# The Project X Physics Study

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June 22nd 2012

U.S. DEPARTMENT OF ENERGY

Fermilab

# Experimental and Theory Thrusts to Develop (15 conveners)

- Neutrino experiments
- Kaon experiments
- Muon experiments
- Electric dipole moments
- Neutron-antineutron oscillations
- Hadronic physics
- [Hidden Sector]

# Conveners for Experimental Concepts and Sensitivities

**Neutrinos:**

**Andre de Gouvea (Northwestern University), Patrick Huber (Virginia Tech) , Geoff Mills (LANL)**
**Ko Nishikawa (University of Chicago/FNAL), Steve Geer (FNAL)**

**Muon Experiments:**

**Bob Bernstein (Fermilab), Graham Kribs, (University of Oregon)**

**Kaon Experiments:**

**Kevin Pitts (University of Illinois UC), Vincenzo Cirigliano (LANL)**

**EDMs:**

**Tim Chupp (University of Michigan) , Susan Gardner (University of Kentucky), Zheng-Tian Lu (ANL)**

**n-nbar oscillations:**

**Chris Quigg (FNAL), Albert Young (North Carolina State University)**

**Hadron physics:**

**Stephen Godfrey (Carleton University), Paul Reimer (ANL)**

# Detector & Theory Technology Thrusts to Develop (16 conveners)

- Lattice QCD
- EM calorimetry
- Tracking
- Time of flight
- Neutrino detectors
- Large-area, cost-effective detectors

# Conveners for Enabling Technologies and Techniques

**High rate Precision Photon Calorimetry:**

**David Hitlin (Caltech), Milind Diwan (BNL)**

**Very Low-Mass High-Rate Charged Particle Tracking:**

**Ron Lipton (FNAL), Jack Ritchie (University of Texas, Austin)**

**Time-of-Flight System Performance below 10 psec:**

**Mike Albrow (FNAL), Bob Wagner (ANL)**

**High Precision Measurement of Neutrino Interactions:**

**Kevin McFarland (Rochester University), Jonghee Yoo (FNAL), Rex Tayloe (University of Indiana)**

**Large Area Cost Effective (LACE) Detector Technologies:**

**Mayly Sanchez (Iowa State University), Yury Kamyshkov (University of Tennessee)**

**Lattice QCD:**

**Ruth Van de Water (BNL), Tom Blum (University of Connecticut)**

# PXPS Overview*

- The Physics Study will engage theorists, experimenters, and accelerator scientists in establishing and documenting a comprehensive vision of the physics opportunities at Project X, and integrating these opportunities within a coherent plan for development of detector capabilities and the accelerator complex.

*(https://indico.fnal.gov/conferenceDisplay.py?confId=5276)

# 2012 PXPS Deliverables

- Brainstorming, work!
- Succinct summary (<5pages) of physics opportunities for each stage.
- Outline and roadmap of work required for Project X to reach science goals for each stage in the following thrusts:
  - **-Experiment concept development**
  - **-Detector R&D**
  - **-Theory development**

# PXPS Meeting Scope

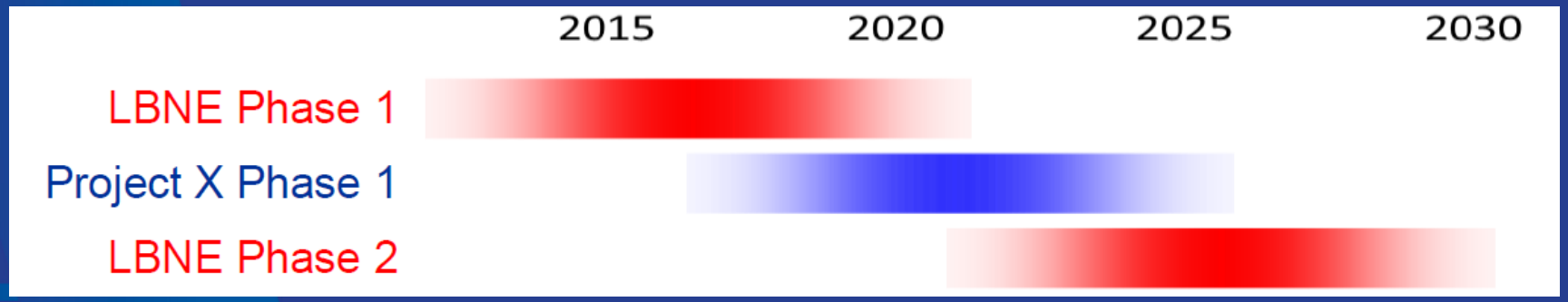
- 220 registrants
- 215 presentations
- 2 days of plenary, 4 days of parallel, 2 days of summary.
- Both vigorous and stimulating discussions.

  (heat & light)
- Mean residency of registrants was 2-3 days, ~500 researcher-days on the Project-X research program. Instantaneous population of 75-100.

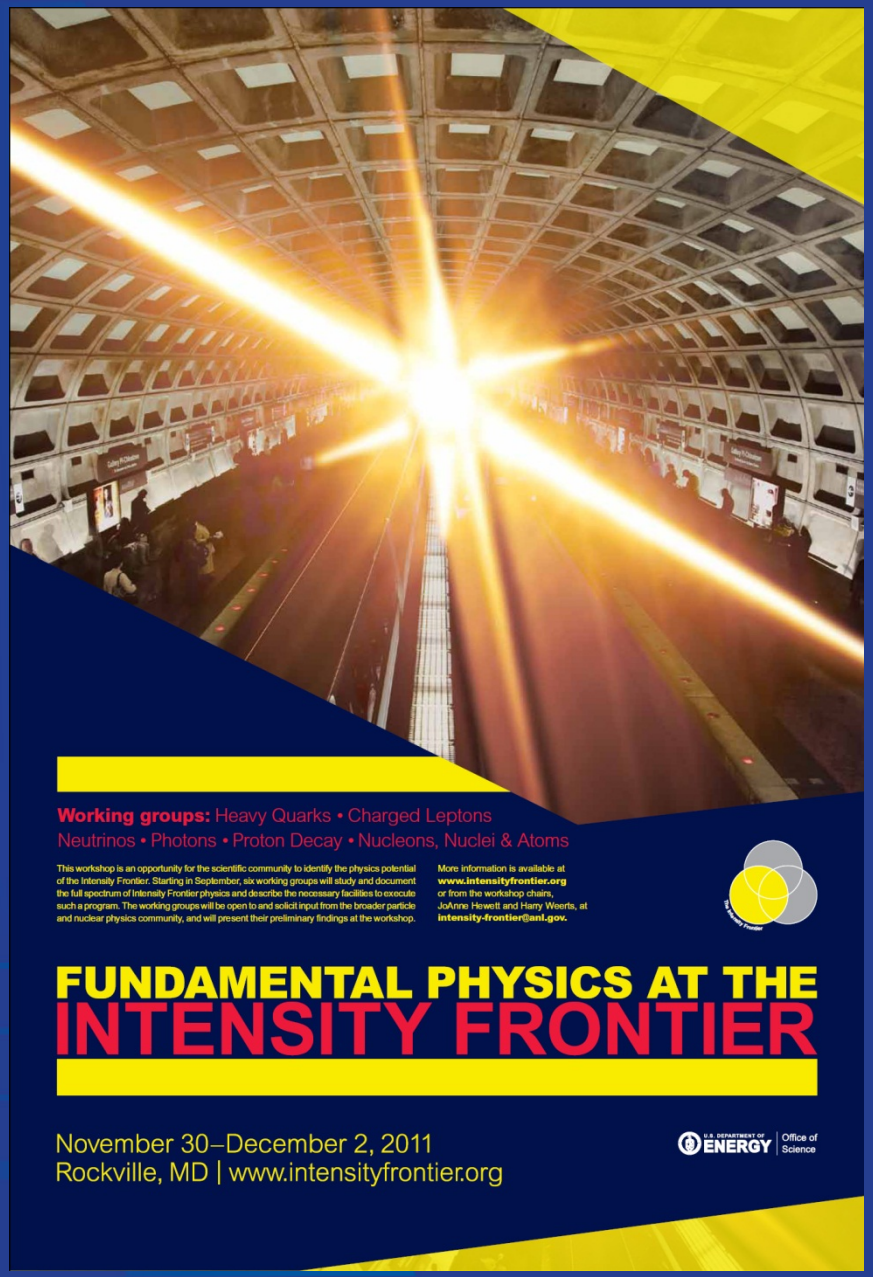
# Why Now?

- We have learned things recently:
  e.g., $\theta_{13}$, explicit limits on the BSM scale.

- Strategic decisions are upon us:
  LBNE, LHC futures, LC futures….'NoMass




***How does the Fermilab program this decade evolve into the future??***




(http://www.intensityfrontier.org/)

- 500+ Attendees
- Six very active working groups:
- Charged leptons
- Heavy Quarks
- Hidden Sector
- Neutrinos
- Nucleons/Nuclei/Atoms
- Proton Decay
- Project X potential discussed in each group

# The Project X Physics Study Follows this Success…

**June 2012 Physics Study:**
**June 14th-22nd**

**Summer 2012 through Spring 2013:**

Continue to evolve existing white papers into a comprehensive staged program with compelling physics at each stage.

**October 11th-13th 2012:**

US particle physics town meeting at Fermilab preparing for “Snowmass”, summer 2013.

**“Snowmass”, summer 2013:**

**July 29th – August 10th**

Event to develop US strategies.

# Project-X:

- Evolution of the existing Fermilab accelerator complex with the revolution in Super-Conducting RF Technology.

# Project-Y: Origins…

- **The Origin of Mass:**

  How do massless chiral fermions become matter particles?
  (buzzword: "Higgs")

- **The Origin of Matter:**

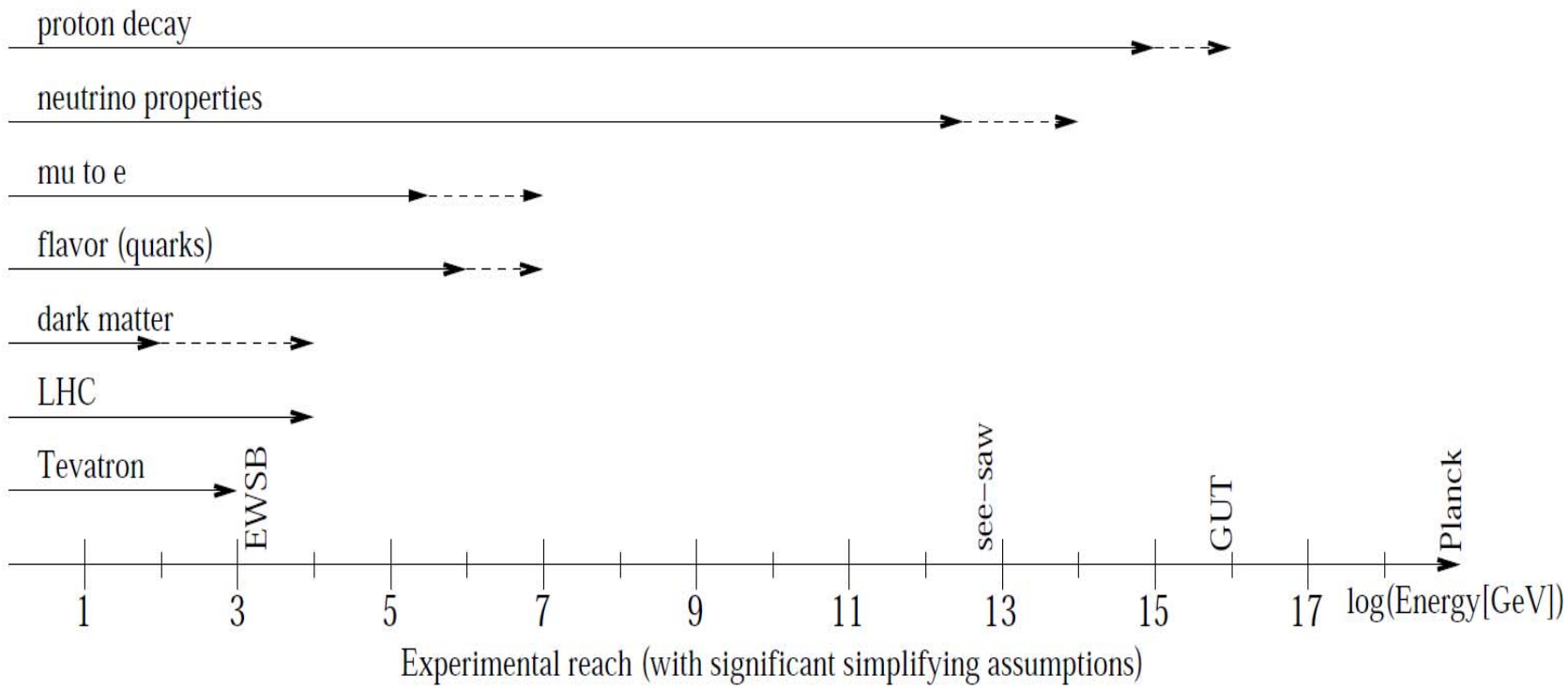
  Why are there so many different kinds of matter particles with different properties?
  (buzzword: "Flavor")

- **The Origin of the Universe:**

  Where did matter come from in the first place and why didn't it all annihilate with antimatter?
  (buzzwords: "Baryogenesis", "Leptogenesis")

-Joe Lykken

# The Zoltan plot




**Yuval Grossman, Plenary PXPS**

# In the absence of new facilities enabling new experiments…

From Hitoshi Murayama , ICFA October 2011

# Project X Killer App? Not a *single* experiment! Beam Power & Flexibility is the Killer App.

Apologies to Jurassic Park and Hitoshi Murayama , ICFA October 2011

# The Project-X Research Program

- ***Neutrino experiments***

A high-power proton source with proton energies between 1 and 120 GeV would produce intense neutrino sources and beams illuminating 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. [**Raja colloquium March '09, Henderson colloquium Feb '12]**

Detailed discussion on Project X website

# There is Plenty of Room at the Bottom…

- Ultra-small cross sections…
  (neutrino physics)
- Ultra-small rates…
  (Rare processes)
- Ultra-small couplings…
  (Hidden Sector)

R. Feynman, 1959

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

## Neutrons

~200

- @ILL
- @ILL,@PNPI
- @PSI
- @FRM-2
- @RCNP,@TRIUMF
- @SNS
- @J-PARC

## Molecules

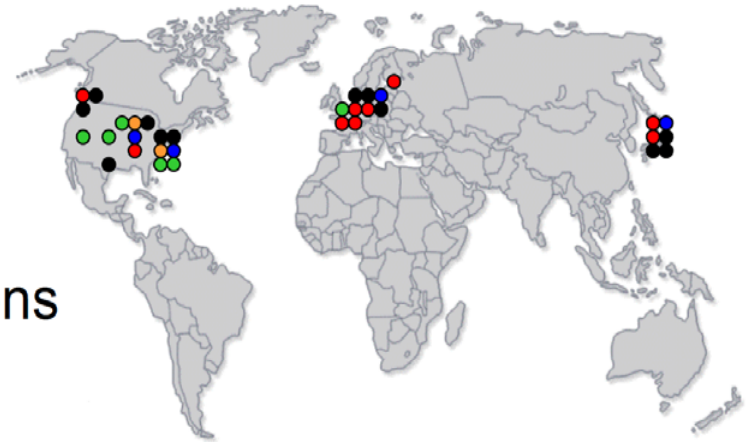
~50

- YbF@Imperial
- PbO@Yale
- ThO@Harvard
- HfF+@JILA
- WC@UMich
- PbF@Oklahoma

## Atoms

~100

- Hg@UWash
- Xe@Princeton
- Xe@TokyoTech
- Xe@TUM
- Xe@Mainz
- Cs@Penn
- Cs@Texas
- Fr@RCNP/CYRIC
- Rn@TRIUMF
- Ra@ANL
- Ra@KVI
- Yb@Kyoto



## Ions-Muons

~200

- @BNL
- @FZJ
- @FNAL
- @JPARC

## Solids

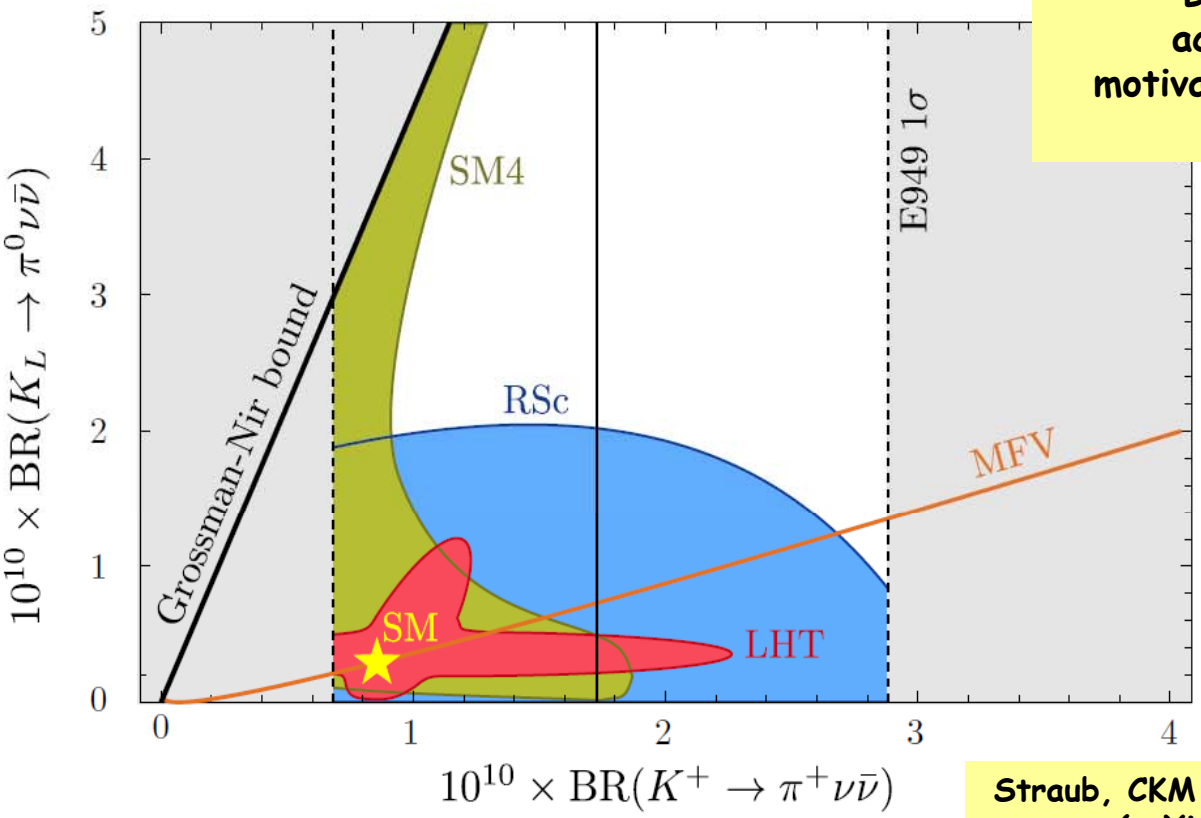
~10

- GGG@Indiana
- ferroelectrics@Yale

**Courtesy Klaus Kirch**
**CIPANP 2012**

# Rare processes sensitive to new physics…
# e.g. Warped Extra Dimensions as a Theory of Flavor??

**Buras et al. SM accuracy of <5%, motivates 1000-event experiments**




**Straub, CKM 2010 workshop (arXiv:1012.3893v2)**

Figure 1: Correlation between the branching ratios of $K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$ in MFV and three concrete NP models. The gray area is ruled out experimentally or model-independently by the GN bound. The SM point is marked by a star.

# Example Research Program, definitive space of accelerator parameters on PXPS Indico site

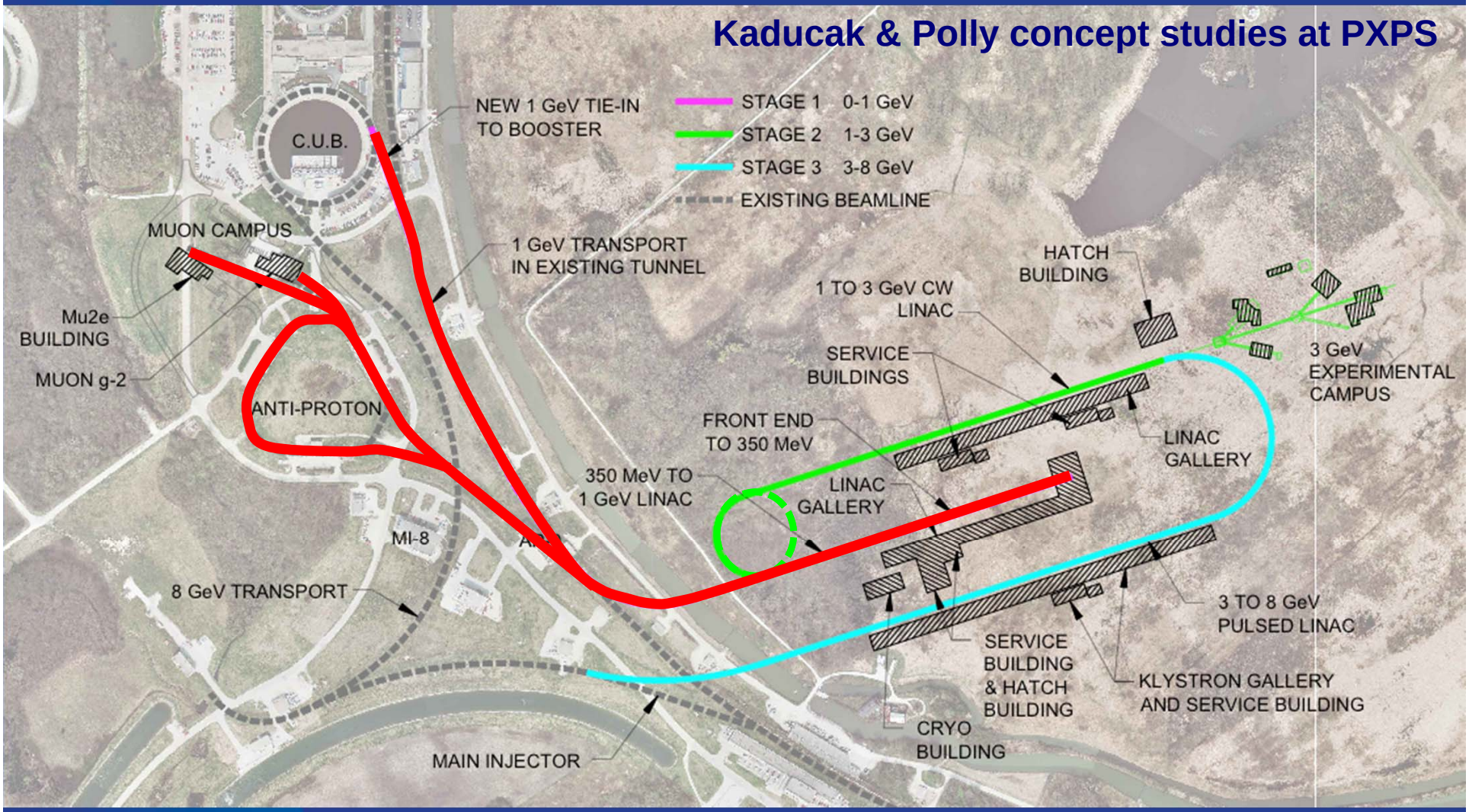
Project X Campaign

| Program: | Onset of NOvA operations in 2013 | Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs | Stage-2: Upgrade to 3 GeV CW Linac | Stage-3: Project X RDR | Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW |
|---|---|---|---|---|---|
| MI neutrinos | 470-700 kW** | 515-1200 kW** | 1200 kW | 2450 kW | 2450-4000 kW |
| 8 GeV Neutrinos | 15 kW +0-50kW** | 0-42 kW* + 0-90 kW** | 0-84 kW* | 0-172 kW* | 3000 kW |
| 8 GeV Muon program e.g, (g-2), Mu2e-1 | 20 kW | 0-20 kW* | 0-20 kW* | 0-172 kW* | 1000 kW |
| 1-3 GeV Muon program, e.g. Mu2e-2 | ----- | 80 kW | 1000 kW | 1000 kW | 1000 kW |
| Kaon Program | 0-30 kW** (<30% df from MI) | 0-75 kW** (<45% df from MI) | 1100 kW | 1870 kW | 1870 kW |
| Nuclear edm ISOL program | none | 0-900 kW | 0-900 kW | 0-1000 kW | 0-1000 kW |
| Ultra-cold neutron program | none | 0-900 kW | 0-900 kW | 0-1000 kW | 0-1000 kW |
| Nuclear technology applications | none | 0-900 kW | 0-900 kW | 0-1000 kW | 0-1000 kW |
| # Programs: | 4 | 8 | 8 | 8 | 8 |
| Total max power: | 735 kW | 2222 kW | 4284 kW | 6492 kW | 11870kW |

* Operating point in range depends on MI energy for neutrinos.

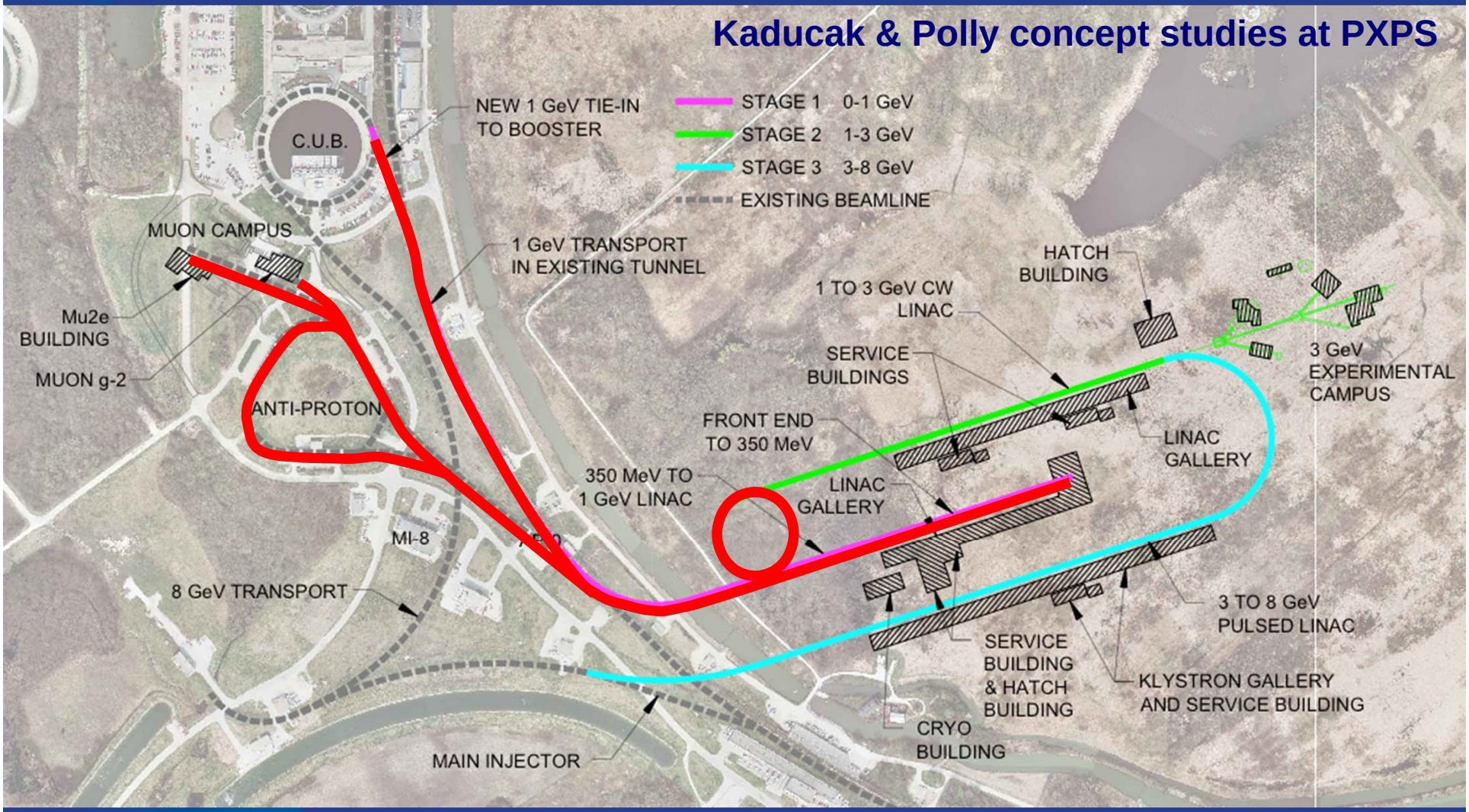
** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

# Kaducak & Polly concept studies at PXPS




Stage 1: CW Linac (1 GeV, 1 mA) feeds Booster allowing 60-70% more beam at 8 and 120 GeV. 900 kW of CW beam remains at 1 GeV, and can be used in combination with existing AP0, former anti-proton rings, and new Muon Campus

# Kaducak & Polly concept studies at PXPS




Stage 1a: A compressor ring allows non-CW experiments to be mounted in the existing 1 GeV experimental areas.



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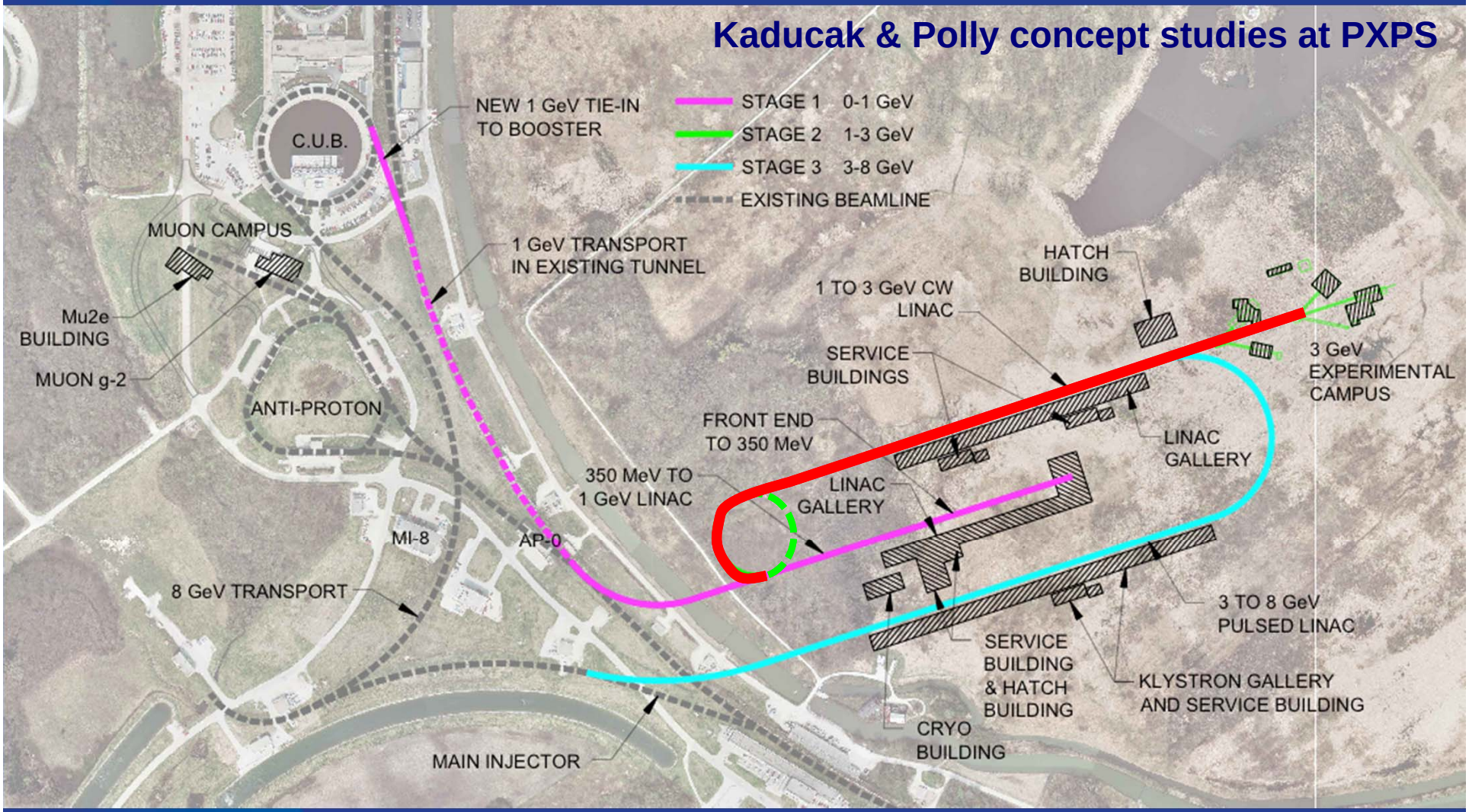
# Kaducak & Polly concept studies at PXPS




Stage 2: CW linac for 1 to 3 GeV constructed to feed new 3 MW experimental campus. Reuses first 180˚ of 1 GeV bunching ring for transport.



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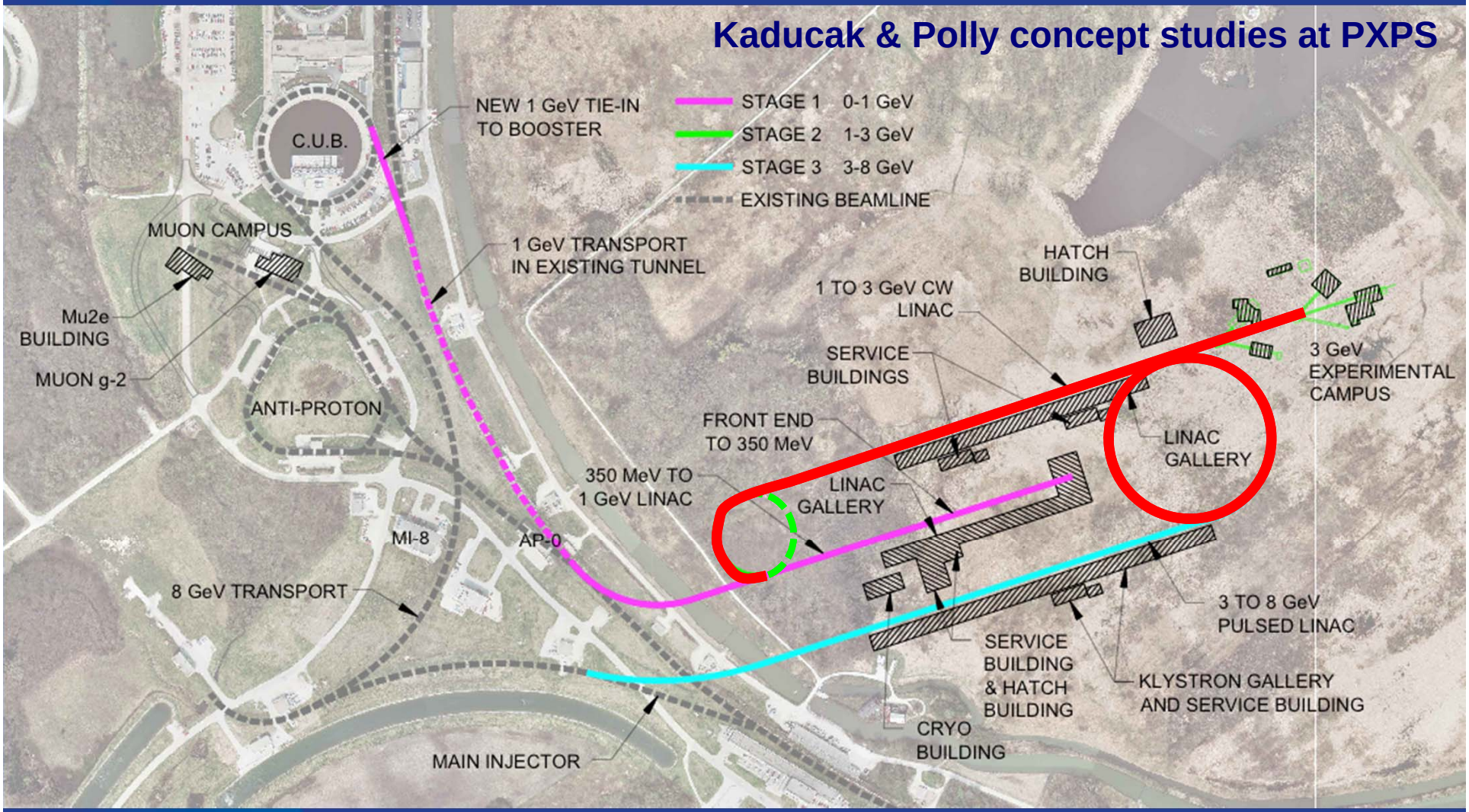
# Kaducak & Polly concept studies at PXPS




Stage 2a: A compressor ring allows non-CW experiments to be mounted in the 3 GeV experimental areas.



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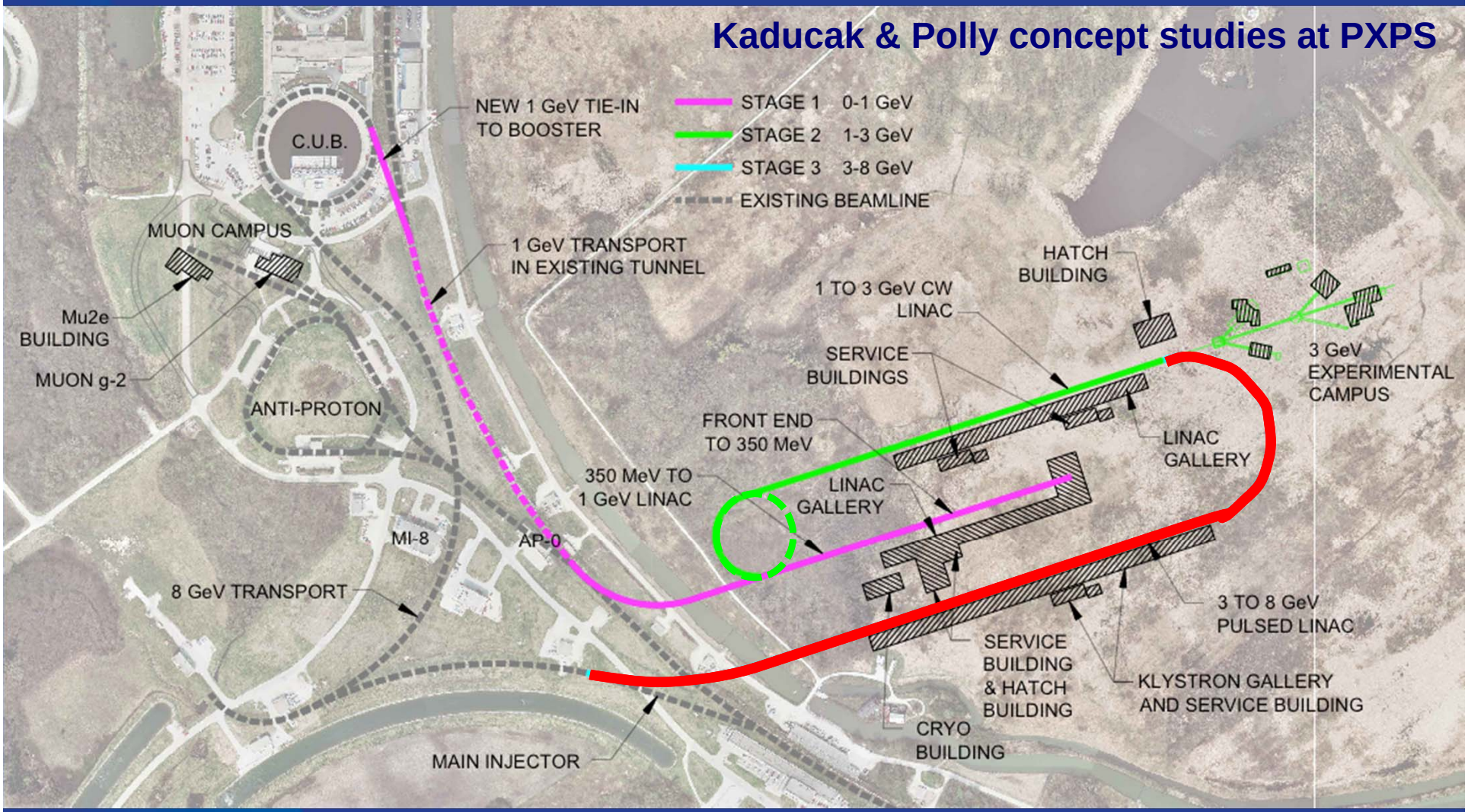
# Kaducak & Polly concept studies at PXPS




Stage 3: Pulsed linac constructed to feed Recycler. Reuses fir
3 GeV bunching ring fo



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# Project-X Accelerator Parameters (see PXPS website)

| | | |
|---|---|---|
| **CW Linac** | | |
| Particle Type | $H^-$ | |
| Beam Kinetic Energy | 1.0-3.0 | GeV |
| Average Beam Current | 1 | mA |
| Linac pulse rate | CW | |
| Beam Power @ 3 GeV | 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 | 170 | 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 | 2450 | kW |

simultaneous

# Science Enabled with Stage-1

- Promotes the Main Injector to a Mega-Watt class machine for neutrinos, and increases the potential beam power for possible slow-spill experiments (e.g. ORKA).
- Potentially unshackles the $\mu \rightarrow e$ (Mu2e) experiment from the Booster complex: Potentially increases sensitivity of Mu2e by x10 - x100 with 1-GeV CW drive beam.
- World class ultra-cold neutron and ISOL-edm programs optimized for particle physics: e.g. edms & neutron$\Leftrightarrow$anti-neutron oscillations.
- Increases the available integrated 8 GeV power for other experiments (e.g. short-baseline neutrinos) from the Booster complex by liberating Mu2e.

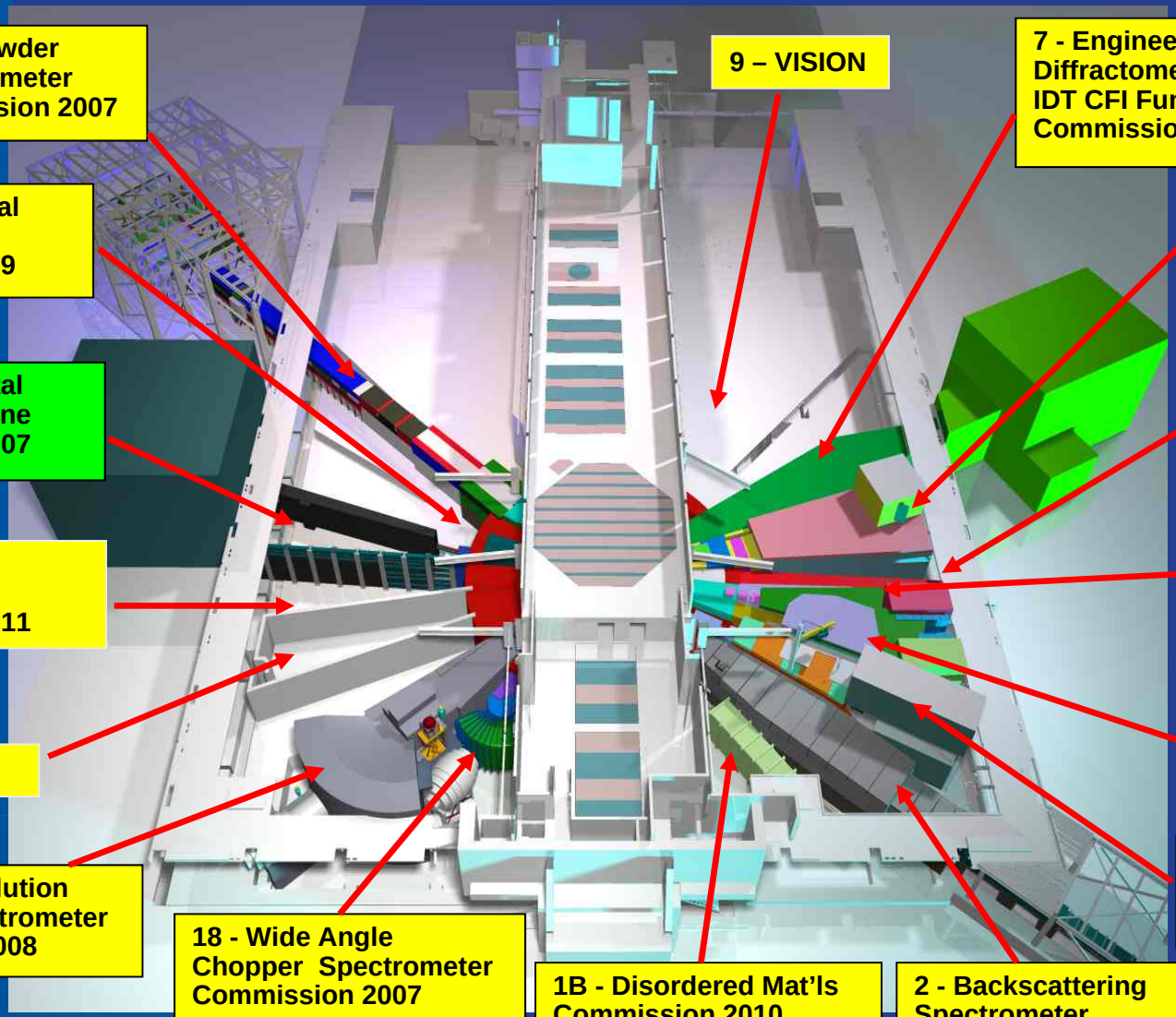
***Broad World-class Program in Neutrinos and Rare Processes***

# A spallation target facility dedicated to particle physics

- The pursuit of edms induced by physics beyond the Standard Model has been a long term interest of US science agencies: NIST, NSF, DOE/NP*, DOE/HEP…***this is core particle physics.***
- Project X presents an opportunity for a spallation target facility optimized for particle physics: ISOL production of edm-enhanced isotopes and ultra-cold neutrons for edm research, n-nbar oscillations, etc.
- Leaders in the nuclear physics community are intrigued.
- The spallation facility is excellent leadership-share opportunity for our Indian colleagues in accelerator science and particle physics, ***and for our field to learn new techniques (e.g. AMO).***
- Much infrastructure can be shared with energy and materials technology development.

*http://science.energy.gov/~/media/np/nsac/pdf/docs/NSAC_NeutronReport.pdf

# *Beamline 13 Has Been Allocated for Nuclear Physics at SNS*




Courtesy
Geoff Greene



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# Science Enabled with Stage-2

- World leading kaon physics program: Megawatt power (x10 over competing facilities) can drive multiple experiments.
- World class muon physics program: Mu2e descendant migrates to a higher power campus. Megawatt power for conversion experiments (x10 over competing $\mu \rightarrow e$ facilities), opportunities for major next steps in other channels (e.g. $\mu \rightarrow 3e$).
- Maintains Main Injector beam power at lower energies (e.g. 60 GeV) enhancing the neutrino spectrum for long baseline experiments.

# Science Enabled with Stage-3 (RDR)

- Main Injector power upgrade to >2 Mega Watts for 60-120 GeV beam, doubling power to long baseline Main Injector Neutrinos and Main Injector near-detector neutrino physics.

- 8 GeV beam power for experiments is doubled to now x10 the MiniBooNE era, which will support a new generation of short-baseline neutrino physics.

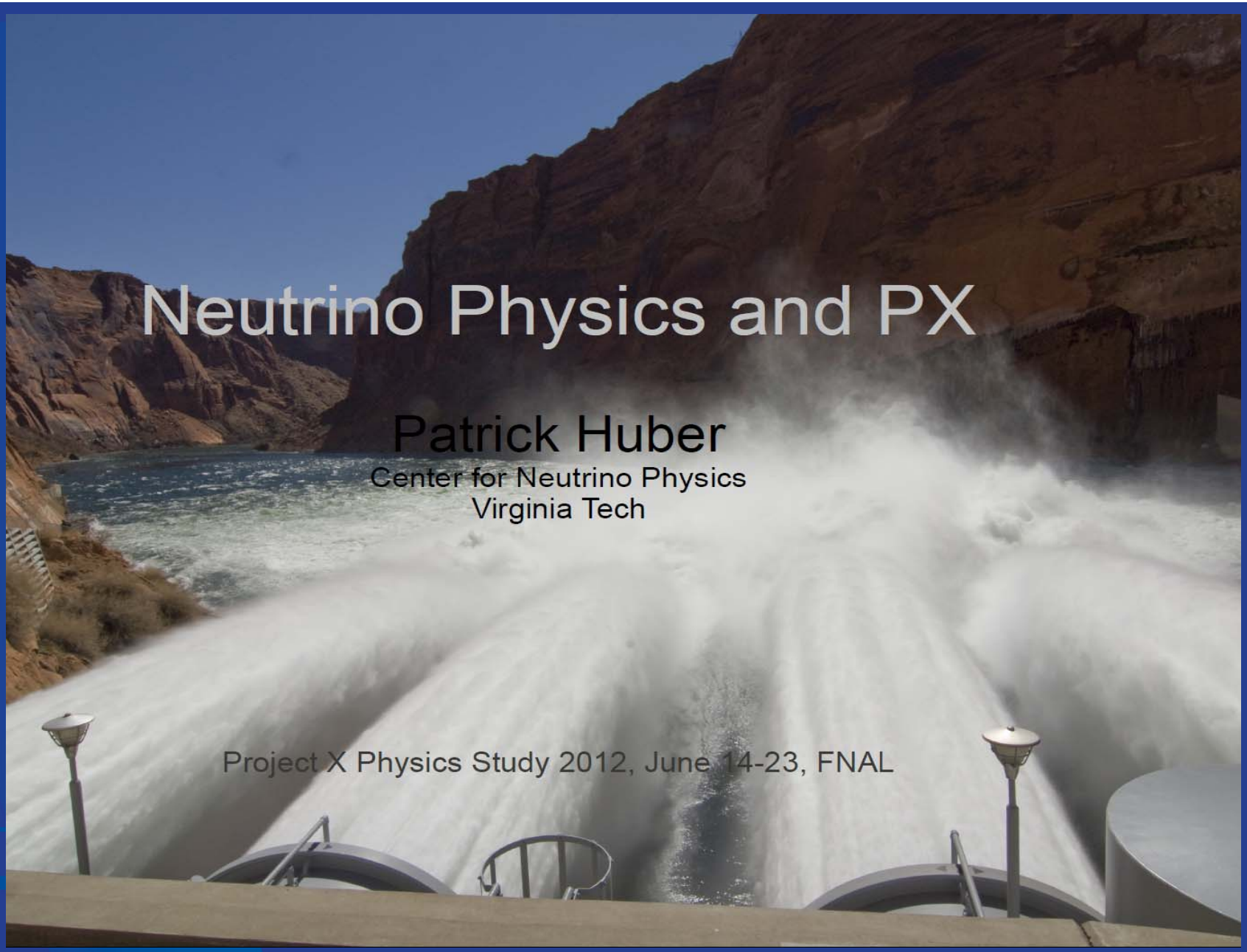
# Science Enabled with Stage-4 (Beyond RDR)

- 4000kW @ 8 GeV and 4000kW at 60 GeV for the ultimate super beams.
- Double beam super-beam technique can tune illumination of the first and second maxima of long-baseline experiments of very massive next generation long-baseline detectors.
- Driver for an extremely powerful muon storage ring neutrino source, driving detectors based existing large magnetized neutrino detector technologies (MINOS), and possibly LAr in the future.

# A Partial Menu of World Class Science Enabled by Project-X

**Neutrino Physics:** **LBNE campaign is a candidate Day-1 program**

- **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 $\nu_e, \bar{\nu}_e \rightarrow X$ experiments….x3 beam power @ 120 GeV, **x10-x20 power @ 8 GeV**.
- Next generation precision cross section measurements.


Neutrino Physics and PX
Patrick Huber
Center for Neutrino Physics
Virginia Tech
Project X Physics Study 2012, June 14-23, FNAL

P. Huber, PXPS

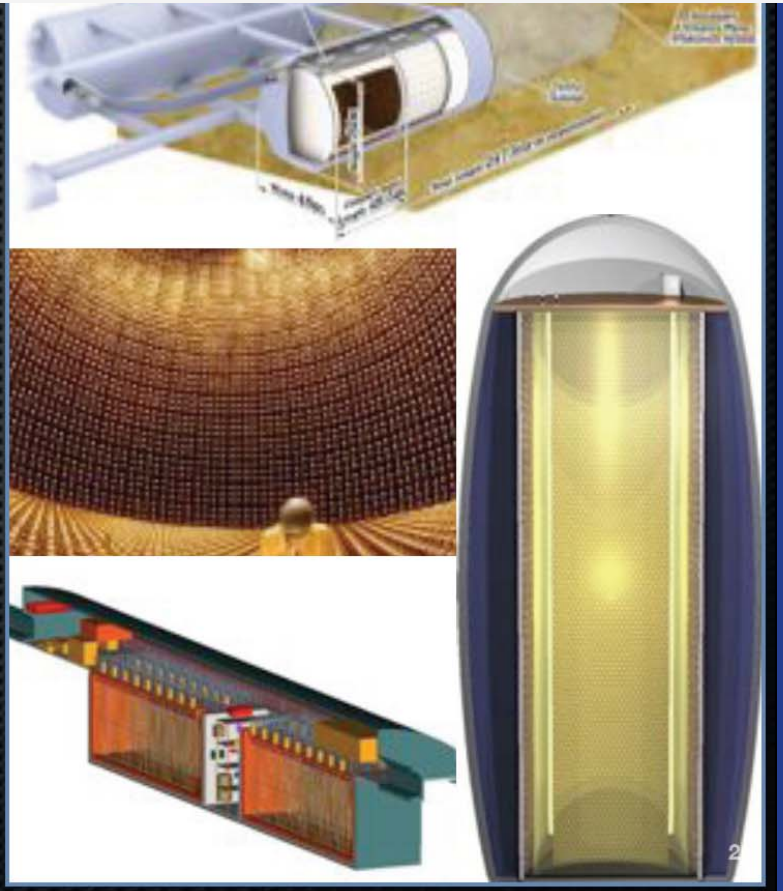
# Next generation long-baseline

## Liquid Argon Operations on the Surface??

detectors to reach the sensitivities needed to measure CP violation, the mass hierarchy, the $\theta_{23}$ octant and non-standard interactions. (See P. Huber's talk)

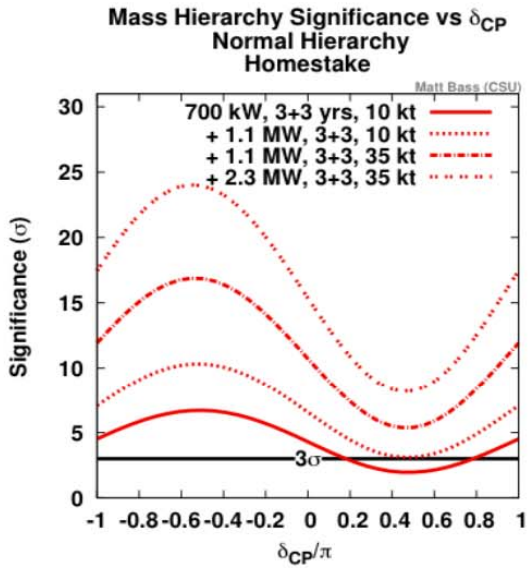
- One or several **large detectors,** can provide the mass required to the next generation of long-baseline experiments.
- A challenge will be instrumenting the **very large surfaces/volumes**.
- A second challenge will be making **multi-purpose detectors** to enable a broader physics program.

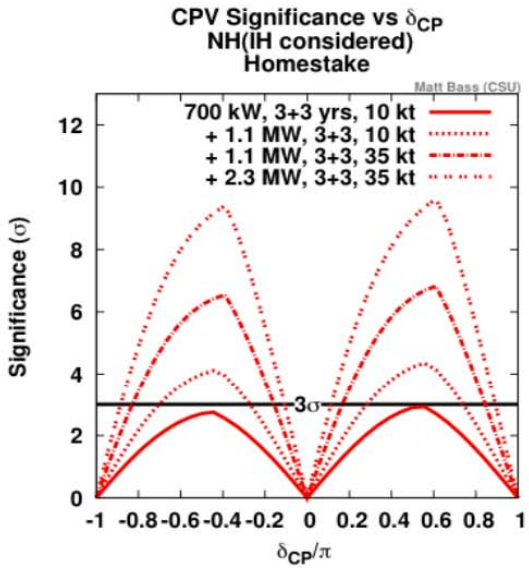
M. Sanchez - ISU/ANL



Mayly Sanchez PXPS

# LBNE Phase 2 + Project X Stage 1




- Stage 1 of PX increases the MI beam power to MW range
- LBNE/Homestake Phase 2 + PX Phase 1 = **Discovery (>5σ) CPV**

Zeynep Isvan (BNL) 6/19/2012 PXPS 9

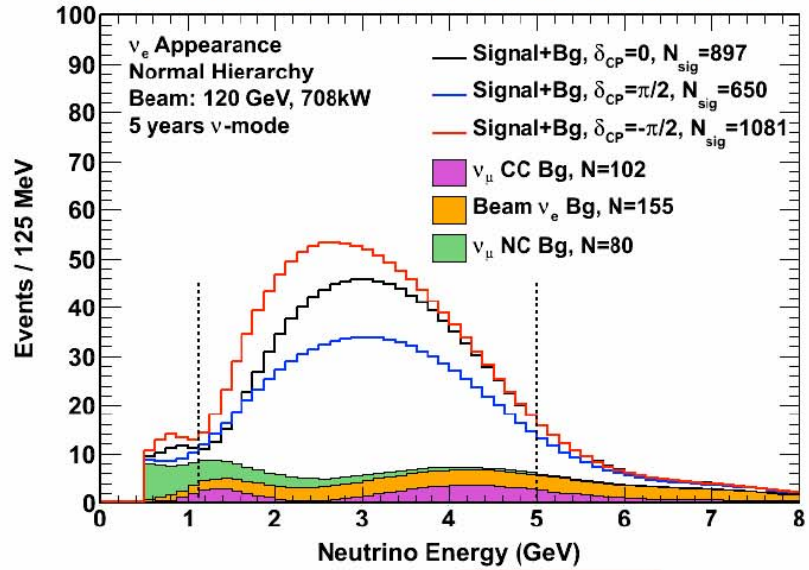
Zeynep Isvan & Mary Bishai (BNL) PXPS

# Project X Stage 2 Possibilities

- Stage 2 will allow MW-power lower energy beams
- Can we gain low energy flux (at long baselines) by going to lower energies?
- This can populate the second maximum and improve the signal/background in the CPV-sensitive region.
- Consider 30, 60, 90 GeV energies and 1MW beam power
- Separation power figure of merit:

$$\frac{N_{-\pi/2} - N_{\pi/2}}{\sqrt{B}} = 23.5$$

Standard 120 GeV 700kW

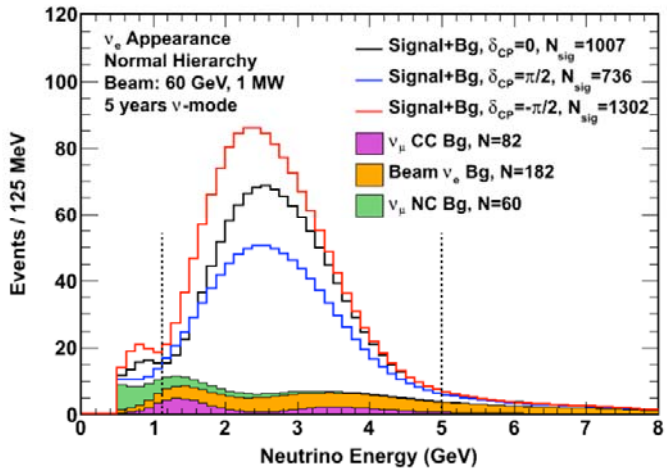


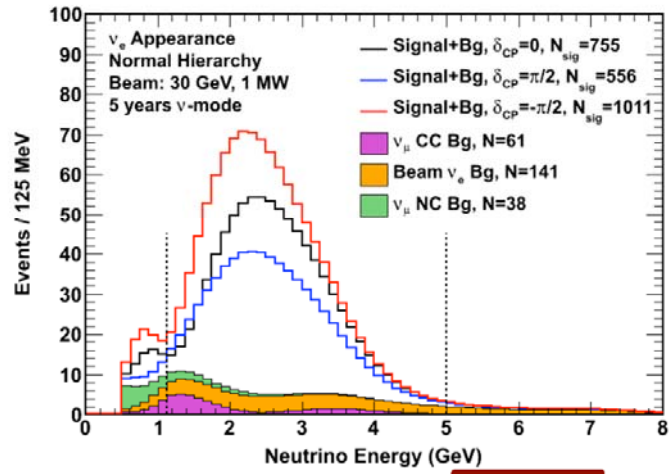

| $\delta_{CP}$ | N | $N_{second}$ | $N_{first}$ | $N/\sqrt{B}$ | $N_{second}/\sqrt{B}$ | $N_{first}/\sqrt{B}$ |
|---|---|---|---|---|---|---|
| 0 | 897 | 14 | 817 | 48.86 | 2.27 | 57.34 |
| $\pi/2$ | 650 | 5 | 597 | 35.41 | 0.81 | 41.90 |
| $-\pi/2$ | 1081 | 24 | 994 | 58.89 | 3.89 | 69.77 |



Zeynep Isvan (BNL) PXPS

# 60 GeV 1MW, 30 GeV 1MW




| $\delta_{CP}$ | N | $N_{second}$ | $N_{first}$ | $N/\sqrt{B}$ | $N_{second}/\sqrt{B}$ | $N_{first}/\sqrt{B}$ |
|---|---|---|---|---|---|---|
| 0 | 1007 | 26 | 955 | 55.94 | 3.92 | 64.83 |
| $\pi/2$ | 736 | 10 | 707 | 40.89 | 1.51 | 47.99 |
| $-\pi/2$ | 1302 | 45 | 1231 | 72.33 | 6.78 | 83.57 |

$$\frac{N_{-\pi/2} - N_{\pi/2}}{\sqrt{B}} = 31.4$$

| $\delta_{CP}$ | N | $N_{second}$ | $N_{first}$ | $N/\sqrt{B}$ | $N_{second}/\sqrt{B}$ | $N_{first}/\sqrt{B}$ |
|---|---|---|---|---|---|---|
| 0 | 755 | 30 | 716 | 48.74 | 4.93 | 55.08 |
| $\pi/2$ | 556 | 11 | 538 | 35.89 | 1.81 | 41.38 |
| $-\pi/2$ | 1011 | 51 | 951 | 65.26 | 8.38 | 73.15 |

$$\frac{N_{-\pi/2} - N_{\pi/2}}{\sqrt{B}} = 29.4$$

- Can do better CPV than 120 GeV with the same amount of running
- Technical: High density graphite target inserted into horn 1 unlike standard NuMI LE at z=-30cm

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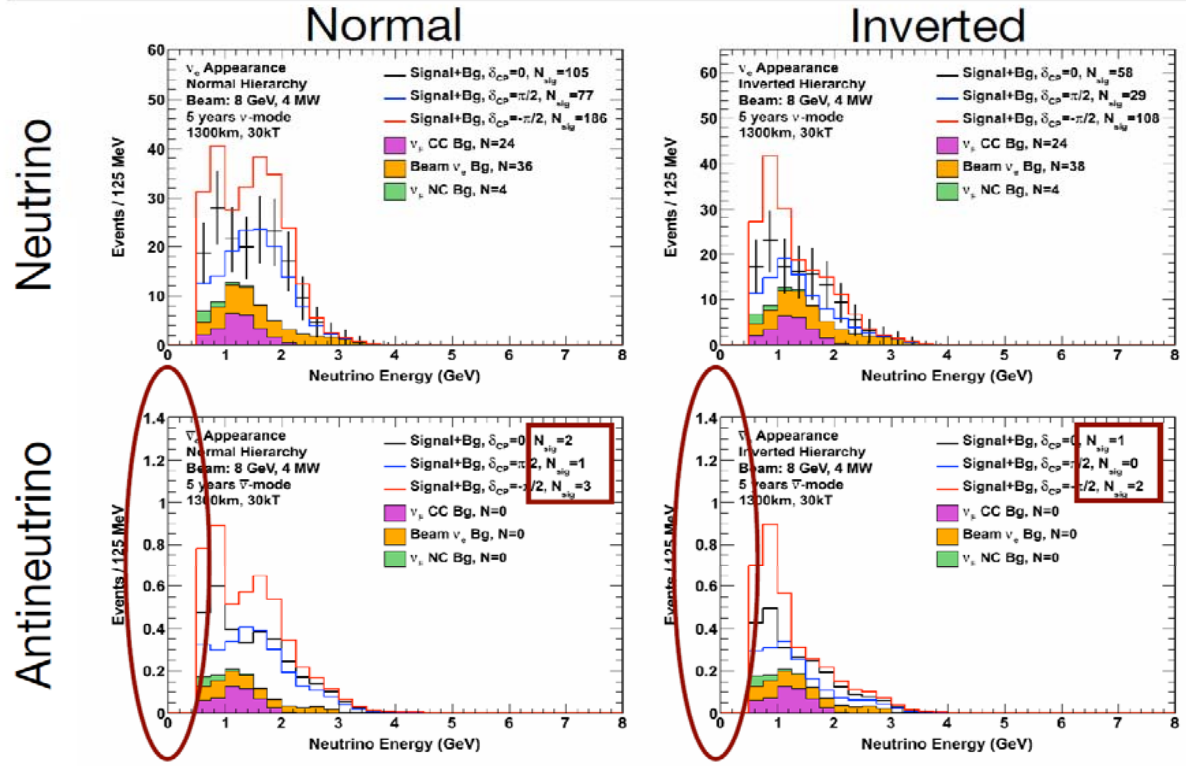
# Stage-4: LBL physics with 8 GeV beam!

## Matter vs CP effect with 8 GeV




- Mass hierarchy and CP asymmetry non-degenerate - they're completely disentangled!

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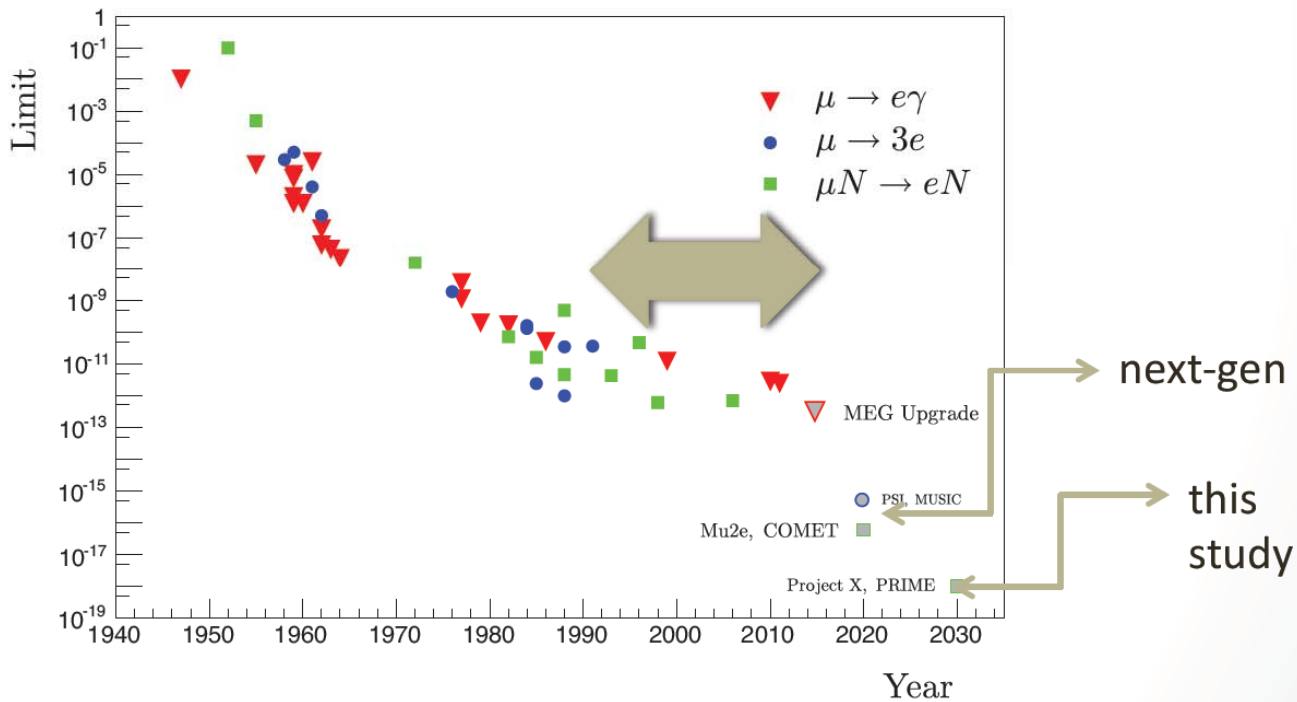
# A Partial Menu of World Class Science Enabled by Project-X

**Muon Physics:** **Mu2e upgrade is a candidate Day-1 experiment**

- **Next generation muon-to-electron conversion experiment, new techniques for higher sensitivity and/or other nuclei.**
- Next generation $(g\text{-}2)_\mu$ 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.

# Muon LFV history

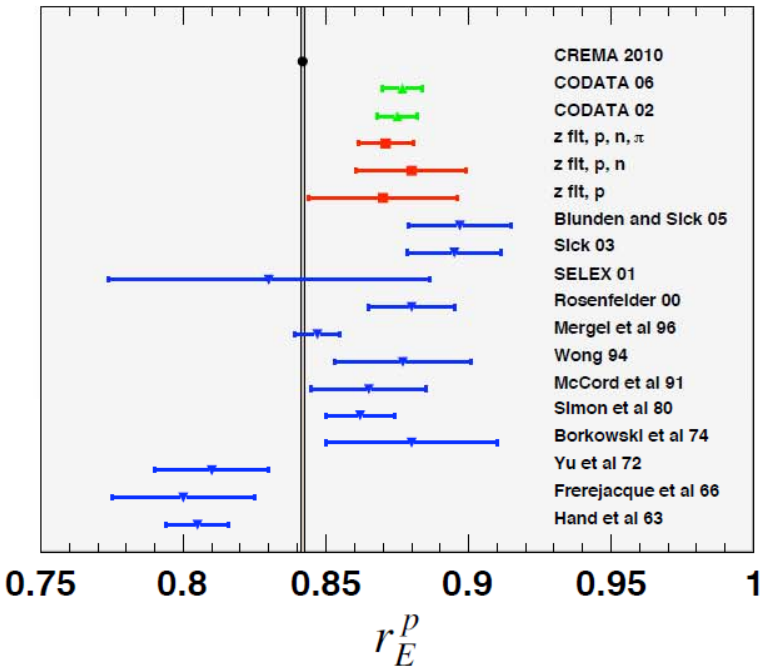
History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$




Bernstein

R. Bernstein and G. Kribs PXPS 2012 20

# the proton radius puzzle



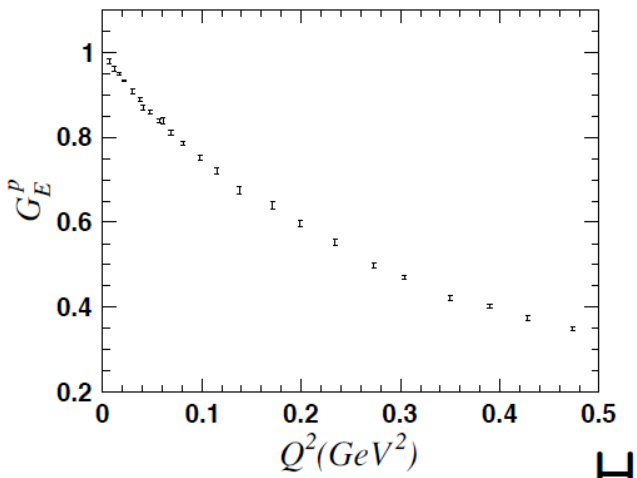

- inferred from muonic H

- inferred from electronic H

- extraction from e p, e n scattering, ππNN data (this talk)

- previous extractions from e p scattering (as tabulated in PDG)

$$G'_E(0) \equiv \frac{1}{6}(r_E^p)^2 + \frac{\alpha}{3\pi m_p^2}\log\frac{m_p}{\lambda}$$




Hill

R. Bernstein and G. Kribs PXPS 2012 17

# Mu2e Search for $\mu^- \rightarrow e^-$ conversion at $10^{-16}$

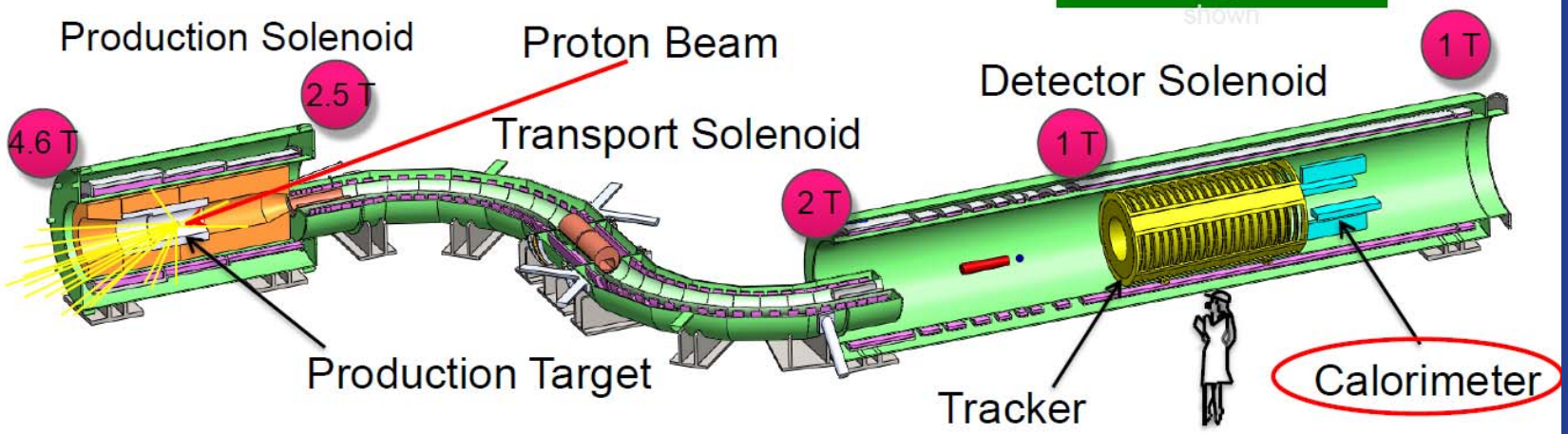
**Production Solenoid**
- Production target
- Graded field

- Delivers ~ 0.0016 stopped $\mu^-$ per incident proton
- $10^{10}$ Hz of stopped muons

**Detector Solenoid**
- Muon stopping target
- Tracker
- Calorimeter
- Warm bore evacuated to $10^{-4}$ Torr

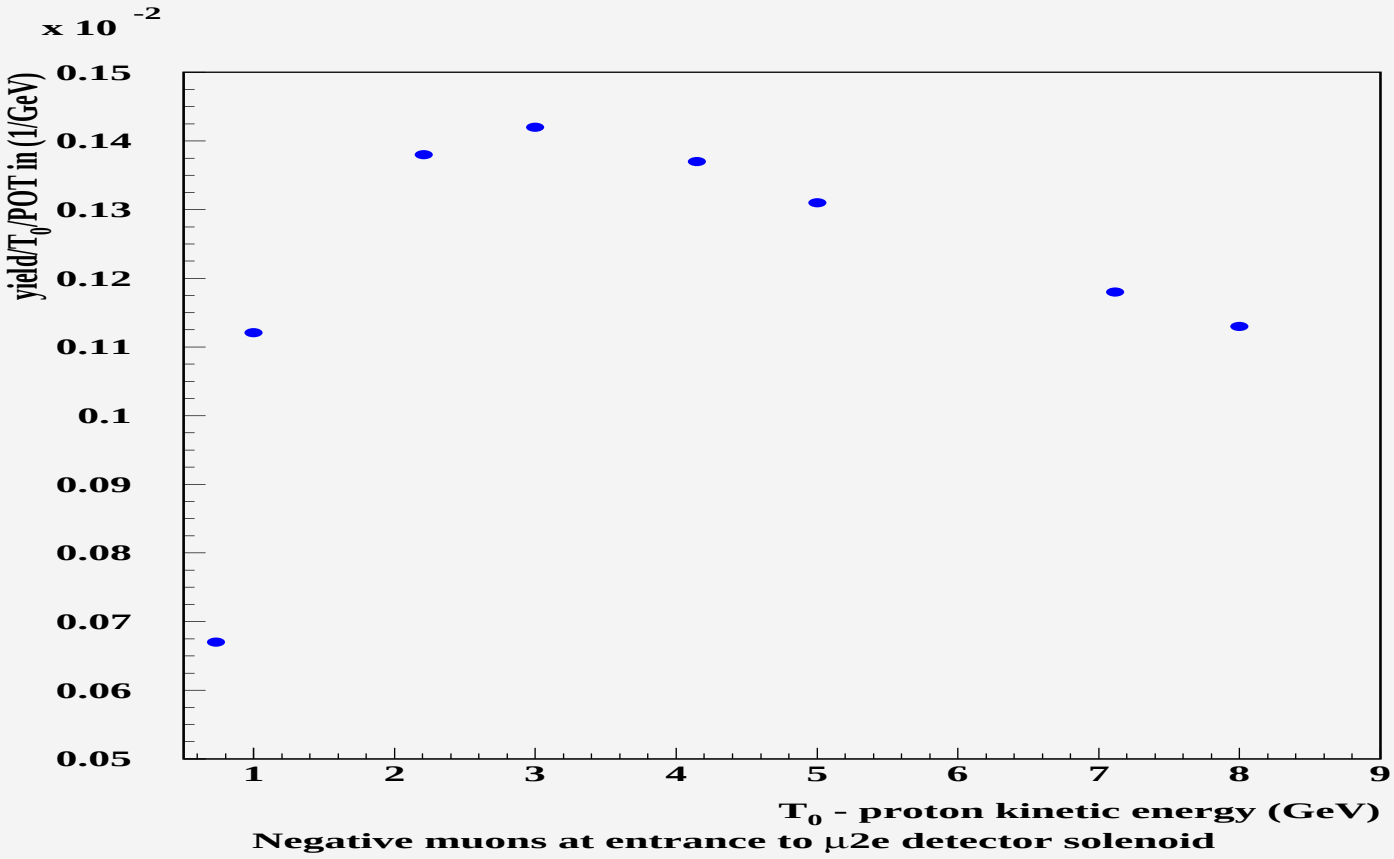
**Transport Solenoid**
- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator

Cosmic Ray Veto not shown



# What is the optimum proton beam energy to drive a MELC/MECO/Mu2E experiment?

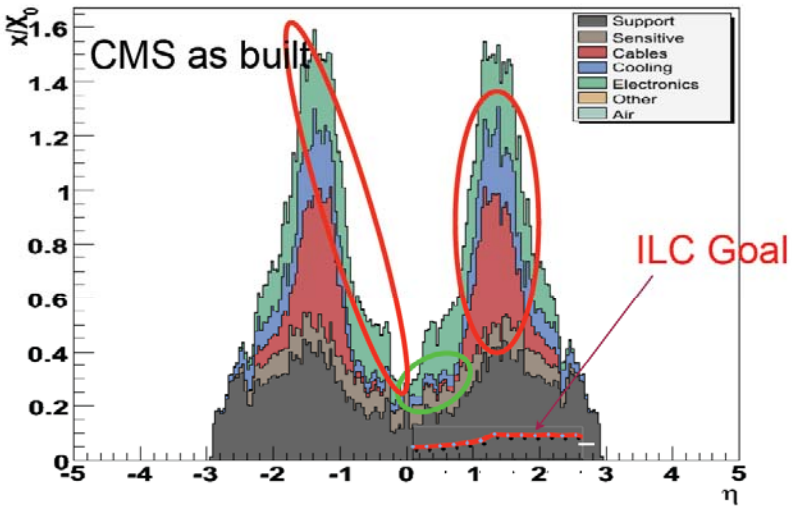
Yield / Watt




S. Striganov et al, work in progress

# Power Consumption

- Limiting Power consumption is crucial for low mass pixelated detectors (CMS Tracker- 17 kAmp)
  - Move electronics off-detector
  - Limit power to allow air cooling
  - Use $CO_2$ cooling
- There are basic power-speed and detector tradeoffs



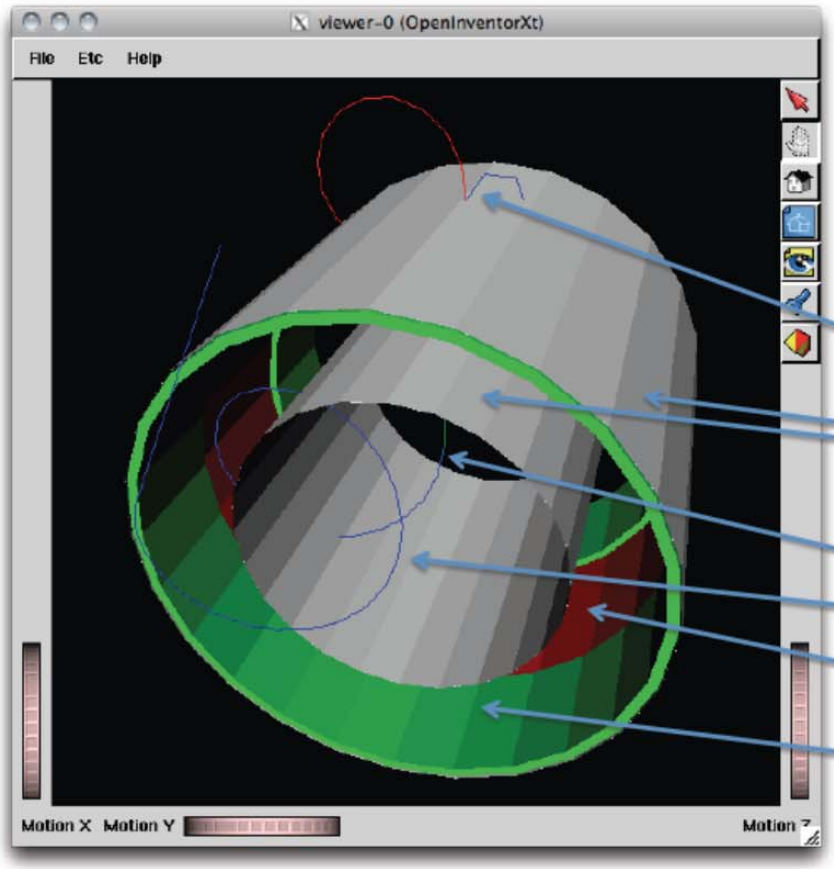

| | # Pixels / chip | Pixel area [mμ²] | Idig [mA] | Iana [mA] | Power/ chip [mW] | Power/ pixel [μW] | Power density [ mW/cm² ] |
|---|---|---|---|---|---|---|---|
| ALICE | 8192 | 21'250 | 150 | 300 | 810 | 99 | 466 |
| ATLAS | 2880 | 20'000 | 35 | 75 | 190 | 67 | 335 |
| CMS | 4160 | 15'000 | 32 | 24 | 121 | 29 | 194 |
| | | | CMS no on-chip regulators | | 87 | 21 | 142 |

(R. Horisberger)

**R. Lipton, Tracking Summary PXPS**

# μ→eγ with converted γ (DeJong)

The simple minded geometry seems to work. Needs many $m^2$ pixel tracking




Target radius ~2 cm

B = 0.5 T
Positron R = 35 cm

Converted photon

Double pixel layers
R = 47 cm and 75 cm

μ -> *e* γ decay from stopped muon

Positron

Converter

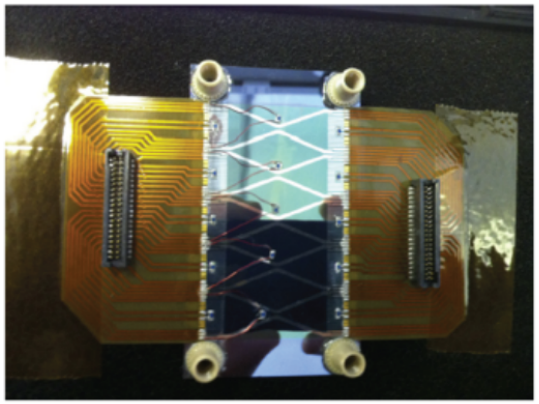
Calorimeters or tof
triggering, tof

Many design constraints and options - need mass to convert photons, minimal mass for tracking, separation of layers, resolutions ....

**Frtiz Dejongh, PXPS**

# Gigatracker - Cooling and Performance (Velghe)

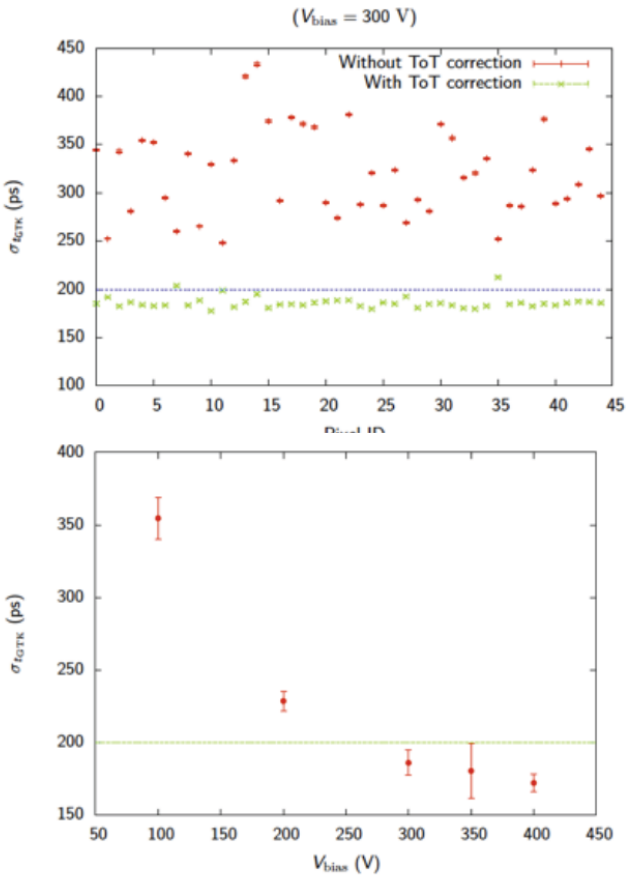
Baseline - micro channel cooling

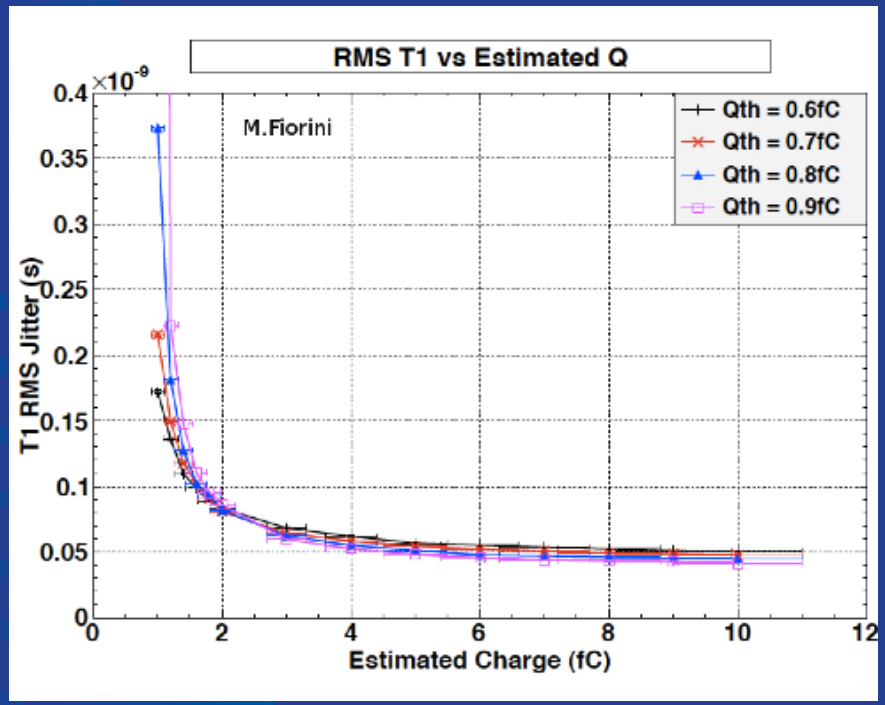


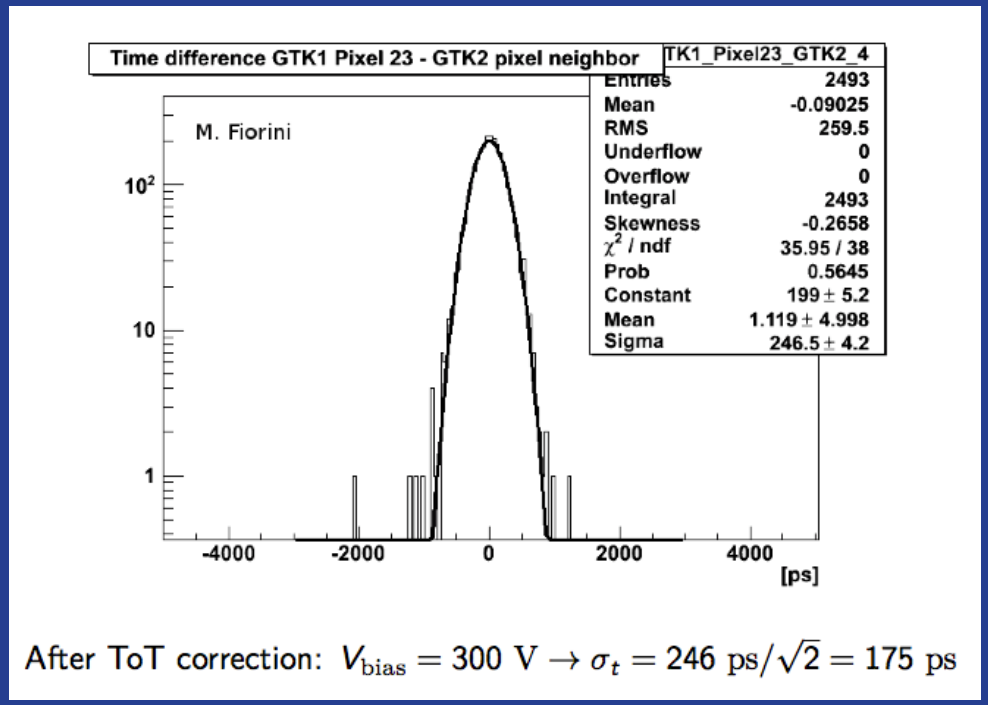
Material in the acceptence area: 0.13%$X_0$

Frame Option

45 pixel prototype performance






After ToT correction: $V_{\text{bias}} = 300$ V $\rightarrow \sigma_t = 246$ ps$/\sqrt{2} = 175$ ps

# Timing depends on:

- Impact position on pixel,
- Sensor bias voltage,
- Electronic noise of the frontend,
- Energy straggling in the sensor bulk,

GigaTracker is

- Fast, $\sigma_t < 175$ ps at $V_{\text{bias}} = 300$ V
- Thin, $X/X_0 < 0.5\%$
- Innovative, it takes advantage of micro channel cooling, the frame option looks promising

GOOD NEWS

Bob Velghe, PXPS

Fermilab

# A Partial Menu of World Class Science Enabled by Project-X

**Kaon Physics:**

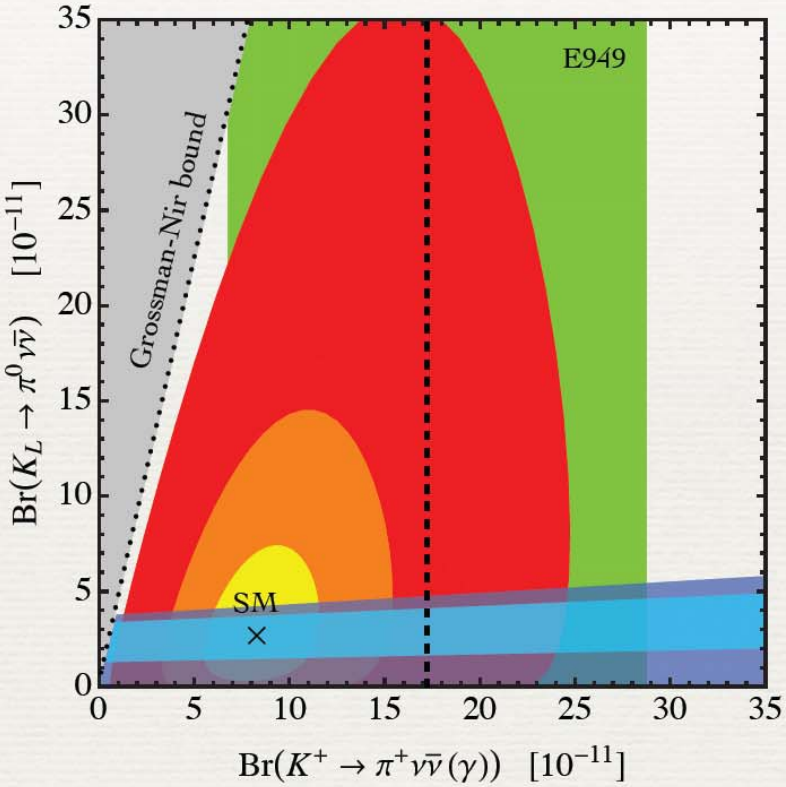
**ORKA is a candidate Day-1 experiment**

- **$K^+ \rightarrow \pi^+\nu\bar{\nu}$: >1000 events, Precision rate and form factor.**
- $K_L \rightarrow \pi^0\nu\bar{\nu}$: 1000 events, enabled by high flux & precision TOF.
- $K^+ \rightarrow \pi^0\mu^+\nu$: Measurement of T-violating muon polarization.
- $K^+ \rightarrow (\pi,\mu)^+\nu_X$: Search for anomalous heavy neutrinos.
- $K^0 \rightarrow \pi^0e^+e^-$: <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 ($\Delta m_K/m_K \sim 1/m_P$)
- $K^0, K^+ \rightarrow$LFV: Next generation Lepton Flavor Violation experiments

...and more

# Some heat and light…

## ε′/ε Strikes Back




stringent correlation between CP-violating kaon observables present in MSSM, RS, compositeness, …

⬇

ε′/ε "sleeping beauty" of flavor physics: when will lattice's kiss wake her?

**U. Haisch, PXPS**

# Proposed/considered experiments

- E06/TREK at JPARC (same group/beamline as P36)
  - T violating transverse muon polarization in $K^+ \rightarrow \pi^0 \mu \nu$.
  - Needs ≥ 100 kW beam (want 270 kW)
  - Timeline for JPARC higher intensity unclear
  - Run after P36
- ORKA at Fermilab Main Injector
  - $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at rest
  - 1000 signal events (@SM), estimates based upon BNL E787/996
- Next generation of KOTO at JPARC
  - $K_L \rightarrow \pi^0 \nu \nu$ in-flight.
  - Not proposed yet.

**Kevin Pitts, PXPS**

# Near-term experiments

- NA 62 at CERN
  - $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in-flight.
  - 100 signal events (@SM), low background
  - Partial detector commissioning this year, Data in 2014
- KOTO at JPARC
  - $K_L \rightarrow \pi^0 \nu \bar{\nu}$ in-flight.
  - Few signal event events (@SM)
  - Low intensity run this year.
- P36 at JPARC
  - Test of lepton universality $\Gamma(K^+ \rightarrow e^+ \nu)/\Gamma(K^+ \rightarrow \mu^+ \nu)$
  - Run in 2015

**Kevin Pitts, PXPS**

21-Jun-12 Kaon Experimental Summary Kevin Pitts (kpitts@illinois.edu) 3

## ORKA measurements & thesis topics

- $K^+ \to \pi^+ +$ missing energy
  - $K^+ \to \pi^+ \nu\bar{\nu}(1)$ $^{T,P}$
  - $K^+ \to \pi^+ \nu\bar{\nu}(2)$ $^{T,P}$
  - $K^+ \to \pi^+ \nu\bar{\nu}\gamma$
  - $K^+ \to \pi^+ X$ $^{P}$
  - $K^+ \to \pi^+ \tilde{\chi}_0 \tilde{\chi}_0$(FF) $^{P}$
- $K^+ \to \pi^+ \pi^0 +$ missing energy
  - $K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$ $^{T,P}$
  - $K^+ \to \pi^+ \pi^0 X$
- $K^+ \to \mu^+ +$ missing energy
  - $K^+ \to \mu^+ \nu_h$ (heavy neutrino) $^{T}$
  - $K^+ \to \mu^+ \nu M$ ($M$ =majoran)
  - $K^+ \to \mu^+ \nu\bar{\nu}\nu$
- $K^+ \to \pi^+ \gamma$ $^{TP}$
- $K^+ \to \pi^+ \gamma\gamma$ $^{P}$
- $K^+ \to \pi^+ \gamma\gamma\gamma$
- $K^+ \to \pi^+ \mathrm{DP}$; $\mathrm{DP} \to e^+ e^-$
- $K^+$ lifetime
- $\mathcal{B}(K^+ \to \pi^+ \pi^0)/\mathcal{B}(K^+ \to \mu^+ \nu)$
- $K^+ \to \pi^+ \pi^0 e^+ e^-$
- $K^+ \to \pi^- \mu^+ \mu^+$ (LFV)
- $\pi^0 \to$ nothing $^{T,P}$
- $\pi^0 \to \gamma \mathrm{DP}$; $\mathrm{DP} \to e^+ e^-$
- $\pi^0 \to \gamma X$

$^{T}$E787/E949 Thesis ; $^{P}$E787/E949 Publication; DP≡Dark Photon

**Elizabeth Worcester**

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# Kaons at Project X

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
  - but hopefully it's already done to a few %.
- $K_L \rightarrow \pi^0 \nu \bar{\nu}$
  - "This experiment was made for Project X" –L. Littenberg
- Many other modes of interest
  - T violation in $K^+ \rightarrow \pi^0 \mu \nu$ (TREK)
  - Universality $\Gamma(K^+ \rightarrow e^+ \nu)/\Gamma(K^+ \rightarrow \mu^+ \nu)$
  - $K_L \rightarrow \pi^0 \mu\mu$ and $\pi^0 ee$ (look at $K_S/K_L$ interference?)
  - $K^+$, $K_L$ lepton flavor violation e.g. $K_L \rightarrow \mu e$
  - $K_L \rightarrow \gamma\gamma$
  - ...

**Kevin Pitts, PXPS**

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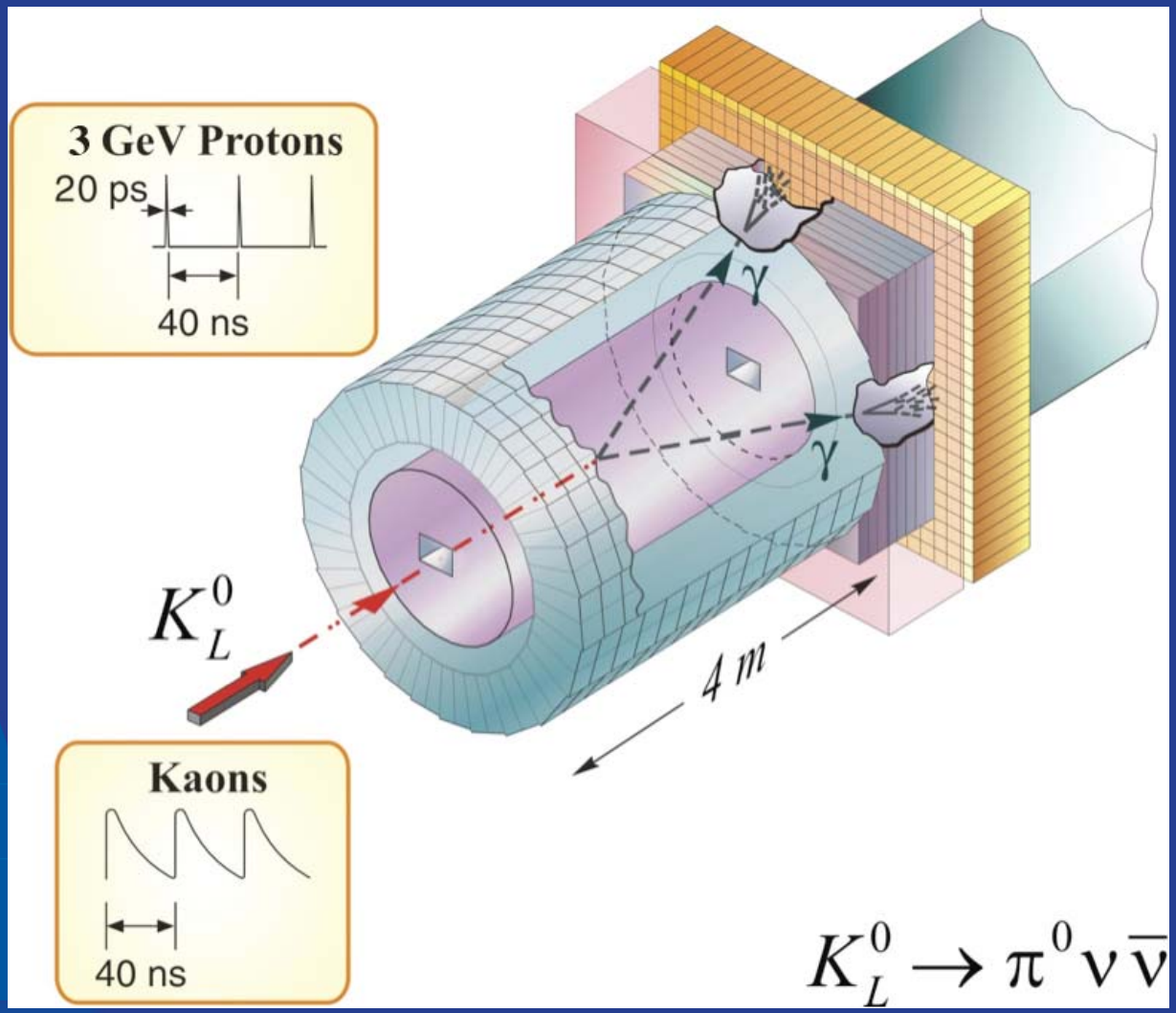
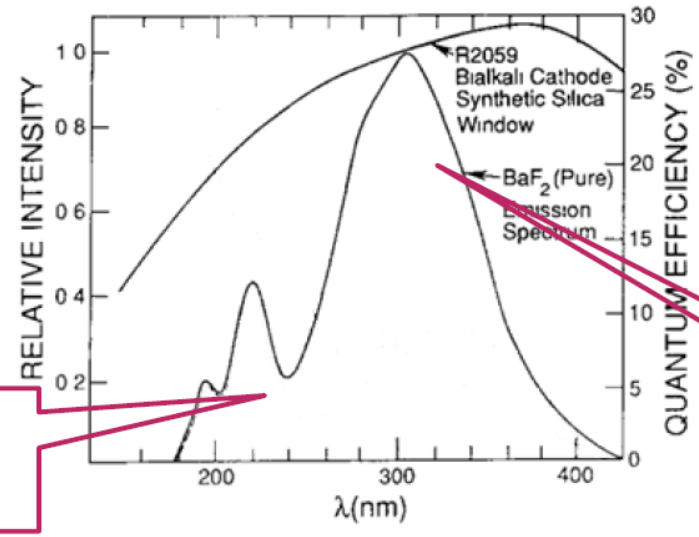
# “Nothing in, nothing out…” Next generation photon measurements crucial.



# "If a tree falls …

- "If a tree falls in a forest and no one is around to hear it, does it make a sound?"
- "If a crystal emits light and no one is around to see it, does it scintillate?"
- $BaF_2$ is among the fastest scintillating crystals (0.6-0.8ns), but it has a larger, slower, component (630ns)




Total light output
$1.2 \times 10^4$ photons/MeV

15%
600-800 ps

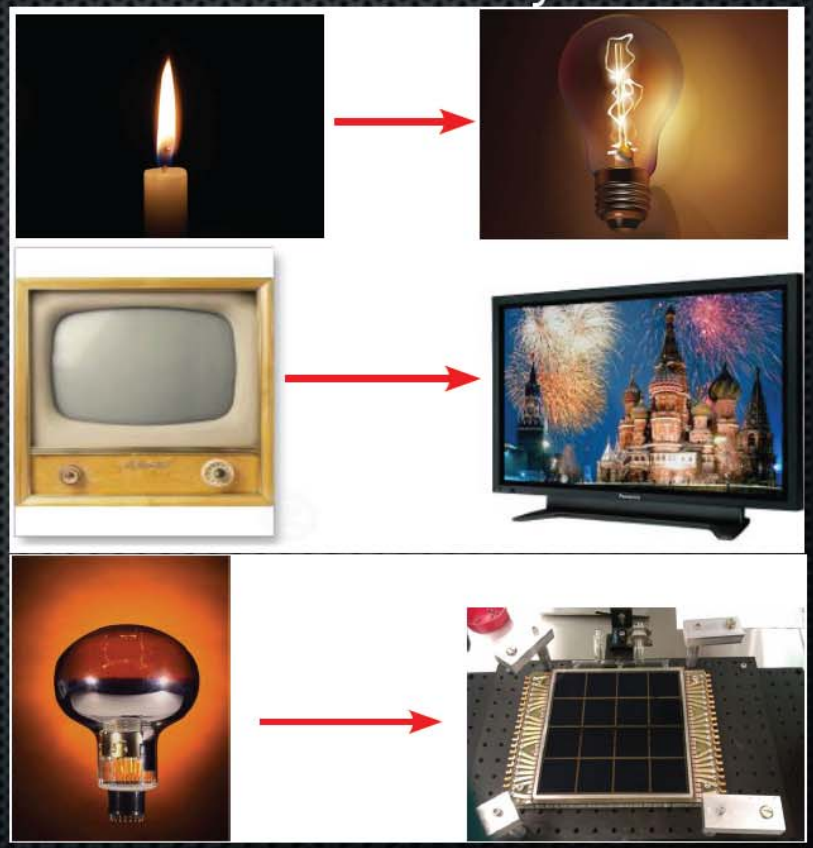
85%
630 ns

A. Elagin (UChicago)

# Photodetector

## Building your detector within the next 10 years

- **Large-area picosecond photodetectors** based on microchannel plates are being developed at Argonne National Laboratory in collaboration with other labs, universities and private companies.
- For this application, these could be tuned to:
  - Timing resolution of ~100 psec
  - Spatial resolution of ~1cm
- Alternatively, worse timing/less spatial resolution could be a lower price.



M. Sanchez - ISU/ANL

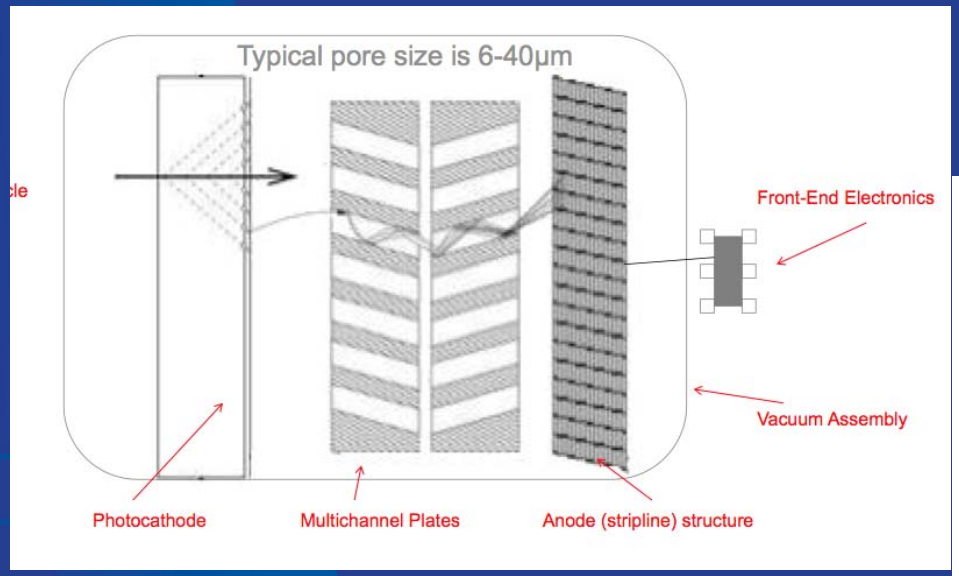
Mayly Sanchez PXPS

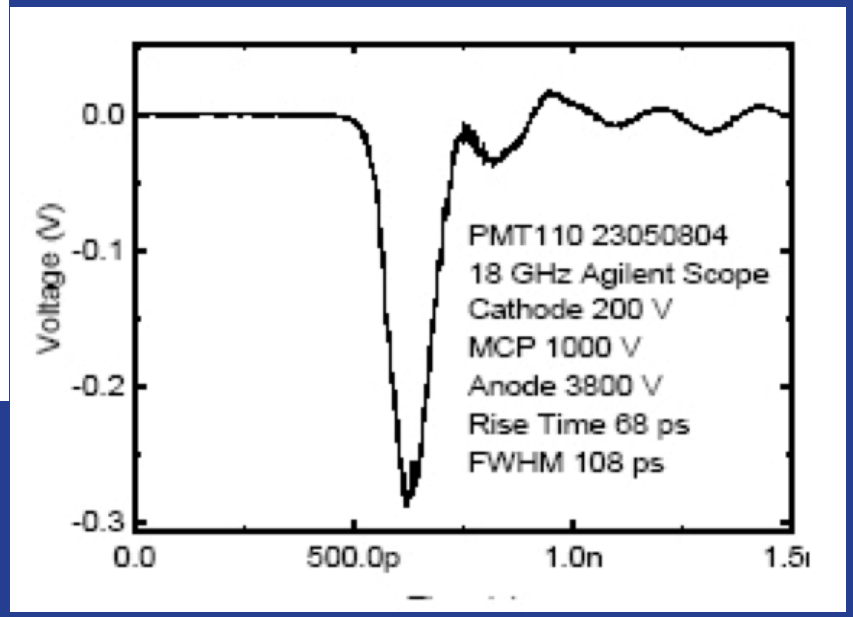
# MicroChannel Plate photomultipliers: MCP-PMT

Faster than conventional PMTs, compact, gains ~ $10^6$.

Commercial are more expensive with modest areas (<~10 cm2)

Large area flat thin being developed (talks here)




Rise time 68 ps!

From Wagner's Intro

Fermilab

# A Partial Menu of World Class Science Enabled by Project-X

## Nuclear Enabled Particle Physics: Candidate Day-1

- **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.**

## Hadron and Baryon Physics:

- **Next generation QCD probes (e.g. evolution of Seaquest)**
- $pp \rightarrow \Sigma^+ K^0 p^+$ ; $\Sigma^+ \rightarrow p^+ \mu^+ \mu^-$ (HyperCP anomaly, and other rare $\Sigma^+$ decays)
- $pp \rightarrow \bar{K}^+ \Lambda^0 p^+$ ; $\Lambda^0$ ultra rare decays
- $\Lambda^0 \leftrightarrow \bar{\Lambda}^0$ oscillations (Project-X operates below anti-baryon threshold)

# How to Search for N-Nbar Oscillations

Figure of merit for probability: $NT^2$

N=total # of free neutrons observed

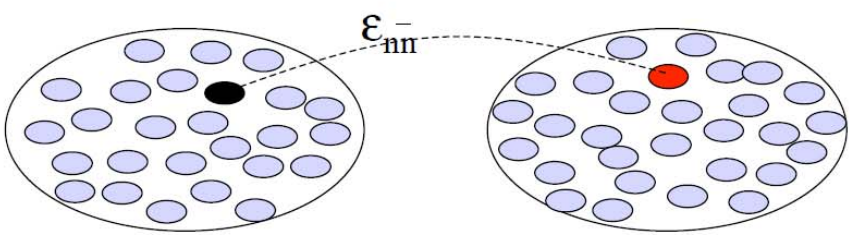
T= observation time per neutron while in "quasifree" condition

When neutrons are in matter or in nucleus, n-nbar potential difference is large->quasifree observation time is short

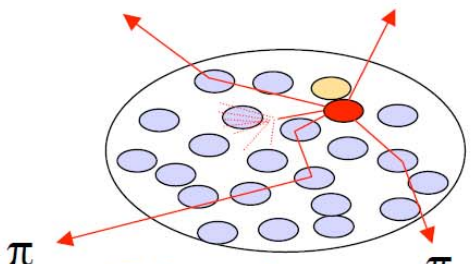
B field must be suppressed to maintain quasifree condition due to opposite magnetic moments for neutron and antineutron

(1) n-nbar transitions in nuclei in underground detectors

(2) Cold and Ultracold neutrons




Nucleus A → A* + $\bar{n}$



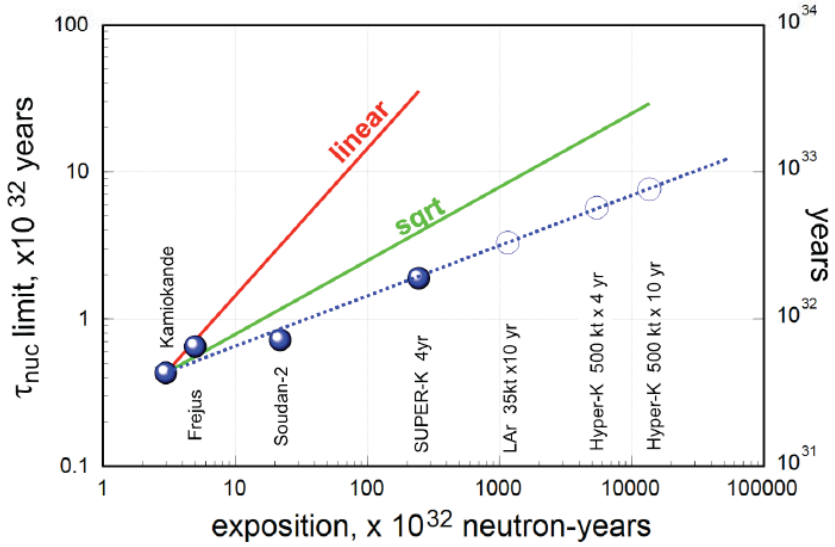

$\bar{n}N$ → pions

**Mike Snow, PXPS**

## Bound neutron N-Nbar search experiments

| Experiment | Year | A | n·year ($10^{32}$) | Det. eff. | Candid. | Bkgr. | $\tau_{nucl}$, yr (90% |
|---|---|---|---|---|---|---|---|
| Kamiokande | 1986 | O | 3.0 | 33% | 0 | 0.9/yr | $>0.43\times10^{32}$ |
| Frejus | 1990 | Fe | 5.0 | 30% | 0 | 4 | $>0.65\times10^{32}$ |
| Soudan-2 | 2002 | Fe | 21.9 | 18% | 5 | 4.5 | $>0.72\times10^{32}$ |
| SNO * | 2010 | D | 0.54 | 41% | 2 | 4.75 | $>0.301\times10^{32}$ |
| Super-K | 2011 | O | 245 | 12.1% | 24 | 24.1 | $>1.89\times10^{32}$ |

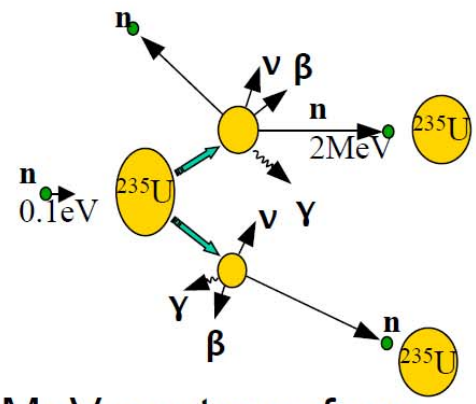
* Preliminary




- From Kamiokande to Super-K atmospheric ν background is about the same ~ 2.5 /kt/yr.
- Large $D_2O$, Fe, $H_2O$ detectors are dominated by backgrounds; LAr detectors are unexplored
- Observed improvement is weaker than SQRT due to irreducible background and uncertainties of efficiency and background.
- Still possible to improve a limit but impossible to claim a discovery.

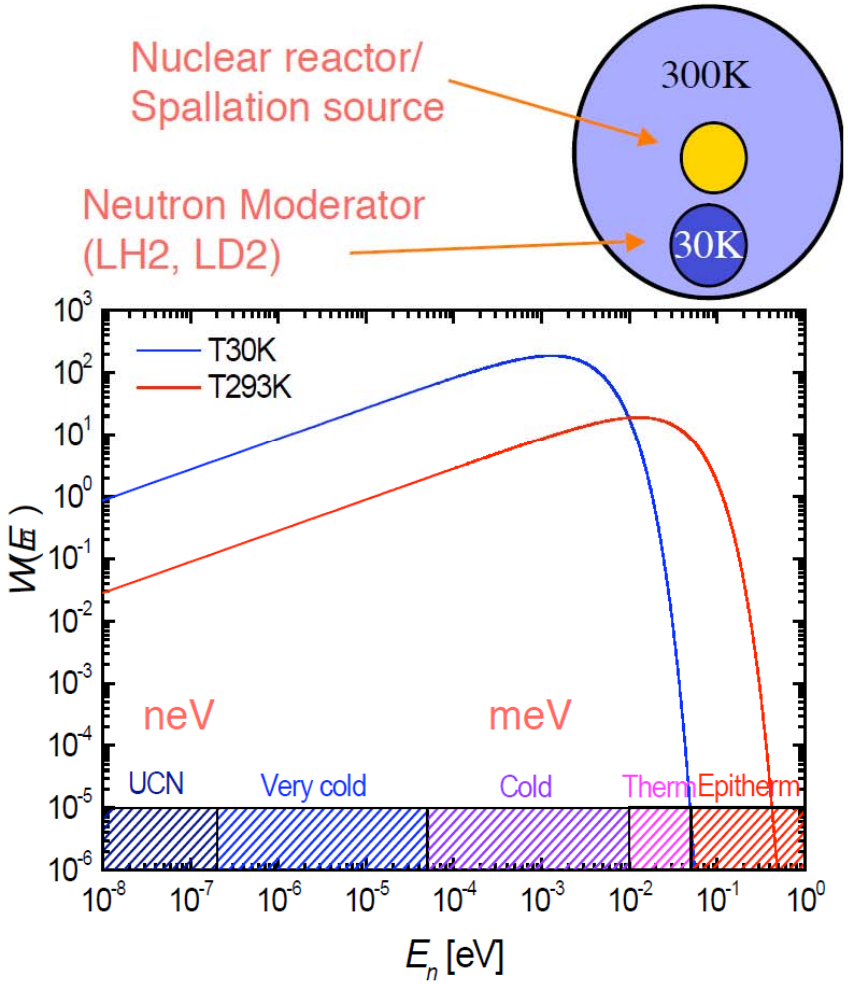
**Mike Snow, PXPS**

# "Slow" Neutrons: MeV to neV




~MeV neutrons from fission or spallation, thermalized in ~ 20 collisions in ~ 100 μs

| T (K) | E (meV) | λ (A) | v (m/sec) |
|---|---|---|---|
| 300 | 25 | 1.6 | 2200 |
| 20 | 2 | 6.4 | 550 |

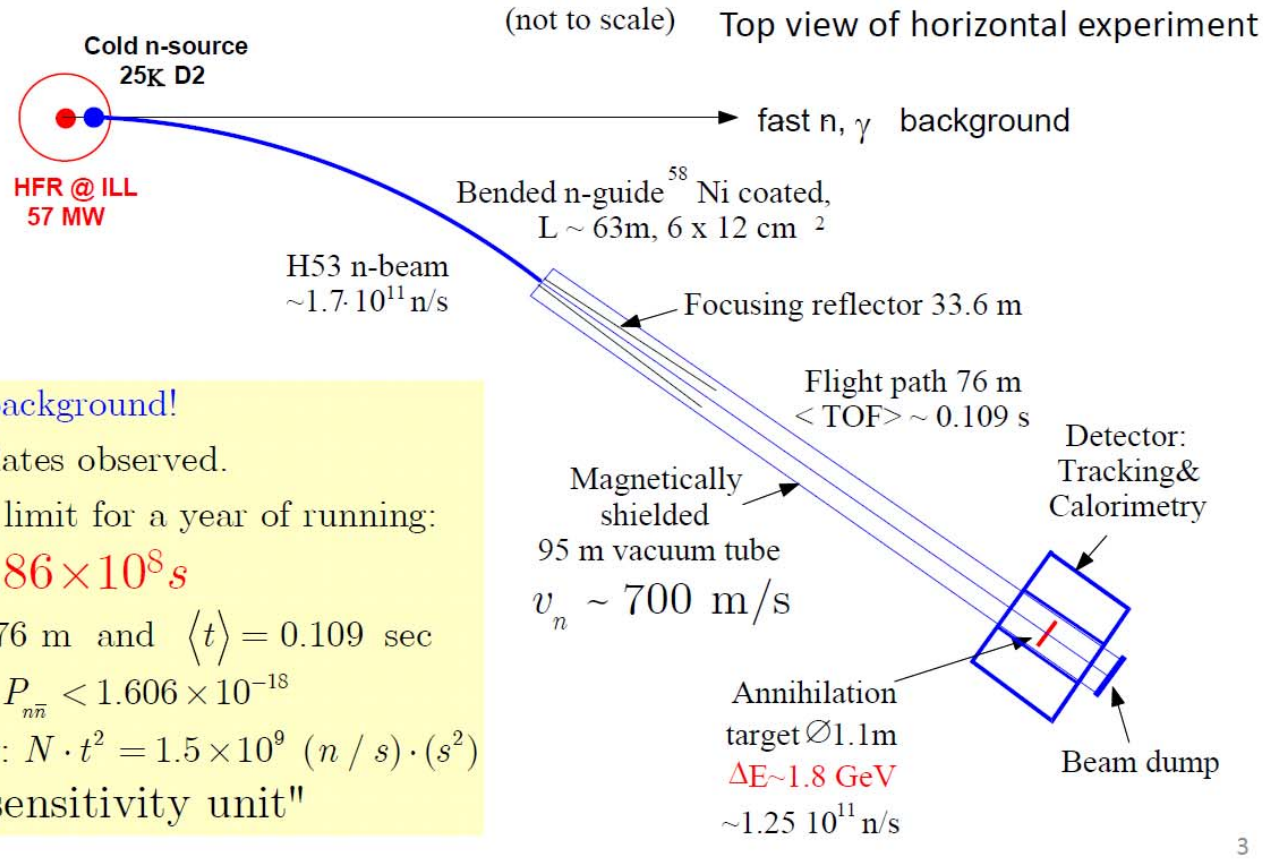



**Mike Snow, PXPS**

# Previous n-nbar search experiment with free neutrons

## At ILL/Grenoble reactor in 89-91 by Heidelberg-ILL-Padova-Pavia Collaboration

**Z. Phys., C63 (1994) 409**




No GeV background!

No candidates observed.

Measured limit for a year of running:

$\tau_{n\bar{n}} > 0.86 \times 10^8 s$

with L ~ 76 m and $\langle t \rangle = 0.109$ sec

measured $P_{n\bar{n}} < 1.606 \times 10^{-18}$

sensitivity: $N \cdot t^2 = 1.5 \times 10^9 \ (n / s) \cdot (s^2)$

$\doteq$ "ILL sensitivity unit"

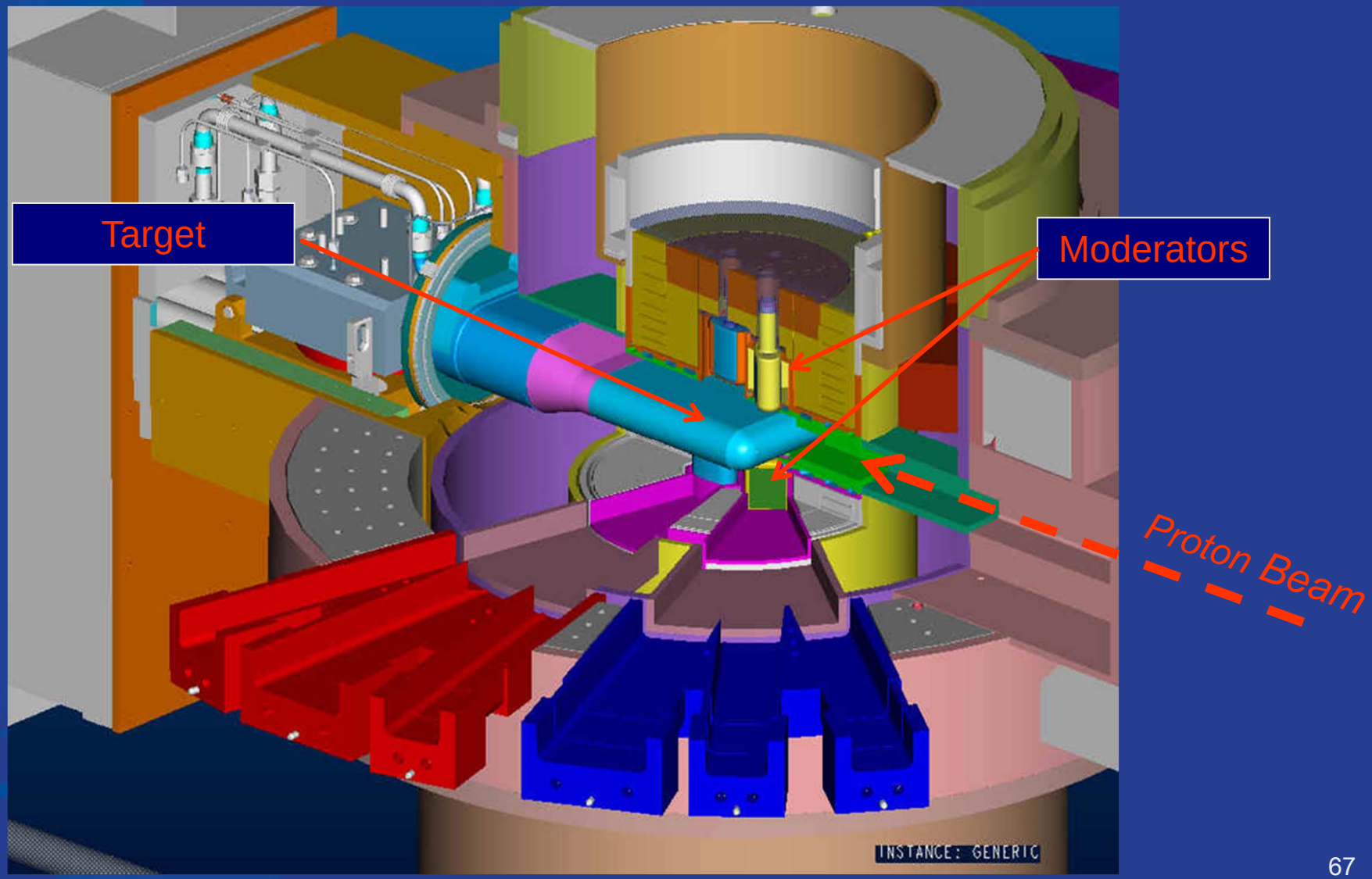
**Dubbers, Kamyshkov PXPS**

# Summary-
# The High Intensity Horizon…

- Project-X is a staged evolution of the best assets of the Fermilab accelerator complex with the revolution in super-conducting RF technology.
- Each Stage of Project-X will raise many boats of the Intensity Frontier in particle physics, with a program scope of more than 20 world-leading particle physics experiments and an associated robust user community.
- The work done and started at PXPS-2012 is a very important foundation for further developing and advancing the research program. This is a good beginning for the "Snowmass" process.

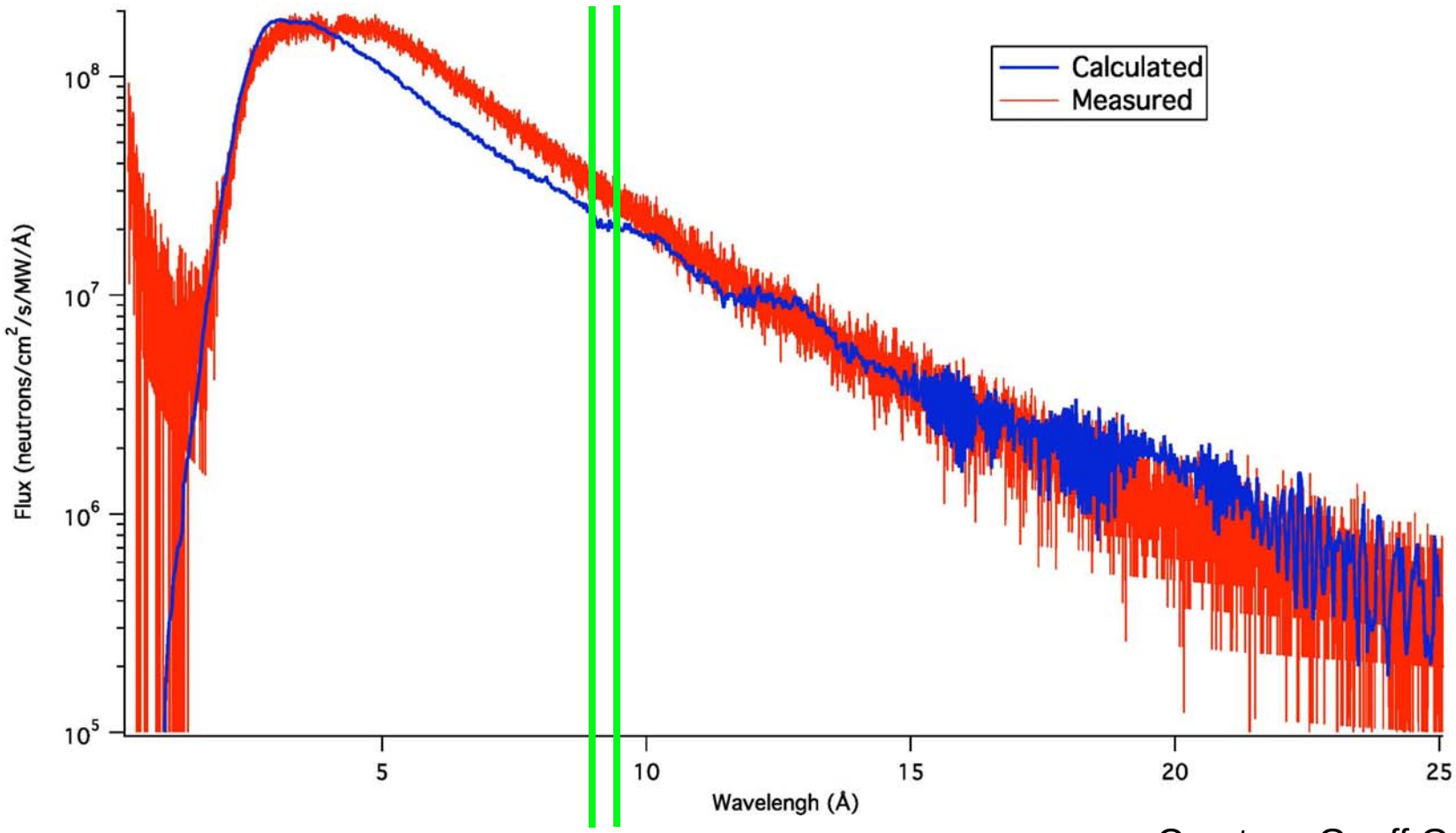
# Spare Slides

# ORNL SNS Spallation target




Courtesy Geoff Greene

*nEDM requires a very narrow wavelength slice at 8.9Å*




Courtesy Geoff Greene

*Only neutrons in this band are efficiently downs-scattered by superfluid $^4$HE to give UCN*