Future Intensity Frontier Initiatives in the US Particle Physics Program

R. Tschirhart
Fermilab

KITP
Snowmass on the Pacific
May 29th 2013

Material drawn from the Ongoing Snowmass Experience in 2013. A fraction of the IF activity…

- February: Winter Workshop on Electric Dipole Moments, Fermilab.
- March: Neutrino Working group meeting, SLAC.
- April: Snowmass Workshop on Frontier Capability, BNL.
- April: Intensity Frontier All Hands Meeting, ANL.
- April: KAON-2013, Ann Arbor Michigan.
- May: First International Conference on Charged Lepton Flavor Violation, Lecce, Italy.
- May: International Symposium on Opportunities for Underground Physics in Snowmass, Asilomar, Ca.
- July: Journey through the Frontiers, SSI-2013, SLAC.
- July: Workshop on Neutrino Physics and Astrophysics, Lead/Deadwood, SD.
- July-Aug: SNOWMASS on the Mississippi.

A Vibrant Community…

Facility subpanel recommendations accepted by the High Energy Physics Advisory Panel: HEPAP

- LBNE: Stage 1 begins a world leading program in neutrino physics +… . Science reach of Stage 1 is *important* and it lays the groundwork for an *absolutely central* facility. *Ready for construction,* planned start in 2016 and completed in 2023.
- MU2E: Will search for muon to electron conversion in the field of a nucleus with unparalleled sensitivity. It is *absolutely central. Ready for construction* starting in 2014, completed in 2018.
- PROJECT X: Unique world leading facility at Fermilab for intensity frontier physics. It is *absolutely central* and although it is pre CD0 it is *ready for construction*.
- nuSTORM: Muon storage ring that would provide neutrino beams with well defined flavor composition and spectrum. While the committee is not aware of major technical challenges in realizing nuSTORM, its performance *requirements are not yet fully defined*. While nuSTORM has great potential we *don't know enough* yet to assess nuSTORM's role in US world-leading science.

Mark Wise, HEPAP March 11th 2013

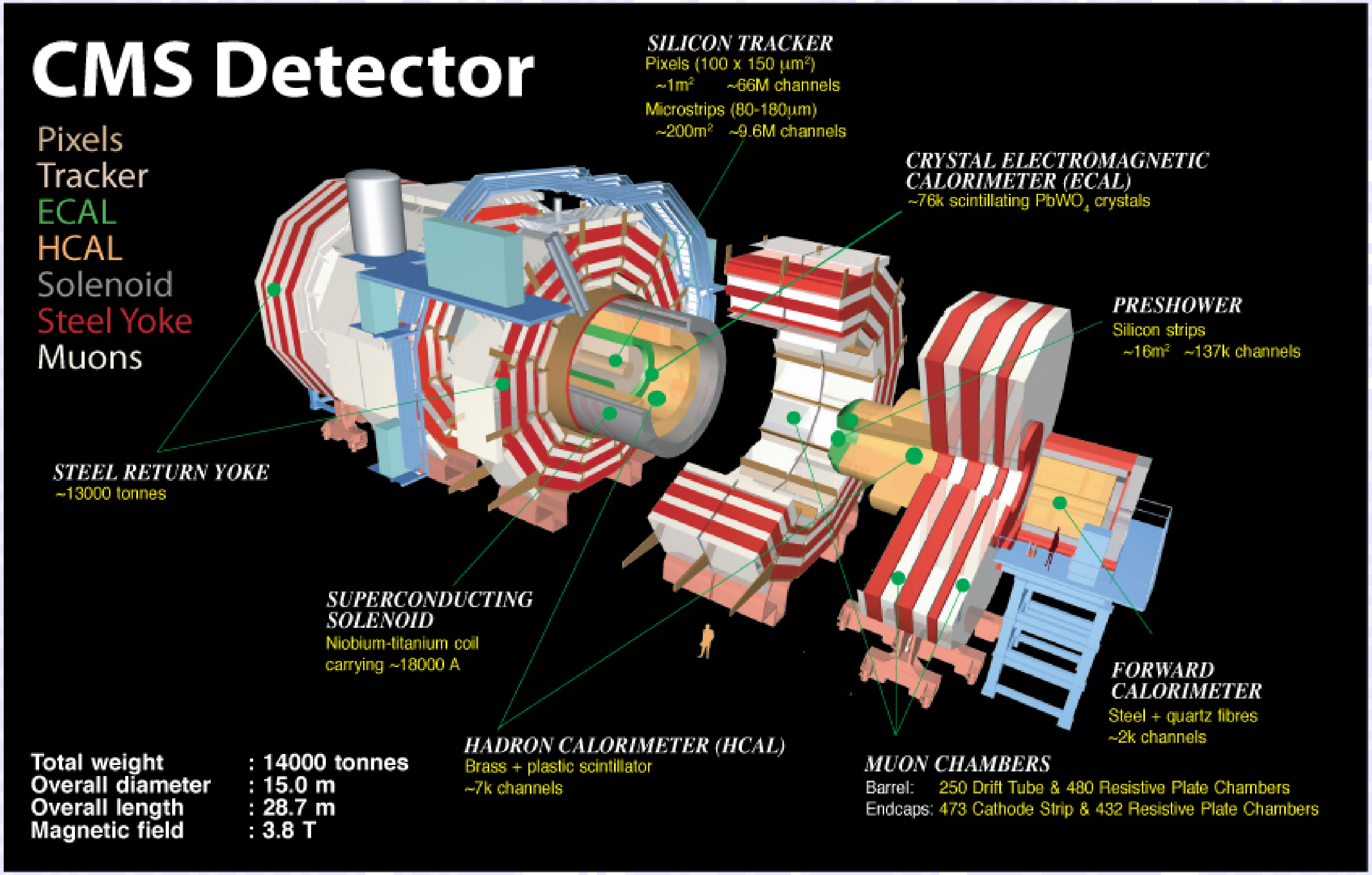
In the absence of new facilities enabling new experiments…

From Hitoshi Murayama , ICFA October 2011

Intensity Frontier Killer App?
Not a single experiment!
The science requires multiple probes.

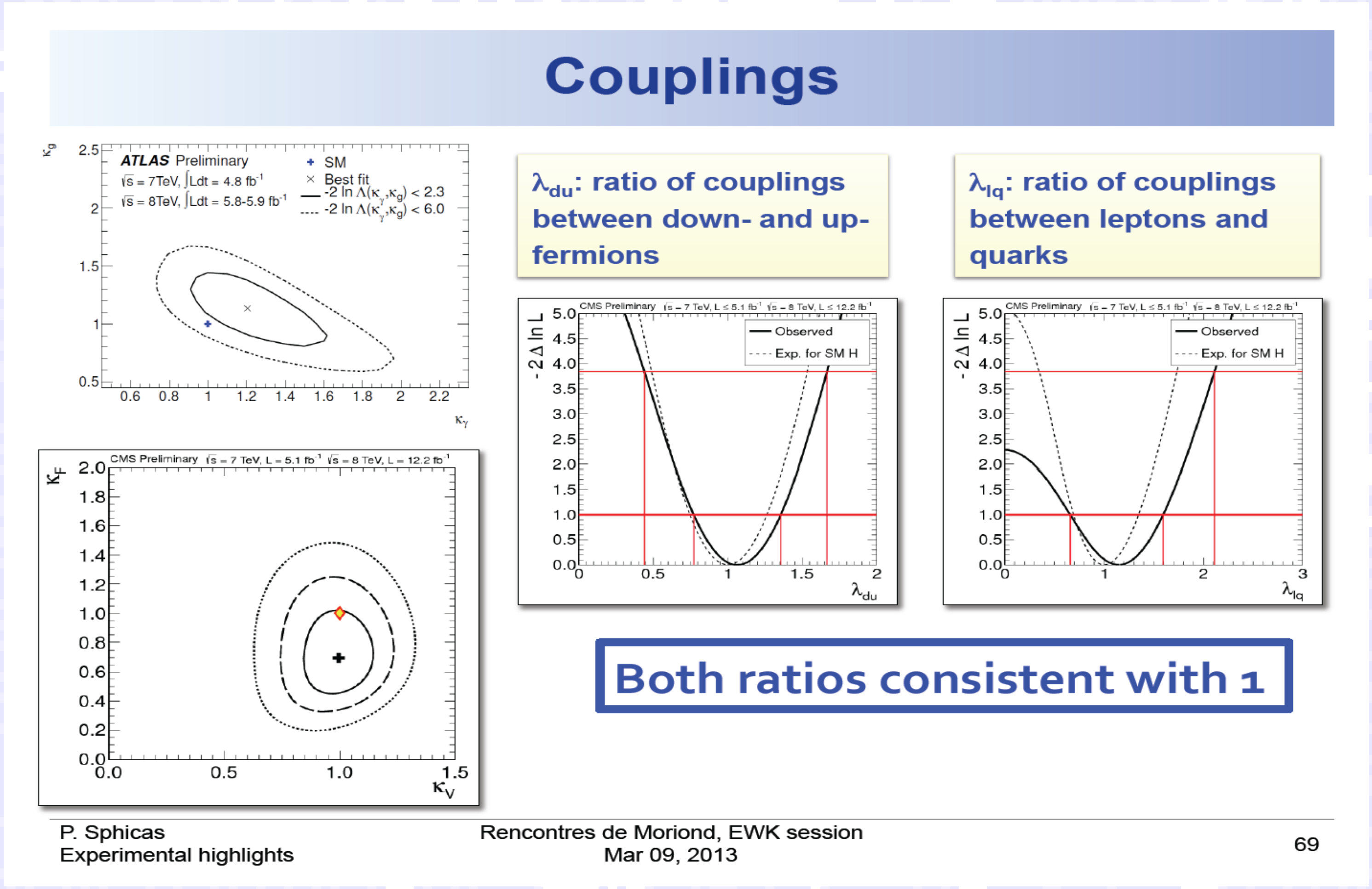
Modified from Hitoshi Murayama , ICFA October 2011

What sub-detector in CMS or ATLAS is the Killer App?



What sub-detector in CMS or ATLAS is the Killer App?

For Discovery of the Standard Model Scalar??



CSS13 Working Groups

SLAC

Quark Flavor Physics:
Joel Butler, Zoltan Ligeti, Jack Ritchie

K, D & B Meson decays/properties

Charged Lepton Processes
Brendan Casey, Yuval Grossman, David Hitlin

Precision measurements with muons, taus

Neutrinos
Andre deGouvea, Kevin Pitts, Kate Scholberg, Sam Zeller

All experiments for properties of neutrinos. Accelerator & non-accel.

Baryon Number Violation
Kaladi Babu, Ed Kearns

Proton decay, Neutron Oscillation

New Light, Weakly Coupled Particles
Rouven Essig, John Jaros, William Wester

“Dark” photons, paraphotons, axions, WISPs

Nucleons, Nuclei & Atoms
Krishna Kumar, Z.-T. Lu, Michael Ramsey-Musolf

Properties of nucleons, nuclei or atoms (EDM), as related to HEP

J. Hewett, IF All Hands Meeting at ANL.

Quark Flavor Physics

The Experimental Quark Flavor Program

Kaons

- KLOE-2
- NA62
- TREK
- KOTO
- ORKA
- Project X experiments

Proposed in U.S.

B-physics

- Belle II
- LHCb + Upgrade
- ATLAS/CMS

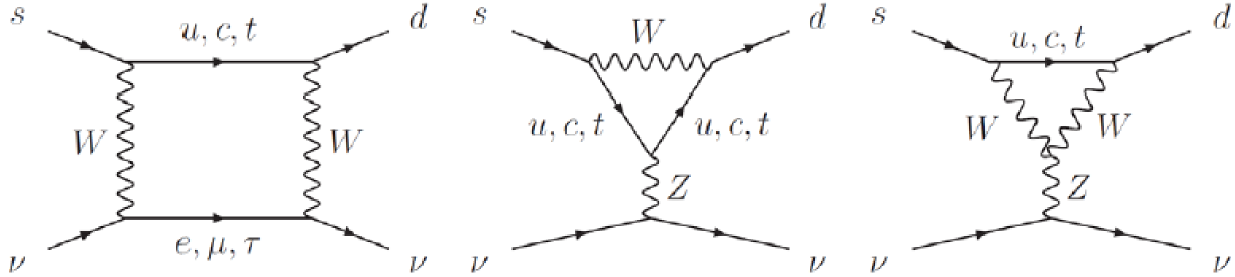
Charm

- Belle II
- LHCb
- ATLAS/CMS
- BESIII
- Panda
- Future τ/c factories

There is not time to discuss everything in this talk.

J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

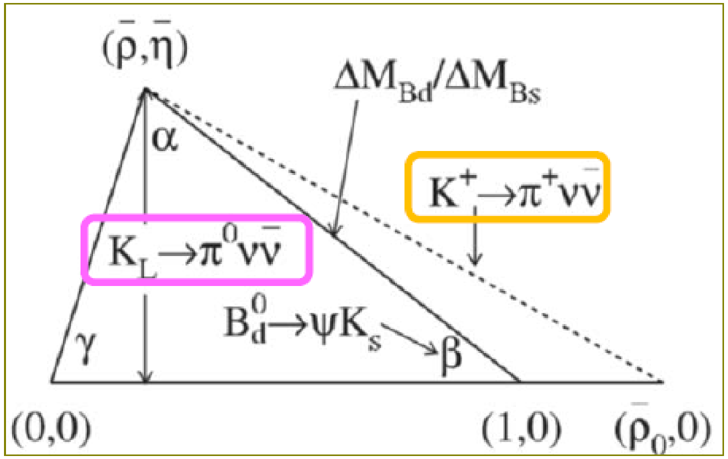
$K \to \pi\nu\bar{\nu}$ in the Standard Model



- A single effective operator

  $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$

- Dominated by top quark
- Hadronic matrix element shared with $K \to \pi e \nu$
- Standard Model predictions precise



$$B(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (7.8 \pm 0.8) \times 10^{-11} \quad \pm 10\% \Rightarrow \pm 5\%$$

$$B(K_L^0 \to \pi^0 \nu\bar{\nu})_{SM} = (2.4 \pm 0.4) \times 10^{-11} \quad \pm 16\% \Rightarrow \pm 11\%$$

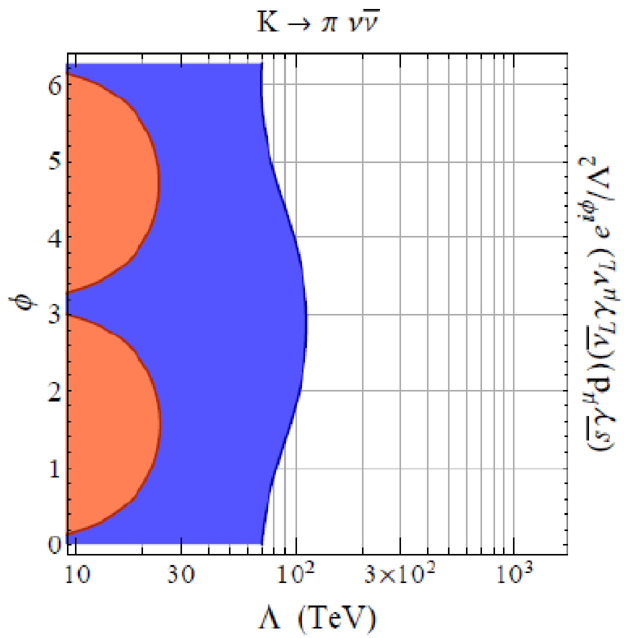
Brod, Gorbahn, and Stamou, PR D **83**, 034030(2011)

- Largest uncertainty from CKM elements (which will improve)
- Remains clean in New Physics models

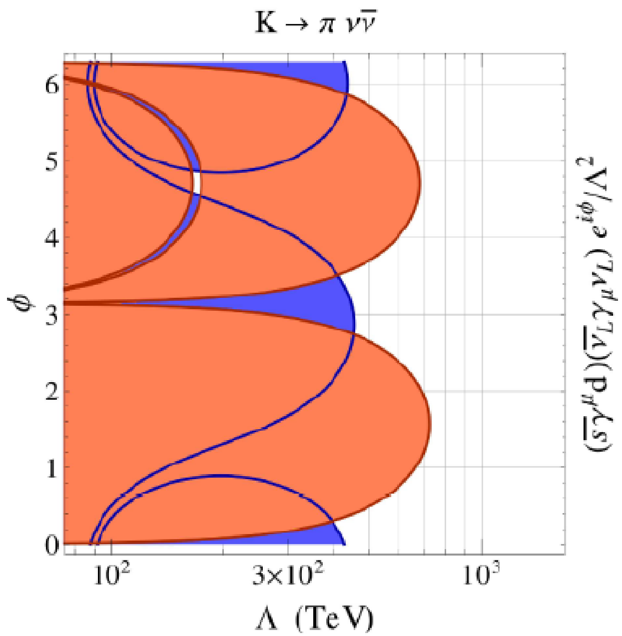
J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

$$(\bar{s}\gamma^{\mu}d)(\overline{\nu_L}\gamma_{\mu}\nu_L)\, e^{i\phi}/\Lambda^2$$

current situation



assuming 5% measurements of both modes



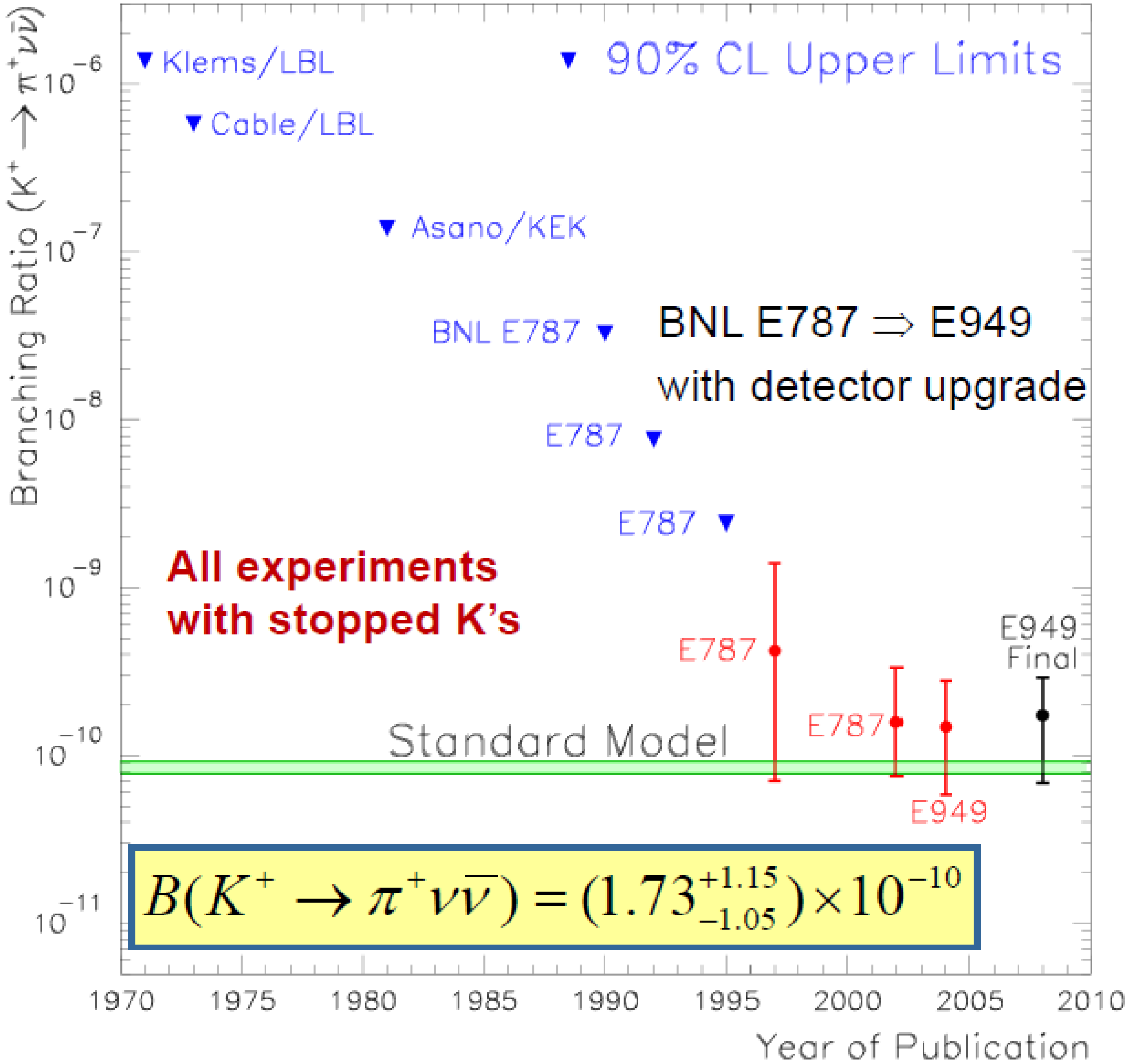
- $K^+ \to \pi^+\nu\bar{\nu}$ already constrains scales of $\sim$ 100 TeV
- $K_L \to \pi^0\nu\bar{\nu}$ bound still above the Grossman-Nir bound $\to$ no additional constraint

- $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ give complementary information
- scales of order 700 TeV are probed

Slide from Wolfgang Altmannshofer's talk

J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

$K^+ \to \pi^+ \nu\bar{\nu}$ History



$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

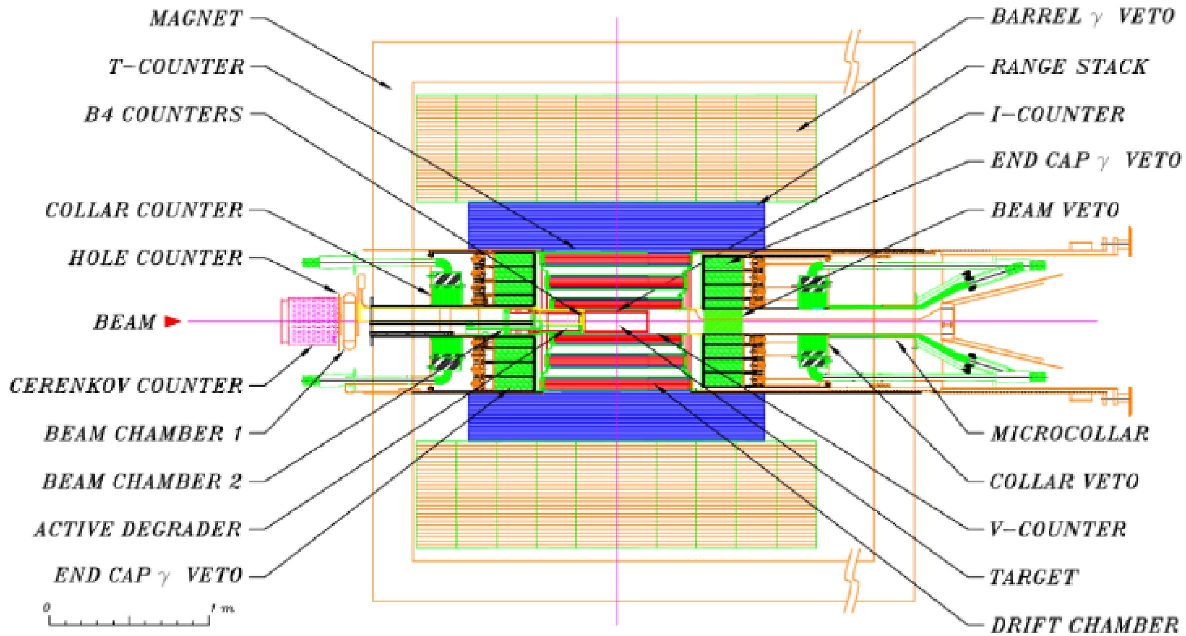
BNL E787/949 observed a total of 7 signal events.

J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

$K^+ \to \pi^+ \nu \bar{\nu}$ at Fermilab

ORKA

PROPOSED

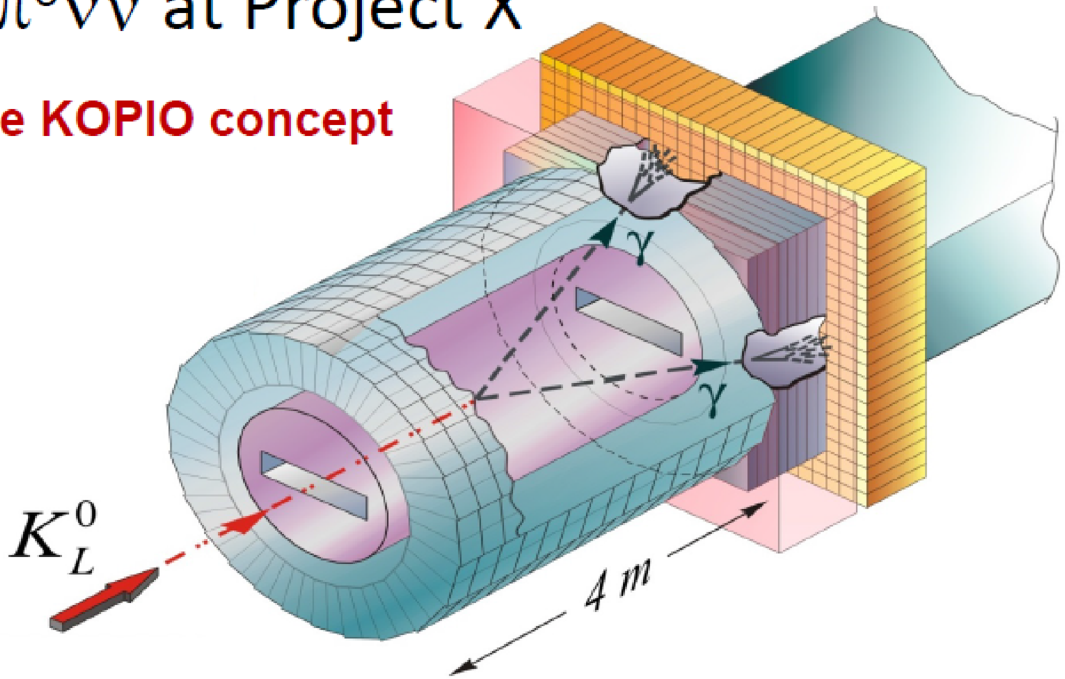


- Will employ the proven technique (stopped K) from BNL E787/949, with beam, detector, and data acquisition improvements
  - Goal to collect 1000 events, ~200 events per year (error ≅ theory)
  - Does not require better background rejection than E949
- Will utilize existing facilities and infrastructure at FNAL (Main Injector protons, B0/CDF Hall, CDF superconducting solenoid)

J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

$K_L \to \pi^0 \nu \bar{\nu}$ at Project X

Based on the KOPIO concept



- Project-X beam energy is well-suited
- CW-linac time structure supports time-of-flight measurement
  - Provides kinematic info for background rejection
- High intensity from Project-X allows small beam (like KOTO)
  - 2-dimn constraint provides additional background rejection
- Reconstruct $\pi^0 \to \gamma\gamma$ with a pointing calorimeter
- 4π photon and charged particle vetos
- Provides opportunity for a high statistics (~1000 event) measurement

J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

Kaon Projections

a few K observables

Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu})$	7.8×10^{-11}	$1.73^{+1.15}_{-1.05} \times 10^{-10}$	∼10% measurement from NA62 ∼5% measurement from ORKA ∼2% with Project X
$\mathcal{B}(K^0_L \to \pi^0 \nu\overline{\nu})$	2.43×10^{-11}	$< 2.6 \times 10^{-8}$	1^{st} observation from KOTO ∼5% measurement with Project X
$\mathcal{B}(K^0_L \to \pi^0 e^+ e^-)_{SD}$	1.4×10^{-11}	$< 2.8 \times 10^{-10}$	∼10% measurement with Project X
$\mathcal{B}(K^0_L \to \pi^0 \mu^+ \mu^-)_{SD}$	3.5×10^{-11}	$< 3.8 \times 10^{-10}$	∼10% measurement with Project X
$\lvert P_T \rvert$ in $K^+ \to \pi^0 \mu^+ \nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 from TREK < 0.0001 with Project X
$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$	2.477×10^{-5}	$(2.488 \pm 0.080) \times 10^{-5}$	$\pm 0.054 \times 10^{-5}$ from TREK $\pm 0.025 \times 10^{-5}$ with Project X
$\mathcal{B}(K^0_L \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ with Project X

From the Report of the Heavy Quarks working group, Fundamental Physics at the Intensity Frontier (2012), arXiv:1205.2671

April 27, 2013 Argonne IF Workshop 21

J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

Message for Snowmass

- Flavor physics probes far above the TeV scale.
  - A necessary complement to LHC if new physics is found there.
  - Probes above the reach of LHC and other foreseeable machines.
- Existing facilities at Fermilab can support unparalleled rare K decay experiments (ORKA, and potentially others).
  - A cost effective way to mount quark-flavor experiments in **this** decade with significant potential to uncover new physics.
  - This opportunity is not open-ended (the world won't wait).
- Project X can open a new regime of sensitivity for rare K decay experiments in the next decade.
  - An order of magnitude beyond other kaon sources in the world.
- B-physics and charm physics will be led by non-U.S. programs for the foreseeable future.
  - These programs will do great physics! The U.S. should be actively involved in these experiments (Belle II and LHCb).

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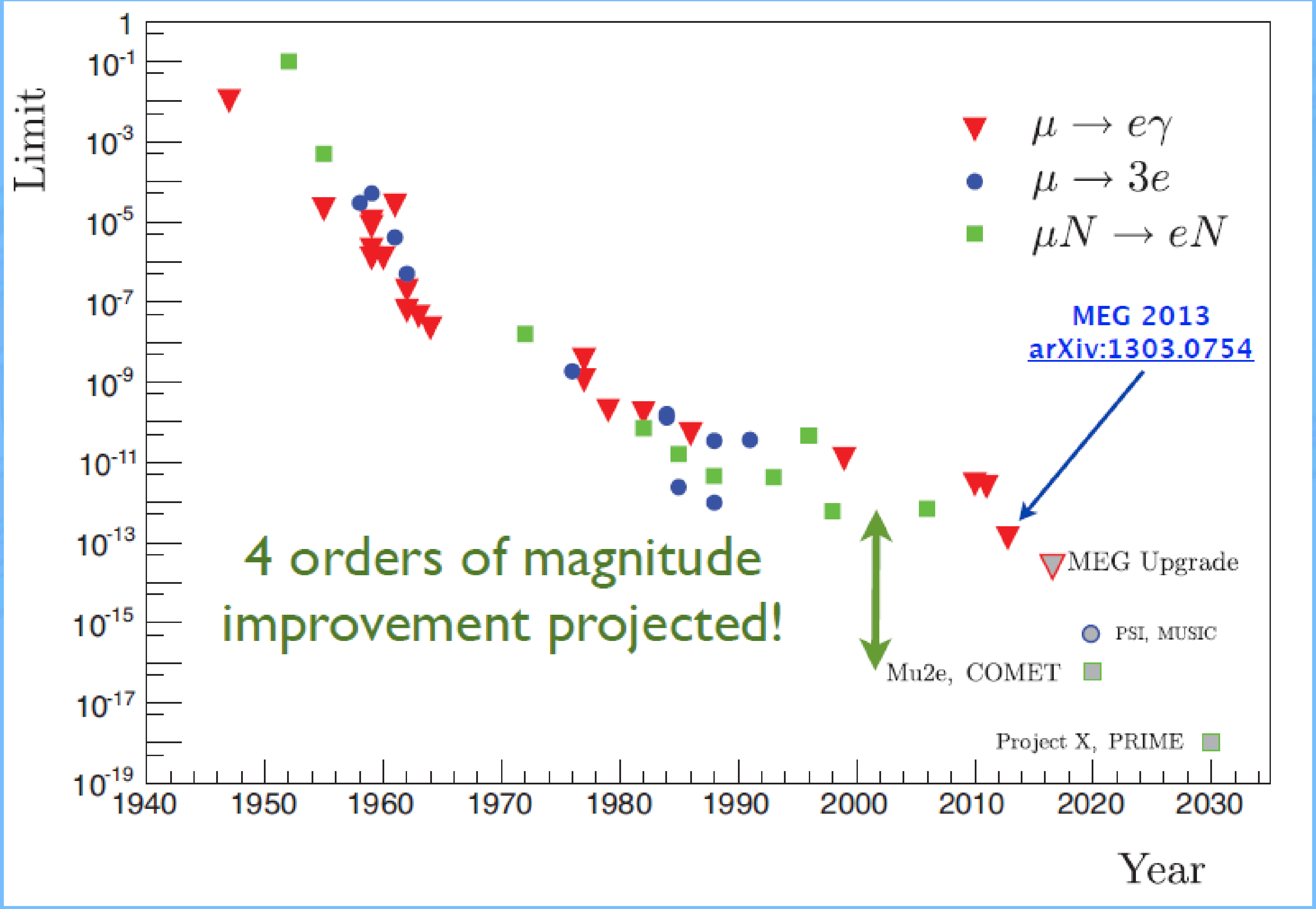
J. Ritchie, QFP Summary, IF All Hands Meeting at ANL.

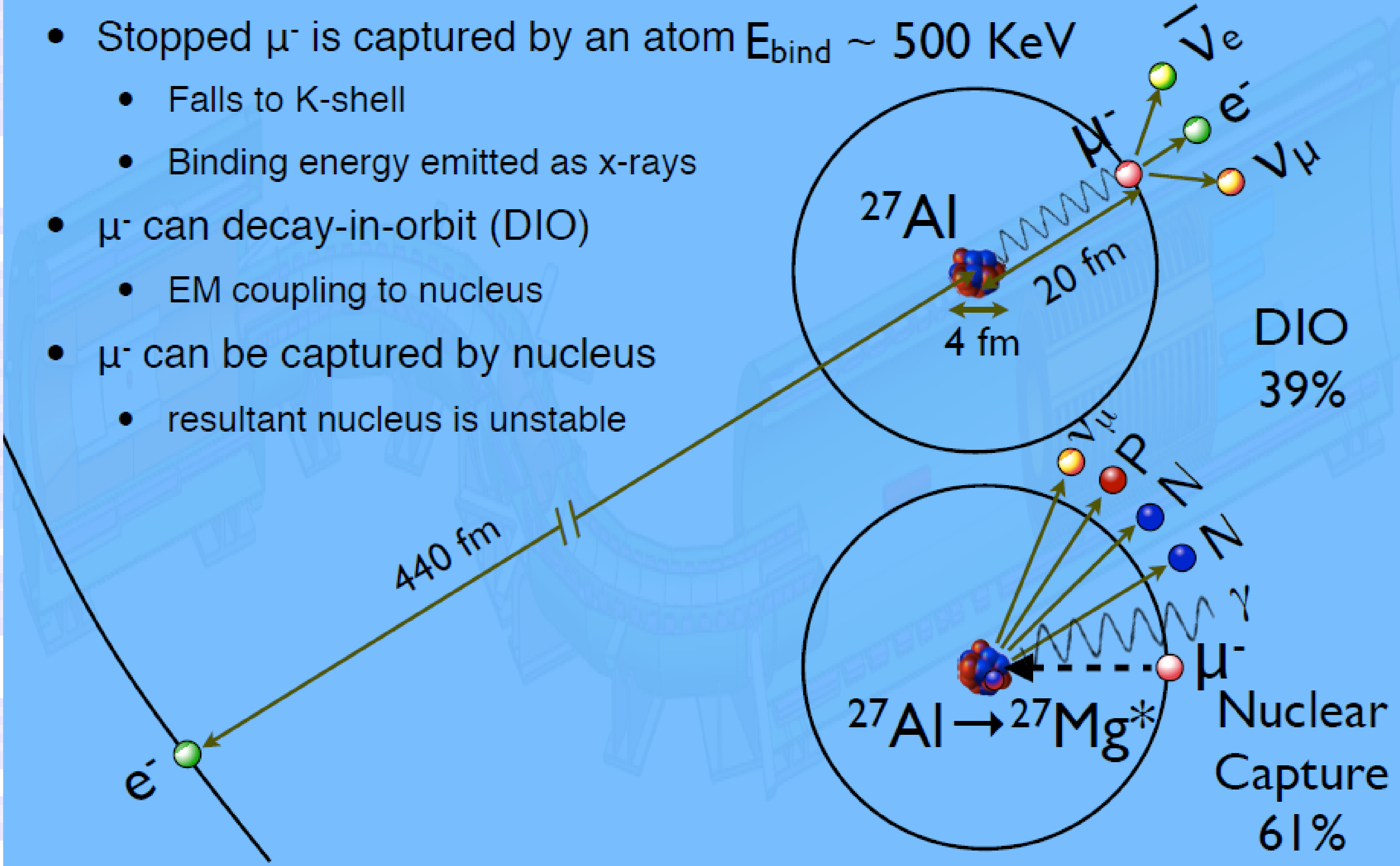
Charged Lepton Processes

Status of CLFV Searches



Atomic Capture of μ^-

- Stopped μ^- is captured by an atom E_{bind} ~ 500 KeV
  - Falls to K-shell
  - Binding energy emitted as x-rays
- μ^- can decay-in-orbit (DIO)
  - EM coupling to nucleus
- μ^- can be captured by nucleus
  - resultant nucleus is unstable

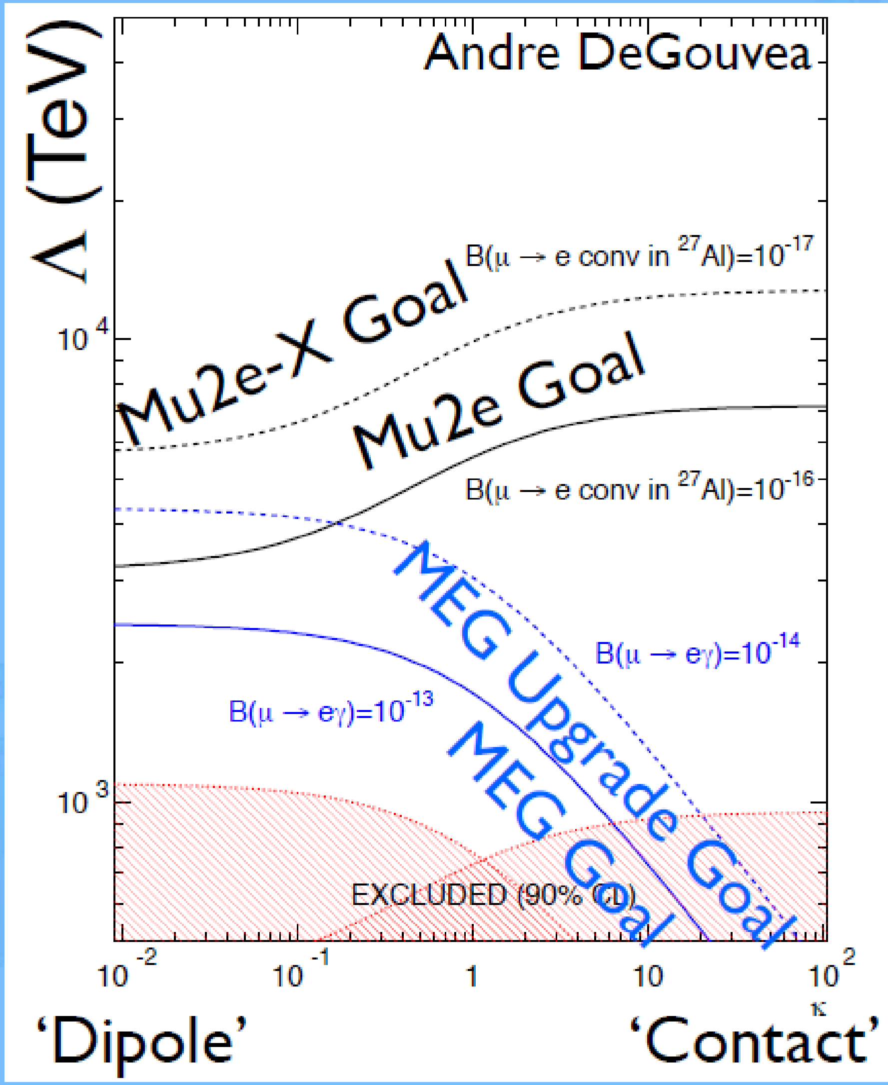


The Mu2e Experiment

- Goal: Discover $\mu N \rightarrow eN$ conversion
- Target sensitivity: $R_{\mu e} = 6\times10^{-17}$ @ 90% C.L.
  - 4 orders of magnitude better than current limits
- Requires ~ 10^{18} stopped muons
  - ~ 4×10^{20} protons on target (3 year run @ 8 KW)
- Requires negligible (<1) background events
- Many challenges for the beamline and detector design

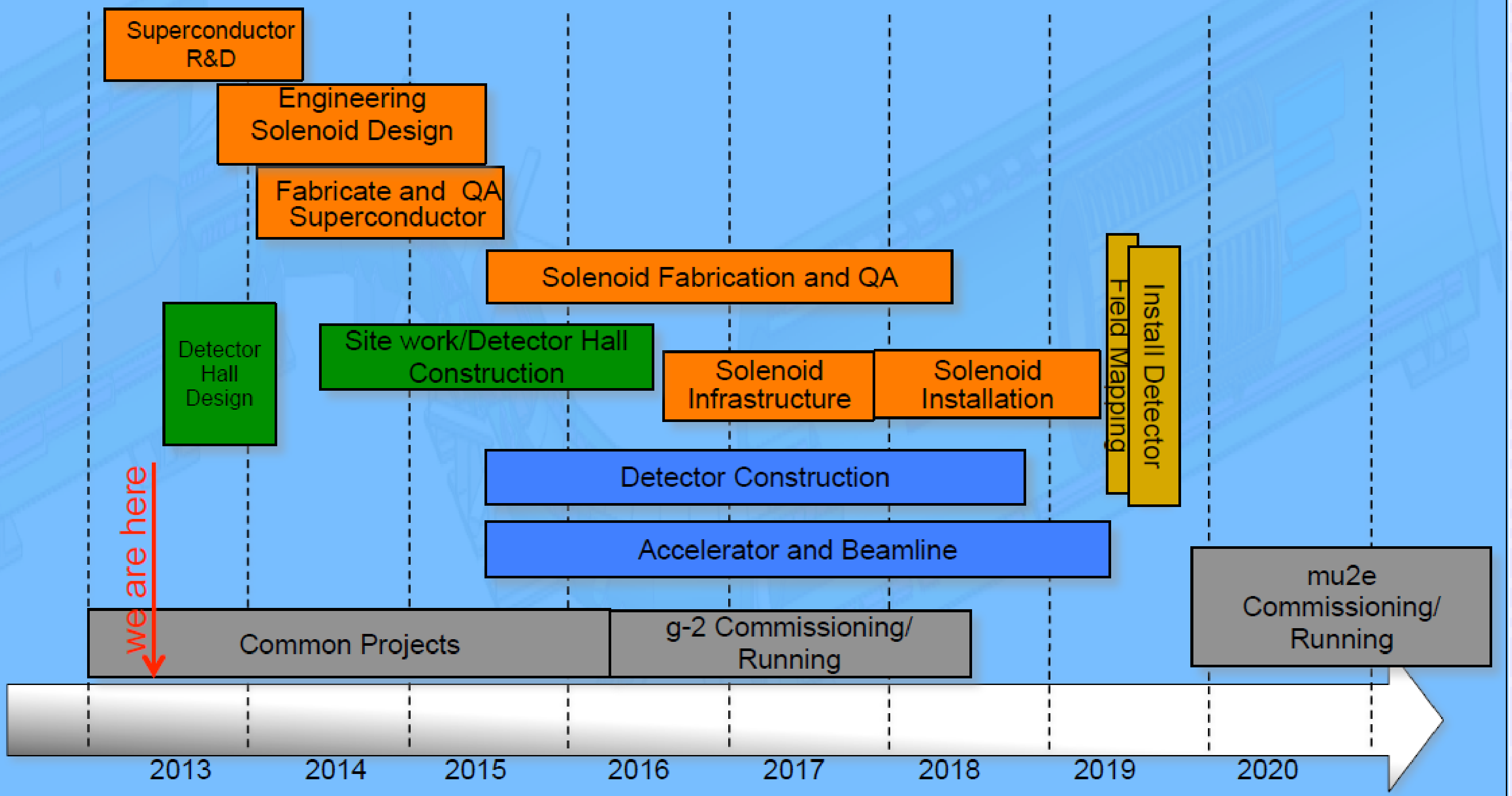
CLFV Sensitivity

- Effective mass scales up to 10^4 TeV are accessible
- Mu2e is sensitive over the full κ range

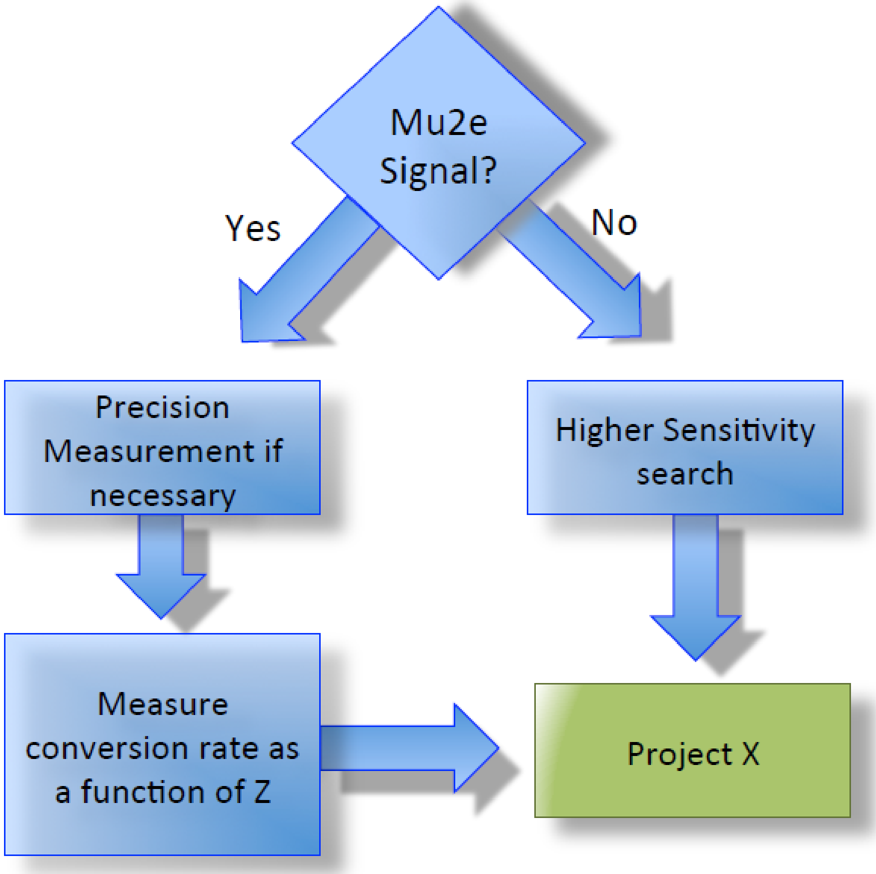


Mu2e Project Status

- Schedule is technically limited



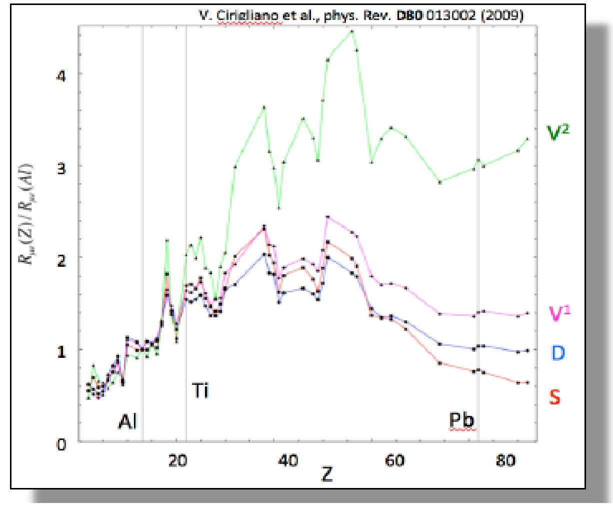
First Phase of Mu2e

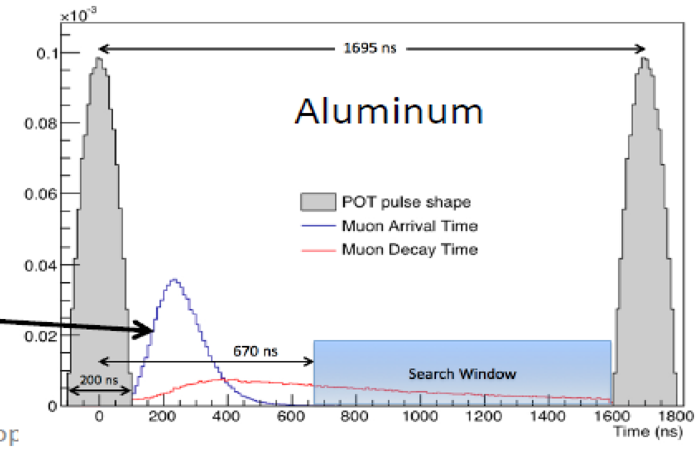


Mu2e Sees a Signal

- If Mu2e sees a signal in its initial run, next step is to map out conversion rate for various target nuclei where model dependent effects vary by a factor of 3.
- However, muon lifetime varies with Z
  - Big impact on execution of measurement

Nucleus (Z)	Muon Lifetime (ns)
Al(13)	864
Ti(22)	329
Au(79)	73





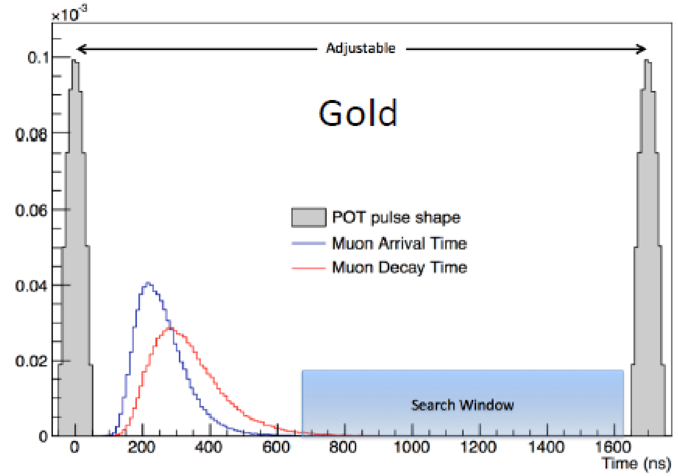
Arrival time of μ/π at stopping target
Increase in muon decays and RPC as one looks earlier in time

April 26, 2013 R. Ray - Intensity Frontier Workshop

Mu2e Sees a Signal

Stage 1 of Project X makes these measurements possible with the existing solenoid system.

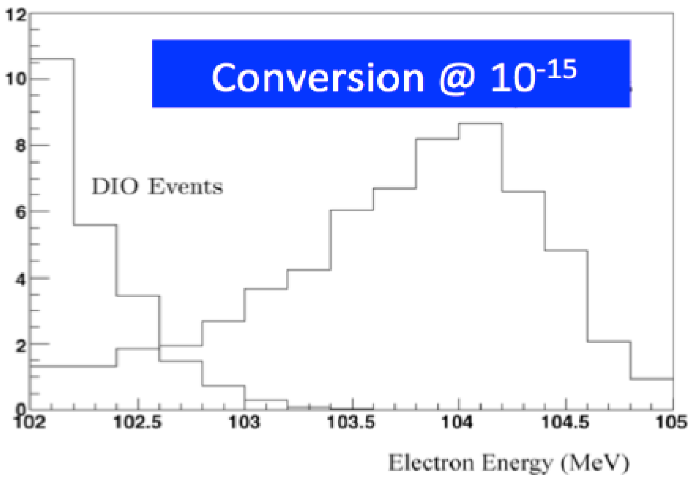
- Narrower proton beam pulse, intrinsic extinction and beam power enables use of stopping targets with shorter muon lifetimes
  - Limit to how early we can search due to muon decay in-flight and RPC background, assuming same background level required.
  - Rely on beam power to wait more muon lifetimes
    - Instantaneous rates decrease with time – reduces backgrounds
  - Flexible time structure allows us to wait longer than 1695 ns if desirable
    - Optimization different for different target nuclei.



Mu2e Does Not See a Signal

Stage I of Project X makes it possible to push the sensitivity another order of magnitude.

- Reductions in background also required. (See Doug Glenzinski's talk)
  - Narrow proton beam pulse and intrinsic extinction provided by Project X reduces prompt backgrounds.
  - No pbar background with 1 GeV protons.
- Improved momentum resolution required to reduce DIO background.



April 26, 2013 R. Ray - Intensity Frontier Work

Neutrinos

Final thoughts on the message for Snowmass

Yuval's talk on first day:

"Once you find an entrance, there will be an explosion in some direction that will carry on for decades"

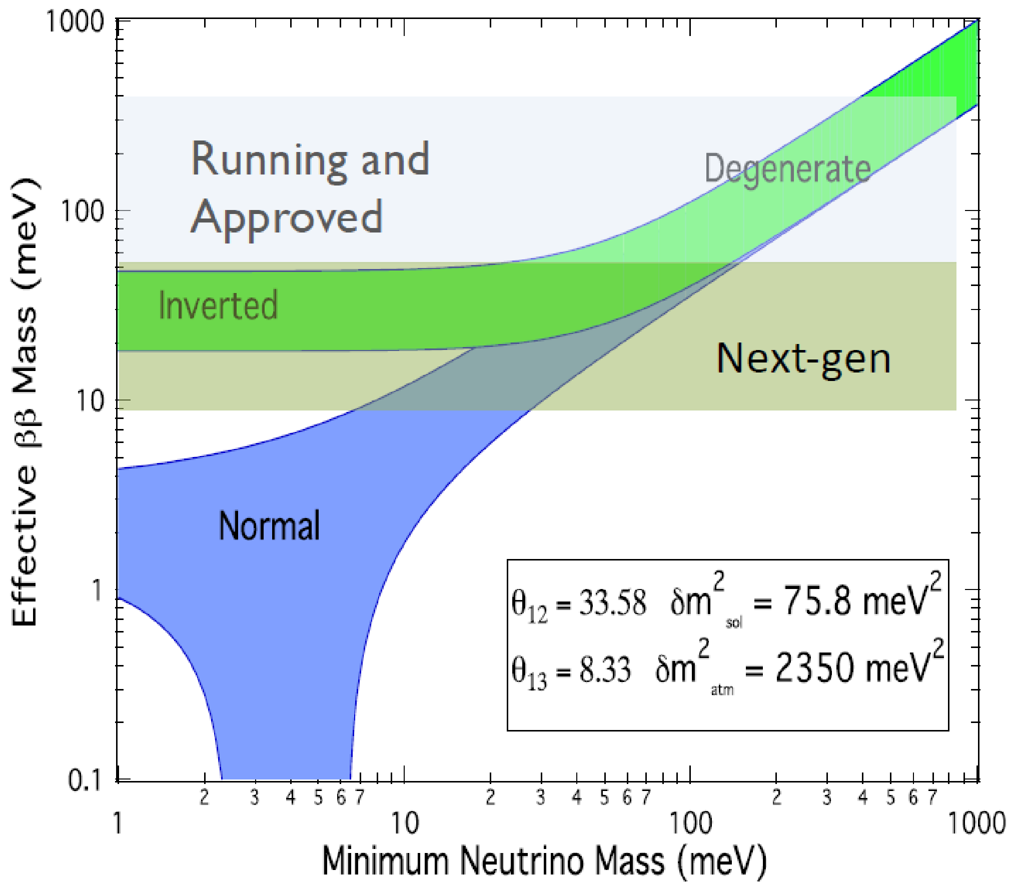
That's happened for neutrinos!

We can build a world-class neutrino program along three lines:

- long-baseline oscillations
- neutrinoless double beta decay
- smaller experiments to search for new physics

Breadth, and connections between Frontiers, are important

Goals for Next-Generation 0νββ



- Majorana vs Dirac
- Absolute Neutrino Mass
- Lepton Number Violation

- Next-generation ββ experiments must cover the entire allowed region of the inverted hierarchy

- Ideas for probing the normal hierarchy exist

Elliot, Kauffman SLAC Snowmass neutrino meeting, March 2013

Several Experiments Running or Nearly Running to get down to 100 meV $m_{\beta\beta}$-scale

- ^{136}Xe
  - EXO-200 and KamLAND-Zen currently running
  - Combined result: $m_{\beta\beta} < 120 - 250$ meV
  - NEXT to be running in 2014
- ^{76}Ge
  - GERDA running
  - MAJORANA DEMONSTRATOR coming online in the next few months
- Tellurium
  - CUORE0 online
  - CUORE online in 2015
- Selenium
  - SuperNEMO Demonstrator online in 2015
- Neodymium
  - SNO+ will come online in 2014

Elliot, Kauffman SLAC Snowmass neutrino meeting, March 2013

Several Ideas to Get US to the Inverted Hierarchy

- Several isotopes and several experiments to exploit them
  - Xenon
    - nEXO (Liquid Xe TPC)
    - NEXT (High pressure Xe Gas EL TPC)
    - KamLAND-Zen
  - Germanium
    - MAJORANA/GERDA
  - Tellurium
    - CUORE/Enriched CUORE
  - Selenium
    - SuperNEMO
  - Molybdenum
    - MOON
  - Neodymium
    - SNO+/Enriched SNO+

Elliot, Kauffman SLAC Snowmass neutrino meeting, March 2013

Theory Issues for $0\nu\beta\beta$

- Support for nuclear theory effort on matrix elements
  - Auxiliary measurements to support understanding the matrix elements
- Support for particle physics theory efforts on exchange mechanism

Elliot, Kauffman SLAC Snowmass neutrino meeting, March 2013

From Michael Salamon at DURA Meeting this week.

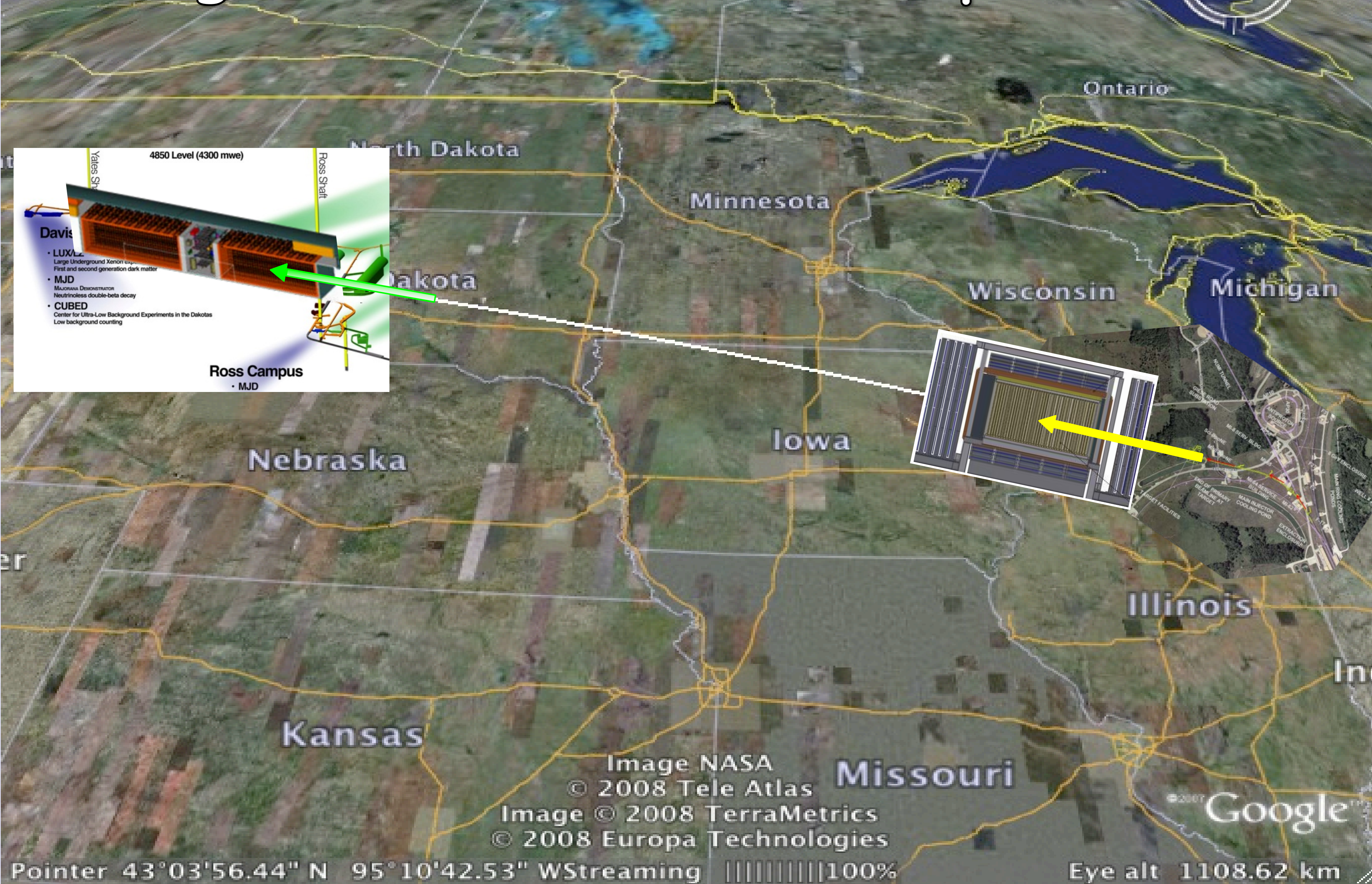
DOE Double Beta Decay: Comments

- DOE/Nuclear Physics is the steward for next-generation double beta decay experiments at DOE.
- DOE/HEP, however, is supporting EXO-200 for historical reasons, along with DOE/NP research and NSF support
- DOE/HEP (along with NSF) also is supporting all the R&D activities for the proposed 1-tonne scale next generation EXO, "nEXO."
- DOE/HEP and NP will establish a joint process to determine a selection process that involves both HEP and NP communities.
- After the time of selection, DOE/NP will become the sole DOE office supporting next-generation DBD projects.

A significant amount of the **technologies** and **facilities** used for double-beta decay overlap with the dark matter community, funded by DOE HEP.

Elliot, Kauffman SLAC Snowmass neutrino meeting, March 2013

Long Baseline Neutrino Experiment



LBNE is…

- A new neutrino beam at Fermilab
  - 700 kW proton beam, 2.3 MW capable
- A near neutrino detector
- An optimal 1300 km baseline: Fermilab-SURF
- A 34 kt Liquid Argon TPC with 4850’ overburden

- This conceptual design…
  - Completed a successful CD-1 Director’s Review (March 2012)
  - Updated cost estimate (July 2012):
    ~$1.5B (incl. contingency + escalation)

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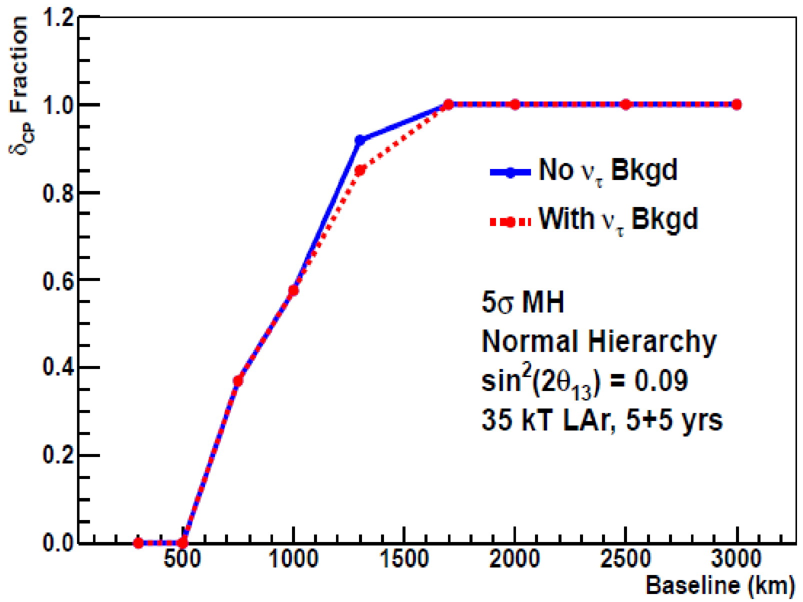

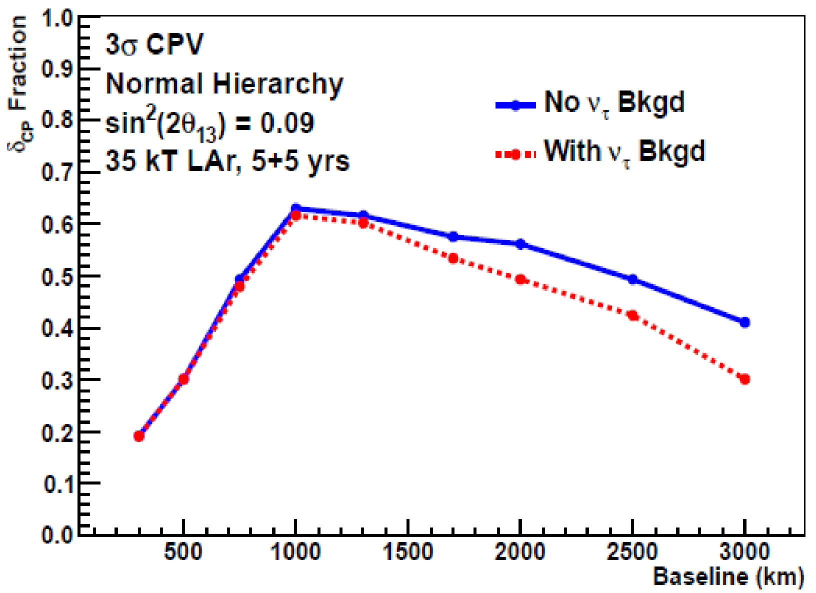

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Staging the Experiment

- March 2012 DOE asked us to stage LBNE construction
- An external review panel considered reconfiguration options including different far sites
  - We accepted the recommendation to proceed with emphasis on the most important aspects: 1300 km baseline and the full capability beam
- December 2012: CD-1 approval for $867M first phase DOE funding
  - We have completed an extensive cost/schedule for 10 kt LAr far detector (LBNE10) on the surface but the design is **not** fixed
  - ***CD-1 approval explicitly allows for scope change enabled by new partners***
- **First phase goal:** *greater than 10 kt* far detector *underground* and a *full capability near detector*
- In the past 3 months there has been considerable progress towards international partnerships (encouraged by European Strategy statement)

LBNE Leadership team, May 2013

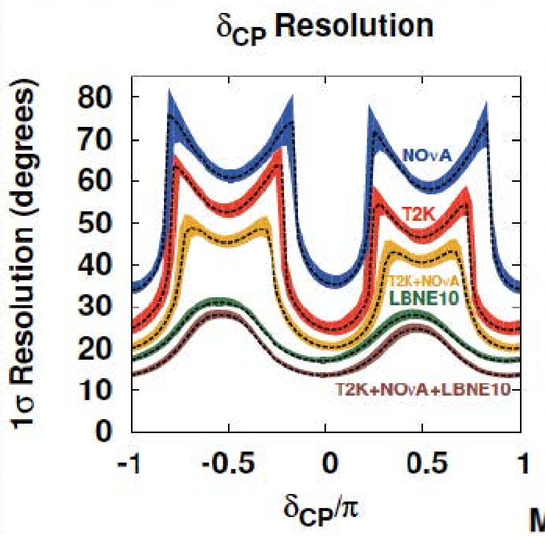
Strawman Plan

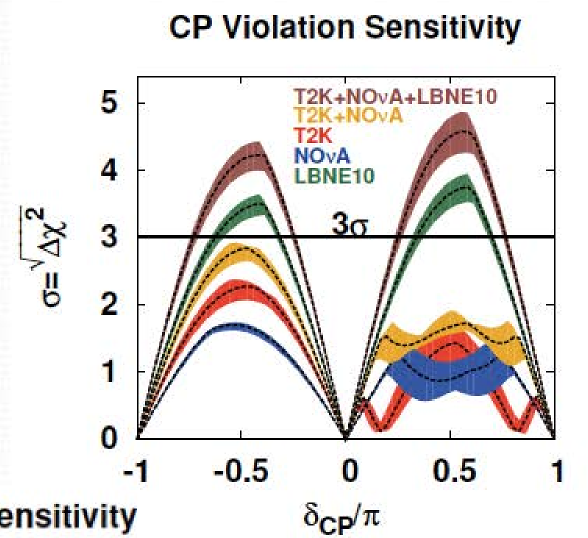
DOE initial investment of $867M

Additional Investment (TPC)	Capability Added	Science Gained	Science Priority
+$140M	Underground placement	ATM nus, p-decay, SNB nus	Very High
+$130-190	Near Detector	Enhanced LB physics, near detector physics	Very High
+$200-350	Add FD mass	Precision CP and other 3-flavor paradigm measurements	Very High

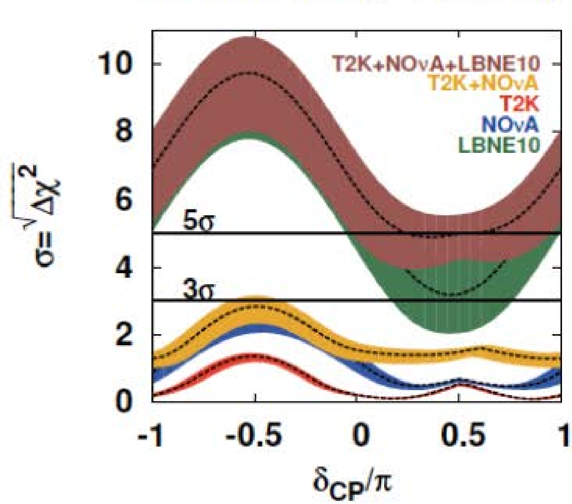
LBNE Leadership team, May 2013

LBNE10 Alone is Major Advance





PRELIMINARY



Bands: 1σ variations of θ_{13}, θ_{23}, Δm_{31}^2
(Fogli et al. arXiv:1205.5254v3)

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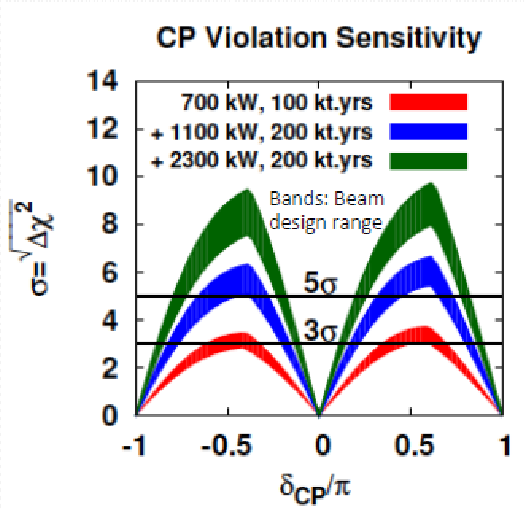
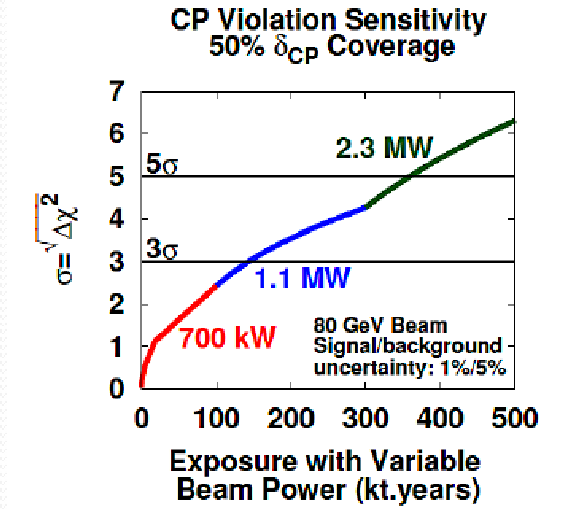
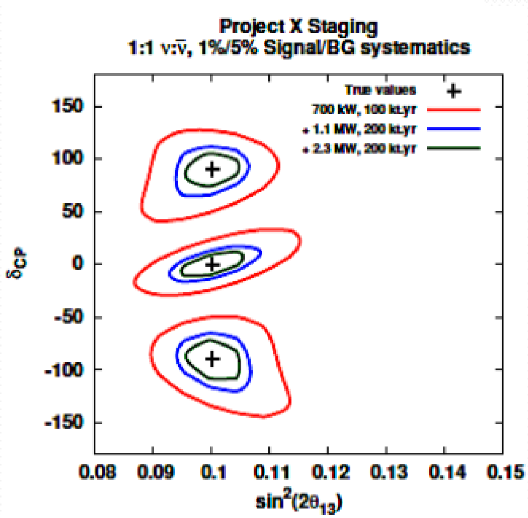
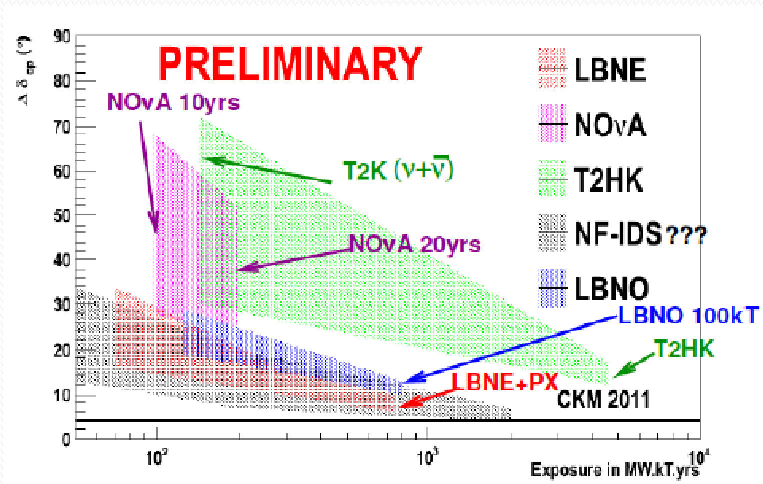
LBNE Leadership team, May 2013

LBNE + Project X is a Full Long-Term Program





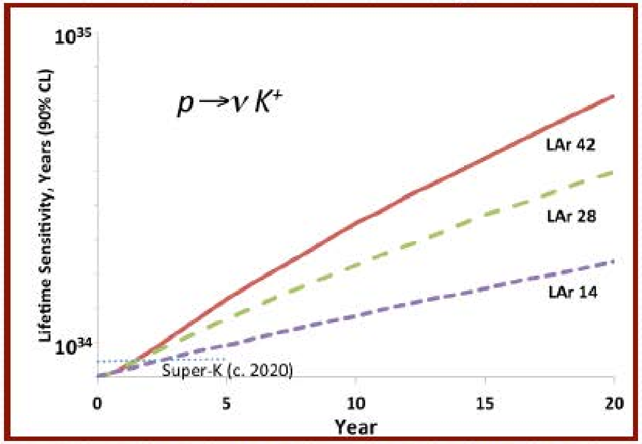




LBNE Leadership team, May 2013

Underground Science

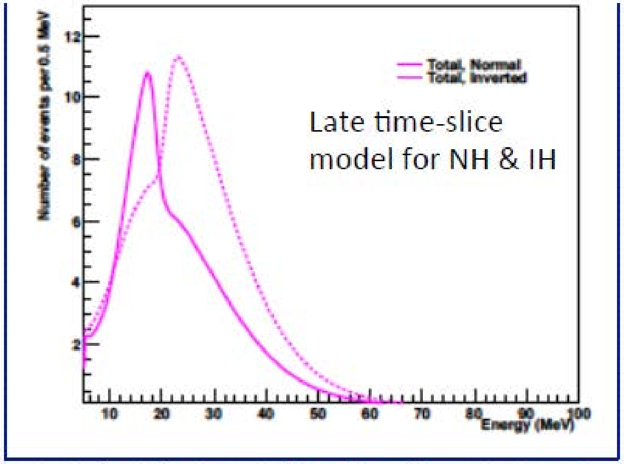
Proton Decay



- LAr has high efficiency for SUSY-favored decay modes
- High spatial precision and energy resolution enable reconstruction of many potential decays modes

Supernova Burst Neutrinos

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



- SN at galactic core (10 kpc) – 1000s interactions in 35 kt LAr in 10s of seconds
- Complementary to WCD
- Fantastic for particle physics and astrophysics (c.f. SN1987A ~dozen events significance)

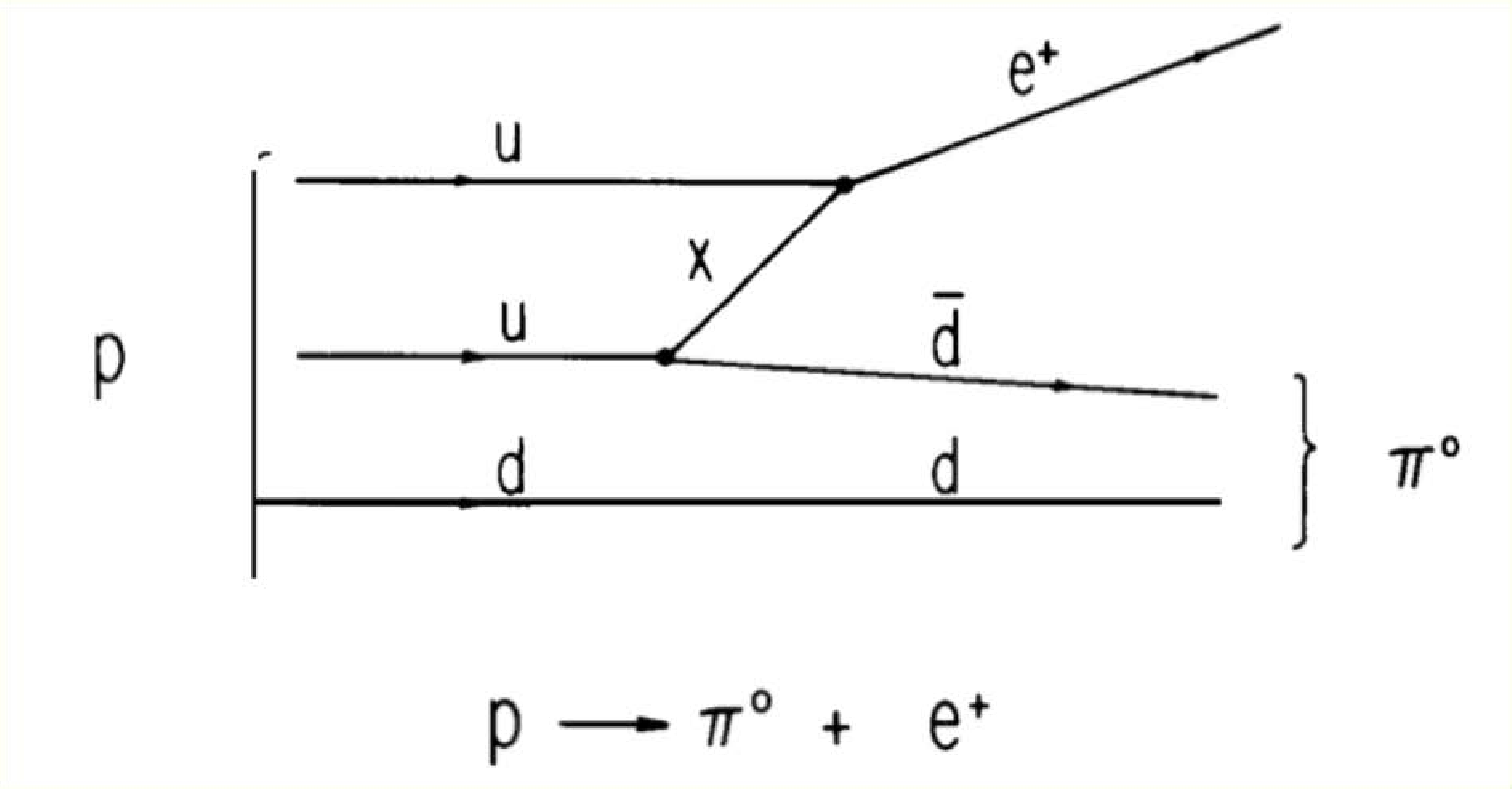
Atmospheric Neutrinos

- Independent determination of mass hierarchy (or add significance to beam measurement)
- θ_{23} octant sensitivity
- Nu-e sensitivity complementary to water Cherenkov detectors (anti-nu-e)

LBNE Leadership team, May 2013

Baryon Number Violation

Proton Decay



Treasure hunt: from which Nobel Lecture is this diagram taken?

Efficiency and Background Rates

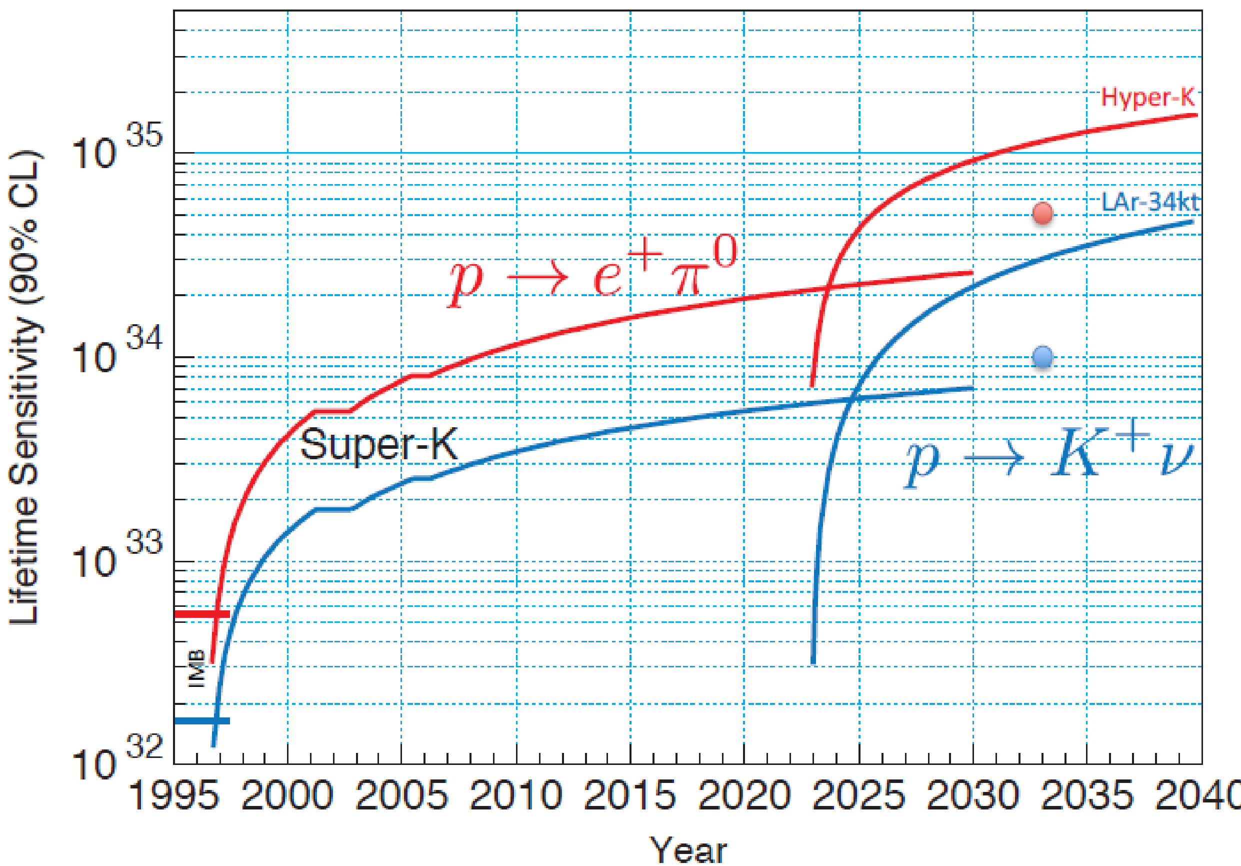
A. Bueno et al.
hep-ph/0701101

		Super-K Water Ch.		LAr (generic)	
	Mode	Efficiency	BG Rate (/Mt y)	Efficiency	BG Rate (/Mt y)
B-L	$e^+\pi^0$	**45%**	**2**	45% (?)	1
B-L	νK^+	15%	2*	**97%**	**1**
B-L	$\mu^+ K^0$	8%	8	**47%**	**<2**
B+L	$\mu^- \pi^+ K^+$	?	?	**97%**	**1**
B+L	$e^- K^+$	10%	3	**96%**	**<2**
$\Delta B=2$	n nbar	12%	260	**?**	**?**

For many modes, high efficiency and low BG rate makes up for smaller mass of Lar detectors

* New analysis (Miura, BLV Heidelberg)

E. Kearns, Intensity Frontier All Hands Meeting, ANL



10 year sample points

τ/B = 5e35
17 evts
1 BG

τ/B = 1e34
9 evts
0.3 BG

~ 0.5 Mt yr exposure by Super-K before next generation experiments

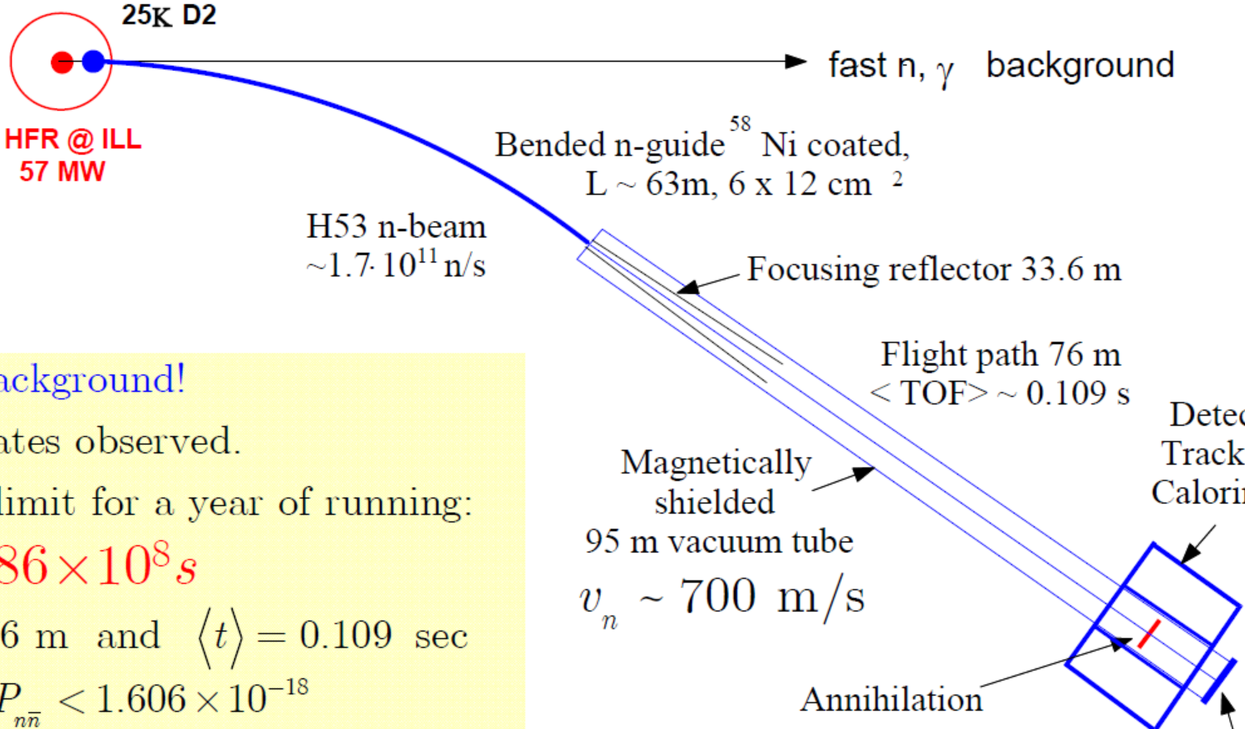
Starting time? Guess 1 decade from now. Adjust starting time as you wish.

E. Kearns, Intensity Frontier All Hands Meeting, ANL

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 Project X Physics Study

Free neutron antineutron oscillation

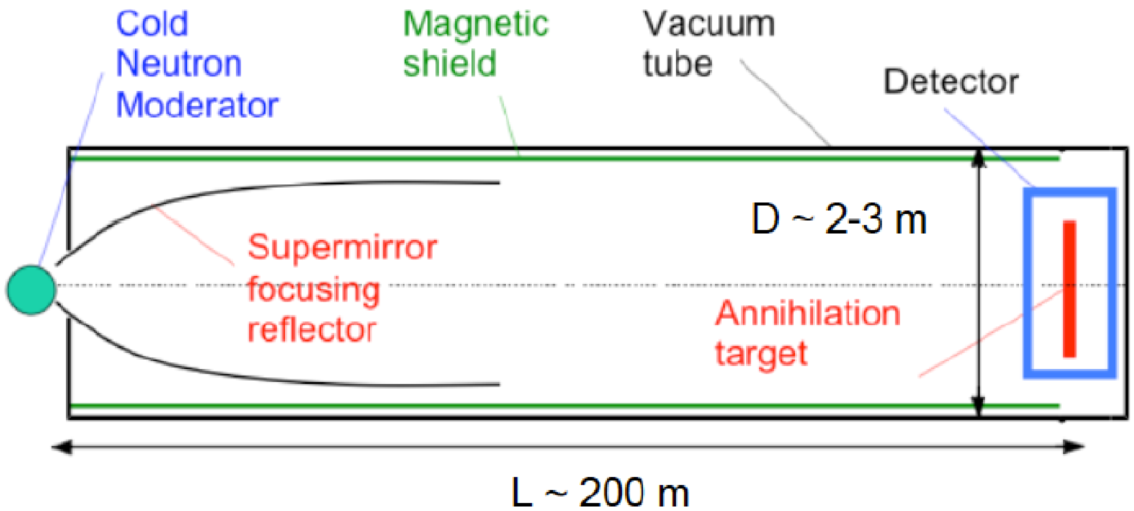
Expression of Interest

Search for Neutron-Antineutron Transformation at Fermilab

The NNbarX Collaboration

need slow neutrons from high flux source, access of neutron focusing reflector to cold source, free flight path of ~200m

Improvement on ILL experiment by factor of ~1000 in transition probability is possible with horizontal experiment at Project X with existing n optics technology, sources, and moderators. Vertical experiment also possible



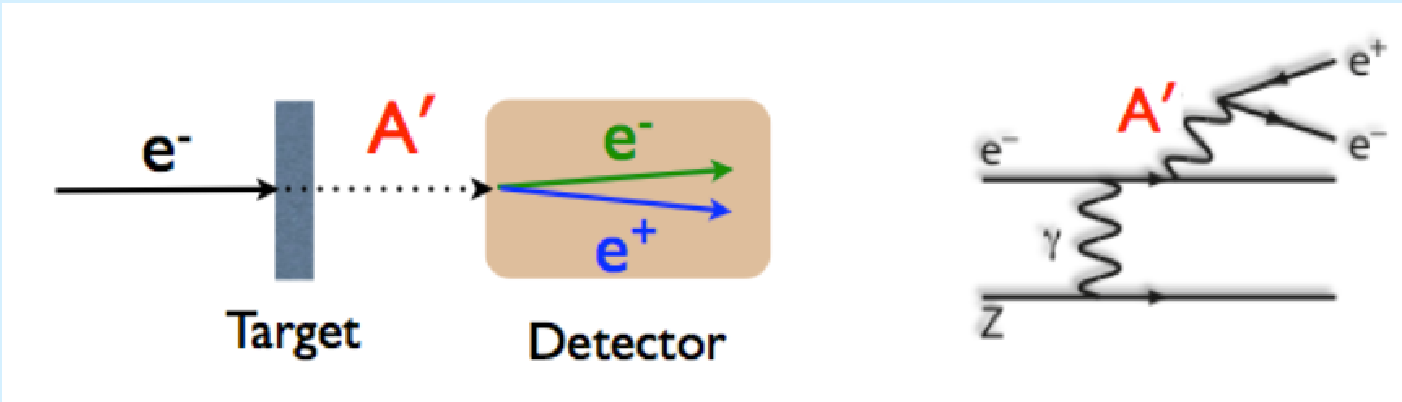
E. Kearns, Intensity Frontier All Hands Meeting, ANL

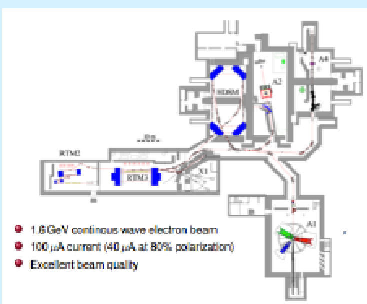
New Light, Weakly Coupled Particles

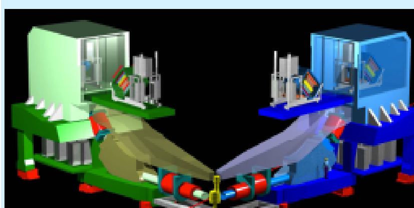
e- fixed targets

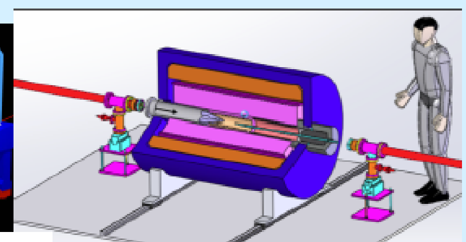
- Jefferson Lab, Mainz, VEPP-3, e- beam dump

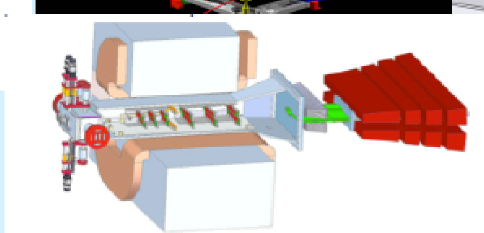
  APEX, HPS, DarkLight

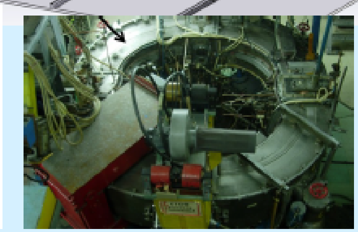


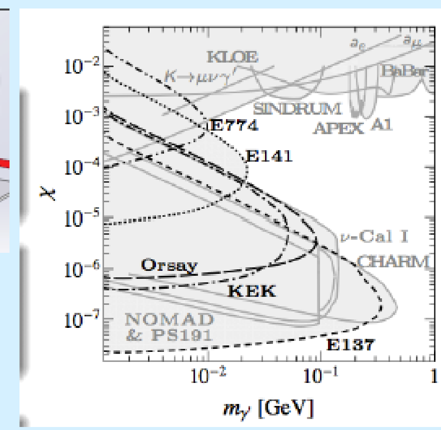










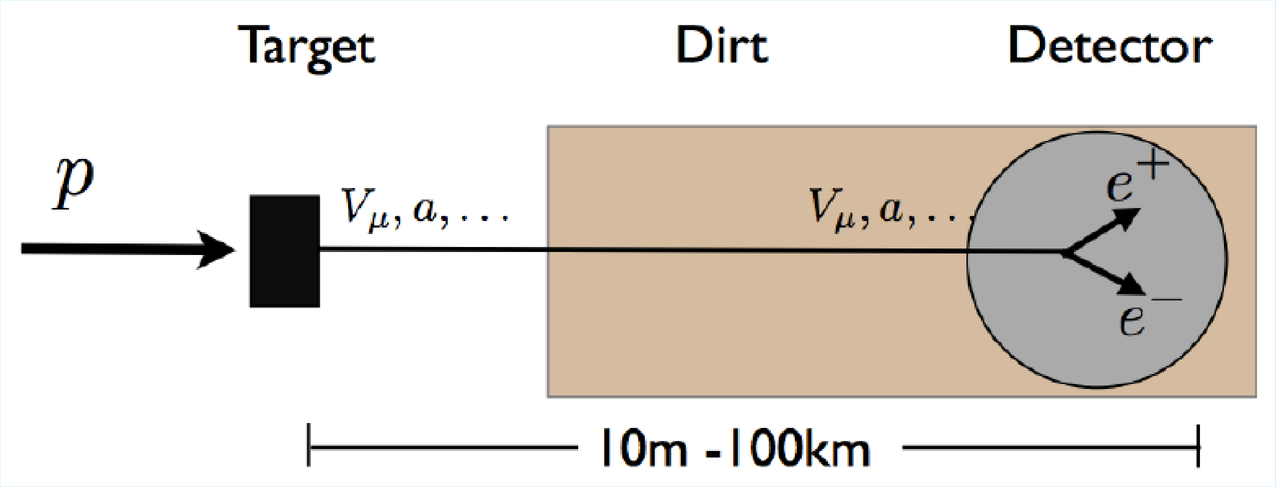


Tobias Beranek
Philip Schuster
Ross Corliss
Stepan Stepanyan

Sarah Andreas

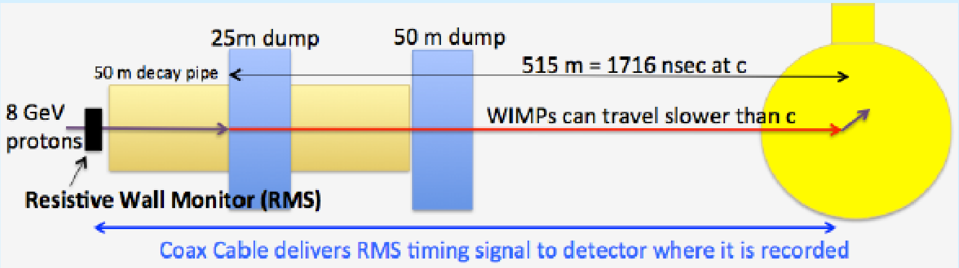
p fixed targets

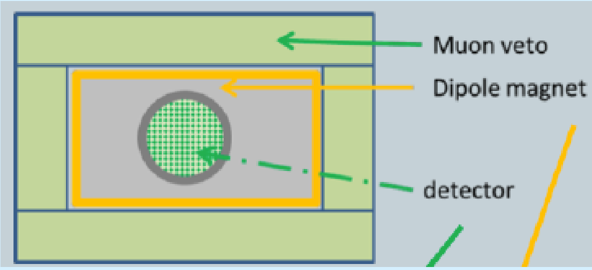
- Neutrino beamlines, Project X, beam dump



Brian Batell

MiniBooNE

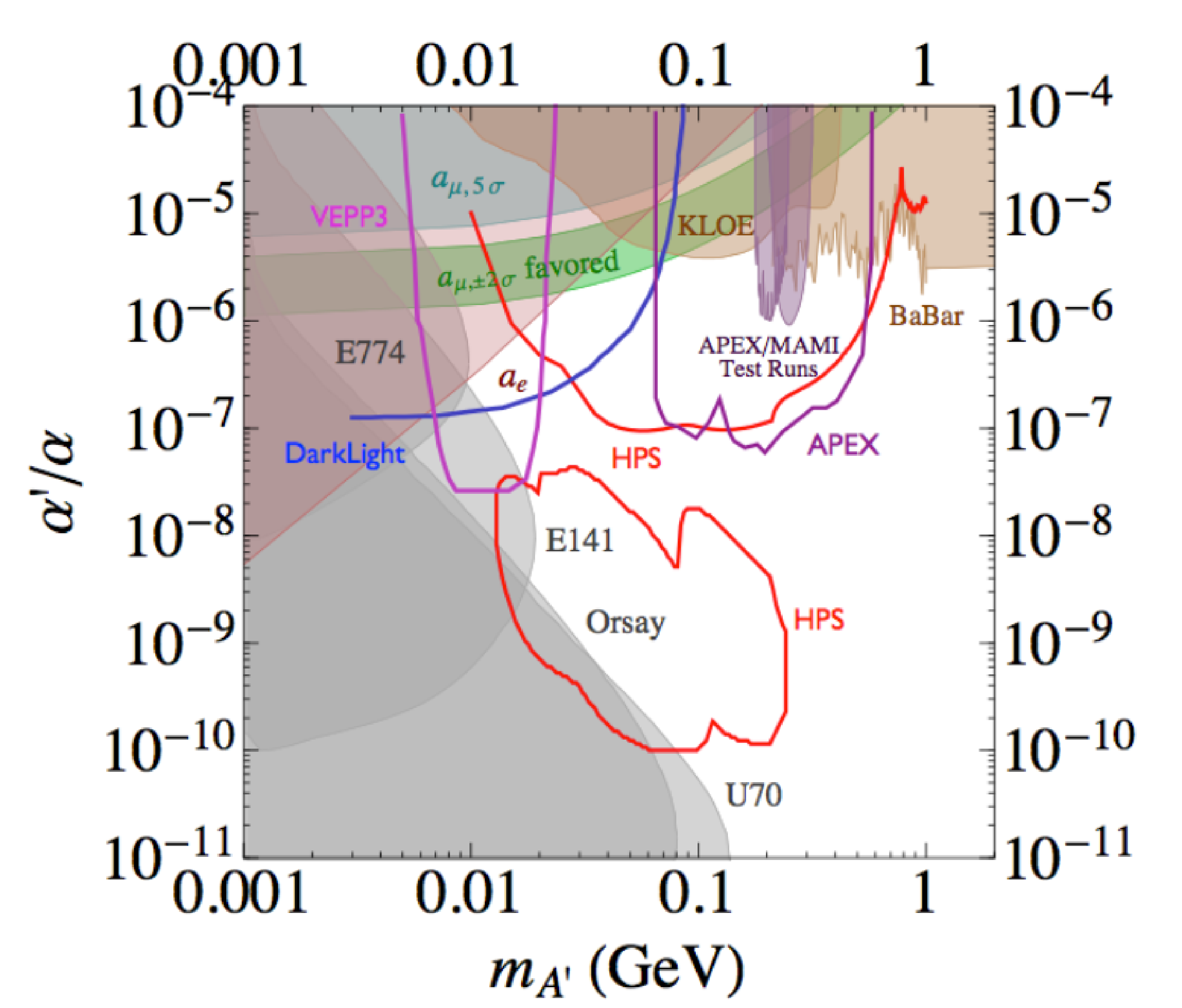




Richard Van de Water

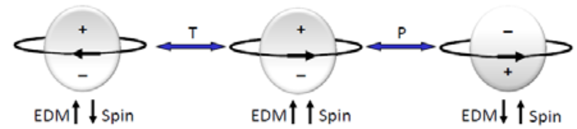
Athanasios Hatzikoutelis

Current and future status



Nucleons, Nuclei, Atoms

EDM Research Worldwide…

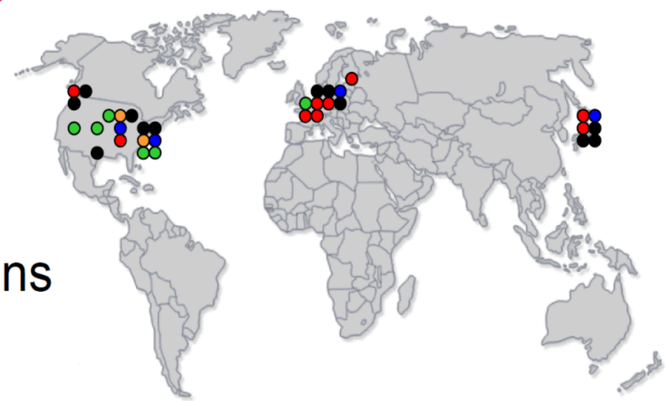


Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- **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



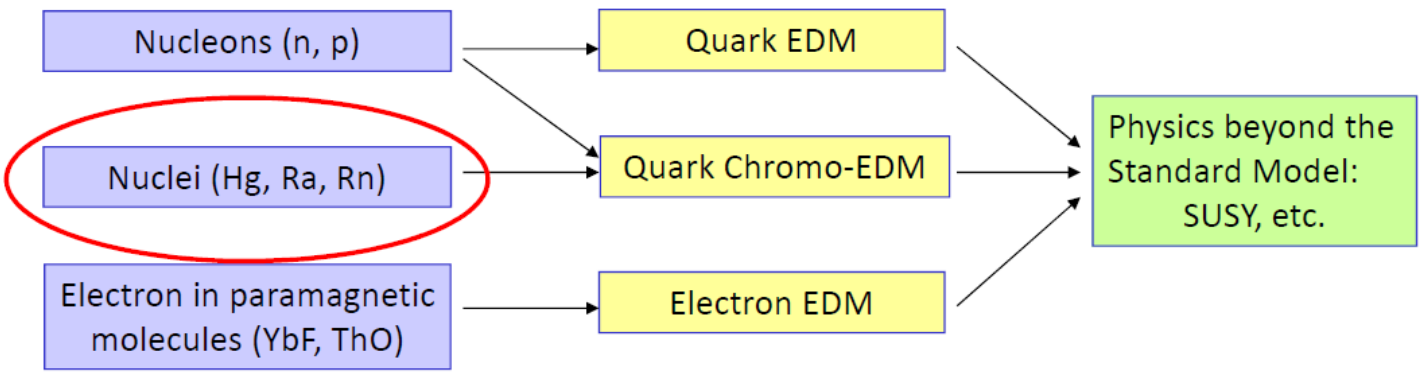
- **Ions-Muons** ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC

- **Solids** ~10
  - GGG@Indiana
  - ferroelectrics@Yale

Courtesy Klaus Kirch CIPANP 2012

EDM Searches in Three Sectors

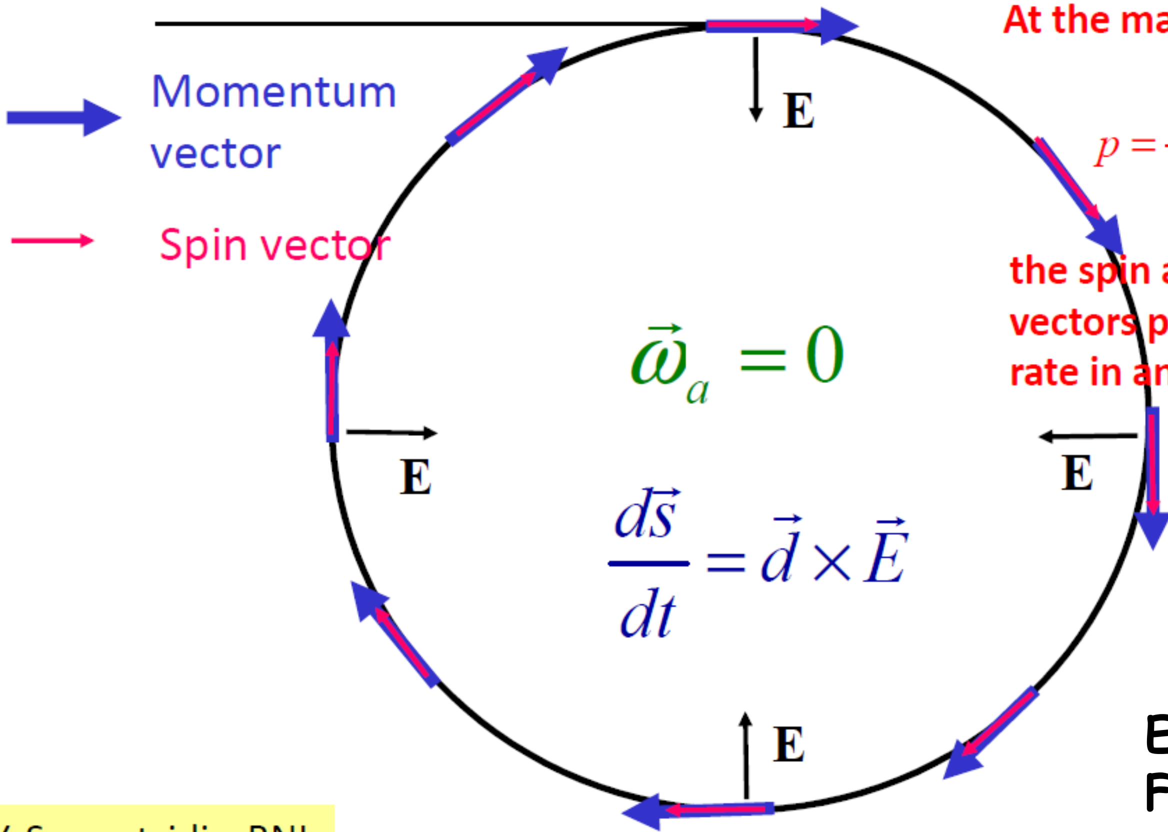
Review article: *EDM of Nucleons, Nuclei, and Atoms*
Engel, Ramsey-Musolf, van Kolck, arXiv:1303.2371 (2013)



Sector	Exp Limit (e-cm)	Method	Standard Model
Electron	1×10^{-27}	YbF in a beam	10^{-38}
Neutron	3×10^{-26}	UCN in a bottle	10^{-31}
^{199}Hg	3×10^{-29}	Hg atoms in a cell	10^{-33}

M. Ramsey-Musolf (2009)

The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector



At the magic momentum

$$p = \frac{m}{\sqrt{a}} = 0.7 GeV/c$$

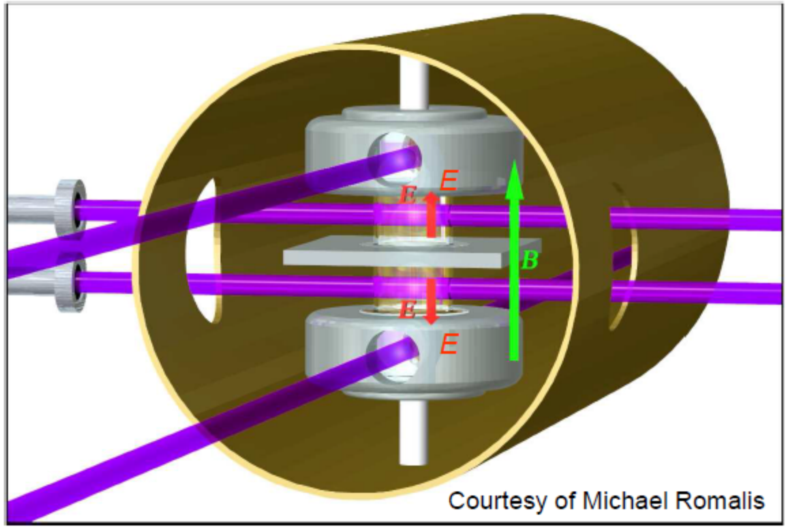
the spin and momentum vectors precess at same rate in an E-field

Y. Semertzidis, BNL

EOI submitted to Fermilab, strongly supported by Fermilab PAC.

The Seattle EDM Measurement (1980's - present)

^{199}Hg stable, high Z, groundstate $^1S_0$, I = ½, high vapor pressure



$$f_+ = \frac{2\mu B + 2dE}{h} \approx 15 \text{ Hz}$$

$$f_- = \frac{2\mu B - 2dE}{h} \approx 15 \text{ Hz}$$

$$|f_+ - f_-| < 0.1 \text{ nHz}$$

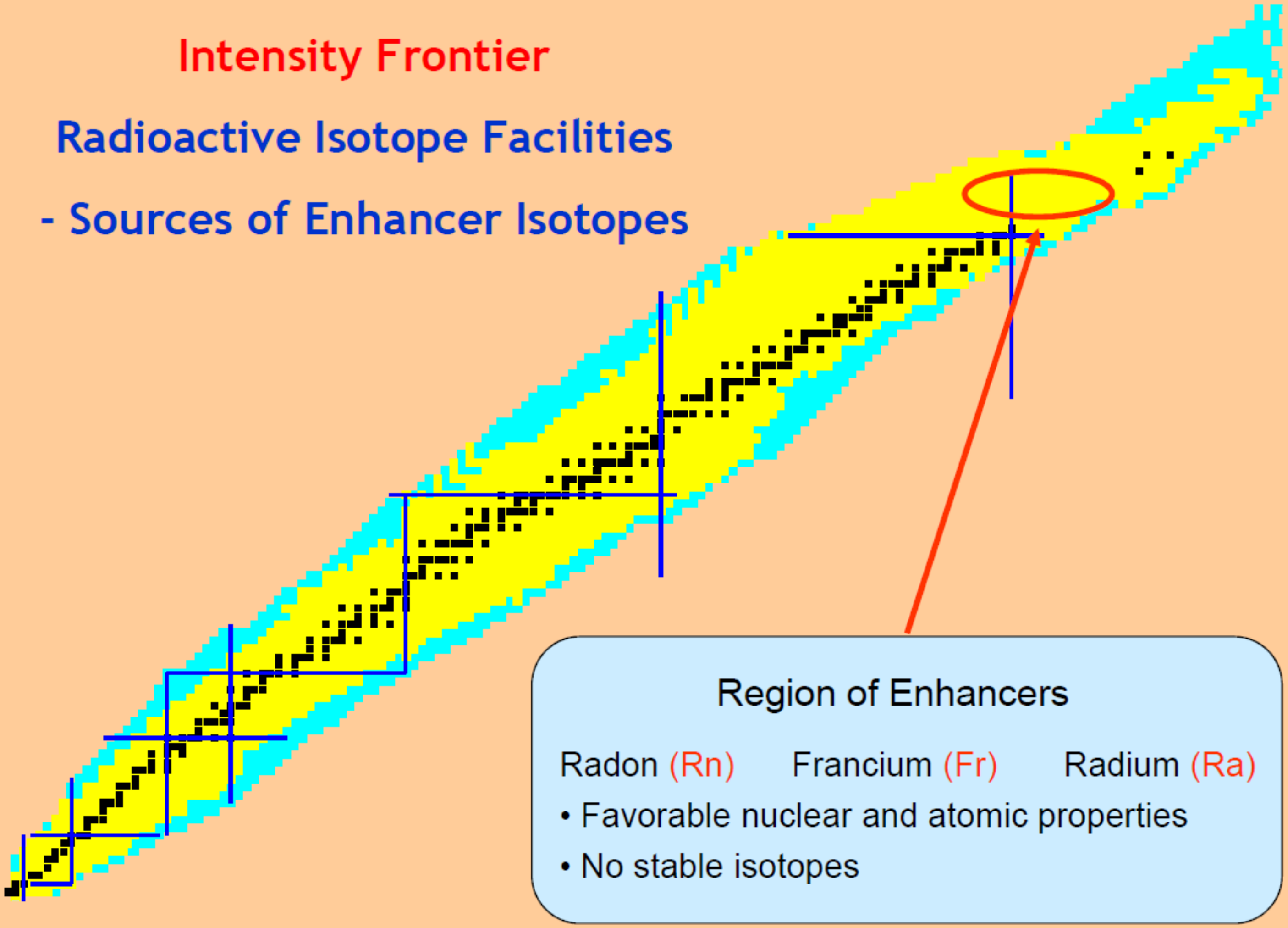
Limits and Sensitivities

- Current: < 0.3 x 10^{-28} e-cm Griffith *et al.*, Phys. Rev. Lett. (2009)
- Next 5 years: 0.03 x 10^{-28} e-cm
- 2020 and beyond: 0.006 x 10^{-28} e-cm

Intensity Frontier

Radioactive Isotope Facilities

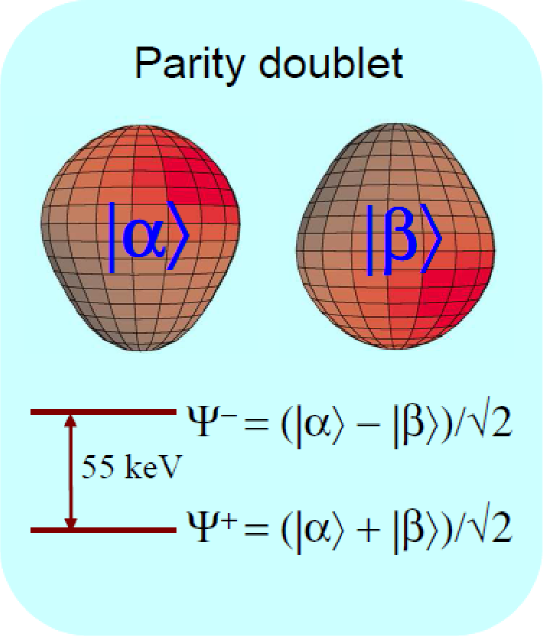
- Sources of Enhancer Isotopes



EDM of ^{225}Ra enhanced

^{225}Ra:
I = ½
$t_{1/2}$ = 15 d

- Closely spaced parity doublet *– Haxton & Henley (1983)*
- Large intrinsic Schiff moment due to octupole deformation *– Auerbach, Flambaum & Spevak (1996)*
- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3) *– Dzuba, Flambaum, Ginges, Kozlov (2002)*



$$S \equiv \langle \psi_0 | \hat{S}_z | \psi_0 \rangle = \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

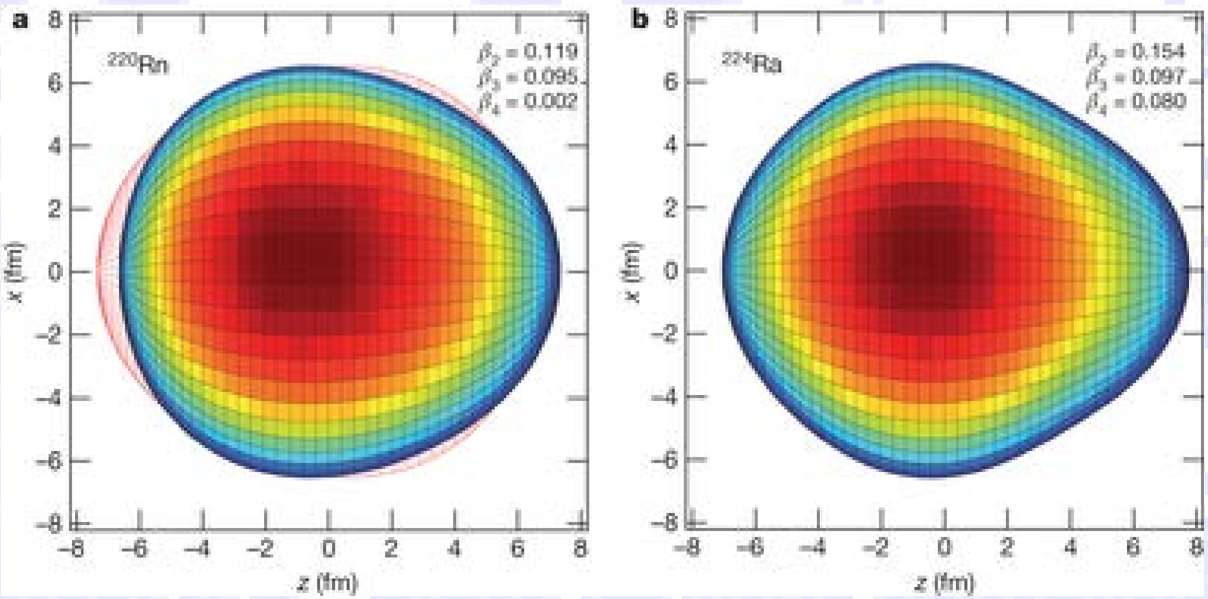
Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

Schiff moment of ^{225}Ra, Dobaczewski, Engel (2005)
Schiff moment of ^{199}Hg, Ban, Dobaczewski, Engel, Shukla (2010)

Studies of pear-shaped nuclei using accelerated radioactive beams

L. P. Gaffney, P. A. Butler, M. Scheck, A. B. Hayes, F. Wenander, M. Albers, B. Bastin, C. Bauer, A. Blazhev, S. Bönig,N. Bree, J. Cederkäll, T. Chupp, D. Cline, T. E. Cocolios, T. Davinson, H. De Witte,J. Diriken,T. Grahn,A. Herzan,M. Huyse,D. G. Jenkins, D.T. Joss,N. Kesteloot,J. Konk

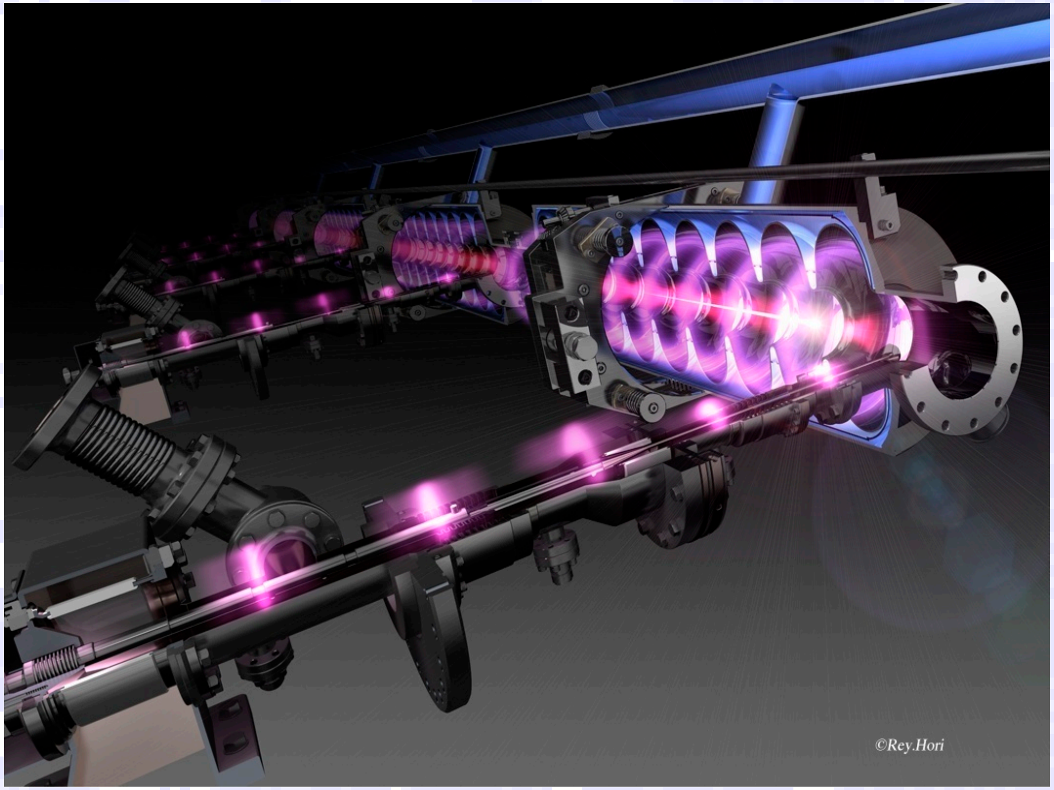
Nature 497,199–204(09 May 2013) doi:10.1038/nature12073



Research performed at the Isolde facility at CERN

Project-X:

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



Project-X:

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

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 & nucleon precision experiments***

These could include world leading experiments searching for lepton flavor violation in muons, atomic, muon, nuclear and nucleon electron dipole moments (edms), precision measurement of neutron properties (e.g. n,nbar oscillations) and world-leading precision measurements of ultra-rare kaon decays.

- ***Platform for evolution to a Neutrino Factory and Muon Collider***

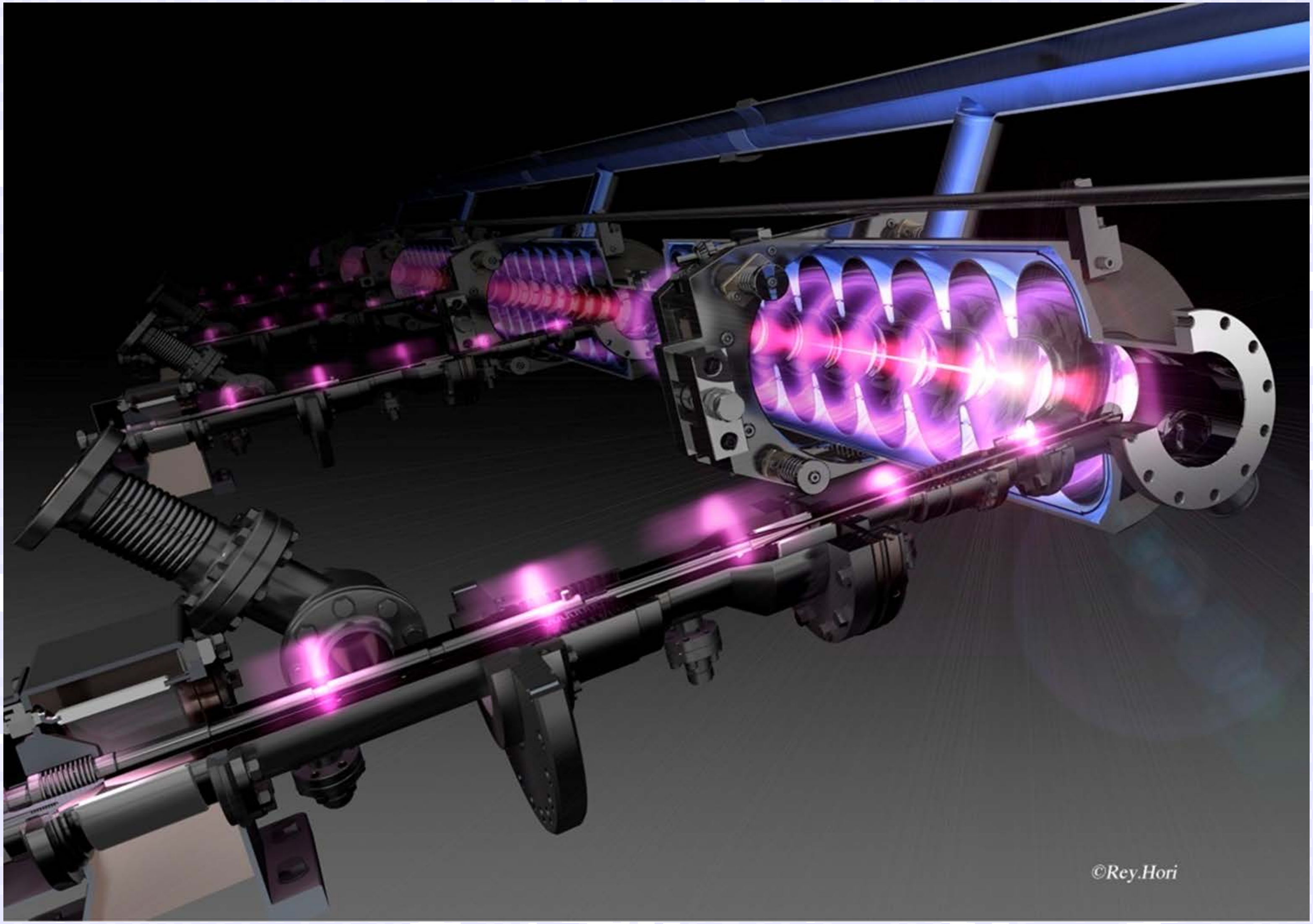
Neutrino Factory and Muon-Collider concepts depend critically on developing high intensity proton source technologies.

- ***Material Science and Nuclear Energy Applications***

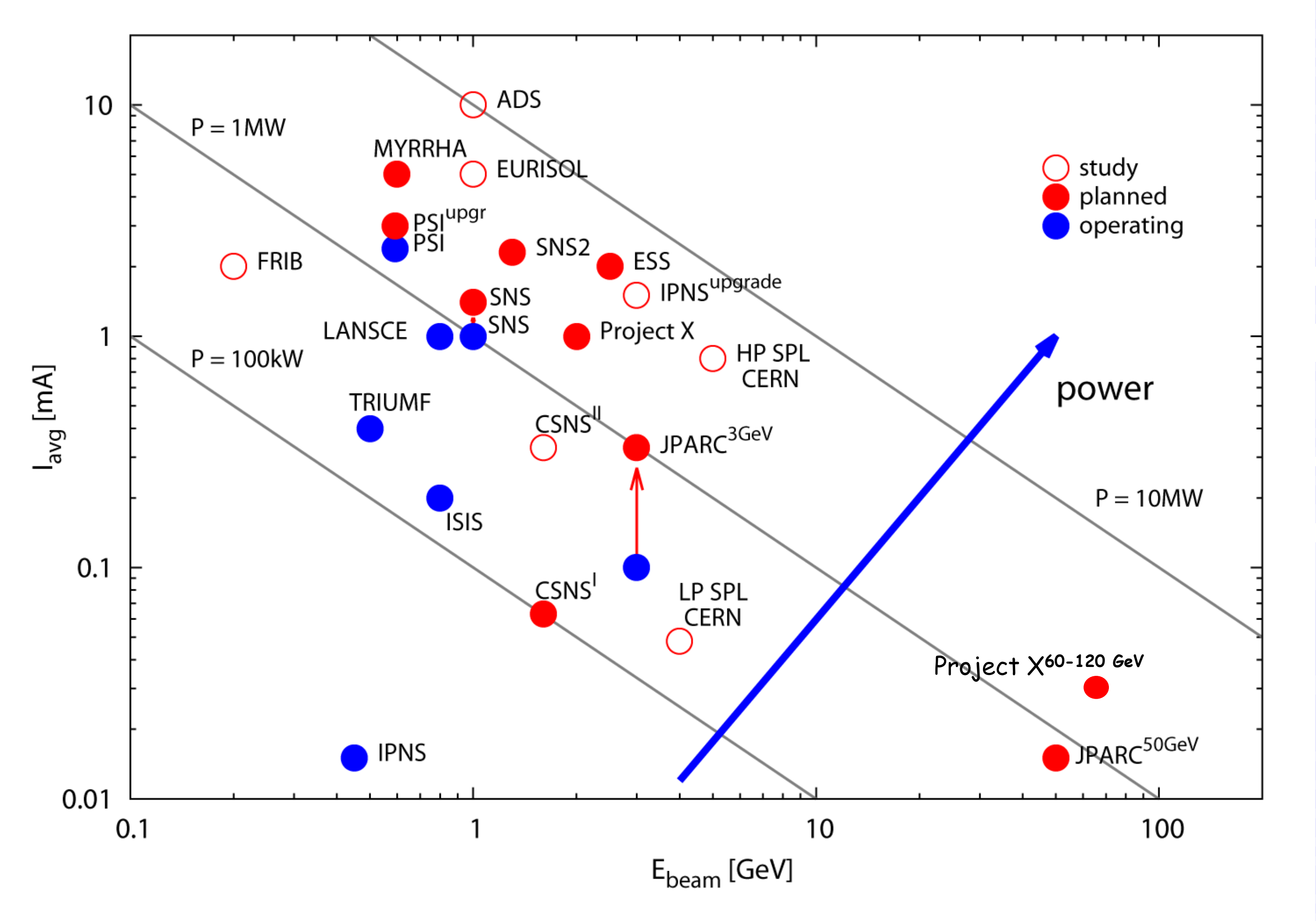
Accelerator, spallation, target and transmutation technology demonstrations which could investigate and develop accelerator technologies important to the design of future nuclear waste transmutation systems and future thorium fuel-cycle power systems. Possible applications of muon Spin Resonance techniques (muSR). as a sensitive probes of the magnetic structure of materials .

Detailed discussion on Project X website

Beam Power is the Gateway to the Intensity Frontier…

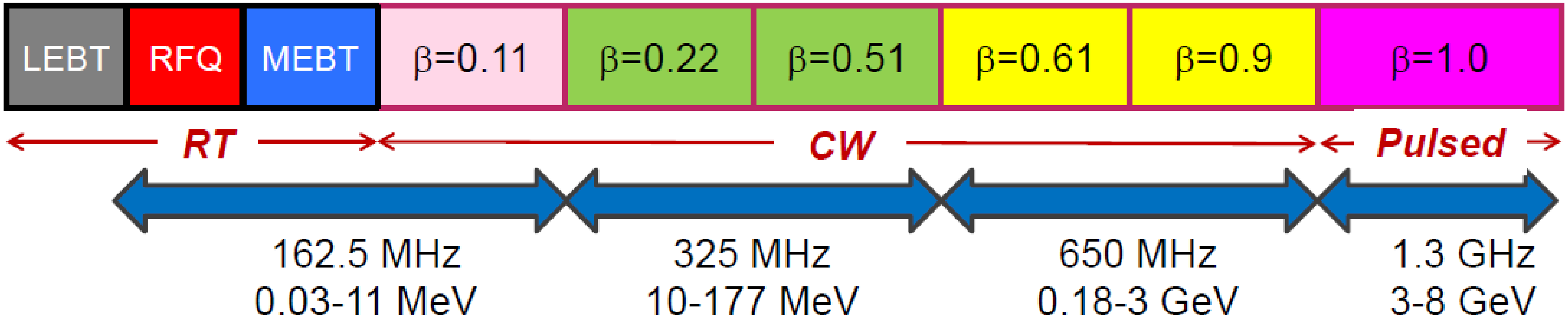


Beam Power is the Gateway to the Intensity Frontier...



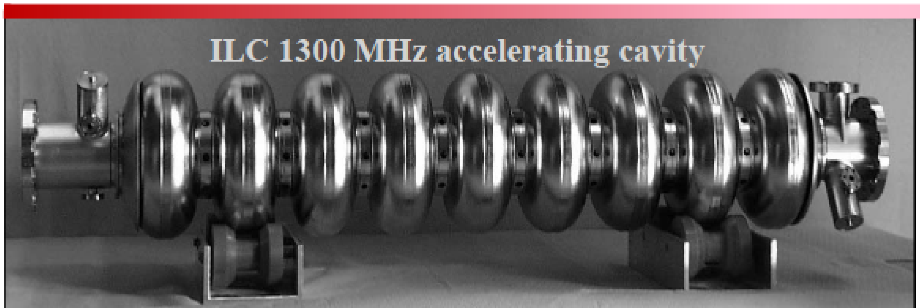
Project X

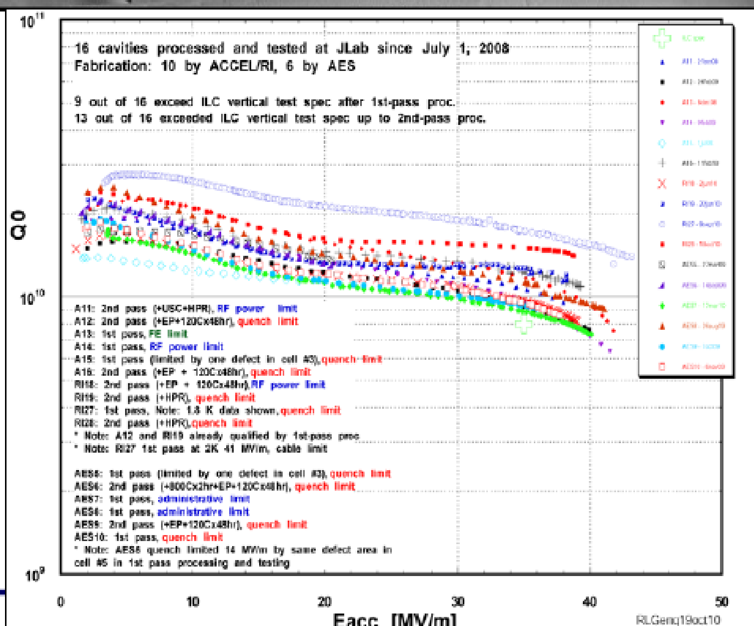
Reference Design
Linac Technology Map



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_G=0.1)	162.5	2.1-11	8/8/1	HWR, solenoid
SSR1 (β_G=0.22)	325	11-38	16/8/ 2	SSR, solenoid
SSR2 (β_G=0.51)	325	38-177	35/21/7	SSR, solenoid
LB 650 (β_G=0.61)	650	177-467	30/20/5	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	467-1000	42/16/7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	1000-3000	120/30/15	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

1.3 GHz pulse linac





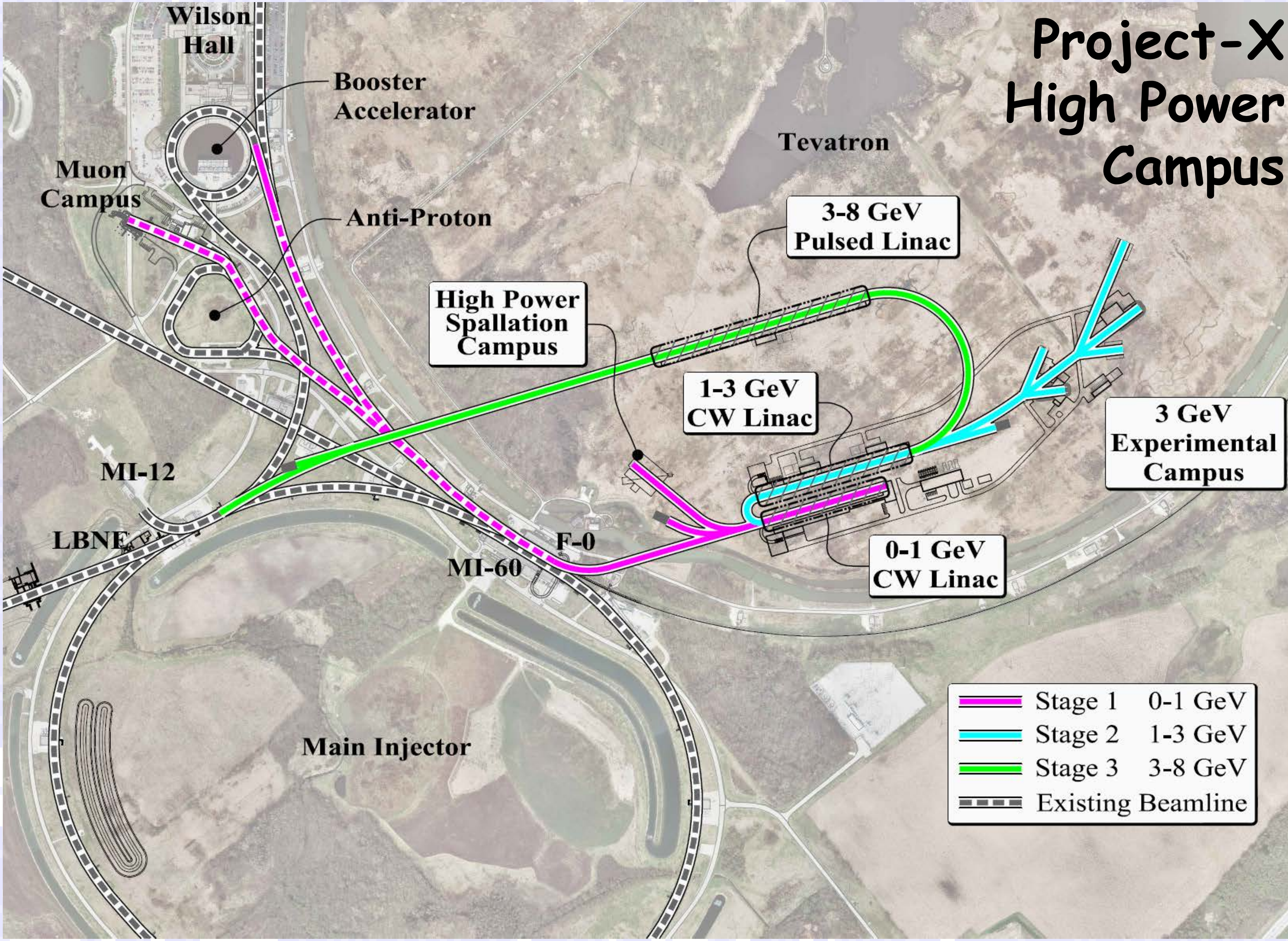
Frequency	GHz	1.3
β_geom		1
Active Length	mm	1038
R/Q	Ω	1036
G-factor	Ω	270
Gradient	MV/m	25
E_surf	MV/m	50
H_surf	mT	106
Q_0 @ 2K		$1.\ 10^{10}$
Q_{Loaded}		$1.\ 10^{7}$
Losses@2K	W	5
Pulse length	ms	7.4
Flat-top	ms	4.4
Rep. rate	Hz	10

RF parameters of the ILC-type 1.3 GHz cavities.

Evolution from the Energy Frontier to the Intensity Frontier at Fermilab…

Evolution from the Energy Frontier to the Intensity Frontier at Fermilab…

Evolution from the Energy Frontier to the Intensity Frontier at Fermilab…


Project-X
High Power
Campus
Wilson Hall
Booster Accelerator
Tevatron
Muon Campus
Anti-Proton
3-8 GeV Pulsed Linac
High Power Spallation Campus
1-3 GeV CW Linac
3 GeV Experimental Campus
MI-12
LBNE
F-0
MI-60
0-1 GeV CW Linac
Main Injector
Stage 1 0-1 GeV
Stage 2 1-3 GeV
Stage 3 3-8 GeV
Existing Beamline

Project X: Evolution of the Fermilab Accelerator Complex

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.**

Summary

- **Framework & Texture:** The U.S. Intensity Frontier has a proposed framework and texture to deliver the science: LBNE & Project-X and a texture of experiments. Given the projected funding environment the framework must be strong enough to stand the test of time.
- **Time:** Large projects in Particle Physics will develop and evolve over decades. We know how to do/survive this, and the Tevatron/LHC is the most recent example of a robust framework in our field.
- **Federation:** Improving communication and ties among the texture of Intensity Frontier experiments and the theory community will strengthen the research program. Again, our field has demonstrated this in the evolution of the Energy Frontier program.
- **Resources:** Intensity Frontier researchers must reach out broadly to the funding agencies to communicate how particle physics spans agencies, and where synergies and leverage can be found. DOE/HEP, NP, NSF/NP, NIST, BES, etc.

What do we *not* know about three-flavor oscillations?

	Free Fluxes + RSBL	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \to 35.89$
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$
$\delta_{CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$

Is θ_{23} non-negligibly greater or smaller than 45 deg?

basically unknown

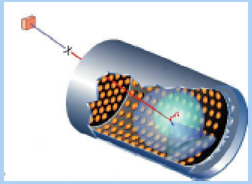
sign of Δm^2 unknown (ordering of masses)

CSS-2013 IF All Hands summary April 25th-27th ANL

Outstanding 'anomalies'

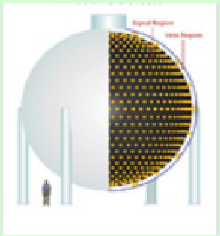
LSND @ LANL (~30 MeV, 30 m)

Excess of $\bar{\nu}_e$ interpreted as $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$



➔ $\Delta m^2 \sim 1\ eV^2$: inconsistent with 3 ν masses

MiniBooNE @ FNAL (ν,$\bar{\nu}$ ~1 GeV, 0.5 km)



- unexplained >3 σ excess for E < 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antineutrinos
  (~consistent with neutrinos)
- small excess for E > 475 MeV in antineutrinos
  (consistent w/ LSND)
- for E>200 MeV, both nu and nubar consistent with LSND

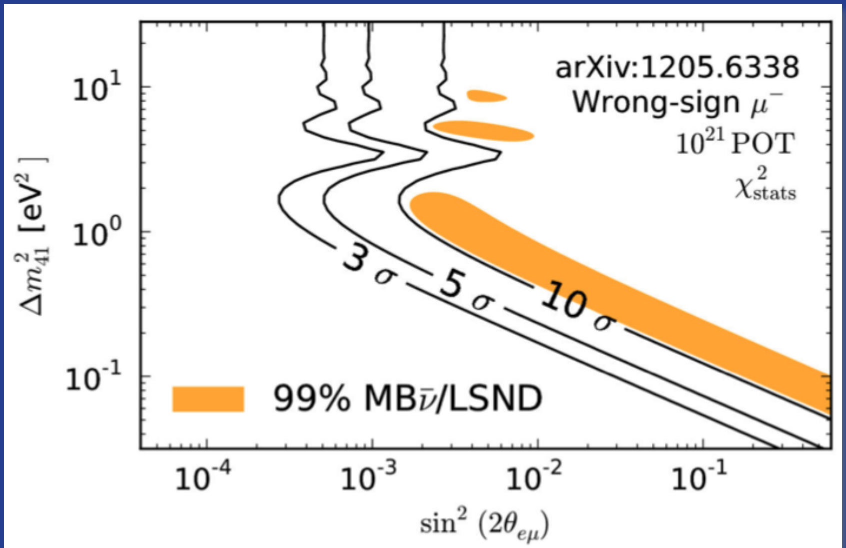
????
more data needed

Also: possible deficits of reactor $\bar{\nu}_e$ ('reactor anomaly') and source ν_e ('gallium anomaly')

Sterile neutrinos?? (i.e. no normal weak interactions)
Some theoretical motivations for this, both from particle physics & astrophysics. **Or some other new physics??**

νSTORM

- ν's from a few-GeV muon storage ring aimed at near & far magnetized iron detectors



(C. Tunnell, Oxford)

- $\nu_e \rightarrow \nu_\mu$ appearance
  (CPT conjugate to MiniBooNE)

- testbed for future μ storage rings

(110 collaborators, 37 institutions)

https://indico.fnal.gov/conferenceDisplay.py?confId=6794

Fermilab

Stage-1 Accelerator Resources:

- Promotes the Main Injector (MI) to a Mega-Watt class machine for neutrinos, and increases the potential beam power for other medium power MI experiments (e.g. ORKA, nu-STORM).
- 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.
- High power spallation target optimized for ultra-cold neutron and atomic-edm particle physics experiments and neutron↔anti-neutron oscillation experiments.
- Capability to drive polarized protons to a proton-edm experiment.
- Increases the available integrated 8 GeV power for other experiments (e.g. short-baseline neutrinos) from the Booster complex by liberating Mu2e.