JUNO Experiment @ CNRS-IN2P3

JUNO CNRS-IN2P3 Collaboration

June 13, 2018

Abstract

This document summaries the JUNO CNRS/IN2P3 scientific activities for the dedicated Scientific Council (CSI) in June 2018. In addition to JUNO activities, the CSI has exceptionally requested an additional description of the legacy contributions from Double Chooz to the JUNO programme. This document starts from the overall international JUNO experiment physics programme and organisation, subsequently focusing down into the specific national CNRS/IN2P3 activities and their scientific impact. A summary of the CNRS/IN2P3 groups is provided in the end. The JUNO CNRS/IN2P3 consortium consists of 5 laboratories APC (Paris), CENBG (Bordeaux), CPPM (Marseille), IPHC (Strasbourg) and SUBATECH (Nantes) commonly supported by the micro-electronics laboratory OMEGA (Paris). The JUNO CNRS/IN2P3 consortium will be referred generally as the "CNRS", unless otherwise specified.

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Acronyms & Terminology

The main acronyms used in the text are defined in Table 1 for easy reference. The Mass Hierarchy is taken as a synonym for Mass Ordering[1].

[1]Some phenomenologists prefer the term Mass Ordering instead.

Term	Definition
δm^2	Δm^2_{12} or Δm^2_{solar}
Δm^2	Δm^2_{ee}: projection of Δm^2_{23} or $\Delta m^2_{atmospheric}$
BG	Background, abbreviation
CD	Central Detector or Neutrino Detector
CC	Charge Current Interaction
CCS	Core Collapse Supernova
DC	Double Chooz experiment
DSNB	Diffuse Supernova Background
DYB	Daya Bay experiment
IBD	Inverse Beta Decay
IBD event	$\bar{\nu}_e$ candidate (typically no BG subtraction)
LPMT	Large PMT JUNO system (20" PMTs)
MC	Monte Carlo based simulation
MH	Mass Hierarchy (or sign of Δm^2)
NC	Neutral Current Interaction
NSI	Non-Standard Interactions
SC	Stereo Calorimetry
SPMT	Stereo-Calorimetric System (or Small 3" PMT)
TT	Top Tracker (inherited from OPERA)

Table 1: **Table with Acronyms used**.

1 The JUNO Experiment

In the last half a century, about every decade there have been reactor neutrino experimental effort providing breakthrough results. The CHOOZ experiment results shaped much of the 90's, KamLAND did similar in the decade of 2000 while reactor-θ_{13} experiments, Double Chooz, Daya Bay and RENO have dominated since around 2010 till now. JUNO is expected to shape much of the neutrino oscillation physics in the 2020 decade, starting data taking around 2021[2].

The JUNO experiment can be considered as the ultimate reactor experiment benefiting for many decades of reactor

[2]Today's official expected start for data taking.

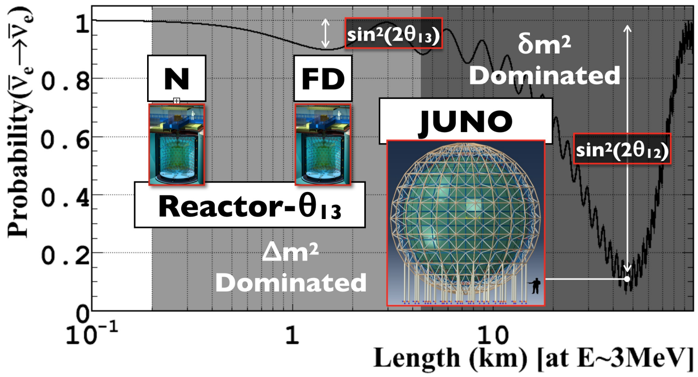


Figure 1: **The $\bar{\nu}_e$ Disappearance Probability.** JUNO detector has been located at first minimal (∼53km baseline) of the disappearance probability to maximise sensitivity to the dominant θ_{12} and the subdominant θ_{13} paced respectively by δm^2 and Δm^2.

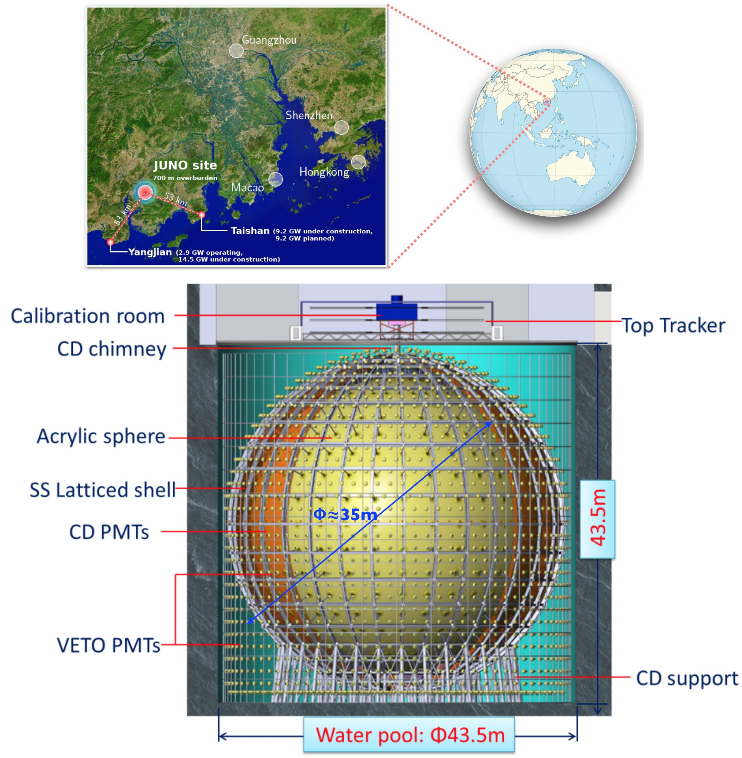


Figure 2: **The JUNO Site & Detector.** The JUNO underground laboratory (700m overburden in construction) is located in the South of China at about 53km baseline from the reactor sites of Taishan and Yangjian. Some reactors are under construction still. The detector is subdivided into two main pieces: the 20 kton central detector (CD), and external vetoes. Neutrino interact in the spherical CD, an acrylic structure supported by a stainless steel structure (SS) containing the liquid scintillator. Calibration sources can be deployed via the CD chimney at the detector top. The vetoes are used to tag cosmogenic backgrounds mainly. The main ≥2m thick water-Cherenkov veto provides 4π μ-tracking coverage while the top-tracker (TT) provides higher precision tracking in a sub-sample. CNRS instrumentation contributions are within both CD and TT sub-systems.

neutrino detection expertise. However, the JUNO detector requirements go well beyond the usual reactor neutrino physics. So, other neutrino detection expertise such as atmospheric (>100 MeV) and solar (< 5MeV) neutrinos as well as low radio-activity background is highly welcome and needed. This is because the JUNO detector is expected to be one of the world largest; i.e. 20 kton fiducial volume of liquid scintillator. Beyond neutrino telescopes, JUNO is comparable to the SK (SuperKamiokaNDE) detector of about 50 kton of water, but typically fiducialised to half (25 kton) the volume for physics. Since most MeV neutrino interactions are on free-protons (i.e. H atoms), the up to 50% larger fraction of proton per unit of mass of liquid scintillator compared to water boosts JUNO as effectively largest neutrino interaction fiducial volume detector in the MeV regime. Likewise, JUNO is expected to be one of the largest proton-decay targets ever built allowing for channels not reachable to SK.

Unlike SK, JUNO targets the low MeV energy range, where the scintillation high light yield is expected to provide a unprecedented exploring window – including maybe discoveries. Indeed, thanks to the large interaction volume the detector is capable to address physics beyond man-made reactor neutrino sources, thus being sensitive to solar, atmospheric, supernova (collapse and remnant) and geo-neutrinos. Still, the highest precision neutrino oscillation research programme is optimised to the detection of reactor neutrinos with an overall baseline of ∼53 km, as shown in Fig. 1. JUNO vast range of neutrinos physics implies the need for a resourceful collaboration with major and vast physics background as well as astrophysics and deep analysis expertise to squeeze the most physics out of the detector. The CNRS team is representative of this requirement, thus spanning from high precision reactor neutrino, neutrino telescope (muon tracking and atmospheric neutrino detection), low radio-purity background techniques (from double-beta background techniques) to astrophysics. The CNRS team count with physics leaders in Double Chooz, NEMO/SuperNEMO and OPERA experiments. Further details on composition are in Section 4.2.

The JUNO detector, described in Fig. 2, provides the necessary size to address simultaneously several important physics challenges. A non-negligible challenge lays inside the central detector (CD), where neutrinos detection takes place for physics. The largest photocathode density (∼77% coverage) is materialised using 18,000 20" (labelled LPMT system) and 25,000 3" (labelled SPMT system) PMTs. PMTs, including implosion system, are a few mm apart; a major engineering challenge involving specialised industry for construction and installation. The LPMT and SPMT systems mean that JUNO has effectively 2 independent readouts; i.e. it is like having two detectors looking at the same physical volume allowing one same event to be characterised by two independent systems with their respective responses features. This concept is called Stereo Calorimetry (SC) and was pioneered and proposed (2015) by the CNRS team, hence the key SPMT system responsibility is driven largely by 80% of the CNRS institutions. JUNO is the first stereo-calorimetric neutrino designed detector due to its extreme calorimetry control requirements. One of the most stringent detector specification is to yield a ≤3% total energy resolution at 1 MeV. Details on the implementation of the novel SC concept will be further described later on. The readout electronics of the LPMT

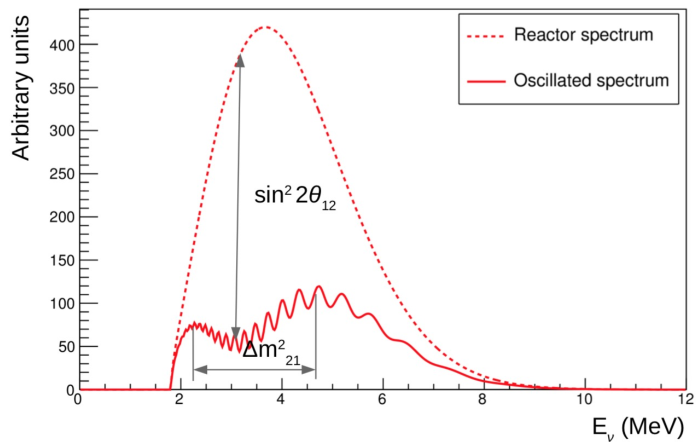


Figure 3: **JUNO Reactor Spectral Distorsions.** The basic logic of JUNO neutrino oscillation observables is here illustrated. Most (∼60%) of the reactor neutrino spectrum disappears due to the (θ_{12},δm^2) oscillations. The rate+shape spectral distorsion allows their measurement. The θ_{13} modulated sub-dominant oscillations is also observable. The fast frequency is due to Δm^2. JUNO unique ability to discern this sub-dominant oscillations, thanks to its excellent energy resolution, allows the combined measurement of θ_{13} and Δm^2exploiting the shape-only constraints. The MH manifests as a small phase difference in the θ_{13} (not shown). This is the most challenging observation. This way, JUNO is expected to show for the first time the 2 dominant neutrino oscillations modes simultaneously distorting the reactor spectrum.

is FADC based. This was also a former responsibility (during conception 2013-2015) entrusted to the CNRS team due to the FADC expertise gathered and demonstrated in the DC experiment. The readout electronics of the SPMT is a custom made designed and made by the CNRS team using ASIC chip technology from the OMEGA laboratory. The readout systems of both LPMT and SPMT electronics are underwater. The SPMT underwater technology and solutions R&D has been led by CNRS team, benefiting from the ANTARES underwater expertise available and French industry. Currently the LPMT system has been re-designed for simplification following some of the solutions originally adopted in the SPMT design. The DAQ system for both SPMT and LPMT merges data as collected onto surface at the network level prior to a computer farm for event building. Hence, the CNRS team is directly involved in the online data handling and the neutrino detector commissioning via the SPMT system. The other important piece of detector provided by the CNRS team is the Top Tracker (TT) system; i.e the tracker inherited from the OPERA experiment. This is a large detector allowing for high precision μ tagging and tracking expected to provide key information about the dominant cosmogenic backgrounds. The role and benefit of the TT in JUNO has been effectively prototyped in DC, where a similar system has been used for years. Further details on the systems led by the CNRS team are elaborated in Section 3.1.

The JUNO physics programme is particularly vast as it is expected to provide among the world most precise measurements in the "solar sector" (δm^2, θ_{12}) and the "atmospheric sector" (Δm^2), as historically named. This is illustrated in Fig. 3. JUNO is also expected to provide one of the most competitive independent measurements[3] of θ_{13} comparable to the current reactor-θ_{13} experiments using a different technique (shape-only) thus possible with a single detector This measurement is expected to be free from today's rate-only dominant systematics and constraints, thus providing a unique accuracy cross-check. JUNO's precision is expected similar to that of DC today, hence the overall precision is not expected to improve much. However, this possibility is particularly welcome in the light of the slight non-statistical difference reported today by DC and DYB. However, the main channel driving JUNO detector design constraints – virtually over-designing for most other physics – is the measurement of the atmospheric[4] Mass Hierarchy (MH); i.e. the sign of Δm^2. JUNO's MH measurement is uniquely performed using vacuum oscillations; i.e. without the influence of matter effects. Instead, most other experiments rely on those matter effects on Earth such as ORCA, PINGU and DUNE using, respectively, atmospheric and beam neutrinos. The JUNO measurement is not influenced or limited by the unknown CP-violation (CPV) or the infamous θ_{23}-octant degeneracy, unlike other experiments. Those observables are however relevant to long baseline neutrino beam searches for neutrino appearance, such as T2K and NOvA and, indeed, that is how CPV could be measured. Beyond neutrino oscillations, JUNO is expected to have key role on the following items: a) high statistics geo-neutrino sensitivity, b) one of the largest and most sensitivity volumes to supernova collapse and remnant neutrino detection and c) one of the largest volumes for proton decay searches articulating different channels as compared to water-Cherenkov detectors such as SK. Despite sensitivity, direct solar and atmospheric neutrino detection is not a priori optimal in JUNO, but dedicated analysis efforts are underway to maximise its physics extraction.

While likely the main goal in the 2020 decade is the measurement of CPV, JUNO unrivalled highest precision on most of the neutrino oscillation parameters is expected to grant indirect further insight to CPV experiments such as DUNE and HyperKamiokaNDE via the precise measurement of the Jarlskog invariant, which is proportional to the maximal amplitude of the sub-dominant neutrino beam appearance directly sensitive to CPV. In this way, JUNO is expected to play a similar role relative to DUNE and HK as today's role by reactor-θ_{13} to boost T2K and NOvA sensitivity to yield the first glimpses of CPV – currently disfavouring null-CPV at 2σ. In brief, JUNO has one of the vastest high precision neutrino oscillation physics program in the field. JUNO is expected to have world leading sensitivity in Δm^2, δm^2, θ_{12} and the MH, as well as interesting articulation on θ_{13} – to be further elaborated in the next section. This way, JUNO is expected to provide critical input aiding current and future experiments to measure neutrino CPV with the highest possible precision. Beyond oscillations, JUNO has the opportunity to explore a window of energy beyond man-made neutrino al-

[3] DUNE has recently claimed its ability yield sensitivity for a standalone θ_{13} measurement with similar precision, upon marginalisation, to that of today's reactor-θ_{13} experiments.

[4] The sign of δm^2 is known from solar neutrino going through resonant matter effects inside the Sun.

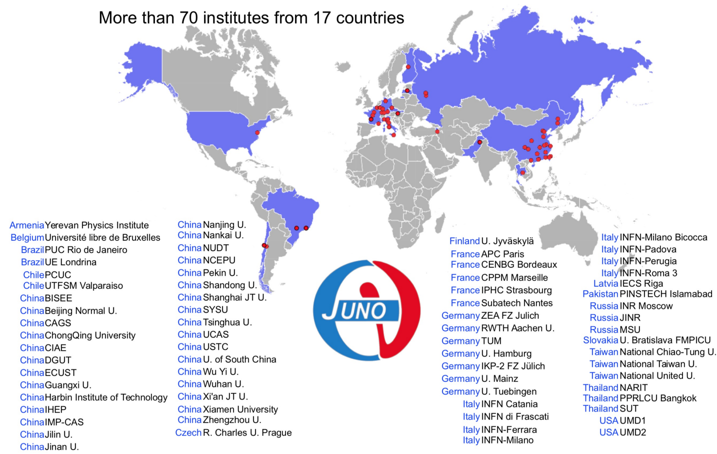


Figure 4: **The JUNO Collaboration Composition.**

lowing the detector to open its sensitivities to the physics from the skies, with the corresponding discovery potential.

1.1 The JUNO Collaboration

Behind the JUNO experiment, there is the JUNO international collaboration consisting of 72 institutions in 17 countries spread over the Americas, Asia and Europe including 591 scientists, as illustrated in Fig.4. The core of the collaboration is led by key members of the Daya Bay collaboration, whose headquarter is the IHEP laboratory (Beijing, China) with leading members from Borexino, Double Chooz, OPERA and other experiments. Together with Germany and Italy, the French (CNRS) team is one of the largest European national teams in JUNO. While not the largest, the CNRS has one of the largest collaboration visibility due to high level responsibilities, as detailed in Section 4.2, largely linked to key and specialised expertise provided into JUNO.

2 JUNO Main Physics

The physics JUNO programme was already briefly introduced in the previous experiment synopsis. Hence, we shall briefly highlight further the expected results in the context of today knowledge, emphasising the overall advance in knowledge expected from JUNO. The final results could be better since further knowledge by other experiments is progressing contemporarily and, as usual, during experiment running novel analyses techniques are found thus boosting the experiment performance as compared to design[5].

High Precision Neutrino Oscillations This program depends on the reactor anti-neutrino detection, as they interact via the Inverse Beta Decay (IBD) process, represented as $\bar{\nu}_e + p \rightarrow n + e^+$. This is the neutrino discovery interaction leading to coincidence prompt (e^+) and delay (n) energy depositions. Despite the large reduction provided by the coincidence, background (BG) is one of the most important topics for high efficiency detection and high precision. A more detailed BG discussion is differed

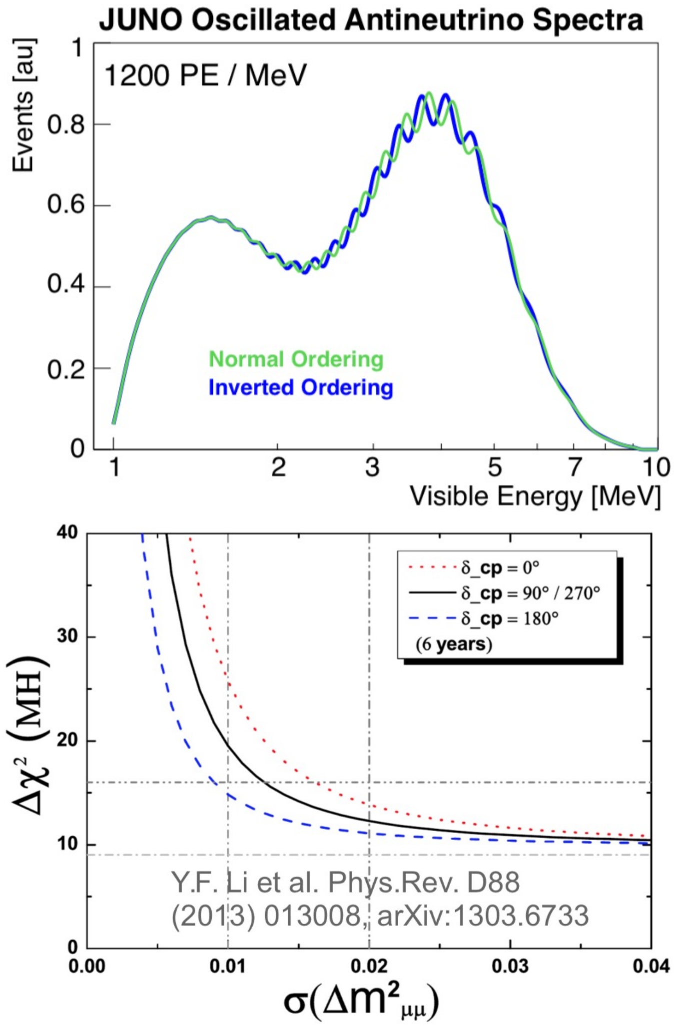


Figure 5: **JUNO Mass Hierarchy Manifestation.** The MH measurement (top) relies on the identification of the two possible patterns associated to the Normal (green) and the Inverted (blue) hierarchies, manifesting as a small (~3%) phase difference. This imposes stringent conditions to the energy resolution (folded) and calorimetry control. The sensitivity ($N\sigma = \sqrt{\Delta\chi^2}$) to MH (bottom) depends strongly on the fit external input uncertainty on Δm^2. Sub-percent precision is not impossible even upon the final results of today running beam and reactor experiments.

since this is a key contribution provided by the CNRS team. The next challenge is high precision calorimetry needed to reach the MH sensitivity. The rationale of the MH measurement is shown in Fig.5. Similarly, the calorimetry discussion will be differed as this is also a key contribution by the CNRS team. Detection systematics and selection are also key topic with much expertise on board due to the efforts on single-detector performed and described in DC (next section). Currently, the CNRS team is particularly focused on the high precision measurement framework for the δm^2-θ_{12} parameters, as part of the SPMT JUNO group. The SPMT system has the ability to realise a similar measurement comparable to that of the LPMT system, thus allowing a novel intra-detector redundancy to validate the high precision expected. This new concept and articulation have been

[5]As example, DC θ_{13} sensitivity is >6× better than designed.

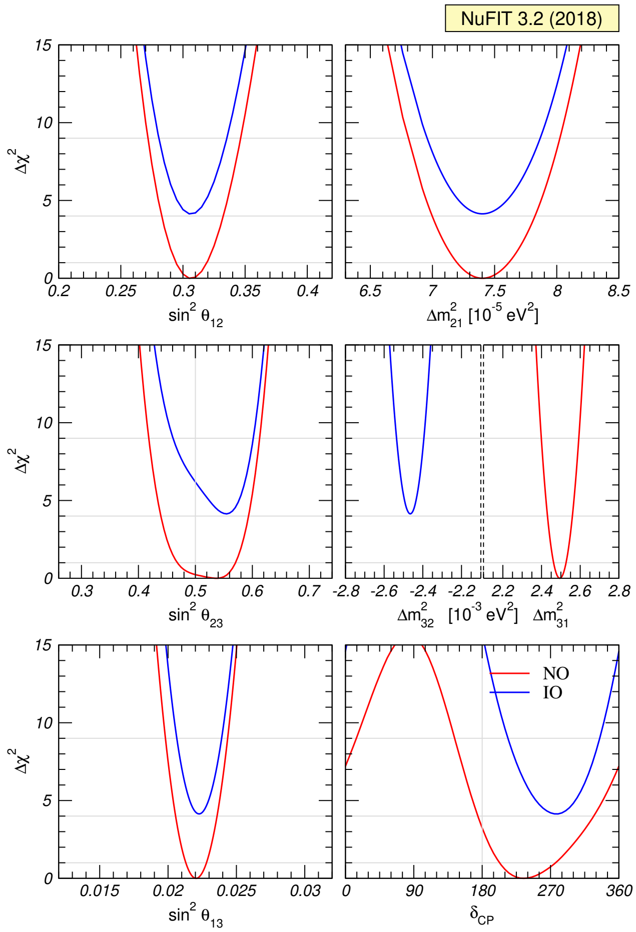


Figure 6: **Neutrino Oscillations Observables: Precision as of Early 2018.** The global precision (i.e. combination of all experiments so far) for the neutrino oscillation parameters (θ_{13}, θ_{12}, θ_{23}, δm^2, Δm^2, δ_{CP}) are shown [NuFit: www.nu-fit.org]. The unknown normal/inverted MH possible solutions are indicated in blue/red, respectively. The high precision yielded in most parameters is evidenced by the sharp gaussian χ^2 (where N$\sigma = \sqrt{\Delta\chi^2}$) distributions. Only in the case of θ_{23}, there is a degenerate solution. This is the famous θ_{23}-ambiguity. One can also see that there is slight preference for the normal MH, but this is considered today rather insignificant.

proposed by the CNRS team. Details will be differed to the corresponding section later on. Therefore, the CNRS team is in a leading position to contributions to δm^2-θ_{12} and the calorimetry articulation needed for the measurements of MH, which involved the measurements of Δm^2-θ_{13}, as byproduct. As described, the main channel of operations for the CNRS team towards neutrino detection and physics is the articulation via the SPMT system, intrinsically part of all neutrino detection and physics in JUNO.

All the neutrino oscillations parameters are to be measured and "plugged" into the Standard Model (SM) to characterise the neutrino mixing sector. The SM has no prediction ability for their flavour mixing sector; neither leptons and quarks. Today's state of the art knowledge on those parameters is illustrated in Fig. 6. JUNO's impact relative to today precision is summarised in Table. 2. JUNO is expected to have a leading role, including the ultimate precision, on about half of the neutrino oscillation parameters yielding sub-percent precision for the first time ever, such as the case of θ_{12}, δm^2 and Δm^2. With this stunning precision and together with the high precision of other experiments world-wide, the neutrino community might be able to address the unitarity of the neutrino mixing matrix. This is a critical topic as other neutrino (physics beyond the SM) might manifest via mixing despite their impossible direct detection. Such is the case of the so called "sterile" neutrinos. Thus, JUNO will provide also unique phase-space to test sub-dominant non-standard interactions (NSI); i.e. possible interactions leading to physics beyond standard neutrino oscillations in a generalised phenomenological framework. The CNRS team is already working with some phenomenologists such as Hiroshi Nunokawa (PUC University, Rio de Janeiro, Brazil) for preparation.

	Precision Now	**Precision JUNO**
θ_{13}	3.5% (reactor-θ_{13})	15% (cross-check)
θ_{12}	4.0% (Solar)	~0.7%
Δm^2	1.5% (several)	~0.5%
δm^2	2.2% (KamLAND)	~0.5%
MH	>80% Normal Hierarchy favoured	up to ~4σ (Δm^2dependence)

Table 2: **JUNO Neutrino Oscillation Parameters.** This table summarised the current precision versus the expected JUNO final precision for each single parameter: θ_{13} (precision dominated by DYB), θ_{12} (precision dominated by SNO), Δm^2 (similar precision obtained from MINOS, T2K, NOvA and DYB) and δm^2(precision dominated by KamLAND). JUNO precision on θ_{13} is comparable to DC today. Today's expected significance is ~4σ using vacuum oscillation due to the short baselines; i.e. negligible matter effects. The MH measurement benefits from further precision on external Δm^2information.

Geo-Neutrino Measurement This is critical topic of high interest to the geology community as neutrino can provide key information on the Earth heat balance from the U-Th decay chains. The IBD interaction threshold (1.8MeV in neutrino energy) does not allow the detection of the intriguing contribution of the ^{40}K geo-neutrinos, whose spectrum ends at 1.3 MeV. The CNRS team involved is not leader or even expert on this topic. However, as a byproduct of all the spectral fits needed for the neutrino oscillation extraction (above topic) knowledge about the integral spectral geo-neutrino contribution is necessary. Geo-neutrinos behave as an irreducible BG for reactor neutrinos. Evidently, reactor-off data would help this observation, however this is highly unexpected[6] in JUNO due to the large number of reactors involved. A dedicated collaboration has started between Ferrara University (Italy) – recognised experts – and the APC for the geo-neutrino physics within and beyond the JUNO collaboration to reduce this gap of knowledge. Further

[6] Reactor-off was even less expected in KamLAND, but it happed as consequence of the Fukushima crisis upon an earthquake.

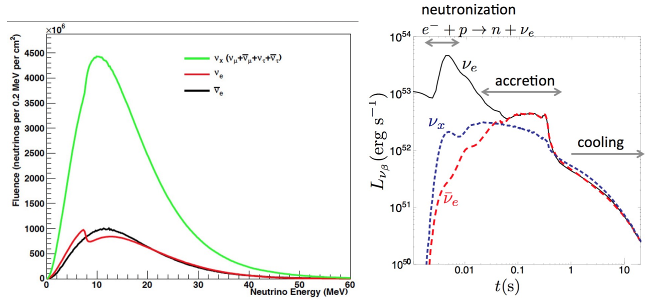


Figure 7: **Core Collapse Supernova Neutrino Spectra and Time Profile.** The spectra (left) of neutrino (higher energies up to 60 MeV) holds neutrino oscillation physics, if several interactions were detected. Different cross-sections exist on free-p (IBD), but also in C nuclei where both CC and NC interactions exist. The time profile (right) is expected to contain major astrophysical information about the supernova collapse physics.

effort might be envisaged in the future depending on interest and/or man-power.

Supernova Neutrino Measurement Supernovae are known to be critical for the production of heavier elements, further understanding of its fundamental physics is very valuable to astro-physics, nuclear physics and particle physics. Hence supernovae neutrinos are expected to be particularly precious source of information. There are two types of supernova neutrinos JUNO can be sensitive to: core collapse (CCS) and remnant supernovae. The latter is often called in the literature Diffuse Supernova Background (DSNB). CCS imply the direct neutrinos from a supernova explosion in the galaxy. These neutrinos manifest as a short blast (a few seconds long) of neutrinos. The event rate depends highly on the location and detector size – JUNO being of the largest available, as highlighted before. The event rate could therefore amount up to a few tens of million IBDs in the case of the closest CCS. Detailed event rate discussion is addressed later on in the context of detector design. The CCS main observables are illustrated in Fig. 7 such as the time profile and the neutrino energy spectrum holding, respectively, astrophysical and particle physics infirmation. The average CCS rate is 3 per century, the last being in 1987 and whose neutrino detection led to a Nobel prize. Hence, a critical element for successful detection is the detector readout which must be specifically designed and optimised to handle this enormous instantaneous rate without crashing, implying an optimal online buffering strategy. During JUNO lifetime (20 years), at best, one CCS is expected, thus the readout system cannot fail, adding further constraints to the readout specifications. The CNRS led SPMT readout and electronics has been specially adapted to this physics and will be detailed later on. So, the CNRS team is a priori in leading position for this physics, additionally benefiting from dedicated expertise on supernova theory/phenomenology available within the CNRS team. The definition of the main CCS readout system is under discussion for JUNO within June 2018. The CNRS team is in leading position to this discussion and definition.

While the rate of CCS is very low, the integral of all so far occurring provide a constant average contribution of supernova neutrino; i.e. the remnant supernovae most often called "diffused supernova background" (DSNB). The observation cannot rely on the time burst of neutrinos for triggering and/or event selection, largely simplifying the case of CCS. Instead, searches rely on specific energy window, typically [10,20]MeV where BG are not overwhelming. The dominant BGs in JUNO are expected to be reactor neutrinos and cosmogenic instable isotopes at low energies as well as atmospheric neutrinos and fast-neutrons, thus limiting the sensitive to DSNB at high energies, respectively. Therefore, impact on the DSNB neutrino sensitivity is also linked to cosmogenic BG knowledge and vetoing where the CNRS is expected to play a key role – to be described later on.

Proton Decay Searches Unlike free-neutrons, free-protons appear so far to be stable, therefore linked to the Universe stability. Many SM extension theories predict the instability of the proton. Hence, a positive observation will be the smoking-gun evidence of physics beyond SM, thus a major discovery. This channel is, therefore, critical and JUNO unique handle to tackle it beyond SK dominating limits so far. This channel is so important it led the construction of several experiments such as KamiokaNDE, IMB, etc. while they shaped much of atmospheric neutrino physics – the main BG to proton decay. Today, however, there is no dedicated CNRS team effort or expertise in this subject. This is nonetheless a very attractive channel where key handles might be available via the SPMT specially adapted to higher energy physics (several 100's of MeV), where the LPMT system is expected to be saturating responses. This channel remains as a possible future goal for the CNRS team, as other subjects settled and/or if man-power allowed.

Solar & Atmospheric Neutrino Detection While JUNO is indeed sensitive to both solar and atmospheric in virtue of its large volume (∼60× the size of Borexino), the detector ability to do leading physics in both fronts is currently expected to be limited as compared to better adapted existing experiments. In the case of the solar neutrinos, the limitation arises from large radiogenic and eventually also cosmogenic BGs. While in atmospheric neutrinos case, the main challenge is to infer all necessary information from reconstruction, where the scintillation light is not ideal for tracking and pointing, unlike Cherenkov light. However, a non-negligible effort exist within JUNO to push the limits of this two precious neutrino sources and their related physics. Currently, however, the CNRS team is not involved on neither fronts.

Further exhaustive description of the JUNO physics is fully published in [1]. Most of the contributions linked to the SPMT and the combination to the LPMT are missing though.

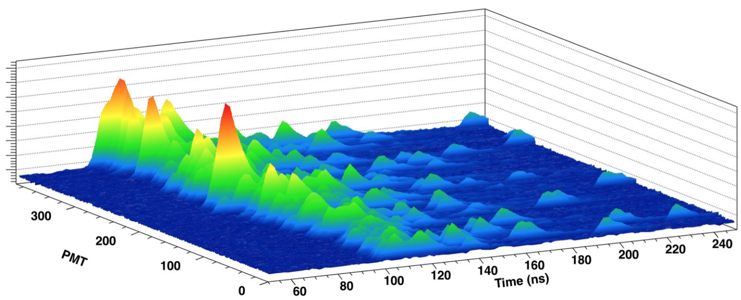


Figure 8: **DC FADC Event (Gd-n Capture).** DC is one of the neutrino detectors first experiment to rely solely on FADC technology – codeveloped between APC and CAEN company (Italy). A new dimension of information and excellent control of energy is possible with this technology.

This is because the SPMT was proposed and approved during the writeup of that document. So, the SPMT related physics description here provided is currently unpublished, although publication is envisaged soon.

2.1 The Double Chooz Legacy to JUNO

In this section, we shall briefly highlight the impact of DC experimental framework into that of JUNO. The conclusions here reported exclude the JUNO-IN2P3 members not within DC-IN2P3 group (APC, a fraction of CENBG and Subatech). Since this document is meant to focus on JUNO, this description will be kept to the minimum. The very latest results presented in the Neutrino 2018 conference (early June 2018) will be used. The DC impact to the CNRS groups affected the readiness to JUNO physics for mainly the APC, a fraction of the CENBG and a fraction of the Subatech groups. There is pertinent reactor neutrino expertise via SOLiD to the Subatech group. There are mainly four fronts benefiting from DC:

Reactor Neutrino Detection DC has excelled in reactor detection technology and instrumentation articulation. All the liquid scintillators are stable, as compared to DYB and RENO. DC FADC electronics is a reference, thus aiding the design goals for JUNO. In fact, one of the first contacts from JUNO to CNRS scientists via DC was to lead the FADC electronics readout, given the success of DC. The rich output information from the FADC, shown in Fig. 8, has translated into major active signal characterisation, allowing for both unprecedented active BG rejection and per mille calorimetry control. The BG will be highlighted next. Also, DC has been able to address the IBD e+ discrimination with some degree of success. While high efficiency e+ remains impractical for IBD-based experiments, such as DC and JUNO, DC has observed important sensitivity to e+ discrimination via ortho-positron formation and light front distorsion due to annihilation – the latter being the most challenging. Regardless, such achievements are currently inspiring some of the analysis exploration within JUNO and beyond.

Background Expertise The main success of DC in BG control is the implementation of the new technique of detection call "Total neutron Capture", by which IBD detection occurs on all possible capturing isotopes in the detector. The challenge is illustrated in Fig.9. Several orders of magnitude of BG rejection are needed while yielding a high efficiency (∼85%) with negligible selection distorsions, as shown. The techniques behind are most pertinent in JUNO, since the most IBD neutrons capture will take place in the H-n peak at 2.2 MeV, otherwise swamped with several orders of magnitude of radiogenic BG. An aggressive BG rejection is a complementary and necessary approach to the radio-purity control – both critical in JUNO. The role of cosmogenic BG rejection is very different from JUNO, however much has been learnt about muon-tracking and impact for BG tagging. All those techniques and expertise have immediate impact to JUNO and is aiding already the leading visibility of CNRS team in the physics analysis arena.

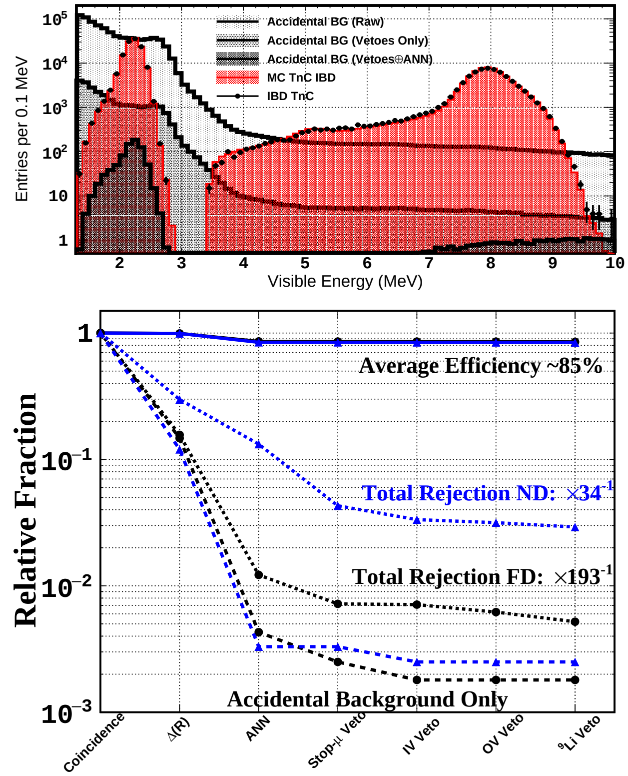
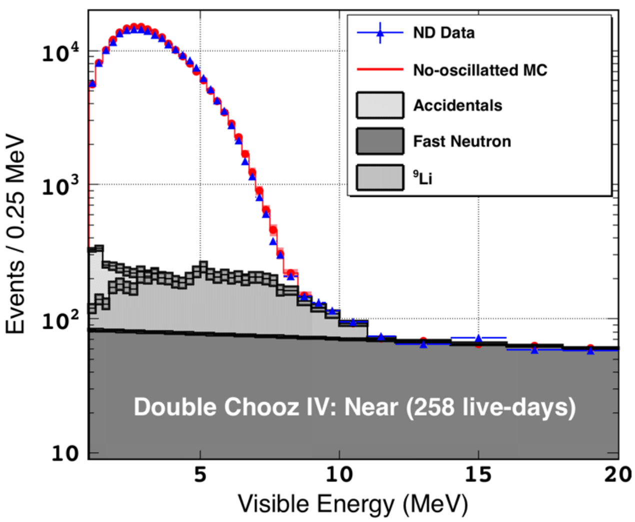


Figure 9: **DC BG Rejection Control Illustration.** Due to the low overburden, DC relies on an aggressive active BG rejection strategy. The top plots show the data (black points) to MC (red) distribution are compared and shown in excellent agreement after several orders of magnitude of BG has been rejected several techniques. The rejection and inefficiency per cut is illustrated in the plot below. The near detector (lower overburden) is more dominated by the irreducible cosmogenic BG, while both detectors are rather free of accidental BG – a minor contribution. This is excellent performance for monolithic reactor neutrino detector; i.e. with no segmentation.

Reactor Neutrino Oscillation Physics DC is a one of the reactor-θ_{13} experiments aiming to yield the most precise θ_{13} measurement to be used by other experiments for CP-Violation searches and MH measurement,



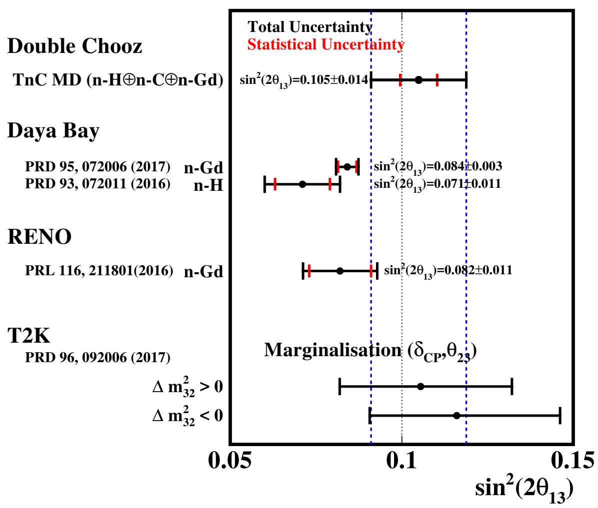


Figure 10: **Measured Reactor Neutrino Spectrum.** DC uses the comparison of the near and far detectors to extract the measurement of θ_{13}. DC latest value exhibits a slight difference relative to the most precise DYB result. A statistical fluctuation alone is disfavoured. Systematics are expected to require revising to address this issue.

such as JUNO. The status of this measurement is shown and described in Fig. 10. DC has long demonstrated leading role in the analysis capability despite the handicap of missing the near detector. In fact, due to the missing ND limitation, DC has yielded the most precise single-detector measurement of θ_{13} to date. This implies mastering simulation accuracy and the control of single detector detection systematics to unprecedented levels. These achievements – and all associated knowledge and techniques – is the most relevant for JUNO whose neutrino oscillation program relies on single detector physics. So, much of this expertise is to be propagated from DC directly into the analysis strategy of JUNO. The CNRS teams are in good position to do this since they have been leading much of the DC analysis for long.

Reactor Neutrino Specific Physics While much of the

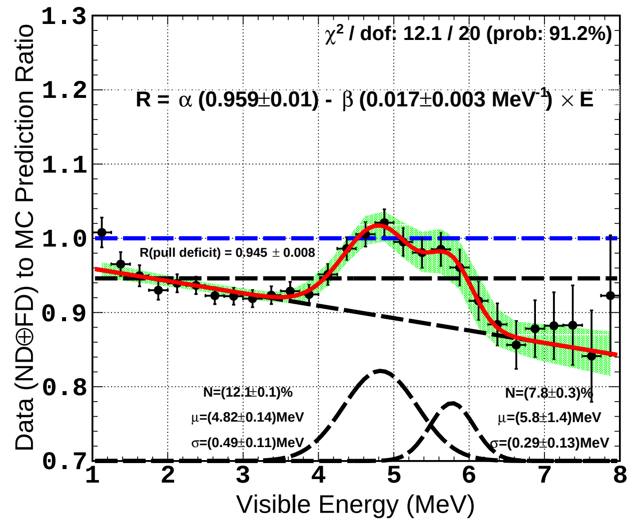


Figure 11: **Reactor Spectrum Rate and Shape Bias.** Reactor prediction exhibit a significant rate deficit (up to ∼6%) and spectral distorsion. For long, the distorsion has been referred as the "5 MeV bump", however, it can be noticed that the 5MeV region is in actual agreement with the prediction (R→1). An empirical two gaussian and slope distorsion is first reported by DC. The gaussians are largely inconsistent with the energy resolution and the slope is not consistent with the measured non-linearities in shape and magnitude.

detection techniques and neutrino oscillation physics is common elsewhere, working with reactors neutrino implies, unavoidably, the understanding of reactor physics and other specific features such as those today existing in the neutrino spectra, first reported by DC in 2014. Actually, the above is true even in the multi-detector scenario for the θ_{13} measurement – at some point of precision one must enter into the details reactor neutrino physics. Fig. 11 illustrates the DC knowledge in both rate and shape for reactor neutrinos, which heavily exploits the single detector articulation. DC provides now the most precise reactor flux normalisation information in the world after superseding Bugey4 experiment results precision (∼1.4%). Future improvements expect the first sub-percent precision. DYB precision is at ∼1.5%, as of Neutrino-2018 conference. DC also reports a updated more precise empirical signature in the measured spectral distorsion in the Neutrino-2018 conference.

JUNO is even more sensitive to reactor neutrino features, again since there is no multi-detector approach to yield cancellation of nuisance correlated effects. In JUNO, the main challenge is the control of the reactor neutrino spectrum, which thanks to its unprecedented resolution it will explore another dimension of precision. Today, it is not evident what is to be found, since all measurements today wash much of the information via limited energy resolution. The existence of "fine structure" is somewhat expected though due to discreet neutrino the reactor isotope end-point contributions. Preliminary studies suggest, some washout migth be expected. Since JUNO challenging measurement of MH relies on the control of such spectra, a critical effort has been launched within the collaboration towards a new small detector to be placed close to a reactor for the reactor reference spectrum measurement. Currently, several members of the CNRS team are experts in much of these subjects, however, the further interplay with reactor nuclear experimentalist and phenomenologist is expected to benefit the overall JUNO related operation. There are several reactor nuclear physicist experts, for example, in the Subatech laboratory but also elsewhere in CNRS. Articulating both the neutrino and reactor CNRS communities is expected to provide a leading CNRS position in this important topic.

Last and not least, the experience of leading DC has forged almost a generation of CNRS scientists in reactor neutrinos, as it had happened in the past via the CHOOZ and Bugey saga experiments. This expertise exists and is well recognised by the international community. Much of this expertise is or has already shaped some of JUNO, reinforcing the JUNO CNRS team into a leading position from the start.

2.2 JUNO within Global Panorama

As highlighted in the introduction, JUNO is expected to have a critical role in the 2020 decade where the discovery and high precision characterisation of CPV is possibly the highest priority for the community. JUNO roles is indeed unique. There is no other experiment (so far planned) able to deliver the precision reachable on some key neutrino oscillation parameters. So, there is a world-wide de facto coherent neutrino oscillation program towards CPV, where DUNE and HK are expected to provide the next CPV generation sensitivity beyond currently T2K and NOvA experiments, while JUNO is to provide high precision virtually elsewhere in the field with the exception of θ_{23} related physics – still challenging due to the aforementioned octant ambiguity.

The knowledge of MH is particularly important in this CPV search scenario, where faked CPV effects are mimicked via the aforementioned matter effects as neutrinos go through the Earth. This is due to the fact that the Earth is made of matter (as opposed to anti-matter) thus affecting the propagation potential for neutrinos but not for anti-neutrinos. This effect, if sizeable, must be accurately considered for long baseline experiments intending to measure CPV. Hence possible MH input from JUNO and/or ORCA/PINGU is welcome.

JUNO has also the unique – and elegant – ability to observe and characterise directly two simultaneous neutrino oscillation modes for the first time ever. While no surprises are expected, this is expected to provide one of the most powerful samples and most beautiful manifestations of neutrino oscillation disappearance so far seen.

In addition, JUNO, however, has the unique and leading opportunity in supernova and proton decay physics, where discoveries cannot be discarded. Beyond the expected, JUNO detector is sizeable enough to be able to address or find physics current beyond our expectations – not the first time. In fact, this is why, the SPMT system has been designed to be trigger-less – unlike the LPMT – so that we leave ample room for new physics manifestation beyond our expectations.

It is clear that JUNO is going to shape alone – but also together with other neutrino experiments – much of the neutrino physics frontier in the following decades, starting from early 2020. The CNRS team is in strategic position to exploit this physics.

3 The CNRS Contributions

At this early stage of the experiment (prior to the detector construction), the physics topics contributions of the CNRS teams are strongly related – even rather confined – to the detector hardware contributions. This is important to ensure the hardware contributions are optimally designed for maximal physics outcome as well as ensuring their delivery in time. This is particularly important for the elements within the neutrino detector undergoing the tightest schedule and co-coordination with all other elements. Hence, we shall here describe the main CNRS detector/instrumentation contributions first and, then, the physics topics related to. However, as time goes beyond the commissioning (around 2021), it is expected that the CNRS team physics goals might diversify beyond the subjects here described. This is, however, too far ahead to anticipate here with precision.

3.1 Main Detector Contributions

The CNRS team has two main hardware contributions fronts: one linked to the **neutrino detector or CD** (4 CNRS laboratories) and another linked to the **TT or Top-Tracker detector** (2 CNRS laboratories). The CENBG laboratory has members working on both SPMT and TT, since they moved from IPHC recently. The neutrino detector is dominated by the operations linked to the SPMT system, however, low radiogenic BG efforts is also folded. A few efforts, such as cosmogenic BG understanding and rejection are expected to join both CD and TT expertise efforts coherently. Else CD and TT are rather independent threats of action.

A national JUNO coordination (J. Martino) aids the two sub-coordinators per system (A. Cabrera and M. Dracos for the CD and TT, respectively) to ensure optimal national followup of the teams and hardware delivery. Further details on the CNRS team organisation is differed to Section 4.

3.1.1 The SPMT or Stereo-Calorimetry System

The SPMT system – or stereo-calorimetry (SC) system – is supported by a sub-collaboration of about 20 institutions located world-wide (America, Asia and Europe). This sub-collaboration was established upon the SPMT proposal and approval led by the CNRS team, as the SPMT had not been foreseen during the original JUNO detector design. This subsystem is considered one of the most innovative instrumentation-wise contribution of JUNO, thus it is actively discussed and presented in conferences recently. Even a dedicated workshop (NEPTUNE, Naples, Italy during July 2018) has been organised together HyperKamiokande, KM3NET, IceCube, etc to put forward similar technology in the context of future neutrino experiments.. The SPMT system was proposed in 2015 and was approved only in late 2016. Major

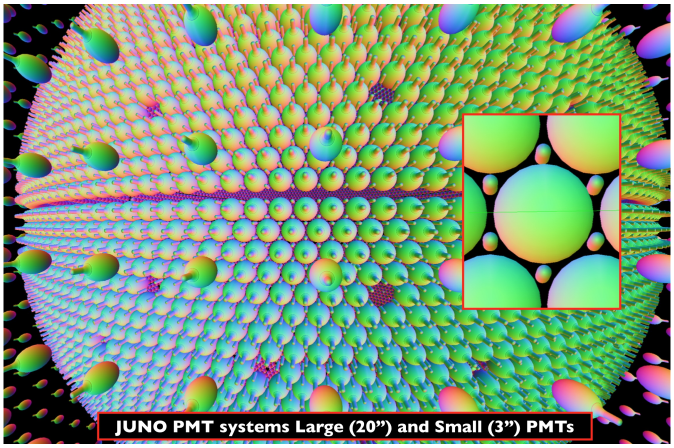


Figure 12: **JUNO PMT Stereo Calorimetry System.** The detector exploits the largest photo-cathode coverage ever reach in a neutrino detector: ∼77% by 20" PMTs and ∼3% by 3" PMTs. The 20"and 3" PMT systems are called LPMT (large) and SPMT (small), respectively. While the LPMT is geared to provide the largest light collection to reduce the energy stochastic resolution term, the SPMT is designed to provide control of systematics and validation of the non-stochastic (i.e. systematics) resolution term. The energy estimator exploiting both pieces of information simultaneously, upon tuning with calibration sources is conceived as the stereo-calorimetry estimator, whose main feature is the control of readout induced non-linearities.

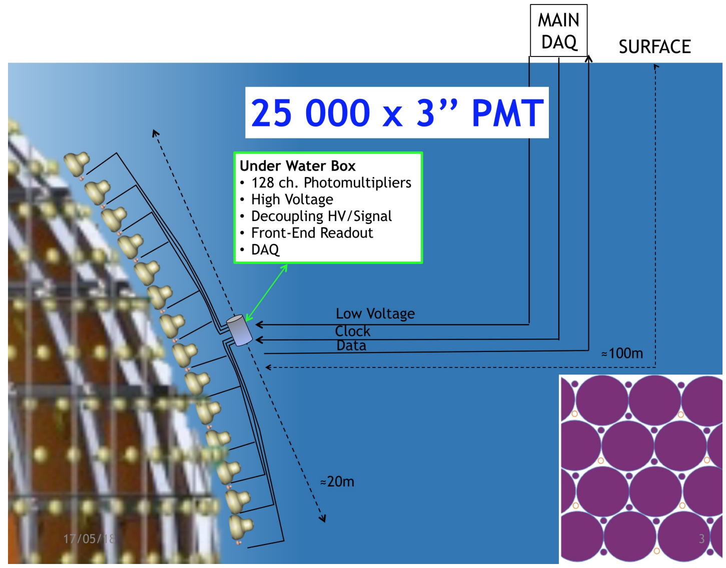


Figure 13: **JUNO SPMT System Articulation.** The location within the CD neutrino detector of one readout-unit of the SPMT system is illustrated. Each readout-unit is based on one under-water box for 128 PMTs. Hence, about 200 total readout units are needed. The signals, control and power are provided from surface via dedicated cables. The common SPMT and LPMT DAQ is located on surface.

studies proving its physics impact took place to ensure higher precision calorimetry in JUNO was possible, as main criterion. However, the SPMT system is now known to be able to deliver several physics channels together or even beyond the main LPMT system. A few examples are i) neutrino oscillation physics (namely the δm^2-θ_{12} measurement), ii) high precision and acceptance supernova core collapse detection, iii) high precision cosmic-μ 4π-tracking (i.e. cosmogenic BG rejection) and, possibly, iv) proton decay. The SPMT physics programme drives much of the CNRS physics programme. A few examples are slightly elaborated later on for further appreciation.

From the instrumentation point of view the SPMT consist of 25,000 3" PMT and the corresponding readout, as illustrated in Fig. 12. The readout is based on a custom made high channel density under-water electronics system – led mainly by CNRS teams. The minimal readout SPMT unit consist on under-water box (housing both analogue and digital readout electronics, HV delivery and communication to surface for data and control) providing independent readout to each 128 PMTs subset, as illustrated in Fig. 13. The SPMT is made of ∼200 independent boxes. Data from all boxes is collected on surface using the common DAQ system for both SPMT and LPMT readout. The LPMT relies on a global trigger system while the SPMT is self-triggered (at PE level) – often called trigger-less – thus maximising its acceptance for possible physics discovery within the dynamic range coverage. The SPMT and LPMT articulation is generally complementary whereby the SPMT provides a non-negligible dynamics and acceptance extension to the LPMT main detector[7]. In terms of channels, the SPMT system is the largest individual PMT system built in neutrino physics so far. In fact, the SPMT is anything but a "small" system.

The SPMT team has realised several instrumentation contributions here briefly highlighted on the following technology fronts:

3" PMT Technology. The JUNO 3" benefited much from existing KM3NeT instrumentation effort with all major PMT companies, such as ETL, Hamamatsu, HZC, MELTZ. However, the timing being a key specification from JUNO, we decided to undergo a fast TTS optimisation co-development with the HZC company to reduce significantly the TTS as compared to the KM3NeT configuration. ETL had an existing PMT significantly better, discarded by the KM3NeT due to shape constraints. Out of this co-development the (∼30%) faster new XP72B22 from HZC was born and adopted now as the official JUNO PMT. CNRS and IHEP (China) teams led much of the rationale to this successful optimisation.

Underwater Electronics Housing Technology A dedicated under-water box was designed for JUNO SPMT electronics exploiting vast under-water expertise in the CPPM laboratory for ANTARES and KM3NeT experiments. The R&D of this development has been fully led by CNRS teams, while the production is to be carried out from Chile institutions. The SPMT simpler underwater box design has inspired the LPMT for a complete re-design (including several other reasons), so now the LPMT also relies on a similar conceptual solution.

[7]Unsettled internal debate exist to confined the LPMT readout to lower energy triggers (where highest calorimetry resolution is needed), thus letting the SPMT drive the higher energy physics acceptance.

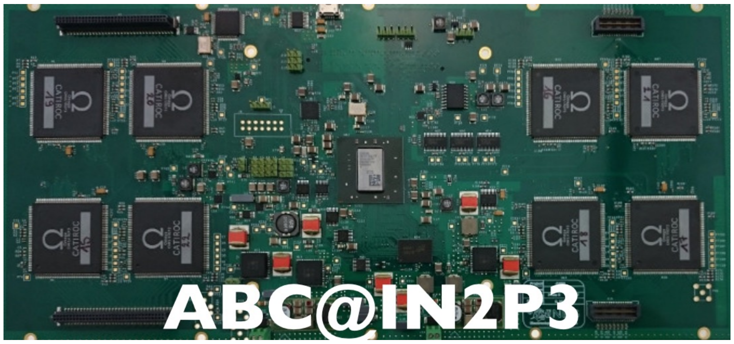


Figure 14: **The JUNO SPMT ABC Card.** The ABC card conceived, designed and developed by CNRS teams provides the readout to each SPMT system readout unit. Serving 128 channels, there are 8 CatiROC ASICs developed by the CNRS team too.

Underwater Connectivity Technology The associated under-water high reliability and low cost connectivity (connector and cables) have been co-developed via CNRS and "Axon' Cable" company (France). Several novel solutions (not yet existing in the market) have been yielded successfully and being in the last stages of prototyping and validation stages now.

High Channel Density Electronics Readout A custom readout electronics card (called ABC, ASIC Battery Card) using several ASICs has been conceived and developed for the core readout of the entire SPMT. This system is a core contribution of the CNRS team. The electronics board services readout to 128 PMTs independently and simultaneously. The CatiROC ASIC chip (16 channels readout each) have been used for the readout. However, CatiROC specifications did not fully match the JUNO readout dynamics, since this ASIC was originally designed for water-Cherenkov detector readout. Instead, the ABC powerful FPGA (Kintex7) has been designed to be able accommodate the CatiROC readout limitations, thus allowing the CatiROC based readout to match the JUNO specifications. A publication is in preparation here. For example, the ABC is expected to be able to provide deadtime-less readout capability up to 10M events per second (instantaneous rate), while the ASIC readout is saturating at $\sim$100 k/s. This readout acceptance extension was designed for to maximise the acceptance for supernova readout capability in JUNO. Implicit within the SPMT readout, there is the intrinsic contribution to the JUNO DAQ system – common to both SPMT and LPMT. Hence the SPMT team is on the frontline of data access and neutrino detector commissioning effort, as byproduct. This implies some long stays in China for detector commissioning are expected. The first ABC prototype, shown in Fig. 14, is under intense testing now. The final prototype version (upon some minor modifications) is expected within 2018, while full production of both ASICs and ABC cards is to take place during 2019. Preliminary negotiations exist for the ABC cards to be industrialised and commercialised, once completed, via the CAEN instrumentation company (Italy).

It is worth highlighting that most of the SPMT developments, including the aforementioned R&D, was in close partnership with European industry, as explained. This implies a SPMT impact beyond fundamental research. All elements co-developed with the JUNO-SPMT are expected to be in the catalogues for further benefit of the scientific community. The technological synergy between the SPMT system and other experiments is to be highlighted in the NEPTUNE workshop (July 2018, Naples, Italy) putting together major experiments such as HyperKamiokande, IceCube, JUNO and KM3NeT.

The entire SPMT system is expected to be fully produced and testes during 2019 and be ready for installation for early 2020 – consistent with the JUNO master schedule for the neutrino detector. Delays in the civil-construction of the underground laboratory has drifted this agenda and it might still happen. Regardless, the SPMT is well on schedule as of today. The technical coordination of the entire system both nationally and internationally is led by the CNRS team.

3.1.2 The Top-Tracker System

The Top Tracker is located above JUNO's Central Detector and Water Pool and is part of JUNO's Veto system. The Veto system is designed to measure and characterise the muon flux in the detector as well as to reduce the cosmogenic isotopes contribution to the antineutrino spectrum. The Top Tracker will mainly help to study the cosmogenic background production mimicking the IBD signal from the reactors. Thus, well knowing the rate of the cosmogenic background will reduce the JUNO systematic errors. The Top Tracker will also provide well reconstructed muon tracks which can be used to calibrate the response of the water pool.

The OPERA Top Tracker was valued as a 3.2 million EUR (in-kind) contribution from IN2P3/CNRS to JUNO. This is the main IN2P3 financial contribution in the project.

The Top Tracker of JUNO will be built using the plastic scintillator modules of the *Target Tracker* of the OPERA experiment, with some parts redesigned to fit JUNO's purpose and environment. The Top Tracker is composed of 62 walls, each with a sensitive area of 6.7×6.7 m^2. Each wall consists of 8 modules, each covering a surface of about 6.7×1.7 m^2, placed in two layers with perpendicular orientations along the 'x' and 'y' axis. Each module consists of 64 scintillating strips, each 6.7 m long and 26.4 mm wide, that are read out on both sides by a Hamamatsu 64-channel multi-anode PMT.

The Top Tracker walls will be placed horizontally in 3 super-layers spaced by 1.5 m. They are positioned on a 7×3 grid on top of the Central Detector and Water Pool in order to cover more than 25% of the area of the top surface of the Water Pool. Due to the chimney occupying the position of the walls at the center of the Top Tracker, these walls will be moved up to sit on top of the chimney. These walls, and due to mechanical constraints they will be spaced vertically only by 20 cm.

While the Top Tracker walls themselves could be assembled as they were used in the OPERA experiment, there is still a substantial amount of work needed to adapt them in horizontal position compared to their vertical position in OPERA. In particular, to adapt the Target Tracker to be used as JUNO's

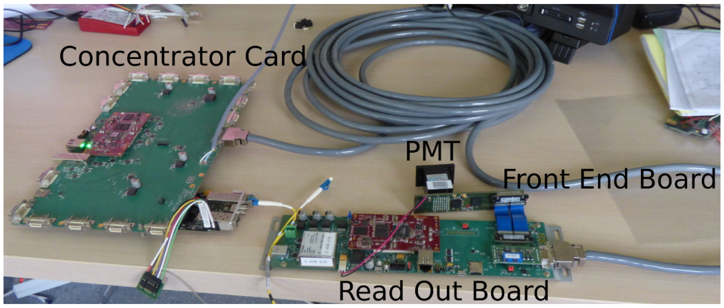


Figure 15: **JUNO Top Tracker System.** Current version of the TT electronics cards being tested. The PMT is also shown connected to the Front-End Board. The cables used for connections have the expected length for installation in JUNO.

Top Tracker it will be required to create a support structure for the Top Tracker, to develop new electronics cards, and to develop a new trigger strategy. The new support structure for the Top Tracker will be essential to insure the modules are not damaged by agging. The new electronics and trigger systems are required to be able to handle the higher radioactive noise rates in the JUNO cavern, compared to the OPERA cavern. The new trigger system has to be adapted to the JUNO environment. All the work related to this adaptation is coordinated from CNRS.

In addition to the coordination of all the work needed to transform OPERA's Target Tracker into JUNO's Top Tracker, the IN2P3 is also engaged in the design of several of the new electronics cards required for such adaption via the efforts of the IPHC team. The Top Tracker electronics are divided in four different cards that are interlinked:

Front-End Board: card responsible for the PMT interface and part of the PMT readout. There will be one of these cards per PMT, and therefore 16 cards per wall for a total of about 1000 cards.

Read-Out Board: card responsible for the Front-End Board readout and for the slow control and power supply of each PMT. It is connected to the Front-End Board through a serial link. There will be one of these cards per PMT, as for the Front-End Board, and therefore 16 cards per wall for a total of about 1000 cards.

Concentrator Board: card responsible for gathering all the information related to each wall. It will also provide an L1 trigger by combining the modules signals. This card is also responsible for time-stamping all Top Tracker hits with a nanosecond precision. These cards will send all TT data to the JUNO data base. There will be one of these cards for each wall for a total of 63 cards.

Coincidence Board: card responsible for combining the information about all the L1 triggers provided by the Concentrator Boards to produce a L2 trigger. There will be a single of these cards in the detector.

The current version under evaluation of the Front-End Board, Read-Out Board and Concentrator Board are shown in Figure 15.

Of the cards listed above, the Front-End, and the Concentrator Boards are being designed at IPHC, while the Read-Out Board is being designed by researchers from the INFN (Frascati University) and engineers from CAEN company, in close collaboration to the IPHC team. The Coincidence Board will also be designed by the IPHC team once the Concentrator Board designed will have developed further.

One of the main challenges in the design of these new boards is the significantly higher noise rate expected in JUNO in comparison to that in OPERA. This increase in the noise rate is related to a natural radiation in the JUNO cavern that was measured to be two orders of magnitude larger than that present in the OPERA cavern. In addition to the increase in the natural radioactivity, the Top Tracker will not be surrounded by lead-emulsion bricks reducing the radioactivity-induced hits as was the case during OPERA operation of the Target Tracker.

These new electronics cards need, therefore, to be developed to support high rates of radioactive noise triggering the system, while still selecting and identifying muons passing through the system, in order to satisfy the requirements for the Veto System of the JUNO detector. In light of these requirements the role of the Concentrator Board will be critical to quickly identify isolated hits as being radiation-like, in which case a quick reset can be sent to the Front-End Boards in order to significantly reduce the deadtime. This is a main concern of the Concentrator Board design. Depending on the achieved efficiency of the Concentrator Board, the Coincidence Board could no longer be needed. However, at the present time the rate reduction provided by the Concentrator Boards alone is not yet sufficient to provide the necessary margin on the affordable acquisition rate in order to cope with higher than expected rate.

TT Schedule The Top Tracker installation should take place during the end of the construction of JUNO central detector. Its installation and commissioning will take about six months. The filling and commissioning of the Central Detector and Water Pool will take place concomitantly to the Top Tracker installation. It is expected that the IPHC team will be heavily involved in the installation of the Top Tracker and will therefore have to be present on-site for long periods during the Top Tracker installation.

In the present JUNO schedule, the installation of the Top Tracker is supposed to start during Spring 2021. The Front End and Concentrator Boards R&D have to be finished at the end of 2018. The BGA encapsulation of the MAROC3 chips (OMEGA) is under realisation, after which all 1500 chips will have to be tested. The design of the Trigger card will start during 2019. The production of the 1200 Front End Boards will start end of 2019 while their tests will take place during 2020. The production of the 80 Concentrator cards is under the responsibility of the INFN.

As soon as a complete electronics chain is ready, it will equip a muon telescope already built at IPHC in order to test the whole system and prepare the online software. The muon telescope consists of 4 layers produced using Target Tracker spare modules and have a reduced surface compared to the Top Tracker walls.

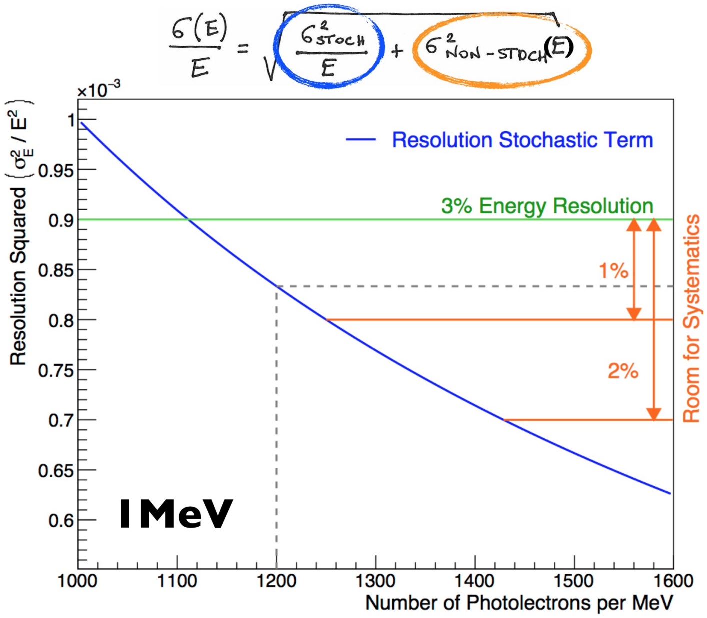


Figure 16: **JUNO High Precision Calorimetry Requirement.** The JUNO overall calorimetry resolution requirement of 3% at 1 MeV, implies a stochastic resolution terms <3%. Hence, the control of calorimetry resolution is critical and should be control <1%. JUNO is the first liquid scintillator detector whose resolution is expected not to be largely dominated by stochastic term. The SPMT system has been design to provide validation and/or control of calorimetry systematics with negligible impact of the readout non-linearity.

3.2 CNRS Main Physics Contributions

The main physics contributions to JUNO materialise via the physics implications of the SPMT. The TT and SPMT, together, are expected to provide critical feedback to μ-tracking for cosmogenic BG tagging – a critical subject for the IBD physics. A short elaboration of the main topics, as of today, is below provided, while details are kept to minimum.

3.2.1 Stereo Calorimetry

The "stereo-calorimetry" concept was put forward by the CNRS team, in collaboration with one INFN physicist. The SPMT system – proposed simultaneously – is the effective instrumentation implementation. The rationale is briefly explained below.

JUNO is expected to control its (total) energy resolution to the level of 3% at 1 MeV for the successful measurement of the MH. Therefore, the LPMT has been used to maximise the highest light level to the unprecedented >1000 PE/MeV, which is expected to provide an excellent stochastic resolution term, as illustrated in Fig. 16. Even if >1200 PE/MeV is expected to be possible in most fraction of the JUNO volume, the remaining non-stochastic energy resolution term budget is typically constrained to be <1%. The main issue is that most existing experiment has reached figures ∼2% at best. Hence, reaching the final JUNO goal of 3% at 1 MeV implies also an unprecedented control of calorimetry systematics, since they are almost, for the first time in this technology, as important as stochastic effects. While no better systematic control has not been reached before is also due to the fact that it was not needed before: most past experiment were dominated by the stochastic term, hence allowing the relax the constraints on the non-dominant calorimetry systematics.

In addition, it is well known that for a shape based physics extraction for MH needed in JUNO, the most dangerous systematic bias is the non-linearity, since non-uniformity and non-stability effects can only smear the energy spectrum. Now, the main challenge here is that JUNO response per channel to reactor IBDs has a unprecedented large dynamic range (>10, actually close to 100) for events at the same energy. Most experiment remain typically well below 5 in dynamic range, instead. This is due to large response variations due to solid-angle acceptance per PMT for the energy deposition happening across the detection volume. This implies that while JUNO aims for the most stringent resolution control so far, JUNO response dynamic has the largest dynamic range ever considered by almost an order of magnitude. This will make the control of non-linearities – whether a precision or an accuracy effect – a far more complex issue.

As this was identified, during final stages of JUNO detector design (2014-2015), we realised that the best solution to this was to consider smaller PMTs all across JUNO, so that the response per channel dynamic range variations across the entire IBD physics (volume and energy range) was significantly smaller, thus making the calorimetry fully immune to non-linearity issues. However, this was found to be impractical due to cost effects, thus a simpler approximation was found by using both 20" (LPMT) and 3" (SPMT) PMTs interleaved. Actually, 3" is the largest possible, but the main criteria was to ensure that the PMTs remain in the photon-counting regime, where by energy estimator is based not only on charge integration of each PE but also on PE counting across a threshold definition. This confines the SPMT dynamic range to virtually zero since both detection and energy estimation is defined across the PE threshold, thus making the SPMT energy estimator non-linearity proved. This way JUNO has two independent but simultaneous energy estimators, the one of the LPMT (large PE statistics) and SPMT (low PE statistics) per event. Due to the poor statistics, the SPMT estimator cannot be used to improve the LPMT in an even-by-event basis, since large response fluctuations dominate, even if perfectly linear. So, the SC relies on the combined energy scale constructed via calibration sources (high statistics) to provide a SPMT corrected energy scale of the LPMT or an independent validation scale to quote LPMT calorimetry systematics as reference.

The full articulation of the SC within JUNO is being constructed via MC data challenge exercises to demonstrate the JUNO calibration scheme, including the SPMT system, can provide the control of calorimetry systematics in JUNO to yield the design goal 3% at 1 MeV. The JUNO collaboration is still going through an intense study of the calibration of the MC for maximal accuracy of the entire calorimetry chain of the experiment. The CNRS team has led much of the above described studies and continue to lead much of the SC in agenda in collaboration with the other SPMT collaboration members. This topic lies at the core of the JUNO MH

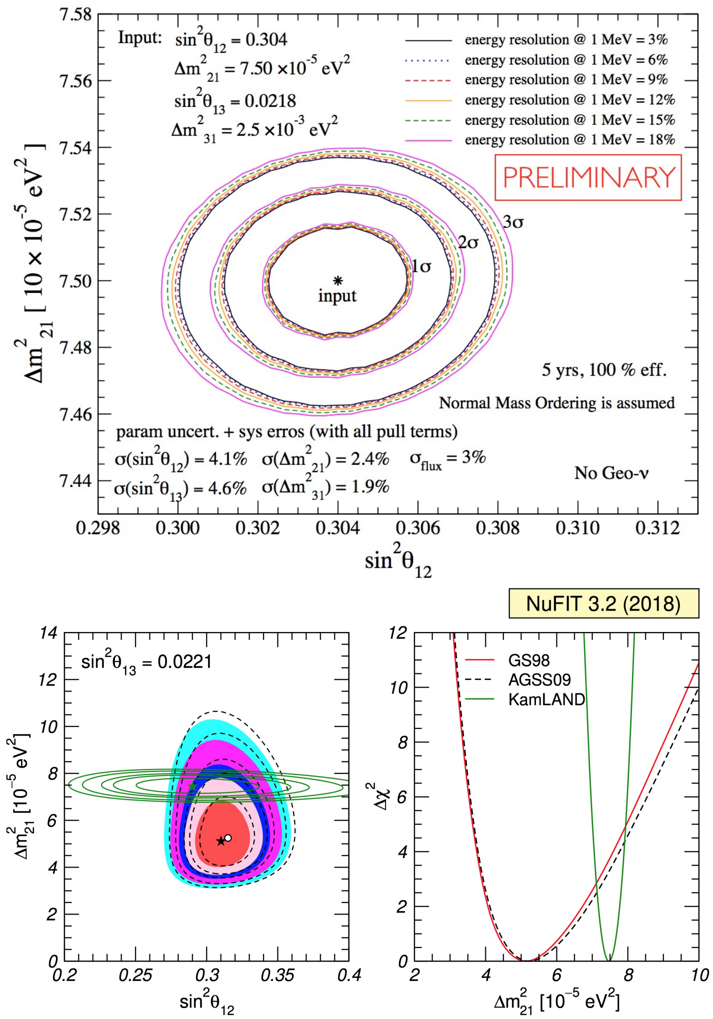


Figure 17: **JUNO SPMT⊕LPMT δm^2-θ_{12} Sensitivity.** The top plot shows that the ultimate precision on the δm^2-θ_{12} measurements depends weakly – as expected – on the energy resolution. The SPMT system (16% resolution) performs almost as good as the LPMT system (3% resolution), thus allowing JUNO to exploit a unique degree of internal consistency check. This is important on the light of a slight discrepancy reported in the δm^2 whose interest is phenomenological as it might suggest differences between solar-ν as compared to Earth reactor solar-$\bar{\nu}$ for the first time.

measurement capability, which is the golden design channel for JUNO. The CNRS team has long led the energy definition of DC, from which much of the SC conceptualisation had already been articulated with a single PMT system. DC is able to reach encouraging per mille calorimetry control with its prototyping SC implementation.

3.2.2 Solar Oscillation Measurement

The original motivation and SPMT approval was granted on the basis of the SC articulation, as explained before. However, soon after, it was realised – again by the CNRS team – that the SPMT alone could address a competitive measurement on both δm^2-θ_{12}, as compared to the LPMT system. As illustrated in Fig. 17(top), the measurement of δm^2-θ_{12} depends very little from the energy resolution since the overwhelming neutrino disappearance and consequent spectral distorsion is very large as indicated in Fig.3. In fact, a simple rate-only measurement (i.e. no energy information) is capable to yield excellent precision in JUNO.

Now, since JUNO has both the SPMT and LPMT sensitive to both δm^2-θ_{12} but they use the same events, JUNO cannot improve its statistical precision by combining both SPMT and LPMT information. In fact, the value of this strategy is to provide JUNO with the unique capability to do self-redundancy for the δm^2-θ_{12} measurement, in terms of systematics. This is particularly precious if we consider that those measurements will be eventually dominated by systematics and there is no experiment[8] foreseen capable to cross-check JUNO. The world knowledge (sub-percent precision) on those parameters will rely fully and solely on JUNO. So, worryingly there will be no redundancy whatsoever – unlike the wise articulation obtained for the θ_{13}-reactor experiments – hence articulating JUNO internal ability to validate systematics is of capital importance to the neutrino oscillation community. This internal redundancy scheme was proposed by the CNRS.

Incidentally, as shown in Fig. 17(bottom), today there is a minor discrepancy between KamLAND and solar best measurement of δm^2 where JUNO precision is expected to improve by almost one order of magnitude. The role of both SPMT and LPMT measurements cross-check is particular important to ensure JUNO's δm^2-θ_{12} measurement is not biassed, as compared to the quoted systematics uncertainties. The high precision measurement of δm^2-θ_{12} measurement to calibrate with IBD the control of energy systematics to be able to address MH measurement. In this way, the SPMT IBD physics provides test-bench and tuning for the stereo-calorimetric energy scale prior to addressing the challenging measurements link to the Δm^2-θ_{13} oscillation. The CNRS teams are behind much of the elaboration of this complete and coherent analysis strategy within JUNO for high precision neutrino oscillation.

3.2.3 Radiogenic & Cosmogenic Background

There are two types of BGs: cosmogenic (link to cosmic μ) and radiogenic (link to radioactivity). Radiogenic BG manifest as random or accidental coincidences mimicking the IBD signature, whereas cosmogenic are typically genuine correlated coincidence; i.e. irreducible relative to IBD correlation since typically there is a neutron in the final state.

The requirement is to have less than 100 events/s coming from the radiogenic BG in the full detector volume. The control of radioactivity during detector design and construction is therefore critical for the reduction of the accidental BG. This implies radioactivity control of the liquid scintillator (intrinsic contamination) but also the detector borders, being the most challenging. The control of the intrinsic contamination has yet to be proved in JUNO, but the precedent of the Borexino is of critical reference. JUNO is not expected to be even near Borexino radio-purity levels. So, JUNO is expected to meet this goal thanks to the ongoing effort, including Borexino ex-

[8] Solar experiments do not have the precision and RENO-50 proposal got cancelled.

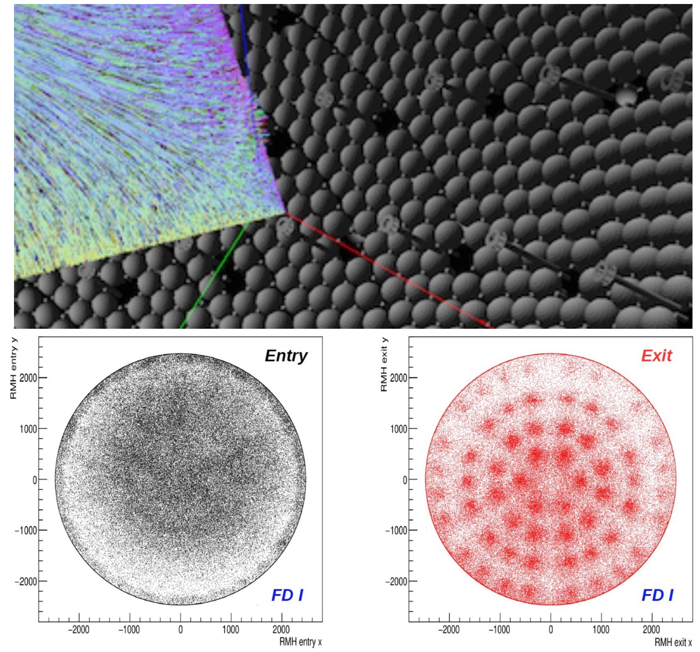


Figure 18: **CD Muon 4π-Tracking Illustration.** The vetoing of cosmogenic ^{9}Li is expected to be strongly link to muon-tracking based on the CD detector. The SPMT has been demonstrated to boost muon precision due to both excellent time resolution and no saturation at high charges, as compared to LPMT specialised for low energy depositions. In addition, to CD the TT is expected to provide unique external input for a sub-set of muons. The combined SPMT-TT muon-tracking contribution, led by CNRS teams, is expected to be decisive for JUNO cosmogenic BG rejection.

pertise from INFN colleagues. Instead, the control of external radiogenic background is critical. CNRS teams – in collaboration with other teams mainly in China and Italy – are strongly involved in radio-purity measurements to guide the detector design and composition. Especially, the expertise in low-level counting acquired from the NEMO3/SuperNEMO double beta decay experiments using low background gamma spectrometry and Radon emanation measurements has already been a key contribution to JUNO and will be pursued in the next years. The main consequence link to radioactivity is the lowest readout energy threshold tolerable by the DAQ and the possible necessity for fidualisation to reduce accidental BG contamination for analysis. This latter is particularly important as it has two critical consequences: i) the sizeable reduction of the total effective volume (small cut in most external radius translates into a large loss of volume) and ii) the control of fidualisation systematics since the physics volume depends on the spacial reconstruction whose biasses are typically largest far from the detector geometrical centre. Hence, today's CNRS team work on control of radioactivity is expected to have key impact to the detection systematics for the different IBD analyses of JUNO.

The control of the cosmogenic is even more important since the signal to cosmogenic BG is expected to be about 1, unless further selection rejection is implemented. The BG in question is the ^{9}Li spallation production on ^{12}C, then decaying ($\tau \approx 250$ms) as mainly[9] β-n in the final state. The fast-neutron rate is expected to be significantly lower due to the overburden and ∼1 ms veto upon each CD crossing μ. Therefore, the aggressive rejection of ^{9}Li is needed. Expected rejection factor is ∼50×. DC has today one of the best background knowledge in the topic given the high rate of muons due to low overburden, hence providing key prototyping knowledge and training for the JUNO final strategy. The most efficient rejection so far found is the tagging of spallation candidates muons – as demonstrated in DC and other experiments. This is done by tagging neutron activity upon the impinging muon. Then, to ensure minimal deadtime, a fiducial cylinder (order ∼1m radius) around the muon-track is needed. Since most of this physics happens inside the CD (neutrino detector), the most efficient strategy (so far) is to use the muon tracking with the CD itself, as illustrated in Fig. 18(top). Here the combined information from the SPMT (faster) and the LPMT systems are expected to provide further precision. However, the main limitation of this CD tracking is that there is no native track topology in detectors like JUNO. In fact, a muon implies a straight extrapolation between a measured entry and exit-points, as illustrated in Fig. 18(bottom) for the DC case. It can be clearly seen that the exit-point is most susceptible to a bias, thus exhibiting an artificial PMT mapping – a reconstruction inaccurate output. Assuming similar performance in JUNO, the advent of the SPMT is expected to significantly improve both entry and exit points due to smaller PMT size and better RMS resolution. The tracking acceptance for both SPMT and LPMT is 4π, hence being the main muon-tracking approach. Handling muons bundles is very complex matter for the CD systems, where the SPMT is expected to aid significantly (under study). However, the TT detector (not covering 4π acceptance) is expected to provide important higher precision information to validate and improve the entry-point knowledge. Reliable exit point is harder since muon random scattering is not negligible in such a large detector, including all metal elements surrounding. However a ∼23cm resolution is expected. The TT is expected to provide a unique handle for muon bundle handling and further precision on stopped-muons samples. In brief, the rejection of ^{9}Li BG is of capital importance for JUNO, so the combined muon-tracking of CD (SPMT+LPMT) and TT is expected to provide the analysis all possible input for the best performance. The CNRS team are leading both TT and SPMT system towards ^{9}Li reduction – one of the most important topics for all IBD analysis of JUNO.

3.2.4 Core Collapse Supernova Detection

As discussed in the introduction, the JUNO combined size and high fraction of proton makes it one of the best possible detector in the world for high precision core collapse supernova (CCS) detection. The relation between CCS location and the IBD rate is shown in Fig. 19, thus illustrating that a higher rate capability is vital to maximise the CCS acceptance in the galaxy. However, yielding both readout and DAQ to handle up to 10M IBDs per second as instantaneous maximal rate is a non-trivial challenge. This would be case

[9]A few α's might also manifest as prompt.

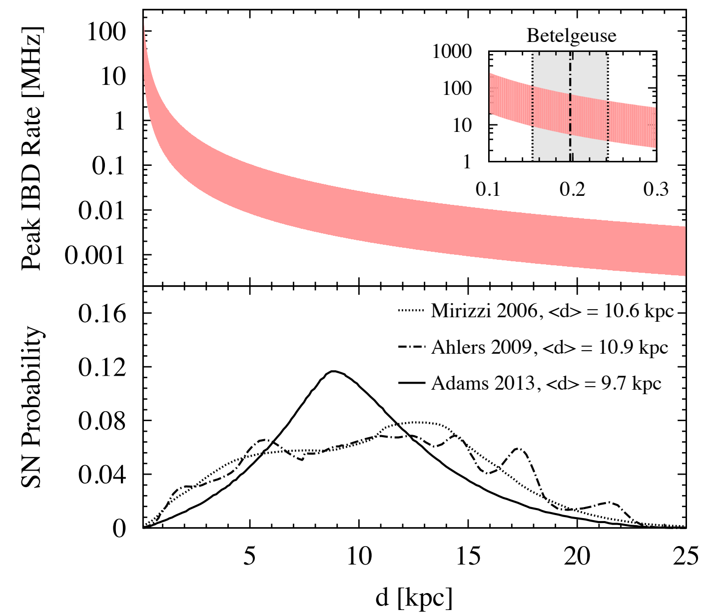


Figure 19: **Supernova Galaxy Distribution.** Given the large detector size of JUNO, the trigger rate per CSS depends strongly on the distance of the CSS to the Earth, as illustrated in top plot, including uncertainties. The distribution of stars in our galaxy is illustrated in the bottom. The goal is to design JUNO to ensure CSS acceptance sensitivity is close to 100%, which involves deadtimeless and efficient readout up to the challenging 100 events/s. JUNO SPMT readout has been developed with CSS capability in mind, thus, to be able to high rates and robust deadtime monitoring. Preliminary tests suggest up to 10 events/s is possible, thus expected to achieve ~99% acceptance sensitivity.

for the closest stars in our galaxy. The LPMT using FADC makes it almost impossible, while large buffering is expected to be help significantly. So, the logic is to ensure the SPMT can yield such high rates. If successful, this would imply JUNO acceptance up to ~99% of the galaxy stars, as shown in Fig. 19. Yielding this rate capability implies the precise control of deadtime, which is to be monitored and corrected to measure accurately the "neutrino rate vs time". This is one of the most important CCS observable providing unique information about the astrophysics of the star collapse, as shown in Fig. 7. The other critical observable is the neutrino energy during the CCS. The energy spectrum is expected be higher energy than reactor neutrinos, hence even more suitable for SPMT precise characterisation. The end point is expected to be around ~50 MeV, where the SPMT system might enjoy up to few percent energy resolution. There is critical particle physics information expected to be in the neutrino energy spectrum. In case of a CSS event, the detail analysis and full extraction of physics will benefit from having close interactions with supernova phonomenolgy experts available in APC for adequate guidance.

Currently, the CNRS team is optimising the SPMT electronics to maximise the acceptance to CSS. In fact, preliminary studies suggest that the ABC electronics will perform deadtime-less readout up to 10M events per second, as instantaneous rate. The logical components of the card has been also optimised to ensure this capability. In fact, currently, there is a discussion in JUNO for a possible decision on the CSS readout where the SPMT is expected to be the leading readout system since the design of the LPMT readout to reach a similar performance is impractical. So, the CNRS team is effectively leading position to the JUNO optimisation for CSS detector design. This is a unexpected outcome since the SPMT was not expected at the JUNO original design.

3.3 Future Interests & Other Possible Contributions

As indicated, the scientific interests so far considered covers (barely) the man-power available and links coherently to the hardware contributions, currently in highest priority and development. While other interests – including those beyond our hardware contributions – are expected to manifest later on, there is not foreseen in our agenda today.

However, a needed contribution possible within JUNO-Europe framework is the computing via the CC-IN2P3 facility. There is discussion for the possible organisation of several European computing facilities towards role in the JUNO data processing. This possibility is under exploration, including the strategical interest of the JUNO-CNRS team – not fully decided yet. The CNRS team, nonetheless, expects to articulate the intense use of the CC-IN2P3 facility for local JUNO data analysis with sizeable data capability needed for JUNO. There is ongoing discussion, estimation and discussion with the CC-IN2P3 to optimise the possible strategy for JUNO in the following years.

3.4 Scientific Contribution Conclusions

The CNRS team is highly involved in the JUNO experiment based in China via two main hardware contributions the SPMT system (CNRS responsible main for the readout electronics), as key part of the neutrino detector, and the TT detector for muon-tracking, provided in kind from OPERA experiment in collaboration with the INFN. These contributions are the highest priority for CNRS prior and during JUNO detector commissioning. However, linked to those operations the CNRS team have articulated scientific contributions towards several physics topics: i) high precision calorimetry with direct impact to the Δm^2-θ_{13} measurement and Mass Hierarchy (SPMT system) ii) high precision δm^2-θ_{12} measurement and physics (SPMT system), iii) high precision muon-tracking (TT and SPMT) for cosmogenic BG rejection, iv) radiogenic BG control (global effort beyond solely the SPMT) and v) high acceptance supernova core collapse detection (SPMT system). In addition, the CC-IN2P3 facilities are expected to be key for the JUNO-CNRS teams data analysis, including possible pan-European cooperation.

4 JUNO CNRS Organisation

In this section, we shall detail slight more the CNRS team composition for maximal appreciation of competences, expertise and collaborations. We shall also contextualise the different efforts, previously highlighted, within the JUNO master schedule.

4.1 The JUNO Experimental Schedule

The JUNO experimental schedule (CD based) can be summarised as follows, considering that the official expected data taking is to start by the end of 2021 at best. The TT detector is expected to be installed as one of the last stages as compared to the CD, hence their preparation might benefit from at least 1 year extra time in comparison to the SPMT system.

2018:

- Continuation of the underground laboratory civil construction.
- JUNO surface building infrastructure delivery.
- PMT potting starts.
- Completion of all preparation operations and start of all elements production.

2019:

- Underground laboratory completion.
- Start of JUNO detector construction.
- SPMT and LPMT electronics production and assembly.

2020:

- Continuation of detector construction.
- SPMT and LPMT electronics installation.

2021:

- Completion of CD detector construction.
- Filling of CD and water-veto detectors.
- Construction of top support detector structure (needed for TT).
- Installation of TT system.
- Start data-taking and commissioning.

So far, the overall schedule has drifted by about 2 years due to unexpected complications with underground water sources during the underground laboratory construction. While the risk of further complication is not negligible, there is no evidence that the situation is critical. Hence, the possibility of extra delays is not impossible.

4.2 The JUNO-IN2P3 Teams & Roles

4.2.1 The APC Laboratory Team

The APC group has a long and recognised reactor neutrino physics legacy such as DC, effectively the national and international headquarter for the experiment. APC members has led most of the scientific and collaboration DC operations for years – still today. The APC also lead the direction of the national underground laboratory facility (LNCA) at Chooz hosting the DC detectors in collaboration in representation of CNRS in partnership with CEA and EDF. Technically, APC has a speciality for readout electronics, acquisition and led key major mechanical contributions in DC. APC was reached by the JUNO leaders and started collaboration operations since 2013, a priori towards the leading the JUNO FADC readout.

PI: Anatael Cabrera (@40%[10]).

PhD Students (1): Yang HAN (@100%)

Scientific Members (2): IN2P3 postdoc starting from Oct./Nov. 2018 and Cristina Volpe (@APC: supernova expert). The group has been heavily weaken by the departure of 2 physicists (H. de Kerret and M. Obolensky).

CNRS Collaboration (5): CENBG, CPPM, OMEGA, Subatech.

Engineer Members (1): Cayetano SANTOS (@30% electronics).

Main Expertise: reactor neutrinos physics (leading DC), readout electronics (including FADC), DAQ, calorimetry, neutrino oscillation physics, supernova physics and phenomenology.

Main Contributions: SPMT national and international coordination, SPMT system, electronics and physics.

Strategic Collaborations: the formation of an international collaboration of ∼20 laboratories (Americas, Asia, Europe) for the implementation of the SPMT system, specially IHEP (China), NTU (Taiwan) and PUC-Santiago University (Chile). Also, collaborations with Ferrara (University and INFN) for geo-neutrino physics (publication in preparation), PUC-Rio de Janeiro for JUNO phenomenology (ongoing studies for JUNO).

Critical Roles: SPMT national (IN2P3) and international (JUNO collaboration) coordination, SPMT electronics coordination, JUNO-LPMT electronics system reviewer (2013-2015: JUNO co-coordination Electronics/DAQ/Trigger system), JUNO-Calibration system reviewer.

4.2.2 The CENBG Laboratory Team

The CENBG neutrino team has a long (more than 25 years) and recognised expertise in double beta decay physics with a leading role in the NEMO3 and SuperNEMO experiments.

[10] This is expected to increase upon DC culmination (end 2019).

Its expertise concerns mainly the development and the characterisation of photodetectors including optical simulations, the development of low background detectors and the control of the background by measurements and MC simulations, data analysis and detector construction. Recently, the CENBG neutrino group has been reinforced by physicists currently involved in the Double Chooz experiment but also in the OPERA experiment in the past. So the CENBG neutrino team has now an expertise in neutrino oscillation physics and especially in data analysis and background simulation. The team is currently involved in both the SPMT and the TT systems in the framework of the JUNO experiment.

PI: Frederic Perrot

PhD Students (1): Clement Bordereau (100% JUNO, co-supervision Bordeaux-Taiwan)

Scientific Members (3): Cedric Cerna, Cecile Jollet, Anselmo Meregaglia.

CNRS Collaboration (4): APC, CPPM, OMEGA and Subatech in the SPMT system and IPHC in the TT system.

Engineer Members (4): Frederic Druillole, Amelie Fournier, Cedric Huss, Abdel Rebii and Patrick Hellmuth (electronics and mechanics for SPMT).

Main Expertise: low background techniques (NEMO3/SuperNEMO), calorimetry using organic scintillators and PMTs (NEMO3/SuperNEMO/Double Chooz), reactor neutrino oscillation physics (Double Chooz), simulation/analysis of accidental and cosmogenic backgrounds (NEMO3/SuperNEMO/Double Chooz). Top Tracker simulation and data analysis (OPERA). Ortho-positronium analysis tagging and generator (NuToPs ANR and Double Chooz)

Main Contributions: simulation of accidental and cosmogenic backgrounds, ortho-positronium study, low background measurements by gamma and alpha spectrometry for material selection in JUNO, conception/prototyping/testing of the UnderWaterBox (UWB), and development/routing/testing of the ABC front-end cards.

Strategic Collaborations: collaboration with Milano-Bicocca University/INFN for low background control in JUNO and with IHEP (China), NTU (Taiwan) and Pontifical Catholic University of Chile for the SPMT system.

Critical Roles: SPMT national (IN2P3) and international (JUNO collaboration) technical coordination, SPMT international physics coordination, co-coordination of the international JUNO low background group, JUNO czar for CC-IN2P3, responsible of the routing/testing of the final ABC front-end card.

4.2.3 The CPPM Laboratory Team

PI: Jose Busto

PhD Students (0)

Scientific Members (0)

CNRS Collaboration (#): APC, CENBG, OMEGA and Subatech in the SPMT system and University of Avignon for Radon measurements.

Engineer Members (2): Stephan Beurthey (mechanical expertise under high pressure water conditions) and Chistian Curtil (radon measurements).

Main Expertise: Main Expertise: low background techniques for Radon (NEMO3/SuperNEMO)

Main Contributions: low background measurements by alpha spectrometry in order to measure the Radon diffusion length of critical materials in JUNO.

Critical Roles: international JUNO member of the low background group

4.2.4 The IPHC Laboratory Team

The IPHC team has successfully contributed in neutrino physics experiments, and particularly those studying neutrino oscillations, since the proposal of the OPERA experiment at the end of 1999. One of the IPHC main contributions to the OPERA experiment was the preparation and construction of the *Target Tracker* which was responsible for triggering the detector and identifying the location of the neutrino interactions. After the conclusion of the OPERA experiment, the IPHC team proposed to use, after some modifications, the *Target Tracker* of OPERA as the *Top Tracker* of the JUNO experiment. The IPHC team's original involvement and experience with the *Target Tracker* is invaluable for the success of the upgrades required towards the realization of the *Top Tracker* in JUNO, and the IPHC group is involved in every part of its preparation to its use within the JUNO experiment. Notably, we are responsible for the the preparation of several of the electronics cards for the data acquisition and for the coordination of the efforts in the JUNO Veto group.

In addition to OPERA and JUNO, the JUNO IPHC team members have contributed to numerous other projects in neutrino physics such as ESSνSB, Double Chooz, EuroNuNet, EXO200, T2K, IceCube, and PINGU.

Current members:

- Joao Pedro Athayde Marcondes de Andra [CR]
- Eric Baussan [MdC]
- Marcos Dracos [DR]
- Qinhua Huang [PhD student from LLR]
- Pascal Poussot [IE]
- Cedric Schwab [TCS]
- Michal Szelezniak [IR]

- Jacques WURTZ [IR]

Future additions:

- 1 IN2P3 post-doctoral fellow starting Nov. 2018
- 1 IR (electronics) starting Dec. 2018
- 1 PhD student starting Oct. 2018

Critical Responsibilities: the Top Tracker of JUNO

4.2.5 The OMEGA Laboratory Team

PI: Christophe de la Taille

CNRS Collaboration (3): APC, CENBG, IPHC and Subatech.

Engineer Members (0): Selma Conforti

Main Expertise: Micro-electronics and ASIC developments.

Main Contributions: both CatiROC (SPMT readout chip) and MaROC (TT readout chip).

4.2.6 The Subatech Laboratory Team

The Subatech physicists involved in JUNO come from neutrino physics (Double Chooz, SoLid) and from astroparticle physics (Pierre Auger Observatory, HESS) and Dark Matter (DAMIC). Their main expertises are the data analysis, simulation and detector construction. The Subatech group has experiences in readout electronics, data acquisition systems development and mechanics. Within the JUNO experiment, the group is currently involved in the sPMT project, contributing to the electronics readout system, the data acquisition and related problems of supernova fluxes. It has the coordination of JUNO at national level.

PI: Frederic Yermia

PhD Students (0):

Scientific Members (2): Mariangela Settimo (DAQ-SPMT coordinator) and Jacques Martino (JUNO France coordinator).

CNRS Collaboration (#): APC, CENBG, CPPM, OMEGA.

Engineer Members (3): Frederic Lefevre, Guillaume Vanroyen (engineers), Louis-Marie Rigalleau (technician)

Main Expertise: reactor neutrinos (Double Chooz, SoLid), neutrino physics, electronics readout and DAQ system.

Main Contributions: the group contributes to the validation of the electronics (mostly CATIROC ASIC), the development of the firmware for the SPMT electronics readout, the DAQ system (collaboration with APC, OMEGA). The group has coordinated a paper (under revision) on the CATIROC ASIC in use for the JUNO-SPMT electronics and is developing the software for the test-bench of the SPMT mass production. The group is starting an activity on the detection of neutrinos from supernova in connection with their handling by the DAQ system.

Critical Roles: JUNO experiment CNRS national coordination and SPMT DAQ responsibility.

References

[1] Neutrino physics with JUNO, J. Phys.G: Nucl. Part. Phys. 43 030401 (2016)