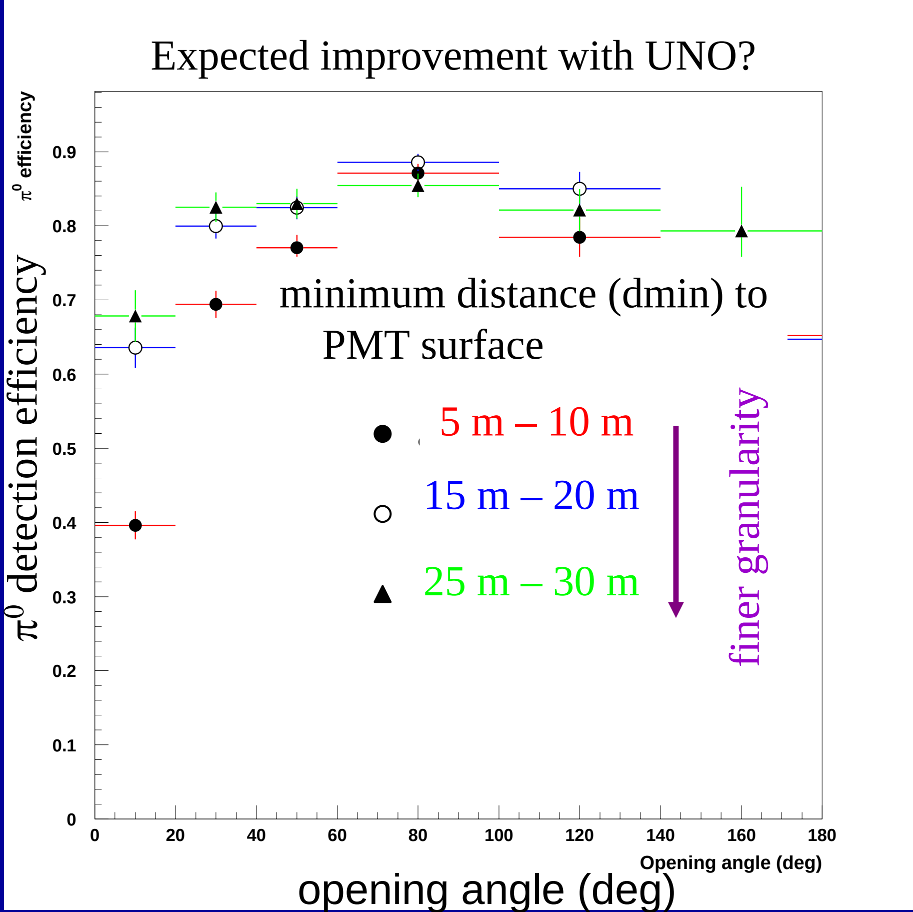
Very Long Baseline Neutrino Oscillation

- Breakdown of sources of signal and background events (2,540 km):

Interaction mode	$0<E_{rec}<1$ GeV		$1<E_{rec}<2$ GeV		$2<E_{rec}<3$ GeV		3 GeV$<E_{rec}$	
	Sig	Bkg π^0	Sig	Bkg π^0	Sig	Bkg π^0	Sig	Bkg π^0
CC QE	82%	7%	69%	1%	28%	0%	50%	0%
$1\ \pi^0$	3%	3%	5%	8%	11%	0%	8%	0%
$1\ \pi^{+-}$	14%	7%	22%	1%	45%	0%	30%	0%
DIS	1%	0%	3%	1%	15%	18%	13%	0%
NC $1\ \pi^0$	0%	39%	0%	68%	0%	23%	0%	25%
$1\ \pi^{+-}$	0%	29%	0%	3%	0%	0%	0%	0%
DIS	0%	11%	0%	9%	0%	59%	0%	75%
Others	0%	3%	1%	10%	3%	0%	0%	0%

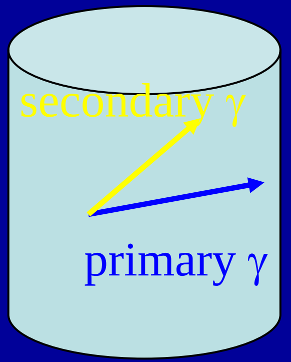
Very Long Baseline Neutrino Oscillation

❑ Granularity and π^0 efficiency for same PMT coverage



Compared with a smaller detector

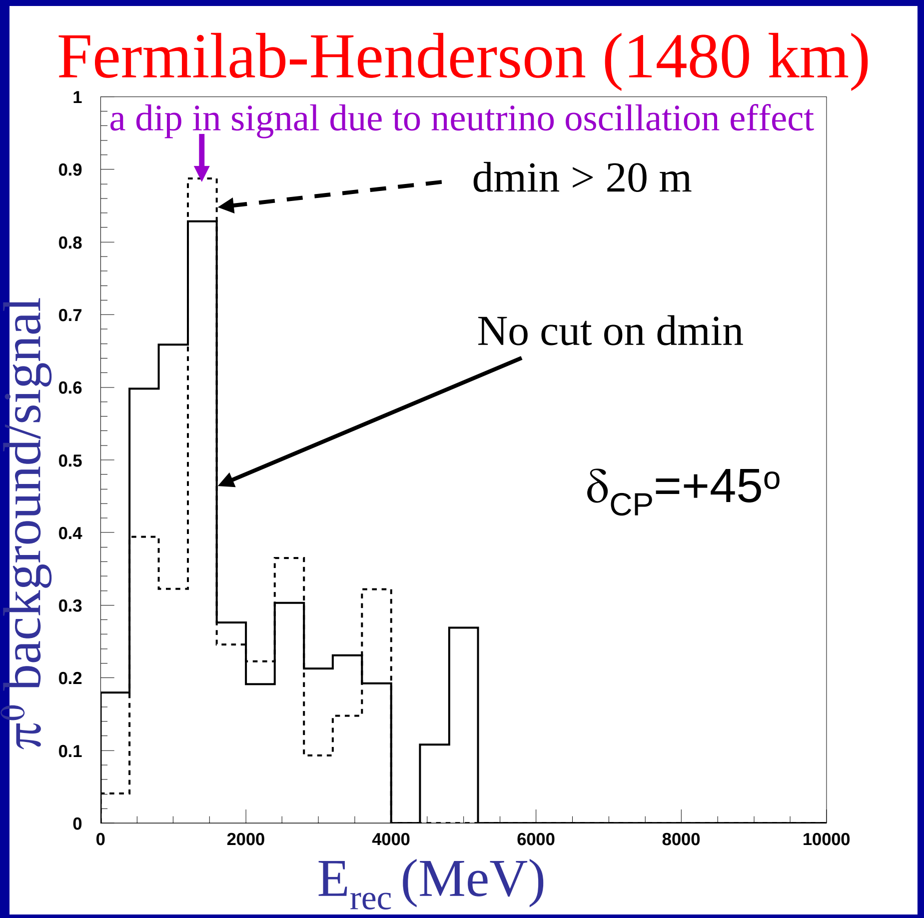
- π^0 efficiency improves when the min. distance increases when the opening of two photons from π^0 is smaller than about 40^0.
- For smaller π^0 opening angle finer granularity is needed.
- What PMT coverage needed? 10,20,40% (SK-I and SK-III has 40% coverage) ?



dist>dmin

Very Long Baseline Neutrino Oscillation

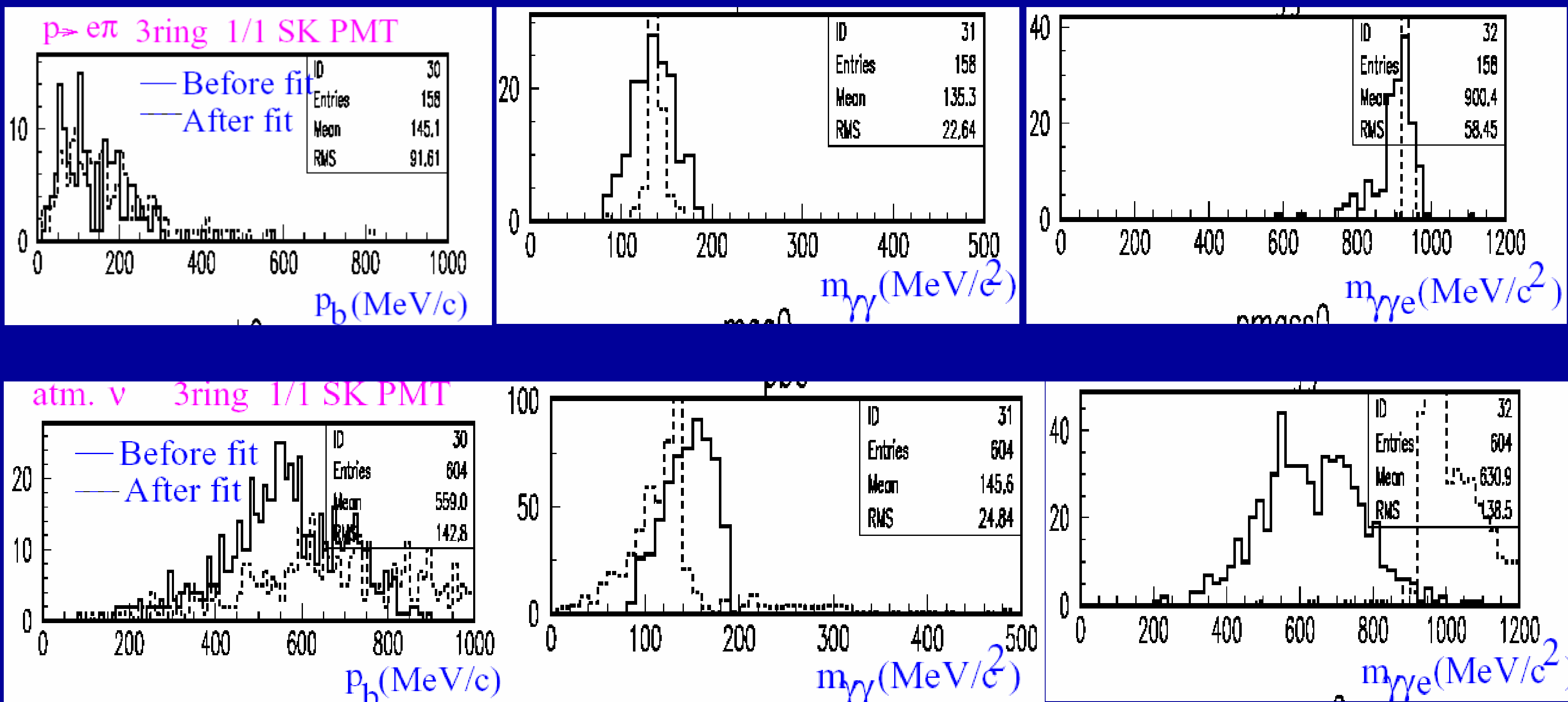
- Effect of granularity on π^0 background/signal



A larger water Cherenkov detector does a better job to distinguish the signal from the π^0 background at the re-constructed energy below 1.2 GeV.

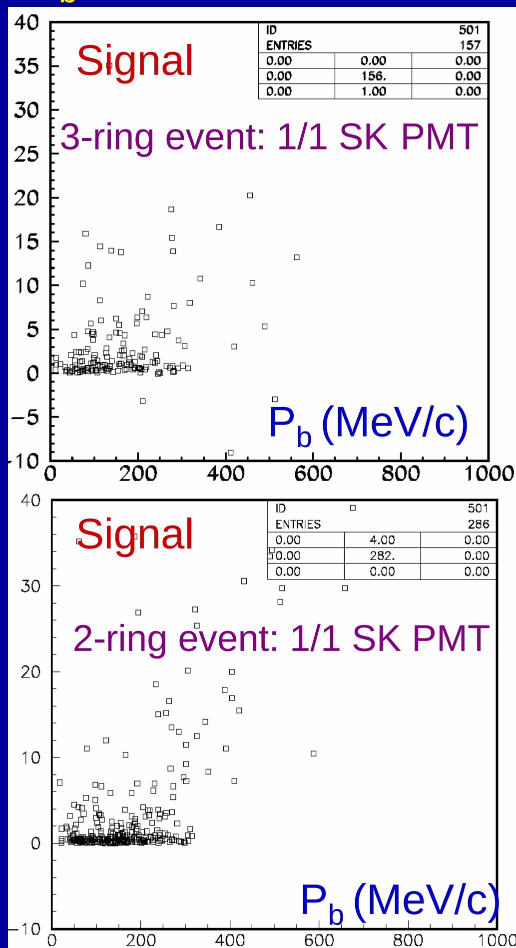
Proton Decay $p \to e^+\pi^0$

- Distributions before and after χ^2 fit (10 iterations)

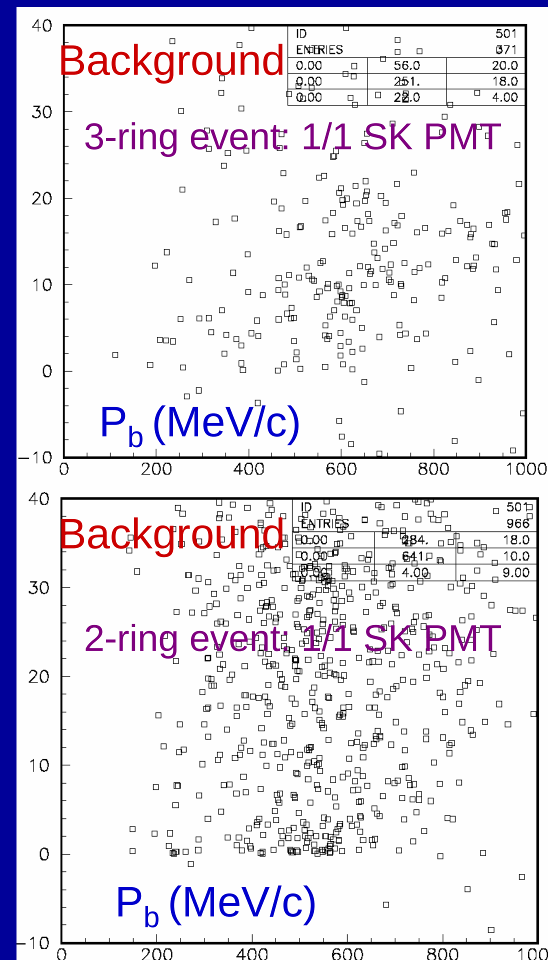


- χ^2 vs. P_b

χ^2

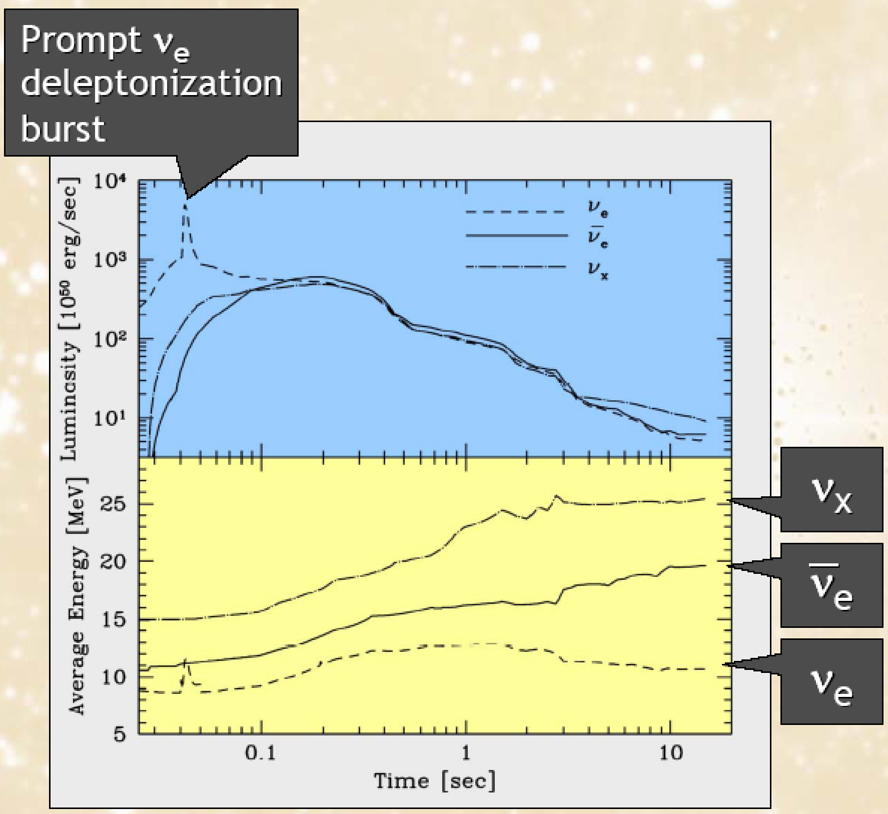


χ^2

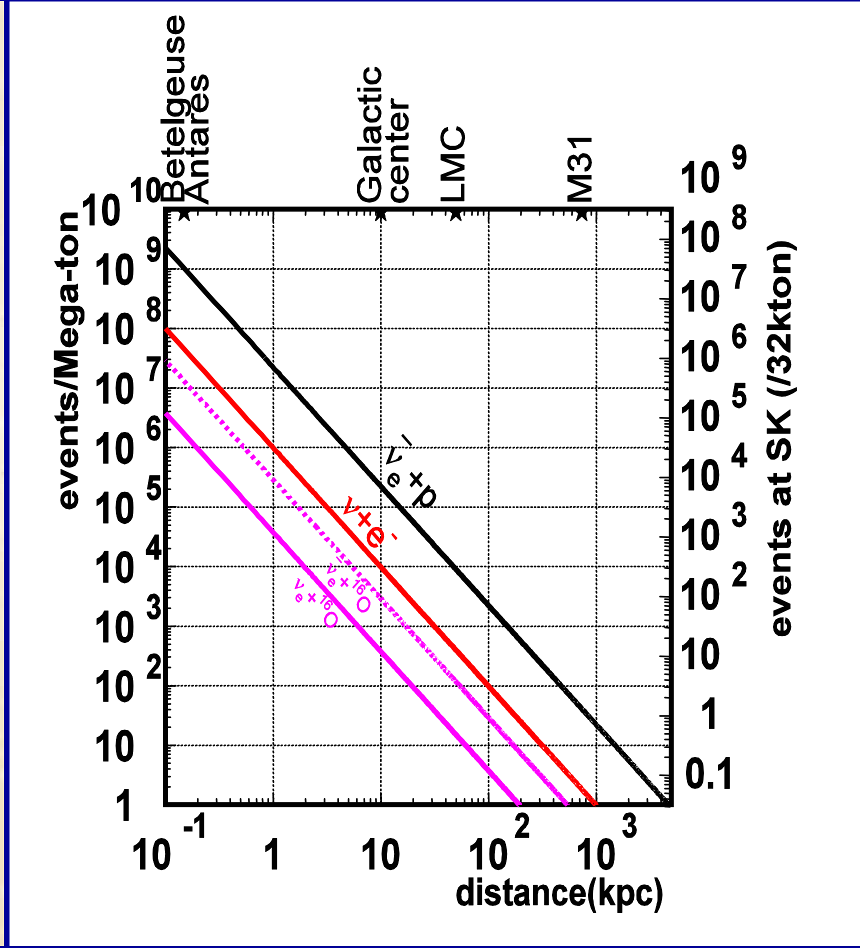


Neutrinos from Supernovae

- New SN explosions from local galaxies (including M31)



Livermore numerical model
ApJ 496 (1998) 216



Neutrinos from Supernovae

- What could UNO do if a SN exploded at 10 kpc?
  - For a SN at 10 kpc, UNO would detect 130k inverse beta decay events, 4.5k elastic scattering events, 4,500 NC events in the central compartment.
  - High statistics might lead to our first observation of the birth of a black hole
  - UNO is big enough to observe a supernova explosion even in Andromeda

Neutral current events $\nu_x + {}^{16}O \rightarrow \nu_x + \gamma + X$

where $X = {}^{15}O, {}^{15}N, \ldots$