A Reactor Experiment At Very Short Baselines

International Context and Experimental Requirements

1956 - First observation
of (anti)neutrinos

Savannah River

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

Chooz

2003 - First observation of reactor
antineutrino disappearance

KamLAND

L~180km

Daya Bay
Double Chooz
Reno

L~1-2km

2011/2012 - The year of θ_{13}

?

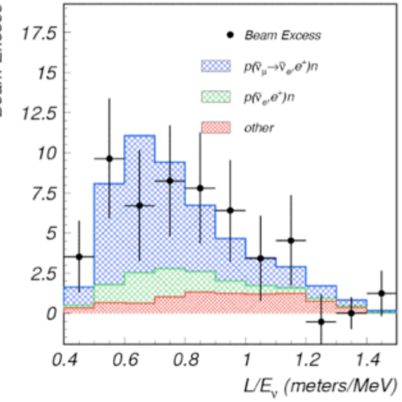
L~10m

Karsten Heeger
University of Wisconsin

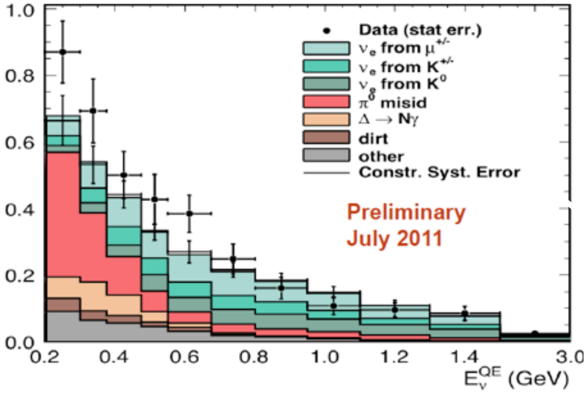
LLNL, December 11-12, 2012

Neutrino Anomalies and Sterile Neutrinos

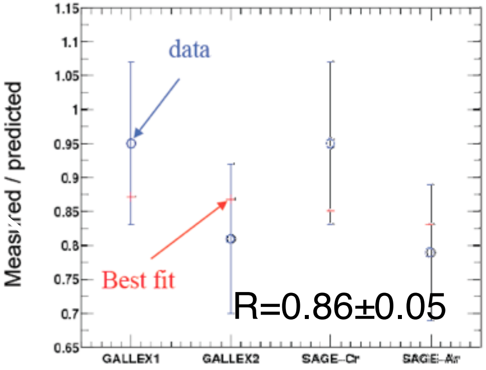
LSND



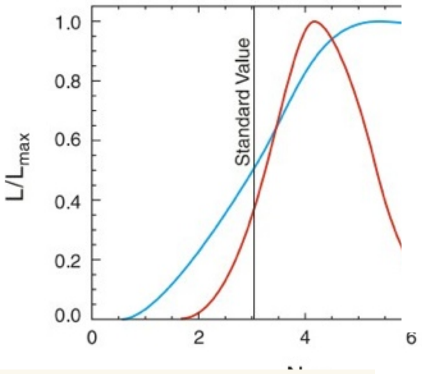
MiniBoone

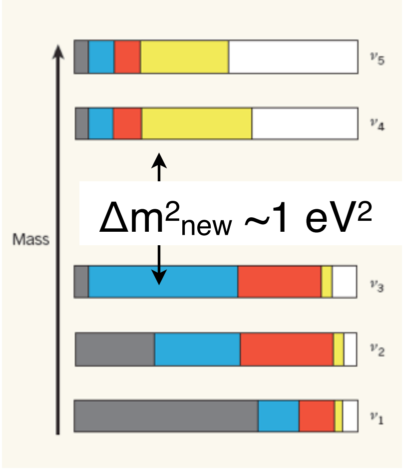


Ga Source



Cosmology (WMAP)





Anomalies in 3-ν interpretation of global oscillation data

LSND ($\overline{\nu}_e$ appearance)
MiniBoone ($\overline{\nu}_e$ appearance)
Ga anomaly
N_{eff} in cosmology
Short-baseline reactor anomaly ($\overline{\nu}_e$ disappearance)

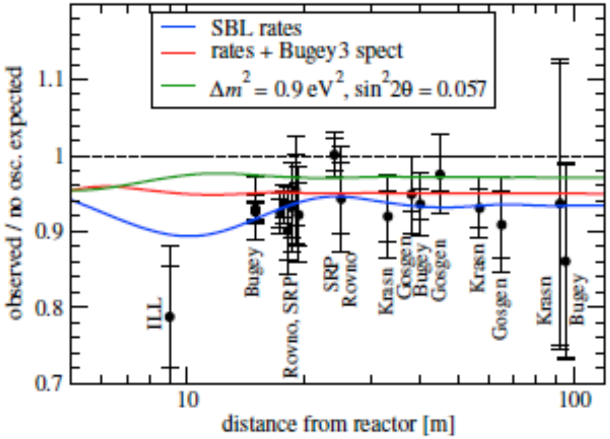
if new oscillation signal, requires $\Delta m^2 \sim O(1 eV^2)$ and $\sin^2 2\theta > 10^{-3}$
systematics or experimental effect? ➔ need to test each effect

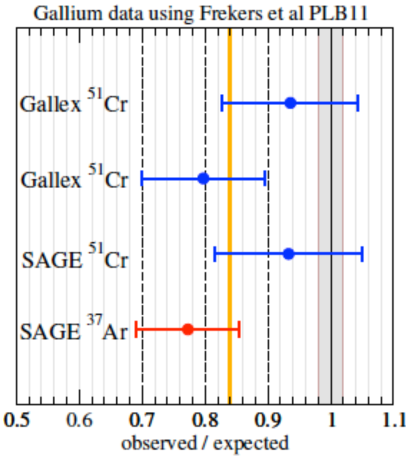
Reactor Anomaly

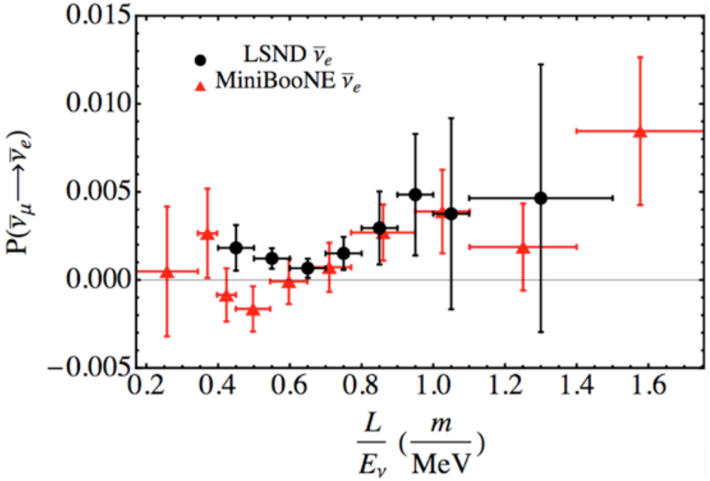
one of several anomalies, could go away with revised flux prediction based on “old” data, no modern reference experiment

Beyond 3ν - Sterile Neutrinos?

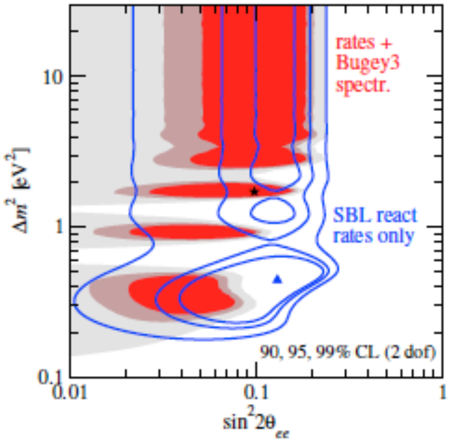
Anomalies

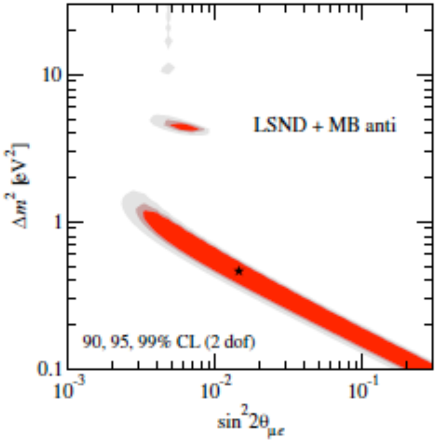


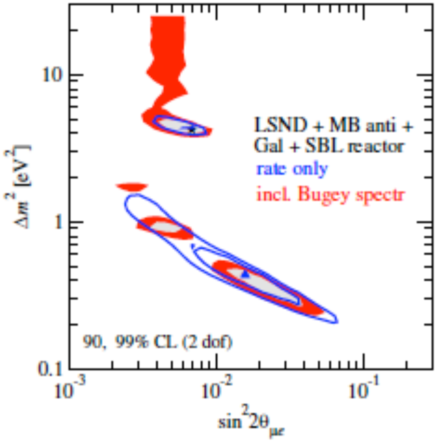




Are $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ consistent?







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

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

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

MicroBoone will provide new data starting ~2014

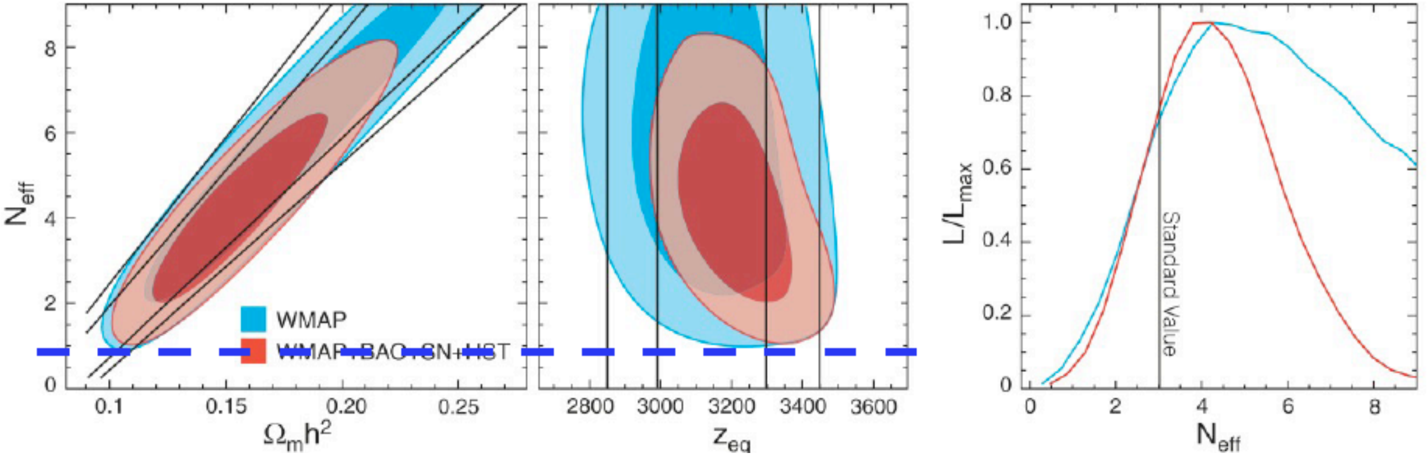
strong tension if all three are combined, tension also in 3+2 fit

Precision Observations in Cosmology

WMAP and Beyond

- Measurement of the anisotropic stress (since WMAP-5) gives lower limit on N_{eff} from CMB alone (without supplementary large-scale structure data).

from Y. Wong



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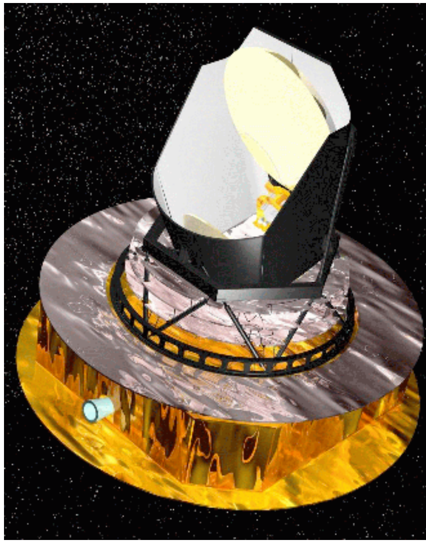
Current cosmological data show a preference for extra relativistic degrees of freedom (beyond 3 neutrinos).

With fist data release in Spring 2014 Planck will place new constraints on total neutrino mass and N_{eff}

Planck



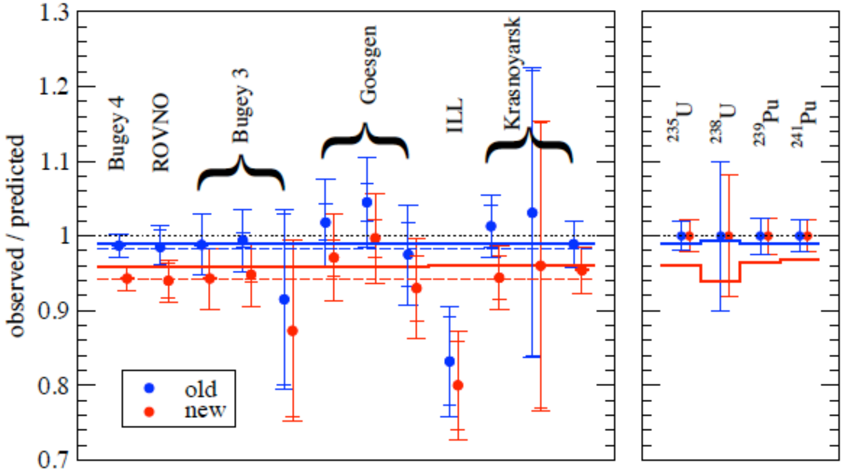
Many experiments and observations will weigh in on N_ν over next few years

Reactor $\bar{\nu}$ Fluxes

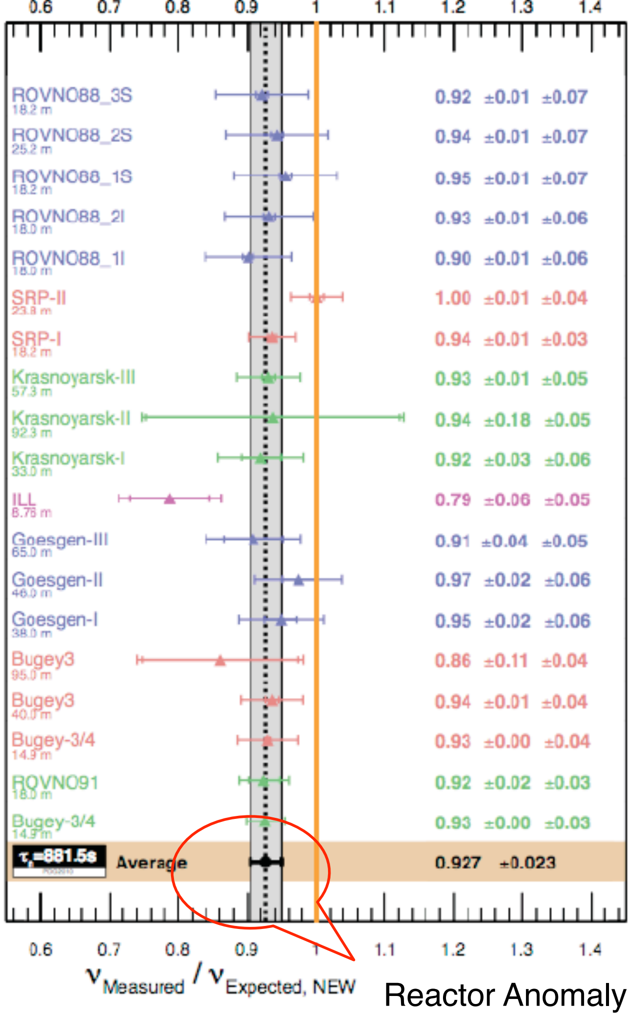
Theory Meets Experiment

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

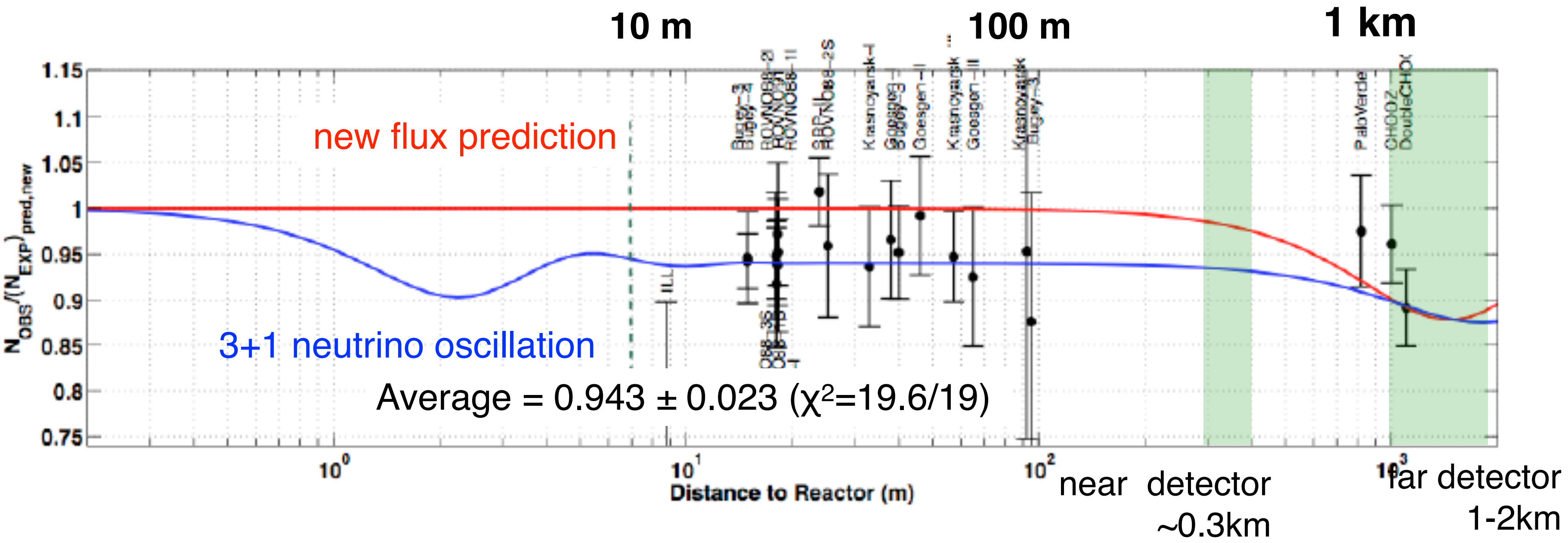
Ref: Mention et al, 1101.2755 (2012 upd)

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 $\bar{\nu}$ Fluxes at Short Baselines

Can the Reactor θ_{13} Experiments Resolve Anomaly?



new flux prediction

3+1 neutrino oscillation

Average = 0.943 ± 0.023 (χ^2=19.6/19)

near detector
~0.3km

far detector
1-2km

adapted from Schwetz, Neutrino2012

Absolute flux measurement

	Double Chooz	RENO	Daya Bay
detector systematic	2.1%	1.5% (correlated)	1.9% (correlated)
reactor systematic	1.8%	2.0% (correlated)	3.0% (correlated)

- difficult to make definitive statement
- work on improving correlated uncertainties

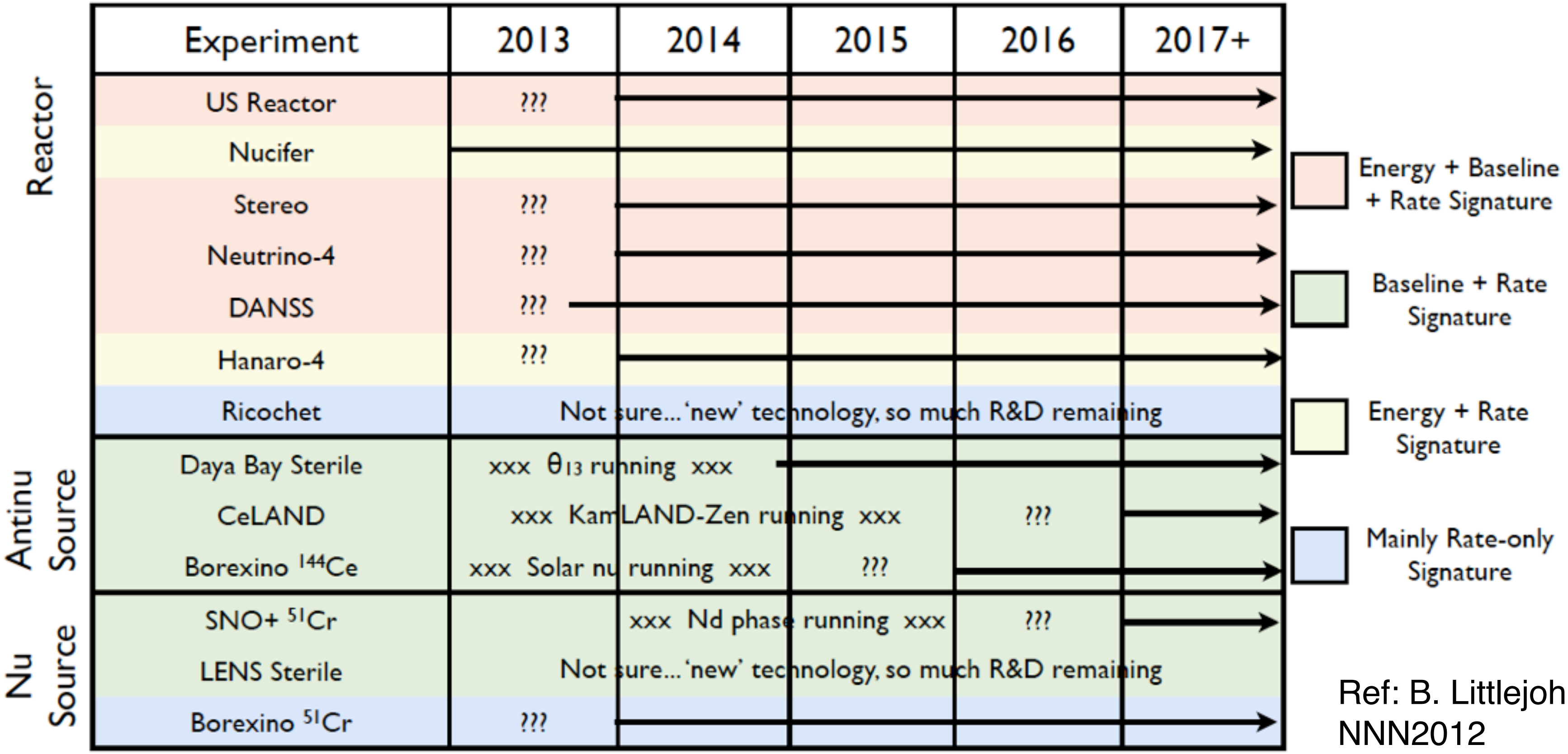
Precision Spectral Measurement

- important to verify that we understand how to predict reactor $\overline{\nu}_e$ spectrum,
- reactor θ_{13} experiments not optimized to resolve 'anomaly'

Worldwide Effort Towards Optimized Sterile ν Search

Non-Accelerator Efforts

Many proposals, several R&D efforts, 1 experiment taking data



	Experiment	2013	2014	2015	2016	2017+
Reactor	US Reactor	???	→	→	→	→
	Nucifer	→	→	→	→	→
	Stereo	???	→	→	→	→
	Neutrino-4	???	→	→	→	→
	DANSS	??? →	→	→	→	→
	Hanaro-4	???	→	→	→	→
	Ricochet	Not sure… 'new' technology, so much R&D remaining				
Antinu Source	Daya Bay Sterile	xxx θ_{13} running xxx		→	→	→
	CeLAND	xxx KamLAND-Zen running xxx			???	→
	Borexino ^{144}Ce	xxx Solar nu running xxx		???	→	→
Nu Source	SNO+ ^{51}Cr		xxx Nd phase running xxx		???	→
	LENS Sterile	Not sure… 'new' technology, so much R&D remaining				
	Borexino ^{51}Cr	???	→	→	→	→

🟥 Energy + Baseline + Rate Signature

🟩 Baseline + Rate Signature

🟨 Energy + Rate Signature

🟦 Mainly Rate-only Signature

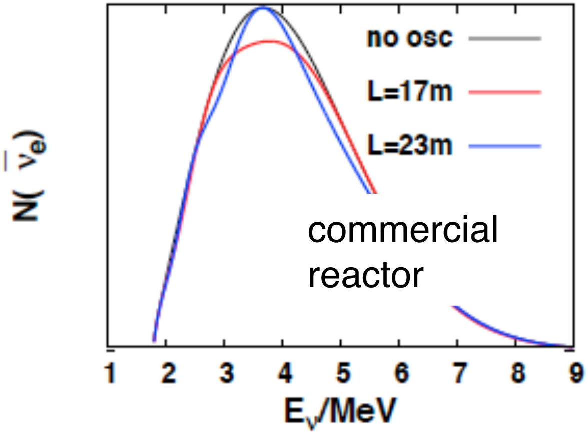
Ref: B. Littlejohn, NNN2012

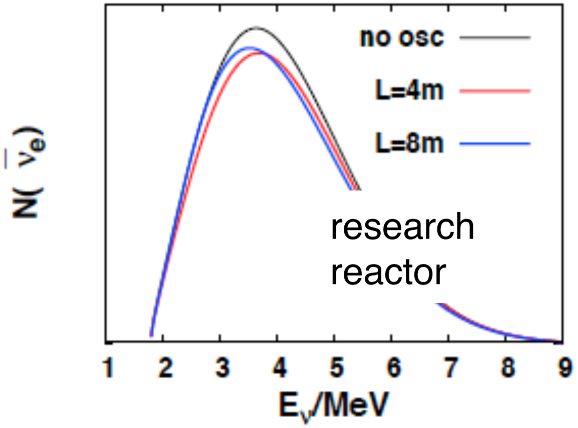
Opportunity for reactor experiments to provide timely input.

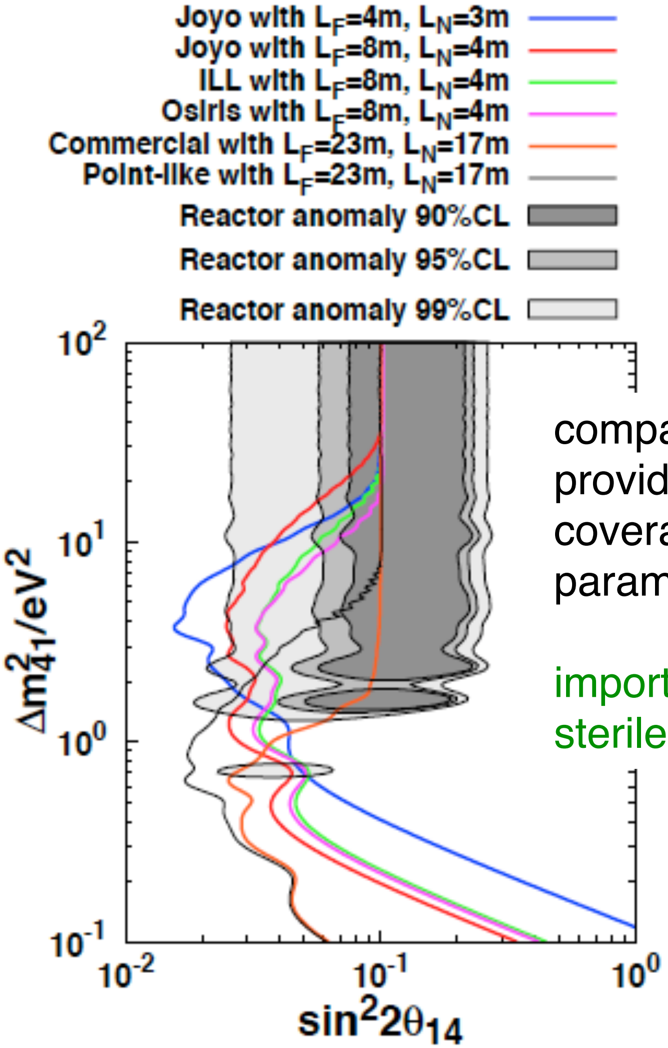
Sterile ν Searches with Very Short Baselines: Reactors

Research vs commercial reactors and compact cores for very short-baseline reactor experiments at L~1-10m

Energy spectrum w/ and w/out oscillation







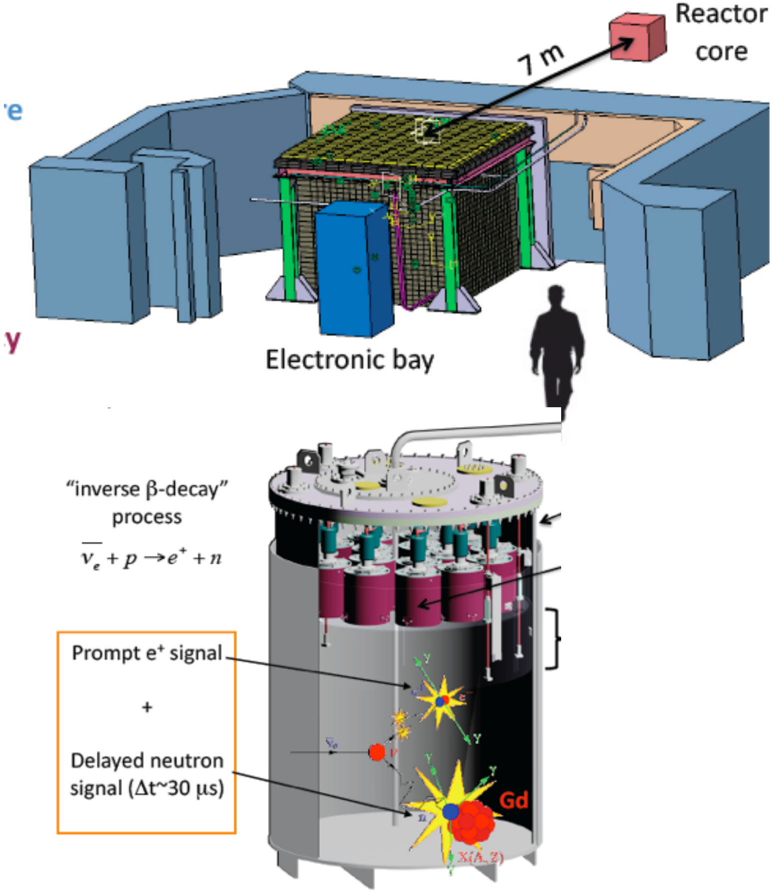
compact research reactors provide generally better coverage of anomaly parameter space

important for definitive sterile nu experiment

Yasuda,
arXive: 1110.2579

Reactor Monitoring Experiments

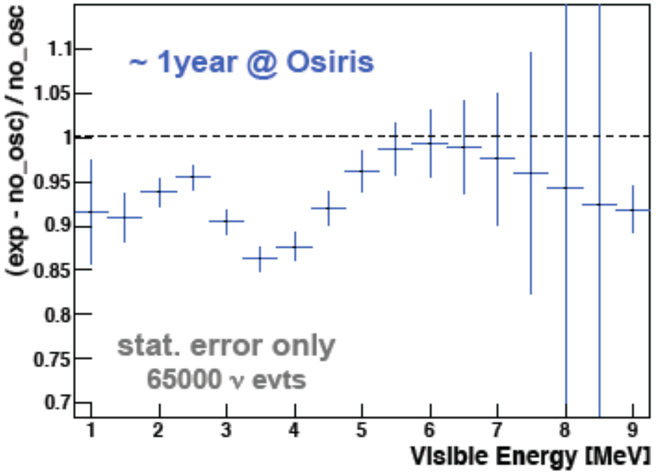
NUCIFER at Osiris

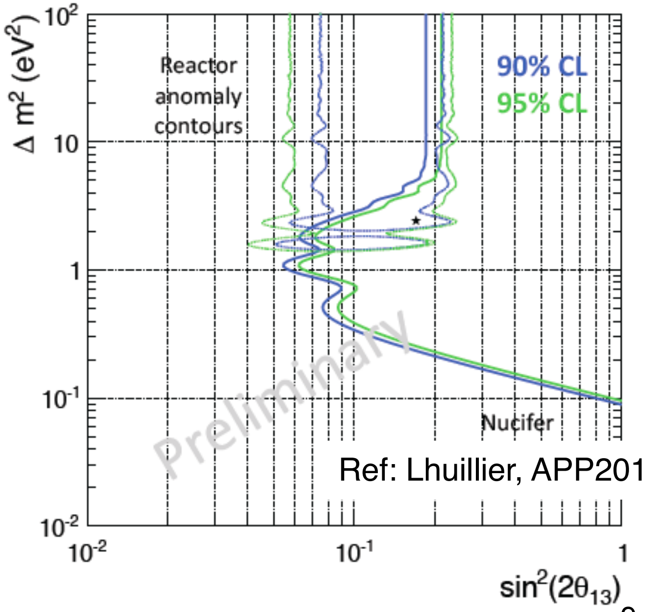


core: σ~0.3m
baseline: 7m

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

Expected E spectrum deformation
with anomaly best fit: $\Delta m^2 = 2.4\ eV^2$ & $\sin^2(2\theta)=0.15$





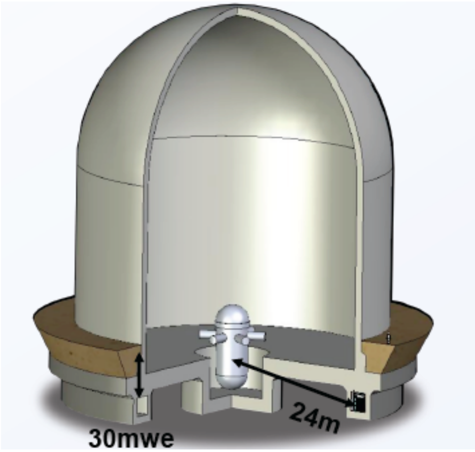
Ref: Lhuillier, APP2011

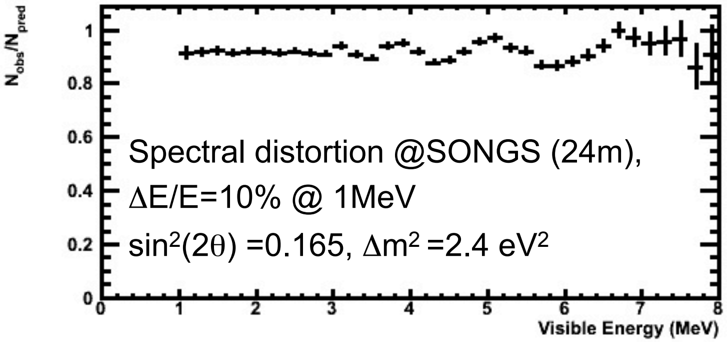
Pre-industrial, unattended reactor neutrino monitor

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

Reactor Monitoring Experiments

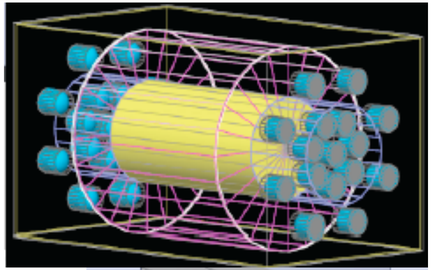
SCRAAM: Southern California Reactor Antineutrino Anomaly Monitor

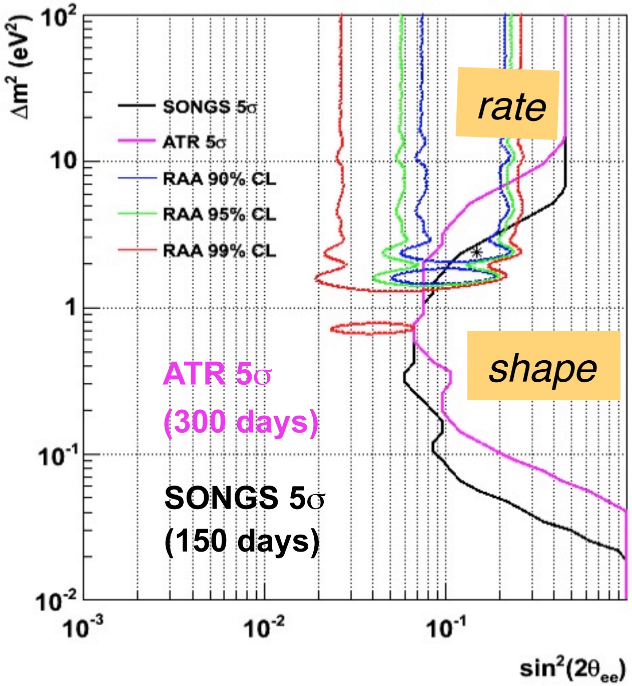




Spectral distortion @SONGS (24m),
$\Delta E/E = 10\%$ @ 1MeV
$\sin^2(2\theta) = 0.165$, $\Delta m^2 = 2.4\ \mathrm{eV}^2$

core ∅: ~3m,
fixed baseline: 24m





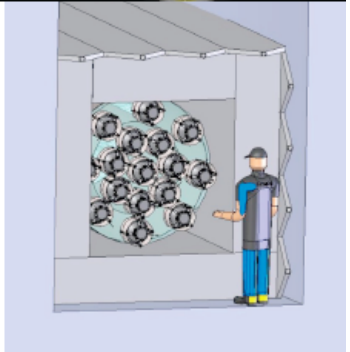
rate

shape

ATR 5σ
(300 days)

SONGS 5σ
(150 days)

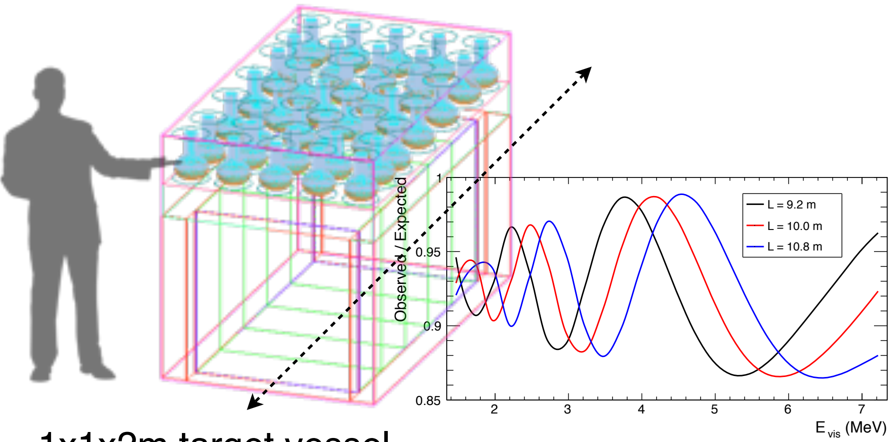
Adapt existing compact detector design/technology, limited by backgrounds



Limitations: Existing designs require overburden for background reduction – limits range of deployment sites, especially very close (<10m) to compact cores

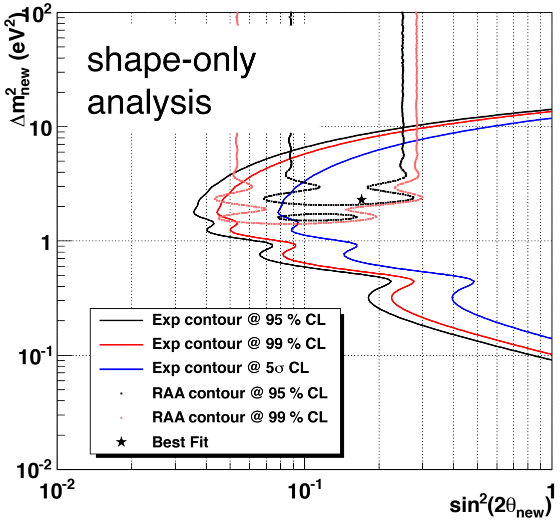
Worldwide Effort Towards Optimized Sterile ν Search

Stereo at ILL, France

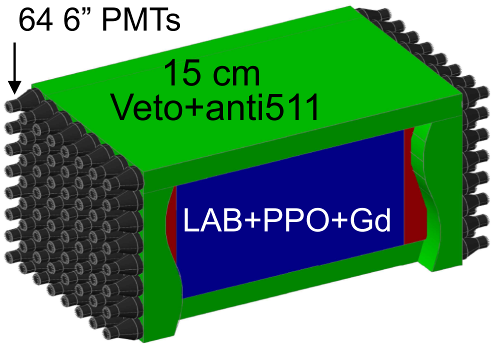


1x1x2m target vessel
filled with Gd-LS
5 baseline bins by foils

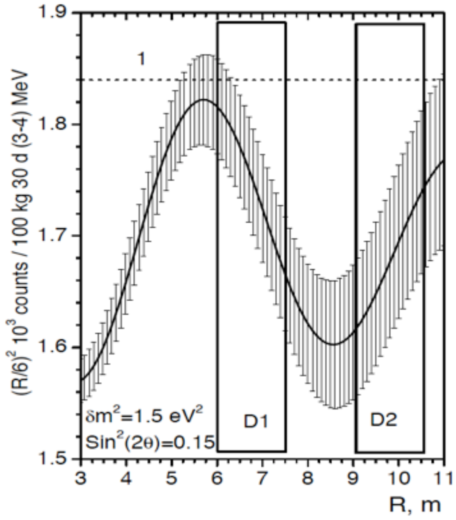
shift detector to verify oscillation signal



POSEIDON at Reactor PIK, Russia



Gd-LS Detector: 2.1x1.3x1.3 m^3
Energy resolution: σ = 7% at 1 MeV
Spatial resolution: σ_x = 15 cm at 1 MeV

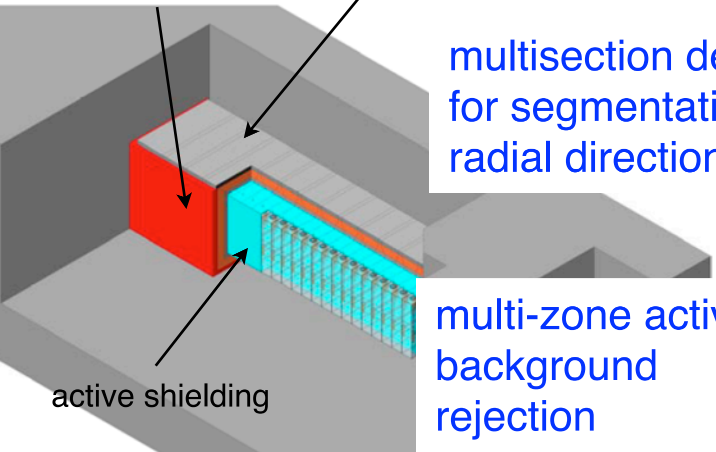


Energy and spatial resolution to measure oscillation curves for different E_ν

aim to detect oscillatory signature

Worldwide Effort Towards Optimized Sterile ν Search

Neutrino4, Russia



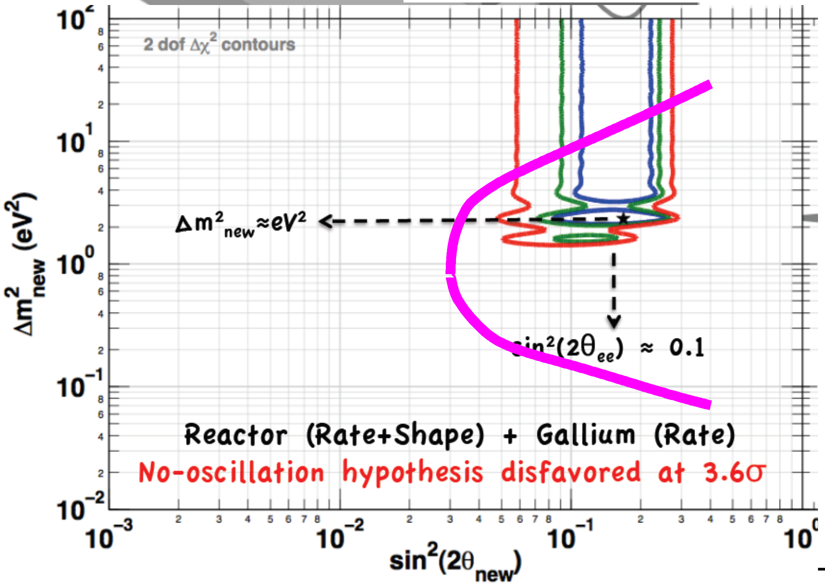
passive shielding
Pb, CH_2(B)

muon veto

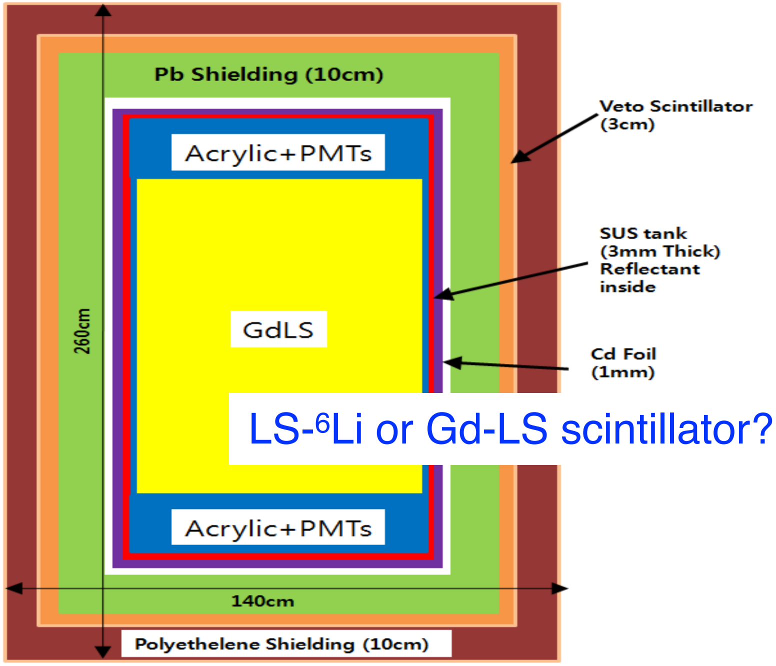
multisection detector for segmentation in radial direction

multi-zone active background rejection

active shielding



Hanaro-SBL, Korea



LS-^{6}Li or Gd-LS scintillator?

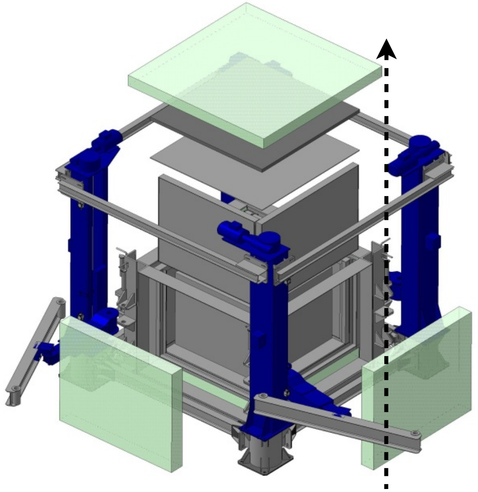
$$n + {}^{155}Gd \rightarrow {}^{156}Gd + 8MeV$$

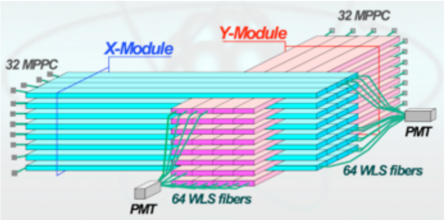
$$n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.8MeV$$

- γ-α coincidence can effectively reject backgrounds
- PSF with ^{6}Li-loaded scintillator may enable on-surface detector with minimal overburden

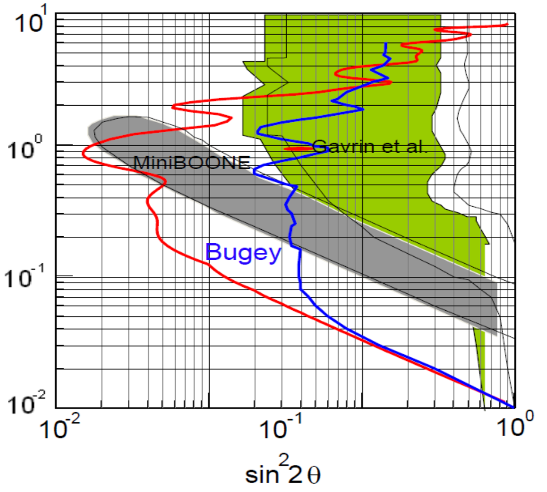
Worldwide Effort Towards Optimized Sterile ν Search

DANSS, Russia



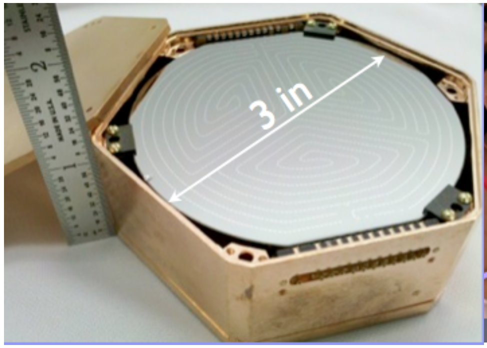


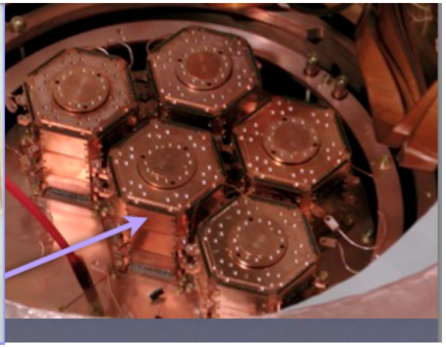
movable distance

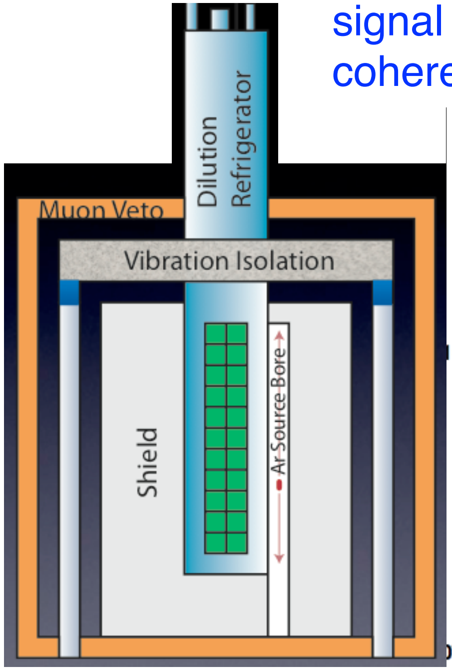


also used for neutrino magnetic moment searches with Ge detectors

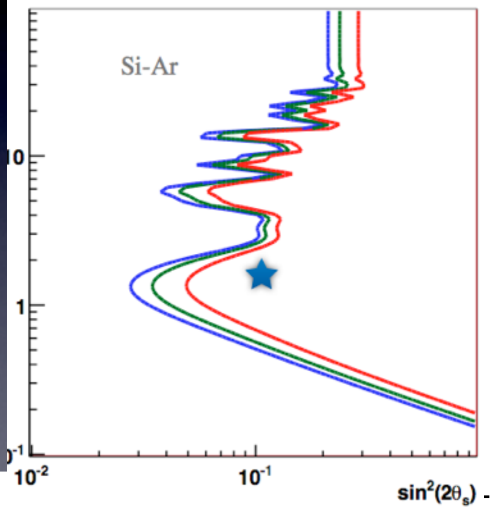
Ricochet, USA





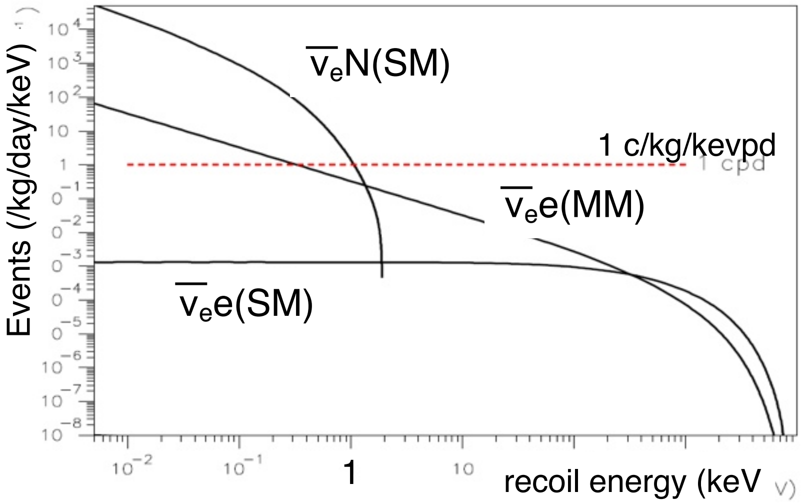


signal detection through coherent scattering

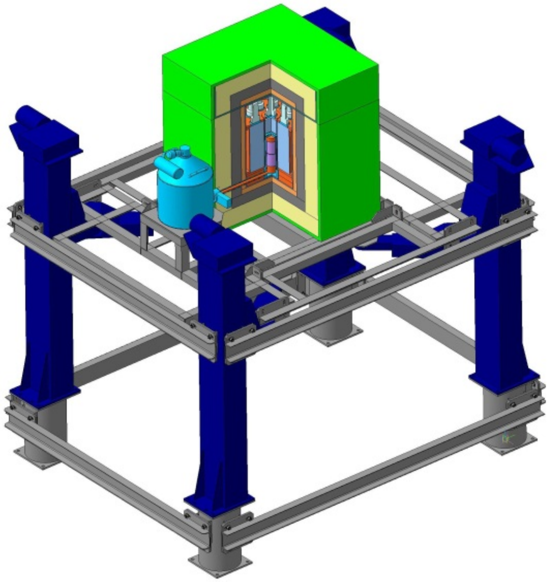


Scattering Studies Near Reactors

Searches for New Physics with $\overline{\nu}_e$ Scattering



Gemma-II, Kalinin NPP, Russia



Requirement: low-background, rare event studies

Goal: Aiming for sub-kev Ge detector for coherent scattering, neutrino magnetic moment, goal sensitivity of 1x 10^{-11} µB

Challenges: excess of sub-kev events,
- not fully explained with background model
- moved to Jinping underground lab, China, to reduce backgrounds

Worldwide Effort Towards Optimized Sterile ν Search

A Submarine Base in Russia or Ukraine?


general_kosmosa.livejournal.com

Sterile ν Searches with Very Short Baselines: Sources

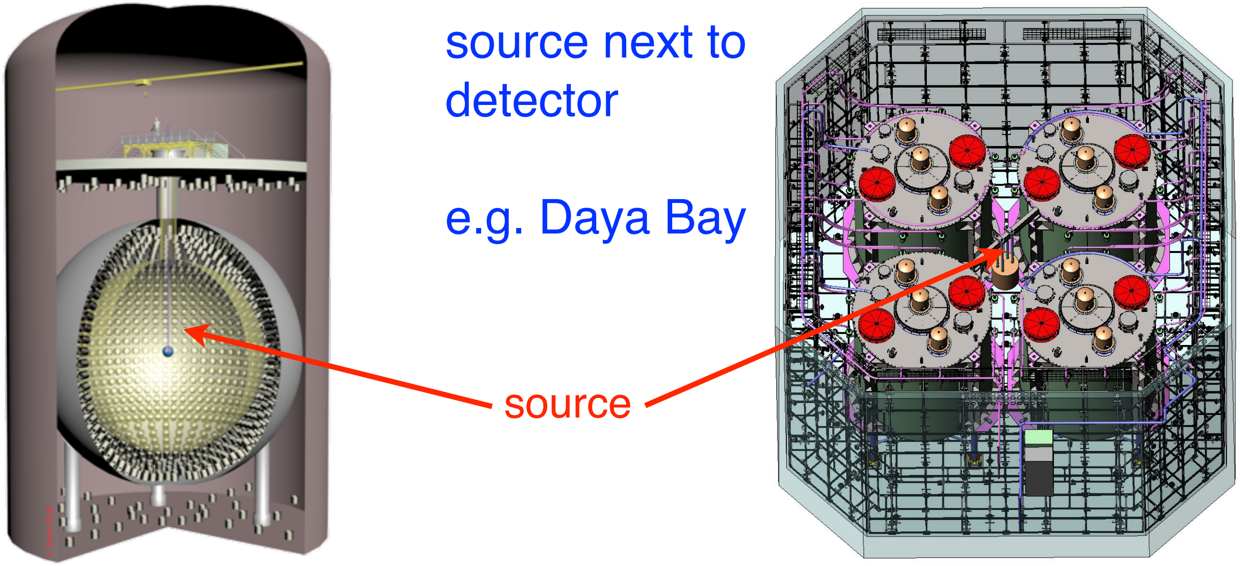
Alternative Approach: Place source near or inside detector and search for ν_e or $\bar{\nu}_e$ disappearance.

Advantages
- baseline can be as short as needed
- detectors can be underground to minimize backgrounds
- potential for oscillometry (i.e. demonstrate oscillation signature vs baseline and energy)
- may be able to re-use existing, well-characterized detectors

Challenges
- construct suitable, intense radioactive source
- regulatory and licensing requirements for radioactive source

source inside detector

e.g. Ce-LAND



source next to detector

e.g. Daya Bay

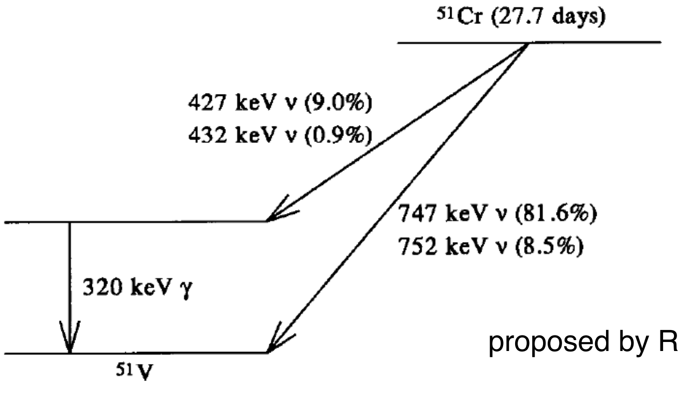
source

Sterile ν Searches with Very Short Baselines: Sources

A Variety of Sources and Detectors Are Feasible

Sources based on EC (^{65}Zn, ^{51}Cr, ^{152}Eu, ^{37}Ar)

e.g. ^{51}Cr, mono-energetic, ν_e, 750 keV

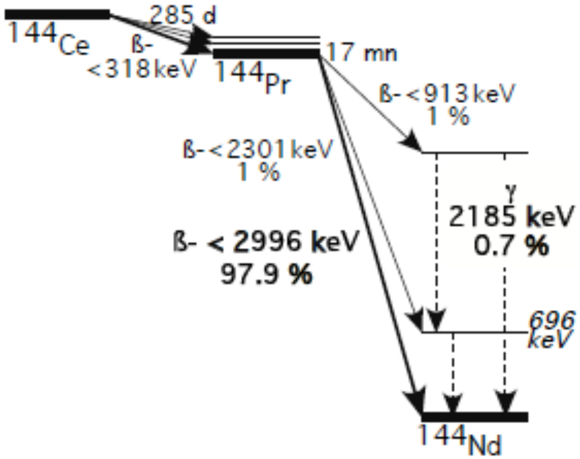


Decay scheme of ^{51}Cr to ^{51}V through electron capture.

proposed by Raghavan

Sources based on beta-decays

e.g. ^{144}Ce-^{144}Pr, $\overline{\nu}_e$, continuous spectrum



arxiv:1107.2335
Cribier et al

Detection Channels & Proposed Experiments

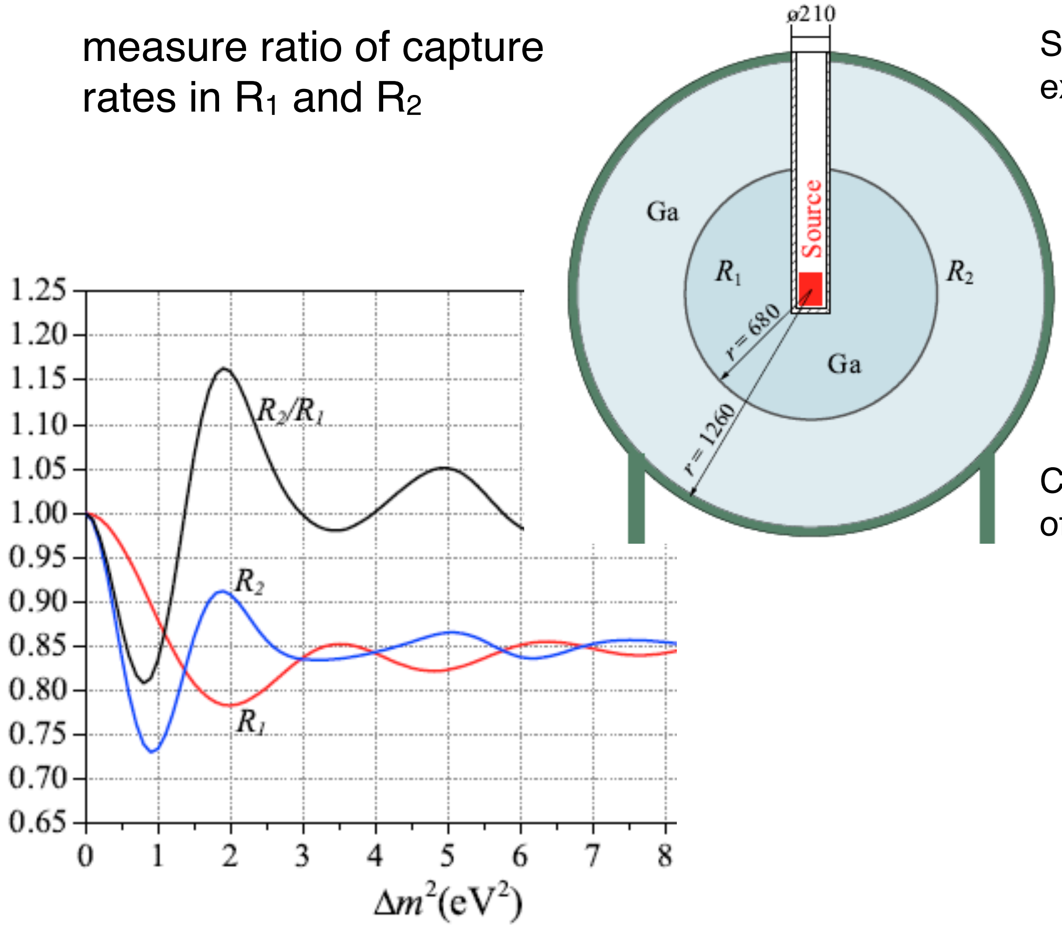
Elastic Scattering:	Borexino, SNO+Cr
Charged Current:	LENS-Sterile, Baksan, Ce-LAND, Borexino, Daya Bay
Neutral Current:	RICOCHET

see following examples

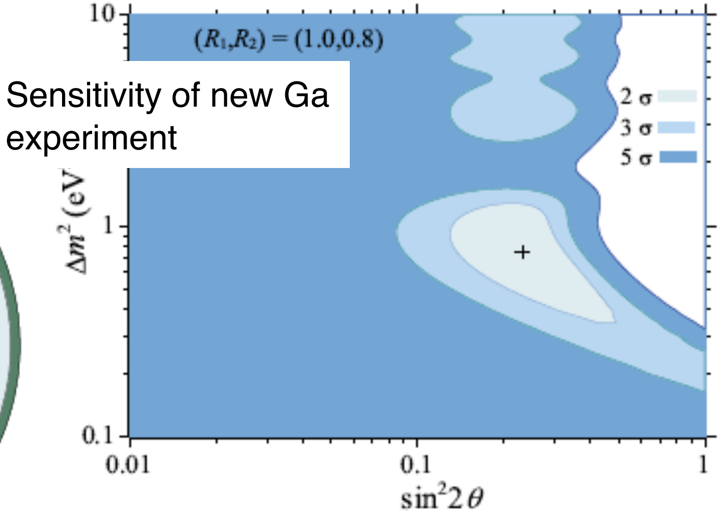
Short Baseline Search with Ga Target

^{51}Cr Source inside Dual Metallic Ga Target

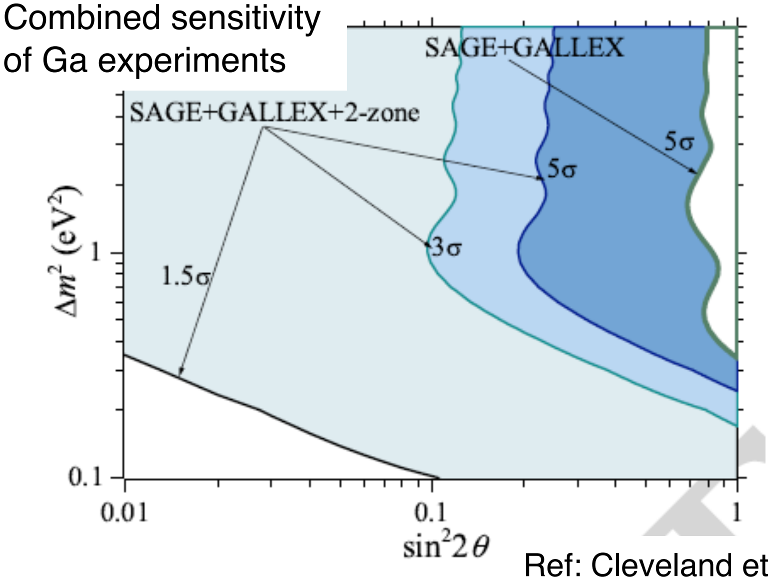
measure ratio of capture rates in R_1 and R_2



ratio of measured capture rates to predicted rate in inner and outer zones and their ratio R_2/R_1



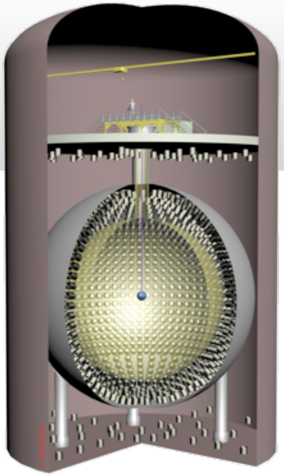
Sensitivity of new Ga experiment



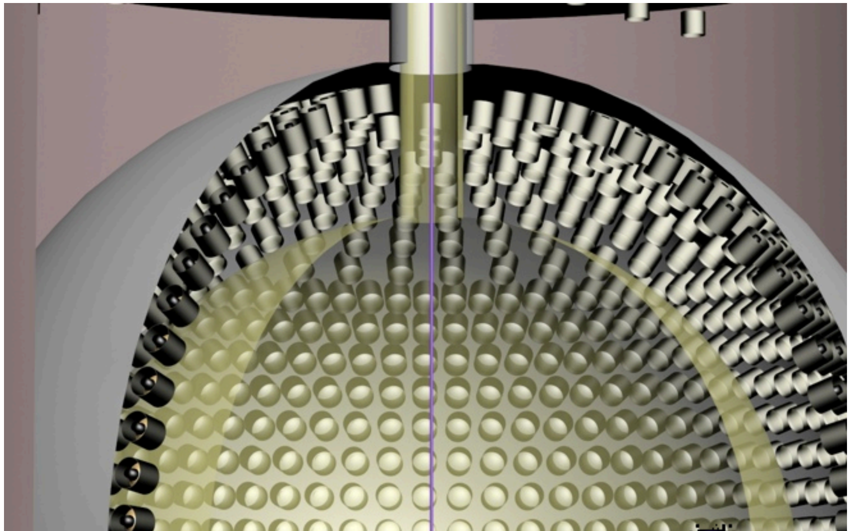
Combined sensitivity of Ga experiments

Ref: Cleveland et al.

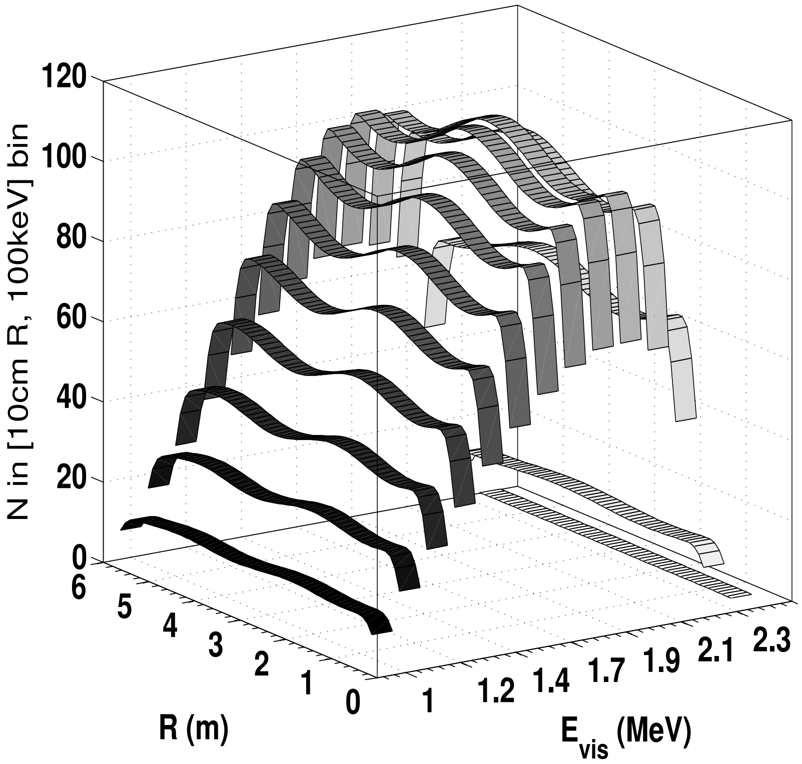
Ce-LAND

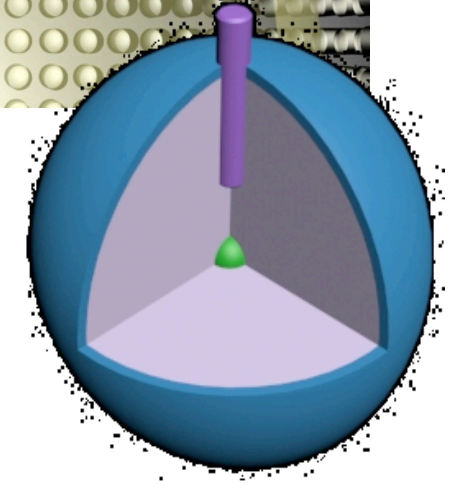


^{144}Ce source inside Liquid Scintillator Detector



map oscillation effect in R and E





Holder & cold finger
R=8cm, 1.5 kg of Ce
R=37 cm, Tungsten
mass= 5 tons,
diameter 82 cm
teflon coating?

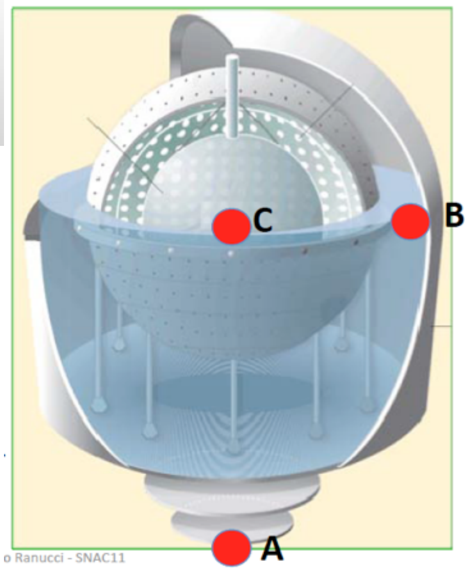
Ref: Lasserre

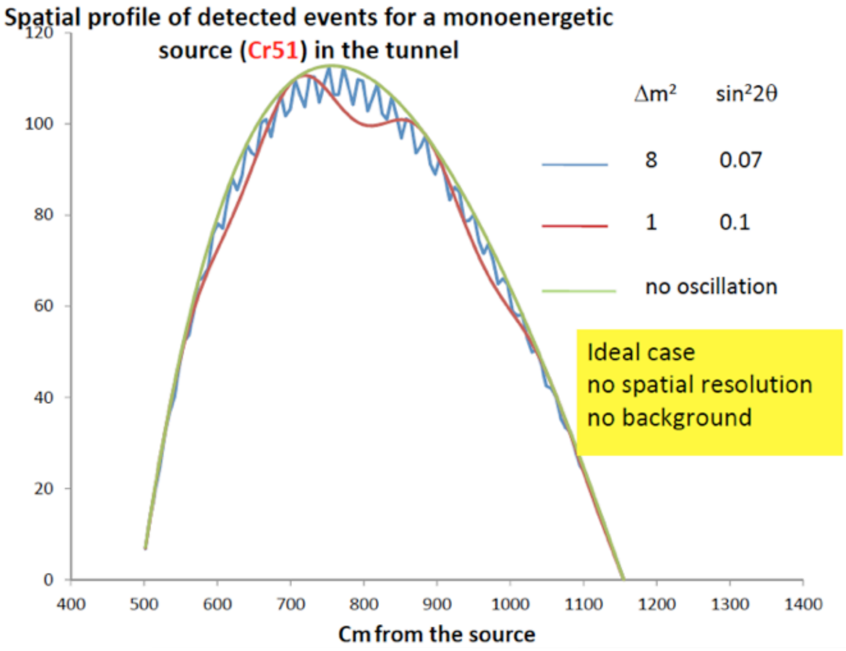
Borexino Source Experiment

Source	decay	τ [days]	Energy [MeV]	Kg/MCi	W/kCi
^{51}Cr	e-capture (E_γ=0.32 MeV 10%)	40	0.746 81%	0.011	0.19
^{90}Sr-^{90}Y	Fission product β^-	15160	<2.28 MeV 100%	7.25	6.7
^{144}Ce-^{144}Pr	Fission product β^-	411	<2.9975 MeV 97.9%	0.314	7.6

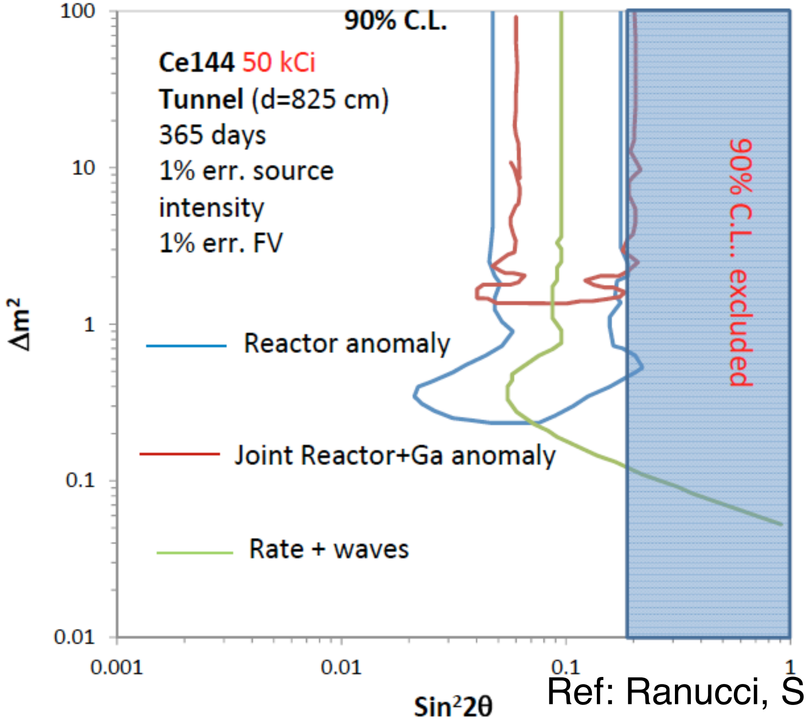
different sources and locations under consideration

inside and outside detector




Spatial profile of detected events for a monoenergetic source (Cr51) in the tunnel

Ideal case
no spatial resolution
no background

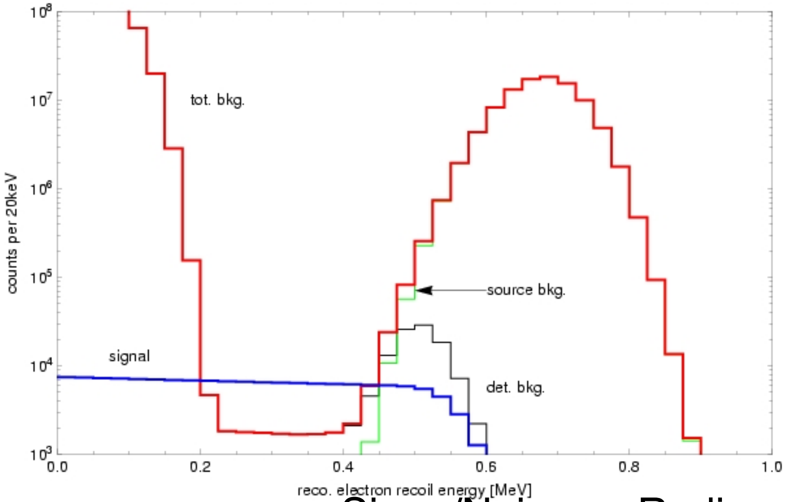

Ce144 50 kCi
Tunnel (d=825 cm)
365 days
1% err. source intensity
1% err. FV

Ref: Ranucci, SNAC

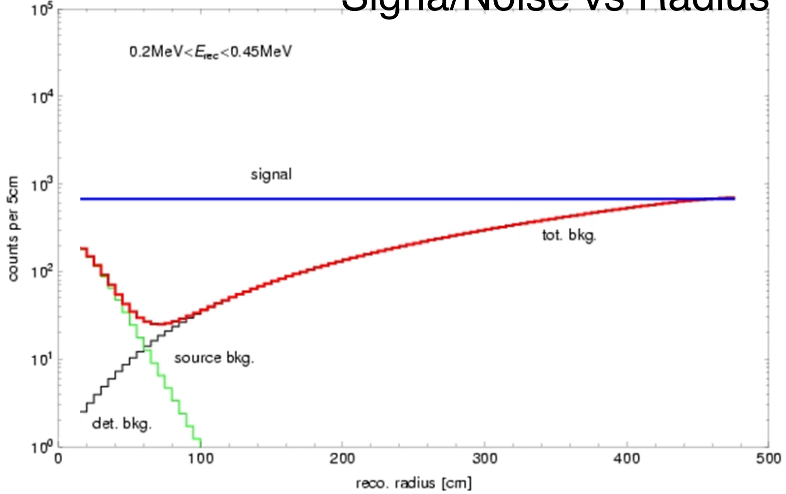
SNO-Cr

^{51}Cr source inside SNO+

Central Source Location in SNO+

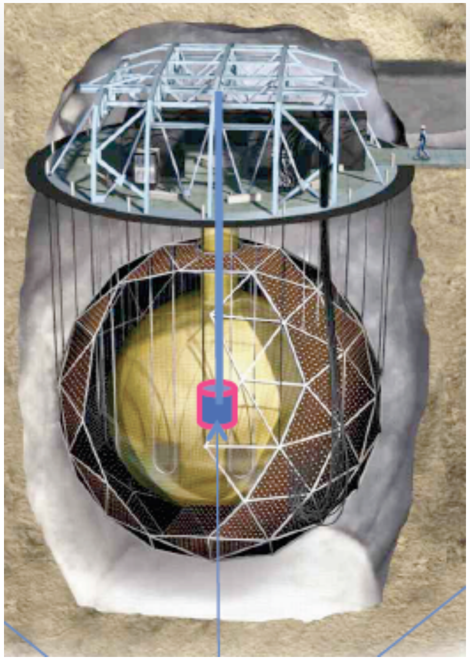


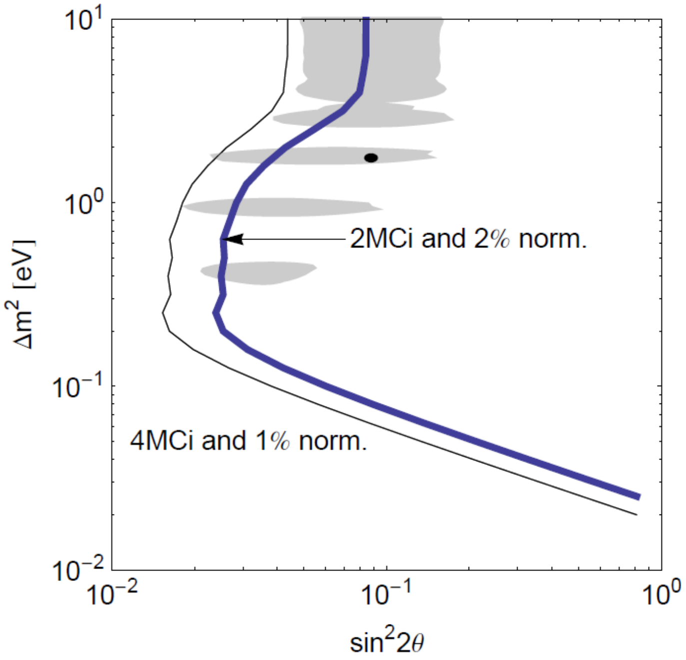
Signa/Noise vs Radius



SNO has widest neck/ chimney of all liquid scintillator detectors

may be able to produce ^{51}Cr source in US at High Flux isotope reactor at ORNL





Ref: Link, Huber

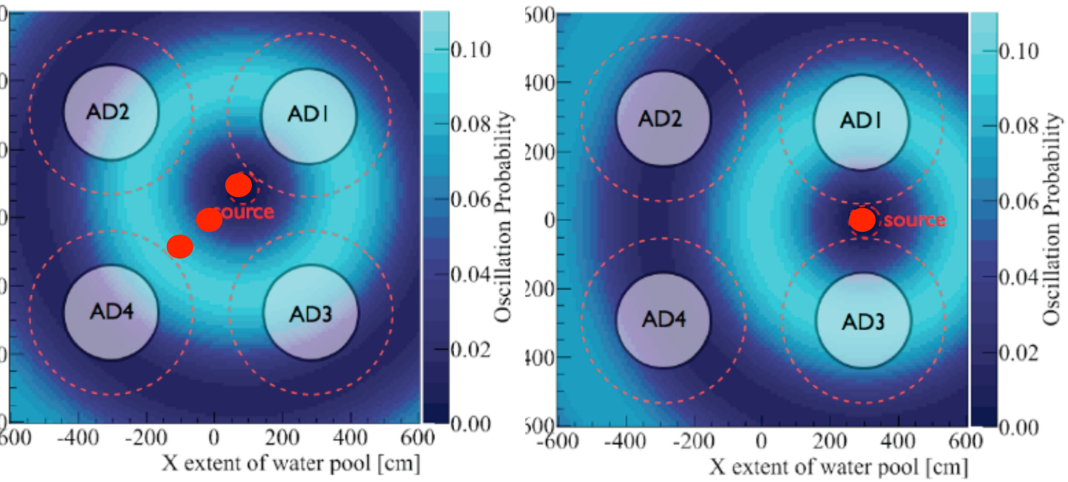
Daya Bay Sterile Neutrino Search

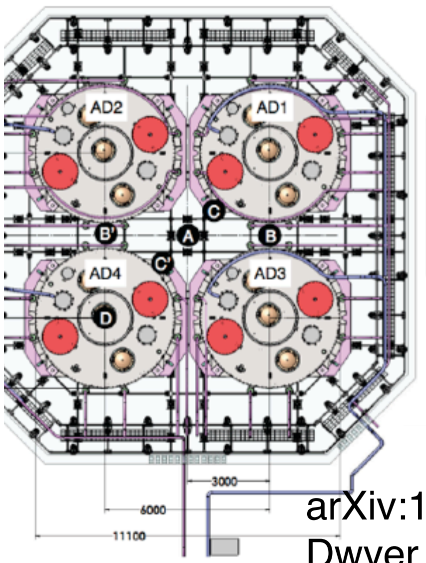
18 PBq ^{144}Ce source at the Daya Bay far site

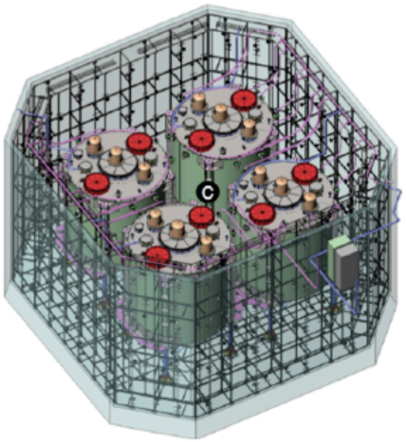
Signal

- baseline range: ~1.5 - 8 m
- ν energy range: 1.8 - 3 MeV
- 30k - 40k inverse beta-decay (IBD) events/per year

- Probing baselines from 1.5-8 m with an antineutrino source in the water pool of the Daya Bay Far Hall
- Advantageous to place source outside detectors in water pool.
- Multiple detectors allow for control of systematics.



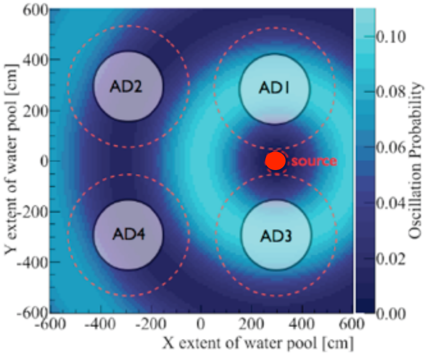


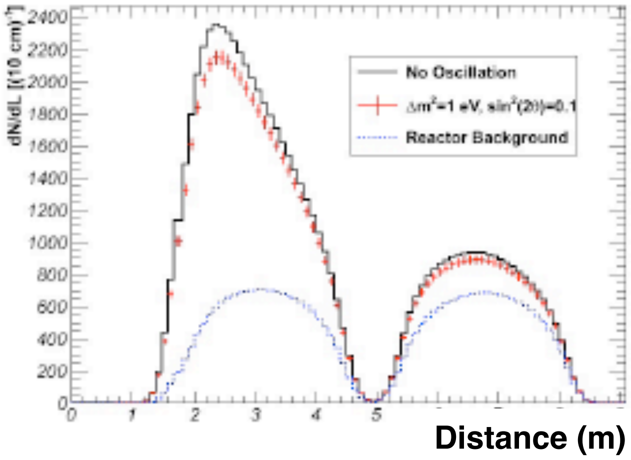


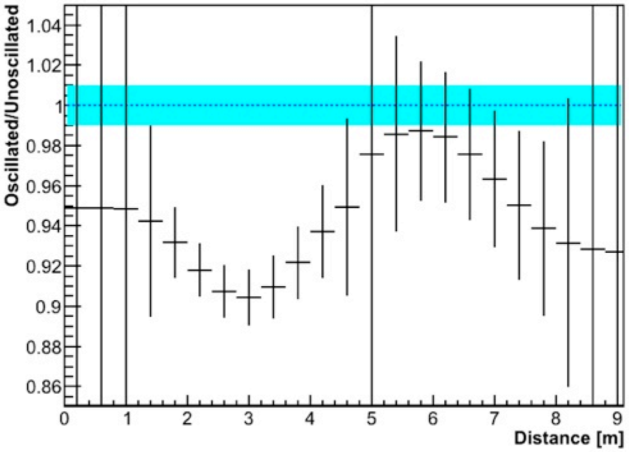
arXiv:1109.6036
Dwyer, Littlejohn, Vogel, KMH

Daya Bay Sterile Neutrino Search

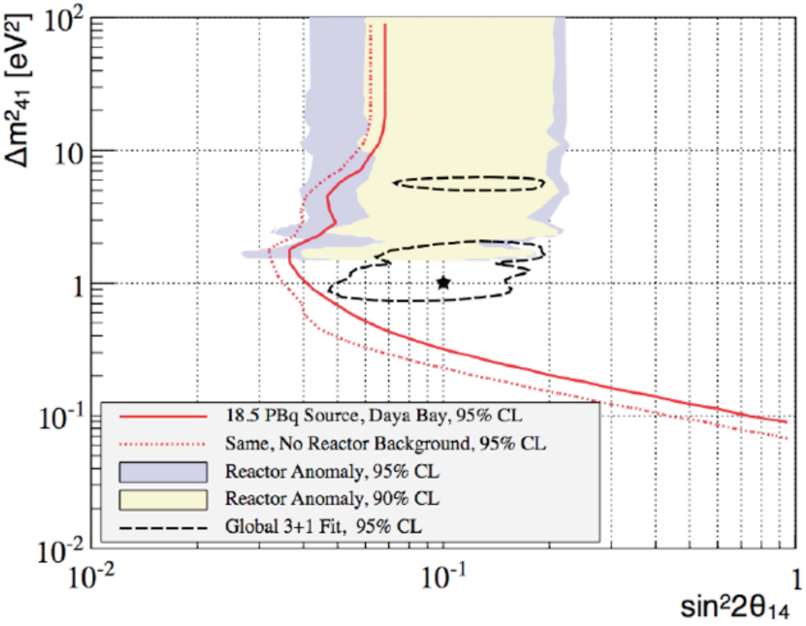
Signal and Event Distributions







arXiv:1109.6036
Dwyer, Littlejohn, Vogel, KMH



Sterile neutrino oscillations with mass > 1eV can be tested using ^{144}Ce source in the Far Hall of the Daya Bay experiment after θ_{13} measurement.

International Context - Conclusions

- Several efforts worldwide. Not a unique experiment. Scientific landscape will evolve over the next few years. Risk of being late vs not being definitive.

- Timeliness and experimental robustness are critical.
  - No “fast” way to resolve the current set of anomalies.
  - Sufficient systematic control, background mitigation, and physics reach to enable a >5σ discovery or exclusion.
  - Experimental program has to stand on its own (oscillation search, spectrum etc).

- Reactor and source experiments provide a complimentary way to probe short baseline oscillations. Builds on decades of experience with low-energy neutrino experiments.

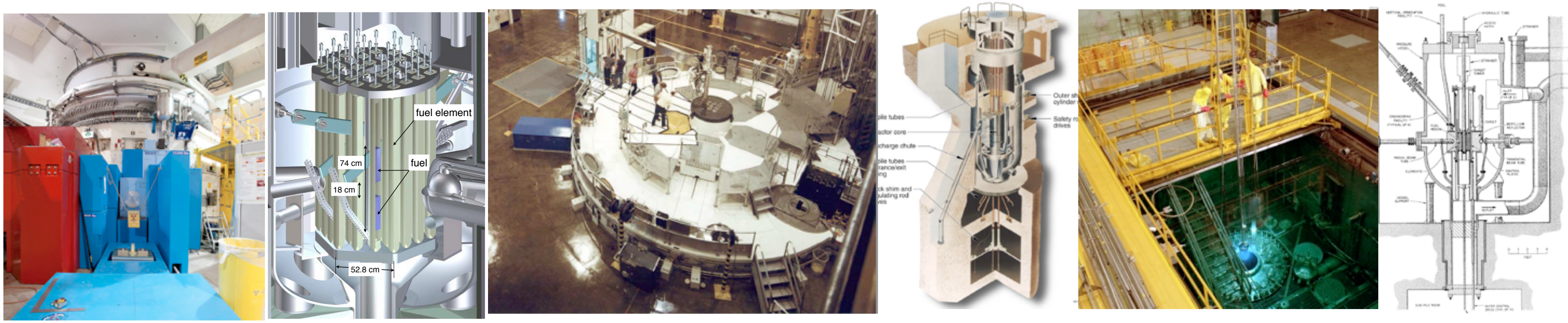
- US has unique research facilities and expertise for this research. Opportunity for a US-based, domestic experiment (or program).

Opportunities for a US Reactor Experiment?

Reactor	Power	Fuel	Baselines
NRL, MIT	5.5 MW	^{235}U	>3-4m
NBSR, NIST	20 MW	^{235}U	4-11 m
ATR, Idaho	250 MW	^{235}U	12 m 6 m
HFIR, Oak Ridge	85 MW	^{235}U	3 m (in water) >7m
SONGS, San Onofre	2700 MW	^{235}, ^{238}U, ^{239}, ^{241}Pu	24 m

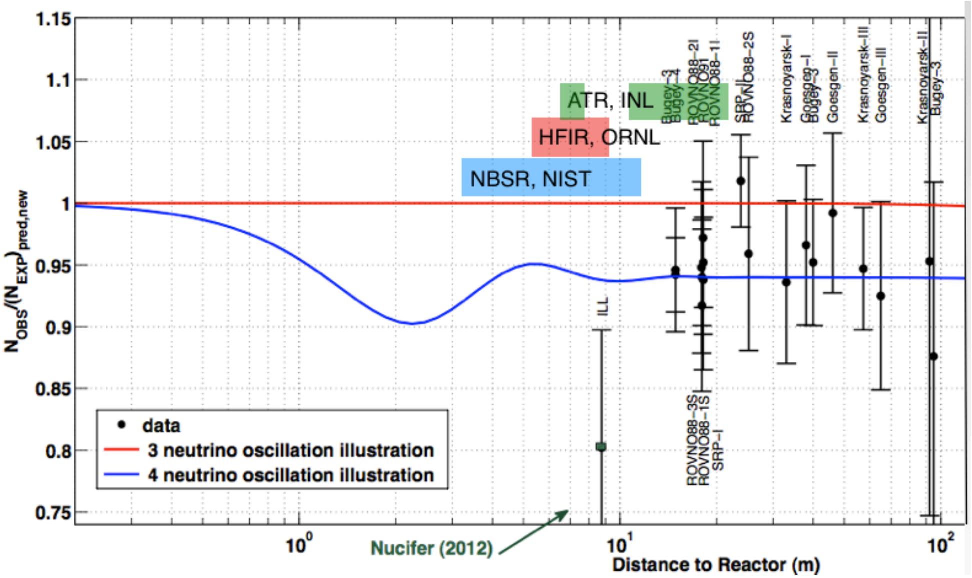
key reactor features: power, baseline, core size, on-off cycle fuel, overburden

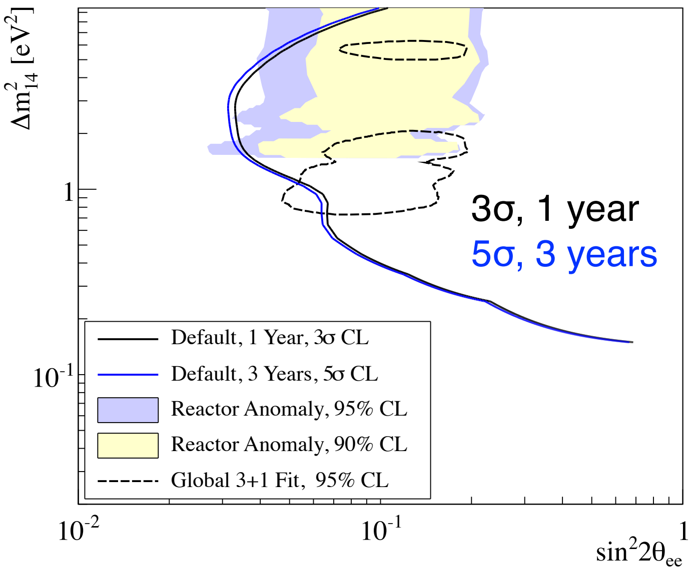
High-Power US Research Reactors



Opportunities for a US Reactor Experiment?

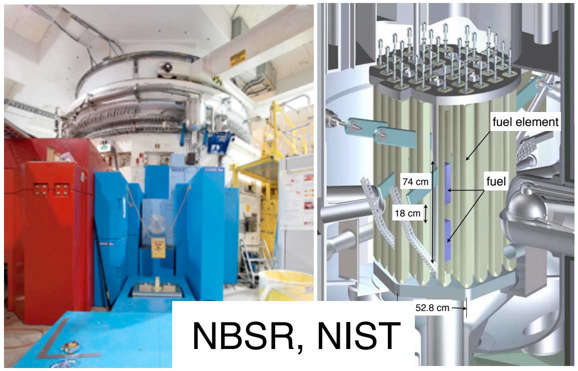
Reactor $\bar{\nu}$ Fluxes at Short Baselines

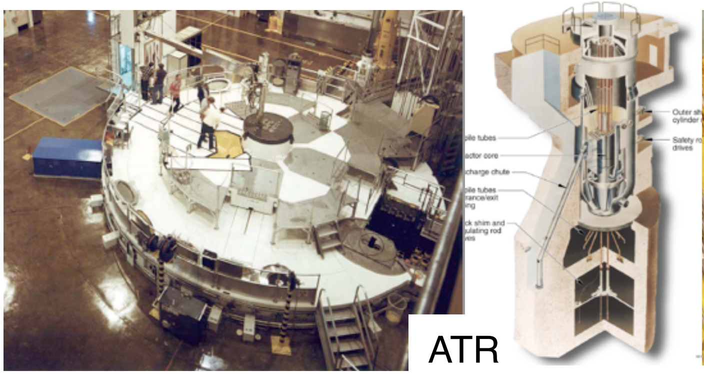


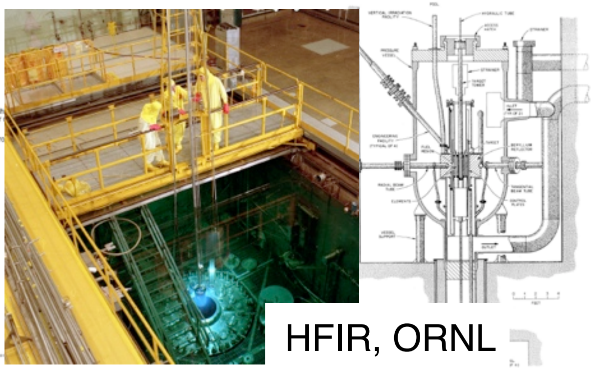


Littlejohn, Mumm, KMH

High-Power US Research Reactors

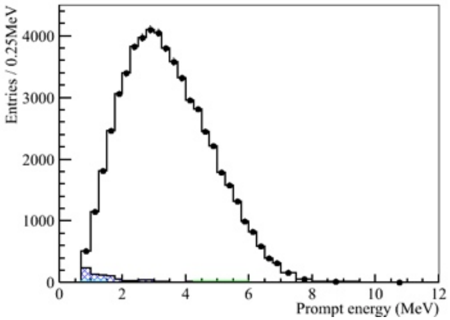






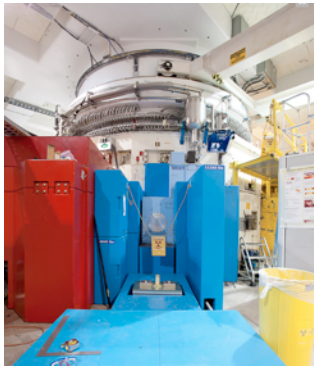
Reactor Experiment at Very Short Baselines

Scientific Opportunities



Reactor cores, fuel, and antineutrino spectra

- precision studies of r**eactor antineutrino spectra**
- studies of **fuel composition**
- studying **HEU to LEU core conversion** at US research reactors

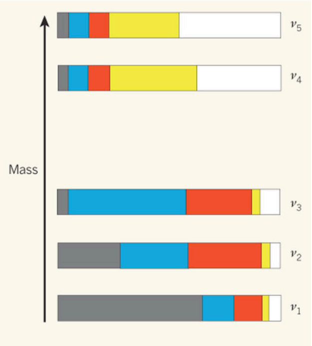


Background studies and detector development

- understand **high n and γ environment** near reactors
- segmented vs monolithic detectors with position reconstruction
- **scintillators for neutron detection** (Gd and Li-doped, LAB vs water)
- test of **on-surface antineutrino detectors** with minimum overburden
- background studies during on-off cycles at research reactor

Searches for new physics

- Understanding **reactor anomaly** & test sterile ν hypothesis
    - requires unique signatures: oscillation in E and distance
- neutrino **magnetic moment** and **coherent scattering** searches



?

A Short-Baseline Reactor Experiment

Experimental Parameters

Reactor Parameters

- reactor power
- fuel type
- duty cycle
- core dimensions

Detector Parameters

- fiducial volume and target mass
- detection efficiency
- position and energy resolution

Backgrounds

- signal to background
- background spectral shape
- background position distribution

Facility Parameters

- detector distance to core
- experimental space and detector volume

Sensitivity and Discovery Potential

- oscillation signature
- systematic cross-checks
- sensitivity in θ, Δm^2
- runtime
- discovery reach (5σ)

A Short-Baseline Reactor Experiment

Experimental Parameters

Reactor Parameters

- **reactor power**
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- runtime
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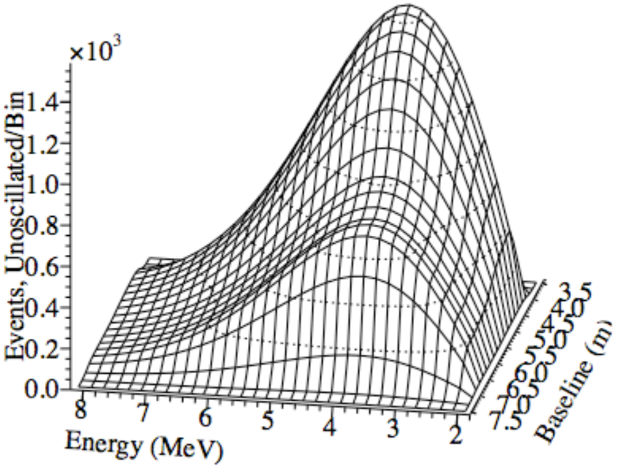
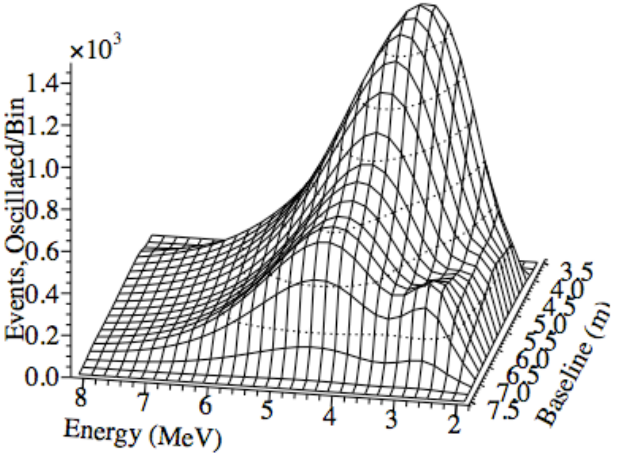
Experimental Parameters

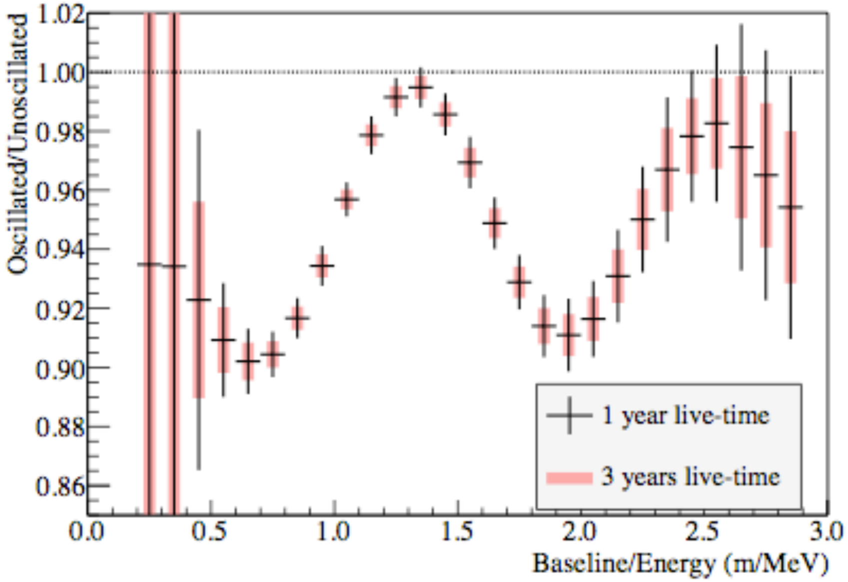
Oscillation Signature

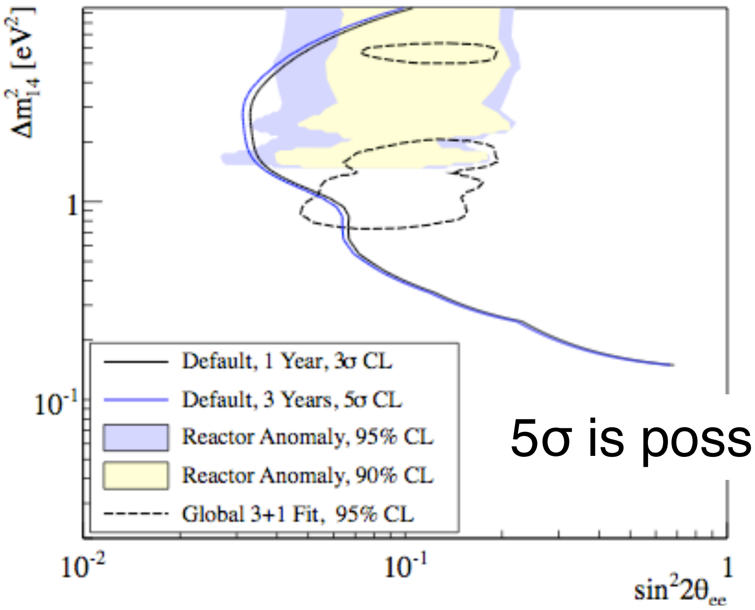
baseline and energy dependence





L/E dependence





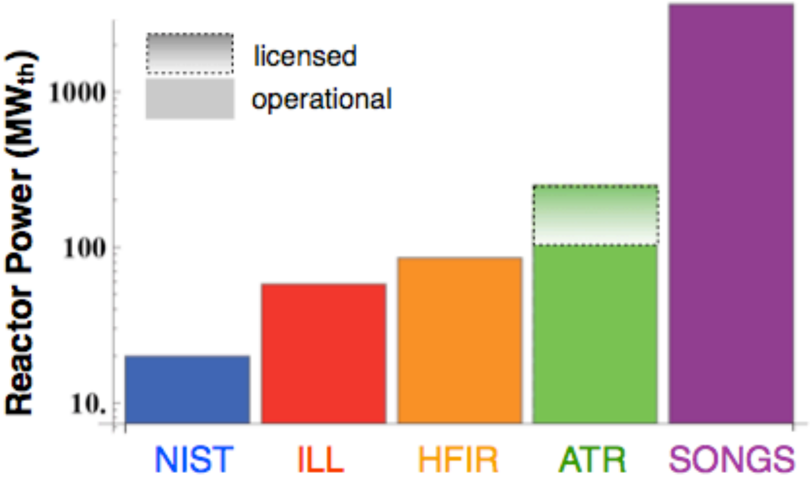
5σ is possible

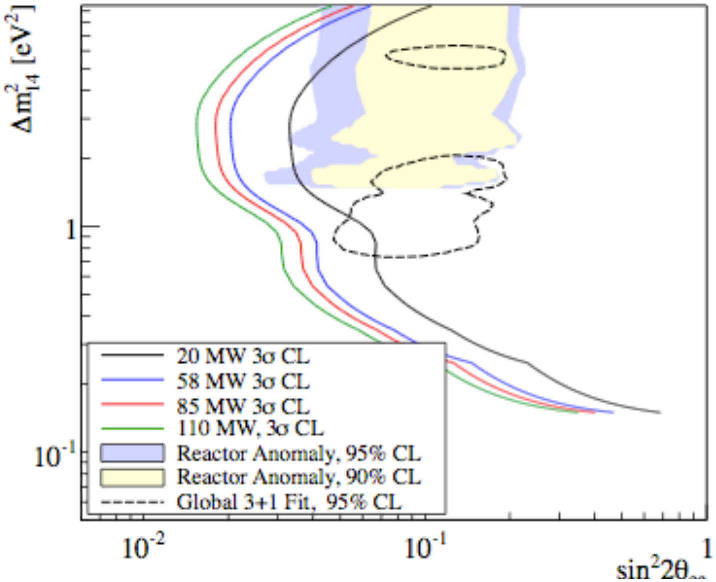
Littlejohn, Mumm, Tobin, KMH
arXiv:1212.2182

Experimental Parameters

Reactor Power

Reactor	Power (MW_{th})	Baselines (m)	Reactor On (Days)	Reactor Off (Days)	Down-Time	Ref.
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%	[? ?]



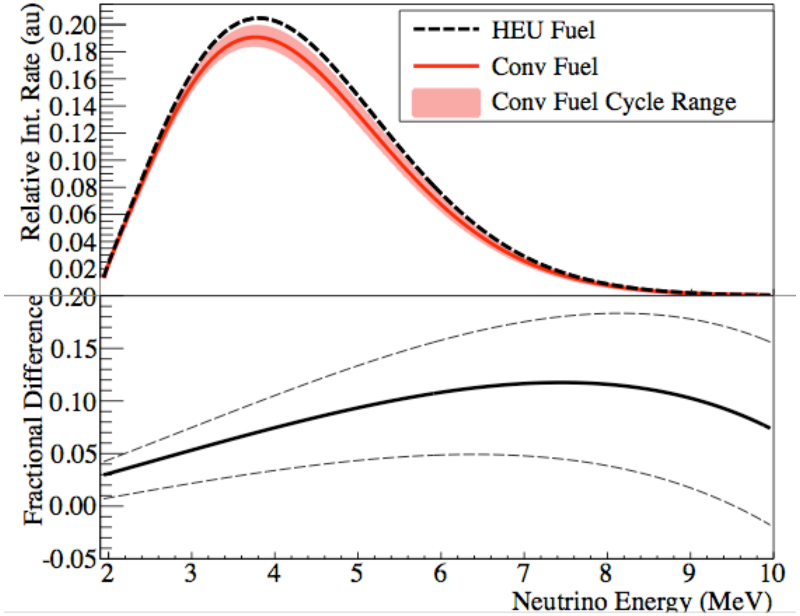


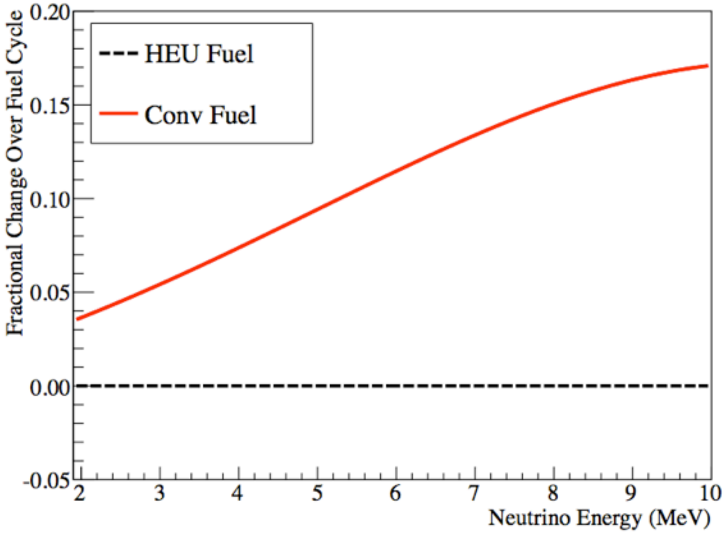
Littlejohn, Mumm, Tobin, KMH
arXiv:1212.2182

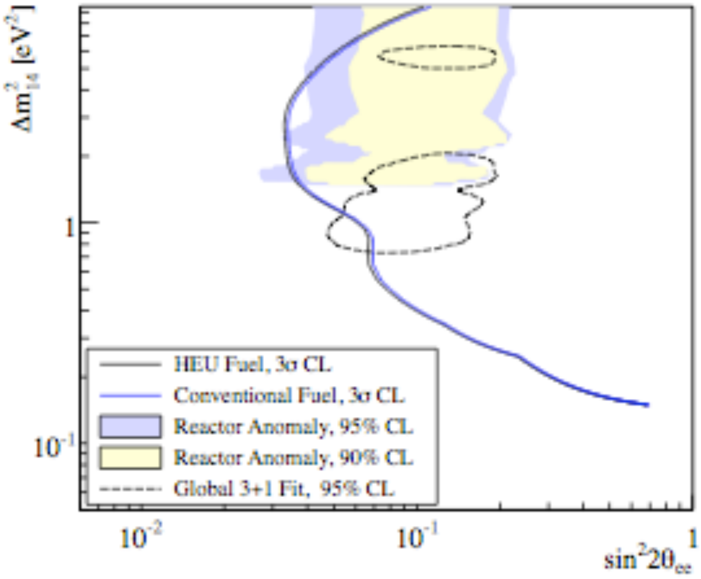
Experimental Parameters

Reactor Fuel

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



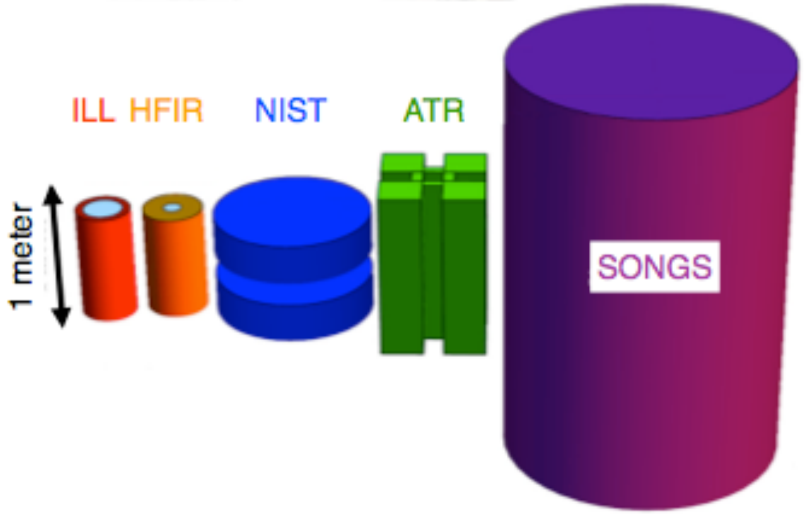


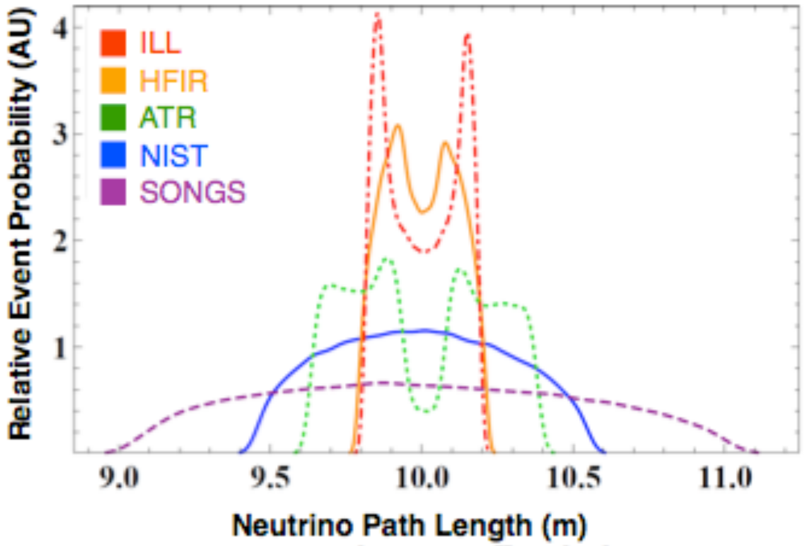


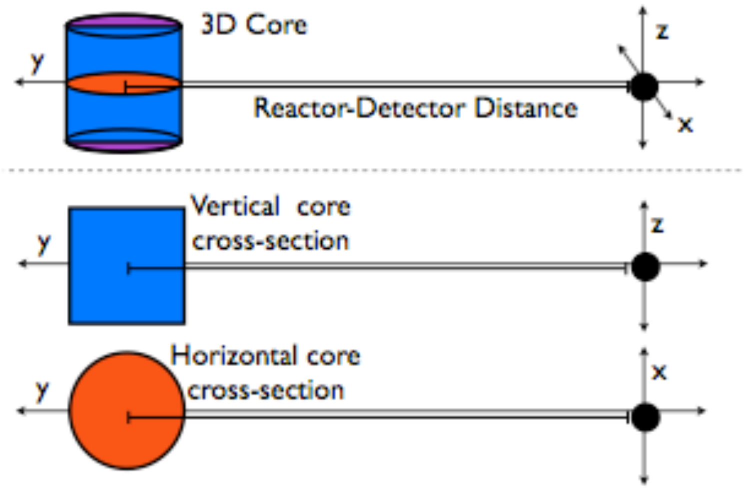
Littlejohn, Mumm, Tobin, KMH
arXiv:1212.2182

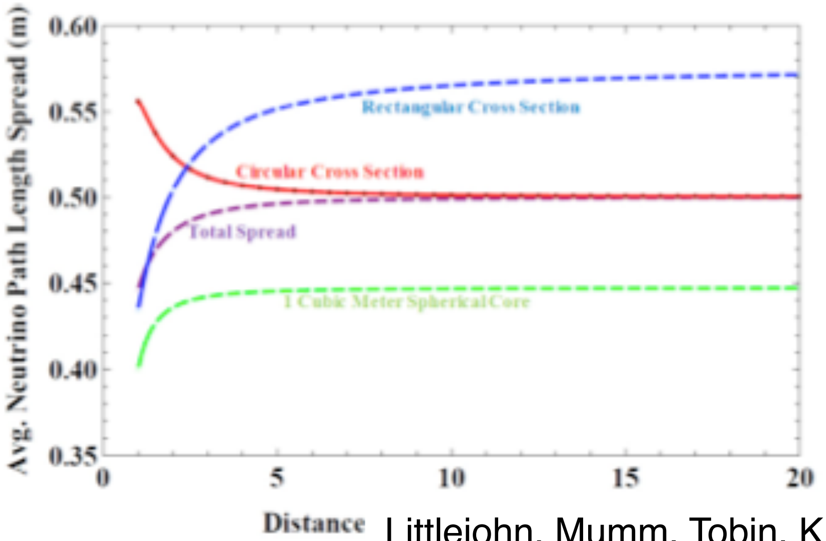
Experimental Parameters

Reactor Cores and Pathlength





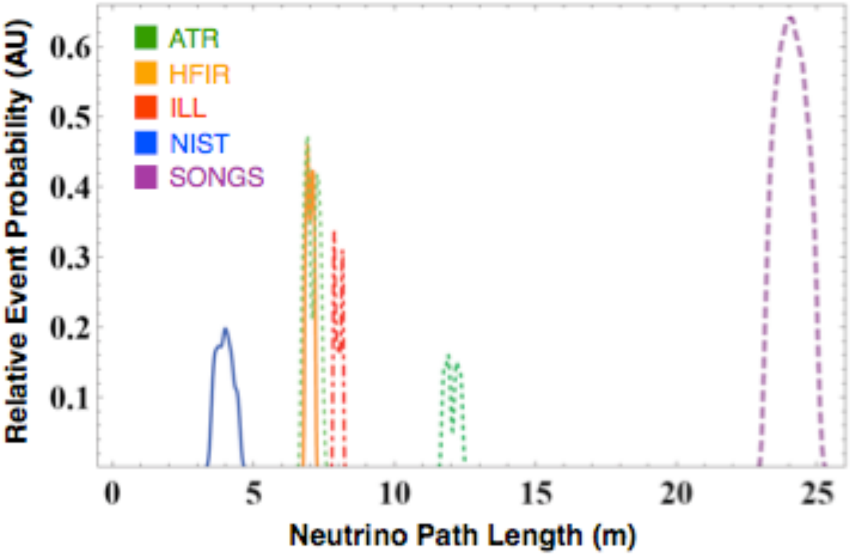




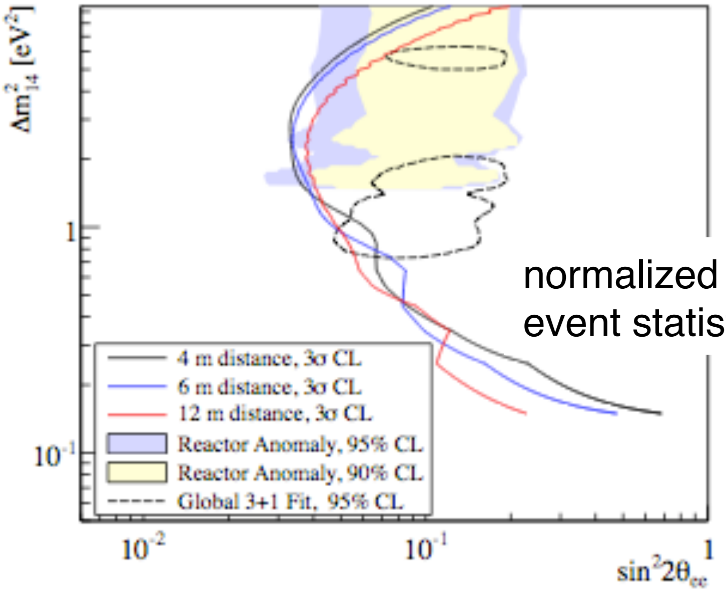
Littlejohn, Mumm, Tobin, KMH
arXiv:1212.2182

Experimental Parameters

Reactor-Detector Distance



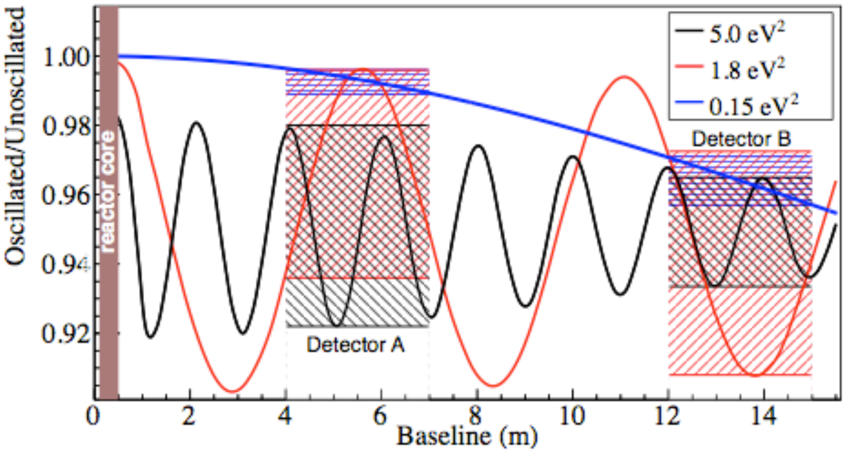
at shortest accessible baseline



normalized to equal event statistics

pointlike detector at closest distance to reactor

detector samples different fractions of oscillation for different Δm^2
2 detectors may be useful.

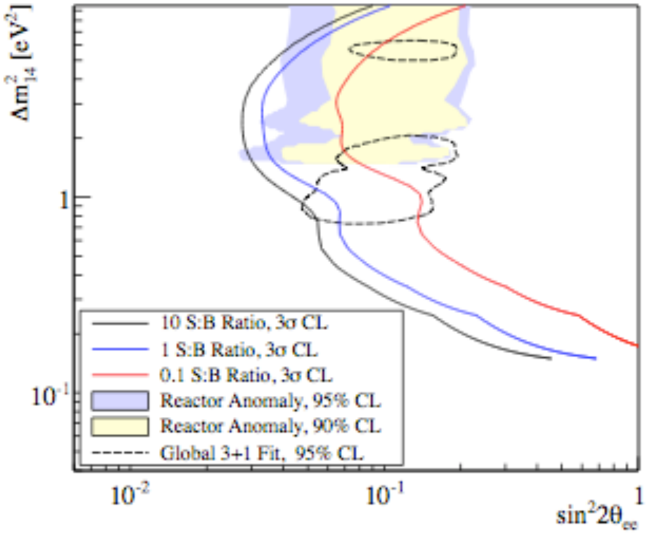


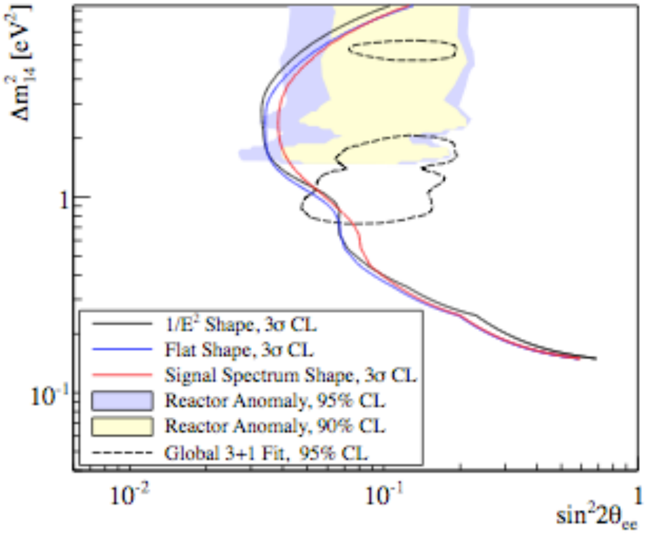
Littlejohn, Mumm, Tobin, KMH
arXiv:1212.2182

Experimental Parameters

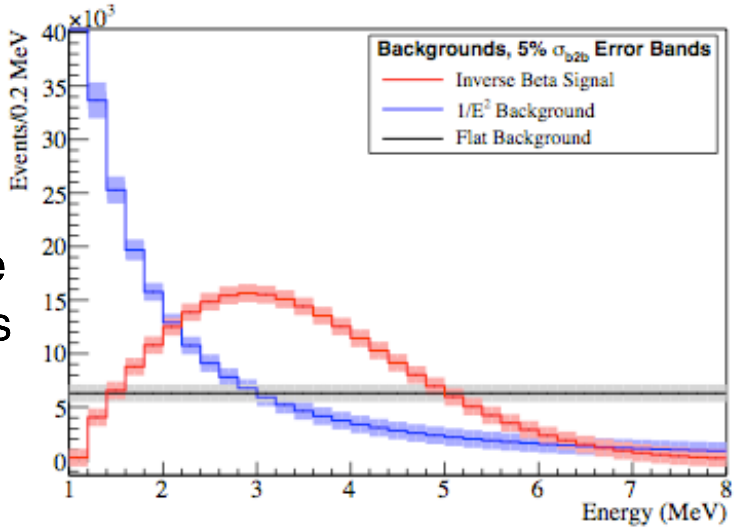
Backgrounds

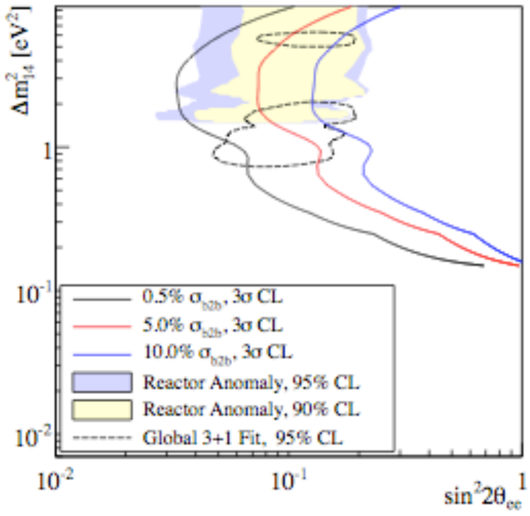
S:B important





critical to know/measure background distributions

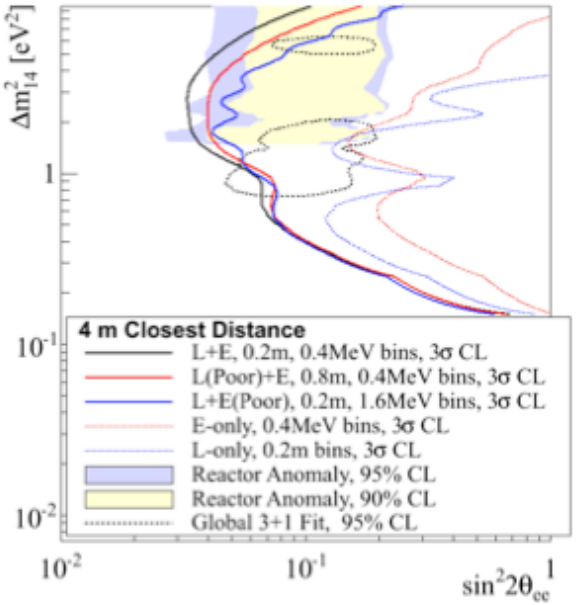


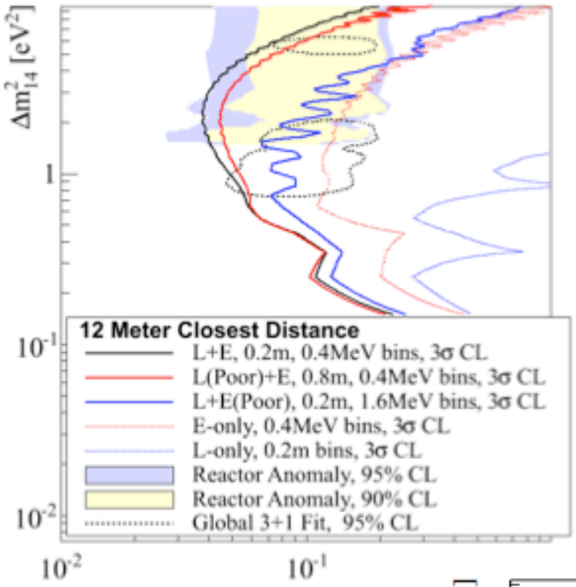


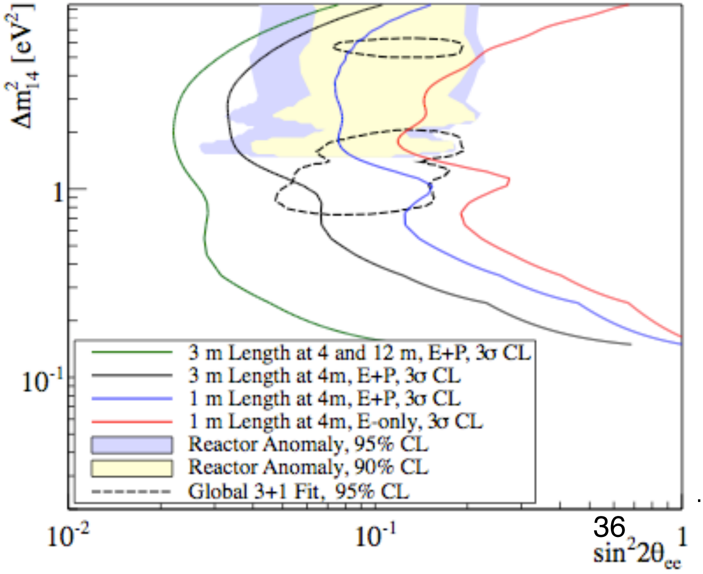
Littlejohn, Mumm, Tobin, KMH
arXiv:1212.2182

Experimental Parameters

Detector Energy and Position Resolution



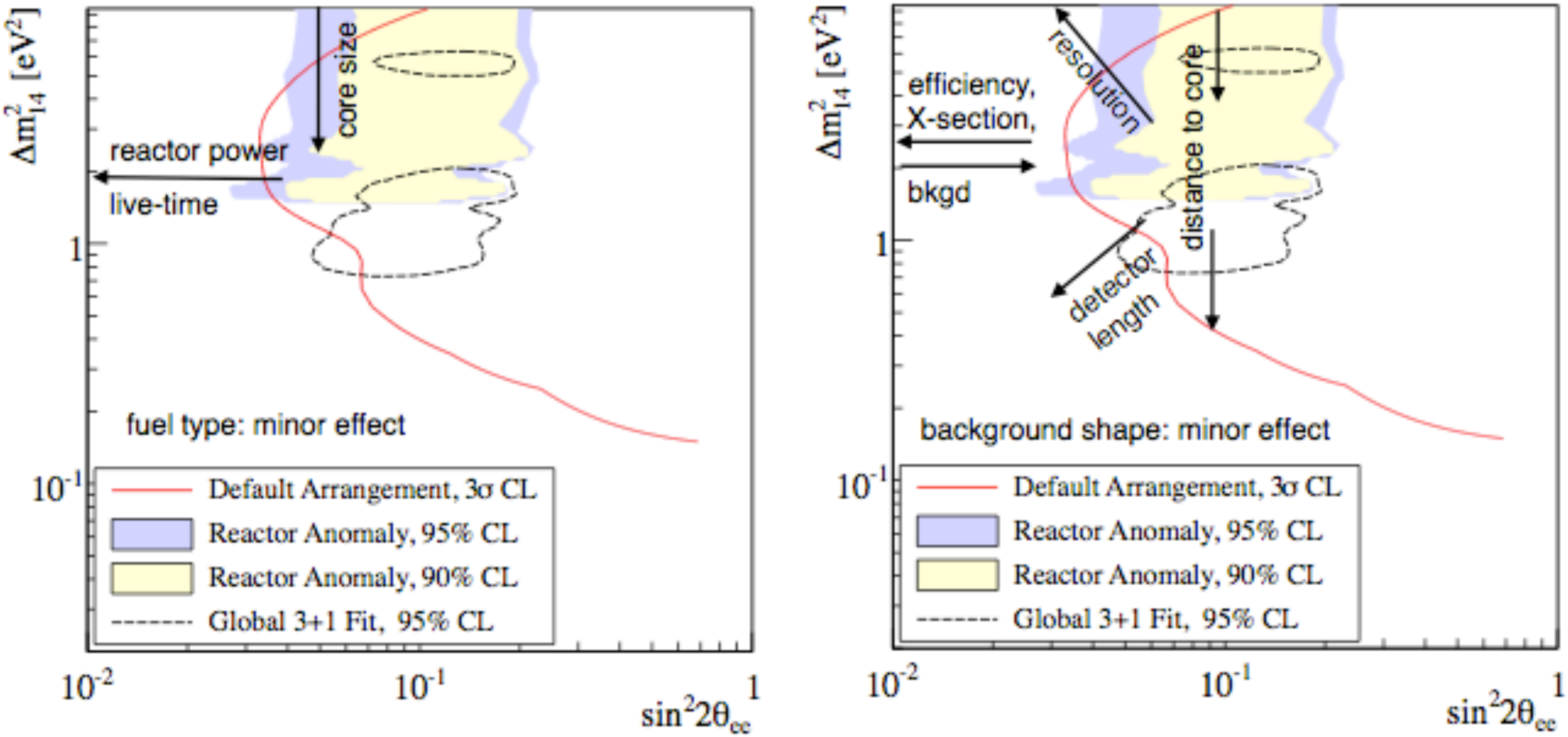




Littlejohn, Mumm, Tobin, KMH
arXiv:1212.2182

Experimental Parameters

Sensitivity, Detector Design, and Reactor Location



Littlejohn, Mumm, Tobin, KMH
arXiv:1212.2182

Experimental Parameters - Summary

- For a definitive measurement, optimization of the experiment is needed to allow for a measurement program including
  - oscillation search in energy
  - oscillation search in baseline
  - systematic cross-checks
  - other physics goals (absolute spectrum measurement etc)

- Optimization of experiment requires understanding facility constraints. Interaction between experimental sites and detector design early in design process.

- Backgrounds will pose a significant challenge, site dependent. Precision measurement of reactor antineutrinos near (or on) surface will pose new challenges.