Baryon Number Violation

K.S. Babu

Department of Physics, Oklahoma State University

CSS2013

Minneapolis, MN

July 29 – August 6, 2013

General Remarks

Baryon Number postulated as a symmetry of Nature to stabilize matter

Weyl (1929), Stueckelberg (1939), Wigner (1949)

Unlike electric charge, which guarantees stability of electron, B is not a "fundamental" symmetry

Weak interactions violate B non-perturbatively

't Hooft (1977)

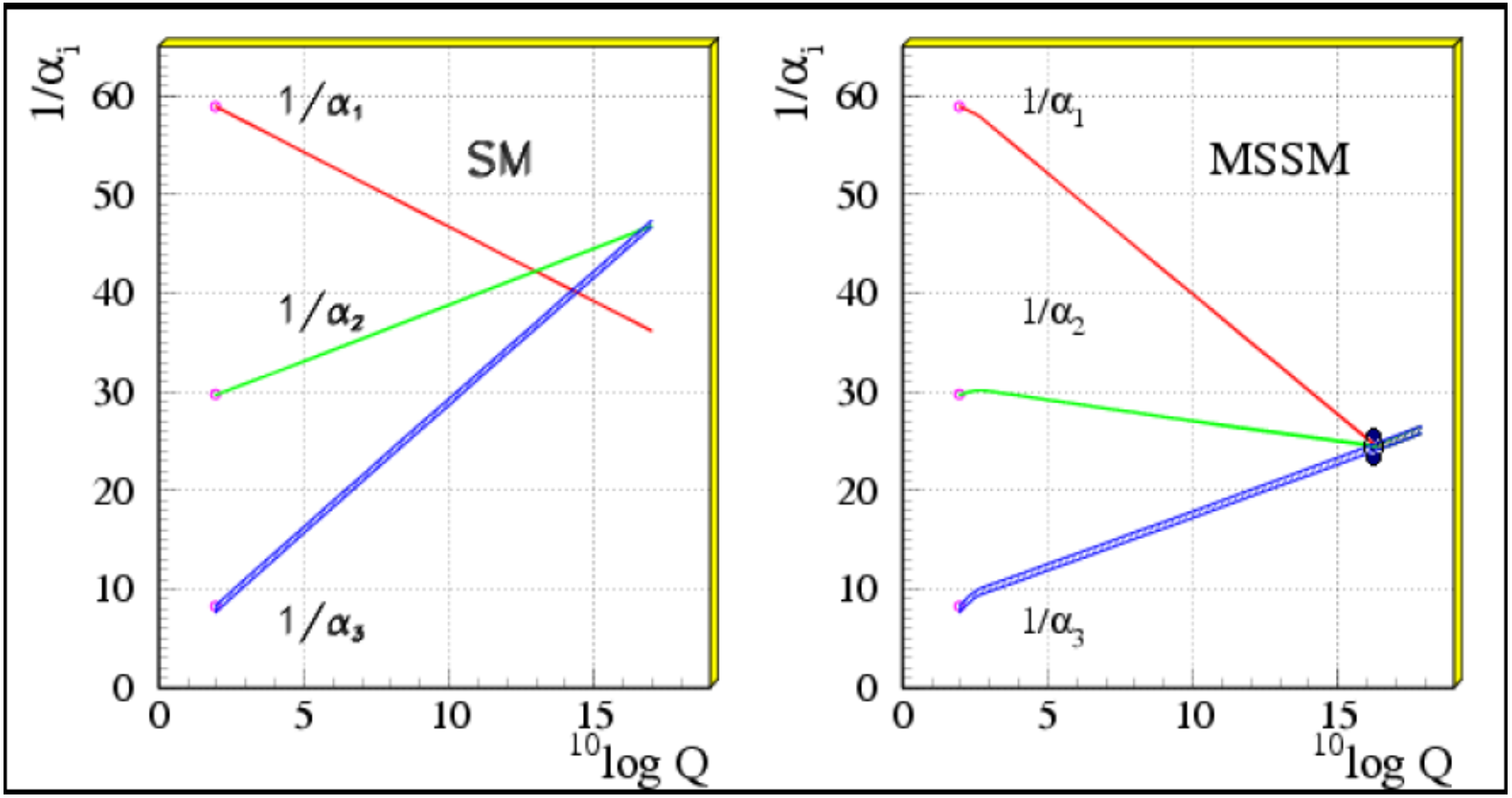
Quantum gravity suspected to violate all global symmetries such as B

Baryon number violation essential for creation of matter asymmetry of the Universe

Sakharov (1967)

Most extensions of Standard Model, notably Grand Unified Theories lead to baryon number violation

Gauge coupling unification



From S. Raby, PDG Review

SO(10) Grand Unification

Unifies all members of a family into a single 16-plet

$u_r : \{-++\ +-\}$	$d_r : \{-++\ -+\}$	$u_r^c : \{+--\ ++\}$	$d_r^c : \{+--\ --\}$
$u_b : \{+-+\ +-\}$	$d_b : \{+-+\ -+\}$	$u_b^c : \{-+-\ ++\}$	$d_b^c : \{-+-\ --\}$
$u_g : \{++-\ +-\}$	$d_g : \{++-\ -+\}$	$u_g^c : \{--+\ ++\}$	$d_g^c : \{--+\ --\}$
$\nu : \{---\ +-\}$	$e : \{---\ -+\}$	$\nu^c : \{+++\ ++\}$	$e^c : \{+++\ --\}$

Predicts right-handed neutrino and thus neutrino masses

Frist 3 spins refer to color, last 2 are weak spins

$$Y = \frac{1}{3}\Sigma(C) - \frac{1}{2}\Sigma(W)$$

Eg: $Y(e^c) = \frac{1}{3}(3) - \frac{1}{2}(-2) = 2$

Such an elegant arrangement very strongly suggestive of GUTs

Grand Unified Theories: Motivations

- Electric charge quantization
  - ◇ $Q_p = -Q_e$ to better than 1 part in 10^{21}
- Miraculous cancellation of anomalies
- Quantum numbers of quarks and leptons
- Existence of ν_R and thus neutrino mass via seesaw
- Unification of gauge couplings with low energy SUSY
- $b - \tau$ unification
- Baryon asymmetry of the universe via leptogenesis

Pati, Salam (1973)
Georgi, Glashow (1974)

Minimal SO(10) Model

$$\mathcal{L}_{\text{Yukawa}} = Y_{10}\,\mathbf{16}\,\mathbf{16}\,\mathbf{10}_H + Y_{126}\,\mathbf{16}\,\mathbf{16}\,\overline{\mathbf{126}}_H$$

Two Yukawa matrices determine all fermion masses and mixings, including the neutrinos

$$\begin{aligned} M_u &= \kappa_u Y_{10} + \kappa'_u Y_{126} \\ M_d &= \kappa_d Y_{10} + \kappa'_d Y_{126} \\ M_\nu^D &= \kappa_u Y_{10} - 3\kappa'_u Y_{126} \\ M_l &= \kappa_d Y_{10} - 3\kappa'_d Y_{126} \end{aligned}$$

$$\begin{aligned} M_{\nu R} &= \langle \Delta_R \rangle\, Y_{126} \\ M_{\nu L} &= \langle \Delta_L \rangle\, Y_{126} \end{aligned}$$

Model has only 11 real parameters plus 7 phases

Babu, Mohapatra (1993)
Fukuyama, Okada (2002)
Bajc, Melfo, Senjanovic, Vissani (2004)
Fukuyama, Ilakovac, Kikuchi, Meljanac, Okada (2004)
Aulakh et al (2004)

Bertolini, Frigerio, Malinsky (2004)
Babu, Macesanu (2005)
Bertolini, Malinsky, Schwetz (2006)
Dutta, Mimura, Mohapatra (2007)
Bajc, Dorsner, Nemevsek (2009)

Specific Example: Type I Seesaw

Input at the GUT scale:

$$m_u = 0.0006745 \qquad m_c = 0.3308 \qquad m_t = 97.335$$
$$m_d = 0.0009726 \qquad m_s = 0.02167 \qquad m_b = 1.1475$$
$$m_e = 0.000344 \qquad m_\mu = 0.0726 \qquad m_\tau = 1.350 \text{ GeV}$$
$$s_{12} = 0.2248 \qquad s_{23} = 0.03278 \qquad s_{13} = 0.00216$$
$$\delta_{CKM} = 1.193 \ .$$

Output for neutrinos:

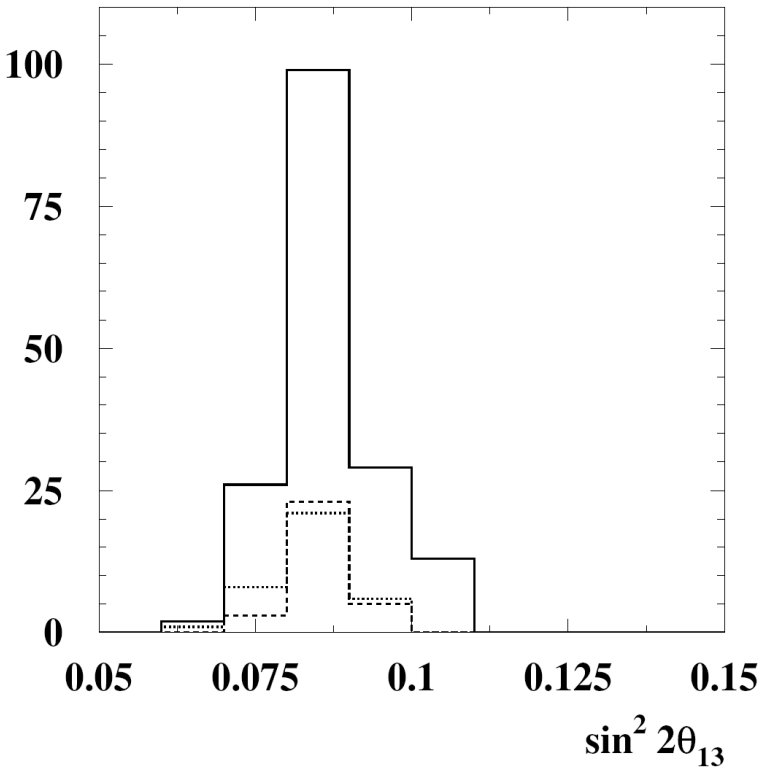
$$\sin^2\theta_{12} \simeq 0.27, \quad \sin^2 2\theta_{23} \simeq 0.90, \quad \sin^2 2\theta_{13} \simeq 0.08$$

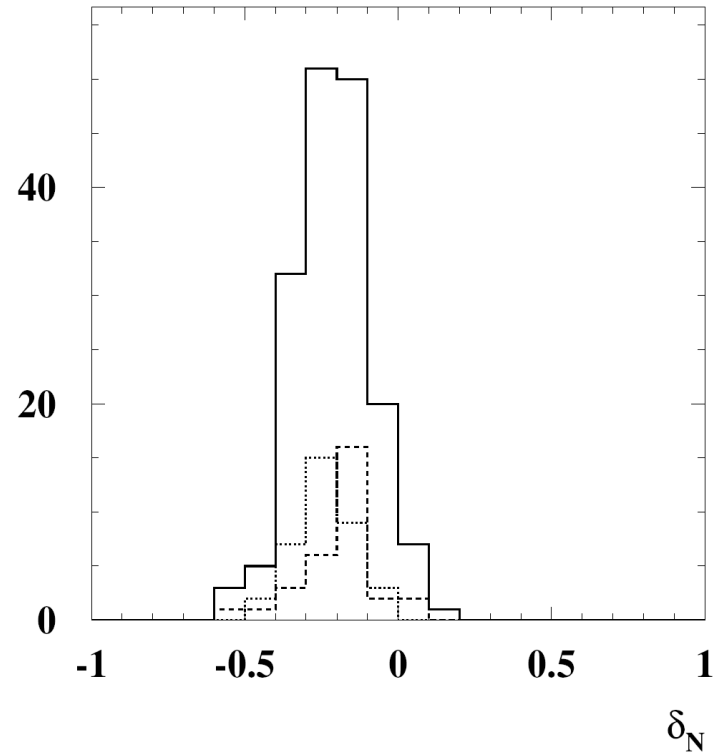
$$m_i = \{0.0021 e^{0.11 i},\ 0.0098 e^{-3.08 i},\ 0.048\} \text{ eV}$$

$$\Delta m^2_{23}/\Delta m^2_{12} \simeq 24$$

K.S. Babu and C. Macesanu (2005)

Theta(13) in Minimal SO(10)





$\sin^2 2\theta_{13}$ and CP violating phase δ_N

K.S. Babu and C. Macesanu (2005)

$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005$ Daya Bay (2012)

Unification and Proton Decay in non-SUSY SO(10)

Unlike $SU(5)$, $SO(10)$ allows an intermediate symmetry

$$SO(10) \to SU(4)_c \times SU(2)_L \times SU(2)_R \times P$$ **Pati-Salam symmetry**

Unification of gauge couplings consistent with data

Intermediate scale may be identified as Peccei-Quinn scale to solve strong CP problem

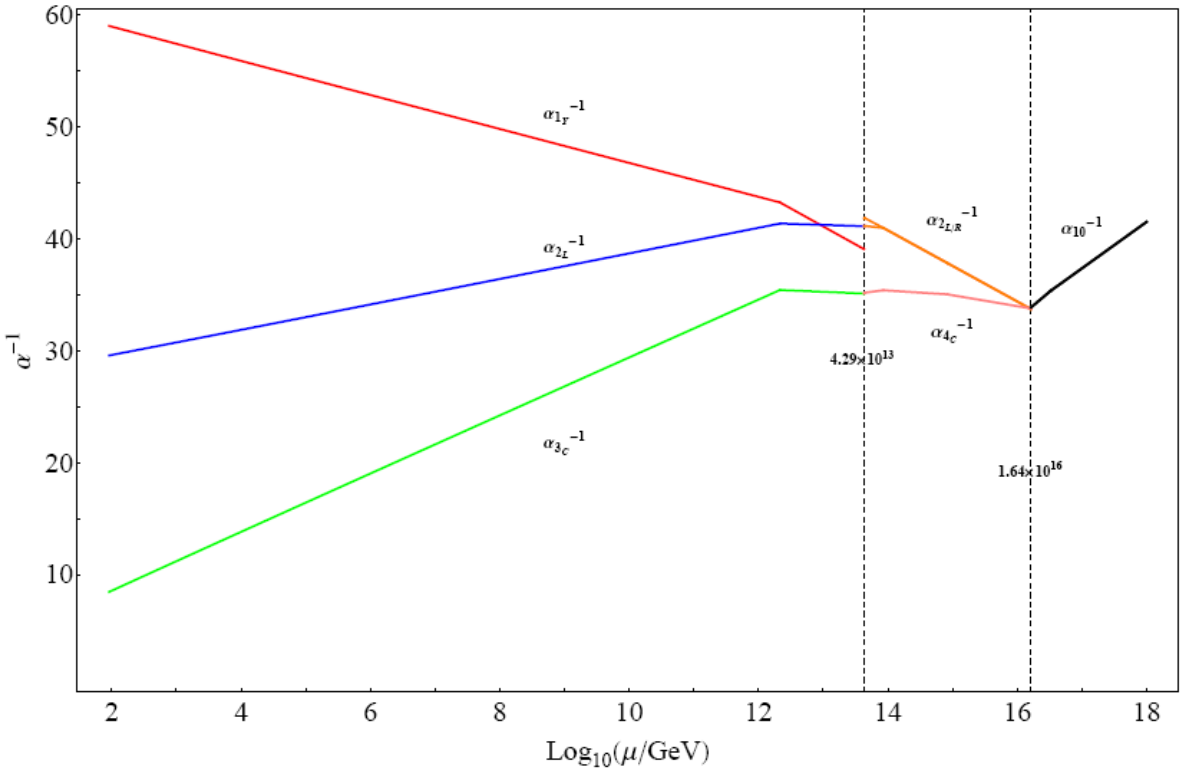
Proton decays via exchange of $SO(10)$ gauge bosons

Lifetime within reach of currently envisioned experiments

Rich literature:

Mohapatra, Parida (1993)
Deshpande, Keith, Pal (1995)
Lee, Mohapatra, Parida, Rani (1995)
Bertolini, Luzio, Malinsky (2012)
Altarelli, Meloni (2013)
Babu, Khan (2013)

Gauge coupling evolution in non-SUSY SO(10)



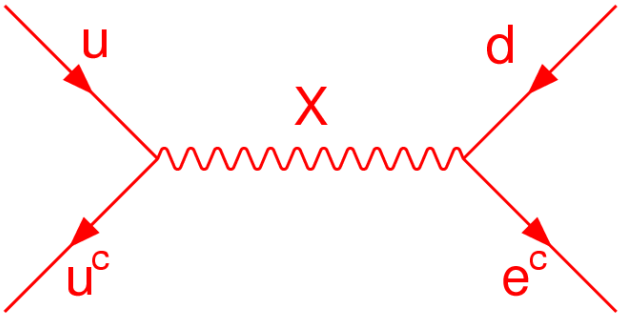
Intermediate symmetry: $SO(10) \to SU(4)_c \times SU(2)_L \times SU(2)_R \times P$

Babu, Khan (2013)

Nucleon decay in non-SUSY SO(10)

$SO(10)$ breaks to an intermediate Pati–Salam symmetry $SU(2)_L \times SU(2)_R \times SU(4)_c \times P$

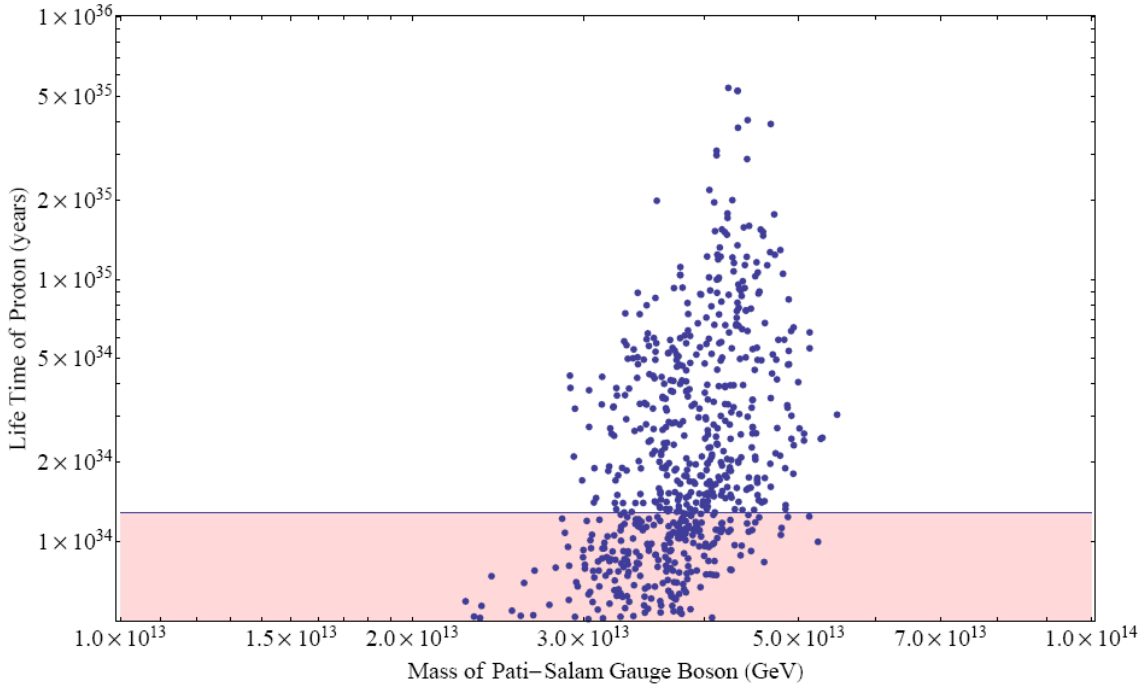
Proton decays to $e^+\pi^0$ via GUT scale X, Y gauge boson exchange



$$\Gamma^{-1}(p \to e^+\pi^0) \approx (8.2 \times 10^{34}\ \text{yr}) \times \left(\frac{\alpha_H}{0.0122\ \text{GeV}^3}\right)^{-2} \left(\frac{\alpha_G}{1/34.7}\right)^{-2} \left(\frac{A_R}{3.35}\right)^{-2} \left(\frac{M_X}{10^{16}\ \text{GeV}}\right)^{4}$$

Threshold corrections play important role

Proton Lifetime in non-SUSY SO(10)



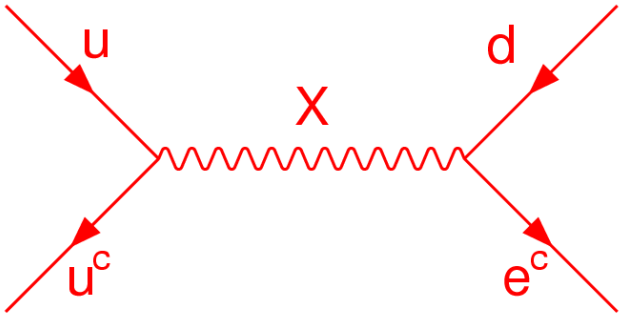
Threshold corrections: All Higgs fields assumed to be in the range $(1/20 - 2)$ of gauge boson mass

Proton lifetime cannot exceed 5×10^{35} yrs in this model

Babu, Khan (2013)

Nucleon decay in SUSY GUTs

Gauge boson exchange



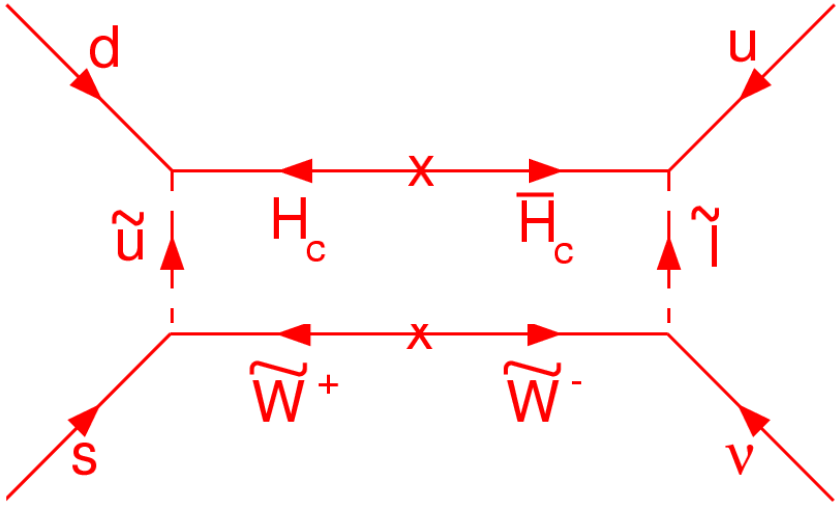
$$\Gamma^{-1}(p \to e^+\pi^0) = (2.0 \times 10^{35}\ \text{yr})$$
$$\times \left(\frac{\alpha_H}{0.01\ \text{GeV}^3}\right)^{-2} \left(\frac{\alpha_G}{1/25}\right)^{-2} \left(\frac{A_R}{2.5}\right)^{-2} \left(\frac{M_X}{10^{16}\ \text{GeV}}\right)^{4}$$

$$(-2\alpha_3^{-1} - 3\alpha_2^{-1} + 3\alpha_Y^{-1})(M_Z) = \frac{1}{2\pi}\left\{36 \ln\left(\frac{M_X}{M_Z}\left(\frac{M_\Sigma}{M_X}\right)^{1/3}\right) + 8 \ln\left(\frac{M_{\text{SUSY}}}{M_Z}\right)\right\}$$

M_Σ: Heavy color octet mass, uncertain: Threshold effect

Hisano, Murayama, Yanagida (1993)
Nath, Perez, Phys. Rept. (2007)

Supersymmetric mode



Sakai, Yanagida (1982)

Weinberg (1982)

$$\Gamma^{-1}_{d=5}(p \to \bar{\nu} K^+) \simeq 1.2 \cdot 10^{31}\,\text{yrs} \times \left(\frac{0.012\,\text{GeV}^3}{\beta_H}\right)^2 \left(\frac{7}{\bar{A}^{\alpha}_S}\right)^2 \left(\frac{1.25}{R_L}\right)^2$$

$$\times \left(\frac{M_T}{2 \cdot 10^{16}\text{GeV}}\right)^2 \left(\frac{m_{\tilde{q}}}{1.5\text{TeV}}\right)^4 \left(\frac{190\,\text{GeV}}{M_{\tilde{W}}}\right)^2 ,$$

Minimal SUSY $SU(5)$

Murayama, Pierce (2002)

Proton Lifetime in a Realistic SUSY SU(5)

$\Gamma^{-1}_{d=5}(p \to \bar{\nu} K^+)$	$4 \cdot 10^{33}$ yrs.
$\Gamma^{-1}_{d=5}(n \to \bar{\nu} K^0)$	$2 \cdot 10^{33}$ yrs.
$\Gamma^{-1}_{d=5}(p \to \mu^+ K^0)$	$1.0 \cdot 10^{34}$ yrs.
$\Gamma^{-1}_{d=5}(p \to \mu^+ \pi^0)$	$1.8 \cdot 10^{34}$ yrs.
$\Gamma^{-1}_{d=5}(p \to \bar{\nu} \pi^+)$	$7.3 \cdot 10^{33}$ yrs.
$\Gamma^{-1}_{d=5}(n \to \bar{\nu} \pi^0)$	$1.5 \cdot 10^{34}$ yrs.

$5 + \overline{5}$ fermions at GUT scale corrects wrong mass relations

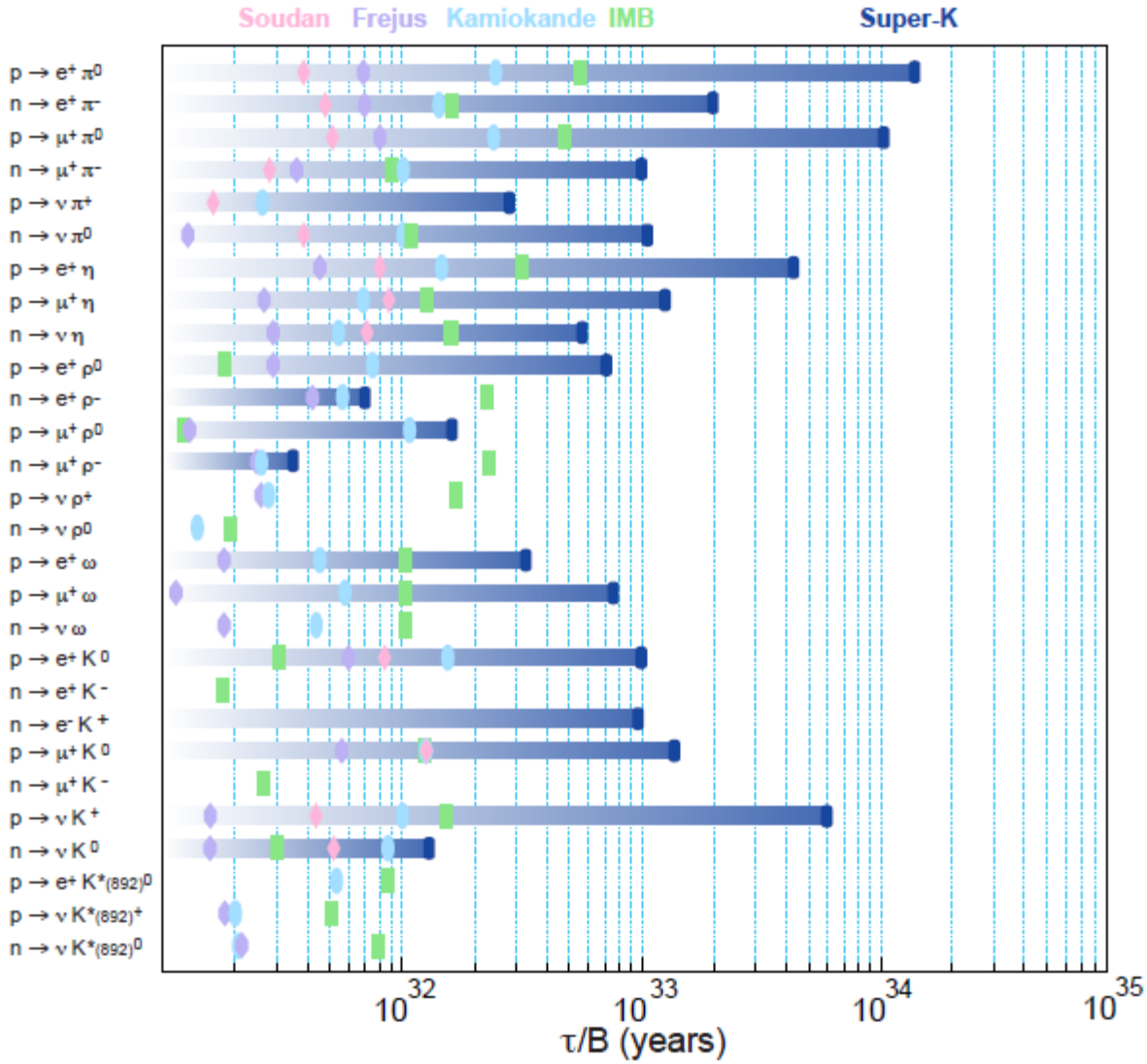
$$m_d^0 = m_e^0 \text{ and } m_s^0 = m_\mu^0$$

SUSY spectrum ≤ 3 TeV assumed

Nucleon lifetime cannot exceed 2×10^{34} yrs

Babu, Bajc, Tavartkiladze (2012)

Antilepton + Meson Two-Body Modes



- Continue Super-K exposure
- Improve analysis
- Search in new channels

} **Near Future**

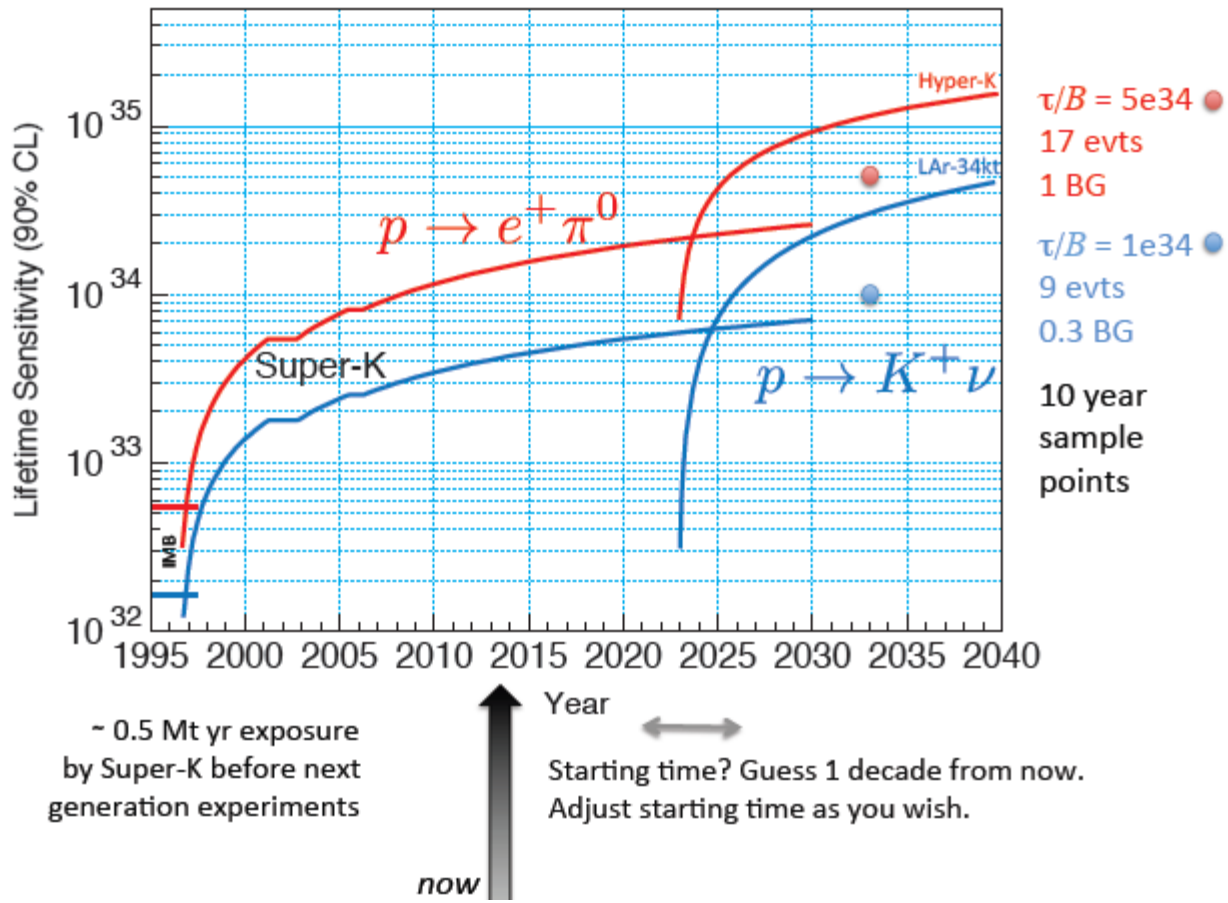
- Next generation experiments
  - Detector R&D
  - Experiment proposals

} **Next Future**

Technique	Examples	Comments
Water Cherenkov	22.5 kton Super-K 560 kton Hyper-Kamiokande	Best for $e^+\pi^0$ Good for all modes
Liquid Argon	34 kton LBNE LAr TPC 20 kton LBNO 2-phase TPC	Best for $K^+\nu$ Good for many other modes
Scintillator	50 kton LENA Next gen. reactor (DB2) ? Water-based LSc ?	Specific to $K^+\nu$

Kearns, Asilomar 2013

Proton Decay Search Territory



τ/B = 5e34
17 evts
1 BG

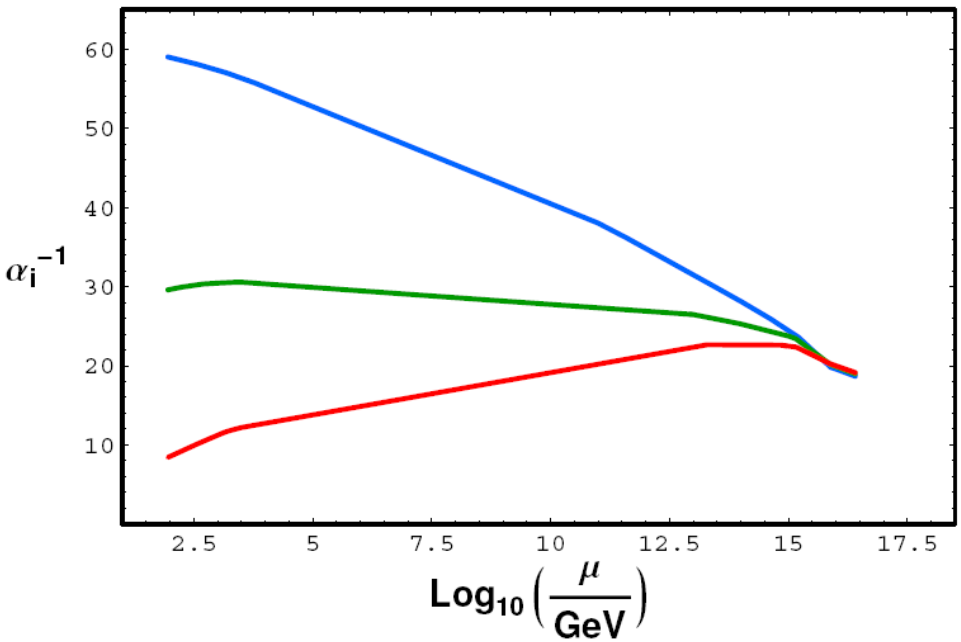
τ/B = 1e34
9 evts
0.3 BG

10 year sample points

~ 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.

Unification of couplings in SUSY SO(10)



Small Higgs representations used for symmetry breaking $(16, \overline{16}, 45, 10)$

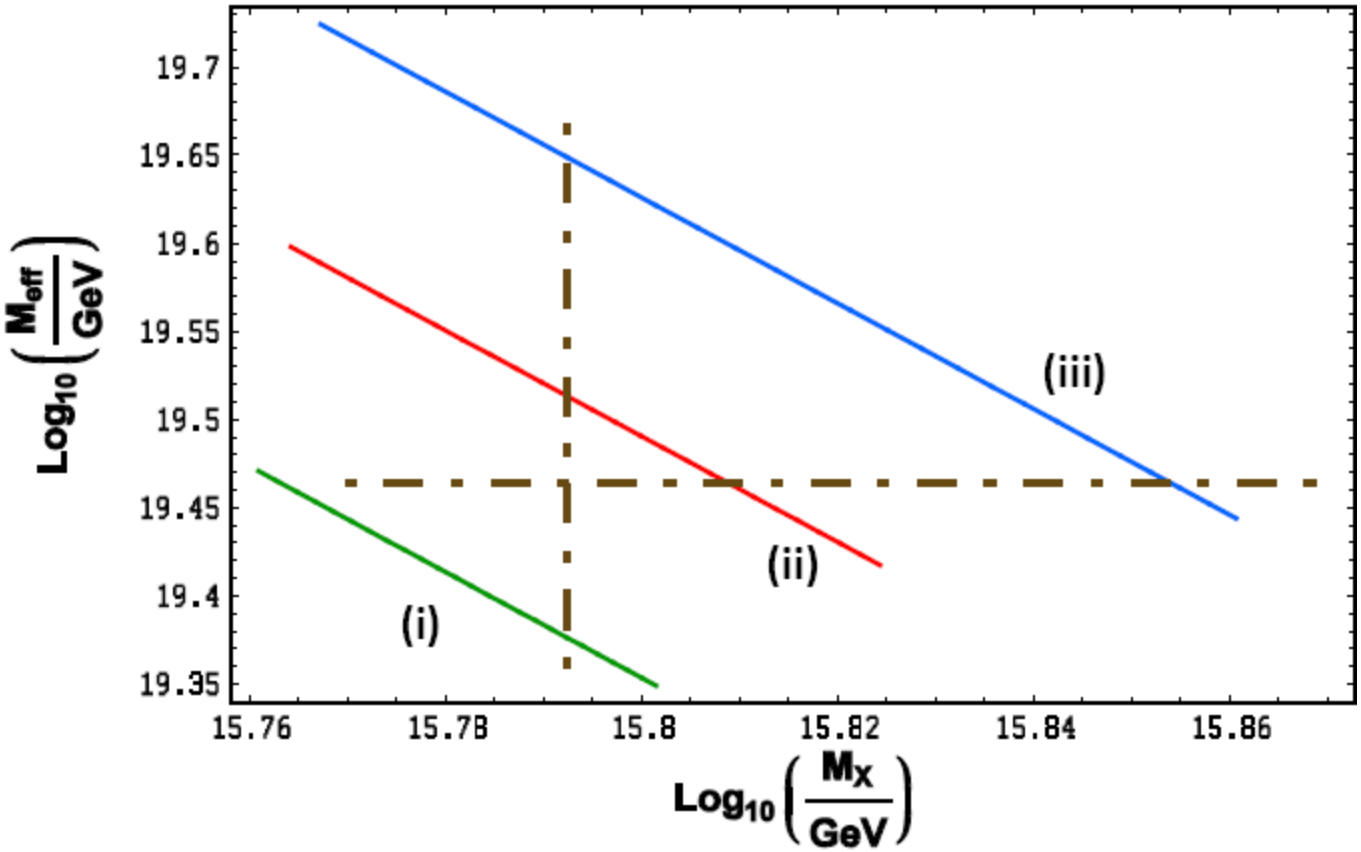
Threshold corrections calculable and small

Higgs doublet mass obtained without fine-tuning

Fairly sharp predictions for proton lifetime possible

Babu, Pati, Tavartkiladze (2010)

Correlation between d = 5 and d= 6 proton decay



Correlation for spectrum with $tan\beta = 7$ and r=1/1200.

(i): $\alpha_3 = 0.1177$. **(ii)**: $\alpha_3 = 0.1184$. **(iii)**: $\alpha_3 = 0.1191$.

Proton Lifetime Predictions

$$\Gamma^{-1}_{d=5}(p \to \bar{\nu} K^+) \simeq 3.6 \cdot 10^{33}\,\text{yrs} \times \left(\frac{0.012\,\text{GeV}^3}{\beta_H}\right)^2 \left(\frac{6.9}{\bar{A}^{\alpha}_S}\right)^2 \left(\frac{1.25}{R_L}\right)^2$$

$$\times \left(\frac{M_{\text{eff}}}{3.4 \times 10^{19}\ \text{GeV}}\right)^2 \left(\frac{500\ \text{GeV}}{M_{\tilde{W}}}\right)^2$$

$$\Gamma^{-1}_{d=6}(p \to e^+ \pi^0) \simeq 1.0 \times 10^{34}\,\text{yrs} \left(\frac{0.012\text{GeV}^3}{\alpha_H}\right)^2 \left(\frac{2.78}{A_R}\right)^2 \left(\frac{5.12}{f(p)}\right) \left(\frac{1/20}{\alpha_G(M_X)}\right)^2 \left(\frac{M_X}{6.24 \times 10^{15}\text{GeV}}\right)^4$$

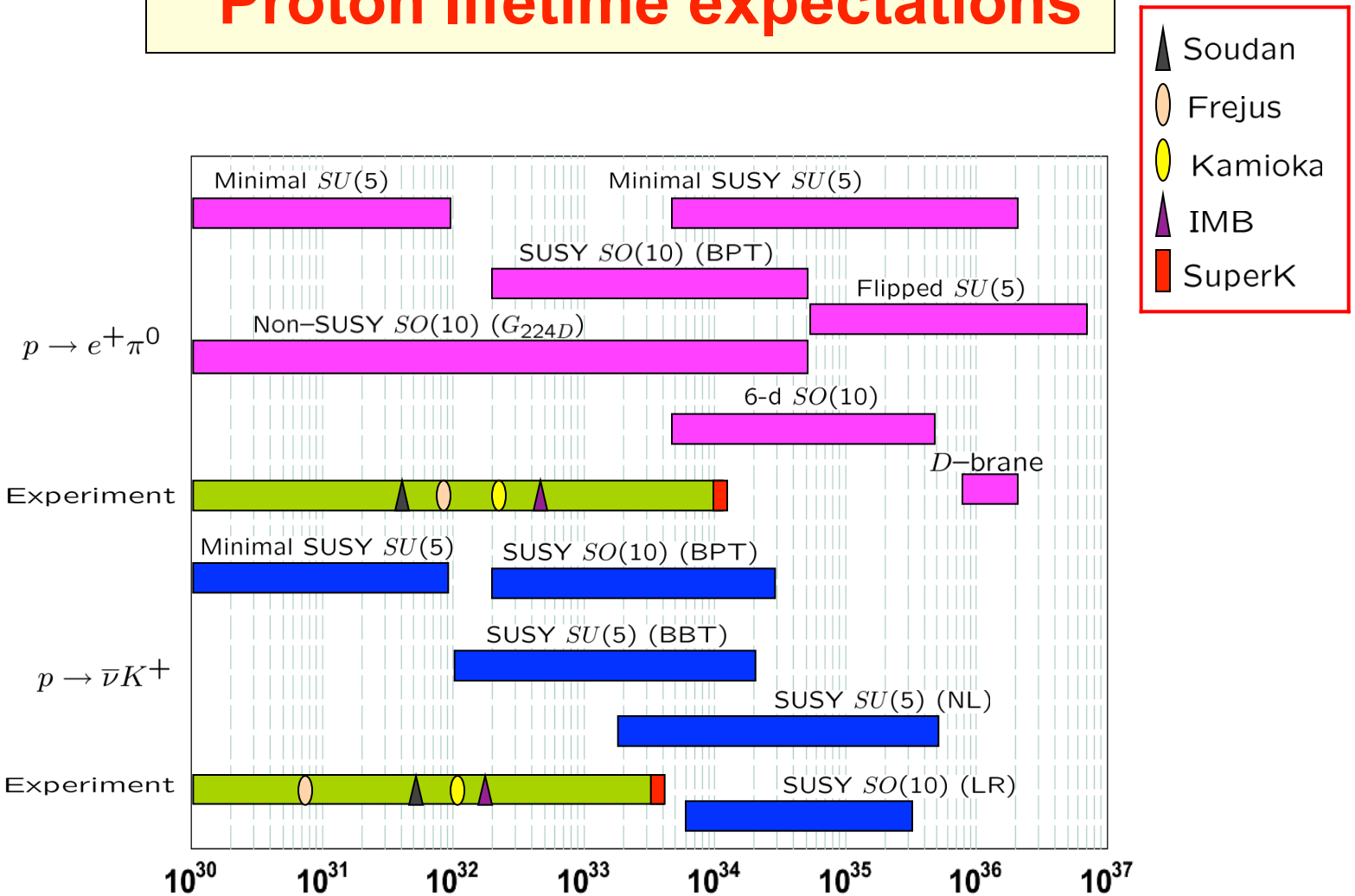
Imposing the correlation equation we obtain the predictions:

$$\Gamma^{-1}_{d=6}(p \to e^+ \pi^0) \lesssim 10^{35}\ \text{yrs}$$

$$\Gamma^{-1}(p \to \bar{\nu} K^+) \leq 7 \times 10^{34}\ \text{yrs.}$$

Both modes should be within reach of experiments!

Proton lifetime expectations



τ/B (years)

Neutron-Antineutron Oscillations

$n - \overline{n}$ oscillations violate baryon number by 2 units

Kuzmin (1970), Mohapatra, Marshak (1980)

Analogous to $K^0 - \overline{K}^0$ mixing

$$\mathcal{M}_{\mathcal{B}} = \begin{pmatrix} m_n - \vec{\mu}_n \cdot \vec{B} - i\lambda/2 & \delta m \\ \delta m & m_n + \vec{\mu}_n \cdot \vec{B} - i\lambda/2 \end{pmatrix}$$

$$P(n \to \overline{n}, t) \simeq [\delta m\, t]^2$$

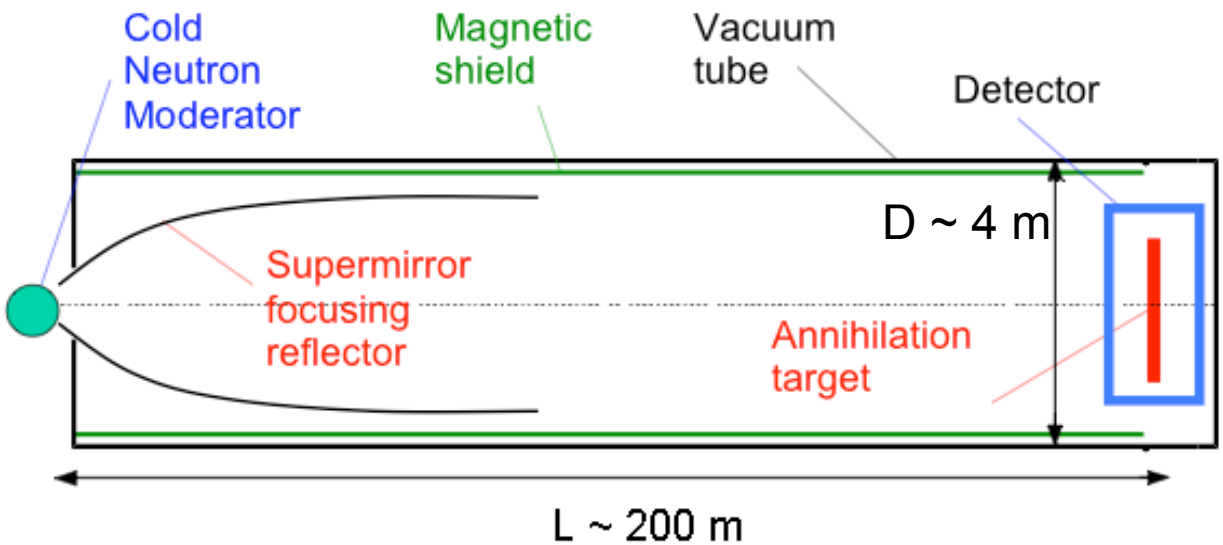
Probes new physics scale of order $10^5 - 10^6$ GeV

Pati-Salam unification predicts transition time $\tau_{n-\overline{n}} \sim 10^{10}$ sec.

Mechanism of $n - \overline{n}$ oscilaltion can explain baryon asymmetry

Conceptual Horizontal NNbarX Search in Project X at Fermilab

with elliptical focusing reflector



Typical initial baseline parameters:

Cold LD_2 source from 1MW spallation target

Luminous source area, dia	30 cm
Annihilation target, dia	200 cm
Reflector starts at	1.5 m
Reflector ends at	40 m
Reflector semi-minor axis	2.0 m
Distance to target	200 m
Super-mirror	m=6
Vacuum	< 10^{-5} Pa
Residual magnetic field	< 1 nT

MC Simulated sensitivity Nt^2:

110 "ILL units" x years

Sensitivity and parameters are subject of optimization by Monte-Carlo including overall cost

N-nbar effect can be suppressed by weak magnetic field.

Summary and Conclusions

- There is strong circumstantial evidence for grand unification
- Proton decay is the missing link
- Proton decay discovery will be transformative to the field
- SUSY and non-SUSY modes should be searched for, along with various unconventional modes
- **Large underground detectors absolutely essential**
- **Free neutron oscillations well motivated and probes a different sector of B violation and should be pursued**

Neutrino Theory

Patrick Huber

Center for Neutrino Physics at Virginia Tech

Snowmass at the Mississippi

July 26 – August 6, 2013, Minneapolis

Status quo

A common framework for all the neutrino data is oscillation of three active neutrinos

- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m^2_{31} \sim 2 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \sim 0.16$

This implies a lower bound on the mass of the heaviest neutrino

$$\sqrt{2 \cdot 10^{-3}\,\mathrm{eV}^2} \sim 0.04\,\mathrm{eV}$$

but we currently do not know which neutrino is the heaviest.

Mixing matrices

Quarks

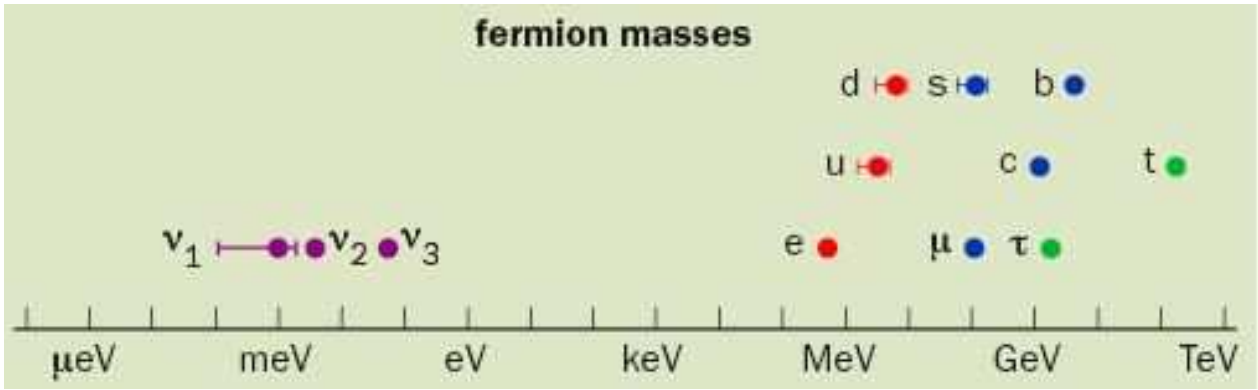
$$|U_{CKM}| = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Neutrinos

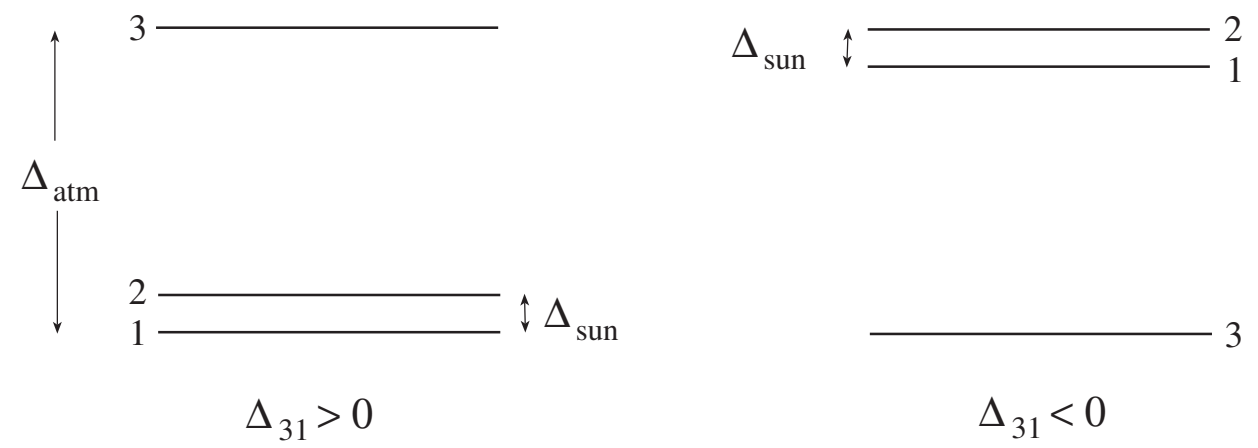
$$|U_\nu| = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Fermion masses

Scale



Ordering – mass hierarchy

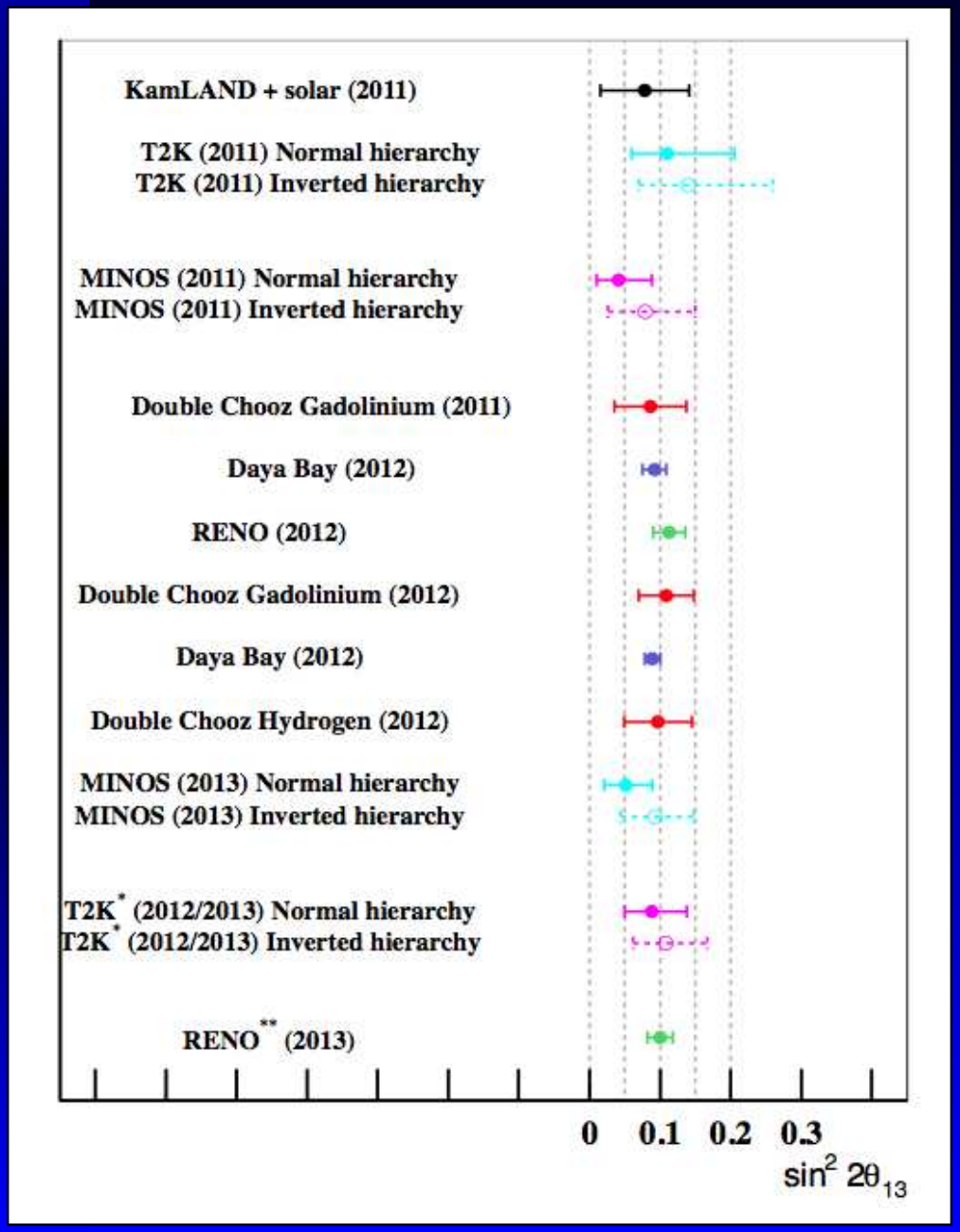


Low energy observables

The most sensitive low energy observables are

- Which one is the heaviest neutrino? –$0\nu\beta\beta$, β-decay endpoint, Oscillation
- Absolute m_ν – β-decay endpoint, Cosmology
- Majorana vs Dirac mass – $0\nu\beta\beta$
- Is θ_{23} maximal? – Oscillation
- Is there leptonic CP violation? – Oscillation
- Are there only 3 light neutrinos? – Oscillation

θ_{13} is large!



Many results from reactor and beam experiments

Some single results exceed $5\,\sigma$ significance

All results agree well

NB – 2 years ago we had only $2\,\sigma$ indications.

Model selection

… a large fraction has been excluded!

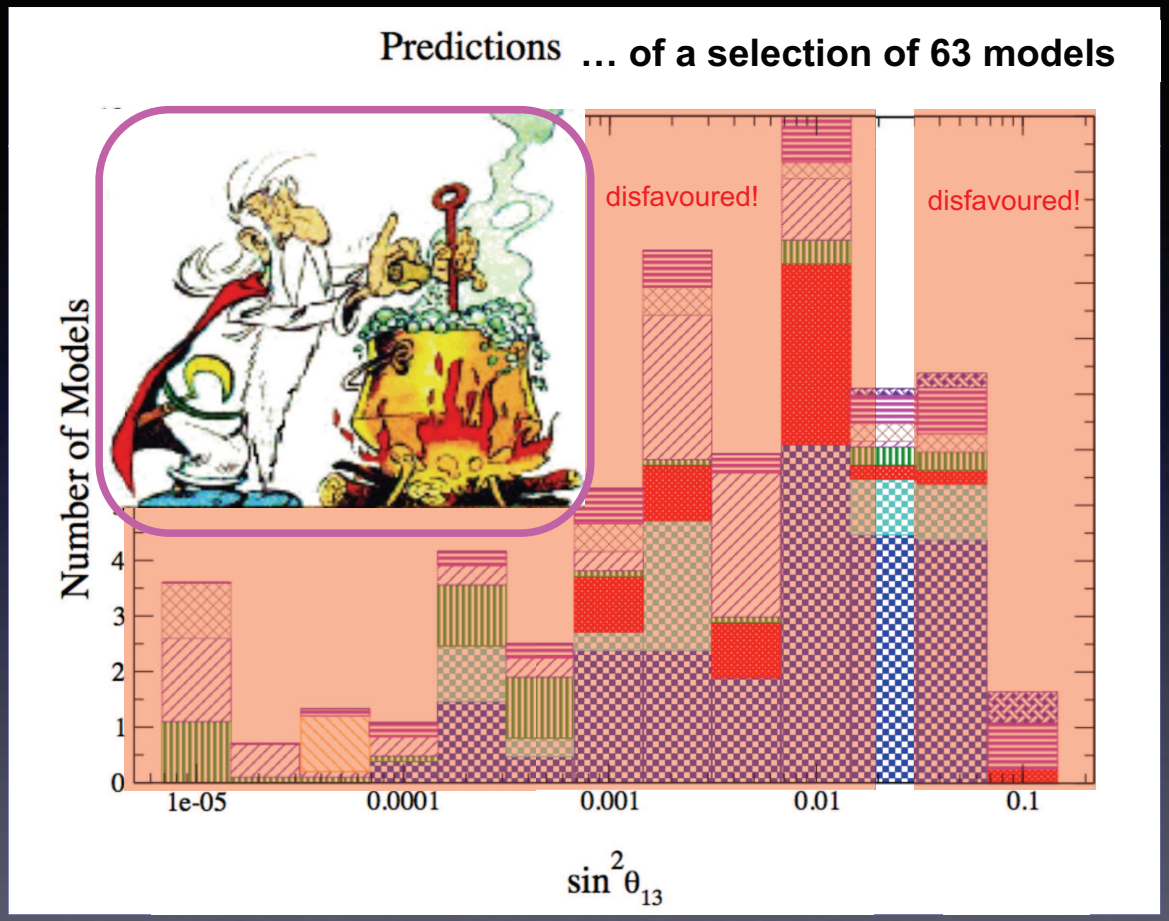


Figure shows only a small subset of the existing models … !

based on figure from Albright, Mu-Chun Chen ('06)

Antusch, 2012

Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless, therefore the discovery of neutrino oscillation, which implies non-zero neutrino masses requires the addition of new degrees of freedom.

We always knew they are ...

The SM, likely,x is an effective field theory, *i.e.* at some high scale Λ new degrees of freedom will appear

$$\mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

The first operators sensitive to new physics have dimension 5. It turns out there is only one dimension 5 operator

$$\mathcal{L}_5 = \frac{1}{\Lambda}(LH)(LH) \rightarrow \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

Thus studying neutrino masses is, in principle, the most sensitive probe for new physics at high scales

Weinberg

Effective theories

The problem in effective theories is, that there are *a priori* unknown pre-factors for each operator

$$\mathcal{L}_{SM} + \frac{\#}{\Lambda}\mathcal{L}_5 + \frac{\#}{\Lambda^2}\mathcal{L}_6 + \ldots$$

Typically, one has $\# = \mathcal{O}(1)$, but there may be reasons for this being wrong

- lepton number may be conserved $\rightarrow$ no Majorana mass term
- lepton number may be approximately conserved $\rightarrow$ small pre-factor for $\mathcal{L}_5$

Therefore, we do not know the scale of new physics responsible for neutrino masses – anywhere from keV to the Planck scale is possible.

Neutrino masses are different

The crucial difference between neutrinos and other fermions is the possibility of a Majorana mass term

$$-\frac{1}{2}m_L(\bar{\psi}_L\psi_R^C + \bar{\psi}_R\psi_L^C) - \frac{1}{2}m_R(\bar{\psi}_R\psi_L^C + \bar{\psi}_L\psi_R^C)$$

on top of the usual Dirac mass term

$$m_D(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

This allows for things like the seesaw mechanism (many versions) and implies that the neutrino flavor sector probes very different physics than the quark sector.

Neutrino mass determination

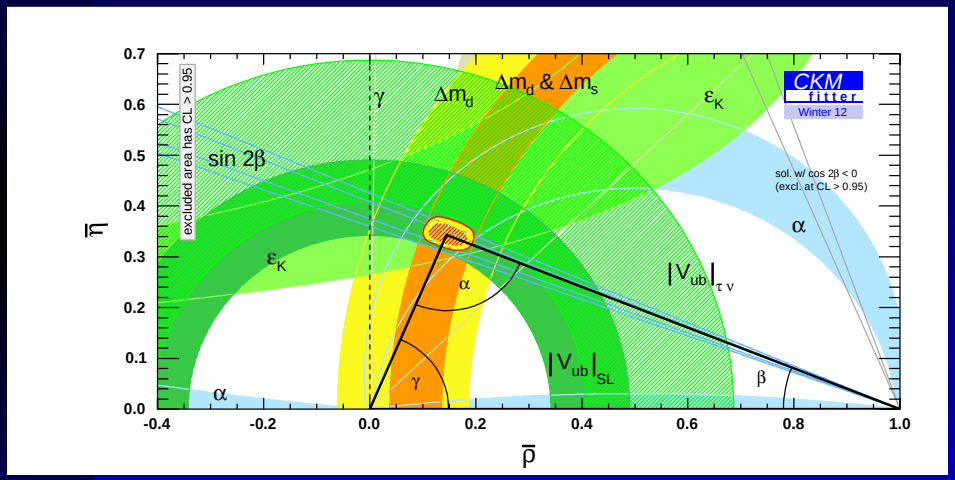
Finding the scale Λ of neutrino mass generation rests crucially on knowing

- Dirac vs Majorana mass
- Absolute size of mass

All direct experimental techniques for mass determination rely on ν_e, which is mostly made up of m_1 and m_2. Thus, the effective mass in both kinematic searches and $0\nu\beta\beta$ has a lower bound only if $m_1, m_2 > m_3$, which we call the inverted mass hierachy.

What did we learn from that?

Our expectations where to find BSM physics are driven by models – but we should not confuse the number of models with the likelihood for discovery.



- CKM describes all flavor effects
- SM baryogenesis difficult
- New Physics at a TeV
  - does not exist or
  - has a special flavor structure

and a vast number of parameter and model space excluded.

Neutrinos are very different from quarks, therefore precision measurements will yield very different answers, relating to physics at scales inaccessible by any collider.

Non-standard interactions

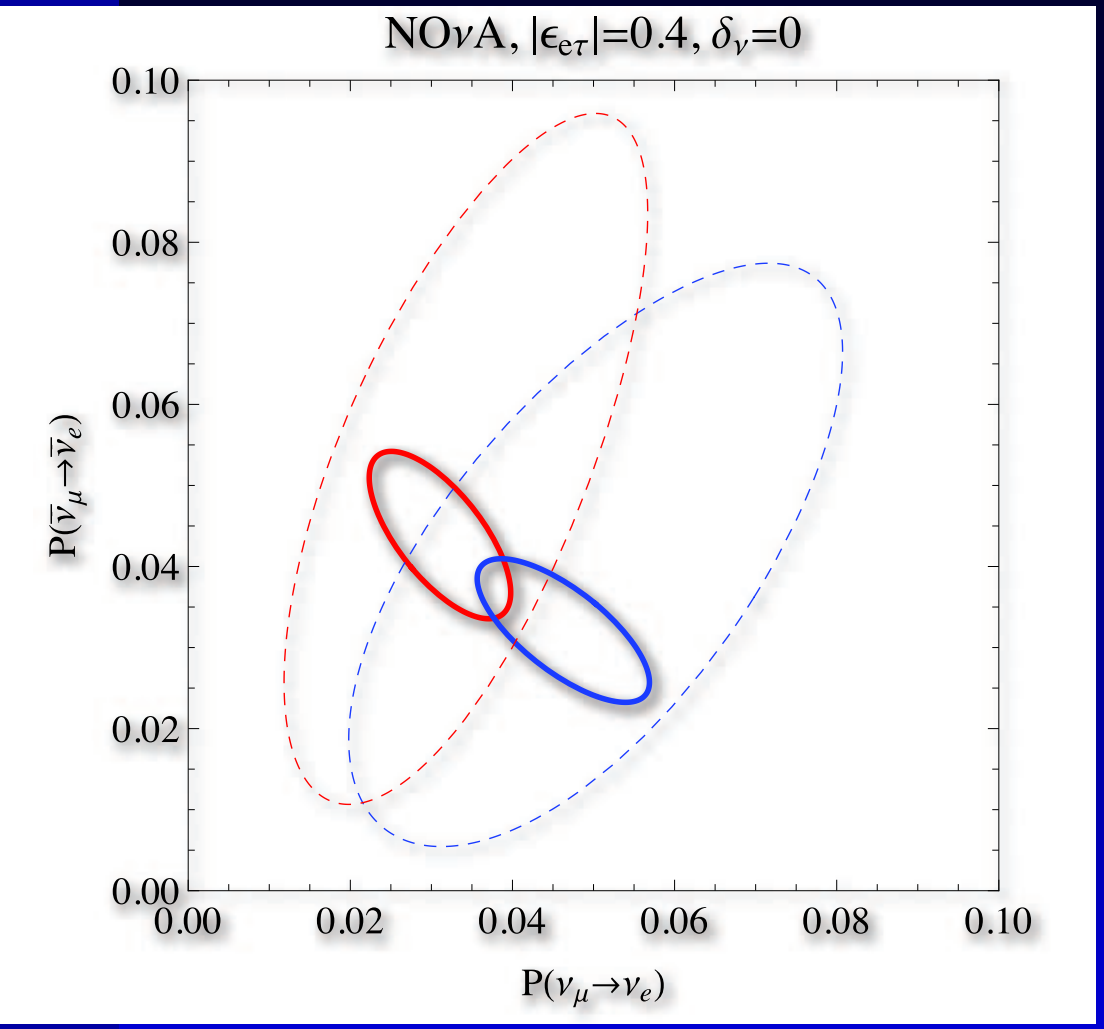
NSI are the workhorse for BSM physics in the neutrino sector. They can be parameterized by terms like this

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_f \epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\rho \nu_\beta)(\bar{f}\gamma_\rho P f)\,,$$

where f can be any fermion and P is the projection onto right and left-handed components. Wolfenstein, 1978

At higher energy, this contact term has to be replaced with a propagating exchange particle. This scale typically is closely related to scale of neutrino mass generation and sizable effects occur if the scale $\ll m_{GUT}$.

Impact on three flavors



Friedland, 2012

Three flavor analysis are not safe from these effects!

Especially, global fits for the phase and mass hierarchy need to be aware of NSI.

CP violation

There are only very few parameters in the νSM which can violate CP

- CKM phase – measured to be $\gamma \simeq 70^\circ$
- θ of the QCD vacuum – measured to be $< 10^{-10}$
- Dirac phase of neutrino mixing
- Possibly: 2 Majorana phases of neutrinos

At the same time we know that the CKM phase is not responsible for the Baryon Asymmetry of the Universe…

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

$$dU = ds_{12}^2\, dc_{13}^4\, ds_{23}^2\, d\delta_{CP}\, d\chi_1\, d\chi_2$$

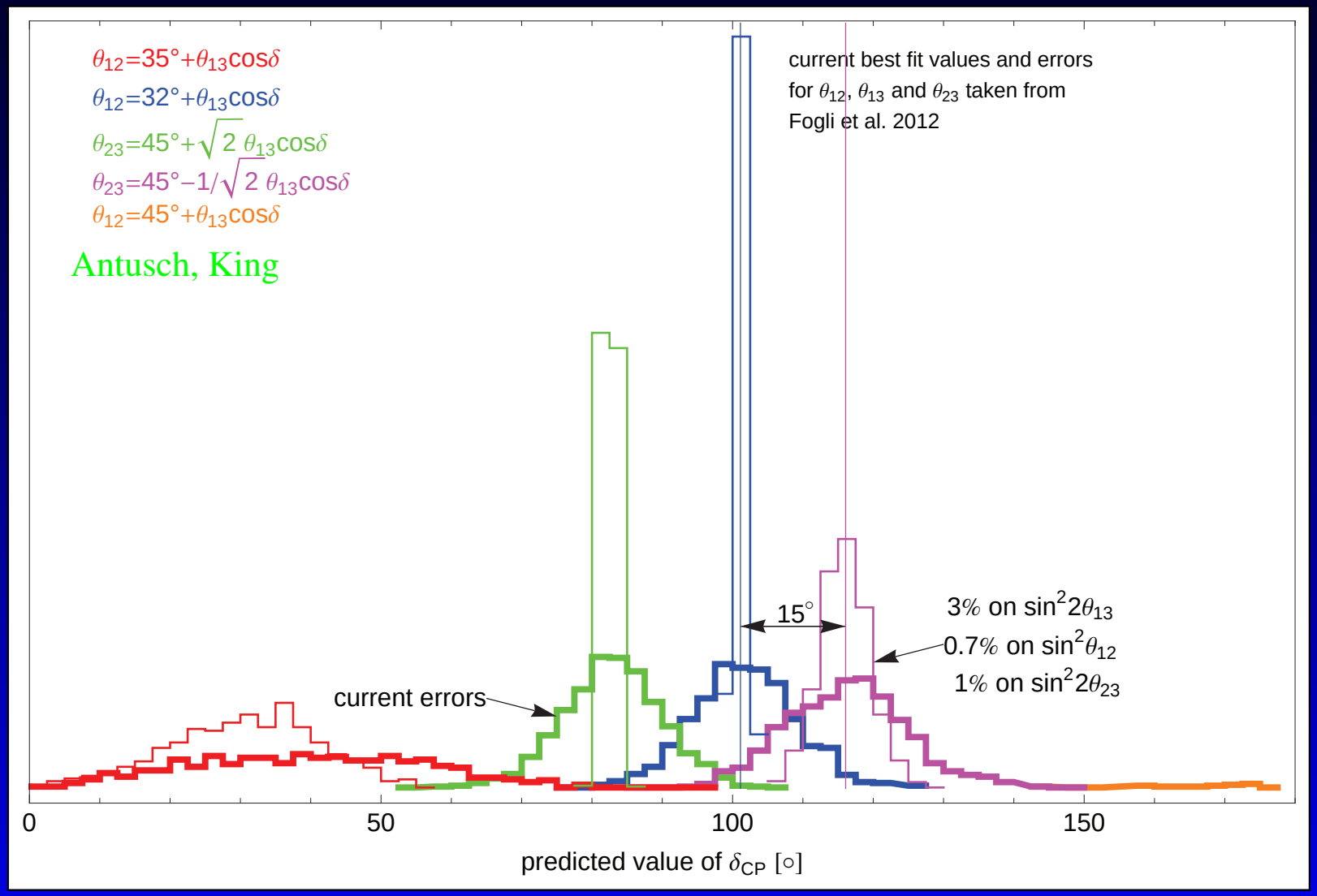
predicts flat distribution in δ_{CP}

Simplest model – Tri-bimaximal mixing Harrison, Perkins, Scott

$$\begin{pmatrix} \sqrt{\frac{1}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

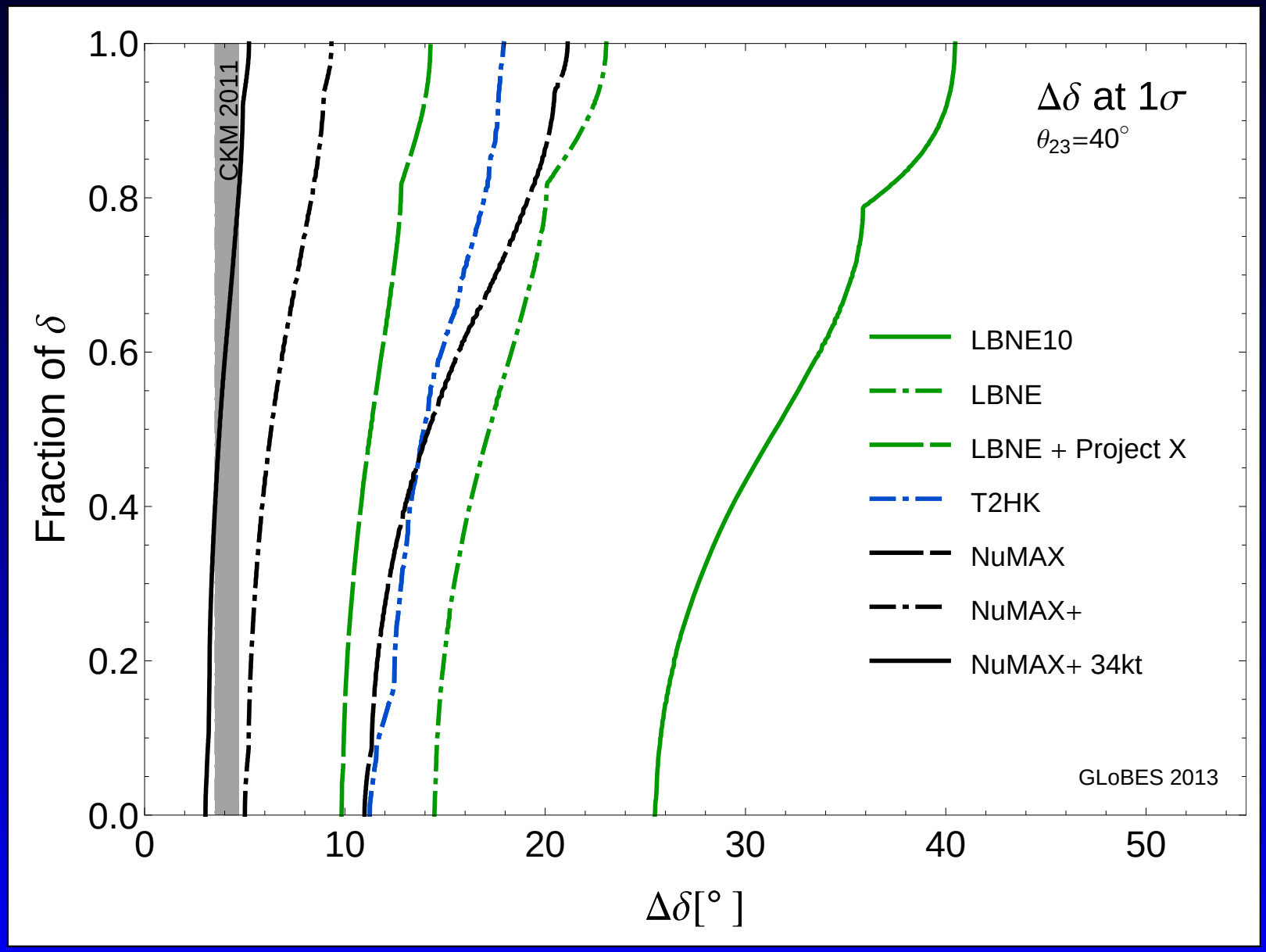
to still fit data, obviously corrections are needed – predictivity?

Sum rules

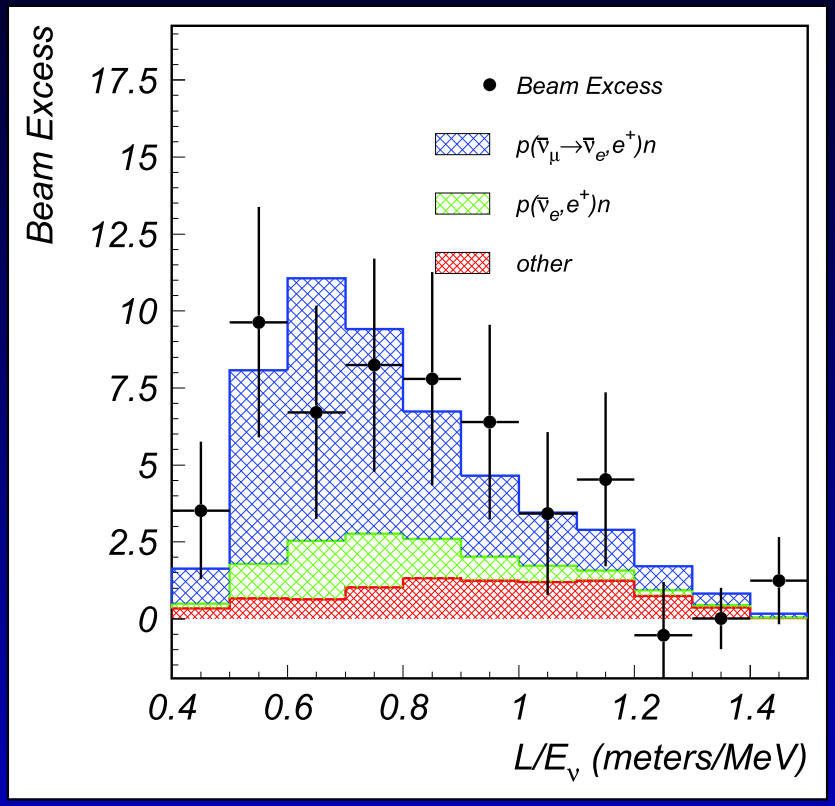


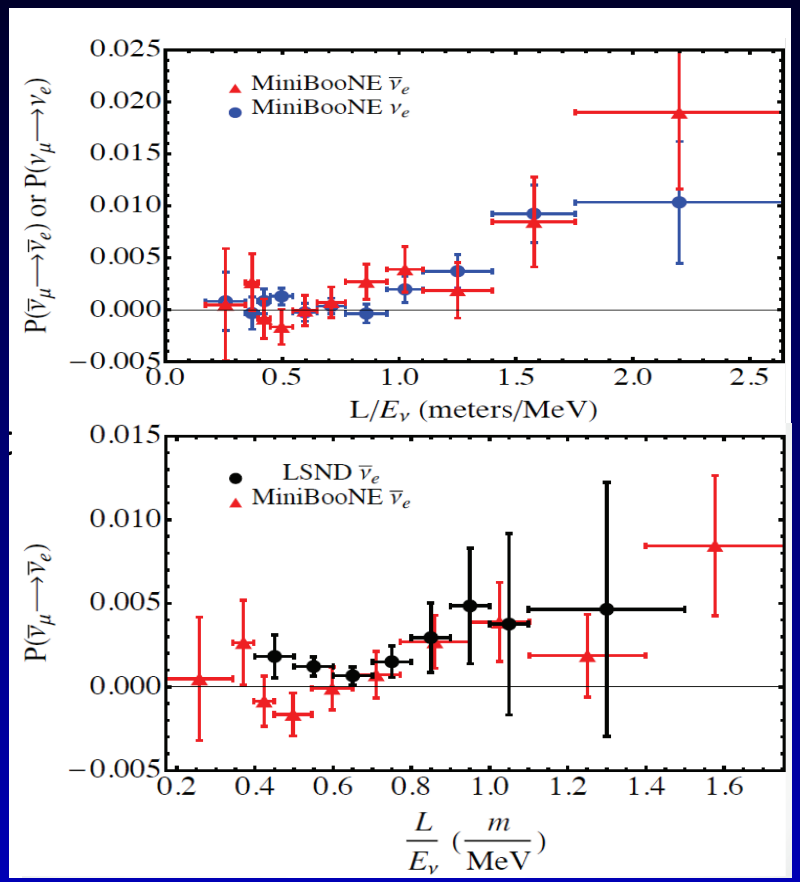
$3\,\sigma$ resolution of 15° distance requires 5° error. NB – smaller error on θ_{12} requires dedicated experiment like JUNO

Is 5° feasible?



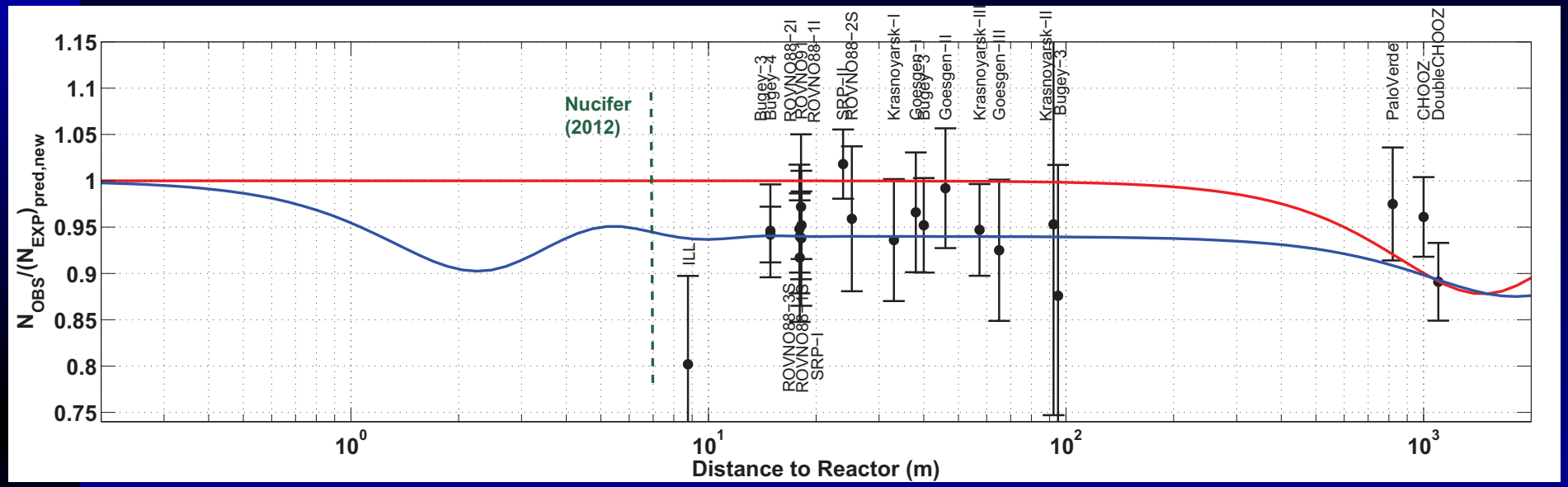
LSND and MiniBooNE





$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 0.003$$

Reactor and Gallium anomalies



	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R_B^k	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm ^{+0.084}_{-0.078}$
R_H^k	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm ^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47	
source height [m]	2.7	2.38	0.72	

Finding a sterile neutrino

All pieces of evidence have in common that they are less than 5 σ effects and they may be all due to the extraordinary difficulty of performing neutrino experiments, if not:

- N sterile neutrinos are the simplest explanation
- Tension with null results in disappearance remains

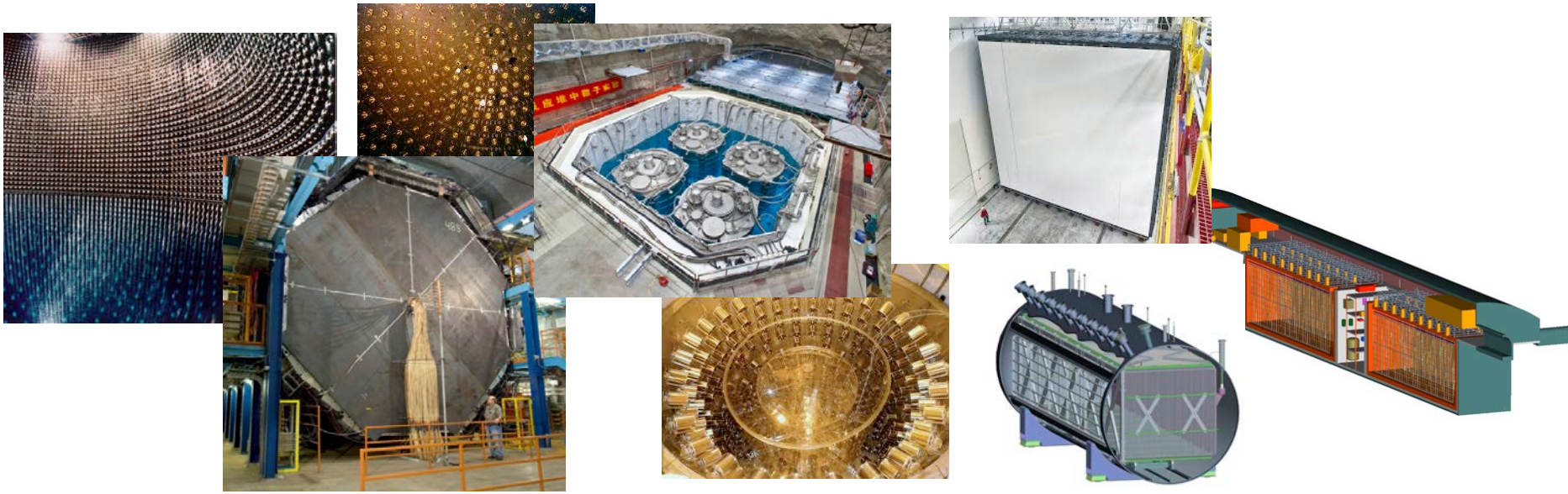
Due to their special nature as SM gauge singlets sterile neutrinos are strong candidates for being a portal to a hidden sector – significant experimental activity.

Summary

- Neutrino oscillation is solid evidence for new physics
- Current data allows $\mathcal{O}(1)$ corrections to three flavor framework
- Precision measurements have the best potential to uncover even "newer" physics
- Sterile neutrinos?

Neutrinos have provided us with many surprises and neutrinos are still largely unexplored !

A Discovery Program of Neutrino Experiments

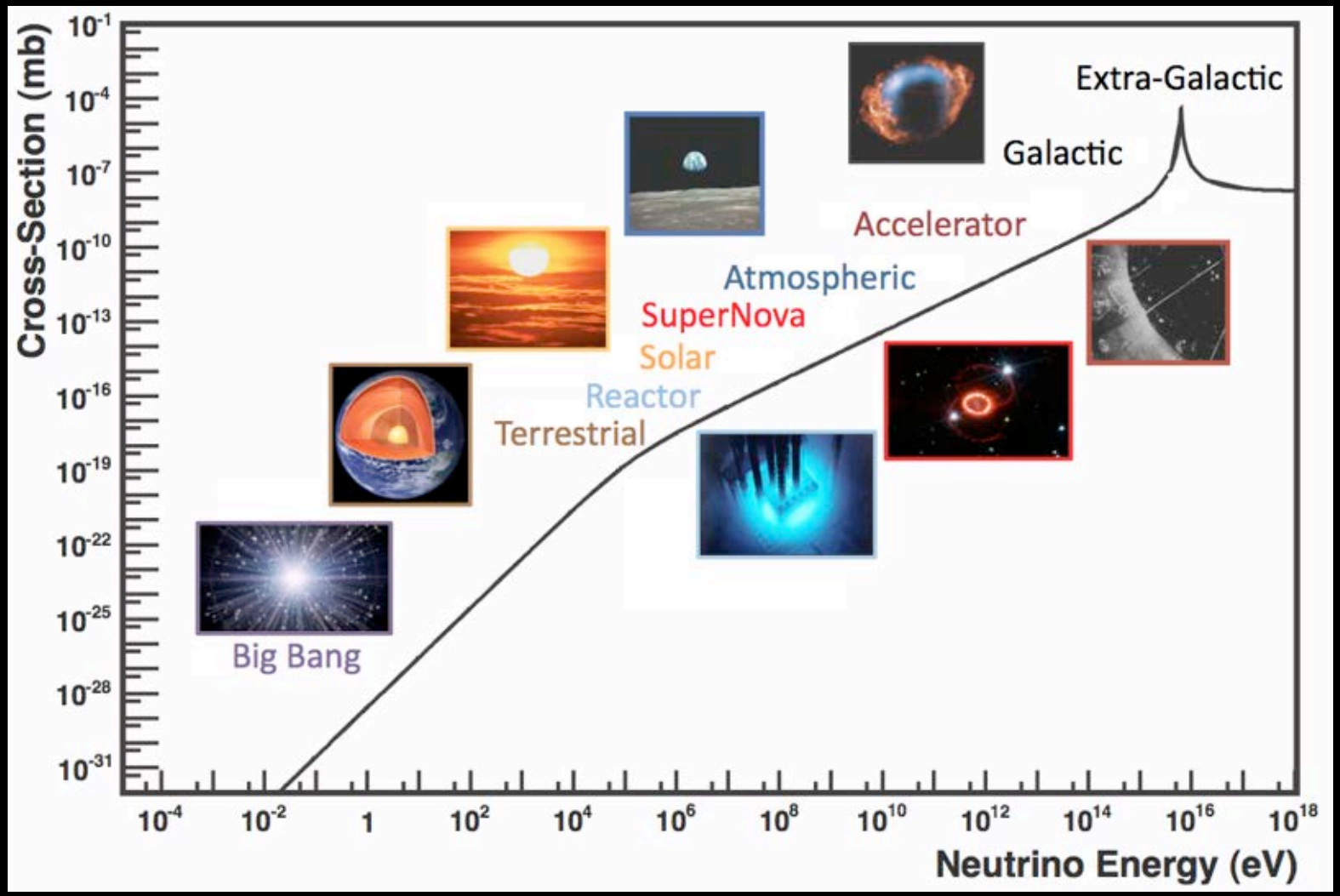


Karsten M. Heeger

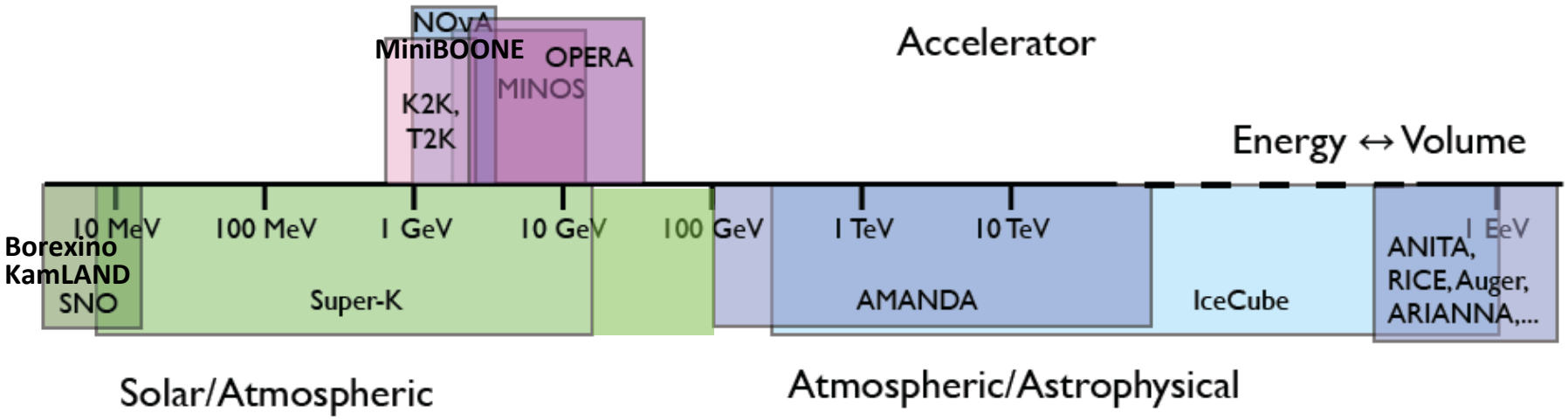
Snowmass on the Mississippi, July 31, 2012

This is not a comprehensive summary. Highlights of opportunities!

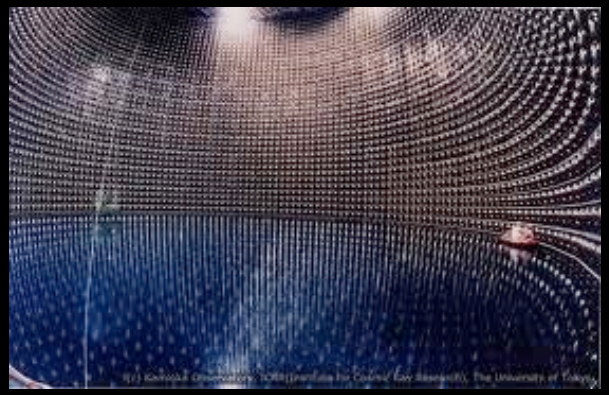
Neutrino sources provide many opportunities



Tools of Discovery - Neutrino Detectors

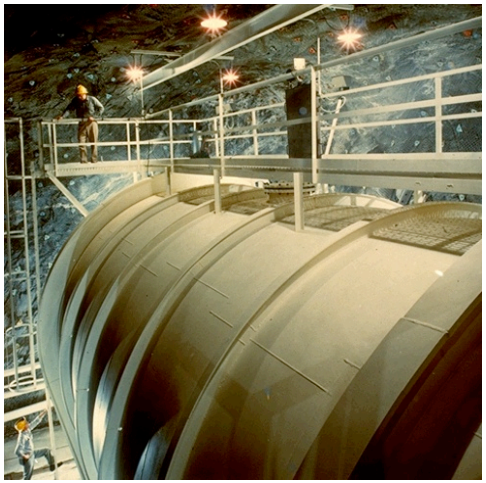


detectors must match requirements of ν sources, leads to a broad field with a variety of detectors and techniques

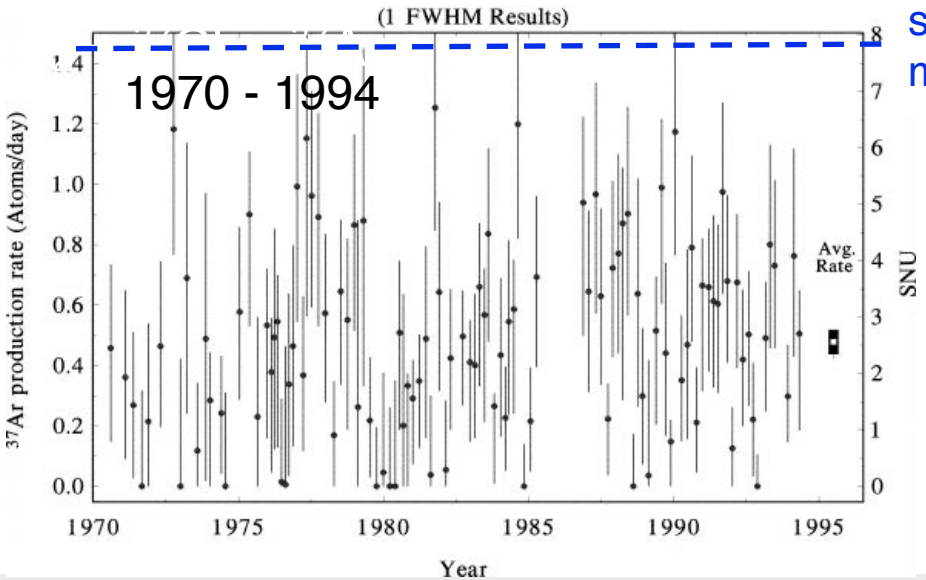


The First Anomaly

Cl-Ar Solar Neutrino Experiment at Homestake

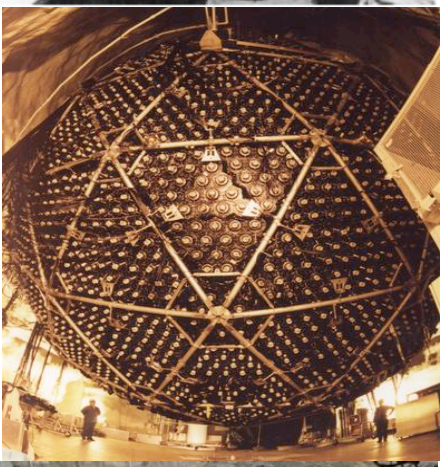


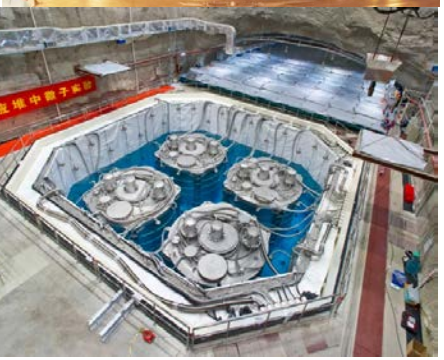
"deficit" of solar neutrinos



experiment only sensitive to ν_e

Discoveries of Neutrino Oscillation





1968 Ray Davis detects 1/3 of expected solar neutrinos.
(Nobel prize in 2002)

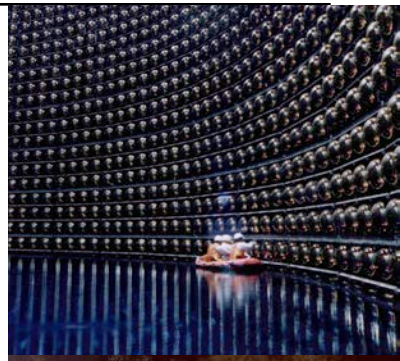
1998 SuperK reports evidence for oscillation of atmospheric neutrinos.

2001/2002 SNO finds evidence for solar ν_e flavor change.

2003 KamLAND discovers disappearance of reactor $\bar{\nu}_e$

2012 Daya Bay, Double Chooz, RENO measure θ_{13}

2013 T2K sees ν_e appearance

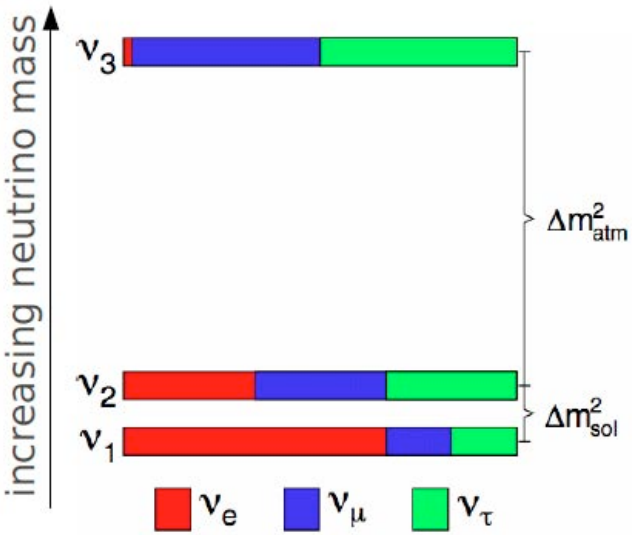


Neutrino Oscillation Implies Neutrino Mass

mass eigenstates ≠ flavor eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

flavor composition of neutrinos changes as they propagate



Observables in oscillation experiments

energy E and baseline L

oscillation frequency Δm^2

oscillation amplitude θ

$$P_{i\to j} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

Parameterized in a mixing matrix

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

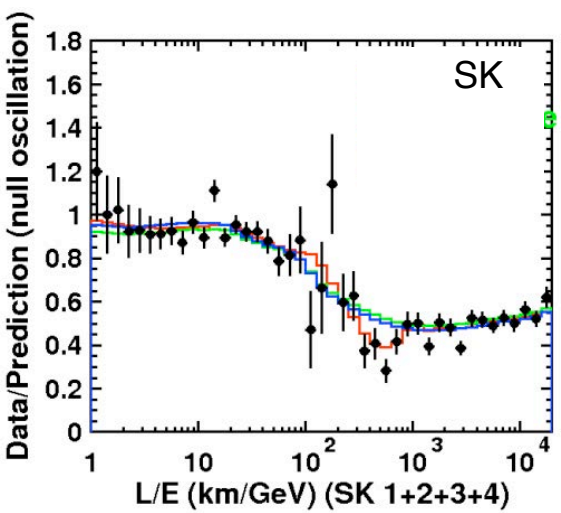
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

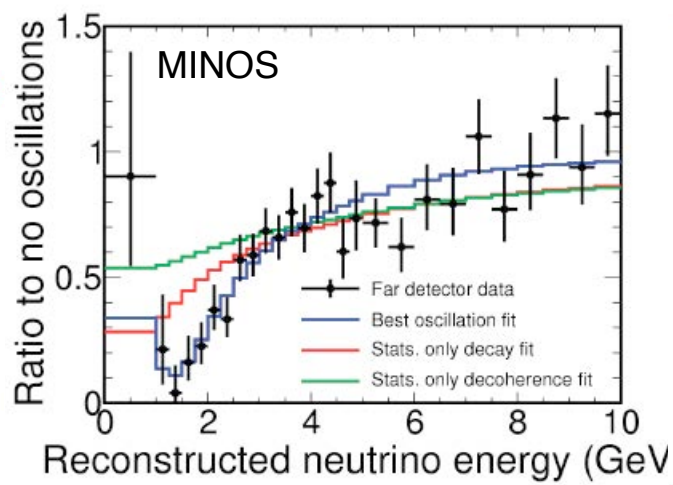
Neutrino Oscillation Measurements

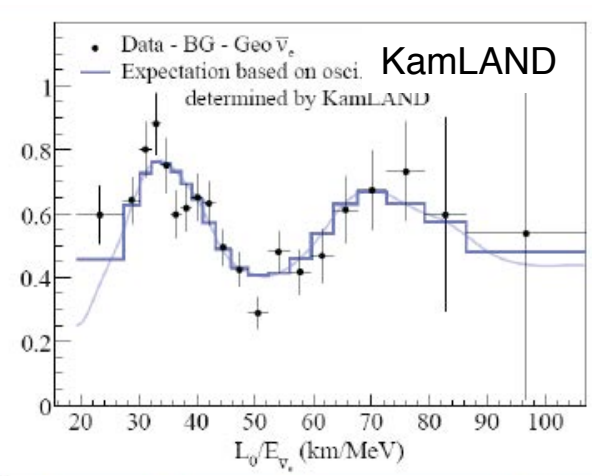
Lots of Experimental Data

- atmospheric ν_μ and $\bar{\nu}_\mu$ disappear most likely to ν_τ (SK, MINOS)
- accelerator ν_μ and $\bar{\nu}_\mu$ disappear at L~250, 700 km (K2K, T2K, MINOS)
- accelerator ν_μ appear as ν_e at L~250, 700 km (T2K, MINOS)
- solar ν_e convert to ν_μ/ν_τ (Cl, Ga, SK, SNO, Borexino)
- reactor $\bar{\nu}_e$ disappear at L~200 km (KamLAND)
- reactor $\bar{\nu}_e$ disappear at L~1 km (DC, Daya Bay RENO)

Experiments have demonstrated oscillation L/E pattern







matter effects can be probed in long-baseline experiments or extreme environments

Neutrino Mixing is Different

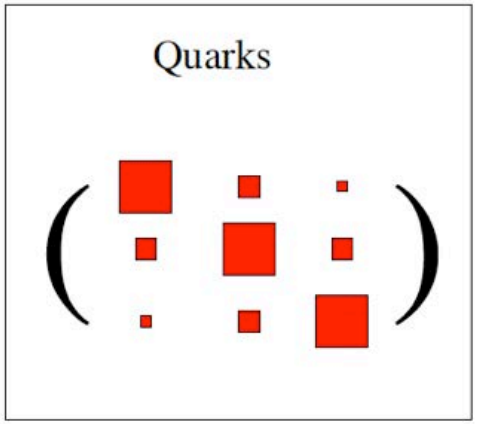
Mixing Angles

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

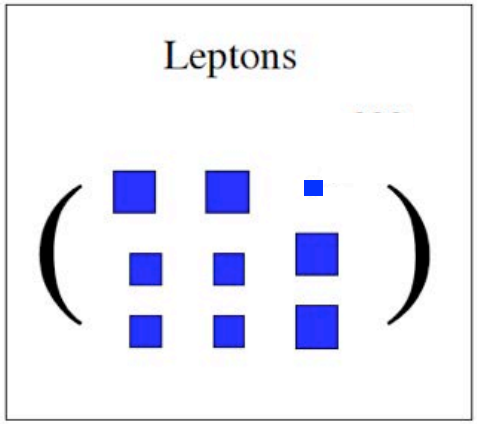
U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, reactor}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$



vs.



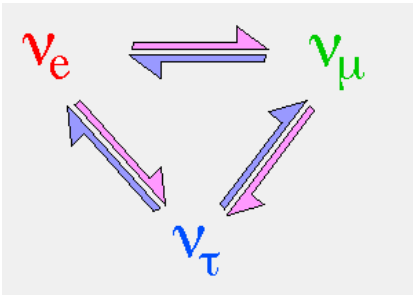
Neutrino Oscillation Measurements

Experiments provide complementary data

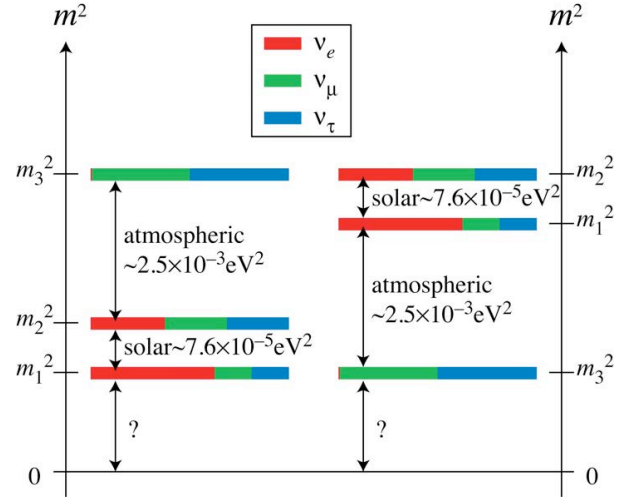
	Dominant	Important
Solar Experiments	$\rightarrow \theta_{12}$	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	$\rightarrow \Delta m^2_{21}$	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	$\rightarrow \theta_{13}$	$\Delta m^2_{\rm atm}$
Atmospheric Experiments	$\rightarrow \theta_{23}$	$\Delta m^2_{\rm atm}$, θ_{13} ,$\delta_{\rm cp}$
Accelerator LBL ν_μ Disapp (Minos)	$\rightarrow \Delta m^2_{\rm atm}$	θ_{23}
Accelerator LBL ν_e App (Minos,T2K)	$\rightarrow \delta_{\rm cp}$	θ_{13} , θ_{23}

Gonzalez-Garcia et al, ICHEP2012

Complete suite of measurements can over-constrain the 3-ν framework

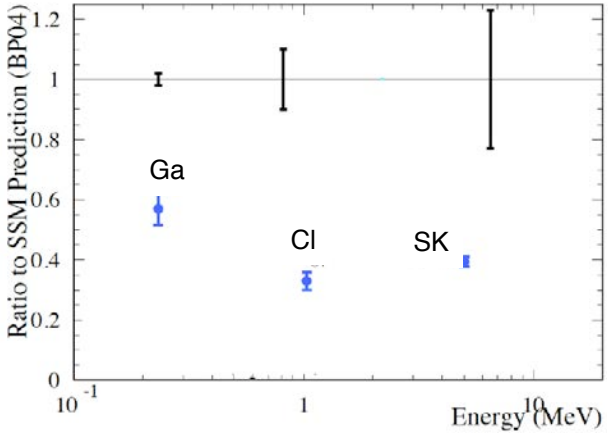


$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

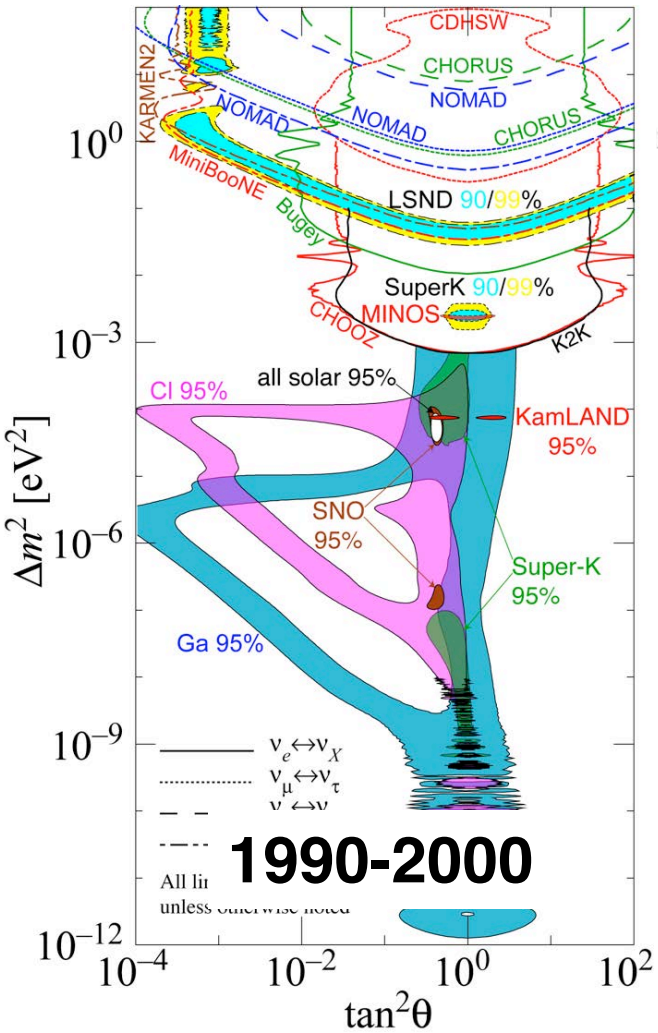


From Anomalies to Precision Oscillation Physics

solar neutrino problem

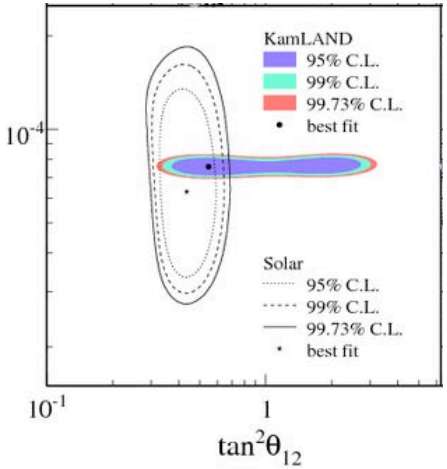


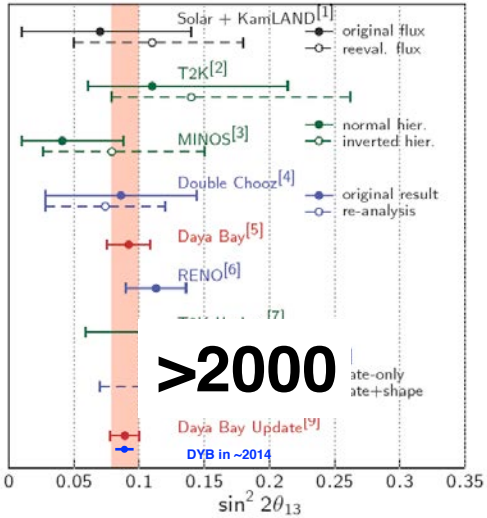
oscillation searches



http://hitoshi.berkeley.edu/neutrino

precision measurements





1960-1990

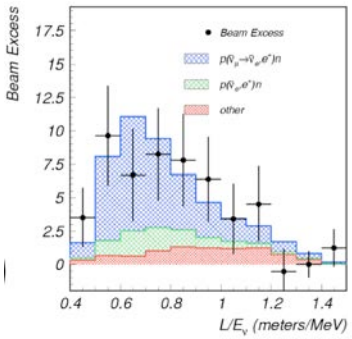
1990-2000

>2000

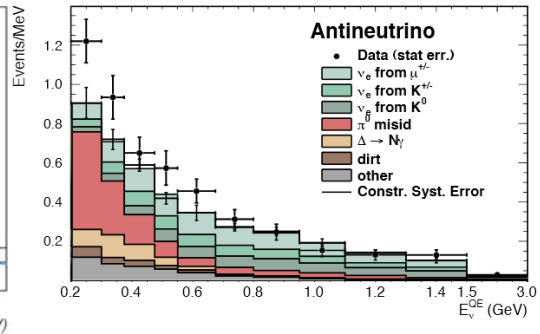
Recent Anomalies

Anomalies in 3-ν interpretation of global oscillation data

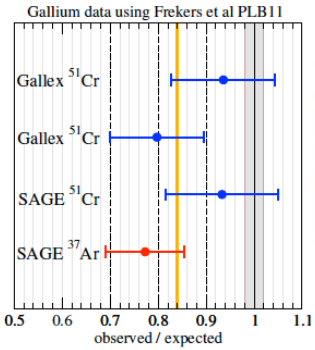
LSND



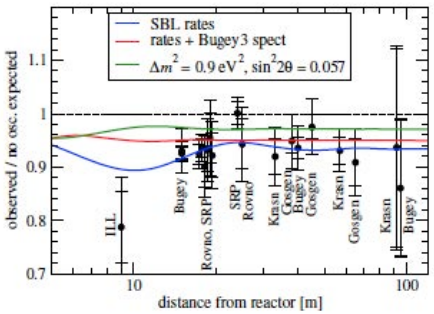
MiniBoone



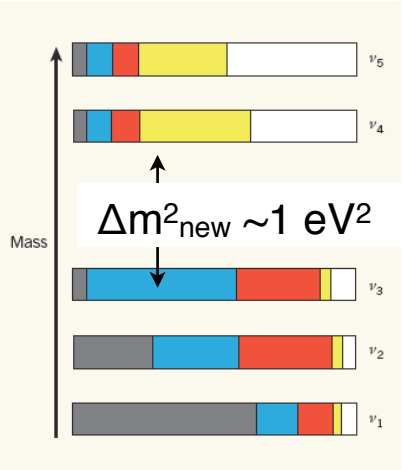
Ga Source



Reactor



LSND ($\overline{\nu}_e$ appearance)
MiniBoone ($\overline{\nu}_e$, ν_e appearance)
Ga anomaly (ν_e appearance)
Reactor anomaly ($\overline{\nu}_e$ disappearance)



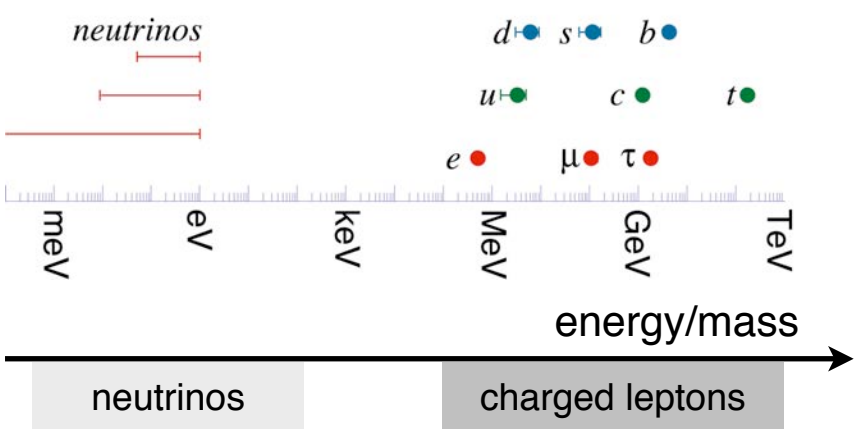
new oscillation signal requires $\Delta m^2 \sim O(1eV^2)$ and $\sin^2 2\theta > 10^{-3}$

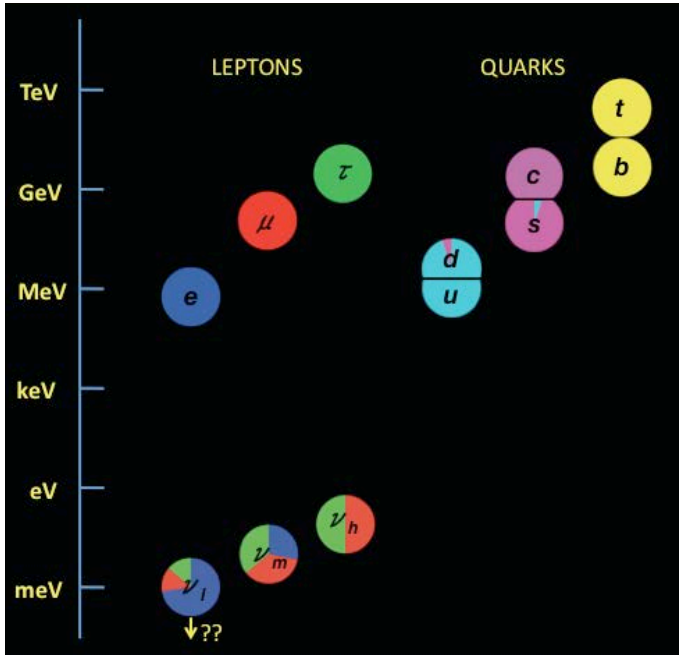
New physics or experimental artifacts?

Planning experiments with reactors, radioactive sources, and accelerators to confirm/refute short-baseline anomalies

Neutrinos - Open Questions

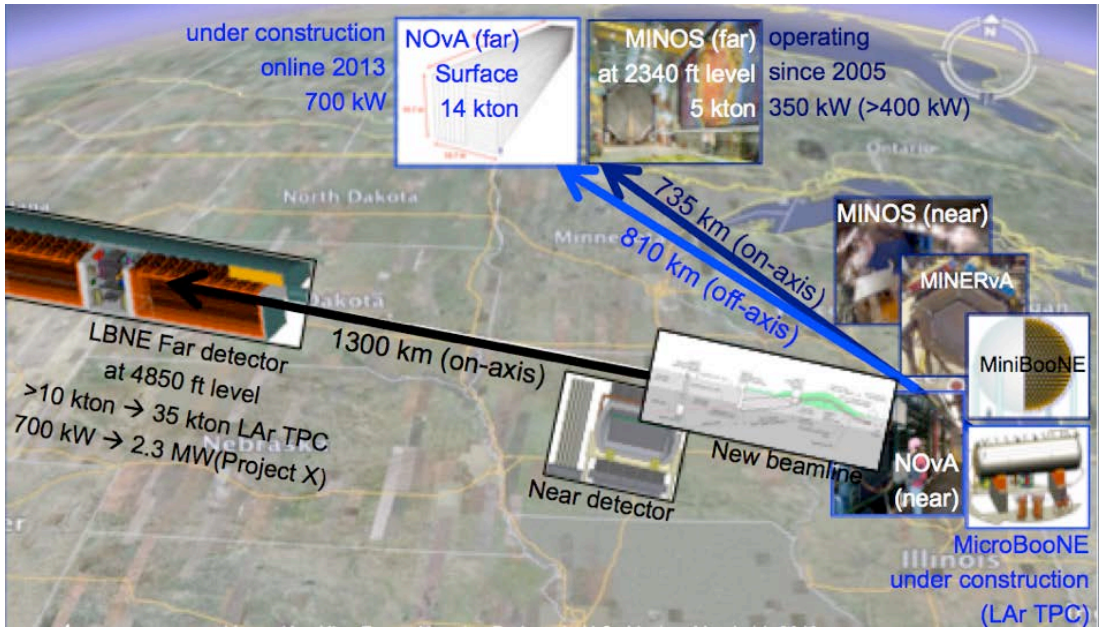
- Neutrino have mass, but why are they so light?
- What is the absolute mass scale?
- Do neutrinos have Majorana mass?
- Normal or inverted mass ordering?
- Is θ_{23} maximal?
- CP violation?
- Are there more than 3ν?





Precision Oscillation Measurements

Studying neutrino flavor change as a function of distance and energy

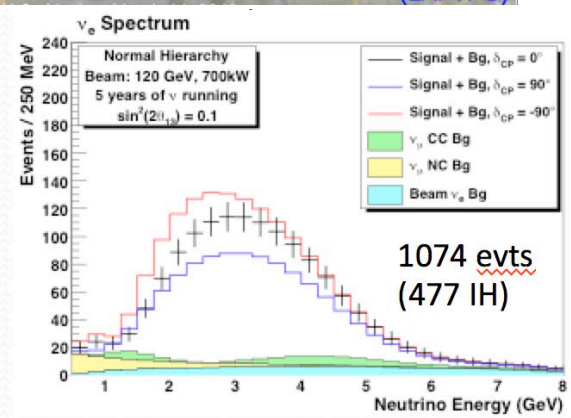


accelerator-based program over short and long baselines

measuring appearance and disappearance

Appearance

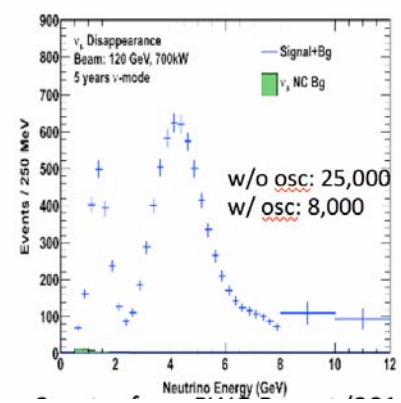
$\nu_\mu \to \nu_e$



Disappearance

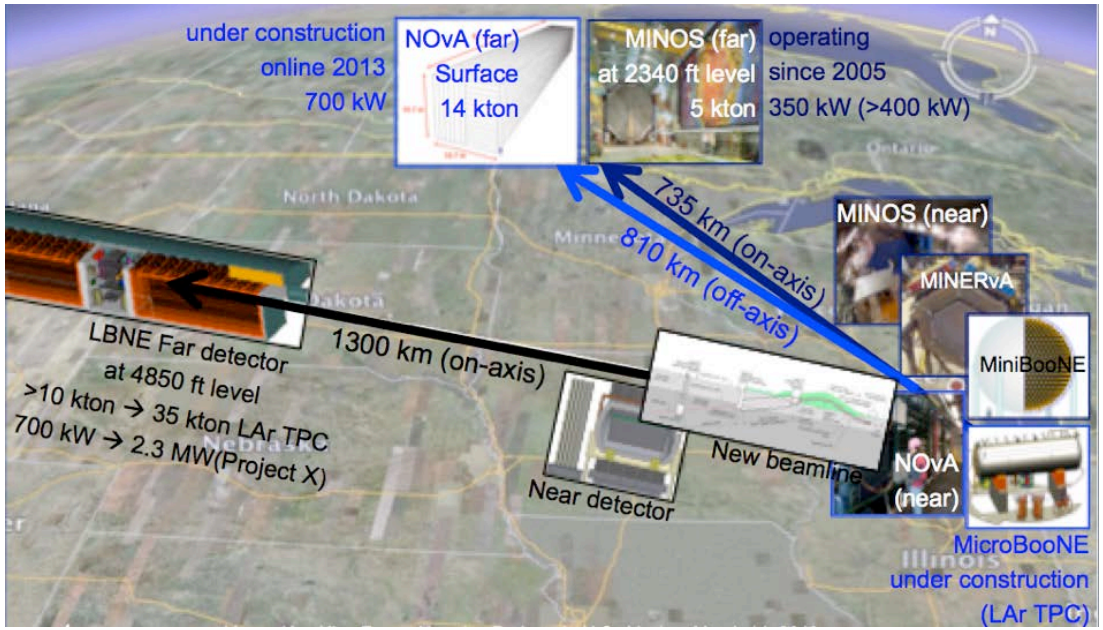
$\nu_\mu \to \nu_\mu$

LBNE 34kt, 5 yrs, ν



Precision Oscillation Measurements

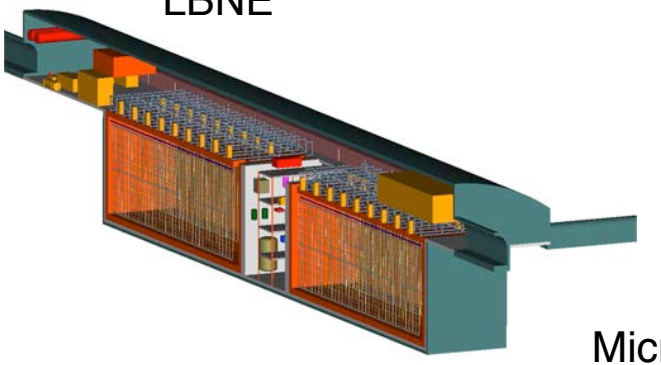
A staged program of experiments for the next decade

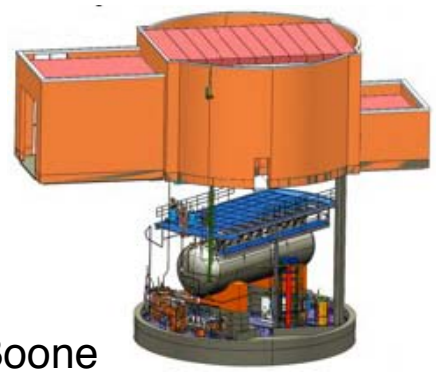


NOvA

MINOS+

LBNE





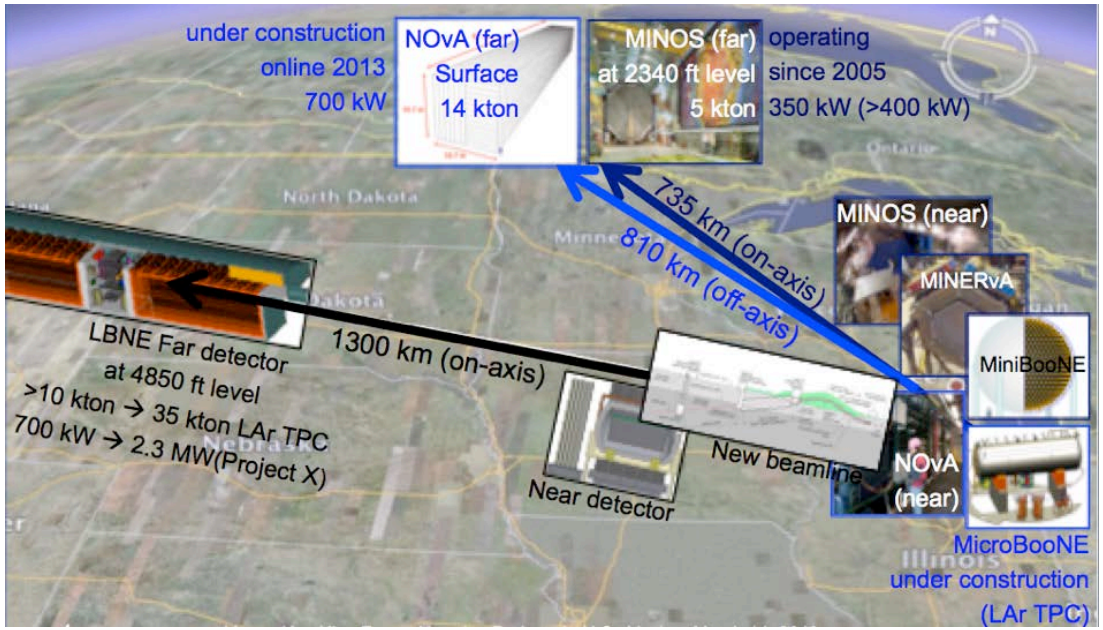
MicroBoone

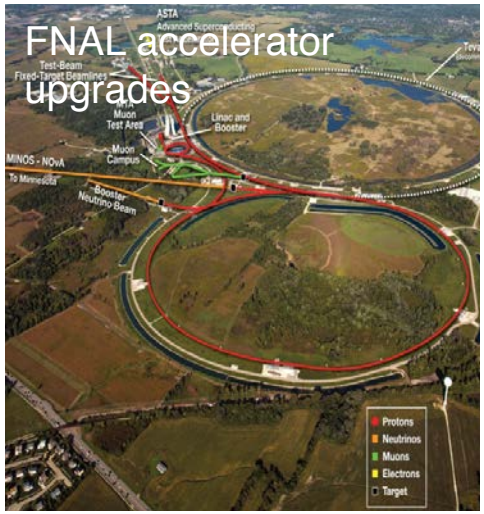
Minerva

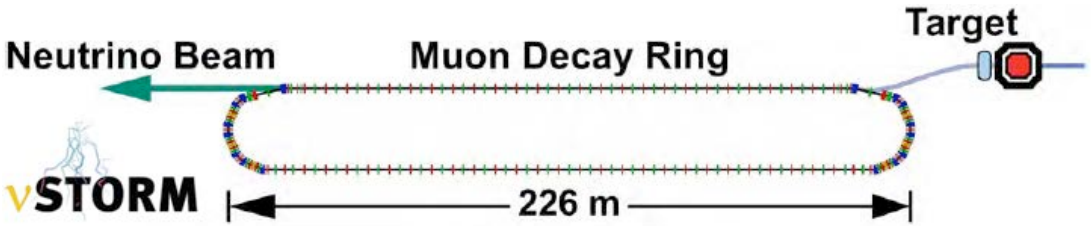
detectors at various scales

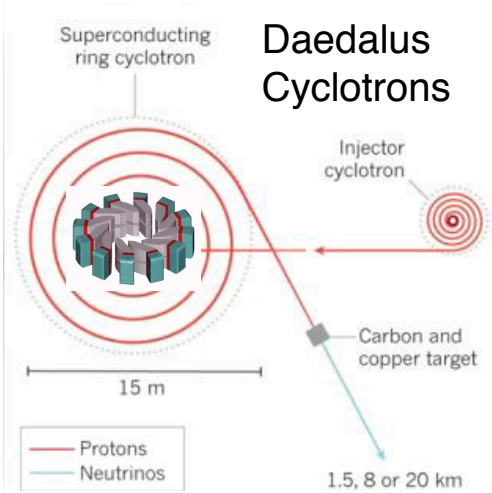
Precision Oscillation Measurements

A phased development of accelerator capabilities



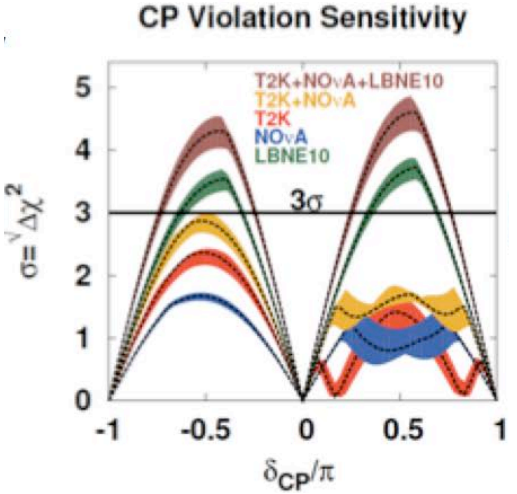


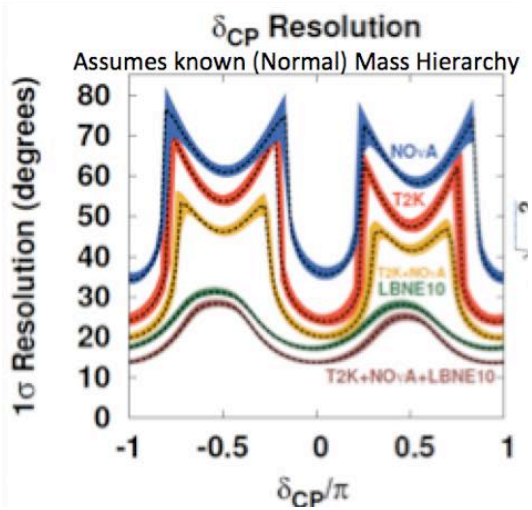


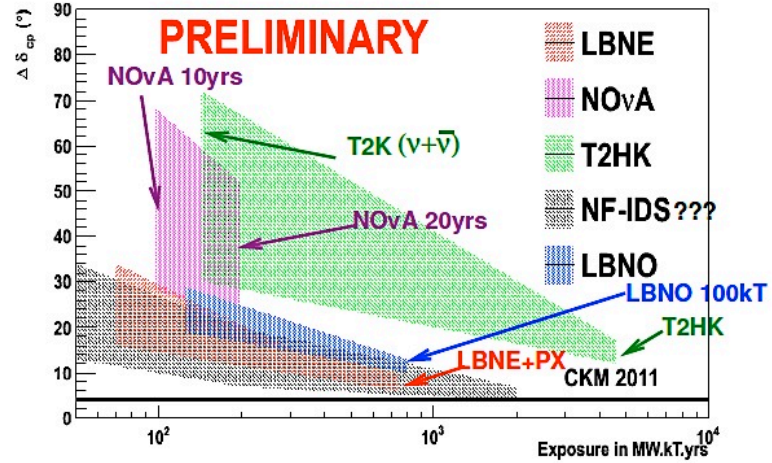


Precision Oscillation Measurements

Searching for CP violation

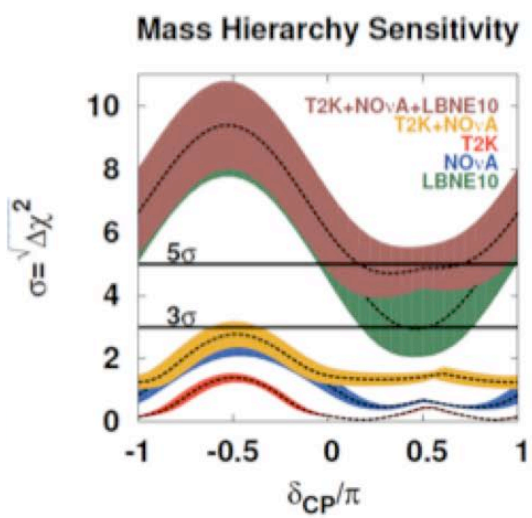




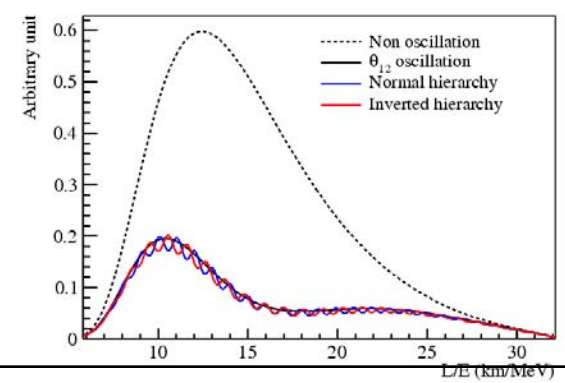


exposure of order of Mt.MW.yr, very long baseline (> 1000 km) and tight control of systematics (< 2% on signal) is needed to reach CKM level precision

Determining the mass hierarchy

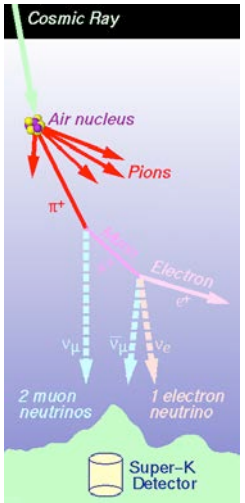


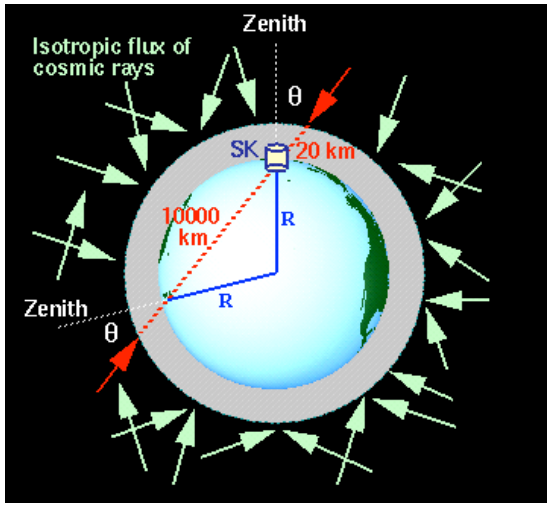
alternative approaches to mass hierarchy:
reactor experiments at ~50km baseline;
atmospheric neutrinos



Oscillation Physics with Atmospheric Neutrinos

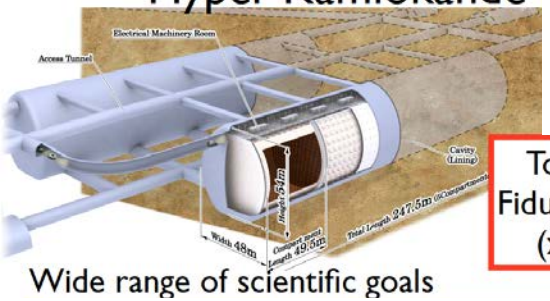
Atmospheric neutrinos observable in a large underground detectors are sensitive to all currently unknown oscillation parameters

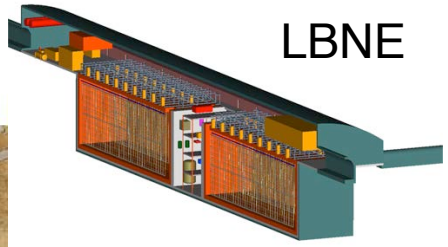




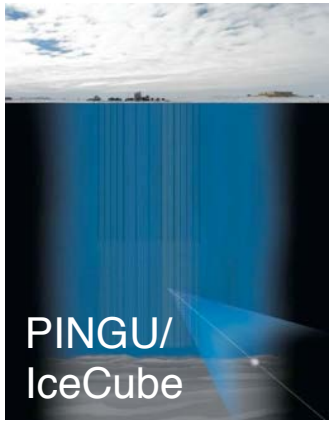
large underground detectors enable other physics, e.g. proton decay searches

multi-purpose detectors when placed in beam



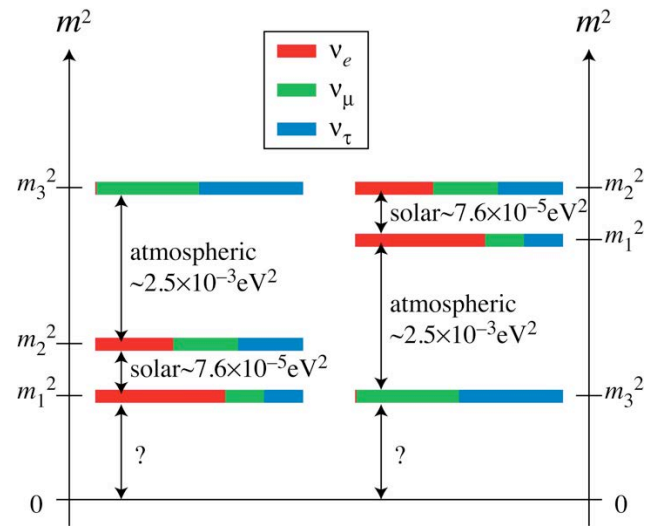


Total mass: 1Mton
Fiducial mass: 560kton
(x25 of Super-K)

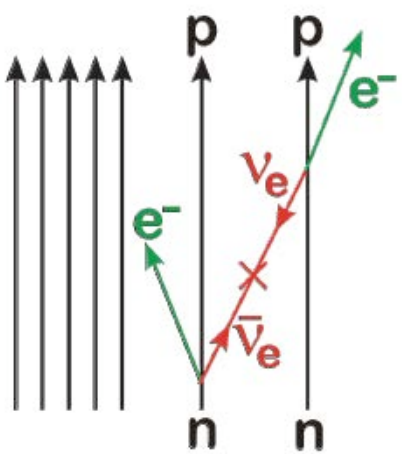


Importance of Mass Hierarchy

What is the flavor content of the lightest neutrino mass state?

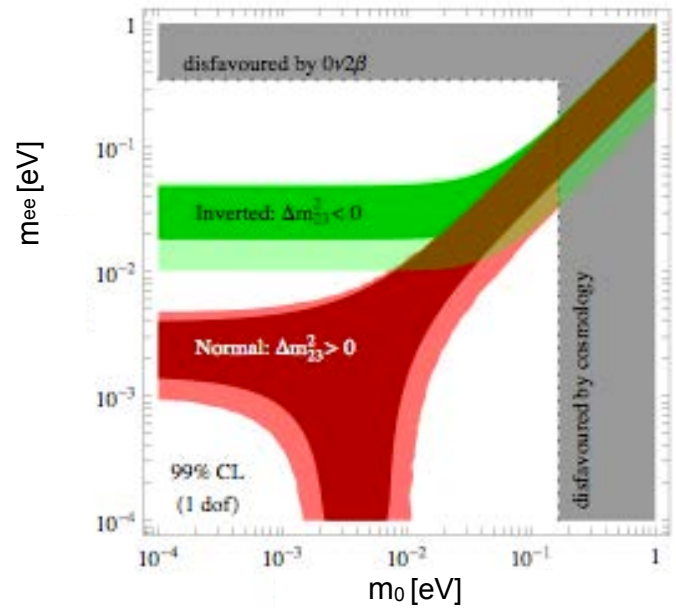


Knowing the mass hierarchy will help us understand the nature of neutrino mass from neutrinoless double beta-decay (0νββ).



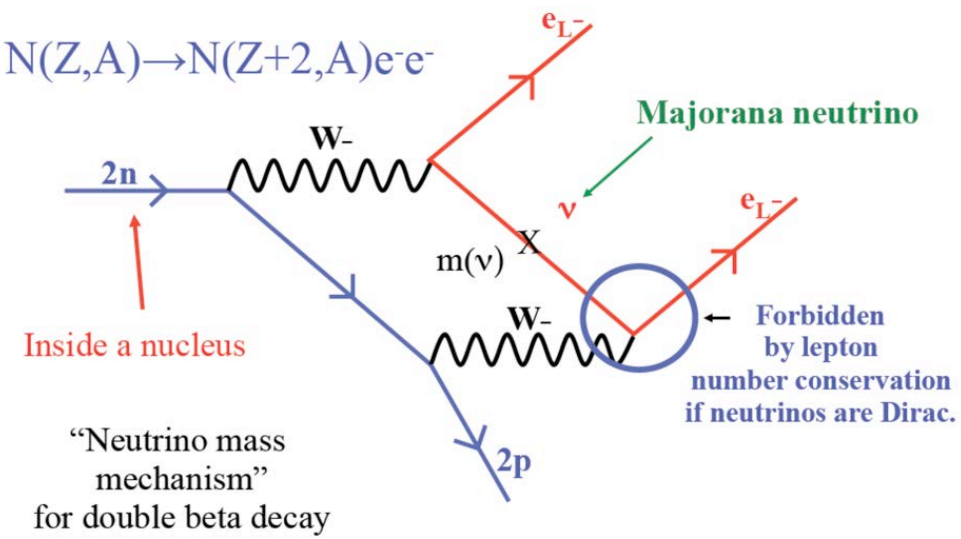
$$\Gamma_{0\nu} = G_{0\nu} \, | M_{0\nu} |^2 \left\langle m_{\beta\beta} \right\rangle^2$$

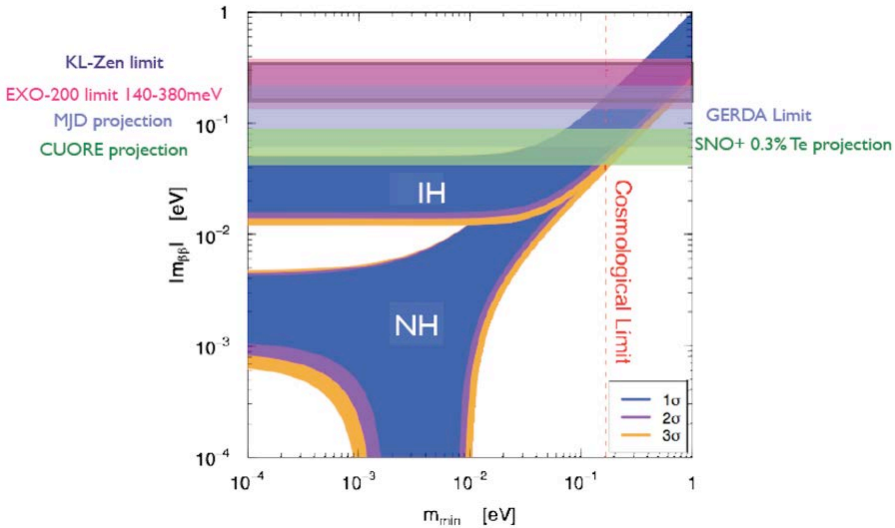
0νββ depends on effective neutrino mass



Majorana or Dirac Neutrino Masses?

Neutrinoless double beta decay is the only feasible experimental approach to establish Majorana mass of neutrinos





observation of $0\nu\beta\beta$ would imply
- lepton number non-conservation
- Majorana nature of neutrinos

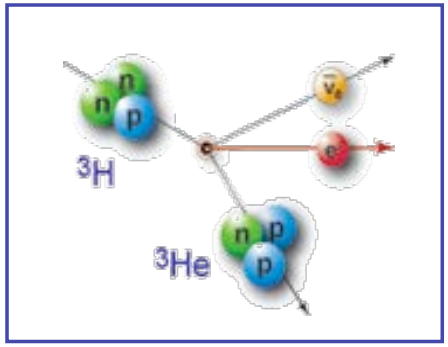
$0\nu\beta\beta$ allow us to determine
- effective neutrino mass

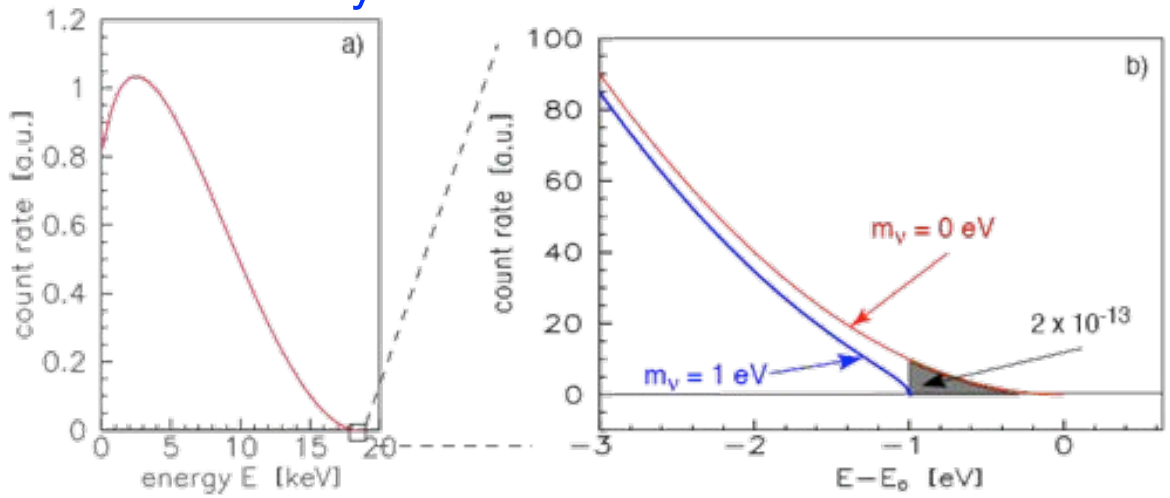
Several technologies feasible. Ready to explore the inverted hierarchy region.

Majorana neutrino mass = beyond SM physics

Absolute Neutrino Mass

Precision measurements of beta decay to determine absolute neutrino mass





$$\frac{dN}{dT} = \frac{G_F \cos\theta_C}{2\pi^3} |M_{\rm nuc}|^2 F(Z,T)(T+m)(T^2+2mT)^{1/2}(T_0-T)\sum_i |U_{ei}|^2 \left[(T_0-T)^2 - m_i^2\right]^{1/2}$$

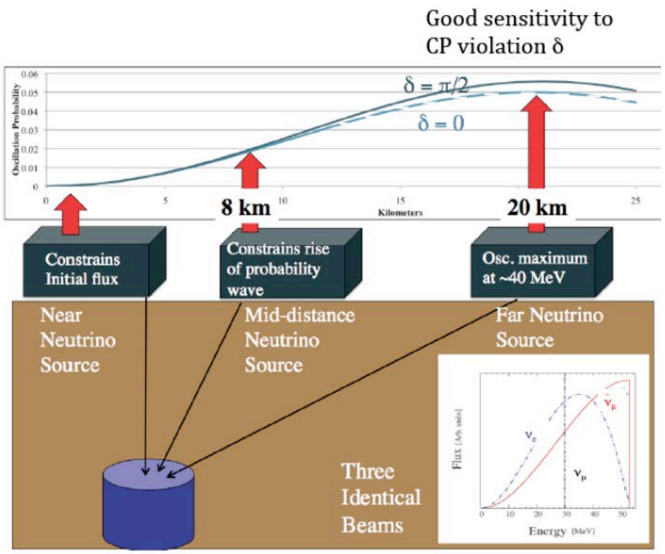
For $m_1 \gtrsim 100$ meV and no sterile neutrinos, the beta spectrum simplifies to an “effective mass”

$$m_\beta = \left[\sum_i |U_{ei}|^2 m_i^2\right]^{\frac{1}{2}}$$

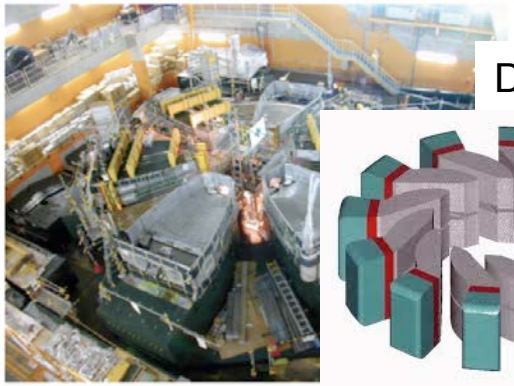
Smallness of neutrino mass may be related to GUT- or Planck-scale physics.

Synergies and Applications - Examples

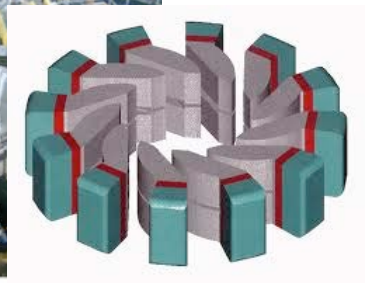
Cyclotrons for neutrino physics
(and industrial applications)



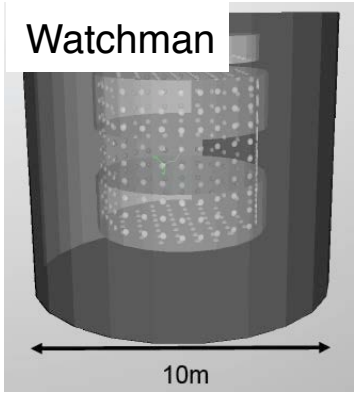
RIKEN K2600 SUPERCONDUCTING RING CYCLOTRON



Daedalus



Neutrino detectors for reactor monitoring and non-proliferation



remote discovery of undeclared nuclear reactors with large detectors at km scale

US Short-Baseline Experiment

reactor antineutrino studies at short baselines

Summary

- Recent discoveries have shown that neutrinos mix and have mass. Evidence for new physics.
- A staged program of neutrino oscillation experiments is underway to make precision measurements of oscillation parameters, test 3-flavor paradigm, and understand neutrino interactions.
- Historic anomalies have turned into discoveries of solar and atmospheric neutrino oscillations. Neutrinos may continue to surprise us!
- The nature of neutrino mass is not yet understood and may hold the clue to physics beyond the Standard Model.
- Synergies with instrumentation and technology developments; connections with other frontiers.

This is not a comprehensive summary. Apologies for any omissions.
Thanks to many colleagues for input, figures, and comments.

Tough Questions for Neutrinos & GUTs

- Several have been answered in the course of the three intro talks: (IF1, IF2, IF17…)
  - What are we testing by pushing proton decay limits?
  - What do we learn from measuring neutrino mixing parameters, and how well do we need to know them?
- We have selected several other Colloquium Questions (or sub-questions– sometimes rephrased for conciseness, or modified) to be addressed in micro-talks by the panelists.
- Will take ~2 questions from the floor per panelist
- After going through all questions, will open floor for general discussion

The Questions

- IF15: Should searches from proton decay be continued in absence of a signal? (Ed Kearns)
- IF10/13: What do CP δ measurements tell us about leptogenesis? (Boris Kayser)
- IF7: Is there an experimental floor to the search for neutrinoless double beta decay? (Josh Klein)
- IF5: How important is breadth of program? (Bonnie Fleming)
- IF7: What is the relative importance of testing the 3-flavor paradigm and exploring anomalies? (Steve Brice)
- IF11/12: What are the priorities and reach of LBNE? (Jon Urheim)
- G1: What are the interfaces with the CF? (Scott Dodelson)
- IF8: What should be the strategy beyond the next decade? (Ken Long)

IF15. Should searches for proton decay be continued in the absence of a signal? What are the benchmarks for limits on proton decay? Is there a point where such searches are no longer motivated?

Theoretical motivation is still profound:

BAU, quark-lepton charges, GUTs, running coupling constants

Many predictive models– not fine-tuned (mostly)

Experiment is achievable:

Hyper-Kamiokande is a straightforward scale up

We have a plan, and a growing community, for a massive LArTPC (e.g. LBNE)

Can be done as part of a multipurpose underground experiment

Benchmarks:

$e^+\pi^0$ – nearly model independent prediction of gauge unification

νK^+ – leading suspect if SUSY plays a role

Many other modes, but these are the benchmarks (experimentally and theoretically)

Experimental goal: exceed previous generation by order of magnitude (15-20 years)

$e^+\pi^0$ – few $\times 10^{35}$ years, νK^+ – many$\times 10^{34}$ years

Reaching these levels does not "rule out" GUT proton decay,

but is in the right territory for discovery and

if none is seen, further confounds a wide range of models.

The Connection Between Leptogenesis and the CP-Violating Phase δ_{CP}

The key ingredients of baryogenesis via leptogenesis are:

1. CP violation in the leptonic sector
2. Nonconservation of lepton number L.

The first would be estabished by finding that the leptonic CP-violating phase δ_{CP} is nonzero, and the second by observing neutrinoless double beta decay.

Leptogenesis is a very natural consequence of the See-Saw picture of why neutrinos are so light.

Owing to the See-Saw relation between high- and low-mass physics, generically, neutrino CP violation and leptogenesis imply each other.

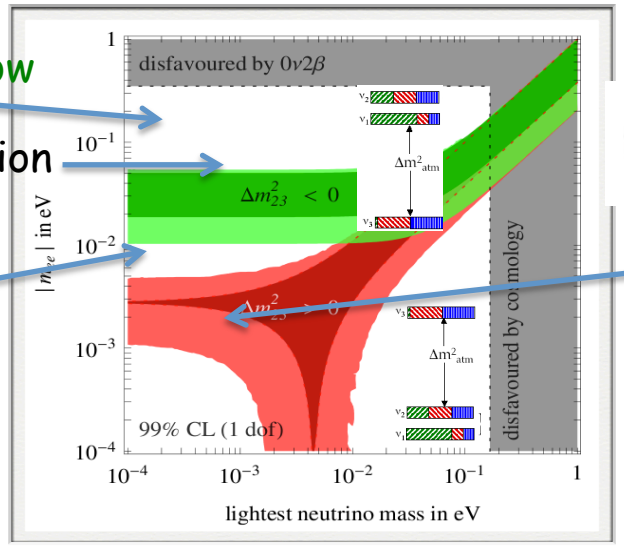
IF7. Is there an experimental floor to the search for neutrinoless double beta decay?

Short answer: Sure, depends on how much time and money you're willing to spend.

Where we are now

Under construction

"tonne-scale"



$$(T_{1/2,0\nu\beta\beta})^{-1} = G_{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

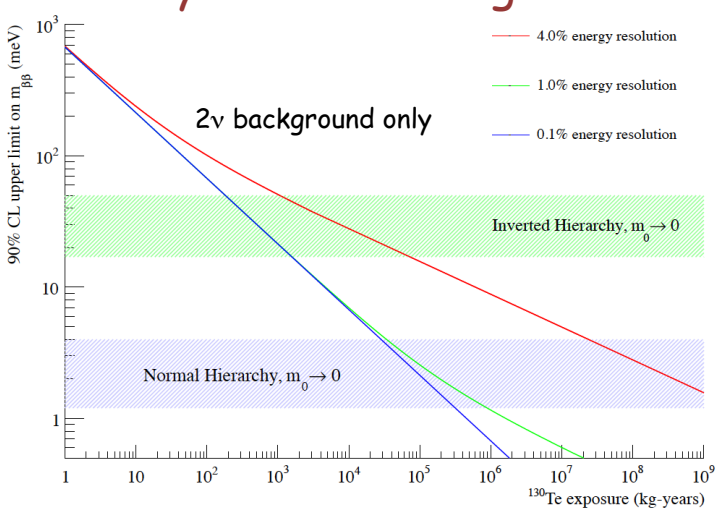
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

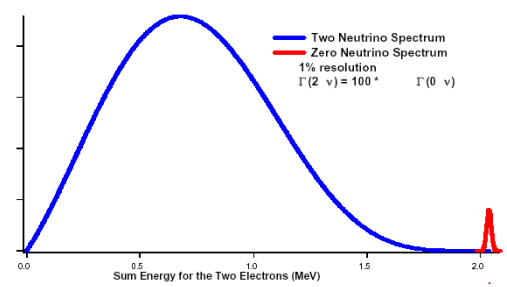
Probing Majorana neutrinos in the regime of the normal mass hierarchy

Steven D. Biller
Department of Physics, University of Oxford, Oxford OX1 3RH, UK
(published in Physical Review D, 071301R, 8 April 2013)

With enough work:

- Radioactive backgrounds can be reduced through purification and tagging
- Even solar neutrinos can be removed through tracking or tagging
- But you can never get around 2ν background:





There may be a tradeoff between achievable mass and achievable resolution.

A. Mastbaum, S. Seibert

IF5. How important is breadth of program for the next-generation neutrino oscillation experiments? If important, how can this be achieved?

Breadth in program = Breadth and depth in physics discovery

What is breadth?

- Complementary techniques to address the physics
  - Different detector technologies (eg: LAr and WCh)
  - Different baselines, different beams
- A variety of physics to address with the same experiments
  - Underground adds proton decay, astrophysical and atmospheric neutrinos, …
  - Near detector physics for oscillations and cross sections

What does breadth give you?

- Comprehensive approach to understanding neutrinos
- Broad program beyond neutrinos
- Enables:
  - Large and small experiments (Range cost and timescale)
  - Program with many Ph.D results!

IF6. What is the relative importance of testing the 3-flavor neutrino paradigm and exploring anomalies?

1. We are charting new territory in neutrino physics and must search all regions available to us
   - Measure 3 flavor mixing parameters
   - Check the validity of the 3 flavor paradigm
   - Be constantly alert for surprises
   - Follow up decisively on anomalies

2. If you pick a fertile region you may make unintended discoveries, but we must devote resources in proportion to the *a priori* likelihood and significance of discovery

3. We have to be able to respond to surprises and reprioritize accordingly

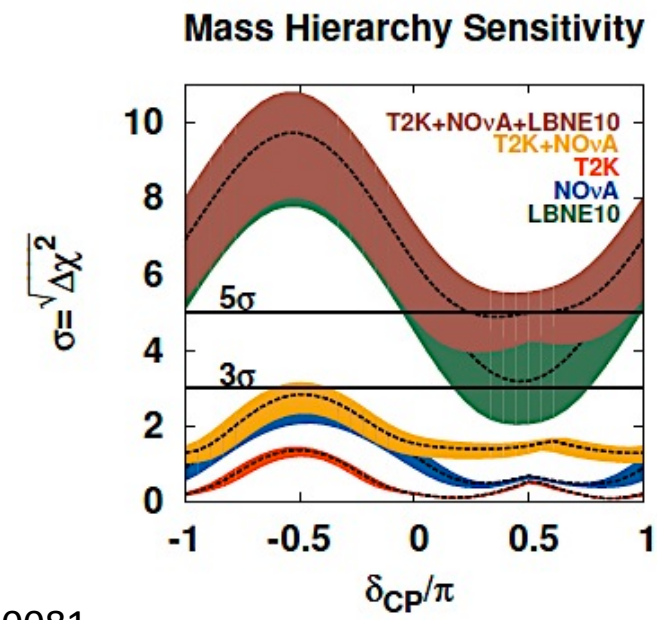
IF 12: In the current configuration for Phase-I of LBNE (assuming no new international support), what 5-sigma discoveries are possible ?

1) LBNE Phase-I will constitute a decisive step for the U.S. particle physics program.
   - Fully realized, LBNE (34kt, underground) is a bold experiment aiming to address a broad array of key questions in particle physics, including leptonic CPV, neutrino MH, tests of 3-flavor mixing picture, searches for proton decay, studies of supernova neutrinos, and precision neutrino interaction measurements, exploiting the cost-effectiveness, scalability, and exquisite capabilities of the LArTPC technology. Its design is mature and costs are well understood.
   - **The first phase will be the enabler for this program.**

2) Strong support from international partnerships is emerging,
   - examples: India (near detector), UK (STFC), Italy (INFN – Icarus), Europe/LBNO, Brazil

3) We can discover the mass hierarchy
   - Signficance > 5σ, LBNE alone, if δ_{CP} has the right sign
     > 5σ, everywhere with LBNE+ NOvA/T2K

4) CP Phase Resolution & Establishing CPV
   - Extended reach in phase-I → δ_{CP} to 15-30°.
   - 3σ to just under 5σ for CPV significance for favorable δ_{CP}



See "Science Opportunities w/ LBNE", arXiv:1307.7335, SNOW13-00081.

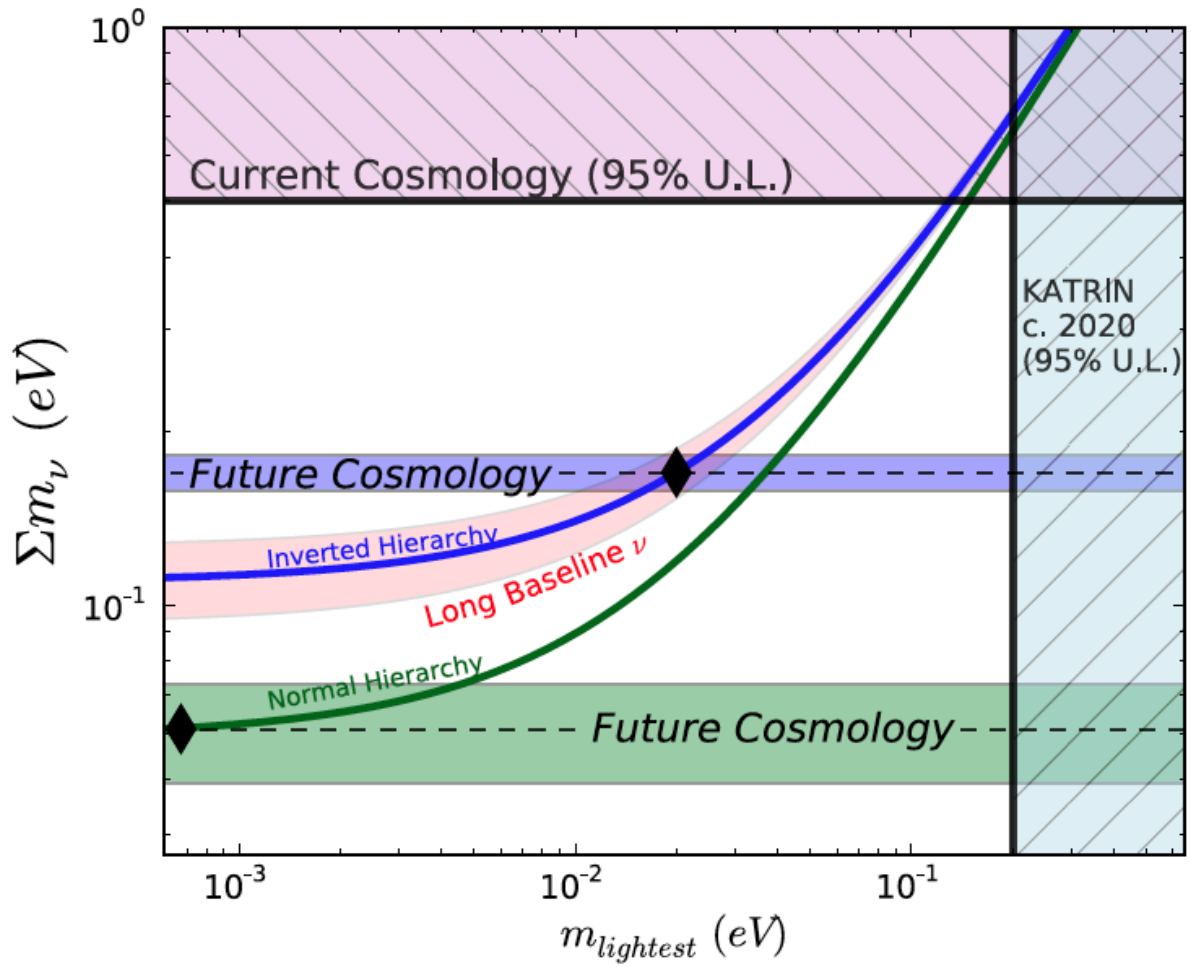
IF 11: If additional resources can be found to restore some of the LBNE scope, what is the highest scientific priority: moving underground, or improving beam and/or detectors ?

- Already have heard comments on:
  - Importance of the breadth of the program
  - Discovery potential in non-beam physics (e.g., proton decay, supernova & atm. ν's)
  - Example: expect ~900 ν_e events in 10kt LArTPC from SN explosion at 10 kpc.
- Moving underground provides infrastructure for further detector expansion at the right baseline & depth for full LBNE program
- Strong consensus within LBNE collaboration to go underground as highest priority given additional resources from new domestic/international partners.
- Potential European partners agree w/ collaboration's goal, namely that LBNE FD should be <u>underground</u> and <u>larger</u> **in the first phase.**
- Geotechnical studies are now being carried out for the underground site, in anticipation of this.

G1. How do we exploit science opportunities at the interfaces between the Frontiers?

<u>Complementarity:</u>

- Oscillation experiments sensitive to mass differences → we live along either blue or green line
- Cosmology experiments sensitive to sum of the masses → where are we on the line
- Long baseline determination → which line we live on
- Anomalies on either or both frontiers could point to a sterile sector



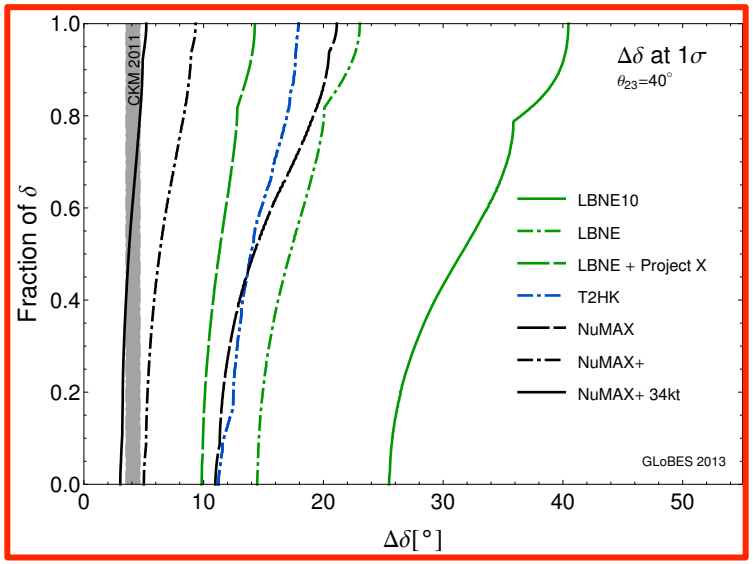
Neutrino strategy beyond the next decade?

- **Neutrino strategy must include search for 0ν2β and search for sterile neutrinos;**
  - **Comments below confined to strategy for oscillations**

- **Beyond the next decade; > 2023:**
  - **i.e. the LBNE (T2HK) era**
    - **The mass hierarchy will be "on the way to being determined"**
    - **First scan of CP-violation underway**
    - **Sterile-neutrino searches underway**
      - **Changes development of field if discovered!**

So, must make detailed, precise measurements to confirm the SvM establish deviations from it: discovery of entirely new phenomena

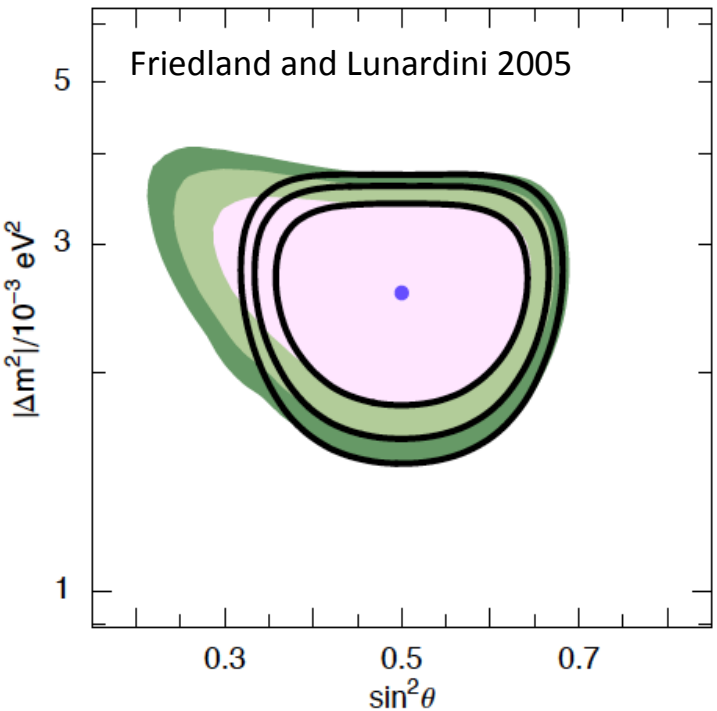
- **The Neutrino Factory is capable of performing "at the quark level":**
  - **Best discovery reach, best precision**
  - **Need to:**
    - **Demonstrate that a muon-accelerator-based facility can serve neutrino science;**
    - **Prove *ionization cooling* technique**



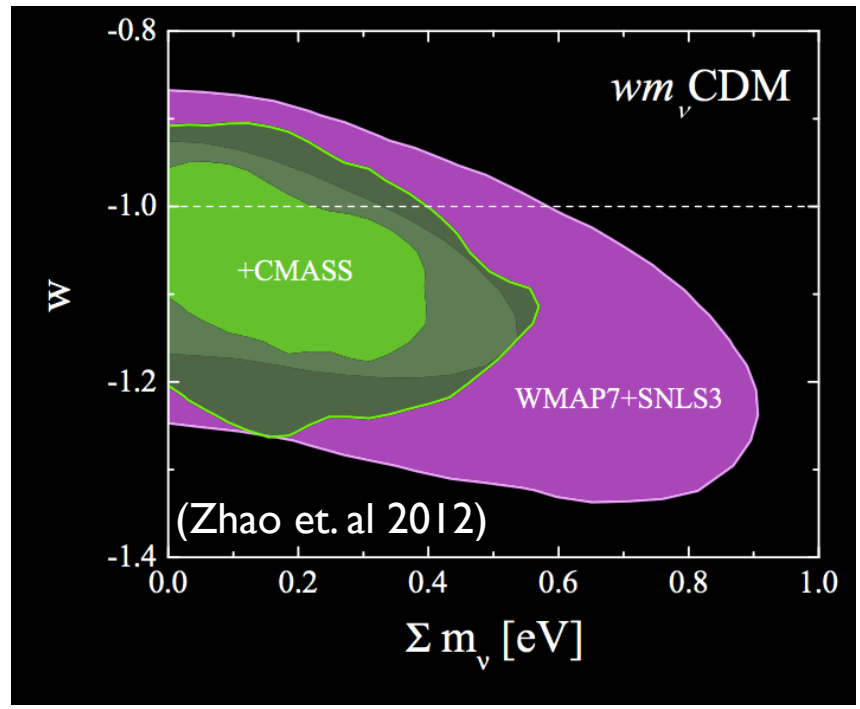
- **So, oscillation strategy must encompass:**
  - **Full exploitation of LBNE (and T2HK):**
    - **Includes programme by which systematic errors are reduced**
  - **Incremental development of muon-accelerator-based facilities for neutrino science:**
    - **nuSTORM:**
      - **Exquisite sensitivity to sterile neutrinos**
      - **Detailed and precise study of ν_e-*N* scattering required to allow LBNE (T2HK) programme to fulfill its potential**
      - **Test-bed for next increment**
    - **Demonstration of ionization cooling (MICE)**
  - **Active review of potential of alternative techniques (cyclotrons, CERN, ESS, etc.) and new results (e.g. sterile neutrino searches, long-baseline ν_e-appearance measurements)**

Backups

Priors



Constraints on neutrino parameters degrade when NSI allowed



Constraints on neutrino parameters degrade when Dark Energy freedom allowed