Anti-neutrino Spectroscopy at the Jiangmen Underground Neutrino Observatory

Frequentist approach to neutrino mass ordering and JUNO reactor neutrino experiment

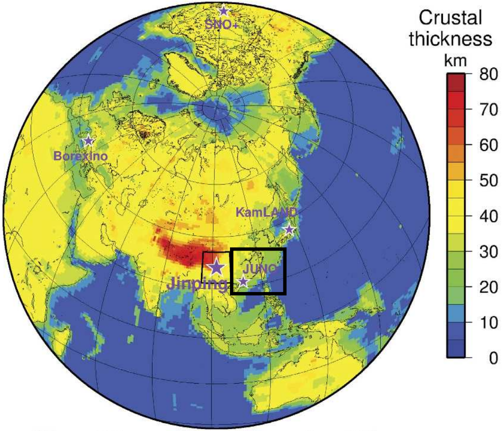
Benda Xu
on behalf of the JUNO collaboration

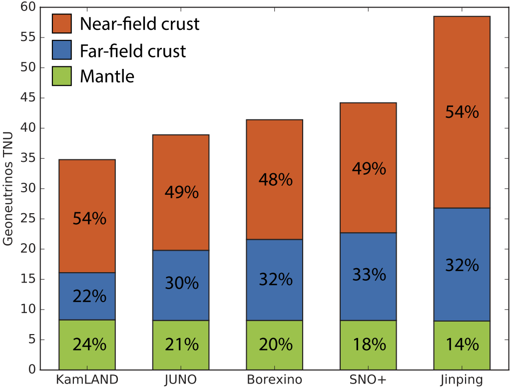
Department of Engineering Physics
Center for High Energy Physics
Tsinghua University

2025-05-02 @ University of Hawai'i Mānoa
Workshop on Ghost Particle Hunting
Neutrino Physics and its Applications to World Peace

Geo-$\bar{\nu}_e$ at JUNO

Global network of geoneutrino detection





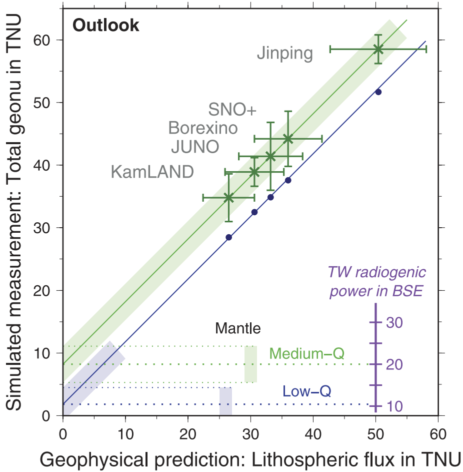
- Sites are with different crustal and almost identical mantle contributions.

TNU: terrestrial neutrino units, $\mathrm{ev}/10^{32}\mathrm{proton}/\mathrm{year}$. Šrámek et al. 2016

Determining the mantle contribution

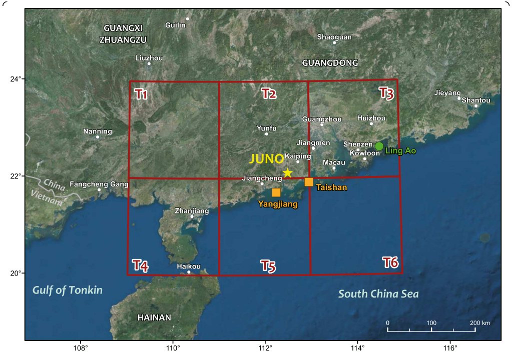
Crustal geo-ν dominates the continental-based detectors.

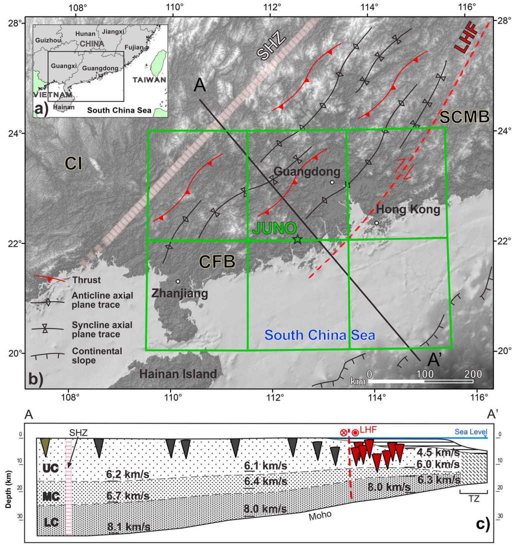
- know thy background: predict the crustal geo-ν with high precision.
- avoid thy background: to bottom of the ocean with Hanohano/OBD.
- separate thy background: directional measurement technology of $\bar{\nu}$.



Šrámek et al. 2016

Predicting the crustal geo-ν with high precision at JUNO

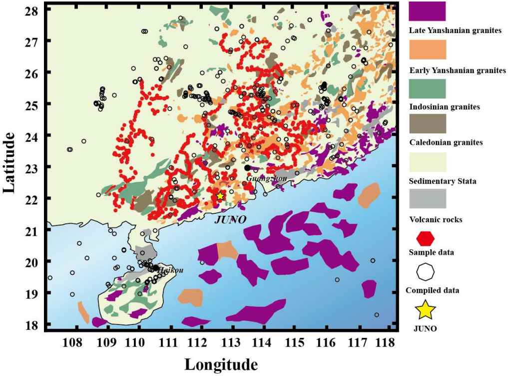


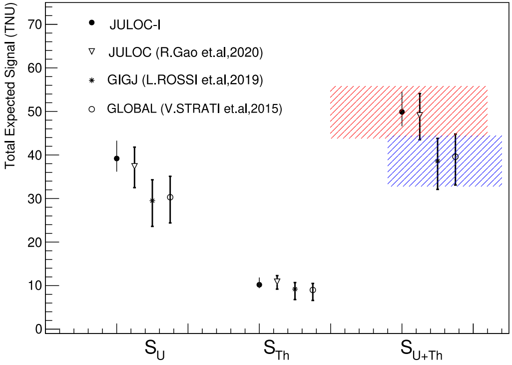


↑ Global model without site-specific assumptions. Strati et al. 2015

→ 3D crustal model with gravity field input. Reguzzoni et al. 2019

Predicting the crustal geo-ν with high precision at JUNO (II)

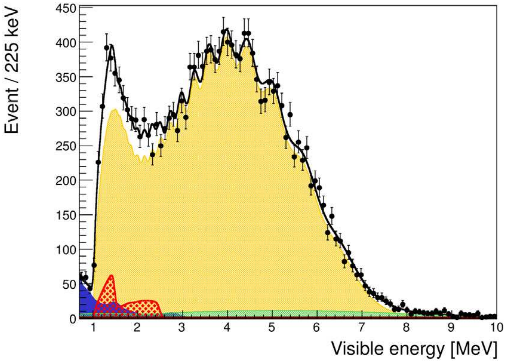


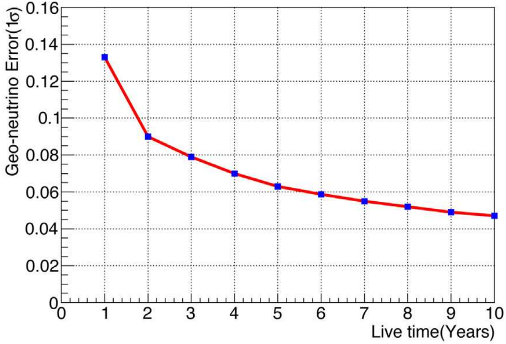


- 3D model with joint gravity and seismic inversion.
- A larger sample of rocks.

Gao et al. 2020, https://doi.org/10.1016/j.pepi.2019.106409 and arXiv:2210.09165

Projected JUNO precision for geo-$\bar{\nu}_e$





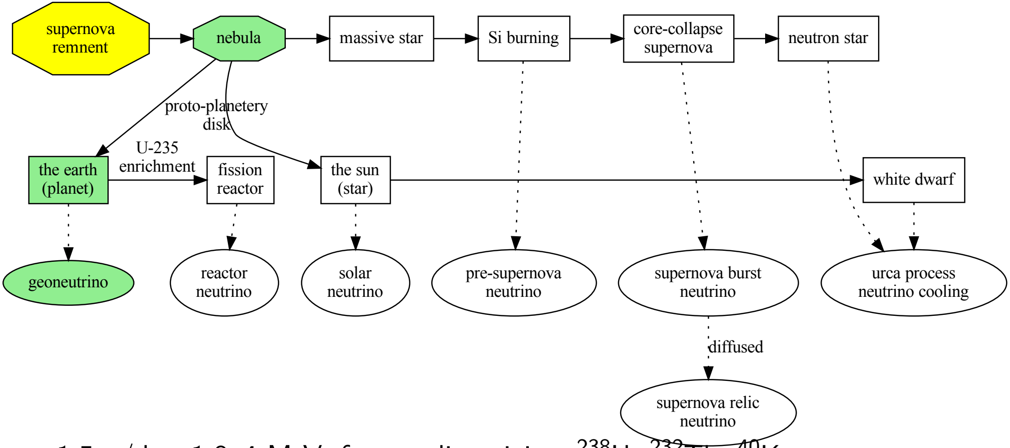
Predicted $\bar{\nu}_e$ spectra with 1-year data. Geo-$\bar{\nu}_e$ in red, reactor $\bar{\nu}_e$ in orange, accidental in blue.

Expected uncertainty of measured Geo-$\bar{\nu}_e$ flux. JUNO physics and detector https://doi.org/10.1016/j.ppnp.2021.103927

- $10\,\%$ precision measurement of geo-$\bar{\nu}_e$ flux after 2 years!

Reactor $\bar{\nu}_e$ and JUNO

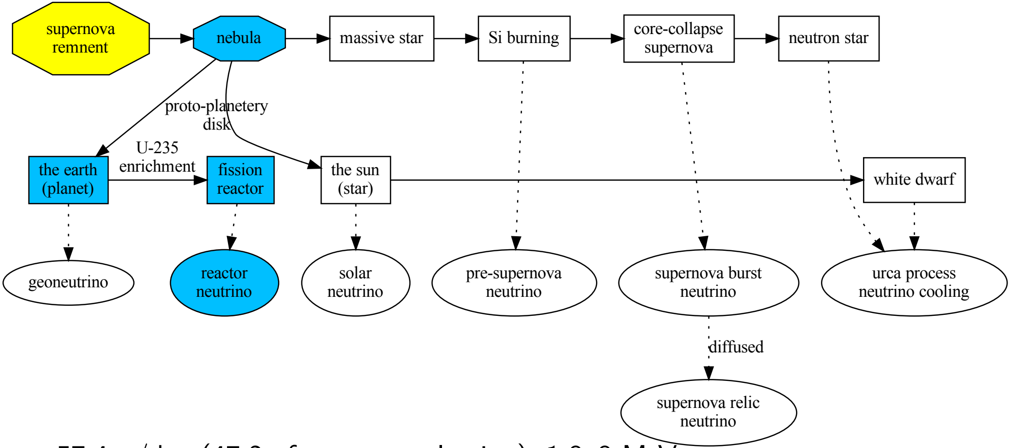
Terrestial $\bar{\nu}_e$



- 1.5 $\bar{\nu}$/day, 1.8–4 MeV. from radioactivity: ^{238}U, ^{232}Th, ~~^{40}K~~.
- JUNO has 1.44×10^{33} free protons.

Chin. Phys. C49 3, 033104 (2025)

Reactor $\bar{\nu}_e$



- 57.4 $\bar{\nu}$/day (47.2 after event selection), 1.8–8 MeV
- JUNO: many reactor ν traveling for just the right distance $52.5\,\mathrm{km}$.

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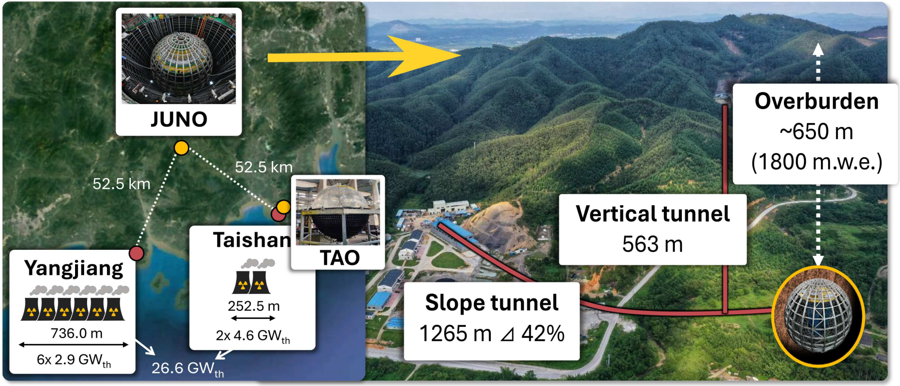
52.5 km: the sweet spot for ν oscillation



John, Steve, Sandip and Bob from PhysRevD 2008

Separation of the (mass ordering) projections is quite good over the entire range examined, from 30–75 km, but degrades at distances less than 40 km and greater than 65 km.

Exploit the oscillation pattern by Fourier transform

JGL at Neutrino 2008

This (Fourier power) self-normalizing, robust method offers a precision measurement of Δm^2_{31} for $\sin^2(2\theta_{13}) > 0.05$, determines neutrino mass hierarchy by evaluating asymmetry of the Fourier power spectrum, and measures θ_{13}; all without the need for a near detector.

$$
\begin{aligned}
P(\bar{\nu}_e \to \bar{\nu}_e) = 1 &- \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E} \\
&- \sin^2 2\theta_{13} \cos^2 \theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} \\
&- \sin^2 2\theta_{13} \sin^2 \theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E}
\end{aligned}
$$

$m^2_{21}/|m^2_{31}| = 3\,\%$

Normal ordering

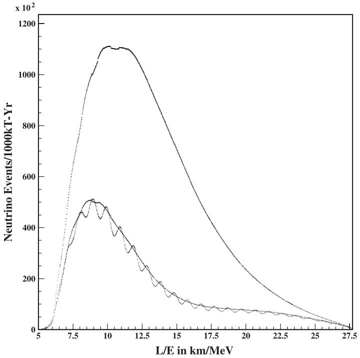
$\Delta m^2_{32} = \Delta m^2_{31} - \Delta m^2_{21}$

Inverted ordering

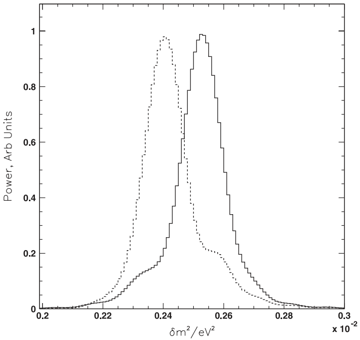
$|\Delta m^2_{32}| = |\Delta m^2_{31}| + \Delta m^2_{21}$

$\cot^4 \theta_{12} \approx 2$

Mass ordering as left (normal) or right (inverted) shoulder



L/E spectra for reactor baseline at the first minimal of 1-2 oscillation.



Relative position of an additional shoulder due to Δm^2_{32}.

- *Learned et al. 2008* is followed by the founding pioneers of JUNO (*Liang Zhan, Yifang Wang, Jun Cao, Liangjian Wen*) in 2 further studies in 2008 and 2009.

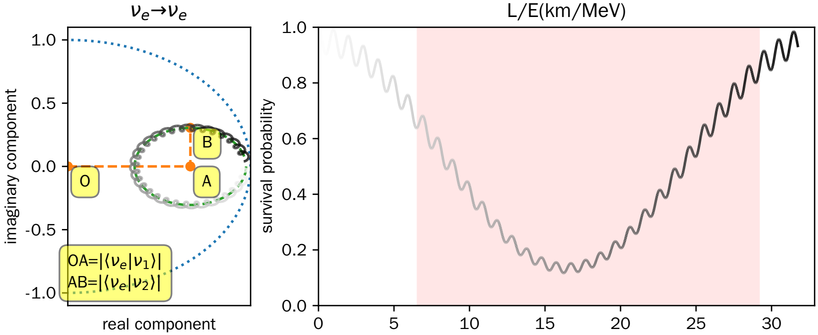
Fourier decomposition on the complex plane: ν oscillation

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

Mixing of different ν mass eigenstates leads to oscillation:

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

describes the survival probability of ν_e as $P(\nu_\mathrm{e} \to \nu_\mathrm{e}) = |\langle \nu_\mathrm{e} \,|\, \nu_\mathrm{e}(t)\rangle|^2$.



Detecting neutrinos with JUNO

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

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

Detecting neutrinos with JUNO

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

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

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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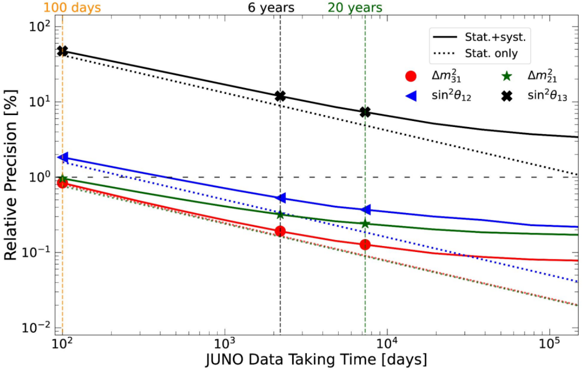
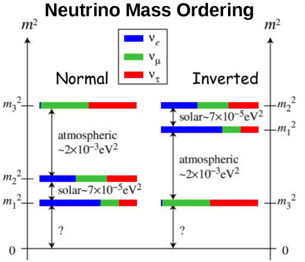


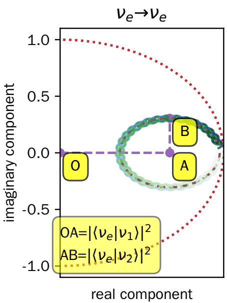
	PDG 2024	JUNO 6 years
$\sin^2\theta_{13}$	3.2%	12%
$\sin^2\theta_{12}$	4.2%	0.5%
Δm^2_{21}	2.4%	0.3%
Δm^2_{31}	1.1%	0.2%

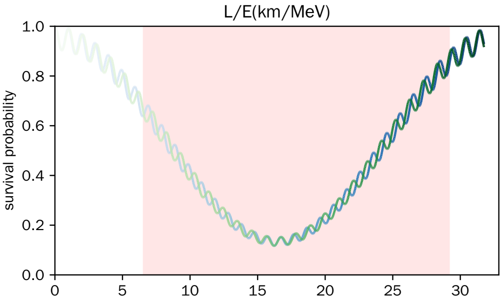
Chin. Phys. C46 12, 123001 (2022)

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

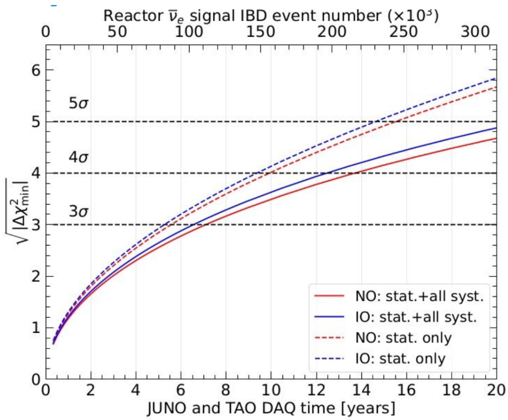


- $\Delta m^2_{21} = m^2_2 - m^2_1 = 7.5 \times 10^{-5}\,\text{eV}^2$
- $\Delta m^2_{31} = m^2_3 - m^2_1 = 2.4 \times 10^{-3}\,\text{eV}^2$
- normal order: $m^2_3 > m^2_1$; inverted order: $m^2_3 < m^2_1$
- imprints subtle difference on energy spectra.





Sensitivity to ν mass ordering



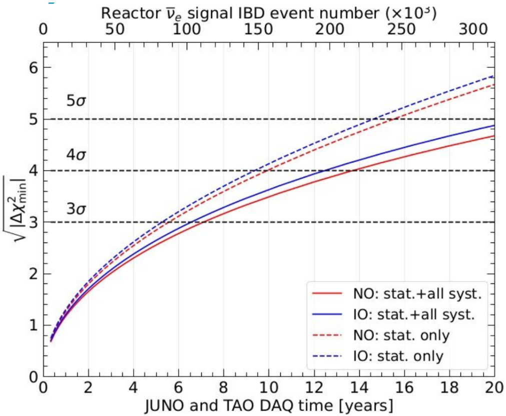
Chin. Phys. C49 3, 033104 (2025)

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

NMO sensitivity

3σ determination in 6.5 years.

Sensitivity to ν mass ordering



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

NMO sensitivity

3σ determination in 6.5 years.

Keys to success

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

$\rightarrow$ see the next JUNO talk by Wei.

Directional Measurement of $\bar{\nu}_e$

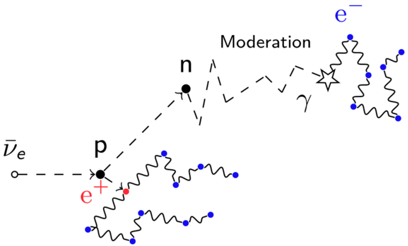
John's insight with Hanohano after the discovery of geo-$\bar{\nu}_e$

JGL at Neutrino 2008

A great challenge for a next generation of low energy $\bar{\nu}_e$ detectors is achieving some directional resolution. . . . The n acquires a tiny (few keV/c) amount of momentum from the striking $\bar{\nu}$. If one can record the e$^+$ appearance location and the n absorption location, one can make a poor ($O(20^\circ)$) angular determination. Imaging can help by permitting one to recognize the annihilation γ's topology and getting a better initial $\bar{\nu}$ interaction vertex. Ditto for the n absorption location.

Improvements in present technology

- better vertex resolution;
- track resolution;
- shorter scintillator emission times;
- heavier materials;
- greater neutron cross sections.

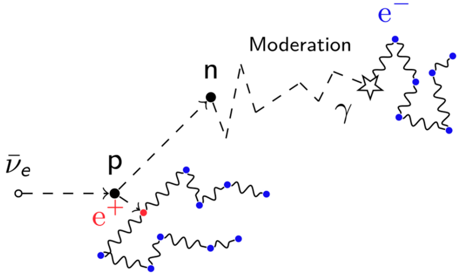


Kinetics of inverse beta decay

Conservation of four-momentum

$$\vec{p}_{\bar{\nu}_e} = \vec{p}_{e^+} + \vec{p}_n$$

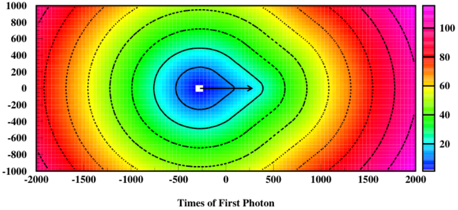
$$E_{\bar{\nu}_e} + (m_p - m_n) = E_{e^+} + m_{e^+} + E_n$$



Restriction in the evaluation of $\bar{\nu}_e$'s direction:

Quantities	Available?	Method
$\vec{p}_n$ (direction)	Yes?	Approximated by $\hat{\vec{r}}_n - \hat{\vec{r}}_{e^+}$
E_n	No?	Restricted by $\lvert\hat{\vec{r}}_n - \hat{\vec{r}}_{e^+}\rvert$ and $t_n - t_{e^+}$
$\vec{p}_{e^+}$	Yes	Cherenkov-scintillation reconstrcution

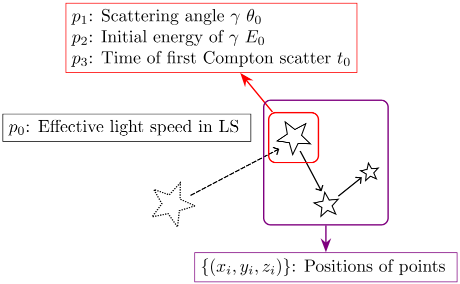
Embedding physics laws into event reconstruction



John applied Fermat's principle backward in time to get image of tracks.
JGL arXiv:0902.4009 (2009)

JUNO directional reconstruction of GeV events by Yang et al. Phys.Rev.D 109, 052005 (2024)

Track-like reconstruction for γ events.



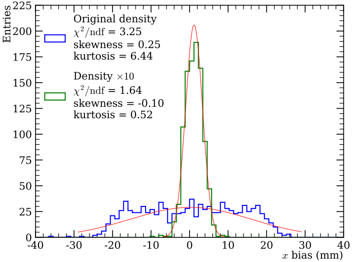
Extend point-like model to a track-like one: 1 point $\rightarrow$ 2 points $\rightarrow \ldots$

Do reconstruction like a physicist:

Embed conservation of four-momentum at each Compton scatter, to restrict the solution space.

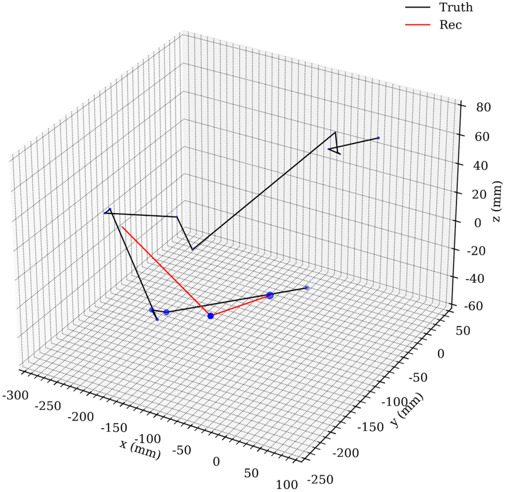
Track effect in liquid scintillator at MeV

Track of 5 MeV e^- would be visible @ JUNO-TAO.



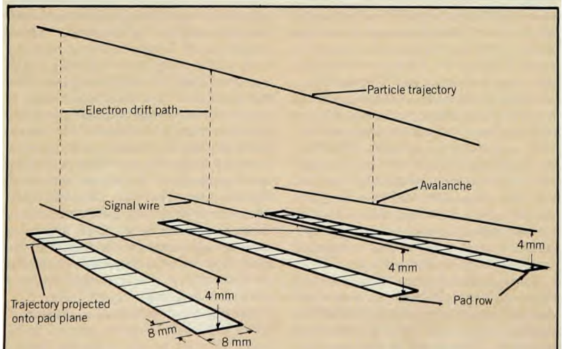
γ are multiple e^- events. The first e$^-$ gives better position for e^+ and n-capture.

Liu et al. EPJC 85 4, 438 (2025)



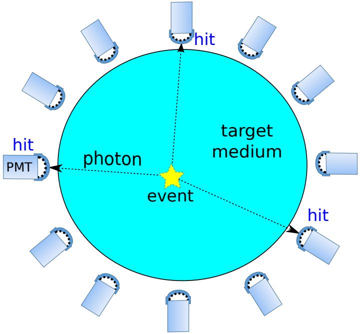
Preliminary 3-point model for 1 MeV γ.

Omnidirectional Photon TPC (Giorgio's system without lenses?)



J. Marx & D. Nygren, Physics Today 31 (10), 46 (1978)

$\rightarrow$



photon in place of e^- as an information carrier

- speed of light vs. electron drifting ($6\,\mathrm{cm}/\mu\mathrm{s}$), need ps PMT-electronics;
- Photons are omnidirectional, mitigate pile-ups with advanced computation.
  1D problem $\Delta z = v\Delta t \quad \rightarrow \quad \vec{r} = \vec{v}\Delta t$ 3D problem

Conclusion

Summary

- John has been a great leader and friend.
  - Your visions are still afresh after decades.
- I covered JUNO topics on terrestrial and reactor $\bar{\nu}_e$, directional measurement.
  - Just a fraction of John's contribution to the field.

Summary

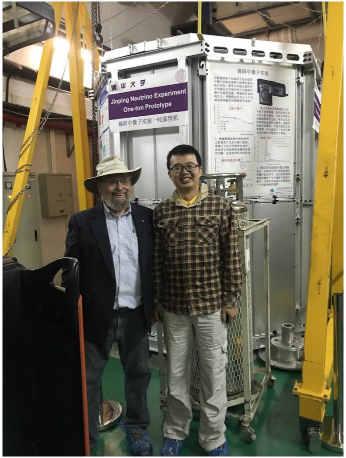
- John has been a great leader and friend.
  - Your visions are still afresh after decades.
- I covered JUNO topics on terrestrial and reactor $\bar{\nu}_e$, directional measurement.
  - Just a fraction of John's contribution to the field.

Detector	Region	Location	Size	Status (Start)
KamLAND	Japan	Mine	1000 T	Operating (2002)
Borexino	Italy	Tunnel	100 T	Operating (2007)
SNO+	Canada	Mine	1000 T	Construction (2010)
Hanohano	Pacific	Ocean	10,000 T	Proposed (2013?)
LENA	Finland?	Mine	50,000 T	Proposed (?)
EARTH	Curacao	Drill Holes	??	Discussed (??)

- JUNO is the >10 kt liquid scintillator envisioned by John in 2008.
  - It carries the torch from LENA, Hanohano and Borexino.
- See the next talk by Wei for JUNO construction and commissioning.

Happy Birthday John!

John at China JinPing underground Laboratory in 2019.



- "People are surprisingly friendly EVERYWHERE!" – John

Happy Birthday John!

Green pepper from CJPL, after raw garlic in Beijing.

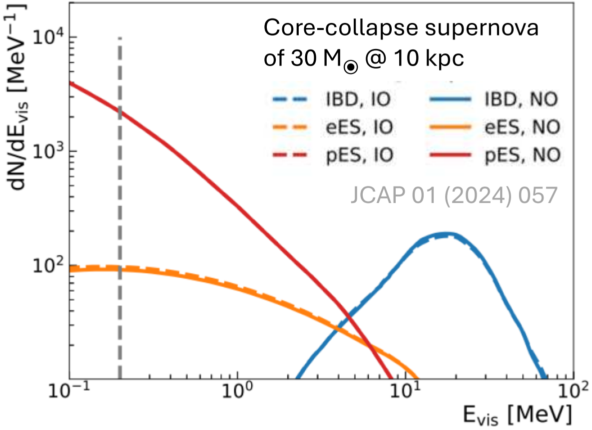
- Welcome to CJPL in August for TAUP 2025
  `https://hep.tsinghua.edu.cn/taup/`

backup

Supernova burst neutrinos

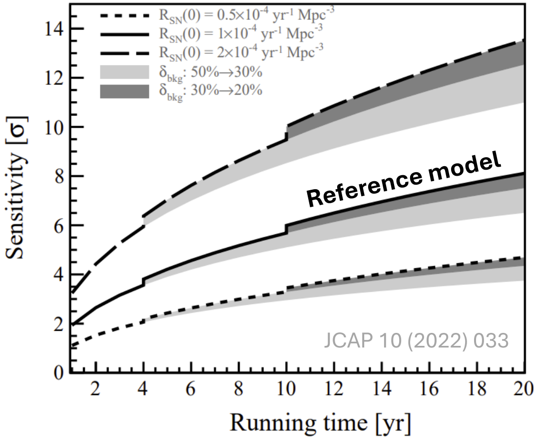
up to 10 kpc. supernova at the local cluster.

- 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

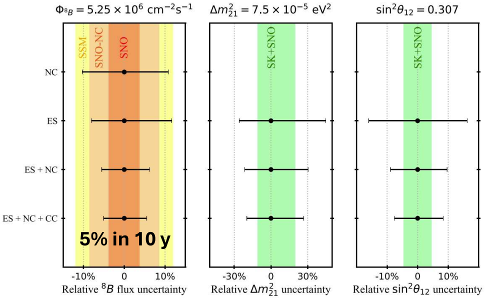
$$^{8}\mathrm{B} \longrightarrow {}^{8}\mathrm{Be}^{*} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$$

- 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}.

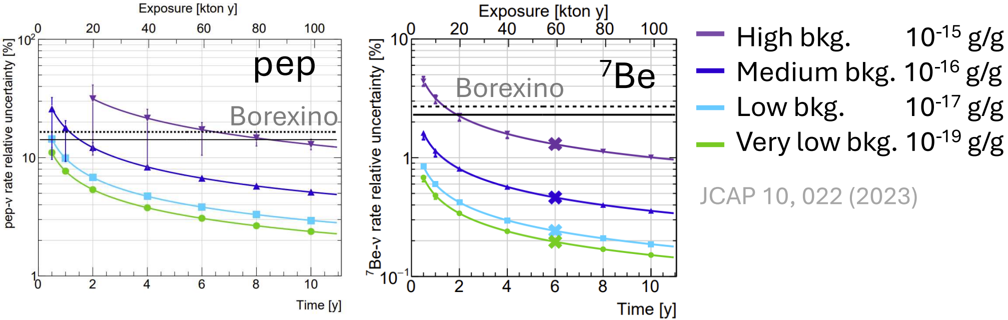
Astrophys. J. 965.2: 122 (2024)



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.

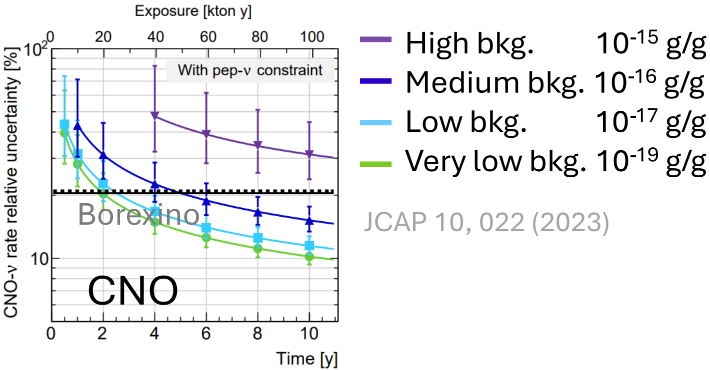


JCAP 10, 022 (2023)

Neutrinos from CNO-cycle

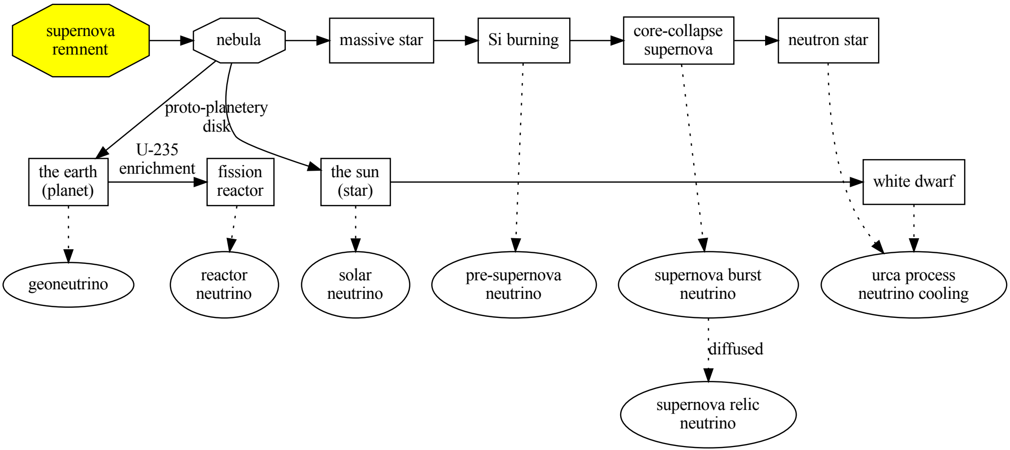
$$^{13}\mathrm{N} \longrightarrow {}^{13}\mathrm{C} + \mathrm{e}^+ + \nu_\mathrm{e}$$
$$^{15}\mathrm{O} \longrightarrow {}^{15}\mathrm{N} + \mathrm{e}^+ + \nu_\mathrm{e}$$
$$^{17}\mathrm{F} \longrightarrow {}^{17}\mathrm{O} + \mathrm{e}^+ + \nu_\mathrm{e}$$

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



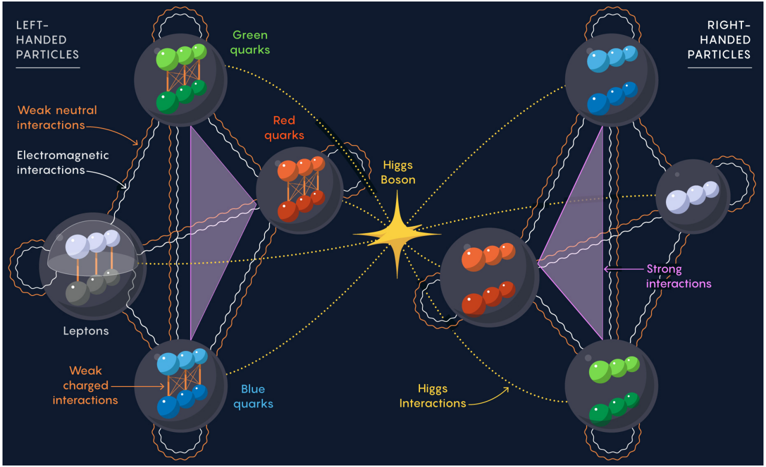
JCAP 10, 022 (2023)

Neutrinos are ubiquitous in nucleosynthesis



- ν accompany weak interactions.

The standard model of particle physics



No right-handed ν.

$$\begin{pmatrix} u_\mathrm{L} \\ d_\mathrm{L} \end{pmatrix} \Longleftrightarrow \begin{matrix} u_\mathrm{R} \\ d_\mathrm{R} \end{matrix}$$

$$\begin{pmatrix} \nu_{e\mathrm{L}} \\ e_\mathrm{L} \end{pmatrix} \Longleftrightarrow \begin{matrix} ? \\ e_\mathrm{R} \end{matrix}$$

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)

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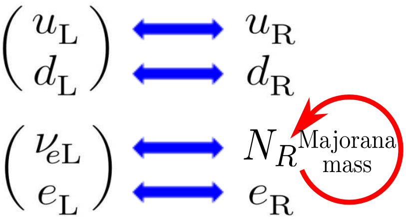

$$\mathcal{L} = \frac{1}{2} M_\mathsf{N} \overline{N_\mathsf{R}^c} N_\mathsf{R} + Y_\nu H \overline{L_\mathsf{L}} N_\mathsf{R} + \cdots + \text{h.c.}$$

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

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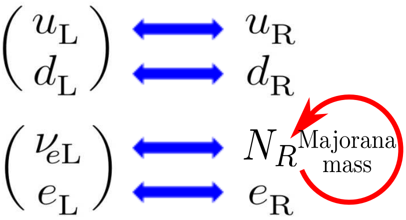

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$M_N \gg m_\nu$ is the mass of majorana right-handed ν.

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

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

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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.
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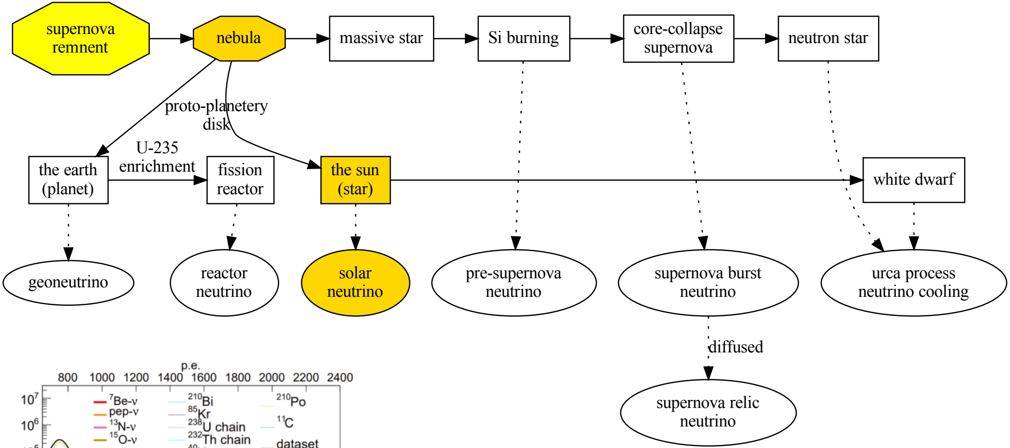
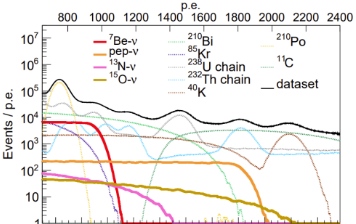
JUNO is the next milestone

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

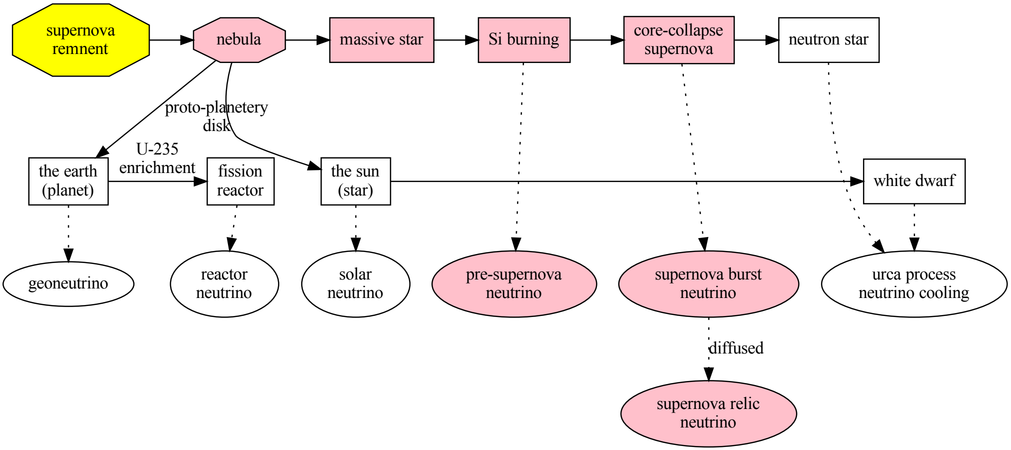
Solar ν





- 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 ~ 10 kpc;