# Project-X

IFW, Rockville Md, Dec 1st 2011

R.Tschirhart
Fermilab

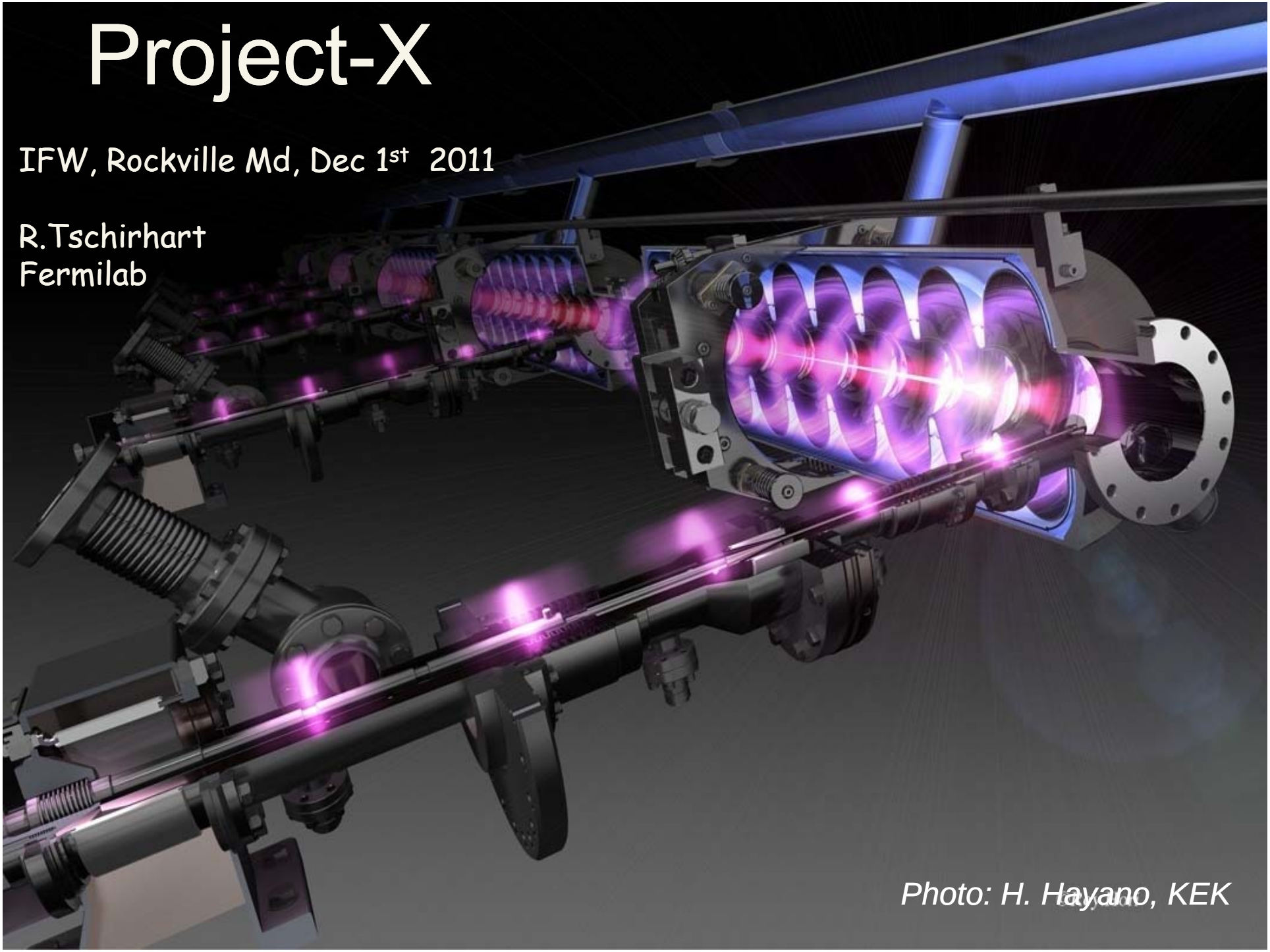


*Photo: H. Hayano, KEK*

# The Project-X Research Program

- ***Neutrino oscillation experiments***
- A high-power proton source with proton energies between 8 (3) and 120 GeV would produce intense neutrino beams directed toward near detectors on the Fermilab site and massive detectors at distant underground laboratories.

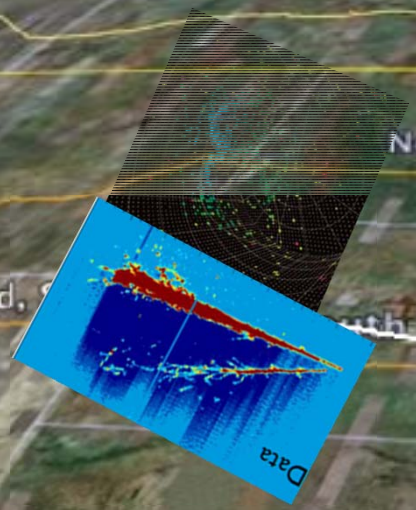
- ***Kaon, muon, nuclei & neutron precision experiments***
- These could include world leading experiments searching for muon-to-electron conversion, nuclear and neutron electron dipole moments (edms), precision measurement of neutron properties and world-leading precision measurements of ultra-rare kaon decays.

- ***Platform for evolution to a Neutrino Factory and Muon Collider***
- Neutrino Factory and Muon-Collider concepts depend critically on developing high intensity proton source technologies.

- ***Nuclear Energy Applications***
- Accelerator, spallation, target and transmutation technology demonstration which could investigate and develop accelerator technologies important to the design of future nuclear waste transmutation systems and future thorium fuel-cycle power systems.

**Detailed Discussion: Project X website**

# Long Baseline Neutrino Experiment




New Neutrino Beam at Fermilab…

…Directed towards a distant detector

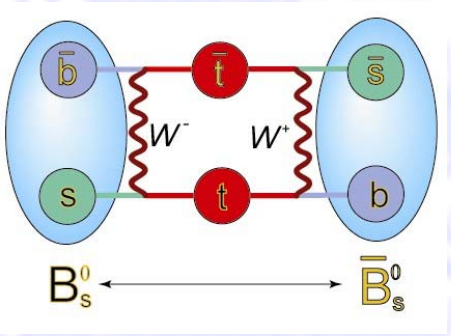
Precision Near Detector on the Fermilab site

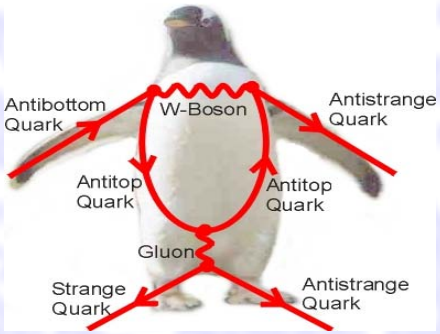
200 kT fiducial volume Water Cherenkov Far Detector

33 kT fiducial volume Liquid Argon TPC Far Detector

# Kaon, Muon and EDM Experiments Deeply Attack the Flavor Problem

**Why don't we see the *Terascale Physics we expect* affecting the flavor physics we study today??**

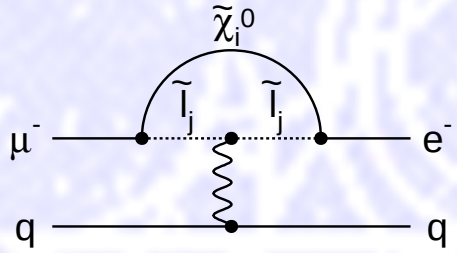


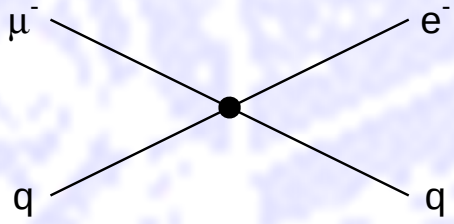




# Deepest Probe of the Flavor Problem: muon-to-electron Conversion Expt at Project-X

Supersymmetry

Predictions at $10^{-15}$



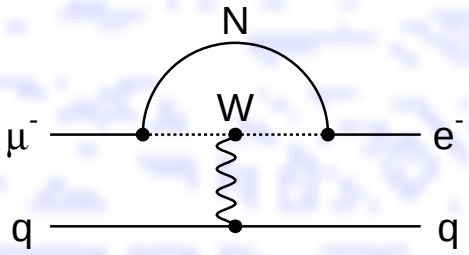



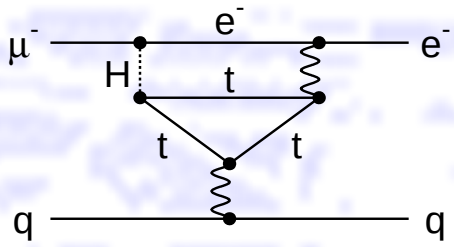

Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

$\left|U^*_{\mu N} U_{eN}\right|^2 = 8 \times 10^{-13}$



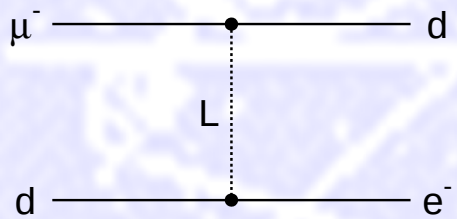



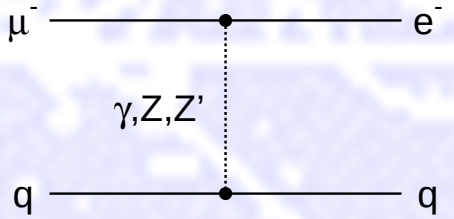

Second Higgs doublet

$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

$M_L = 3000\sqrt{\lambda_{\mu d}\lambda_{ed}}$ TeV/$c^2$



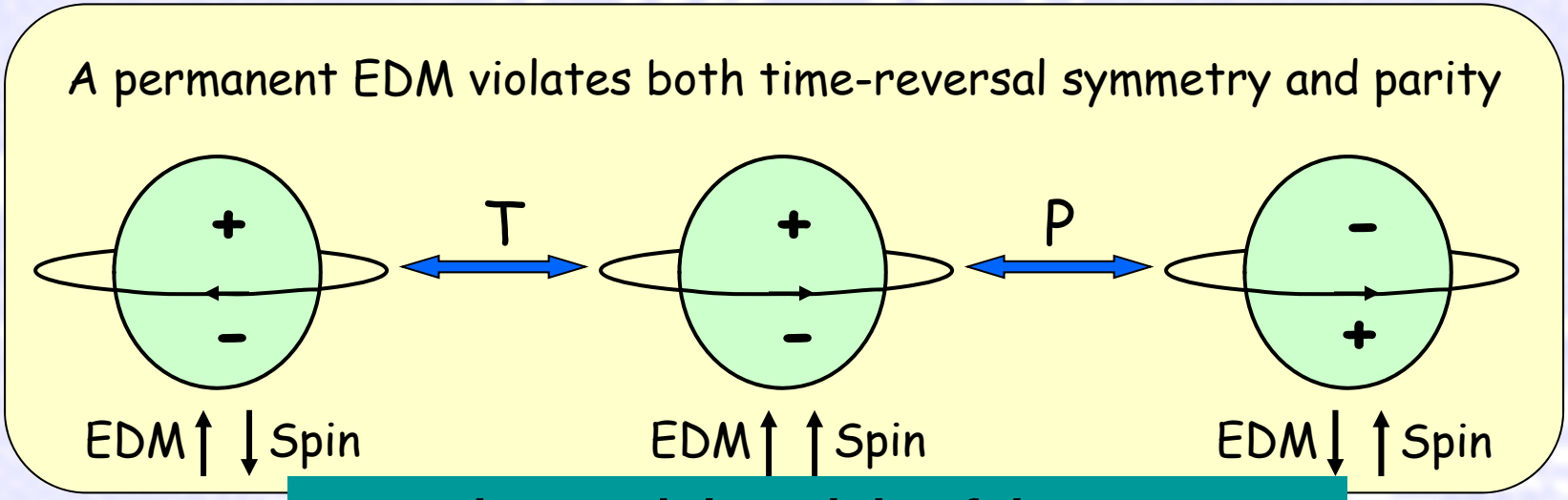

Heavy Z', Anomalous Z coupling

$M_{Z'} = 3000$ TeV/$c^2$

$B(Z \to \mu e) < 10^{-17}$

After W. Marciano

# The Quest for Electric Dipole Moments




***To understand the origin of the symmetry violations, you need many experiments!***

Neutron → Quark EDM

Diamagnetic Atoms (Hg, Xe, Ra, Rn) → Quark Chromo-EDM

Paramagnetic Atoms (Tl, Fr) Molecules (PbO) → Electron EDM

Quark EDM, Quark Chromo-EDM, Electron EDM → Physics beyond the Standard Model: SUSY, Strings …

Guy Savard, ANL

# This Science has attracted Competition: The Proton Source Landscape This Decade...

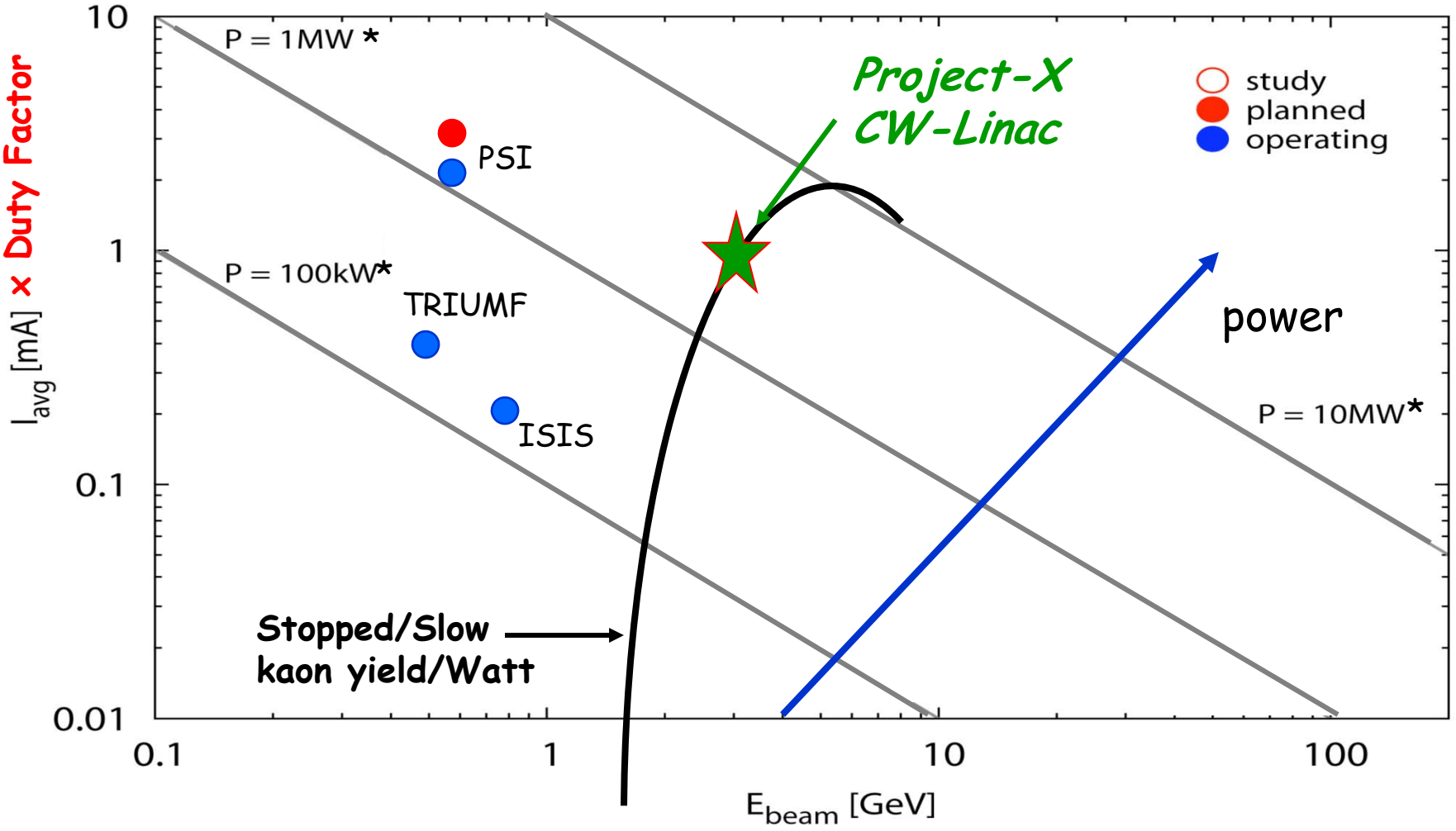
- Pulsed machines driving neutrino horns:
  SPS (0.5 MW), Main Injector ( 0.3 MW now, 0.7 MW for Nova),
  JPARC (plan for 1.7 MW)

- Cyclotrons and synchrotrons driving muon programs
  PSI (1.3 MW, 600 MeV), JPARC RCS (0.1-0.3 MW)

- Synchrotrons driving kaon physics programs.
  SPS (0.015 MW), JPARC (goal of >0.1 MW), Tevatron (0.1 MW)

- Linear machines driving nuclear and neutron programs:
  SNS, LANL, FRIB….not providing CW light-nuclei beams.

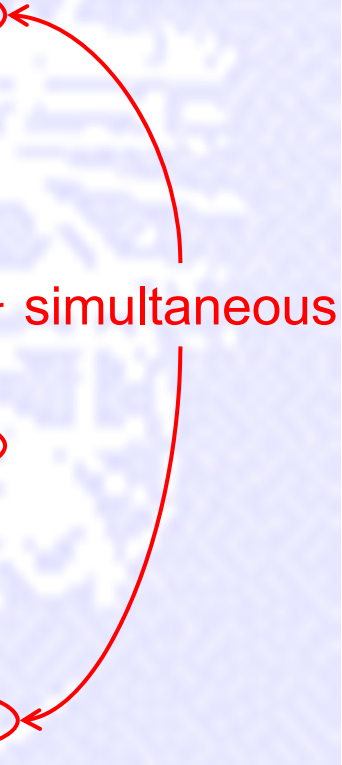
# The High Duty Factor Proton Source Landscape This Decade...



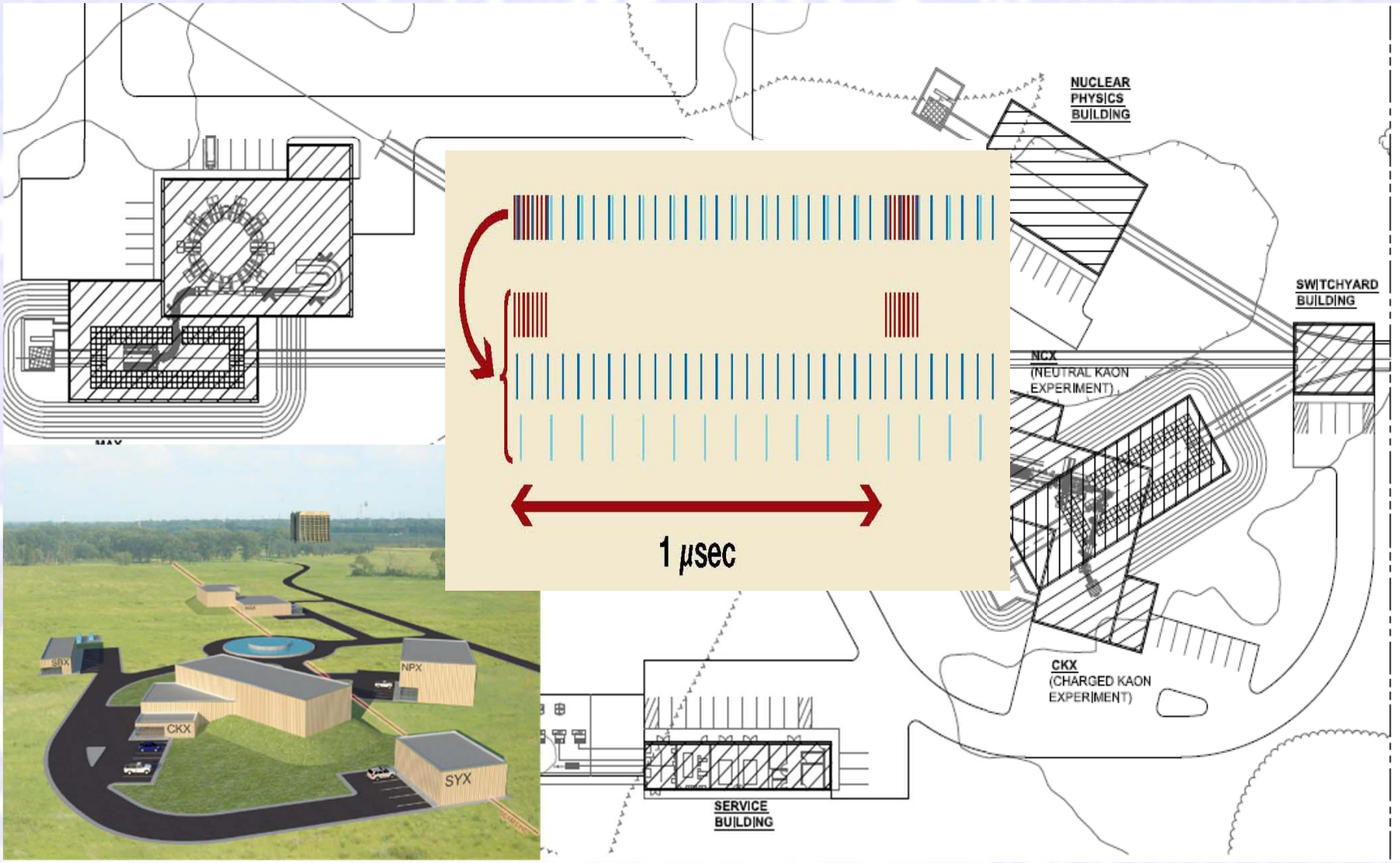

* Beam power x Duty Factor

# Project-X Accelerator Functional Requirements

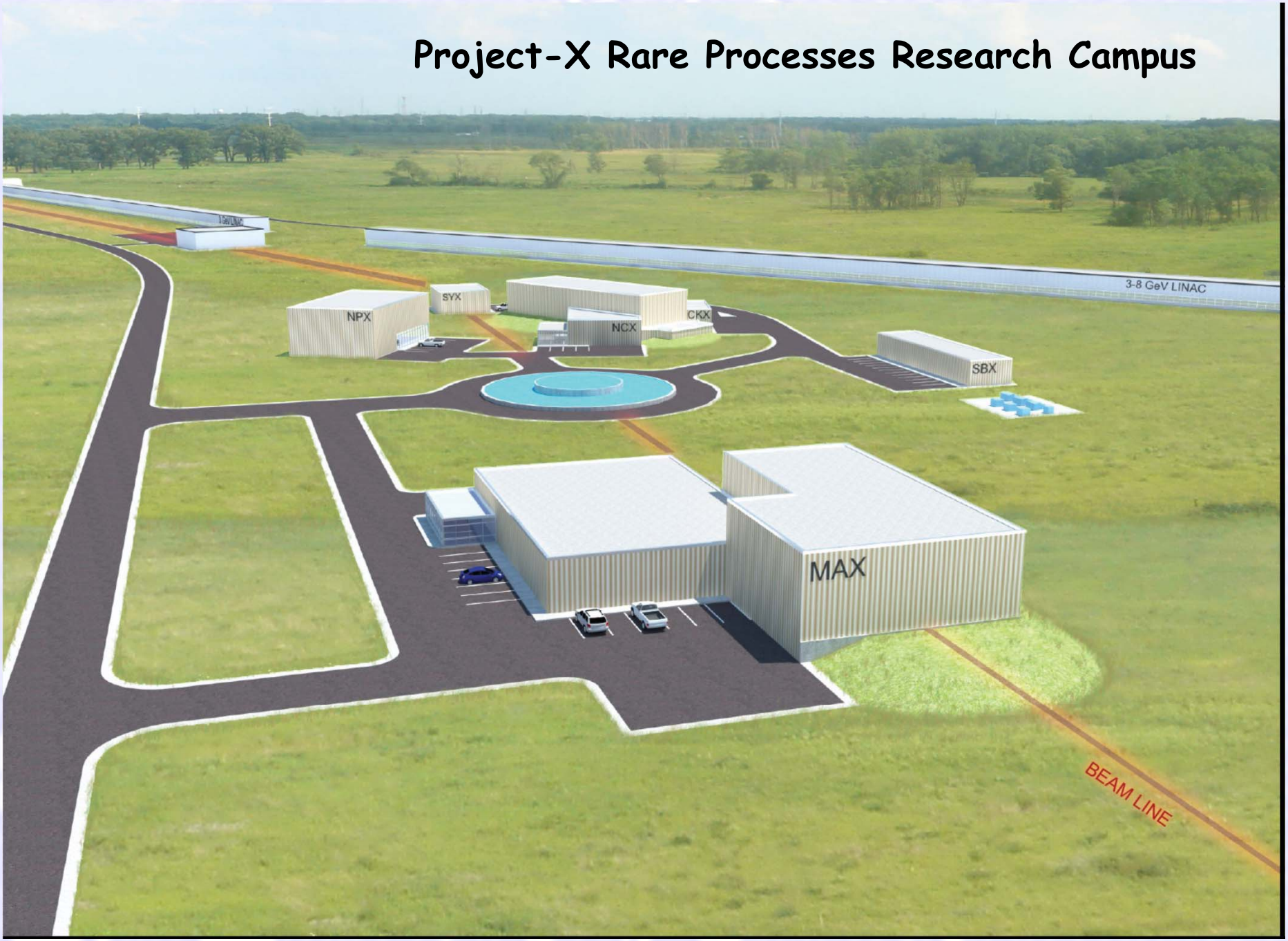
| | | |
|---|---|---|
| **CW Linac** | | |
| Particle Type | $H^-$ | |
| Beam Kinetic Energy | 3.0 | GeV |
| Average Beam Current | 1 | mA |
| Linac pulse rate | CW | |
| Beam Power | 3000 | kW |
| Beam Power to 3 GeV program | 2870 | kW |
| **RCS/Pulsed Linac** | | |
| Particle Type | protons/$H^-$ | |
| Beam Kinetic Energy | 8.0 | GeV |
| Pulse rate | 10 | Hz |
| Pulse Width | 0.002/4.3 | msec |
| Cycles to MI | 6 | |
| Particles per cycle to Recycler | $2.6\times10^{13}$ | |
| Beam Power to 8 GeV program | 190 | kW |
| **Main Injector/Recycler** | | |
| Beam Kinetic Energy (maximum) | 120 | GeV |
| Cycle time | 1.3 | sec |
| Particles per cycle | $1.6\times10^{14}$ | |
| Beam Power at 120 GeV | 2200 | kW |



# Project-X High-Intensity Campus



# Project-X Rare Processes Research Campus



# An Incomplete Menu of World Class Research Targets Enabled by Project-X

## Muon Physics:

Day-1 Experiment

- **Next generation muon-to-electron conversion experiment, new techniques for higher sensitivity and/or other nuclei.**
- Next generation $(g-2)_\mu$ if motivated by next round, theory, LHC. New techniques proposed to JPARC that are beam-power hungry…
- $\mu$ edm
- $\mu \rightarrow 3e$
- $\mu^+e^- \rightarrow \mu^-e^+$
- $\mu^- A \rightarrow \mu^+ A'$ ; $\mu^- A \rightarrow e^+ A'$ ; $\mu^- e^-(A) \rightarrow e^- e^-(A)$
- Systematic study of radiative muon capture on nuclei.

# An Incomplete Menu of World Class Research Targets Enabled by Project-X

## Kaon Physics:

Possible Day-1 Experiments

- $K^+ \to \pi^+ \nu\bar{\nu}$: >1000 events, Precision rate and form factor.
- $K_L \to \pi^0 \nu\bar{\nu}$: 1000 events, enabled by high flux & precision TOF.
- $K^+ \to \pi^0 \mu^+ \nu$: Measurement of T-violating muon polarization.
- $K^+ \to (\pi,\mu)^+ \nu_x$: Search for anomalous heavy neutrinos.
- $K^0 \to \pi^0 e^+ e^-$: <10% measurement of CP violating amplitude.
- $K^0 \to \pi^0 \mu^+ \mu^-$: <10% measurement of CP violating amplitude.
- $K^0 \to X$: Precision study of a pure $K^0$ interferometer: Reaching out to the Plank scale ($\Delta m_K/m_K \sim 1/m_P$)
- $K^0, K^+ \to$ LFV: Next generation Lepton Flavor Violation experiments

...and more

# An Incomplete Menu of World Class Research Targets Enabled by Project-X

Possible Day-1 Experiment

## Nuclear Enabled Particle Physics:

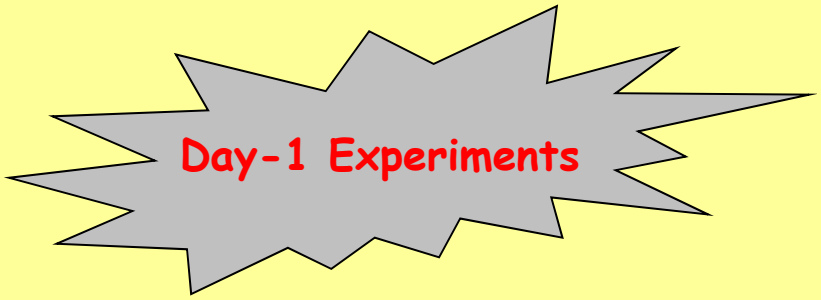
- **Production of Ra, Rd, Fr isotopes for nuclear edm experiments that are uniquely sensitive to Quark-Chromo and electron EDM's. Production of Very-cold and Ultra-cold neutrons for EDM and n-nbar.**

## Baryon Physics:

- $pp \rightarrow \bar{\Sigma}^{+} K^{0} p^{+}$ ; $\Sigma^{+} \rightarrow p^{+} \mu^{+} \mu^{-}$ (HyperCP anomaly, and other rare $\Sigma^{+}$ decays)
- $pp \rightarrow K^{+} \Lambda^{0} p^{+}$ ; $\Lambda^{0}$ ultra rare decays
- neutron – antineutron oscillations
- $\Lambda^{0} \leftrightarrow \bar{\Lambda}^{0}$ oscillations (Project-X operates below anti-baryon threshold)
- neutron EDMs

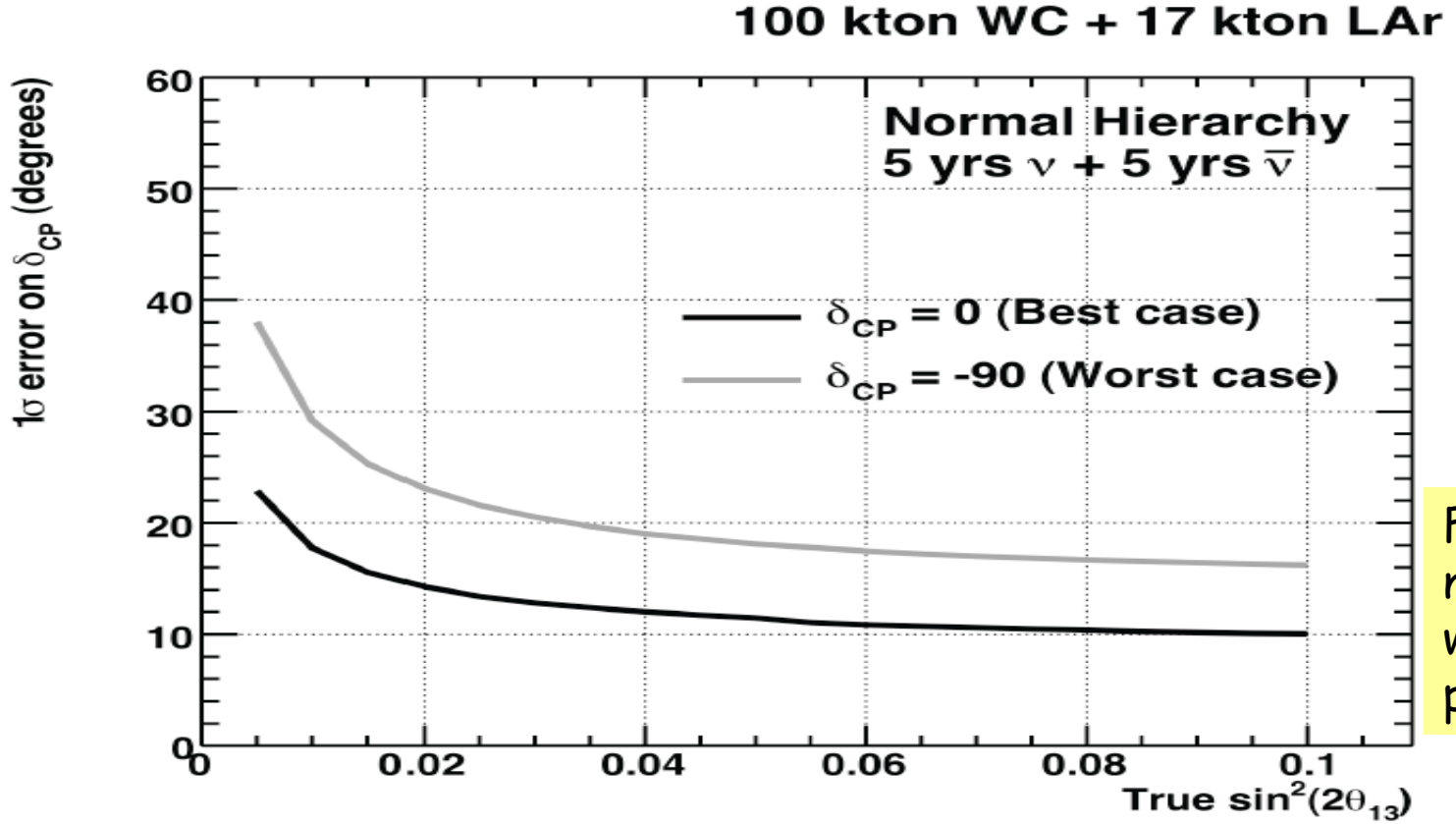
# An Incomplete Menu of World Class Research Targets Enabled by Project-X

**Neutrino Physics:**




- **Mass Hierarchy**
- **CP violation**
- **Precision measurement of the $\theta_{23}$ (atmospheric mixing). Maximal??**
- Anomalous interactions, e.g. $\nu_\mu \rightarrow \nu_\tau$ probed with target emulsions (Madrid Neutrino NSI Workshop, Dec 2009)
- Search for sterile neutrinos, CP & CPT violating effects in next generation $\nu_e, \overline{\nu}_e \rightarrow X$ experiments….x3 beam power @ 120 GeV, **x10-x20 power @ 8 GeV**.
- Next generation precision cross section measurements.

# Pursuing next-generation neutrino parameters is beam-power hungry: **Project-X *Triples* LBNE (Power x Mass) Reach**




From the neutrino white paper

**Figure 3: Plot showing 1 sigma error (in degrees) on $\delta_{CP}$ at an LBNE far detector complex composed of a 100−kT water Cherenkov detector and a 17−kT liquid argon detector. The exposure assumes a 700−kW proton beam. [Plot courtesy of Lisa Whitehead, Brookhaven National Laboratory]**


# Project-X Opportunities

- Follow leads on 3+N sterile neutrinos:

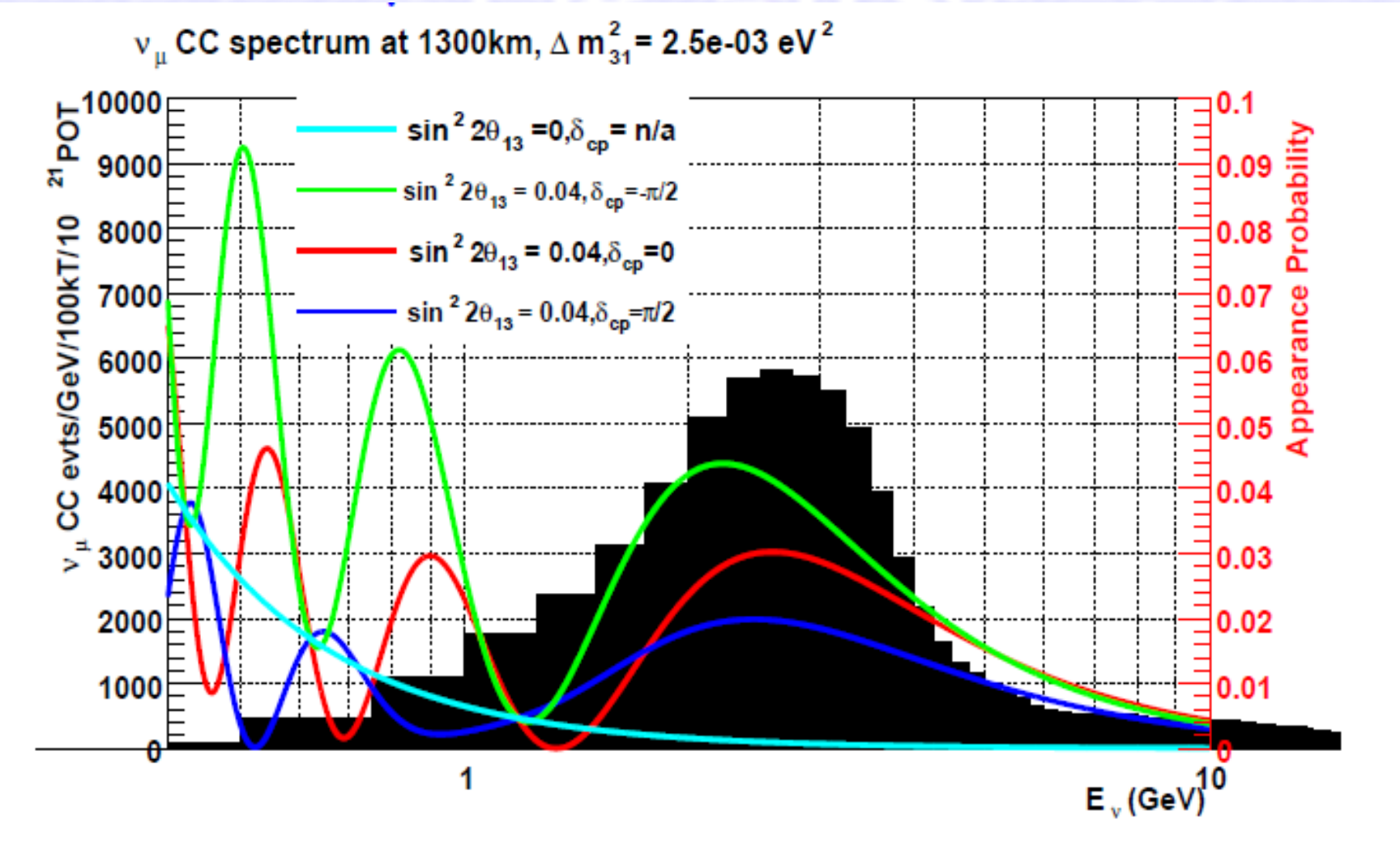
190 kW 8-GeV beam power
1000 kW class 3-GeV DIF driver

Higher 8-GeV beam power??

- Beam dump exotics search
- Precision neutrino cross sections
- Flux measurements with $H/D_2$

SBNW11 Summary : R. Van de Water (LANL)

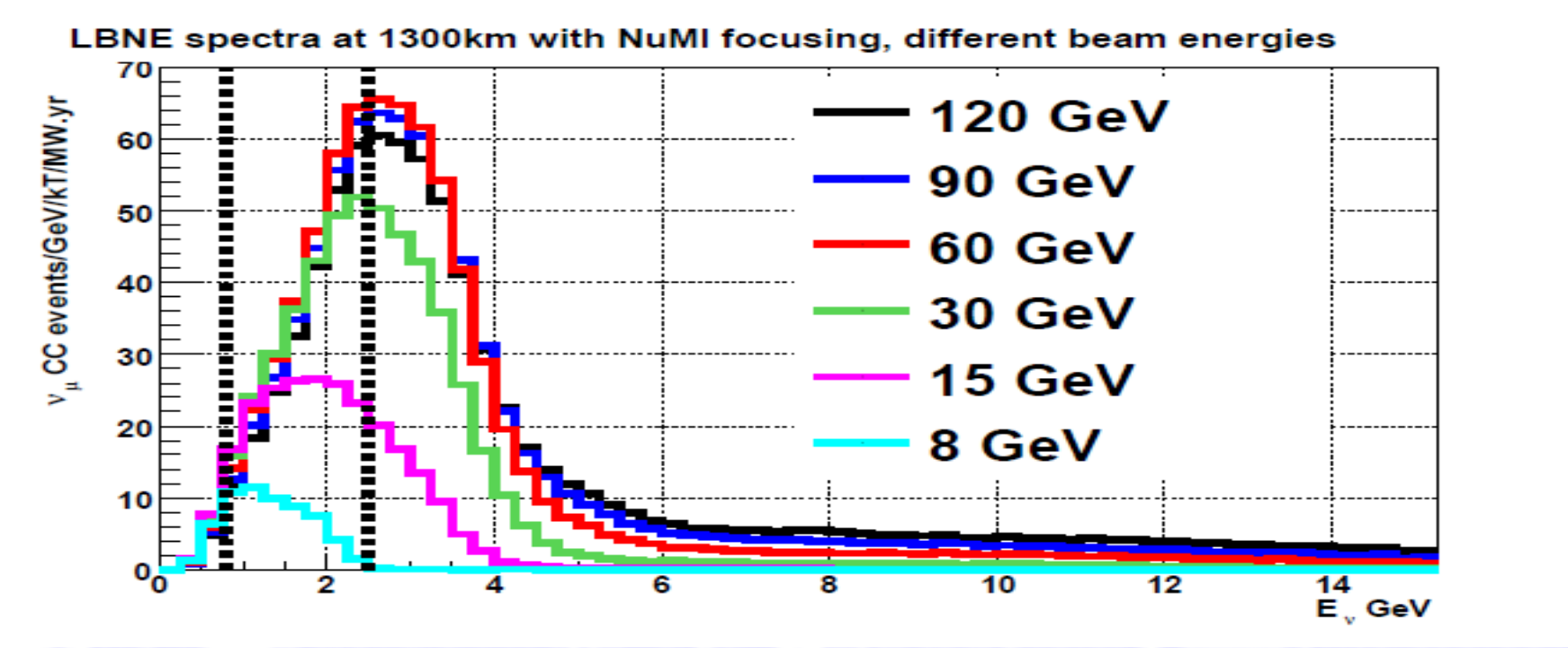
# Tuning the LBNE spectrum




Mary Bishai, Neutrino Working Group meeting October 24th, 2011

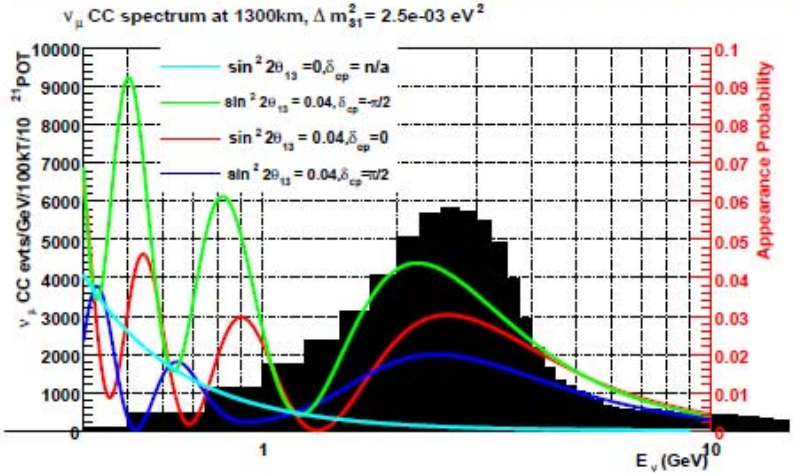
- A task force (K. Gollwitzer) to develop a path from Project-X to a Neutrino-Factory/Muon-Collider has recently reported a concept to raise available 8 GeV beam power from 190kW to 4000kW! This path re-uses 75% of the Project-X facility.

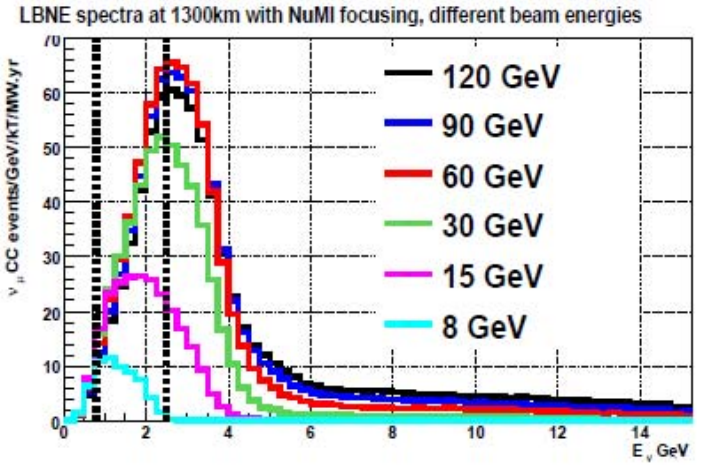
- The joint reach of simultaneous 2MW@60 GeV and 4MW@8 GeV is very interesting. This idea has been long been considered (D Michael) and more recently by Mary Bishai and Jeff Nelson.



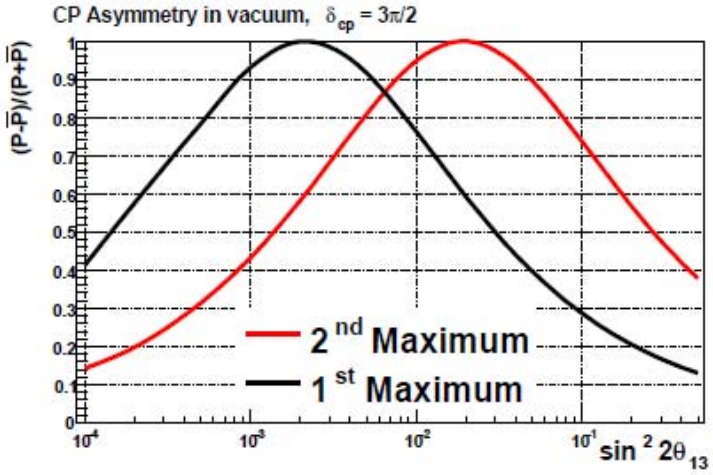

Mary Bishai, Neutrino Working Group meeting October 24th, 2011

# Wide-band beam to cover BOTH oscillation maxima for best CP Violation/Mass Hierarchy sensitivity

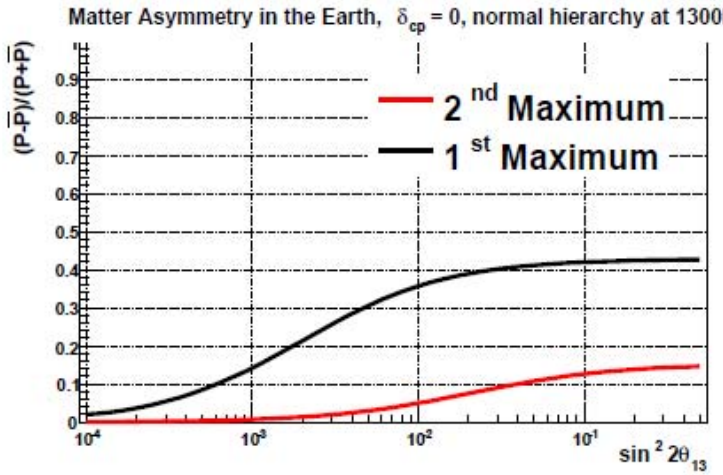



## CP Asymmetry (vacuum)




## Matter Asymmetry (no CPV)




Mary Bishai, Neutrino Working Group meeting October 24th, 2011

# Neutrinos, Project-X and you…

- Project-X will reduce the tyranny in long-baseline experiments of (Beam-Power x Detector-Mass) by x3.

- Many opportunities for high power short-baseline experiments exist for 3-8 GeV beam power. More development is needed, directions will depend on how the 3+N sterile-neutrino saga unfolds.

- Development of Project-X includes consideration of a 4MW proton driver at 8 GeV for a neutrino factory and Muon Collider.

A beam power path to consider for long-baseline experiments:

700kW at 120 GeV this decade.

>2000kW at 60-120 GeV in the Project X era (2022+)

>2000kW at 60-120 GeV and 4000kW at 8-GeV on the NF/MC road.

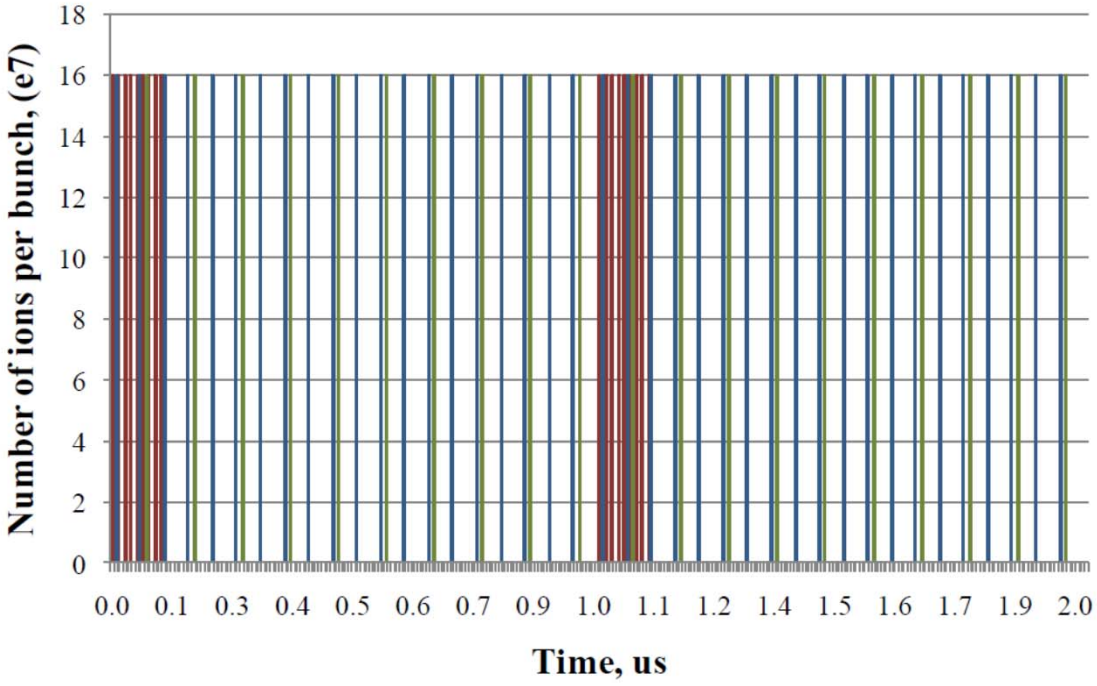
# Spare Slides

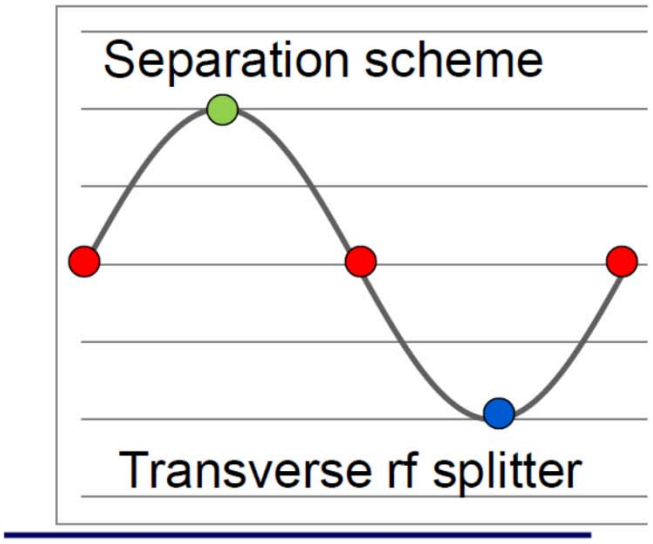
# Chopping and splitting for 3-GeV experiments

1 μsec period at 3 GeV

| | |
|---|---|
| Muon pulses (16e7) 81.25 MHz, 100 nsec at 1 MHz | 700 kW |
| Kaon pulses (16e7) 20.3 MHz | 1540 kW |
| Nuclear pulses (16e7) 10.15 MHz | 770 kW |

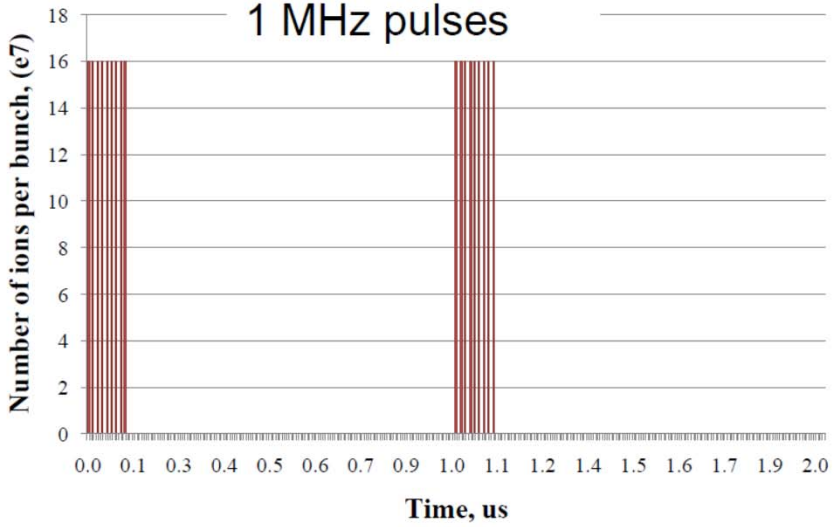
Ion source and RFQ operate at 4.2 mA
75% of bunches are chopped at 2.5 MeV after RFQ

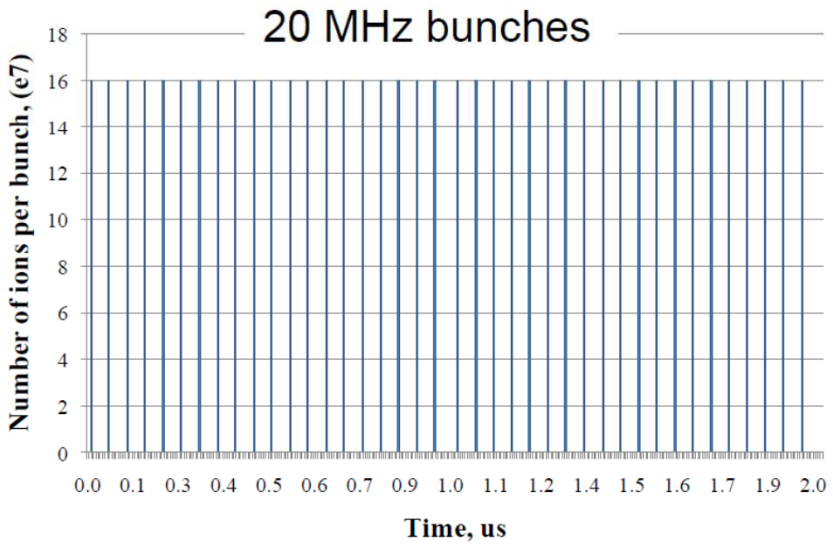


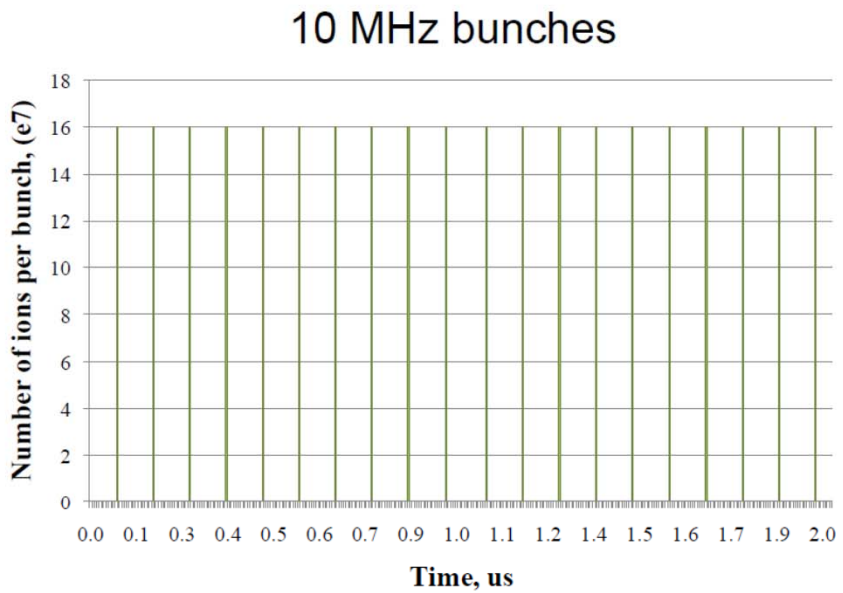




Courtesy of Nagaitsev

# Beam after splitter

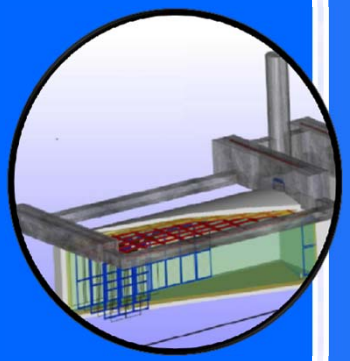


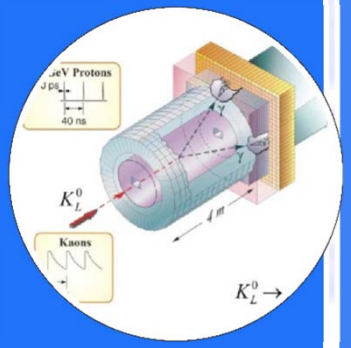

Courtesy of Nagaitsev

# Project X: new experiments



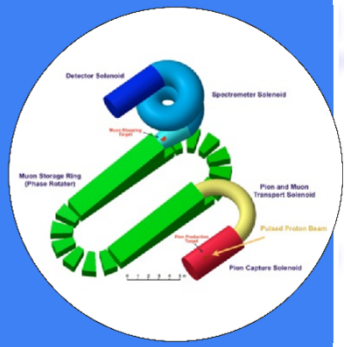
## Neutrinos

- Matter-antimatter asymmetry
- Neutrino mass spectrum
- Neutrino-antineutrino differences
- Anomalous interactions
- Proton decay
- SuperNova bursts



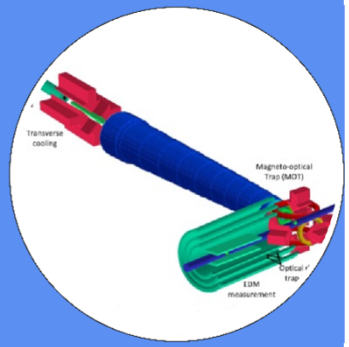

## Kaons

- Physics beyond the Standard Model
- Elucidation of LHC discoveries
- Two to three orders of magnitude increase in sensitivity



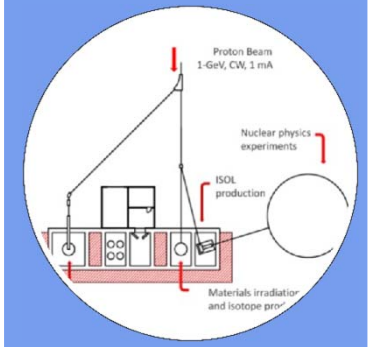

## Muons

- Oscillation in charged leptons
- Physics beyond the Standard Model
- Elucidation of LHC physics
- Sensitive to energy/mass scales three orders of magnitude beyond LHC




## Nuclei

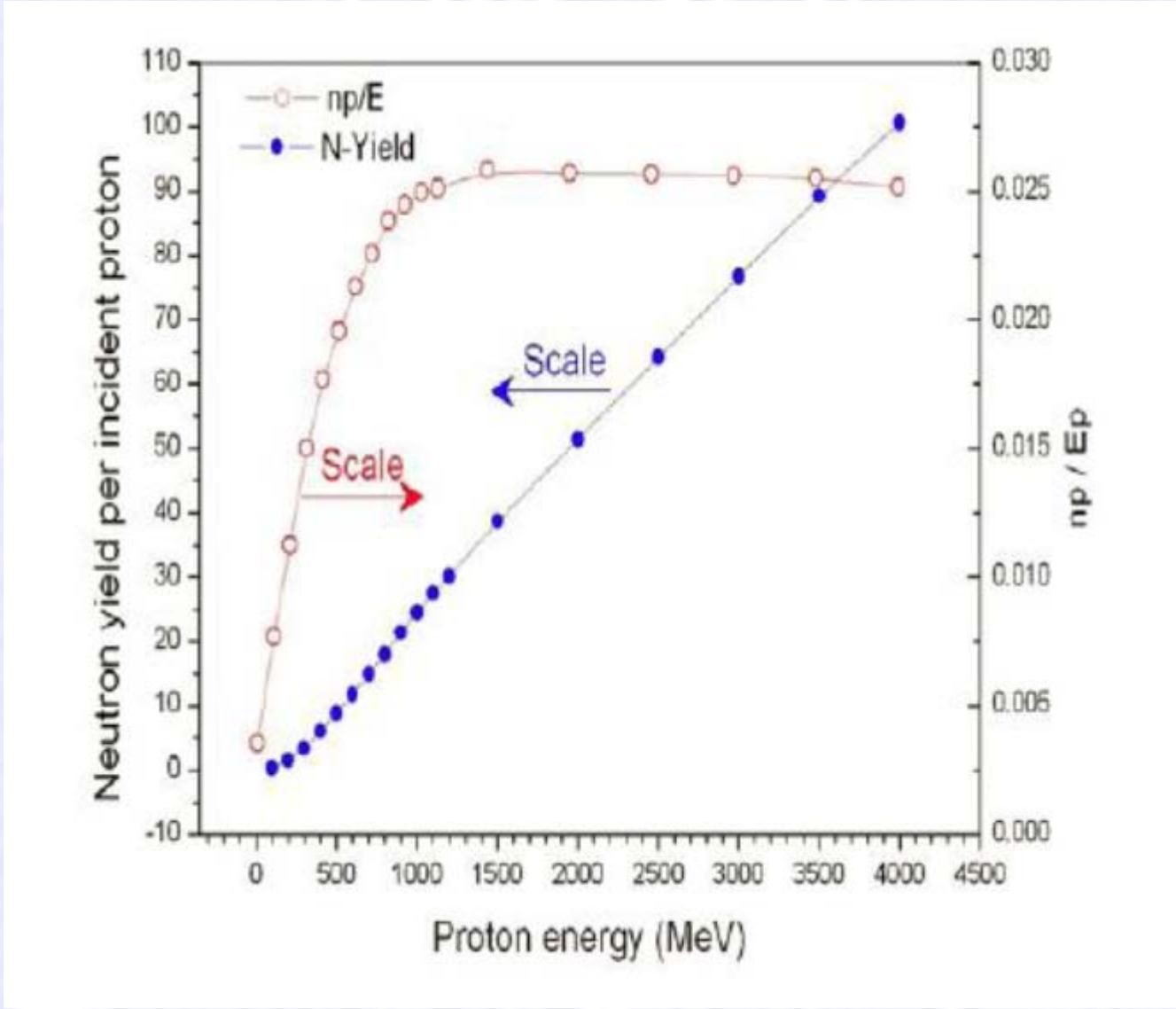
- New generation of symmetry-test experiments
- Electric Dipole Moments
- Three or more orders of magnitude increase in Francium, Radium, Actinium isotopes




## Energy Applications

- Transmutation experiments with nuclear waste
- Spallation target configurations
- Materials test under high irradiation
- Neutron fluxes relevant to ADS

# Optimum Energy for ADS R&D



# *High Duty-Factor Proton Beams*
# Why is this important to Rare Processes?

- Experiments that reconstruct an "event" to a particular time from sub-detector elements are intrinsically vulnerable to making mistakes at high instantaneous intensity (I). The probability of making a mistake is proportional to $I^2 x \delta t$, where $\delta t$ is the event resolving time.
- Searching for rare processes requires high intensity.
- Controlling backgrounds means minimizing the instantaneous rate and maximizing the time resolution performance of the experiment.
- This is a common problem for Run-II, LHC, Mu2e, High-School class reunions, etc.

# Kaon Yields at Constant Beam Power

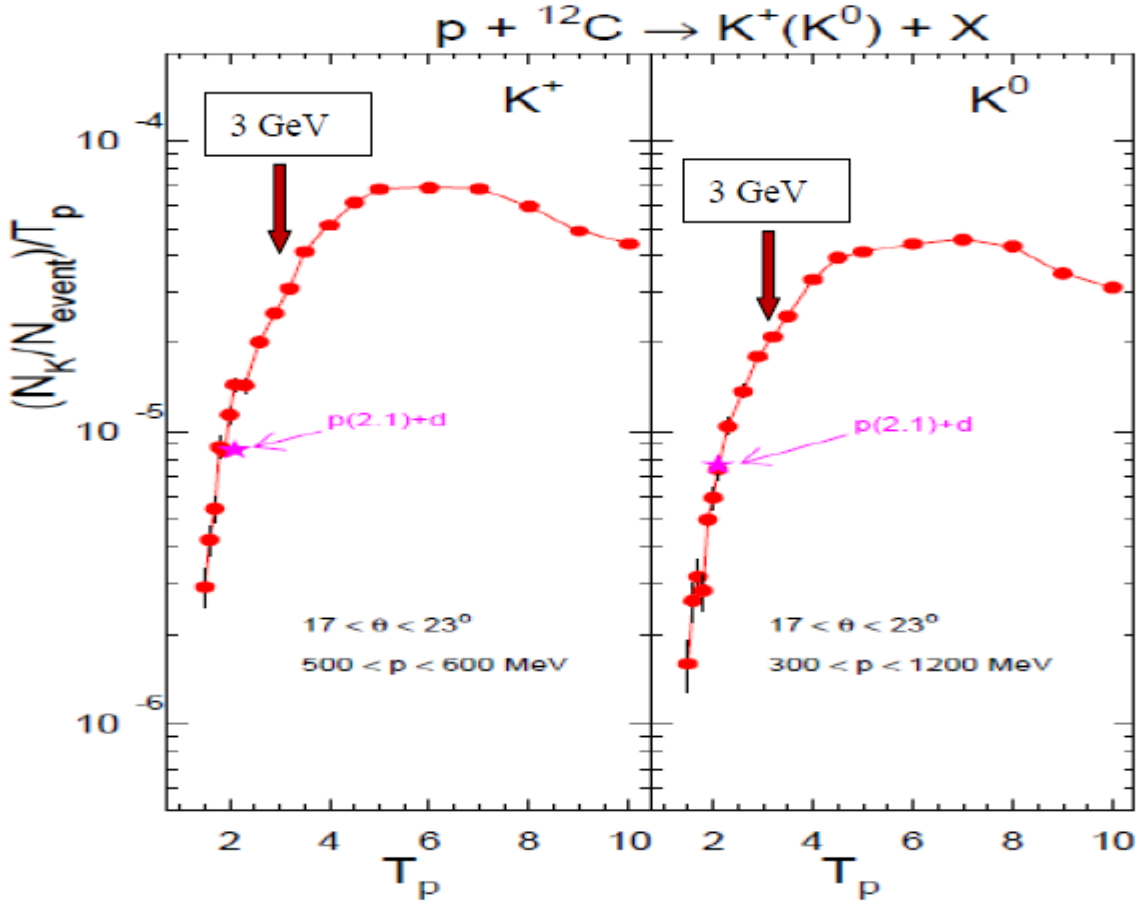
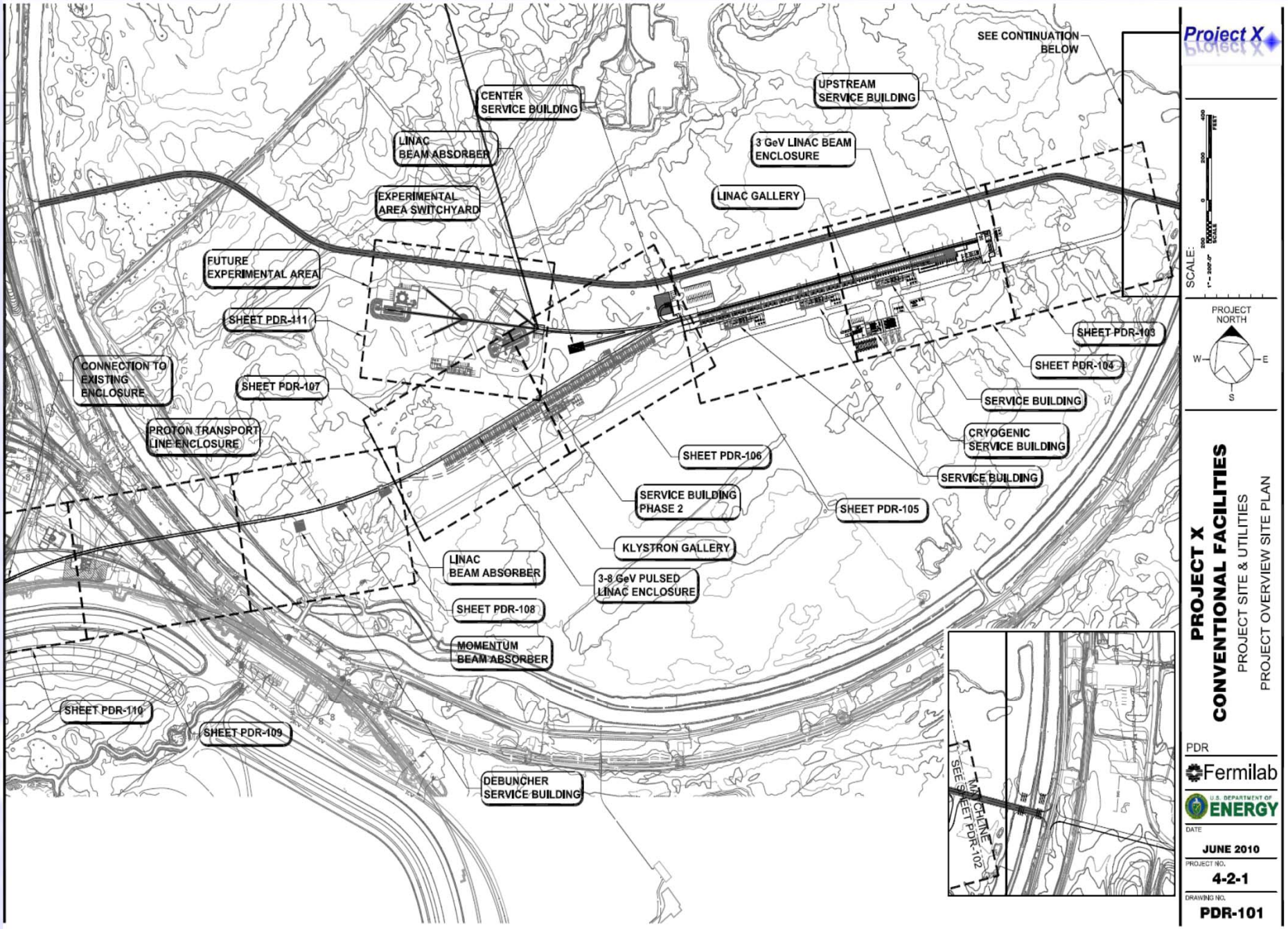
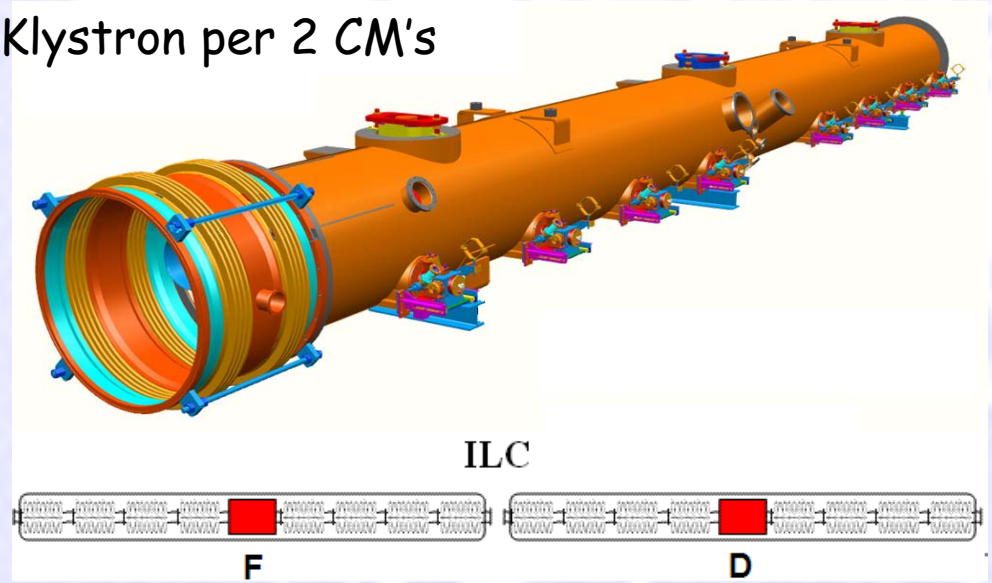



**Figure 2**: The estimated (LAQGSM/MARS15) kaon yield at constant beam power (yield/$T_p$) for experimentally optimal angular and energy regions as a function of $T_p$ (GeV).

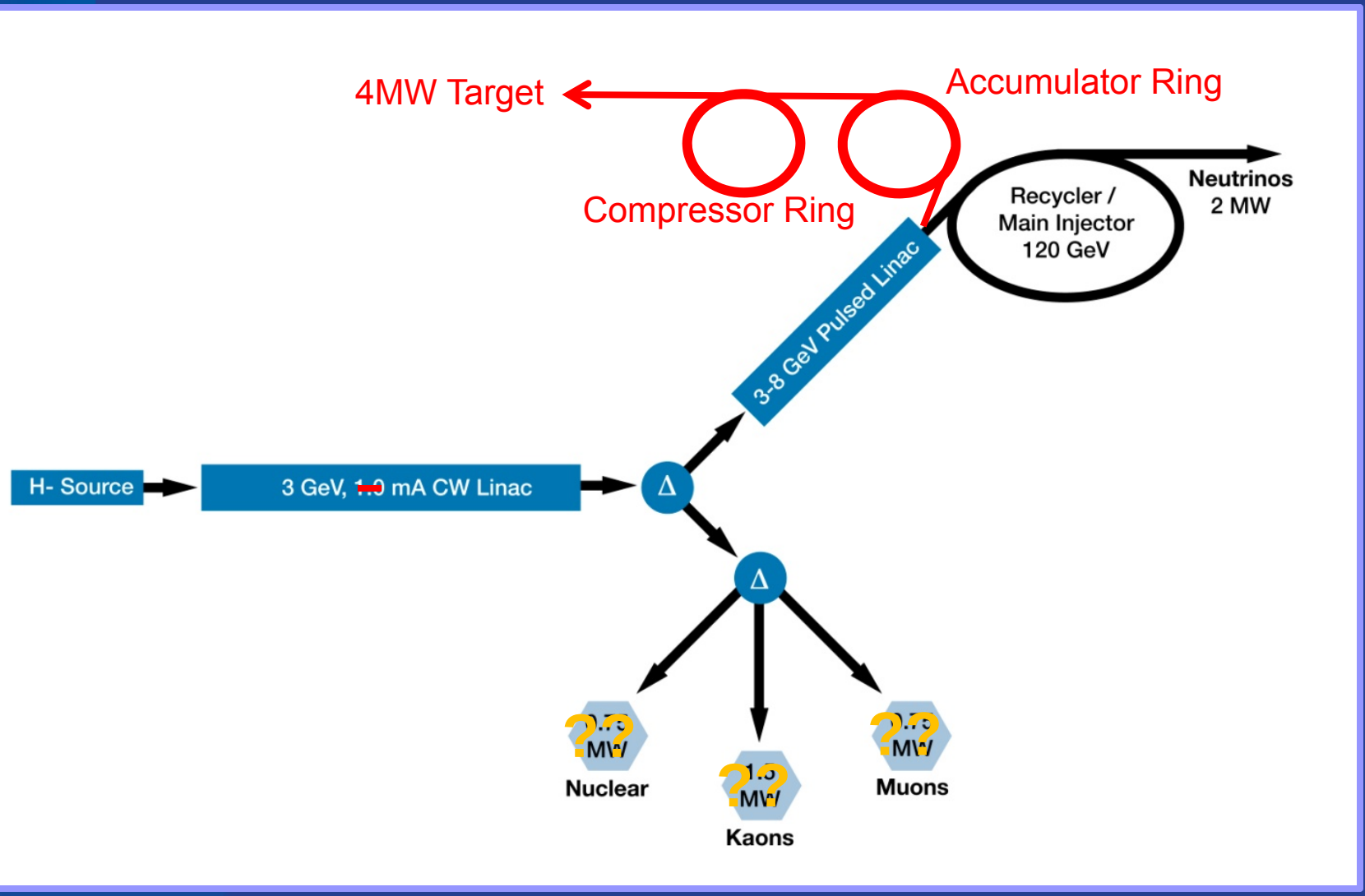

Project X
SEE CONTINUATION BELOW
CENTER SERVICE BUILDING
UPSTREAM SERVICE BUILDING
LINAC BEAM ABSORBER
3 GeV LINAC BEAM ENCLOSURE
EXPERIMENTAL AREA SWITCHYARD
LINAC GALLERY
FUTURE EXPERIMENTAL AREA
SHEET PDR-111
SHEET PDR-103
SHEET PDR-104
CONNECTION TO EXISTING ENCLOSURE
SHEET PDR-107
SERVICE BUILDING
PROTON TRANSPORT LINE ENCLOSURE
CRYOGENIC SERVICE BUILDING
SHEET PDR-106
SERVICE BUILDING
SERVICE BUILDING PHASE 2
SHEET PDR-105
KLYSTRON GALLERY
LINAC BEAM ABSORBER
3-8 GeV PULSED LINAC ENCLOSURE
SHEET PDR-108
MOMENTUM BEAM ABSORBER
SHEET PDR-110
SHEET PDR-109
DEBUNCHER SERVICE BUILDING
TO MI-8 LINE SEE SHEET PDR-102
SCALE:
PROJECT NORTH
W
E
S
PROJECT X
CONVENTIONAL FACILITIES
PROJECT SITE & UTILITIES
PROJECT OVERVIEW SITE PLAN
PDR
Fermilab
U.S. DEPARTMENT OF ENERGY
DATE
JUNE 2010
PROJECT NO.
4-2-1
DRAWING NO.
PDR-101

# 3 – 8 GeV acceleration

- Pulsed linac based on the ILC technology
  - ✓1.3 GHz, 25 MV/m gradient, ≤5% duty cycle
  - ✓considering 8-30 ms pulse length
  - ✓~250 cavities (28 ILC-type cryomodules) needed.
  - ✓Simple FODO lattice
  - ✓1 Klystron per 2 CM's



# MAP Layout based upon Project X



# Project X Upgrade Proton Driver - 3

## Pulsed Linac

1.3GHz SRF

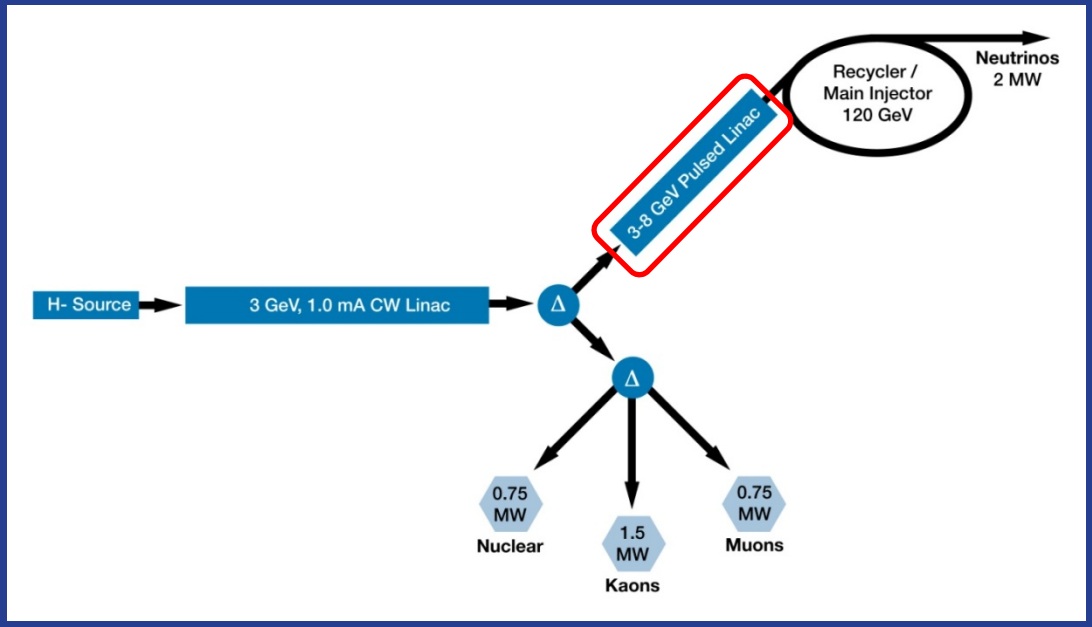
3-8 GeV

10% ~~5%~~ duty factor at ~~10Hz~~ 15Hz

More RF power

Upgrade of couplers

More cryo capicity




Fermilab

# Rings' Concepts & Concerns

- Simple numbers to start
  - $T_{rev}$ ~ 800 ns
  - $f_{rf}$ ~ 10 MHz
  - h = 8
  - Injection scheme
    - ~50 ns beam ON followed by ~50 ns NO beam

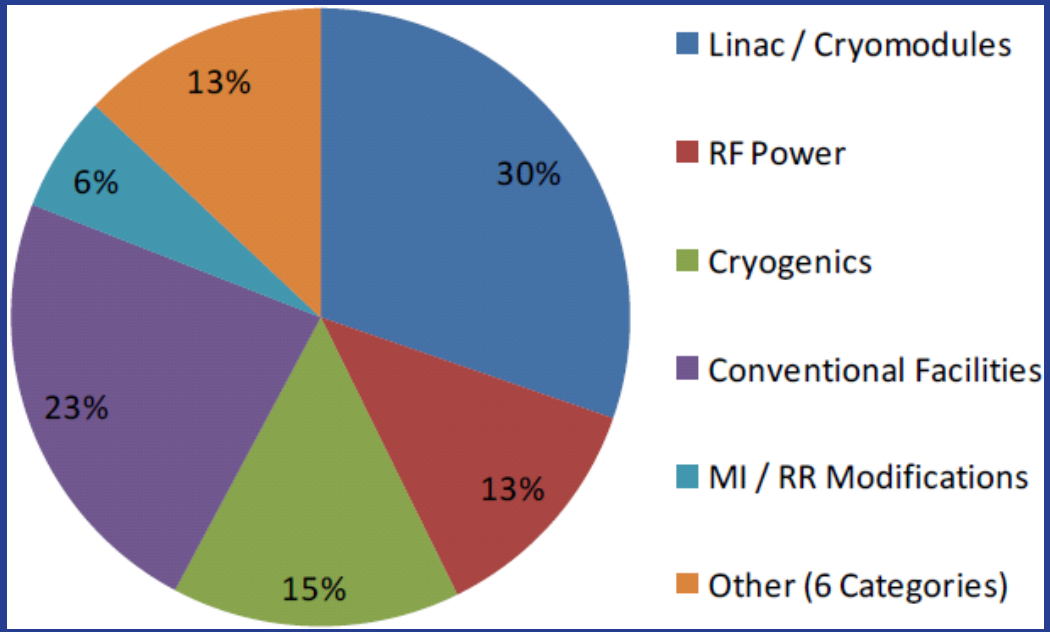

- Evolution of design
  - Increase of circumference (~300m)
  - Space for RF and Injection/Extraction components
  - Several designs and will settle on one
- Concerns
  - Injection: Stripping
  - Instabilities
  - Beam size in Compressor Ring after bunch rotation

# Ring Concern: Injection/Stripping

- Stationary foil will not survive
- Solutions are being investigated by other groups; will have to keep informed of progress
  - Will need to build upon Project X R&D for stripping at 8 GeV in to Recycler/Main Injector
  - Rotating foils
  - Laser
- Should not forget about un-stripped beam (~1%) needs to be “absorbed”

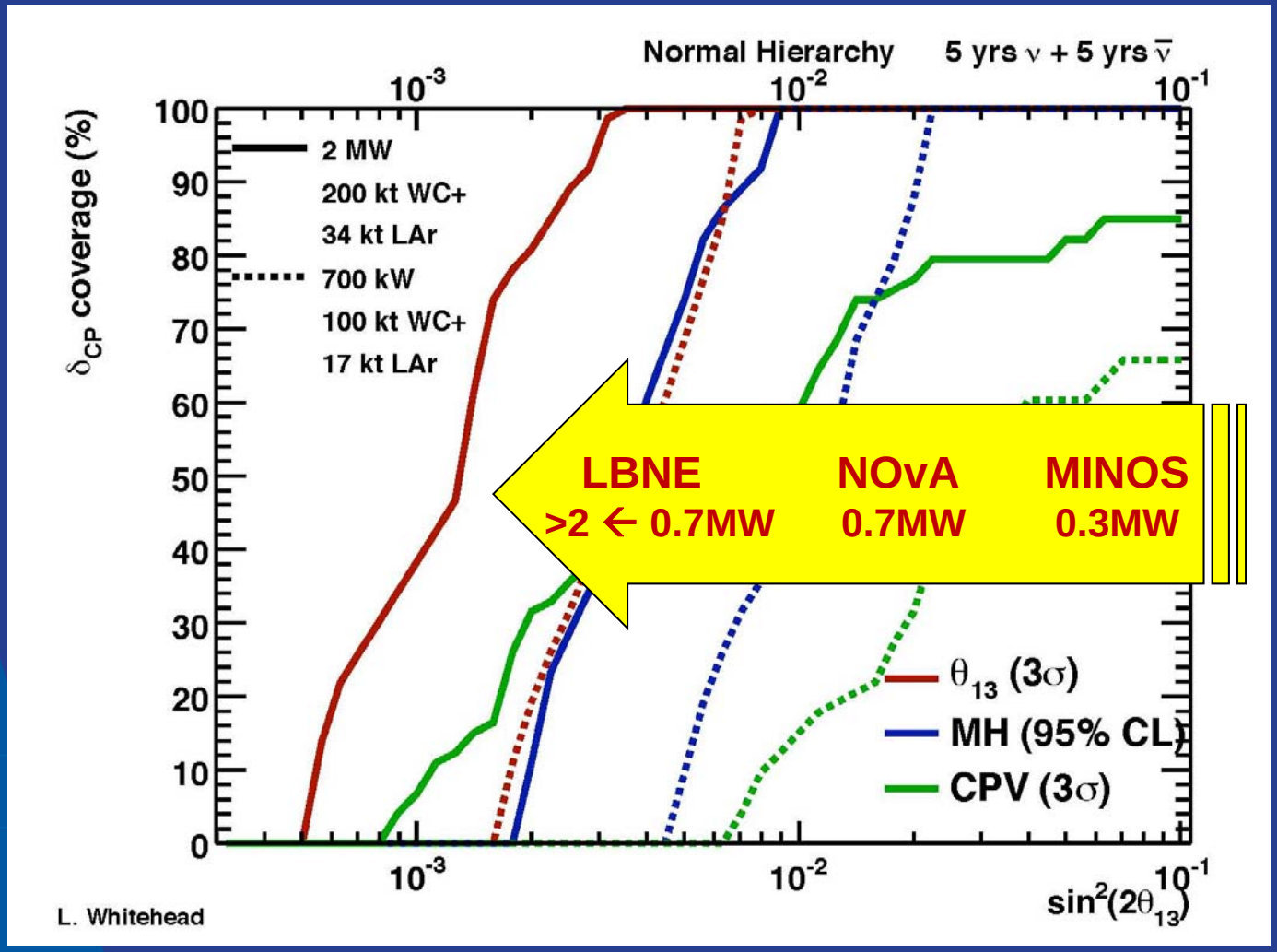
# Project X Upgrade Proton Driver - 4

- Conventional facilities
  - More water cooling
  - Building space
    - More cryo capacity
    - More Klystrons




- An upgrade re-uses >75% of RDR cost

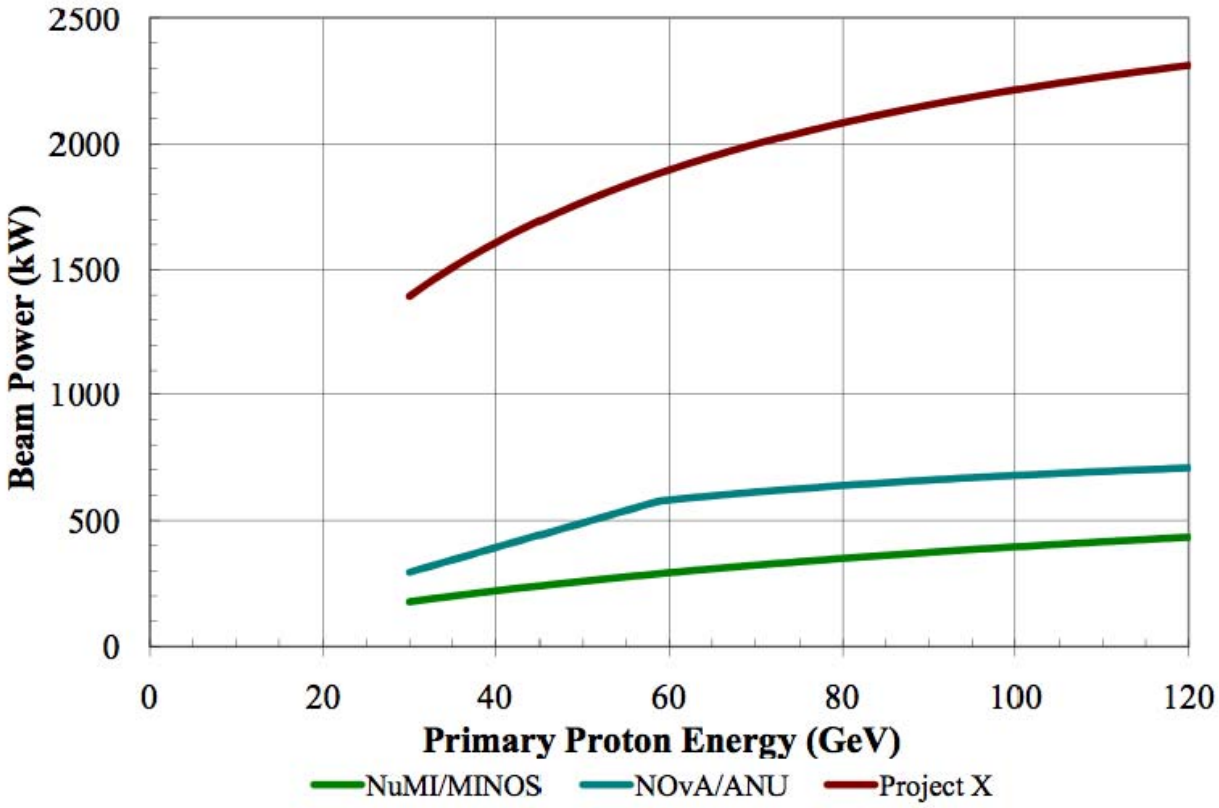
# Evolution of Neutrino Sensitivities



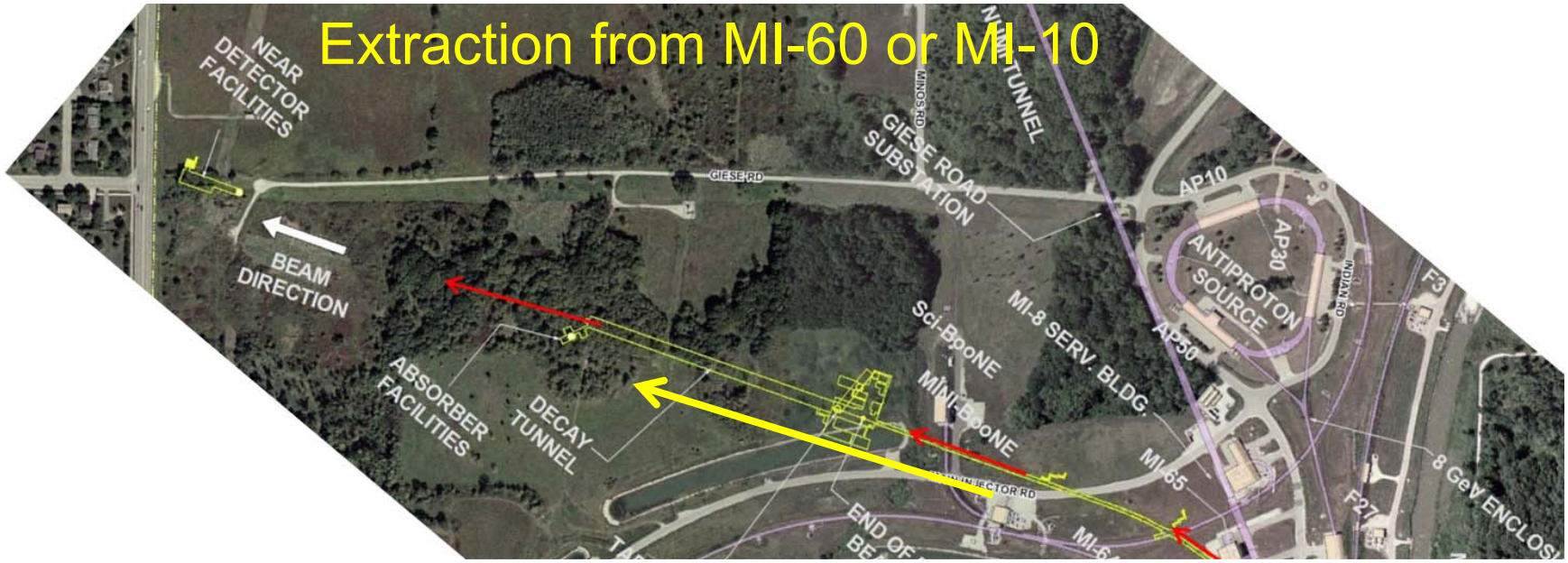
# Main Injector Primary Proton Beam Power (R. Zwaska)



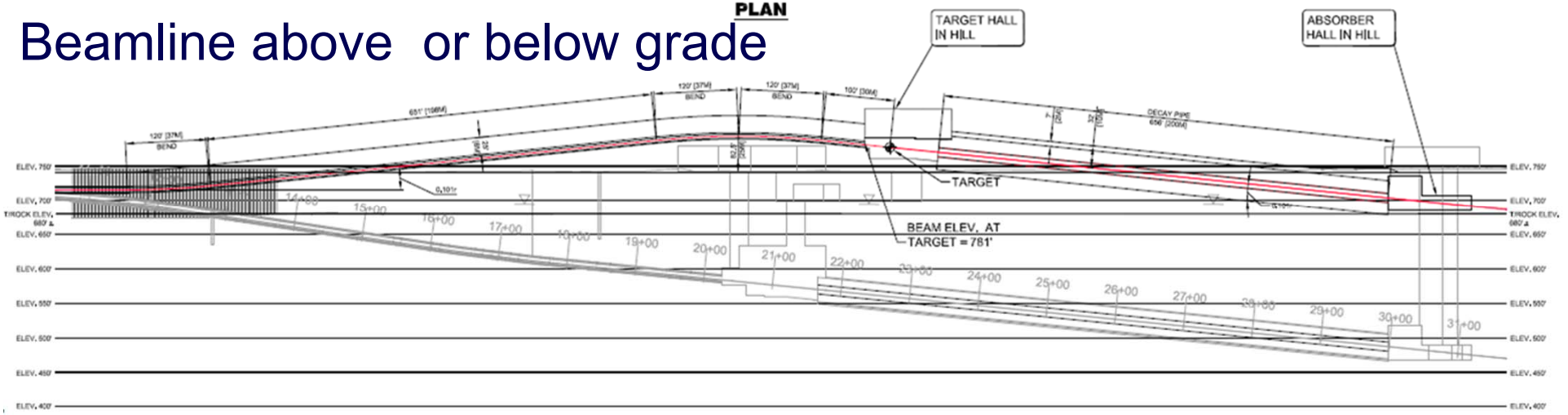
**With Project X:**



# Neutrino Beam Alternate Designs



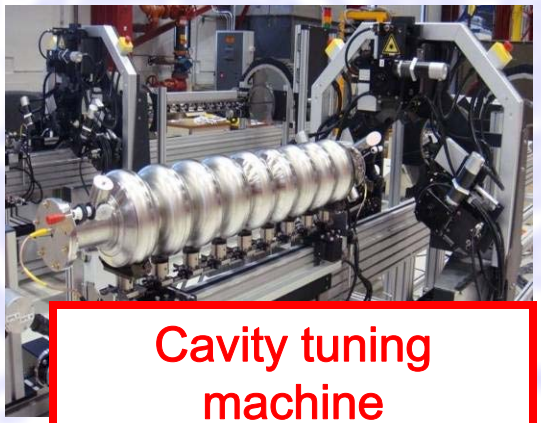

## Beamline above or below grade



# New FNAL SRF infrastructure


VTS


VTS


Cavity tuning machine

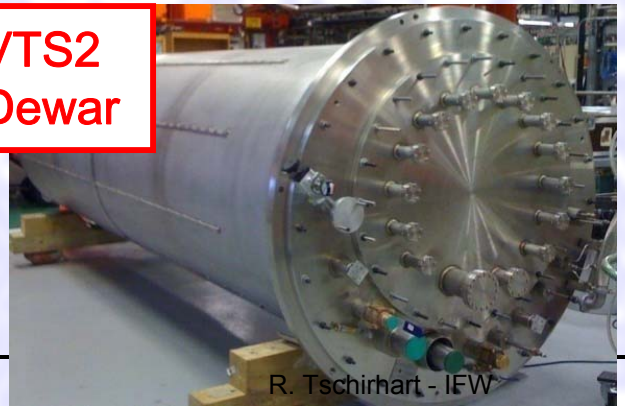

HTS


String Assembly


MP9 Clean Room


Final Assembly

VTS2 Dewar




New Vacuum Oven for 1300 MHz

# ANL/ FNAL cavity processing infrastructure

EP tool for 1300 MHz at ANL

New EP tool for ¼ wave and 650 MHz cavities at ANL

HPR and clean Rooms

New EP tool at FNAL

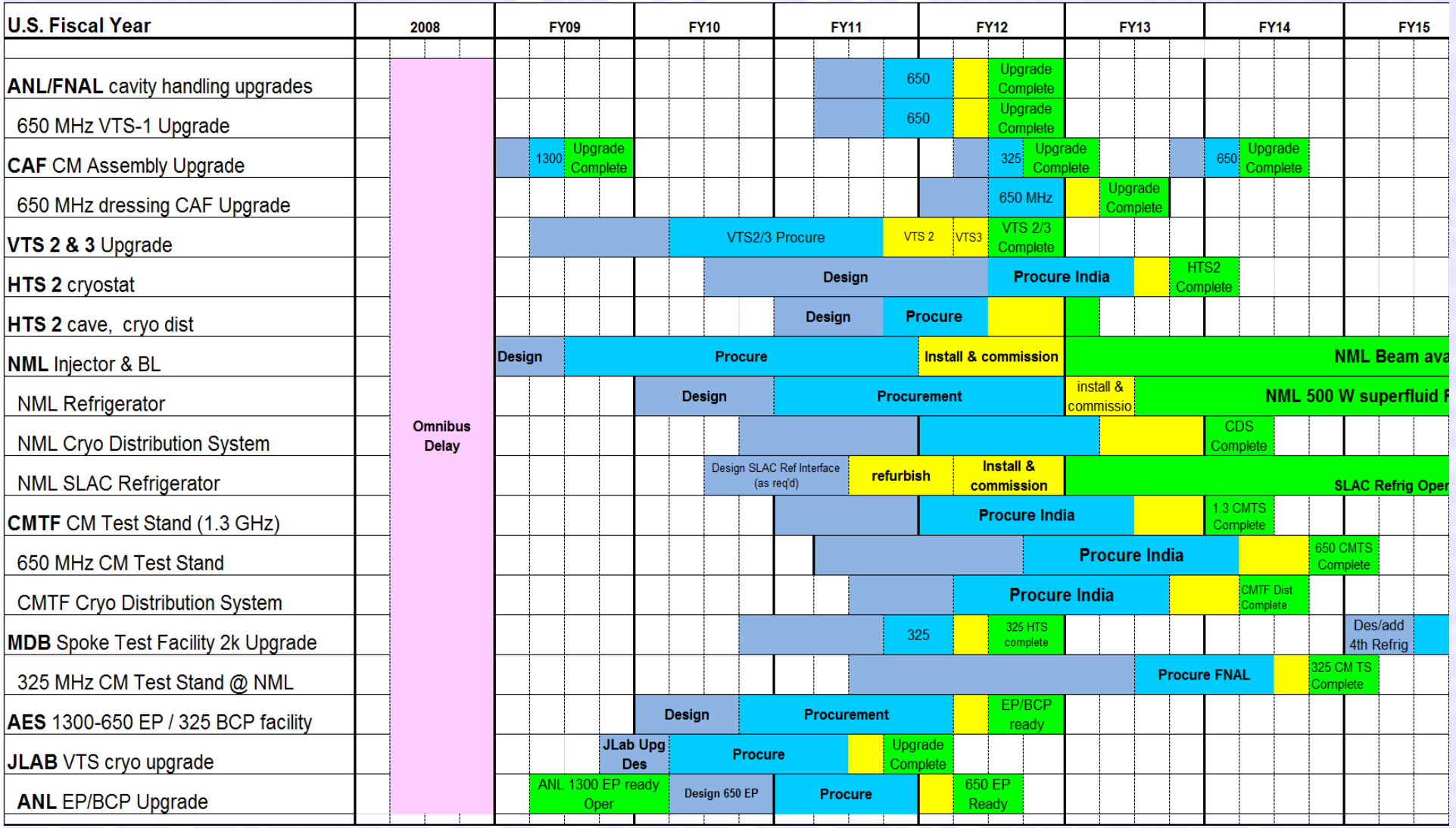
New Vacuum Oven for 650 MHz + SSR

# Industrial Capabilities--AES


- BCP and EP Tools for 1300 MHz 9-cell or 650 MHz 5-cell. (commissioning)
- HPR up to 1000 lb structures. (commissioned)
- BCP up to 1000 lb. structures. (commissioned)
- Clean Room Area is planned in the future

Also developing capability at Roark-Niowave, PAVAC

# Integrated SRF Schedule - Infrastructure




**Shows only remaining items, many completed items are now not shown (VTS-1, HTS, STF, CAF)**

# Integrated SRF Schedule - Cryomodules