DUSEL Experiment Development and Coordination (DEDC)

NSF Visit

March 19 & 20, 2008

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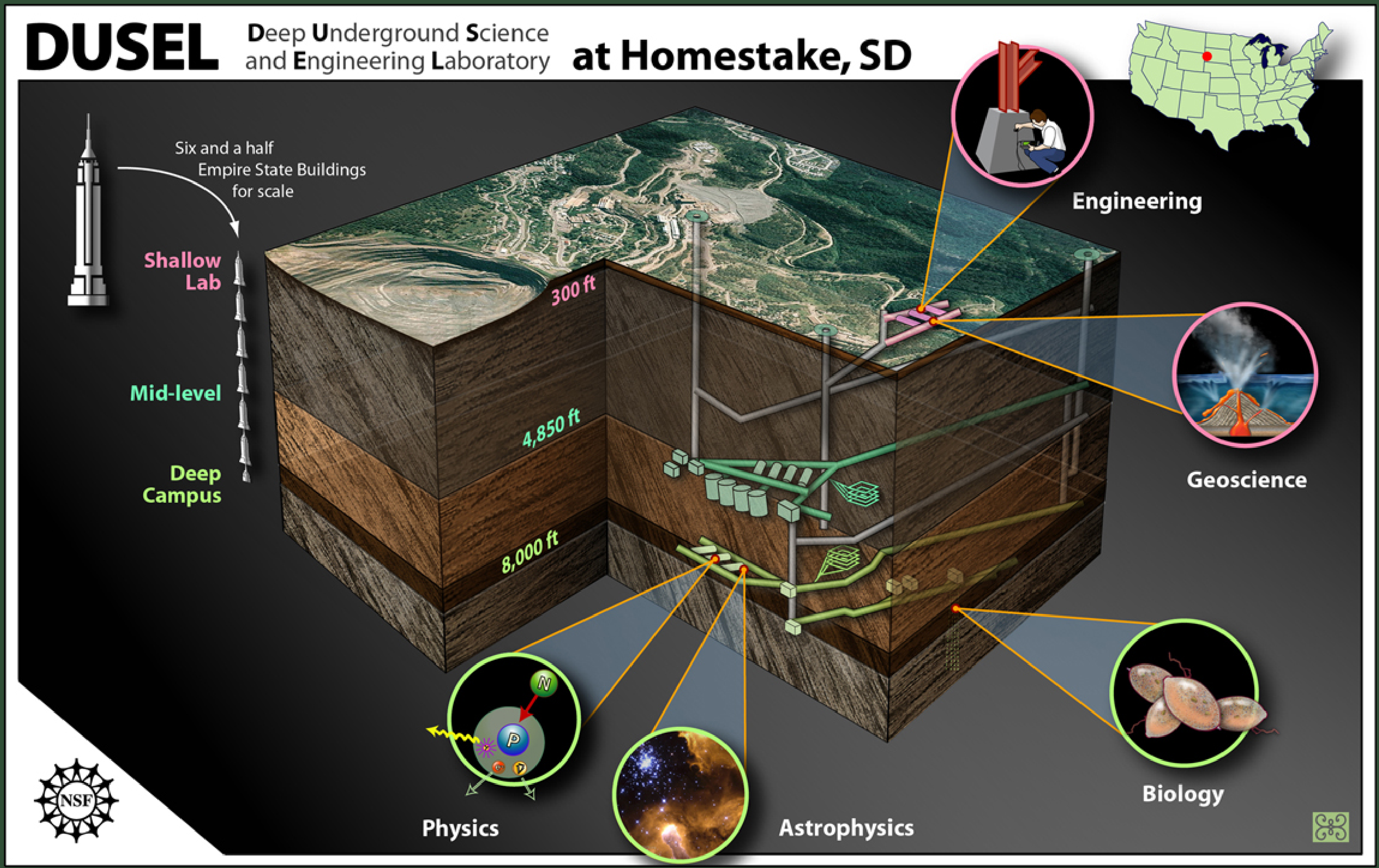


Physics Experiments at DUSEL

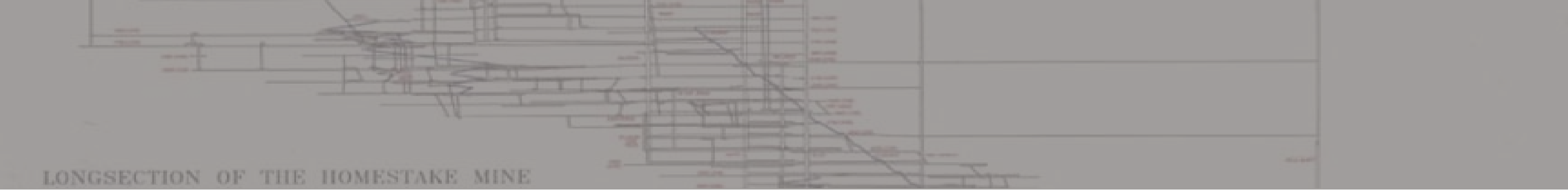
- Long Baseline Neutrino Beam/Nucleon Decay
- Dark Matter

Hank

- Neutrino-less Double Beta Decay
- Solar Neutrinos

Steve

- Nuclear Astrophysics
- Gravity Waves
- Some others
  - n-nbar, atom interferometry, cloud physics
  - Energetic particle effects

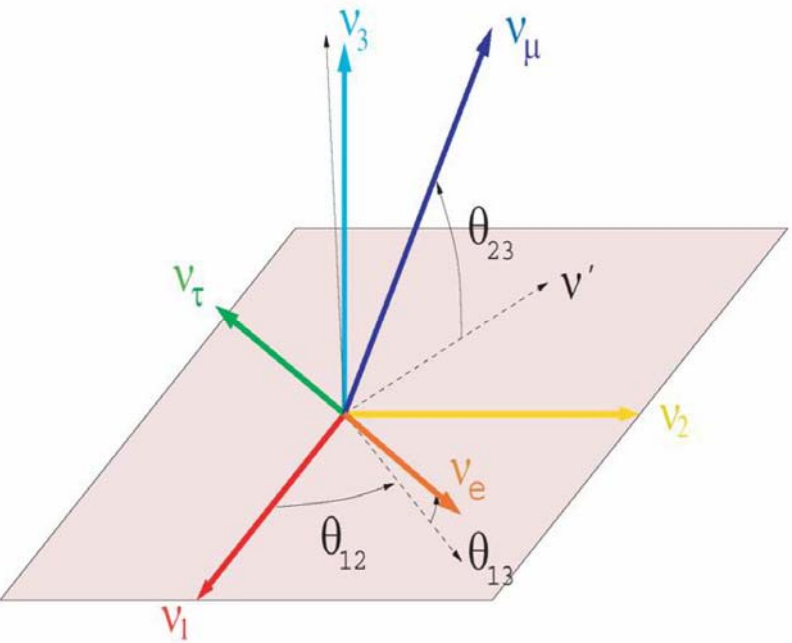


Neutrino Physics

Long Baseline Neutrino/Proton Decay

- There has been a revolution in Neutrino Physics.
  - Observation of Atmospheric Neutrino oscillations - Super-Kamiokande 1998.
  - Confirmation by K2K, MINOS.
  - Observation of Solar Neutrino oscillations (Chlorine, Super-K, SAGE, Gallex, SNO)
  - Confirmation by KamLAND

Three Neutrino Picture



The physical neutrino eg. ν_μ is a mixture of eigenstates such that:

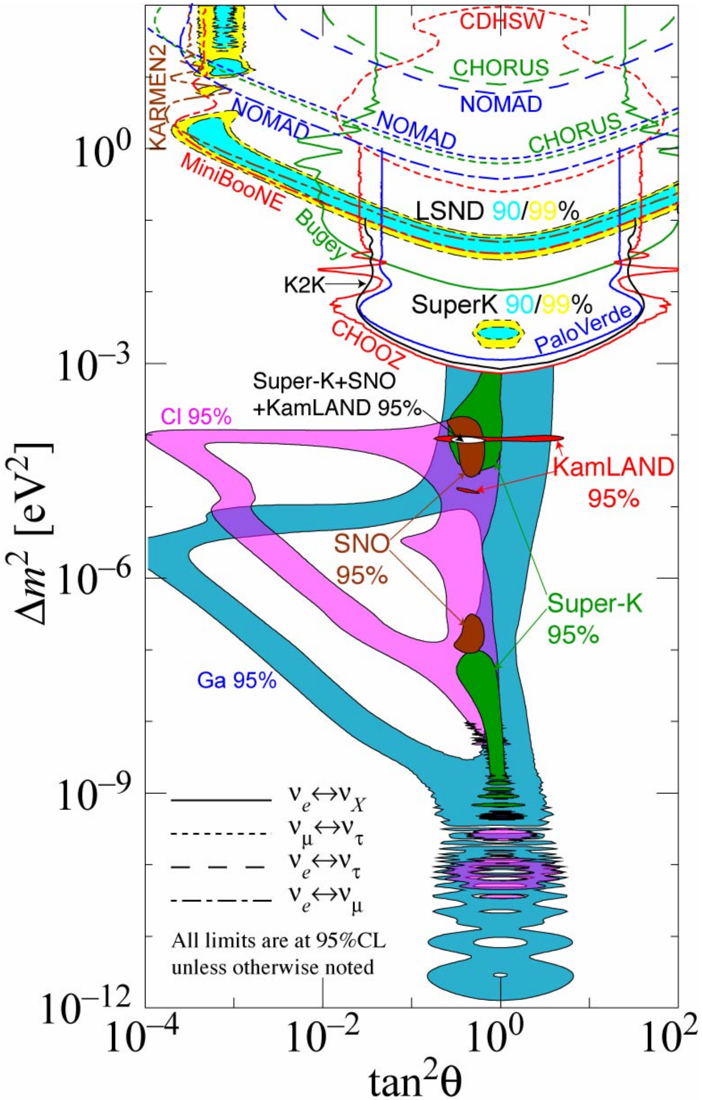
$$\nu_\mu = U_{\mu 1}\nu_1 + U_{\mu 2}\nu_2 + U_{\mu 3}\nu_3 \quad \text{etc.}$$

Flavor States	MNS Maki-Nakagawa-Sakata mixing matrix	Mass eigenstates

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

3 independent parameters
+ 1 complex phase
θ_{12}, θ_{23}, θ_{13}, δ

Subsequent Developments 1998 to Present

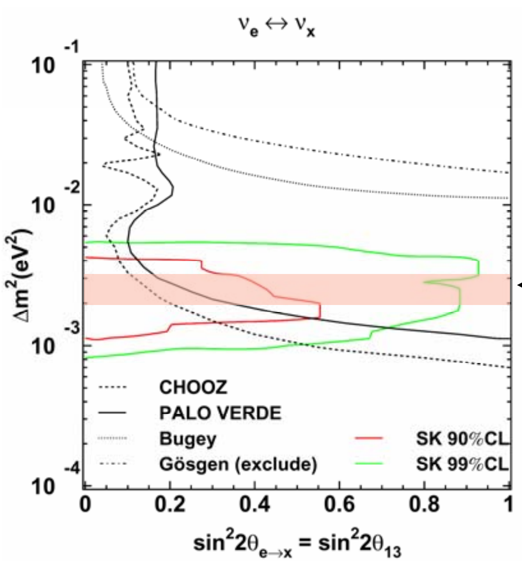


Trying for a complete understanding of the mixing.

Atmospheric ν_μ | Reactor $\overline{\nu}_e$ Accelerator ν_μ | Solar ν_e

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

Where: $C_{23} = \cos\theta_{23}$, etc.



CHOOZ exclusion
90% cl

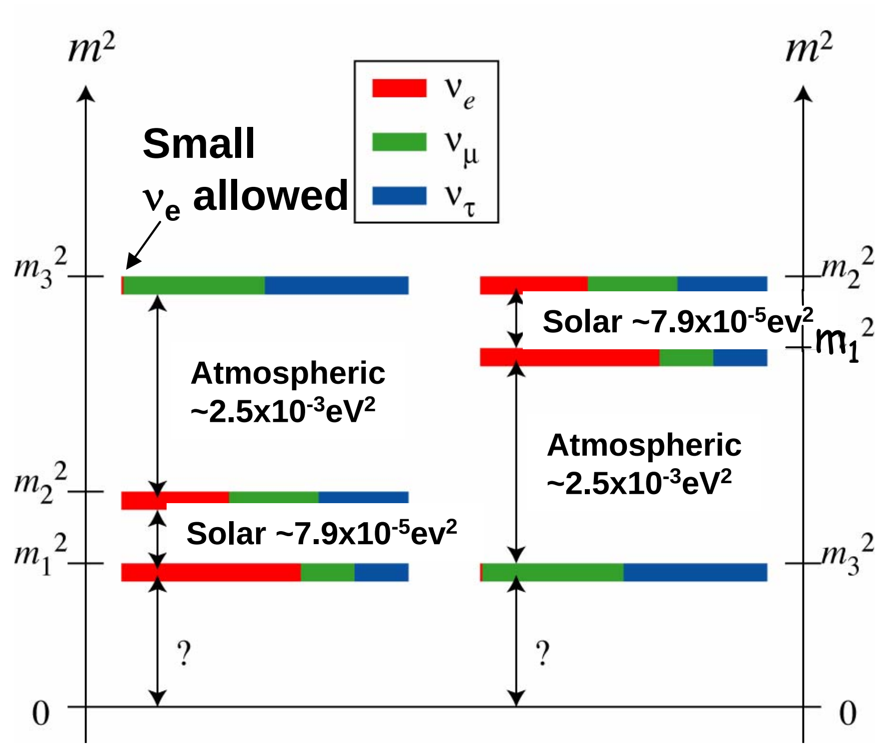
← δm^2_{23} allowed range

@$\delta m^2 = 2.5\times10^{-3}$ ev^2 $\sin^2 2\theta_{13} < 0.16$ or $\theta <$ ~11.5^o

Remaining Questions

LB-L
- Mass hierarchy?
- How small is θ_{13}?
- CP Violation?

ββ
- Absolute mass scale?
- Dirac or Majorana?



Long Baseline Physics Program

LONGSECTION OF THE HOMESTAKE MINE

Long baseline oscillation experiment can probe remaining unknown parameters.

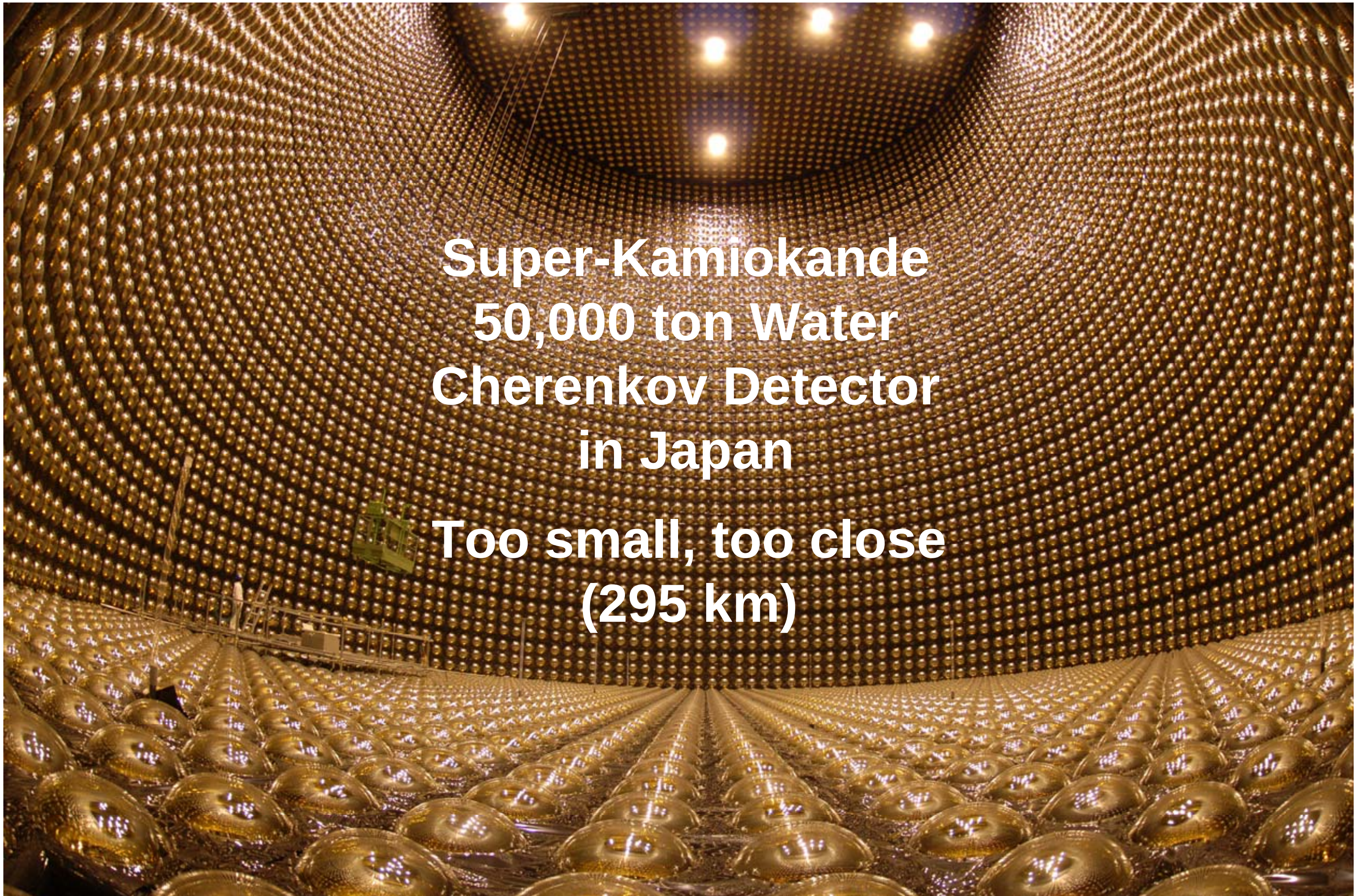
- Neutrino interactions in the Earth probe the hierarchy. Need long travel distance
- CP violation may be observable with intense neutrino and anti-neutrino beams.
  - Signature of CP violation:

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = -16 J_{\alpha\beta} \sin\Delta_{12} \sin\Delta_{23} \sin\Delta_{31}$$

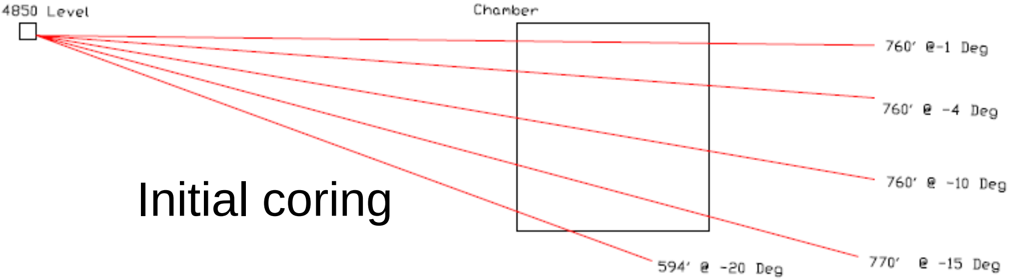
$$J \equiv s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin\delta$$

  - Possible only if θ_{13} large enough
  - Rates are low, need very large detectors.

Sample Detector

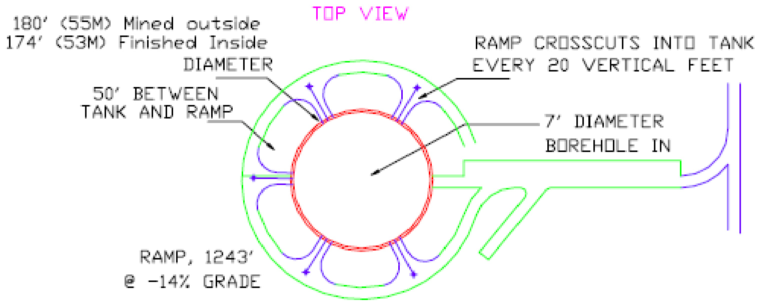


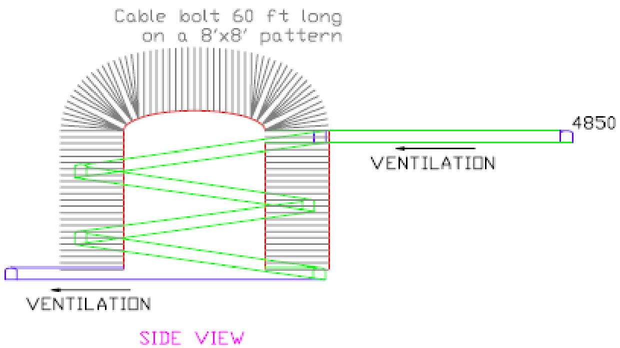
Modular Detector Design @ Homestake



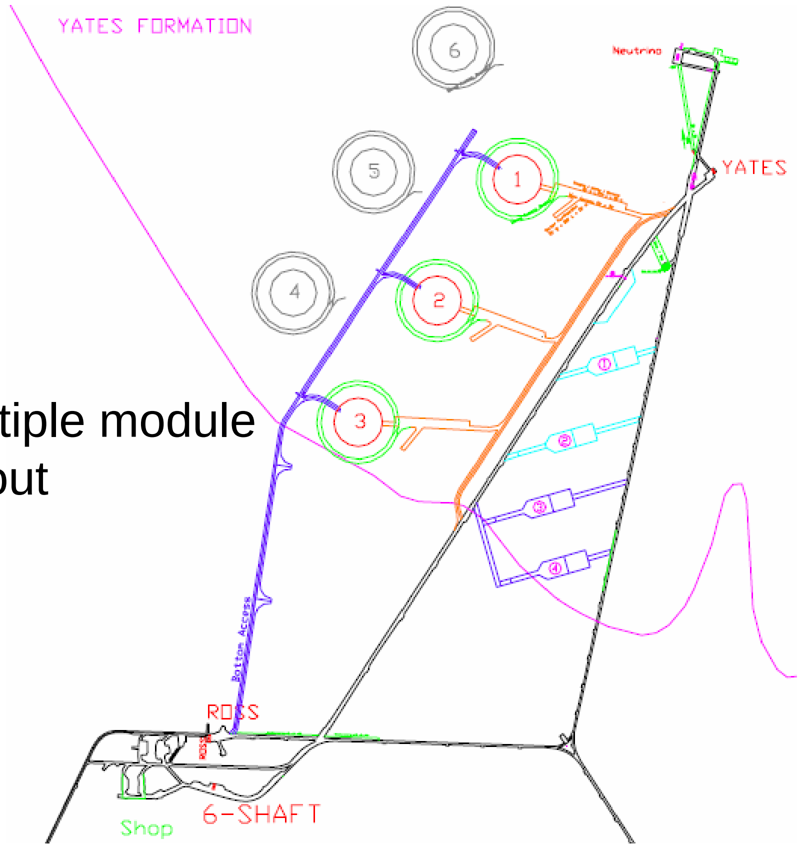
Initial coring

Design by Homestake Chief Engineer





Single 130,000 ton Module construction



Multiple module layout

Neutrino Beam From Fermilab

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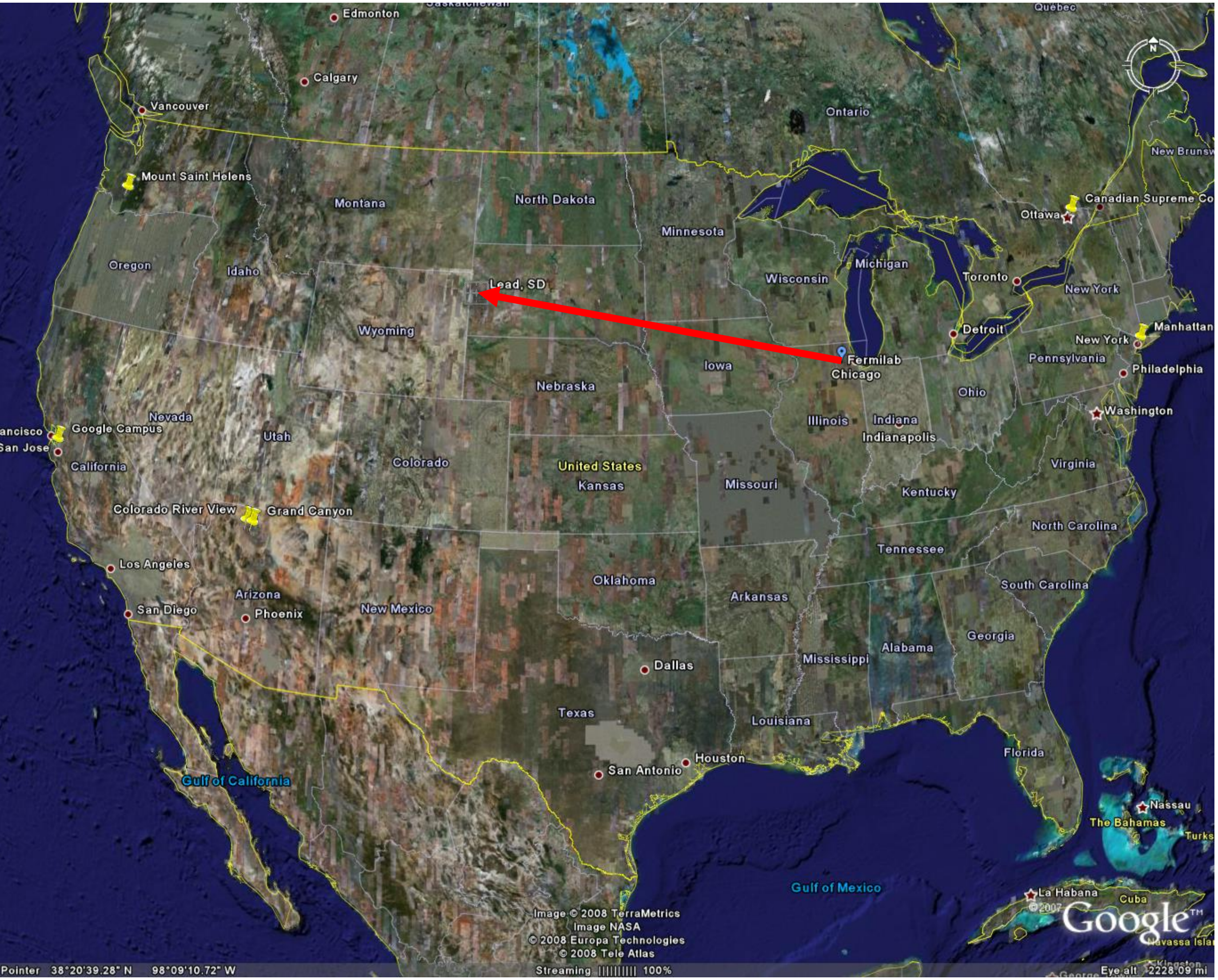
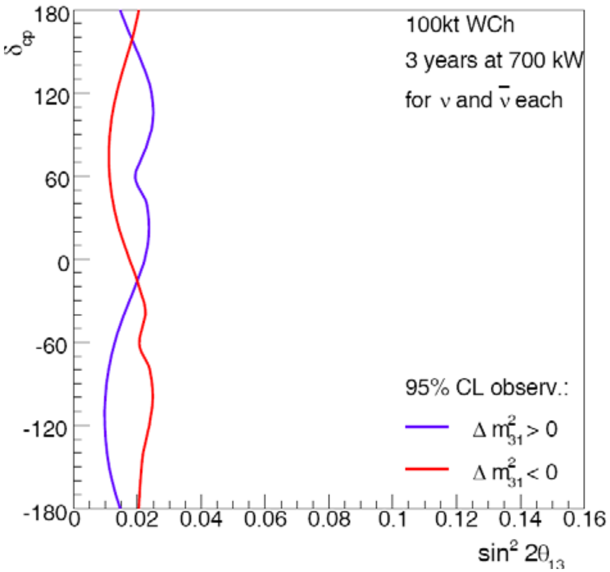
1300 km Beam Travel



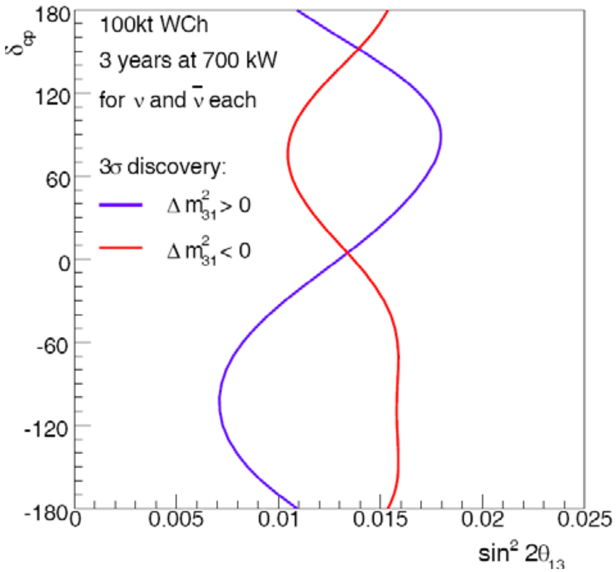
Fermilab (L ~ 1300 km)
700 kw @ 120 GeV →
~6x10[20] POT/year
Will have this by 2012

Then Project X:
2.3 Mw @60-120 GeV
Could be by 2015

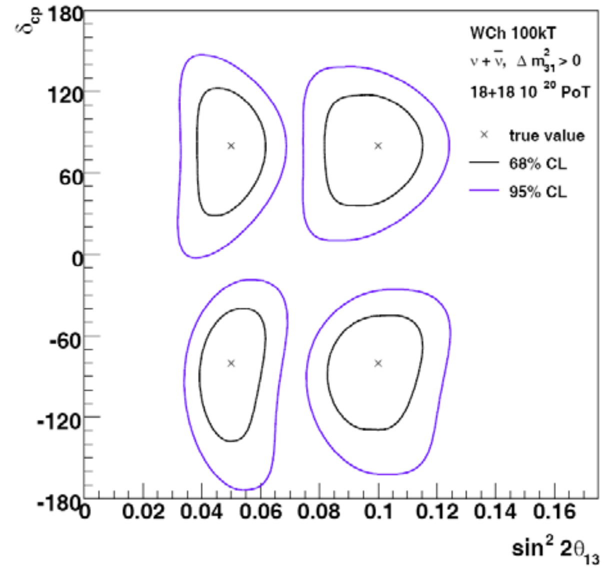
Sensitivity



Hierarchy

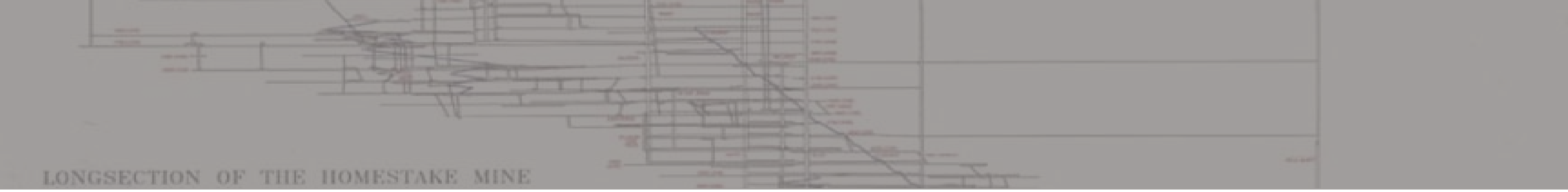


θ_{13}



CP Violation

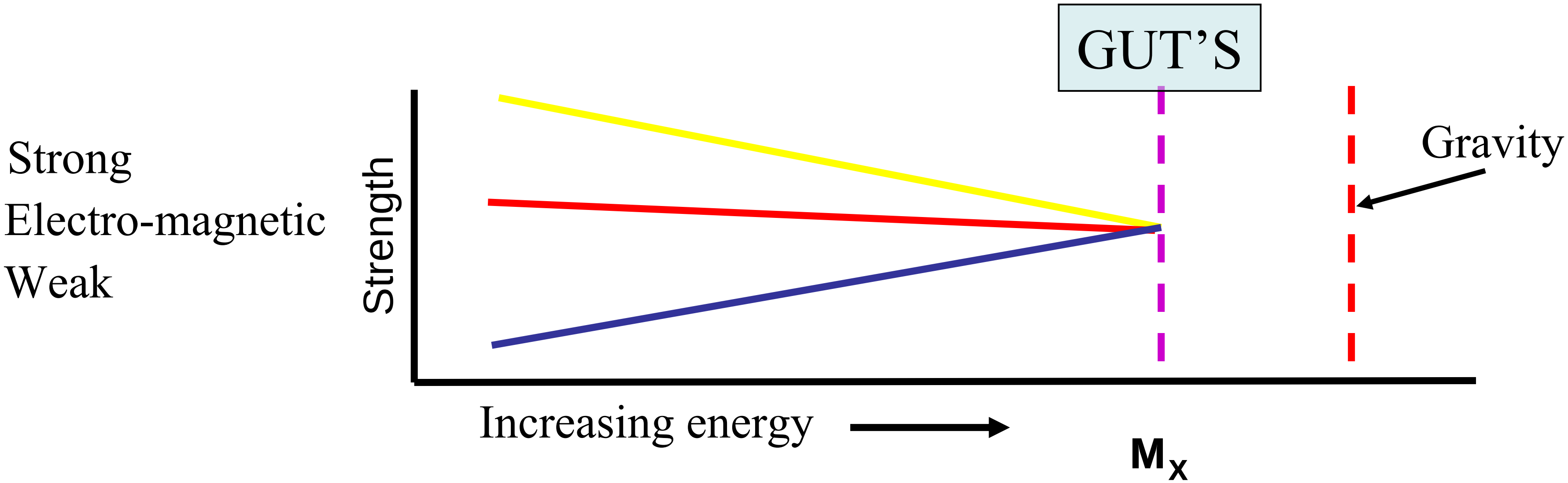
Initial sensitivity of 100 kt detector



Nucleon Decay

Grand Unification

General idea:
All forces are manifestations of a single force perhaps with only one strength.



Proton decay is a generic prediction of most unified theories

- The study of neutrino mass and nucleon stability is a probe of high energy physics beyond the reach of any current or future accelerator

SU(5) GUT

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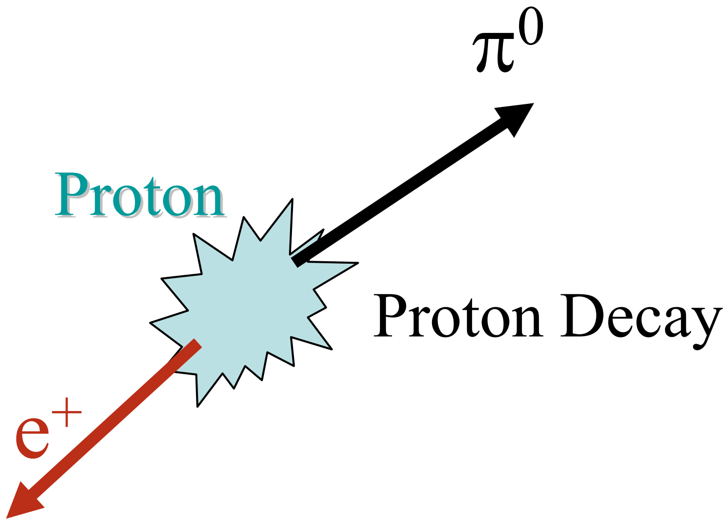
- Early SU(5) predicted:
  - lifetime ~ $10^{29 +/- 2}$ yr
  - 40-60% $p \rightarrow e^{+} p^{0}$
- Requires comparable number of protons
  - (~$6x10^{29}$ nucleons/ton)



First Dedicated Detector - IMB

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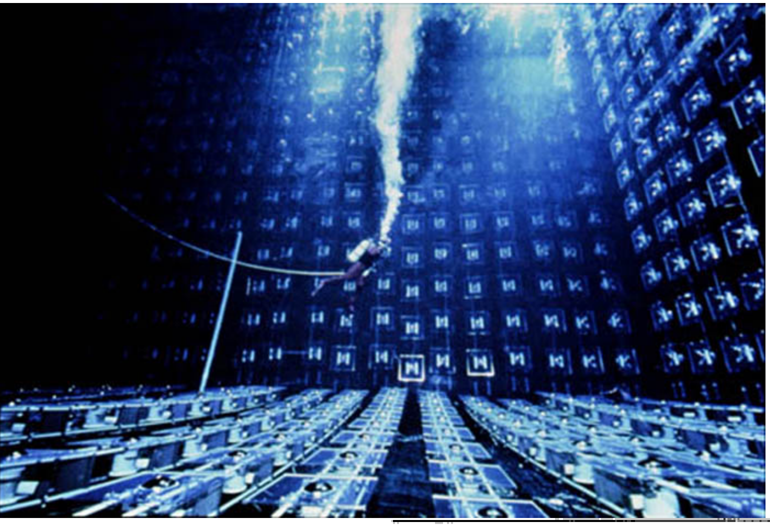

8kton detector

1570 mwe

~2×10^{33} nucleons in fv

(3.3kt)

1983:
$\tau/\beta > 6.5\times10^{31}$ yr

PHYSICAL REVIEW LETTERS 4 JULY 1983

Search for Proton Decay into $e^+\pi^0$

R. M. Bionta, G. Blewitt, C. B. Bratton, B. G. Cortez,[a] S. Errede, G. W. Forster,[a] W. Gajewski, M. Goldhaber, J. Greenberg, T. J. Haines, T. W. Jones, D. Kielczewska,[b] W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, P. V. Ramana Murthy,[c] H. S. Park, F. Reines, J. Schultz, E. Shumard, D. Sinclair, D. W. Smith,[d] H. W. Sobel, J. L. Stone, L. R. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

The University of California at Irvine, Irvine, California 92717, and The University of Michigan, Ann Arbor, Michigan 48109, and Brookhaven National Laboratory, Upton, New York 11973, and California Institute of Technology, Pasadena, California 91125, and Cleveland State University, Cleveland, Ohio 44115, and The University of Hawaii, Honolulu, Hawaii 96822, and University College, London WC1E 6BT, United Kingdom

(Received 13 April 1983)

Observations were made 1570 meters of water equivalent underground with an 8000-metric-ton water Cherenkov detector. During a live time of 80 d no events consistent with the decay $p\to e^+\pi^0$ were found in a fiducial mass of 3300 metric tons. It is concluded that the limit on the lifetime for bound plus free protons divided by the $e^+\pi^0$ branching ratio is $\tau/B > 6.5\times10^{31}$ yr; for free protons the limit is $\tau/B > 1.9\times10^{31}$ yr (90% confidence). Observed cosmic-ray muons and neutrinos are compatible with expectations.

PACS numbers: 13.30.Eg, 11.30.Ly, 14.20.Dh

Extensions to SU(5) and Supersymmetry

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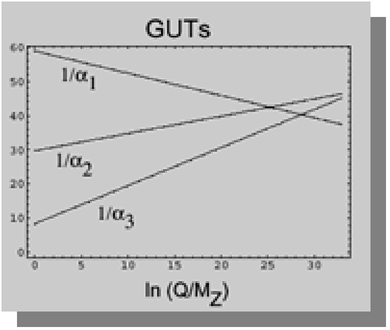
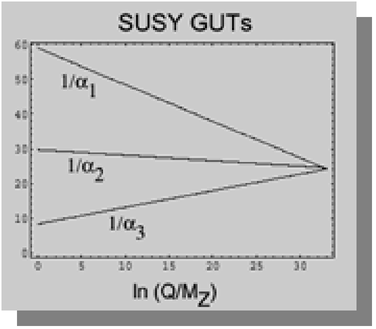
- Since the time of IMB, a wide variety of alternative GUTs have been developed including:
  - assumption that fundamental symmetry is bigger than SU(5).

Possibility of supersymmetry





Some attractive models stress connection between neutrino masses, mixing and proton decay.

=> New modes of decay and longer lifetimes.

Some Current Limits and Predictions

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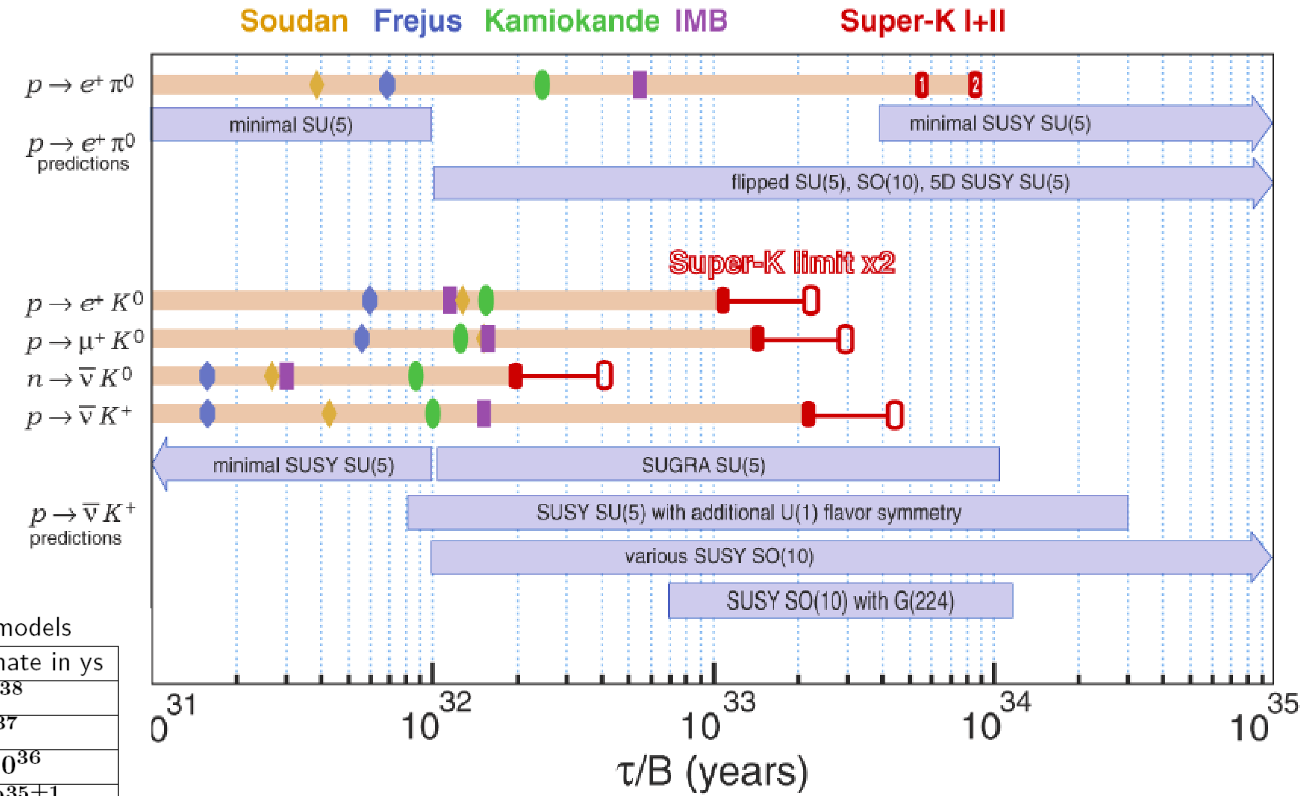

Lifetime estimates for $p \to e^+\pi^0$ for various models

Ref	Model	Lifetime estimate in ys
LMPR	Non-SUSY GUTs	10^{33-38}
DP	SU(5)	$\sim 10^{37}$
JH	SUSY GUTs	1.6×10^{36}
JCP	SUSY-SO(10)	$\sim 5 \times 10^{35\pm1}$
HM-R	5D models	$\sim 4 \times 10^{36}$
KR	5D -SO(10)	$\sim 7 \times 10^{33\pm2}$
BCEW	6D models	$\sim 5 \times 10^{34\pm1}$
KW	D-brane models	$(0.8 - 1.9) \times 10^{36}$
PR	Black holes, worm holes	$\sim 10^{45}$

Proton lifetime estimates for $p \to \bar{\nu}K^+$ for various models

	Model	Lifetime/ys
BPS, EW, DMN	SUSY SU5)	$\sim 10^{34}$
BPW	SUSY SO(10)	$(1/3 - 2) \times 10^{34}$
LR	SUSY SO(10)	$(6.6 - 3 \times 10^2) \times 10^{33}$
DMM, NS	SUSY GUTs	$\geq (2 - 3) \times 10^{33}$
AN	Calabi-Yau Strings	$\sim 10^{34-35}$

Large Detector Depth

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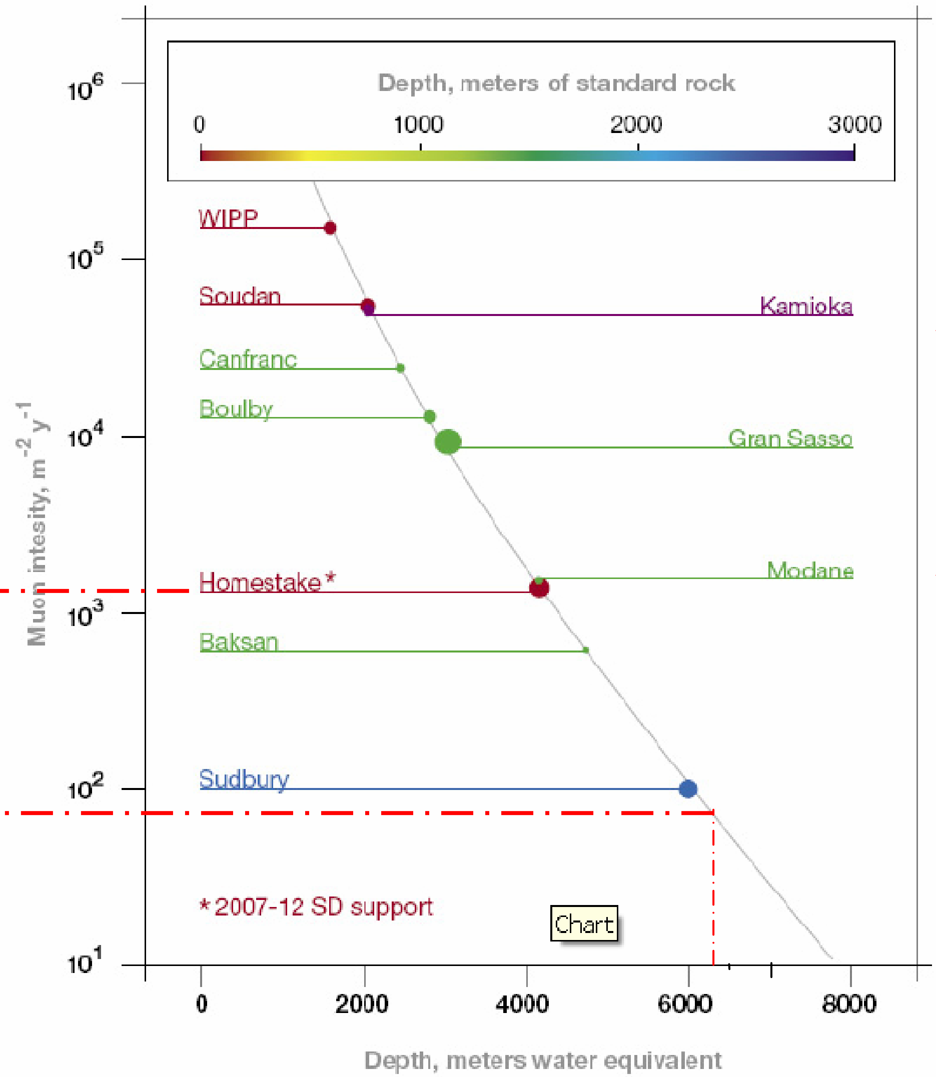
4850’ Campus

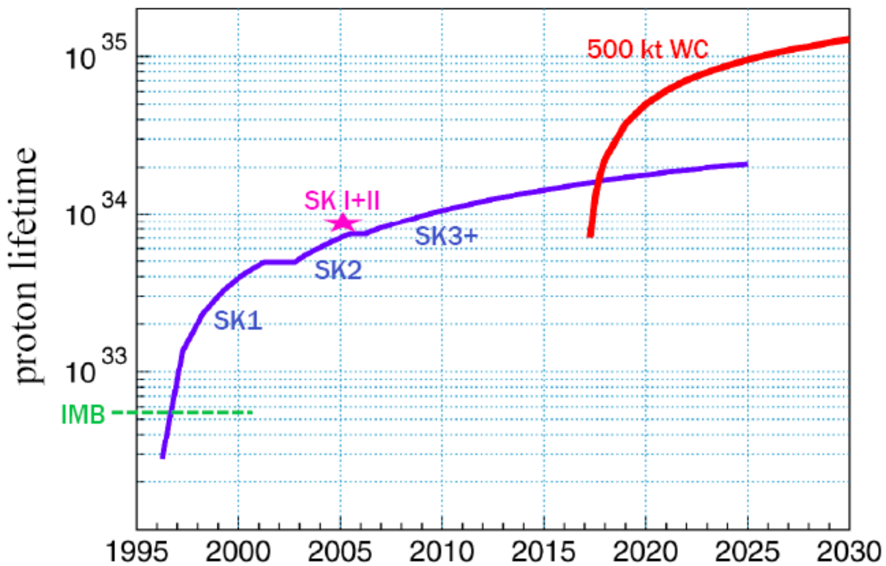
7400’ Campus



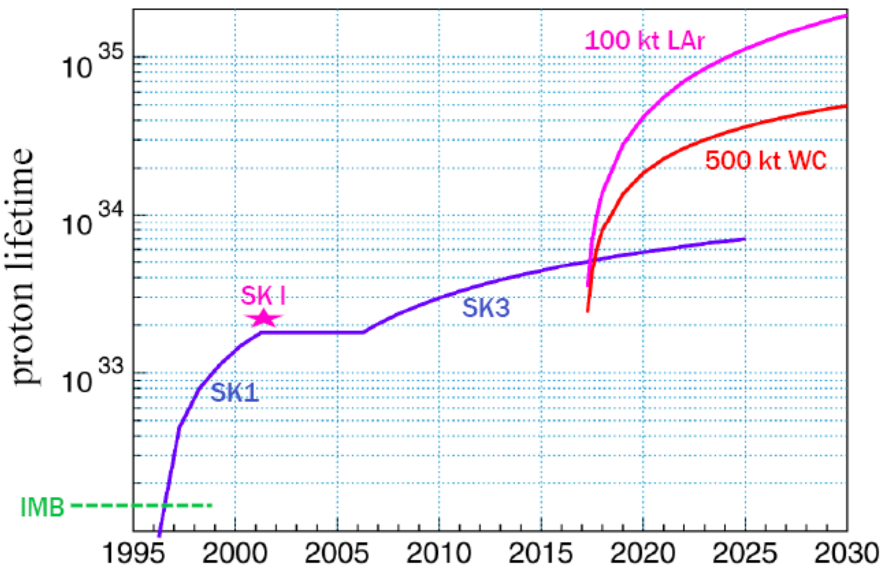
~factor of 100 less muon background than S-K

Sensitivity vs. Time

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

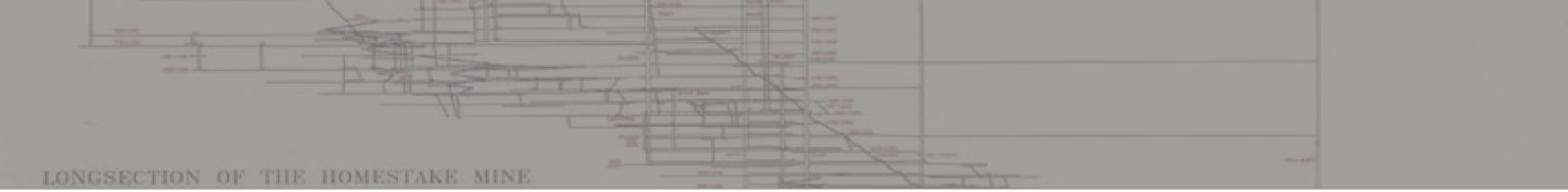


$$p \rightarrow K^+ \nu$$



Water Cherenkov detectors can do both
$e^+\pi^0$ and νK^+

Liquid Argon detectors not competitive for $e^+\pi^0$
but more sensitive per unit volume for νK^+



The Direct Detection of Dark Matter

Breakthroughs in cosmology have transformed our understanding of the Universe.

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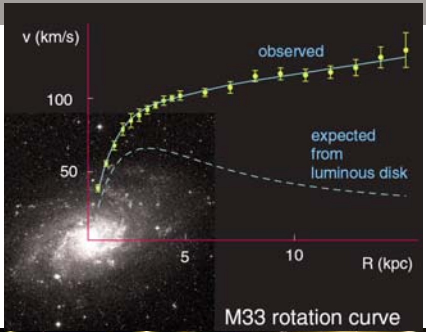
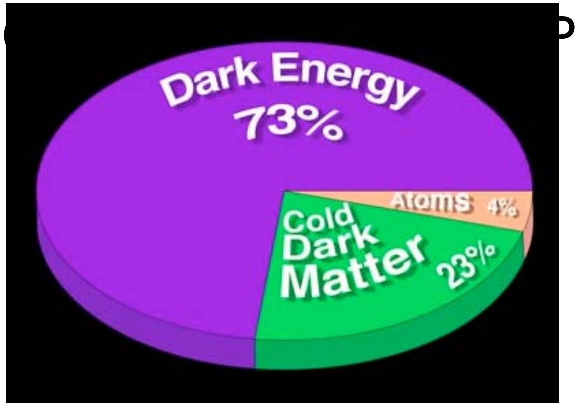
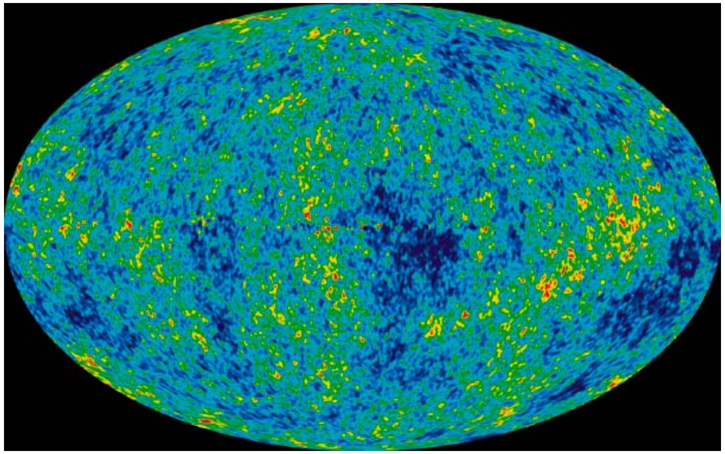
- Spiral galaxies
    - rotation curves
- Clusters & Superclusters
    - Weak gravitational lensing
    - Strong gravitational lensing
    - Galaxy velocities
    - X rays
- Large scale structure
    - Structure formation





Evidence for Dark matter now overwhelming – amount becoming precisely known



Despite this progress, the identity of dark matter remains a mystery

- Constraints on dark matter properties ⇨ the bulk of dark matter cannot be any of the known particles.
  - One of the strongest pieces of evidence that the current theory of fundamental particles and forces, is incomplete.
- Because dark matter is the dominant form of matter in the Universe, an understanding of its properties is essential to attempts to determine how galaxies formed and how the Universe evolved.
  - Dark matter therefore plays a central role in both particle physics and cosmology, and the discovery of the identity of dark matter is among the most important goals in basic science today.

Dark Matter

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What we know:

- How much:

  $\Omega_{DM} = 0.23 \pm 0.04$
- What it's not:

  Not short-lived: $\tau > 10^{10}$ years

  Not baryonic: $\Omega_B = 0.04 \pm 0.004$

  Not hot: "slow" DM is required to form structure

What we don't know:

- Mass?
- Spin?
- Other quantum numbers and interactions?
- Absolutely stable?
- One particle species or many?
- How produced?
- When produced?
- Why does Ω_{DM} have the observed value?
- Role in structure formation?
- How distributed now?

The Properties of a Good Dark Matter Candidate

- stable (protected by a conserved quantum number)
- no charge, no color (weakly interacting)
- cold, non dissipative
- relic abundance compatible to observation
- motivated by theory (vs. “ad hoc”)

Dark Matter Candidates

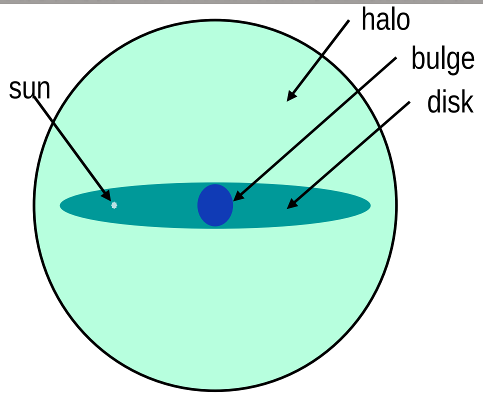
- The theoretical study of dark matter is very well-developed, and has led to many concrete and attractive possibilities.
- Two leading candidates for dark matter are Axions and weakly-interacting massive particles (WIMPs). These are well-motivated, not only because they resolve the dark matter puzzle, but also because they simultaneously solve longstanding problems associated with the standard model of particle physics.

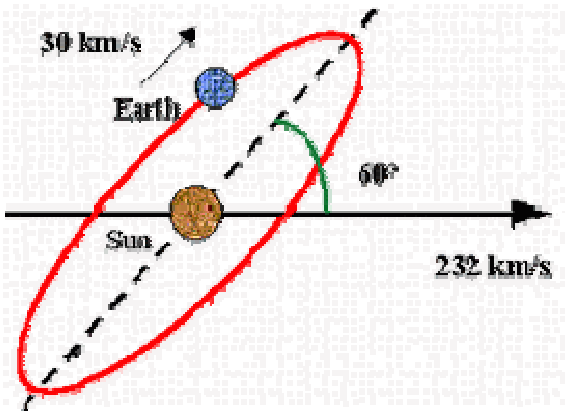
WIMPs

- In many supersymmetric models, the lightest supersymmetric particle is, stable, neutral, weakly-interacting, mass ~ 100 GeV. All the right properties for WIMP dark matter!
- In addition:

Ω_{DM} = 23% ± 4% stringently constrains models

Direct Detection of WIMPs





Dark matter responsible for galaxy formation (including ours).
We are moving through a dark matter halo.

Usually assume spherical distribution with Maxwell-Boltzmann velocity distribution.
V=230 km/s, ρ=0.3 GeV/cm^3

WIMP nucleus scattering rate calculated from theory.
Elastic nuclear scattering: interactions are either spin-dependent or spin-independent.
Low velocity →coherent interaction

Experimental Challenges

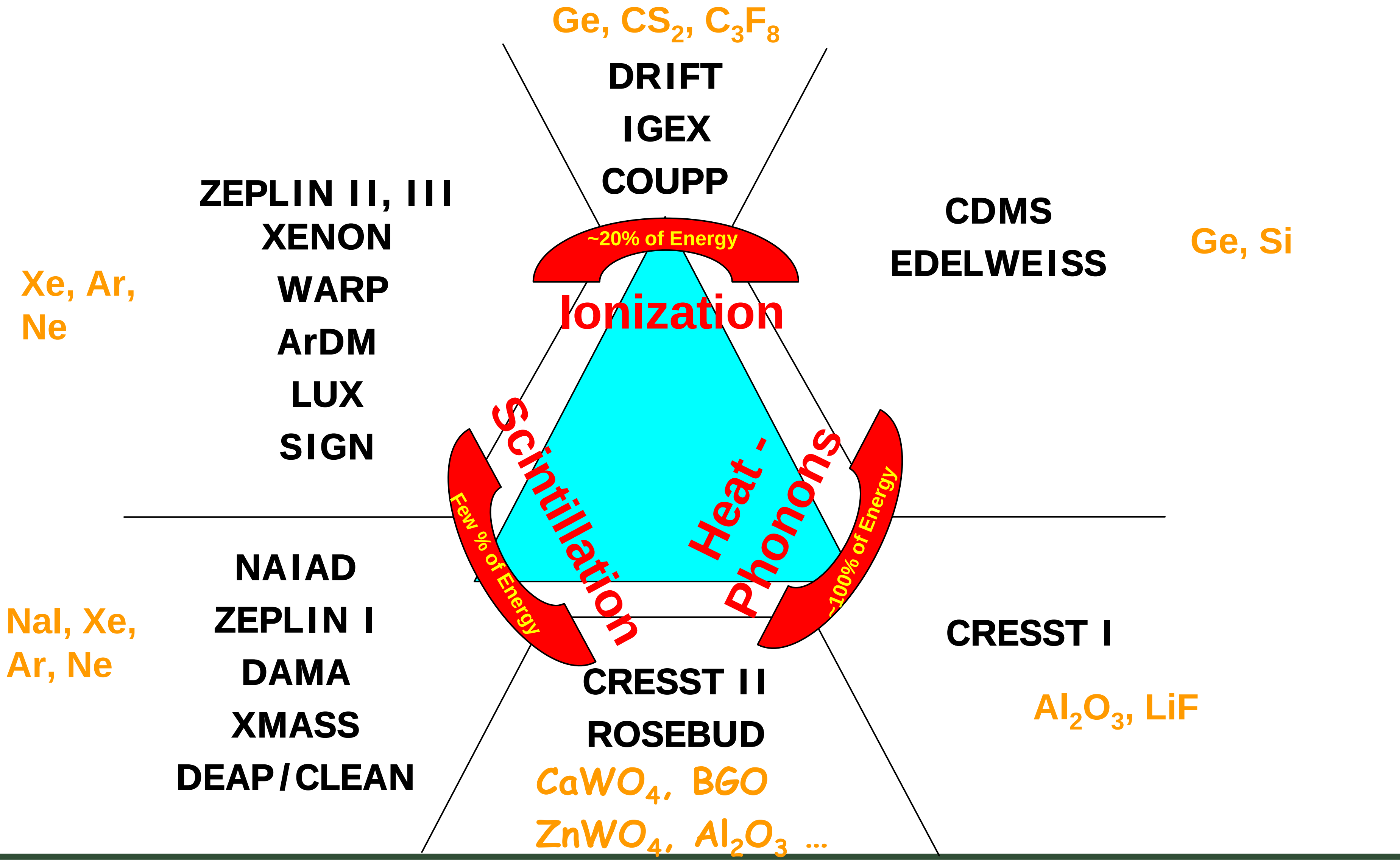
The WIMP "signal" is a low energy (10-100 keV) nuclear recoil.

- Overall expected rate is very small ($\sigma=10^{-42}cm^2$ gives about 1 event/kg/day , limit now $\sigma< 10^{-43}cm^2$, mSUGRA models go to ~ $10^{-46}cm^2$).
- Need a large low-threshold detector which can discriminate against various backgrounds.
  - Photons scatter off electrons.
  - WIMPs and neutrons scatter off nuclei.
- Need to minimize internal radioactive contamination.
- Need to minimize external incoming radiation.
  - Deep underground location

Current State of Experiments

- Rapid advances in detector technology have reached interesting sensitivity limits and should be able to go further.
- Broad spectrum of technologies.
- New ideas, and new collaborations are appearing…

Direct Detection/Discrimination Techniques



CDMS (Brown, Caltech, CWRU, FNAL, LBNL, MIT, Queens, Santa Clara, Stanford, Syracuse, UCB, UCSB, Colorado, Florida, UM, Zurich)

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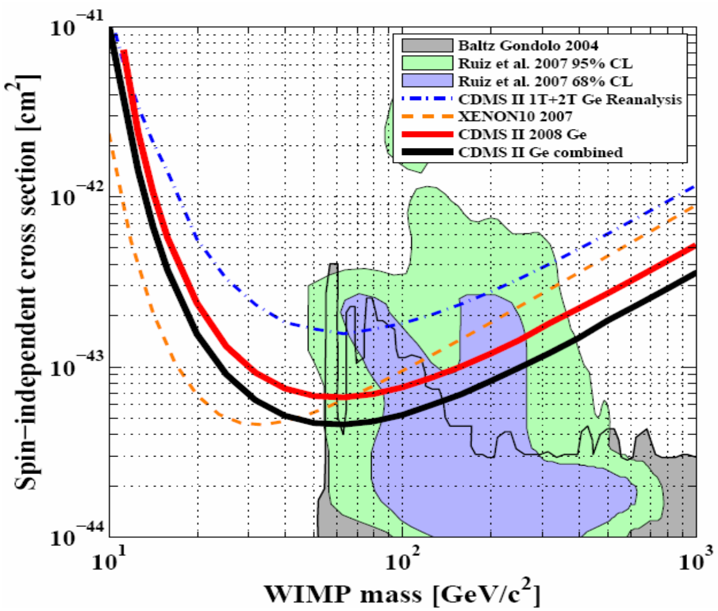
- The Cryogenic Dark Matter Search (CDMS) Collaboration, currently operating in the Soudan mine in Minnesota has pioneered the use of low temperature phonon-mediated Ge or Si crystals.
- A combination of passive and active shielding, phonon and charge energy measurement and phonon pulse timing has produced an almost background-free experiment.



<u>Has been the Gold-Standard for many years</u>

- Pre-DUSEL plans for 25kg in SNOLab
- Earliest operation FY09
- SuperCDMS one-Tonne for DUSEL

New Technologies

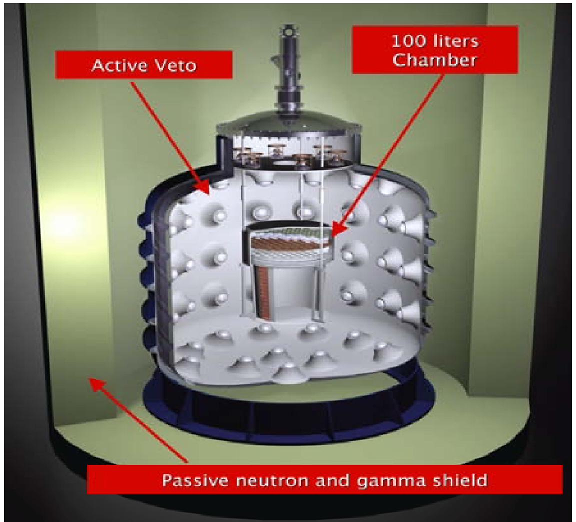
- The field has been energized by the emergence of noble liquids (argon, xenon, neon) in various detector configurations, as well as new ideas for use of warm liquids and various gases under high or low pressure.
- These offer several things, some are:
  - An increased reach in sensitivity by at least three orders of magnitude for WIMP's .
  - The possibility of recoil particle direction measurement.
  - Detector sizes well beyond the ton scale.
- The complementarity of detector capabilities provides:
  - A range of target types suitable for establishing WIMP signature
  - Diverse background control methods (e.g., single phase vs. two-phase in noble liquids; various combinations of multiple signatures).

Noble Liquids

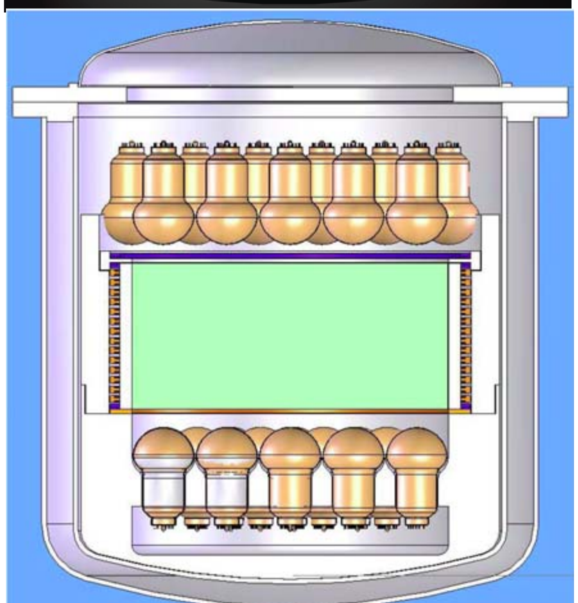
- Relatively inexpensive, easy to obtain, dense target material.
- Easily purified as contaminants freeze out at cryogenic temperatures.
- Very small electron attachment probability.
- Large electron mobility (Large drift velocity for small E-field).
- High scintillation efficiency
- Possibility for large, homogenous detectors.
- Problem - ^{39}Ar, ^{85}Kr

Current Detectors Under Construction

~100 kg Fiducial Volume

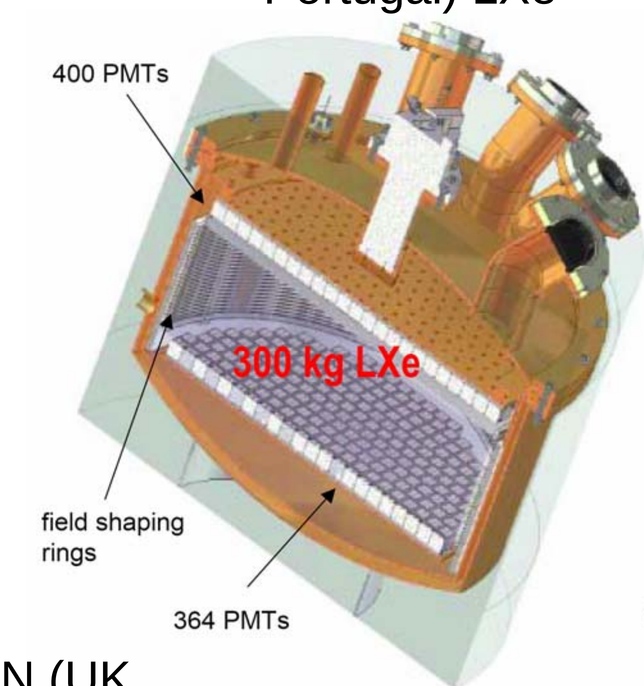


WARP (Italy, U.S., Poland) LAr

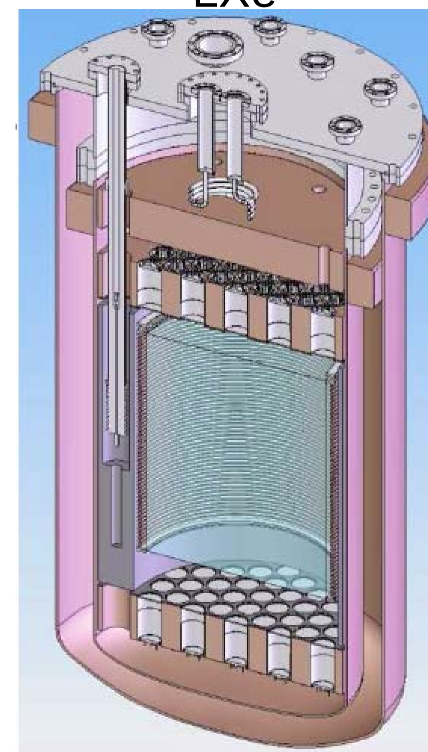


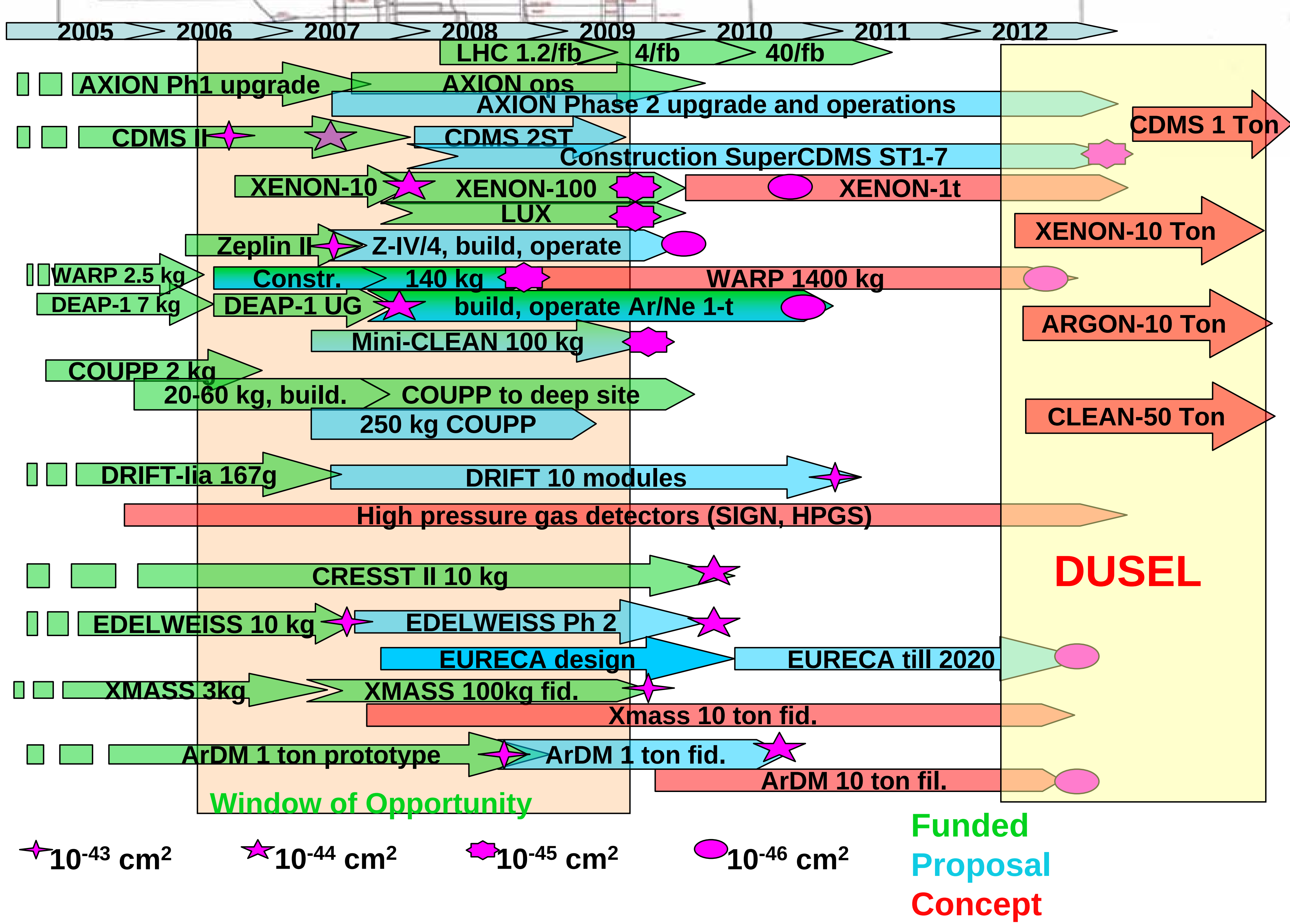
ZEPLIN (UK, U.S.) LXe

XENON-100 (U.S., Germany, Italy, Portugal) LXe

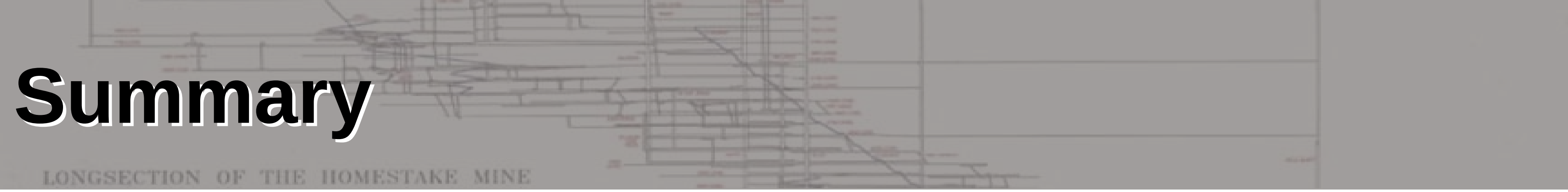


LUX (U.S.) LXe




2005
2006
2007
2008
2009
2010
2011
2012
LHC 1.2/fb
4/fb
40/fb
AXION Ph1 upgrade
AXION ops
AXION Phase 2 upgrade and operations
CDMS 1 Ton
CDMS II
CDMS 2ST
Construction SuperCDMS ST1-7
XENON-10
XENON-100
XENON-1t
LUX
XENON-10 Ton
Zeplin II
Z-IV/4, build, operate
WARP 2.5 kg
Constr.
140 kg
WARP 1400 kg
DEAP-1 7 kg
DEAP-1 UG
build, operate Ar/Ne 1-t
ARGON-10 Ton
Mini-CLEAN 100 kg
COUPP 2 kg
20-60 kg, build.
COUPP to deep site
250 kg COUPP
CLEAN-50 Ton
DRIFT-Iia 167g
DRIFT 10 modules
High pressure gas detectors (SIGN, HPGS)
CRESST II 10 kg
DUSEL
EDELWEISS 10 kg
EDELWEISS Ph 2
EURECA design
EURECA till 2020
XMASS 3kg
XMASS 100kg fid.
Xmass 10 ton fid.
ArDM 1 ton prototype
ArDM 1 ton fid.
ArDM 10 ton fil.
Window of Opportunity
10-43 cm2
10-44 cm2
10-45 cm2
10-46 cm2
Funded
Proposal
Concept

Summary



- DUSEL is a vital component of a continuing neutrino program.
  - The distance from Fermilab and the depth make for a world-leading program.
- The mega-tonne scale detector will significantly advance the search for nucleon decay and evidence for grand unification.
- Dark Matter experiments are growing larger and more sensitive. DUSEL depth, space and infrastructure are necessary components in this program.