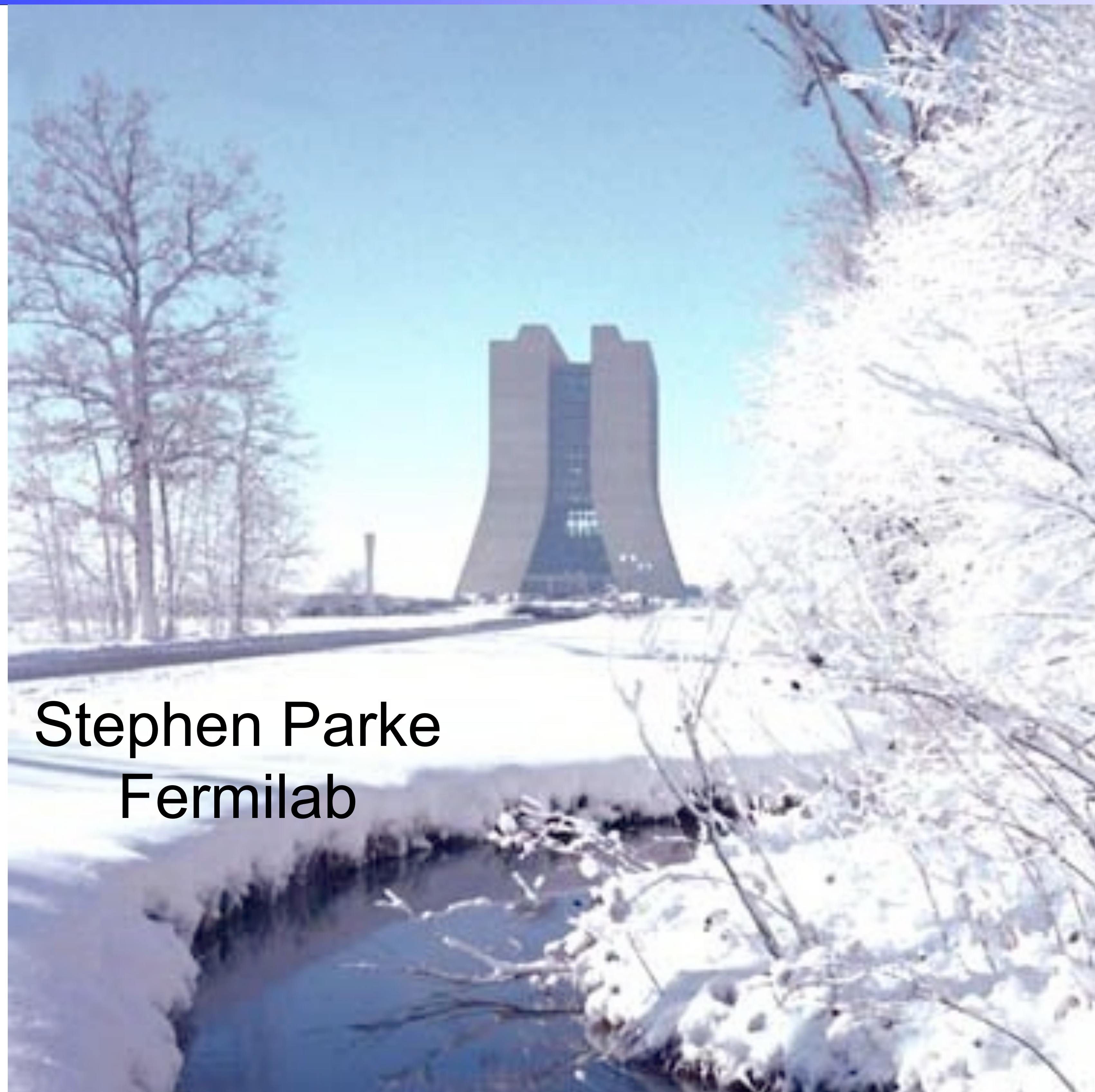
Neutrino SuperBeams at Fermilab



Stephen Parke
Fermilab

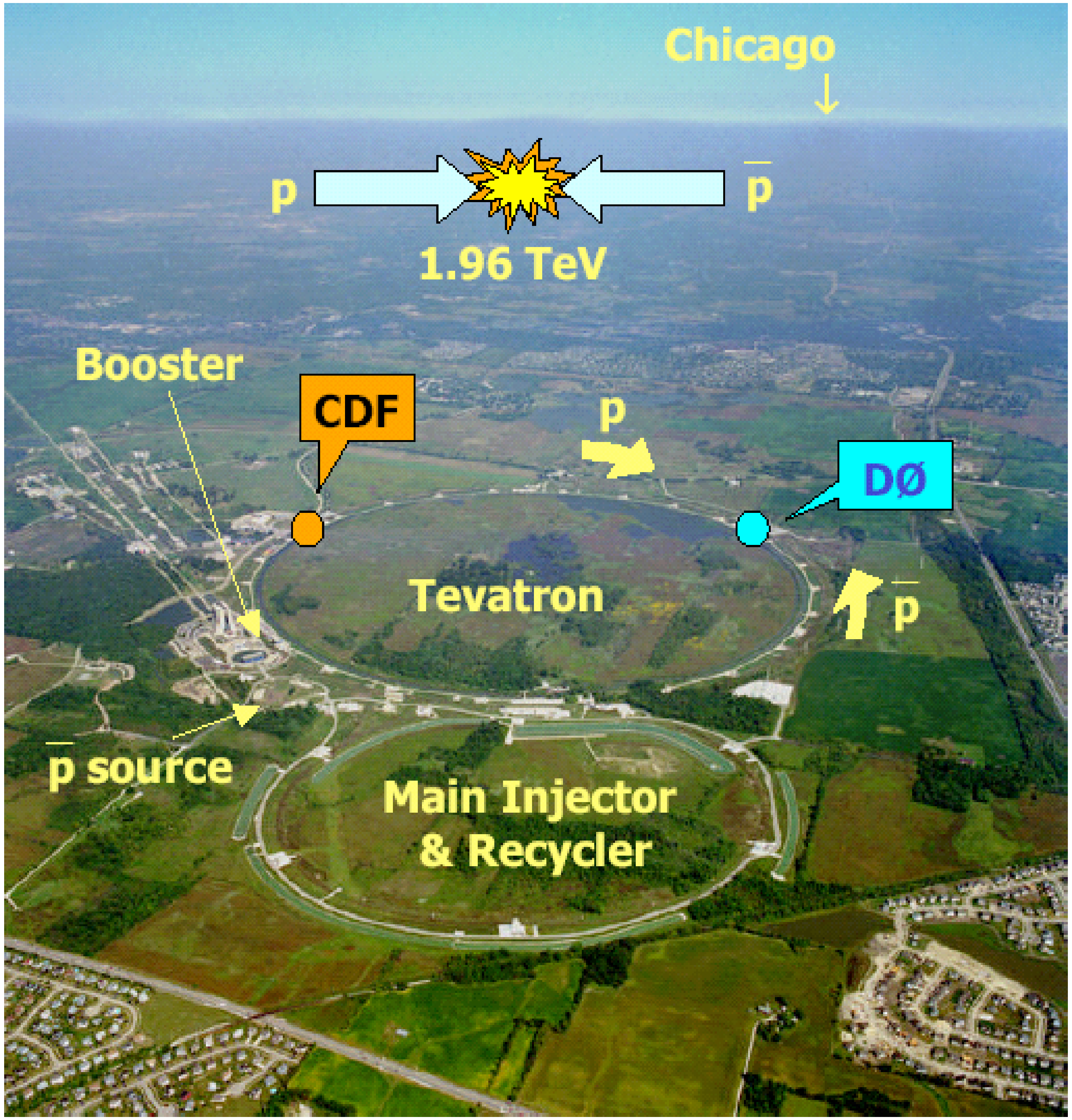
Neutrino SuperBeams at Fermilab

Stephen Parke
Fermilab

Many Thanks to my Colleagues

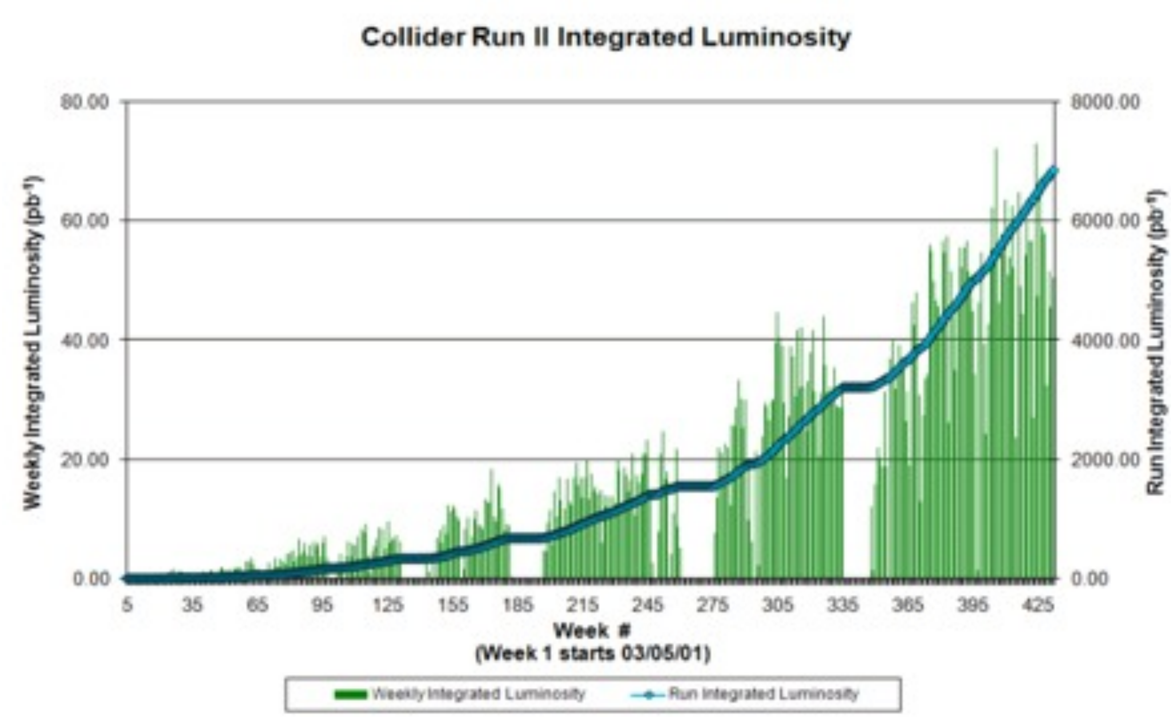

ν's

Tevatron: CDF & D0



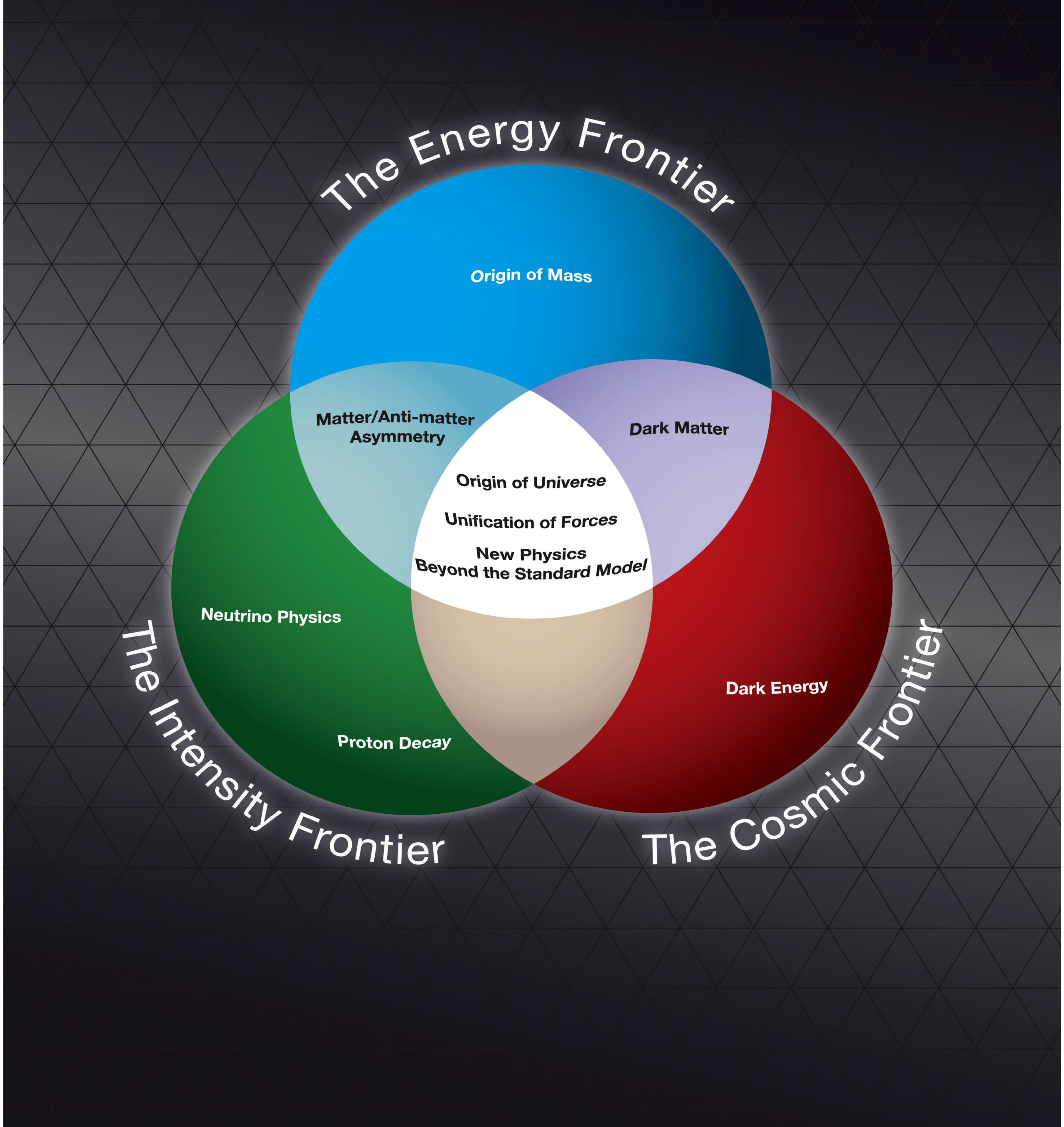
- 36x36 bunches
- bunch crossing 396 ns
- Run II started in March 2001
- Peak Luminosity:3.5E32 cm^{-2} sec^{-1}
- Run II delivered ~10 fb^{-1}

Peak Intergrated Luminosity:
$3.5 \times 10^{32}\ cm^{-2} sec^{-1} \times 3 \times 10^{7} sec \approx 10 fb^{-1}/yr$

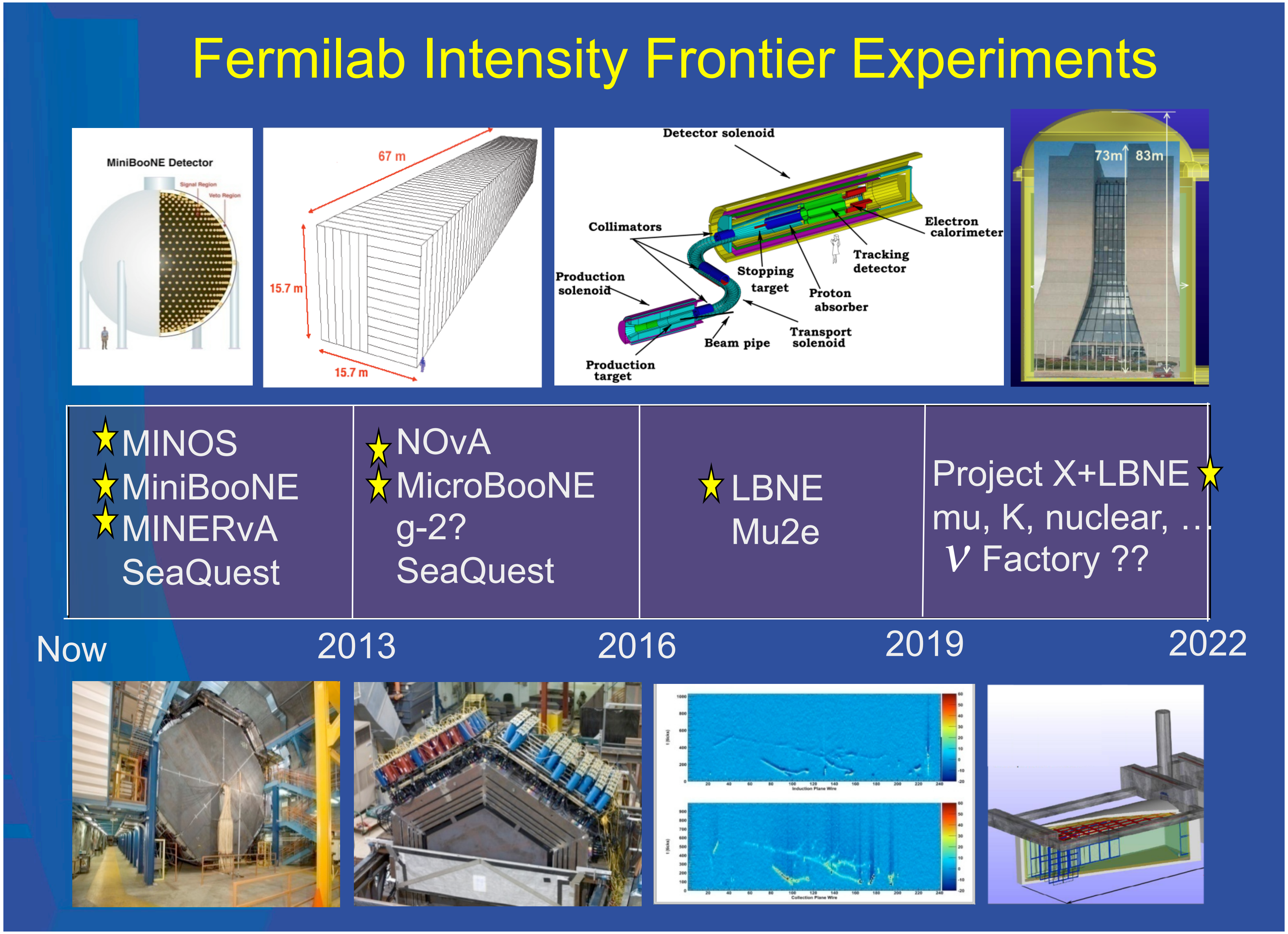


Peak $\bar{p}$ Collection Rate:
$7 \times 10^{7}/sec$

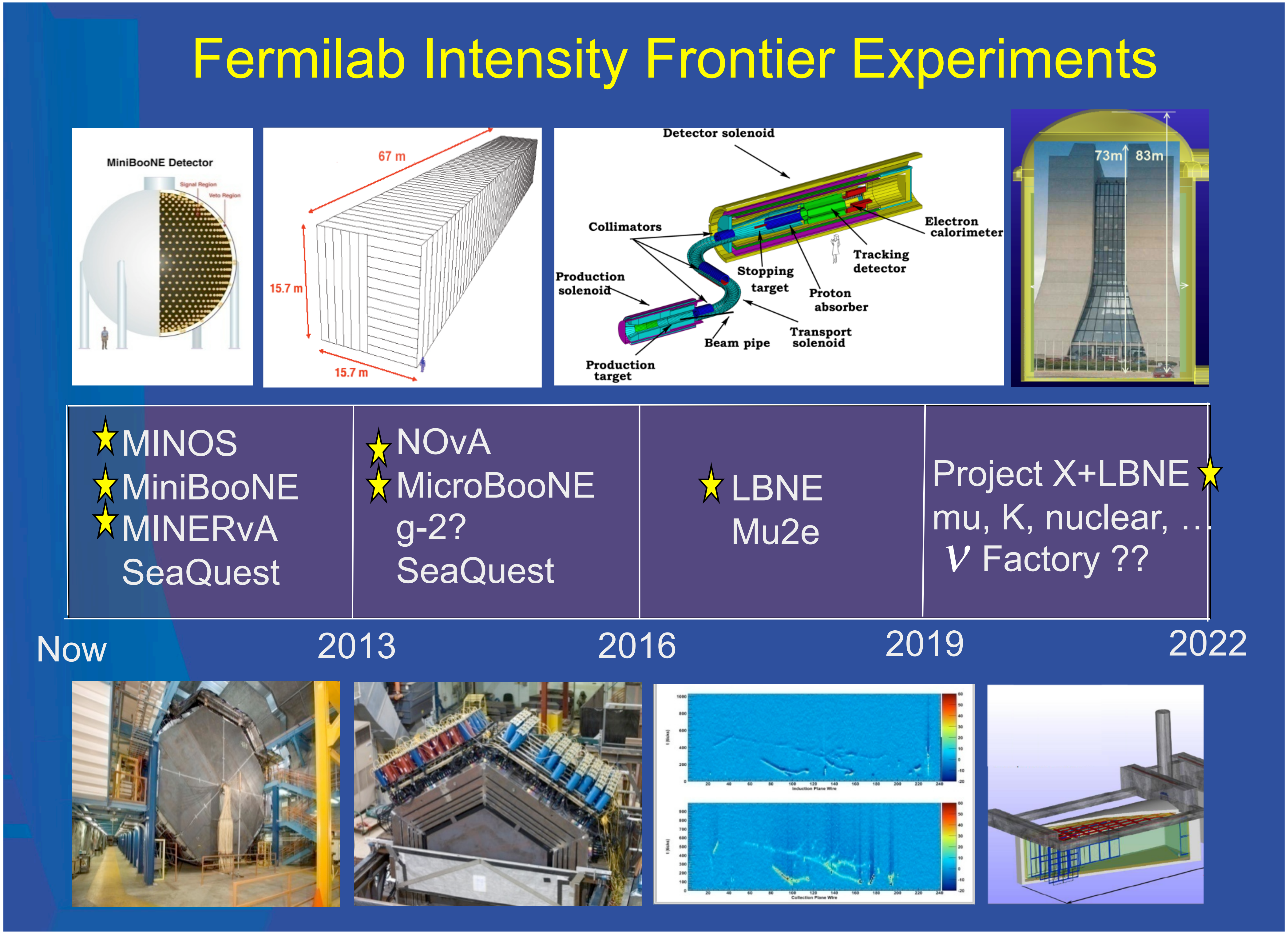
Peak $\bar{p}$ Burn Rate:
$3.5 \times 10^{32}\ cm^{-2} sec^{-1} \times 100\ mb = 3.5 \times 10^{7}/sec$


The Energy Frontier
Origin of Mass
Matter/Anti-matter
Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics
Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
The Intensity Frontier
The Cosmic Frontier

Intensity Frontier:

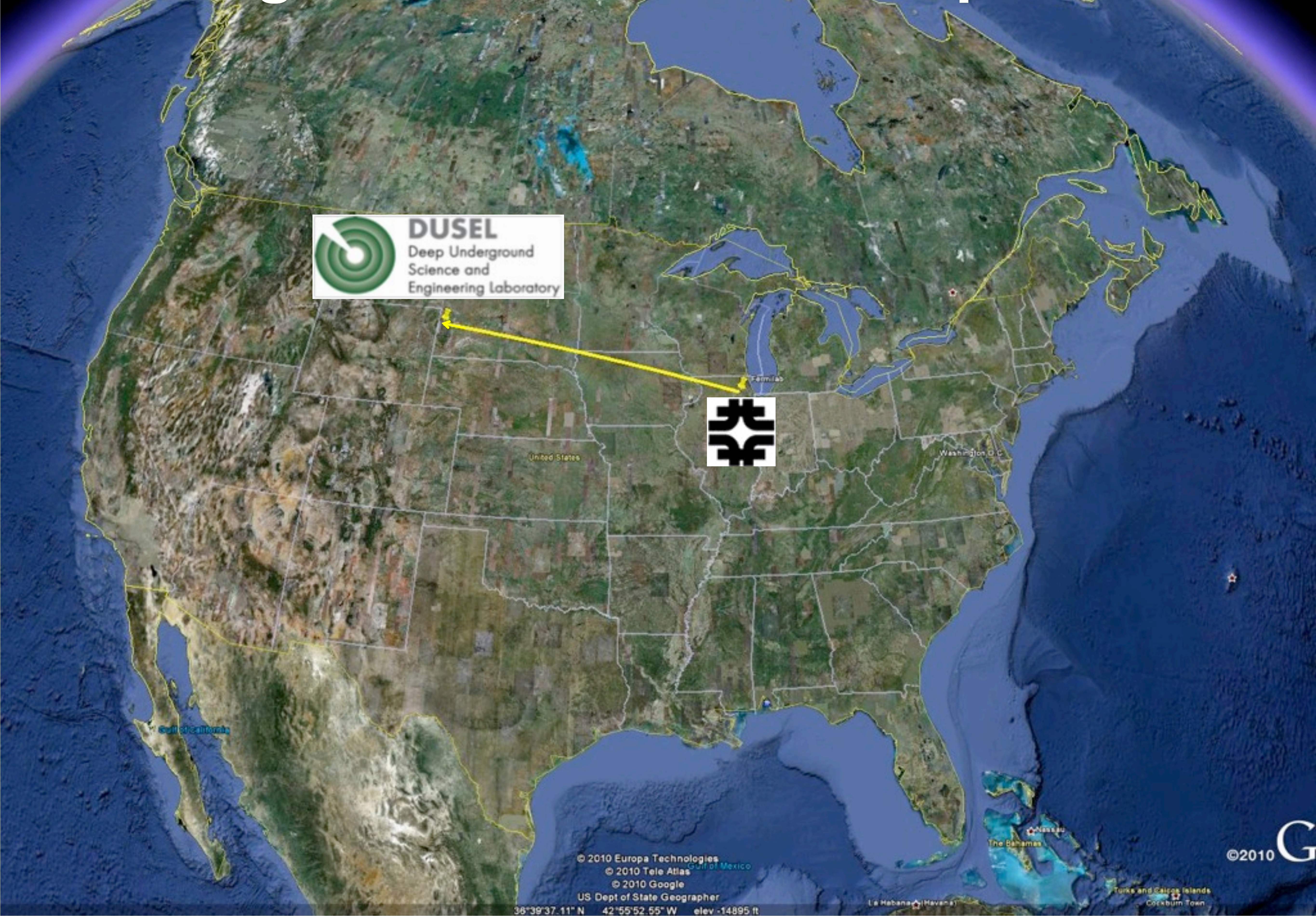


Intensity Frontier:

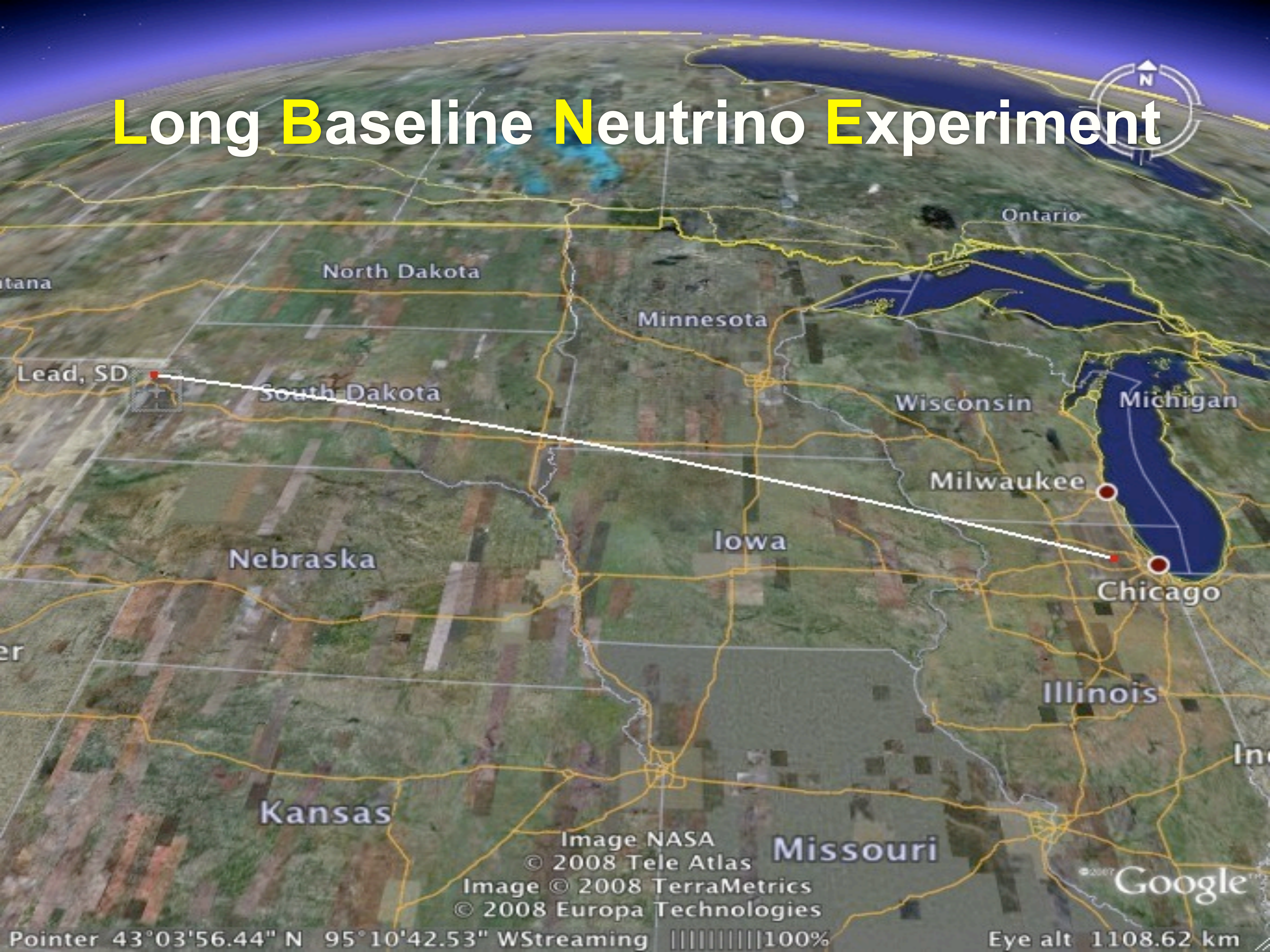


Maybe back to Energy Frontier with Muon Collider

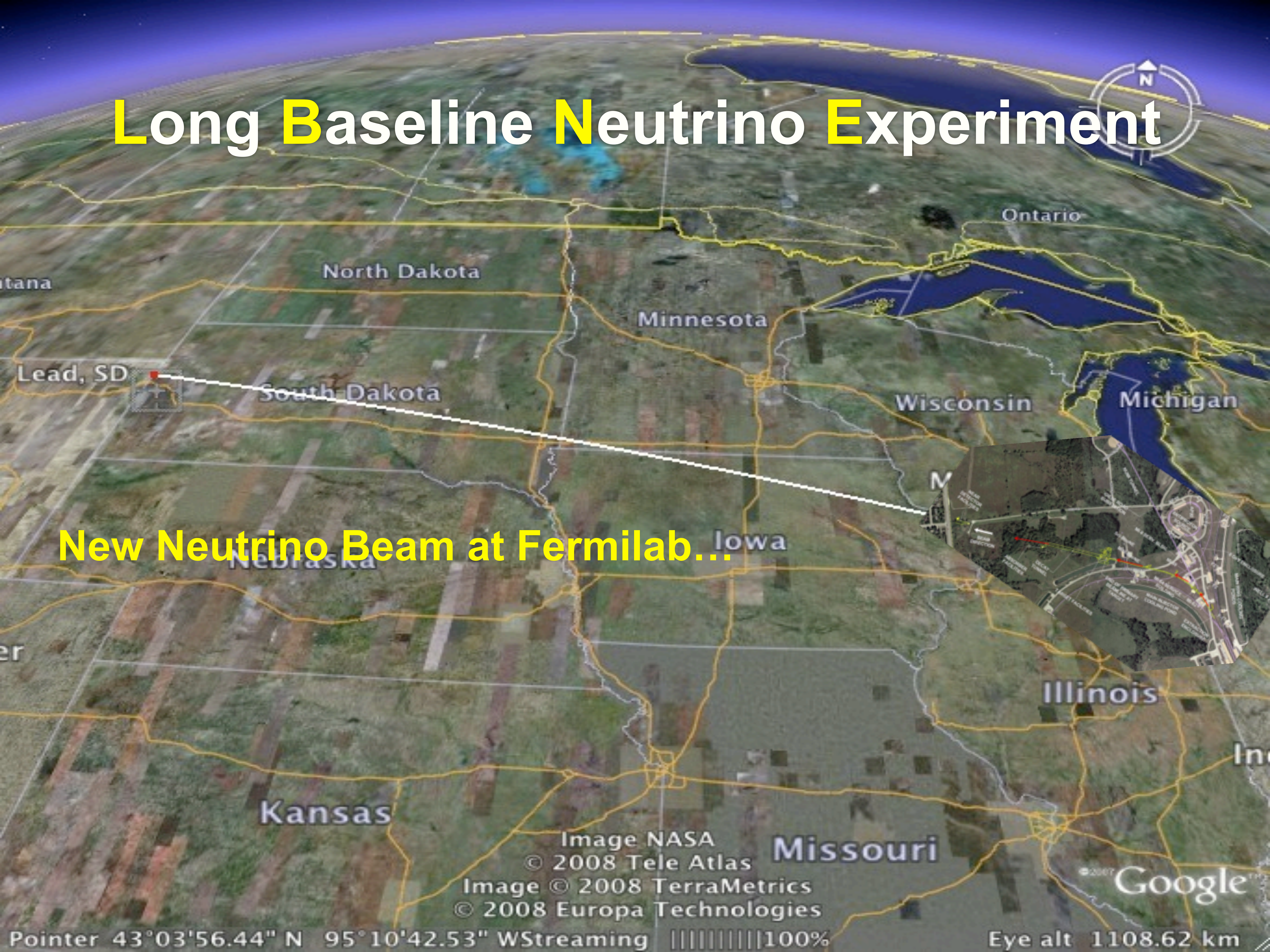
Long Baseline Neutrino Experiment



Long Baseline Neutrino Experiment



Long Baseline Neutrino Experiment



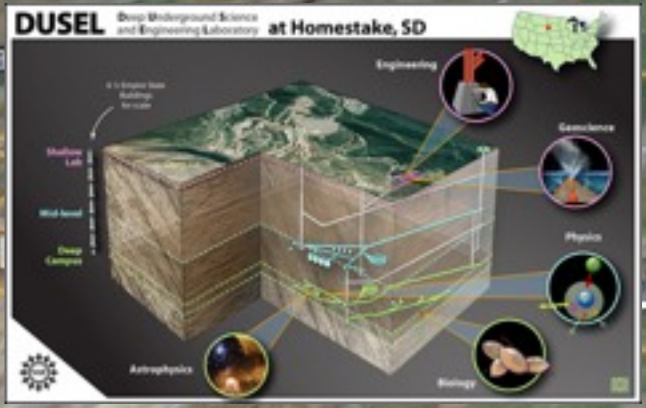
New Neutrino Beam at Fermilab…

Long Baseline Neutrino Experiment

New Neutrino Beam at Fermilab…

…Directed towards NSF's proposed DUSEL

Long Baseline Neutrino Experiment



New Neutrino Beam at Fermilab…

…Directed towards NSF's proposed DUSEL

Precision Near Detector on the Fermilab site

Long Baseline Neutrino Experiment

New Neutrino Beam at Fermilab…

…Directed towards NSF's proposed DUSEL

Precision Near Detector on the Fermilab site

100 kT Water Cherenkov Detector

Long Baseline Neutrino Experiment

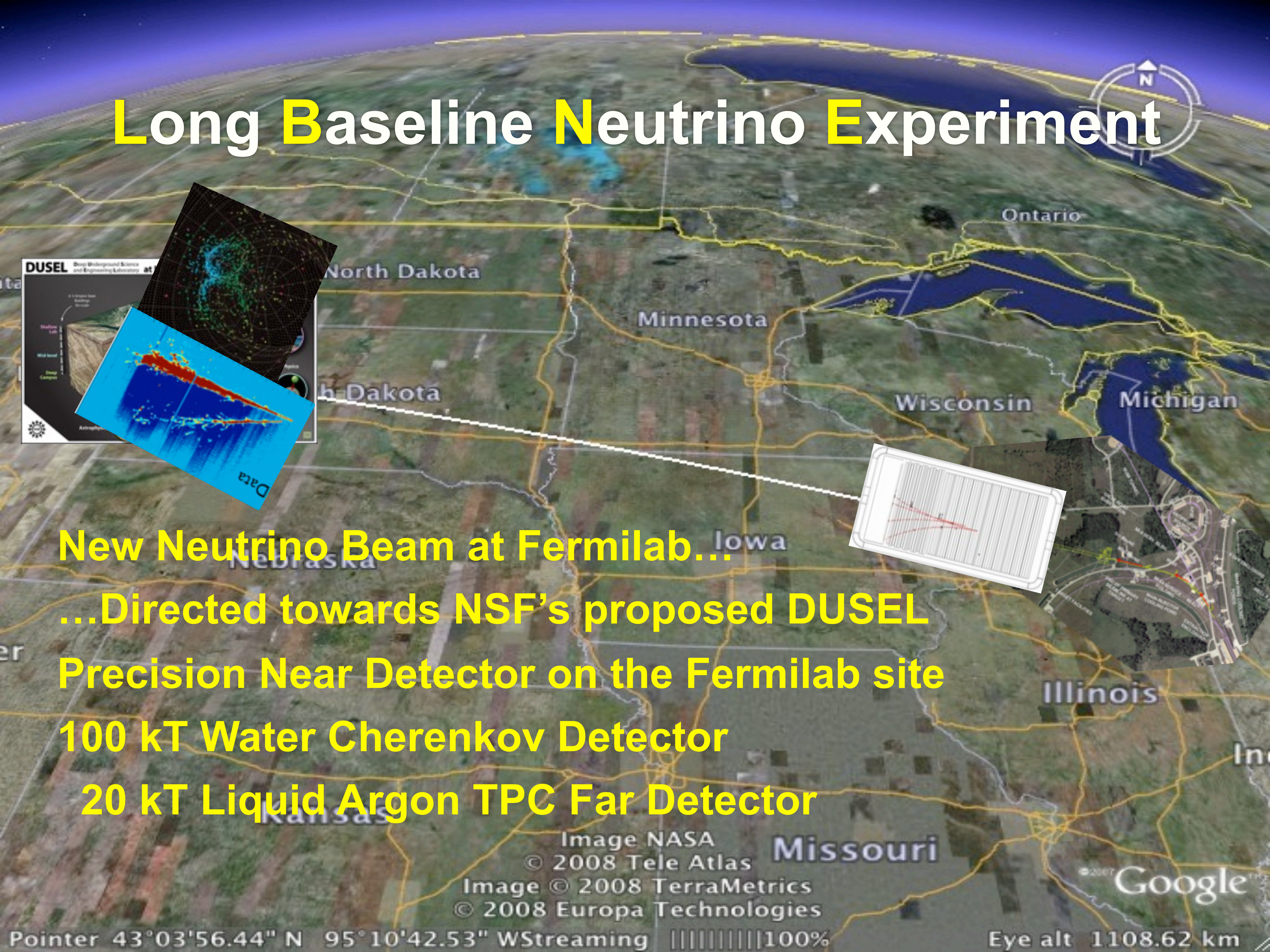
New Neutrino Beam at Fermilab…

…Directed towards NSF's proposed DUSEL

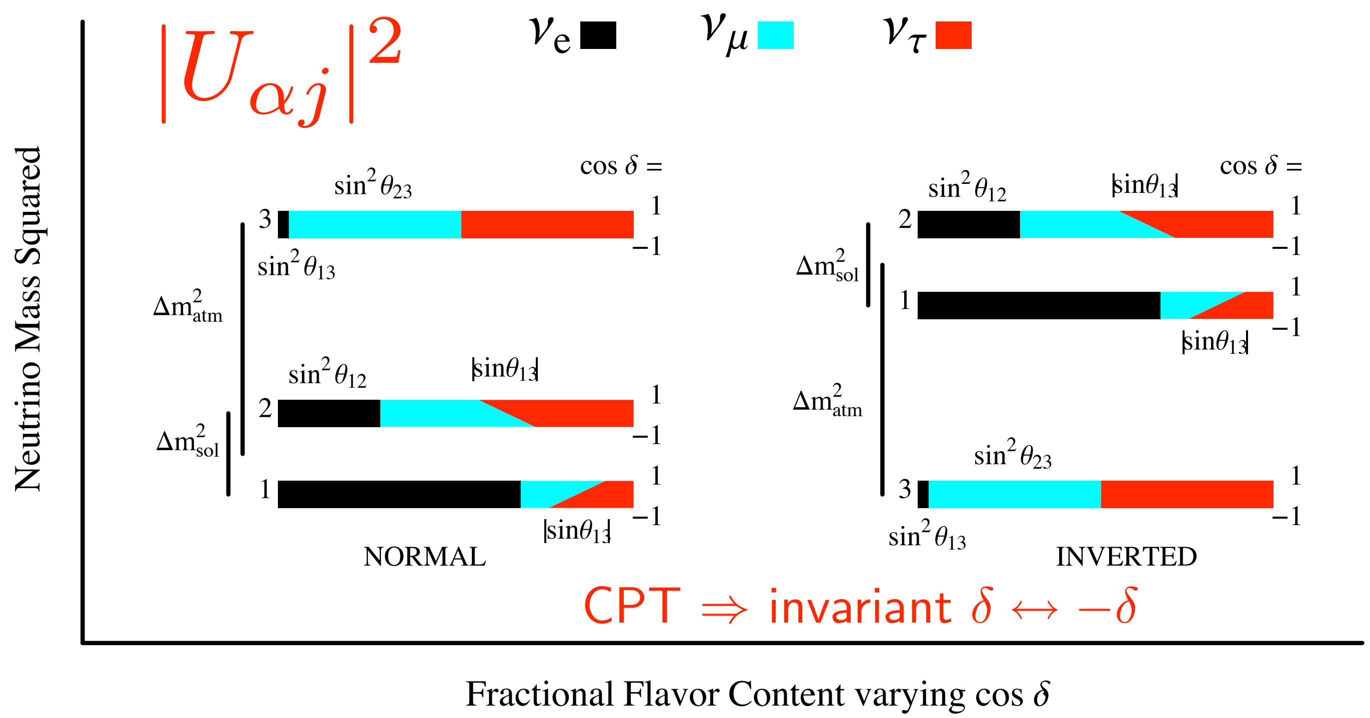
Precision Near Detector on the Fermilab site

100 kT Water Cherenkov Detector

20 kT Liquid Argon TPC Far Detector



Masses & Mixings:



$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

$$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

$$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$$

$$\sin^2\theta_{13} \equiv |U_{e3}|^2, \quad \sin^2\theta_{12} \equiv \frac{|U_{e2}|^2}{(1-|U_{e3}|^2)}, \quad \sin^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{(1-|U_{e3}|^2)}$$

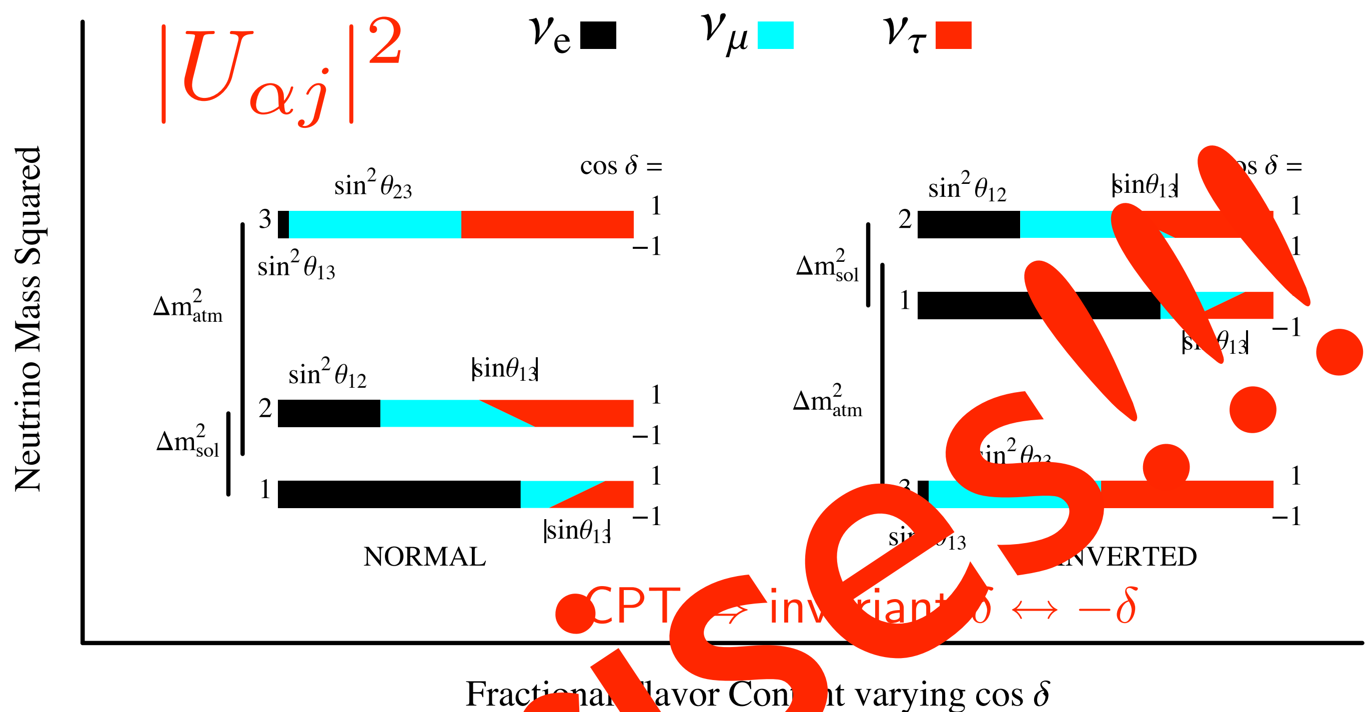
$$\sin^2\theta_{12} \sim 1/3$$

$$\sin^2\theta_{23} \sim 1/2$$

$$\sin^2\theta_{13} < 3\%$$

$$0 \leq \delta < 2\pi$$

Masses & Mixings:



Surprise!!!

$$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$$

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$$\sin^2\theta_{13} < 3\%$$

$$0 \le \delta < 2\pi$$

In Matter:

$$P_{\mu\to e} \approx |\ \sqrt{P_{atm}} e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\ |^2$$

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\ \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\ \Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\ \frac{\sin(aL)}{(aL)}\ \Delta_{21}$

$$a\ =\ G_F N_e/\sqrt{2}\ =\ (4000\ \ km)^{-1},$$

$$\Delta = \frac{\delta m^2 L}{4E}$$

In Matter:

$$P_{\mu\to e} \approx |\ \sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\ |^2$$

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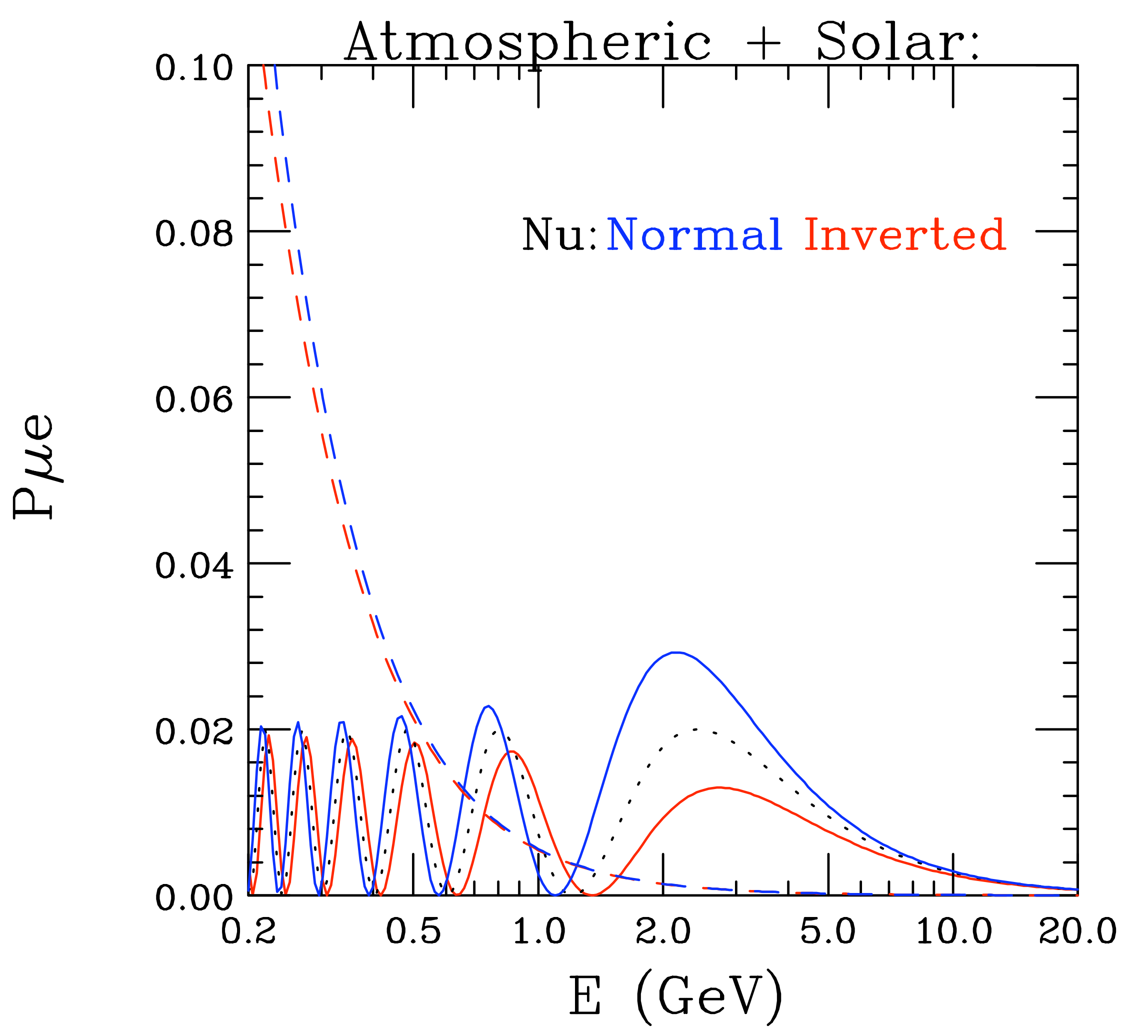
$$a\ =\ G_F N_e/\sqrt{2}\ =\ (4000\ \ km)^{-1},$$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

$$\Delta = \frac{\delta m^2 L}{4E}$$



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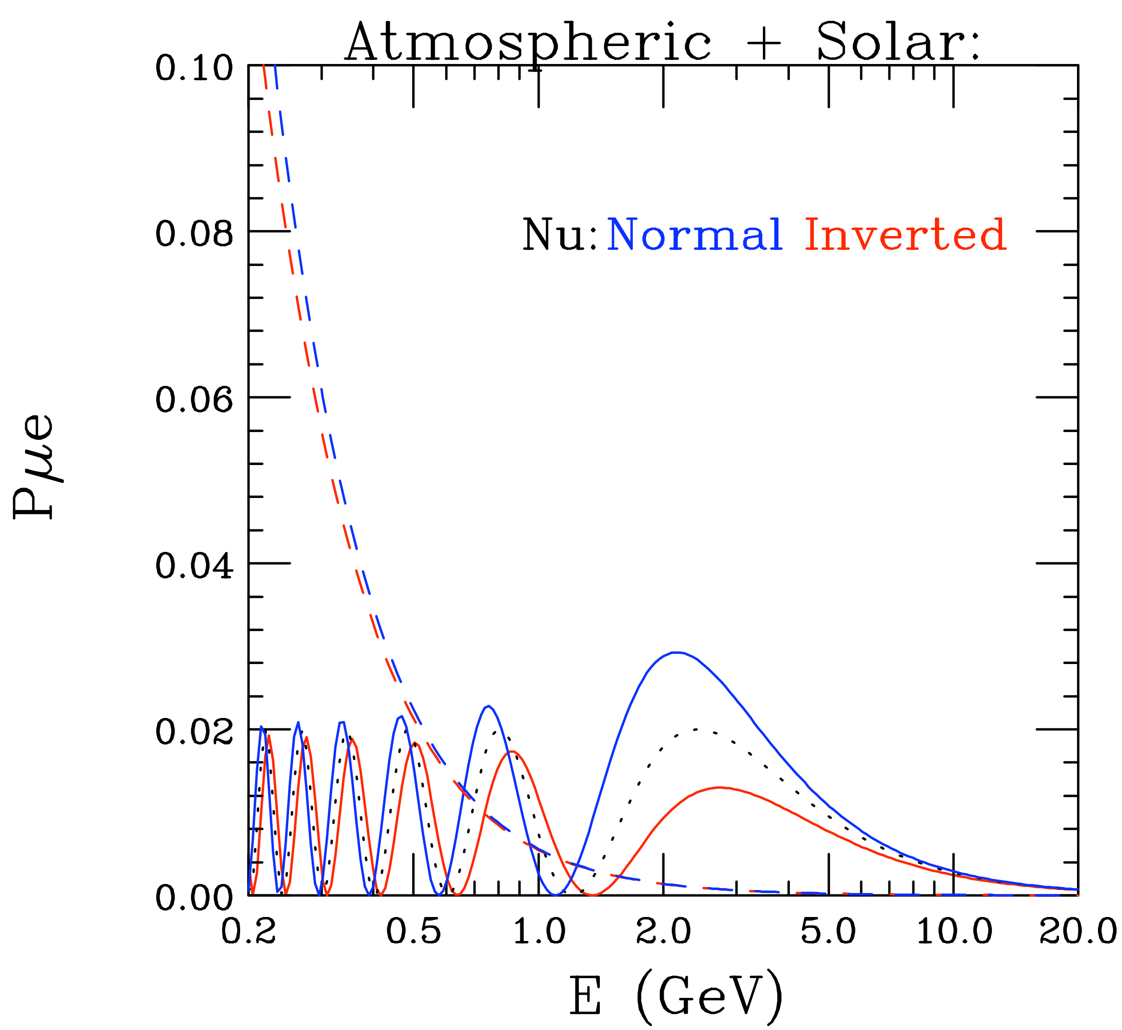
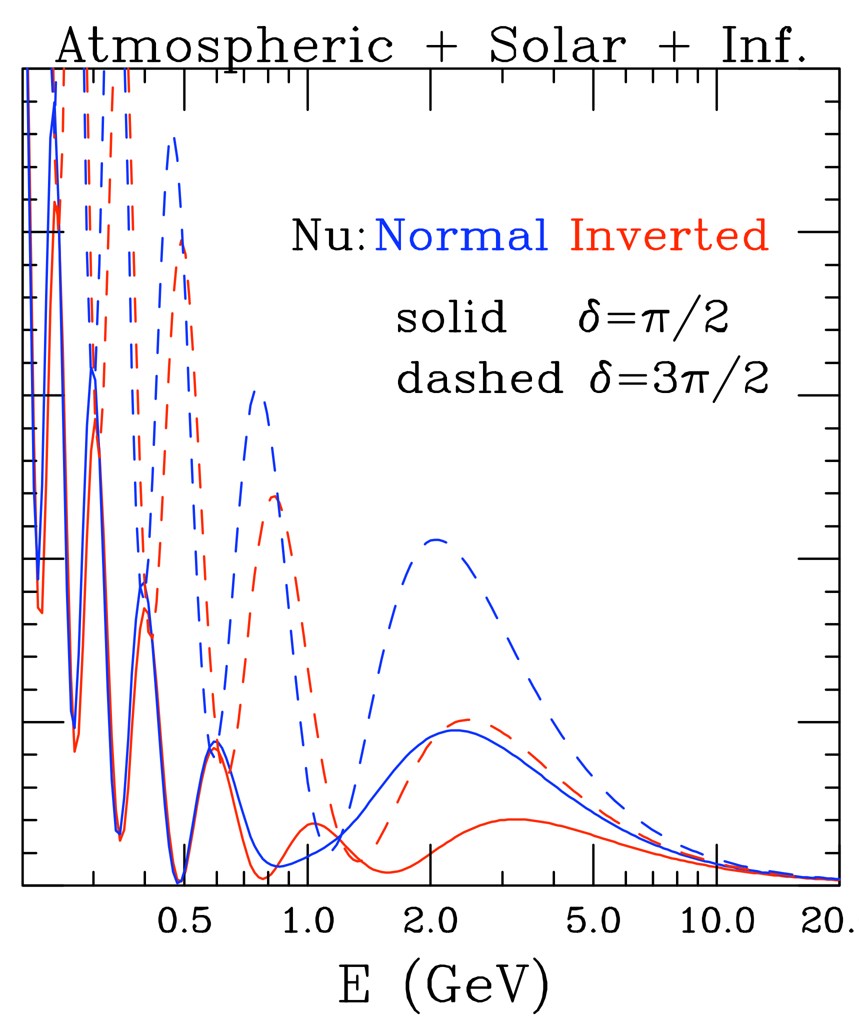
For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

$$\Delta = \frac{\delta m^2 L}{4E}$$

Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$

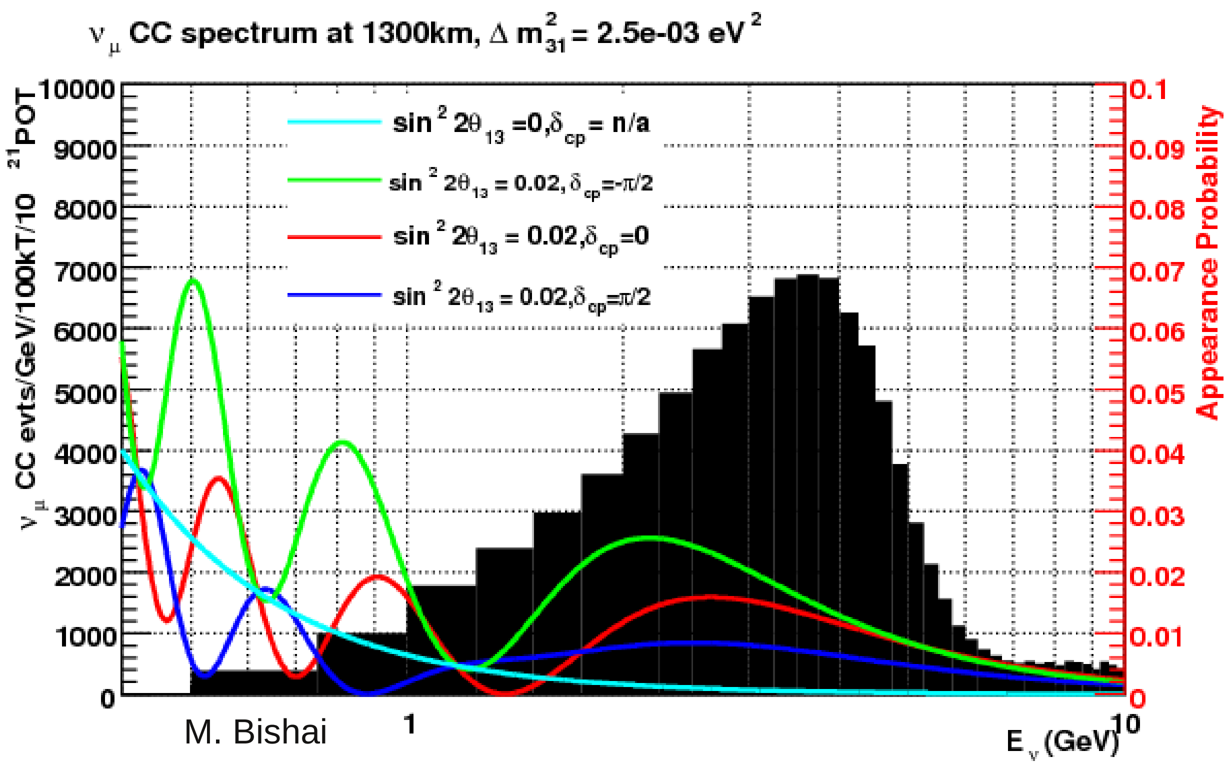




Neutrino Beam:

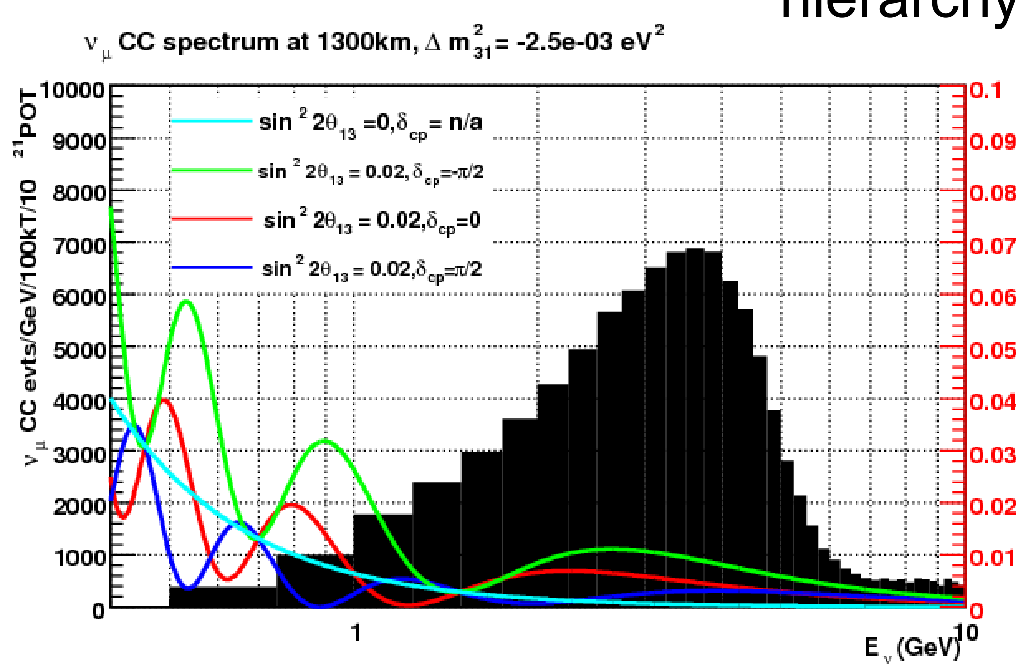
Beam requirements (driven by ν_e appearance):

- wide band beam to cover both 1st and 2nd oscillation maxima
- minimize flux above 5 GeV to avoid feed down of NC background to low energy
- minimize beam ν_e contamination

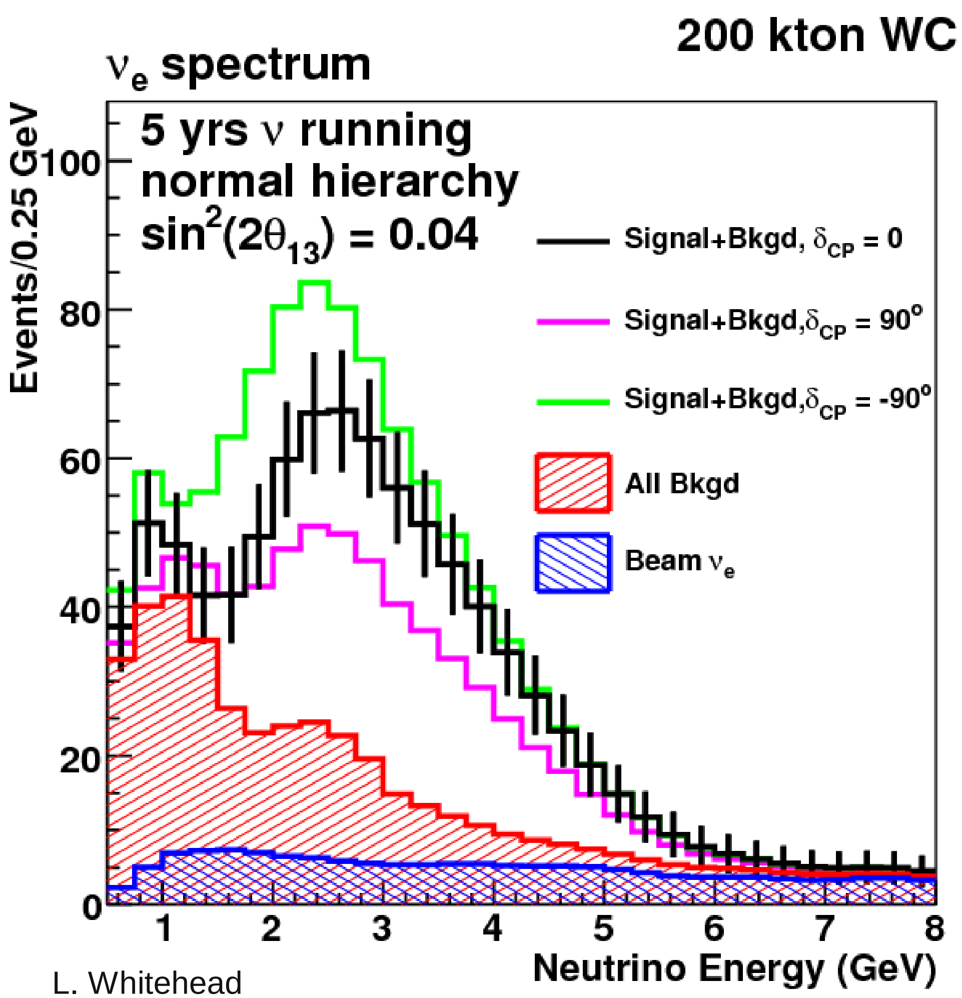


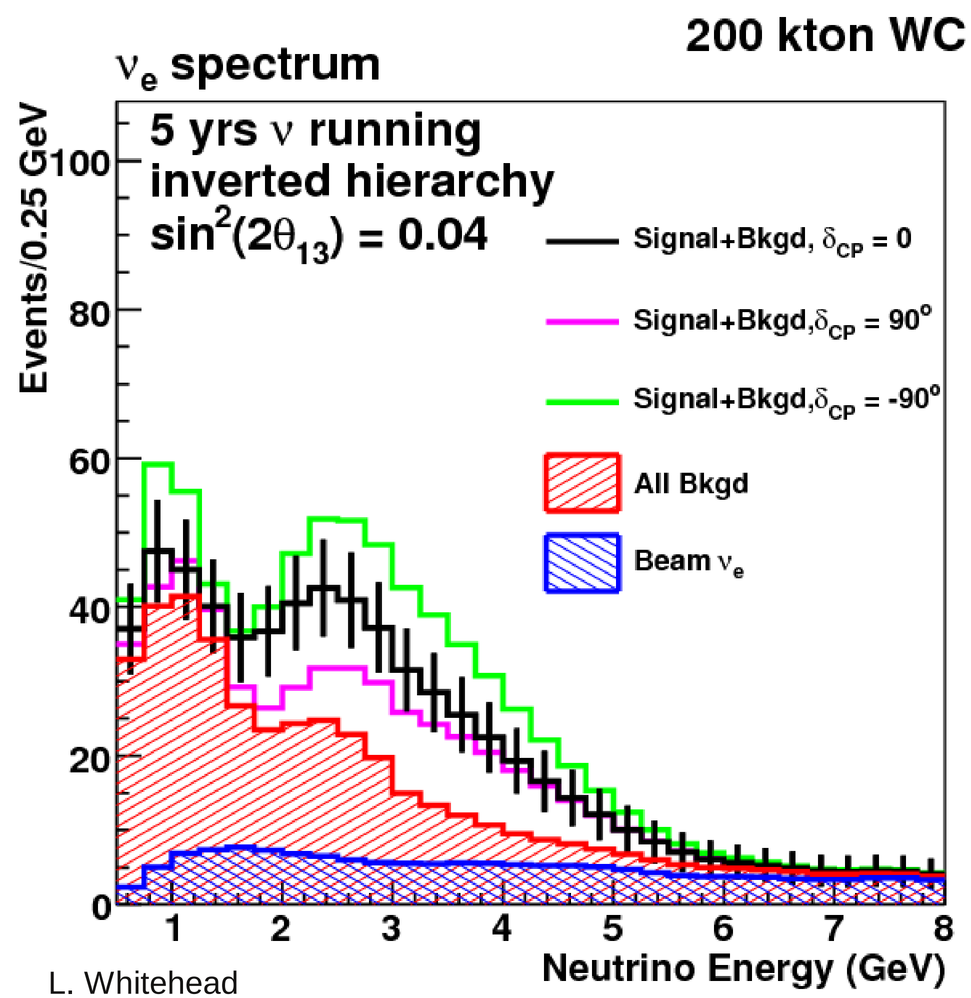
Normal hierarchy

Inverted hierarchy



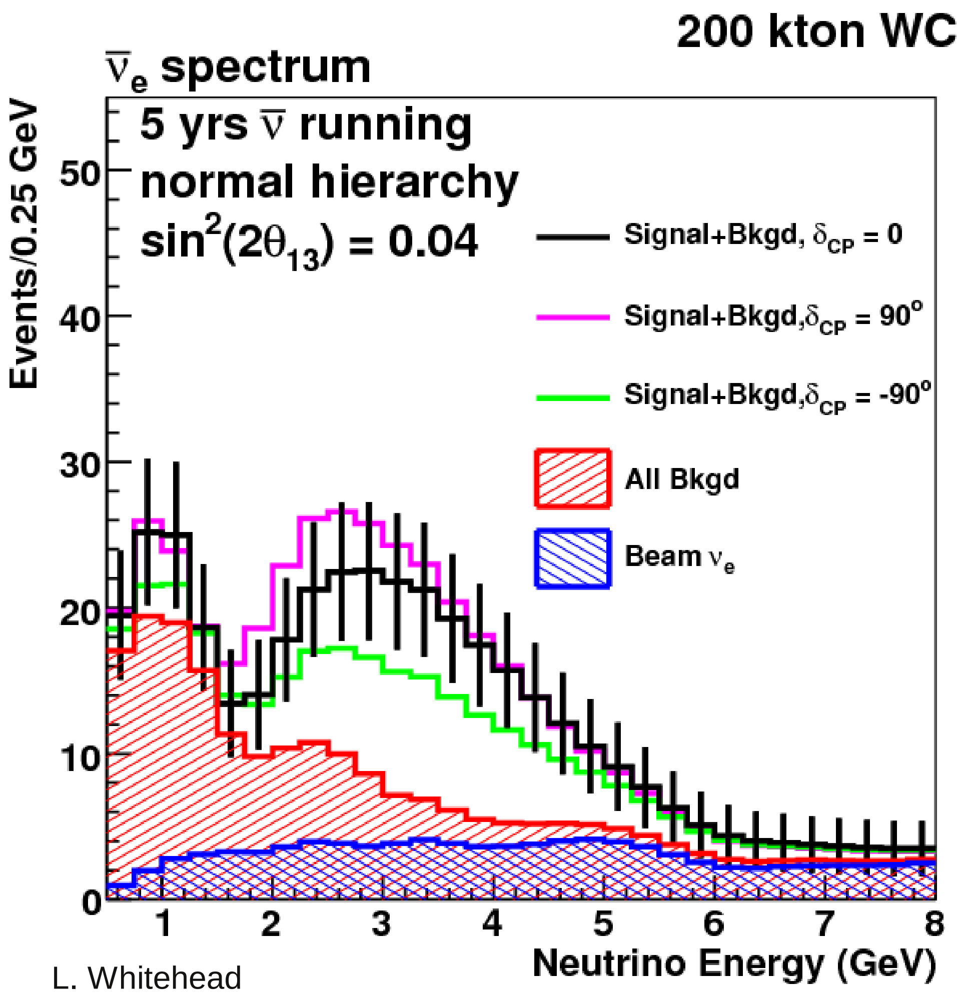
Neutrino

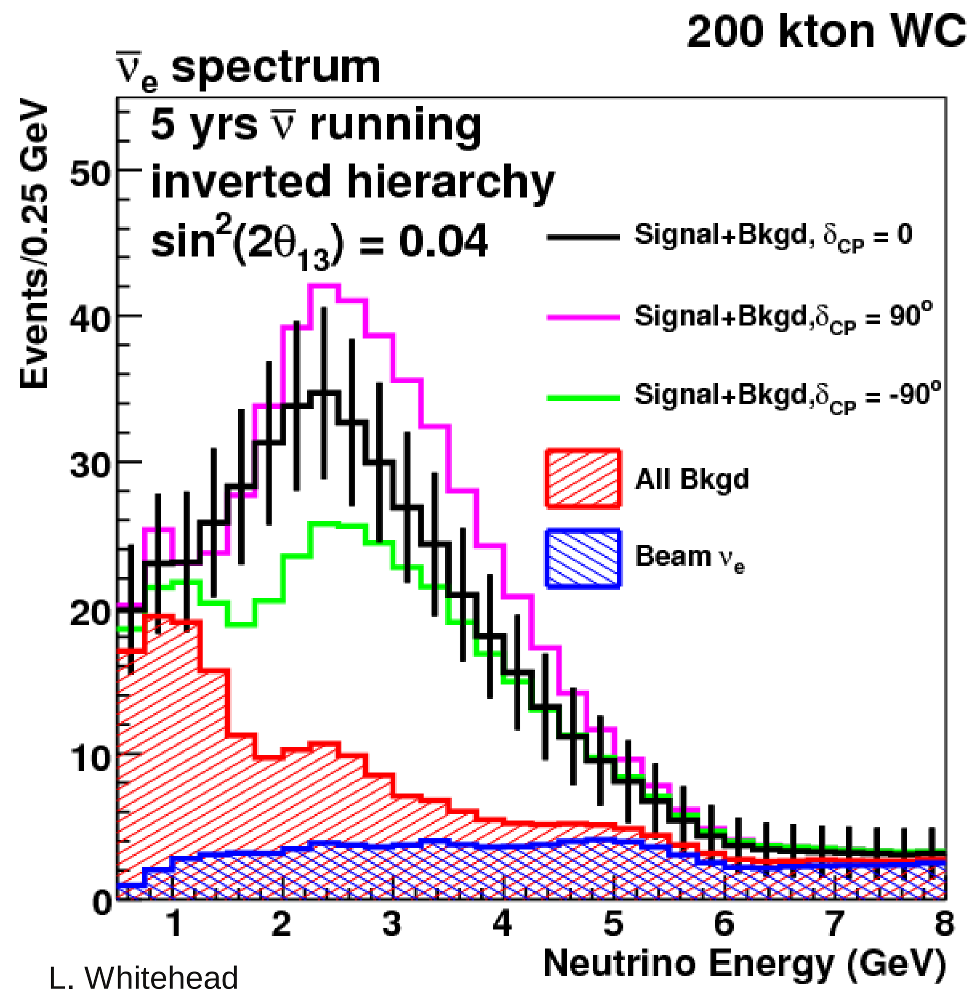




δ=0	signal	beam νe	NC	νμ CC
Normal hier	484	218	276	15
Inverted hier	212	221	276	15

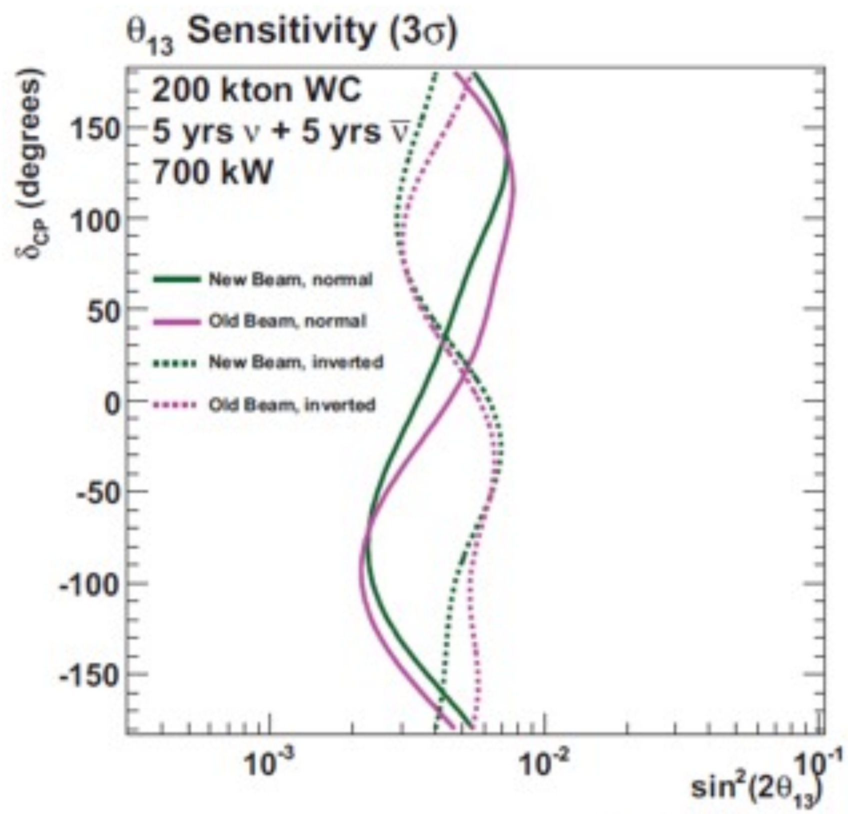
Anti-Neutrino

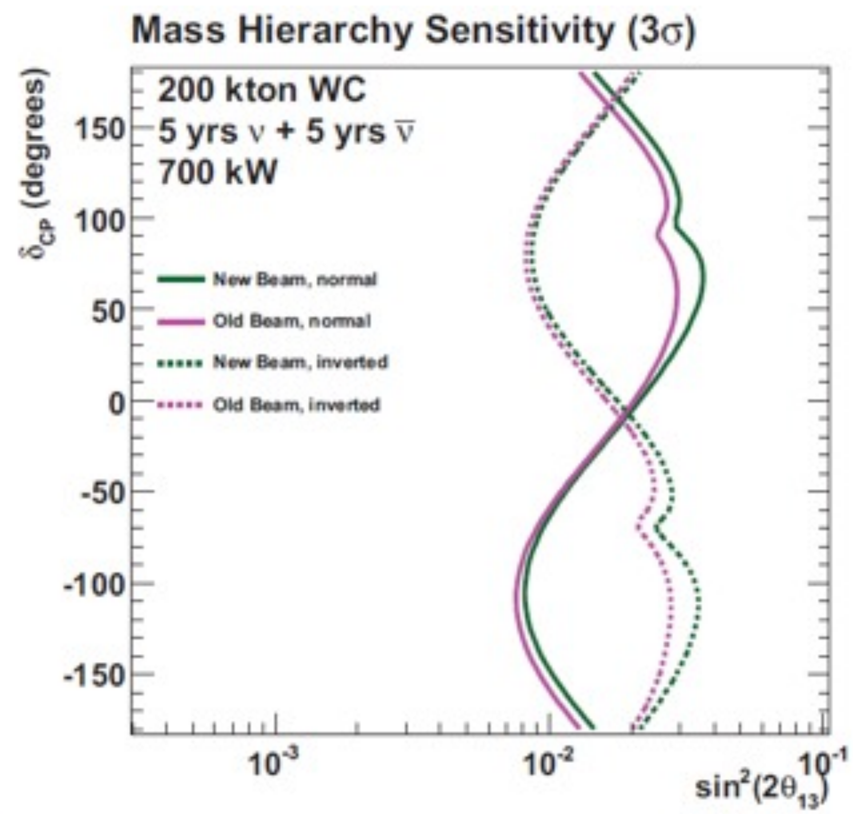




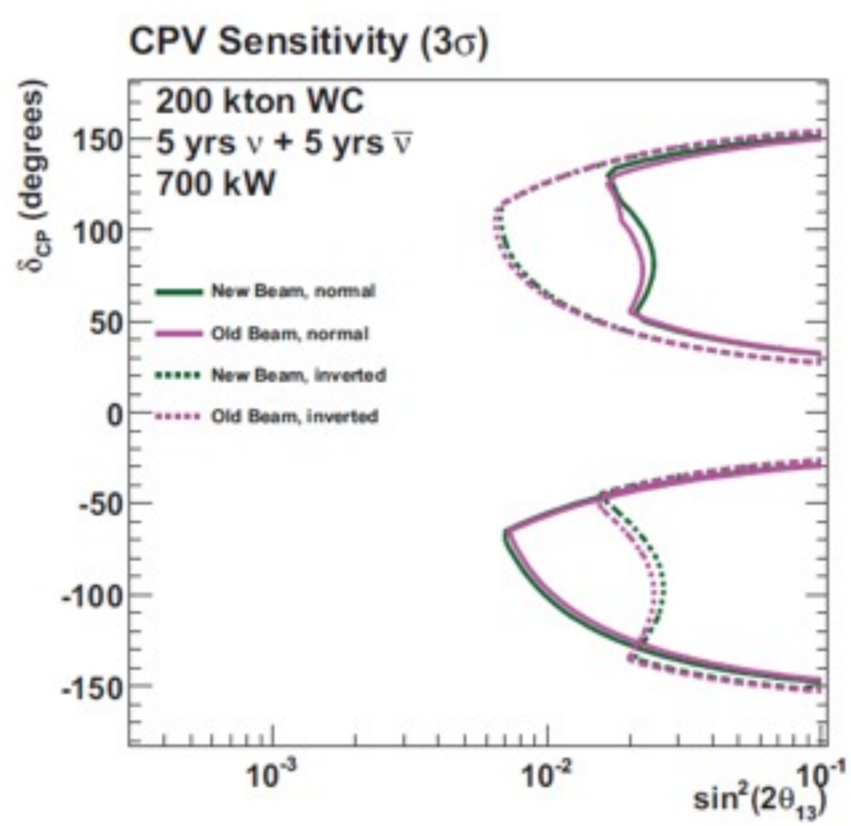
$\delta=0$	νe signal	$\bar{\nu} e$ signal	beam νe	NC	$\nu\mu$ CC	Beam $\bar{\nu} e$	$\bar{\nu}\mu$ CC
Normal hier	35	145	88	118	2	27	5
Inverted hier	15	246	27	118	2	87	5

LBNE Sensitivities:





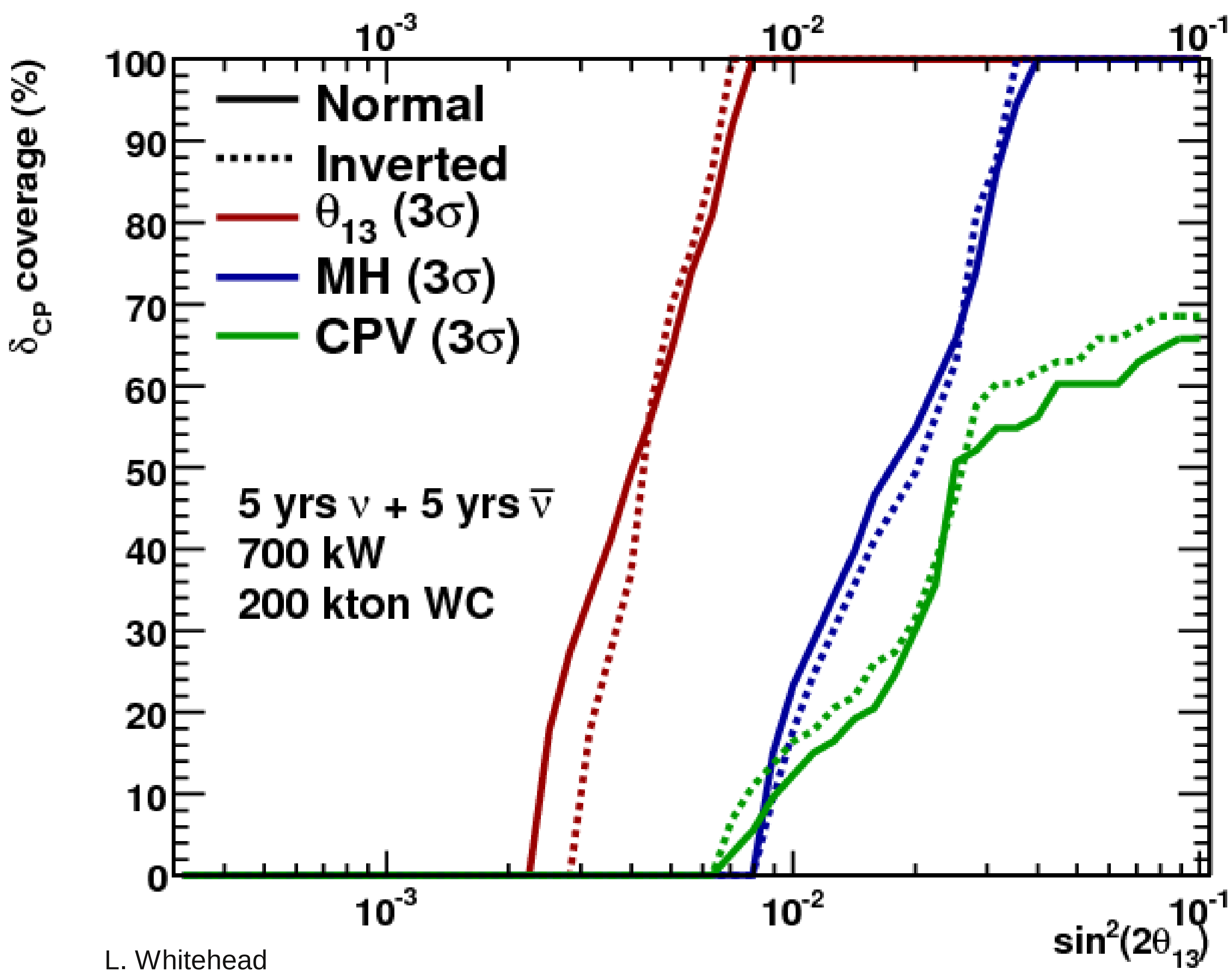
Sensitivities shown are for 200 ktons WCD.
With 34 ktons LAr, the sensitivities are equivalent.



Sensitivities shown are for 10 years with 700 kW proton beam.
With Project X (≥2 MW), the same sensitivity would be reached in 1/3 the time … or ~$\sqrt{3}$ greater sensitivity for the same running period.

Fall 2010 Report from the LBNE Physics Working Group

Sensitivities:



-3σ non-zero θ_{13} for 100% of δ_{cp} values at $\sin^2 2\theta_{13}=0.008$

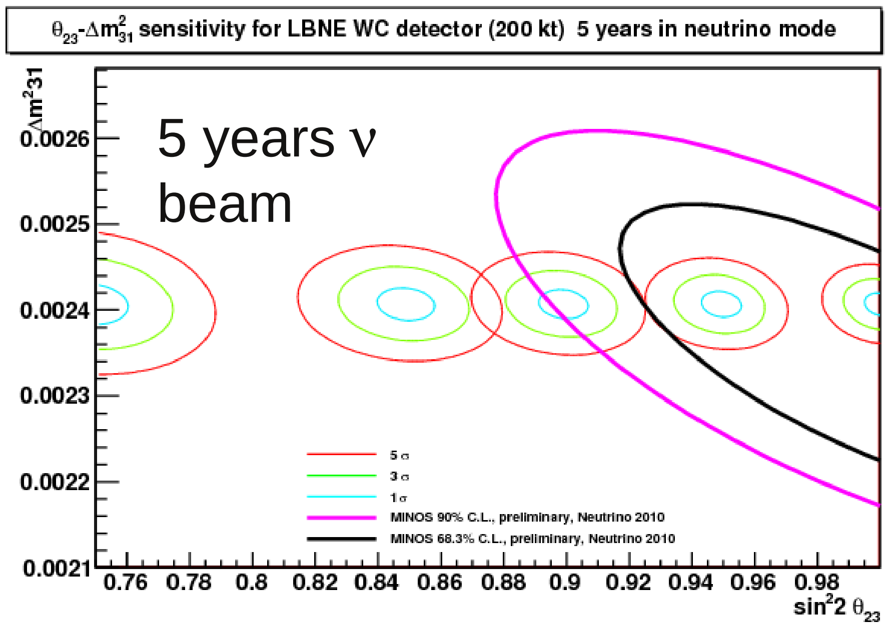
- 3σ mass hier. for 100% of δ_{cp} values at $\sin^2 2\theta_{13}=0.04$

- 3σ CP violation for 50% of δ_{cp} values at $\sin^2 2\theta_{13}=0.03$

(all assuming normal hierarchy)

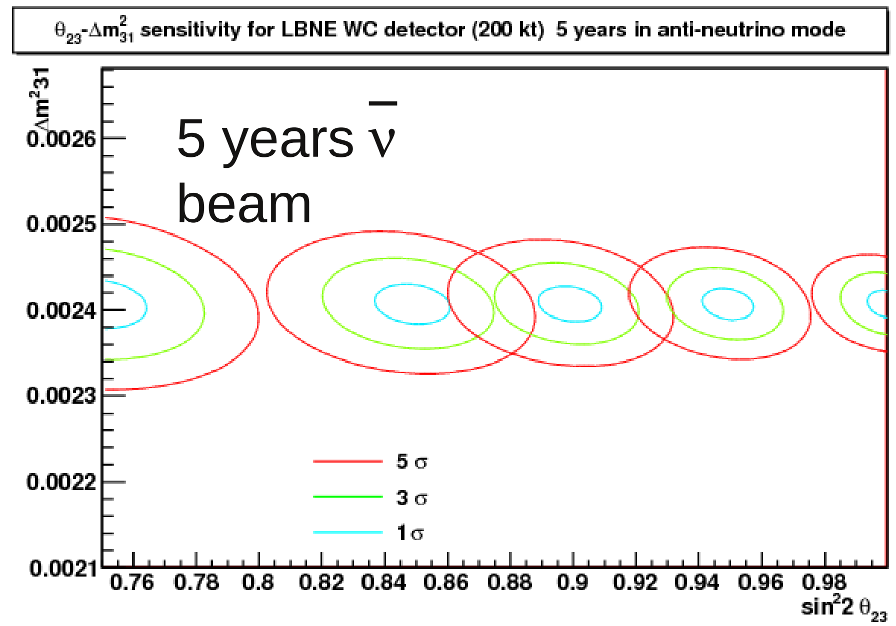
Disappearance

Δm^2 vs $\sin^2 2\theta_{23}$



R. Guenette

$\Delta \overline{m}^2$ vs $\sin^2 2\overline{\theta}_{23}$



R. Guenette

$$\delta m^2_{\mu\mu} = \frac{|U_{\mu 1}|^2\ \delta m^2_{31} + |U_{\mu 2}|^2\ \delta m^2_{32}}{|U_{\mu 1}|^2 + |U_{\mu 2}|^2}$$

$$= \delta m^2_{32} + [\sin^2\theta_{12} + \mathcal{O}(\sin\theta_{13})]\ \delta m^2_{21}$$

$$|\delta m^2_{32}| = |\delta m^2_{\mu\mu}|(1 \mp 0.01)$$

1% difference: sign depends on hierarchy

- signal is CCQE events (97% efficiency)
- 5% normalization and 3% energy scale uncertainty for signal
- 10% normalization and 3% energy scale uncertainty for background

Which Octant?

At Vac. Osc. Max. $(\Delta_{31} = \frac{\pi}{2})$

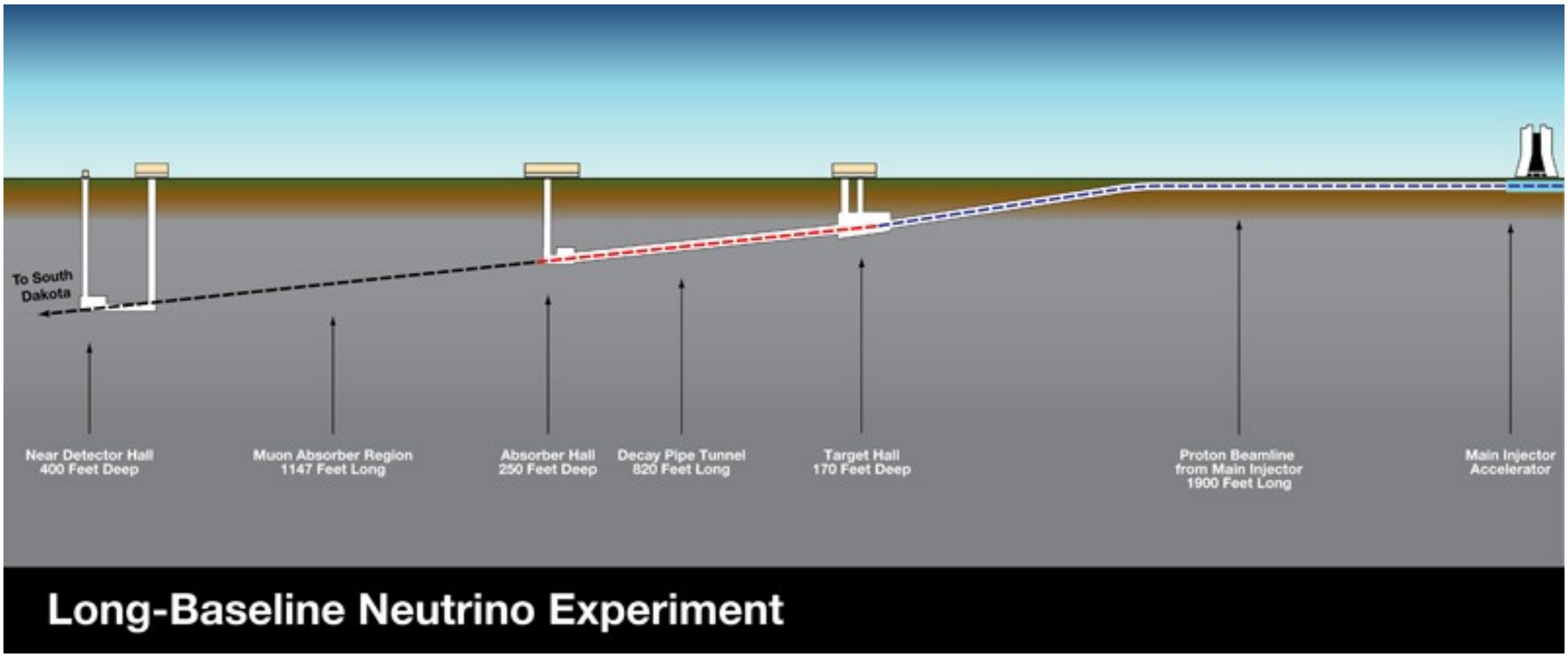
$$P(\nu_\mu \to \nu_e) + P(\bar\nu_\mu \to \bar\nu_e) \approx 2\sin^2\theta_{23}\sin^2 2\theta_{13} \quad + \quad \mathcal{O}[(aL)\sin\delta]$$

directly comparable to reactor

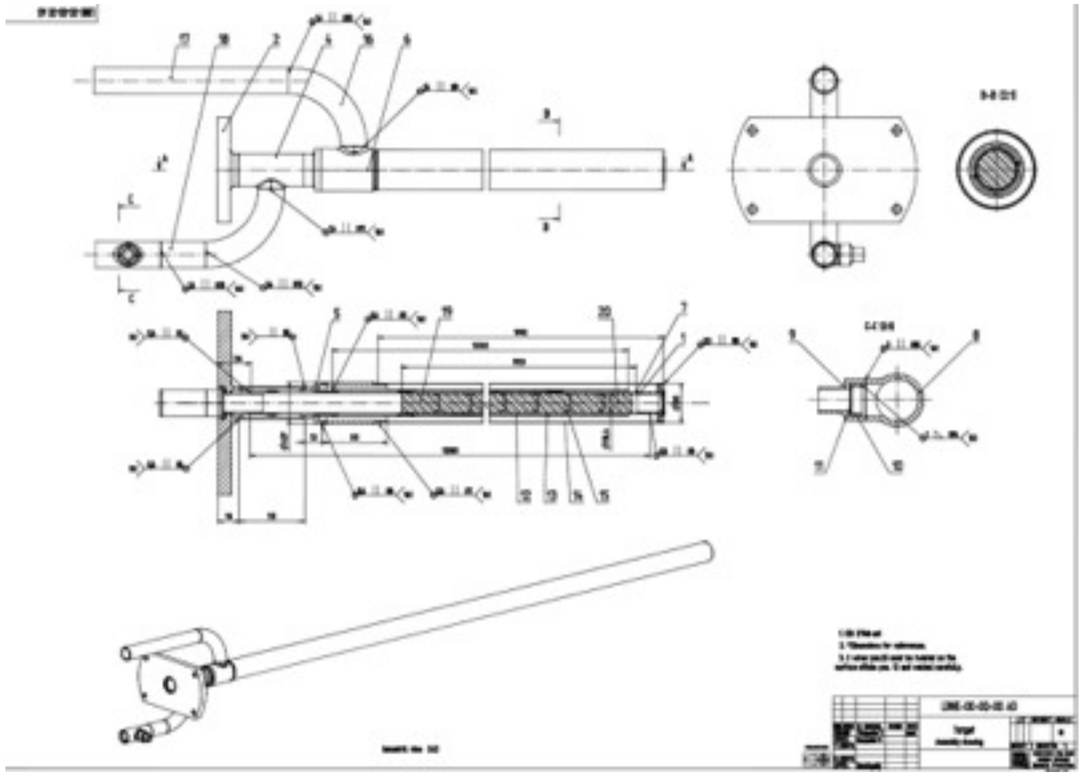
$$1 - P(\bar\nu_e \to \bar\nu_e) = \sin^2 2\theta_{13}$$

New Neutrino Beamline at Fermilab

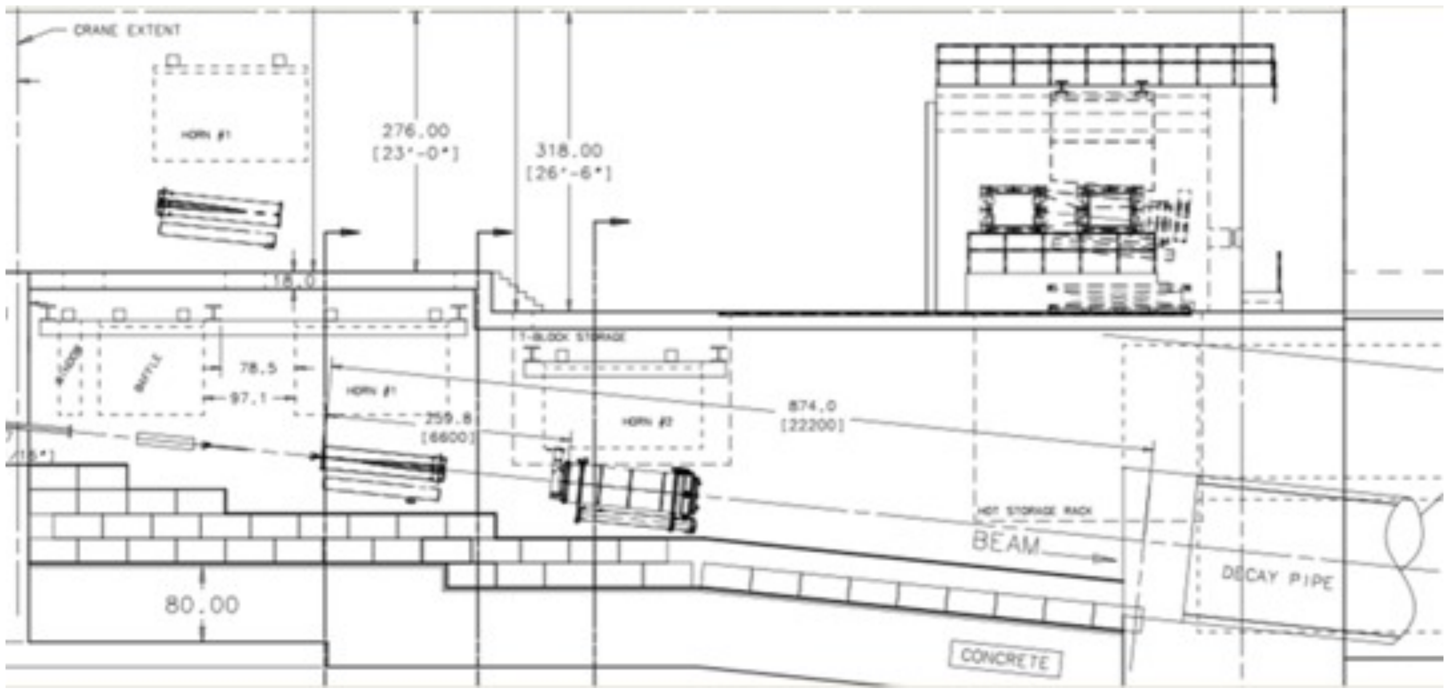
Aiming the Beam to DUSEL

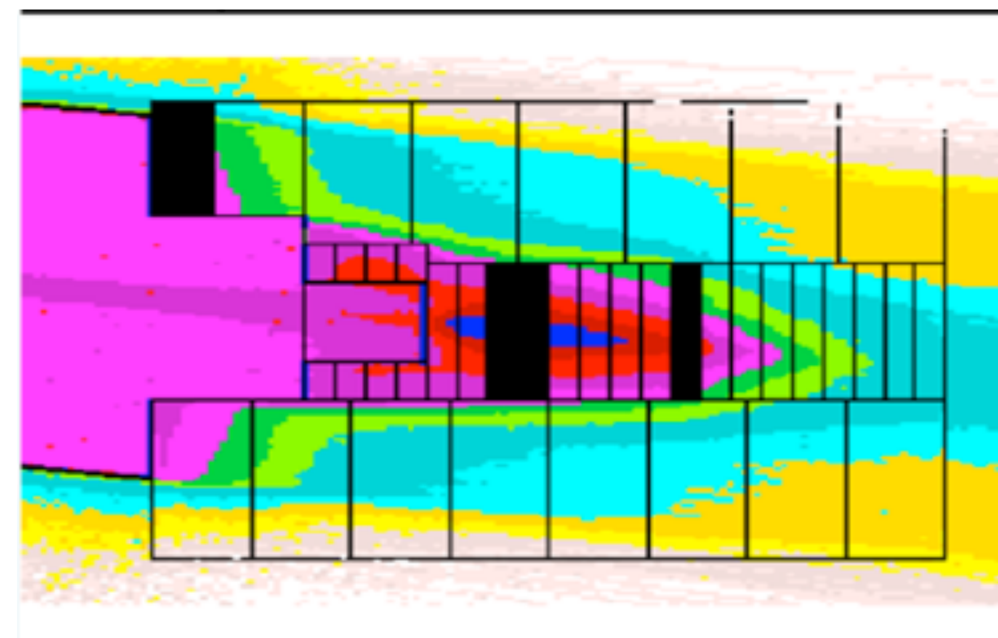


Target and Horns



Target, Horn, Decay Pipe, and Absorber Engineering

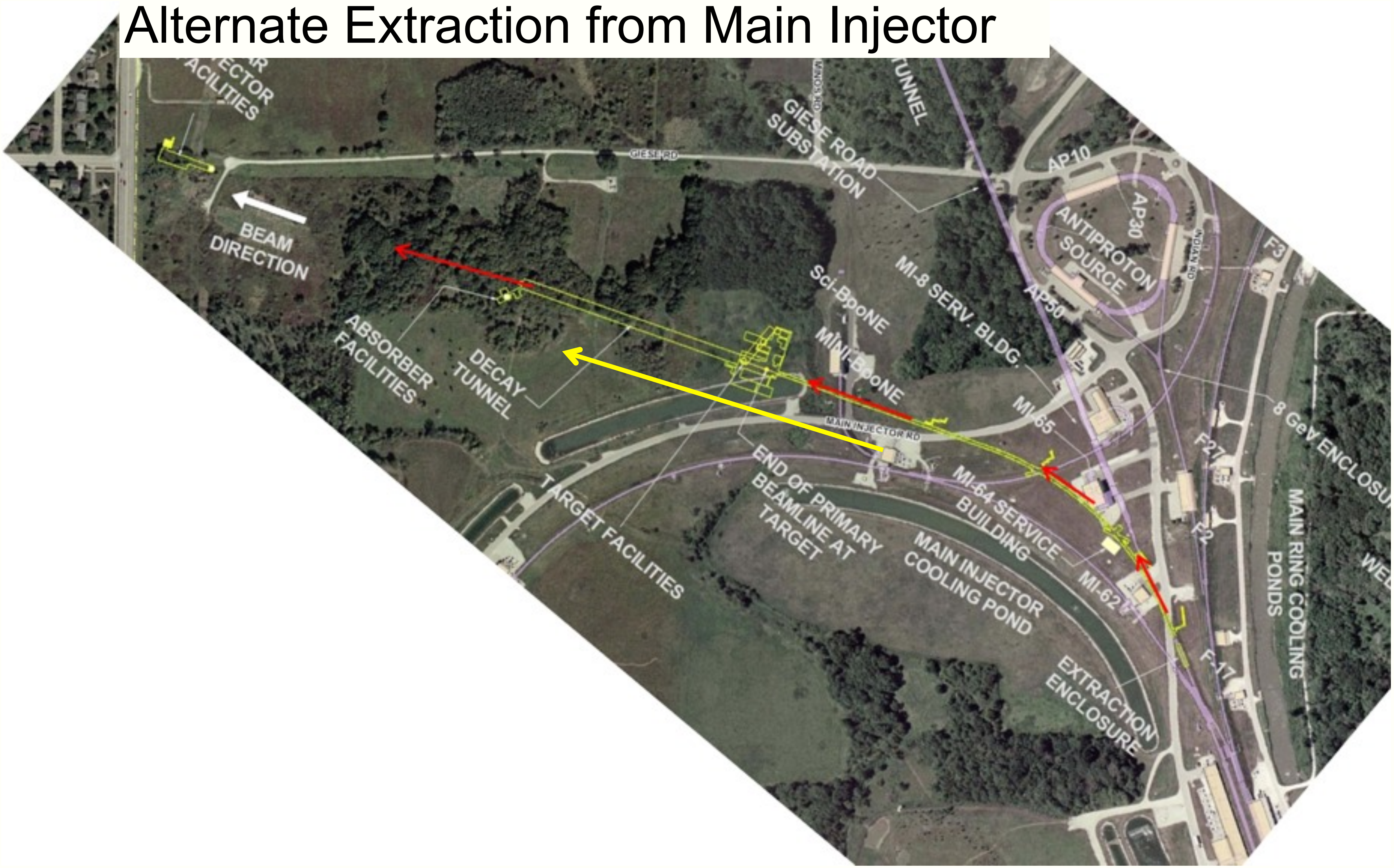




- Technical components designed for 700 kW beam (Main Injector with NOvA upgrades.
- Facilities designed to handle 2.3 MW beam (Project X).

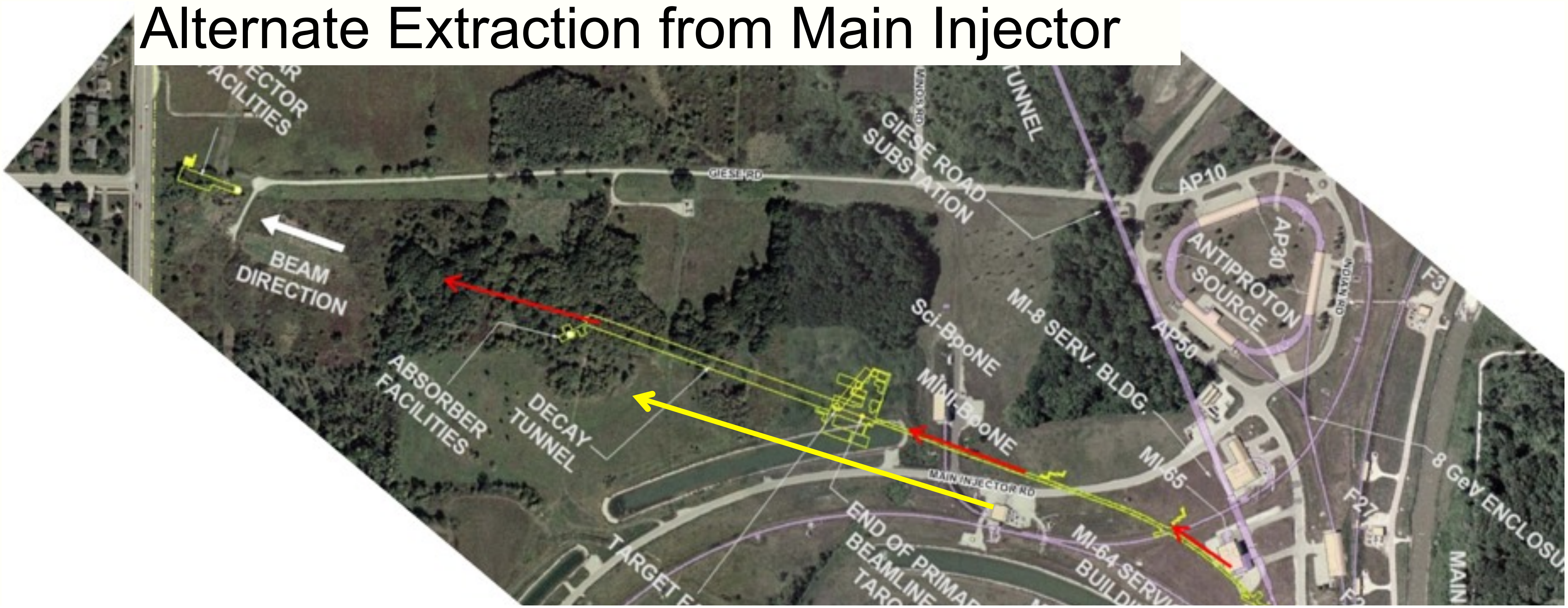
Alternate Neutrino Beam Designs

Alternate Extraction from Main Injector

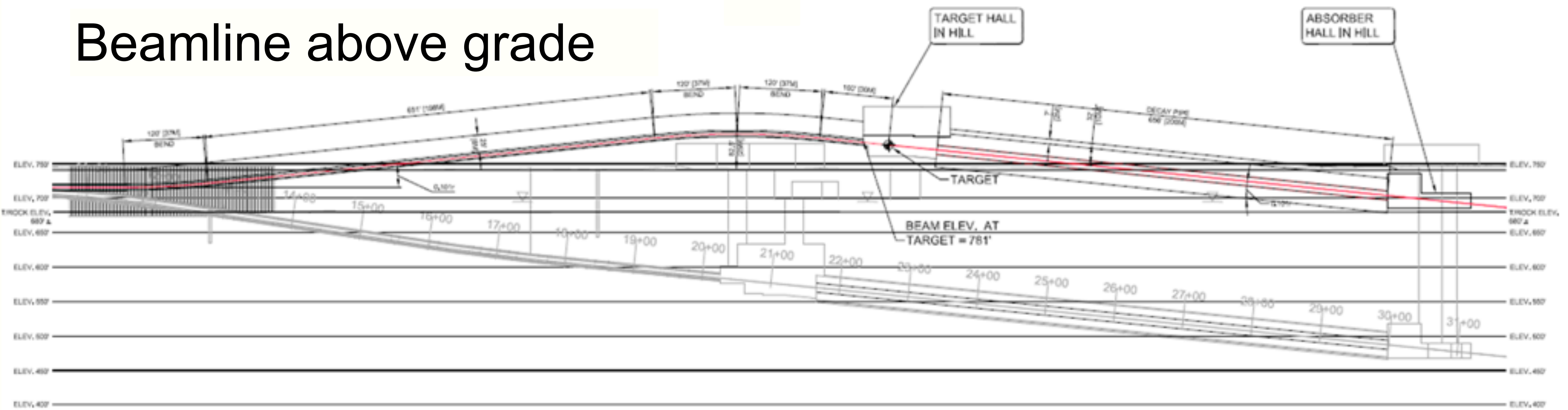


Alternate Neutrino Beam Designs

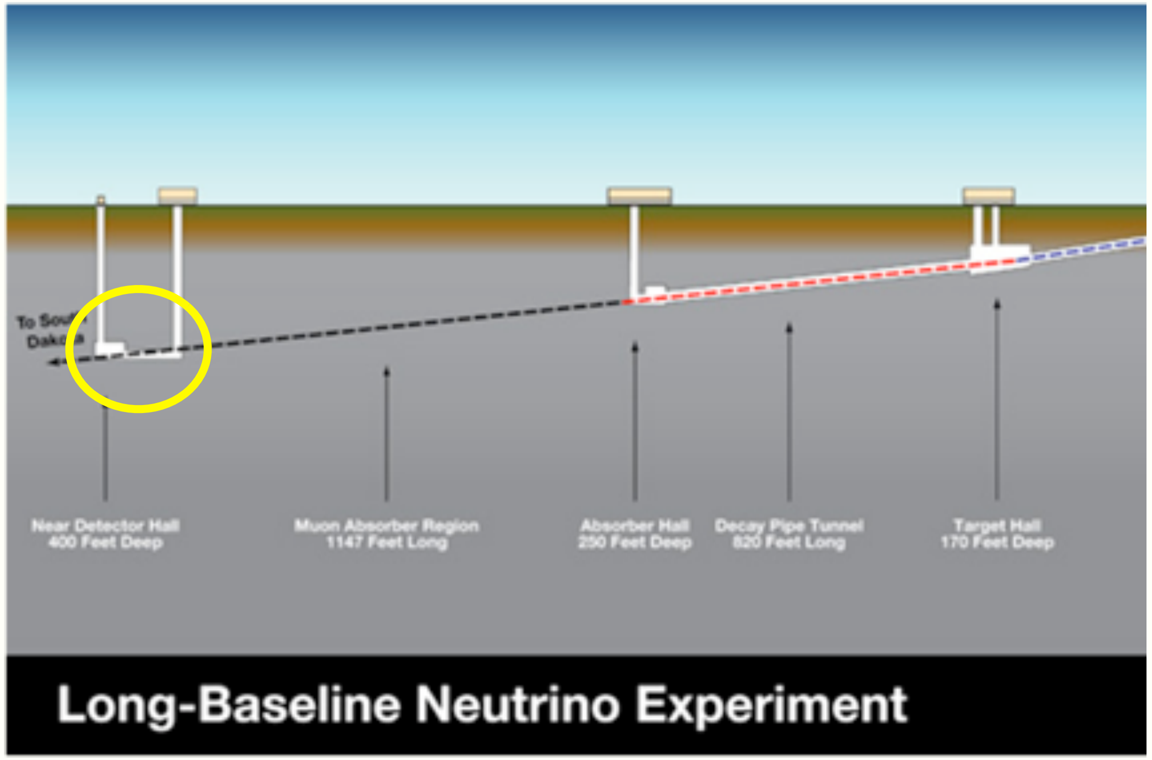
Alternate Extraction from Main Injector



Beamline above grade

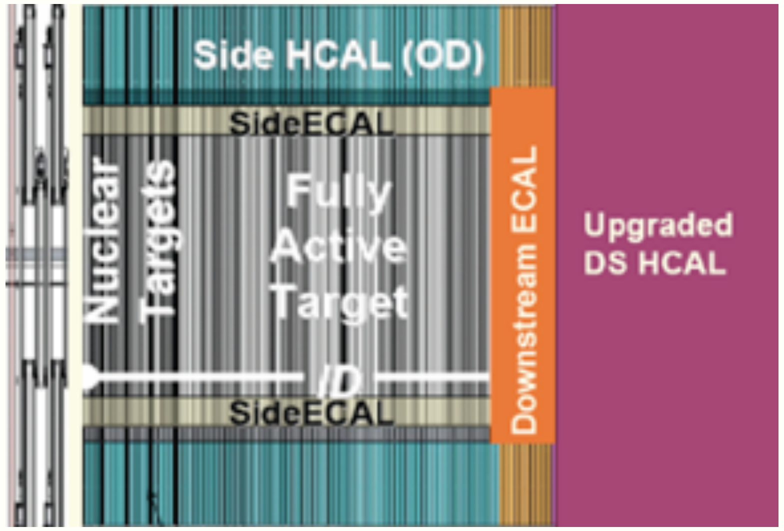


Near Detector

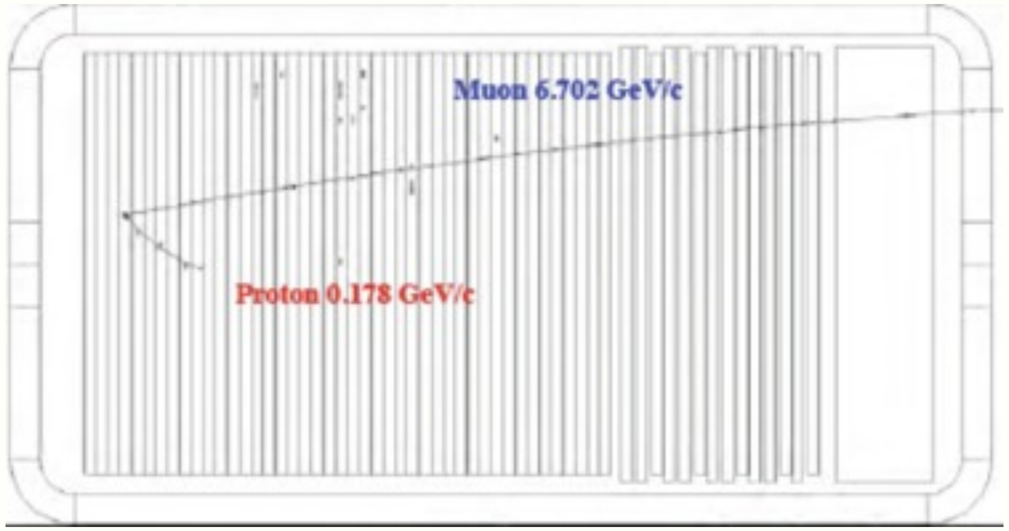


Several options under consideration:

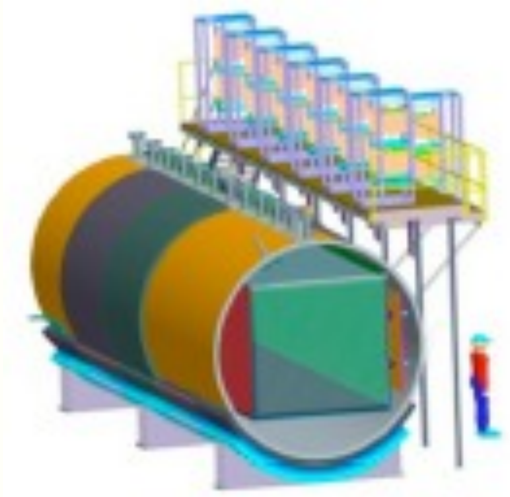
Scintillator tracker



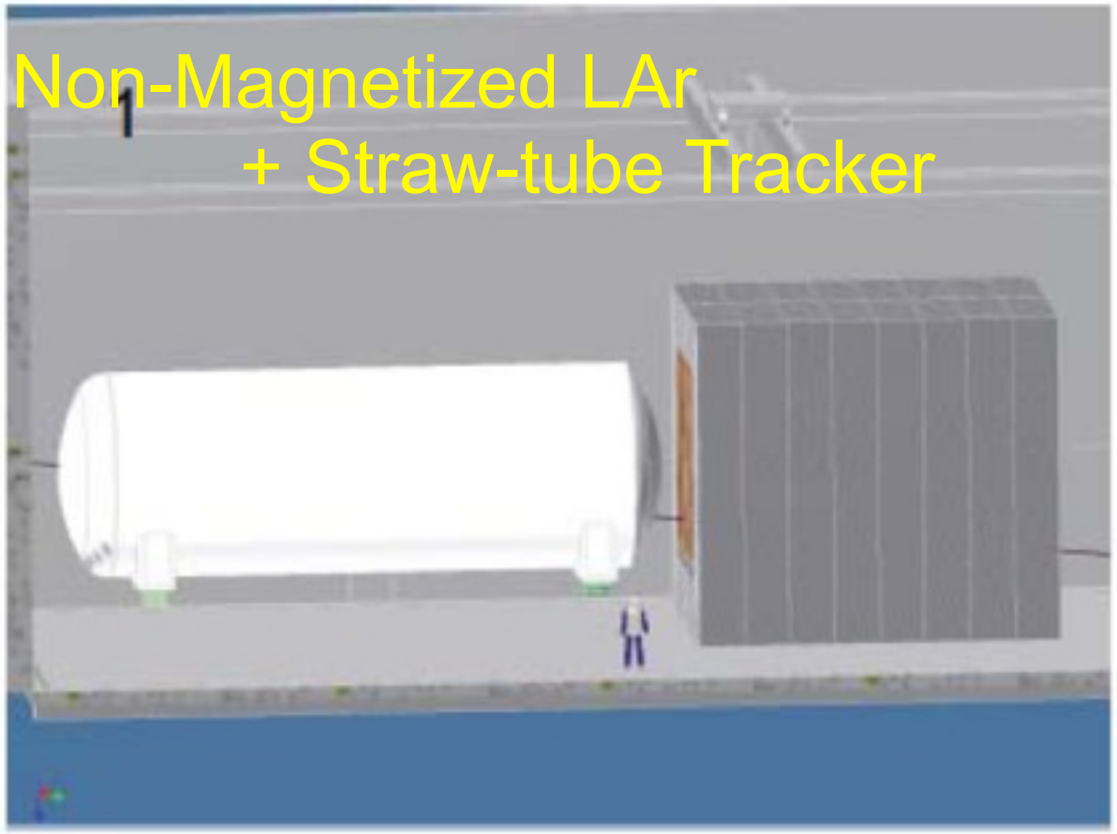
Straw-tube tracker

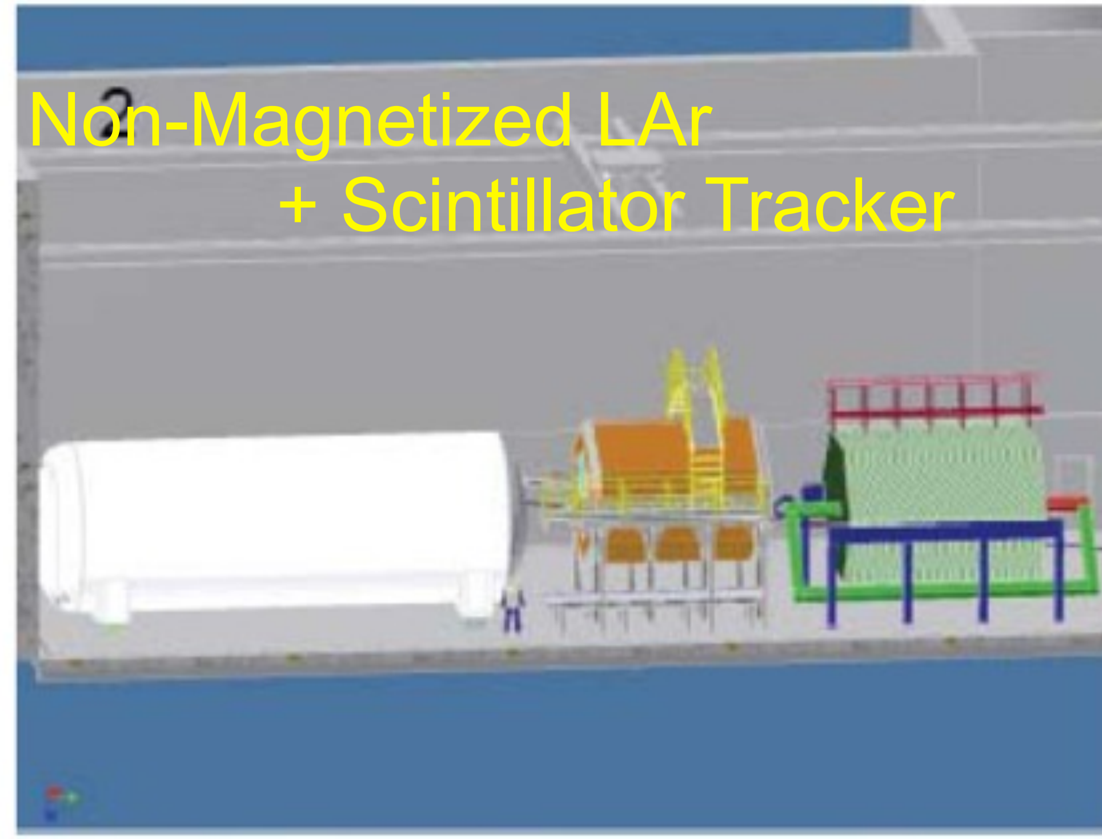


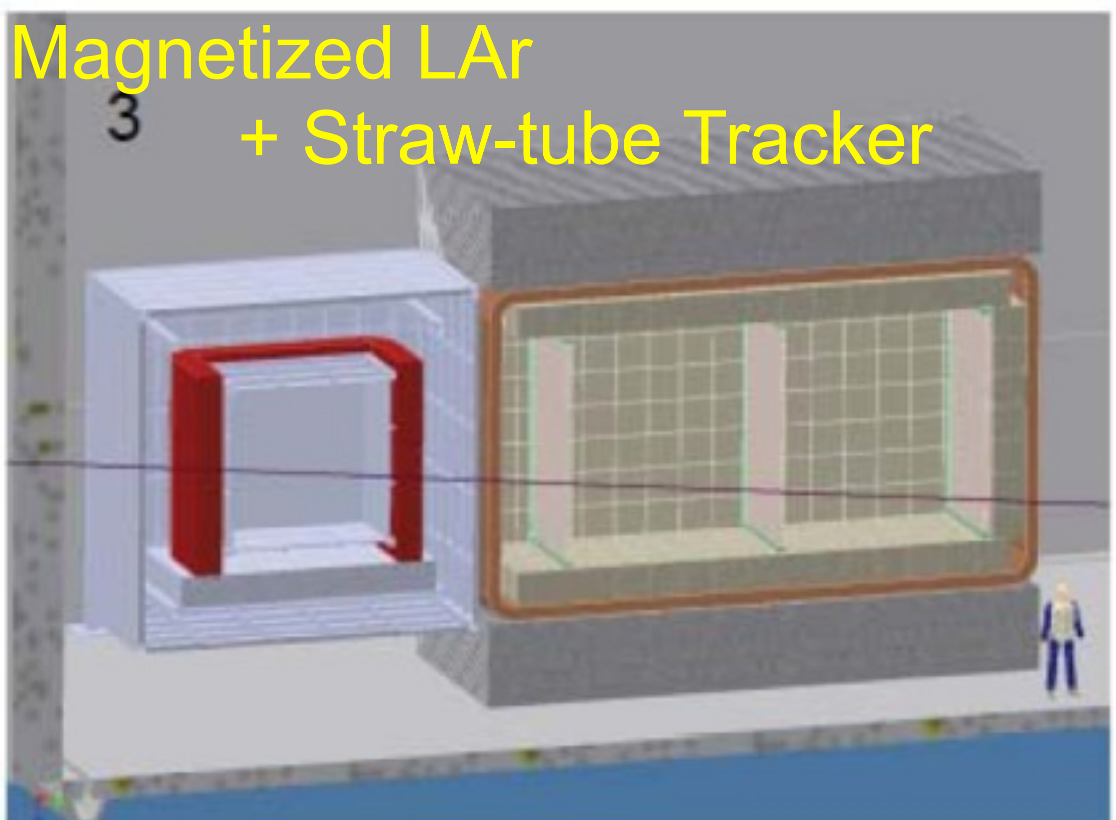
LAr TPC

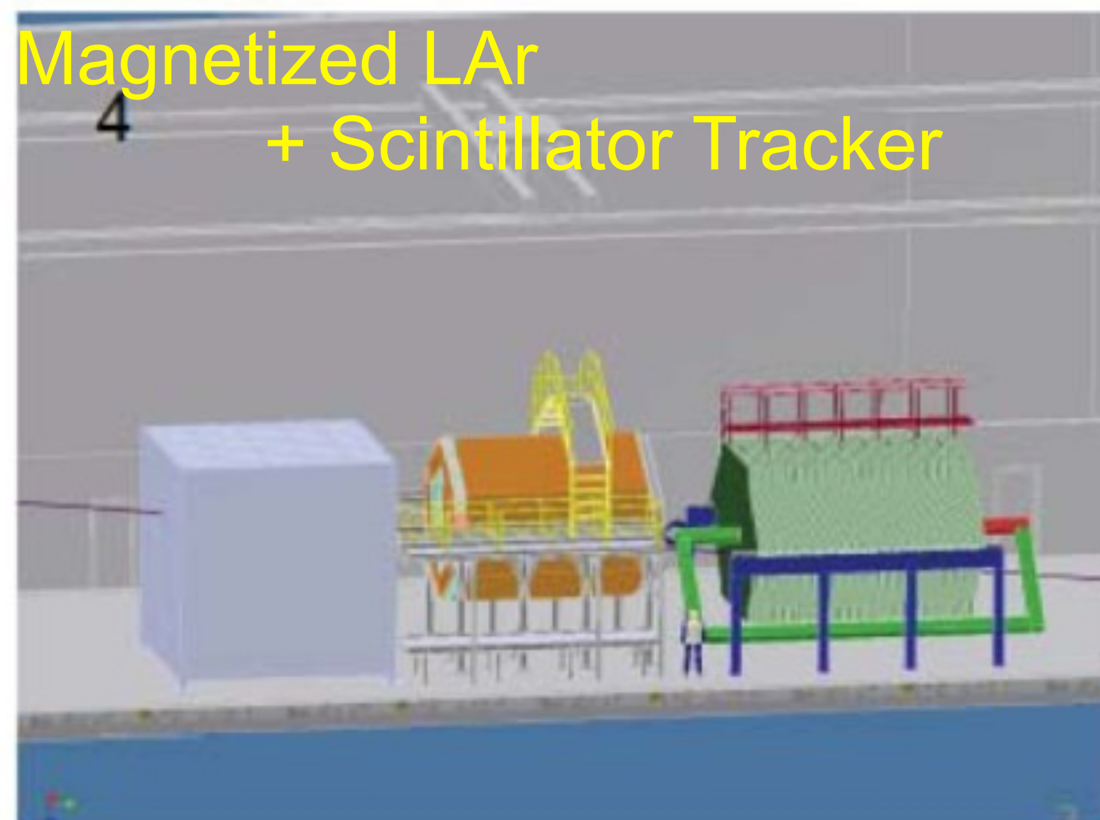


Near Detector Options



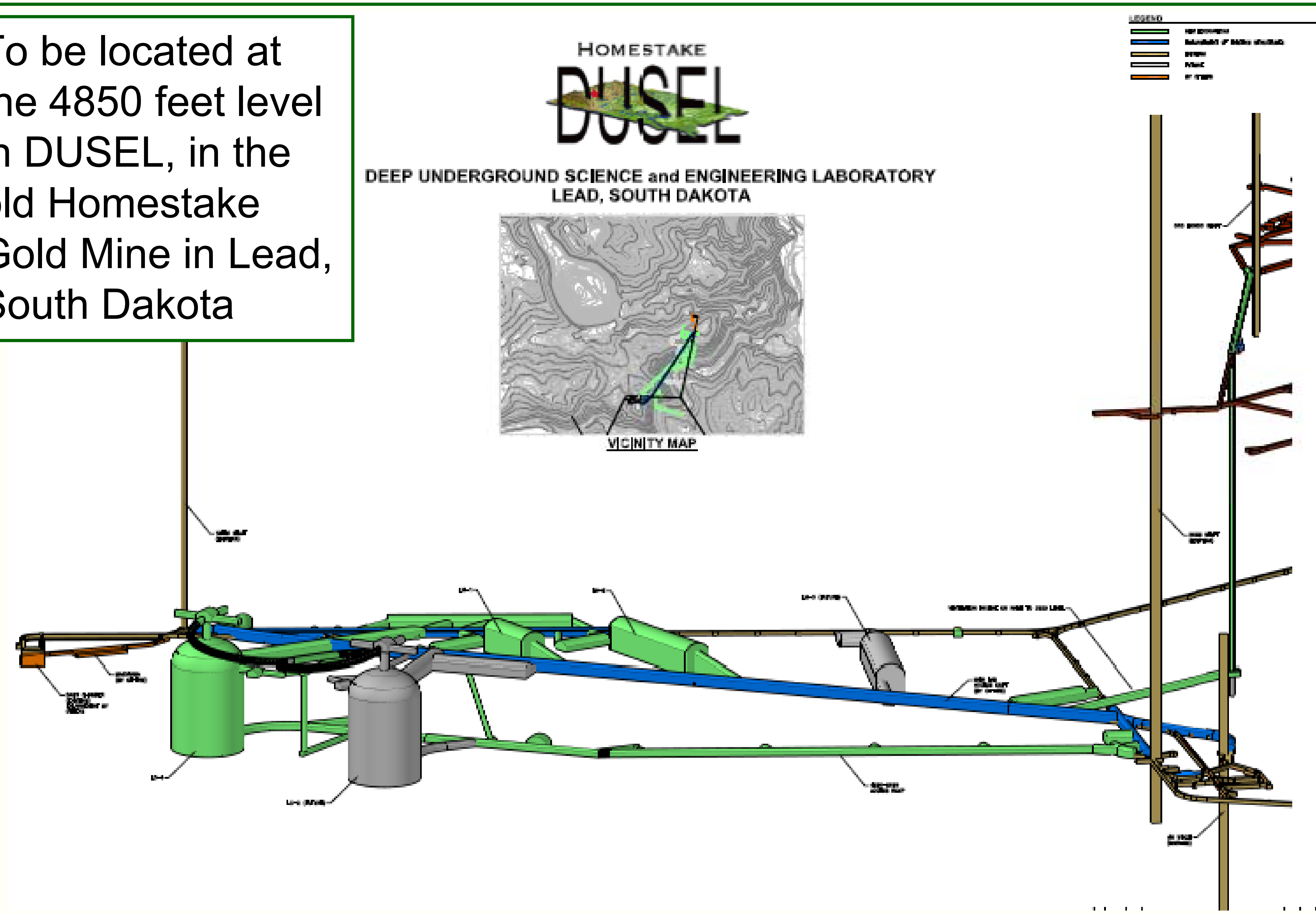




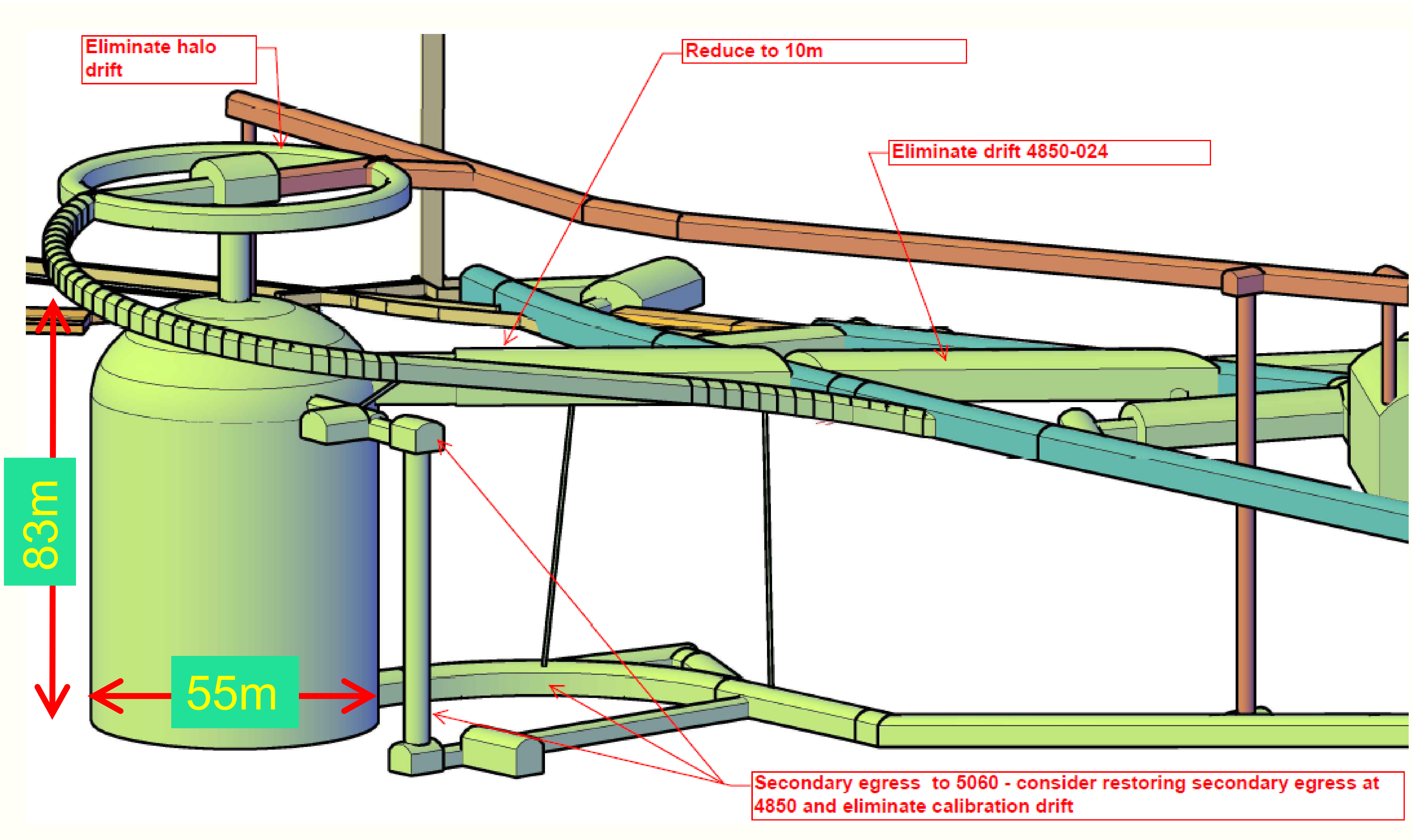


Water Cherenkov Far Detector

To be located at the 4850 feet level in DUSEL, in the old Homestake Gold Mine in Lead, South Dakota

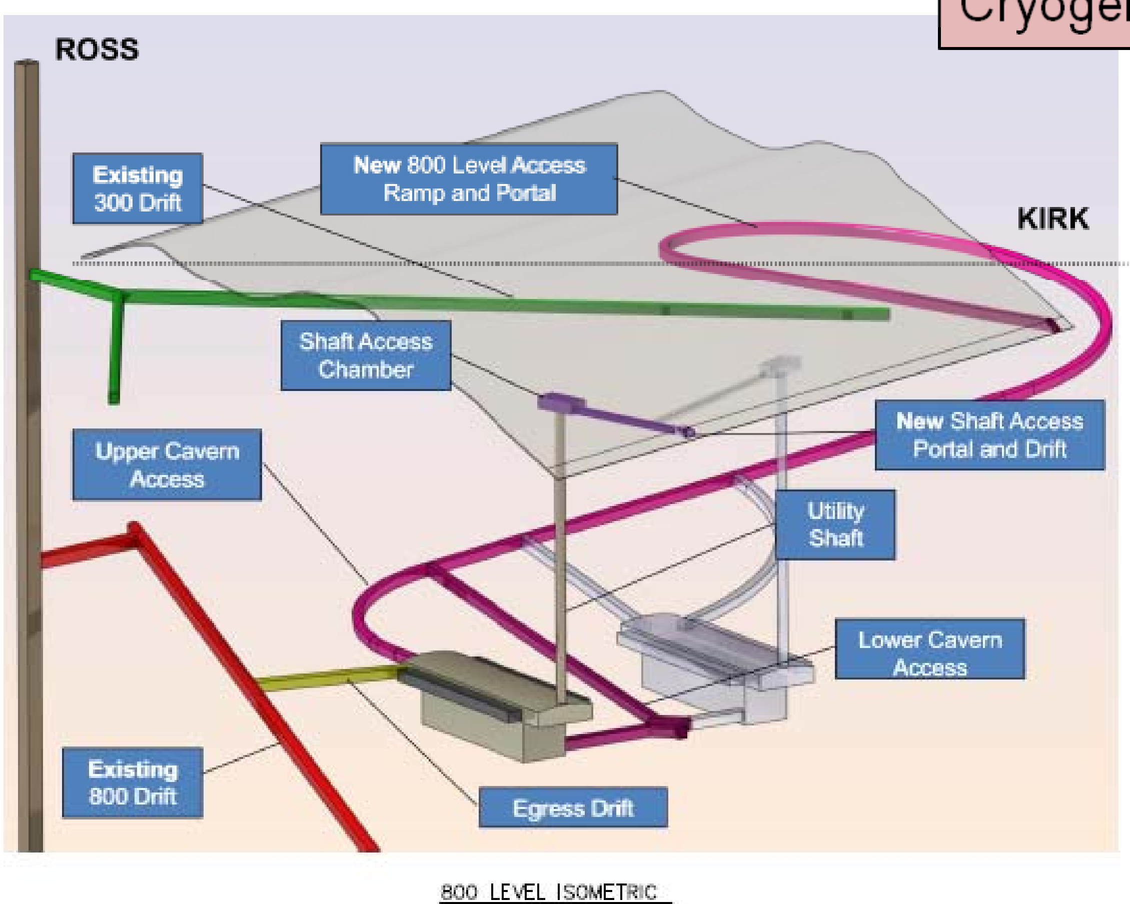


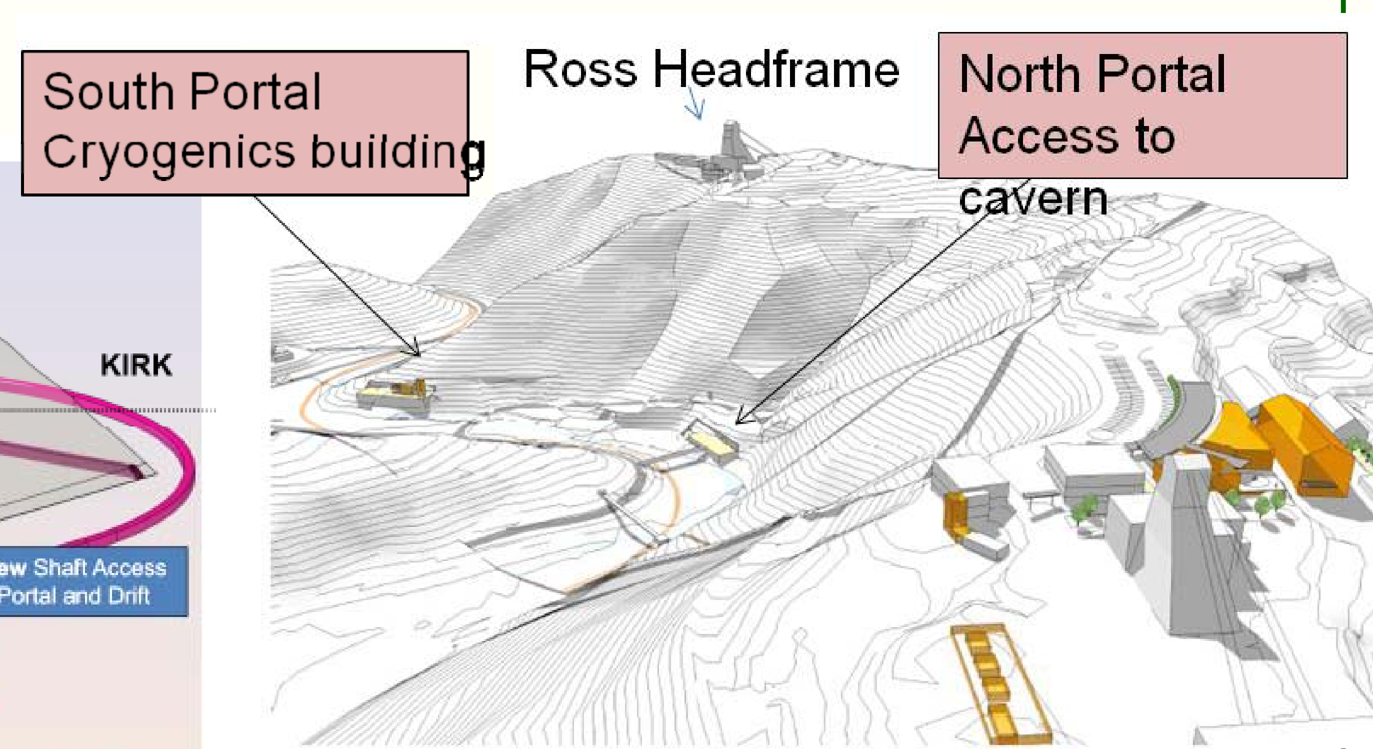
Water Cherenkov Detector



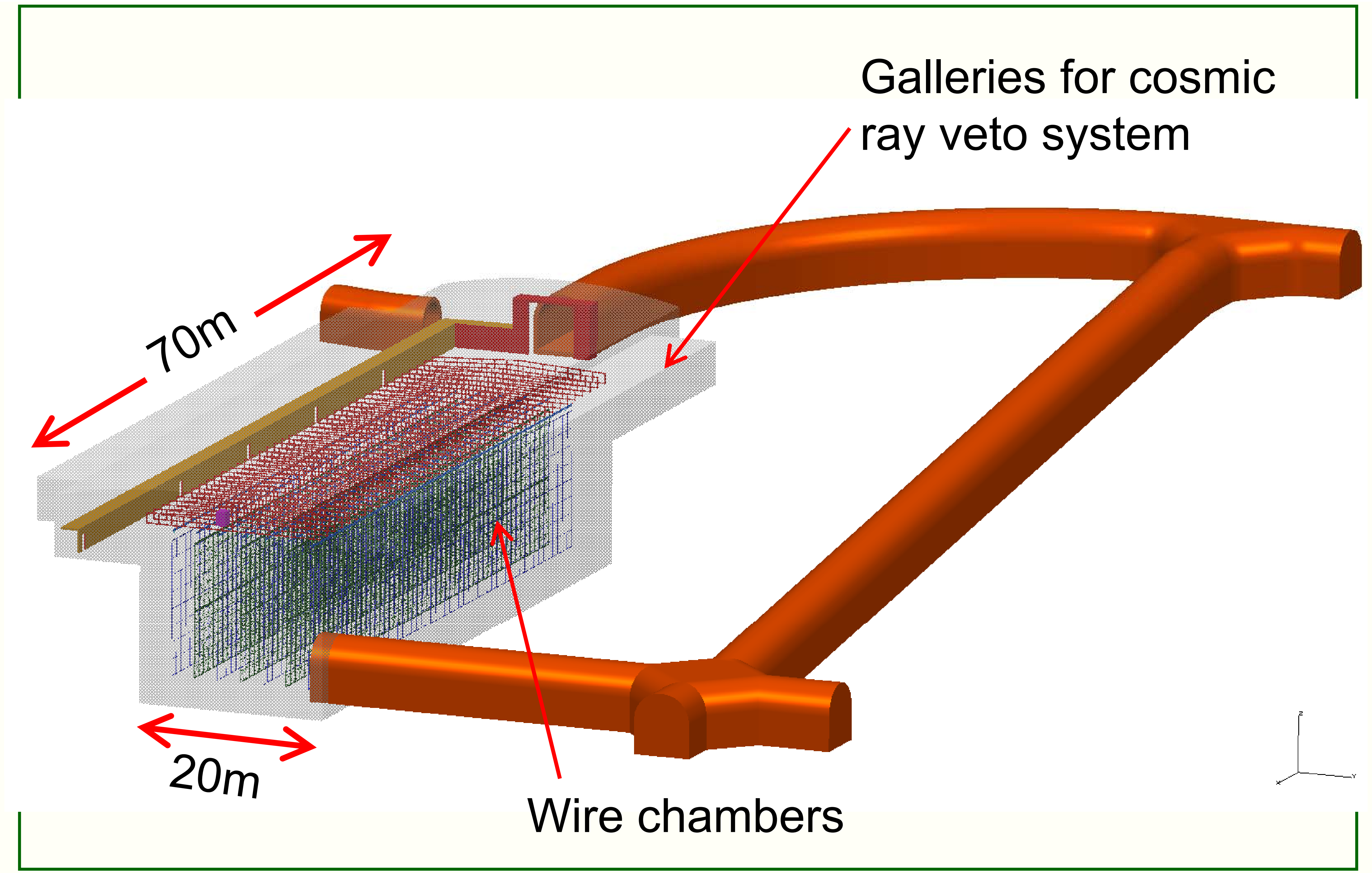
Liquid Argon TPC Far Detector

To be located 800 feet underground in DUSEL, in the old Homestake Gold Mine in Lead, SD

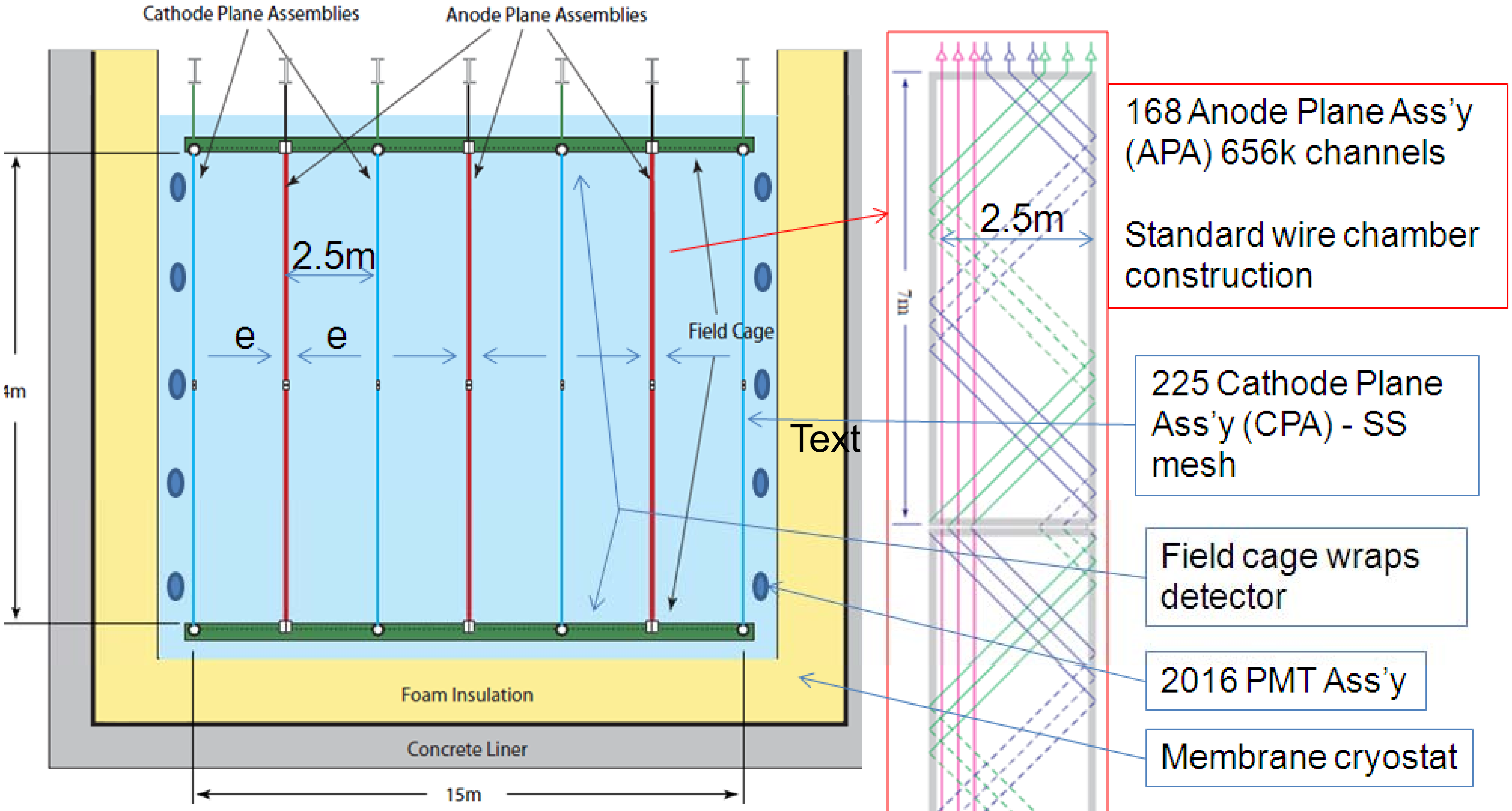




Liquid Argon TPC



Liquid Argon TPC



Also considering designs: 3.75 m drift; two detectors in a common cavern.

Time Line

LBNE Project Time Line

- DOE CD-0 (Approve Mission Need) January 2010
- CD-1 2nd half CY2011*
- CD-2 (Project baseline) depending on funding . . . mid/late FY2013
- CD-3 (start construction) depending on funding . . . 2014 ~ 2015
- Project complete : no sooner than 2020

Currently dealing with TPC (total project funding) issues and DOE-NSF partnership issues

45 Rameika - NNN10 Fermilab

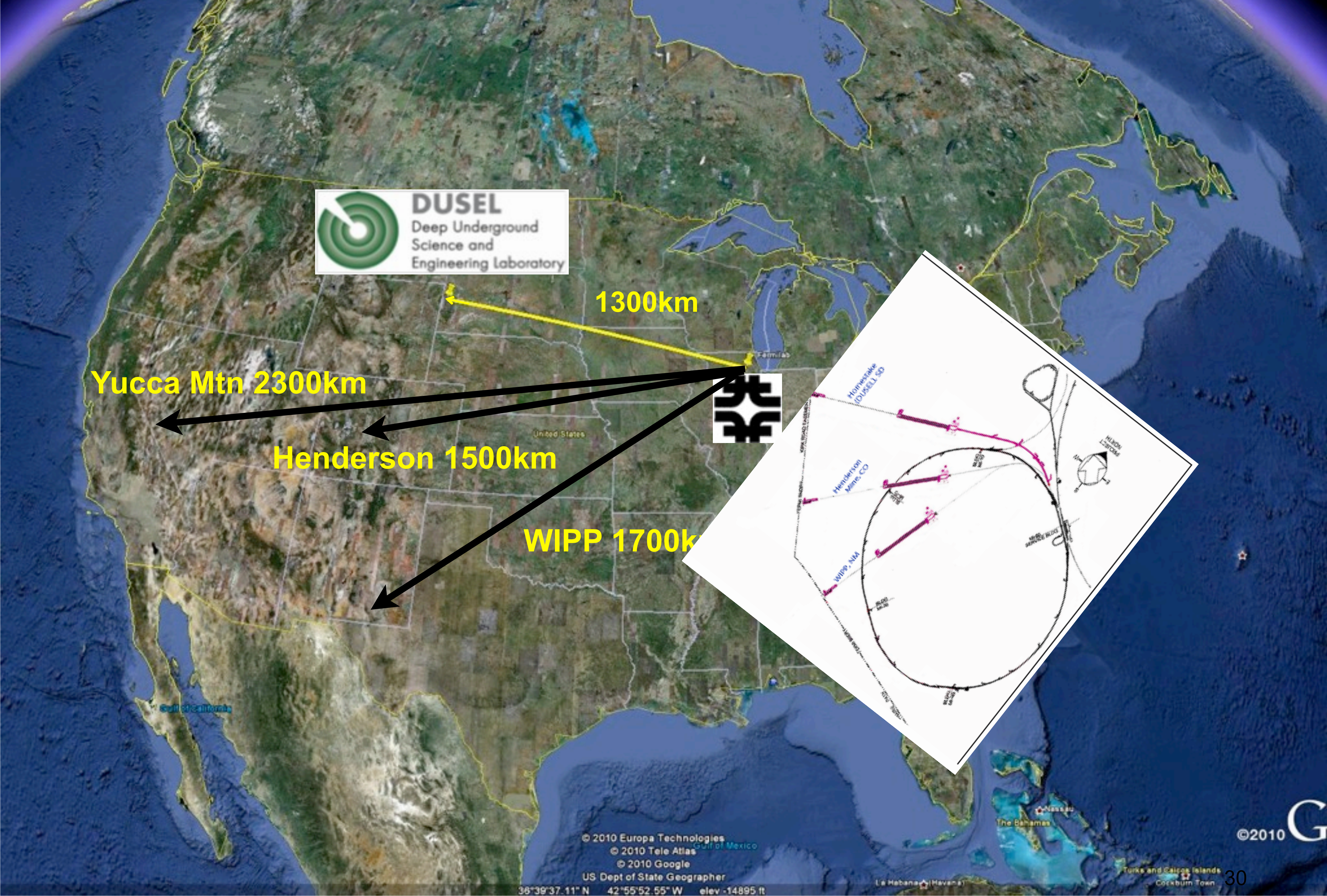
Alternative Sites

Alternative Sites

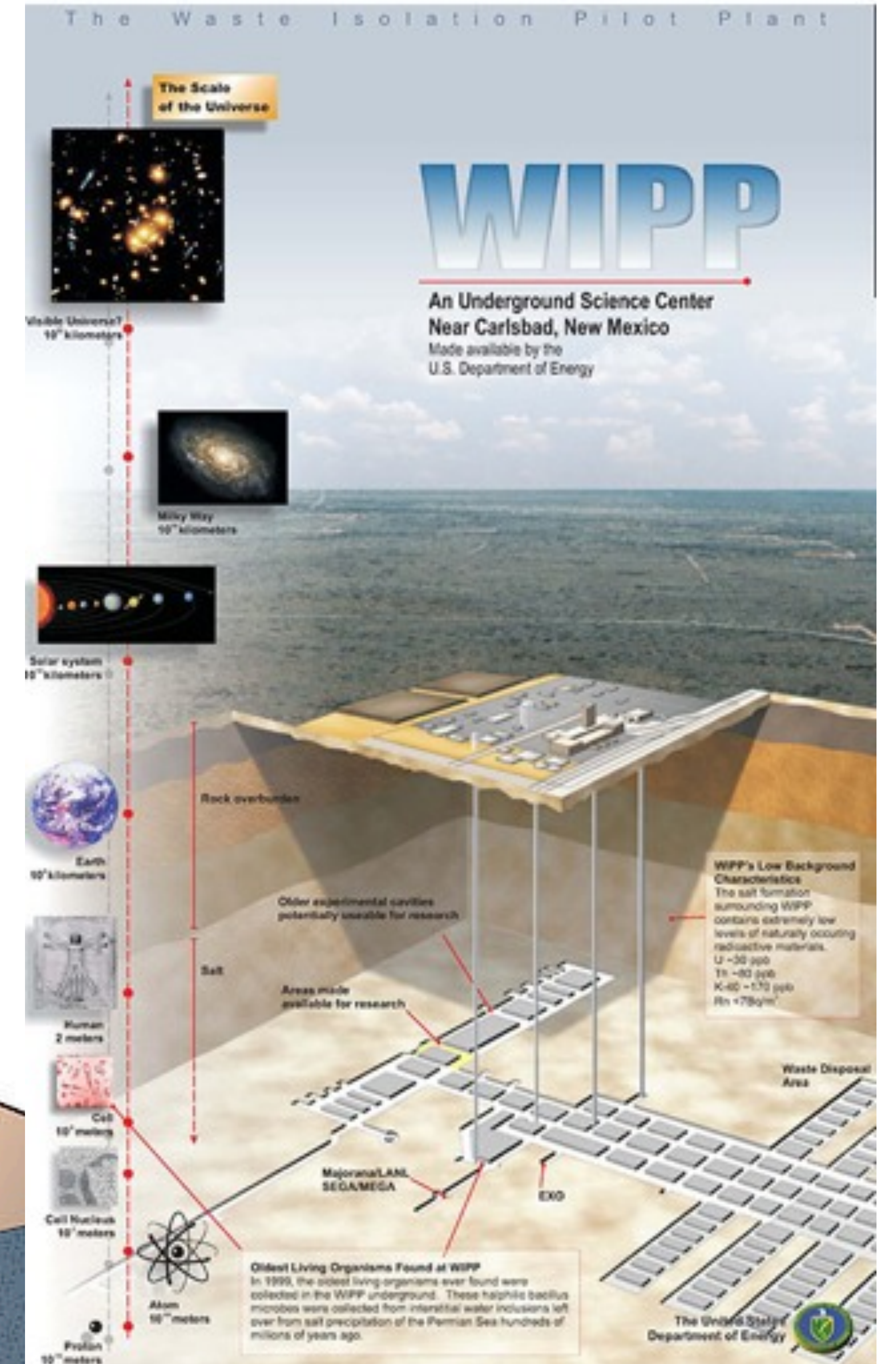
Alternative Sites

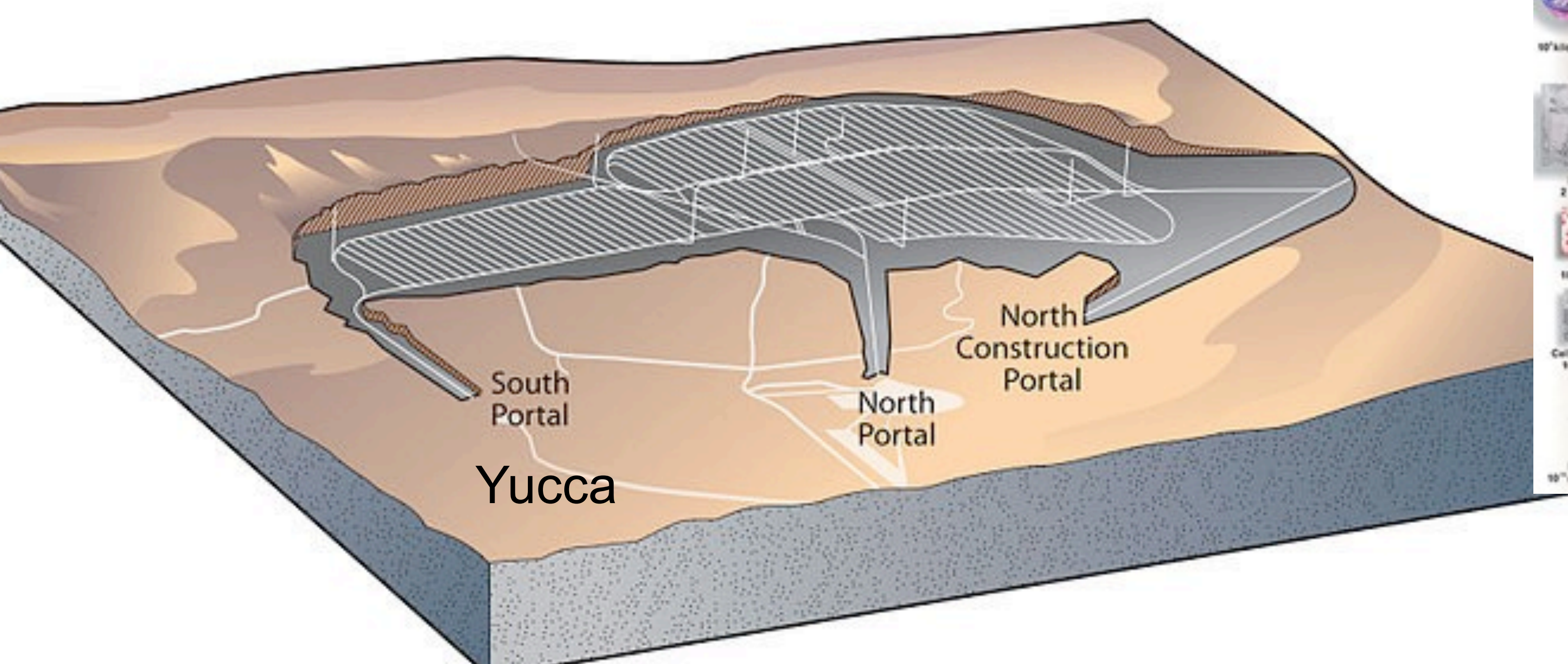
Alternative Sites

Alternative Sites



Henderson-WIPP-Yucca Mtn





In Matter:

Bi-Magic Baseline:

$$P_{\mu\rightarrow e} \approx |\ \sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}\ |^2$$

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\ \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\ \Delta_{31}$

and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\ \frac{\sin(aL)}{(aL)}\ \Delta_{21}$

$$a\ =\ G_F N_e/\sqrt{2}\ =\ (4000\ \ km)^{-1},$$

In Matter:

Bi-Magic Baseline:

$$P_{\mu\to e} \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}|^2$$

0

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\ \frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\ \Delta_{31}$

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Max for one Hierarchy and 0 other

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$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

Sushant K. Raut, Ravi Shanker Singh, S.Uma Sankar **arXiv:0908.3741**

Amol Dighe, Srubabati Goswami, Shamayita Ray **arXiv:1009.1093**

"Bi-Magic" Baseline and Energy

Choose L such that

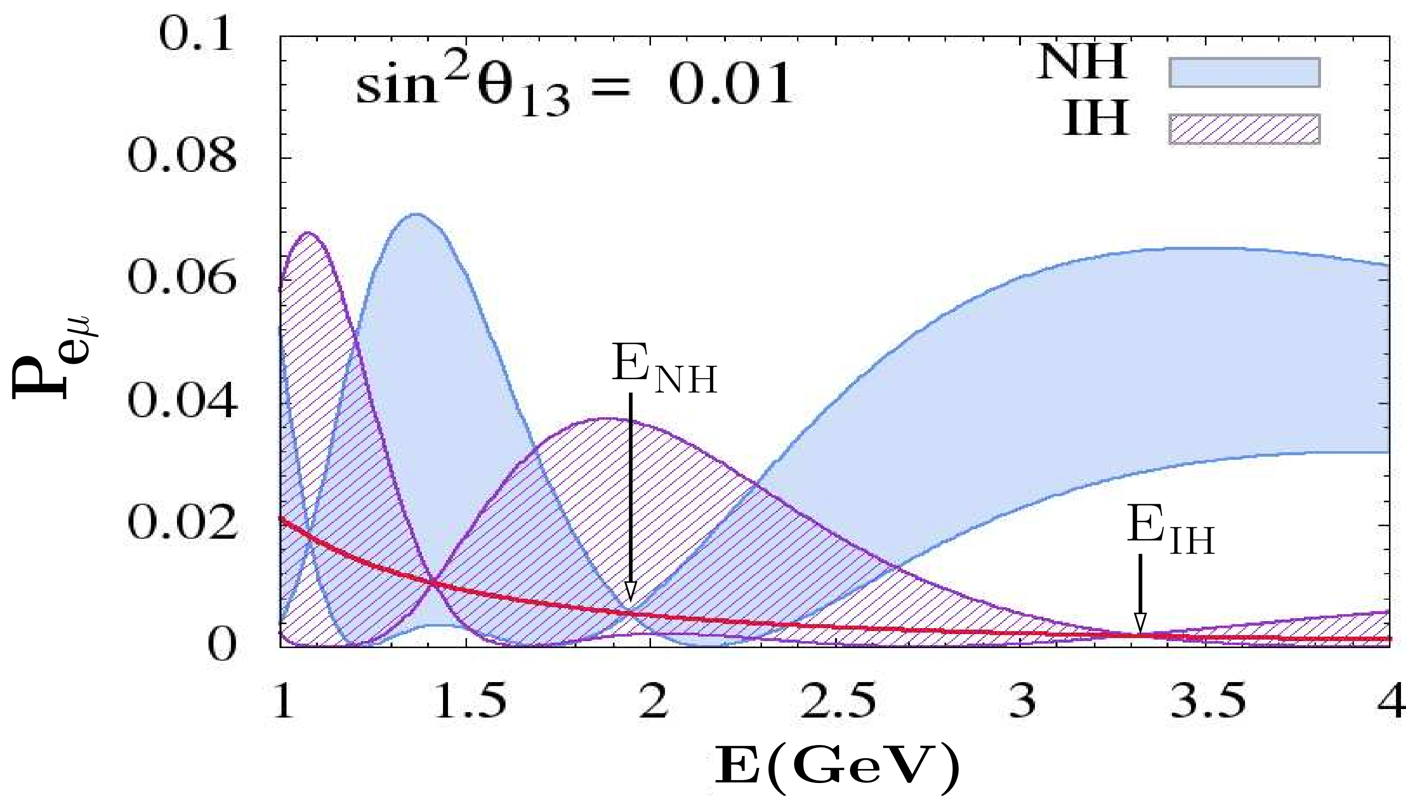
$P_{atm}|_{IH} = 0$ and $P_{atm}|_{NH}$ is max. at E_{IH}

and

$P_{atm}|_{NH} = 0$ and $P_{atm}|_{IH}$ is max. at E_{NH}

L=2540 km and E_{IH}=3.3 GeV and E_{NH}=1.9 GeV

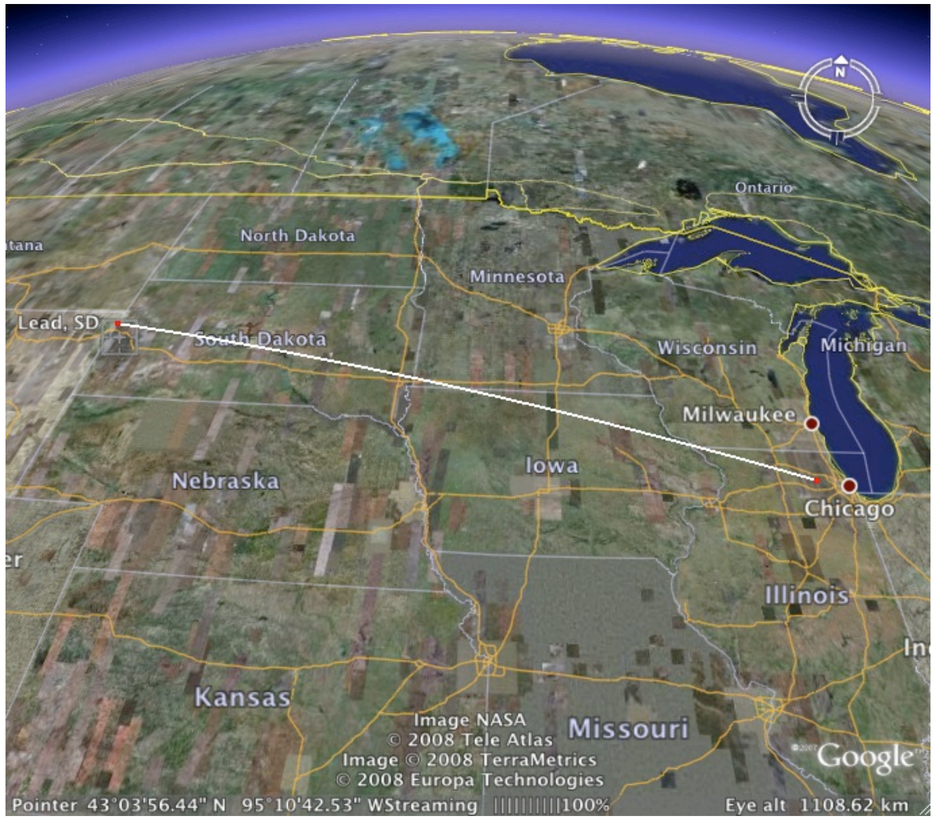
flip when ν and $\bar{\nu}$ interchange



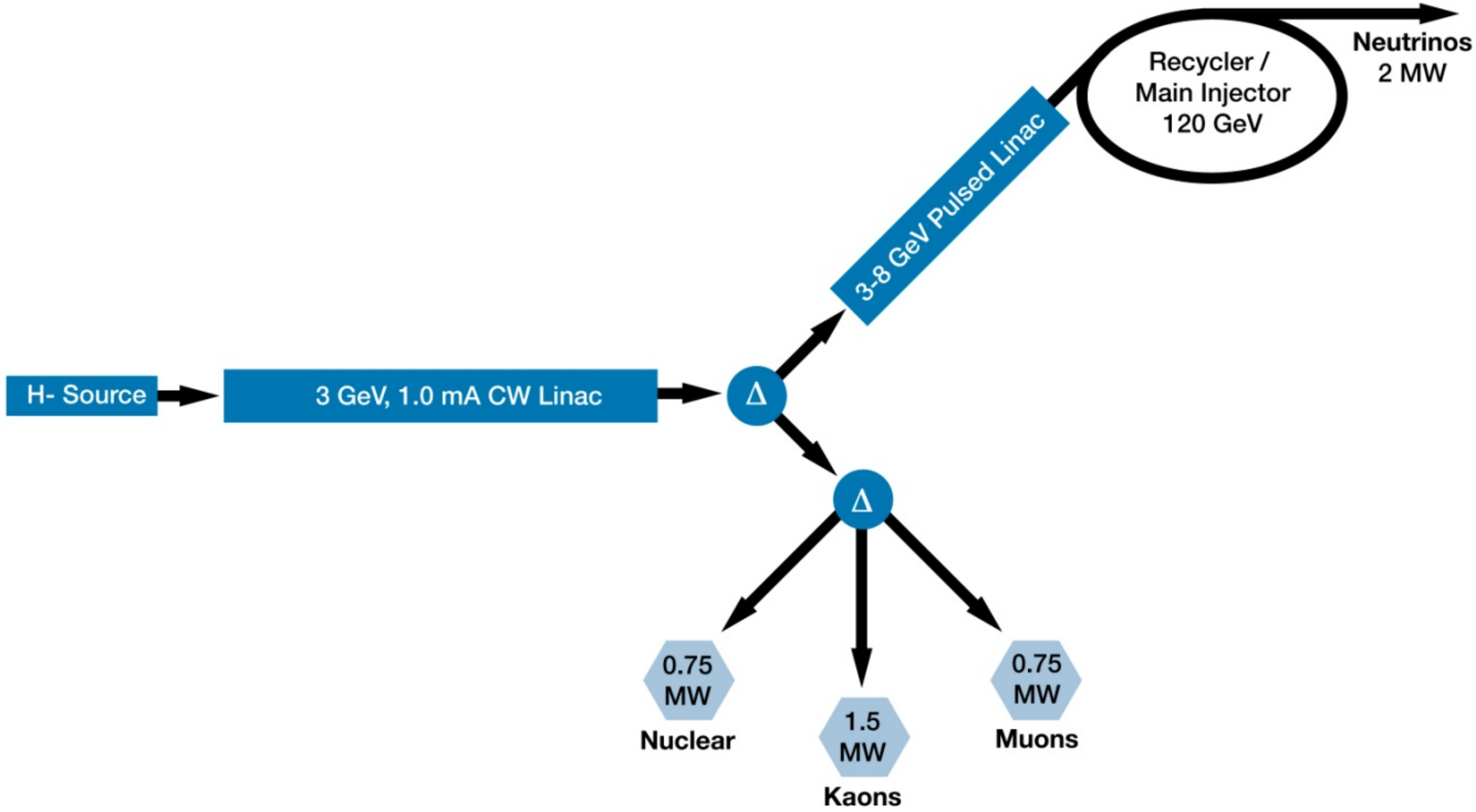
Approx. Fermilab to Yucca Mtn:

Project X

- A neutrino beam for long baseline neutrino oscillation experiments
  - 2 MW proton source at 60-120 GeV
- High intensity, low energy protons for kaon and muon based precision experiments
  - Operations simultaneous with the neutrino program
- A path toward a muon source for possible future Neutrino Factory and/or a Muon Collider
  - Requires ~4 MW at ~5-15 GeV
- Possible missions beyond P5
  - Standard Model Tests with nuclei and energy applications



Reference Design

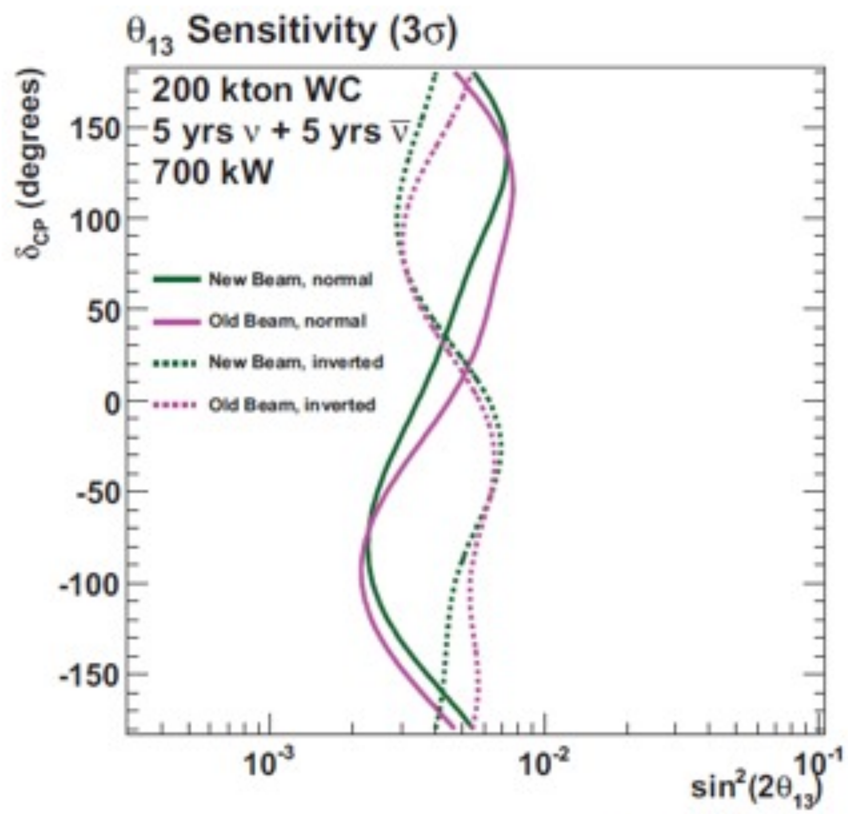


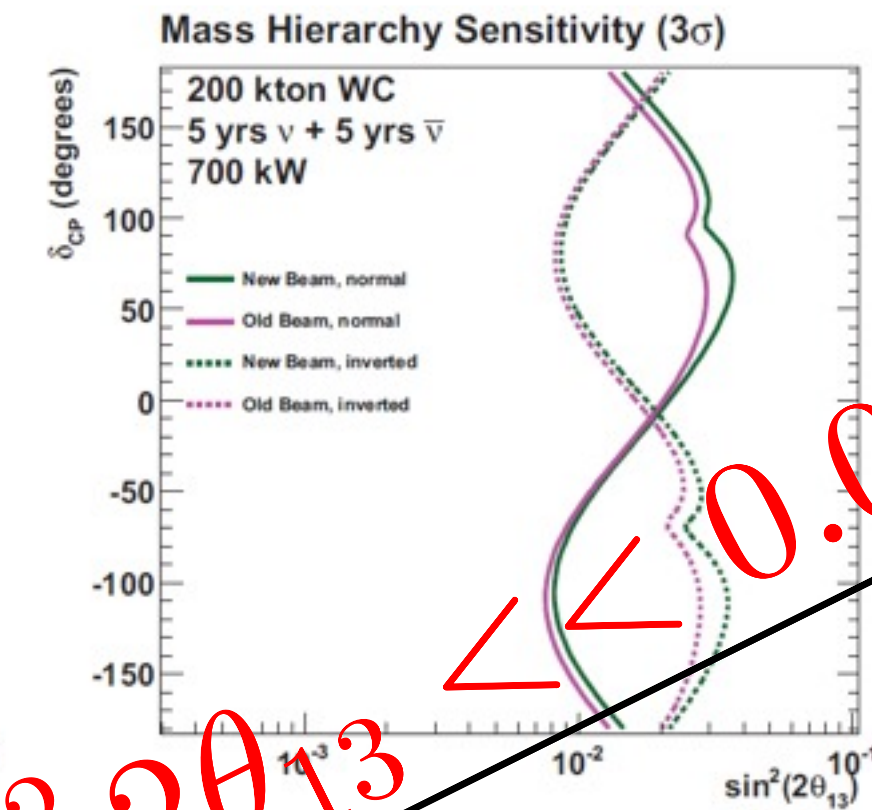
Reference Design Capabilities

- 3 GeV CW superconducting H- linac with 1 mA average beam current.
  - Flexible provision for variable beam structures to multiple users
    - CW at time scales >1 μsec, 10% DF at <1 μsec
  - Supports rare processes programs at 3 GeV
  - Provision for 1 GeV extraction for nuclear energy program
- 3-8 GeV pulsed linac capable of delivering 300 kW at 8 GeV
  - Supports the neutrino program
  - Establishes a path toward a muon based facility
- Upgrades to the Recycler and Main Injector to provide ≥ 2 MW to the neutrino production target at 60-120 GeV.

⇒ Utilization of a CW linac creates a facility that is unique in the world, with performance that cannot be matched in a synchrotron-based facility.

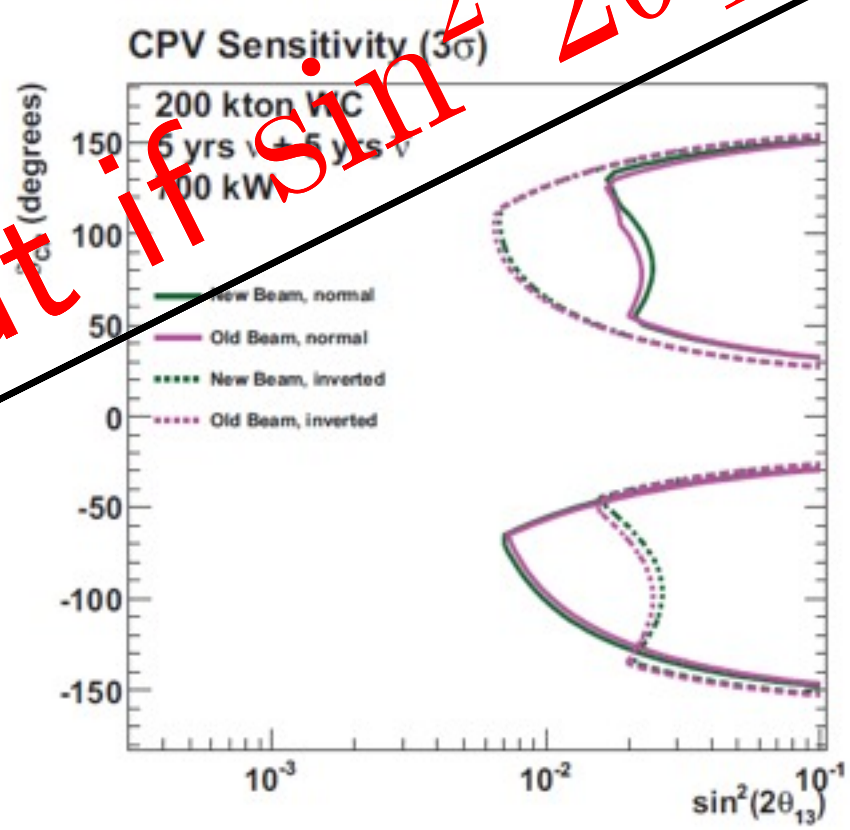
LBNE Sensitivities:





Sensitivities shown are for 200 ktons WCD.
With 34 ktons LAr, the sensitivities are equivalent.

What if $\sin^2 2\theta_{13} \ll 0.01$????

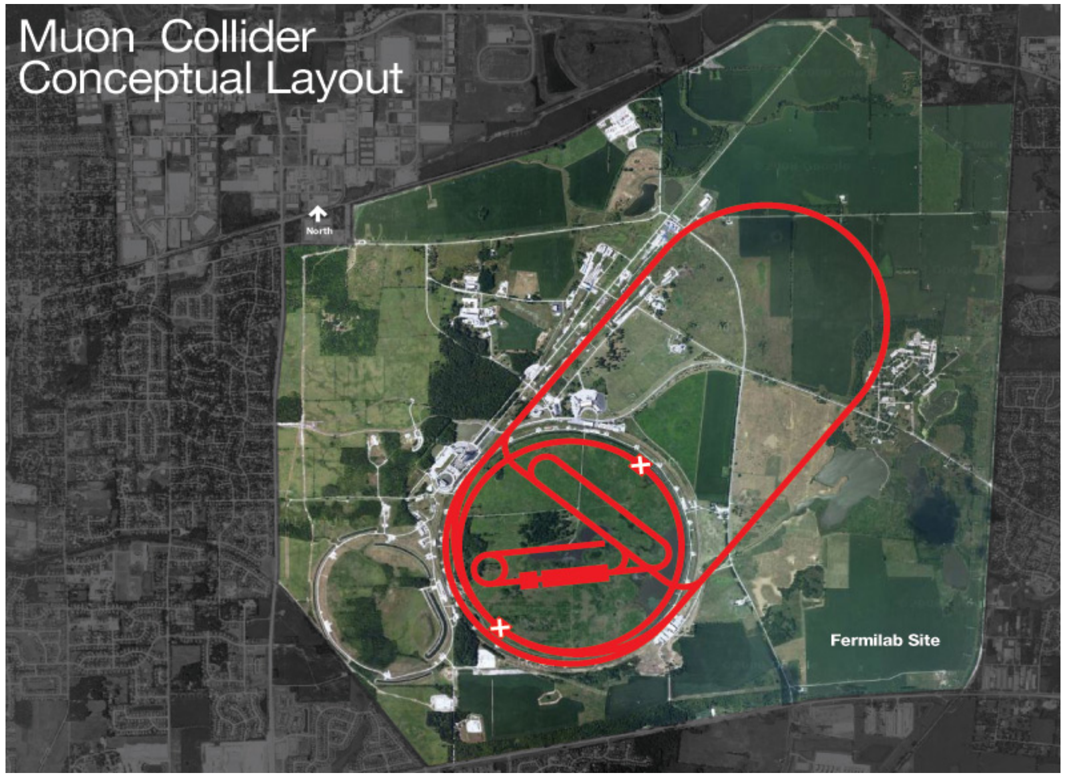


Sensitivities shown are for 10 years with 700 kW proton beam.
With Project X (≥2 MW), the same sensitivity would be reached in 1/3 the time … or ~$\sqrt{3}$ greater sensitivity for the same running period.

Fall 2010 Report from the LBNE Physics Working Group

Project X — Joint PX/NF/MC Strategy

- Project X shares many features with the proton driver required for a Neutrino Factory or Muon Collider
  - NF and MC require ~4 MW @ 10± 5 GeV
  - Primary issues are related to beam “format”
    - NF wants proton beam on target consolidated in a few bunches; Muon Collider requires single bunch
  - Project X linac is not capable of delivering this format



⇒ It is inevitable that a new ring(s) will be required to produce the correct beam format for targeting.

IHEP Workshop - S. Holmes

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Project X: Time Line

Project X Timeline

- Assumed Critical Decision dates
  - CD-0: January 2011
  - CD-1: July 2012
  - CD-2: August 2013
  - CD-3: September 2014
  - CD-4: September 2019

5 yr construction

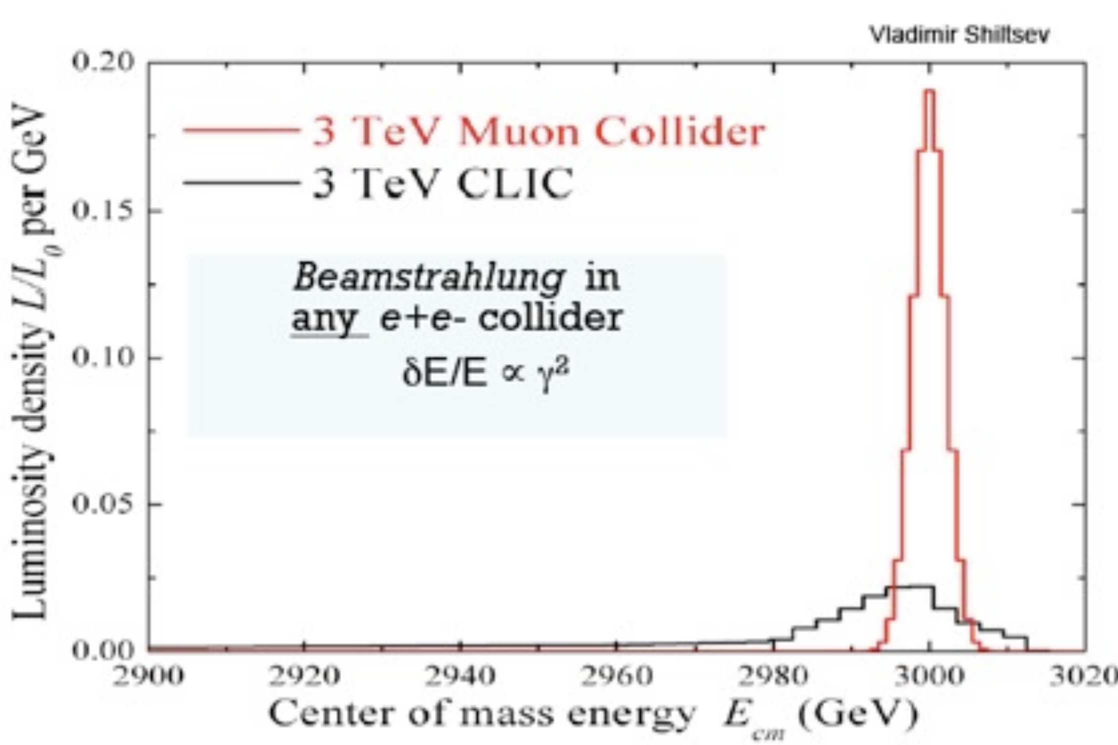
Project X could also be up and running in ~2020 :

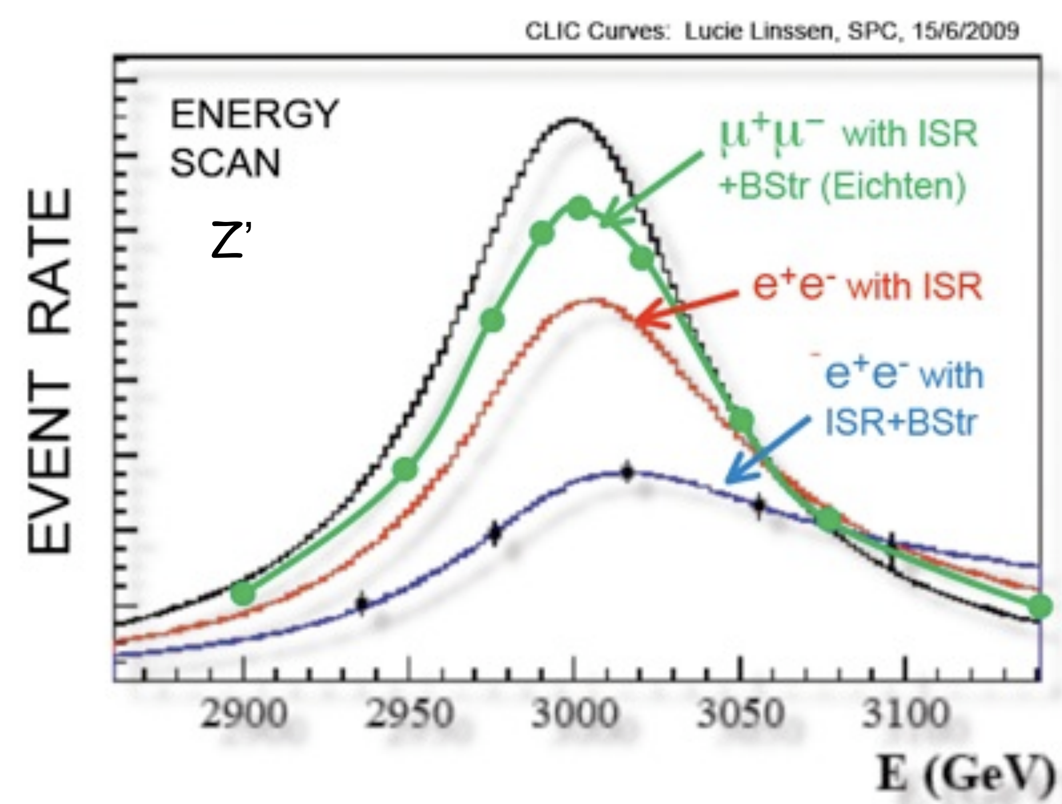
All depends on funding profiles…

46 Rameika - NNN10 Fermilab

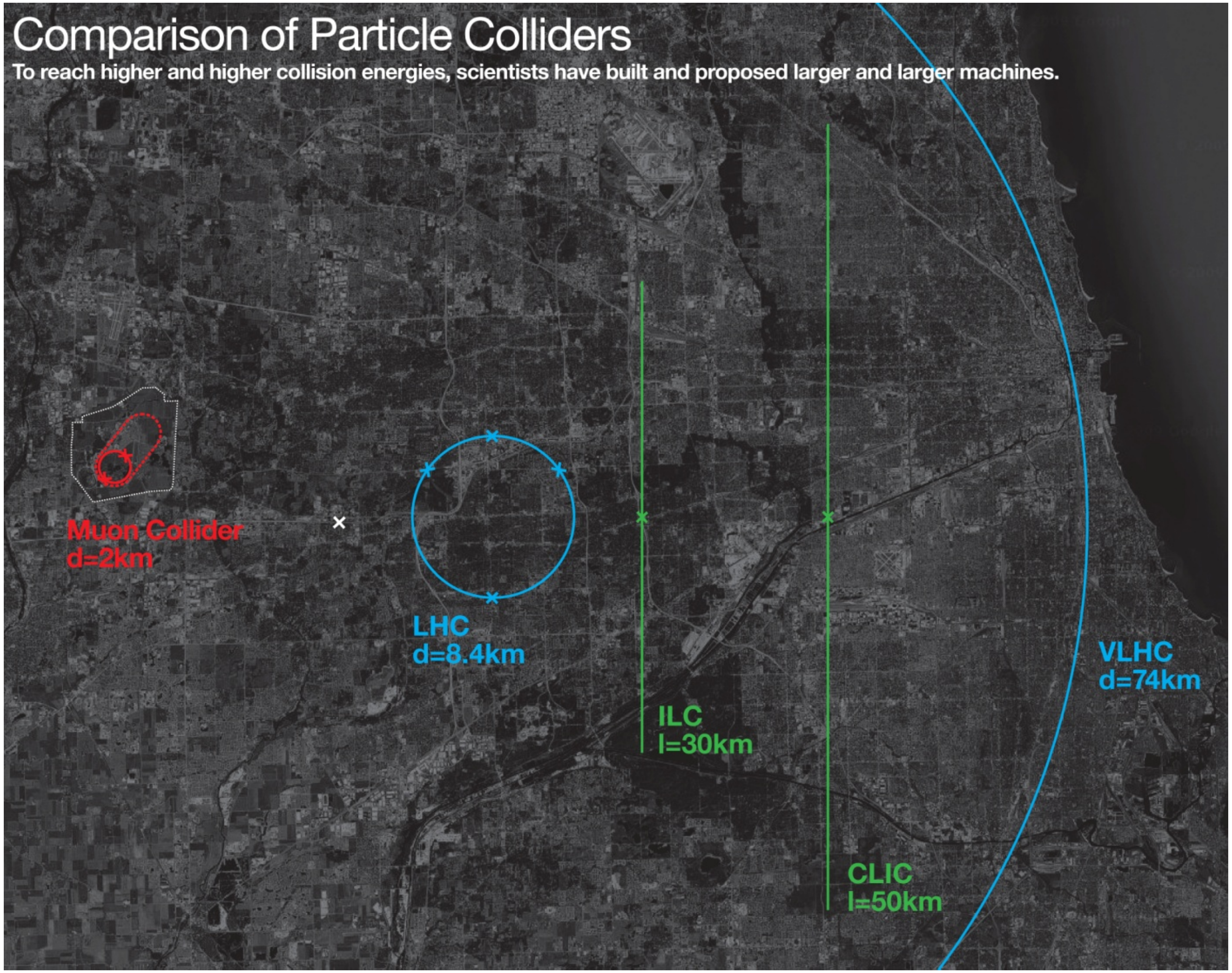
Muon Collider

- $\mu^+\mu^-$ Collider:
- Center of Mass energy: 1.5 - 5 TeV (focus 3 TeV)
- Luminosity > 10^{34} cm^{-2} sec^{-1} (focus 400 fb^{-1} per year)
- Compact facility
- Superb Energy Resolution
  - MC: 95% luminosity in dE/E ~ 0.1%
  - CLIC: 35% luminosity in dE/E ~ 1%





Muon Collider:



Minimum Luminosity for Muon Collider

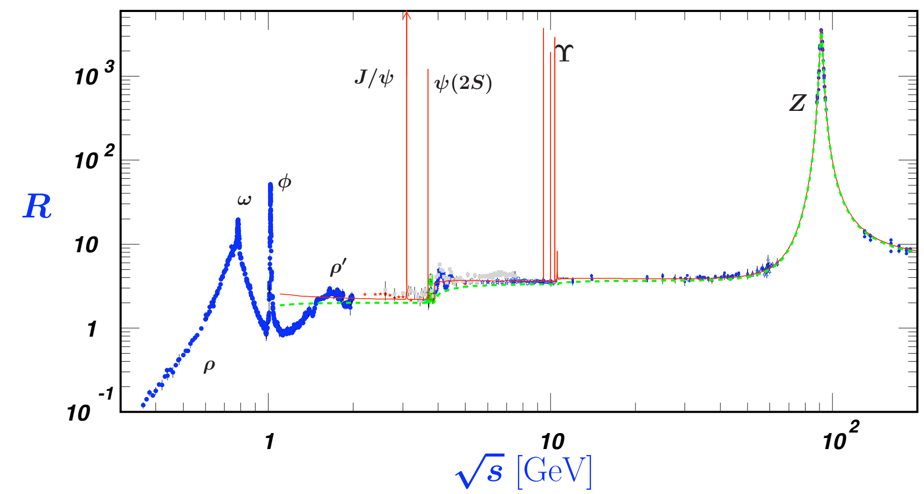
- Universal behavior for s-channel resonance

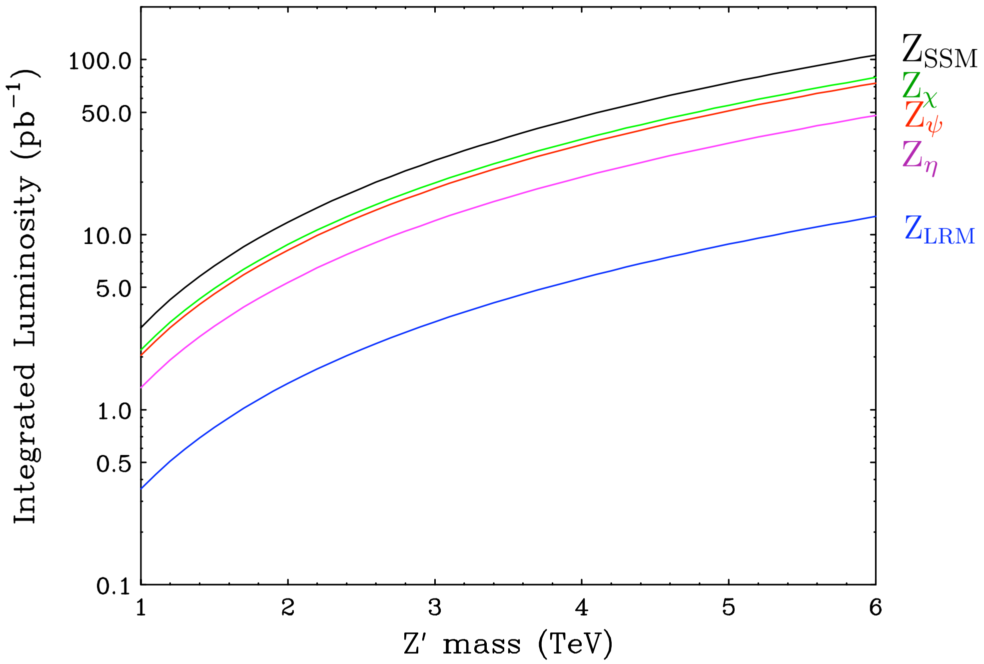
$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k^2} \left[\frac{\Gamma^2/4}{(E-E_0)^2+\Gamma^2/4}\right] B_{in} B_{out}$$

Convolute with beam resolution ΔE.
If $\Delta E \ll \Gamma$

$$R_{\text{peak}} = (2J+1) 3 \frac{B(\mu^+\mu^-) B(visible)}{\alpha^2_{\text{EM}}}$$

- Can use to set minimum required luminosity
  - Likely new physics candidates:
    - scalars: h, H^0, A^0,...
    - gauge bosons: Z′
    - new dynamics: bound states
    - ED: KK modes
  - Example – new gauge boson: Z′
    - SSM, E6, LRM
    - 5σ discovery limits: 4-5 TeV at LHC (@ 300 fb^{-1})

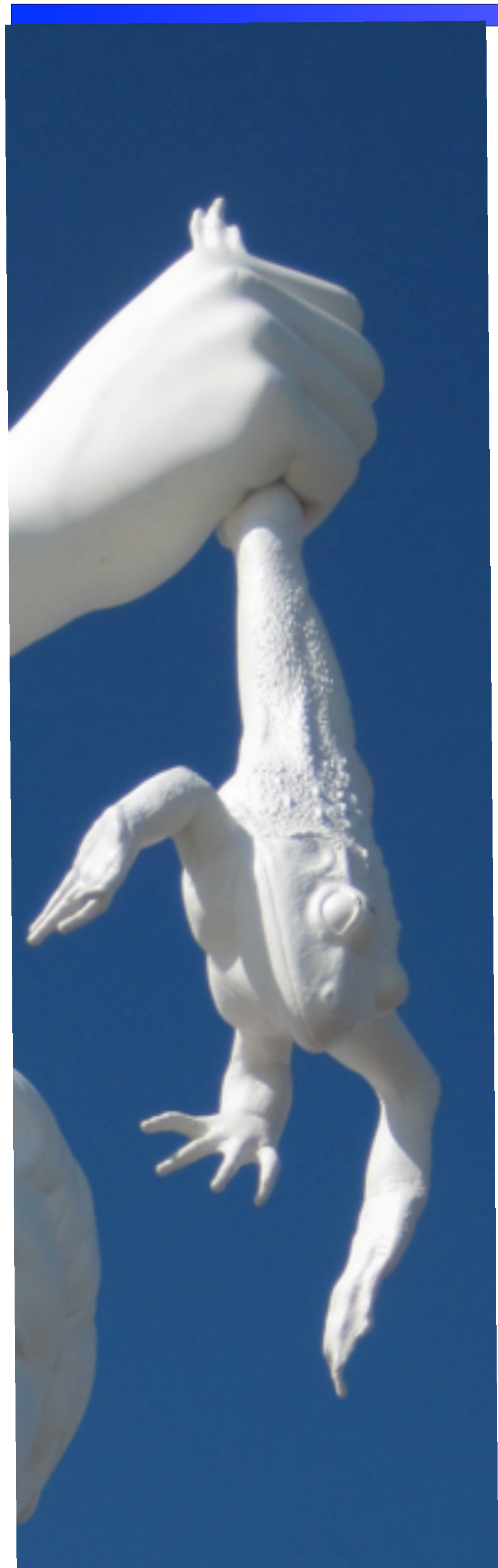




The integrated luminosity required to produce 1000 $\mu^+\mu^-$ -> Z′ events on the peak

Minimum luminosity at Z′ peak:
$\mathcal{L}$ = 0.5-5.0 x 10^{30} cm^{-2} sec^{-1}
for M(Z′) -> 1.5-5.0 TeV

Summary:



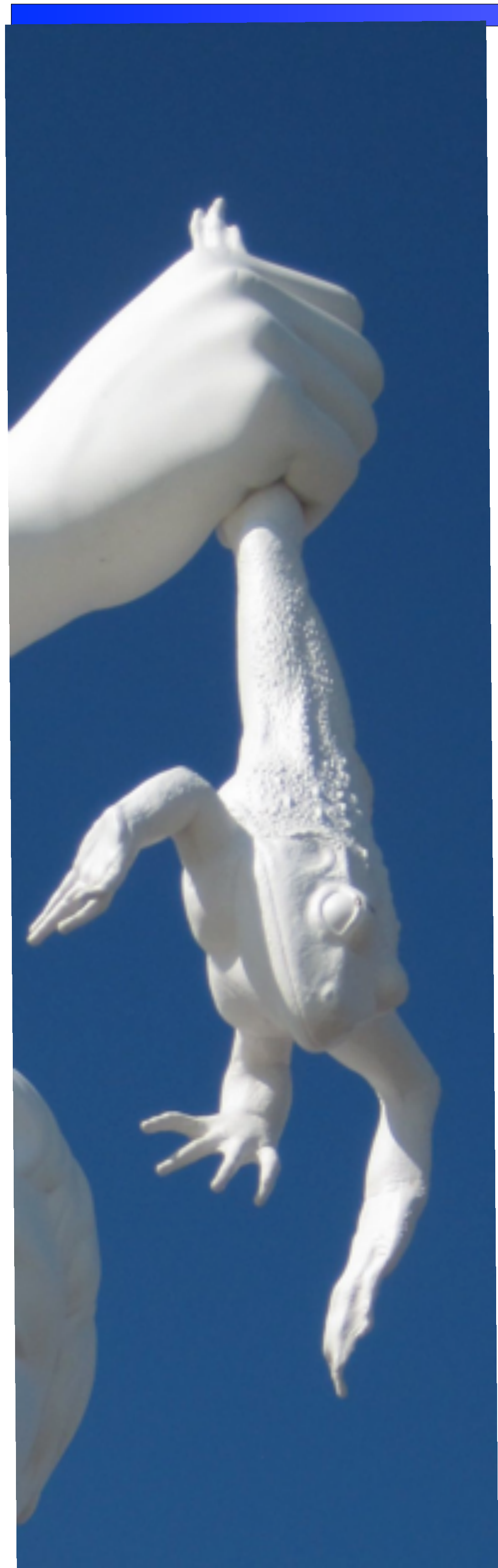
- LBNE: Fermilab to DUSEL (or ?) will probe leptonic CPV and determine the mass hierarchy down to $\sin^2 2\theta_{13} \sim 0.01$

- Project X: Increases the beam power from 700kW to 2MW and provide another 3MW at 3 GeV for K's, μ/s, ...

- If $\sin^2 2\theta_{13} < 0.01$ a Neutrino Factory is a possible option. Maybe Low Energy NuF.

- This could be a natural stepping stone to a Muon Collider. New physics such as a Z' would make this very compelling.

Summary:



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funding ?

extras

LBNE Collaboration

288 Scientists and Engineers
57 Institutions
… And still growing!

Alabama: J. Goon, I Stancu
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Pennsylvania: J. Klein, K. Lande, A. Mann, M. Newcomer, R. vanBerg
Pittsburgh: D. Naples, V. Paolone
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Rochester: R. Bradford, K. McFarland
SDMST: X. Bai, R. Corey
SMU: T. Liu, J. Ye
South Carolina: H. Duyang, S. Mishra, R. Petti, C. Rosenfeld
South Dakota State: B. Bleakley, K. McTaggert
Texas: S. Kopp, K. Lang, R. Mehdiyev
Tufts: H. Gallagher, T. Kafka, W. Mann, J. Schnepps
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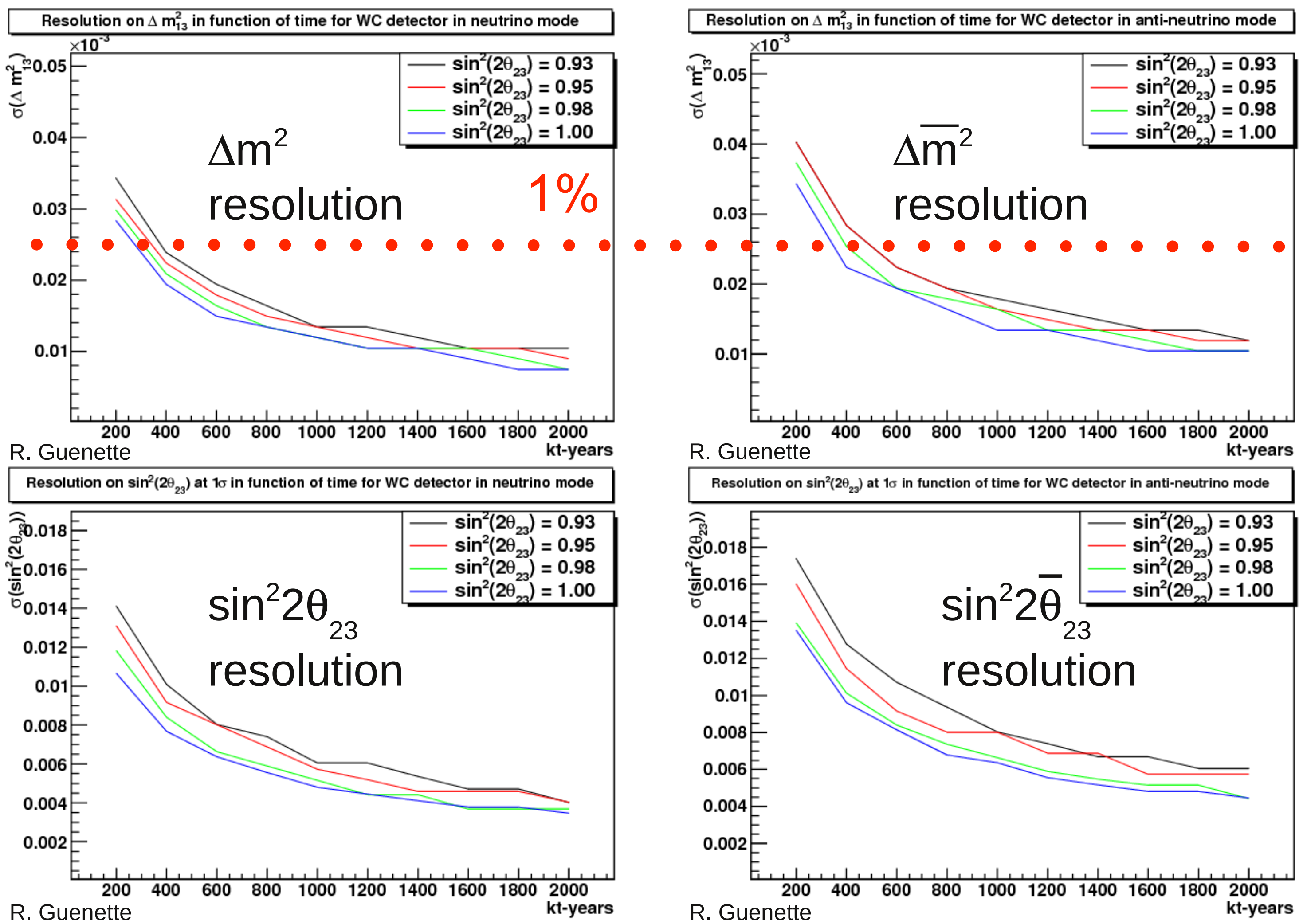
Wisconsin: B. Balantekin, F. Feyzi, K. Heeger, A. Karle, R. Maruyama, D. Webber, C. Wendt
Yale: E. Church, B. Fleming, R. Guenette, M. Soderberg, J. Spitz

Resolution:

What's measured



hep-ph/0503283

$$\delta m^2_{\mu\mu} = \frac{|U_{\mu 1}|^2\ \delta m^2_{31} + |U_{\mu 2}|^2\ \delta m^2_{32}}{|U_{\mu 1}|^2 + |U_{\mu 2}|^2}$$

$$= \delta m^2_{32} + [\sin^2\theta_{12} + \mathcal{O}(\sin\theta_{13})]\ \delta m^2_{21}$$

$$|\delta m^2_{32}| = |\delta m^2_{\mu\mu}|(1 \mp 0.01)$$

1% difference:
sign depends on hierarchy