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Institute of High Energy Physics
Chinese Academy of Sciences

Ultra-Pure Liquid Scintillator for JUNO and Beyond

Xilei Sun

IHEP

On behalf of the JUNO Collaboration

Siena, 28/09/2023

Outline

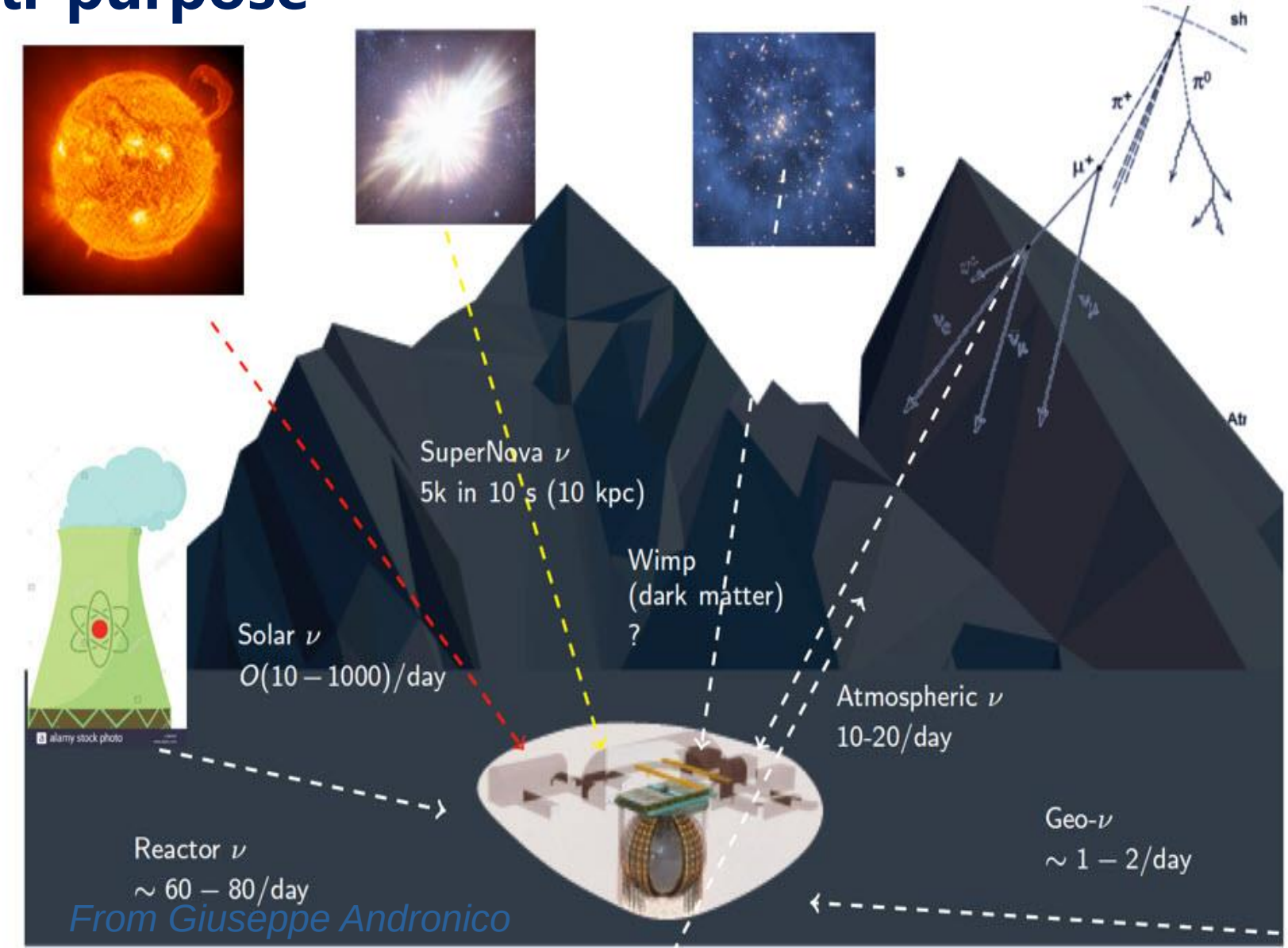
- Introduction
- Requirements and Challenges
- Production Process
- Plant Construction and Commissioning Status
- Future Plans for the Project
- Potential Applications in Radiation Detection
- Summary

The JUNO experiment

- 26.6 GW_{th} of 8 reactors, 700 m overburden

The JUNO physics

- **Multi-purpose**



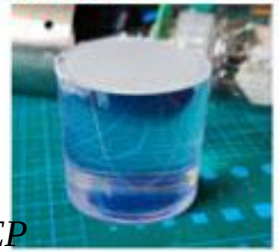
The JUNO detector

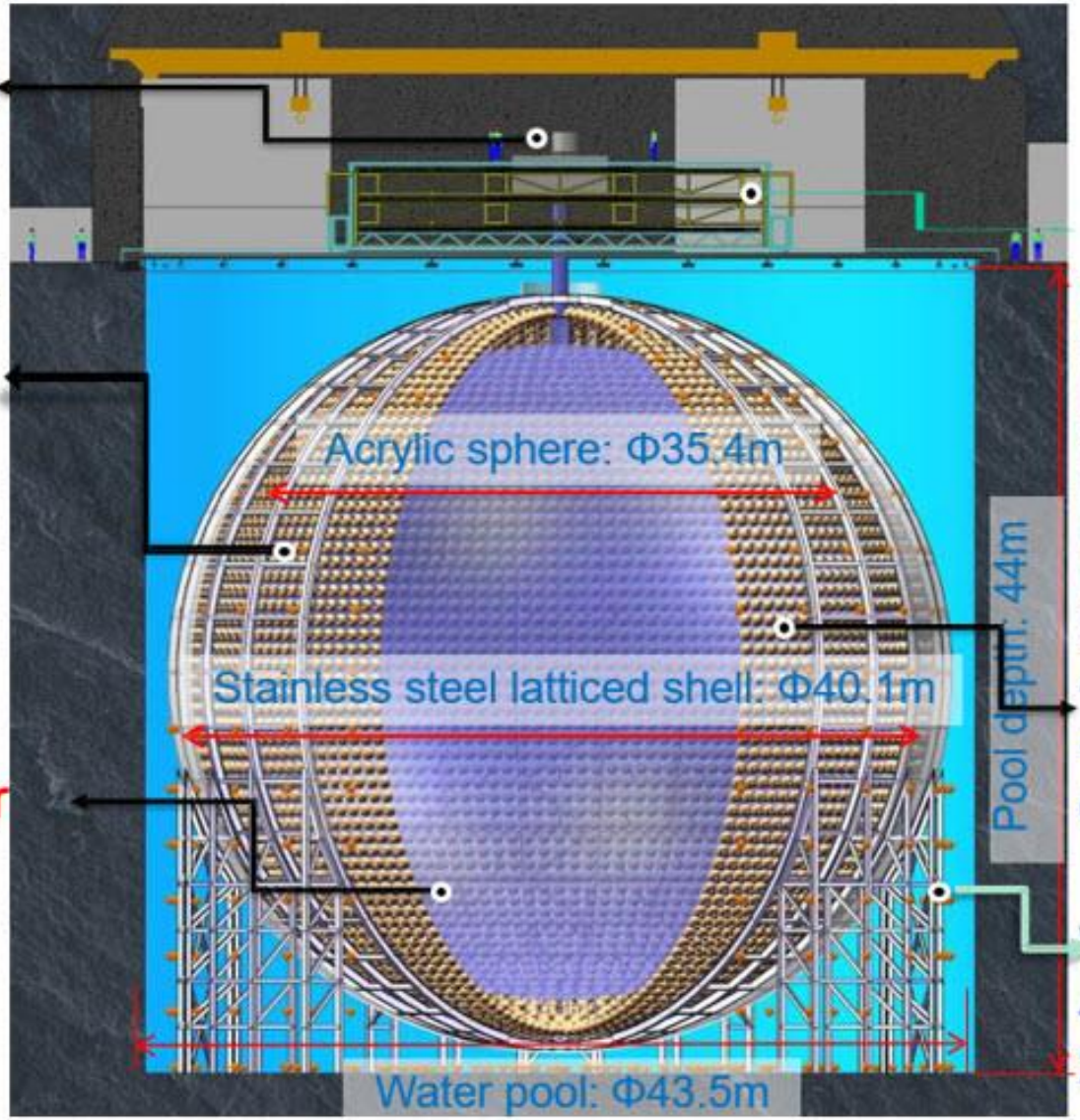
- **20 kton ultra-Pure LS, 3% energy resolution@1 MeV**

Calibration room

Central detector
SS latticed shell
Acrylic sphere

Liquid scintillator
20 kton





Top Tracker

PMT
~17612 20" PMTs
+ ~25600 3" PMTs:
coverage ~78%

Veto
40 kton pure water
2400 20" veto PMTs

The JUNO collaboration

700+ Collaborators, 16 Countries, 75 Institutions

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	SYSU	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	PUC	China	UCAS	Italy	INFN Catania
Brazil	UEL	China	USTC	Italy	INFN di Frascati
Chile	PCUC	China	U. of South China	Italy	INFN-Ferrara
Chile	SAPHIR	China	Wu Yi U.	Italy	INFN-Milano
Chile	UNAB	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	BISEE	China	Xi'an JT U.	Italy	INFN-Padova
China	Beijing Normal U.	China	Xiamen University	Italy	INFN-Perugia
China	CAGS	China	Zhengzhou U.	Italy	INFN-Roma 3
China	ChongQing University	China	NUDT	Latvia	IECS
China	CIAE	China	CUG-Beijing	Pakistan	PINSTECH (PAEC)
China	DGUT	China	ECUT-Nanchang City	Russia	INR Moscow
China	Guangxi U.	China	CDUT-Chengdu	Russia	JINR
China	Harbin Institute of Technology	Czech Rep.	Charles U.	Russia	MSU
China	IHEP	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	LP2i Bordeaux	Taiwan-China	National Taiwan U.
China	Nanjing U.	France	CPPM Marseille	Taiwan-China	National United U.
China	Nankai U.	France	IPHC Strasbourg	Thailand	NARIT
China	NCEPU	France	Subatech Nantes	Thailand	PPRLCU
China	Pekin U.	Germany	RWTH Aachen U.	Thailand	SUT
China	Shandong U.	Germany	TUM	U.K.	U. Warwick
China	Shanghai JT U.	Germany	U. Hamburg	USA	UMD-G
China	IGG-Beijing	Germany	FZJ-IKP	USA	UC Irvine

Requirements and Challenges of Liquid Scintillator

- **Ultra-Pure**
  - Optical purity: Attenuation Length>20 m
  - Radioactivity purity: dust< 10 mg, leakage rate< 10^{-6} mbar·L/s
- **Production and Inspection are very difficult**
  - Large scale, high requirements
  - Ordinary chemical equipment cannot meet the requirements
  - Quality inspection is difficult for 10^{-17} g/g, ICPMS only to 0.01 ppt

^{238}U	^{226}Ra	^{222}Rn (online)	^{210}Pb
10^{-17} g/g	5×10^{-24} g/g	0.1 μBq/m^3	10^{-24} g/g
^{232}Th	^{40}K	^{222}Rn (Filling)	^{85}Kr/^{39}Ar
10^{-17} g/g	10^{-18} g/g	5 mBq/m^3	50 μBq/m^3

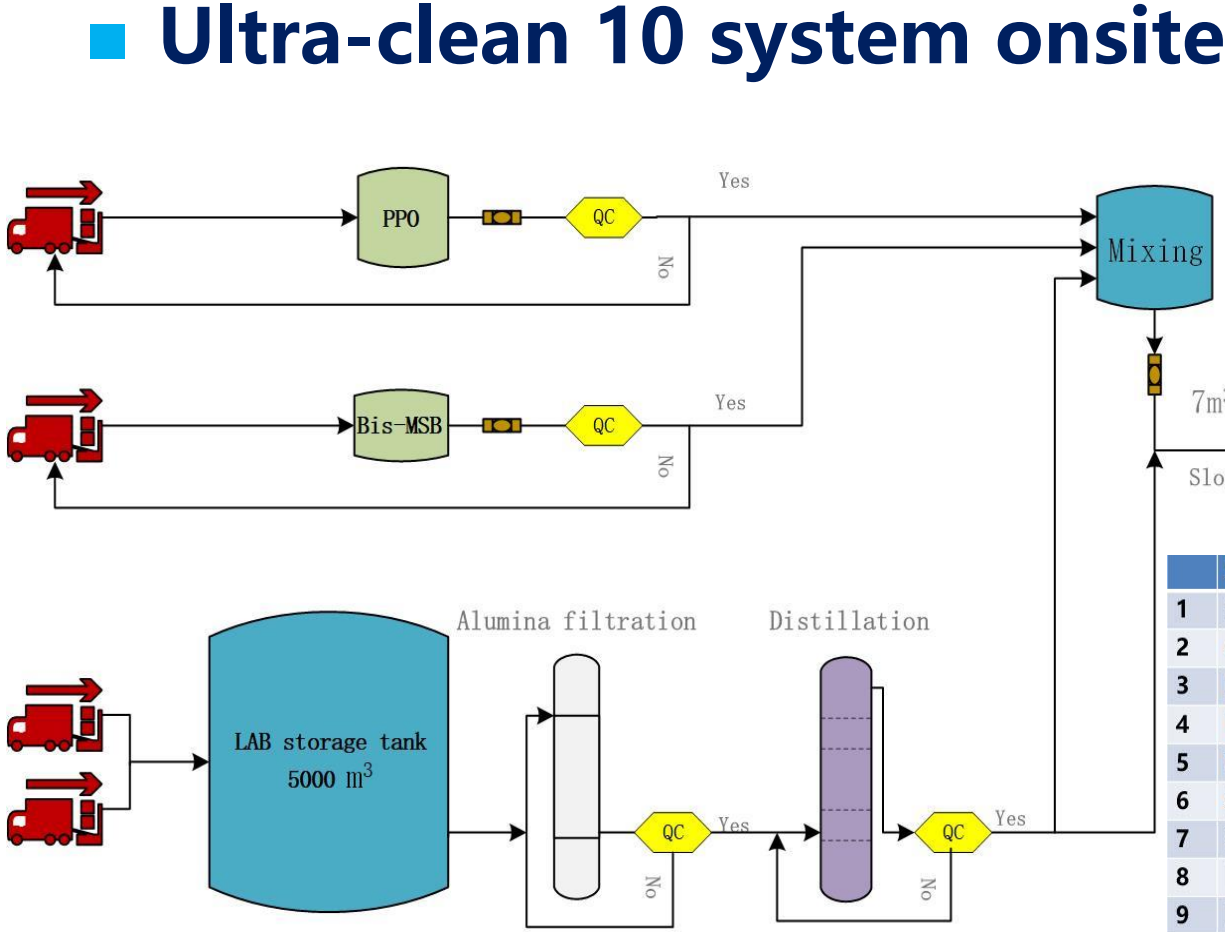
rice-sized dust>10 mg

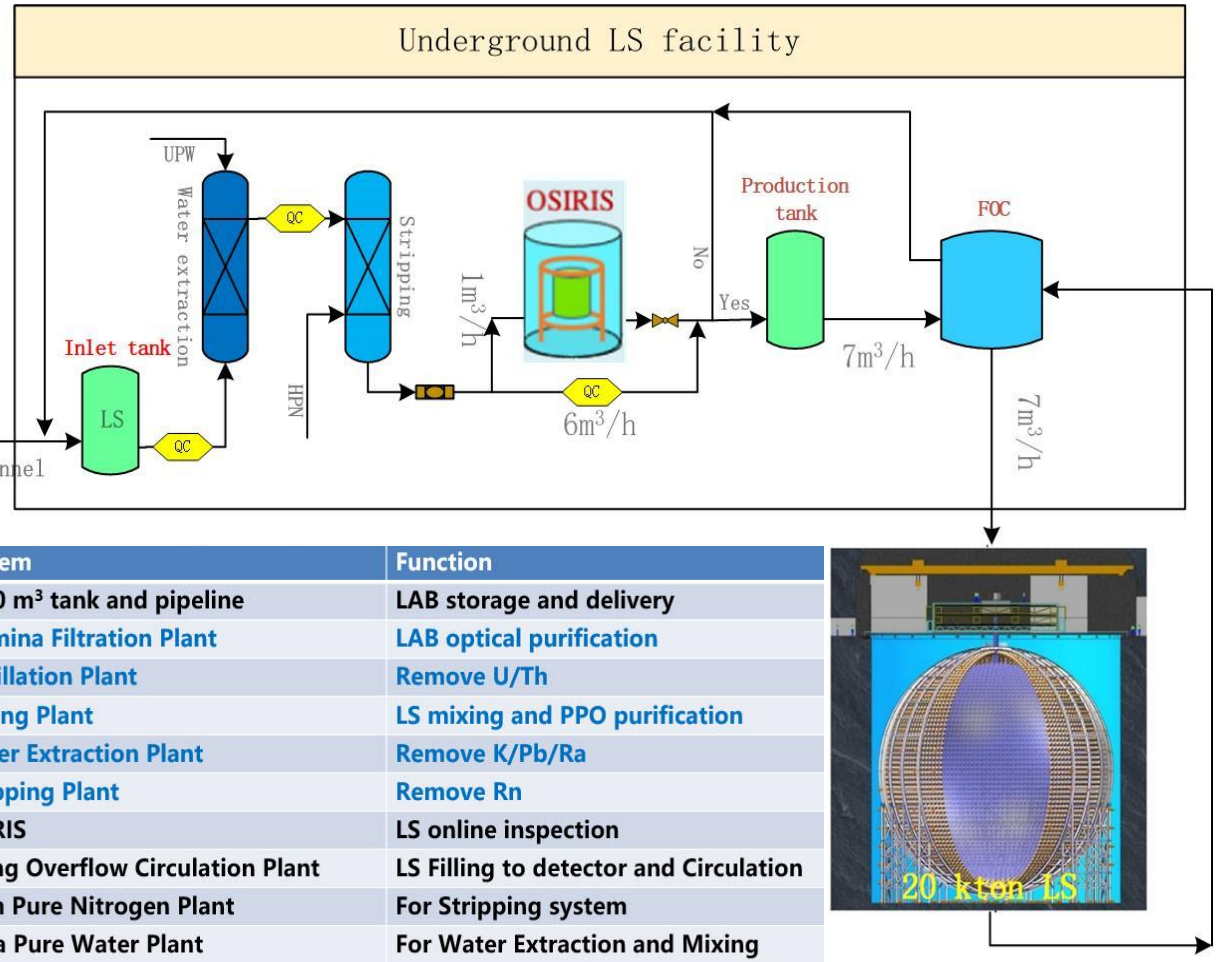
^{40}K in banana
~10^{-10} g/g

U/Th in pure water
~10^{-15} g/g

LS Production Process Flow and System

- **Ultra-clean 10 system onsite**





	System	Function
1	5000 m³ tank and pipeline	LAB storage and delivery
2	Alumina Filtration Plant	LAB optical purification
3	Distillation Plant	Remove U/Th
4	Mixing Plant	LS mixing and PPO purification
5	Water Extraction Plant	Remove K/Pb/Ra
6	Stripping Plant	Remove Rn
7	OSIRIS	LS online inspection
8	Filling Overflow Circulation Plant	LS Filling to detector and Circulation
9	High Pure Nitrogen Plant	For Stripping system
10	Ultra Pure Water Plant	For Water Extraction and Mixing

LS Quality Inspection Systems

- 11 systems in total, 7 self-developed systems

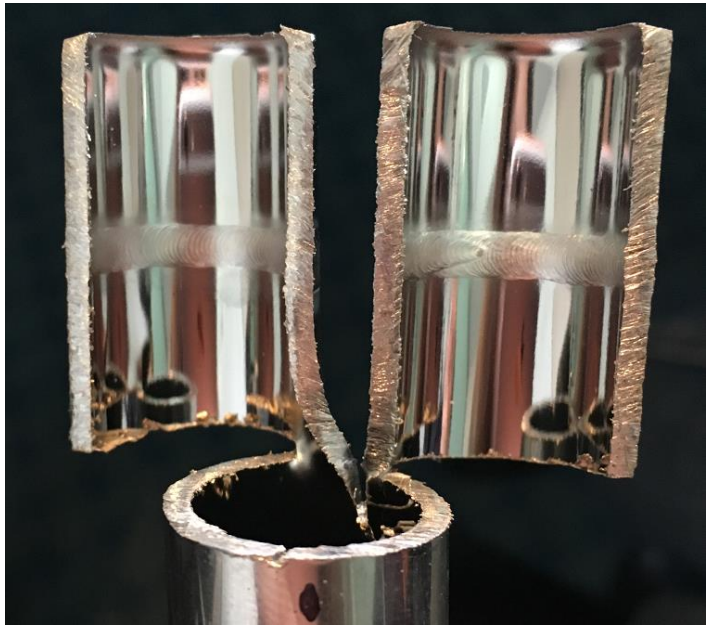
	System	Function
1	Attenuation Length measurement system	LAB and LS AL inspection
2	ICPMS system	U/Th content inspection for LAB, PPO, et.
3	Rn measurement system	Rn content inspection for N_2, LS
4	Particle measurement system	Particle inspection for cleaning water
5	HPGe system	Radioactivity content inspection
6	Water content measurement system	Water content in LS/MS inspection
7	Oil content measurement system	LS/MS in water inspection
8	Oxygen measuring system	Oxygen inspection for LS/MS
9	Spectrophotometer system	Spectrum inspection for LAB, MS, LS
10	Light yield measurement system	LY inspection for LS
11	LS aging system	Aging performance study

LS System construction and cleaning standards

- **Materials requirement for LS plant**
  - Tanks/pipeline：SS304L/SS316L/LB SS316L
  - O ring and other parts: Viton A and PTFE/PFA
- **Welding and surface treatment**
  - High purity argon gas shielded orbital welding
  - Electropolishing(EP), roughness Ra≤0.4 μm
- **Cleanness**
  - Degrease, Picking, Passivation, Water rinsing, Drying
  - Residual dust on the surface < 0.1 mg/m^2
  - ICP-MS U/Th<0.01 ppt in rinsing water
  - Clean installation

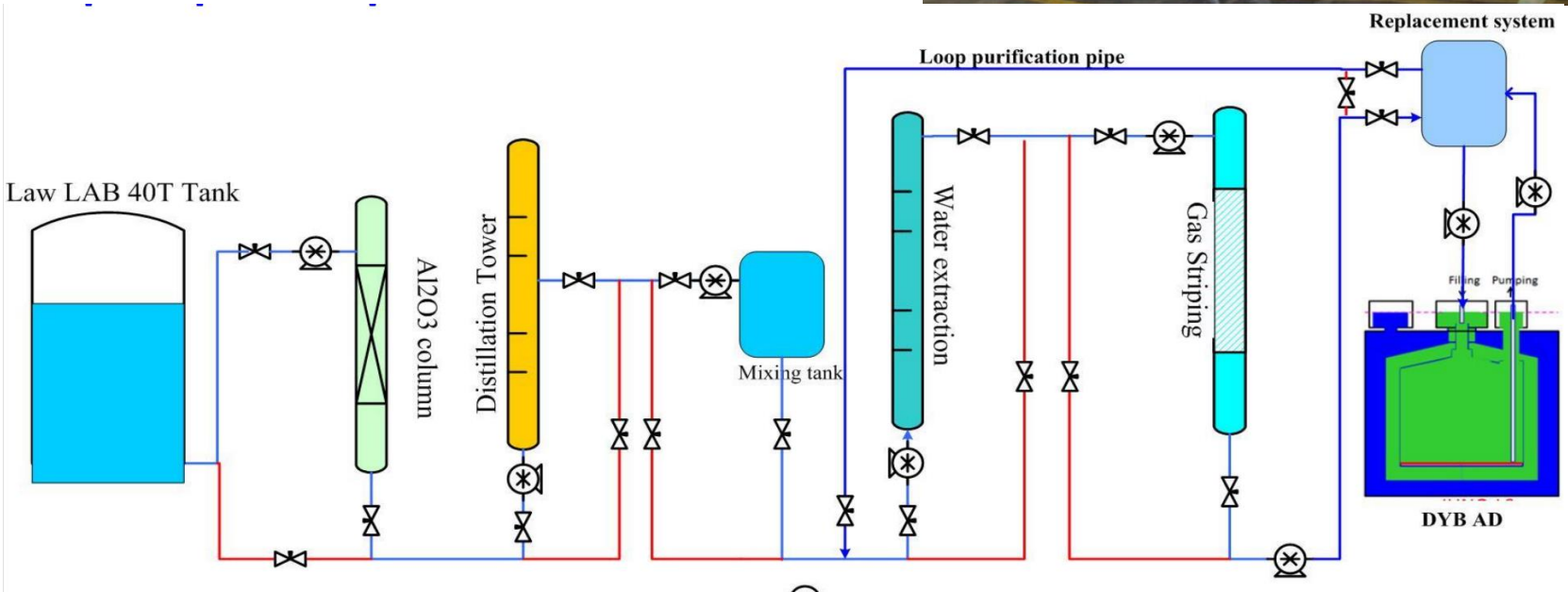
Particle Size. μm	Count per liter
5	1660
15	250
25	73
50	10

JUNO 50 level standard



Pilot Plant at DYB (2015-2017)

- 20t LS detector DYB AD
- Verified cleaning scheme
- Verified purification scheme
- Determined the LS recipe



Status of LAB Storage & transportation

- **Storage:**
  - 5000 m^3 tank is ready，SS304L, Ra≤0.4 μm, sealed with N_2
  - 200 tons LAB has been in tank for commissioning
- **Transportation:**
  - 200 ISO tanks, cleaned according JUNO 50 level and sealed with ~1 bar N_2

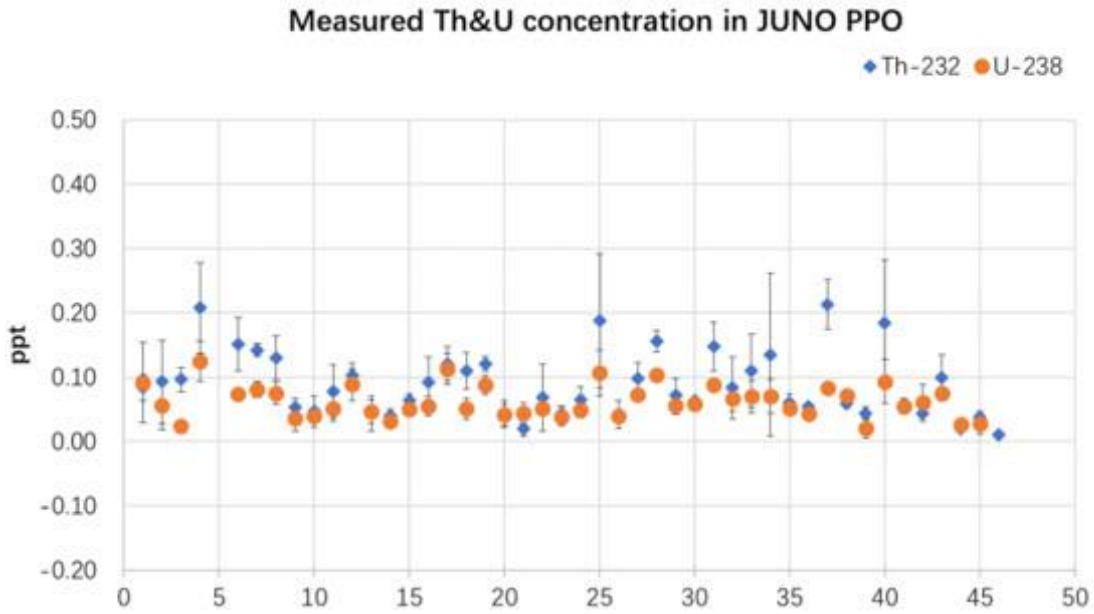
5k m^3 Tank


Tank cleanning

ISO tank

Status of PPO and bis-MSB

- Vacuum packaging to ensure air isolation
- 35.4 Tons/60 Tons PPO have been delivered to JUNO
- U=0.066 ppt, Th=0.099 ppt for 34.5 ton PPO
- bis-MSB has signed a contract with the company



Status of Alumina Filtration Plant

- Composed of 8 filtration columns
- Filled with alumina (Al_2O_3) as adsorbent
- Adsorbing optical impurities to increase the attenuation length
- Joint commissioning is done
  - 40 m^3 LAB has been purified
  - Attenuation length >24 m
  - ICP-MS test is in progress

Status of Distillation Plant

- Built and operated by the Italian collaboration members
- Heating with thermal oil
- Vacuum distillation
- Joint commissioning is done
  - Absorption spectra expectation
  - A.L. meets requirements
  - ICP-MS test is in progress

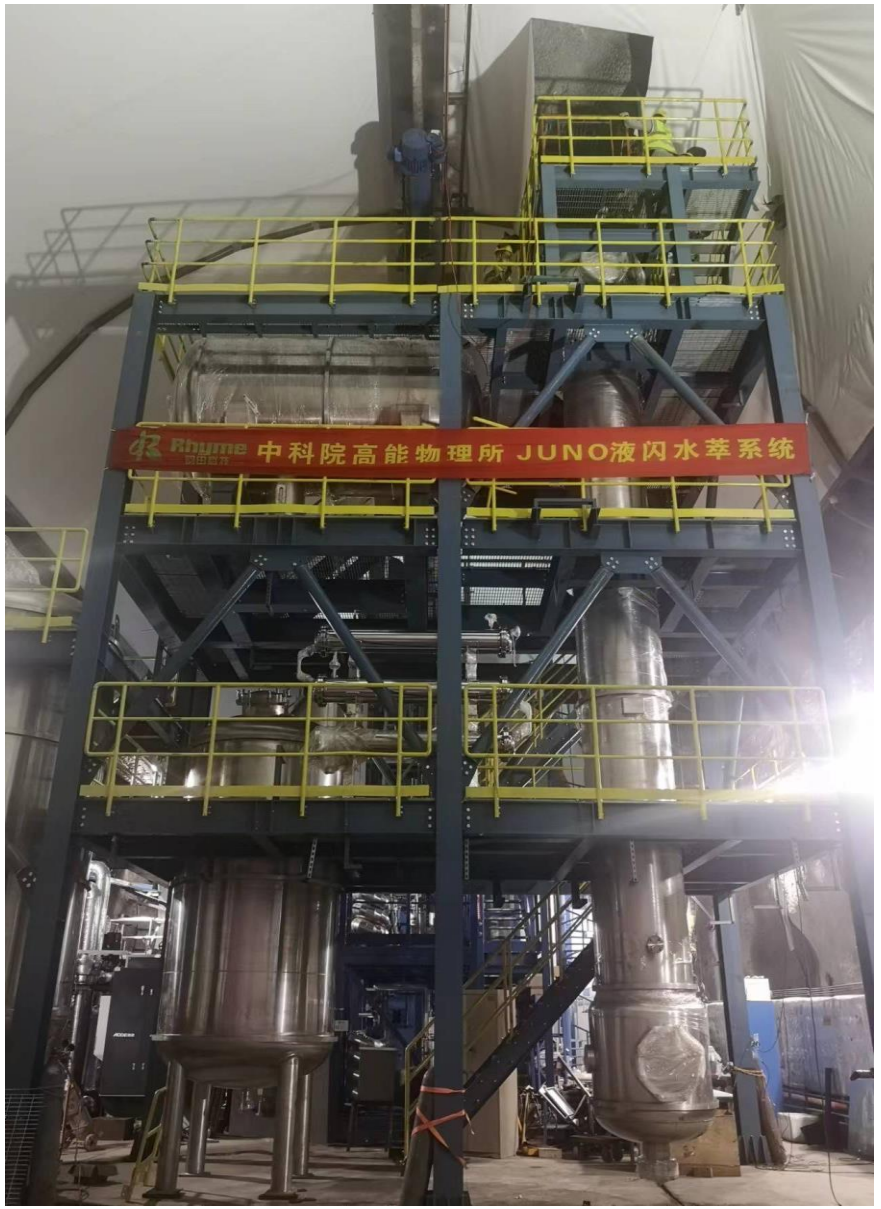

Distillation plant

Status of Mixing Plant

- PPO feed with glove box for air isolation
- Magnetic fluid stirring seal technology
- PPO purification
  - Acid extraction 1 time
  - water extraction 2 times in 40°C
  - Functional Group Filters
- Joint commissioning is done
  - 2000L MS was produced
  - Acid/water extraction
  - Mixing ~28 m^3 LS bump to underground
  - The ICP-MS test is in progress

Status of Water Extraction Plant

- **Water extraction tower**
  - Hight of 13 m
  - Diameter of 1 m
  - Extraction at 80 ℃
  - Purification efficiency of 90%
  - U/Th from 10^{-16}g/g to 10^{-17}g/g
- **Installation completed**
- **Joint commissioning next month**

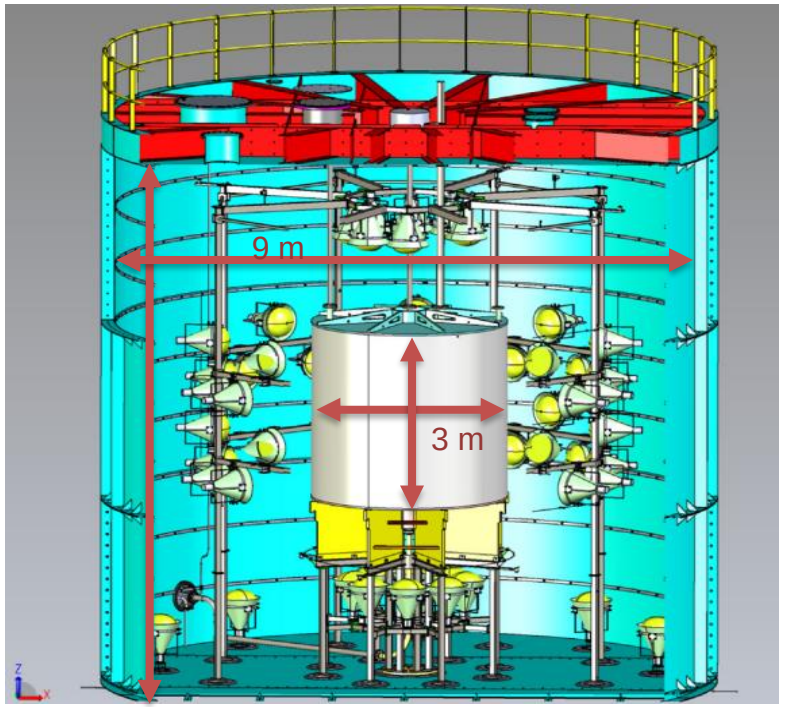


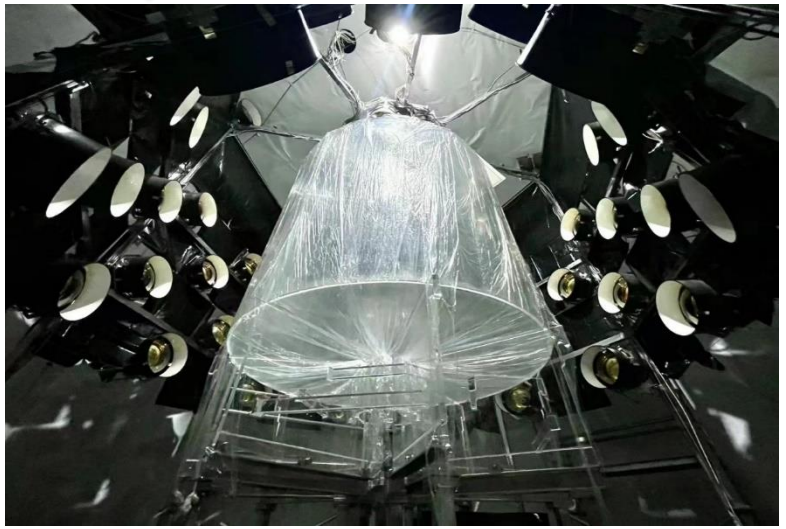
Status of Striping Plant

- Built and operated by the Italian collaboration members
- Removing Rn，Kr and Ar
- Joint commissioning is done
  - with both HP-N2 and HP water steam
  - with hot oil and cooling water device
  - ~28 m^3 LS was stripped
  - Optical results meets requirement
  - The ICP-MS test is in progress

Status of OSIRIS(Online Scintillator Internal Radioactivity Investigation System)

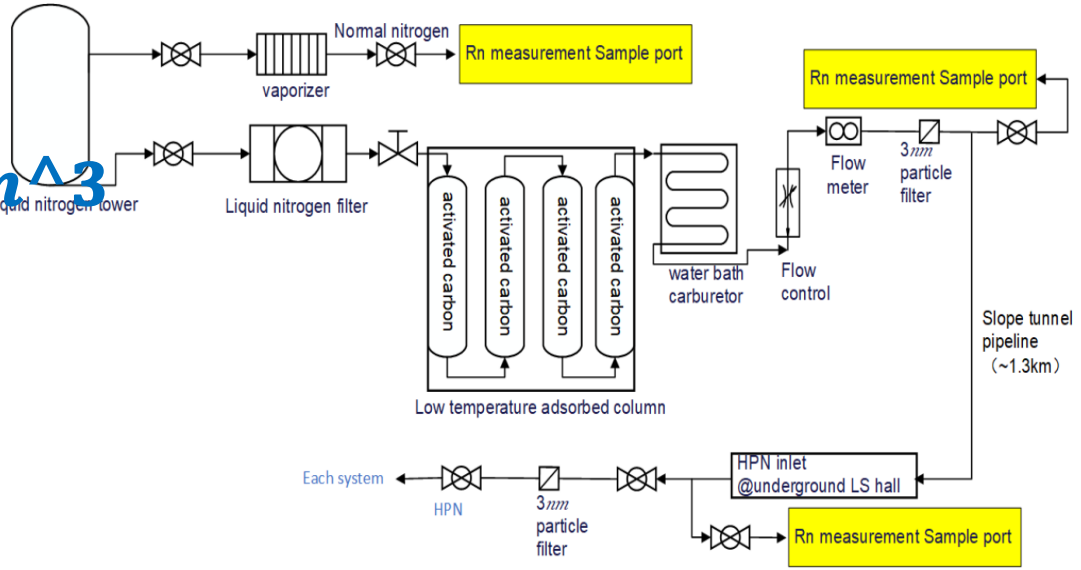
- 20-t detector in underground LS hall
- monitor radiopurity of LS before and during filling
  - Few days: U/Th~ 1×10^{-15} g/g
  - 2~3 weeks: U/Th~ 1×10^{-17} g/g
- Installation and cleaning completed
- Joint commissioning next month





Status of High Pure Nitrogen Plant

- Purge gas for Central Detector, Water Extraction, Stripping, OSIRIS, UPW and FOC systems
- Activated carbon low-temperature adsorption technology for Rn, Kr, Ar
- Commissioning is done
  - Radon : 5.5± 0.6 uBq/m^3 <10 uBq/m^3
  - Krypton : 18.5 ppt <50 ppt.
  - Argon concentration is under test
  - 50-100 Nm^3/h flux rate

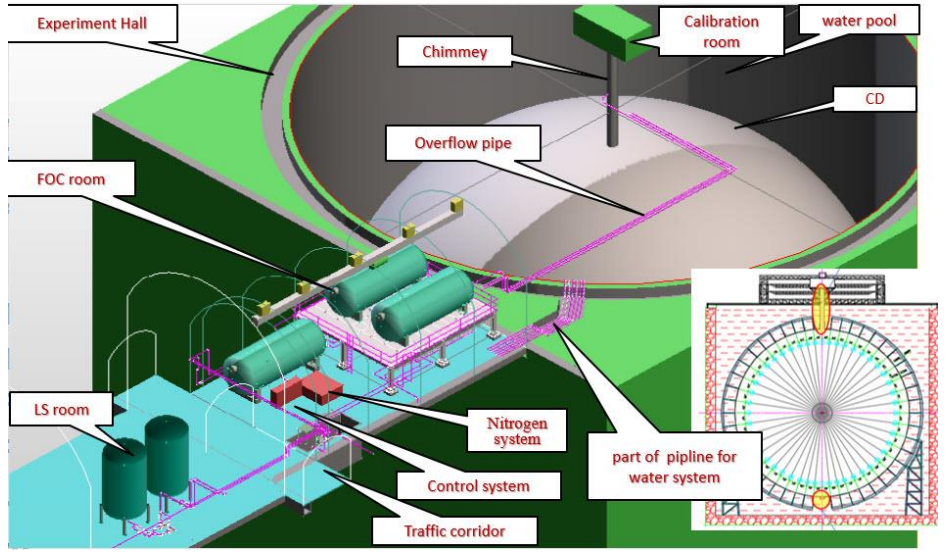


Status of Ultra Pure Water Plant

- **Ultra pure water for Water Extraction**
  - U&Th < 1e-16 g/g
  - Rn < 1 mBq/m^3
  - 2.5 T/h
- **Commissioning is done**
  - The pressure/flow rate
  - The temperature
  - Resistivity
  - Particles >0.05 μm
  - U/Th/Rn/Anios measurement is in progress

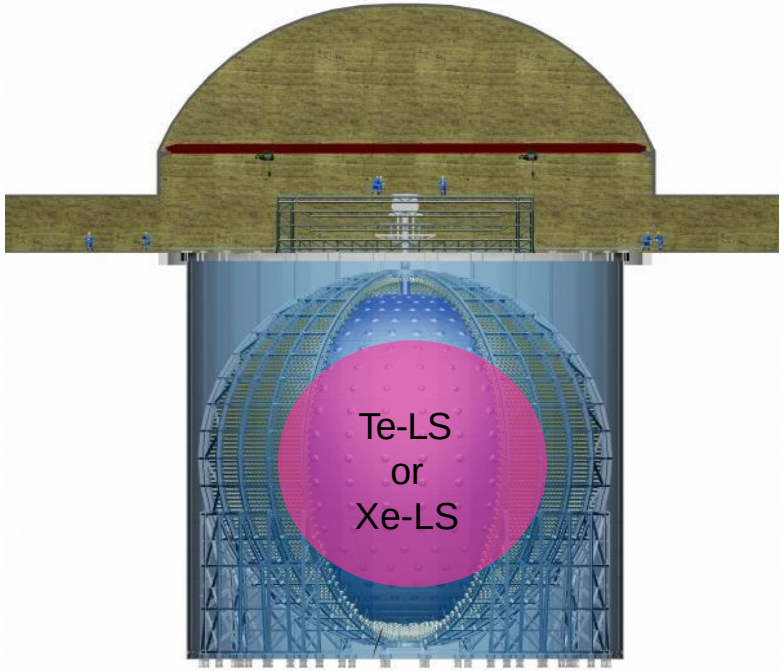
Status of FOC Plant and Filling plan

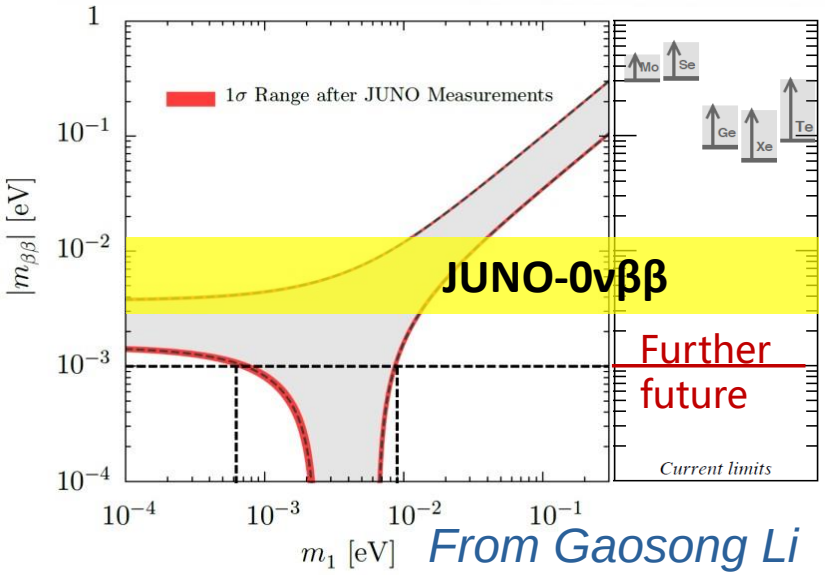
- **Function of FOC**
  - **Water filling first, then LS/water exchange**
  - **Overflow and circulation**
  - **Cover gas for FOC and CD**
- **Installation and cleaning completed**
- **Joint commissioning next month**
- **Filling are expected to be completed in the second half of next year**



Future Plans for the Project

- upgraded to 0νββ detector
  - 100-ton scale
  - extremely low background
  - excellent energy resolution
  - reach a sensitivity of |mββ|~meV
- Dedicated R&D program is in progress
  - Tellurium-doped LS development
  - cosmogenic backgrounds on Tellurium
  - background rejection



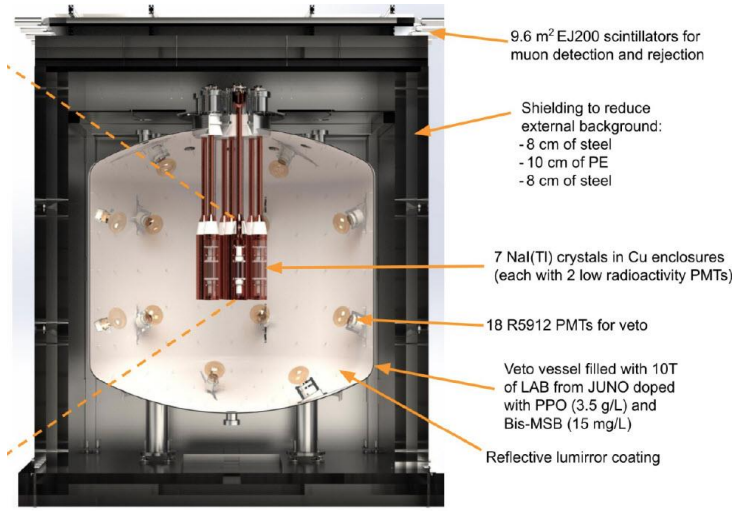


From Gaosong Li

Potential Applications in Radiation Detection

- **Liquid Scintillator Counter for Environmental Monitoring**
  - Ultra-purity means higher sensitivity
  - low levels of ^{3}H and ^{14}C environmental monitoring (like water, air, soil, animals, plants, etc.)
  - Nuclear power plants
  - Environmental protection
  - Food science
- **Others**
  - active shielding anti-coincidence detector

SIM-MAX LSA3000



SciPost Phys. Proc. 12, 029 (2023)

Summary

- **Ultra-pure liquid scintillator technology has been developed**
  - **Production processes**
  - **Production equipment**
  - **Inspection equipment and methods**
- **JUNO is expected to start filling next year**
- **Ultra-pure liquid scintillator can be used in other areas**

Thank you for your attention!