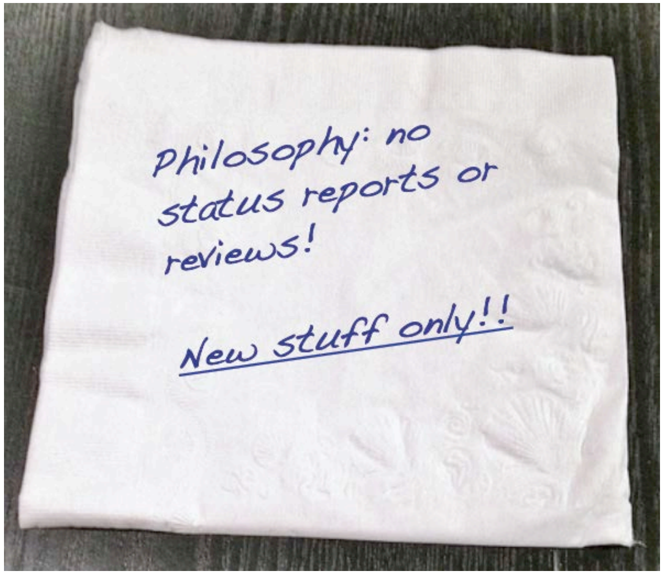
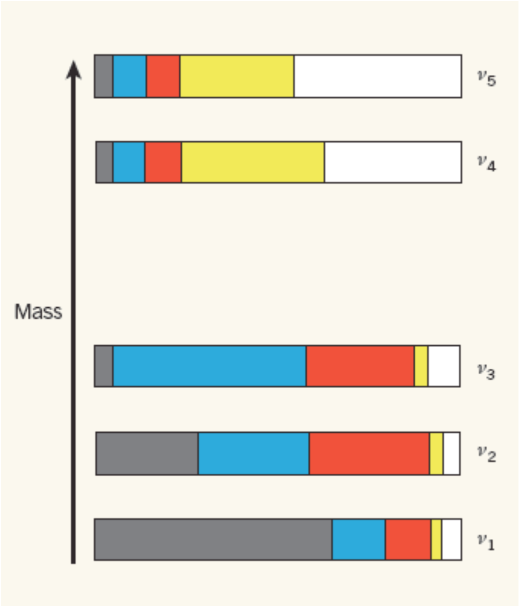
Probing Neutrino Oscillations At Very Short Baselines
with Reactors and Radioactive Sources



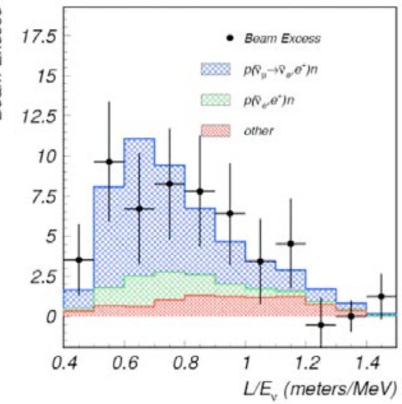


Karsten Heeger
University of Wisconsin

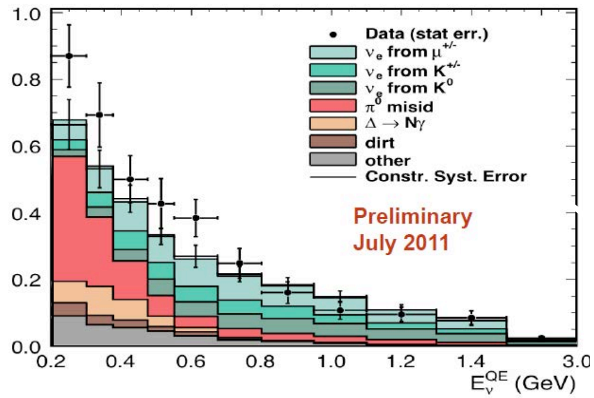
Aspen, February 8, 2013

Neutrino Anomalies and Sterile Neutrinos

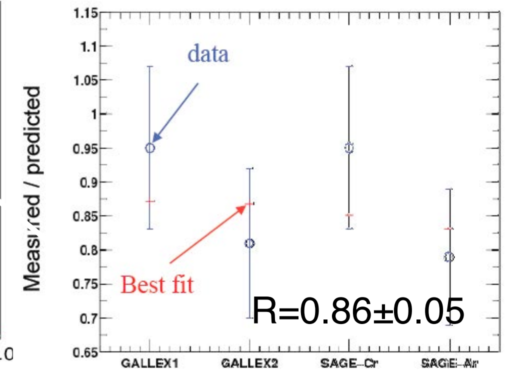
LSND



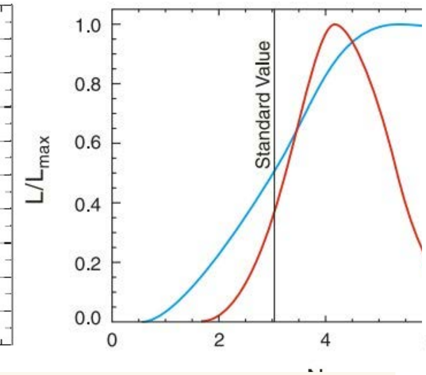
MiniBoone



Ga Source

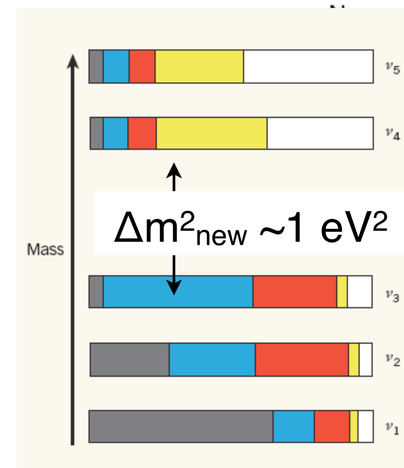


Cosmology (WMAP)



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)



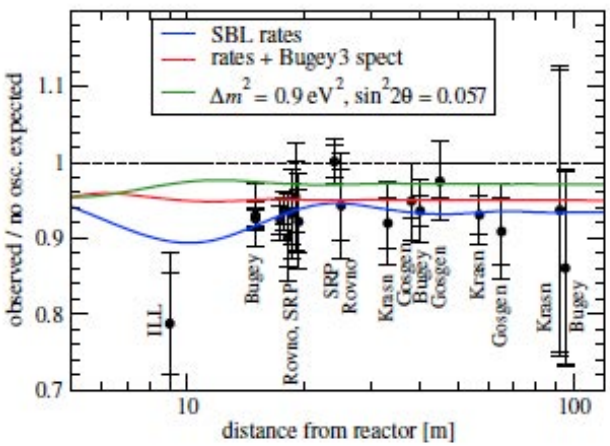
new oscillation signal requires $\Delta m^2 \sim O(1 eV^2)$ and $\sin^2 2\theta > 10^{-3}$
systematics or experimental effect? ➔ need to test each effect

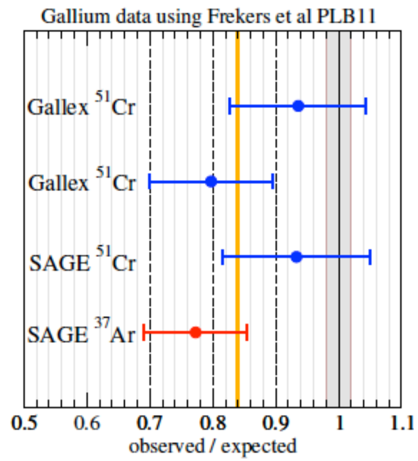
Reactor Anomaly

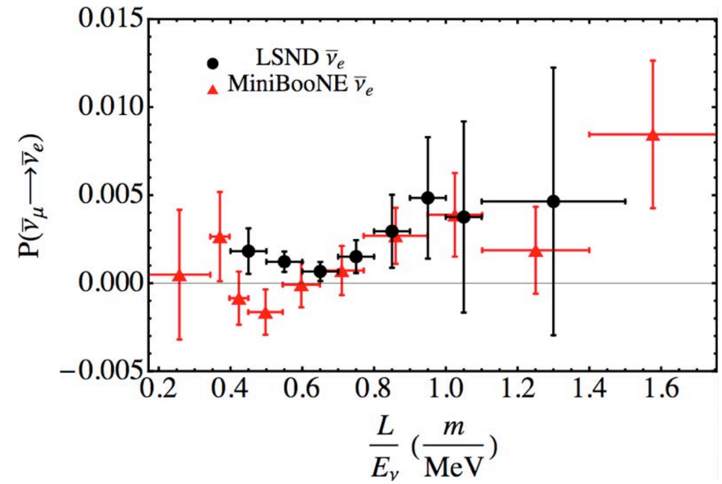
one of several anomalies, could go away with revised flux prediction based on "old" data, no modern reference experiment

Beyond 3ν - Sterile Neutrinos?

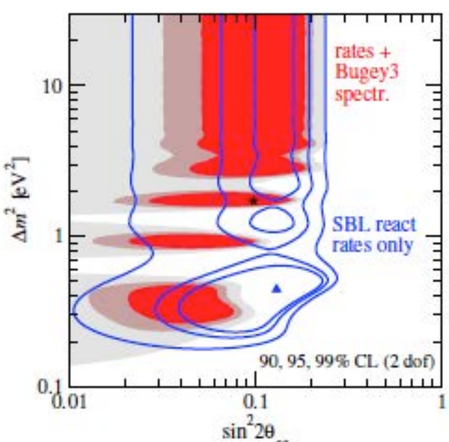
Anomalies

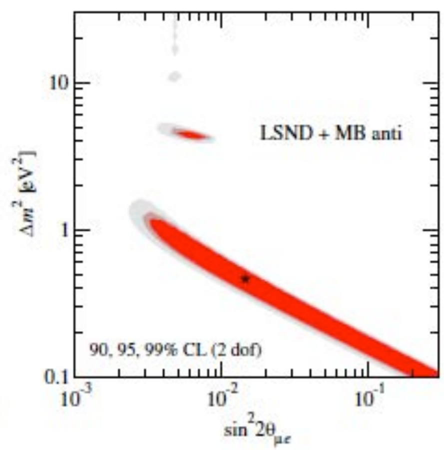


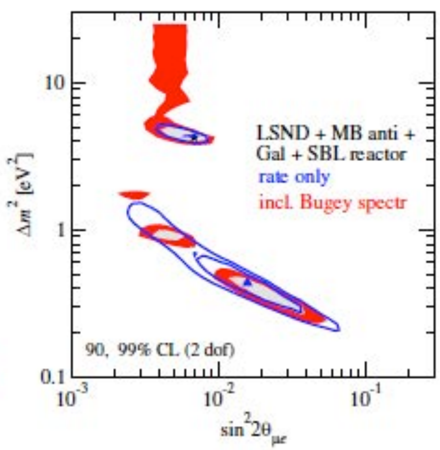




Are $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_e$ consistent?







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

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

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

MicroBoone will provide new data starting ~2014

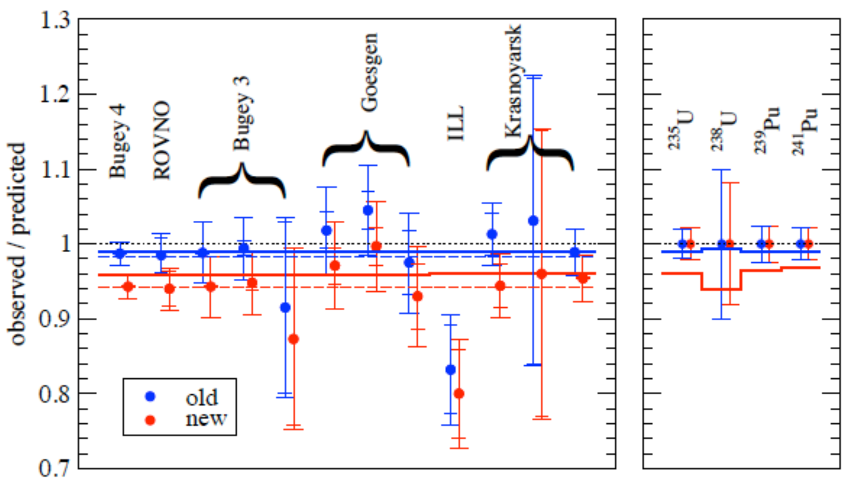
strong tension if all three are combined, tension also in 3+2 fit

Reactor $\bar{\nu}$ Fluxes

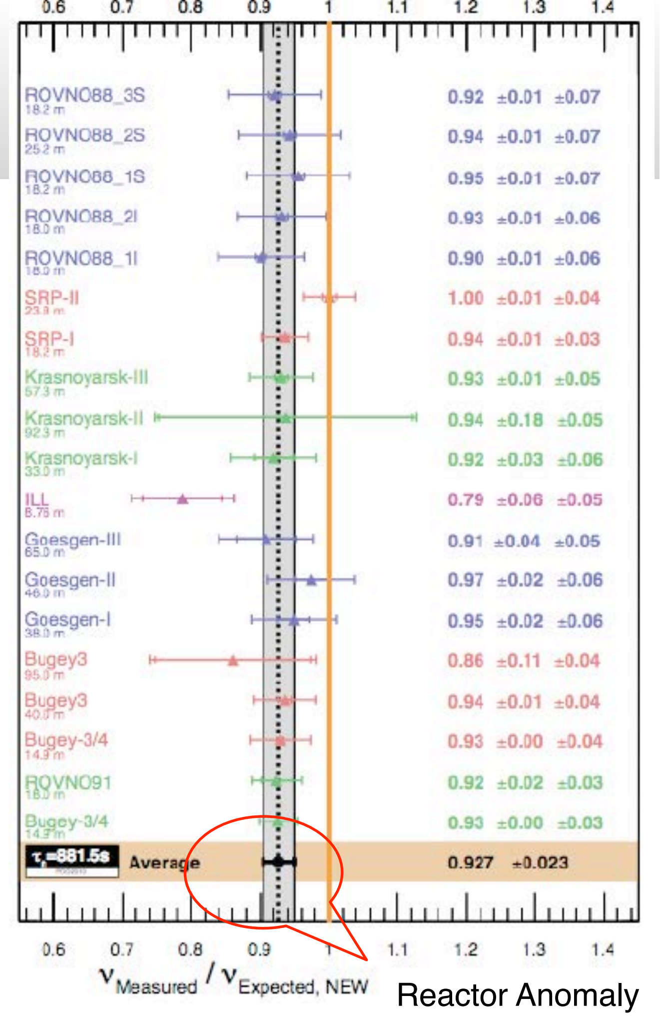
Theory Meets Experiment

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%

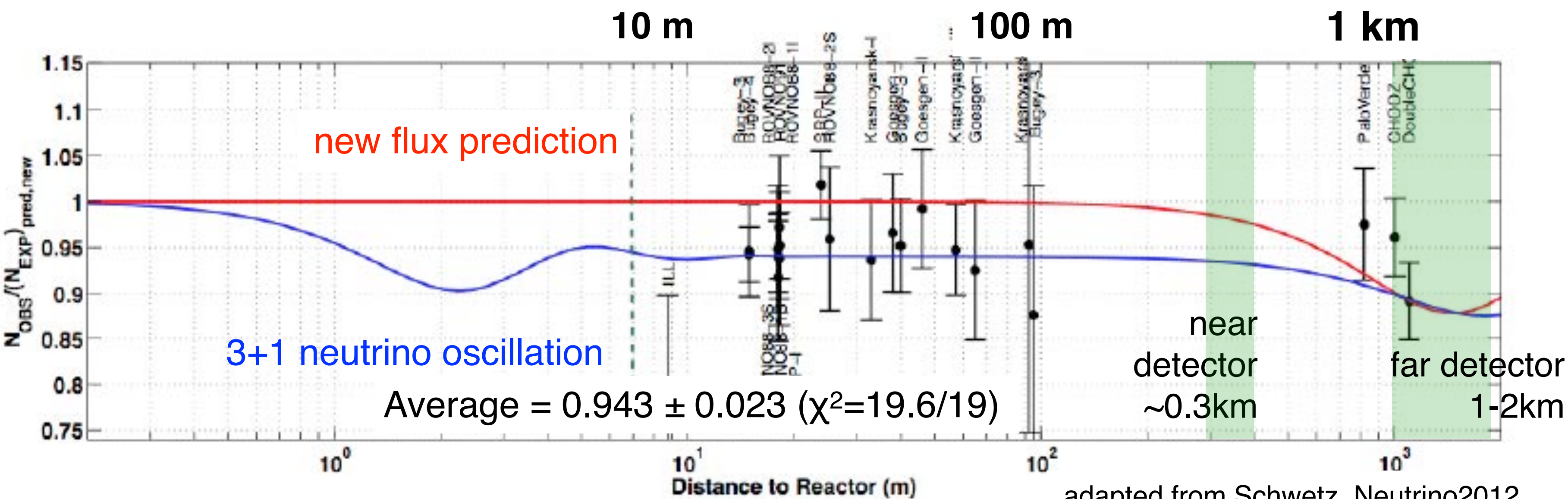


Ref: Mention et al, 1101.2755 (2012 upd)

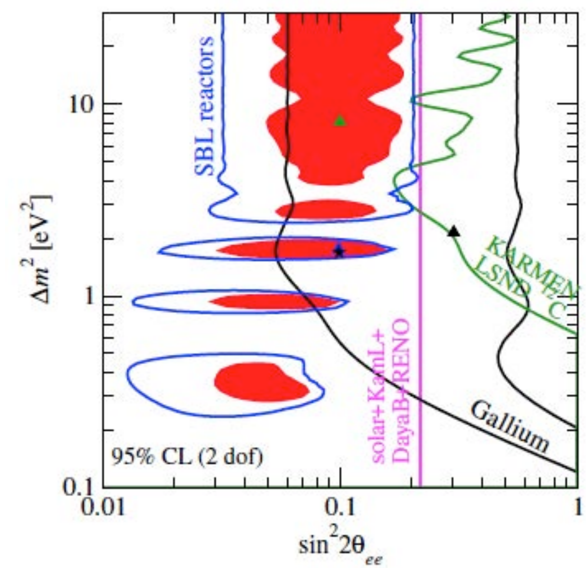
Two issues:

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?

θ_{13} Experiments and the Reactor Anomaly



adapted from Schwetz, Neutrino2012



Absolute flux measurement

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

Precision spectral measurement

verify that we understand how to predict reactor $\overline{\nu}_e$ spectrum

Source Experiments

Sterile ν Oscillation Searches with Radioactive Sources

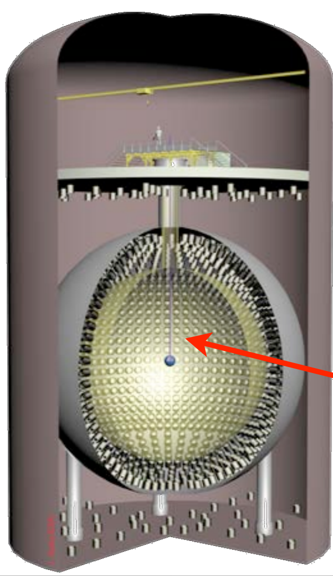
Place source near or inside existing detector, search for $\bar{\nu}_e$ or ν_e disappearance.

Advantages
- baseline can be as short as needed
- detectors can be underground to minimize backgrounds
- demonstrate oscillation signature vs baseline and energy
- re-use existing, well-characterized detectors

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

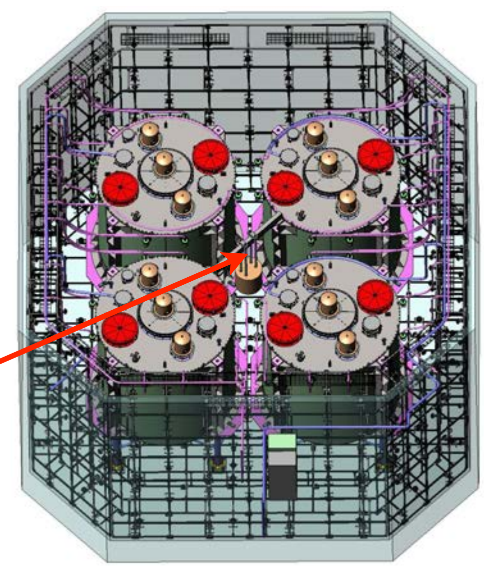
source inside detector

e.g. CeLAND



source next to detector

e.g. Daya Bay



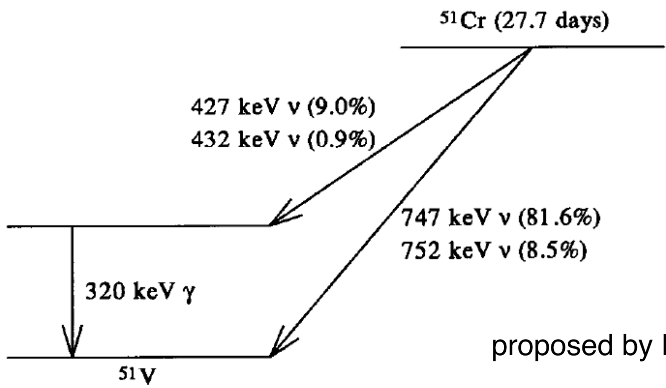
source

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

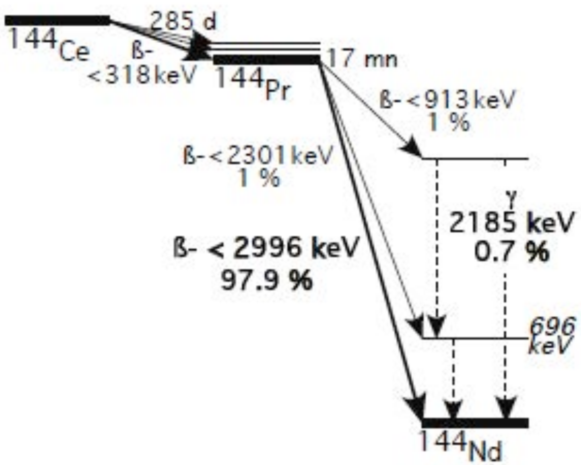


Decay scheme of ^{51}Cr to ^{51}V through electron capture.

proposed by Raghavan

Sources based on beta-decays

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



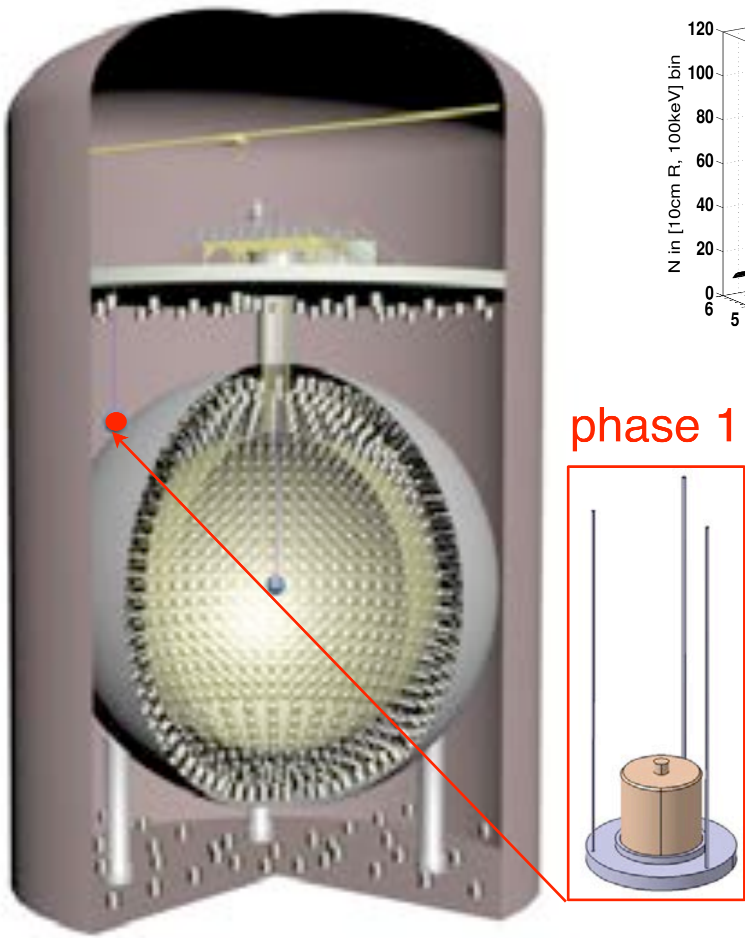
arxiv:1107.2335
Cribier et al

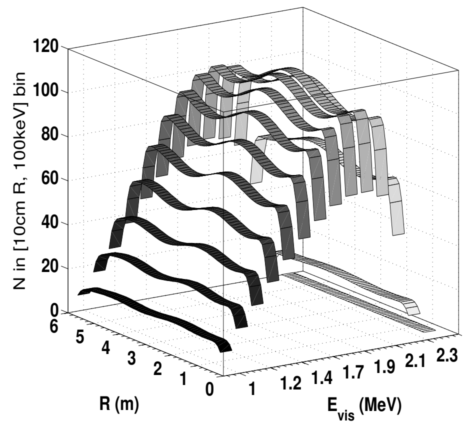
Detection Channels & Proposed Experiments

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

CeLAND

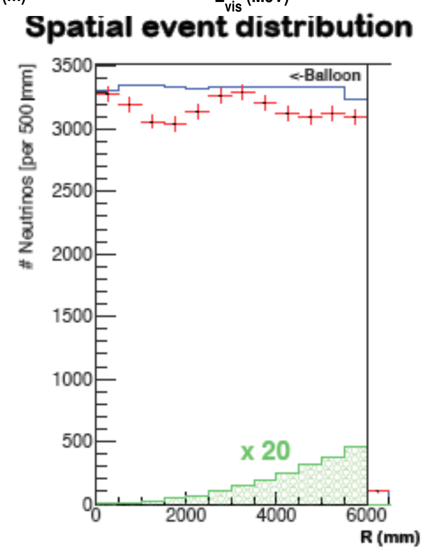
^{144}Ce source inside and outside KamLAND

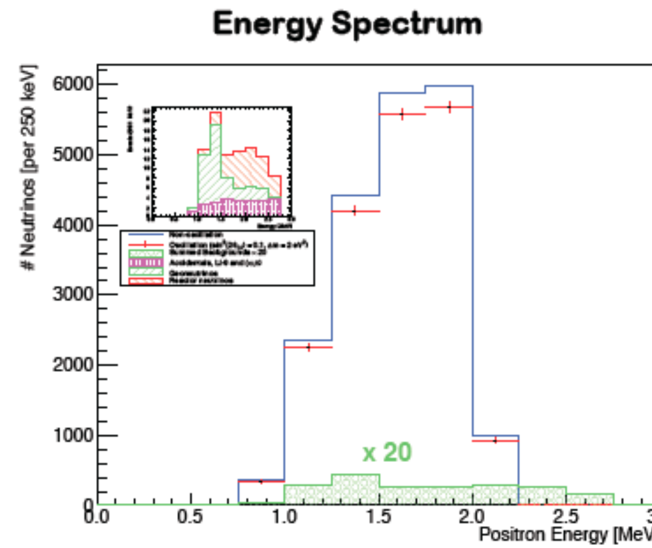




map oscillation effect in R and E

KamLAND exists, 1kt liquid scintillator detector

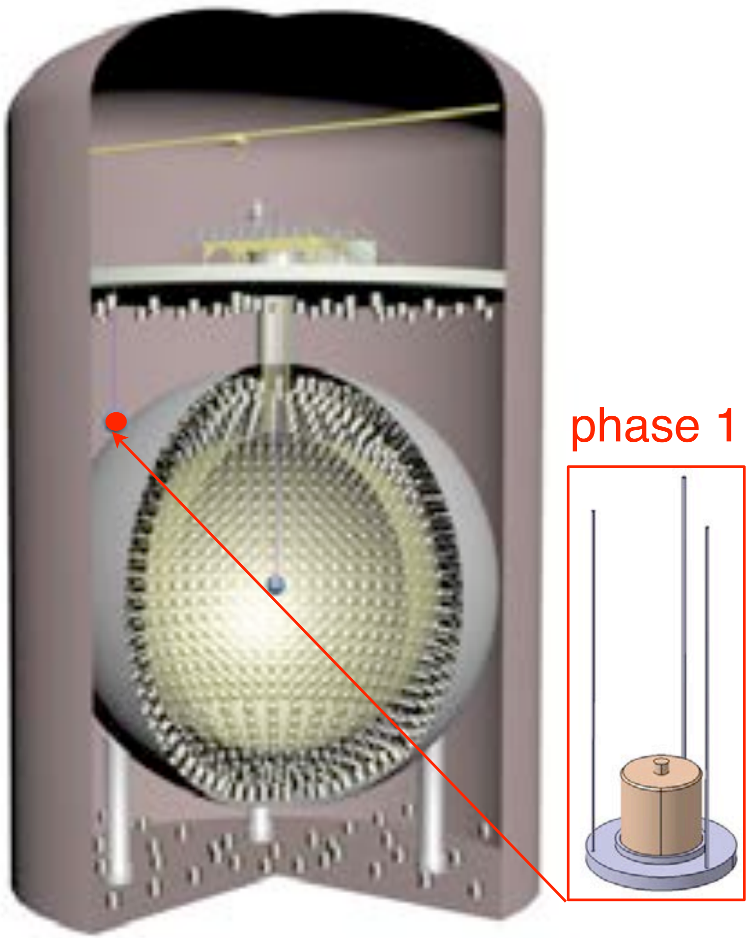




Ref: Lasserre

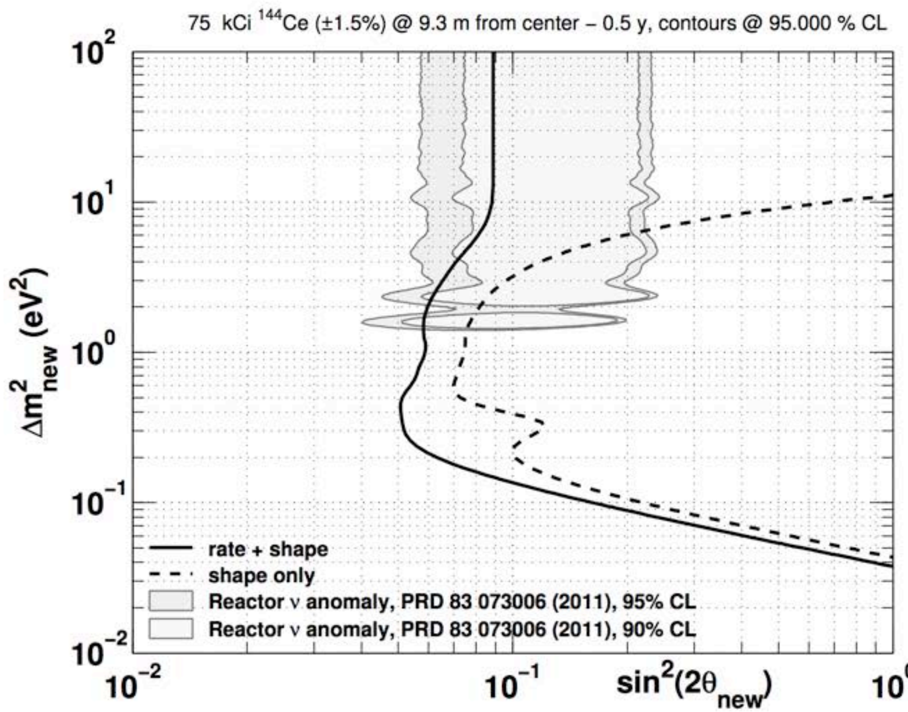
CeLAND

^{144}Ce source inside and outside KamLAND



75kCi

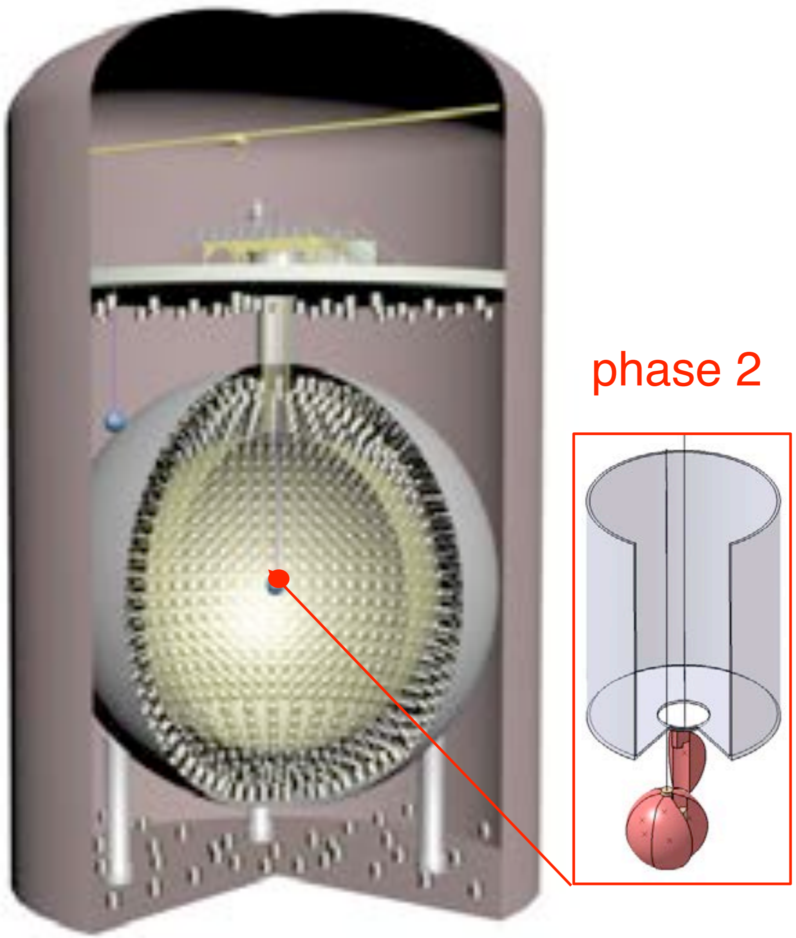
0.5 yrs outside, 95%CL



Ref: Lasserre

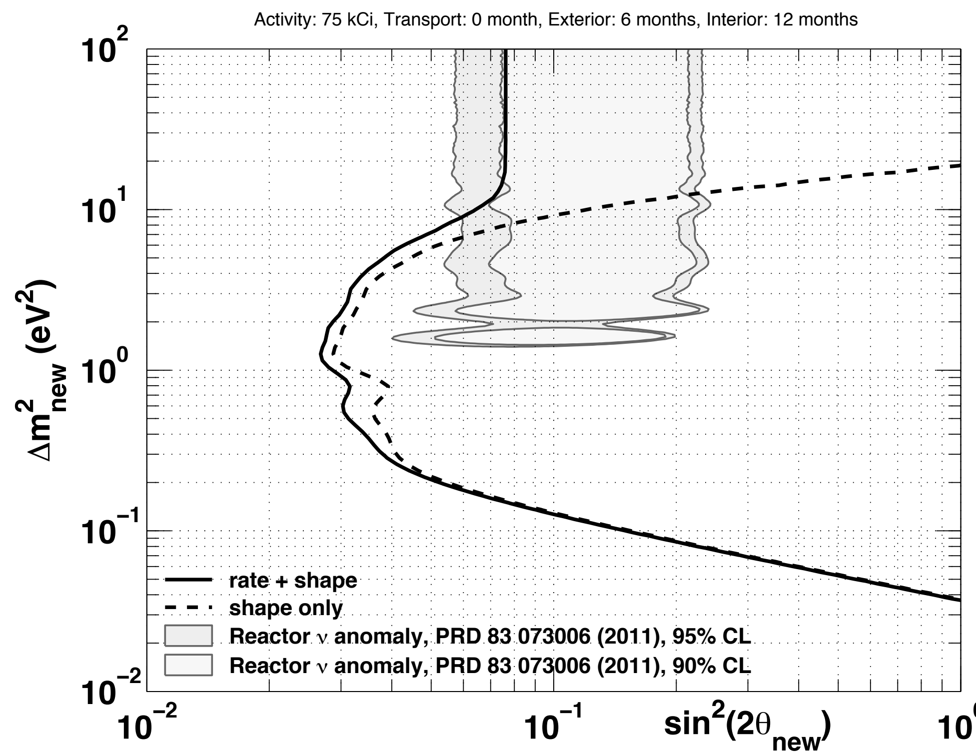
CeLAND

^{144}Ce source inside and outside KamLAND



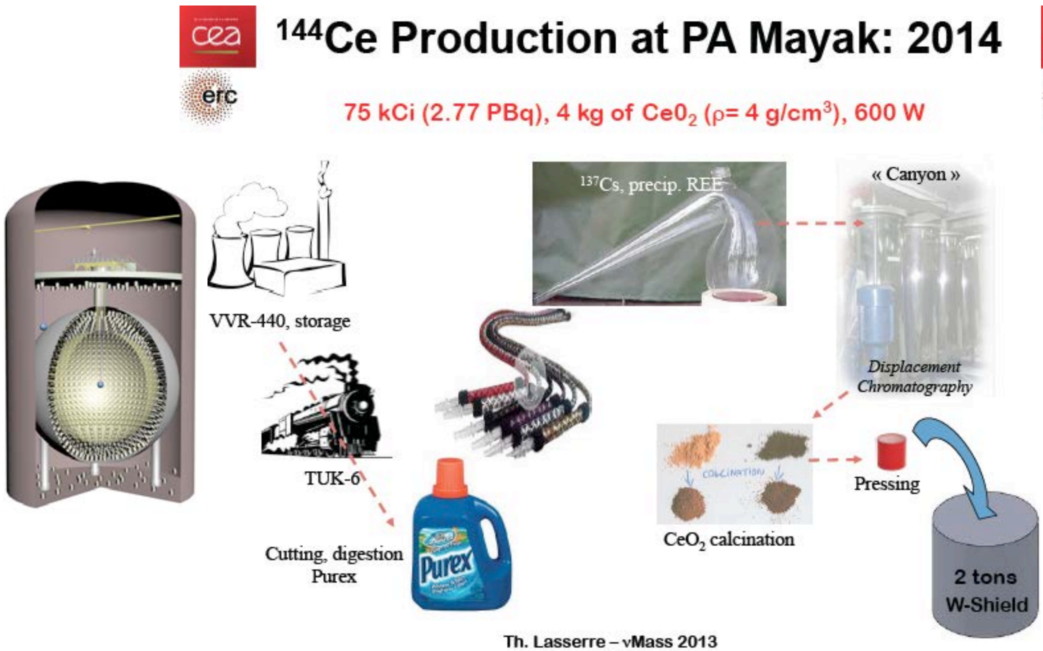
75kCi

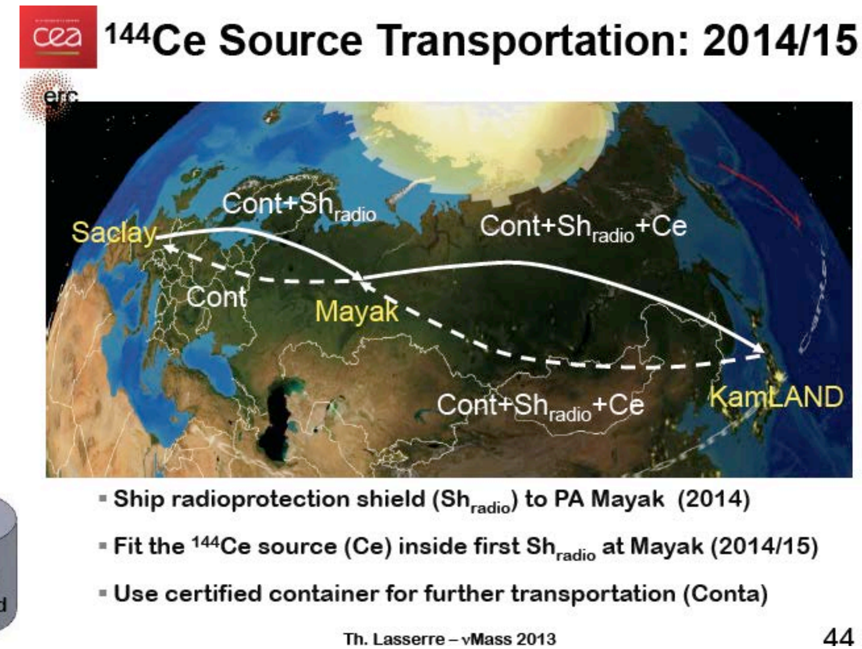
0.5 yr outside + 1 yr in center, 95%CL



Ref: Lasserre

^{144}Ce-^{144}Pr Source Production and CeLAND Status





Source Production

- agreements for production between CEA and Rosatom
- currently working on the source production (samples will be available soon), transportation (of course a real issue), activity measurement (<1% seems feasible)

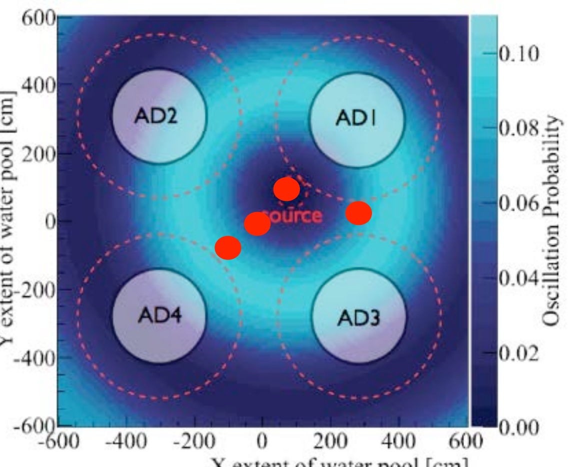
CELAND Plans and Status

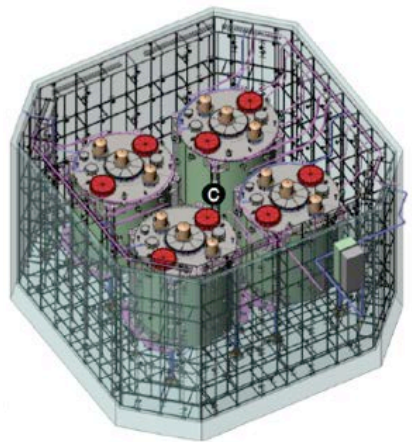
- deploy 75 kCi in KamLAND outer detector (phase 1) in 2015.
- aim for deployment in center with the same source if there is a hint (much more challenging)
- Japan working on authorizations, expect to know more in March at the collaboration meeting

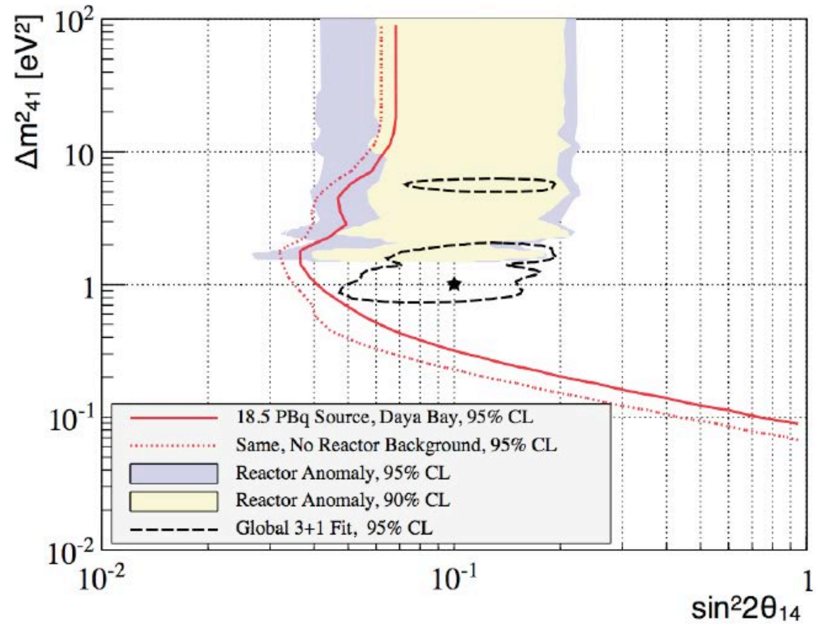
Daya Bay Sterile Neutrino Search

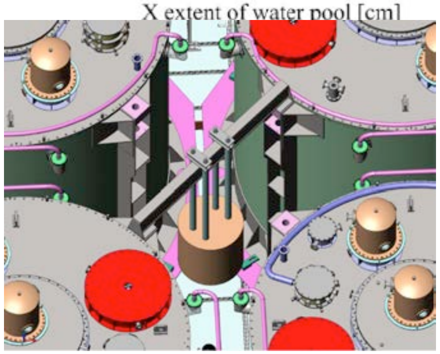
^{144}Ce-^{144}Pr source can Probe baselines from 1.5-8 m with an source in the water pool of the Daya Bay Far Hall

- Advantageous to place source outside detectors in water pool.
- Multiple detectors allow for control of systematics.







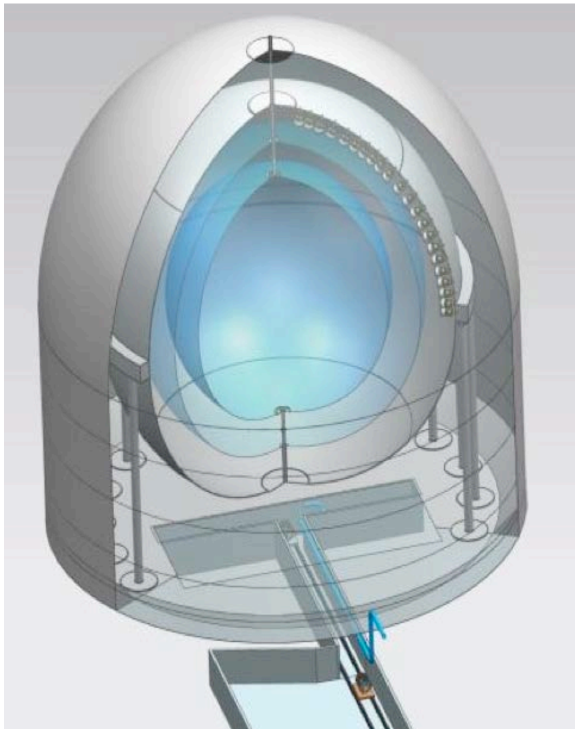


source experiment feasible in Far Hall of the Daya Bay experiment after θ_{13} measurement.

arXiv:1109.6036
Dwyer, Littlejohn, Vogel, KMH

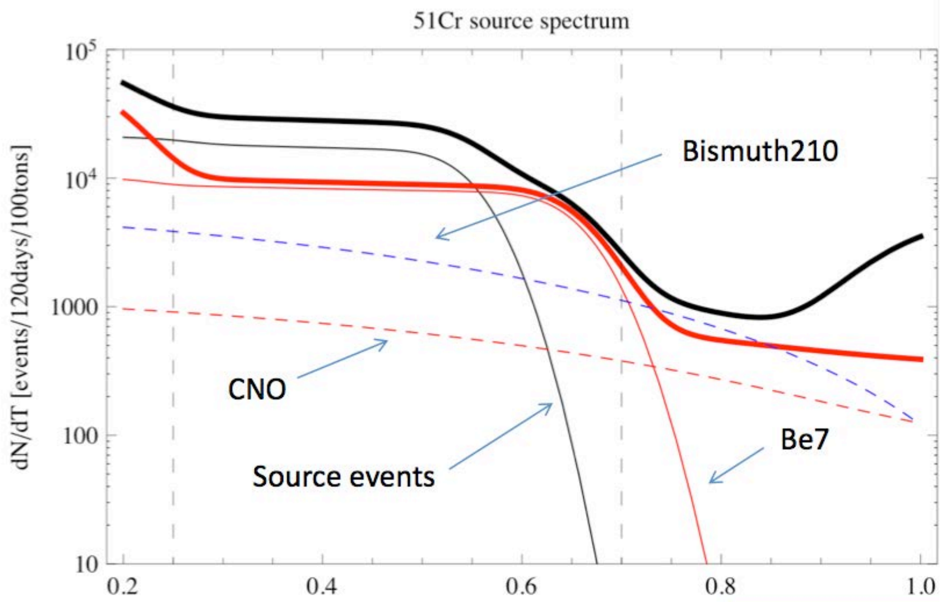
SOX - Short Distance Oscillations with Borexino

^{51}Cr source next to Borexino



existing tunnel, source at 8.25 m from the LS target

ν_e elastic scattering signal versus distance



Detection as ^{7}Be solar ν

Well known background in 0.25-0.7 MeV: solar ν's & ^{210}Bi

1% fiducial volume error

10-15 MCi ^{51}Cr

Re-use Gallex 36 kg of enriched chromium (38%)

need add. enriched 50Cr

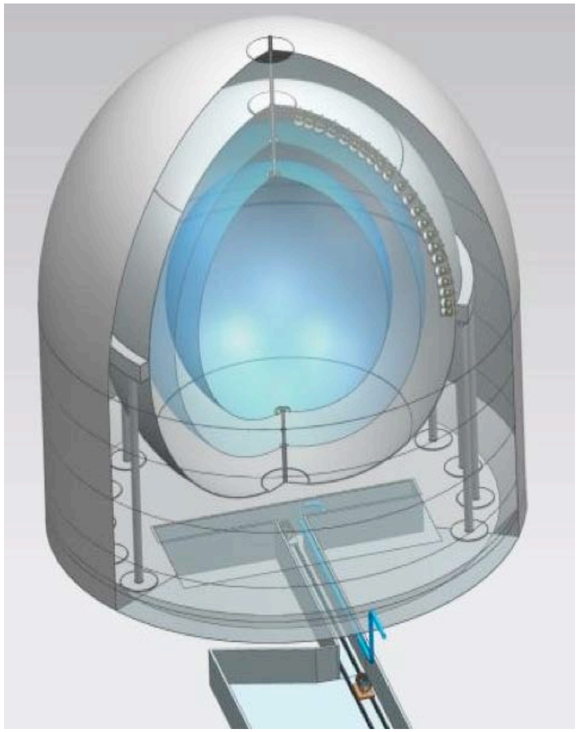
Reactors (Petten, Ludmila, US)

nth ≈ 1015 n/cm2/sec

Space to accommodate 50Cr

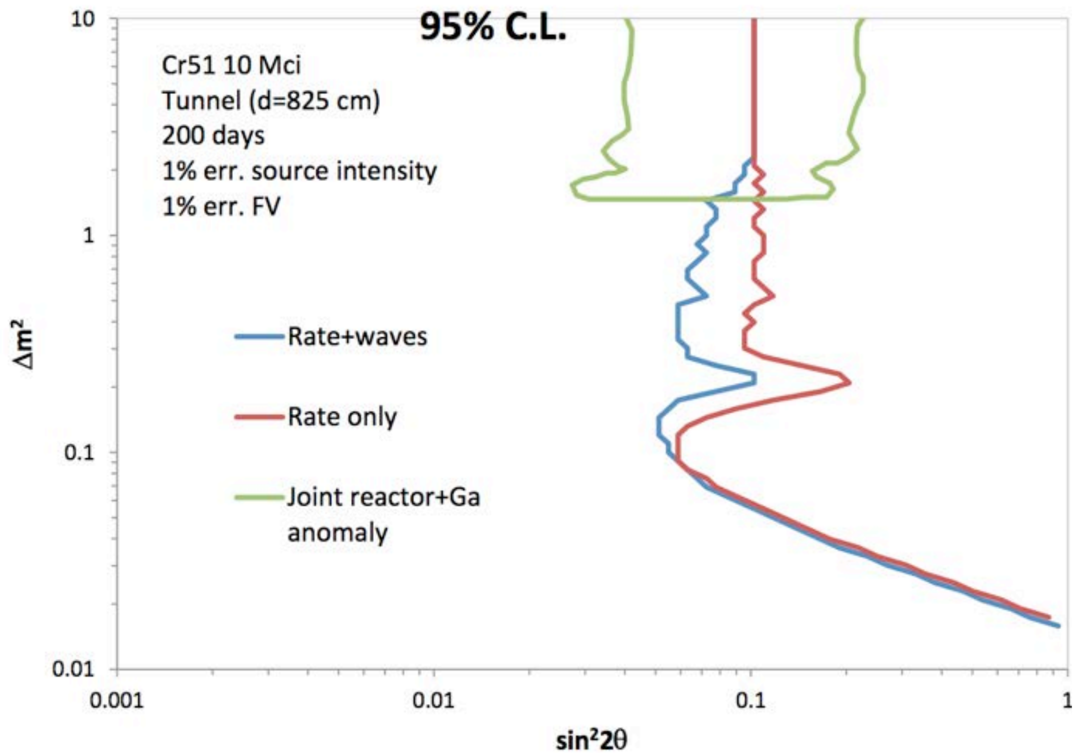
SOX - Short Distance Oscillations with Borexino

^{51}Cr source next to Borexino



existing tunnel, source at 8.25 m from the LS target

^{51}Cr 10 MCi, 95% CL



10-15 MCi ^{51}Cr

Re-use Gallex 36 kg of enriched chromium (38%)

need add. enriched 50Cr

Status

ERC funding obtained

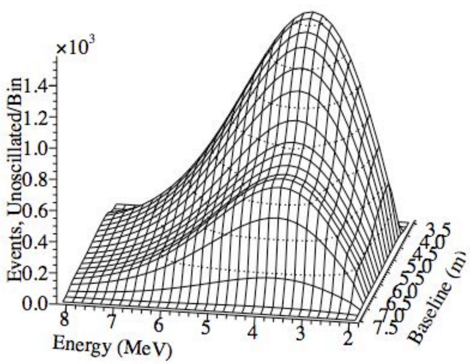
source production by 2015

Reactor Experiments

Reactor Experiments at Very Short Baselines

Energy and Baseline Dependent Effect

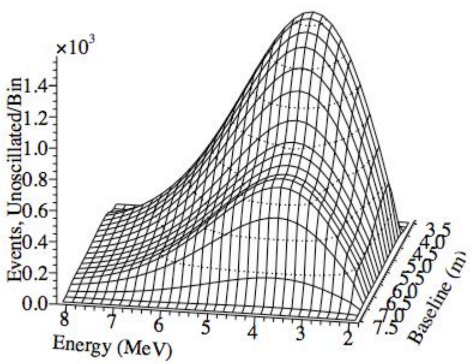
Reactor Antineutrinos



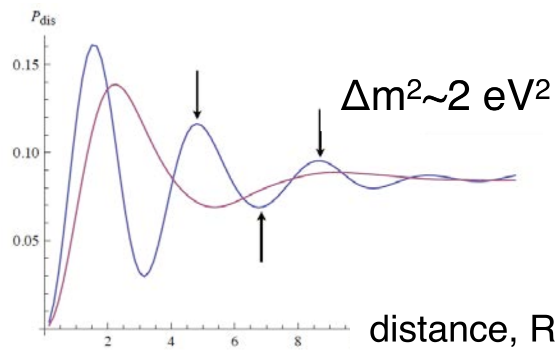
Reactor Experiments at Very Short Baselines

Energy and Baseline Dependent Effect

Reactor Antineutrinos



$\overline{\nu}_e$ Oscillation

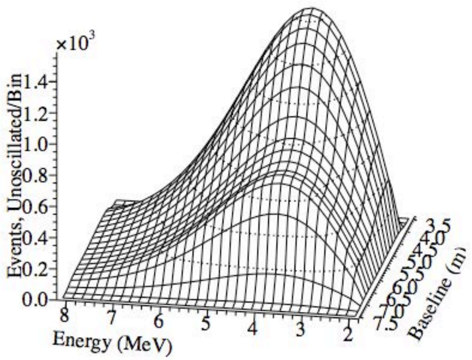


~O(10)m

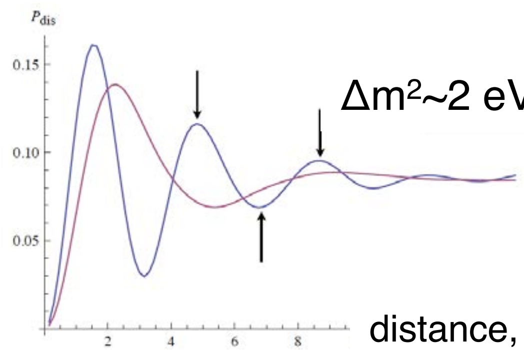
Reactor Experiments at Very Short Baselines

Energy and Baseline Dependent Effect

Reactor Antineutrinos

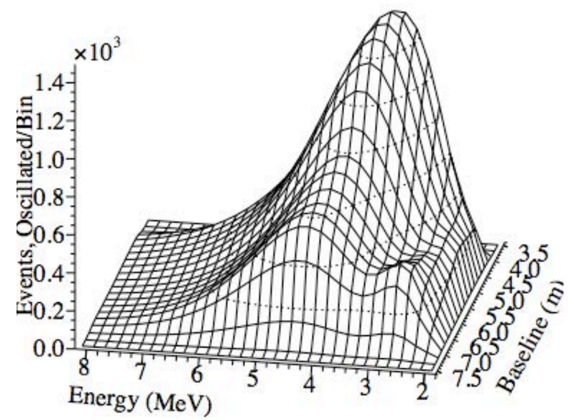


$\overline{\nu}_e$ Oscillation



Δm^2~2 eV^2

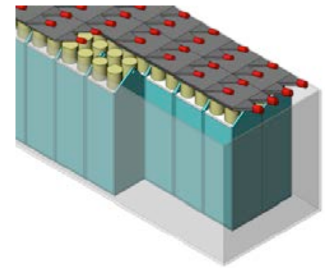
distance, R



~O(10)m

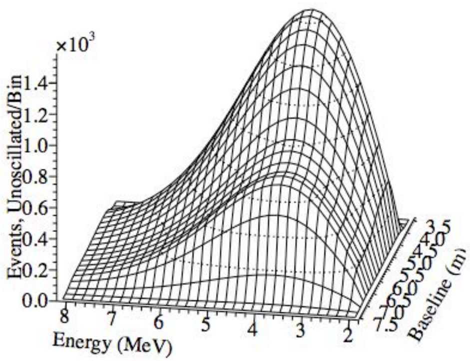
Reactor Experiments at Very Short Baselines

Energy and Baseline Dependent Effect

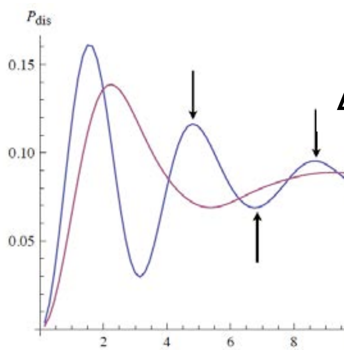


segmented, extended detector

Reactor Antineutrinos



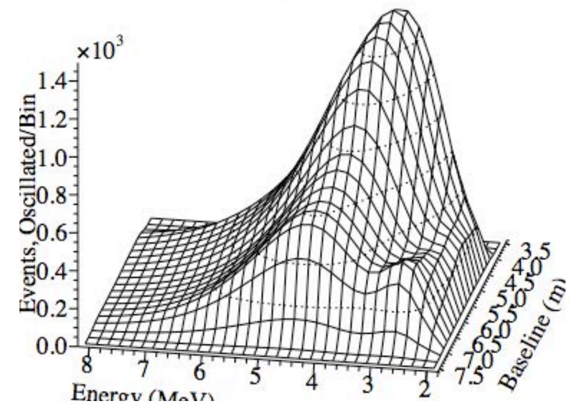
$\overline{\nu}_e$ Oscillation

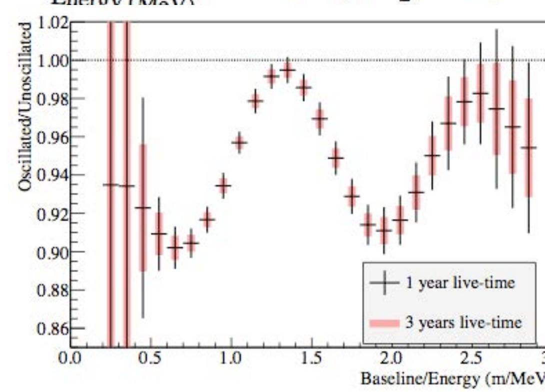


$\Delta m^2 \sim 2\ eV^2$

distance, R

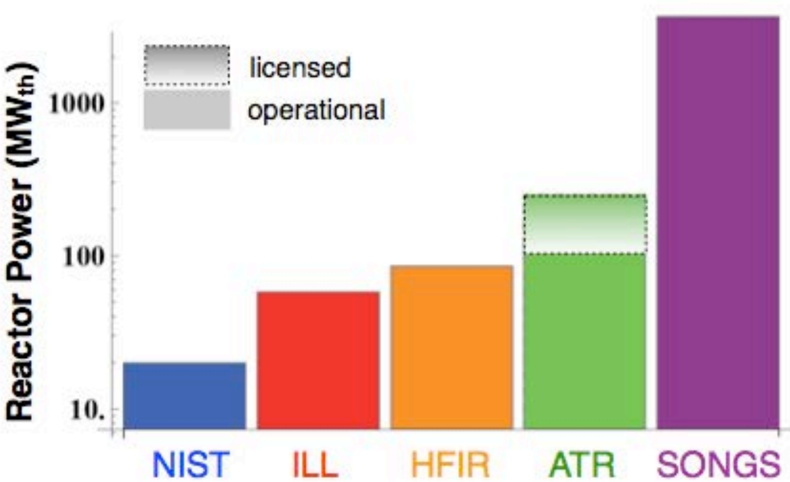
~O(10)m





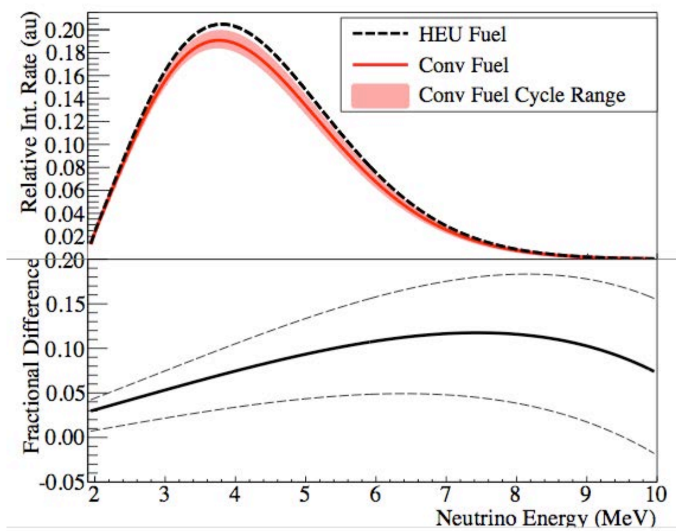
Reactor Experiments at Very Short Baselines

Reactor Power and Duty Cycle

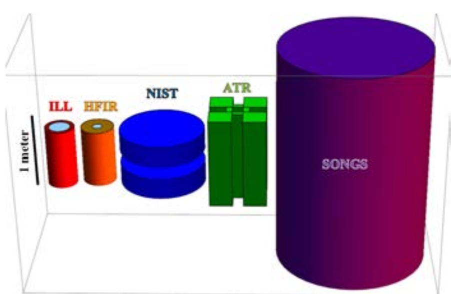


Reactor	Power (MW$_{th}$)	Baselines (m)	Reactor On (Days)	Reactor Off (Days)	Down-Time
NIST	20	4-13	42	10	~32%
HFIR	85	6-8	24	18	~50%
ATR	250 (licensed) 110 (operational)	7-8 (restricted) 12-20 (full access)	48-56	14-21	~27%
ILL	58	7-9	50	41	~45%
SONGS	3438	24	639	60	8.6%

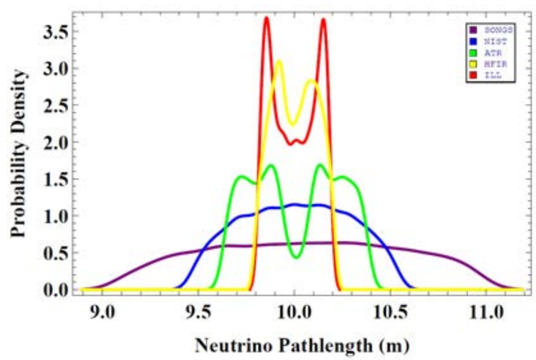
Reactor Fuel



Reactor Core Size



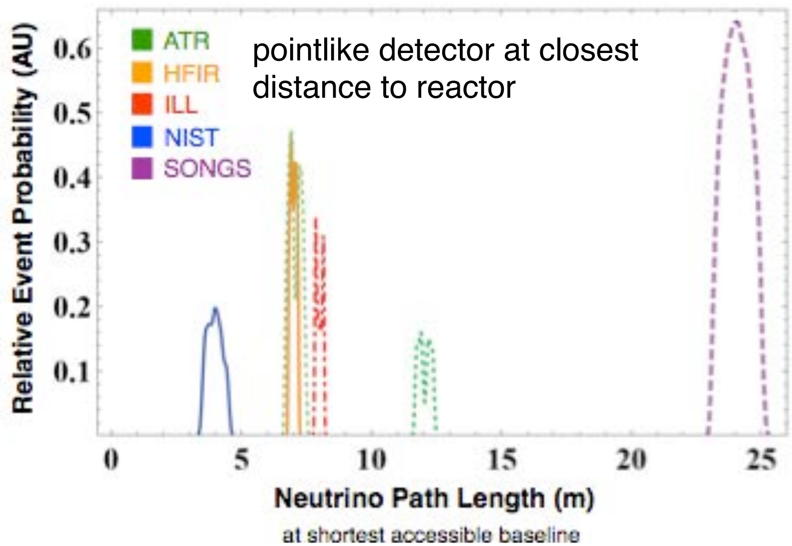
Pathlength spread at detector from core

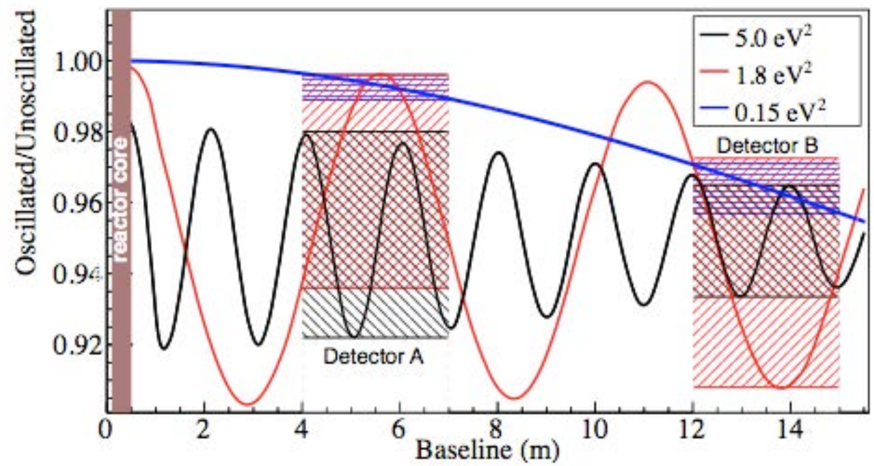


arXiv:1212.2182
Littlejohn, Mumm, Tobin, KMH

Reactor Experiments at Very Short Baselines

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



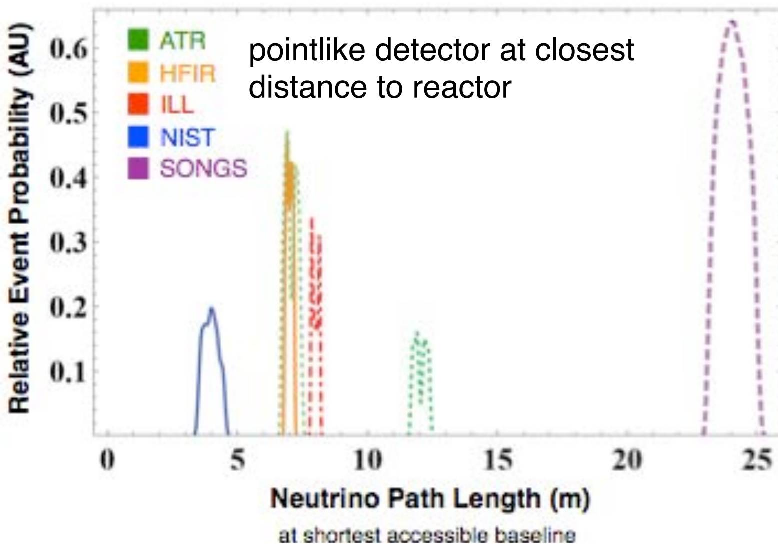


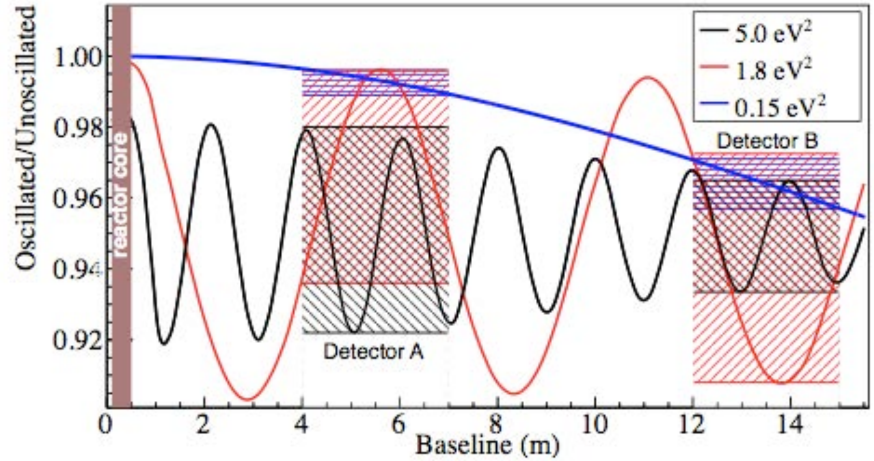
detector samples different oscillations for different Δm^2, → multiple detectors useful

arXiv:1212.2182
Littlejohn, Mumm, Tobin, KMH

Reactor Experiments at Very Short Baselines

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

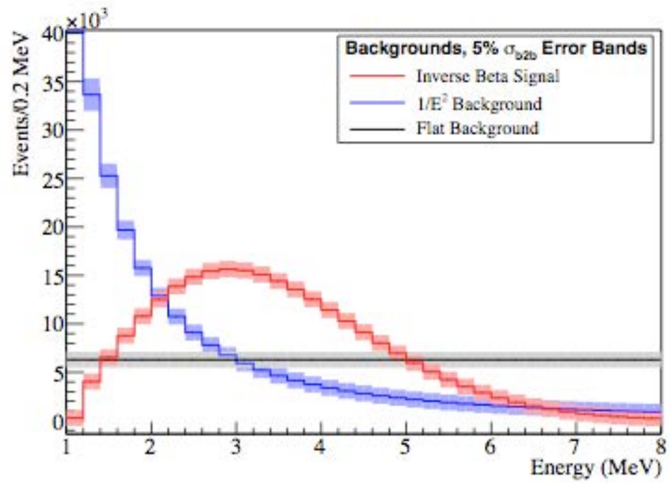


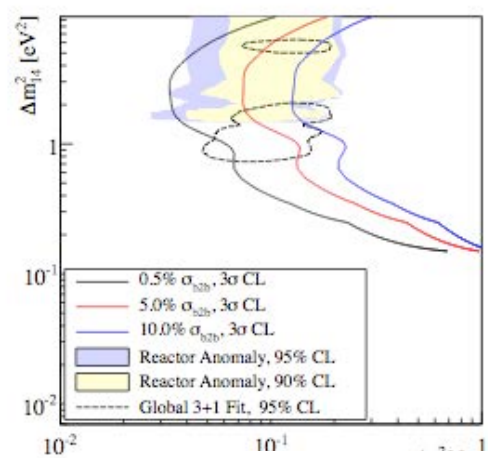


detector samples different oscillations for different Δm^2, → multiple detectors useful

Backgrounds

significant challenge, critical to know/measure background distributions

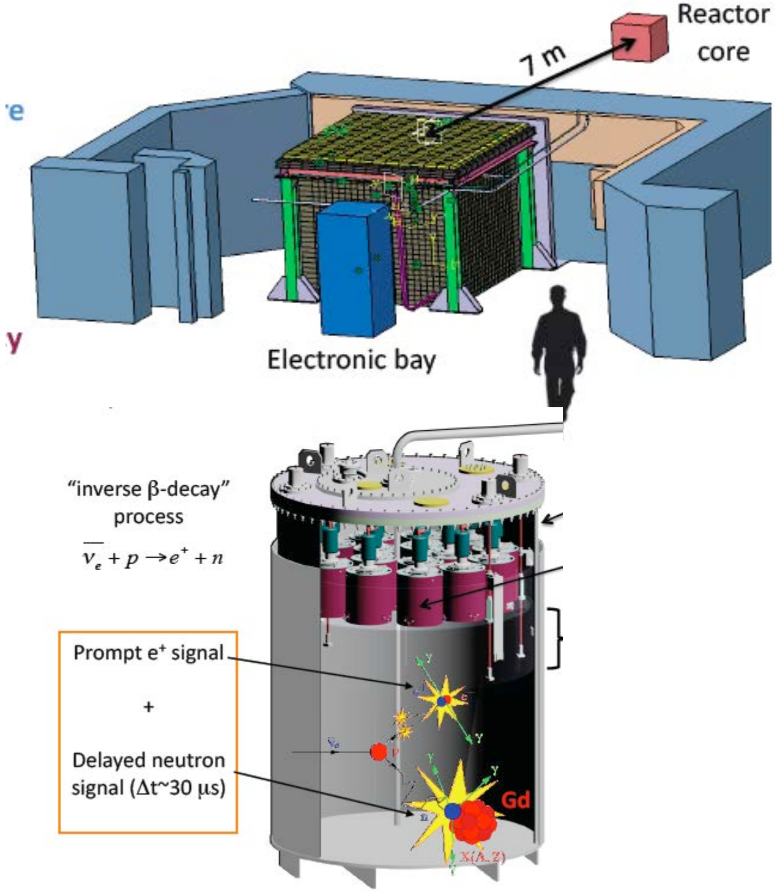




arXiv:1212.2182
Littlejohn, Mumm, Tobin, KMH

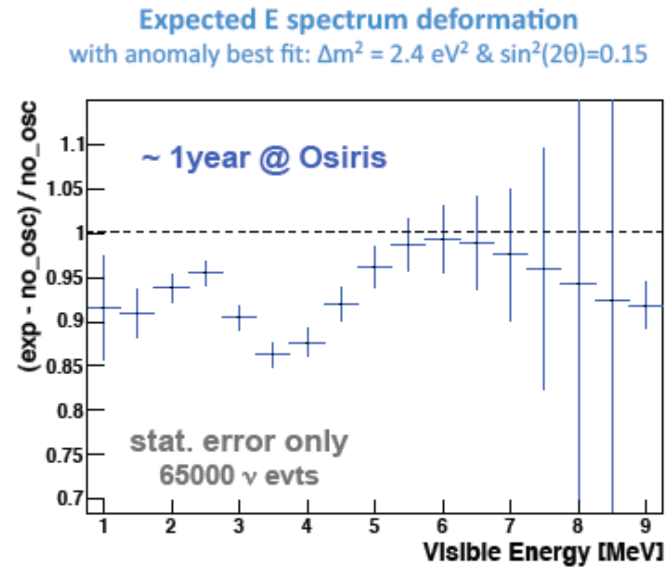
Reactor Monitoring Experiments

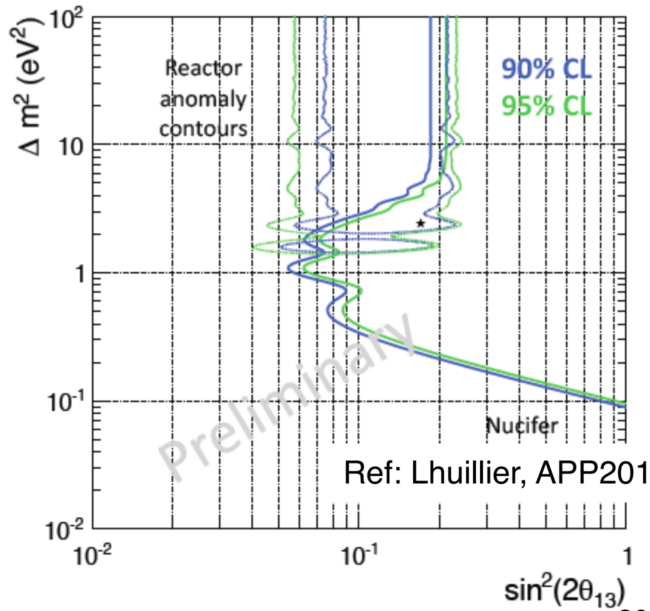
NUCIFER at Osiris



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

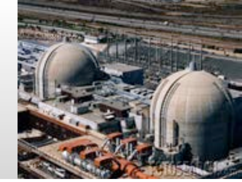




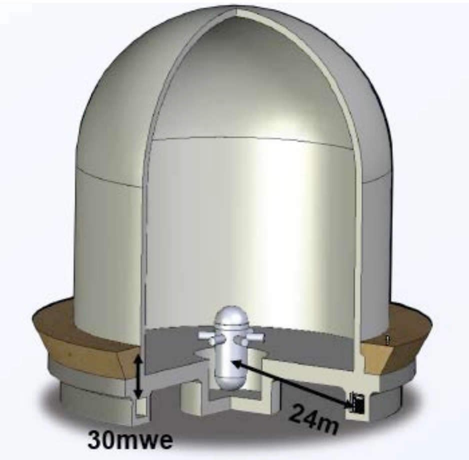
Ref: Lhuillier, APP2011

Pre-industrial, unattended reactor neutrino monitor
May be used to test reactor anomaly with compact core.
PSD R&D for background rejection.

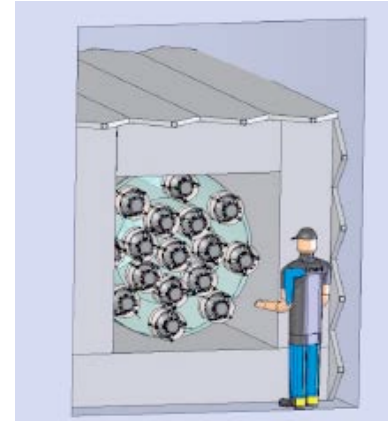
Reactor Monitoring Experiments

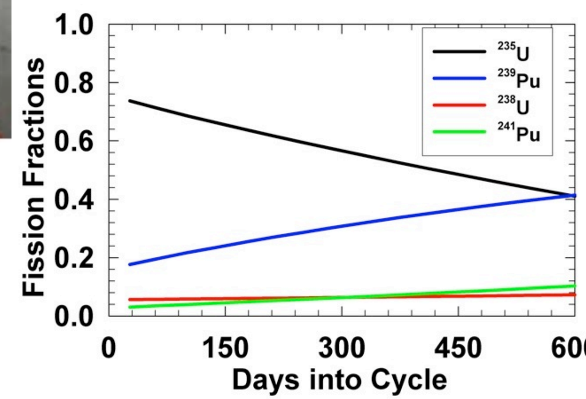


SONGS - San Onofre Nuclear Power Generating Station



core ∅: ~3m,
fixed baseline: 24m





For many years, applied antineutrino physics studies have used SONGS tendon galleries

Ideal for detector R&D and characterization, coherent scattering studies

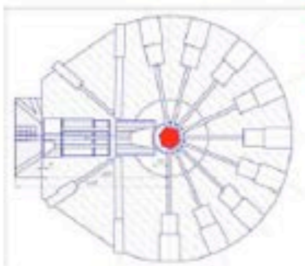
SONGS currently offline since early 2012. Unit 2 restart anticipated this summer. More frequent outages (background measurement opportunities) likely for several years

Ref: Bowden

New Short Baseline Reactor Experiments

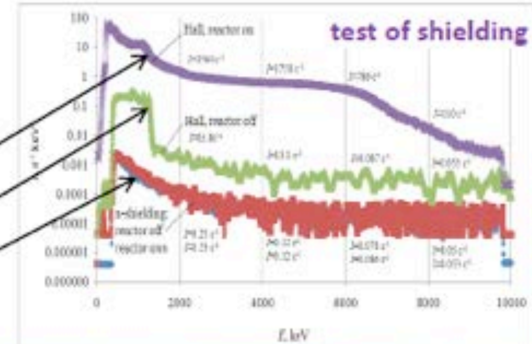
NEUTRINO-4 experiment

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



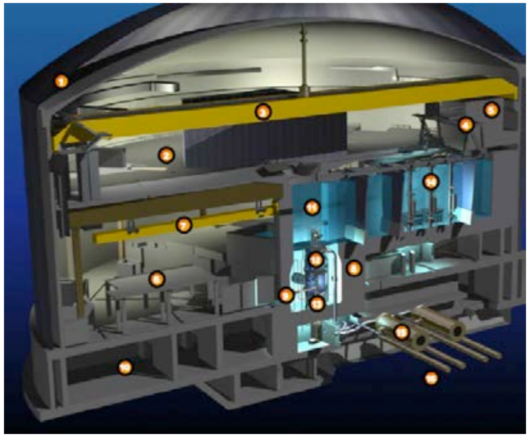
Installation of 2 sections test antineutrino detector with liquid scintillator (total volume 0.4 m^3)

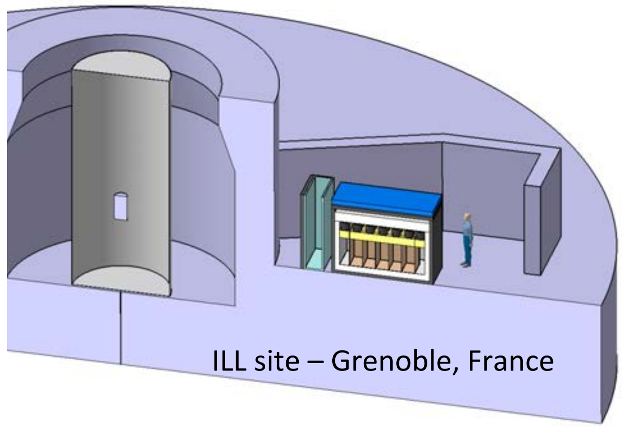
Installation of anticoinsidence shielding from plastic scintillator 0.5x0.5x0.125 m^3 with PMT (32 pieces)

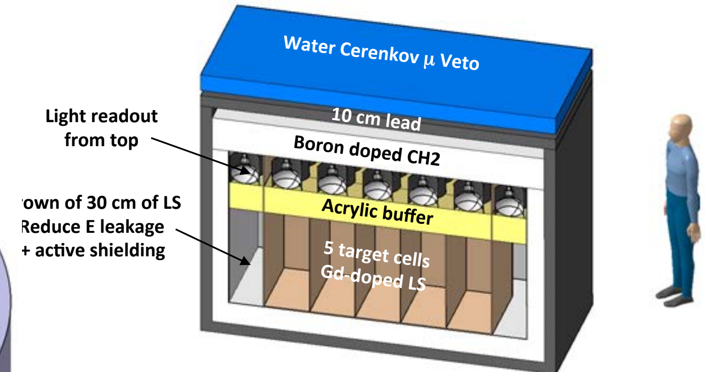
A.Serebrov, PNPI

New Short Baseline Reactor Experiments

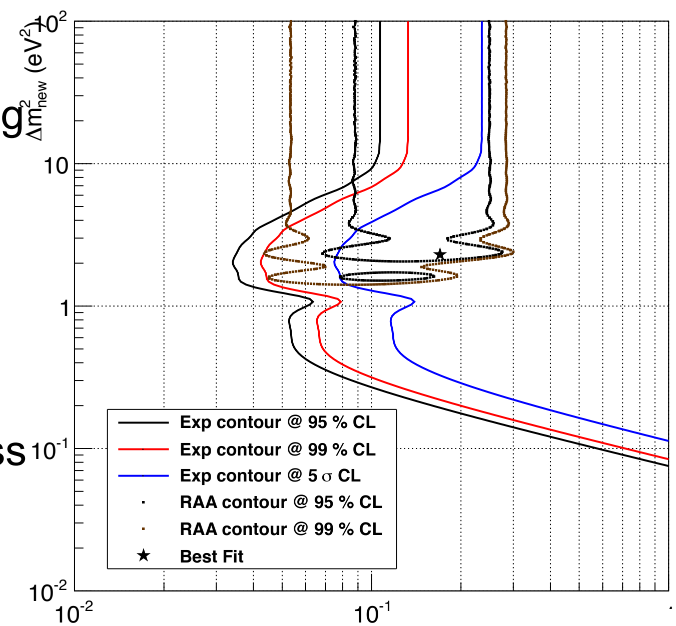
STEREO at ILL







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

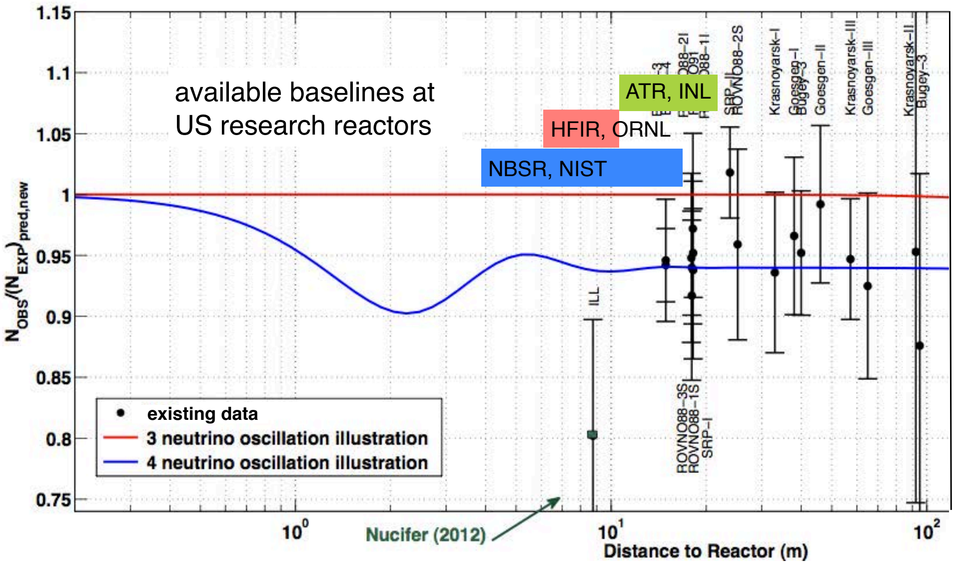
Segmented detector

On-site measurements in progress

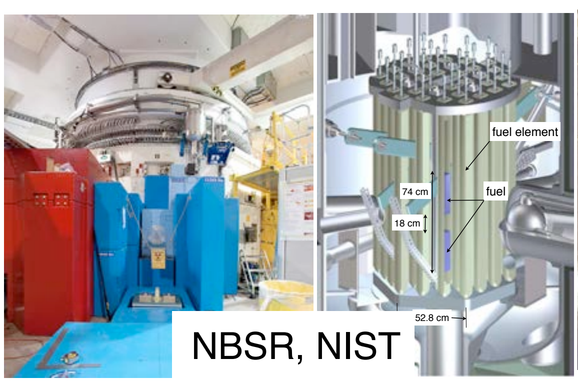
Aim for first data in 2015
Funding decision in 2013

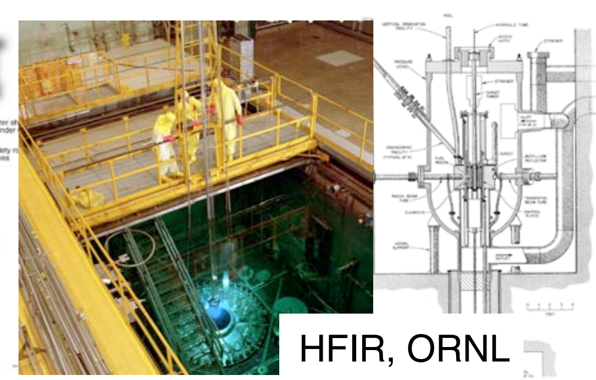
Opportunities for Experiment at US Reactor?

Shortest Accessible Baselines



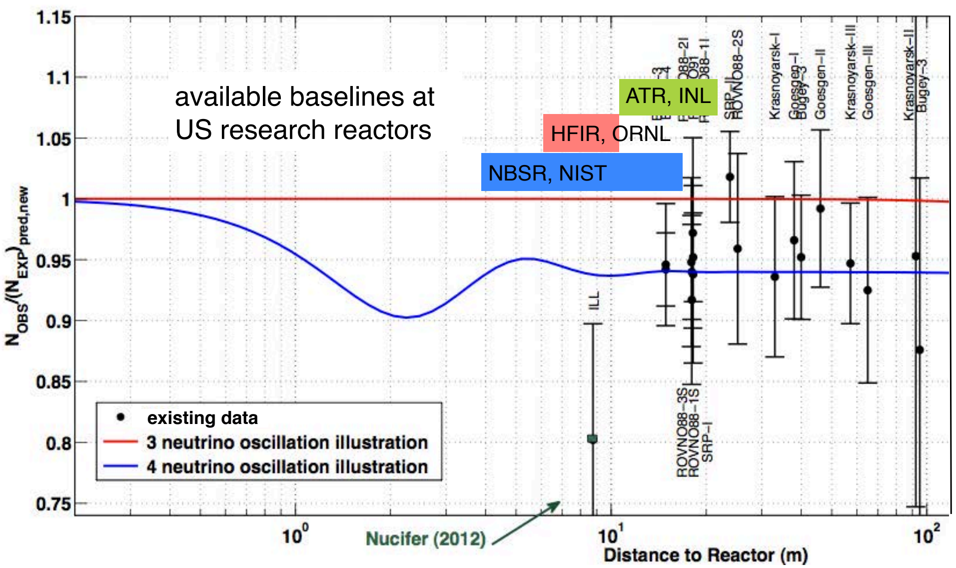
High-Power US Research Reactors



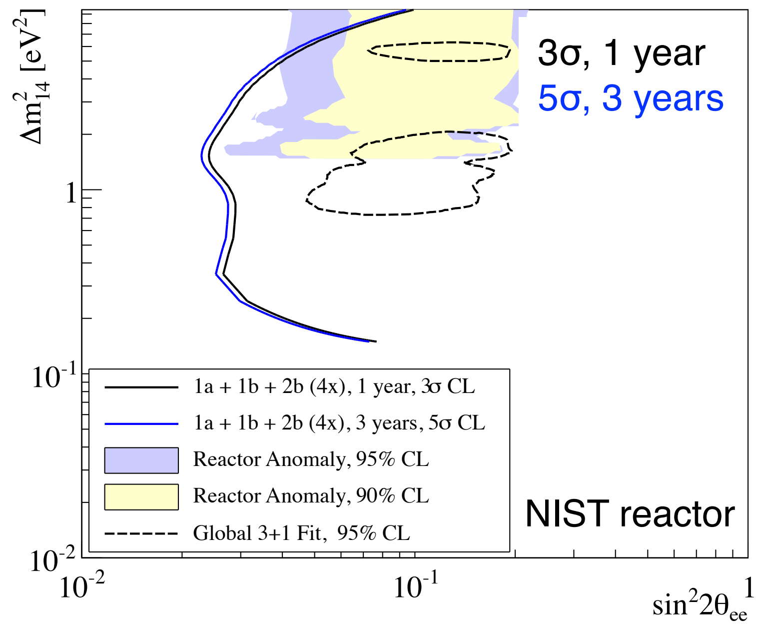


Opportunities for Experiment at US Reactor?

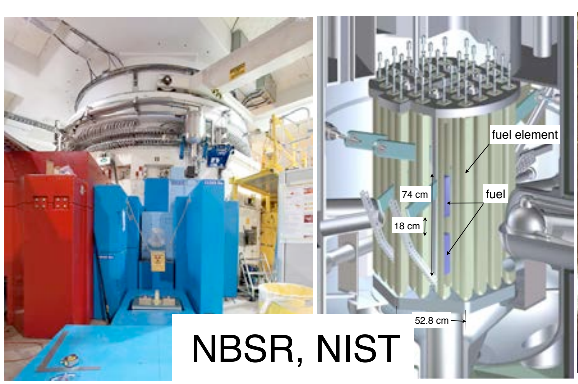
Shortest Accessible Baselines

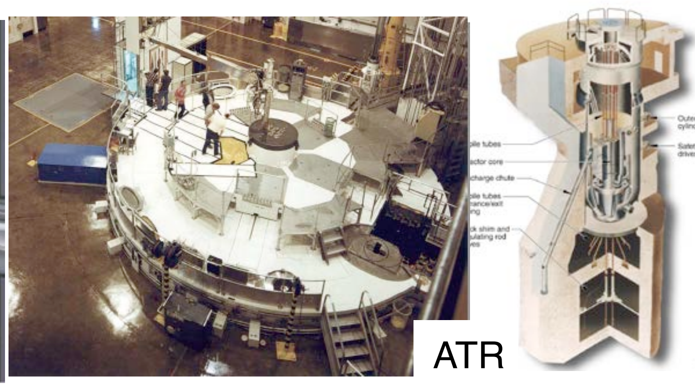


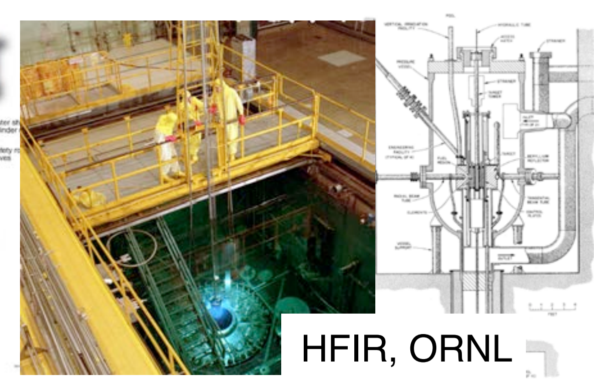
Discovery Potential



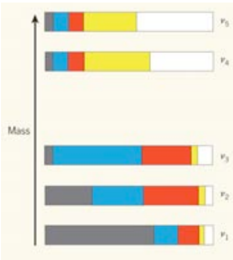
High-Power US Research Reactors





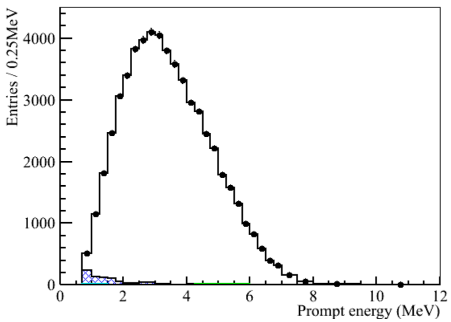


Scientific Opportunities for a US Reactor Experiment



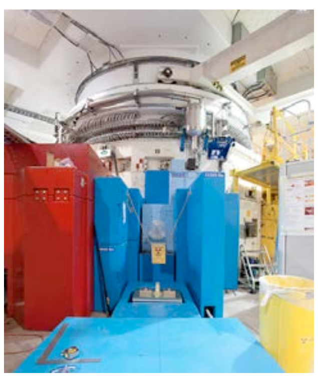
Searches for new physics

- test **sterile ν hypothesis** and **short-baseline oscillations**
- probe and understand **reactor anomaly**
- neutrino **coherent scattering** and **magnetic moment** searches



Reactor cores, fuel, and antineutrino spectra

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

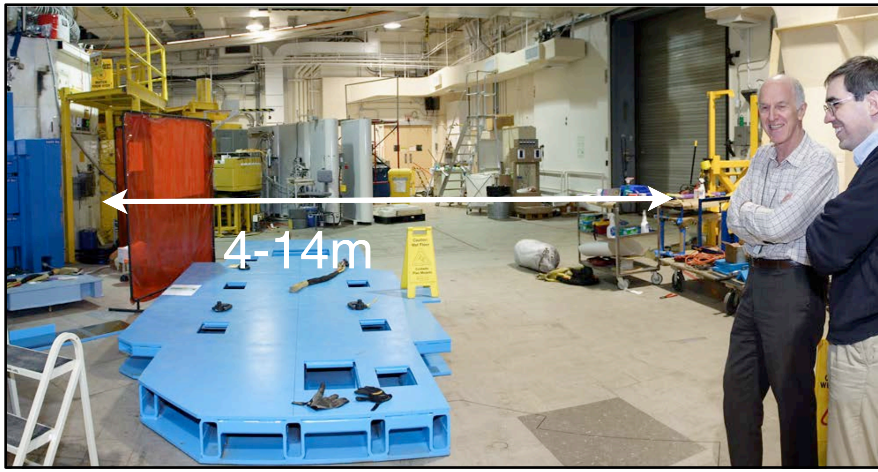


Background studies and detector development

- 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)

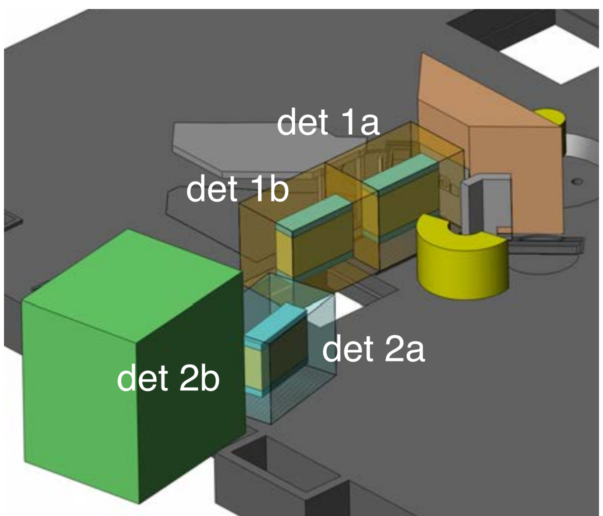
US community interested in pure and applied reactor antineutrino studies

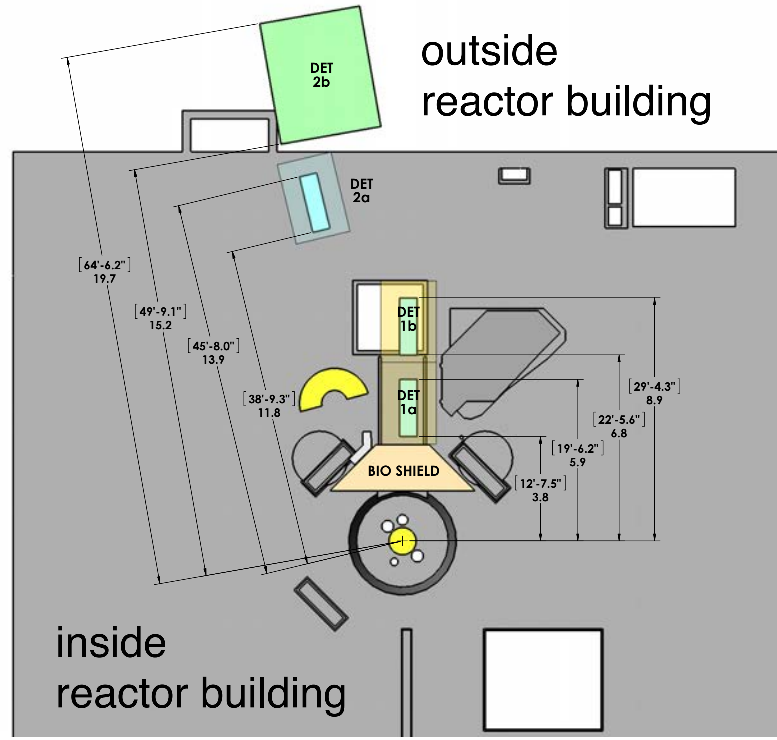
NIST: An Example in the US



Possible detector baselines at NIST

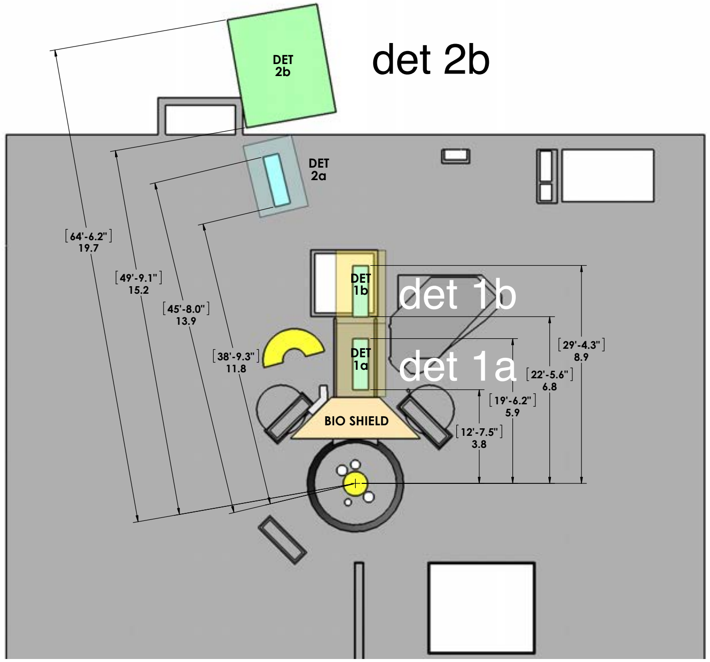
3.8m, 6.8m, 11.8, 15.2m (up to 20m)

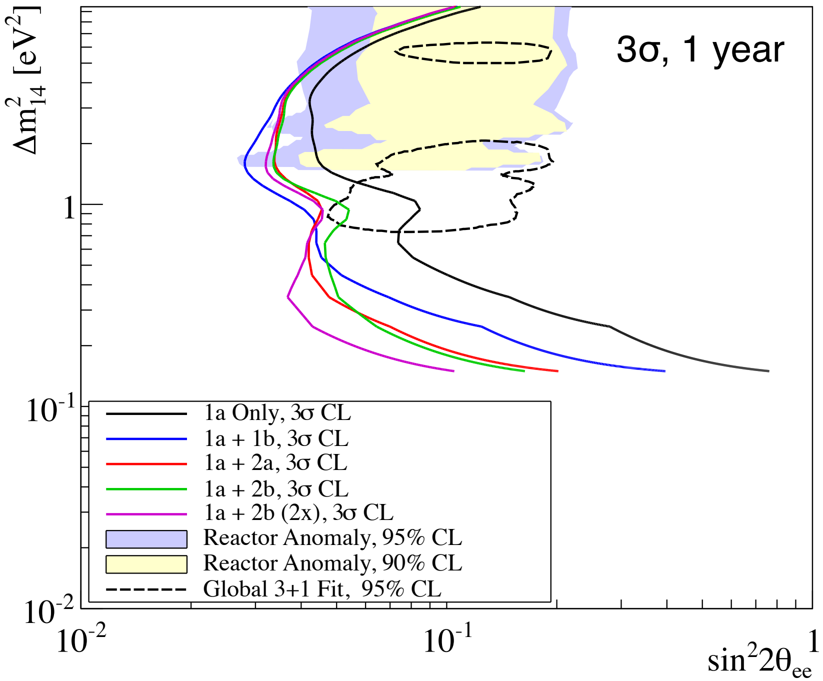


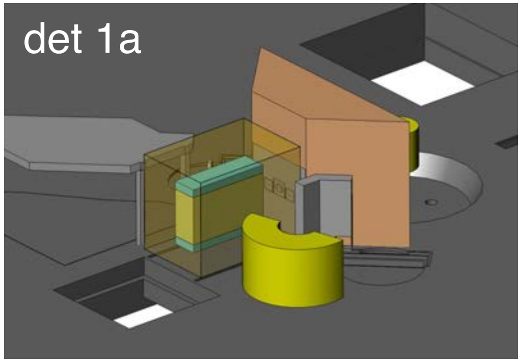


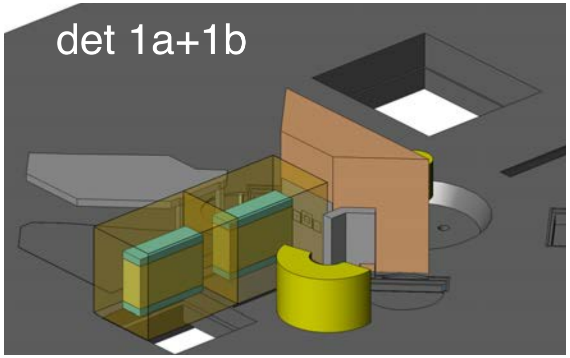
NIST: An Example in the US

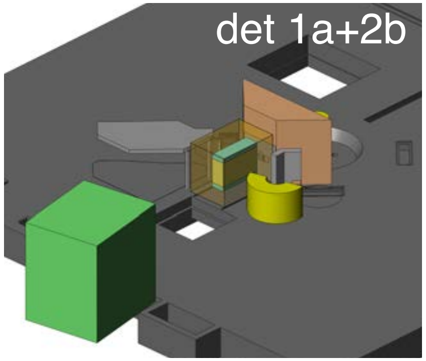
Opportunity for a 2-Detector Experiment







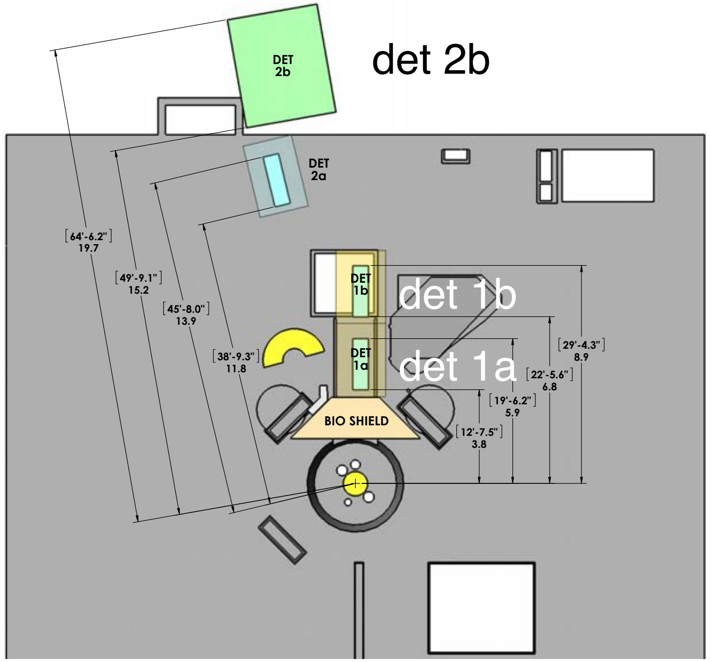


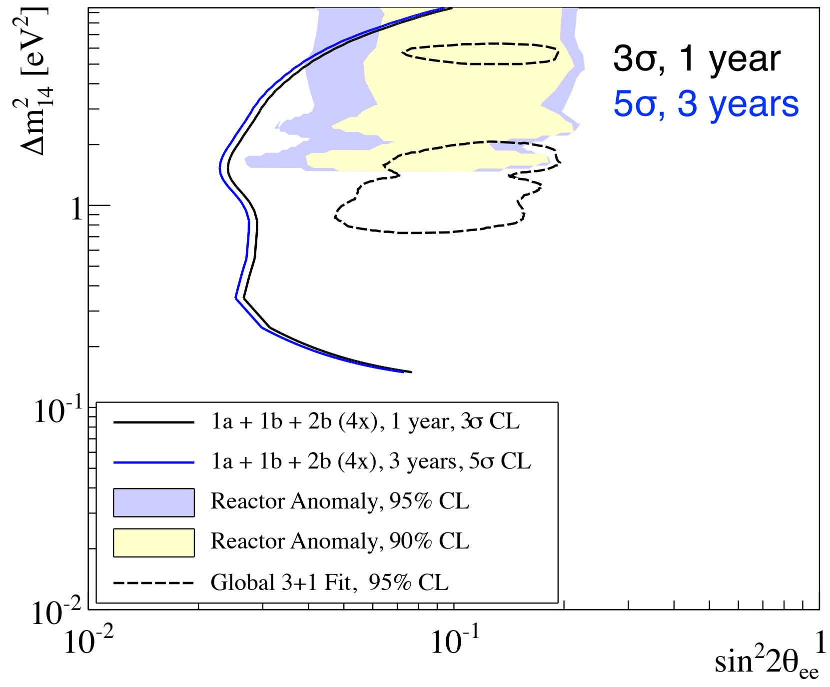


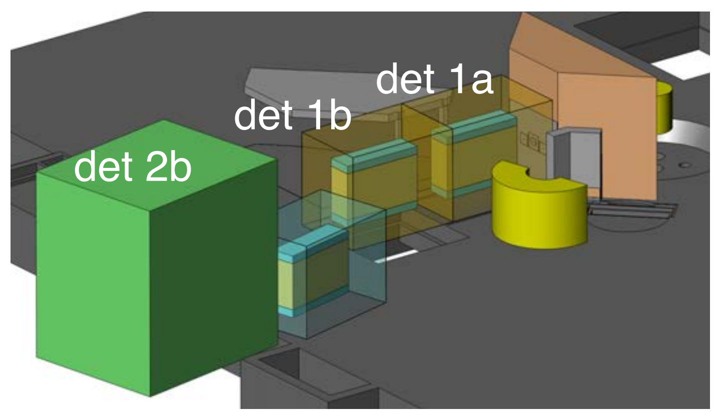
Cherwinka, Mumm, Littlejohn, KMH

NIST: An Example in the US

Opportunity for a Multi-Detector Experiment

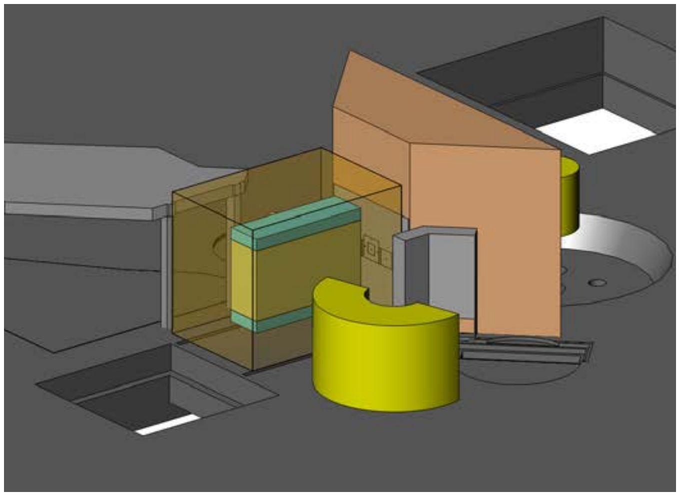


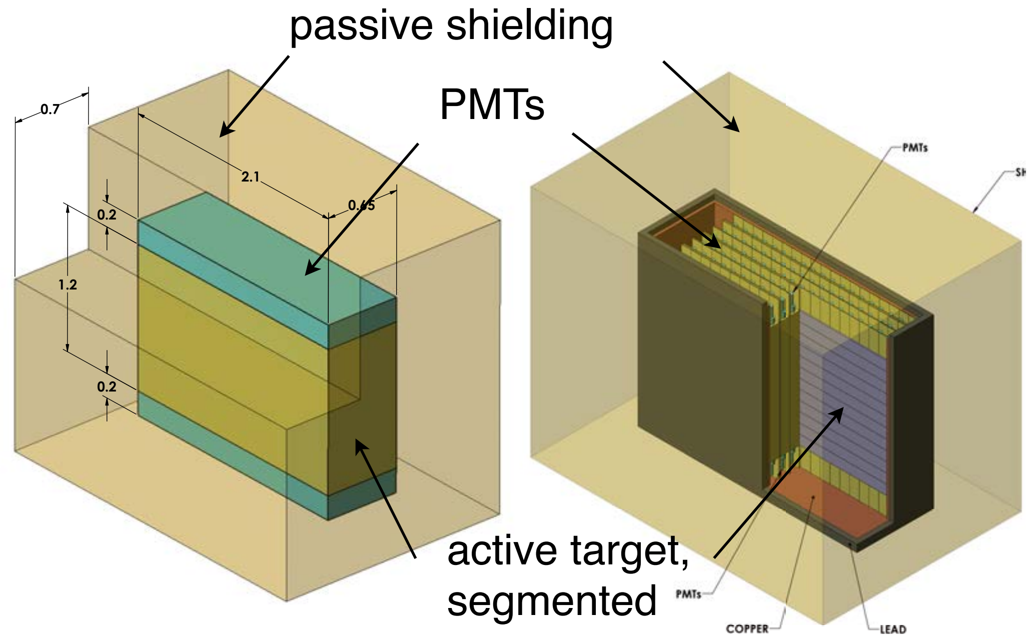




NIST: An Example in the US

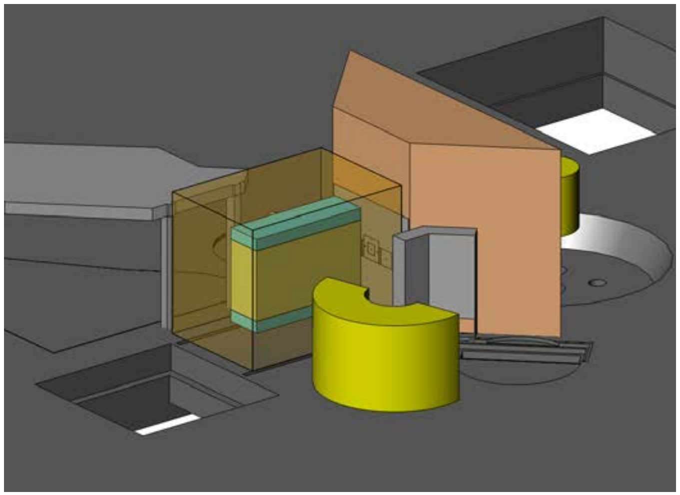
Detector Module

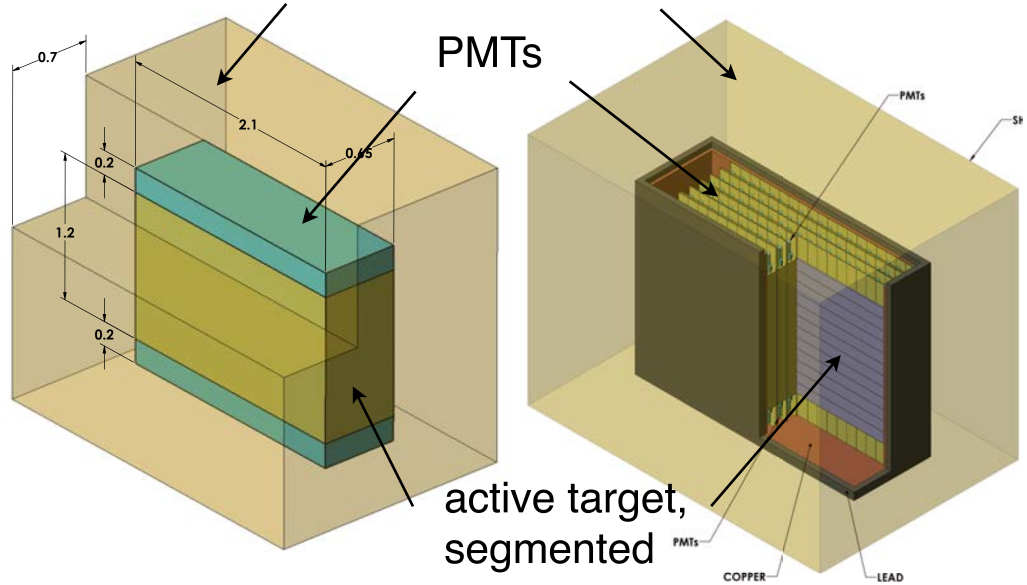




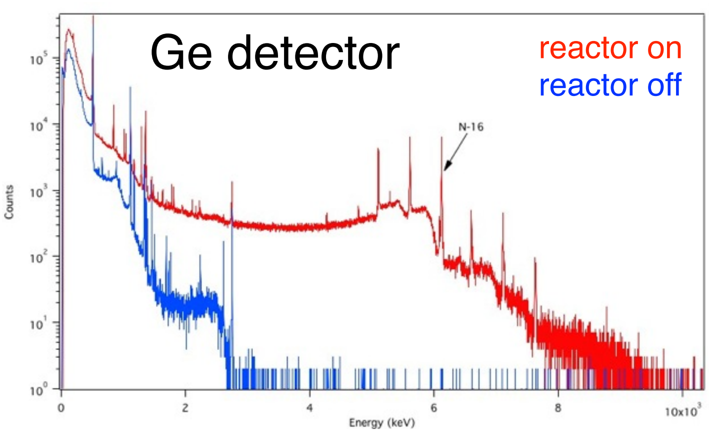
NIST: An Example in the US

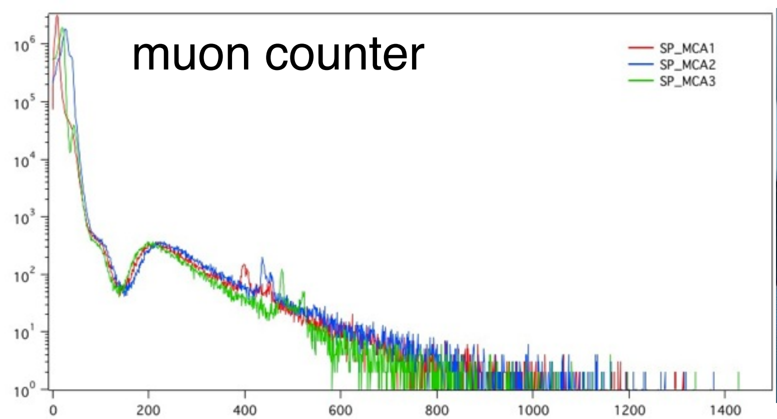
Detector Module

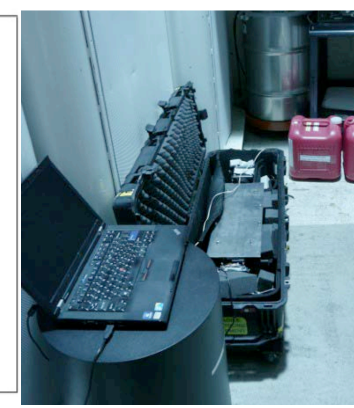




Background studies near reactor in progress







Bowden, Cherwinka Mumm, Littlejohn, Pettus, KMH

Summary

Science Objectives with Discovery Potential

- For > 50 years reactor experiments have played an important role in neutrino physics, in both discoveries and precision measurements.
- Very short baseline **(L~10m)** measurements offer opportunities for precision studies of the **reactor spectra** and searches for **new physics**.

Reactors as a Unique Experimental Tool

- Reactor and source experiments provide a complimentary way to probe short baseline oscillations.
- **Reactors are only way to definitely understand reactor anomaly**
- Reactors allow multiple cross-checks (no special source production needed)
- **US has some of the most powerful research reactors.**

Challenges and Synergies

- **Background mitigation** and **systematic controls w**ill be key.
- Several R&D efforts. **US site can accommodate multiple detectors.**
- On-surface **reactor neutrino monitors** useful **for safeguards** applications.

Thanks to many colleagues for slides and material: N. Bowden, A. Derbin, Y. Kim, T. Lasserre, D. Lhuillier, M. Pallavicini, A. Serebrov, A. Starostin, M. Yeh, Y. Wang, H. Wong, et al..

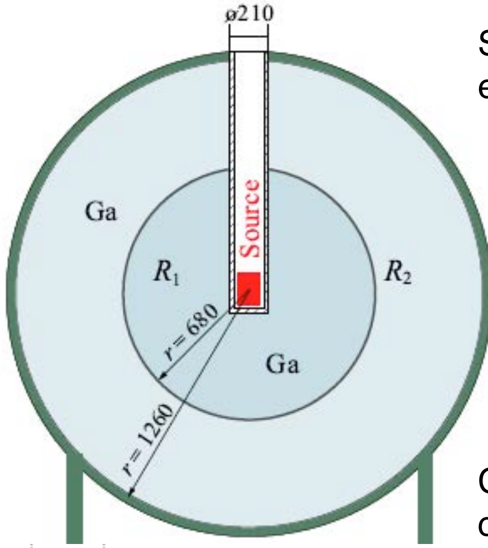
Disclaimer: Several R&D efforts worldwide. Could not present all in this talk. My apologies to those I missed.

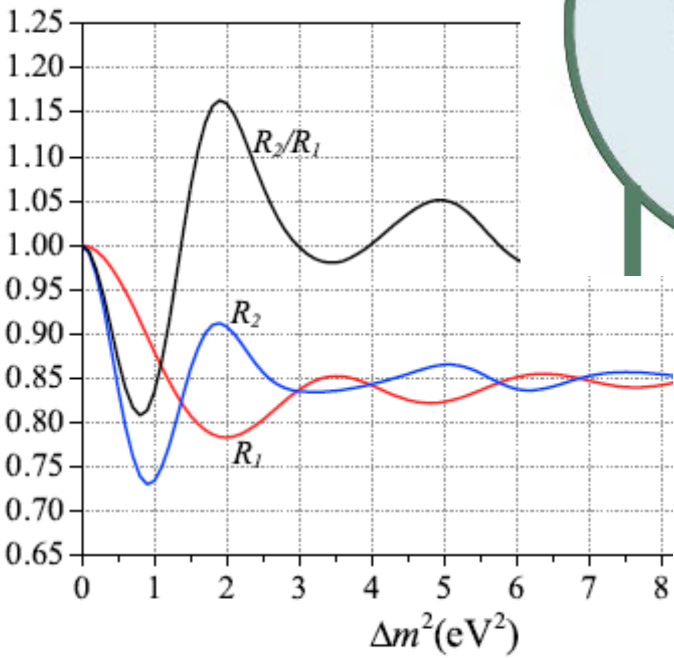
End & Backup

Short Baseline Oscillation with Ga Target

^{51}Cr Source inside Dual Metallic Ga Target

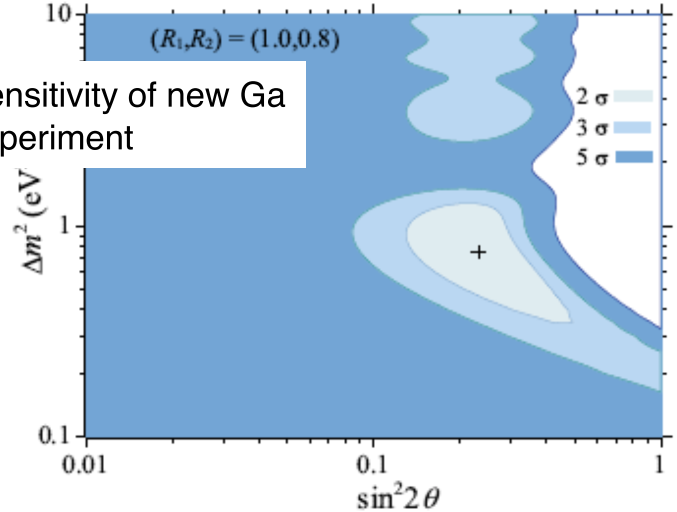
measure ratio of capture rates in R_1 and R_2



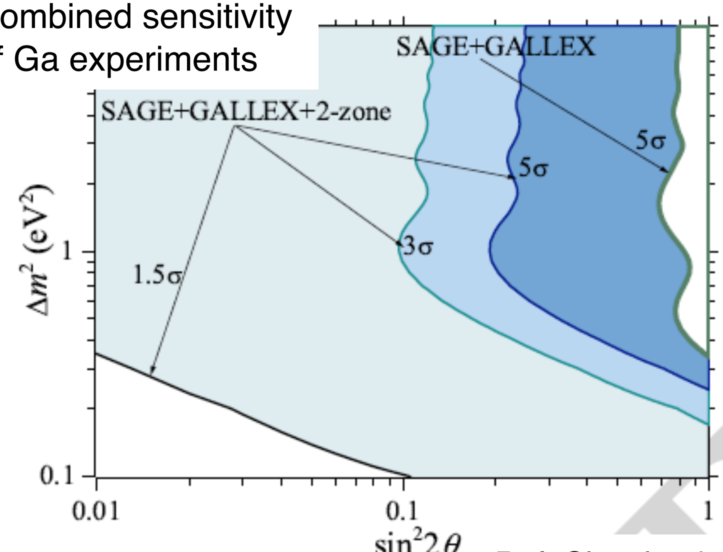


ratio of measured capture rates to predicted rate in inner and outer zones and their ratio R_2/R_1

Sensitivity of new Ga experiment



Combined sensitivity of Ga experiments

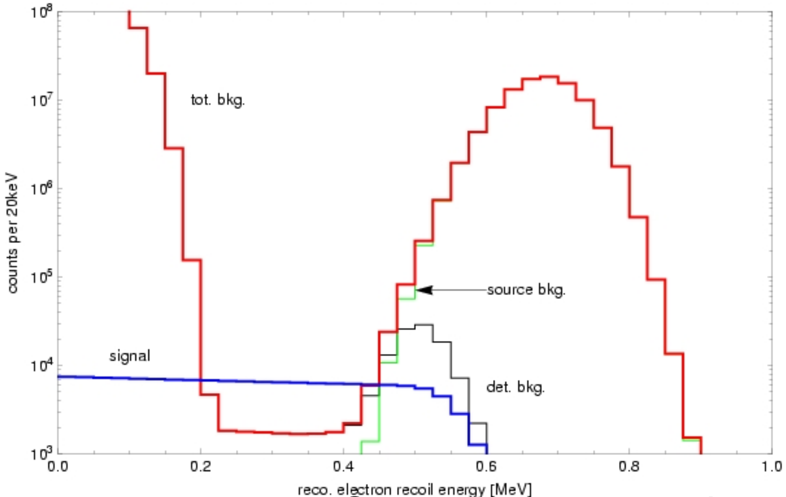


Ref: Cleveland et al.

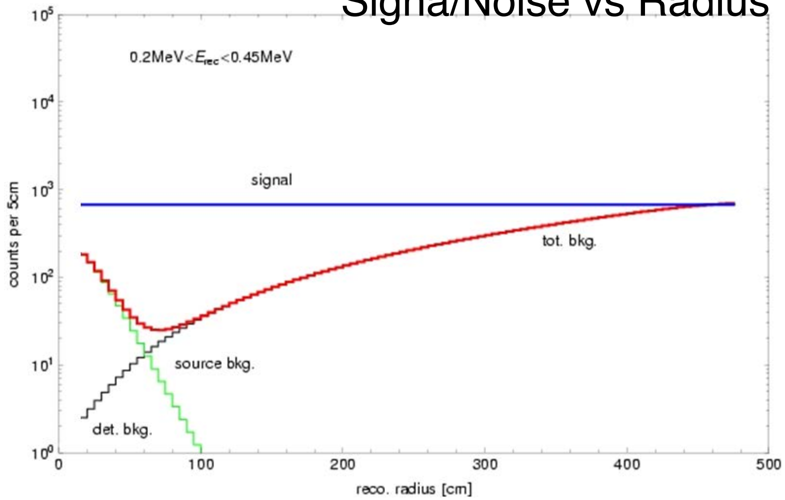
SNO-Cr Source Experiment

^{51}Cr source inside SNO+

Central Source Location in SNO+

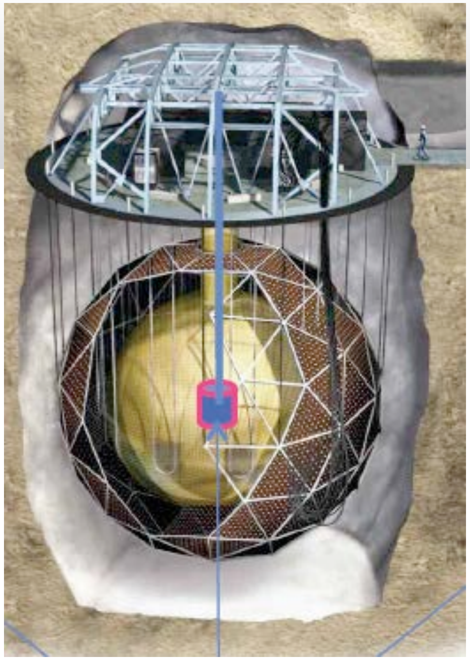


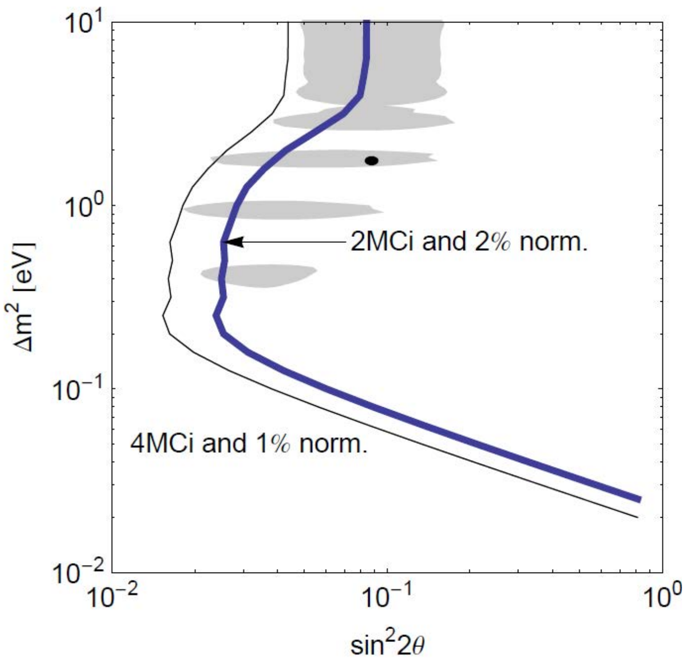
Signa/Noise vs Radius



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

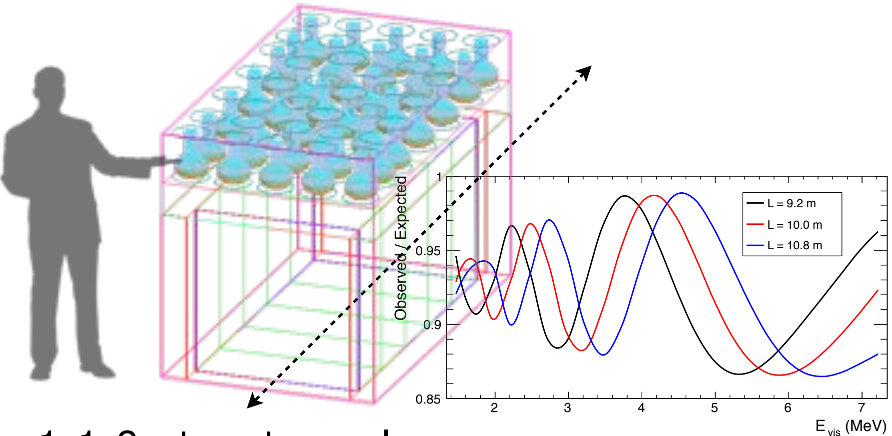




Ref: Link, Huber

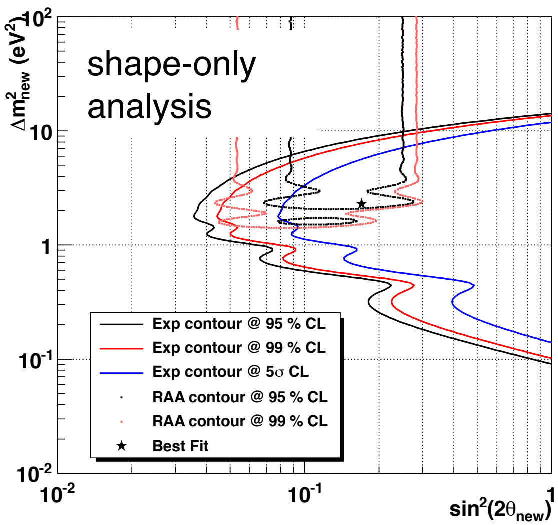
Worldwide Effort Towards Sterile ν Search

Stereo at ILL, France

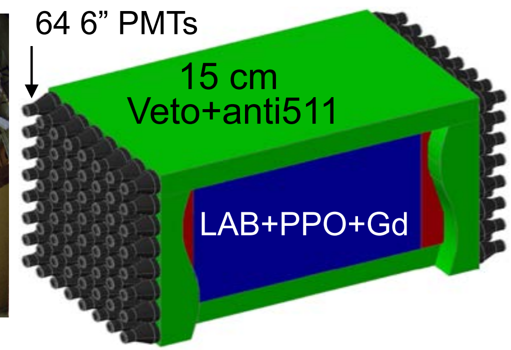


1x1x2m target vessel
filled with Gd-LS
5 baseline bins by foils

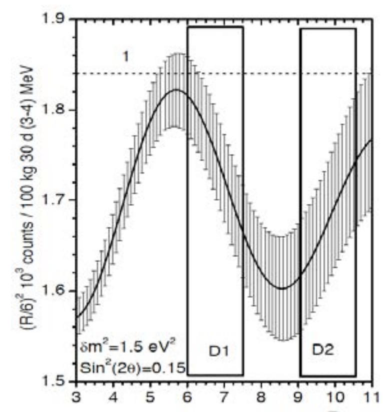
shift detector to verify
oscillation signal



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

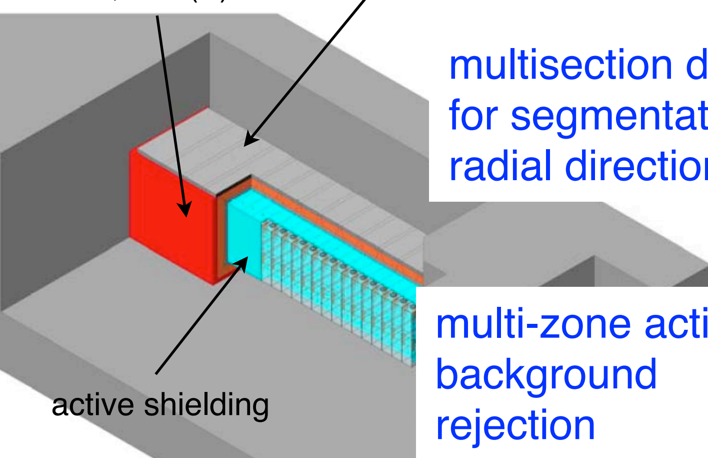


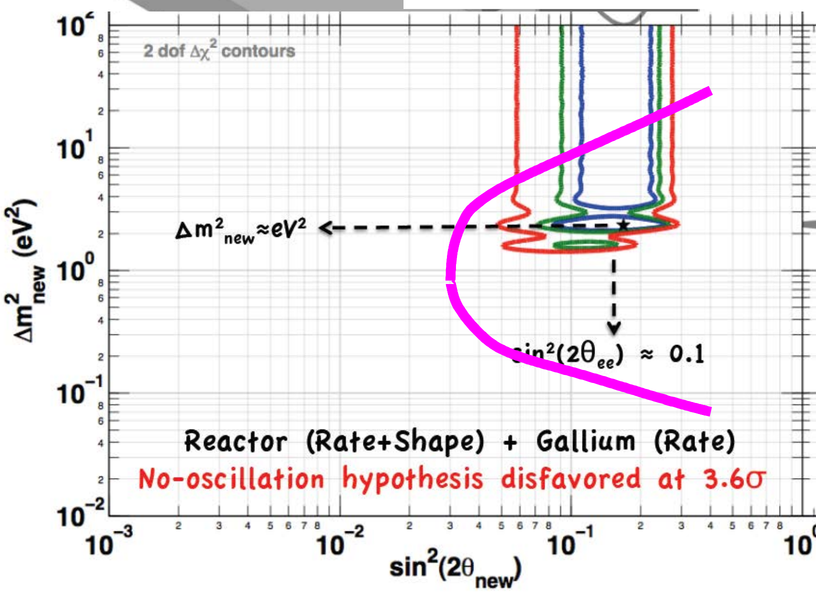
detector can be placed
at 5-8m

100MW research reactor being built in
Gatchina (~2014yr)

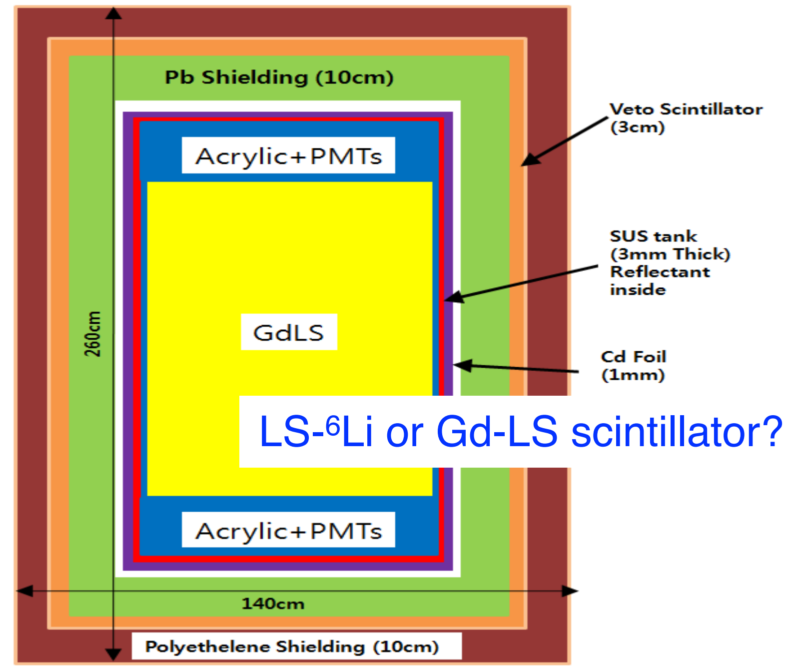
Worldwide Effort Towards Sterile ν Search

Neutrino4, Russia





Hanaro-SBL, Korea



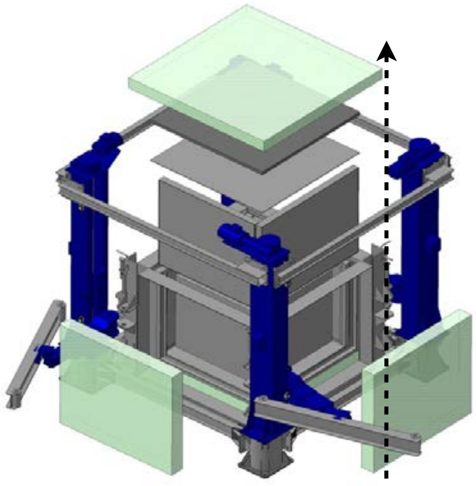
$$n + {}^{155}Gd \rightarrow {}^{156}Gd + 8MeV$$

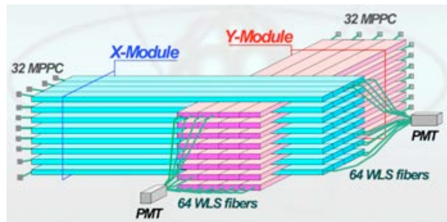
$$n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.8MeV$$

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

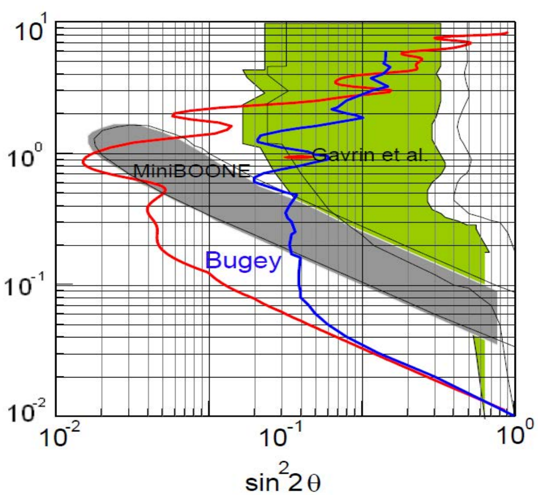
Worldwide Effort Towards Sterile ν Search

DANSS, Russia



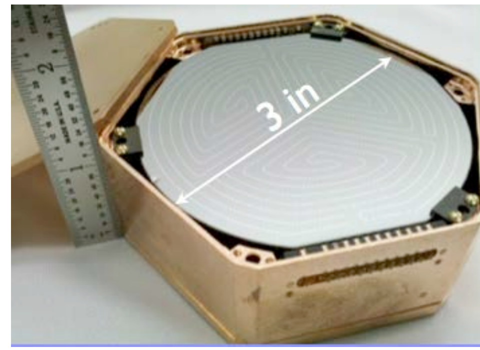


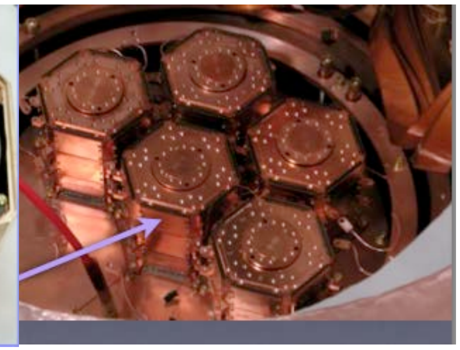
movable distance



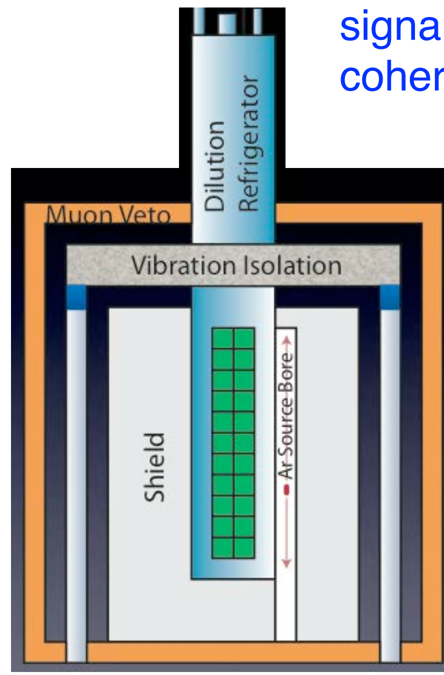
also used for neutrino magnetic moment searches with Ge detectors

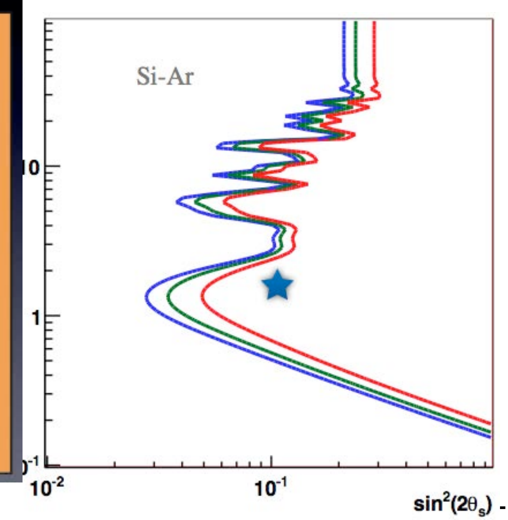
Ricochet, USA





signal detection through coherent scattering





Worldwide Effort Towards Sterile ν Search

A Submarine Base in Russia or Ukraine?