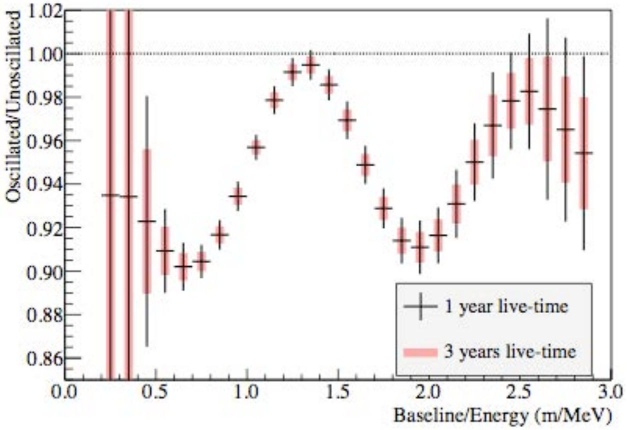
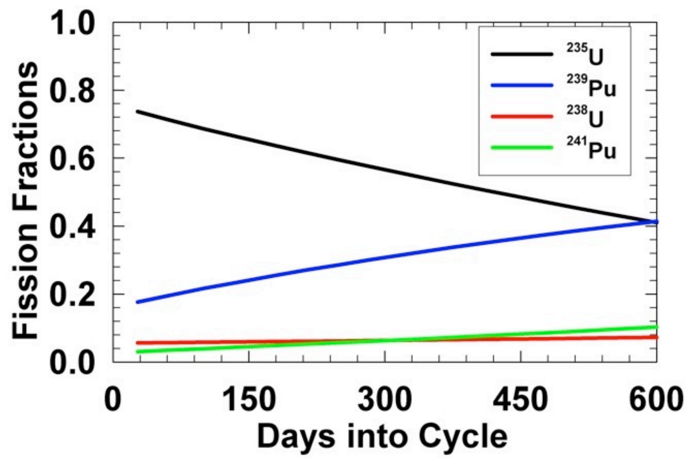
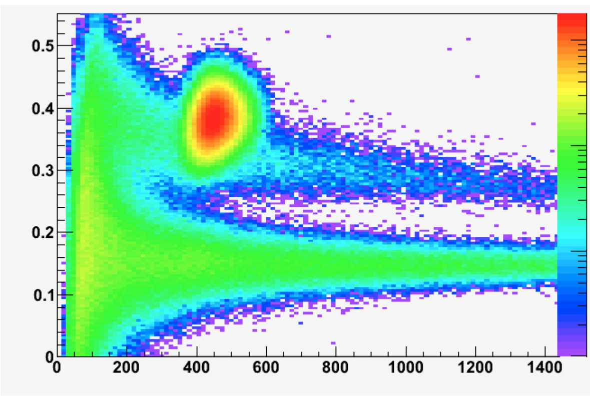
Neutrino Oscillations, Nuclear Safeguards, and Advanced Detector Development with Reactor Antineutrinos







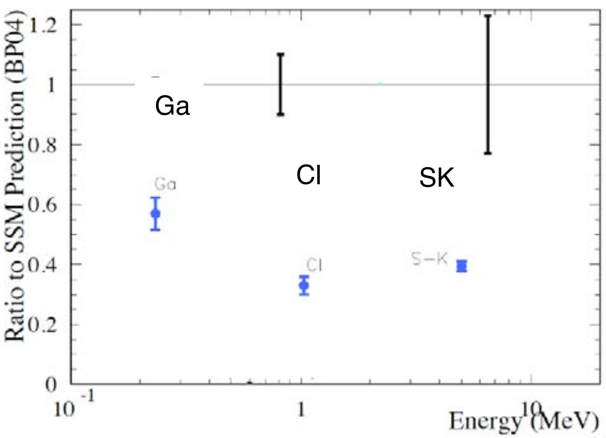
Karsten Heeger
University of Wisconsin

BNL, March 29, 2013

Towards Precision Neutrino Physics

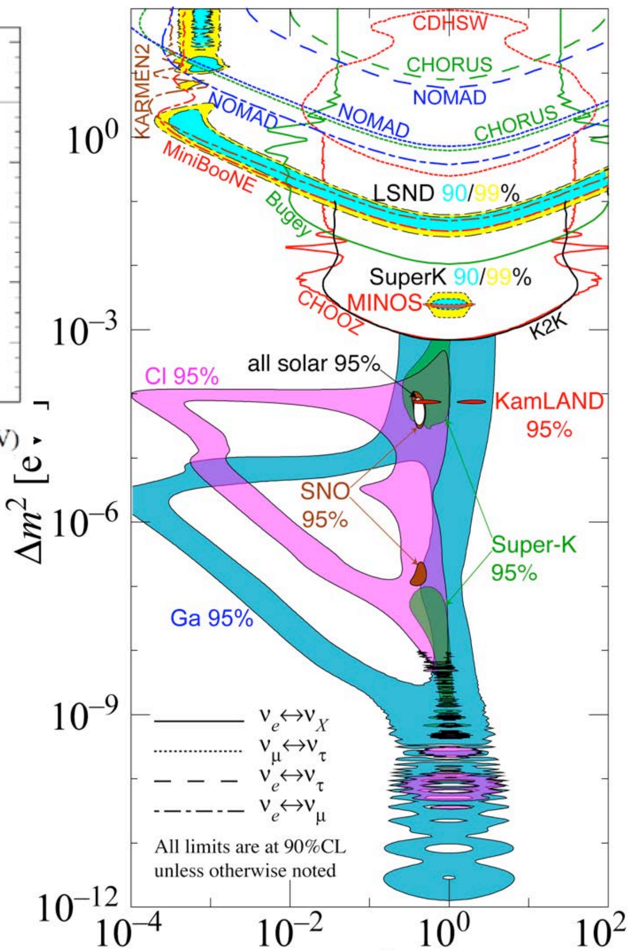
solar neutrino problem

1960-1990



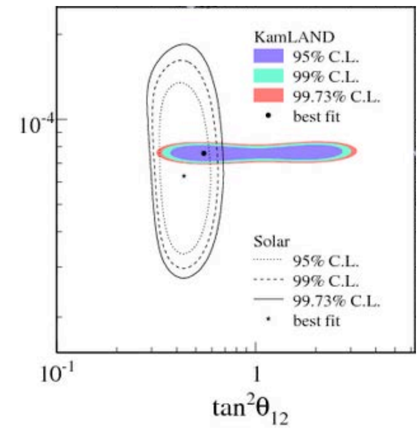
oscillation searches

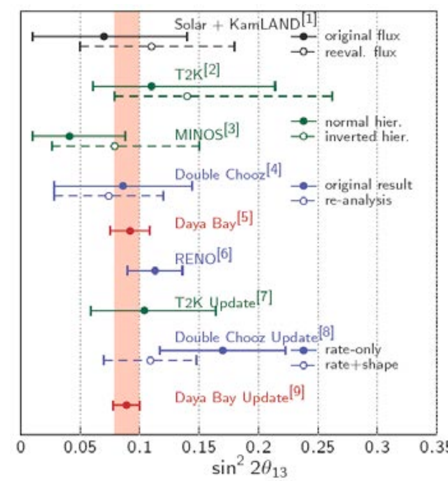
1990-2000



precision measurements

2000 - Present



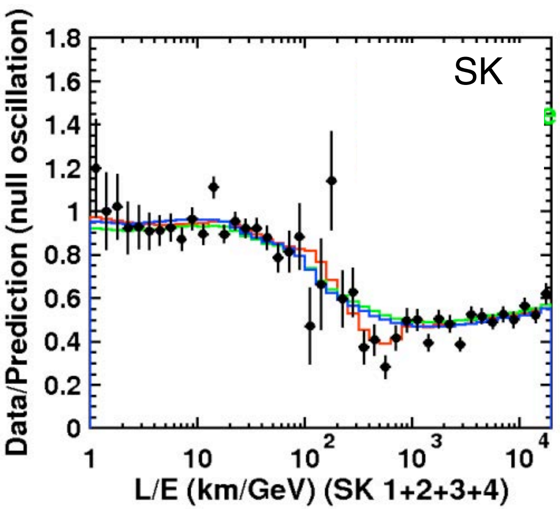


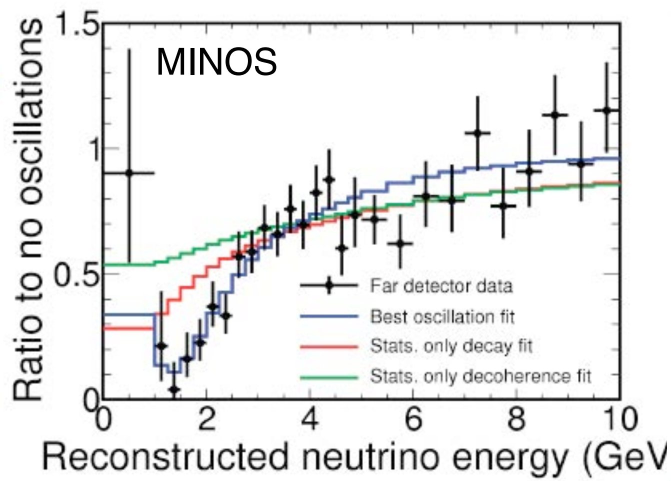
Anomalous results have led to a field of precision oscillation physics

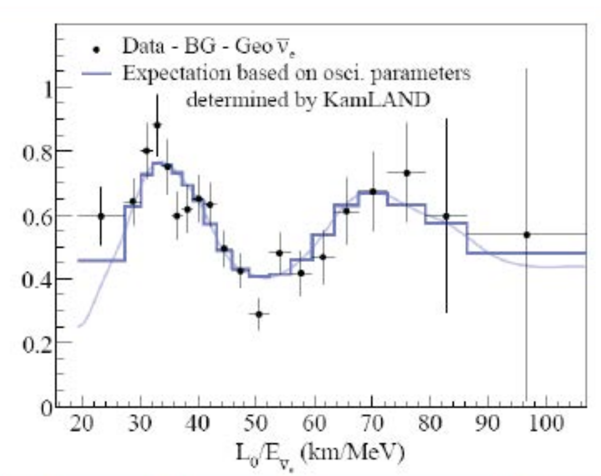
Neutrino Oscillation Measurements

Recent Observations

- 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)
- some accelerator ν_μ appear as ν_μ 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 vacuum oscillation L/E pattern

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

Neutrino Oscillation Measurements

Recent Observations

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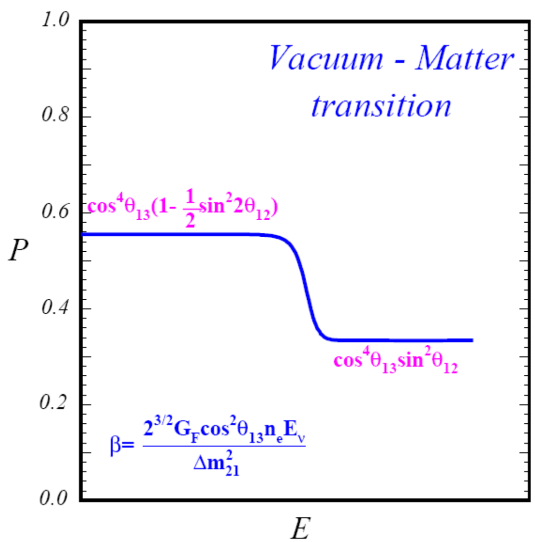

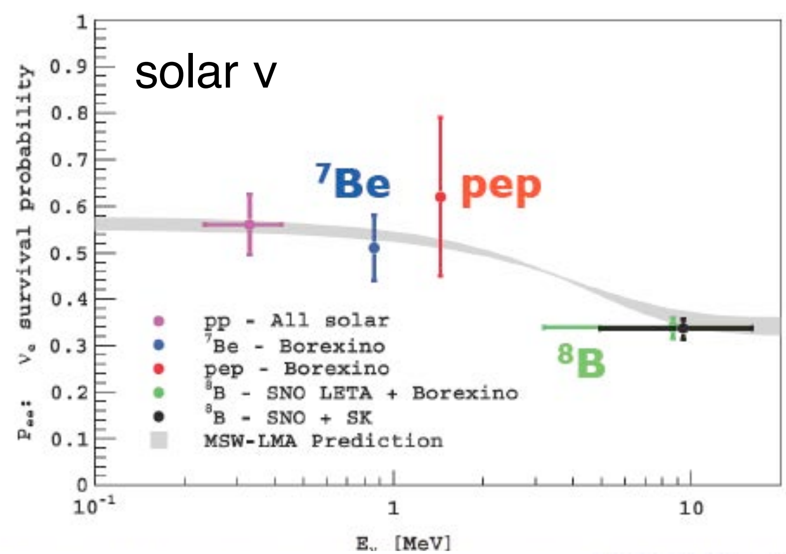

Vacuum to matter transition (MSW conversion) in Sun has been observed

Neutrino Oscillation Measurements

Recent Observations

- 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)
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- reactor $\bar{\nu}_e$ disappear at L~1 km (DC, Daya Bay RENO)

	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)	$\rightarrow \theta_{13}$	Δm^2_{atm}
Atmospheric Experiments	$\rightarrow \theta_{23}$	Δm^2_{atm}, θ_{13} ,δ_{cp}
Accelerator LBL ν_μ Disapp (Minos)	$\rightarrow \Delta m^2_{\text{atm}}$	θ_{23}
Accelerator LBL ν_e App (Minos,T2K)	$\rightarrow \delta_{\text{cp}}$	θ_{13} , θ_{23}

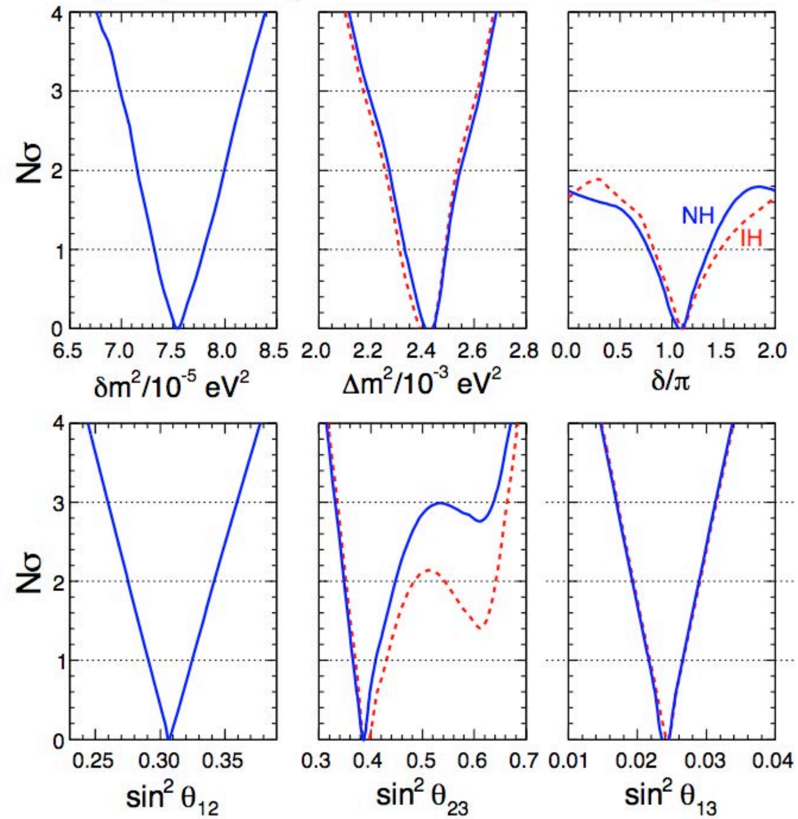
Gonzalez-Garcia et al, ICHEP2012

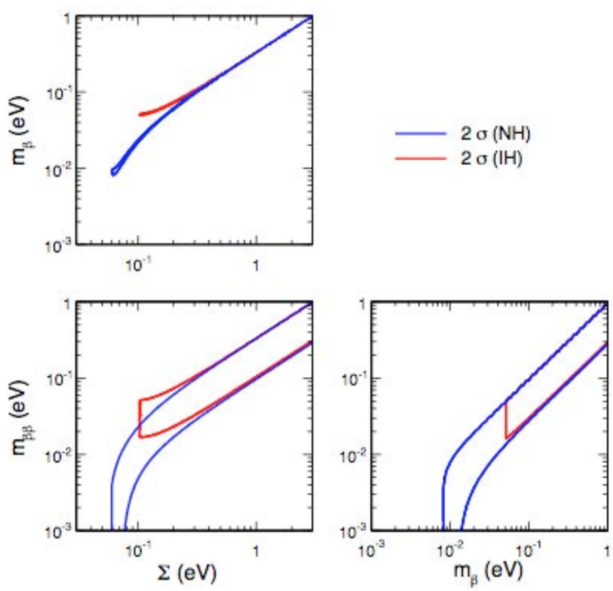
complete suite of measurements can over-constrain the 3-ν framework

Neutrino Oscillation - 2012

3-ν Global Analyses

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49		
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49		
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66		
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67		
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10		
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31		
δ/π (NH)	1.08	0.77 – 1.36		
δ/π (IH)	1.09	0.83 – 1.47		

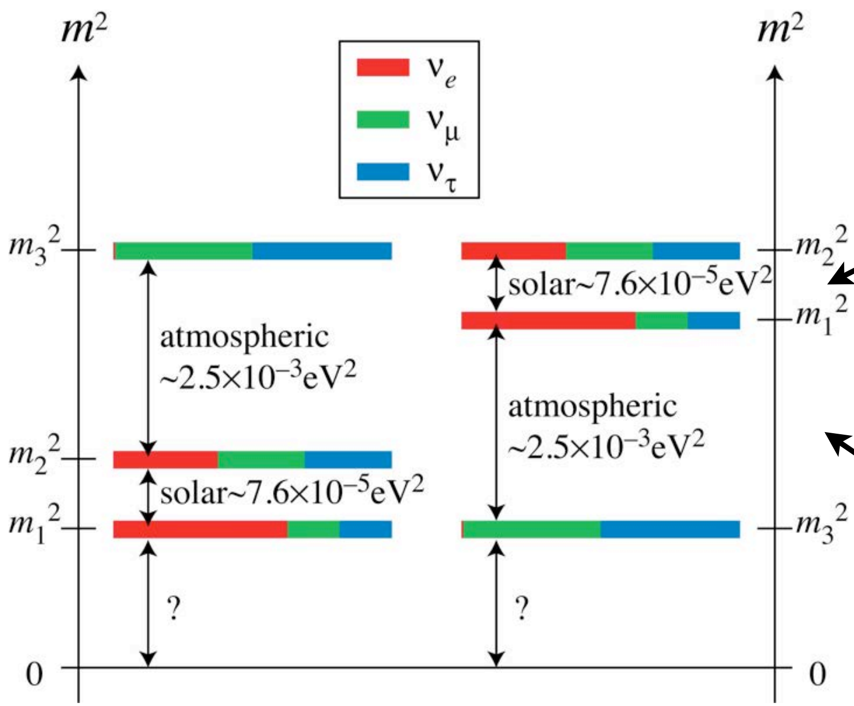




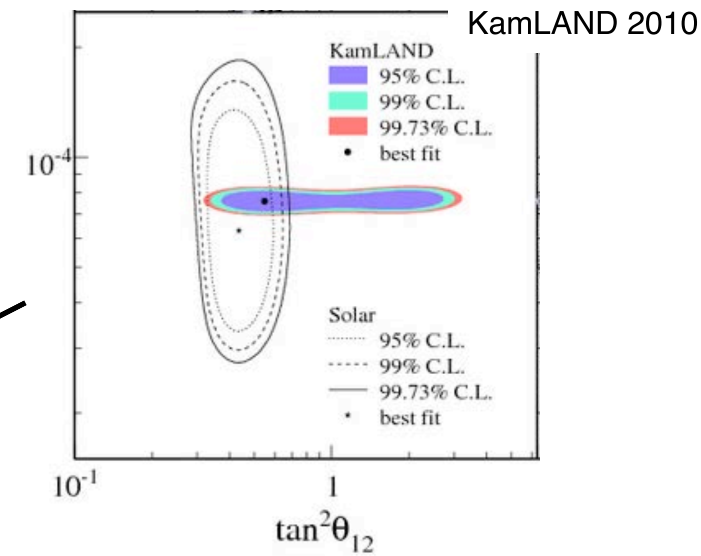
Ref: Fogli et al
1205.5254 and Nu2012

Measurement of Fundamental Parameters

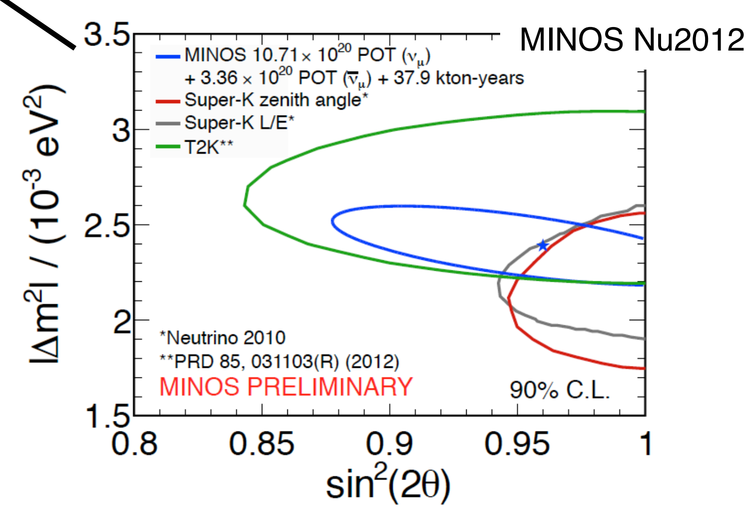
Mass Splittings



normal inverted



KamLAND has measured Δm_{12}^2 to ~2.8%



Reactor Neutrinos

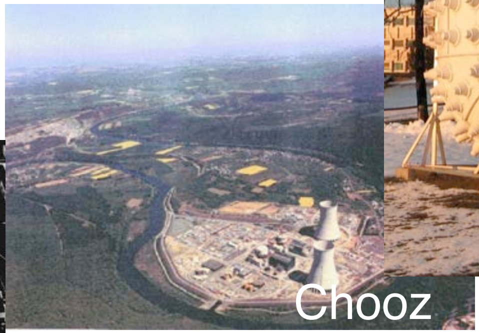
2012 - Measurement of θ_{13} with Reactor Neutrinos

2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe



1956 - First observation of (anti)neutrinos

Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

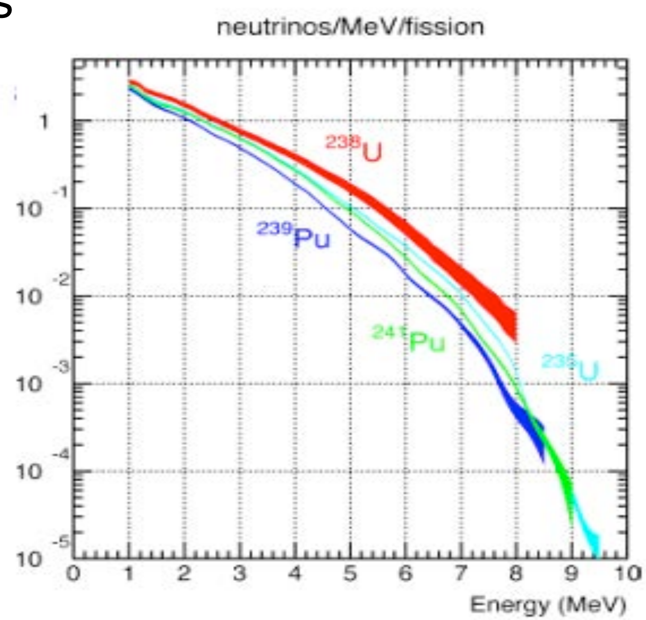
55 years of liquid scintillator detectors
a story of varying baselines...

Reactor Antineutrinos

Source

$\bar{\nu}_e$ from β-decays

of n-rich fission products



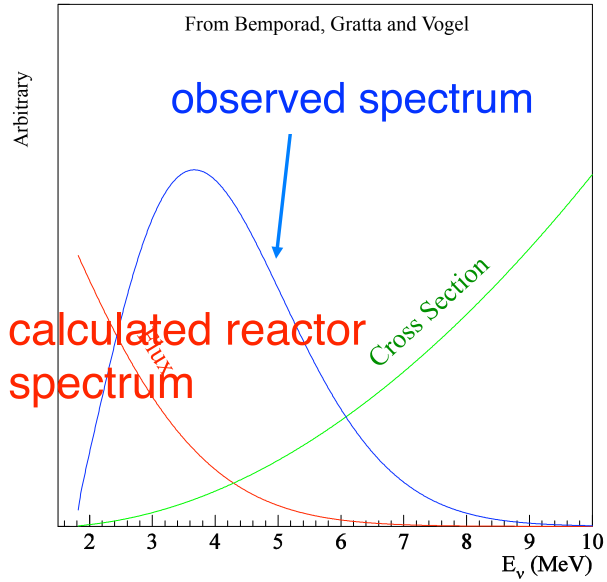
pure $\bar{\nu}_e$ source

> 99.9% of $\bar{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Detection

inverse beta decay

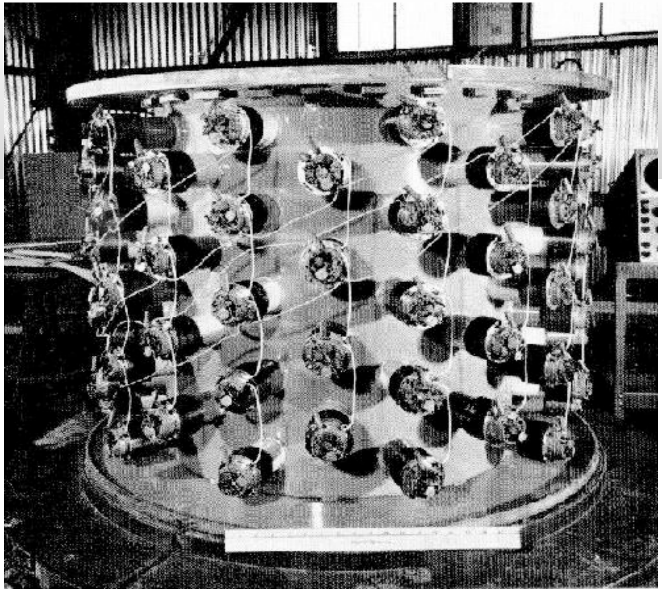
$\bar{\nu}_e + p \rightarrow e^+ + n$



mean energy of $\bar{\nu}_e$: 3.6 MeV

only disappearance experiments possible

Hanford Experiment

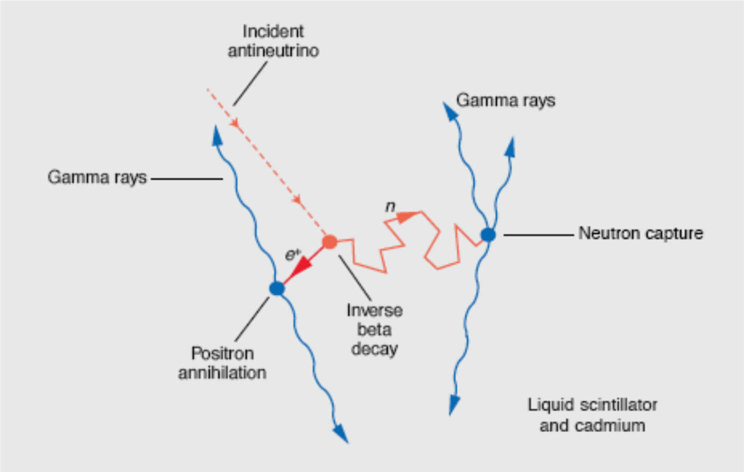


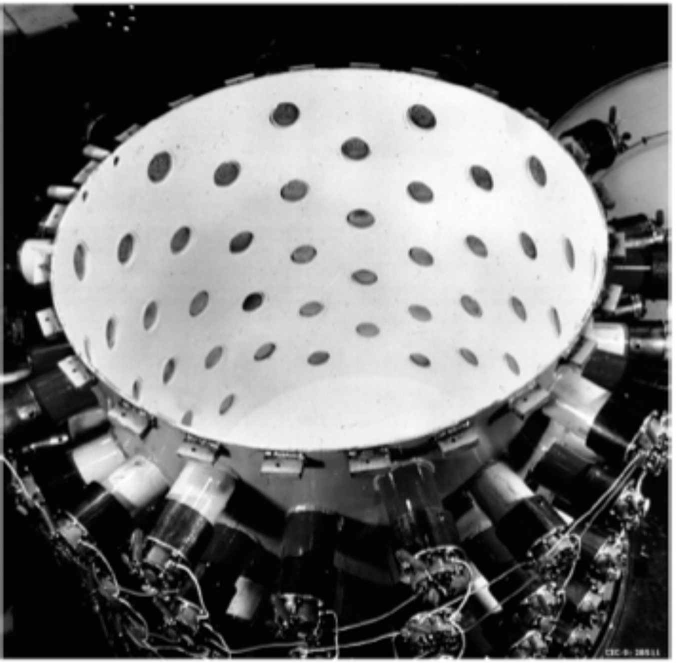
Reines, Cowan

inverse beta decay

$\bar{\nu}_e + p \rightarrow e^+ + n$

300 liters of liquid scintillator loaded with cadmium





signal: delayed coincidence between positron and neutron capture on cadmium

0.41+/- 0.20 events/minute

high background (S/N ~ 1/20) made the experiment inconclusive

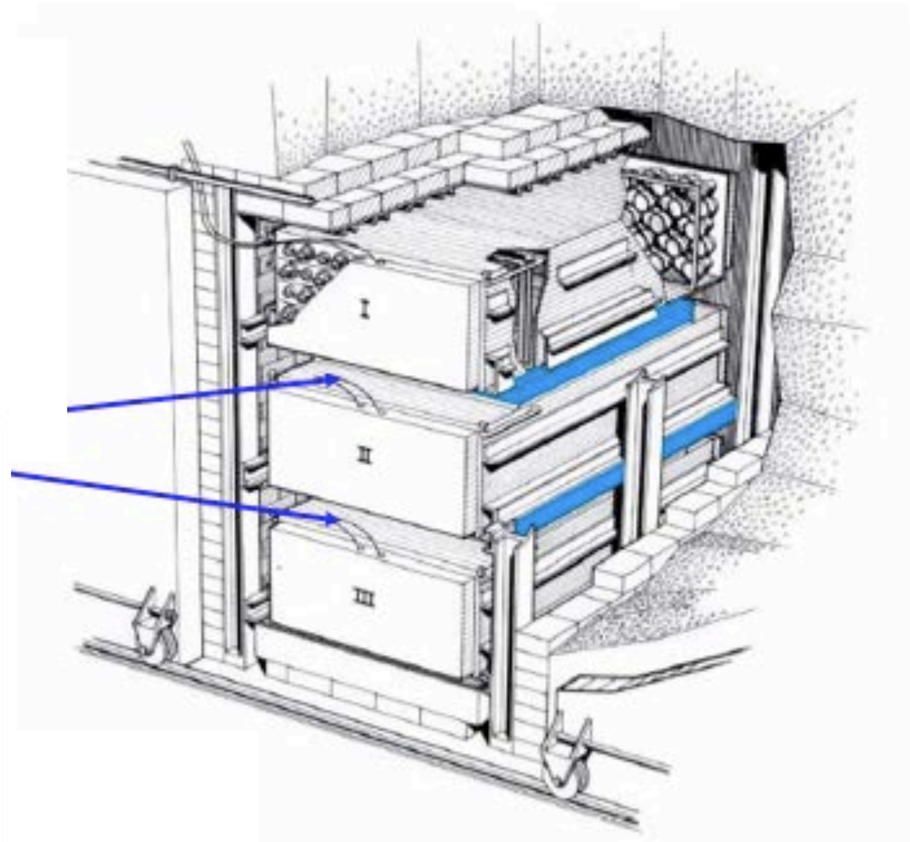
The Savannah River Detector

A new design (1959)

tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs

target tanks (blue) were filled with water+cadmium chloride

Shielding: 4 ft of soaked sawdust



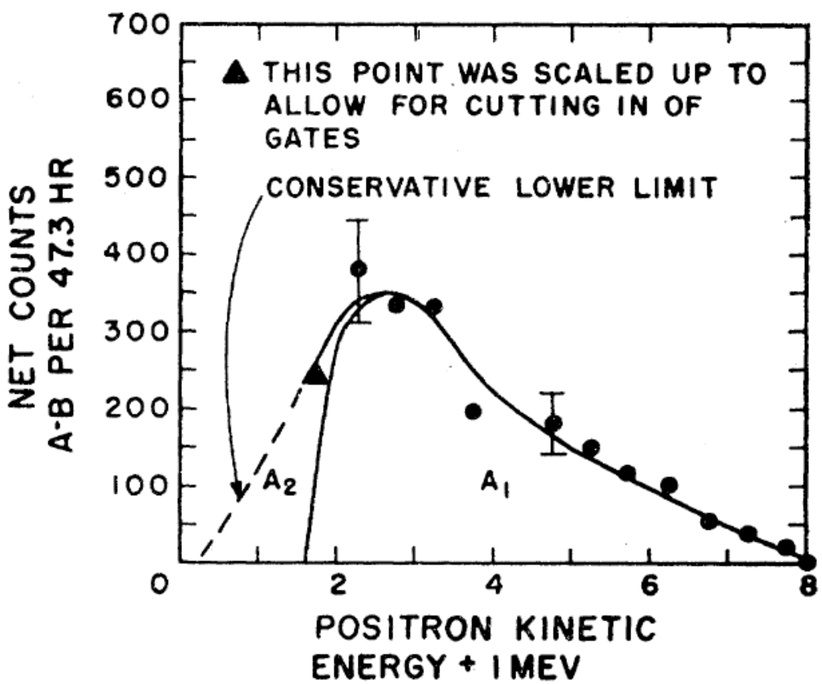
shielding and background reduction is important

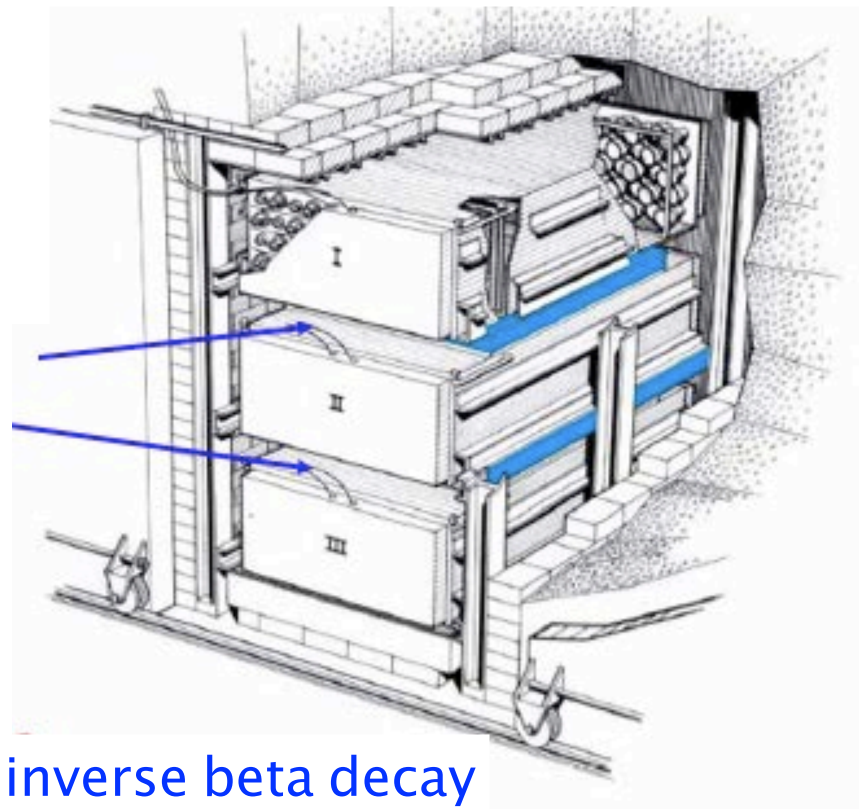
The Savannah River Detector

First Observation of Antineutrinos (1959)

tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs

first reactor $\overline{\nu}_e$ spectrum





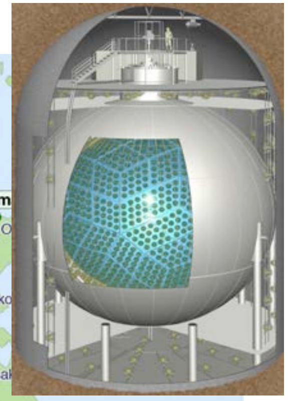
inverse beta decay

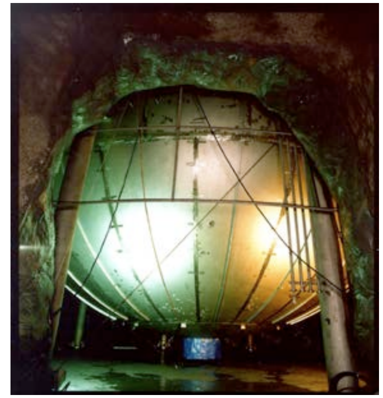
$\overline{\nu}_e + p \rightarrow e^+ + n$

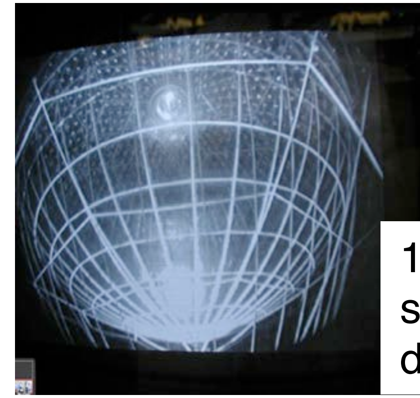
Reines, Cowan, Phys Rev 113, (1959)273

Observation of Reactor $\overline{\nu}_e$ Disappearance

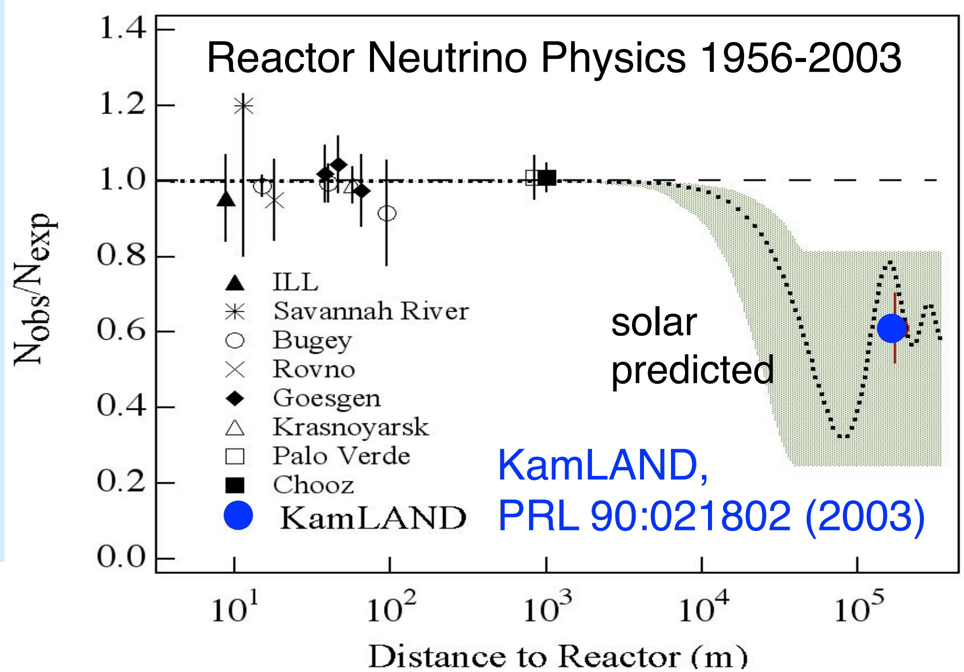
KamLAND 2003







1kt liquid scintillator detector



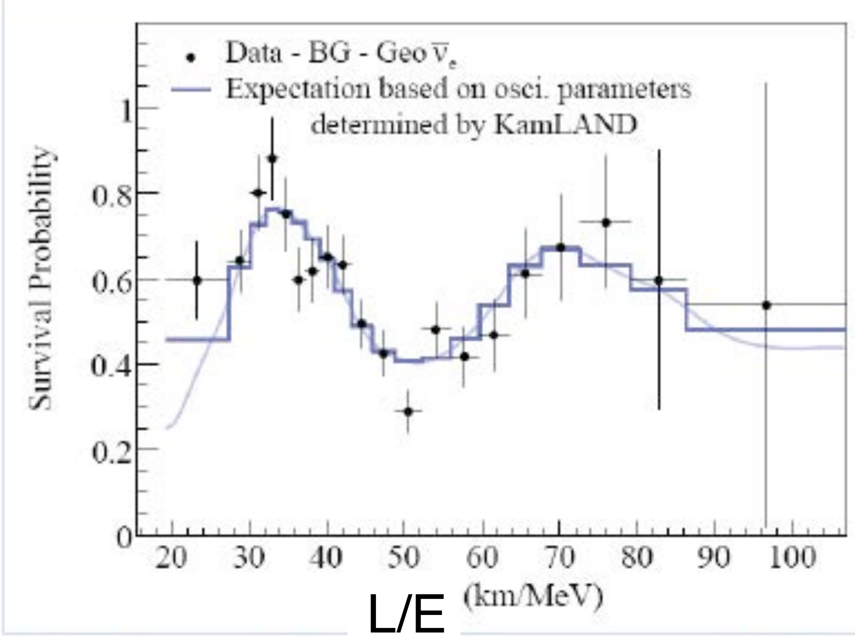
KamLAND, PRL 90:021802 (2003)

mean, flux-weighted reactor distance ~ 180km

Direct Evidence for Neutrino Oscillations

KamLAND

Reactor $\bar{\nu}_e$ with KamLAND



BOARD ON PHYSICS AND ASTRONOMY — NP2010 Committee

Neutrino Oscillation Imply 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

2-neutrino case

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

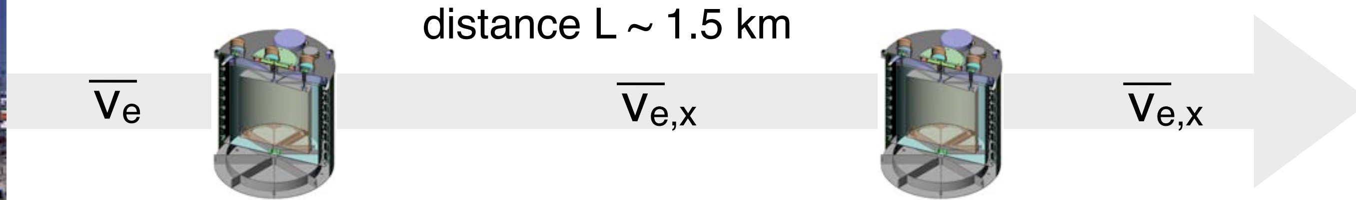
energy and baseline dependent

osc frequency depends on Δm^2

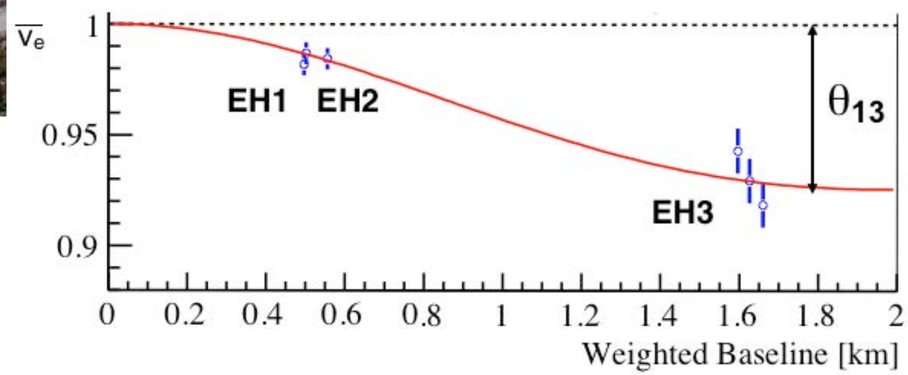
amplitude depends on θ

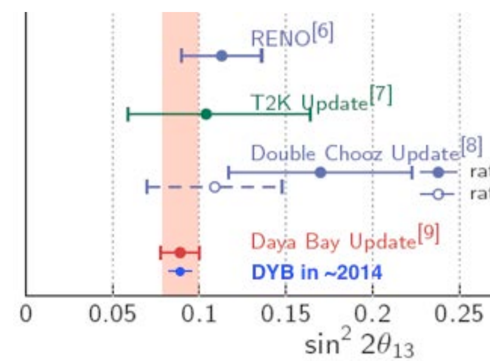
Neutrino Oscillations are Physics Beyond the Standard Model

Measurement of the Neutrino Mixing Angle θ_{13}



Data taking since 2011



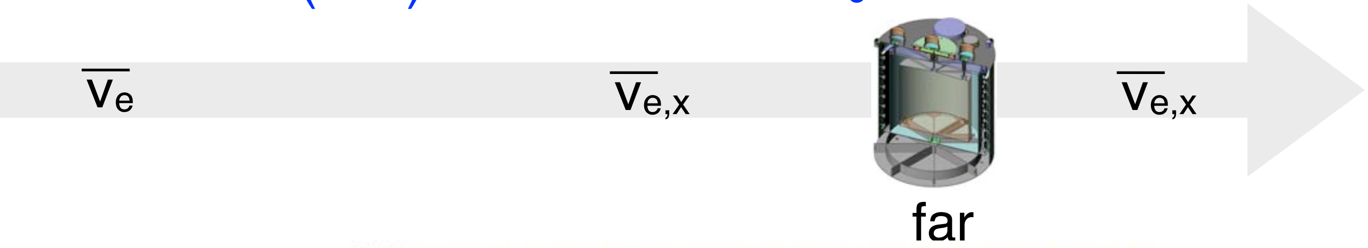


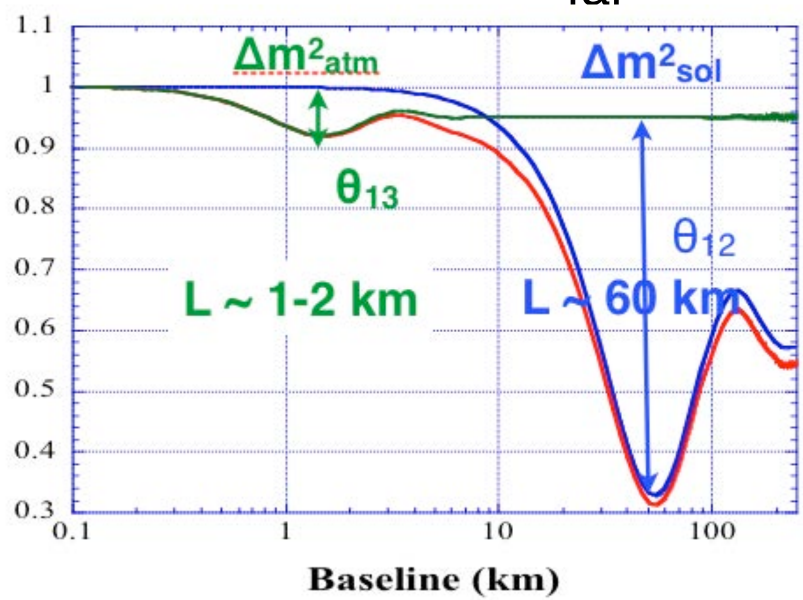
First observation of electron antineutrino disappearance over km-long baselines

Science Magazine
Daya Bay one of the *"Breakthroughs of the Year 2012"* after Higgs discovery

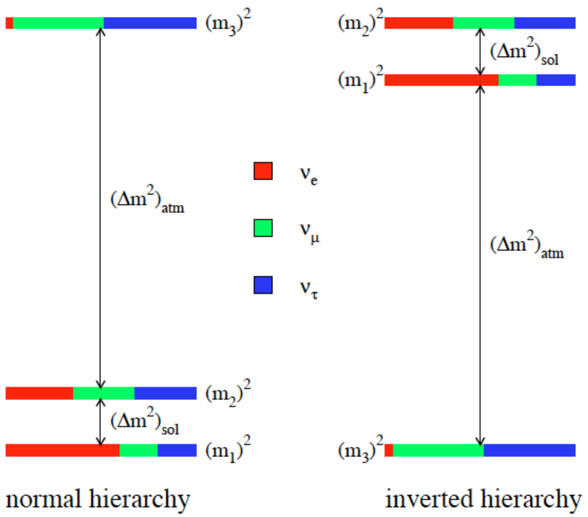
Reactor Neutrino Oscillation Experiments

Measure (non)-1/r² behavior of $\bar{\nu}_e$ interaction rate





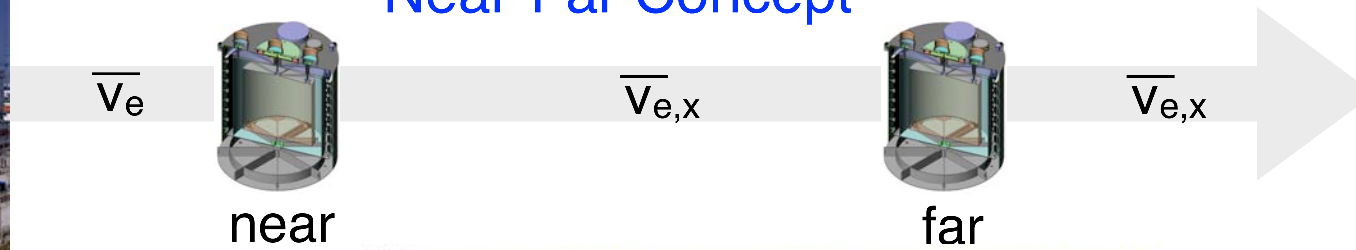
for 3 active ν, two different oscillation length scales: Δm^2_{12}, Δm^2_{23}

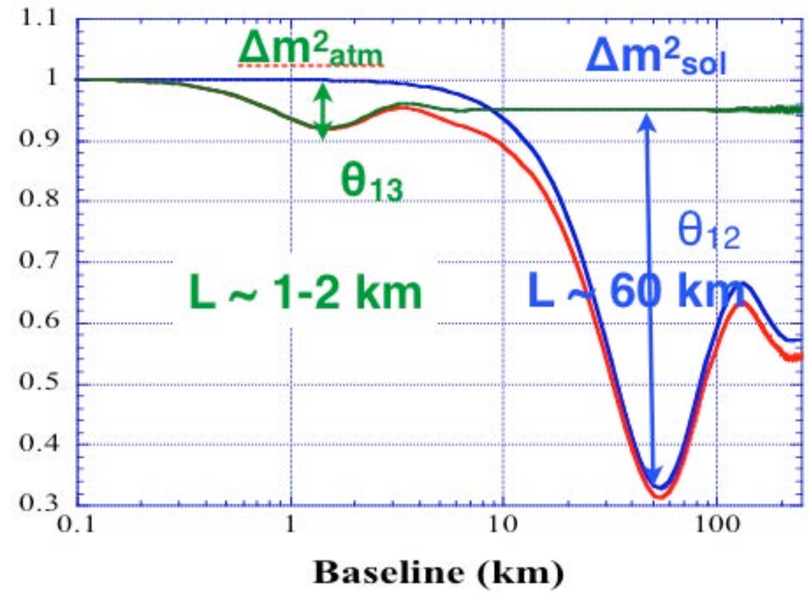


L/E → Δm^2 amplitude of oscillation → θ

Reactor Neutrino Oscillation Experiments

Near-Far Concept





Absolute Reactor Flux
Largest uncertainty in previous measurements

Relative Measurement
Removes absolute uncertainties!

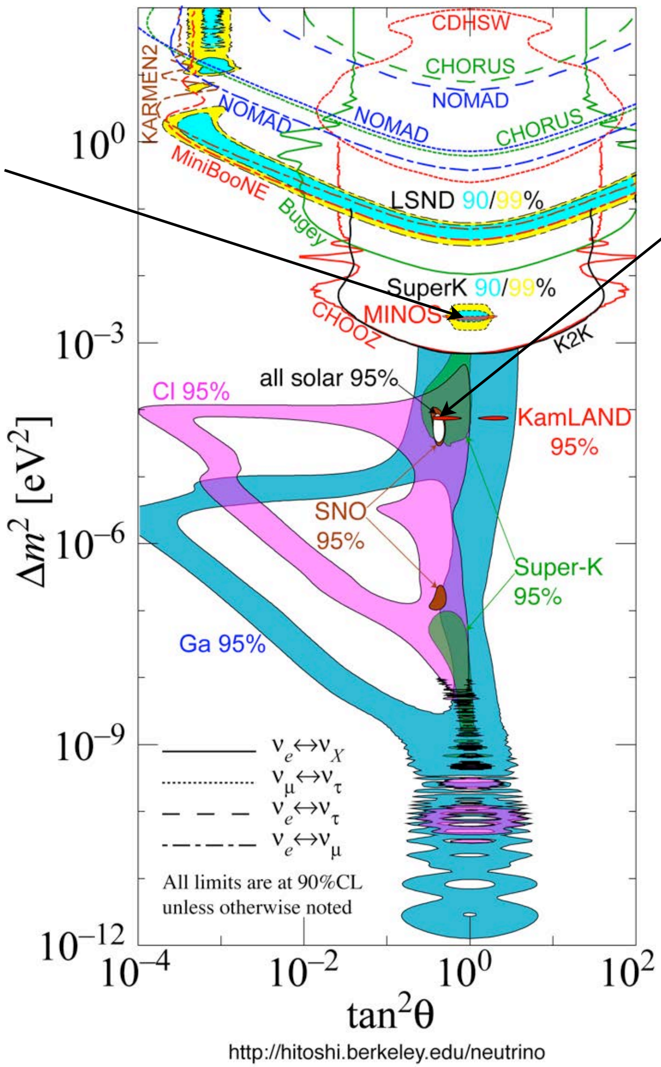
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E,L_f)}{P_{sur}(E,L_n)}\right]$$

far/near $\overline{\nu}_e$ ratio — target mass — distances — efficiency — oscillation deficit

Completing the 3-ν Oscillation Picture

atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}

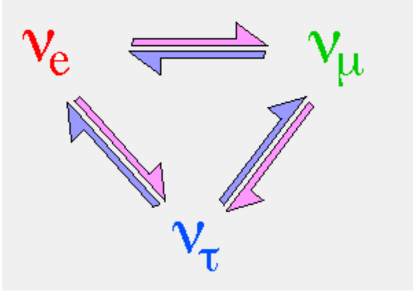


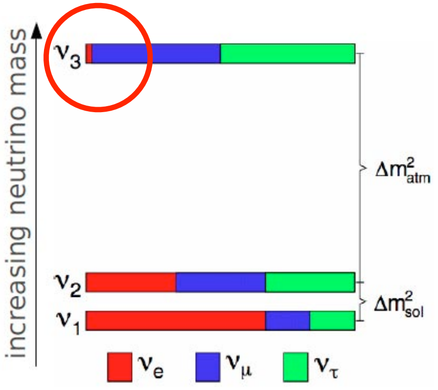
solar/reactor neutrinos

θ_{12}, Δm^2_{12}

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

3-flavor picture needed





Neutrino Oscillation

Mixing Angles & Mass Splittings

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

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

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

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, K2K}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor and accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

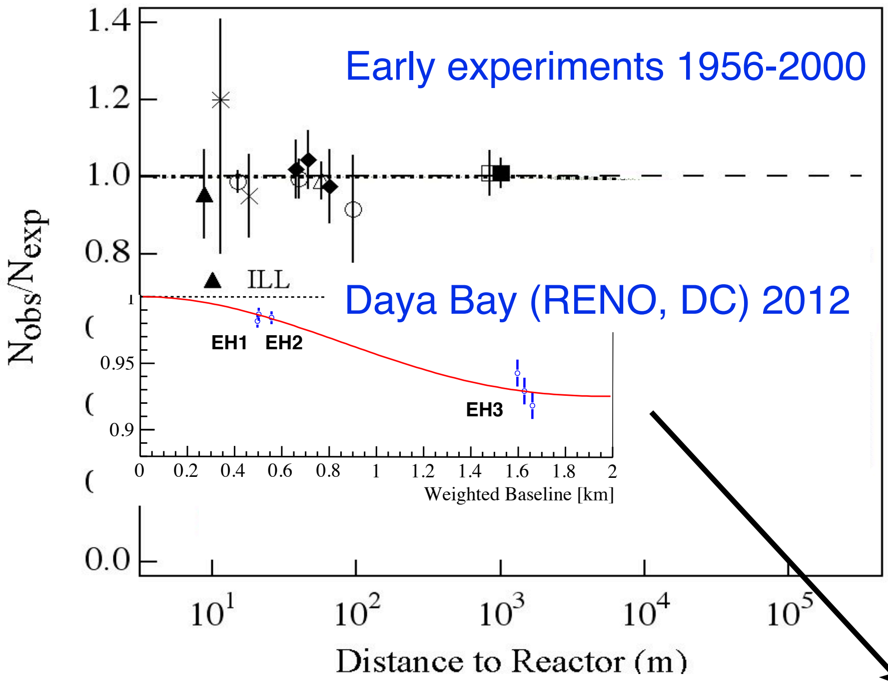
$\theta_{23} = 40.4^\circ {}^{+0.8^\circ}_{-1.8^\circ}$ — maximal?

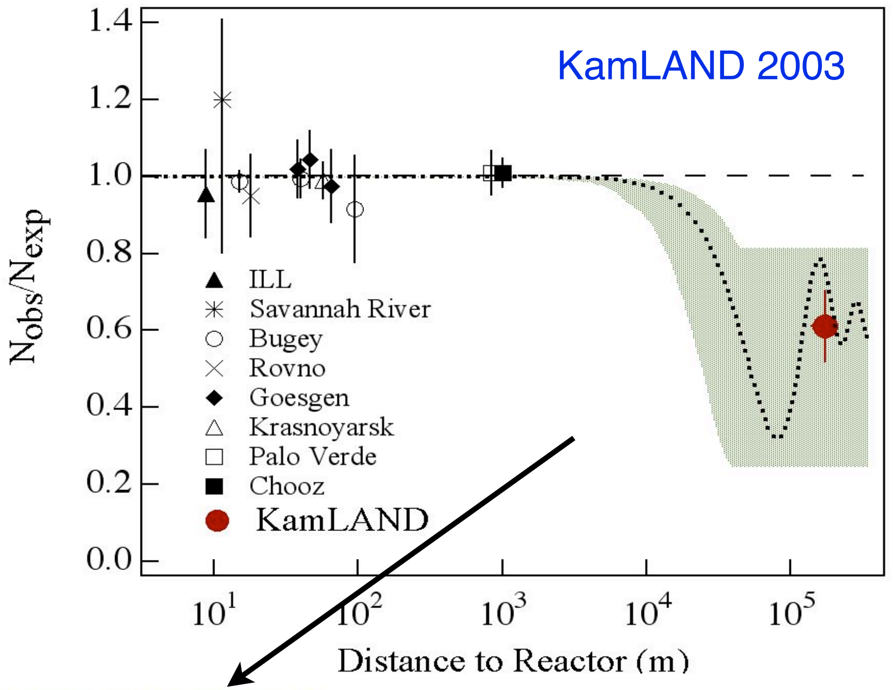
$\theta_{13} = 8.7^\circ \pm 0.45^\circ$ — not so small

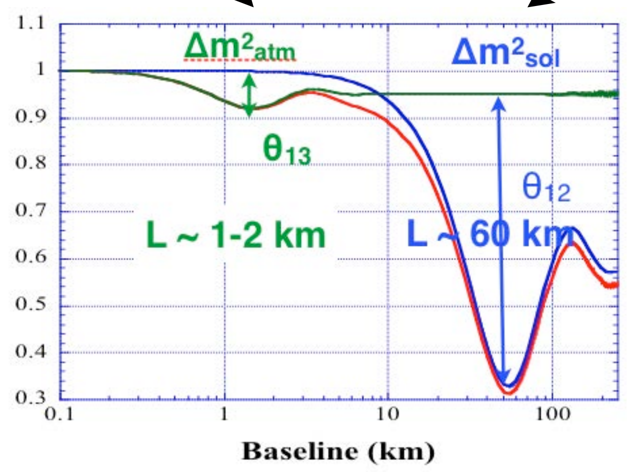
$\theta_{12} = 32.4^\circ \pm 0.8^\circ$ — large, but not maximal!

All three neutrino mixing angles are now known!

Reactor Antineutrino Oscillations

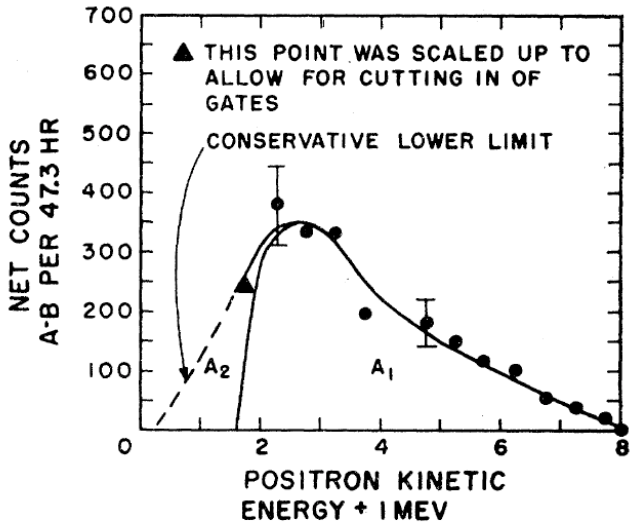




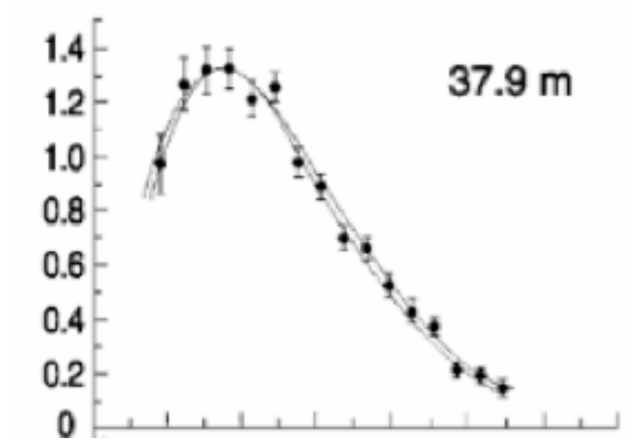


Towards a Precision Reactor Spectrum

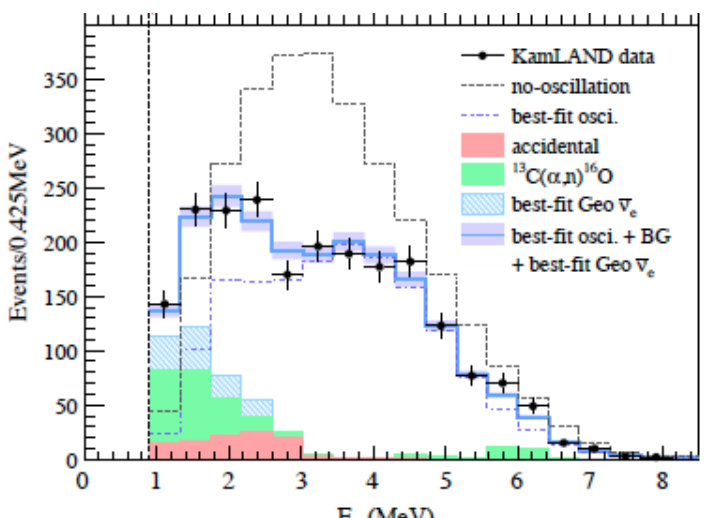
Reines 1959



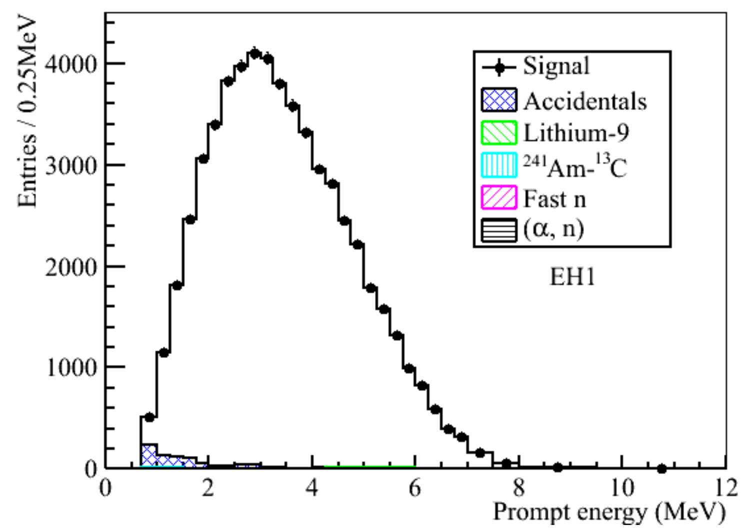
Goesgen 1986



KamLAND 2010



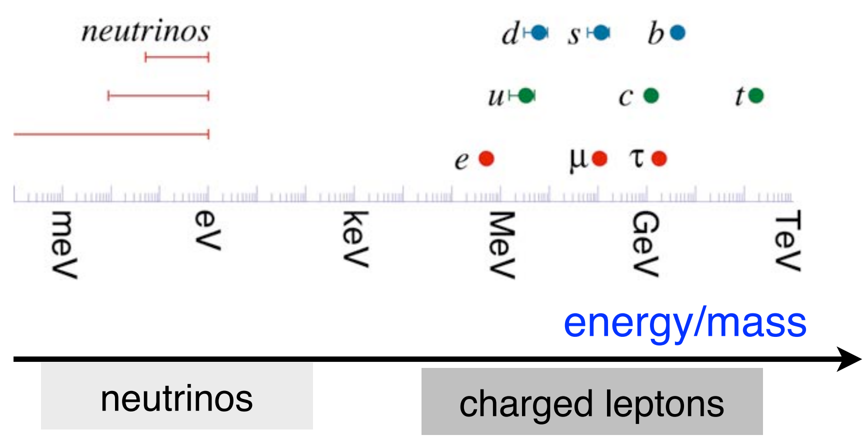
Daya Bay (> 200,000 events at near site)



Neutrinos - Open Questions

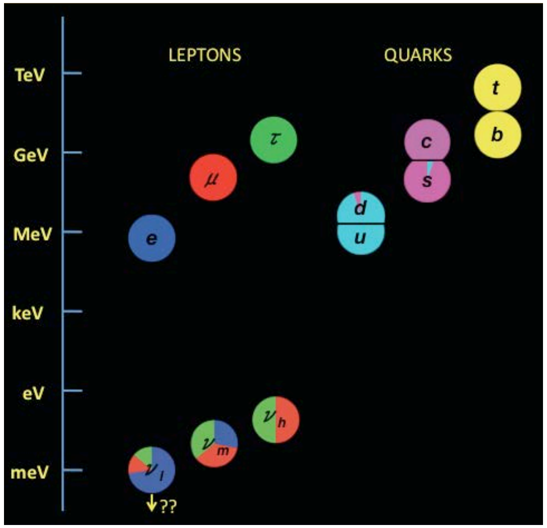
The Origin of Mass

- Why are neutrinos so light?
- Do neutrinos have Majorana mass?
- What is the absolute mass scale?
- Normal or inverted mass ordering?
- Are there more than 3ν?



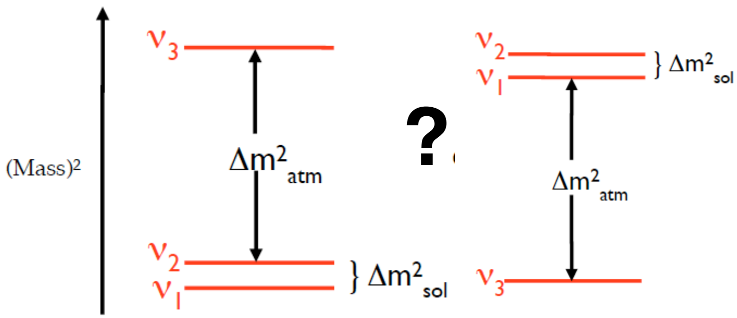
The Flavor Puzzle

- Why is lepton mixing so different from quarks?
- CP violation?
- θ_{23} octant?

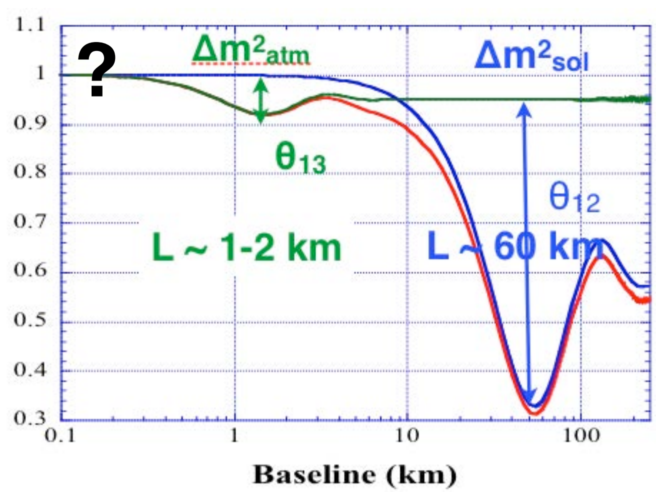


Reactor Neutrinos Beyond Daya Bay

Normal or inverted mass ordering?

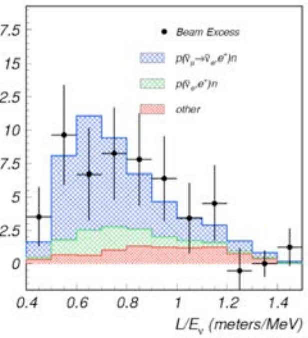


Short-baseline oscillations? Are there more than 3ν?

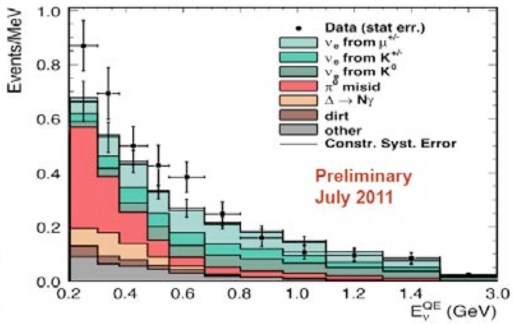


Neutrino Anomalies

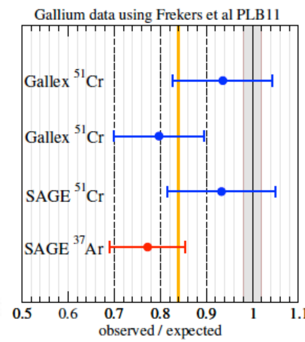
LSND



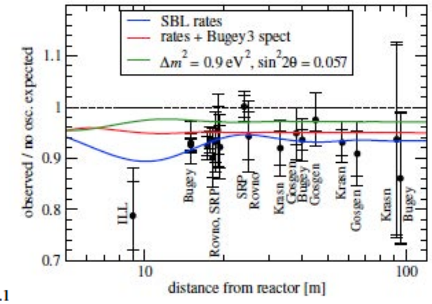
MiniBoone



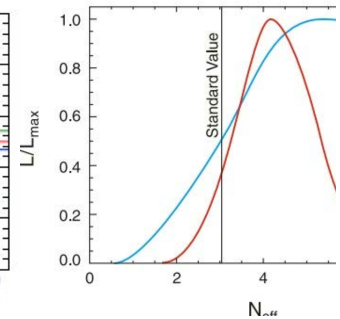
Ga Source



Reactor



Cosmology (WMAP)

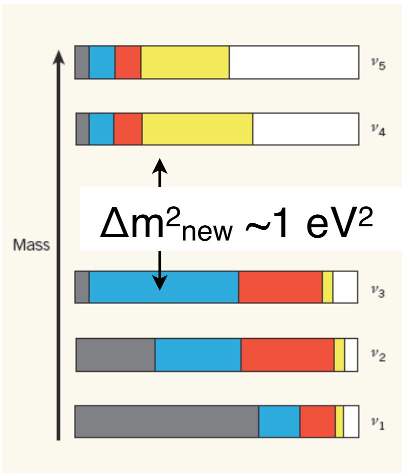


Anomalies in 3-ν interpretation of global oscillation data

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

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

systematics or experimental effect? ➔ need to test effects

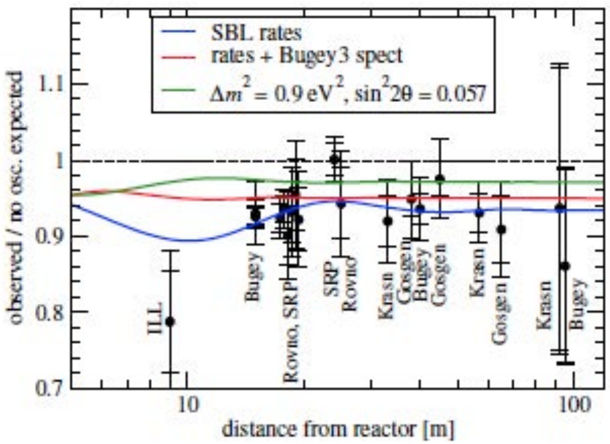


Cosmology suggests higher radiation density

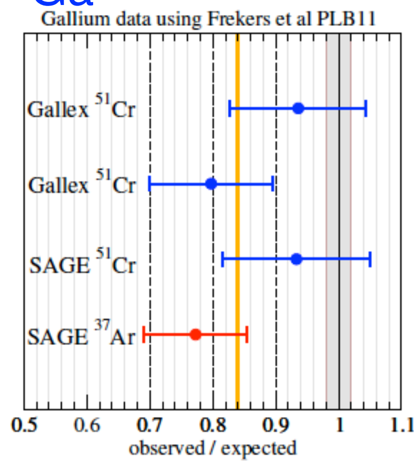
$N_{eff} > 3$

Neutrino Anomalies - Beyond 3ν?

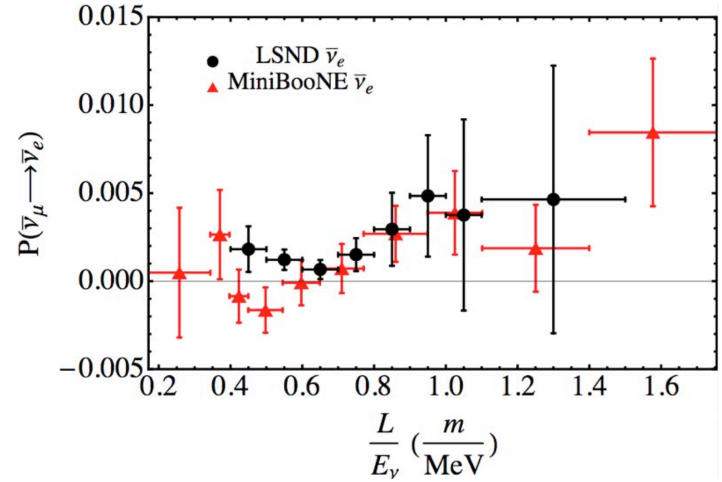
Reactor



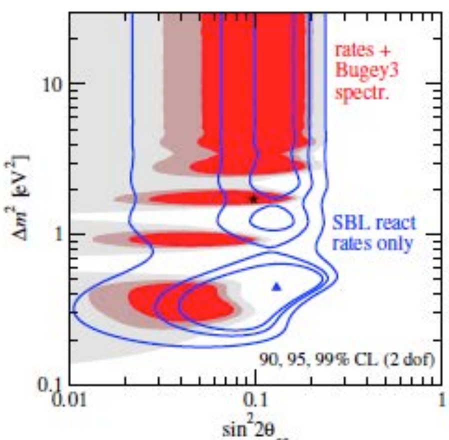
Ga

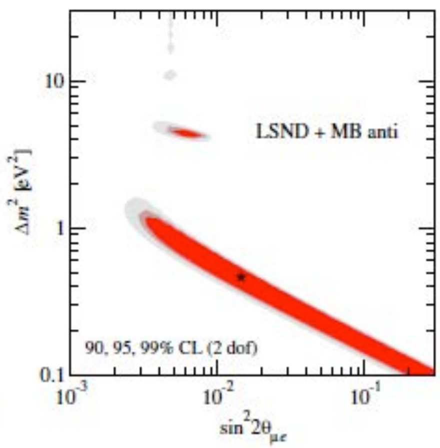


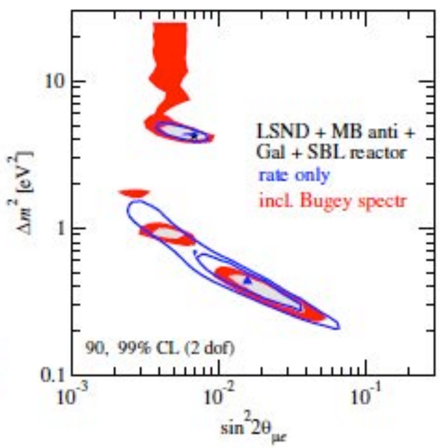
LNSD/MiniBoone



Are $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ consistent?







$\nu_e \rightarrow \nu_e$ disappearance $\sin^2 2\theta_{ee}$

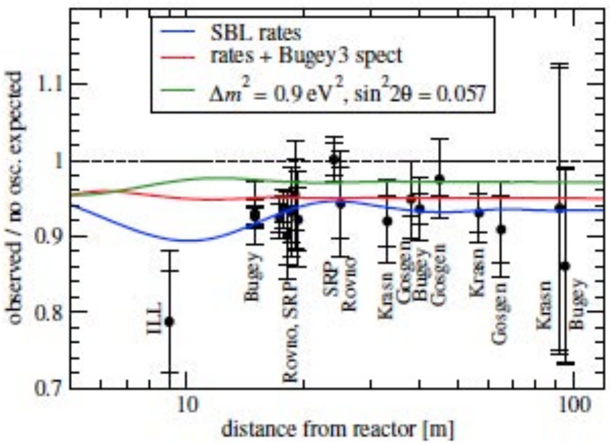
$\nu_\mu \rightarrow \nu_\mu$ disappearance $\sin^2 2\theta_{\mu\mu}$

$\nu_\mu \rightarrow \nu_e$ appearance $\sin^2 2\theta_{\mu e}$

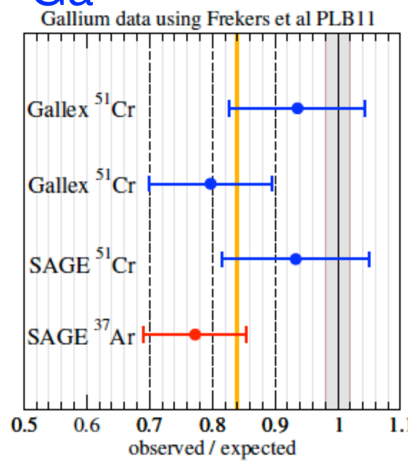
strong tension if all three are combined, tension also in 3+2 fit, consistent interpretation difficult
future data at the eV² scale will help, as well as cosmology

Neutrino Anomalies - Beyond 3ν?

Reactor

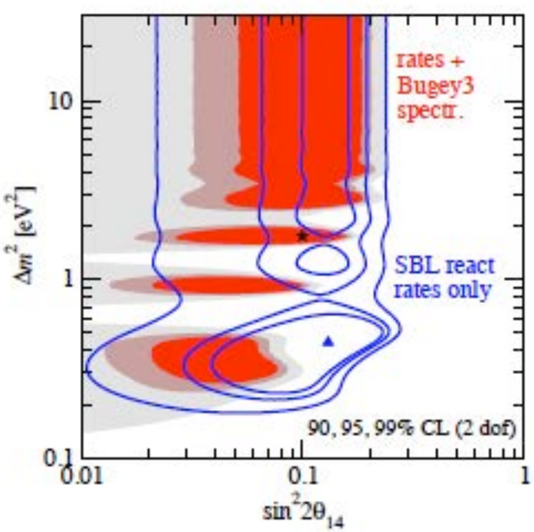


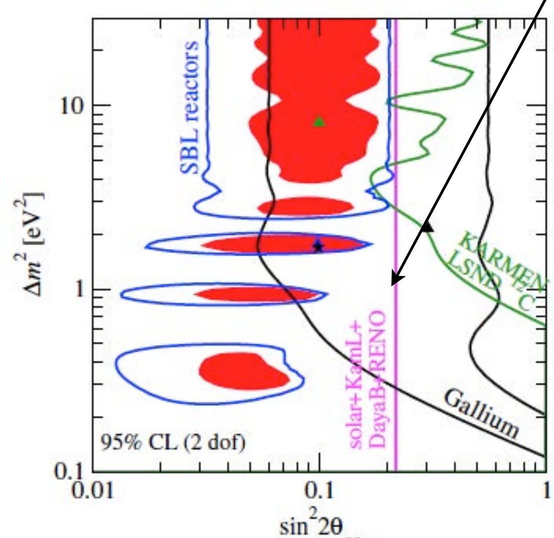
Ga



Oscillation Interpretation of ν_e disappearance

$\Delta m^2 \sim O(1 eV^2)$





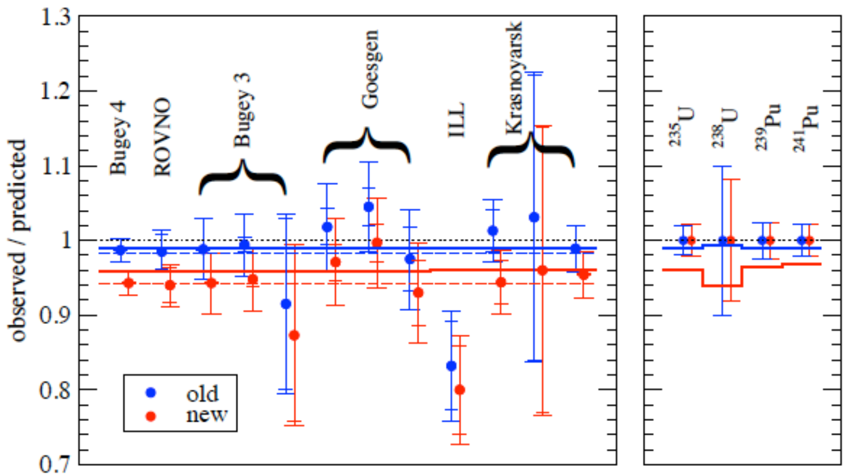
at ~1km reactor θ_{13} experiments probe overall suppression

Reactor $\bar{\nu}$ Fluxes

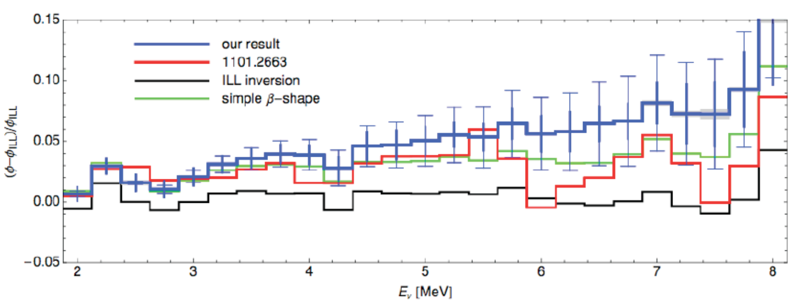
Theory Meets Experiment

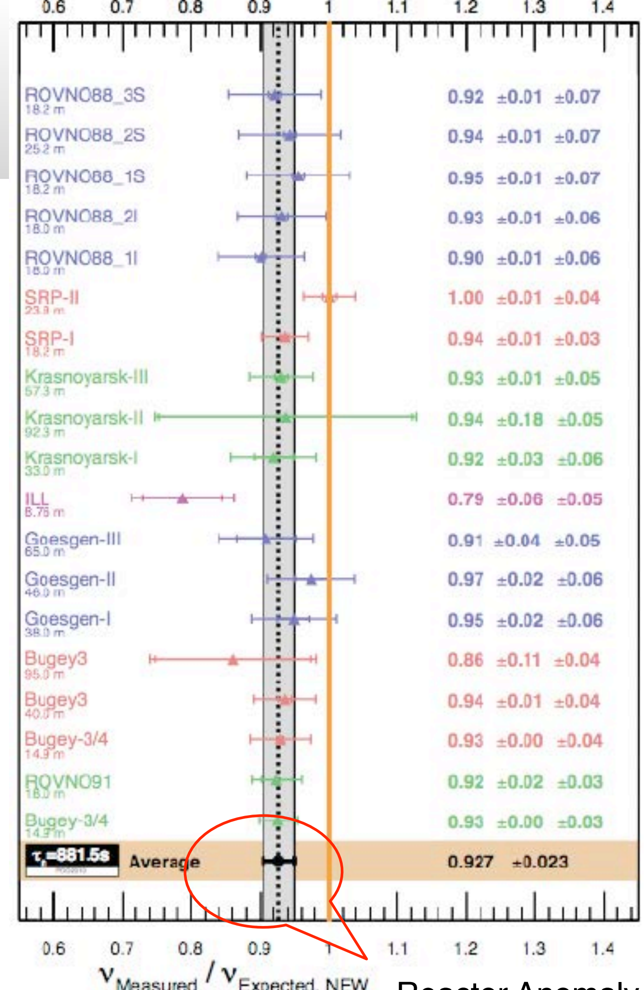
Recently the reactor $\bar{\nu}_e$ fluxes have been recalculated

T.A. Mueller et al.,[arXiv:1101.2663].;P. Huber, [arXiv:1106.0687].



re-evaluations find higher fluxes by about 3.5%





Reactor Anomaly

Ref: Mention et al, 1101.2755 (2012 upd)

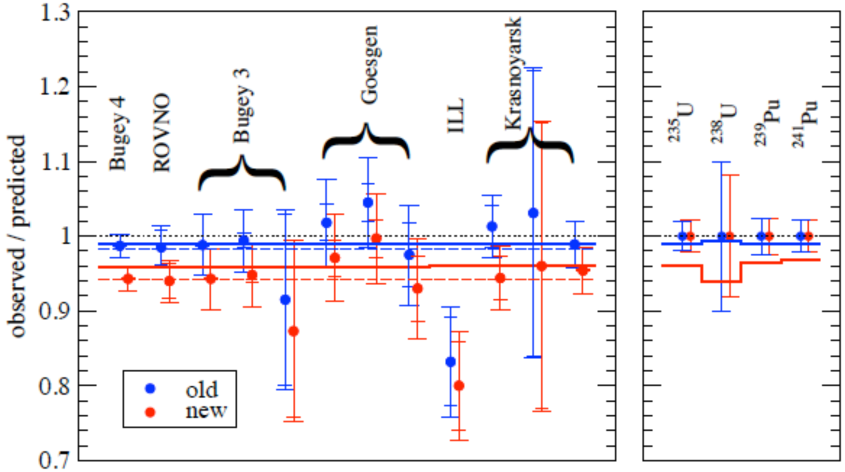
Missing nuclear physics or new physics?

Reactor $\bar{\nu}$ Fluxes

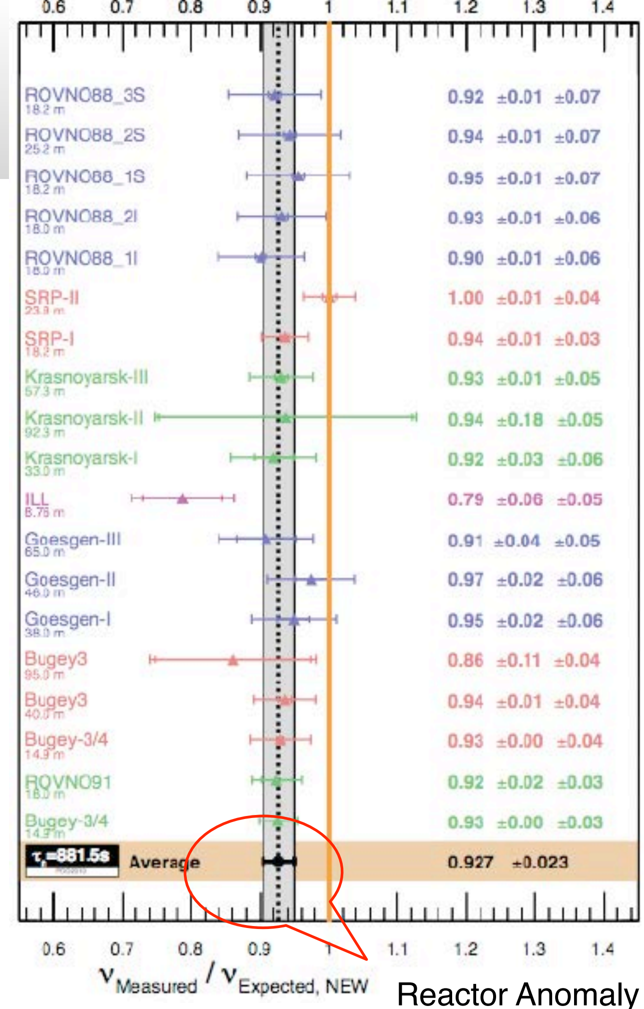
Theory Meets Experiment

Recently the reactor $\bar{\nu}_e$ fluxes have been recalculated

T.A. Mueller et al.,[arXiv:1101.2663].;P. Huber, [arXiv:1106.0687].



re-evaluations find higher fluxes by about 3.5%



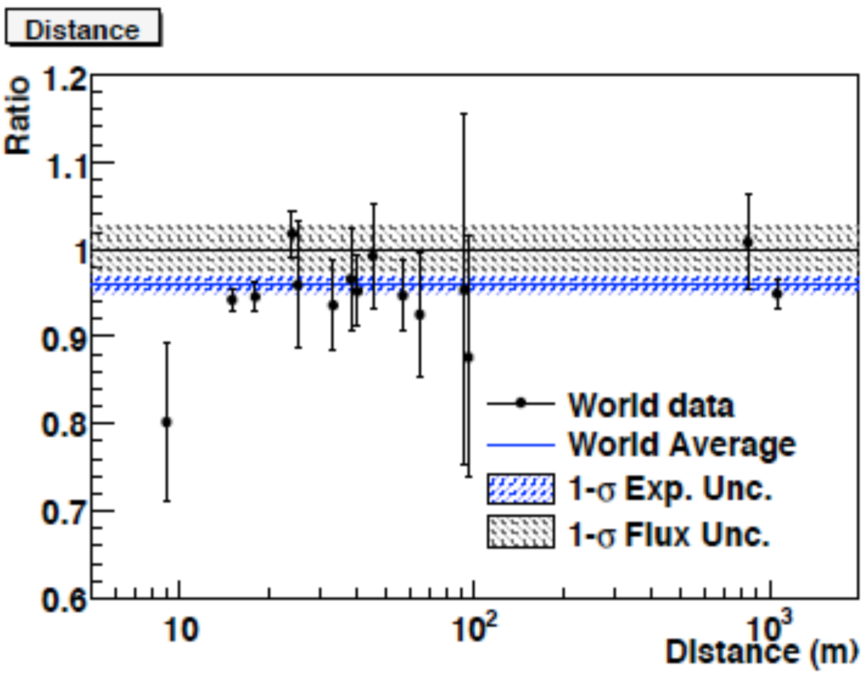
Ref: Mention et al, 1101.2755 (2012 upd)

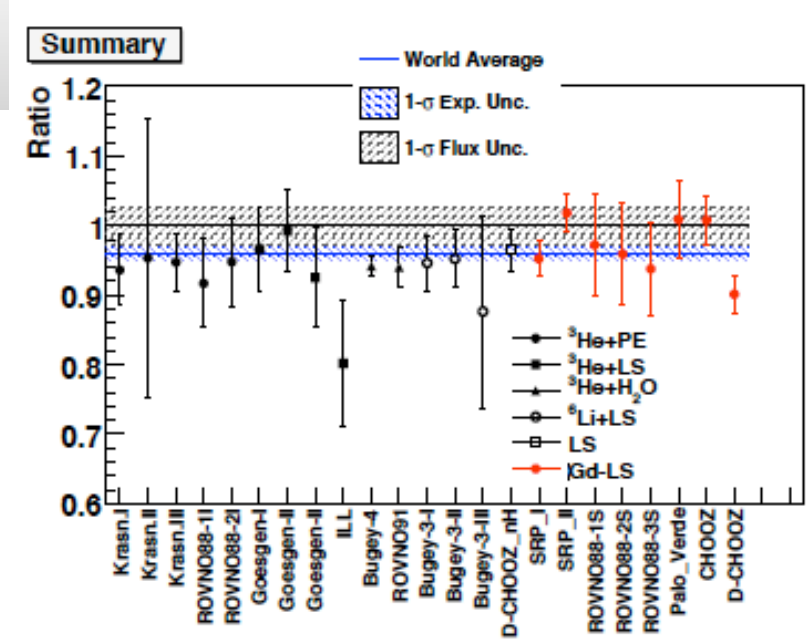
Two issues:

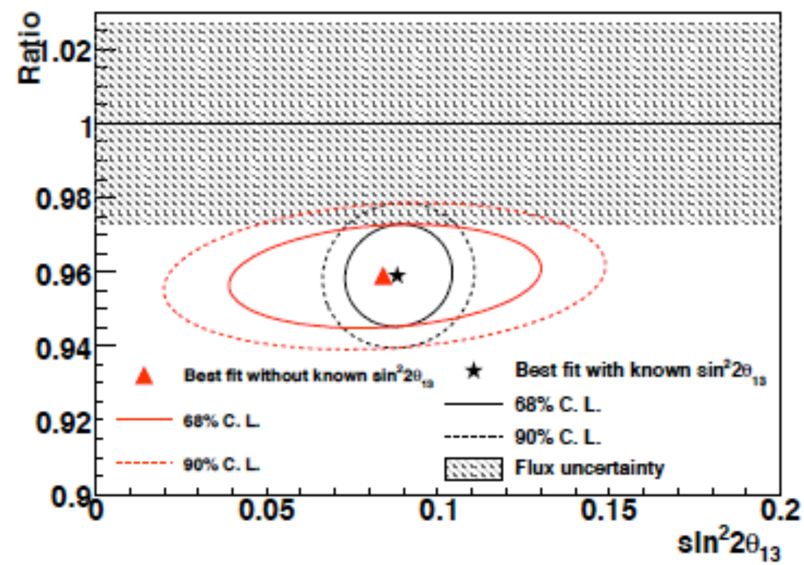
1. Model-dependence of physics determining the increase in the spectra?
   - SM physics for GT and Fermi Transitions
   - some transitions are forbidden transitions, corrections unknown
2. Overall uncertainties in reactor antineutrino fluxes?

Reactor Flux Measurements

The “Anomaly”



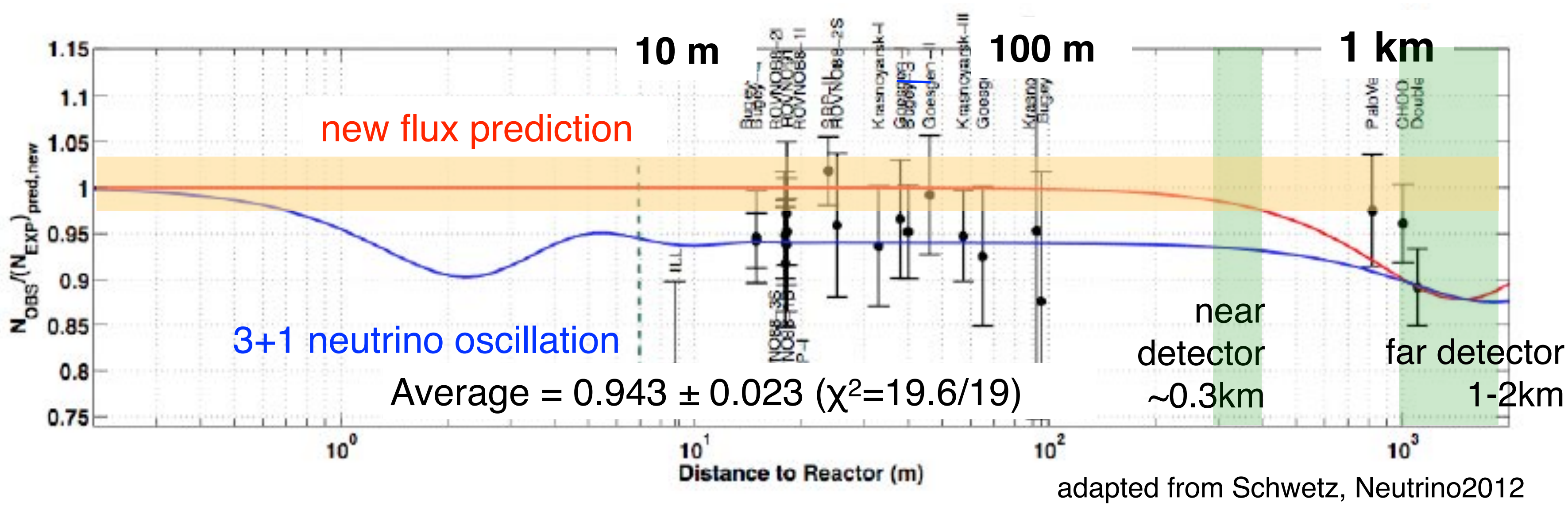




Perhaps no anomaly at all?

Ref: arXiv: 1303.0900

What about the θ13 experiments?

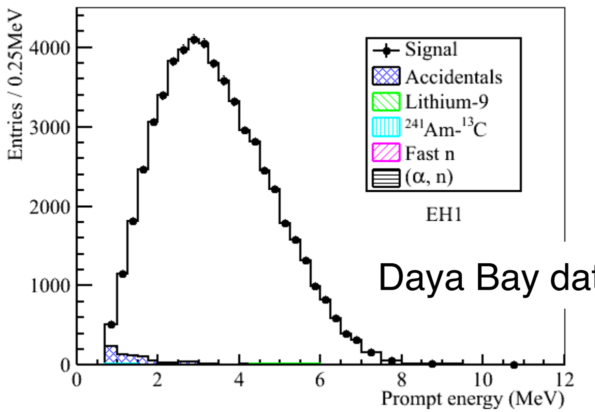


Reactor θ_{13} can test flux predictions within theoretical uncertainties but not directly search for short-baseline oscillations

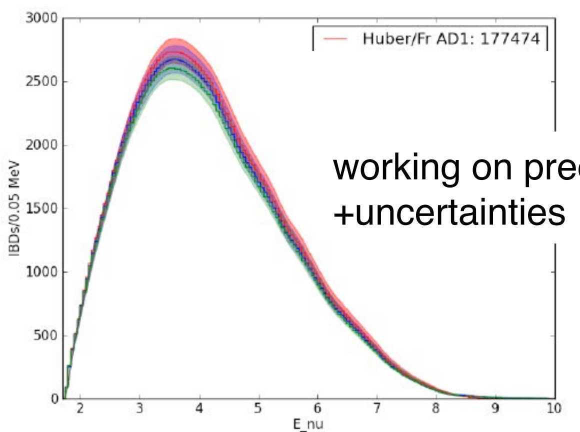
Reactor Fluxes, Spectra, and θ_{13} Experiments

Compare Reactor Spectra and Fluxes to Predictions

spectrum



Daya Bay data



working on predictions +uncertainties

absolute flux measurements

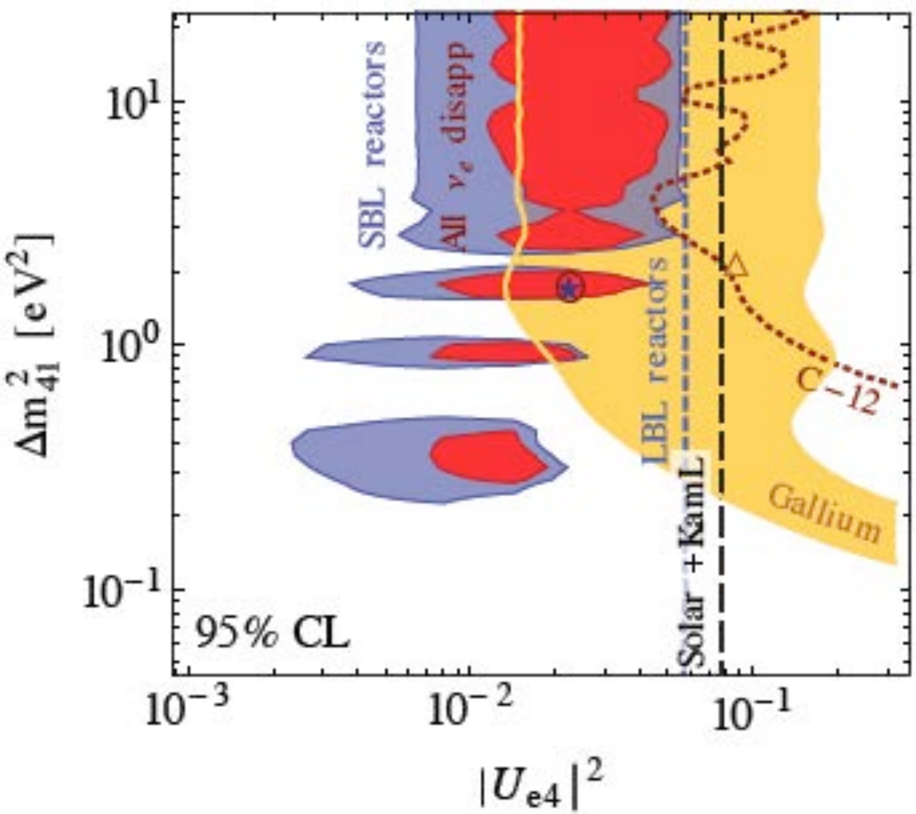
	Double Chooz	RENO	Daya Bay
detector syst	2.1%	1.5% (correlated)	1.8% (correlated)
reactor syst	1.8%	2.0% (correlated)	2.7% (correlated)

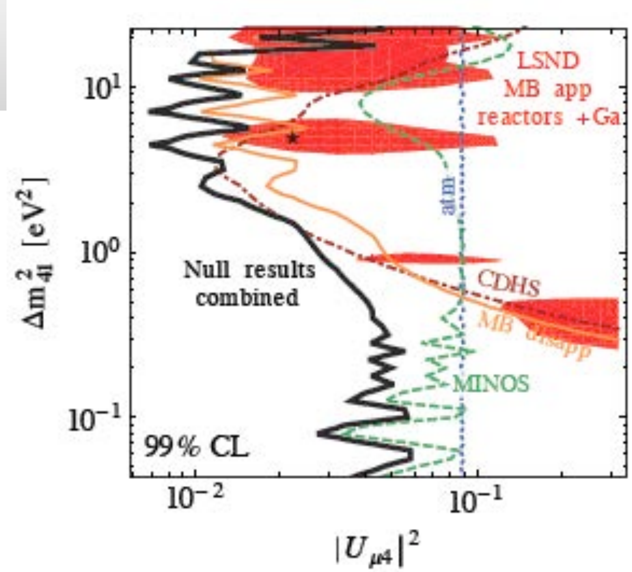
Source	Item	Abs Uncertainty (%)	
		Current	Goal
Statistics		**0.2**	**0.1**
Detector	H/Gd n-Capture Ratio	0.5	0.2
	Delayed Energy	0.6	0.3
	Number of Protons	0.47	0.3
	Spill-in Effects	1.5	0.3
	Subtotal	**1.8**	**0.6**
Reactor	Thermal power uncertainty	0.5	0.5
	Fission fraction	0.6	0.6
	Spent fuel contribution	0.3	0.3
	Subtotal	**0.8**	**0.8**
Flux normalization	Theoretical prediction	2.7	
	Bugey-4 anchor		1.4
	subtotal	**2.7**	**1.4**

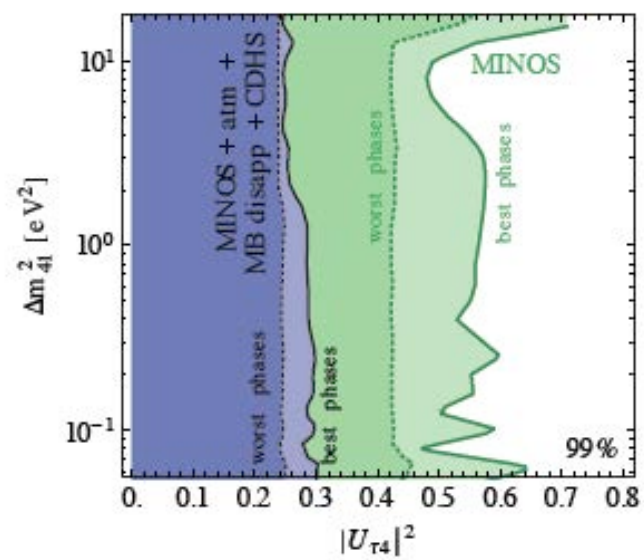
Ref:Daya Bay run plan

will test predictions of spectrum and flux within uncertainties

Disappearance Searches

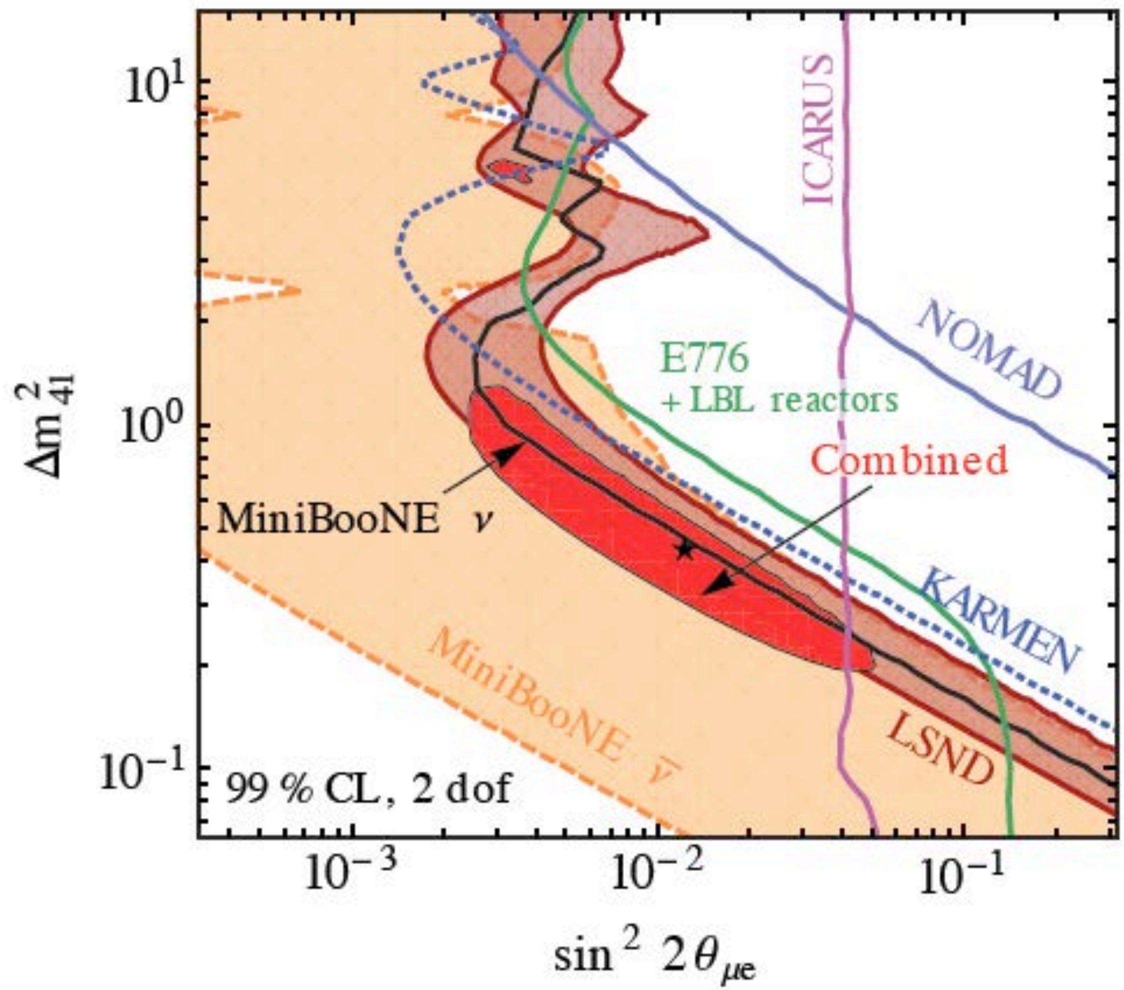






Ref: arXiv: 1303.3011

$\nu_\mu \rightarrow \nu_e$ Appearance Searches

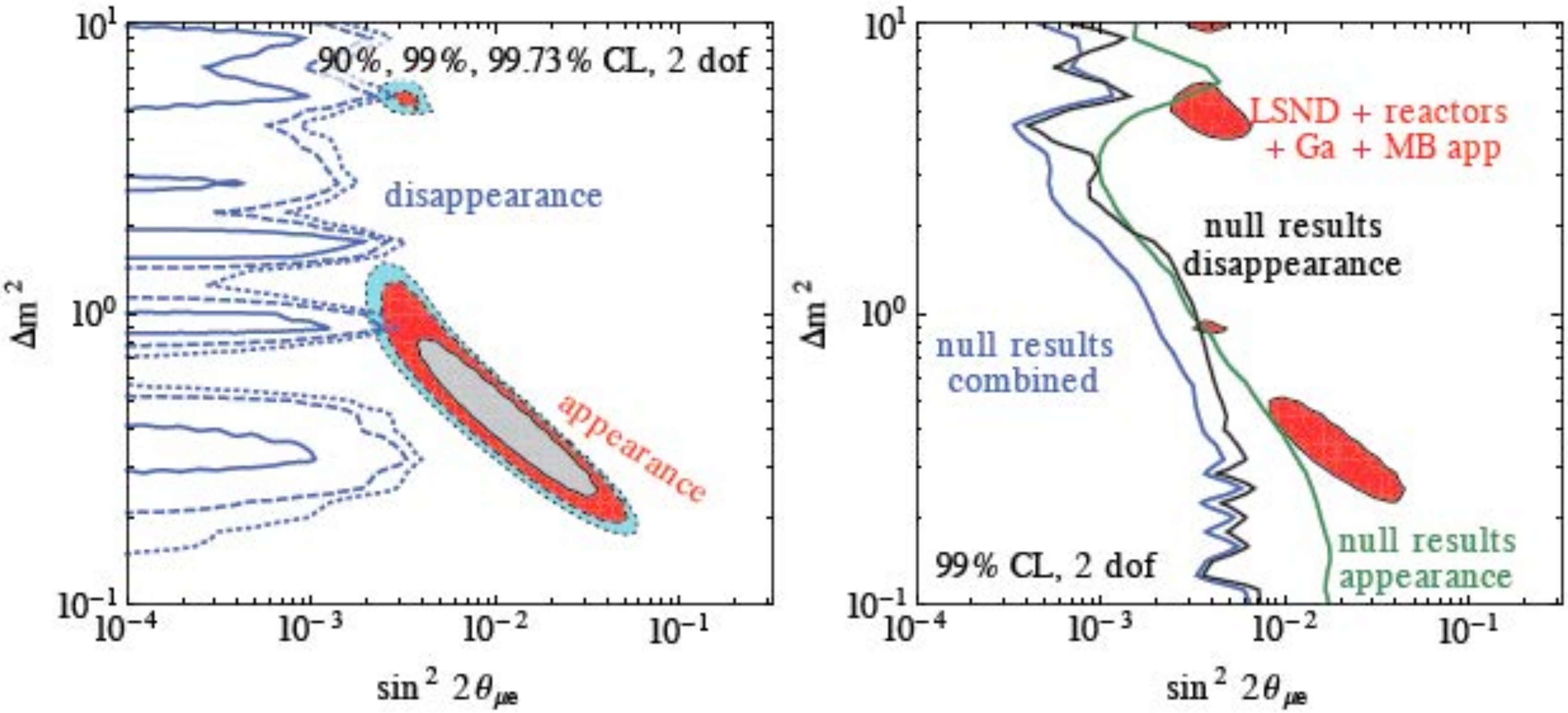


Ref: arXiv: 1303.3011

Global Analysis

appearance data vs exclusion limit

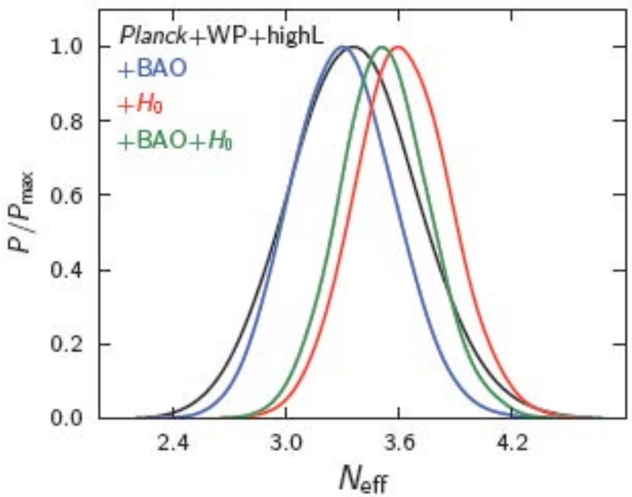
experiments with signal vs constraints from other data



Ref: arXiv: 1303.3011

Neutrinos and Cosmology

Radiation density in universe typically parameterized by N_{eff}



Joint constraints on N_{eff} and Σm_ν are always model-dependent

For Neff < 3.036, no extra species

$$\left.\begin{aligned} N_{eff} &= 3.29^{+0.67}_{-0.64} \\ \sum m_\nu &< 0.60\,\mathrm{eV} \end{aligned}\right\} \quad (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}). \qquad (78)$$

These bounds tighten somewhat with the inclusion of BAO data, as illustrated in Fig. 28; we find

$$\left.\begin{aligned} N_{eff} &= 3.32^{+0.54}_{-0.52} \\ \sum m_\nu &< 0.28\,\mathrm{eV} \end{aligned}\right\} \quad (95\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}+\mathrm{BAO}). \qquad (79)$$

For ΔNeff ≠ 0

$$\left.\begin{aligned} N_{eff} &< 3.91 \\ m^{eff}_{\nu,\,\mathrm{sterile}} &< 0.59\,\mathrm{eV} \end{aligned}\right\} \quad (95\%;\ \mathrm{CMB\ for}\ m^{\mathrm{thermal}}_{\mathrm{sterile}} < 10\,\mathrm{eV}). \qquad (82)$$

Combining further with BAO these tighten to

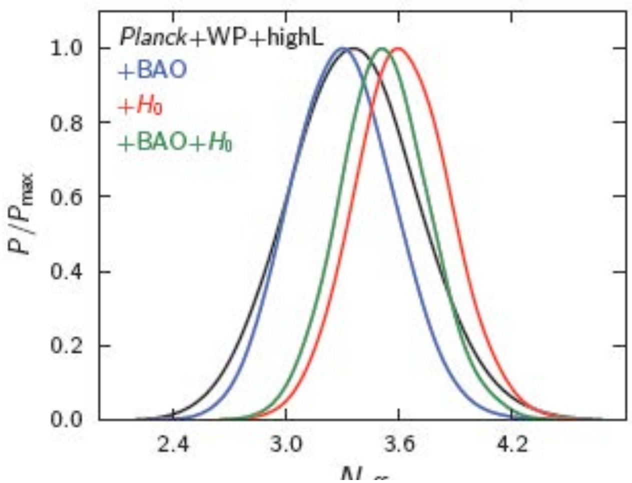
$$\left.\begin{aligned} N_{eff} &< 3.80 \\ m^{eff}_{\nu,\,\mathrm{sterile}} &< 0.42\,\mathrm{eV} \end{aligned}\right\} \quad (95\%;\ \mathrm{CMB+BAO\ for}\ m^{\mathrm{thermal}}_{\mathrm{sterile}} < 10\,\mathrm{eV}). \qquad (83)$$

bounds are only marginally compatible with a fully thermalized sterile neutrino (Neff≈4) with sub-eV mass < 0.5 eV that could explain the oscillation anomalies.

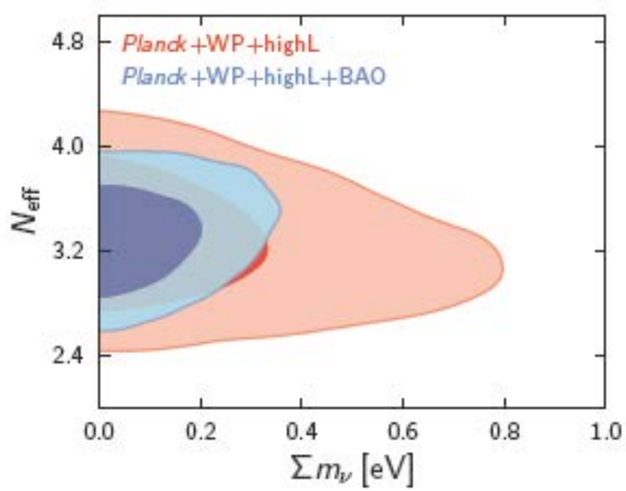
Ref: Planck results 2013

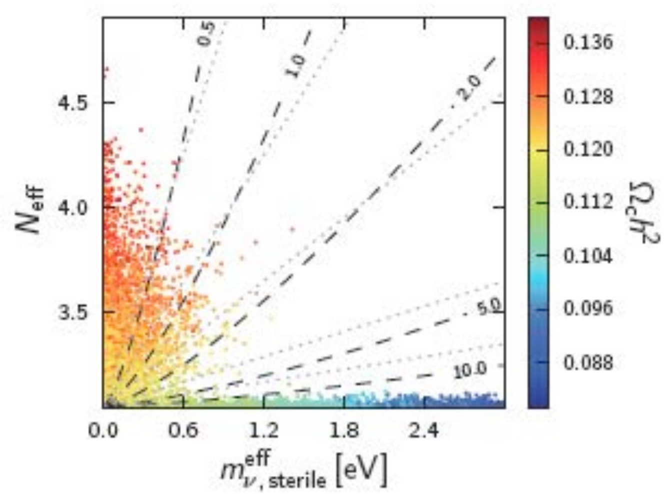
Neutrinos and Cosmology

Radiation density in universe typically parameterized by N_{eff}



Joint constraints on N_{eff} and Σm_ν are always model-dependent



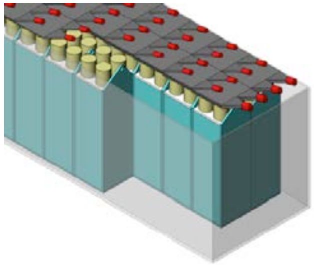


great progress in cosmology, but model-dependent

Ref: Planck results 2013

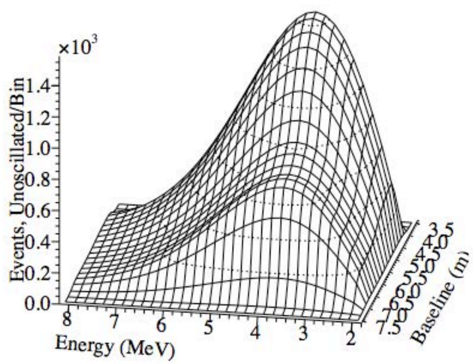
Reactor Experiments at Very Short Baselines

Sterile Neutrinos would require $\Delta m^2 \sim O(1eV^2)$

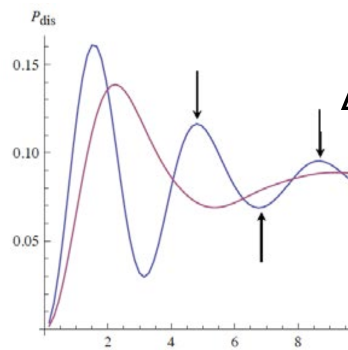


segmented, extended detector

Reactor Antineutrinos

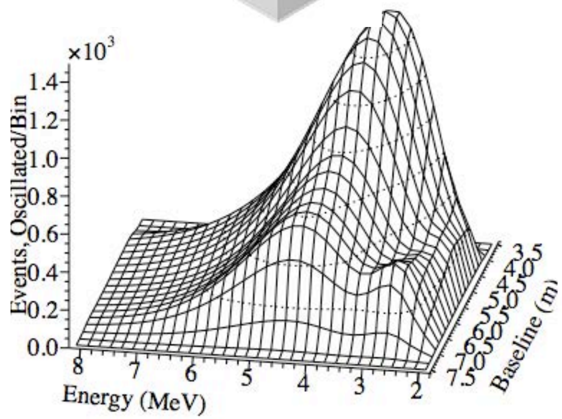


$\overline{\nu}_e$ Oscillation

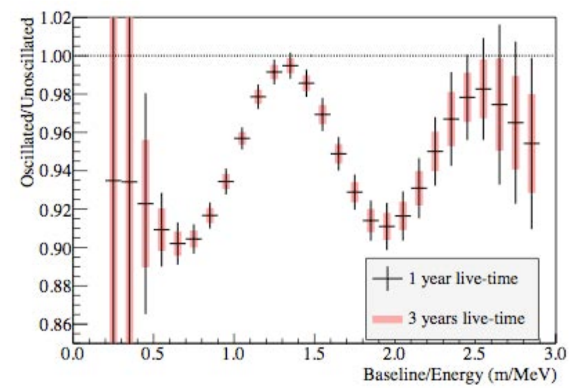


Δm^2~2 eV^2

distance, R



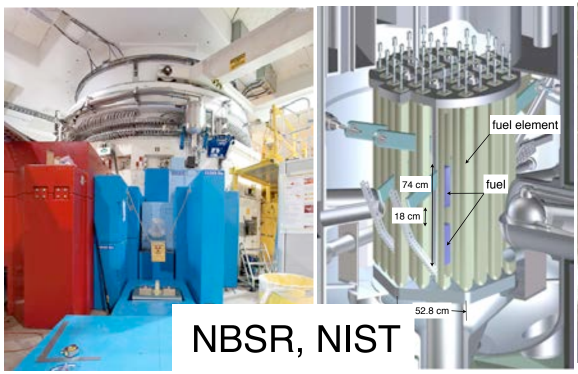
~O(10)m

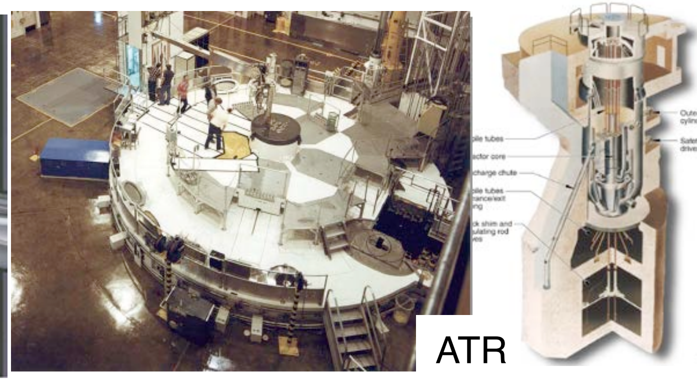


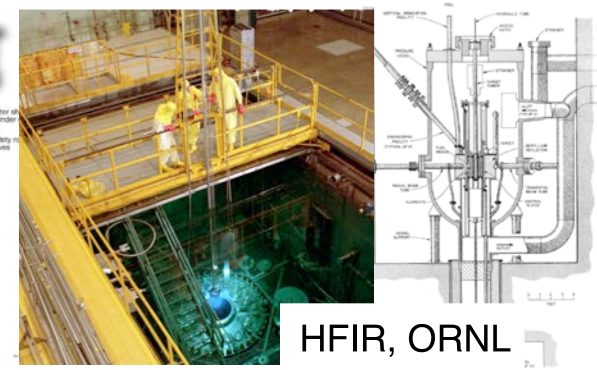
Energy and baseline dependent effect

Opportunity for US Reactor Experiment

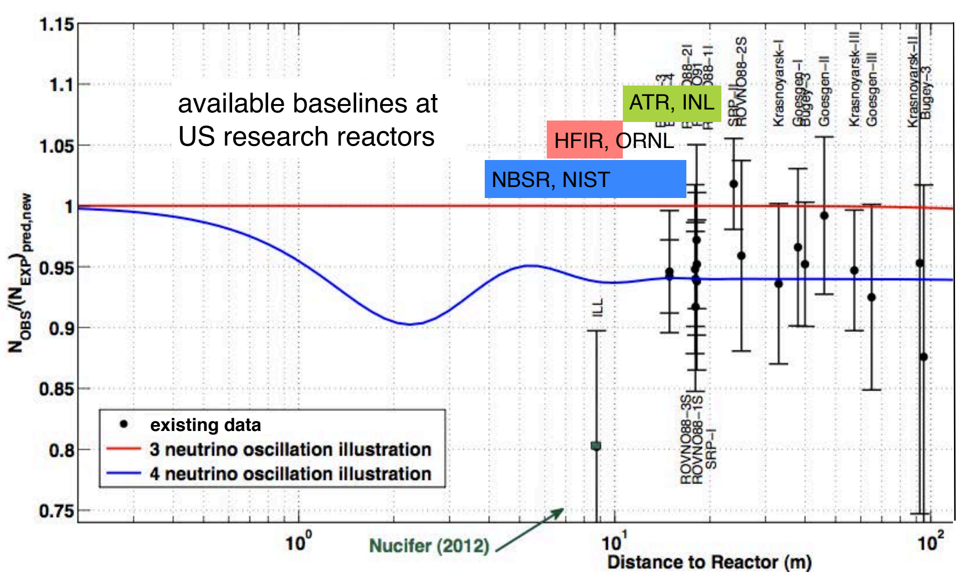
High-Power US Research Reactors







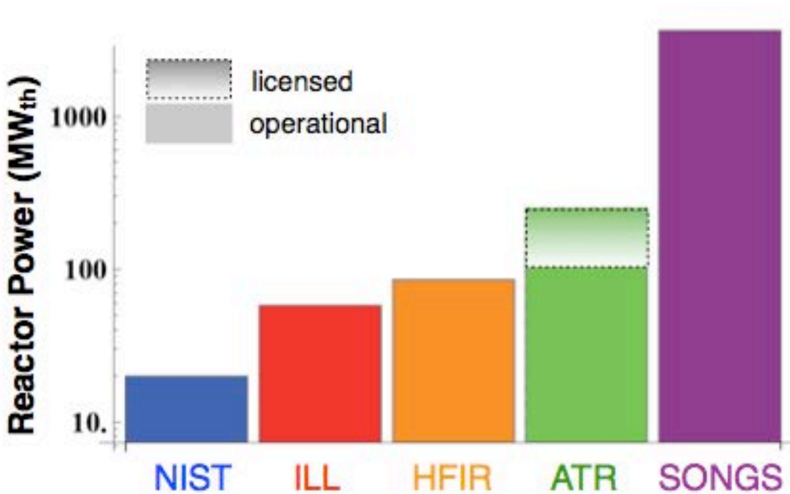
Shortest Accessible Baselines

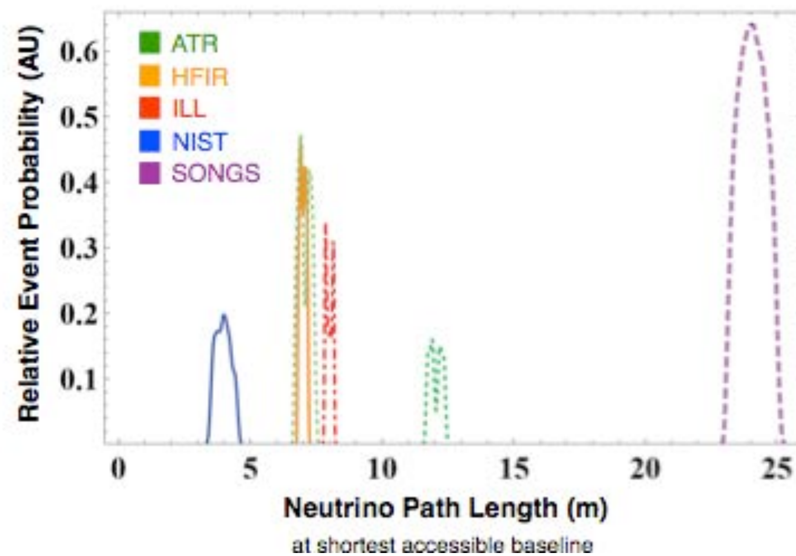


A Short-Baseline Reactor Experiment

Reactor Power and Duty Cycle

Reactor	Power (MW_{th})	Baselines (m)	Reactor On (Days)	Reactor Off (Days)	Down-Time
NIST	20	4-13	42	10	~32%
HFIR	85	6-8	24	18	~50%
ATR	250 (licensed) 110 (operational)	7-8 (restricted) 12-20 (full access)	48-56	14-21	~27%
ILL	58	7-9	50	41	~45%
SONGS	3438	24	639	60	8.6%

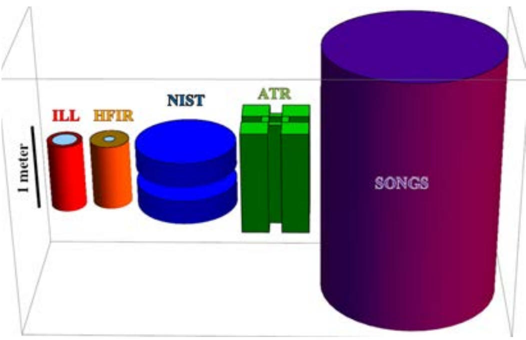




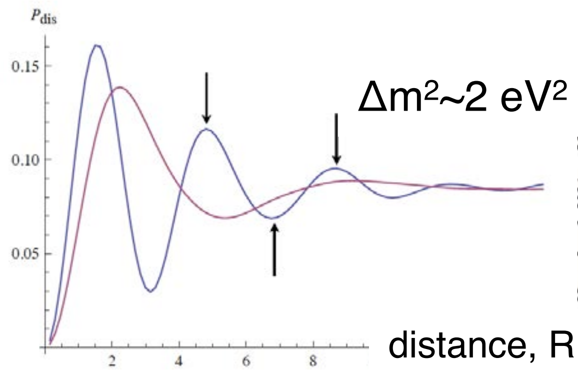
arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH

A Short-Baseline Reactor Experiment

Reactor Core Size

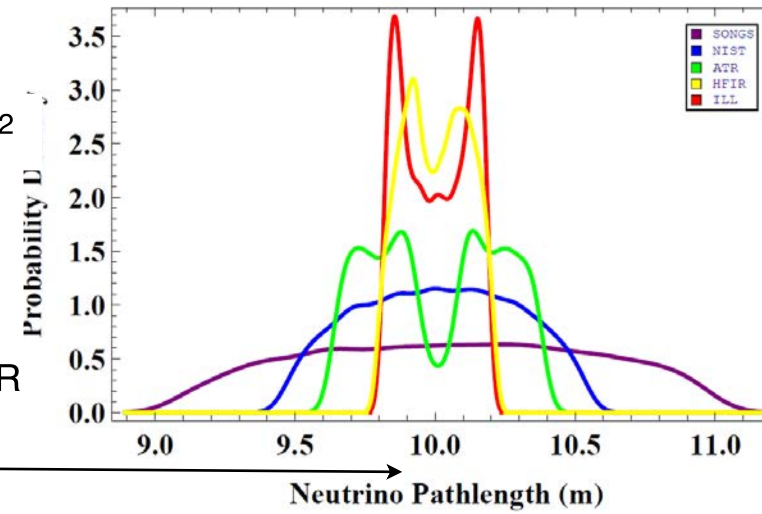


$\overline{\nu}_e$ Oscillation



Pathlength Spread

at detector from core



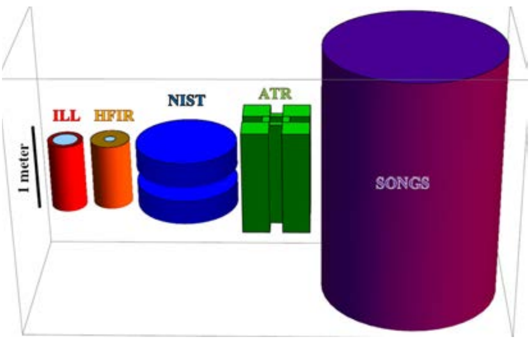
~10m

small core preferred to avoid
washing out oscillation effect

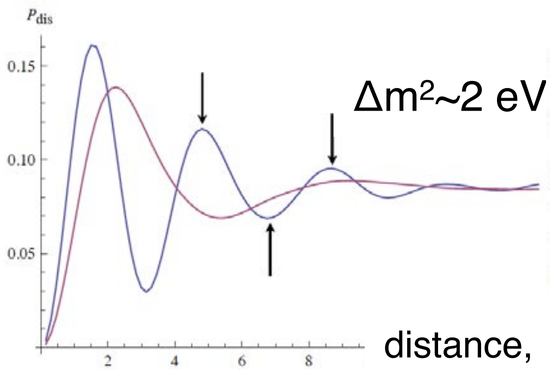
arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH

A Short-Baseline Reactor Experiment

Reactor Core Size



$\overline{\nu}_e$ Oscillation

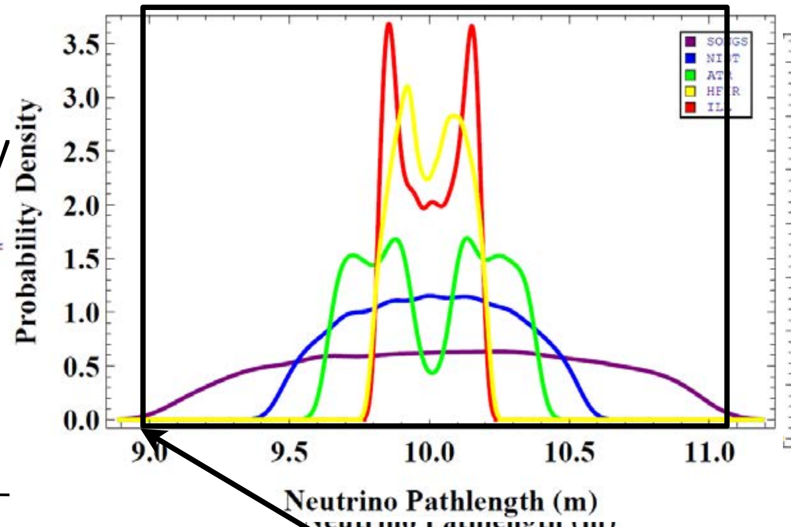


Δm^2~2 eV

distance,

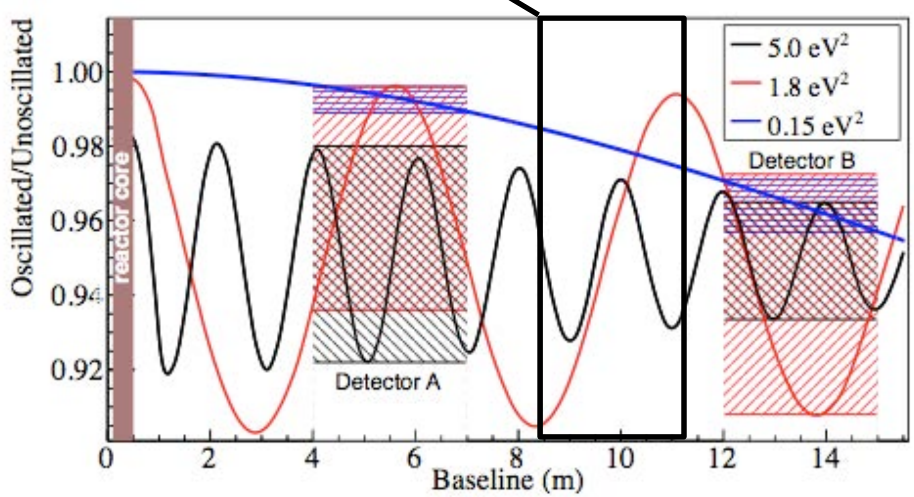
Pathlength Spread

at detector from core



~10m

small core preferred to avoid washing out oscillation effect

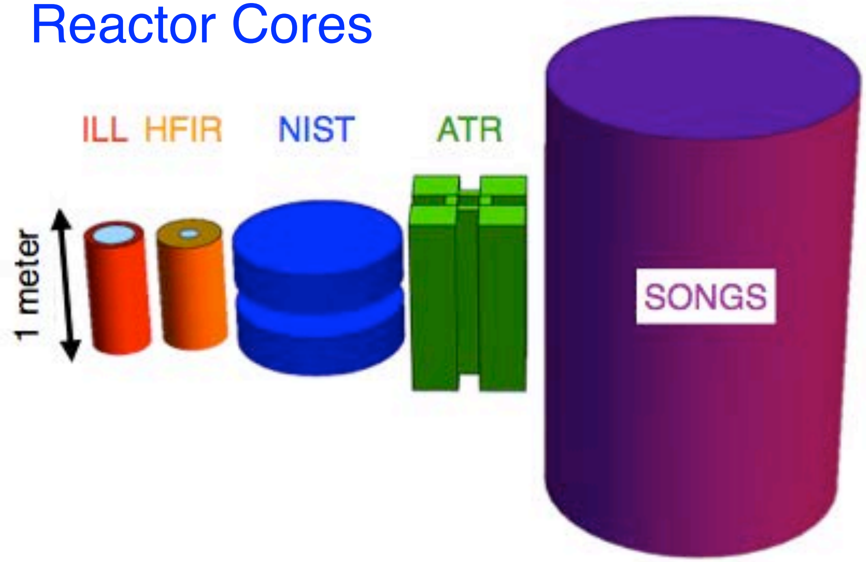


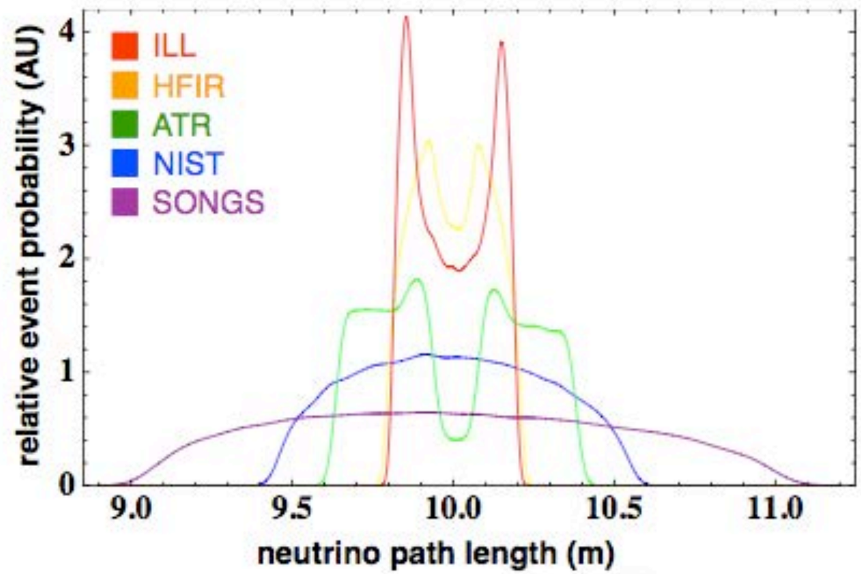
arXiv:1212.2182, PRD in press

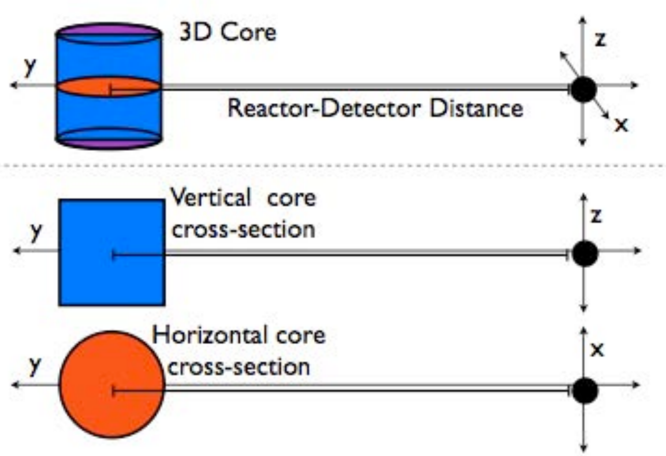
Littlejohn, Mumm, Tobin, KMH

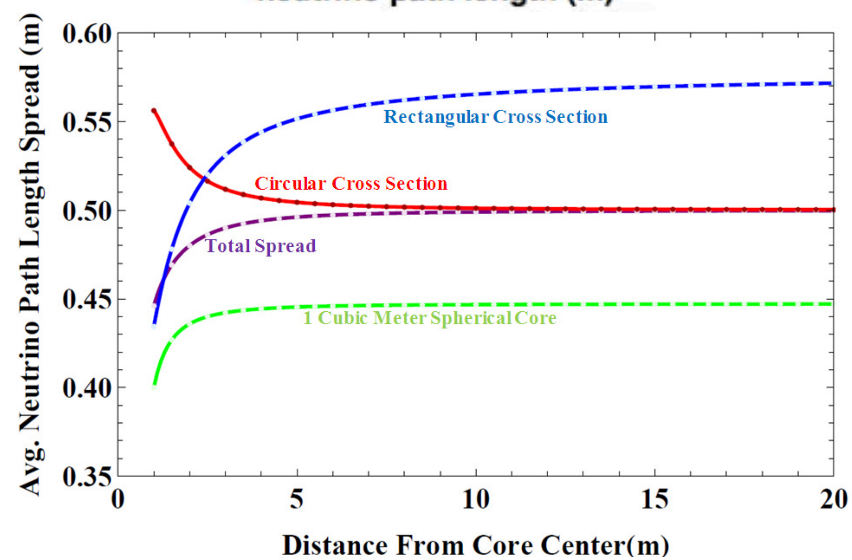
A Short-Baseline Reactor Experiment

Reactor Cores





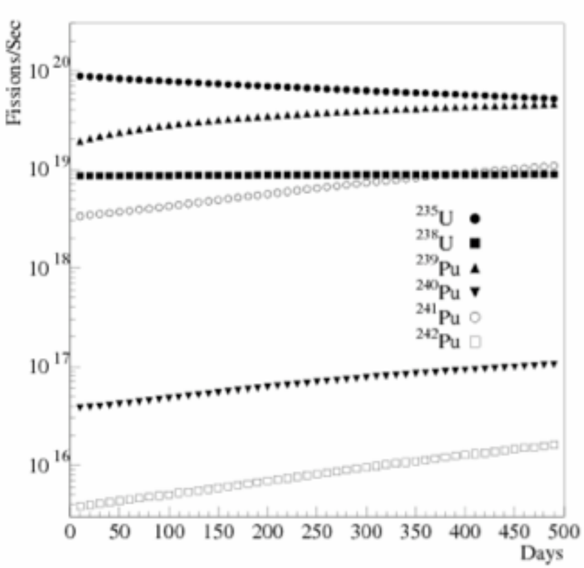




arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH

A Short-Baseline Reactor Experiment

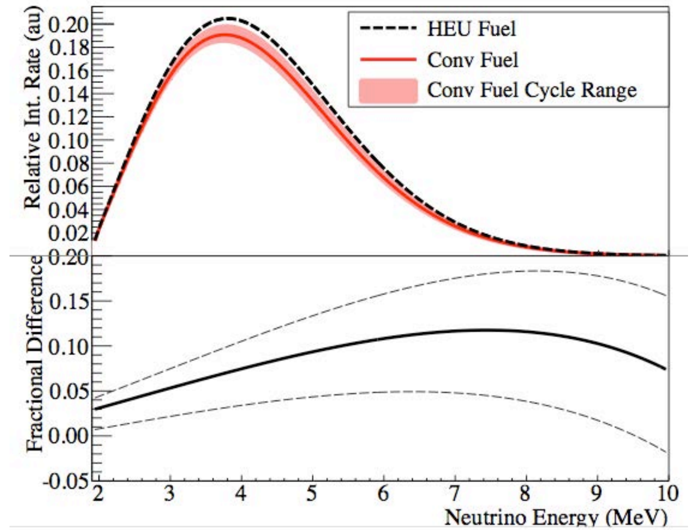
Burnup of Reactor Fuel

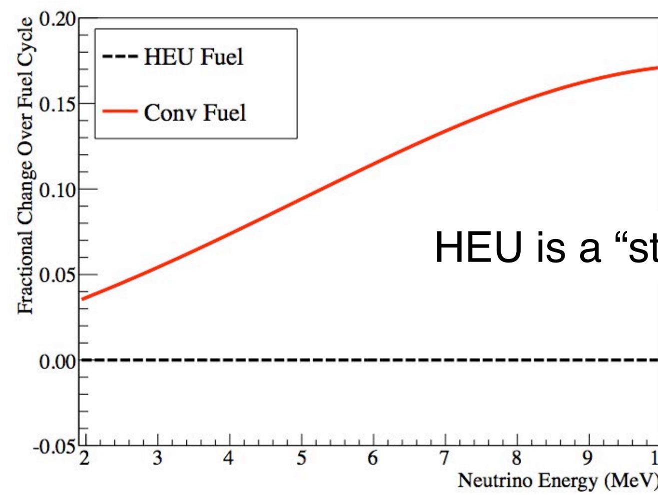


> 99.9% of detected $\overline{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Fuel Isotope	Time-Averaged Fission Fraction	
	Conventional Fuel	HEU fuel
^{235}U	0.59	>0.99
^{238}U	0.07	<0.01
^{239}Pu	0.29	<0.01
^{241}Pu	0.05	<0.01

HEU vs LEU Reactor Cores



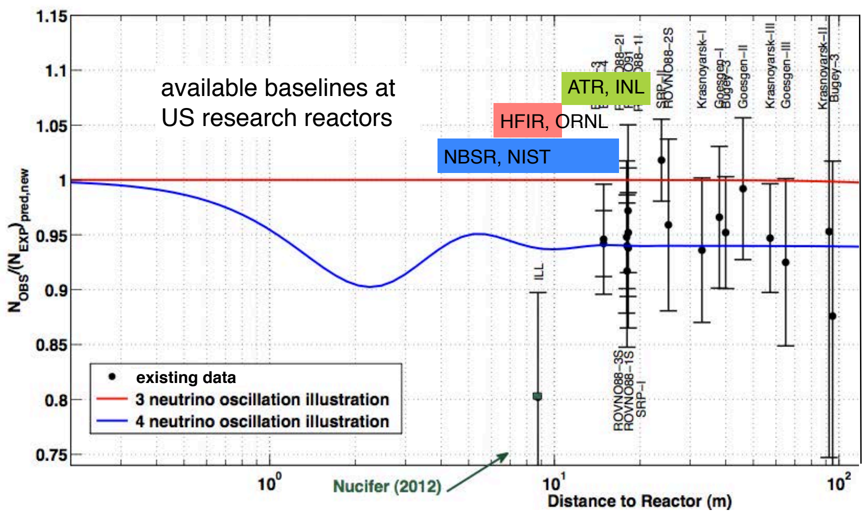


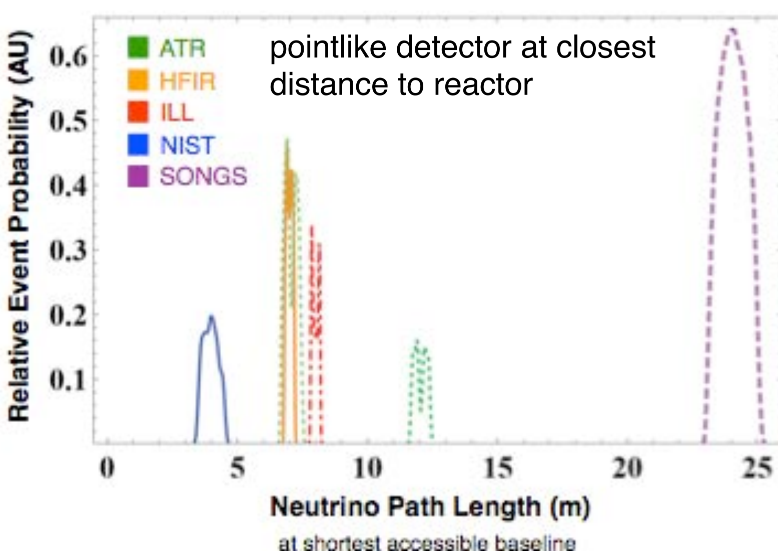
HEU is a “static” core

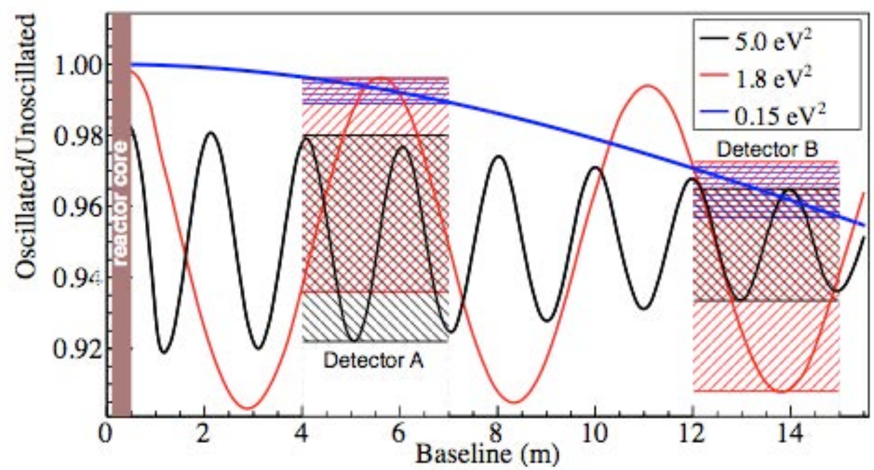
arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH

A Short-Baseline Reactor Experiment

Reactor-Detector Distance: How close do we need to be?





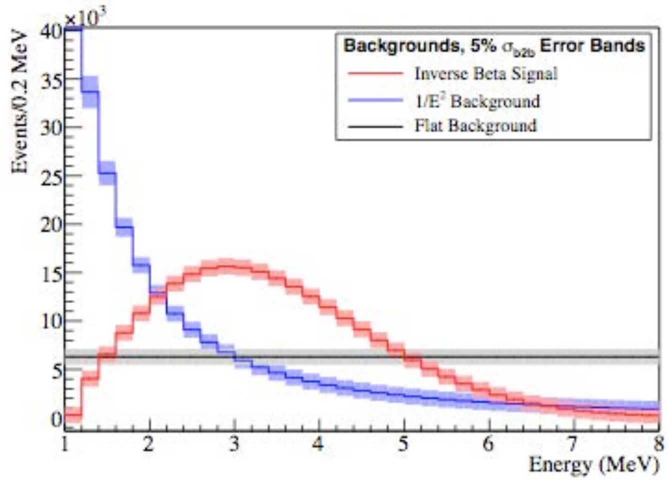


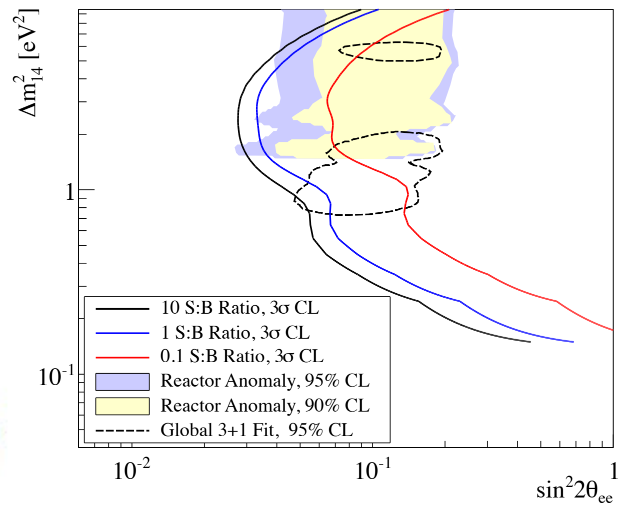
detector samples different oscillations for different Δm^2, → multiple detectors useful

A Short-Baseline Reactor Experiment

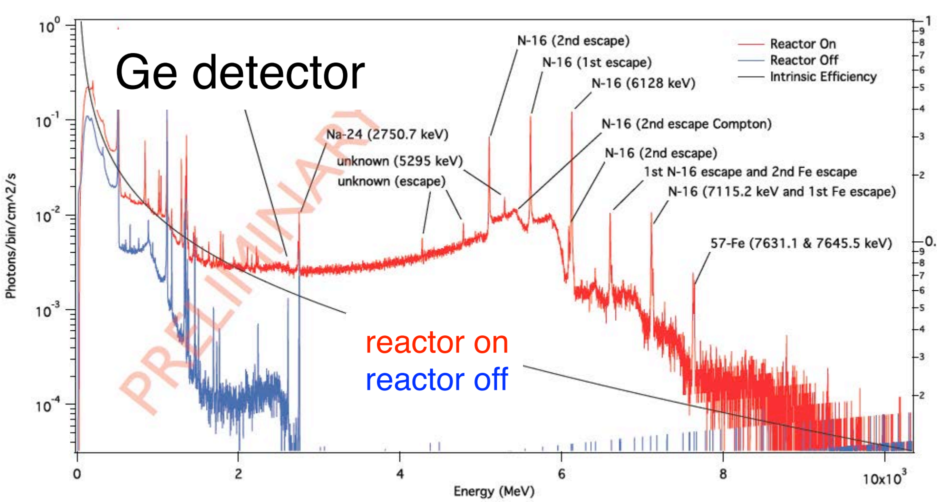
Backgrounds

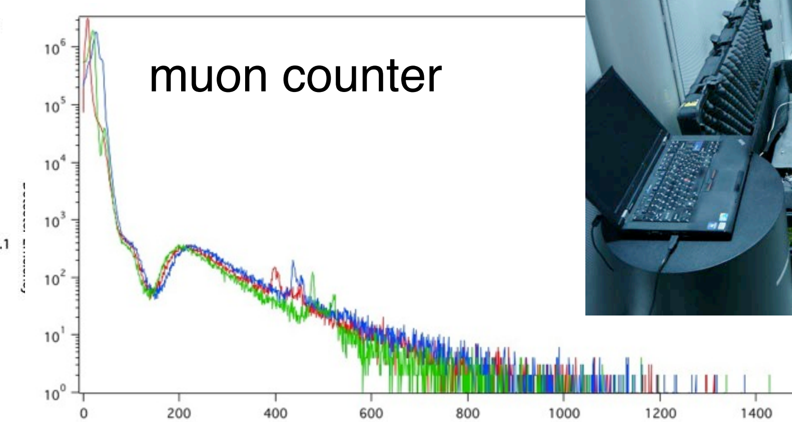
significant challenge, critical to know/measure background distributions

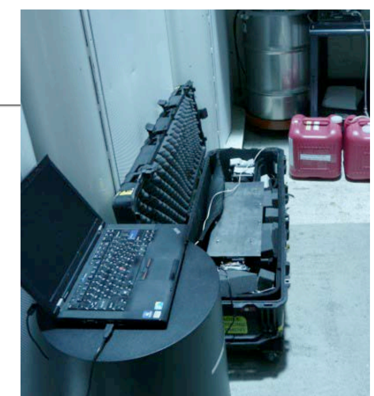




Background studies in progress at NIST

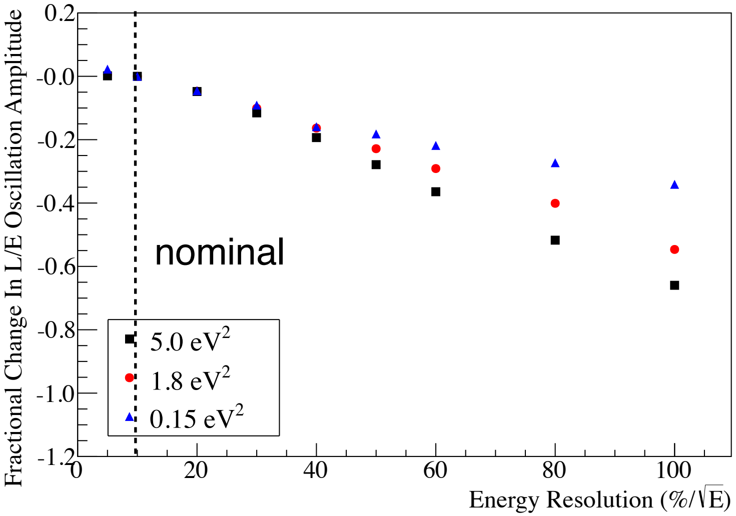


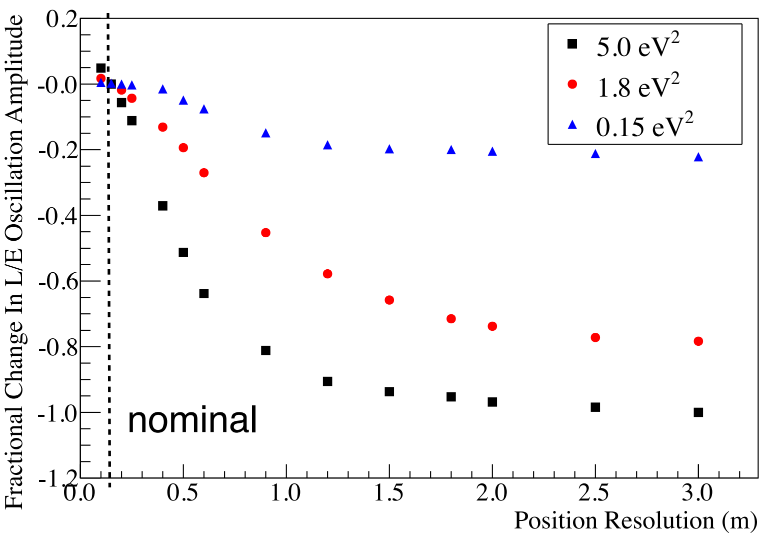


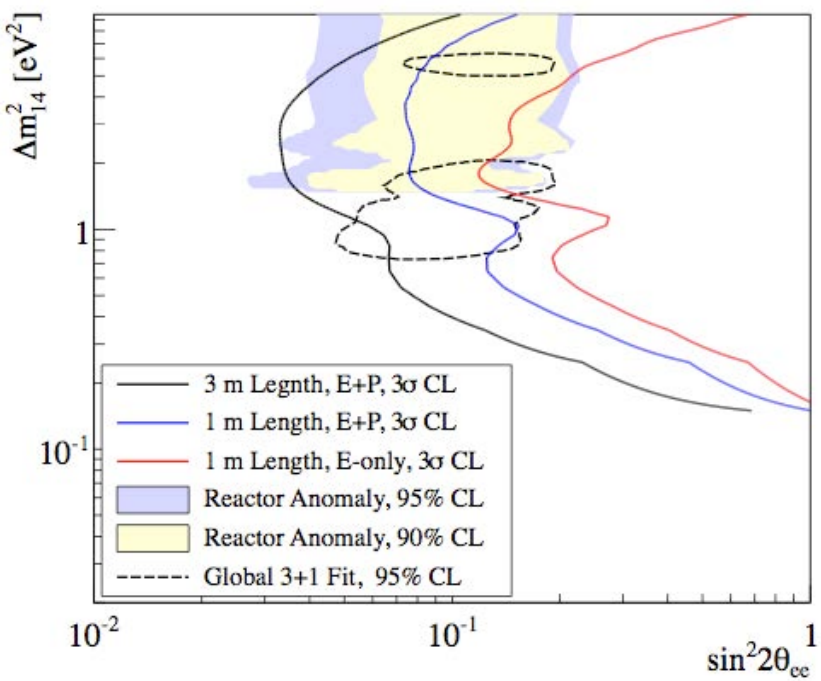


A Short-Baseline Reactor Experiment

Detector Resolution



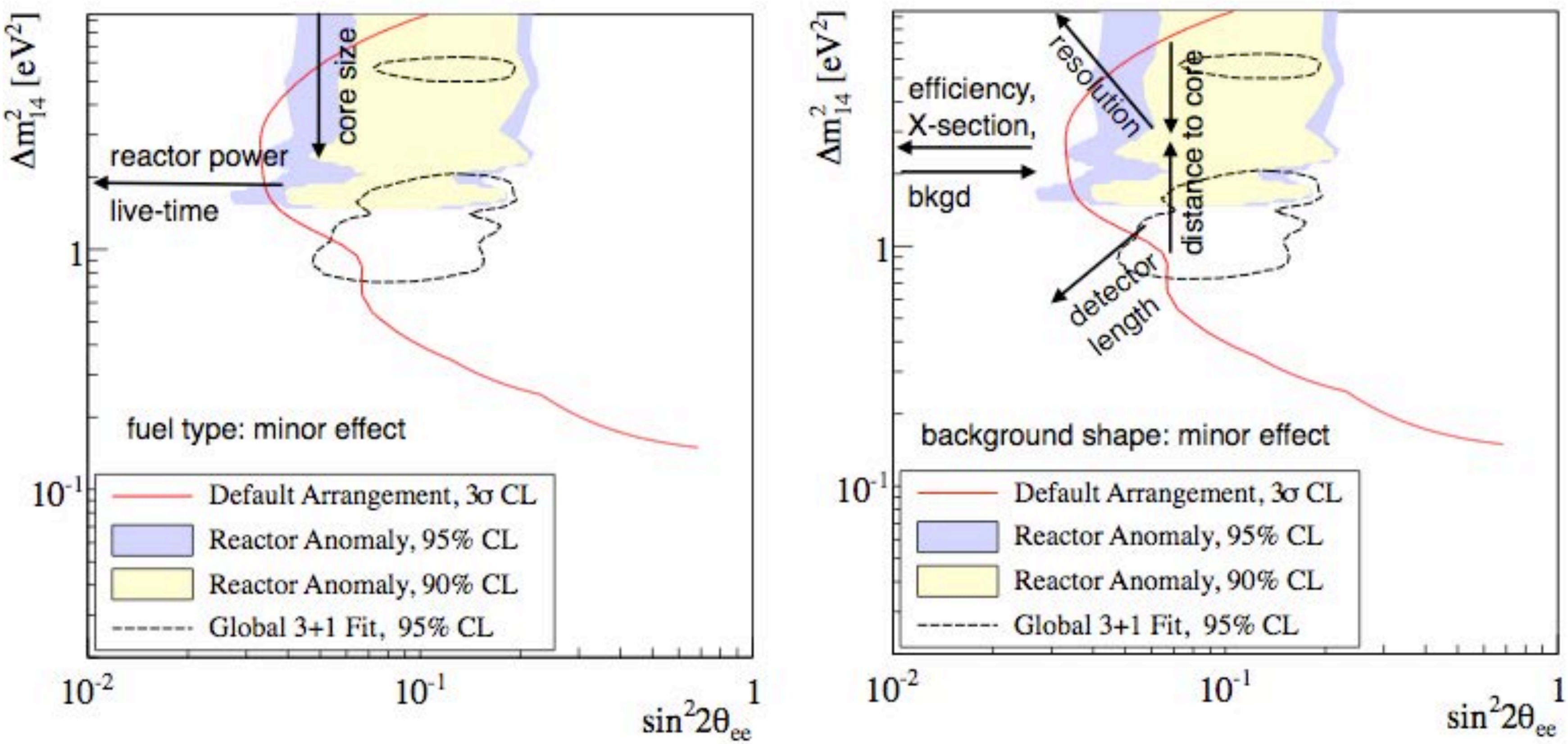




arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH

A Short-Baseline Reactor Experiment

Experimental Parameters



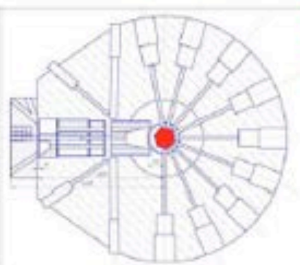
detailed experimental design site specific

arXiv:1212.2182, PRD in press
Littlejohn, Mumm, Tobin, KMH

New Short Baseline Reactor Experiments

NEUTRINO-4 experiment

Preparation at WWR-M reactor (18 MW) in PNPI (Gatchina)



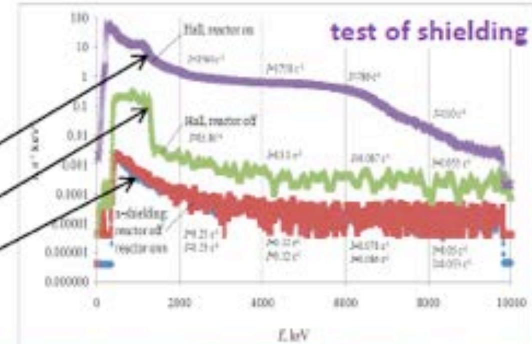
Reactor power - 18 MW

Size of active core – 0.6 m

reactor on without shielding

reactor off without shielding

reactor on/off with shielding



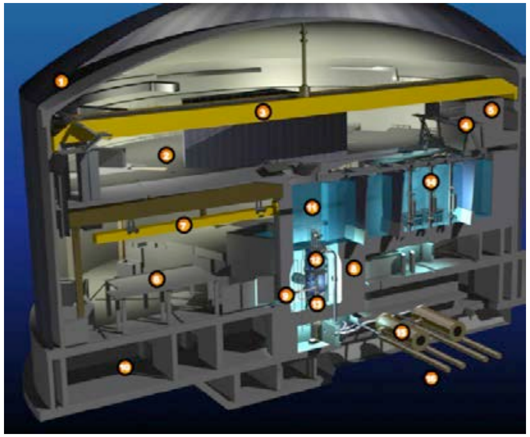
Installation of 2 sections test antineutrino detector with liquid scintillator (total volume 0.4 m^3)

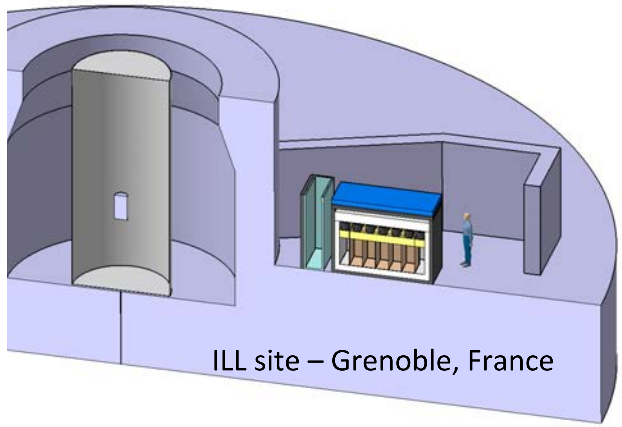
Installation of anticoinsidence shielding from plastic scintillator 0.5x0.5x0.125 m^3 with PMT (32 pieces)

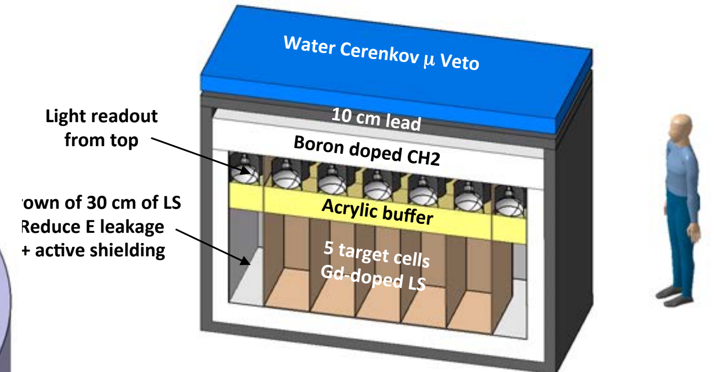
A.Serebrov, PNPI

New Short Baseline Reactor Experiments

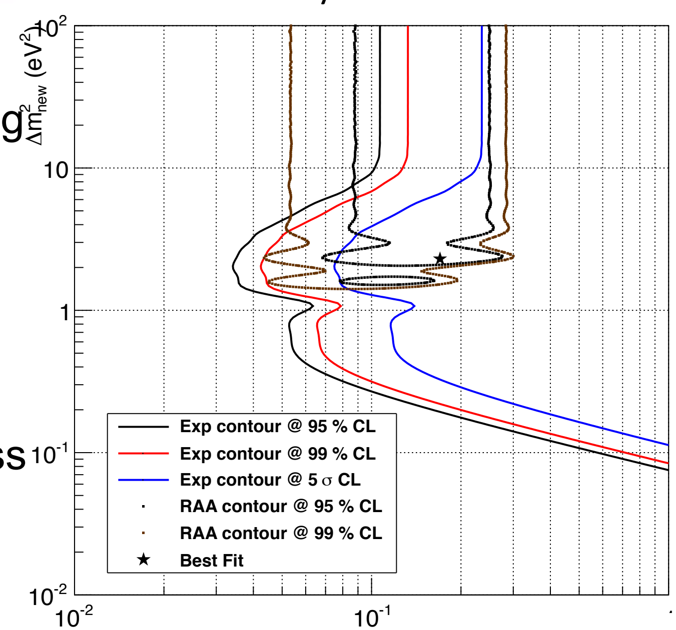
STEREO at ILL







Shape analysis +
3.5 % uncertainty on normalization



Ref: Lhuillier

Reactor Site

50 MW compact core
(φ=40cm, h=80 cm)

Short baseline
[7-9] m

Pure ^{235}U spectrum

Background Rejection

Large passive and active shielding
15 m.w.e. overburden

Pulse Shape Discrimination

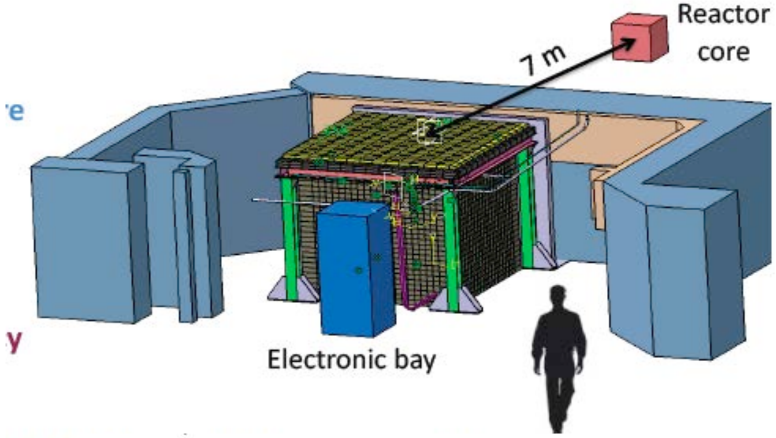
Segmented detector

On-site measurements in progress

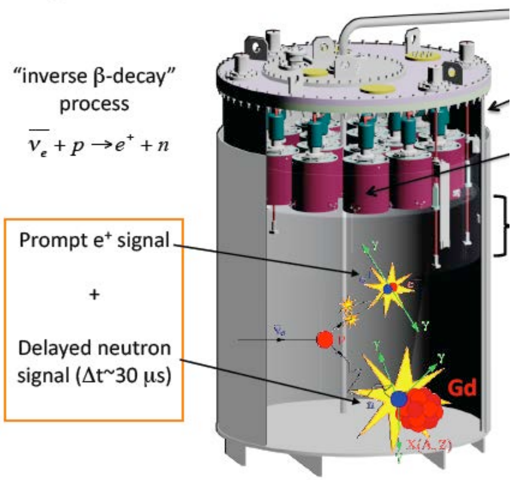
Aim for first data in 2015
Funding decision in 2013

Reactor Monitoring Experiments

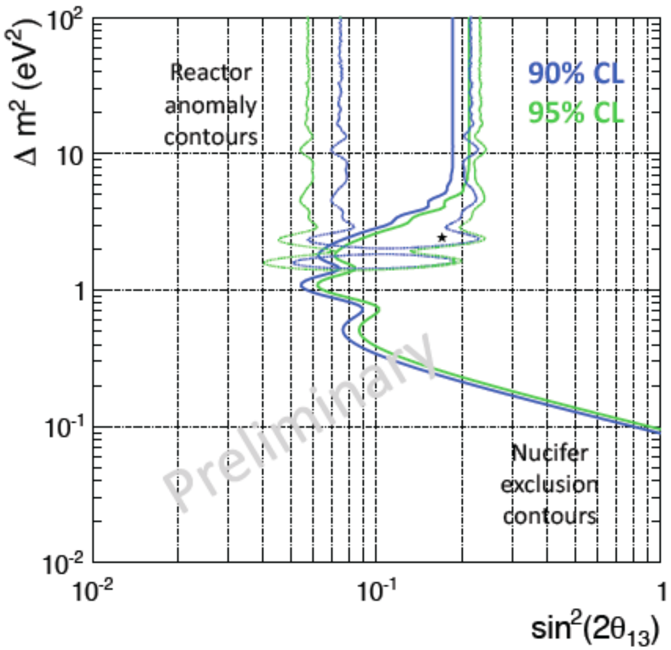
NUCIFER at Osiris



core: σ~0.3m
baseline: 7m



- Norm error = 4%
- 100 days full power @ Osiris
- S/B = 1 (?), assuming same shapes (worst case).
- E resol = 0.15*E

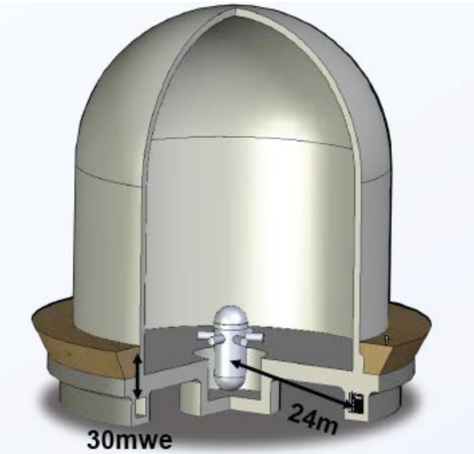


Pre-industrial, unattended reactor neutrino monitor

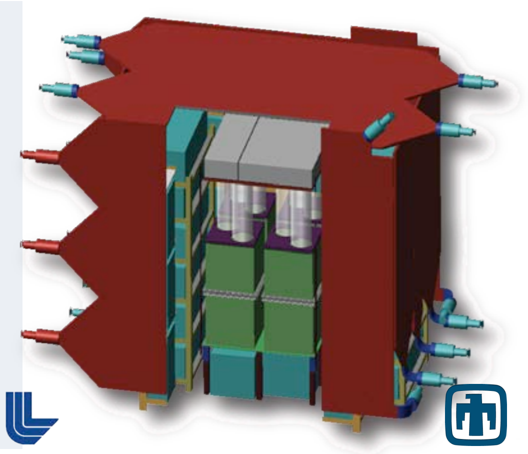
May be used to test reactor anomaly with compact core. PSD R&D for background rejection.

SONGS Reactor Monitoring Experiment

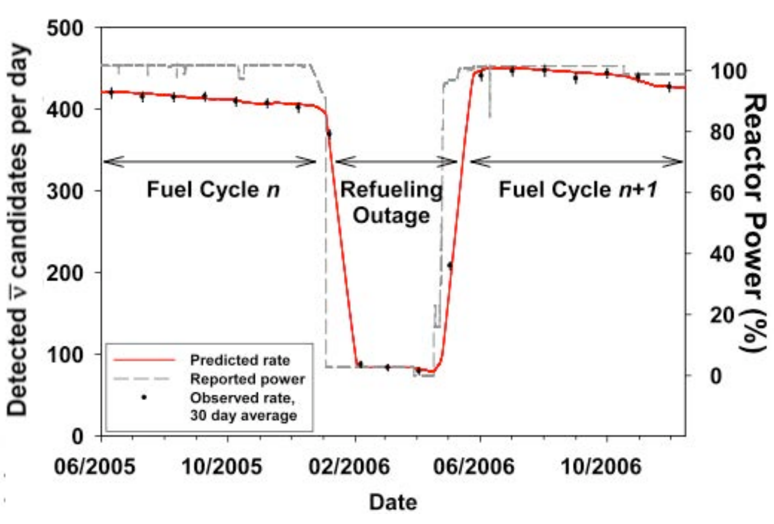
SONGS - San Onofre Nuclear Power Generating Station



- High Flux: ~10^{17} ν/m²/s
- 130-180m to other reactor
- Gallery is annular – unfortunately no possibility to vary baseline



Fuel diversion sensitivity determined by effect on burnup slope, possibility of power changes



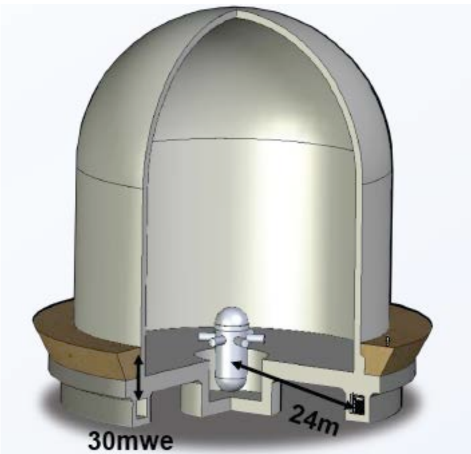
SONGS1 detector (0.64t GdLS) deployed 24m from PWR, with ~25mwe overburden

Provided verification of operational history, fuel loading through burnup

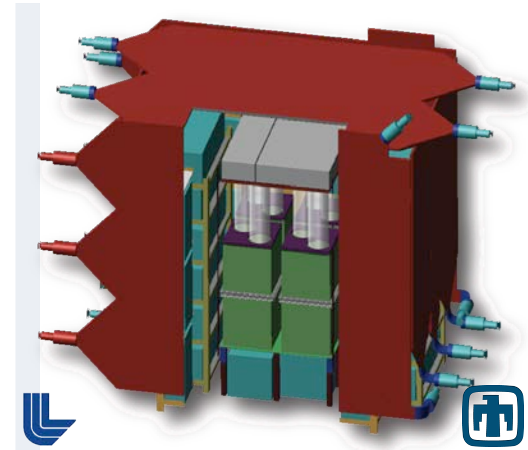
Signal rate depends on power and fuel composition

SONGS Reactor Monitoring Experiment

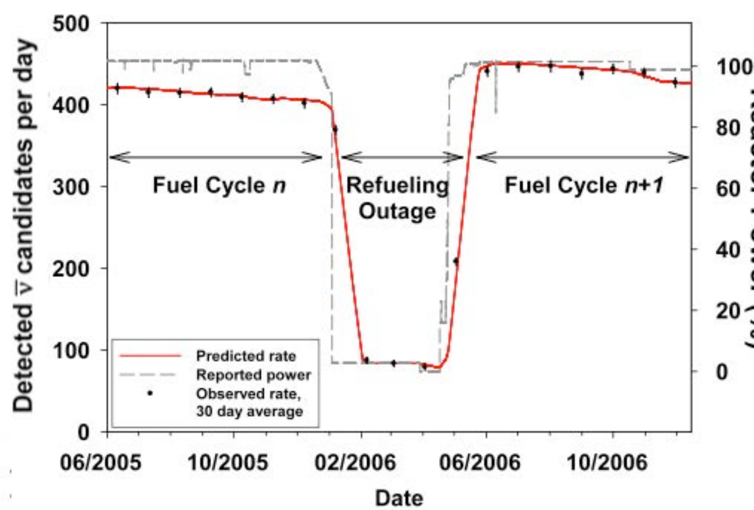
SONGS - San Onofre Nuclear Power Generating Station

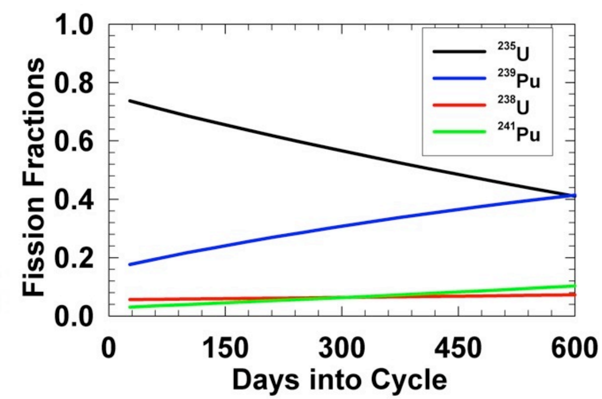


- High Flux: ~10^{17} $\nu/m^2/s$
- 130-180m to other reactor
- Gallery is annular – unfortunately no possibility to vary baseline



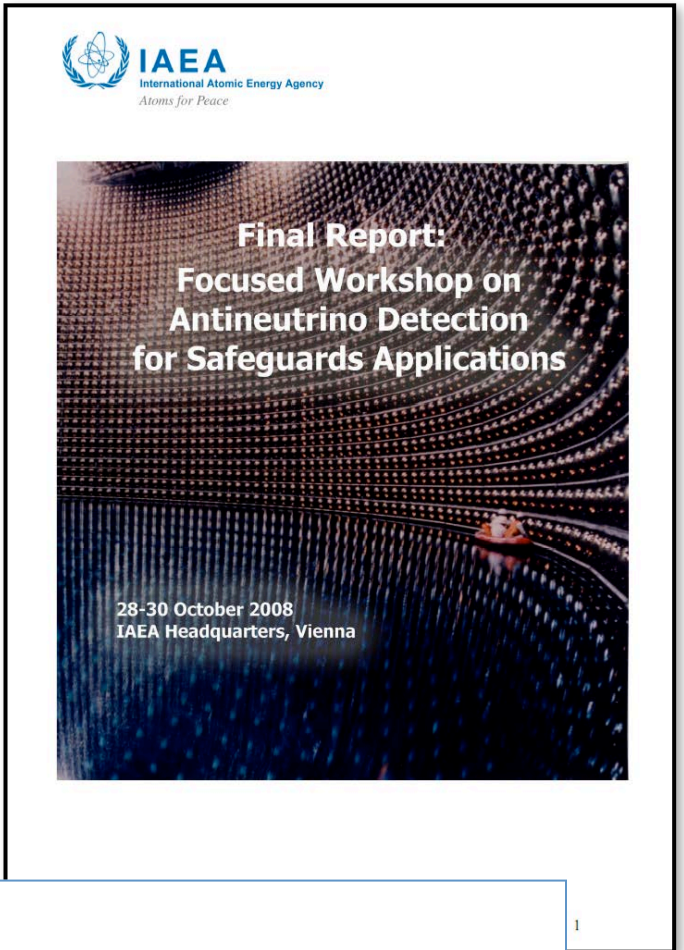
Fuel diversion sensitivity determined by effect on burnup slope, possibility of power changes





IAEA and Nuclear Non-Proliferation

- IAEA Interest:
  - Improved knowledge of input plutonium mass at reprocessing facility or repository – currently no better than 5-10%
  - Research reactor power monitoring – currently uses intrusive tech.
  - Verification of bilateral agreements – maybe future role for agency
  - Detection with minimal overburden – allows widespread deployment



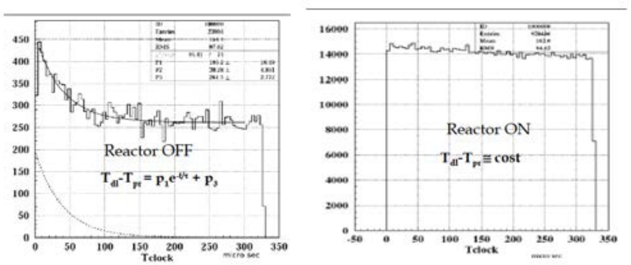
IAEA
International Atomic Energy Agency
Atoms for Peace

AGENDA

Ad Hoc Working Group on Safeguards Applications of Antineutrino Detectors, 14 September 2011, Vienna, Austria

Operation with Minimal Overburden and in High Backgrounds

CORMORAD: Gd/Plastic segments, no shield/veto



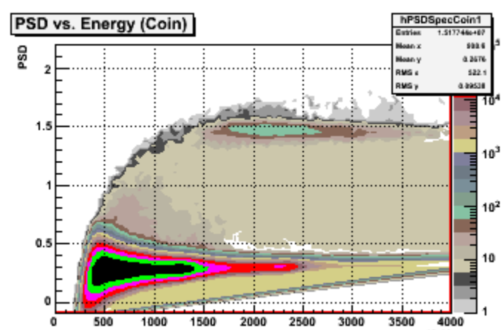
Rnd. Bkg x10^2 Rx On/Off

LLNL/SNL: Gd-Water Cerenkov, poly shield/veto

Exp.signal/Obs.bkg ~1/100

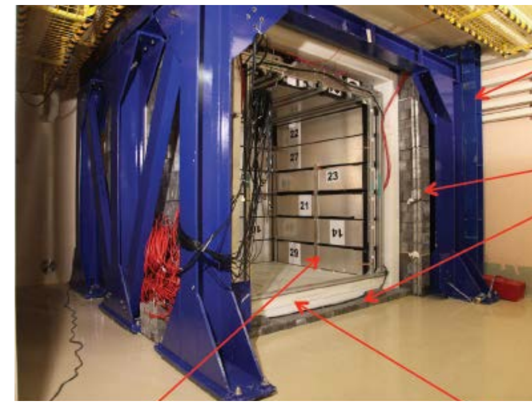
PANDA36: Gd/Plastic segments, no shield/veto

SNL/LLNL: LiZnS/Plastic, poly shield/veto



Neutron capture PSD gives >10^2 bkg rejection

Nucifer: GdLS, lead/poly/ veto, 7m from RR

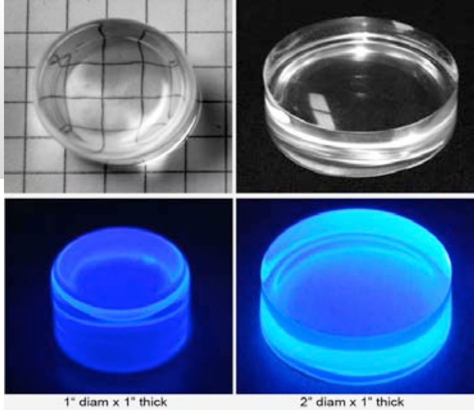


Careful assessment of cosmogenic and reactor background required

Detectors with high selectivity of e+ and/or neutron capture required

Ref: Bowden, LLNL

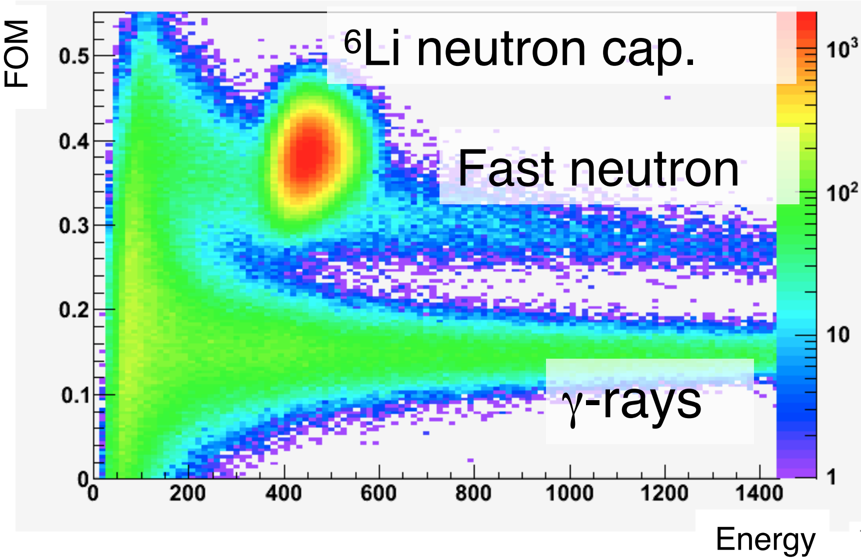
Scintillator R&D Interests



Develop organic crystals, liquids and plastics with good PSD and ^{6}Li loading

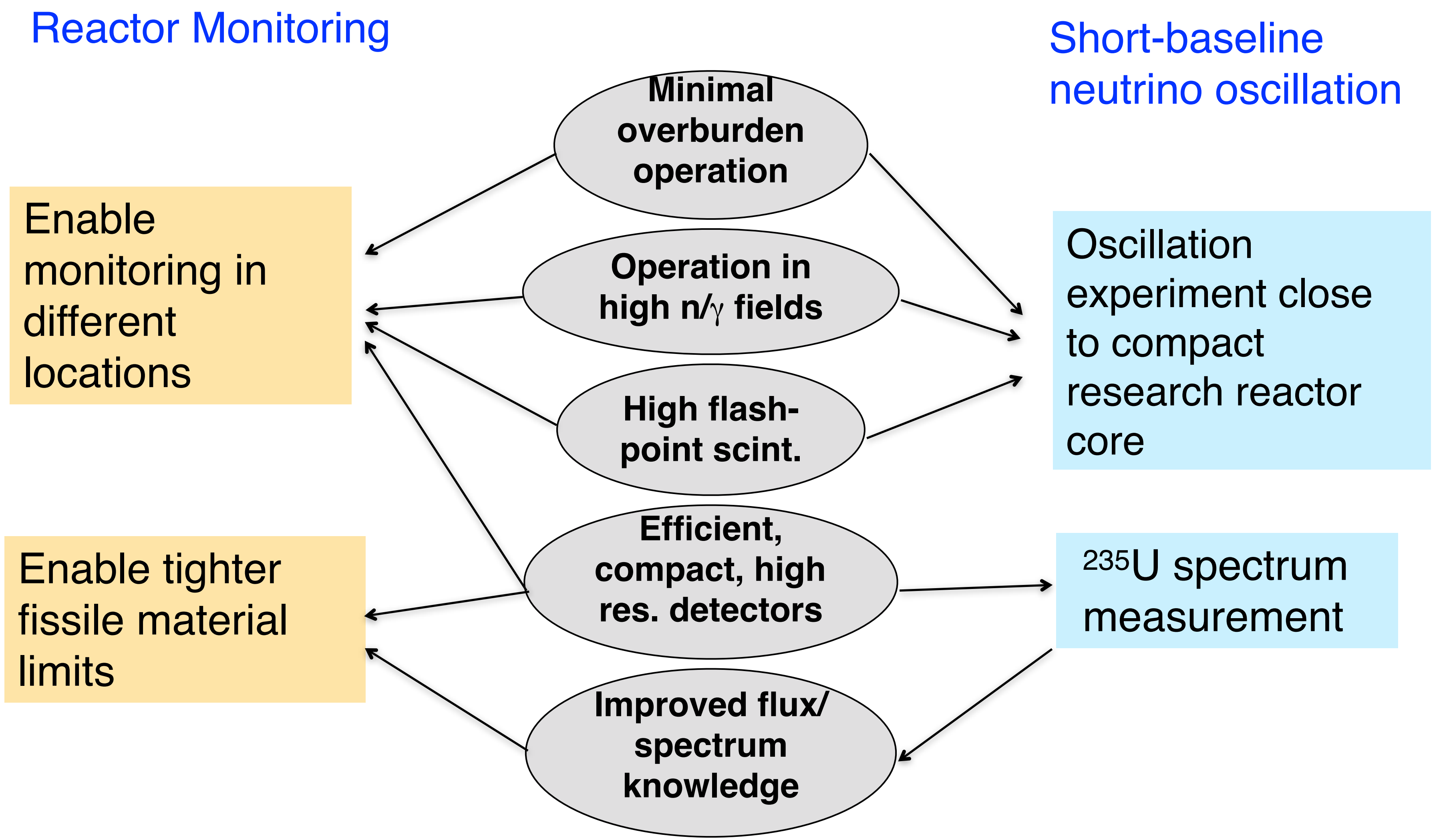
Status

- Good PSD obtained in plastic – now available commercially (undoped)
- Incorporated ^{6}Li, ^{10}B in plastic and liquid
- ^{6}Li plastic not quite ready for large scale production
- Long term stability of ^{6}Li liquid not yet tested



Ref: Bowden, LLNL

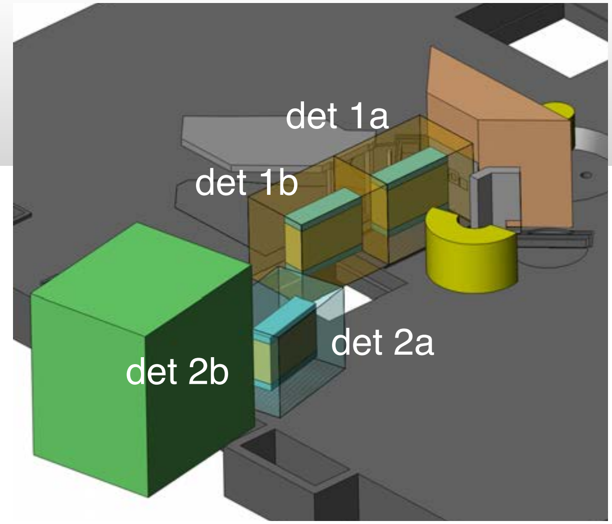
Reactor Monitoring and Neutrino Oscillations

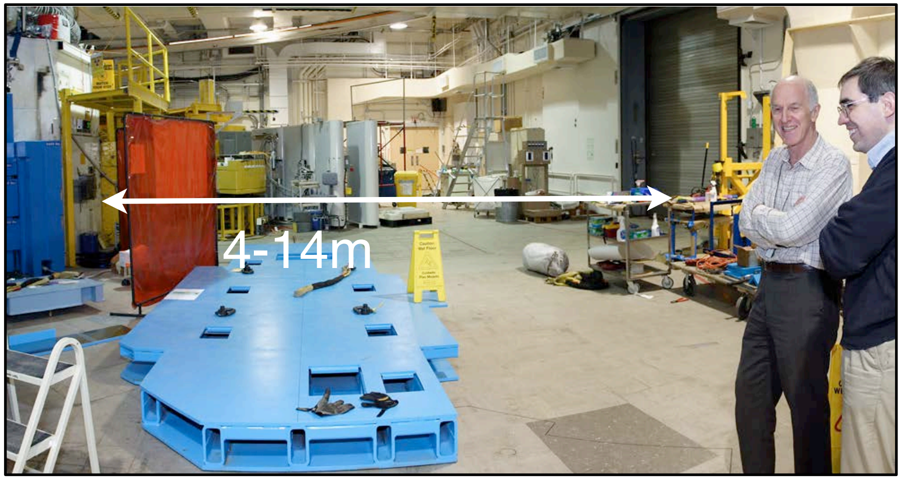


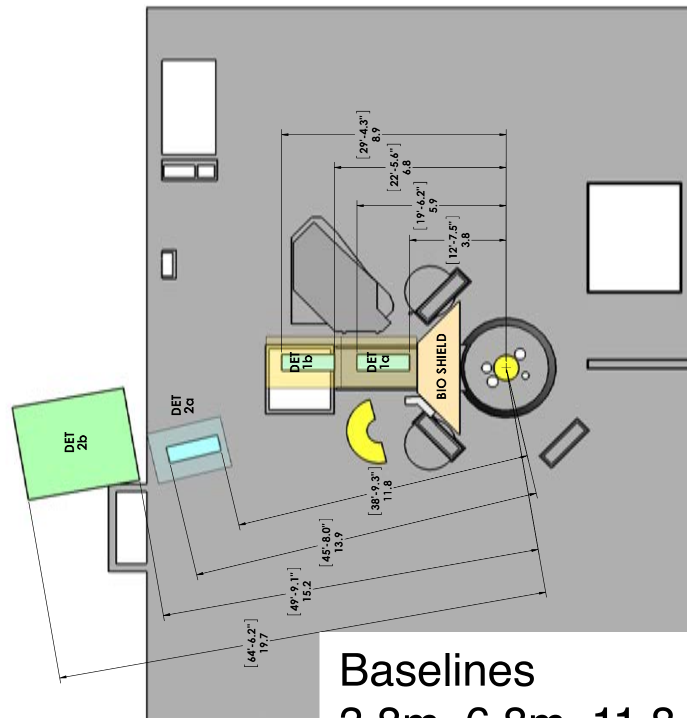
Ref: Bowden, LLNL

A Reactor Experiment at NIST?

Possible Detector Locations



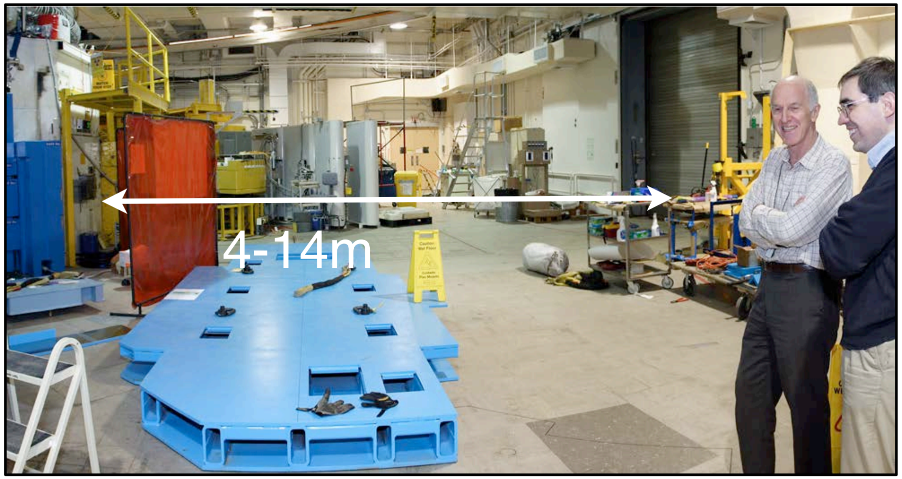


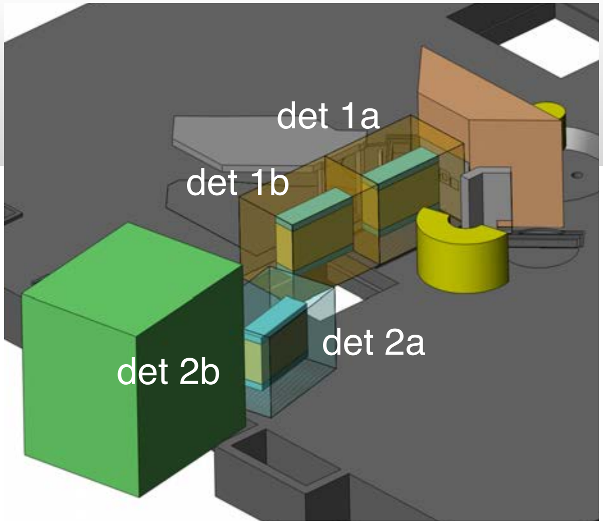


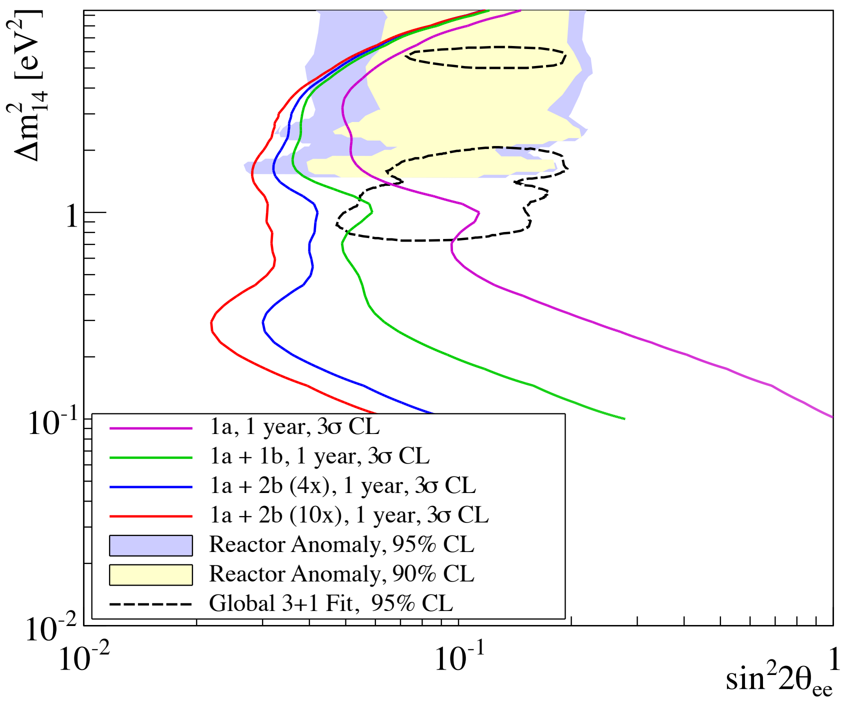
Baselines
3.8m, 6.8m, 11.8, 15.2m
(up to 25m?)

A Reactor Experiment at NIST?

Possible Detector Locations

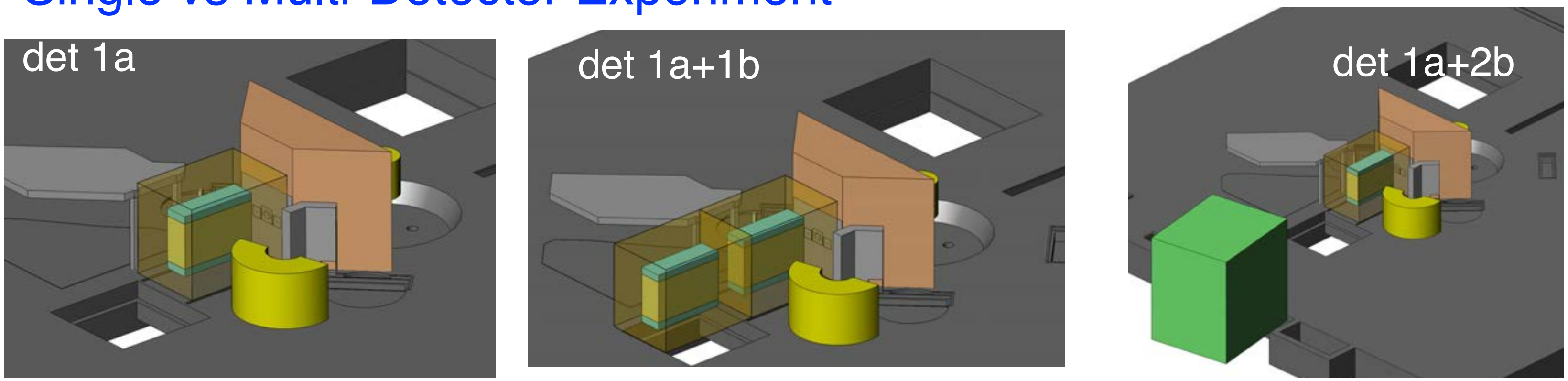




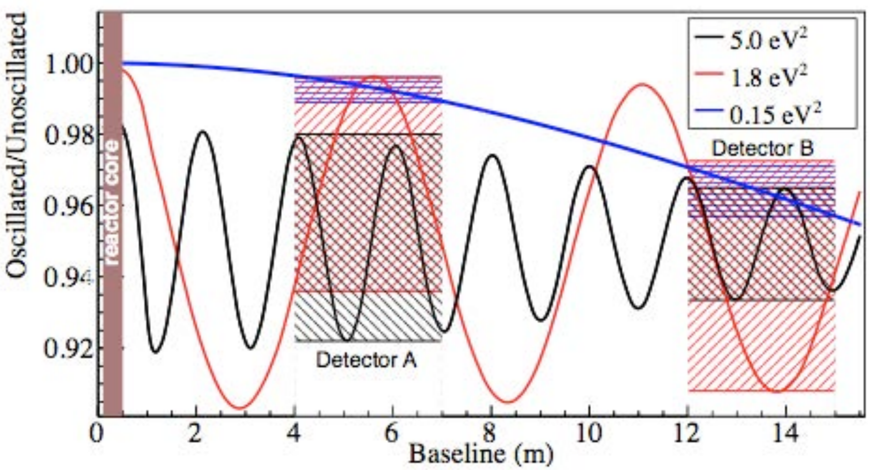


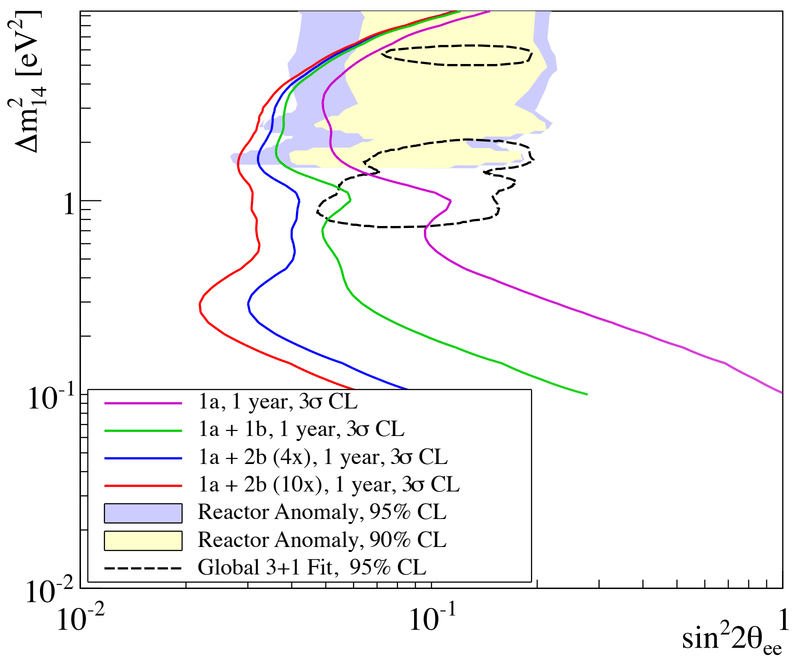
A Reactor Experiment at NIST?

Single vs Multi-Detector Experiment



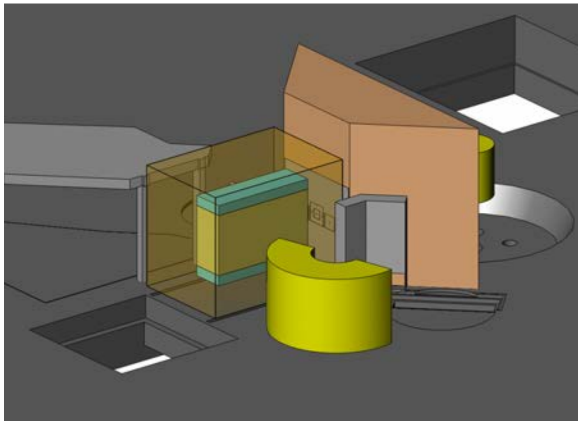
2 detectors significantly increase the sensitivity of experiment, optimization in progress

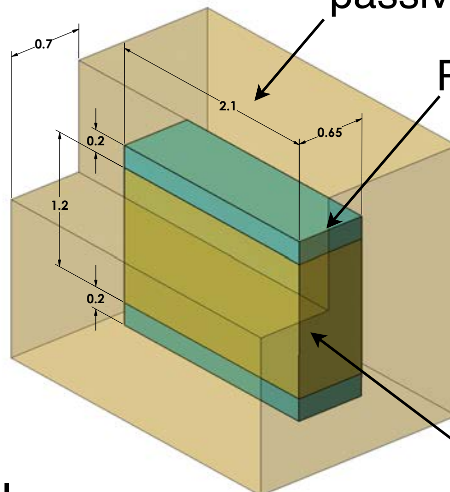




A Reactor Experiment at NIST?

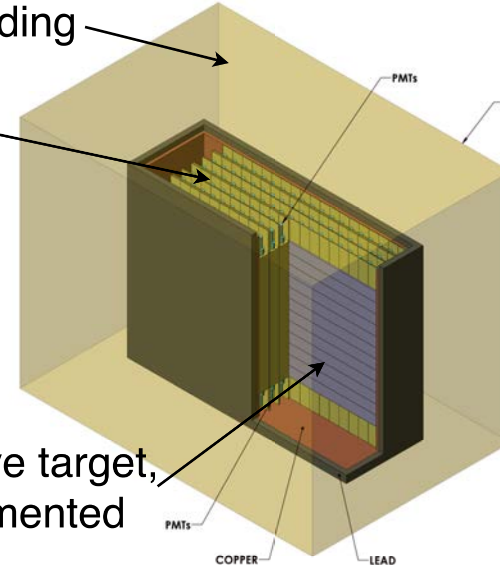
Detector Module





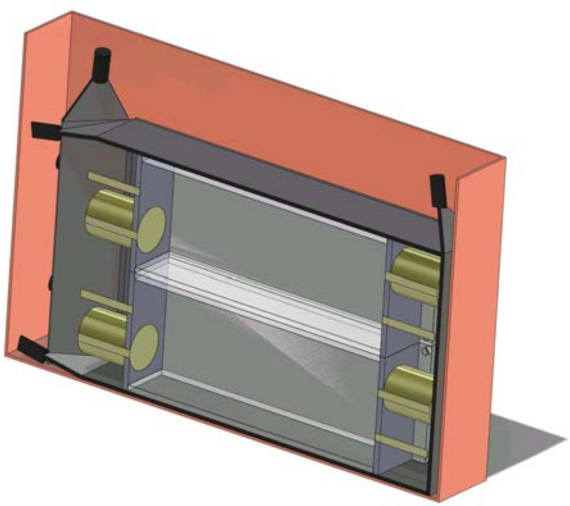
passive shielding

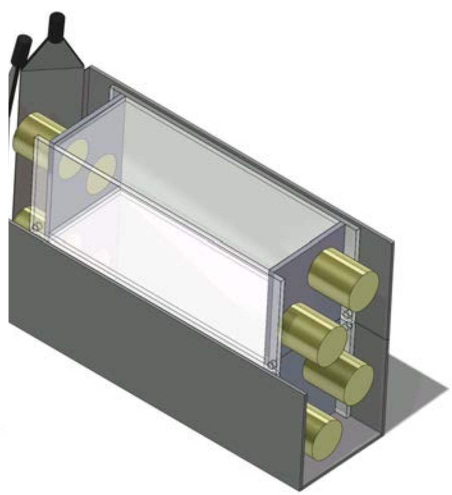
PMTs



active target, segmented

detector modules are movable
low-utility use





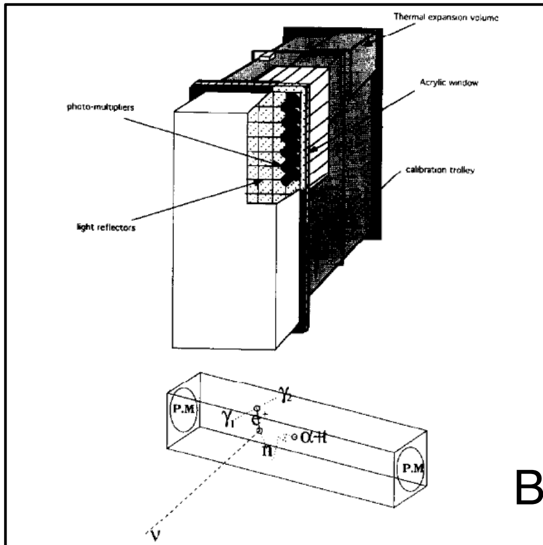
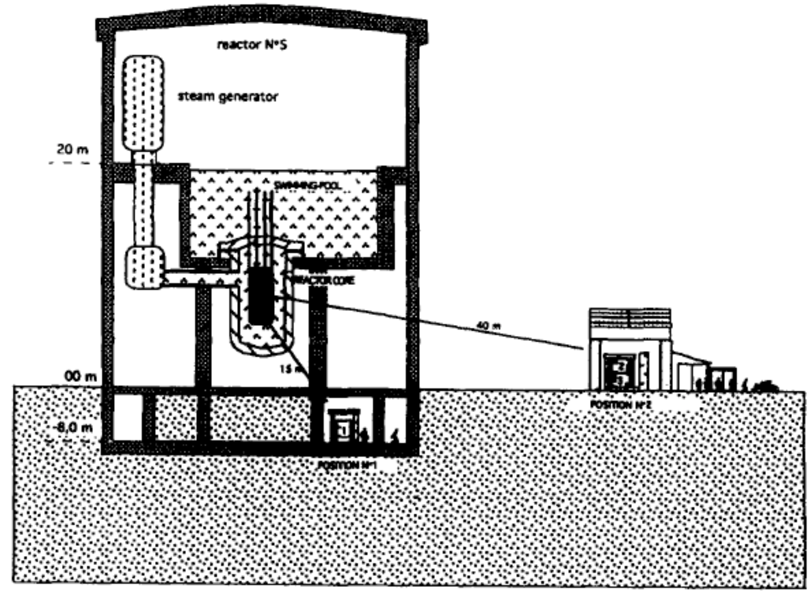


Fig. 1. A schematic view of one detection module and of the detection principle.

Bugey

What are the expected improvements over Bugey-3?

- smaller core size
  - Bugey ran at a PWR, and to make matters worse, the shortest baselines were almost below it, looking along the long axis of that core

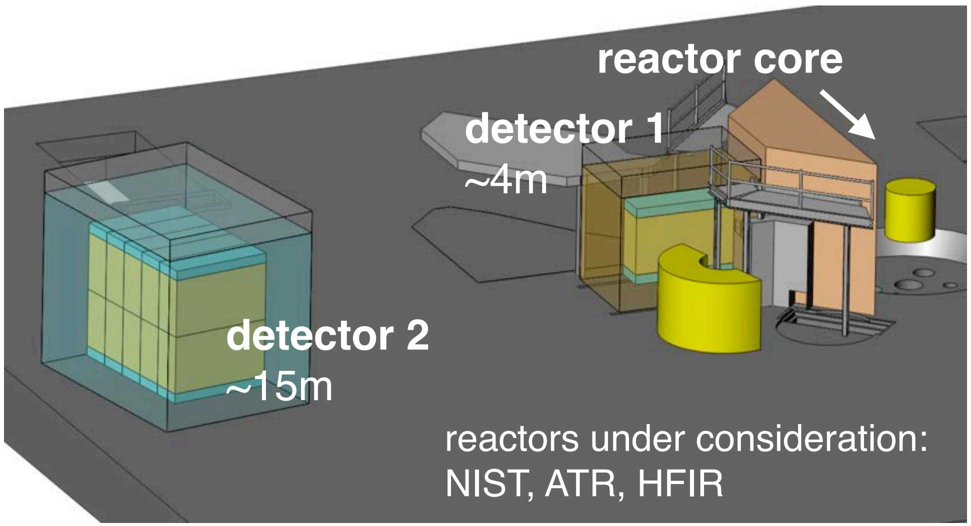


- shorter baseline
  - at US research reactors can get as close as 4m (Bugey > 15 m)
- better scintillator stability
  - some of the Bugey modules/detectors deteriorated
  - demonstrated stability of Gd-LS at Daya Bay for several years. Daya Bay scintillator produced by BNL
- possibly better pulse shape discrimination (PSD)?

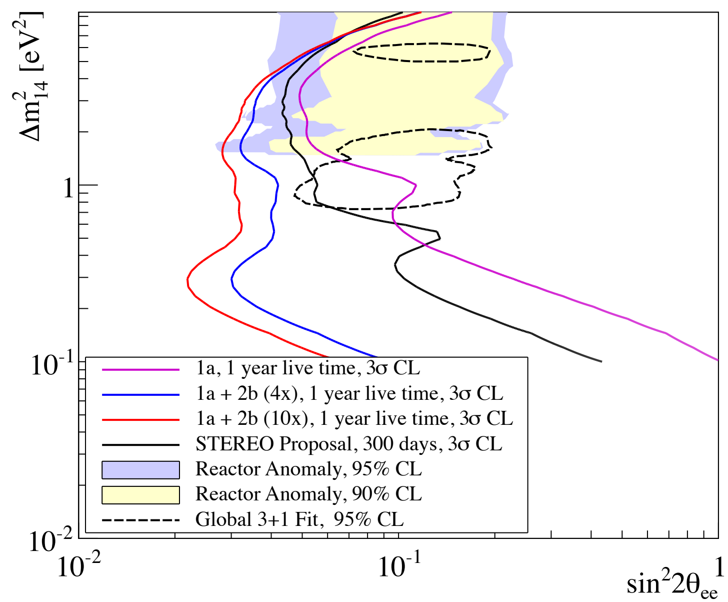
US Short-Baseline Reactor Experiment

Objectives: - short-baseline sterile neutrino oscillation search
- precision measurement of reactor $\overline{\nu}_e$ spectrum for physics and safeguards
- develop antineutrino-based reactor monitoring technology for safeguards

2-detector oscillation experiment



discovery potential



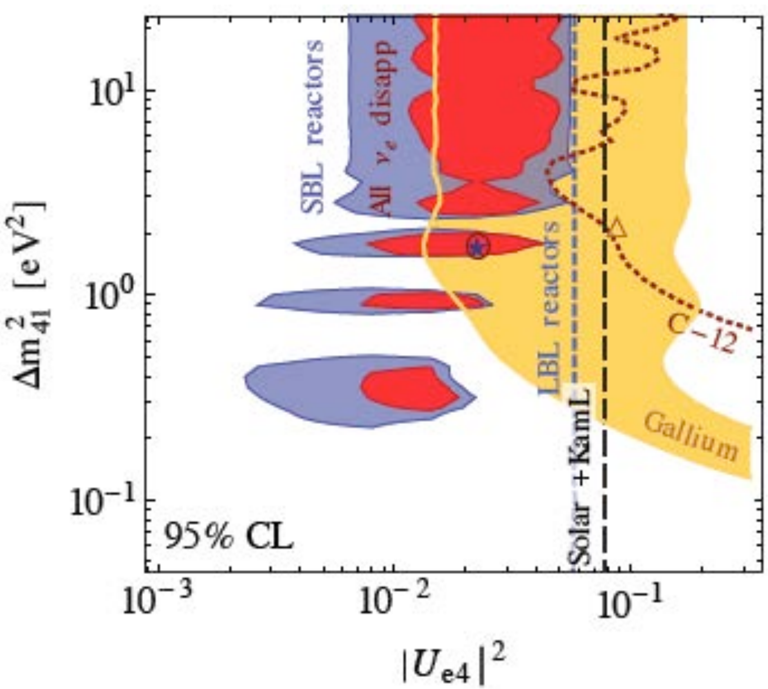
current R&D:
- novel ^{6}Li scintillator
- segmented detector and shielding design
- background measurements in progress
- background rejection and pulse shape analysis

FY13-14 - R&D
FY14-15 - design&construction
FY 2016 - first data? (technically limited schedule)

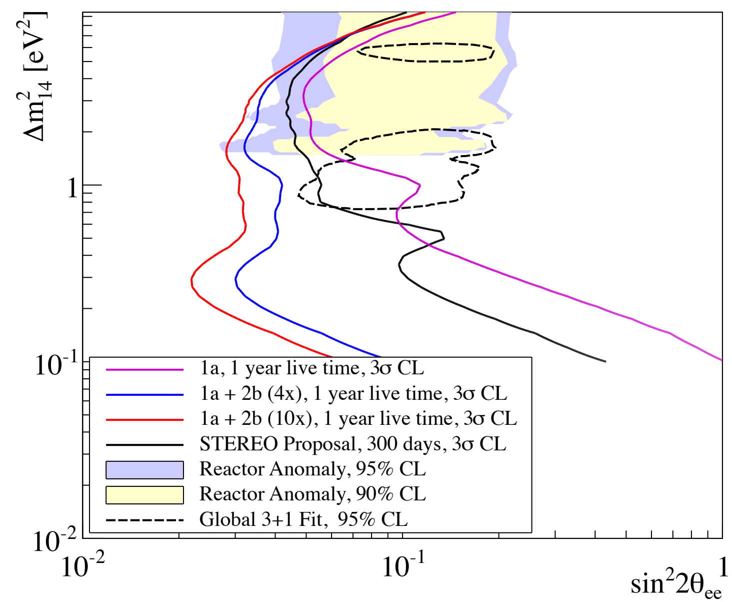
US Short-Baseline Reactor Experiment

Objectives:
- short-baseline sterile neutrino oscillation search
- precision measurement of reactor $\overline{\nu}_e$ spectrum for physics and safeguards
- develop antineutrino-based reactor monitoring technology for safeguards

current constraints



discovery potential



FY13-14 - R&D
FY14-15 - design&construction
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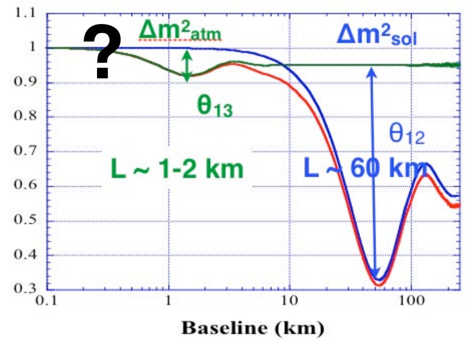
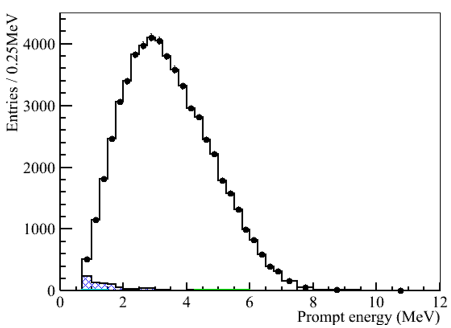
Scientific Opportunities for a US Reactor Experiment

Searches for new physics

- probe **short-baseline oscillations** and test **sterile ν hypothesis**



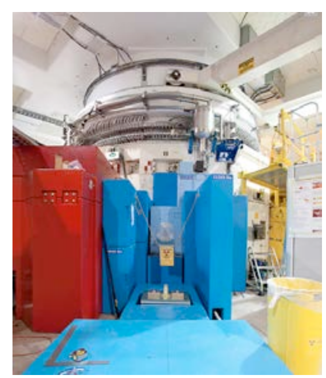


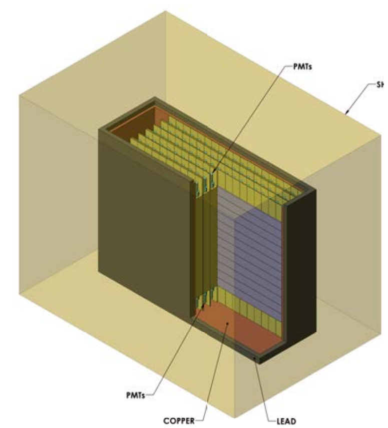
Reactor cores, fuel, and antineutrino spectra

- precision measurement of **HEU reactor antineutrino spectrum**
- studying **HEU to LEU core conversion** at US research reactors

Detector development

- demonstrate operation of **on-surface antineutrino detectors**
- synergies with **safeguard** and reactor monitoring
- develop **scintillators for neutron detection** with PSD (Gd and Li-doped, LAB vs water)





US community interested in pure and applied reactor antineutrino studies

US Interest Group in Reactor Antineutrino Studies

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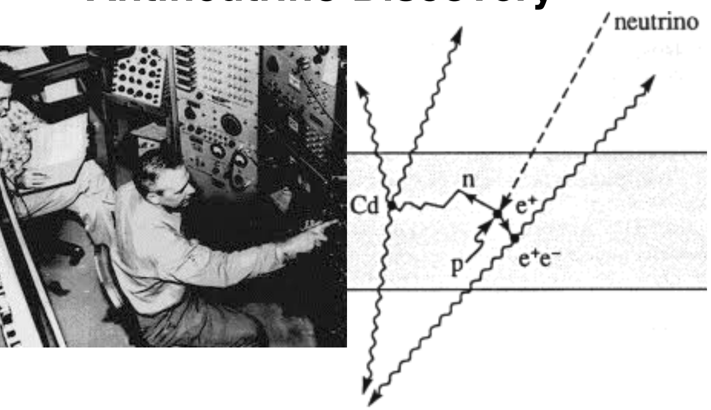
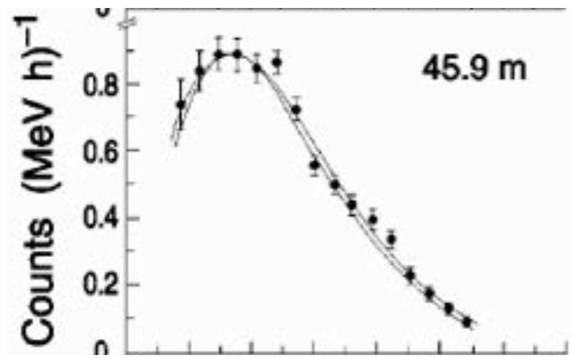
A Rich History of Reactor Neutrino Physics

Precision Studies with Reactor Antineutrinos

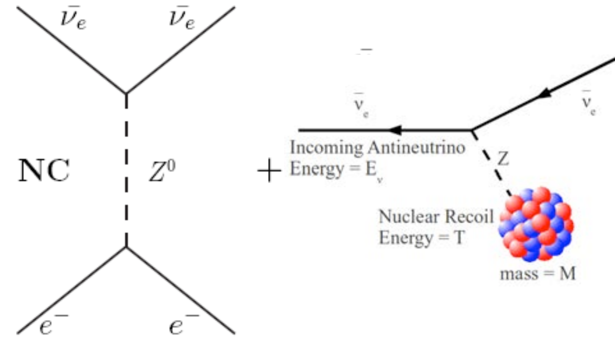
Antineutrino Discovery



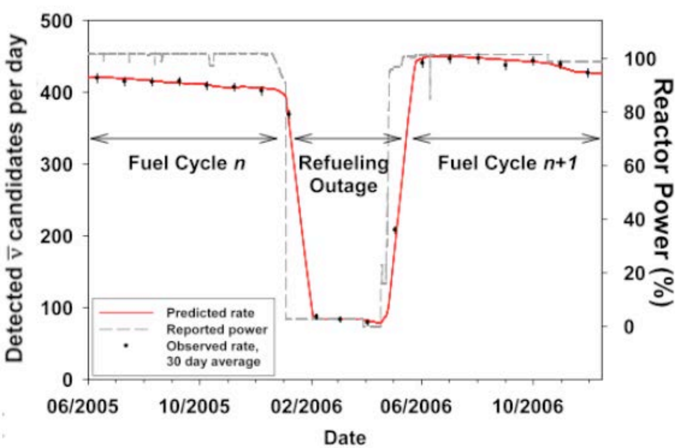
Reactor $\overline{\nu}_e$ Spectra



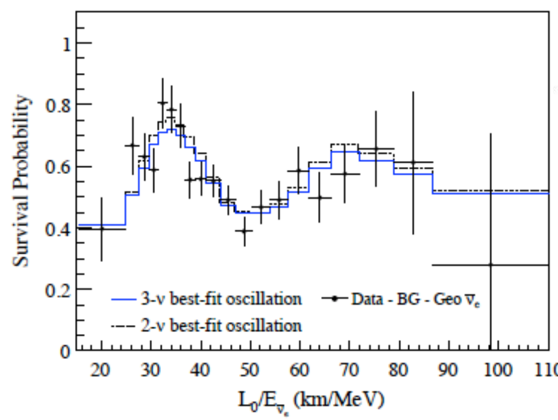
neutrino magnetic moment and **coherent scattering** searches

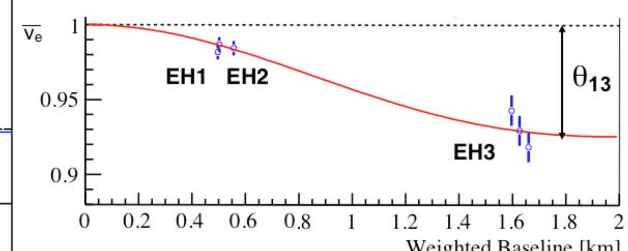


fuel burnup



$\overline{\nu}_e$ Oscillations





And more is yet to come...