1854-12

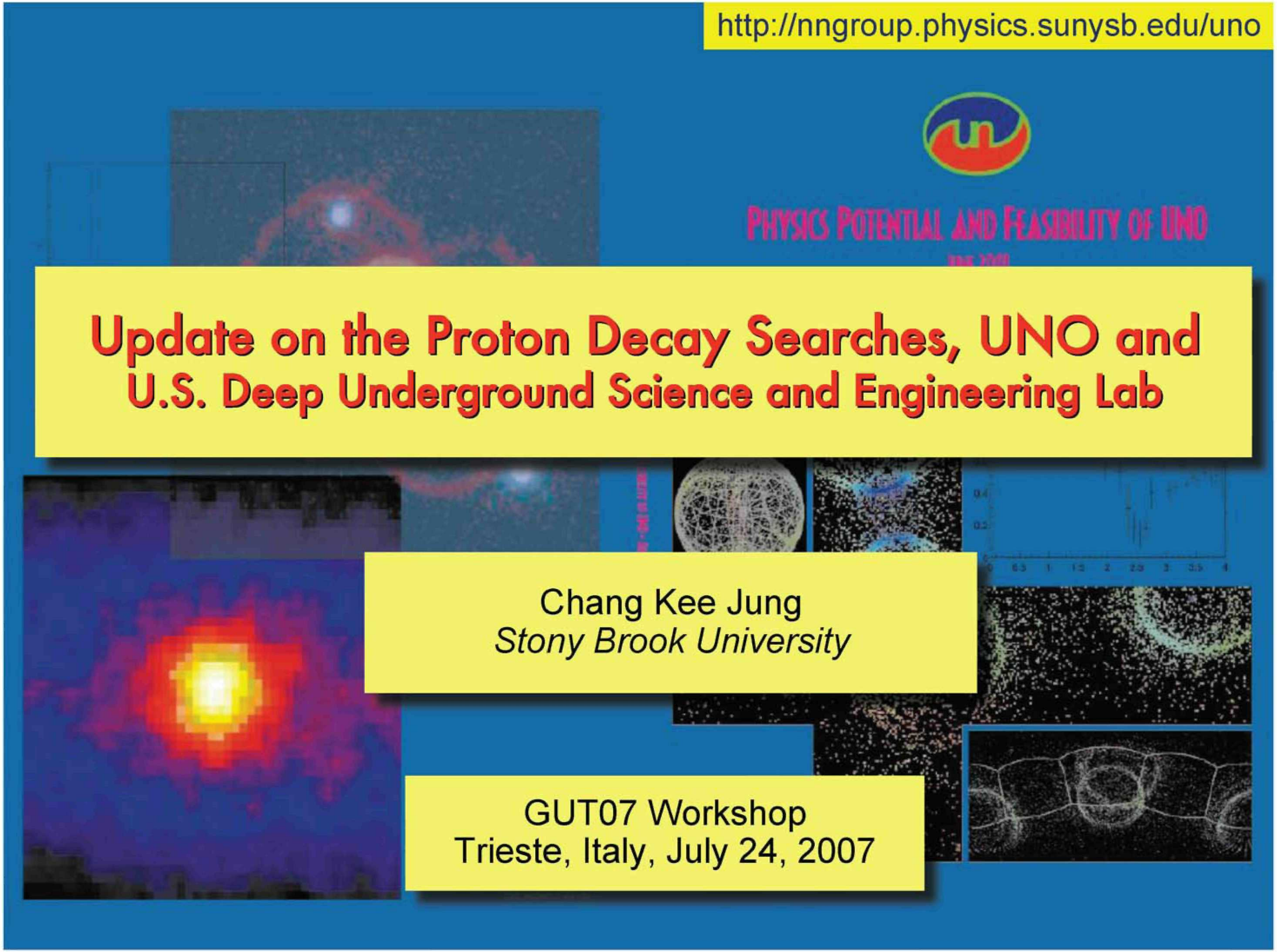
Workshop on Grand Unification and Proton Decay

22 - 26 July 2007

Update on the proton decay searches, UNO and U.S. DUSEL

Chang Kee JUNG
The State University of New York at Stony Brook
Stony Brook, NY, USA

http://nngroup.physics.sunysb.edu/uno

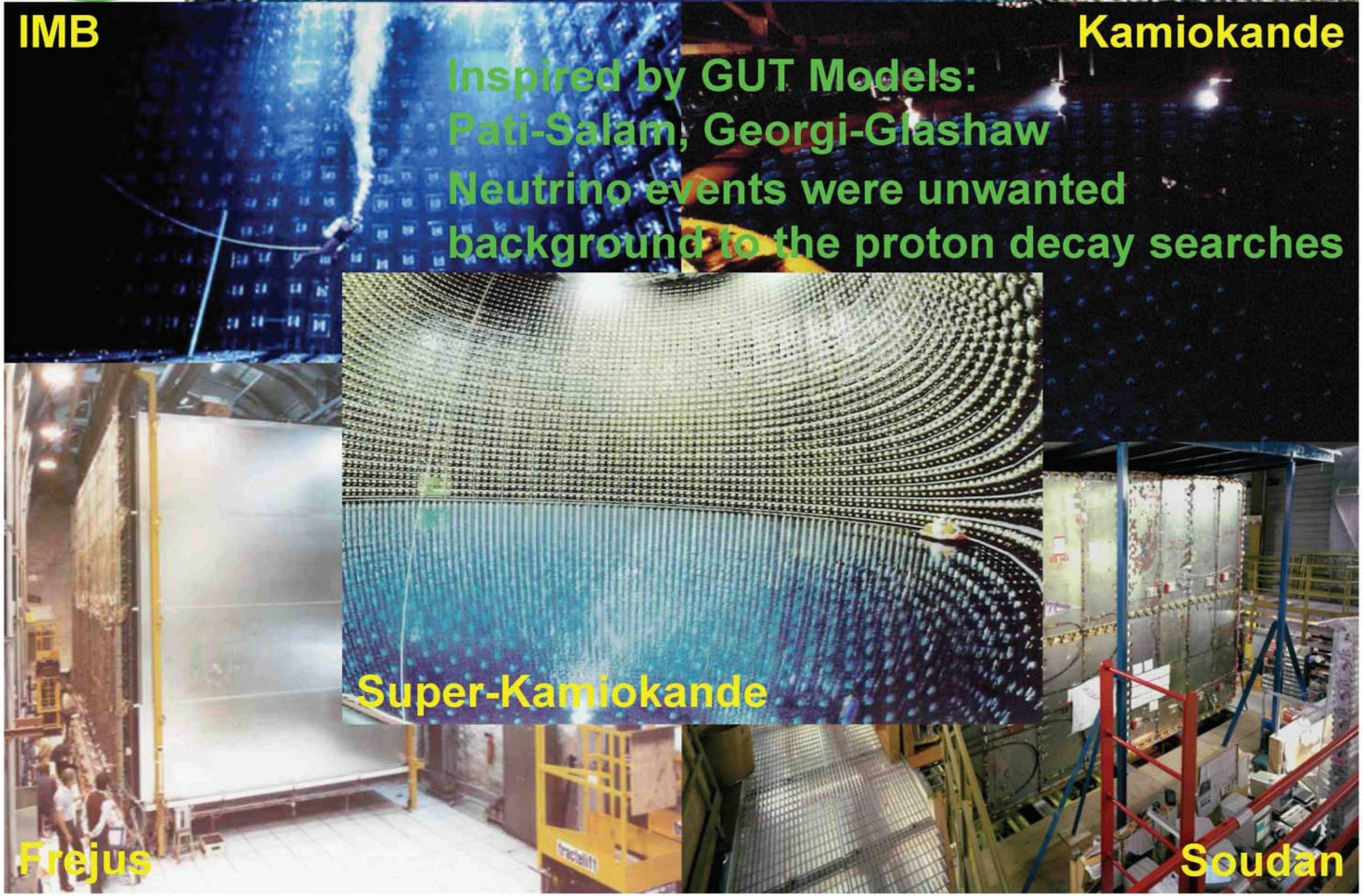


Update on the Proton Decay Searches, UNO and U.S. Deep Underground Science and Engineering Lab

Chang Kee Jung
Stony Brook University

GUT07 Workshop
Trieste, Italy, July 24, 2007

Proton Decay Detectors

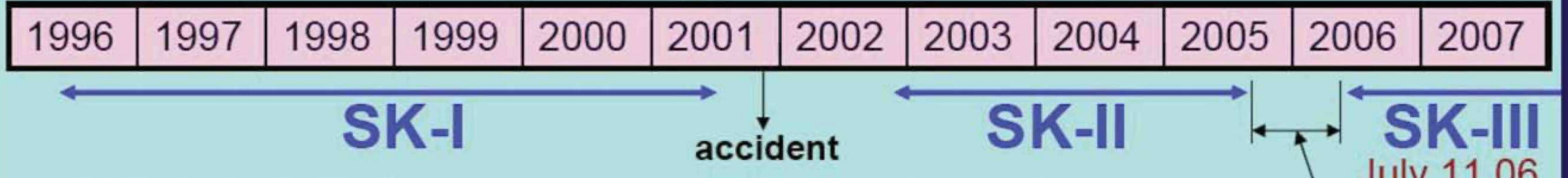


Inspired by GUT Models:

Pati-Salam, Georgi-Glashaw

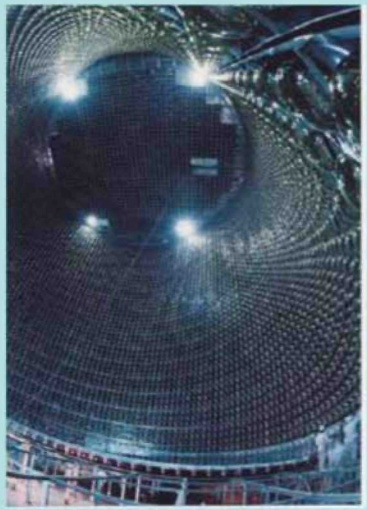
Neutrino events were unwanted background to the proton decay searches

Super-Kamiokande Update



July 11,06

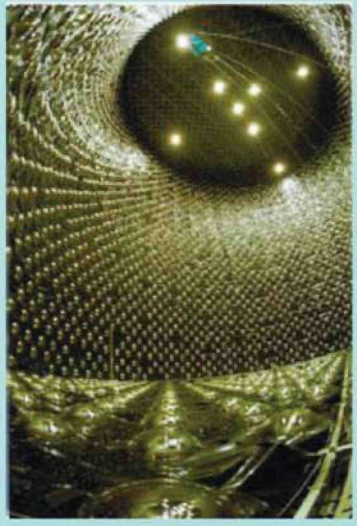
SK full reconstruction



32kton photosensitive, 22kton fiducial volume

1000m underground

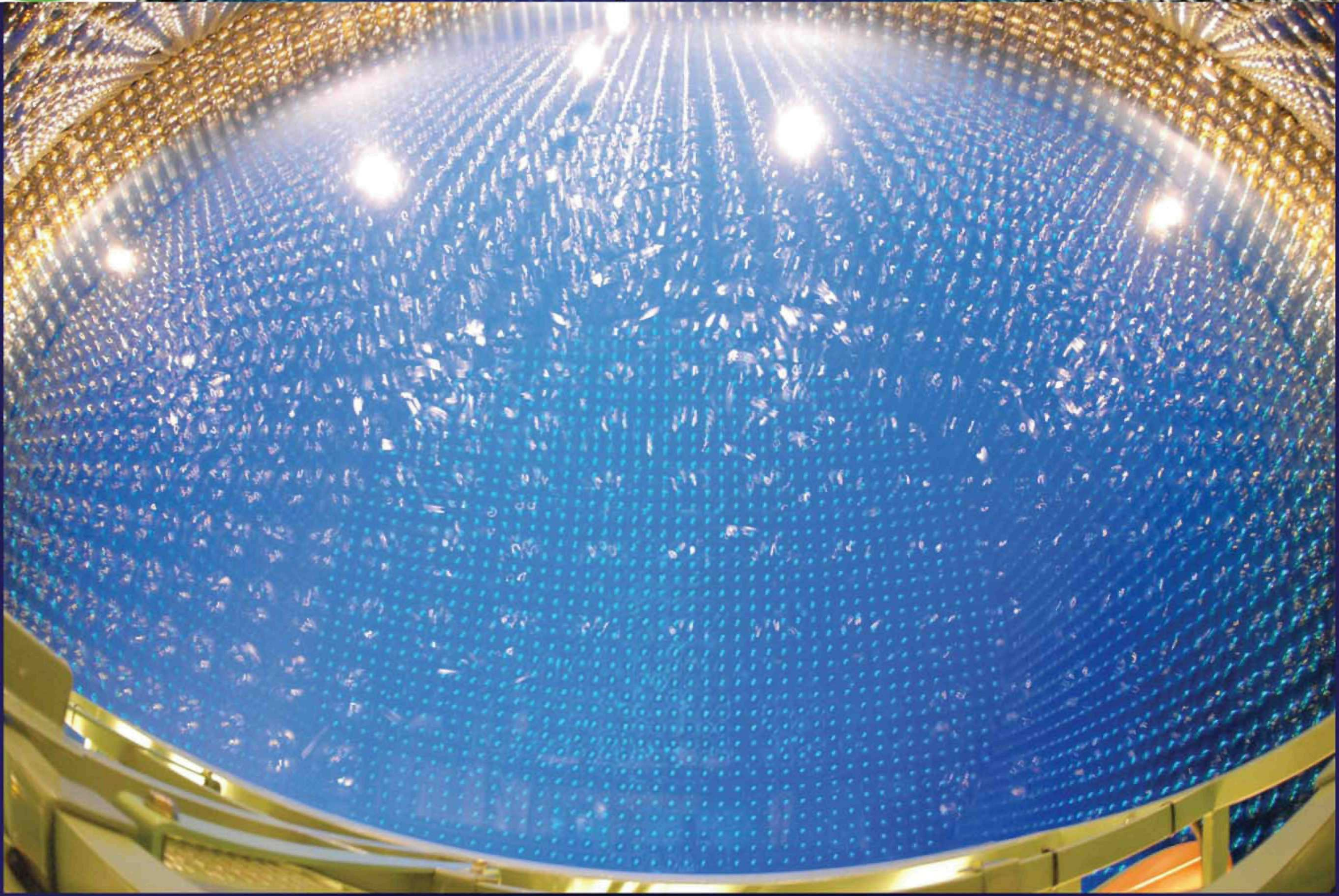
Water Cherenkov detector



SK-I		SK-II	SK-III
11,146	Number of ID(*) PMTs	5,182	11,146
40%	Photocathod coverage	19%	40%
~6 p.e./MeV	Cherenkov light yield	~2.8 p.e./MeV	
		with Acrylic+FRP cases	
4.1MeV (Sep.2000~)	Trigger threshold (90 %eff.)	5.5 MeV	

(*) Inner Detector

Super-Kamiokande-III Ready!!!
(July 2006)



Update on the Proton Decay Searches at SuperK

SuperK Vital Parameters

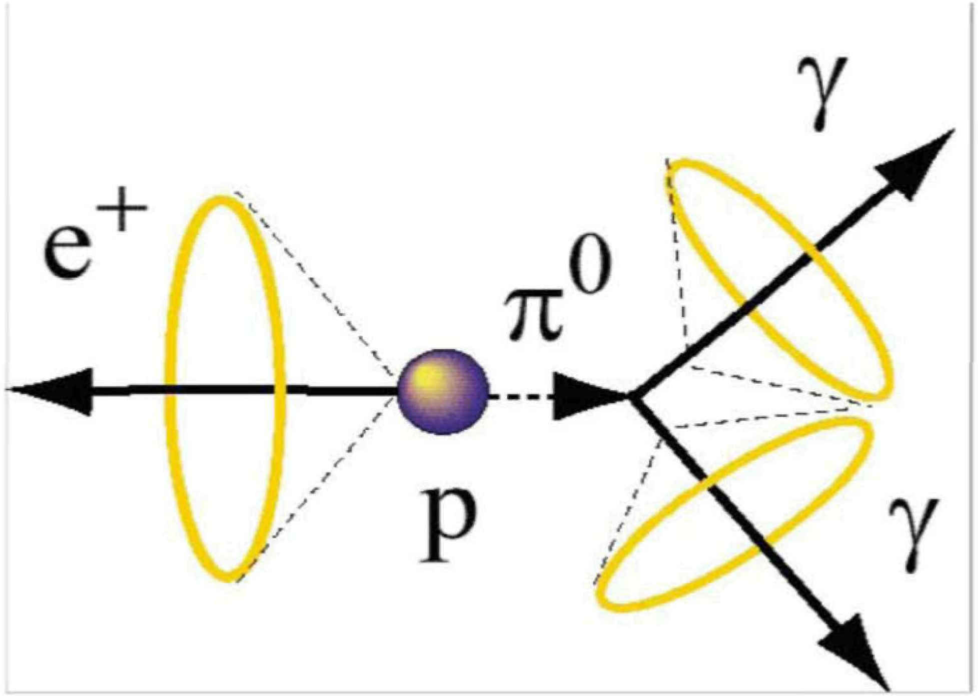
Fiducial 22.5kton H_2O
→ 8×10^{33}protons

- 2/10 free protons
  → no nuclear effect
  → no Fermi motion
  high efficiency

- 8/10 binding protons
  → de-excitation γ-ray

- Trigger efficiency
  ··· 100% (most decay modes)
- Vertex resolution
  ··· 30cm (1-ring)
  ··· 15cm ($p \rightarrow e^+\pi^0$)
- Energy resolution ($\Delta E/E$)
  ··· ~ 3% (1GeV e, μ)
  ··· ~ 4% (236MeV μ)
- Particle identification
  ··· ~ 99% (1-ring e, m)
  ··· ~ 97% ($p \rightarrow e^+\pi^0$)

$p \rightarrow e^+ \pi^0$ Decay Event Signature

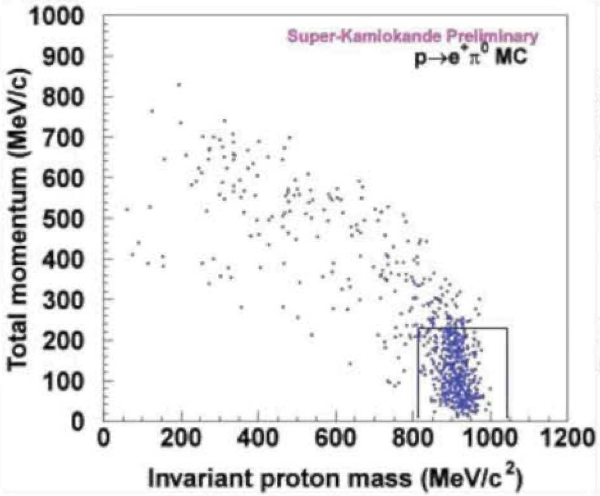


selection criteria

- 2,3-ring, all e-like
- no Michel electron
- $85 < m_\pi < 185 \mathrm{MeV}/c^2$ (3-ring)
- $p_p < 250 \mathrm{MeV}/c$
- $800 < m_p < 1050 \mathrm{MeV}/c^2$

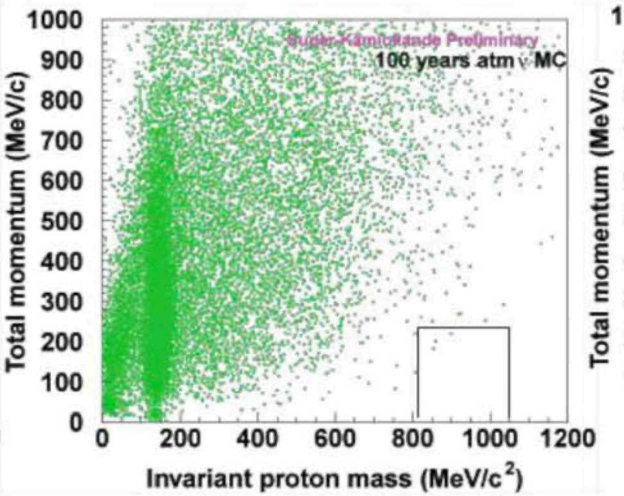
$p \rightarrow e^+ \pi^0$ Search in SuperK

$p \rightarrow e^+ \pi^0$ MC



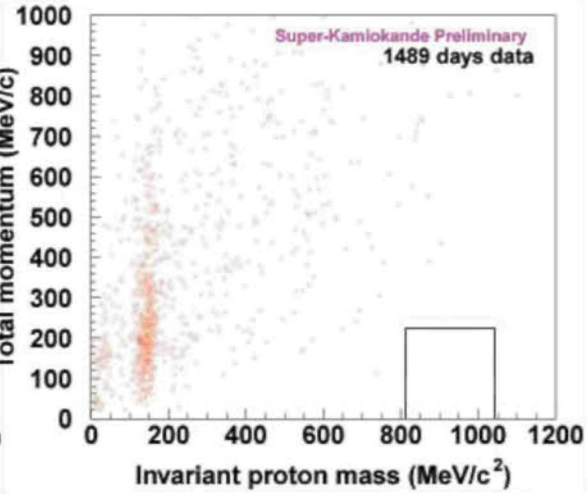
41% Signal efficiency

atm ν BG MC



0.3 expected Background

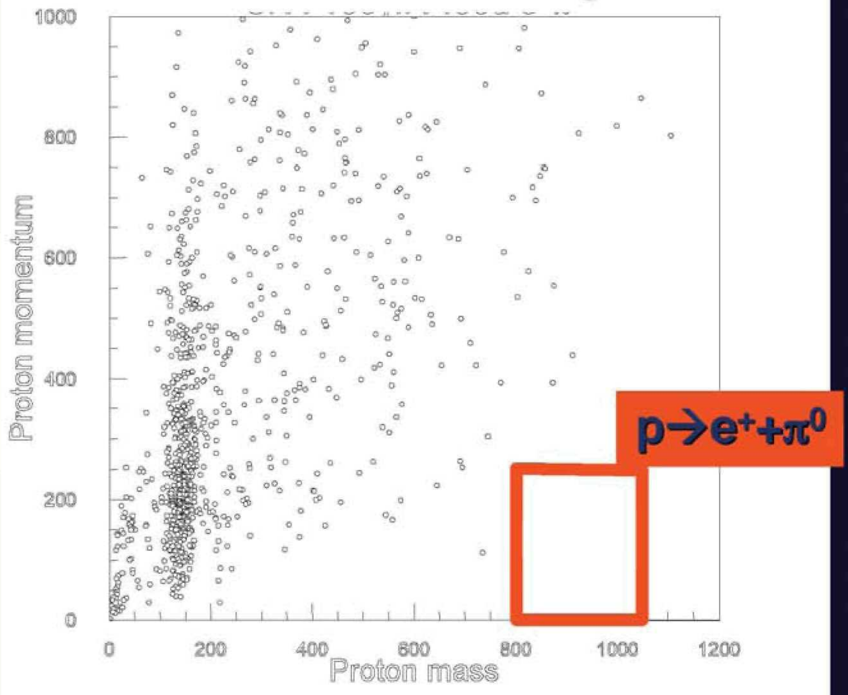
data

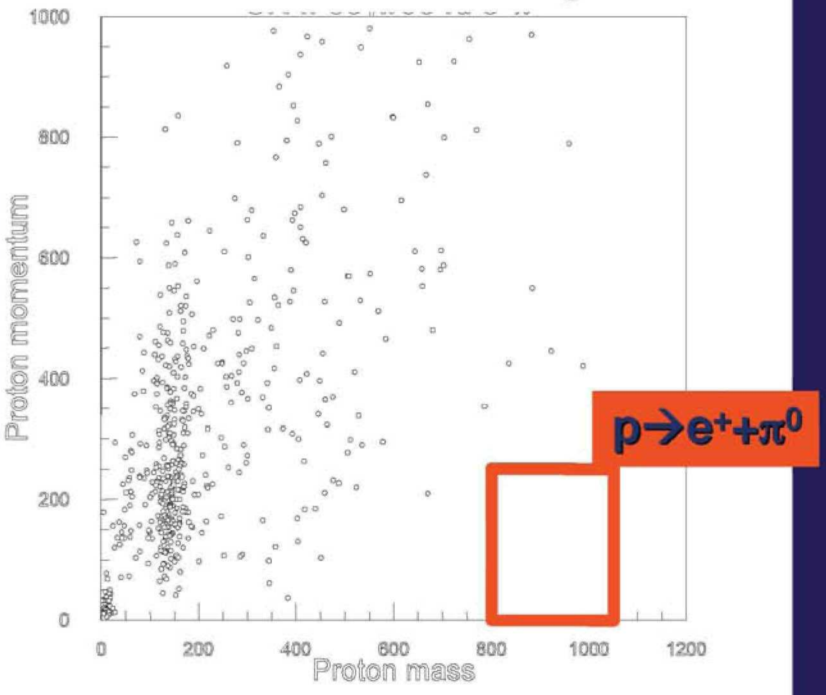


0 candidate in Data

$\tau/B(p \rightarrow e^+\pi^0) > 5.4\times10^{33}$ years (90%CL, w/ SK-I 1489 days data)

SK-I and SK-II Combined Result


SK-I 1489days

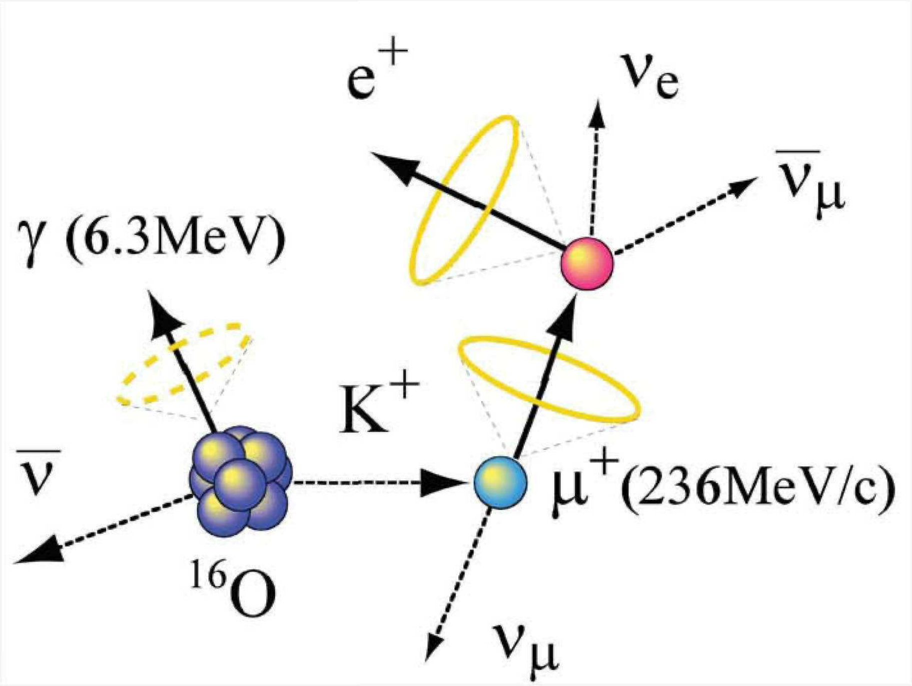

SK-II 799days

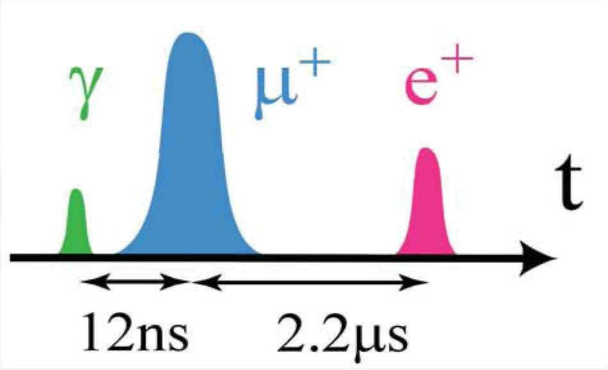
$\tau/B(p \rightarrow e^+\pi^0) > 8.4\times10^{33}$years（90%CL, SK-I & SK-II data)

$\sim(8\times10^{33}$protons)(1489+799days)/365 $*0.4/2.3=8.7\times10^{33}$years

$p \rightarrow K^+ \nu$ Decay Event Signature

$^{16}O \rightarrow \nu K^{+15}N\gamma$, $K^+ \rightarrow \mu^+\nu$ search (SK-I)

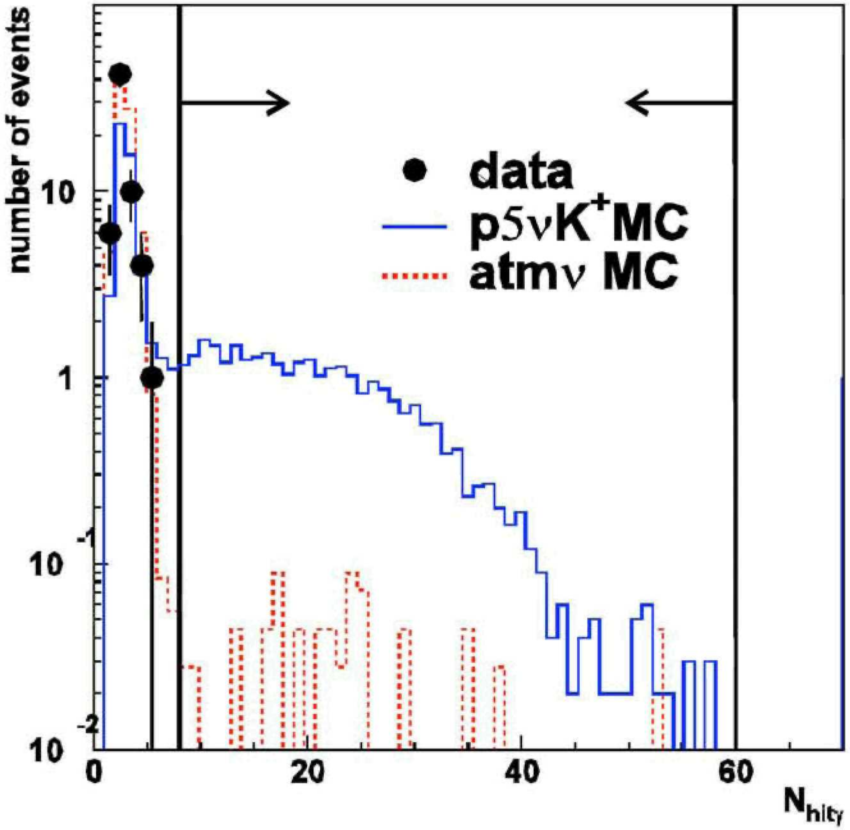




selection criteria

- 1 μ-like ring
- 1 Michel electron
- $210 < p_{\mu^+} < 260$MeV/c
- proton rejection cut
- $7 < N_{hit\gamma} < 60$

$p \rightarrow K^+ \nu$ search in SuperK



efficiency = 8.6%
0.7 exp'd BKG
0   candidate

Other K^+ decay modes searhes:
$p \rightarrow \nu K^+$, $K^+ \rightarrow \pi^+ \pi^0$
$p \rightarrow \nu K^+$, $K^+ \rightarrow \mu^+ \nu$ (no γ tagging)

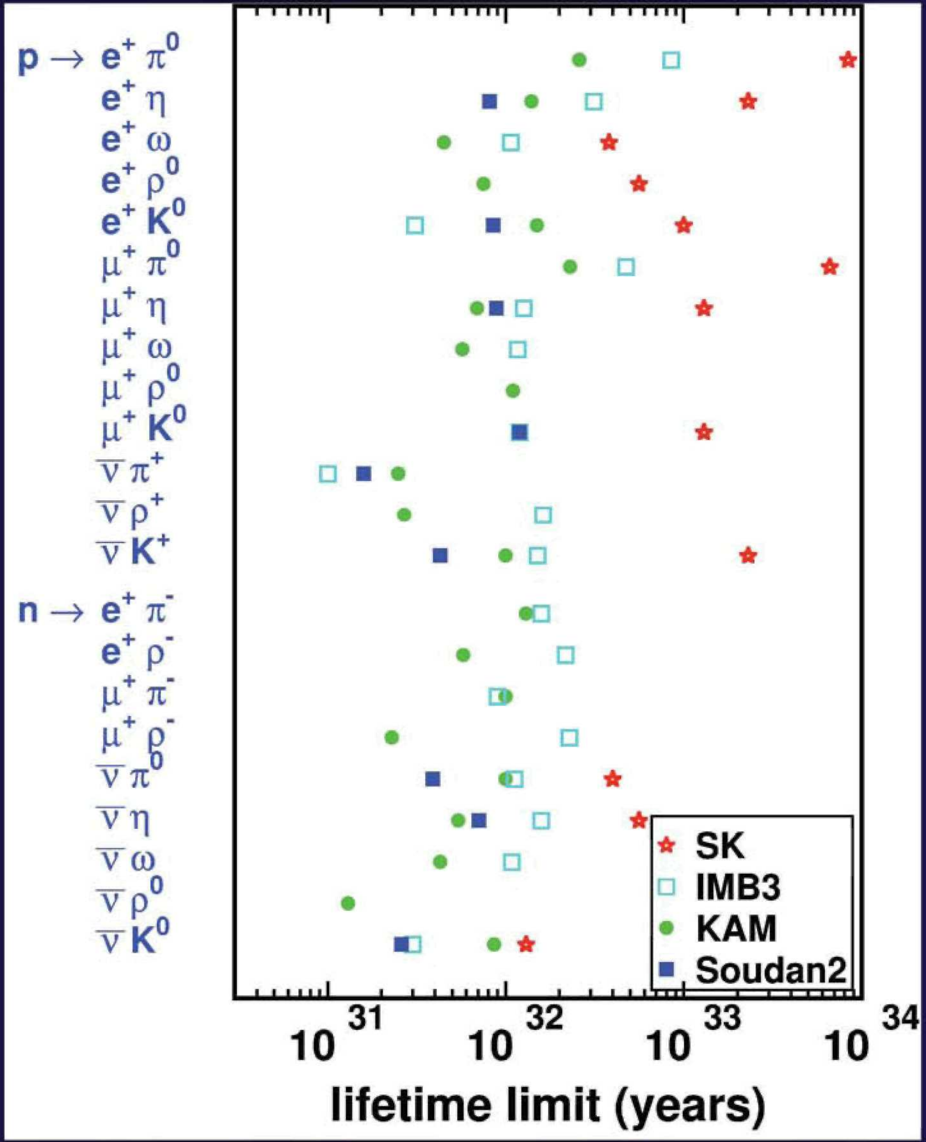
→ three searches combine

$\tau/B(p \rightarrow \nu K^+) > 2.3 \times 10^{33}$ years（90%CL）

Summary SuperK Nucleon Decay Search Results

mode	exposure (kt· yr)	εB_m (%)	observed event	B.G.	τ/B limit (10^{32} yrs)
$p \to e^+ + \pi^0$	141	41	0	0.4	84
$p \to \mu^+ + \pi^0$	141	32-31	0	0.2	66
$p \to e^+ + \eta$	92	17	0	0.2	23
$p \to \mu^+ + \eta$	92	9	0	0.2	13
$n \to \bar{\nu} + \eta$	45	21	5	9	5.6
$p \to e^+ + \rho$	92	4.2	0	0.4	5.6
$p \to e^+ + \omega$	92	2.9	0	0.5	3.8
$p \to e^+ + \gamma$	92	73	0	0.1	98
$p \to \mu^+ + \gamma$	92	61	0	0.2	82
$p \to \bar{\nu} + K^+$	92				23
$K^+ \Rightarrow \nu\mu^+$ (spectrum)		36	--	--	6.4
prompt $\gamma + \mu^+$		8.6	0	0.7	10
$K^+ \Rightarrow \pi^+\pi^0$		6.0	0	0.6	7.8
$n \to \bar{\nu} + K^0$	92				1.3
$K^0 \Rightarrow \pi^0\pi^0$		6.9	14	19.2	1.3
$K^0 \Rightarrow \pi^+\pi^-$		5.5	20	11.2	0.69
$p \to e^+ + K^0$	92				10
$K^0 \Rightarrow \pi^0\pi^0$		9.2	1	1.1	8.4
$K^0 \Rightarrow \pi^+\pi^-$					
2-ring		7.9	5	3.6	3.5
3-ring		1.3	0	0.04	1.6
$p \to \mu^+ + K^0$	92				13
$K^0 \Rightarrow \pi^0\pi^0$		5.4	0	0.4	7.0
$K^0 \Rightarrow \pi^+\pi^-$					
2-ring		7.0	3	3.2	4.4
3-ring		2.8	0	0.3	3.6

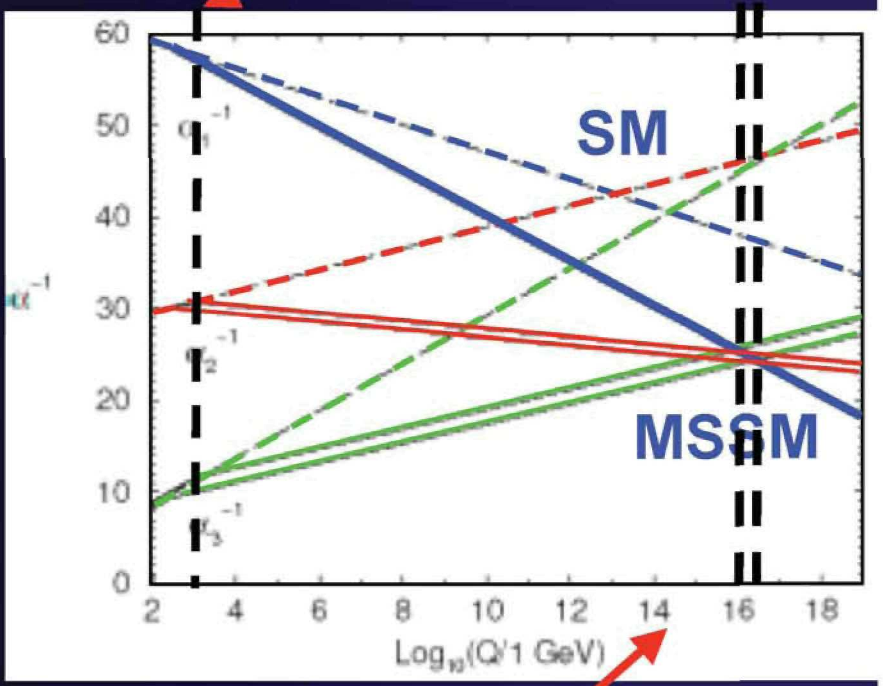
Summary Proton Decay Search Results



Current Status

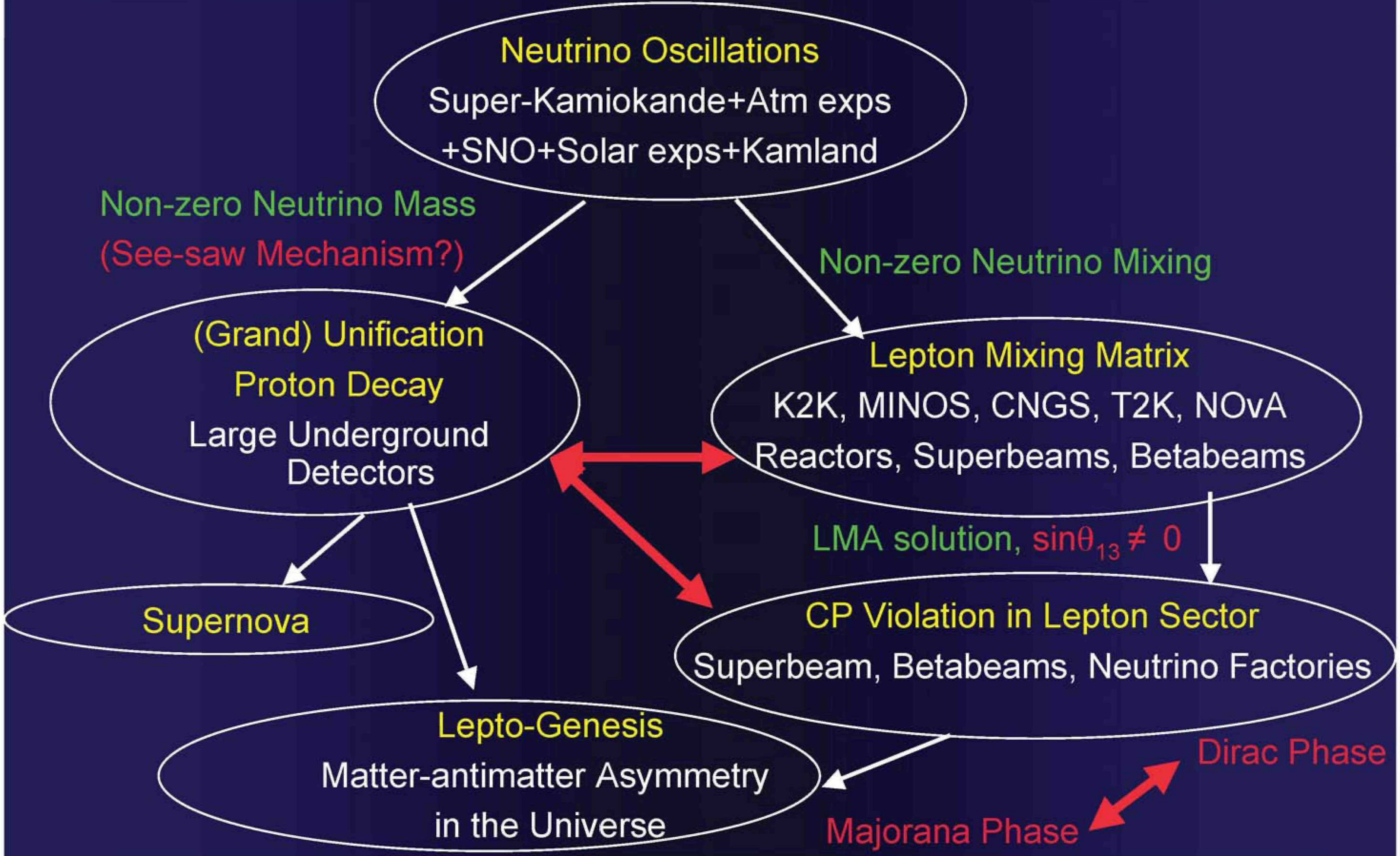
- So far, no evidence for proton decay
- However, there are tantalizing hints for unification
  - Small but finite neutrino mass
    - ⇒ see-saw mechanism?
  - Convergence of the running coupling constants
    - ⇒ Especially with supersymmetry
  - This provides a new meaning to the seemingly accidental relationship between proton decay and neutrino

SUSY Breaking



$M_{GUT} = 10^{16} \sim 2\mathrm{x}10^{16}$ GeV (?)

1998 Neutrino Revolution and Physics Goals for NNN Experiments



Neutrino Oscillations

Super-Kamiokande+Atm exps

+SNO+Solar exps+Kamland

Non-zero Neutrino Mass

(See-saw Mechanism?)

Non-zero Neutrino Mixing

(Grand) Unification

Proton Decay

Large Underground Detectors

Lepton Mixing Matrix

K2K, MINOS, CNGS, T2K, NOvA

Reactors, Superbeams, Betabeams

LMA solution, $\sin\theta_{13} \neq 0$

Supernova

CP Violation in Lepton Sector

Superbeam, Betabeams, Neutrino Factories

Lepto-Genesis

Matter-antimatter Asymmetry in the Universe

Dirac Phase

Majorana Phase

Physics Beyond SuperK, T2K, NOVA

- Requires a Next generation Nucleon decay and Neutrino (NNN) detector with physics sensitivities an order of magnitude better than those of SuperK, T2K and NOVA
  - Water Cherenkov Detector: > 500 kton
  - LAr Detector: ~100 kton

    ⇒ a great technical challenge
  - by the time a NNN Detector is built, SuperK will have accumulated more than 20 years of data

UNO Design and NNN Workshops

- UNO first proposed in 1999 at the Next generation Nucleon decay and Neutrino Detector Workshop (NNN99)

  ckj
  "Feasibility a Next Generation Underground Water Cherenkov Detector: UNO",
  [hep-ex/0005046], NNN99 Proceedings

- After rigorous discussion within the UNO collaboration, the baseline design remains the same as the original
- Design optimization needed for specific detector site

  local geology can force the design to be two or three separate modules and/or narrower width

- Continuing international discussions at the NNN series workshops

NNN Workshop Series

- Initiated and first organized by ckj in 1999 at Stony Brook
  - NNN09-Stony Brook
  - NNN00-Irvine
  - NNN00-Fermilab
  - NNN02-CERN
  - NNN05-Aussois (France)
  - NNN06-Seatle
  - NNN07-Hamamatsu (Japan)
  - NNN08-Paris
- Provides an international forum for cooperation, coordination and collaboration among the next generation large nucleon decay and neutrino detector community
- Permanent Workshop Steering Committee
  - K. Nakamura (Japan), S. Katsanevas (France), ckj (U.S.)

UNO Detector Conceptual (Baseline) Design

A Water Cherenkov Detector

optimized for:

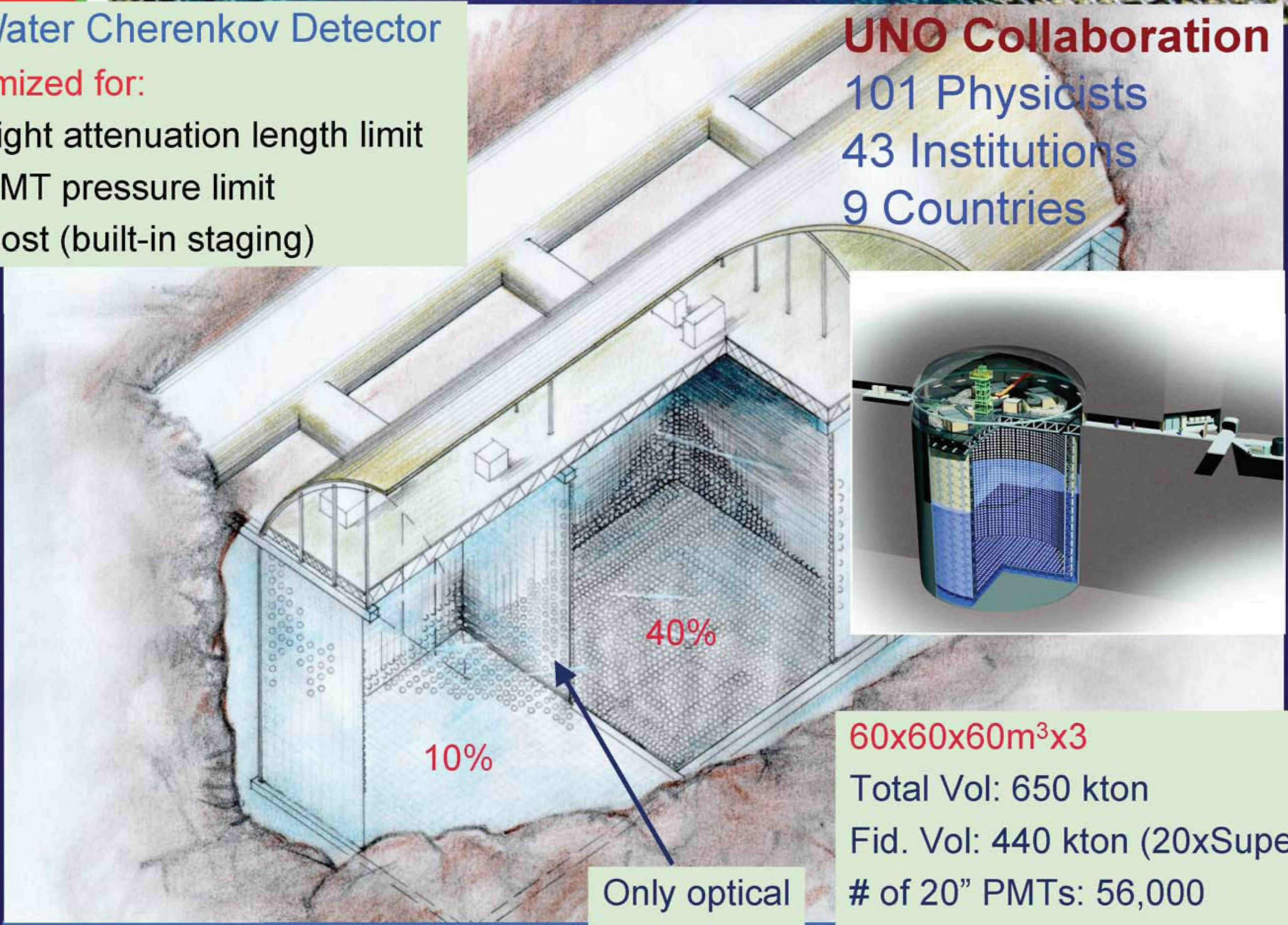
- Light attenuation length limit
- PMT pressure limit
- Cost (built-in staging)

UNO Collaboration

101 Physicists

43 Institutions

9 Countries



Only optical separation

60x60x60m^{3}x3

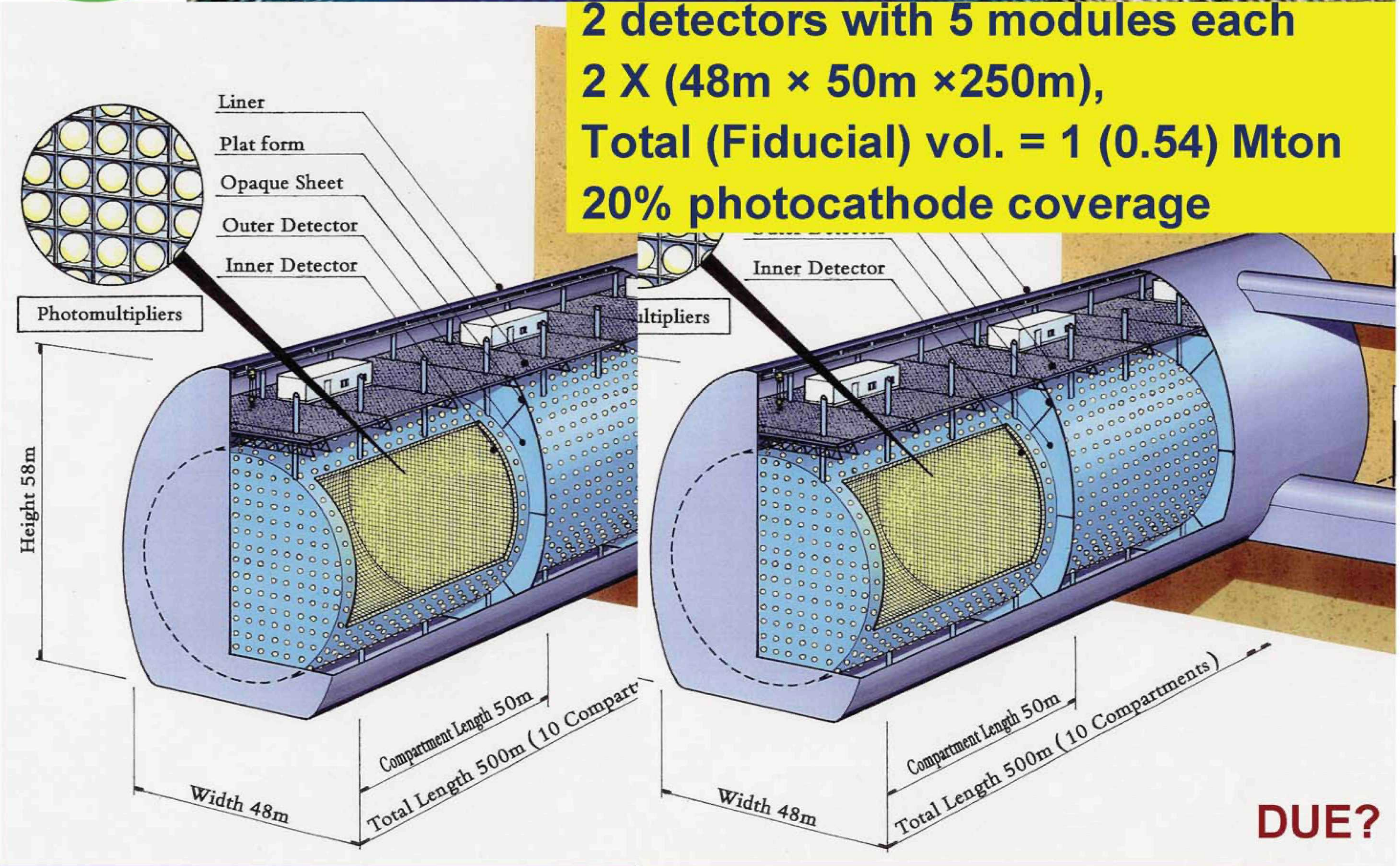
Total Vol: 650 kton

Fid. Vol: 440 kton (20xSuperK)

# of 20” PMTs: 56,000

# of 8” PMTs: 14,900

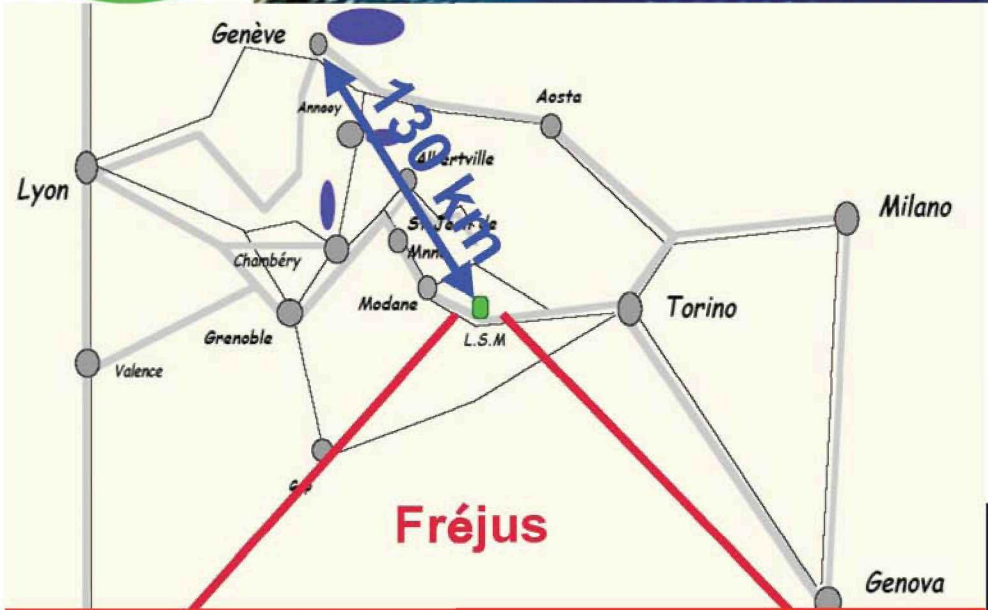
Hyper-Kamiokande Current Design

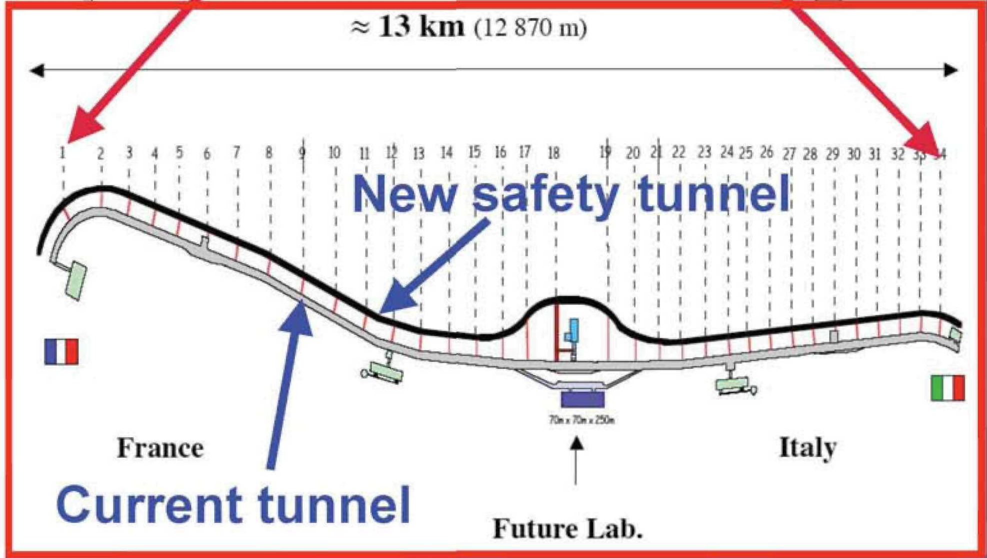


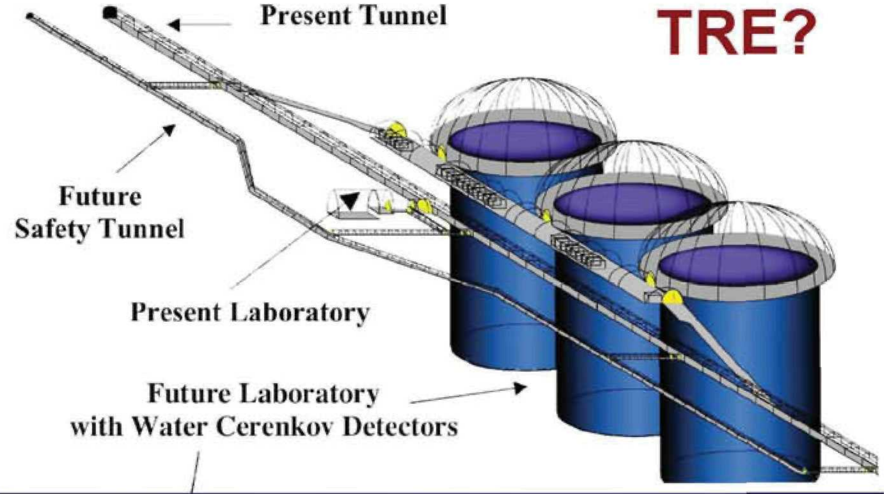
2 detectors with 5 modules each
2 X (48m × 50m ×250m),
Total (Fiducial) vol. = 1 (0.54) Mton
20% photocathode coverage

DUE?

1Mton Class WC Detector at Fréjus

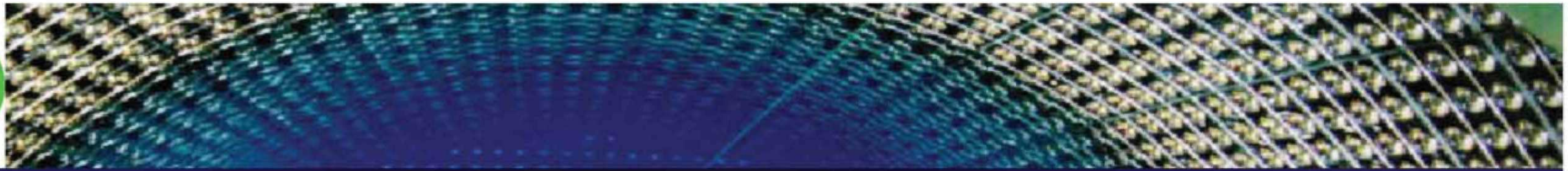






TRE?

- Considered in conjunction w/ an ambitious CERN "Physics with a MMW proton source" initiative
- Window of opportunity with the planned new safety tunnel construction
- Variety of detector design is considered: 3 detectors, UNO-like detector, etc.



No proposals for Quattro

…

…

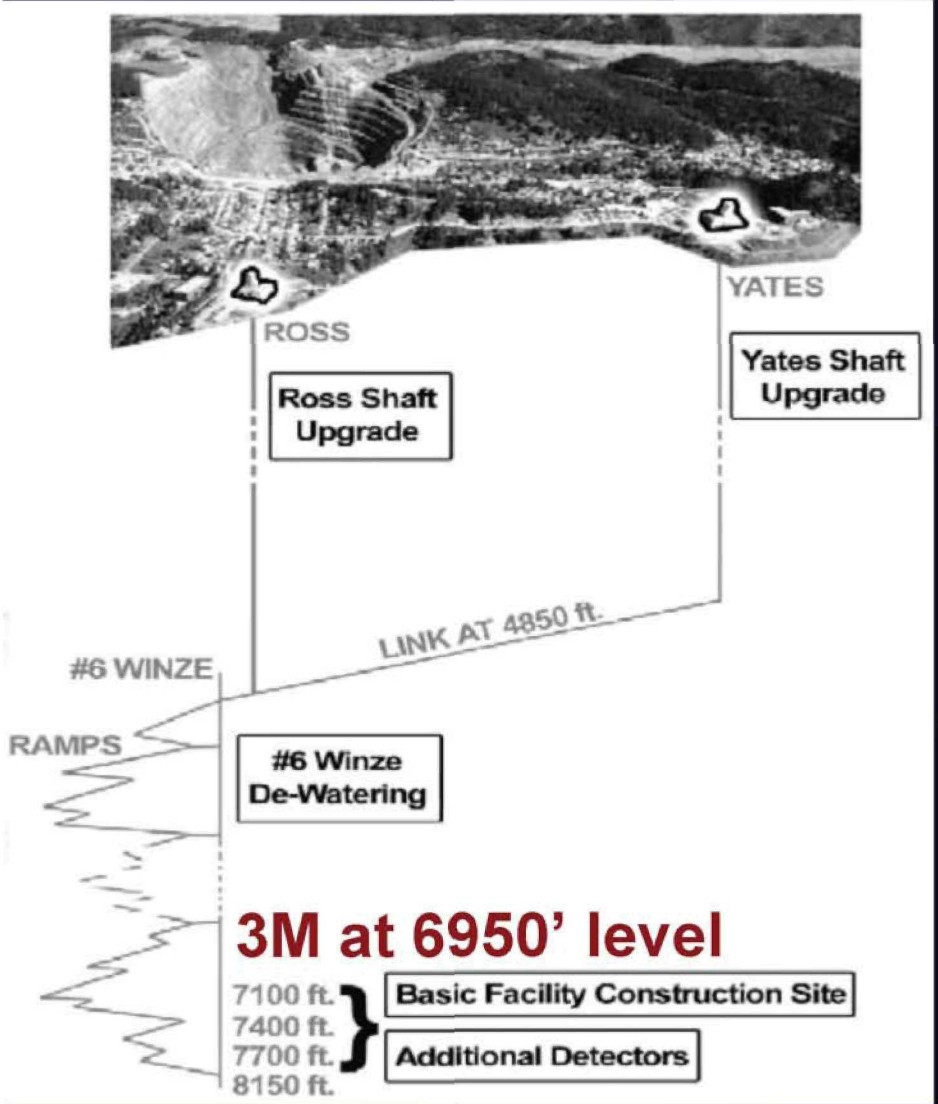
…

…

Nove Detectors, yet!

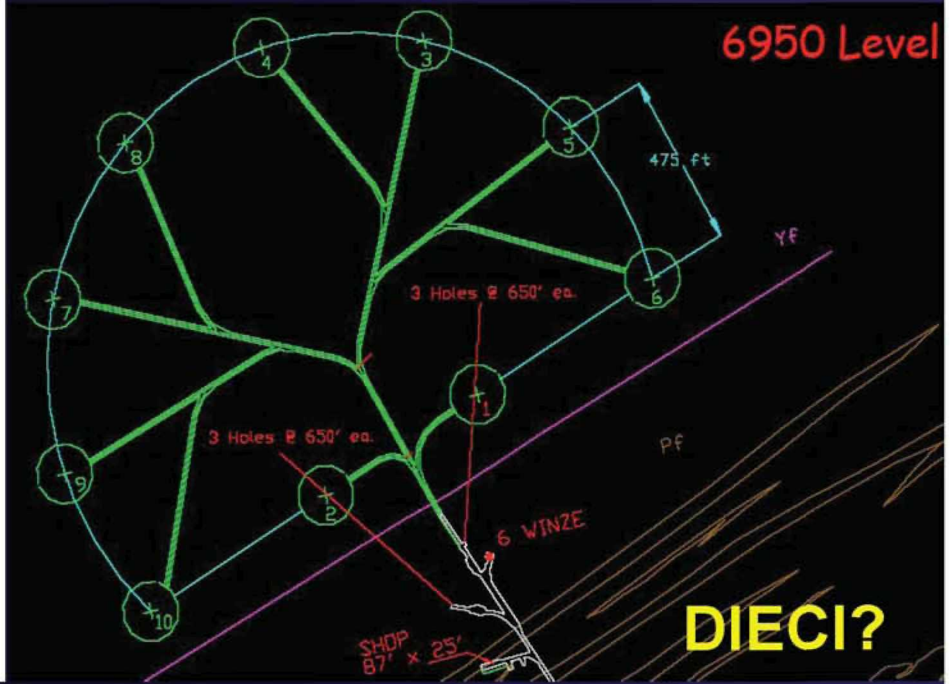
However…

3M Detector at Homestake Mine



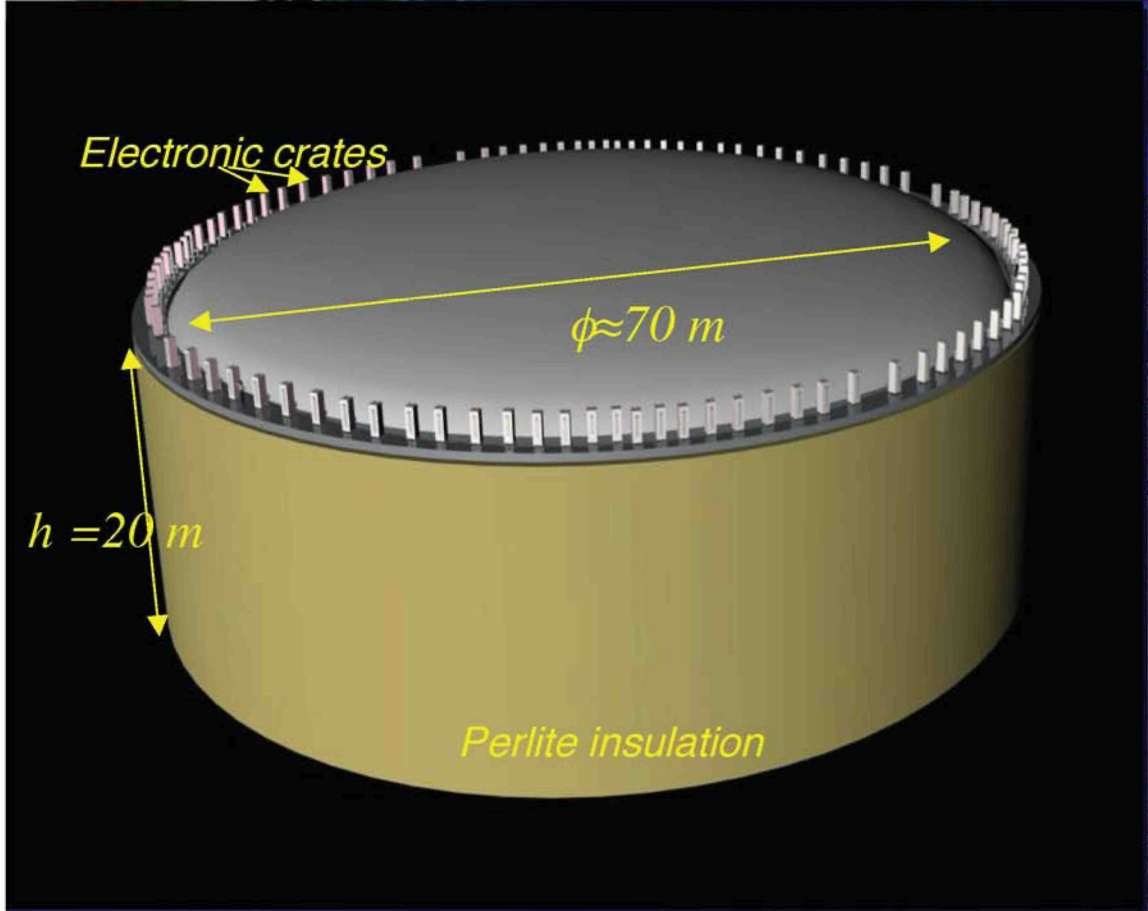
3M at 6950' level

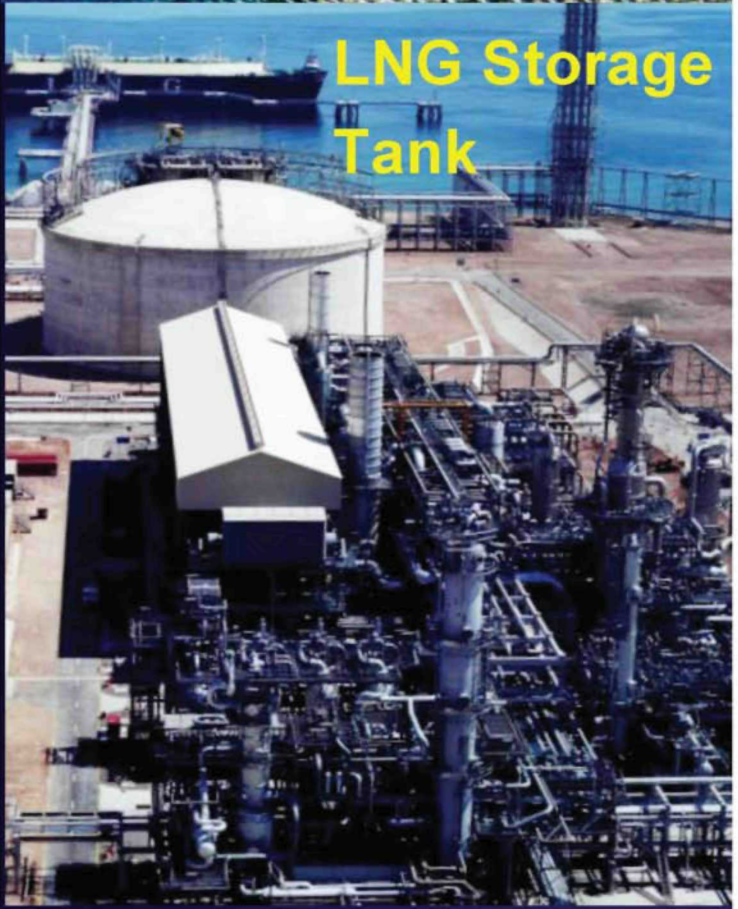
- 10 cylindrical detectors (50m x 50mϕ), 100 kton each
- Total (Fiducial) vol.: 1 (0.8) Mton
- No veto region
- 10% photocathode coverage



DIECI?

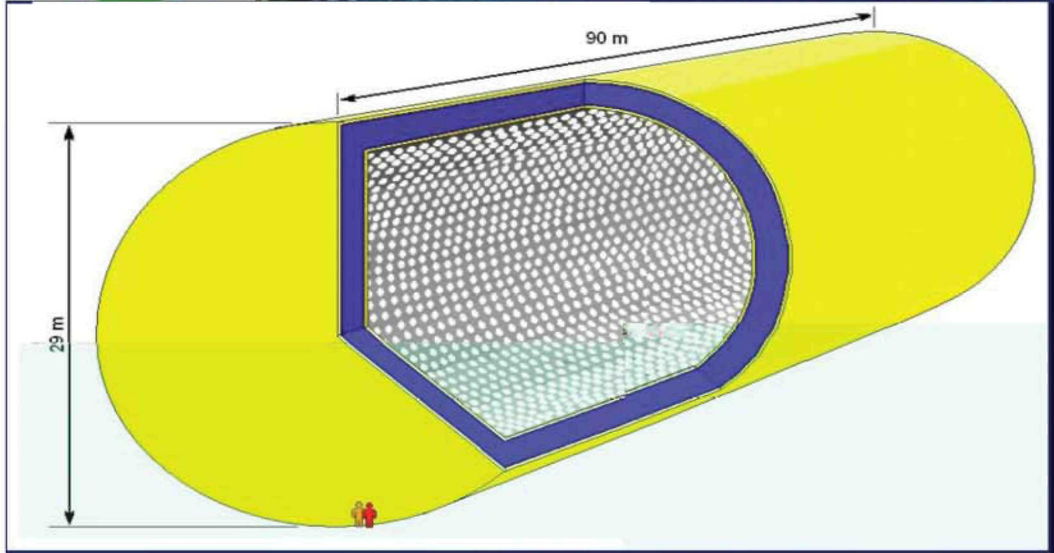
100kt LAr TPC in Europe





- New approach:
  - single plane readout with long drift distance (20 m max)
  - In situ cryogenic LAr production plant

LENA



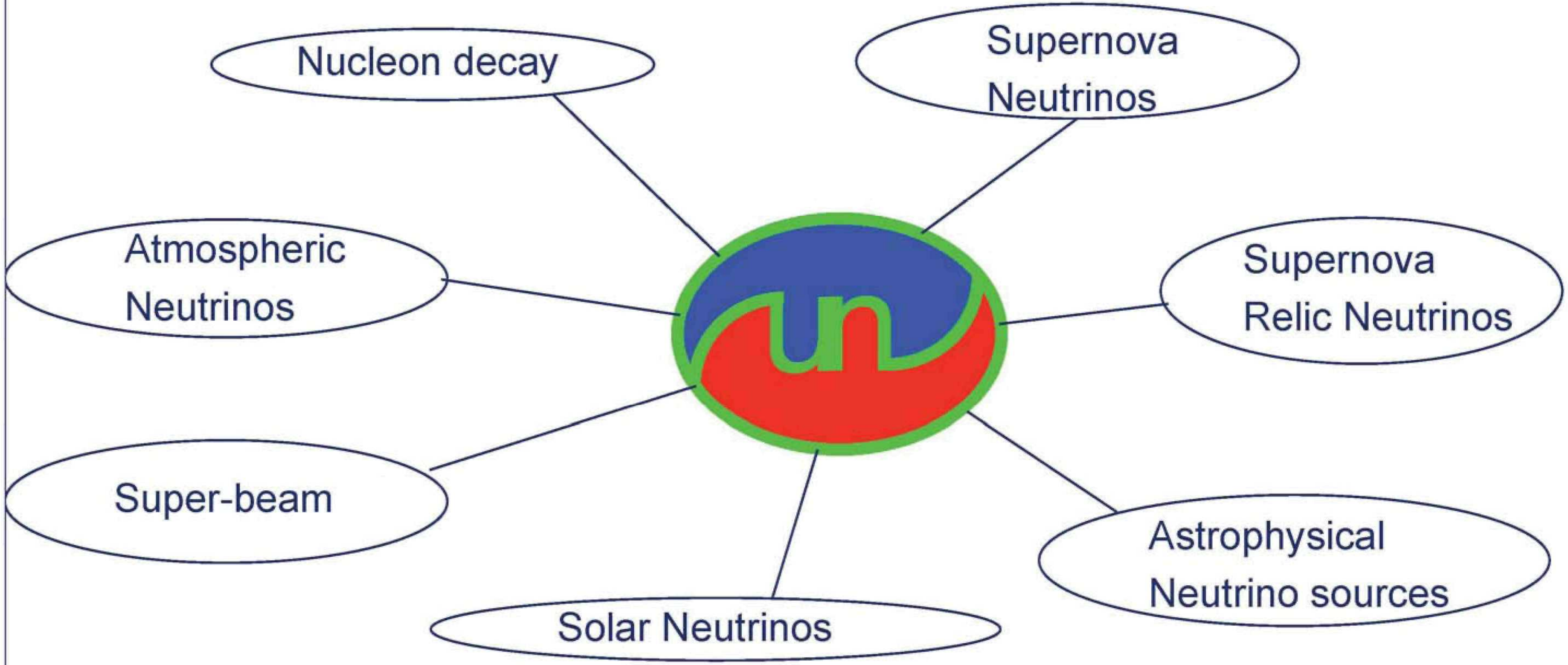
- Large Liquid Scintillator Detector for **L**ow **E**nergy **N**eutrino **A**stronomy
- Total (Fiducial) volume: 50 (22) kton
- Scintillator: PXE (~12 m light attenuation length @450 nm)
- 12,000 20" PMTs (30% coverage)
- ~120 pe/MeV

- Physics Goals
  - – SN burst

  (flavor specific galactic SN neutrinos)

  - – SRN
  - – Solar nu (high stat.)
  - – Atmospheric nu
  - – LBL
  - – Geoneutrinos
  - – Proton decay

UNO Physics Goals



Nucleon decay

Supernova Neutrinos

Atmospheric Neutrinos

Supernova Relic Neutrinos

Super-beam

Astrophysical Neutrino sources

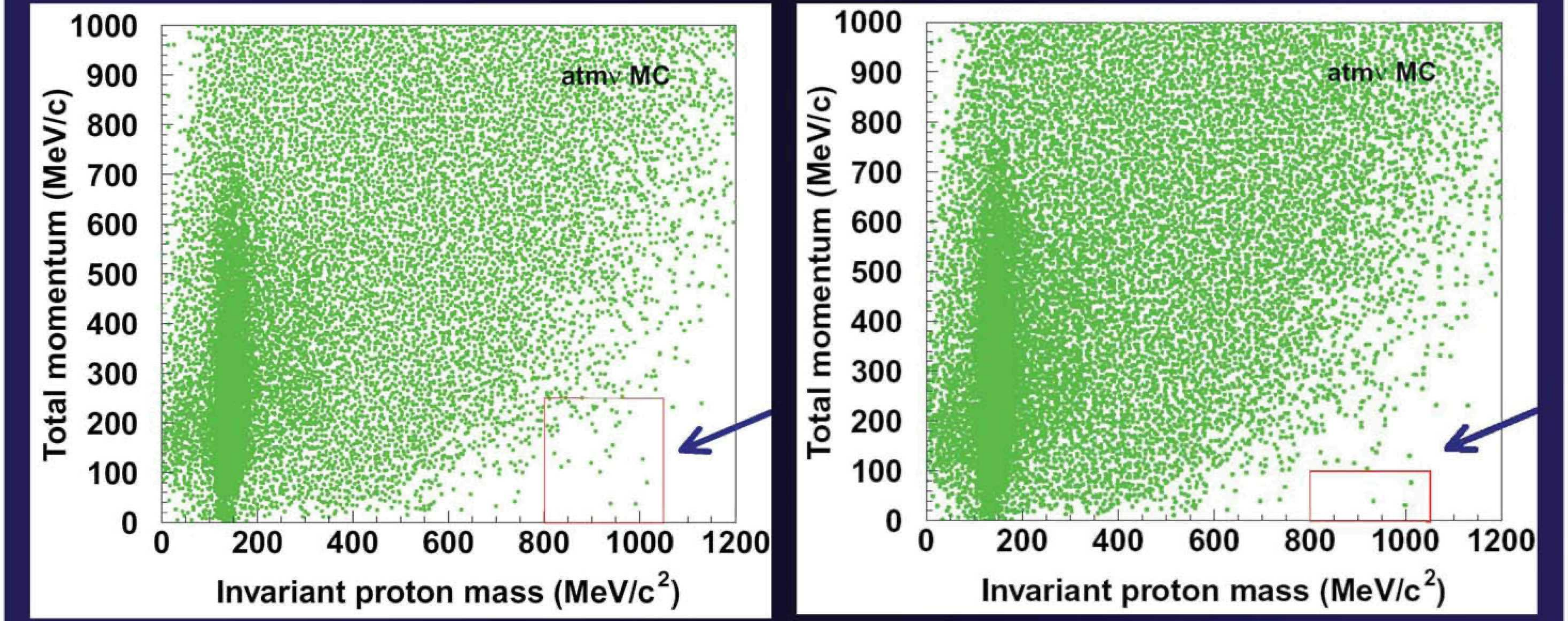
Solar Neutrinos

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

⇒ Synergy between accelerator physics and non-accelerator physics

$p \to e^+ \pi^0$ Search Background

20 Mton-yr Atm nu Background MC



SuperK Standard Cuts

==> 2.2 events/Mton-yr

==> signal eff.: 43.0%

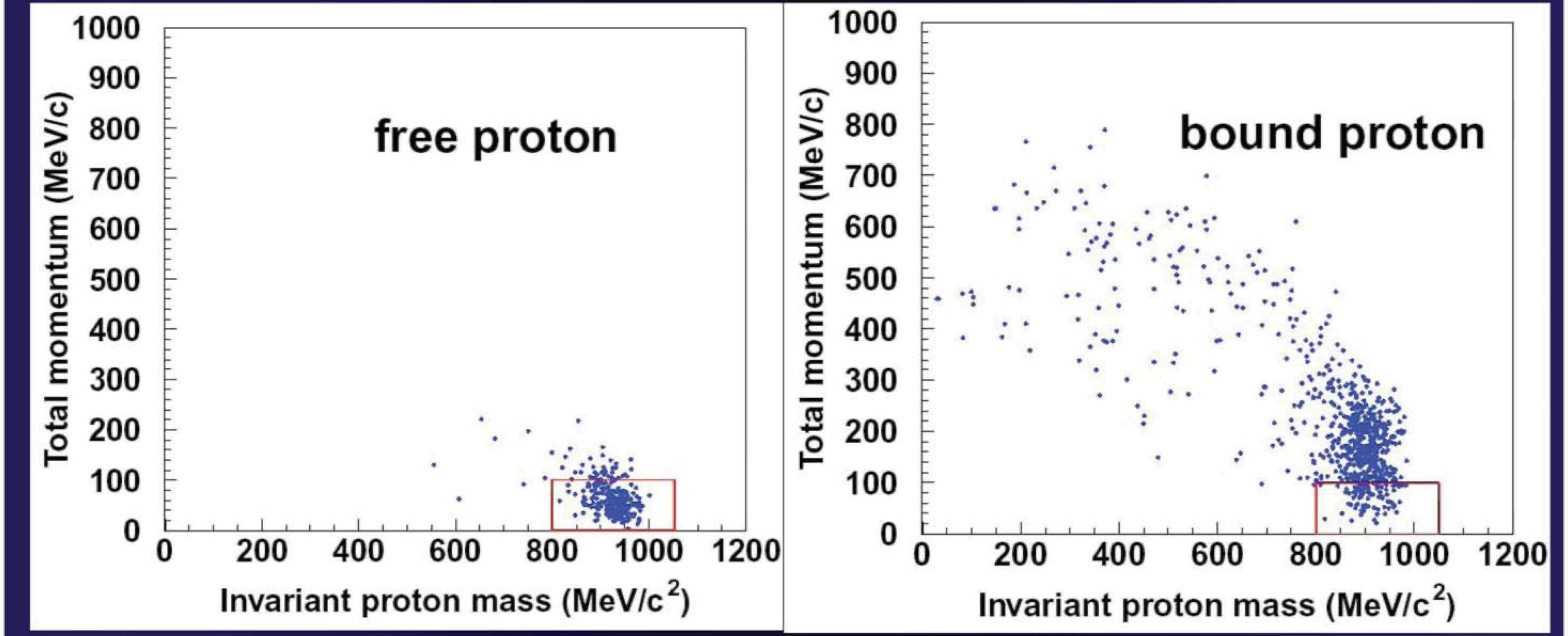
Tighter Momentum Cut

==> 0.15 events/Mton-yr

==> signal eff.: 17.4%

$p \to e^+ \pi^0$ Search Signal

Signal Events w/ Tighter Momentum Cut



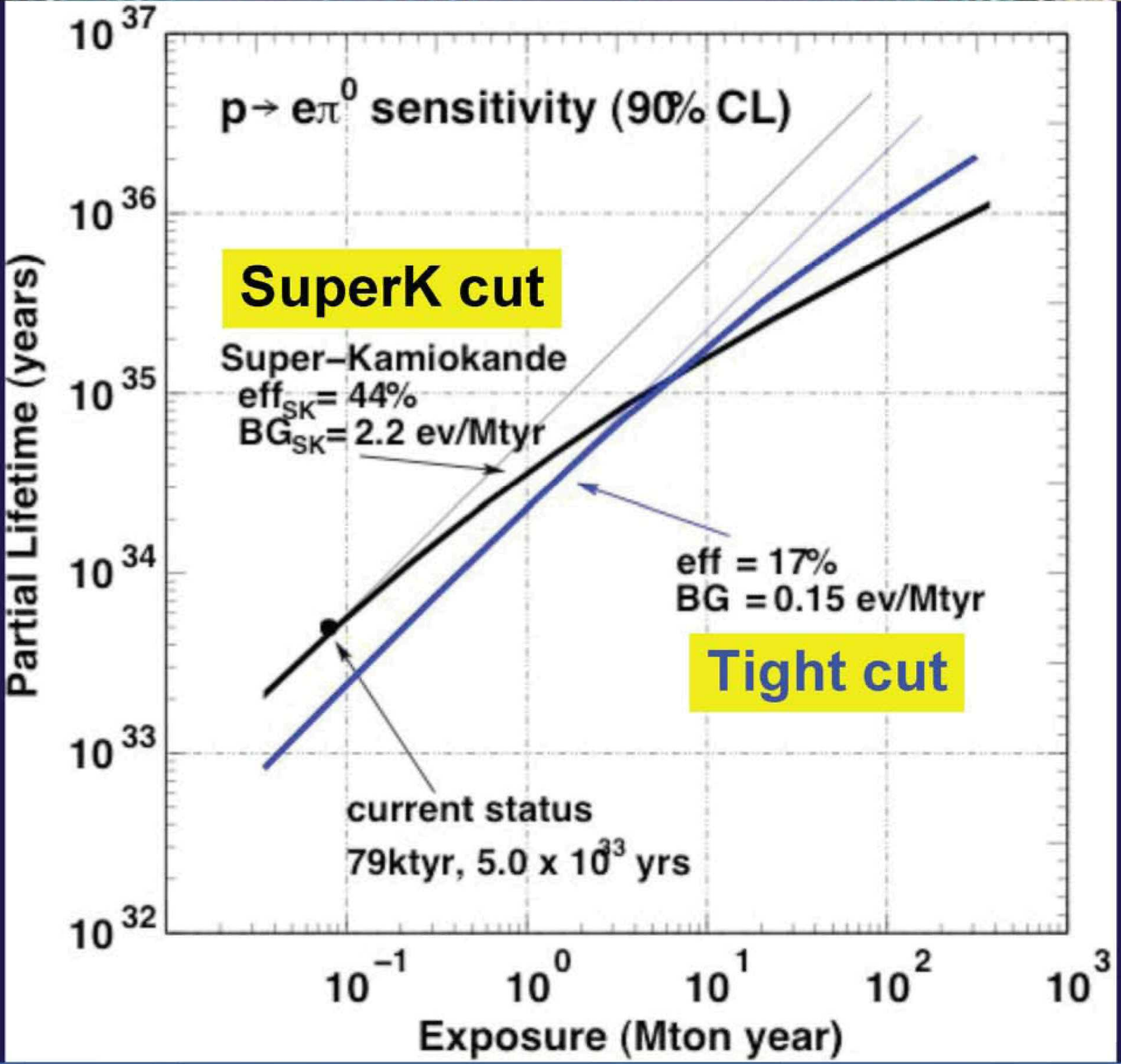
No Fermi Momentum

No Binding energy

No Nuclear effect (π^0 scattering, absorption and charge exchange)

⇒ Important to have a medium with free protons

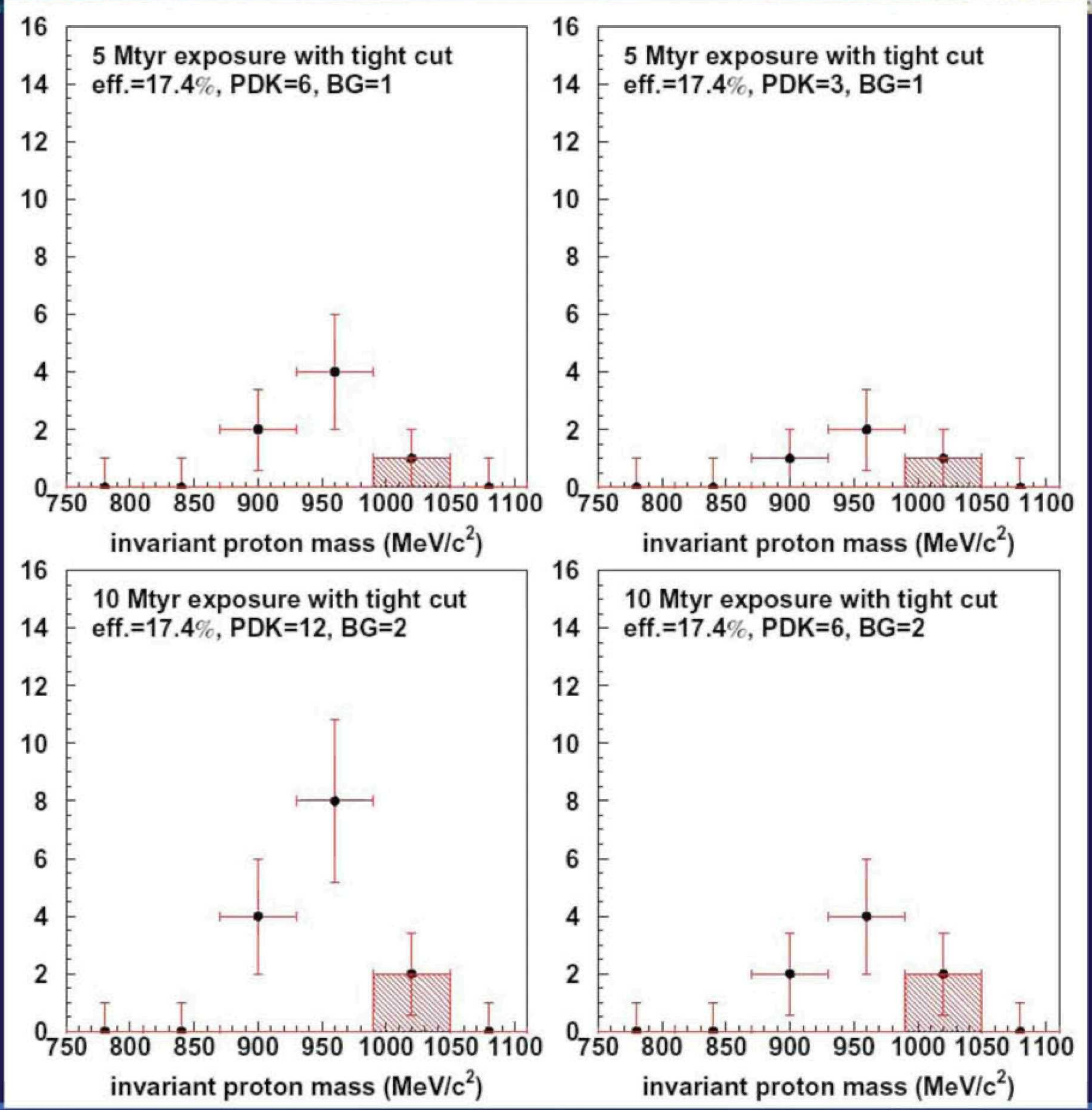
Comparison of the Standard SuperK Analysis and the HyperK/UNO Analysis



Room to Improve…

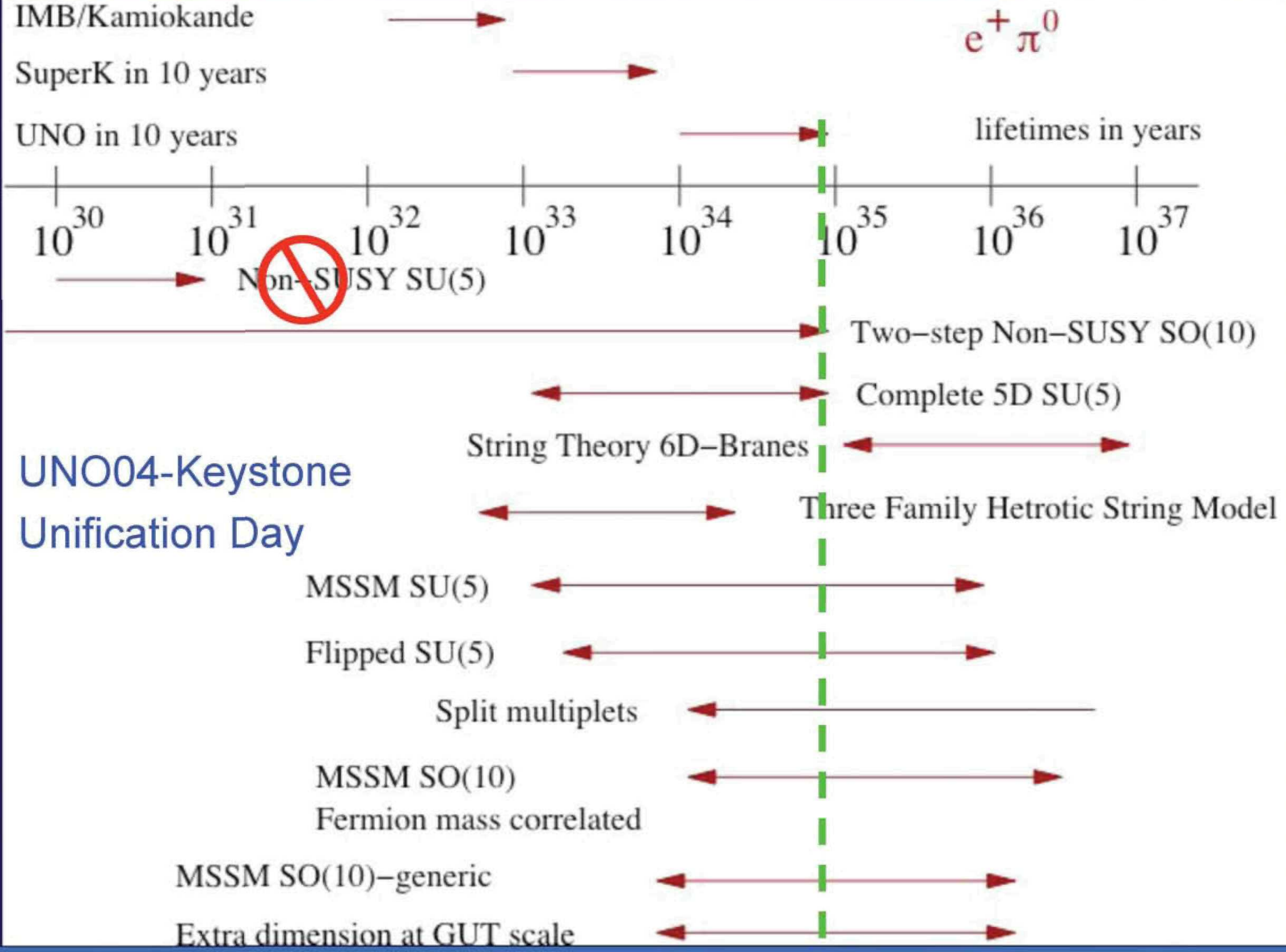
Reconstructed Mass Peak from $p \rightarrow e^+ \pi^0$

$\tau/B(p \rightarrow e^+ \pi^0)$
= 5×10^{34} years
1 candidate
event/~1.5 yrs



$\tau/B(p \rightarrow e^+ \pi^0)$
= 1×10^{35} years
1 candidate
event/~3 yrs

UNO Proton Decay Sensitivity and Updated Theoretical Predictions ($e^+\pi^0$)



$e^+\pi^0$

lifetimes in years

IMB/Kamiokande

SuperK in 10 years

UNO in 10 years

Non-SUSY SU(5)

Two−step Non−SUSY SO(10)

Complete 5D SU(5)

String Theory 6D−Branes

Three Family Hetrotic String Model

MSSM SU(5)

Flipped SU(5)

Split multiplets

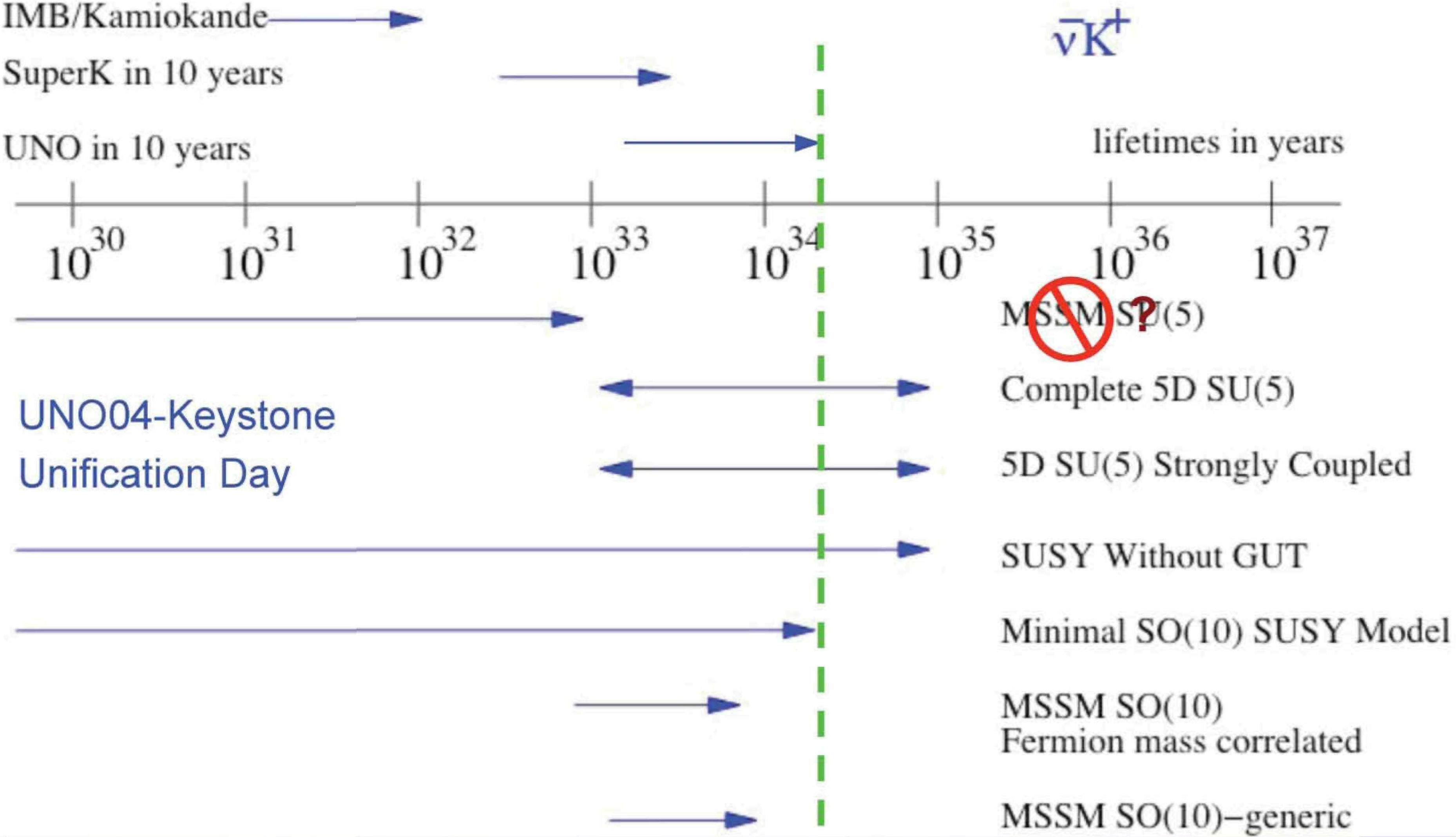
MSSM SO(10)
Fermion mass correlated

MSSM SO(10)−generic

Extra dimension at GUT scale

UNO04-Keystone
Unification Day

UNO Proton Decay Sensitivity and Updated Theoretical Predictions ($K^+\nu$)



$\bar{\nu}K^+$

lifetimes in years

IMB/Kamiokande

SuperK in 10 years

UNO in 10 years

10^{30} 10^{31} 10^{32} 10^{33} 10^{34} 10^{35} 10^{36} 10^{37}

MSSM SU(5) ?

Complete 5D SU(5)

5D SU(5) Strongly Coupled

SUSY Without GUT

Minimal SO(10) SUSY Model

MSSM SO(10)
Fermion mass correlated

MSSM SO(10)−generic

UNO04-Keystone
Unification Day

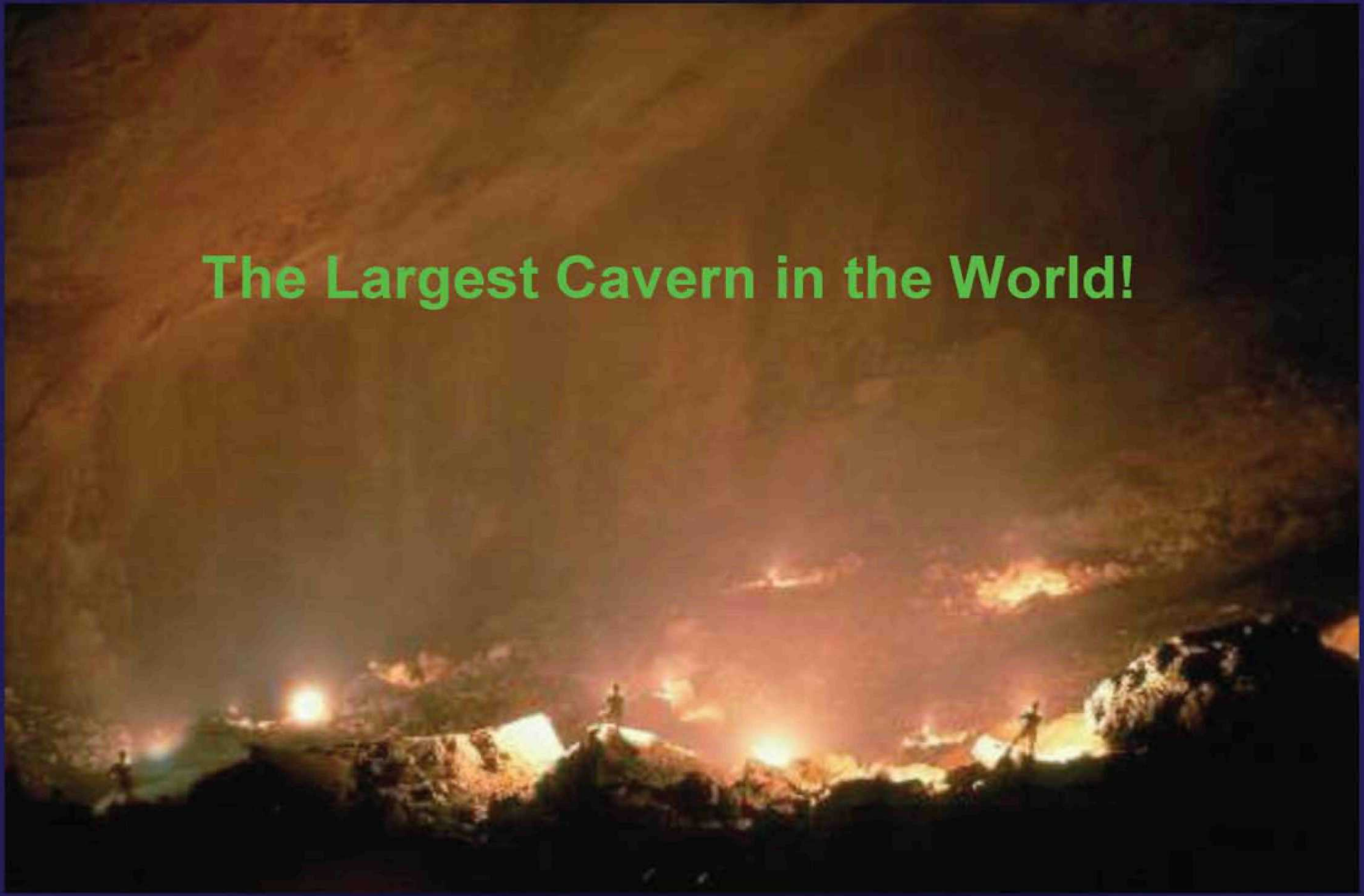
How big a cavern can we construct underground?
A challenge to the mining engineering community
(a sexy topic)

Possible application in the future:
Large underground facility/storage
Large underground living space

Good Luck Cave
Sarawak, Borneo

Gunung Mulu National Park, a Karst cave (limestone)

Dimensions: L=600m, W=400m, H=100m, Ar=162,700m^2

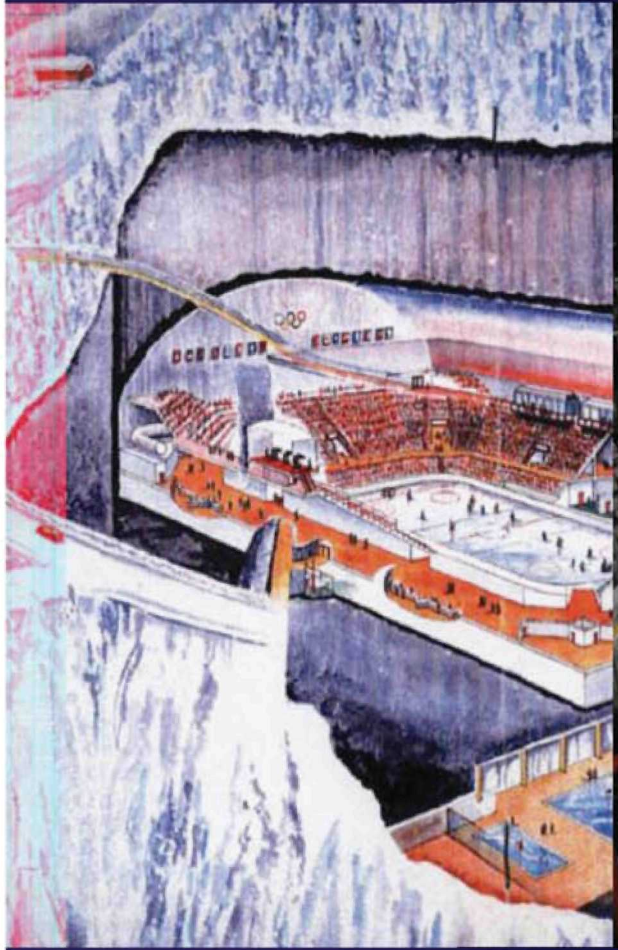


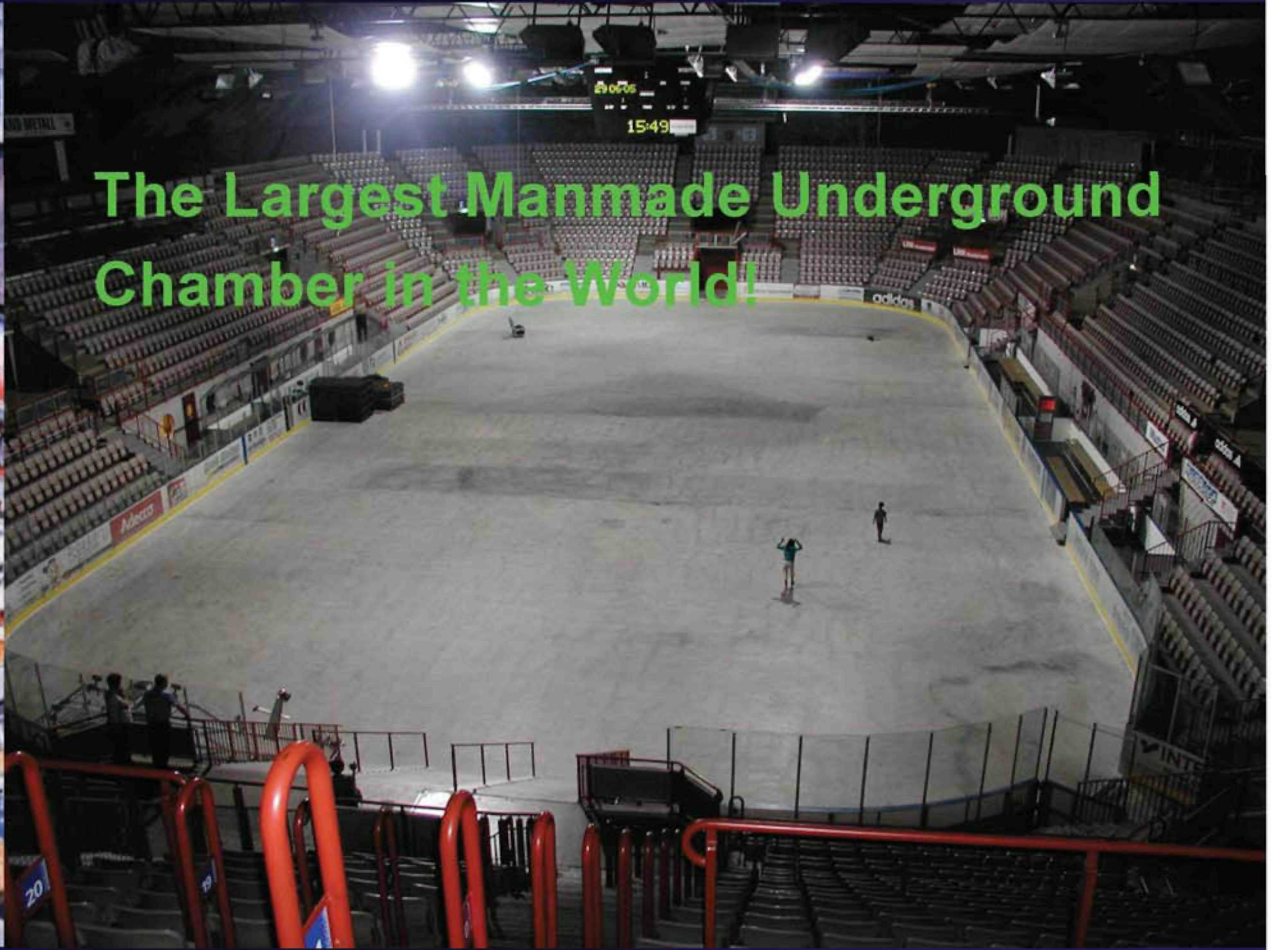
The Largest Cavern in the World!

Norwegian Hockey Arena
Gjøvik, Norway

Dimensions: L=91m, W=61m, H=25m, Ar=15,000m^2

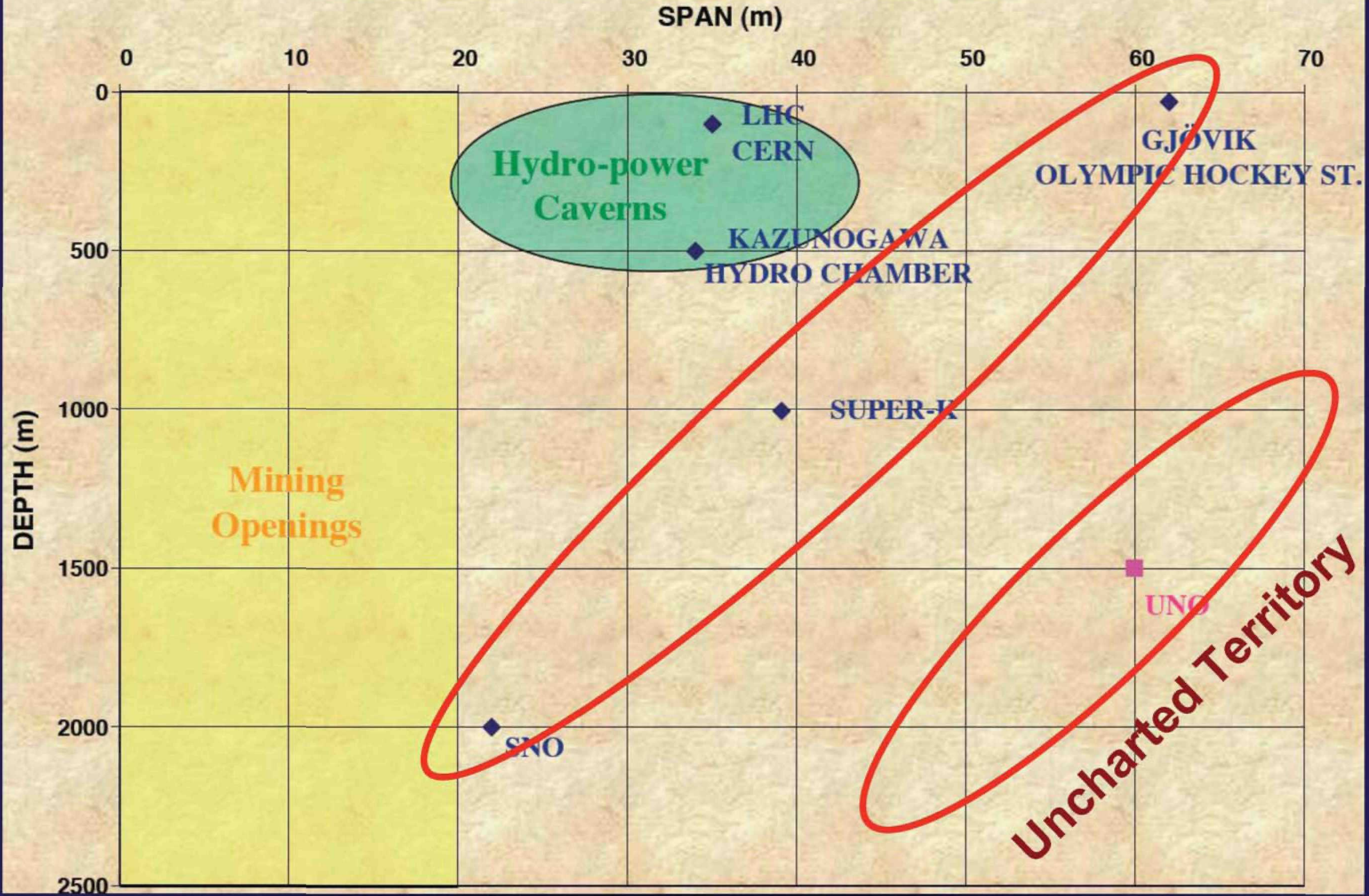
Construction Cost: $20M USD (1992)



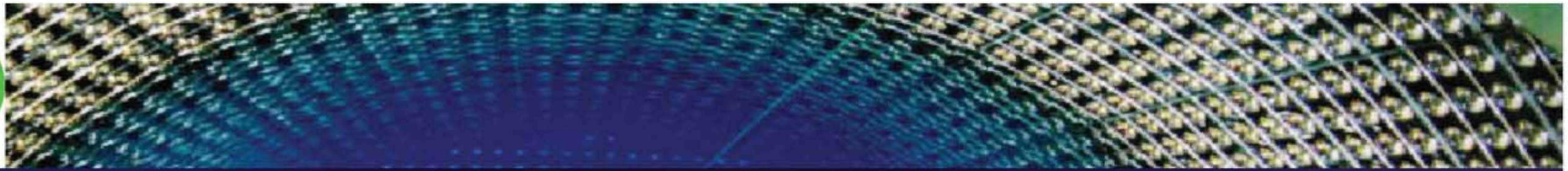


The Largest Manmade Underground Chamber in the World!

Bench Marking
(P. Varona, Itasca)



Gotthard Rock Burst



DUSEL Status

Deep Underground Science and Engineering Lab

= A national laboratory for comprehensive underground science and engineering research

An National Science Foundation (NSF) Initiative

A *possible* site for UNO or other NNN detectors

NSF DUSEL Process (laid out in March 2004)

Solicitation 1 (S1): Science case and infrastructure requirements

one or more interdisciplinary teams to develop a site independent preliminary plan

Solicitation 2 (S2): Conceptual design proposal

Fund grants for conceptual planning of infrastructure as related to the site

award 3~5 sites ($300k~$500k each)

Solicitation 3 (S3): Technical design proposal

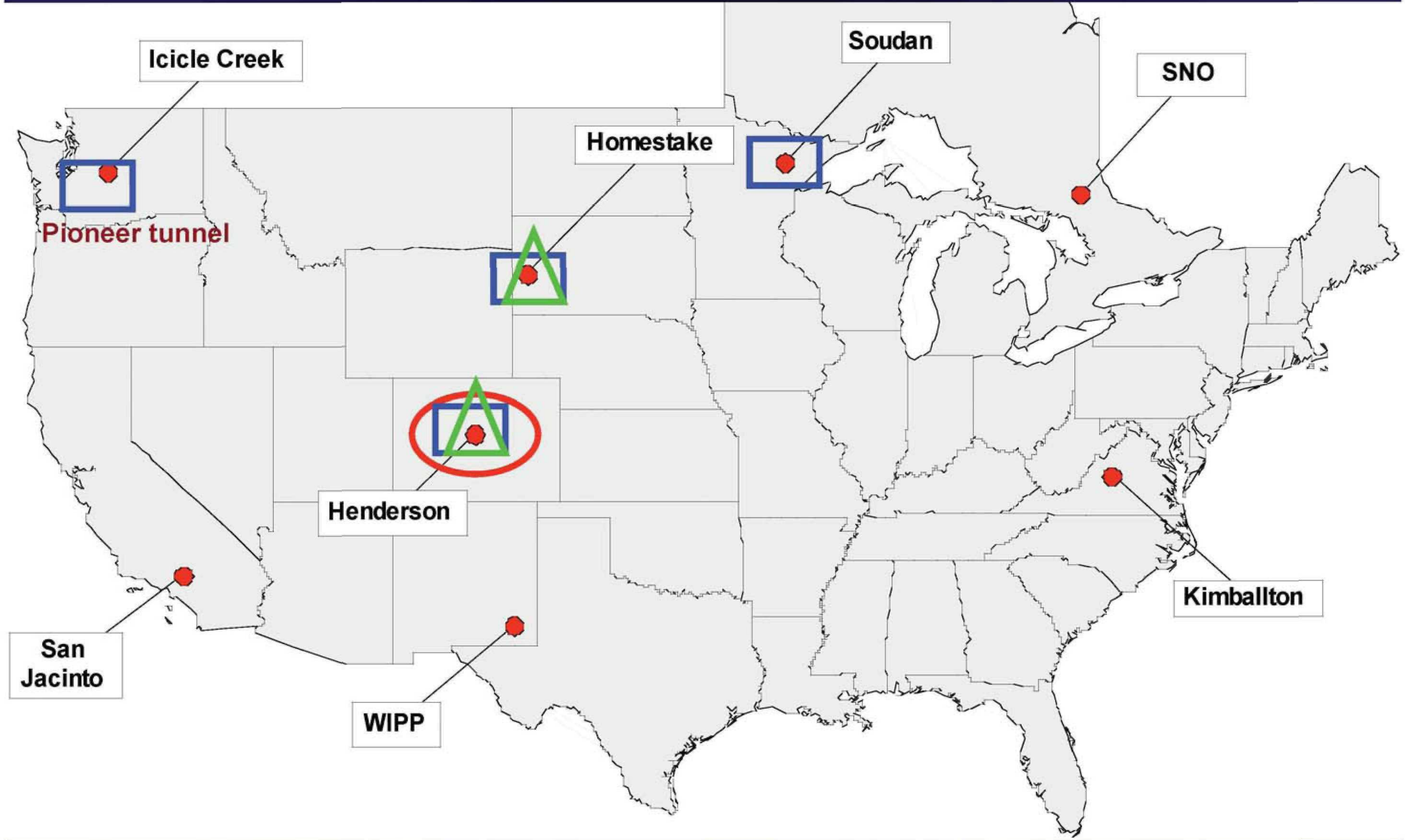
Fund technical designs including initial research projects

award 1 to 2 sites ($2M~$3M each)

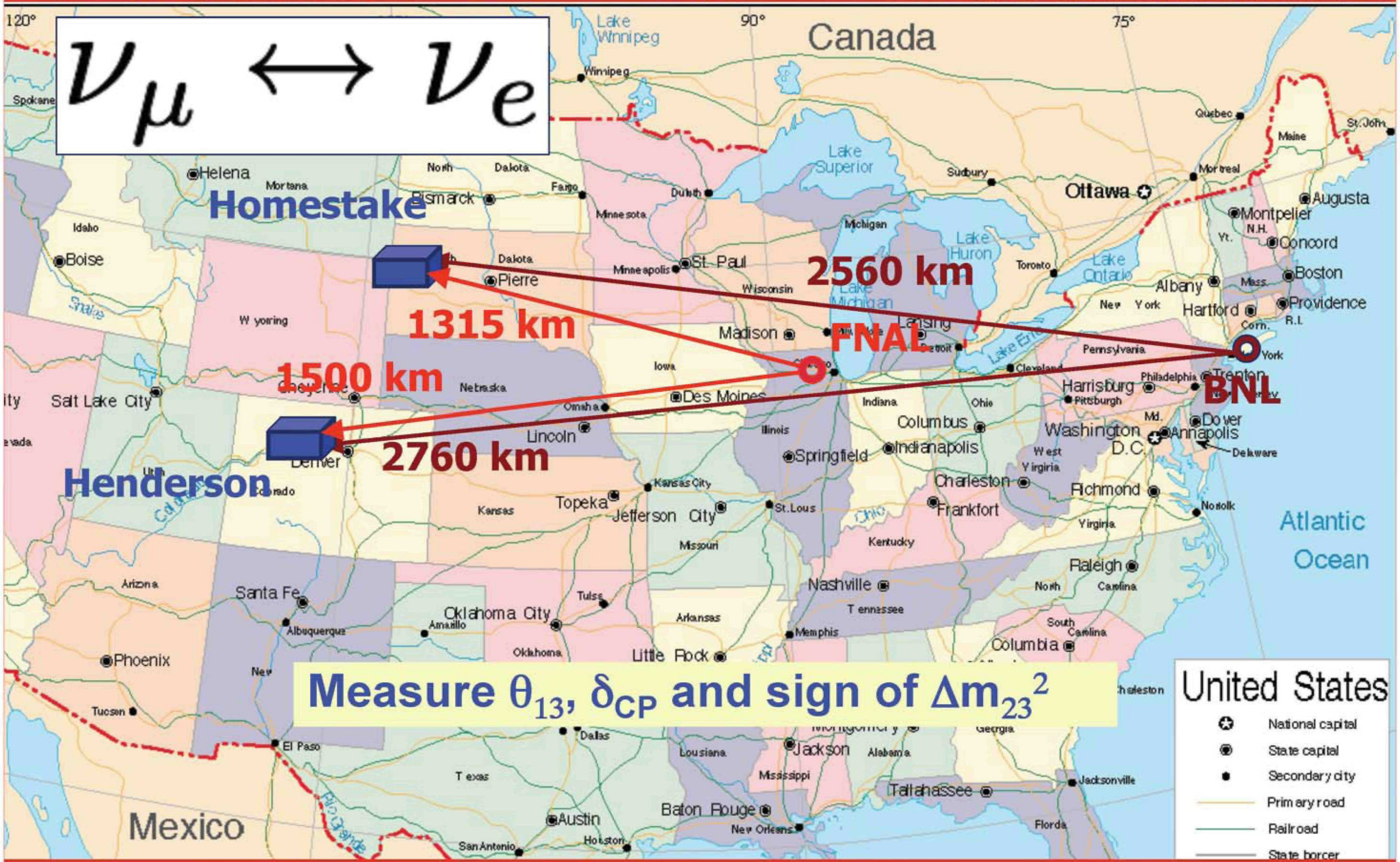
DUSEL Timeline

- DUSEL S1 Announcement: Jun. 04
- DUSEL S2 Announcement: Oct. 04
- Approval of S1 Proposal: Dec. 04
- S2 Proposal Deadline: Feb. 05
  - 8 site proposals submitted
- S2 Award Decision: Jul. 05
  - Henderson and Homestake ($500k each for conceptual design)
- S2 Report Due: June 23, 2006
  - Site down-selection decision deferred
- DUSEL S3 Announcement: Sep. 29, 2006
- S3 Proposal due: Jan. 09, 2007
  - four proposals (Henderson, Homestake, Soudan, Pioneer) submitted
- S3 Award Decision: Jul. 2007
  - Homestake ($15M for three years for final technical design)
- Expected National Science Board Decision: ~2008
- Expected DUSEL ground breaking: ~2010 (more likely 2011)

DUSEL (S2) Proposed Sites



Very Long Baseline Neutrino Oscillation Experiment



$$\nu_\mu \leftrightarrow \nu_e$$

Measure θ_{13}, δ_{CP} and sign of Δm_{23}^2

Henderson Mine Location (Empire, Colorado)

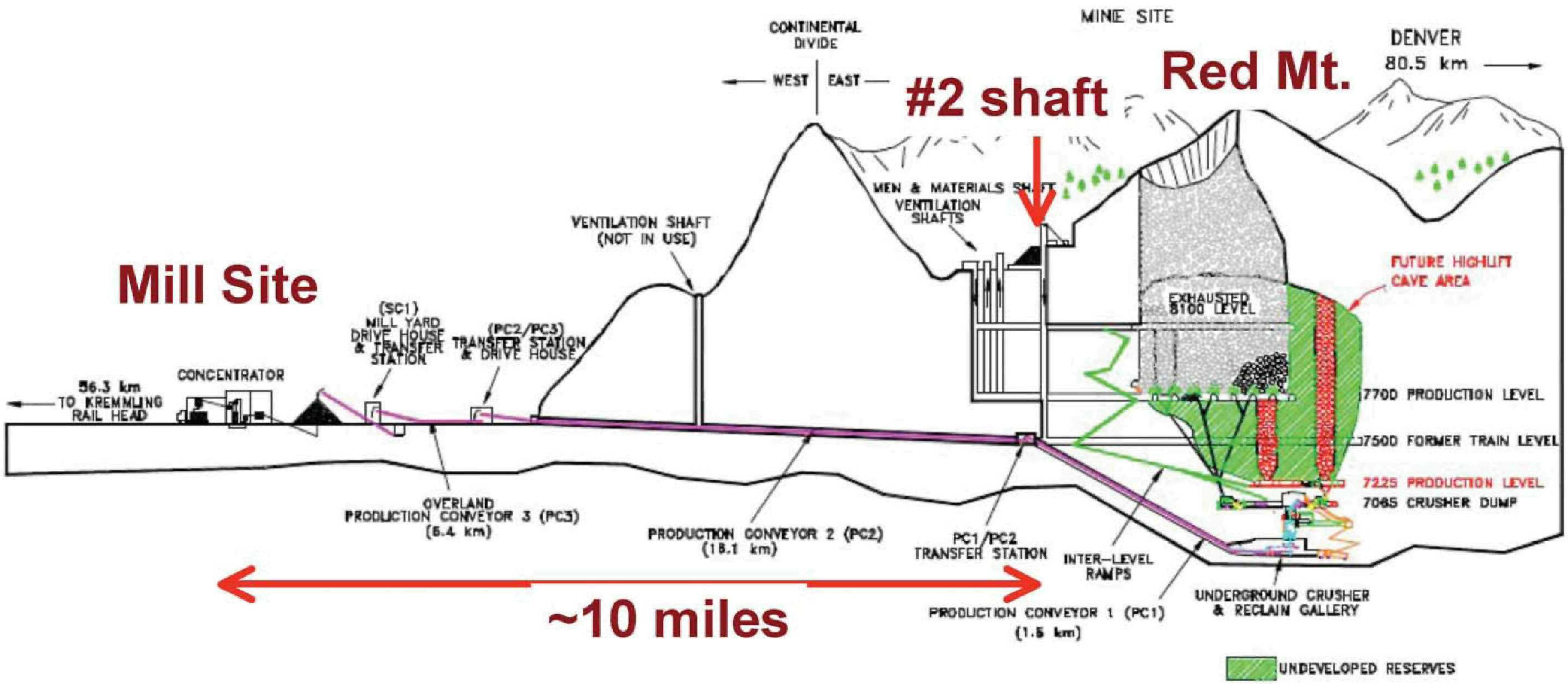
Henderson Mine

Airport

~60 miles

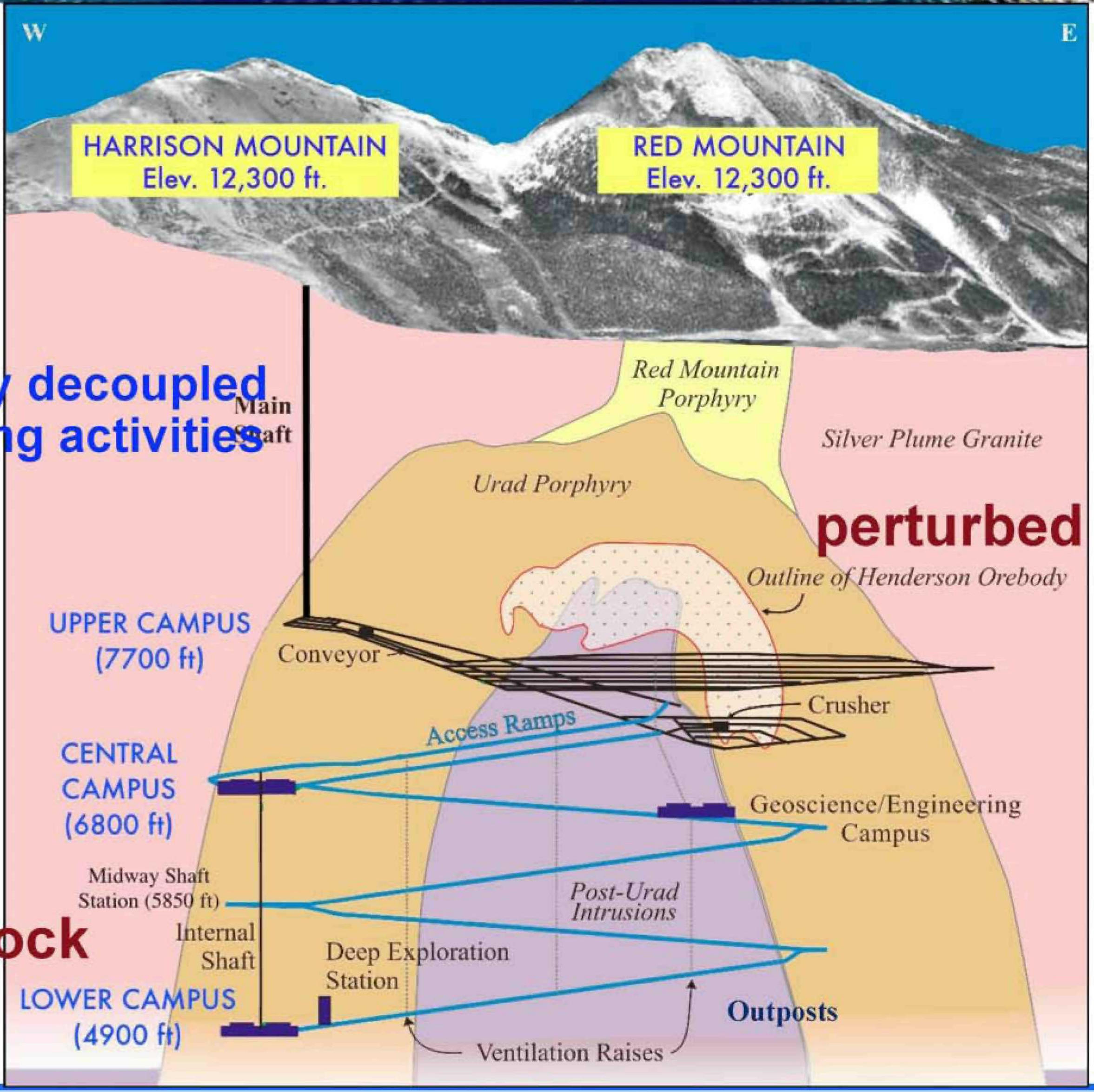
Denver

Vast Infrastructure



- Existing tailing site and all necessary environmental permits
- Henderson 2000 modernization project: ~$150M

Henderson DUSEL Conceptual Design

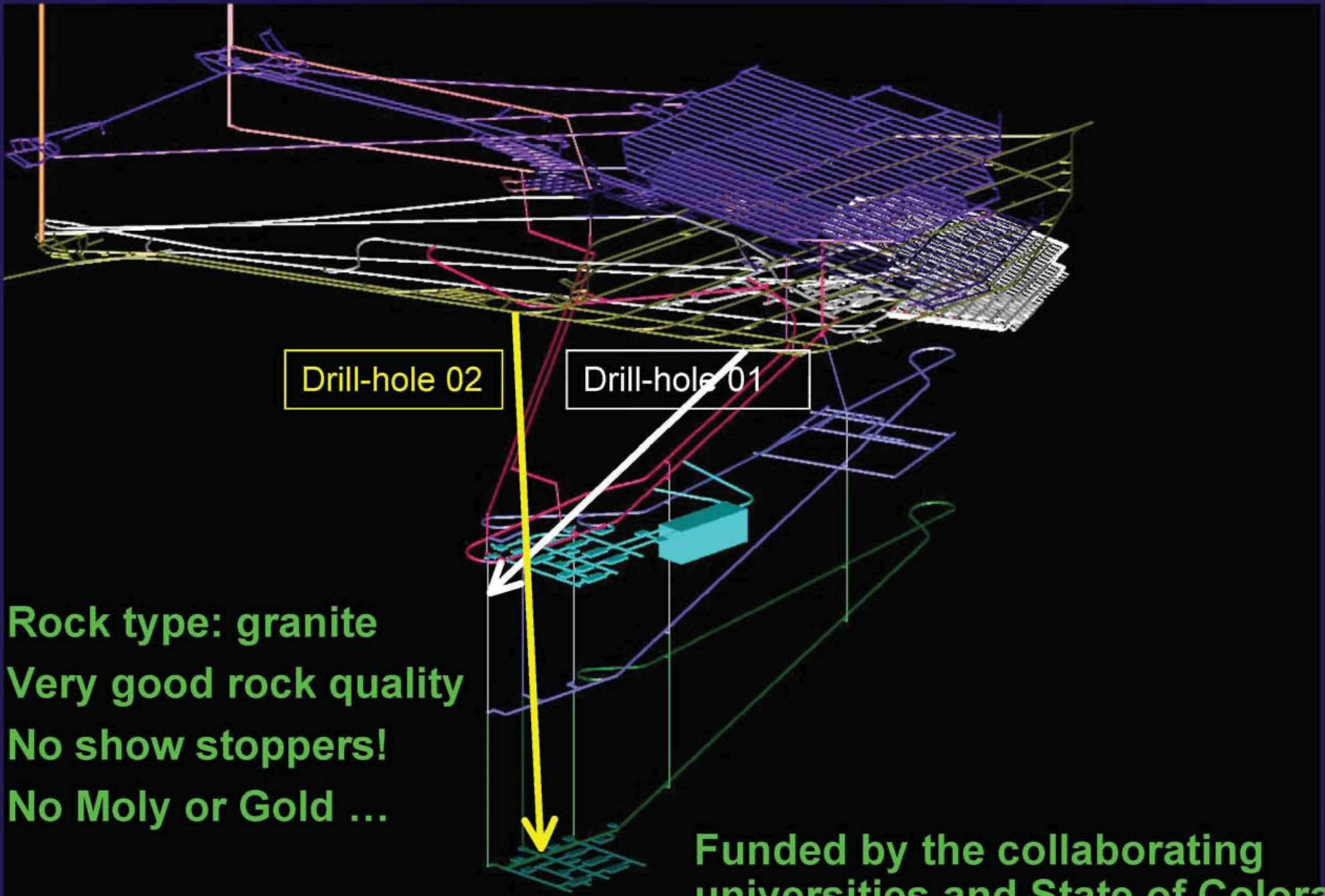


DUSEL mostly decoupled from the mining activities

perturbed rock

pristine rock

Henderson DUSEL Exploration Core Drill Holes



Rock type: granite

Very good rock quality

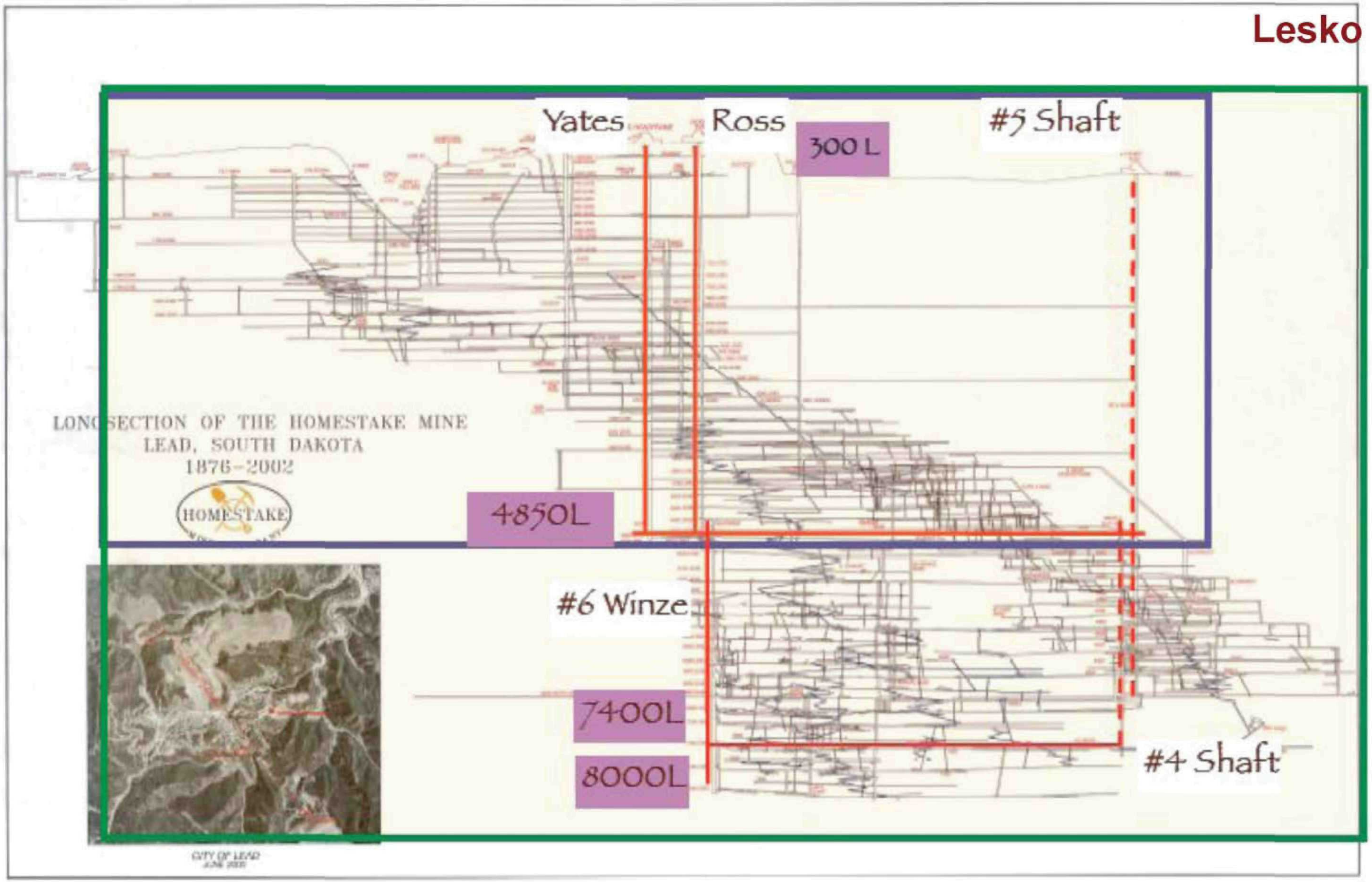
No show stoppers!

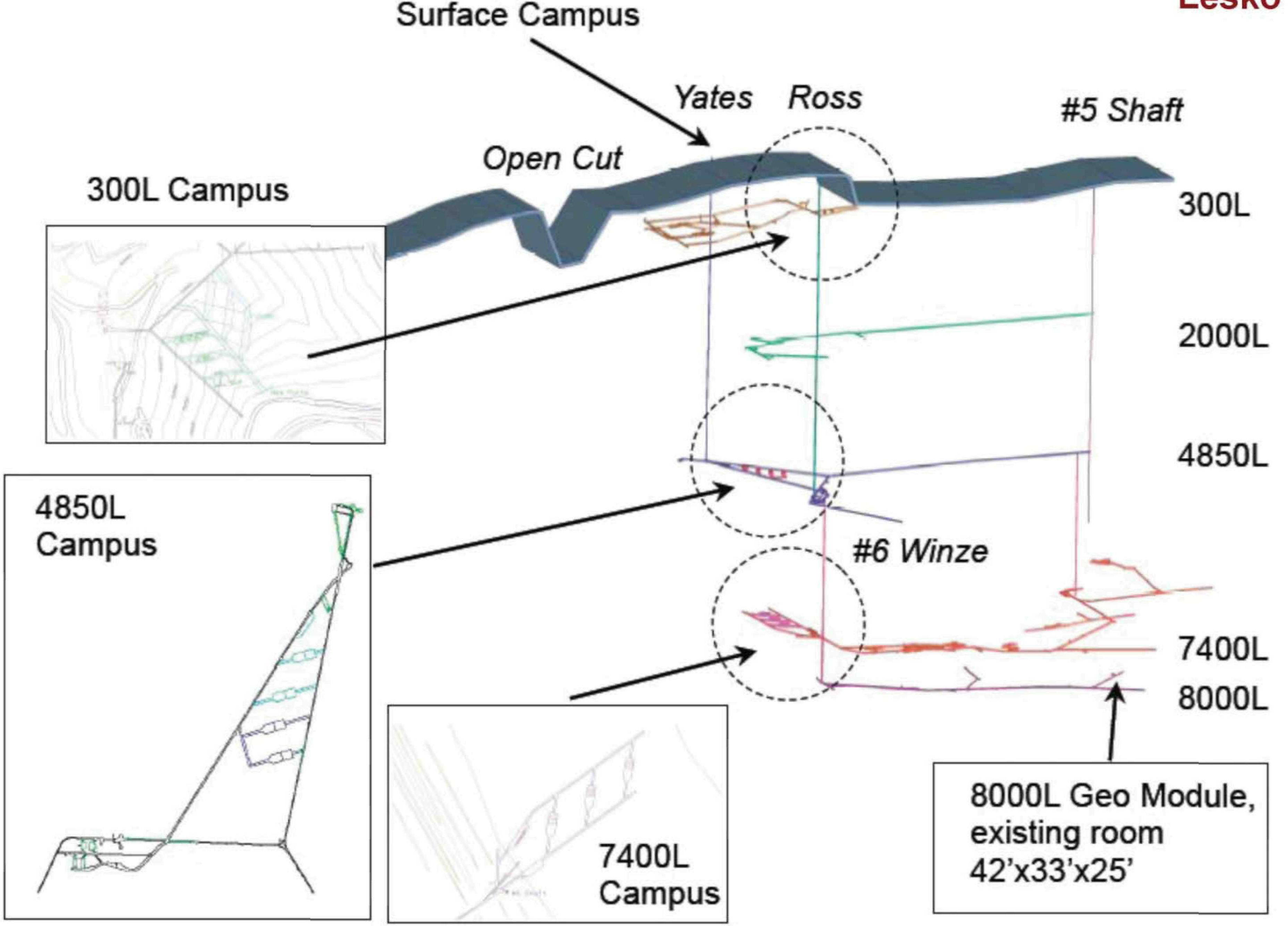
No Moly or Gold …

Funded by the collaborating universities and State of Colorado

Homestake EIP and DUSEL

Lesko





8000L Geo Module, existing room 42'x33'x25'

The Homestake Mine

- Very old closed gold mine, more than 100 years old
  - – old infrastructure (needs to be refurbished)
  - – Relatively small shafts (must be used for equipment and people transportation as well as the rock removal)
- Being flooded
  - Water close to 5,000 ft level
- Strong state government support
  - Establishment of S. Dakota Science and Technology Authority
  - ~\$40M contribution to DUSEL (including \$10M federal funding)
- EPSCoR (Experimental Program to Stimulate Competitive Research) State
  - = states that historically receive less federal R&D funding
- Large (\$70M) Private Donation
  - ⇒ SUSEL (Sanford Underground Science and Engineering Lab)

NSF Defined Scope of S3 Award

- S3 selection constitutes commitment to site and design team only
- Award intended to prepare DUSEL for MREFC consideration
- Not a commitment to construction
- Also beyond scope of S3:
  - Management organization for the DUSEL
  - Further development of initial suite of experiments, associated R&D and project planning
  - Ultimate construction and operations plan or team
- These will be decided in subsequent steps or solicitations
- MREFC funding would require approval of the National Science Board, NSF Director, the Administration and Congress

National Committee Reviews on UNO/LMPD

- HEPAP Long Range Plan Sub-panel (2001)
- CPU: Quarks to Cosmos (2002)
- NFAC, NRC/NAS (2002)
- HEPAP Facilities Sub-panel (2003)
- Physics of Universe (2004)
- APS Neutrino Study (2004)
  - All positive recommendations
- EPP2010 (2005)
- P5 (2006)
- NuSAG (2006)

EPP2010 Recommendations on Proton Decay Search and Multi-purpose Detector

- In their Finding 5: Neutrino and Proton Decay Probes

  A program of neutrino physics, including, eventually, a detector large enough for sensitivity to proton decay, offers a probe of unification physics.

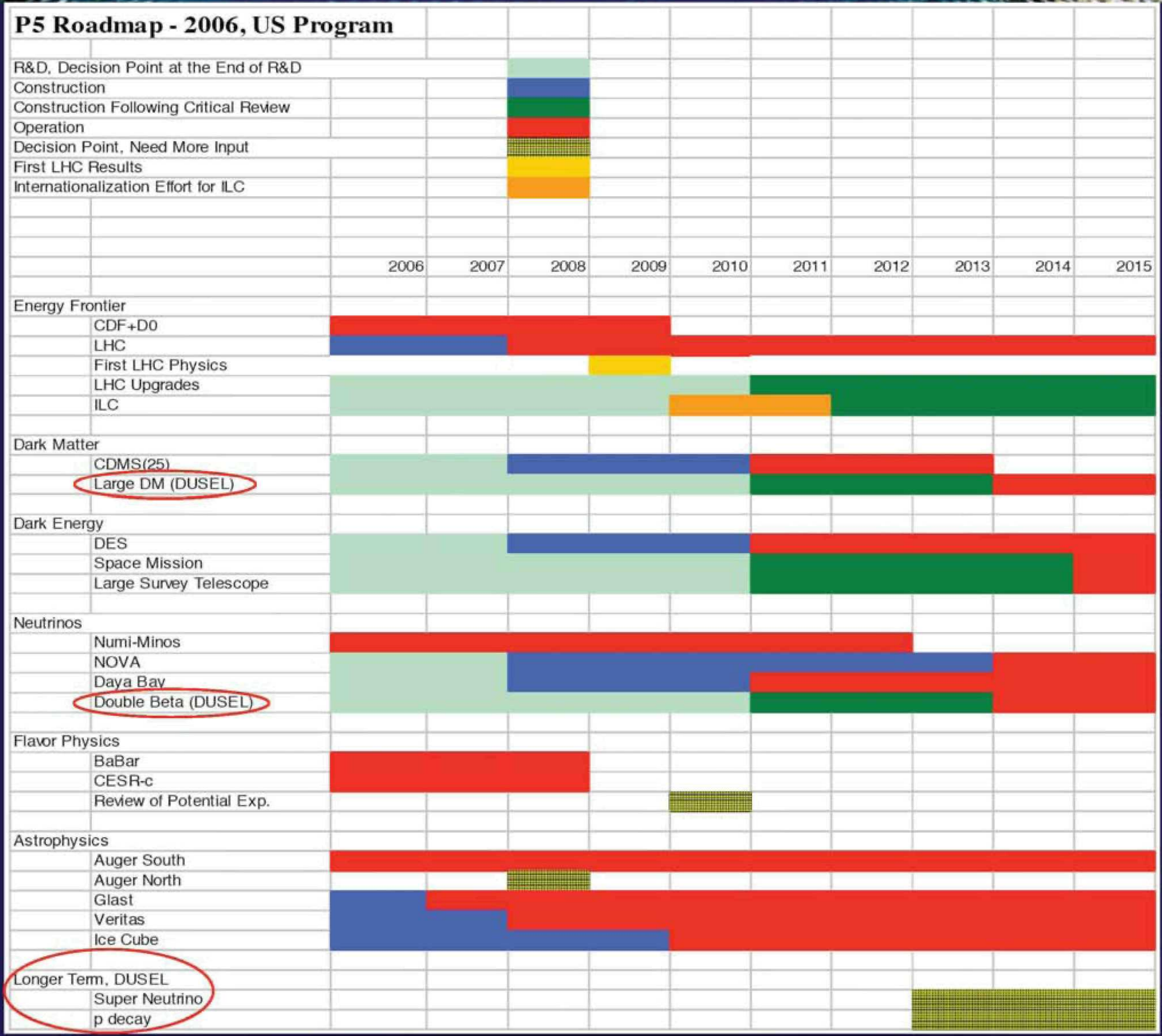
  ``In the past ten years, it has become clear that neutrinos have tiny but nonzero masses. This was a departure from the Standard Model and may be a signal of the unification of particle forces. There are now opportunities to extend this hint of unification. Proton decay experiments might show that the proton is unstable, a monumental discovery that would confirm one of the most basic predictions of unified theories.''

continue: EPP2010 Recommendations

- In their Action Item 5: A Staged Neutrino and Proton Decay Research Program

> *``Longer term goals should include experiments to unravel possible charge-parity violation in the physics of neutrinos and renewed searches for proton decay. There may be a valuable synergy between these important objectives, as the neutrino charge-parity violation measurements may require a very large detector that, if placed deep underground, will also be the right instrument for detecting proton decay."*

P5 Roadmap - 2006, US Program



P5 Roadmap - 2006, US Program

R&D, Decision Point at the End of R&D	░
Construction	🟦
Construction Following Critical Review	🟩
Operation	🟥
Decision Point, Need More Input	▨
First LHC Results	🟨
Internationalization Effort for ILC	🟧

		2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Energy Frontier											
	CDF+D0	🟥	🟥	🟥	🟥						
	LHC	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	First LHC Physics				🟨						
	LHC Upgrades	░	░	░	░	░	🟩	🟩	🟩	🟩	🟩
	ILC	░	░	░	░	🟧	🟧	🟩	🟩	🟩	🟩
Dark Matter											
	CDMS(25)	░	░	🟦	🟦	🟦	🟥	🟥	🟥		
	Large DM (DUSEL)	░	░	░	░	░	🟩	🟩	🟩	🟥	🟥
Dark Energy											
	DES	░	░	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟥
	Space Mission	░	░	░	░	░	🟩	🟩	🟩	🟩	🟥
	Large Survey Telescope	░	░	░	░	░	🟩	🟩	🟩	🟩	🟥
Neutrinos											
	Numi-Minos	🟥	🟥	🟥	🟥	🟥	🟥	🟥			
	NOVA	░	░	🟦	🟦	🟦	🟦	🟦	🟦	🟥	🟥
	Daya Bay	░	░	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟥
	Double Beta (DUSEL)	░	░	░	░	░	🟩	🟩	🟩	🟥	🟥
Flavor Physics											
	BaBar	🟥	🟥	🟥							
	CESR-c	🟥	🟥	🟥							
	Review of Potential Exp.					▨					
Astrophysics											
	Auger South	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Auger North			▨							
	Glast	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Veritas	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Ice Cube	🟦	🟦	🟦	🟦	🟥	🟥	🟥	🟥	🟥	🟥
Longer Term, DUSEL											
	Super Neutrino								▨	▨	▨
	p decay								▨	▨	▨

NuSAG Recommendations (2007)

Recommendation 1. The US should prepare to proceed with a long baseline neutrino oscillation program to extend sensitivity to $\sin^2 2\theta_{13}$, to determine the mass ordering of the neutrino spectrum, and to search for CP violation in the neutrino sector. Planning and R&D should be ready for a technology decision and a decision to proceed when the next round of results on $\sin^2 2\theta_{13}$ becomes available, which could be as early as 2012. A review of the international program in neutrino oscillations and the opportunities for international collaboration should be included in the decision to proceed.

continue: NuSAG Recommendations

Recommendation 2. Research and development towards an intense, conventional neutrino beam suitable for these experiments should be supported. This may be in the form of intensity upgrades to the existing NuMI beam, as well as development of a new beam directed towards DUSEL, which would likely employ the wide-band beam approach.

continue: NuSAG Recommendations

Recommendation 3. Research and development required to build a large water Cherenkov detector should be supported, particularly addressing questions of minimum required photocathode coverage, cost, and timescale.

Recommendation 4. A phased R&D program with milestones and using a technology suitable for a 50-100 kton detector is recommended for the liquid argon detector option. Upon completion of the existing R&D project to achieve purity sufficient for long drift times, to design low noise electronics, and to qualify materials, construction of a test module that could be exposed to a neutrino beam is recommended.

Conclusions

- Proton decays provide unique signature for Unification Physics
  - Perhaps the only direct probe of the Unification Scale (~10^{16} GeV)
- Experimental search for proton decays resulted so far no evidence, but set stringent limits
  - Many theoretical models ruled out
- However, large detectors inspired by the GUT models and built for proton decay searches resulted in major discoveries
  - Lesson learned: if we make good instrument, good things can happen
  - Unexpected discoveries are often more revolutionary than the expected
  - Importance of theorists' role in realization of an experiment

Observation of neutrino oscillations (mass)

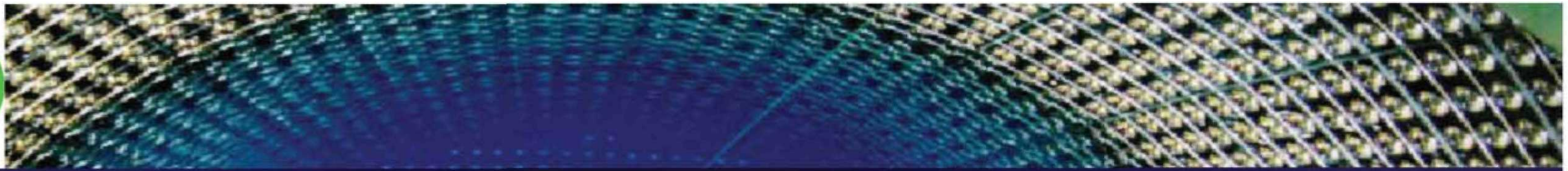
Observation of neutrinos from SN1987A

First real time and directional observation of solar neutrinos

Confirmation of the solar neutrino flux deficit

Continue: Conclusions

- UNO tackles some of the most important physics questions today w/ potential of major discoveries
- An excellent site exists at the Henderson mine
  - Competitive DUSEL process has ultimately helped UNO
    - ⇒ 90% of work done (notably two core drillings) for Henderson DUSEL is useful for UNO
- Homestake site needs to be explored for UNO feasibility
  - NSF's DUSEL decision is not a decision on UNO or UNO site
- If built, it will provide a comprehensive nucleon decay and neutrino physics program for the US and world science community for the 21th century
- Intersection of interests from HEP, NP and AP communities; and international community (Japan: Hyper-Kamiokande, Europe: CERN/Fréjus initiatives)
- We are one step closer to a realization of the Einstein's dream of unifying all known forces with the discovery of the neutrino oscillations. Hopefully more forward steps can be taken in the near future with major new discoveries.



The End