# A $^{14}C$ Screening Setup for Liquid Scintillator at JUNO

Mingxia Sun (IHEP)

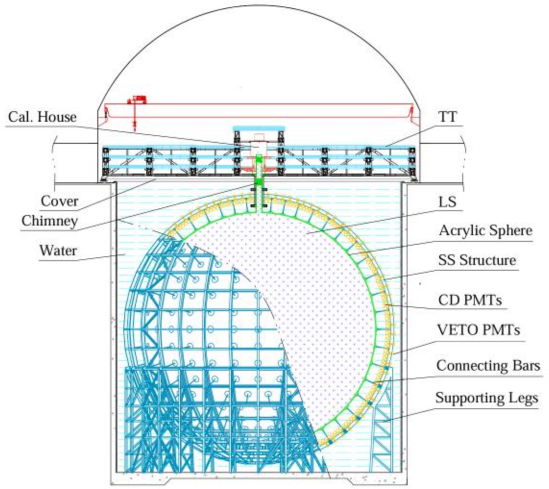
on behalf of the $^{14}C$ measurement group

Chuanya Cao, Gaosong Li, Xiaojie Luo,
Yuanxia Li, Liangjian Wen, Wei Wang,
Fei Xiao, Yijun Xie, Jiaxuan Ye,
Jie Zhao

Low Radioactivity Techniques (LRT 2024)

1-4 October 2024, Kraków, Poland

# Jiangmen Underground Neutrino Observatory




- Schematic design of JUNO

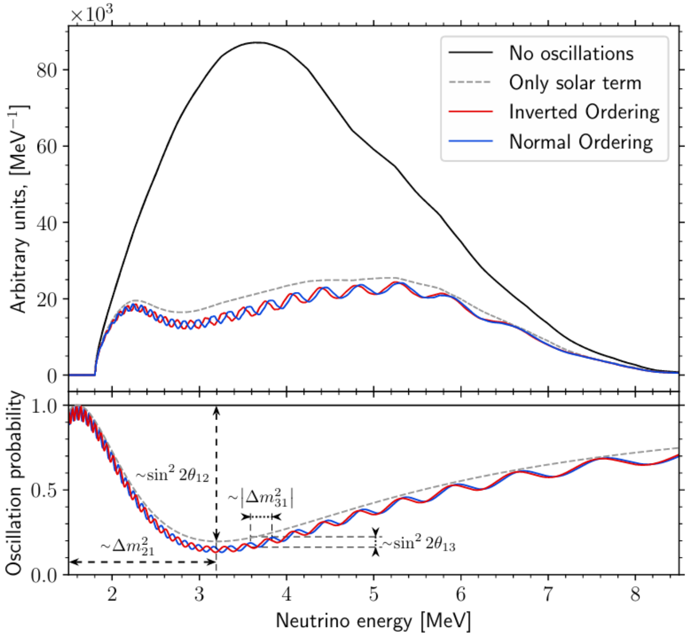
(Photograph by Chenyang at 20,09,2024)

## 1) Detector Design

- Target mass: **~20 kton** linear alkylbenzene (LAB) based liquid scintillator
- Equipped with **17,612 20-inch PMTs** + **25,600 3-inch PMTs**
  → **78%** photocathode coverage
- Light yield: **~1665 p.e./Mev**
- Energy resolution: **~3%@1MeV**

## 2) Physics Potential*

- **The Neutrino Mass Ordering**
- **Precise determination of the neutrino oscillation parameters**
- Solar neutrino
- Atmospheric neutrino
- Supernova neutrinos
- Geoneutrinos




*Paper: "Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO"

# Why measure $^{14}C$ ?

## 1) Intrinsic characteristic of $^{14}C$:

- Q of β decay: **156 keV**

## 2) $^{14}C/^{12}C$ concentration influence on JUNO :

Main source in LAB based liquid scintillator:

→ LAB - $C_6H_5C_nH_{2n+1}$ (n=10 ~ 13)

- High rate of **$^{14}$C pile-up** will affect the energy resolution

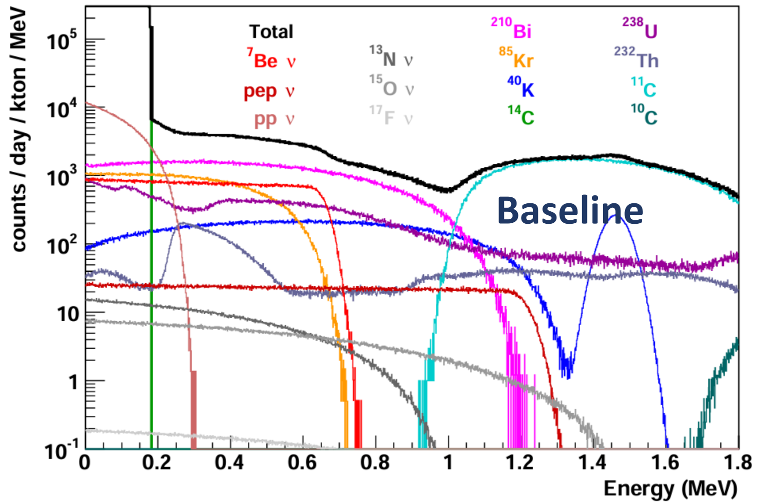
→ $1 \times 10^{-17}$ g/g 20 kton LS ~30 kHz contribution

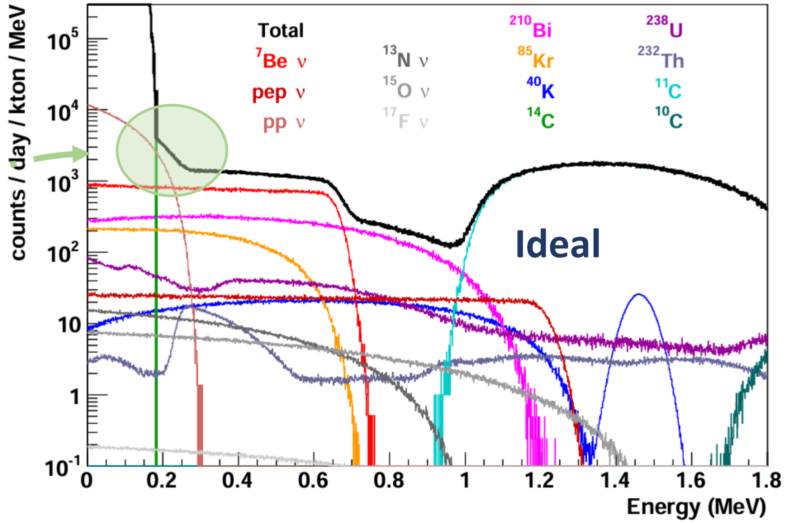
- Low energy solar neutrino measurements*

→ baseline: $1 \times 10^{-17}$ [g/g]

→ ideal: $1 \times 10^{-18}$ [g/g] possible for *pp solar neutrino*

*Paper: "Neutrino Physics with JUNO"



# Previous $^{14}C$ measurement experiments

| Setup | Borexino CTF[1] | LZ Screener[2] | Pyhäsalmi[3] | A setup at BNO[4] | A setup at GSNL[5] |
|---|---|---|---|---|---|
| Sample Volume( L ) | 4800 (PC based) | 28 (LAB based) | 1.4 (LAB based) | 1.5 (LAB based) | 2 (PXE based ) |
| $^{14}C/^{12}C$ concentration sensitivity(g/g) | **$10^{-20}$** | **$10^{-19}$** | ------ | **$\sim10^{-18}$** | **$\sim10^{-19}$** |
| Spectral fitting model | Theoretical beta-spectrum ($^{14}C$) convolved detector response + **one function (background)** | | | | |

- High sensitivity like CTF and LZ screener needs large LS volume and sophisticated design
- Simple parameterized background model

**Design goal : $\sim10^{-18}$ g/g sensitivity (90% CL) on ~1 week scale with ~1L sample for fast screening**

[1] Borexino CTF: "Counting test facility for the Borexino experiment"
[2] LZ Screener: "A liquid scintillation detector for radioassay of gadolinium-loaded liquid scintillator for the LZ Outer Detector"
[3] Pyhäsalmi: "New Low-Background Laboratory in the Pyhäsalmi Mine, Finland"
[4] BNO: "Measurement of the 14C Content in Liquid Scintillators by Means of a Small-Volume Detector"
[5] GSNL: "Measuring the 14C isotope concentration in a liquid organic scintillator at a small-volume setup"

# Key challenges

1) **Low energy detection threshold**
   - High photon collection efficiency + low trigger threshold

2) **Low-background control**
   - Cleanliness  of detector materials
   - Muon flux shielding → set on JUNO site, ~650 m rock overburden, muon flux in the detector is ~0.004 Hz/$m^2$
   - Reducing radon concentration inside detector
   - Shielding from background emitted from surrounding rocks

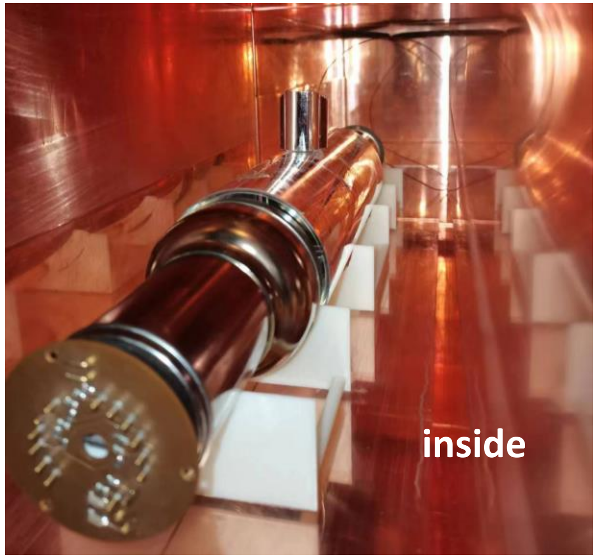
3) **Fast screening**
   - Easy to operate and change sample

4) **Good understanding of background**

# Physical Detector

**1) Detector:**

- **One acrylic vessel for a 1 L LS container**
  - → LS based on JUNO formula: 2.5 g/L PPO and 3 mg/L bis-MSB
  - → Vessel wrapped with ESR film
- **Two ultra-low-background PMTs R11410 borrowed from PandaX**
  - → Th/U ~2 mBq/pc



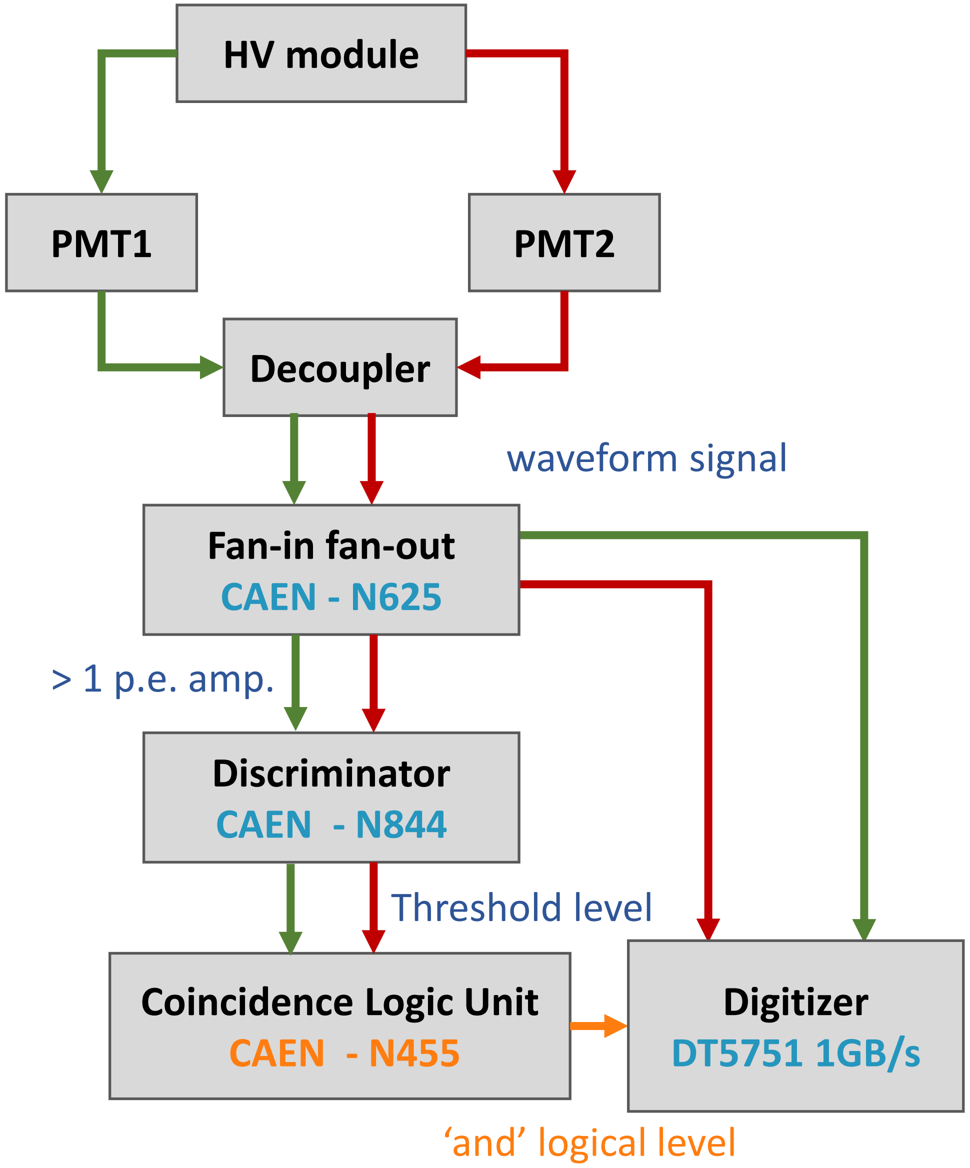

**2) Passive shielding:**

- **~50 cm lead layer**
- **~20 cm OFHC (Oxygen-Free High-Conductivity) copper**
  - → Surface treatment + nylon film to protect from dust and radon
- **~20cm thickness Boron-born PE on the bottom**


**3) Cleanliness control**

- **Nitrogen purge into chamber**
- **Several covers to avoid light and radon ingress**

# Electronic




## 1)Cable from PMT to decoupler:

- Kapton coaxial cable inside detector
  → less outgassing, light mass
- RG316 coaxial cable outside
  → more durable

## 2)Trigger condition:

- PMT coincidence within 64 ns window (threshold at 1.p.e.)
- PMT performance:
  → each PMT: ~500 Hz dark count rate

## 3)Data Acquisition:

- Digitized window: ~2 us
- Waveform recorded for off-line analysis

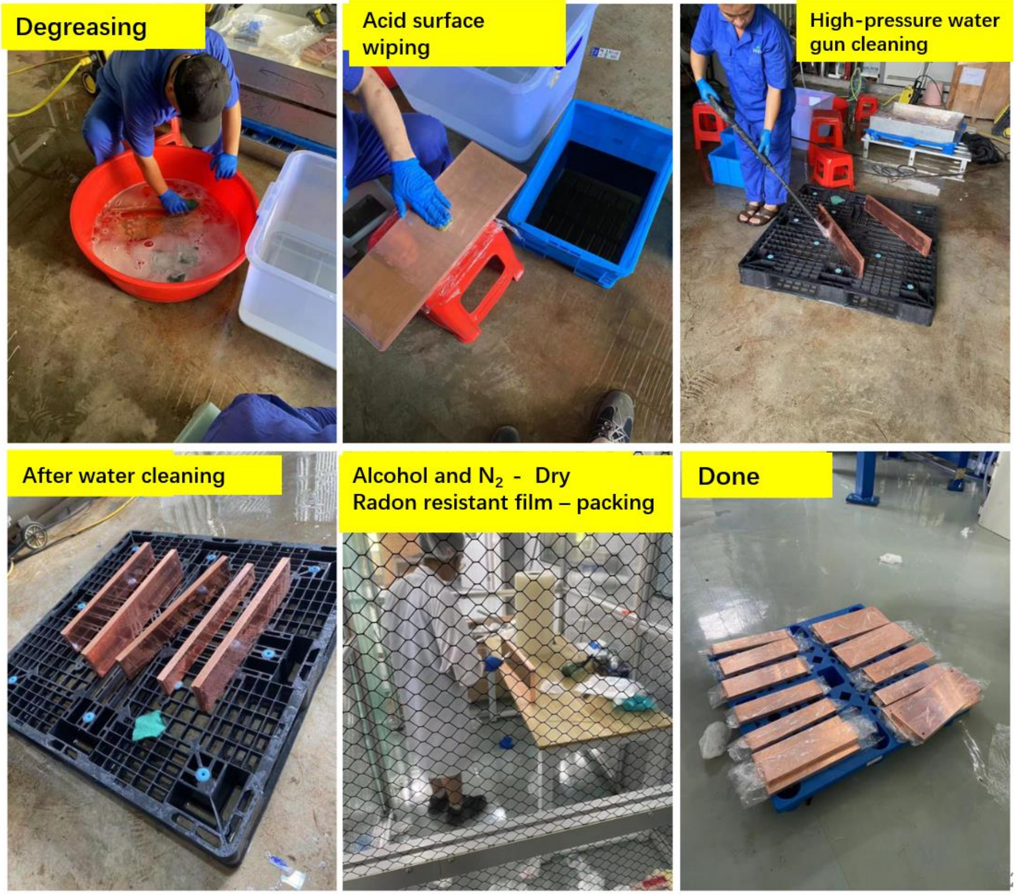
# Copper Surface Process

## 1) Factory processing

- Surface roughness < 0.4 um → reduce dust depositing on the surface

copper recycled from a >10-year old HPGe detector

Total copper shield mass: ~500 kg




## 2) Cleaning treatment on JUNO site

- Degreasing
- Acid surface wiping
- Washing with high-pressure water gun
- Alcohol cleaning and nitrogen drying
- Radon-resistant nylon film packaging

**ICP-MS* measurement result comparison:**

| Surface measurement(~0.2mm) | Th/U |
|---|---|
| Original | ~10 ppb |
| After surface cleaning | ~ 0.1 ppb |

*Paper: "Co-precipitation approach to measure amount of $^{238}$U in copper to sub-ppt level using ICP-MS"

# Detector sensitivity improvement

- $^{14}C$ measurement setup: started in 2022, with **two background-control works** scheduled in 2023.

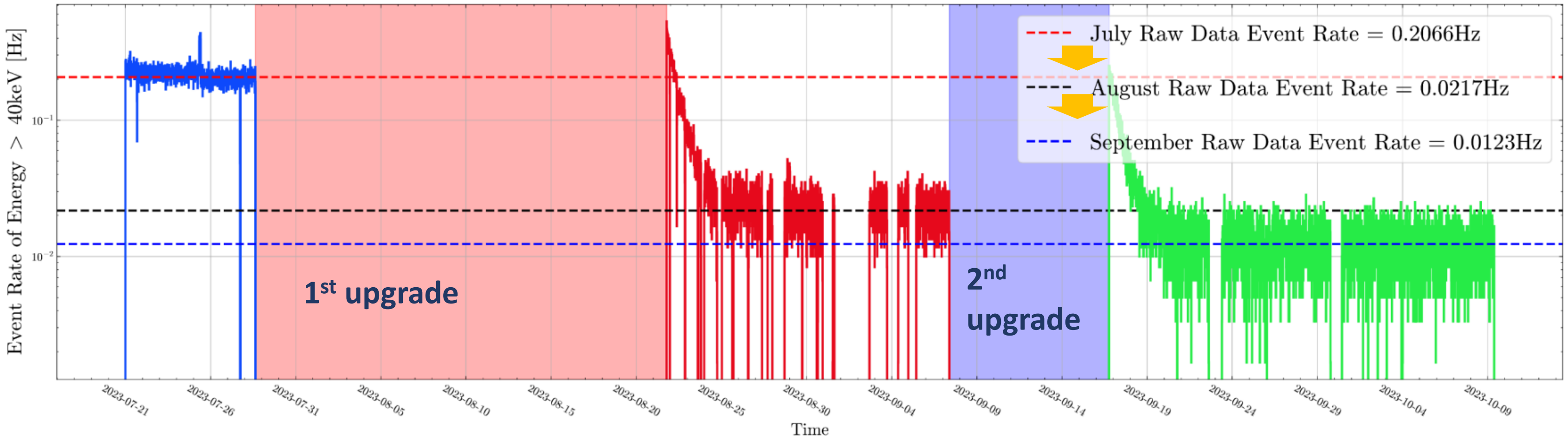
**1) 1st (from ~0.207 Hz → ~0.022 Hz):**

- Increasing shielding thickness
- Surface process on the copper closer to detector chamber*

**2) 2nd (from ~0.022 Hz → ~0.012 Hz):**

- Surface process on all copper*


→ The raw event rate above threshold 40 keV has **decreased by a factor of 10**



# Detector sensitivity improvement

- $^{14}C$ measurement setup: started in 2022, with **two background-control works** scheduled in 2023.

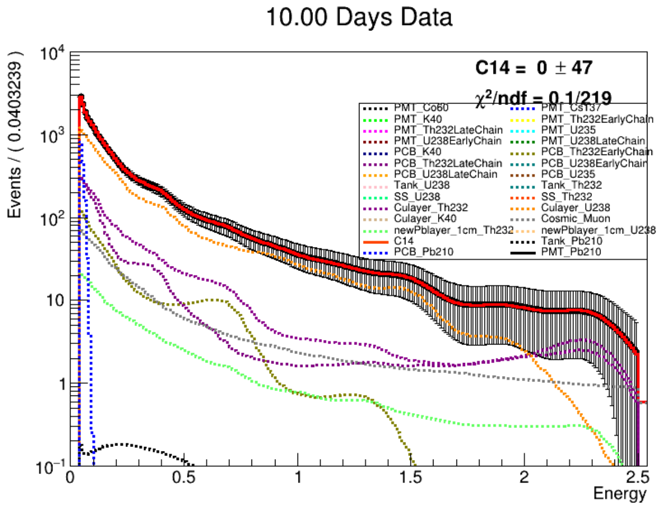
  **1) $1^{st}$ (from ~0.207 Hz → ~0.022 Hz):**
  - Increasing shielding thickness
  - Surface process on the copper closer to detector chamber*

  **2) $2^{nd}$ (from ~0.022 Hz → ~0.012 Hz):**
  - Surface process on all copper*


→ The raw event rate above threshold 40 keV has **decreased by a factor of 10**

→ Detector sensitivity reaches **$1 \times 10^{-18}$ g/g** (90% C.L.) for 10 day running and 40 keV energy threshold

- Stat. only and based on measured background data



# Calibration

**1) Light yield:**

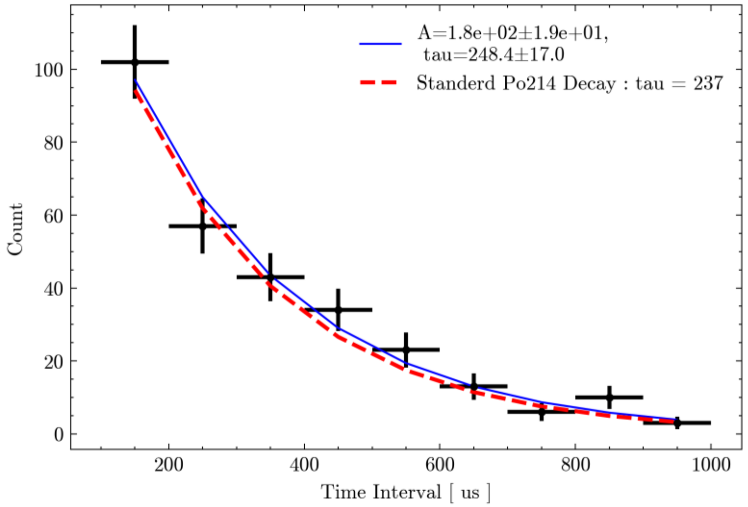
- $^{241}$Am : <u>~60 keV</u> gamma  ~450 p.e. /MeV

→ 40keV energy threshold: > ~18 p.e.

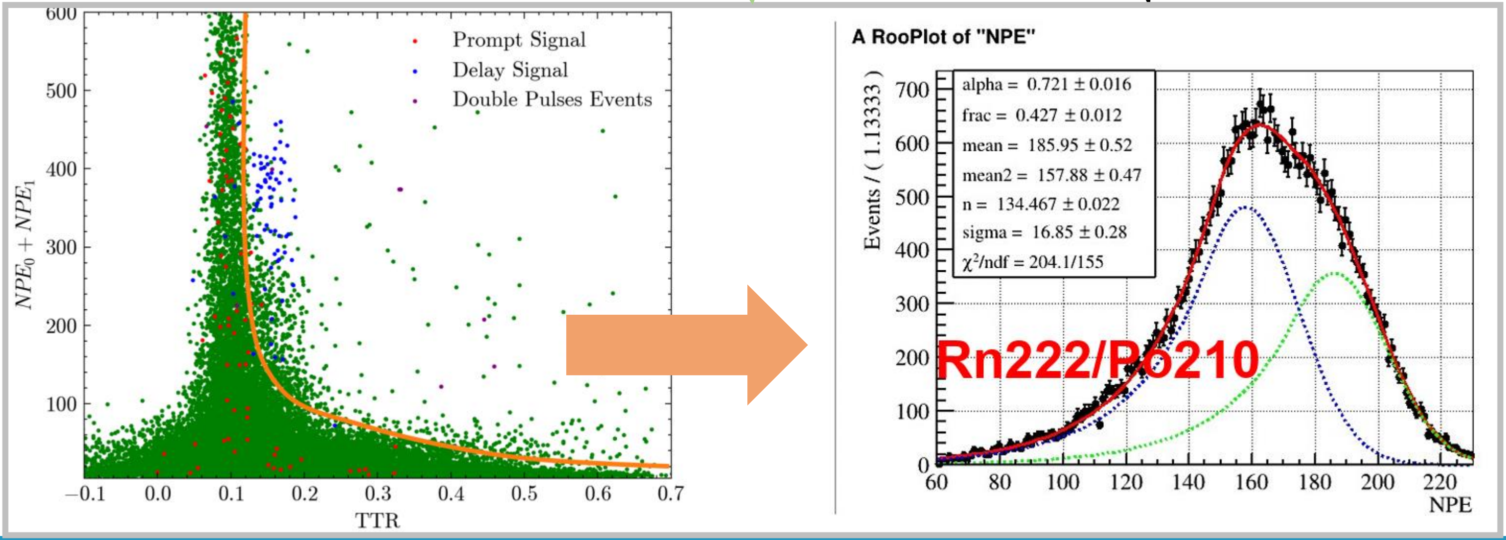
**2) Detector response :**

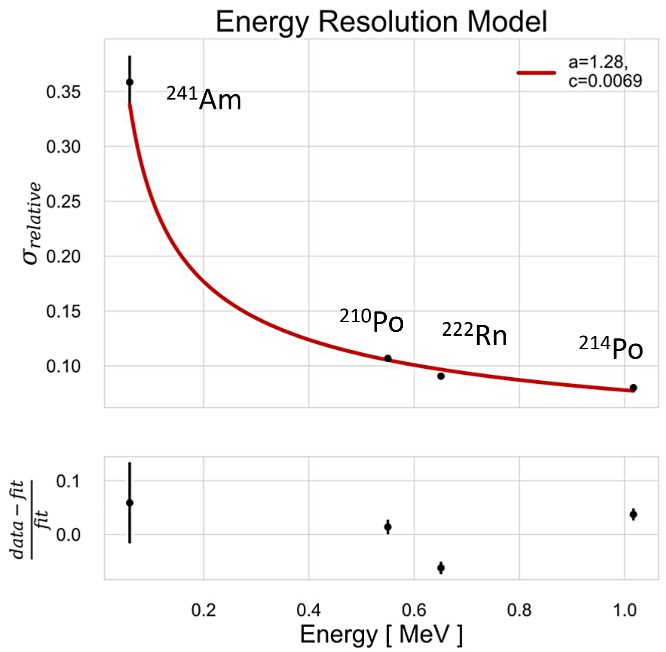
- The real data used in calibration:

**1. $^{241}$Am  2. $^{222}$Rn/$^{210}$Po (PSD)  3. $^{214}$Po (BiPo selection)**




- Two parameter energy resolution: $\frac{\sigma}{E} = \sqrt{\frac{a^2}{E * LY} + \frac{c^2}{E^2}}$



# Off-line Analysis

**1) Waveform rec.**

------------------------

- Filter
- Record waveform features

→

**2) Event cut**

----------------------------

- Waveform quality
- After-pulse event
- Accident coincidence event

→

**3) γ/β spectrum extraction**

----------------------

- PSD
- BiPo selection

→

**4) Fitter**

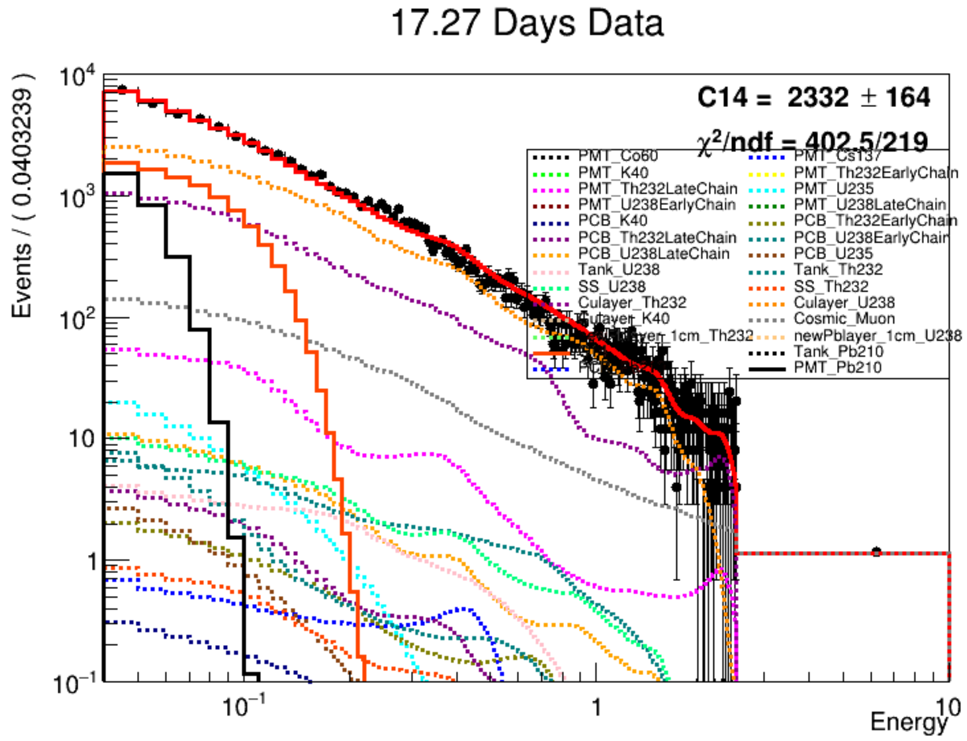
--------------------------

- Bkg. spectrum input from simulation
- Energy > 40 keV

- Adding other measurement results on bkg. contribution

- Fitting result:

  $^{14}$C concentration of LAB samples screened so far range in ~(1-3) × $10^{-17}$ g/g
  - <10% stat. error
  - ~20% syst. error from energy scale and background model



# Summary

- A small setup for fast screening of low $^{14}C$ LS was built and operated at JUNO  site
- Careful detector materials selection and low background control is essential for such a simple detector design
- A comprehensive background model is built to describe the data
- The setup satisfies the designed screening requirements

# Back up

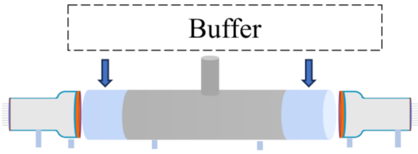
# Check the radioassay of PMT $^{235}$U

| Bkg. model | w/ PMT $^{235}$U | w/o PMT $^{235}$U |
|---|---|---|
| $^{14}$C Concentration ($10^{-17}$ g/g) | **0.59±0.43** | **2.14±0.19** |
| $^{235}$U in PMTs (mBq) | 6.45±2.06 | ---- |

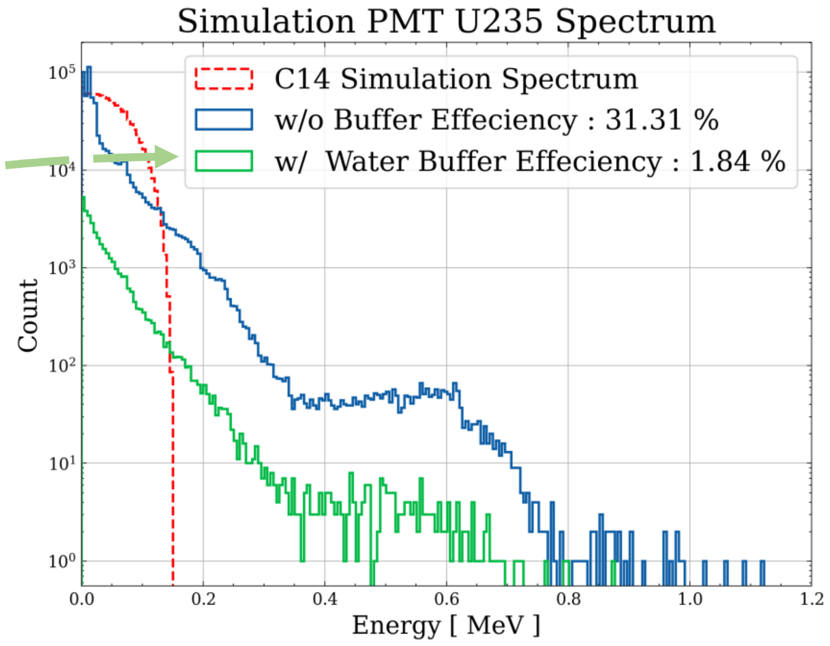
- PMT U235 has high correlation with $^{14}$C : ~0.8
- The constrain is based on PandaX measurement: (13 ± 9)mBq with error of ~65%

**→ Adding extra buffer to eliminate uncertainty introduced by $^{235}$U from PMT**

1) Updated experiment setup
   - w/ water buffer




2) Hit efficiency of $^{235}$U in PMT will decrease by a factor of 10 in simulation




3) Real data shows spectrums are consistent in high energy region for w/o buffer and w/ buffer data

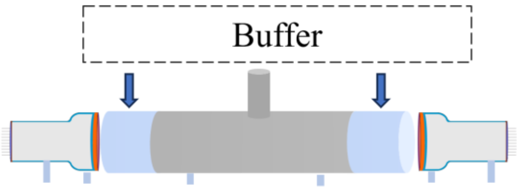
# Check the radioassay of PMT $^{235}U$

| **Bkg. model** | **w/ PMT $^{235}U$** | **w/o PMT $^{235}U$** |
|---|---|---|
| $^{14}C$ Concentration ($10^{-17}$ g/g) | **0.59±0.43** | **2.14±0.19** |
| $^{235}U$ in PMTs (mBq) | 6.45±2.06 | ---- |

- PMT U235 has high correlation with $^{14}C$ : ~0.8
- The constrain is based on PandaX measurement: (13 ± 9)mBq with error of ~65%

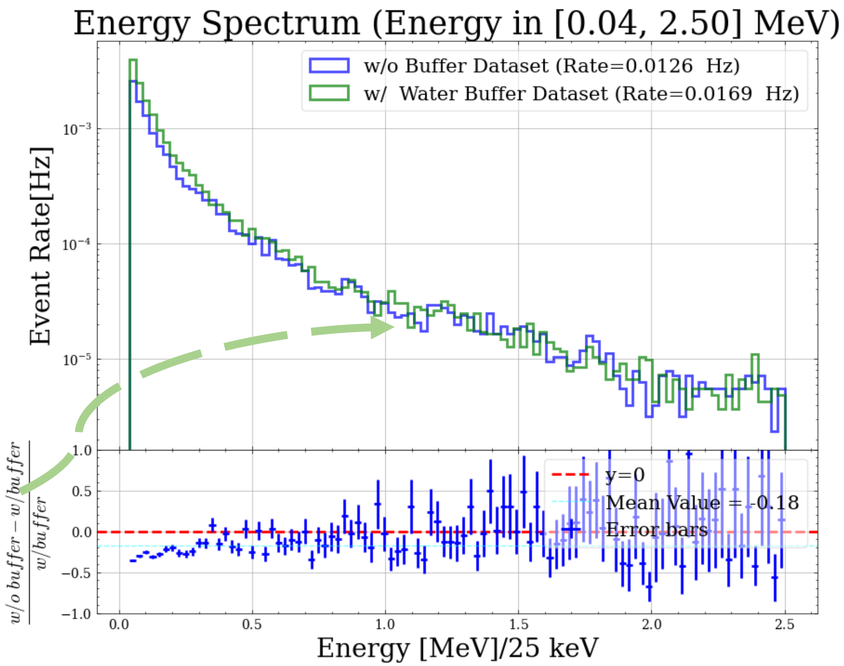
**→ Adding extra buffer to eliminate uncertainty introduced by $^{235}U$ from PMT**

1) Updated experiment setup
   - w/ water buffer




2) Hit efficiency of $^{235}U$ in PMT will decrease by a factor of 10 in simulation

3) Real data shows spectrums are consistent in high energy region for w/o buffer and w/ buffer data



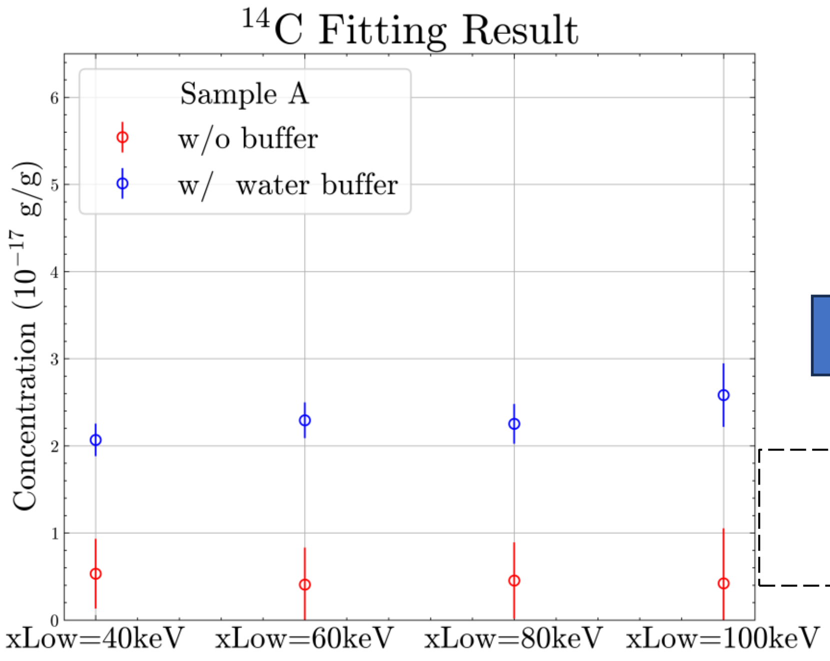
# New Constrain on PMT $^{235}U$

No significant change in real data with ~10cm buffer in front of PMT

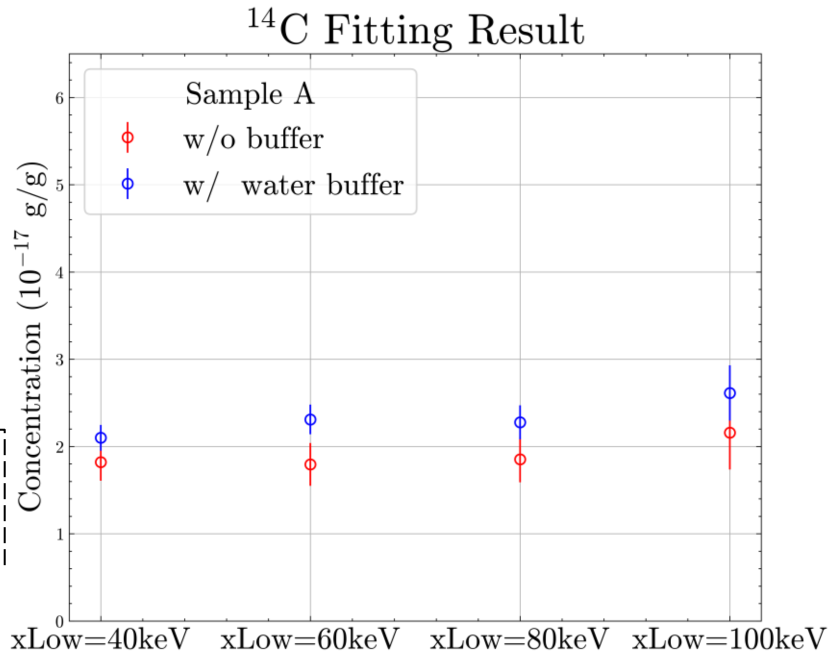
- Update more stringent PMT $^{235}U$ constraint

  13.13±8.53 (direct measurement) → 1.2±0.8 (scaled by $^{238}U$ from PandaX measurement result)

  → Different setup configurations shows **reasonable consistent results** for same tested LAB sample

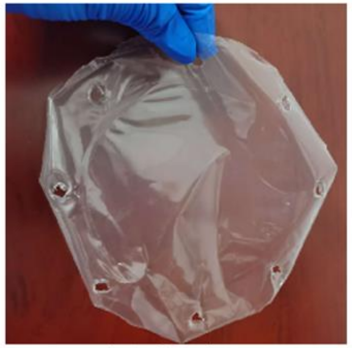



Update $^{235}U$ Constrain



# Nylon film resistant ability

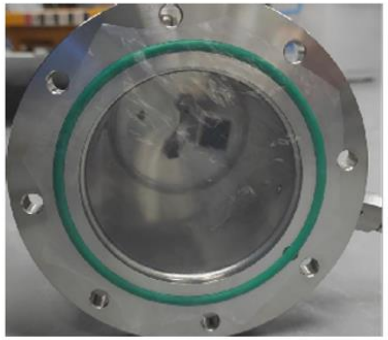
Measured by Yue Meng's Group



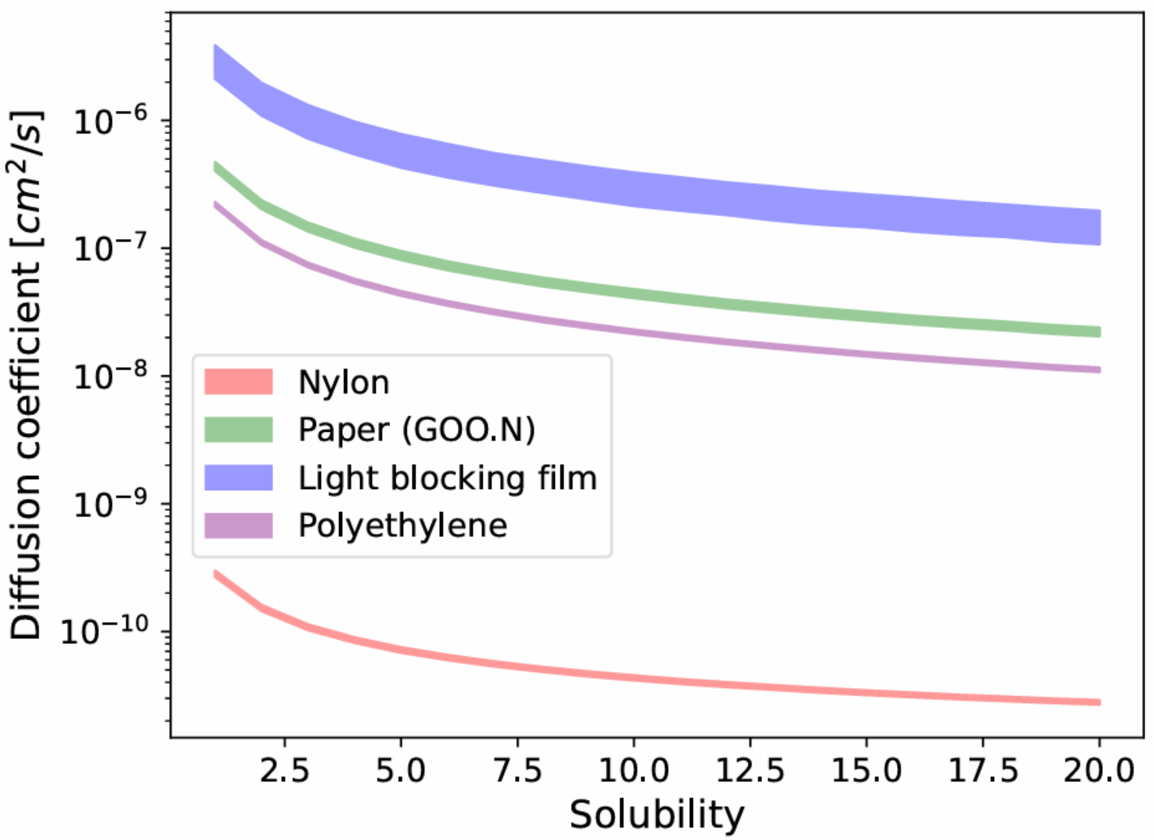
(a) Nylon

(b) Paper (GOO.N)

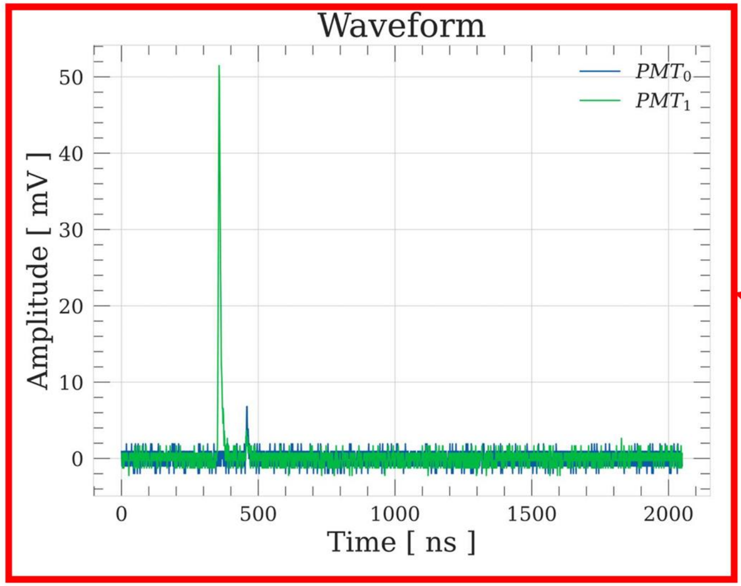
(c) Light blocking film



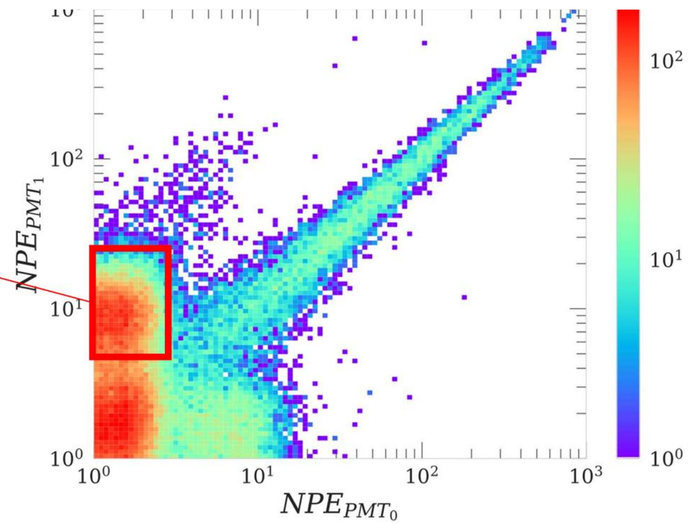
(d) Polyethylene



# Accidental coincidence event




Before acc. coincidence event selection




**Selection Criteria:**

- Δt of two PMTs maximum
- Charge difference between PMTs: $R_{NPE} = \frac{|NPE_{PMT_0} - NPE_{PMT_1}|}{NPE_{PMT_0} + NPE_{PMT_1}}$
- Amplitude difference between PMTs: $R_{Amplitude} = \frac{|Max_{PMT_0} - Max_{PMT_1}|}{Max_{PMT_0} + Max_{PMT_1}}$