Future Reactor Neutrino Experiments

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What I'm going to talk about

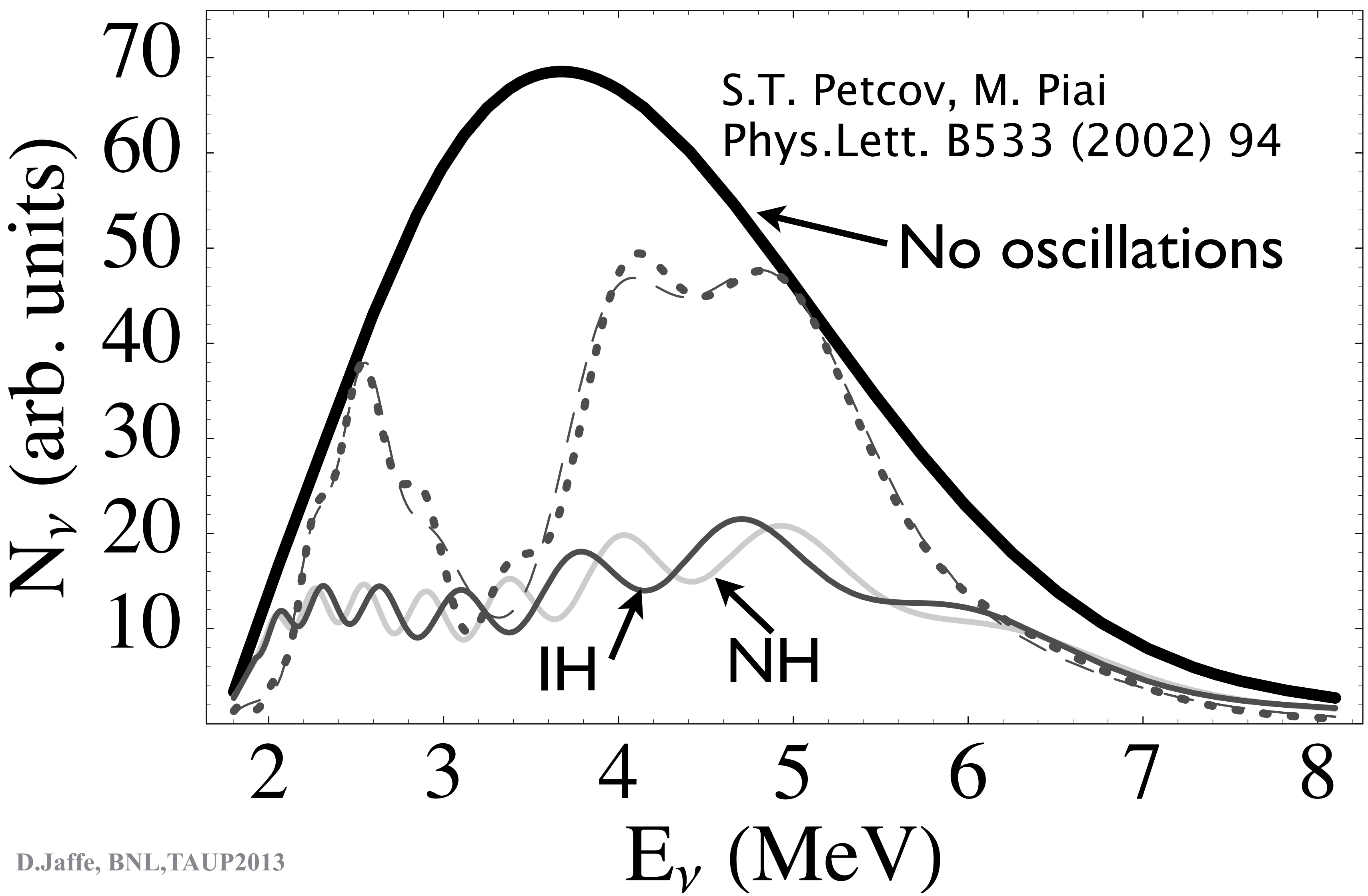
- I won't talk about proposed reactor experiments at ~10 m baseline.
- I will focus on experiments that I call
  Radical **R**eactor **N**eutrino **O**scillation **L**iquid scintillator **D**etector experiments...RRNOLD
  - JUNO in China and RENO-50 in S.Korea
- RRNOLD characteristics
  - Detect reactor $\overline{\nu}_e$ via Inverse Beta Decay(IBD), ~20kton, ~50km baseline, unprecedented energy resolution
- RRNOLD goals
  - Resolve mass hierarchy(MH) & measure $\sin^2\theta_{12}, \Delta m^2_{23}, \Delta m^2_{12}$ precisely

Thanks to Dan Dwyer, Xin Qian and Chao Zhang for comments and suggestions.

RRNOLD & MH

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$
$$- \boxed{\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}$$

$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$



- Precise spectral measurement can resolve MH and osc. parameters to <1%
- Independent of CP phase
- Minimal matter effect

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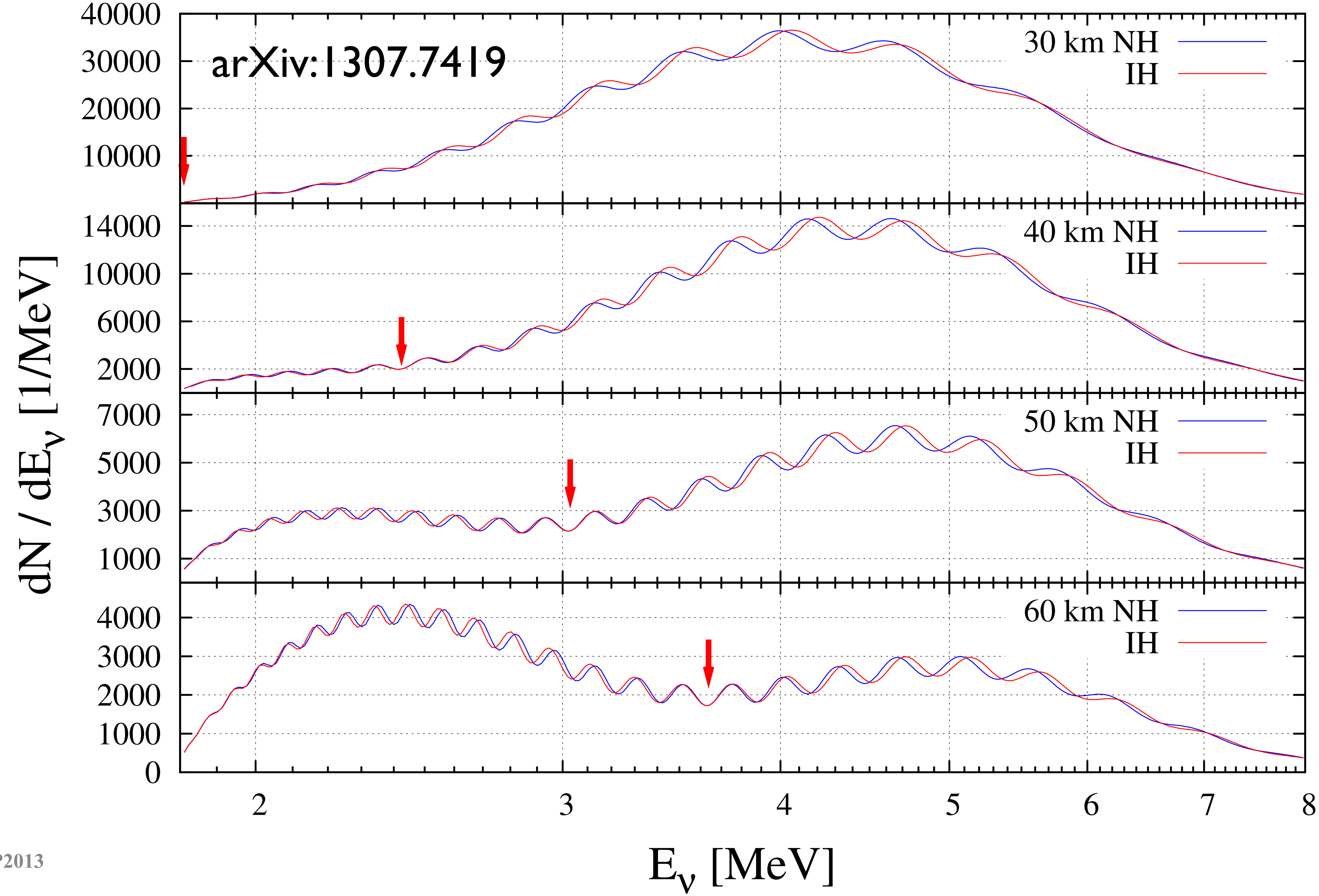
RRNOLD basic principle

- Rewrite P to express Δm^2_{32}, Δm^2_{31} as a phase $\phi(E_\nu)$

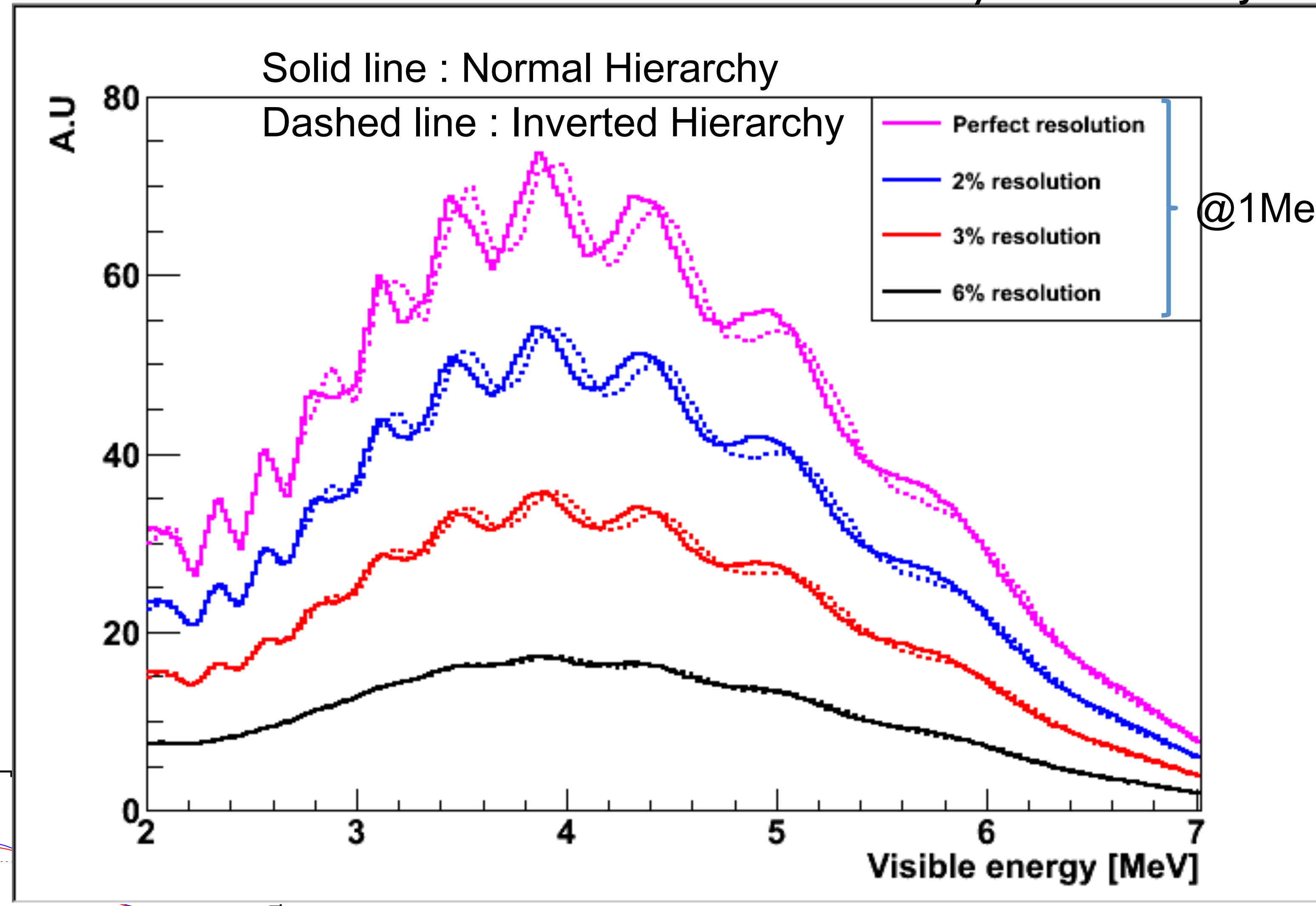
$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1-\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31}+\sin^2\theta_{12}\sin^2\Delta_{32})-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

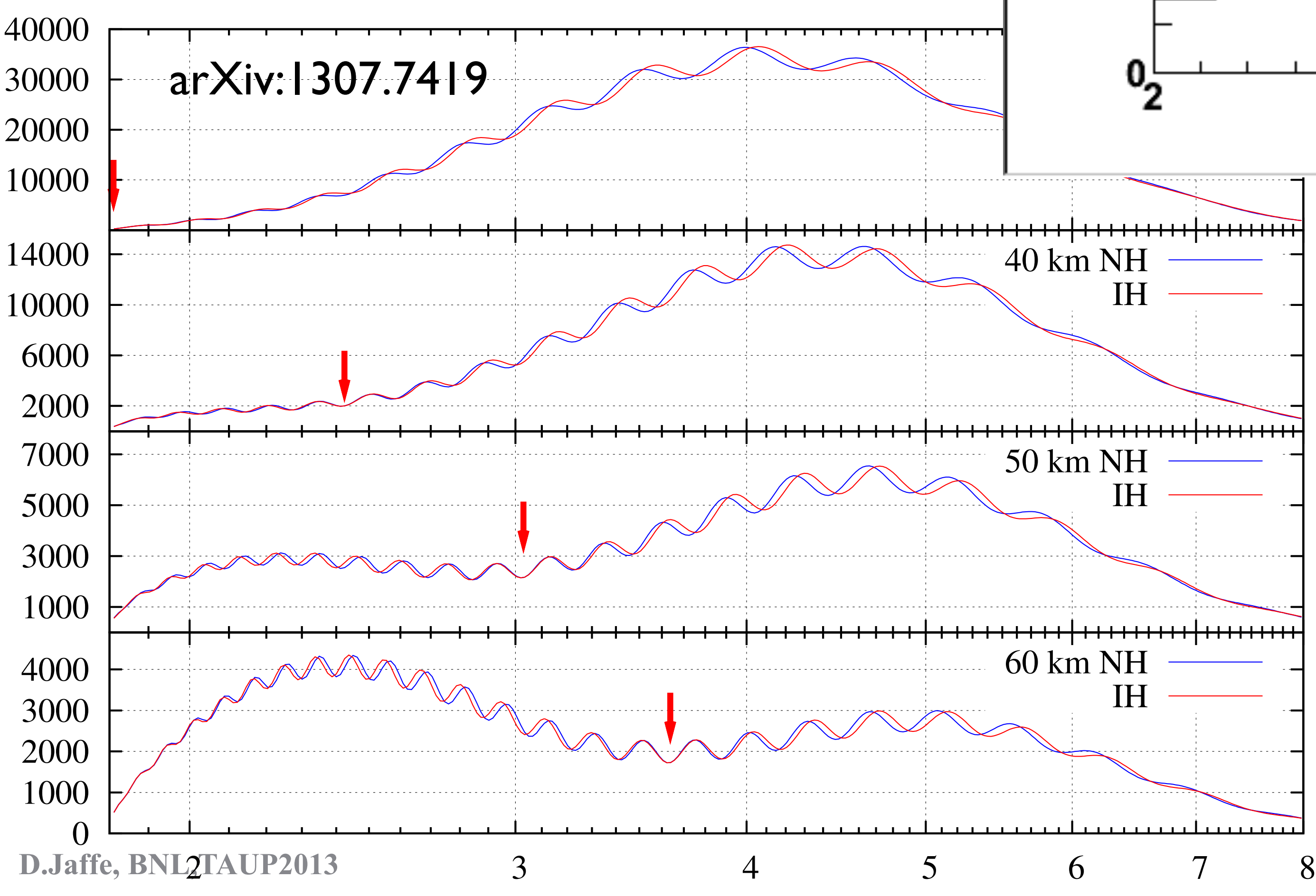
$$= 1-2s^2_{13}c^2_{13}-4c^2_{13}s^2_{12}c^2_{12}\sin^2\Delta_{21}+2s^2_{13}c^2_{13}\sqrt{1-4s^2_{12}c^2_{12}\sin^2\Delta_{21}}\cos(2\Delta_{32}\pm\phi)$$



Intrusion of reality

Simulation study of RENO-50, J.S.Park



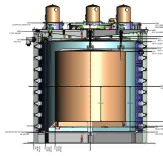


	KamLAND	RRNOLD
σ_E/E	$6\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250pe/MeV	1200pe/MeV

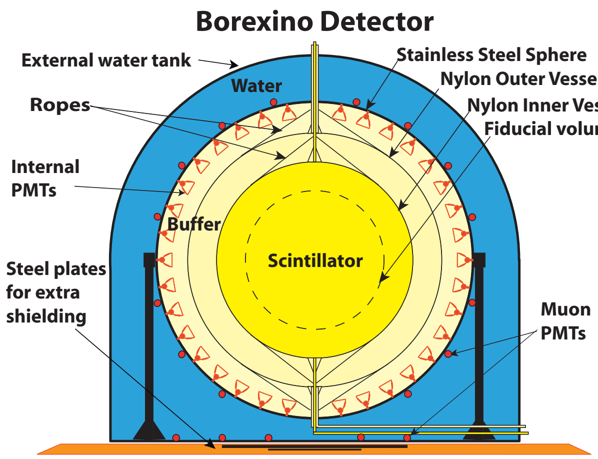
RRNOLD requirements

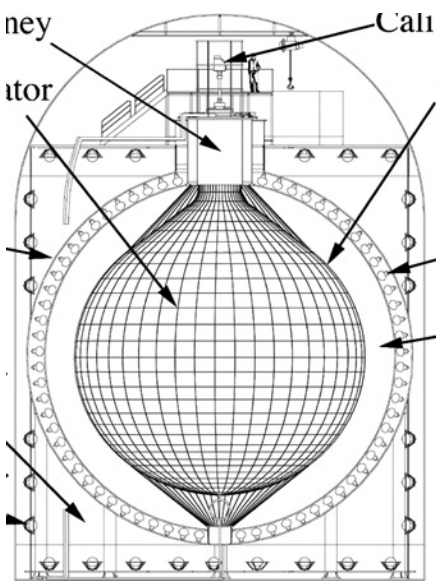
- High statistics (~10^5 IBD in 5 years)
  - Massive detector (~20kt JUNO, ~18kt RENO-50)
  - Huge multi-reactor power (~36GW_{th} JUNO, ~16.5GW_{th} RENO-50) with baseline differences < 500m
- Energy scale
  - Fabulous resolution (~3%/$\sqrt{E(MeV)}$)
    - High photocathode coverage (~80% JUNO, ~67% RENO-50)
    - High QE (~35%) photodetectors
    - High transparency liquid scintillator (LS) (>=35m atten. length)
    - High light yield LS (~1.5X that of KamLAND)
  - Understand non-linearity to <1%
- Suppress cosmogenic background (~500 m rock overburden at JUNO site)

RRNOLD: How big is it?

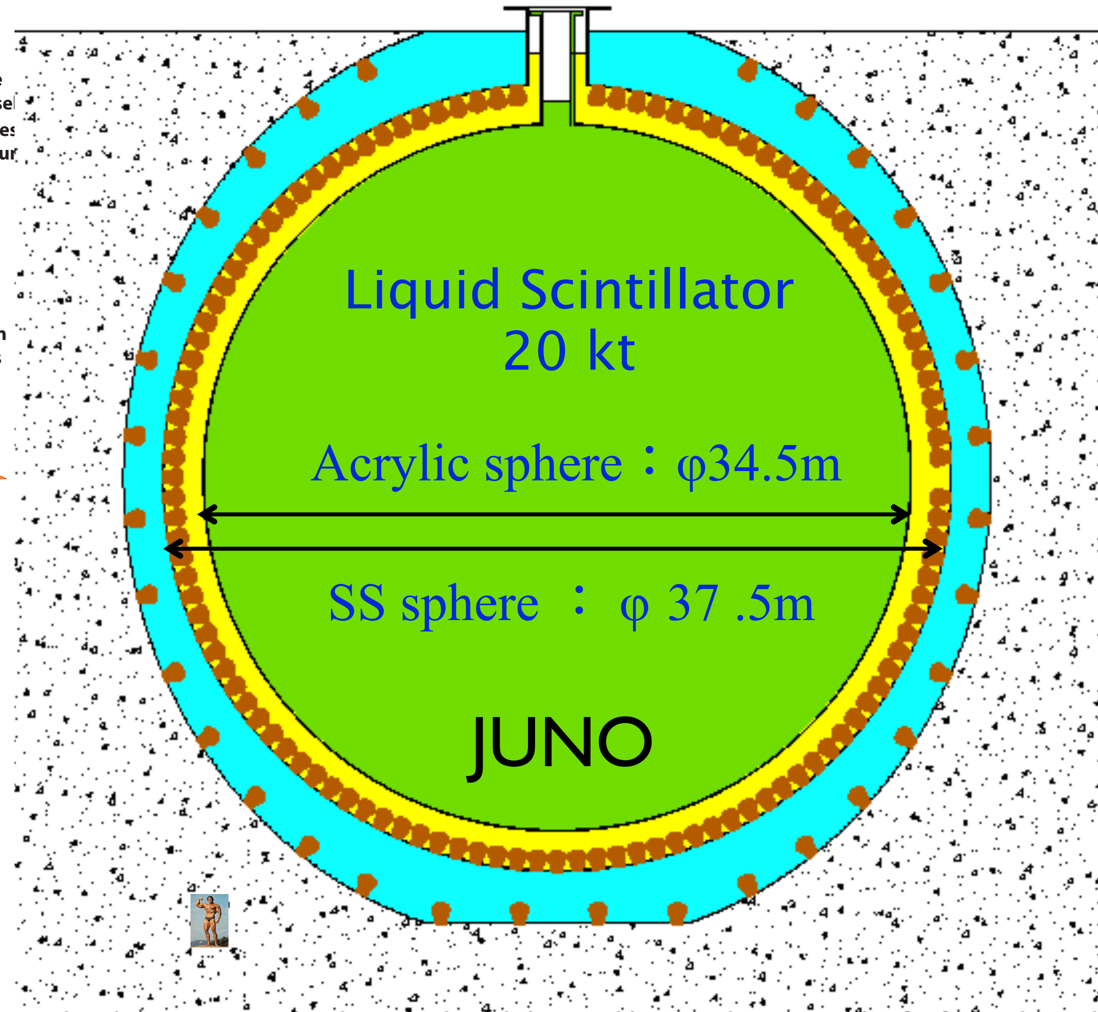


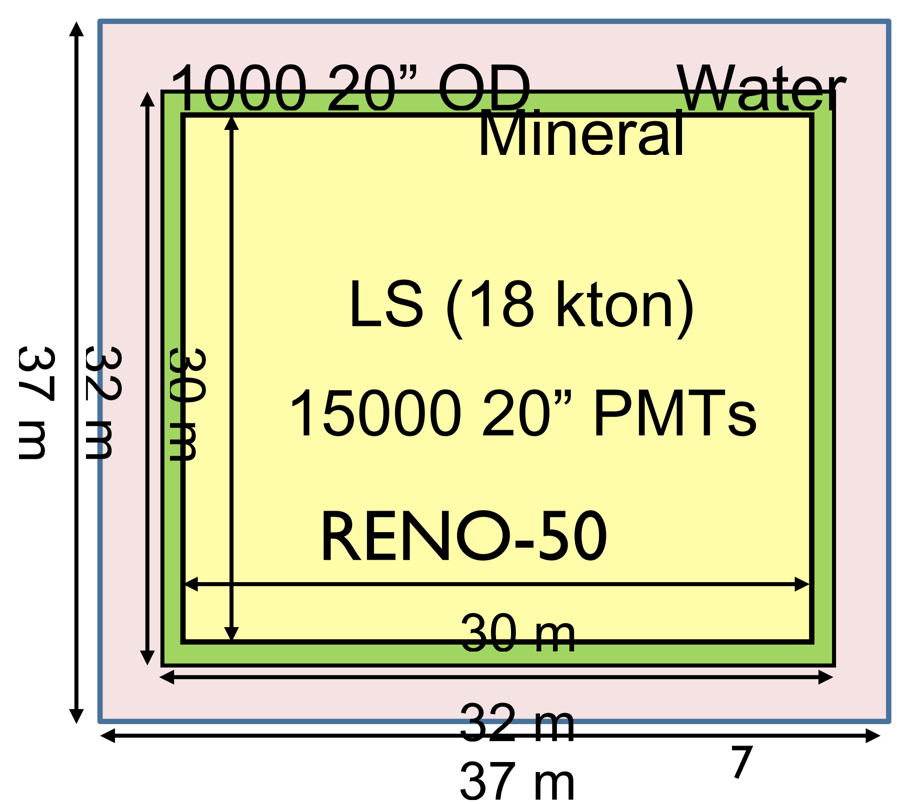
Daya Bay AD

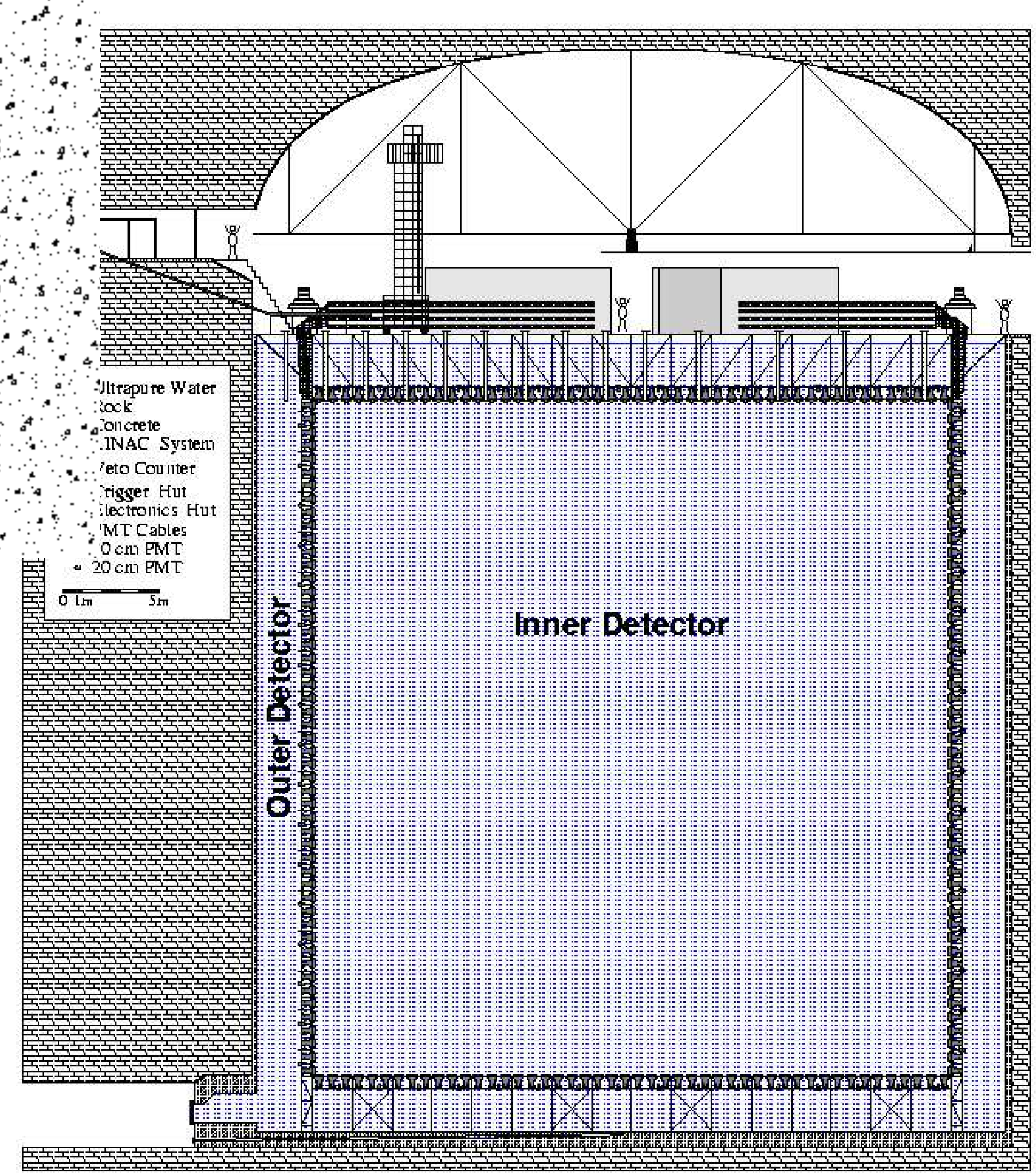




KamLAND



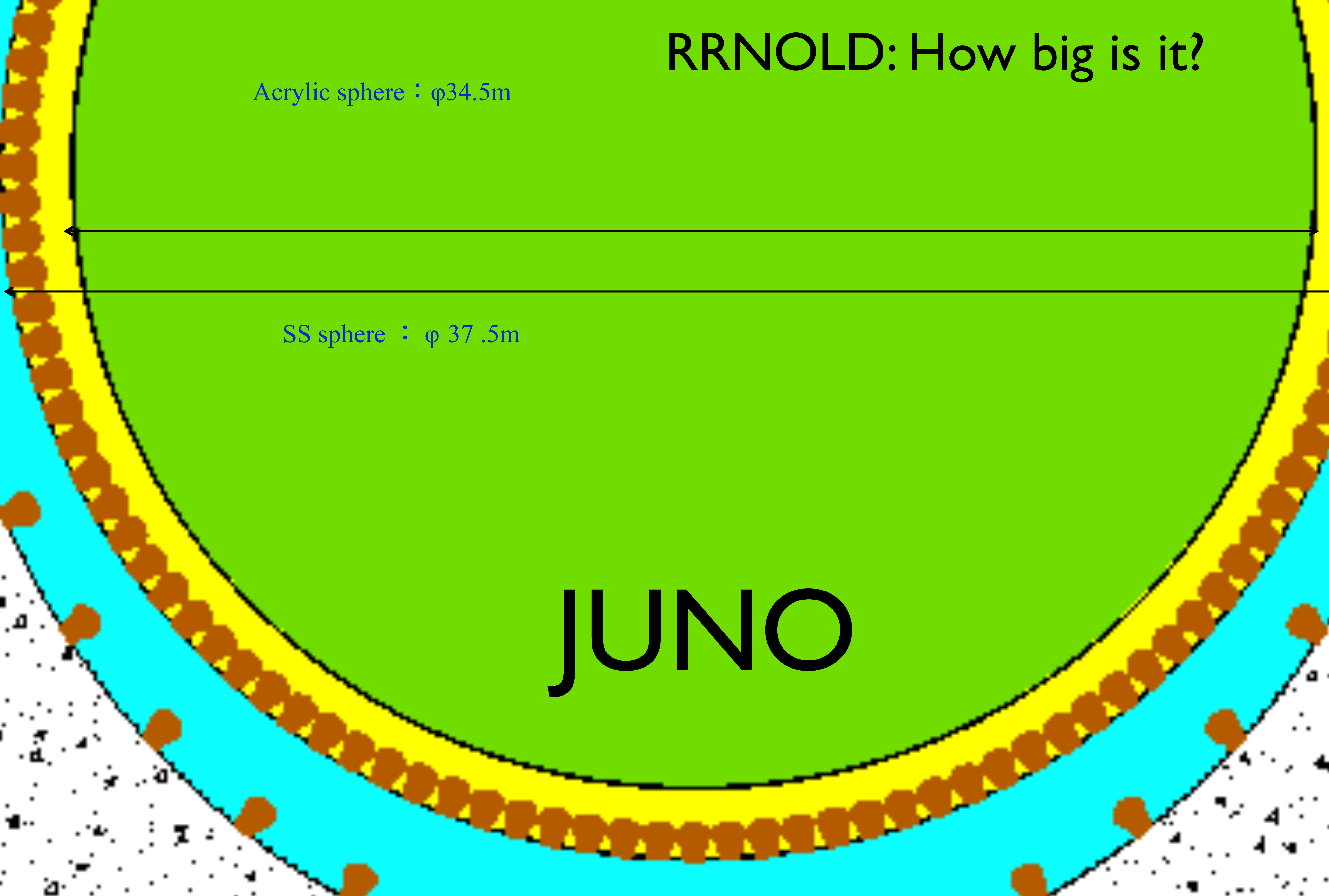




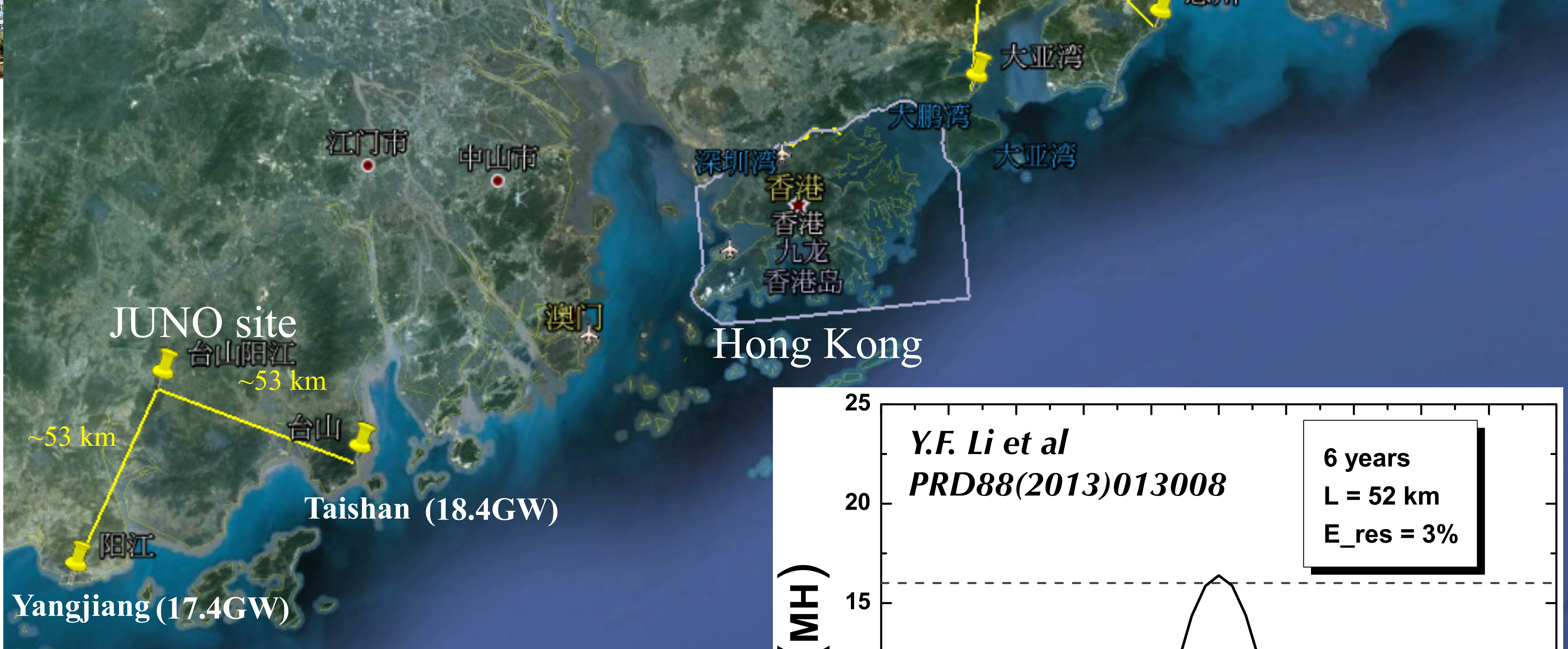
Super-Kamiokande

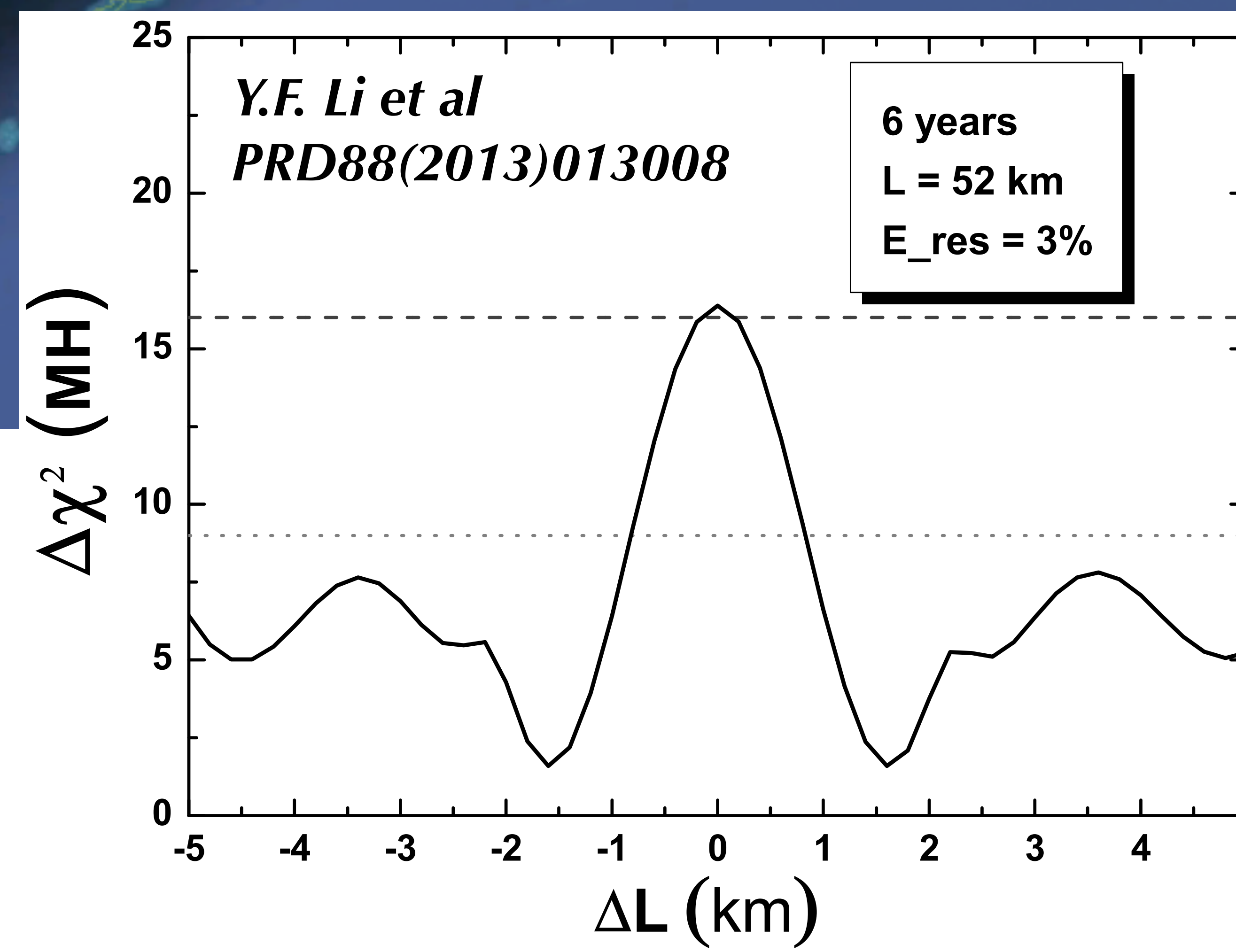
Approximate size comparison

RRNOLD: How big is it?



Arnold Schwarzenegger





Huge multi-reactor power (~36GW$_{th}$ ~ 72e20 $\bar{\nu}_e$/s)
with baseline differences < 500m

Energy resolution

More photons, how and how many ?

Y.F. Wang, Daya Bay II: current status and future plan, in Daya Bay II First Meeting, 2013.

- **Highly transparent LS:**
  - ⇨ **Attenuation length/D: 15m/16m → 30m/34m ×0.9**
- **High light yield LS:**
  - ⇨ **KamLAND: 1.5g/l PPO → 5g/l PPO**

    Light Yield: 30%→ 45%; × 1.5
- **Photocathode coverage :**
  - ⇨ **KamLAND: 34% → ~80% × 2.3**
- **High QE "PMT"：**
  - ⇨ **20" SBA PMT QE: 25% → 35% × 1.4**

    or New PMT QE： 25% → 40% × 1.6

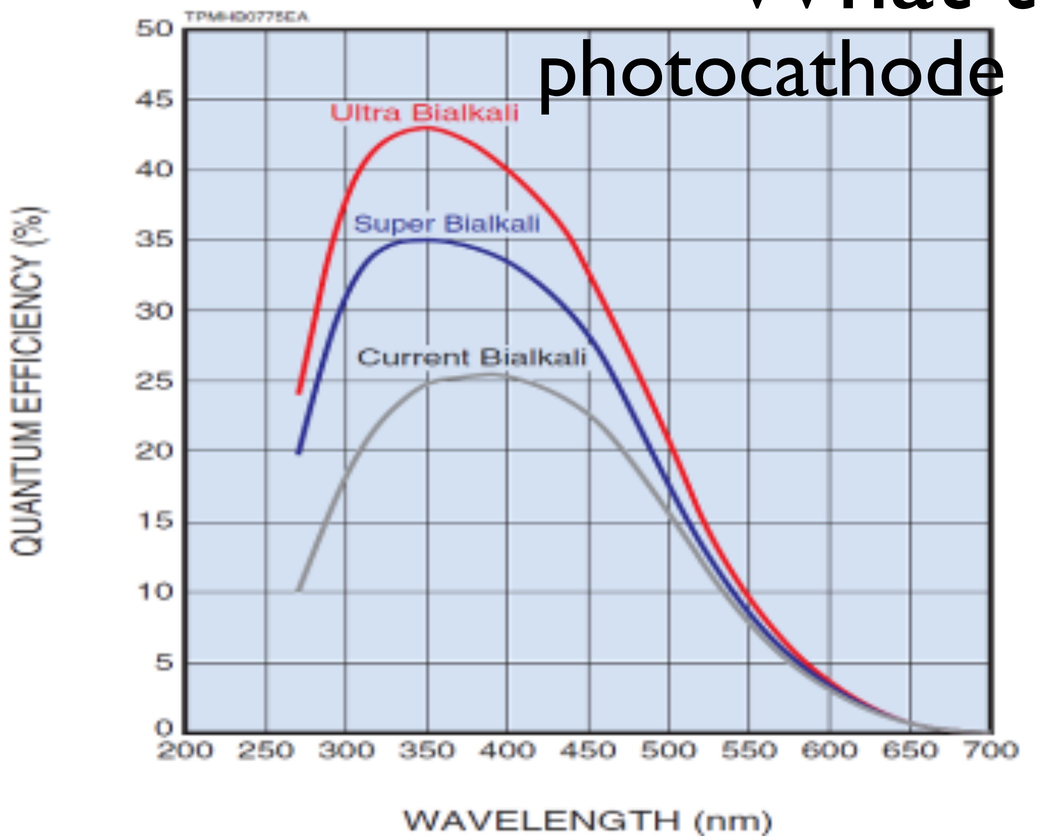
    Both： 25% → 50% × 2.0

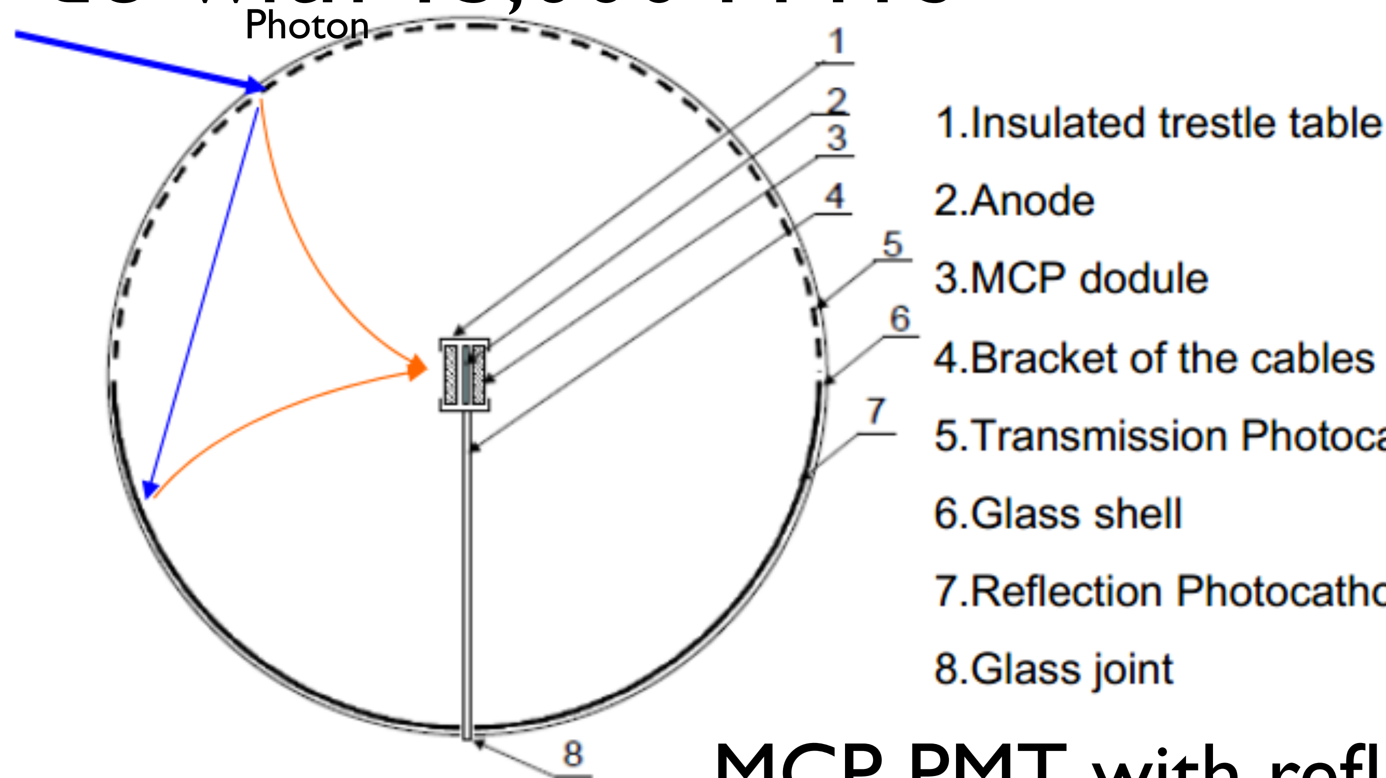
4.3 – 5.0 ➔ (3.0 – 2.5)% /√E

Other contributions： 0.5% constant term & 0.5% neutron recoil uncertainty

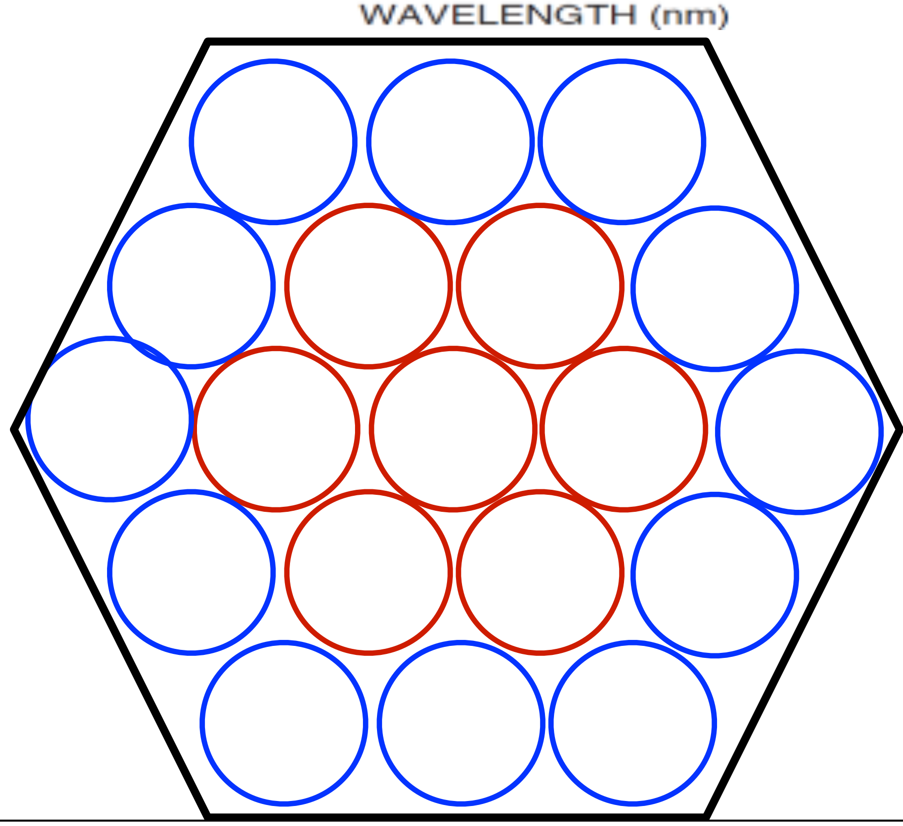
More Photoelectrons -- JUNO or What to do with 15,000 PMTs

photocathode





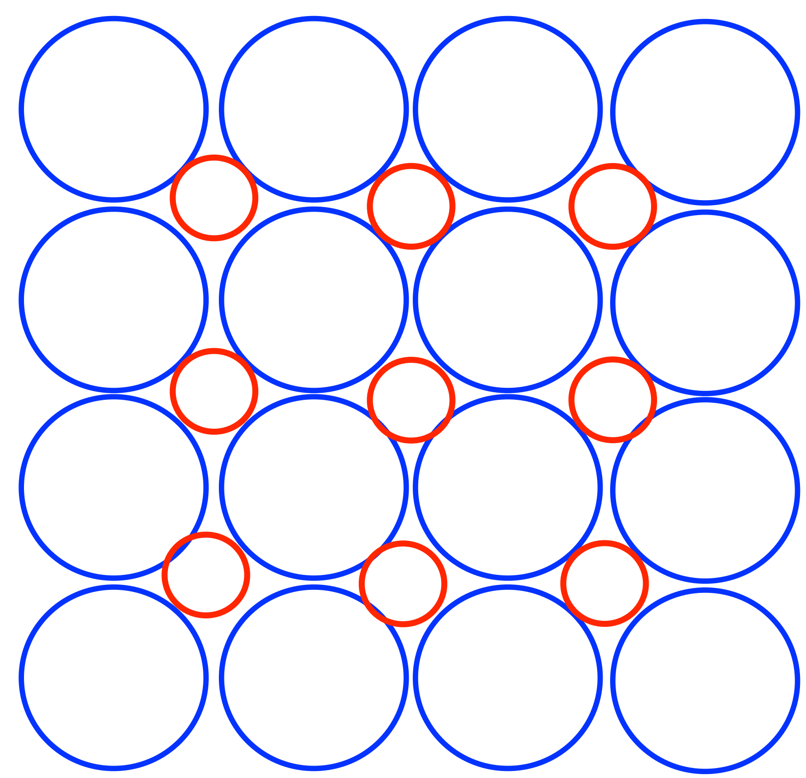
MCP PMT with reflection photocathode at bottom



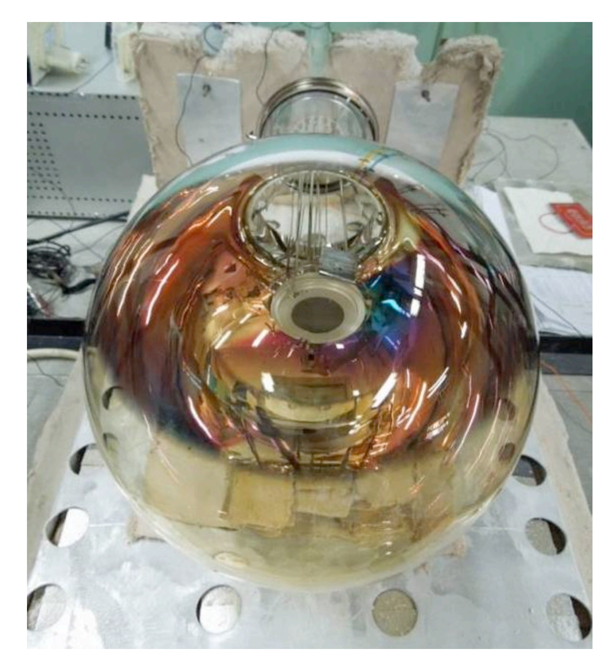
No clearance: coverage 86.5%
1cm clearance: coverage: 83%

20" + 8" PMT

8" PMT better timing

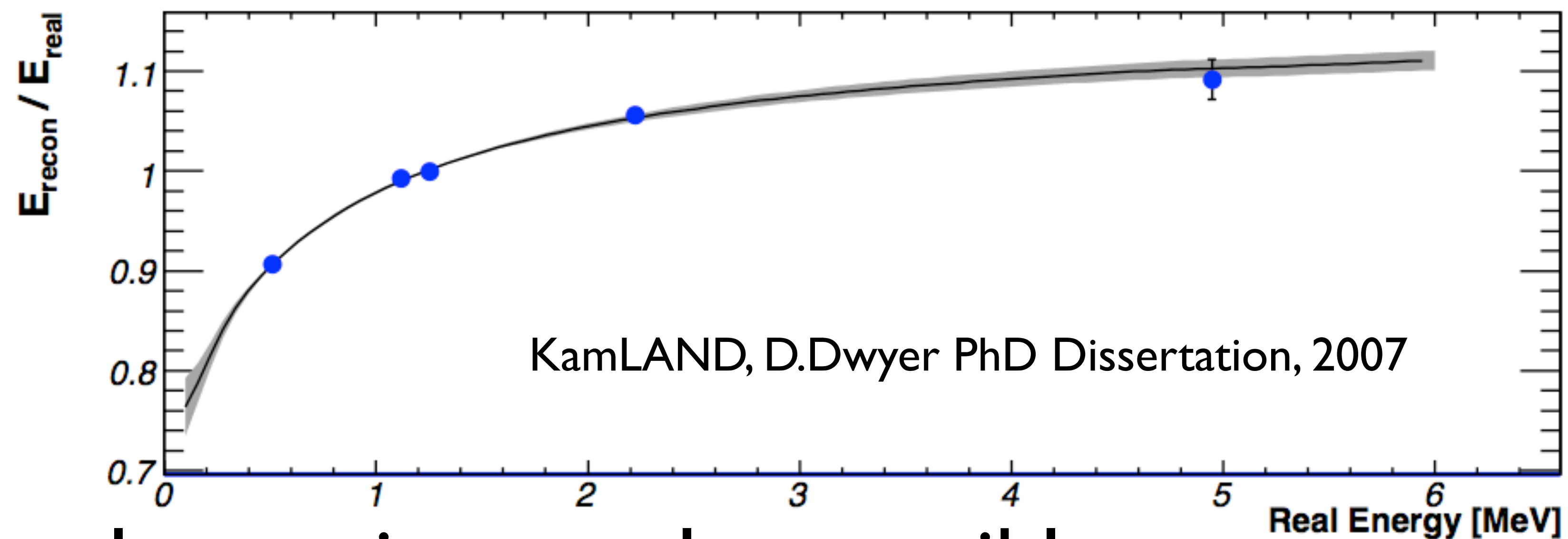


MCP-PMT prototype



Non-linear energy response

- Liquid scintillator energy response is non-linear
    - Quenching
    - Cerenkov
    - Particle-dependent



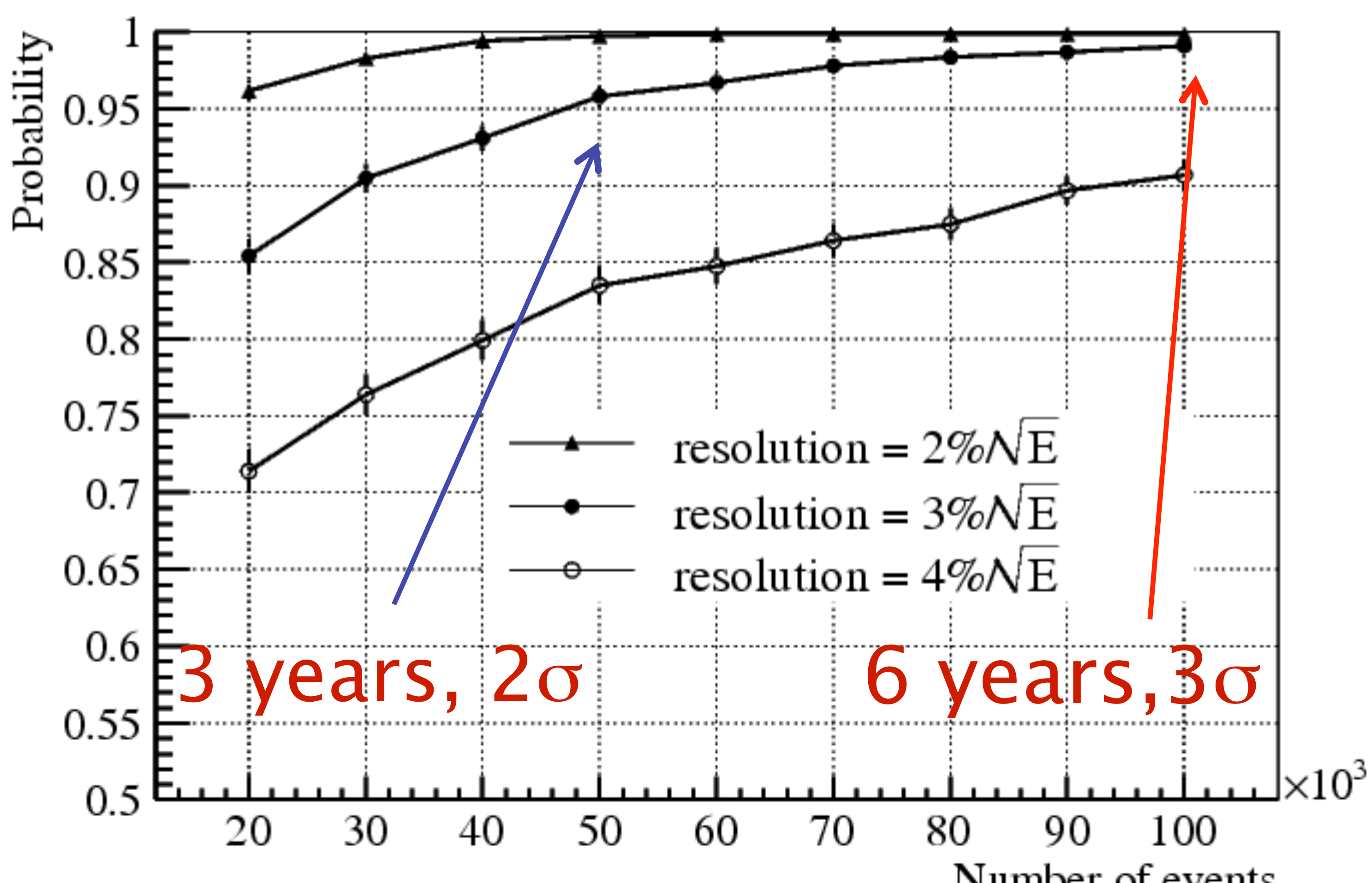
- Non-linear effects due to electronics are also possible
- Pernicious non-linear energy response can fake or mask MH, X.Qian et al, PRD87 (2013) 033005.
- Mitigate using known spectral features, Y.F.Li et al., PRD88 (2013) 013008.
- Comprehensive calibration program essential
    - β^+ sources essential in my opinion (cosmogenic ^{11}C, ^{12}N?; deployed?; dissolved?; $e^{\pm}$ accelerator [arXiv:1307.7419]?)

Expected RRNOLD performance

- $\Delta\chi^2 \equiv \chi^2(NH) - \chi^2(IH)$
- Discrete hypotheses confounds usual $n\sigma = \sqrt{\Delta\chi^2}$
- PRD86(2012)113011;JHEP1305 (2013)131;arXiv:1305.5150

- Fourier analysis
- Difficult to handle systematic uncertainties
- PRD78(2008)111103;PRD79(2009) 037007

⇒Determine probability to resolve MH with MC

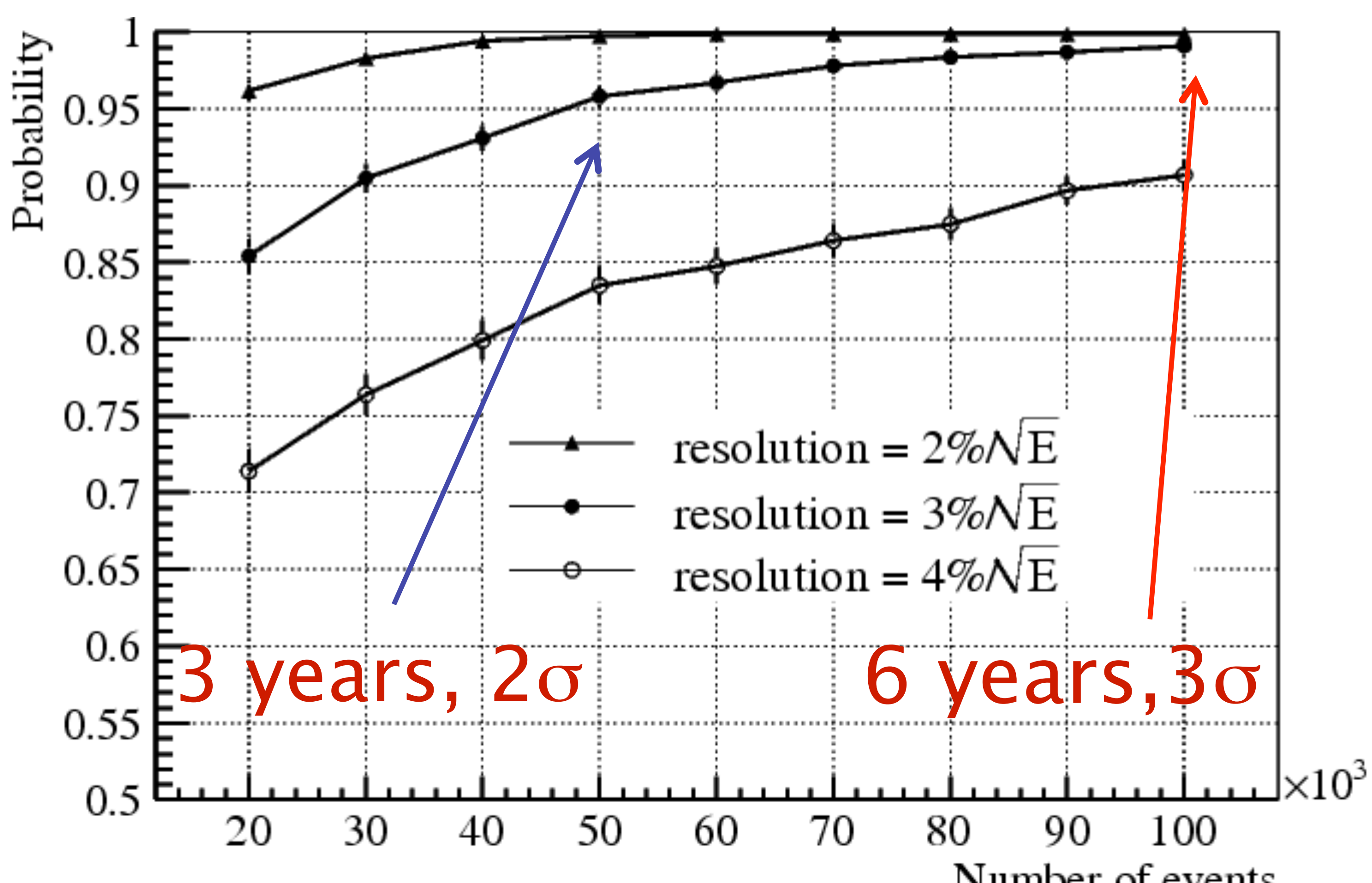


Hypothesis testing

CDMS II Si result: arXiv:1304.4279

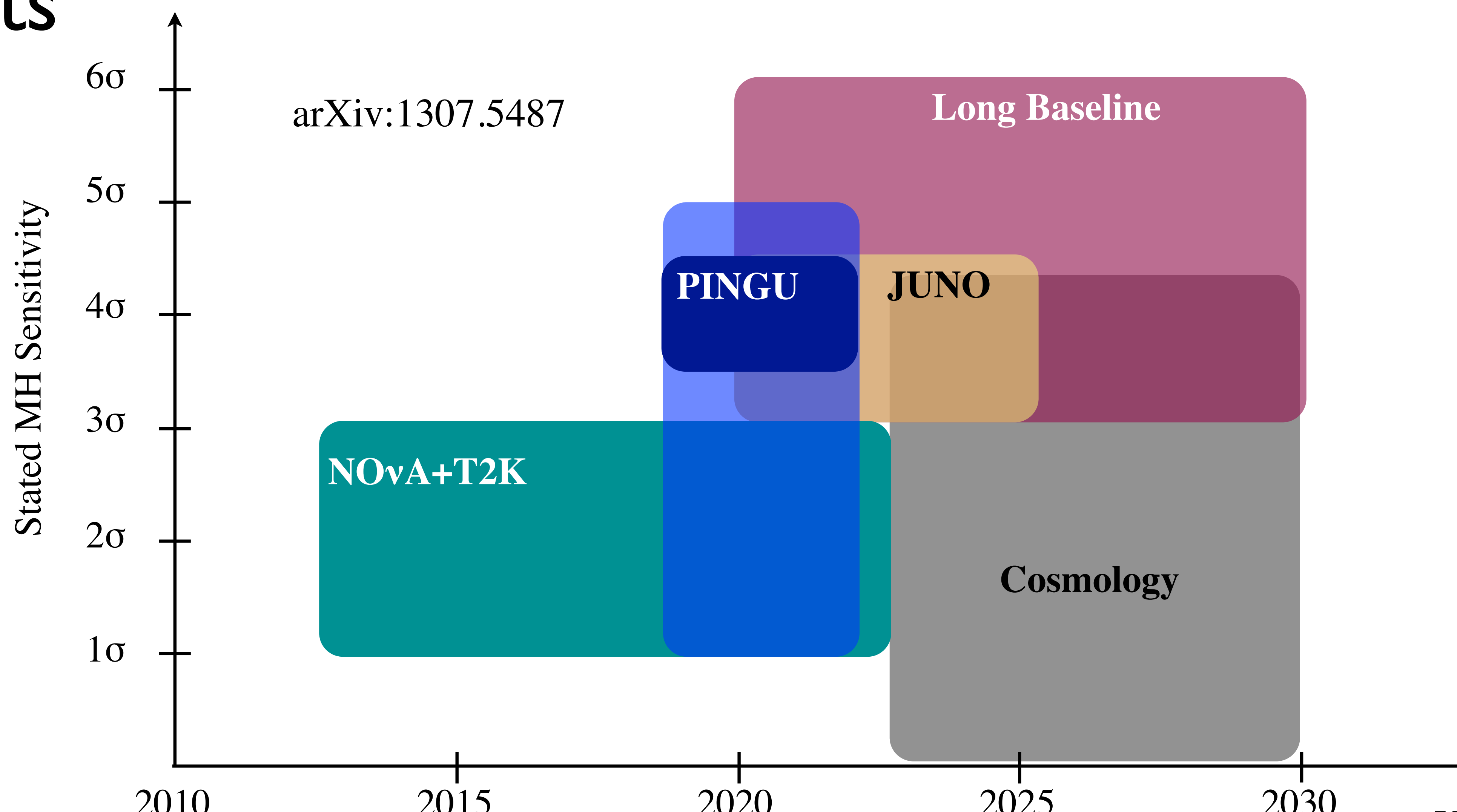
Note that 0.19% is >3 standard deviations

A profile likelihood ratio test finds that the data favor the WIMP+background hypothesis over our background-only hypothesis with a p-value of 0.19%. Though this result favors a WIMP interpretation over the known-background-only hypothesis, we do not believe this result rises to the level of a discovery.



Prognosis

- Single RRNOLD unlikely to resolve MH at 5 standard deviations in statistical significance
  - Would like confirmation with second RRNOLD
  - Would like confirmation by complementary experiments

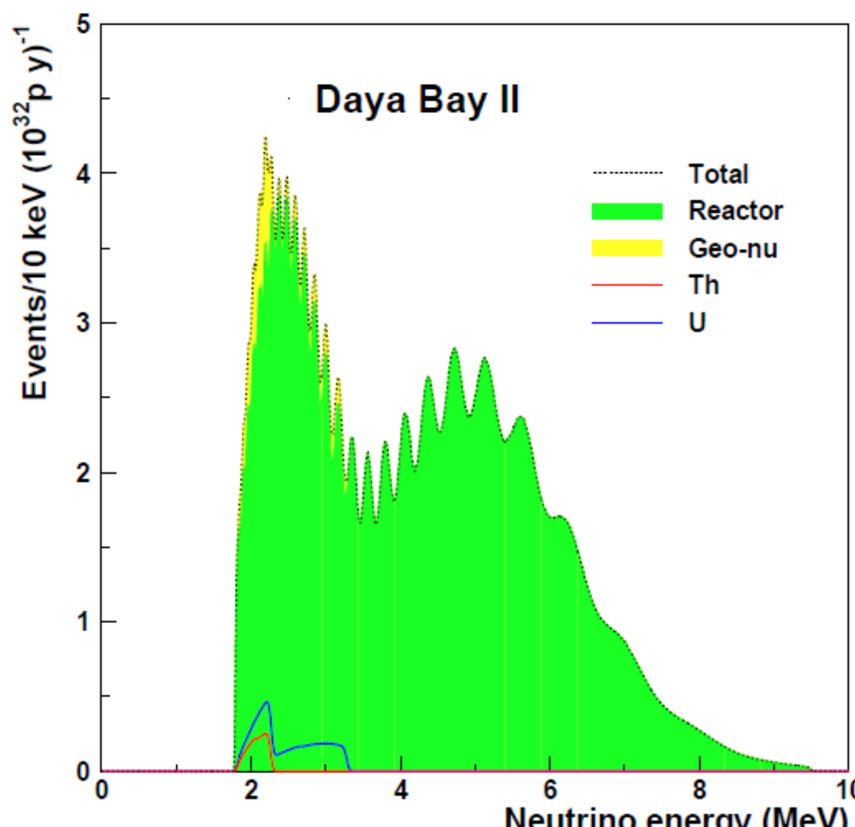


Other RRNOLD Physics

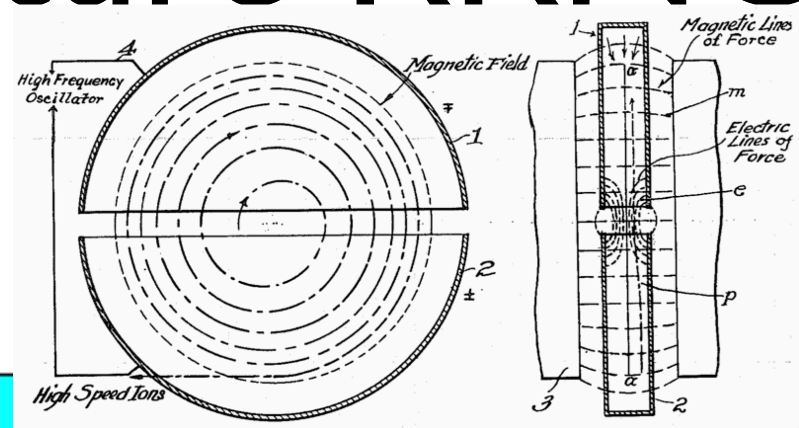
- Precision $\sin^2\theta_{12}$, Δm^2_{23}, Δm^2_{12} measurements.

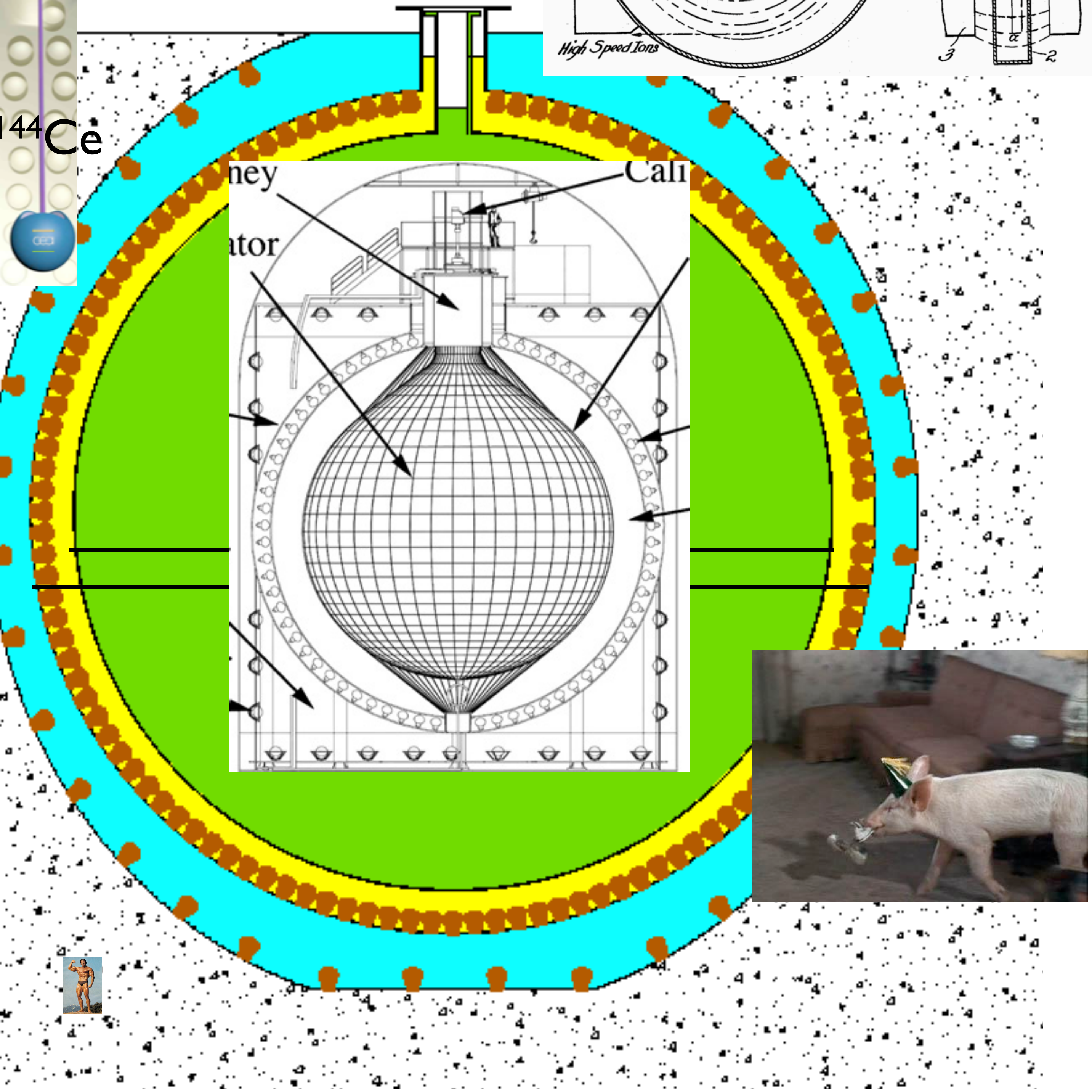
	Current	JUNO
Δm^2_{12}	~3%	~0.6%
Δm^2_{23}	~5%	~0.6%
$\sin^2\theta_{12}$	~6%	~0.7%

- Supernova neutrinos
- Atmospheric and solar neutrinos
- Accelerator neutrinos(T2RENO-50)
- Proton decay: Sufficient mass to reach $\tau(p\rightarrow K^+\nu) > 2.4\times10^{34}$yr(90%CL) in 10 years
- Geo-neutrinos



Future RRNOLD Physics?





- RRNOLD-DAEδALUS (Decay–At–rest Experiment for δ_{CP} studies At the Laboratory for Underground Science)
- KamLAND-Zen => RRNOLD-ZFFL (Zero neutrino Fermion,Fermion Lepton number violation)
- Ce-RRNOLD (^{144}Ce $\overline{\nu}_e$ source)

RRNOLD schedules

- JUNO
  - Approved 1Feb2013 by CAS "special fund for advancement"
  - Construction: 2013-2019. Filling & data taking: 2020
- RENO-50
  - Facility/detector construction: 2013-2018
  - Operation: 2019

RRNOLD

- Aims to resolve the neutrino mass hierarchy and make precision neutrino mixing measurements
- Complements other approaches to resolve MH (accelerator or atmospheric neutrinos, [0νββ])
- Faces significant technical challenges
- "... don't do that just casually."-K.Gorski,this conference

Resources for this talk

- W.Wang, NuFact2013, "Facing the Challenges in Medium-Baseline Reactor Oscillation Experiments"
- M.He, NuFact2013, ``Future Reactor Experiments"
- S.Kettell et al, arXiv:1307.7419, "Neutrino mass hierarchy determination and other physics potential of medium-baseline reactor neutrino oscillation experiments"
- Y. F.Wang, "Daya Bay II: current status and future plan", in Daya Bay II First Meeting, 2013.
- S.B. Kim, "Proposal for RENO-50; detector design & goals (30): S.B. Kim (SNU), International Workshop on "RENO-50" toward Neutrino Mass Hierarchy, June 2013