Project-X

R.Tschirhart - Fermilab

July 12th, 2013 ; SSI-2013

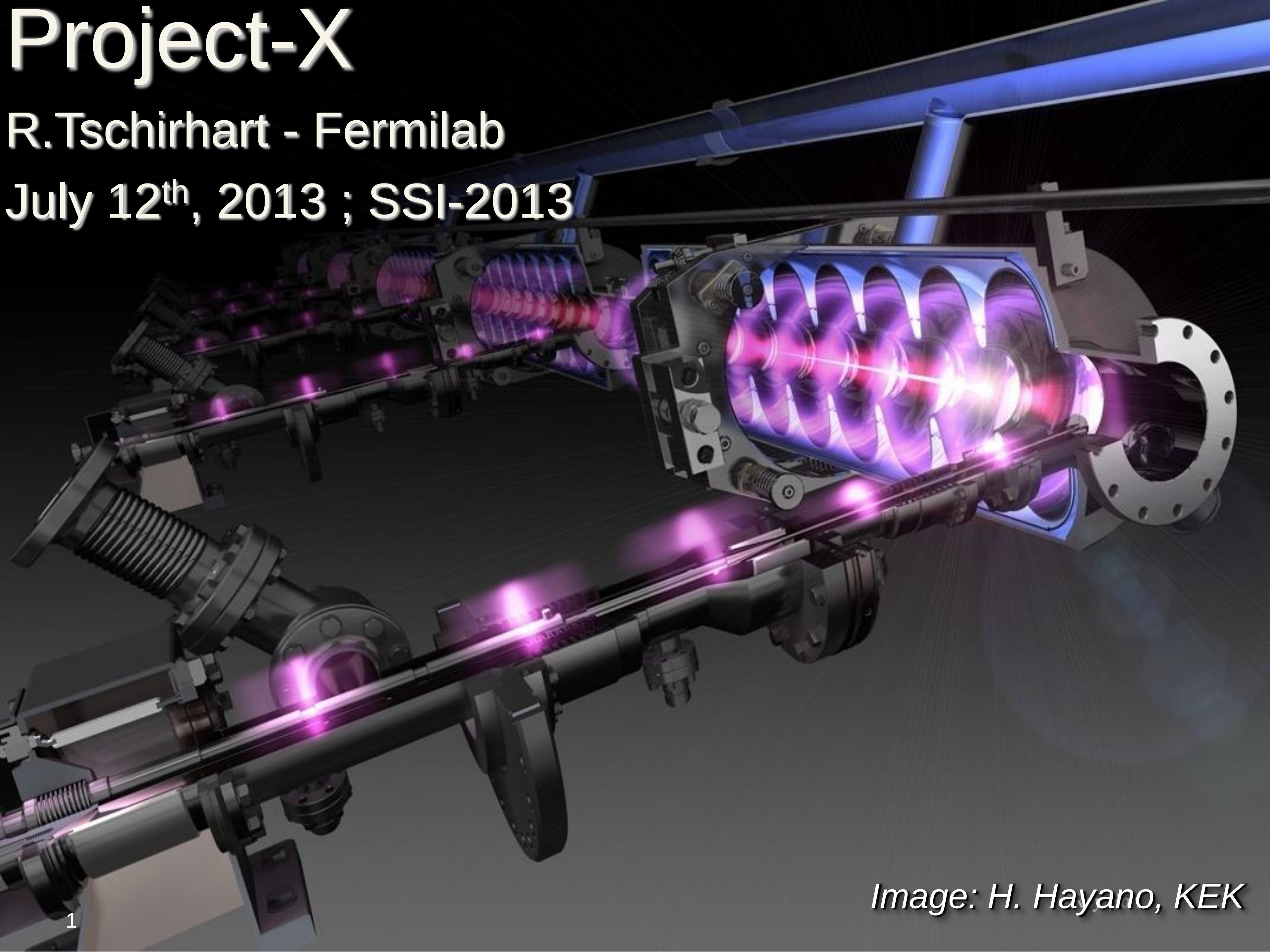


Image: H. Hayano, KEK

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, Muon Collider, ILC.***

Neutrino Factory and Muon-Collider concepts depend critically on developing high intensity proton source technologies. Project X accelerator elements have much in common with ILC accelerator systems.

- ***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 in "*The Book*" on the Project X website

The Project-X Research Program…Redux

- ***New Forces***

  Lepton Flavor Violation (e.g. $\mu \rightarrow e$)

  Baryon Number Violation ($n \rightarrow \bar{n}$ oscillations)

  Non-standard flavor changing neutral currents

- ***New properties of matter***

  CP violation in neutrinos, charged leptons, quarks

- ***New dimensions***

  e.g. super-symmetric amplitudes via EDMs

  Warped dimensions via kaon decays

In the absence of new facilities enabling new experiments…

From Hitoshi Murayama , ICFA October 2011

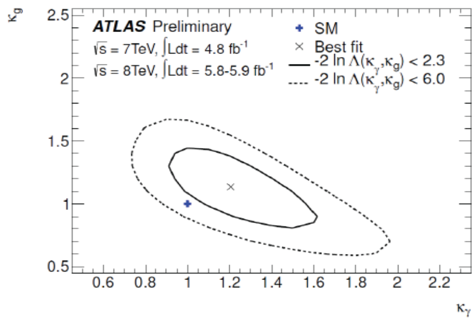
Intensity Frontier Killer App? Not a *single* experiment! The *science* requires multiple probes.

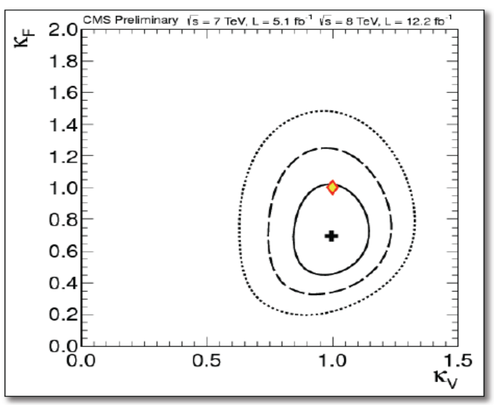
Apologies to Jurassic Park and Hitoshi Murayama, ICFA October 2011

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

For Discovery of the Standard Model Scalar??

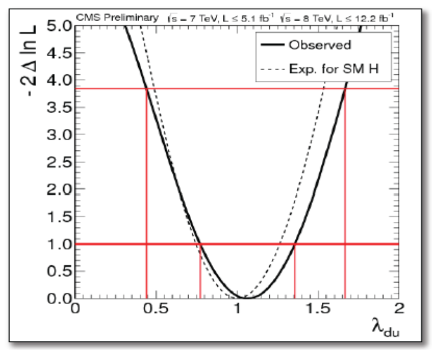
Couplings

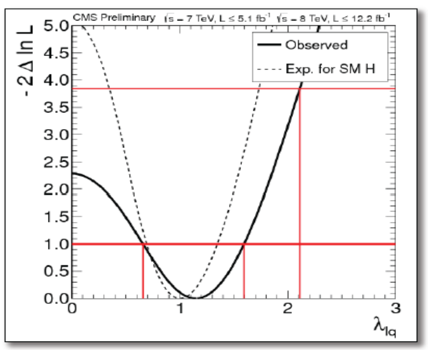




λ_{du}: ratio of couplings between down- and up-fermions

λ_{lq}: ratio of couplings between leptons and quarks





Both ratios consistent with 1

Searches for BSM physics

P. Sphicas
Experimental highlights

Rencontres de Moriond, EWK session
Mar 09, 2013

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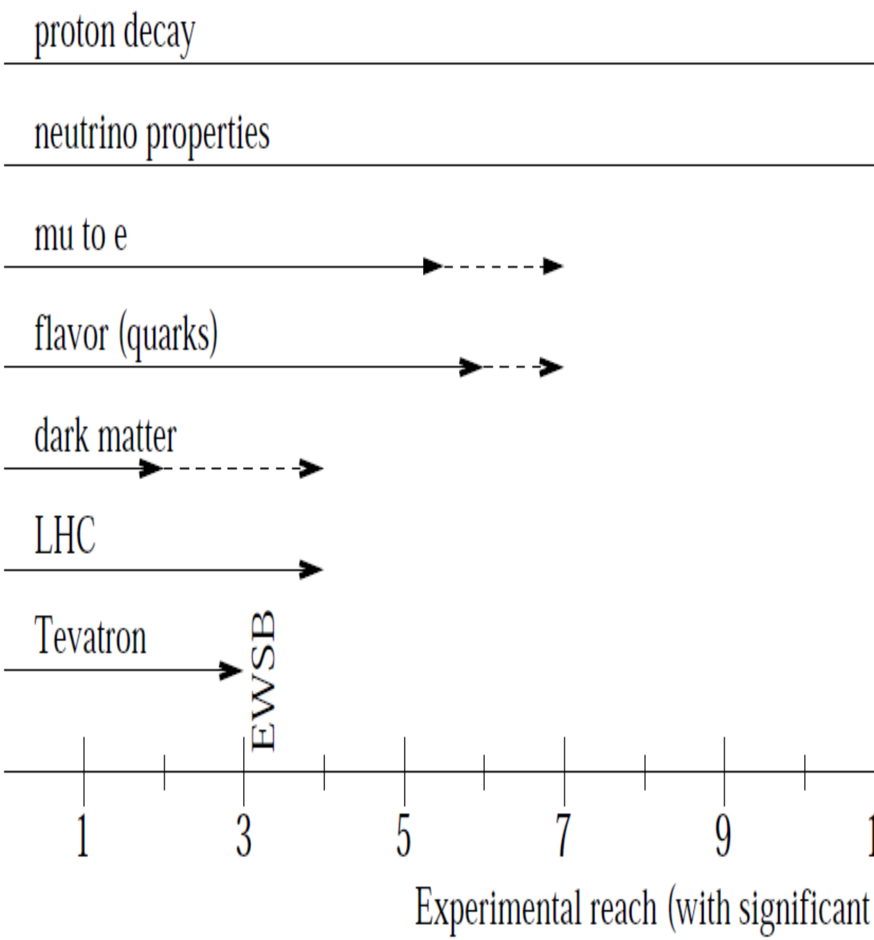
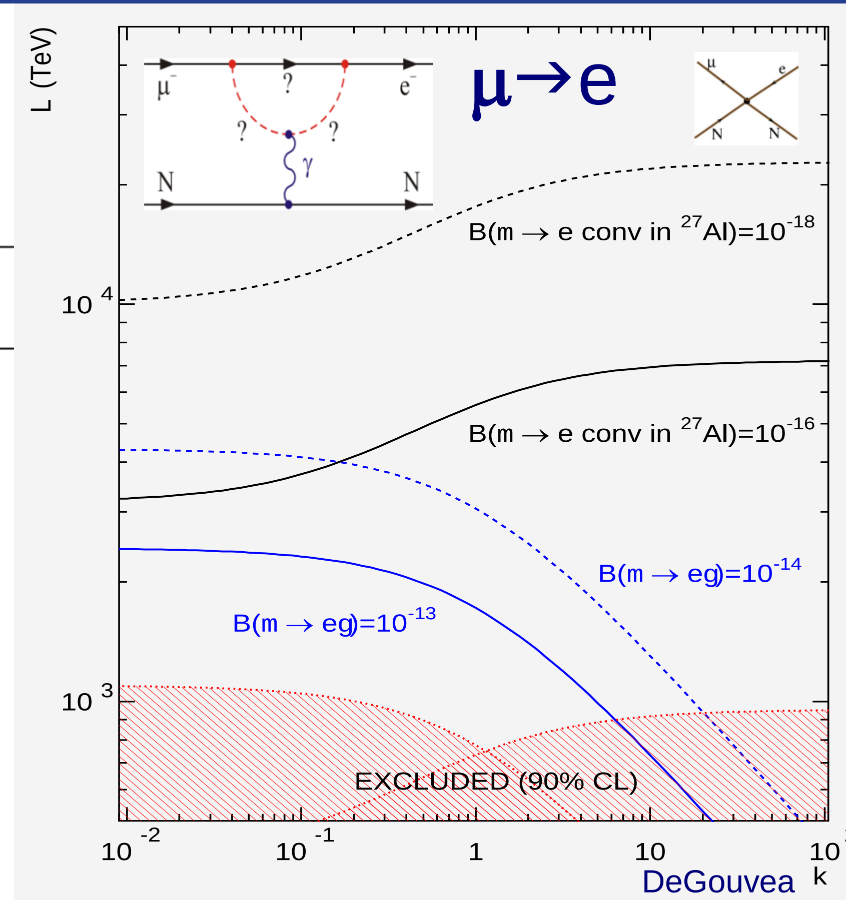
Indirect Pursuit of BSM from the Intensity Frontier…

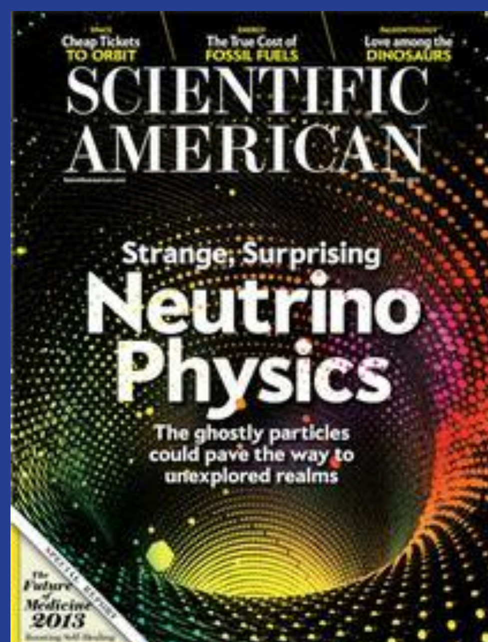


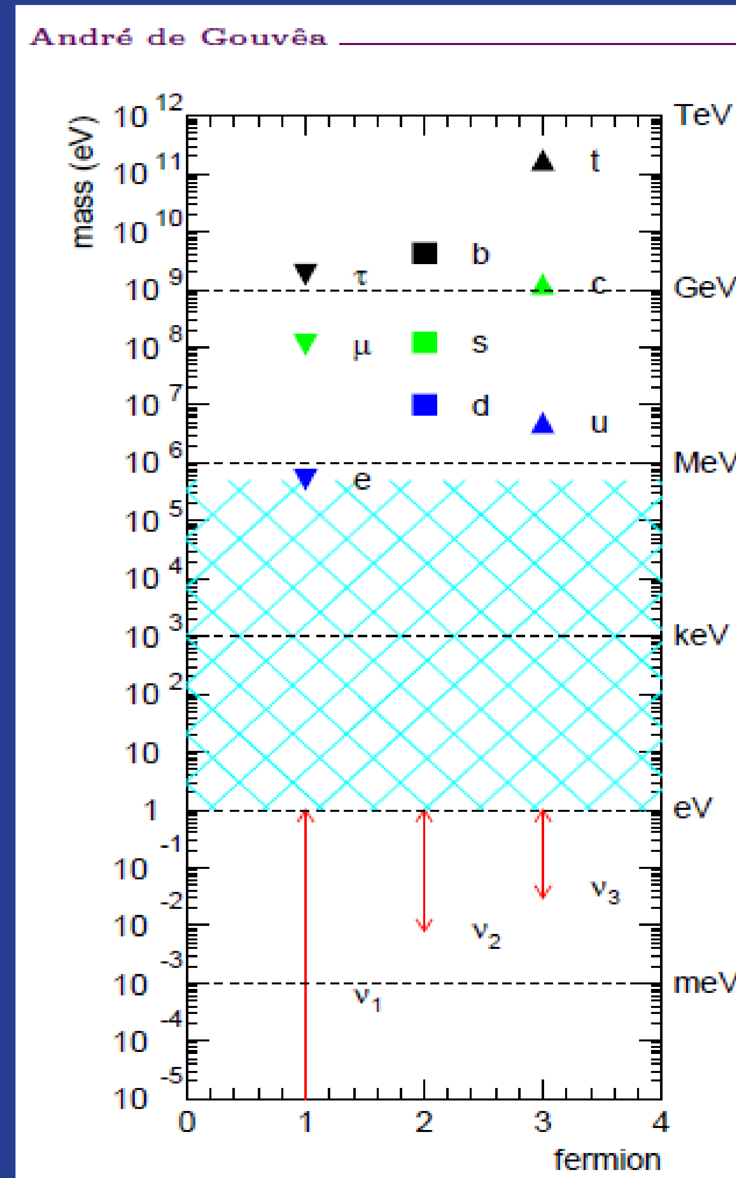


Y. Grossman, Z. Ligeti, Project X Physics Study (PXPS)

Physics Beyond the Standard Model has been discovered….

What does it mean?





On Electroweak Symmetry Breaking

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC and charged-lepton flavor violation may provide more information.

Searches for nucleon decay provide the only handle on a new energy scale (3) if that new scale happens to be very small. Unique capability!

A Really Reasonable, Simple Paradigm:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Definition of neutrino mass eigenstates (who are ν_1, ν_2, ν_3?):

- $m_1^2 < m_2^2$ — $\Delta m_{13}^2 < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$ — $\Delta m_{13}^2 > 0$ – Normal Mass Hierarchy

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

[For a detailed discussion see e.g. AdG, Jenkins, PRD78, 053003 (2008)]

Three-Flavor Paradigm Fits All* Data Really Well (arXiv:1209.3023):

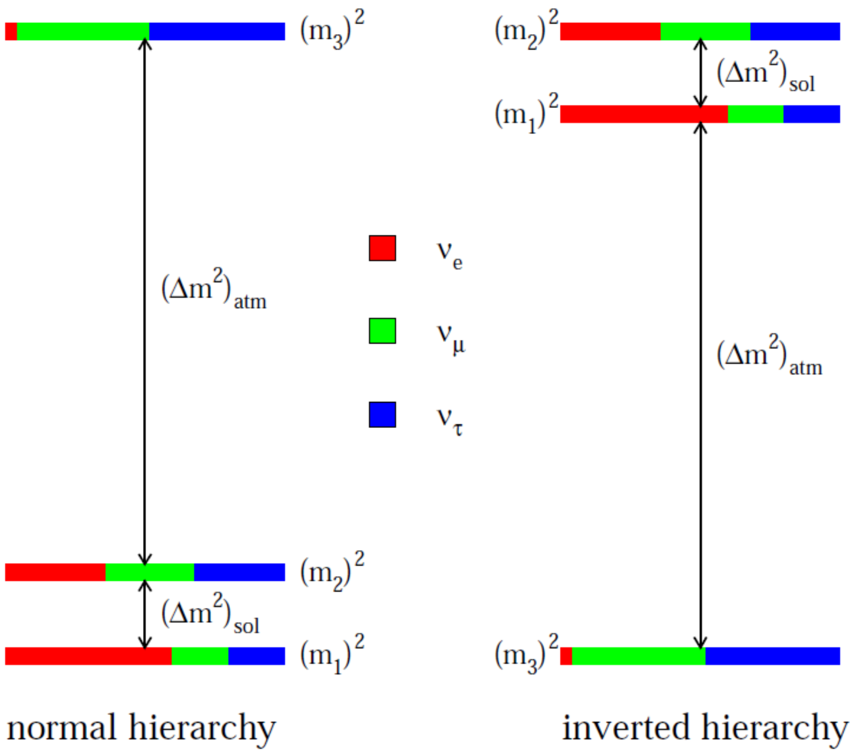
	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$	0.31 ± 0.013	$0.27 \to 0.35$
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$	33.9 ± 0.8	$31 \to 36$
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$	$0.41^{+0.030}_{-0.029} \oplus 0.60^{+0.020}_{-0.026}$	$0.34 \to 0.67$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$	$40.1^{+2.1}_{-1.7} \oplus 50.7^{+1.1}_{-1.5}$	$36 \to 55$
$\sin^2\theta_{13}$	0.023 ± 0.0023	$0.016 \to 0.030$	0.025 ± 0.0023	$0.018 \to 0.033$
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$	$7.2 \to 9.5$	$9.2^{+0.42}_{-0.45}$	$7.7 \to 10.$
$\delta_{CP}/^\circ$	240^{+102}_{-74}	$0 \to 360$	238^{+95}_{-51}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	7.50 ± 0.185	$7.00 \to 8.09$	$7.50^{+0.205}_{-0.160}$	$7.04 \to 8.12$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$	$2.49^{+0.055}_{-0.051}$	$2.29 \to 2.71$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$	$-2.47^{+0.073}_{-0.064}$	$-2.68 \to -2.25$

Table 1: Three-flavour oscillation parameters from our fit to global data after the Neutrino 2012 conference. For "Free Fluxes + RSBL" reactor fluxes have been left free in the fit and short baseline reactor data (RSBL) with $L \lesssim 100$ m are included; for "Huber Fluxes, no RSBL" the flux prediction from [42] are adopted and RSBL data are not used in the fit.

* Modulo Short-Baseline Anomalies

Snowmass neutrino working group meeting, SLAC, March 6th-7th

What We Know We Don't Know: "Missing" Oscillation Parameters



- ~~What is the ν_e component of ν_3?~~ $(\theta_{13} \neq 0!)$
- Is CP-invariance violated in neutrino oscillations? $(\delta \neq 0, \pi?)$
- Is ν_3 mostly ν_μ or ν_τ? $(\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4?)$
- What is the neutrino mass hierarchy? $(\Delta m^2_{13} > 0?)$

$\Rightarrow$ All of the above can "only" be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)

Understanding Fermion Mixing – Precision

The other puzzling phenomenon uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

It means that lepton mixing is very different from quark mixing:

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

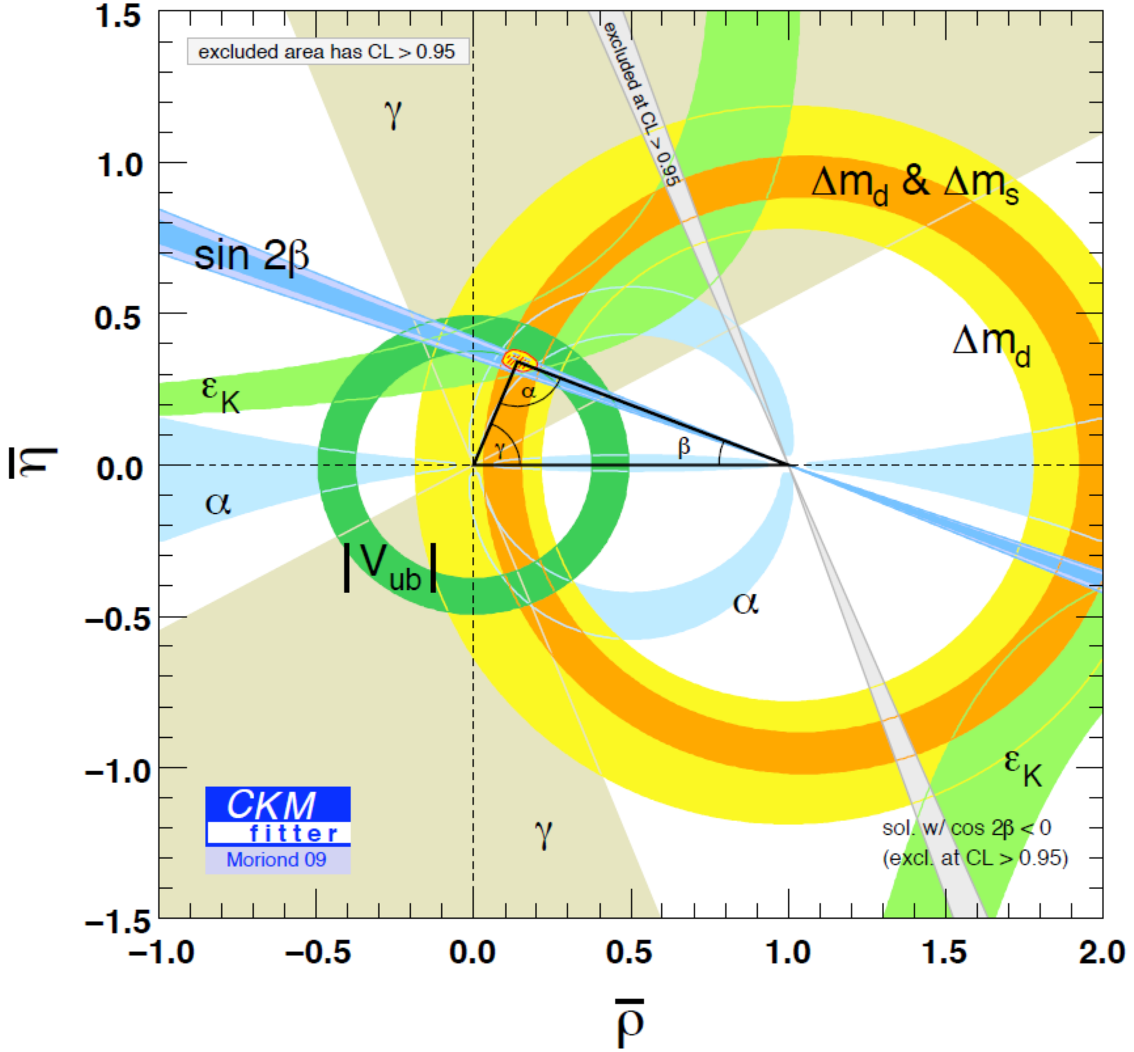
$[|(V_{MNS})_{e3}| < 0.2]$

WHY?

They certainly look VERY different, but which one would you label as "strange"?

Snowmass neutrino working group meeting, SLAC, March 6th-7th

What we ultimately want to achieve:

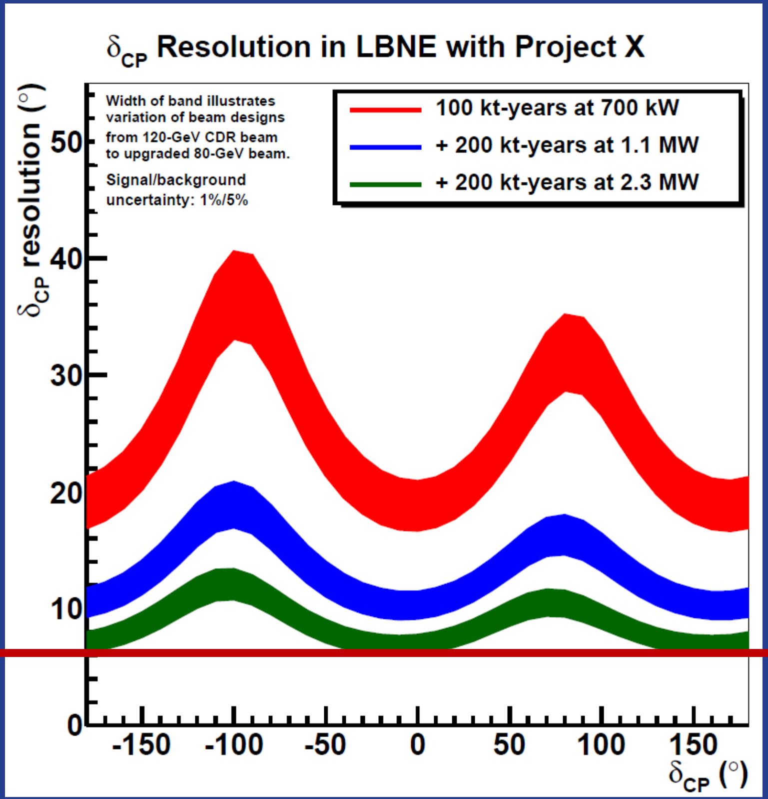


We need to do <u>this</u> in the lepton sector!

Snowmass neutrino working group meeting, SLAC, March 6th-7th

Project X era CP violation research opportunities

Neutrinos: > x3 increase in the Long Baseline Neutrino Experiment (LBNE) neutrino statistics.



CP violation in quarks

Electric **D**ipole **M**oments:

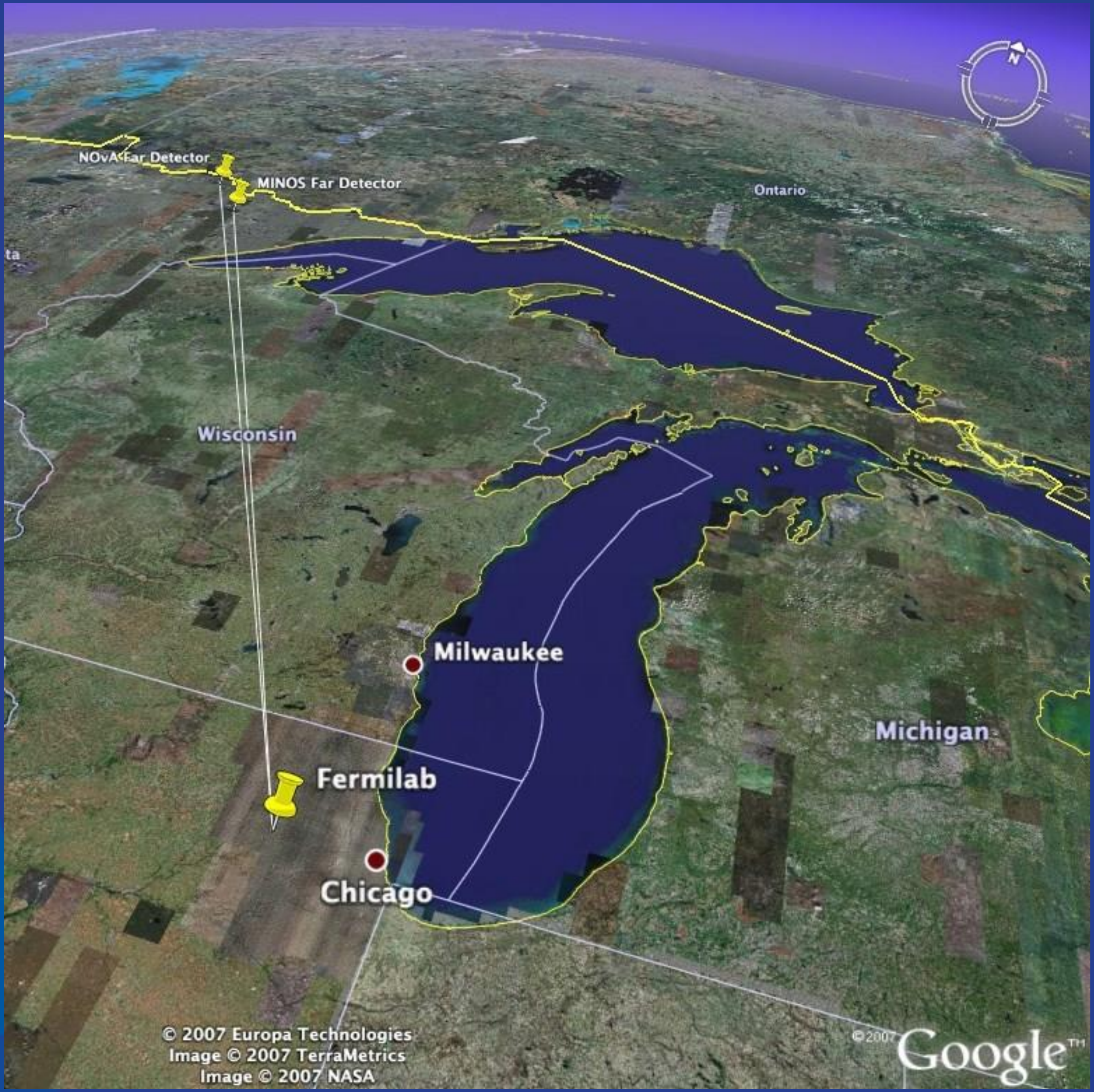
- Proton-EDM, x10^6 reach, *new capability*
- Muon-EDM, x10^4 reach, *new capability*
- Neutron EDM, x10^2-10^3 reach
- Atomic EDMs. x10^3-10^4 reach, goal of matching Hg!

Table 2: SM predictions and current and expected limits on selected examples of EDMs.

EDMs	SM	current limit	Project X
electron	$\sim 10^{-38}\,e$ cm	$1.0 \times 10^{-27}\,e$ cm	$\sim 10^{-30}\,e$ cm
muon	$\sim 10^{-35}\,e$ cm	$1.1 \times 10^{-19}\,e$ cm	$\sim 10^{-23}\,e$ cm
neutron	$\sim 10^{-31}\,e$ cm	$2.9 \times 10^{-26}\,e$ cm	$\sim 10^{-29}\,e$ cm
proton	$\sim 10^{-31}\,e$ cm	$6.5 \times 10^{-23}\,e$ cm	$\sim 10^{-29}\,e$ cm
nuclei	$\sim 10^{-33}\,e$ cm (^{199}Hg)	$3.1 \times 10^{-29}\,e$ cm (^{199}Hg)	$\sim 10^{-29}\,e$ cm (^{225}Ra)

Project-X Stage-1 capability, described in The Book

The Scale of Neutrino Mixing

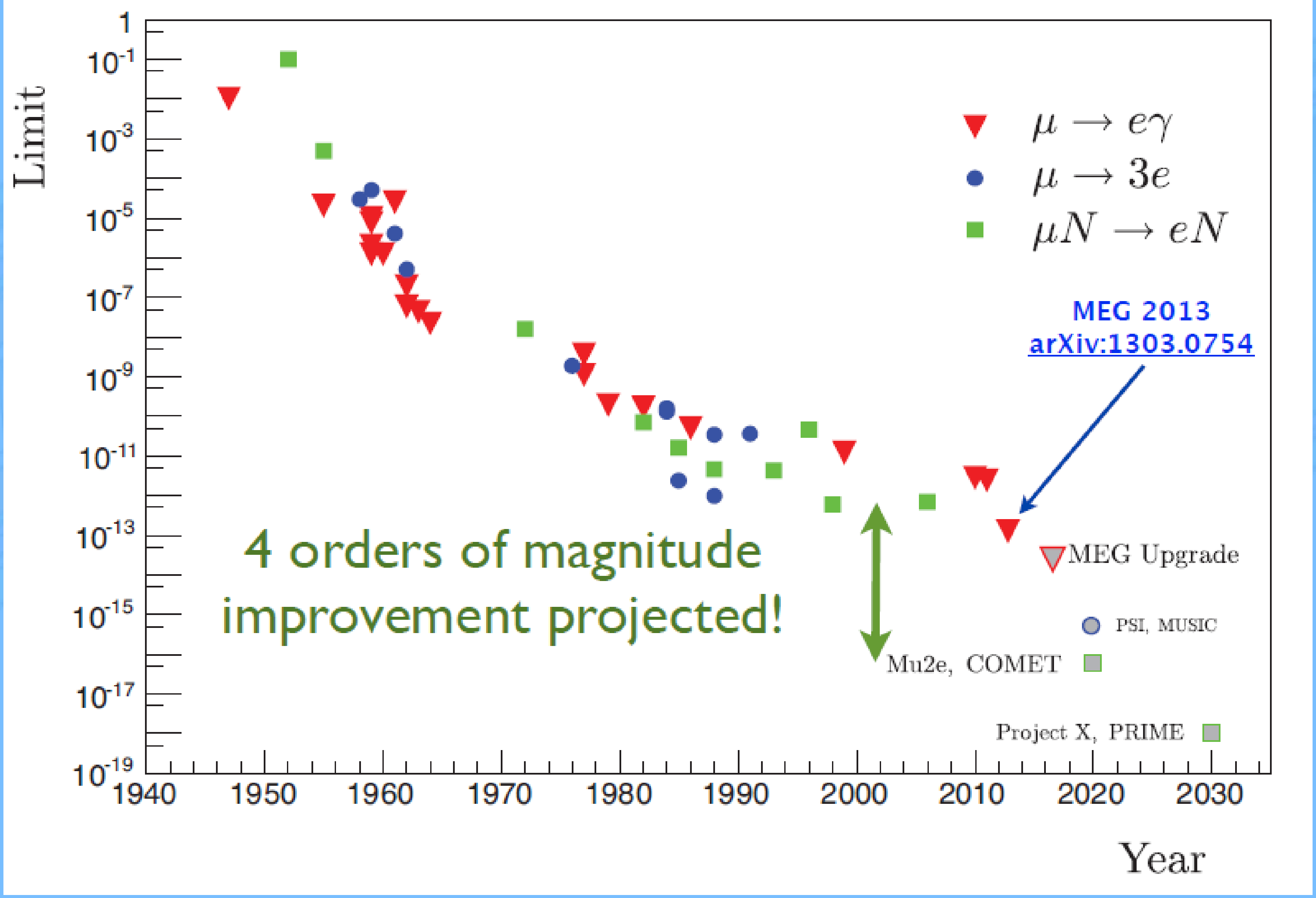


NOvA Facility in Soldier Field

Next Generation Technologies for Neutrino Detectors…Liquid argon on a massive scale…

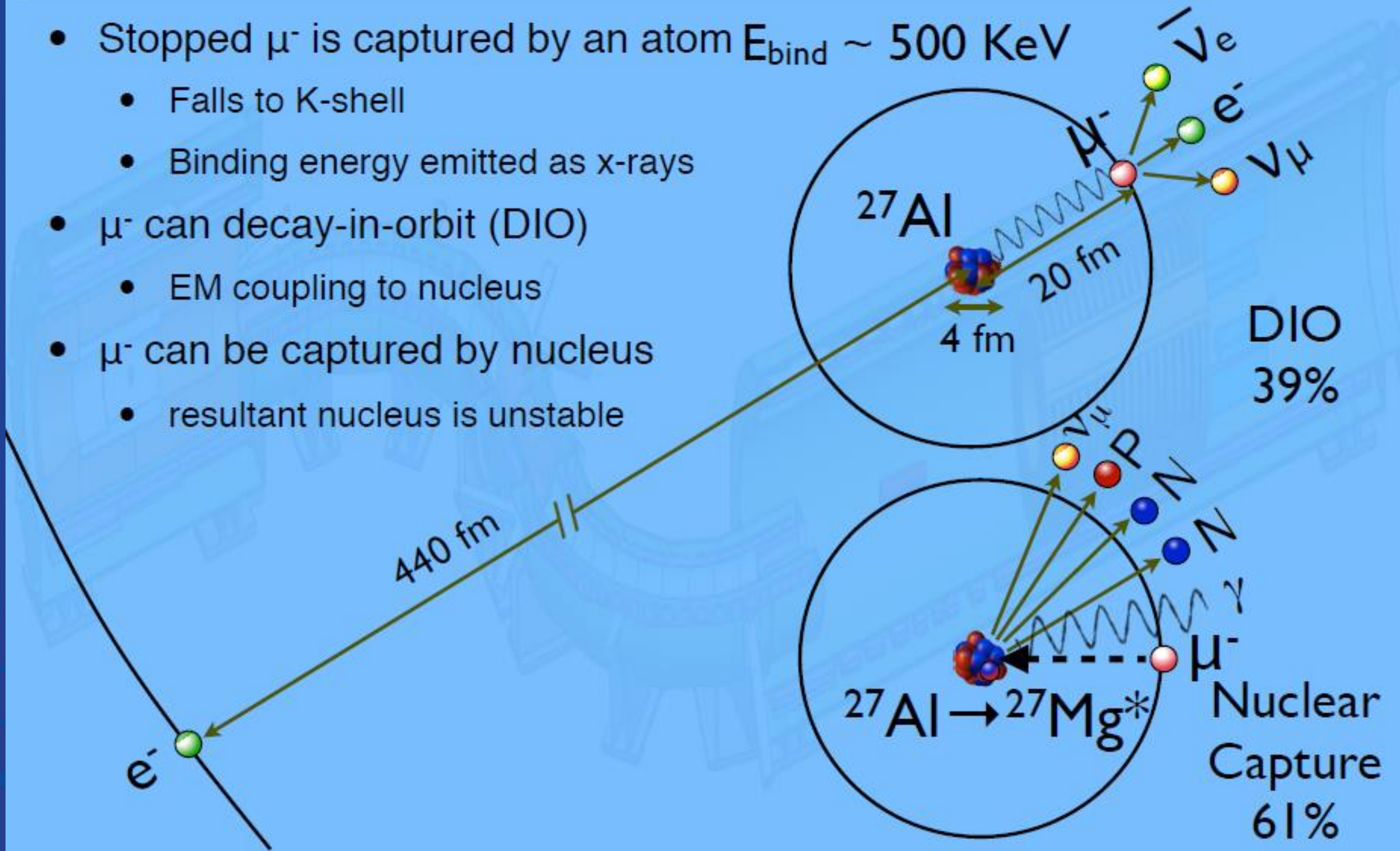
Rare Processes

Status of CLFV Searches



Atomic Capture of μ^-

- Stopped μ^- is captured by an atom
  - 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



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

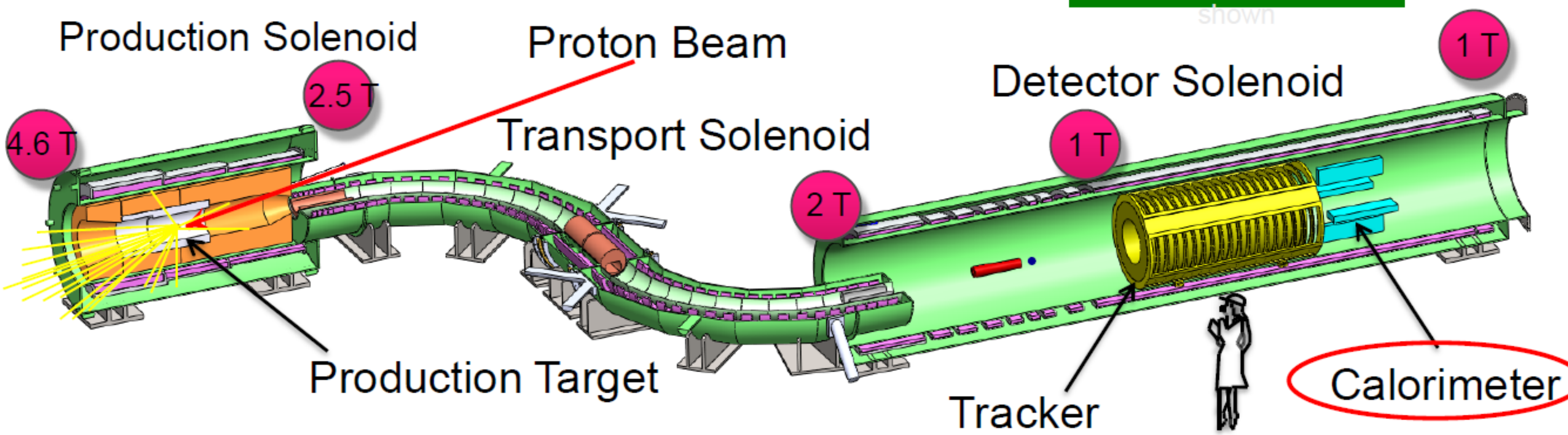
Production Solenoid
- Production target
- Graded field

- Delivers ~ 0.0016 stopped μ^- per incident proton
- 10^{10} Hz of stopped muons

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

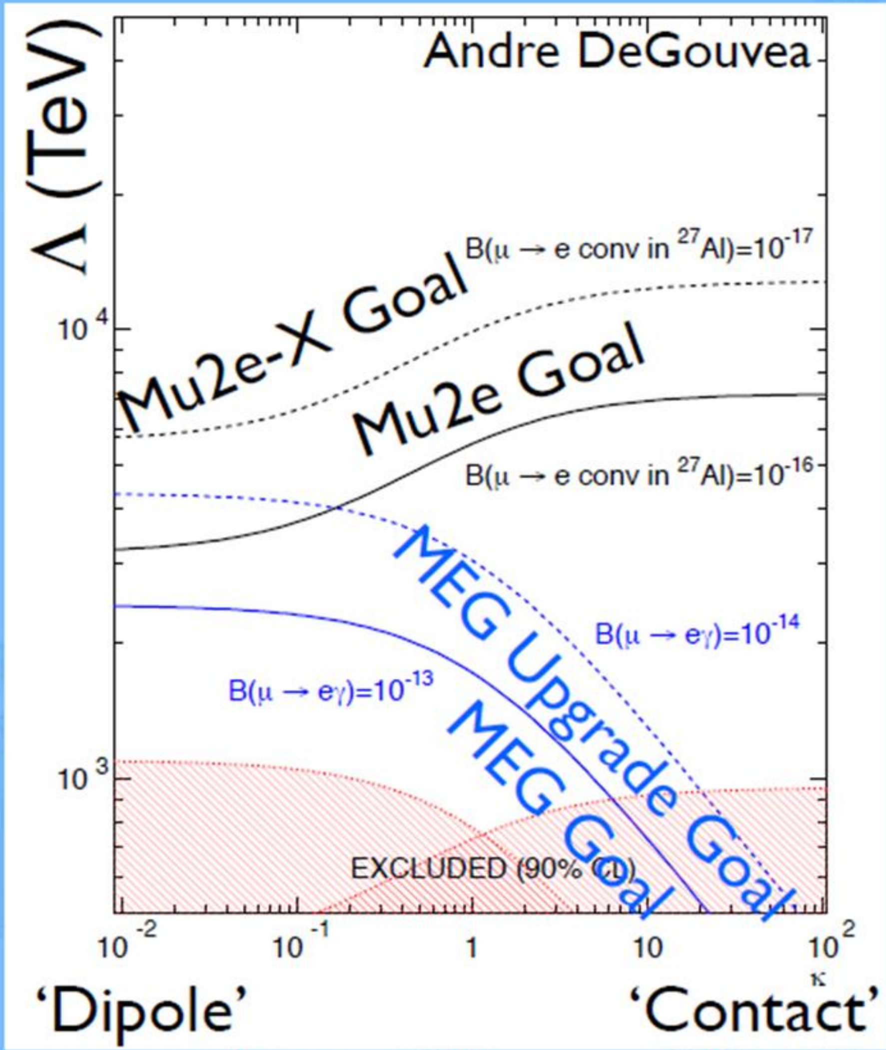
Transport Solenoid
- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator

Cosmic Ray Veto not shown

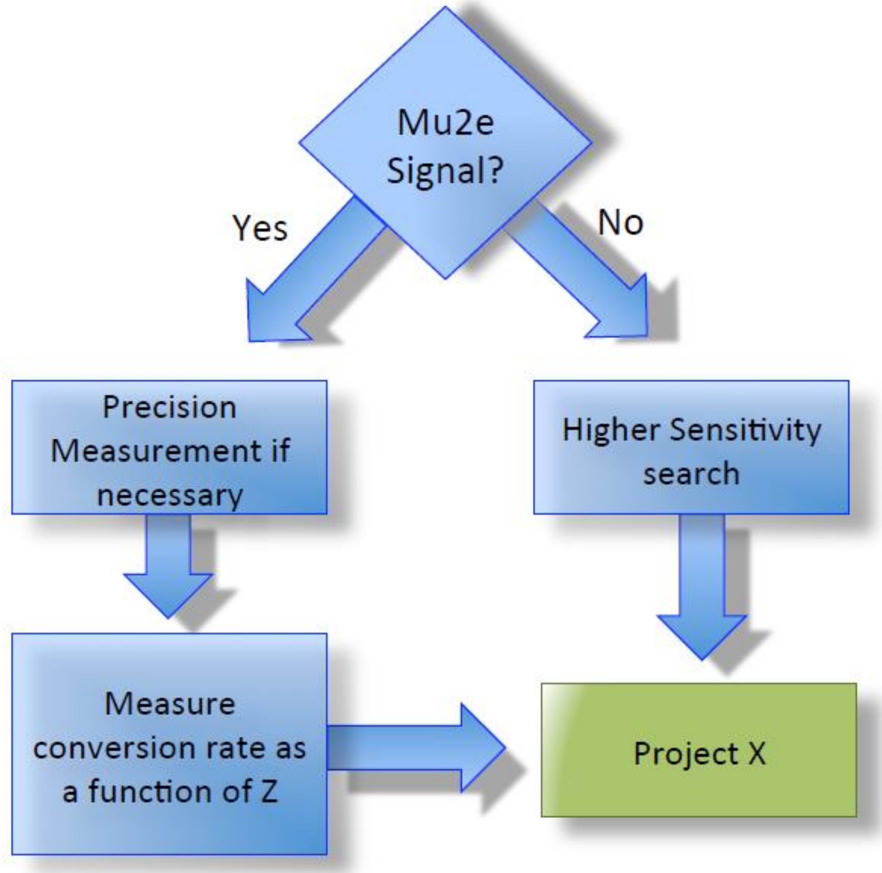


CLFV Sensitivity

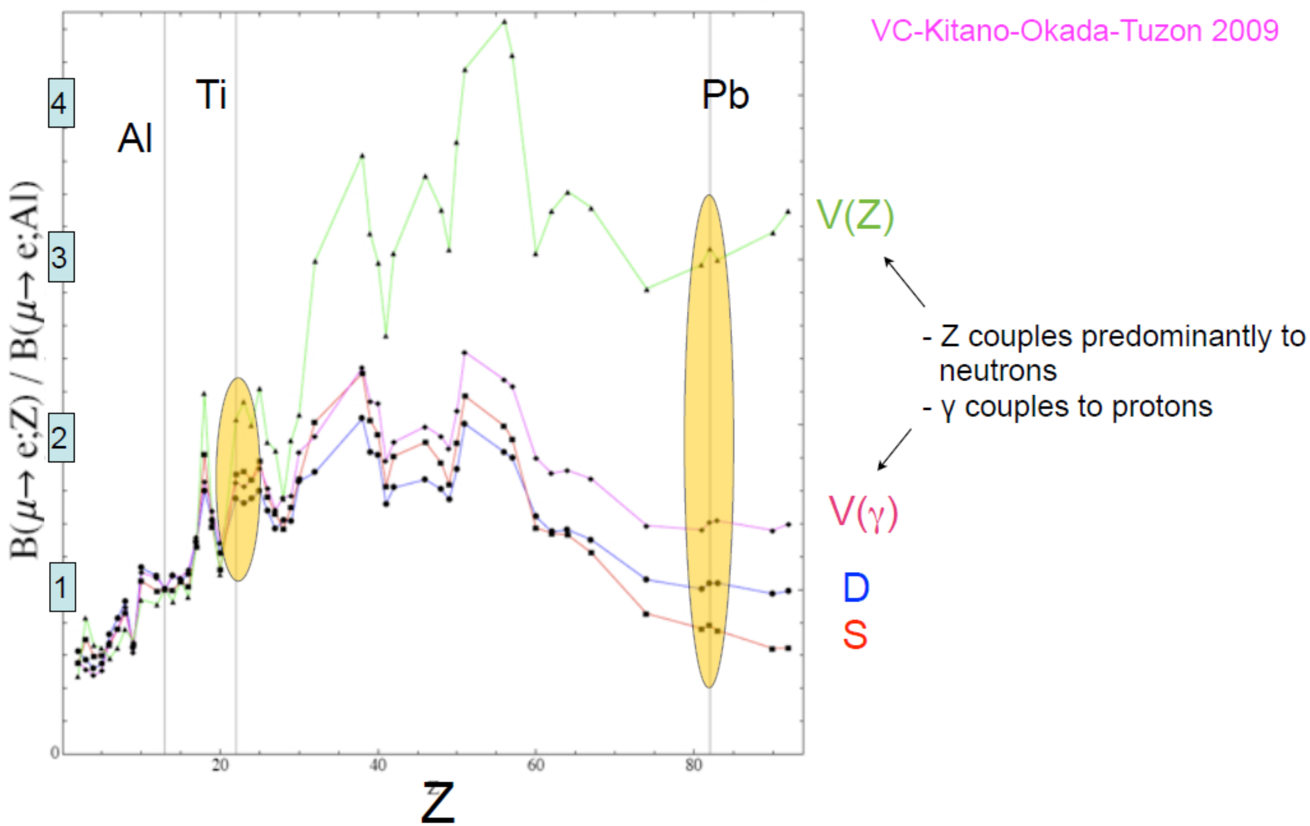
- Effective mass scales up to 10^4 TeV are accessible
- Mu2e is sensitive over the full κ range



First Phase of Mu2e

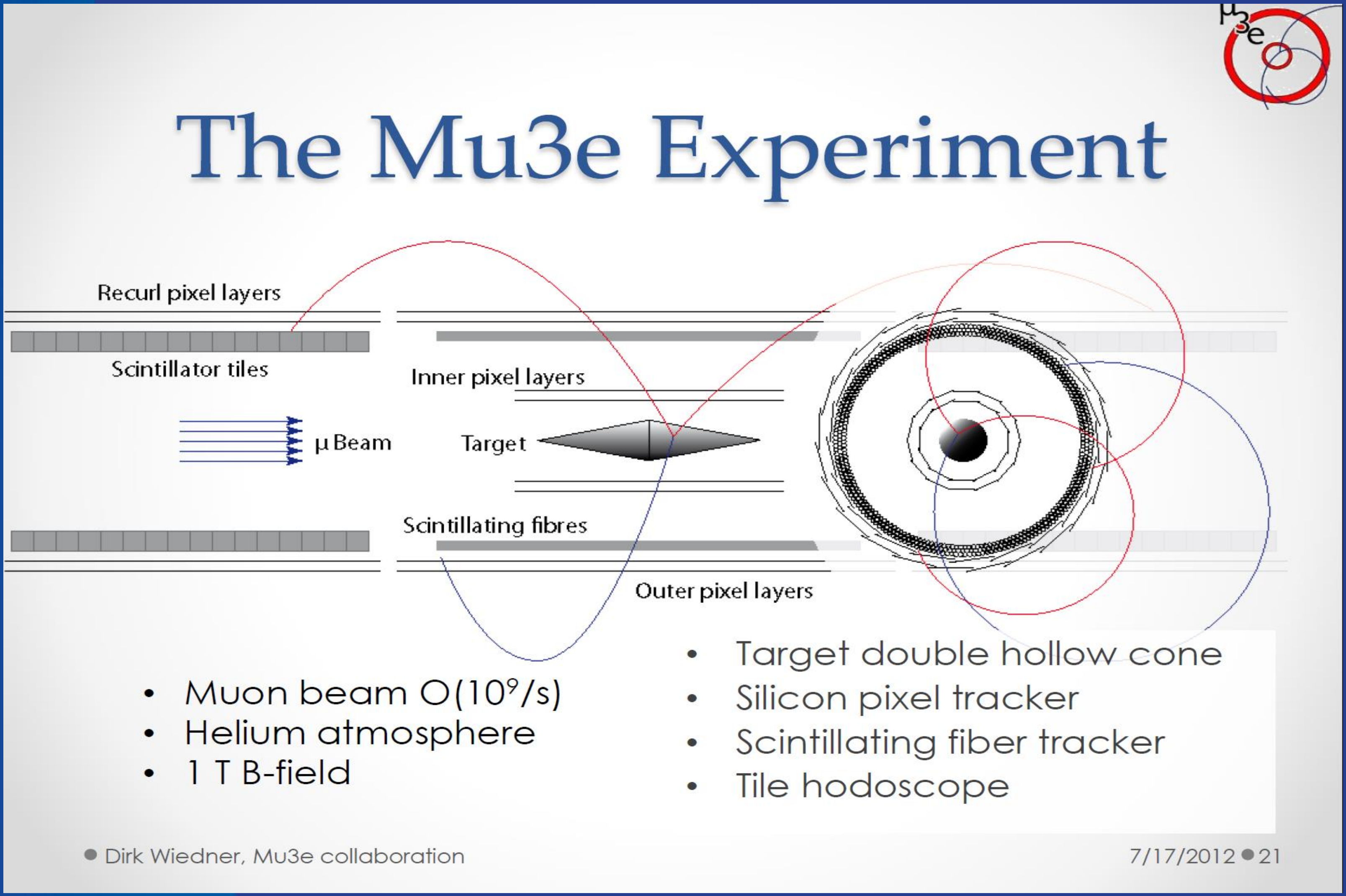


- Test any single-operator model via target-dependence of μ→e rate



- Essentially free of theory uncertainty (largely cancels in ratios)
- Discrimination: need ~5% measure of Ti/Al or ~20% measure of Pb/Al
- Ideal world: use Al and a large Z-target (D,V,S have largest separation): challenge for experiments

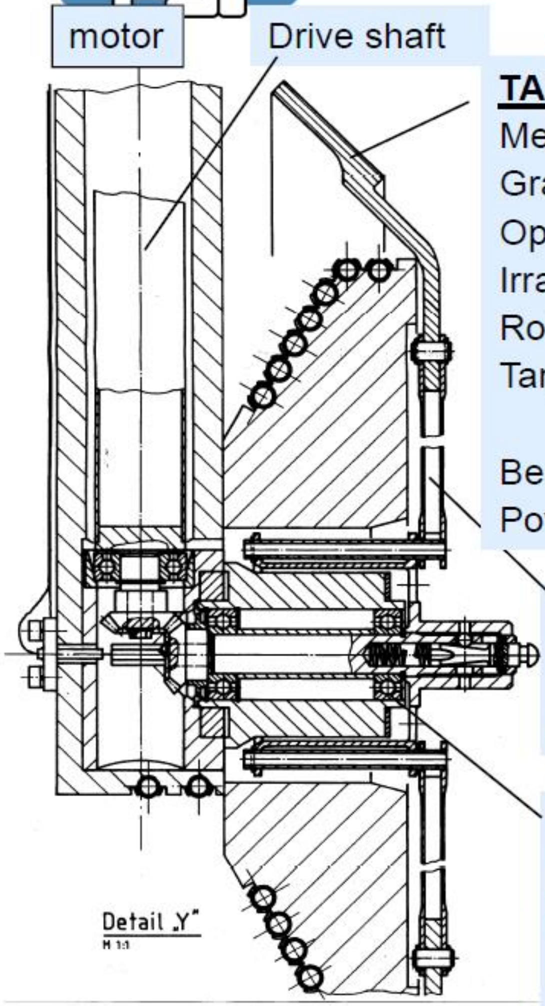
0.1% X_0 per layer, 100 psec track timing…



Dirk Wiedner, Mu3e Initiative at PSI

PAUL SCHERRER INSTITUT PSI

Target-E design



TARGET CONE

Mean diameter:	450 mm
Graphite density:	1.8 g/cm^3
Operating Temperature:	1700 K
Irradiation damage rate:	0.1 dpa/Ah
Rotational Speed:	1 Turn/s
Target thickness:	60 / 40 mm
	10 / 7 g/cm^2
Beam loss:	18 / 12 %
Power deposition:	30 / 20 kW/mA

SPOKES

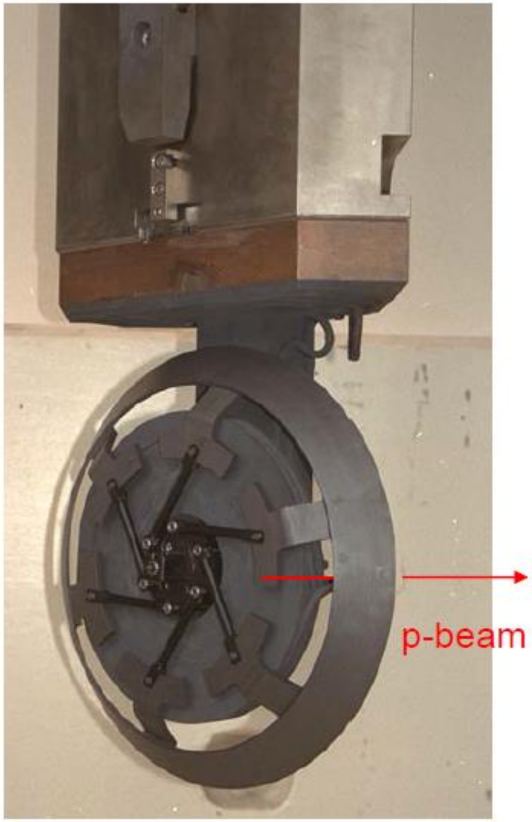
To enable the thermal expansion of the target cone

BALL BEARINGS *)

Silicon nitride balls, coated with MoS2

Rings and cage silver coated

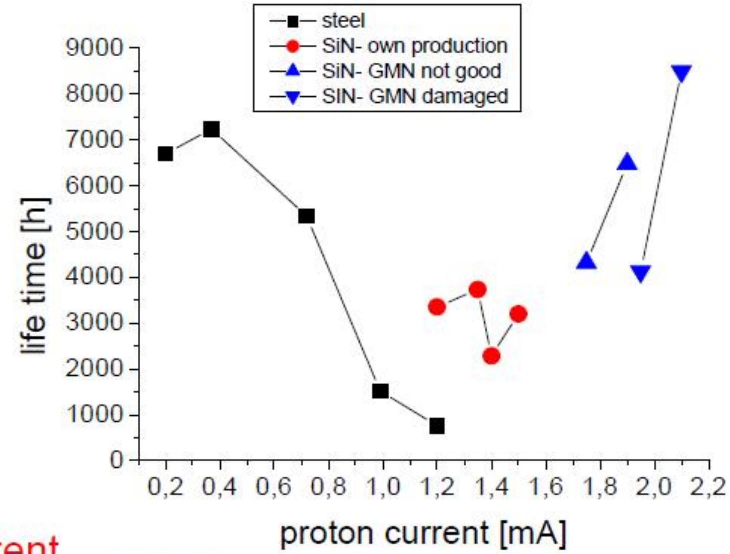
*) GMN, Nürnberg, Germany



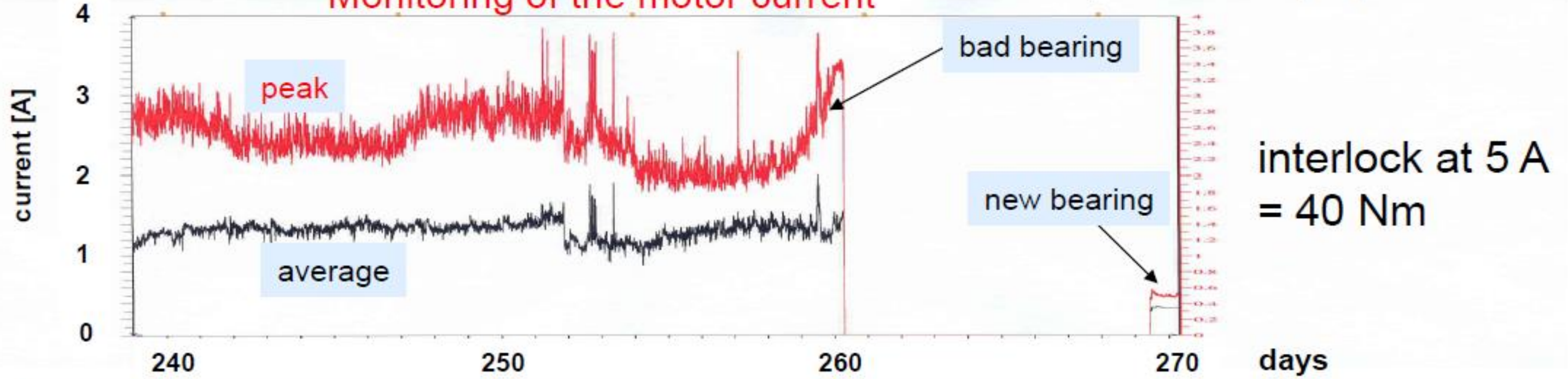
wheel cooled by radiation

muSR Workshop at FNAL Oct 17-19, 2012, Daniela Kiselev, Paul Scherrer Institut

Life time of the ball bearings



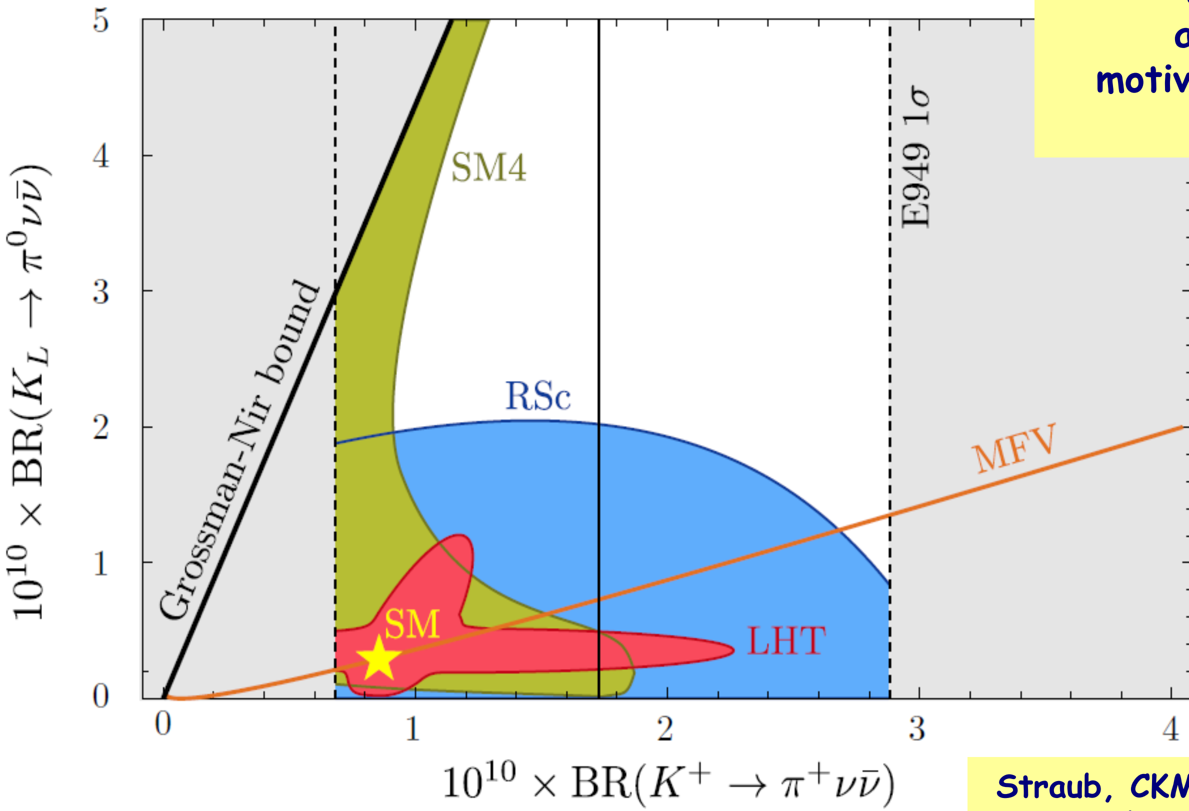
Monitoring of the motor current



muSR Workshop at FNAL Oct 17-19, 2012, Daniela Kiselev, Paul Scherrer Institut

Rare processes can dissect new physics…
e.g. Warped Extra Dimensions as a Theory of Flavor??

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

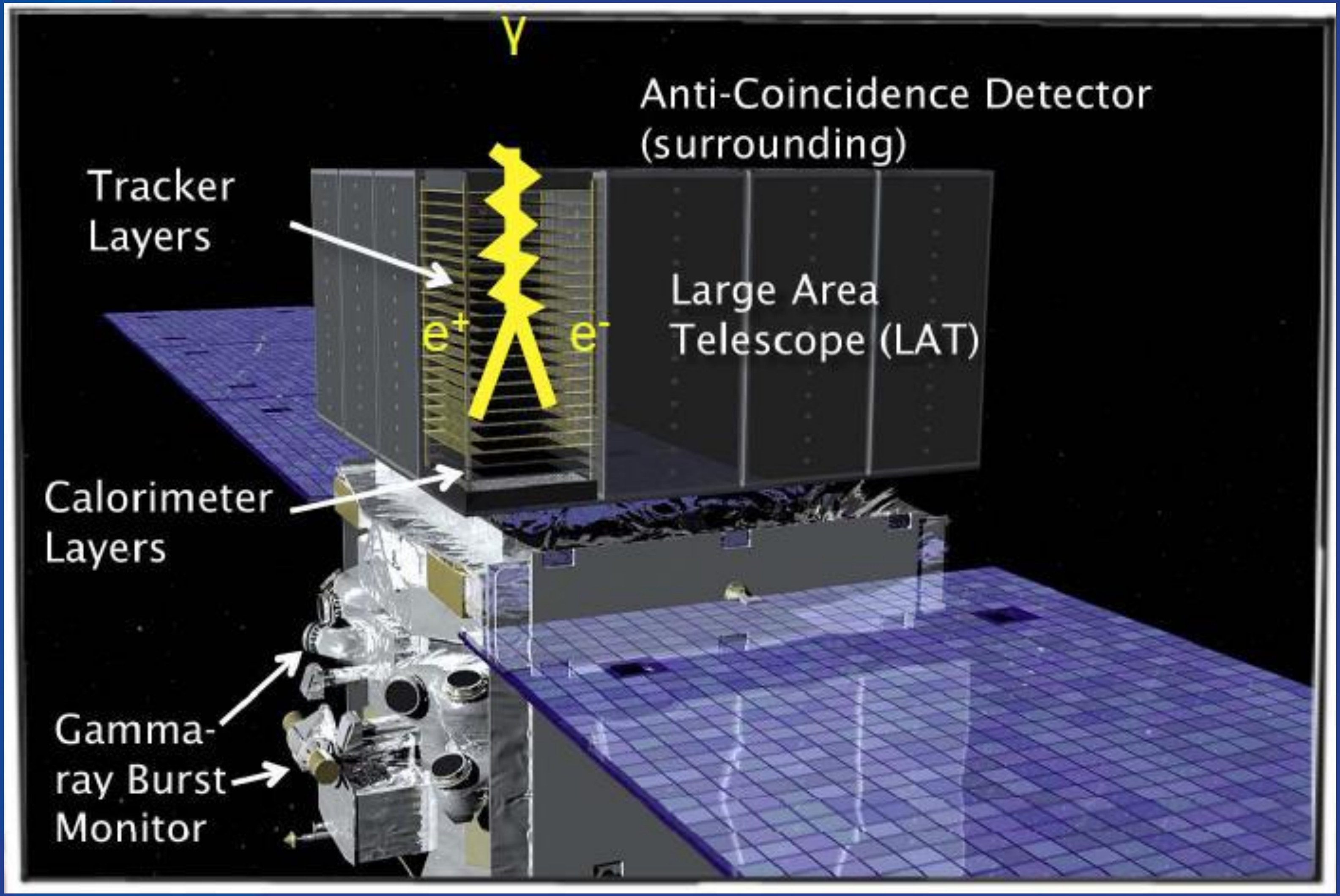


Straub, CKM 2010 workshop (arXiv:1012.3893v2)

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.

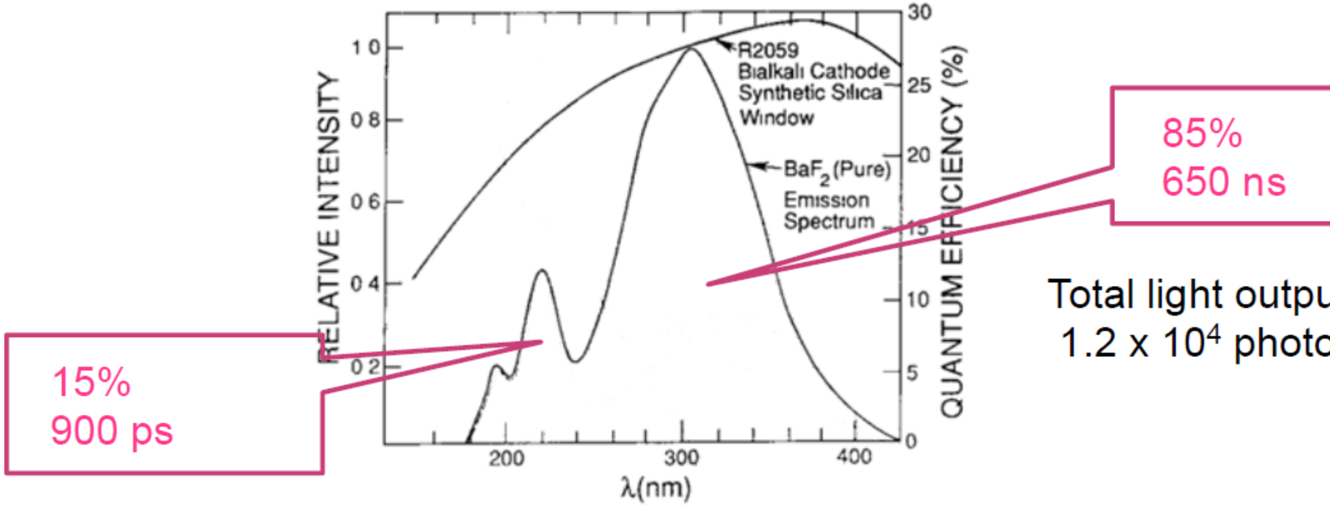
Fermilab

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



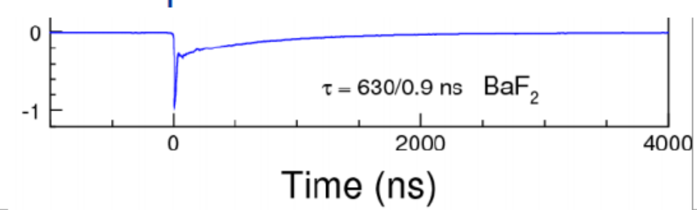
BaF_2 is a potentially attractive high rate crystal

- BaF_2 is among the fastest scintillating crystals (0.9ns), but there is a much larger, slower, component (650ns)



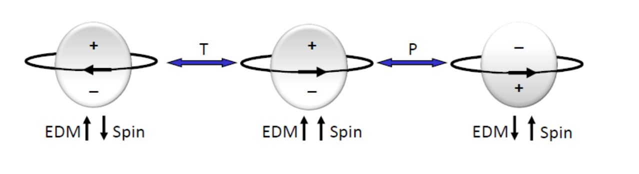
Total light output
1.2×10^4 photons/MeV

- In order to take advantage of the fast component, it is necessary to suppress the slow component




EDM
ELECTRONIC DANCE MUSIC

EDM Research Worldwide…

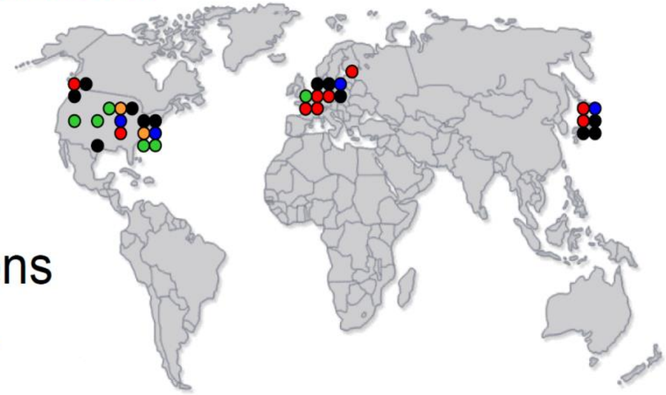


Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- **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



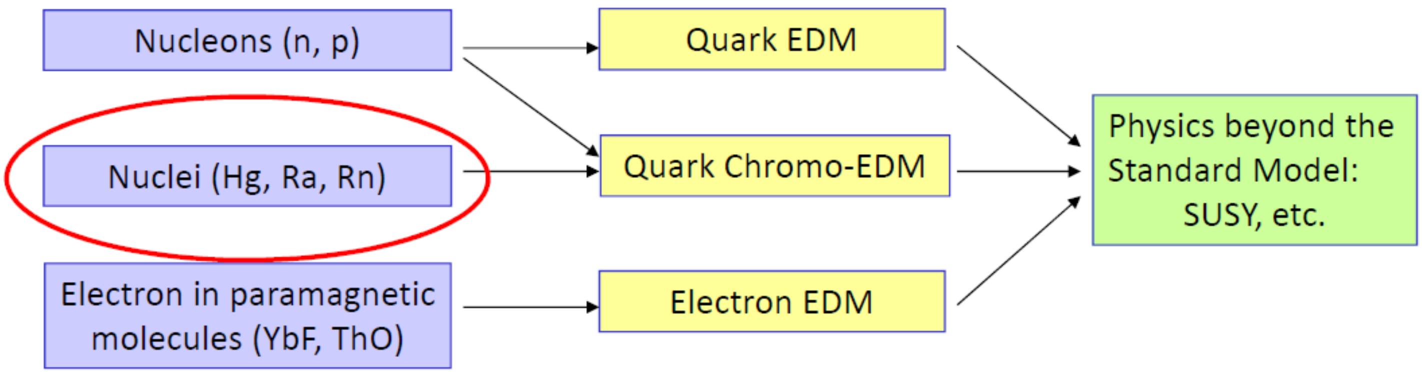
- **Ions-Muons** (~200)
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC

- **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)



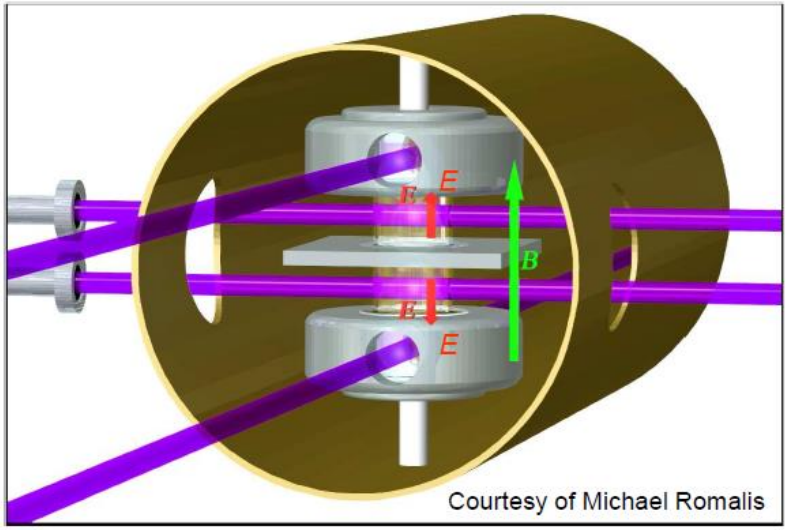
Sector	Exp Limit (e-cm)	Method	Standard Model
Electron	1×10^{-27}	YbF in a beam	10^{-38}
Neutron	3×10^{-26}	UCN in a bottle	10^{-31}
^{199}Hg	3×10^{-29}	Hg atoms in a cell	10^{-33}

M. Ramsey-Musolf (2009)

Zheng-Tian Lu, Snowmass IF All Hands meeting ANL, April 25^{th}-27^{th} 2013

The Seattle EDM Measurement (1980's - present)

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



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

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

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

Limits and Sensitivities

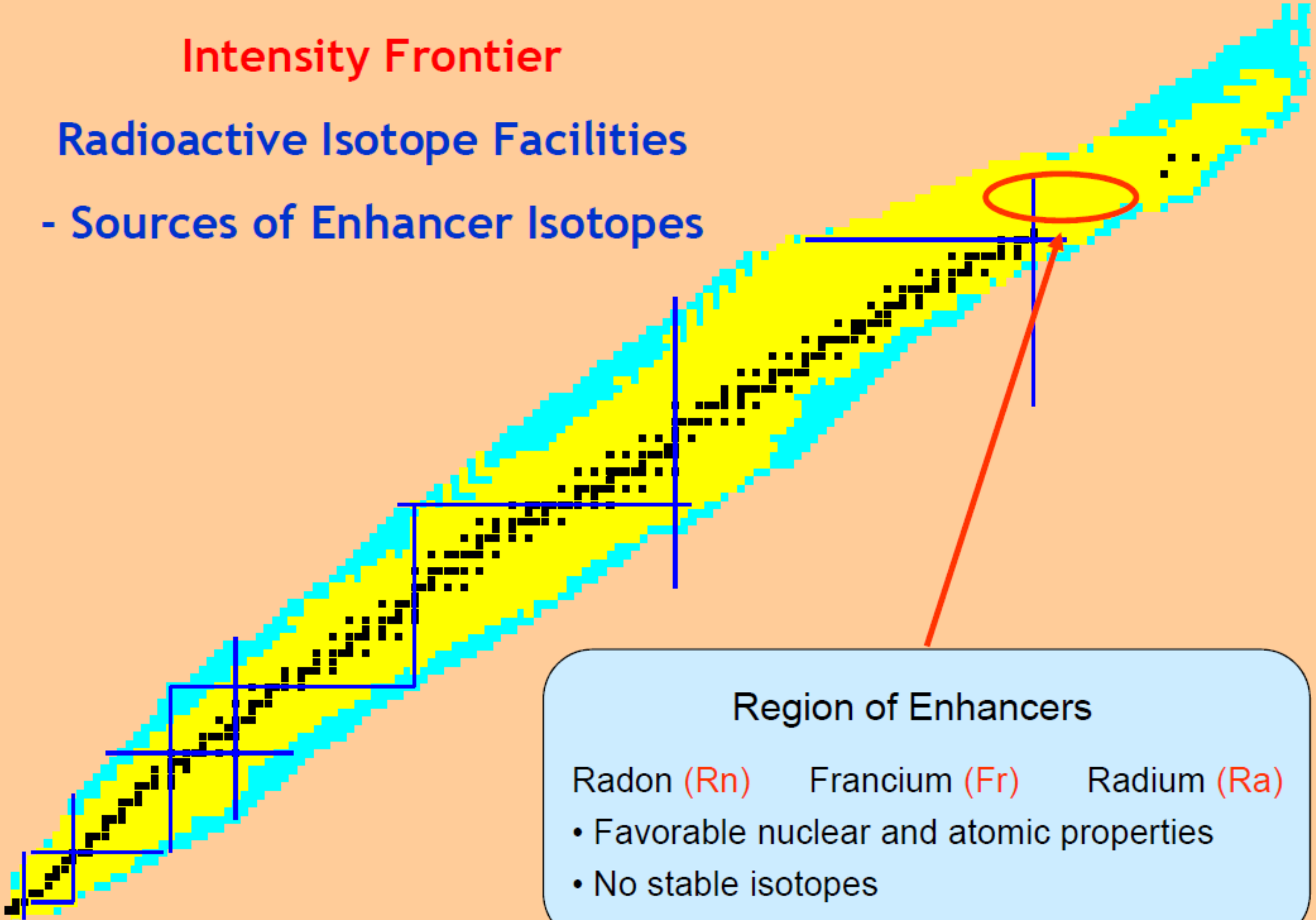
- Current: < 0.3 x 10^{-28} e-cm Griffith *et al.*, Phys. Rev. Lett. (2009)
- Next 5 years: 0.03 x 10^{-28} e-cm
- 2020 and beyond: 0.006 x 10^{-28} e-cm

Zheng-Tian Lu, Snowmass IF All Hands meeting ANL, April 25th-27th 2013

Intensity Frontier

Radioactive Isotope Facilities

- Sources of Enhancer Isotopes



Region of Enhancers

Radon (Rn) Francium (Fr) Radium (Ra)

- Favorable nuclear and atomic properties
- No stable isotopes

Zheng-Tian Lu, Snowmass IF All Hands meeting ANL, April 25th-27th 2013

EDM of ^{225}Ra enhanced

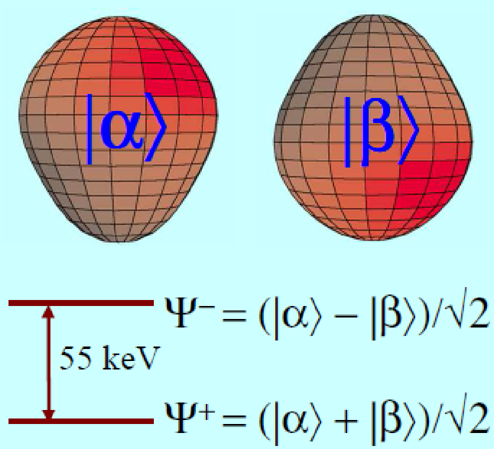
^{225}Ra:
I = ½
$t_{1/2}$ = 15 d

- 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)*

Parity doublet



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

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)

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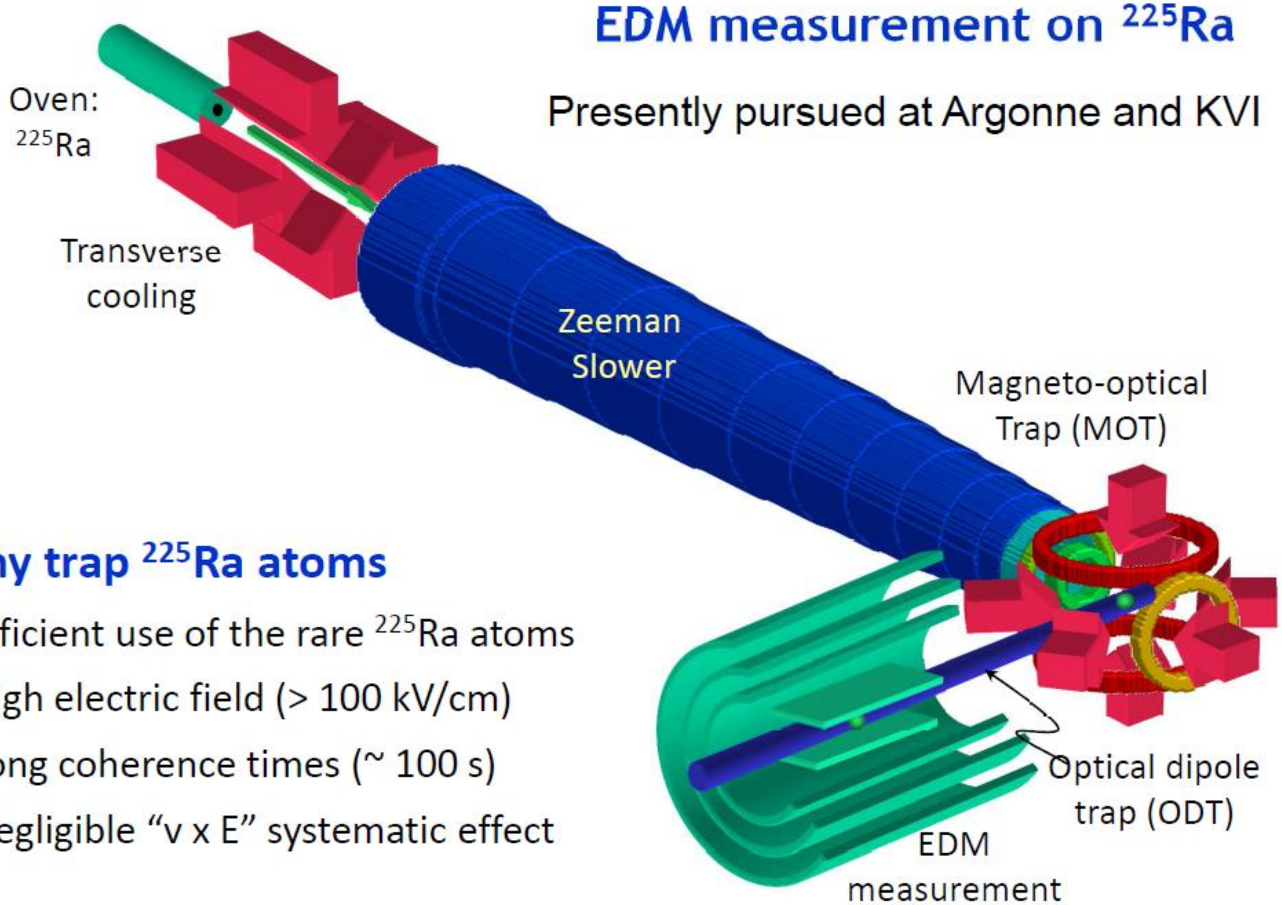
EDM measurement on ^{225}Ra

Presently pursued at Argonne and KVI



Why trap ^{225}Ra atoms

- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence times (~ 100 s)
- Negligible “v x E” systematic effect

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Radium EDM Search at Argonne

Progress

- 2007 – Magneto-optical trap (MOT) of radium realized;

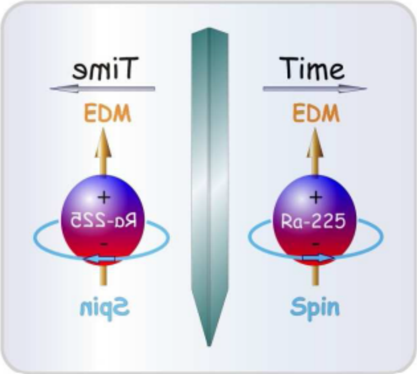
  J.R. Guest *et al.*, Phys. Rev. Lett. (2007)
- 2010 – Optical dipole trap (ODT) of radium realized;
- 2011 – Atoms transferred to the measurement trap;

  R.H. Parker *et al*. Phys. Rev. C (2012)
- 2012 – Spin precession of Ra-225 observed.

Outlook

- Next 5 years: 10 – 100 x 10^{-28} e-cm
- 2020 and beyond: 1 x 10^{-28} e-cm *

  * at an accelerator-based isotope production facility



We acknowledge support by DOE, Office of Nuclear Physics

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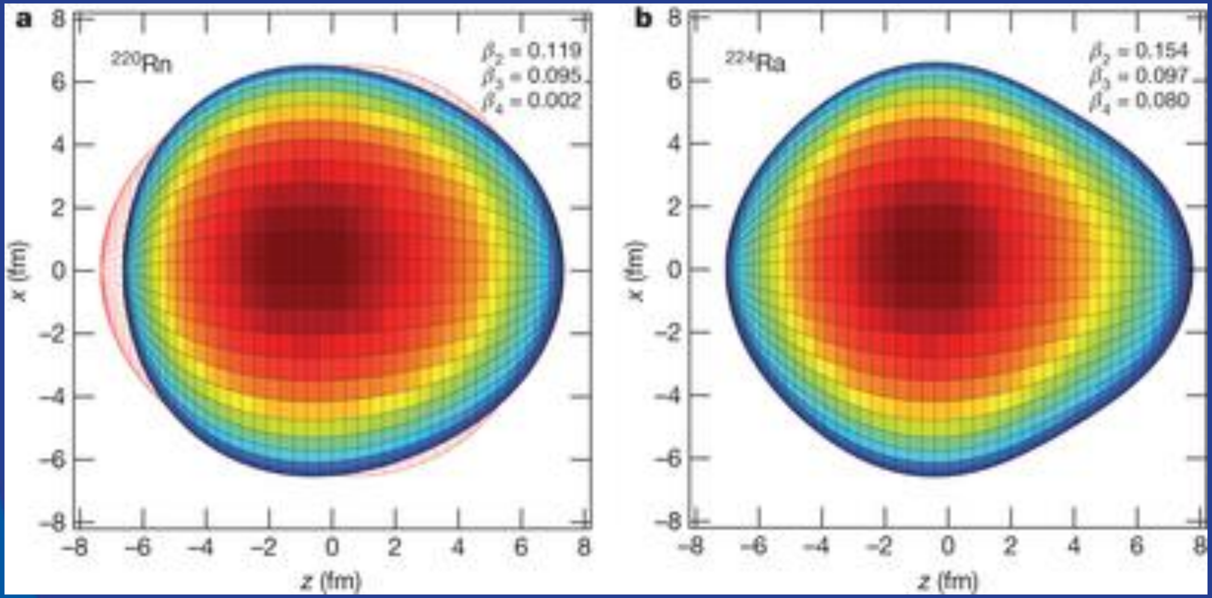
Studies of pear-shaped nuclei using accelerated radioactive beams

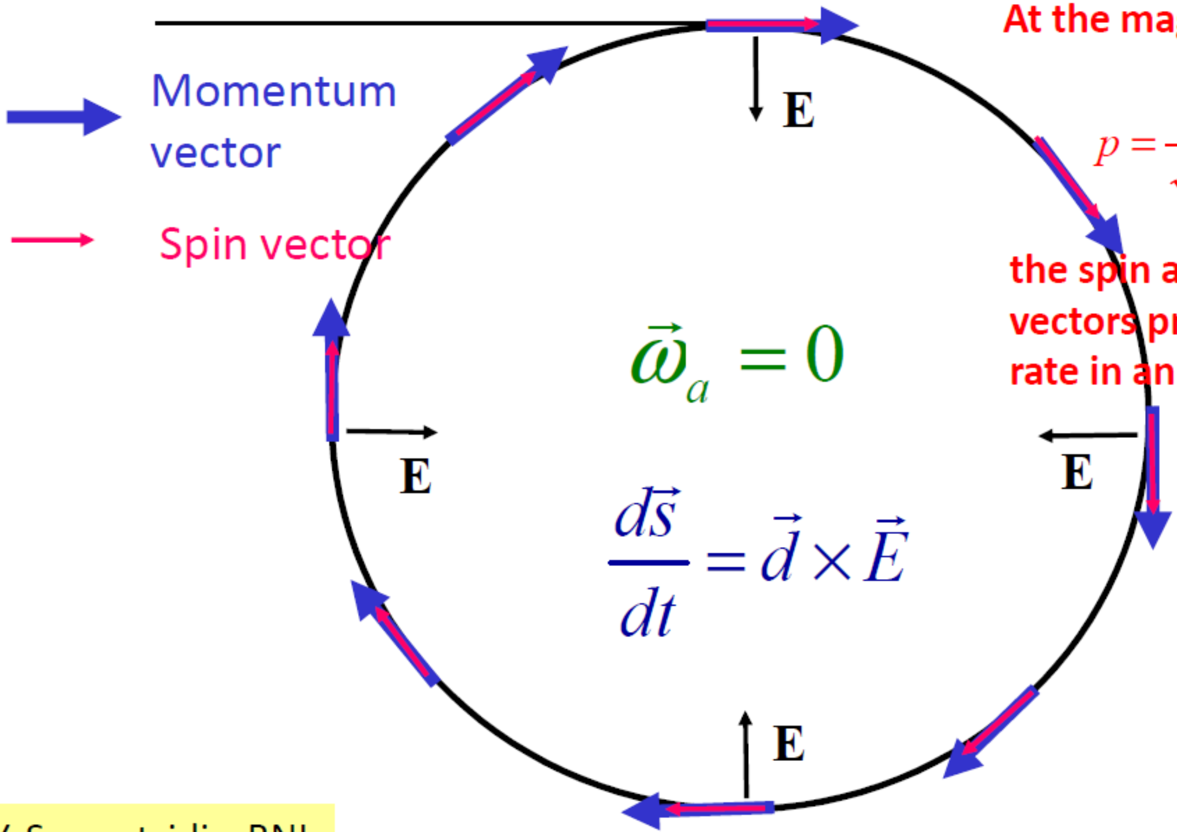
L. P. Gaffney, P. A. Butler, M. Scheck, A. B. Hayes, F. Wenander, M. Albers, B. Bastin, C. Bauer, A. Blazhev, S. Bönig,N. Bree, J. Cederkäll, T. Chupp, D. Cline, T. E. Cocolios, T. Davinson, H. De Witte,J. Diriken,T. Grahn,A. Herzan,M. Huyse,D. G. Jenkins, D.T. Joss,N. Kesteloot,J. Konk

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



Research performed at the Isolde facility at CERN

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



$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

At the magic momentum

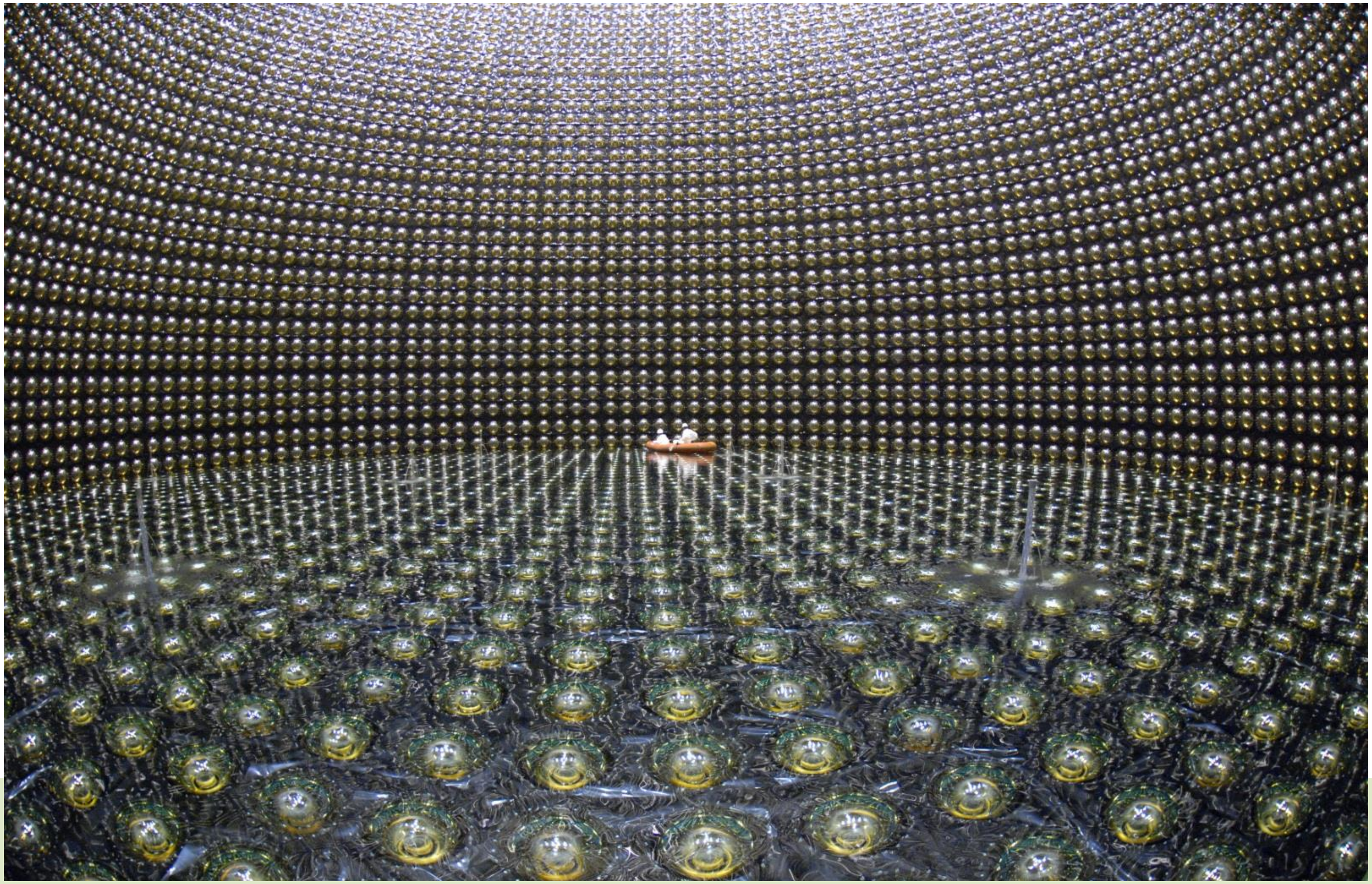
$$p = \frac{m}{\sqrt{a}} = 0.7GeV/c$$

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

Y. Semertzidis, BNL

Zheng-Tian Lu, Snowmass IF All Hands meeting ANL, April 25th-27th 2013

Proton Decay



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

E. Kearns, Intensity Frontier All Hands Meeting, ANL

Efficiency and Background Rates

A. Bueno et al.
hep-ph/0701101

	Mode	Super-K Water Ch. Efficiency	Super-K Water Ch. BG Rate (/Mt y)	LAr (generic) Efficiency	LAr (generic) 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

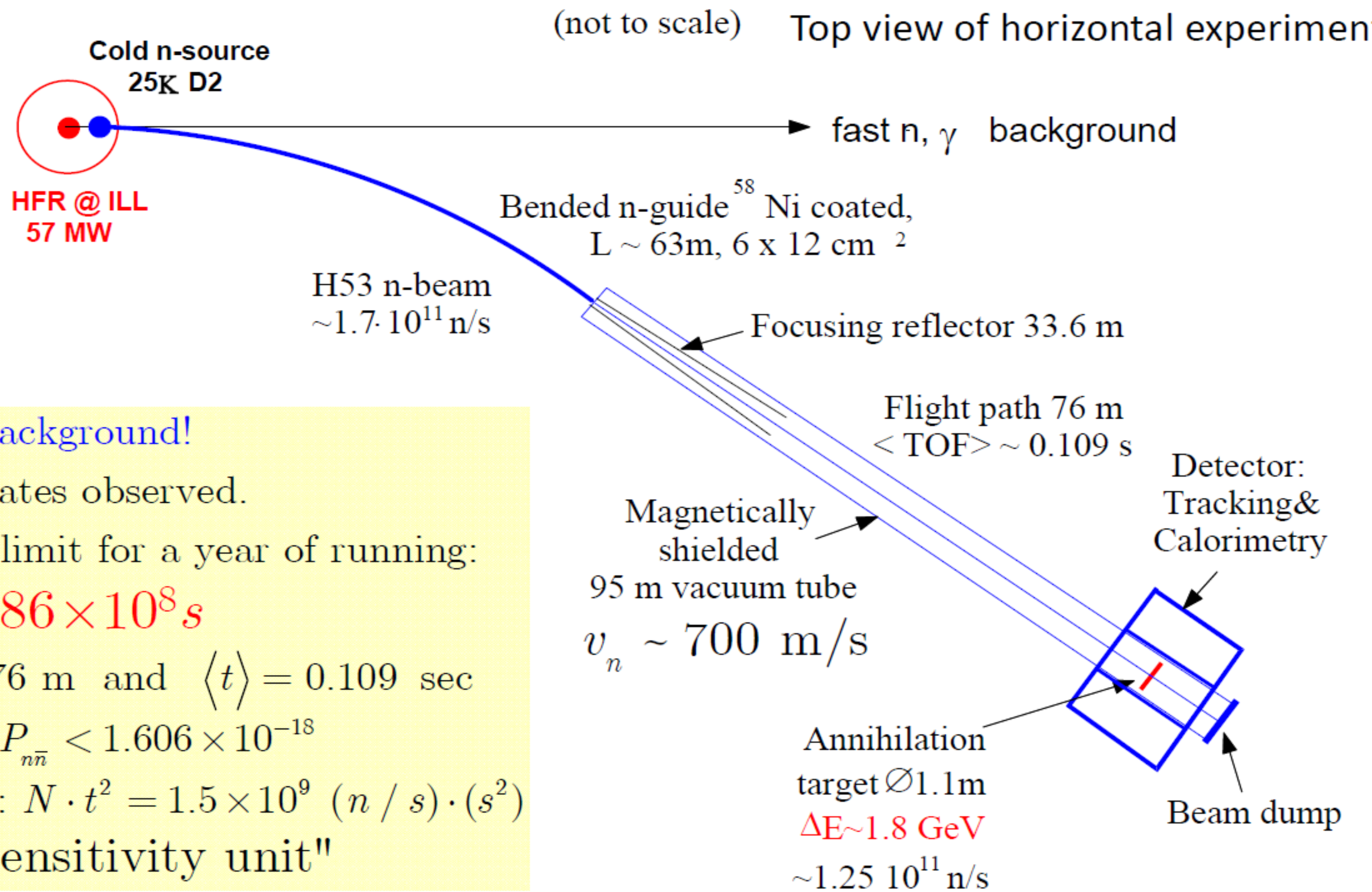
* New analysis (Miura, BLV Heidelberg)

E. Kearns, Intensity Frontier All Hands Meeting, ANL

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

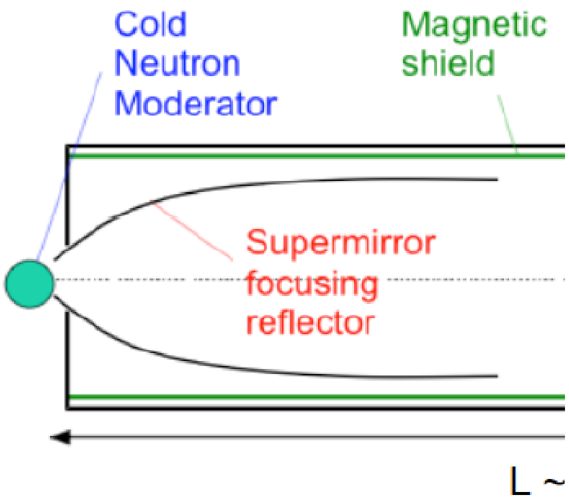
Expression of Interest

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



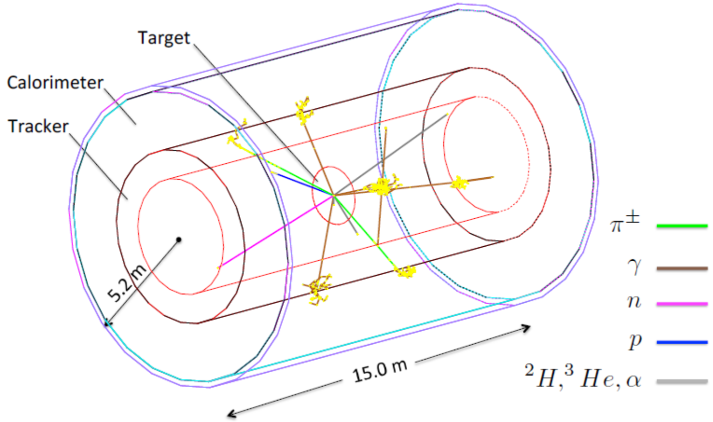
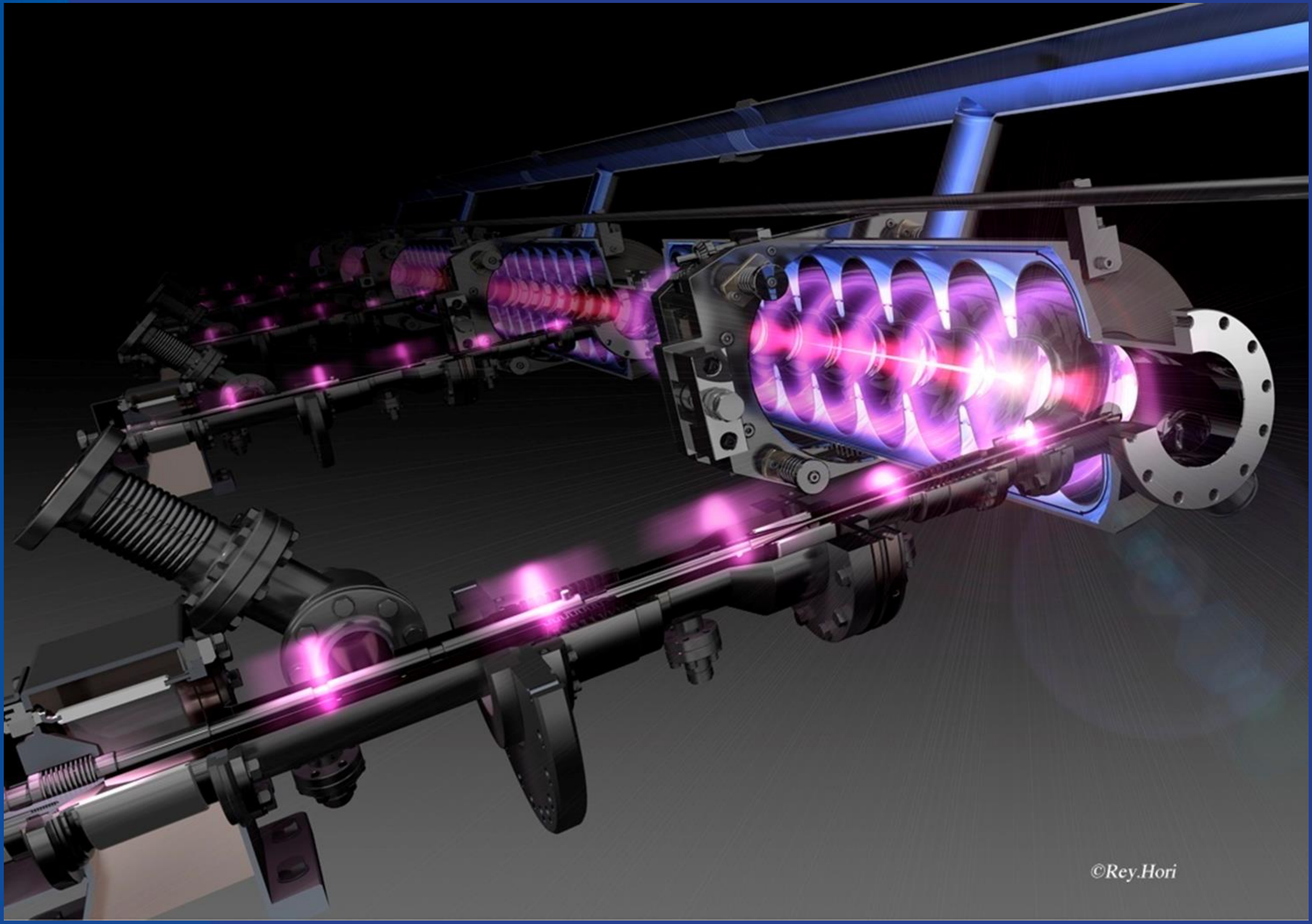


Figure VI-5: Event display generated in our preliminary Geant4 [78] simulation for a $\pi^+\pi^-2\pi^0$ annihilation event in a generalized NNbarX detector geometry. Given the short lifetime of the π^0, they decay immediately to 2γ, as shown above.

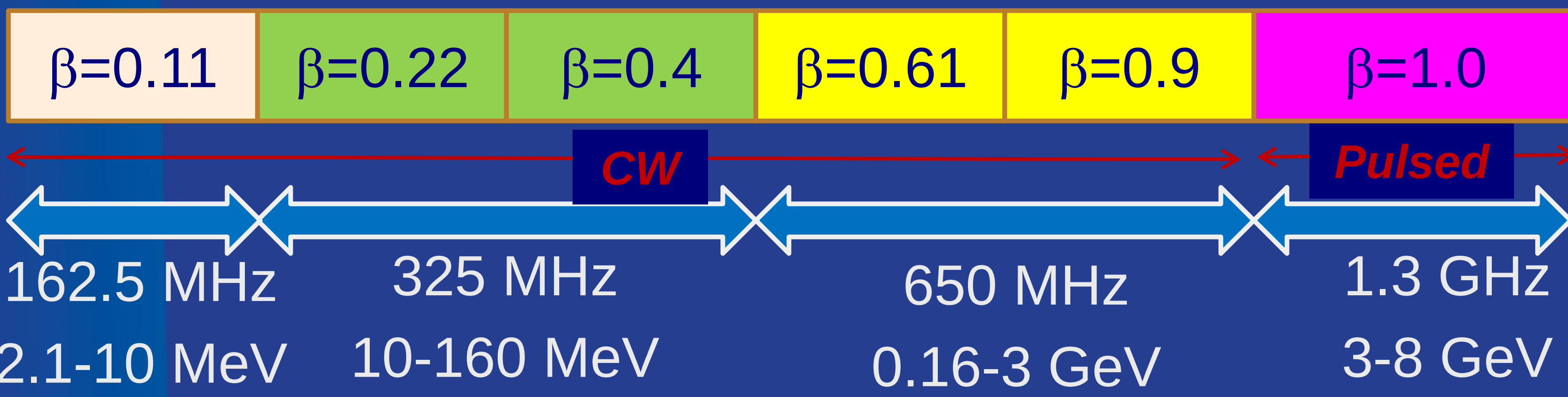
E. Kearns, Intensity Frontier All Hands Meeting, ANL

Fermilab

Beam Power is the Gateway to the Intensity Frontier…



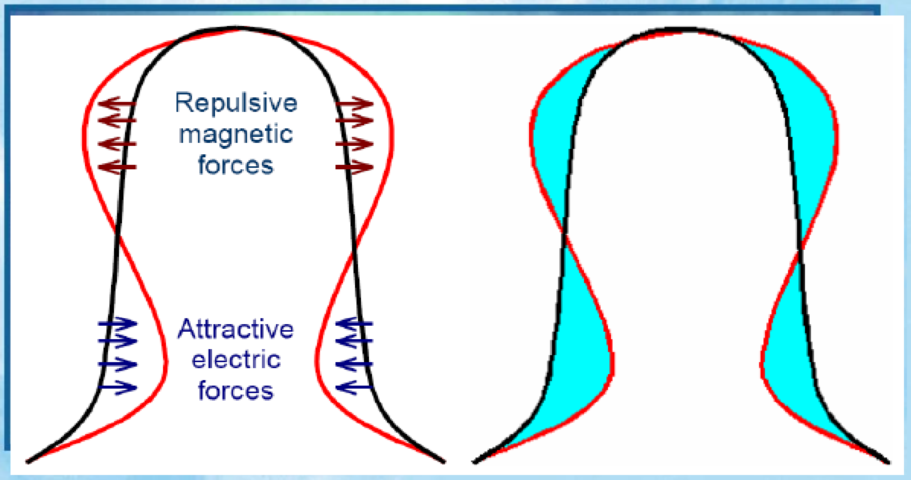
Project X SRF Linac Technology Map



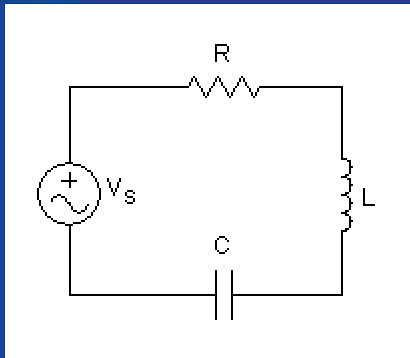
Section	Freq	Energy (MeV)	Cav/mag/CM	Type
HWR (β_G=0.1)	162.5	2.1-10	9/6/1	HWR, solenoid
SSR1 (β_G=0.22)	325	10-42	16/18/ 2	SSR, solenoid
SSR2 (β_G=0.47)	325	42-160	36/20/4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-460	42 /14/7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	152/19/19	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

Resonance Control in SCRF Cavities

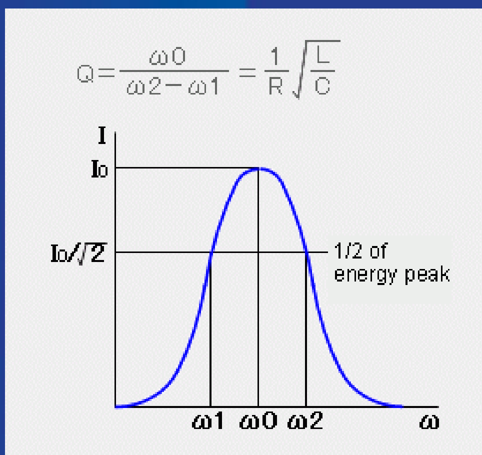
- SCRF cavities are designed with thin walls to maximize heat transfer to liquid He bath
- The thin walls lack stiffness making the cavities susceptible to mechanical oscillations
- Longitudinal oscillations can change the resonance frequency of the cavity
- Oscillations can be excited
  - Deterministically (**Lorentz Force**)
  - Non-Deterministically (Microphonics)

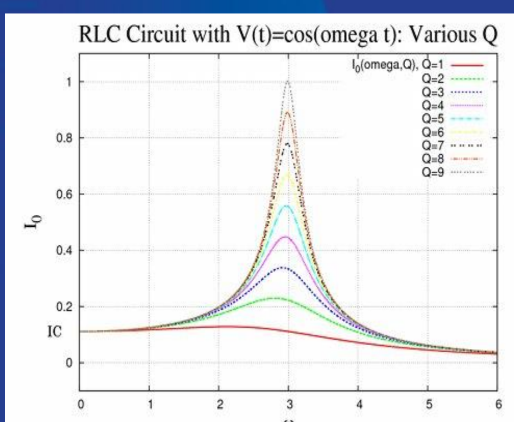


Courtesy of Yuriy Pischalnikov



$$Q = 2\pi \times \frac{\text{Energy-Stored}}{\text{Energy-Lost-per-Cycle}}$$

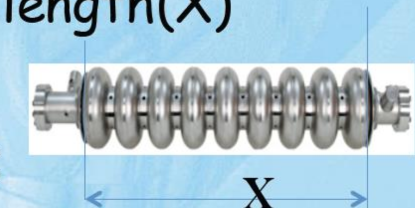




Typical Parameters for 1.3GHz 9 cell ILC/Tesla cavities

- Cavity frequency (F) VS. cavity length(X)

  $\Delta F/\Delta x$ ~300 Hz/um;



- Slow tuner range (DF &DX):

  ΔF ~500 kHz == Δx ~+/-1 mm

- Cavity bandwidth ($F_{1/2}$ at Q_L~$3*10^6$)

  $F_{1/2}$~400 Hz;

- Requirements to slow tuner to tune cavity within +/-10Hz to nominal value (1.3GHz) limit hysterezis of mechanical system

  +/-30 nm;

Courtesy of Yuriy Pischalnikov

Piezoelectrical actuators

PIEZOELECTRIC ACTUATORS

- ***Commercially available from multiple sources***
- ***Typically used at room temperature (stroke~50µm for 50mm long Piezostack at RT)***
- ***Work at cryogenic temperatures with reduced stroke (6-10% of RT stroke ~ 4-5µm at 4K)***
- ***Deliver high forces ~5000N for 10*10mm² cross-section***
- ***Low voltage (150-200V) actuators used for fast tuner***
- ***~10uF for stack 10*10*50mm (at RT) and 10% at LiqHe***
- ***Actuator of main choice at many labs for detuning compensation studies***
- ***Piezo can work as a sensor***
- ***Widely used in different industrial applications (diesel engine , etc...)***

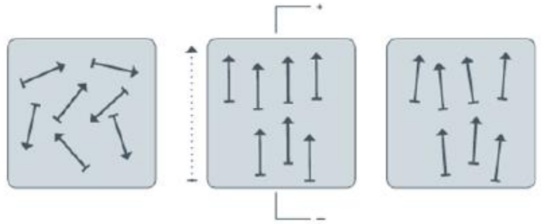


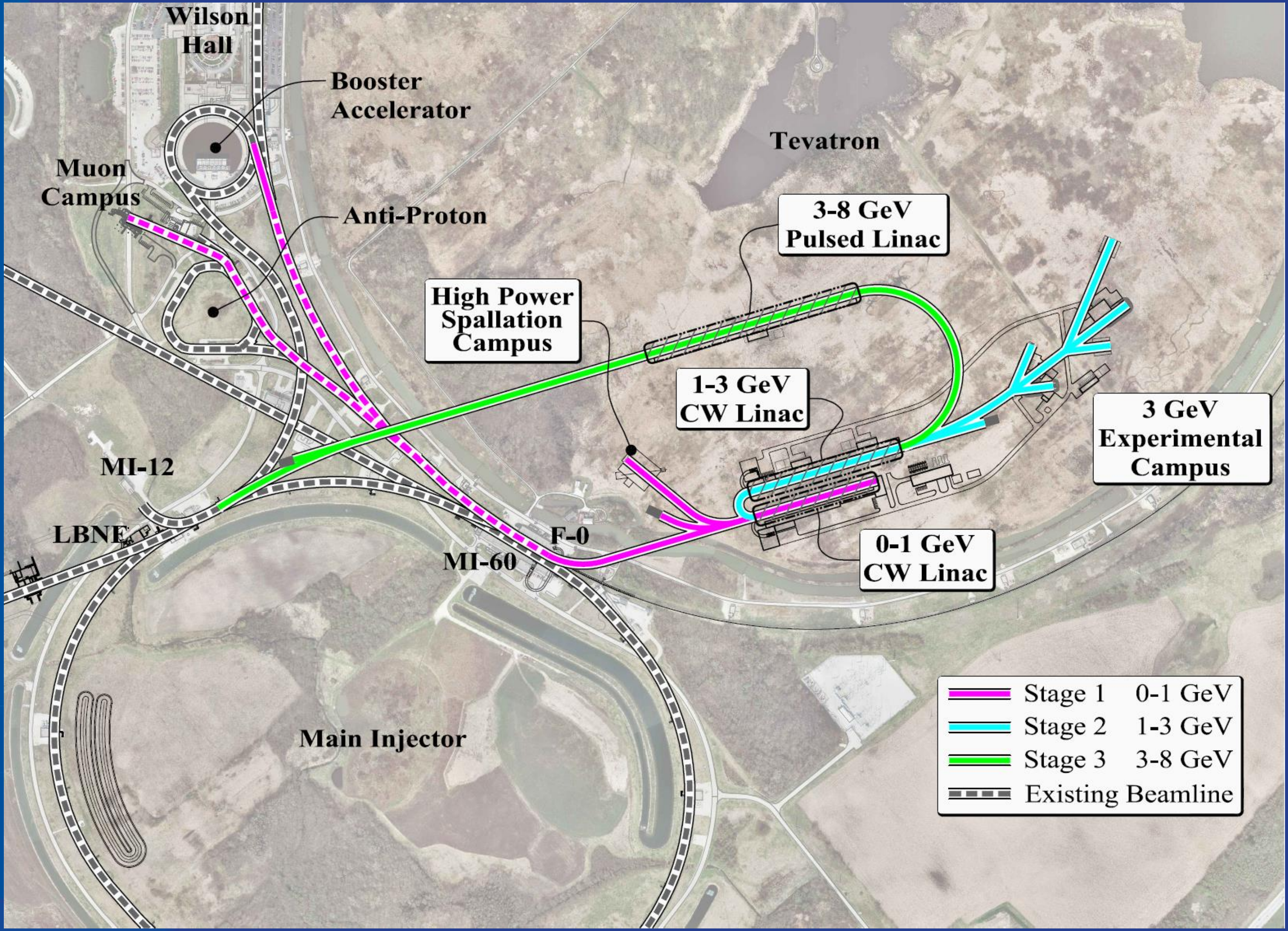
Fig.2 Electric dipoles in piezoelectric materials before, during and after poling.

Stacked multilayer piezoelectric actuators are made of two or several linear actuators glued together. The purpose of the stacking is to obtain more displacement than can be achieved by a single linear actuator.

250um

Courtesy of Yuriy Pischalnikov

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

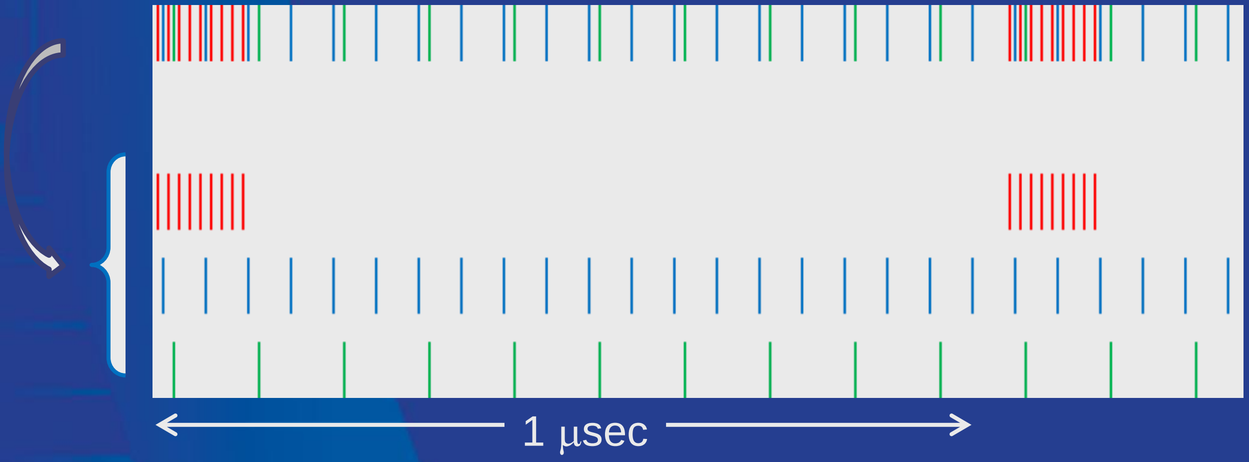


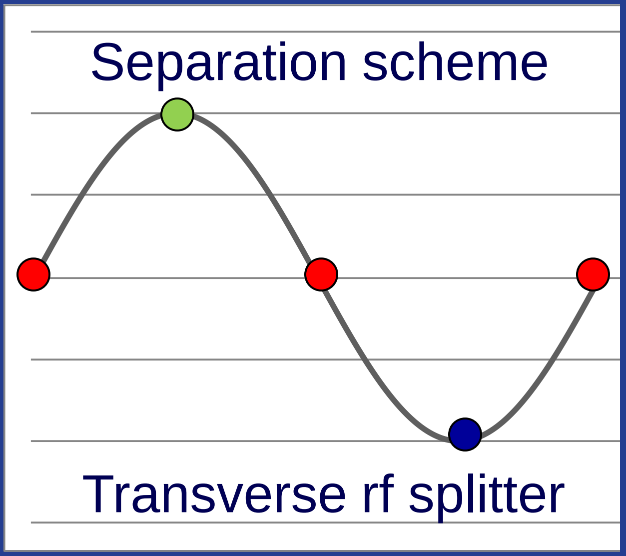
Multiple Pulse Trains can Superimpose within Linac

1 μsec period at 3 GeV

Muon pulses (12e7) 162.5 MHz, 80 nsec	700 kW
Kaon pulses (12e7) 27 MHz	1540 kW
Nuclear pulses (12e7) 13.5 MHz	770 kW

Ion source and RFQ operate at 4.4 mA; 77% of bunches are chopped @ 2.1 MeV $\Rightarrow$ maintain 1 mA over 1 μsec





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Example Research Program, definitive space of accelerator parameters on Project X website

← 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.

Intensity Frontier Science

SLAC

The Intensity Frontier addresses fundamental questions:

Are there new sources of CPV?

Is there CPV in the leptonic sector?

Are ν's Majorana or Dirac?

Do the forces unify?

Is there a weakly coupled Hidden Sector linked to Dark Matter?

Are apparent symmetries (B,L) violated at high scales?

What is the flavor sector of new physics?

Can we expand the new physics reach of the energy frontier?

JoAnne Hewett, March 2013

Opportunities…

- Much of the Project X Day-1 research program is under construction and development now: (g-2), LBNE, MicroBooNE, Minerva, MINOS, Mu2e, NOvA, ORKA, EDM research, etc. There are leadership opportunities in this relatively small experiments in detector design, construction, operations and analysis.

- Many of the later-day Project X experiments require detector systems that do not exist today: Ultra-low mass trackers, "Perfect" photon measurements beyond calorimetry, etc which have good synergy with future collider challenges.

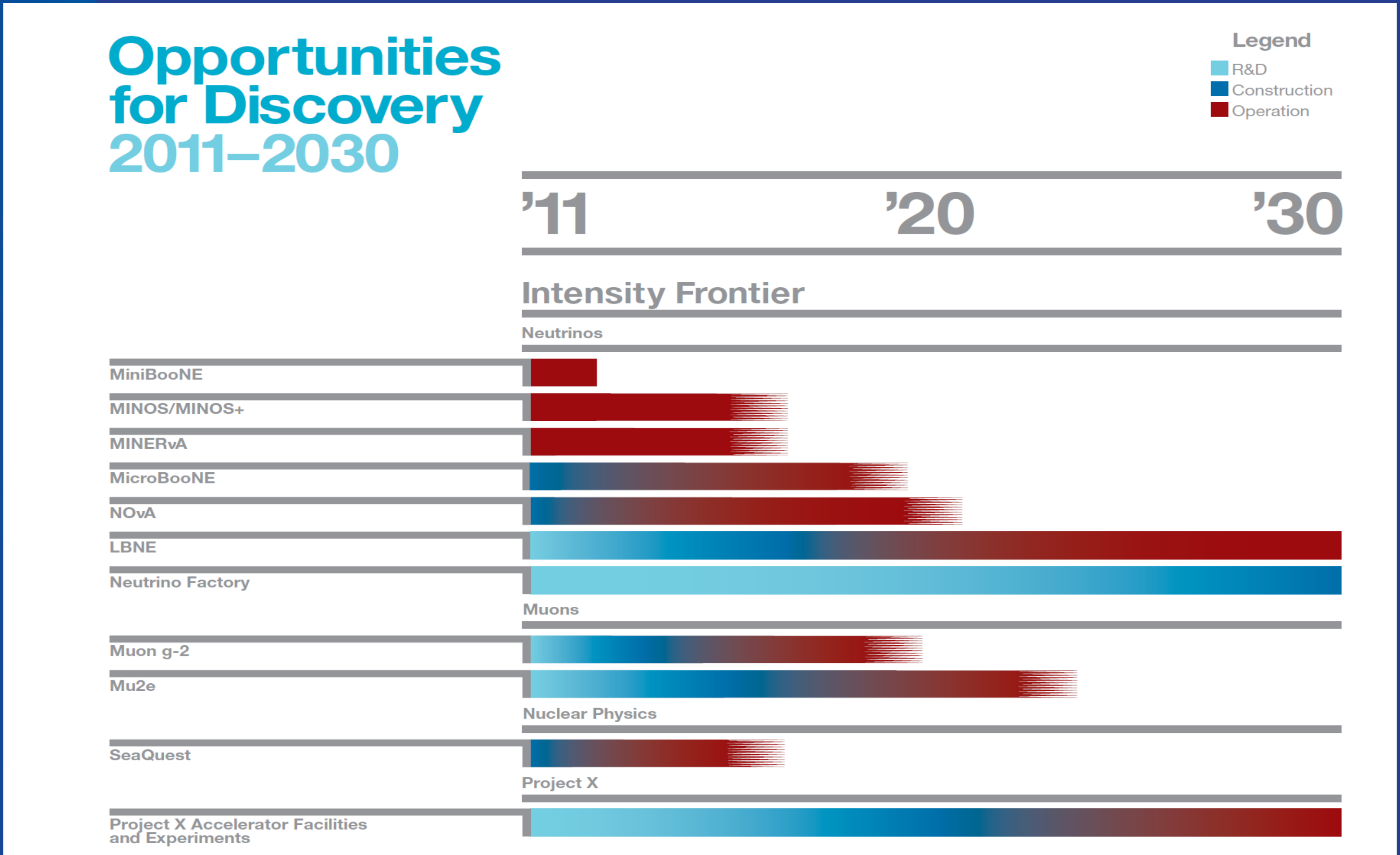
- Intensity frontier phenomenology: There is a great need in the US, and this is beginning to be seen by the agencies.

Summary

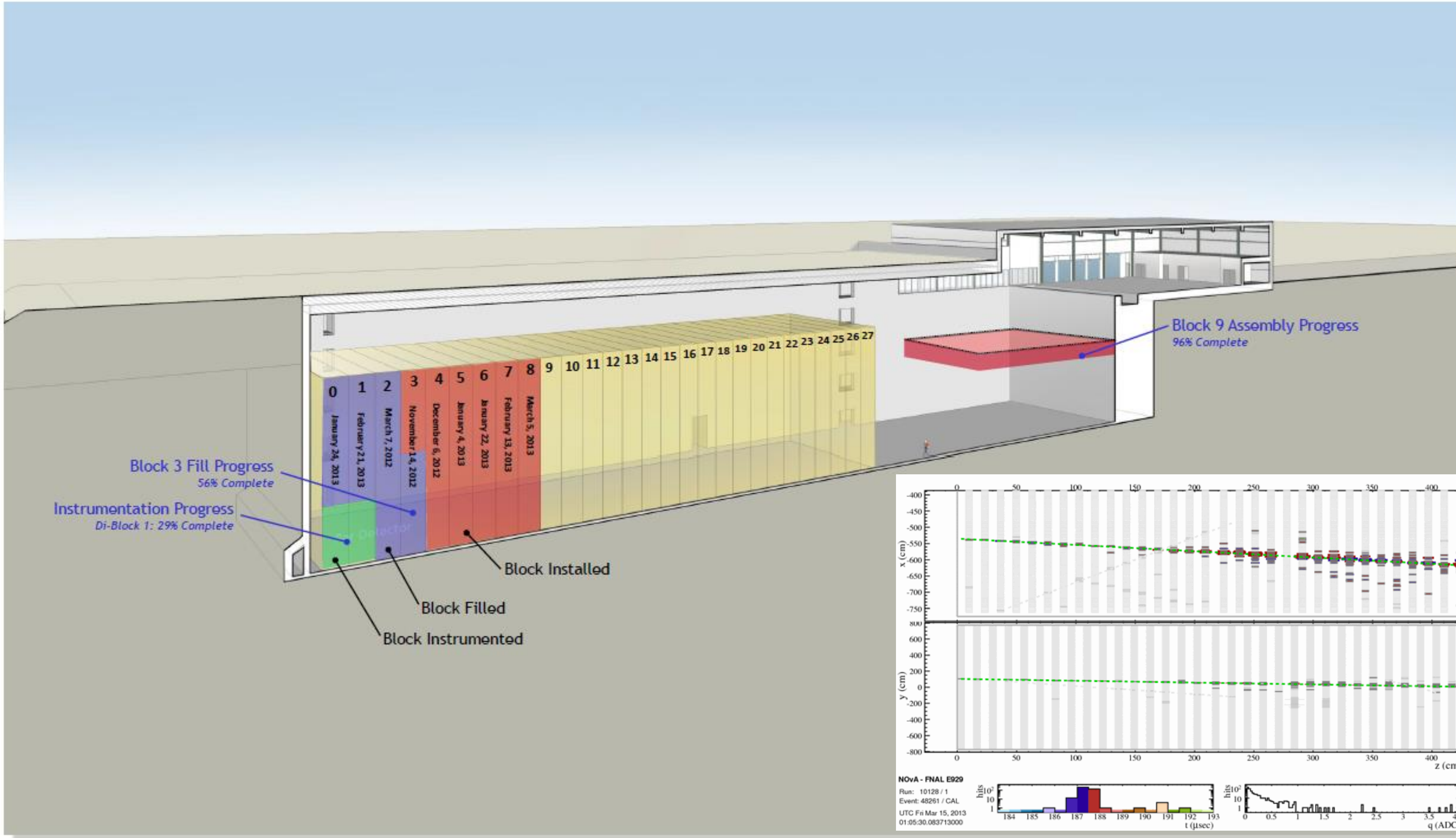
- Project-X is a staged evolution of the best assets of the Fermilab accelerator complex with the revolution in super-conducting RF technology.
- Each Stage of Project-X will raise many boats of the Intensity Frontier in particle physics, with a program scope of more than 20 world-leading particle physics experiments and an associated robust user community.
- Stage-1 of Project X can host a program of world class experiments, with “Day-1” experiments inherited from the investments being made now in advance of Project-X operations which could commence at the close of this decade.

Spare Slides

Plan for discovery…



NOvA Far Detector Assembly Progress



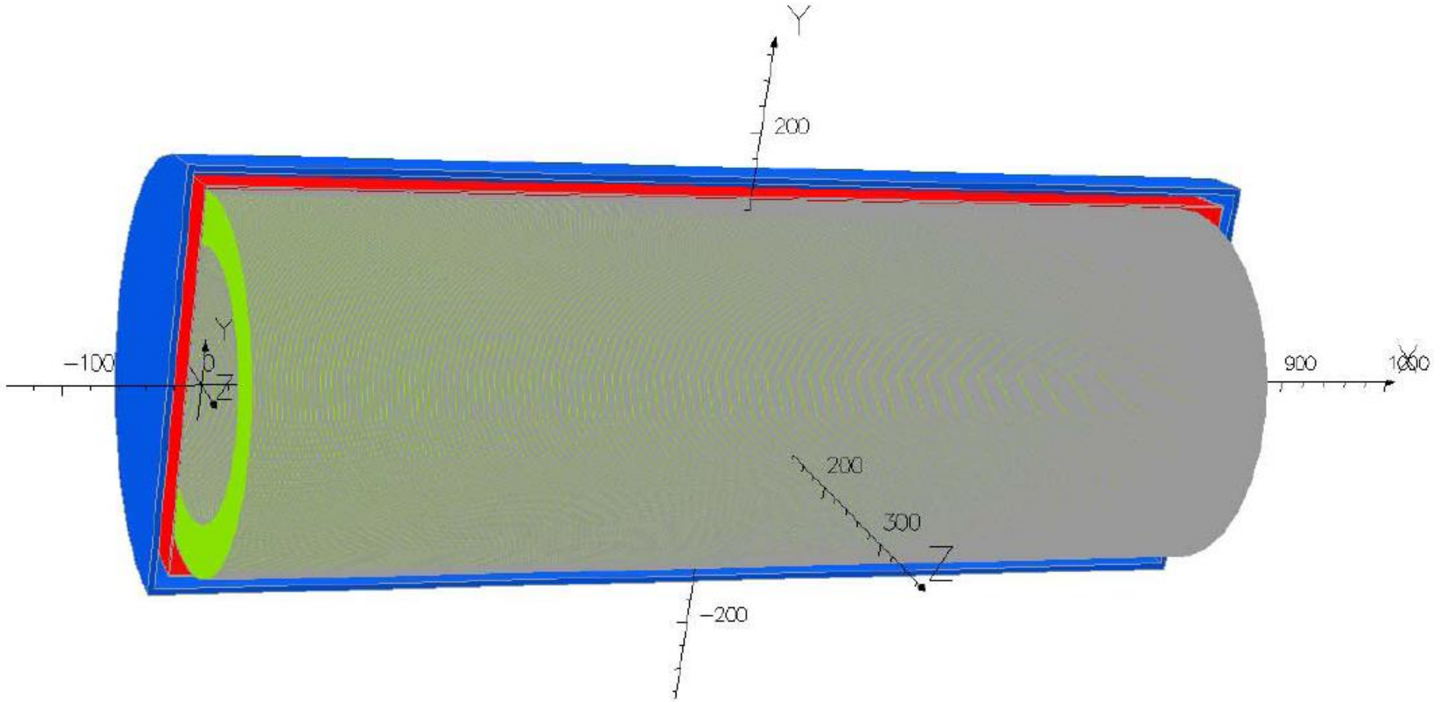
19MAR13

U.S. Department of Energy | Office of Science

Fermilab

NOvA

500-kW thorium target concept
for ^{225}Ra edm research



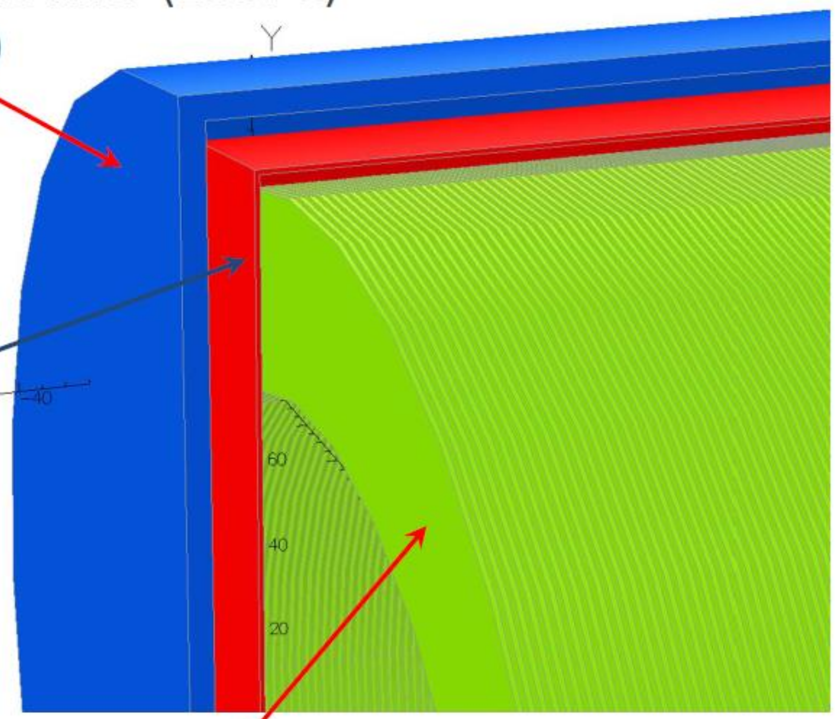
500-kW thorium target concept

12

J. Nolen, ANL – Project X Spallation forum

500-kW thorium target concept - close-up

Carbon felt insulation w/ graphite liner (1800 C) and water-cooled outside (30 C)



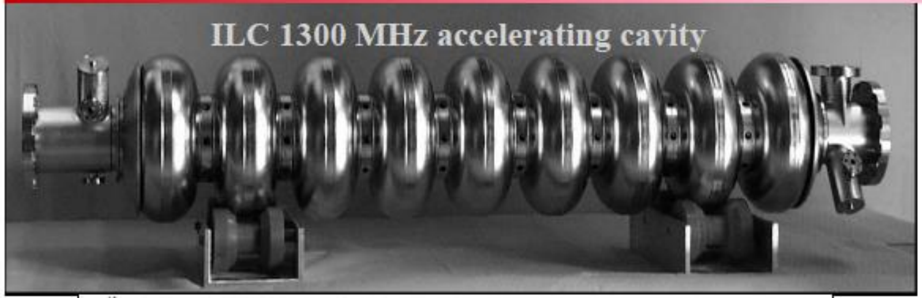
Tungsten container, heat shield, 2200 C

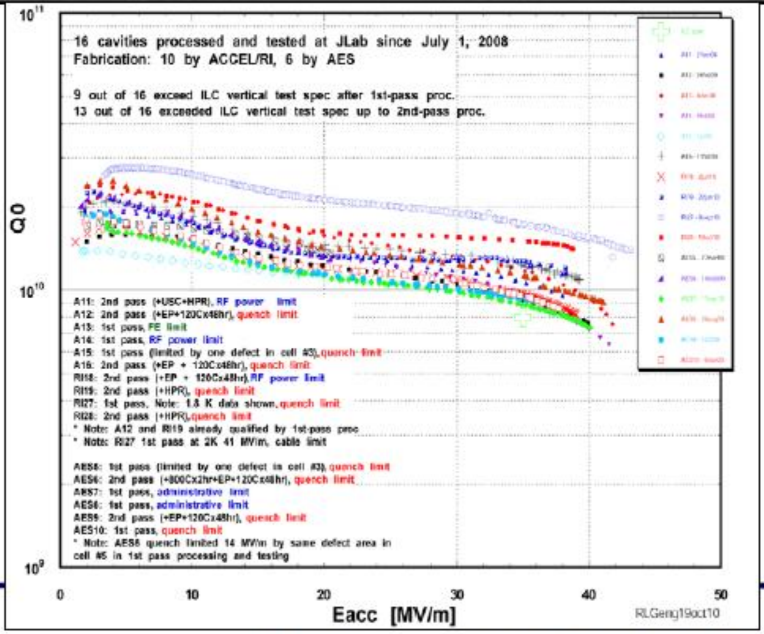
1-mm thick Th rings @ 1-mm spacing, 400 total, 2000 C

J. Nolen, ANL – Project X Spallation forum

Project X

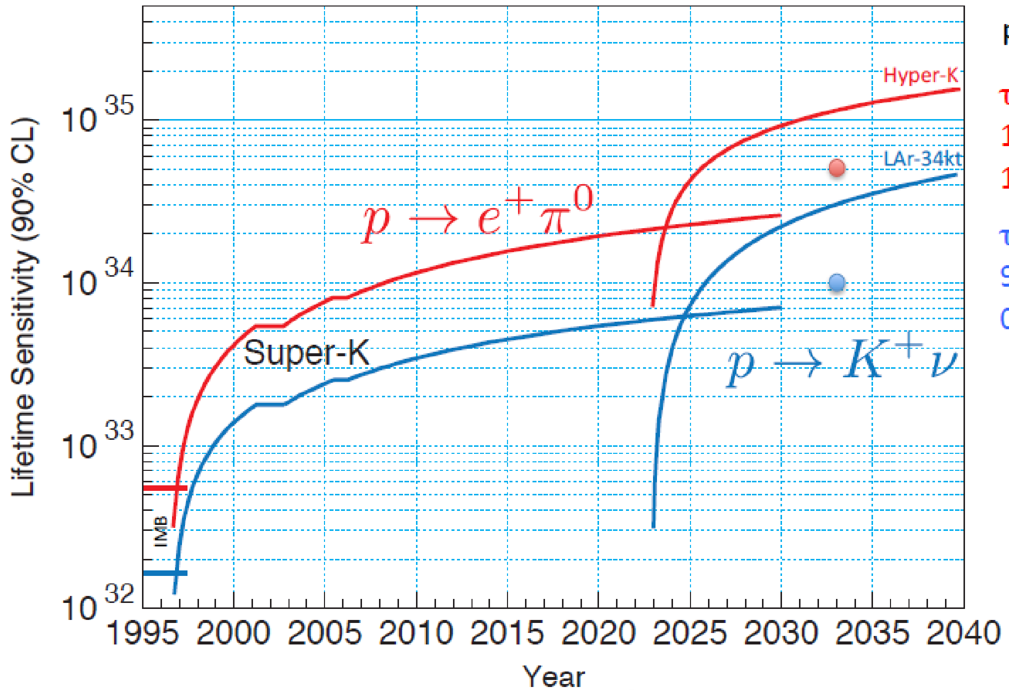
1.3 GHz pulse linac





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.



10 year sample points

τ/B = 5e35
17 evts
1 BG

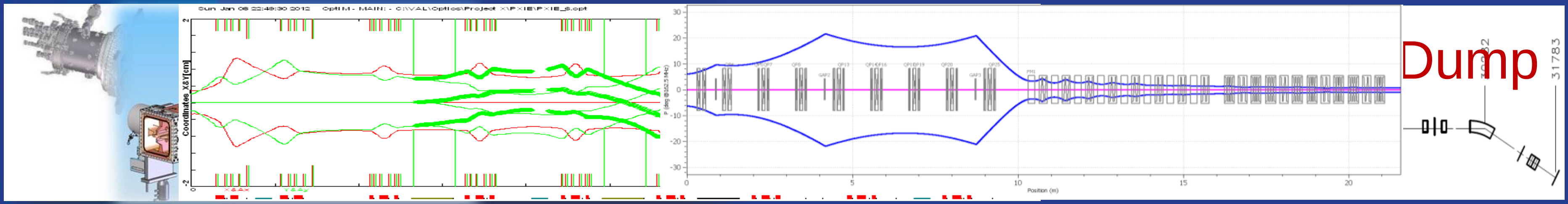
τ/B = 1e34
9 evts
0.3 BG

~ 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.

Fermilab

Project X Integration Experiment (PXIE)



LBNL FNAL,SLAC ANL FNAL

← 32 m, 30 MeV →

PXIE will address the address/measure the following:

- Ion source lifetime
- LEBT pre-chopping
- Vacuum management in the LEBT/RFQ region
- Validation of chopper performance
- Kicker extinction
- Effectiveness of MEBT beam absorber
- MEBT vacuum management
- Operation of HWR in close proximity to 10 kW absorber
- Operation of SSR with beam
- Emittance preservation and beam halo formation through the front end