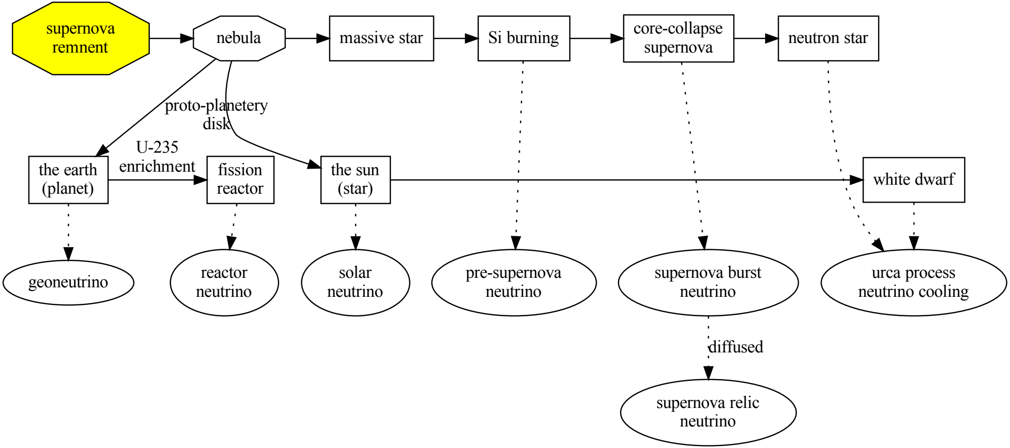
Jiangmen Underground Neutrino Observatory

Benda Xu
on behalf of the JUNO collaboration

Tsinghua University, Center for High Energy Physics

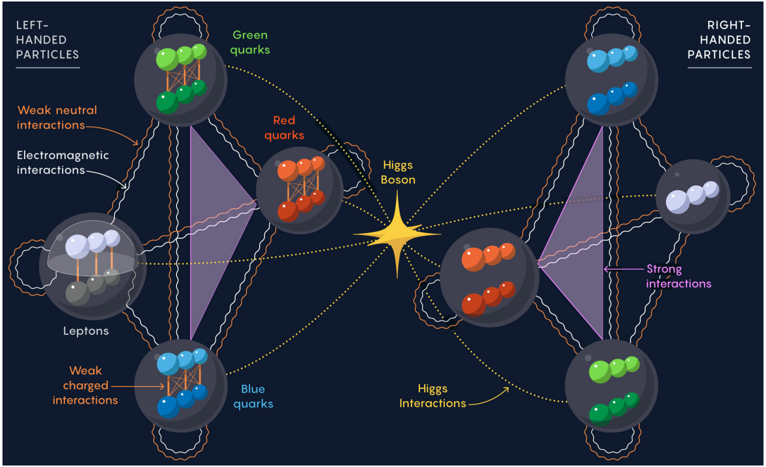
2024-09-08 OMEG2024 @ Chengdu

Neutrinos are ubiquitous in nucleosynthesis



- ν accompany weak interactions.

The standard model of particle physics



No right-handed ν.

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \Longleftrightarrow \begin{matrix} u_R \\ d_R \end{matrix}$$

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \Longleftrightarrow \begin{matrix} ? \\ e_R \end{matrix}$$

We thought $m_\nu = 0$.

Standard model had tremendous success for half a century.
credit: quantamagazine.org

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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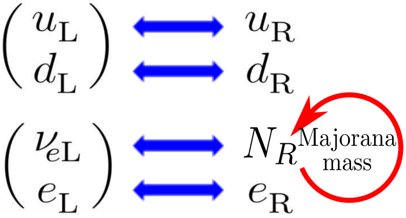
Indicates the existance of right-handed counterparts:

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



$$\mathcal{L} = \frac{1}{2} M_\mathsf{N} \overline{N_\mathsf{R}^c} N_\mathsf{R} + Y_\nu H \overline{L_\mathsf{L}} N_\mathsf{R} + \cdots + \text{h.c.}$$

$M_\mathsf{N} \gg m_\nu$ is the mass of majorana right-handed ν.

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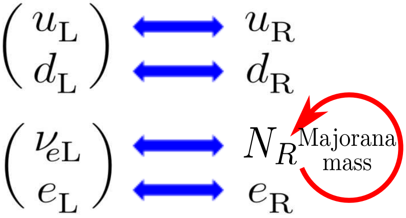

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The standard solar model defeated standard model of particle physics.

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

The inevitable majorana term and seesaw mechanism

$$\mathcal{L} = \frac{1}{2} M_\mathsf{N} \overline{N^c_\mathsf{R}} N_\mathsf{R} + Y_\nu H \overline{L_\mathsf{L}} N_\mathsf{R} + \cdots + \text{h.c.}$$

Seesaw mechanism $m_\nu \propto 1/M_\mathsf{N}$ is a minimal extension to the standard model.

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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 ($< 1\,\text{eV}$).
2. If lepton number is violated i.e. if there are majorana fermions in nature.
3. If leptogensis created the matter-antimatter asymmetry.
   $\rightarrow$ the origin of matter preluding nucleosynthesis.
4. ν_{R} is among the dark matter candidates.
   $\rightarrow$ gravitational evolution of galaxies.

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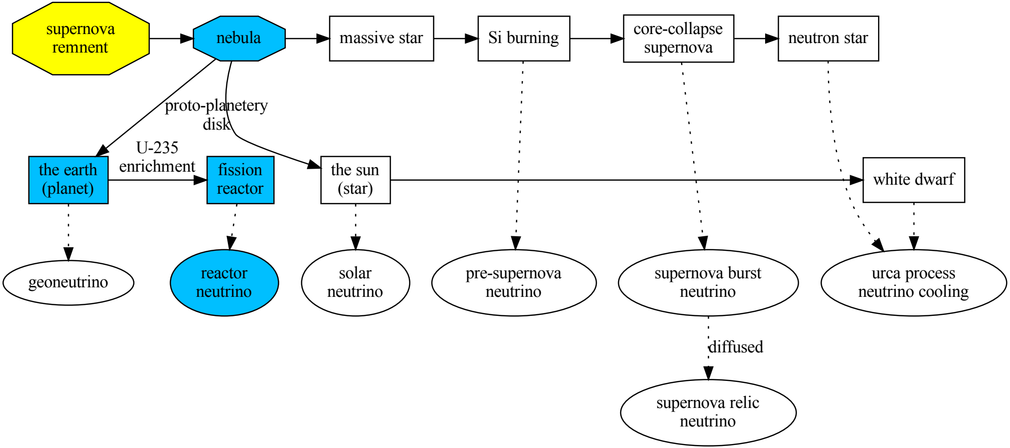
JUNO is the next milestone

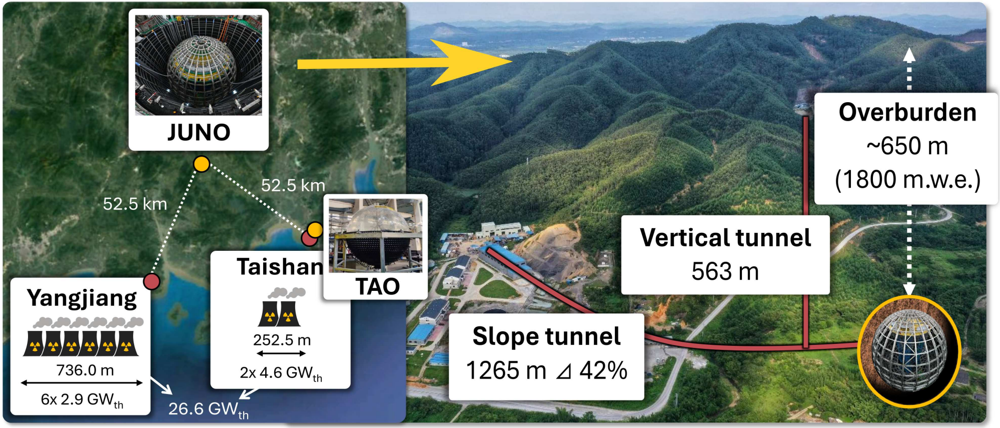
to measure the ν mass spectra and falsify ν_L-N_R mixing.

Roadmap of nucleosynthesis and neutrino



- 60 $\bar{\nu}$/day, 1.8–8 MeV
- JUNO: many reactor ν traveling for just the right distance $52.5\,\mathrm{km}$.

Jiangmen Underground Neutrino Observatory



- 52.5 km is the sweet spot for ν oscillation.

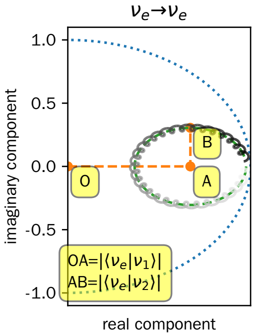
ν oscillation

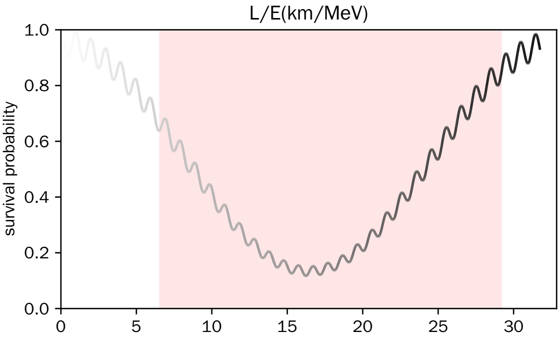
$$|\nu_\alpha(t)\rangle = \sum_{i=1,2,3} U^*_{\alpha i} |\nu_i(t)\rangle$$

Mixing of different ν mass eigenstates leads to oscillation:

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

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





Detecting neutrinos with JUNO

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

$$\begin{cases} |\langle \nu_\mathrm{e} \,|\, \nu_1 \rangle| = \cos\theta_{12}\sin\theta_{13} \\ |\langle \nu_\mathrm{e} \,|\, \nu_2 \rangle| = \sin\theta_{12}\cos\theta_{13} \\ |\langle \nu_\mathrm{e} \,|\, \nu_3 \rangle| = \sin\theta_{13} \end{cases}$$

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Non-unitarity $\sum_{i=1}^{3} |\langle \nu_\mathrm{e} \,|\, \nu_i \rangle|^2 < 1$ indicates the existance of N_R and $\langle \nu_\mathrm{e} \,|\, N_\mathsf{R} \rangle > 0$.

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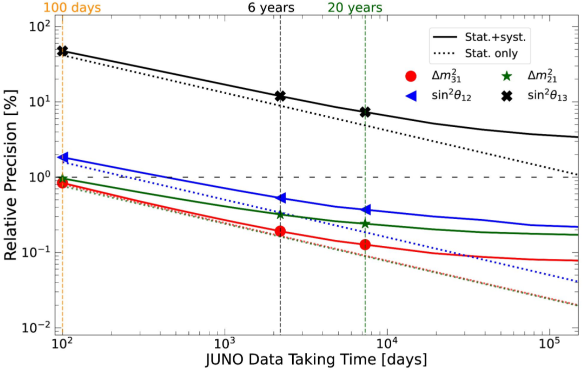
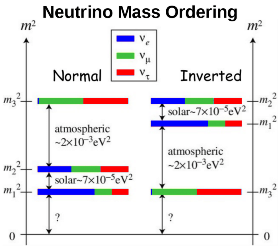


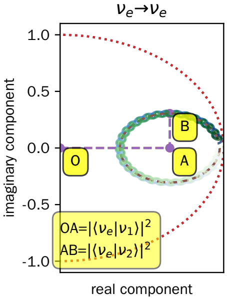
	PDG 2024	JUNO 6 years
$\sin^2\theta_{13}$	3.2%	12%
$\sin^2\theta_{12}$	4.2%	0.5%
Δm^2_{21}	2.4%	0.3%
Δm^2_{21}	1.1%	0.2%

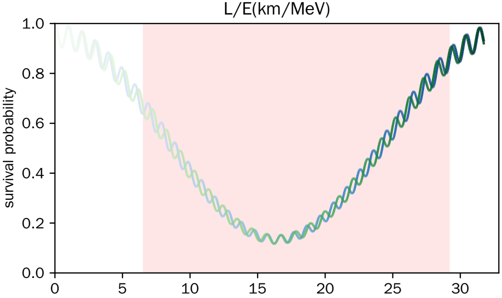
Chin. Phys. C46 12, 1230001 (2022)

ν mass ordering (NMO): sign of Δm^2_{31}



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





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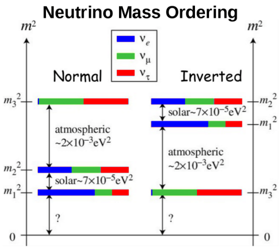

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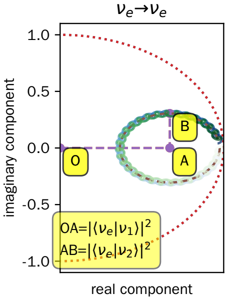

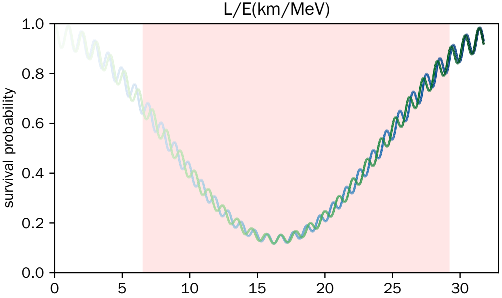

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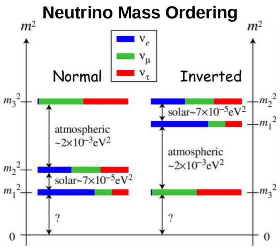

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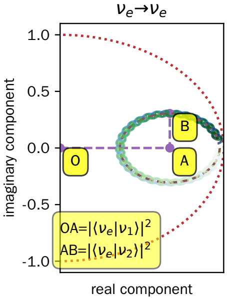
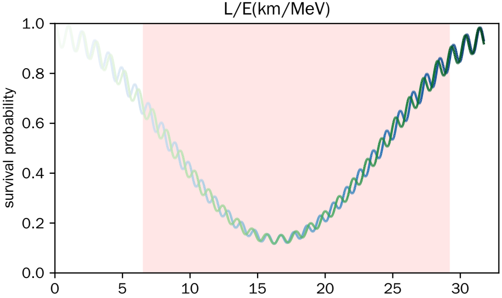
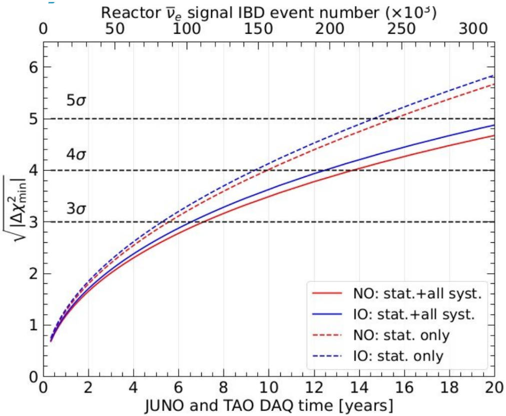




Sensitivity to ν mass ordering



arXiv:2405.18008

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

NMO sensitivity

3σ determination in 6.5 years.

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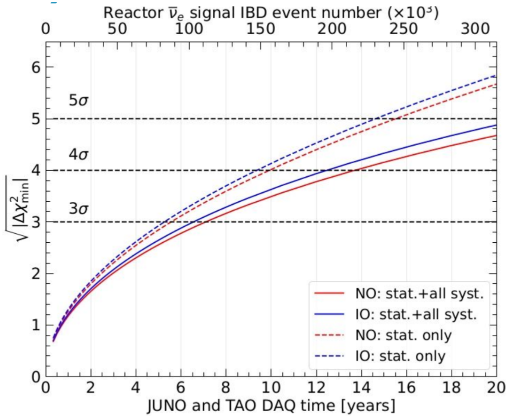

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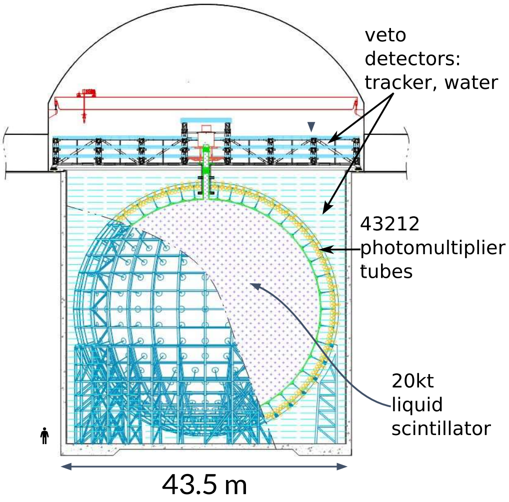
Keys to success

- large exposure;
- measurement of ν energy;
- understanding and control of backgrounds.

JUNO design: a liquid scintillator detector



large exposure:

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

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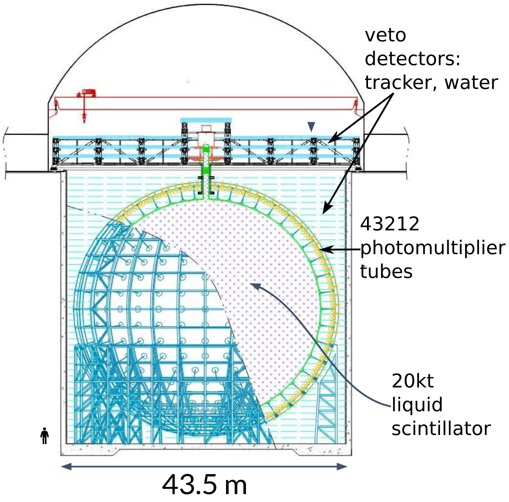

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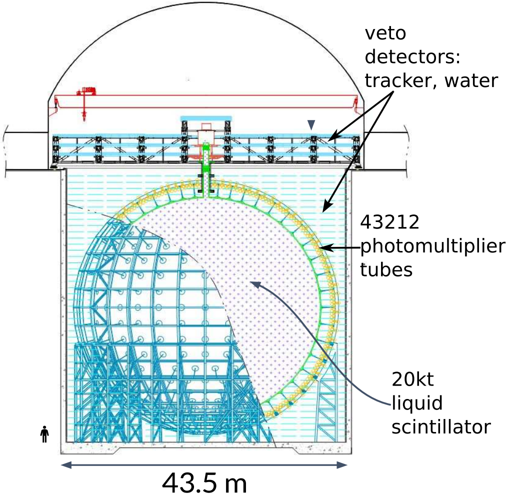
measurement of ν energy;

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

JUNO design: a liquid scintillator detector



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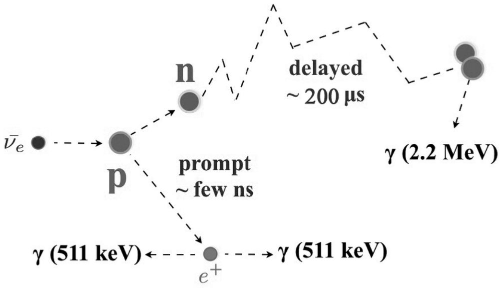
control of backgrounds.

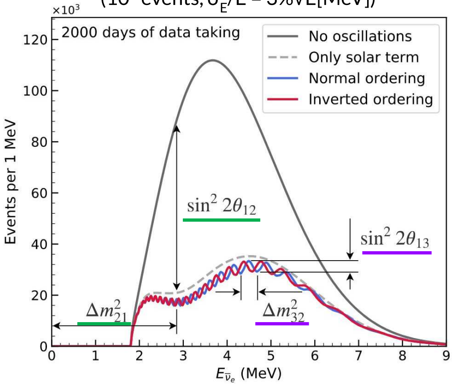
- effective impurity removal: filteration, distillation, absorption.
- active shield of water and μ tracker.

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

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

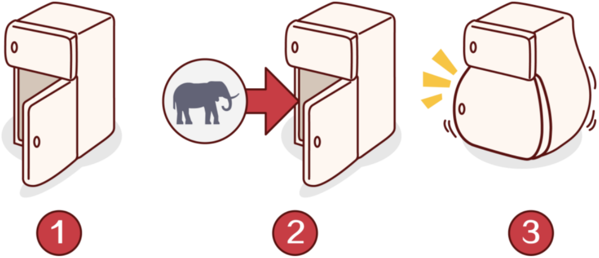


Exemplary spectrum, 6y
(10^5 events, $\sigma_E/E = 3\%\sqrt{E[\text{MeV}]}$)



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

Steps



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 expected.

JUNO collaboration since 2014

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

Snapshots construction progress

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

Status of acrylic sphere

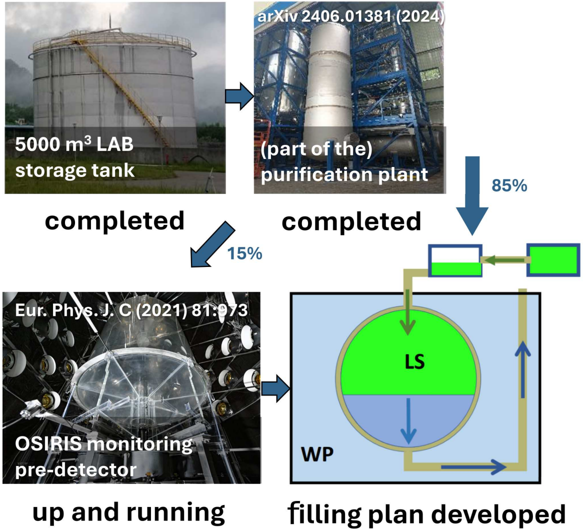
- Construction layer by layer.
  At final stage, closing the bottom this year.

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	15012	30%	31	7.0
	dynode	5000	29%	17	1.3
$\varnothing 7.6$ cm	dynode	25600	25%	0.5	1.6

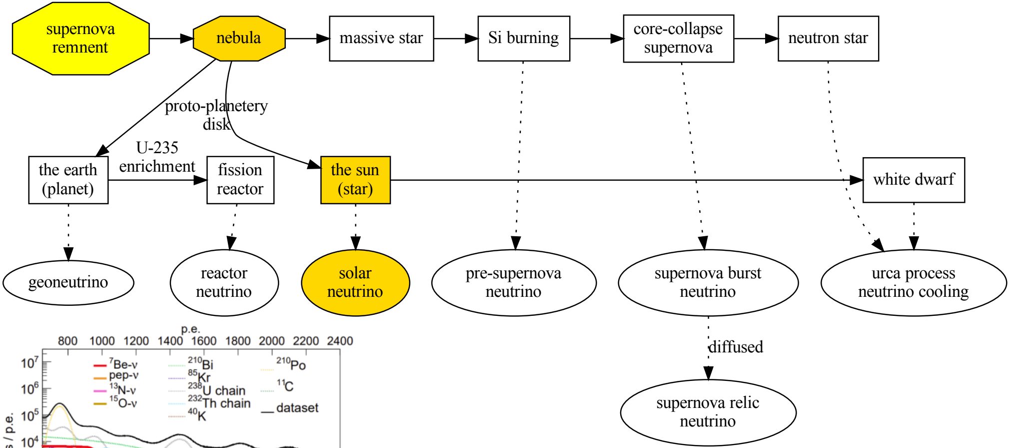
Eur.Phys.J.C82 12, 1168(2022)

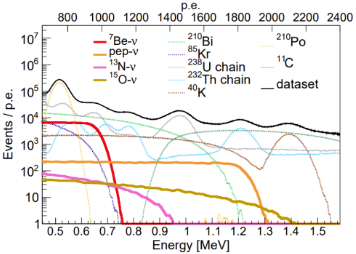
Liquid scintillator handling system



- LAB solvent, $2.5\,\mathrm{g/L}$ PPO, $3\,\mathrm{mg/L}$ bis-MSB
- Attenuation length $>20\,\mathrm{m}$
- U/Th $< 1 \times 10^{-15}\,\mathrm{g/g}$

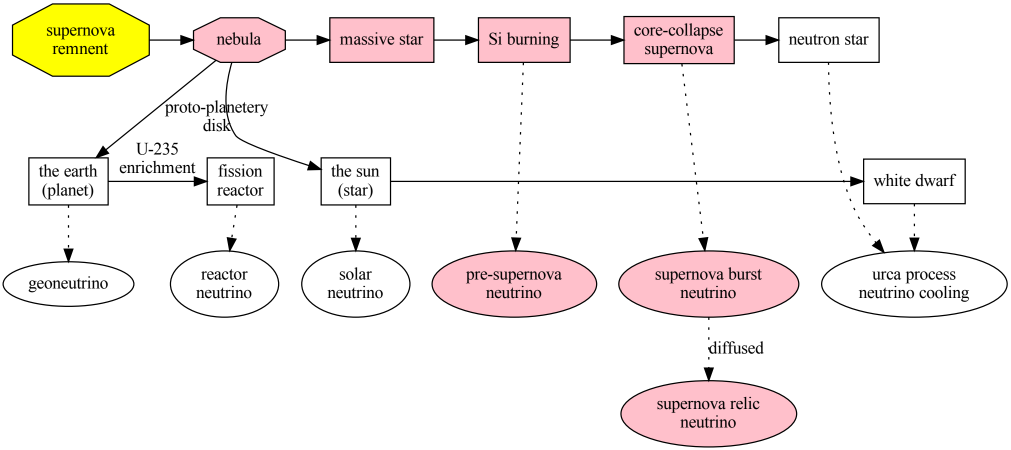
Solar ν





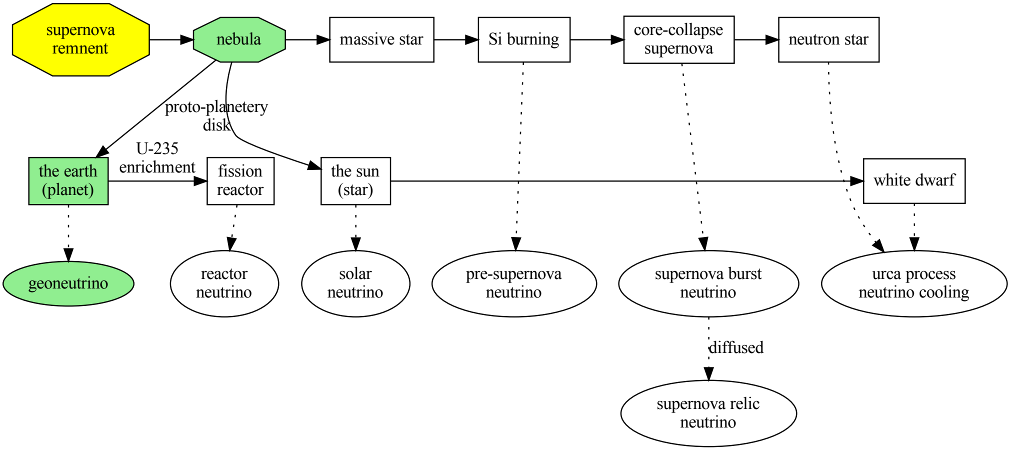
- 10000 ν/day, 0–19 MeV.
- directly confirm the stellar nuclear reactions.

Supernova ν



- ν is the energy distributor of supernova explosion – neutrino nucleosynthesis.
- alert: pre-supernova; burst: up to $\sim 10\,\text{kpc}$;
- diffused supernova ν background: discovery potential.

Terrestial ν



- 1 $\bar{\nu}$/day, 1.8–4 MeV. from radioactivity: ^{238}U, ^{232}Th, ^{40}K.

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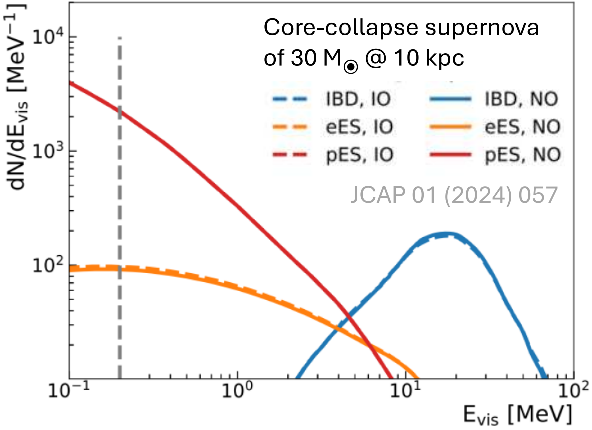
- Understanding non-zero m_ν takes us beyond the standard model.
- ν mass ordering and precise mixing parameters motivate JUNO.
  - see also astrophysical studies with JUNO by Yufeng Li.
- JUNO represents state-of-the-art of liquid scintillator detector.
- Construction is to complete in 2024.

Supernova burst neutrinos

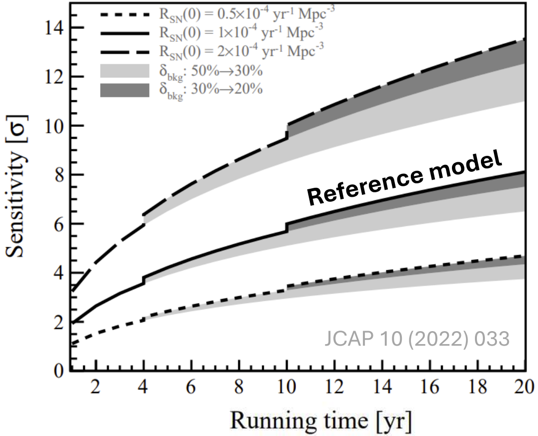
up to 10 kpc. supernova at the local cluster.

- 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 presure equation constitutes the standard solar model.

Cleanness of the detector

Solar sensitivity study.

^{8}B neutrinos

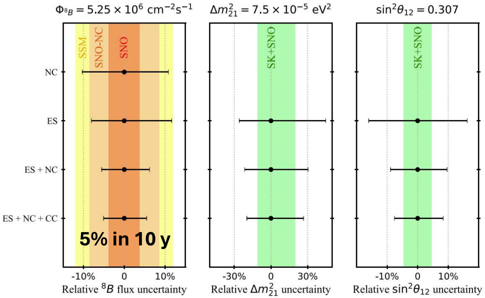
$$^{8}\mathrm{B} \longrightarrow {}^{8}\mathrm{Be}^{*} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$$

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

$$^{13}\mathrm{C} + \nu_{\mathrm{e}} \longrightarrow {}^{13}\mathrm{N} + \mathrm{e}^{-}$$

- measurement of θ_{12} and Δm^2_{12}.

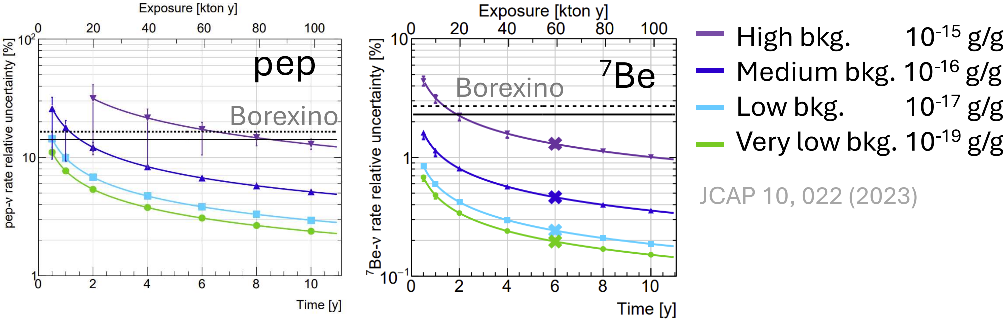
Astrophys. J. 965.2: 122 (2024)



pep and ^{7}Be neutrinos

$$^7\mathrm{Be} + \mathrm{e}^- \longrightarrow {}^7\mathrm{Li} + \nu_\mathrm{e}$$
$$\mathrm{p} + \mathrm{e}^- + \mathrm{p} \longrightarrow {}^2\mathrm{H} + \nu_\mathrm{e}$$

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

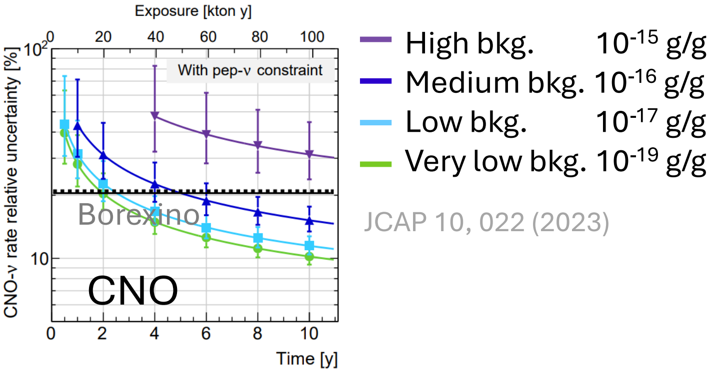


JCAP 10, 022 (2023)

Neutrinos from CNO-cycle

$$^{13}\mathrm{N} \longrightarrow {}^{13}\mathrm{C} + \mathrm{e}^+ + \nu_\mathrm{e}$$
$$^{15}\mathrm{O} \longrightarrow {}^{15}\mathrm{N} + \mathrm{e}^+ + \nu_\mathrm{e}$$
$$^{17}\mathrm{F} \longrightarrow {}^{17}\mathrm{O} + \mathrm{e}^+ + \nu_\mathrm{e}$$

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



JCAP 10, 022 (2023)