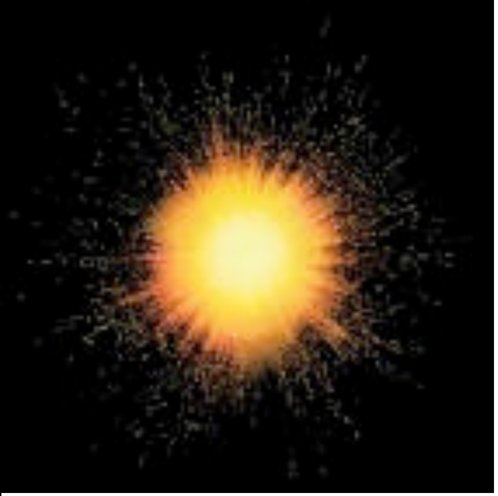
Reactor Neutrinos II

Karsten M. Heeger

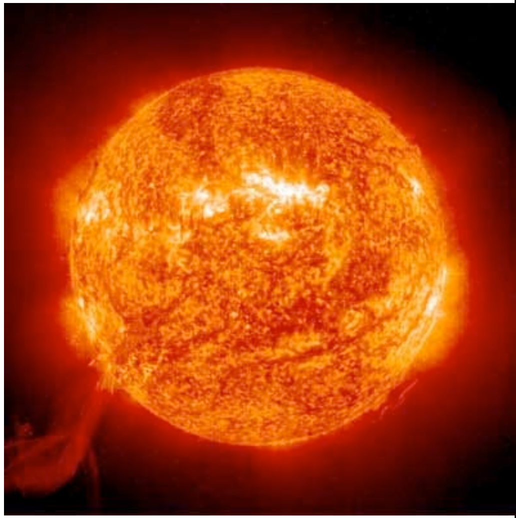
University of Wisconsin

2012 Pontecorvo Neutrino School
Alushta, Ukraine

From the first observation of reactor antineutrinos to oscillation



Neutrino Energies



Big-Bang neutrinos ~ 0.0004 eV

Neutrinos from the Sun < 20 MeV
depending of their origin.

Atmospheric neutrinos ~ GeV

Antineutrinos from nuclear reactors < 10.0 MeV

Neutrinos from accelerators up to GeV (10^9 eV)

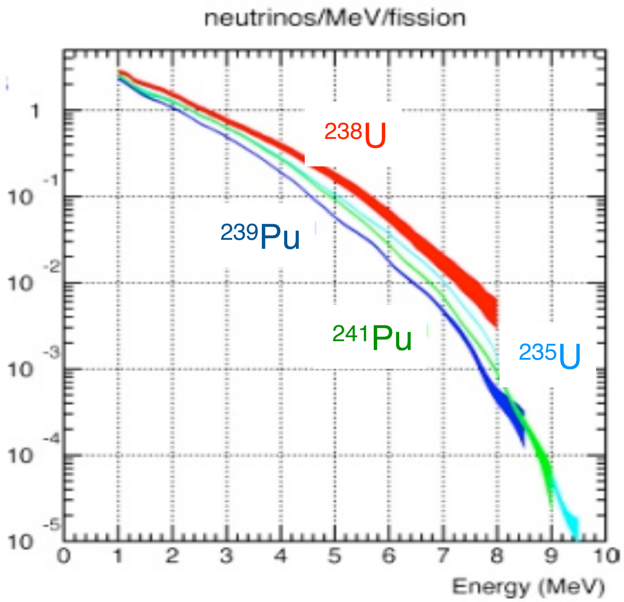
Reactor Antineutrinos

Source

$\overline{\nu}_e$ from β-decays

of n-rich fission products

pure $\overline{\nu}_e$ source



$^{235}U : ^{238}U : ^{239}Pu : ^{241}Pu$ =
0.570: 0.078: 0.0295: 0.057

~ 200 MeV per fission

~ 6 $\overline{\nu}_e$ per fission

~ 2 x 10^{20} $\overline{\nu}_e/GW_{th}$-sec

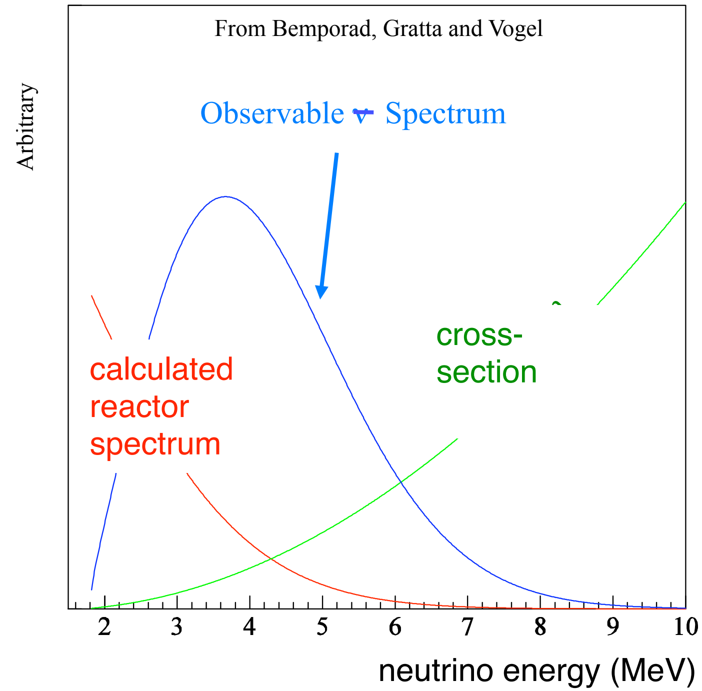
Detection

inverse β-decay

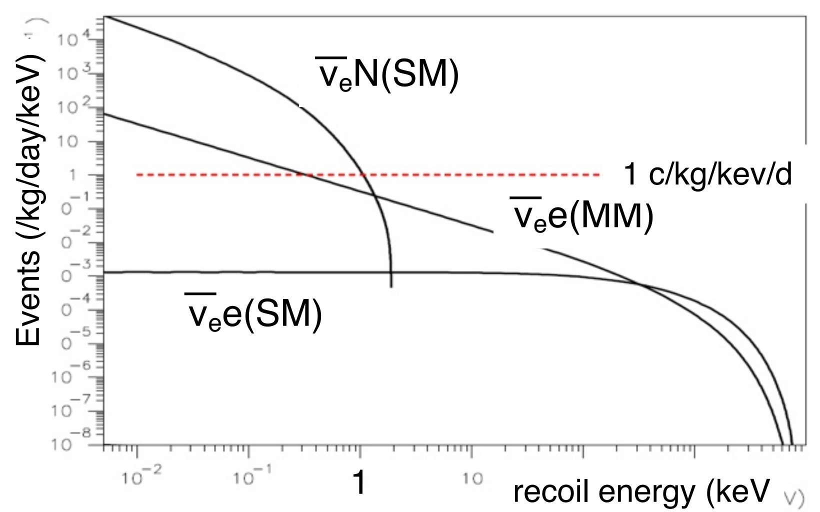
$\overline{\nu}_e + p \rightarrow e^+ + n$

observable **rate** and energy **spectrum**

only disappearance experiments possible



$\overline{\nu}_e$ scattering

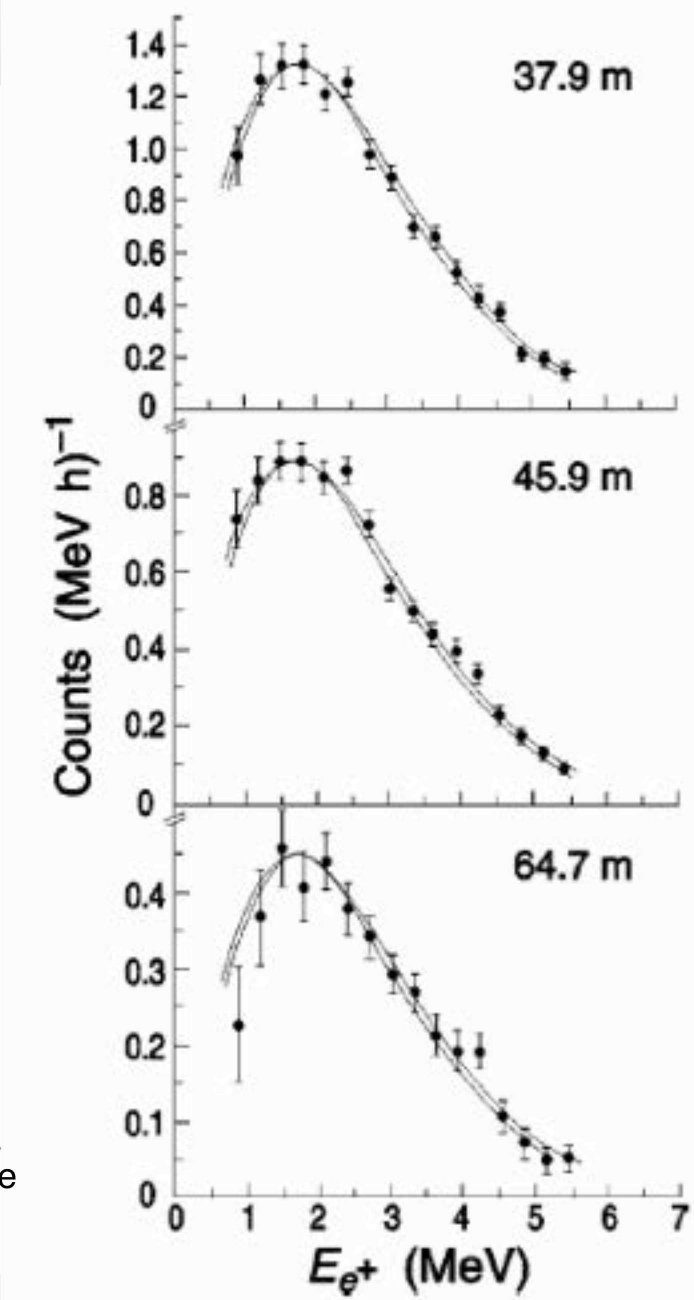


Goesgen Experiment (1986)

Comparison of Predicted Spectra to Observations

two curves are from fits to data and from predictions based on Schreckenbach et al.

3 baselines with one detector

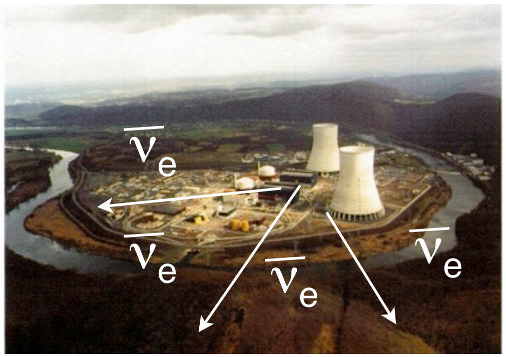


flux and energy spectrum agree to ~ 1-2%

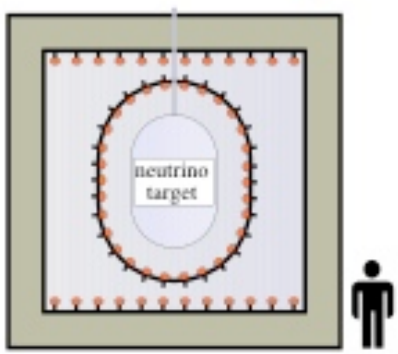
reactors are a “well-calibrated” source of $\overline{\nu}_e$

Chooz

Best Oscillation Limit at ~1km



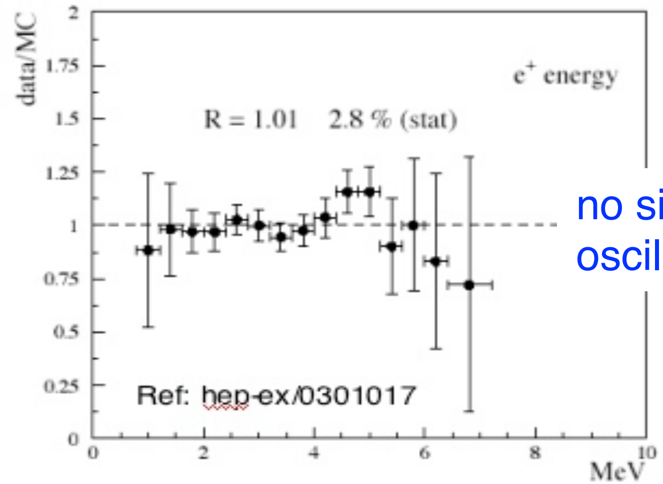
Distance: 1km



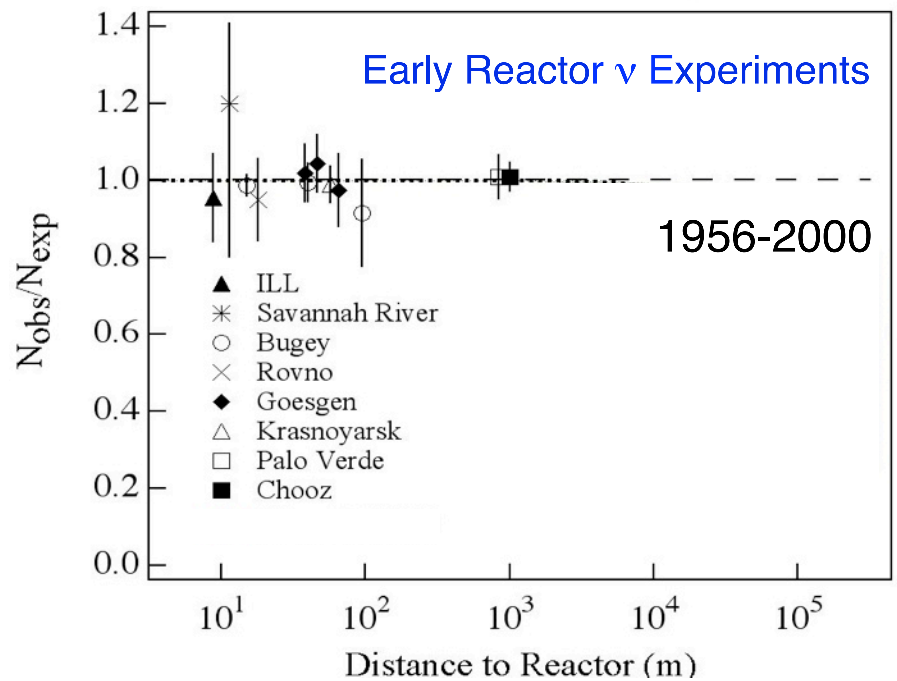
$\bar{\nu}_e + p \rightarrow e^+ + n$

~3000 events in
335 days
2.7% uncertainty

absolute measurement with 1 detector
scintillator problems

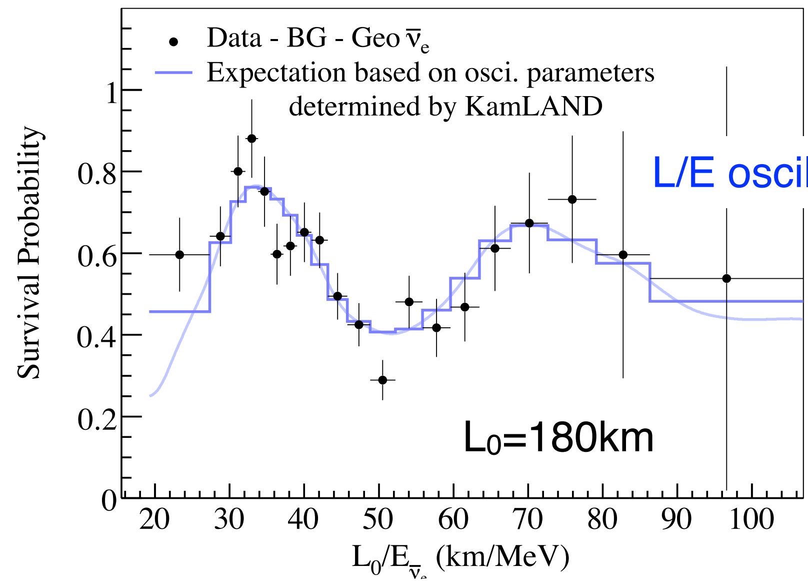


no sign of oscillation



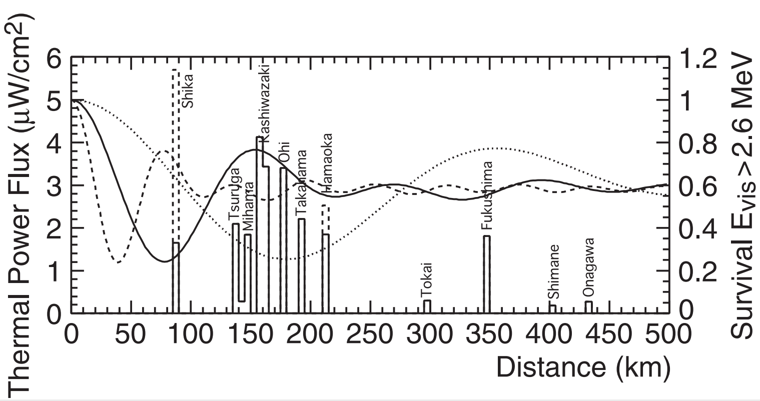
KamLAND

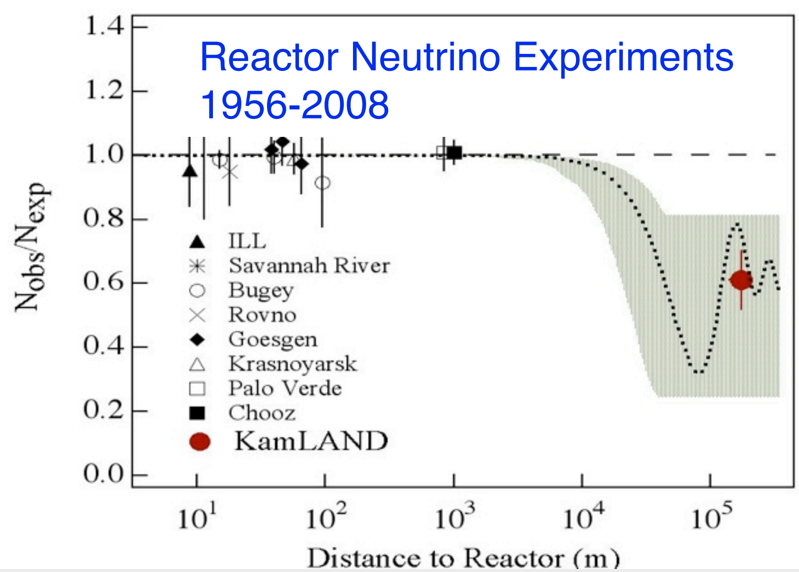
First Observation of Reactor Antineutrino Disappearance at ~180km



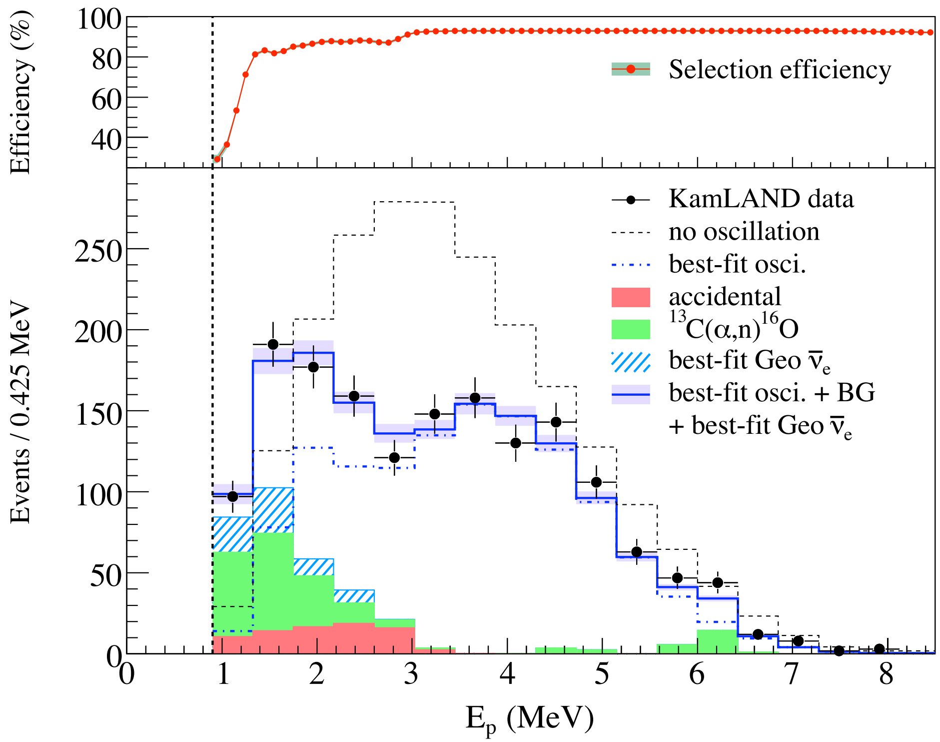
L/E oscillation

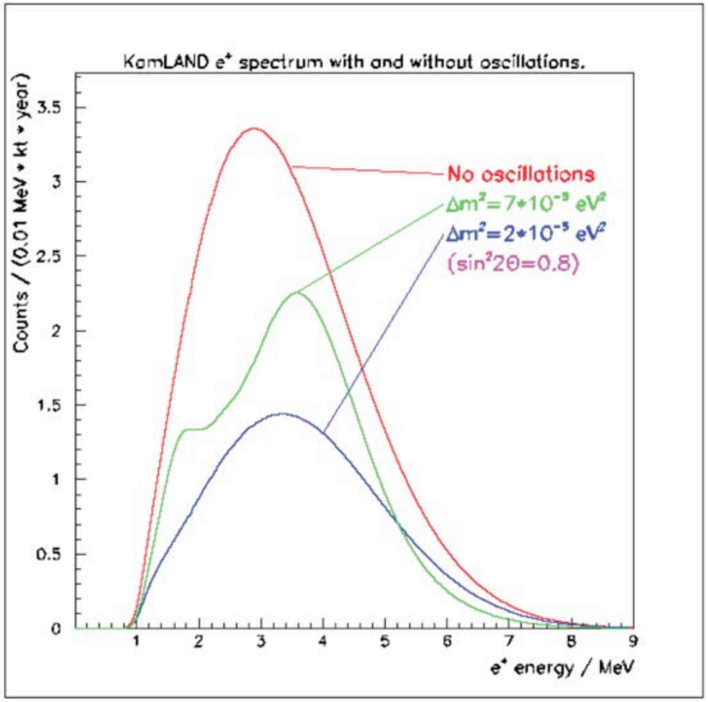
mean, flux-weighted reactor distance ~ 180km





Oscillation effect in rate and Spectrum

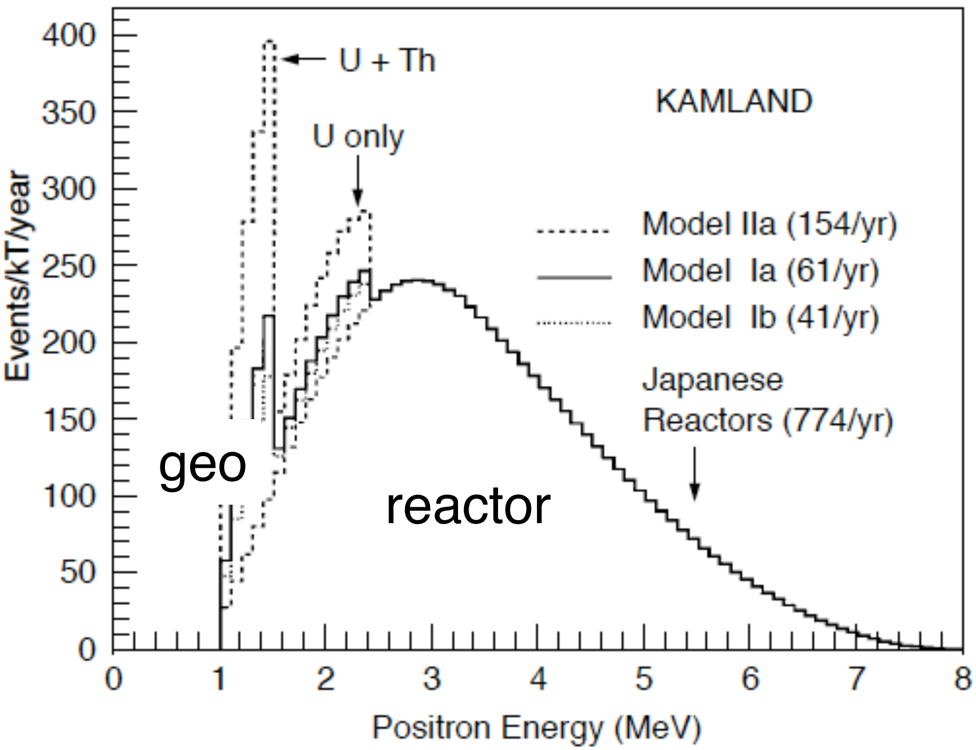




- deficit in count rate
- spectral distortion

KamLAND

Terrestrial antineutrino signal



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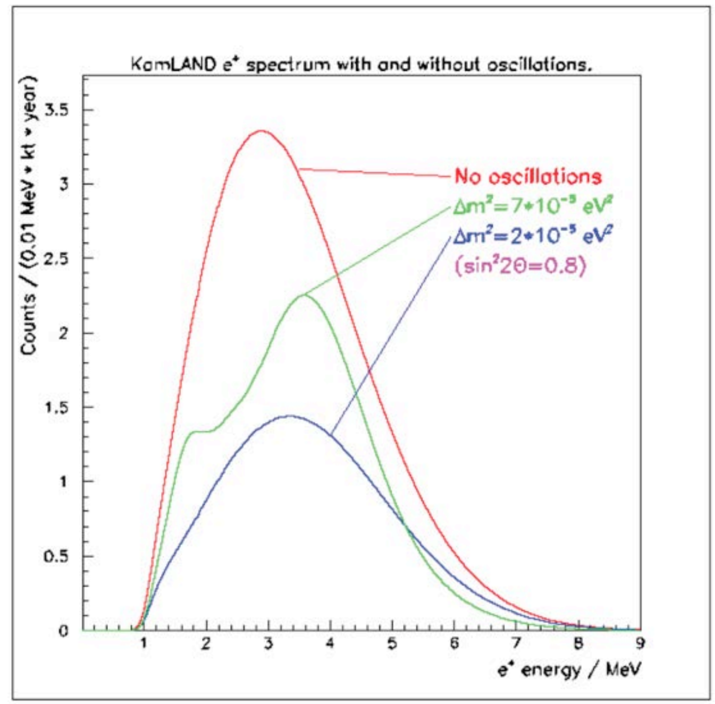


- deficit in count rate
- spectral distortion

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

?

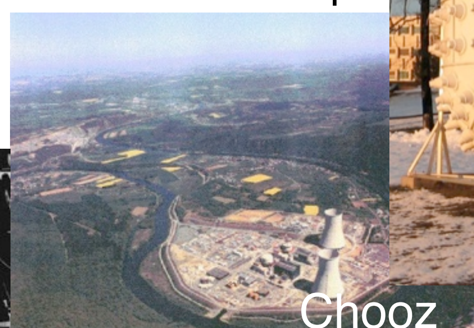
2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

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...

2011/2012 -
The year of θ_{13}

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

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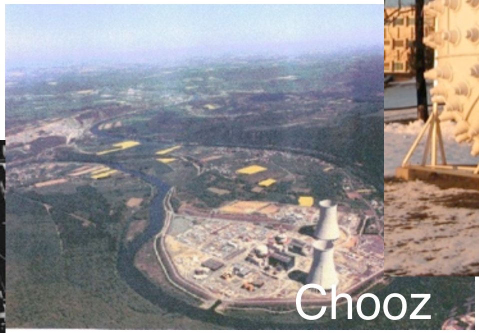


1956 - First observation of (anti)neutrinos

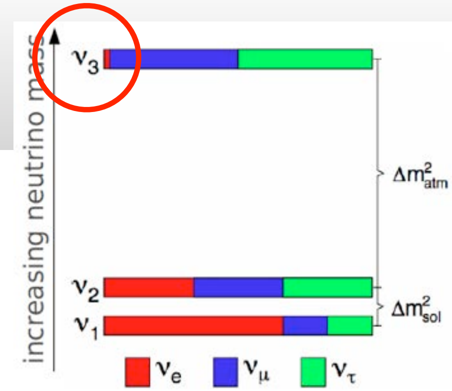
Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

Outline

- Lecture 2
  - precision oscillation physics: theta13 and beyond
  - the reactor anomaly
  - future reactor experiments
    - θ_{12}
    - mass hierarchy
    - sterile neutrino searches
  - experiments with antineutrino sources
  - searches for new physics
    - magnetic moments
    - coherent scattering
    - NSI
  - applications of reactor antineutrinos

θ_{13}

Neutrino Oscillation - Before 2011



Mixing Angles

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

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

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

$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	$\sin^2\theta_{12}$
$0.50^{+0.07}_{-0.06}$	small? zero?	$0.318^{+0.019}_{-0.016}$
maximal?		large, but not maximal!

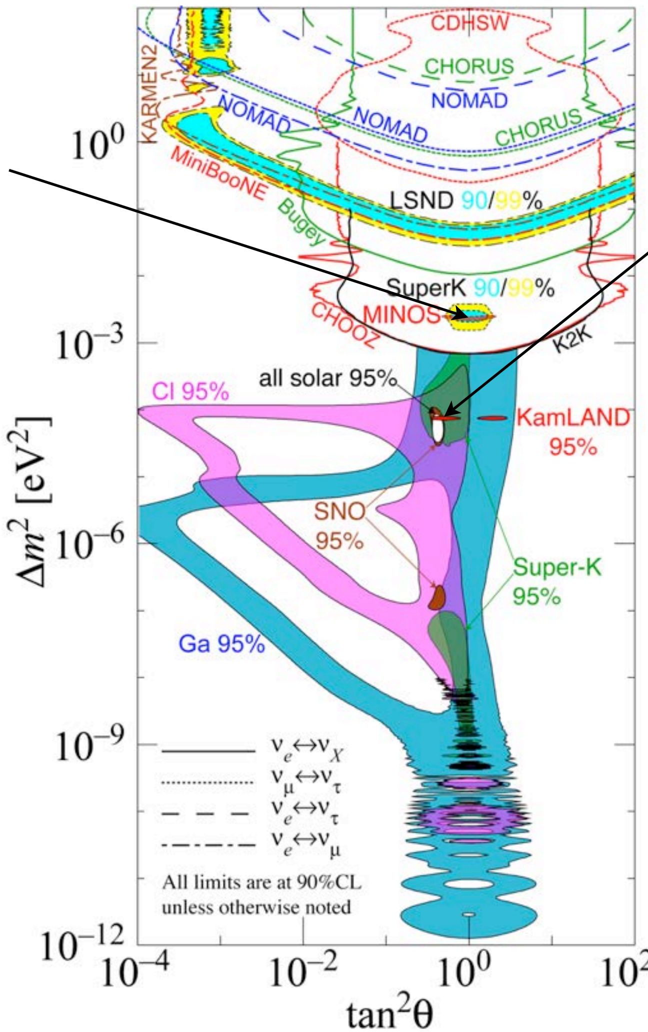
Completing the 3-ν Oscillation Picture

atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}

solar/reactor neutrinos

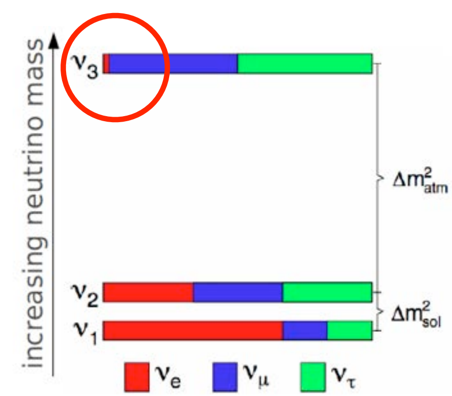
θ_{12}, Δm^2_{12}



http://hitoshi.berkeley.edu/neutrino

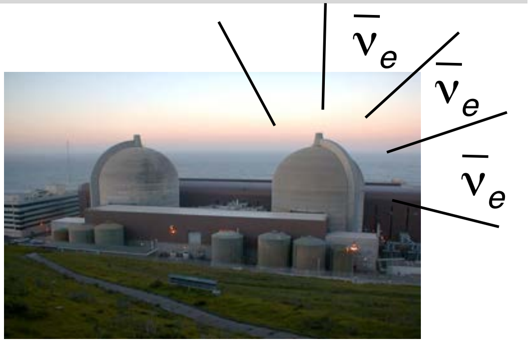
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

3-flavor picture needed



Reactor and Accelerator Experiments

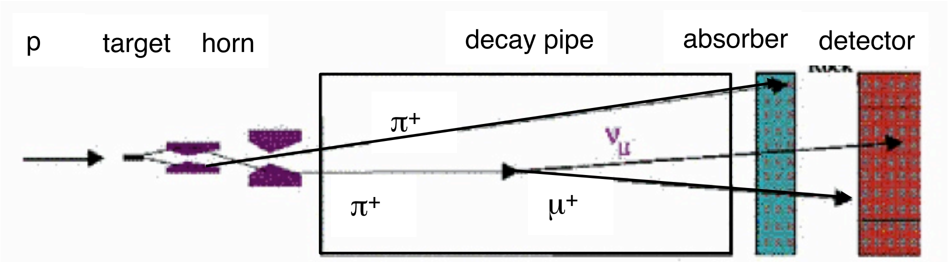
reactor ($\bar{\nu}_e$ disappearance)



$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

- disappearance experiment $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline *O(1 km)*, no matter effects

accelerator (ν_e appearance)



$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{4E_\nu} + \ldots$$

- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ yields θ_{13}, δ_{CP}
- baseline *O(100 -1000 km)*, matter effects present

Reactor and Accelerator Experiments

reactor **($\bar{\nu}_e$ disappearance)**

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

- Clean measurement of θ_{13}
- No matter effects

mass hierarchy

CP violation

matter

accelerator **(ν_e appearance)**

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\ & + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta] \sin \Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\ & + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta] \sin^2 \Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin \Delta_{31} \left[\cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

- $\sin^2 2\theta_{13}$ is missing key parameter for any measurement of δ_{CP}

Reactor and Accelerator Experiments

reactor antineutrinos

measurement of θ_{13}

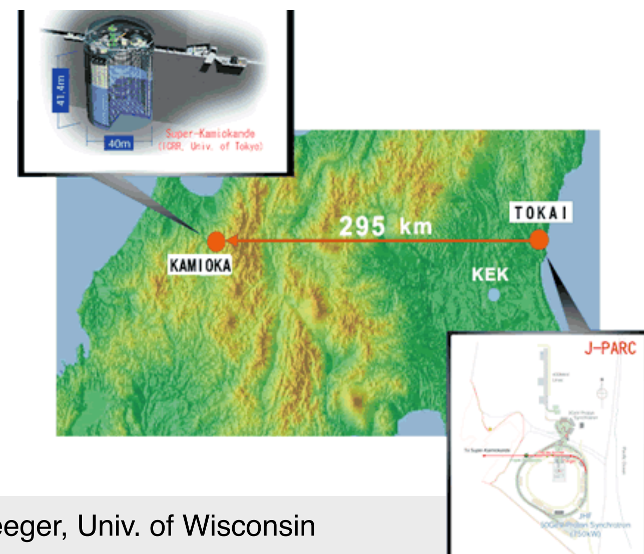
reactor spectra, fuel evolution and monitoring

mass hierarchy? sterile neutrinos? θ_{12}?

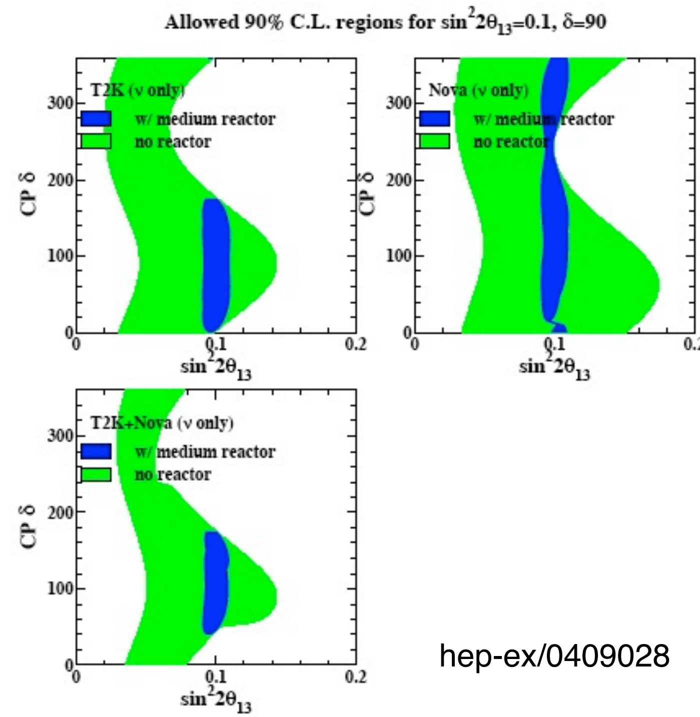
accelerator neutrinos

oscillation parameters

mass hierarchy, CPV



Determining oscillation parameters in combined analysis



hep-ex/0409028

Recent Indications for θ_{13}

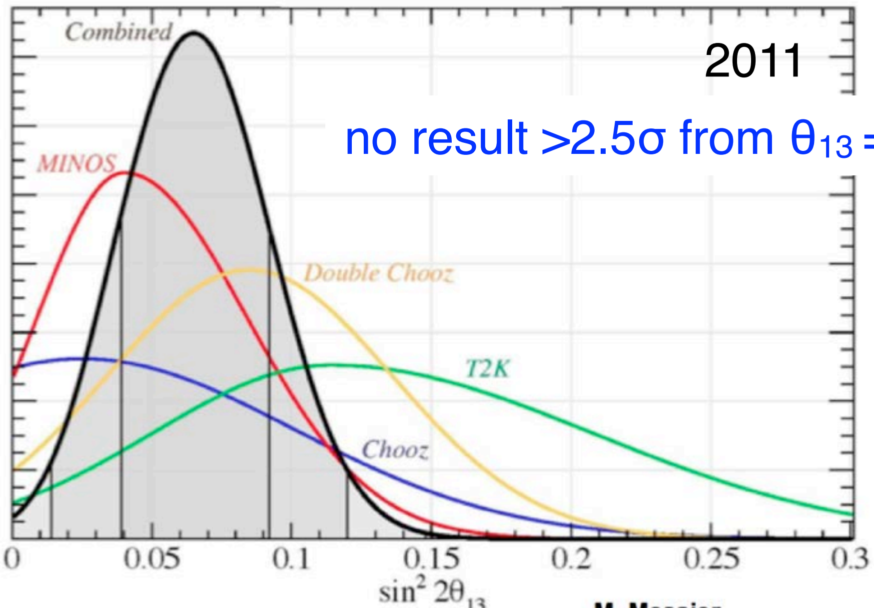
T2K $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$

θ_{13}=0 disfavored @ 2.5σ

MINOS $2\sin^2(\theta_{23})\sin^2(2\theta_{13}) = 0.041^{+0.047}_{-0.031}$

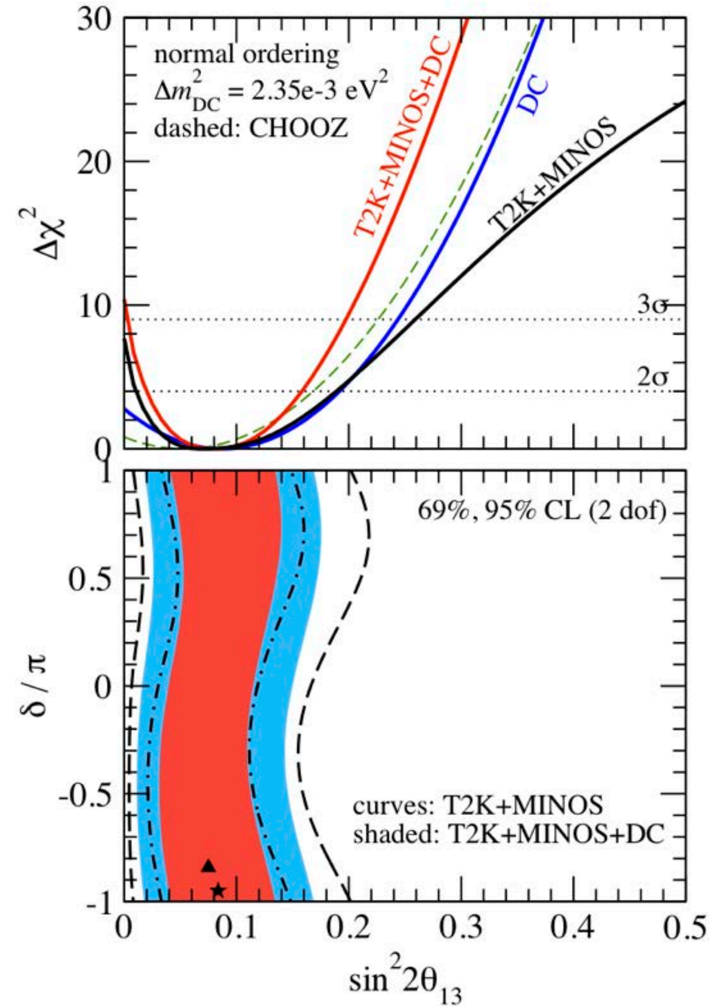
θ_{13}=0 disfavored @ 89% C.L.

Double Chooz $\sin^2(2\theta_{13})$=0.086 ± 0.041(stat) ± 0.030(syst)



2011

no result >2.5σ from θ_{13} =0



a precision experiment needed

Oscillation Experiments with Reactors

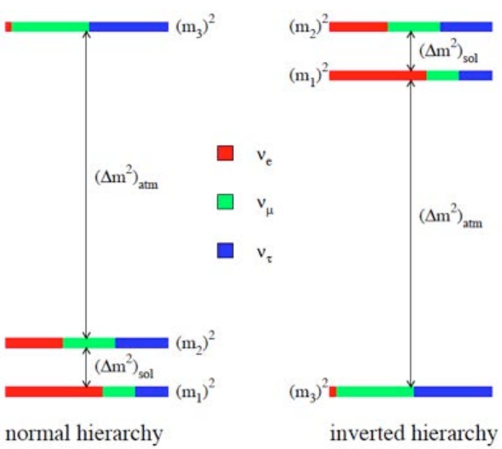
Measure (non)-1/r² behavior of $\overline{\nu}_e$ interaction rate

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^{\ 2} L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^{\ 2} L}{4E_\nu}\right)$$

L/E → Δm^2

amplitude of oscillation → θ

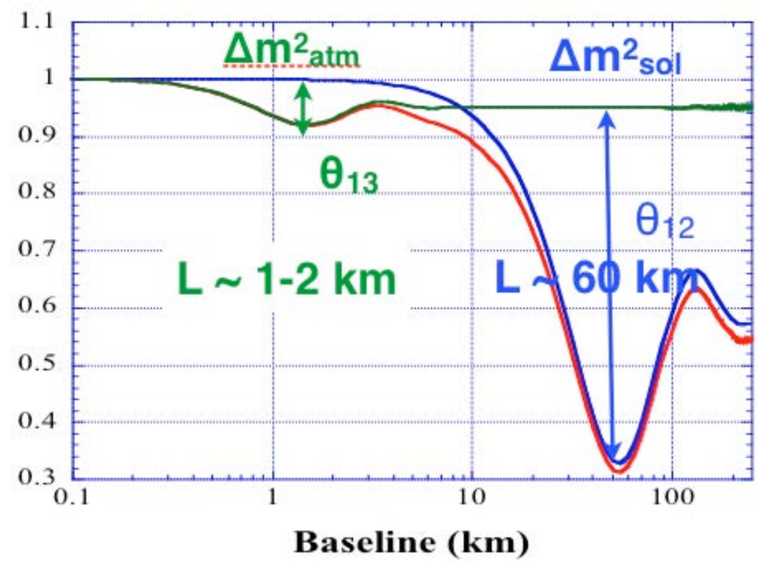
for 3 active ν, two different oscillation length scales: Δm^2_{12}, Δm^2_{23}



$\Delta m^2_{12} \sim 7.6 \times 10^{-5}\ \mathrm{eV}^2$

$\Delta m^2_{23} \sim 2.4 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{23} \approx \Delta m^2_{13}$



Oscillation Experiments with Reactors

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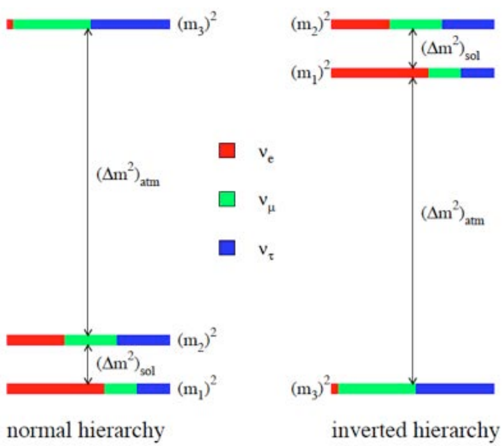

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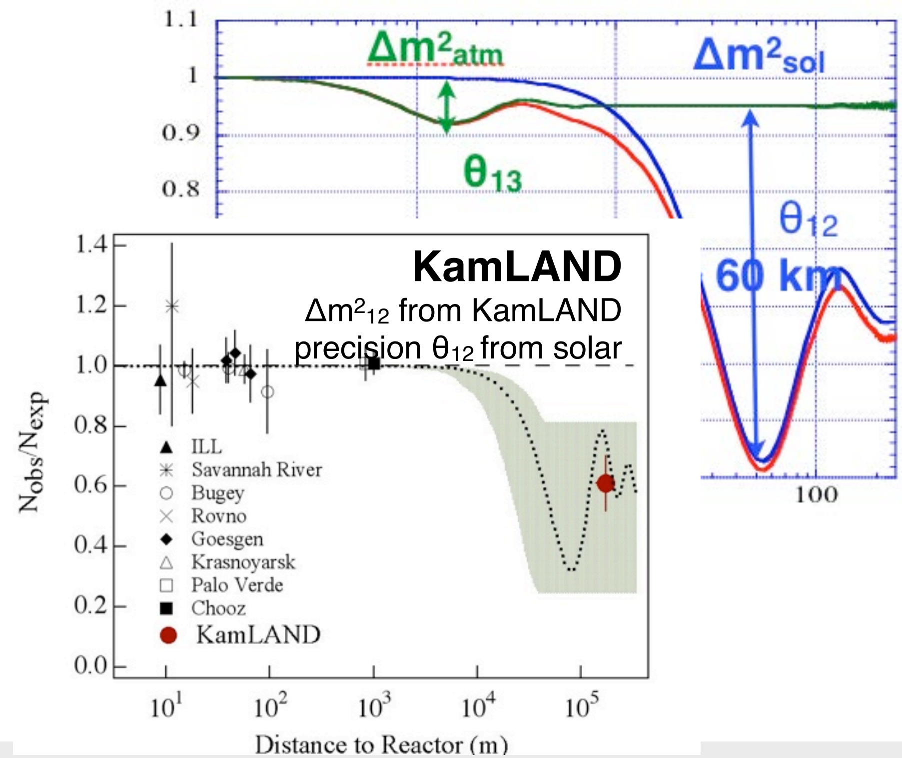
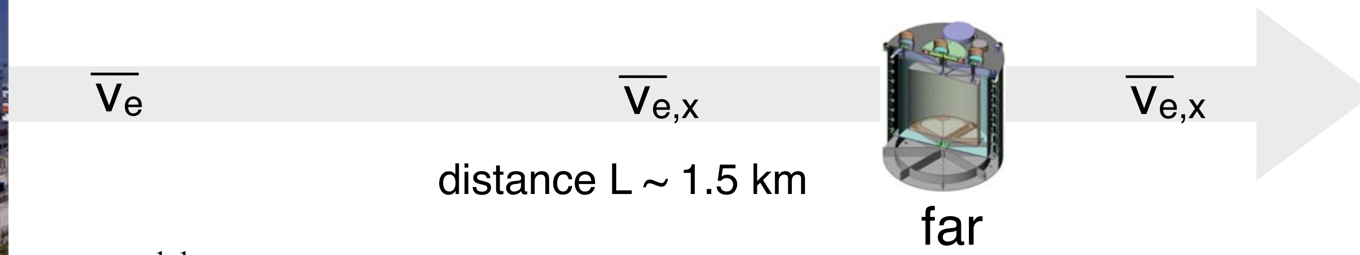
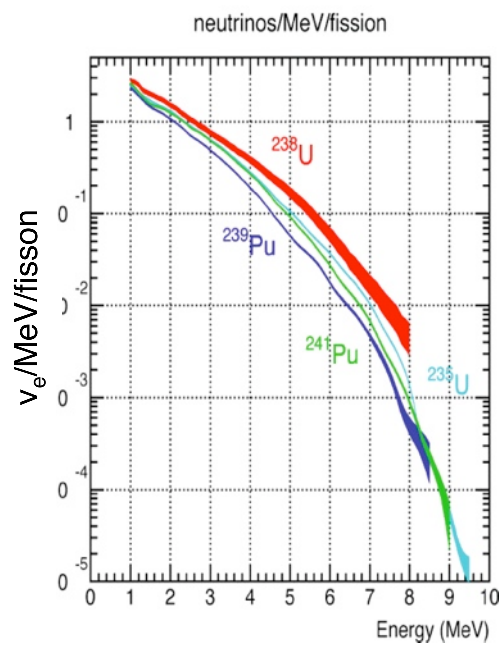
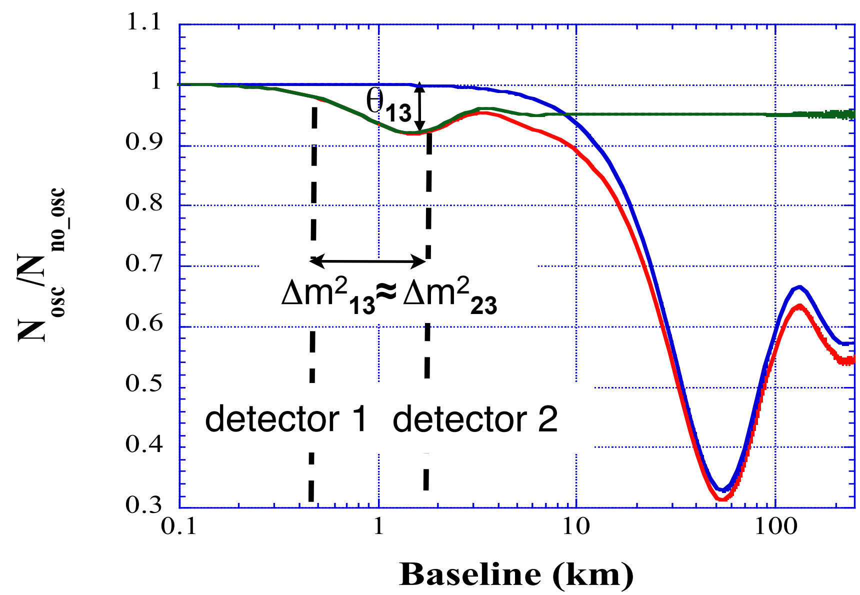


Measuring θ_{13} with Reactor Experiments

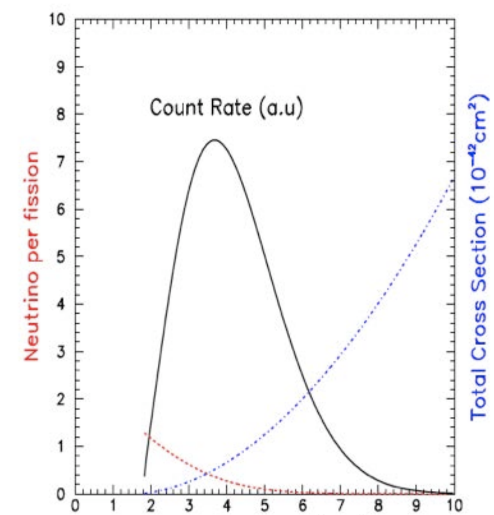




Energy (MeV)



$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$



Neutrino Energy (MeV)

Precision Physics with Reactor $\bar{\nu}_e$

How to improve on previous reactor experiments?

1. **Eliminate dependence on absolute reactor flux prediction.**
   → relative measurement

2. **Optimize baseline** for oscillation.
   → use knowledge of Δm^2

3. **Eliminate position reconstruction** and fiducial volume
   → use total target

4. **Stable scintillator**

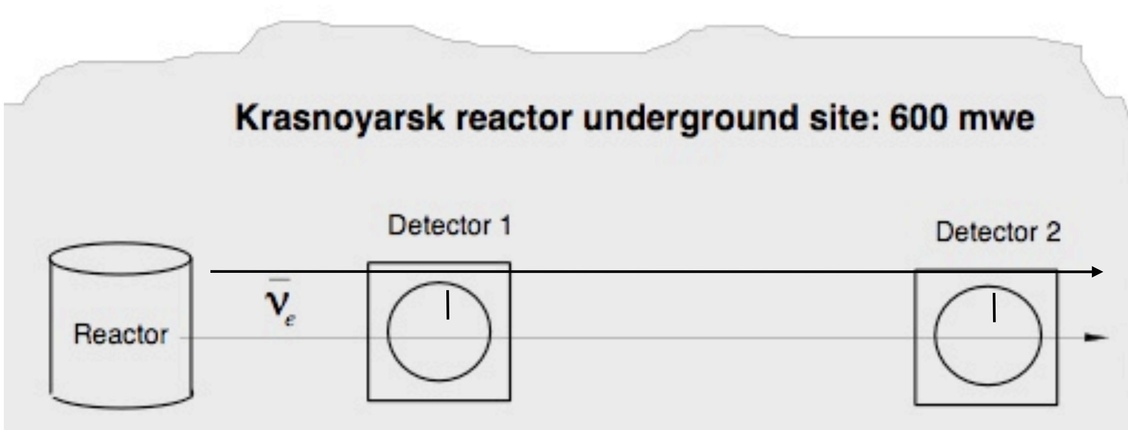
5. **Reduce backgrounds**.

6. **Multiple functionally identical detectors**.
   → only relative acceptance of detectors is needed
   → cross-checks of systematics

Relative Measurement: A 2-Detector Experiment

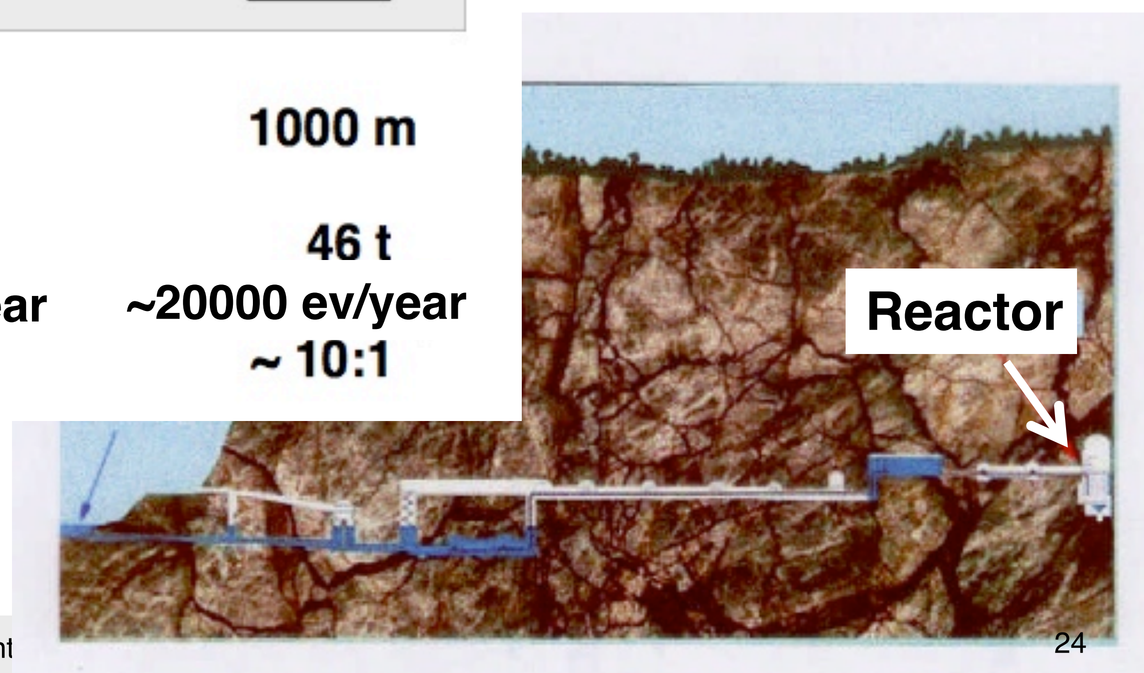
Krasnoyarsk, Russia

first proposed at Neutrino2000



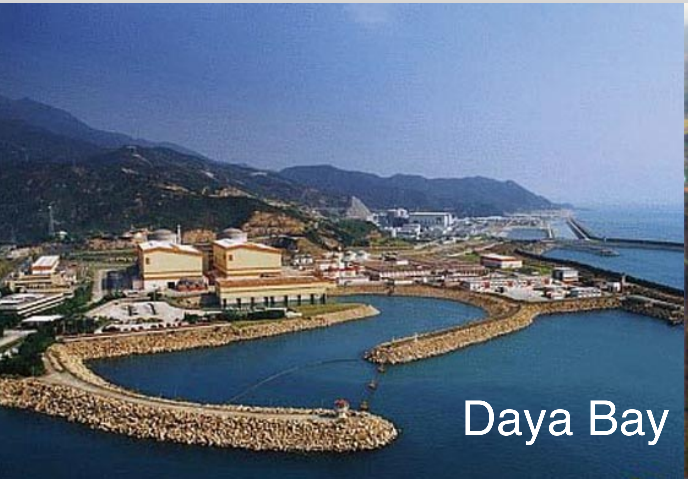
	115 m	1000 m
Target:	46 t	46 t
Rate:	~1.5 x 10^6 ev/year	~20000 ev/year
S:B	>>1	~ 10:1

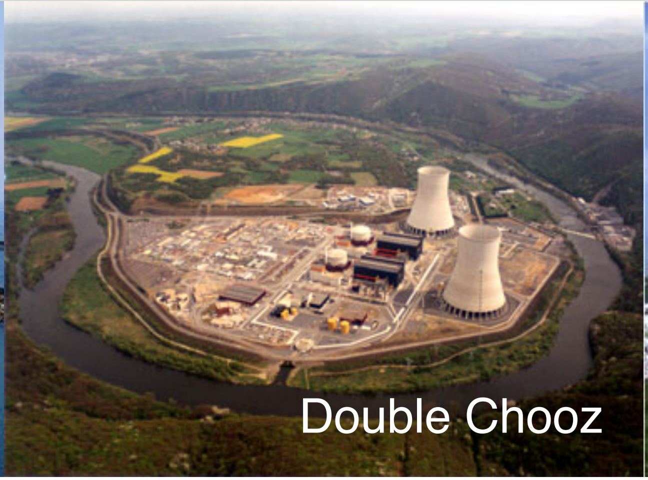
Krasnoyarsk
- underground reactor
- detector locations determined by infrastructure

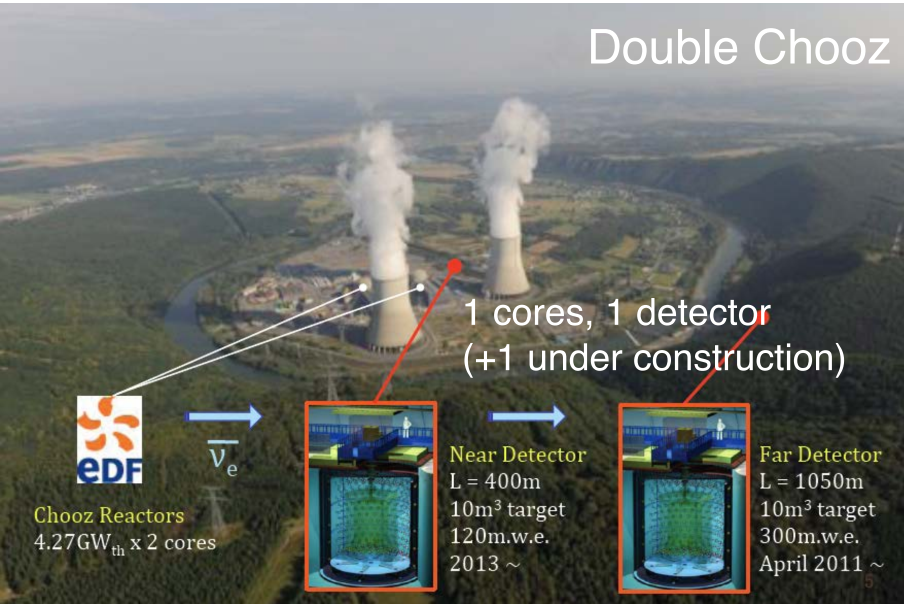


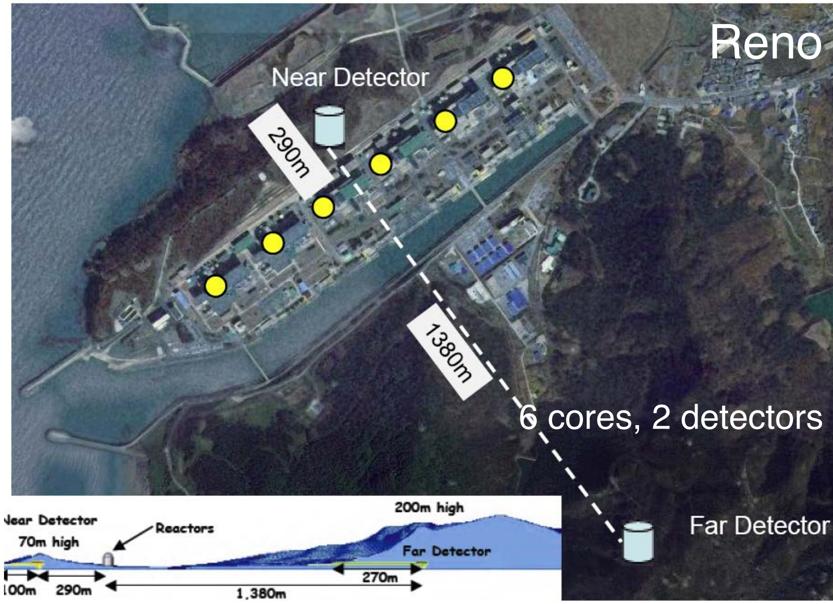
Ref: Marteyamov et al, hep-ex/0211070

Reactor θ_{13} Experiments



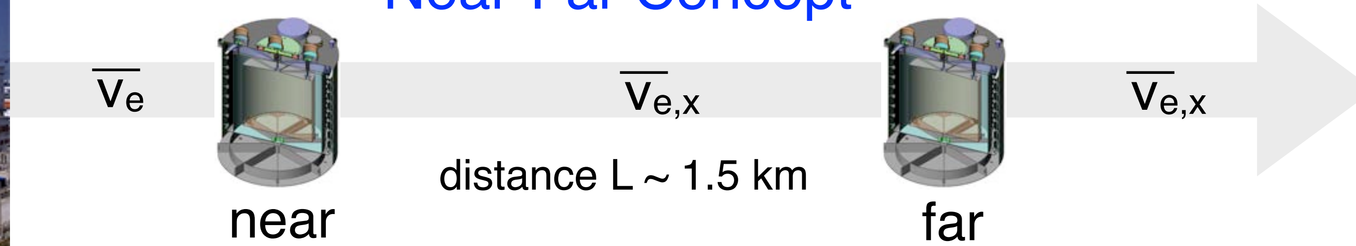


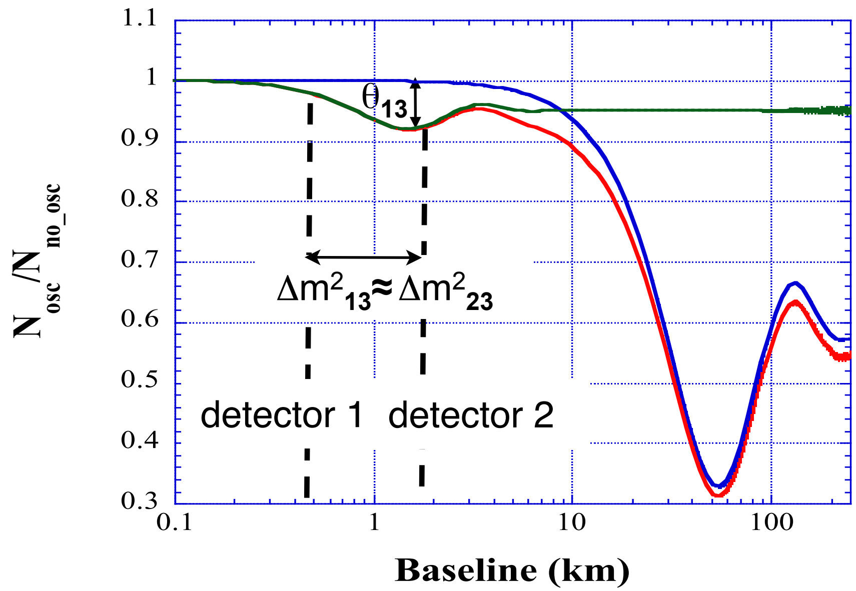




Measuring θ_{13} with Reactor Experiments

Near-Far Concept





Absolute Reactor Flux
Largest uncertainty in previous measurements

Relative Measurement
Removes absolute uncertainties!

First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)

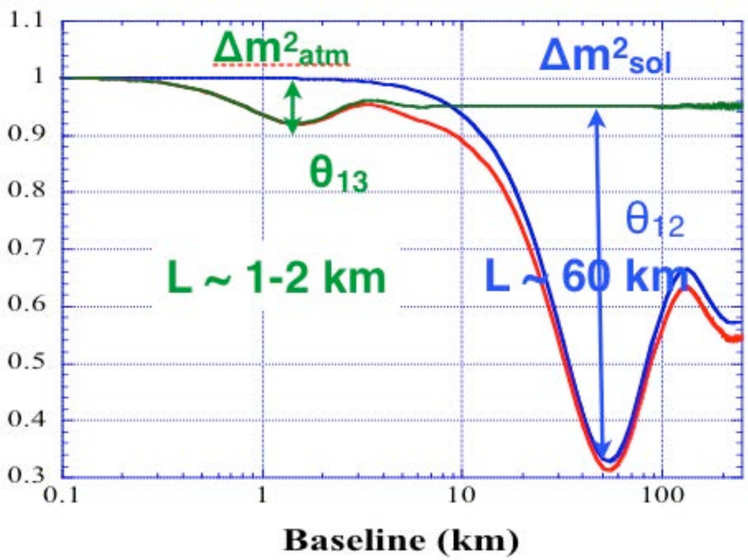
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$

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

Baseline Optimization: What is best baseline?

Rate Effect

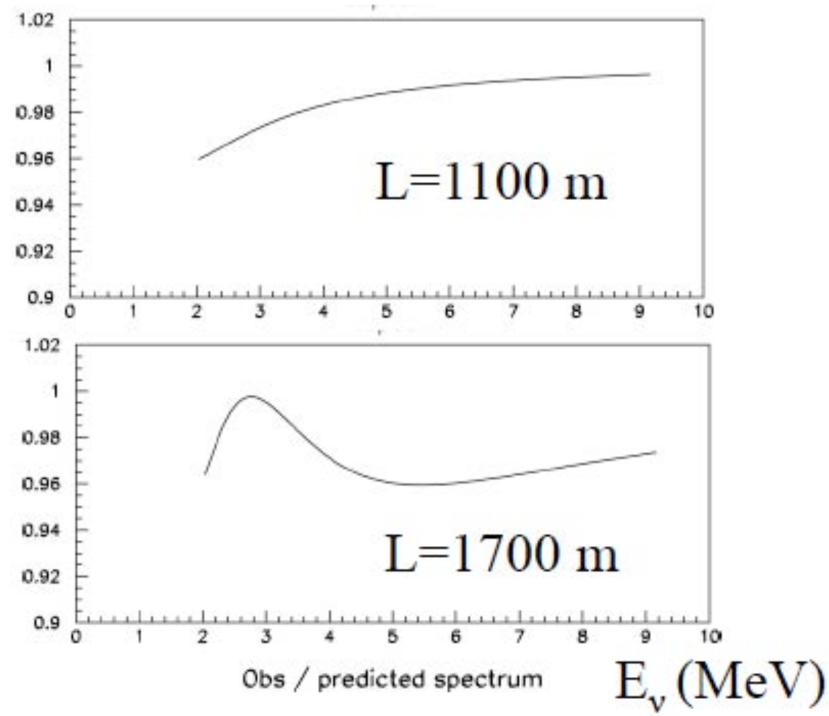
deficit in counting rate



for rate effect, competition between $1/R^2$ (statistics) and sinusoidal oscillation

Spectral Distortions

energy dependent signature

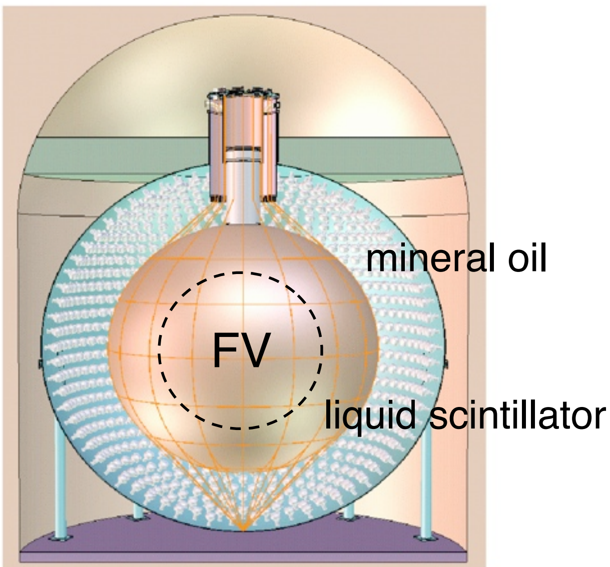


for shape, distortion different at different baselines

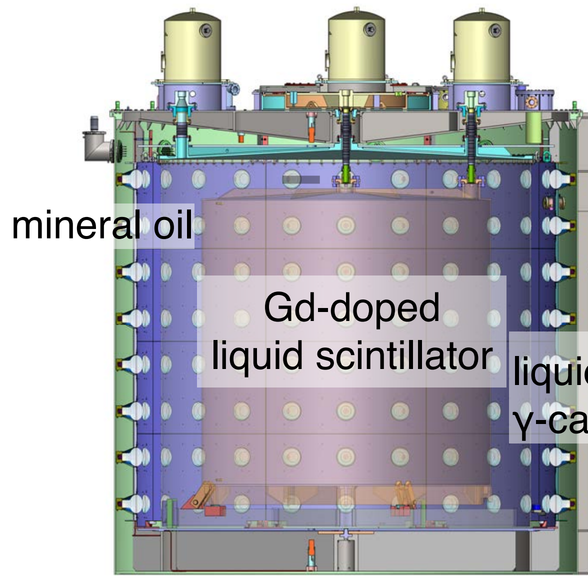
balance statistical and systematic errors

Upgrade from 2-zone to 3-zone Detector

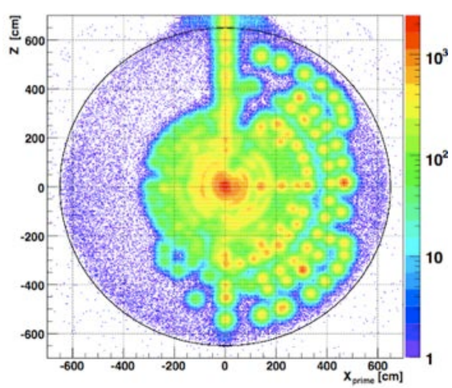
KamLAND
2-zone



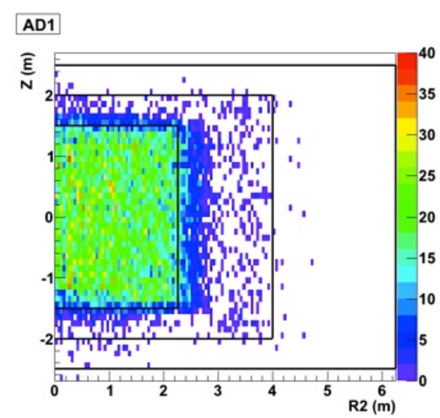
Daya Bay (RENO, Double Chooz)
3-zone

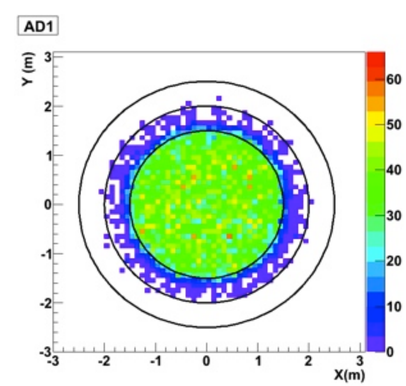


3-zone detector eliminates FV cut
→ we simply count # of protons in target



fiducial volume established based on position reconstruction of events





Improved Target: Gd-Loaded Scintillator

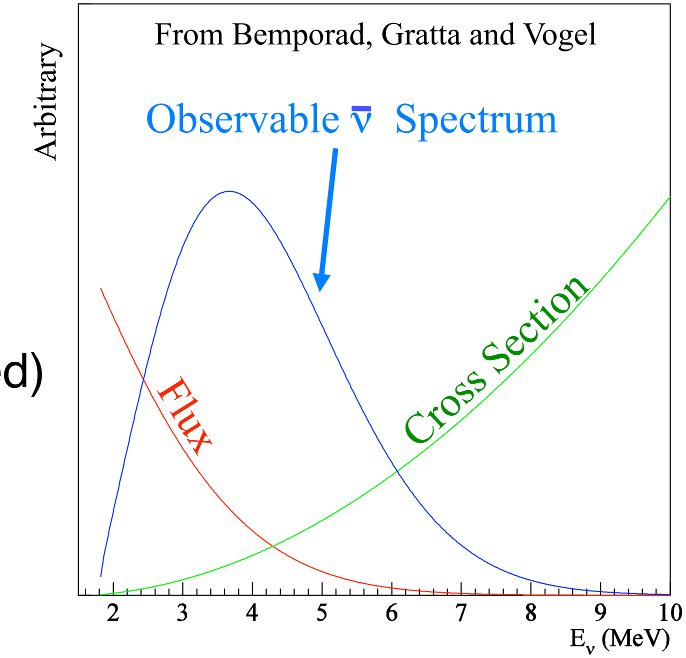
$\overline{\nu}_e + p \rightarrow e^+ + n$

0.3 b $\rightarrow + p \rightarrow D + \gamma$ (2.2 MeV) (delayed)

49,000 b $\rightarrow + Gd \rightarrow Gd^*$

$\rightarrow Gd + \gamma$'s (8 MeV) (delayed)

coincidence signal allows background suppression



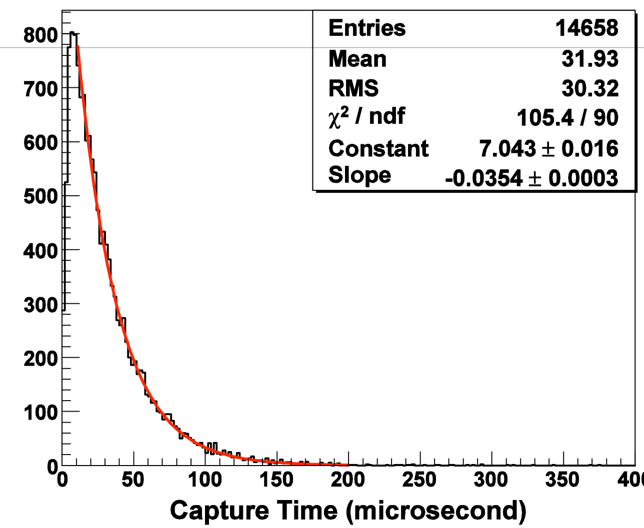
0.1% Gadolinium-Liquid Scintillator

- Proton-rich target
- Easily identifiable n-capture signal above radioactive backgrounds
- Short capture time (τ~28 μs)
- Good light yield

^{155}Gd $\Sigma\gamma$=7.93 MeV

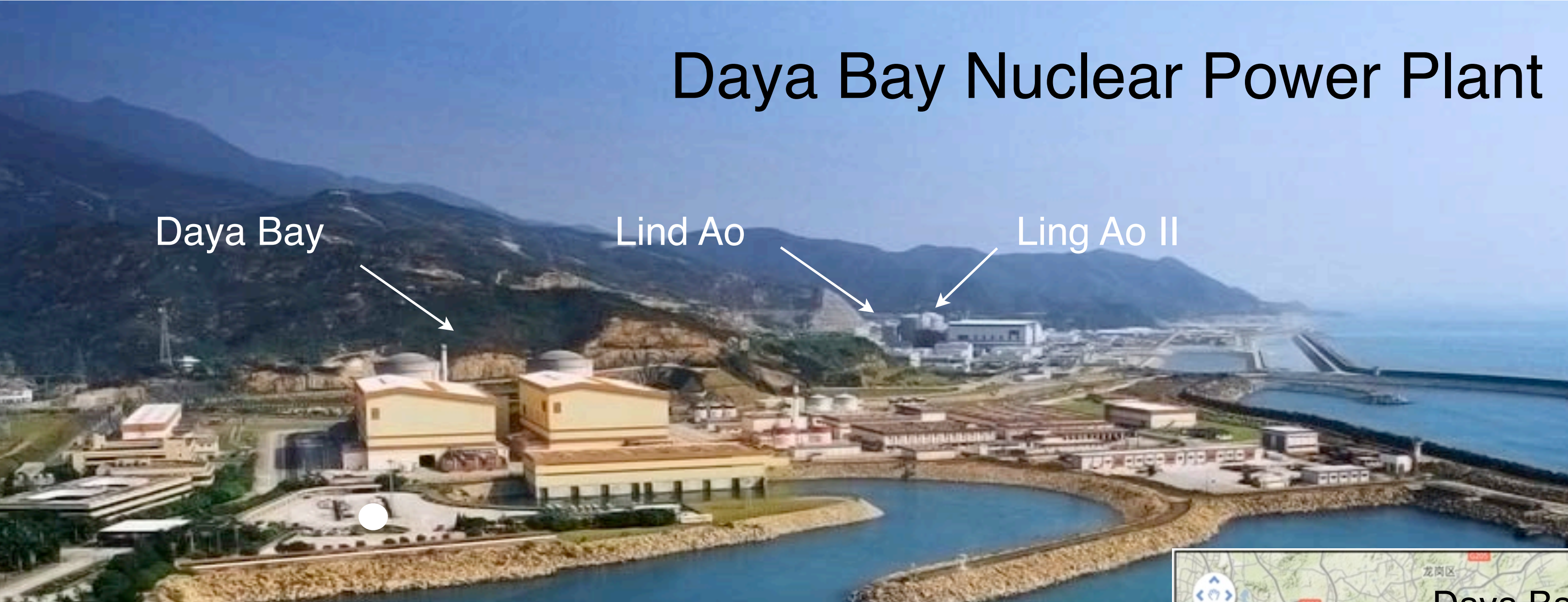
^{157}Gd $\Sigma\gamma$=8.53 MeV

other Gd isotopes with high abundance have very small neutron capture cross sections



For 0.1% Gd, about 85% of neutrons are captured by Gd

Daya Bay Nuclear Power Plant

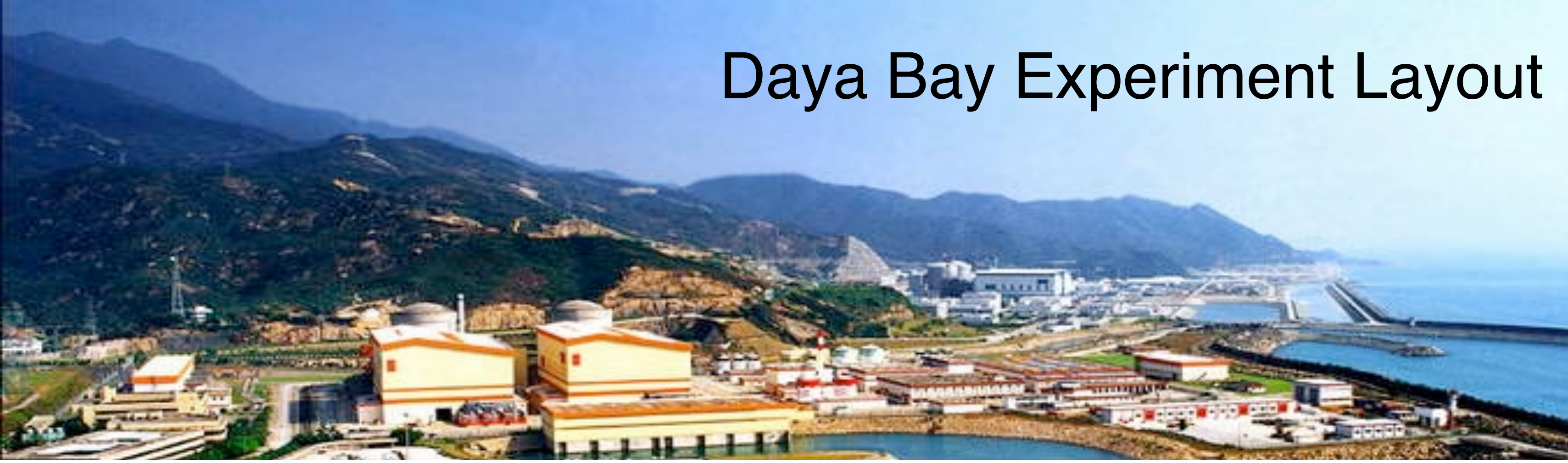


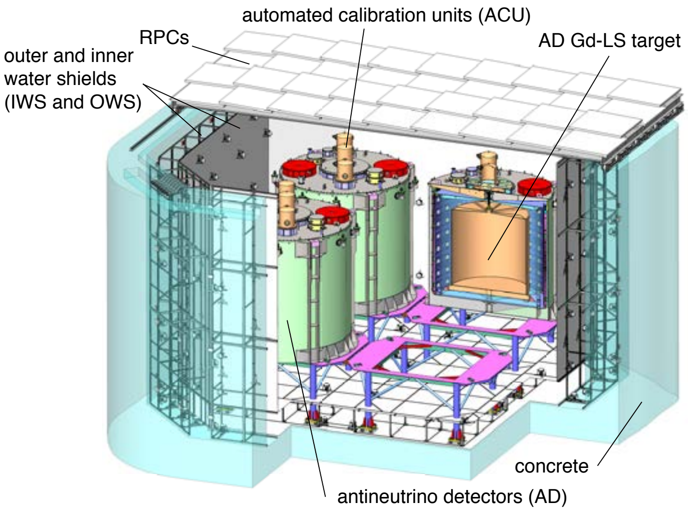
A Powerful Neutrino Source

- Among the top 5 most powerful reactor complexes in the world, producing 17.4 GW_{th} (6 x 2.95 GW_{th})
- All 6 reactors are in commercial operation
- Adjacent to mountains; convenient to construct tunnels and underground labs with sufficient overburden to suppress cosmic rays

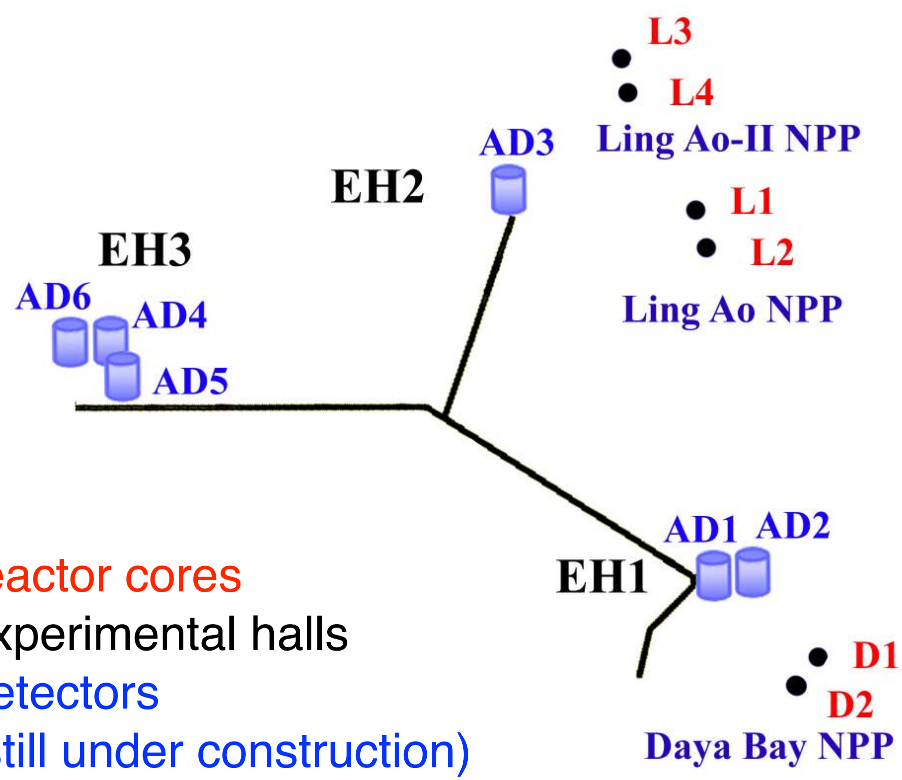
Reactors produce ~2×10^{20} antineutrinos/sec/GW

Daya Bay Experiment Layout



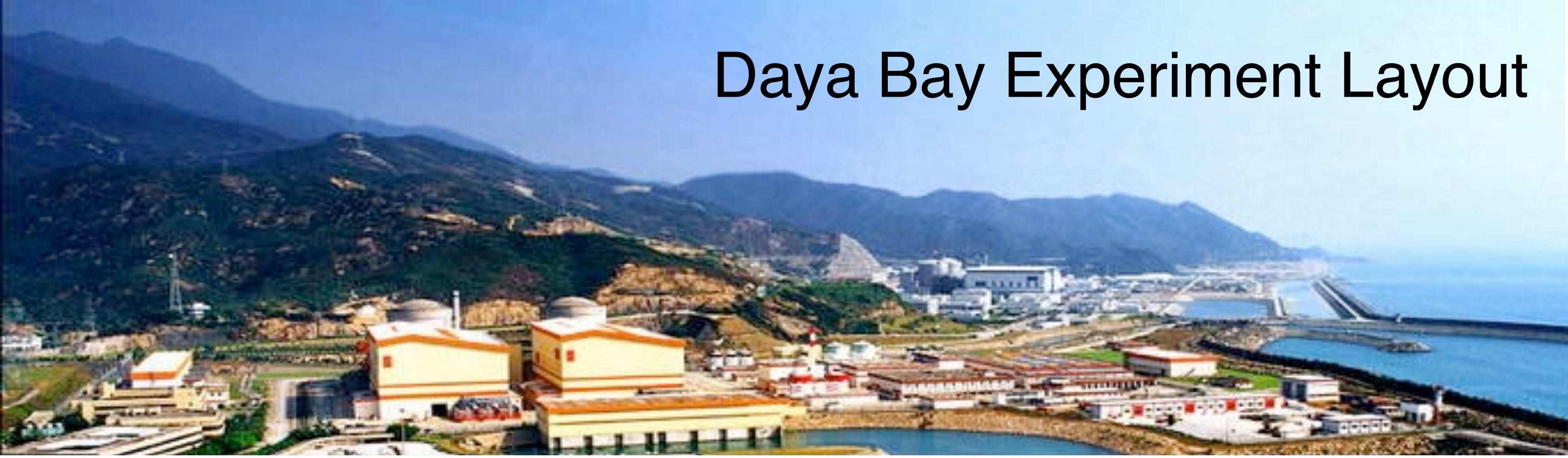


	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

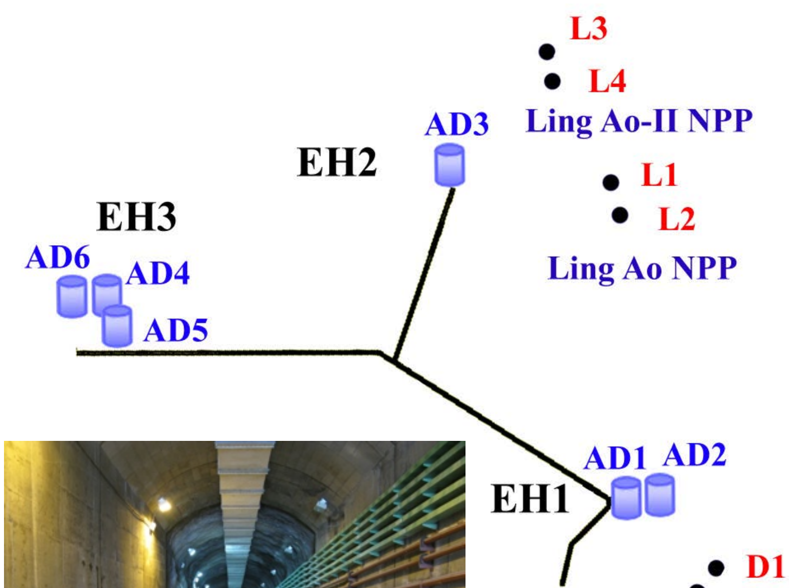


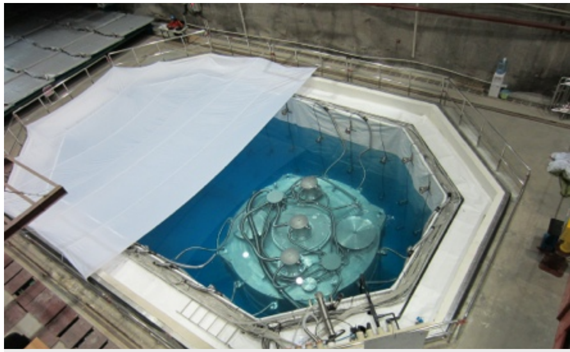
6 reactor cores
3 experimental halls
6 detectors
(2 still under construction)

Daya Bay Experiment Layout

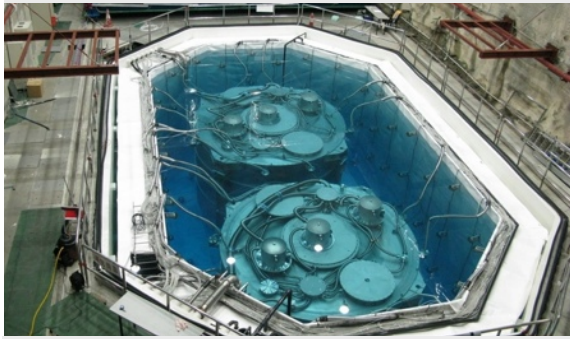


Hall 3: began 3 AD operation on Dec. 24, 2011





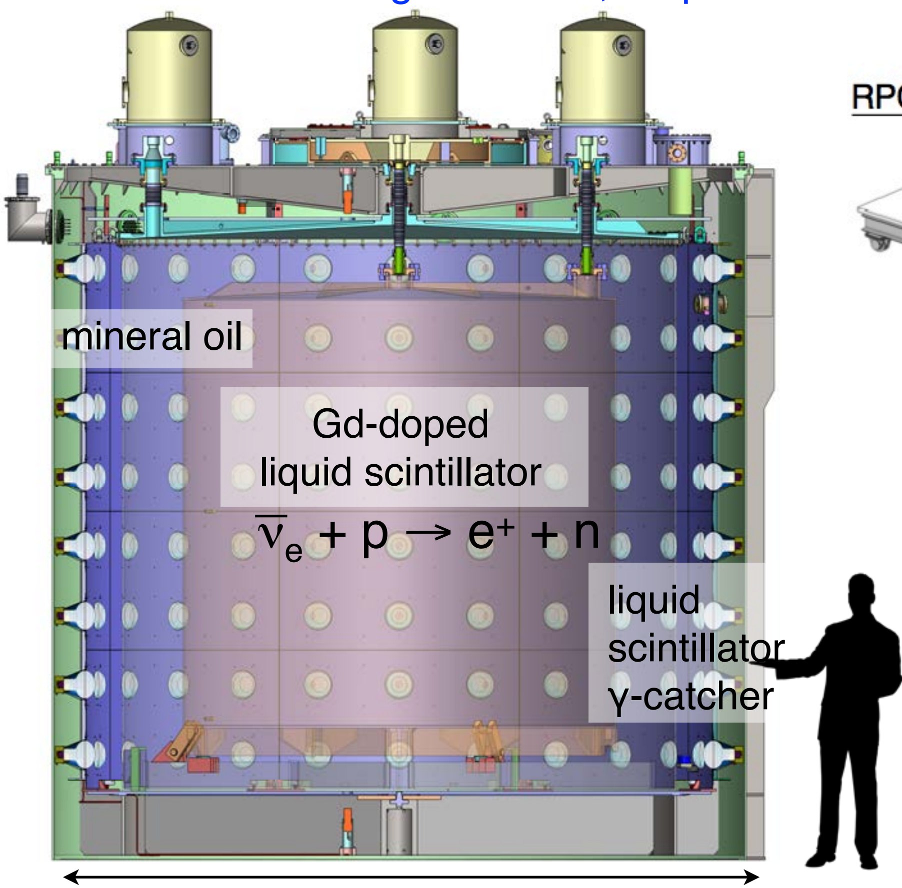
Hall 2: began 1 AD operation on Nov. 5, 2011



Hall 1: began 2 AD operation on Sep. 23, 2011

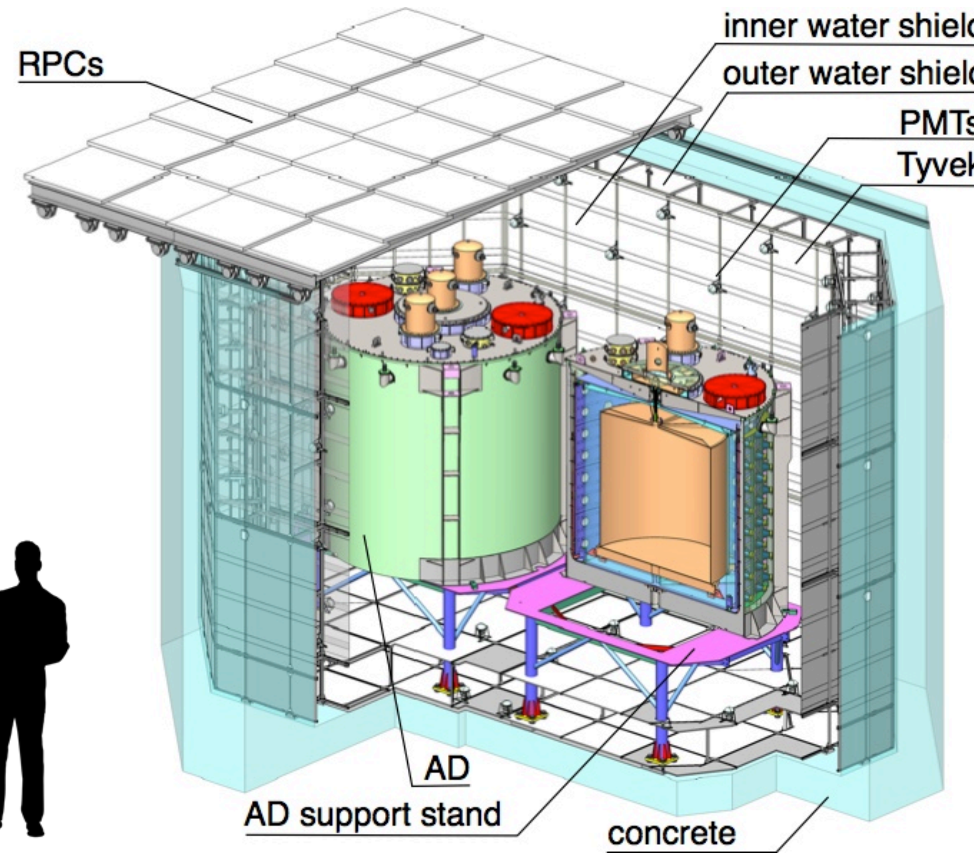
Daya Bay Detectors

6 “functionally identical” detectors
Gd-LS defines target volume, no position cut



target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

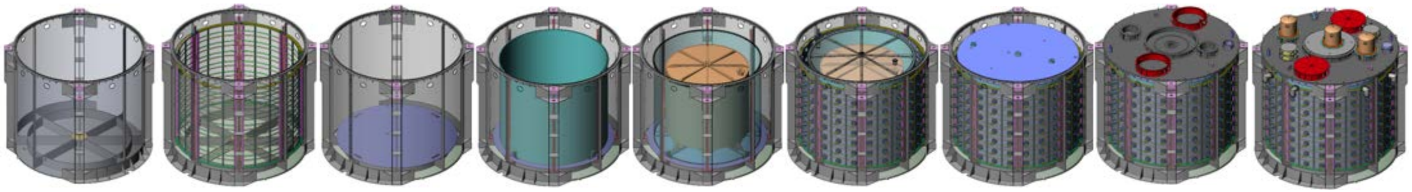
Dual tagging systems: 2.5 meter water shield and RPCs

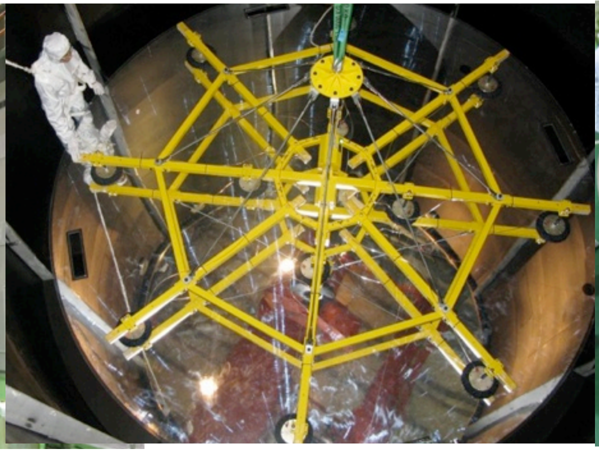


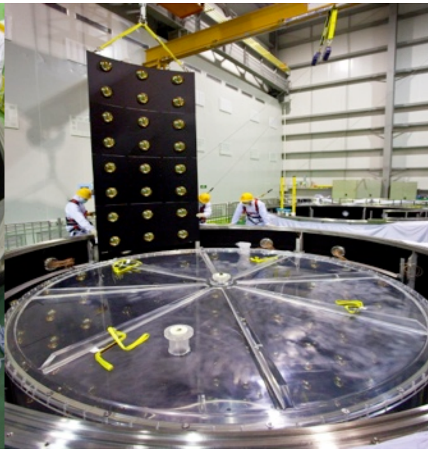
Two-zone ultrapure water Cherenkov detector

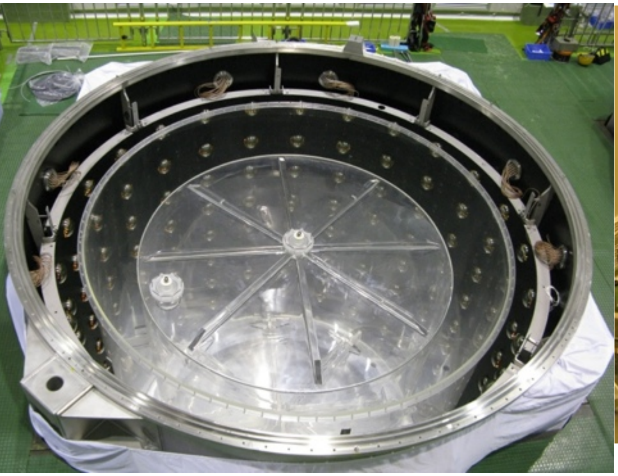
multiple detectors allow comparison and cross-checks

Antineutrino Detector Assembly



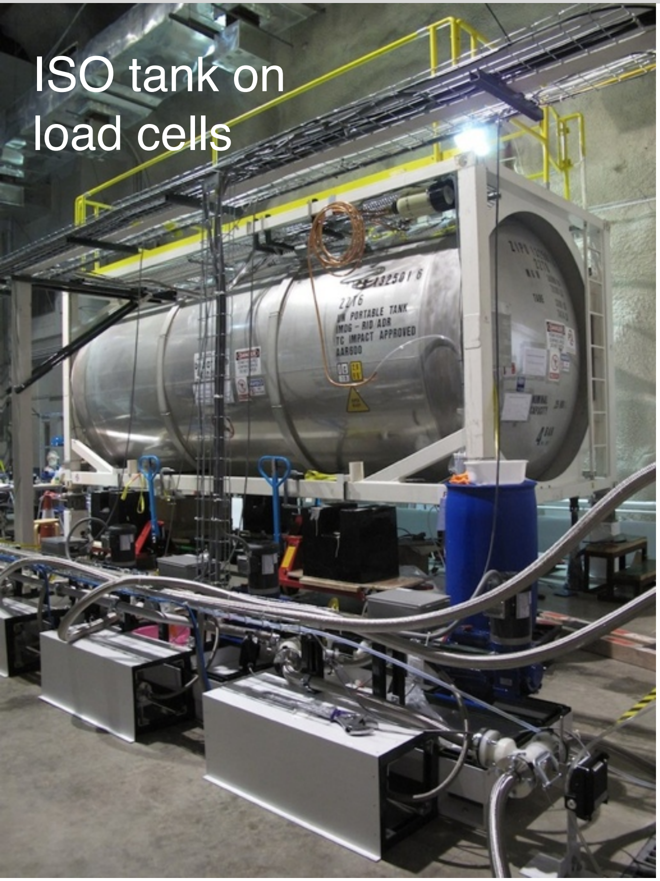


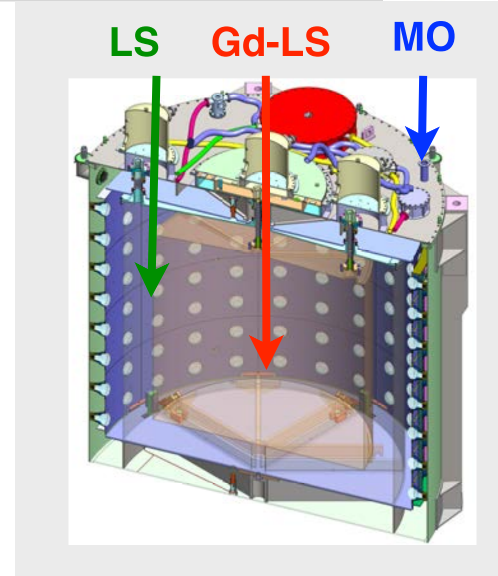


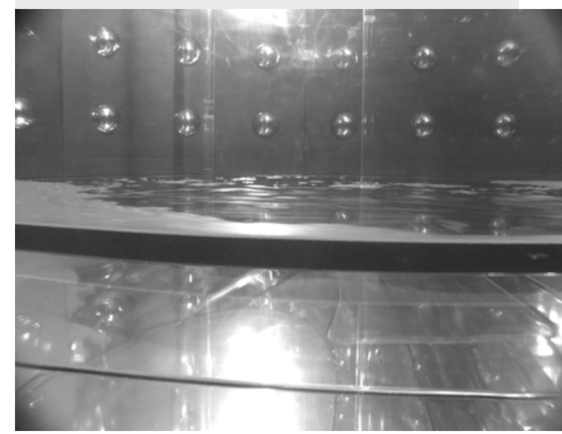


detector assembly in pairs
6 ADs operational, AD7,8 in assembly

Detector Filling and Target Mass Measurement







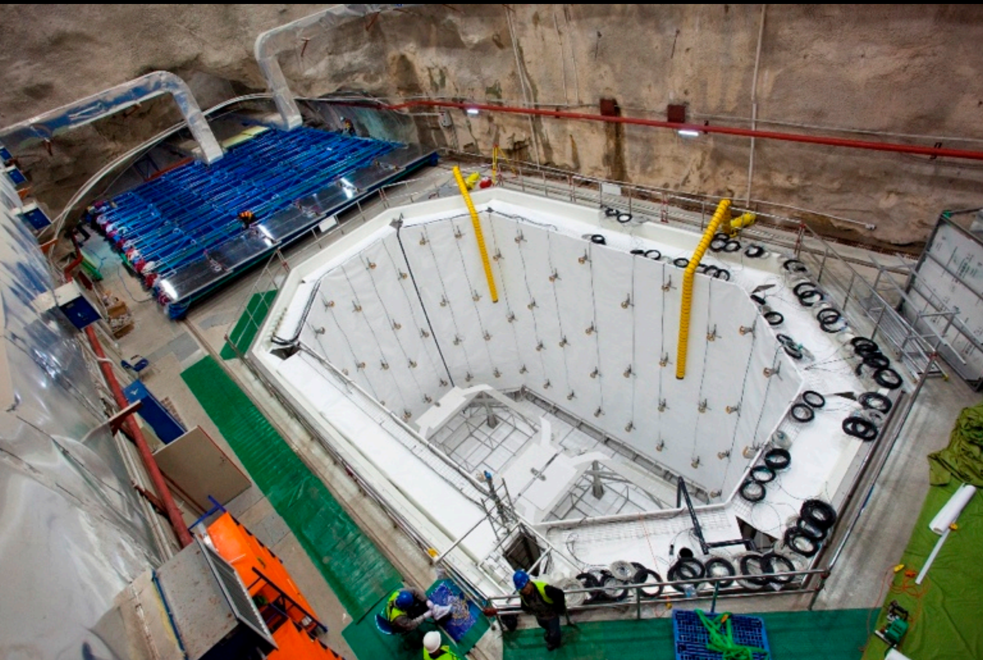
Quantity	Relative	Absolute
protons/kg	neg.	0.47%
Density (kg/L)	neg.	neg.
Total mass	0.015%	0.015%
Overflow tank geometry	0.0066%	0.0066%
Overflow sensor calibration	0.0043%	0.0043%
Bellows Capacity	0.0025%	0.0025%
Target mass	0.017%	0.017%
Target protons	0.017%	0.47%

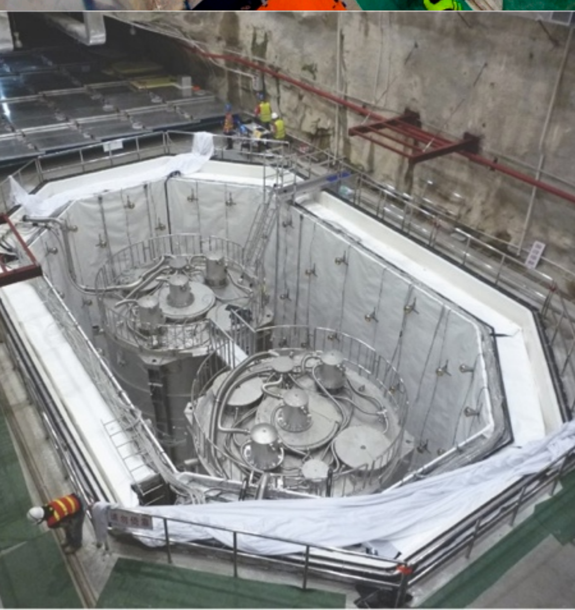
Target mass determination error
± 3kg out of 20,000

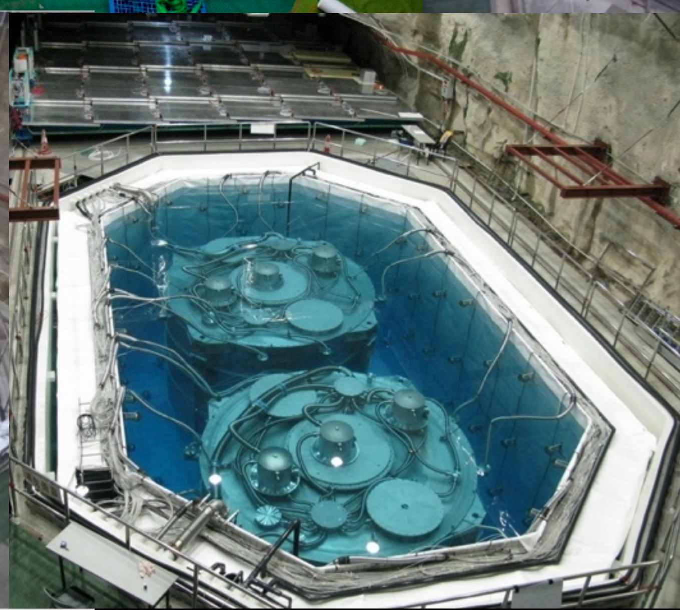
<0.03% during data taking period

Detectors are filled from same reservoirs *"in-pairs"* within < 2 weeks.

Antineutrino Detector Installation - Near Hall







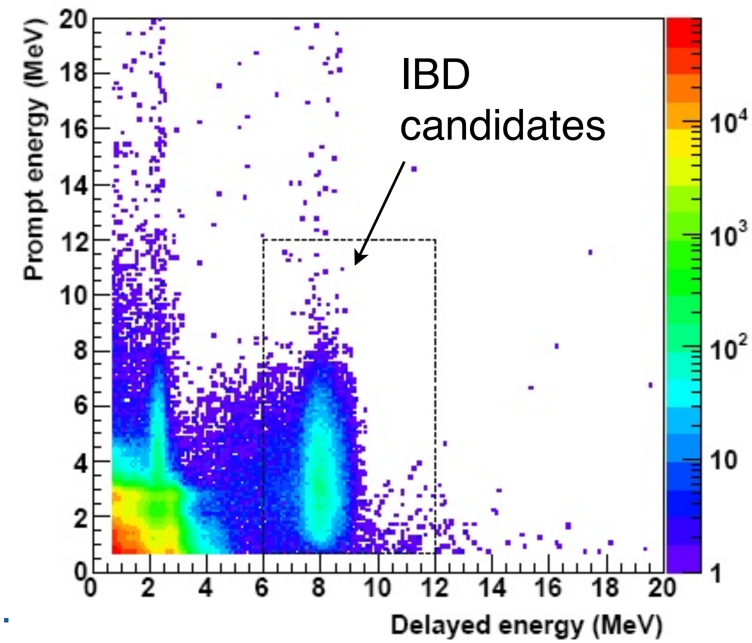
Antineutrino Candidates (Inverse Beta Decay)

Prompt + Delayed Selection

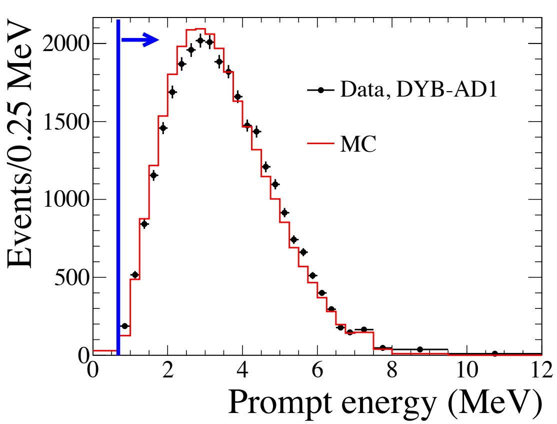
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- Reject Flashers
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:

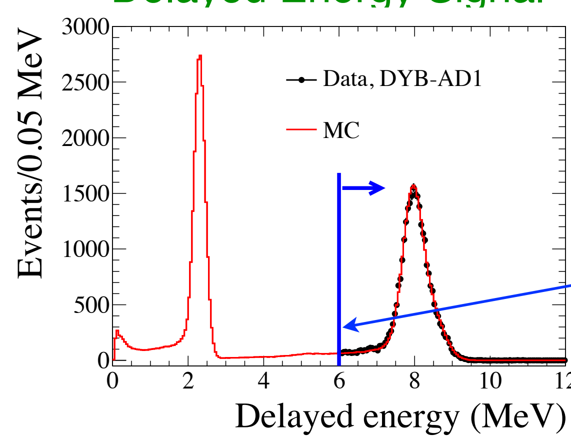
  No other signal > 0.7 MeV in -200 μs to 200 μs of IBD.



Prompt Energy Signal



Delayed Energy Signal



Uncertainty in relative E_d efficiency (0.12%) between detectors is largest systematic.

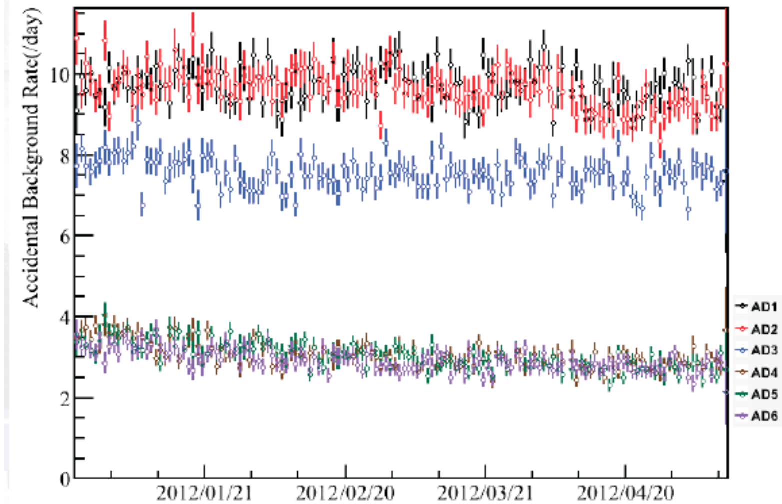
Background Summary

Total backgrounds: 5%(2%) in far(near) halls.

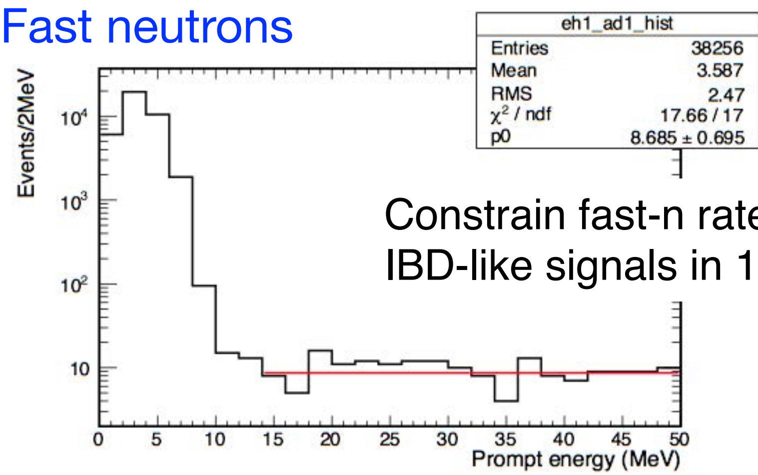
	Near Halls		Far Hall	
	B/S %	$\sigma_{B/S}$ %	B/S %	$\sigma_{B/S}$ %
Accidentals	1.5	0.02	4.0	0.05
fast neutrons	0.12	0.05	0.07	0.03
$^{8}He/^{9}Li$	0.4	0.2	0.3	0.2
^{241}Am-^{13}C	0.03	0.03	0.3	0.3
$^{13}C(\alpha, n)^{16}O$	0.01	0.006	0.05	0.03

Backgrounds uncertainties are 0.3%(0.2%) in far(near) halls.

Accidentals

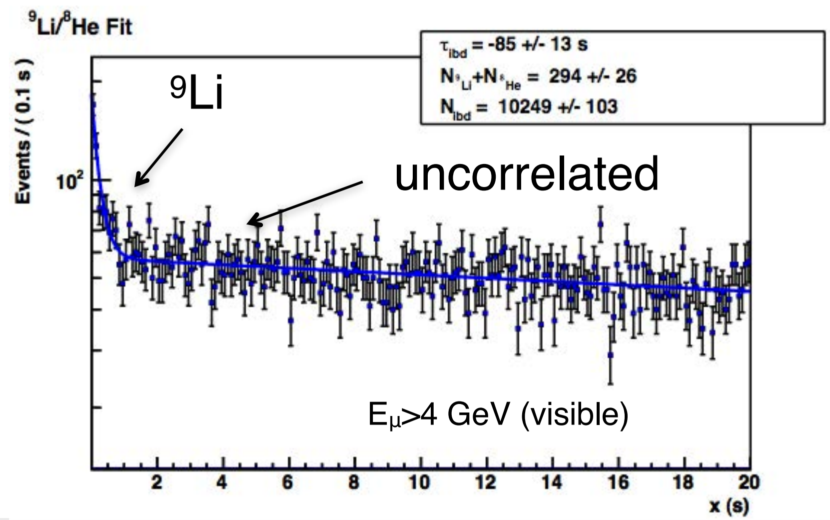


Fast neutrons



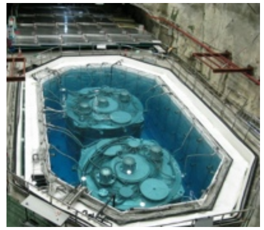
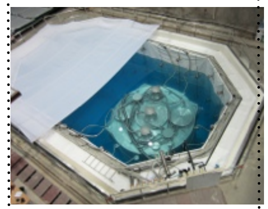
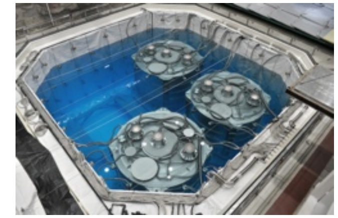
Constrain fast-n rate using IBD-like signals in 10-50 MeV

Correlated β-n decay



Daya Bay Data Set Summary

~200k near
~30k far detector
antineutrino interactions

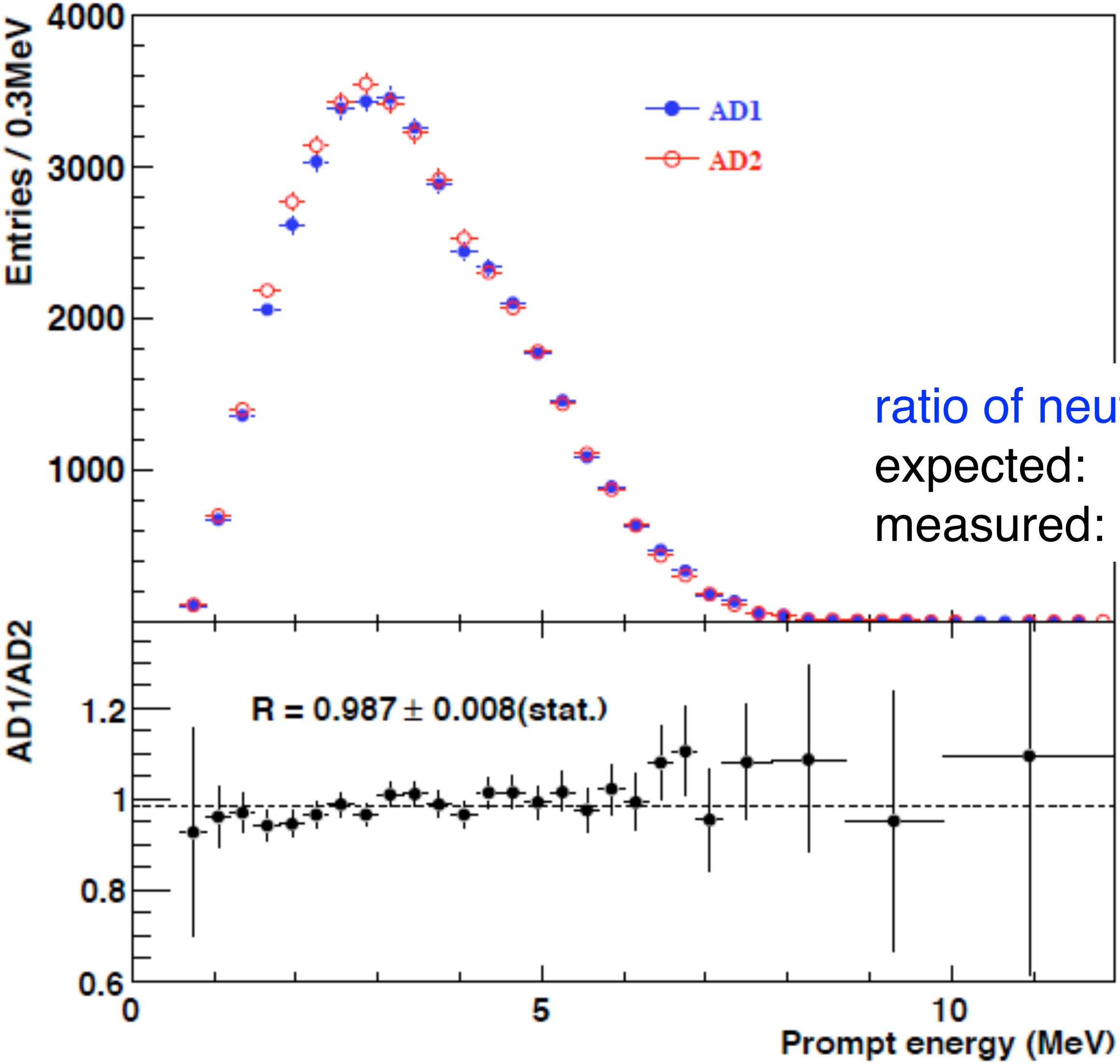




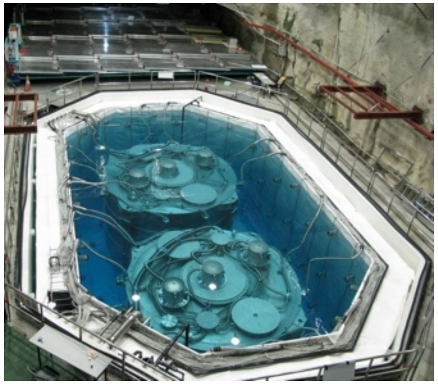
	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	**69121**	**69714**	**66473**	**9788**	**9669**	**3452**
DAQ live time (day)	127.5470		127.3763	126.2646		
Efficiency	0.8015	0.7986	0.8364	0.9555	0.9552	0.9547
Accidentals (/day)	9.73±0.10	9.61±0.10	7.55±0.08	3.05±0.04	3.04±0.04	2.93±0.03
Fast neutron (/day)	0.77±0.24	0.77±0.24	0.58±0.33	0.05±0.02	0.05±0.02	0.05±0.02
^{8}He/^{9}Li (/day)	2.9±1.5		2.0±1.1	0.22±0.12		
Am-C corr. (/day)	0.2±0.2					
^{13}C(α, n)^{16}O (/day)	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
Antineutrino rate (/day)	**662.47 ±3.00**	**670.87 ±3.00**	**613.53 ±2.69**	**77.57 ±0.85**	**76.62 ±0.85**	**74.97 ±0.84**

rates /day/AD

consistent rates for side-by-side detectors
uncertainty dominated by statistics

Side-by-Side Comparison in Near Hall





ratio of neutrino events in AD1 and AD2

expected: **0.981**

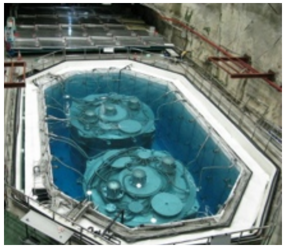
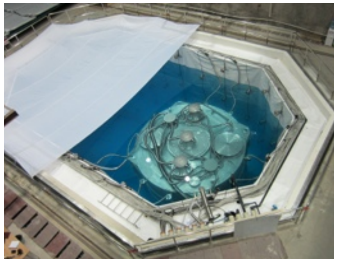
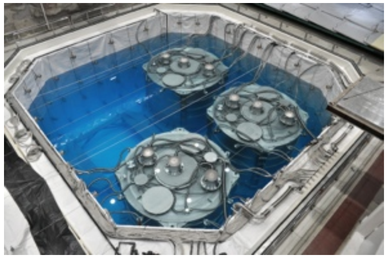
measured: **0.987± 0.008 (stat) ± 0.003**

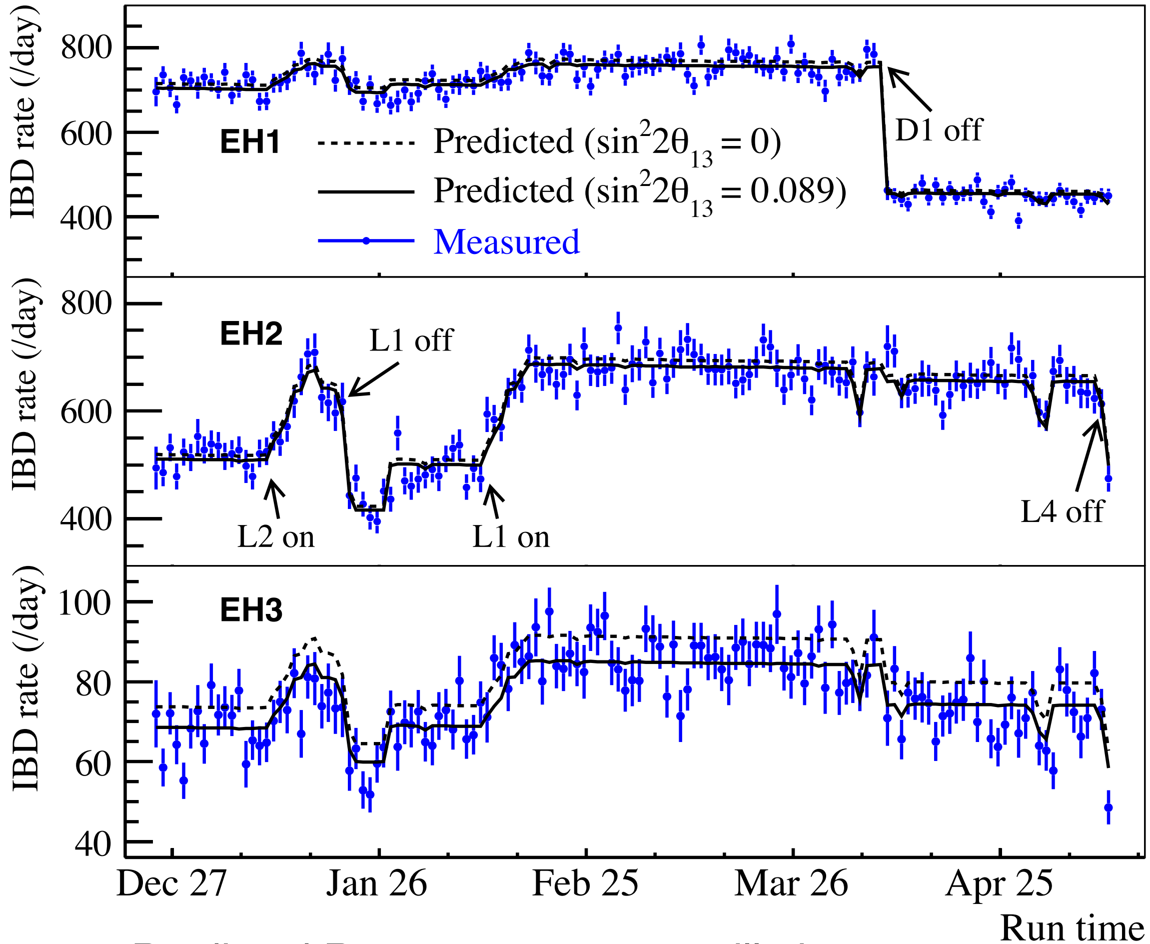
ratio is not 1 because of baseline difference

Daya Bay Collab. arXiv:1202:6181 (2012)

Antineutrino Rate vs. Time

Detected rate strongly correlated with reactor flux expectations



Predicted Rate assumes no oscillation.
Normalization is determined by fit to near detector data.

Uncertainty Summary

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

For near/far oscillation, only uncorrelated uncertainties are used.

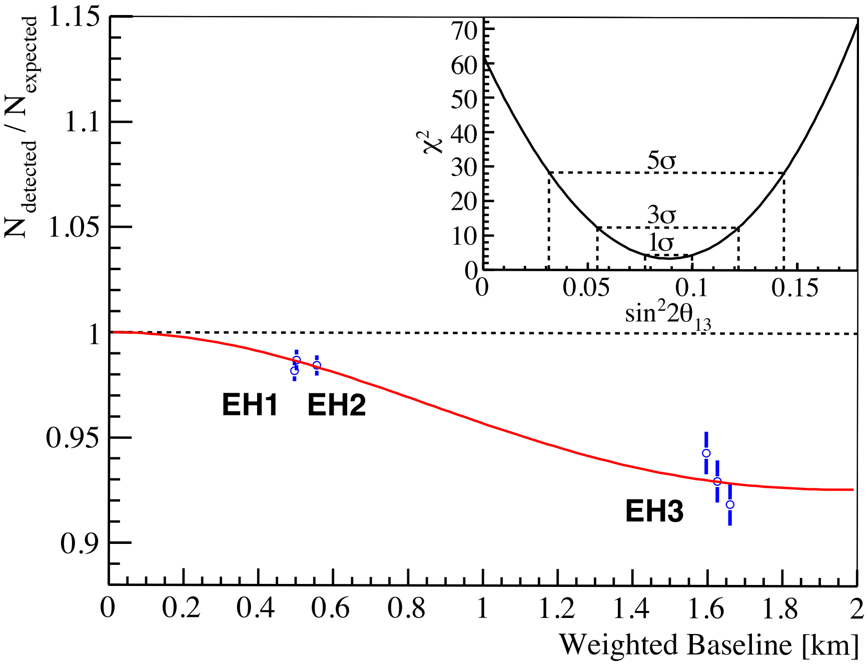
Largest systematics are smaller than far site statistics (~1%)

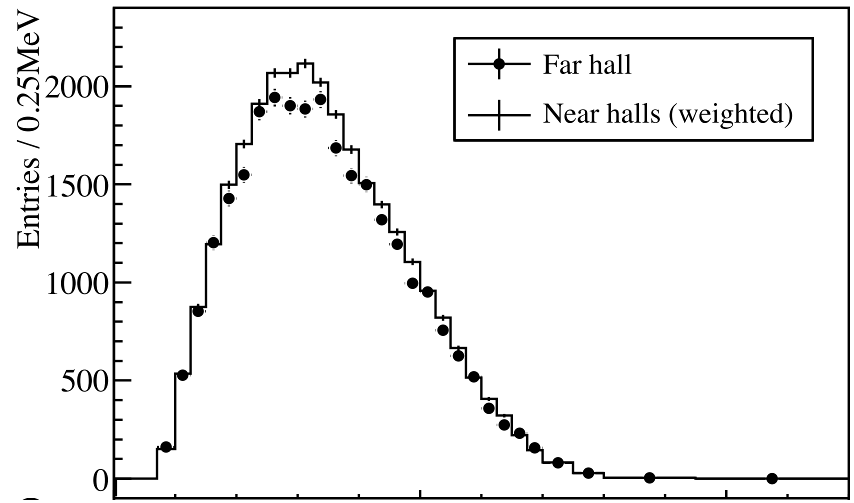
uncorrelated detector uncertainty

Influence of uncorrelated reactor systematics is reduced to by far vs near measurement.

uncorrelated reactor uncertainty

Rate Deficit & Near/Far Ratio





$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

Far vs. near relative measurement.
Absolute rate is not constrained.

$\sin^2 2\theta_{13} =$
$0.089 \pm 0.010\ (\text{stat}) \pm 0.005\ (\text{syst})$

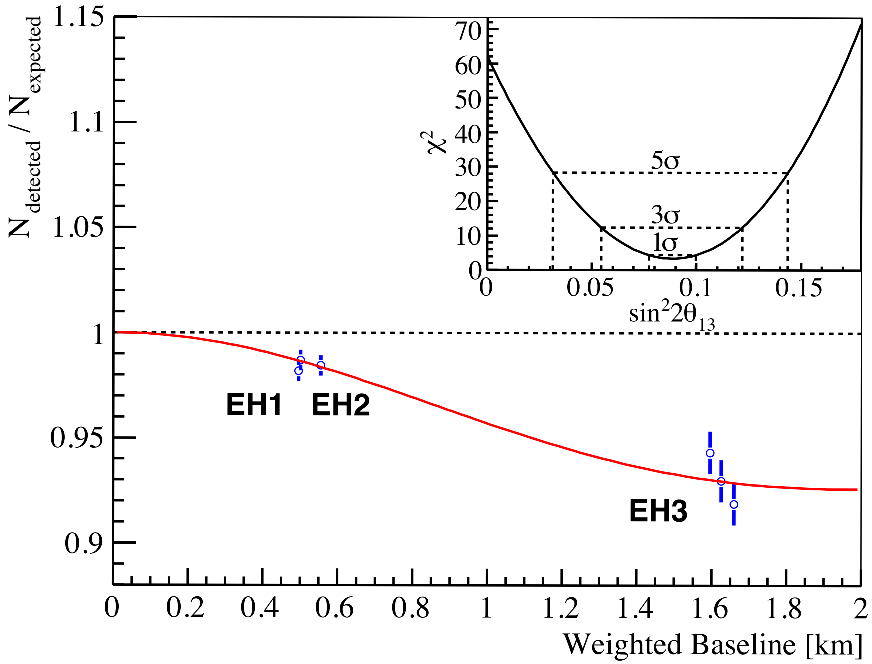
Most precise measurement of $\sin^2 2\theta_{13}$ to date.

M_n are the measured rates in each detector. Weights α_i, β_i are determined from baselines and reactor fluxes.

$R = 0.944 \pm 0.007\ (\text{stat}) \pm 0.003\ (\text{syst})$

Clear observation of far site deficit.

Rate Deficit & Near/Far Ratio

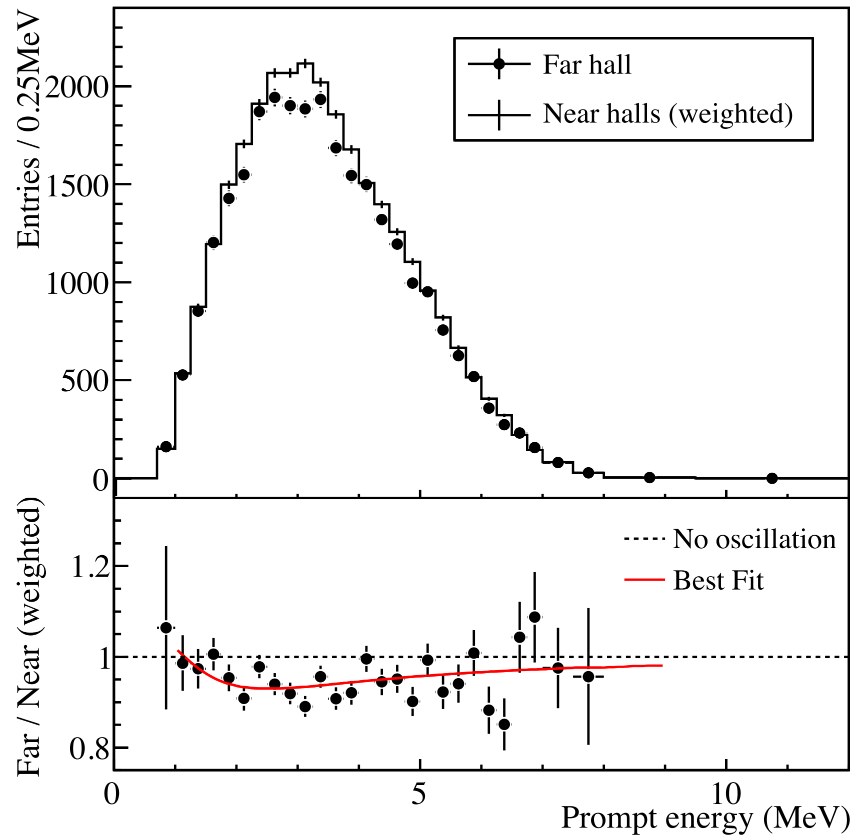


Far vs. near relative measurement.
Absolute rate is not constrained.

$\sin^2 2\theta_{13}$ =

0.089 ± 0.010 (stat) ± 0.005 (syst)

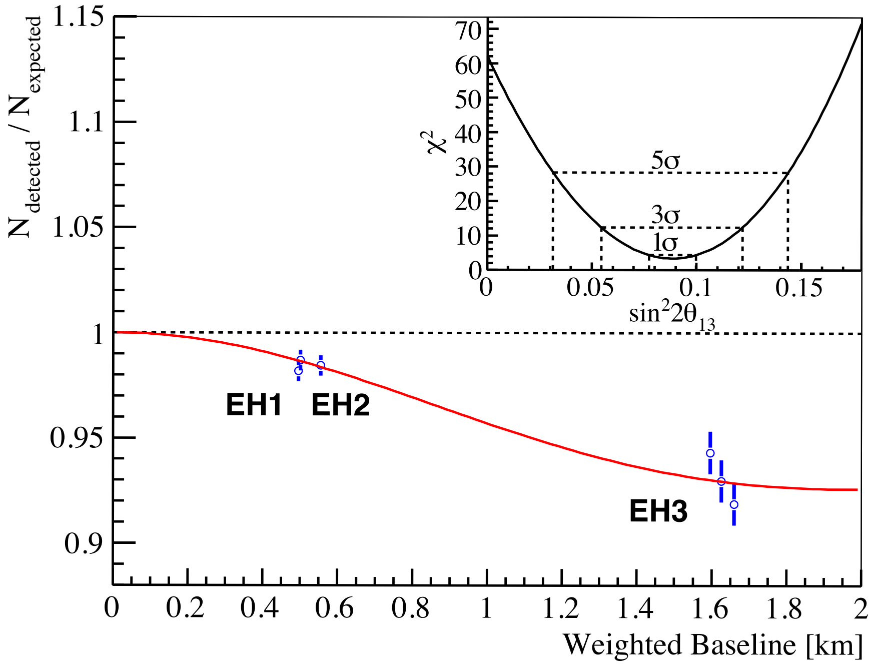
Most precise measurement of $\sin^2 2\theta_{13}$ to date.

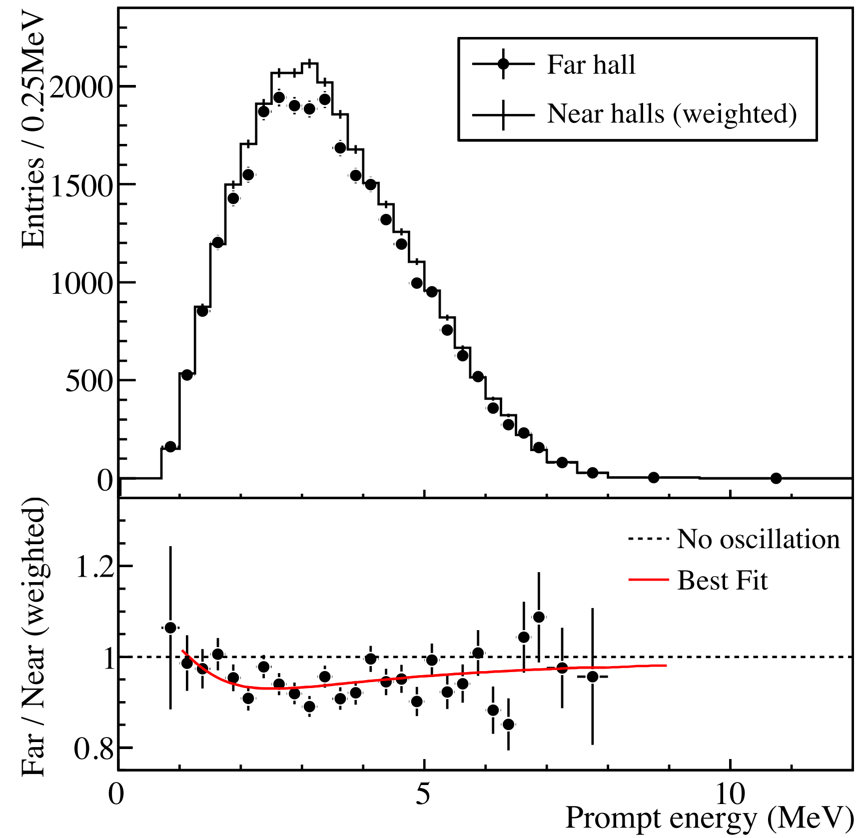


Spectral distortion consistent with expected oscillation from rate analysis*

(* Caveat: Spectral systematics not yet fully studied)

Rate Deficit & Near/Far Ratio





Far vs. near relative measurement.
Absolute rate is not constrained.

$\sin^2 2\theta_{13}$ =
0.089 ± 0.010 (stat) ± 0.005 (syst)

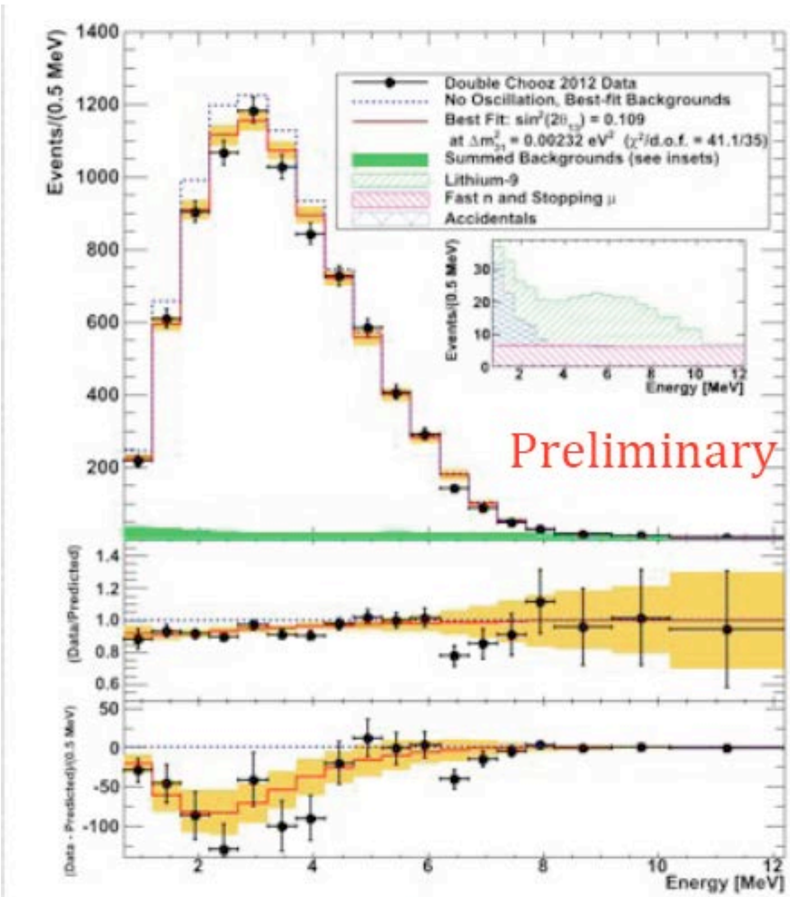
Most precise measurement of $\sin^2 2\theta_{13}$ to date.

Next
- shape analysis for oscillation (θ_{13},Δm_{13}^2)
- spectral shape vs reactor prediction
- absolute flux normalization

stay tuned!

Other Reactor Experiments

Double Chooz

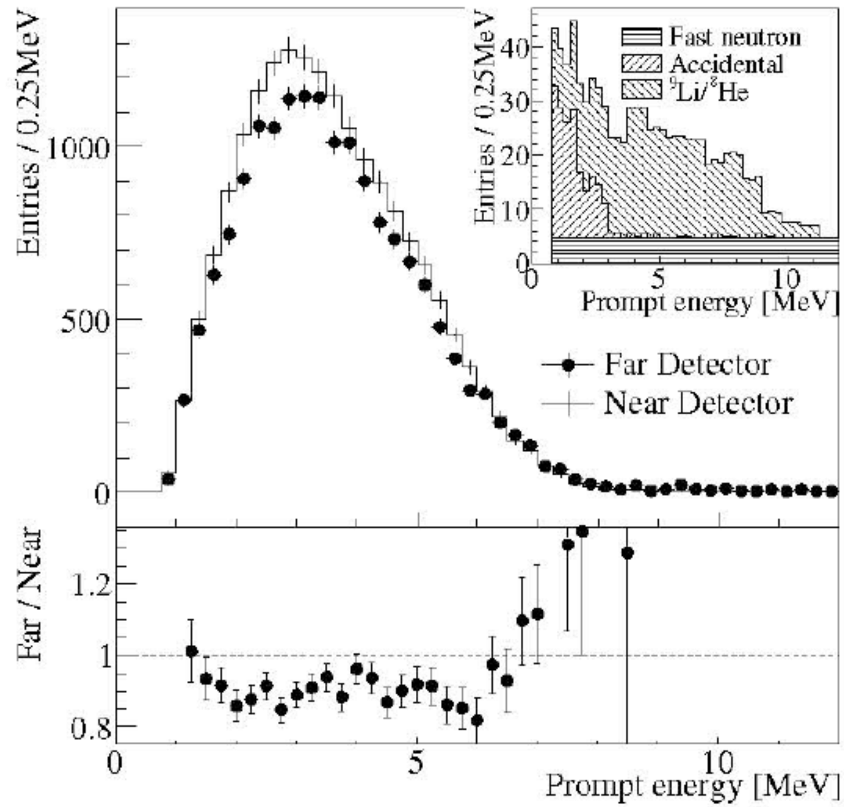


Rate only: $\sin^2 2\theta_{13} = 0.170 \pm 0.035(\text{stat}) \pm 0.040(\text{syst})$

Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$

Ref: Ishitsuka, Neutrino2012

RENO



$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$$

PRL, 108 (2012) 191802

Global θ_{13} Measurements

2011/2012 -The year of θ_{13}

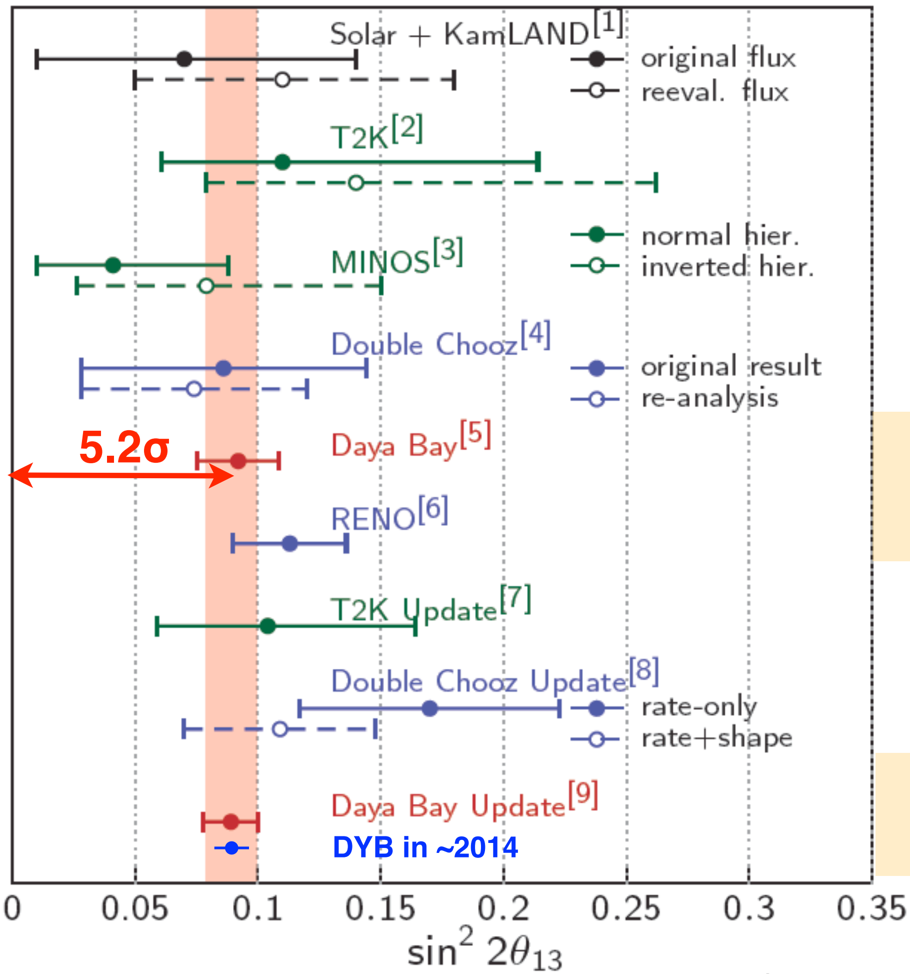


Fig adapted from S.Jetter

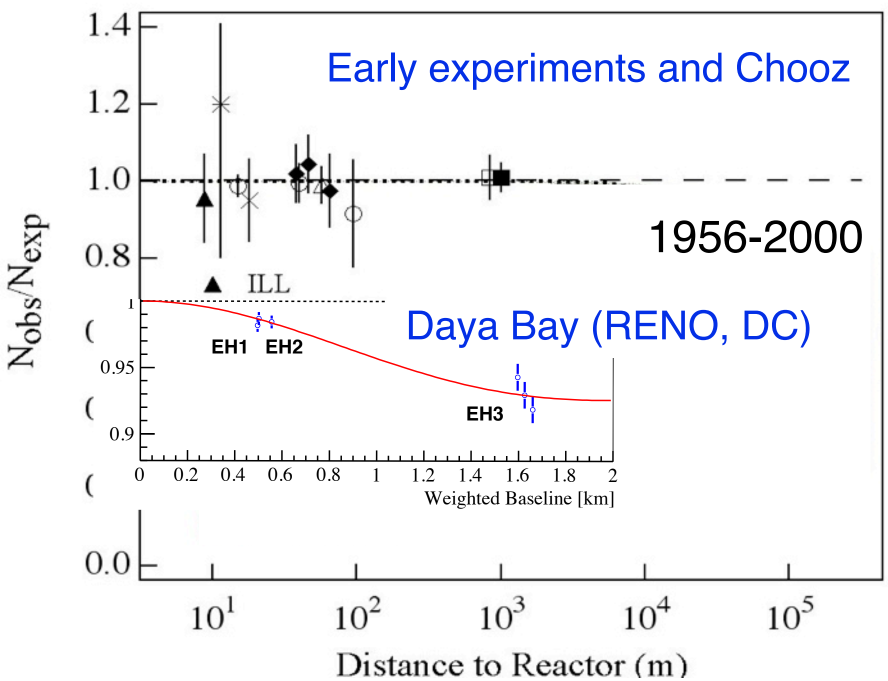
2011 - Early indications of

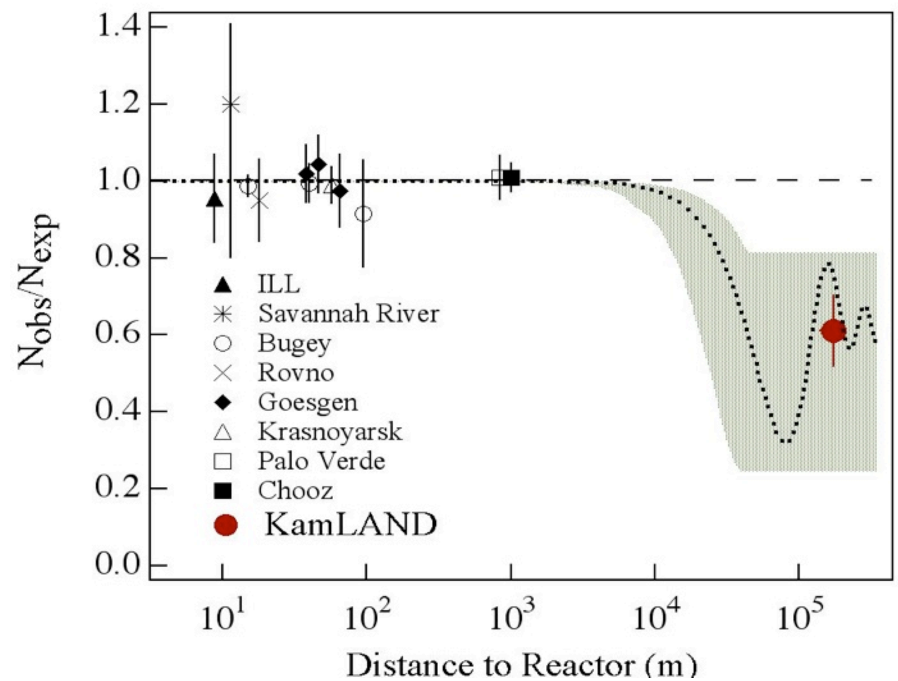
2012 Mar - Daya Bay observes non-zero θ_{13}
2012 Apr - Reno confirms

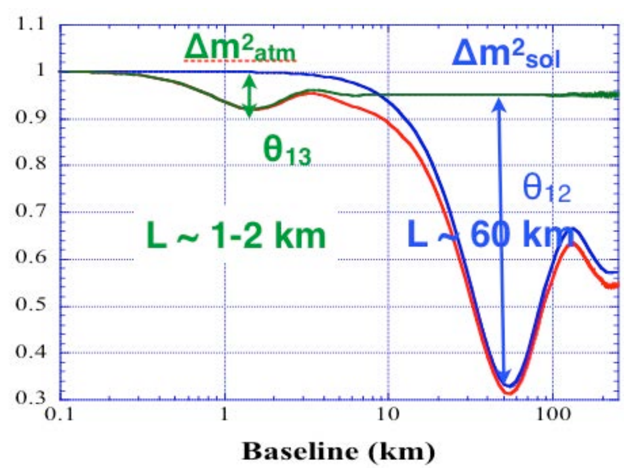
2012 Jun - Updates at Neutrino2012

With ~3 years of Daya Bay running, reduce uncertainty from ~10% to ~4%.

Reactor Oscillation Measurements





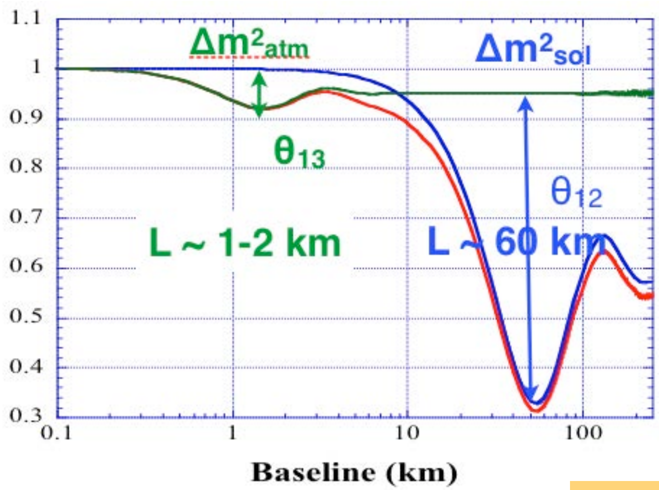


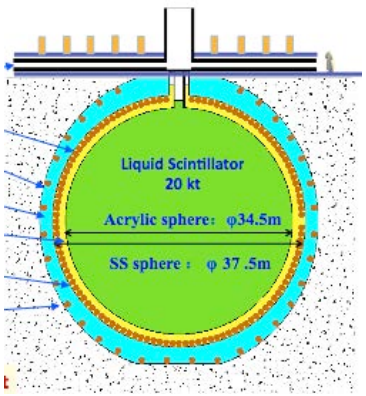
Mass Hierarchy and θ_{12}

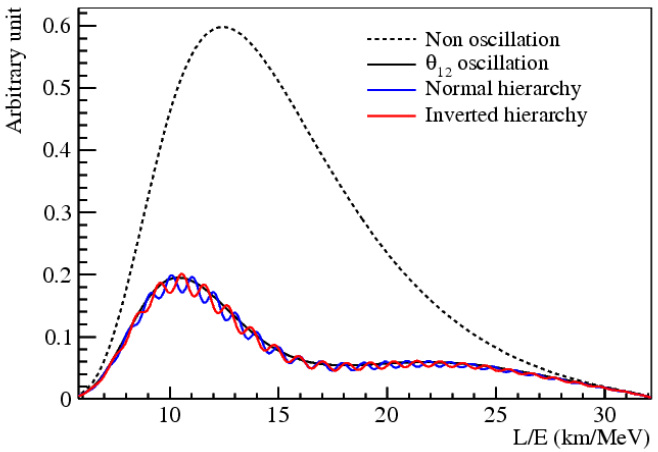
Future (proposed experiments and R&D)

Determining Mass Hierarchy with Reactor Antineutrinos

Daya Bay II (and RENO 50km)

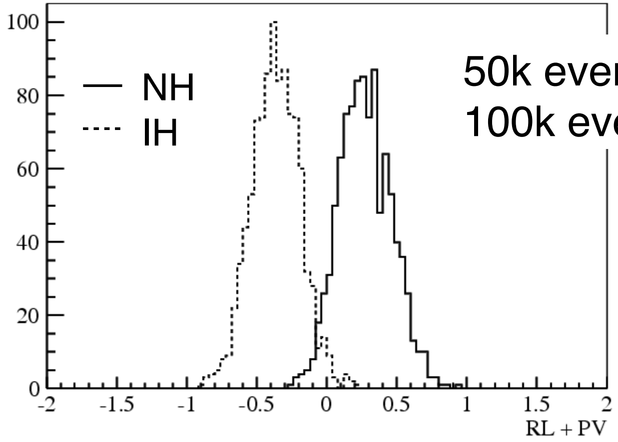






Daya Bay II
proposed

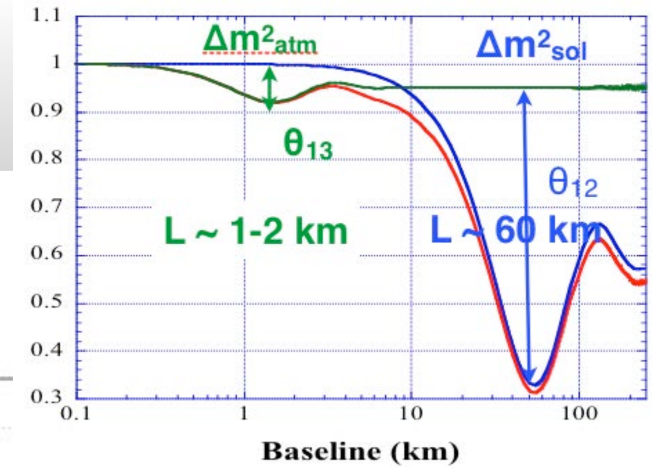
Daya Bay II R&D from 2012-2015
Construction start ~ 2015/16?

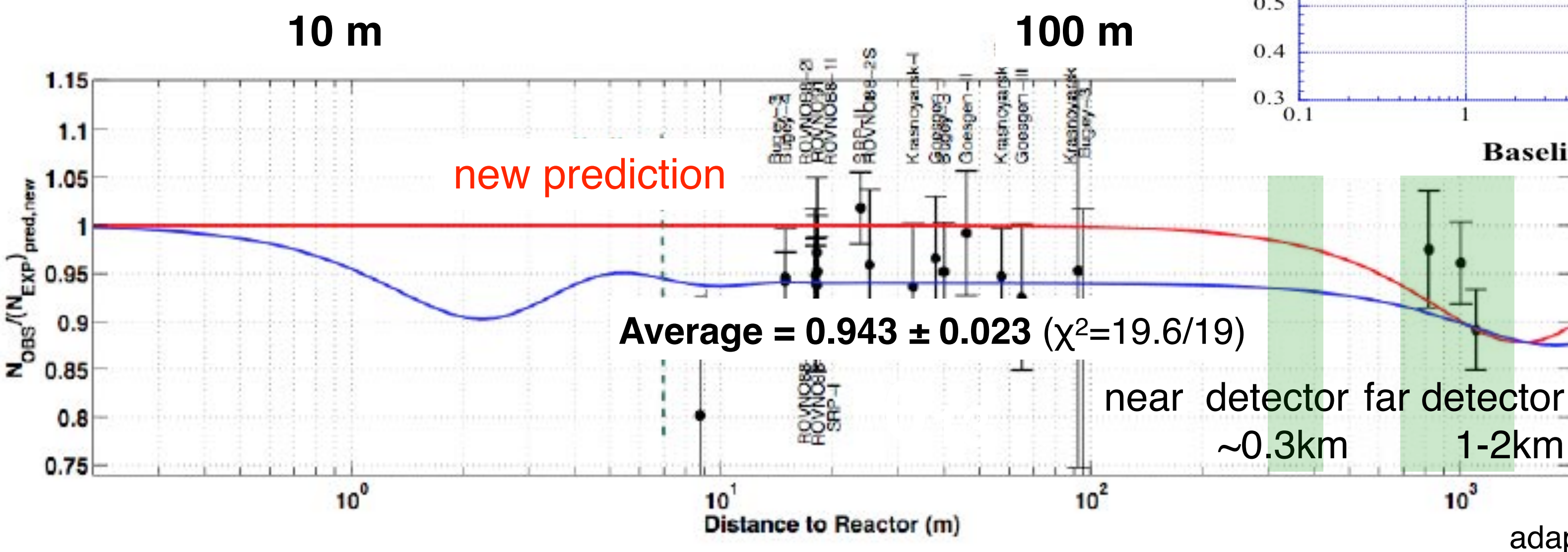


50k events, 3 years → 96%
100k events → 3σ

Reactor Anomaly
and Sterile Neutrino Hypothesis

Beyond 3-ν Mixing with Reactor ν





adapted from Schwetz
Neutrino2012

2011 $\overline{\nu}_e$ flux predictions
- new reactor antineutrino spectra
- re-analysis of 19 short-baseline reactor results
- neutron lifetime correction, off-equilibrium effects

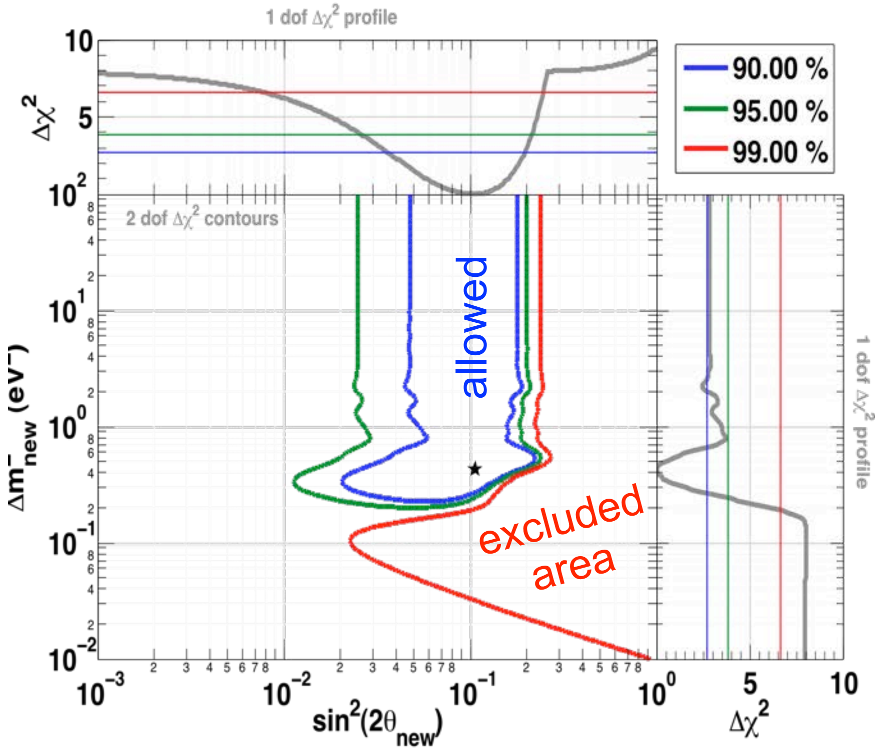
net 3% upward shift in energy averaged fluxes

deficit from flux normalization problem or from additional oscillation at L~O(1-10m)?

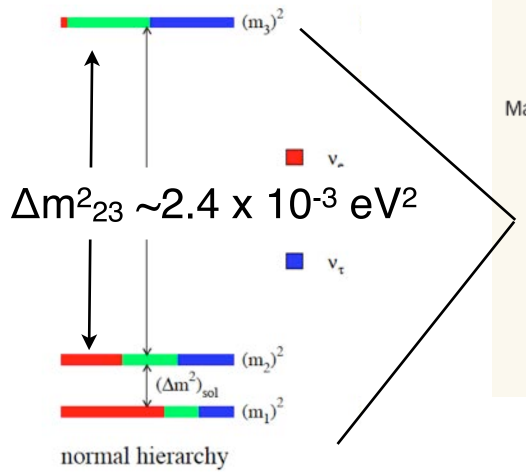
nuclear physics or new physics?

Sterile Neutrino Hypothesis

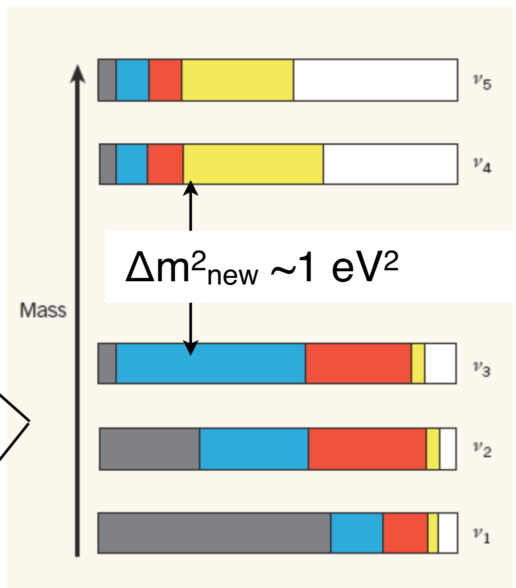
Combine all rate measurements, no spectral-shape information
Fit to anti-ν_e disappearance hypothesis



suggests extra neutrino state with
$\Delta m^2 \sim 1$ eV^2



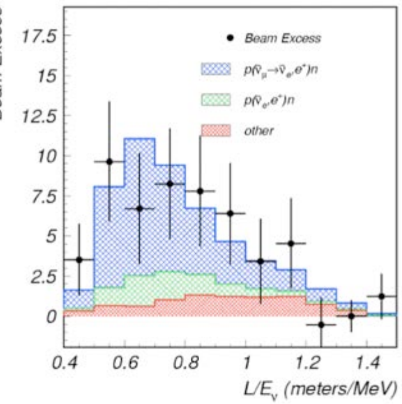
3 ν states



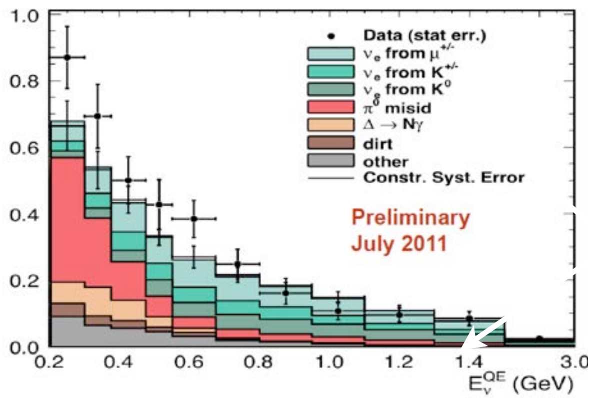
3+? ν states

Neutrino Anomalies & Sterile ν Hypothesis

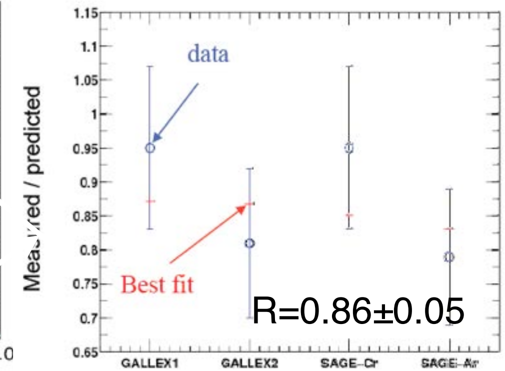
LSND



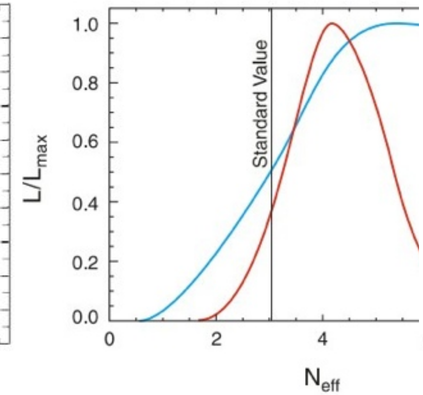
MiniBoone



Ga Anomaly



Cosmology (WMAP)



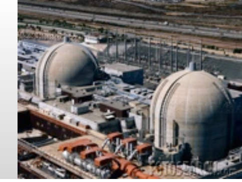
Anomalies in 3-ν interpretation of global neutrino oscillation data

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 $\Delta m^2 \sim O(1eV^2)$ and $\sin^2 2\theta > 10^{-3}$
➔ very short baseline oscillation for reactor ν, $L_{osc} \sim$ 2-10m

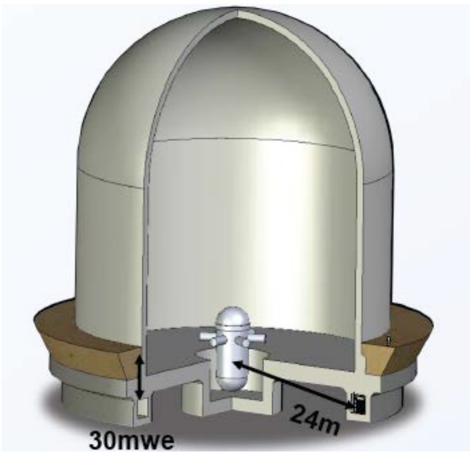
systematics or experimental effects?
➔ need to test each experimental effect

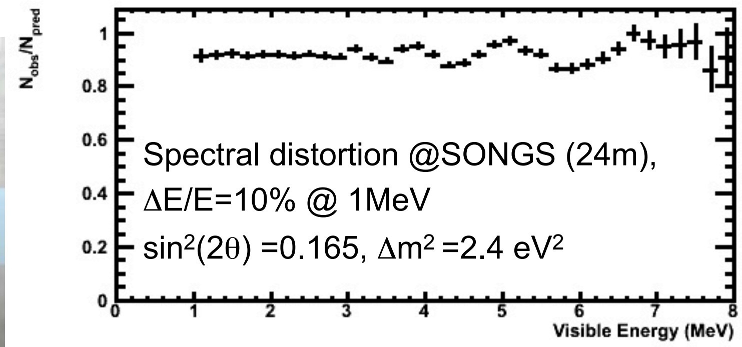
"Light sterile neutrinos: A white paper"
arXiv:1204.5379

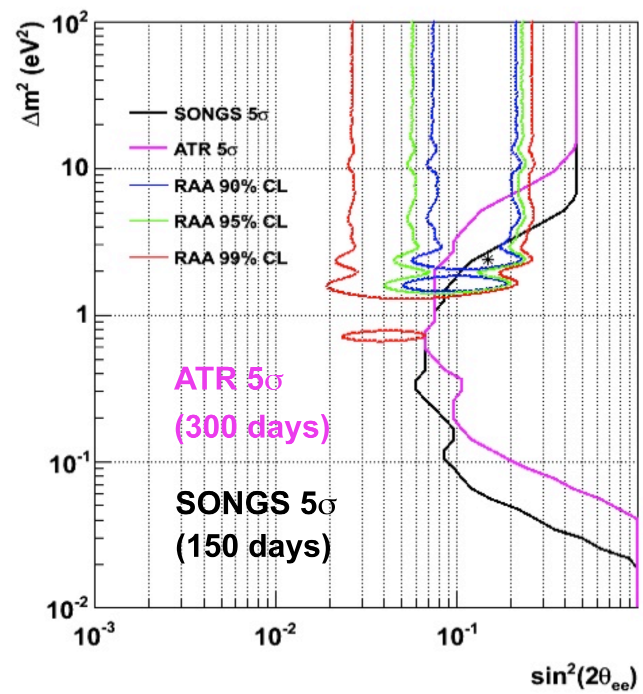


Reactor Monitoring Experiments for Sterile ν Searches

SCRAAM: Southern California Reactor Antineutrino Anomaly Monitor

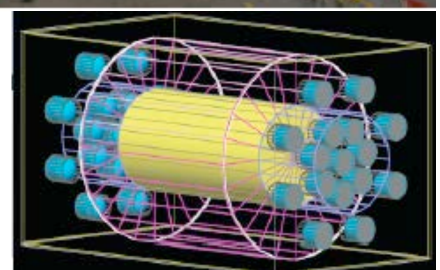




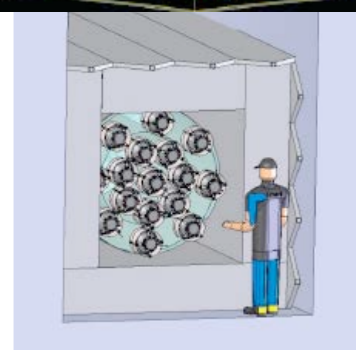


core ∅: ~3m,

fixed baseline: 24m



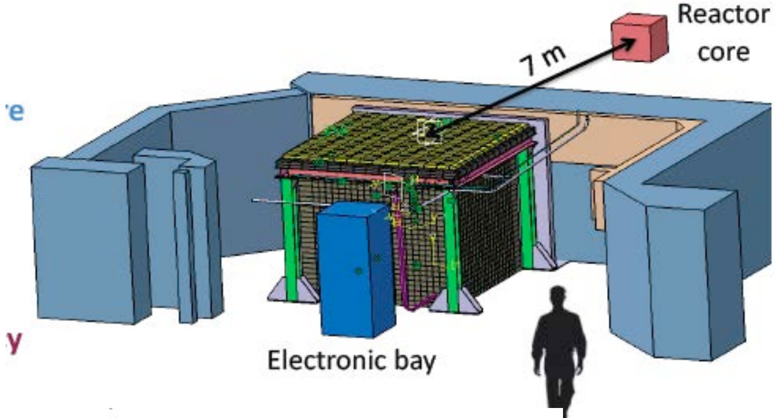
Adapt existing compact detector design/technology, limited by backgrounds

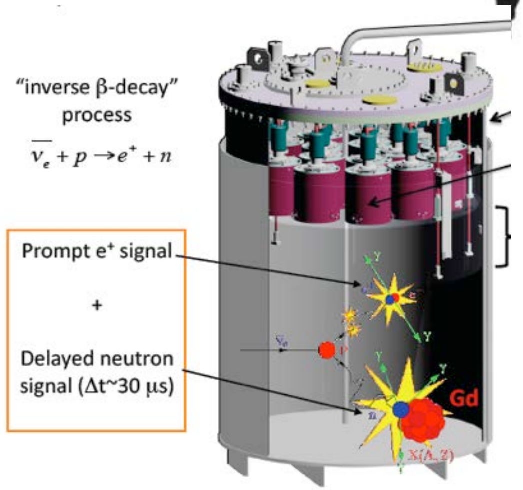


Limitations: Existing designs require overburden for background reduction – limits range of deployment sites, especially very close (<10m) to compact cores

Reactor Monitoring Experiments for Sterile ν Searches

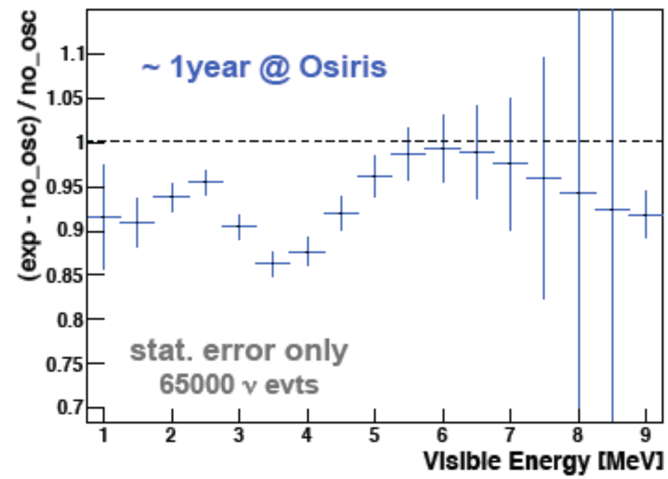
NUCIFER at Osiris

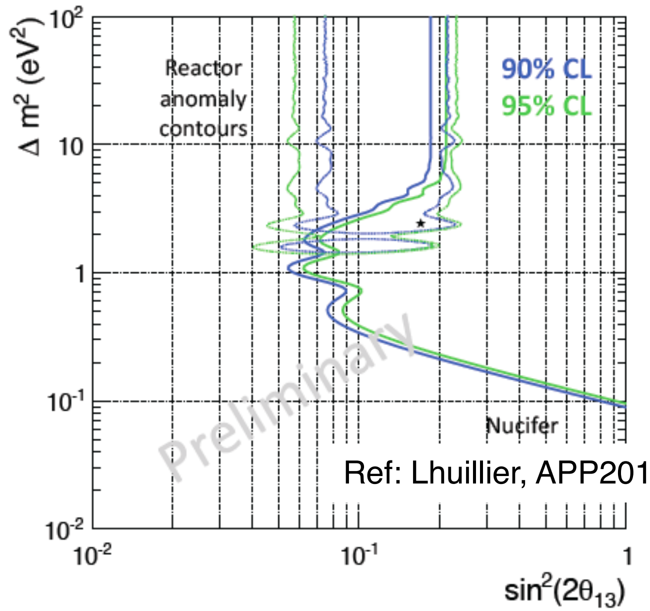




core: σ~0.3m
baseline: 7m

- 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

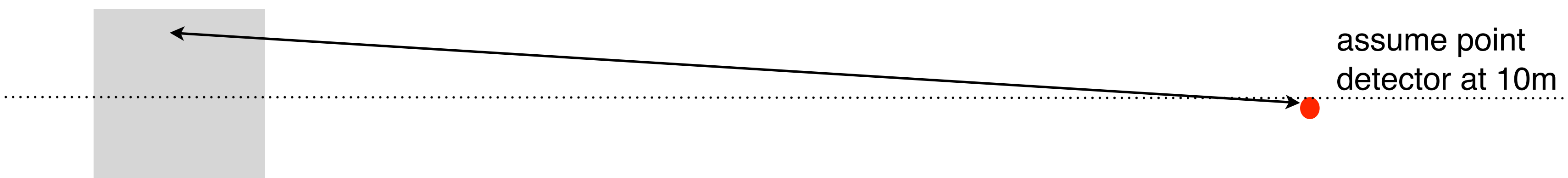
May be used to test reactor anomaly with compact core.
PSD R&D for background rejection.

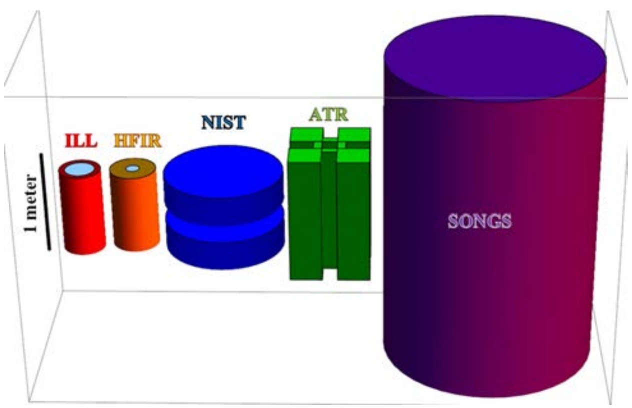
Towards an Optimized Short Baseline Experiment

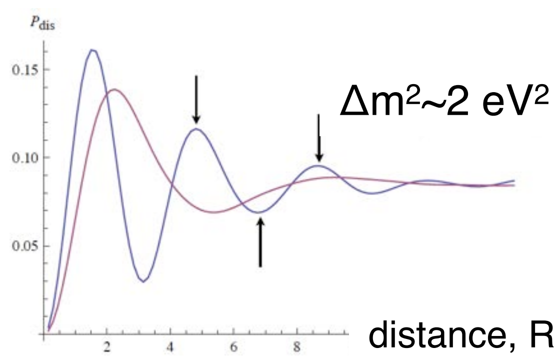
Some Experimental Issues

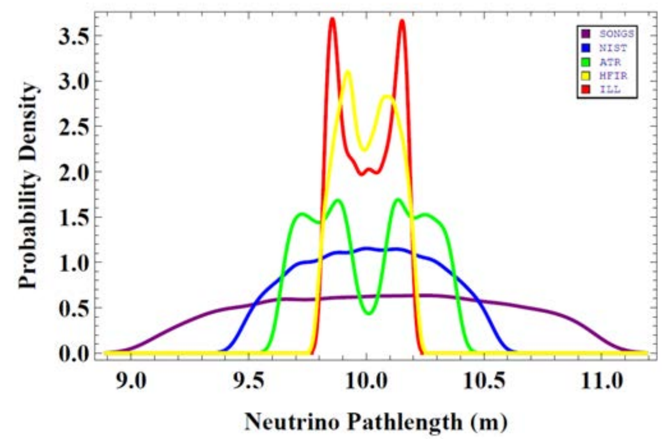
Reactor Core Size

Pathlength Spread
at detector from core

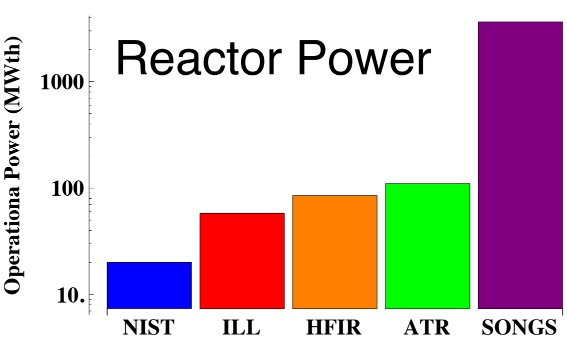








Tobin, Littlejohn, KMH



small core preferred to avoid washing out oscillation effect

antineutrino flux (event statistics) scales with reactor power

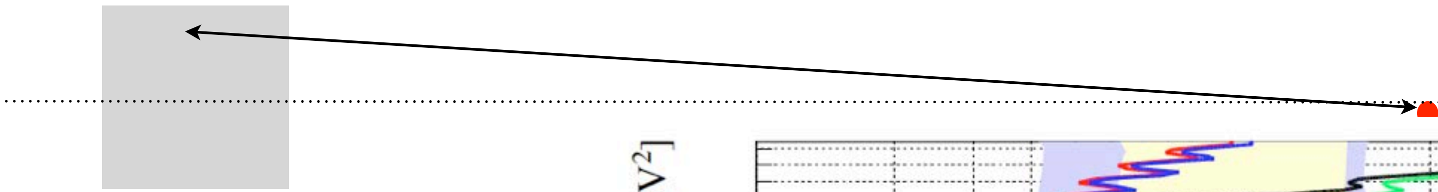
Towards an Optimized Short Baseline Experiment

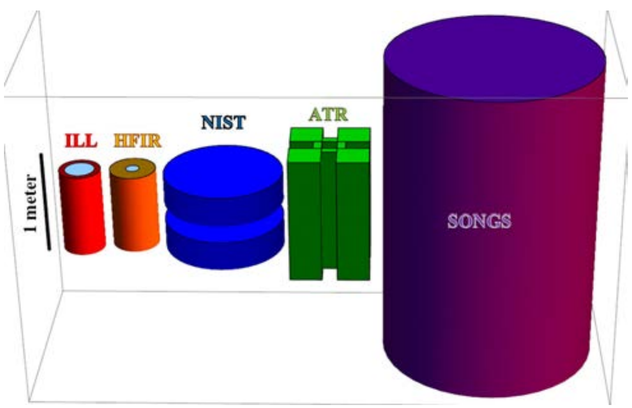
Some Experimental Issues

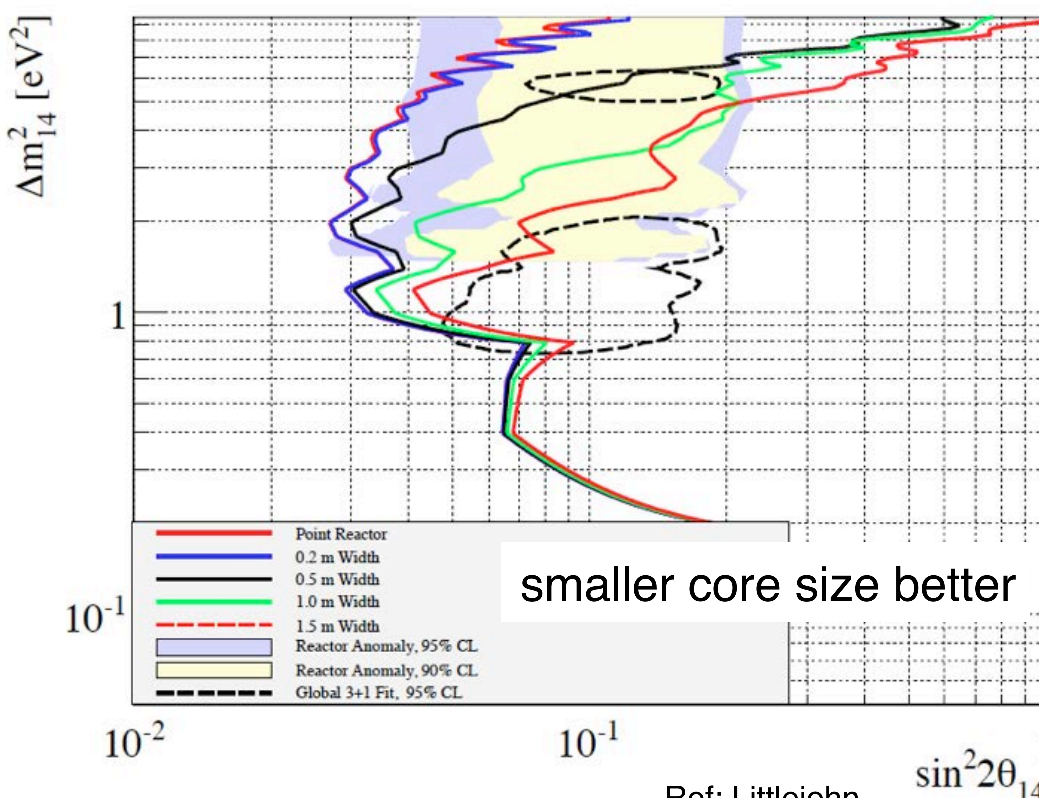
Reactor Core Size

Pathlength Spread
at detector from core

assume point detector at 10m







smaller core size better

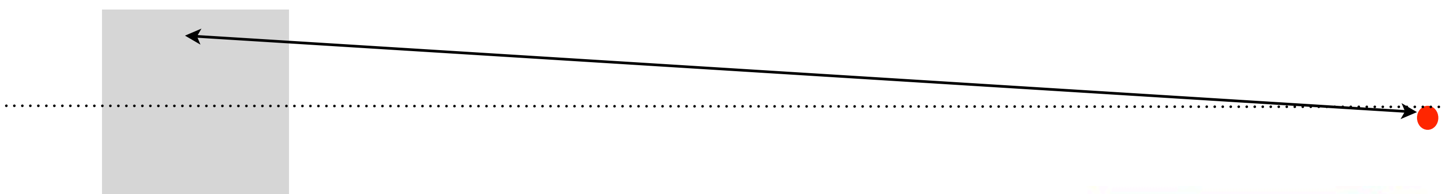
Ref: Littlejohn

Towards an Optimized Short Baseline Experiment

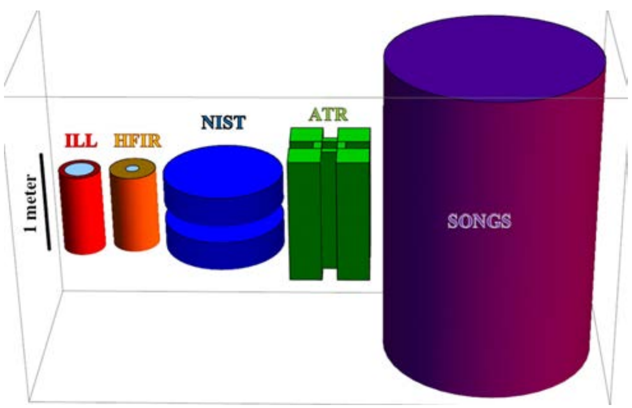
Some Experimental Issues

Reactor Core Size

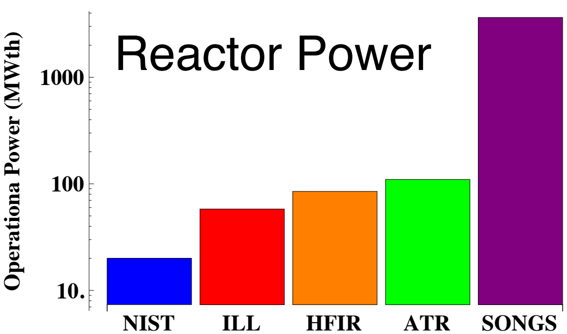
Pathlength Spread
at detector from core

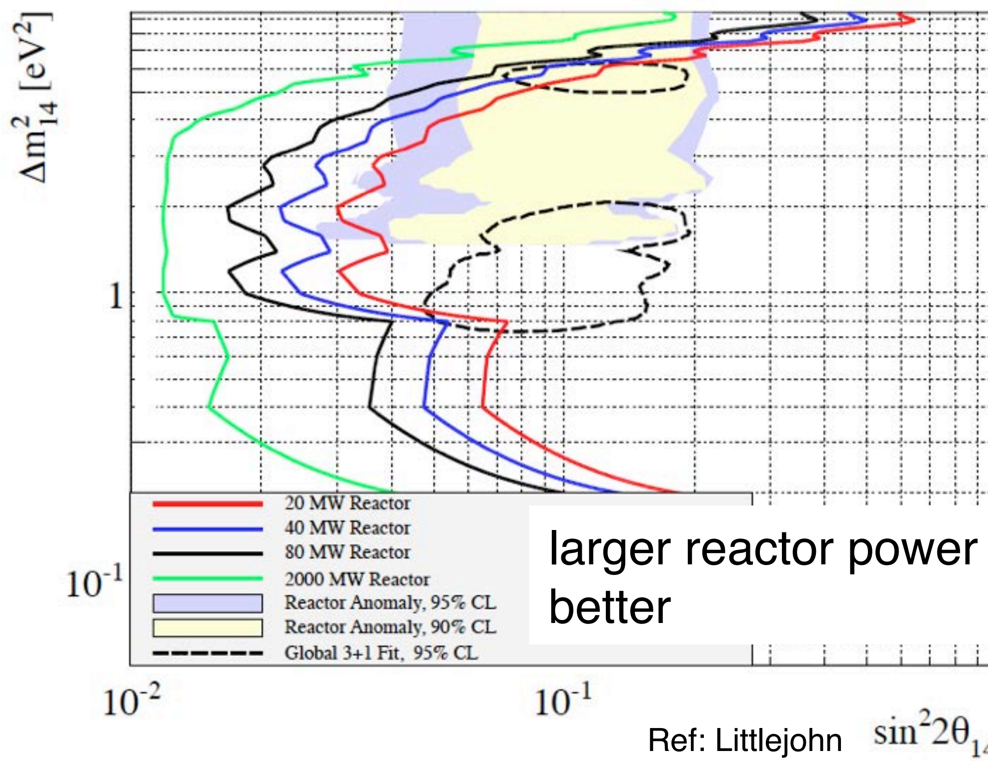


assume point
detector at 10m



Reactor Power





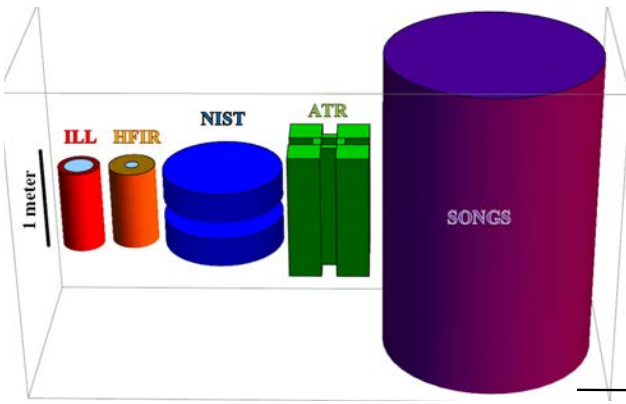
larger reactor power better

Ref: Littlejohn

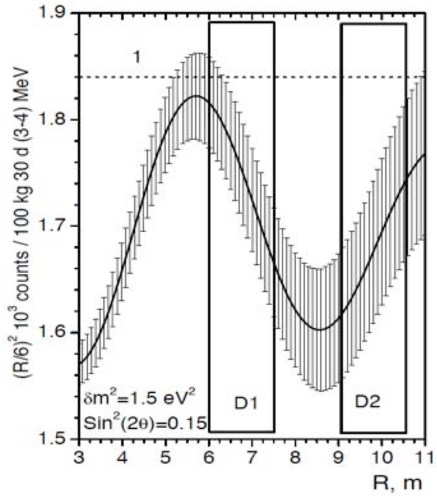
Towards an Optimized Short Baseline Experiment

Some Experimental Issues

Reactor Core



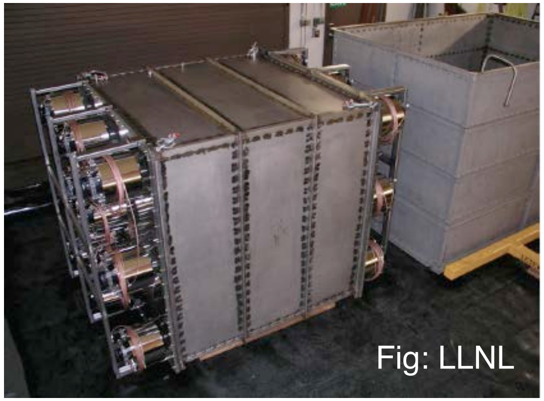
$\overline{\nu}_e$ Oscillation

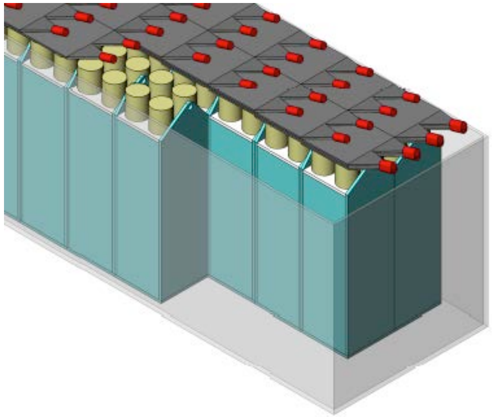


distance from core, R

Detector Technology

single volume





Mumm, KMH

segmented, extended detector

map out oscillation as a function of energy
- determine event energy

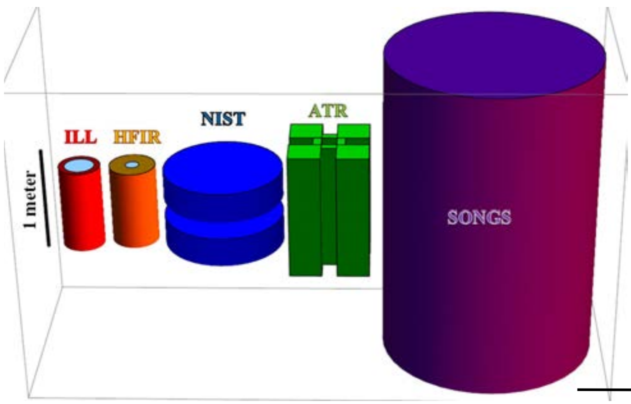
map out oscillation as a function of distance
- move detector
- event position reconstruction
- extended, segmented detector

background rejection
- passive shielding
- identify and localize (PSD?)

Towards an Optimized Short Baseline Experiment

Some Experimental Issues

Reactor Core



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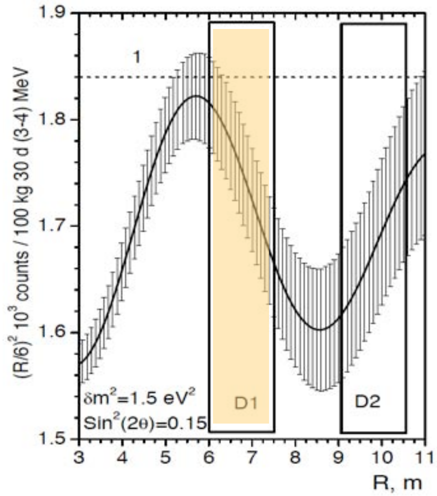

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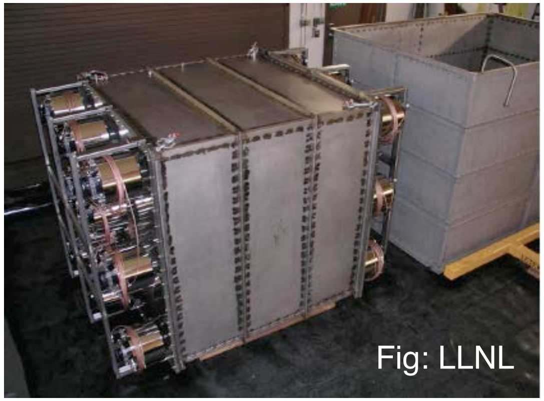

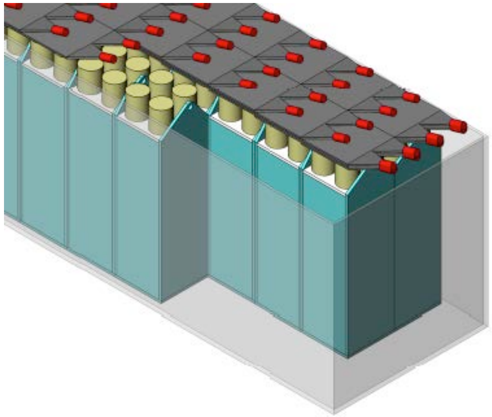

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Some Experimental Issues

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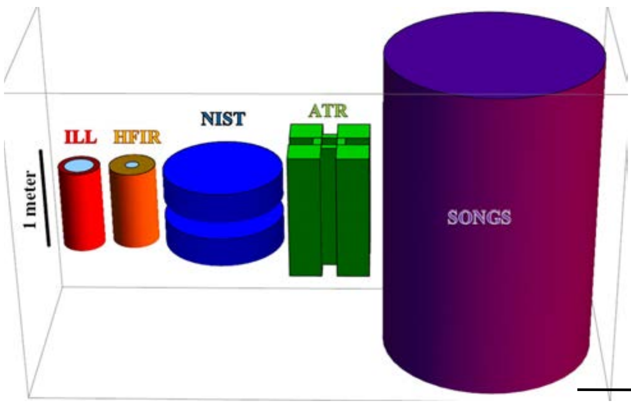

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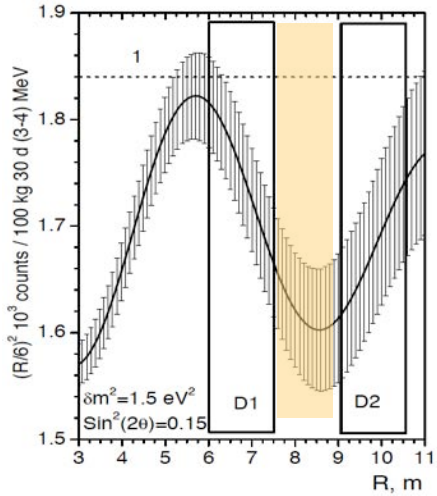

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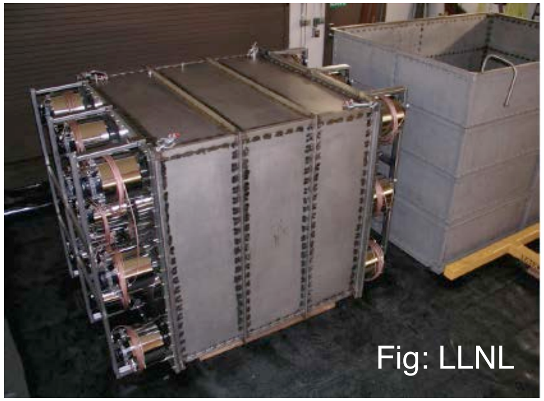

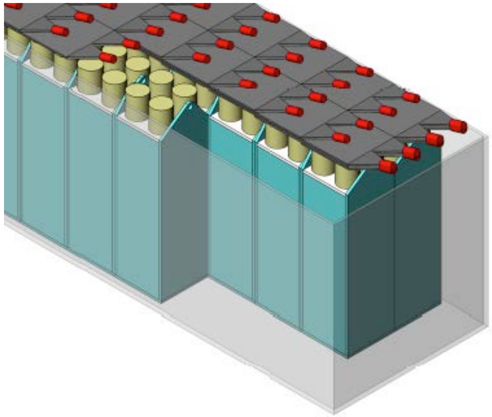

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Some Experimental Issues

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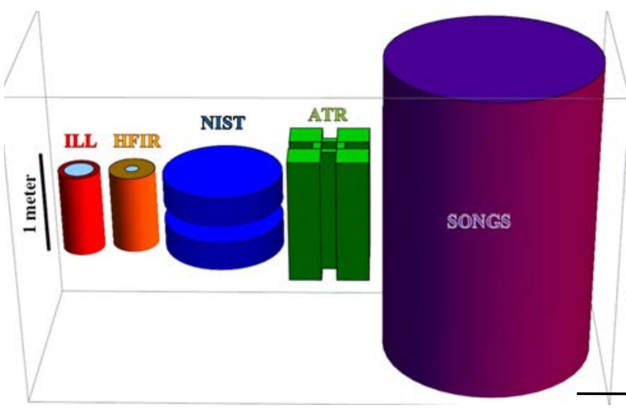

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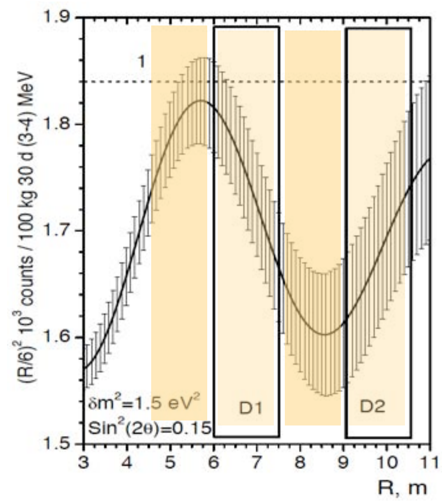

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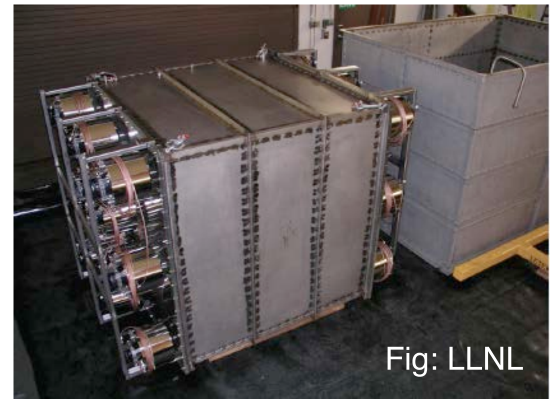

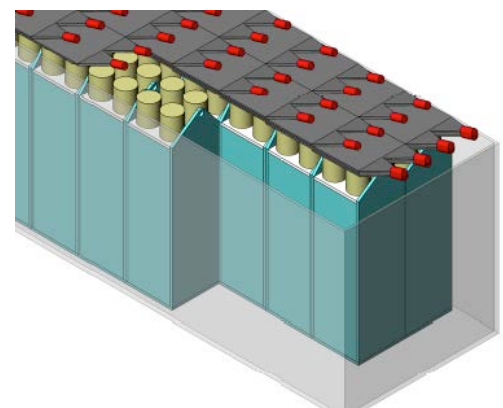

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Some Experimental Issues

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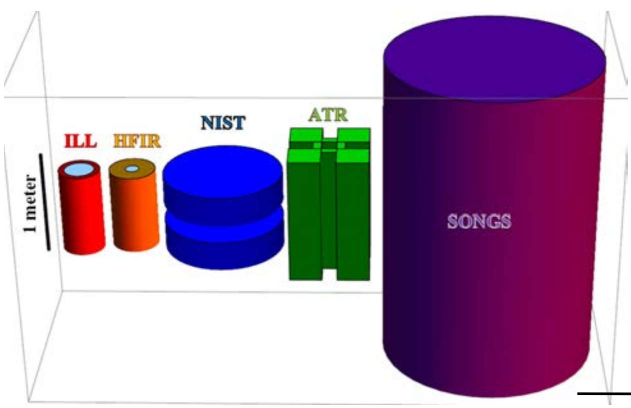

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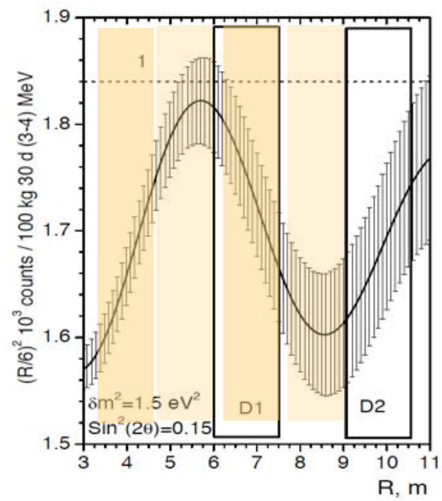

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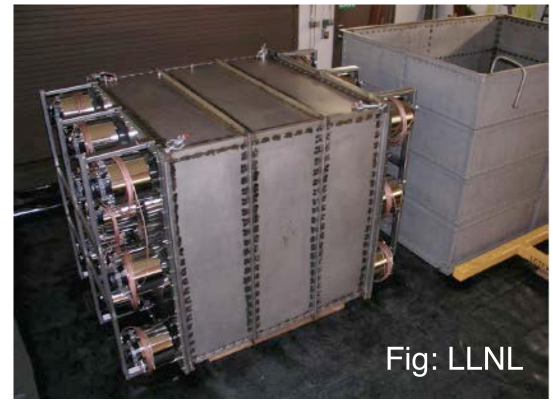

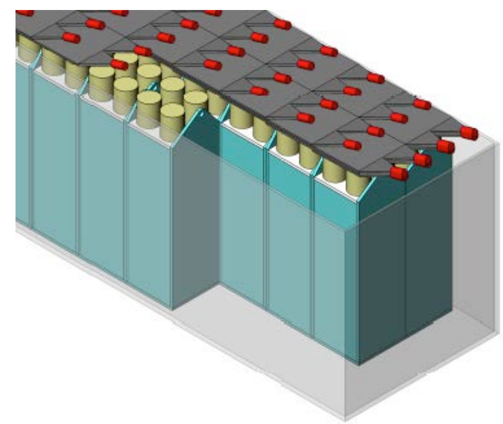

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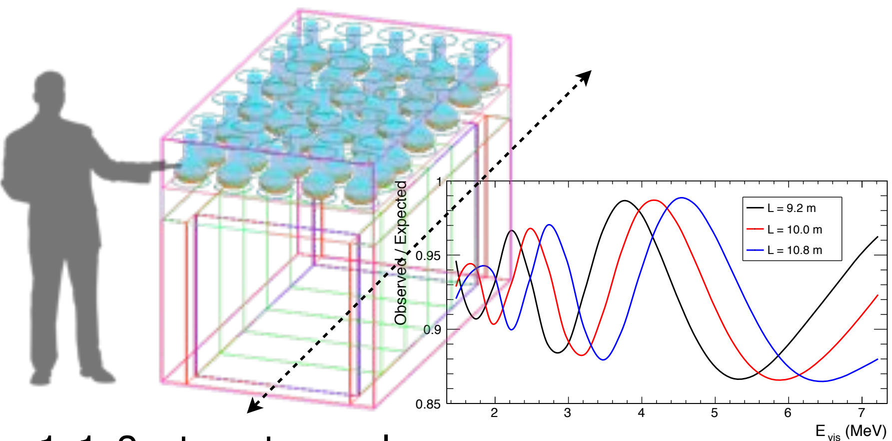
map out oscillation as a function of distance
- move detector
- event position reconstruction
- extended, segmented detector

background rejection
- passive shielding
- identify and localize (PSD?)

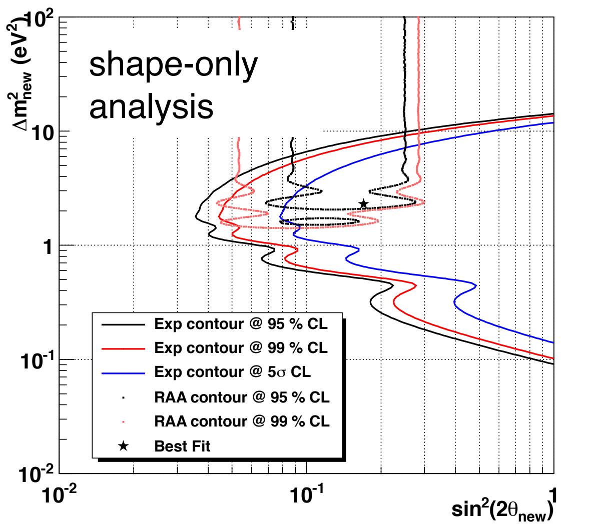
Worldwide Effort Towards Optimized Sterile ν Search

Stereo at ILL, France

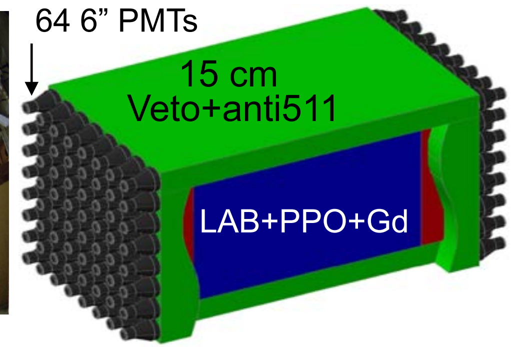


1x1x2m target vessel
filled with Gd-LS
5 baseline bins by foils

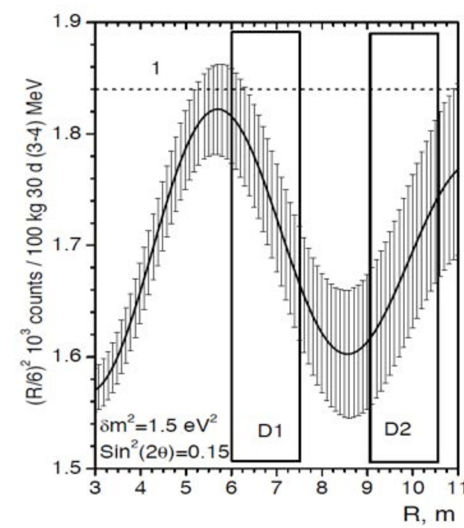
shift detector to verify
oscillation signal



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

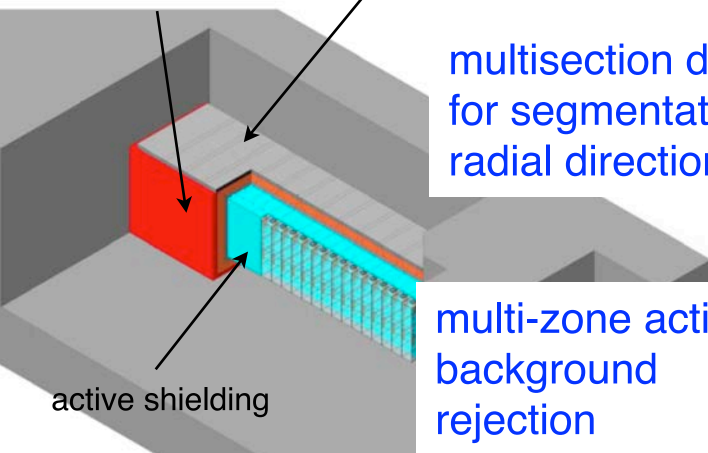


Energy and spatial resolution to measure oscillation curves for different E_ν

aim to detect oscillatory signature

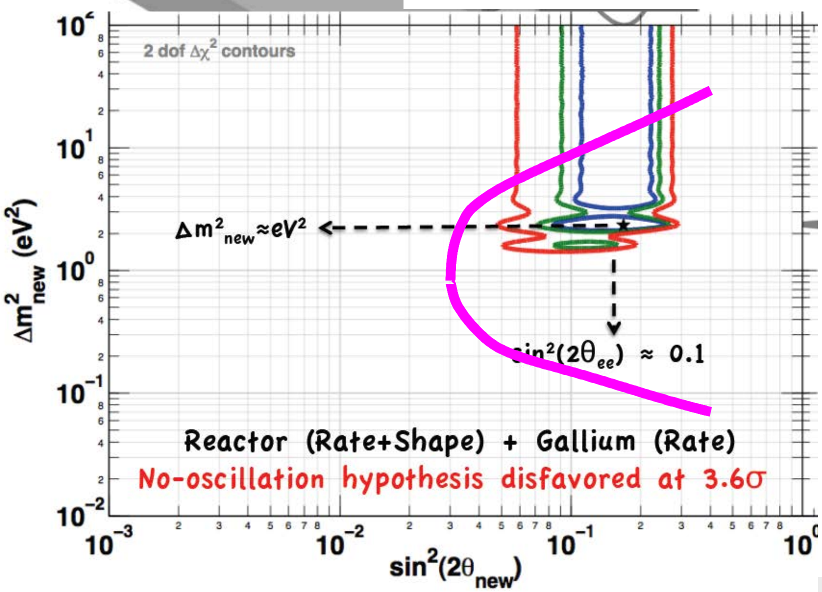
Worldwide Effort Towards Optimized Sterile ν Search

Neutrino4, Russia

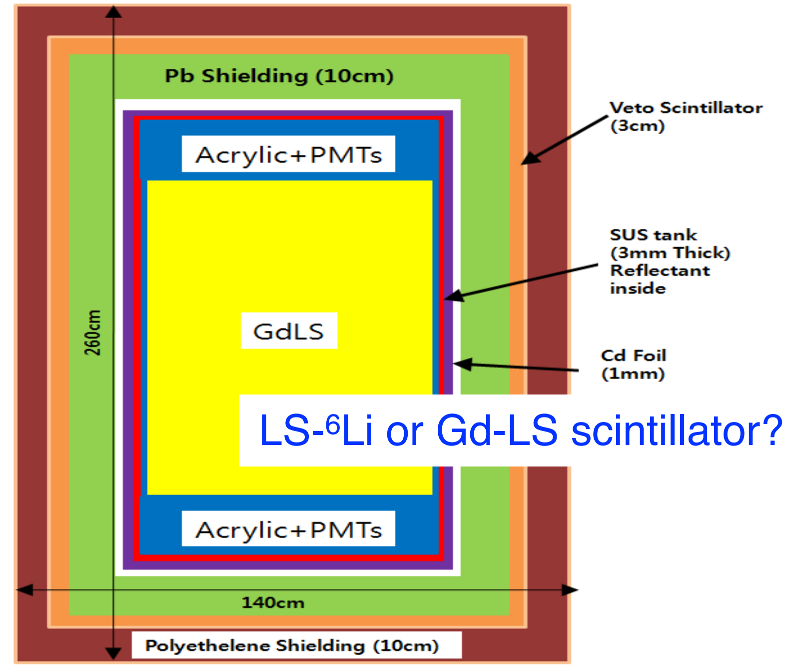


multisection detector for segmentation in radial direction

multi-zone active background rejection



Hanaro-SBL, Korea



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

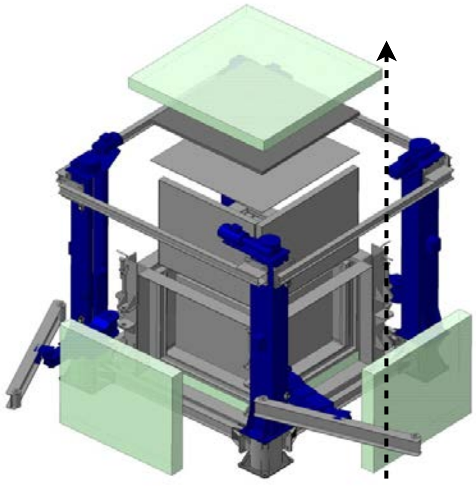
$$n + {}^{155}Gd \rightarrow {}^{156}Gd + 8MeV$$

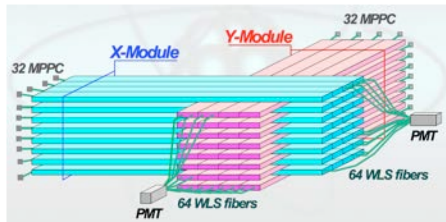
$$n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.8MeV$$

- 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

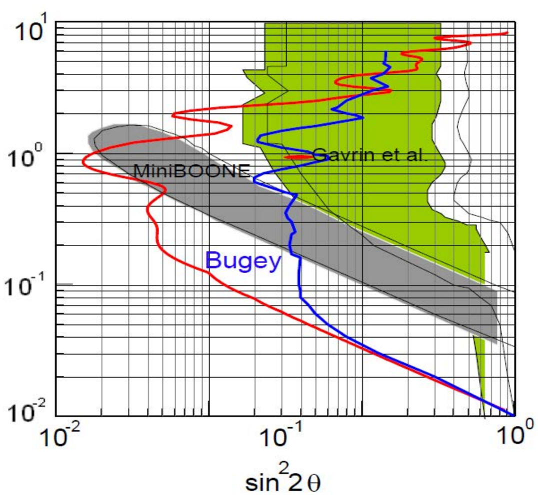
DANSS, Russia



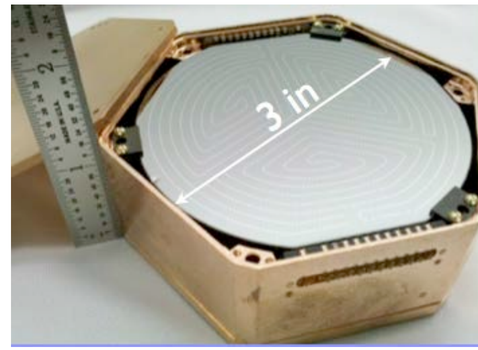


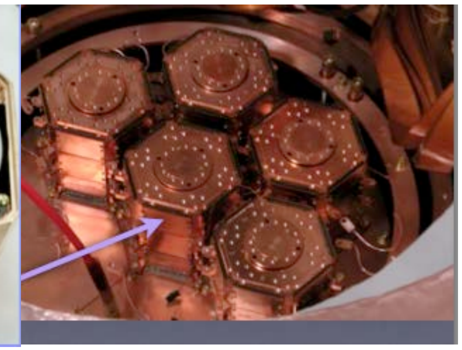
movable distance

also used for neutrino magnetic moment searches with Ge detectors

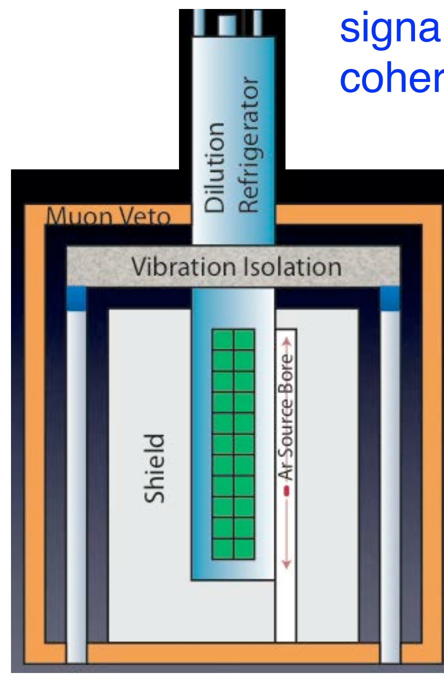


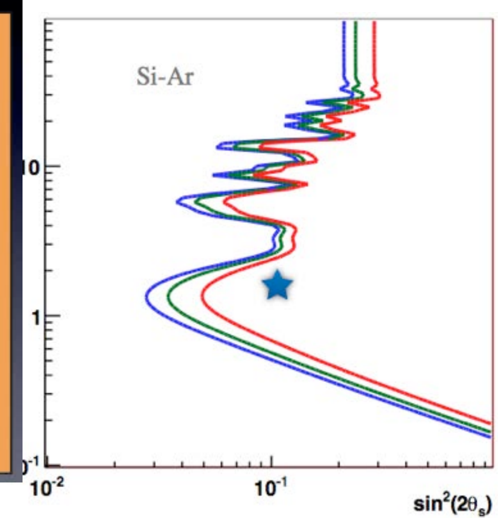
Ricochet, USA





signal detection through coherent scattering





Experiments with Antineutrino Sources

Sterile ν Searches with Very Short Baselines: Sources

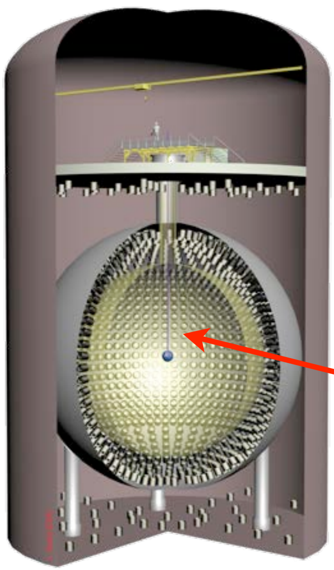
Alternative Approach: Place source near or inside detector and search for ν_e or $\bar{\nu}_e$ disappearance.

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

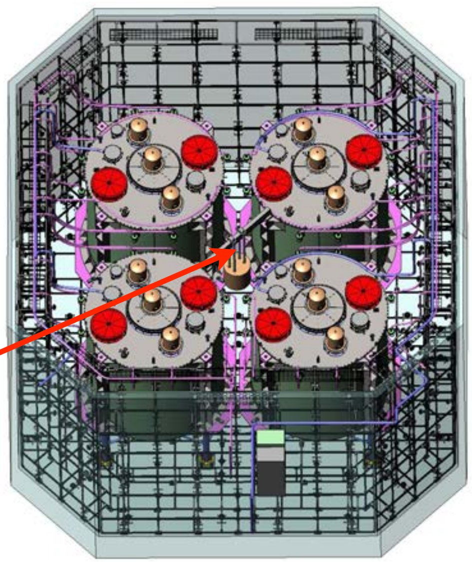
e.g. Ce-LAND



source next to detector

e.g. Daya Bay

source

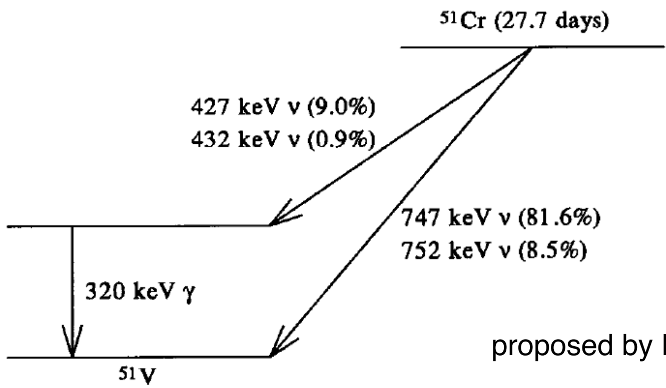


Sterile ν Searches with Very Short Baselines: Sources

A Variety of Sources and Detectors Are Feasible

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

e.g. ^{51}Cr, <u>mono-energetic</u>, ν_e, 750 keV

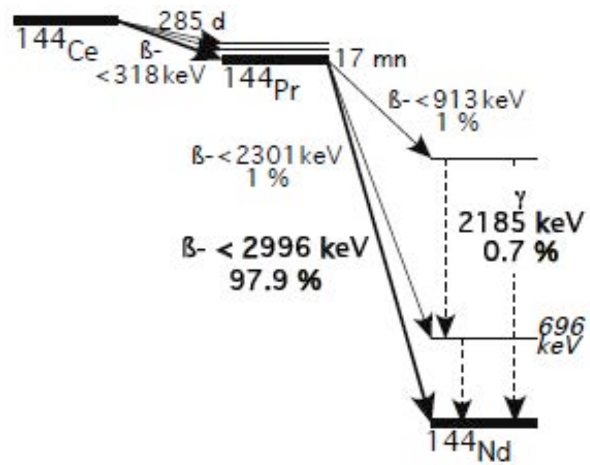


Decay scheme of ^{51}Cr to ^{51}V through electron capture.

proposed by Raghavan

Sources based on beta-decays

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



arxiv:1107.2335
Cribier et al

Detection Channels & Proposed Experiments

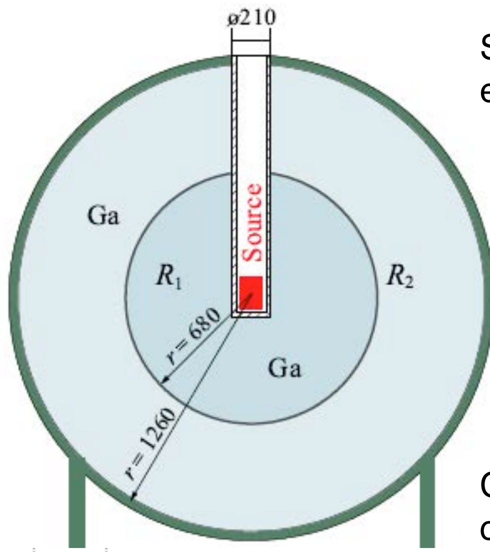
Elastic Scattering: Borexino, SNO+Cr
Charged Current: LENS-Sterile, Baksan, Ce-LAND, Borexino, Daya Bay
Neutral Current: RICOCHET

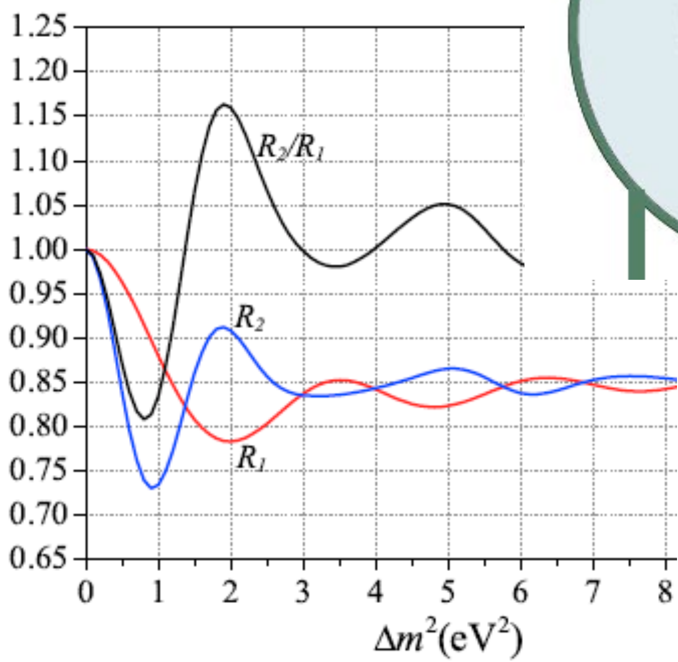
see following examples

Short Baseline Search with Ga Target

^{51}Cr Source inside Dual Metallic Ga Target

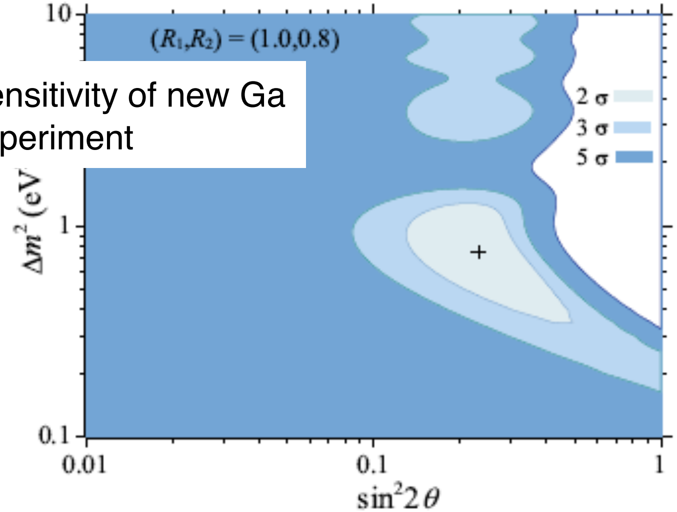
measure ratio of capture rates in R_1 and R_2



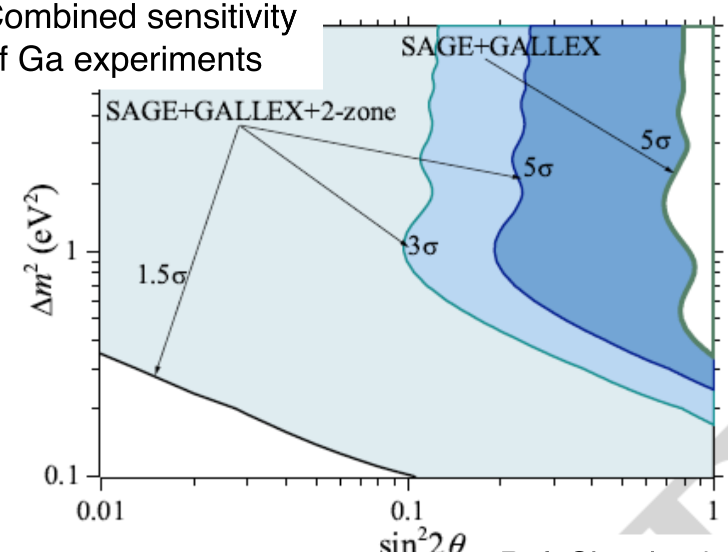


ratio of measured capture rates to predicted rate in inner and outer zones and their ratio R_2/R_1

Sensitivity of new Ga experiment

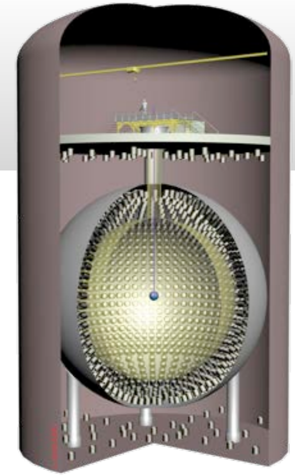


Combined sensitivity of Ga experiments

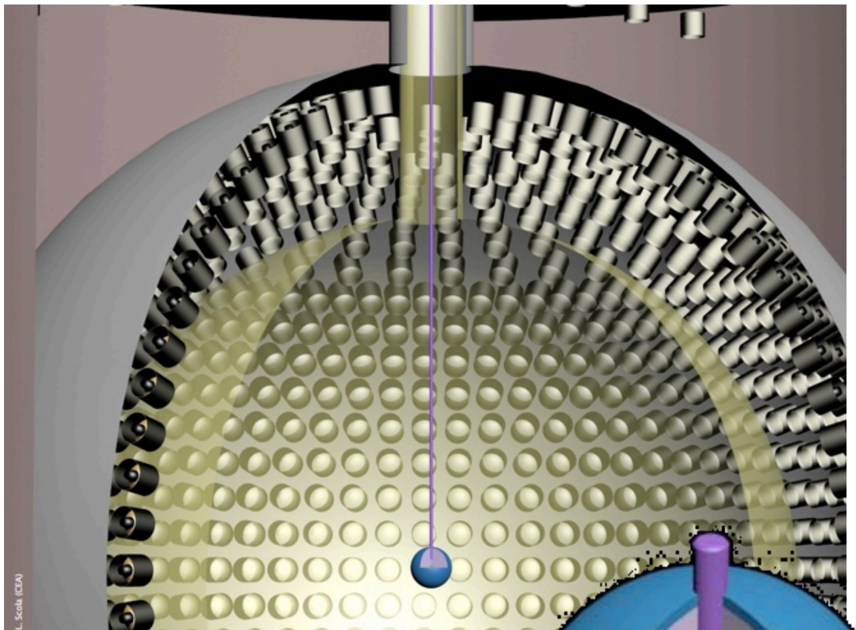


Ref: Cleveland et al.

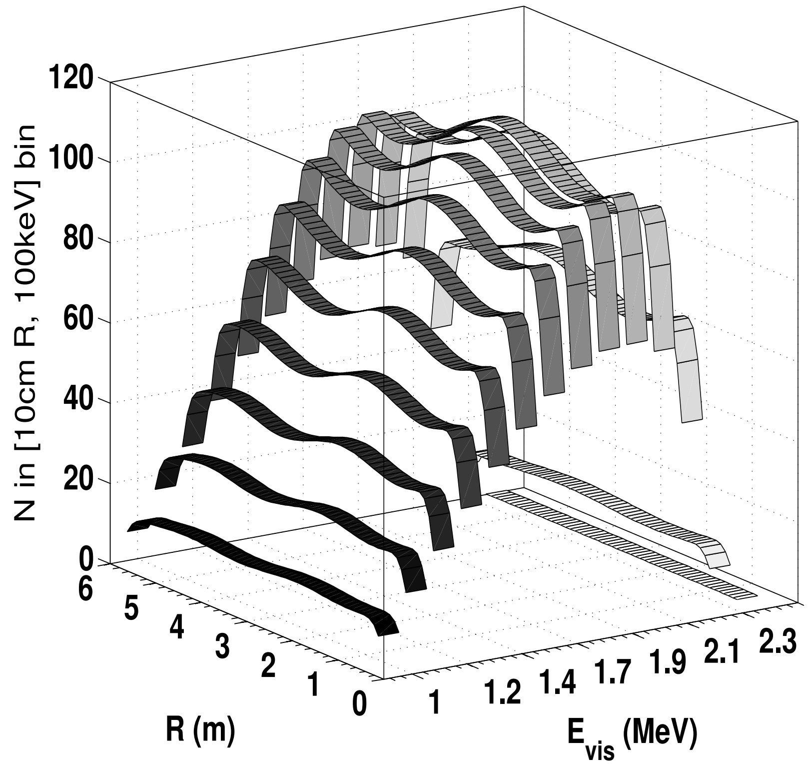
Ce-LAND



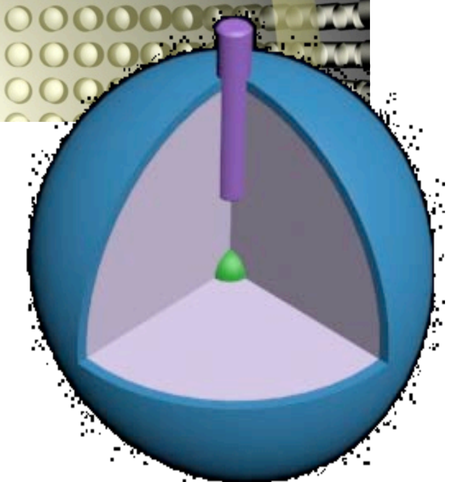
^{144}Ce source inside Liquid Scintillator Detector



map oscillation effect in R and E



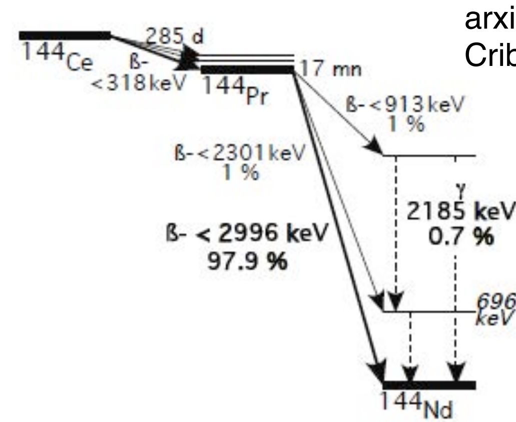
Holder & cold finger
R=8cm, 1.5 kg of Ce
R=37 cm, Tungsten
mass= 5 tons,
diameter 82 cm
teflon coating?



Ref: Lasserre

Daya Bay Sterile Neutrino Search

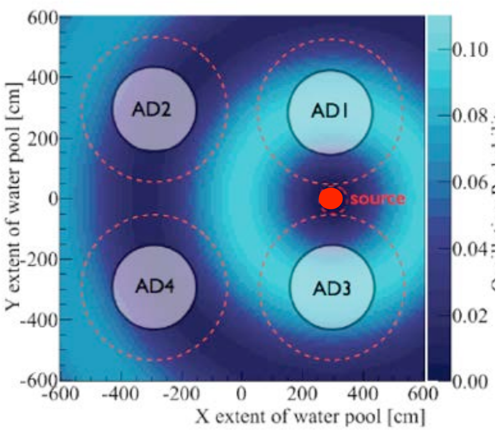
^{144}Ce source in Daya Bay Far Hall

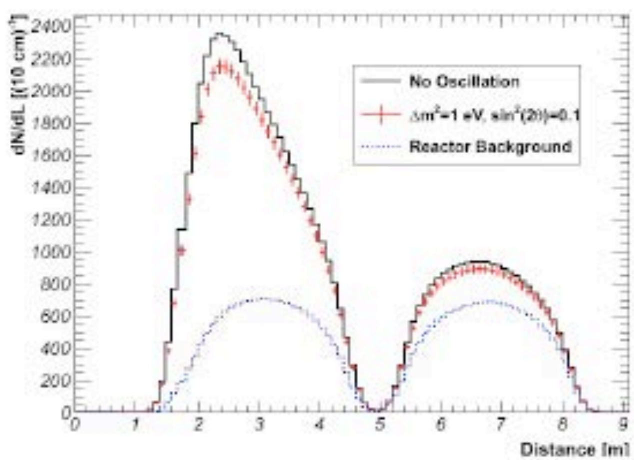


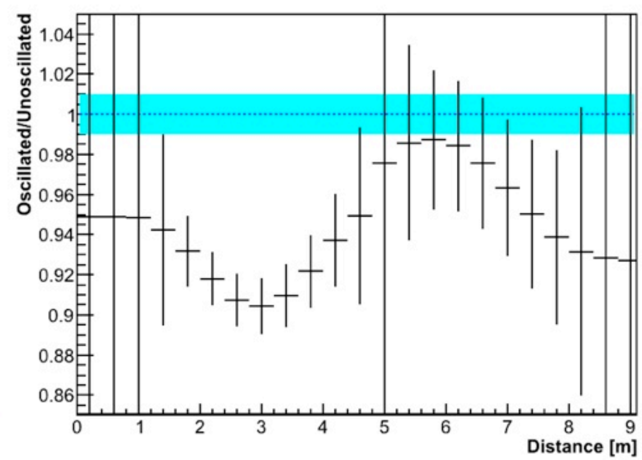
arxiv:1107.2335
Cribier et al

^{144}Ce-^{144}Pr Antineutrino Source

- Q_β> 1.8 MeV (IBD threshold)
- lifetime long enough to allow for production and transport
- $T_{1/2}$ (^{144}Ce)=285 days, $T_{1/2}$ (^{144}Pr)=17.3 min
- contained in fission fragments of spent nuclear fuel



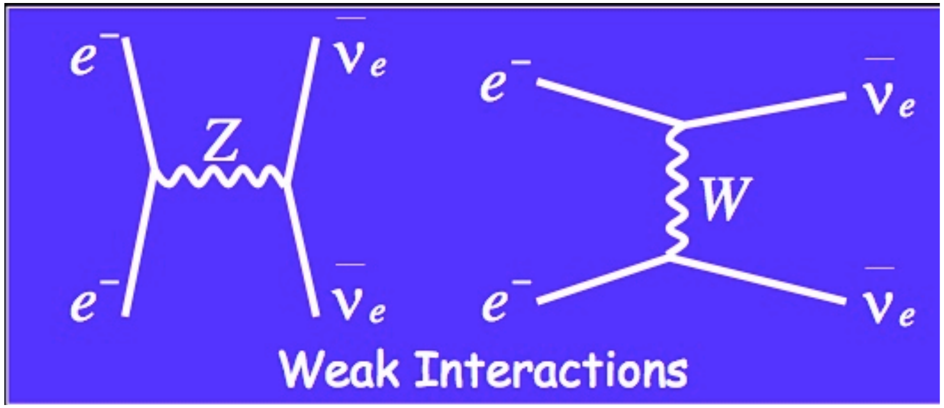


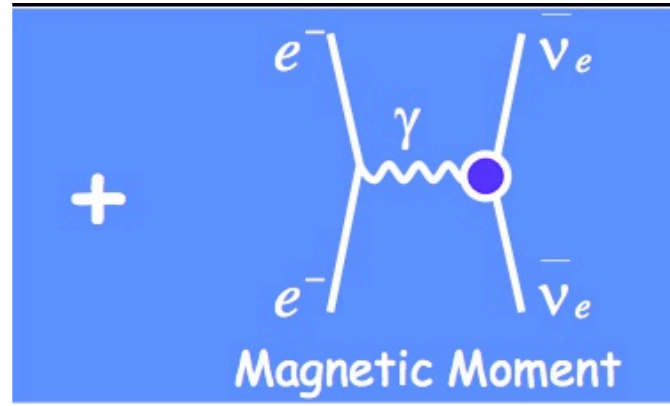


arXiv:1109.6036
Dwyer, Littlejohn, Vogel, KMH

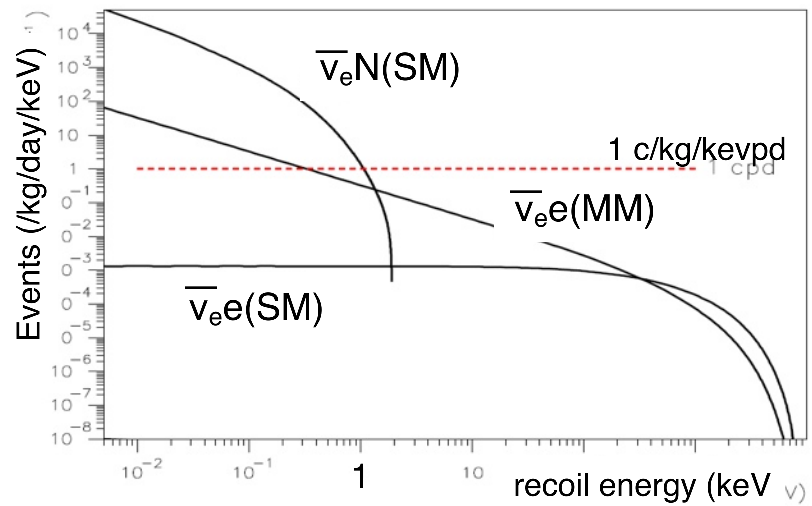
Scattering Experiments with Reactor Antineutrinos

Neutrino Magnetic Moment Searches





$$\frac{d\sigma}{dT_e} = weak\,\mathrm{int} + \frac{\pi\alpha^2\mu_\nu^{\ 2}}{m_e^{\ 2}}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$

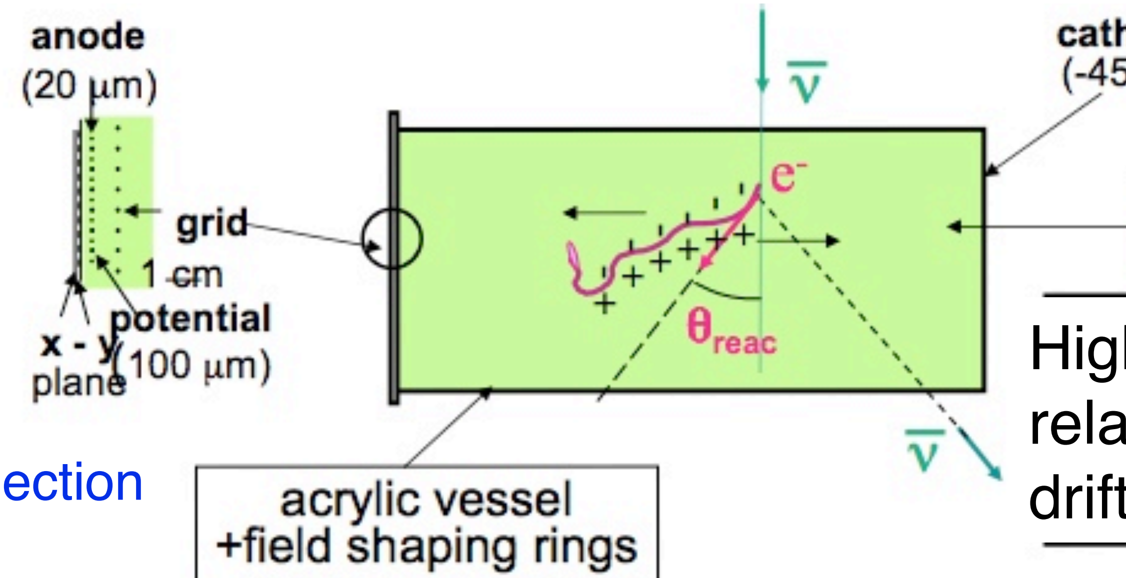


Reactor Experiments

UC Irvine	$\mu_\nu^{reac} < 2\text{-}4 \times 10^{-10}\ \mu_B$
Kurchatov	$\mu_\nu^{reac} < 2.4 \times 10^{-10}\ \mu_B$
Rovno	$\mu_\nu^{reac} < 1.9 \times 10^{-10}\ \mu_B$
MUNU	$\mu_\nu^{reac} < 1.0 \times 10^{-10}\ \mu_B$

Scattering Studies with TPC

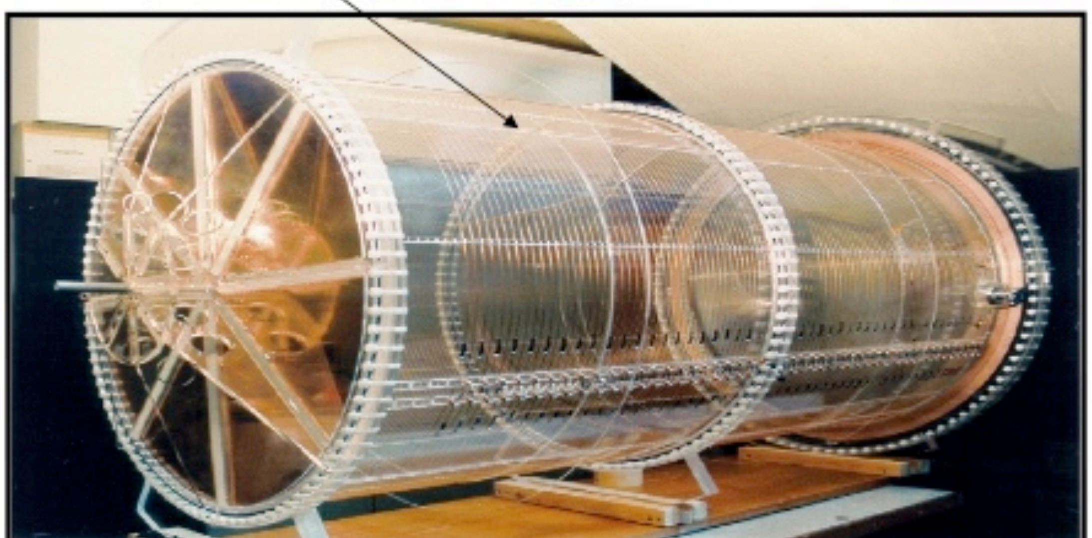
Experiment at Nuclear Reactors (low energy source of $\overline{\nu}_e$)



3bar CF_4 gas

High density, relatively low Z, good drifting properties

Time Projection Chamber



V=1 m^3

L=1.6 m

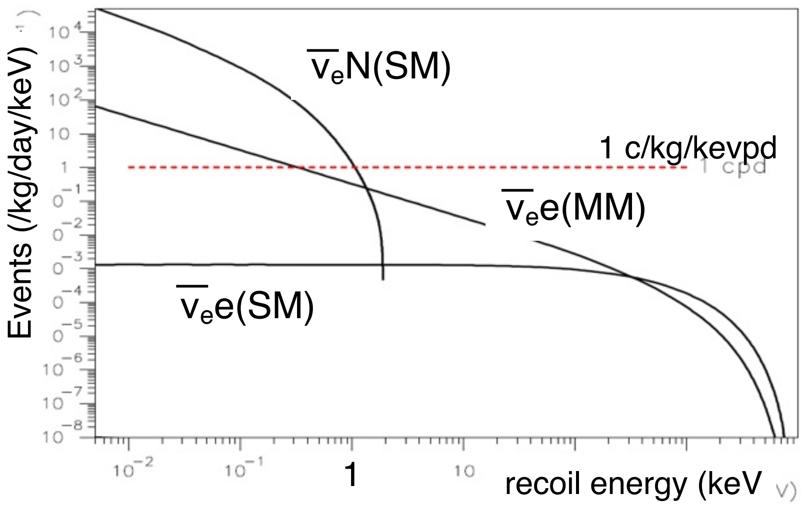
D=0.9 cm

L =160 cm

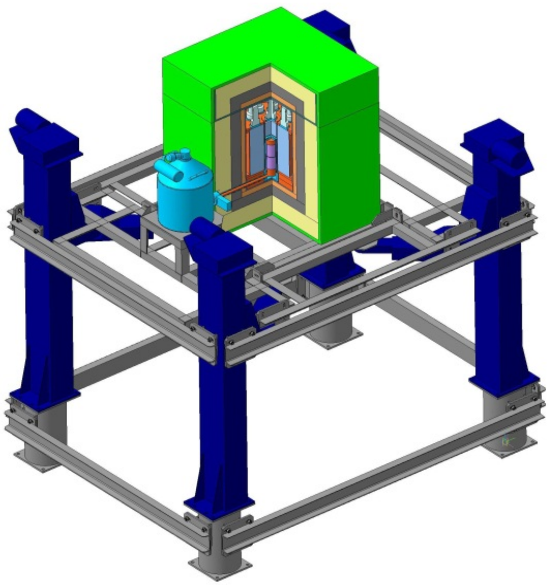
Φ = 90 cm

Scattering Studies with Germanium Detectors

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

Reactor Antineutrinos
and Safeguard Applications

Monitoring Reactor Fuel with Antineutrinos

Pu Production in Reactor

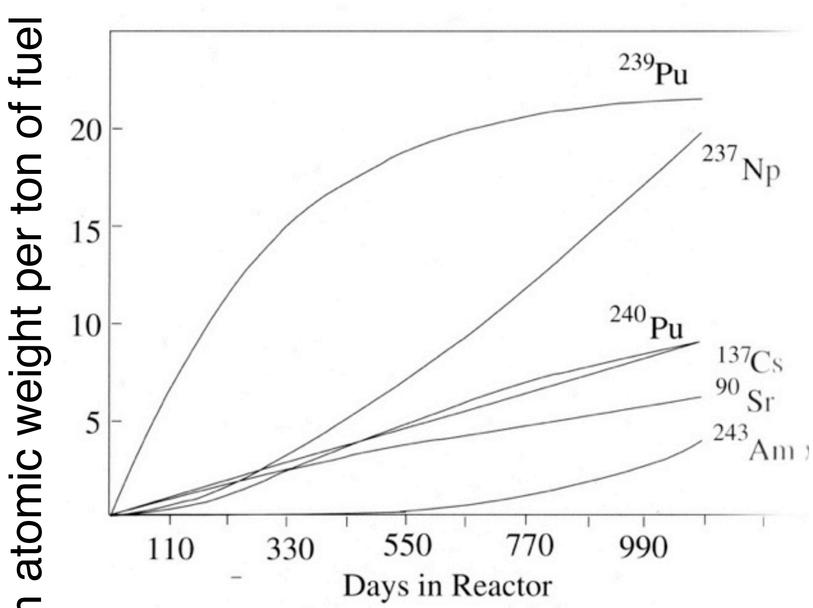
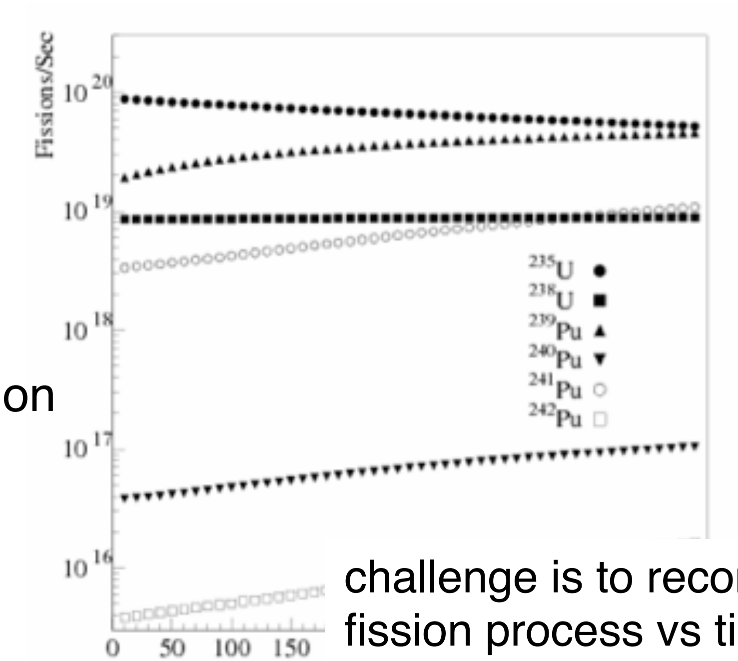


Fig: Basdevant et al.

reactor is producing ^{239}Pu which can be used to make nuclear weapons

8kg of ^{239}Pu is enough for one nuclear device

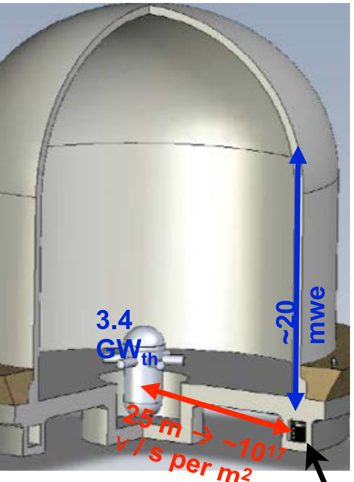


$\overline{\nu}_e$ rate and spectrum carries information on
- fuel cycle
- fuel composition
- fuel changes

monitor reactor from outside,
information cannot be shielded or scrambled

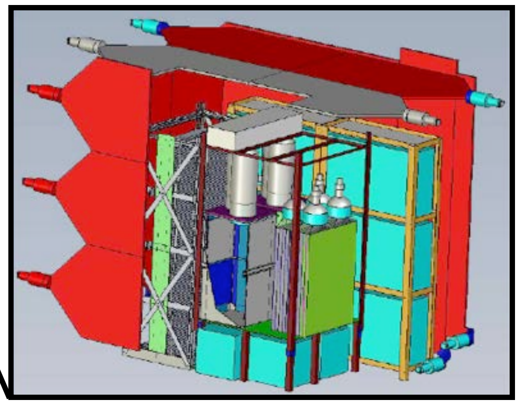
challenge is to reconstruct fission process vs time from neutrino information

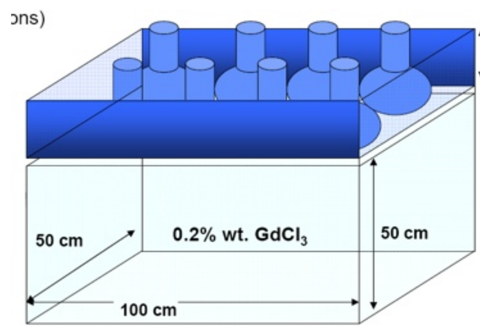
Reactor Monitoring

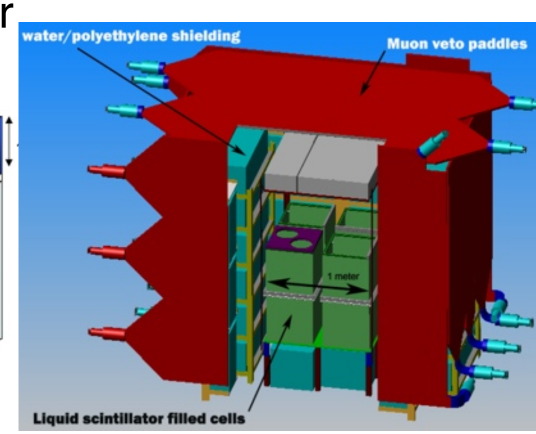


Targets under consideration

Liquid Scintillator
Plastic Scintillator
Gd-doped Water

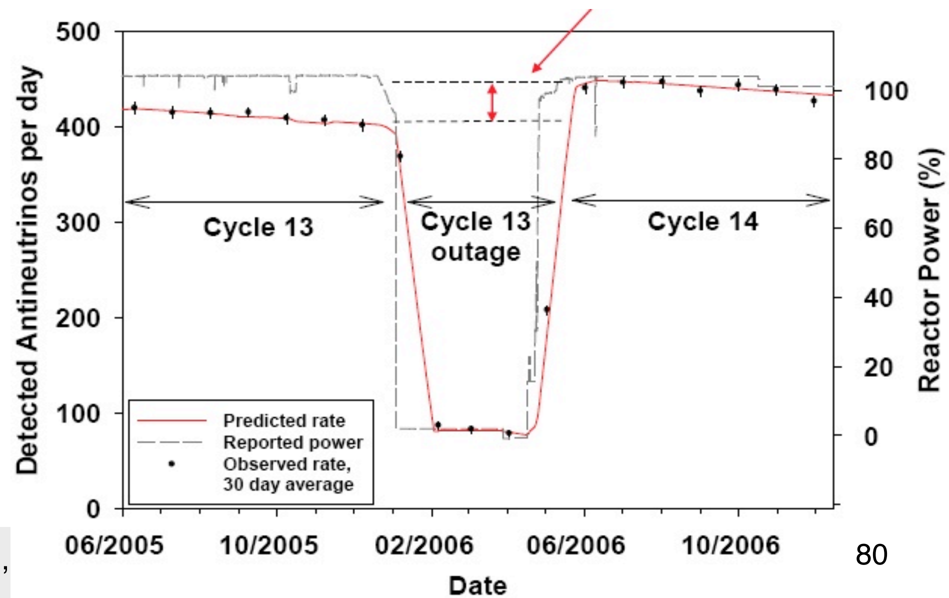






Removal of 250 kg of ^{239}Pu followed by replacement with 1.5 tons of fresh ^{235}U fuel

thermal power with neutrinos -
3% precision achievable



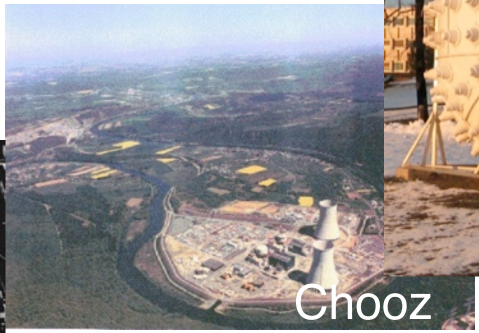
2011/2012 - The year of θ_{13} and reactor neutrinos

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...

Summary

For > 50 years reactor experiments have played an important role in neutrino physics, in both discoveries and precision measurements.

Current reactor experiments **(L~1-2km)** provide precision data on $\boldsymbol{\theta_{13}}$, and **reactor antineutrino spectra** from power reactors. Data taking for next ~3-5 years.

Intermediate-baseline **(L~60km**) reactor antineutrino experiments may be used for a precision measurement of $\boldsymbol{\theta_{12}}$, and determination of the **mass hierarchy**.

Very short baseline **(L~10m)** measurements offer opportunities for precision studies of the **reactor spectra**, **fuel evolution** and searches for **new physics**. On-surface **neutrino monitors** may be developed.

Reactor $\overline{\nu}_e$ enable a rich program in probing neutrino properties, detector development, and nuclear monitoring with neutrinos.

There are lots of opportunities!
Join the excitement.