

Cutting-Edge Machine-Learning Advancements at JUNO

towards ν probabilistic machine learning

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on behalf of the JUNO collaboration

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2025-10-27 NPML2025 @ Tokyo

ν oscillation

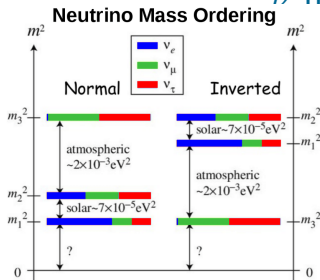
$$|\nu_\alpha(t)\rangle = \sum_{i=1,2,3} U_{\alpha i}^* |\nu_i(t)\rangle$$

Mixing of different ν mass eigenstates leads to oscillation:

$$\langle \nu_e | \nu_e(t) \rangle = |\langle \nu_e | \nu_1 \rangle|^2 + e^{-i \frac{\Delta m_{21}^2 L}{2E}} |\langle \nu_e | \nu_2 \rangle|^2 + e^{-i \frac{\Delta m_{31}^2 L}{2E}} |\langle \nu_e | \nu_3 \rangle|^2$$

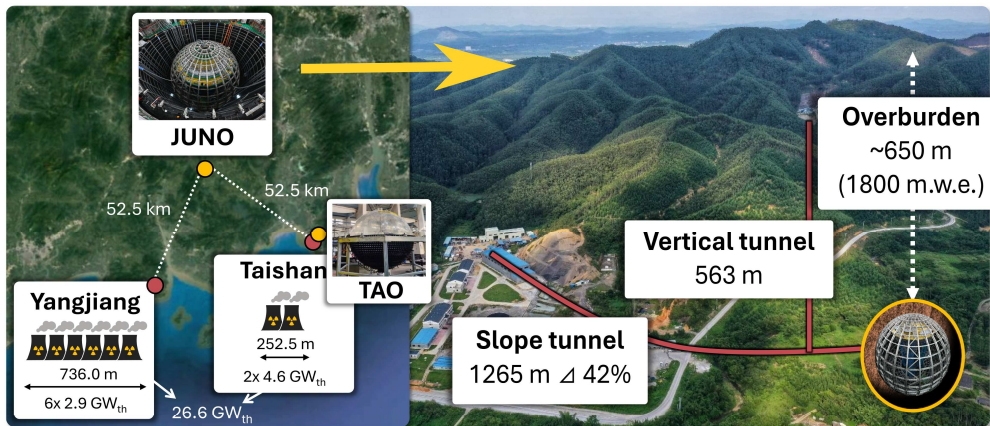
describes the **survival probability** of ν_e as $P(\nu_e \rightarrow \nu_e) = |\langle \nu_e | \nu_e(t) \rangle|^2$.

'' mass ordering (NMO): sign of Δm_{31}^2



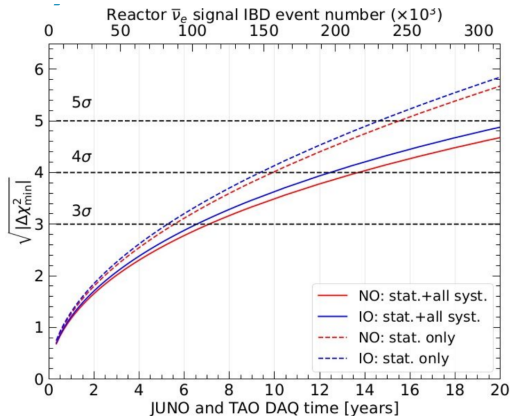
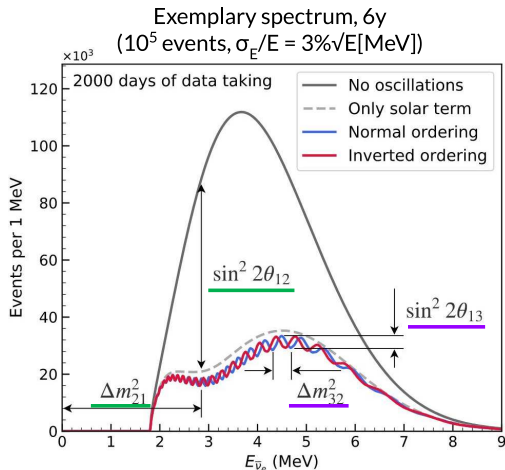
- $\Delta m_{21}^2 = m_2^2 - m_1^2 = 7.5 \times 10^{-5} \text{eV}^2$
- $\Delta m_{31}^2 = m_3^2 - m_1^2 = 2.4 \times 10^{-3} \text{eV}^2$
- normal order: $m_3^2 > m_1^2$;
 - inverted order: $m_3^2 < m_1^2$
- imprints subtle difference on energy spectra.

Jiangmen Underground Neutrino Observatory



- 52.5 km is the sweet spot for $\bar{\nu}$ oscillation.
- Detected via inverse β decay $\bar{\nu}_e + p \longrightarrow e^+ + n$.

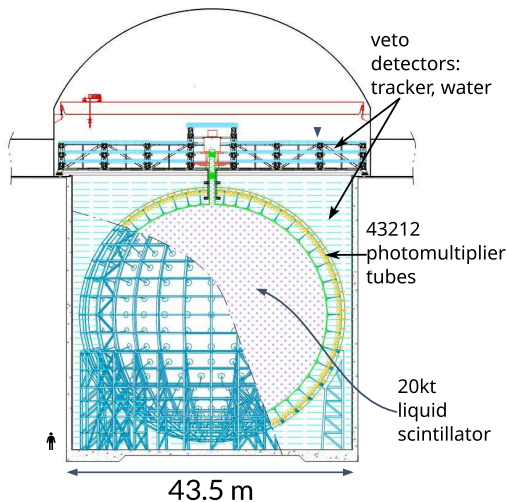
Sensitivity to ν mass ordering



$\Delta\chi^2$ is the χ^2 different between correct and wrong hypothesis.

3 σ determination in 6.5 years. [Chin. Phys. C 49 033104](#)

JUNO design: a liquid scintillator detector



large exposure:

- proven technology to scale up.
- world's largest by $20\times$.

measurement of ν energy;

- bright liquid scintillator.
- maximize the coverage of photomultiplier tubes.
- > 1300 photo-electrons/MeV.

control of backgrounds.

- effective impurity removal:
filtration, distillation, absorption.
- active shield of water and μ tracker.

Measurement of ν energy

Replacing KamLAND as the world's largest liquid scintillator detector

	KamLAND (reference)	JUNO	KamLAND2 (future)
PE yield per MeV	250	~ 1600	1200
Photocoverage/%	34	78	61
Light yield	1	1.5	1.4
PMT QE $\times$ CE/%	12	30	23

- 52.5 km is the first minimal of $\langle \nu_e | \nu_2 \rangle$.
- $\langle \nu_e | \nu_3 \rangle$ oscillations 30 times faster.
 - Requires energy resolution better than 3% at 1 MeV.

Configuration of photo-multiplier tube array



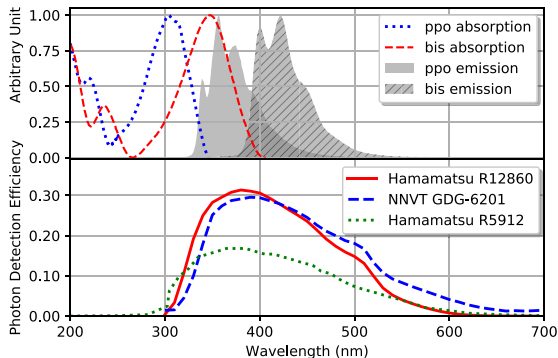
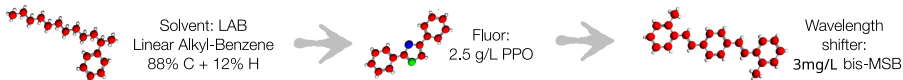
size	type	quantity	detection efficiency	dark noise rate/kHz	transit time spread 1σ /ns
$\varnothing 50$ cm	micro-channel plate	15057	30%	31	7.0
	dynode	4939	29%	17	1.3
$\varnothing 7.6$ cm	dynode	25600	25%	0.5	1.6

Eur. Phys. J. C 82 12, 1168(2022)

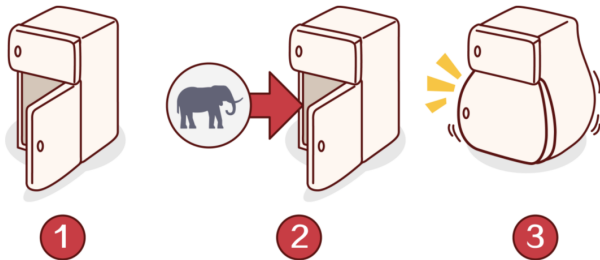
- Carefully designed liquid scintillation cocktail.
- Efficient transmission of ionization energy to scintillation photons.

NIM A 967, 163860 (2020)

Liquid scintillator



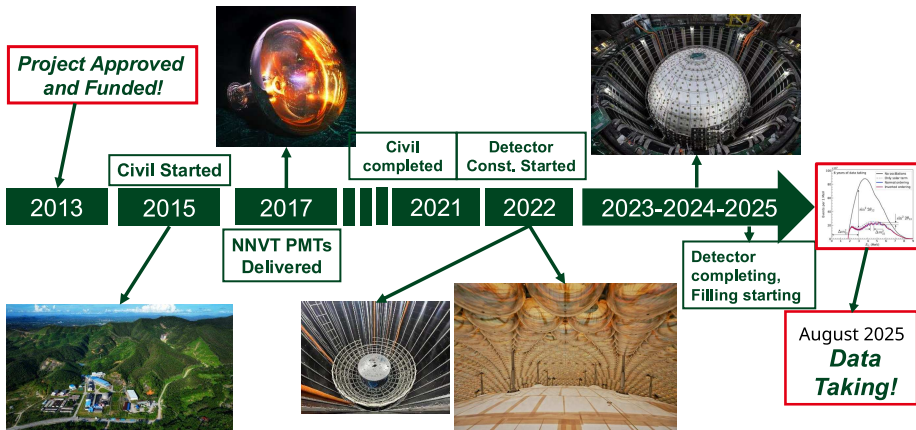
Timeline



How to put an elephant into a fridge?

- ① dig a experimental hall: 2015–2021;
- ② put a detector inside: 2021–2024;
- ③ top out the water pool: 2024;
- ④ official data taking: 2025.

Milestones of JUNO



Snapshots construction progress

- Stainless steel frame bottom-up, acrylic sphere top-down.

Construction of acrylic sphere



- Construction layer by layer.

Layer inspection



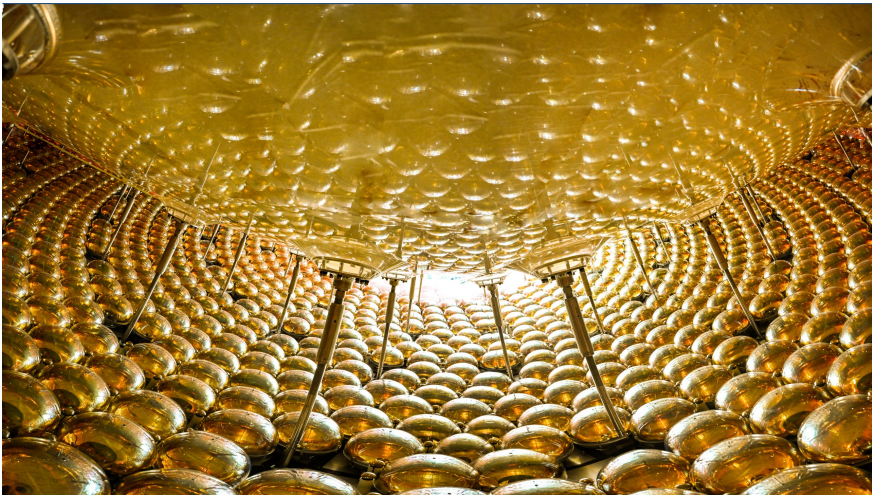
Inspection of bonding lines.

Final layer



All the panels are welded together *in situ*.

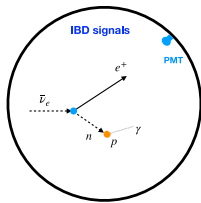
Completion of construction



- Dense packing of PMTs.

Reconstruction as inverse problems

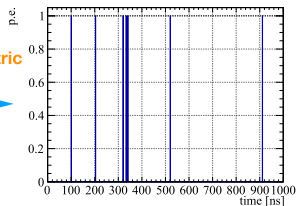
Charged particles deposit energy and produce scintillation light



Photoelectric effects



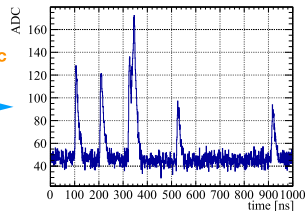
PE count and time



Electronic effects



Waveform



Event reconstruction



Event energy, vertex etc.

PE count and time and other waveform features

Waveform reconstruction

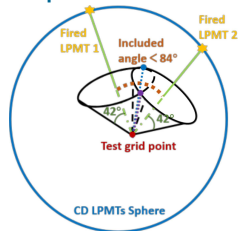


Waveform

Reconstruction with pure water

Pattern recognition

- Inspired by SuperK NIM A 433 (1999) 240–246
- Narrow peak in residual time for vertex.
- Hough transformation for direction.



Likelihood estimator

- Inspired by fitQun MiniBooNE and SuperK, but without Q.

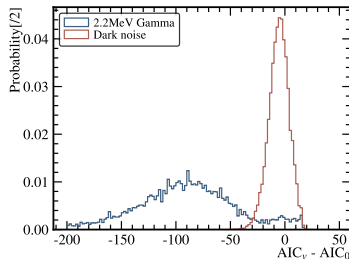
$$\mathcal{L} = \prod_{N_j > 0} \left\{ \exp \left[-v_E \lambda_{j, [\underline{T}-t_0, T_j-t_0]}^0(\vec{r}) \right] v_E R_j^0(T_j - t_0; \vec{r}) \right\} \times \prod_{N_j = 0} \exp \left[-v_E \lambda_{j, [\underline{T}-t_0, \bar{T}-t_0]}^0(\vec{r}) \right].$$

- $\vec{r}$: position (x, y, z) and momentum (p_x, p_y, p_z) .
- Employ Markov Chain Monte Carlo (MCMC) to avoid local extrema.
- Simulated annealing is adopted to accelerate convergence.

AIC for removal of dark noise

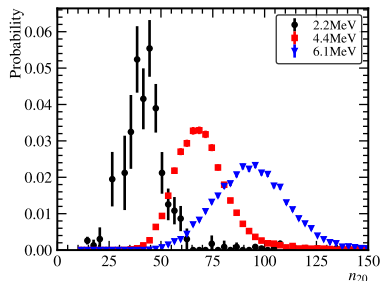
$$\text{AIC} = -2 \ln \mathcal{L} + 2k$$

- $\mathcal{L}$: The minimum likelihood of the event
- Use $dA = \text{AIC}_v - \text{AIC}_0$ to decide whether the event is a **signal or background**.
- Dataset: Simulation
 - ① 2.2 MeV gamma uniformly distributed in the detector.
 - ② Events triggered by dark noise.
- It is possible to remove dark noise from 2.2 MeV gamma by AIC.



Demonstrated low energy threshold in water phase

- From **AmBe** calibration $\rightarrow$ **4.4 MeV γ** ;
- From **AmC** calibration $\rightarrow$ **6.1 MeV γ** ;
- **Coincident analysis** $\rightarrow$ **2.2 MeV γ** ;
- n_{20} : The total count of PE hits in $[-20, 20]$ ns, **primary measure of energy**.
- Demonstrates JUNO's **low energy threshold and clear neutron capture detection** with pure water.



Photon counting with time

Photon counting is chance to improve JUNO energy resolution.

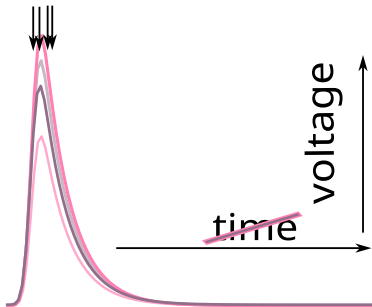


Figure: Total charge from overlapping pulses.

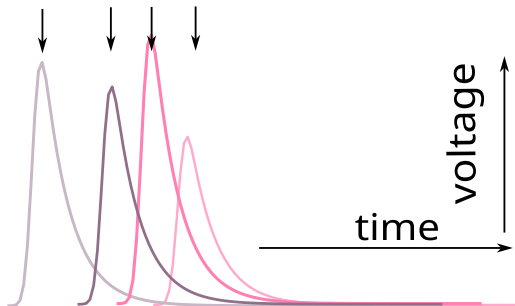


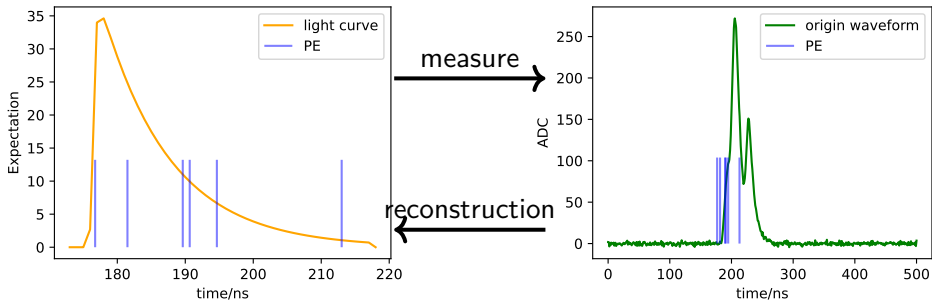
Figure: Time helps recovering pulses from fluctuation and noise.

Go directly from waveforms to event *time, location and energy*.

Photon counting

Given a **light curve** $\mu\phi(t - t_0)$ received **photoelectron** (PE), their times being $\vec{z} := (t_1, t_2, \dots, t_N)$. **waveform** $\vec{w}$ is a time series.

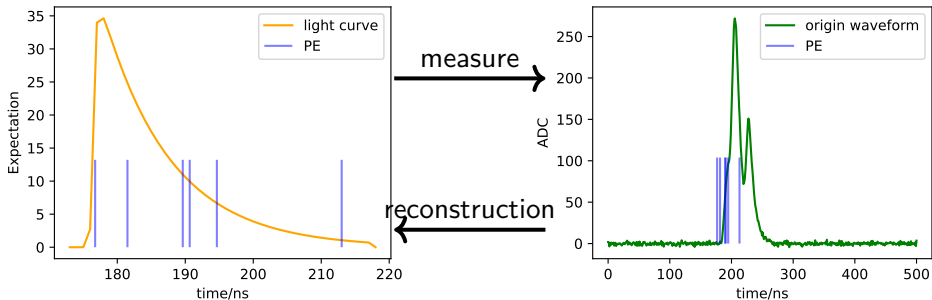
$$\mu, t_0 \rightarrow \vec{z} \rightarrow \vec{w}$$



Photon counting

Given a light curve $\mu\phi(t - t_0)$ received photoelectron (PE), their times being $\vec{z} := (t_1, t_2, \dots, t_N)$. waveform $\vec{w}$ is a time series.

$$\mu, t_0 \rightarrow \vec{z} \rightarrow \vec{w}$$

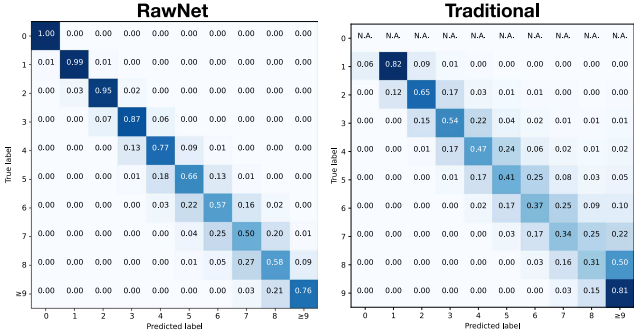


$$\mu, t_0 \xleftarrow{\text{fit}} \vec{z} \xleftarrow{\text{analyze}} \vec{w}$$

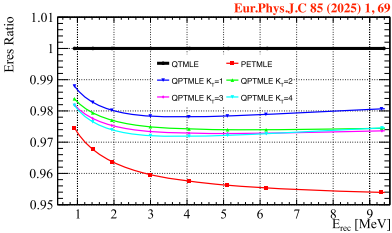
- overlapping pulses, cannot measure $\vec{z}$ precisely. Big challenge.

Waveform reconstruction with NN classifier

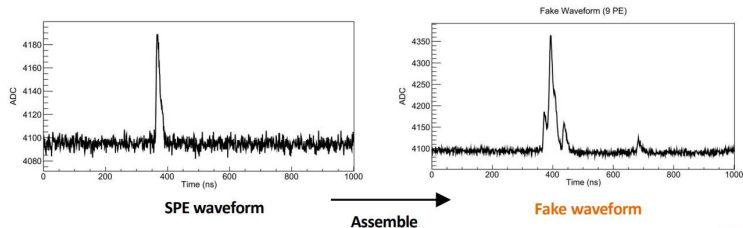
Layer	Input	Output shape
Strided -conv	Conv(3,3,128) BN LeakyReLU	(128, 140)
Res block	$\begin{pmatrix} \text{Conv}(3, 1, 128) \\ \text{BN} \\ \text{LeakyReLU} \\ \text{Conv}(3, 1, 128) \\ \text{BN} \\ \text{LeakyReLU} \\ \text{Max Pool}(3) \end{pmatrix} \times 2$	(128, 46)
Res block	$\begin{pmatrix} \text{Conv}(3, 1, 256) \\ \text{BN} \\ \text{LeakyReLU} \\ \text{Conv}(3, 1, 256) \\ \text{BN} \\ \text{LeakyReLU} \\ \text{Max Pool}(3) \end{pmatrix} \times 2$	(256, 1)
GRU	GRU(1024)	(1024,)
Speaker embedding	FC(128)	(128,)
Output	FC(10)	(10,)



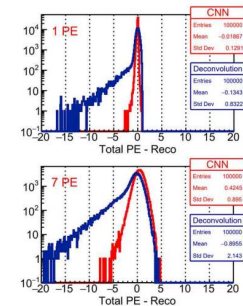
- A customized RawNet model to predict the probability of PE counts of each PMT.
- Show improvement over traditional waveform reconstruction methods.
- With the potential to further improve JUNO's energy resolution



Data-driven photo-electron counting



- ML training with simulation datasets is vulnerable to potential uncertainties in waveform modeling.
- Build “fake waveforms” from calibration data from radioactive sources for a data-driven ML training.



Reversible jump Markov Chain Monte Carlo

NPE is the uncertain count of elements
in $\vec{z}$.

$$\begin{aligned}
 p(\vec{w}|t_0, \mu) &= \underbrace{p(\vec{w}|\emptyset)p(\emptyset|t_0, \mu)}_{\text{no integral}} \\
 &+ \underbrace{\int_{\vec{z} \in T} p(\vec{w}|\vec{z})p(\vec{z}|t_0, \mu)d\vec{z}}_{\text{single integral}} \\
 &+ \underbrace{\iint_{\vec{z} \in T^2} p(\vec{w}|\vec{z})p(\vec{z}|t_0, \mu)d\vec{z}}_{\text{double integral}} \\
 &+ \underbrace{\iiint_{\vec{z} \in T^3} p(\vec{w}|\vec{z})p(\vec{z}|t_0, \mu)d\vec{z}}_{\text{triple integral}} \cdots .
 \end{aligned}$$

- Use Markov chain, having $\vec{z}$ jumping over different terms.

JINST 17 P06040, NIM A 1082(2026) 170986

Waveforms to event time, location and energy

- Fusion of waveform analysis and event reconstruction.

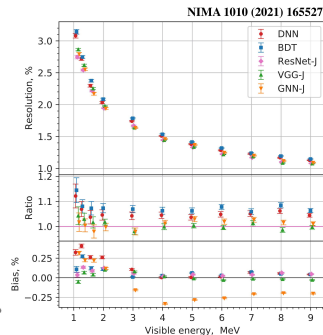
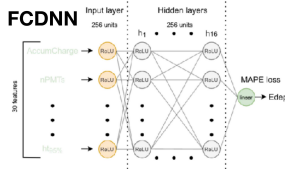
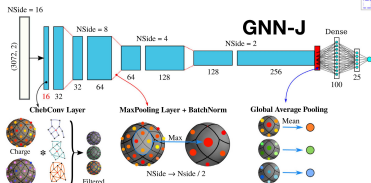
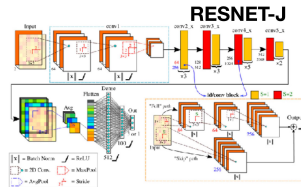
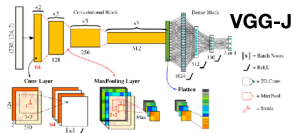
$$\begin{aligned}\mathcal{L}(\{\vec{w}_i\} | E, t_0, \vec{r}) &= \prod_i p[\vec{w}_i | R_i(t; E, t_0, \vec{r}) + b_i] \\ &= \prod_i \sum_j p(\vec{w}_i | \vec{z}_j) p[\vec{z}_j | R_i(t; E, t_0, \vec{r}) + b_i]\end{aligned}$$

Diagram annotations:

- $\vec{w}_i$: waveform
- b_i : dark noise
- $\sum_j$: all PE times (sampled)
- $p(\vec{w}_i | \vec{z}_j) p[\vec{z}_j | R_i(t; E, t_0, \vec{r}) + b_i]$: total probability
- $\vec{z}_j$: SPE charge spectrum embedded

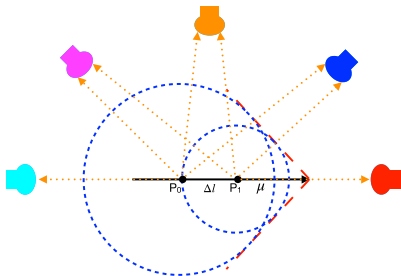
- The PEs on PMT i follow inhomogeneous Poisson process $R_i(t; E, t_0, \vec{r})$. It captures scintillation profile, time-of-flight, scattering, re-emission, etc.
- Interfacing with trans-dimensional $\vec{z}$ space allow full propagation of uncertainty.

End-to-end Neural Networks

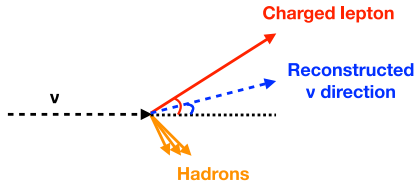


- Multiple ML models explored for the energy and vertex reconstruction for reactor neutrinos. (NIMA 1010 (2021) 165527, Eur.Phys.J.C 82 (2022) 11, 1021, Nucl.Sci.Tech. 33 (2022) 7, 93)

Atmospheric ν



Scintillation light photon distribution from a charged particle track in space and time is not isotropic



- PMTs at different angles wrt the track see distinct shapes of $R(t)$
- Exactly how $R(t)$ looks depends on:
 - Track direction;
 - Track starting and stopping points;
 - Track $dE/dx...$

Directionality
Energy
PID...

- Machine learning for GeV atmospheric $\nu \rightarrow$ Milo Charavet's talk

Probabilistic machine learning

- Recent break-throughs e.g. diffusion model are synergy between probability, neural network and physics.

Table: table of synonyms

Statistics	Computer Science	Physics
estimation	learning	determinate
classification	supervised learning	
clustering	unsupervised learning	
data	training sample	
covariates	features	
guess		estimate

- Wasserman, Larry. All of Statistics: A Concise Course in Statistical Inference. Springer, 2003.
- James, Frederick. Statistical Methods In Experimental Physics. 2nd edition. Wspc, 2006.

Conclusion

Personal vision on ν experiments

- an inner **machine learning** and outer **statistical** approach.
 - the **statistical** part captures well-understood distributions.
 - the **machine learning** part handles complexity of the reality.
- → Andrea Serafini's talk on calibration and detector surrogates.

Conclusion

Personal vision on ν experiments

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Summary

- ν mass ordering motivate JUNO and machine learning studies.
- JUNO represents state-of-the-art of liquid scintillator detector.
- Liquid scintillator filling completed and data taking started.
- Expecting much excitement in physics!

JUNO collaboration since 2014

17 countries/regions, 74 institutes, >700 people.

Ladders of likelihood

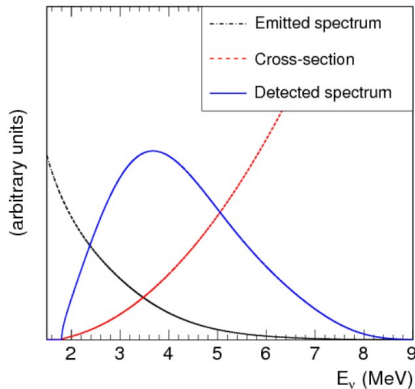
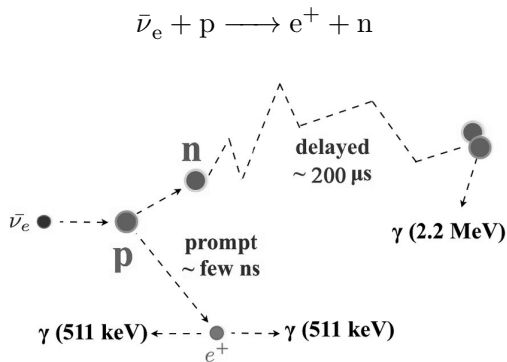
Note	Algo. Name	Observable	Likelihood: $\kappa \leq K_T$	Likelihood: $\kappa > K_T$
Charge, Time, Maximum Likelihood Estimation	QTMLE (reference)	q (charge)	$\mathcal{L}(q_i \mu_i) = \sum_{k=1}^{+\infty} P_Q(q_i k)P(k, \mu_i)$	
PE, Time, Maximum Likelihood Estimation	PETMLE (ideal)	k (true PEs)	$\mathcal{L}(k_i \mu_i) = P(k_i, \mu_i)$	
Charge, Probability, Time, Maximum Likelihood Estimation	QPTMLE (realistic)	{p _k }, q	$\mathcal{L}(\{p_k^i\} \mu_i) = \sum_{k=0}^9 R_{K_T k} p_k^i P(k, \mu_i).$	$\mathcal{L}(q_i \mu_i) = \sum_{k=1}^{+\infty} P_Q(q_i k)P(k, \mu_i)$
Charge, PE, Time, Maximum Likelihood Estimation	QPETMLE (100% accuracy)	k(p _k =1), q	$\mathcal{L}(k_i \mu_i) = P(k_i, \mu_i)$	
Charge, Confusion Matrix, Time, Maximum Likelihood Estimation	QCTMLE	κ (p _κ :max), q	$) = \sum_{k=0}^9 C_{k\kappa_i} \times P(k, \mu_i)$	

where μ_i is the expected nPEs for the i-th PMT, $P(k, \mu_i)$ is just the Poisson probability of observing k p.e. given μ_i and $P_Q(q_i|k)$

$$R_{K_T k} = \sum_{\kappa=0}^{K_T} C_{k\kappa},$$

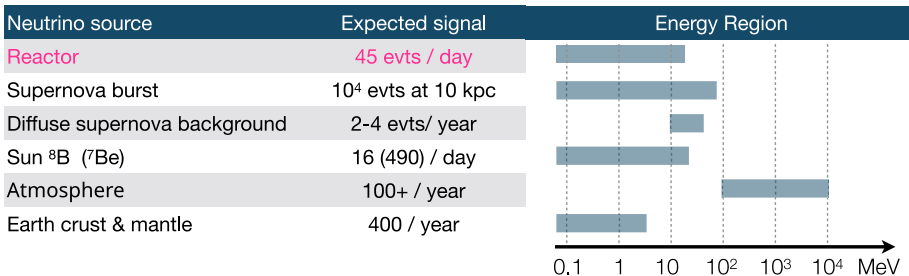
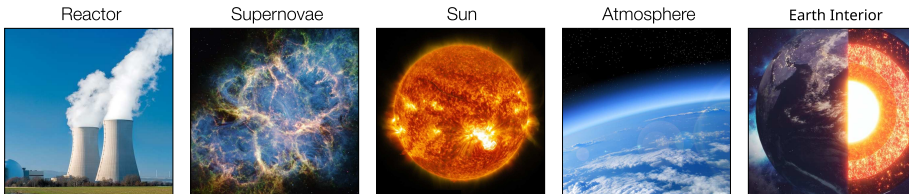
confusion matrix $C_{k\kappa'}$

$\bar{\nu}$ detection with inverse beta decay (IBD)



e^+/γ scintillation light are collected by photomultipliers.

ν research enabled by large 20 kt target

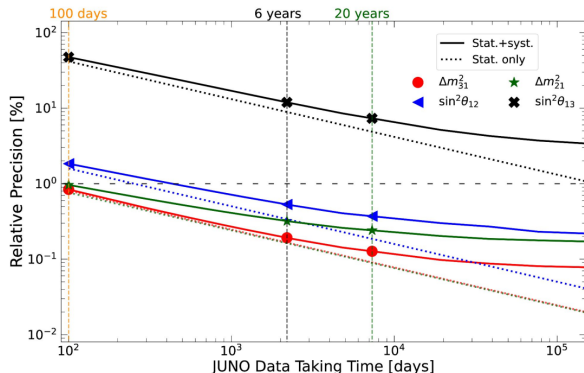


Precision Measurement of Oscillation Parameters

Sensitive to mass differences $\Delta m_{31}^2, \Delta m_{21}^2$ and mixing angles θ_{12}, θ_{13} .

$$\begin{cases} |\langle \nu_e | \nu_1 \rangle| = \cos \theta_{13} \cos \theta_{12} \\ |\langle \nu_e | \nu_2 \rangle| = \cos \theta_{13} \sin \theta_{12} \\ |\langle \nu_e | \nu_3 \rangle| = \sin \theta_{13} \end{cases}$$

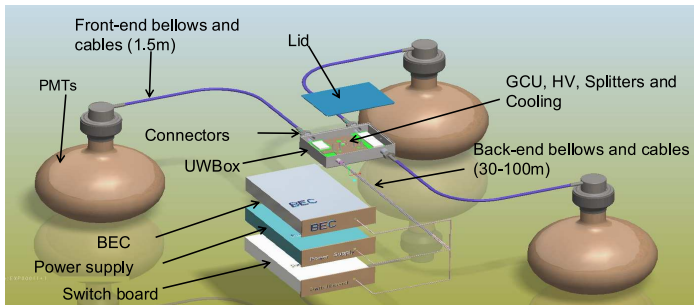
Non-unitarity $\sum_{i=1}^3 |\langle \nu_e | \nu_i \rangle|^2 < 1$ indicates the existence of N_R and $\langle \nu_e | N_R \rangle > 0$.



	PDG 2024	JUNO 6 years
$\sin^2 \theta_{13}$	3.2%	12%
$\sin^2 \theta_{12}$	4.2%	0.5%
Δm_{21}^2	2.4%	0.3%
Δm_{31}^2	1.1%	0.2%

Chin. Phys. C46 12, 1230001 (2022)

Underwater electronics system



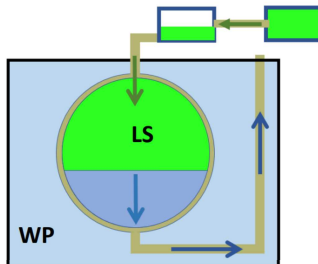
- The 1F3 system cases Splitter, HV FEC, ADC, GCU&FPGA underwater boxes
- Two cable supply low voltage DC power, timing signal and data transfer



Liquid scintillator handling system



monitor



- Attenuation length >20 m
- $U/Th < 1 \times 10^{-15}$ g/g

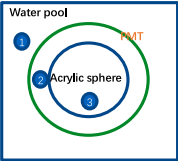
procedures

- Al_2O_3 for transparency.
- Water extraction.
- Rn and O_2 gas stripping.

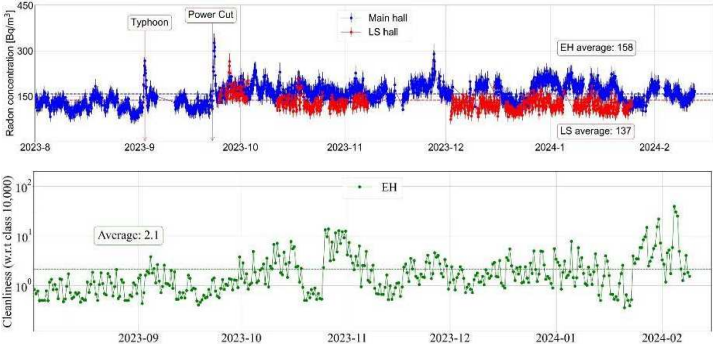
Radiopurity

- ❖ Average radon and cleanliness:
 - Radon concentration: ~160 Bq/m³ in the EH, ~140 Bq/m³ in the LS hall
 - Cleanliness: class 20,000

Region	Level
1	Class 100,000
2	Class 10,000
3	Class 1000



Radon concentration
in air: < 200 Bq/m³



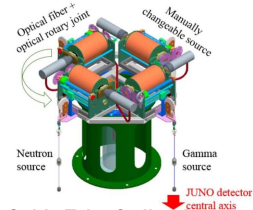
Removal of radio-purity preserving paper film



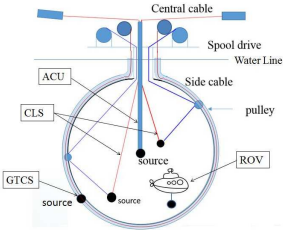
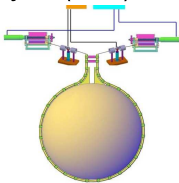
Water washing with hand picking.

Calibration system

Automatic Calibration Unit (ACU)

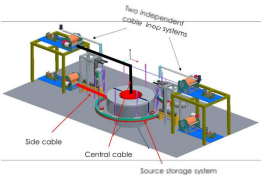


Guide Tube Calibration System (GTCS)

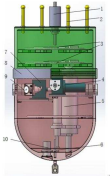


- Complementary for covering entire energy range of reactor neutrinos and full-volume position coverage inside JUNO central detector

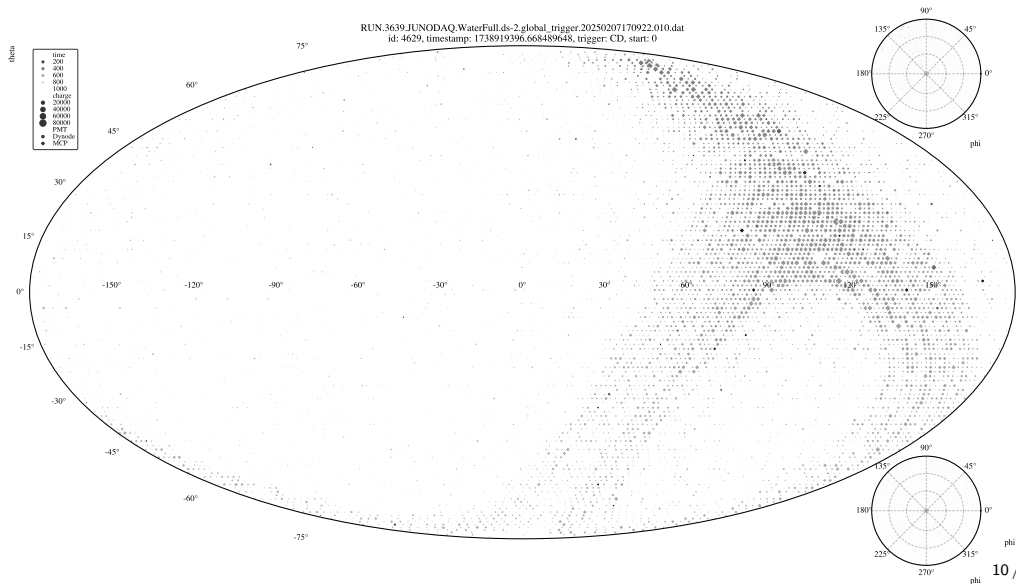
Cable Loop System (CLS)



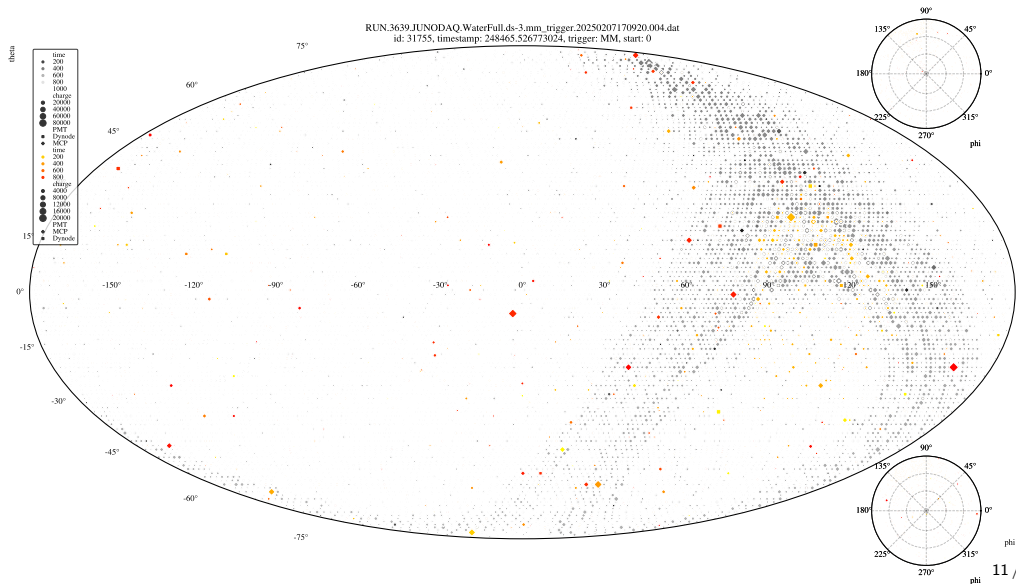
Remotely Operated under-liquid-scintillator Vehicles (ROV)



Water phase: stopping muon



Water phase: michel electron



Status of the detector

PMTs

- Gains are stable.
- 8 are dead, about 200 are unstable. (out of 17596)

Radiopurity

- $^{214}\text{Bi}/^{214}\text{Po}$ from ^{238}U chain and $^{212}\text{Bi}/^{212}\text{Po}$ from ^{232}Th chain
- $^{238}\text{U}/^{232}\text{Th}$ less than $1 \times 10^{-16} \text{ g/g}$

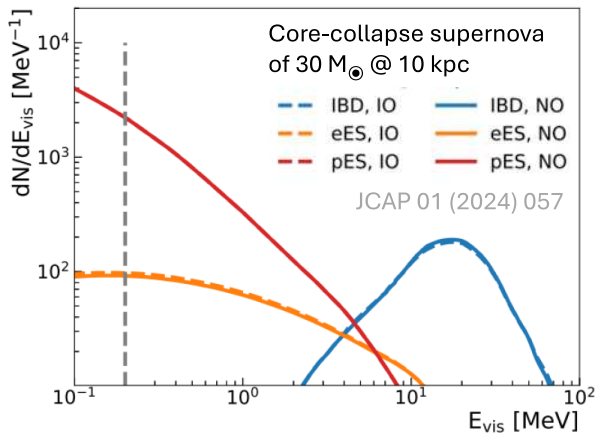
Water phase comparison with SK

- The fitted light-yield in water phase is $14.0 \pm 0.1 \text{MeV}^{-1}$
 - Higher PMT PDE than SK~(16 %)
 - Higher PMT coverage rate than SK~(40 %)
 - Smaller size of detector than SK
 - The light of SK is around 10MeV^{-1}

Supernova burst neutrinos

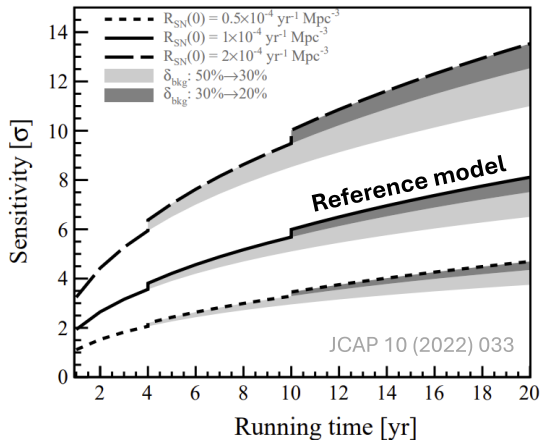
up to 10 kpc. supernova at the local cluster.

- supernovae observer
- pre-supernova alert



Supernova relic neutrinos

- Discriminate against atmospheric neutrino background;
- 5σ discovery potential with reference model.



Solar fusion process

- JUNO is an solar neutrino detector by elastic scattering on the electrons.

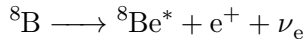
predictions of solar neutrino flux

- fusion cross sections are critical inputs
 - together with the abundance, temperature and gravity-radiation pressure equation constitutes the standard solar model.

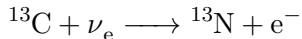
Cleanness of the detector

Solar sensitivity study.

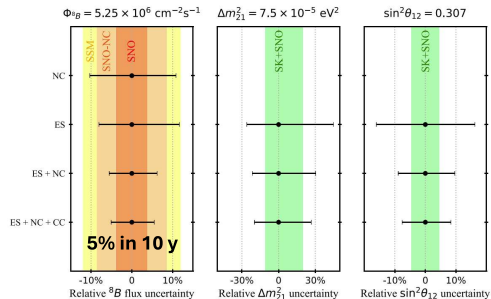
^8B neutrinos



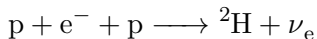
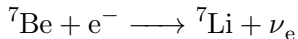
- capable to detect ^8B in a model independent way.
- combination of charged and neutral on ^{13}C .



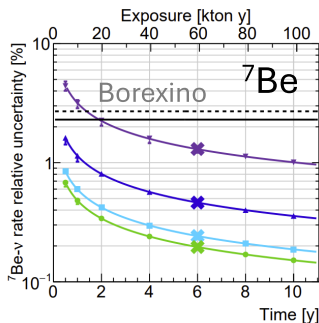
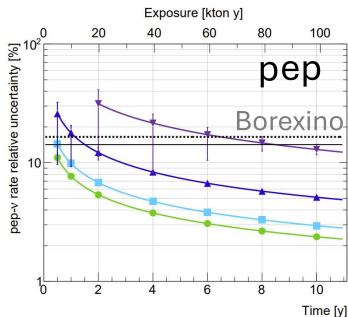
- measurement of θ_{12} and Δm_{12}^2 .
Astrophys. J. 965.2: 122 (2024)



pep and ^7Be neutrinos



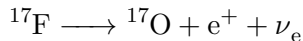
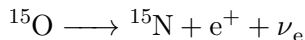
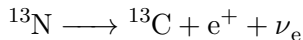
- better than Borexino (state of the art) in 2 years.



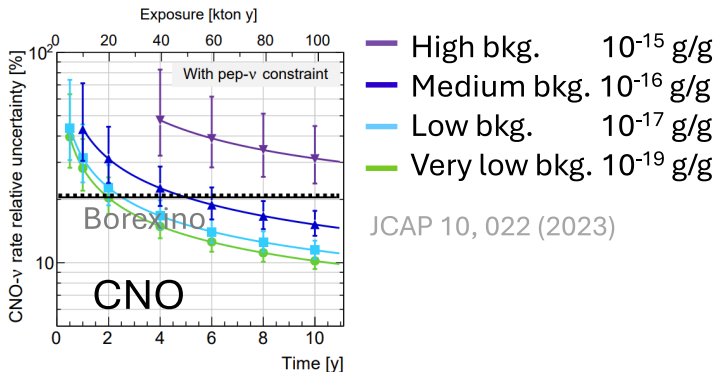
- High bkg. 10^{-15} g/g
- Medium bkg. 10^{-16} g/g
- Low bkg. 10^{-17} g/g
- Very low bkg. 10^{-19} g/g

JCAP 10, 022 (2023)

Neutrinos from CNO-cycle



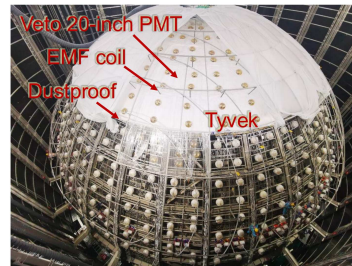
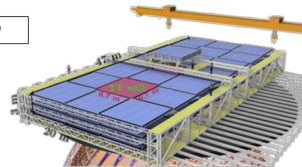
- better than Borexino (state of the art) in 6 years.



Veto

- **Water Cherenkov + Top tracker**
- Water Cherenkov detector
 - **35 kton** water to shield backgrounds from the rock
 - Instrumented w/ **2400 20-inch PMTs** on SS structure
 - Water pool lining: 5mm HDPE (black) to keep the clean water and to stop Rn from the rock, covered w/ tyvek
 - **100 ton/h pure water system**
Requirement: $U/Th/K < 10^{-14}$ g/g and $Rn < 10$ mBq/m³, attenuation length > 40 m, temperature controlled to $(21 \pm 1)^\circ\text{C}$
- Top tracker
 - Refurbished OPERA scintillators
 - 3 layers, $\sim 60\%$ coverage on the top
 - $\Delta\theta \sim 0.2^\circ$, $\Delta D \sim 20$ cm
- Earth Magnetic Field compensation coil

NIMA 1057 (2023) 168680



Non-zero ν mass beyond the standard model (BSM)

Non-zero m_ν is established as a solution to the **solar neutrino problem**.

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Indicates the existence of right-handed counterparts:

- Lorentz: try travel faster than a ν_L .
- Higgs: right-handed ν to have mass.

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Majorana mass

$$\mathcal{L} = \frac{1}{2} M_N \overline{N_R^c} N_R + Y_\nu H \overline{L}_L N_R + \cdots + \text{h.c.}$$

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The standard solar model defeated standard model of particle physics.

- Solar physicists won the battle against their particle colleagues;
- Particle physicists are **excited** to lose!

The inevitable majorana term and seesaw mechanism

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Clues to the difficult problems of physics, astronomy and cosmology:

- ① How ν have mass and why the m_ν is so small (< 1 eV).
- ② If lepton number is violated i.e. if there are majorana fermions in nature.
- ③ If leptogenesis created the matter-antimatter asymmetry.
→ the **origin of matter** precluding nucleosynthesis.
- ④ ν_R is among the dark matter candidates.
→ gravitational **evolution of galaxies**.

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JUNO is the next milestone

to measure the ν **mass spectra** and falsify ν_L - N_R **mixing**.

Filling timeline

