Conseil scientifique IN2P3
26-27 Octobre 2021

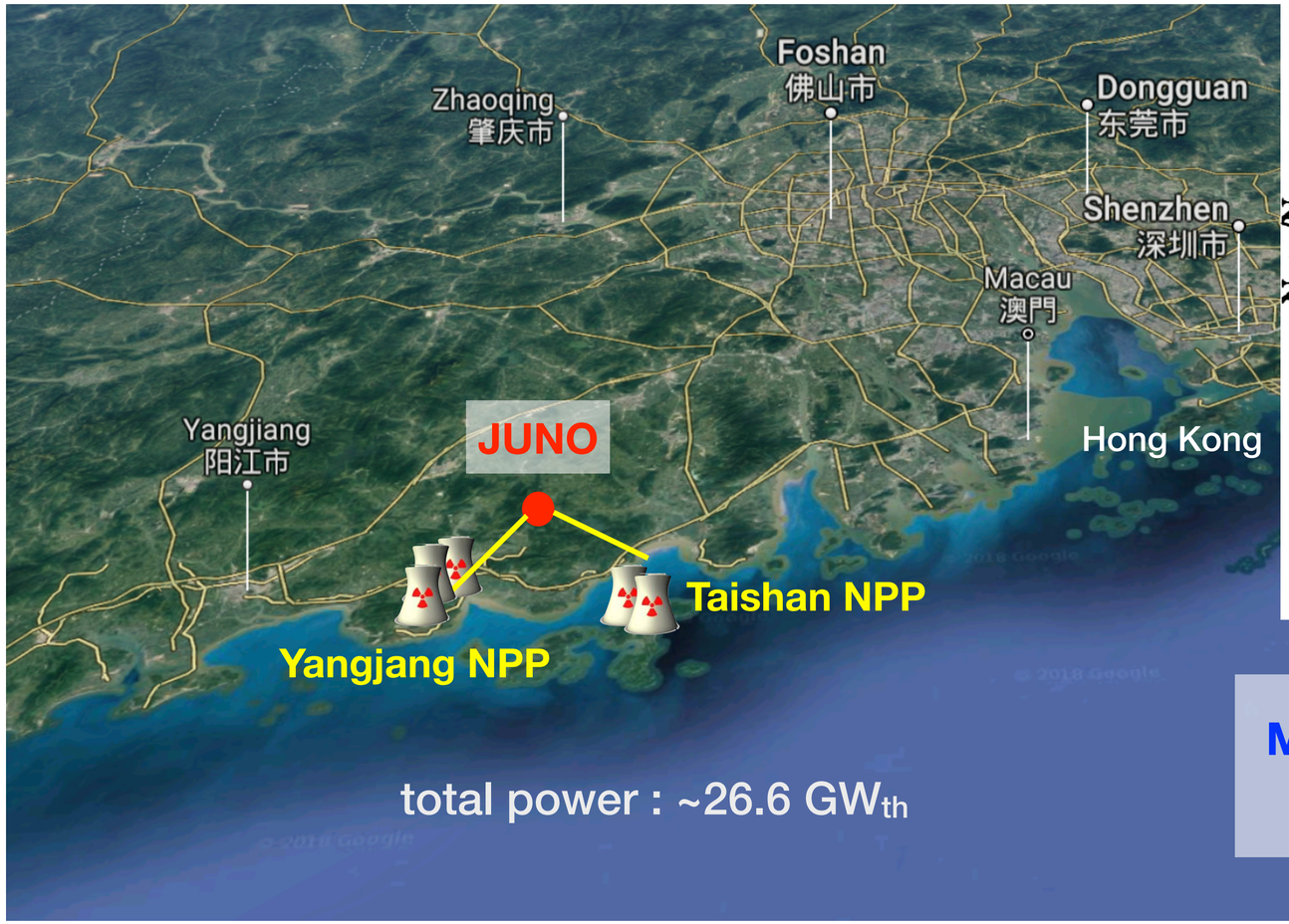
Jiangmen Underground Neutrino Observatory (JUNO) at IN2P3

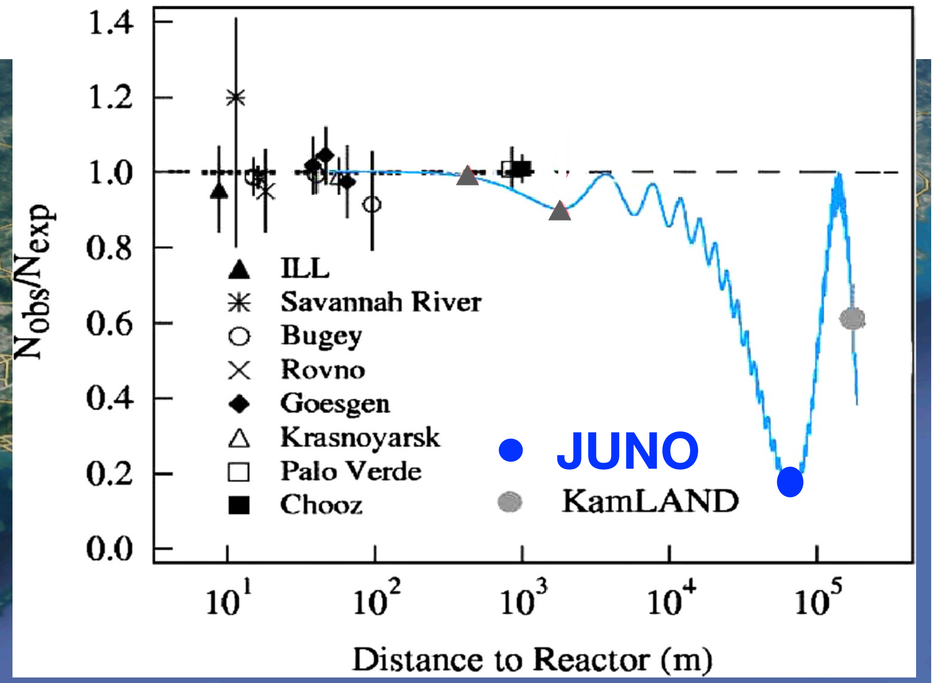
Status of the project

Mariangela Settimo[1] on behalf of the JUNO-France collaboration

[1] SUBATECH, Université de Nantes, IMT-Atlantique, CNRS

The Jiangmen Underground Neutrino Observatory



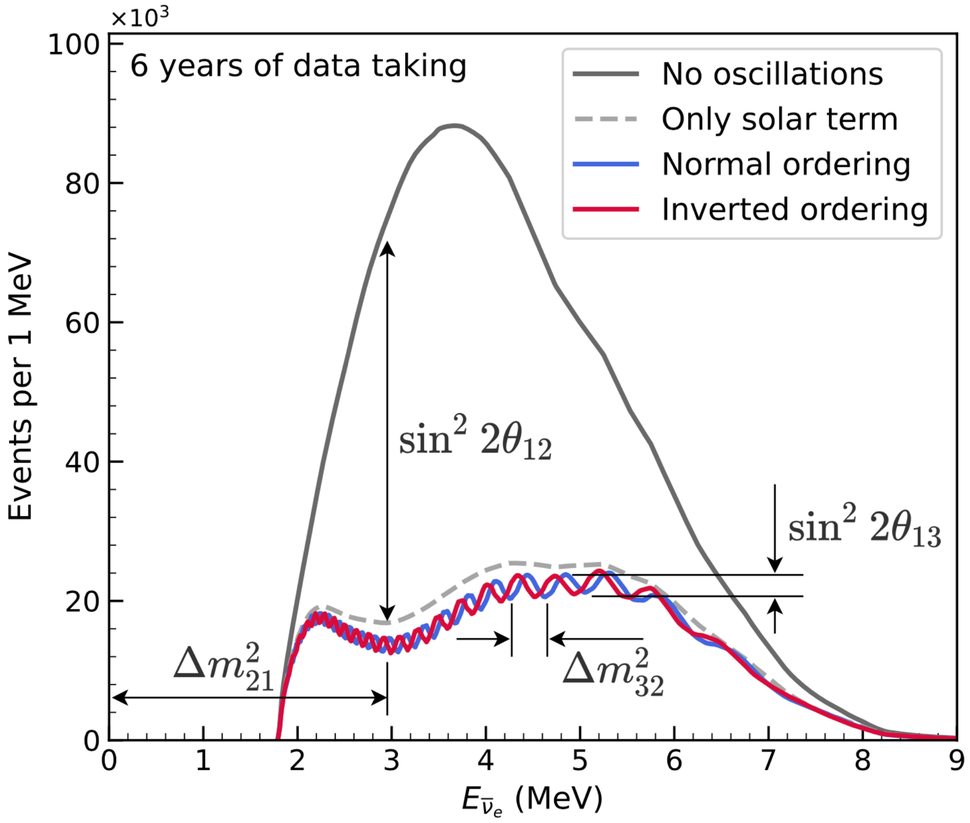


Medium-baseline experiment:
53 km from nuclear reactors

$\bar{\nu}_e$ interaction: Inverse Beta Decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$

The main goal: the neutrino Mass Ordering (MO)

Mass Ordering (quasi) in-vacuum (independent of δ_{CP}): unique result!



Interference between slow (solar) and fast (atmospheric) oscillation modes

- **Large detector volume** (20 kilo-tons of Liquid scintillator)
- **Unprecedented energy resolution**: 3%/√E (MeV) and **energy scale accuracy** (<1%)

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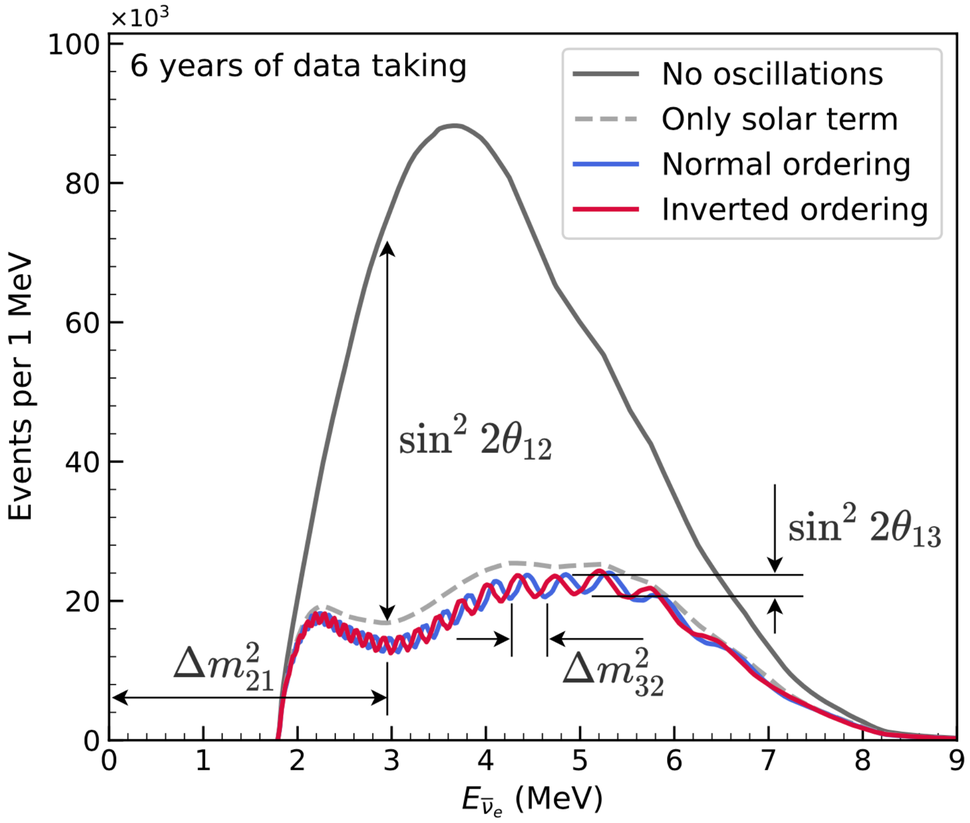

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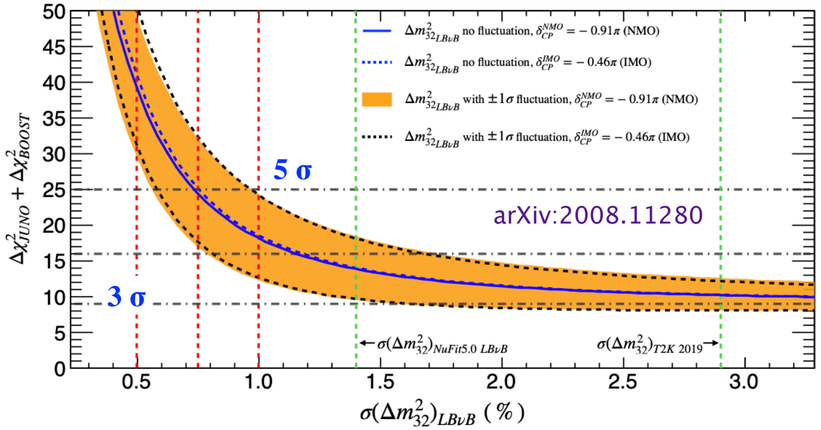
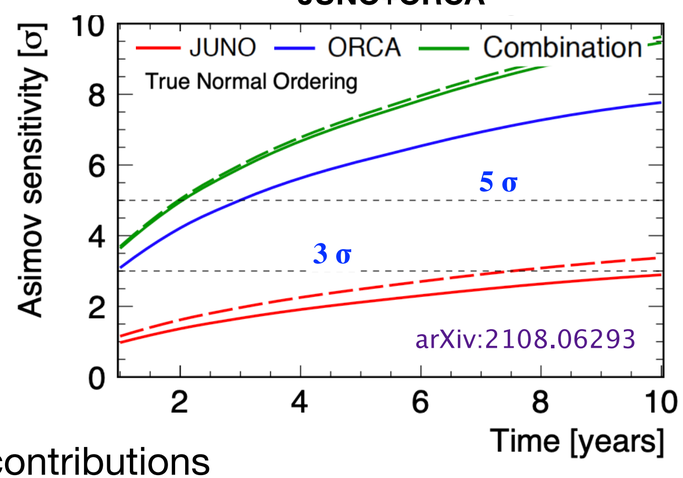
- **Unprecedented energy resolution**: 3%/√E (MeV) and **energy scale accuracy** (<1%)

3σ sensitivity in 6 years
(≳ 5σ from combined analyses with ORCA or T2K/NOνA)

JUNO+LBνB



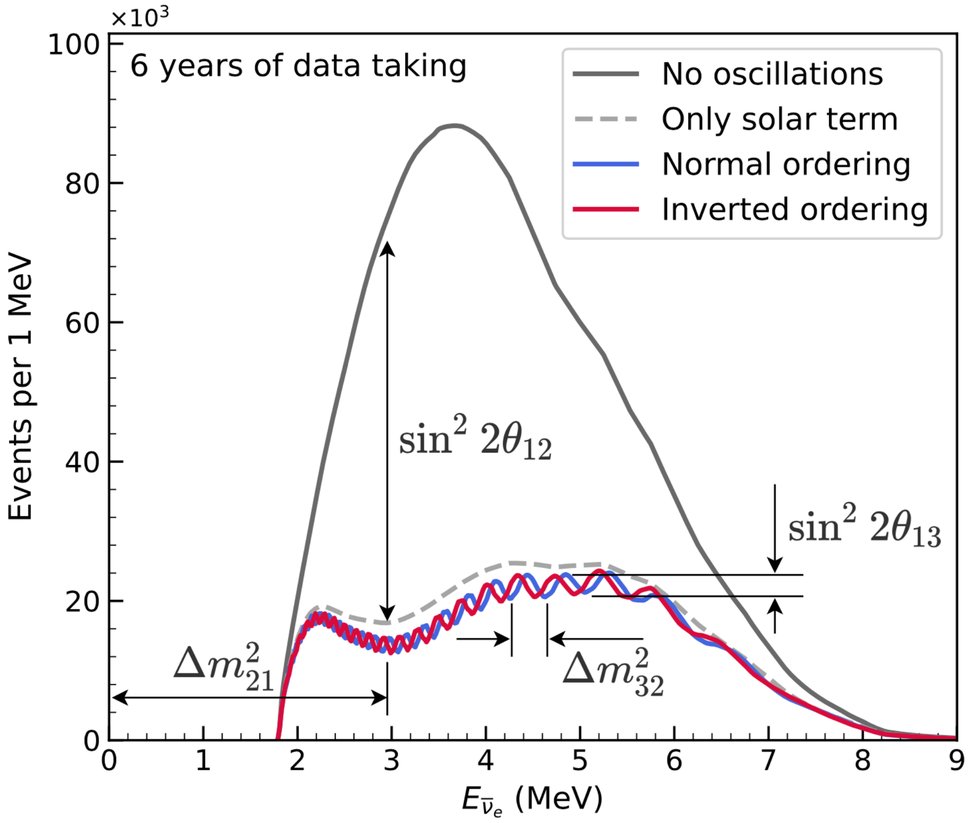
JUNO+ORCA



French contributions

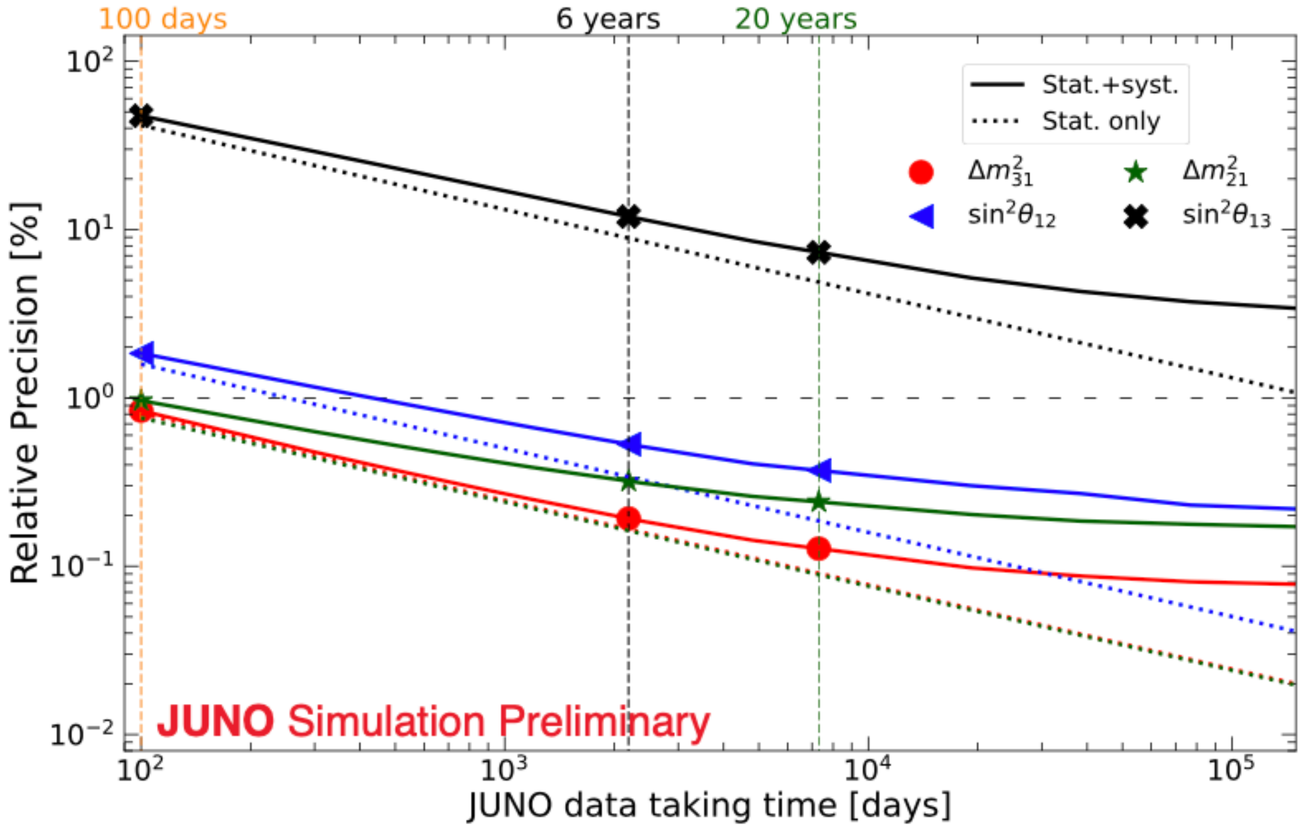
Oscillation parameters determination

Precision to sub-percent level for Δm^2_{21}, $\sin^2\theta_{12}$ and Δm^2_{31} in 6 years of data



Interference between slow (solar) and fast (atmospheric) oscillation modes

	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%



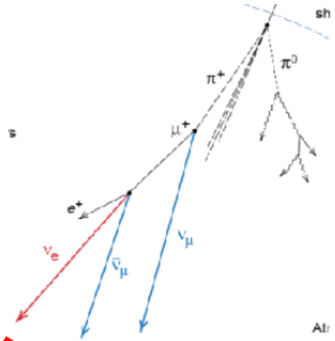
A vast physics program

Details in J. Phys. G 43 (2016) no.3, 030401 and arXiv:2104.02565
(Also presented in CS IN2P3 2018)

Supernova ν
~ 5k in 10s for 10kpc

Diffuse Supernova Background (DSNB) ν
2-4/year

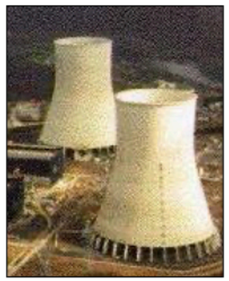
Atmospheric ν
several/day



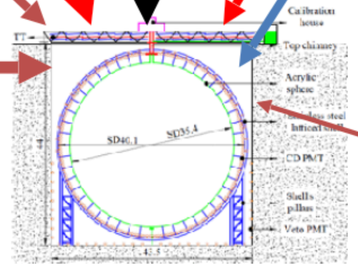
Solar ν
tens / day

700 m

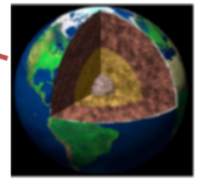
Cosmic muons
~ 250k/day
0.004 Hz/m², 207 GeV
10% multiple-muon



26.6 GWth, 53 km



Reactor ν
~ 60/day
NMO, oscillation parameters



Geo-ν
1-2/day

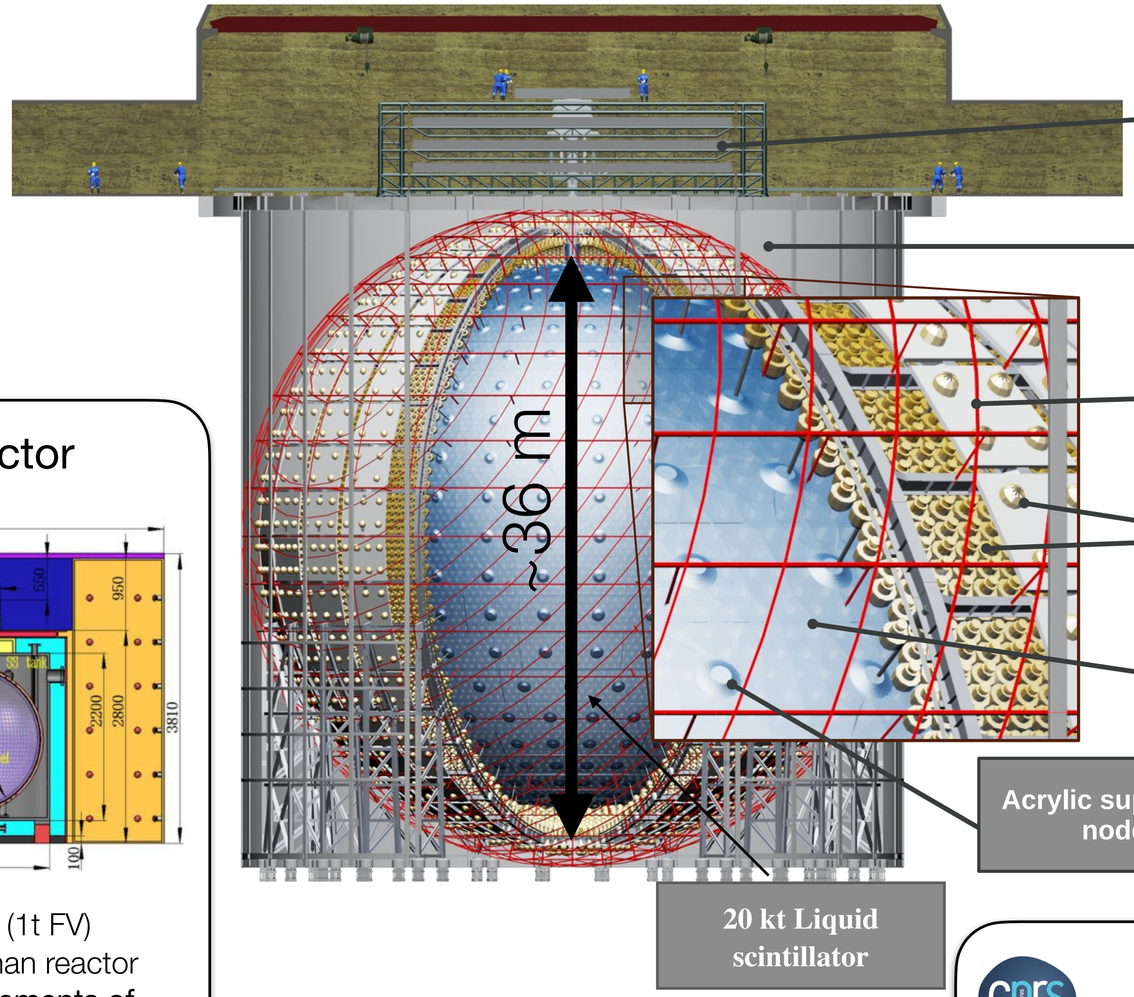
Main IN2P3 contributions

- Additional rare events physics studies (proton decay, sterile ν,…)

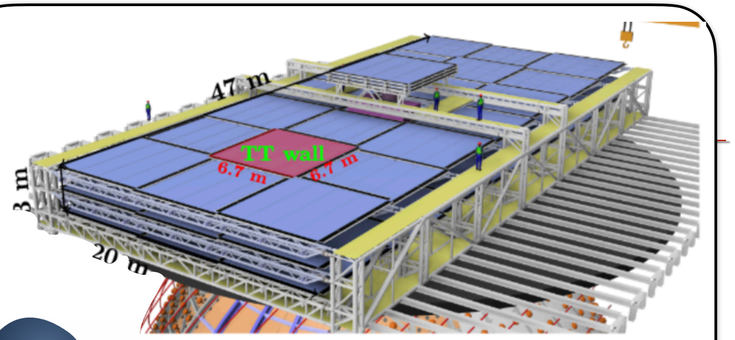
The JUNO Detector

Details in : J. Phys. G 43 (2016) no.3, 030401,
Updates: JUNO Collaboration, arXiv:2104.02565

700 m underground



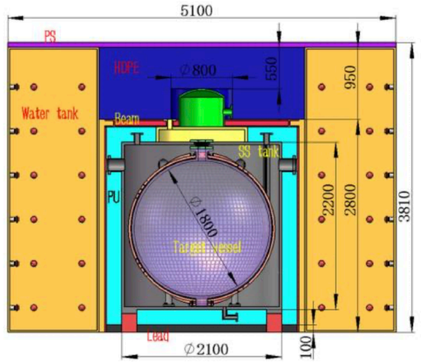
- Top tracker and calibration house
- Water pool
- Earth magnetic field compensation coils
- Photo-multiplier tubes
- Acrylic spherical vessel filled with liquid scintillator
- Acrylic supporting nodes
- 20 kt Liquid scintillator



Top Tracker

Muon tracking for cosmogenic background reduction

TAO detector



- 2.8 tons Gd-LS (1t FV)
- 30 m from Taishan reactor
- precise measurements of reactor anti-υ spectrum

17612 Large PMT (20″)

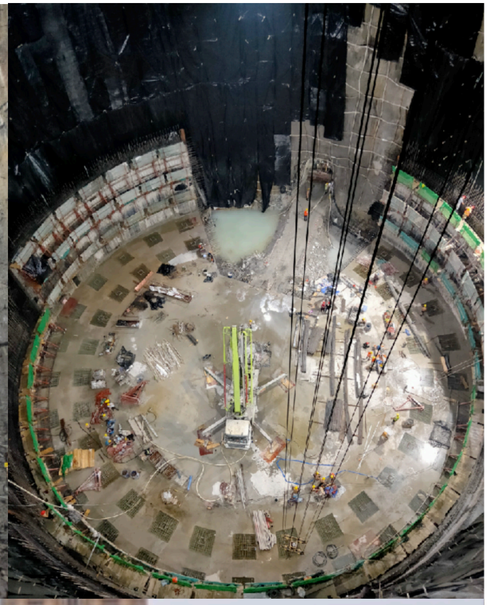
25600 Small PMT (3″)

Dual Calorimetry

Radiopurity control (Central Detector)

To reduce accidental background

Where we are: Civil construction



Where we are: Instrumentation

LPMT (20″)

22416 LPMT produced and tested;
Electronics under mass production

SPMT (3″)

All 26000 SPMT produced and tested
Potting and acceptance test ongoing. Electronics under production

Acrylic sphere

100% flat panel produced; Radiopurity control in progress
Cleaning strategy being defined

Top Tracker

Already at JUNO site, full electronics chain being finalized, mechanical structure well defined

Liquid Scintillator

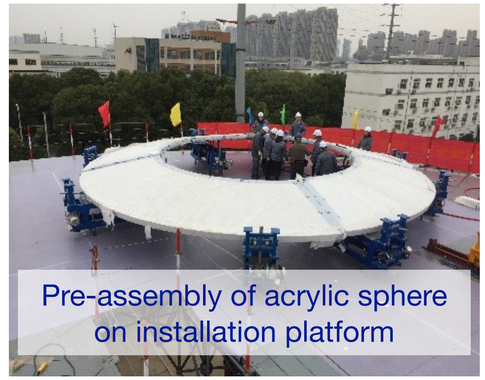
200 tons of LAB filled into the 5 kt LAB tank
Al_2O_3 column plant installed in the LS surface hall

Calibration system

Calibration house: Production completed

Steel structure

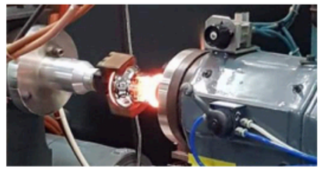
Production: 95% finished
anchors of SS structure and lifting platform: installed

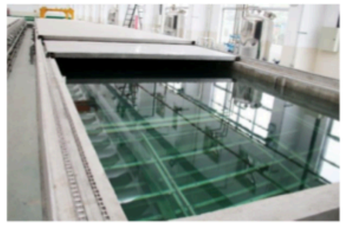


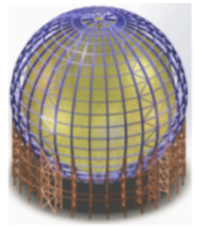
…. (and many more)

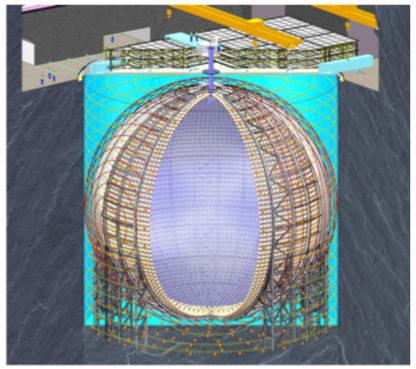
Project timeline

Detector Installation in 2022









2014
- Int. Collaboration established!

2015
- PMT production line setup
- Start civil construction
- CD parts R&D

2016
- Start PMT production
- Start CD parts production

2017
- Start PMT testing
- Top Tracker arrived!
- Daya Bay LS tests

2018
- PMT potting start
- Delivery of surface buildings
- Start production of acrylic sphere
- OSIRIS was funded
- TAO working group formed

2019-20
- Electronics production starts
- Civil work and lab preparation
- Det. construction starts

2021-22
- Det. assembly completed
- Det. filling & comissioning
- TAO construction

Data Taking

JUNO collaboration

Country	Institute
Armenia	Yerevan Physics Institute
Belgium	Universite libre de Bruxelles
Brazil	PUC
Brazil	UEL
Chile	PCUC
Chile	SAPHIR
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	DGUT
China	ECUST
China	Guangxi U.
China	Harbin Institute of Technology
China	IHEP
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
China	NCEPU
China	Pekin U.
China	Shandong U.
China	Shanghai JT U.
China	IGG-Beijing
China	IGG-Wuhan

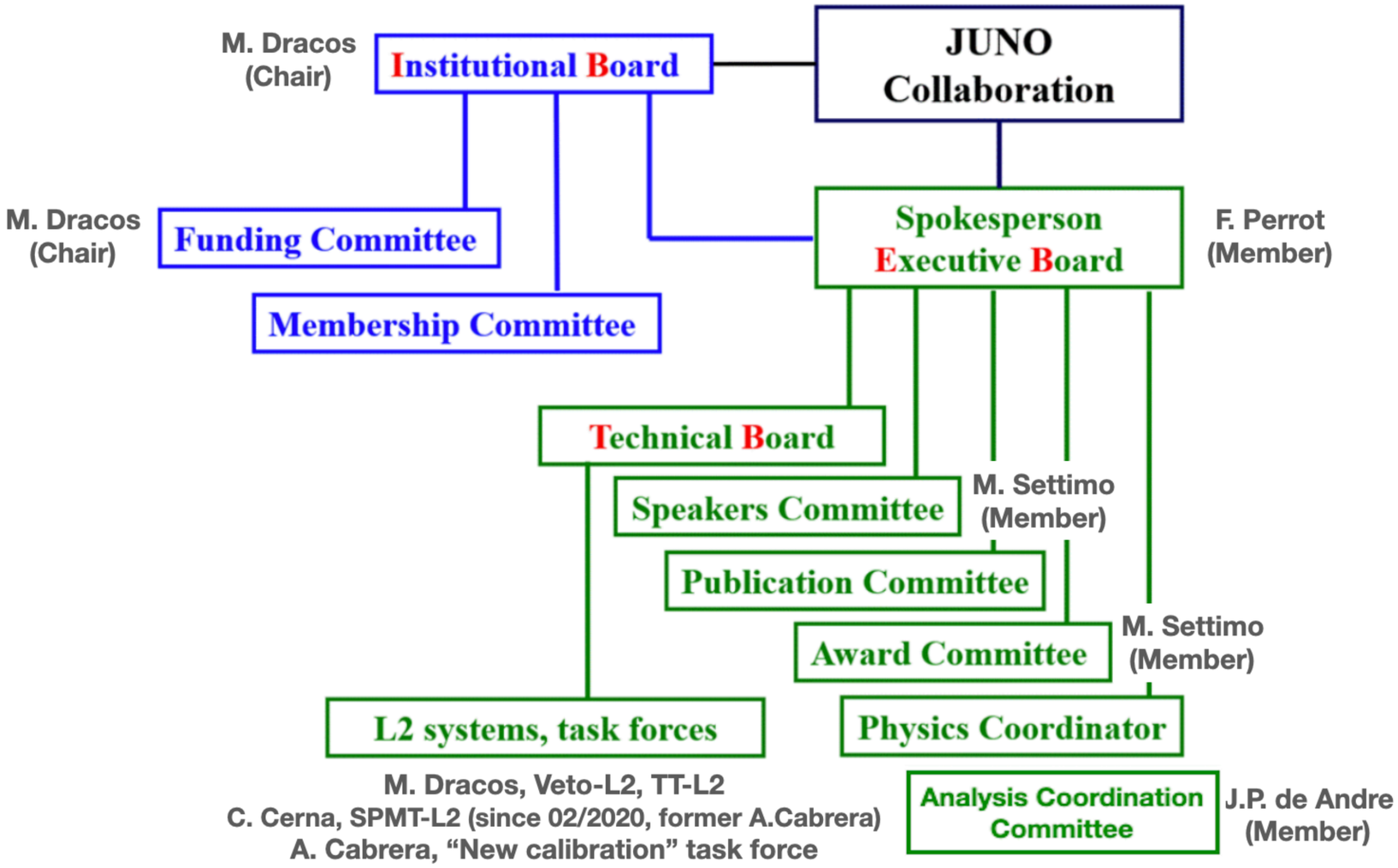
Country	Institute
China	IMP-CAS
China	SYSU
China	Tsinghua U.
China	UCAS
China	USTC
China	U. of South China
China	Wu Yi U.
China	Wuhan U.
China	Xi'an JT U.
China	Xiamen University
China	Zhengzhou U.
China	NUDT
China	CUG-Beijing
China	ECUT-Nanchang City
Croatia	UZ/RBI
Czech	Charles U.
Finland	University of Jyvaskyla
France	IJCLab Orsay
France	CENBG Bordeaux
France	CPPM Marseille
France	IPHC Strasbourg
France	Subatech Nantes
Germany	FZJ-ZEA
Germany	RWTH Aachen U.
Germany	TUM
Germany	U. Hamburg

Country	Institute
Germany	FZJ-IKP
Germany	U. Mainz
Germany	U. Tuebingen
Italy	INFN Catania
Italy	INFN di Frascati
Italy	INFN-Ferrara
Italy	INFN-Milano
Italy	INFN-Milano Bicocca
Italy	INFN-Padova
Italy	INFN-Perugia
Italy	INFN-Roma 3
Latvia	IECS
Pakistan	PINSTECH (PAEC)
Russia	INR Moscow
Russia	JINR
Russia	MSU
Slovakia	FMPICU
Taiwan-China	National Chiao-Tung U.
Taiwan-China	National Taiwan U.
Taiwan-China	National United U.
Thailand	NARIT
Thailand	PPRLCU
Thailand	SUT
USA	UMD-G
USA	UC Irvine

Collaboration established in 2014

Now : ~700 collaborators, 77 institute members

JUNO International structure

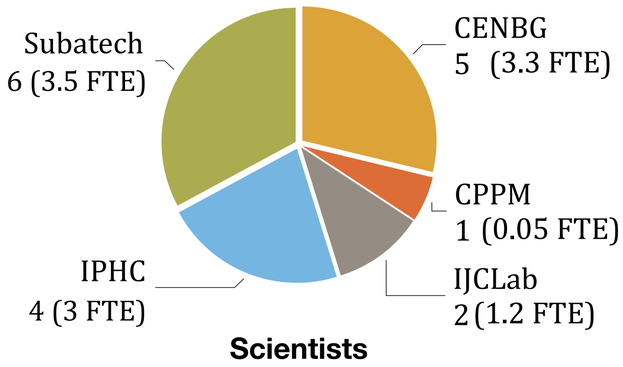


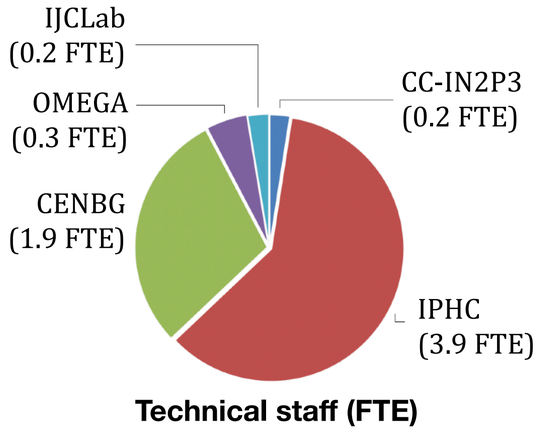
Several other responsibilities at L3-level and in review committee

- **International Scientific Committee**
- Kate Scholberg (Chair)
- Serguey Petkov
- Schönert Stefan
- Yoichiro Suzuki
- Atsuto Suzuki
- Berrie Giebel
- Victor Matveev
- Yuanning Gao
- Marco Palaviccini
- Jennifer Thomas

+ Bylaws
+ Speaker committee rules
+ Publication committee rules
+ Code of Conduct

The IN2P3 teams



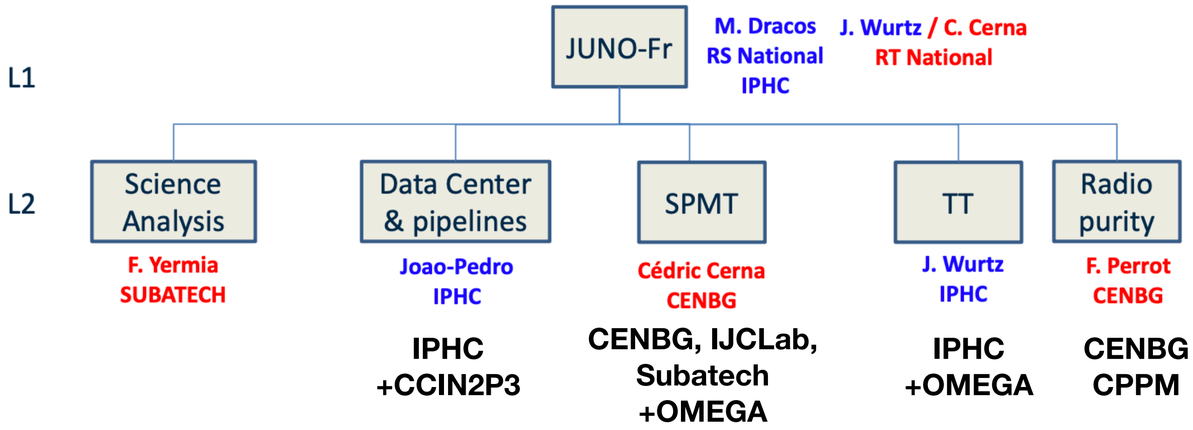


48 members: 18 scientists and 30 technical staff members

3 PhD completed and 3 ongoing

Based on NSIP 2021 (1st semester)

National organisation chart and main sub-systems and contributions

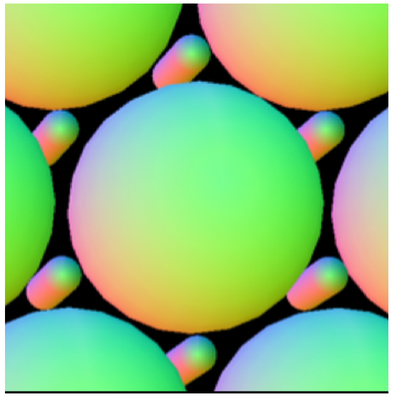


Main physics contributions

- Measurement of ν oscillations
- Dual calorimetry calibration for MO
- Radioactivity control for MO
- Muon reconstruction and cosmogenic background for MO
- Core Collapse Supernova Neutrinos (CCSN)

Scientific contributions

The SPMT and dual calorimetry for MO



Dual Calorimetry System: proposal lead by APC+Subatech groups in 2014, approved in 2016

SPMT (3'' PMT) system to control the non-stochastic terms in the energy resolution at <1%

- SPMTs in photon-counting mode: (~ 1 P.E./PMT in 95% of reactor ν cases) vs LPMT in charge mode (possible non-linearity)
- Possible quasi-independent cross-check and analyses (e.g., solar oscillation parameters, muon reconstruction, core-collapse supernova)

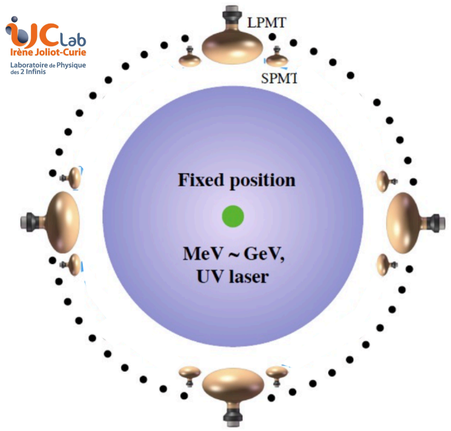
$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

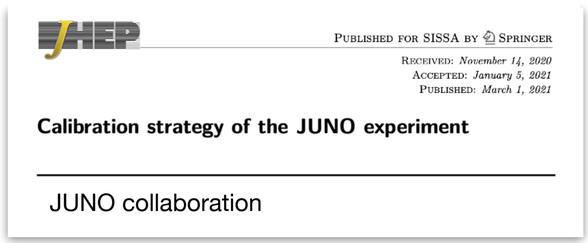
stochastic Non-stochastic

Dual Calorimetry Calibration

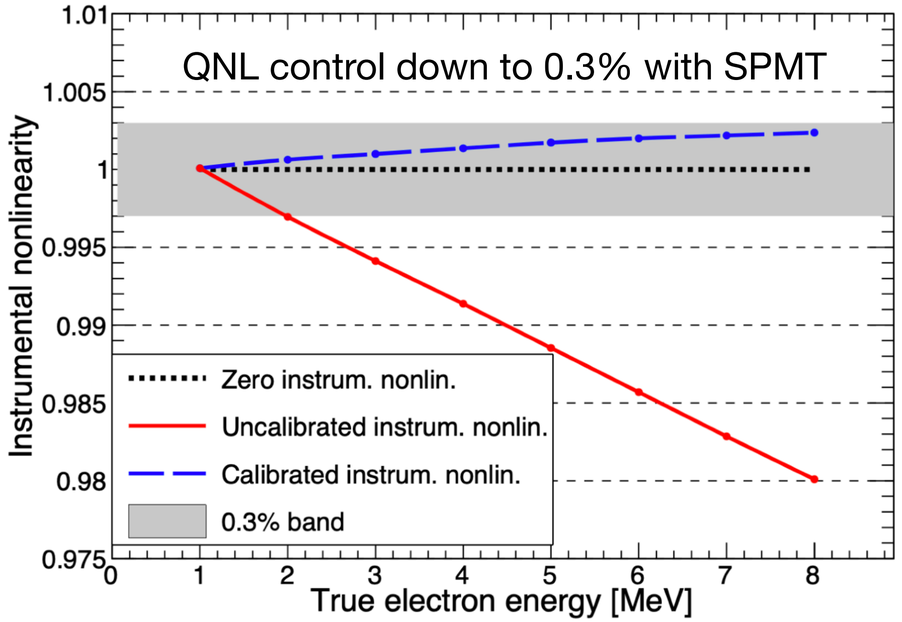
Correct the charge non-linearity (QNL) of the LPMT at single channel level

- UV laser at detector center: SPMT as linear reference for the LPMT





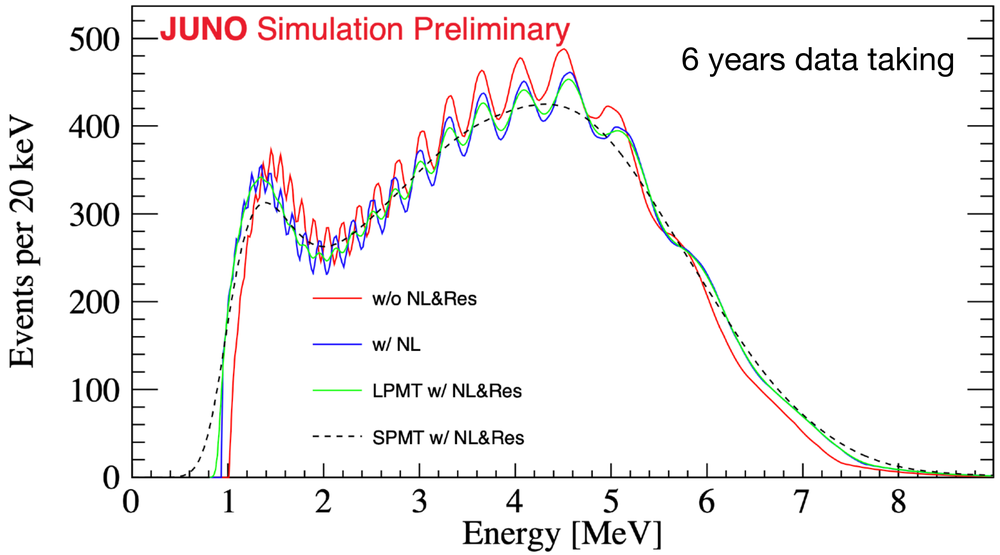
JHEP03 (2021) 004
(Participation to the Edition)



Oscillation parameters determination

JUNO (6 years): measurement of (θ_{12}, Δm^2_{21}, $|\Delta m^2_{31}|$) to a precision better than 1%

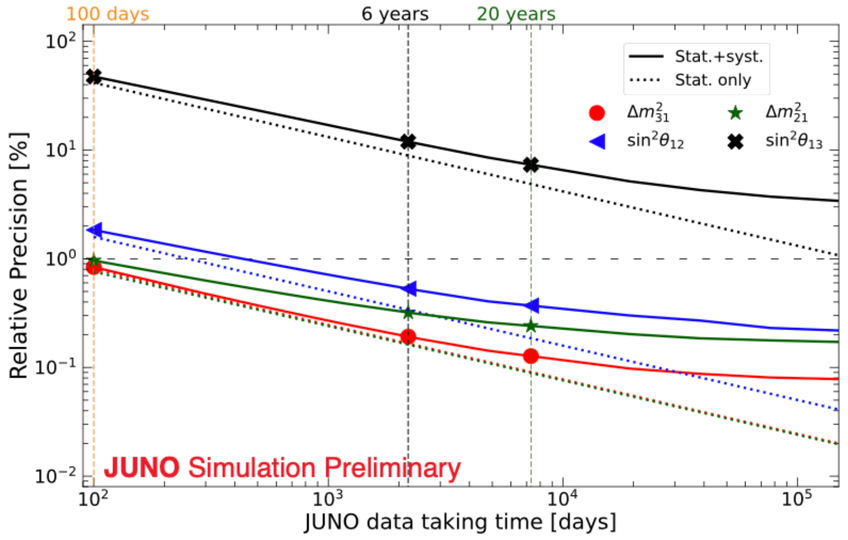
	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%



- **General analysis**
  - 4 independent approaches (IN2P3 in two of them)
  - Common inputs (energy resolution, non-linearities, backgrounds)

Sub-percent Precision Measurements of Neutrino Oscillation Parameters with JUNO

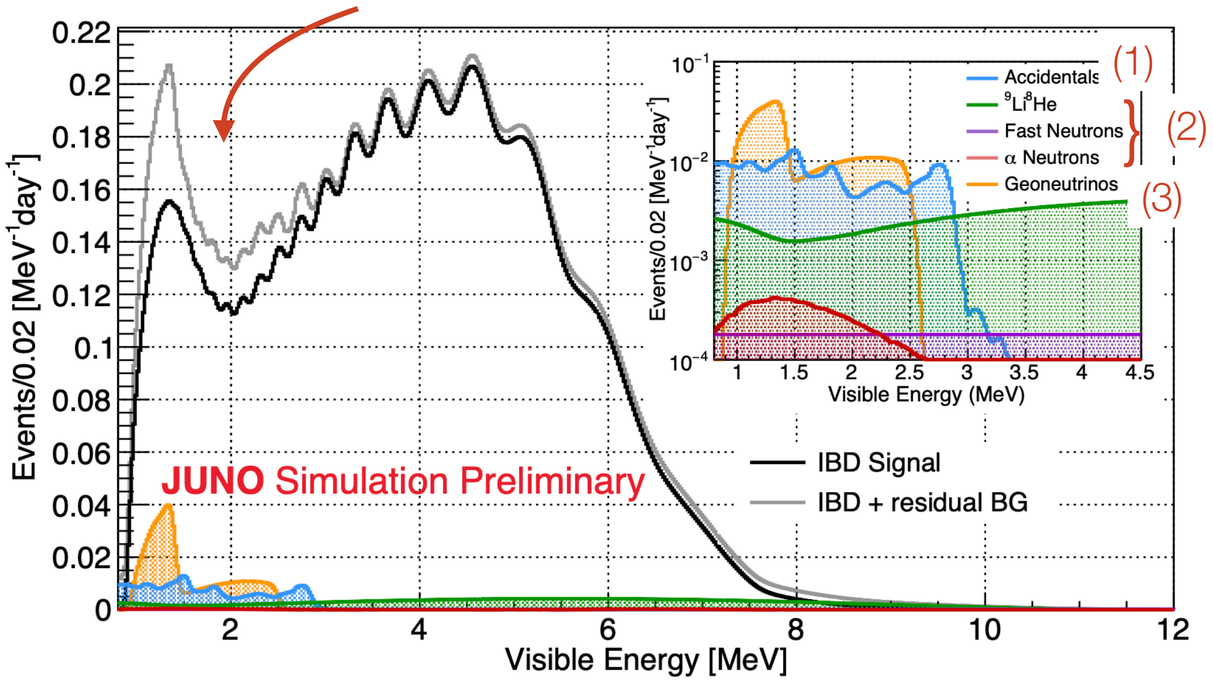
Draft for Collaboration publication (Participation to the Edition)



- **SPMT independent analysis (event correlated with LPMT)** for solar oscillation parameters (θ_{12}, Δm^2_{21})

Background control for $\bar{\nu}_e$ spectrum

Impact of residual background on the neutrino spectrum



Blue: IN2P3 contributions

(1) Accidentals (material radioactivity)

- **Radiopurity control**
- Fiducial volume cuts
- Time/space coincidence for prompt and delayed signals

(2) Cosmogenic (^{9}Li/^{8}He)

- **Muon reconstruction/veto (Top Tracker, Central detector,** Water Pool)

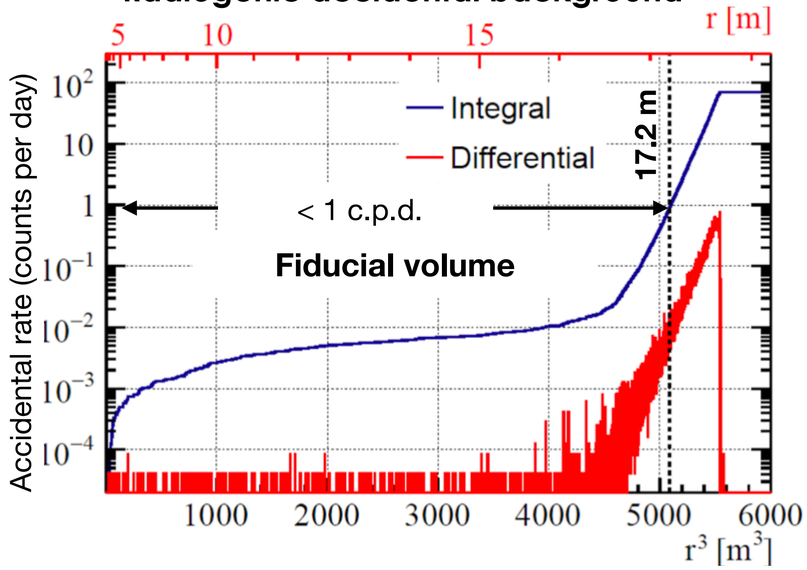
(3) Geo-neutrino

- U/Th decays in the Earth's mantle/crust

Event rate per day

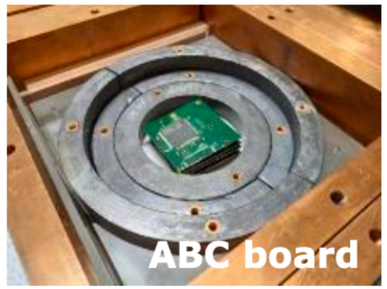
Selection	IBD efficiency	IBD (Signal)	Geo-νs (Background)	Accidental (Background)	^{9}Li/^{8}He (Background)	Fast n (Background)	(α, n) (Background)
-	-	83	1.5	-	84	-	-
Fiducial volume	91.8%	76	1.4	410	77	0.1	0.05
Energy cut	97.8%	73	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.75				

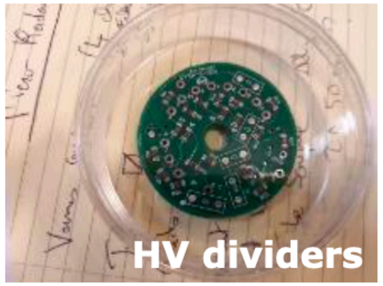
Radiogenic accidental background

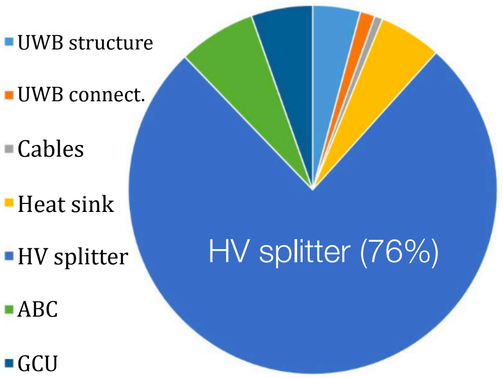


Radioactivity measurements

Measurements by gamma spectroscopy at PRISNA and LSM







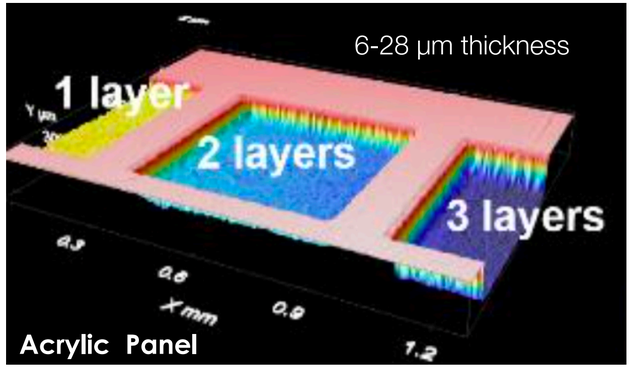
SPMT contributions: PMT+ HV divider: 66%, UWB: 21%, Potting: 13% (150 mHz in fiducial volume, <300 mHz requirement)

Total SPMT-UWB:
30 mHz in fiducial volume
Requirement 200 mHz achieved!

Acrylic sphere: K/U/Th <10^{-12} g/g requirement (256 panels, 580 tons)

3 complementary methods to select the acrylic panels:

- Neutron activation (Milano) → concentration K/U/Th in volume
- ICPMS (IHEP) → U/Th in volume
- **Laser Ablation-ICPMS (CENBG/IPREM)**: U/Th on surface



- **Radon requirement** in the Water Pool : **Activity < 10 mBq/m³**
- Radon measurements of critical materials in 2018-2021: PMTs, electronics, liner
- Validation of the liner and the critical materials by Radon diffusion and Radon emanation measurements


Prepared for submission to JHEP

Radioactivity control strategy for the JUNO detector

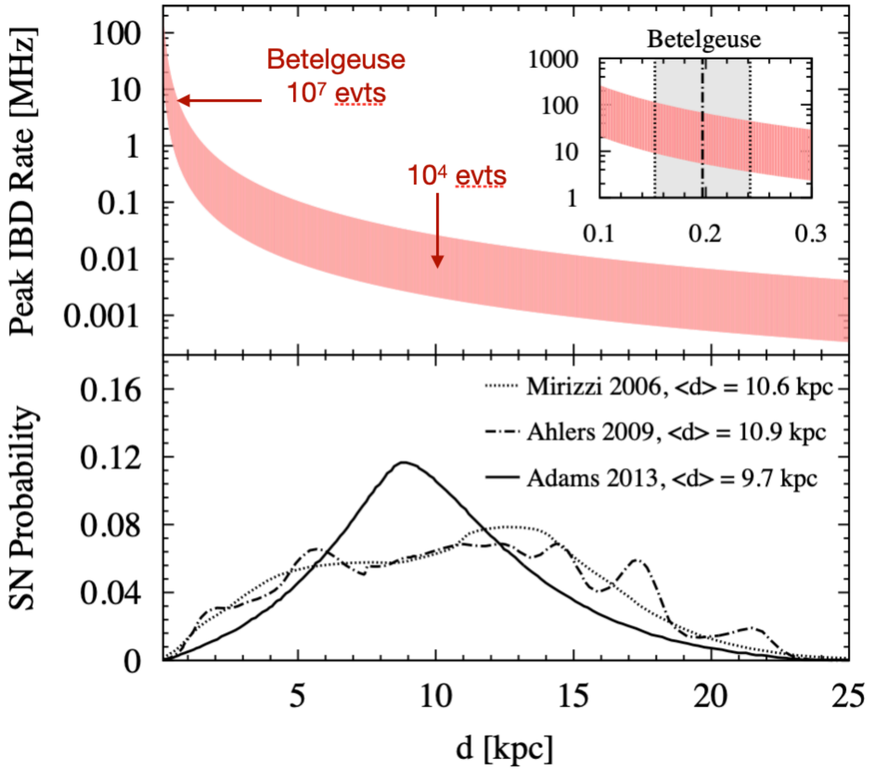
Angel Abusleme[5] Thomas Adam[45] Shakeel Ahmad[66] Rizwan Ahmed[66] Sebastiano

JHEP 111 0721 (2021)
(Co-editor of the paper)

Core Collapse Supernova Neutrinos (CCSN)

- **Galactic CCSN rate ~ 1-3 / century. One expected during JUNO operation**
- **Energy spectrum** and **Real time evolution** of the neutrino signals
  - Constrains CCSN **models and progenitor masses;** Hints on ν properties
- Multiple detection channels, dominated by IBD and pES (~ 7000 events at 10 kpc)

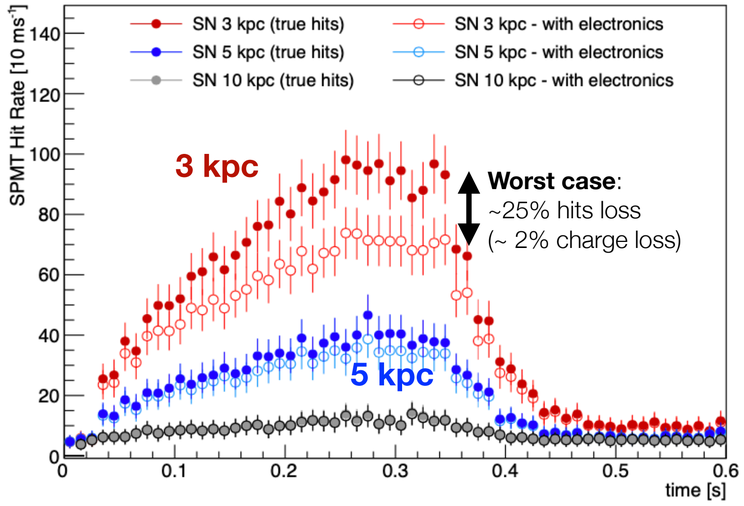
Channel	Type	Num. event expected (SN@10kpc)
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	$\simeq 5000$
$\nu + p \rightarrow \nu + p$	NC	$\simeq 2000$
$\nu + e^- \rightarrow \nu + e^-$	NC	$\simeq 300$
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	$\simeq 300$
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	$\simeq 100$
$\overline{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	$\simeq 100$



Enormous explosion and rate of events : Major challenge for electronics and DAQ

- Impact of SPMT electronics on CCSN **detection and ensure** enough buffer on readout board
- <5% charge loss at the maximum peak rate for a SN at 3 kpc

Impact of SPMT electronics



Analysis in preparation:

- **Vertex/Energy** Reconstruction of CCSN events;
- Event selection for multiple detection channels and spectrum unfolding
  - Extension to **MM-trigger and transient sources**

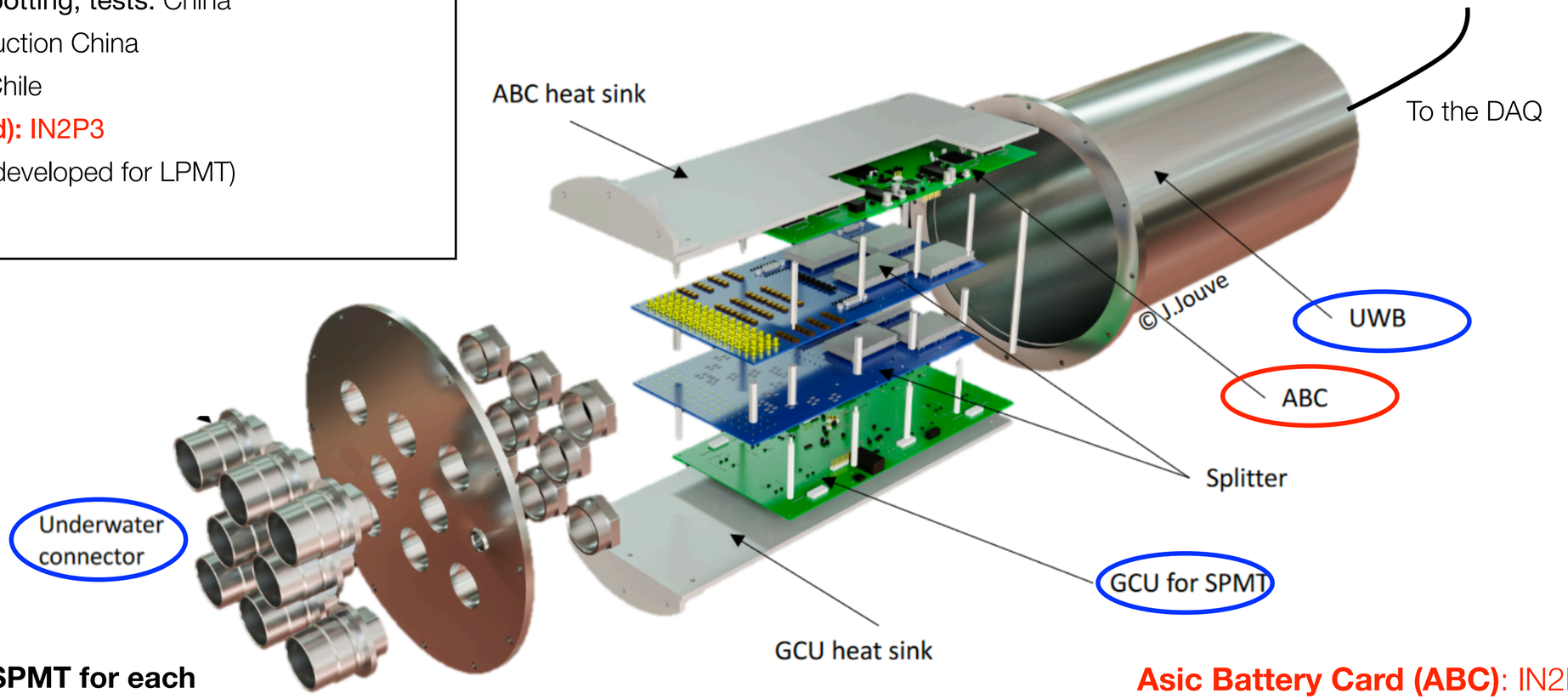
Technical contributions

Overview SPMT system

Main responsibilities

SPMT production, potting, tests: China
UWB: Chile → production China
HV splitter board: Chile
ABC (readout board): IN2P3
GCU: China + Italy (developed for LPMT)
DAQ: China

A total of 200 UWB for 25600 SPMTs



128 SPMT for each Under Water Box

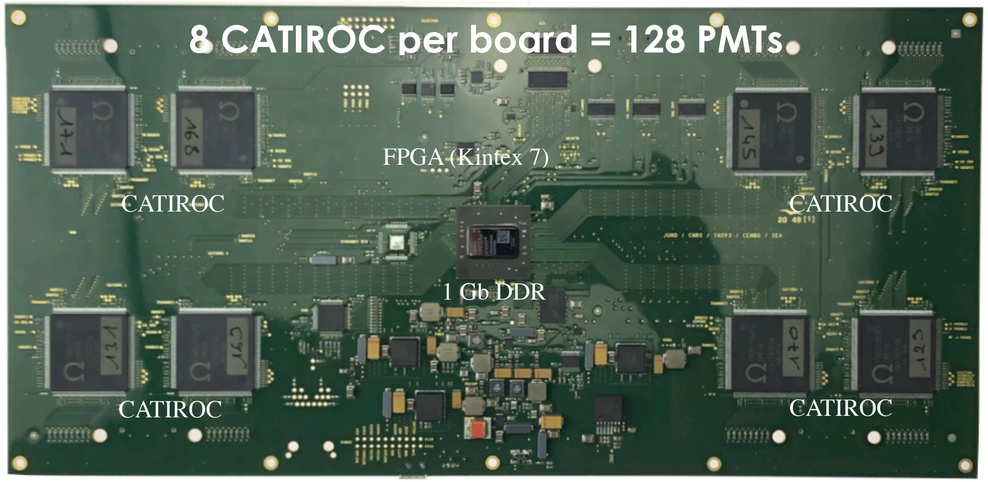
Asic Battery Card (ABC): IN2P3 responsibility

Participation to:

- SPMT specifications and company selection
- UWB conception and preliminary tests
- UW Connectors and cables (designed by AXON-France, produced by AXON-China)
- GCU board: participation to the interface firmware with ABC
- DAQ: collaboration with China

Readout board: ASIC Battery Card (ABC)

(Int. Responsibility)



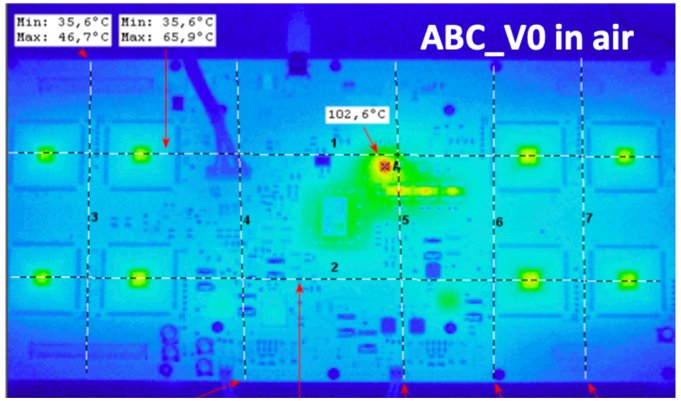
- Charge and time measurements
- Trigger-less operation mode
- Discriminator Signal digitized on FPGA to overcome CATIROC dead time

2000 CATIROC produced and tested in 2019

JINST 16 P05010 2021 (S.A.L., Main authors)

PUBLISHED FOR SISSA MEDIALAB
RECEIVED: December 2, 2020
REVISED: January 30, 2021
ACCEPTED: February 21, 2021
PUBLISHED: May 11, 2021

CATIROC: an integrated chip for neutrino experiments using photomultiplier tubes



Hardware

Designed in 2016 → 4 prototype versions produced

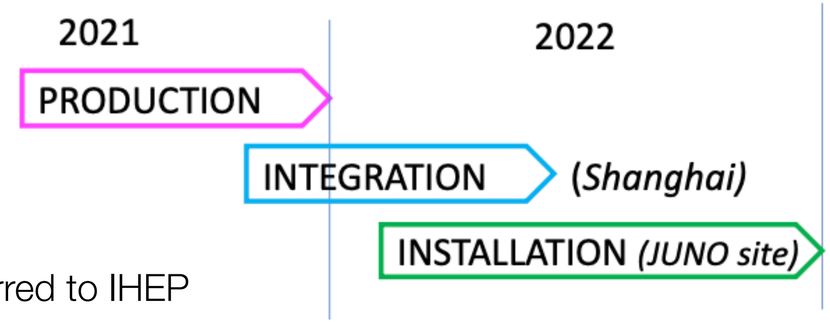
Performance tests and thermal studies → ABC_v0 for SPMTs acceptance tests in China

ABC_v1.2 mass production @ FEDD (June - Oct 2021): 220 boards

→ ABC acceptance tests and calibration

- **Deliver to China by December 2021**

Time schedule OK



Firmware and DAQ

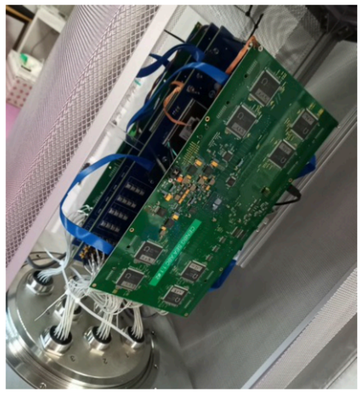
- ABC test firmware (successfully used for SPMT acceptance tests)
- ABC final (physics) firmware : *in progress*
- ABC+GCU firmware *in progress*

Remote integration/installation (2022)

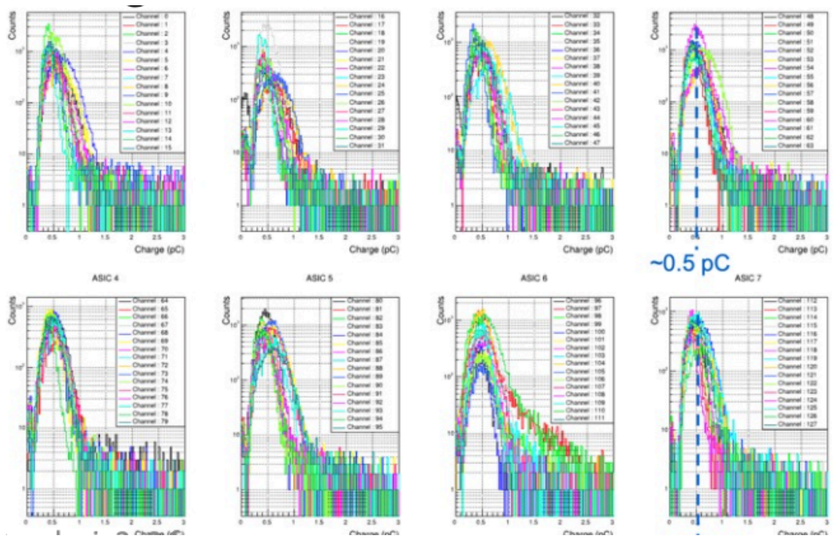
Integration/installation responsibility transferred to IHEP

ABC and SPMT acceptance tests

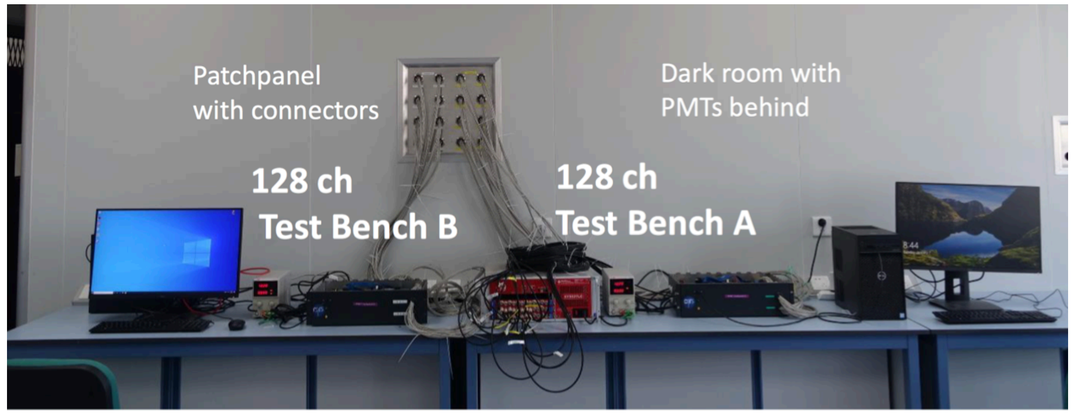
- **Acceptance and calibration of the 220 ABC**
- Final (physics) Firmware test on the complete SPMT electronics chain (ABC+GCU)



Example of measured SPE (128 SPMTs)

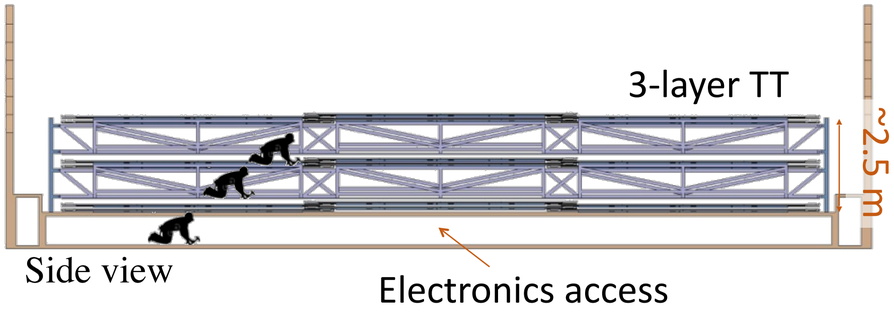


3 test-benches (HV splitter + ABC_v0 and software) delivered to China; commissioned Jan 2020

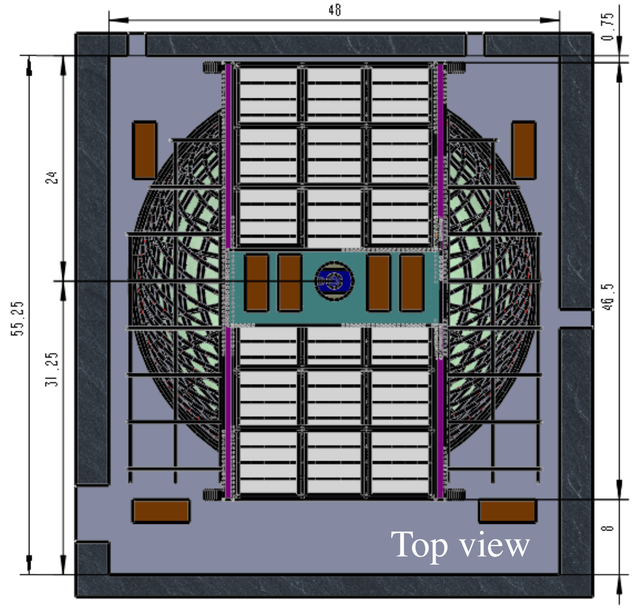


- **Acceptance Test of all the 26000 SPMTs** at Guangxi University
- **10000 SPMTs already tested,** 1% rejected or to be re-tested *(JUNO-SPMT publication)*

The Top Tracker system : overview

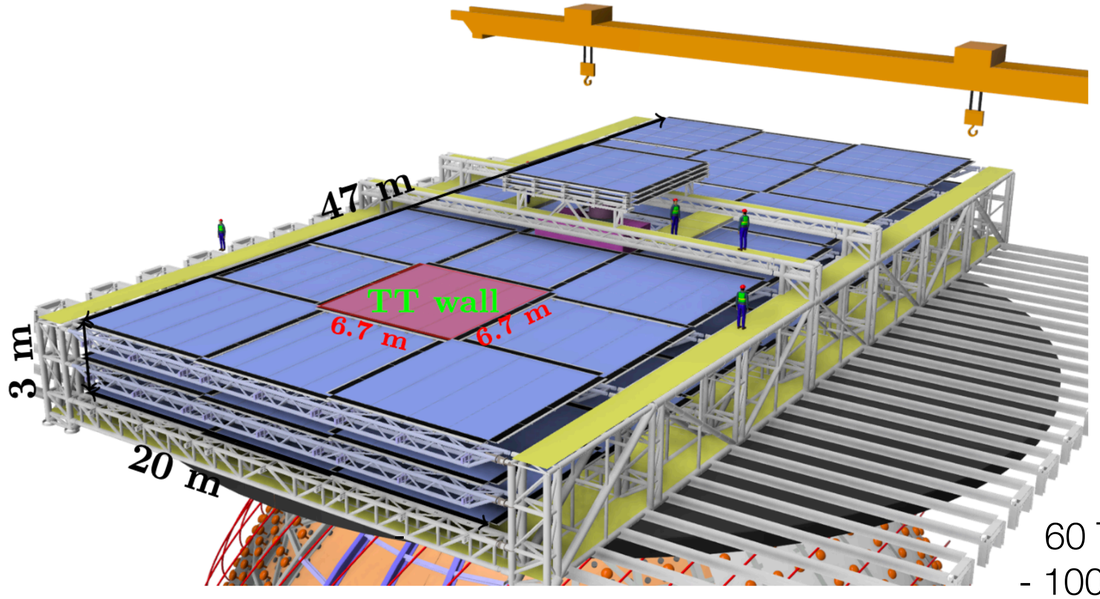


60% coverage of the JUNO projected surface



Use existing modules from OPERA's Target Tracker

New electronics chain and supporting structure



60 Tonnes
- 1000 PMT
- 64000 electronic channels
- Expected rate (radioactivity) 50 kHz/PMT
- Muon Track reconstruction: 0.2° precision

Main responsibilities

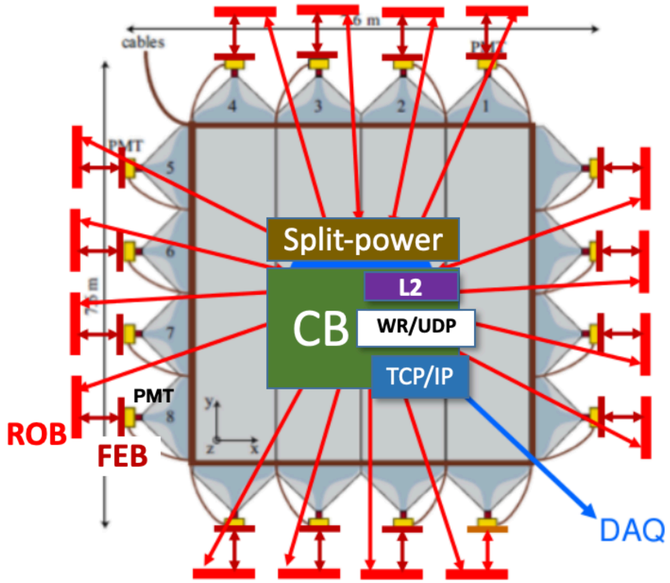
Modules (OPERA): IN2P3

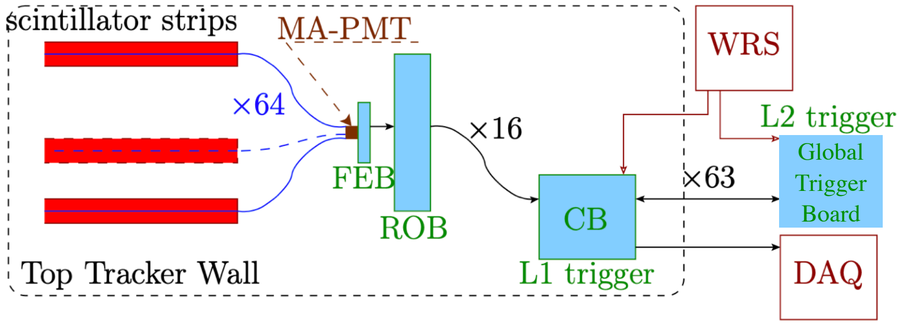
Mechanical Structure: JINR

Electronics: IN2P3 + INFN/CAEN (see next slide)

DAQ: JINR

Electronics developments for the TT



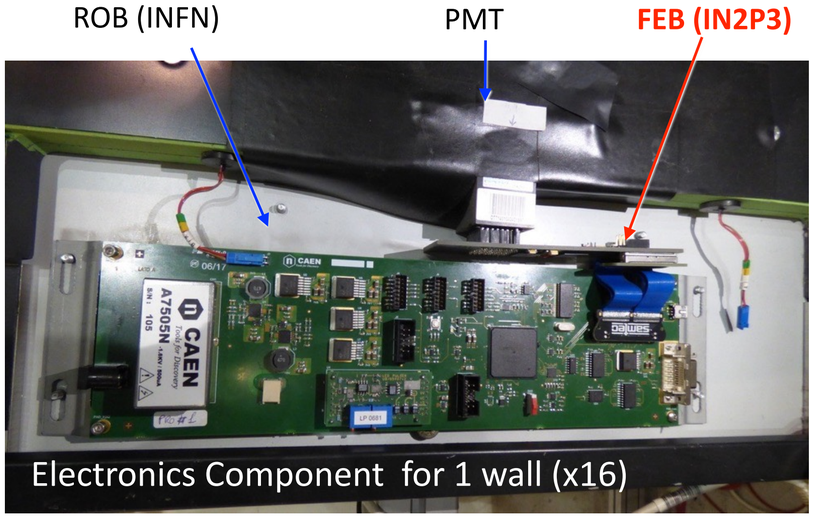


Components of a TT wall :

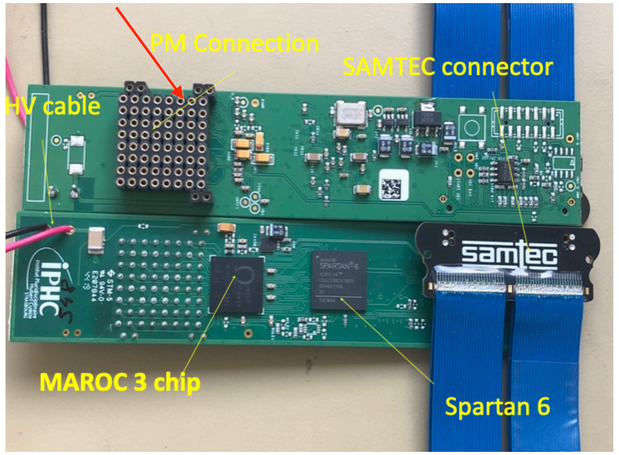
- 16 PMTs
- 16 Front End Board (with MAROC by OMEGA)
- 16 Read Out Board (ROB)
- 1 Concentrator Board (CB): responsible for the L1 trigger

Components Global system

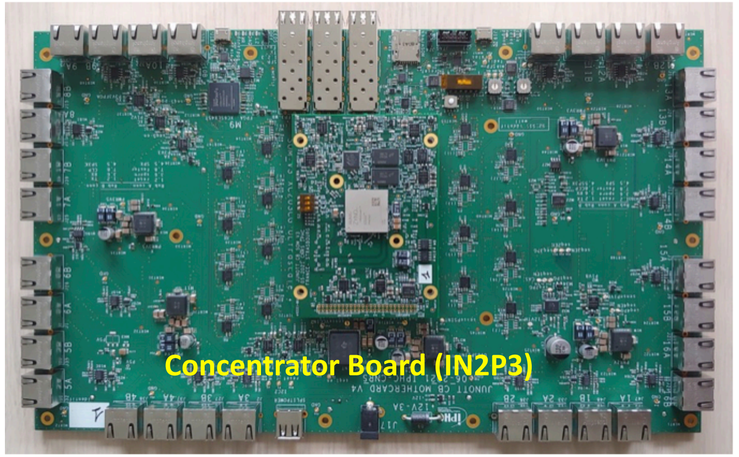
- Global Trigger Board (GTB): 2 kHz event rate



1200 FEB produced and tested



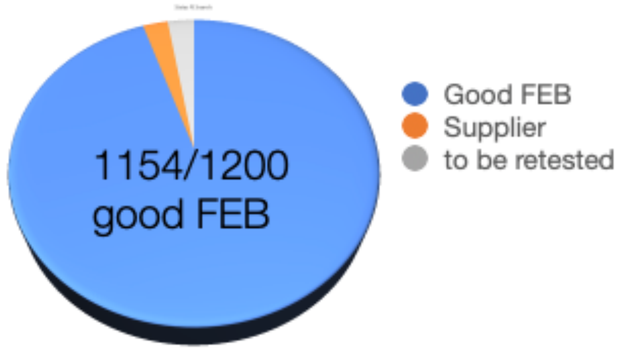
80 boards



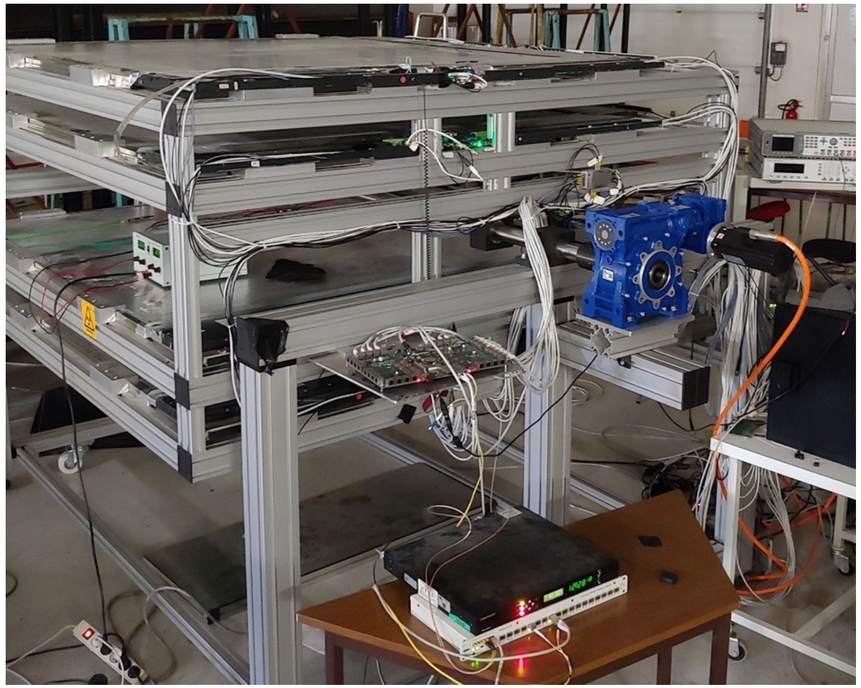
TT electronics tests and prototype

All FEB and connection cables delivered to China in August 2021

Concentrator Board start mass production by end of 2021



16 ROB arrived from INFN for CB+ROB tests



TT prototype @ IPHC

- 4 layers of scintillateur, 1/16 of a TT wall surface
- 2 FEB + ROBs per layers
- CB validation (HW/FW)
- Also used for μ flux measurement and simulation/reconstruction validation

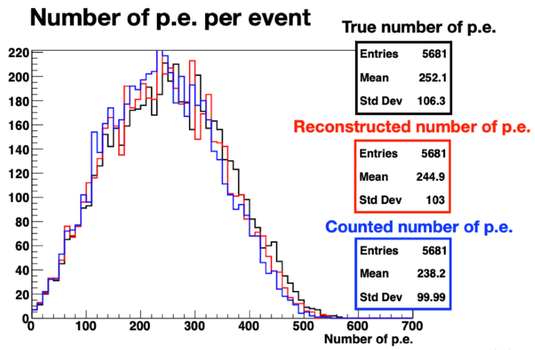
Software contributions

General / Geant4

- Orto-positronium generator and ^{8}He/^{9}Li correct decay

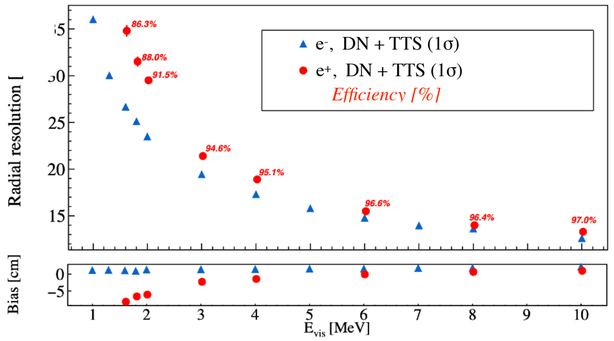
SPMT simulations and reconstruction

- Implementation of the **electronics simulations in the official JUNO software**
- Vertex and energy reconstruction
- ML studies (just started) for event reconstruction and selection



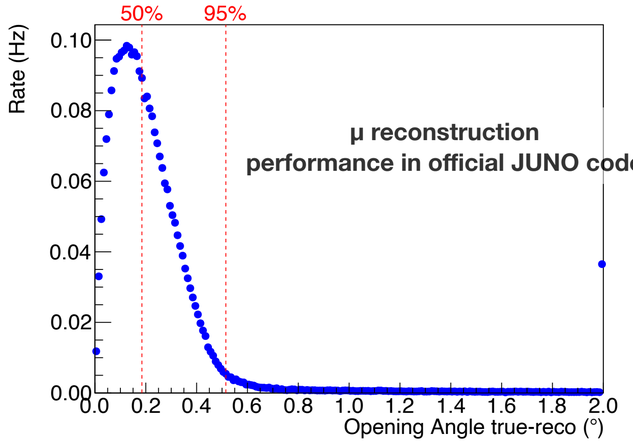
Vertex reconstruction

Example of charge reconstruction

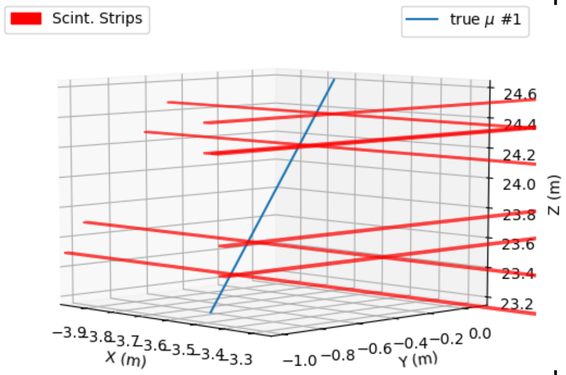


Muon simulations and reconstruction with the Top Tracker

- **Standard approach** (released in JUNO software):
  - 3D points defined from x-y strips coincidences;
  - fit all combinations in different TT layers
  - 0.2° median resolution
- **Hough method** under development to improve performances

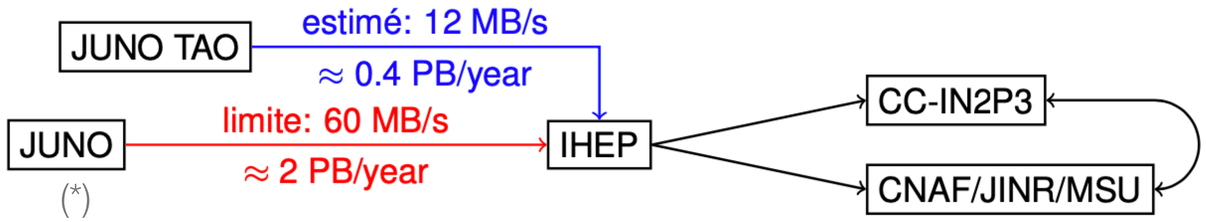


Event display of the TT prototype



Synergies with SPMT analyses and cosmogenic background studies

Computing resources



(*) 40 GB/s produced at DAQ level, event selection on the local farm to reduce data to 60-70 MB/s before transfer to IHEP

Disk requirement: ~ 3PB/year

- Raw data : 2.4 PB/year
- Calibration: 36 TB/year
- Reconstructed : 600 TB/year

Computing resources: ~ 12k CPU cores

- Data quality: 1000 cores
- Reconstruction: 6000 cores
- Simulation: 3000 cores
- TAO: 2000 cores

Data Backup in the European Computing Center:

- Shared resources between Italy (CNAF), France (CCIN2P3) and Russia (JINR and MSU)
- MoU under definition
- **in-kind participation** to running costs (under evaluation)

Estimated CC-IN2P3 contribution:

2000 cores	200 TB (disk)	1PB/yr (tape)

Financial resources

Top Tracker (in-kind contribution) : ~3.2 M€

Hardware contributions:
SPMT: ~600 k€
TT: ~700 k€

Yearly contributions:
Functioning costs: ~200 k€
Running costs: ~100k€

Computing costs (in-kind contribution): under evaluation

Conclusions

JUNO **on the forefront in neutrinos physics** in the next decade

JUNO detector installation in 2022

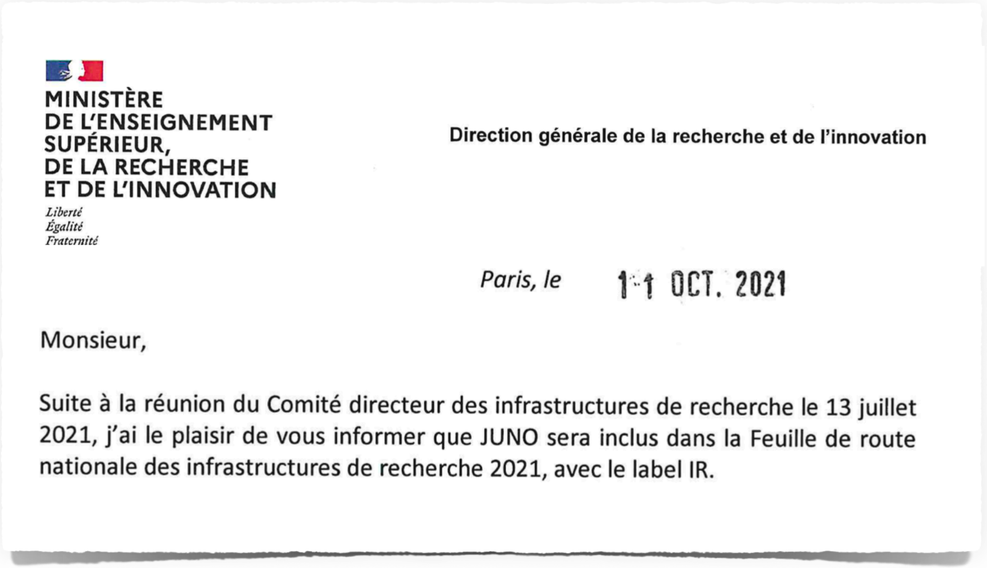
- IN2P3 participation to the installation reduced by covid pandemic (remote installation strategies or limited on-site participation under evaluation)

Data taking expected soon

IN2P3 leading role in SPMT and TT systems

- French expertises recognized and demanded.
- Further technical participation to TAO (limited to supply 4 ABC).
- Solid and coherent participation to the physics program

JUNO included in the national roadmap of the research infrastructure 2021



MINISTÈRE
DE L'ENSEIGNEMENT
SUPÉRIEUR,
DE LA RECHERCHE
ET DE L'INNOVATION
Liberté
Égalité
Fraternité

Direction générale de la recherche et de l'innovation

Paris, le 11 OCT. 2021

Monsieur,

Suite à la réunion du Comité directeur des infrastructures de recherche le 13 juillet 2021, j'ai le plaisir de vous informer que JUNO sera inclus dans la Feuille de route nationale des infrastructures de recherche 2021, avec le label IR.