Neutrino physics with JUNO and SoLid

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Université Libre de Bruxelles (ULB)

November 15^{th} 2023

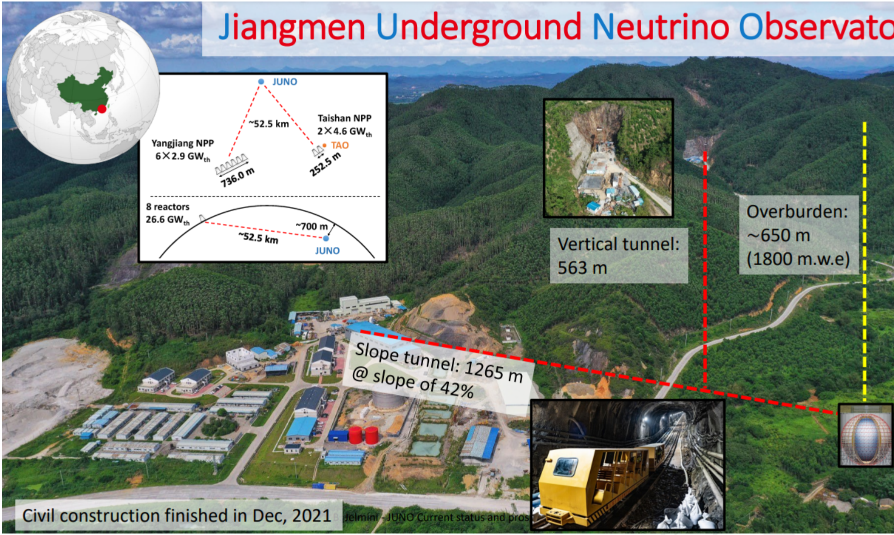
The JUNO and Solid people at IIHE

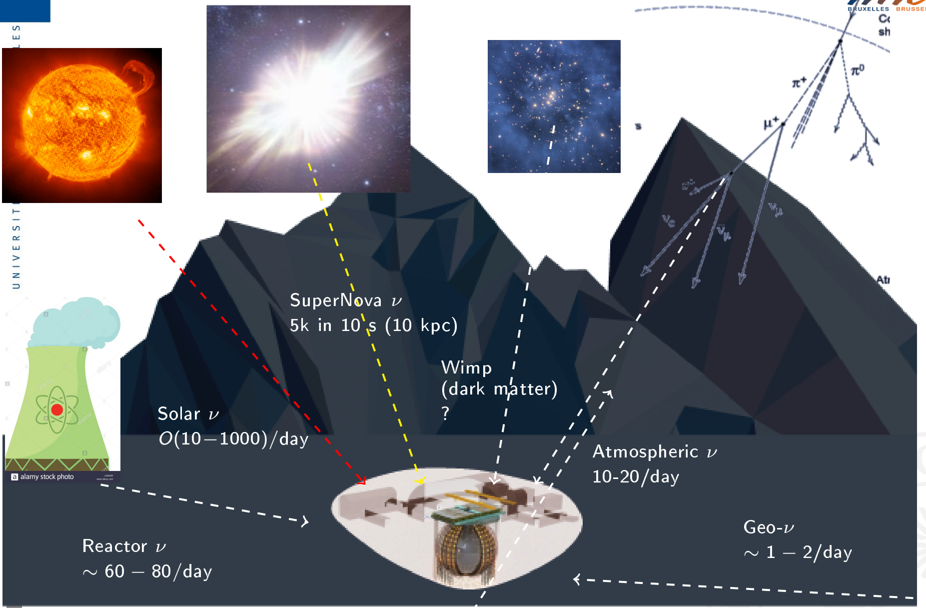
JUNO

- Pr., Dr., B. Clerbaux (Group leader)
- Dr., Ir., Y. Yang (Electronics engineer)
- Dr., M. Colomer (Post-doc started in 10/2020)
- Dr., F. Gao (Post-doc started in 10/2022)
- P.-A Petitjean (PhD started in 10/2018)
- T. Guide (Master thesis defended in August 2023)

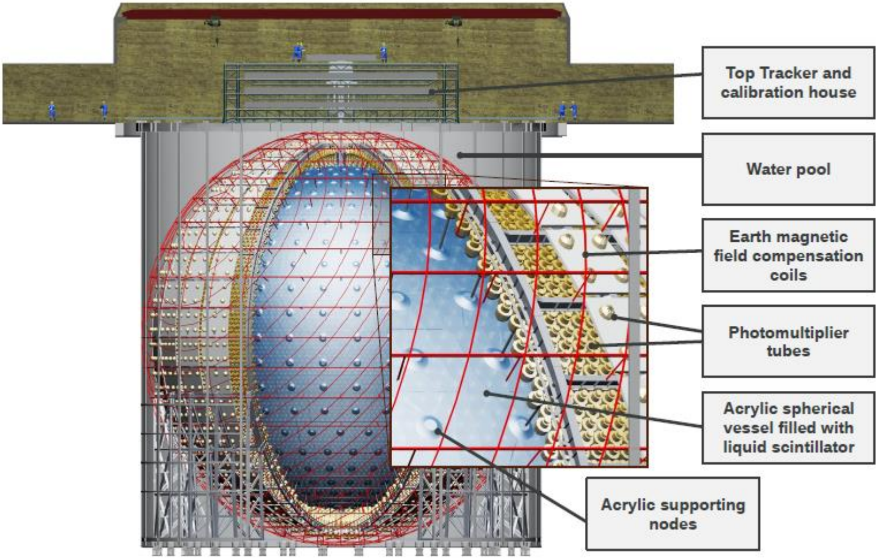
SoLid

- Pr., Dr. , J. D'hont (Group leader)
- Dr. , R. Keloth (Post-doc started in 10/2020)


Jiangmen Underground Neutrino Observato
JUNO
~52.5 km
Taishan NPP
2×4.6 GW$_{th}$
TAO
252.5 m
Yangjiang NPP
6×2.9 GW$_{th}$
736.0 m
8 reactors
26.6 GW$_{th}$
~700 m
~52.5 km
JUNO
Vertical tunnel:
563 m
Overburden:
~650 m
(1800 m.w.e)
Slope tunnel: 1265 m
@ slope of 42%
Civil construction finished in Dec, 2021

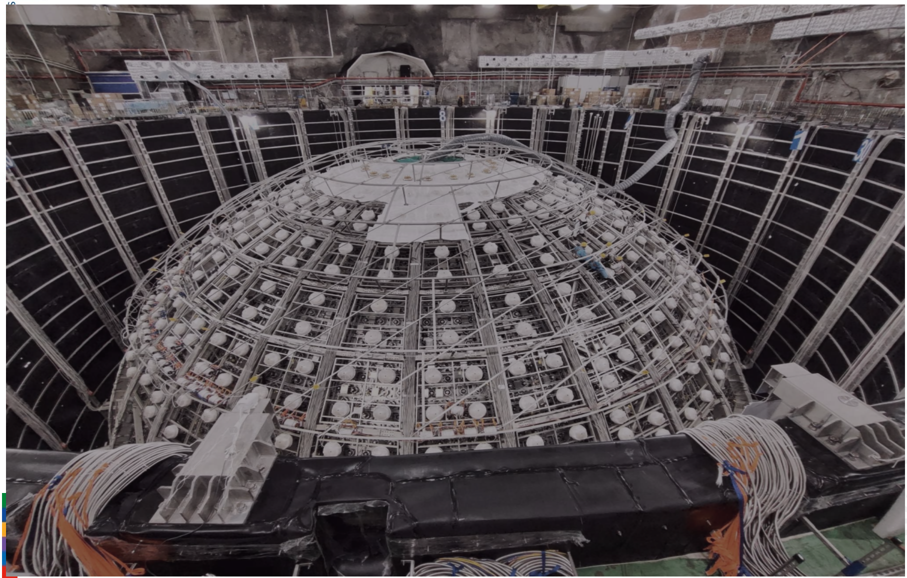

SuperNova ν
5k in 10 s (10 kpc)
Wimp
(dark matter)
?
Solar ν
$O(10-1000)$/day
Atmospheric ν
10-20/day
Reactor ν
$\sim 60-80$/day
Geo-ν
$\sim 1-2$/day
π^+
π^0
μ^+
ν_e
$\bar{\nu}_\mu$
ν_μ
alamy stock photo

The JUNO detector

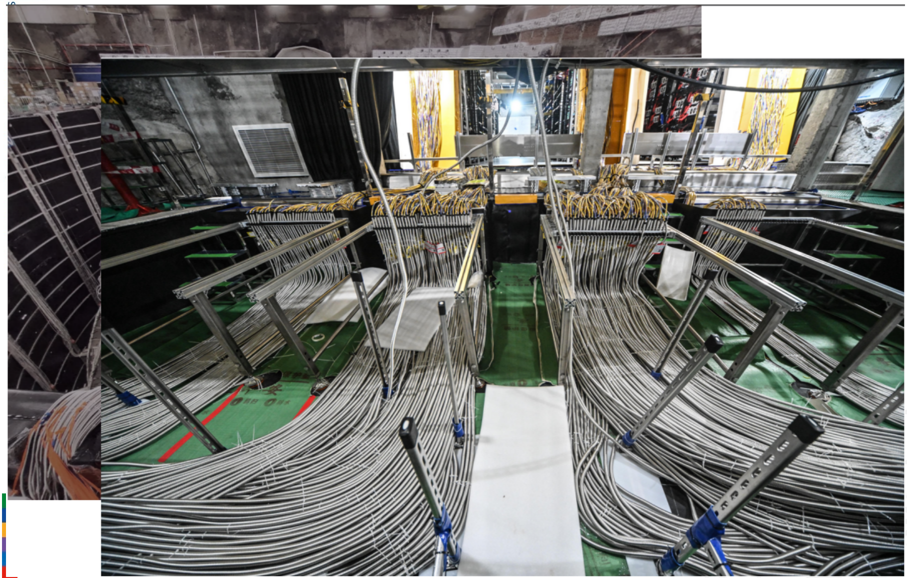


JUNO electronics

The JUNO electronics



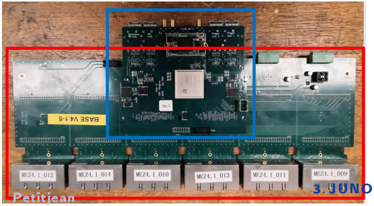
The JUNO electronics



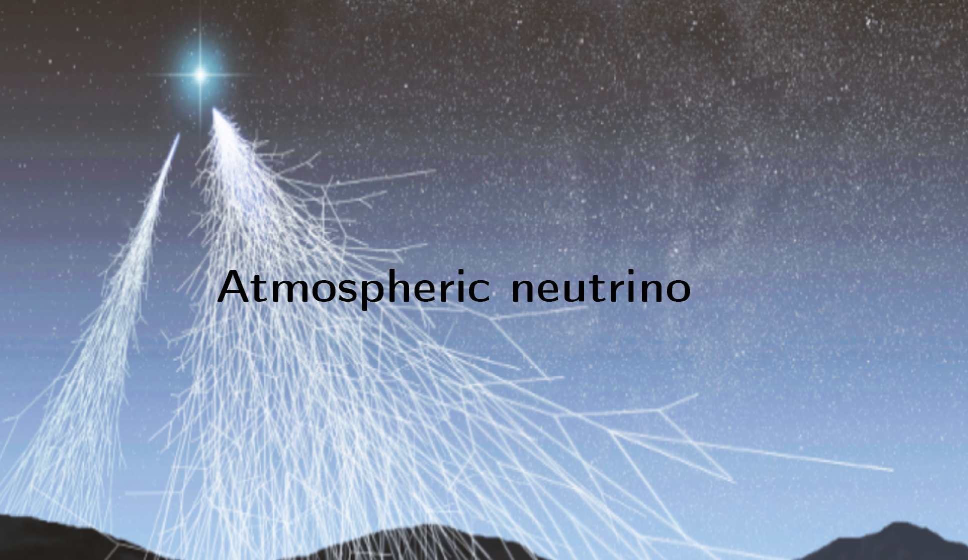

BEC
2-6-1a
2-6-1b
2-6-2a

Back-end electronics

- LPMT electronics is composed with two main subsystems: underwater electronics and dry electronics.
- IIHE is involved in the BEC development and production.
- A total of 180 BEC were produced for the different systems of the JUNO experiment. All have been tested successfully.
- All the BEC for JUNO central detector have been installed in the two electronics room.
- The BEC are for the moment under commissioning and tested with their corresponding GCU following the installation of the underwater electronics.



Atmospheric neutrino

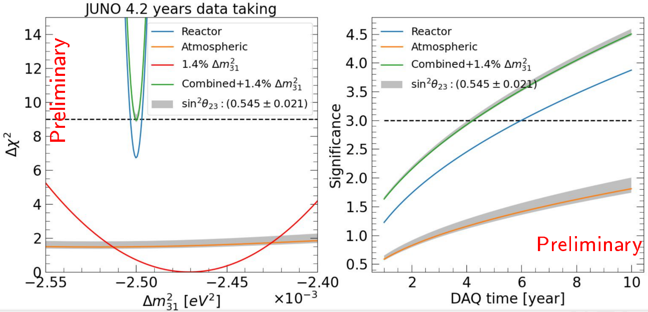


Atmospheric neutrinos

- Precise measurement of atmospheric neutrino
- Independent NMO measurement from reactor antineutrinos
- Combine the data from atmospheric and rector sensitivity up to 3σ in 4.2 year.

Challenges for atmo-ν:

1. $\sim$4 muons per second VS $\sim$4 neutrinos per day
   - $\rightarrow$ Reduce the background level by $\sim$ 5 orders of magnitude
2. Good energy ($\sim$ 10%) and direction ($\sim 20^\circ$) reconstruction
   - $\rightarrow$ High energy deposited in a small detector, non-contained events



Classify atmospheric neutrinos and muon

Challenge 1: ∼4 muons per second VS ∼4 neutrinos per day:

- The remaining muon contamination: ∼ 0.001%.
- The neutrinos eff.: 78.5%

Challenge 2: Good energy and direction reconstruction

- Use PMT detection light pattern to reconstruct the light emission probability map

→ Particle direction reconstruction uncertainty $< 1^\circ$ for muon.

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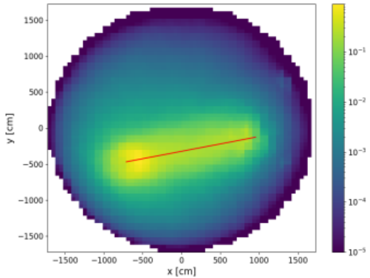
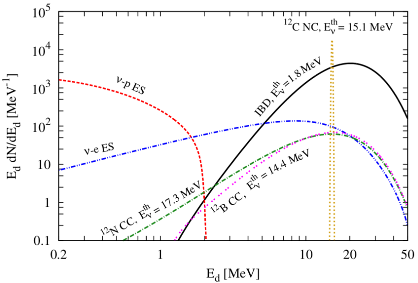


Reconstruction of 3 GeV ν_μ

Supernova neutrino with JUNO

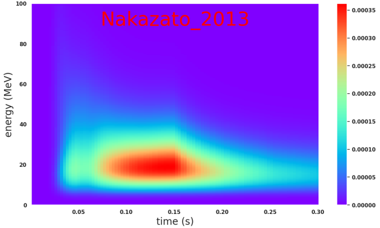
Core-Collapse Supernova (CCSN)

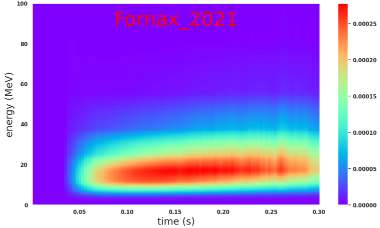
- JUNO has a great potential to observe several astronomical events in neutrinos:
  - Supernovae such as Core-Collapse Supernova (CCSN)
  - Neutron star mergers
  - Gamma ray bursts
- A CCSN releases 99% of its energy in neutrinos and antineutrinos of all flavors.
- Rate of CCSN in the Milky Way is 1.63 ± 0.46 per century [**New Astronomy Vol.83**, **101498**]
- JUNO with 20 kt LS has excellent capability of detecting all neutrino flavors through Charge current (CC), Neutral current (NC) and Elastic scatering (ES)
- Good energy and time resolution and flavor classification → constrain CCSN physics by measuring :
  - CCSN neutrino spectrum
  - CCSN lightcurve



Type	detailed process	Event number at 10 kpc
CC (IBD)	$\overline{\nu_e} + p \to e^+ + n$	~ 5000
eES	$\nu + e \to \nu + e$	~ 300
pES	$\nu + p \to \nu + p$	~ 2000
NC	$\nu + {}^{12}C \to \nu + {}^{12}C^*$	~ 300
CC	$\nu + {}^{12}C \to \nu + {}^{12}N$ $\nu + {}^{12}C \to \nu + {}^{12}B$	~ 200

Table: JUNO physics and detector, 10.1016/j.ppnp.2021.103927





Events rate for inverse-beta decay event for two different CCSM models.

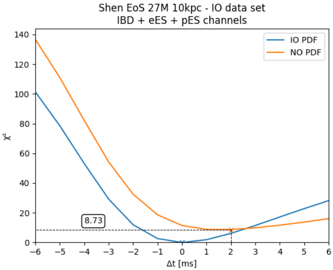
Results:

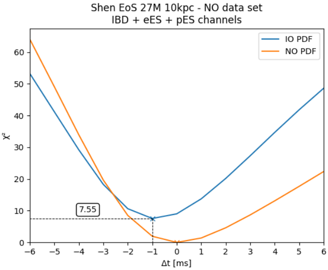
true model	Bollig	Fornax	Nakazato	Sukhbold	Tamborra	Warren
Bollig	69%	0.0 %	0.0 %	2.3 %	12.2 %	16.5 %
Fornax	0.1 %	99.8 %	0.0 %	0.0 %	0.1 %	0.0 %
Nakazato	0.0 %	0.0 %	100%	0.0%	0.0 %	0.0%
Sukhbold	2.6 %	0.0%	0.0%	92.3 %	0.3 %	4.8 %
Tamborra	11.3 %	0.2 %	0.0 %	0.4 %	81.5 %	6.6 %
Warren	21.3 %	0.0 %	0.0 %	4.1 %	8.1 %	66.5 %

Table: Binned ΔL for a distance $\pm 40 kpc$

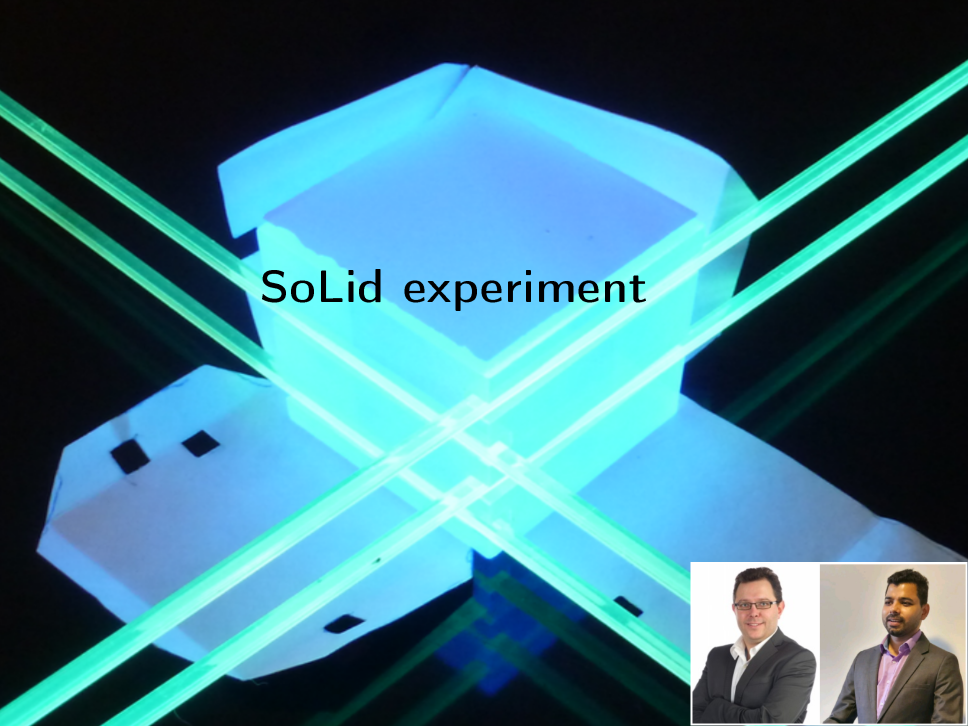
NMO sensitivity with CCSN (T. Guide master thesis)

- JUNO will be sensitive to more flavor than water Cherenkov experiment => more interaction channel.
- Thanks to CCSN flux, we want to determine the NMO thanks matter effect inside the star.
- Main advantage: in case of explosion detected by JUNO, we don't need to wait 10 year of data taking from reactor anti-neutrino to be able to discriminate between the two NMO.
- Method used : χ^2 test using Asimov method, sensitivity $\sim 3\sigma$.



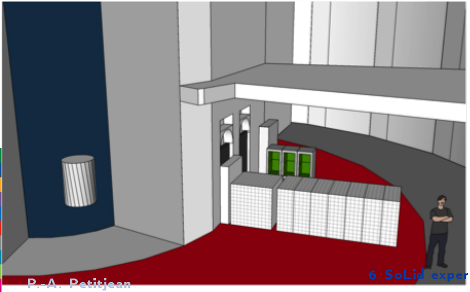


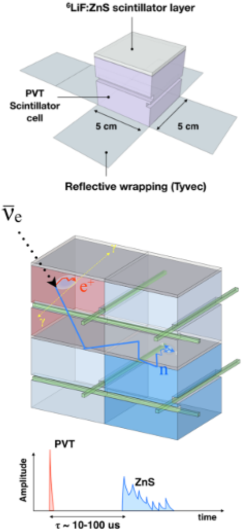
SoLid experiment



The SoLid experiment

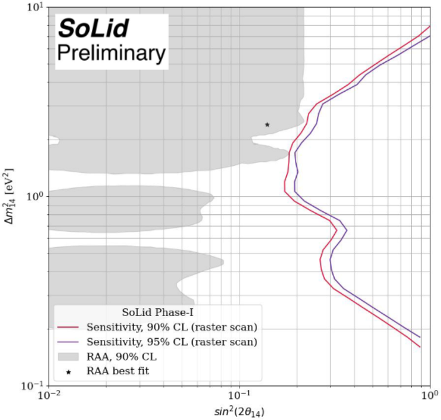
- Short-baseline neutrino oscillation experiment (vs medium baseline for JUNO)
- Investigates reactor antineutrino anomaly (RAA)
- 1.6 ton detector constructed 2016-2017 (vs 20 kt for JUNO)
- Solid-state scintillator design (vs liquid scintillator for Juno)
- Utilizes dense, segmented PVT-based scintillators
- Data collection: July 2018–June 2020





SoLid preliminary results

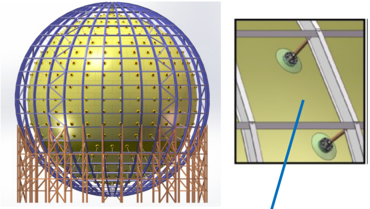
- Probe the reactor neutrino anomaly at close distance
- Very precise measurement of the ^{235}U spectrum.
- Very preliminary result, yet statistically dominated
- Signal over background improvement: went now from 1/5 to 1/3 with same efficiency
- Preparation of the final release with full dataset ongoing → results soon

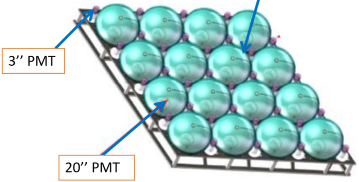


Thank you for your attention

Detector main components

- CD: Acrylic sphere with steel truss containing the LS (20 kton): large volume for gaining statistics.
- Double calorimetry :
  17612 20 inch PMTs cover 75% of the surface and 25600 3 inch cover 2.5% of the surface. Large coverage and double calorimetry to improve energy resolution.
- Muon veto : uses the OPERA tracker layers. Provides a tagged muon sample to study muon reconstruction and background contamination in the CD
- Calibration : 4-complementary systems: Automatic calibration unit (1D- centralaxis scan), Cable loop and guide tube calibration systems (2D), remotely operated vehicules (3D) – radiative sources (photon, positrons, neutrons)





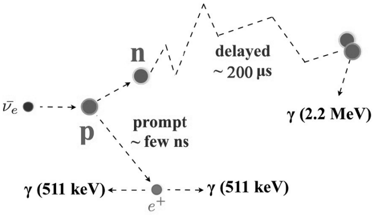
Neutrino mass ordering study with JUNO

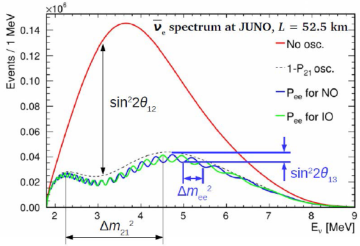
- Reactors anti-neutrinos are detected via inverse beta decay (1) where delayed signal comes from neutron capture on H (2):

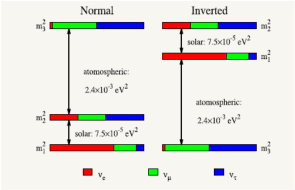
$$\overline{\nu}_e + p \rightarrow e^+ + n \qquad (1)$$

$$n + p \rightarrow d + \gamma \qquad (2)$$

- the prompt-delayed signal spatial and temporal coincidence works as a huge background suppressor.
- energy range of the anti-neutrino detected 2-8 MeV







Key issues:

- Energy resolution and scale
- Statistics

Neutrino Physics with JUNO

JUNO have a rich physics potential :

- Neutrino mass ordering with reactor $\overline{\nu_e}$
- Earth's atmospheric neutrino
- Solar neutrino from ^8B
- Core collapse supernova (CCSN) neutrino studies → this talk
- Supernova diffuse neutrino background studies → this talk
- Geo-neutrinos coming from desegregation of Uranium (U) and Thorium (Th) in the mantle and the crust → this talk

Summary of the expected number of event with JUNO for the different neutrino sources :

Source	signal rate	Energy range
Reactor	~ 47 events$/day$	0-12 MeV
Sun ^8B	$O(100)$ events$/year$	0-16 MeV
Earth's atm.	~ 400 events$/year$	0.1-100 GeV
SN burst	$\sim 10^4$ events @10kpc	0-80 MeV
SN Background	$2-4$ events$/year$	10-40 MeV
Earth (geo-ν)	~ 400 events$/year$	0-3 MeV

JUNO atmospheric sensitivity on NMO

- No detector effect included (ideal case)
- Statistical limit (Asimov method)
- Results:
  -

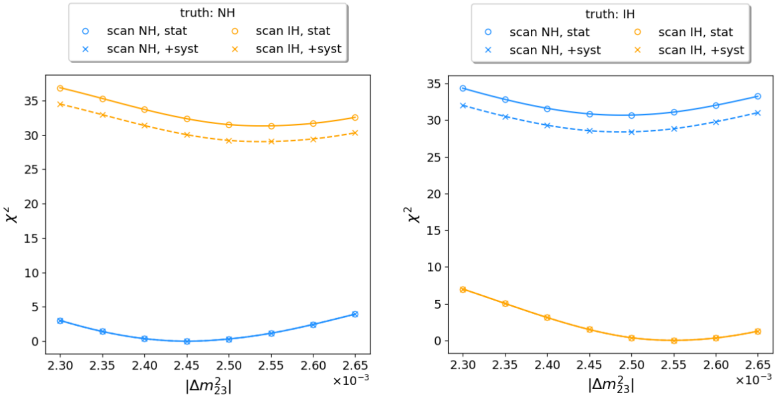
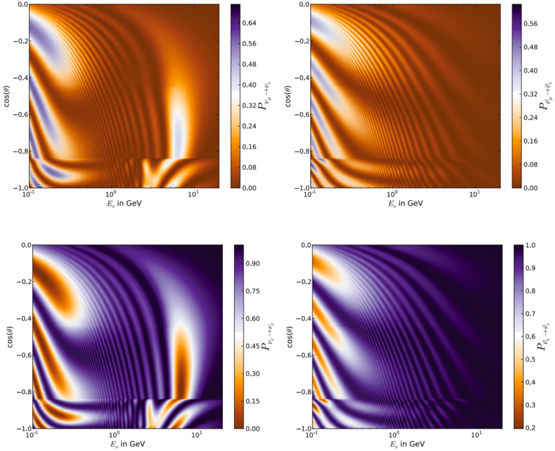


Figure: Expected NMO sensitivity using 10 year of data


cos(θ)
E_ν in GeV
$P_{\nu_\mu \to \nu_e}$
$P_{\bar{\nu}_\mu \to \bar{\nu}_e}$
$P_{\nu_e \to \nu_e}$
$P_{\bar{\nu}_e \to \bar{\nu}_e}$

Figure