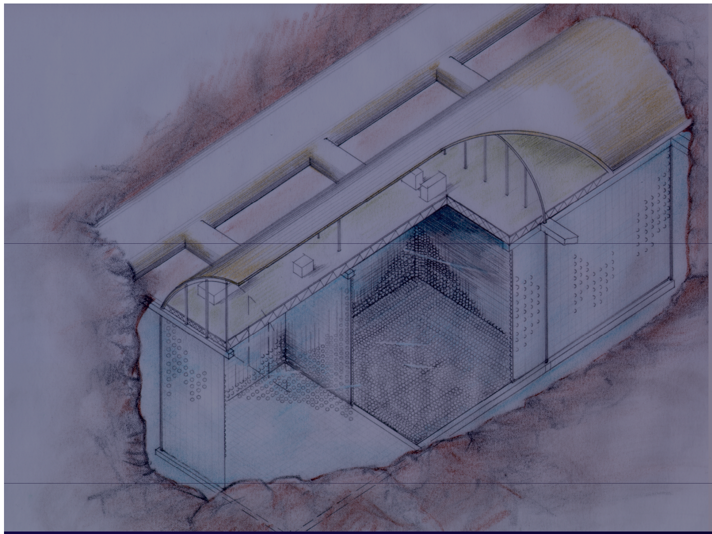
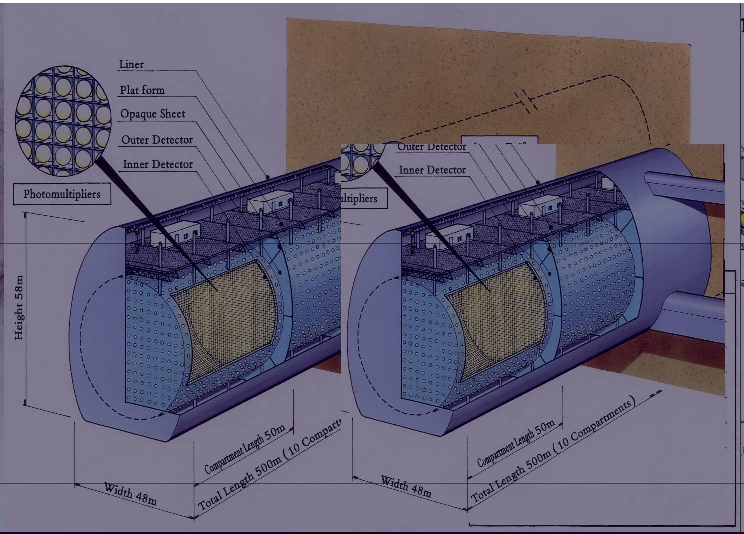
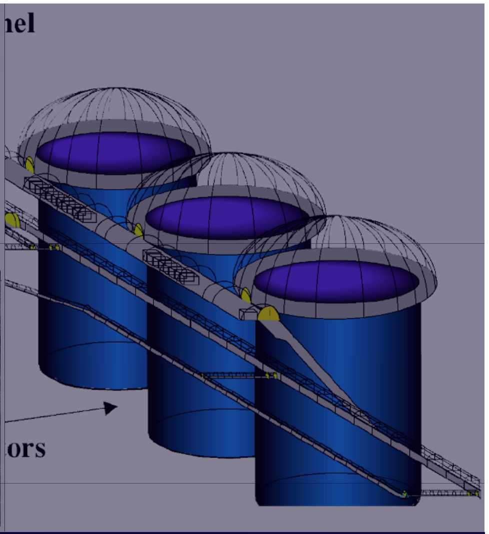
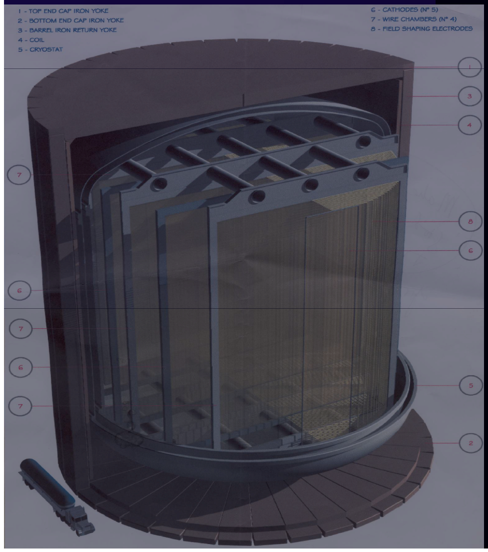
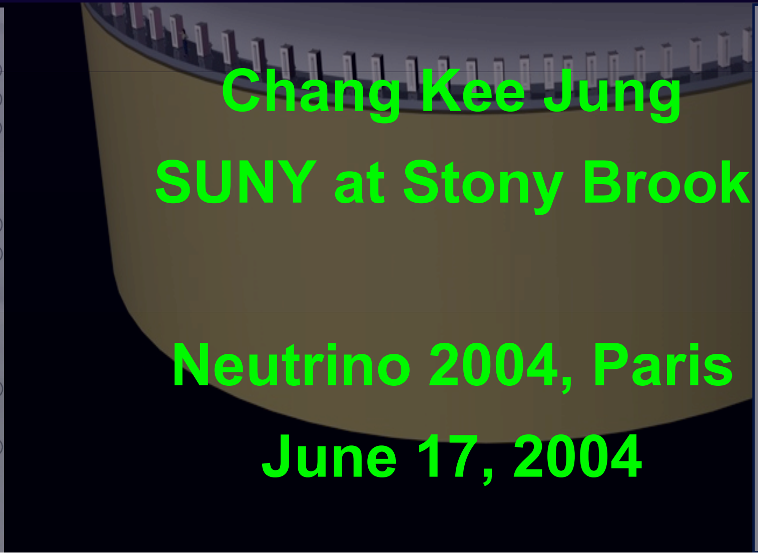






Future Large Underground Neutrino and Nucleon decay (NNN) Detectors



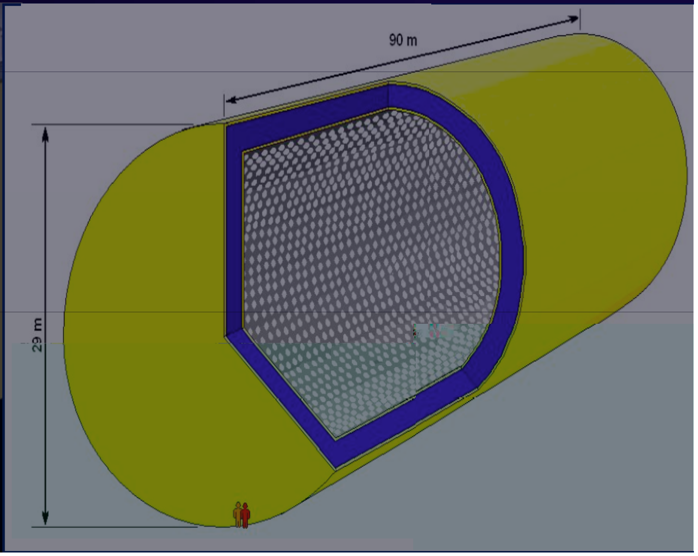


Chang Kee Jung

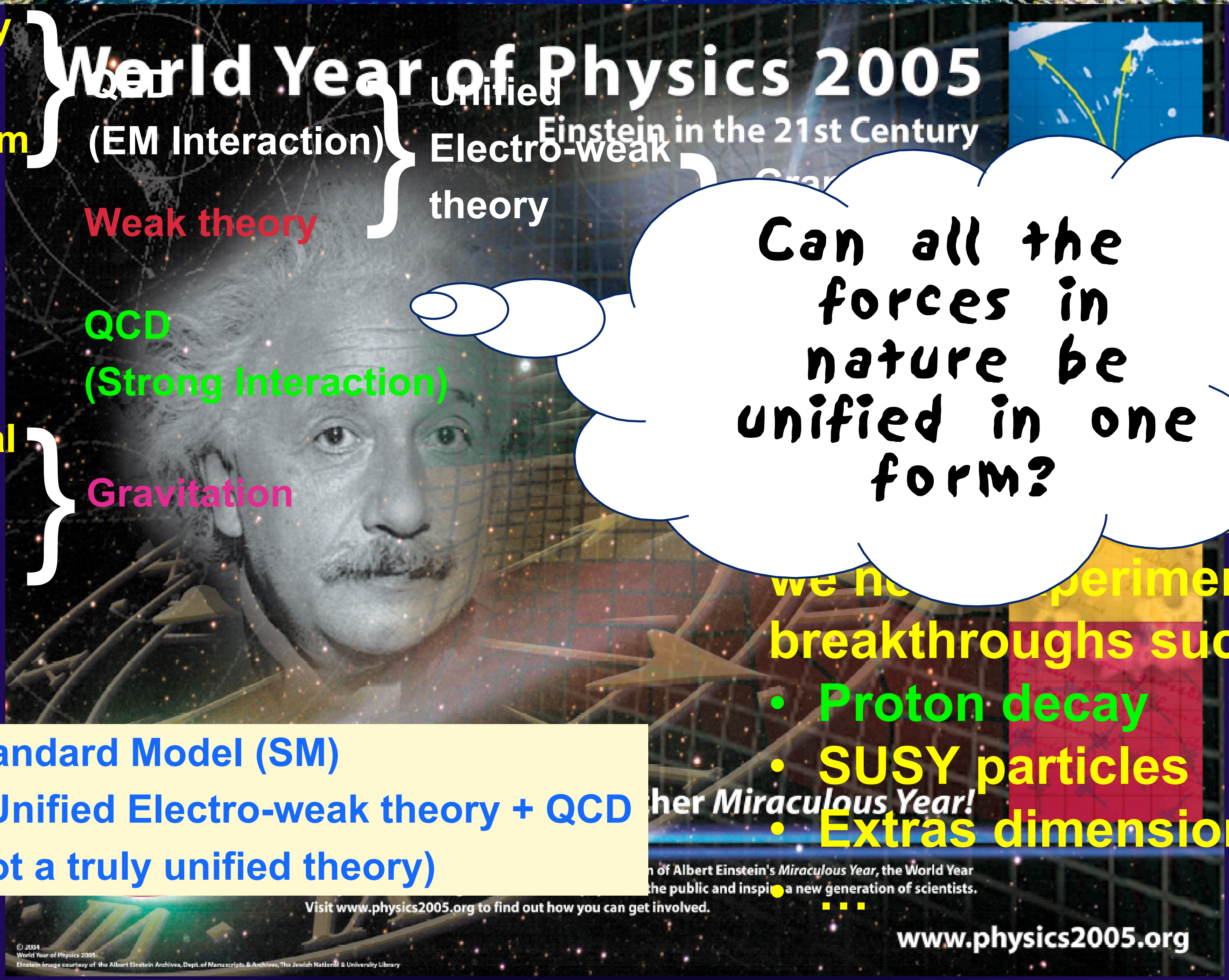
SUNY at Stony Brook

Neutrino 2004, Paris

June 17, 2004



Einstein's Dream: Unification of All Particle Interactions



Electricity
Magnetism } QED (EM Interaction) } Unified Electro-weak theory } Gra

Weak theory

QCD (Strong Interaction)

(?)

Terrestrial
Celestial } Gravitation

Can all the forces in nature be unified in one form?

am

we ne perimental breakthroughs such as:

- Proton decay
- SUSY particles
- Extras dimensions
- …

Standard Model (SM)
= Unified Electro-weak theory + QCD
(not a truly unified theory)

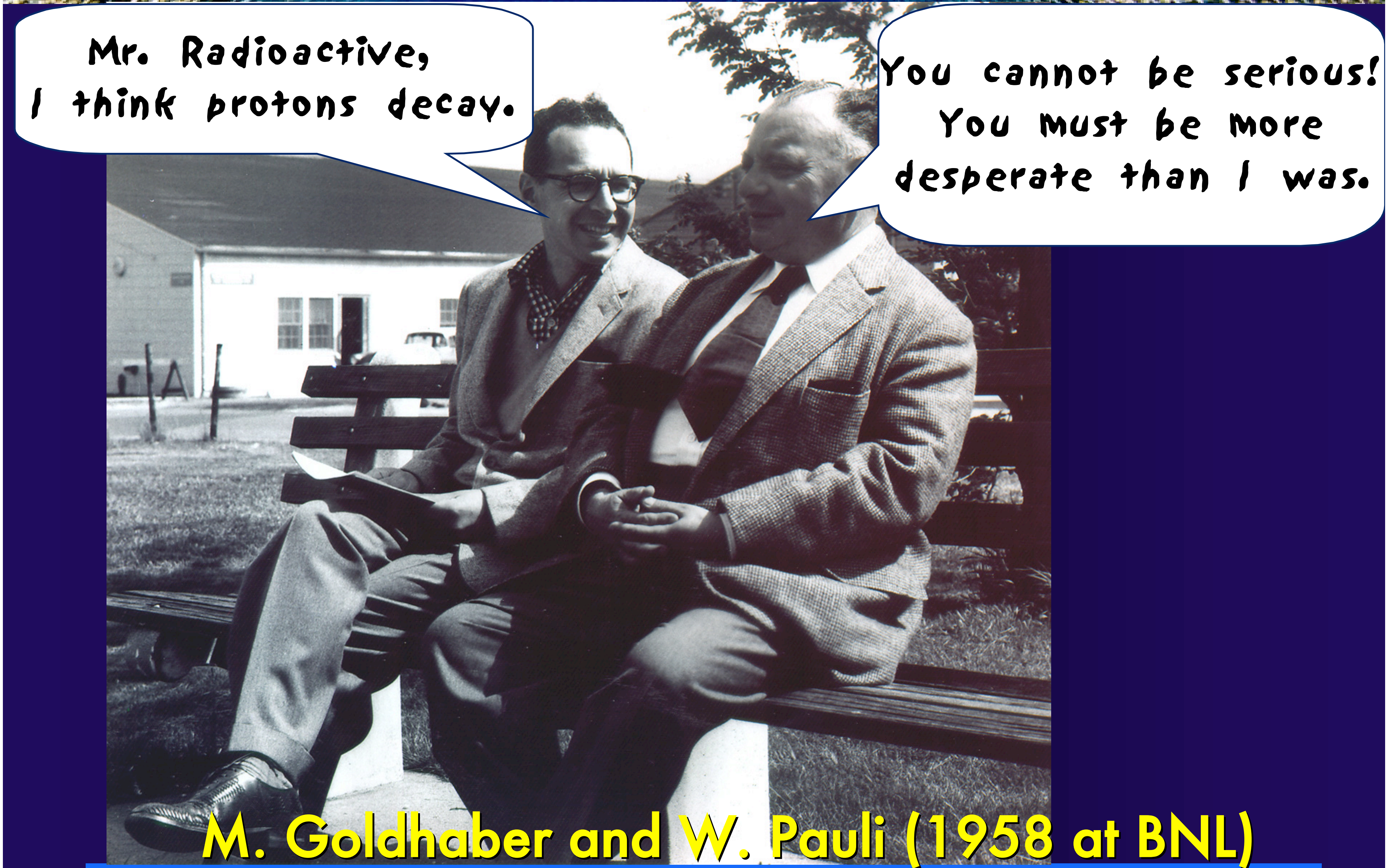
First Experimental Pursuit of Proton Decays

- 1954: M. Goldhaber (w/ Reines and Cowan, Jr.) publishes the first experimental result on proton lifetime inspired by “Continuous Creation” theory
  - using a liquid scintillator detector (shielded w/ paraffin+lead) containing ~$3\text{x}10^{28}$ protons, he obtains lower limits on τ_p

⇒ $\tau_p > 10^{21}$ years (for free protons)

⇒ $\tau_p > 10^{22}$ years (for bound nucleons)

Proton decay meets Neutrino…

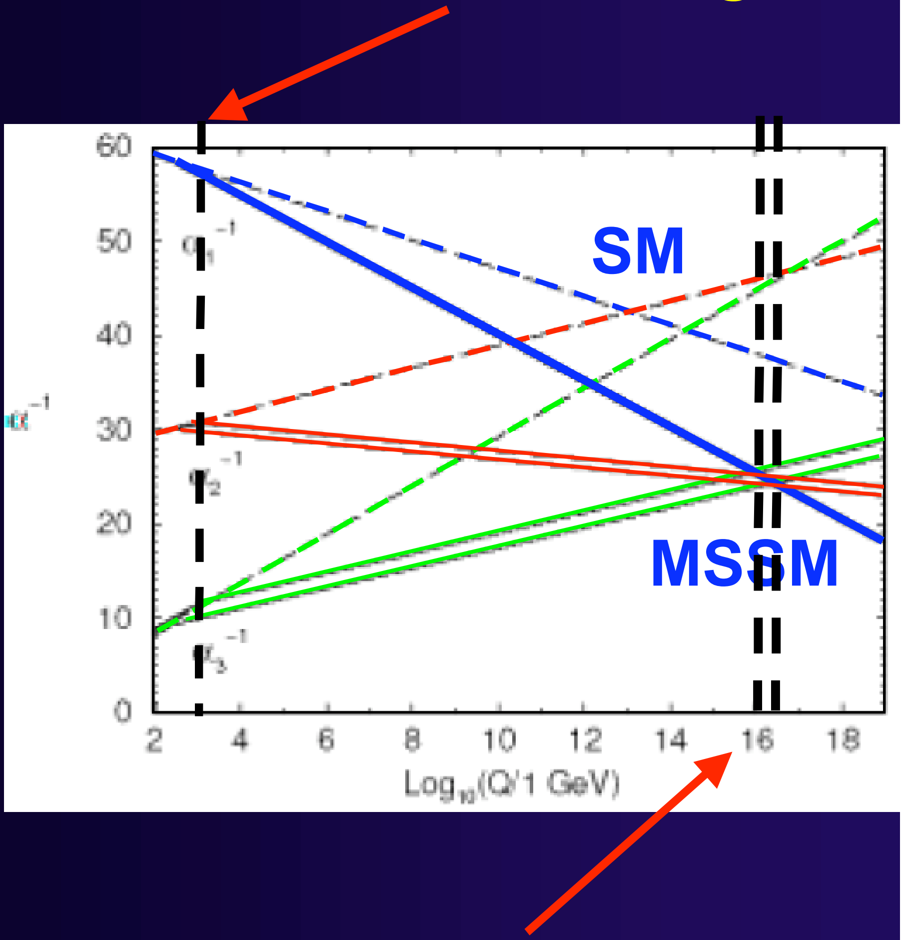


M. Goldhaber and W. Pauli (1958 at BNL)

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

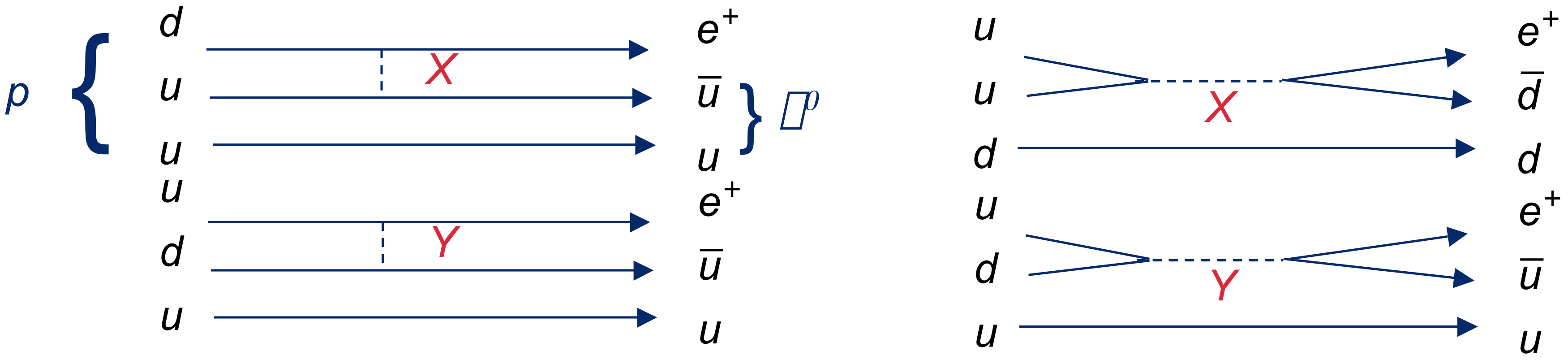
SUSY Breaking



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

Proton decays in SUSY GUTs

- Dimension=6 operator gauge boson mediated decays



$(X^{\pm 4/3}, Y^{\pm 1/3}$: new gauge bosons)

$$\tau/_{B}(p \to e^{+}\pi^{0}) \approx \left(2.5/A_{R}\right)^{2}\left(0.04/\alpha_{GUT}\right)^{2}\left(M_{X}/10^{16}\,\mathrm{GeV}\right)^{4} \times 10^{35}\ \text{years}$$

where $M_X \approx M_{GUT}$

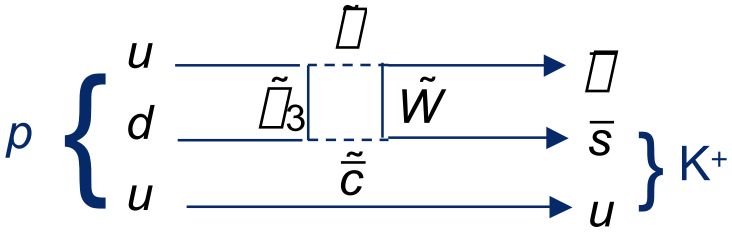
$\approx 10^{35}$ years

$\Rightarrow$ within experimental reach (Marciano)

$\tau/_{B}(p \to e^{+}\pi^{0}) > 5.4 \times 10^{33}$ yrs (current SuperK Lower Limit @90% C.L.)

Continue: Proton decays in SUSY GUTs

- D=5 op. (color Higgs triplet, q=1/3) mediated decays
  - Dominating decay mode



$M_3 \sim 3 \times 10^{16}$ GeV, $M_{susy} \sim 1$ TeV

$$\tau_B(p \to K^+\bar{\nu}) \propto \left(\frac{M_{\tilde{q}}}{1\mathrm{TeV}}\right)^2 \left(\frac{M_3}{10^{16}\mathrm{GeV}}\right)^2 \cdots 4\mathrm{x}10^{30}\ \mathrm{years}$$

$$\leq 10^{34}\ \mathrm{years}$$

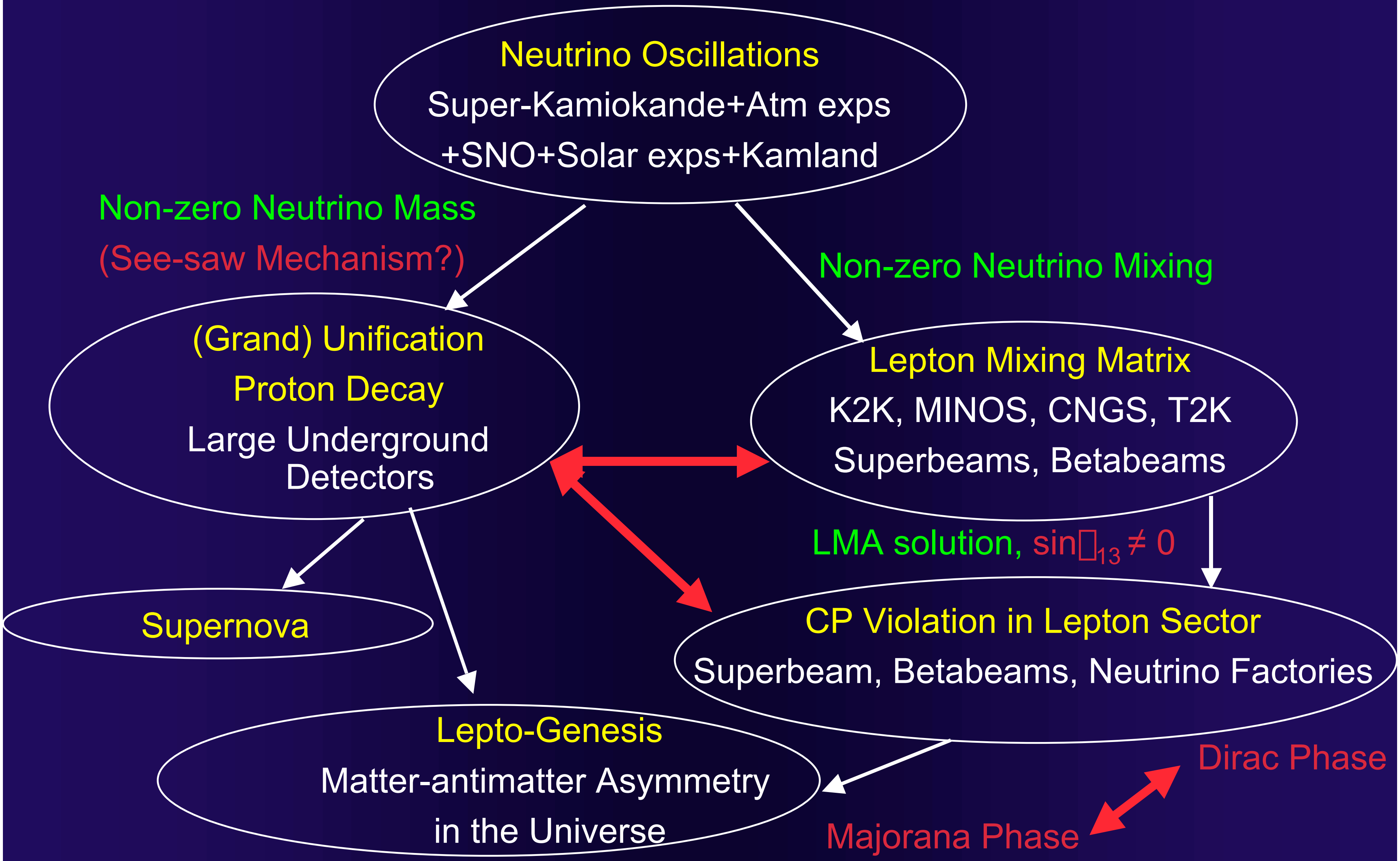
Theory is seriously being challenged!

$\tau_B\,(p \to K^+\bar{\nu}) > 2.3 \times 10^{33}$ yrs (Current SuperK Lower Limit @90% C.L.)

continue: SUSY GUTs

- Many models may have been already ruled out!
  - Especially MSSM SU(5) is considered to be completely ruled out (See: H. Murayama & A. Pierce, Phys.Rev.D65:055009,2002, hep-ph/0108104)
- Some say SUSY-SO(10) models are also in trouble.

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
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

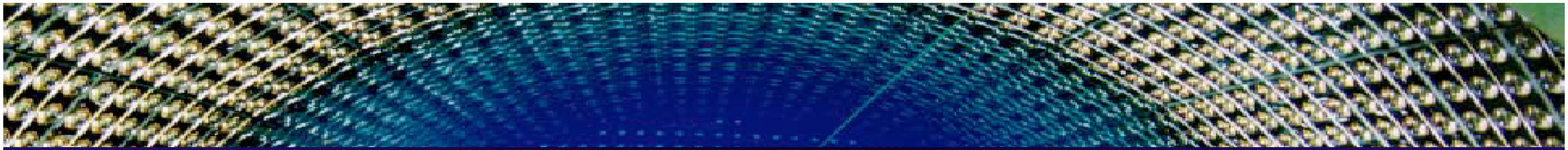
Dirac Phase

Majorana Phase

NNN Underground Detector
Current Proposals and Ideas

- Water Cherenchov Detectors
  - – 3-M, Hyper-Kamiokande, Mton-Frejus, UNO
- Liquid Argon Detectors
  - – 100kton-Europe, LANDD
- Liquid Scintilator Detectors
  - – LENA (a la SciPIO)
- Magnetized Iron Detectors
  - – INO (India-based Neutrino Observatory: a la MONOLITH)
    - Focused on atmospheric neutrinos detection

      (covered in H. Gallagher’s talk)



Future Large Water Cherenkov Detectors

Design Considerations

- Goal: physics capability ↑ detector cost ↓
- Topology and Size
  - Light attenuation length limit in pure water:
    - ⇒ ~80 m at 400 nm
  - PMT pressure limit:
    - ⇒ ~6 atm (60 m of water)
  - Largest possible width of underground cavity:
    - ⇒ ~60 m

⇒ Single largest active module size: ~60m x 60m x 60m

- PMT (photocathode) coverage
  - Need relatively high coverage (~ 40%) for low energy physics (solar and SRN), and 6 MeV γ detection from $p \rightarrow K^+ \nu$ in oxygen
  - Need fine granularity for LBL ν_e appearance experiments to reject π^0 background

Continue: Design Considerations

- Number and size of the modules for a fixed fiducial volume
  - Module size □ detector cost □
    - □ Larger surface area to fiducial volume ratio

      Requires more PMTs
    - □ Smaller fiducial to total volume ratio
    - □ Need more drifts and auxiliary/service space

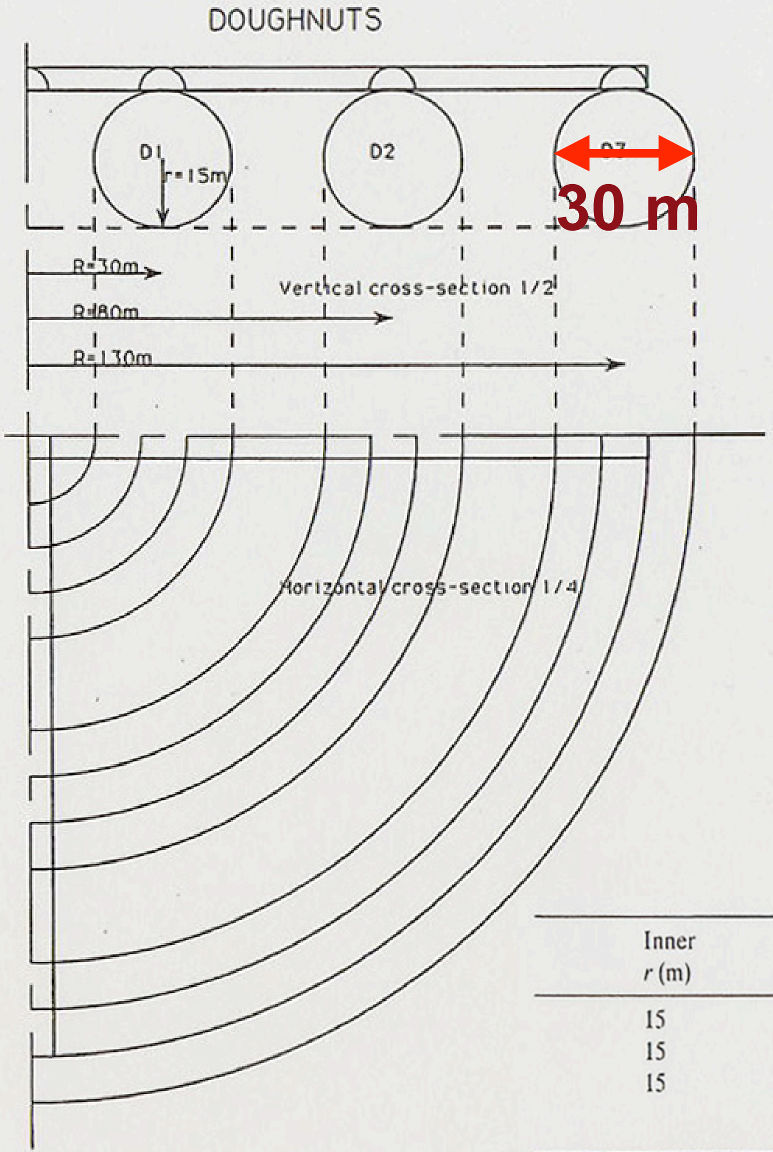
      typically excavation costs for drifts are more expensive than for large volume excavation
  - Module size □ Energy Containment □
    - □ especially crucial in atm nu studies, such as L/E study
  - Module size □ Pattern Recognition Capability (with same photocathode coverage) □

□ Keep the module size as large as possible

Detector Site Issues

- Depth □
  - cosmogenic background □
  - rock instability □ rock temperature □ detector cost □
- Optimal Depth
  - ~4000 mwe (~5000 ft)
    - □ Driven by the SRN search and Solar nu study
      Reduce spallation background
    - □ also reduce the risk of possible unknown B.G. to PDK searches at shallow depths
    - □ minimize detector dead time
    - □ keep some amount of cosmic rays for calibration purposes
- Distances from Major Proton Accelerator Labs
  - Different baselines present vastly different physics potential

DOUGHNUTS (a historical reference):
The first megaton class detector discussed



Detector of Under-Ground Hideous Neutrinos from Universe and from Terrestrial Sources

M. Koshiba, Phys. Rep. 220 (1992) 229

- Three concentric tori w/ 30 m cross-sectional diameter
- Relatively low photocathode coverage (6.5%)
- No veto region
- Total volume: 1.07 Mton
- Focused on astrophysical neutrino detection

Inner r (m)	Outer R (m)	Total M (t)	Fiducial M (t)	Hor. S (m^2)	Total S (m^2)	No. of PMTs	Cost in US$
15	30	133 k	100 k	4.9 k	17.6 k	5.5 k	11.0 M
15	80	355 k	267 k	13.1 k	47.0 k	16.2 k	32.4 M
15	130	577 k	433 k	21.2 k	76.4 k	23.9 k	47.8 M
		1.07 M	0.80 M	39.2 k	141 k	45.6 k	91.2 M

UNO Conceptual Baseline Design
(proposed at NNN99)

A Water Cherenkov Detector

optimized for:

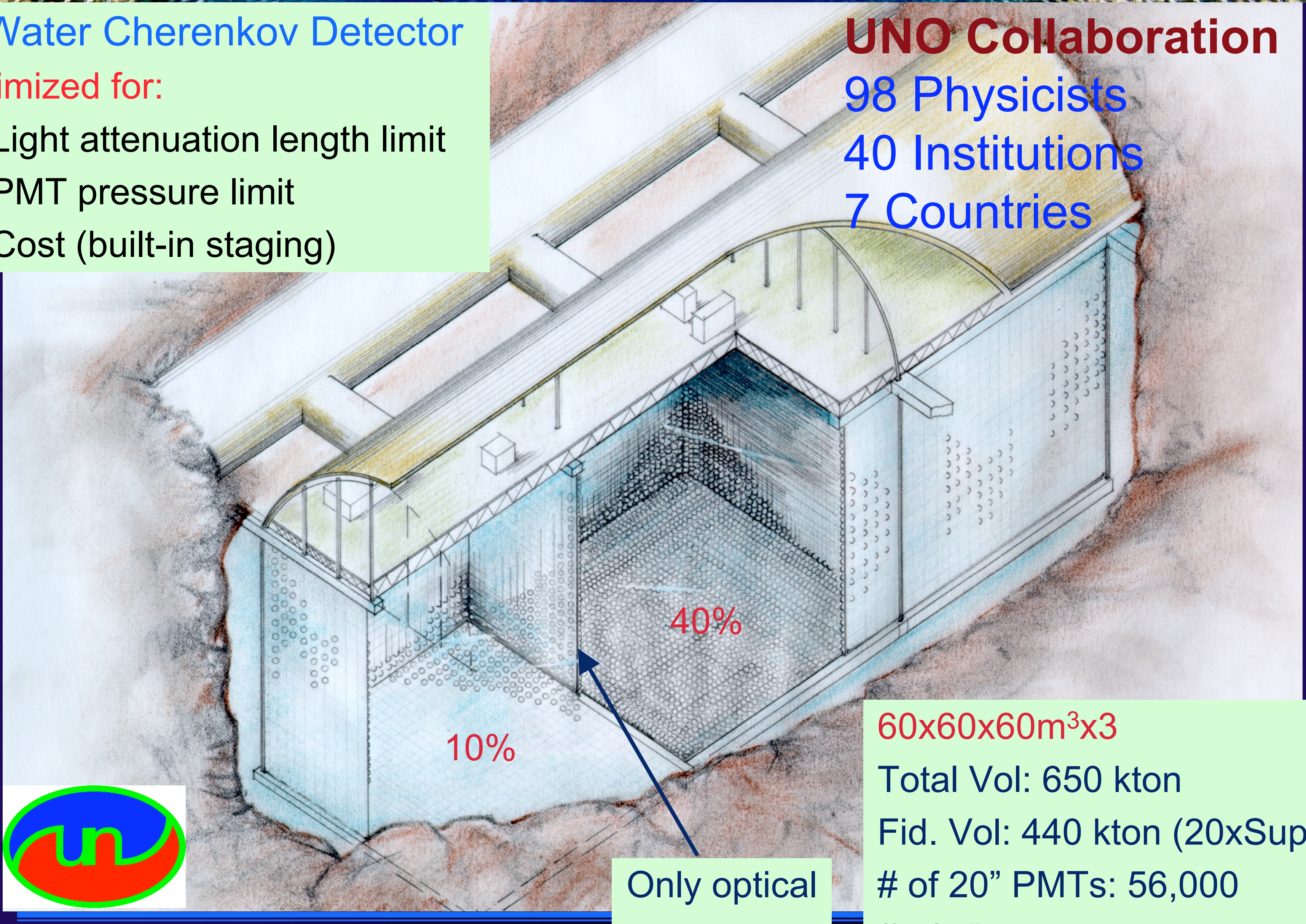
- Light attenuation length limit
- PMT pressure limit
- Cost (built-in staging)

UNO Collaboration

98 Physicists

40 Institutions

7 Countries



Only optical separation

60x60x60m^{3}x3

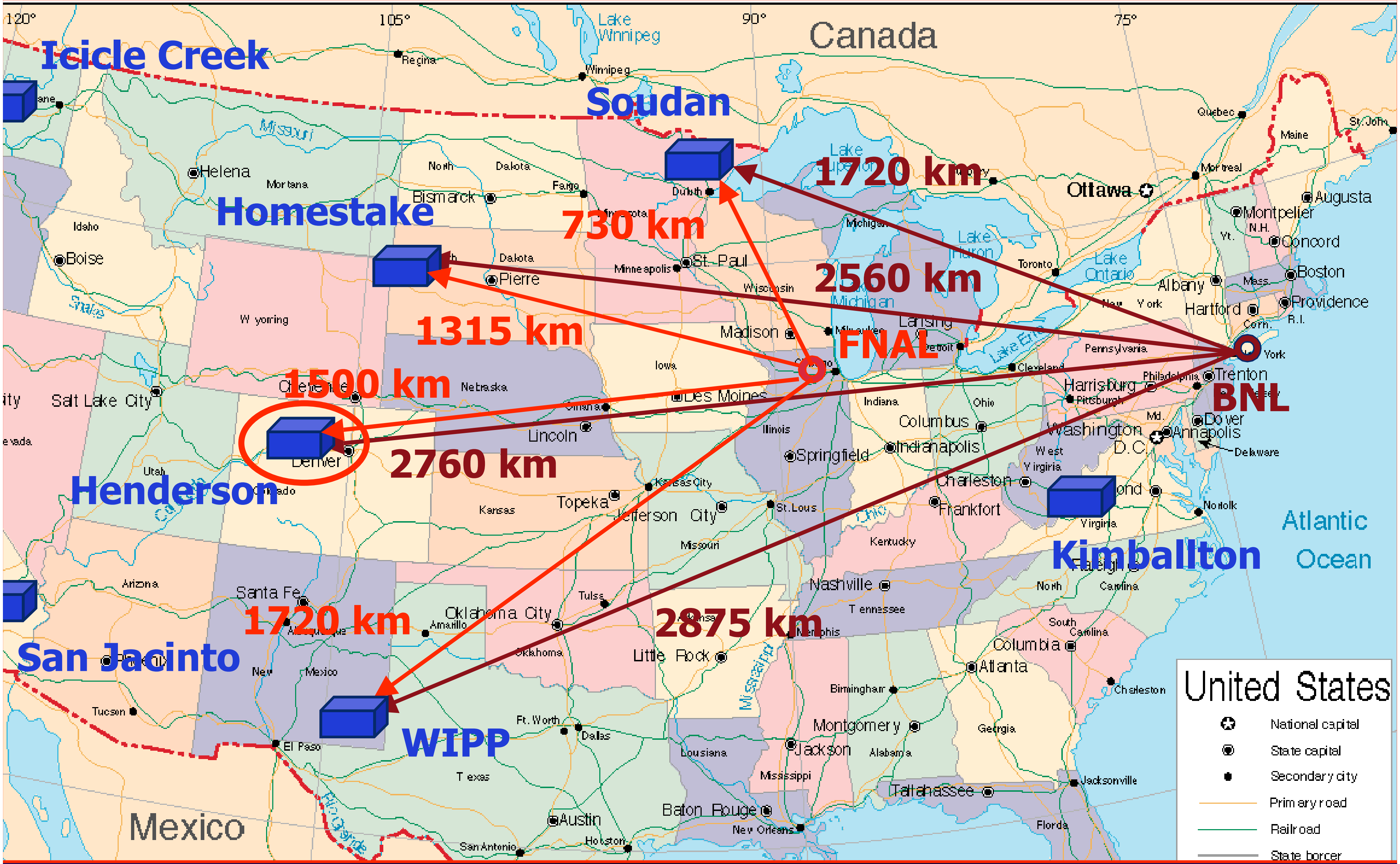
Total Vol: 650 kton

Fid. Vol: 440 kton (20xSuperK)

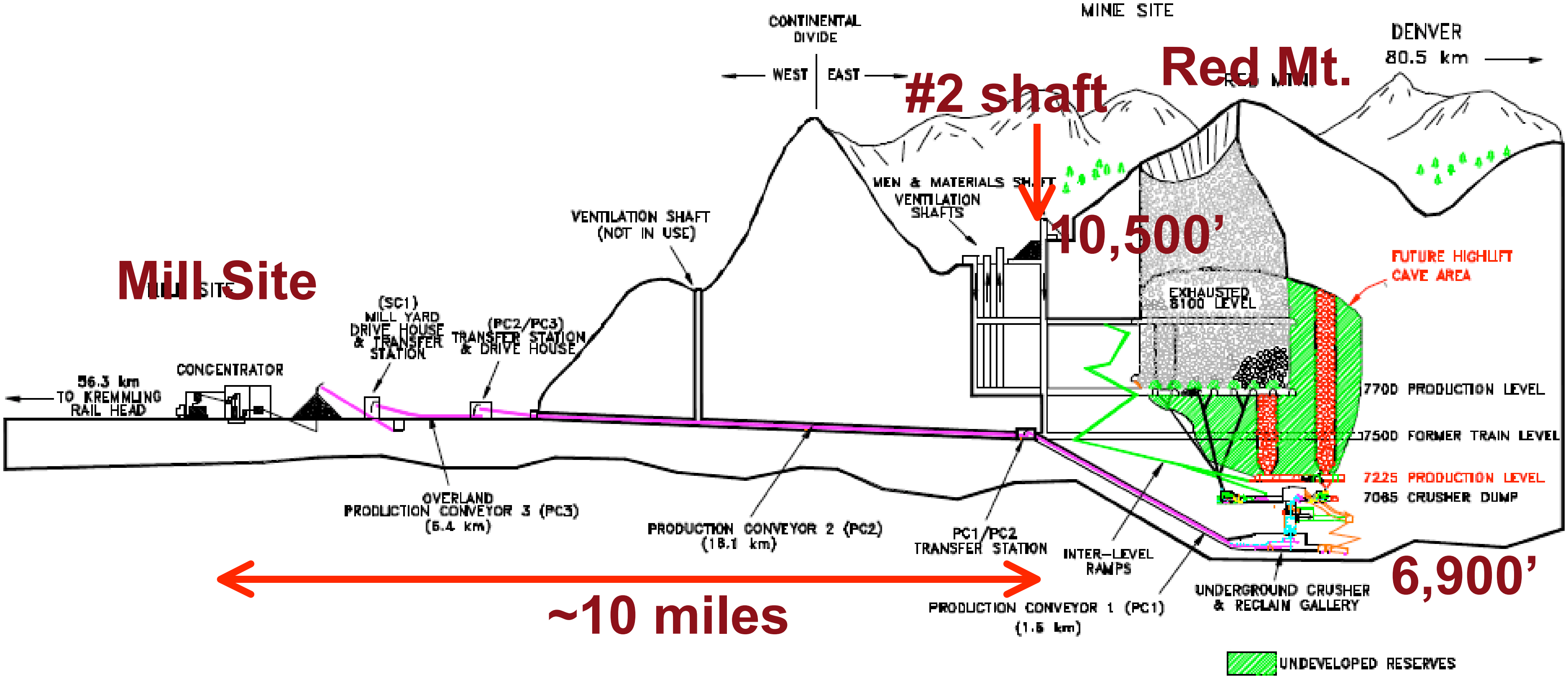
# of 20” PMTs: 56,000

# of 8” PMTs: 14,900

US DUSEL Candidate Sites and Potential Superbeam Experiments

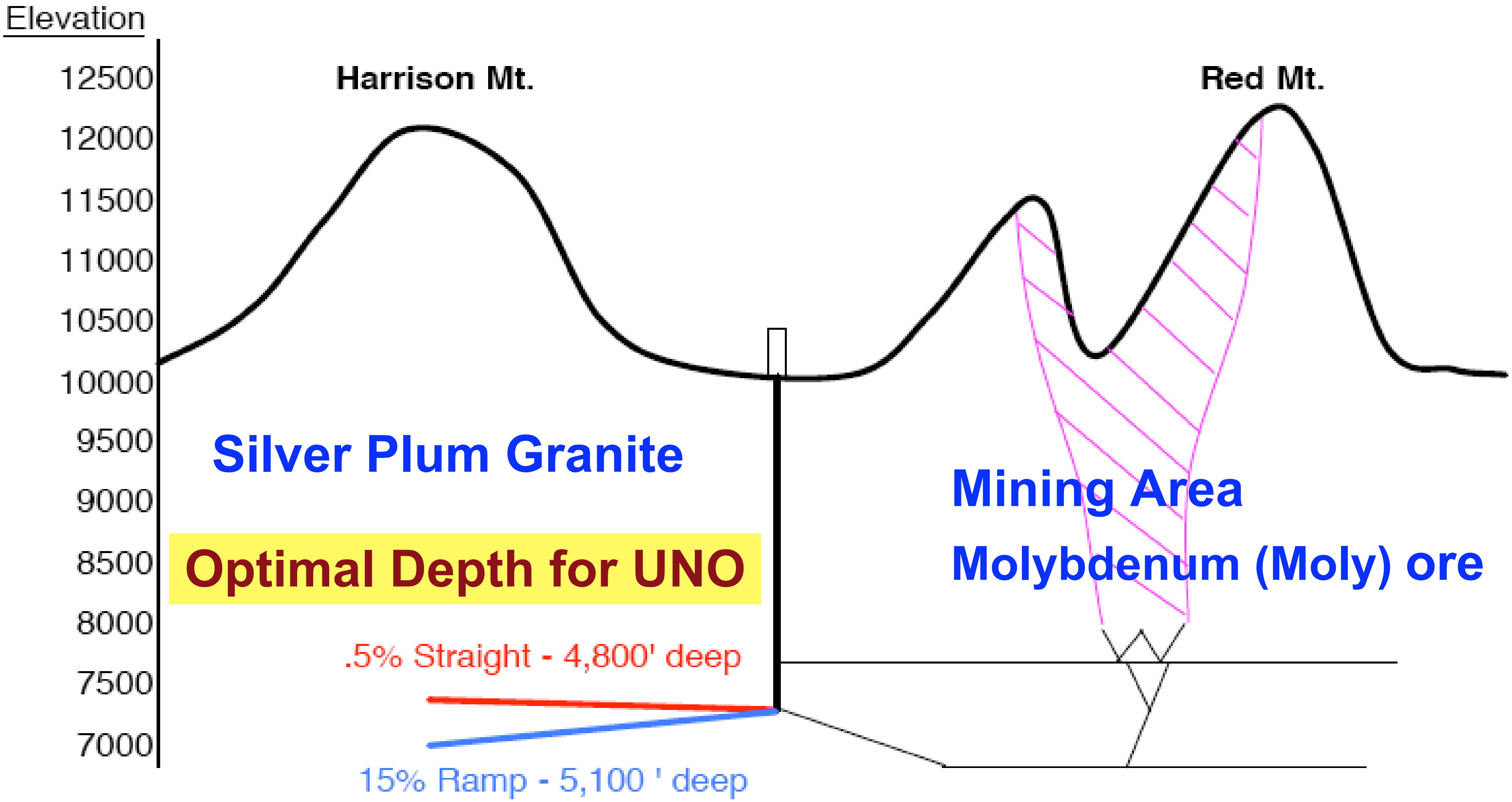


The Henderson Mine, Empire, Colorado



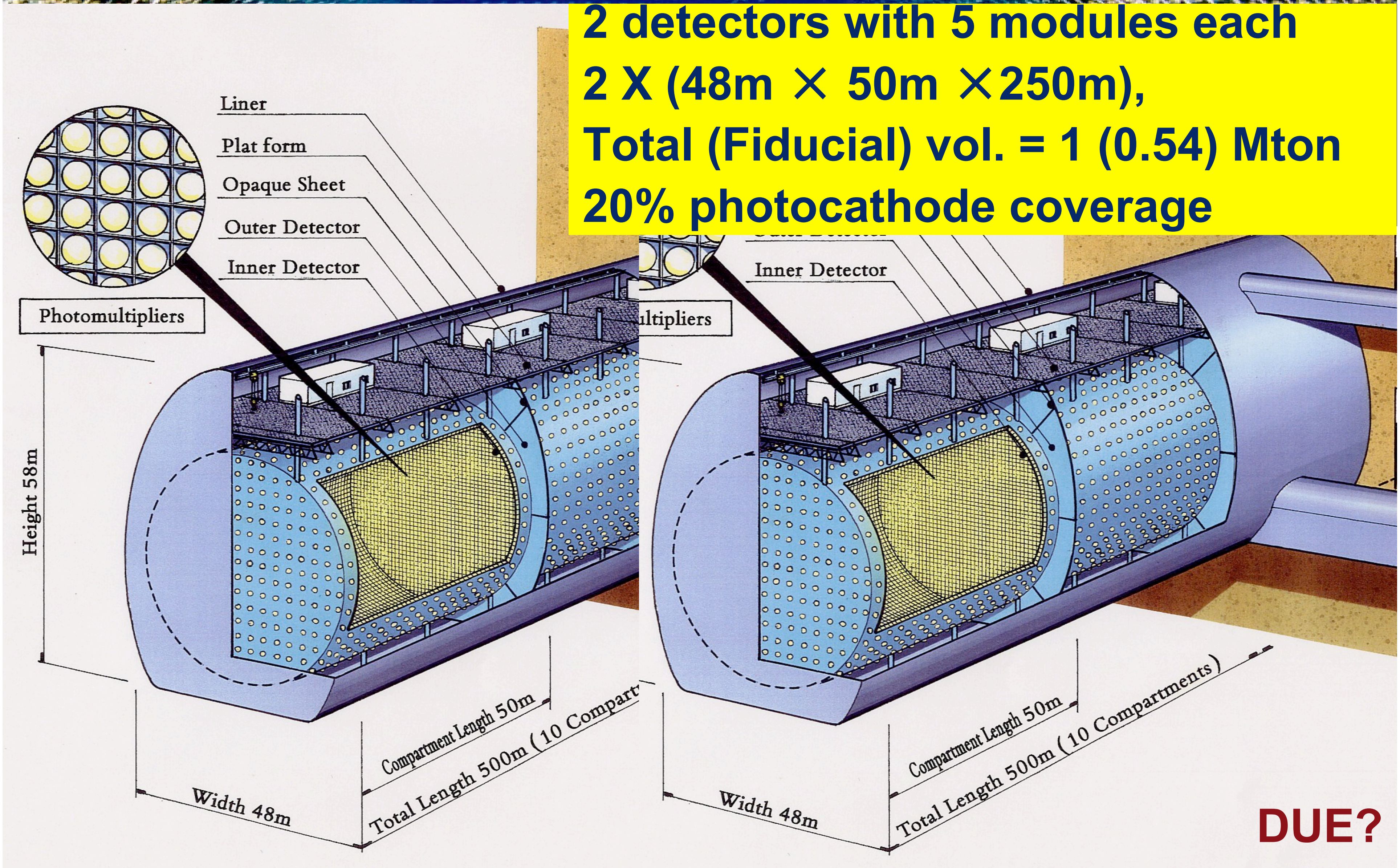
- One of the largest mining operation with large modern shafts
- Large capacity high speed conveyor system (~40 kton/day)
- Existing tailing site and all necessary environmental permits

Possible Depths for UNO at Henderson



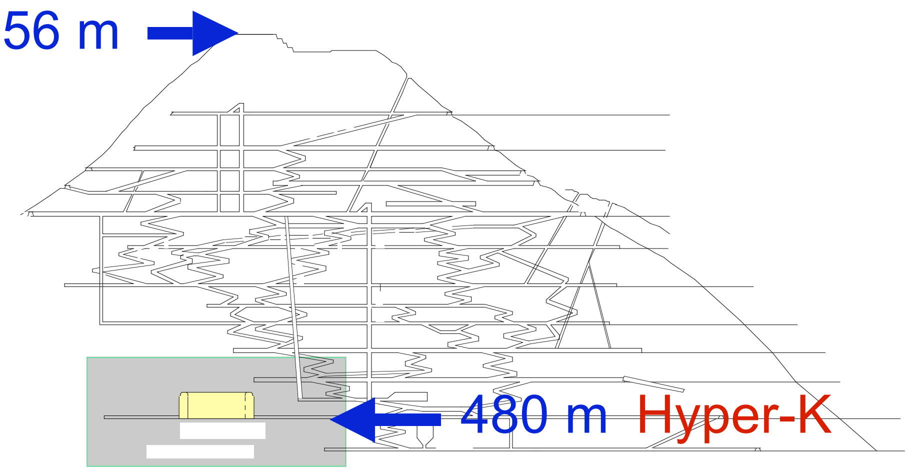
Hyper-Kamiokande Current Design

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



DUE?

Hyper-K Candidate Site: Tochibora Mine



Super-K (Depth:2700mwe)

8km

295km

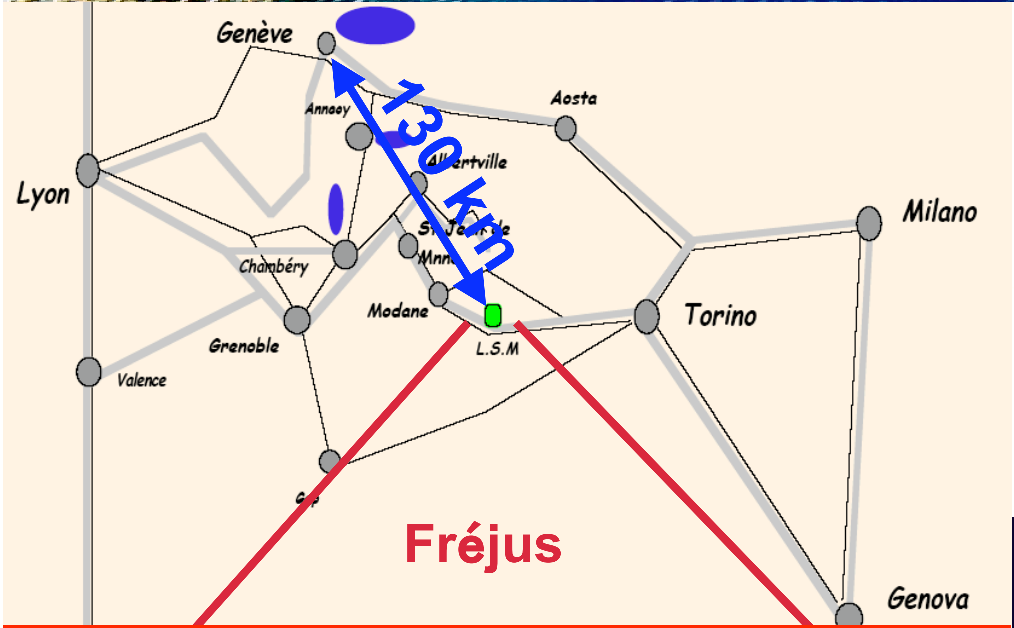
JHF

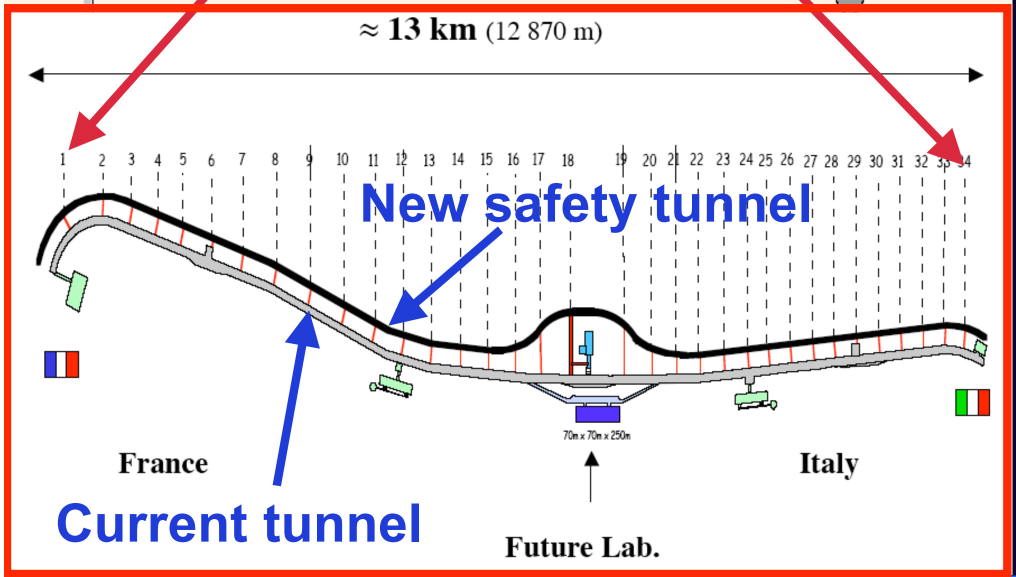
Hyper-K (Depth: 1400 – 1900mwe not decided yet)

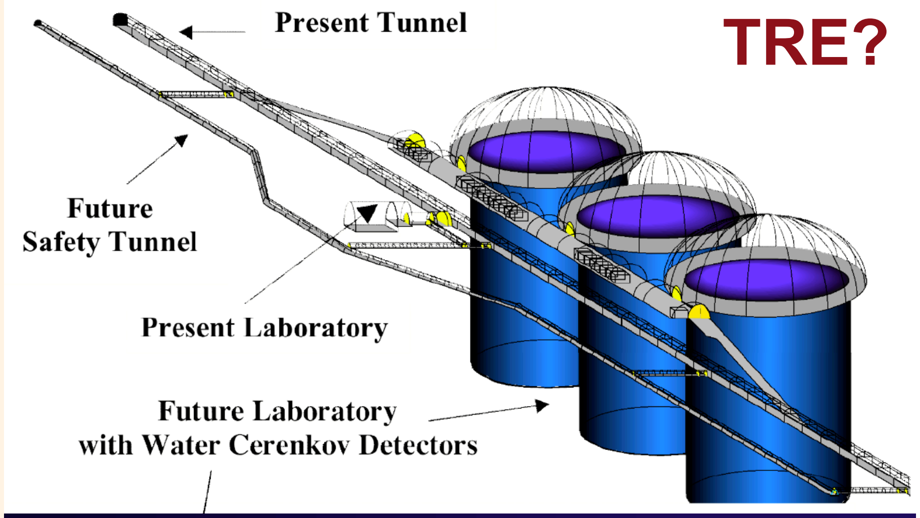
(Tochibora-mine of the Kamioka mining company)

Physics focus: CPV, proton decay, supernova burst

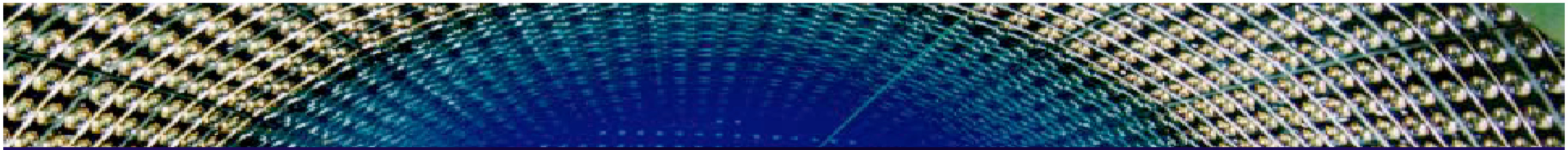
1Mton Class WC Detector at Fréjus







- 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

…

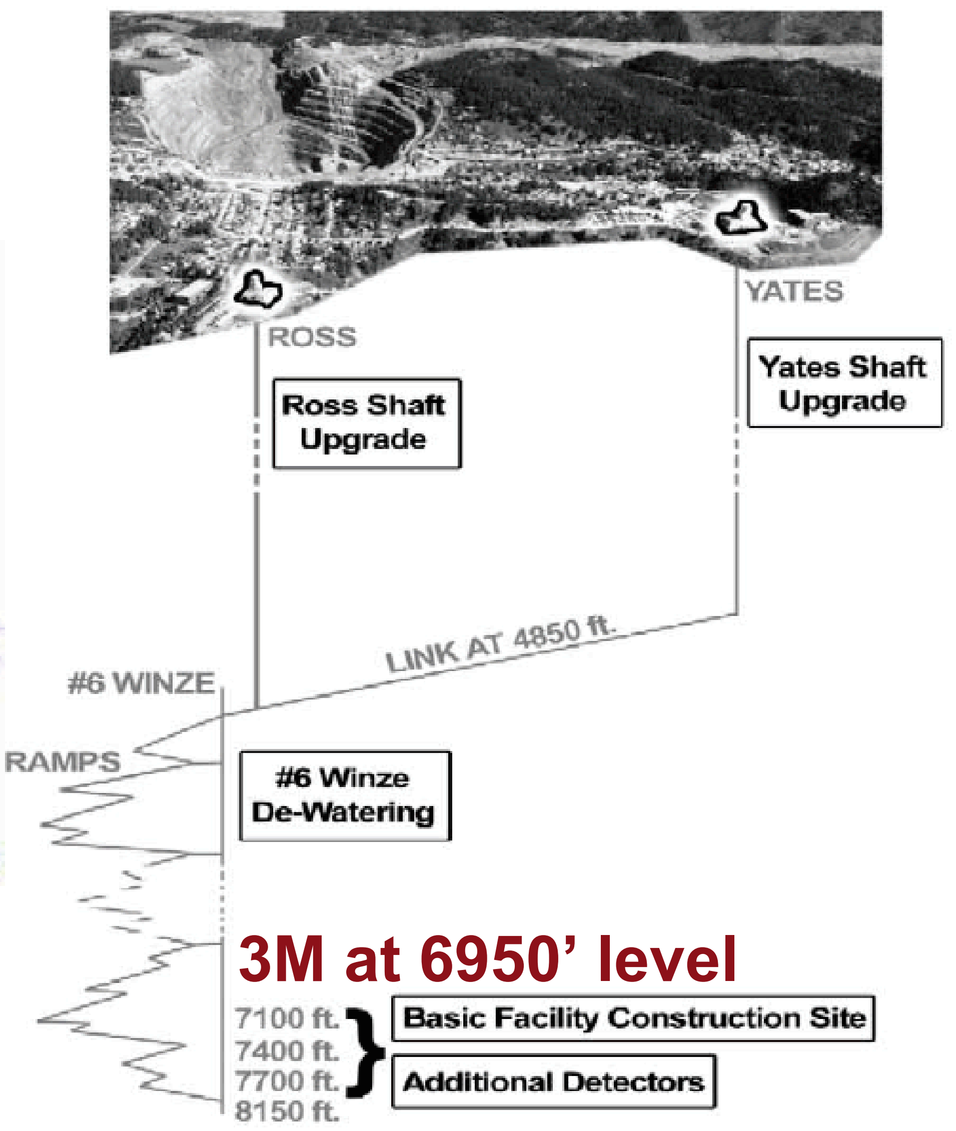
…

…

…

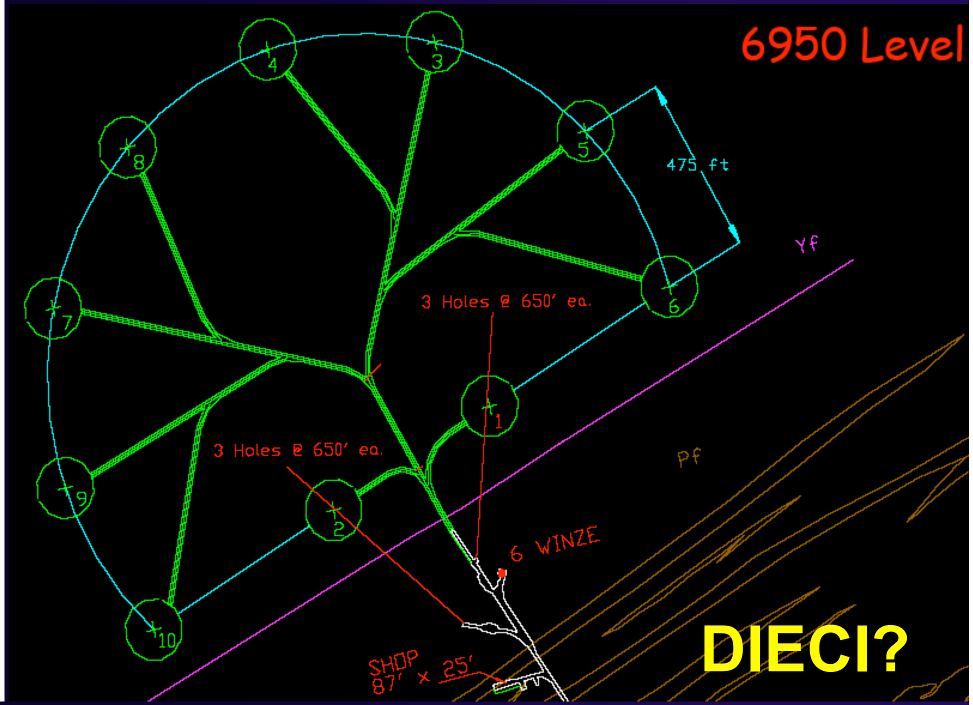
Nove
Detectors, yet!
However…

3M Detector at Homestake Mine



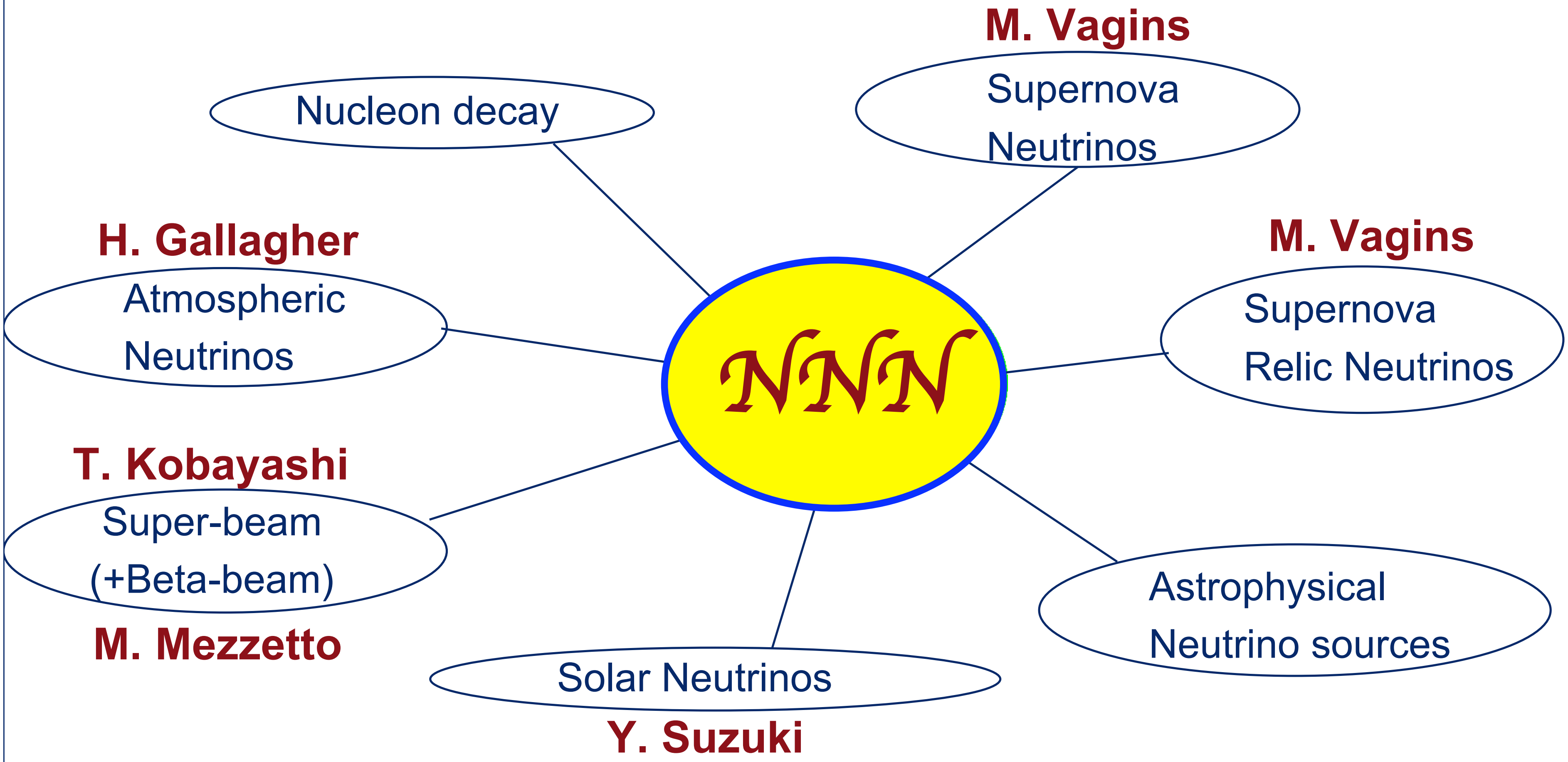
3M at 6950' level

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



DIECI?

UNO Physics Goals



NNN

M. Vagins
Supernova Neutrinos

Nucleon decay

H. Gallagher
Atmospheric Neutrinos

M. Vagins
Supernova Relic Neutrinos

T. Kobayashi
Super-beam (+Beta-beam)
M. Mezzetto

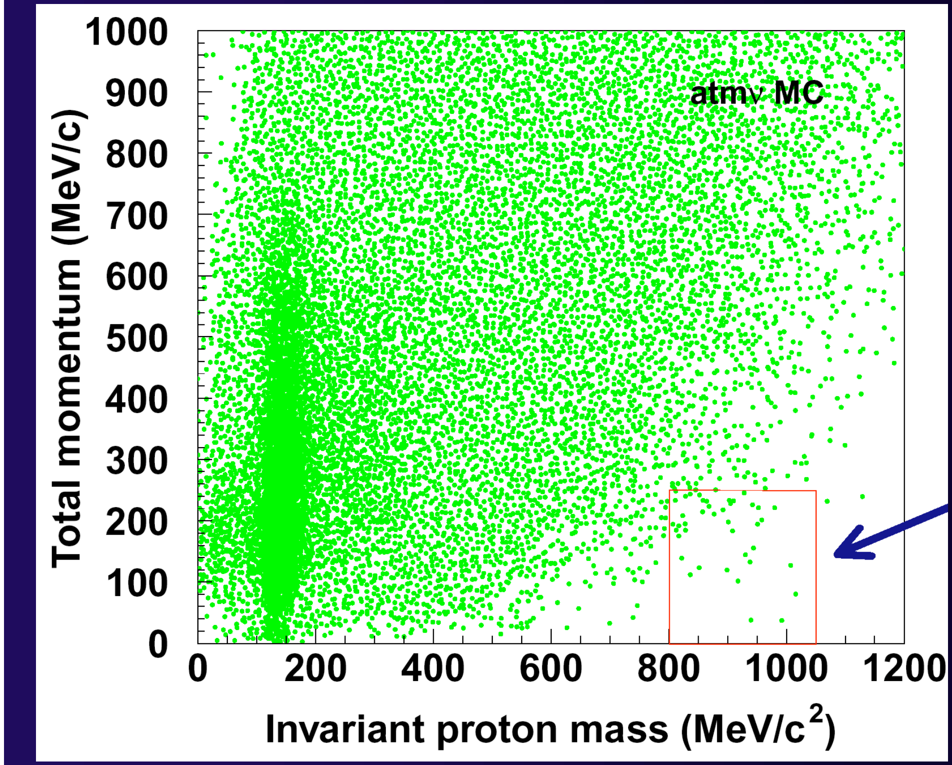
Astrophysical Neutrino sources

Solar Neutrinos
Y. Suzuki

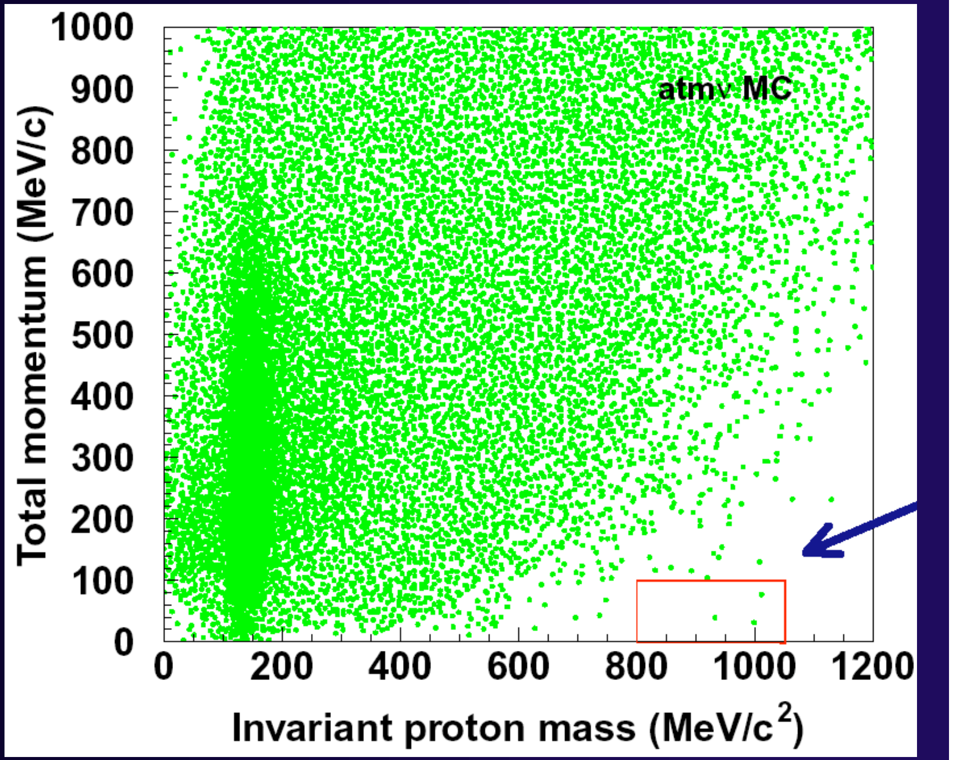
- **Multi-purpose detector with comprehensive physics programs for astrophysics, nuclear physics and particle physics**
- **Synergy between accelerator physics and non-accelerator physics**

p –> e^+ π^0 Search Background

20 Mton-yr Atm nu Background MC



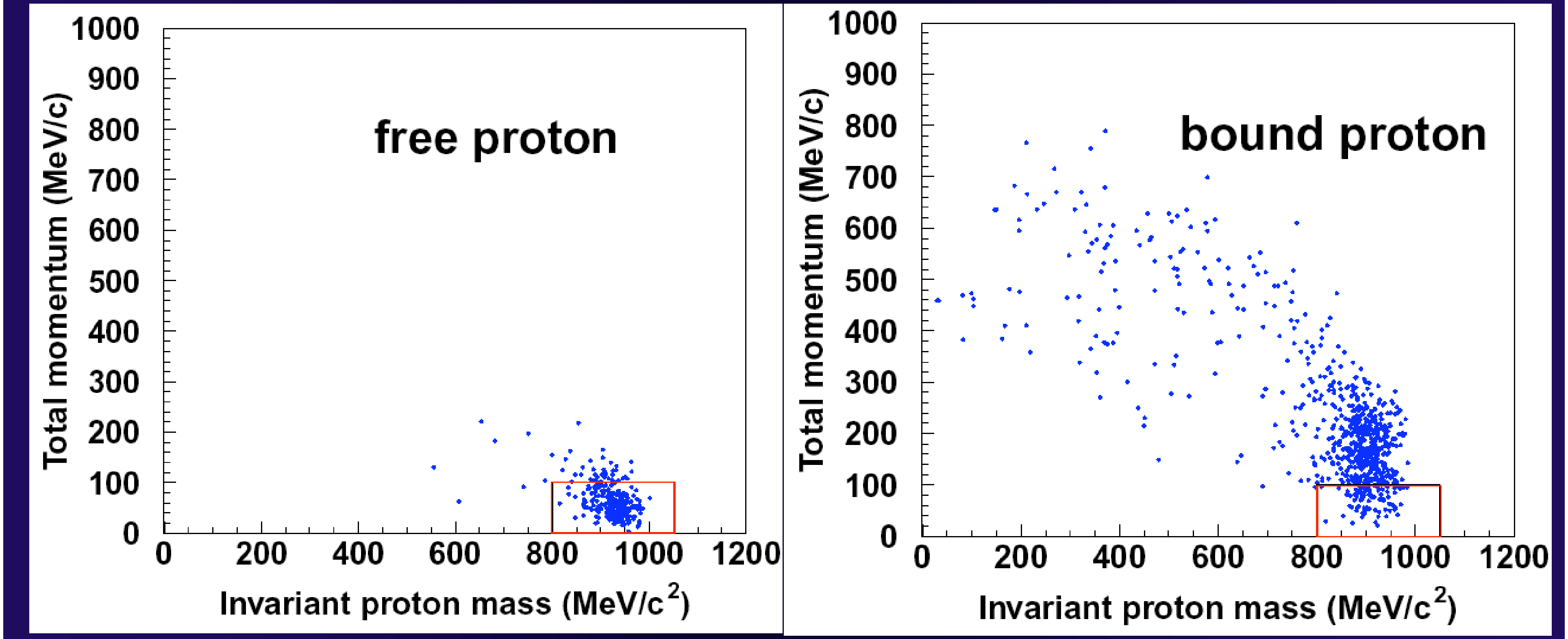
SuperK Standard Cuts
==> 2.2 events/Mton-yr
==> signal eff.: 43.0%



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



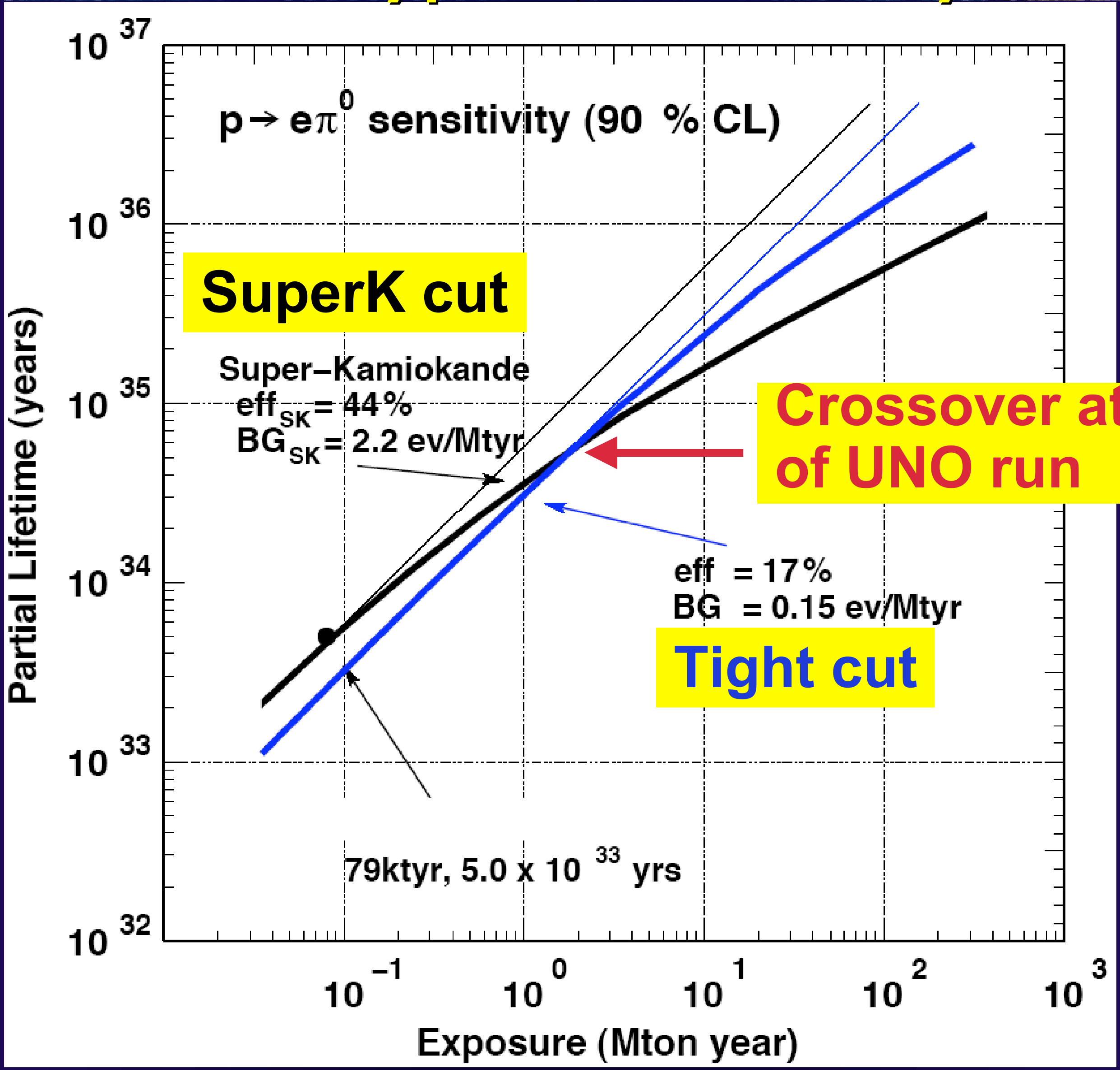
No Fermi Momentum

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

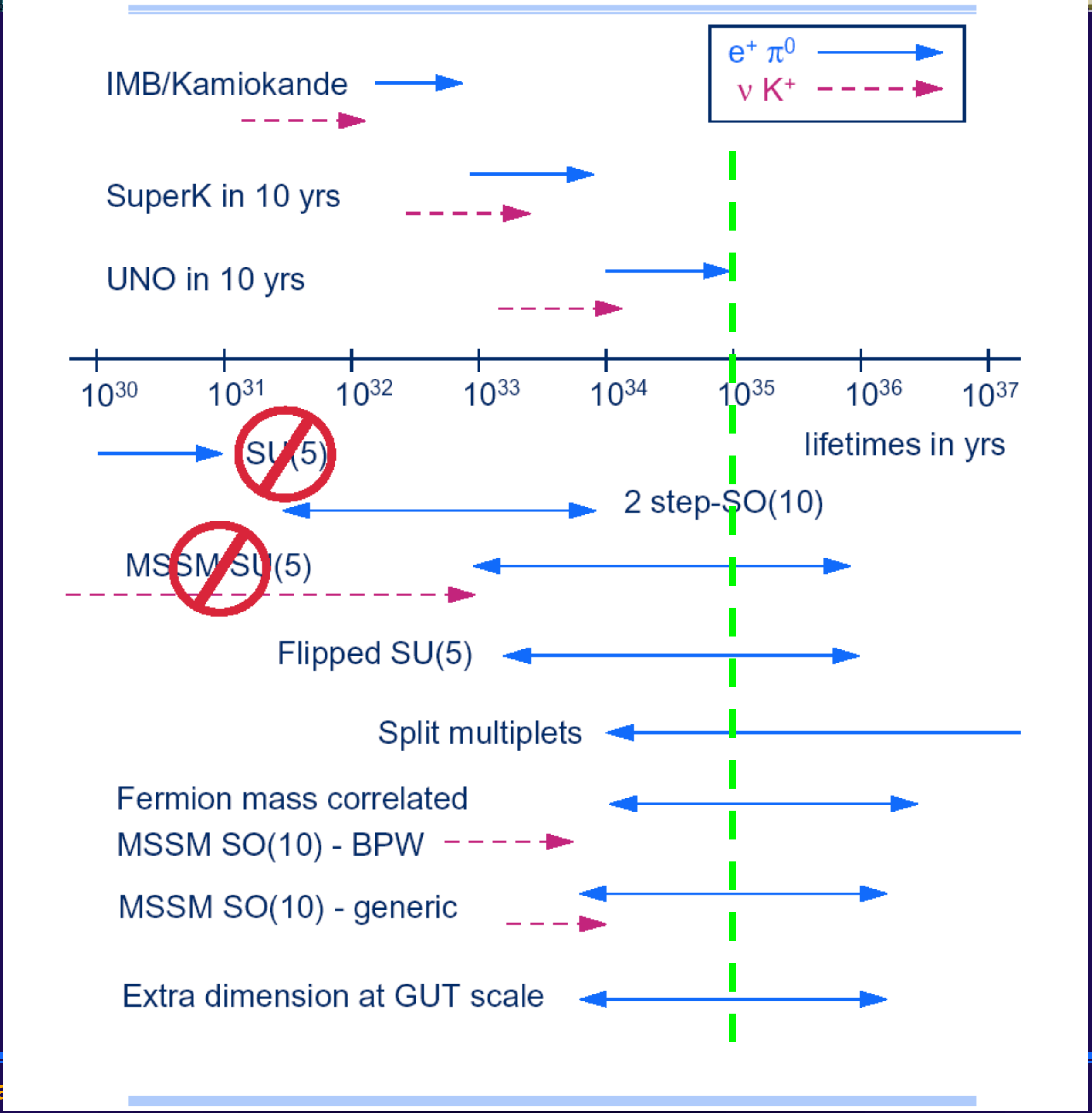


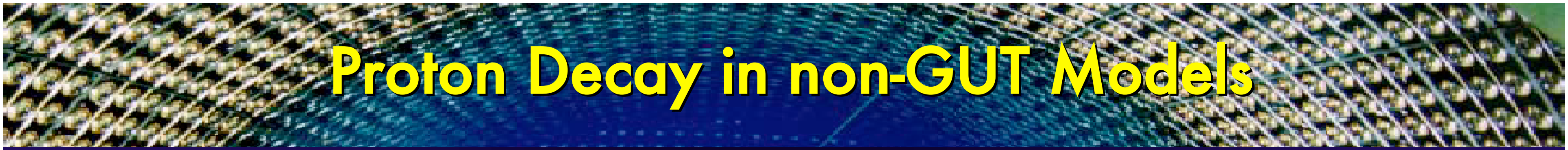
SuperK cut

Tight cut

Crossover at ~4 years of UNO run

HyperK/UNO Proton Decay Sensitivity





Proton Decay in non-GUT Models

"Proton Decay in Intersecting D-brane Models",
I. Klebanov and E. Witten, hep-th/0304079
□ one of the first few testable calculations/predictions based on string theory
□ □/□$_{\text{predicted}}$ (D=6 operators) = ~10^{36} years
(assuming $M_{GUT} = 2\times10^{16}$ GeV)

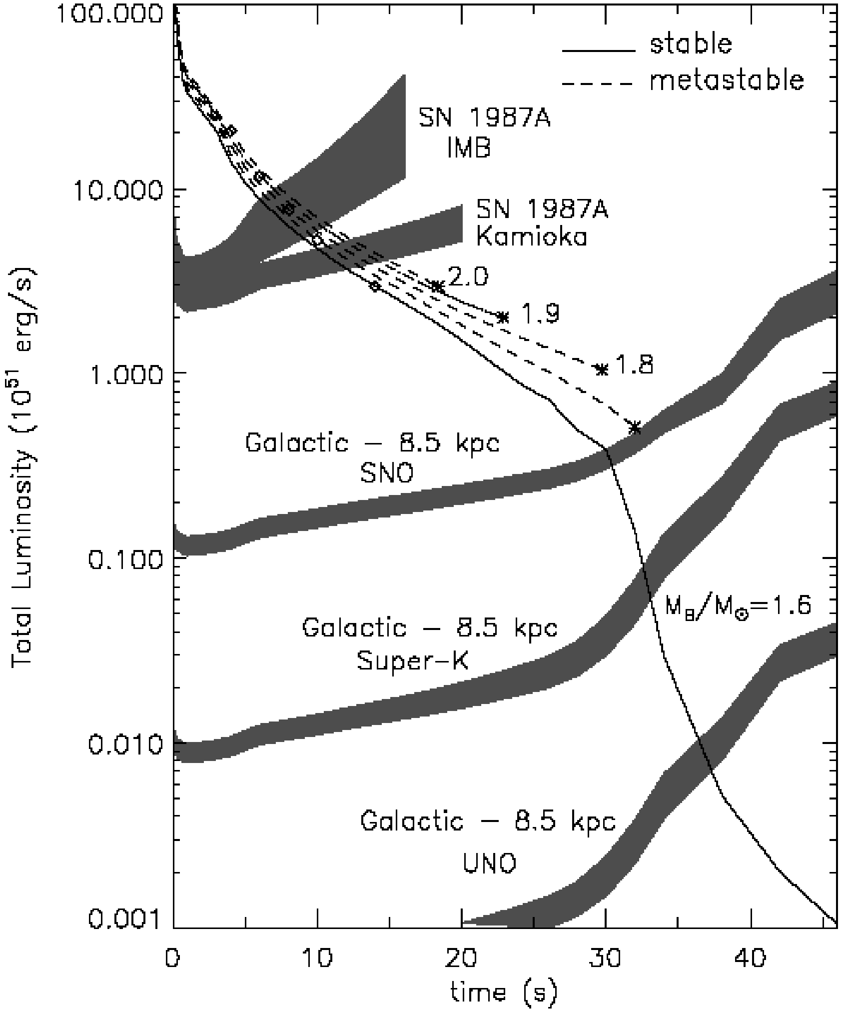
"Probing the Plank Scale with Proton Decay",
R. Harnik, D. T. Larson, H. Murayama, and M. Thormeier, hep-ph/0404260
□ Proton decays in models with a string-inspired anomalous $U(1)_X$ family symmetry
Proton decays probes Plank scale rather than GUT scale
Predicted proton lifetimes similar to the GUT model predictions

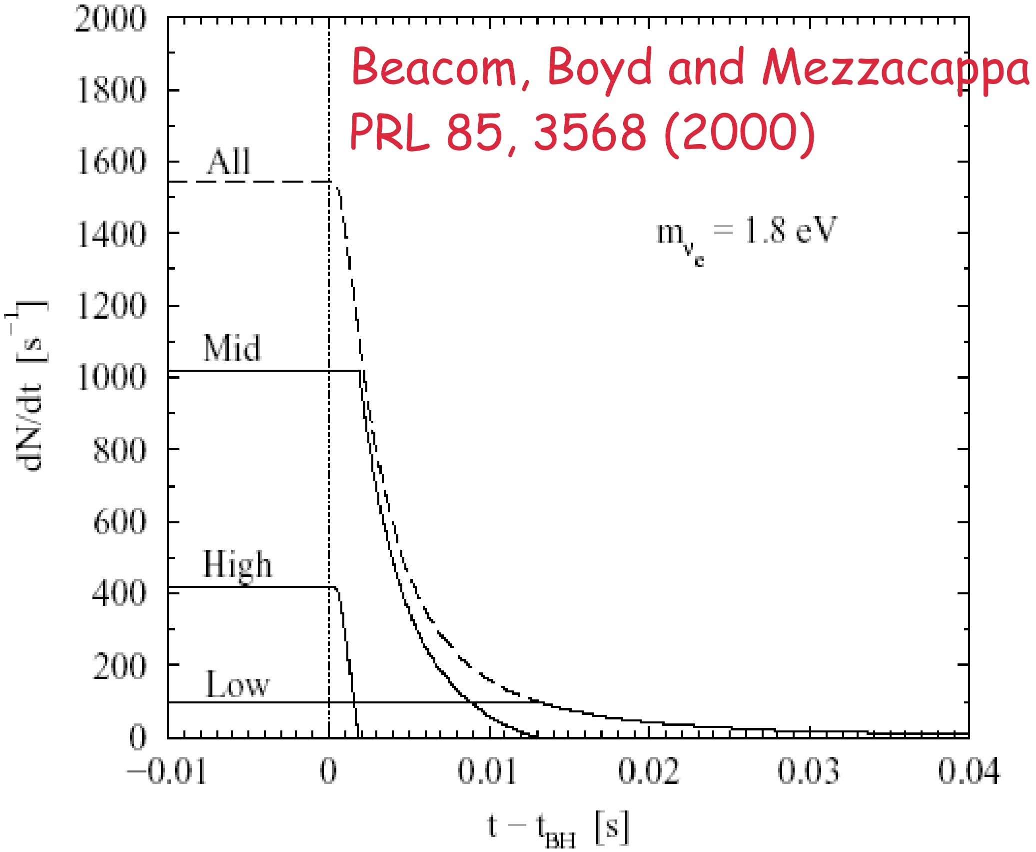
Andromeda Galaxy

Supernova
Reach
~ 1 Mpc
(local group
of galaxies)

Supernova
Rate
~ 1/10 or
15 yrs

Galactic Supernova





Beacom, Boyd and Mezzacappa
PRL 85, 3568 (2000)

~140,000 events in UNO, ~1/30 years

** msec timing structure of the flux **

** Determination of core collapse mechanism**

** Possible Observation of Birth of a Black Hole!**

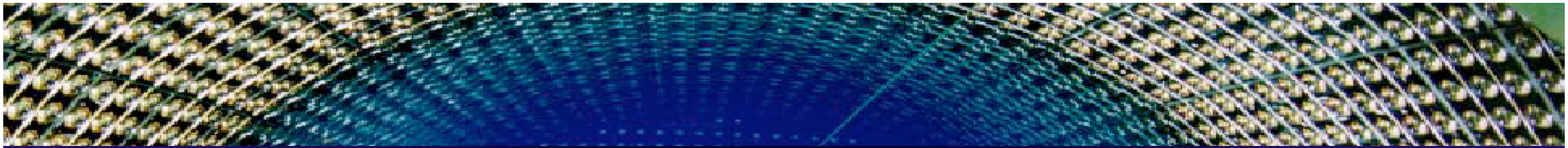
An example of unstable Eq. Of State
Pons et al., PRL 86, 5223 (2001)

SuperK SNR □ Search Limits

Theory Model	SK SRN Rate Limit (Efficiency Corrected)	SK SRN Flux Limit (18 MeV < Ee < 82 MeV)	SK SRN Flux Limit (Full Spectrum)	Predicted SRN Flux (Full Spectrum)
Galaxy evolution (Totani et al., 1996)	$3.2\ \frac{\text{events}}{\text{year}\ \ 22.5\ \text{kton}}$	$< 1.2\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$	$< 130\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$	$44\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$
Heavy metal abundance (Kaplinghat et al.,2000)	$3.0\ \frac{\text{events}}{\text{year}\ \ 22.5\ \text{kton}}$	$< 1.2\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$	$< 29\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$	$< 54\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$
Constant supernova rate (Totani et al., 1996)	$3.4\ \frac{\text{events}}{\text{year}\ \ 22.5\ \text{kton}}$	$< 1.2\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$	$< 20\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$	$52\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$
LMA neutrino oscillation (Ando et al., 2002)	$3.5\ \frac{\text{events}}{\text{year}\ \ 22.5\ \text{kton}}$	$< 1.2\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$	$< 31\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$	$11\ \frac{\bar{\nu}_e}{\text{cm}^2\ \ \text{sec}}$

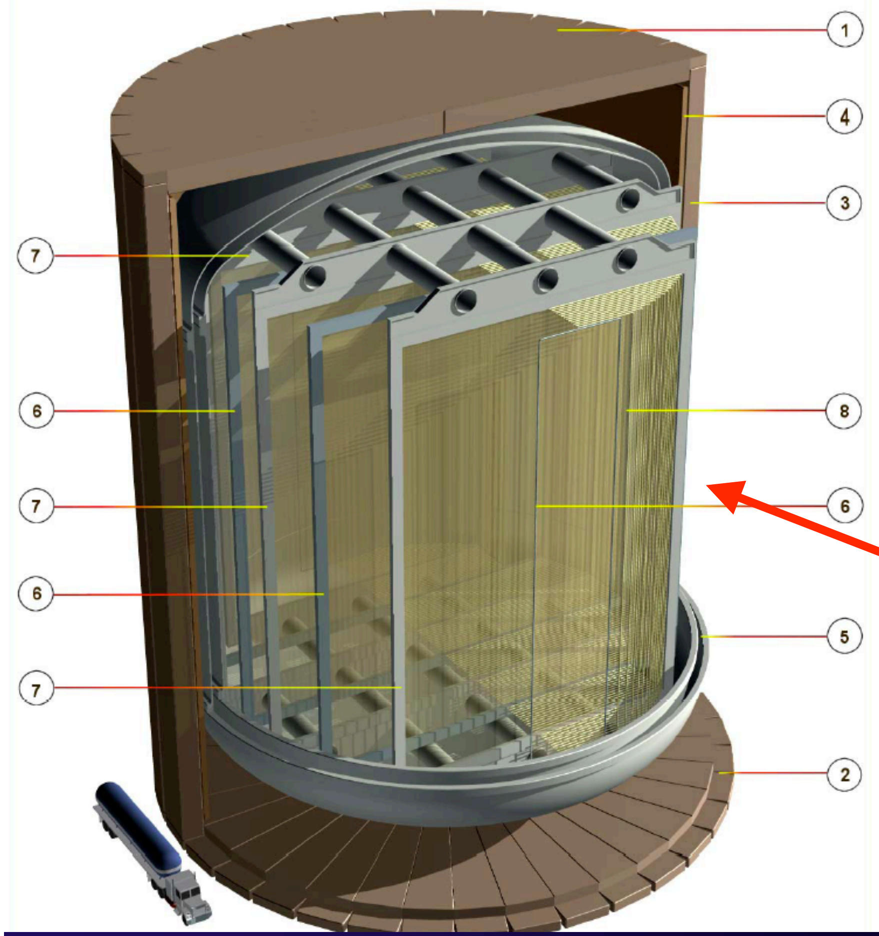
M.S. Malek et. al, Phys. Rev. Lett. 90, E-ID 061101 (2003)

UNO at 4000 mwe can rule out all models within 3~5 years or discover SNR

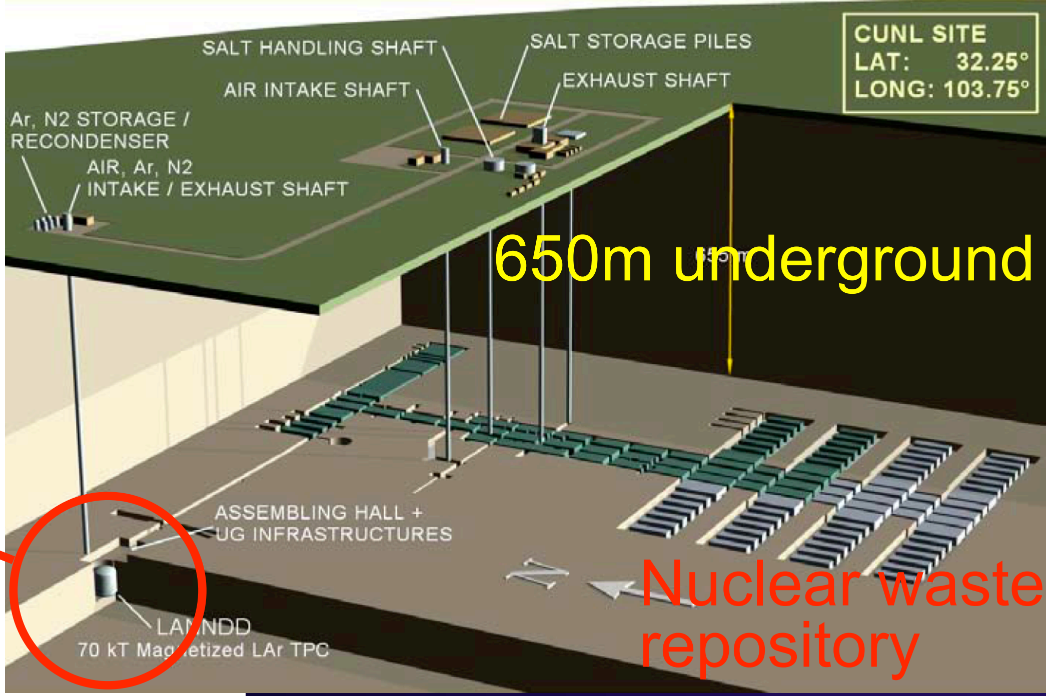


Future Large Liquid Argon Detectors

LANDD at WIPP (Waste Isolation Pilot Plant) in New Mexico, USA



1 *Top iron end cap*
2 *Bottom iron end cap*
3 *Iron yoke barrel*
4 *Solenoid coil*
5 *Cryostat*
6 *Cathodes*
7 *Wire chambers*



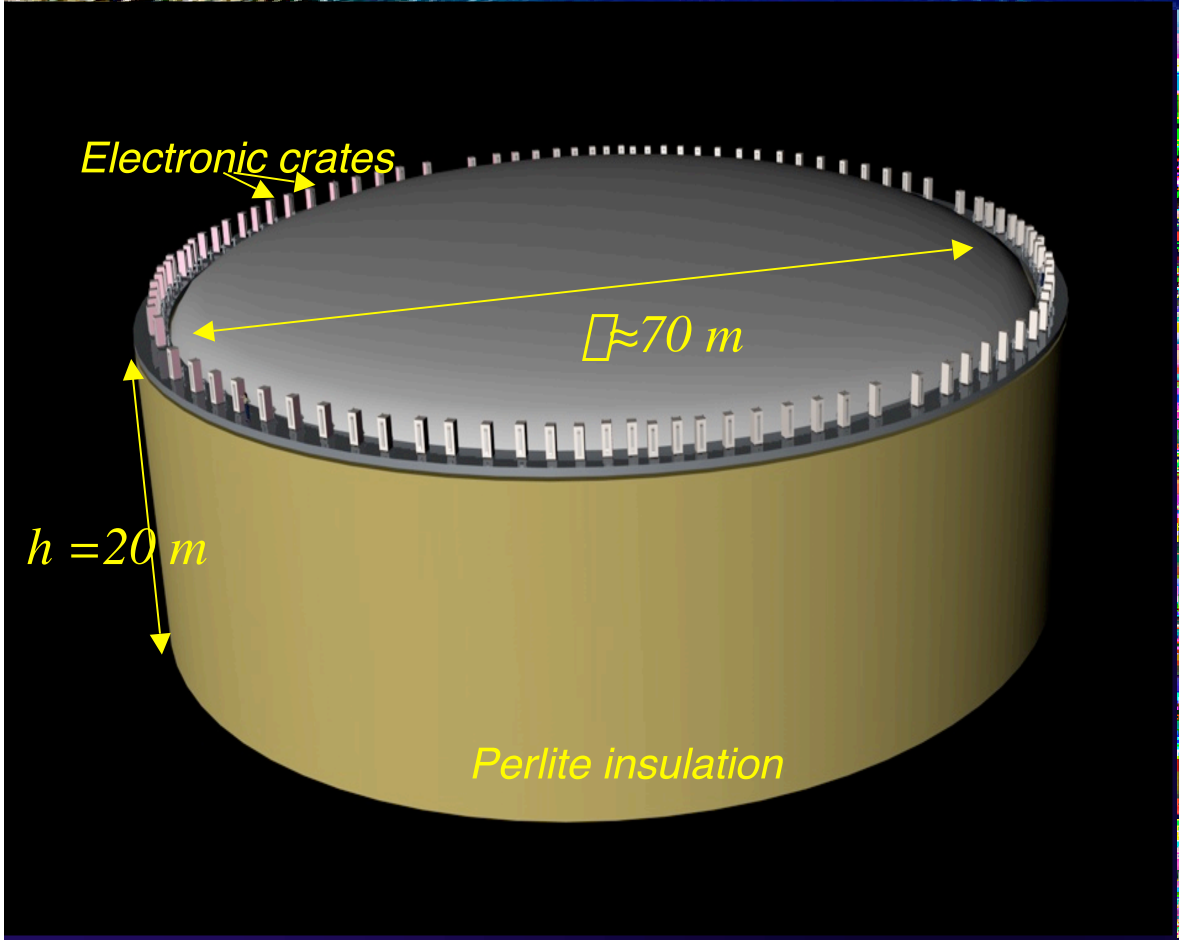
650m underground

Nuclear waste repository

- 70 kton active volume
- 0.5 kV/cm E-field
- 5 m max. drift distance
- Solenoid around the cryostat

- Magnetized LAr Detector
- Extrapolation of ICARUS technology

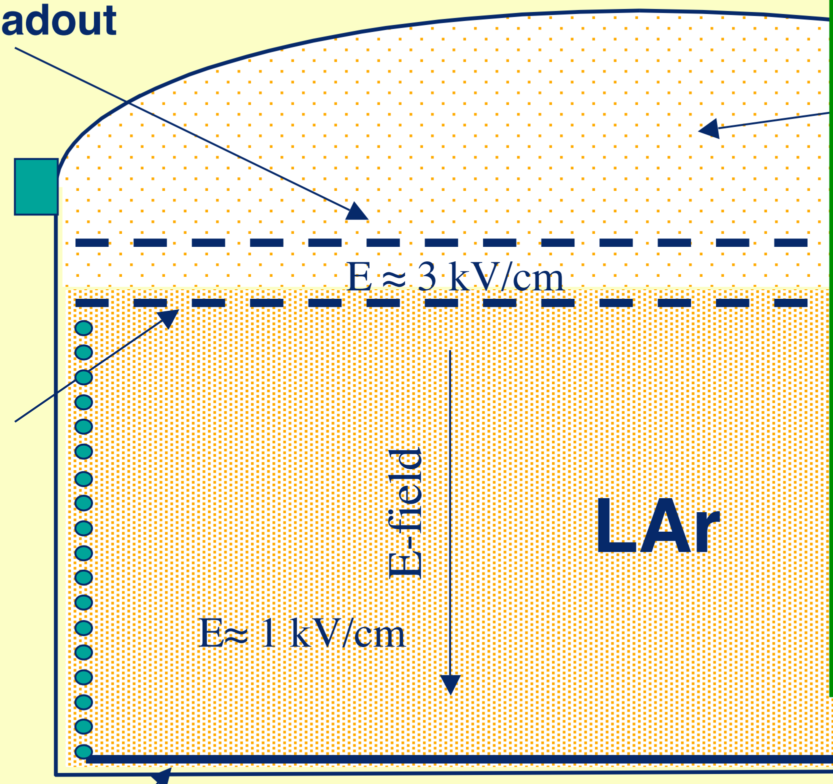
100kt LAr TPC in Europe



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

100 kton LAr Detector Principle and a Tentative Layout

- E = 1 kV/cm (HV = 2MV)
- 20 m max. drift distance

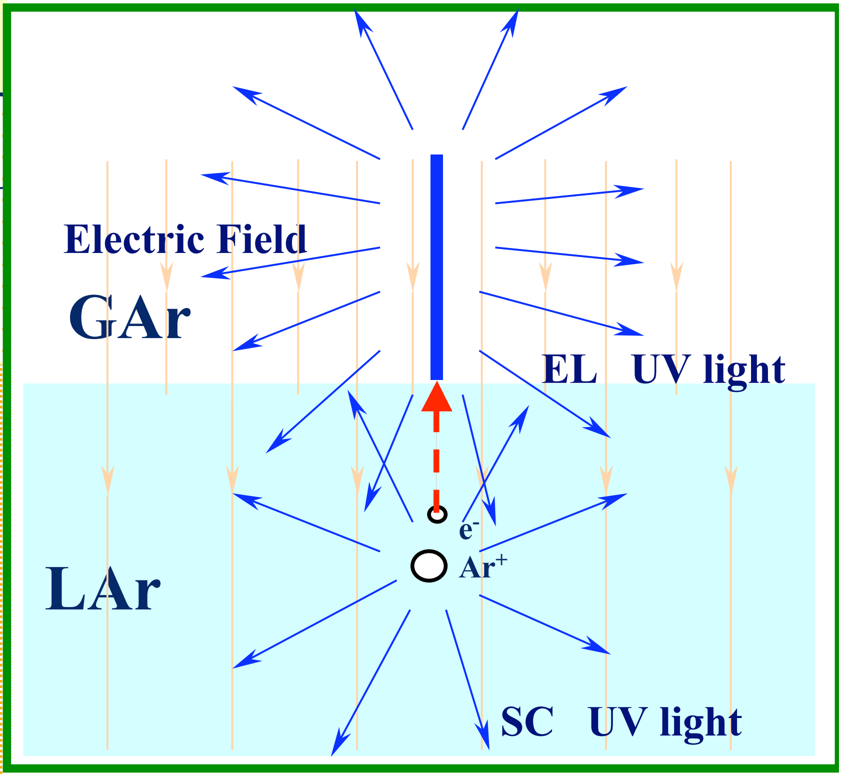


Charge readout plane

Extraction grid

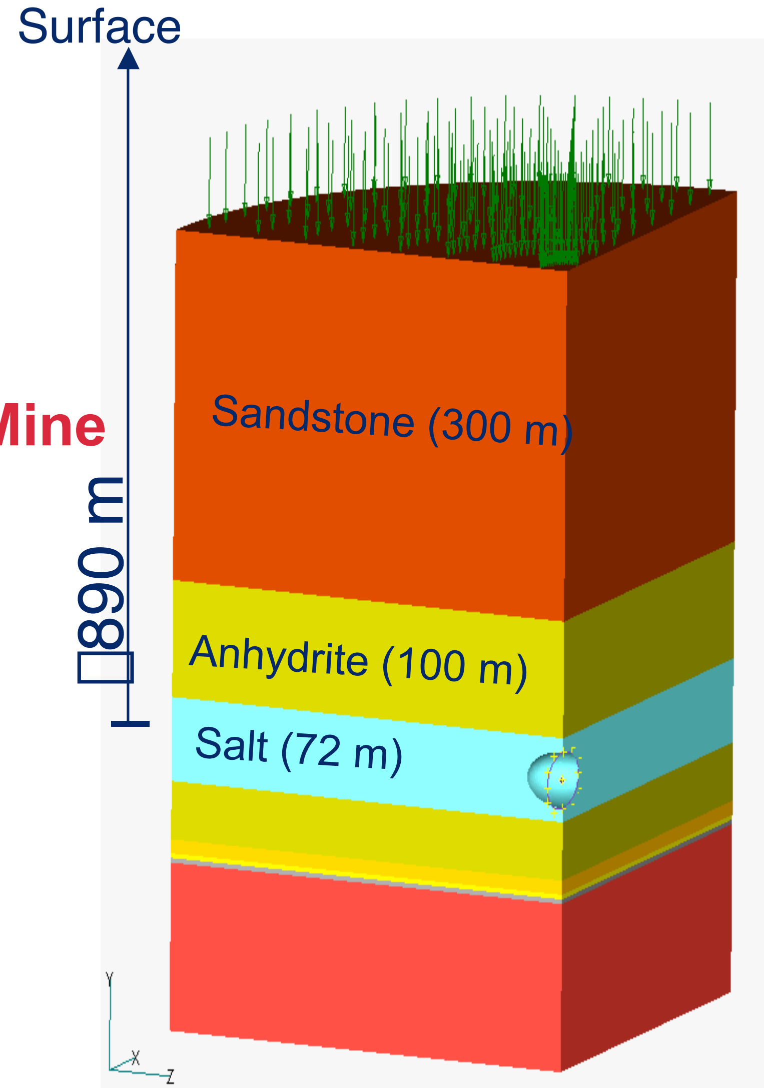
Cathode (- HV)

Particle produces excitation (Ar*) and ionization (Ar^+, e)



Both SC and EL can be detected by the same photo-detector

100kt LAr Detector Candidate Sites



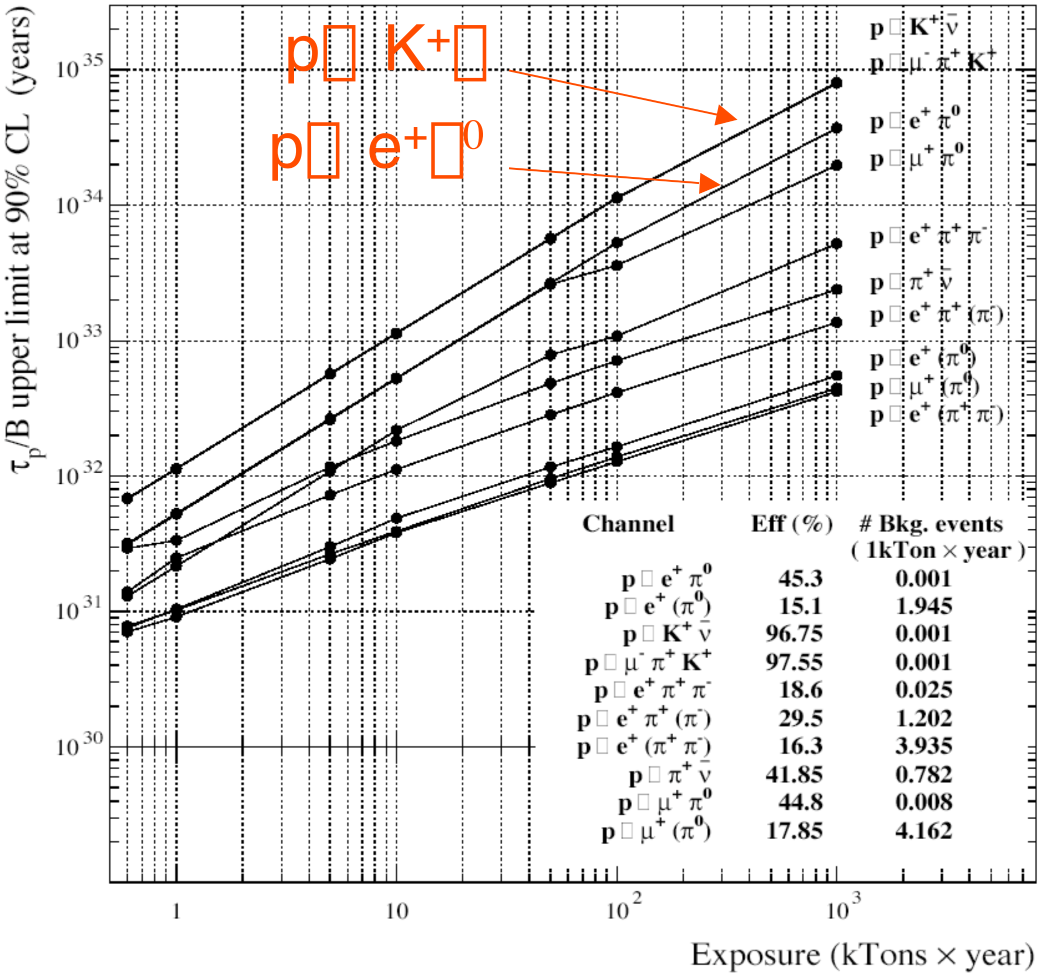
Geology of the Polish Mine

Finite element analysis for Polish

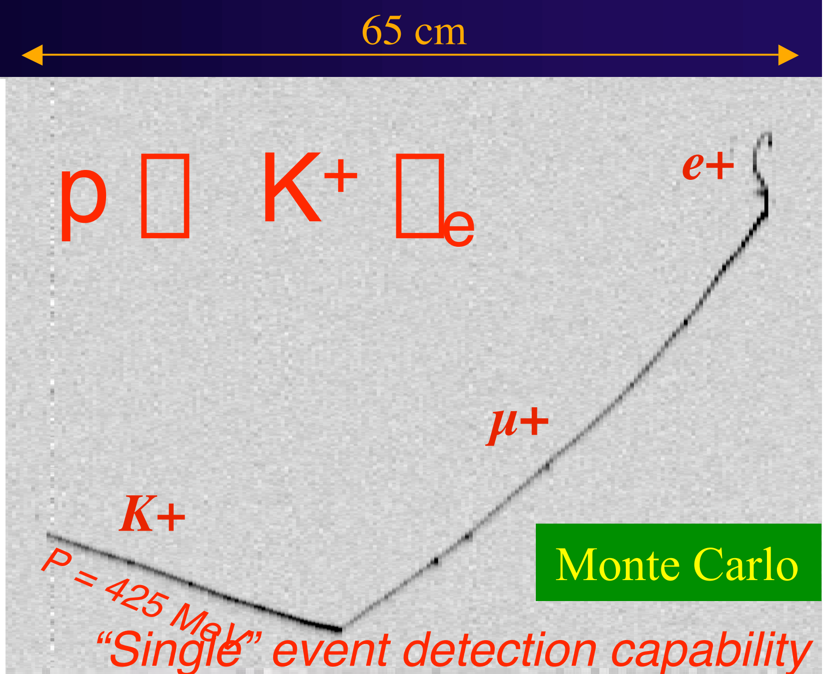
100kton LAr Sensitivity for Proton Decays

p□ K^+□ in 10 years: 8 x 10^{34} years @ 90% C.L.

p□ e^+□^{0} in 10 years: 3 x 10^{34} years

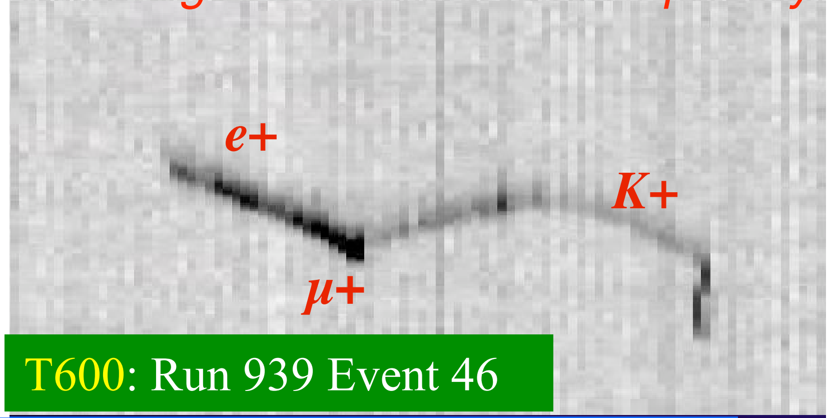


Channel	Eff (%)	# Bkg. events (1kTon × year)
p□$e^+\pi^0$	45.3	0.001
p□$e^+(\pi^0)$	15.1	1.945
p□$K^+\bar{\nu}$	96.75	0.001
p□$\mu^-\pi^+K^+$	97.55	0.001
p□$e^+\pi^+\pi^-$	18.6	0.025
p□$e^+\pi^+(\pi^-)$	29.5	1.202
p□$e^+(\pi^+\pi^-)$	16.3	3.935
p□$\pi^+\bar{\nu}$	41.85	0.782
p□$\mu^+\pi^0$	44.8	0.008
p□$\mu^+(\pi^0)$	17.85	4.162

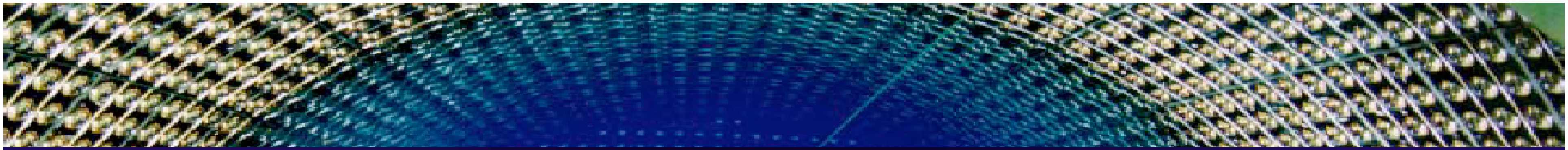


Monte Carlo

“Single” event detection capability

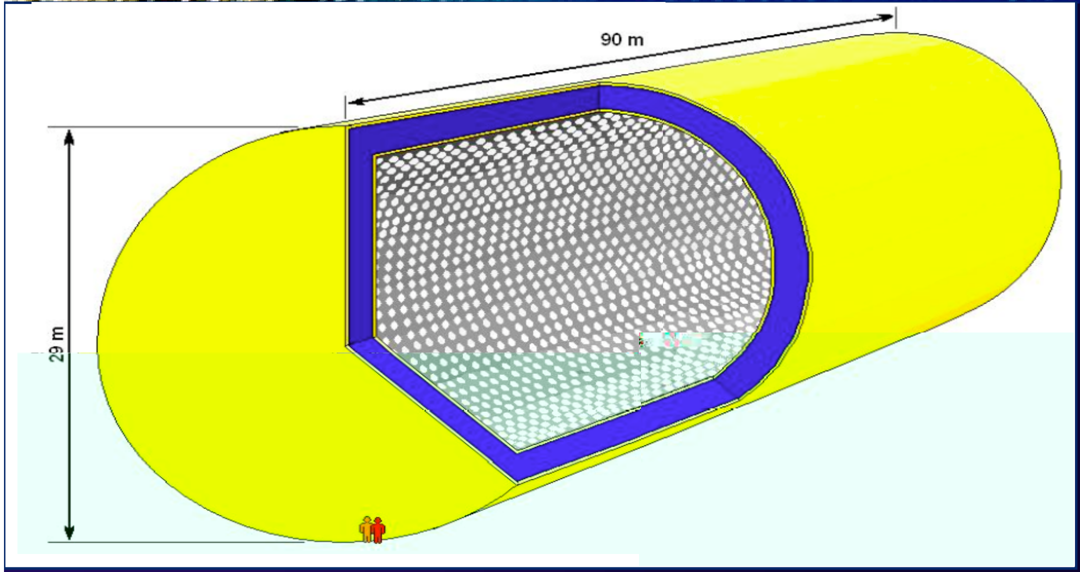


T600: Run 939 Event 46



Future Large Liquid Scintillator Detector

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

Candidate Sites for LENA

CENTRE FOR UNDERGROUND
PHYSICS IN PYHÄSALMI MINE

Pyhasälmi mine in Finland

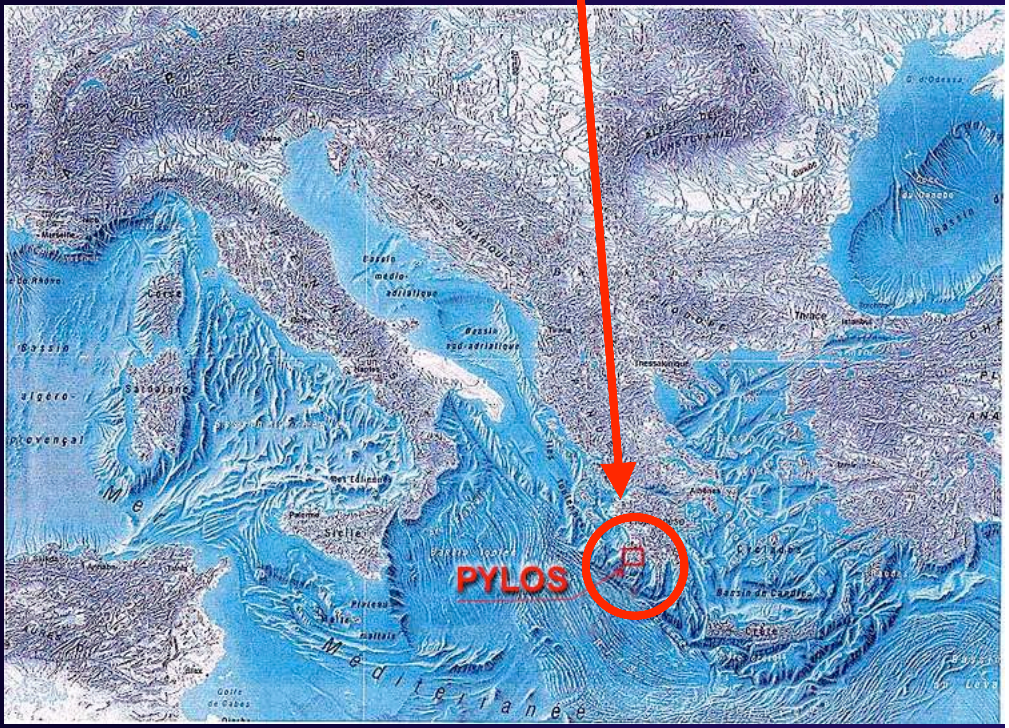
4060 mwe

Under sea

Coast of Pylos (Greece)

~5000 m

Off-axis of CNGS beamline



LENA Sample Physics Sensitivities

Event rates for a SN type IIa in the galactic center (10 kpc)

(1) $\bar{\nu}_e + p \to e^+ + n$ $(Q = 1.8 \text{ MeV})$

(2) $\bar{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$ $(Q = 13.4 \text{ MeV})$

(3) $\nu_e + {}^{12}C \to e^- + {}^{12}N$ $(Q = 17.3 \text{ MeV})$

(4) $\nu_x + {}^{12}C \to \nu_x + {}^{12}C^*$ with ${}^{12}C^* \to {}^{12}C + \gamma$ $(Q = E_\gamma = 15.1 \text{ MeV})$

(5) $\nu_x + e^- \to \nu_x + e^-$ (elastic scattering off electrons) ~ 480

(6) $\nu_x + p \to \nu_x + p$ (elastic scattering off protons).

Electron Antineutrino spectroscopy ~7800

Electron ν spectroscopy ~ 65

Neutral current interactions; info on all flavours ~ 4000 and ~ 2200

$\tau/B(p \to K^+\bar{\nu})$ limit in 10 years: a few 10^{34} years utilizing triple coincidence of (K^+, μ^+, e^+) signals from $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^0$ decay chains

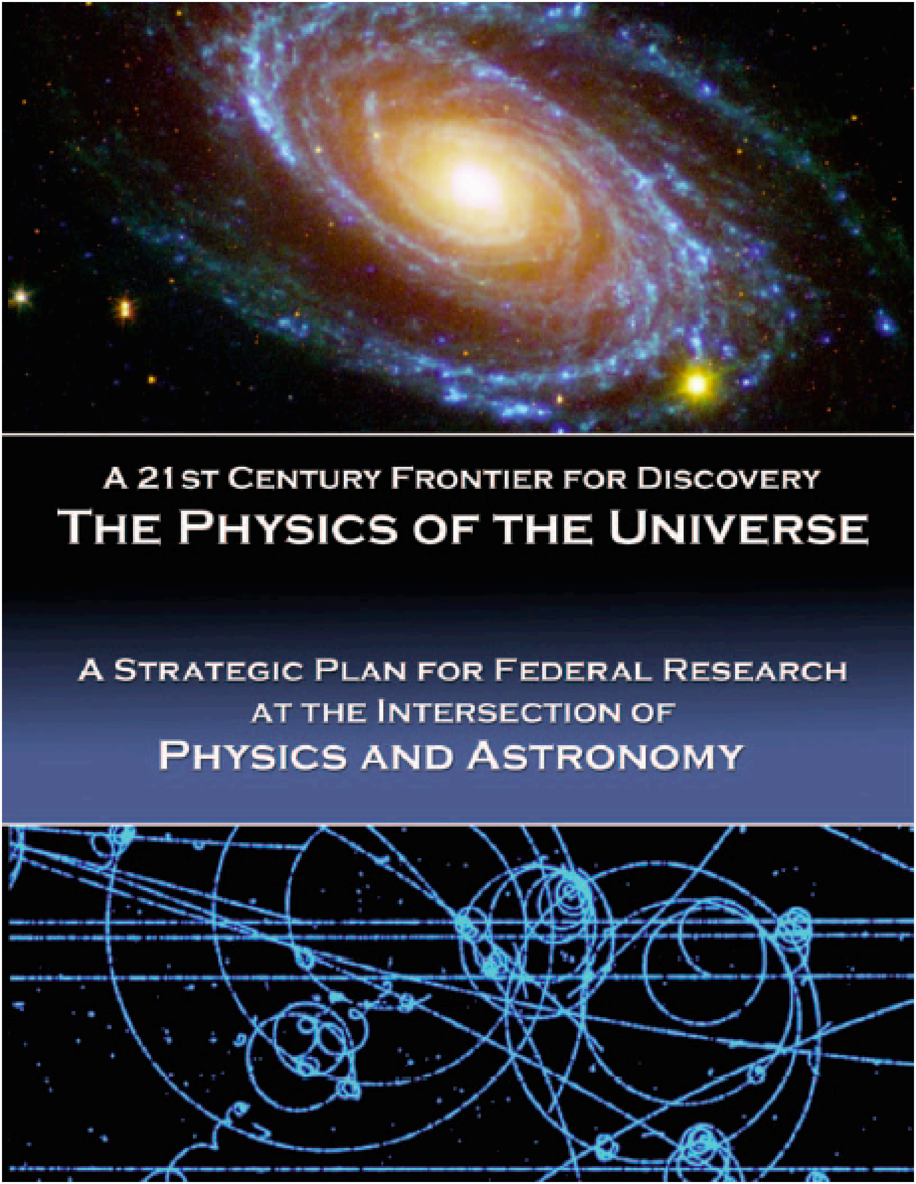
NNN Status Summary

- Water Cherekov Detectors
  - Mature technology
    - Reasonable extrapolation from the current experiments (10~20)
    - no critical R&D item
    - Ready to be built (R&D needed mostly to reduce cost)
- LAr Detectors
  - Idea/R&D stage
    - need to extrapolate the technology from 300 ton to 100 kton (300)
    - success of ICARUS (physics output) is critical

      It will provide a base for extrapolation (physics reach, cost, safety, etc.)
- Liquid Scintillator Detectors
  - Idea/R&D stage but mature technology
    - extrapolation not unreasonable (~1kton ▯ ~50 kton) (50)
    - environmental concern and long term property of the scintillator

A Report of the Intragency Working Group on Physics of Universe

- Released in April 2004
- Response to CPU report
- Coordinated by NSTC
- Intragency Working Group
  - DOE, NSF, OMB, OSTP
- Summary of Recommendations
  - Ready for Immediate Investment and Directions Known
    - Dark Energy
    - Dark Matter, Neutrinos and Proton Decay
    - Gravity



A 21ST CENTURY FRONTIER FOR DISCOVERY

THE PHYSICS OF THE UNIVERSE

A STRATEGIC PLAN FOR FEDERAL RESEARCH
AT THE INTERSECTION OF
PHYSICS AND ASTRONOMY

Conclusions

- NNN detectors with LBL neutrino beams tackle some of the most important physics questions today w/ potential of major discoveries
  - Rich physics program comparable to LHC/LC
- If built, they will provide a comprehensive nucleon decay and neutrino physics program for the world science community for the 21th century
  - Despite the phenomenal scientific success achieved by the neutrino experiments during the last decade, we do not have any major experiments approved that go beyond 10 years from now
    - ▯ long lead time for large experiments
    - ▯ in order to sustain our community, we must plan ahead
- Intersection of interests from HEP, NP and AP communities; and international community (Europe, Japan and USA)
  - A well organized international effort with common physics goals and strong mutual support can bring a successful experiment somewhere in the world

Announcements

Unification Day

One day workshop on Proton Decay in Unification Theories
(as part of the UNO collaboration meeting)
Oct. 15, 2004, Colorado, U.S.A.
(co-organized by E. Witten and CKJ)

NNN05

Next generation Nucleon decay and Neutrino detector Workshop
Spring 2005, Fréjus, France
(contacts: S. Katsanevas and CKJ)