First Measurement of $\sin^2 2\theta_{13}$ at Daya Bay

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On behave of the Day Collaboration

References
Result: arXiv:1203.1669
Detector: arXiv:1202.6181
Proposal: hep-ex/0701029

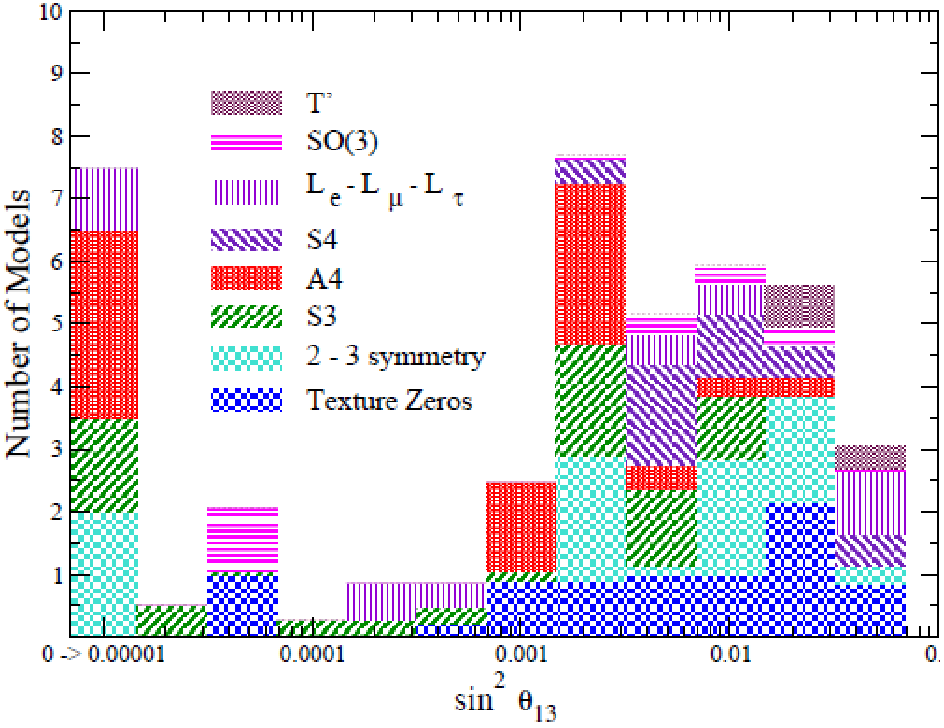
Outline

- Overview of θ_{13}: from theories to experiments
- Daya Bay Experiment
- Data analysis
- Determination of $\sin^2 2\theta_{13}$
- Summary and outlook

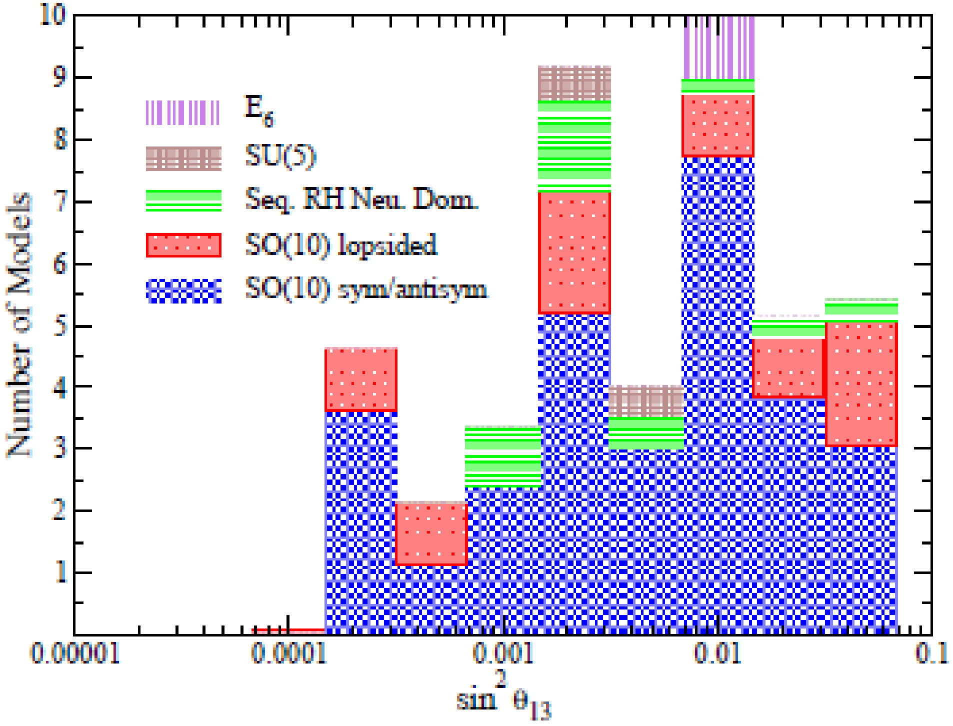
Overview of θ_{13}: from theories to experiments

Model Predications for θ_{13}

Lepton flavor models



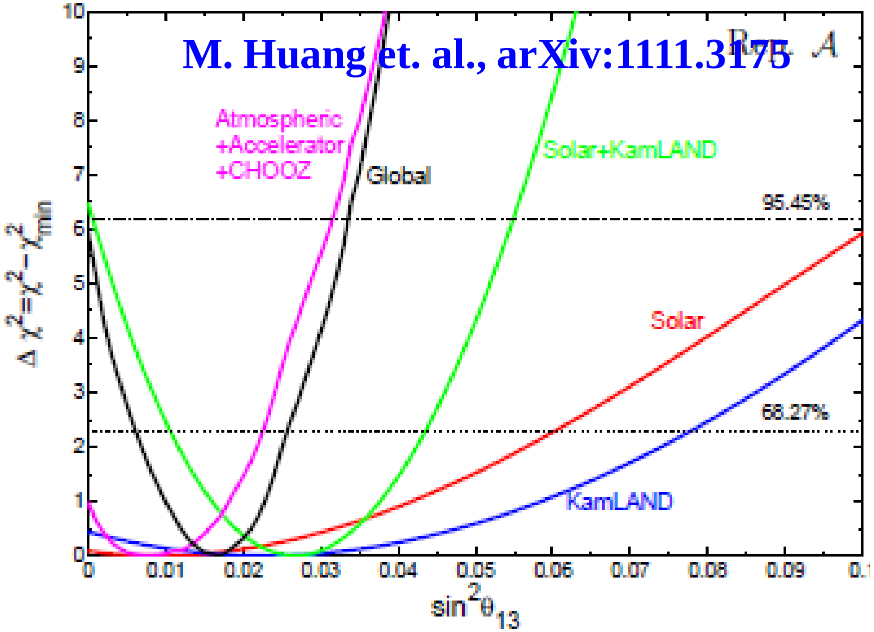
GUT models



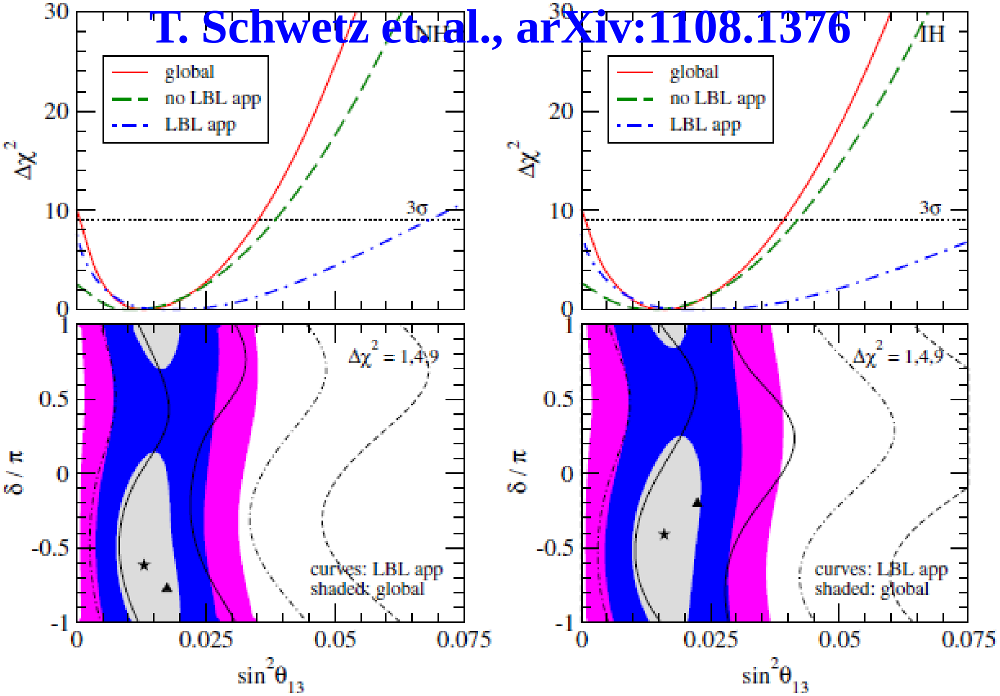
Up to 2009, more than 86 models for θ_{13} predications.

arXiv:0911.2437

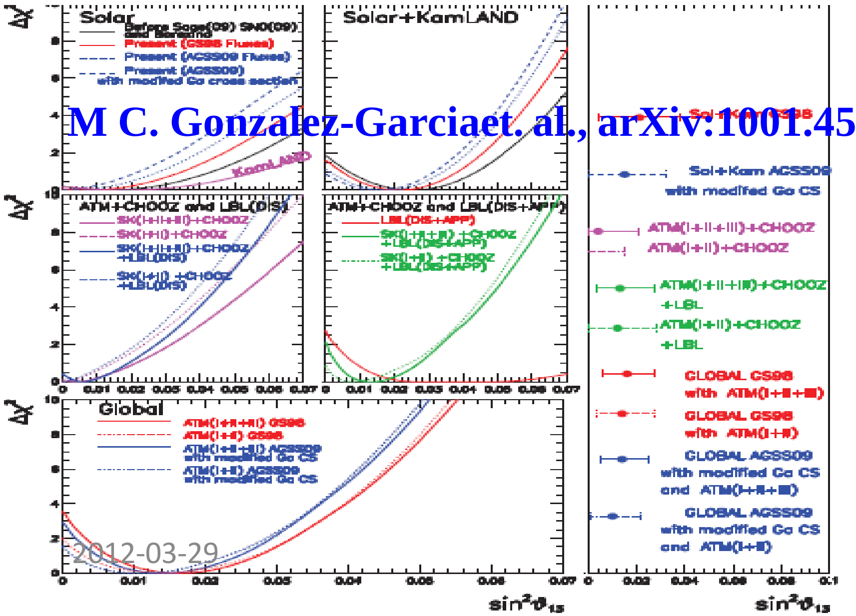
Hints of θ13≠0 from Global Fits



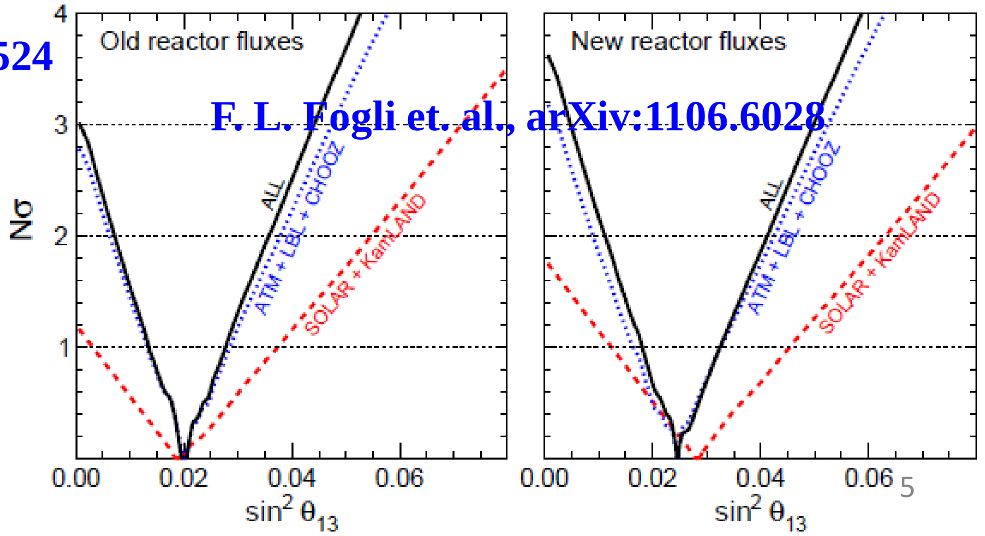
M. Huang et. al., arXiv:1111.3175



T. Schwetz et. al., arXiv:1108.1376

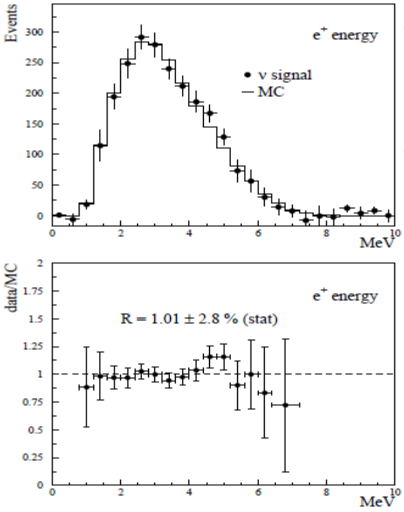


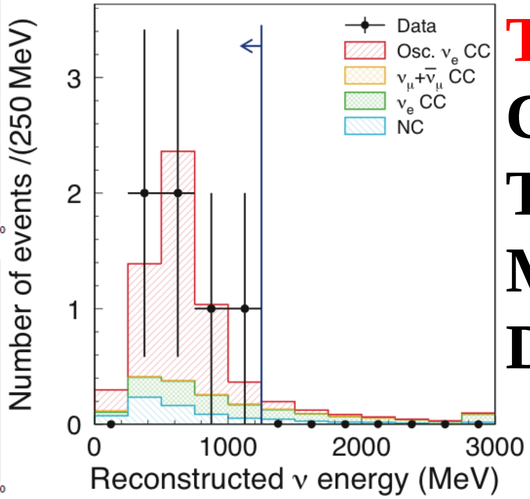
M C. Gonzalez-Garciaet. al., arXiv:1001.4524



F. L. Fogli et. al., arXiv:1106.6028

Hints of $\theta_{13}\neq 0$ from Experiments





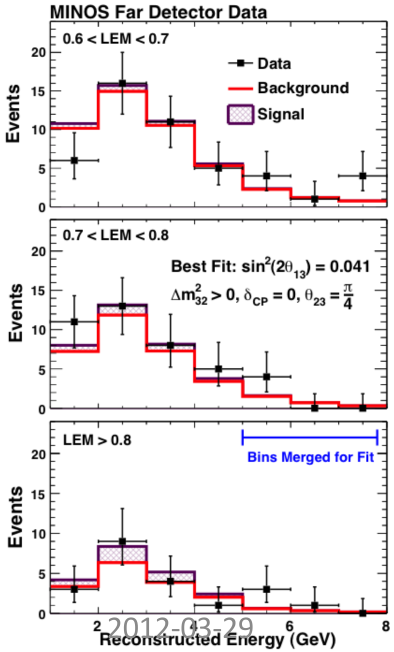
Title highlights

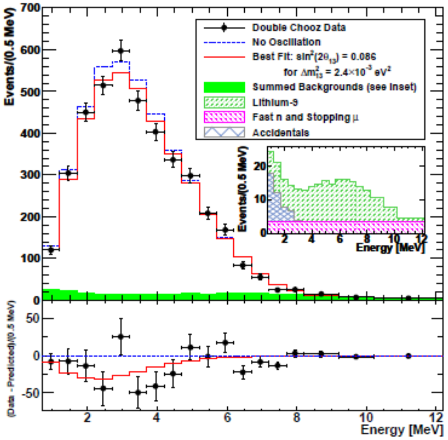
Chooz(2003): Search…

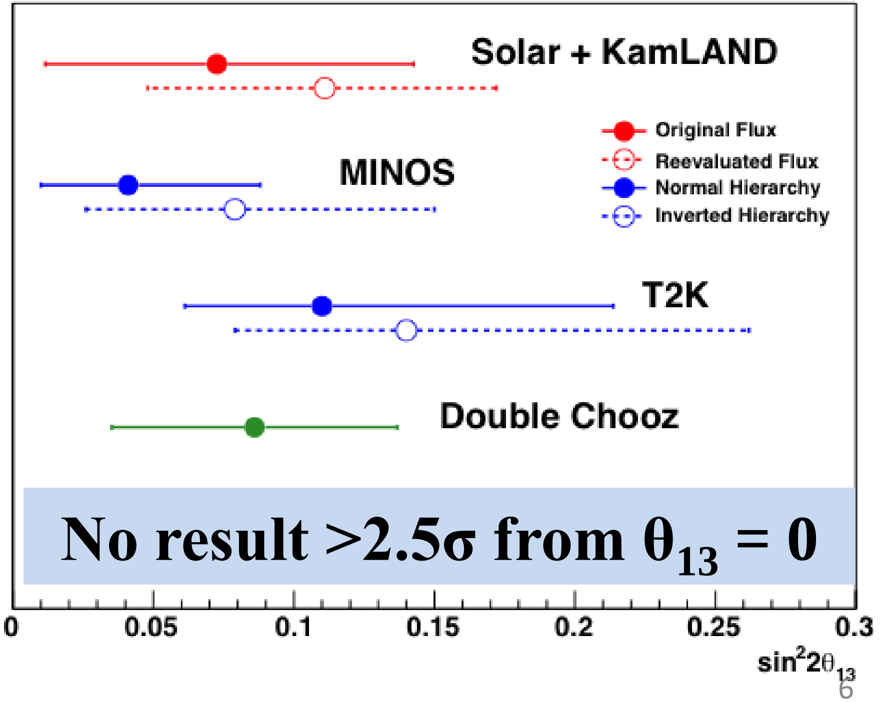
T2K(2011): Indication…

MINOS(2011): Improved Search…

DC(2011): Indication…







No result >2.5σ from $\theta_{13} = 0$

Initiate DayaBay Project in China

Meeting brief for the 250th Xiangshan (Fragrant Hill Hotel) Scientific Meeting (2005)

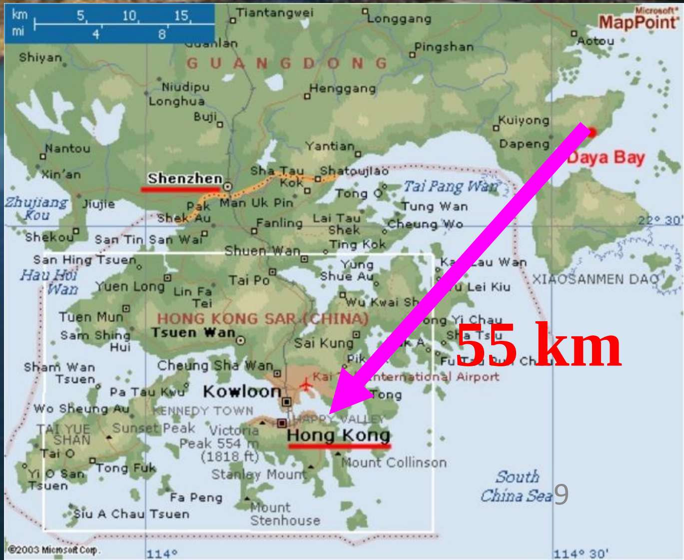
…

2. **Neutrino mixing angle θ_{13} is one of the fundamental parameters in nature,…a key issue to be resolved.**
3. **…have mature technology and get strong support from Daya Bay Nuclear Power Plant. … get preparations … to complete this experiment.**
4. **International competition in determining θ_{13} is very vigorous,…getting the project approved promptly is a key to win the competition.**

Daya Bay Experiment

Daya Bay Power Plant Complex

- Three-pair reactor cores: $2.9 \times 6 = 17.4$GWth
- Each core produces 6×10^{20} anti-ν_e's/s
- Mountains near by



55 km

Reactor Anti-ν_e oscillation

Survival probability:

$$P(\bar{\nu}_e \to \bar{\nu}_e)$$

$$= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(1.267\cdot\Delta m^2_{21}\cdot\frac{L}{E})$$

$$-\cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(1.267\cdot\Delta m^2_{31}\cdot\frac{L}{E}) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(1.267\cdot\Delta m^2_{32}\cdot\frac{L}{E})$$

$$+\frac{1}{2}\sin^2 2\theta_{13}\sin^2\theta_{12}[\cos\frac{1.267(\Delta m^2_{31}-\Delta m^2_{21})L}{2E} - \cos\frac{1.267\Delta m^2_{31}L}{2E}]$$

Approximated to

Well measured by MINOS, SK

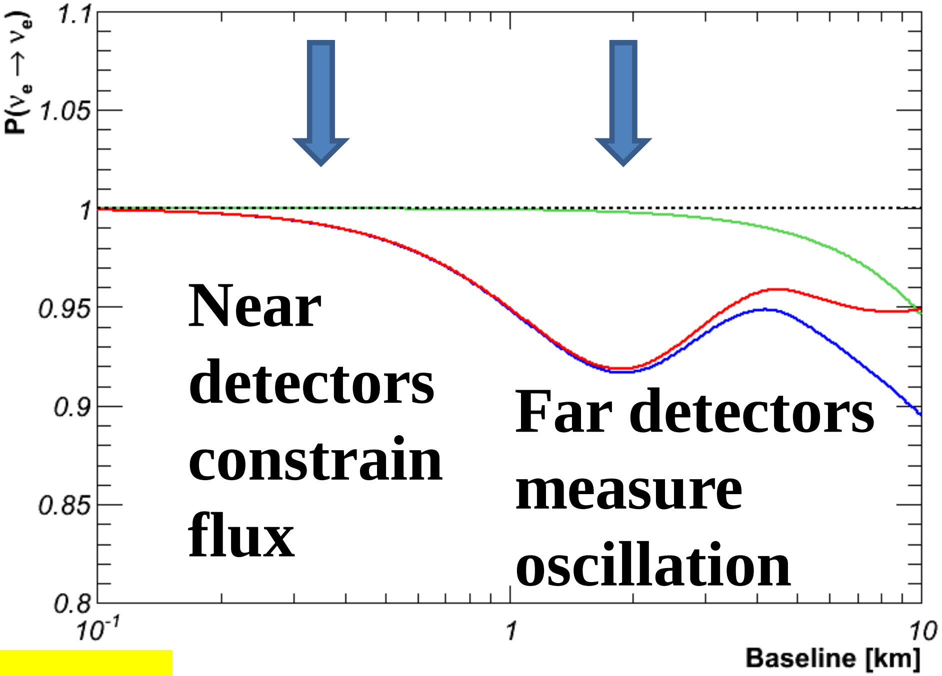
$$P(\bar{\nu}_e \to \bar{\nu}_e)$$

$$\simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(1.267\cdot\Delta m^2_{21}\cdot\frac{L}{E}) - \sin^2 2\theta_{13}\sin^2(1.267\cdot\Delta m^2_{32}\cdot\frac{L}{E})$$

Well measured by KamLAND

How to Measure $\sin^2 2\theta_{13}$?

- Use relative measurement
- Avoid large uncertainty from predicted reactor flux
- First proposed by L. A. Mikaelyan and V.V. Sinev, PAN 63 1002 (2000)
- Key inputs



Near detectors constrain flux

Far detectors measure oscillation

Base lines

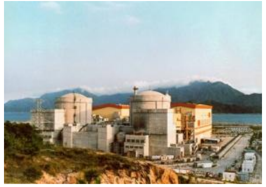
$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left[\frac{P_{\mathrm{sur}}(E,L_{\mathrm{f}})}{P_{\mathrm{sur}}(E,L_{\mathrm{n}})}\right]$$

Far/near ν_e counts

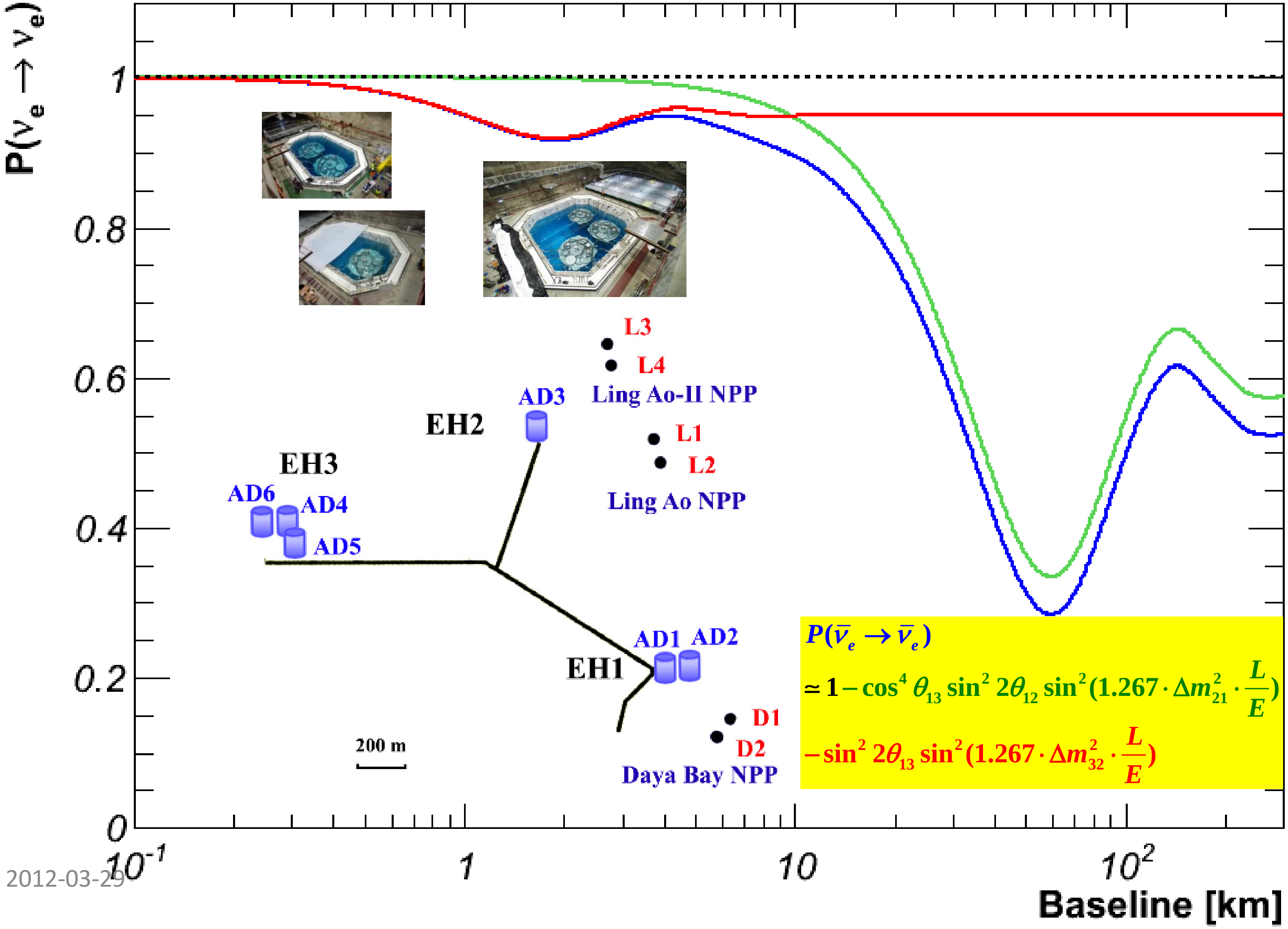
Detector Target Masses

Detector efficiencies

Oscillation deficit



Baseline Selection

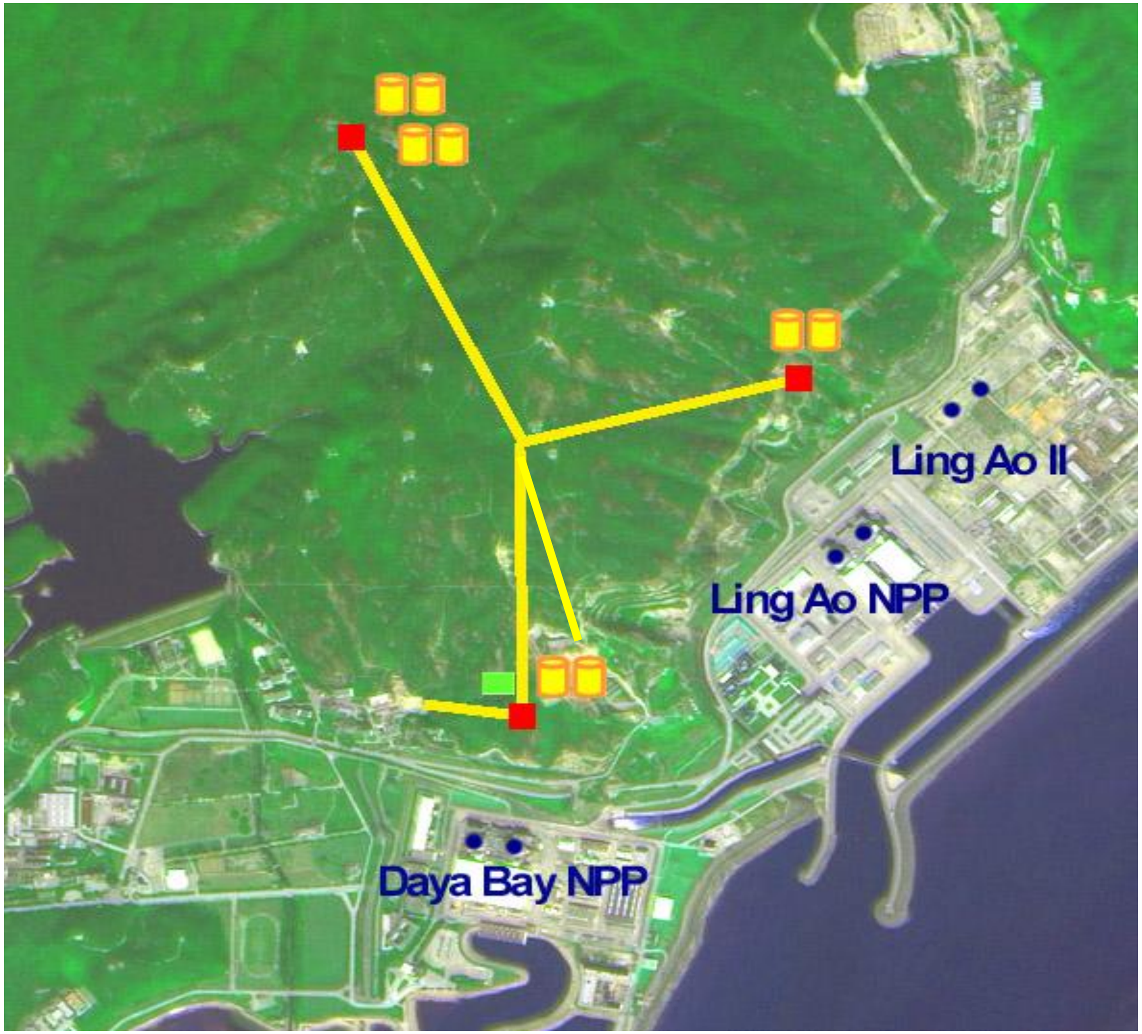


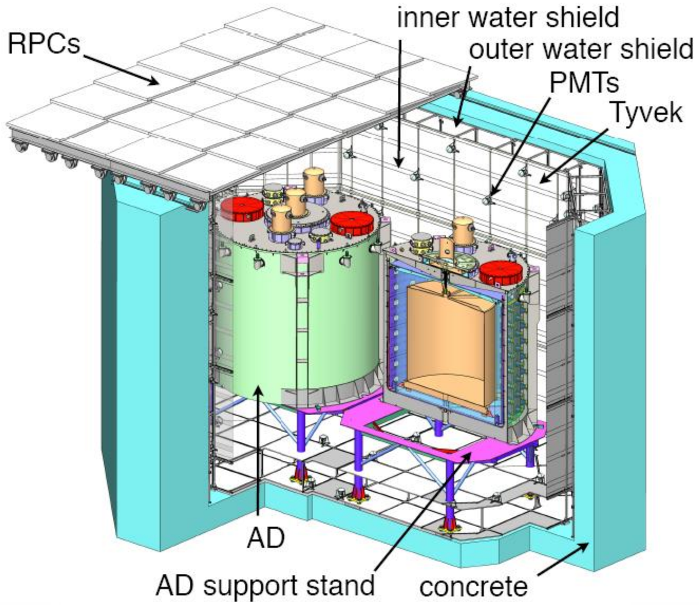
$$P(\bar{\nu}_e \to \bar{\nu}_e)$$

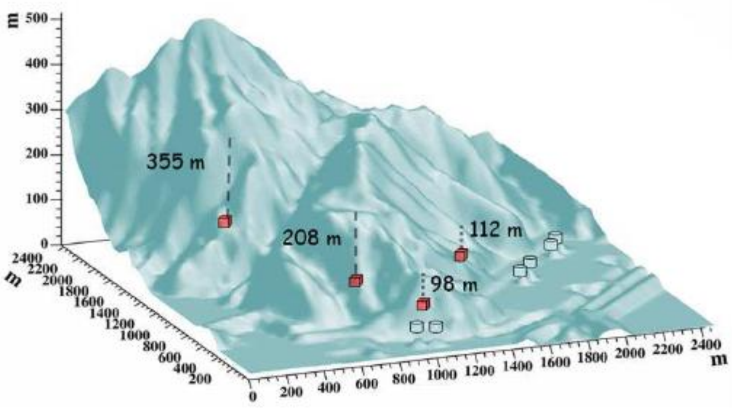
$$\simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(1.267\cdot\Delta m^2_{21}\cdot\frac{L}{E})$$

$$-\sin^2 2\theta_{13}\sin^2(1.267\cdot\Delta m^2_{32}\cdot\frac{L}{E})$$

Experimental Layout







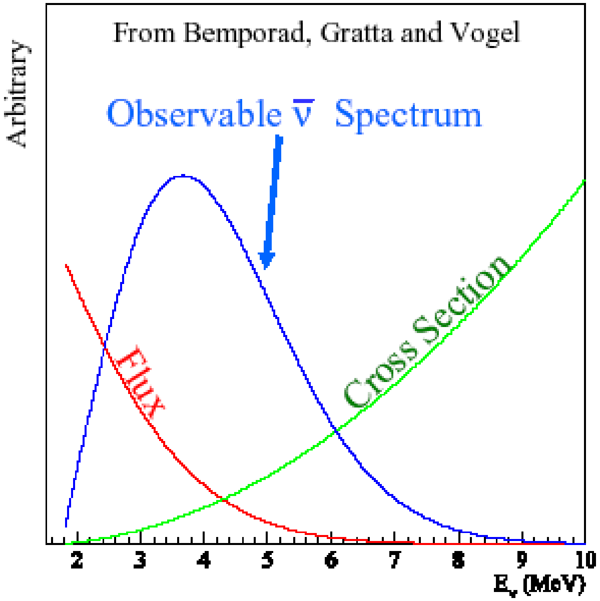
Neutrino Detection at DayaBay

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

Prompt signal: $e^+ + e^- \rightarrow 2\gamma\text{'s}$ $\quad (E_{e^+} > 2m_e = 1.022\,\mathrm{MeV})$

Delayed signal: $\mathrm{n} + \mathrm{Gd} \rightarrow \mathrm{Gd}' + \gamma\text{'s}$ $\quad (\sum E_\gamma \sim 8\,\mathrm{MeV},\ \tau_0 \sim 28\mu s)$

Delayed signal: $\mathrm{n} + \mathrm{p} \rightarrow \mathrm{d} + \gamma$ $\quad (E_\gamma = 2.2\,\mathrm{MeV},\ \tau_0 \sim 180\mu s)$



Neutrino energy: Threshold=**1.8 MeV**

$$E_{\bar{\nu}} \cong T_{e^+} + T_\mathrm{n} + (M_\mathrm{n} - M_\mathrm{p}) + m_{e^+}$$

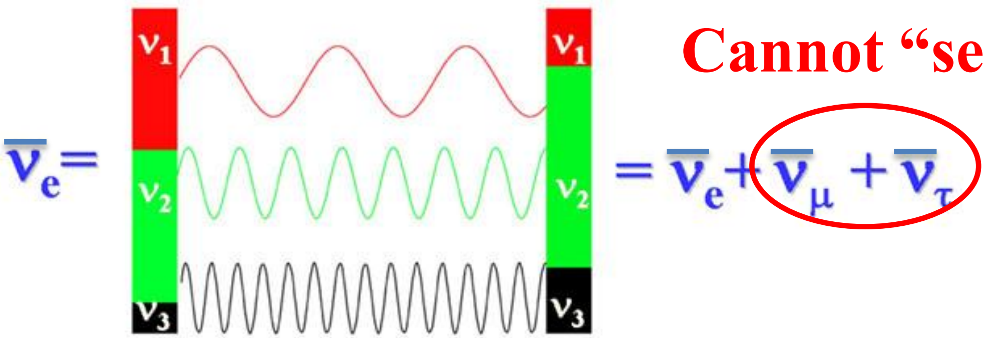
Antineutrino Interaction Rate

(events/day per AD module, 100%eff.)

Daya Bay near site	**960**
Ling Ao near site	**760**
Far site	**90**

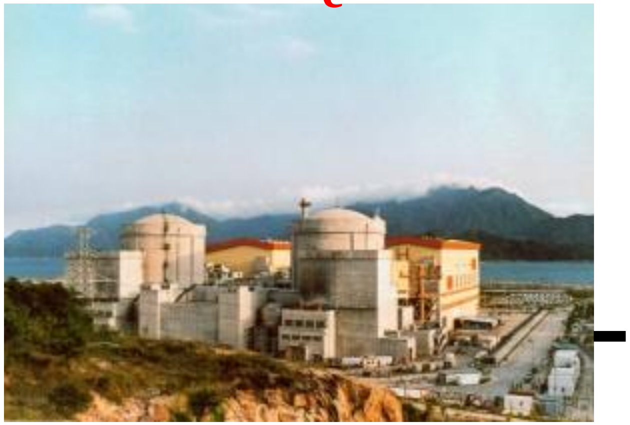
No Oscillation

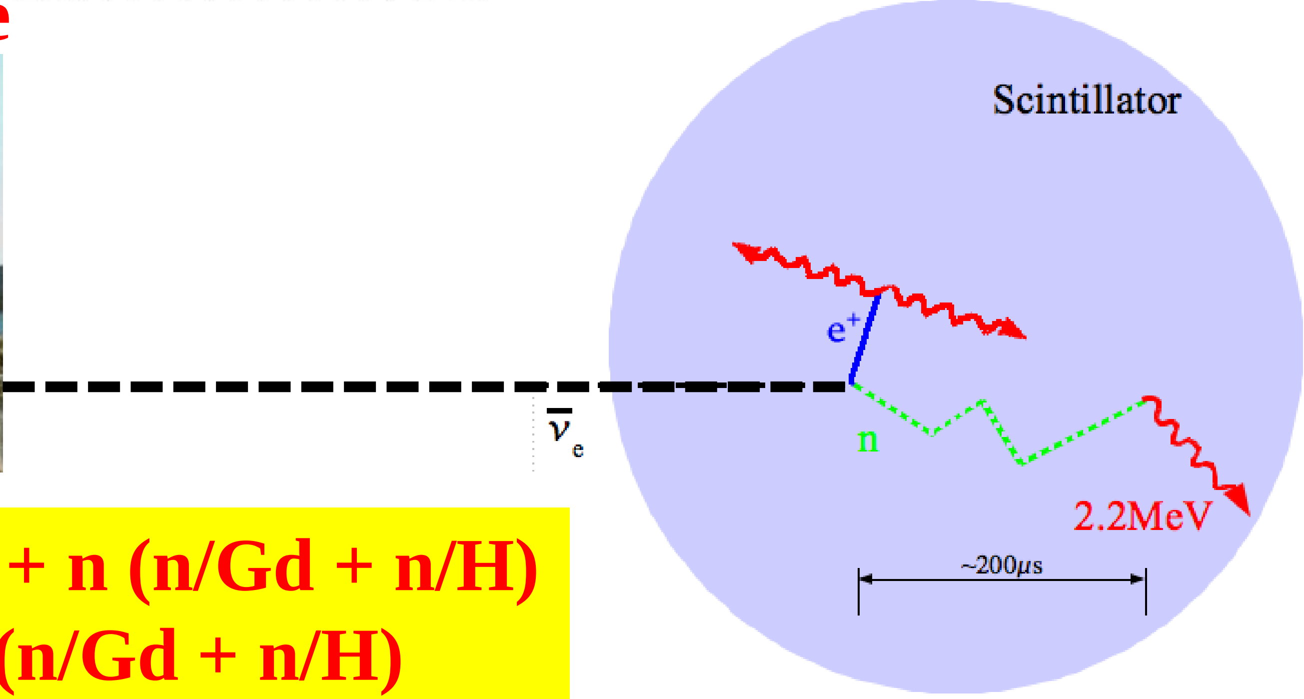
Signature of an IBD Signal



Cannot "see" at Daya Bay

6×10^{20} $\bar{\nu}_e$'s/s/core

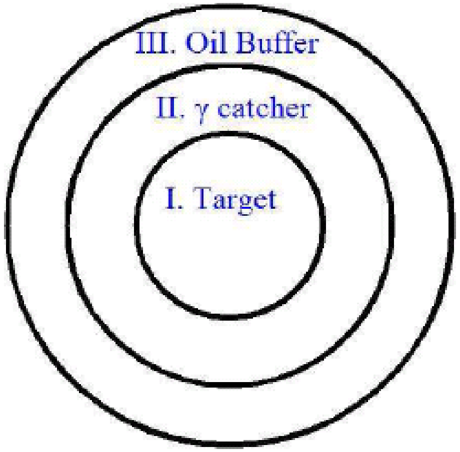


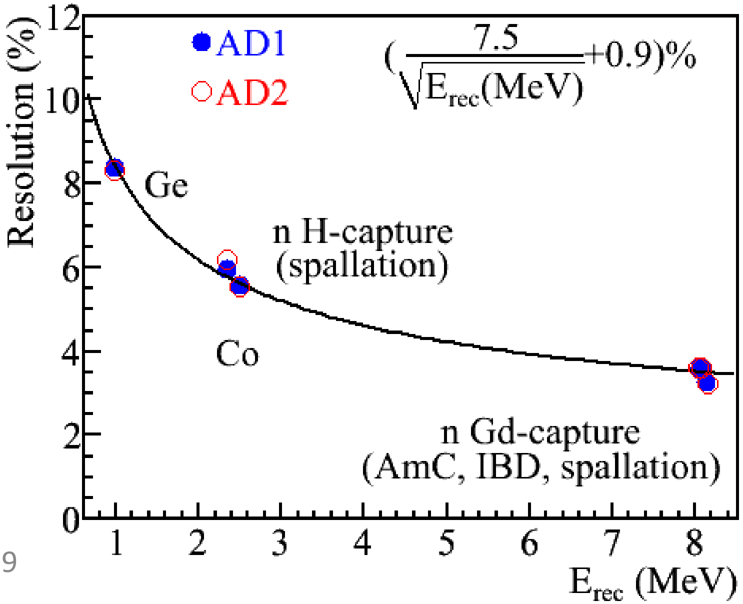


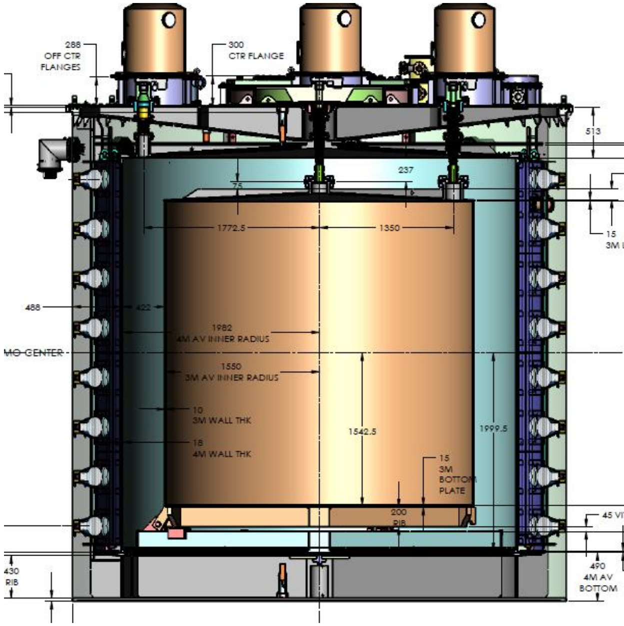
- ✓LS+Gd zone: e^+ + n (n/Gd + n/H)
- ✓LS zone: e^+ + n (n/Gd + n/H)
- ✓Uniform scintillation light

Anti-neutrino Detector

- **Three zones modular structure:**
  - Target: 20t, 1.6m Gd-loaded scintillator
  - γ-catcher: 20t, 45cm normal scintillator
  - Buffer shielding: 40t, 45cm oil
- **Reflector at top and bottom**
- **192 8”PMT/module**
- **PMT coverage: 12%(with reflector)**

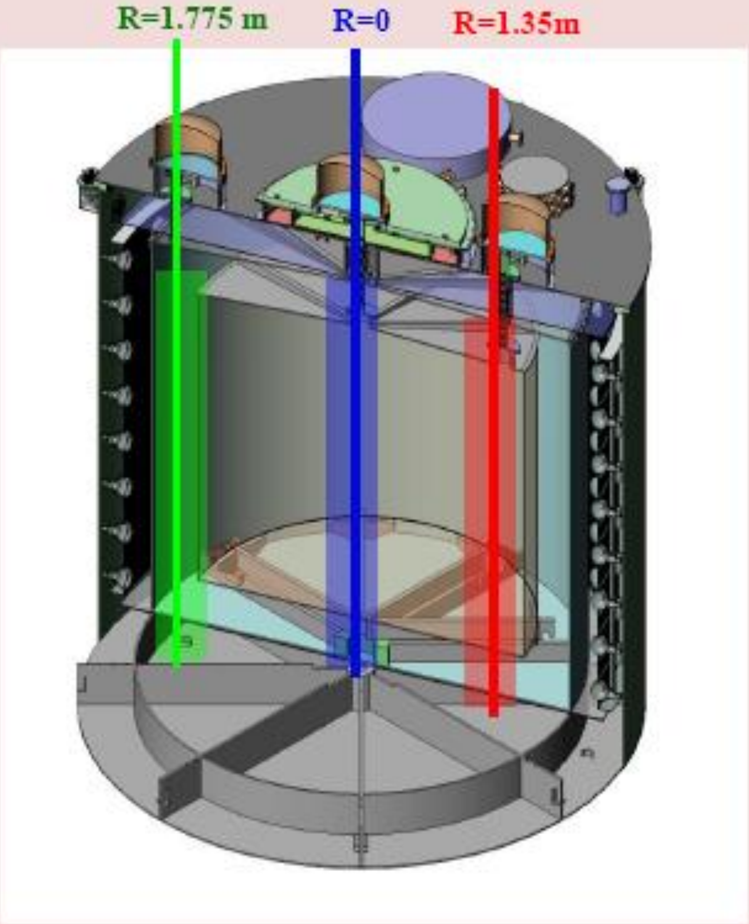






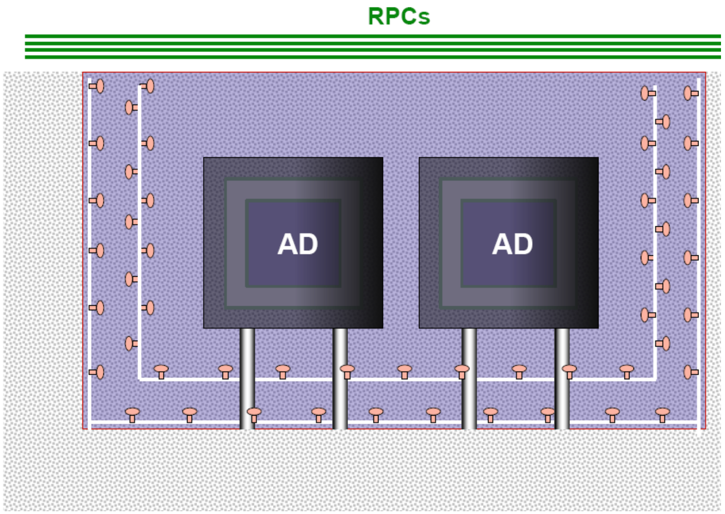
Automatic Calibration Unit

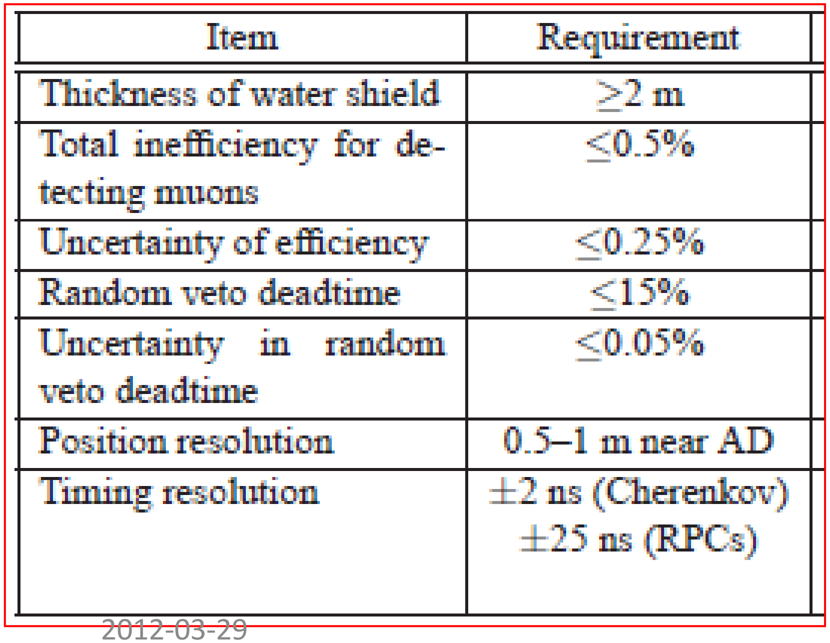
- ☐ **Three Z axis:**
  - – **Center, edge, γ-catcher**
- ☐ **Each axis with 3 sources:**
  - – **LED**
    - **t_0, gain and relative QE**
  - – **^{68}Ge (2×0.511 MeV γ's)**
    - **Threshold & non-linearity…**
  - – **^{241}Am-^{13}C + ^{60}Co (1.17+1.33 MeV γ's)**
    - **Neutron capture time, …**
    - **Energy scale, response function, …**
- ☐ **Once per week**



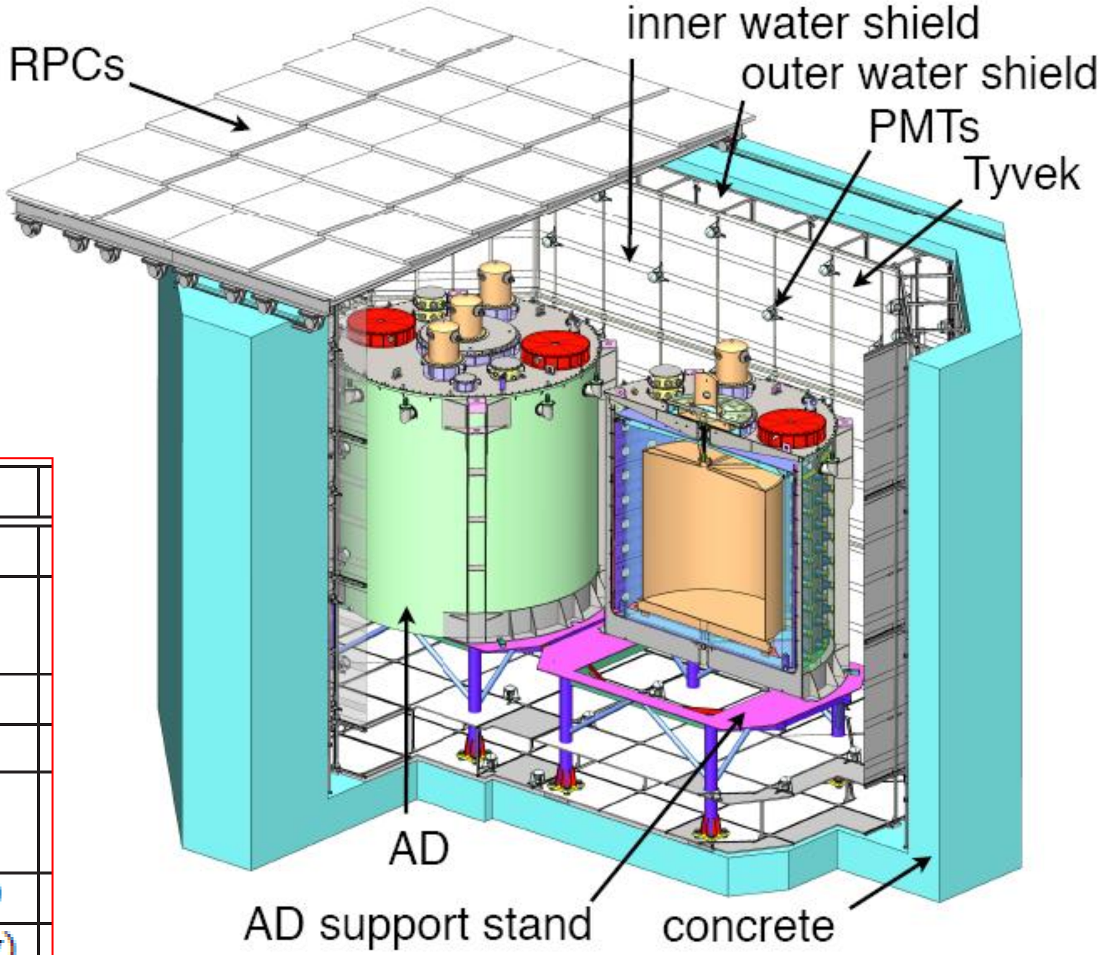
Automated Calibration

Muon Veto Detector

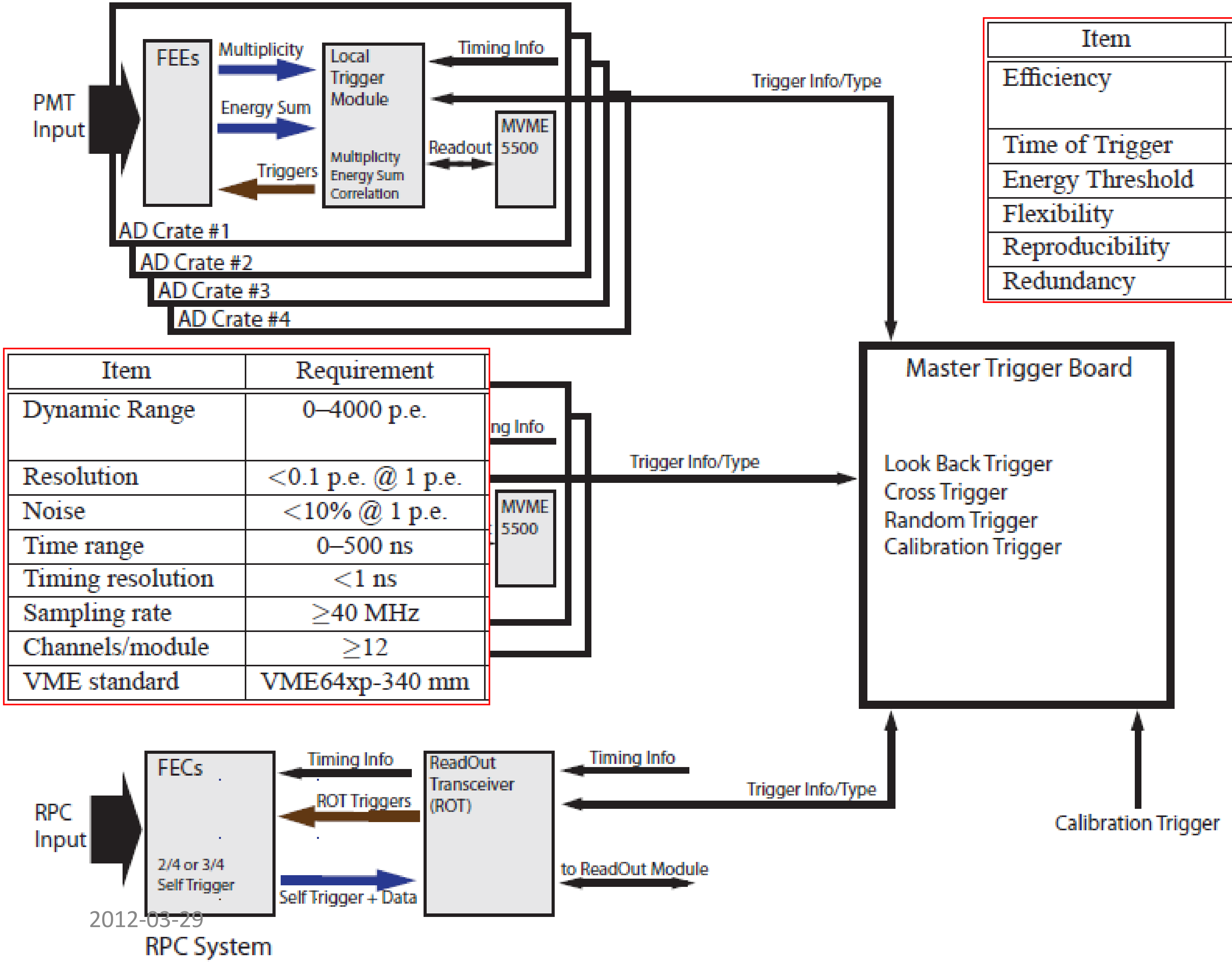




Item	Requirement
Thickness of water shield	≥2 m
Total inefficiency for detecting muons	≤0.5%
Uncertainty of efficiency	≤0.25%
Random veto deadtime	≤15%
Uncertainty in random veto deadtime	≤0.05%
Position resolution	0.5–1 m near AD
Timing resolution	±2 ns (Cherenkov) ±25 ns (RPCs)



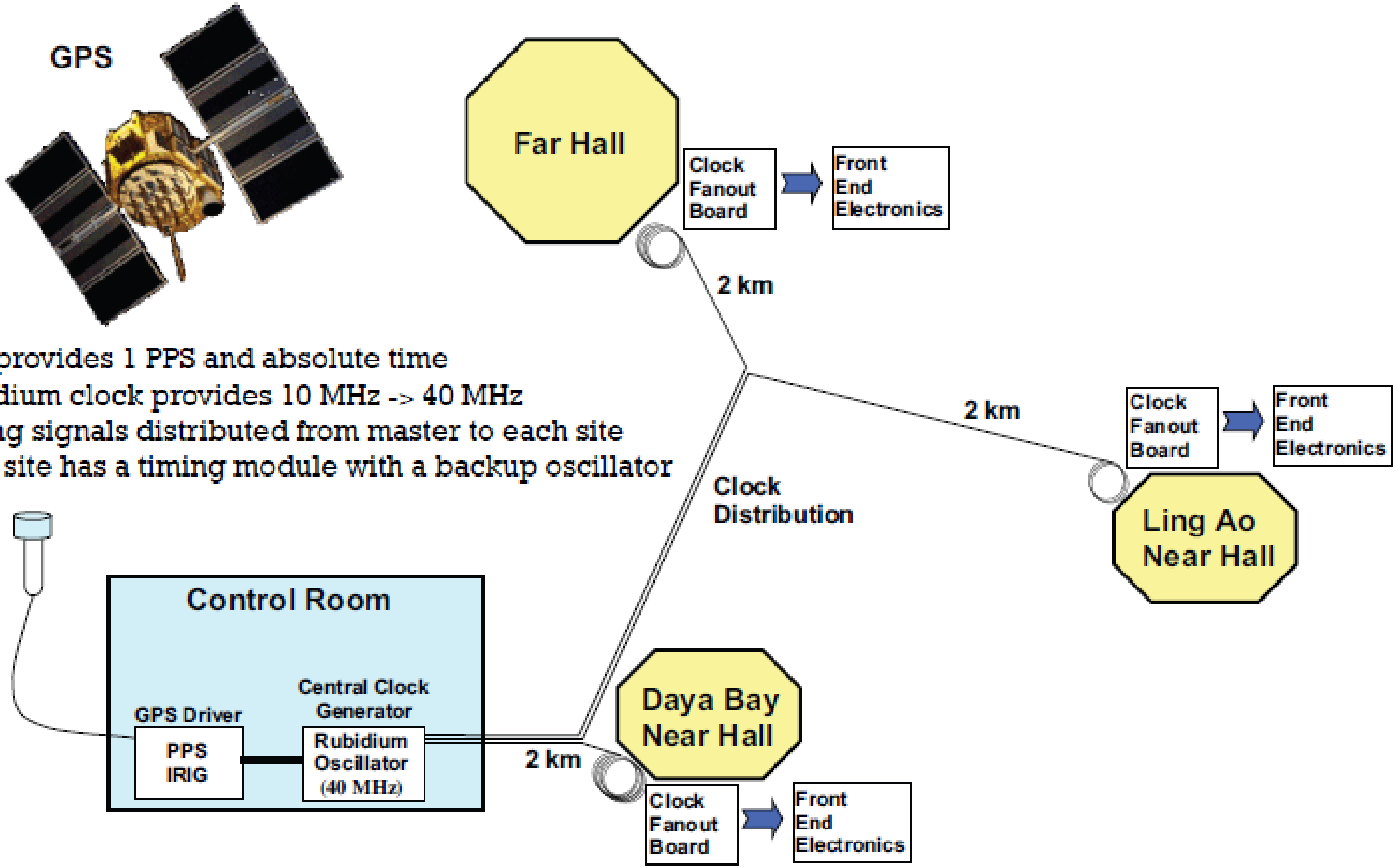
FEE and Trigger System



Item	Requirement
Efficiency	>99%
Time of Trigger	13 ns
Energy Threshold	~0.7 MeV
Flexibility	dynamic algorithms
Reproducibility	< a few ns
Redundancy	>1 algorithm

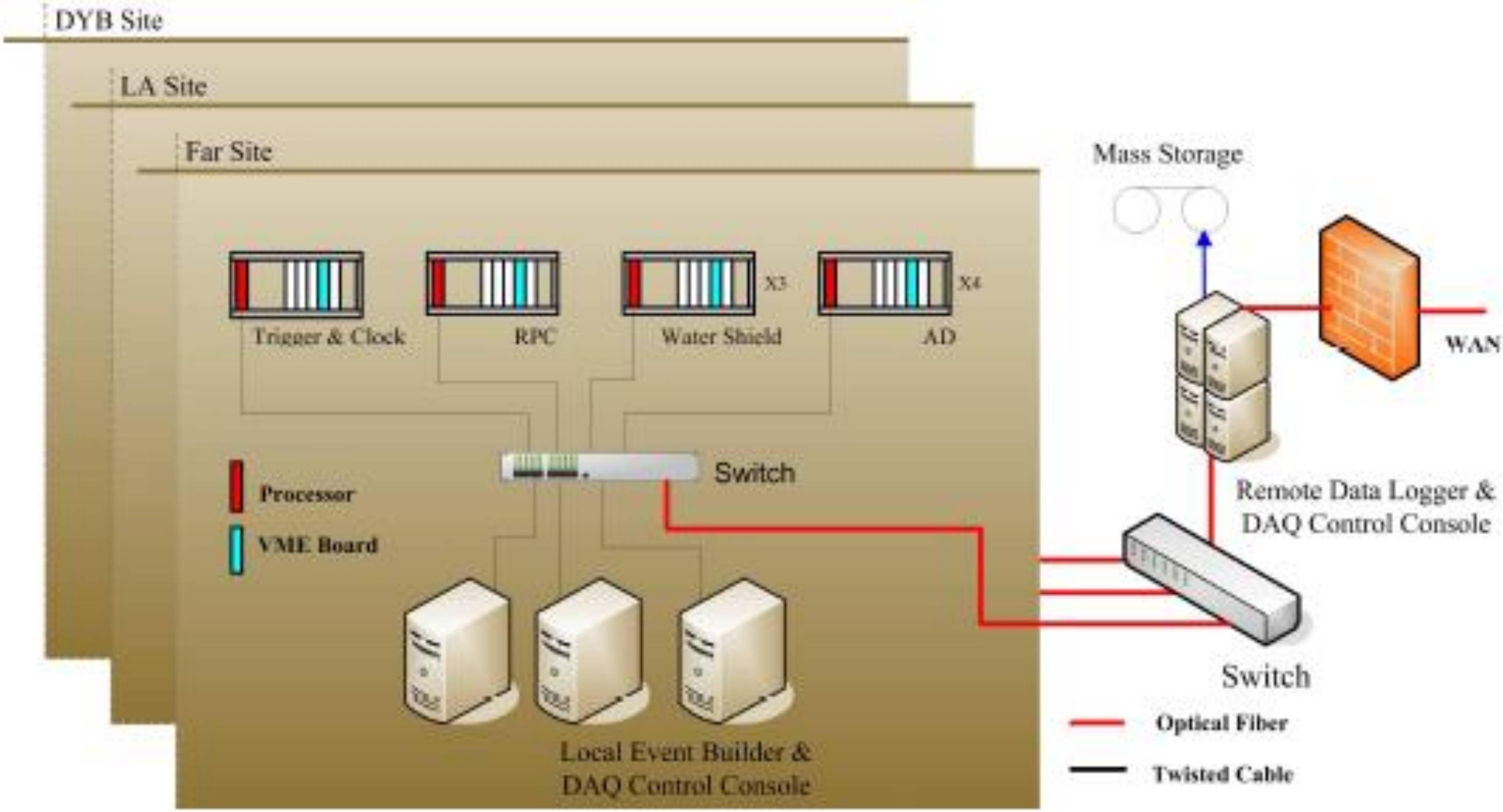
Item	Requirement
Dynamic Range	0–4000 p.e.
Resolution	<0.1 p.e. @ 1 p.e.
Noise	<10% @ 1 p.e.
Time range	0–500 ns
Timing resolution	<1 ns
Sampling rate	≥40 MHz
Channels/module	≥12
VME standard	VME64xp-340 mm

Clock System

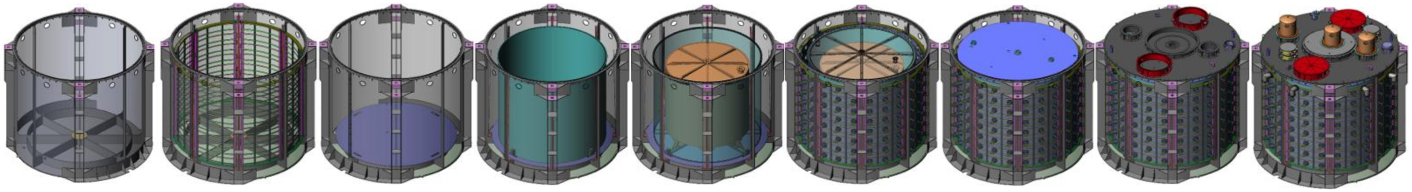


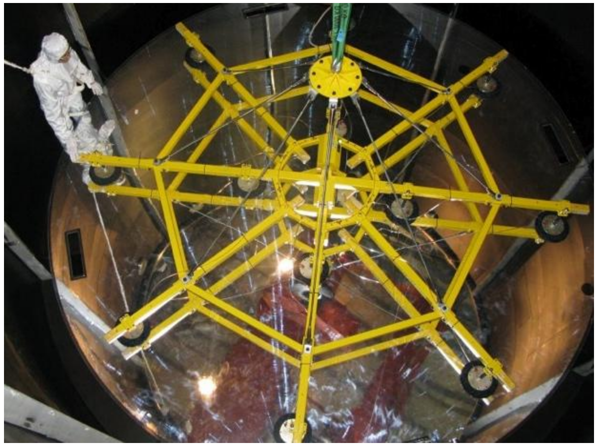
- GPS provides 1 PPS and absolute time
- Rubidium clock provides 10 MHz -> 40 MHz
- Timing signals distributed from master to each site
- Each site has a timing module with a backup oscillator

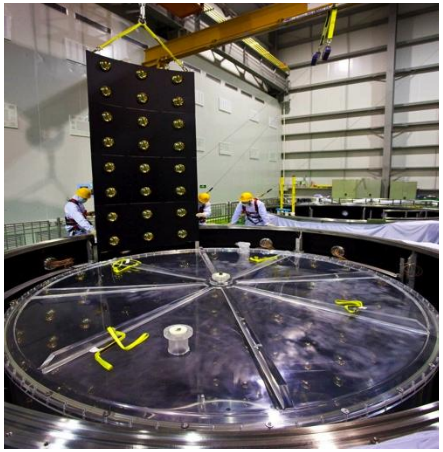
Data Acquisition System

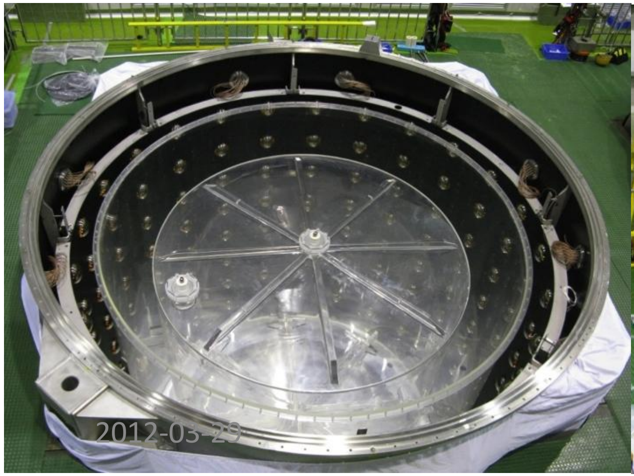


Antineutrino Detector Assembly

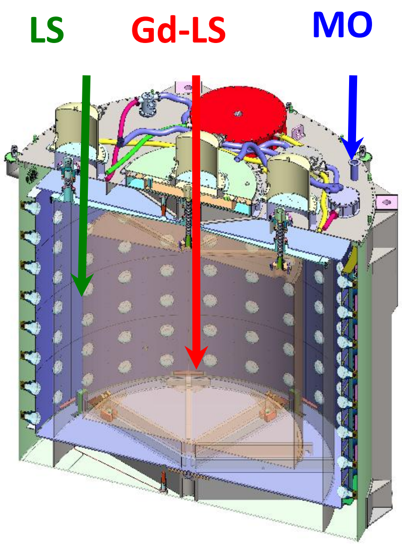


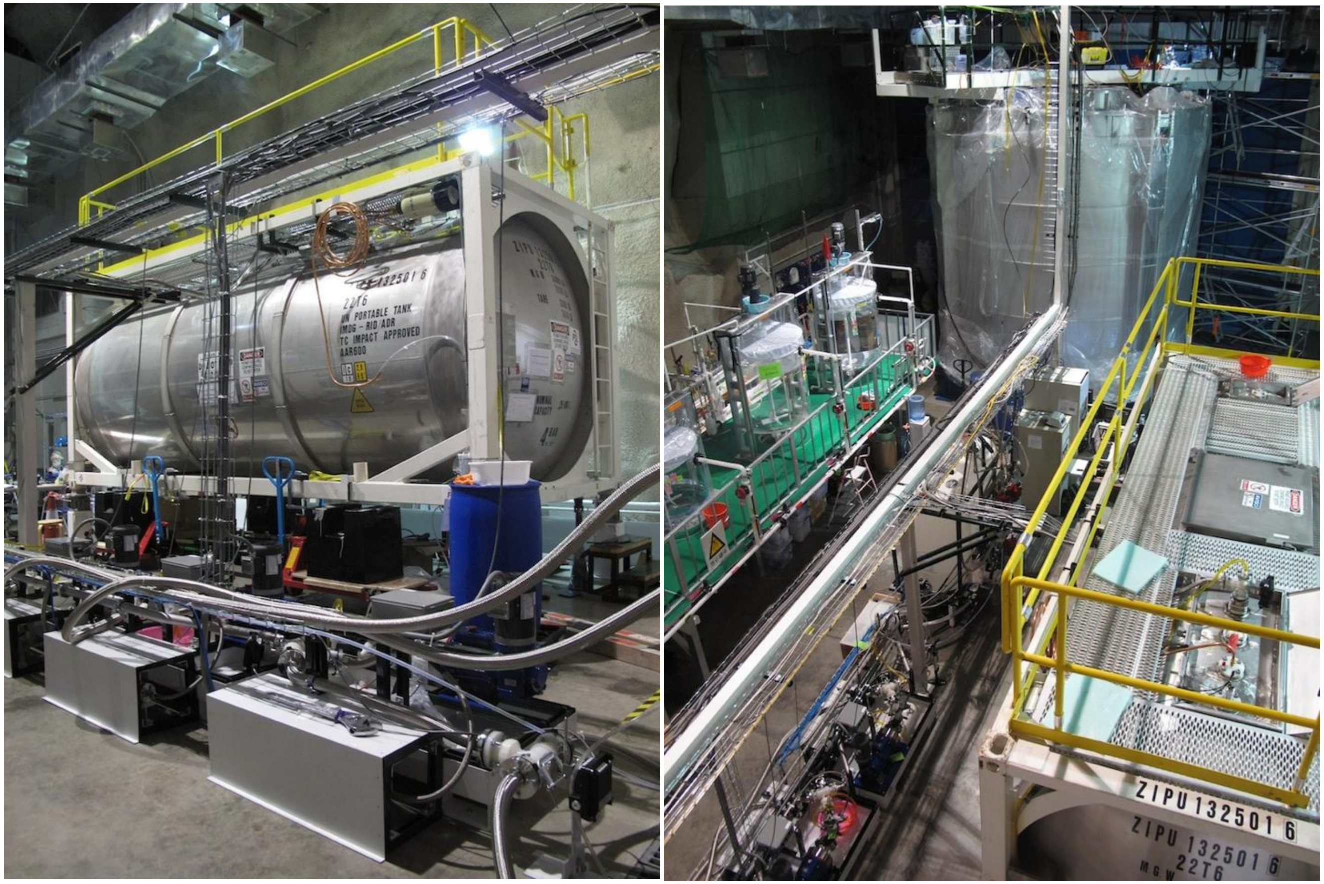






Detector Filling

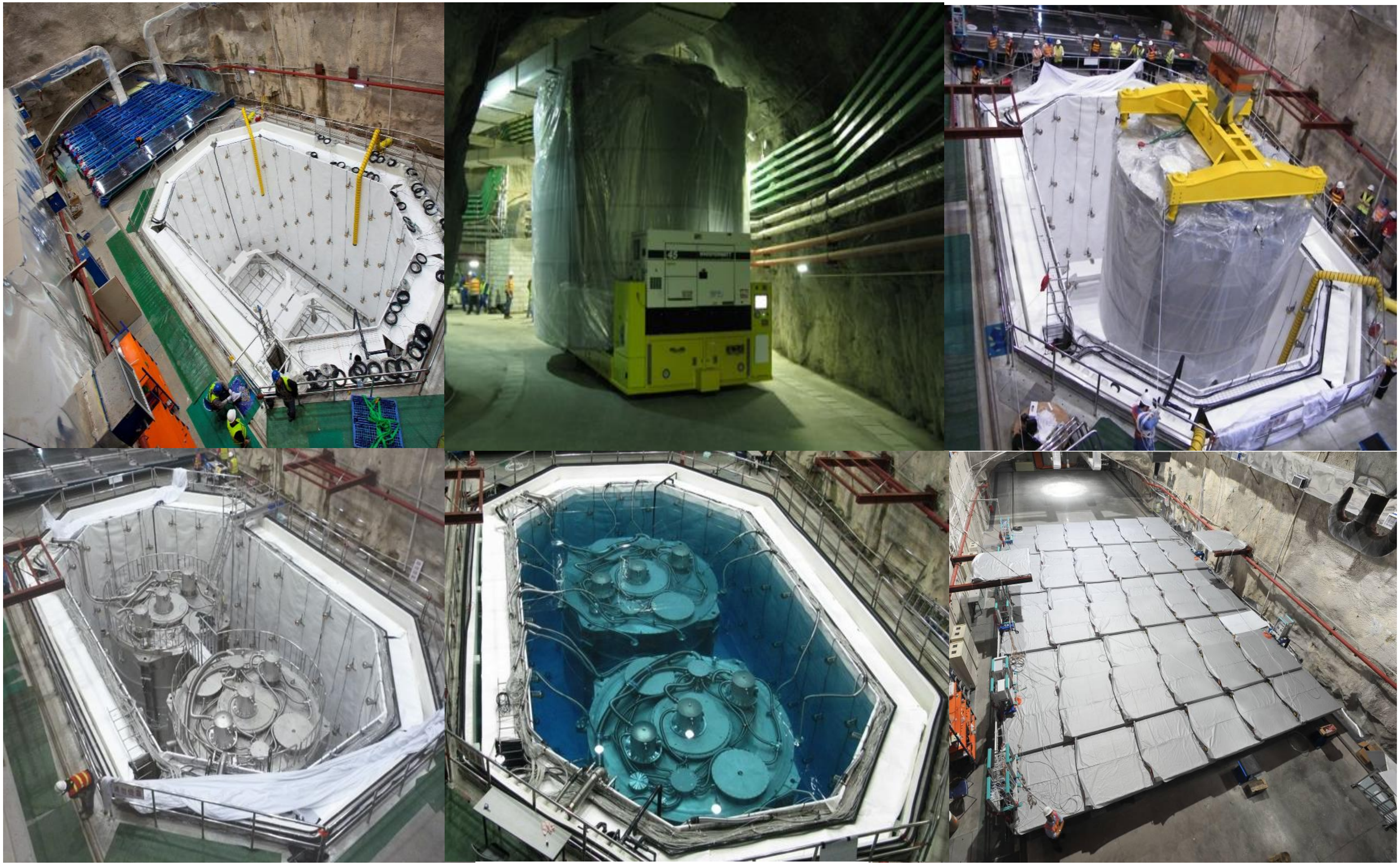




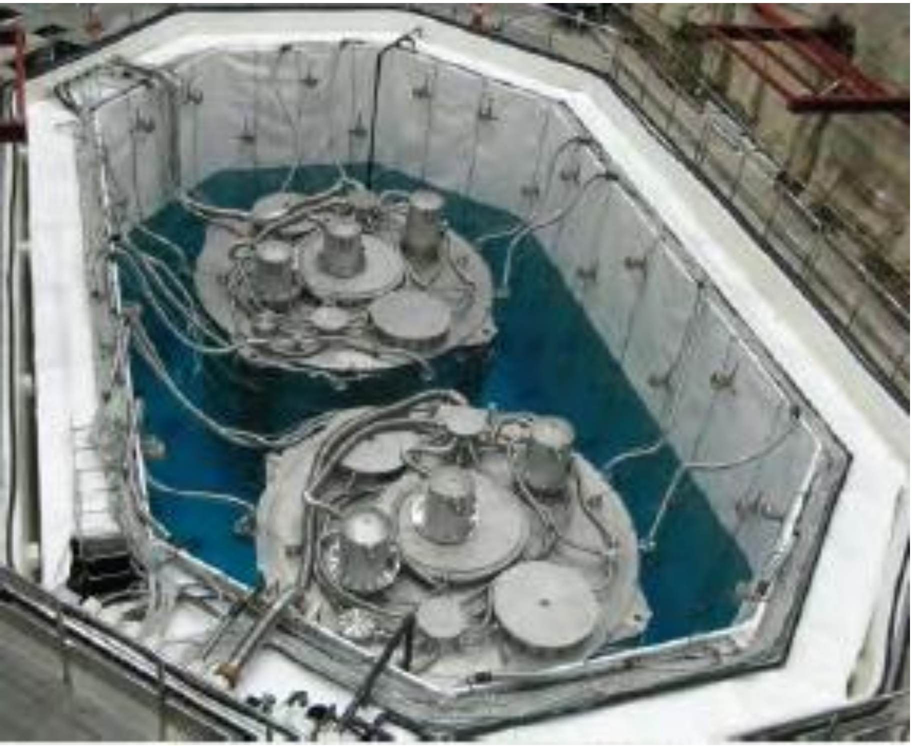
Detectors are filled from same reservoirs *"in-pairs"* within < 2 weeks.

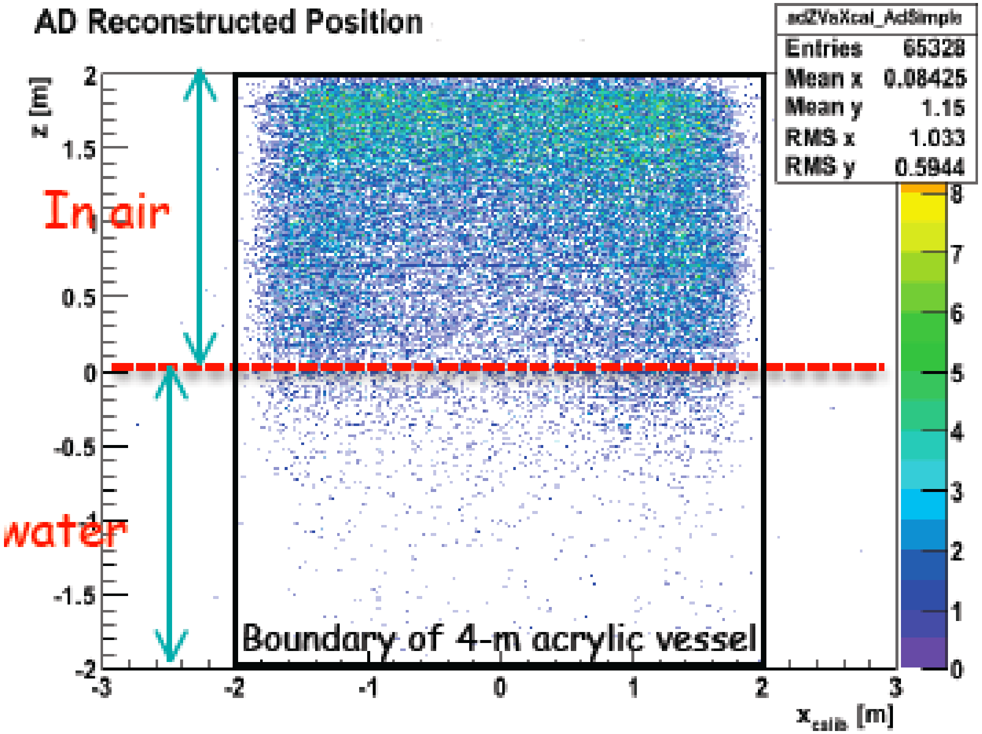
Target mass determination error ± 3kg out of 20,000 <0.03% during data taking period

Detector Deployment

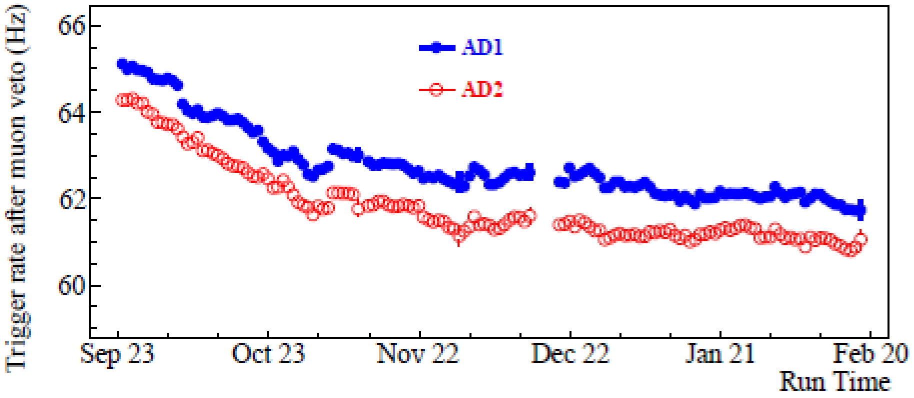


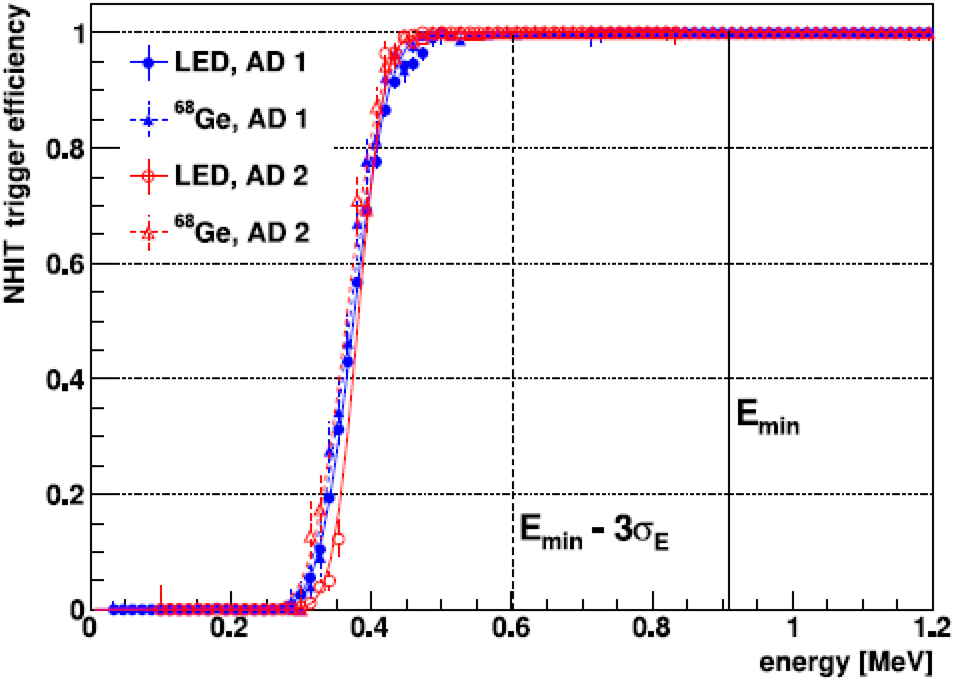
Radioactivity Background Shielding

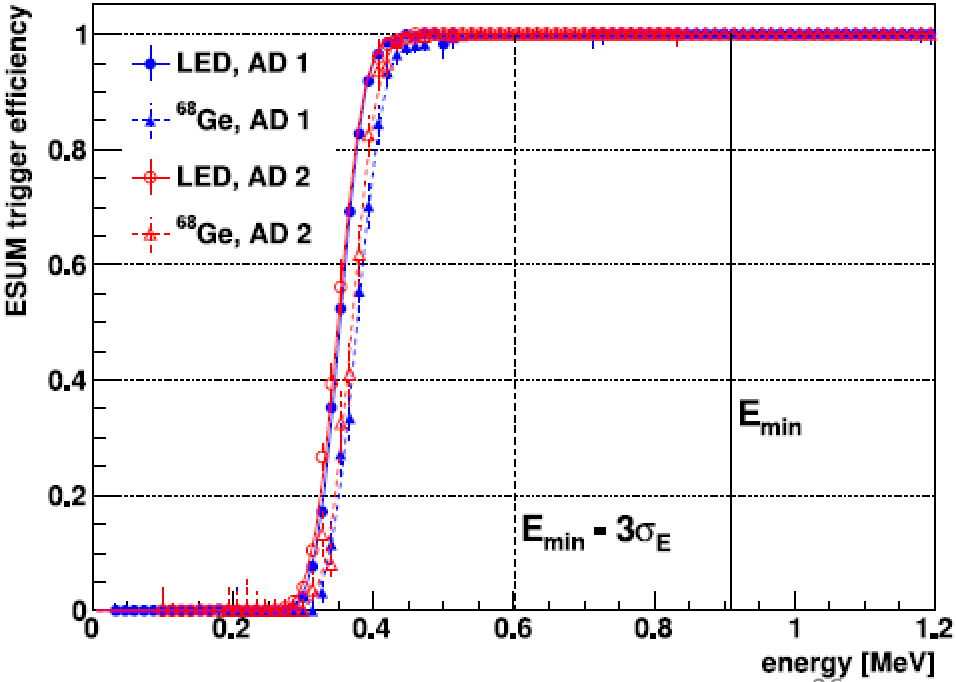




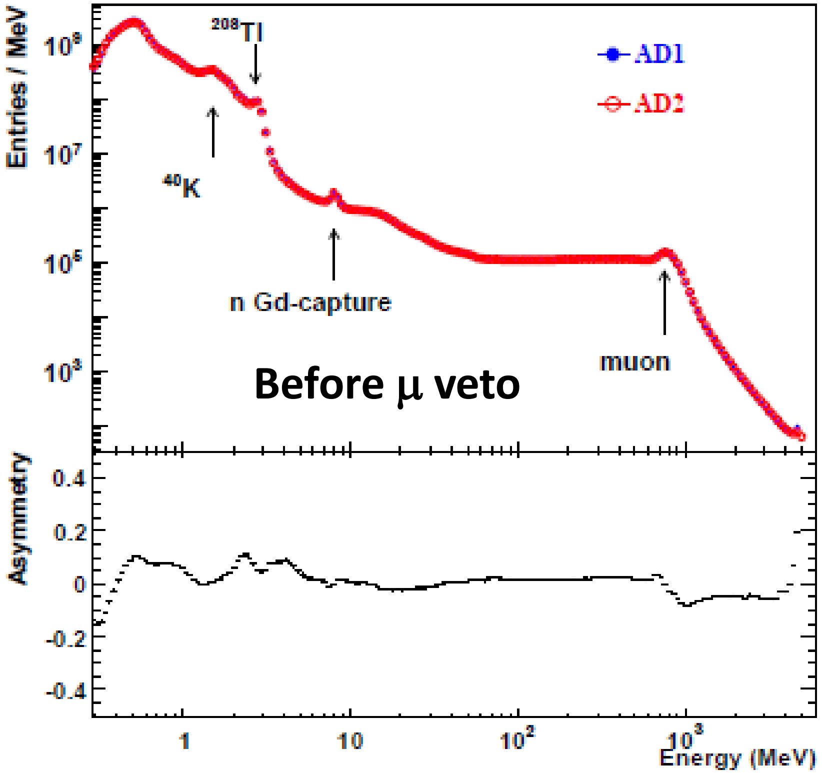
Trigger performance

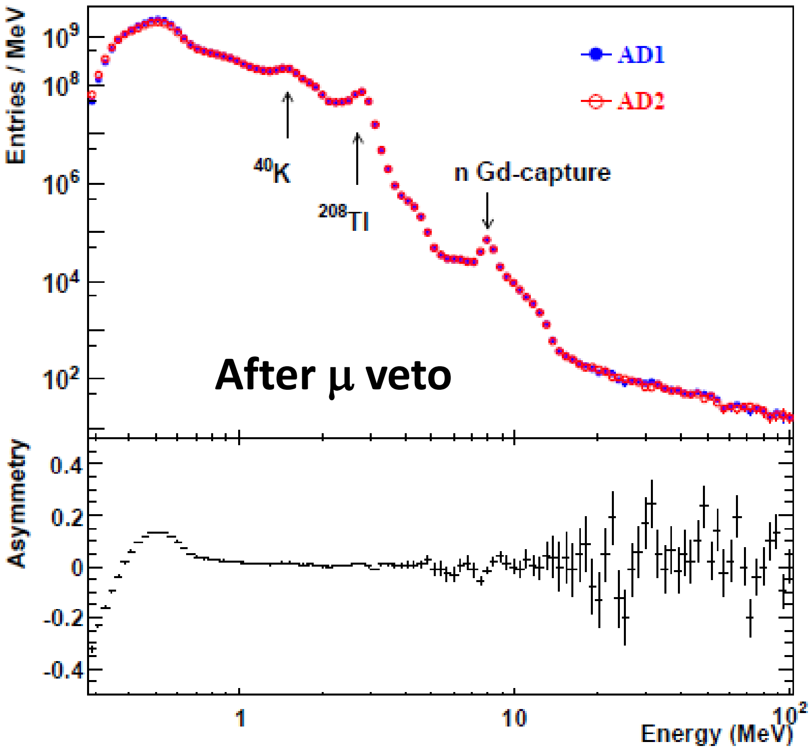






Spectrum for all AD triggers



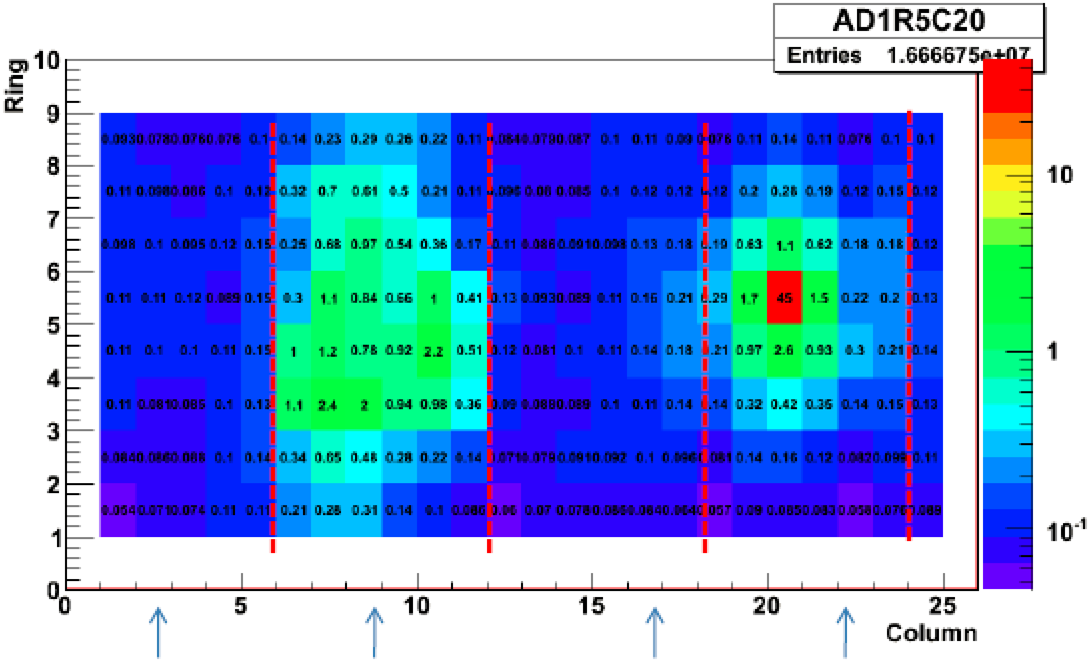


Trigger threshold 0.4 MeV

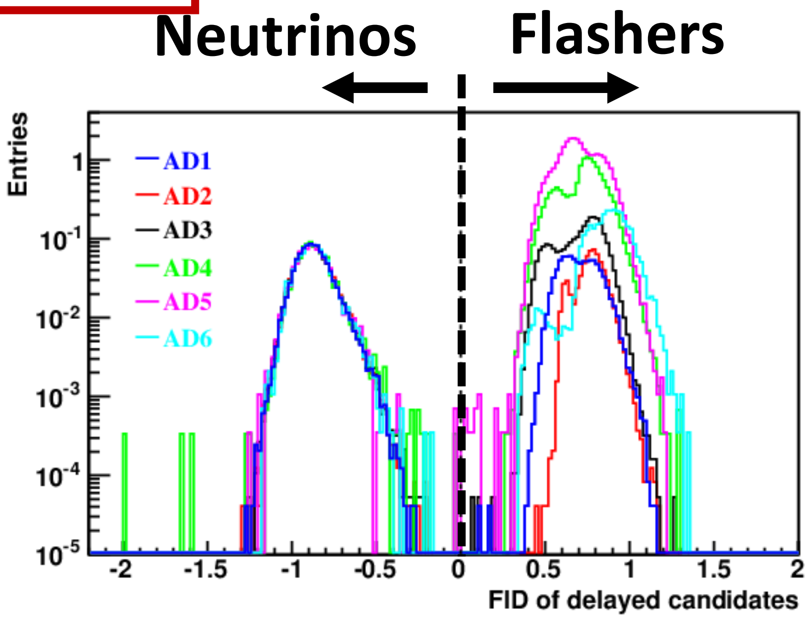
AD1	AD2	AD3	AD4	AD5	AD6	
~285	~270	~230	~180	~150	~150	Hz

Unexpected PMT Feature

Inefficiency to neutrinos:
0.024% ± 0.006%(stat)
Contamination: < 0.01%

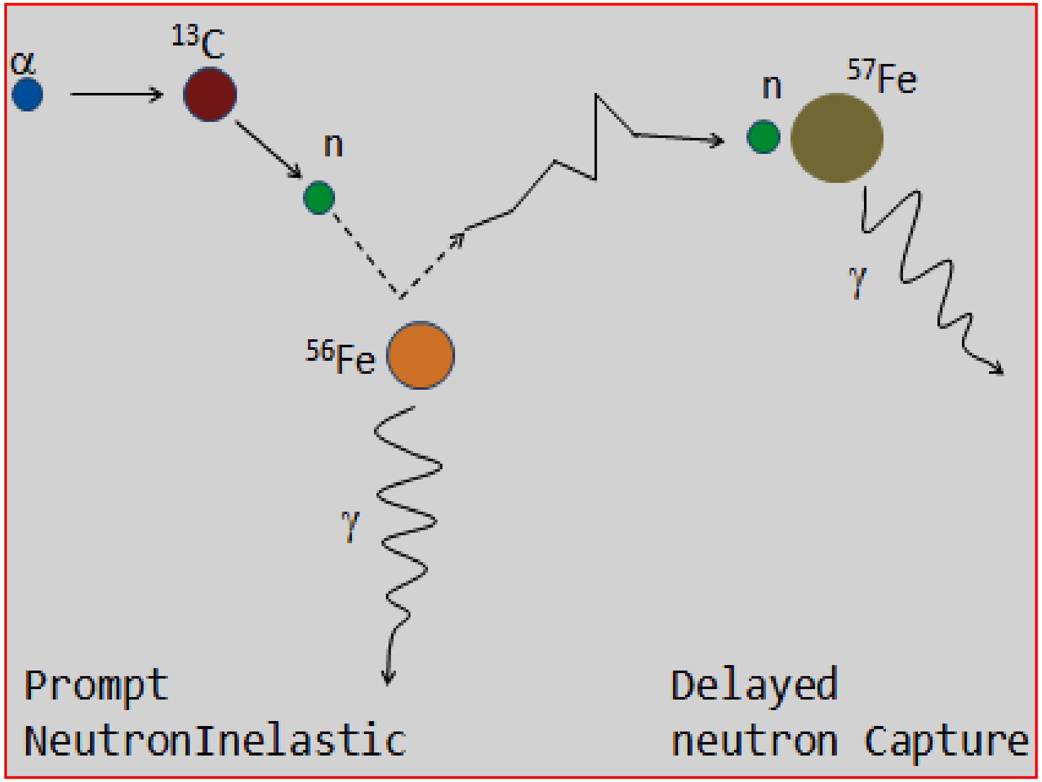


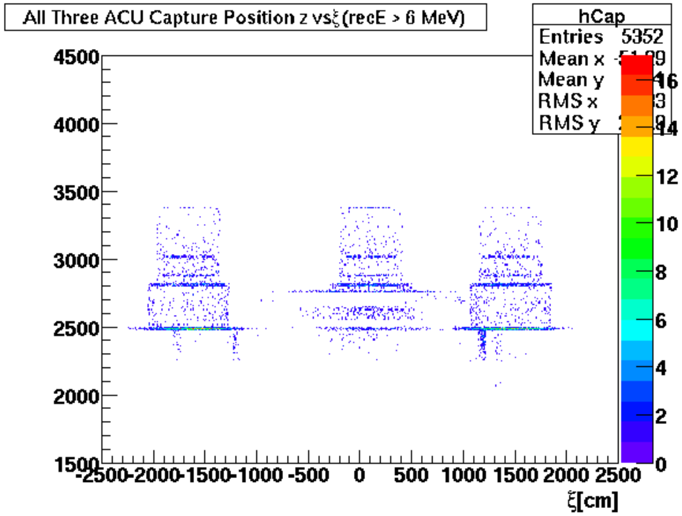
Quadrant 4 Quadrant 3 Quadrant 2 Quadrant 1, where the hottest PMT locates



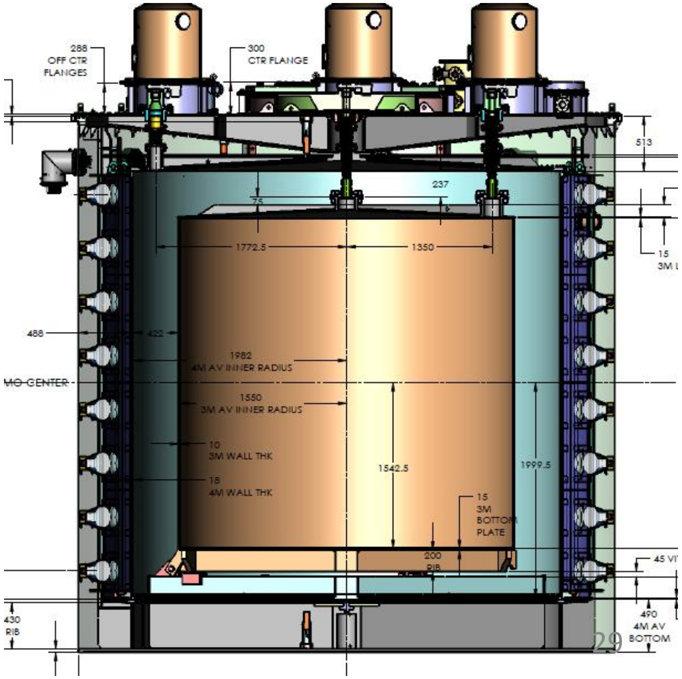
$$\log_{10}\left((\frac{Quadrant}{1.})^2 + (\frac{MaxQ}{0.45})^2\right) < 0$$

Unexpected Bkg from ACU





- ☐ ^{241}Am-^{13}C leakage
- ☐ Uncorrelated: 230evts/day/AD
- ☐ Correlated: 0.2evts/day/AD



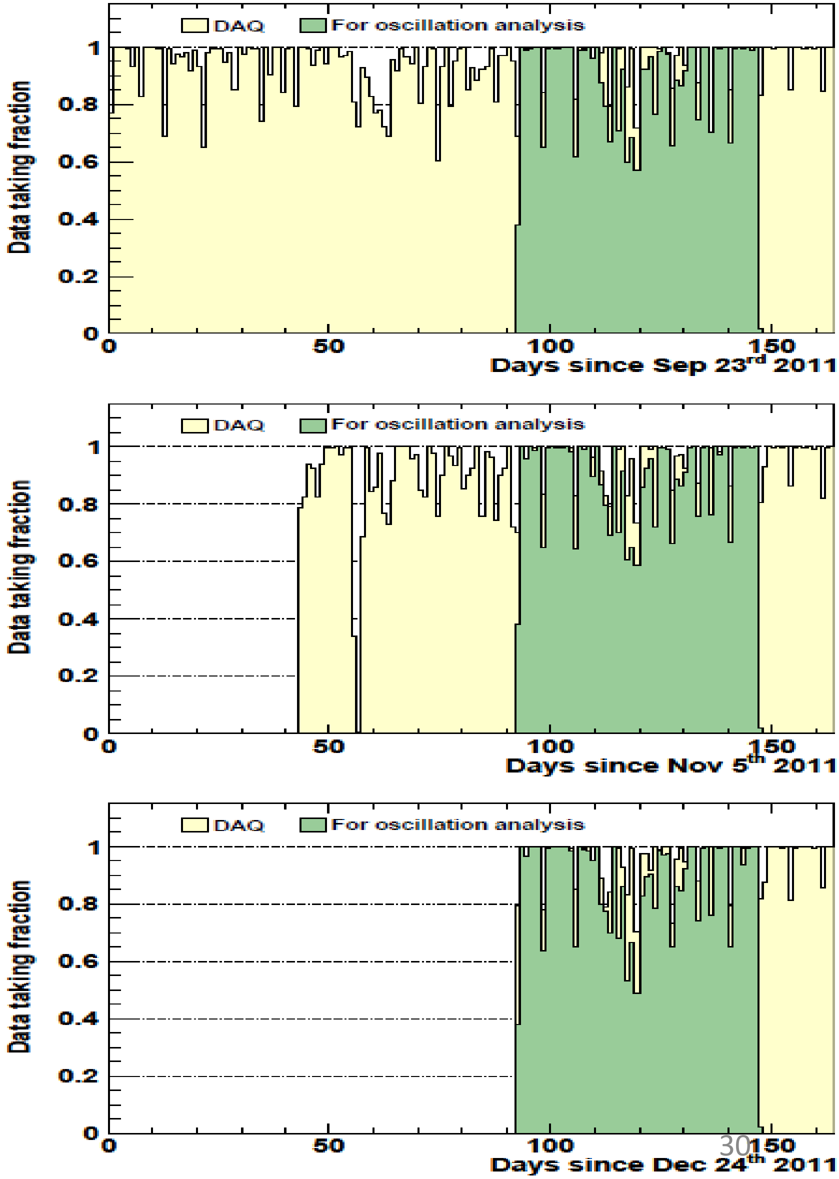
Detector live days

Current Oscillation Analysis:

- Dec. 24, 2011 – Feb. 17, 2012
- All 3 halls (6 ADs) operating
- DAQ uptime: >97%
- Antineutrino data: ~89%

Two Detector Comparison:

- Sep. 23, 2011 – Dec. 23, 2011
- Side-by-side comparison
- Demonstrated detector systematics better than requirements.
- Details presented in: arXiv:1202.6181 (2012)



Data Analysis

Blind Analysis

Motivation: Conceal the true value of $\sin^2 2\theta_{13}$

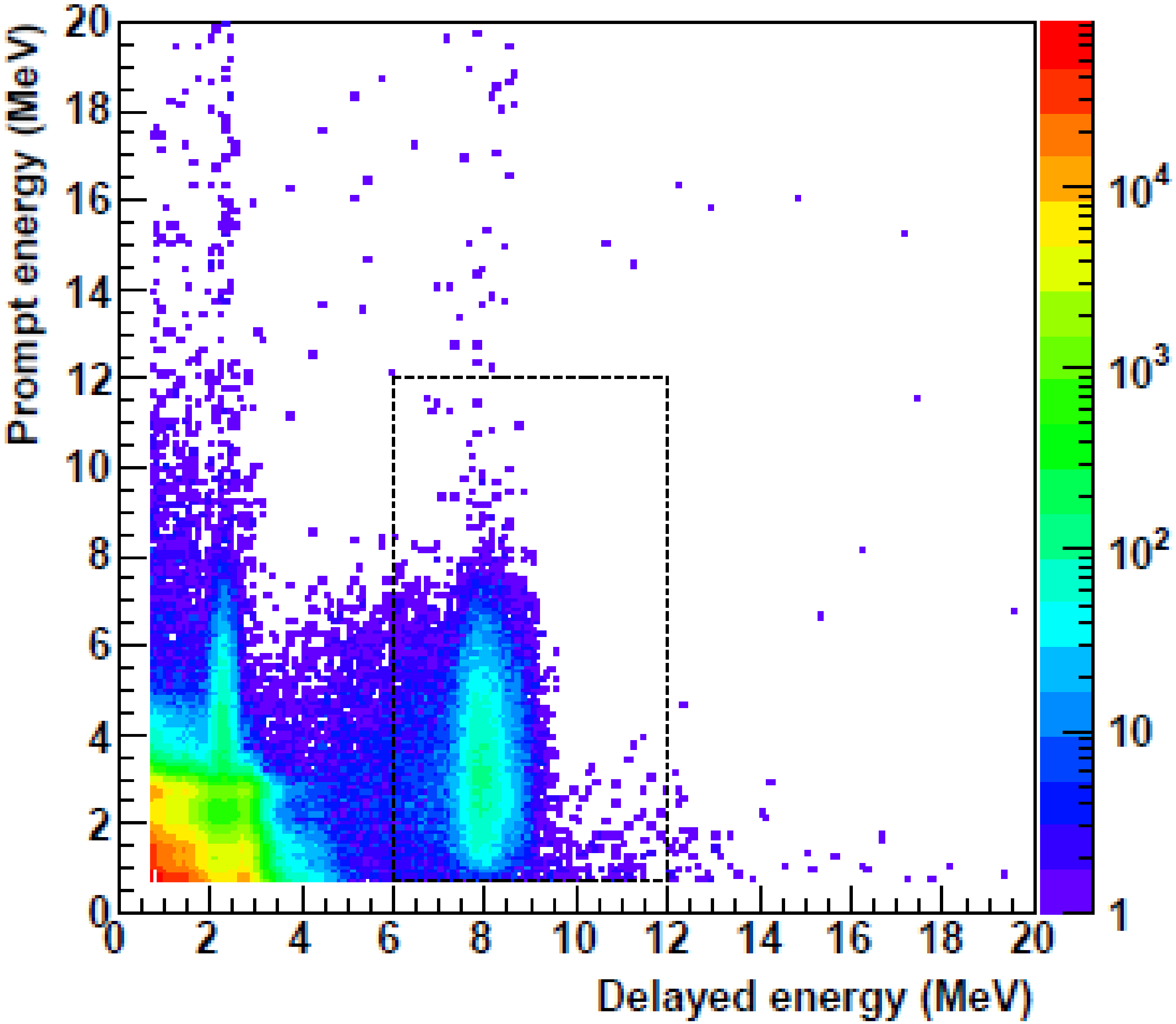
Parameter	Set uncertainty	Actual precision
Target mass	0.5%	0.1%
Base line	5m	30cm
Reactor flux	10%	0.13%

- Nominal values initially assigned with large uncertainties.
- Precise values provided when all the analyses are finalized and frozen.

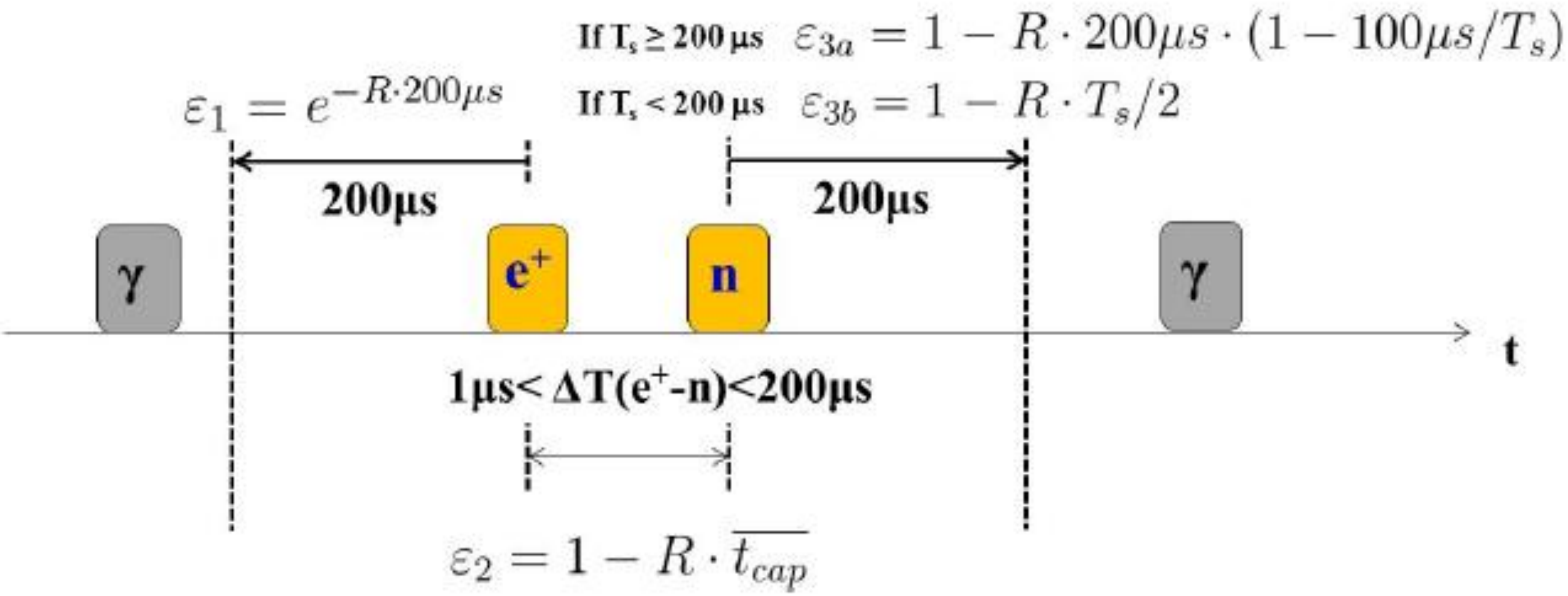
$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left[\frac{P_{\mathrm{sur}}(E, L_{\mathrm{f}})}{P_{\mathrm{sur}}(E, L_{\mathrm{n}})}\right]$$

Background Classification

- **Multiplicity**
  - ✓ γ + e/n
- **Accidentals**
  - ✓ 2 γ's
- **Fast neutrons**
  - ✓ γ + n
- **^{8}He/^{9}Li**
  - ✓ β+n
- **Am-C**
  - ✓ 2 γ's
- **^{13}C(α,n)^{16}O**

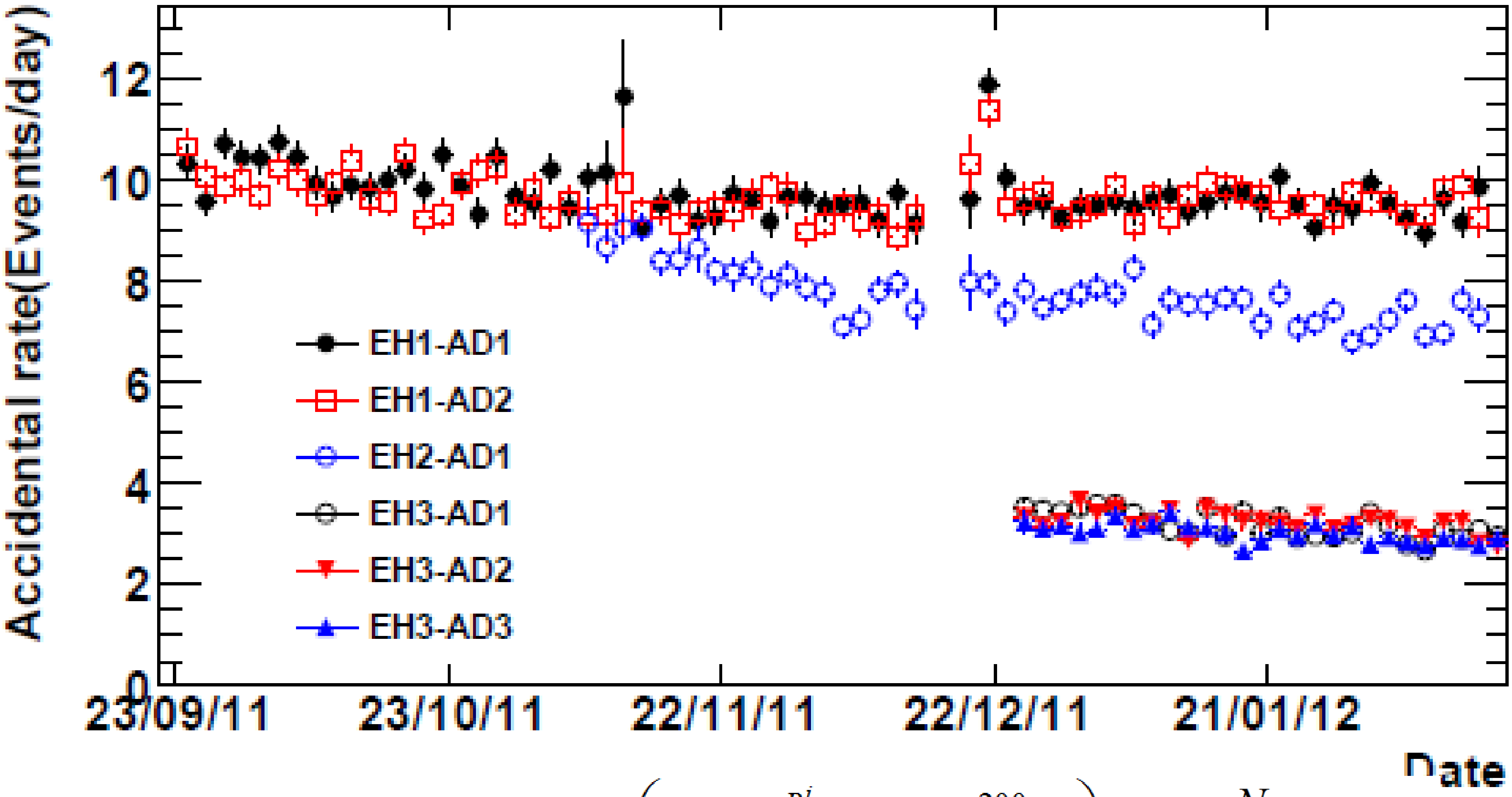


Multiplicity Cuts



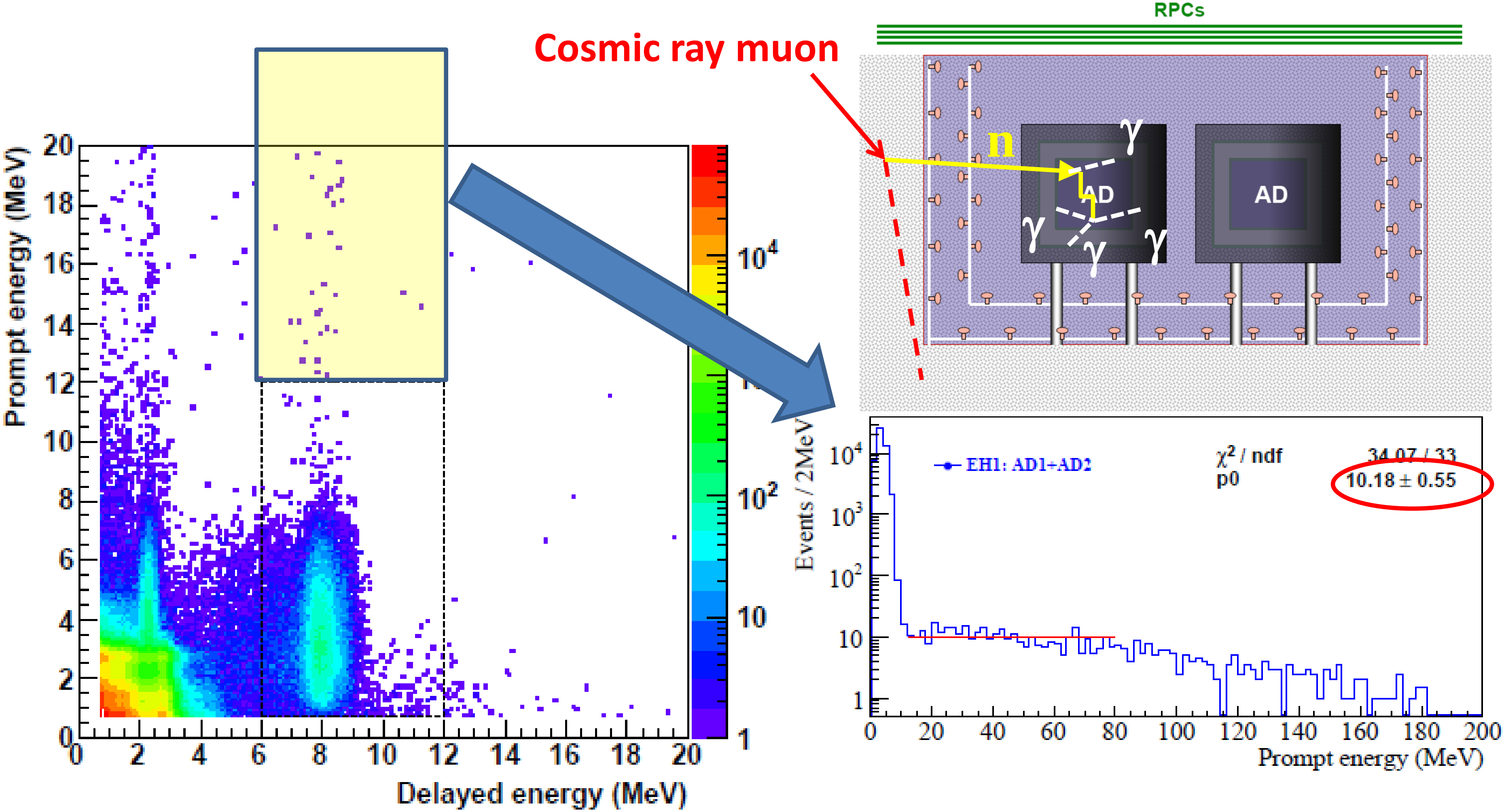
Multiplicity cut Efficiency = $\varepsilon_1 \times \varepsilon_2 \times \varepsilon_3$

Accidental Background



$$N_{\mathrm{accBkg}} = \sum_i N^i_{\text{n-like singles}} \bullet \left(1 - e^{-R^i_{e^+\text{-like triggers}} \bullet 200\,\mu s}\right) \pm \frac{N_{\mathrm{accBkg}}}{\sqrt{\sum_i N^i_{\text{n-like singles}}}}$$

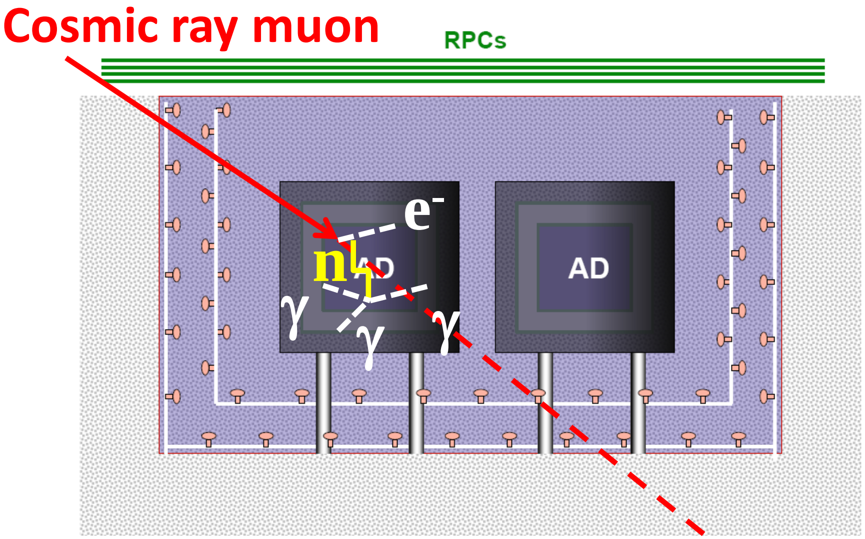
Fast Neutron Background



Prompt: n collides/stops in target
Delayed: n/Gd

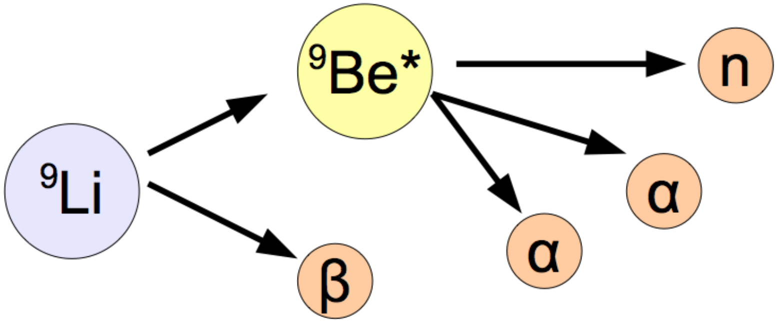
Background estimate: extrapolation method

^{8}He/^{9}Li Background



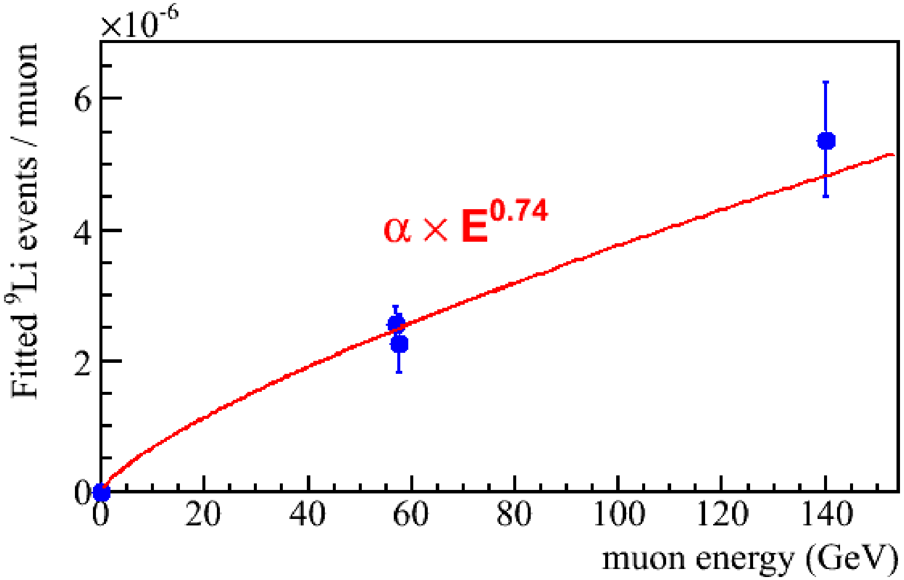
β-n decay:

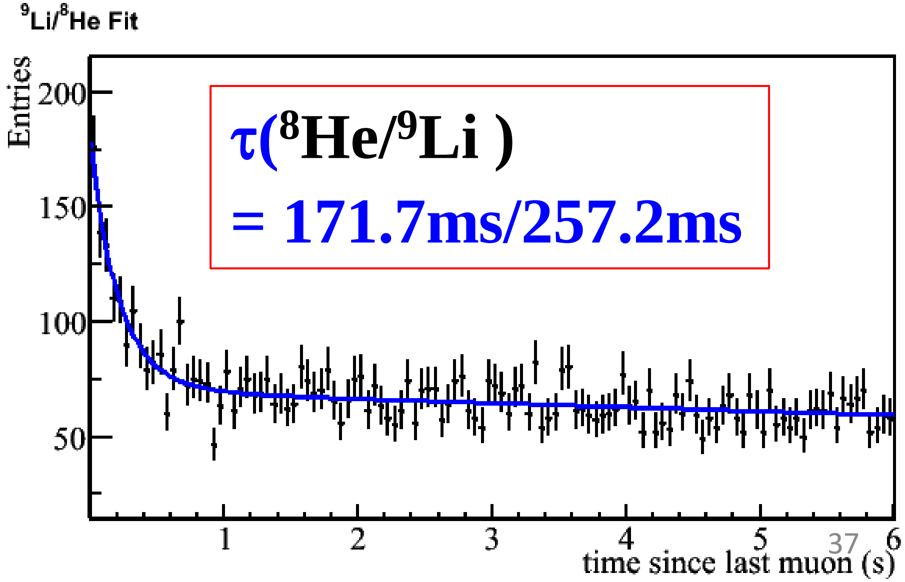
- Prompt: β-decay
- Delayed: neutron capture



Background estimate:

fit with known τ(^{8}He/^{9}Li)



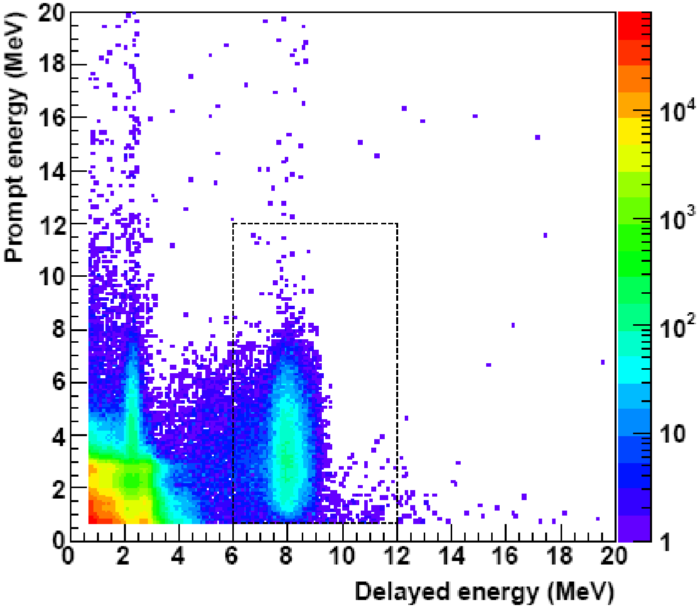


τ(^{8}He/^{9}Li)

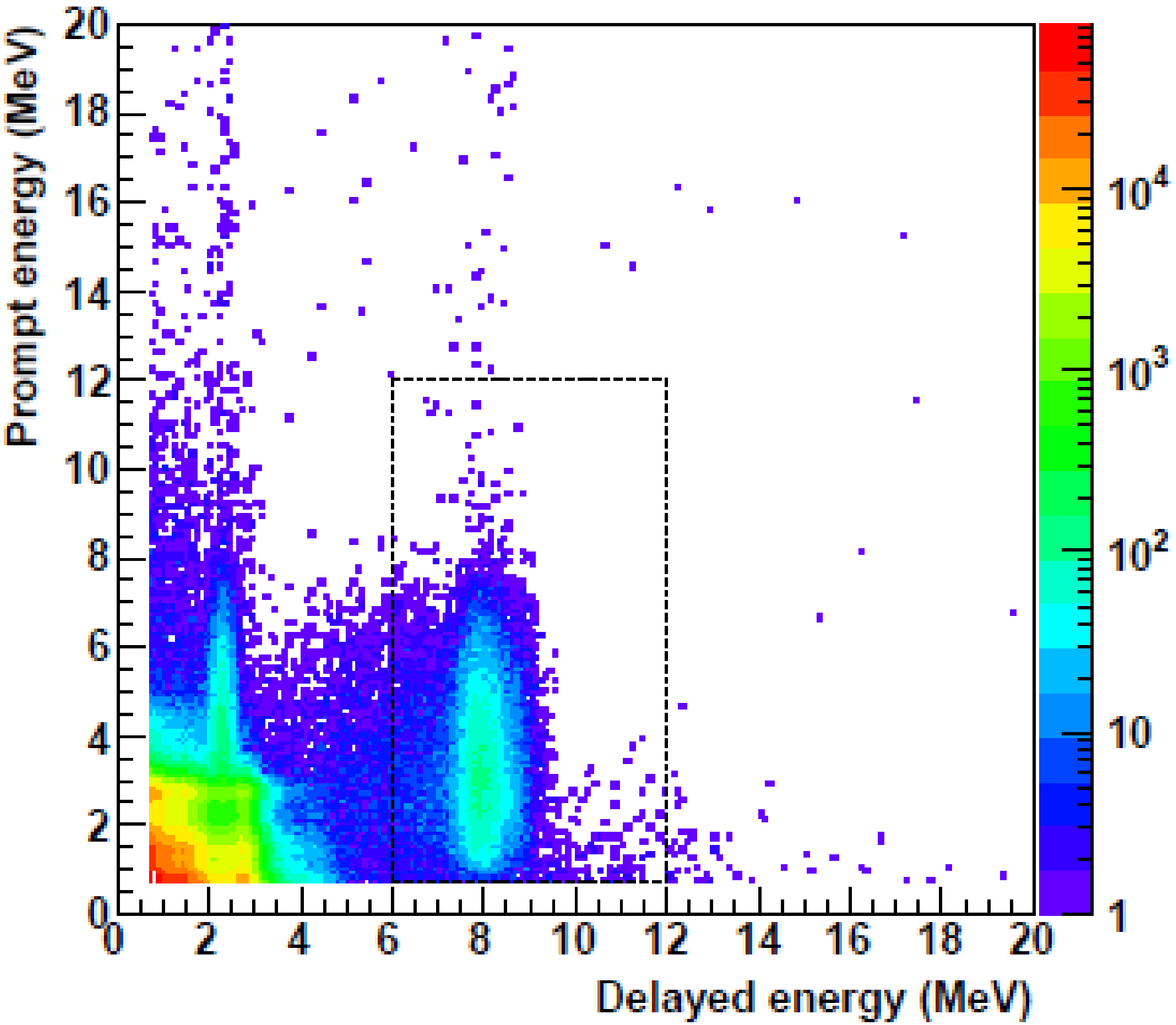
= 171.7ms/257.2ms

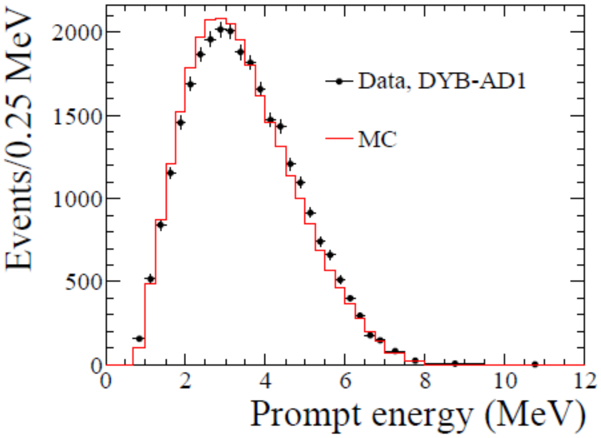
Selection Criteria

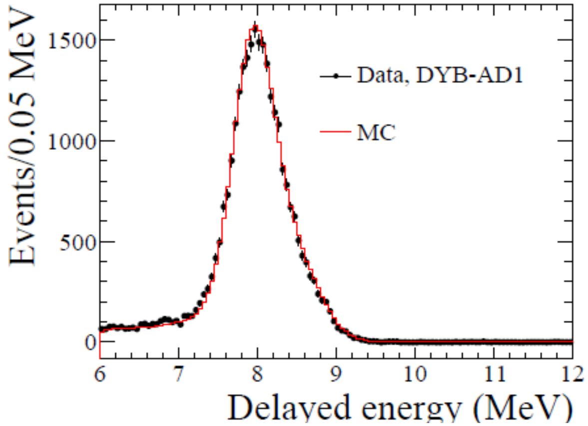
- **Pre-selection**
  - No flasher + no trigger (-2 μs, 200 μs) to a WP muon
- **Neutrino event selection**
  - Multiplicity cuts
    - $(t_n - T_e) < 200\ \mu s$
    - No triggers before e^+ and after n
  - Muon veto cuts
    - 1s after an AD shower muon
    - 1ms after an AD muon
    - 0.6ms after a WP muon

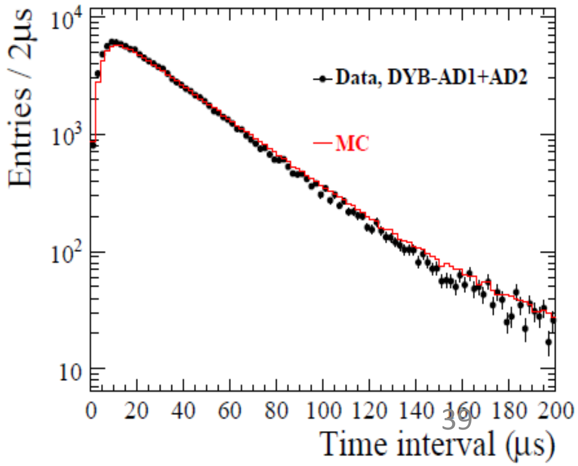


IBD Events

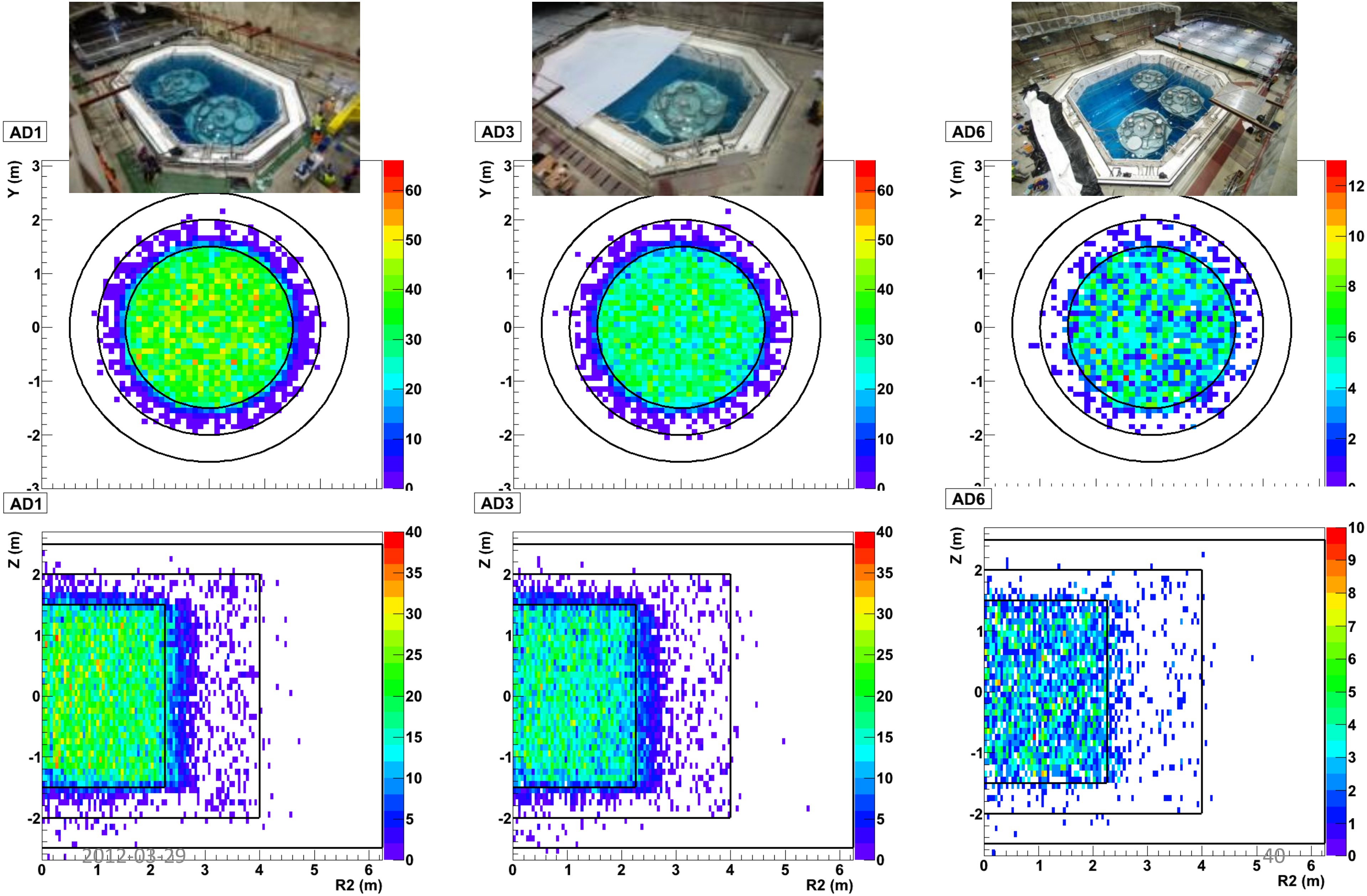

Prompt energy (MeV)
0
2
4
6
8
10
12
14
16
18
20
Delayed energy (MeV)
0
2
4
6
8
10
12
14
16
18
20
1
10
10^2
10^3
10^4


Events/0.25 MeV
0
500
1000
1500
2000
Data, DYB-AD1
MC
0
2
4
6
8
10
12
Prompt energy (MeV)

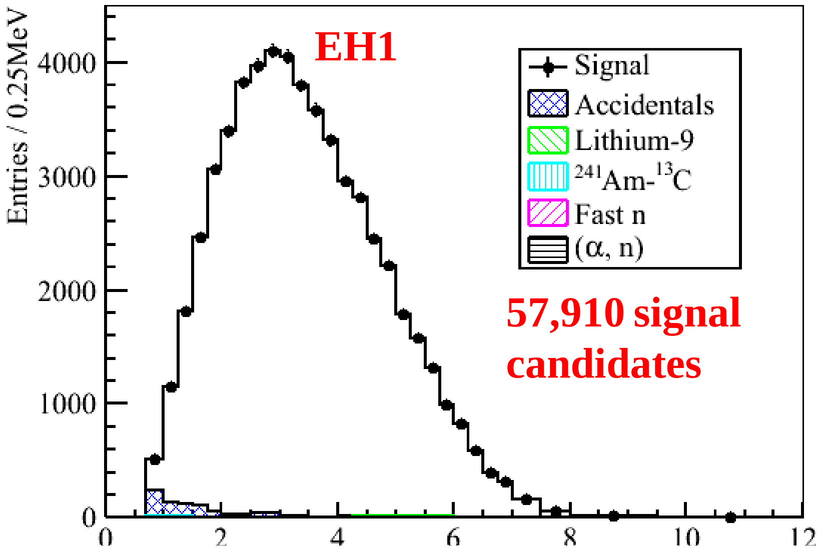

Events/0.05 MeV
0
500
1000
1500
Data, DYB-AD1
MC
6
7
8
9
10
11
12
Delayed energy (MeV)


Entries / 2μs
10
10^2
10^3
10^4
Data, DYB-AD1+AD2
MC
0
20
40
60
80
100
120
140
160
180
200
Time interval (μs)

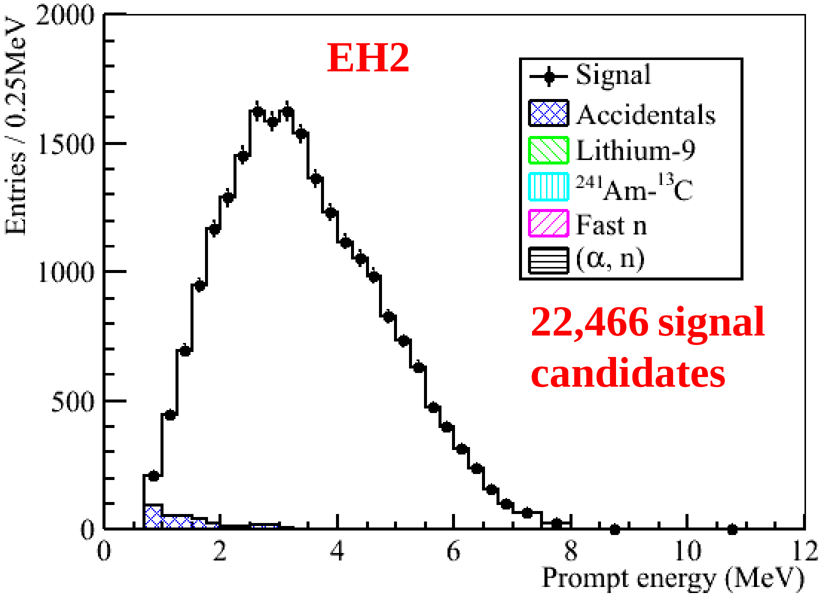
IBD Reaction Positions



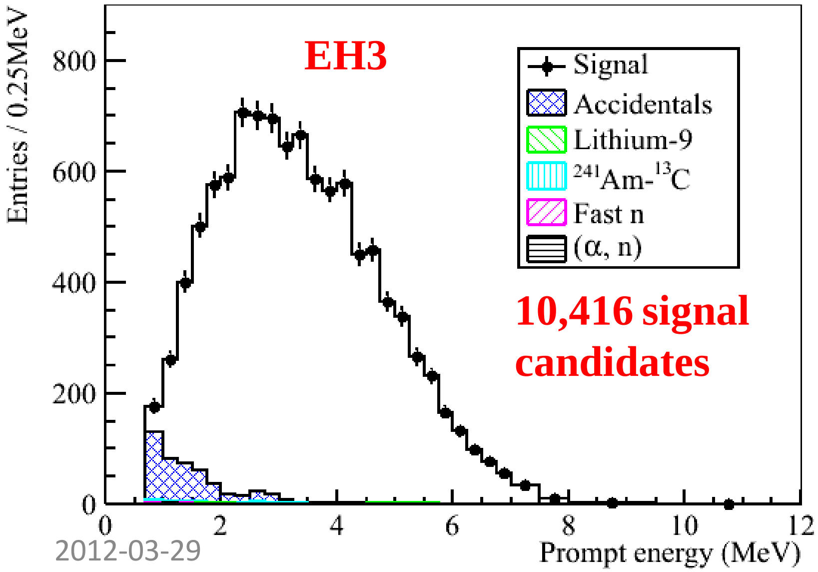
IBD Candidates at Each Hall



57,910 signal candidates

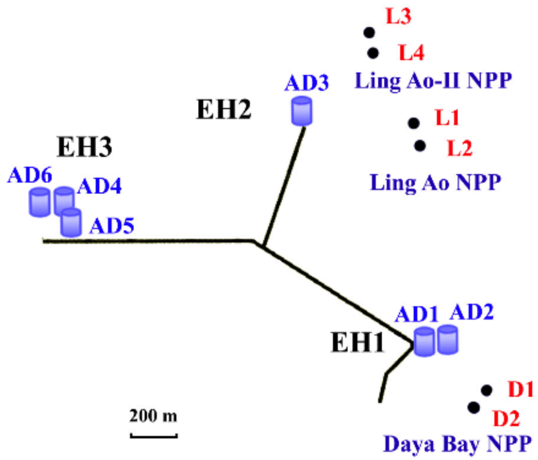


22,466 signal candidates



10,416 signal candidates

$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$



Data Set Summary

	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	28935	28975	22466	3528	3436	3452
DAQ live time (day)	49.5530		49.4971	48.9473		
Efficiency	0.8019	0.7989	0.8363	0.9547	0.9543	0.9538
Accidentals (/day)	9.82 ±0.06	9.88 ±0.06	7.67 ±0.05	3.29 ±0.03	3.33 ±0.03	3.12 ±0.03
Fast neutron (/day)	0.84 ±0.28	0.84 ±0.28	0.74 ±0.44	0.04 ±0.04	0.04 ±0.04	0.04 ±0.04
^{8}He/^{9}Li (/day)	3.1±1.6		1.8±1.1	0.16±0.11		
Am-C corr. (/day)	0.2±0.2					
^{13}C(α, n)^{16}O (/day)	0.04 ±0.02	0.04 ±0.02	0.035 ±0.02	0.03 ±0.02	0.03 ±0.02	0.03 ±0.02
Antineutrino rate (/day)	714.17 ±4.58	717.86 ±4.60	532.29 ±3.82	71.78 ±1.29	69.80 ±1.28	70.39 ±1.28

Determination of $\sin^2 2\theta_{13}$

Base lines

$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

Far/near ν_e counts

Detector Target Masses

Detector efficiencies

Oscillation deficit

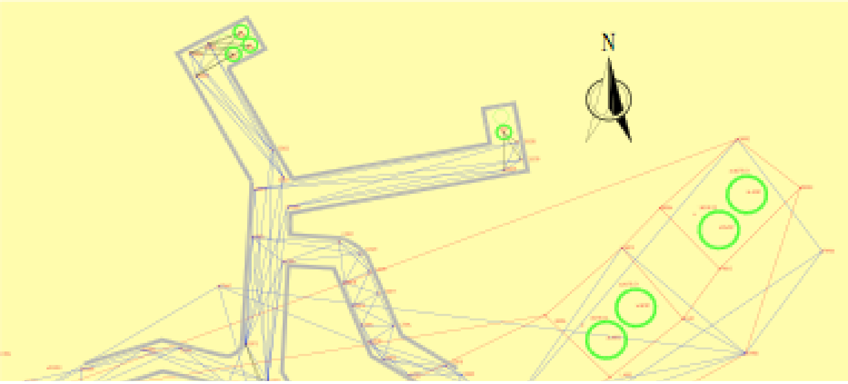
Distances from Reactors to ADs

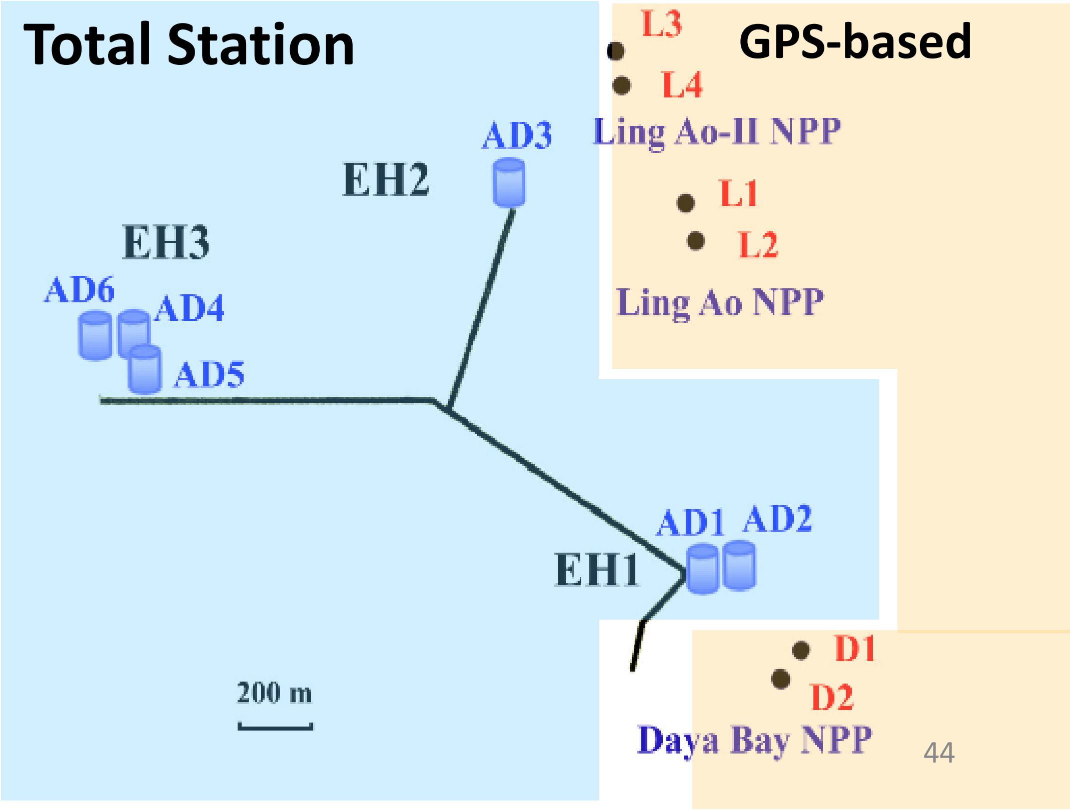
Detailed Survey

- GPS above ground
- Total Station underground
- Final precision: 28mm

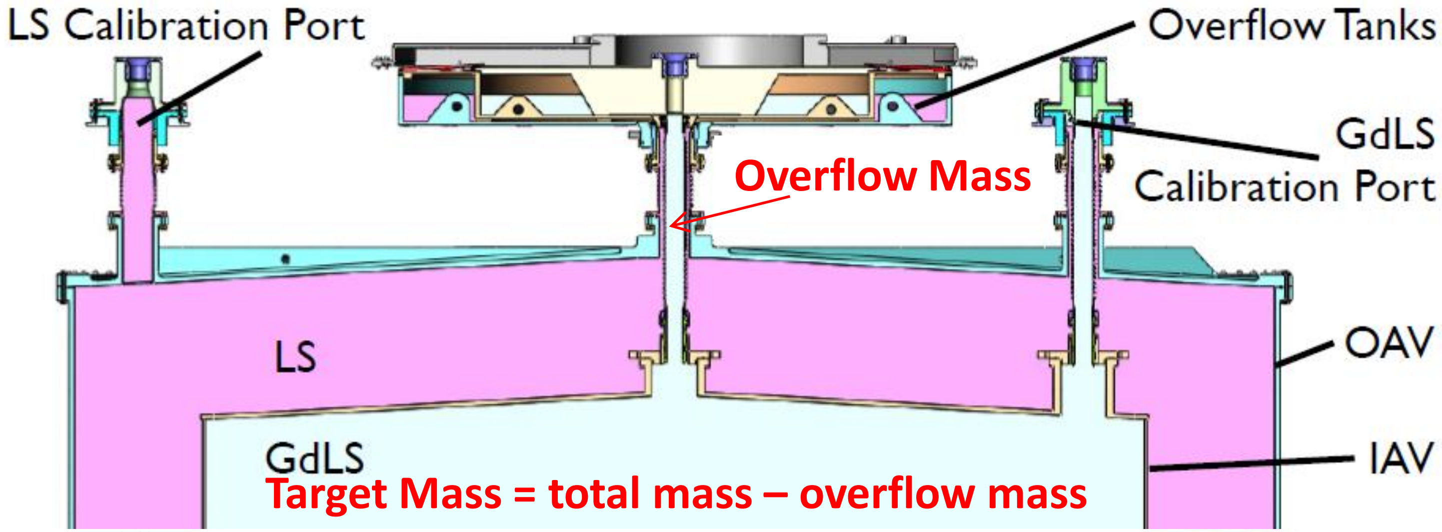
Validation

- Three independent calculations
- Cross-check survey
- Consistent with reactor plant and design plans



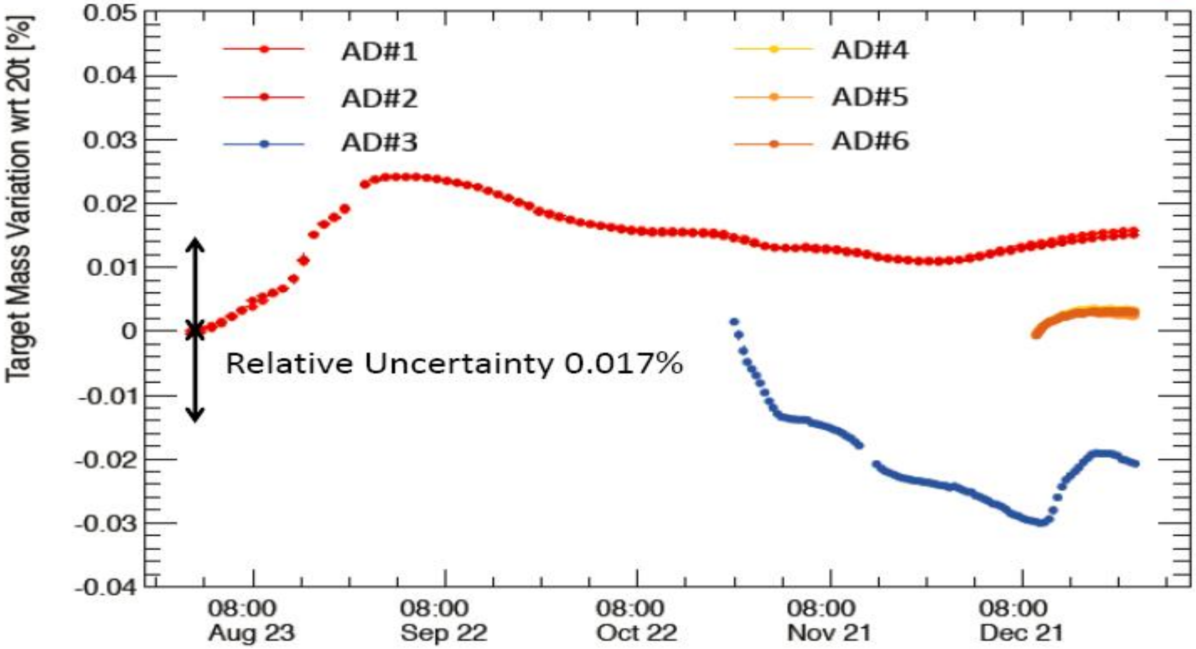


Target Mass



Overflow Mass

Target Mass = total mass – overflow mass



Relative Uncertainty 0.017%

Reactor Antineutrino Flux

Flux estimated using:

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F)e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

✓**Reactor operators provide:**

- Thermal power data: W_{th}
- Relative isotope fission fract.: f_i

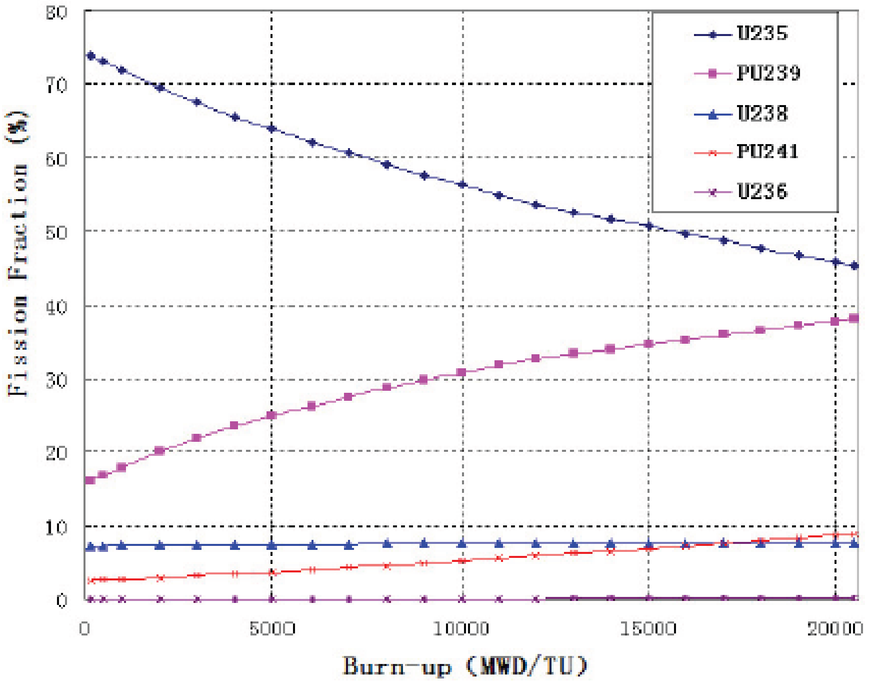
✓**Energy released/fission: e_i**

V. Kopekin et al., PAN 67, 1892 (2004)

✓**Anti-ν_e spectra/fission: $S_i(E_\nu)$**

P. Huber, PRC84, 024617 (2011)
T. Mueller et al., PRC83, 054615 (2011)
A. A. Hahn et al., PLB218, 365 (1989)
P. Vogel et al., PRC24, 1543 (1981)
K. Schreckenbach et al., PLB160, 325 (1985)

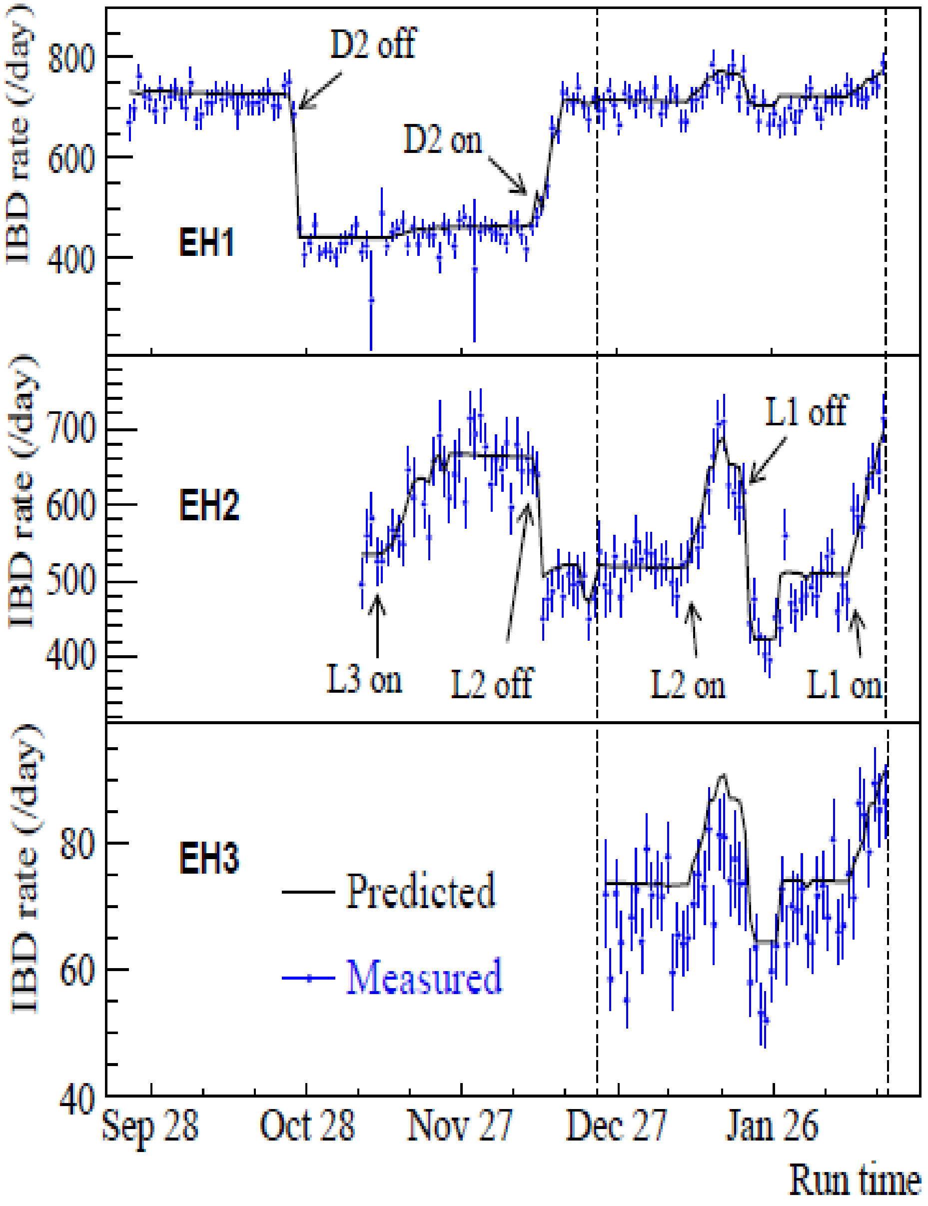
Isotope fission rates vs. reactor burnup



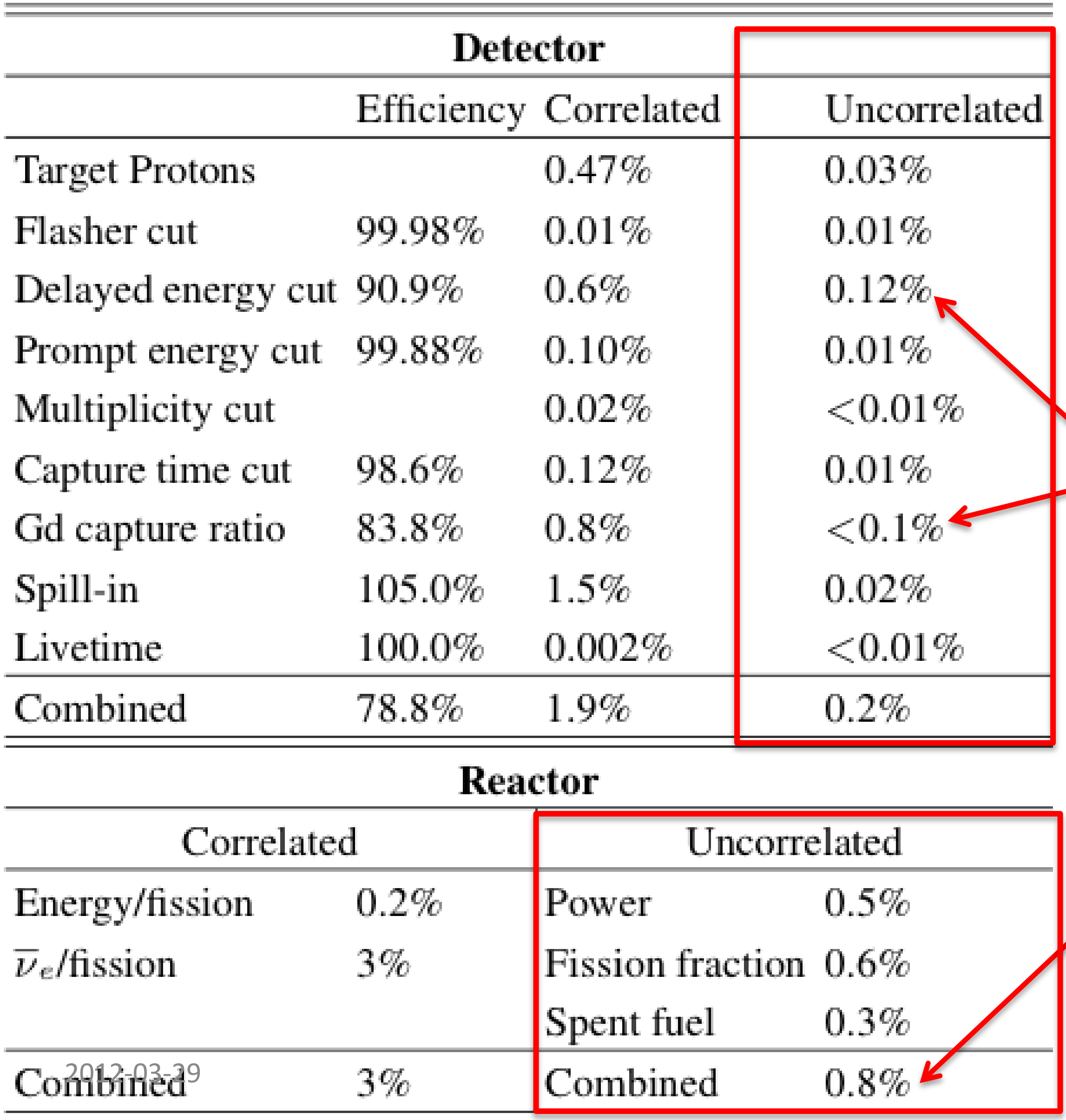
Flux model has negligible impact on far vs. near oscillation measurement

Antineutrino Rate vs. Time

- Detected rate strongly correlated with reactor flux expectations.
- Predicted Rate:
  - Assume no oscillation.
  - Normalization is determined by fit to data.
  - Absolute normalization is within a few percent of expectations.



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%

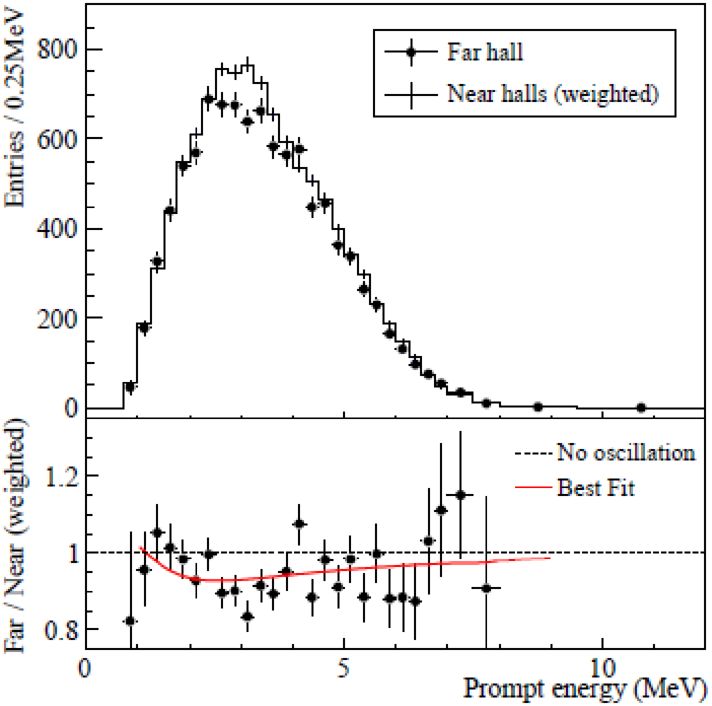
For near/far oscillation, only uncorrelated uncertainties are used.

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

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

Far/Near Ratio

$$R = \frac{N_f}{N_n} = \frac{\sum_{i=4}^{6} M_i}{\sum_{i=4}^{6} [\alpha_i (M_1 + M_2) + \beta_i M_3]}$$

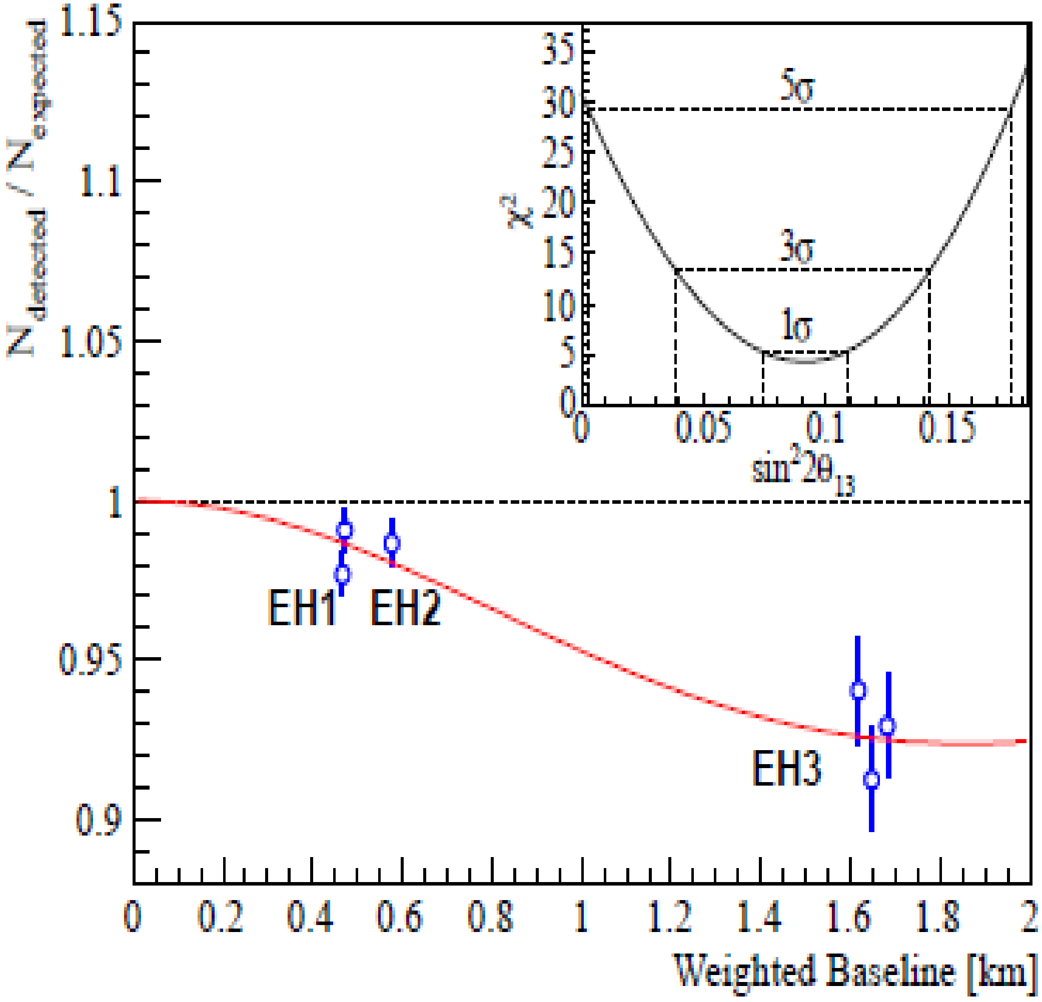


M_i : **measured antineutrino rates**

α_i, β_i : **determined from base lines and reactor fluxes.**

R = 0.940 ± 0.011 (stat) ± 0.004 (syst)

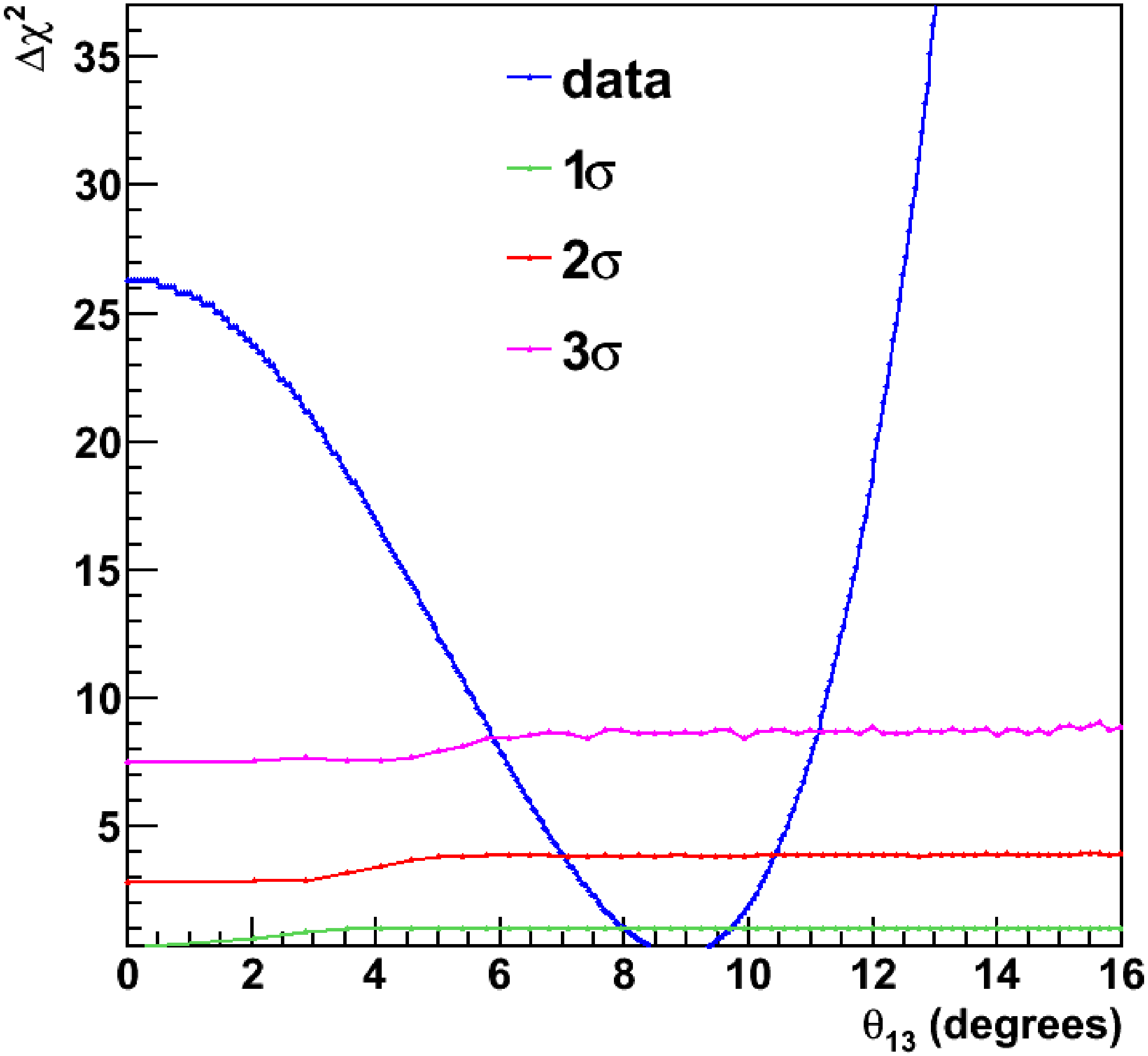
$\sin^2 2\theta_{13}$ Measurement



$\sin^2 2\theta_{13}$
$= 0.092$
± 0.016 (stat)
± 0.005 (syst)

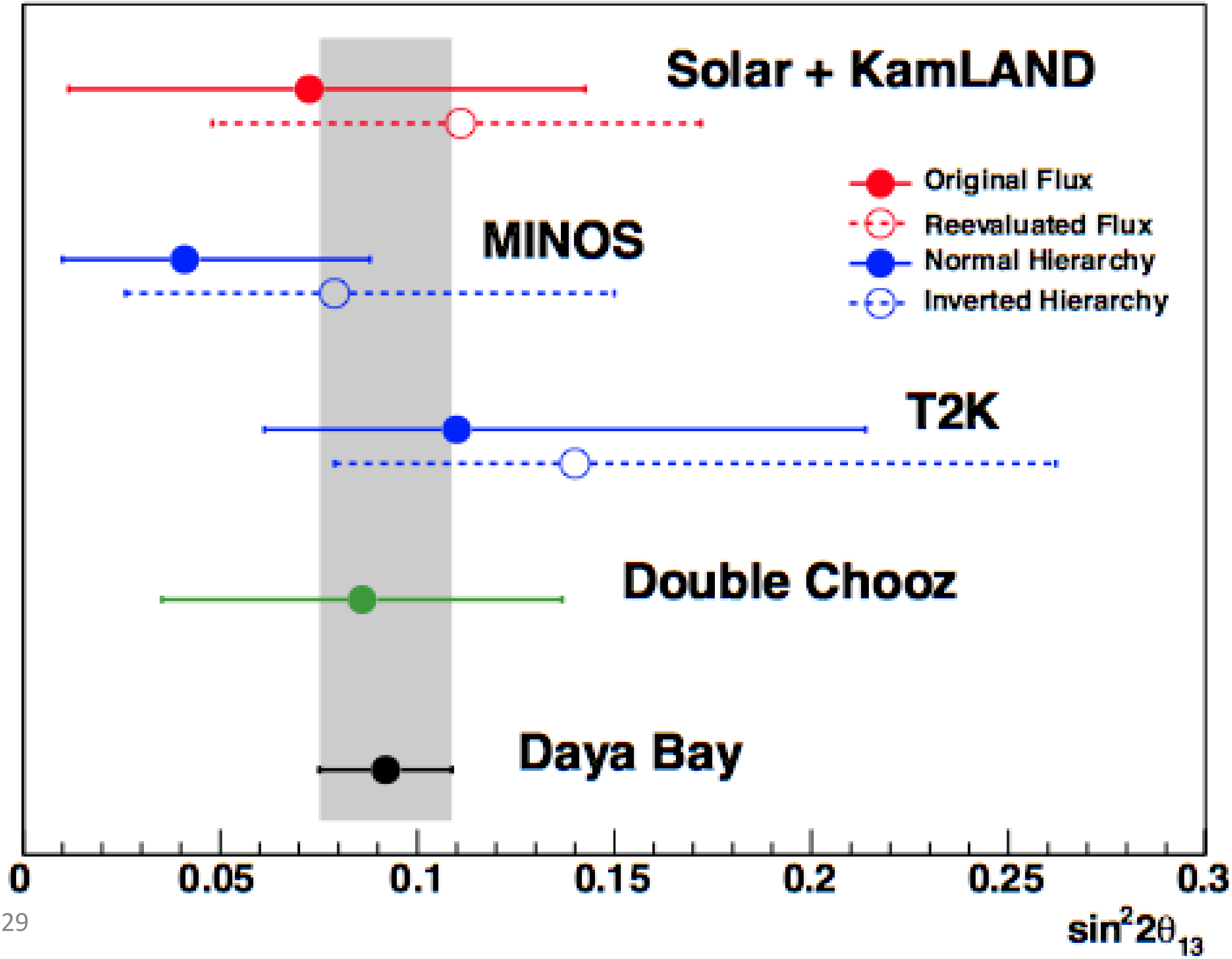
$\sin^2 2\theta_{13} = 0$
excluded at
5.2σ

Asymmetric CI in θ_{13}

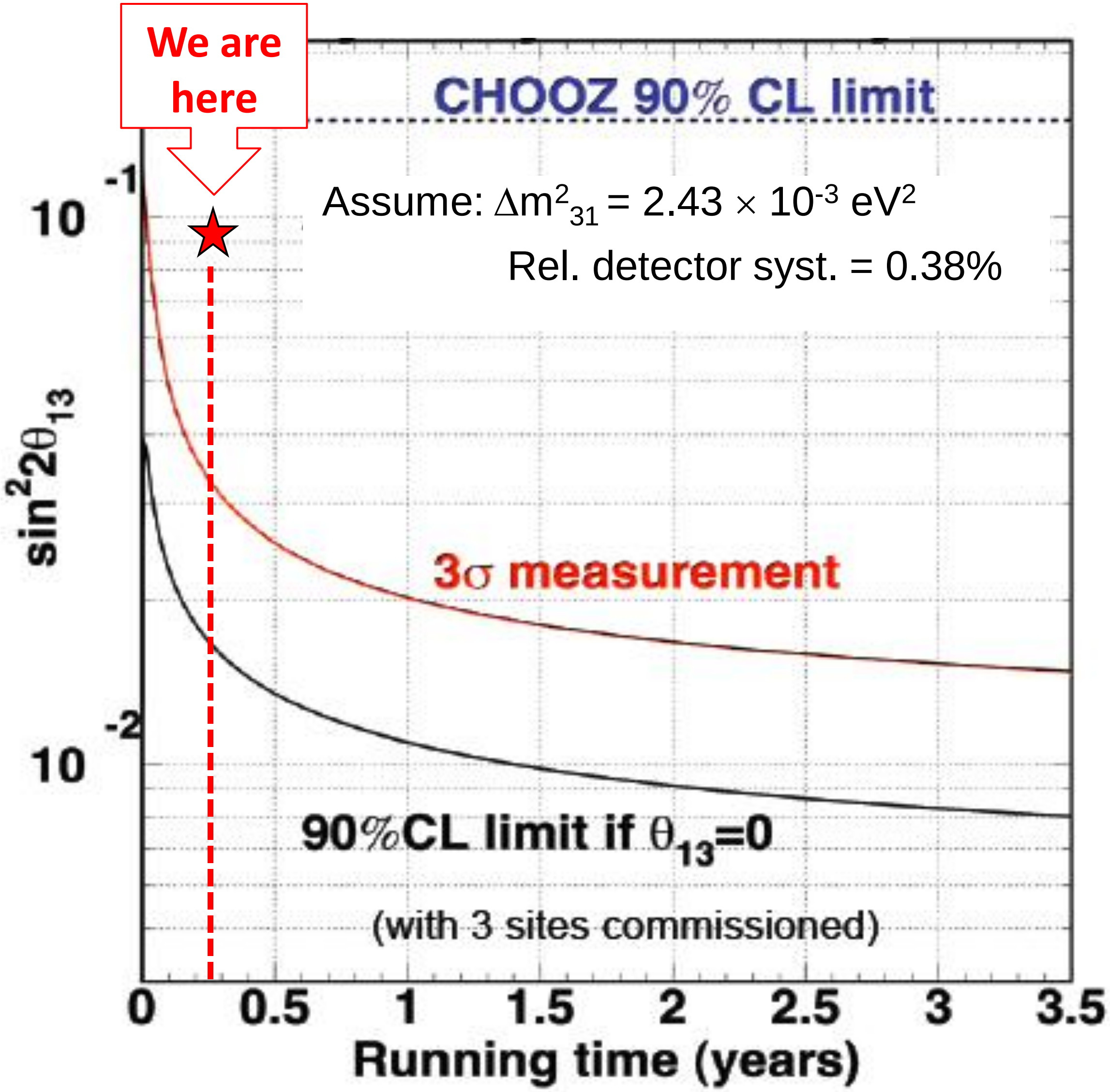


Where Are We Now?

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$$



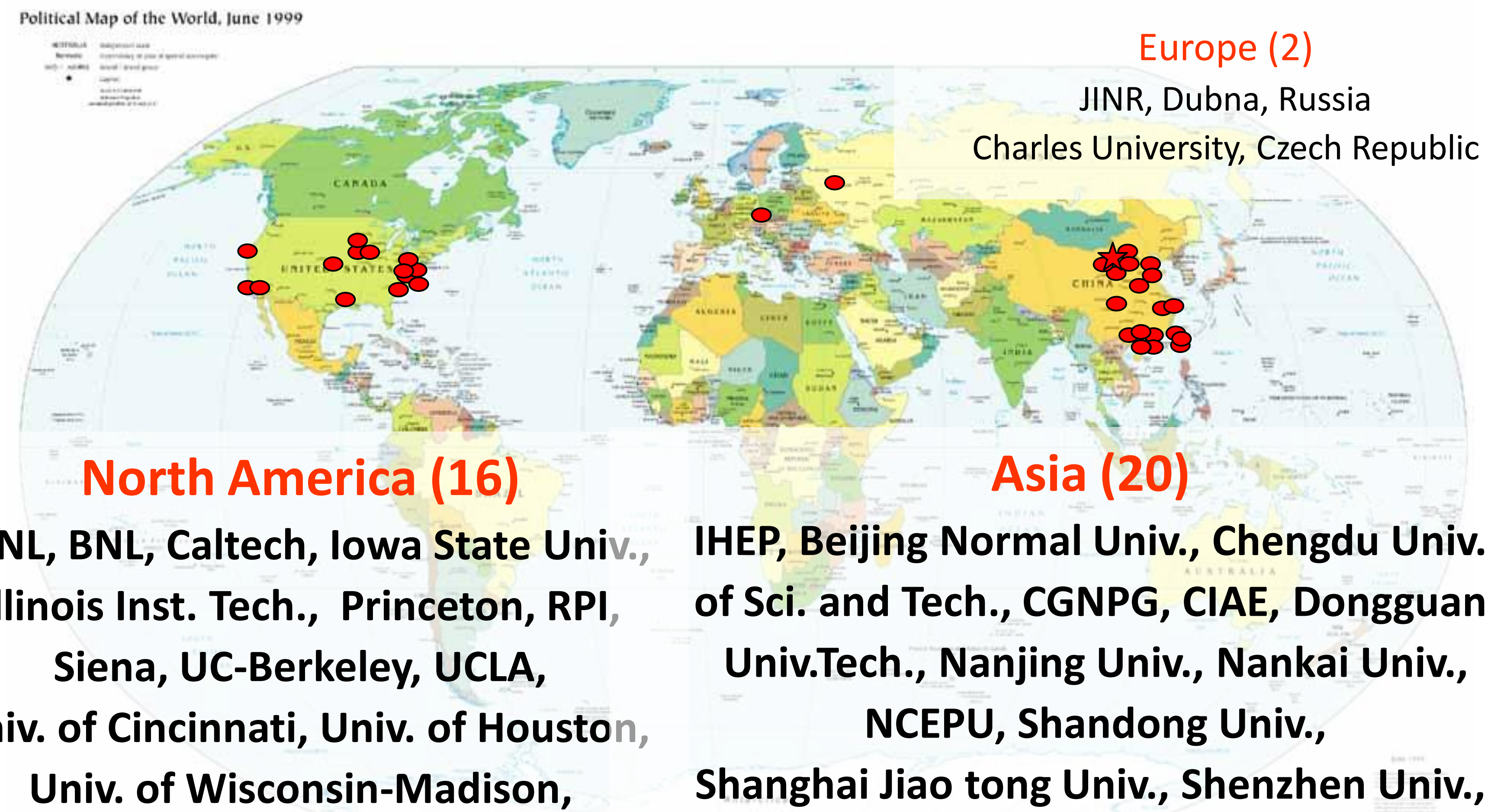
Daya Bay Goal for 3 years



Assume: $\Delta m^2_{31} = 2.43 \times 10^{-3}$ eV^2

Rel. detector syst. = 0.38%

The Daya Bay Collaboration



Europe (2)

JINR, Dubna, Russia

Charles University, Czech Republic

North America (16)

LBNL, BNL, Caltech, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Univ. of Illinois-Urbana-Champaign, Virginia Tech., William & Mary

Asia (20)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Univ.Tech., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

~230 Collaborators

Roadmap of Daya Bay

- **2005.04: Got green light at 250th Xiangshan Meeting**
- **2006.10:Passed DOE scientific review**
- **2007.01:CDR released (hep-ex/0701029)**
- **2007.10: Ground breaking ceremony**
- **2009.07: Planed to deploy first detector**
  - **2011.08.15: EH1 started operation**
- **2010.09: Planed to take data with final configuration**
  - **2011.11.05: EH2 started data taking**
  - **2011.12.24: Took data with 2-1-3 configuration**
  - **2012.06: Expected with final configuration**

Summary and Outlook

- ✓ **An unambiguous observation of electron-antineutrino disappearance at Daya Bay**

  $R = 0.940 \pm 0.011$ (stat) $\pm$ 0.004 (syst)

- ✓ **Interpretation of disappearance as neutrino oscillation yields:**

  $\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) $\pm$ 0.005 (syst)

  ruling out zero at 5.2 standard deviations.
- ✓ **More statistics expected before this June**
- ✓ **Installation of final pair of ADs this summer**