Project-X

Physics Opportunities

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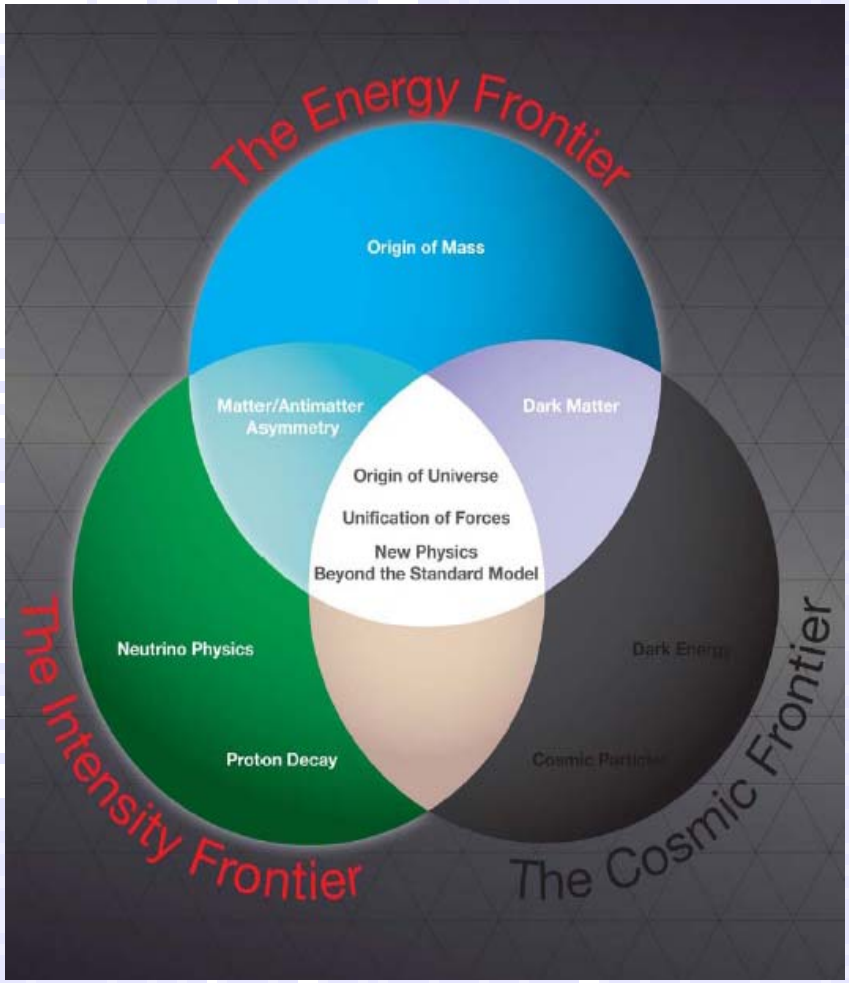
Fermilab

March 18th , 2010

The Promise of the Intensity Frontier

Project-X drives next generation experiments in rare processes and long-base neutrino physics that explore:

- ***The origin of the universe***
- ***Unification of Forces***
- ***New Physics Beyond the Standard Model.***



Recent Activity to Engage and Build the Project-X Research Community

- **Workshops:**

Applications of High Intensity Proton Accelerators: **October 19-21st, 2009**

4th Project-X Physics Workshop: **November 9-10th, 2009**

- Ongoing R&D and Projects toward the Research Program:

- **Project-X accelerator R&D.**
  (Presentation today by Steve Holmes)
- **The muon to electron conversion experiment (Mu2e)**
  (Presentation today by Doug Glenzinski)
- **The Long Baseline Neutrino Experiment (LBNE)**
  (Presentation today by Jim Strait)
- **The Muon Accelerator Program (MAP)**
  (Presentation today by Steve Geer)

The Project-X Research Program

- ***Long baseline neutrino oscillation experiments:***

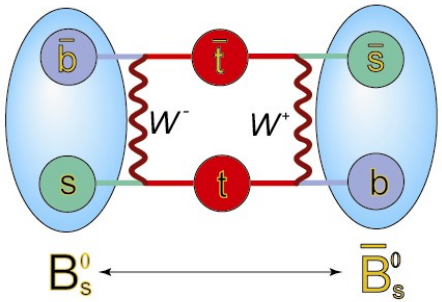
  Driven by a high-power proton source with proton energies between 50 and 120 GeV that would produce intense neutrino beams directed toward massive detectors at a distant deep underground laboratory.

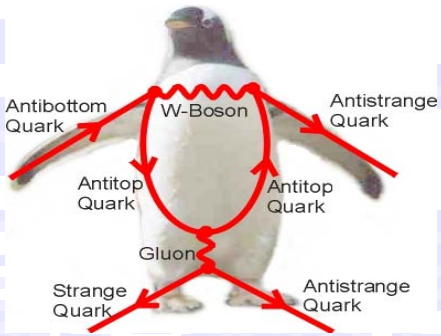
- ***Kaon, muon, nuclei & neutron precision experiments driven by high intensity proton beams running simultaneously with the neutrino program:***

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

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??

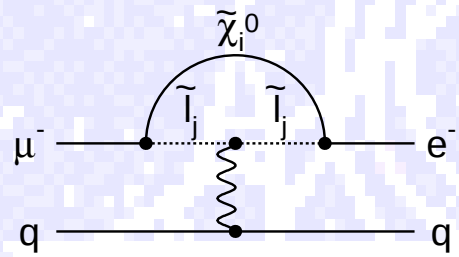


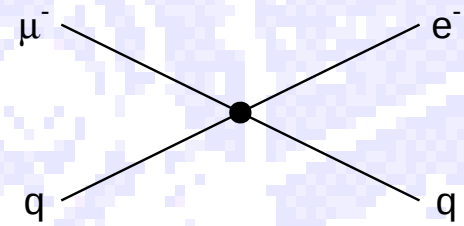


Rare muon decays in Project-X: $\mu^- N \rightarrow e^- N$ Sensitivity to New Physics

Supersymmetry

Predictions at 10^{-15}



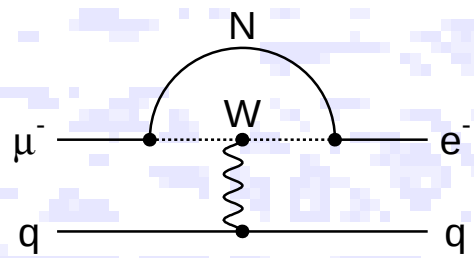


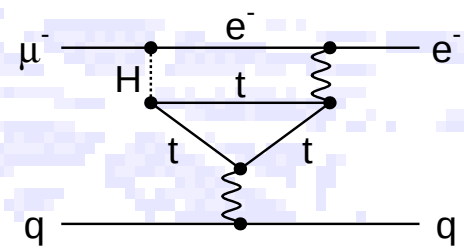
Compositeness

$\Lambda_C = 3000$ TeV

Heavy Neutrinos

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



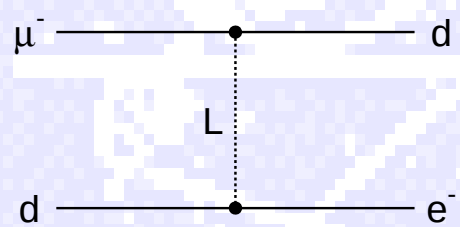


Second Higgs doublet

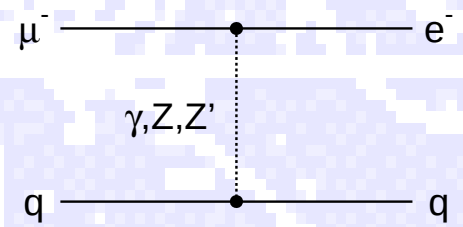
$g_{H_{\mu e}} = 10^{-4} \times g_{H_{\mu\mu}}$

Leptoquarks

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



After W. Marciano

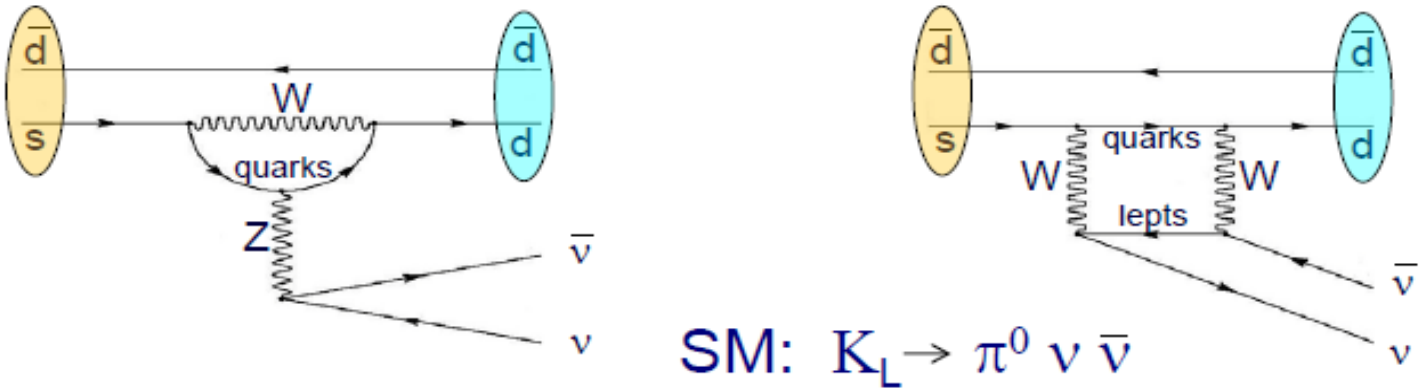


Heavy Z', Anomalous Z coupling

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

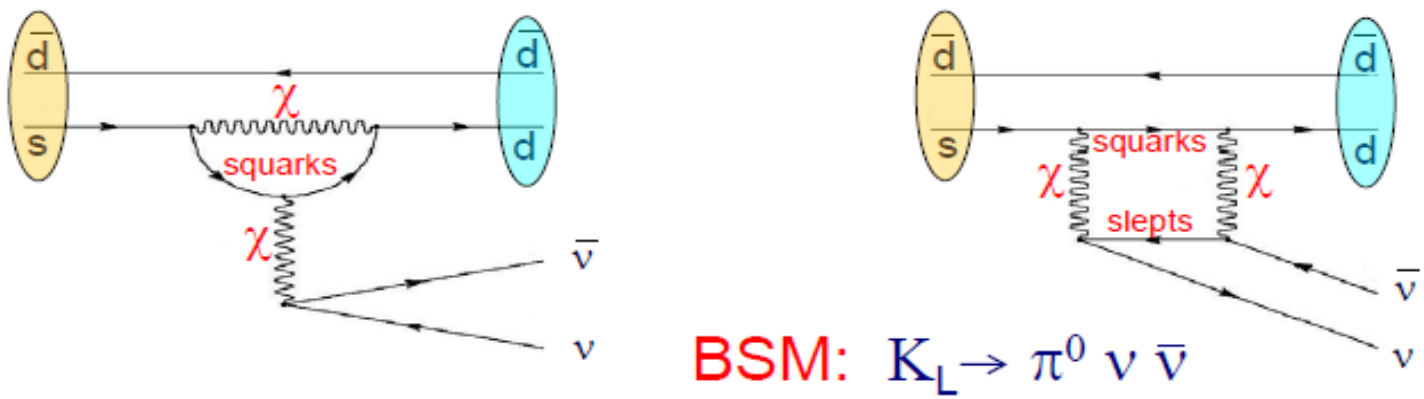
$B(Z \rightarrow \mu e) < 10^{-17}$

The Window of Ultra-rare Kaon Decays in Project X



SM: $K_L \to \pi^0 \nu \bar{\nu}$

Standard Model rate of 3 parts per 100 billion!

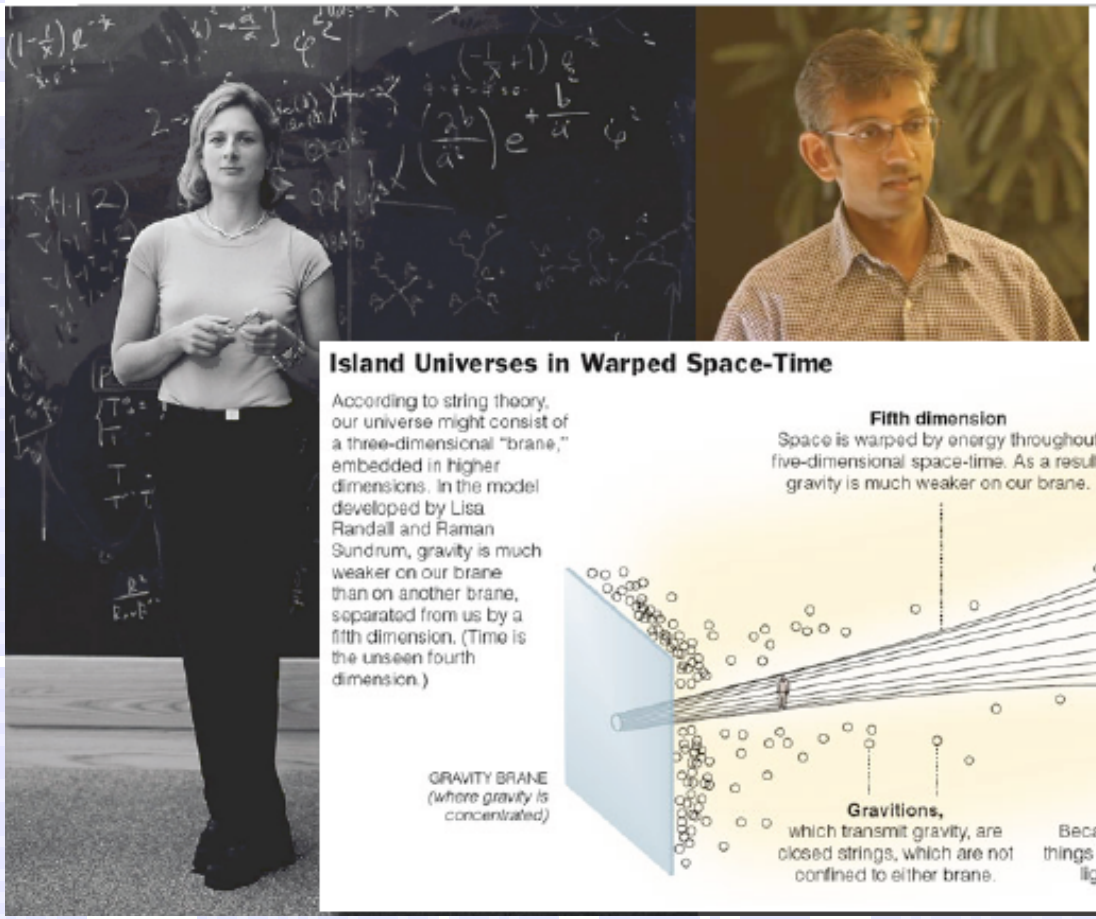


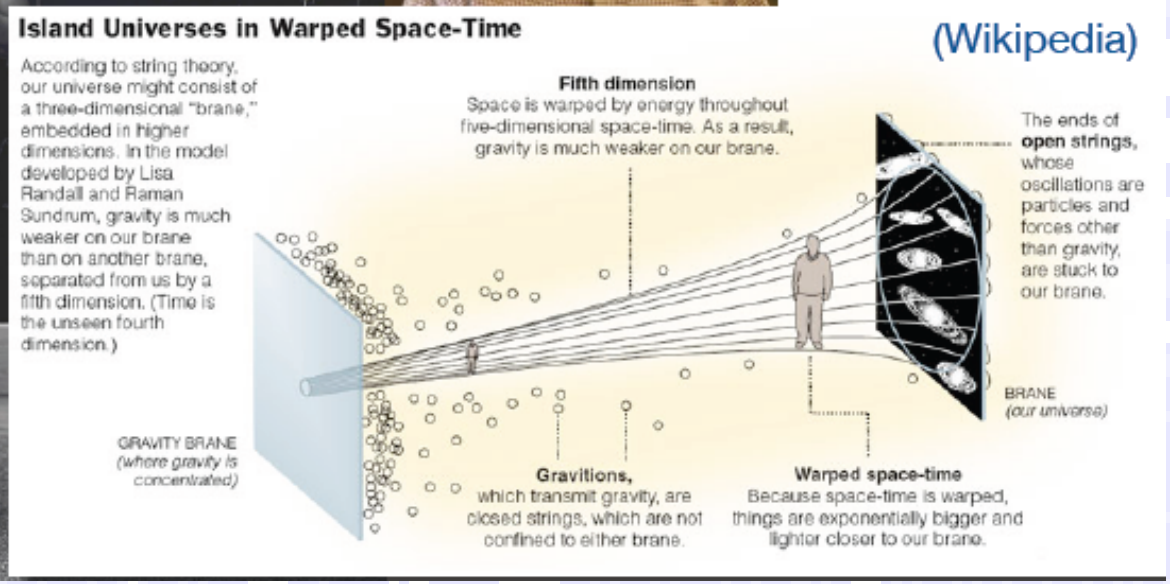
BSM: $K_L \to \pi^0 \nu \bar{\nu}$

BSM particles within loops can increase the rate by x10 with respect to SM.

Rates sensitive to other BSMs: Warped Extra Dimensions as a Theory of Flavor??

The Randall-Sundrum (RS) idea

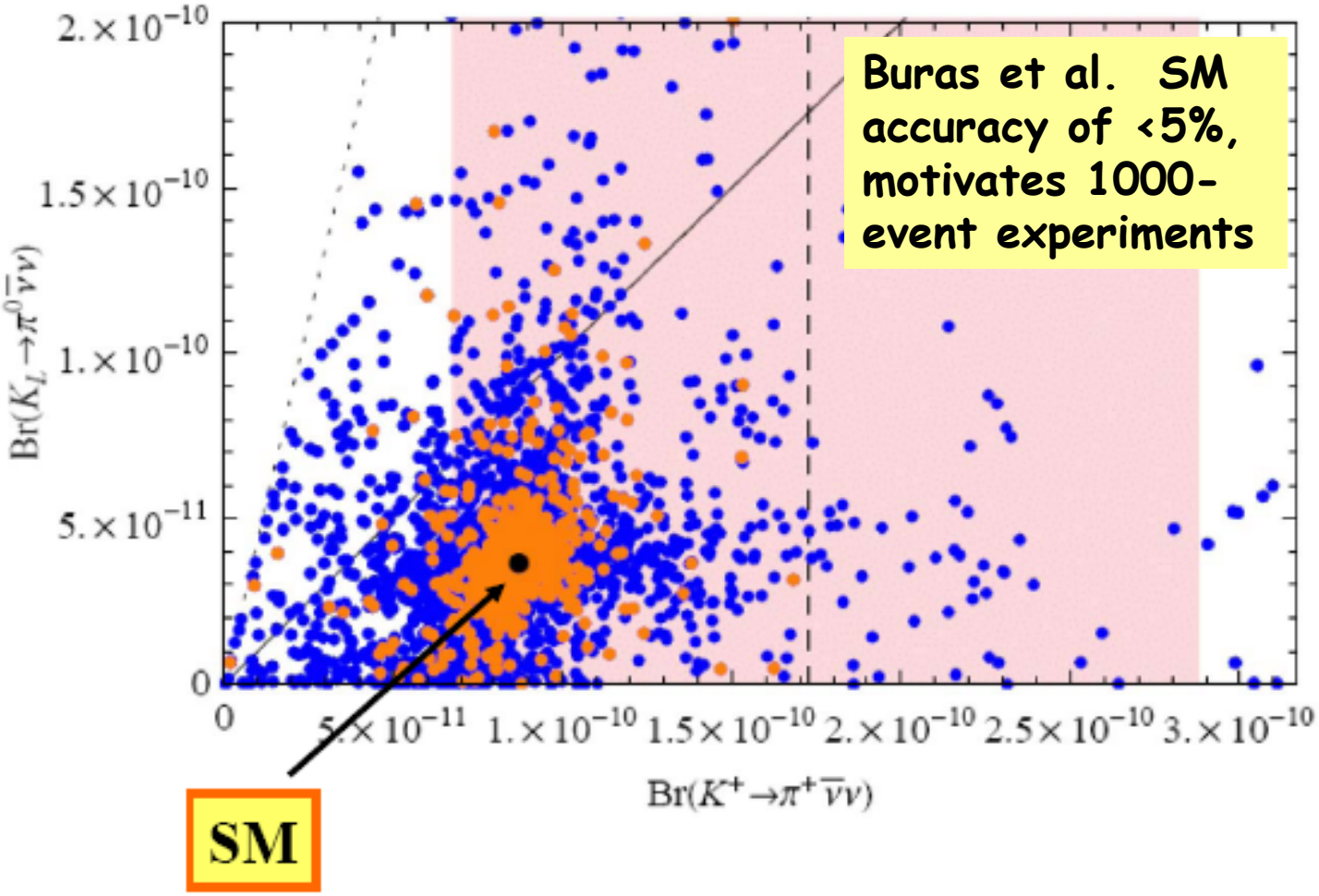




(Wikipedia)

$$K_L \to \pi^0 \nu\bar{\nu} \text{ vs. } K^+ \to \pi^+ \nu\bar{\nu}$$ (RS)

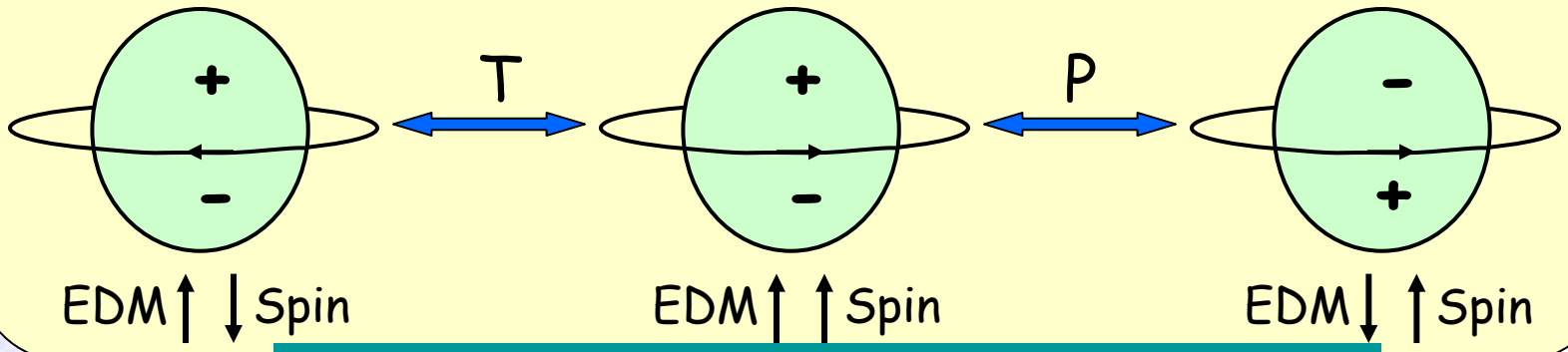
(Up to Factor 3 and 2 Enhancements)



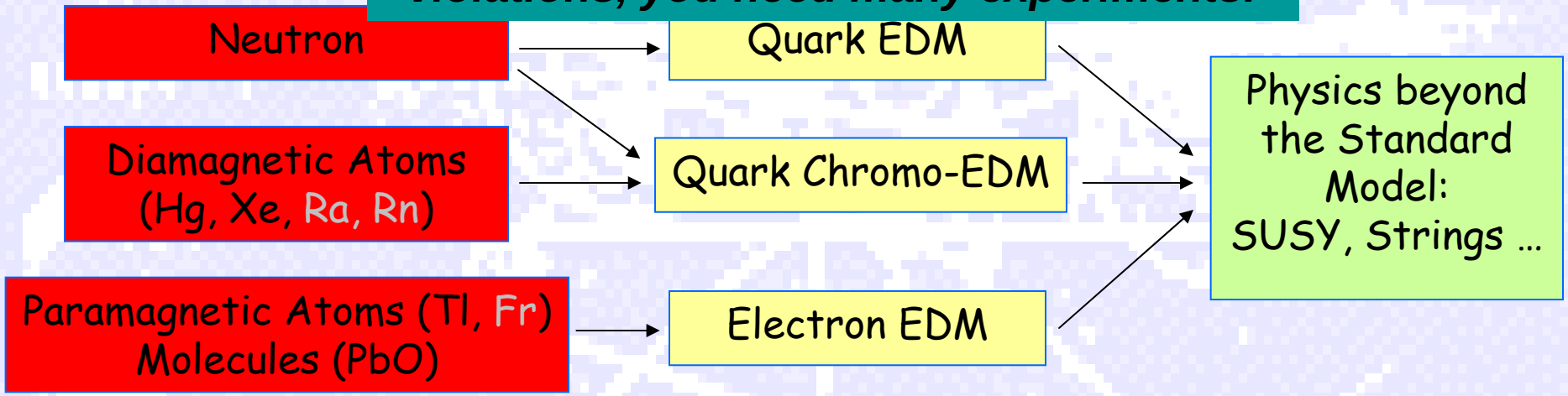
Effect of Warped Extra Dimension Models on Branching Fractions

Search for an electric dipole moment and physics beyond the standard model

A permanent EDM violates both time-reversal symmetry and parity



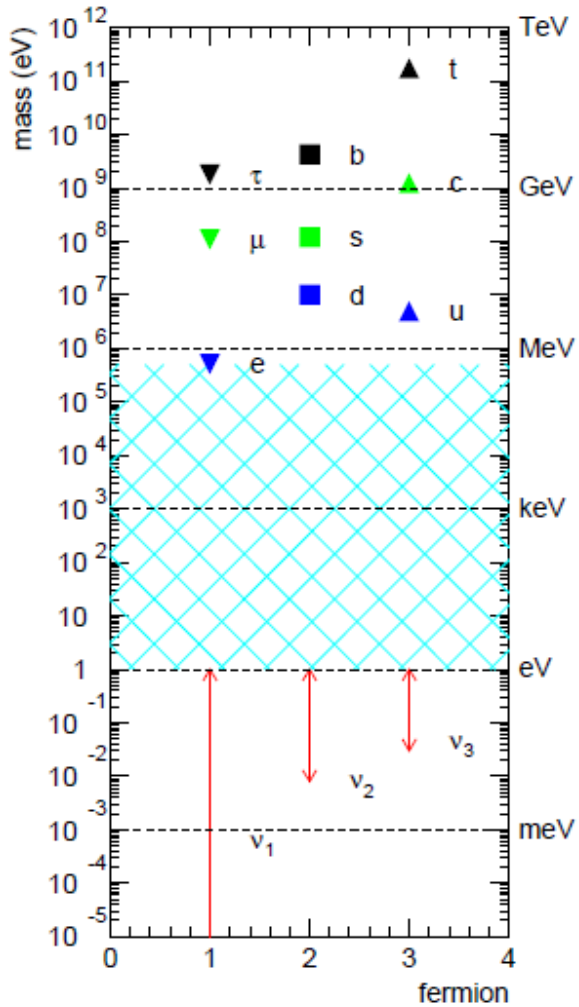
To understand the origin of the symmetry violations, you need many experiments!



Guy Savard, ANL

What are Neutrinos Telling Us?

André de Gouvêa — Northwestern



What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

⇓ LEPTON MIXING IS "WEIRD" ⇓

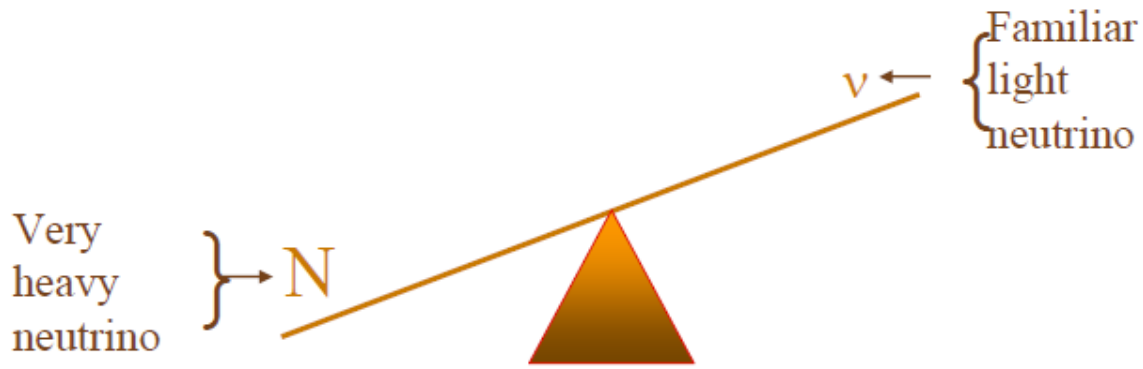
$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

Andre de Gouvea

Leveraging to the Unification Scale

See-Saw Mechanism



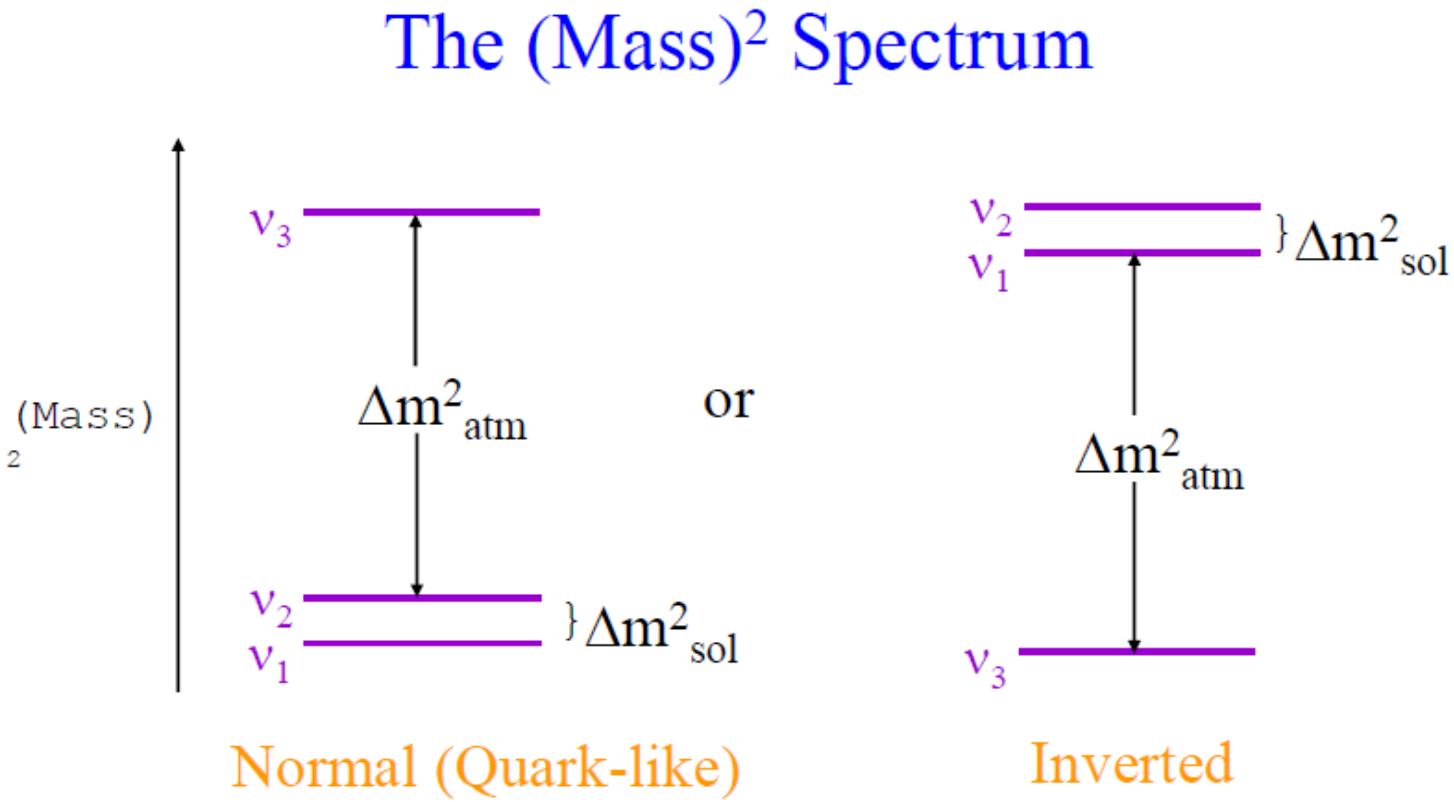
Mass(N) ~ 10^{15} GeV

The strong, EM, and weak forces unify at ~ 10^{16} GeV

Unification? Leptogenisis?

Boris Kayser

What is Normal?

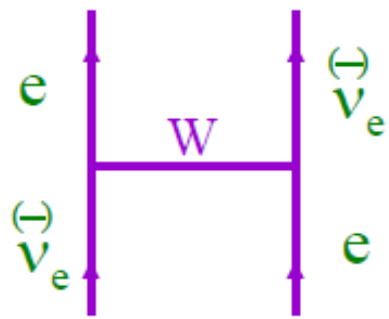


$\Delta m^2_{sol} \cong 7.6 \times 10^{-5}\ eV^2$, $\Delta m^2_{atm} \cong 2.4 \times 10^{-3}\ eV^2$

Boris Kayser

How To Determine If The Spectrum Is Normal Or Inverted

Exploit the fact that, in matter,

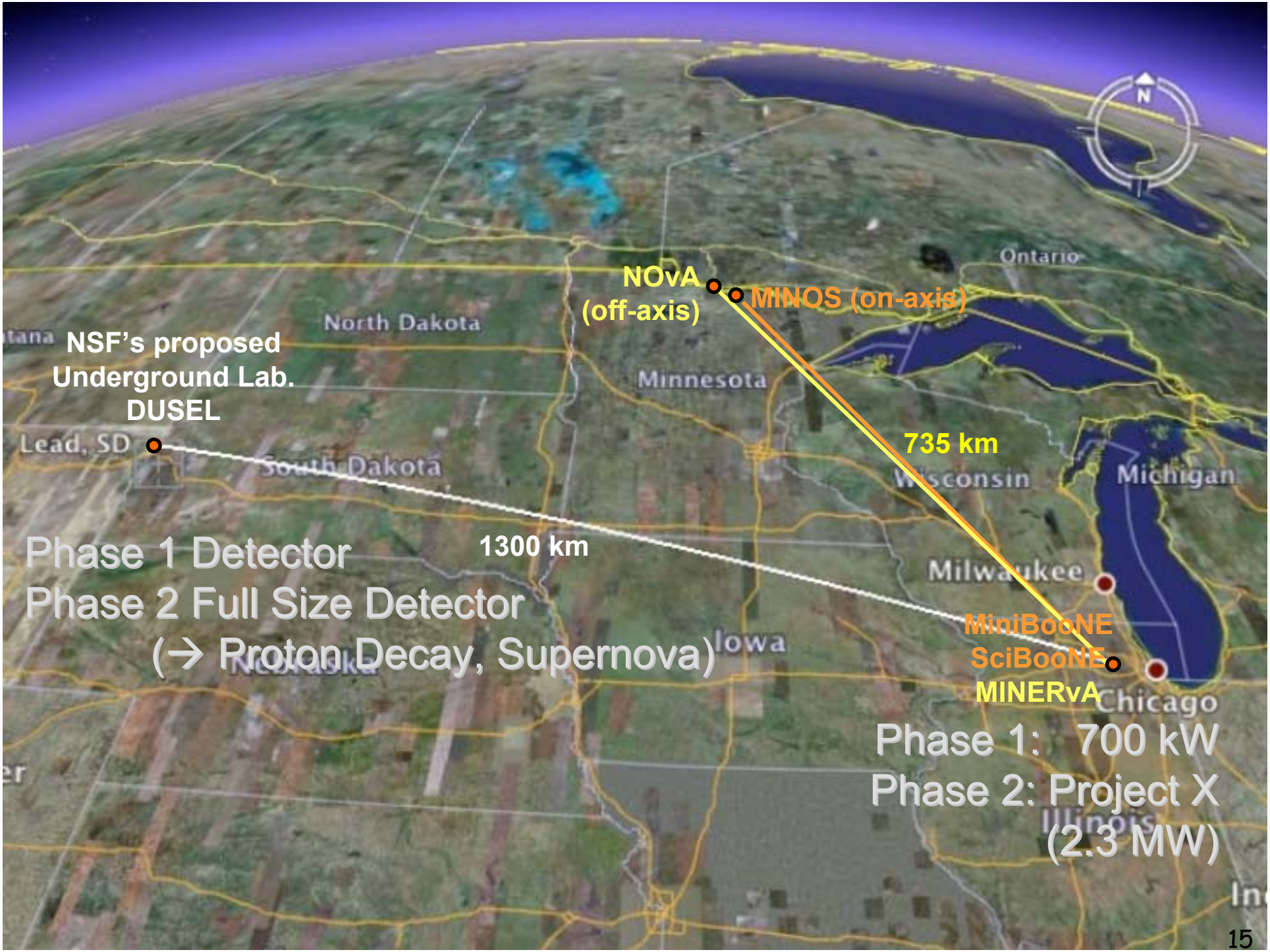


raises the effective mass of ν_e , and lowers that of $\bar{\nu}_e$.

This leads to —

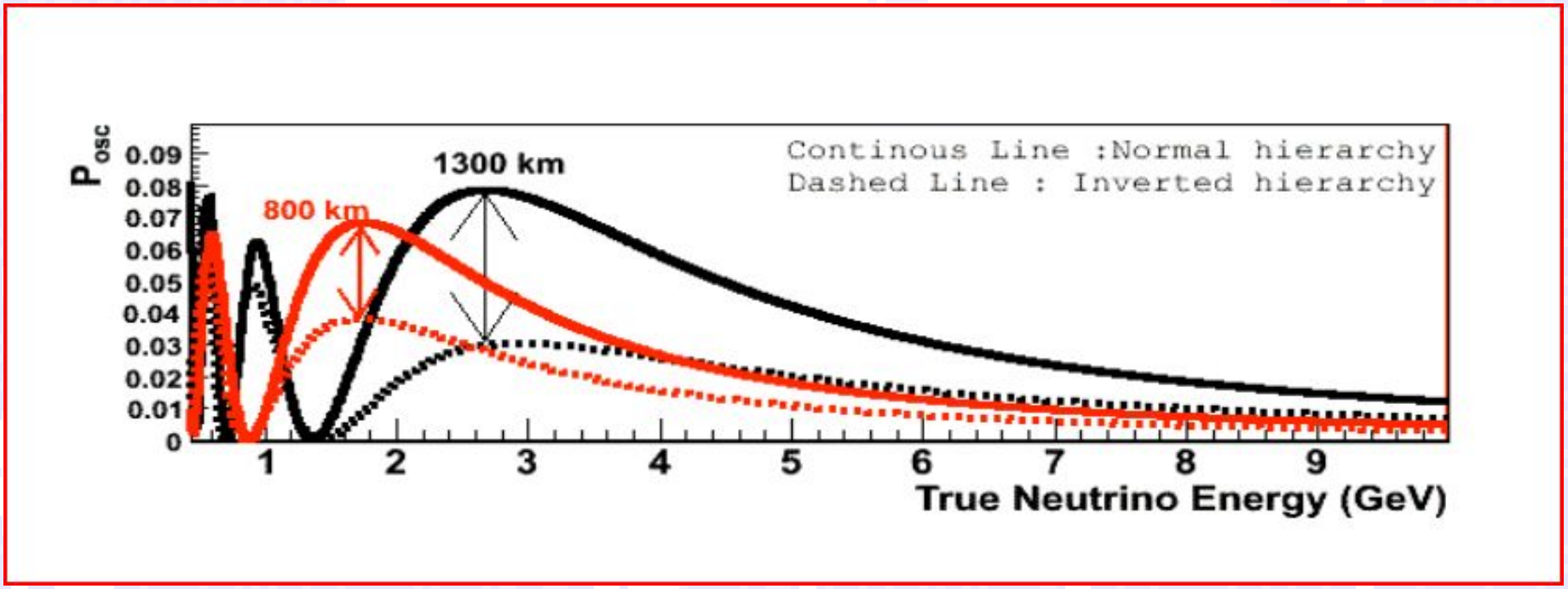
$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \begin{cases} > 1 \; ; \\ < 1 \; ; \end{cases}$$

Boris Kayser


NOvA
(off-axis)
MINOS (on-axis)
NSF's proposed
Underground Lab.
DUSEL
Lead, SD
735 km
1300 km
MiniBooNE
SciBooNE
MINERvA
Phase 1 Detector
Phase 2 Full Size Detector
(→ Proton Decay, Supernova)
Phase 1: 700 kW
Phase 2: Project X
(2.3 MW)
North Dakota
Minnesota
South Dakota
Ontario
Wisconsin
Michigan
Milwaukee
Chicago
Iowa
Nebraska
Illinois

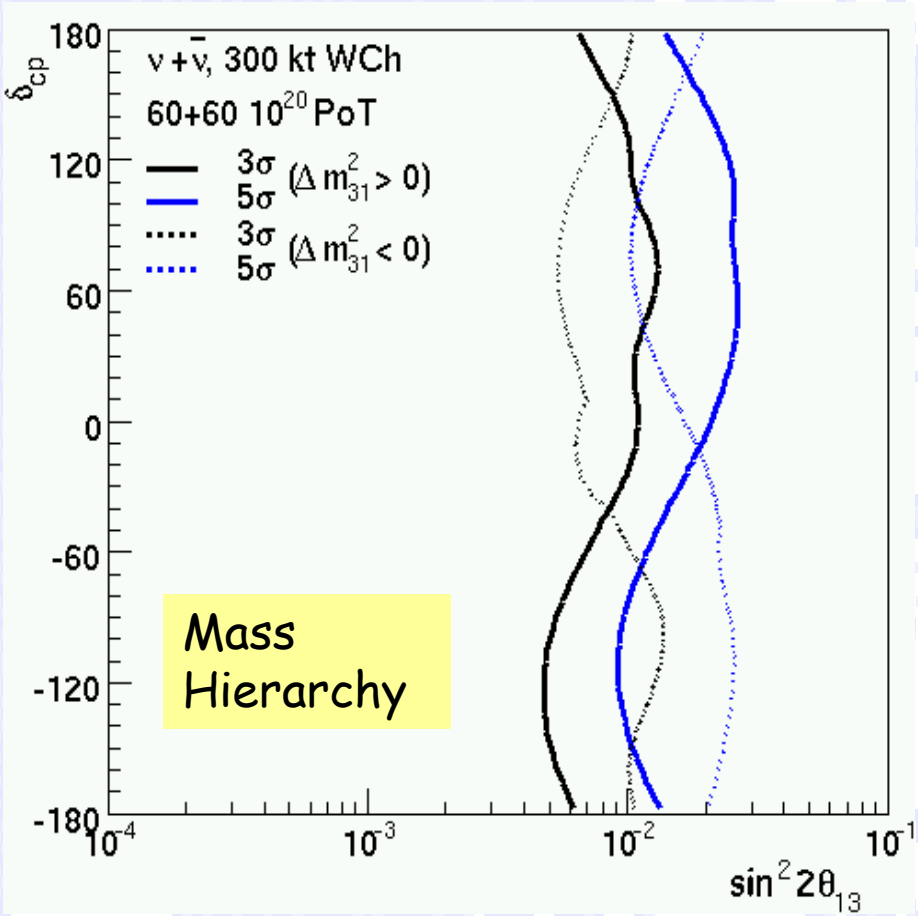
Why DUSEL?

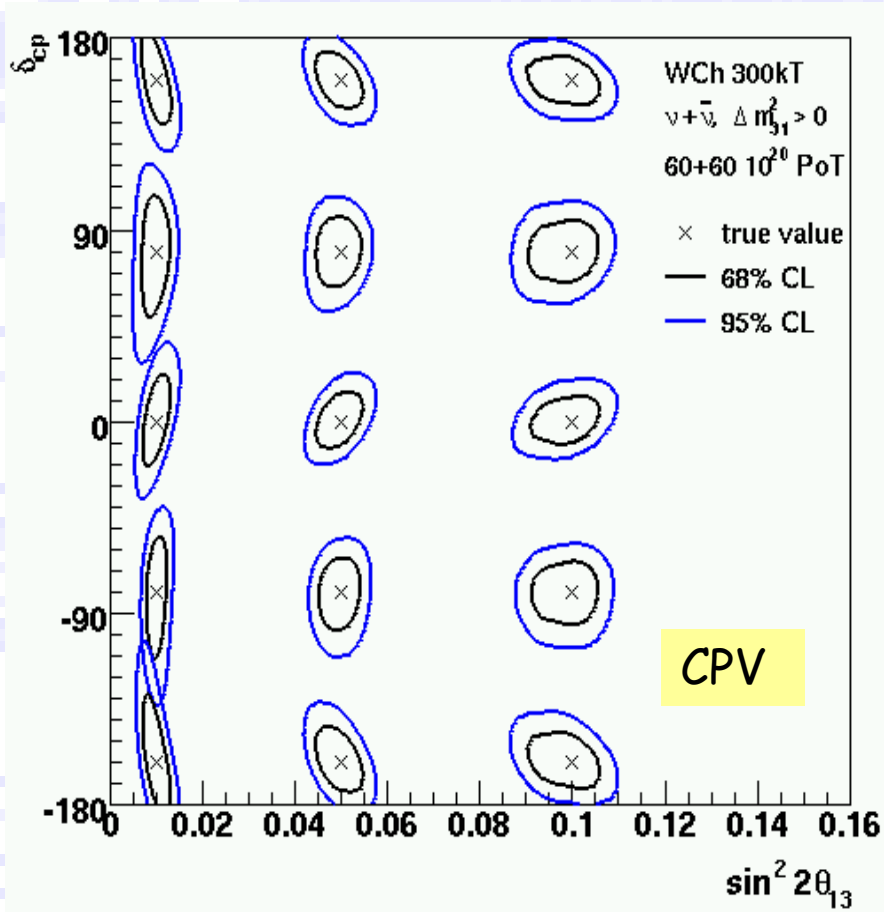
- 1300 km distance is a good compromise of mass-hierarchy and CP violation sensitivities
- Deep underground site allows rich physics program in addition to LB neutrinos



Bob Svoboda, 4th PXP Workshop

DUSEL LBNE Sensitivities

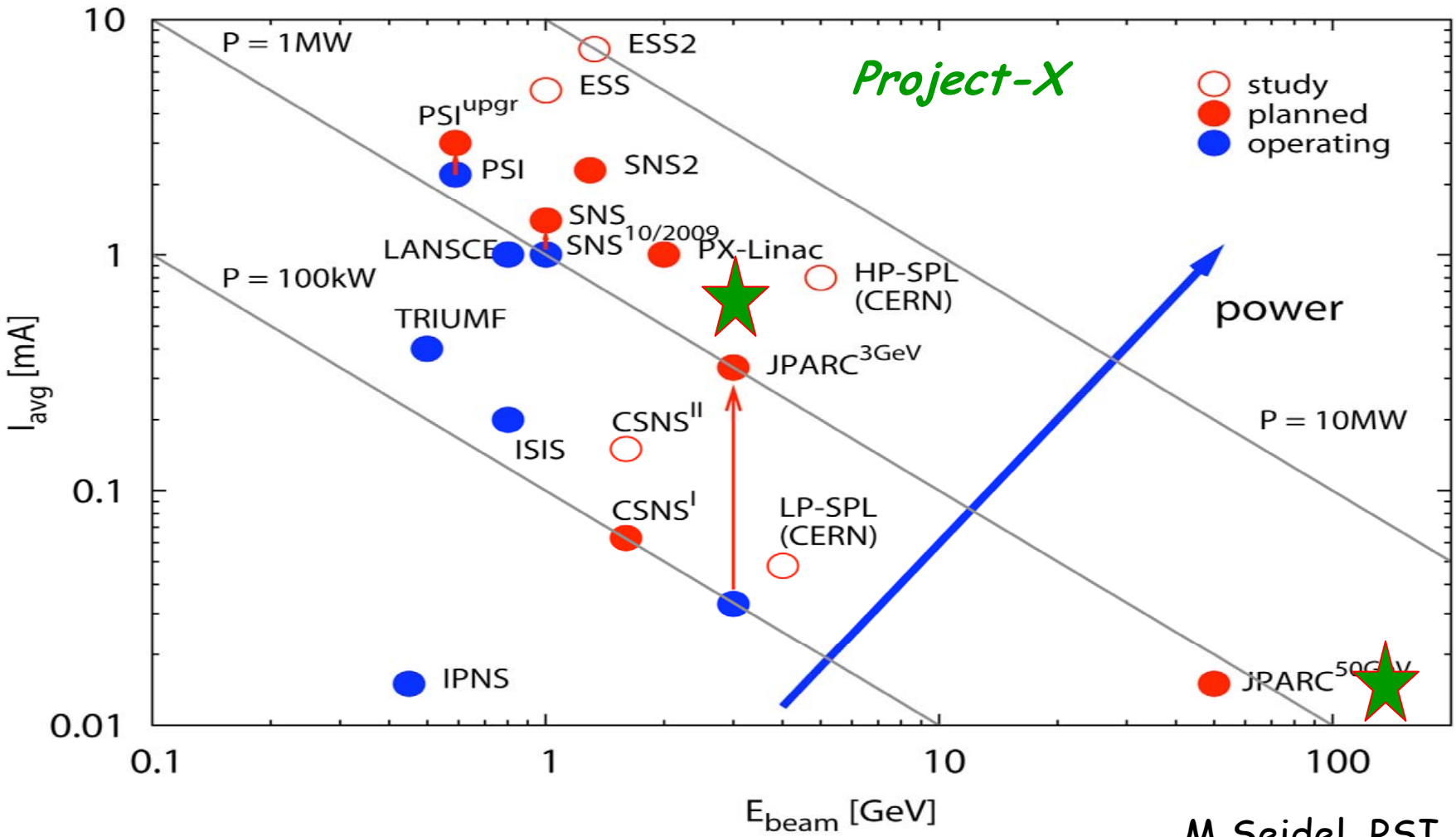




Sensitivities for (300 kT H_2O)x(2 MW)x(3+3 ν/ν̄ years)

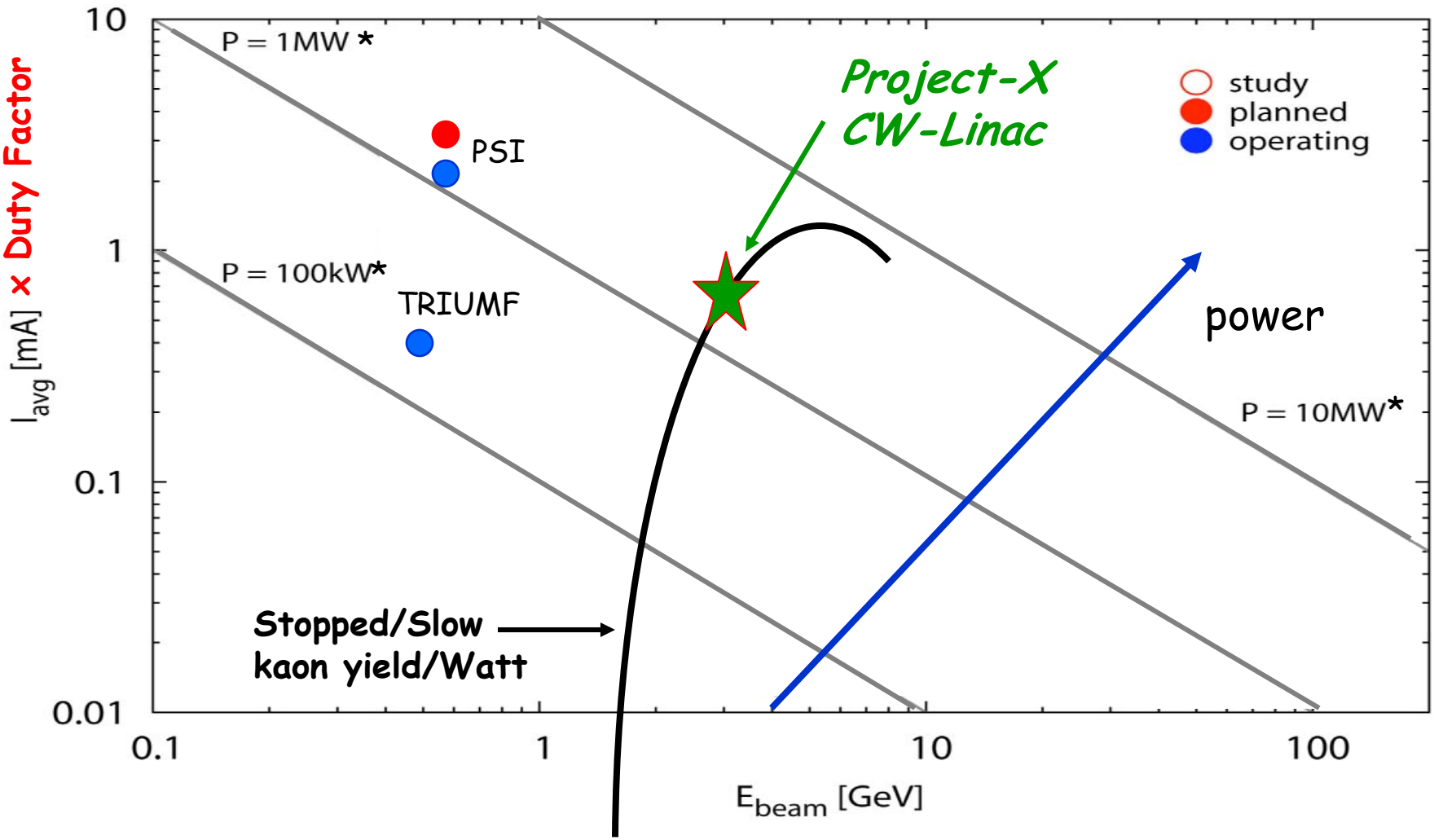
Bob Svoboda, 4th PXP Workshop

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



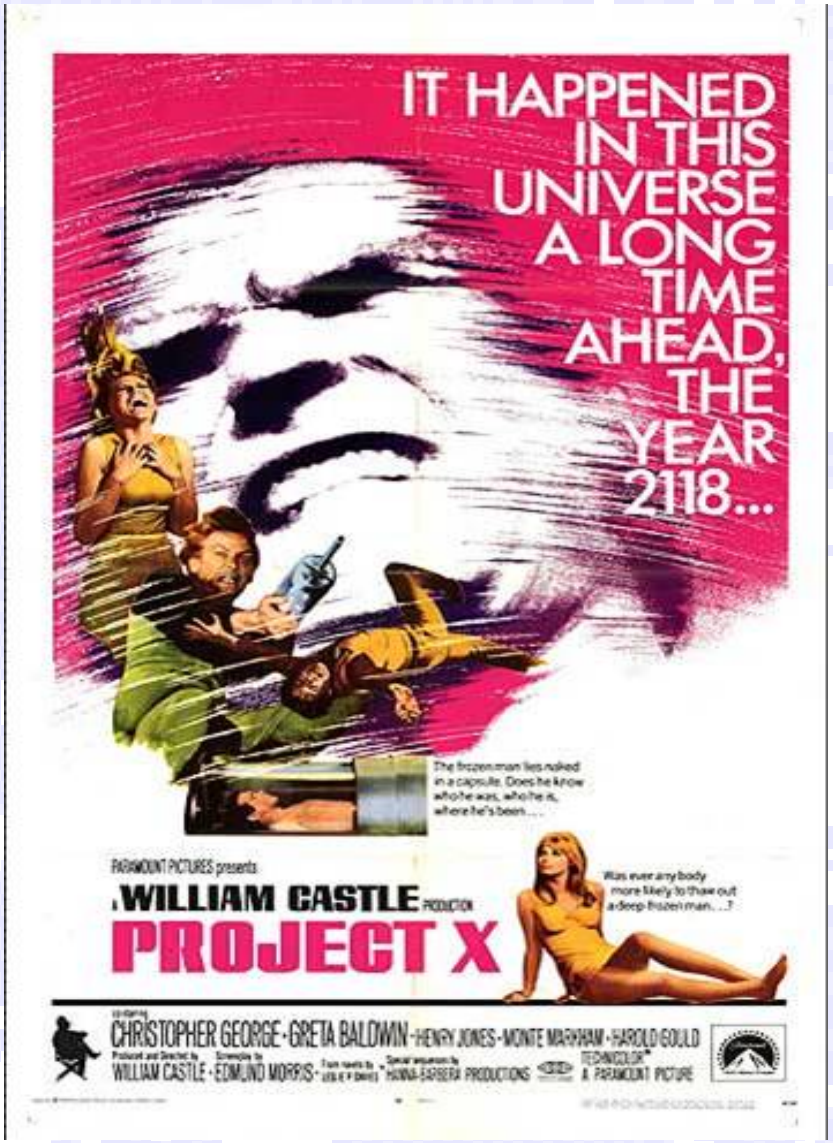
M Seidel, PSI

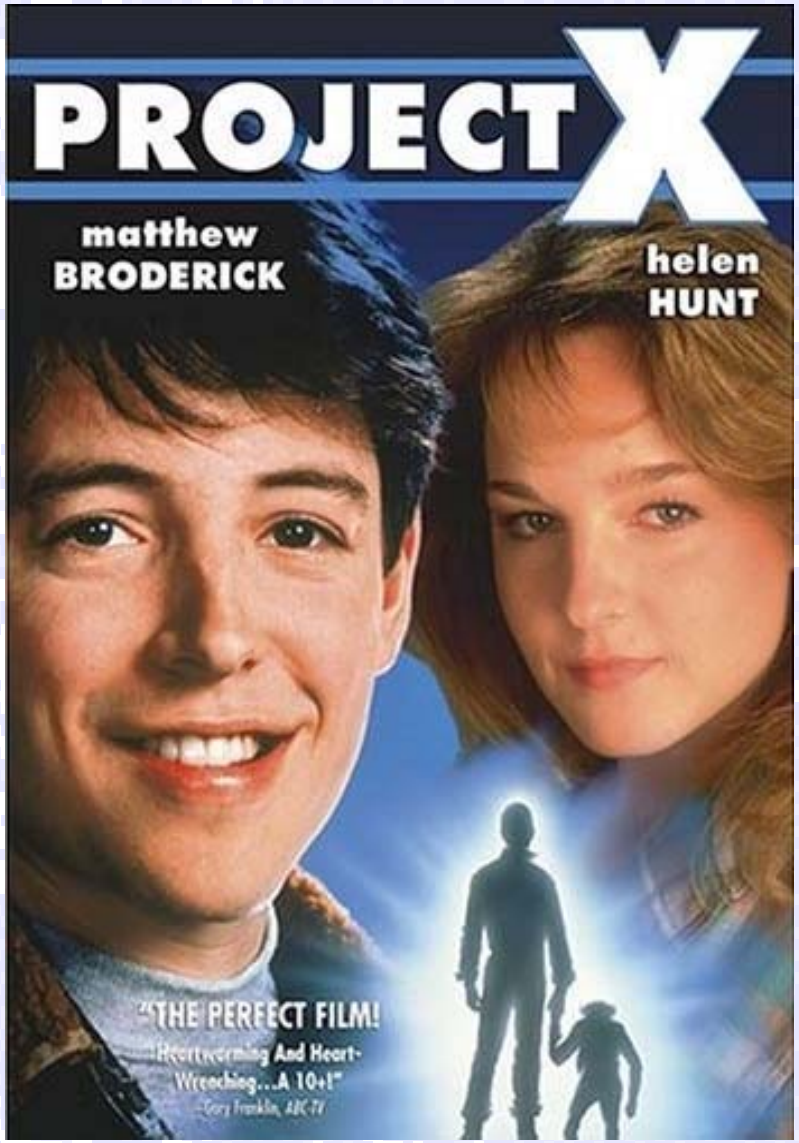
The High Duty Factor Proton Source Landscape This Decade...



* Beam power x Duty Factor

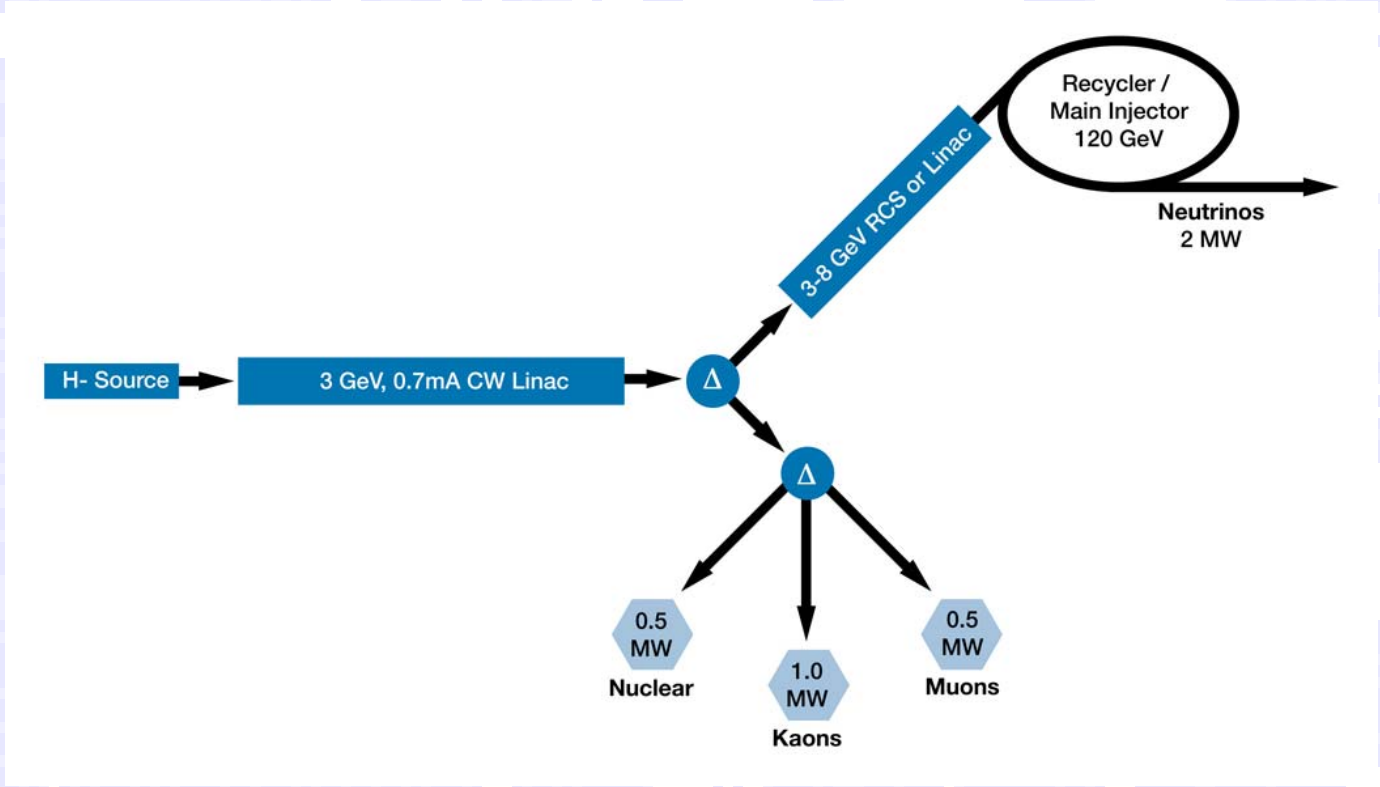
Project-X, What it's not…





What it is…

- Project X Design Criteria
  - ✓ 2 MW of beam power over the range 60 – 120 GeV;
  - ✓ Simultaneous with 2 MW beam power at 3 GeV;
  - ✓ Compatibility with future upgrades to 2-4 MW at 8 GeV



Steve Holmes, APS Meeting Feb 2010.

"CW" Linac for Rare Processes…

- Beam extraction challenge is finessed.
- Duty factor is very high.
- The high frequency bandwidth intrinsic to a Linac can be exploited to generate excellent time resolution (*small* δt) crucial to survival in a high intensity environment.
- JLAB has demonstrated that beam can be cleanly multiplexed between many targets with minimal losses. These "touchless" RF beam multiplexers are enabled by the high linac bandwidth.
- The intrinsic properties of this SCRF CW Linac enables the physics rather than fighting with it. Excellent beam power scaling.

Beam Requirements for a World Leading Rare Processes Program

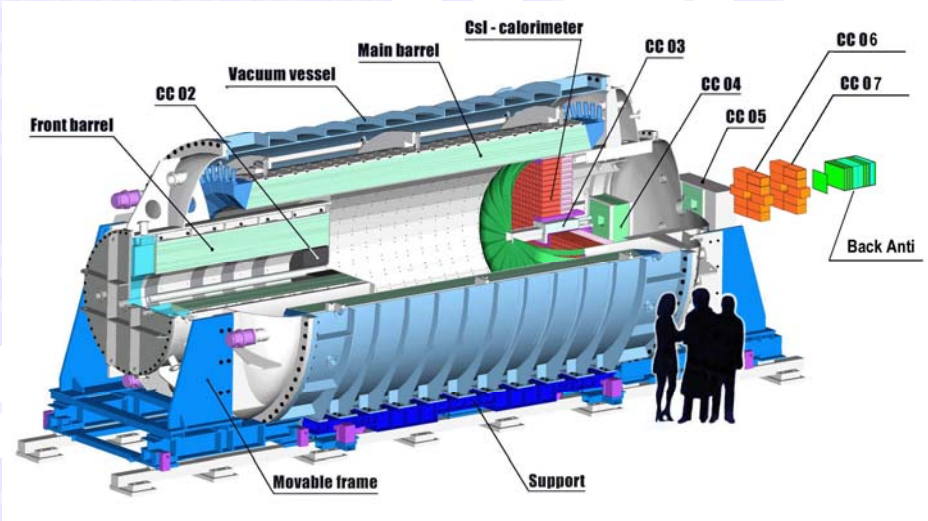
	Proton Energy (kinetic)	Beam Power	Beam Timing
Rare Muon decays	2-3 GeV	>500 kW	1 kHz – 160 MHz
(g-2) measurement	8 GeV	20-50 kW	30- 100 Hz.
Rare Kaon decays	2.6 – 4 GeV	>500 kW	20 – 160 MHz. (<50 psec pings)
Precision K^0 studies	2.6 – 3 GeV	> 200kW (100μA internal target)	20 – 160 MHz. (<50 psec pings)
Neutron and exotic nuclei EDMs	1.5-2.5 GeV	>500 kW	> 100 Hz

$K_L \to \pi^0 \nu\nu$ Experimental Challenge: "Nothing-in nothing out"

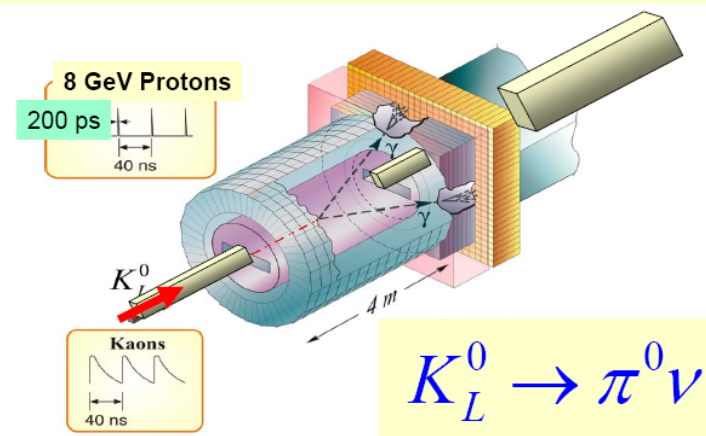
•KEK/JPARC approach emphasizes high acceptance for the two decay photons while vetoing everything else:

A hermetic "bottle" approach.

•The original KOPIO concept measures the kaon momentum and photon direction…Good! But costs detector acceptance and requires a large beam to compensate. Project-X Flux can get back to small kaon beam!



Another $K_L^0 \to \pi^0 \nu\bar{\nu}$ Experiment Concept



- Use TOF to work in the K_L^0 c.m. system
- Identify main 2-body background $K_L^0 \to \pi^0\pi^0$
- Reconstruct $\pi^0 \to \gamma\gamma$ decays with pointing calorimeter
- 4π solid angle photon and charged particle vetos

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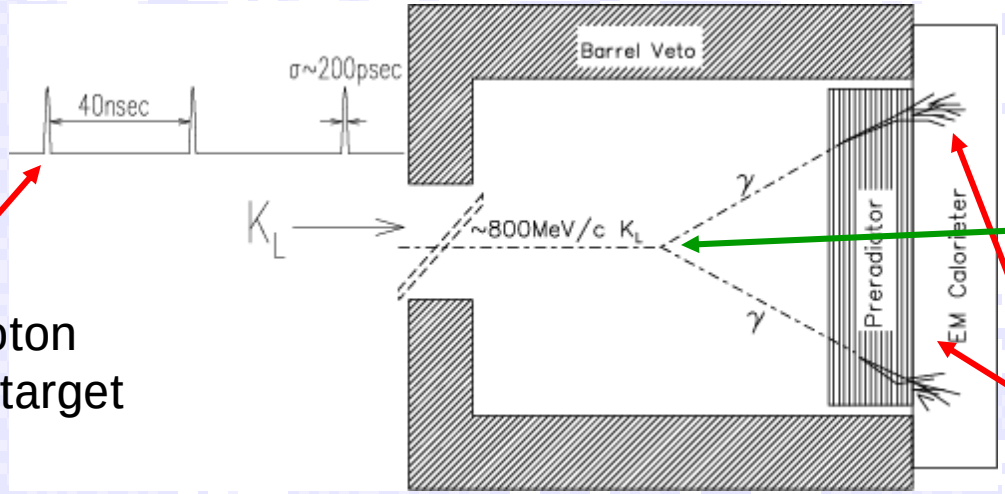
KOPIO inspired: Micro-bunch the beam, TOF determines K_L momentum.

Fully reconstruct the neutral Kaon in $K_L \rightarrow \pi^0 \nu \bar{\nu}$ measuring the Kaon momentum by time-of-flight.



Start when proton beam hits the target

End at the decay time and decay point reconstructed from the two photons.

Timing uncertainty due to microbunch width should not dominate the measurement of the kaon momentum; requires RMS width < 200ps. CW linac pulse timing of less than 50ps is intrinsic.

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

Neutrino Physics:

- Mass Hierarchy
- CP violation
- Precision measurement of the θ_{23} (atmospheric mixing). Maximal??
- Anomalous interactions, e.g. $\nu_\mu \rightarrow \nu_\tau$ probed with target emulsions (Madrid Neutrino NSI Workshop, Dec 2009)
- Next generation precision cross section measurements

An Incomplete Menu of World Class Research Targets Enabled by Project-X. continued…

Muon Physics:

- 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…
- μ 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. continued…

Kaon Physics:

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

…and more

An Incomplete Menu of World Class Research Targets Enabled by Project-X. continued…

Baryons:

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

Nuclei:

- Production of Ra, Rd, Fr isotopes for nuclear edm experiments that are uniquely sensitive to Quark-Chromo and electron EDM's.

Summary

Project-X is a research platform that can deliver:

Neutrinos: An after-burner for LBNE that reduces the tyranny of (Detector-Mass **x** Running-time) by **x3**, and a foundation for a Neutrino Factory.

Rare Processes: Game-changing beam power and timing flexibility that can support a broad range of HEP experiments.

Muon Collider: A foundation from which to build toward the Muon Collider.