Opportunities and Status: Long-Baseline Neutrino Experiment in the US

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Exploring the Neutrino Sky and Fundamental Particle Physics on the Megaton Scale”

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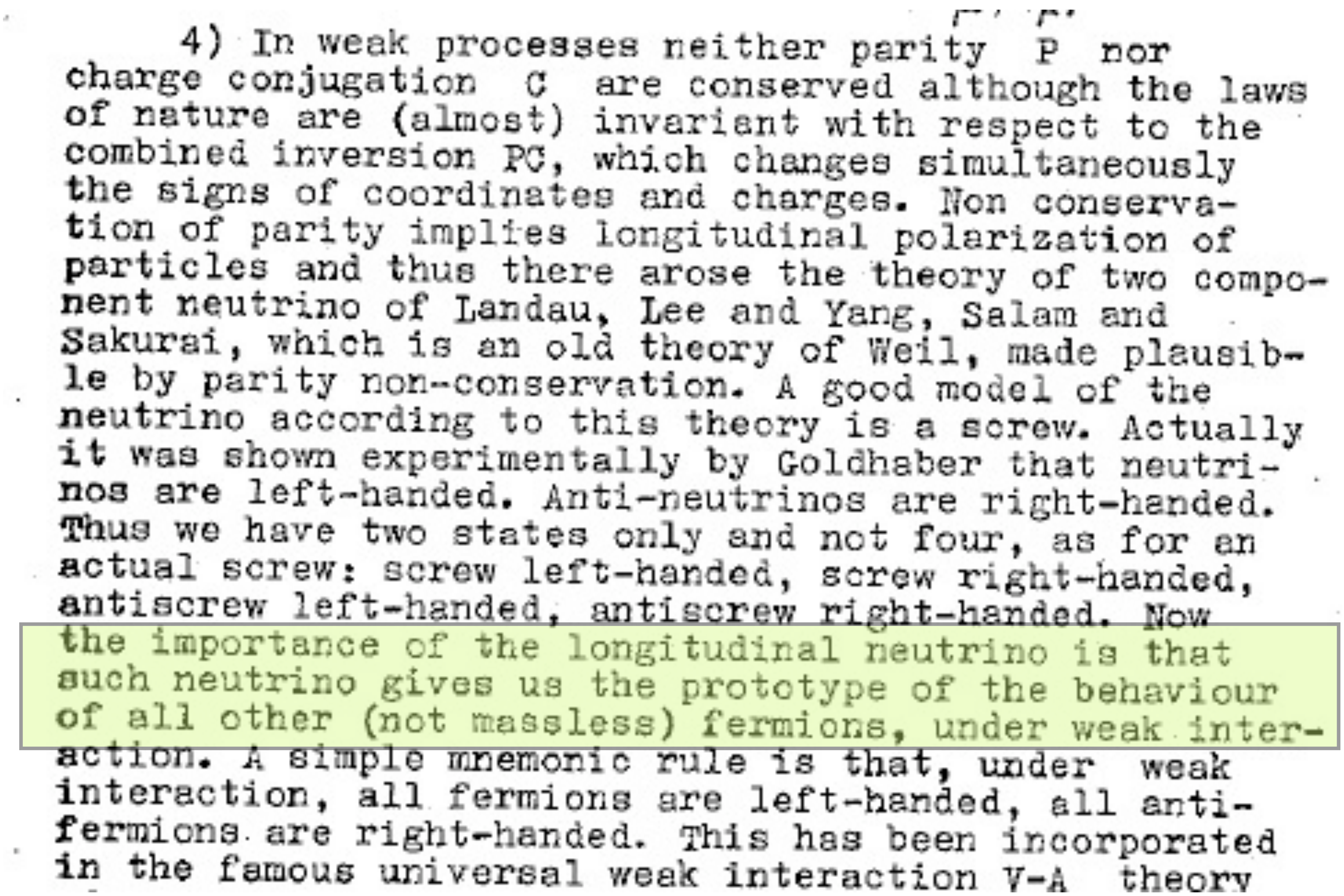
Wilhelm and Else Heraeus Seminar

BROOKHAVEN
NATIONAL LABORATORY

Outline

- Neutrino properties summary. What do we know and what do we want to measure ?
- Why a new accelerator Long-Baseline experiment ? How much flux, energy, event rate can we get ? What limitations ?
- Strategies for the detector. What are the key differences between a water detector and a tracking calorimeter ?
- What is the full physics agenda ?
- Technical information for a liquid argon TPC.
- Description and Status of LBNE (US) design.

Why Neutrinos ?

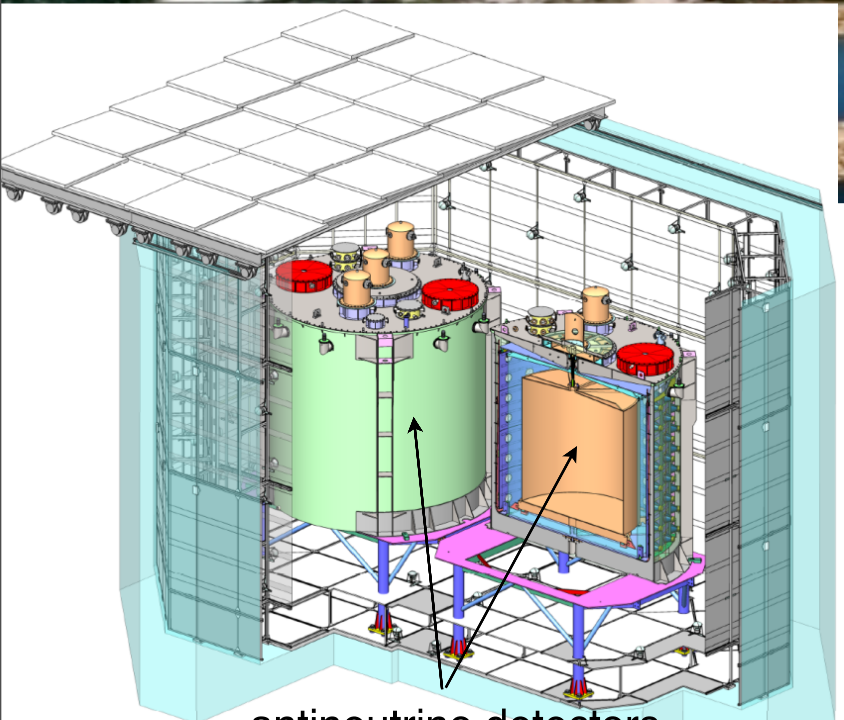


4) In weak processes neither parity P nor charge conjugation C are conserved although the laws of nature are (almost) invariant with respect to the combined inversion PC, which changes simultaneously the signs of coordinates and charges. Non conservation of parity implies longitudinal polarization of particles and thus there arose the theory of two component neutrino of Landau, Lee and Yang, Salam and Sakurai, which is an old theory of Weil, made plausible by parity non-conservation. A good model of the neutrino according to this theory is a screw. Actually it was shown experimentally by Goldhaber that neutrinos are left-handed. Anti-neutrinos are right-handed. Thus we have two states only and not four, as for an actual screw: screw left-handed, screw right-handed, antiscrew left-handed, antiscrew right-handed. Now the importance of the longitudinal neutrino is that such neutrino gives us the prototype of the behaviour of all other (not massless) fermions, under weak interaction. A simple mnemonic rule is that, under weak interaction, all fermions are left-handed, all anti-fermions are right-handed. This has been incorporated in the famous universal weak interaction V-A theory

Pontecorvo 1981

Daya Bay θ_{13} Results

Sometimes nature is kind !



antineutrino detectors

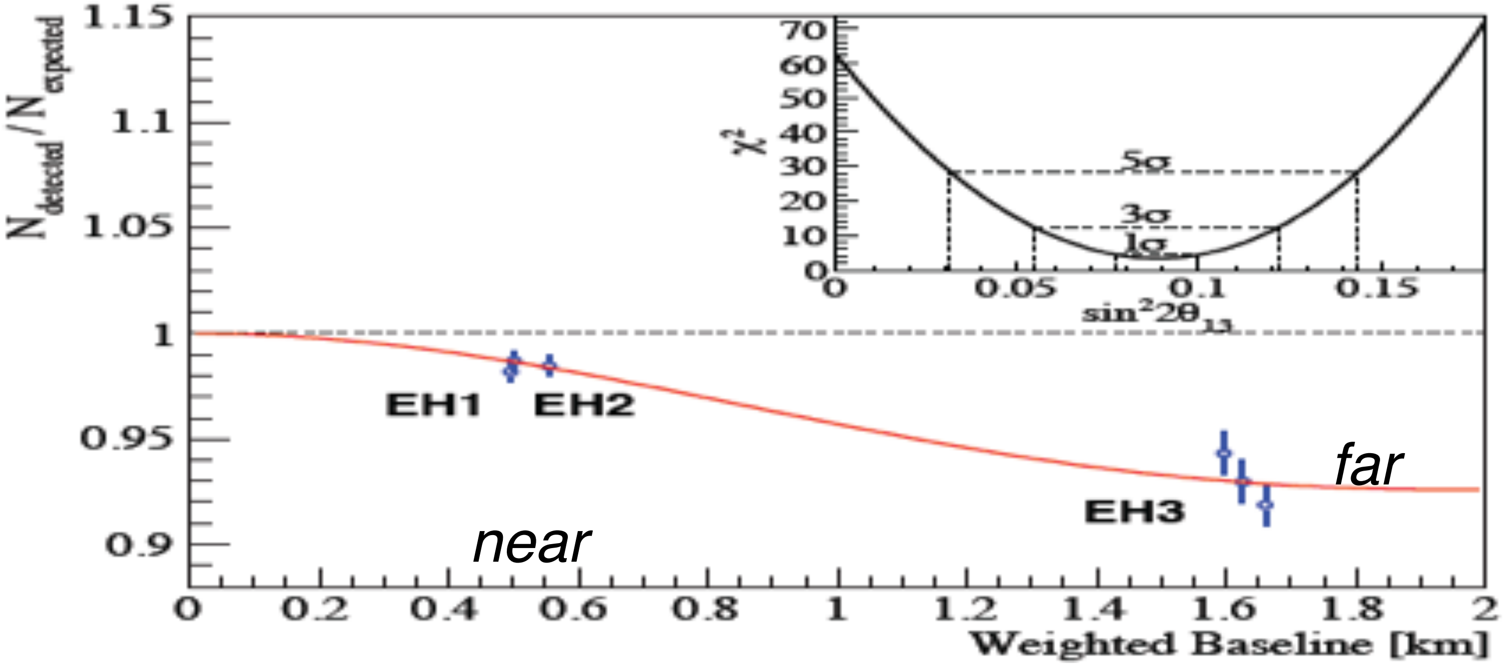
Observe electron-antineutrino disappearance

six 2.9 GWth reactors

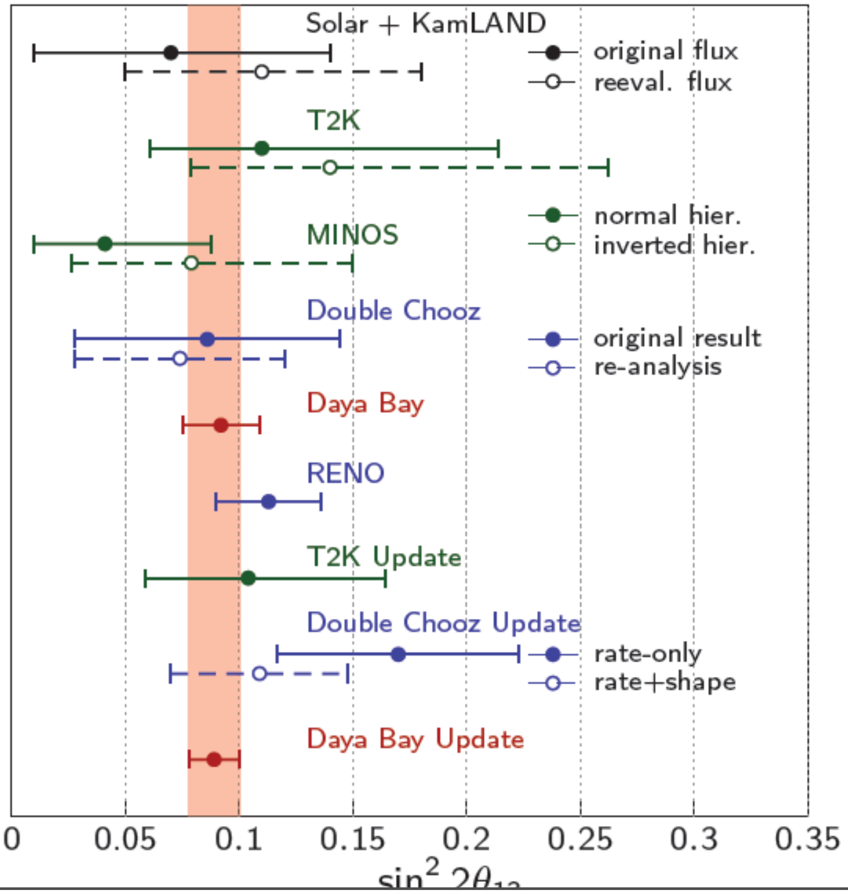
six 20-ton detectors: 3 near (~500m), 3 far (~1650m)

139 days of running

$\sin^2 2\theta_{13}$=0.089+-0.010(stat)+-0.005(syst)



Rate only. Normalization floating



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu2}|^2 + |U_{\tau2}|^2$ – solar data;
- $|U_{e2}|^2|U_{e1}|^2$ – KamLAND;
- $|U_{\mu3}|^2(1 - |U_{\mu3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2(1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2|U_{\mu3}|^2$ (upper bound → hint) – MINOS, T2K.

We still have a ways to go!

S. Parke

Best fit to all data.

arXiv:1205.5254v3 Fogli et al

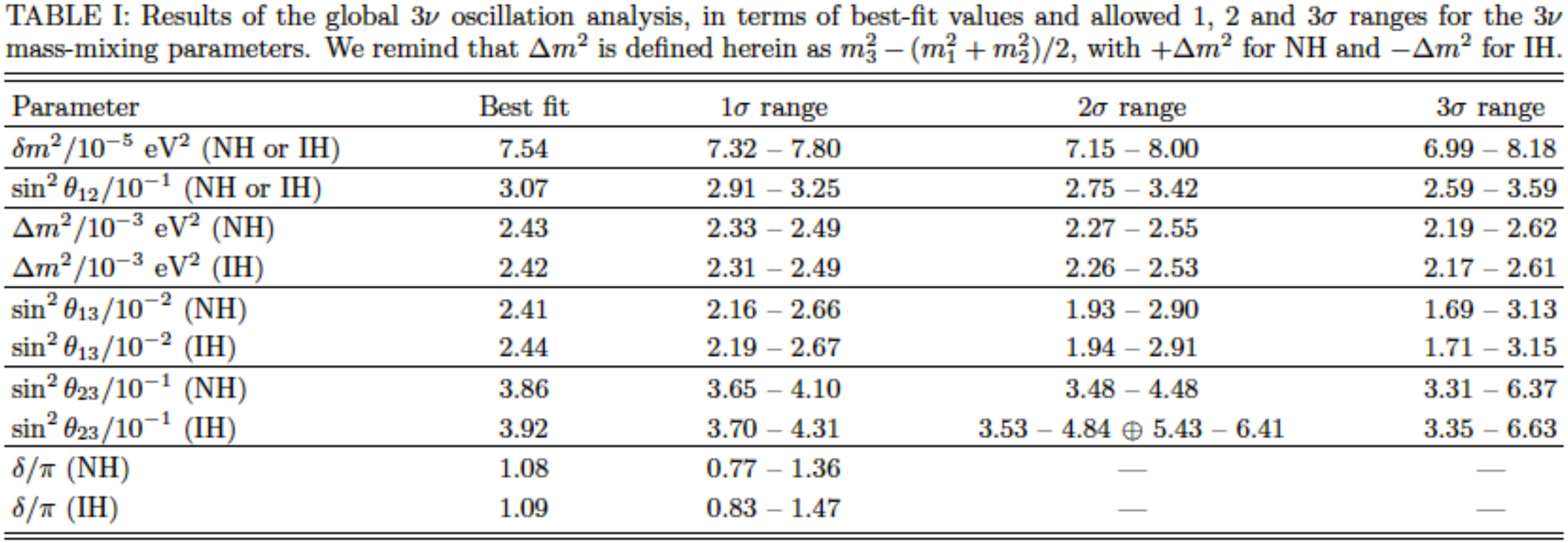


TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

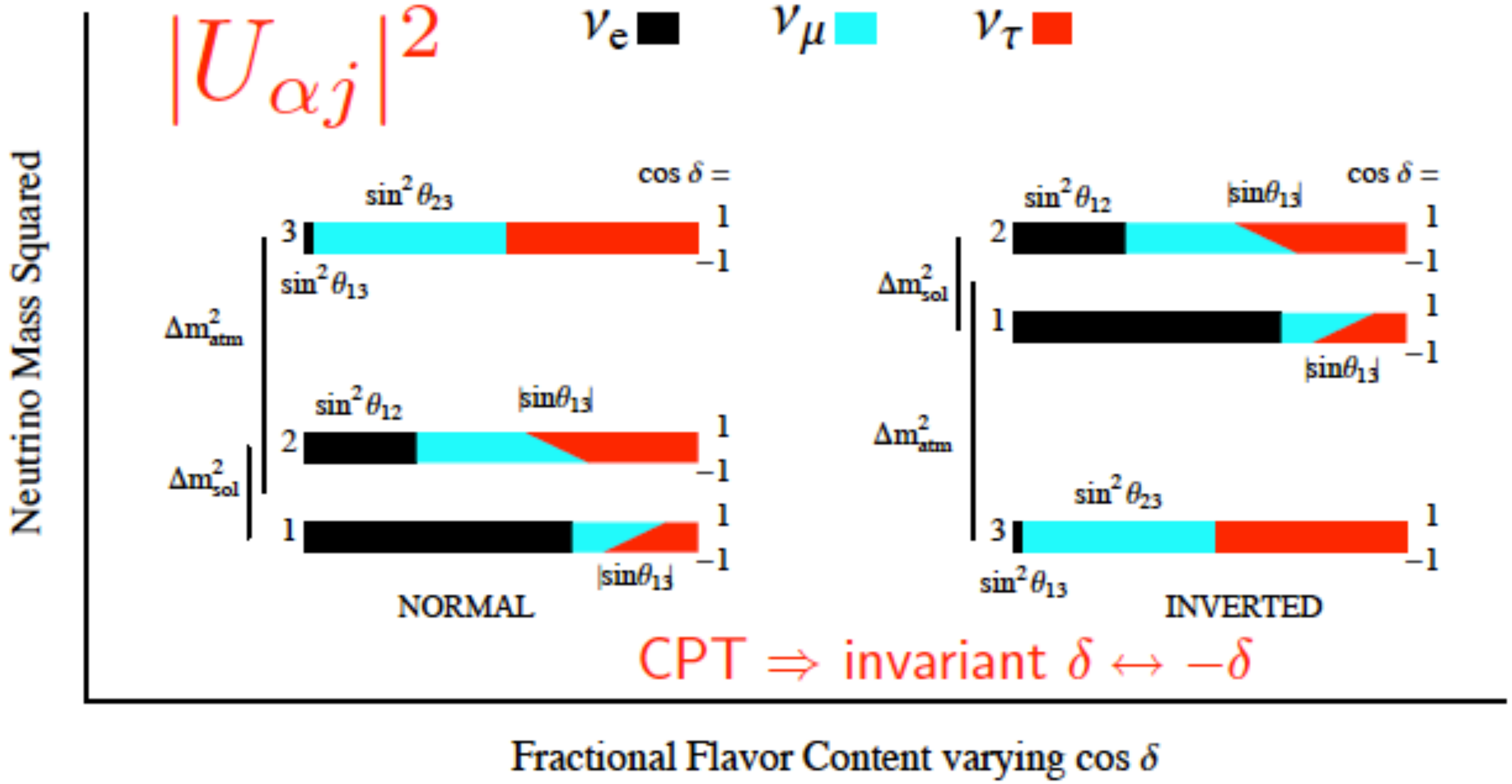
Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 $\oplus$ 5.43 – 6.41	3.35 – 6.63
δ/π (NH)	1.08	0.77 – 1.36	—	—
δ/π (IH)	1.09	0.83 – 1.47	—	—

???

If viewed as a collection of parameters with 3-generations, we need to measure mass ordering, CP phase, Θ_{23} octant.

Parameters are such that a practical accelerator based experiment is possible to see 3 generation mixing !

Connections to more fundamental issues



- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)

Credibility of leptogenesis

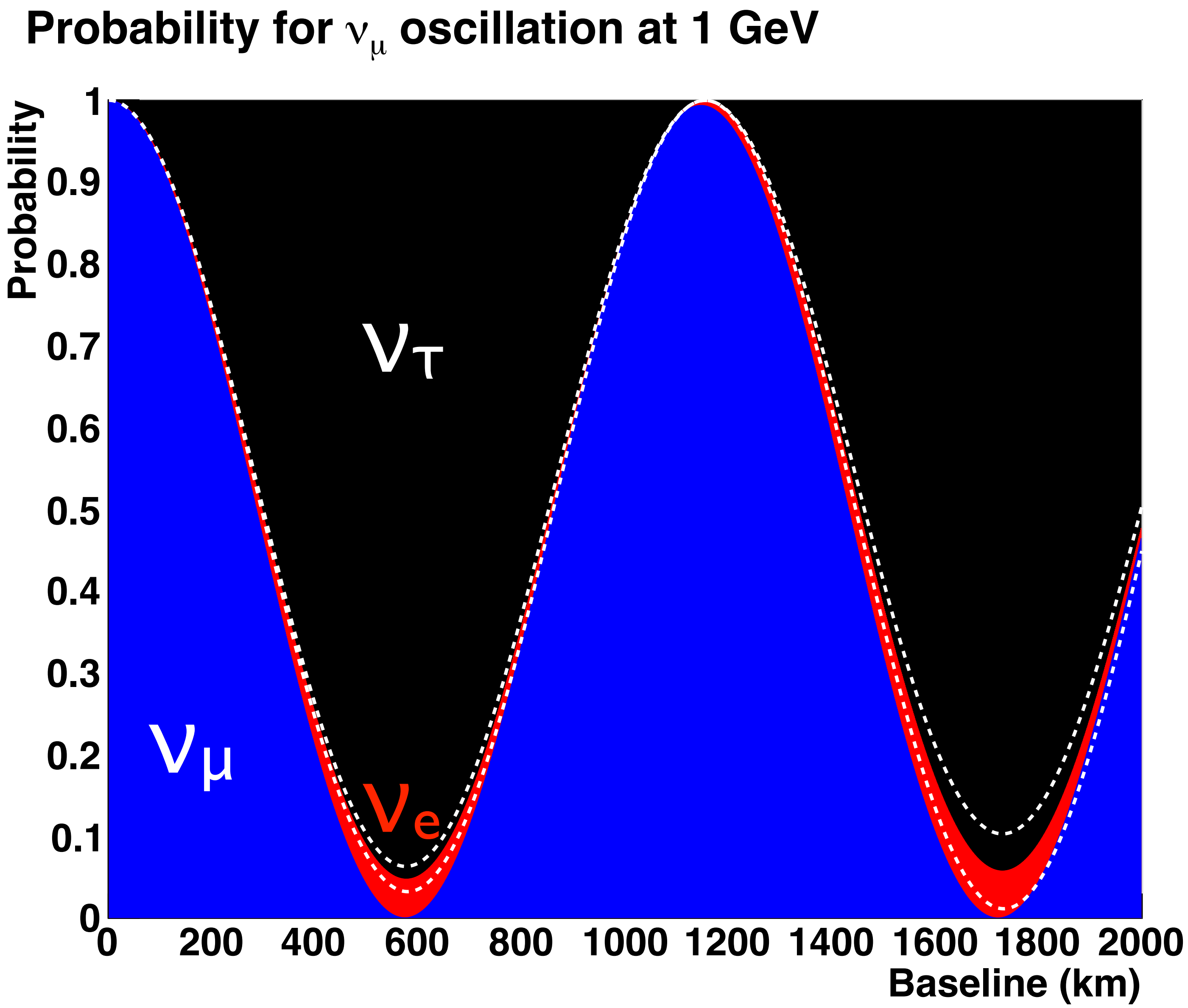
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)

Impacts GUT models

- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

Observability of double beta decay, and the problem of generations.

The full picture of the oscillation effect

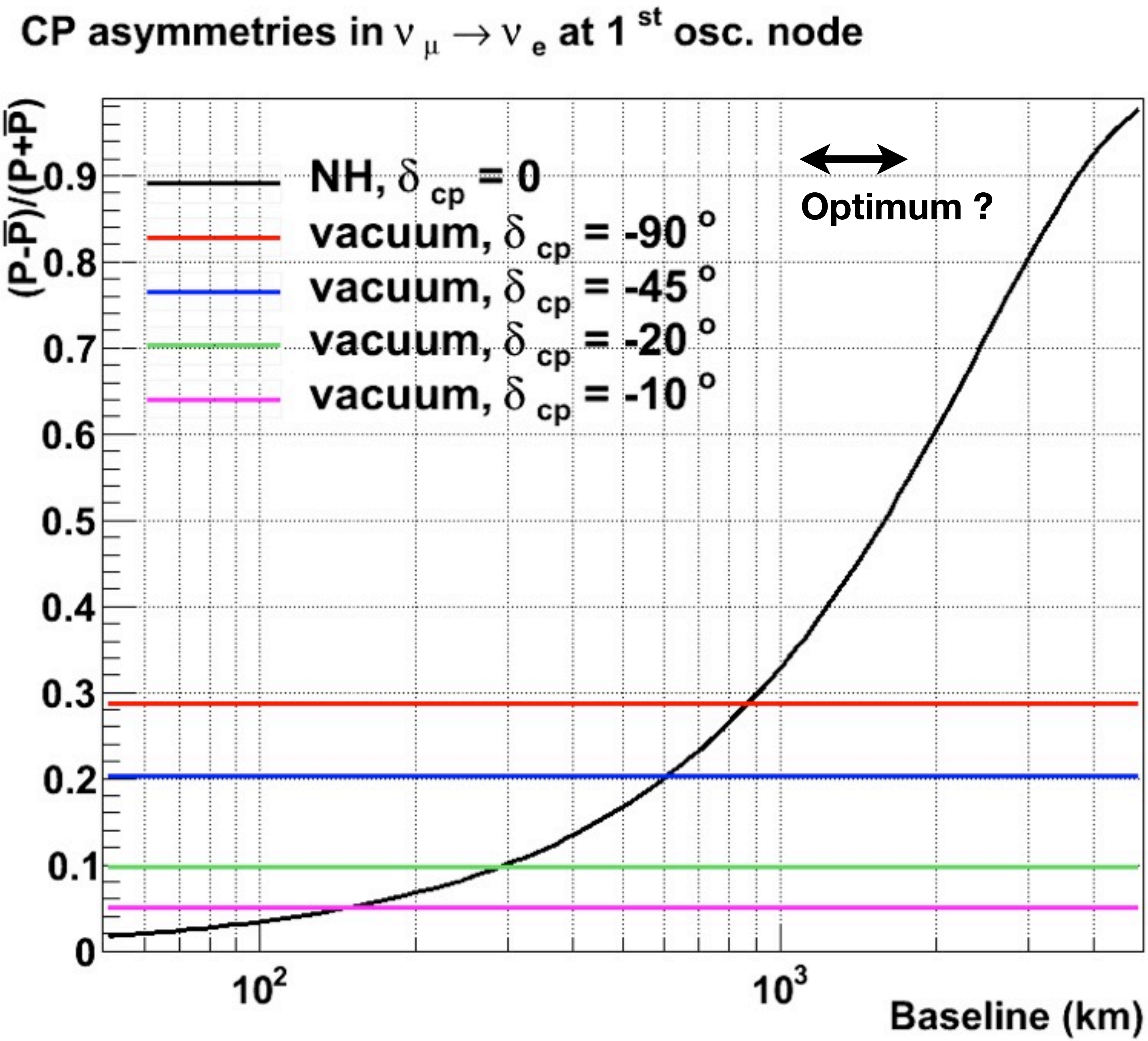


Brett Viren

Dashed white lines correspond to CP violation

It is best to do this experiment with a pure broad band beam

- The neutrino oscillation model is based on limited dataset
- With very precise predictions:
  - Large Matter Effects (not yet seen in a laboratory experiment)
  - Potentially large CP violation (not yet seen)
  - We should measure this picture with a detailed spectrum



Optimum ?

L/E = 515 km/GeV $\sin^2 2\theta_{13}=0.1$

$$\begin{tikzcd}
\nu_\mu \to \nu_e \arrow[rr, Leftrightarrow, "\text{CP}"] \arrow[d, Leftrightarrow, "\text{T}"'] & & \bar{\nu}_\mu \to \bar{\nu}_e \arrow[d, Leftrightarrow, "\text{T}"] \\
\nu_e \to \nu_\mu \arrow[rr, Leftrightarrow, "\text{CP}"'] & & \bar{\nu}_e \to \bar{\nu}_\mu
\end{tikzcd}$$

CPT across diagonals

- First Row: Superbeams where ν_e contamination $\sim$1 %
- Second Row: ν-Factory or β-Beams, no beam contamination

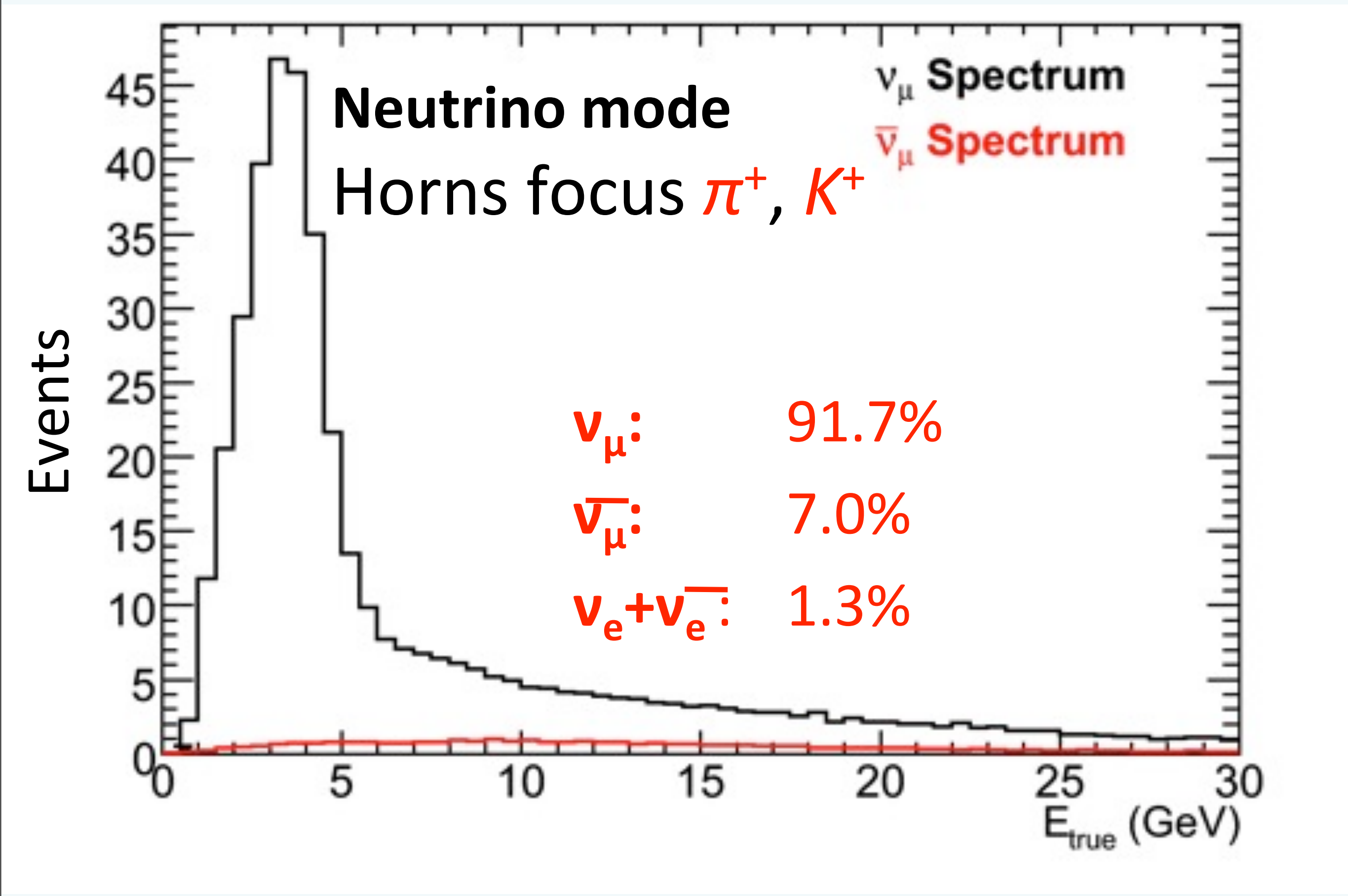
However

for ν-Factory: Distinguish μ^+ from μ^- at 10^{-4}

for β-Beam: Distinguish μ from e in Water Cerenkov or LAr

Although the conventional beam has a small contamination. The expected signal is now much larger than the contamination because of $\sin^2 2\theta_{13}$~0.09

Making a neutrino beam. Example from NUMI at FNAL



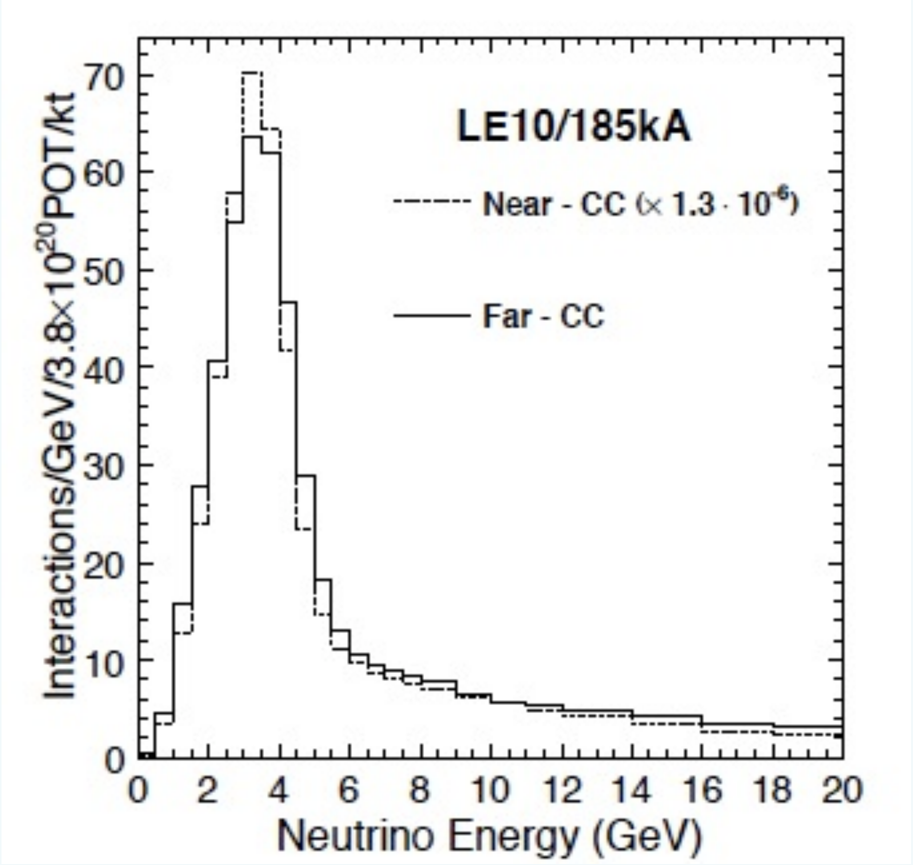
Neutrino mode

Horns focus π^+, K^+

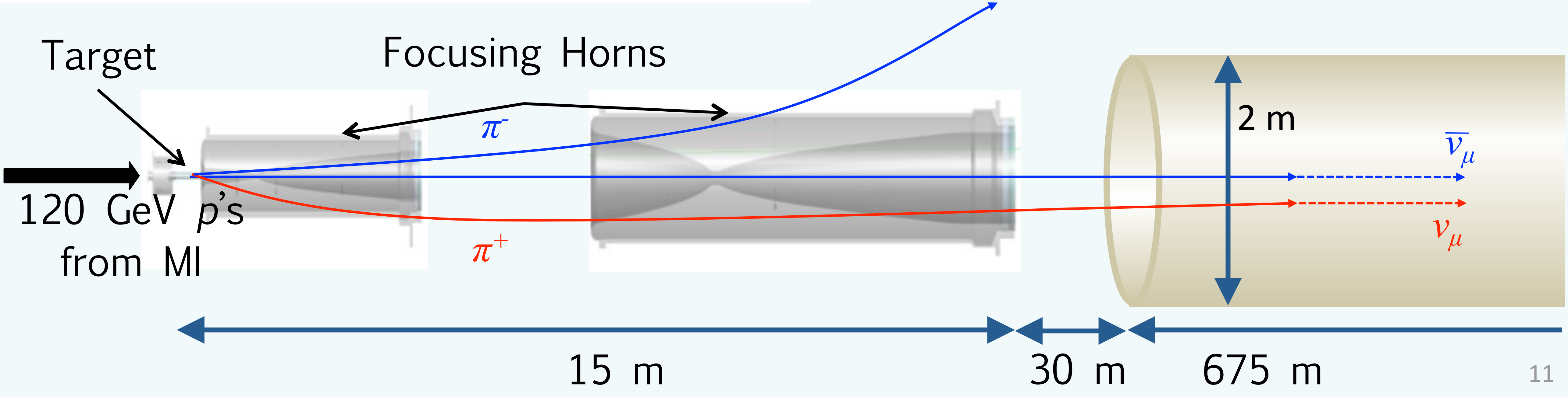
ν_μ: 91.7%

$\bar{\nu}_\mu$: 7.0%

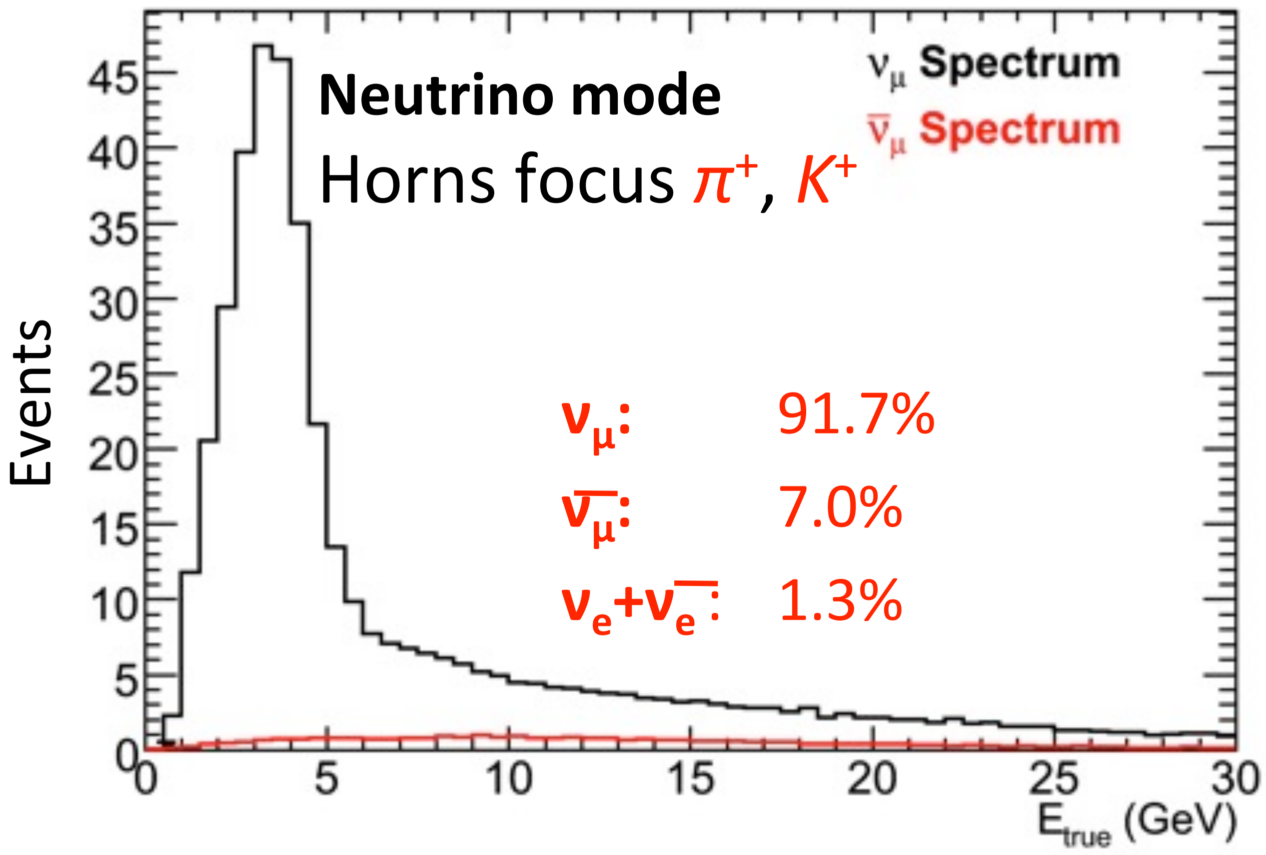
$\nu_e+\bar{\nu}_e$: 1.3%



Source size makes near and far different



Making an anti-neutrino beam: NUMI at FNAL



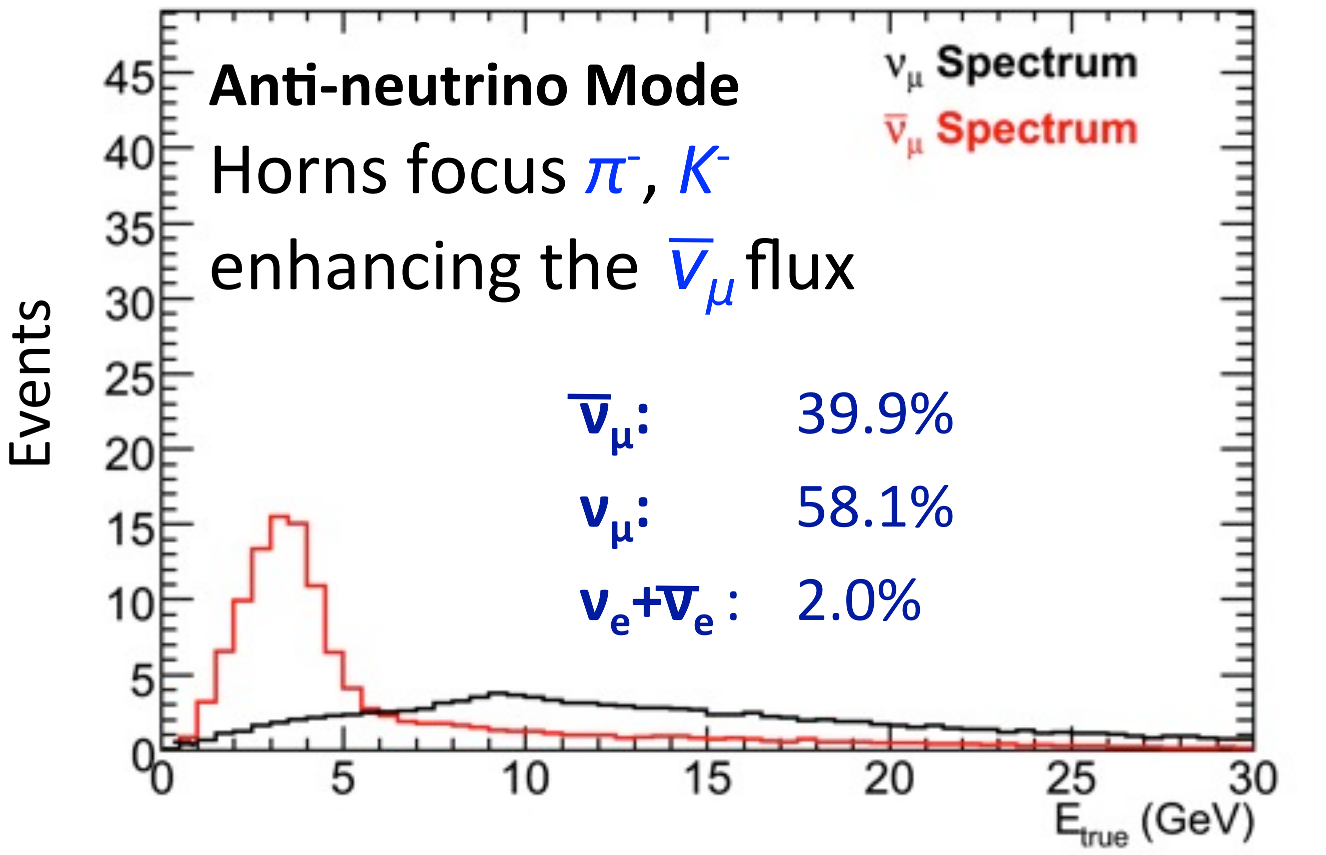
Neutrino mode

Horns focus π^+, K^+

ν_μ: 91.7%

$\bar{\nu}_\mu$: 7.0%

$\nu_e+\bar{\nu}_e$: 1.3%



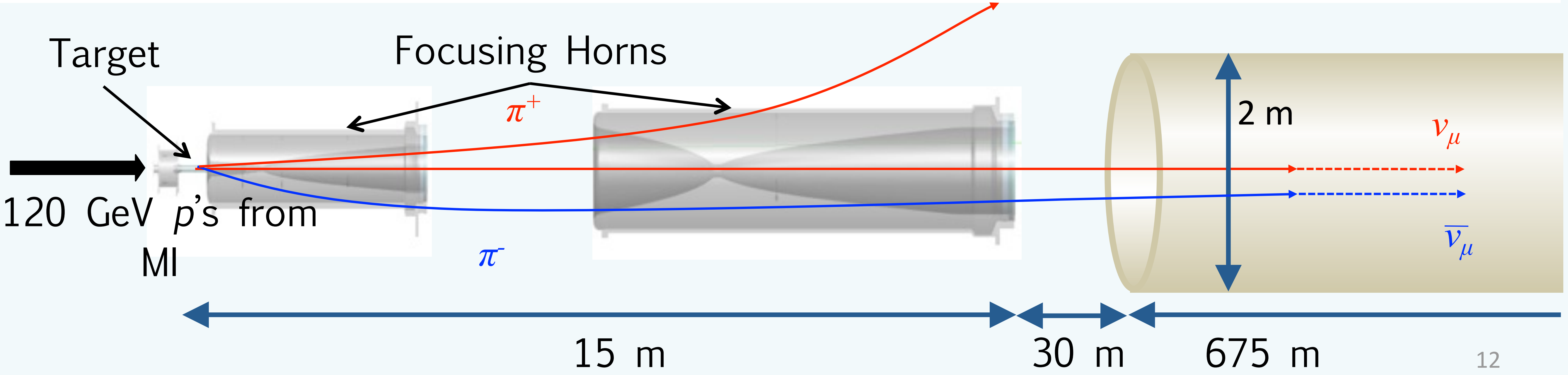
Anti-neutrino Mode

Horns focus π^-, K^- enhancing the $\bar{\nu}_\mu$ flux

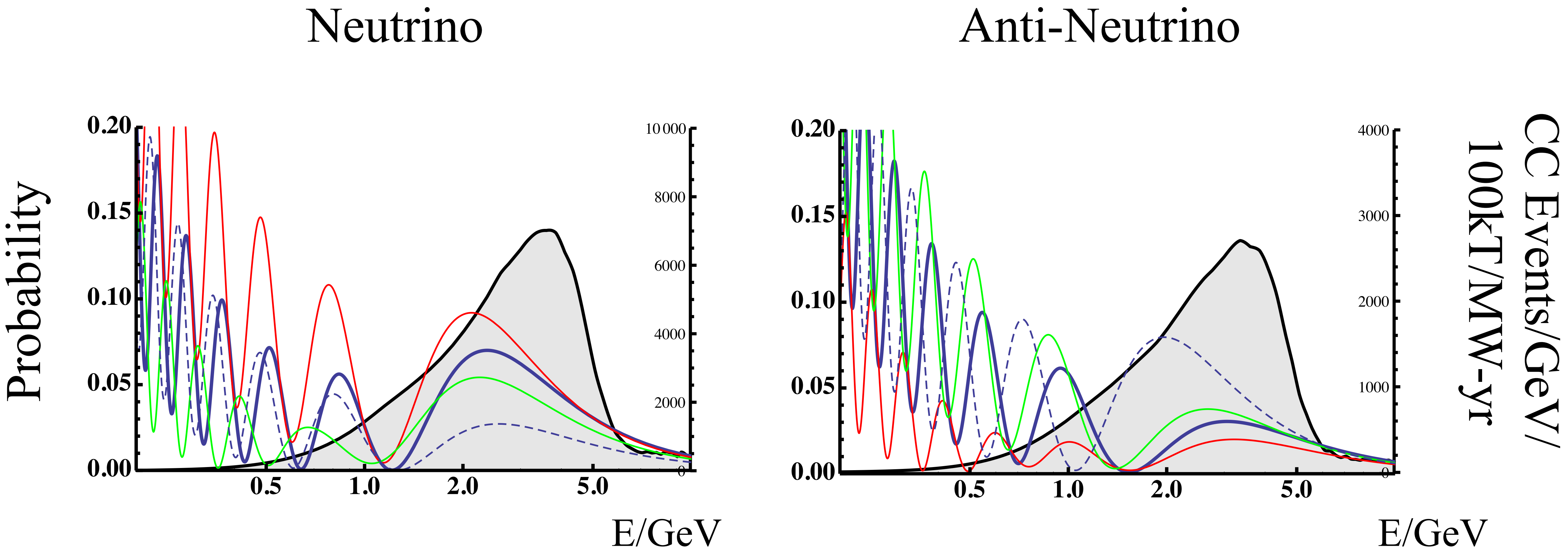
$\bar{\nu}_\mu$: 39.9%

ν_μ: 58.1%

$\nu_e+\bar{\nu}_e$: 2.0%



Oscillation and Beam Spectrum. As designed for LBNE



θ_{13}= 9°, δ_{CP} r:+90, b: 0, g: -90, dashed: Inverted Hierarchy, L: 1300 km

- With 700 kW of 120 GeV protons from the Main Injector, we have designed a beam optimized for the 0.5 to 5 GeV. (yr=2 10^7sec)
- The baseline and energy allows us to measure the spectral distortion and disentangle MH from CPV.
- Measure asymmetries of event rates versus energy for both polarities.

Beam Constraints

Beam must be designed with many constraints that affect the configuration of the experiment. Beam must be broad band (on-axis) to measure the spectrum.

- For fixed L/E the neutrino flux per pion in the forward direction is independent of distance since the $1/L^2$ is compensated by the solid angle factor.

$$E_\nu \approx \frac{0.42 E_\pi}{(1+\gamma^2\theta^2)}$$

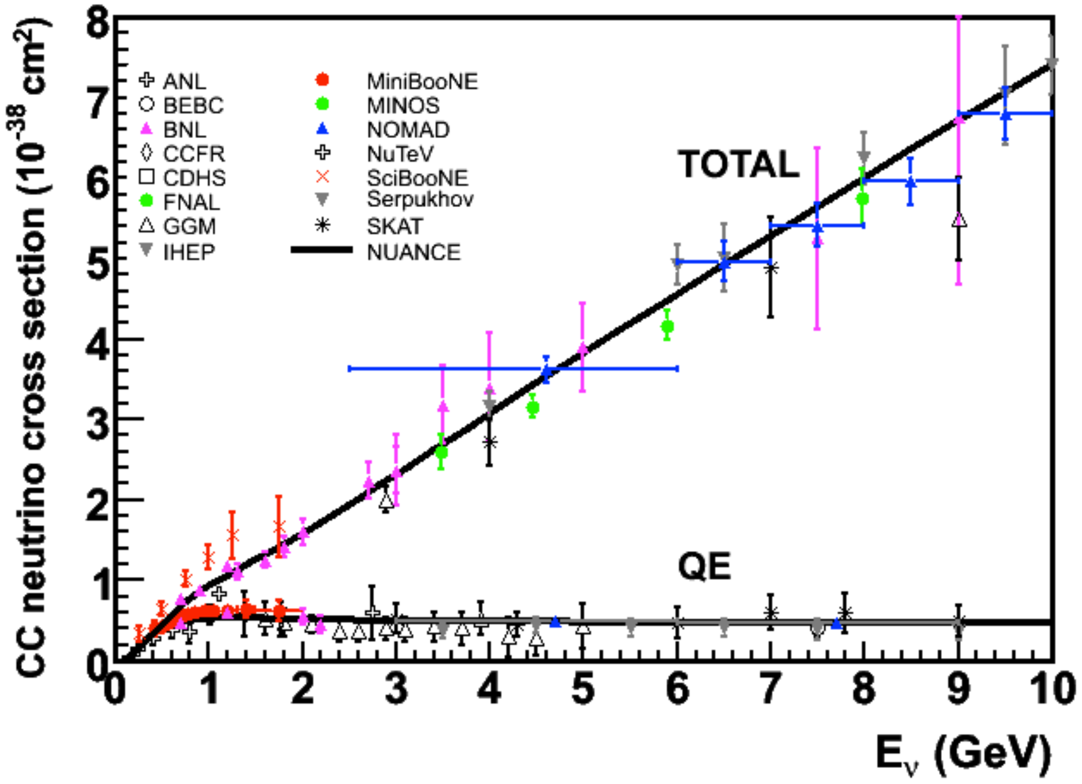
- It is difficult to overcome the solid angle factor by the pion yield at low energies.

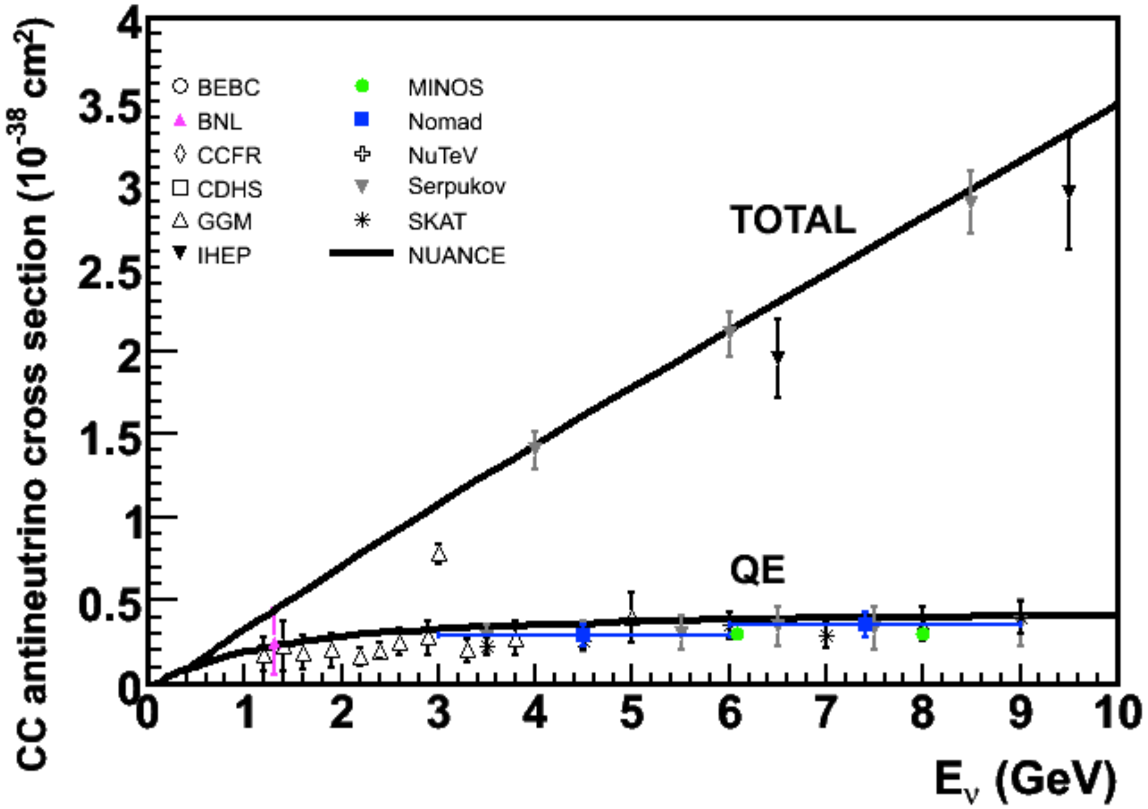
$$\frac{dN}{d\Omega_{lab}} \propto \gamma^2/L^2$$

- Highest available beam power is at 120 GeV because the current is limited by the booster in the current scheme at FNAL.
- The beam costs rise fast with primary beam bending angle and the near detector depth.

1300 km is a good compromise

Cross sections





- Given the choice of beam and distance two different visions for the detector are possible:
  - Use all charged current events and identify each one and measure the total energy of each one. This requires a high granularity detector that can handle multiple tracks. But it can be smaller since using all cross section. A LAr detector is a natural candidate.
  - Or use primarily the simplest topology events that can be reconstructed and measured. This leads to a detector that can measure single leptons well, but has limited track reconstruction. The detector must be large. WCD is a natural candidate.

Total event rate

	Neutrino beam		Anti-neutrino beam	
Event type	200 kTon WCD	34 kTon LAD	200 kTon WCD	34 kTon LAD
CC ν_μ	35000 (11200)	5900 (1900)	4200 (2400)	720 (410)
CC ν_e (beam only)	260	44	38	6
CC $\overline{\nu}_\mu$	1400 (770)	240 (130)	13000 (4000)	2200 (675)
CC $\overline{\nu}_e$	10	2	90	15
Efficiency for useful events	10-20 %	70-90%	10-20%	70-90%

- For 0.7 MW per yr. Detector mass above is fiducial mass.
- Total charged current event rate with no selection cuts and no oscillation. (with oscillations in brackets)

Detector Strategies

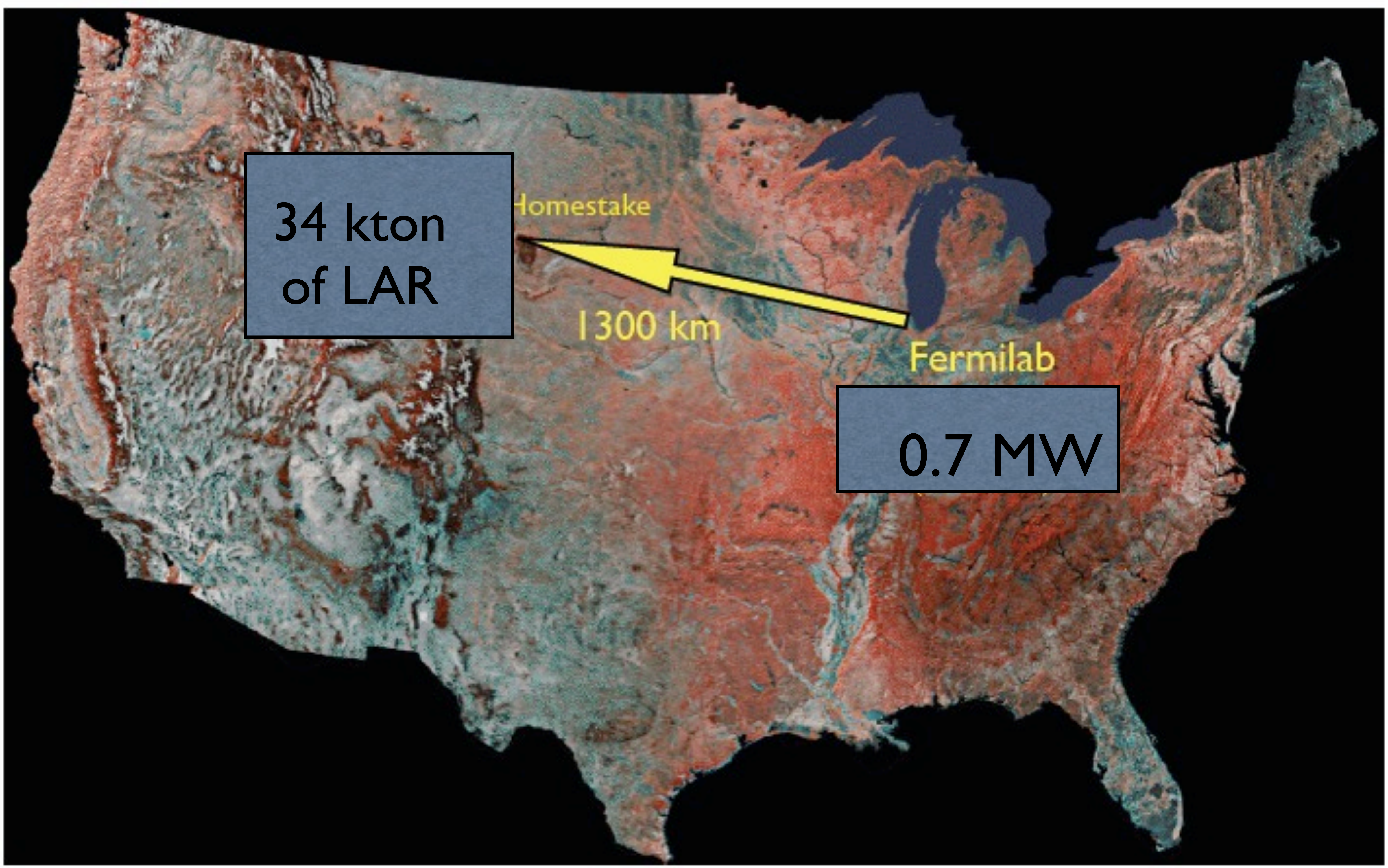
200 kTon Water Cherenkov

- Use a crude detector, but only select well identified single electron events(QE) to keep background low and energy resolution high.
- Known, successful technology with wide dynamic range (5 MeV-50GeV).
- Can perform both p-decay, astrophysical sources,
- Can be deployed deep scaled up: 50kT to fewX100kTon.
- Will have low efficiency and need very large mass.

34 kTon Liquid argon

- Very high resolution detector should allow use of much higher fraction of cross section including multi-track events.
- Energy resolution might need attention if using all cross section.
- Could use the fine resolution and below Cher threshold for background tagging.
- Could do the specialized proton decay searches very well. Sensitive to supernova nues (not anti-nue).
- Dynamic range for physics is less well-known.
- Scale up factor needs to be substantial ~100.

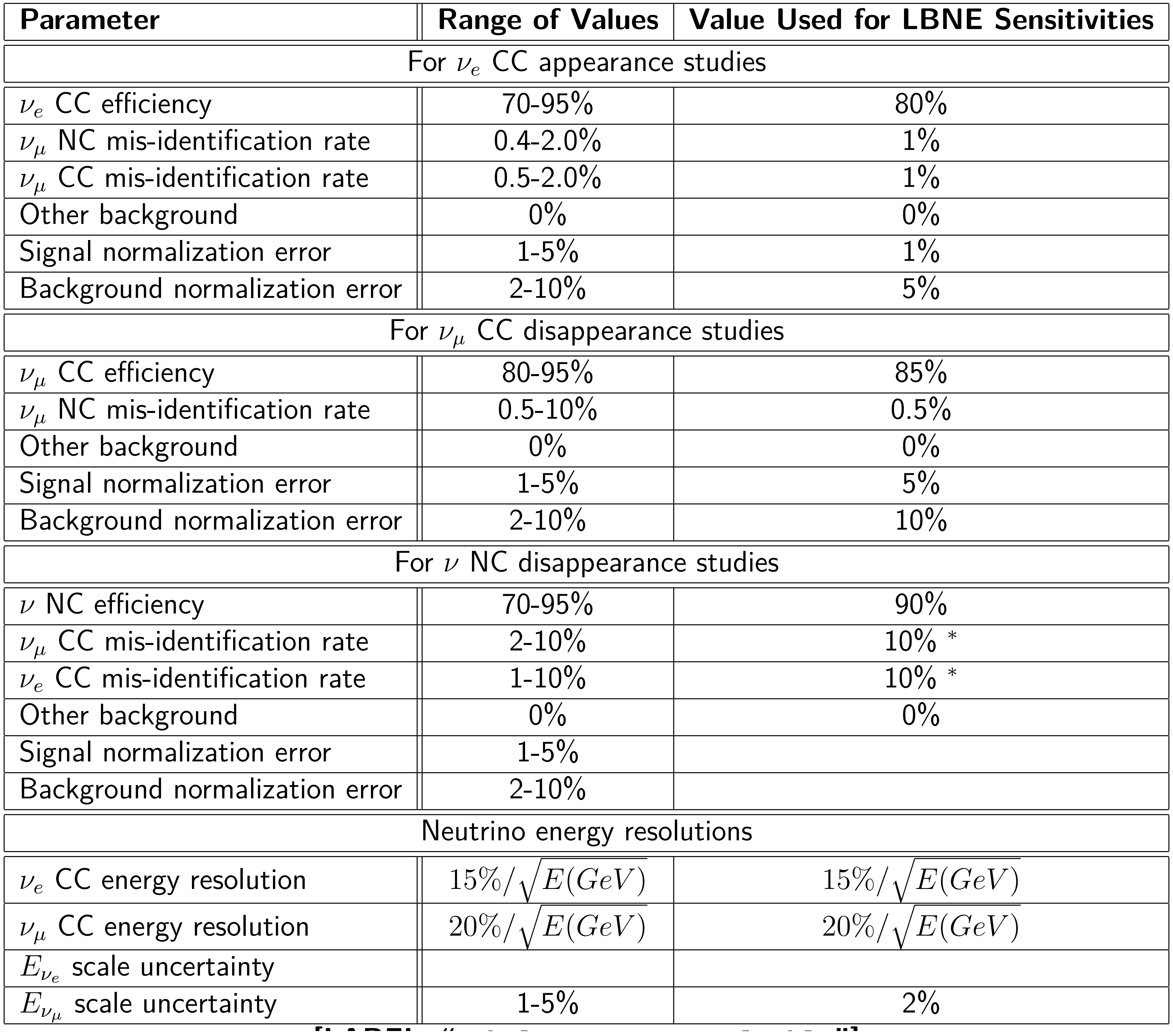
Long-Baseline Neutrino Experiment in US



34 kton
of LAR

0.7 MW

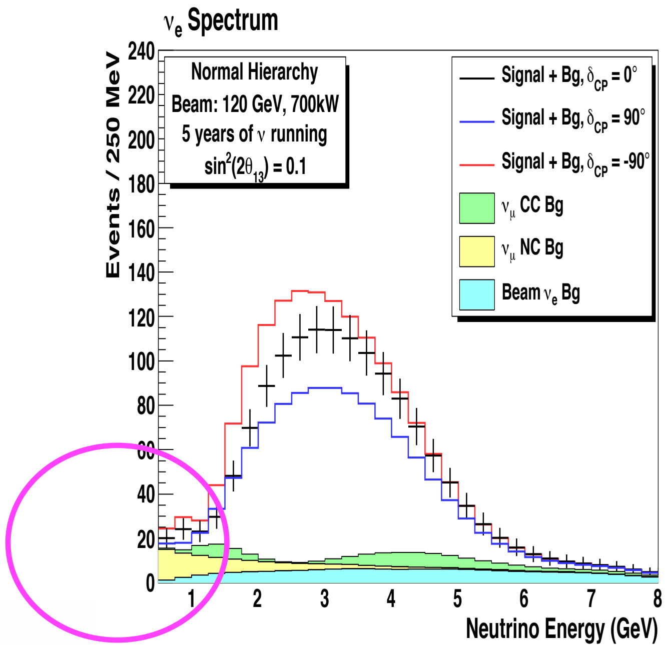
For LBNE the detector selection was extremely difficult.
LAr choice was driven by scientific, technological
considerations.



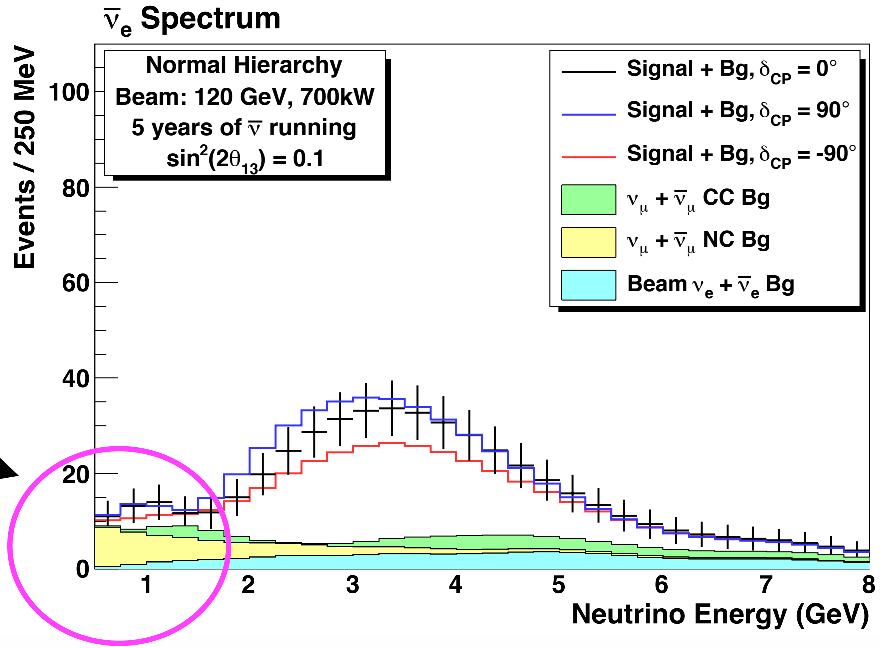
Parameter	**Range of Values**	**Value Used for LBNE Sensitivities**
For ν_e CC appearance studies		
ν_e CC efficiency	70-95%	80%
ν_μ NC mis-identification rate	0.4-2.0%	1%
ν_μ CC mis-identification rate	0.5-2.0%	1%
Other background	0%	0%
Signal normalization error	1-5%	1%
Background normalization error	2-10%	5%
For ν_μ CC disappearance studies		
ν_μ CC efficiency	80-95%	85%
ν_μ NC mis-identification rate	0.5-10%	0.5%
Other background	0%	0%
Signal normalization error	1-5%	5%
Background normalization error	2-10%	10%
For ν NC disappearance studies		
ν NC efficiency	70-95%	90%
ν_μ CC mis-identification rate	2-10%	10% *
ν_e CC mis-identification rate	1-10%	10% *
Other background	0%	0%
Signal normalization error	1-5%	
Background normalization error	2-10%	
Neutrino energy resolutions		
ν_e CC energy resolution	$15\%/\sqrt{E(GeV)}$	$15\%/\sqrt{E(GeV)}$
ν_μ CC energy resolution	$20\%/\sqrt{E(GeV)}$	$20\%/\sqrt{E(GeV)}$
E_{ν_e} scale uncertainty		
E_{ν_μ} scale uncertainty	1-5%	2%

Detector performance parameters for LBNE

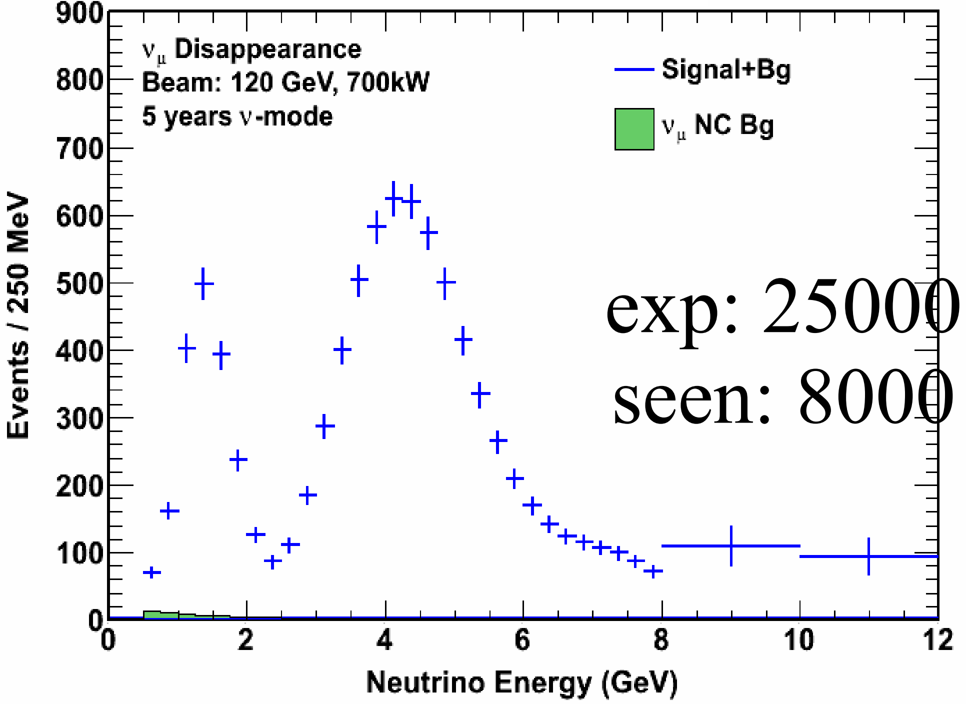
1300 km expectation with 34 kTon



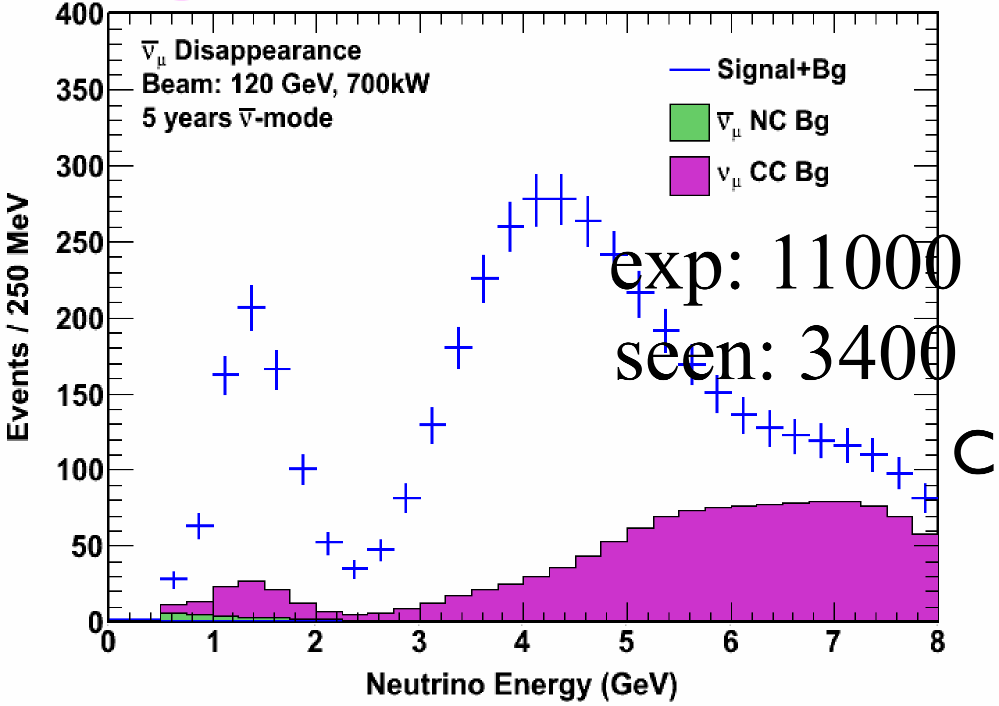
These events are very important



For each bin, conversion fraction of electrons can be calculated. Matter effect can be substracted to obtain explicit CP signal.



exp: 25000
seen: 8000



exp: 11000
seen: 3400

Potential surprises:

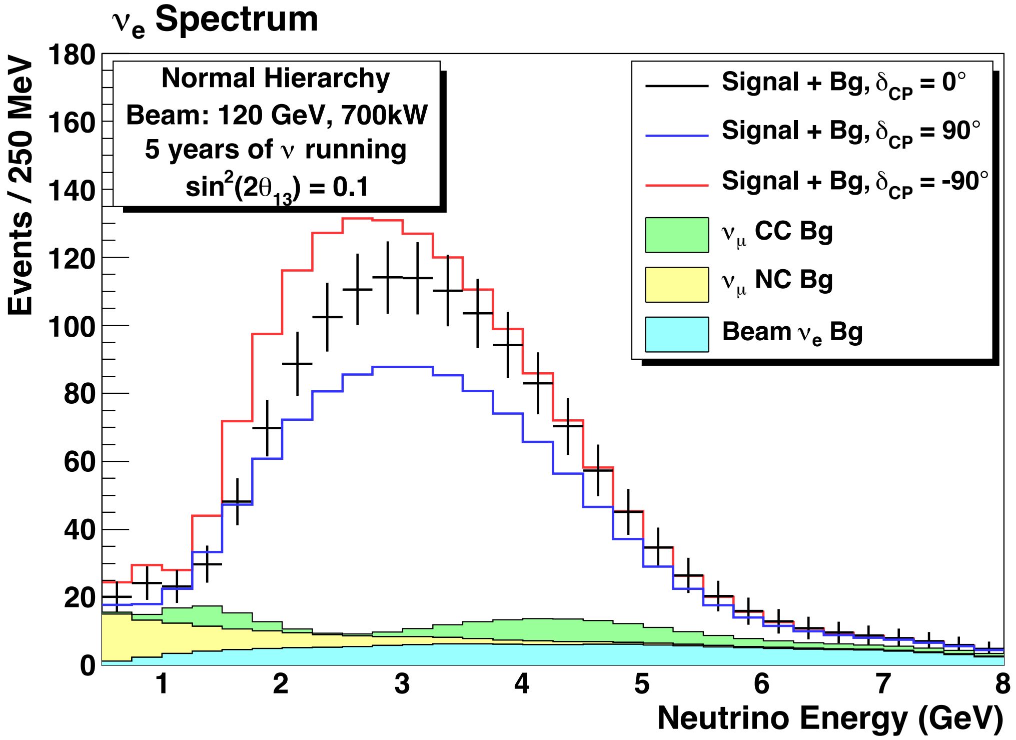
Matter effect is not what is expected !

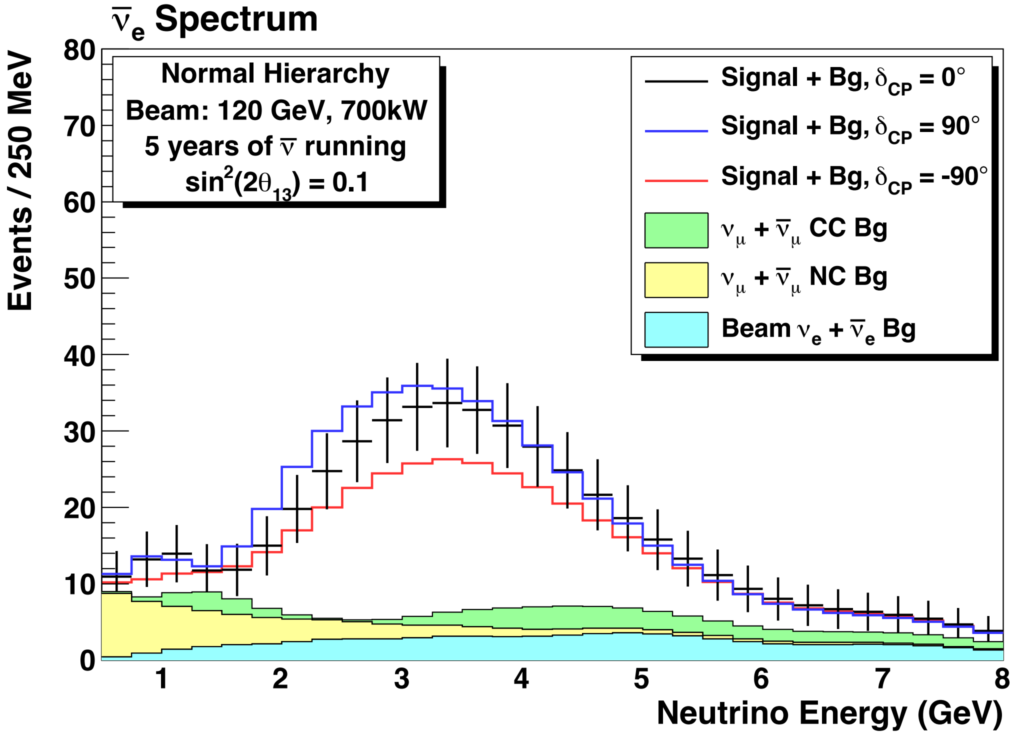
CPV does not have the proper energy 1/E dependence.

- With 1300 km the full structure of oscillations is visible in the energy spectrum. This spectral structure provides the unambiguous parameter sensitivity in a single experiment.

LBNE 34 kTon performance

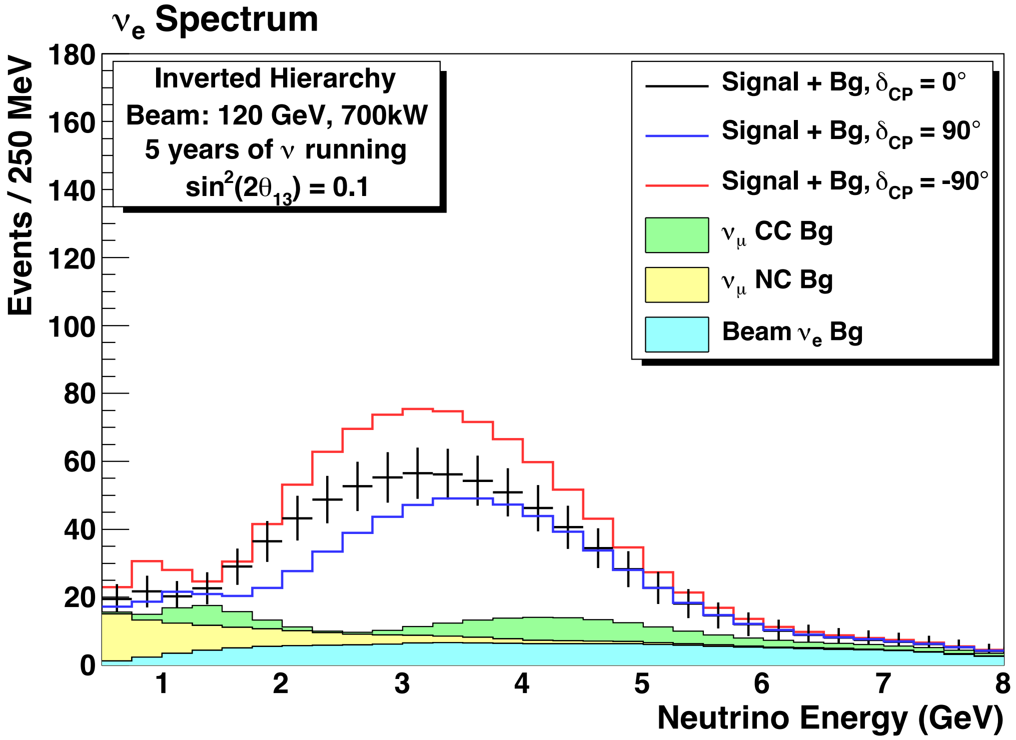
1074

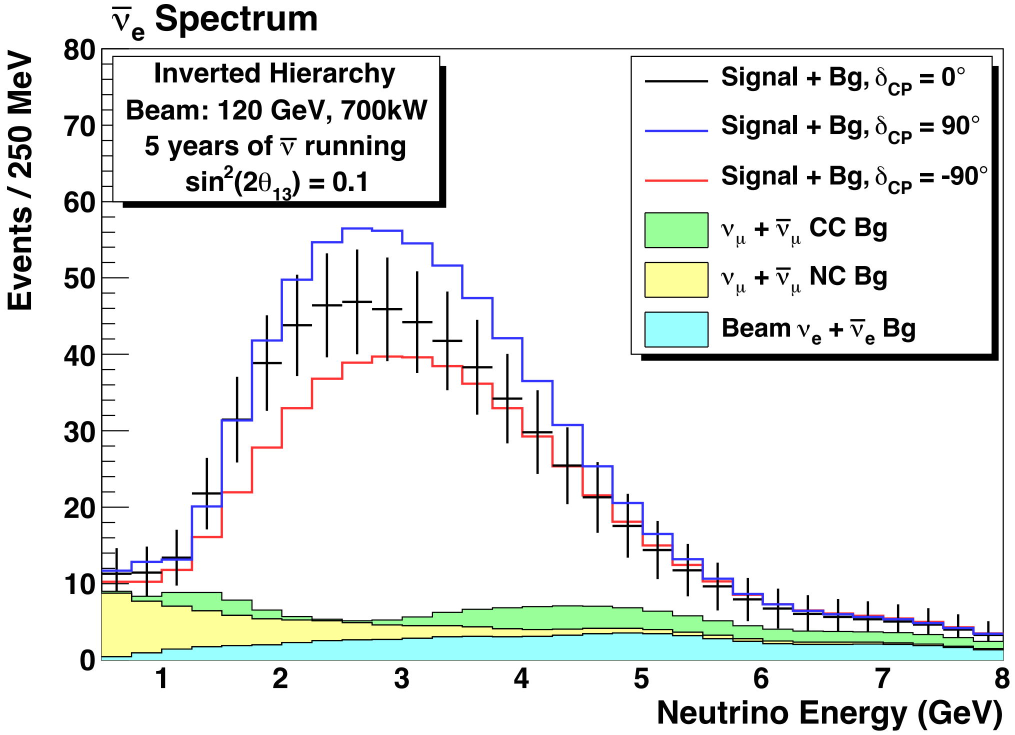




279

477



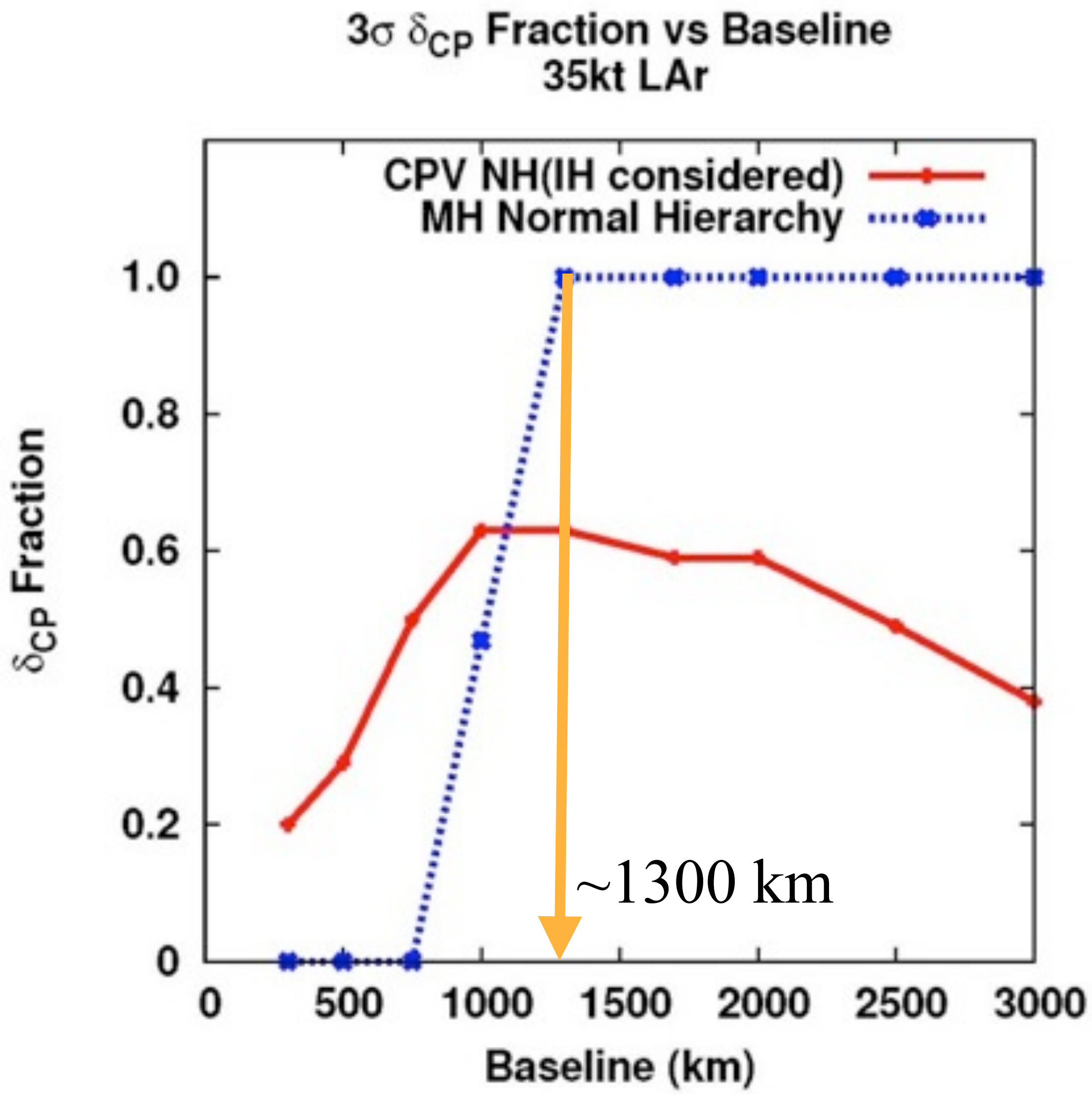


440

Small tau background expected.

Baseline Choice !

- The design for a US based CP violation program started ten years ago before we knew the solar LMA solution and θ_{13}
- The scale of the program needed is only weakly dependent on θ_{13} because the CP asymmetry is smaller for larger θ_{13}
- The scientific choice for 1300 km is close to optimum.
- Additional backgrounds at longer baselines and strong matter suppression



This calculation optimizes the beam from the Fermilab Main injector for each distance and calculates the full sensitivity for θ_{13}= 9 deg.

Major scientific choices are associated with length.

300 km

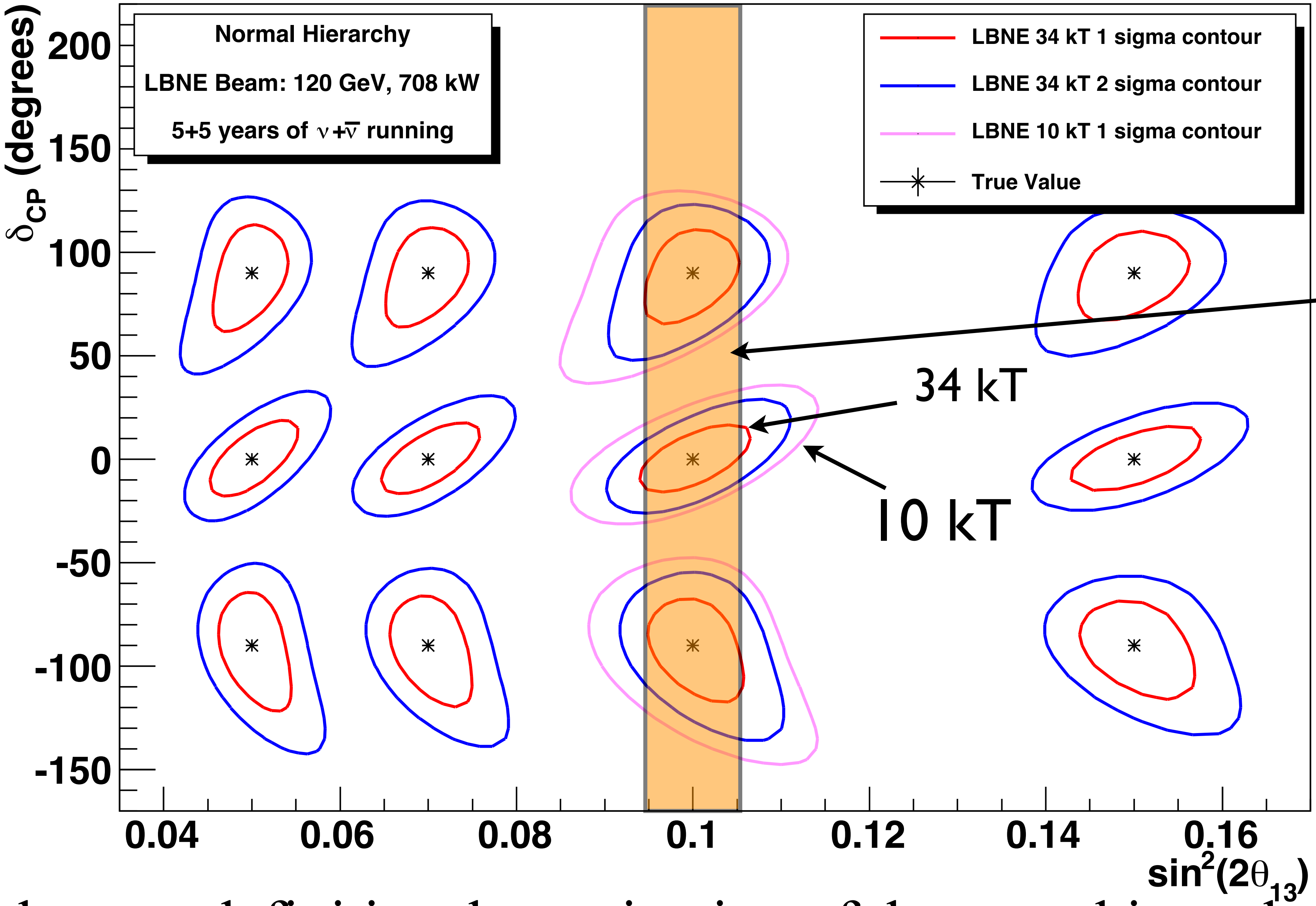
1300 km

2300 km

Low energy, less dynamic range	Better to get spectral pattern
smaller matter effect, degeneracies	Larger matter effect resolve MH
Better matched for huge water det.	Better matched for tracking LAr det
Explicit CP asymmetry measured	Matter suppression CP asym difficult
No backgrounds from taus	More tau production background
No signal from taus	Can see tau appearance in high res det

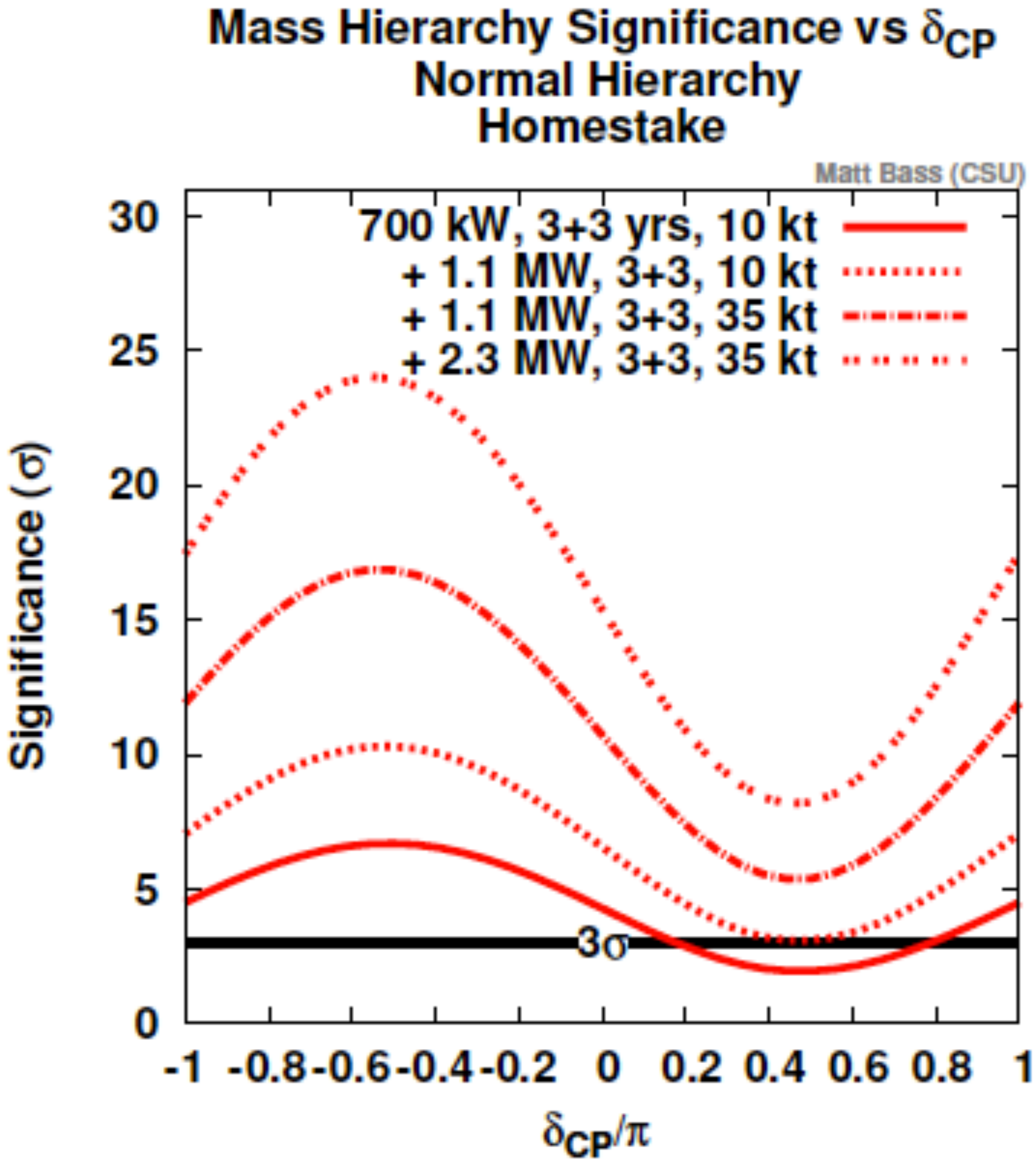
LBNE Parameter measurement

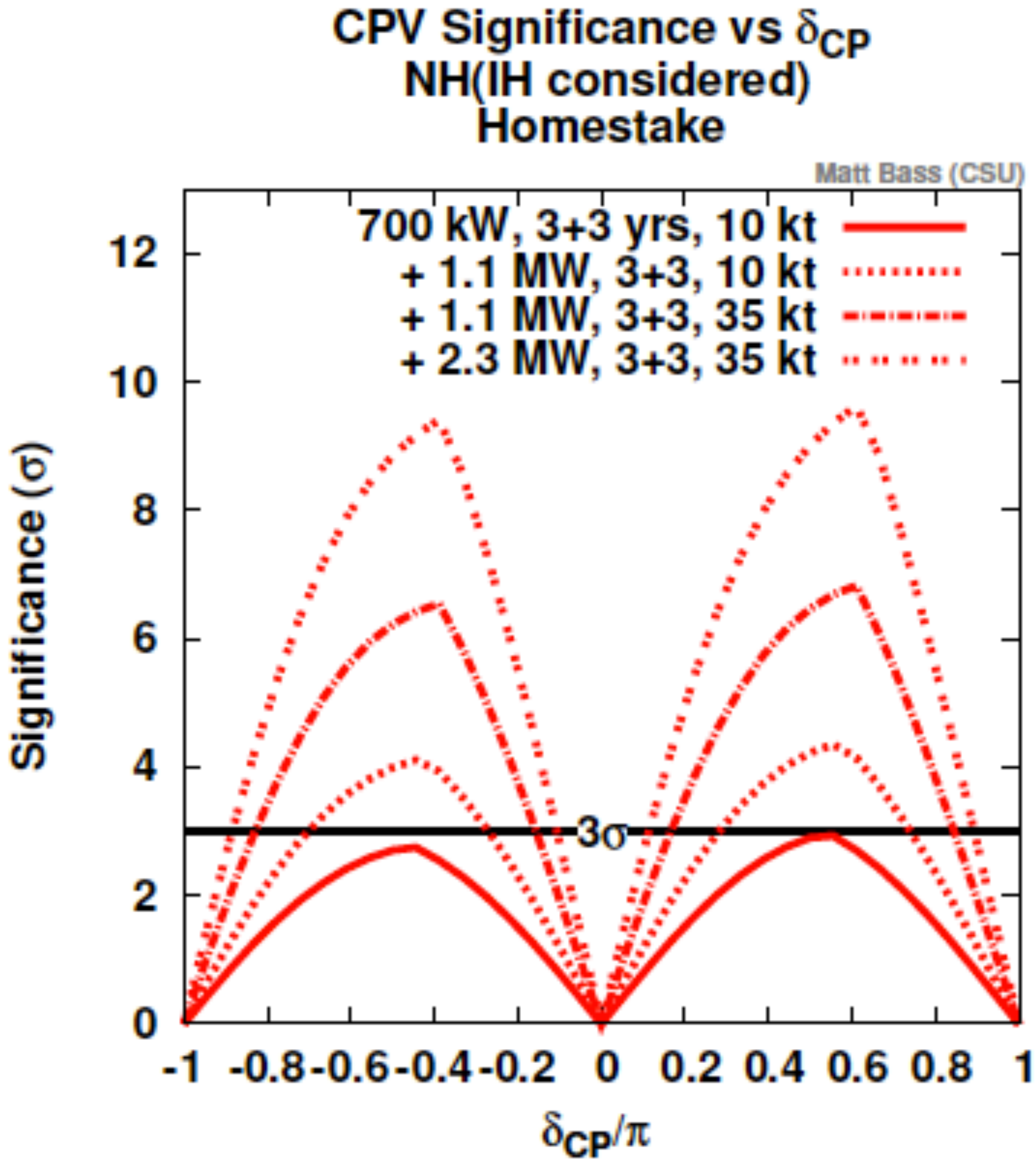
Phase I ν_e(anti-ν_e) ~50 (~20) events per year with >50% modulation



Expected final 1 sigma error from reactors (centered on 0.1)

- LBNE will have a definitive determination of the mass hierarchy.
- LBNE will have a measurement of the phase and θ_{13} with no ambiguities.
- The phase measurement will range from ±20 to ±30 deg for Phase I when combined with reactor data.
- Parameter measurement will continue to improve with statistics.





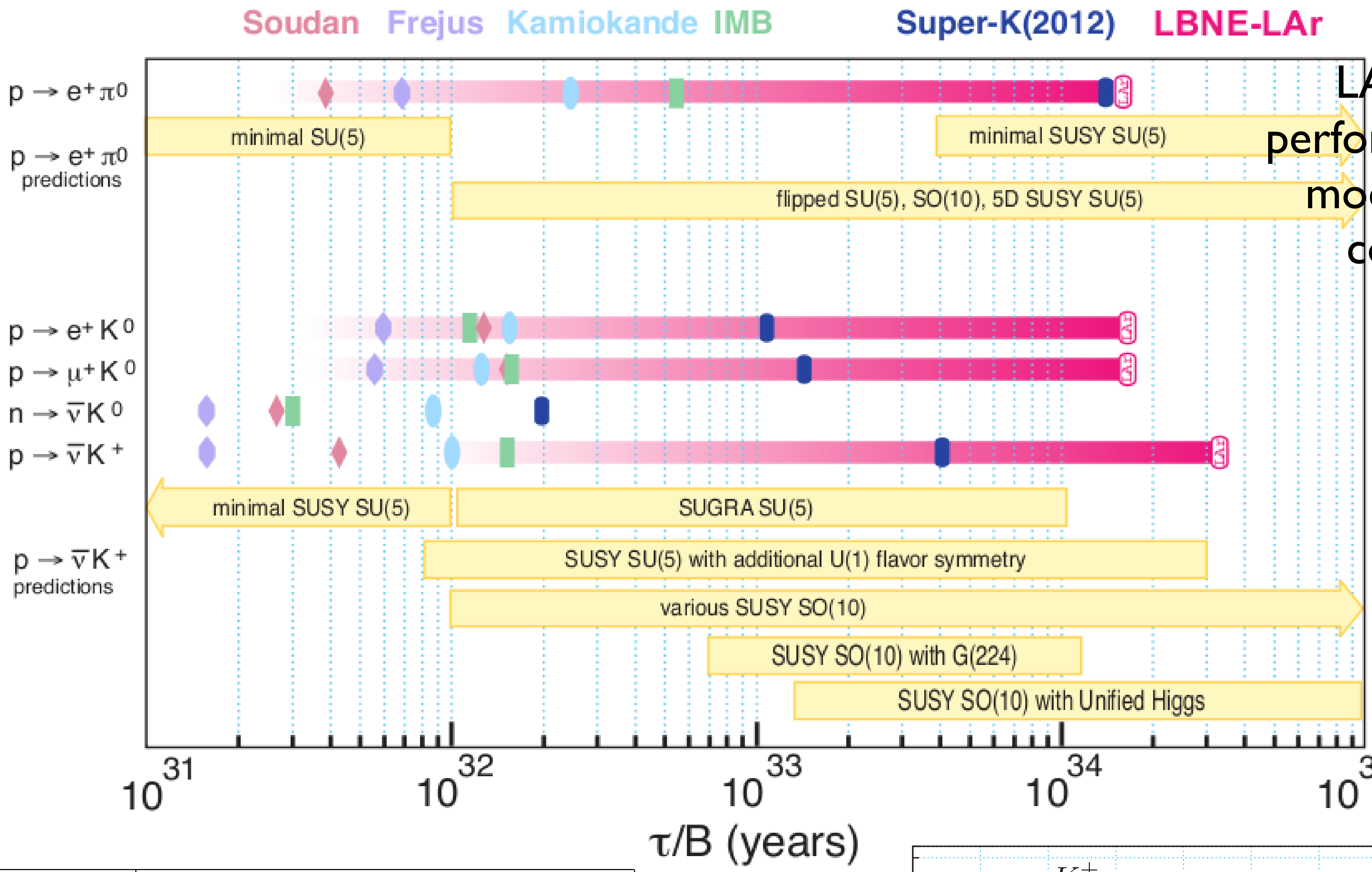
LBNE sensitivity will grow with exposure

Far Detector Depth (numbers are within x2)

Depth (mwe)	LAR40 (hz)	LAR40 in-time
265	2300	230,000
880	120	12,000
2300	3	300
2960	0.9	90
3490	0.4	40
3620	0.3	30
4290	0.13	13

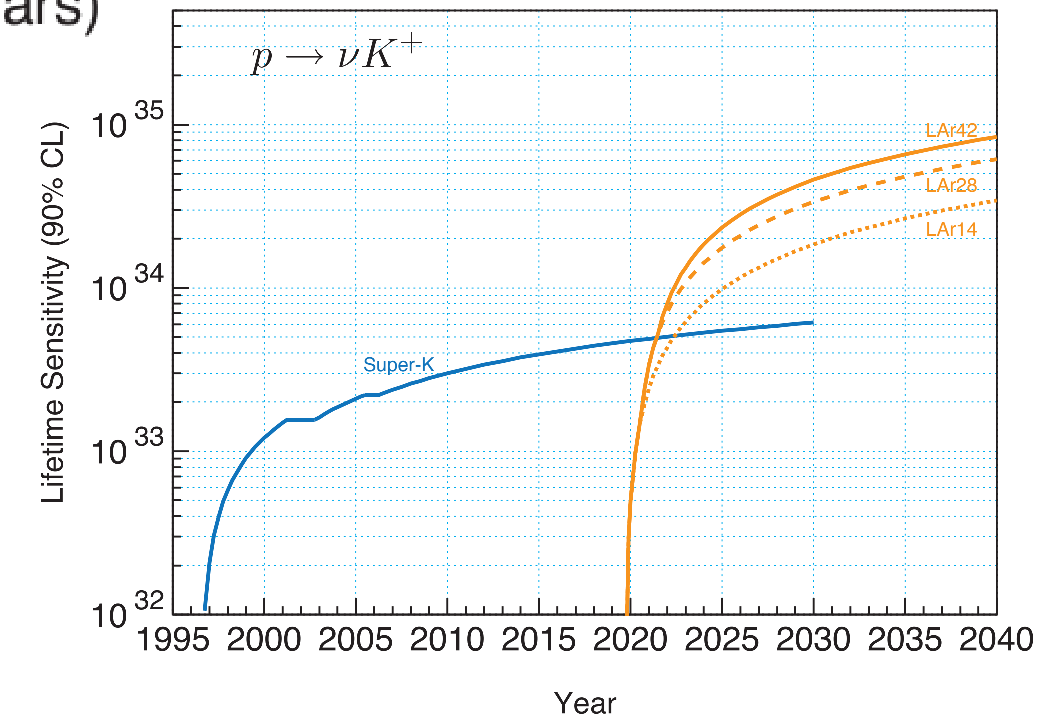
- In-time rate is calculated assuming 10 micro-sec beam gate for 10^7 pulses.
- Using potential available levels at Homestake (Flat overburden:2.8gm/cc)
- LAR spallation not well understood.1202.5000 predicts large rate due to ^{40}Cl. Depth will reduce the rate to manageable level. (<5k counts/day <10 MeV)
- Main Injector fine structure 53 Mhz with few ns bunches not used.

Proton Decay



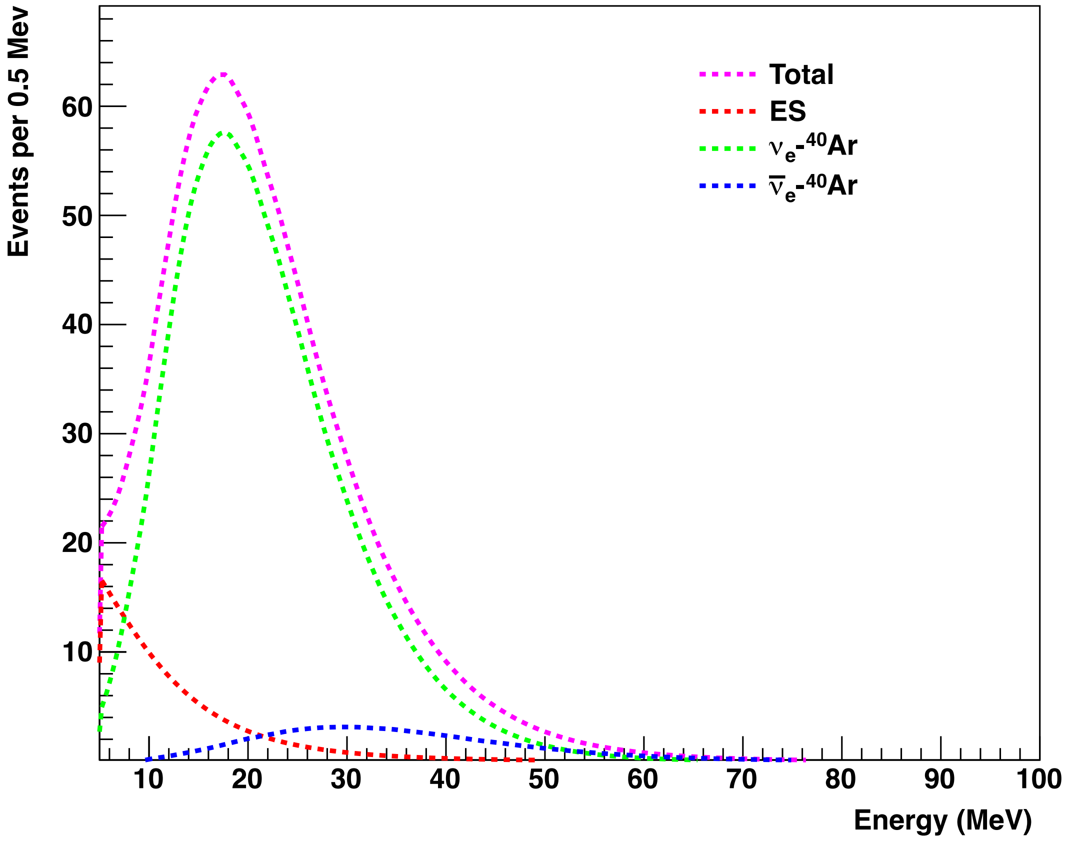
LAr inclusive performance on B-L modes might be competitive

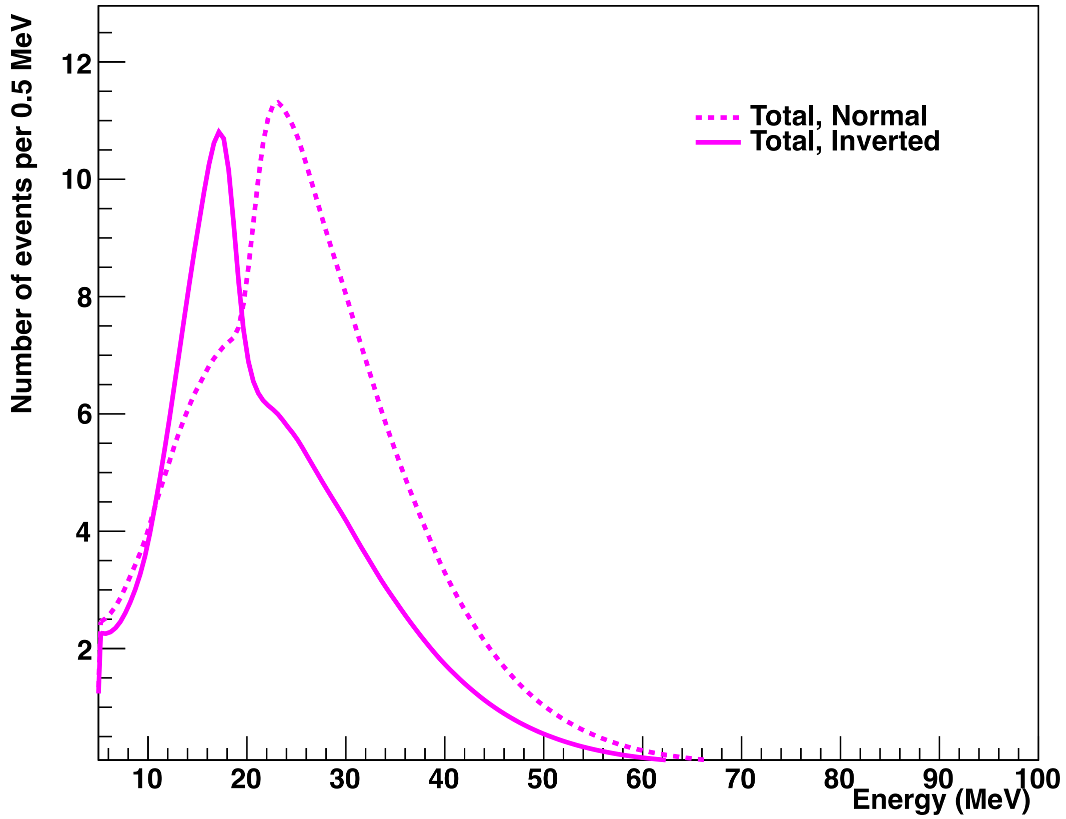
Mode	Efficiency	Background Rate (evts/100 kton-y)
	B-L	
$p \to e^+\pi^0$	45%	0.1
$p \to \nu K^+$	97%	0.1
$p \to \mu^+ K^0$	47%	< 0.2
	B+L	
$p \to \mu^-\pi^+K^+$	97%	0.1
$p \to e^+K^+$	96%	< 0.2
	$\Delta B = 2$	
$N\bar{N} \to n(\pi)$	TBD	TBD



Measurement is well justified, but any hint of SUSY from the LHC or other experiments will make this a must do experiment

Supernova





Channel	Events, “Livermore” model	Events, “GKVM” model
$\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$	2308	2848
$\bar{\nu}_e + ^{40}\mathrm{Ar} \rightarrow e^+ + ^{40}\mathrm{Cl}^*$	194	134
$\nu_x + e^- \rightarrow \nu_x + e^-$	296	178
Total	2794	3160

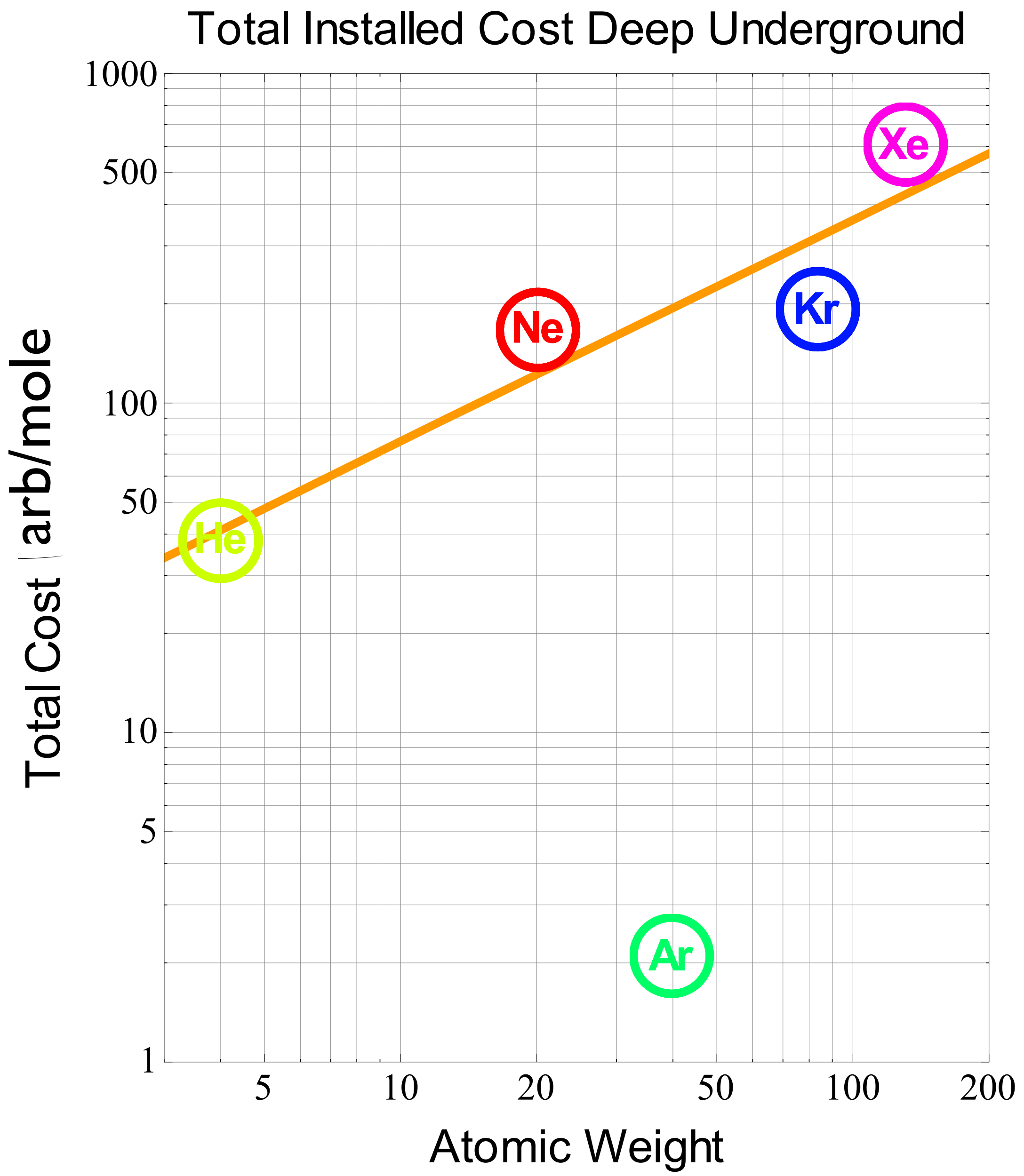
@10 kpc

Table 6–7: Supernova burst neutrino event rates for different models in 34 kton of LAr.

Liquid Argon is sensitive to electron neutrinos. Water is sensitive to electron anti-neutrinos. Must have 10 MeV threshold for this physics.

Why Liquid Argon ?

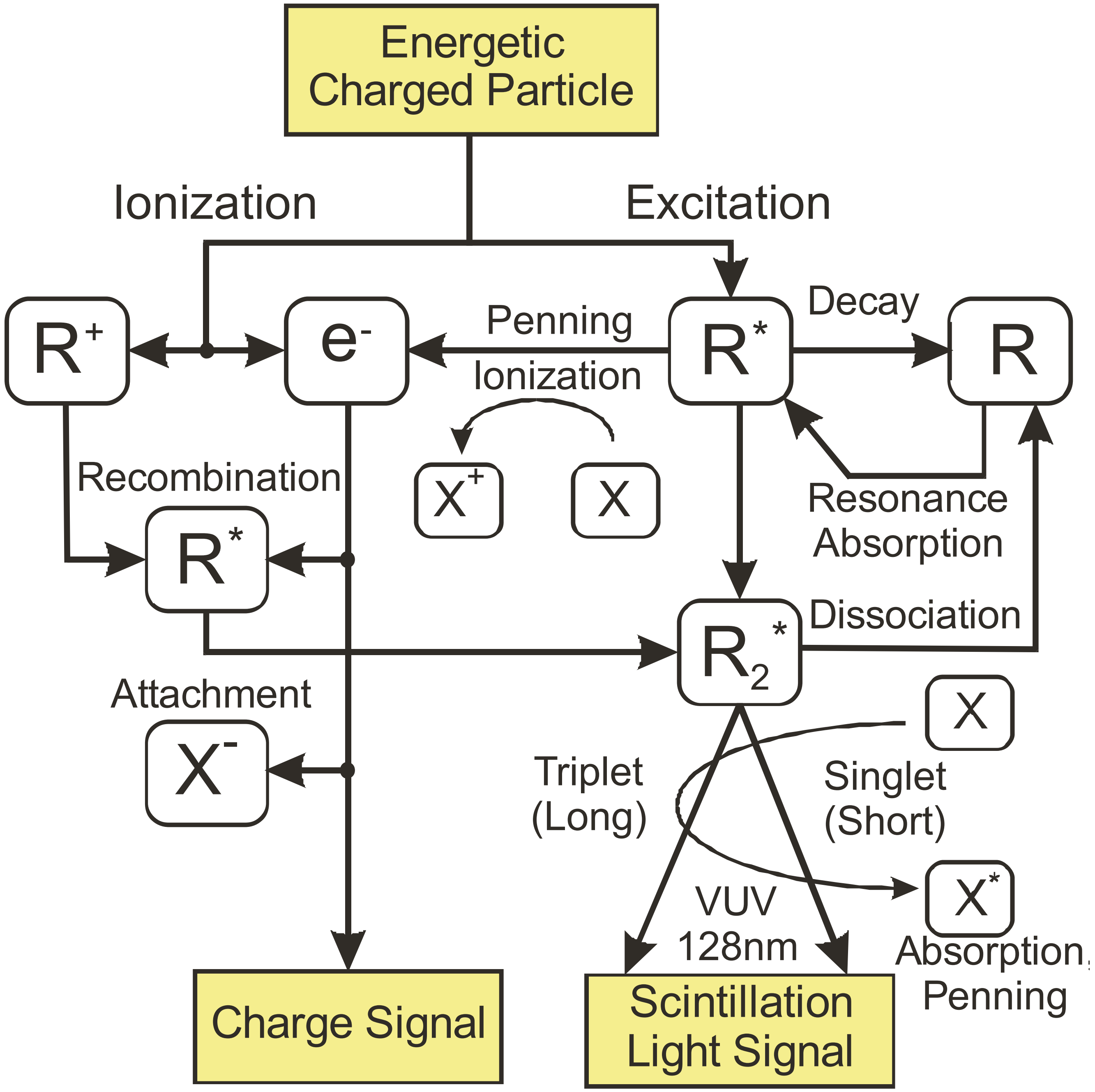
- It is one of the few pure and inexpensive substances that allow long electron lifetime, therefore can be used for ionization detection.



	In Air (ppm)	In Crust (ppb)
He	**5.2**	**8**
Ne	**18**	**0.07**
Ar	**9300**	**1200**
Kr	**1.14**	**0.01**
Xe	**0.086**	**0.047**

Craig Thorn
(BNL)

What happens to the energy as a charged particle traverses in LAr?



Energetic Charged Particle

Ionization

Excitation

R^+

e^-

Penning Ionization

R^*

Decay

R

Recombination

X^+

X

Resonance Absorption

R^*

R_2^*

Dissociation

Attachment

X^-

X

Triplet (Long)

Singlet (Short)

X^*

VUV 128nm

Absorption, Penning

Charge Signal

Scintillation Light Signal

E→∞

42,000 e/MeV

8980 e/mm for MIP

E→0

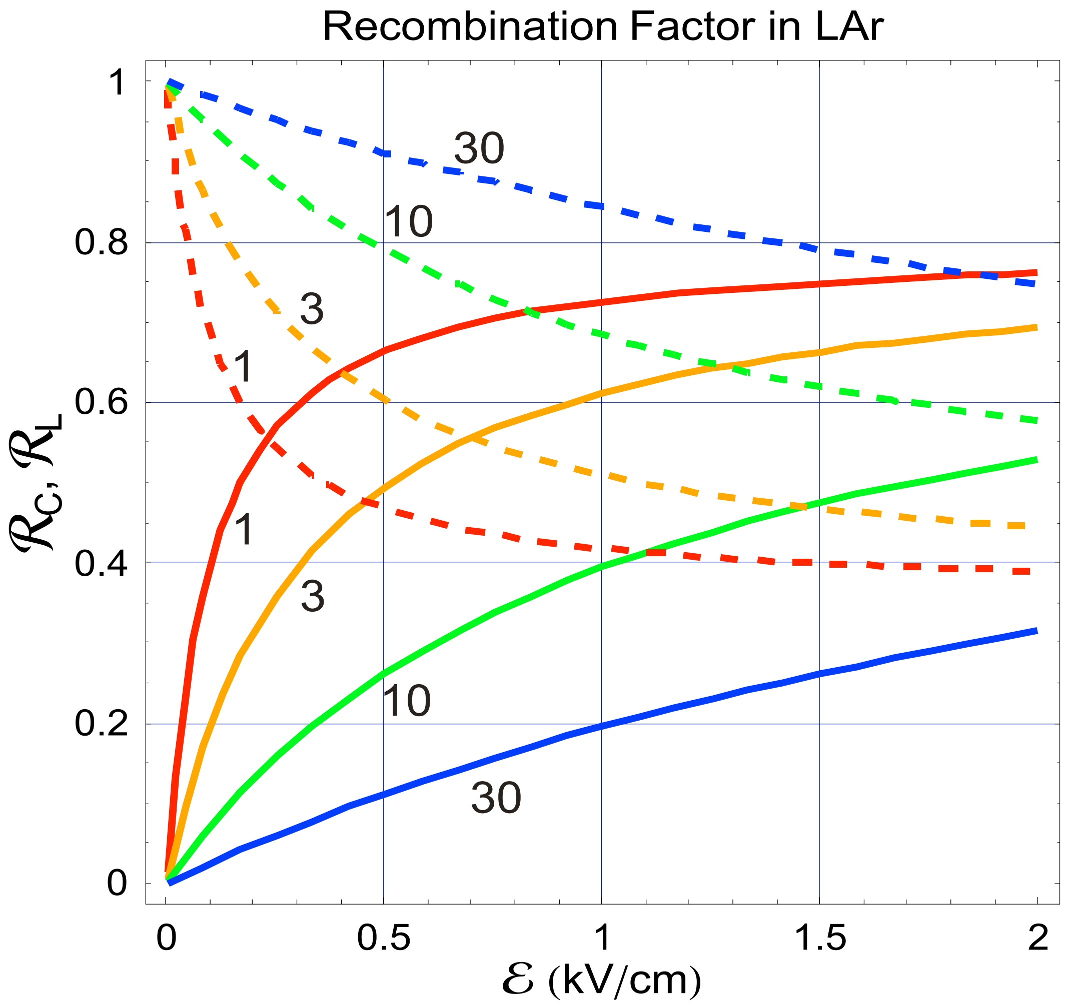
51,300 ph/MeV

10,900 ph/mm for MIP

R={LNe, LAr, LKr, LXe}

X={N_2, O_2, H_2O, …}

Recombination Factor in LAr

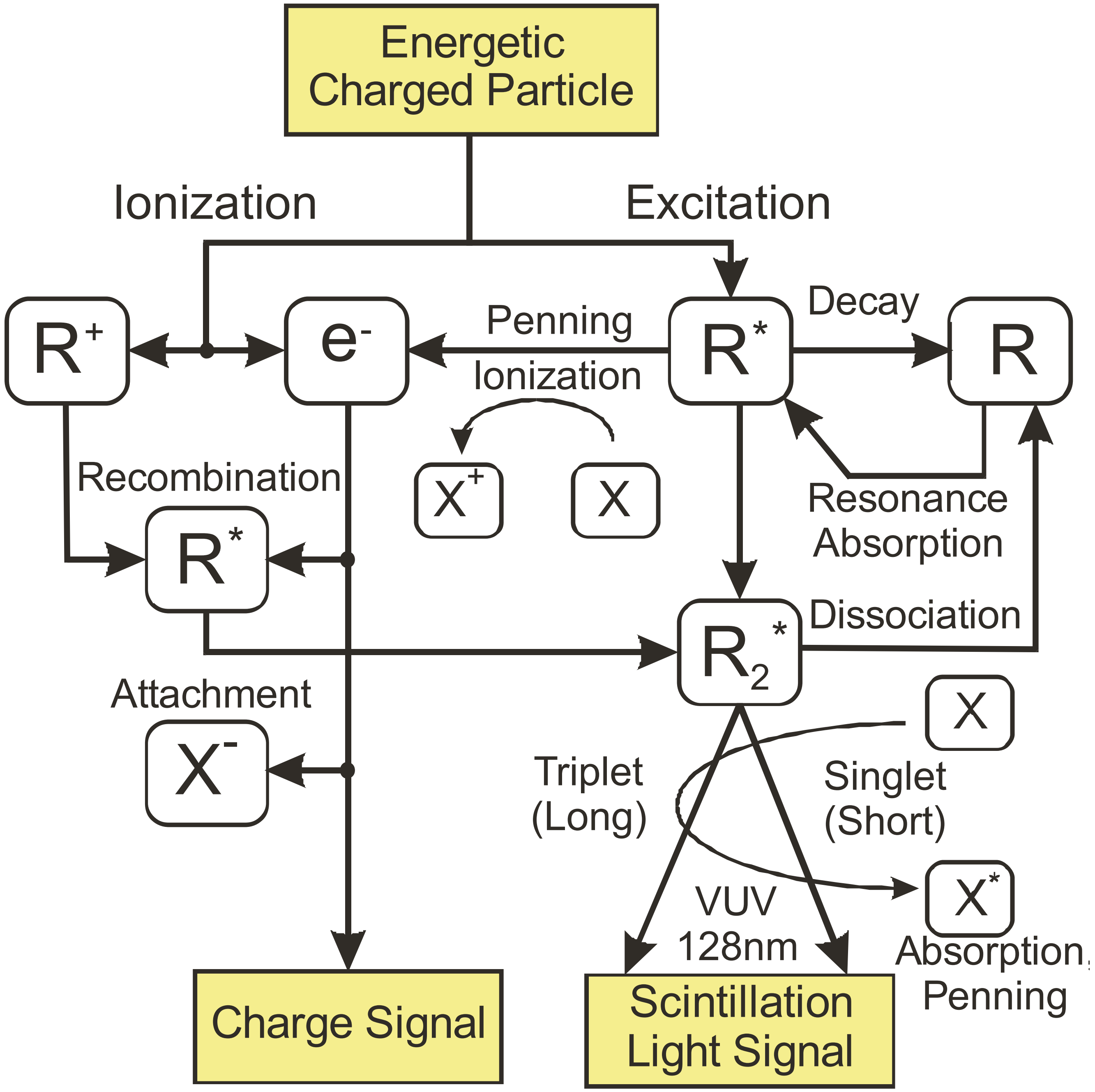


Ratio w/r/t full yield

Solid: charge, Dashed: light

Numbers: Specific Eloss in MIPs

What happens to the energy as a charged particle traverses in LAr?



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Excitation

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(40,000 for NaI(Tl))

R={LNe, LAr, LKr, LXe}

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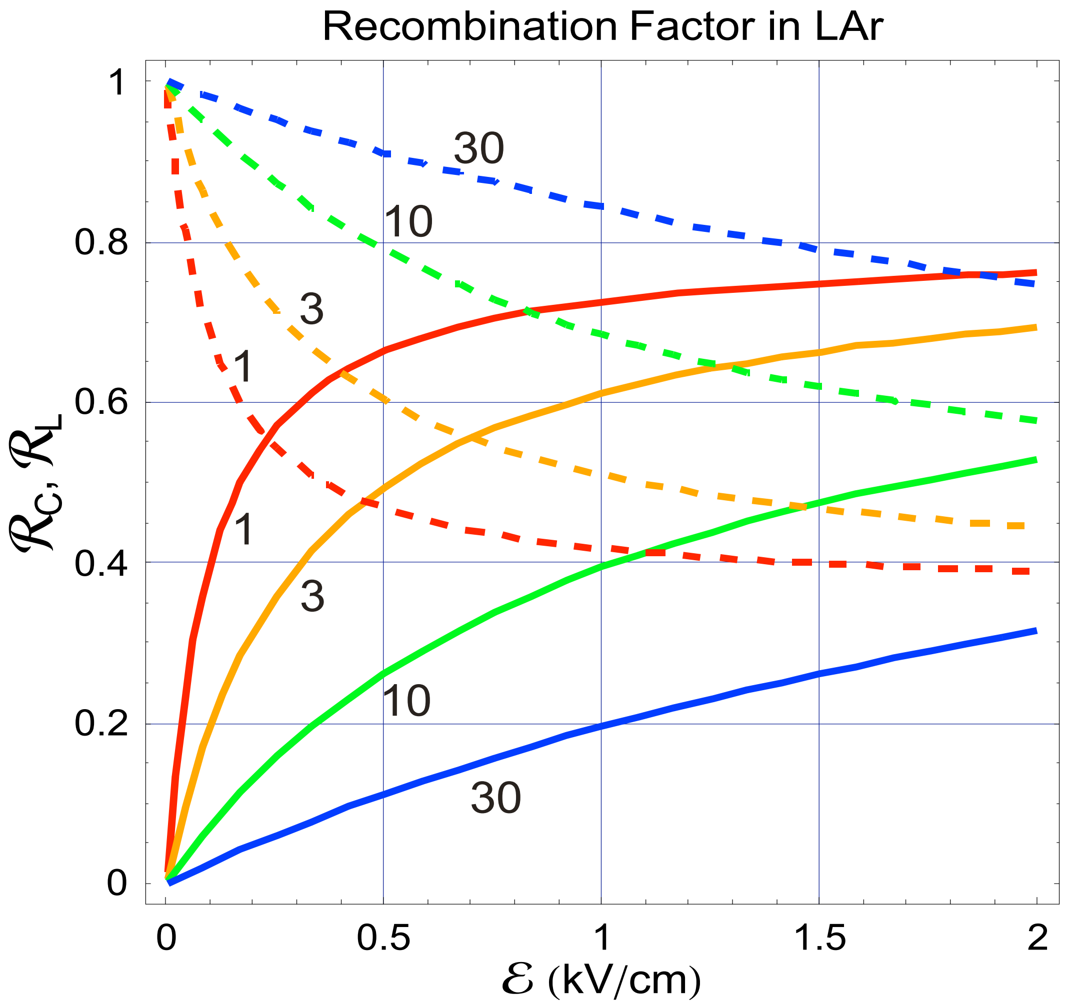

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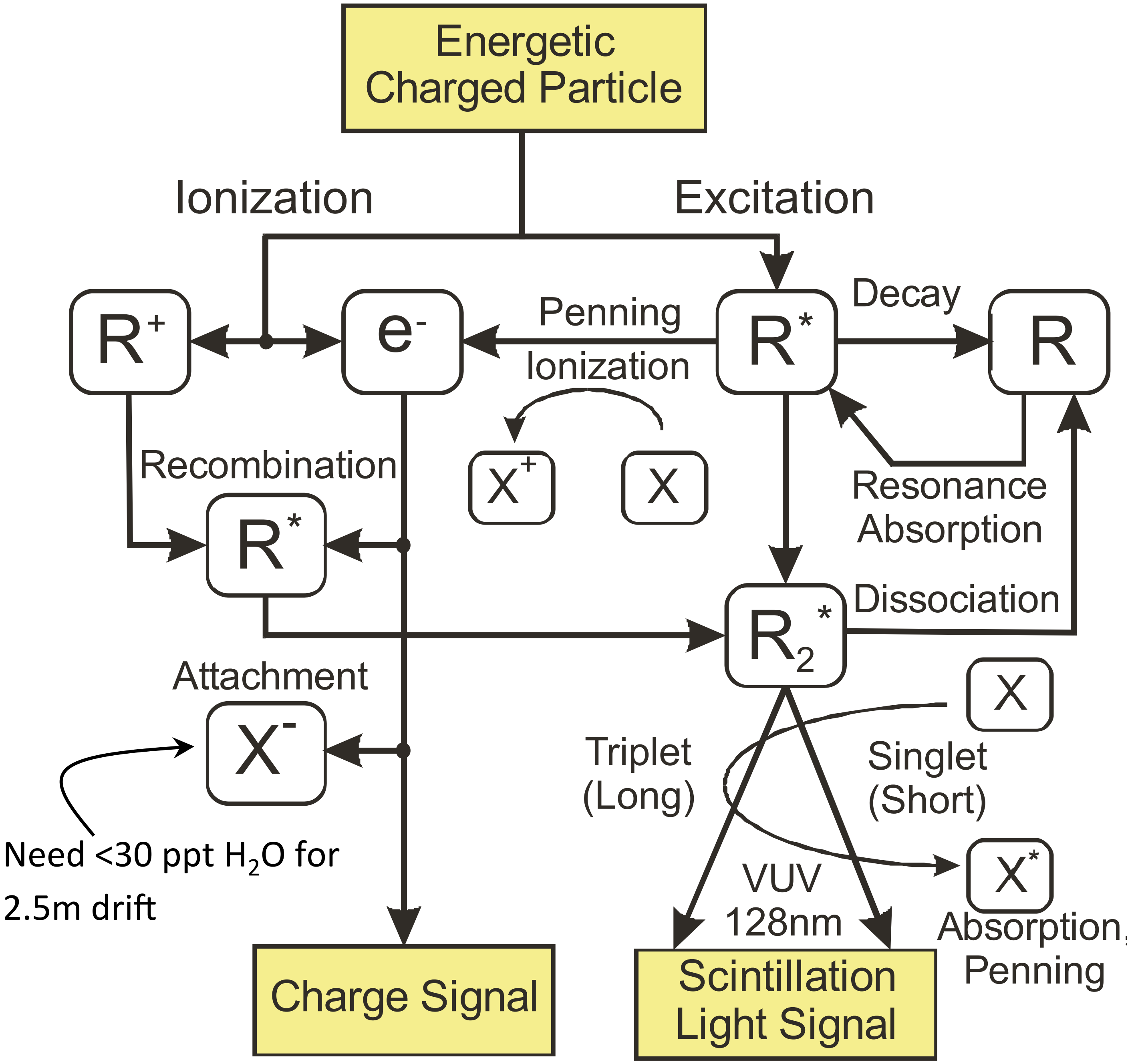
Energetic Charged Particle

Ionization

Excitation

R^+

e^-

Penning Ionization

R^*

Decay

R

X^+

X

Recombination

R^*

Resonance Absorption

R_2^*

Dissociation

Attachment

X^-

X

Triplet (Long)

Singlet (Short)

VUV 128nm

X^*

Absorption, Penning

Need <30 ppt H_2O for 2.5m drift

Charge Signal

Scintillation Light Signal

E→∞

42,000 e/MeV

8980 e/mm for MIP

E→0

51,300 ph/MeV

10,900 ph/mm for MIP

(40,000 for NaI(Tl))

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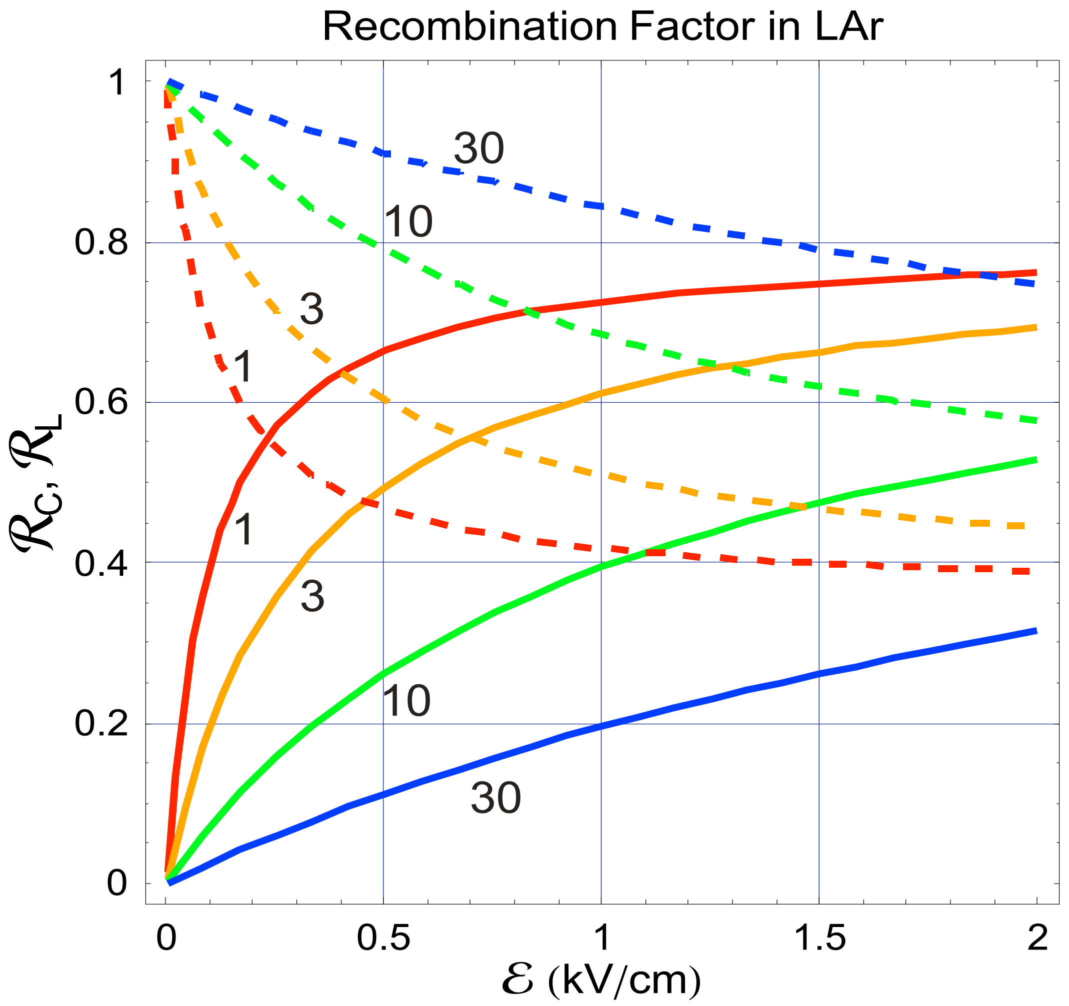


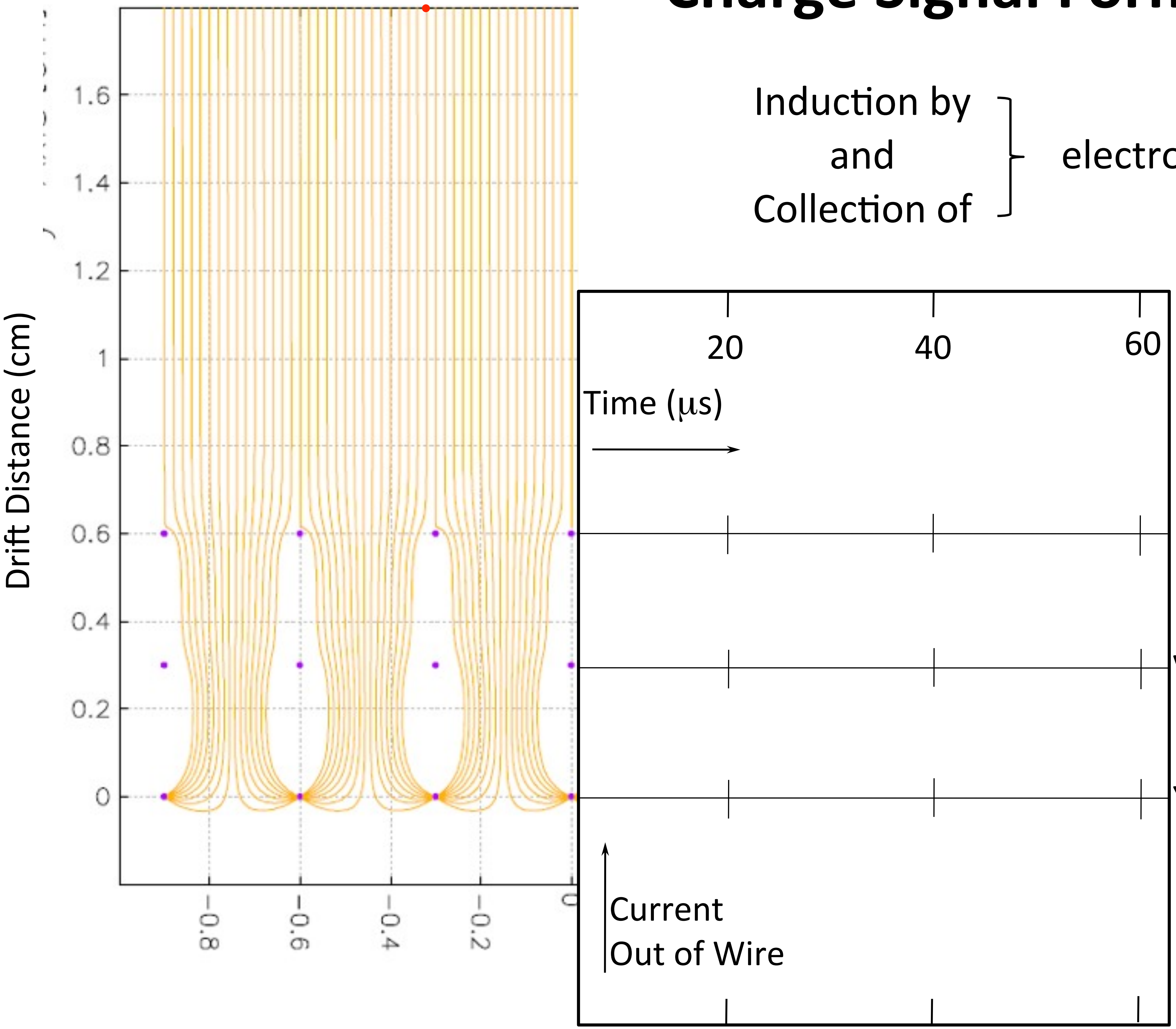
Ratio w/r/t full yield

Solid: charge, Dashed: light

Numbers: Specific Eloss in MIPs

Charge Signal Formation

Induction by
and
Collection of
electrons on wires



U Induction
(small, bipolar)

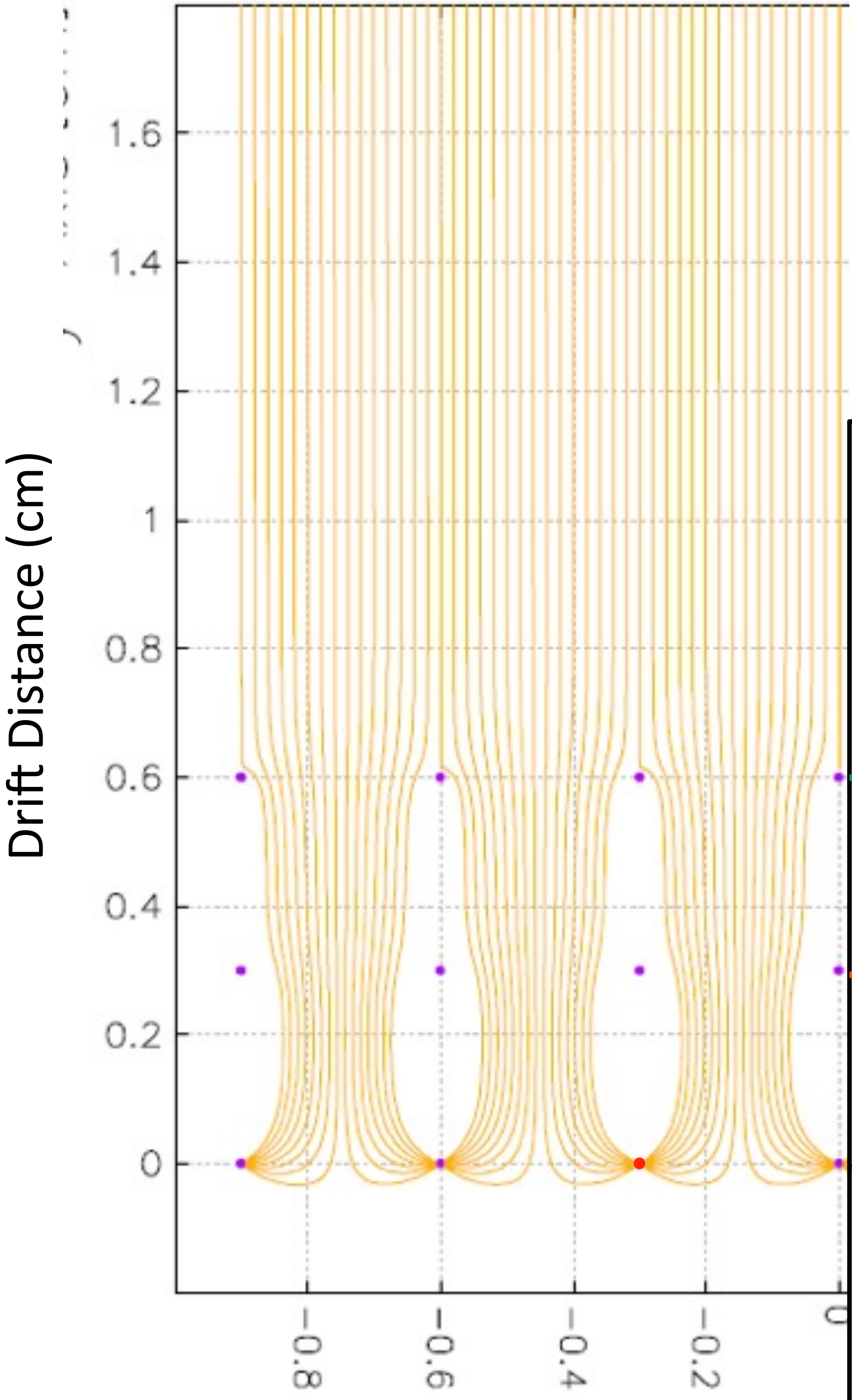
V Induction
(small, bipolar)

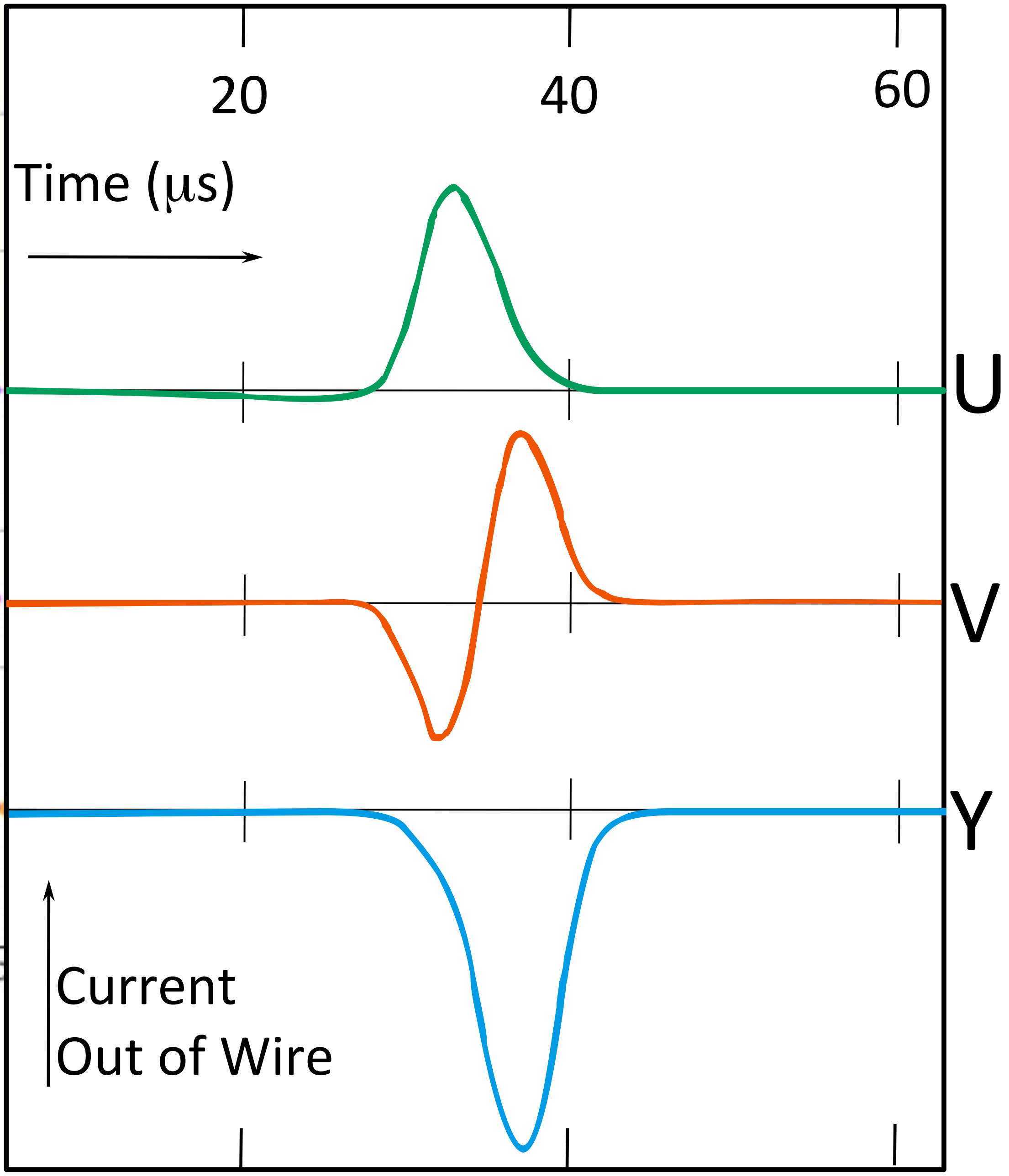
Y Collection
(large, unipolar)

Bo Yu (BNL)

Charge Signal Formation

Induction by
and
Collection of
} electrons on wires





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Charge Signal Formation

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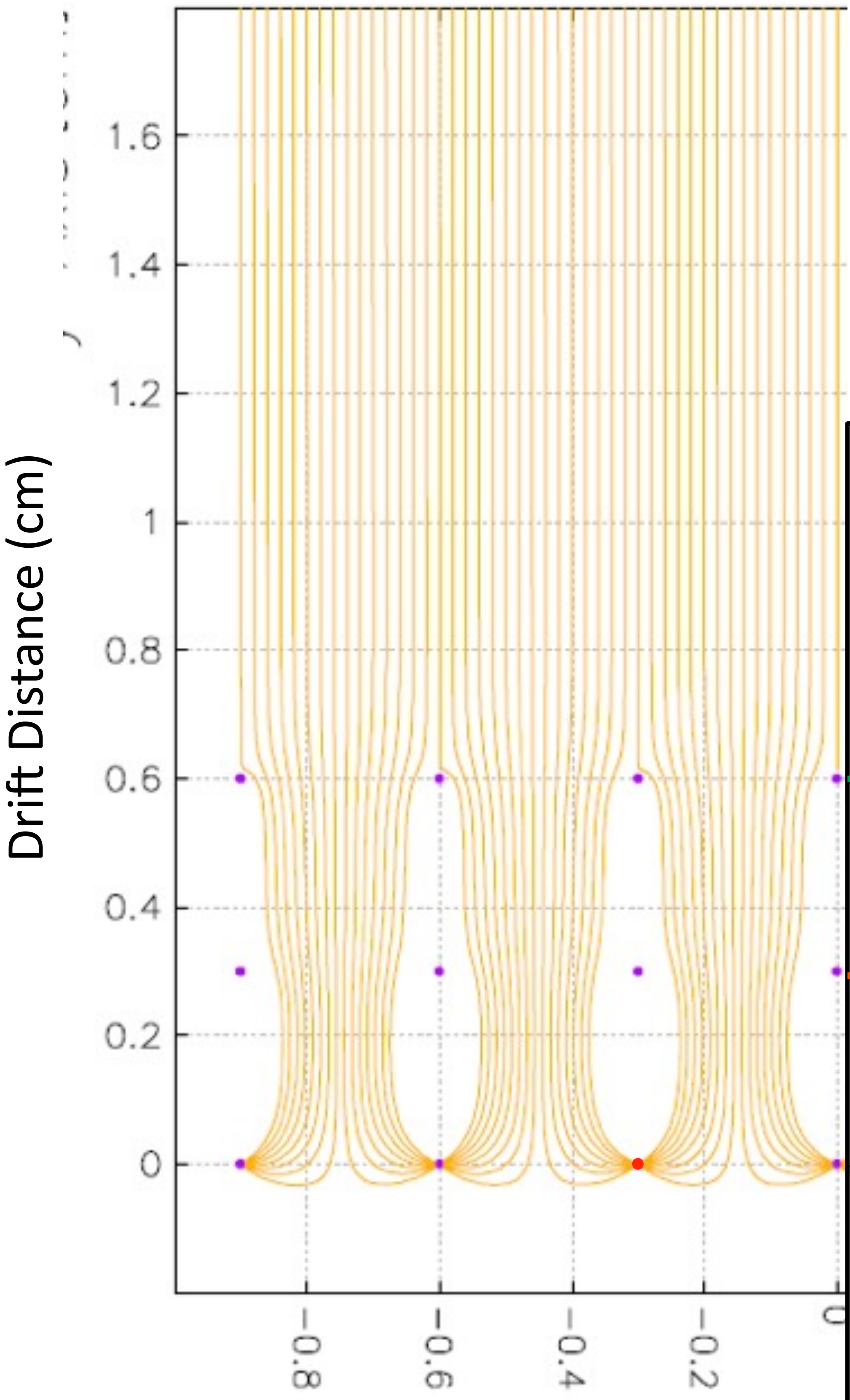
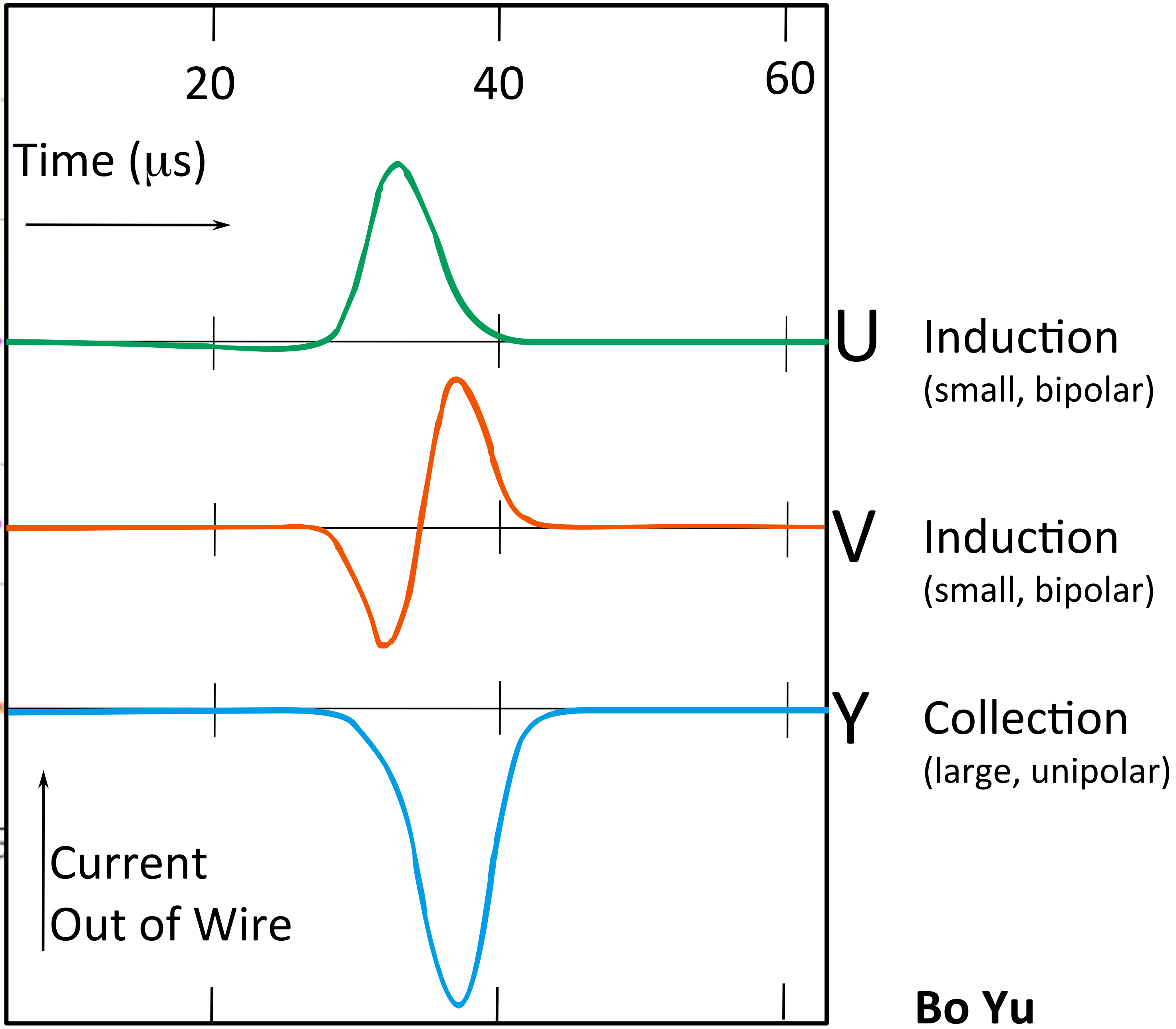


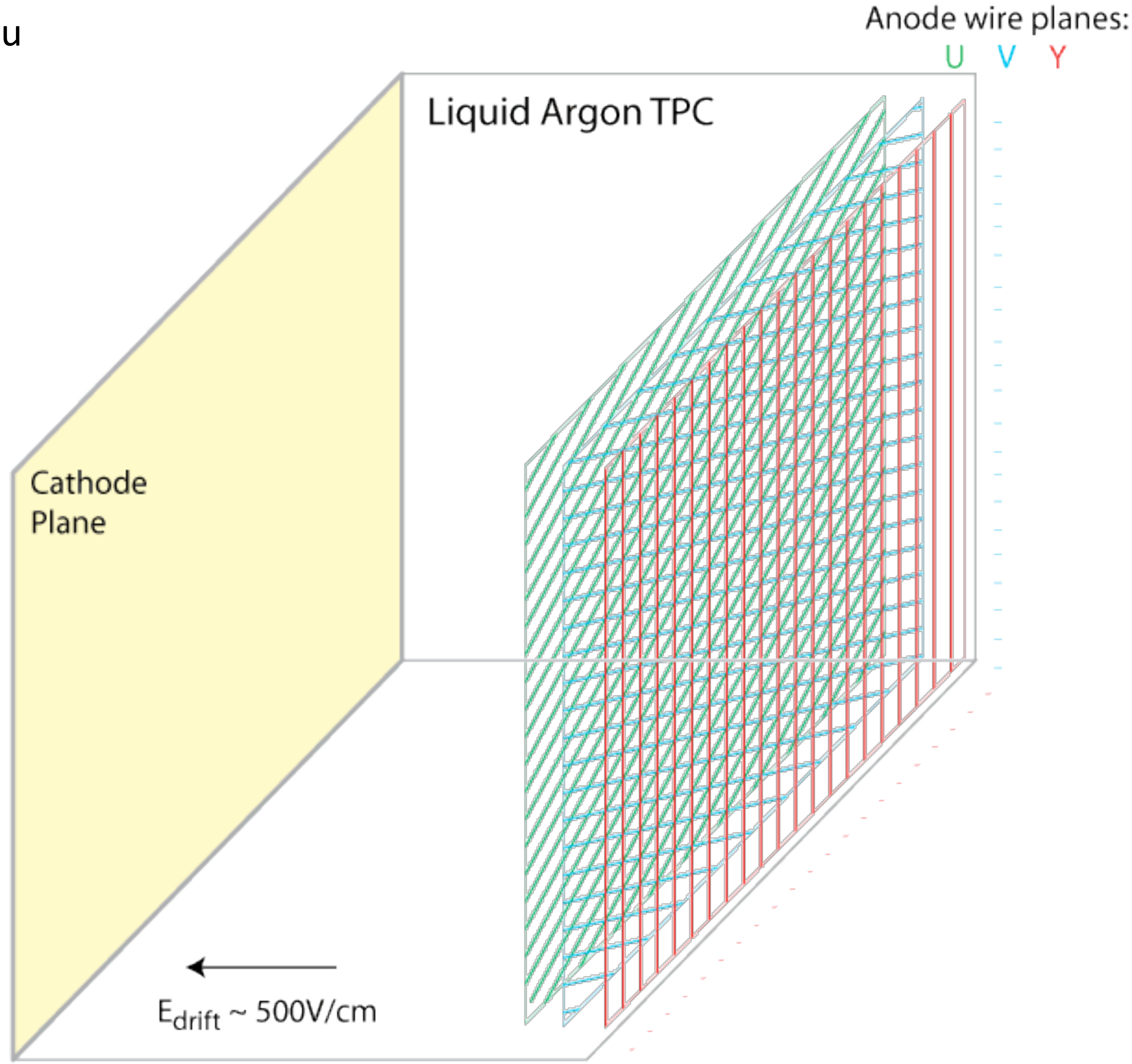


Signal formation starts upon motion of the charge.

Bo Yu (BNL)

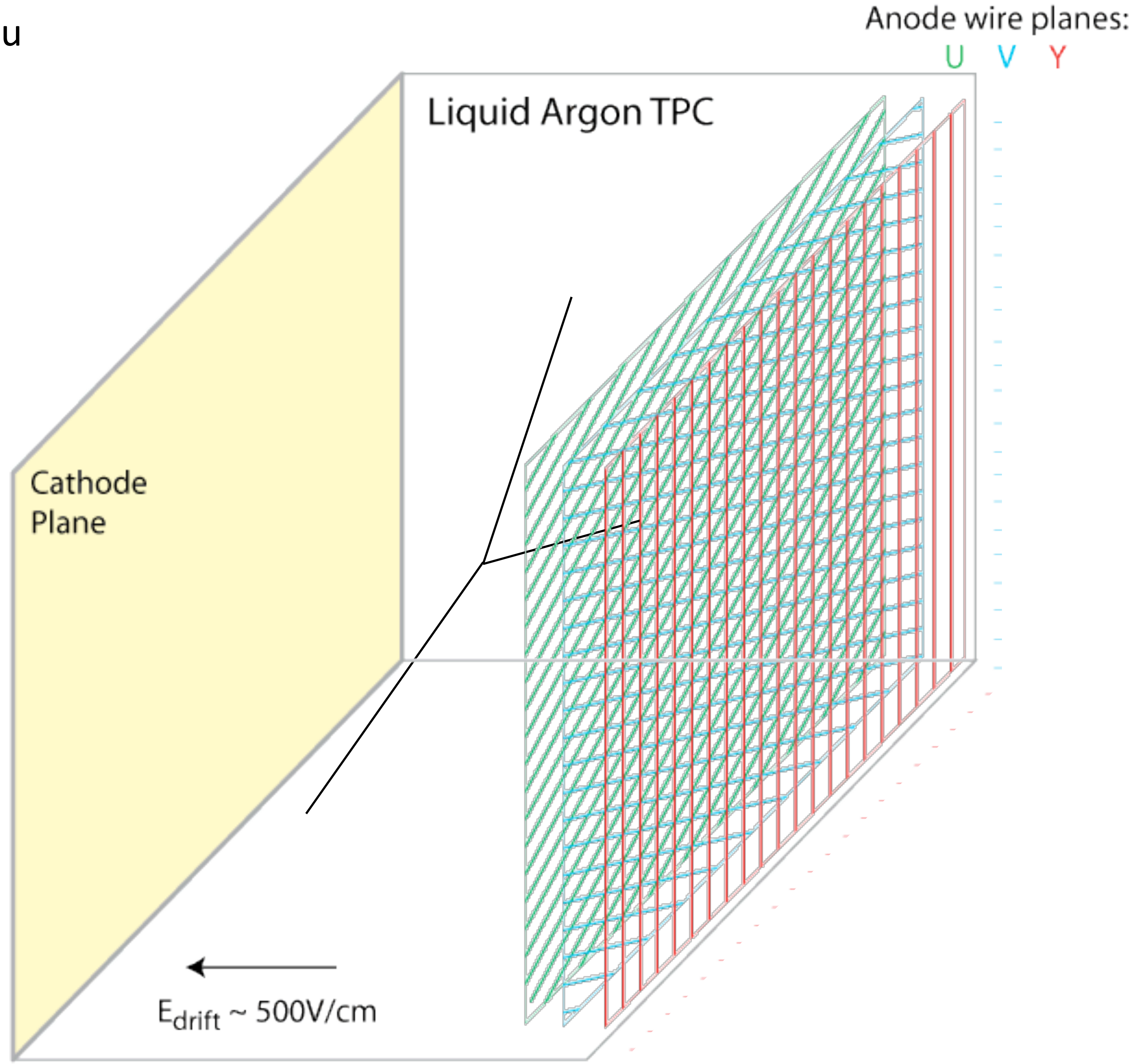
How Does a LArTPC Work?

Bo Yu



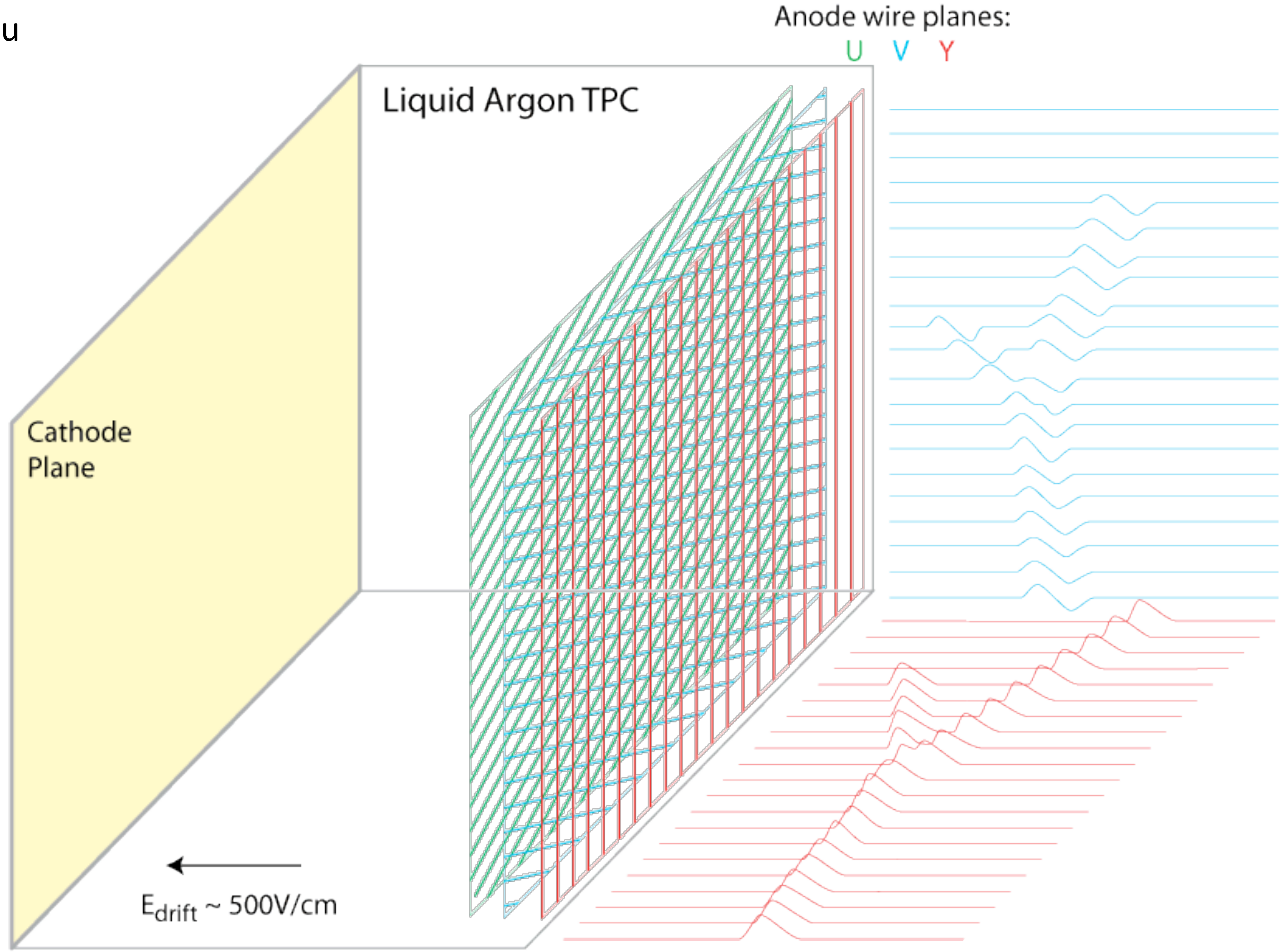
How Does a LArTPC Work?

Bo Yu



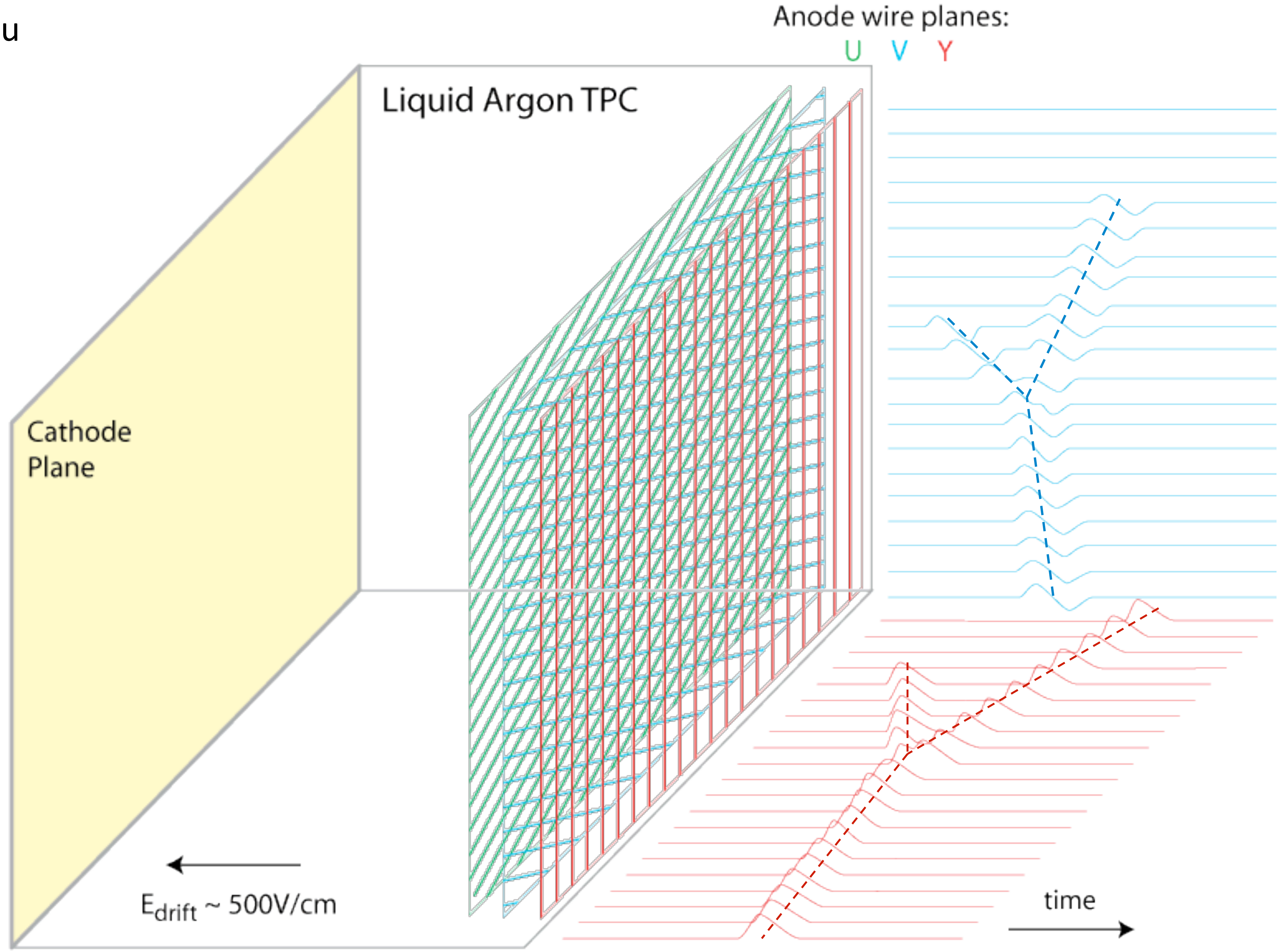
How Does a LArTPC Work?

Bo Yu



How Does a LArTPC Work?

Bo Yu



What can a LAr TPC do?

- Tracking to identify events by topology

  mm position resolution

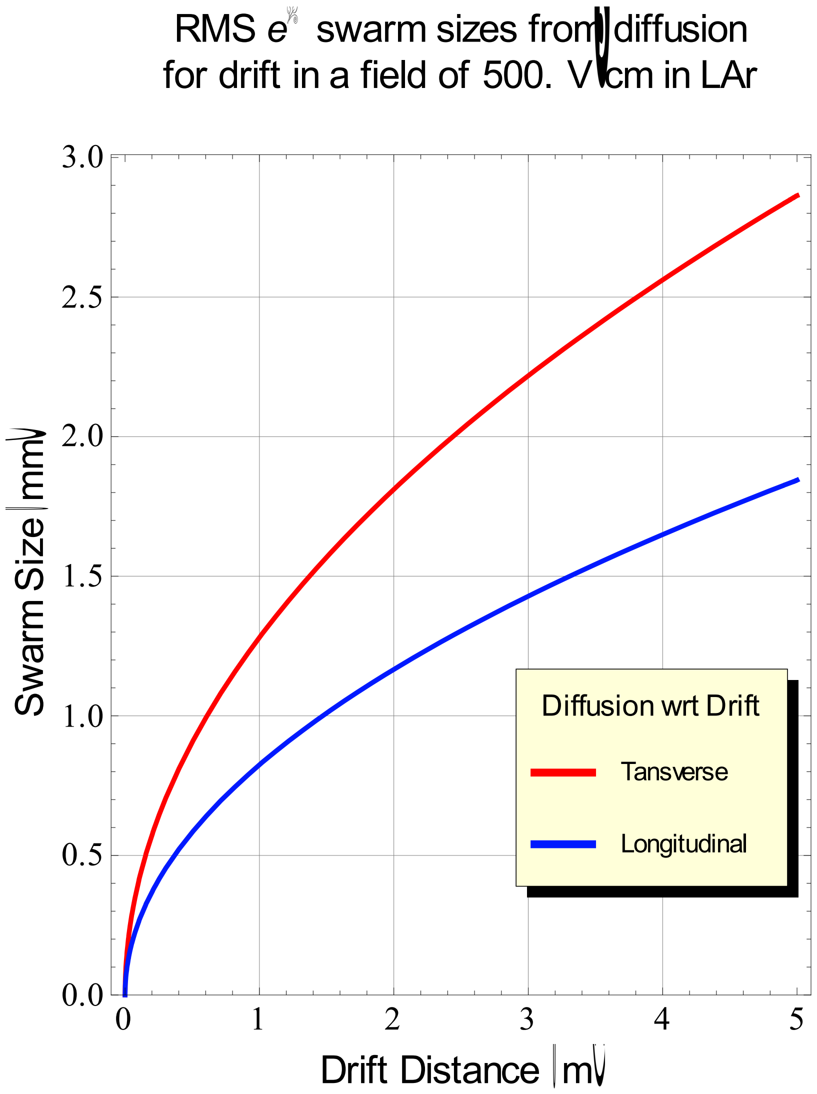
- dE/dx for particle ID

  electron/gamma separation >90%

- Low energy threshold

  particle energies < 5 MeV

- Scalable to multi-kiloton size



This detector still requires a R&D and technological development for scale up.

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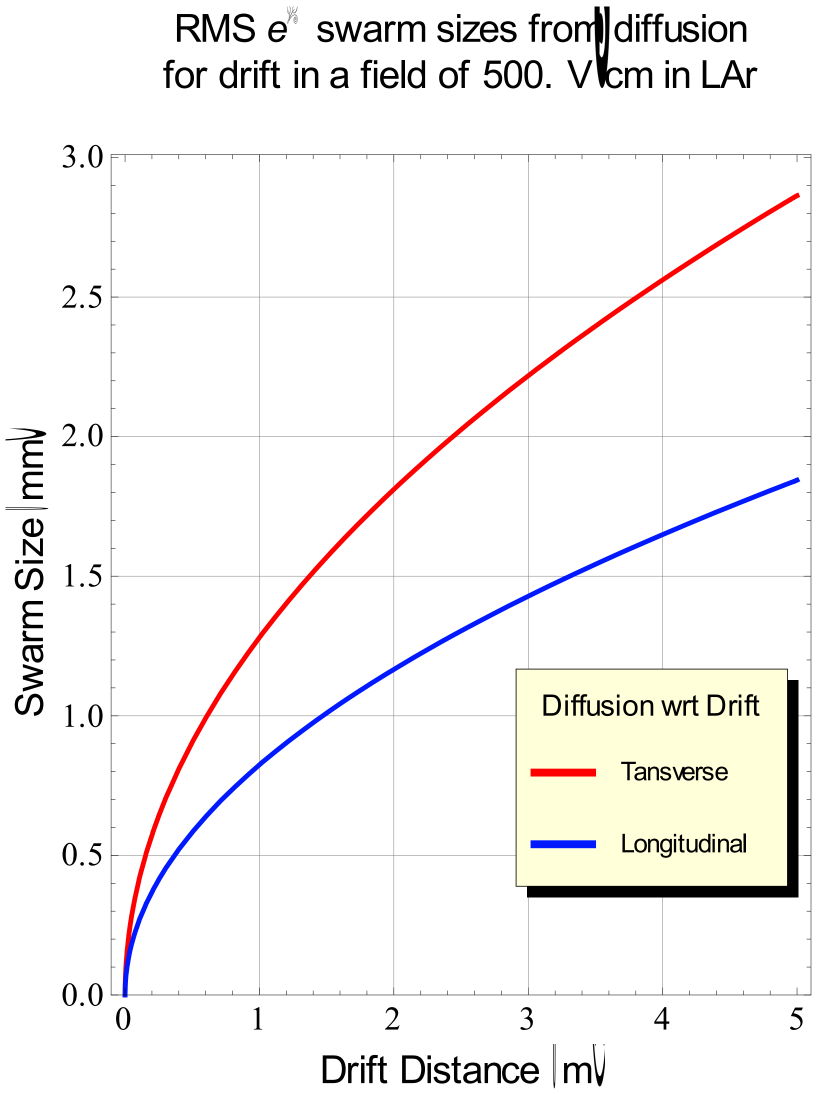

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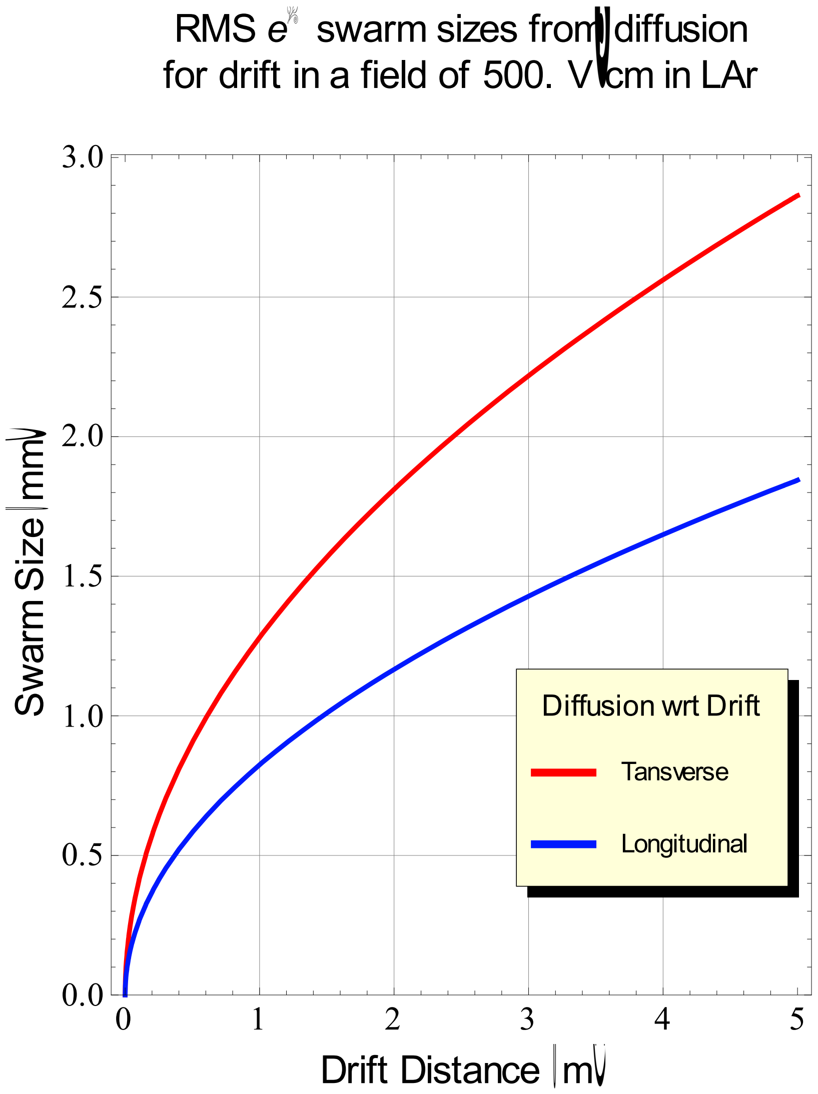

$$kT = eD/\mu \longrightarrow \begin{array}{l} T_{TRAN} = 480K \\ T_{LONG} = 200K \end{array}$$

This detector still requires a R&D and technological development for scale up.

What can a LAr TPC do?

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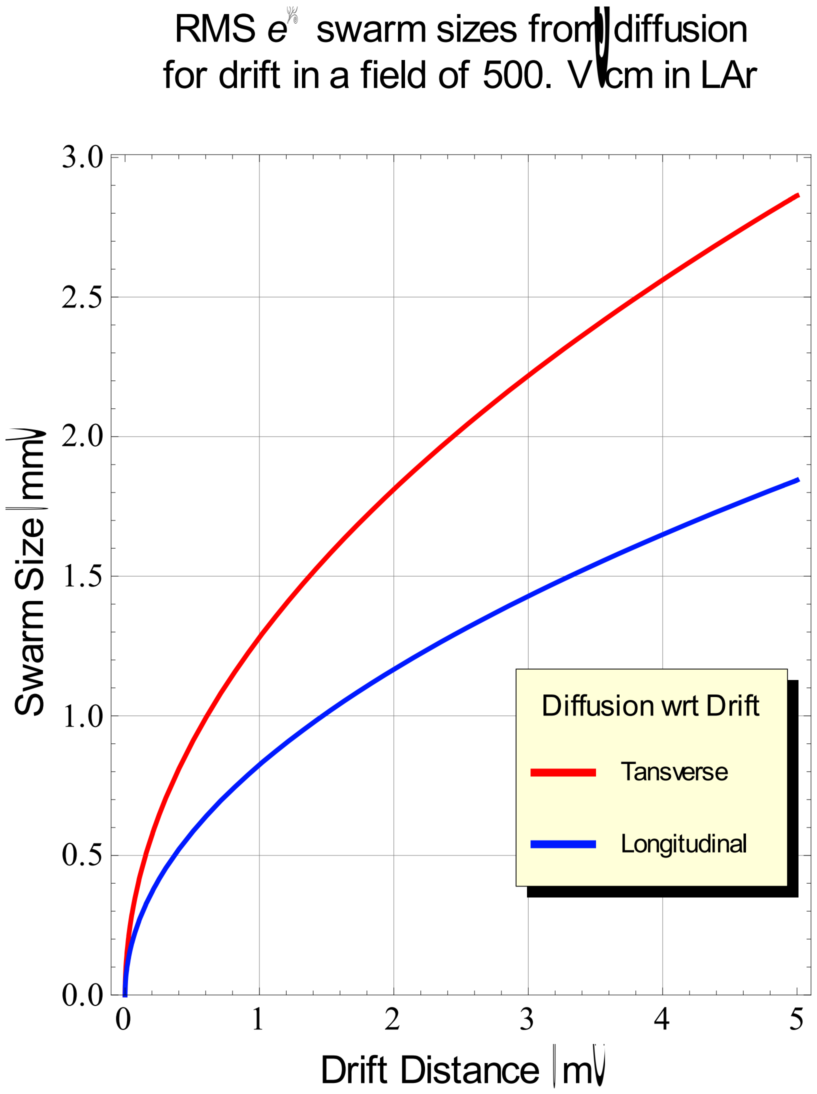
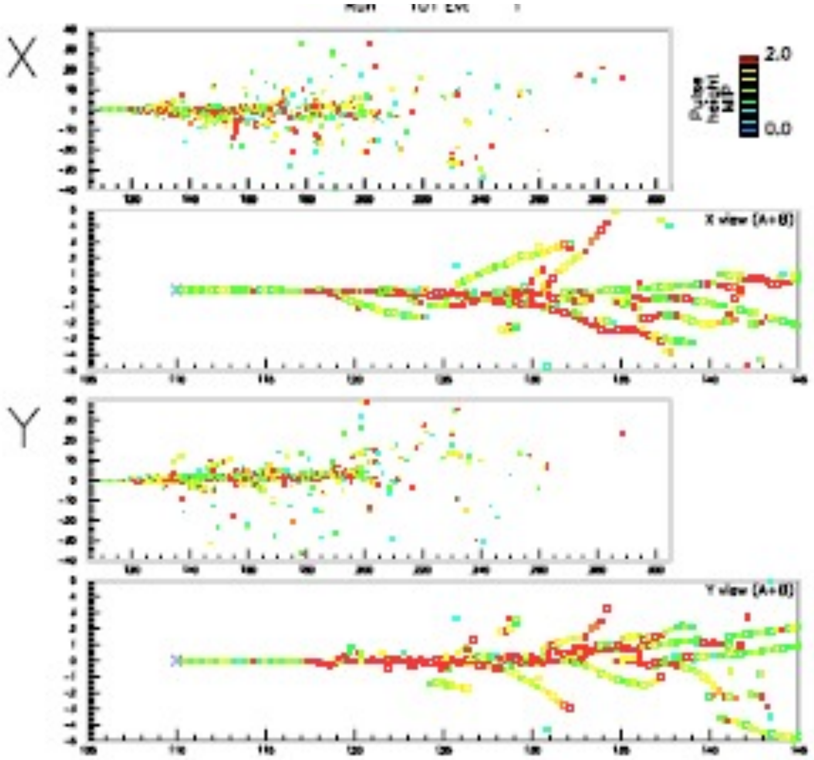
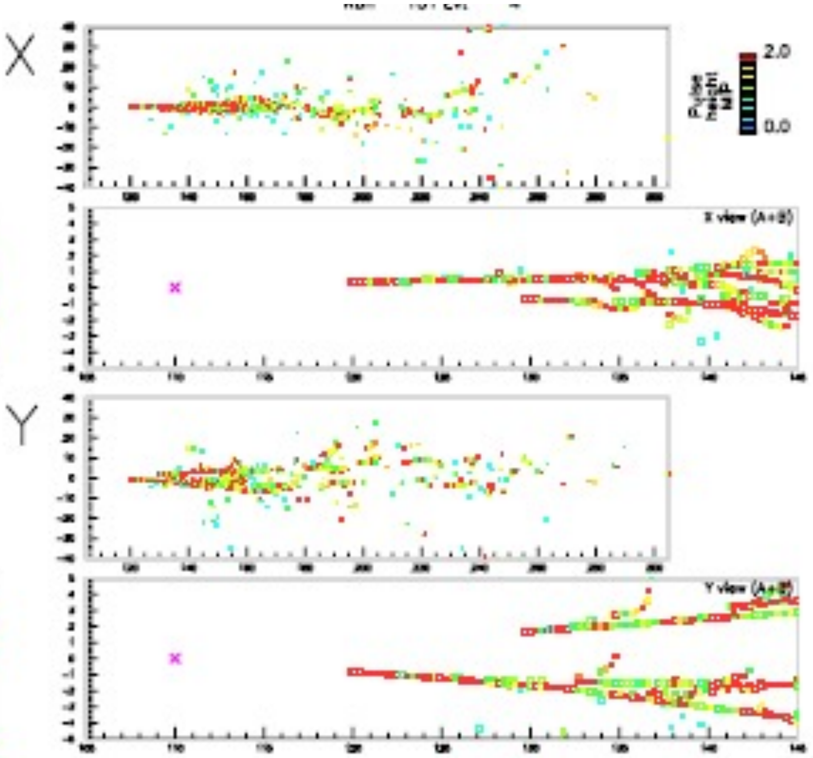


Electron



$\pi^0 \rightarrow$ 2 Gammas



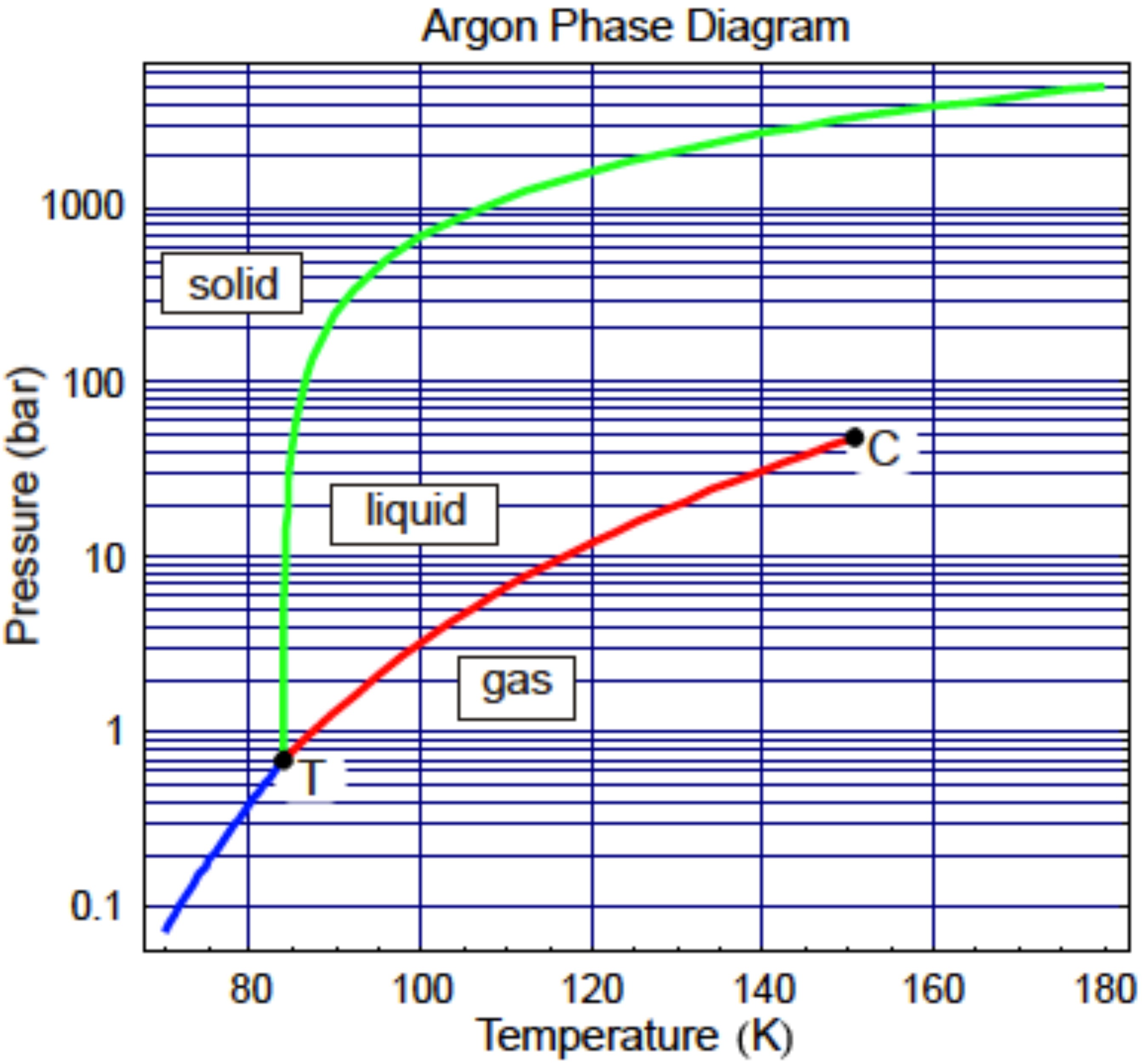
$$kT = eD/\mu \longrightarrow \begin{array}{l} T_{TRAN} = 480K \\ T_{LONG} = 200K \end{array}$$

Green < 1.2 MIP

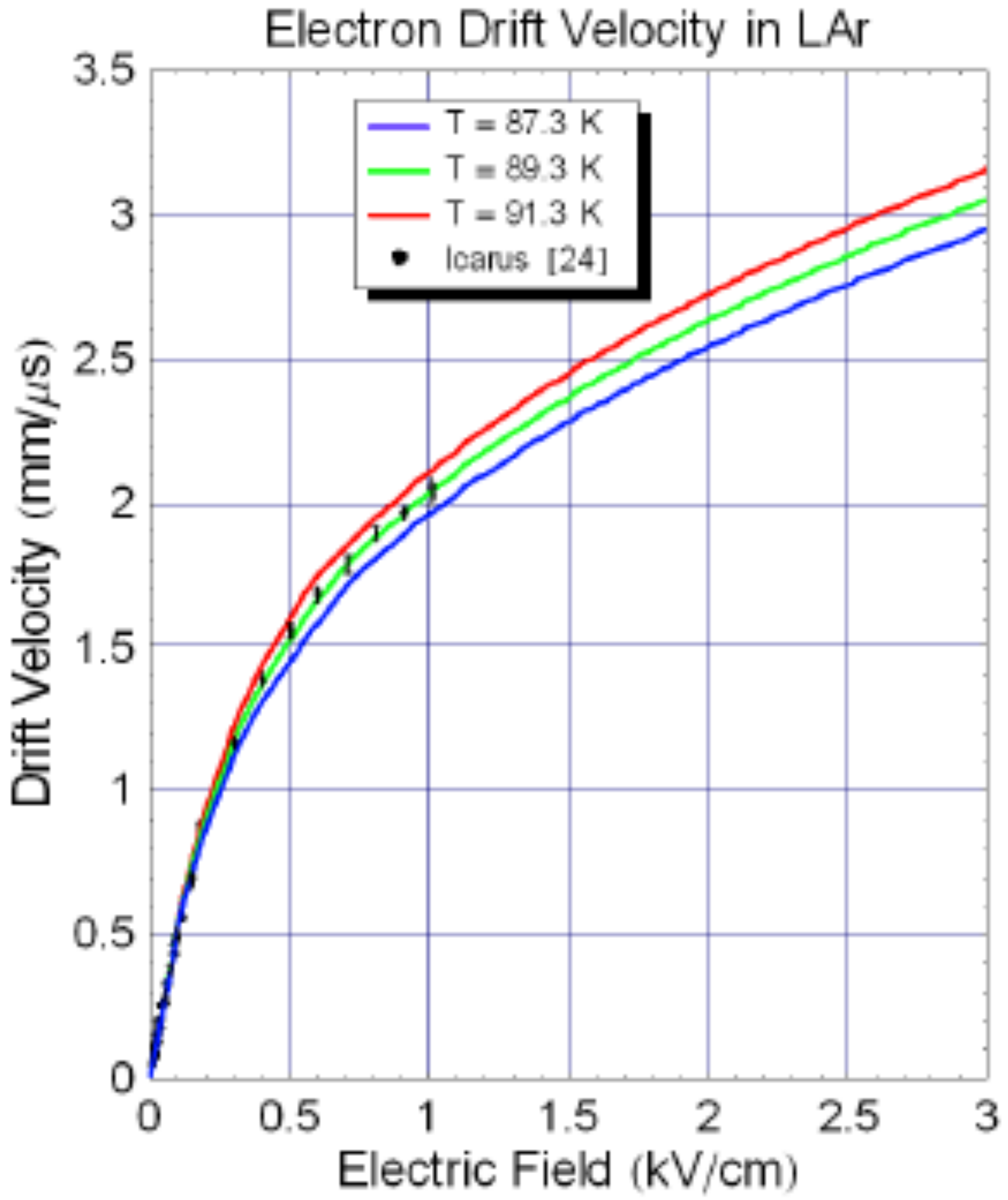
Red > 1.8 MIP

This detector still requires a R&D and technological development for scale up.

Key Technical Issues for a Liquid Argon Detector



It is cold ! And this makes it inaccessible and difficult to work with.



It is slow ! Electrons drift slowly. Drives many issues of design.

Key enabling technology: Cold (87K) Electronics?

Channel Count

Lower limit

- **10 m** sense wire length
- **5 x 5 mm** sense wire spacing
- **2.5 m** electron drift distance

⇒ **~18/ton**
369k/20kt

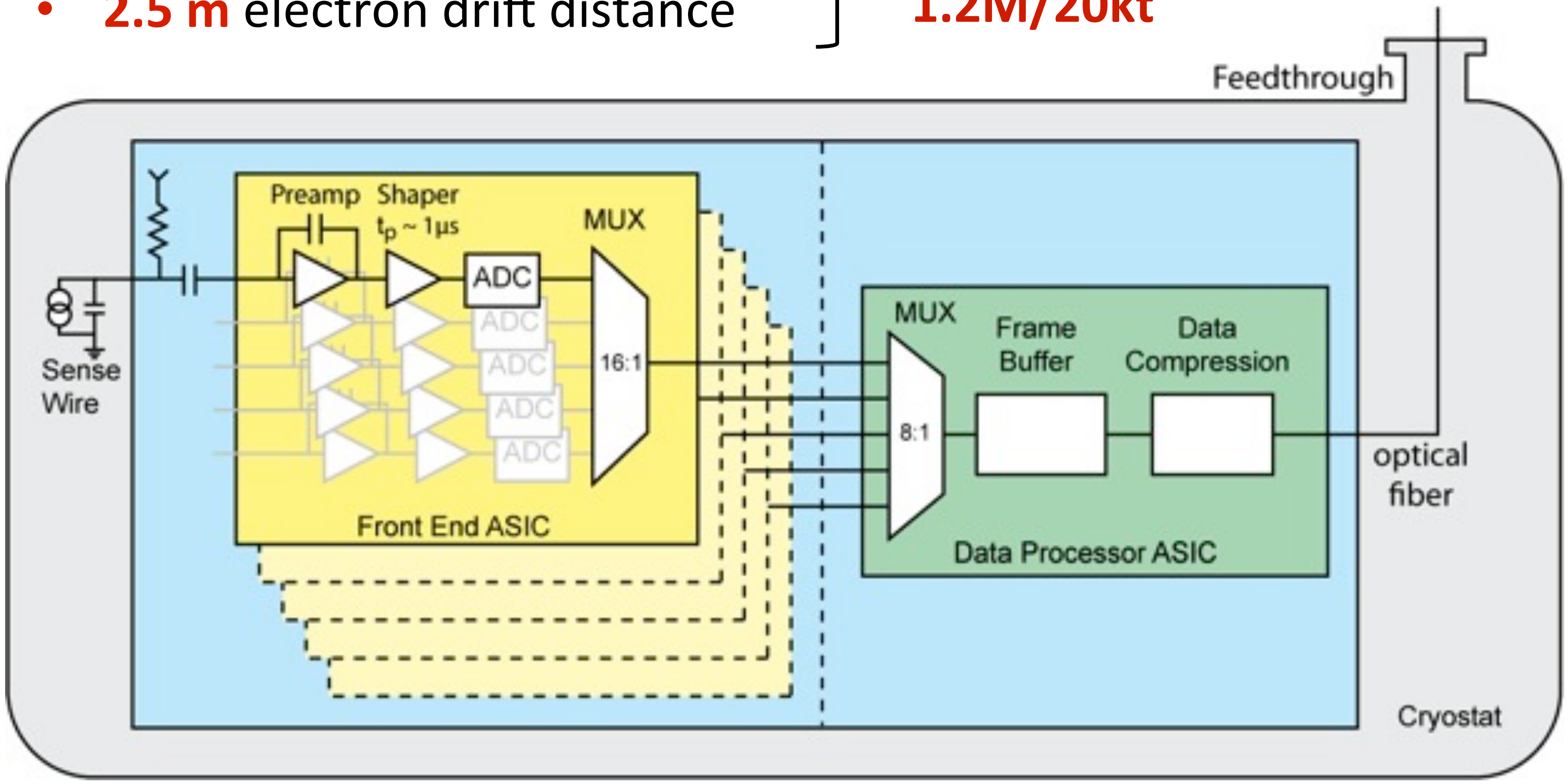
Upper limit

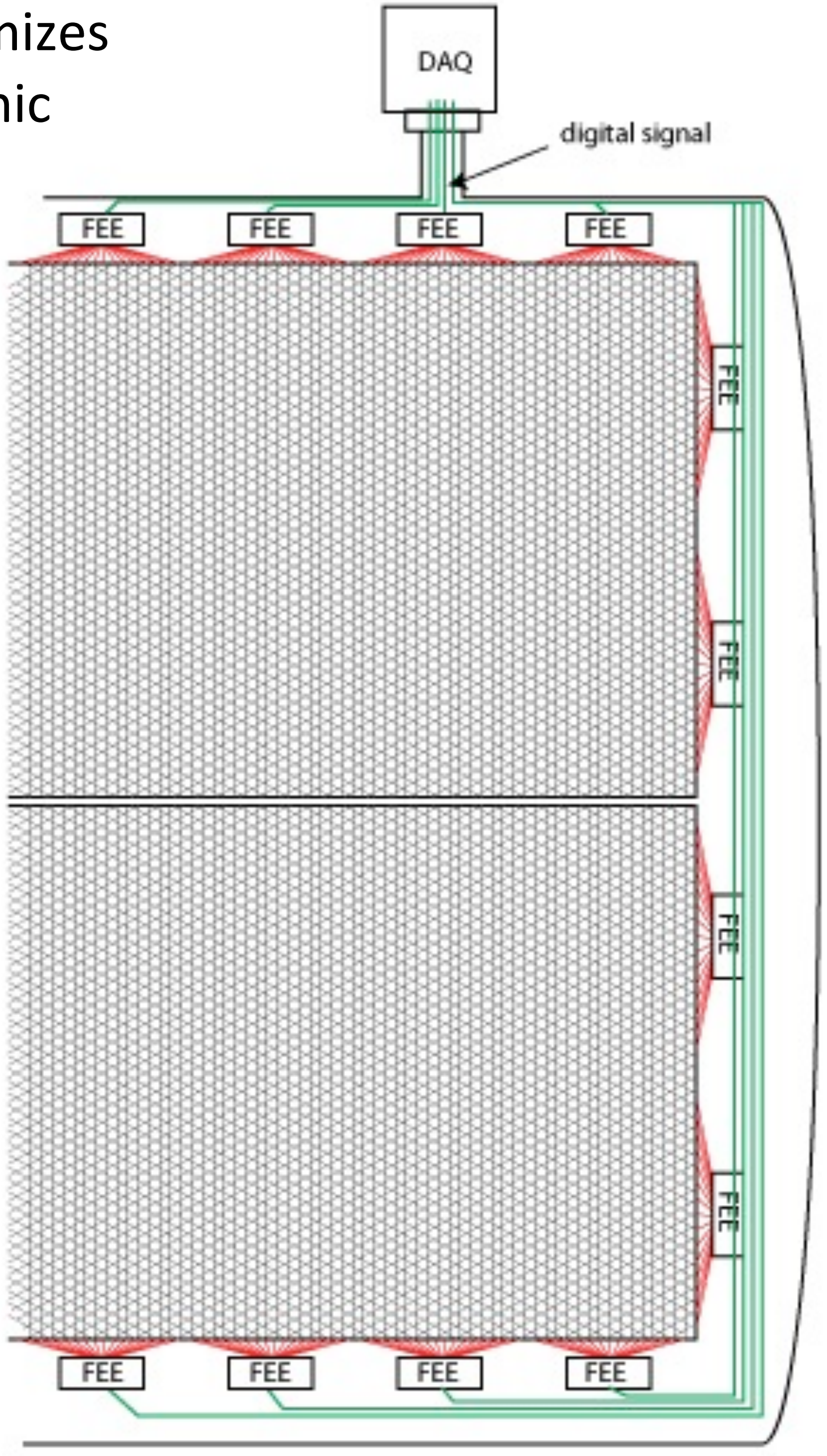
- **5 m** sense wire length
- **3 x 3 mm** sense wire spacing
- **2.5 m** electron drift distance

⇒ **~60/ton**
1.2M/20kt

Cold electronics (in LAr) keeps cable lengths and capacitance small, increasing SNR.

Multiplexing minimizes number of cryogenic penetrations.





A CMOS, or a BiCMOS, technology with circuit design and operating conditions for long term operation in LAr will be used. A preliminary goal is **multiplexing in two steps by 16 x 8=128**. Power dissipation has been estimated to be ≤10mW/signal wire.

Must have extremely high reliability !

Long-Baseline Neutrino Experiment Collaboration

Alabama: S.Habib, I.Stancu

Argonne: M.D'Agostino, G.Drake.Z.Djurcic, M.Goodman, V.Guarino, S.Magill, J.Paley, H.Sahoo, R.Talaga, M.Wetstein

Boston: E.Hazen, E.Kearns, S.Linden

Brookhaven: M.Bishai, R.Brown, H.Chen, M.Diwan, J.Dolph, G.Geronimo, R.Gill, R.Hackenburg, R.Hahn, S.Hans, Z.Isvan, D.Jaffe, S.Junnarkar, S.H.Kettell, F.Lanni, Y.Li, L.Littenberg, J.Ling, D.Makowiecki, W.Marciano, W.Morse, Z.Parsa, V.Radeka, S.Rescia, N.Samios,R.Sharma, N.Simos, J.Sondericker, J.Stewart, H.Tanaka, H.Themann, C.Thorn, B.Viren, S.White, E.Worcester, M.Yeh, B.Yu, C.Zhang

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Cambridge: A.Blake, M.Thomson

Catania/INFN: V.Bellini, F.La Zia, F.Mammoliti, R.Potenza,

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Columbia: R.Carr, L.Camillieri, C.Y.Chi, G.Karagiorgi, C.Mariani, M.Shaevitz, W.Sippach, W.Willis

Crookston: D.Demuth

Dakota State: B.Szcerbinska

Davis: M.Bergevin, R.Breedon, D.Danielson, J.Felde, C.Maesano, M.Tripanthi, R.Svoboda, M.Szydagis

Drexel: C.Lane, S.Perasso

Duke: T.Akiri, J.Fowler, A.Himmel, Z.Li, K.Scholberg, C.Walter, R.Wendell

Duluth: R.Gran, A.Habig

Fermilab: D.Allspach, M.Andrews, B.Baller, E.Berman, R.Bernstein, V.Bocean, M.Campbell, A.Chen, S.Childress, A.Drozhdin, T.Dykhuis, C.Escobar, H.Greenlee, A.Hahn, S.Hays, A.Heavey, J.Howell, P.Huhr, J.Hylen, C.James, M.Johnson, J.Johnstone, H.Jostlein, T.Junk, B.Kayser, M.Kirby, G.Koizumi, T.Lackowski, P.Lucas, B.Lundberg, T.Lundin, P.Mantsch, A.Marchionni, E .McCluskey, S.Moed Sher, N.Mokhov, C.Moore, J.Morfin, B.Norris, V.Papadimitriou, R.Plunkett, C.Polly, S.Pordes, O.Prokofiev, J.L.Raaf, G.Rameika, B.Rebel, D.Reitzner, K.Riesselmann, R.Rucinski, R.Schmidt, D.Schmitz, P.Shanahan, M.Stancari, A.Stefanik, J.Strait, S.Striganov, K.Vaziri, G.Velev, T.Wyman, G.Zeller, R.Zwaska

Hawai'i: S.Dye, J.Kumar, J.Learned, J.Maricic, S.Matsuno, R.Milincic, S.Pakvasa, M.Rosen, G.Varner

Houston: L.Whitehead

Indian Universities: V.Singh (BHU); B.Choudhary, S.Mandal (DU); B.Bhuyan [IIT(G)]; V.Bhatnagar, A.Kumar, S.Sahijpal(PU)

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Iowa State: I.Anghel, G.S.Davies, M.Sanchez, T.Xin

IPMU/Tokyo: M.Vagins

Irvine: G.Carminati, W.Kropp, M.Smy, H.Sobel

Kansas State: T.Bolton, G.Horton-Smith

LBL: B.Fujikawa, V.M.Gehman, R.Kadel, D.Taylor

Livermore: A.Bernstein, R.Bionta, S.Dazeley, S.Ouedraogo

London: A.Holin, J.Thomas

Los Alamos: M.Akashi-Ronquest, S.Elliott, A.Friedland, G.Garvey, E.Guardincerri, T.Haines, D.Lee, W.Louis, C.Mauger, G.Mills, Z.Pavlovic, J.Ramsey, G.Sinnis, W.Sondheim, R.Van de Water, H.White, K.Yarritu

Louisiana: J.Insler, T.Kutter, W.Metcalf, M.Tzanov

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Michigan State: E.Arrieta-Diaz, C.Bromberg, D.Edmunds, J.Huston, B.Page

Minnesota: M.Marshak, W.Miller

MIT: W.Barletta, J.Conrad, B.Jones, T.Katori, R.Lanza, A.Prakash, L.Winslow

NGA: S.Malys, S.Usman

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Oxford: G.Barr, J.de Jong, A.Weber

Pennsylvania: S.Grullon, J.Klein, K.Lande, T.Latorre, A.Mann, M.Newcomer, S.Seibert, R.vanBerg

Pittsburgh: D.Naples, V.Paolone

Princeton: Q.He, K.McDonald

Rensselaer: D.Kaminski, J.Napolitano, S.Salon, P.Stoler

Rochester: L.Loiacono, K.McFarland, G.Perdue

Sheffield: V.Kudryavtsev, M.Richardson, M.Robinson, N.Spooner, L.Thompson

SDMST: X.Bai, C.Christofferson, R.Corey, D.Tiedt

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South Carolina: H.Duyang, B.Mercurio, S.Mishra, R.Petti, C.Rosenfeld, X Tian

South Dakota: D.Barker, J.Goon, D.Mei, W.Wei, C.Zhang

South Dakota State: B.Bleakley, K.McTaggert

Syracuse: M.Artuso, S.Blusk, T.Skwarnicki, M.Soderberg, S.Stone

Tennessee: W.Bugg, T.Handler, A.Hatzikoutelis, Y.Kamyshkov

Texas: S.Kopp, K.Lang, R.Mehdiyev

Tufts: H.Gallagher, T.Kafka, W.Mann, J.Schnepps

UCLA: K.Arisaka, D.Cline, K.Lee, Y.Meng, A.Teymourian, H.Wang

Virginia Tech.: E.Guarnaccia, J.Link, D.Mohapatra

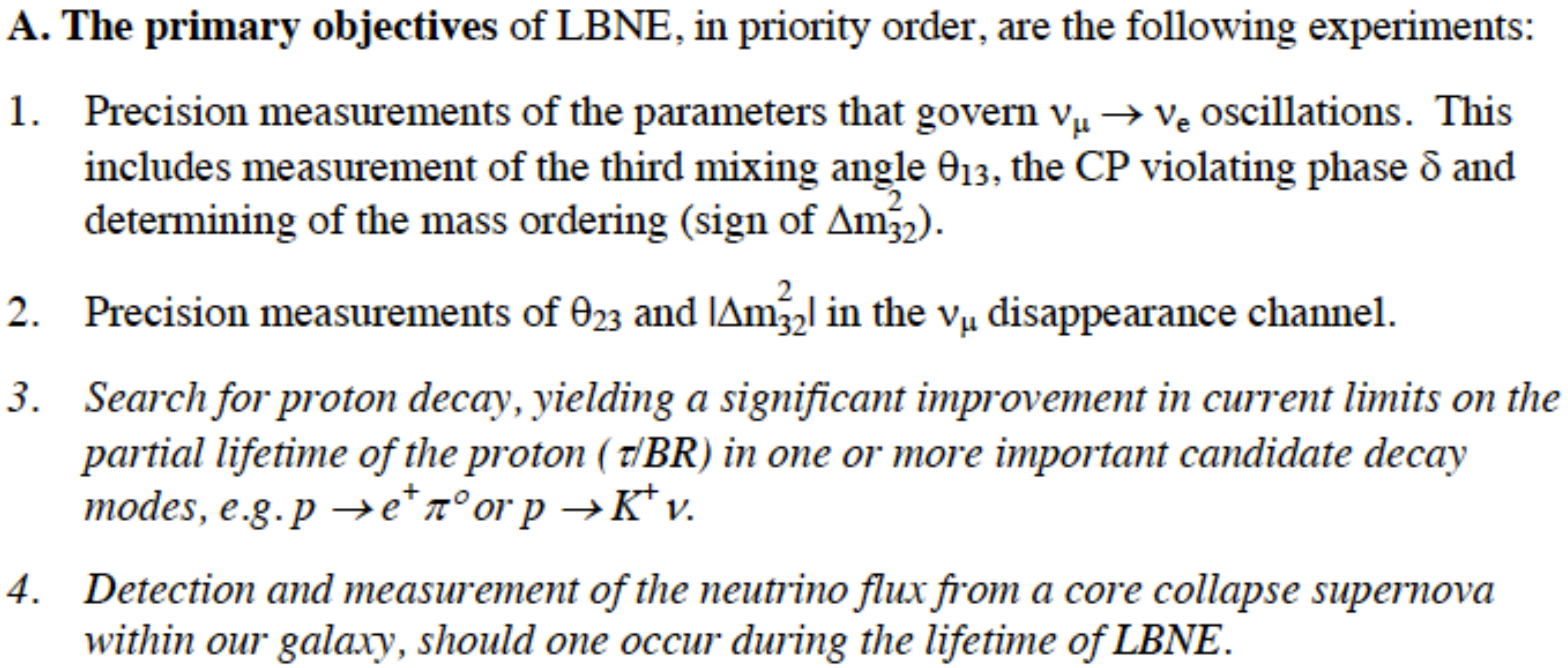
Washington: H.Berns, S.Enomoto, J.Kaspar, N.Tolich, H.K.Tseung

Wisconsin: B.Balantekin, F.Feyzi, K.Heeger, A.Karle, R.Maruyama, B.Paulos, D.Webber, C.Wendt

Yale: E.Church, B.Fleming, R.Guenette, K.Partyka, A.Szelc

347 Members
59 Institutions
25 US States
5 Countries

19 July 2012 (347)



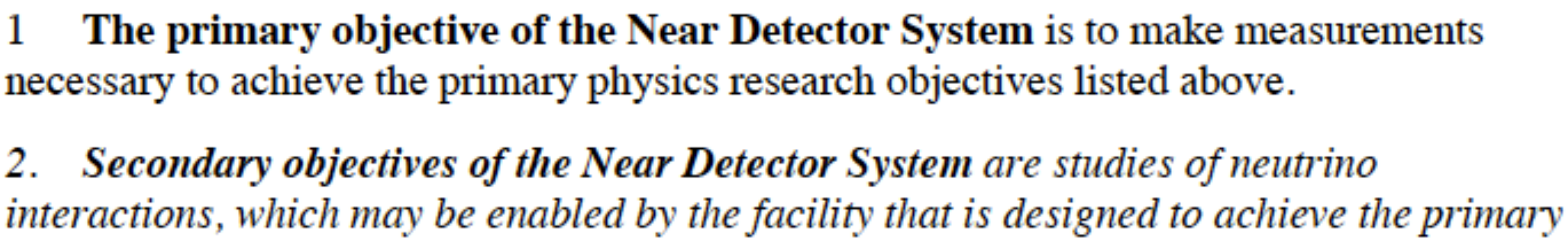
A. The primary objectives of LBNE, in priority order, are the following experiments:

1. Precision measurements of the parameters that govern $\nu_\mu \rightarrow \nu_e$ oscillations. This includes measurement of the third mixing angle θ_{13}, the CP violating phase δ and determining of the mass ordering (sign of Δm^2_{32}).

2. Precision measurements of θ_{23} and $|\Delta m^2_{32}|$ in the ν_μ disappearance channel.

3. *Search for proton decay, yielding a significant improvement in current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g.* $p \rightarrow e^+\pi^\circ$ *or* $p \rightarrow K^+\nu$.

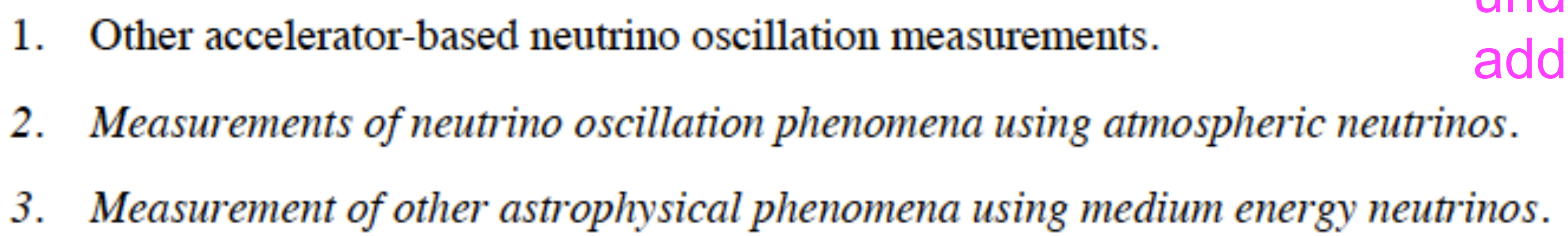
4. *Detection and measurement of the neutrino flux from a core collapse supernova within our galaxy, should one occur during the lifetime of LBNE.*



1 **The primary objective of the Near Detector System** is to make measurements necessary to achieve the primary physics research objectives listed above.

2. ***Secondary objectives of the Near Detector System*** *are studies of neutrino interactions, which may be enabled by the facility that is designed to achieve the primary*

Secondary objectives

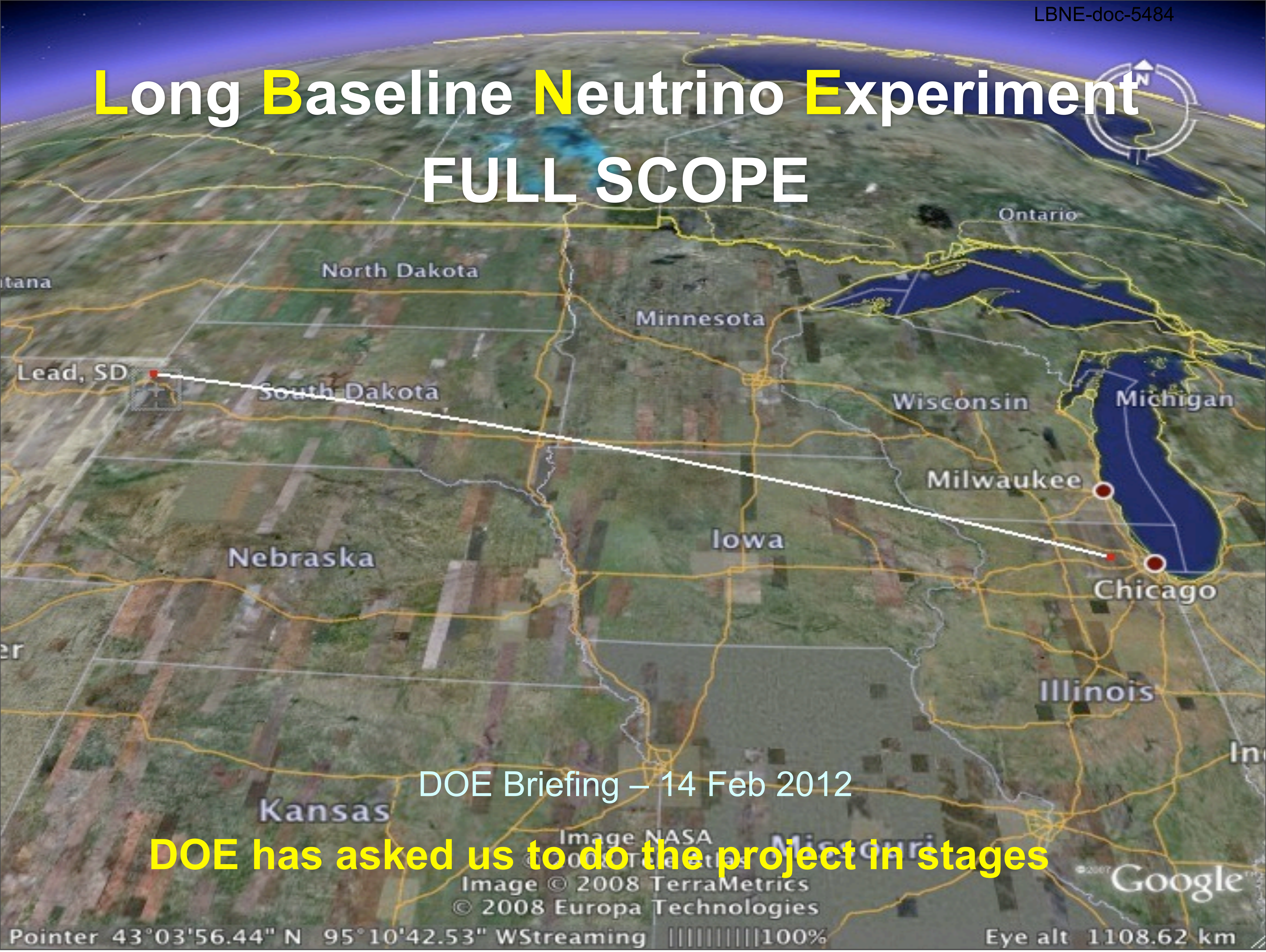


1. Other accelerator-based neutrino oscillation measurements.
2. *Measurements of neutrino oscillation phenomena using atmospheric neutrinos.*
3. *Measurement of other astrophysical phenomena using medium energy neutrinos.*

Italized parts either require an underground location or additional resources.

LBNE-doc-5484

Long Baseline Neutrino Experiment
FULL SCOPE

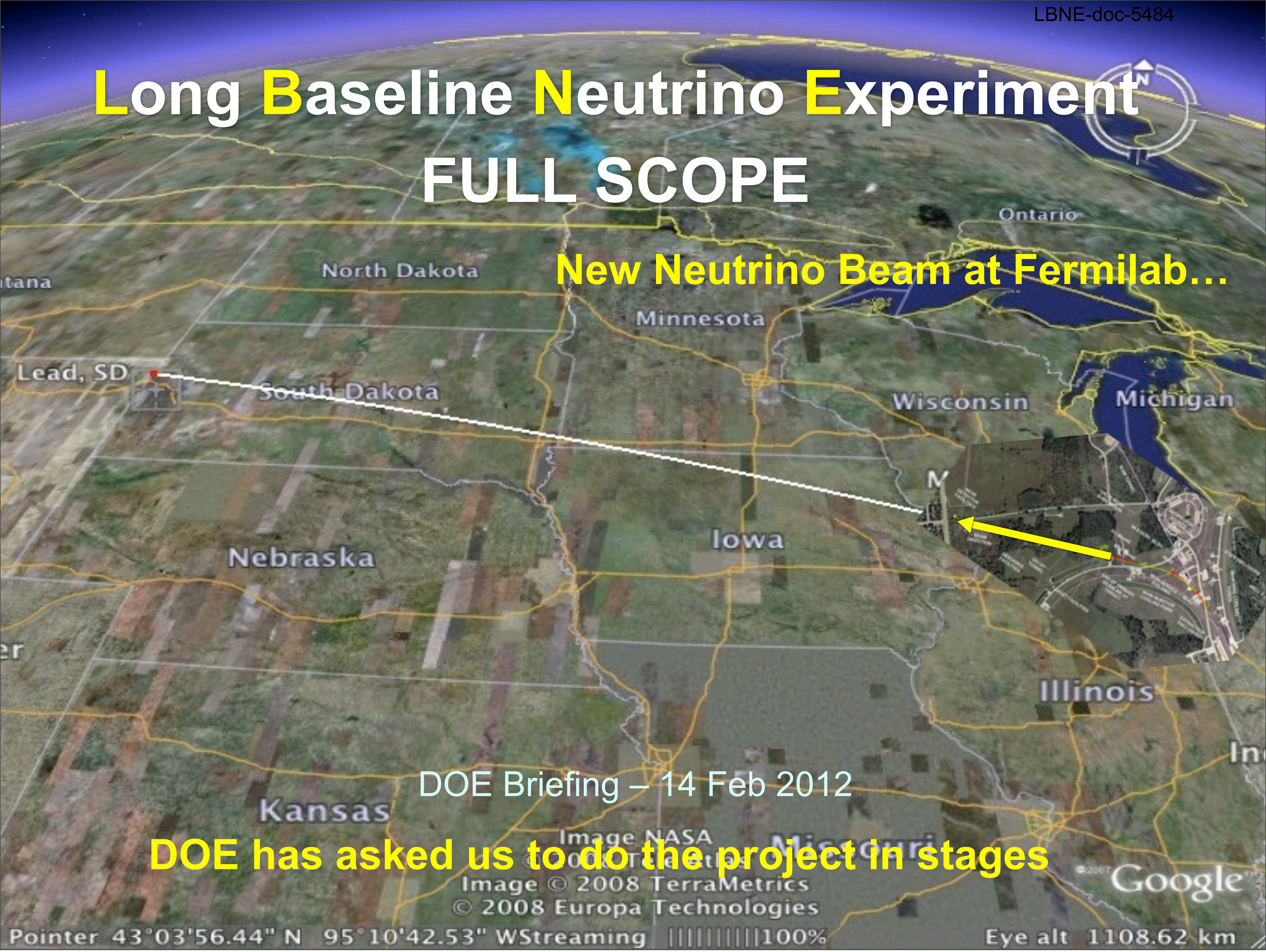


DOE Briefing – 14 Feb 2012

DOE has asked us to do the project in stages

Long Baseline Neutrino Experiment

FULL SCOPE



New Neutrino Beam at Fermilab…

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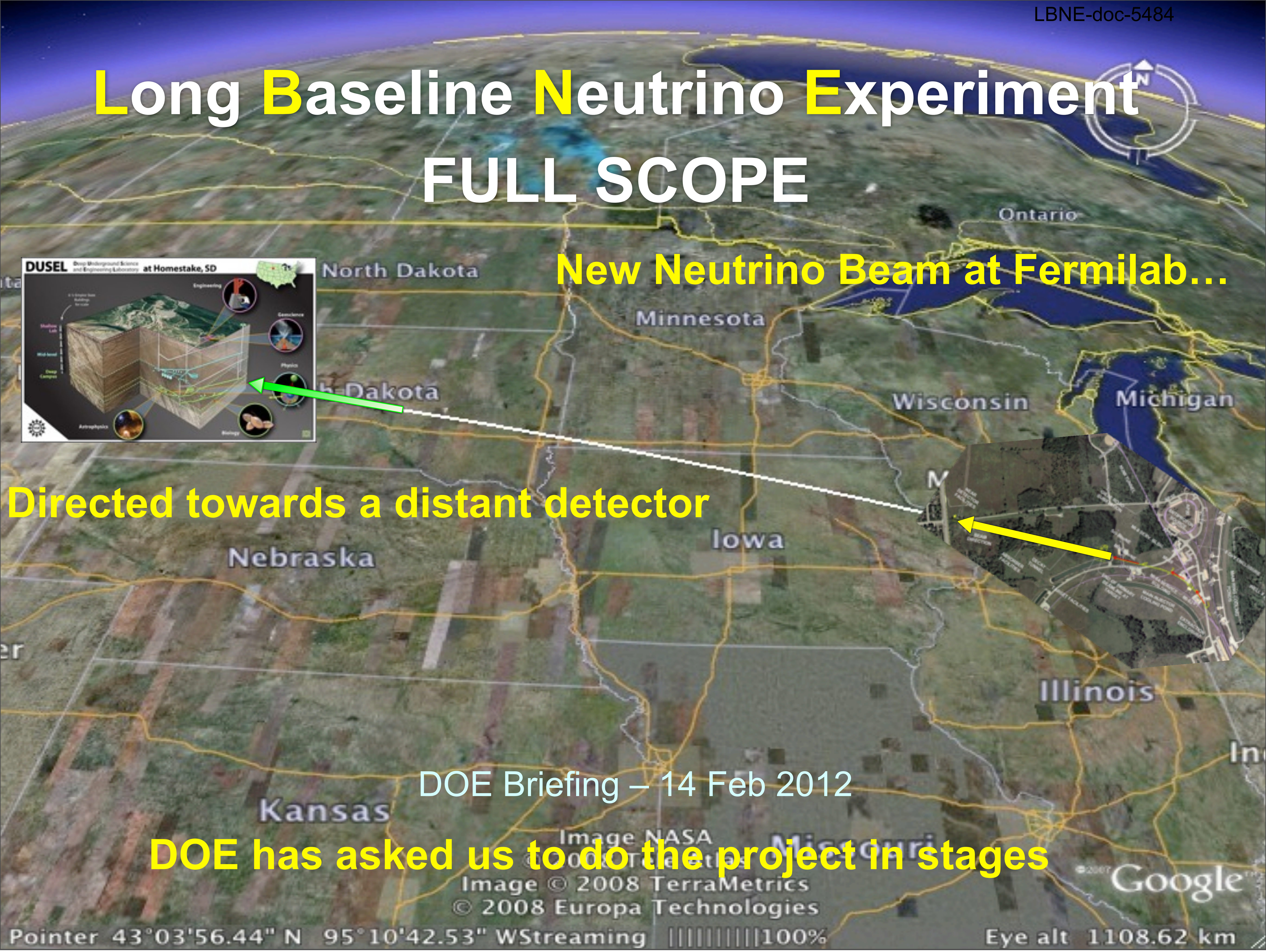

New Neutrino Beam at Fermilab…

Directed towards a distant detector

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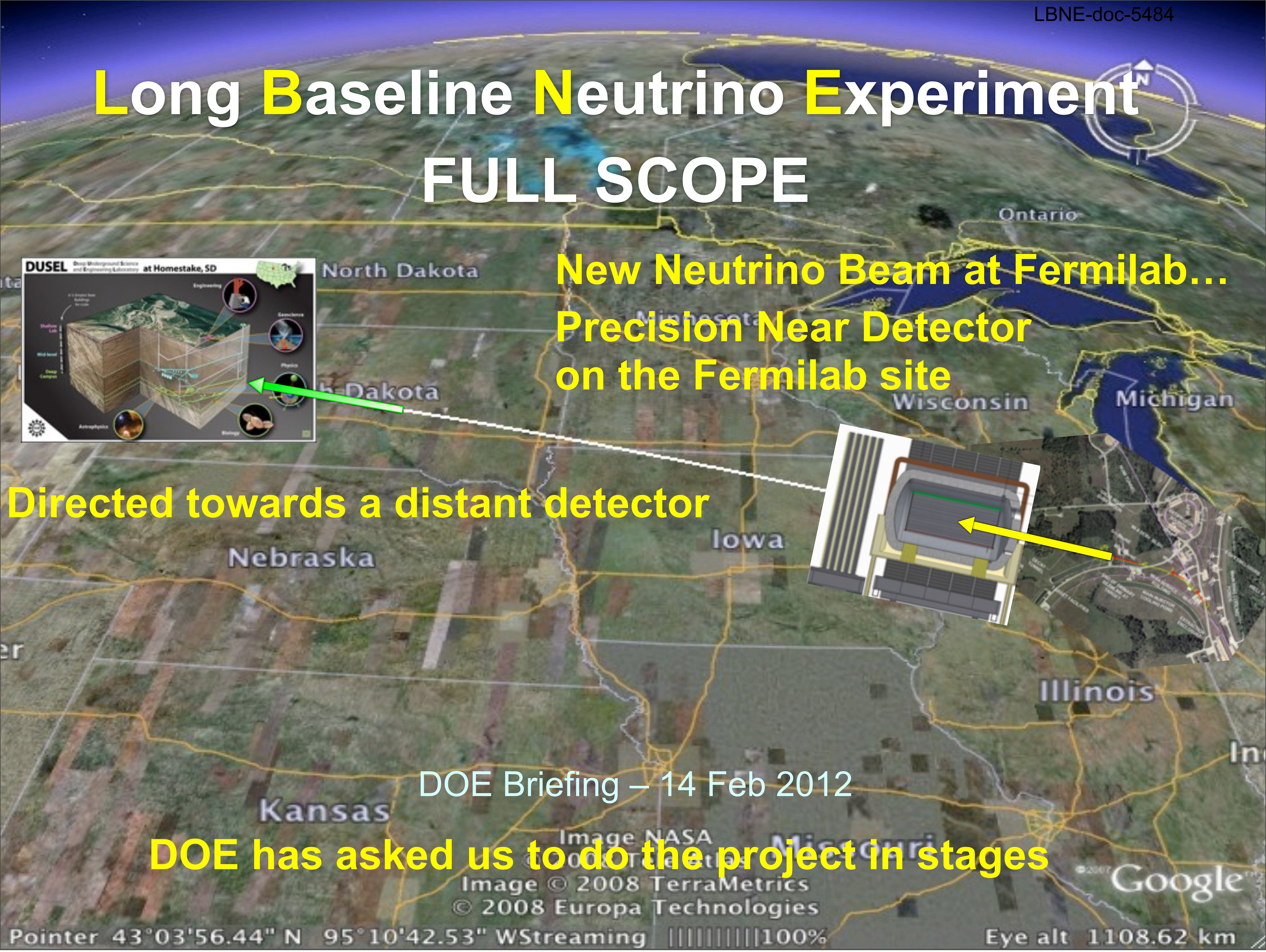

New Neutrino Beam at Fermilab…

Precision Near Detector on the Fermilab site

Directed towards a distant detector

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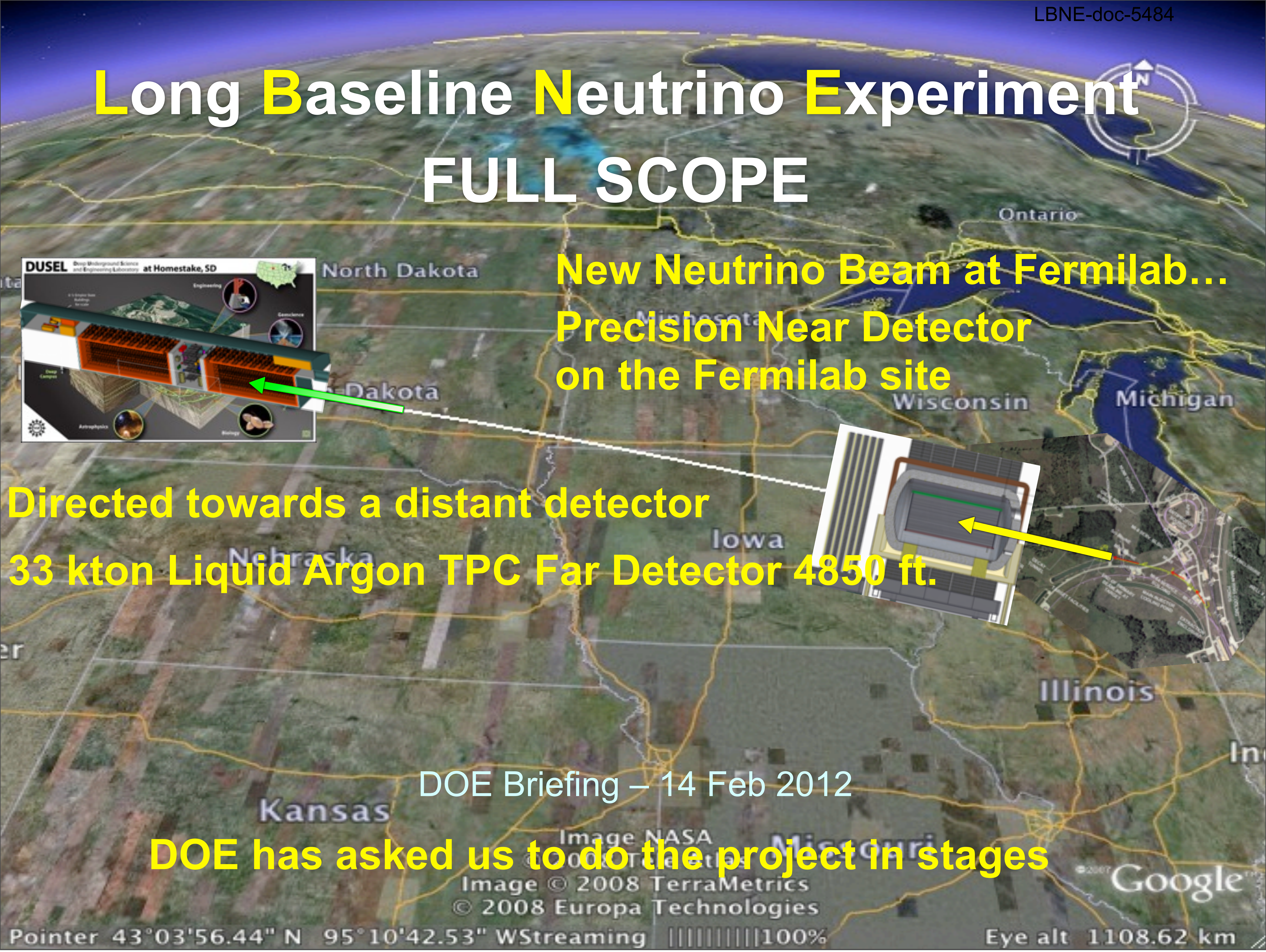

Long Baseline Neutrino Experiment
FULL SCOPE

New Neutrino Beam at Fermilab…

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33 kton Liquid Argon TPC Far Detector 4850 ft.

DOE Briefing – 14 Feb 2012

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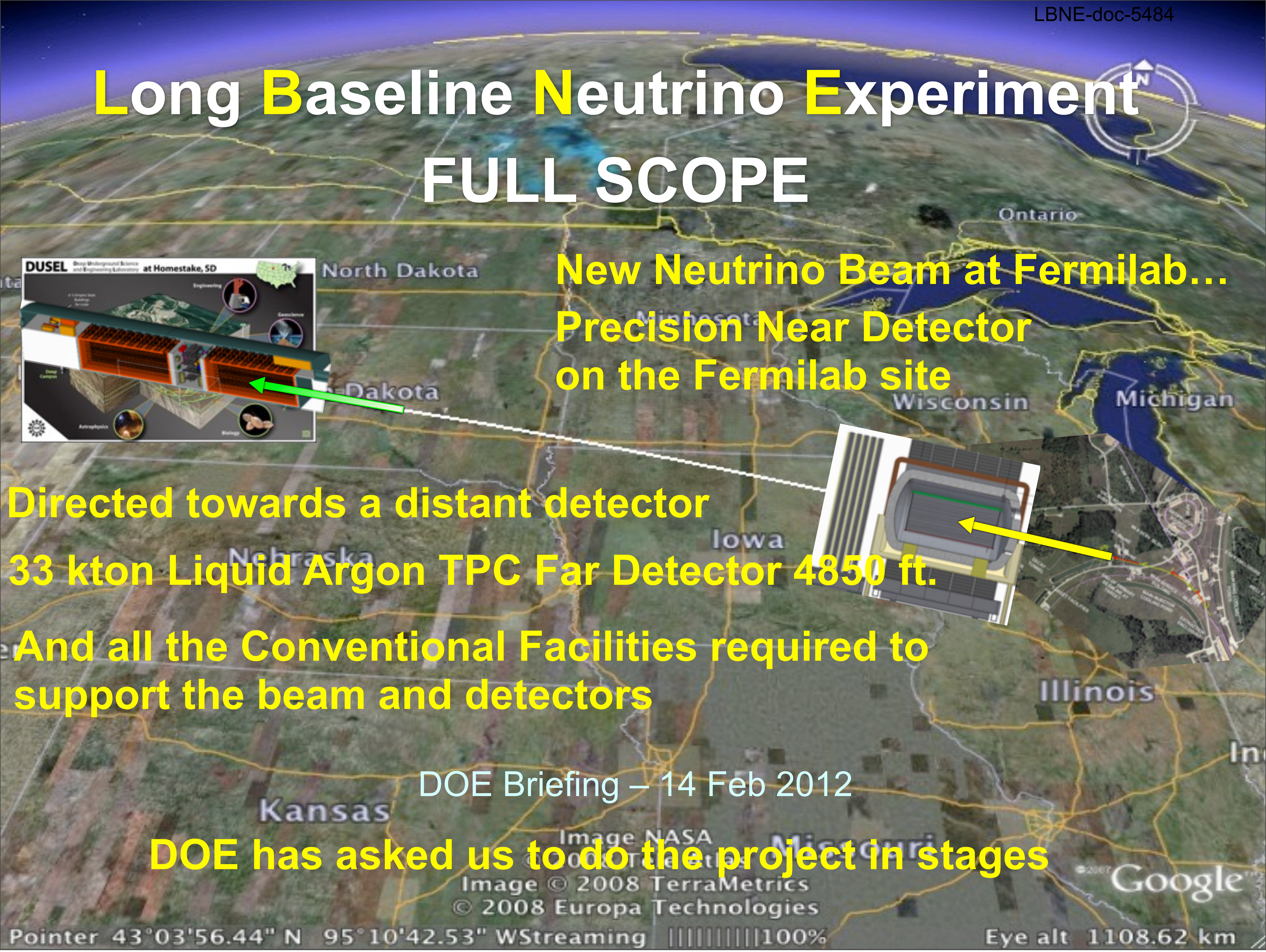
Long Baseline Neutrino Experiment

FULL SCOPE



New Neutrino Beam at Fermilab…

Precision Near Detector on the Fermilab site

Directed towards a distant detector

33 kton Liquid Argon TPC Far Detector 4850 ft.

And all the Conventional Facilities required to support the beam and detectors

DOE Briefing – 14 Feb 2012

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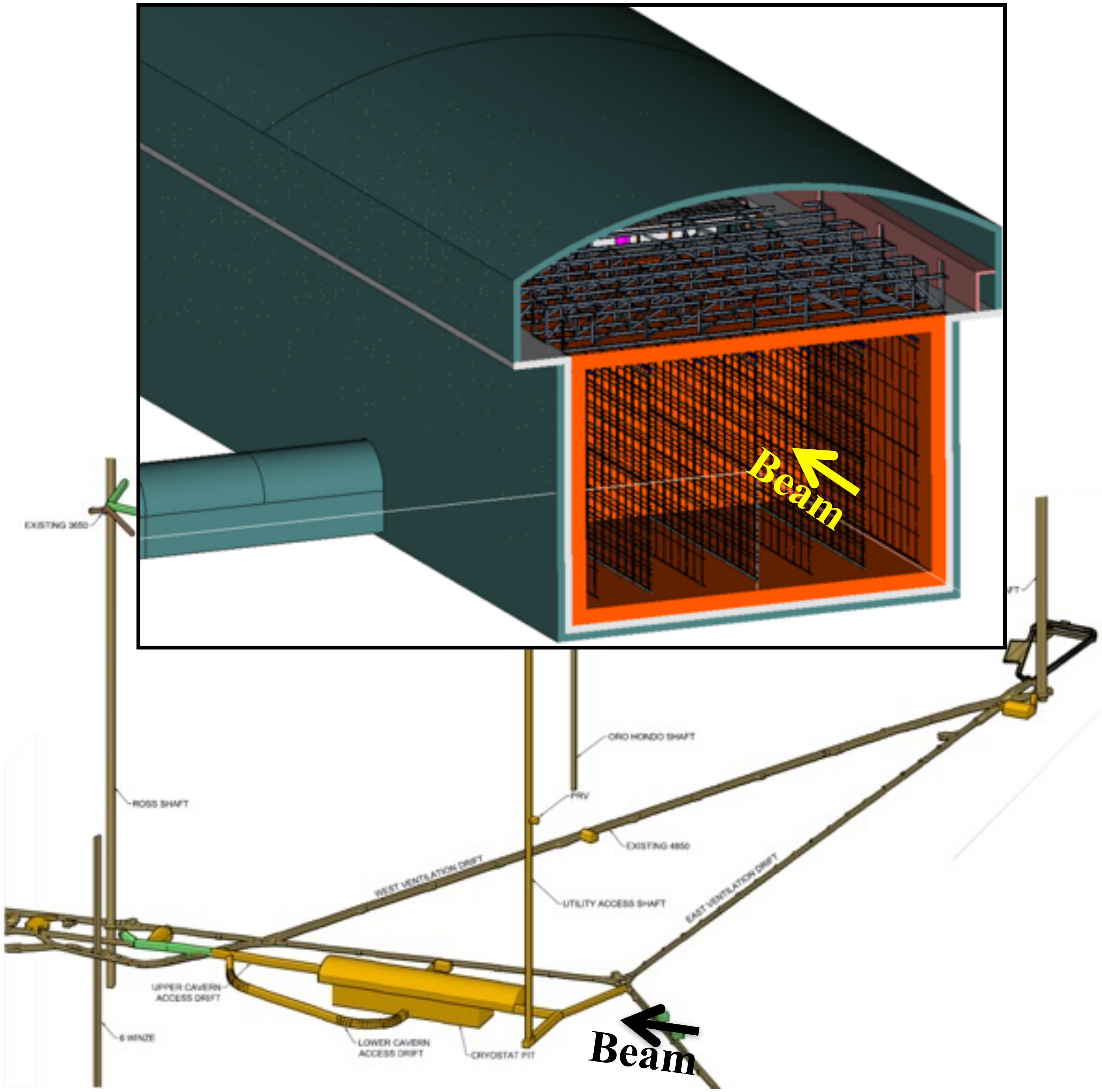
Far Detector Design at depth (not in current plan): LAr TPC Detector at 4850 ft



- Two detectors in a common cavern at 4850 ft. depth
- Active volume of each detector: 22.4 x 14 x 45.6 m^3
- 33 kt fiducial mass
- TPC design:
  - ○3.7 m drift length
  - ○5 mm wire spacing
  - ○three stereo views

Long Baseline Neutrino Experiment Currently Planned

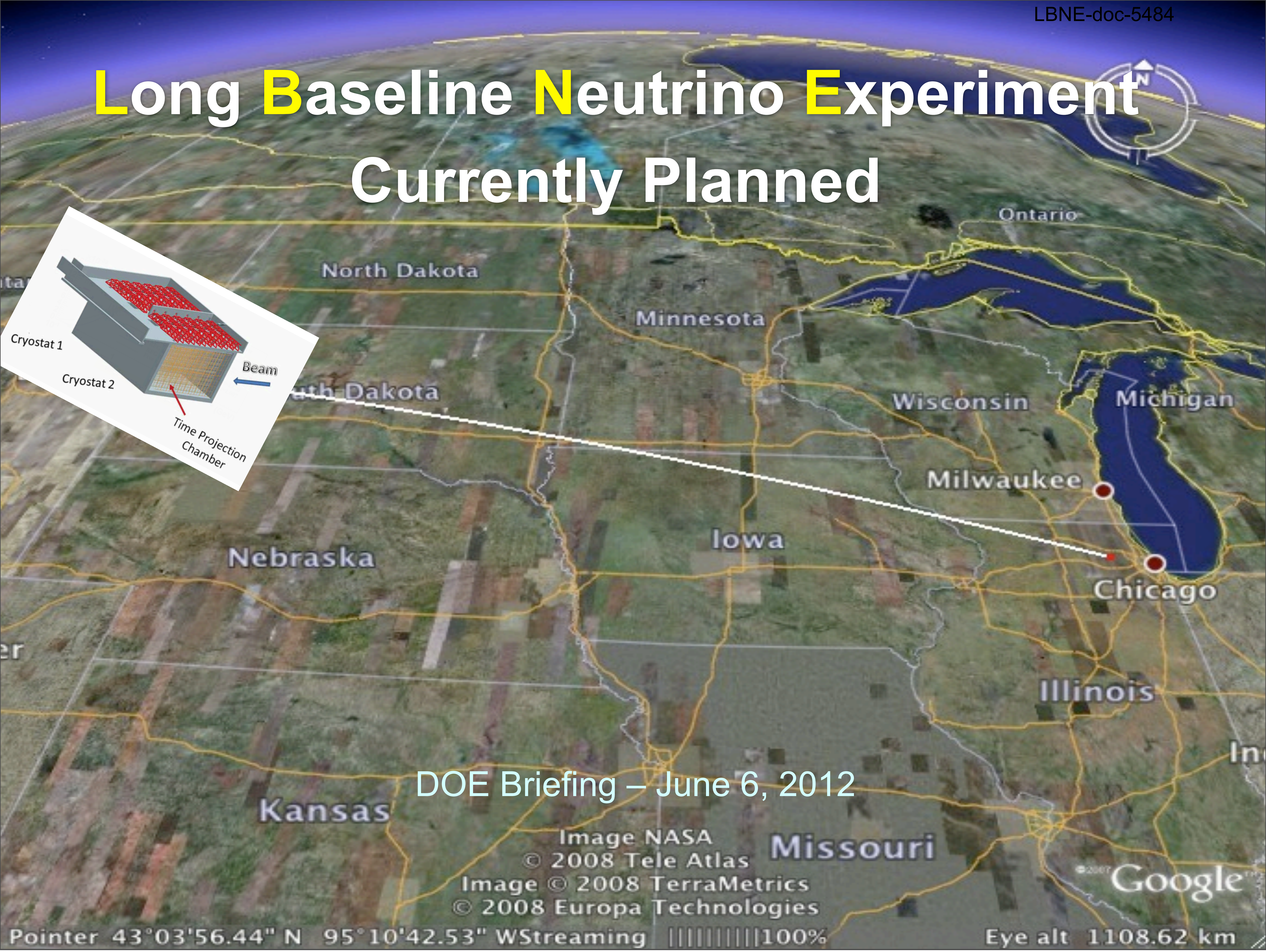


Image NASA
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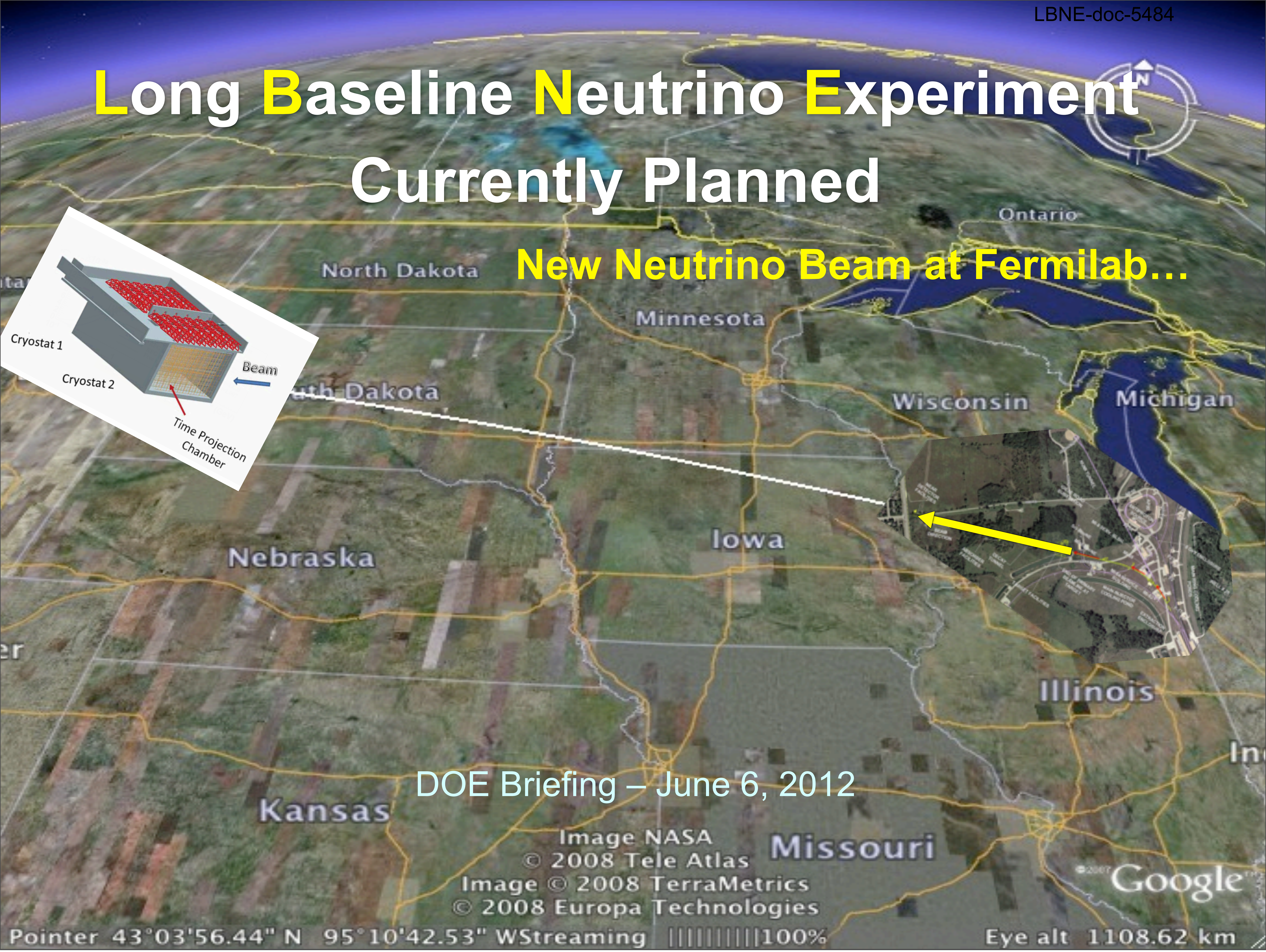
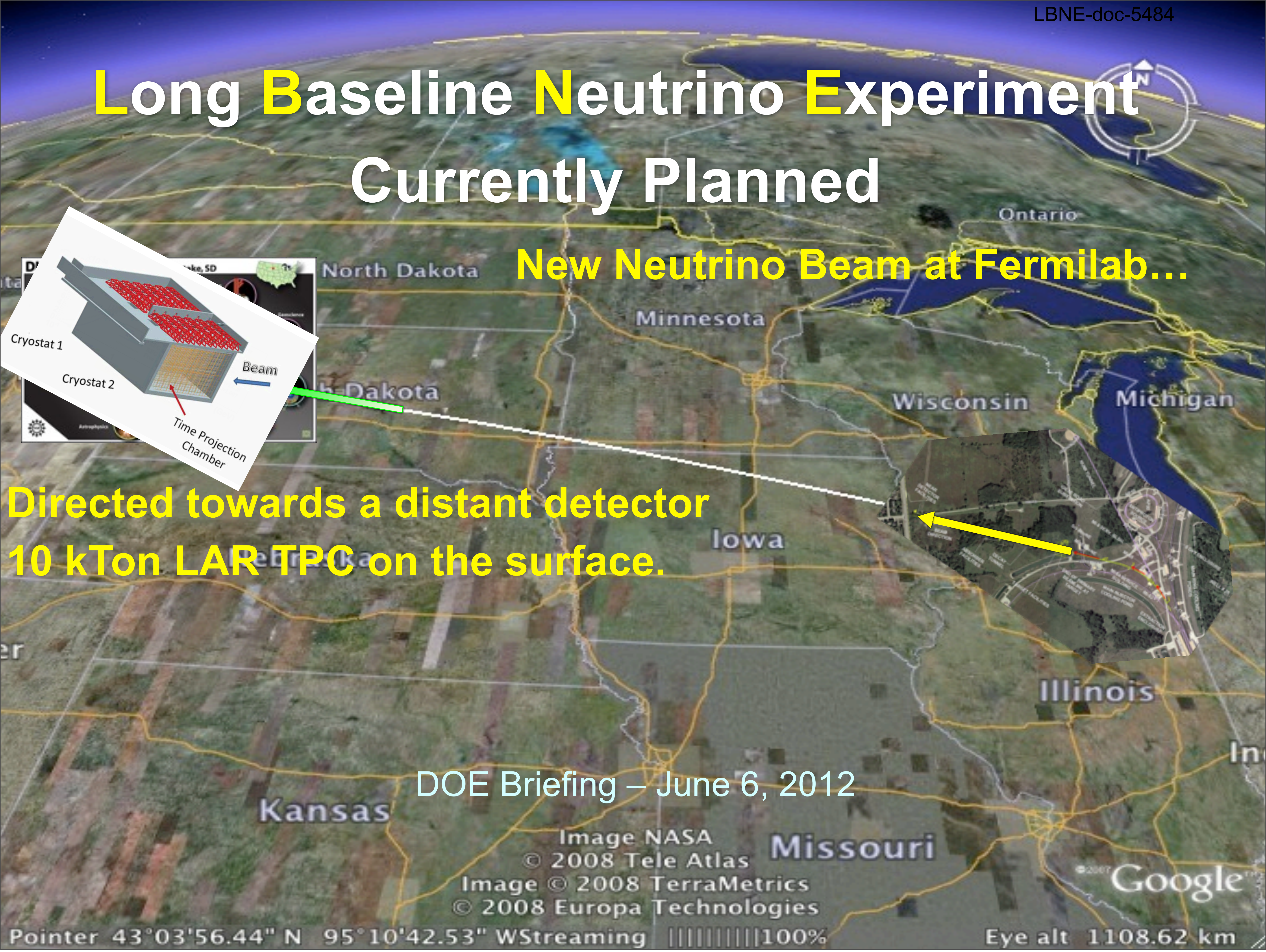
Long Baseline Neutrino Experiment Currently Planned



New Neutrino Beam at Fermilab…

DOE Briefing – June 6, 2012

Long Baseline Neutrino Experiment
Currently Planned



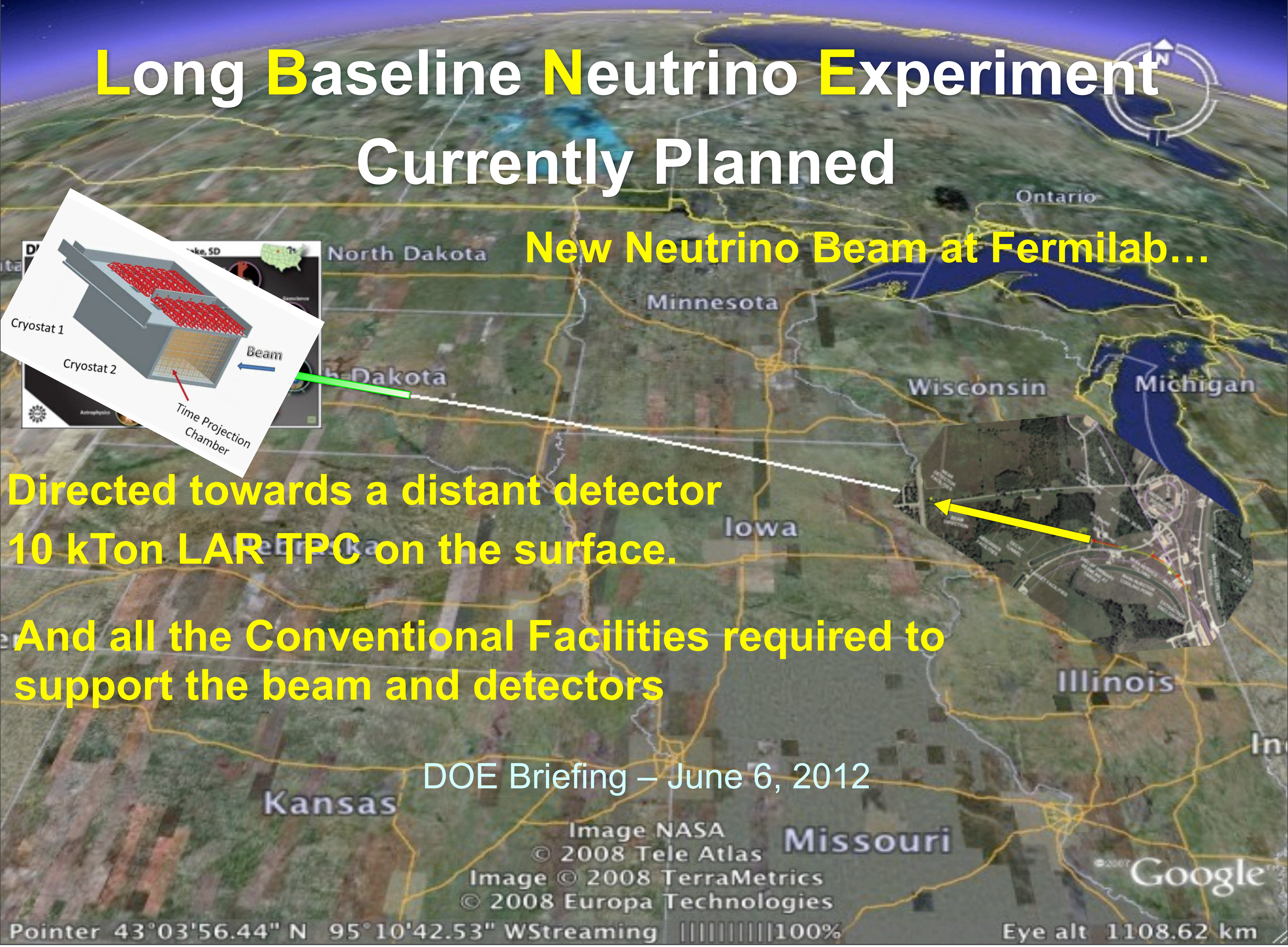
New Neutrino Beam at Fermilab…

Directed towards a distant detector

10 kTon LAR TPC on the surface.

DOE Briefing – June 6, 2012

Long Baseline Neutrino Experiment
Currently Planned



New Neutrino Beam at Fermilab…

Directed towards a distant detector

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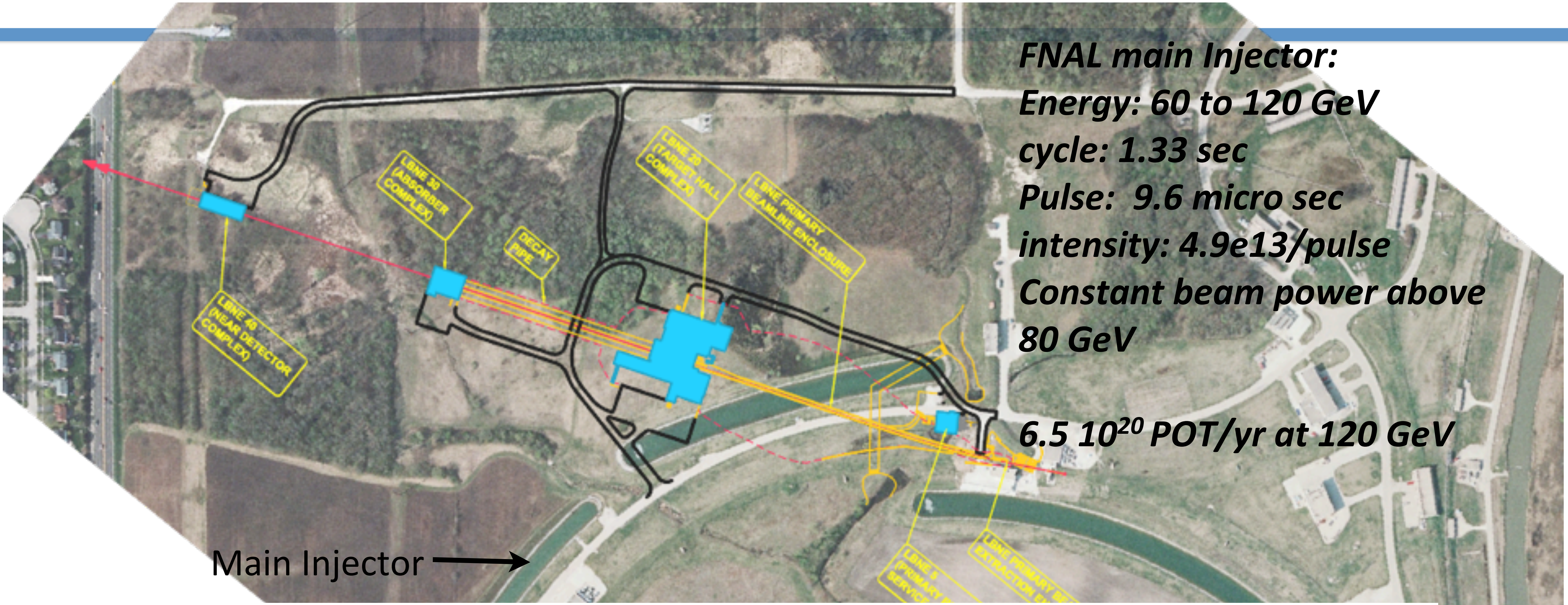
And all the Conventional Facilities required to support the beam and detectors

DOE Briefing – June 6, 2012

The LBNE New Beam Design

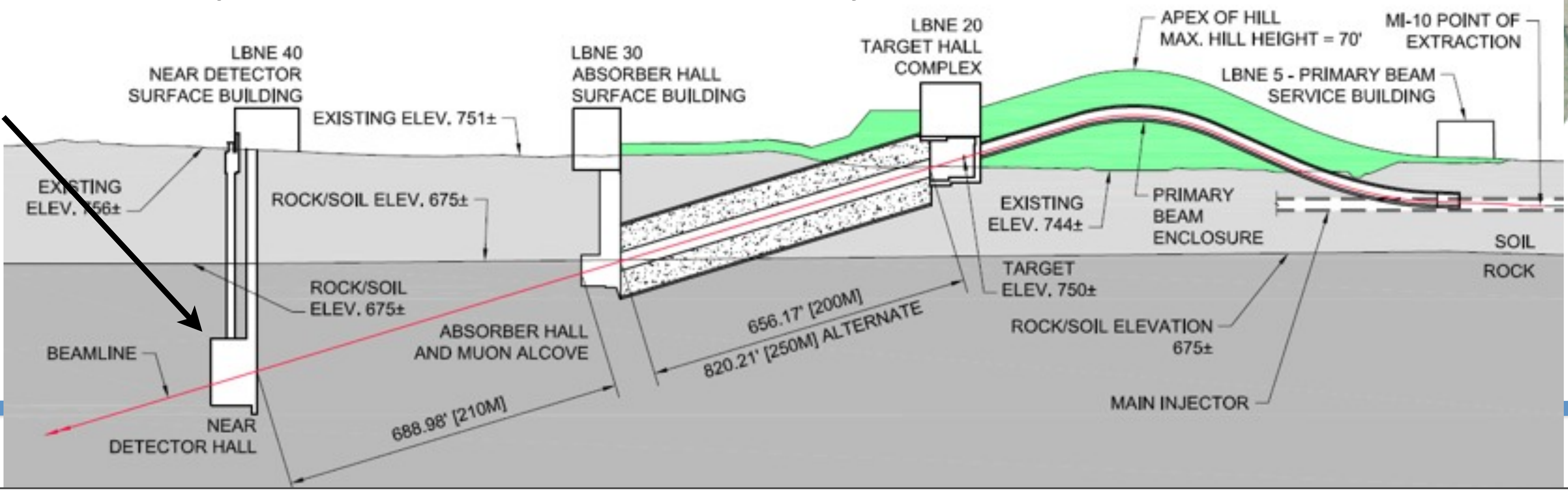


FNAL main Injector:
Energy: 60 to 120 GeV
cycle: 1.33 sec
Pulse: 9.6 micro sec
intensity: 4.9e13/pulse
Constant beam power above 80 GeV

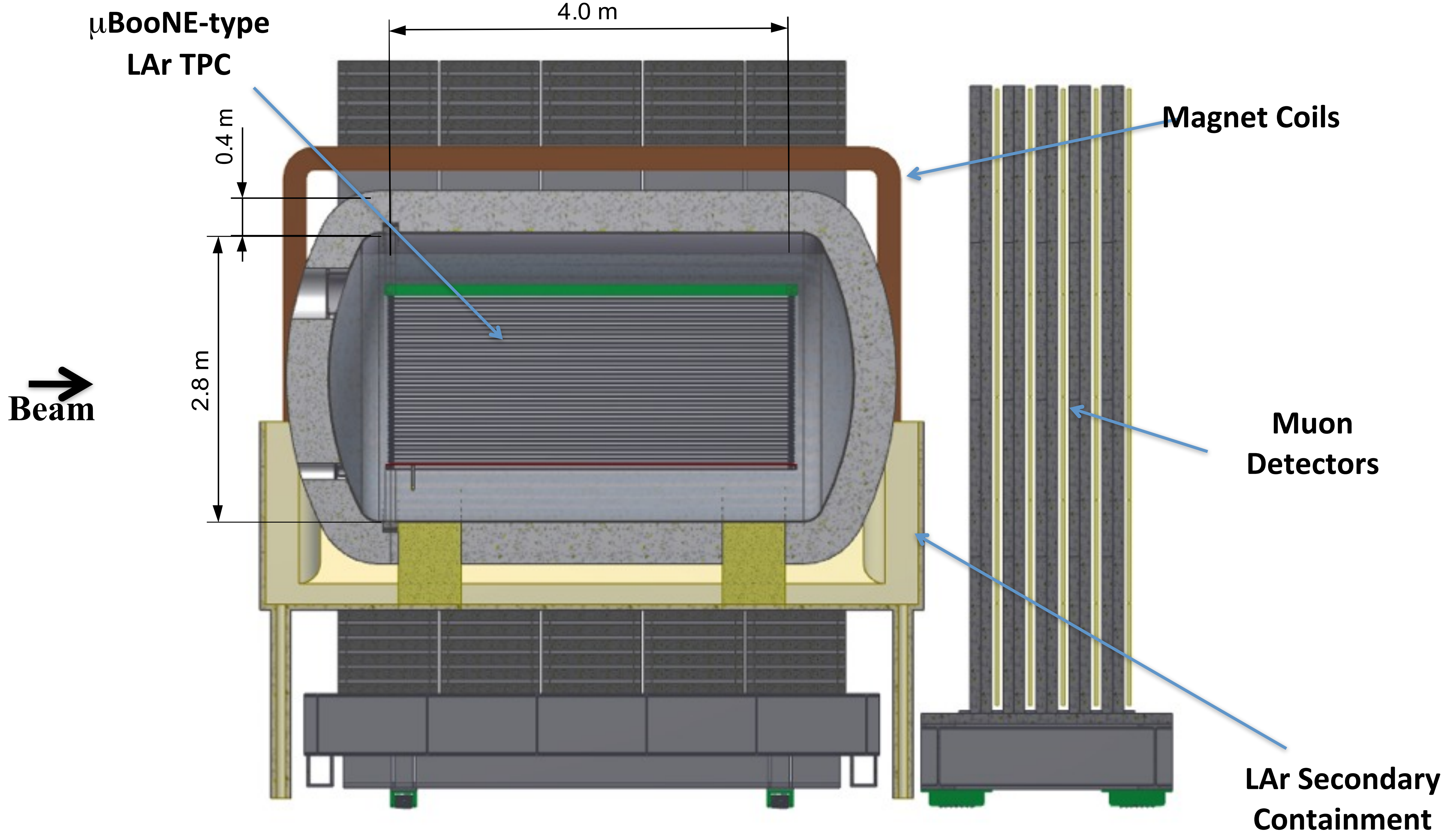
6.5 10^{20} POT/yr at 120 GeV

Less expensive and better for safety

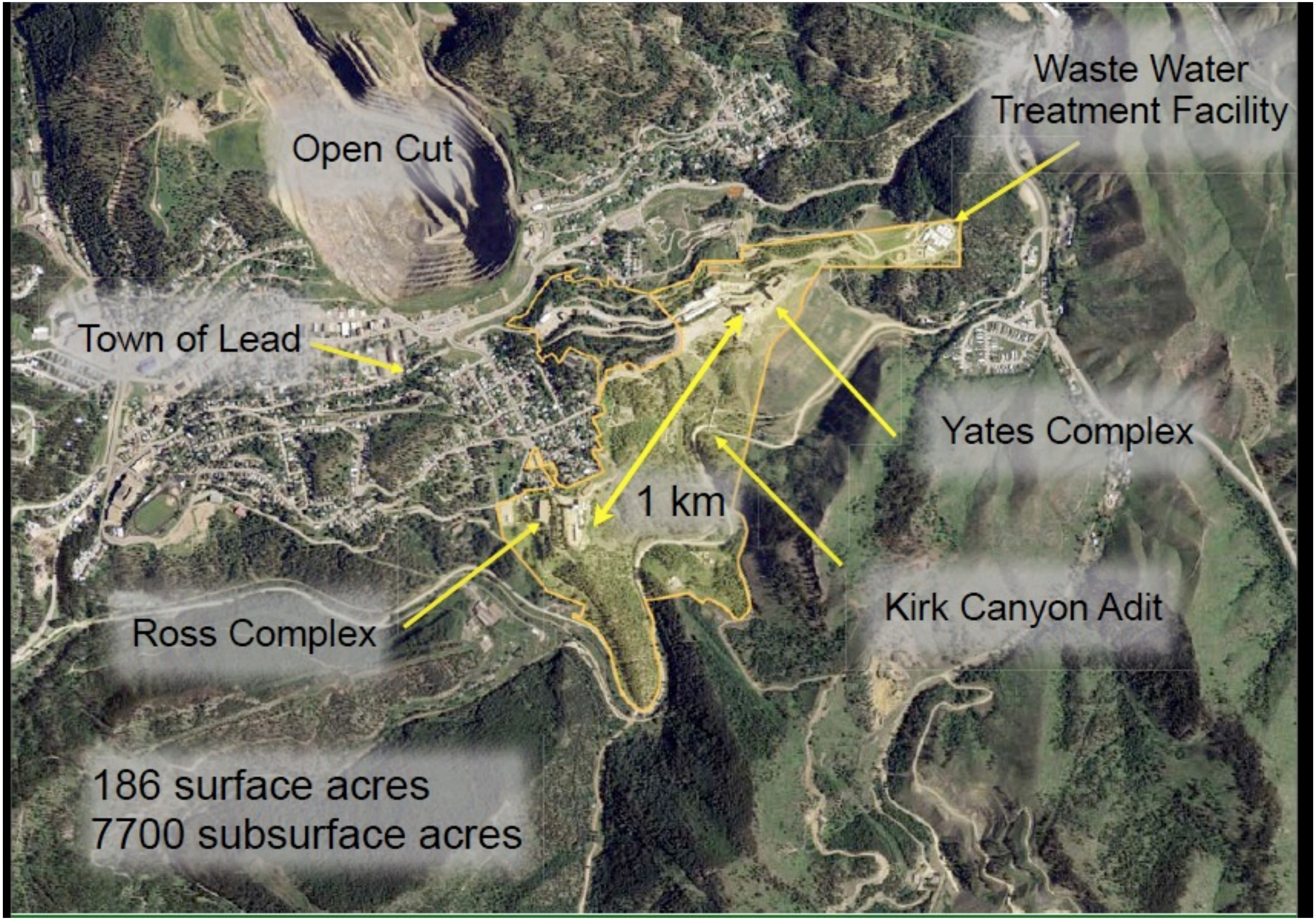
Not in current plan



Near Detector Design: Straw tube tracker or a small Liquid Argon TPC; both magnetized.

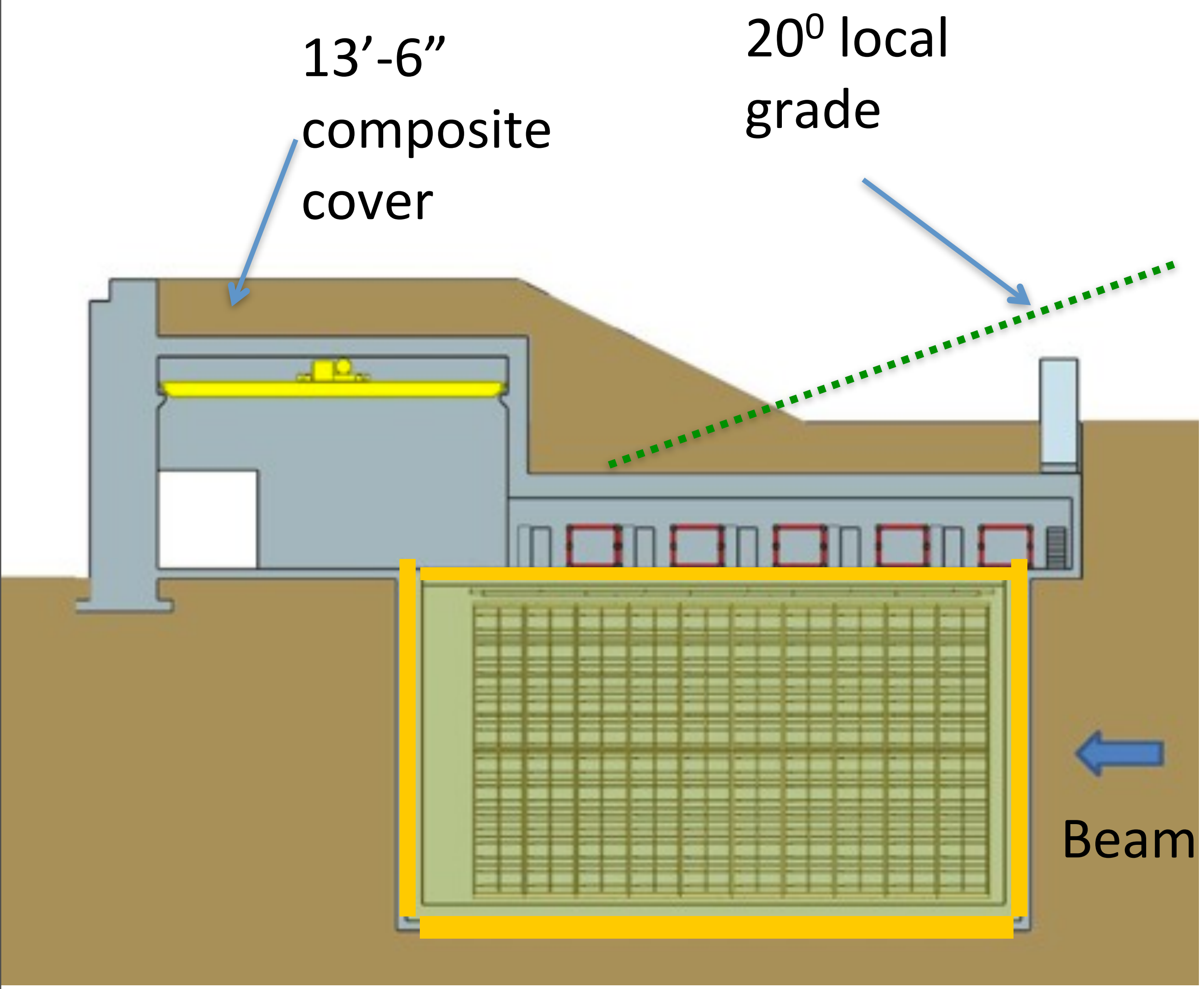


Status of the Homestake site

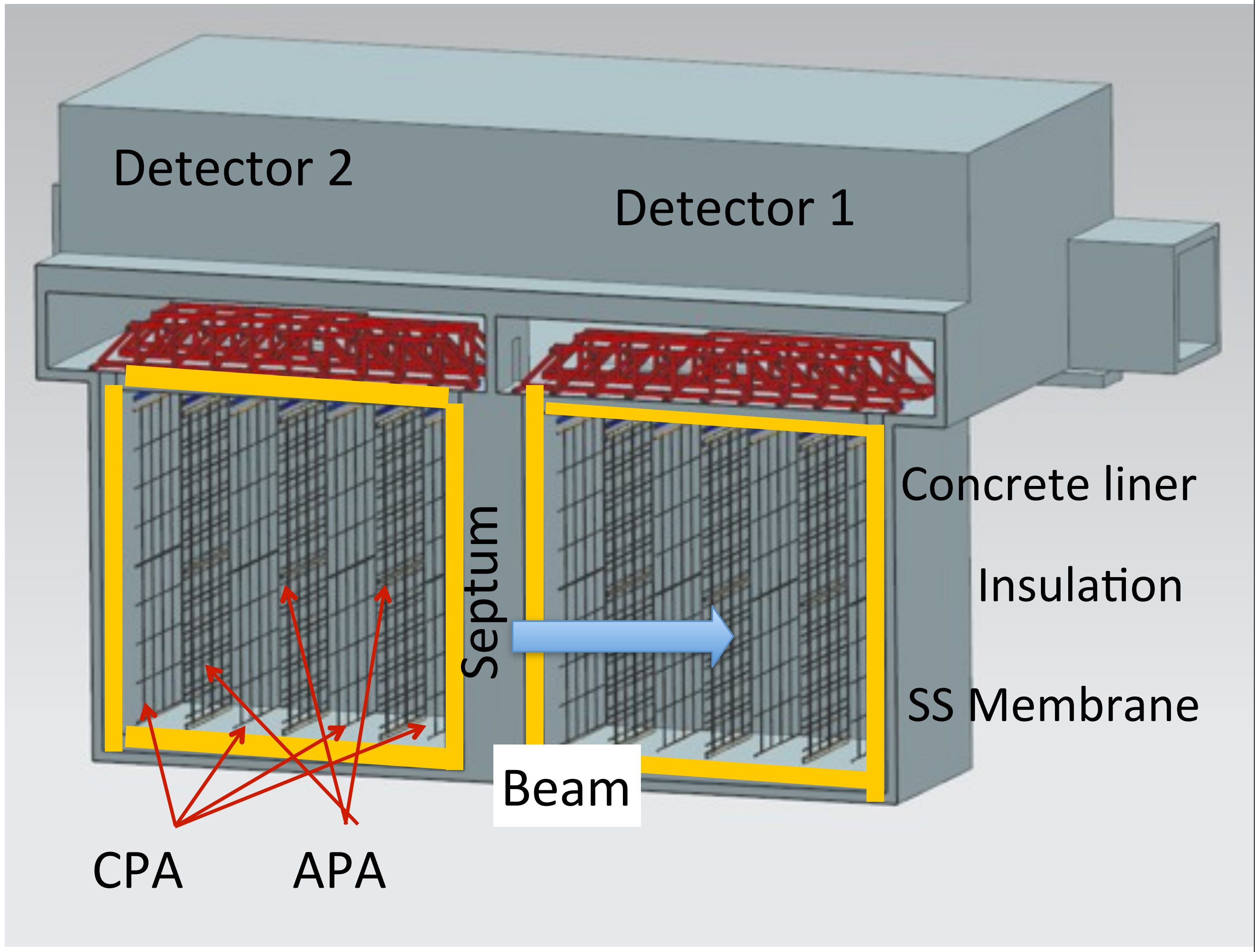


LBNE Far Detector (current plan)

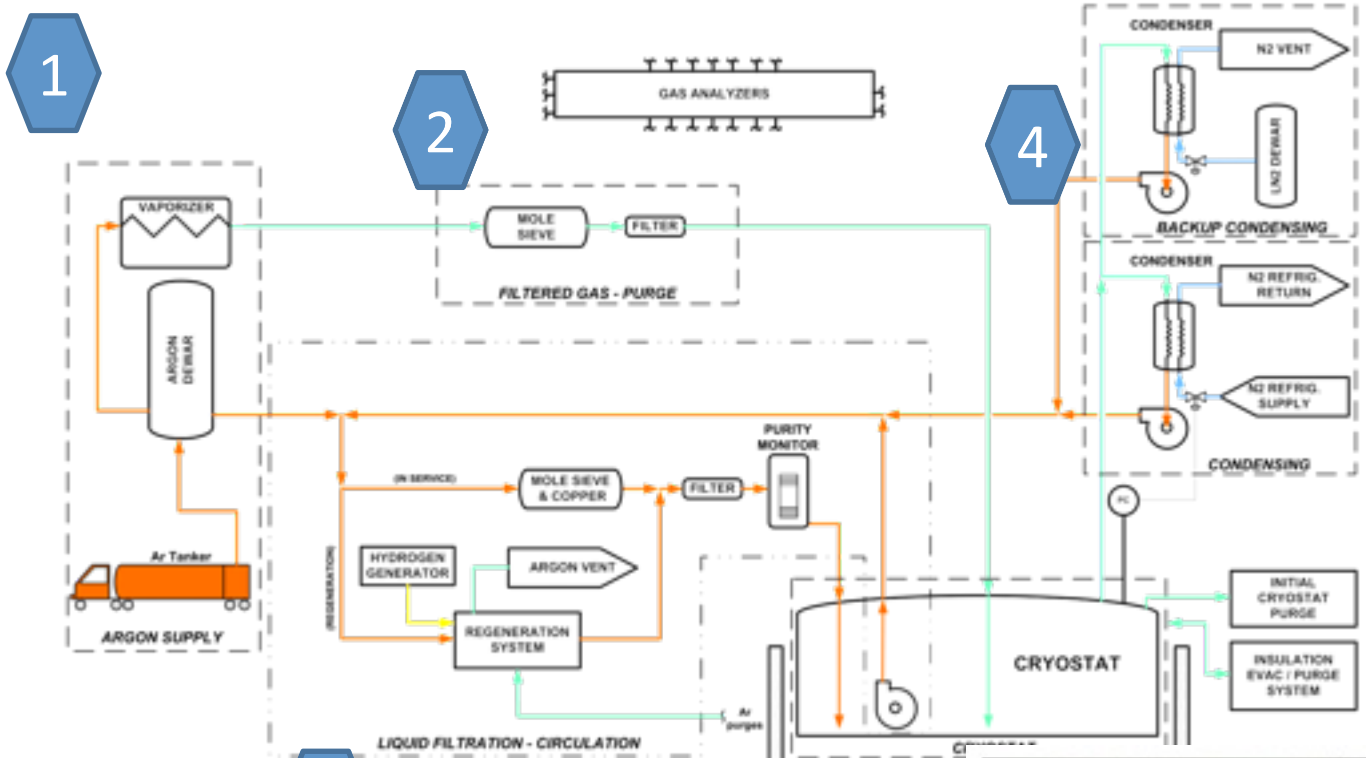
- 10 kton fiducial mass Liquid Argon (LAr) detector located on the surface in Lead, SD (two 5 kton modules)
- Detector designed to detect accelerator neutrinos

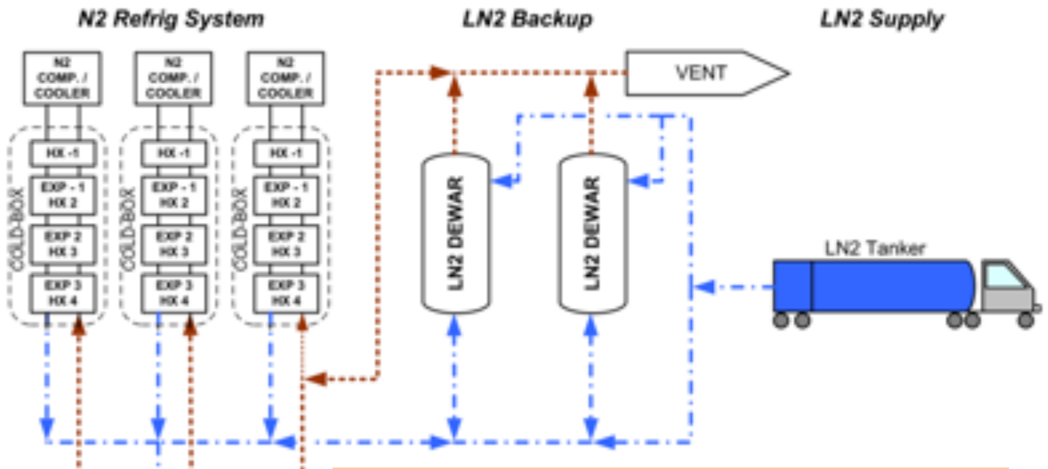


Side View



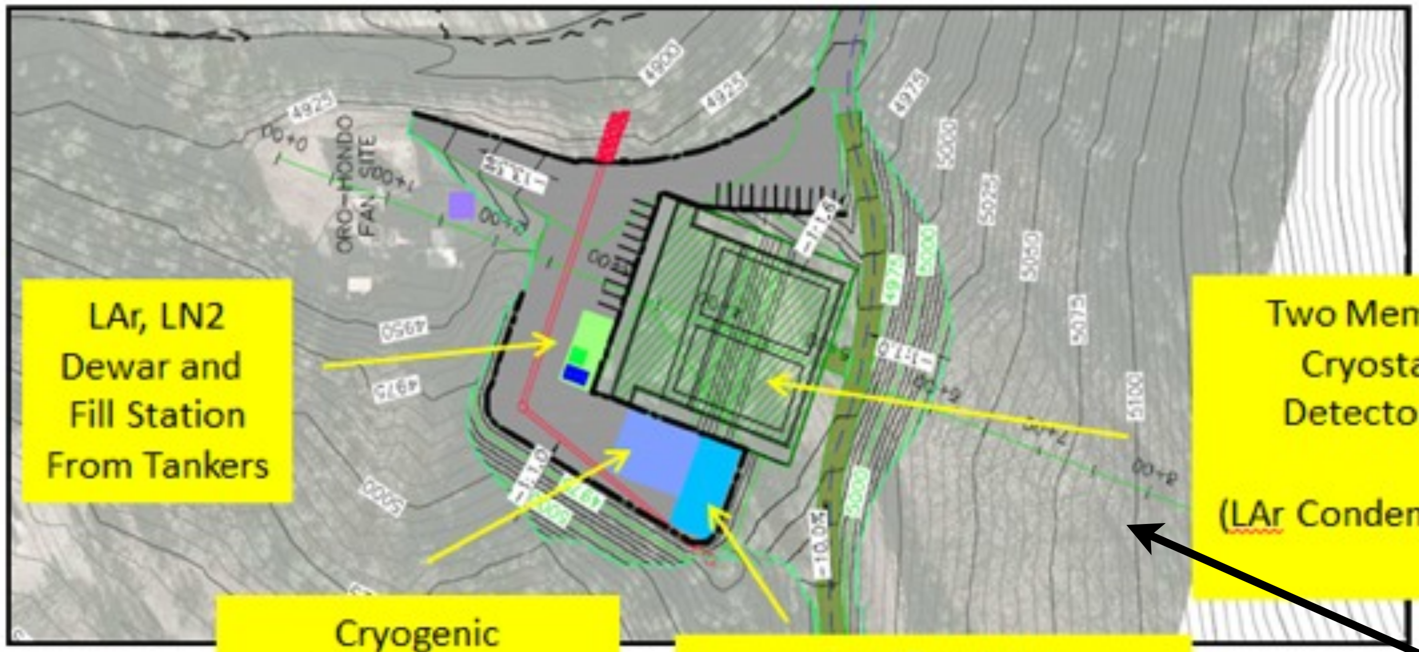
Cryogenic and Cryostat Proposed Layout





Three LN2 Plants (55 kW)
And Storage Dewars

Design Layout for Cryo
1. LAr/GAr Delivery
2. Gas Purge & Filtering
3. Cryostat with Pumps
4. Refrig & Condensers
5. Liquid Filters & Regeneration



LAr, LN2 Dewar and Fill Station From Tankers

Two Membrane Cryostats In Detector Hall.

(LAr Condensers here)

Cryogenic Equipment Building

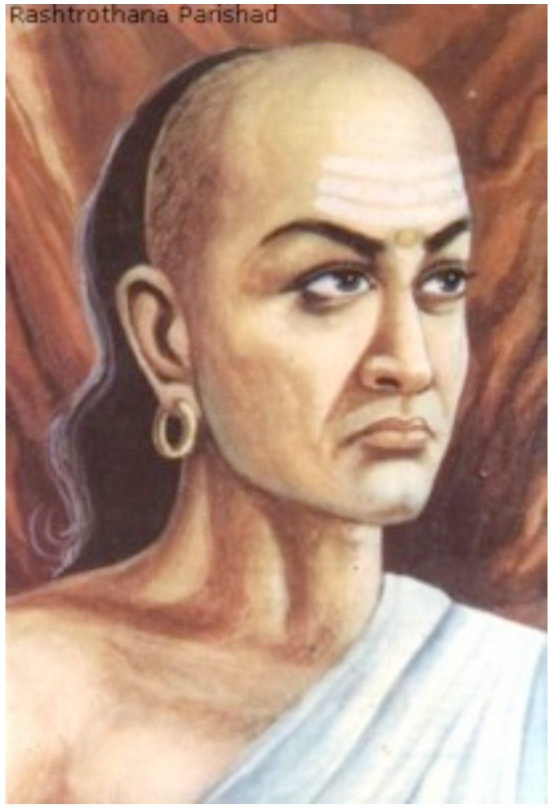
(Compressors and LN2 plants here)

Purification Equipment

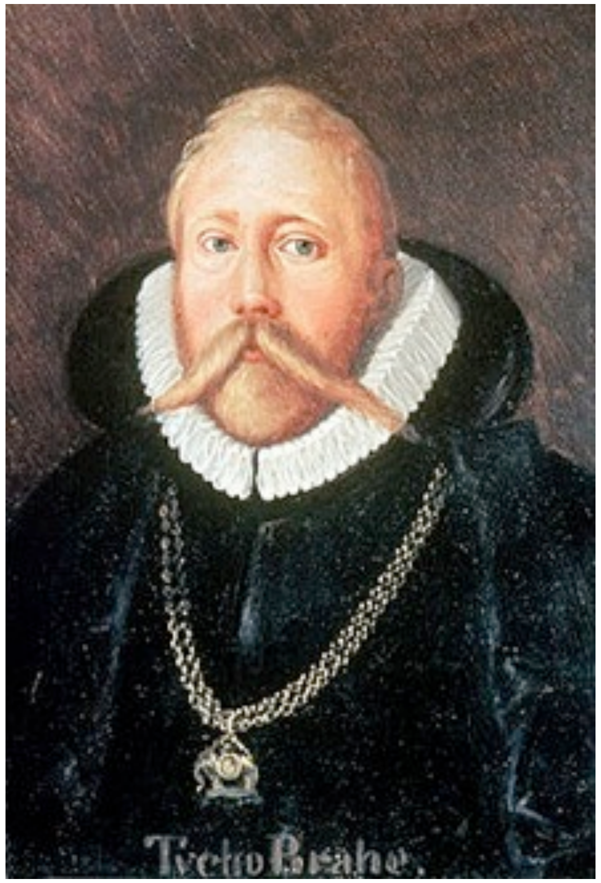
(LAr/GAr filtration and regeneration here)

Plan View of Cryo Systems

Fundamental Equations of Physics



Kautilya: Check the King's treasury before starting a project. (Koshpurvaa Sarvaarambha')



Brahe: drink with the King for the sake of science.

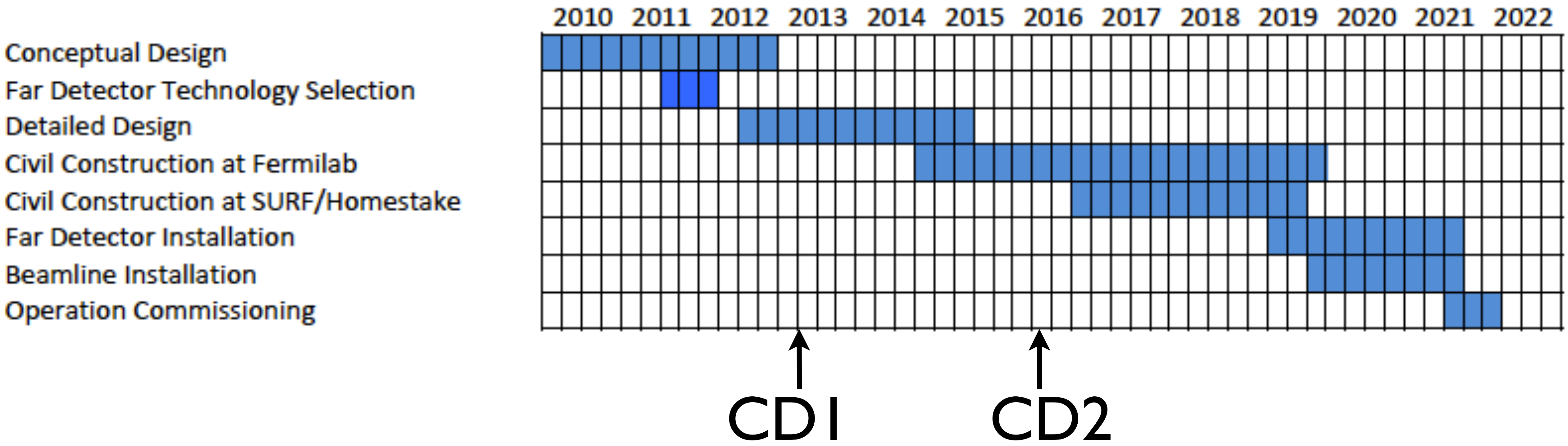
Columbus: find a king bold enough to support you.

Costs after Reconfiguration

US cost estimate includes labor, contingency, escalation.

Scope	Cost (TPC)
LBNE 34 kTon@4850L and near detector	$1.440B
LBNE Phase I, 10 kTon surface	$0.789B
+Place Underground	$0.924B
+ Near Detector	$1.054B

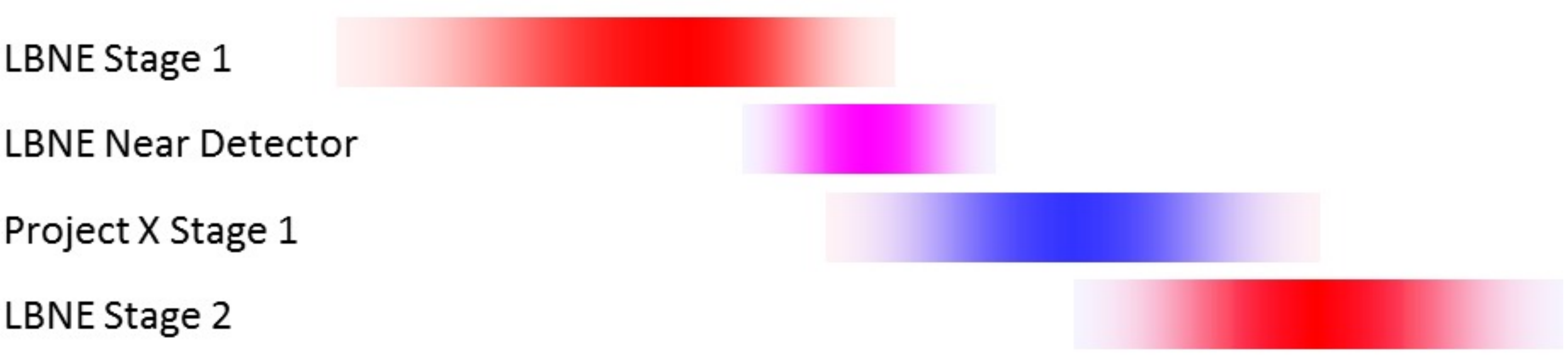
LBNE Phase 1 Schedule



- This is the review driven schedule. Current funding profile is expected to cause 11 month delay.
- The period up to far detector construction start offers good opportunity to seek major non-DOE and international partners.
- Deep placement of far detector as well as a near detector expansion can be accommodated in the current plan by CD2. CD3 is construction start; it will be split in CD3a and CD3b.

Phased LBNE Program: Possible Example

1) 10 kt LAr detector on surface at Homestake + LBNE beamline (700 kW)
2) Near Neutrino Detector at Fermilab
3) Project X stage 1 → 1.1 MW LBNE beam
4) Additional 20-30 kt detector deep underground (4300 mwe)



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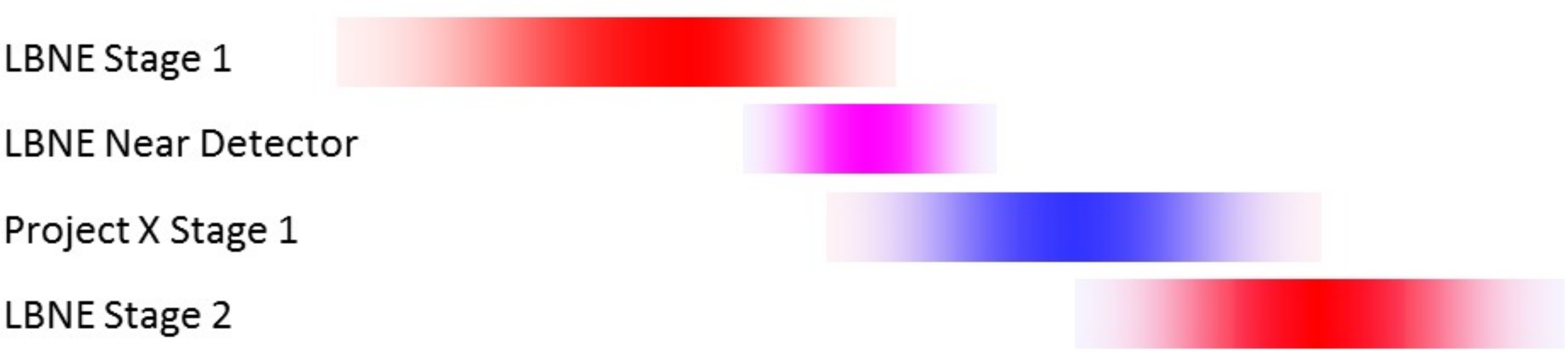
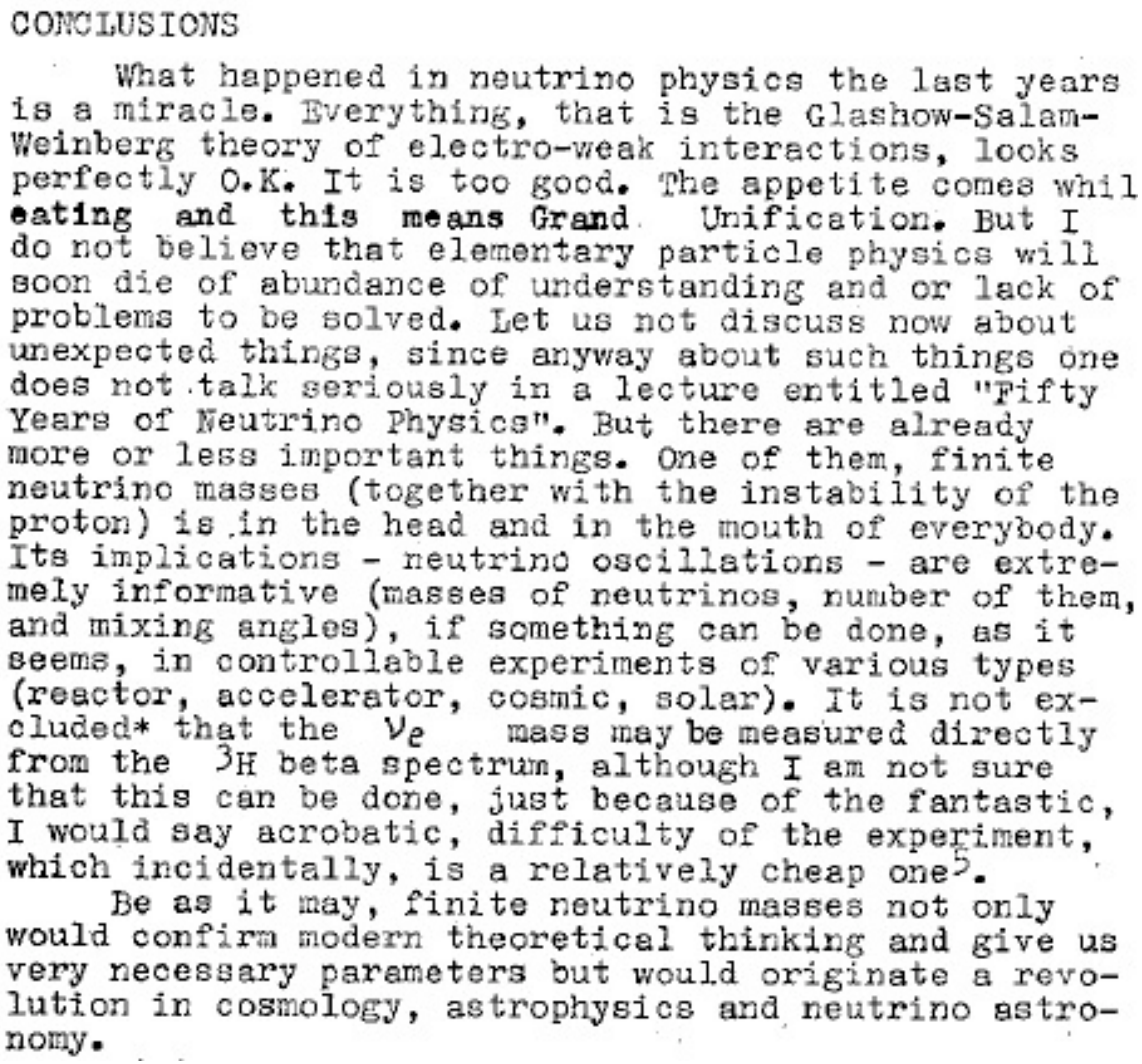


Additional national or international collaborators could help accelerate the implementation of the full LBNE program.

Conclusion

- The goal of finding the phenomena of CP violation in the neutrino sector is extraordinary and has been strongly endorsed.
- Current technology can be pushed to achieve desirable sensitivity.
- High intensity (~1-2MW) accelerators and very large detectors (~30-50kTon efficient mass) with good particle identification and energy resolution needed.
- Liquid Argon technology is well matched to the desired distance of >1000 km.
- The LBNE collaboration and project are well organized and ready to construct and operate LBNE in the US.
- The US/DOE is proceeding with the plan for construction in stages. These could be accelerated with additional US national and international collaborations.

Conclusions



CONCLUSIONS

What happened in neutrino physics the last years is a miracle. Everything, that is the Glashow-Salam-Weinberg theory of electro-weak interactions, looks perfectly O.K. It is too good. The appetite comes whil **eating and this means Grand** Unification. But I do not believe that elementary particle physics will soon die of abundance of understanding and or lack of problems to be solved. Let us not discuss now about unexpected things, since anyway about such things one does not talk seriously in a lecture entitled "Fifty Years of Neutrino Physics". But there are already more or less important things. One of them, finite neutrino masses (together with the instability of the proton) is in the head and in the mouth of everybody. Its implications - neutrino oscillations - are extremely informative (masses of neutrinos, number of them, and mixing angles), if something can be done, as it seems, in controllable experiments of various types (reactor, accelerator, cosmic, solar). It is not excluded* that the ν_e mass may be measured directly from the ^{3}H beta spectrum, although I am not sure that this can be done, just because of the fantastic, I would say acrobatic, difficulty of the experiment, which incidentally, is a relatively cheap one[5].

Be as it may, finite neutrino masses not only would confirm modern theoretical thinking and give us very necessary parameters but would originate a revolution in cosmology, astrophysics and neutrino astronomy.

Pontecorvo 1981

1. WILSON HALL - 16 WEST (BEFORE)

1. WILSON HALL - 16 WEST (AFTER)