Neutrino Physics with JUNO

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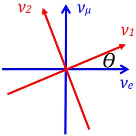
Neutrino oscillations

- neutrinos are created in one flavour, but can be detected in another

- each flavour state is a superposition of mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



Three flavour oscillation

- The mixing matrix (PMNS matrix) can be written in terms of 3 angles and 1 phase. Usually factorized into components directly related to the experiments:

- the (12) sector: Solar and Reactor — L/E ∼ 15,000 km/GeV
- the (23) sector: Atmospheric and Accelerator — L/E ∼ 500 km/GeV
- the (13) sector: Reactor and Accelerator — L/E ∼ 500 km/GeV

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

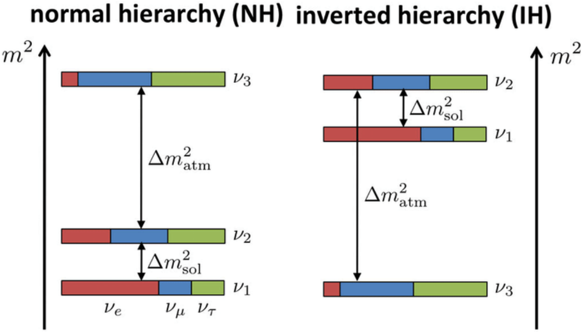
$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

Neutrino Δmass^2 and ordering

- neutrino oscillation experiments can access the mass square differences:

  $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2 \qquad |\Delta m^2_{32}| = (2.453 \pm 0.033) \times 10^{-3}\ \mathrm{eV}^2$

  R. L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)



- ν_1 is (by convention) the mass eigenstate with the largest ν_e component
- we do not know which mass eigenstate is the lightest $\rightarrow$ mass hierarchy (ordering)problem:
- normal ordering: ν_1 lightest
- inverted ordering: ν_3 lightest

JUNO contribution to neutrino oscillations

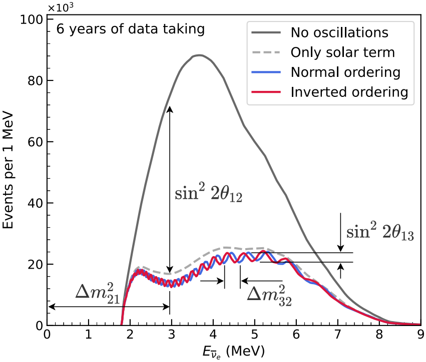
- JUNO will detect reactor $\overline{\nu}_e$ and

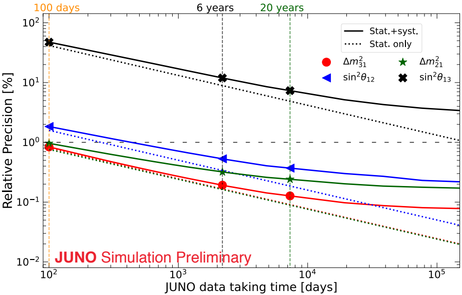
➜ determine neutrino mass ordering, at $\sim 3 - 4\sigma$ with 6 years of reactor data

- the measurement is independent of δ_{CP} and $\sin^2\theta_{23}$

➜ measure at sub-percent level the neutrino oscillation parameters

- $\sin^2 2\theta_{12}$, Δm^2_{21} and $|\Delta m^2_{32}|$

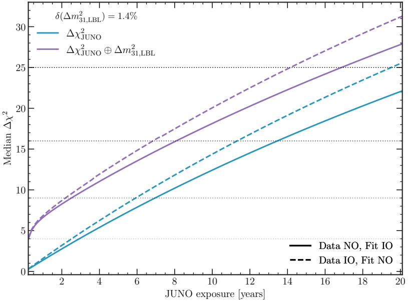


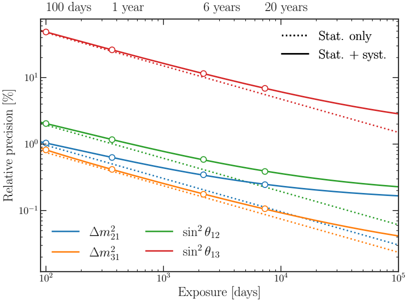


	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%

A. Abusleme at al., Chin. Phys. **C 46** (2022) 123001

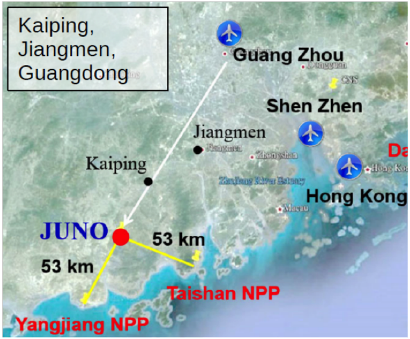
- First experiment to be simultaneously sensitive to two oscillation frequencies
- Neutrino Mass Ordering at 3σ with 6 years of data-taking
- No dependence on δ_{CP} and θ_{23}
- Complementary to long baseline experiments
- Sub-percent precision in less than 2 years on three parameters: Δm^2_{21}, $\sin 2\theta_{12}$, and Δm^2_{31}
- Precision measurement of oscillation parameters as a powerful tool to test the standard 3-flavor neutrino framework
- Unitarity of the PMNS matrix (Electron Row Unitarity test)

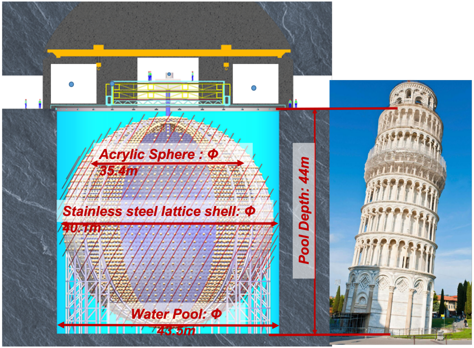


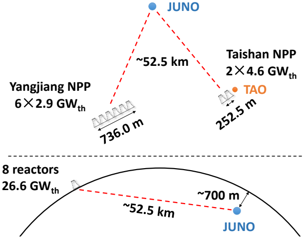


JUNO in a nutshell

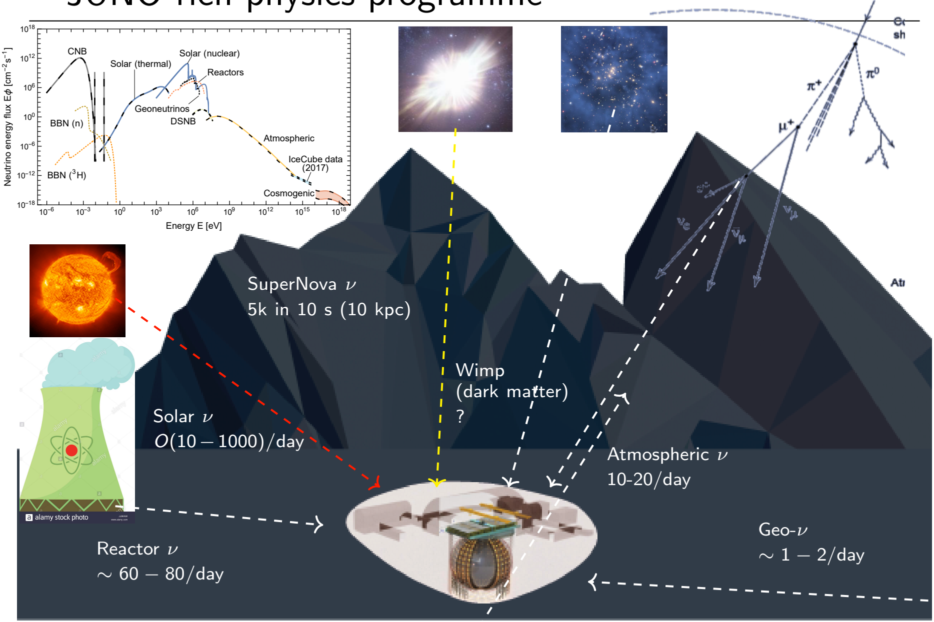
- it's going to be the largest ever built liquid scintillator (LS) detector for neutrino and rare events physics (including dark matter)
- the main target is the determination of the neutrino mass hierarchy, one of the still unanswered questions in neutrino physics
- thanks to the large mass (20 kt) and overburden (1800 m.w.e.), JUNO will be able to exploit several neutrino physics channels





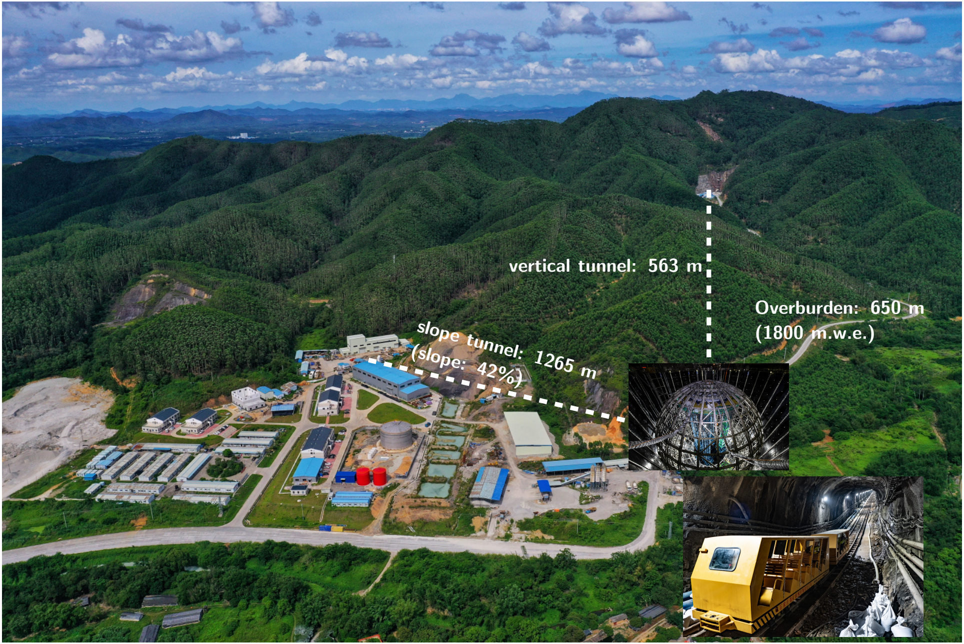


JUNO rich physics programme

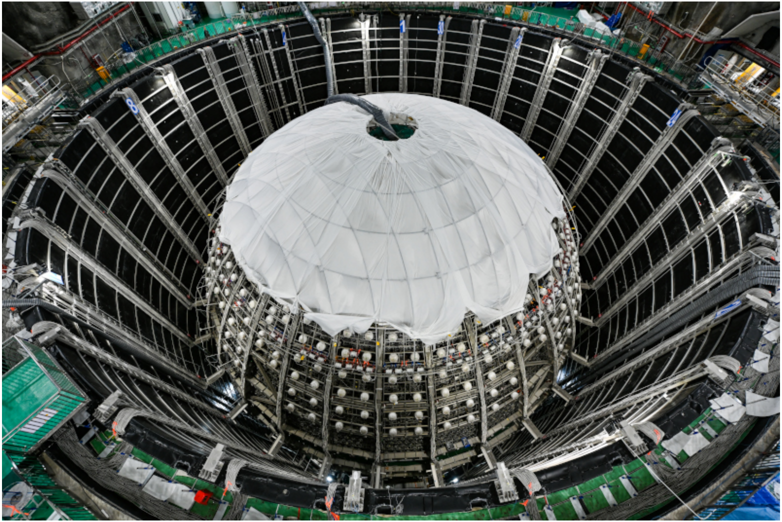


F. An et al., *Neutrino Physics with JUNO*, J. Phys. **G 43** (2016) 030401, arXiv:1507.05613
A. Abusleme at al., Prog. Part. Nucl. Phys. **123** (2022) 103927 arXiv:2104.02565

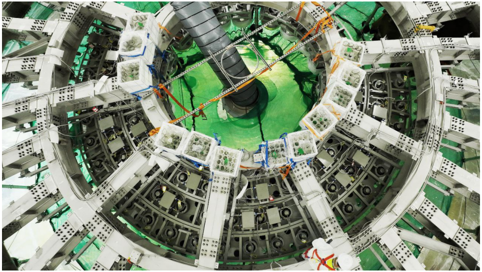
The JUNO experimental site

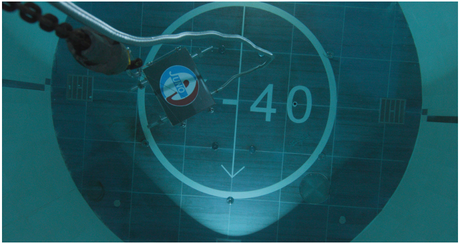


The JUNO detector construction



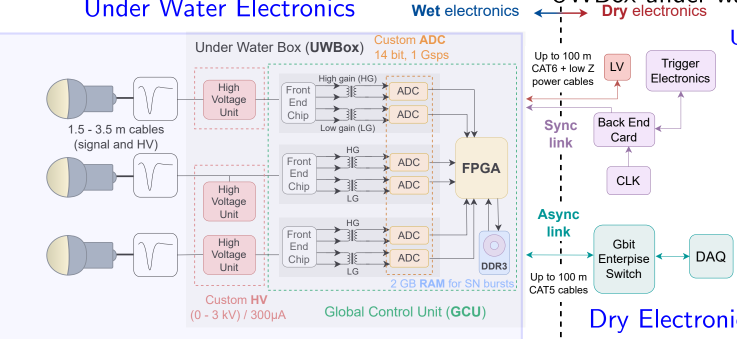
JUNO large PMT Electronics





UWBox under water (-40 m)

Under Water Electronics



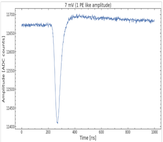
Dry Electronics

UWBox with electronics

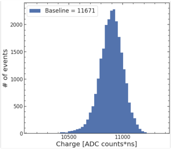
Real-Time charge reconstruction in JUNO

- real-time monitoring of transient phenomena acquired by the JUNO detector (PMT tubes)
- based on a Baseline Tracking algorithm and a Continuous Over-Threshold Integration (COTi)
- firmware developing (VHDL) for the FPGAs of the GCUs

PMT

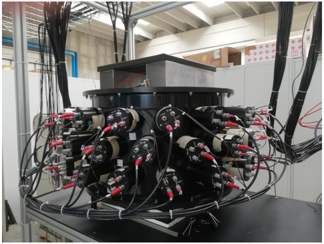


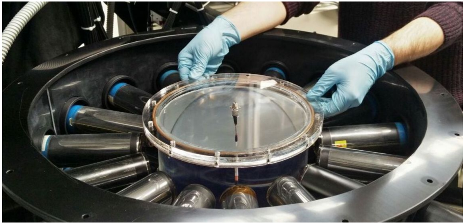
GCU acquisition



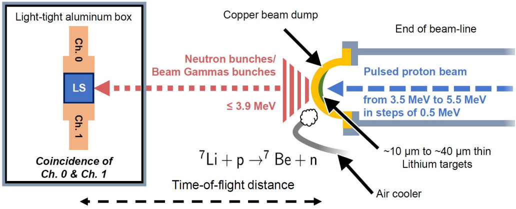
Reconstruction

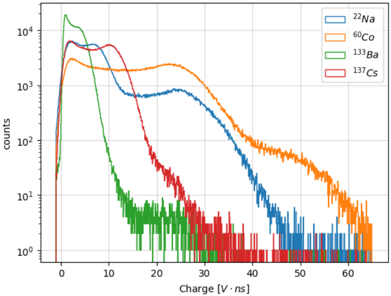
JUNO Electronics setup (LNL)





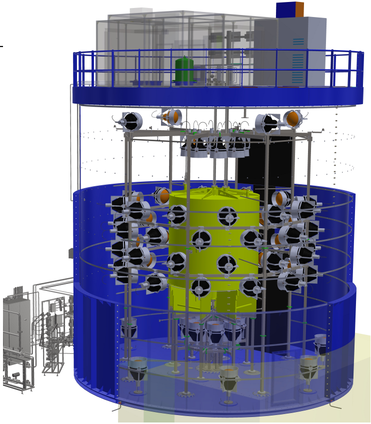
- small complete setup with LS (20 liters), 48 PMTs + JUNO electronics readout (full chain)
- allows several measurements with different sources: laser, γs, cosmic μs and test beam particles

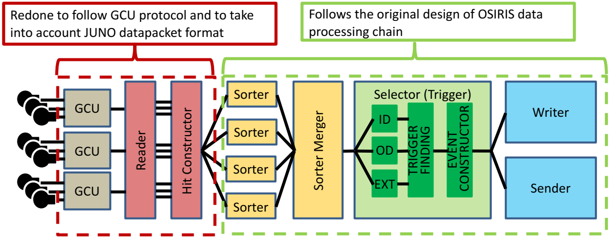




JUNO Electronics for OSIRIS

- Online Scintillator Internal Radioactivity Investigation System (OSIRS) : stand-alone (20 t) LS detector to verify the quality and radiopurity of JUNO LS during filling
- OSIRIS : *small* JUNO : 20 t LS read by 75 LPMTs
- in installation phase: it's commissioning will help to verify the performances of electronics and the whole DAQ and reconstruction phase
- now detector filled with water, replacement with LS ongoing
- the JUNO LNL setup is fundamental in commissioning the radout software and analysis chain





The JUNO Padova Group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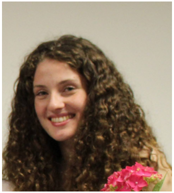
B. Rasera

Recent Publications

- R. Triozzi et al., *Implementation and performances of the IPbus protocol for the JUNO Large-PMT readout electronics*, submitted to Nucl. Instr. Meth. **A**
  https://arxiv.org/abs/2302.10133,
- A. Coppi et al., *Mass testing of the JUNO experiment 20-inch PMTs readout electronics*, submitted to Nucl. Instr. Meth. **A**
  https://arxiv.org/abs/2301.04379,
- V. Cerrone et al., *Validation and integration tests of the JUNO 20-inch PMTs readout electronics*, submitted to Nucl. Instr. Meth. **A**
  https://arxiv.org/abs/2212.08454,
- A. Abusleme et al., JUNO Collaboration, *JUNO physics and detector*, Progr. Part. Nucl. Phys. **123**, (2022) 103927
  https://arxiv.org/abs/2104.02565
  https://doi.org/10.1016/j.ppnp.2021.103927
- Z. Qian et al., *Vertex and Energy Reconstruction in JUNO with Machine Learning Methods*, Nucl. Instr. Meth. **A 1010** (2021) 165527.
  https://arxiv.org/abs/2101.04839
  doi:10.1016/j.nima.2021.165527
- A. Bellato et al., *Embedded readout electronics R&D for the large PMTs in the JUNO experiment*, Nucl. Instr. Meth. **A 986** (2021) 164600.
  https://arxiv.org/abs/2003.08339
  doi:10.1016/j.nima.2020.164600

JUNO thesis topics

- analysis of the first data collected by JUNO and determination of the neutrino oscillation parameters
- supernova detection in JUNO: development of online triggering algorithms and data reconstrution
- machine learning inspired algorithms applied to event reconstruction, data selection and analysis in JUNO
- commissioning of the OSIRIS detector and reconstruction of the first physics events: calibration data, cosmic muons, radioactive background (U/Th chains)
- real-time charge reconstruction with the large PMTs of the JUNO detector
- measurement of LS performances with test beam particle at LNL