Neutrino Group

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Outlook

- Neutrino Oscillations
- Neutrinos @ IPHC

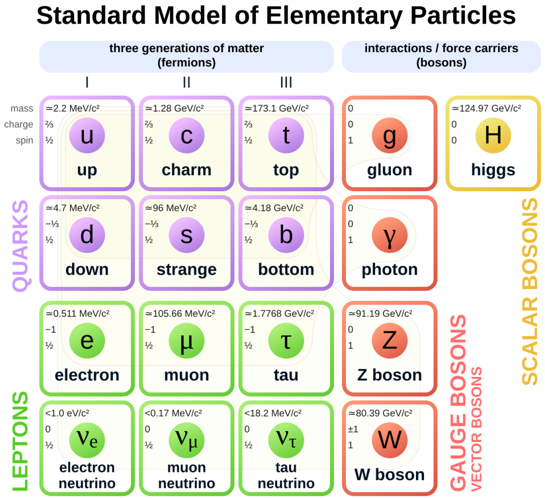
The Standard Model and Neutrinos

ν properties:

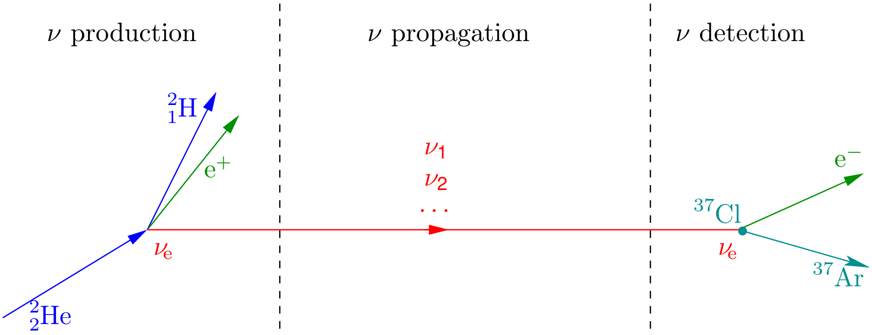
- charge = 0
- spin = 1/2
- only interact weakly
  - in SM: ν_L, but no ν_R
- mass = 0 in SM
  - From oscillations, $m_\nu > 0$
    - ★ Discovered in 1998—2002
    - ★ Nobel Prize 2015
  - $m_\nu \ll m_{u,d,e}$
- 3 families:

flavor: ν_e, ν_μ, ν_τ

mass: ν_1, ν_2, ν_3



Neutrino Oscillation (in vacuum) – overview



$|\nu_e\rangle = \sum_j U^*_{ej} |\nu_j\rangle$ $\qquad$ $|\nu_j\rangle \rightarrow e^{-iE_j t} |\nu_j\rangle$ $\qquad$ $|\nu_j\rangle = \sum_\alpha U_{\alpha j} |\nu_\alpha\rangle$

$$P(\nu_e \rightarrow \nu_e, t) = ||\langle \nu_e | \nu_e, t\rangle||^2$$

- For oscillations to happen $\{|\nu_\alpha\rangle\}$ and $\{|\nu_j\rangle\}$ different $\Rightarrow$ ν has non zero mass

Neutrino Oscillations – simplest case

2 flavor case, vacuum

- 2 ν interaction flavours (ν_e and ν_μ)
- mass eigenstates $\{|\nu_j\rangle\} = \{|\nu_1\rangle, |\nu_2\rangle\} \neq \{|\nu_\alpha\rangle\} = \{|\nu_e\rangle, |\nu_\mu\rangle\}$ flavour eigenstates
- mixing matrix U: $|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$ with $UU^\dagger = \mathbb{1}$ (ie, U rotation matrix)

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- Propagate through space time as plane waves in mass state:

$$|\nu_e, t\rangle = \sum_j U^*_{ej} e^{-iE_j t} |\nu_j\rangle = \cos\theta e^{-iE_1 t} |\nu_1\rangle + \sin\theta e^{-iE_2 t} |\nu_2\rangle$$

- $P(\nu_e \to \nu_e, t) = ||\langle\nu_e|\nu_e, t\rangle||^2 = 1 - \sin^2(2\theta)\sin^2[(E_2 - E_1)t/2]$
- Given m_i small: $E_i = \sqrt{m_i^2 + p^2} \approx p + \frac{1}{2}\frac{m_i^2}{p}$ and $t \approx L$, therefore $(E_2 - E_1)t \approx \frac{1}{2}\frac{m_2^2 - m_1^2}{p} L \approx \frac{\Delta m^2 L}{2E}$

$\Rightarrow$ $P(\nu_e \to \nu_e, L) = 1 - \sin^2(2\theta)\sin^2\left(\Delta m^2 \frac{L}{4E}\right)$

Neutrino Oscillations

3 flavor case, vacuum

$$P(\nu_\alpha \to \nu_\beta) = \sum_{j,k} U_{\beta j} U^*_{\alpha j} U^*_{\beta k} U_{\alpha k} e^{-i\Delta m^2_{jk} \frac{L}{2p}}, \qquad \Delta m^2_{jk} = m^2_j - m^2_k$$

- 3 known ν interaction flavours : ν_e, ν_μ and ν_τ $\Rightarrow$ matrix U is 3×3

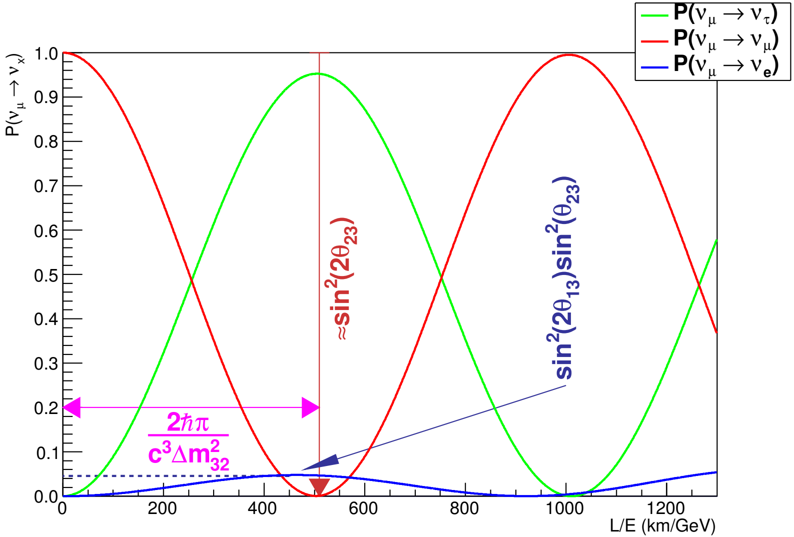
$$U = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{“atmospheric sector”}} \times \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}^{\text{“reactor sector”}} \times \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{“solar sector”}}$$

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

- θ_{23}, θ_{13}, θ_{12}: ν mixing angles
- δ_{CP}: leptonic CP violation phase
- Δm^2_{32}, Δm^2_{21}: ν mass splitting
  - Note: $\Delta m^2_{31} = m^2_3 - m^2_1 = \Delta m^2_{32} + \Delta m^2_{21}$

Neutrino Oscillations

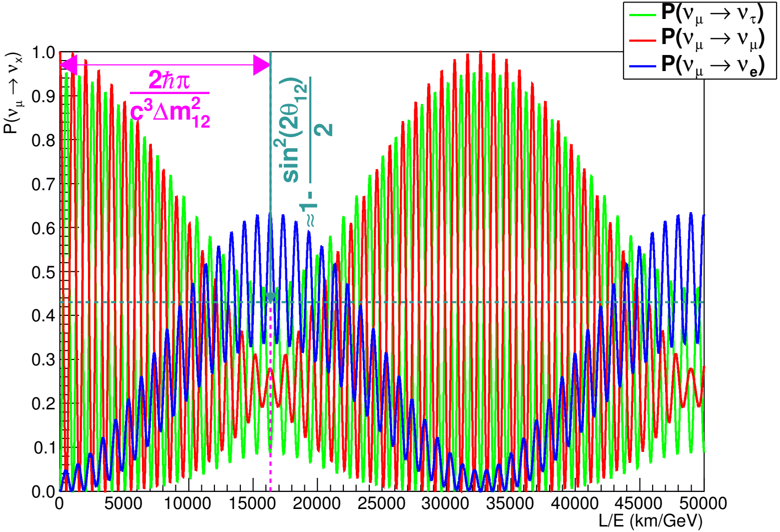
3 flavor case, vacuum



$\theta_{12} = 34^\circ$, $\theta_{13} = 8.8^\circ$, $\theta_{23} = 45^\circ$, $\Delta m^2_{21} = 7.59 \cdot 10^{-5}$ eV^2/c^4, $\Delta m^2_{32} = 2.43 \cdot 10^{-3}$ eV^2/c^4, $\delta_{CP} = 0^\circ$.

Neutrino Oscillations

3 flavor case, vacuum



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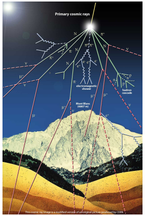
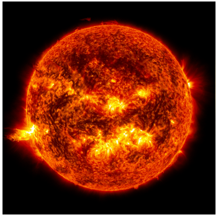
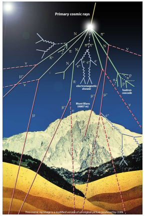
Studying Neutrino Oscillations: Neutrino Sources

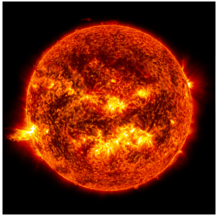




- Sun & atmosphere: two main natural sources
  - Good: “free” abundant ν sources
  - Bad: can’t adjust L, E or composition
  - Tricky: understanding ϕ emmitted essential
- Reactors
  - Good: Reactors exist independently of ν research (ie, we’re not paying the bill!)
  - Good: can control L (within a certain range. . .)
  - Bad: We cannot control it’s ‘burning’ power
  - Good/Bad: $\bar{\nu}_e$ energy spectra fixed, and hard to predict. Adding detectors $\rightarrow$ expensive
- Accelerator ν

Studying Neutrino Oscillations: Neutrino Sources



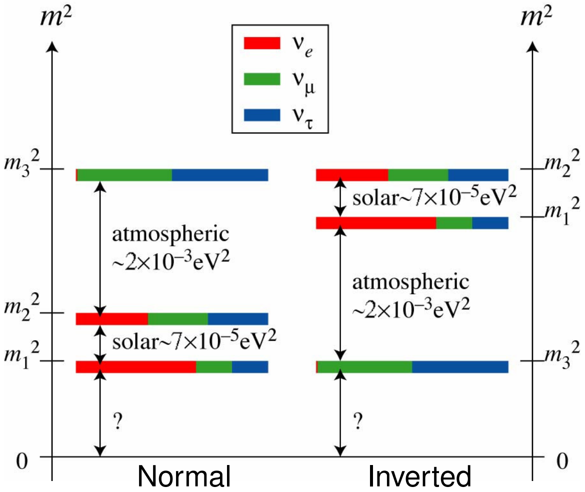


- Sun & atmosphere: two main natural sources
  - Good: “free” abundant ν sources
  - Bad: can’t adjust L, E or composition
  - Tricky: understanding ϕ emmitted essential
- Reactors
- Accelerator ν
  - Good: Control L, E and if ν_μ or $\bar{\nu}_\mu$ produced (for a traditional beam)
  - Bad: “Expensive” ν
  - Good and Bad: extra detectors useful to understand ϕ emmitted, but also expensive

Open questions in neutrino physics...

- Absolute Scale of Neutrino Masses
- Neutrino Mass Ordering
  $\Rightarrow$ JUNO
- $P(\nu_\alpha \to \nu_\beta) \stackrel{?}{=} P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$
  - Tied to Universe Matter/AntiMatter asymmetrie?

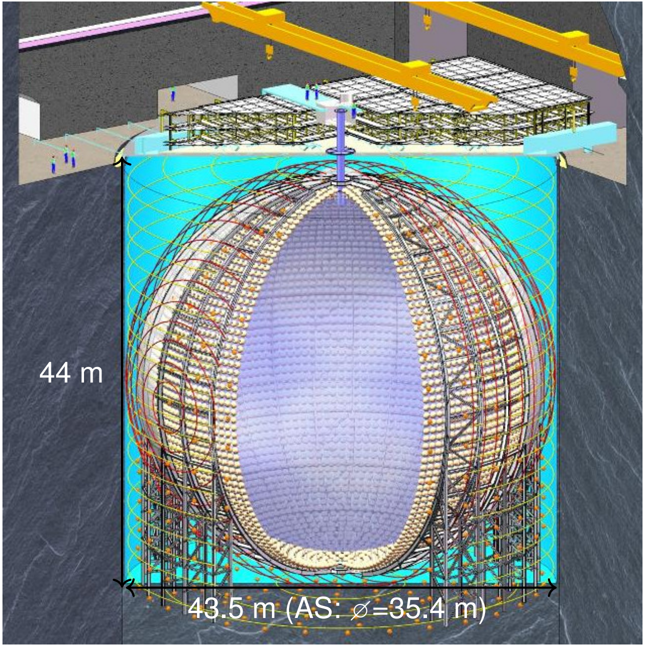
  $\Rightarrow$ ESSνSB
- Mixing Matrix U is Unitary?
  $\Rightarrow$ both via precision measurements
- Are there Sterile ν?
- ν Majorana or Dirac Particle
  $\Rightarrow$ JUNO phase 2 (maybe)



Neutrinos @ IPHC

NMO ⟶ JUNO : reactor + . . .

CP-violation ⟶ ESSνSB : accelerator + . . .

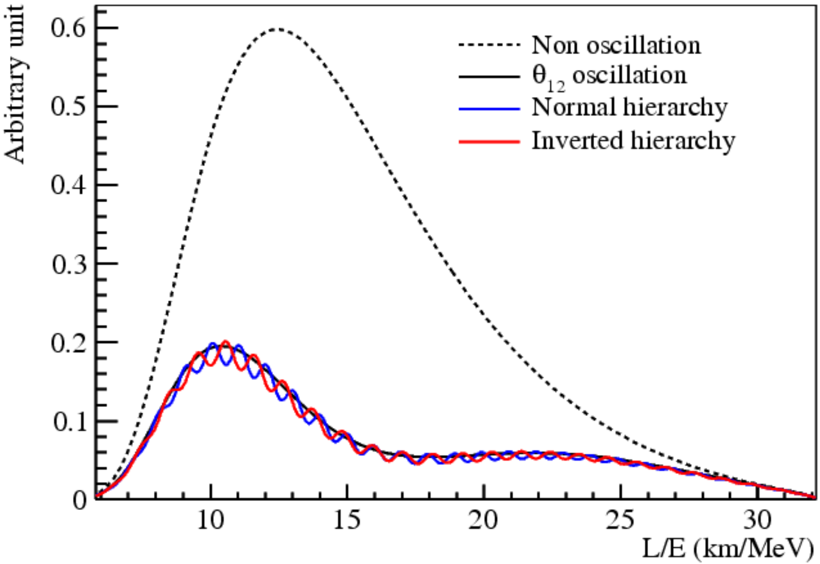


- Located in China
- 20 kton ν target mass
- built to detect $\bar{\nu}_e$ from nuclear reactors
  - Can only measure $\bar{\nu}_e$ survival: $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- excellent energy resolution
- observe fast oscillations
  - first time to observe Δm^2_{32} and Δm^2_{21} together
- main goal: NMO
- Start data taking: 2022
  - construction on-going

JUNO site

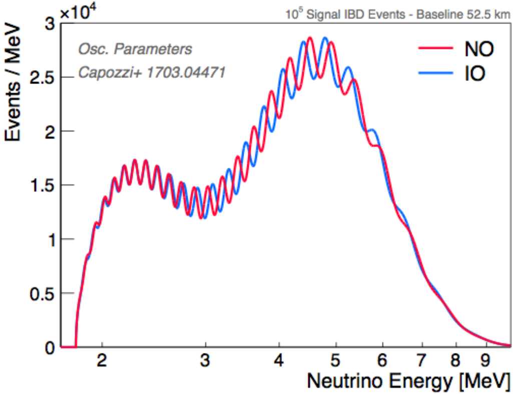
Guang Zhou
Huizhou
Zhaoqing
Huizhou NPP
CNS
Shen Zhen
Lufeng NPP
Jiangmen
Kaiping
Daya Bay NPP
Zhongshan
Hong Kong
Macau
JUNO
53 km
53 km
Taishan NPP
Yangjiang NPP

Neutrino Oscillations in JUNO



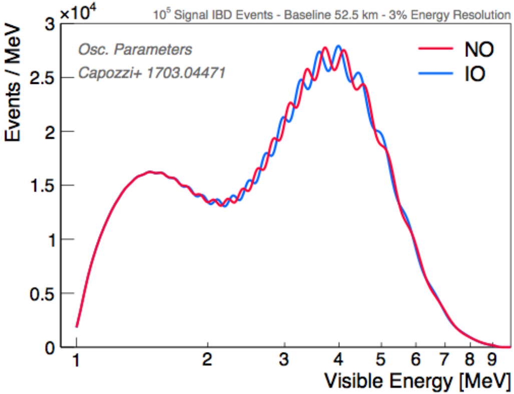
Neutrino Oscillations in JUNO: what we really will measure

$\bar{\nu}_e$ oscillated spectrum



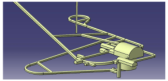
- Ideal case
- Exposure: 20 kt · 6 years

+ energy resolution



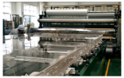
- E_{vis} from e^+ used rather than E_ν
- Assuming $3\%/\sqrt{E[\text{MeV}]}$ energy resolution

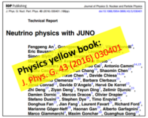
JUNO schedule



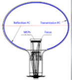
2014
- International collaboration established
- Conceptual design

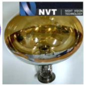
2015
- PMT production line setup
- CD parts R&D
- Civil construction start



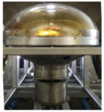


2016
- PMT production start
- CD parts production start
- Yellow book published

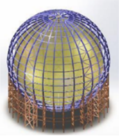




2017
- PMT testing start
- TT arrived



2018
- PMT potting
- Start delivery of surface building
- Start production of acrylic sphere

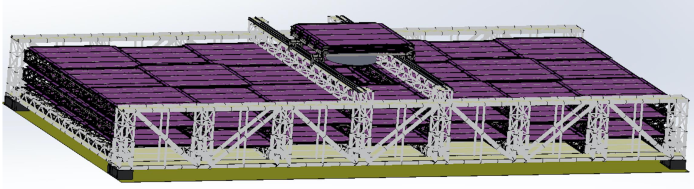


2019-2021
- Electronics production starts
- Civil construction and lab preparation completed
- Detector construction

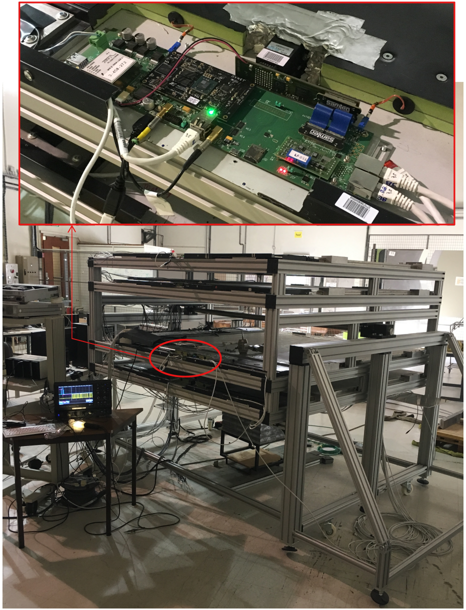
2022
- Detector ready for data taking

- Great timing to start PhD $\rightarrow$ first data expected after first year

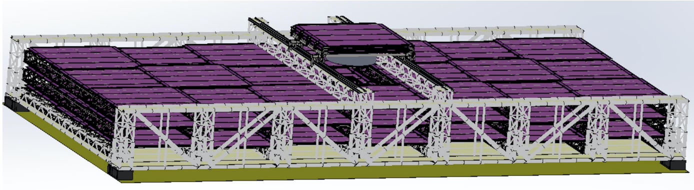
JUNO @ IPHC



- Top Tracker modules originally built at IPHC
  - TT part of JUNO veto strategy
  - IPHC group leading TT efforts
- Now developping new electronics cards for TT
- Prototype detector @IPHC
  - Let us know if you want a tour!
  - VR visit of JUNO also possible!
- Thesis not restricted to TT either



JUNO @ IPHC



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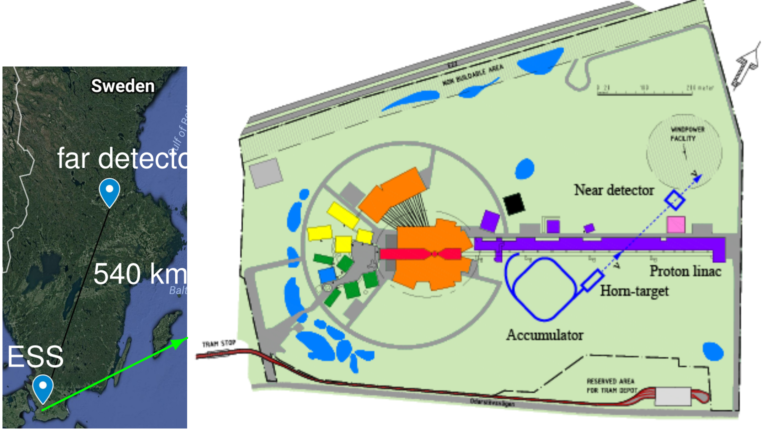
M2 Internships & Ph.D. thesis

- Large focus on JUNO, as data taking starting soon
- Student project/TIPP:
  - study sensitivity to neutrino mass ordering with JUNO
- M2 internship:
  - TT prototype data taking & tuning of JUNO MC
- Ph.D. thesis: JUNO
  - Will participate in the end of building JUNO and the beginning of the data taking



- Located in Sweden
- Upgrade ESS facility to produce ν beam
- $\mathcal{O}$(1 Mton) far detector
- Started design recently

- Main goal: measure CP violation
- Optimally placed at 2nd oscillation maxima
  - better for CPV, worse for NMO
- IPHC responsible for “horn” design

M2 Internships & Ph.D. thesis

- Large focus on JUNO, as data taking starting soon
- Student project/TIPP:
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  - ESSνSB horn design optimization with genetic algorithm (to be confirmed)
- M2 internship:
  - TT prototype data taking & tuning of JUNO MC
- Ph.D. thesis: JUNO
  - Will participate in the end of building JUNO and the beginning of the data taking
- Contact me for more info (jpandre@iphc.cnrs.fr).
- Also feel free to talk to our current Ph.D. students (Bat 22, room 220):
  - Luis Felipe PIÑERES RICO – 3rd year [JUNO]
  - Julie THOMAS – 2nd year [ESSνSB]