Geoneutrino Measurement at JUNO

Bedřich Roskovec
(on behalf of the JUNO collaboration)
University of California, Irvine

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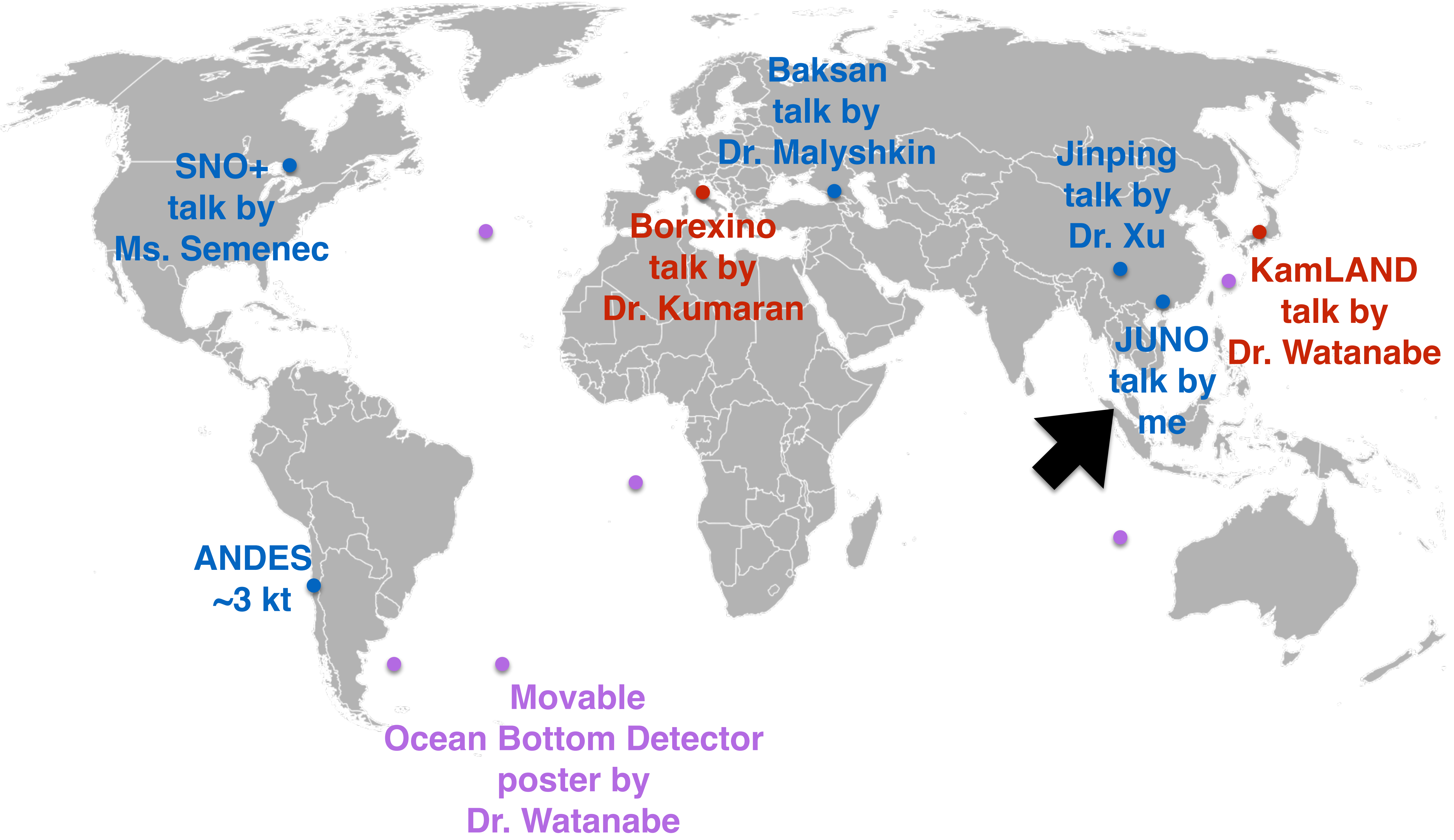
October 22, 2019

Geoneutrino Experiments World Map



SNO+
talk by
Ms. Semenec

Baksan
talk by
Dr. Malyshkin

Borexino
talk by
Dr. Kumaran

Jinping
talk by
Dr. Xu

KamLAND
talk by
Dr. Watanabe

JUNO
talk by
me

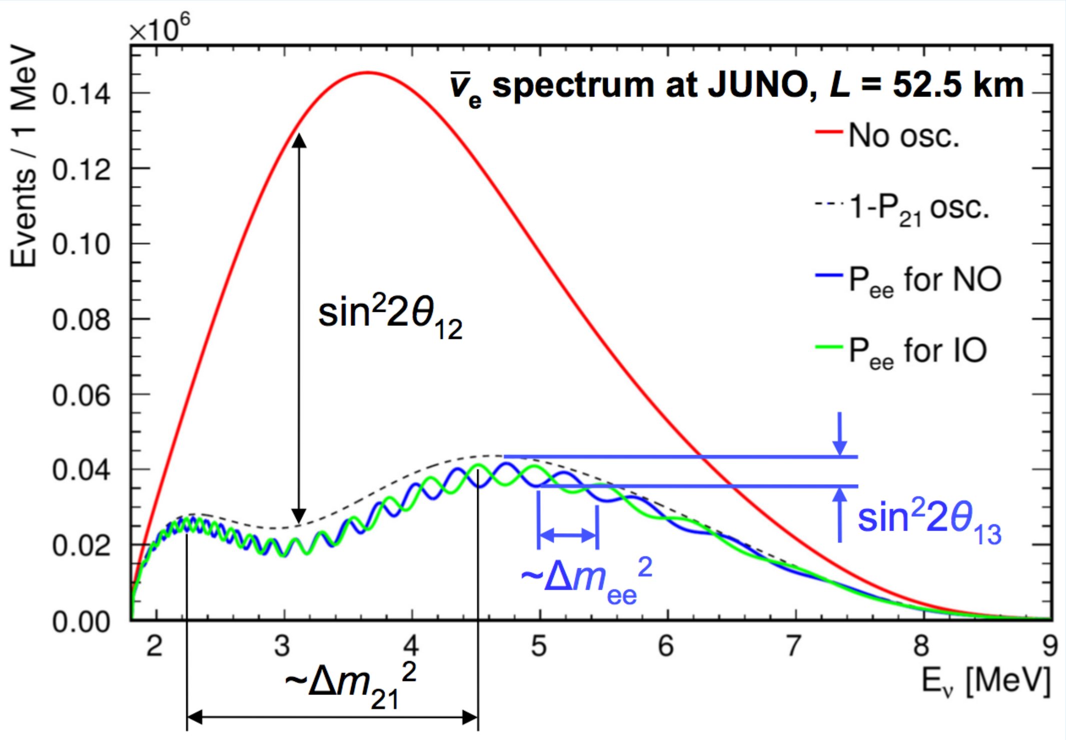
ANDES
~3 kt

Movable
Ocean Bottom Detector
poster by
Dr. Watanabe

JUNO - Multipurpose Experiment

Reactor neutrino oscillations:

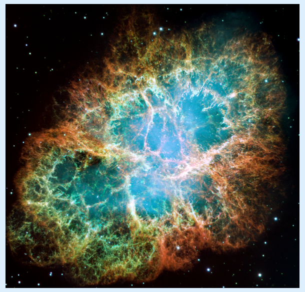
- Mass hierarchy determination
- Precise measurement of three oscillation parameters

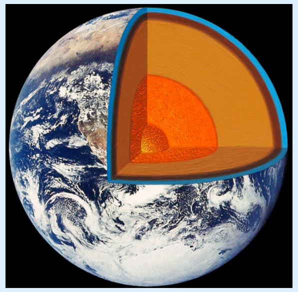


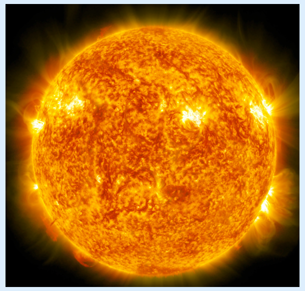
Parameter	Current precision (1σ)	Improvement by JUNO
$\sin^2 2\theta_{12}$	5%	<0.7%
Δm_{21}^2	2.3%	<0.6%
Δm_{31}^2	2.5% sign unknown	<0.5% sign determination

Other physics:

- **Supernova (SN) neutrinos**
  - 10^4 events from SN @ 10 kpc
  - Testing SN models
  - Possibility of independent determination of MH
- **Diffuse SN neutrinos**
  - 1-4 events per year
  - Possible discovery
- **Geoneutrinos**
  - ***Scope of this talk***
- **Solar neutrinos**
  - ^{7}Be, ^{8}B neutrinos detected via elastic scattering
- **Proton decay**
  - $p \to K^+ + \nu$
- **…and more**





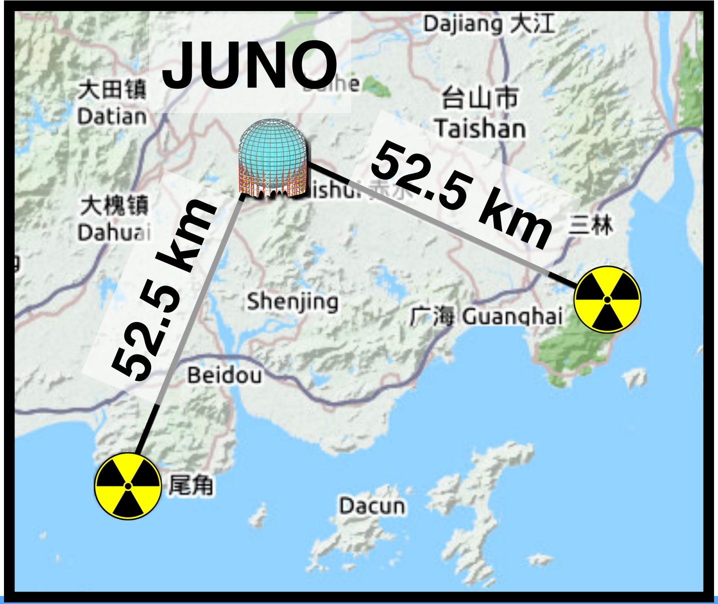


JUNO Location & Collaboration

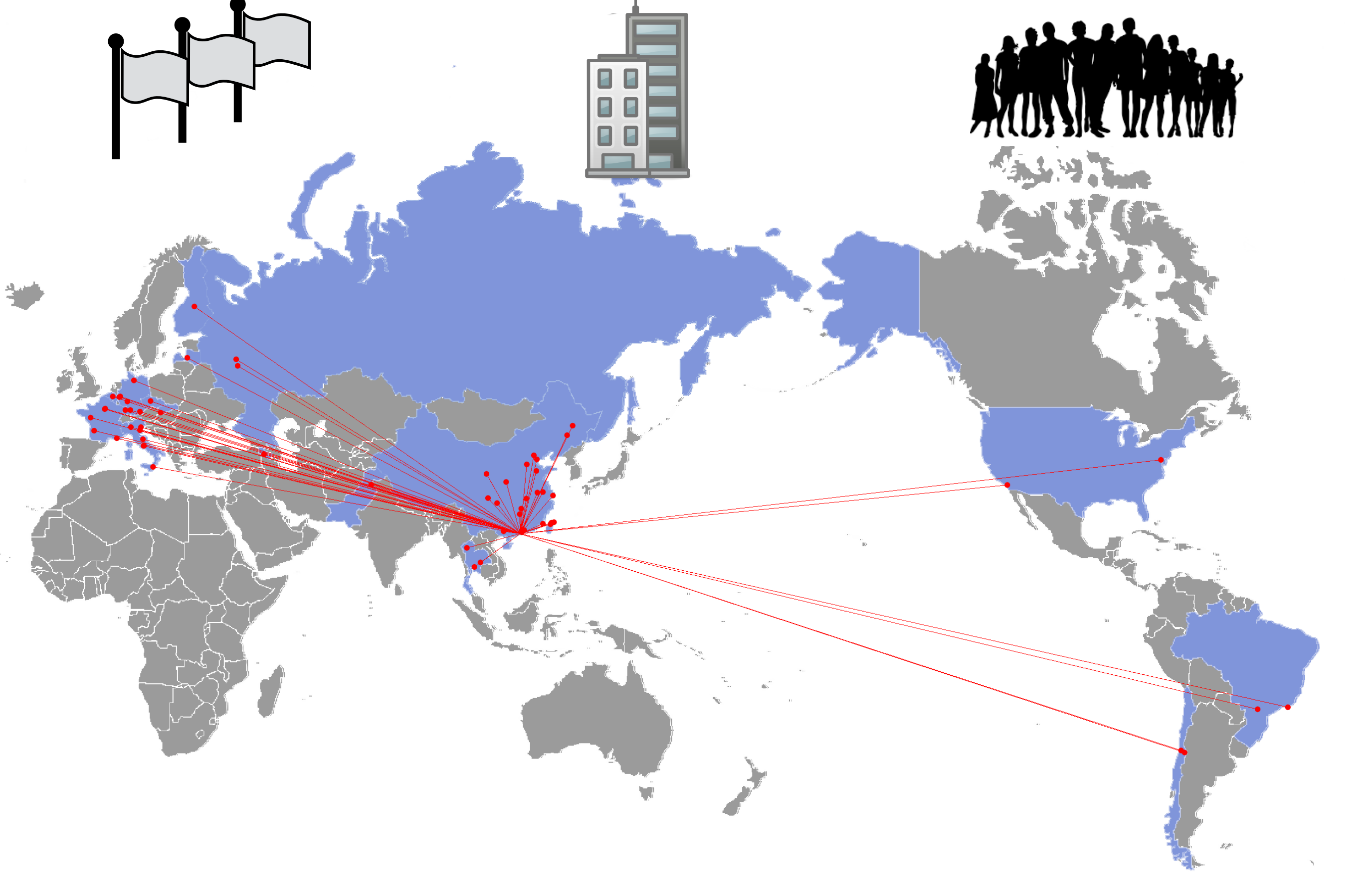
- JUNO=Jiangmen Underground Neutrino Observatory


Southern China

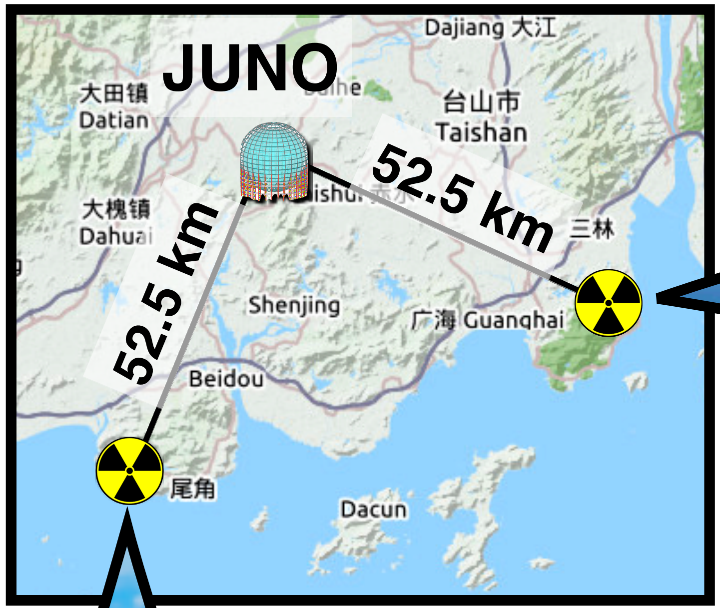
N 22°07'05", E 112°31'05"
Jinji town, Kaiping city,
Jiangmen city, Guangdong province



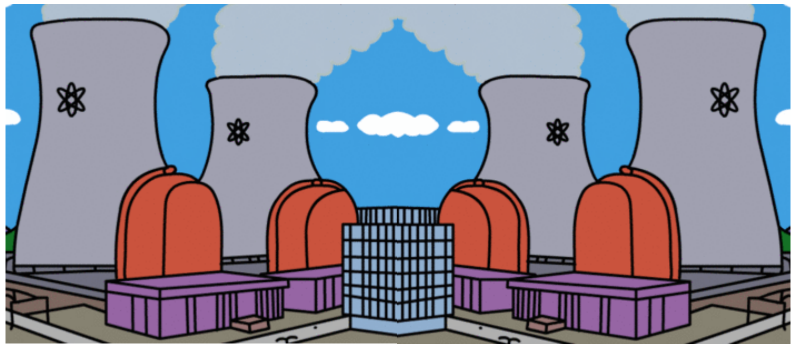
The JUNO collaboration:
17 states, 77 institutions, 639 members



Reactor Neutrino Sources



Two other Taishan cores come later



26.6 GW_{th} by 2020: Better for geoneutrinos ✔

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21

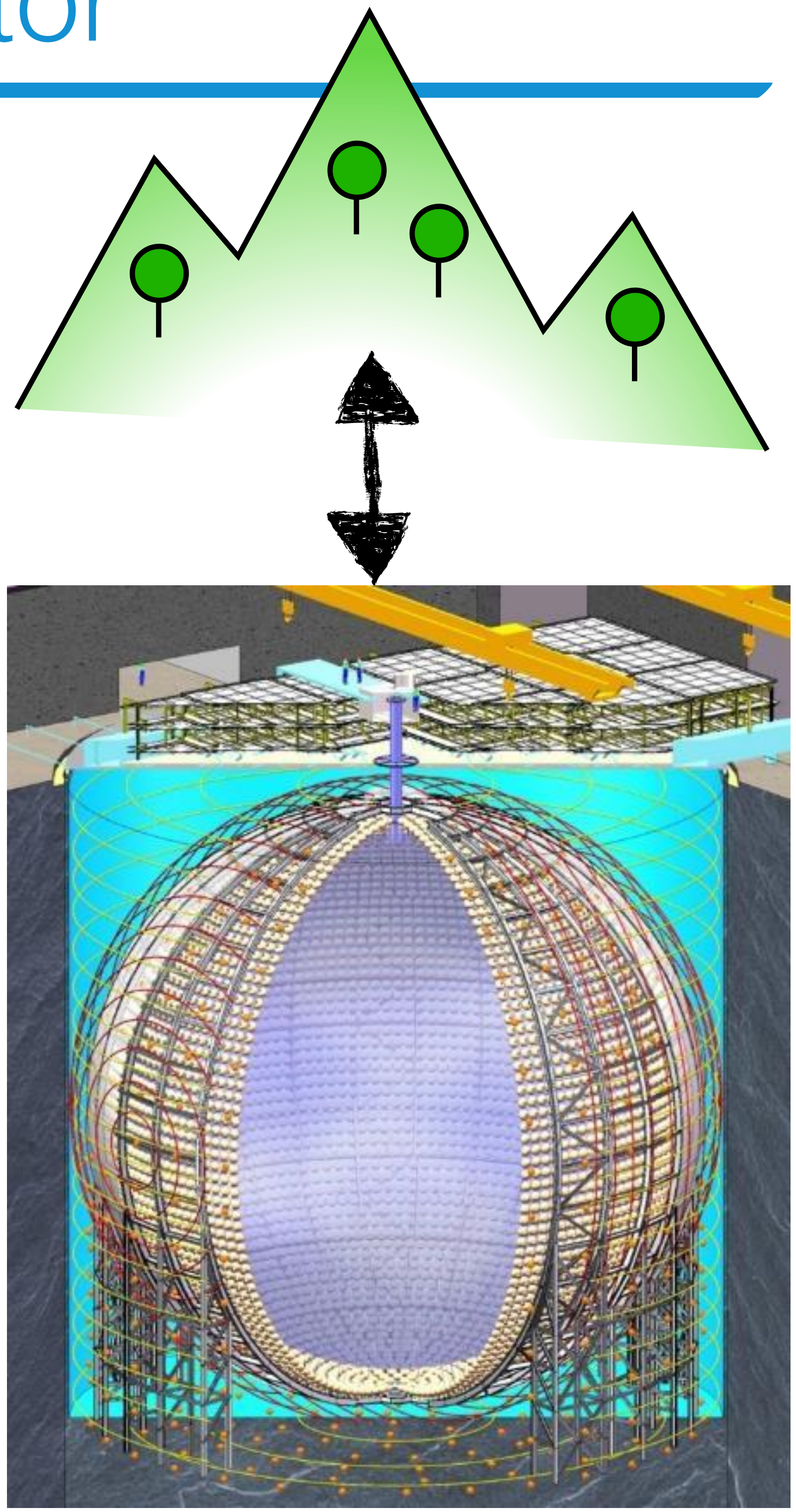
Cores	TS-C1	TS-C2	TS-C3	TS-C4
Power (GW)	4.6	4.6	4.6	4.6
Baseline(km)	52.76	52.63	52.32	52.20

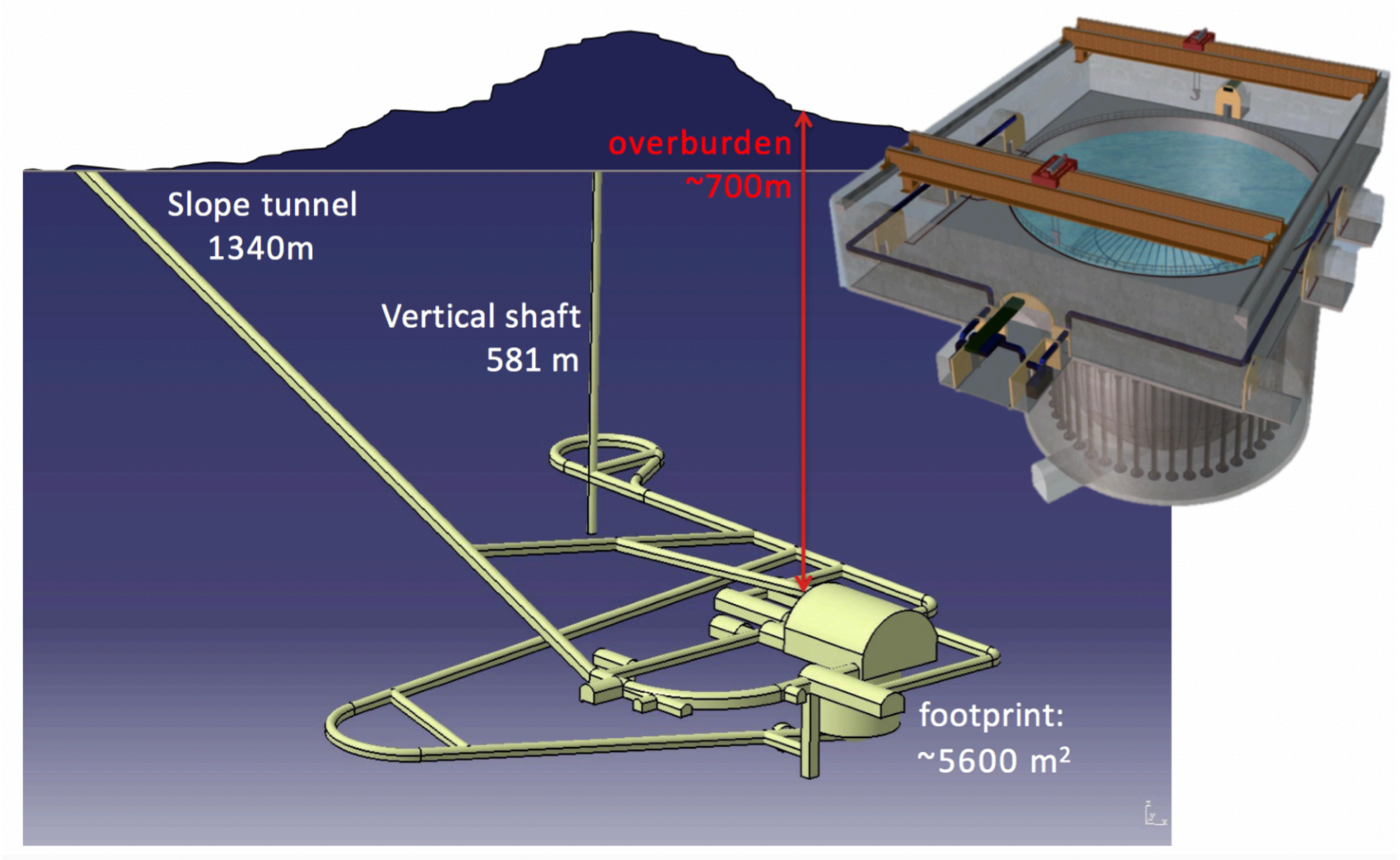
Each core emits $\mathcal{O}(10^{20})\ \bar{\nu}_e/\mathrm{s}$

JUNO Detector

Experimental Cavern

- Overburden ~700 m
- Ultra pure water pool:
  h=44 m, ⌀=43.5 m

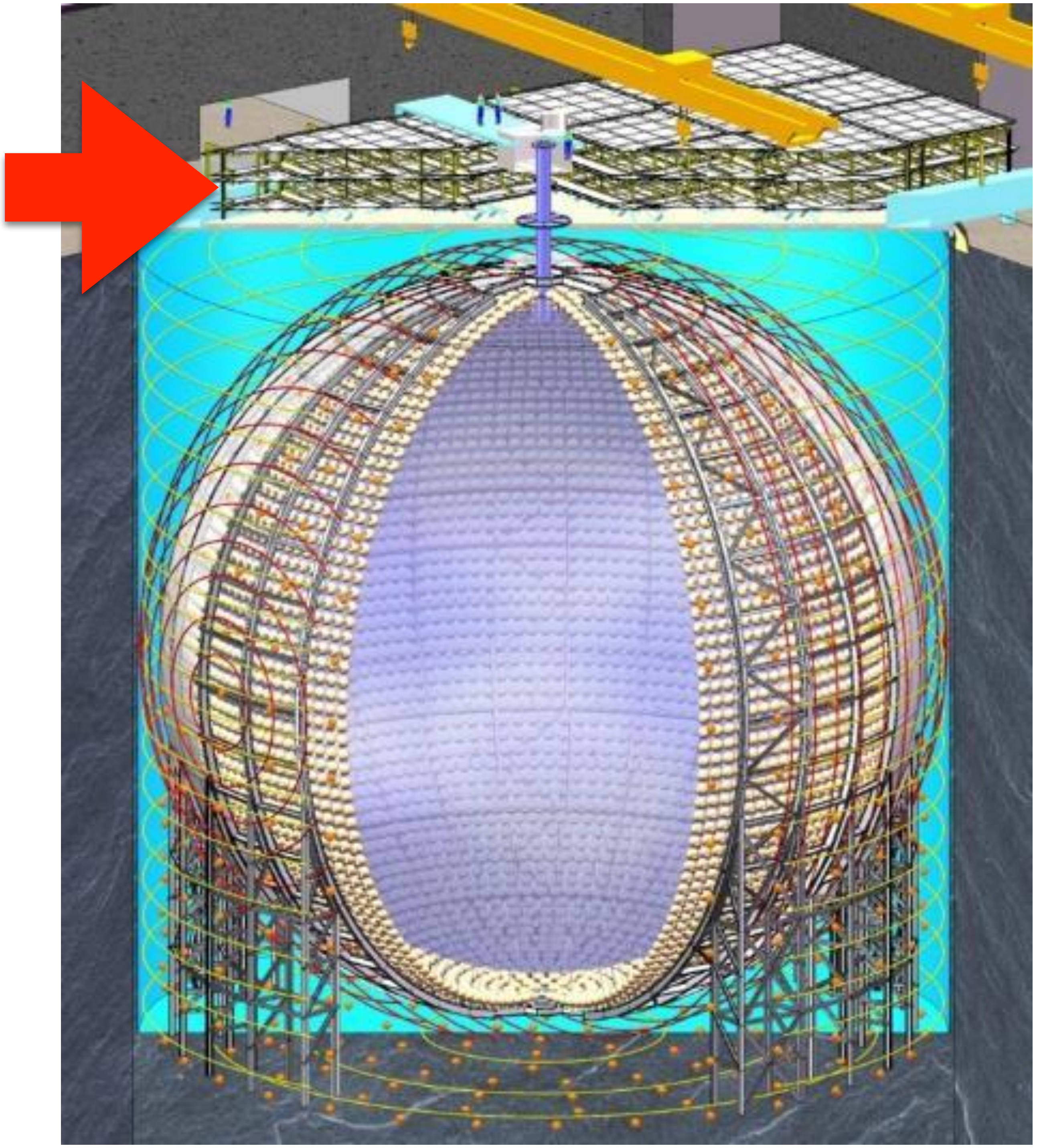




JUNO Detector

Top tracker

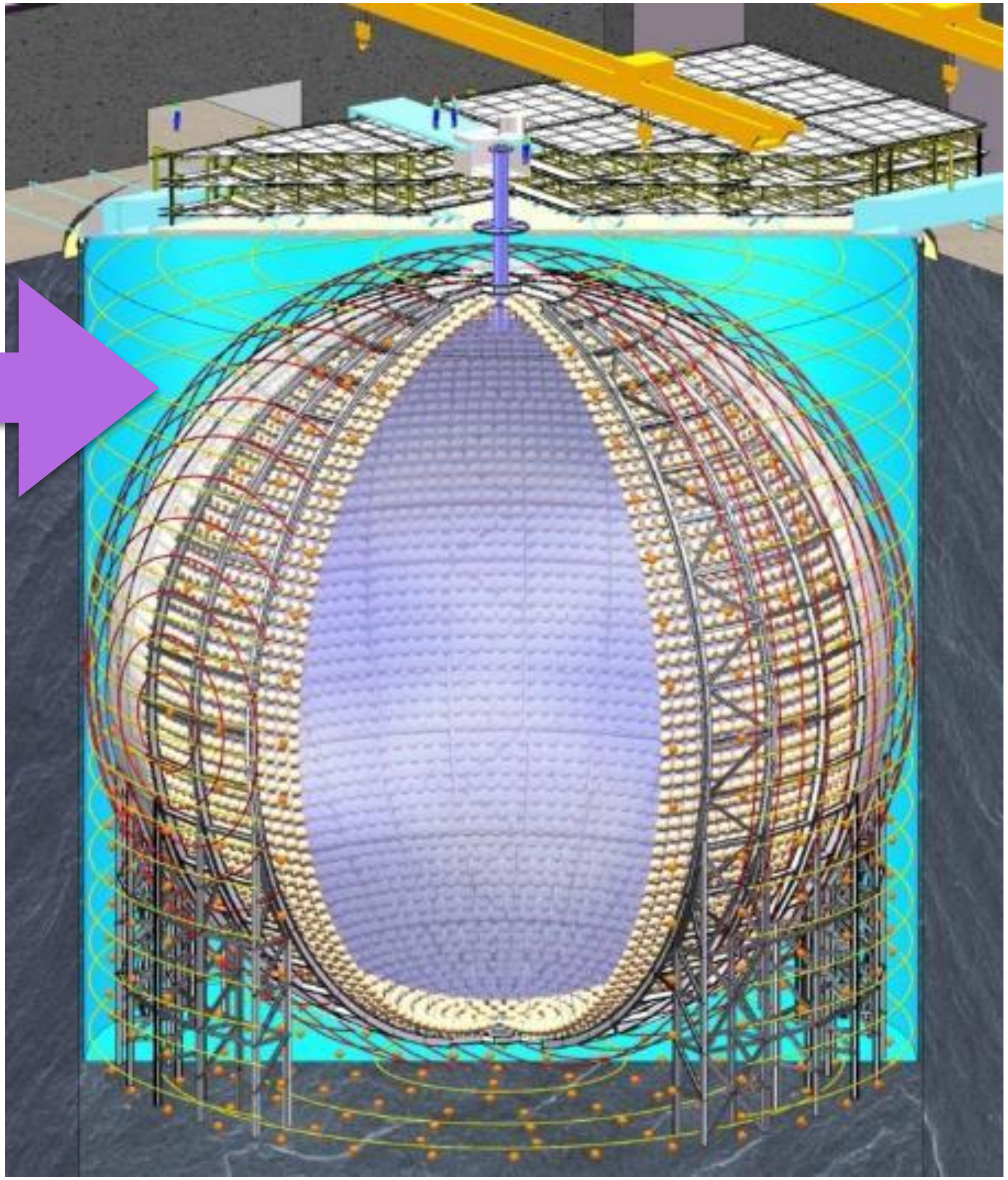
- Three layers of plastic scintillator
- Reused from OPERA experiment
- Covers ~$^2/_3$ of the water pool area
- Provides independent and precise cosmic-ray muon tracking



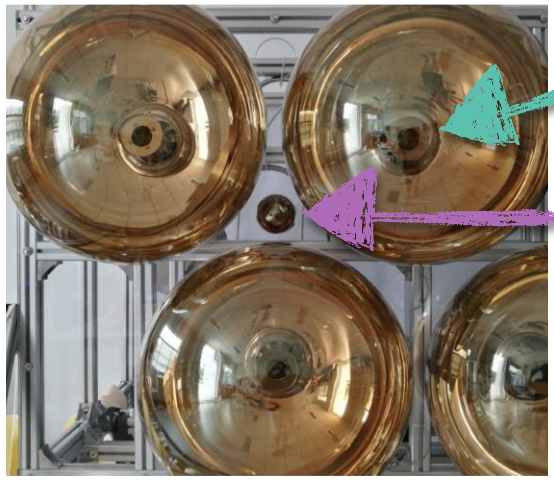
JUNO Detector

Water Pool

- 40 kt of ultra pure water
- Passive shielding
- Instrumented with 2k 20-inch PMTs
- Active Cherenkov detector for cosmic-ray muon tagging (>95% efficiency)
- System of coils to suppress Earth’s magnetic field



JUNO Detector

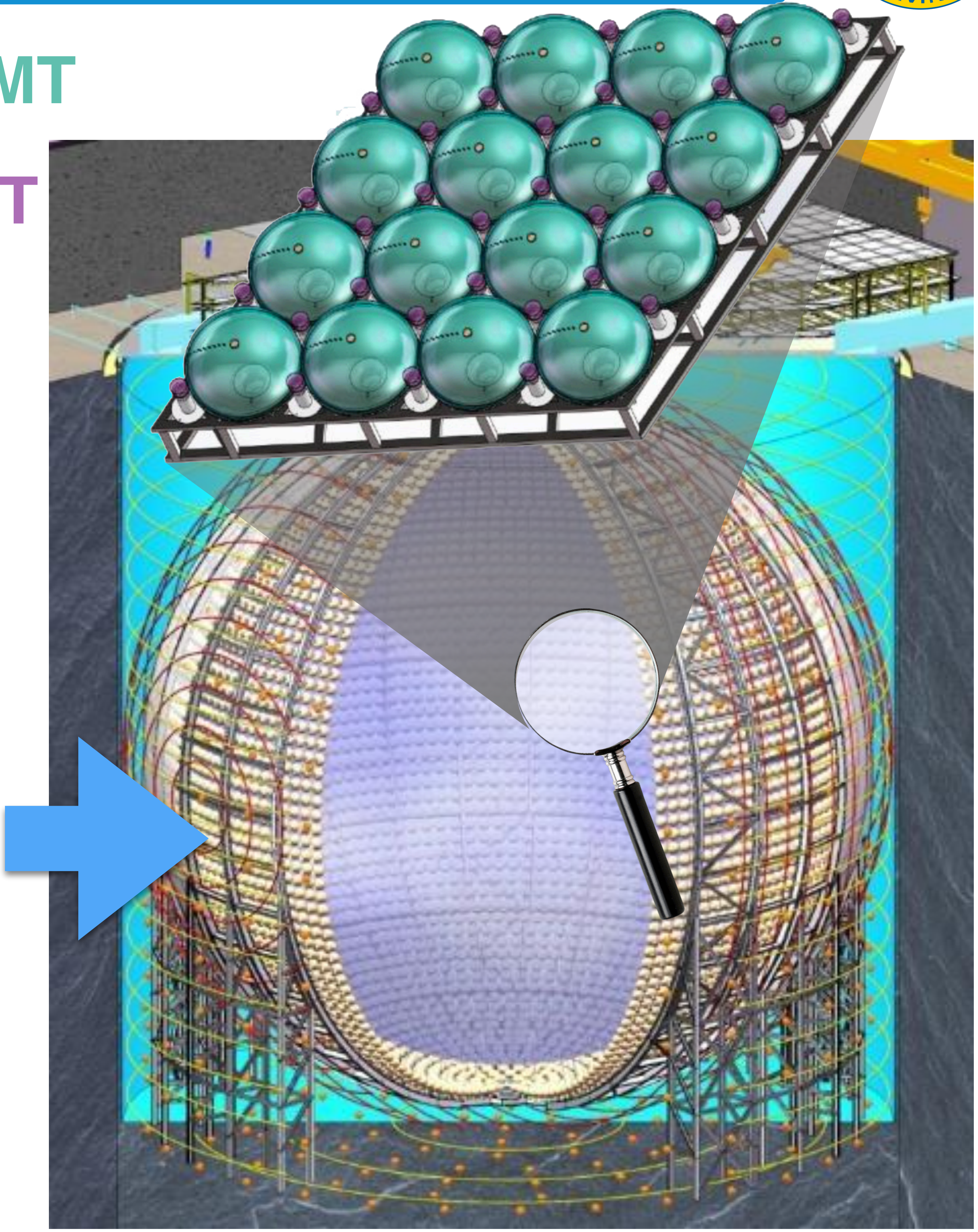


Large 20-inch PMT

Small 3-inch PMT

Central Detector

- 20 kt of liquid scintillator
- **Largest of its kind in the world**
- Unique system of
  18k 20-inch LPMTs and
  25k 3-inch SPMTs
  for double calorimetry
- LPMT ~75% photocoverage ➔ superb energy resolution
- LPMT photon detection efficiency ~30%

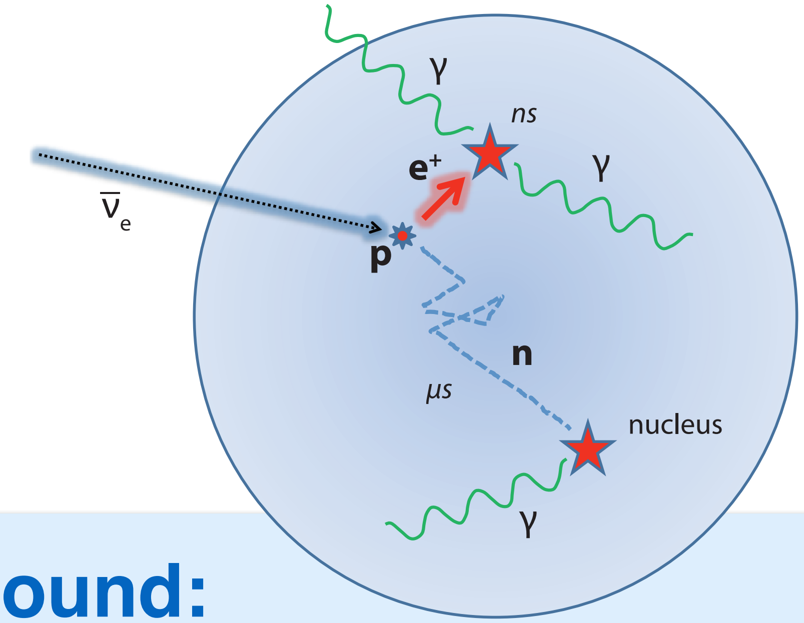


Reactor Electron Antineutrino Detection

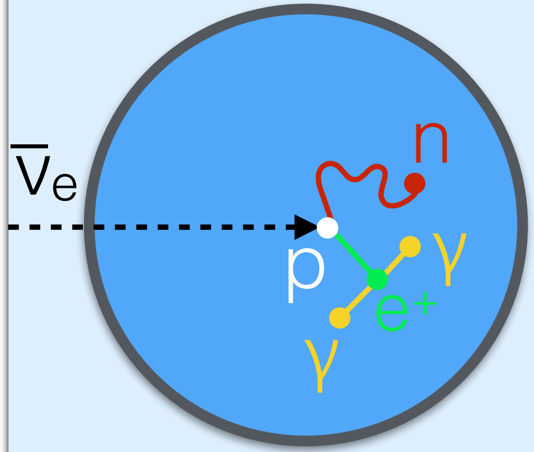
Time coincidence

Prompt signal **Delayed signal**

Inverse beta decay: $\bar{\nu}_e + p \to e^+ + n$



Signal:



Reactor $\bar{\nu}_e$

Positron losses and annihilation

Neutron capture on H

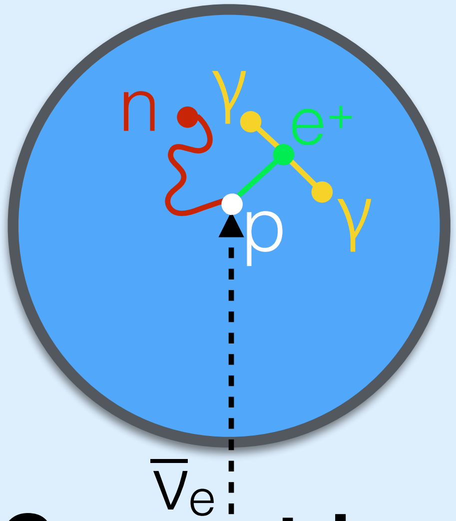
Uncorrelated:

Accidental coincidence

Radioactivity γ

High-energy β decay

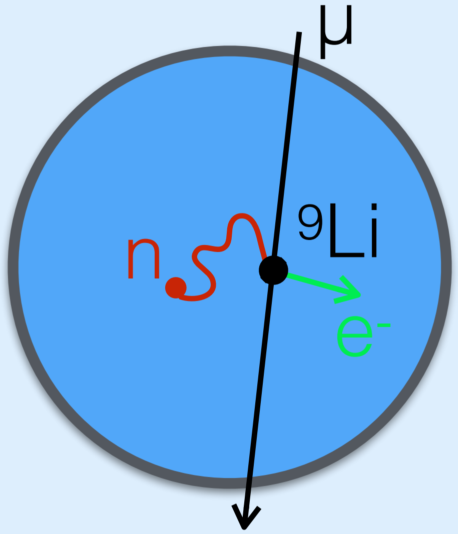
Correlated background:



Geoneutrino

Positron losses and annihilation

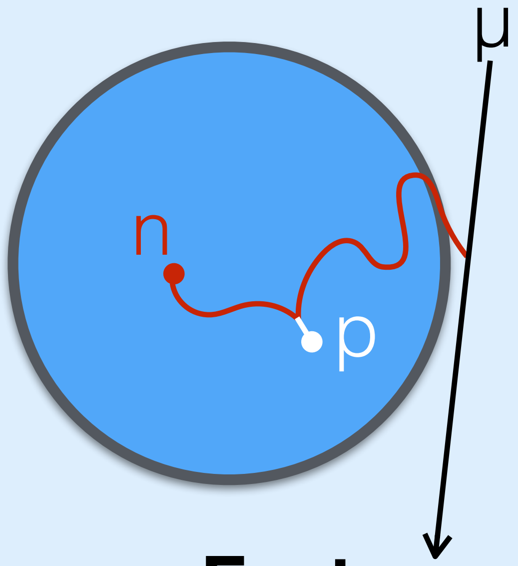
Neutron capture on H



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

β decay

Neutron capture on H



Fast neutrons

Recoil on p

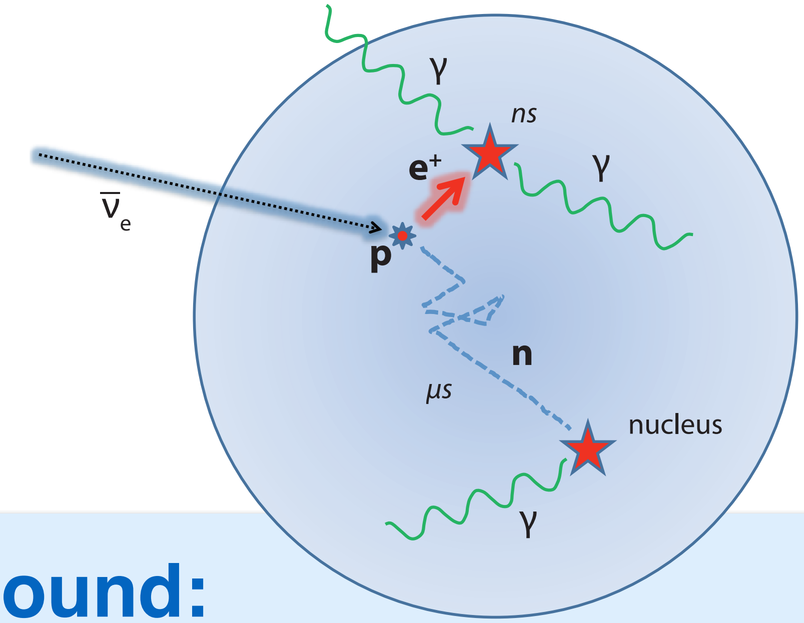
Neutron capture on H

Geoneutrino Detection

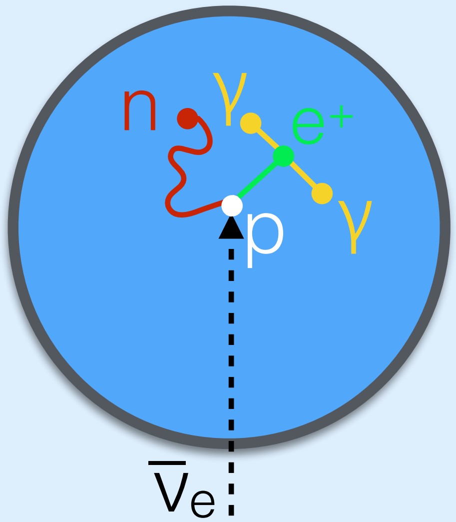
Time coincidence

Prompt signal **Delayed signal**

Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$



Signal:



Geoneutrino

Positron losses and annihilation

Neutron capture on H

Uncorrelated:

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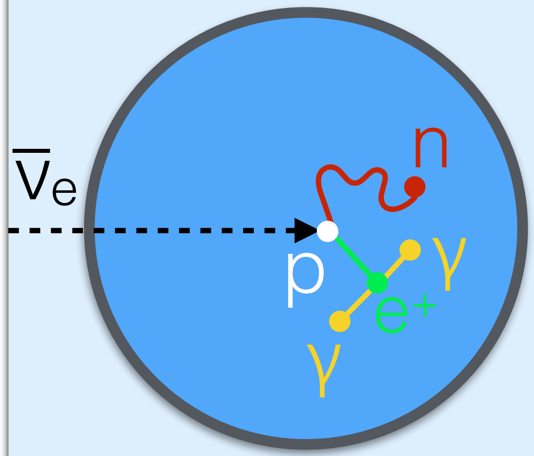
Radioactivity γ

High-energy β decay

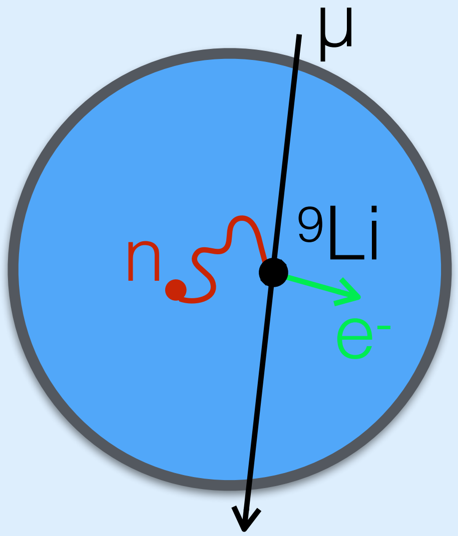
Correlated background:



Reactor ν̄e

Positron losses and annihilation

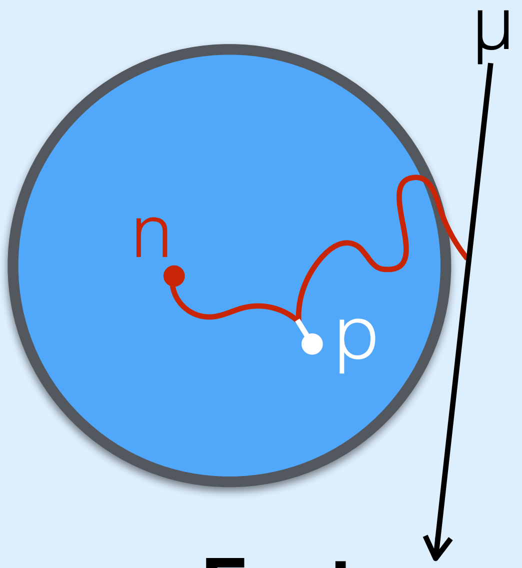
Neutron capture on H



⁹Li/⁸He Isotopes

β decay

Neutron capture on H

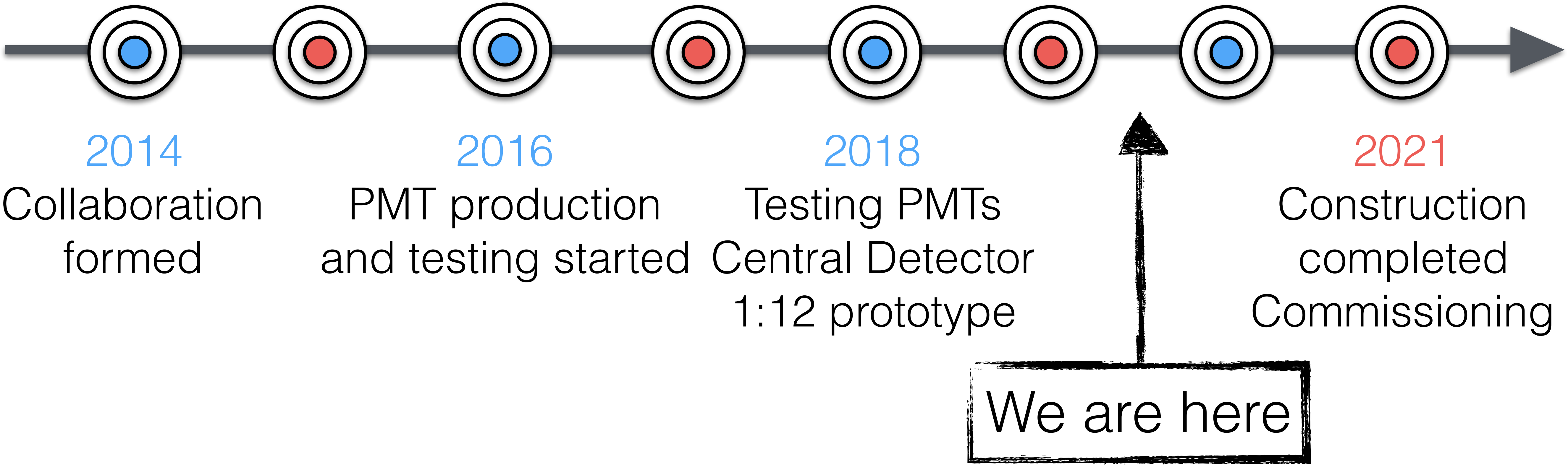


Fast neutrons

Recoil on p

Neutron capture on H

JUNO Timeline



2014
Collaboration formed

2015
Civil construction started

2016
PMT production and testing started

2017
Testing PMTs

2018
Testing PMTs
Central Detector 1:12 prototype

2019-2020
Acrylic production
Detector assembly
LS production and filling
Electronics production
…

2021
Construction completed
Commissioning

We are here

Geoneutrinos in a Nutshell

Mostly electron antineutrinos

$$^{238}_{92}\mathrm{U} \rightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\ \mathrm{MeV}$$

$$^{235}_{92}\mathrm{U} \rightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\ \mathrm{MeV}$$

$$^{232}_{90}\mathrm{Th} \rightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\ \mathrm{MeV}$$

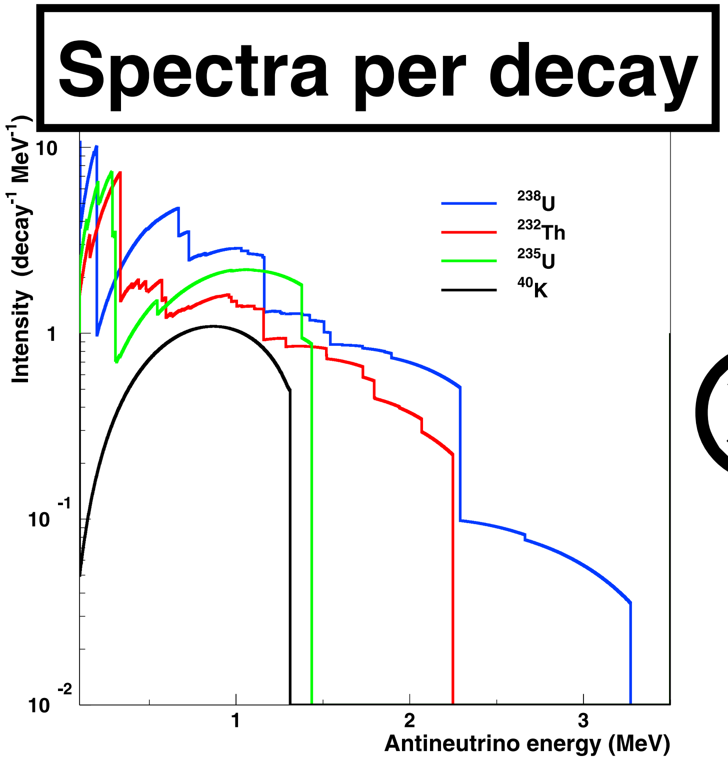
$$^{40}_{19}\mathrm{K} \xrightarrow{89.3\%} {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\ \mathrm{MeV}$$

$$^{40}_{19}\mathrm{K} \xrightarrow{10.7\%} {}^{40}_{18}\mathrm{Ar} + \nu_e + 1.505\ \mathrm{MeV}$$

Geoneutrinos detected by particle physicists

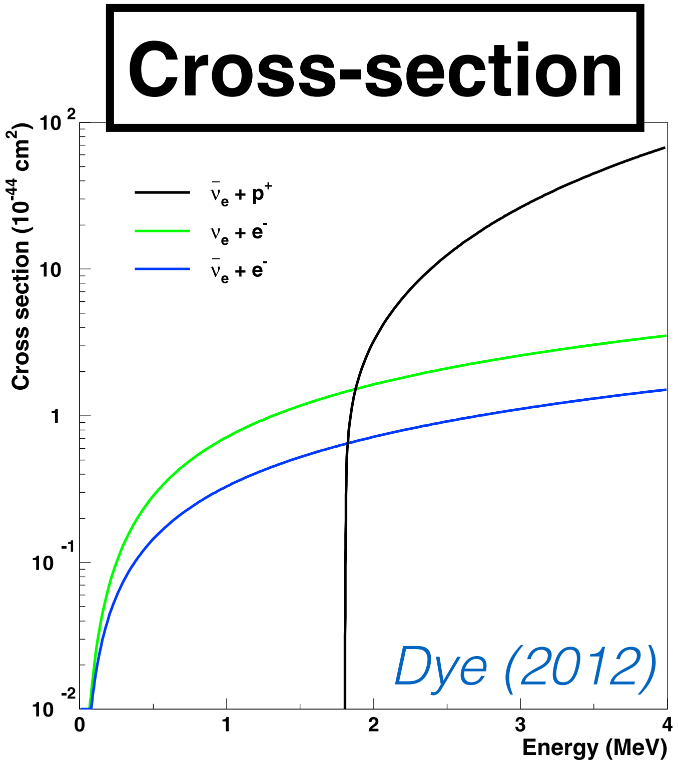
Detection method: Inverse β decay (IBD)

Inverse beta decay threshold 1.8 MeV



Spectra per decay

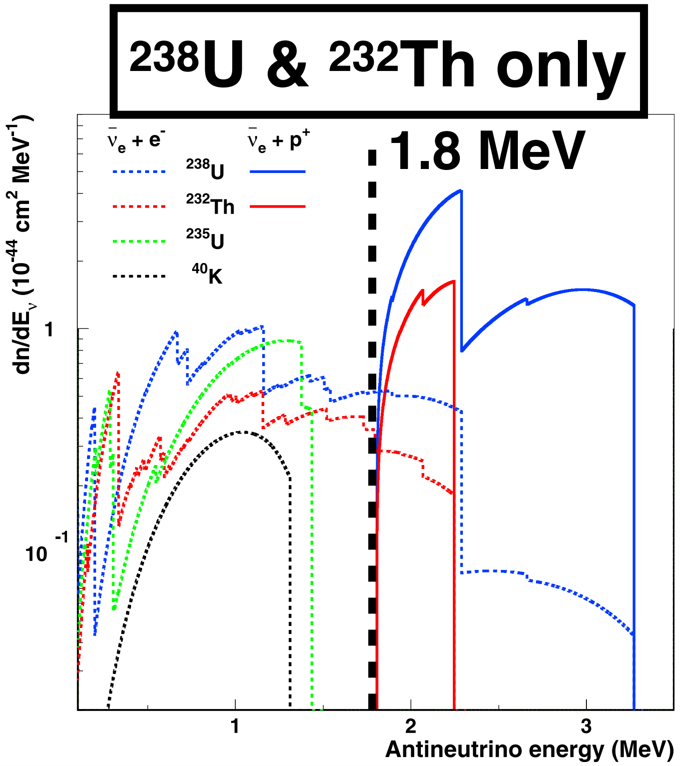
⊗



Cross-section

Dye (2012)

=



^{238}U & ^{232}Th only

Geoneutrinos in a Nutshell

$$^{238}_{92}\mathrm{U} \rightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^{-} + 6\bar{\nu}_e + 51.698\ \mathrm{MeV}$$

$$^{235}_{92}\mathrm{U} \rightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^{-} + 4\bar{\nu}_e + 46.402\ \mathrm{MeV}$$

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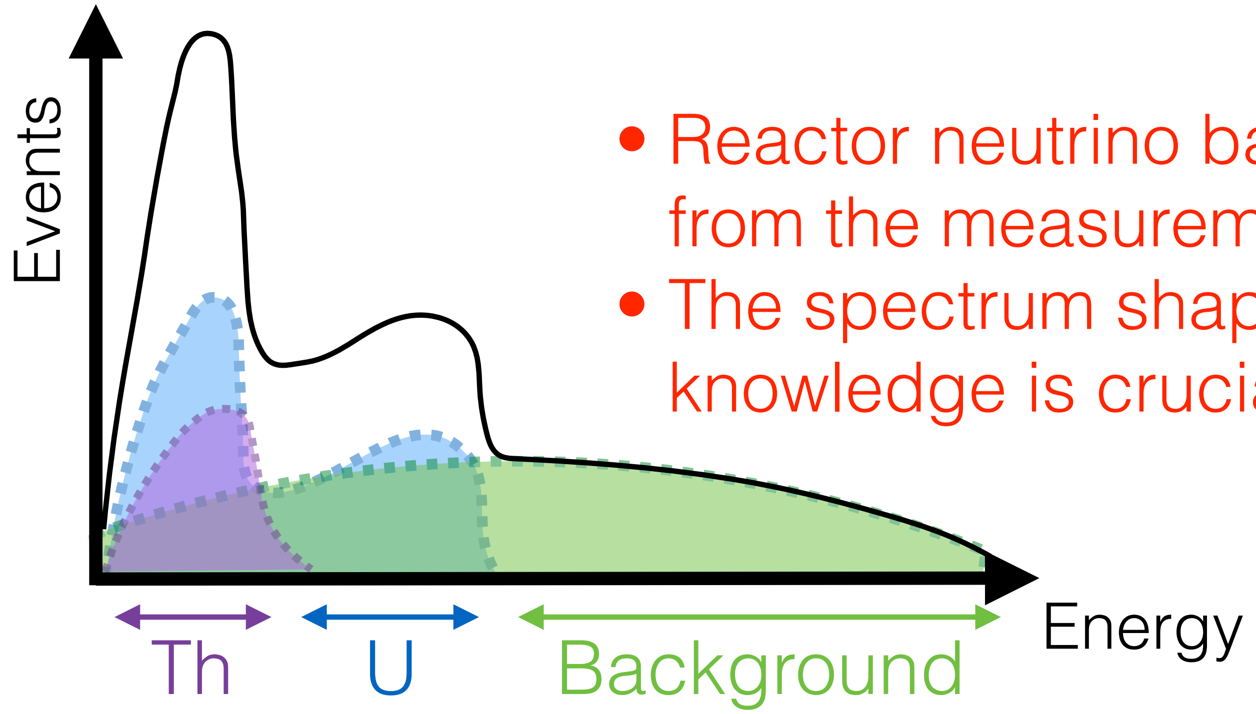
Energy per decay

- Fraction carried away by geoneutrinos
- The rest converts to radiogenic heat

Geophysicists interested in total heat production in the Earth

Key Aspects of Geoneutrino Measurement

- What is needed to perform a good geoneutrino measurement?
  - Low cosmic ray muon flux ➔ Be underground **JUNO±**
  - Low reactor neutrino background ➔ Be far from reactors **JUNO✗**
  - Or know your reactor background well ➔ Measure it **JUNO✓?!?**
  - Low radioactivity ➔ Purification of the scintillator **JUNO✓**
  - High statistics ➔ Large detector **JUNO✓**
  - Sufficient energy resolution for Th/U ratio (for fixed Th/U ratio not needed) ➔ Design your detector accordingly **JUNO✓**



- Reactor neutrino background rate can be extracted from the measurement at higher energies
- The spectrum shape cannot and its prior knowledge is crucial for JUNO

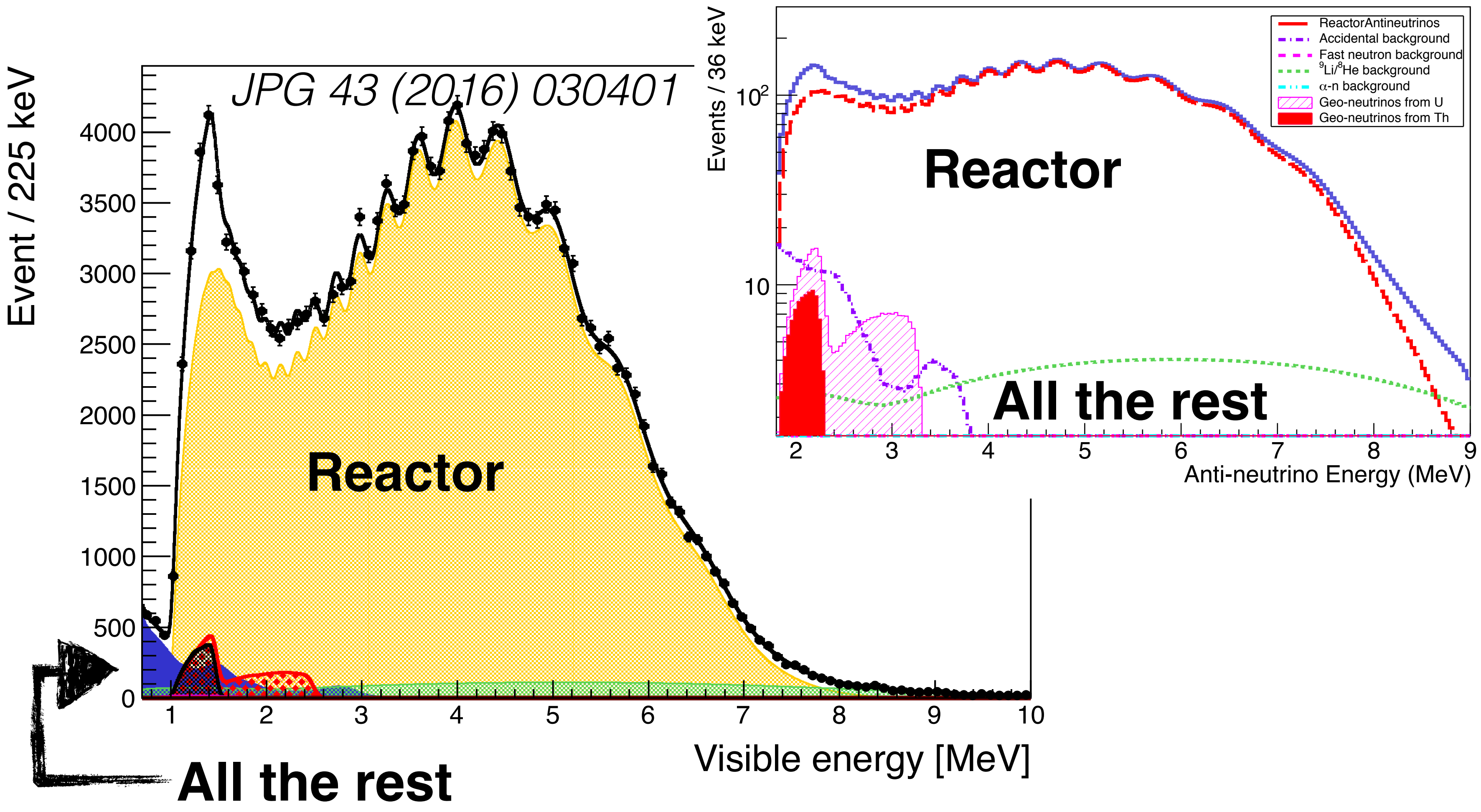
Geoneutrinos at JUNO

- **JUNO will get the largest geoneutrino sample in <1 year**
  - We have so far ~164 events from KamLAND and ~53 events from BOREXINO
- Challenge for JUNO is however huge reactor neutrino background
  - **At what precision can JUNO extract the geoneutrino signal?**

source	events/year
Geo-νs	408 (406)
Reactor	16100 (3653)*
^{9}Li$-^8$He	657 (105)
Fast ns	36.5 (7.66)
^{13}C$(\alpha, n)^{16}$O	18.2 (12.16)
Accidental	401 (348)

1.8-9.0 (1.8-3.3) MeV

*assuming full 35.8 GW_{th}



Impressive JUNO Geoneutrino Measurement

- JUNO's potential with geoneutrinos is impressive

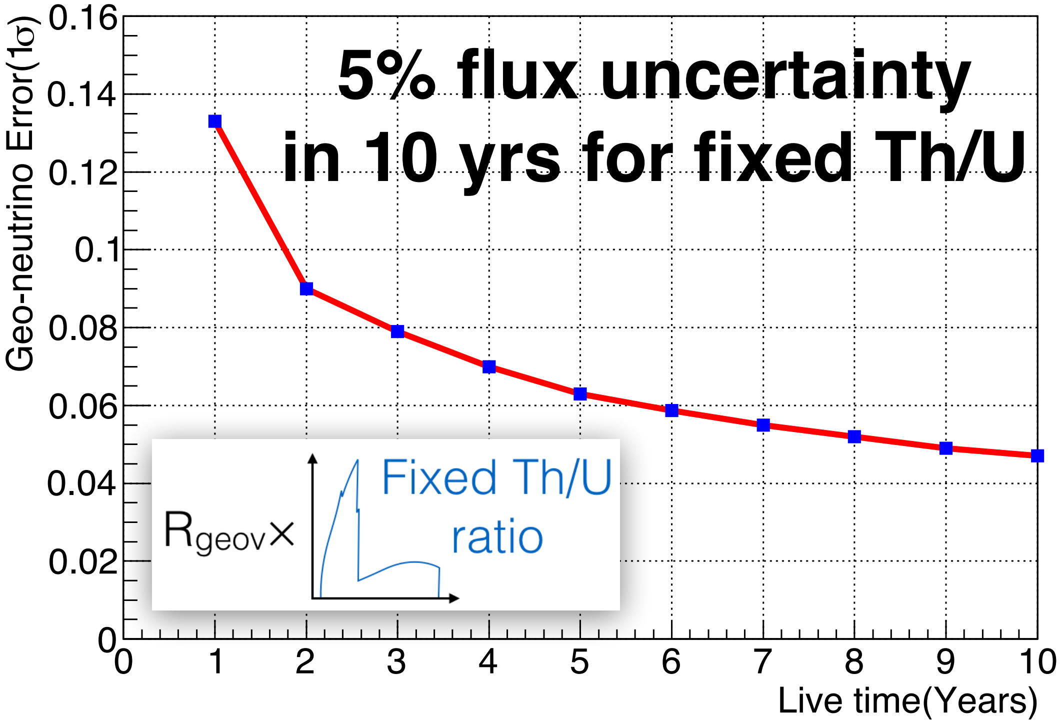
source	events/year	rate uncertainty (%)	shape uncertainty (%)
Geovs	408 (406)	NA	NA
Reactor	16100 (3653)*	2.8	1
$^9\mathrm{Li}-^8\mathrm{He}$	657 (105)	20	10
Fast ns	36.5 (7.66)	100	20
$^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$	18.2 (12.16)	50	50
Accidental	401 (348)	1	negl.

*assuming full 35.8 $\mathrm{GW_{th}}$

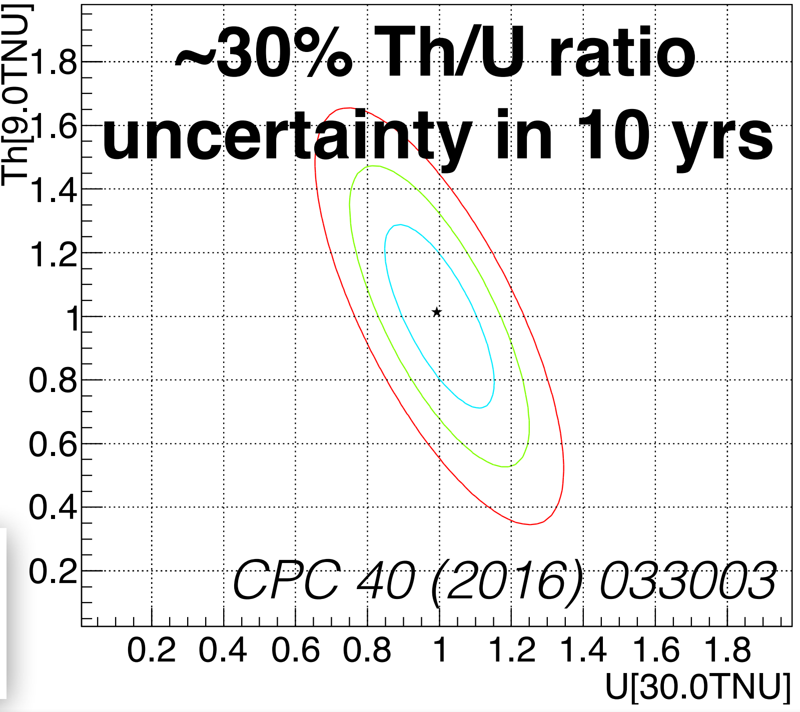
In total (geov region)
1.8-9.0 (1.8-3.3) MeV

$$\chi^2 = \min\left(\sum_{i=1}^{100}\frac{(N_i^{\mathrm{obs}}-N_i^{\mathrm{pred}})^2}{\sigma_{i,\mathrm{stat}}^2+\sigma_{i,\mathrm{sys}}^2}+\frac{\varepsilon_{\mathrm{rea}}^2}{\sigma_{\mathrm{rea}}^2}+\sum_{\mathrm{ibg}=1}^{4}\frac{\varepsilon_{\mathrm{ibg}}^2}{\sigma_{\mathrm{ibg}}^2}\right)$$

$$\sigma_{i,\mathrm{sys}}^2 = (N_{i,\mathrm{rea}}^{\mathrm{obs}}\cdot\sigma_{\mathrm{rea}}^{\mathrm{shape}})^2+\sum_{\mathrm{ibg}=1}^{4}(N_{i,\mathrm{ibg}}^{\mathrm{obs}}\cdot\sigma_{\mathrm{ibg}}^{\mathrm{shape}})^2$$

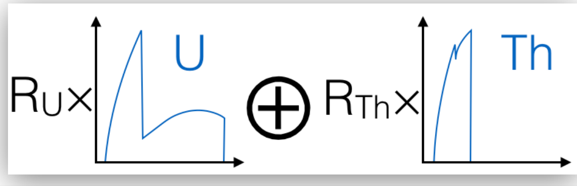


5% flux uncertainty in 10 yrs for fixed Th/U



~30% Th/U ratio uncertainty in 10 yrs

CPC 40 (2016) 033003



Assumptions Were Made

- The precision depends on the reactor neutrino spectral shape uncertainty
- Assumed shape uncertainty 1% for ~80 keV bin width is quite aggressive

source	events/year	rate uncertainty (%)	shape uncertainty (%)
Geovs	408 (406)	NA	NA
Reactor	16100 (3653)*	2.8	1
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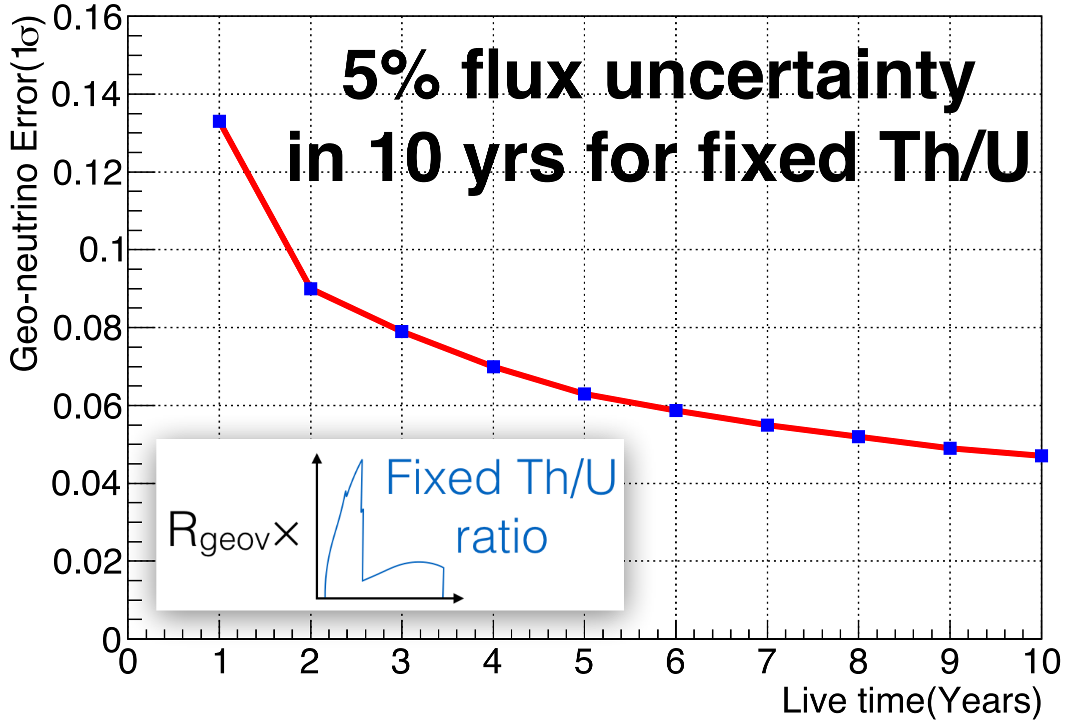
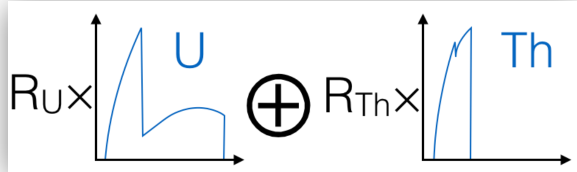
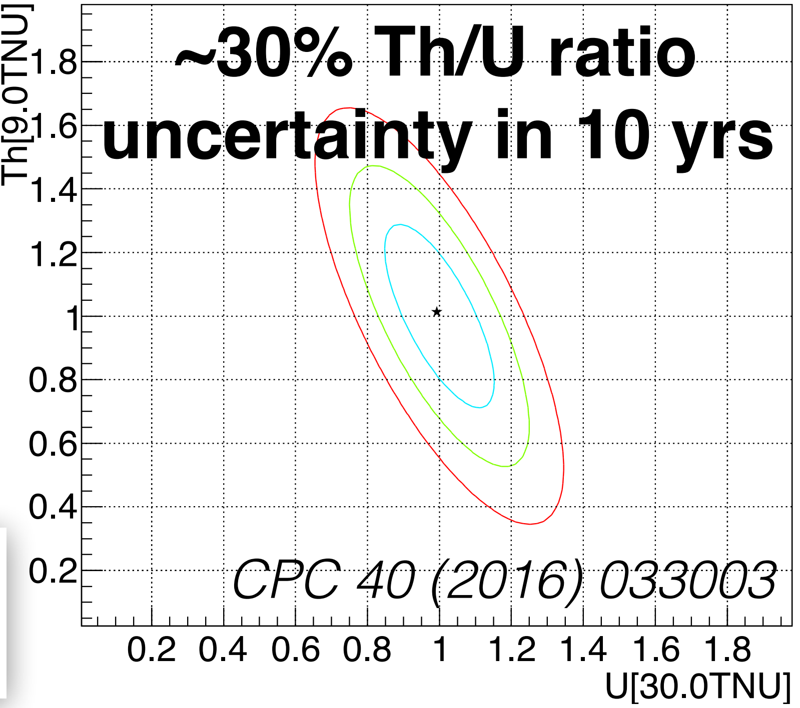
$$\chi^2 = \min\left(\sum_{i=1}^{100}\frac{(N_i^{\rm obs}-N_i^{\rm pred})^2}{\sigma_{i,\rm stat}^2+\boxed{\sigma_{i,\rm sys}^2}}+\frac{\varepsilon_{\rm rea}^2}{\sigma_{\rm rea}^2}+\sum_{\rm ibg=1}^{4}\frac{\varepsilon_{\rm ibg}^2}{\sigma_{\rm ibg}^2}\right)$$

$$\sigma_{i,\rm sys}^2=(N_{i,\rm rea}^{\rm obs}\boxed{\cdot\,\sigma_{\rm rea}^{\rm shape}})^2+\sum_{\rm ibg=1}^{4}(N_{i,\rm ibg}^{\rm obs}\cdot\sigma_{\rm ibg}^{\rm shape})^2$$

1% for ~80 keV bin width


5% flux uncertainty in 10 yrs for fixed Th/U




~30% Th/U ratio uncertainty in 10 yrs

CPC 40 (2016) 033003

Current Reactor Neutrino Spectrum Precision

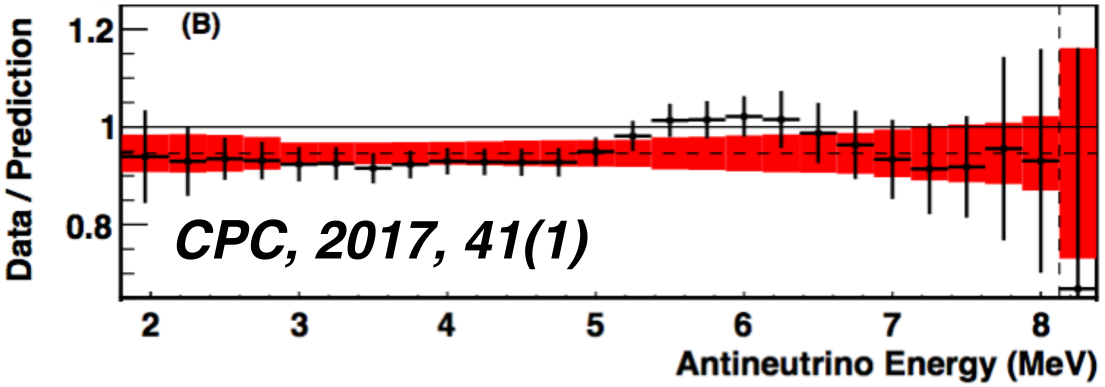
Prediction

- Experiments observe discrepancy in shape from state of the art prediction, e.g. as so-called Huber+Mueller model
- **Using theoretical predictions for a reactor neutrino spectrum shape can bias the geoneutrino measurement!**

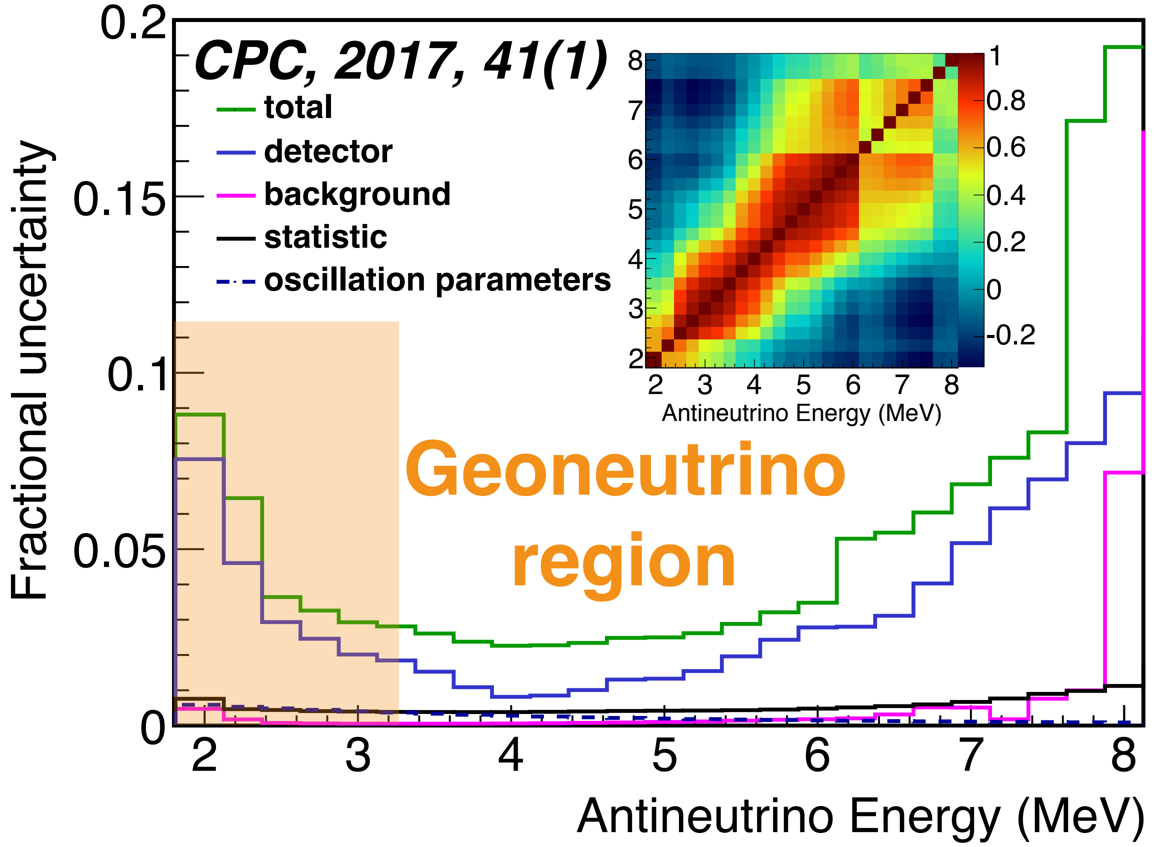
Measurement

- Current best knowledge from Daya Bay (as nicely explained by Dr. Zhang)
- Precision not at 1% (80 keV bin width) and Daya Bay measurement with lower energy resolution:
  - Daya Bay σE≃8.5%√E(MeV)
  - JUNO σE≲3%√E(MeV)

Daya Bay Reactor Neutrino Spectrum Ratio Data/Prediction



CPC, 2017, 41(1)



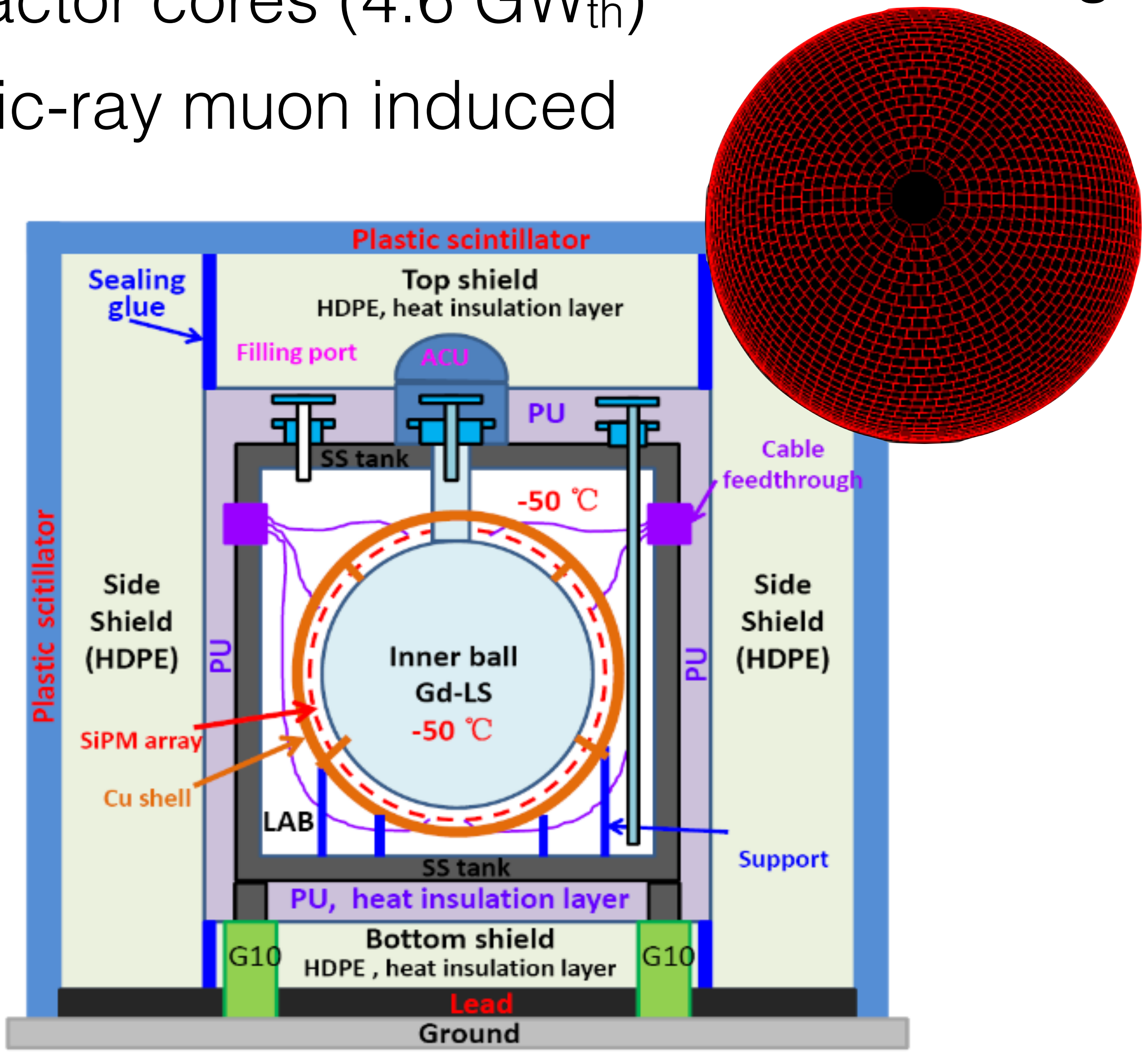
CPC, 2017, 41(1)

Geoneutrino region

Introducing JUNO-TAO

- The precise knowledge of the reactor neutrino spectrum is crucial for JUNO: matters in neutrino mass hierarchy determination, measurement of the oscillation parameters, **geoneutrino signal measurement**, …
- Solution: **JUNO-TAO: a reference detector**
    - 30-35 m from one of the Taishan reactor cores (4.6 GW_{th})
    - About 10 m underground but cosmic-ray muon induced background is under control
    - Full coverage SiPM readout (>50% photon detection efficiency)
    - Operating at -50˚C to suppress SiPM dark rate
    - New detector concept ➔ **challenging but feasible**
    - R&D and prototyping ongoing
    - Start data taking 2021 (like JUNO)

~95% coverage

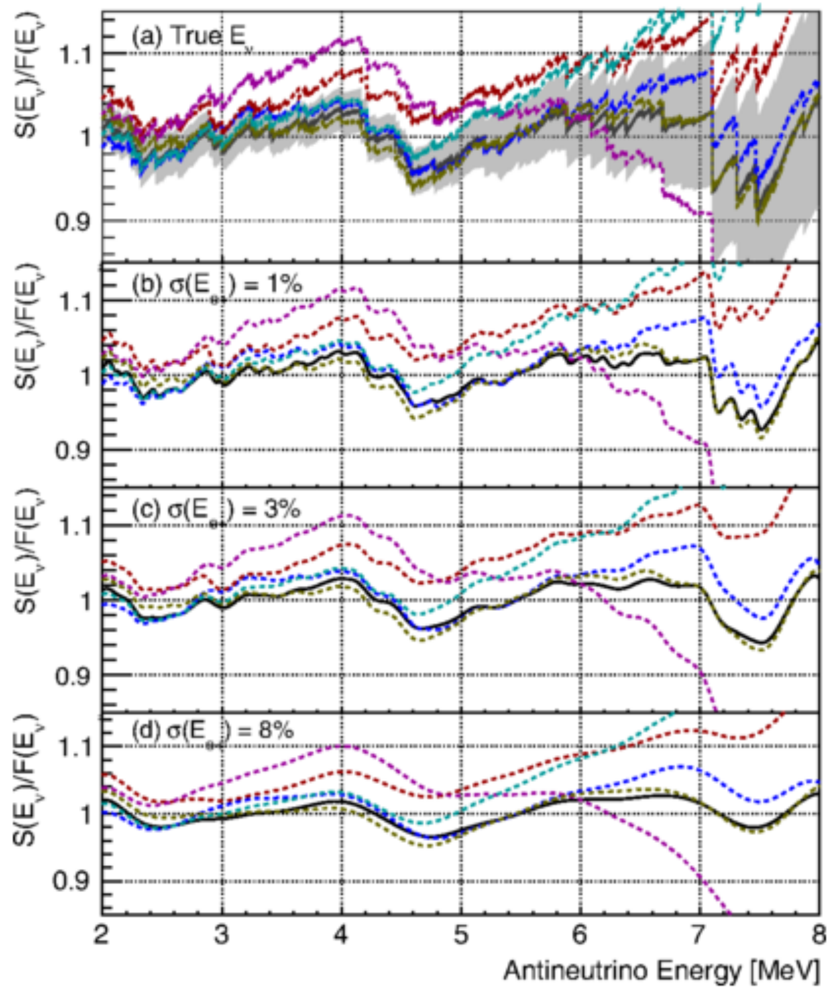


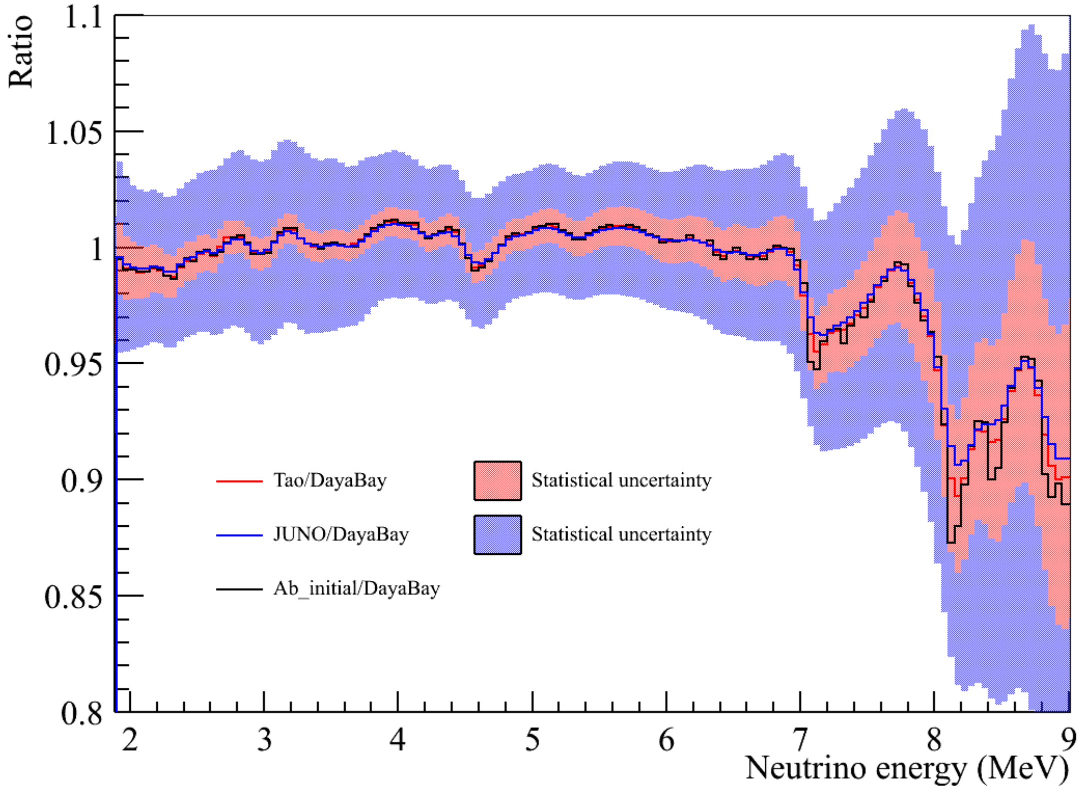
Key JUNO-TAO Features

Superb energy resolution:

- Energy resolution $\sigma_E<2\%\sqrt{E(\mathrm{MeV})}$ (must and is better than JUNO)
- Provide reactor neutrino spectrum with unprecedented precision
- Expecting fine resolution spectrum structures never observed before

D. Dwyer et al. PRL114, 012502 (2015)



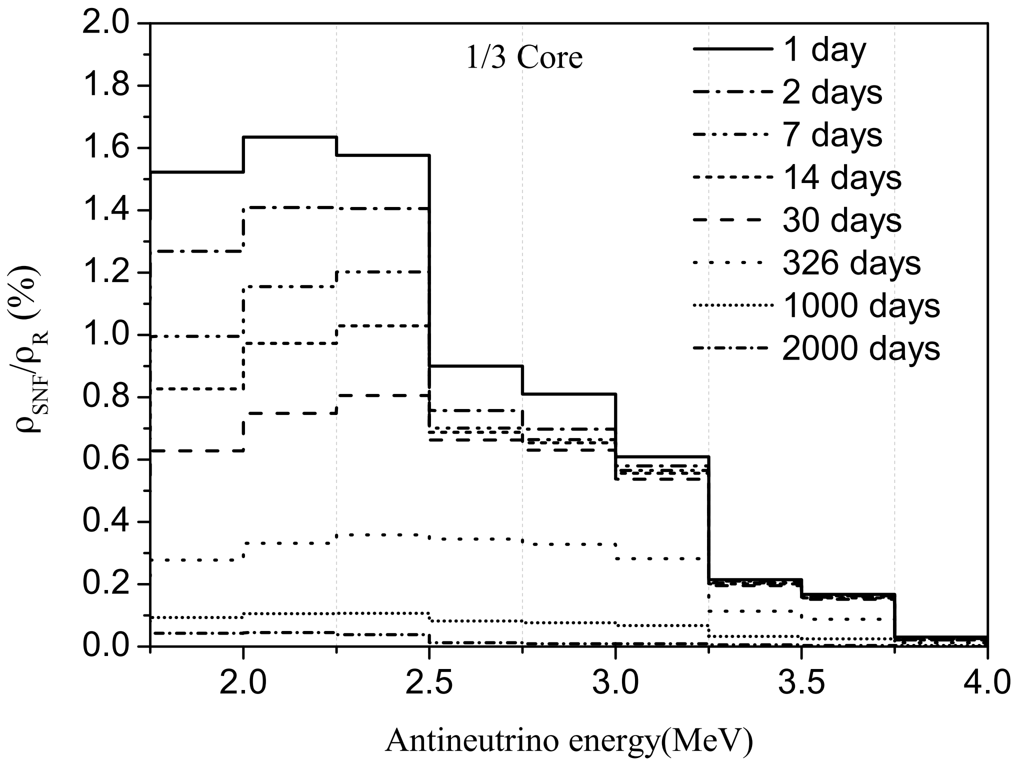


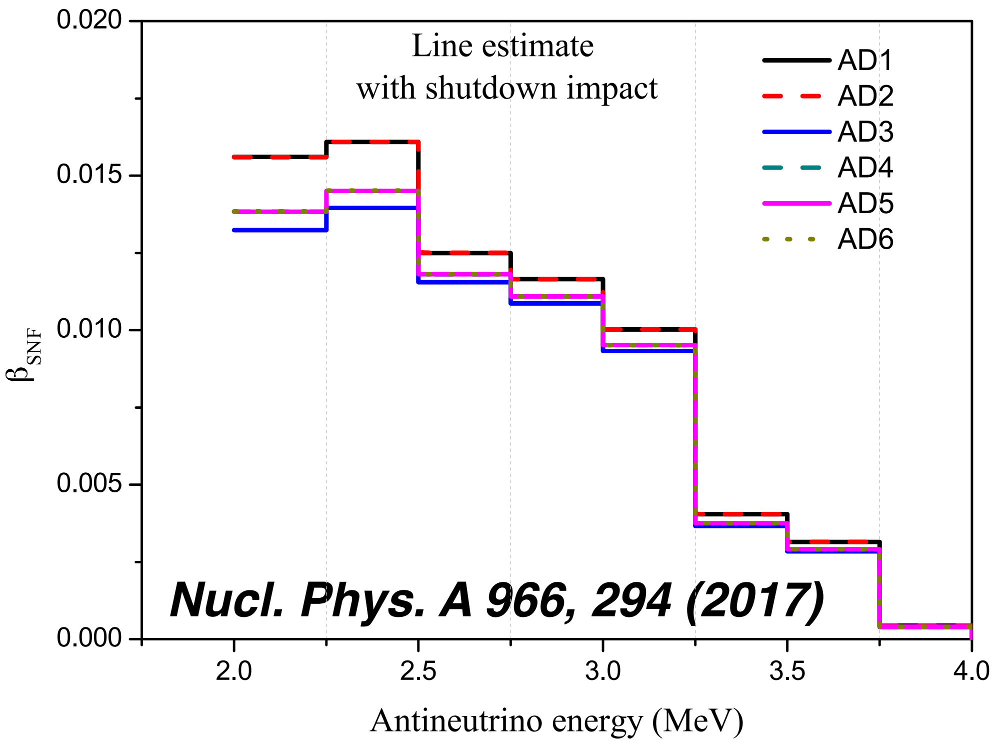
Statistics:

- 2.6 t Gd-doped liquid scintillator
- 1 t fiducial volume
- 2000 $\bar{\nu}'s/$day
- Huge statistics (30×JUNO)

Spent Nuclear Fuel Uncertainty

- Even with JUNO-TAO measurement, we have to face the spent nuclear fuel (SNF) contribution uncertainty (not specially included in the initial JUNO sensitivity study)
- SNF: just used reactor fuel removed and stored in adjacent pools
- SNF still produces electron antineutrinos for some time - Rate and energy spectrum shape of SNF comes with uncertainty
- The Daya Bay Experiment example: ~1% contribution in geov region, in DYB treated with 30% uncertainty (*PRL 121, 241805 (2018)*)





Nucl. Phys. A 966, 294 (2017)

Somewhat similar contribution and uncertainty expected also for JUNO!

Conclusions

- JUNO is a multipurpose experiment aiming to determine neutrino mass hierarchy and much more…
- **JUNO will collect world leading geoneutrino statistics in ~½ year**
- **JUNO will be the most precise geoneutrino experiment in near future**
- Main limitation is a large reactor neutrino flux (7-9 to 1 ratio in region of interest) ➔ irreducible
- Combined with reactor neutrino energy spectrum shape uncertainty (directly from reactor as well as spent nuclear fuel) ➔ hopefully reducible
- JUNO-TAO will play a leading role in the spectrum shape measurement and significantly improve its knowledge
- With a very good precision of the reactor neutrino energy spectrum shape:
  - Measurement of geoneutrinos flux with 5% precision in 10 years
  - Th/U ratio with ~30% precision

Use of Precise Geoneutrino Measurement

Testing local geoneutrino emission models:

- ~50% of the geoneutrino signal comes from nearest $\mathcal{O}(100\ \text{km})$
- Local geological and geochemical models of the crust developed for precise geoneutrino signal prediction
- Tension between global prediction and use of local model prediction:
  - Global model prediction for JUNO: $39.7^{+6.5}_{-5.2}$ TNU (*V. Strati et al., PEPS 2:5, 2015*)
  - Using local model for JUNO: $49.1^{+5.6}_{-5.0}$ TNU (*arXiv:1903.11871*)
- Precise JUNO measurement will hopefully resolve this

Use of Precise Geoneutrino Measurement

Getting the Earth (mantle) composition ⟺ Earth radiogenic power:

- Interpretation of geoneutrino signal can tell, how many U and Th is in the mantle. How to get it?
  - Subtract crustal contribution from total signal (land-based experiments)
  - Go to the ocean where your signal is up to 80% from the mantle - see a poster from Dr. Watanabe
- For the former, local model matters - see a poster from Prof. Mantovani
- Currently, tension in the measurement interpretations using local models:
  - BOREXINO: $38.2^{+13.6}_{-12.7}$ TW (*arXiv:1909.02257*)
  - KamLAND: ~ 14 TW (calculated based on *PRD 88(3), 033001, 2013*)
- Soon new kid on the block: JUNO

Search for hidden reservoirs using comparison with other experiments (assuming "we know the crust") (see a talk on Wednesday)

- …

Geoneutrino Measurement at JUNO

Stay tuned!
JUNO will get back to you in a few years