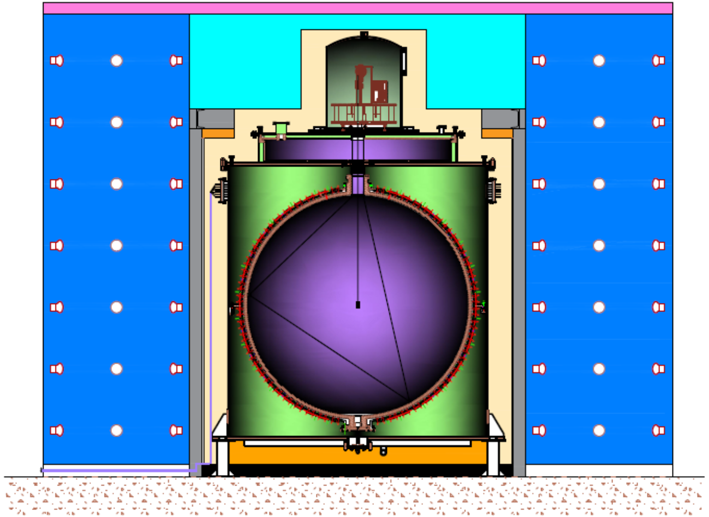
JUNO-TAO:
Status and prospects



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(on behalf of the **JUNO** Collaboration)

26 February 2021

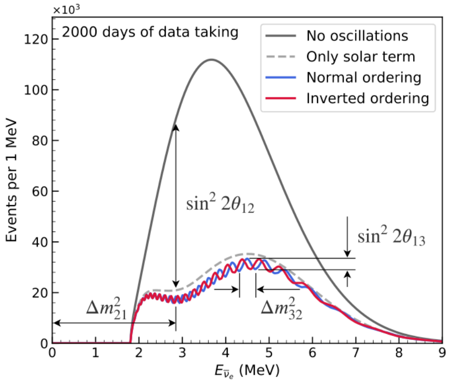
JUNO & JUNO-TAO

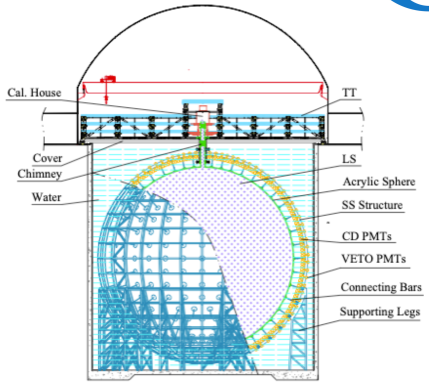
Jiangmen **U**nderground **N**eutrino **O**bservatory:

- a "medium-baseline" (53km) reactor neutrino experiment, in construction in China (data taking foreseen in 2023)
- **Goals** : Measure the **neutrino mass hierarchy (NMH)** + oscillation parameters + astroparticle and rare processes

Several talks already for JUNO in this conference

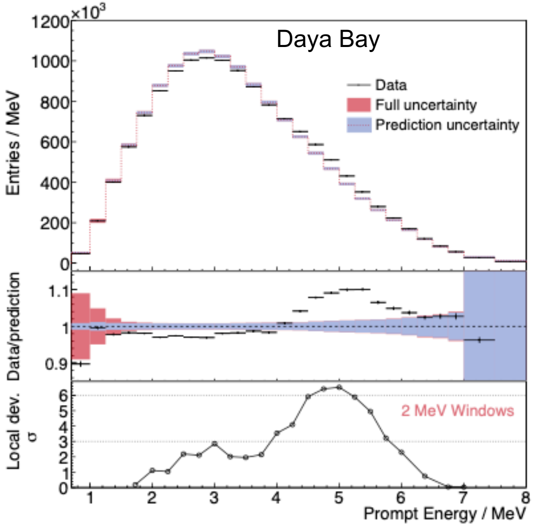
→ more details given there!





Reactor $\bar{\nu}_e$ input flux

- **Current models cannot provide** a reliable reference spectrum;
- Existing measurements have not enough resolution to reveal **fine structures** (though unlikely to follow oscillation pattern…)
- However, a near detector can reduce model dependences of the unknown fine structures → **more robust measurement**

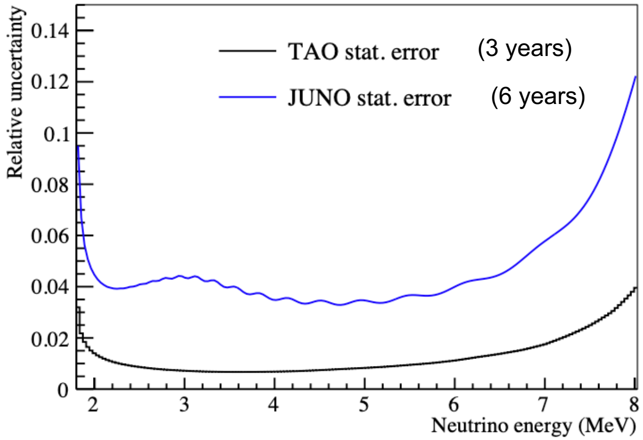


JUNO & JUNO-TAO

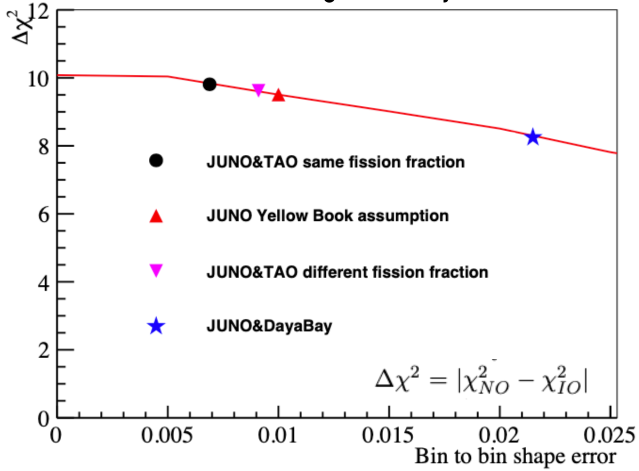
Taishan Antineutrino Observatory (TAO) is a satellite exp. of JUNO
a ton-level, **state-of-the-art liquid scintillator detector with high energy resolution.**

More than a near detector for JUNO:

- **Measure reactor neutrino spectrum w/ sub-percent E resolution.**
  1. Provide a reference spectrum for JUNO:
     - $\frac{\sigma_E}{E}$~3% (like JUNO) + 10 X statistics would be enough (and could be achieved with LS+PMT)
  2. Provide a benchmark measurement to test nuclear databases:
     - Highest possible energy resolution ($\frac{\sigma_E}{E} < 2\%$ → SiPMs);
  3. Increase reliability in isotopic IBD yields;
  4. Can improve nuclear physics knowledge;
  5. Reactor monitoring, sterile neutrino, etc.



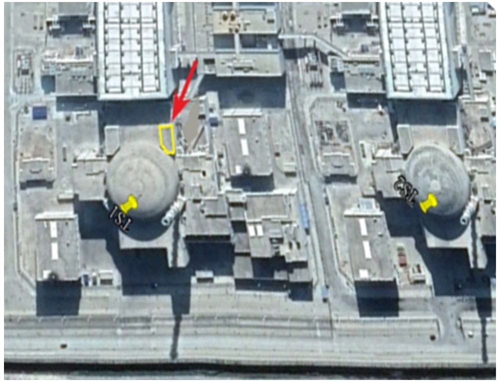
Mass Ordering sensitivity of JUNO

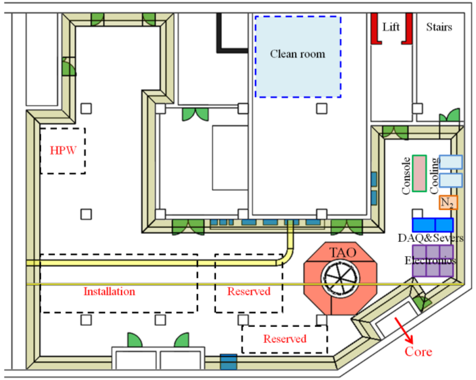


JUNO-TAO: location

- Nuclear Power Plant in Taishan city in Guangdong province;
- 53 km from the JUNO experiment;
- Two cores currently in operation (other two cores might be built later);
- All reactors are European Pressurized Reactor (EPR) 4.6 GW power.

- **TAO detector**:
  - ~30 m from core 1;
  - Outside of the concrete containment shell of the reactor core;
  - In a basement, 9.6 m underground
  - Access via a 1.4 × 2 × 2.7 m³ lift





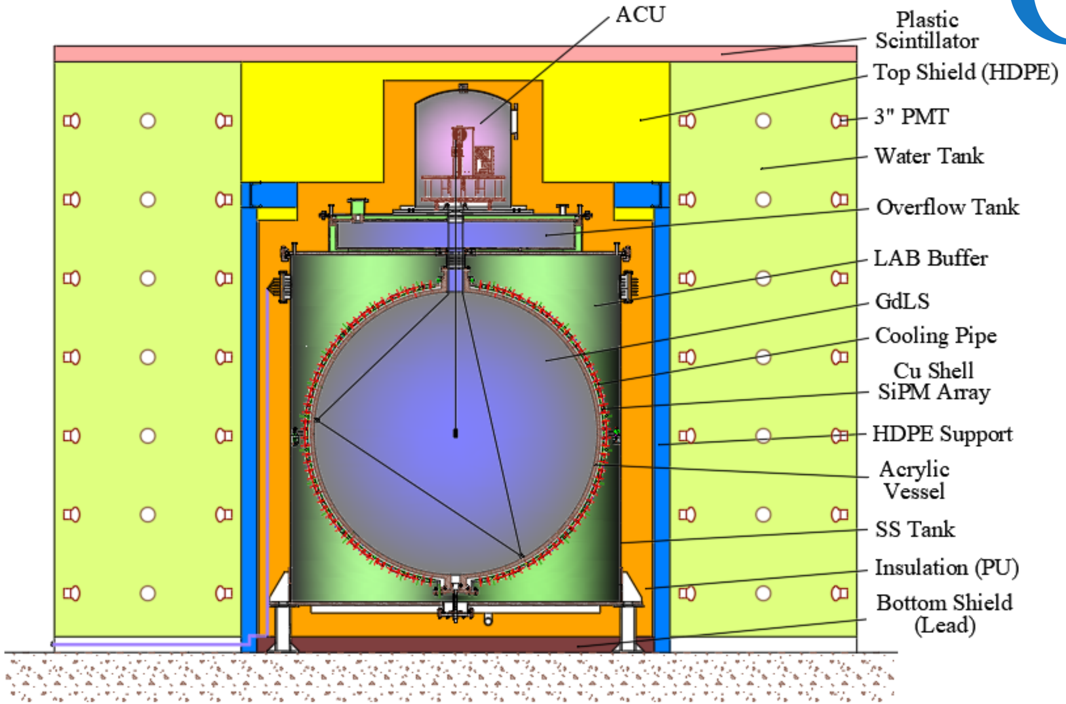
Far core contributes about 1.5% to the total antineutrino rate in TAO

JUNO-TAO detector overview

- 2.8 ton Gd-LS in a spherical vessel;
- 1-ton Fiducial Volume
- **10 m² SiPM with 50% PDE**;
- operated at **-50°C** to reduce Dark Noise;
- Light Yield: ~4500 p.e./MeV;
- 50% efficiency mainly due to neutron tagging.

From Inner to Outside:

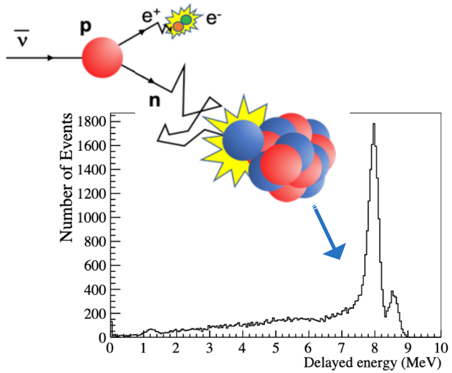
1. Gd-LS;
2. Acrylic vessel;
3. SiPM and support (Cu shell);
4. Buffer liquid, LAB: (rad. shield)
5. Cryogenic vessel (SS + insulation);
6. 1.2 m water; HDPE shielding;
7. Active Muon veto.



w.r.t. JUNO:

- **Coverage** of photon sensors: 75% (with PMTs) → ~95% (with SiPMs)
- Photon detection **efficiency**: ~27% (with PMTs) → ~50% (with SiPMs)
- Smaller dimension → less γ absorbed. → **p.e. statistics** increased by 40%.

Signal



- inverse β-decay (IBD) in the Gd-doped LS
- $\bar{\nu}$ signature: e^+e^- prompt scintillation + delayed n capture signal
- $E_{\nu_e} \approx E_{e^+} + (m_n - m_p - m_e)$ neglecting K_n O(10 keV)
- neutron capture by Gd (87%):
  - several γ's for ~8 MeV;
  - Average capture time is about 30 μs with 0.1% loaded Gd by mass.

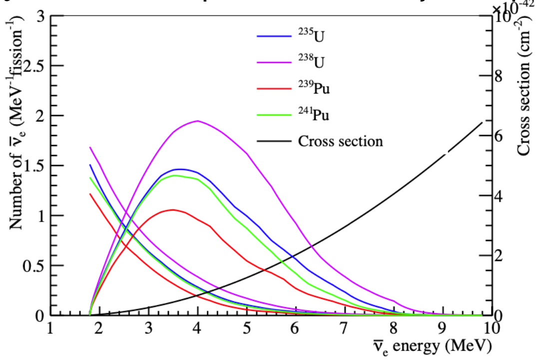
- N_P: target number of p;
- L: distance from reactor;
- $\sigma(E_\nu)$: IBD cross section;
- $\phi(E_\nu)$: reactor $\bar{\nu}_e$ flux;
- ϵ: **detection efficiency (~0.5):**
  1. Gd capture fraction: 0.87
  2. 7–9 MeV energy cut on delayed signal: ~0.6 efficiency
  3. Less relevant contributions: prompt energy cut, prompt-delayed coincidence and muon veto.

Signal energy spectrum:

$$S(E_\nu) = \frac{N_p \epsilon \sigma(E_\nu)}{4\pi L^2}\phi(E_\nu)$$

→ TAO will detect ~2000 IBD events/day in the fiducial volume

$\bar{\nu}_e$ from the fission products of four major isotopes



Backgrounds

Muons rate in TAO hall (-9.6m): ~70Hz

- Muon veto: 20 μs veto signal by Top Veto or Water Tank → less than 10% dead time.

Natural radioactivity, major source of prompt events:

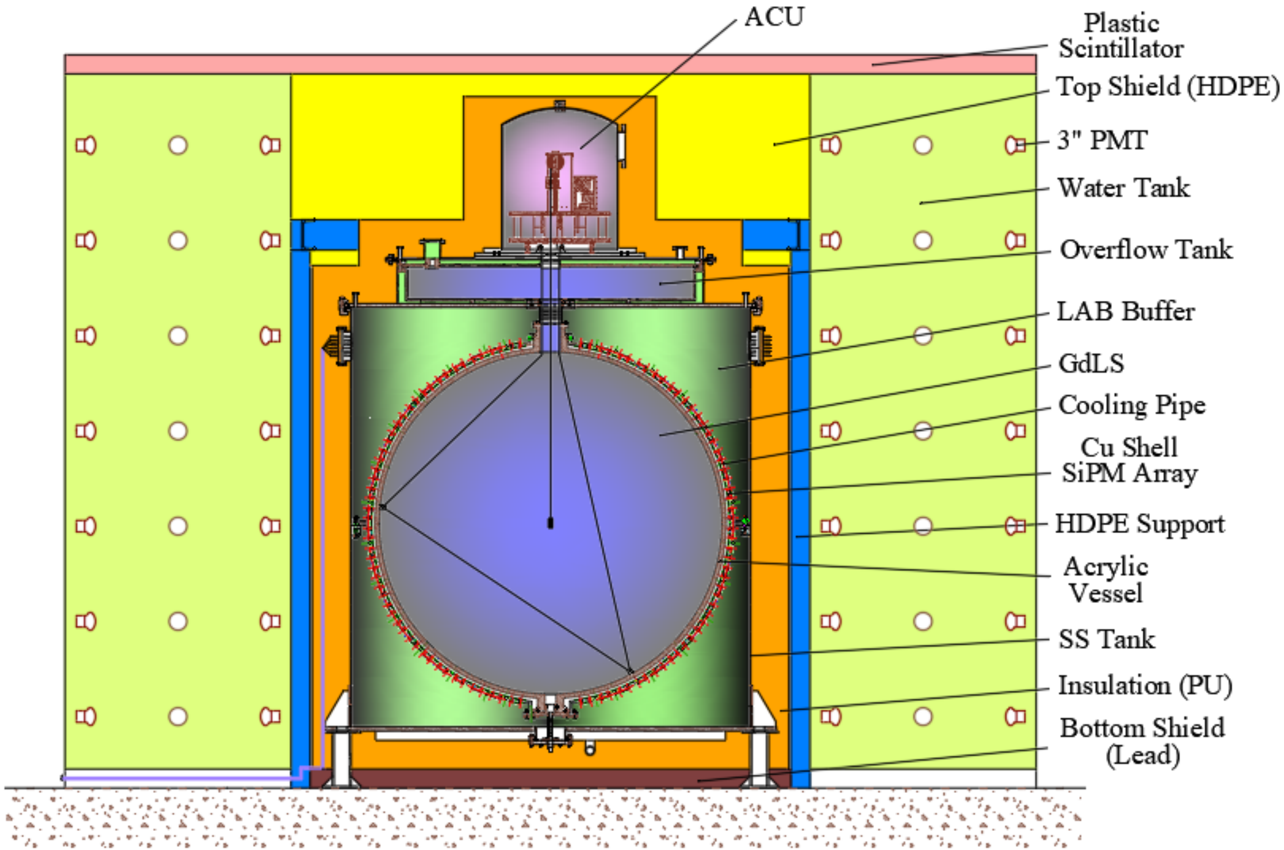
- From concrete walls: use passive shielding
- Careful material selection (PCBs in SiPMs and electronics).

Muon-induced backgrounds:

- **Fast neutrons**: recoil proton (prompt) + thermalized neutron capture (delayed) → mimic IBD
  - Muon veto time cuts most of the fast neutrons.
- **Delayed-like signals**: neutron captures not rejected by the muon veto (rate ~0.2 Hz)
  - mimic IBD signal if in coincidence with a prompt from radioactivity
- **Cosmogenic radioactive isotopes**: ^{9}Li and ^{8}He can decay emitting a prompt e + delayed n

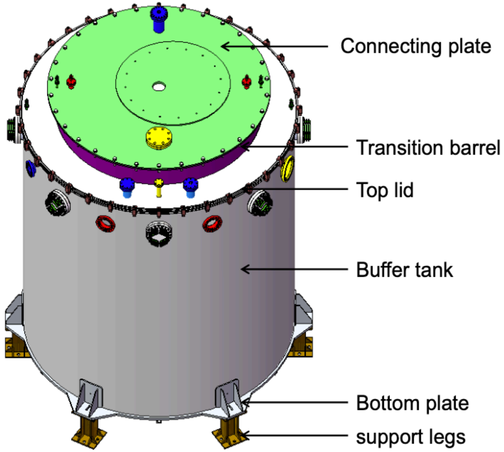
IBD signal	2000 events/day
Muon rate	70 Hz/m^2
Fast neutron background before veto	1880 events/day
Fast neutron background after veto	$<$ 200 events/day
Singles from radioactivity	$<$ 100 Hz
Accidental background rate	$<$ 190 events/day
^{8}He/^{9}Li background rate	$\sim$ 54 events/day

The JUNO-TAO detector: details and status



Stainless Steel Tank and Acrylic Vessel

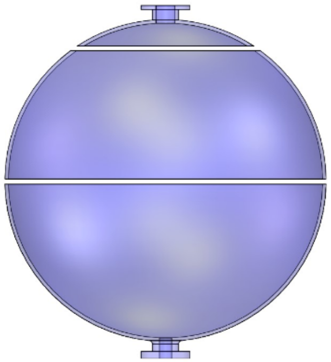
SST

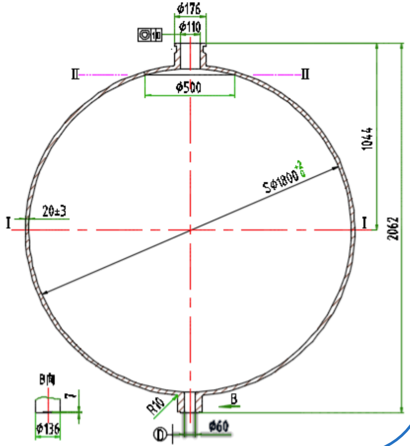


- -50°C inside the SST, surrounded by a layer of PU insulator
- Air-tight environment for the liquid scintillator
- Support for internal components + Automatic Calibration Unit + overflow tank.
- Shipped in parts and welded in the lab
- **Ready for bidding**

Acrylic Vessel

- Contains the GdLS inner diameter: 1.8 m; thickness: 20 mm.
- 3 pieces to be bonded together on site
- Upper chimney connecting to the overflow tank;
- Bottom chimney connects to the GdLS outlet.
- **Design finished.**

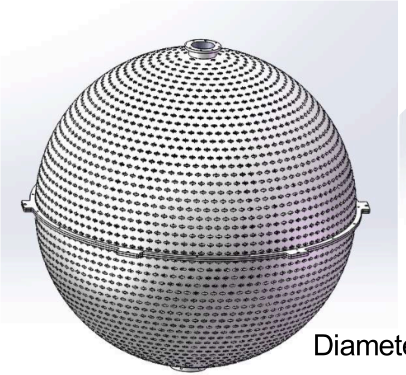


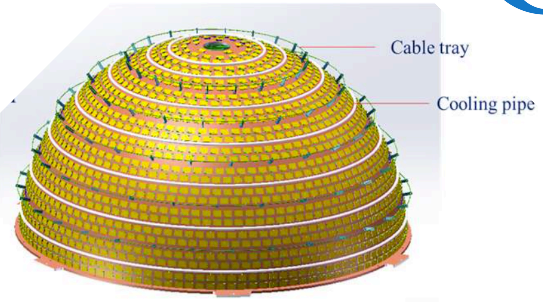


Copper Shell

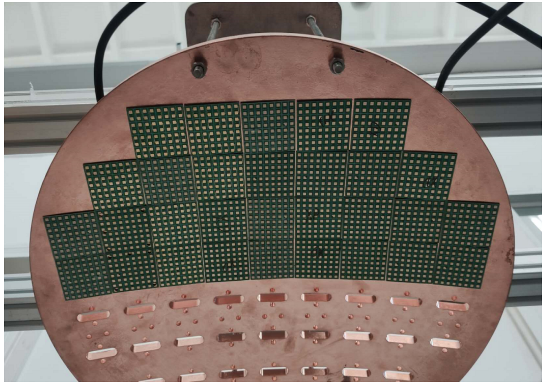
- **Support for SiPMs tiles and their readout electronics**
- Support for acrylic vessel;
- Support for cooling pipes (dissipate the heat of SiPMs and electronics) and cable routing.
- Design of the structure:
  - 2 pieces bolted onsite (for transportation)
  - oxygen-free copper (TU2):
    - good thermal conductivity;
    - Good mechanical strength;
    - low background.

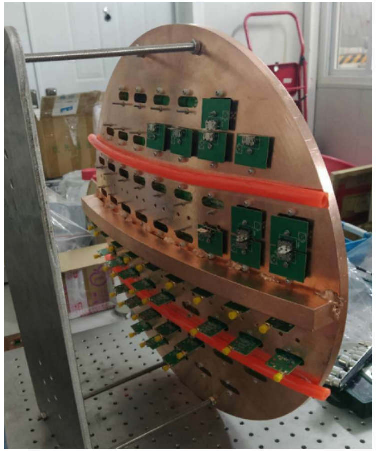
- **Construction to start soon**:
  - Manufacturing process confirmed
  - Raw material purchased
  - welding technique to be qualified





Diameter: 1886(+2/0)mm - Thickness: 12±1mm





~5x5 cm^2 SiPM tiles arrangement optimized → 4024 tiles, ~94% coverage

Liquid Scintillator

- **GdLS at -50°C** to lower SiPMs dark noise;
- **transparency** at -50°C: A.L. >10m;
- **light yield** at -50°C: ~4500 p.e./MeV (including SiPMs PDE, coverage and A.L.);
- **long-term stability**;
- **safety** (we are in a Nuclear Power Plant…).

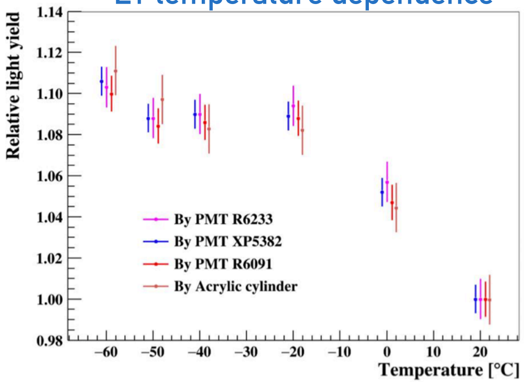
Recipe:

LAB + 0.1%Gd + 3g/L PPO + 2mg/L bis-MSB + 0.5% DPnB

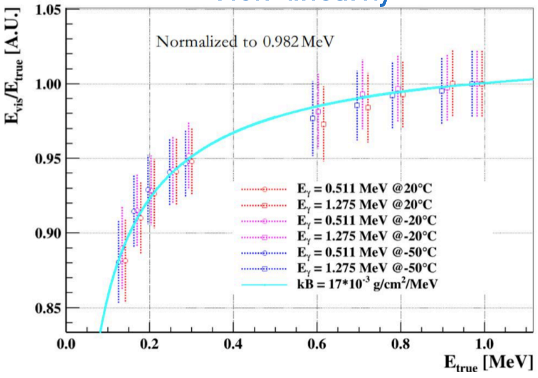
- **Linear Alkylbenzene (LAB)** as solvent (JUNO, Daya Bay) + **DPnB** as co-solvent (for low T);
- **PPO** as fluorescent
- **bis-MSB** as wave-shifter
- Recipe improved

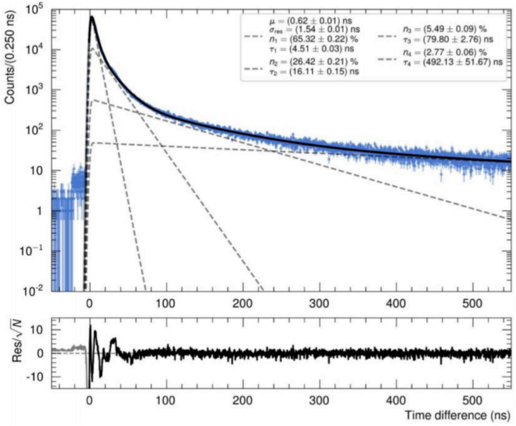
  → **preparing for mass production**

LY temperature dependence

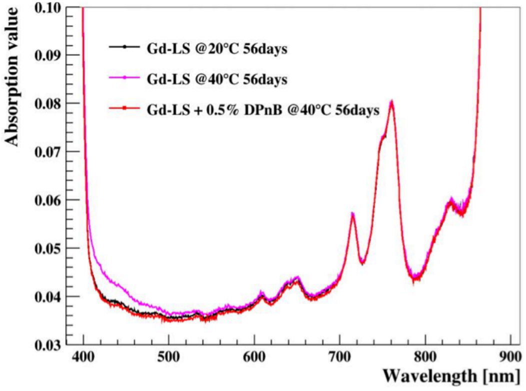


Non-linearity





Decay time: τ_1 ~ 4.5 ns

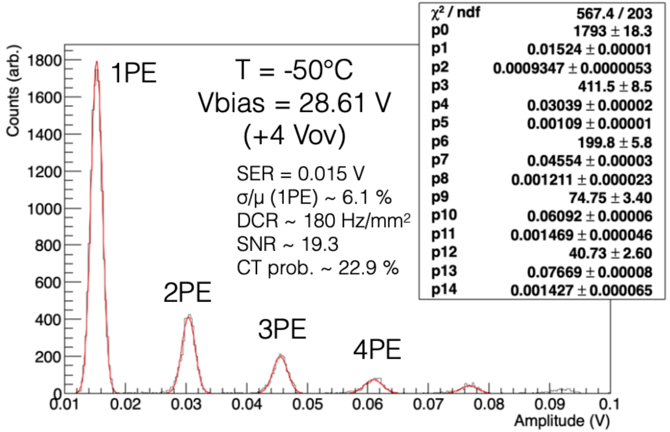


Long-term stability

SiPM

- photodetectors with **efficiency** higher than PMTs needed for the **desired energy resolution → SiPMs**
- **PDE** correlates with **Dark Noise** and correlated noise → find the optimal **tradeoff**

- **R&D** with different companies almost finished



Example of SiPM lab qualification at low-T

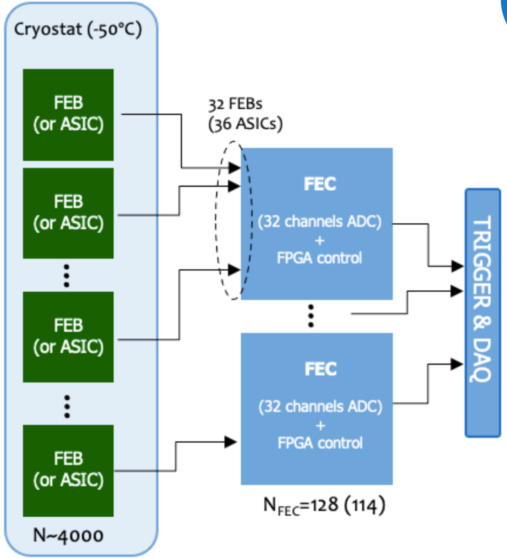
Parameter	Specification	Comments
PDE	>=50%	at 400 nm
Dark counts rate	<100 Hz/mm²	at -50°C
Correlated noise	<20%	cross-talk and afterpulses
Uniformity of V_{bd}	<10%	to avoid bias voltage tuning
SiPM size	>=6x6 mm²	for simplicity and high coverage
SiPM tile size	~50x50 mm²	reduce number of channels
SiPM coverage in a tile	>90%	not included in PDE

Low-background materials are needed for PCBs (for both tiles and electronics) to meet the overall requirement on radioactivity rate <100 Hz.

	CuFlon [mBq/Kg]	Arlon NT [mBq/Kg]	Pyralux [mBq/Kg]	Aramid [mBq/Kg]
^{226}Ra	1,4	-	2,6	
^{228}Th	1,2	100	1,4	260
^{40}K	140	1000	4	1000

Frontend Readout

- **Noise**: equivalent noise charge <0.1 p.e.;
- **Charge resolution**: <=15%;
- **Timing**: Fast τ_1 ~4 ns in GdLS → time resolution <1 ns;
- **Dynamic range**: <15 p.e./cm^2 on SiPMs for events in the FV
  → 1-375 p.e (or 1-12 p.e.) depending on the number of channels/tile
- **Power consumption**: inside the cryostat <3 kW (ΔT below ±0.5°C)
- **Radio-purity**: same consideration as for the PCB hosting the SiPM.



Two options are being developed (decision before the summer)

design ready, prototypes made, well characterized, working at low-T

Discrete option: 1 channel/tile
- Easy, reliable and robust option with commercial IC
- Series/parallel connection to handle SiPMs capacitance.
- 4 different Transimpedance Amplifier.
- Two gain stages to reduce TIA instability at high gain.
- ADC in the FEC board

ASIC option: 32 (or16) channels/tile
- Integrated ADC for charge measurement
  - 10 or 12-bit quantization resolution
- Integrated TDC for time measurement
  - 200 ps bin-sized event timestamps

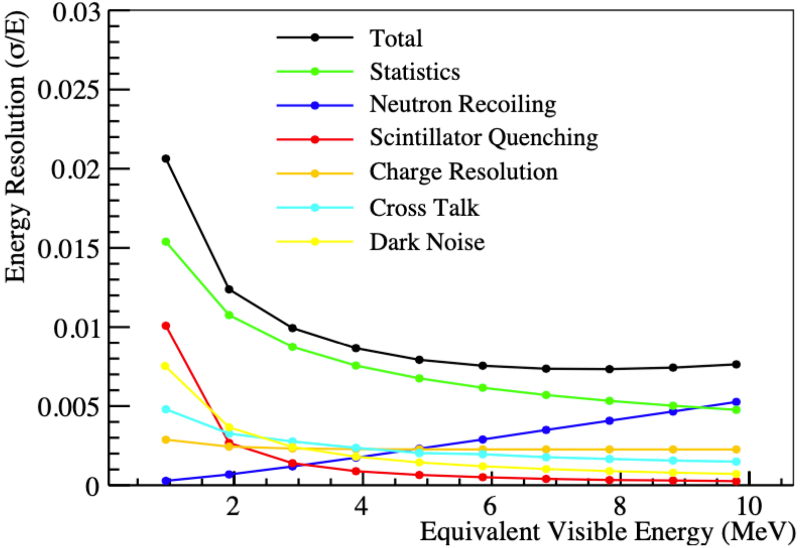
Energy resolution

- p.e. yield: ~4500 p.e./MeV → **p.e. statistics** contribution to resolution: $\frac{\sigma_E}{E} = \frac{0.015}{\sqrt{E[MeV]}}$

- **At high energies**, the smearing due to kinetic energy of the **recoiling neutron** in IBD becomes relevant.

- **LS quenching effect** relevant at **low energies** (simulated but preliminary and model dependent)

- **Other (minor) contributions** to energy resolution:
  - **Charge resolution**: assumed 15% for one SiPM channel. 2800 to 4000 channels in the range 1-10 MeV;
  - **Cross talk**: assumed to be 10%;
  - **Dark noise**: rate of about 250 kHz/mm^2 at room T. Reduced to 100 Hz/mm^2 at -50 °C. Readout time window ~1 μs.



Shielding and Veto system

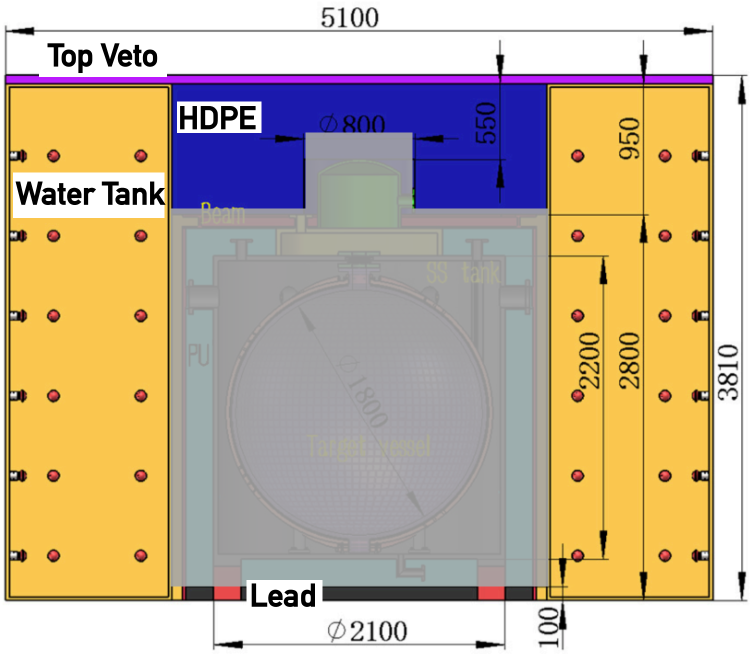
- **Shielding**:
  - 1 m HDPE (top);
  - 1.2 m water, divided in 3 parts (side);
  - 10 cm Lead (bottom).
- **Top Veto** (99% efficiency):
  - 4 layers Plastic Scintillators

    (2 m (L) * 10 cm (W) * 1.5 cm (H))
  - fiber+ SiPMs;
- **Side Veto** (99% efficiency):
  - Water Cherenkov + 300 JUNO 3-in PMTs ;

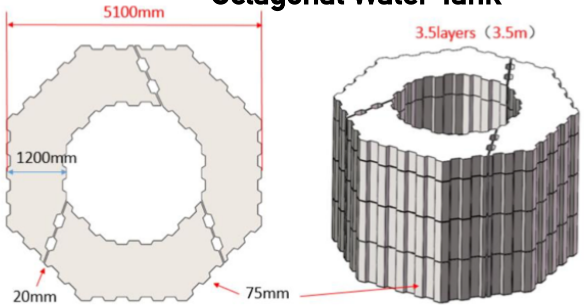
- Design optimized with simulation, meet requirements

  → further optimization + mechanical design

  → design review in the summer



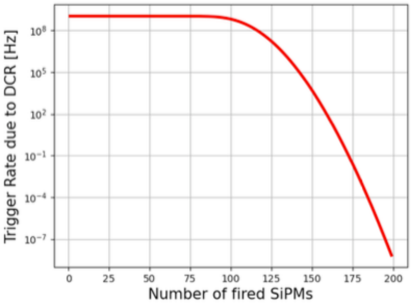
Octagonal Water Tank

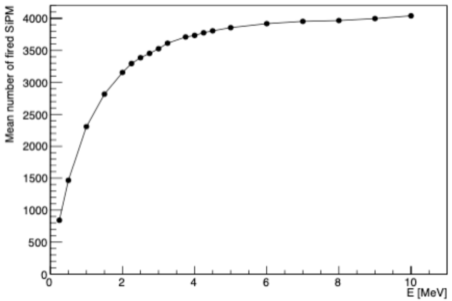


Trigger and DAQ

- Full efficiency ($\varepsilon \sim 1$) for $\bar{\nu}_e$ IBD events;
- Suppress SiPMs dark counts (DCR ~1 GHz);
- Suppress other detector-related backgrounds;
- Data throughput < 100 Mbps (limit from network bandwidth at the experimental site).

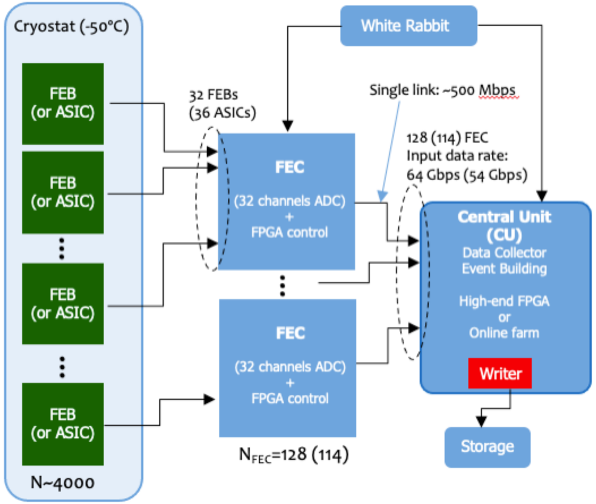
A **global majority logic** can suppress the DCR down to ~0 with no effect on the signal efficiency.





TDAQ baseline schema:

- Process raw data in a **TDAQ system based on high-end FPGA boards**
- Write out **high-level information (charge, time);**
- A global majority (Nhit) trigger is the baseline;
- Include CD, Water Tank and Top Veto in a single DAQ chain;
- CU based on a high-end FPGA:
  - Data collection + Event building;
  - Global majority trigger.



Conclusions and outlook

- JUNO-TAO: ton-level LS detector with sub-percent energy resolution is being constructed
- ~30 m from one core of the Taishan NPP;
- SiPM photodetectors → operate at -50°C
- a lot of challenges for a new concept detector

- Unprecedented energy resolution allows:
  - Reference spectrum for JUNO
  - Nuclear database testing
  - New findings?

- 1:1 prototype this summer @IHEP
  - Mainly to validate CD design + LS study if possible

- Final onsite assembly/installation in late 2022

Thanks for your attention!