Reactor Experiments and Underground Capabilities

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Yale University

Snowmass on the Mississippi, July 30, 2013

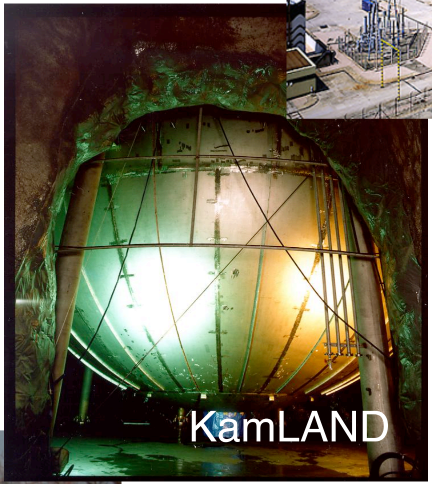
Reactor Neutrinos

55 years of liquid scintillator detectors with varying baselines.

2012 - Measurement of θ_{13} with Reactor Neutrinos

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

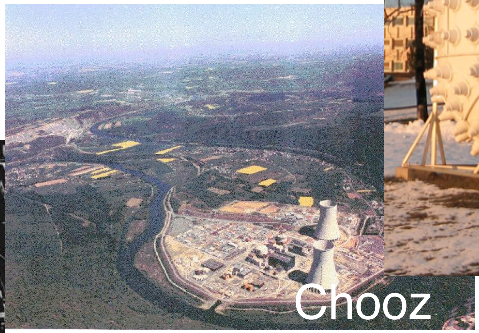
2003 - First observation of reactor antineutrino disappearance



1995 - Nobel Prize to Fred Reines at UC Irvine

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

1956 - First observation of (anti)neutrinos



Past Reactor Experiments

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

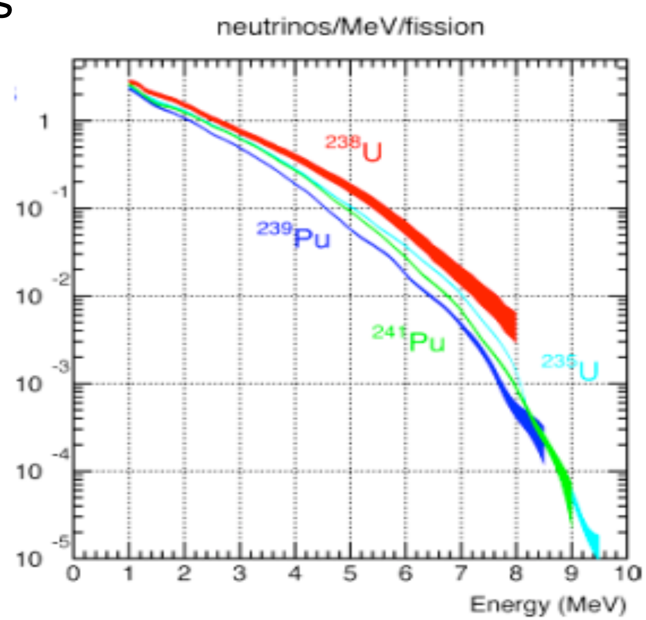
Finding the right underground location near reactors....

Reactor Antineutrinos

Source

$\bar{\nu}_e$ from β-decays

of n-rich fission products



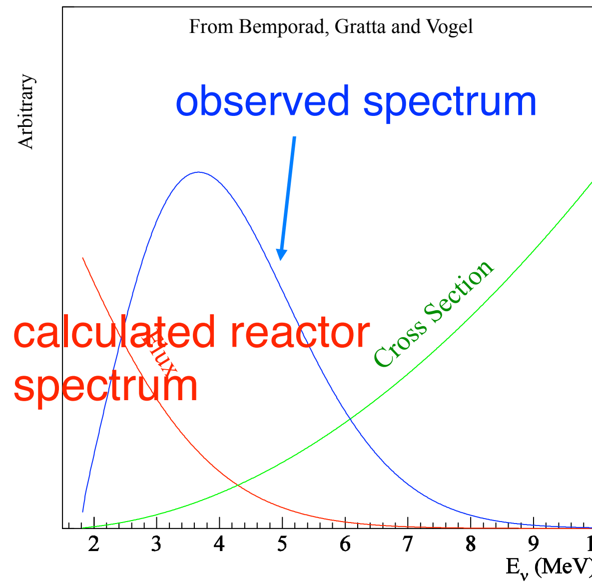
pure $\bar{\nu}_e$ source

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

Detection

inverse beta decay

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



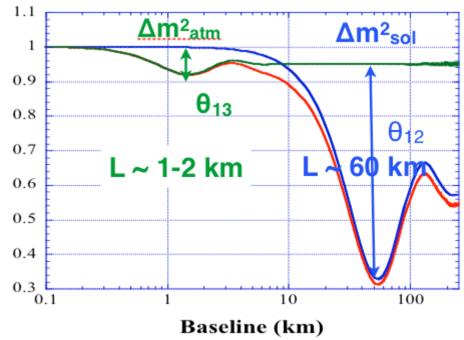
mean energy of $\bar{\nu}_e$: 3.6 MeV

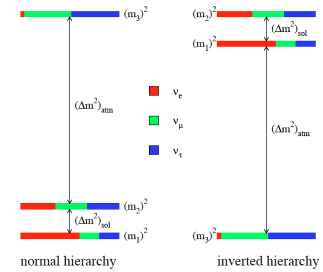
only disappearance experiments possible

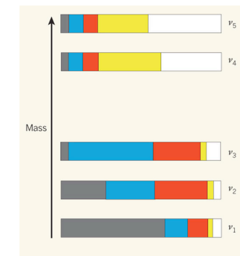
Scientific Accomplishments and Goals

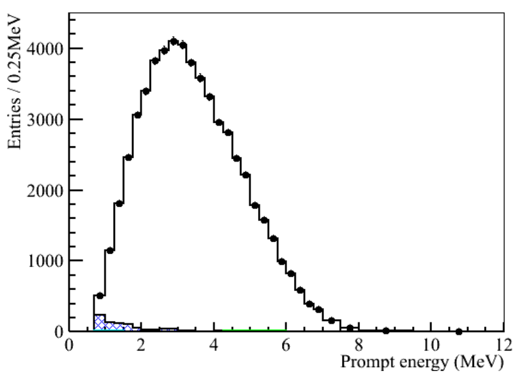
Neutrino Oscillation Experiments

- precision measurement of oscillation parameters Δm^2_{21}, Δm^2_{ee}, $\sin^2 2\theta_{13}$
- search for short-baseline oscillations
- probing the mass hierarchy







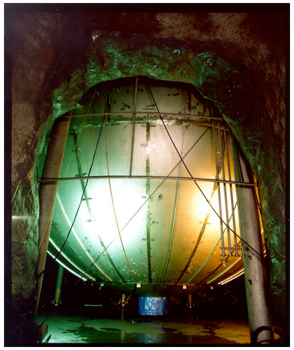


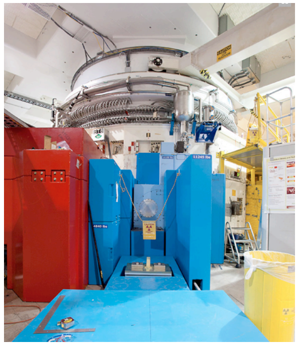
Reactor Antineutrino Spectra, Fuel, Cores

- precision measurement of reactor antineutrino spectrum
- studying reactor core evolution
- absolute measurement of reactor antineutrino flux

Detector development

- large, homogeneous low-background scintillator detectors underground
- R&D towards segmented detectors near surface



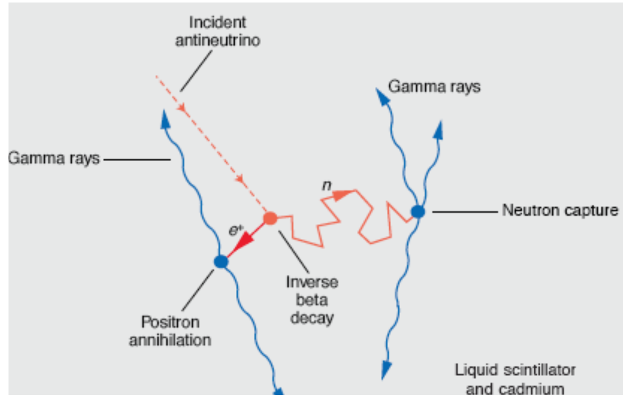


US researchers have played leading roles in recent and past experiments

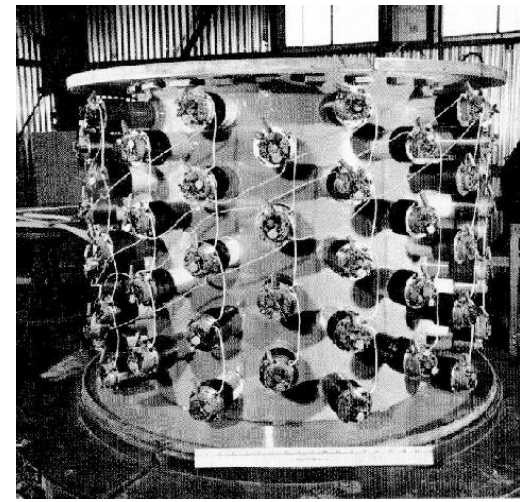
Detecting Antineutrinos

inverse beta decay

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

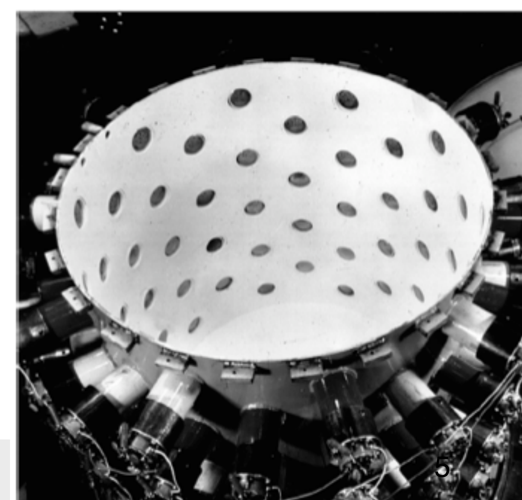


signal: delayed coincidence between positron and neutron capture



Shielding: 4 ft of soaked sawdust

pioneering efforts by Reines and Cowan in the US



early experiments founds that shielding and background reduction are essential

Backgrounds in Reactor Experiments

accidentals

cosmogenic-induced backgrounds

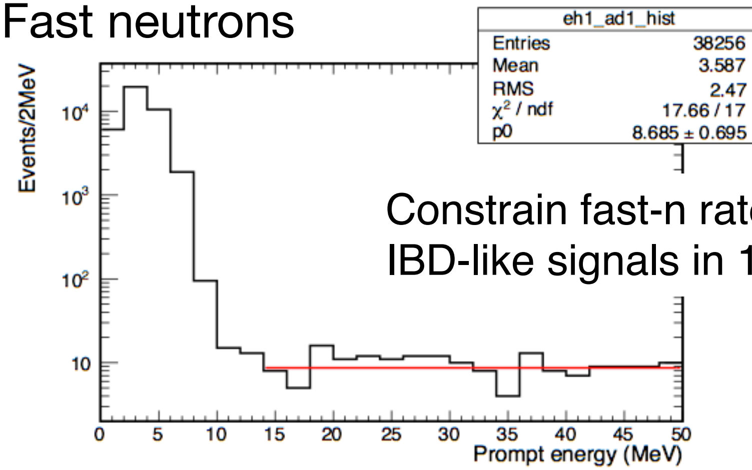
correlated events can mimic antineutrino signal

- prompt: β-decay
- delayed: neutron capture

$$^{9}Li \rightarrow {}^{9}Be + e^{-} + \nu_e$$
$$\quad \hookrightarrow n + 2\alpha$$

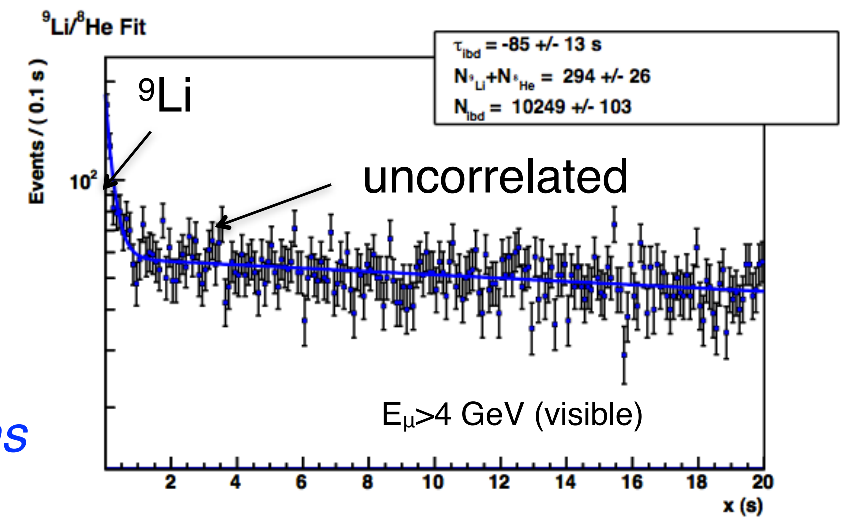
background considerations require radiopure detectors in underground locations

Fast neutrons

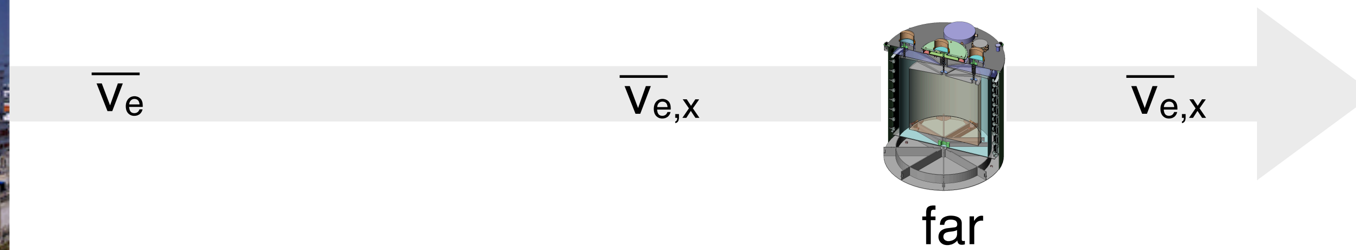


Constrain fast-n rate usin
IBD-like signals in 10-50

Correlated β-n decay



Reactor Neutrino Oscillation Experiments

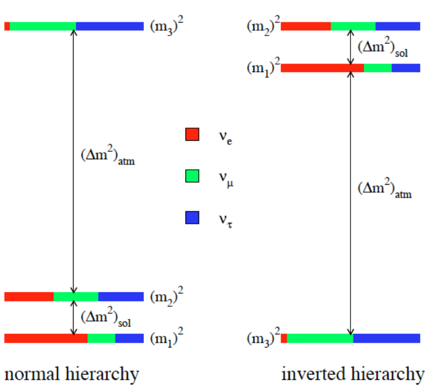


Measure (non)-1/r² behavior of ν_e interaction rate

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

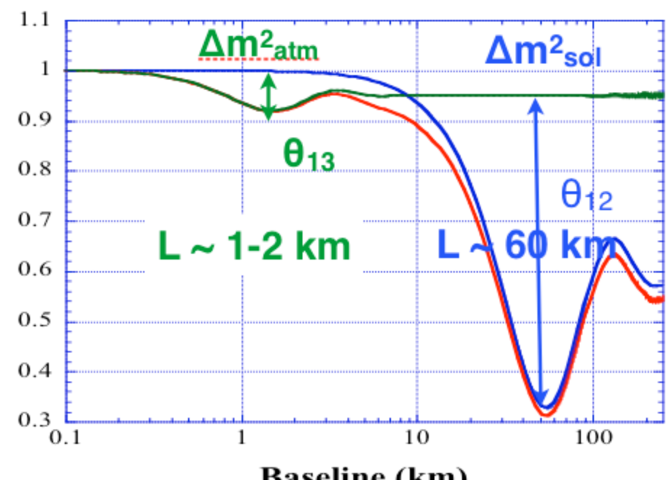
for 3 active ν, two different oscillation length scales: Δm^2_{12}, Δm^2_{23}

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



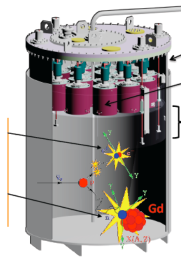
$\Delta m^2_{12} \sim 7.6 \times 10^{-5}$ eV²

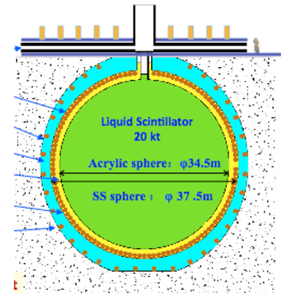
$\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV²



Reactor Experiments at Different Scales

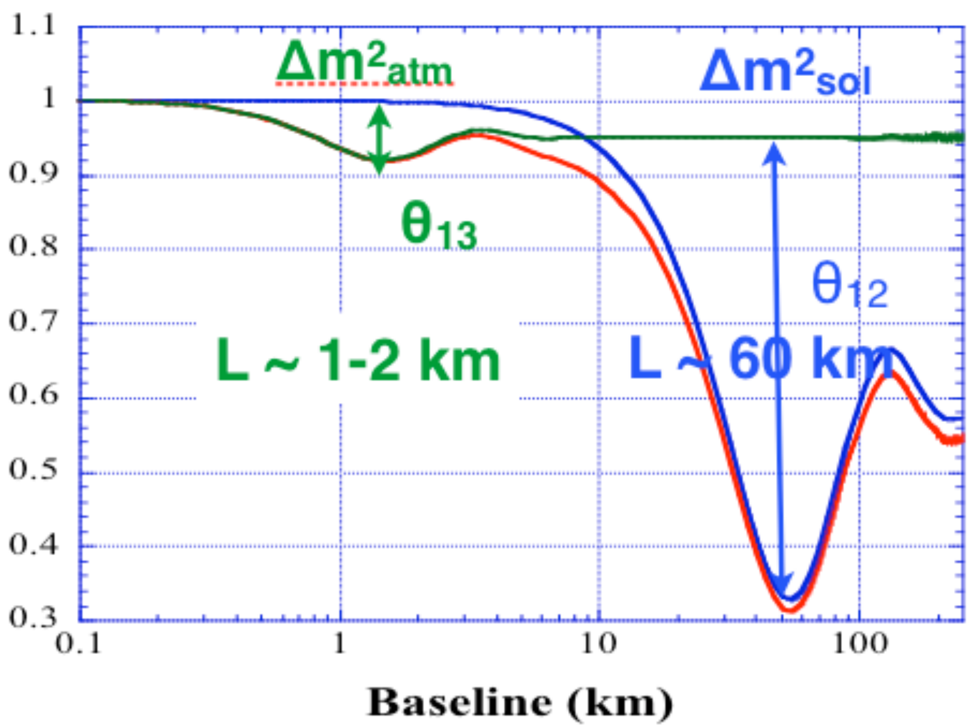
Past&Present



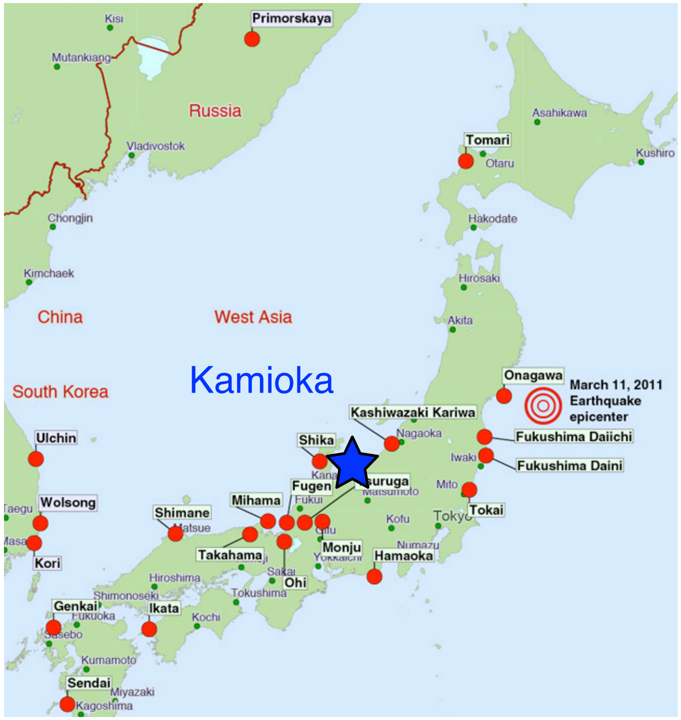


Future

1 ton/10m | **20 ton/1km** | **20 kton/50km** | **1 kton/180km**



KamLAND at ~180km Baseline

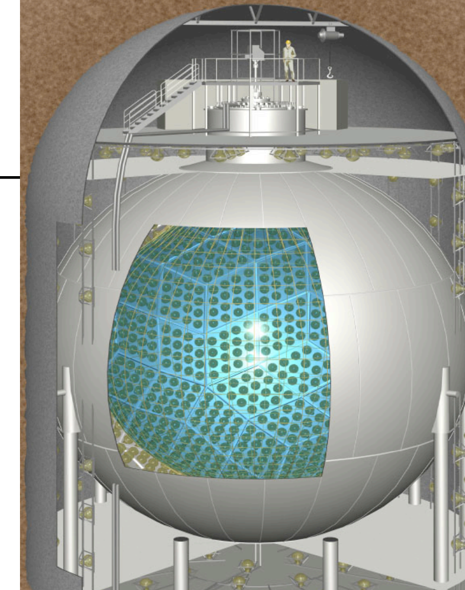


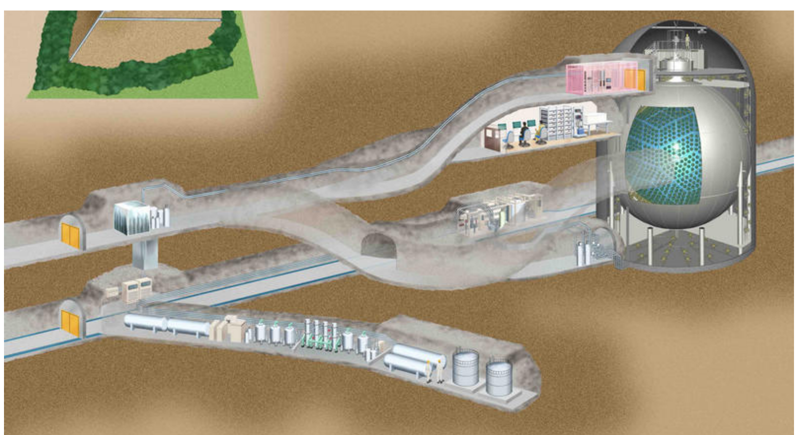
measures antineutrinos from 55 reactors

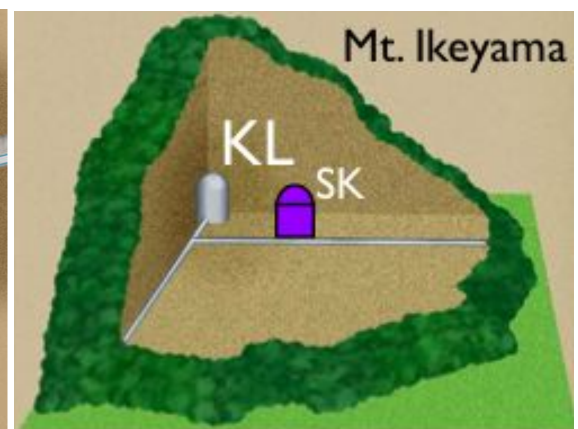
mean, flux-weighted reactor distance ~ 180km

2700 mwe overburden

1kt liquid scintillator detector in dedicated underground facility

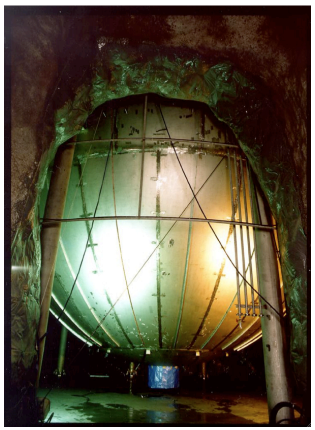


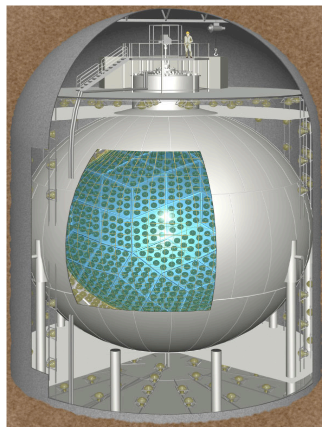


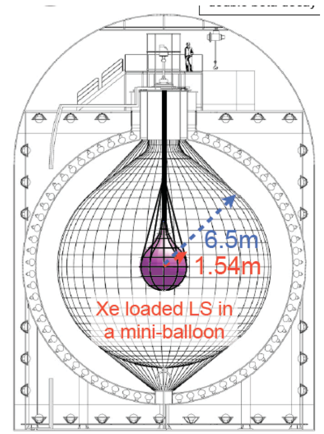


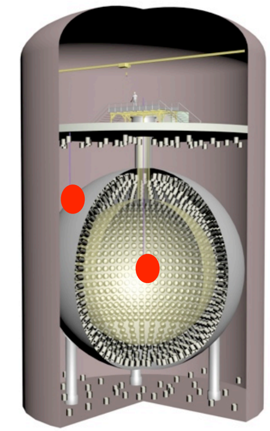
Kamiokande → KamLAND → KamLAND-Zen

Underground excavation at Kamioka has enabled a long-term program of underground science



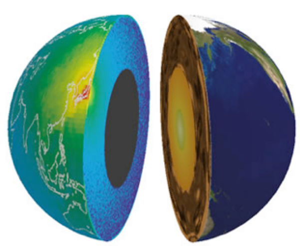




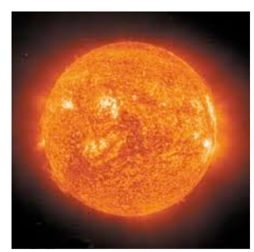


reactor ν

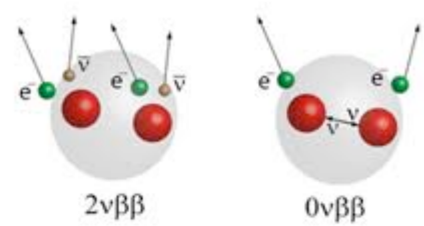
geo ν



solar ν



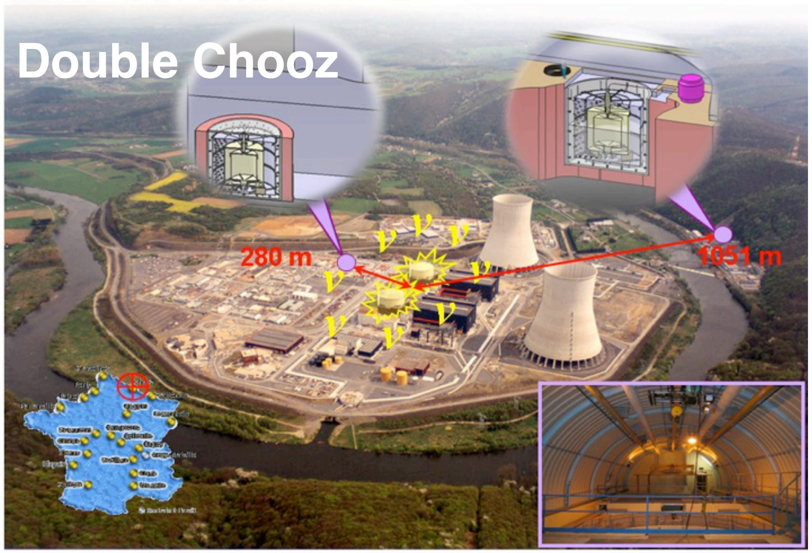
0νββ

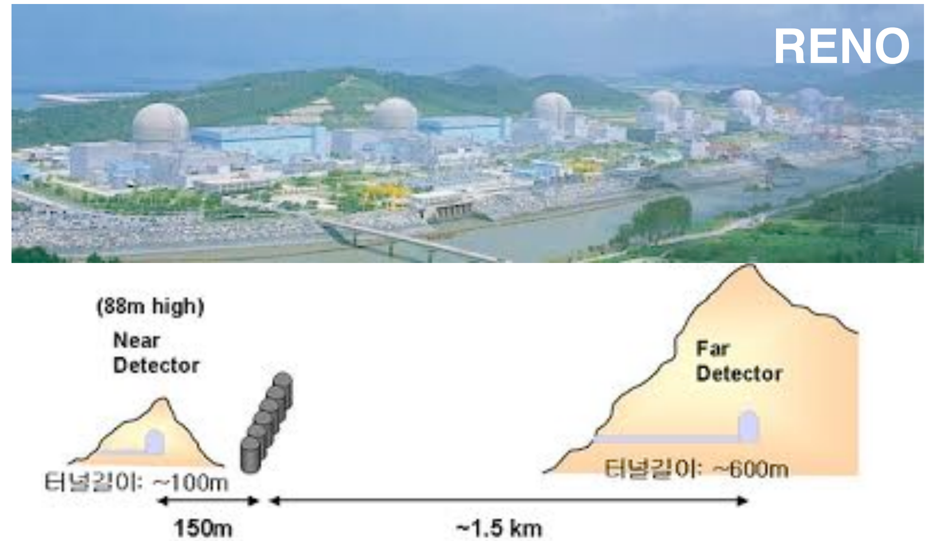


sterile ν?

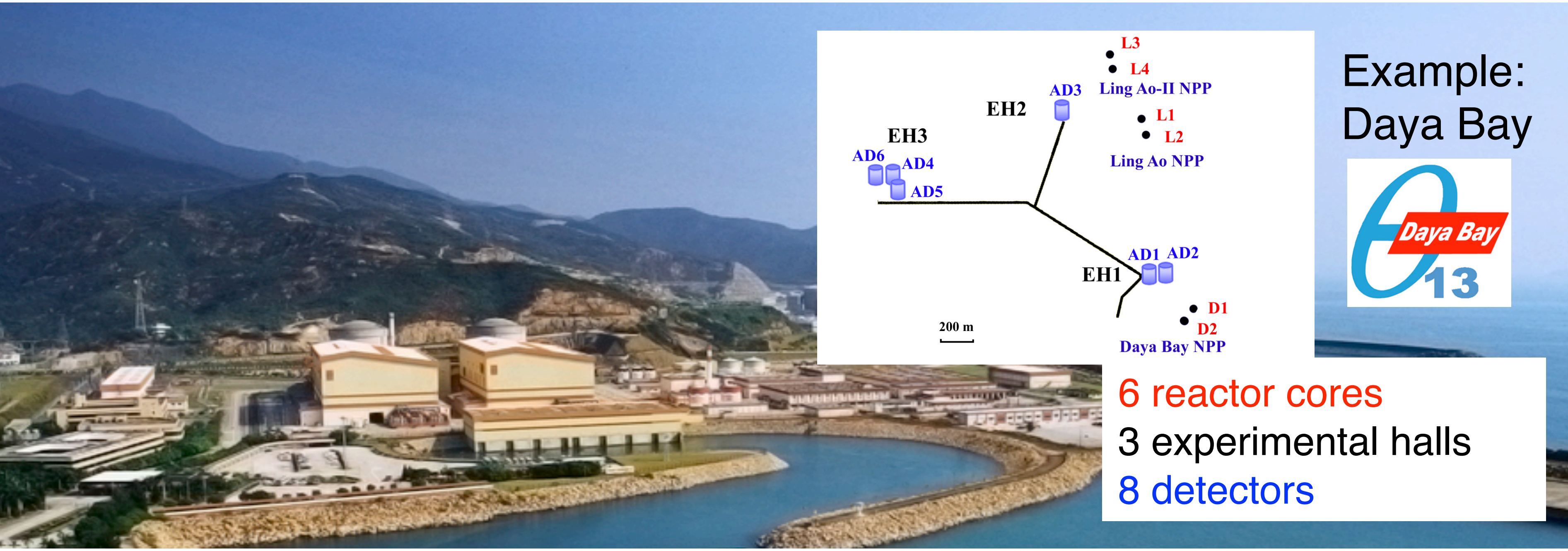
Reactor Experiments at ~1km Baseline

Facilities Designed for an Optimized Oscillation Measurement



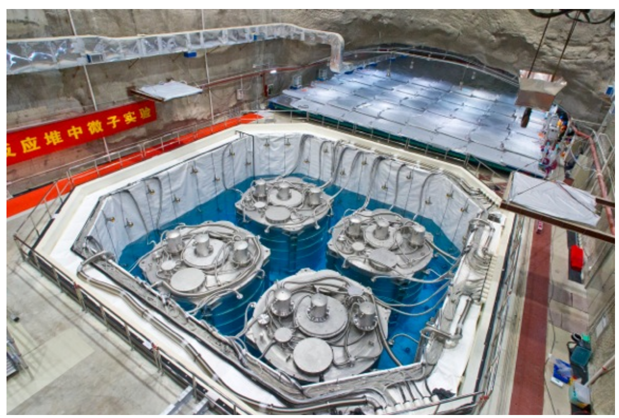


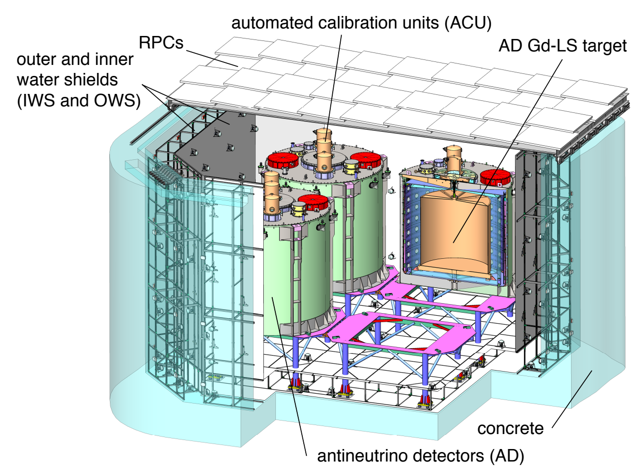
Reactor Experiments at ~1km Baseline



Example:
Daya Bay

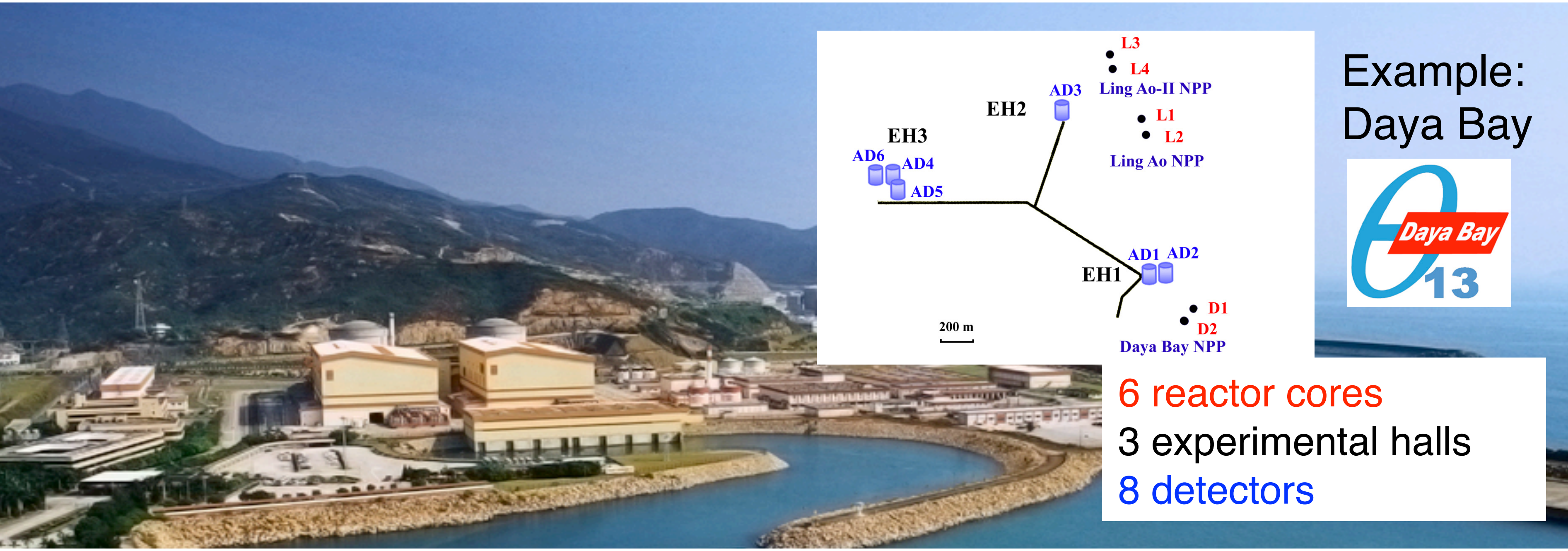
6 reactor cores
3 experimental halls
8 detectors





specialized underground infrastructure

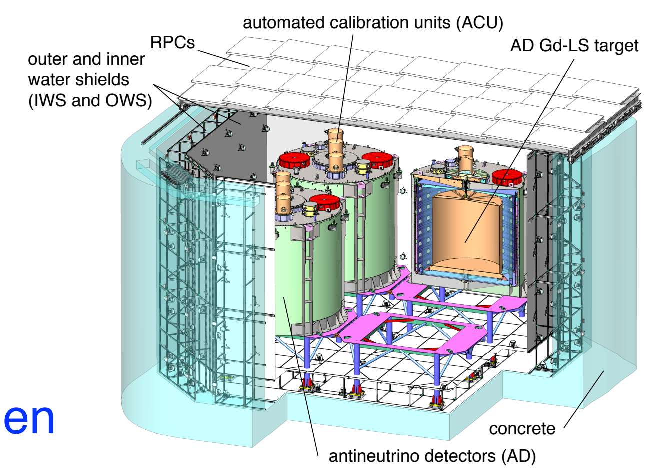
Reactor Experiments at ~1km Baseline



Example:
Daya Bay

6 reactor cores
3 experimental halls
8 detectors

	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



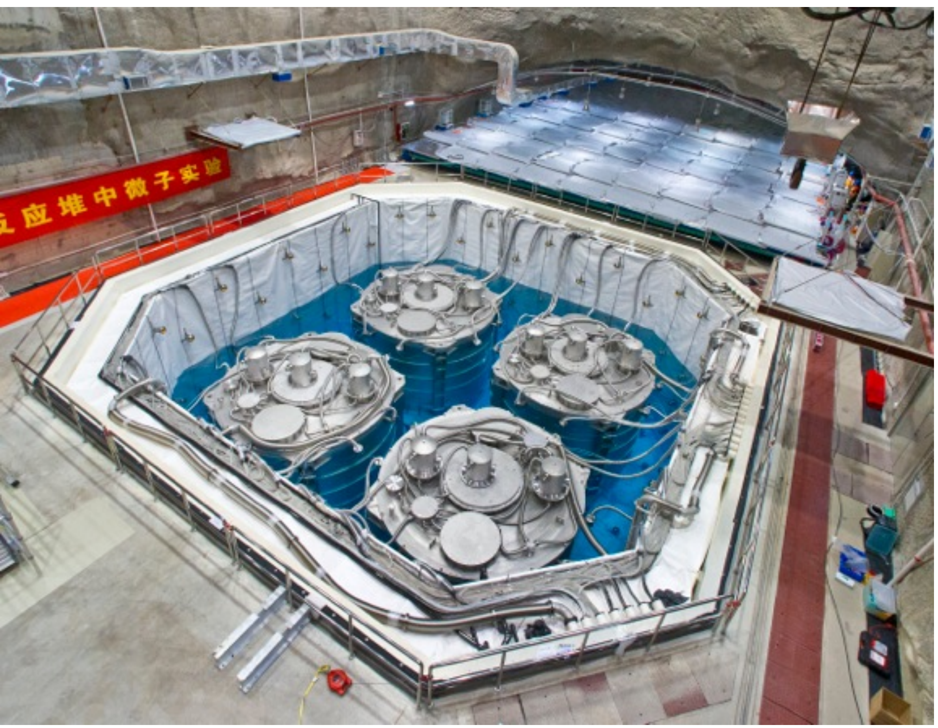
experimental halls with several hundred mwe overburden

Reactor Experiments at ~1km Baseline

Experimental halls and underground infrastructure enable new R&D and auxiliary underground measurements

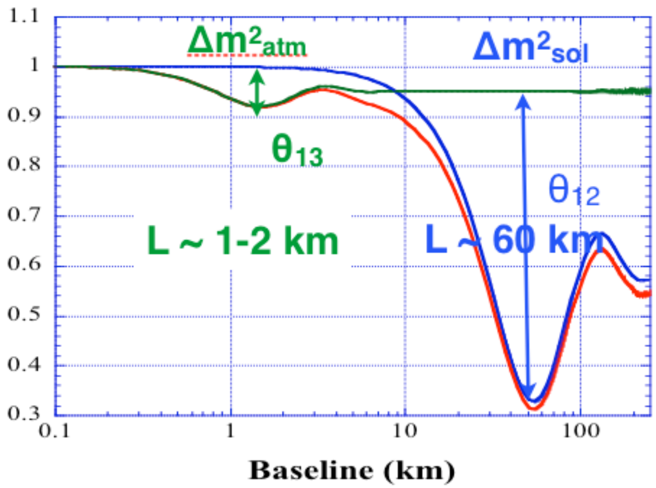
Example: Daya Bay

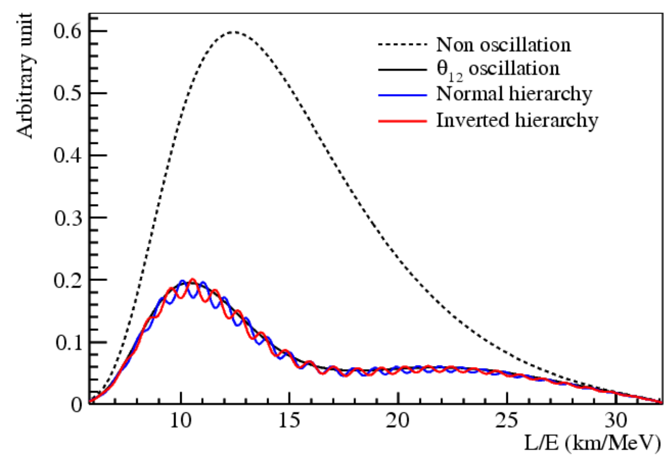
- R&D towards dark matter experiment in liquid storage pools
- muon and cosmogenic background studies



Reactor Experiments at ~50km Baseline

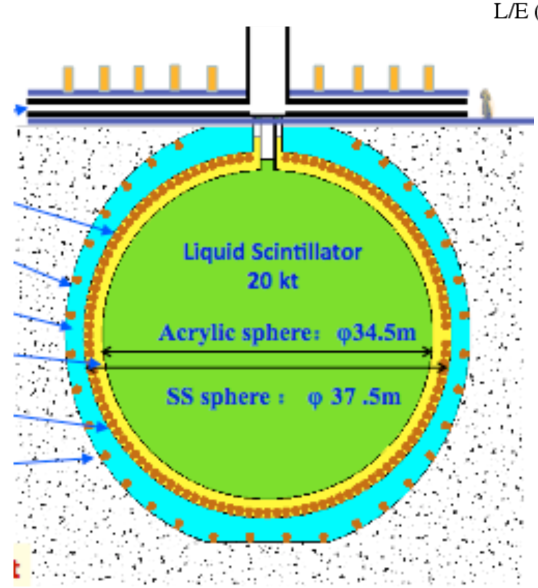
JUNO and RENO-50 (proposed)

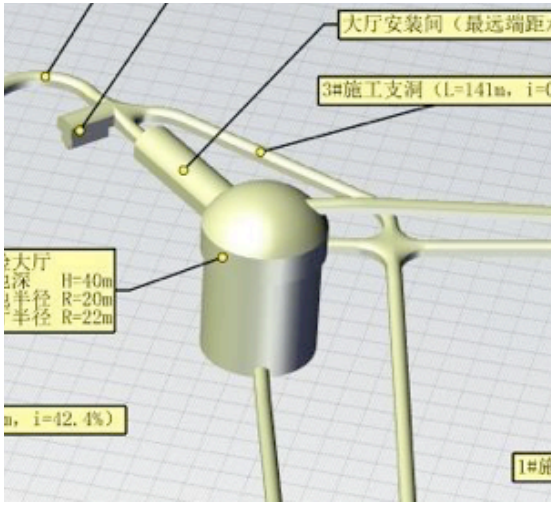




aim to make precision measurement of reactor spectrum to determine mass hierarchy

20x larger than KamLAND

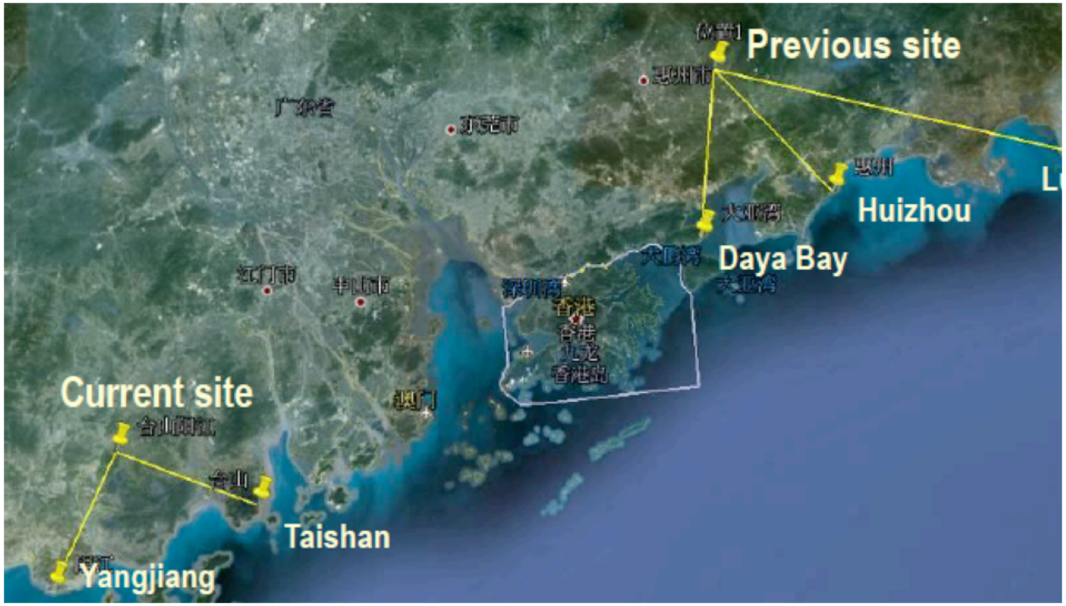




baseline requires large precision detectors, and supporting underground facilities

Reactor Experiments at ~50km Baseline

JUNO (proposed)



Site selection

- Allowed region determined
- Experimental hall selected:
  - ⇨ In granite
  - ⇨ Mountain height: 270 m
- Preliminary geological survey completed:
  - ⇨ Review held on Dec. 17, 2012
  - ⇨ No show-stoppers
- Detailed geological survey started and first round data are available now
- Contacts with local government established, good support

From Y. Wang

R&D from 2012-2015

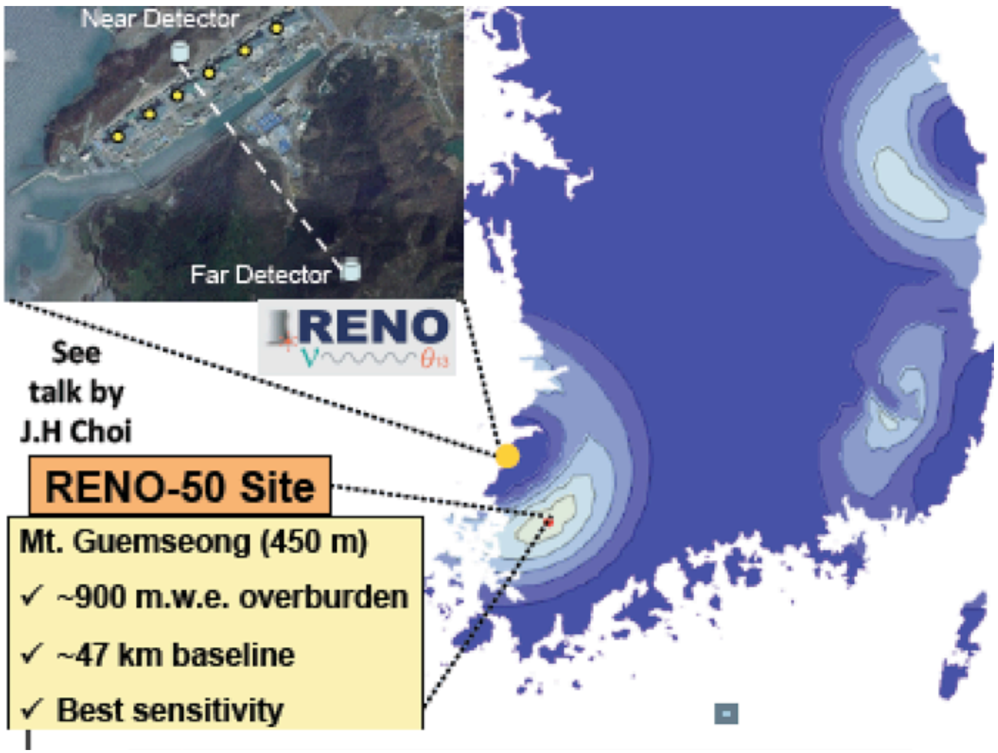
Construction start ~ 2015/16?

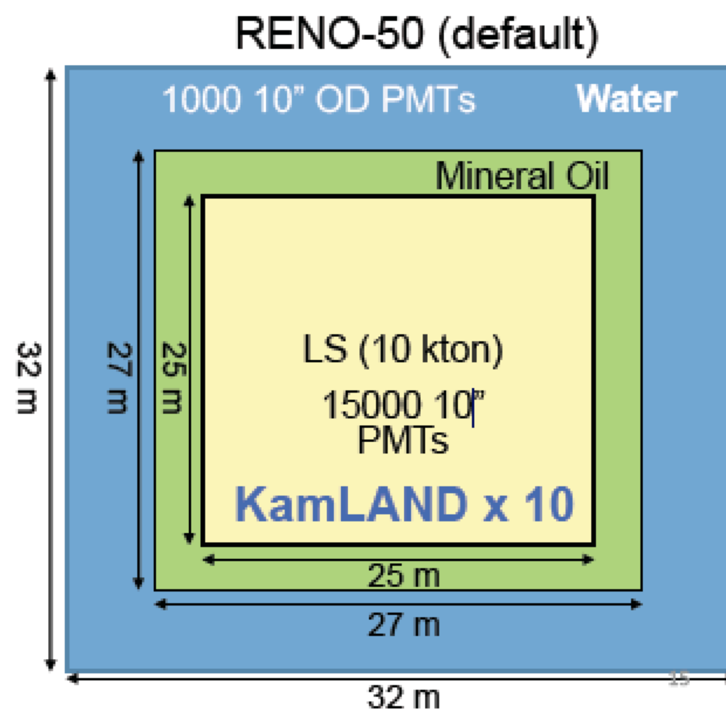
Early funding commitments in host country (China)

Reactor Experiments at ~50km Baseline

RENO-50 (proposed)

- Utilizing the current 6 RENO reactors
- Baseline ~47km
- Target mass 10kt
- Cylinder-shaped detector
- ➡ Simulation resolution is ~6% at 1MeV
- ➡ Need to improve photoelectrons





From W. Wang and RENO-50 workshop

Reactor Experiments at ~50km Baseline

Challenges of a 20kt LS Detector

- Large detector: >10 kt LS
- Energy resolution: < 3%/√E → 1200 p.e./MeV

	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20t	~300t (100t F.V.)	~1 kt	20kt
Photocathode Coverage	~12%	~34%	~34%	?
Energy Resolution	~7.5%/√E	~5%/√E	~6%/√E	3%/√E
Light yield	~160 p.e./MeV	~500 p.e/MeV	~250 p.e./MeV	1200 p.e./MeV

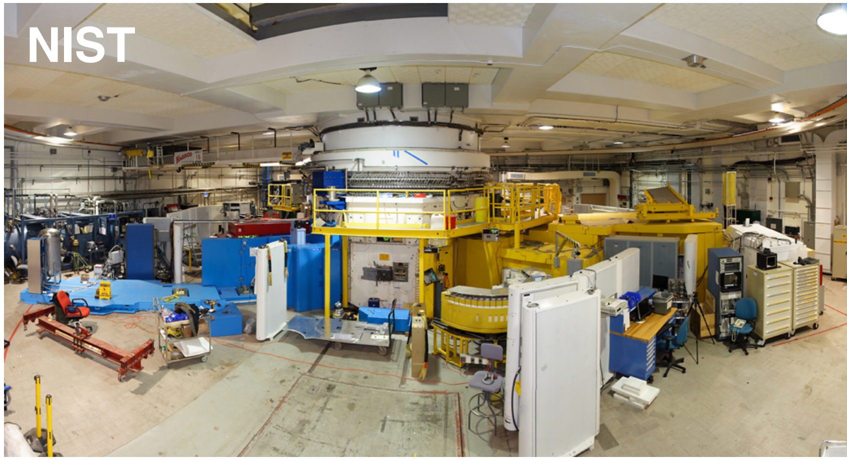
From Y. Wang

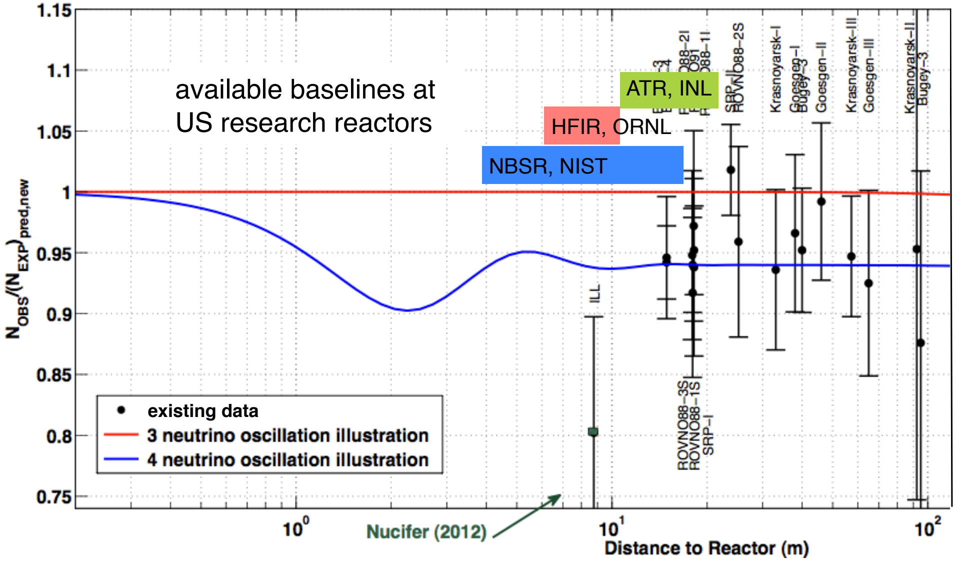
50-km baseline reactor experiments require large underground facilities and precision reactor antineutrino detectors

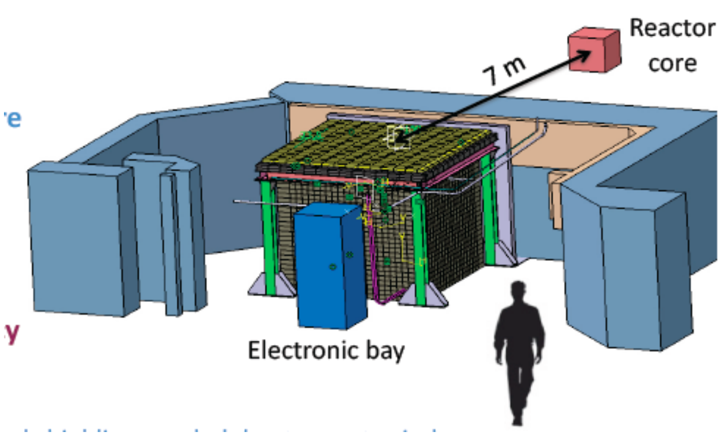
Reactor Experiments at Short Baseline (~10m)

Short-Baseline Experiments

- short-baseline requires much smaller detectors (ton-scale)
- several proposed experiments worldwide
- most of them near surface with little overburden
- considering segmented detector to mitigate backgrounds







Conclusions

- Reactor antineutrinos as probe of neutrino properties (oscillation parameters, mass hierarchy, short-baseline searches, magnetic moment)
- Detectors for reactor experiments at > 100m baseline require medium-depth underground laboratories (several hundred mwe overburden).
- Strong US involvement in recent reactor experiments overseas (KamLAND, Daya Bay, Double Chooz)
- Reactor neutrino experiments and associated underground spaces have enabled R&D and development of new neutrino experimental initiatives overseas:
  - KamLAND ➔ KamLAND-Zen, CeLAND
  - Daya Bay ➔ JUNO, R&D for dark matter experiments in Daya Bay halls
  - RENO ➔ RENO-50
- Worldwide efforts towards future reactor experiments at medium baseline (~50km) and short-baseline (~10m). Funding commitments from host countries (RENO-50, JUNO, STEREO). May have US involvement. Opportunities for short-baseline searches in US.
- Future reactor experiments and underground space:
  - planned construction of dedicated underground space overseas for medium-baseline reactor experiments
  - multi-purpose use of underground space for neutrino and dark matter R&D in host countries
  - synergies with non-proliferation effort in US (see A. Bernstein's talk)