

# **Nuclear Science and the New Standard Model**

## ***Neutrinos and Fundamental Symmetries in the Next Decade***

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Thanks to talks at Galveston by:

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**June 18, 2007**

**Jefferson Laboratory Users Meeting**

**The next decade presents Nuclear Physics with a unique opportunity to develop the “new Standard Model”, with potentially profound physics implications and recognition beyond our field.**

# LRP: Primary Recommendations

- We recommend completion of the 12 GeV Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.
- We recommend construction of the Facility for Rare Isotope Beams, FRIB, a world-leading facility for the study of nuclear structure, reactions and astrophysics. Experiments with the new isotopes produced at FRIB will lead to a comprehensive description of nuclei, elucidate the origin of the elements in the cosmos, provide an understanding of matter in the crust of neutron stars, and establish the scientific foundation for innovative applications of nuclear science to society.
- We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet unseen violations of time-reversal symmetry, and other key ingredients of the new standard model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to US leadership in core aspects of this initiative.
- The experiments at the Relativistic Heavy Ion Collider have discovered a new state of matter at extreme temperature and density—a quark-gluon plasma that exhibits unexpected, almost perfect liquid dynamical behavior. We recommend implementation of the RHIC II luminosity upgrade, together with detector improvements, to determine the properties of this new state of matter.

# Recommendation 1

**We recommend completion of the 12 GeV Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.**

A fundamental challenge for modern nuclear physics is to understand the structure and interactions of nucleons and nuclei in terms of quantum chromodynamics. Jefferson Lab's unique electron microscope has given the US leadership in addressing this challenge. Its first decade of research has already provided key insights into the structure of nucleons and the dynamics of finite nuclei.

Doubling the energy of this microscope will enable three-dimensional imaging of the nucleon, revealing hidden aspects of its internal dynamics. It will complete our understanding of the transition between the hadronic and quark/gluon descriptions of nuclei, and test definitively the existence of exotic hadrons, long-predicted by QCD as arising from quark confinement. Through the use of parity violation, it will provide low-energy probes of physics beyond the Standard Model complementing anticipated measurements at the highest accessible energy scales.

# Recommendation 3

**We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet unseen violations of time-reversal symmetry, and other key ingredients of the new standard model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to US leadership in core aspects of this initiative.**

*The discovery of flavor oscillations in solar, reactor, and atmospheric neutrino experiments – together with unexplained cosmological phenomena such as the dominance of matter over anti-matter in the Universe – call for a new standard model of fundamental interactions. Nuclear physicists are poised to discover the symmetries of the new standard model through searches for neutrinoless double beta decay and electric dipole moments, determination of neutrino properties and interactions, and precise measurements of electroweak phenomena.*

*The Deep Underground Science and Engineering Laboratory will provide the capability needed for ultra-low background measurements in this discovery-oriented program. Experiments also will exploit new capabilities at existing and planned nuclear physics facilities. Assembling the new standard model using the breadth of new experimental results will require enhanced theoretical efforts.*

# Community Input

- *Pre-Town Meetings: Santa Fe (neutrinos) & Caltech (Symmetries)*
- *DNP Town Meeting: Chicago Jan 2007 (~ 370 participants)*

## Organizing Committees

Balantekin	Baha	University of Wisconsin
Drexlin	Guido	University of Karlsruhe
Elliott	Steve	Los Alamos National Lab
Fuller	George	UC San Diego
Herzog	Dave	University of Illinois
Holstein	Barry	University of Massachusetts
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Klein	Josh	University of Texas, Austin
Kumar	Krishna	University of Massachusetts
Marciano	Bill	Brookhaven National Lab
McLaughlin	Gail	North Carolina State University
Ramsey-Musolf	Michael	University of Wisconsin /Caltech
Nico	Jeff	NIST
Opper	Allena	George Washington University
Poon	Alan	Lawrence Berkeley National Lab
Robertson	Hamish	University of Washington
Savard	Guy	Argonne, Chicago
Vogelaar	Bruce	Virginia Tech
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Greene	Geoff	Oak Ridge National Lab/U. Tennessee

## ***Combined White Paper Editors***

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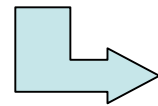
# Probing the New Standard Model

Recent discoveries in **Nuclear**, **Particle**, **Astrophysics** & Astronomy have provided us with a modified picture of matter constituents, its interactions and evolution

**High Energy Colliders**  
*as well as*  
**Low Energy:  $Q^2 \ll M_Z^2$**

**Low  $Q^2$  offers complementary probes of physics at high energy scales:**

- *Neutrino Physics*
  - Oscillations and the MSNP matrix
  - Single and Double Beta Decay
- *Muon Physics*
  - Precision measurement of the g-2 anomaly
  - Precision muon decay parameter measurements
  - Charged lepton number violation searches
- *Semi-leptonic Weak Decays*
  - Standard Model CP Violation
  - Tests of CKM unitarity
  - Anomalous charged current interactions
  - Search for Proton decay
- *Dark Matter Searches*
- *Electric Dipole Moment Searches*
- *Neutral Weak Interaction Studies*

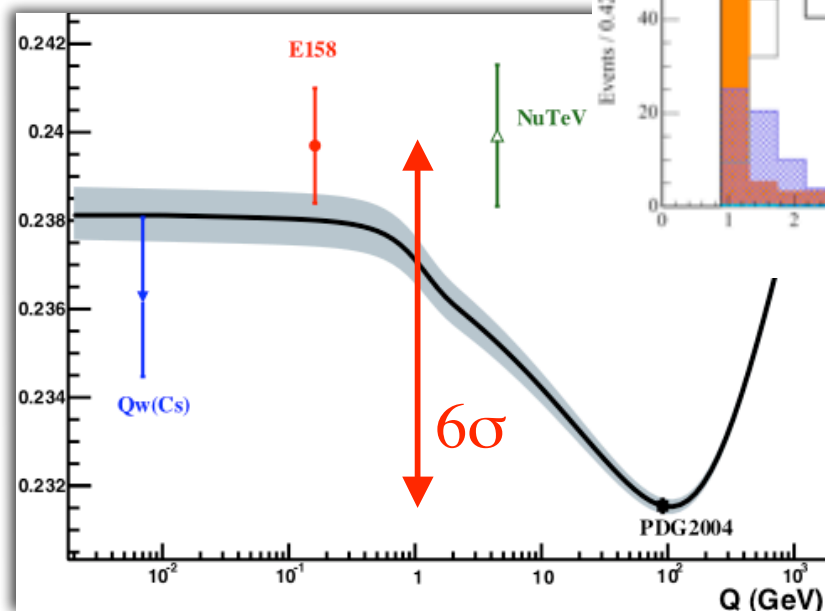
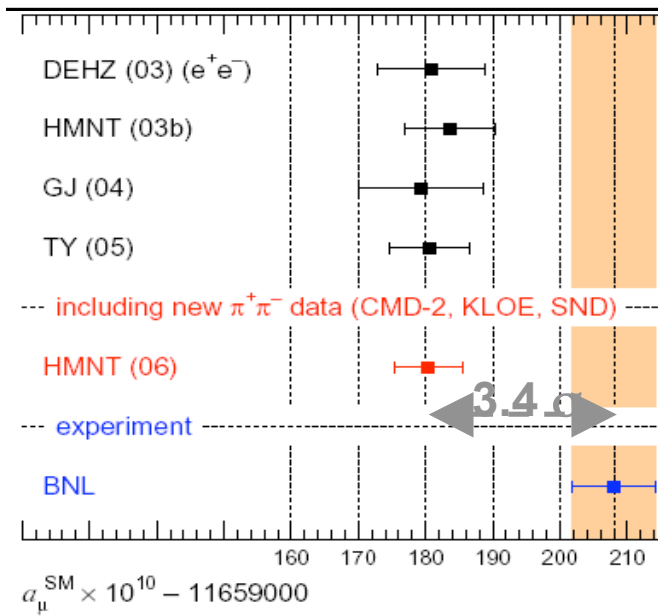
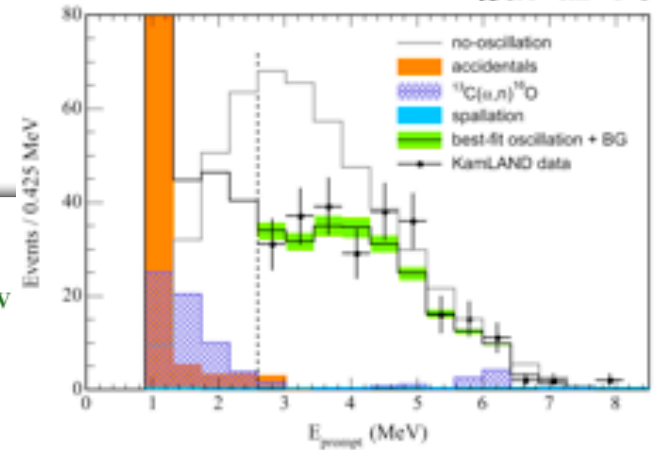
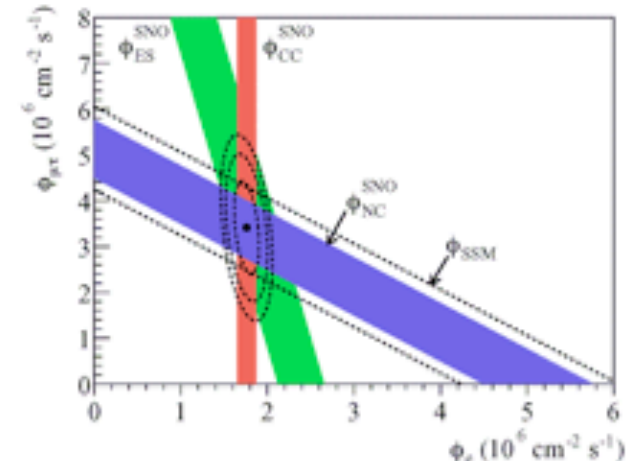


**Evolution of the early Universe**

***Nuclear theorists and experimentalists have played and will continue to play an essential role in our quest for a complete picture of the evolution and properties of the fundamental building blocks of matter***

# Some Recent Achievements

- *Discovery of flavor oscillations in solar neutrinos; Solution of the solar neutrino problem*
- *Discovery of flavor oscillations in reactor neutrinos; Identification of LMA solution*
- *World's most precise measurement of  $(g_\mu - 2)$  Possible first indications of supersymmetry;*
- *Most precise measurement of  $\sin^2\theta_W$  off the  $Z^0$  resonance using PV Moller scattering; constrains new physics at the TeV scale ( $Z'$ , RPV SUSY...)*





# Questions Driving the Field

- *What are the masses of neutrinos and how have they shaped the evolution of the universe?  $0\nu\beta\beta$  decay,  $\theta_{13}$ ,  $\beta$  decay,...*
- *Why is there more matter than antimatter in the present universe? EDM, DM, LFV,  $0\nu\beta\beta$ ,  $\theta_{13}$  ...*
- *What are the unseen forces that disappeared from view as the universe cooled? Weak decays, Parity-Violating Electron Scattering,  $g_\mu-2$ ,...*

Answering these questions could have wide-ranging implications

## “Spinoffs” important to Nuclear Physics

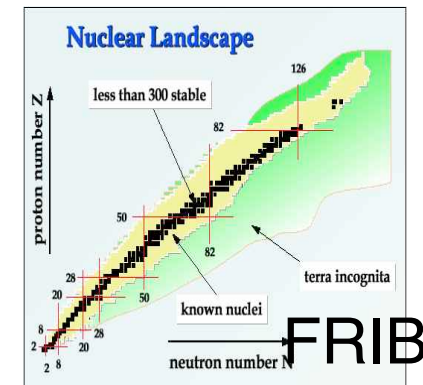
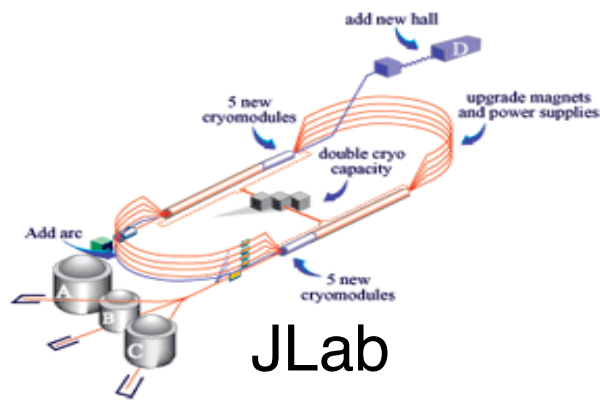
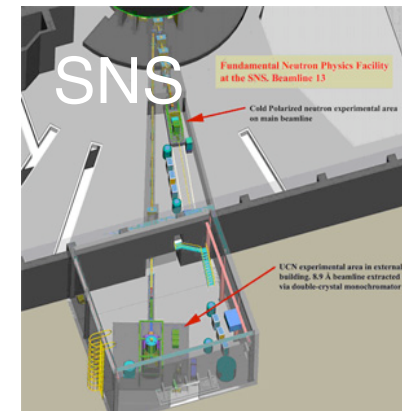
- *What is the internal landscape of the proton? Parity-Violating Electron Scattering, hadronic PV,  $\nu$  scattering,...*
- *What causes stars to explode? Large scale supernova simulations,  $\nu$  flavor transformation...*
- *What is the origin of the heavy elements from iron to uranium? Weak interactions and  $\nu$  interactions in heavy nuclei,...*



# Specific Opportunities

- *Major Discovery Potential*  
 *$0\nu\beta\beta$ -decay & EDM*
- *Precision measurements*  
*Neutrino mixing & hierarchy*  
*Weak decays, PVES,  $g_\mu-2$*
- *Electroweak probes of QCD*  
*PVES, Hadronic PV,  $\nu N$  scatt...*

**DUSEL**



# Neutrino Physics

## Open Questions

*Is there CP Violation in the Leptonic Sector?*

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

*What is the pattern of neutrino mixing?*

$$\theta_{23} = (45 \pm 7)^\circ$$

$$\theta_{13} < 13^\circ$$

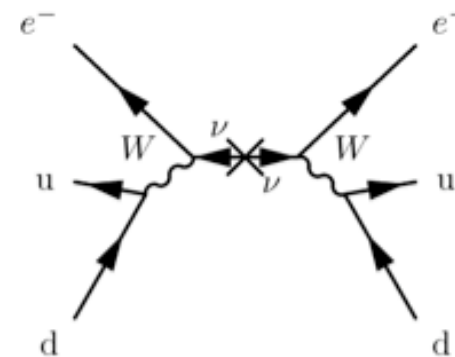
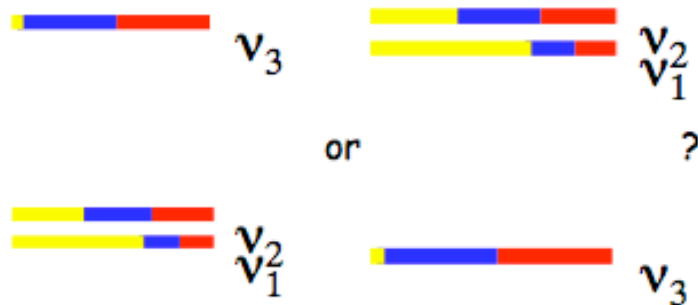
$$\delta = ?$$

$$\theta_{12} = (33.9^{+2.4}_{-2.2})^\circ$$

$$\alpha = ?$$

$$\beta = ?$$

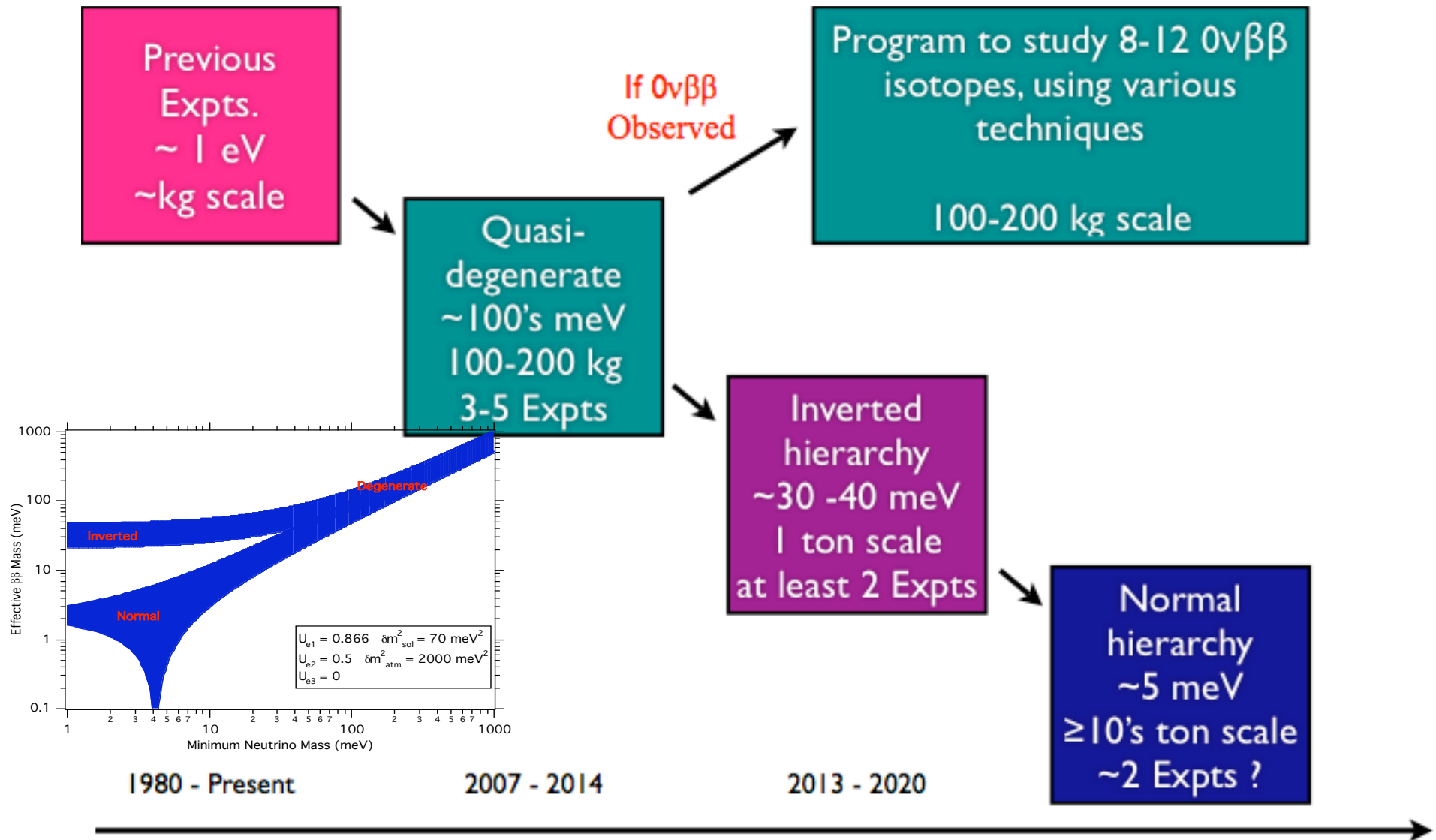
*What are the masses of the neutrinos?*



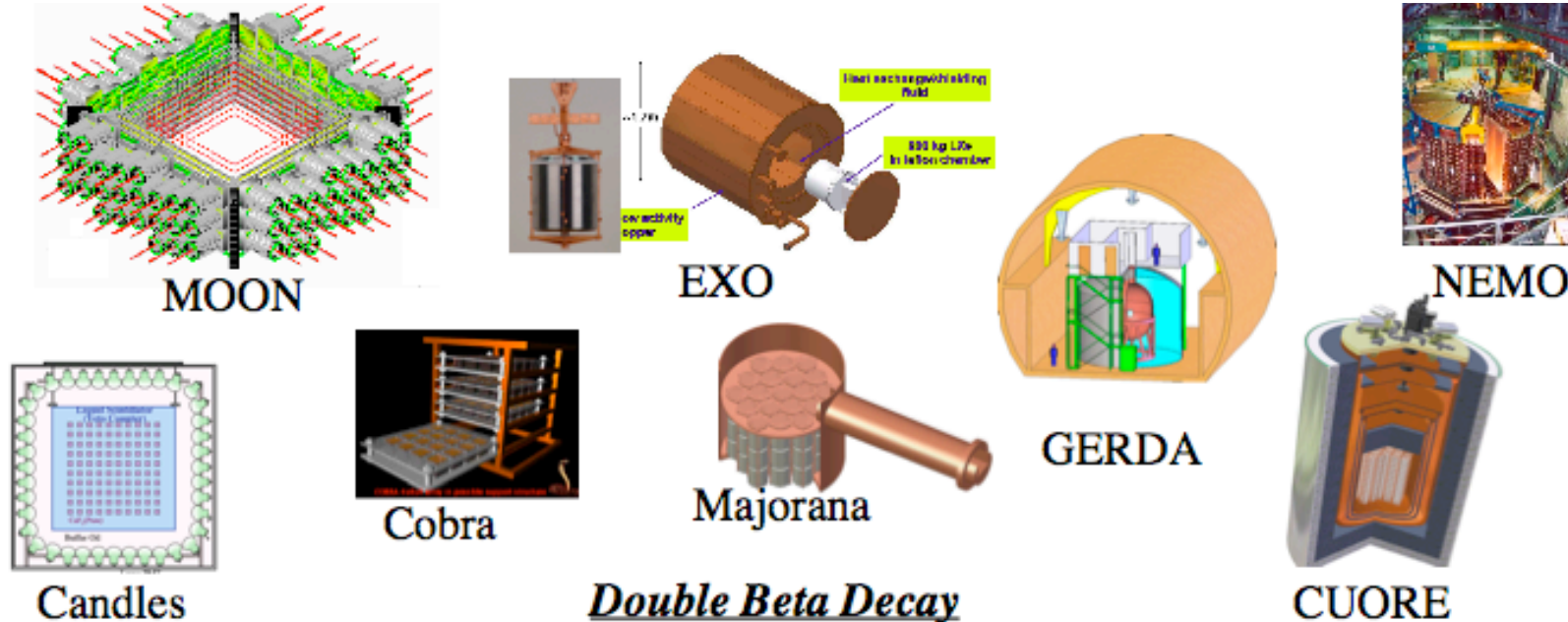
Majorana or Dirac?

*Are neutrinos their own antiparticles?*

# World Strategy for Double-Beta Decay



# World Program

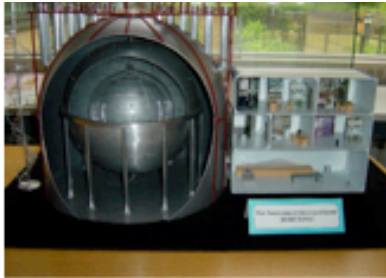


## Double Beta Decay

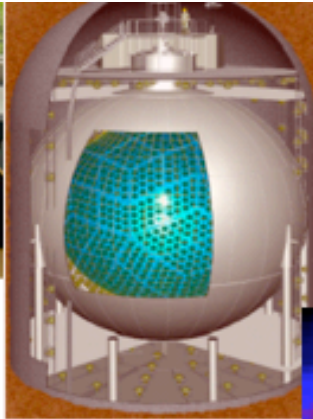
*As a result of the review-panel recommendations, DOE has approved CD-0, a statement of mission need, for a generic double-beta-decay program. The EXO  $^{136}\text{Xe}$  double beta decay experiment is under construction at the 200-kg level. CUORE is a European double-beta-decay experiments with substantial US involvement; US capital for CUORE is in the FY08 Presidential Budget. The COBRA CdTe double-beta decay experiment is receiving R&D support. A European  $^{76}\text{Ge}$  experiment, GERDA, is moving ahead towards a 45-kg enriched isotope array. In the US, the Majorana collaboration is now requesting support for a 60-kg enriched array in an aggressive R&D program aimed at a future 1-ton Ge experiment. In Japan, the MOON and CANDLES double beta decay experiments ( $^{100}\text{Mo}$  and  $^{48}\text{Ca}$  respectively) are under construction at the several-Kg scale.*



# Solar Neutrinos



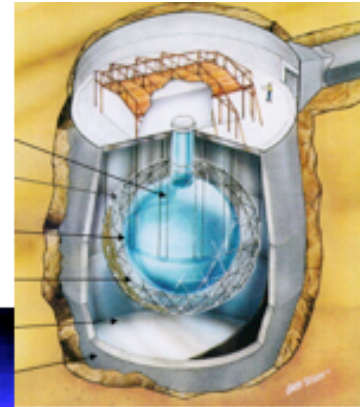
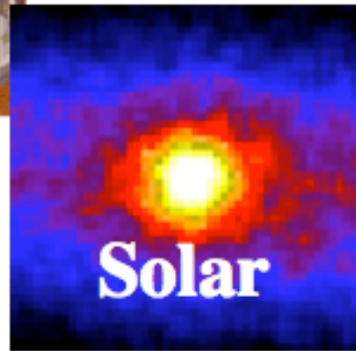
Borexino



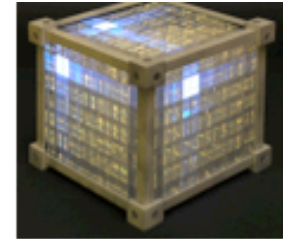
KamLAND



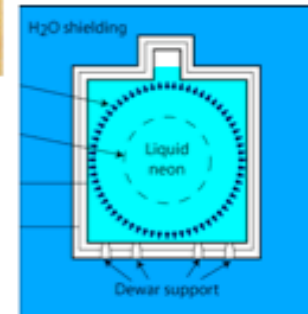
SAGE



SNO+

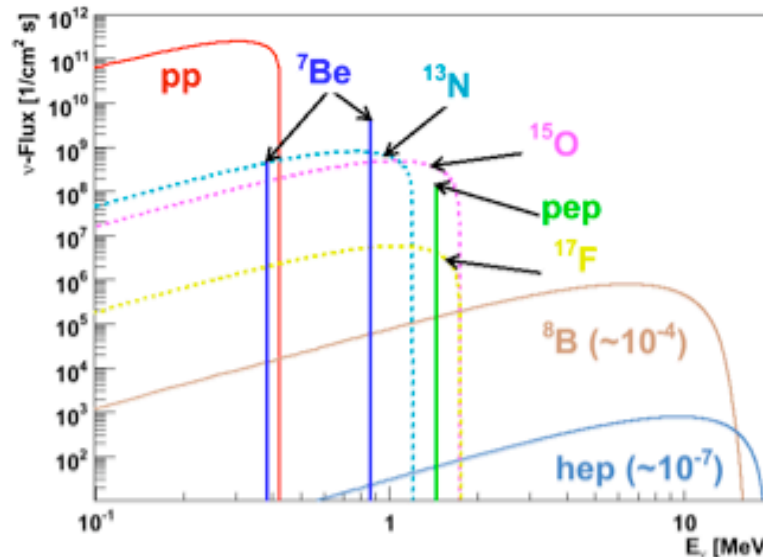


LENS



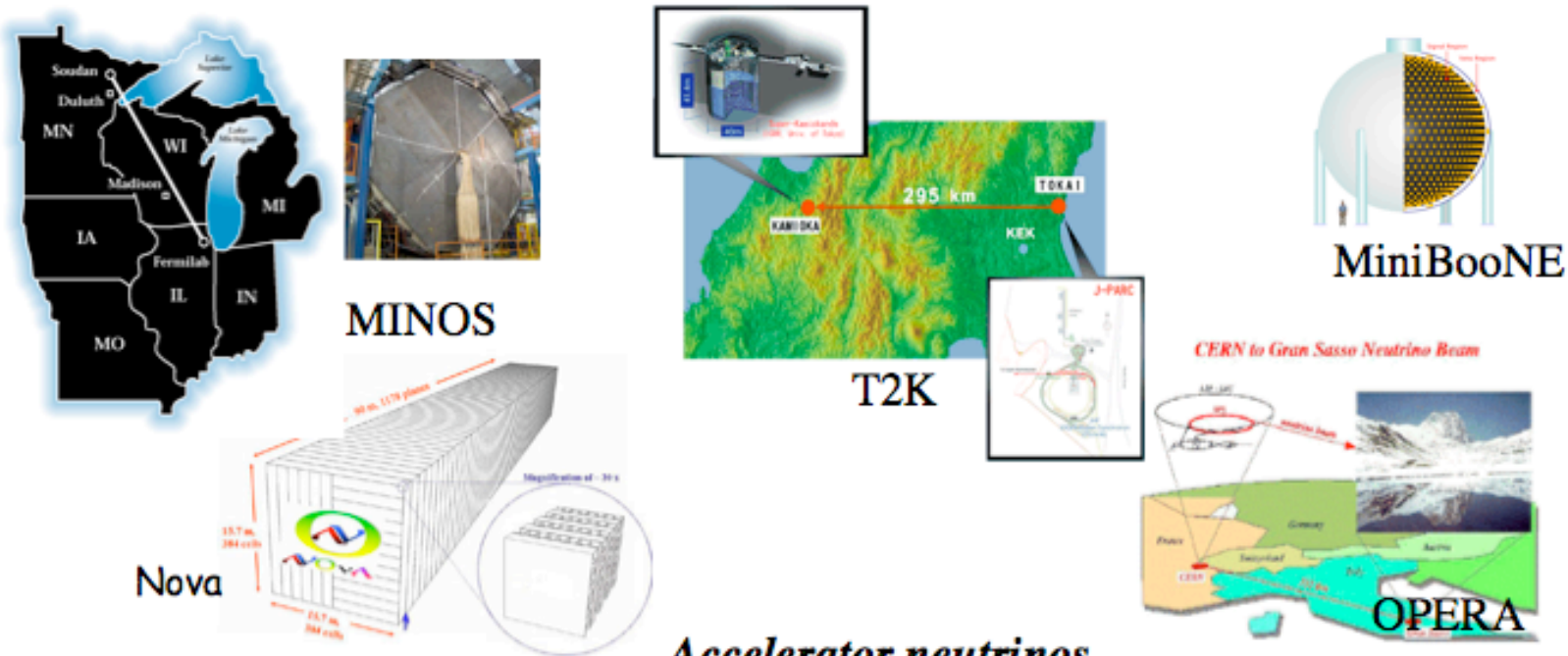
CLEAN

**Present  
and next  
five years  
Focus on  
 ${}^7\text{Be}$**



**Present  
and next  
ten years  
Focus on  
 $pp$**

# Accelerator Neutrinos



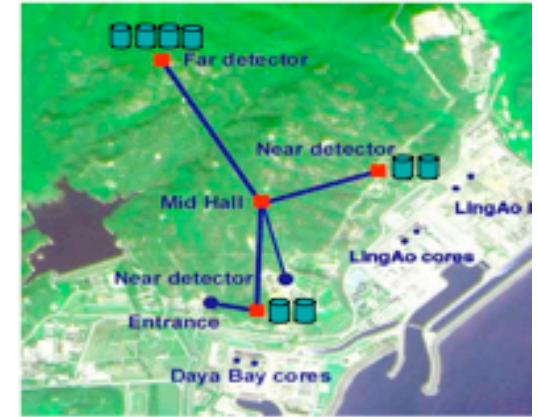
## Accelerator neutrinos

*The MiniBooNE experiment looking for electron neutrino appearance in the muon neutrino beam from the Fermilab 8 GeV Booster completed its running with neutrinos and recently announced evidence refuting LSND. The MINOS long-baseline experiment has is providing precise values for the atmospheric splitting and mixing. There is considerable US involvement in the T2K long-baseline experiment in Japan. Both are funded by DOE HEP. Super-Kamiokande, recently refurbished with new PMTs, is in operation collecting solar and atmospheric neutrino data, and preparing to receive the neutrino beam from J-PARC. The first neutrinos from CERN have recently been detected in the OPERA experiment at Gran Sasso. The NOvA experiment at Fermilab aims to measure  $\theta_{13}$  and to resolve the hierarchy problem.*

# Other Interdisciplinary Initiatives

## Reactor Theta 13

*A large collaborative project between the US and China, Daya Bay, is being supported by DOE HEP. Many NP scientists participate. The Double Chooz project in Europe has US participation from HEP and NP at a much lower level.*



Daya Bay

5. We recommend support for nuclear physicists involved in interdisciplinary efforts such as measurements of the neutrino mixing angle  $\theta_{13}$  through reactor and long baseline experiments, direct and indirect searches for dark matter and sensitive tests of charged lepton flavor violation.

*Examples of other topics primarily funded by other subfields:*

- Searches for Dark Matter
- Neutrino Astronomy
- Muon-to-Electron Conversion (LFV)

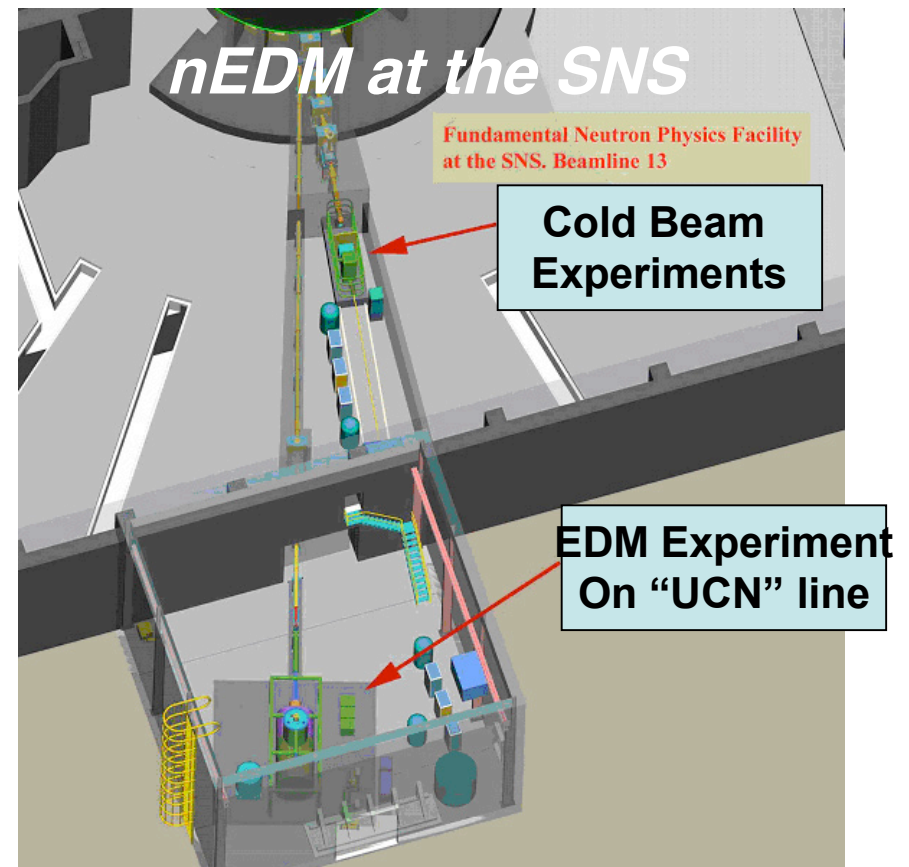


# Search for Permanent EDMs

*A non-zero permanent electric dipole moment of a fundamental particle would signal a new source (e.g. SUSY) of T-violation, hence CP-violation:  
Profound implications for the Baryon Asymmetry in the Universe*

**Must measure several different particle EDMs to unfold physics**

	Present Limit (90% CL) (e-cm)	Laboratory	Possible Sensitivity (e-cm)	Standard Model (e-cm)
e <sup>-</sup> (Tl) e <sup>-</sup> (PbO) e <sup>-</sup> (YbF) e <sup>-</sup> (GGG)	1.6 x 10 <sup>-27</sup>	Berkeley Yale Sussex LANL/Indiana	10 <sup>-29</sup> 10 <sup>-29</sup> 10 <sup>-30</sup>	<10 <sup>-40</sup>
m m	9.3 x 10 <sup>-19</sup>	CERN BNL	<10 <sup>-24</sup>	<10 <sup>-36</sup>
n n n n	6.3 x 10 <sup>-26</sup>	ILL ILL PSI SNS	1.5 x 10 <sup>-26</sup> ~ 2 x 10 <sup>-28</sup> ~ 7 x 10 <sup>-28</sup> < 1 x 10 <sup>-28</sup>	~10 <sup>-32</sup>
<sup>199</sup> Hg <sup>129</sup> Xe <sup>225</sup> Ra <sup>223</sup> Rn d	1.9 x 10 <sup>-27</sup>	Seattle Princeton Argonne TRIUMF BNL/JPARC?	5 x 10 <sup>-28</sup> 10 <sup>-31</sup> 10 <sup>-28</sup> 1 x 10 <sup>-28</sup> <10 <sup>-29</sup>	~10 <sup>-33</sup> ~10 <sup>-34</sup>



# Precision Tests of Electroweak Theory

LHC might find new phenomena, but deciphering the underlying dynamics will require other indirect signatures

- **Neutrons**

- Lifetime, P- & T-Violating Asymmetries

- *LANSCE, NIST, SNS*

- **Parity-Violating Electron Scattering**

- Weak mixing angle, Strange quark structure, Ground State Neutron Distribution

- *MIT-Bates, SLAC, Mainz, Jefferson Lab*

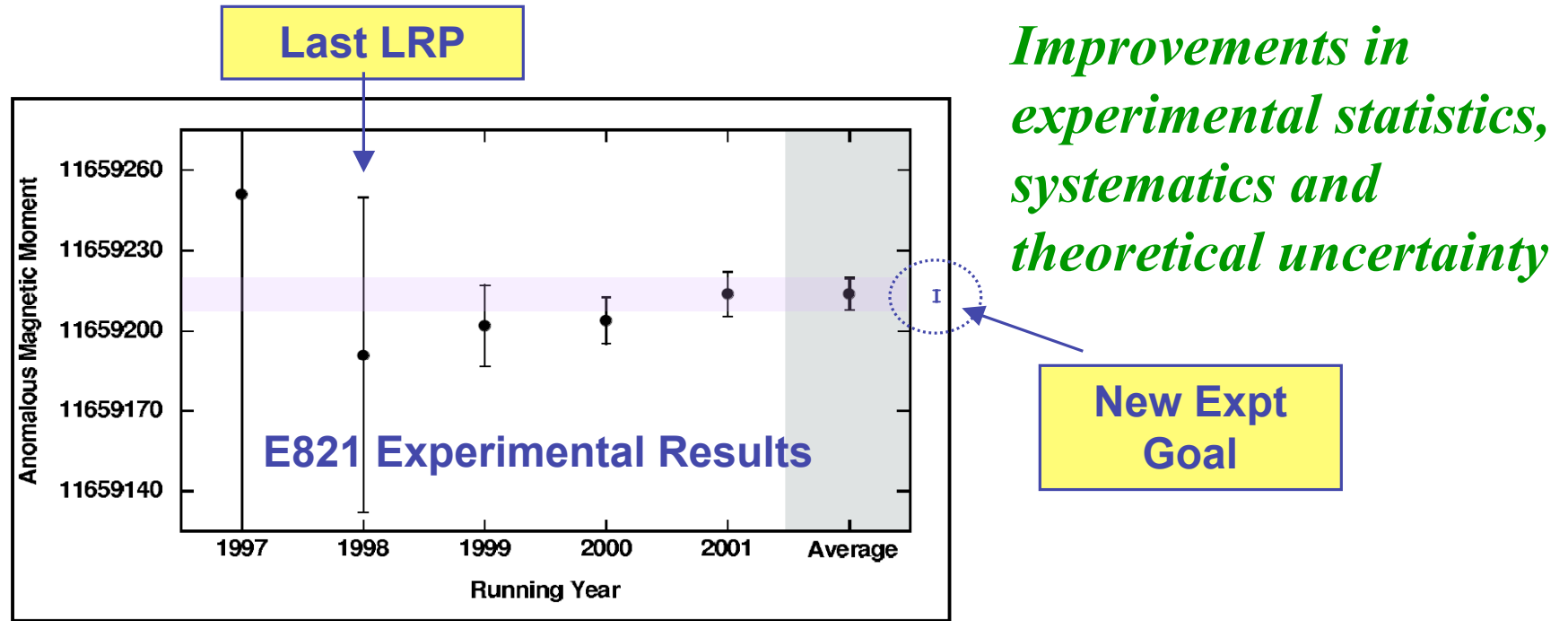
- **Muons**

- Michel parameters, lifetime, muon capture, g-2 anomaly, charged lepton flavor violation

- *PSI, TRIUMF, BNL, FNAL*

# Muon g-2 Anomaly

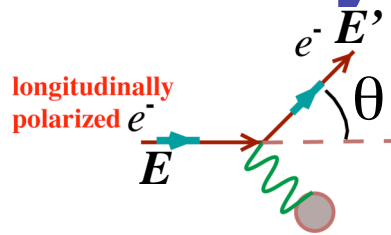
*An upgraded experiment has been proposed at BNL*



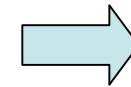
Particularly important in the context of disentangling SUSY parameters

- $\text{sign}(\mu)$ : can't get at collider
- Precision determination of  $\tan\beta$

# Parity-Violating Electron Scattering

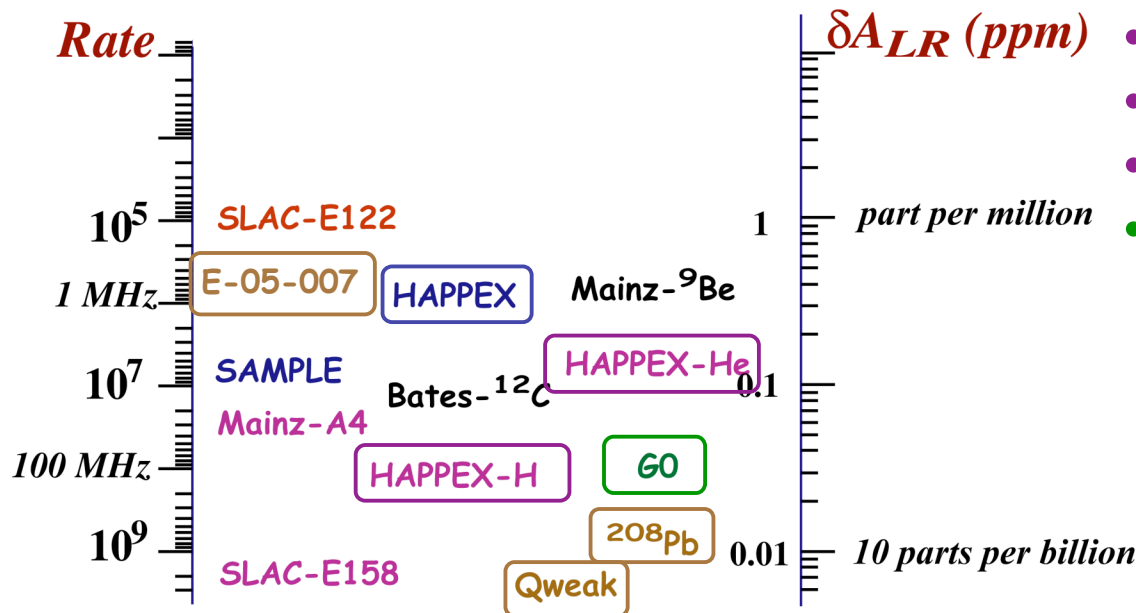


$$A_{PV} \sim 10^{-5} \cdot Q^2 \text{ to } 10^{-4} \cdot Q^2$$



*~ 0.1 to ~100 ppm*

SLAC, MIT-Bates, Mainz & JLab



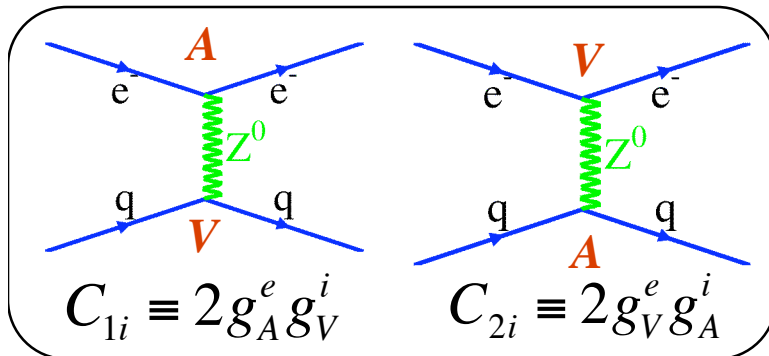
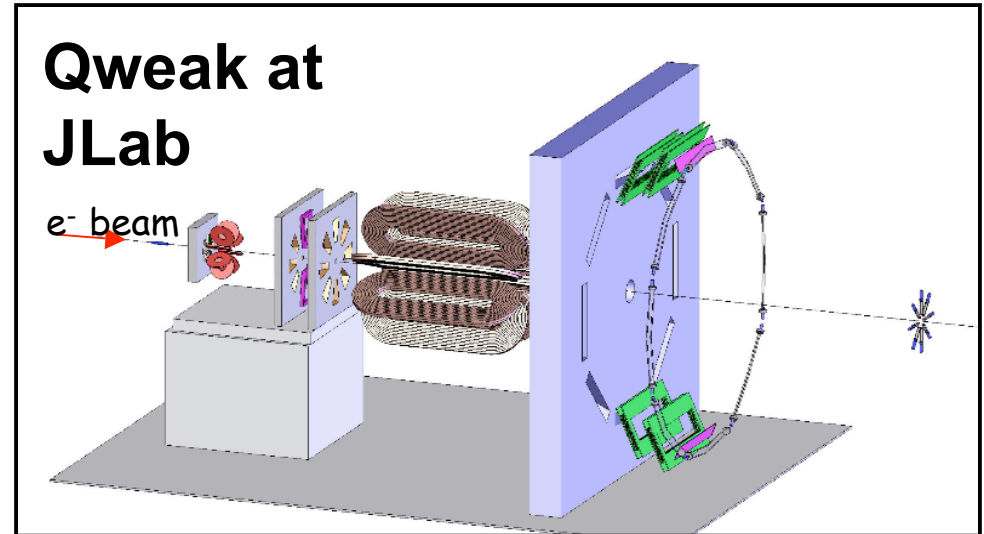
- *Steady progress in technology*
- *part per billion systematic control*
- *1% normalization control*
- *Jefferson Lab now takes the lead*
  - Photocathodes
  - Polarimetry
  - Targets
  - Diagnostics
  - Counting Electronics

Parity-violating electron scattering has become a **precision tool**

- *Many-Body Nuclear Physics: PREX (Lead Radius Expt)*
- *Nucleon Structure Physics: (HAPPEX, G0)*
- *Valence Quark Physics: PVDIS Experiments*
- *Search for New TeV Physics: Qweak, Møller*

# Weak Mixing Angle Measurements

- Atomic Parity Violation
  - $^{133}\text{Cs}$  6s to 7s transition
  - Future: isotope measurements
- E158: purely leptonic
  - Running of weak mixing angle
- Neutrino DIS: NuTeV
  - 3  $\sigma$  deviation
  - Many hadronic physics issues
  - Look at other l-q couplings?



**$A_{PV}$  in elastic  $e$ - $p$  scattering:  $Q_{weak}$  at JLab**

$$A(Q^2 \rightarrow 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}} \left[ Q^2 Q_{weak}^p + Q^4 B(Q^2) \right]$$

$$Q_{weak}^p = 2C_{1u} + C_{1d} \propto 1 - 4\sin^2 \vartheta_W \quad \text{Data} \sim 2010$$

- With  $Q_{weak}$  data, 2 of 4 couplings will be precisely constrained
- Opportunity to measure 2 other couplings via **parity-violating deep inelastic scattering at 6 and 11 GeV**: also provide unique new information on parton distribution functions, with implications for the NuTeV anomaly

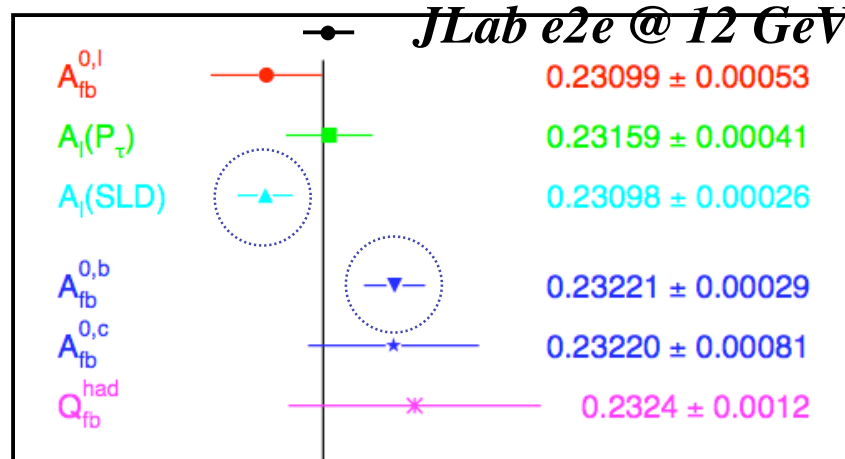
# PV Møller Scattering at 11 GeV

Luminosity and Stability makes feasible a factor of 5 improvement over E158

$$\sin^2 \theta_W \text{ to } \pm 0.00025$$

$$\Lambda_{ee} \sim 25 \text{ TeV reach}$$

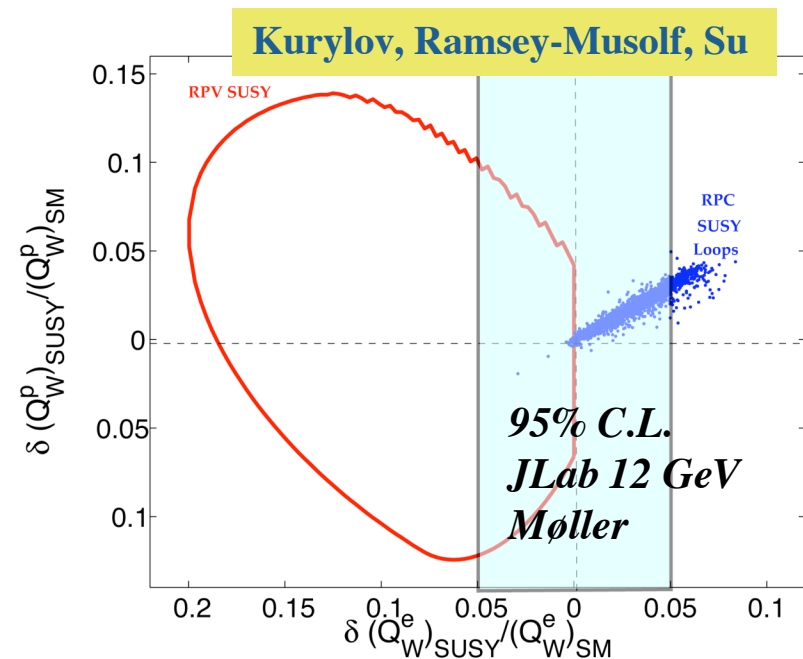
2 best collider measurements disagree ( $> 3\sigma$ )



Best new measurement until Linear Collider or Neutrino Factory

*Does Supersymmetry (SUSY) provide a candidate for dark matter?*

- Neutralino is stable if baryon (B) and lepton (L) numbers are conserved
- B and L need not be conserved (RPV): neutralino decay



# Summary & Outlook: A Roadmap

- *A robust neutrino program: DUSEL (+ exp) & immediate  $0\nu\beta\beta$*
- *An EDM program: nEDM (SNS), atomic,  $^2\text{H}$  R&D*
- *Precision Electroweak: PVES,  $\beta$ -decay,  $g_\mu-2$*
- *Supernova simulation & observation*
- *Cross-disciplinary research support:  $\theta_{13}$ , DM, CLV*
- *Theory: focus on problems & junior theorists*
- *Recruit, educate, support students*

Our subfield has attracted many bright experimental and theory students and continues to create many new faculty positions at leading universities